

Title: Light Shows from Supermassive Binary Black Hole Mergers

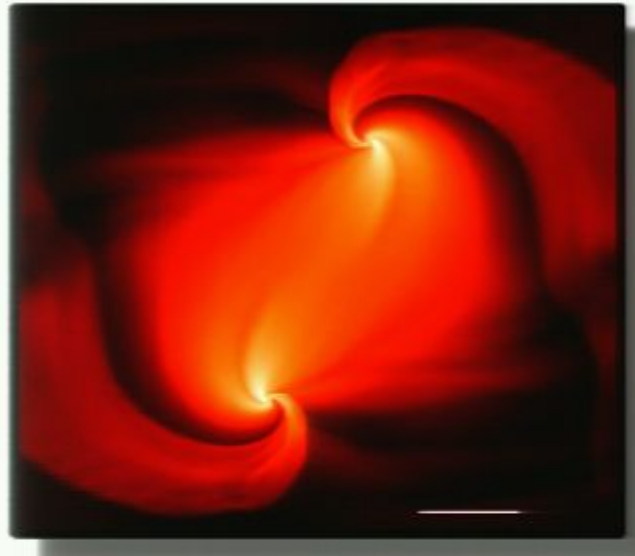
Date: Apr 08, 2010 01:00 PM

URL: <http://pirsa.org/10040002>

Abstract: Coincident detections of electromagnetic and gravitational wave signatures from the merger of supermassive binary black holes are the next observational grand challenge. Such detections will provide a wealth of opportunities to study gravitational physics, accretion physics, and cosmology. Understanding the conditions under which coincidences of electromagnetic and gravitational wave signatures arise during supermassive black hole mergers is therefore of paramount importance, requiring multi-scale/physics computational modeling. I will give an overview of these numerical studies and in particular focus on our effort to model the merger of supermassive black hole binaries in the presence of gaseous environments.

Light Shows from Supermassive Binary Black Hole Mergers

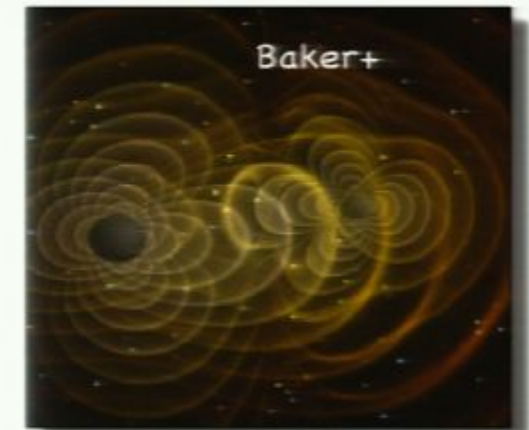
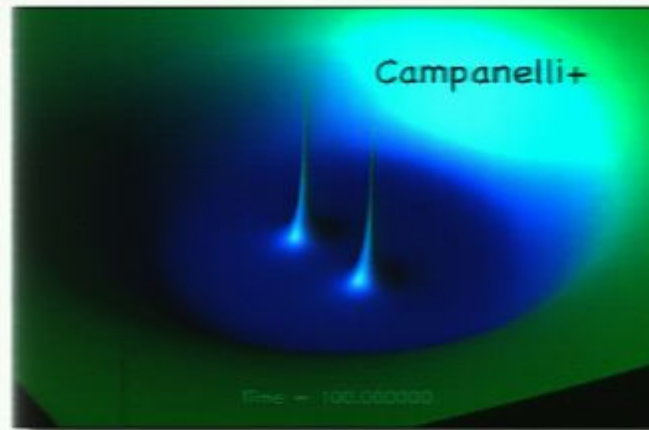
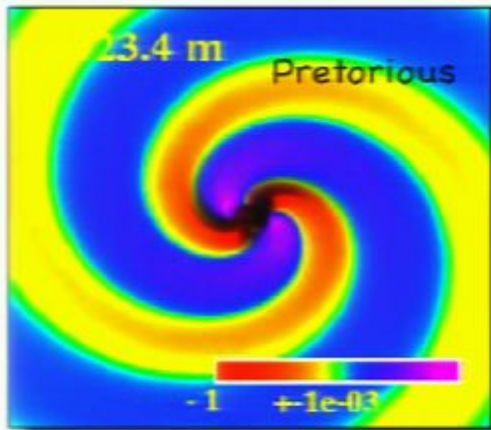
Pablo Laguna
Center for Relativistic Astrophysics
Georgia Tech



Collaborators:

Tanja Bode, Tamara Bogdanovic (Maryland), Roland Haas, Deirdre Shoemaker

Numerical Relativity Breakthroughs



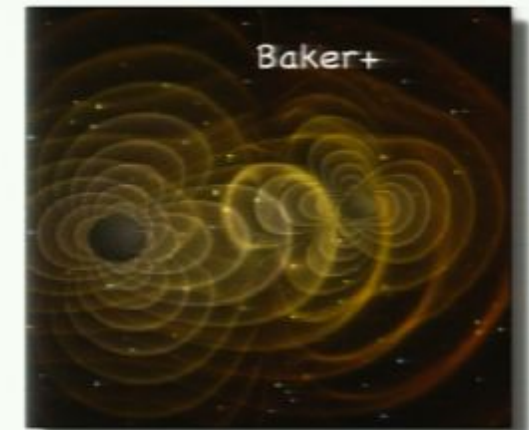
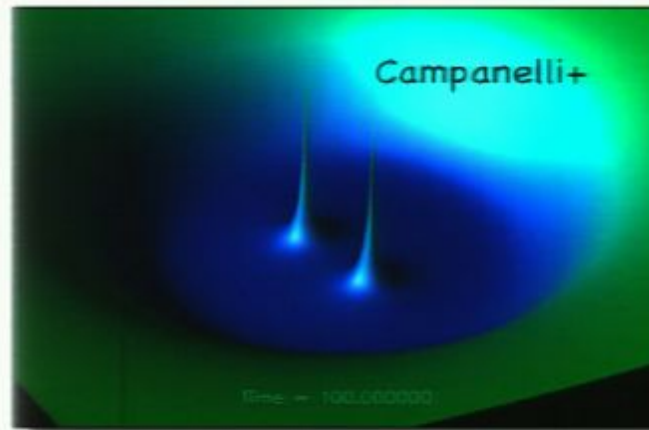
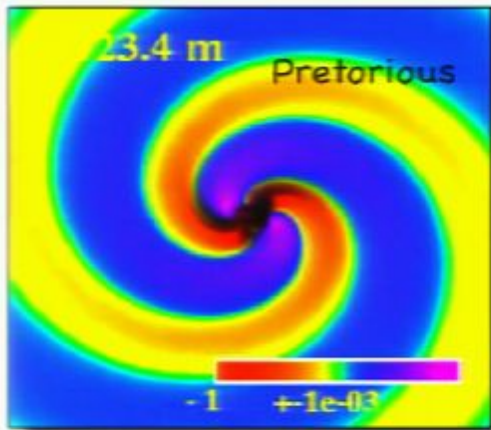
Pretorius, PRL 95, 121101 (2005)

Campanelli, Lousto, Marronetti, and Zlochower, PRL 96, 111101 (2006)

Baker, Centrella, Choi, Koppitz, and Van Meter, PRL 96, 111102 (2006)



Numerical Relativity Breakthroughs



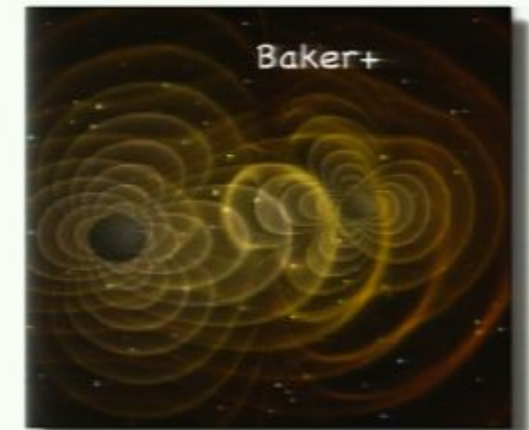
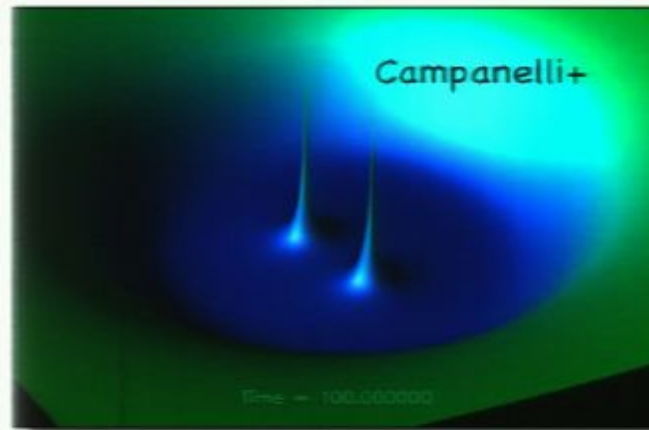
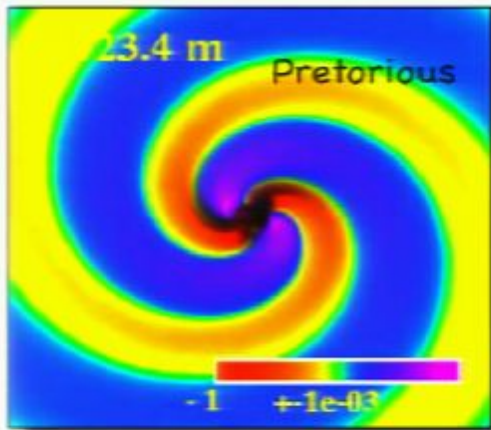
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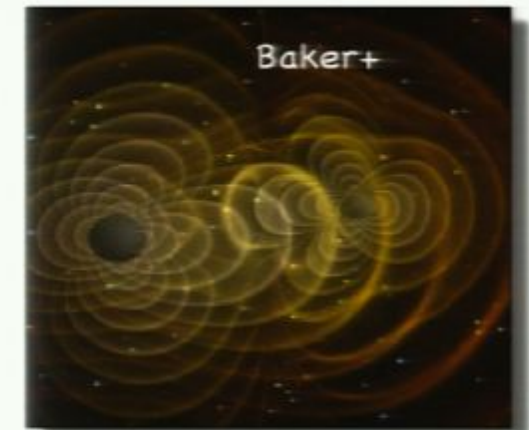
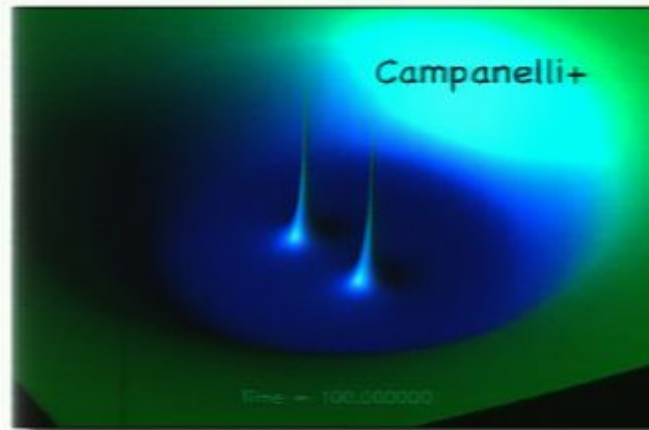
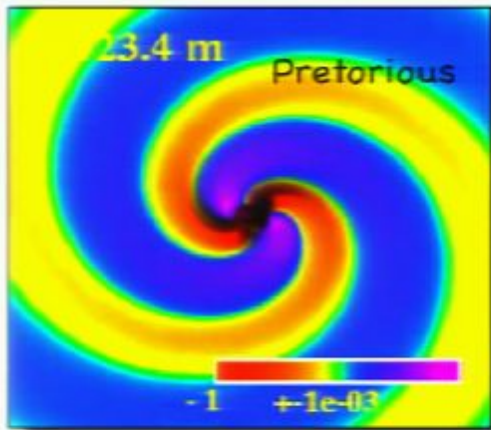
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Numerical Relativity Breakthroughs



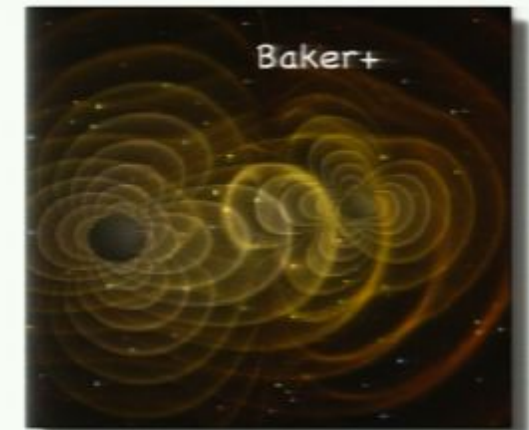
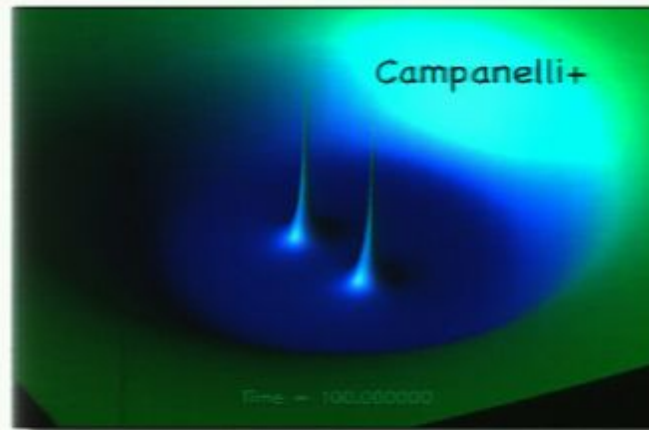
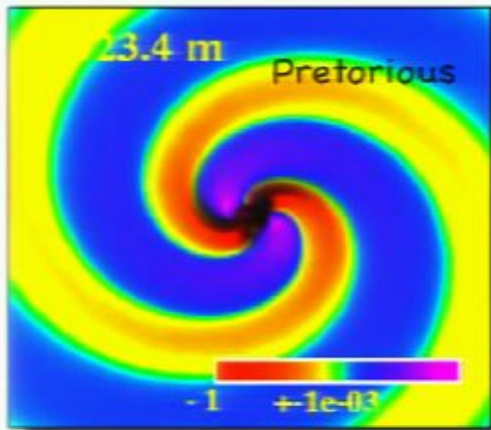
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Numerical Relativity Breakthroughs



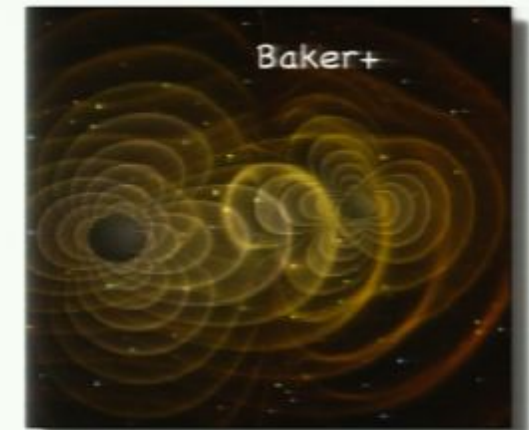
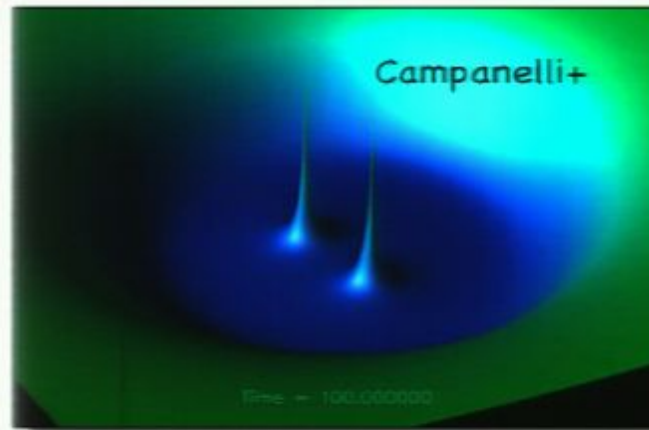
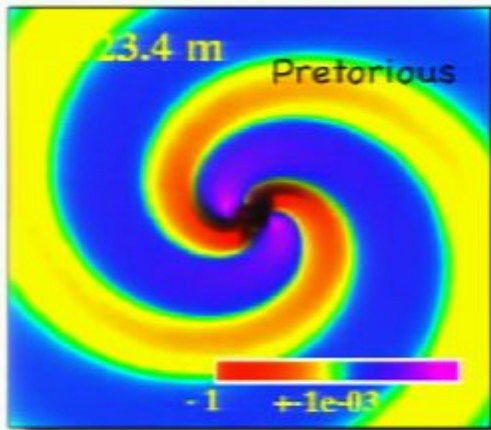
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Numerical Relativity Breakthroughs



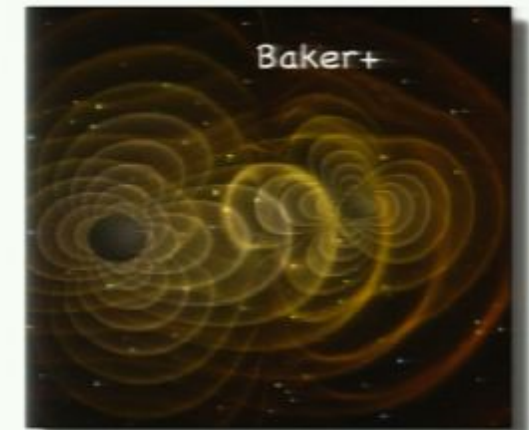
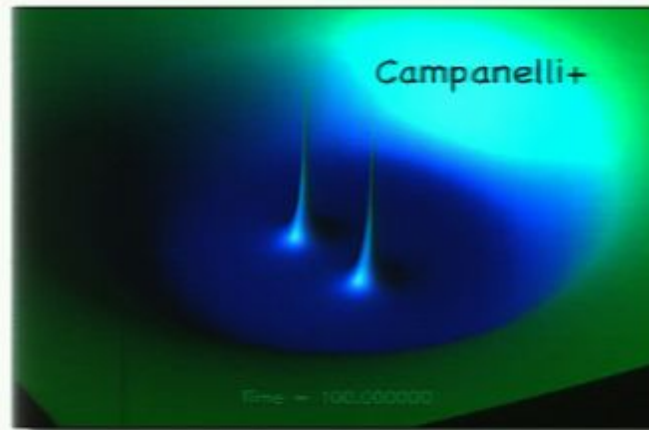
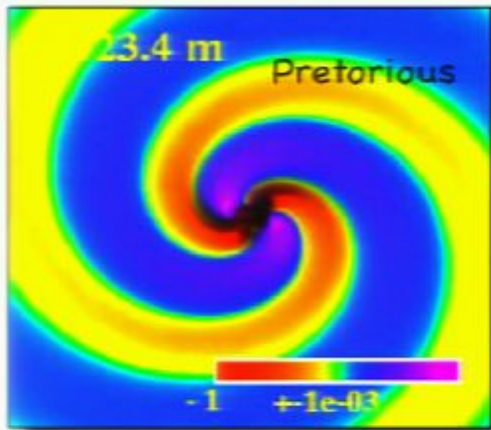
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Numerical Relativity Breakthroughs



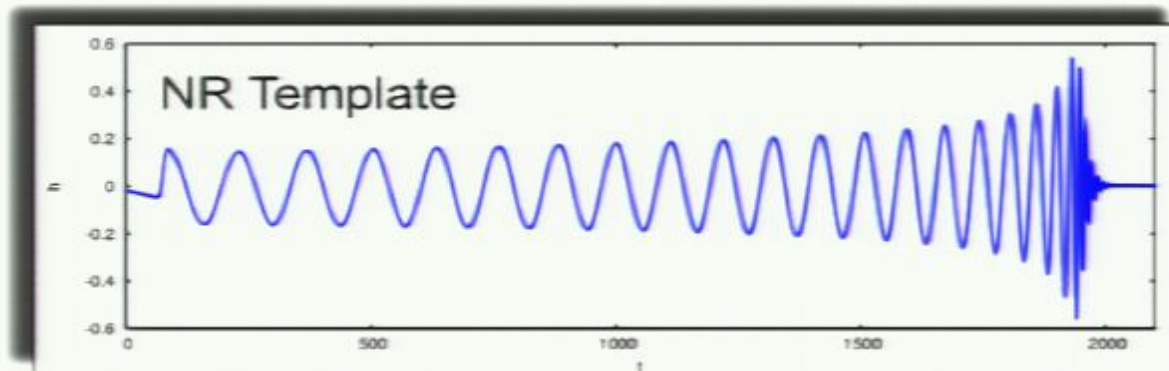
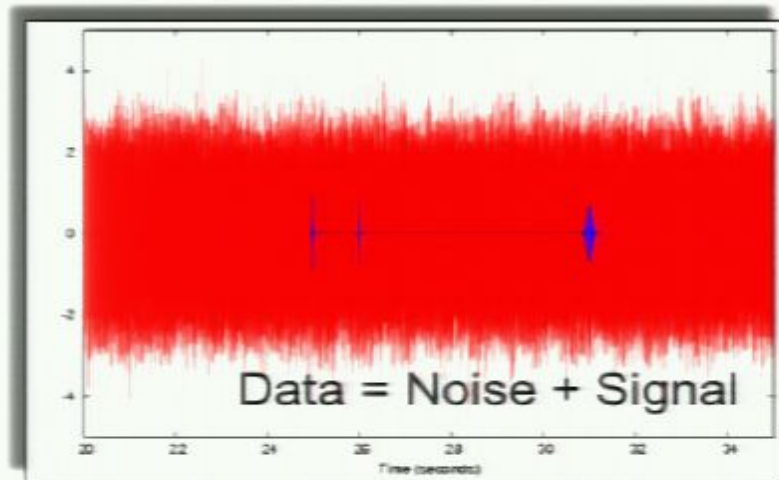
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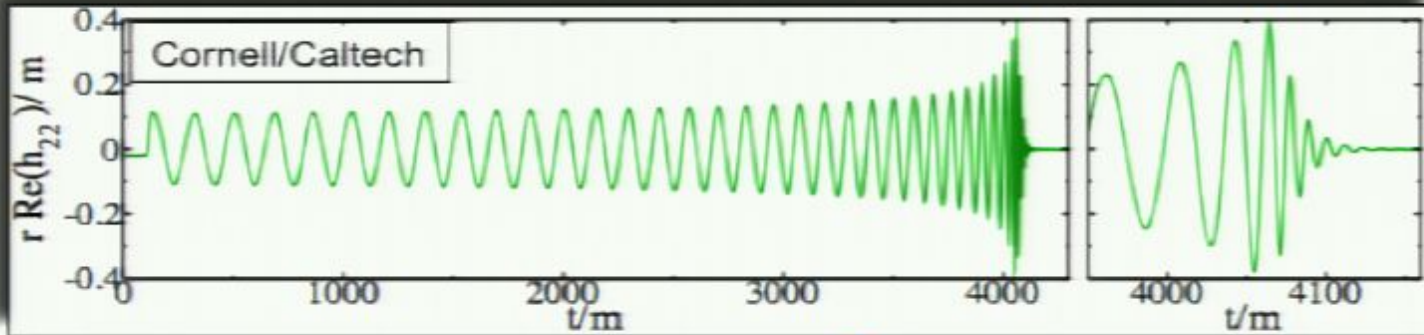
The Driving Force in Gravitational Physics Modeling



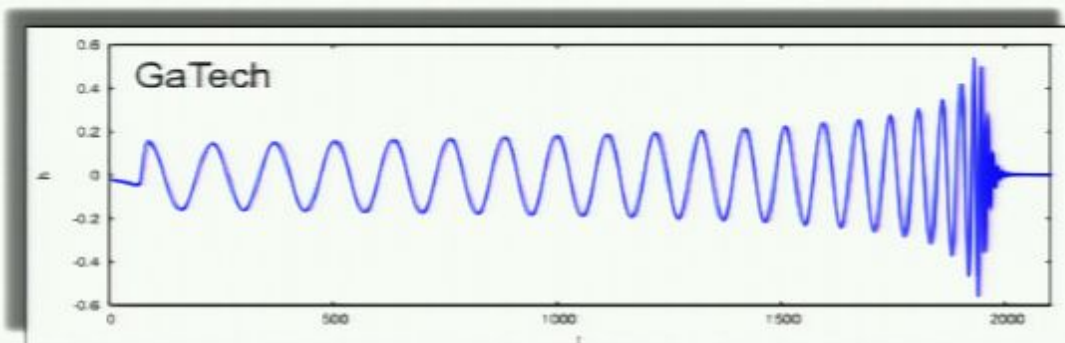
Without the input from numerical relativity, detection and characterization of sources will be very difficult.

Binary Black Hole Codes Today

Multiple codes and approaches:
Ensuring that results are right!

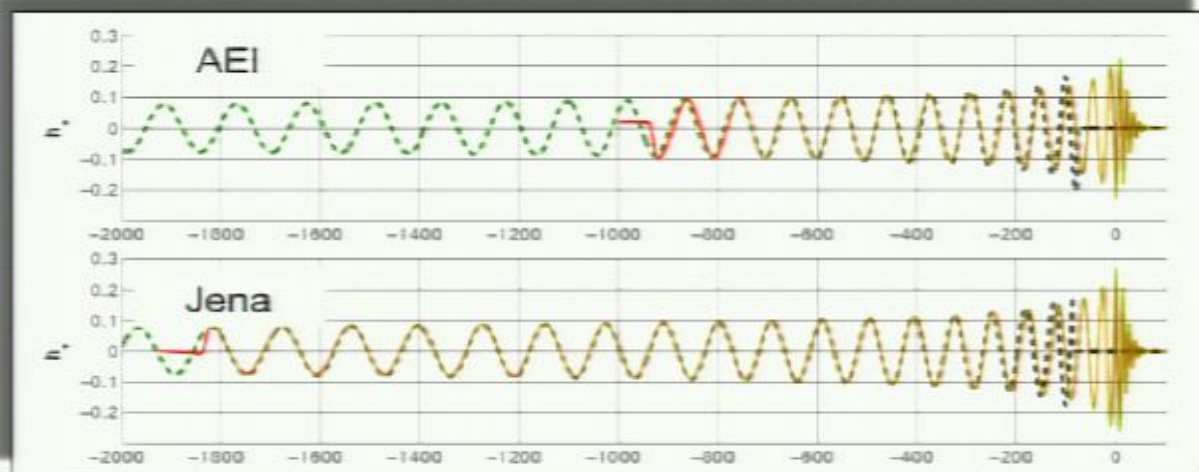


Harmonic formulation +
pseudo-spectral methods



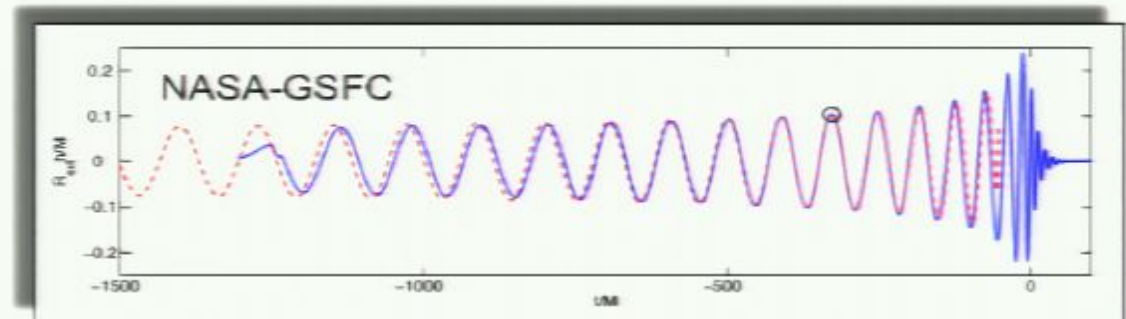
BSSN formulation +
finite difference methods

Beyond Numerical Relativity Templates

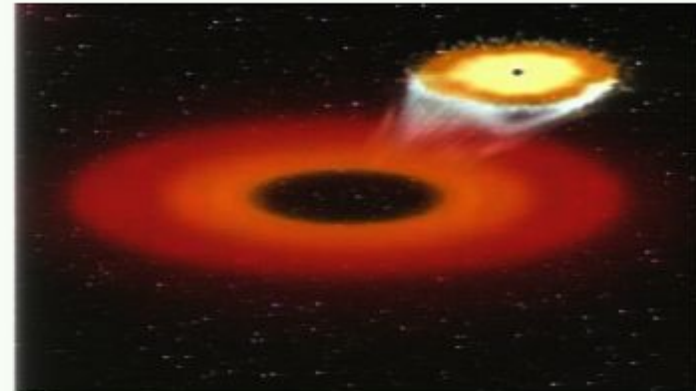
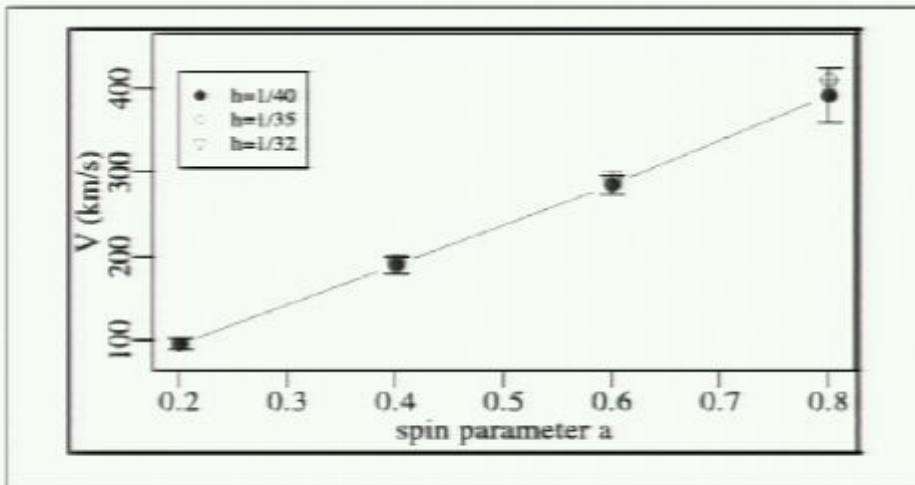


Comparisons with
Post-Newtonian:
Finding the limits
of validity!

NRAR & NINJA
Collaborations:
building the best
analytical template
family & interfacing
with data analysts.



Gravitational Recoil or BH kicks

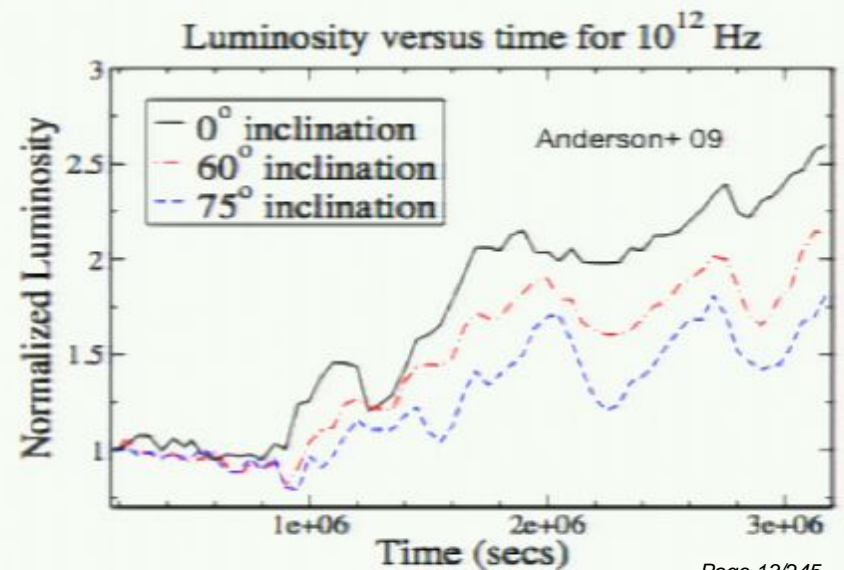


Herrmann, Hinder, Shoemaker, Laguna, Matzner, ApJ 661430 (2007)

Superkicks ~ 2,400 km/s

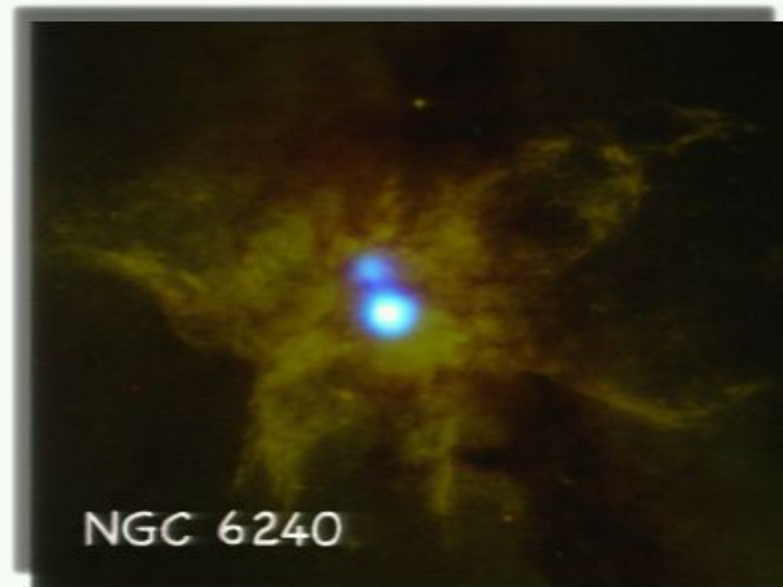
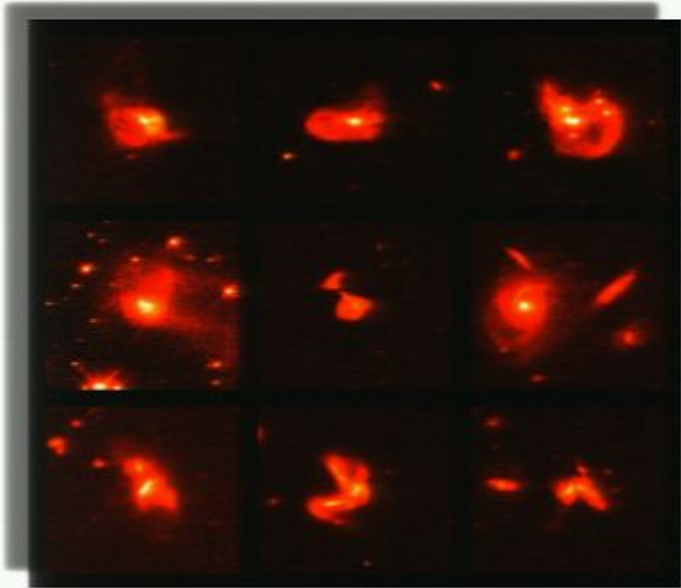
Sperhake+ 08 & Campanelli+ 08

Electromagnetic signature: a recoiling black hole changes abruptly the gravitational potential the gas probes



Supermassive BH Mergers

Galaxies merge and very often host a massive BH, leading to massive BHs coalescences.



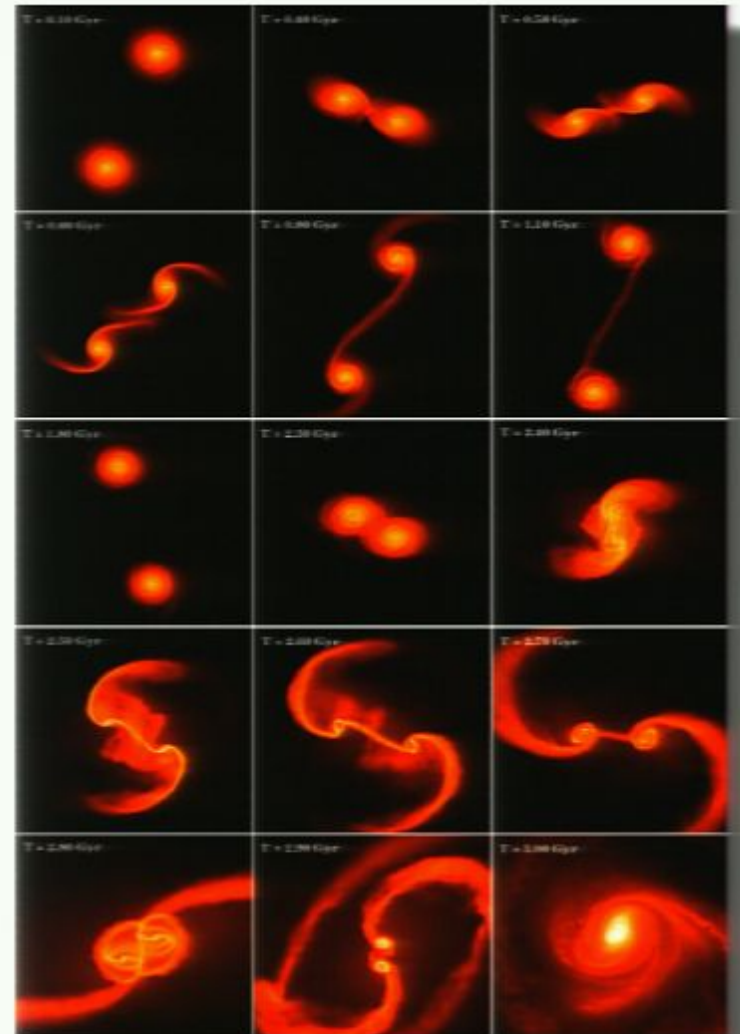
X-ray: NASA/CXC/MPE/S.Komossa et al.; Optical: NASA/STScI/R.P.van der Marel & J.Gerssen

- Galaxy mergers scales: hundred kpc scales
- BH binaries scales: few pc when binding and AU near coalescence
- How do BHs reach the gravitational wave inspiral regime?
- It depends on the environment

SMBBH History in Gas-rich Environments

STAGE I:

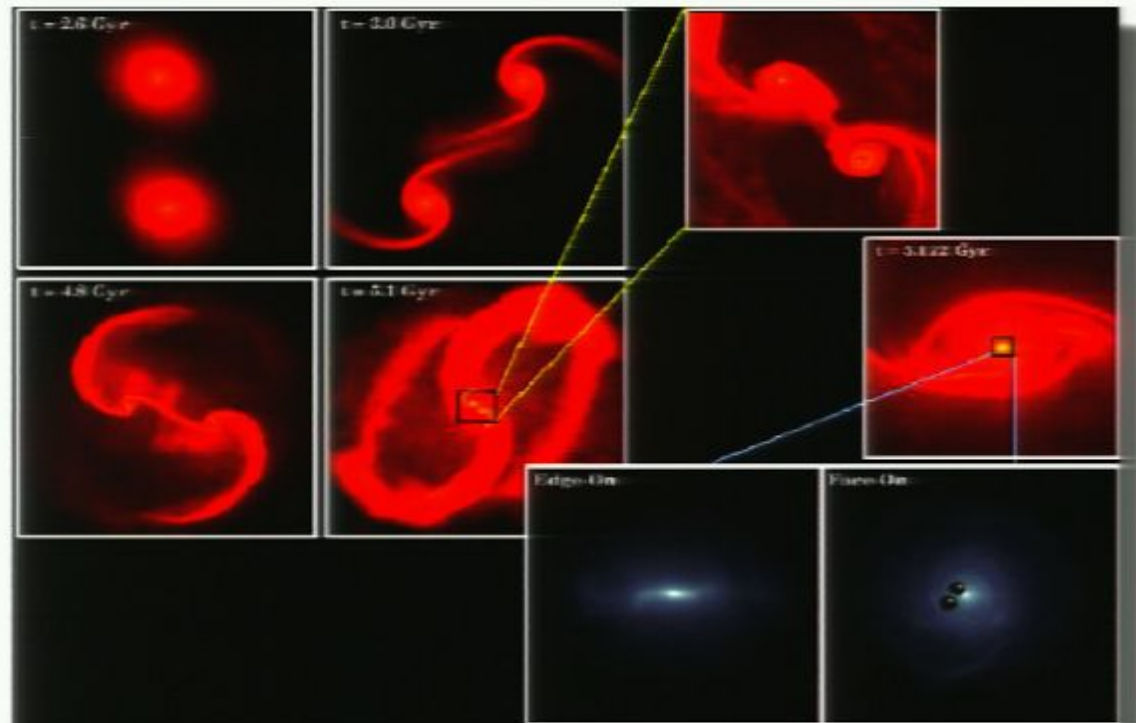
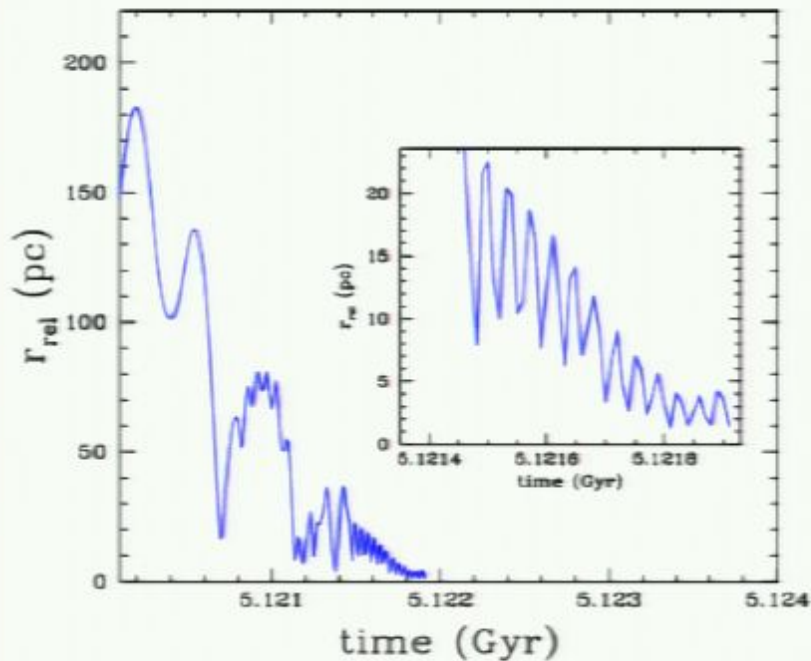
- Galactic cores drag the BHs with them.
- Each BH (e.g. $10^6 M_{\text{sun}}$) is surrounded by a stellar and gaseous disk ($10^8 M_{\text{sun}}$).
- Disk merge, and gas-dynamical friction sinks the BHs to the center.



SMBBH History in Gas-rich Environments

STAGE II ($r_{\text{sep}} < 10.0$ pc) :

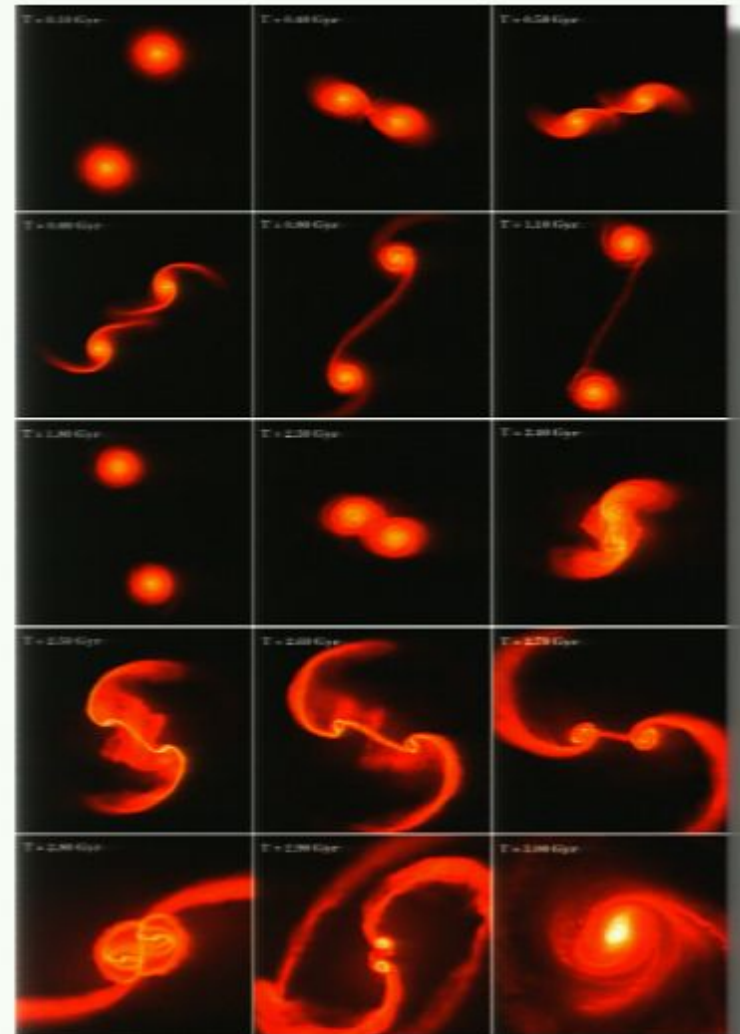
When the mass within their separation is less than the binary mass, the BHs bind and form a Keplerian binary.



SMBBH History in Gas-rich Environments

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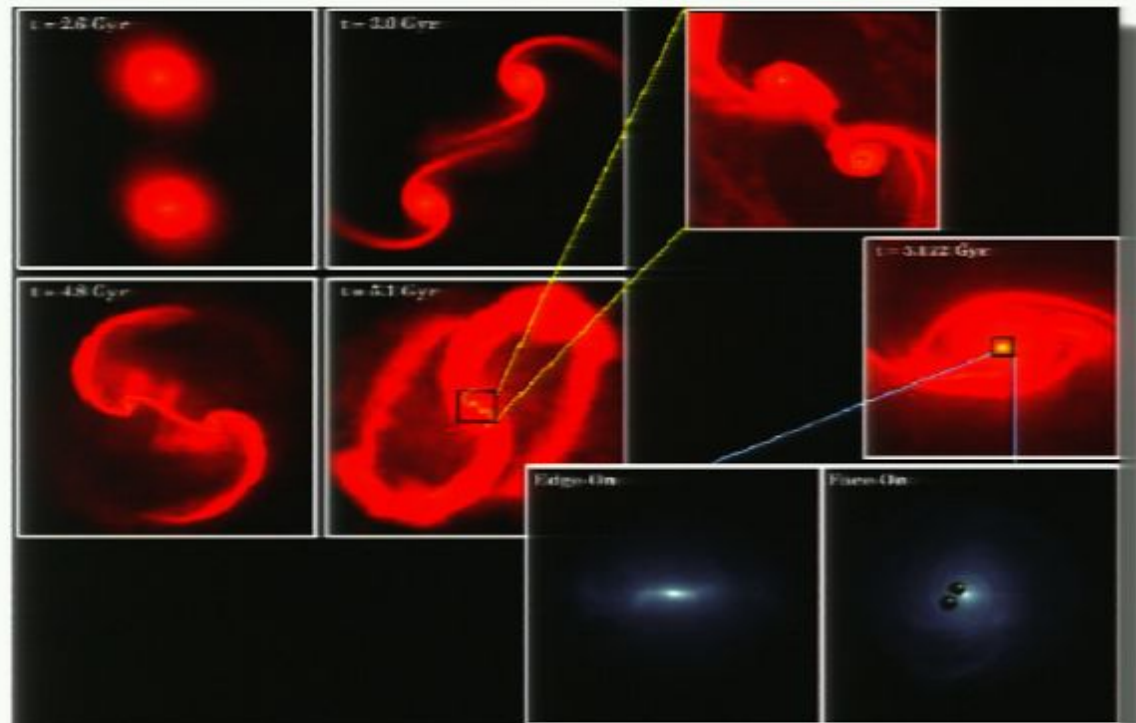
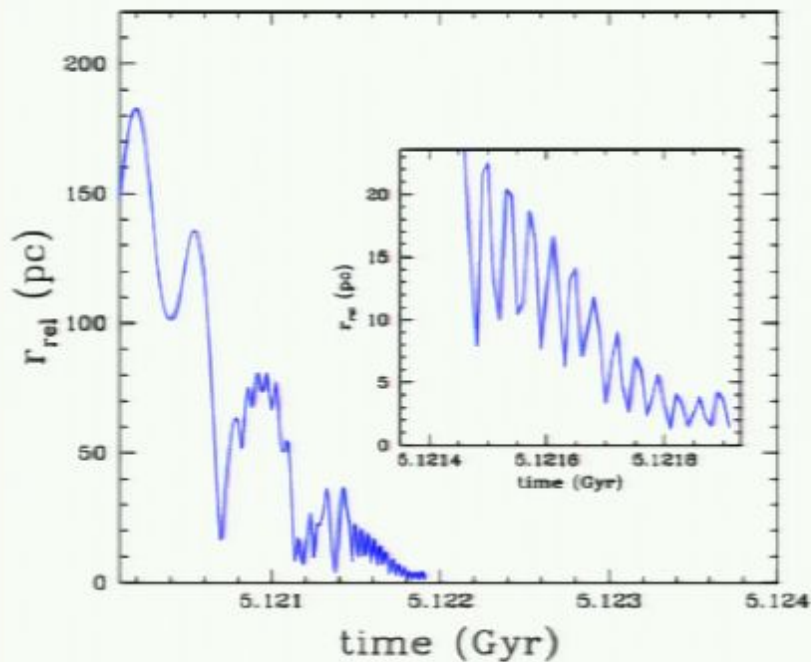
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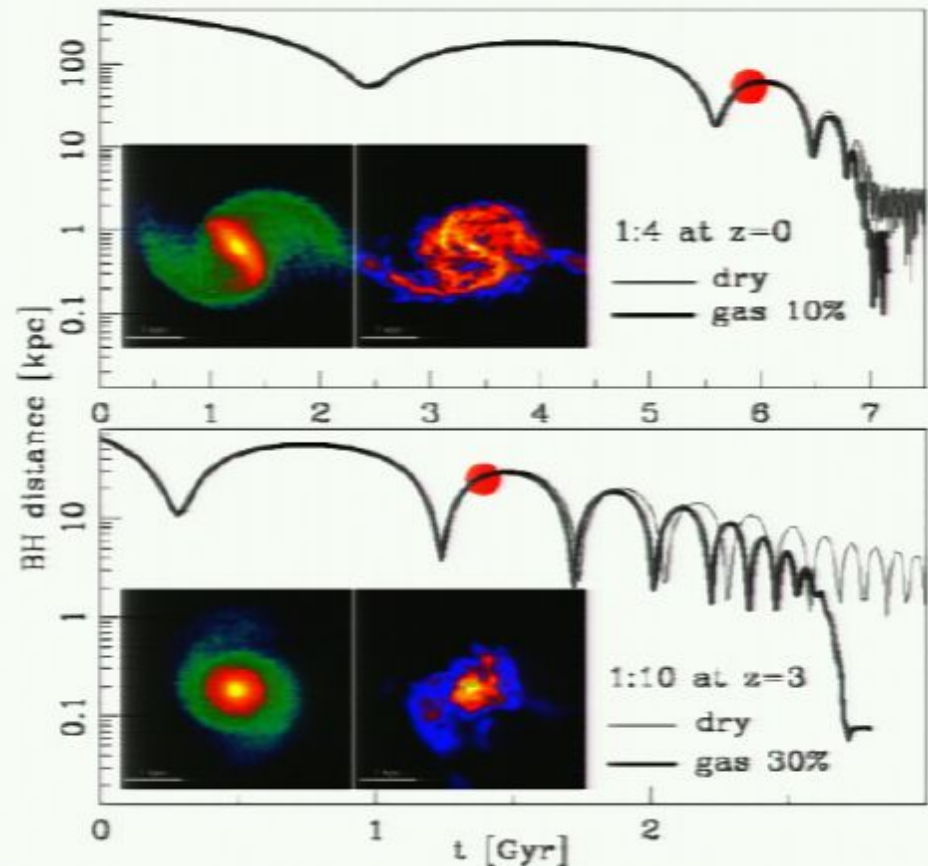
When the mass within their separation is less than the binary mass, the BHs bind and form a Keplerian binary.



SMBBH History in Gas-rich Environments

STAGE III ($r_{\text{sep}} < 1.0$ pc) :

- 3-body interactions with the surrounding stars also contributes to shrink the BBH separation.
- However, shrinking stalls when reservoir of stars is depleted.

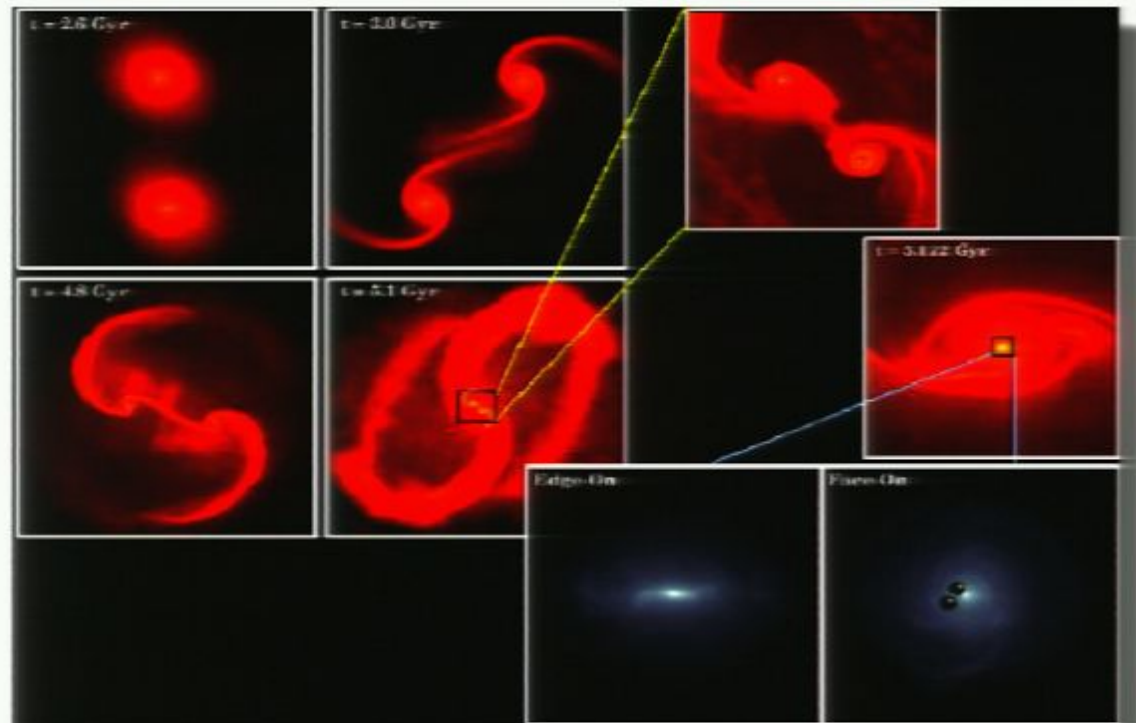
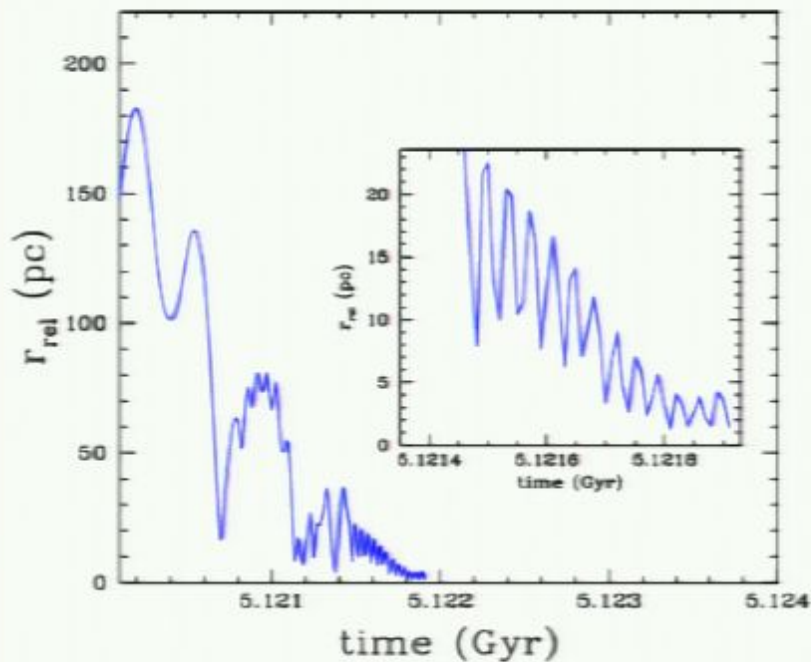


Colpi, Calleggeri, Dotti & Mayer

SMBBH History in Gas-rich Environments

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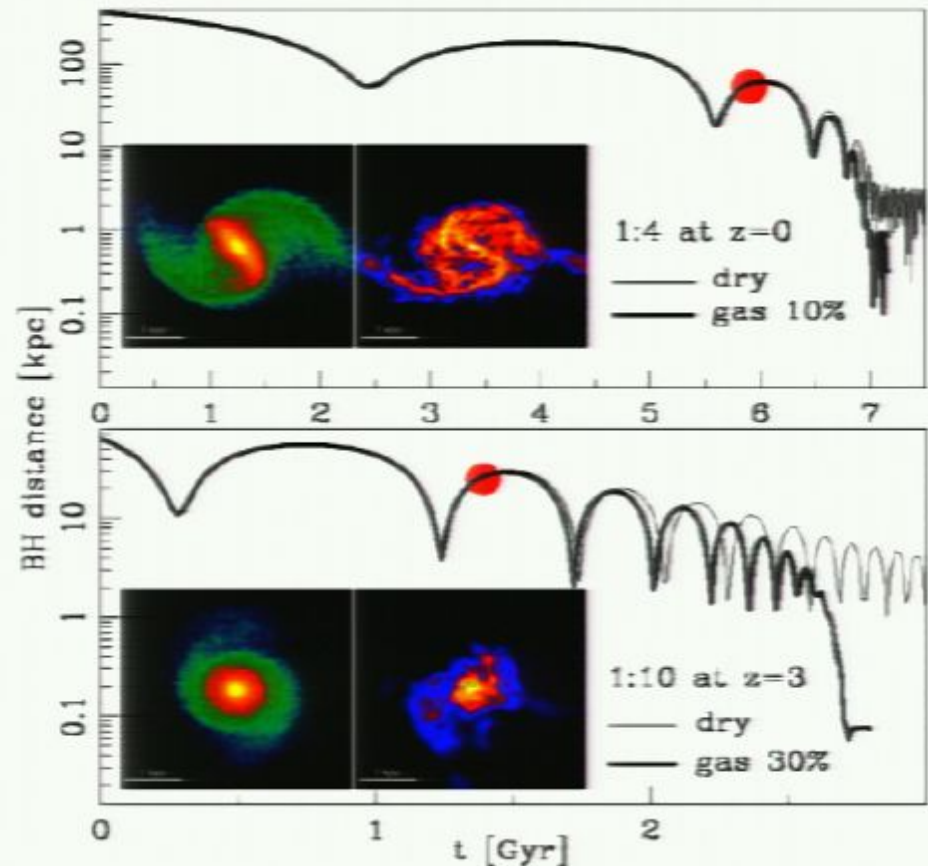
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SMBBH History in Gas-rich Environments

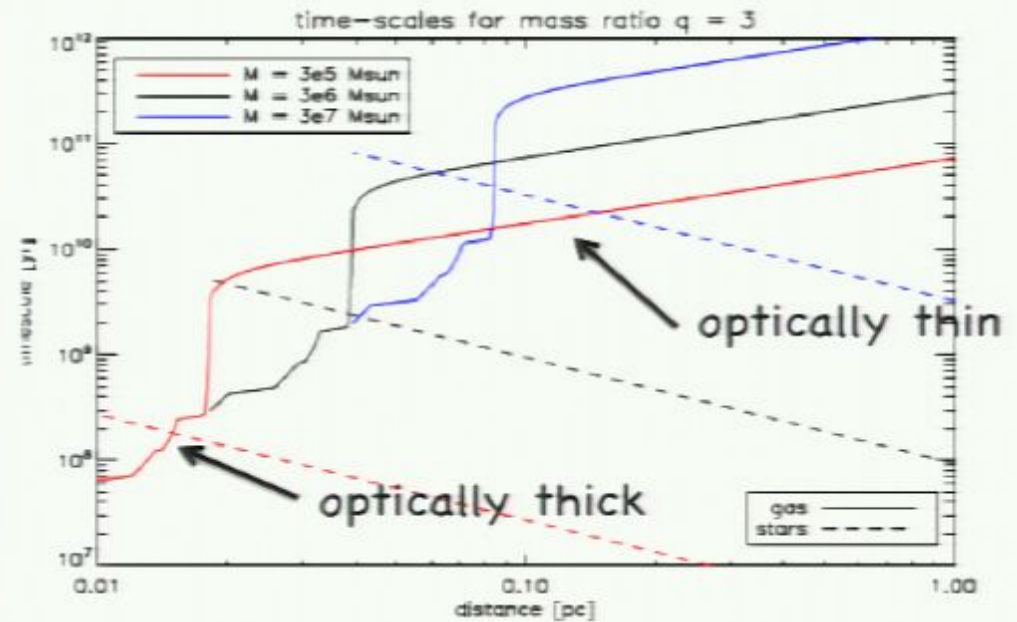
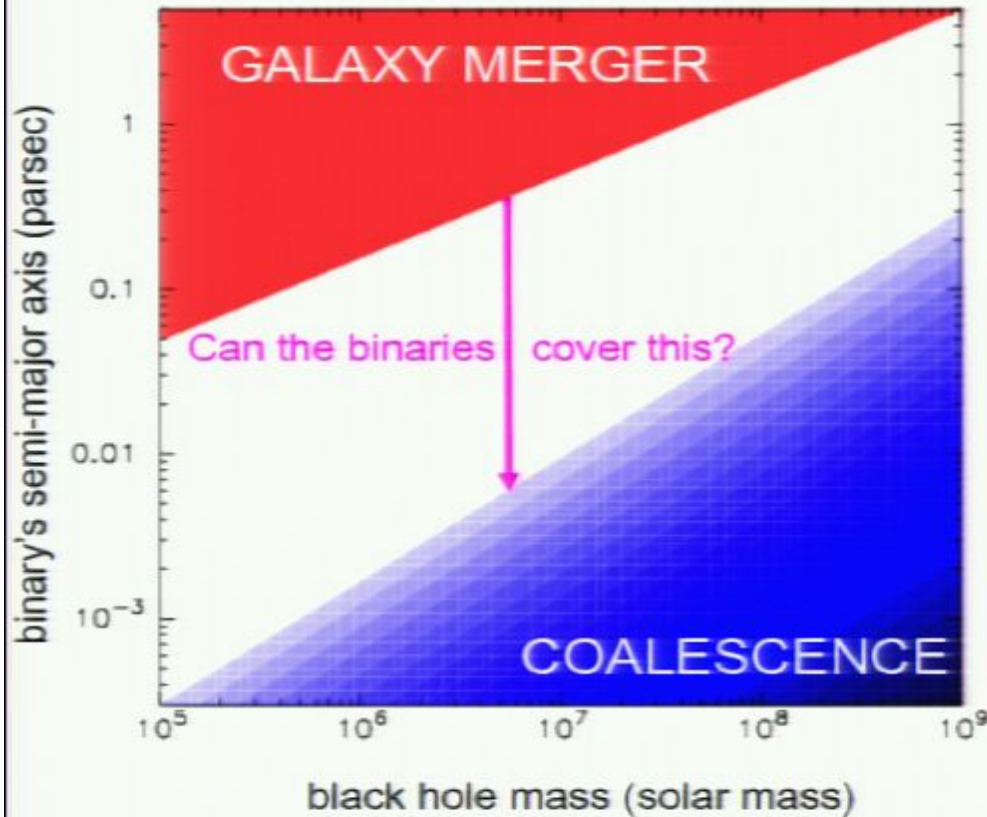
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Colpi, Calleggeri, Dotti & Mayer

The Last Parsec Problem



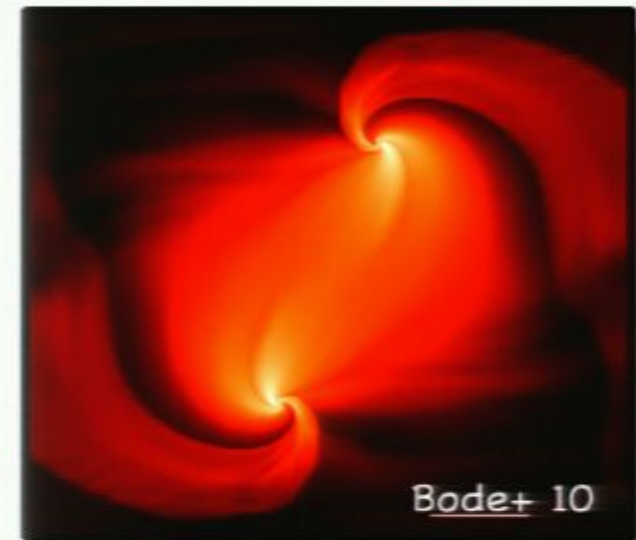
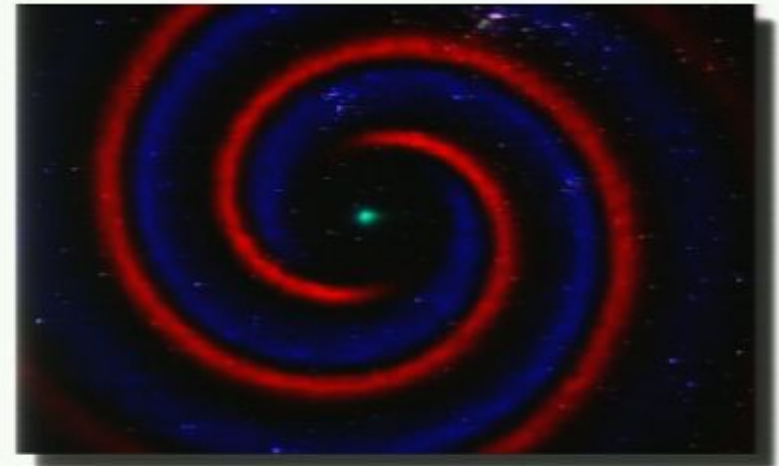
Disk assisted binary shrinkage:

- Requires a geometrically-thin circum-binary accretion disk.
- More effective for un-equal mass binaries.

SMBBH History in Gas-rich Environments

STAGE IV ($r_{\text{sep}} < 10^{-3}$ pc):

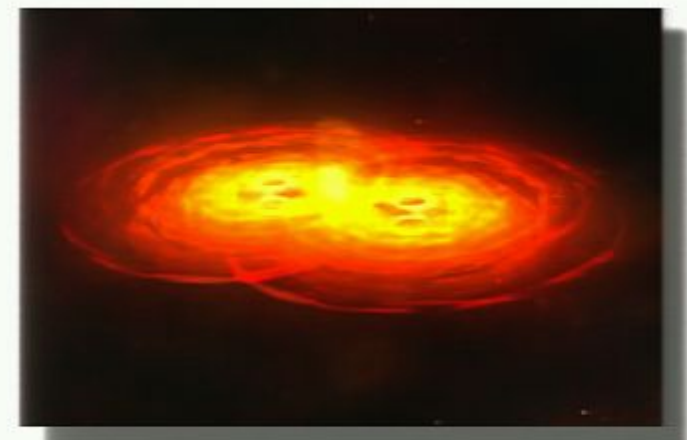
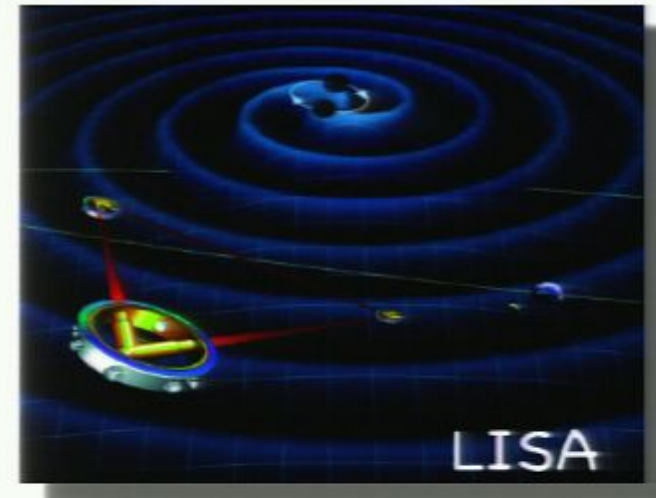
- Gravitational radiation dominates the BBH dynamics.
- The most luminous sources of gravitational radiation in the universe ($\sim 10^{57}$ erg s $^{-1}$)
- The coalescence could in addition produce a variable or transient EM signal.
- A unique opportunity for multi-messenger astrophysics.



Synergy of EM & GW signatures

EM + GW Observations:

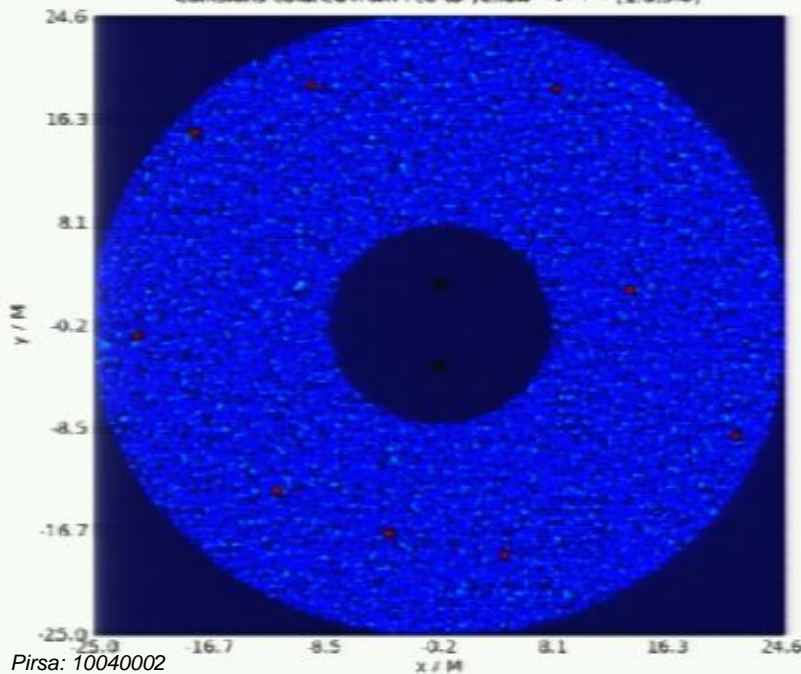
- Improves sky localization
- Rates of detection for GW experiments
- Luminosity distance (GWs) and redshift (EM) yields cosmological standard sirens.
[D. E. Holz and S. A. Hughes, Astrophys. J. 629, 15 \(2005\)](#)
- BH accretion physics. [B. Kocsis, Z. Frei, Z. Haiman, and K. Menou, Astrophys. J. 637, 27 \(2006\)](#)
- Test ground for GR (e.g. graviton's speed) [B. Kocsis, Z. Haiman, and K. Menou, Astrophys. J. 684, 870 \(2008\)](#)



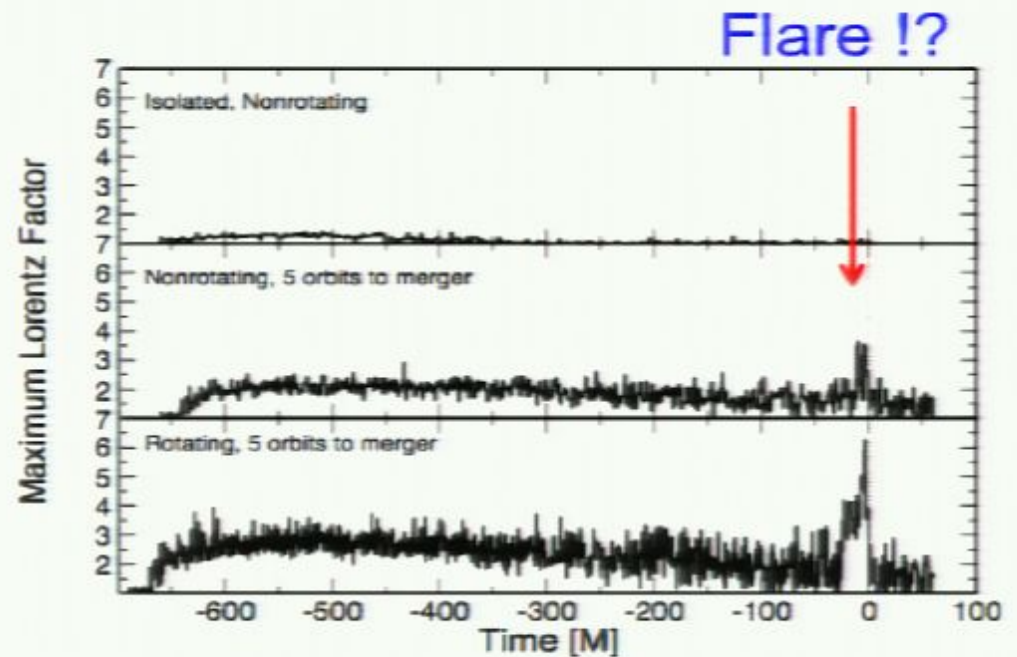
Modeling Matter in the Vicinity of BH Mergers

- **Goal:** For astrophysical relevant systems, one only need to model gas and magnetic fields in the *dynamical* spacetime of merging BHs
- **First step:** Map the flow of test particles around the merging BHs and estimate energetics of the flow from “collisions”
- **Setup:** 25,000 particles, uniformly distributed, velocities Keplerian with random directions

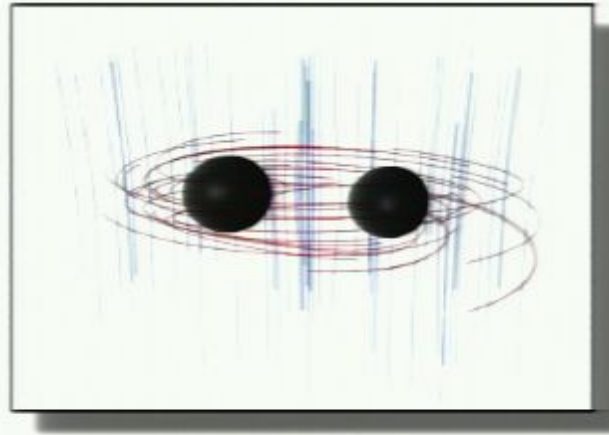
QC6, Thermal, All collisions :: Time = 0.00
Collisions colored from red to yellow => $\gamma = [1.0, 5.0]$



Pirsa: 10040002



SMBH Mergers Surrounded by EM Fields



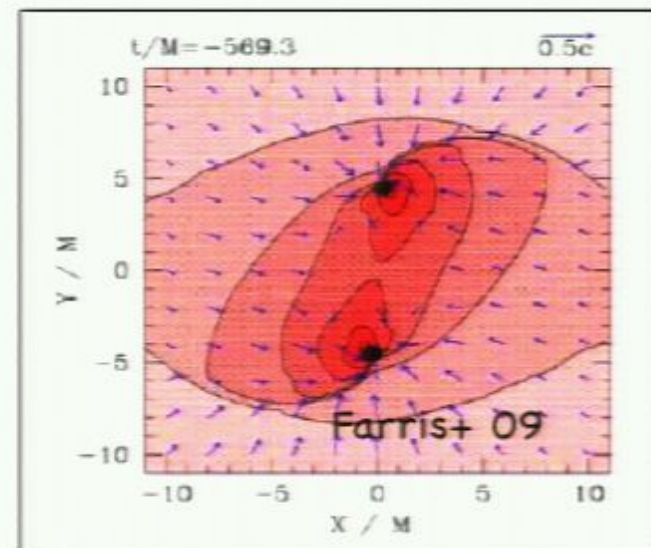
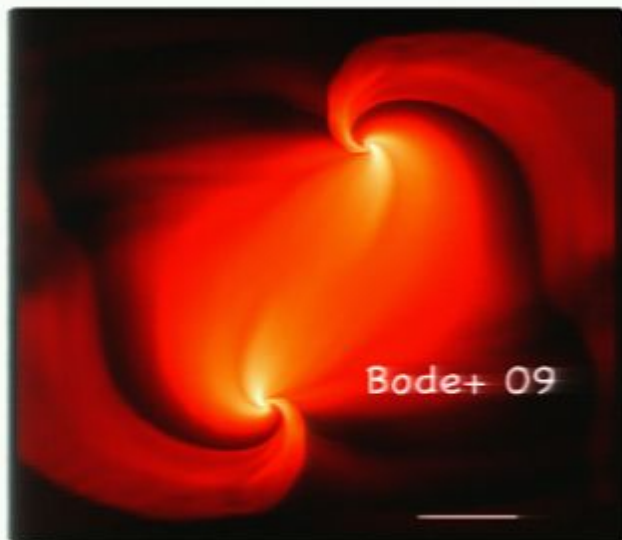
(Palenzuela+ 09a, 09b; Mösta+ 09)

$$\frac{E_{em}}{E_{gw}} \approx 10^{-13} \left(\frac{M}{10^8 M_{\odot}} \right)^2 \left(\frac{B}{10^4 \text{ G}} \right)^2$$

$$f_{em} \approx 10^{-4} \left(\frac{M}{10^8 M_{\odot}} \right)^{-1} \text{ Hz}$$

- Unlikely that this EM emission can be detected directly.
- The EM emission could be observable indirectly from its effects on the BH accretion rate.

SMBH Mergers Surrounded by Gas



Relativistic Mergers of Supermassive Black Holes and their Electromagnetic Signatures
Bode, Haas, Bogdanovic, Laguna, Shoemaker,
arXiv:0912.0087

Binary Black Hole Mergers in Gaseous Environments: "Binary Bondi" and "Binary Bondi-Hoyle-Lyttleton" Accretion
Farris, Liu, Shapiro
arXiv:0912.2096

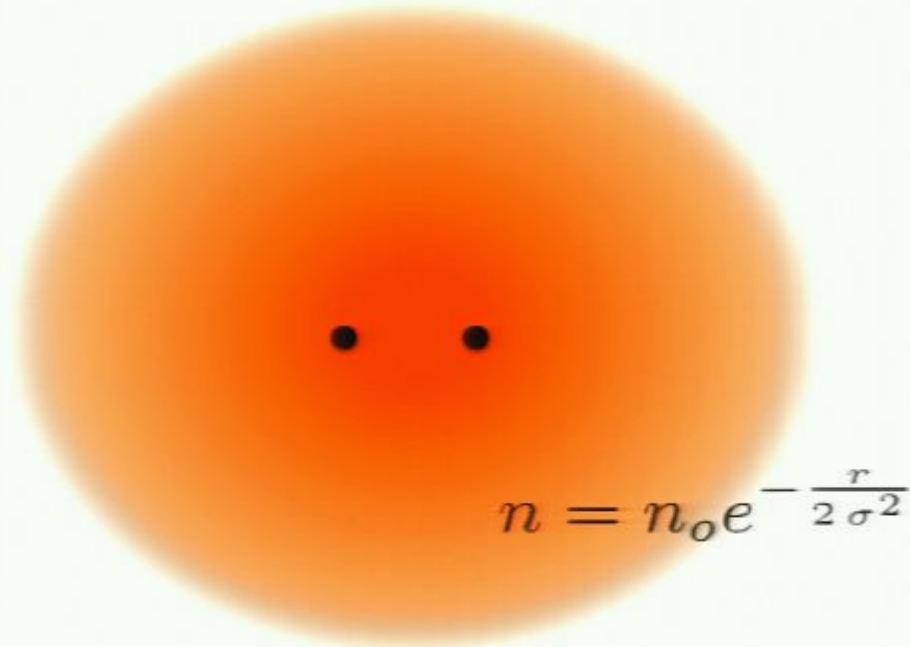
What is the environment in the vicinity of BBHs?

- Not well know at scales $< 0.01 \text{ pc}$
- Two physically motivated scenarios depending on the balance of heating and cooling:

Gas Cloud Model: If cooling is inefficient, the BBH is immersed in a pressure supported, geometrically thick torus or cloud.

Circumbinary Disk Model: If cooling is relatively efficient, the gas settles into a rotationally supported geometrically accretion disk around the BBH.

We focus on the gas cloud case



Computational Infrastructure (MayaKranc):

- BSSN form of Einstein Eqs
- 4 & 6 order accurate FD
- CACTUS (parallelization)
- CARPET (AMR, 9 levels)
- WHISKY (Hydro)
- Horizon trackers
- BH spin from killing vectors

$$M = 10^7 M_\odot$$

$$d = 8 M = 10^{-5} M_7 \text{ pc}$$

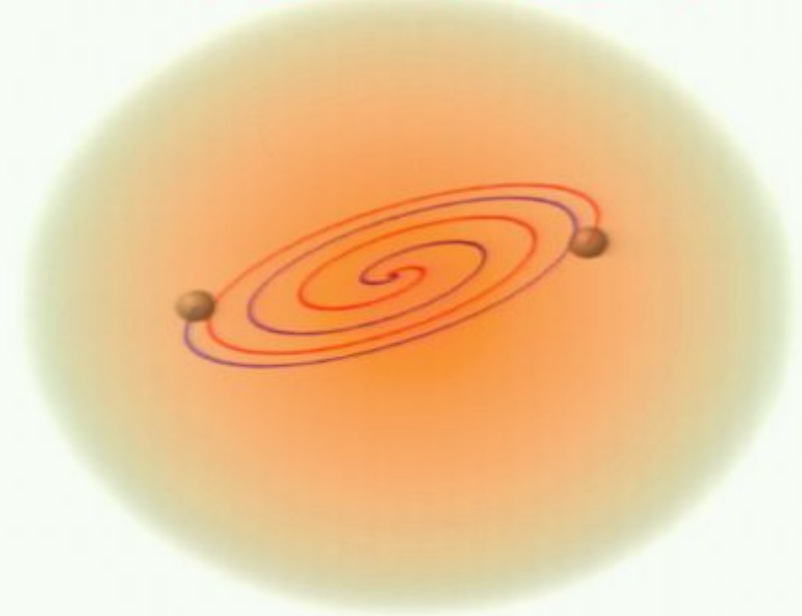
$$n_0 = 4 \times 10^{12} M_7^{-2} \text{ cm}^{-3}$$

$$T_e = 10^{10} \text{ K}^\circ$$

Relativistic mergers of SMBHs

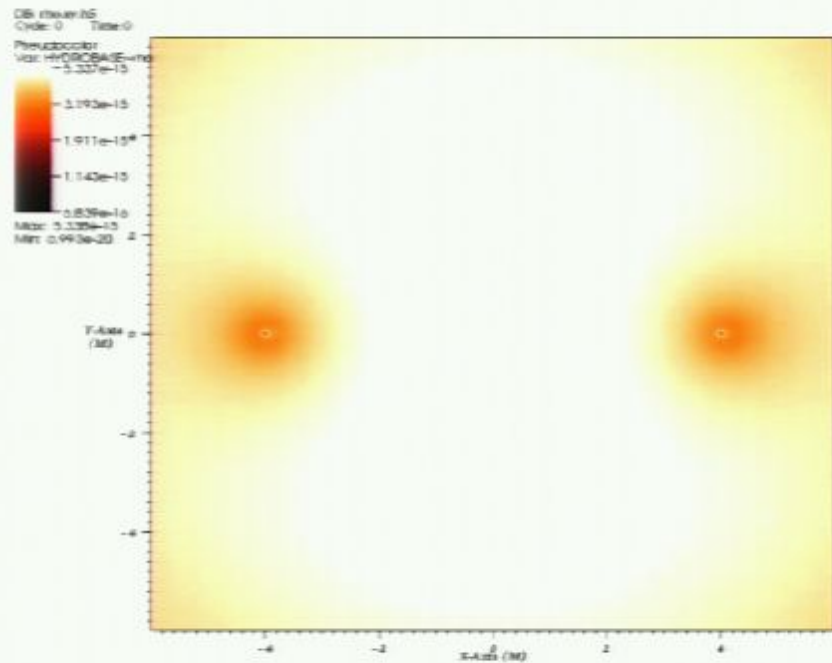
(Bode+ arXiv:0912.0087)

- Fully relativistic hydro study
- Late inspiral and merger
- Equal mass, spinning SMBHs
- Initial BH separation of $8M$
- Surrounded by hot gas ($T_p \sim 10^{12}K$)
- Radiatively inefficient accretion flow (opposite of the circumbinary disk)
- No AGN feedback, no magnetic fields, no radiative transfer.

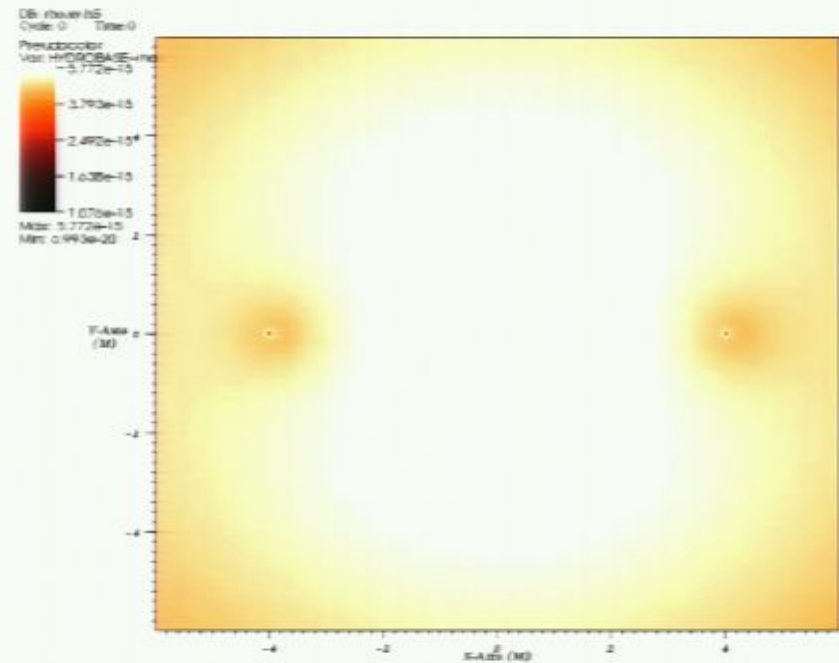


runs	S ₁	S ₂
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

Gas Density

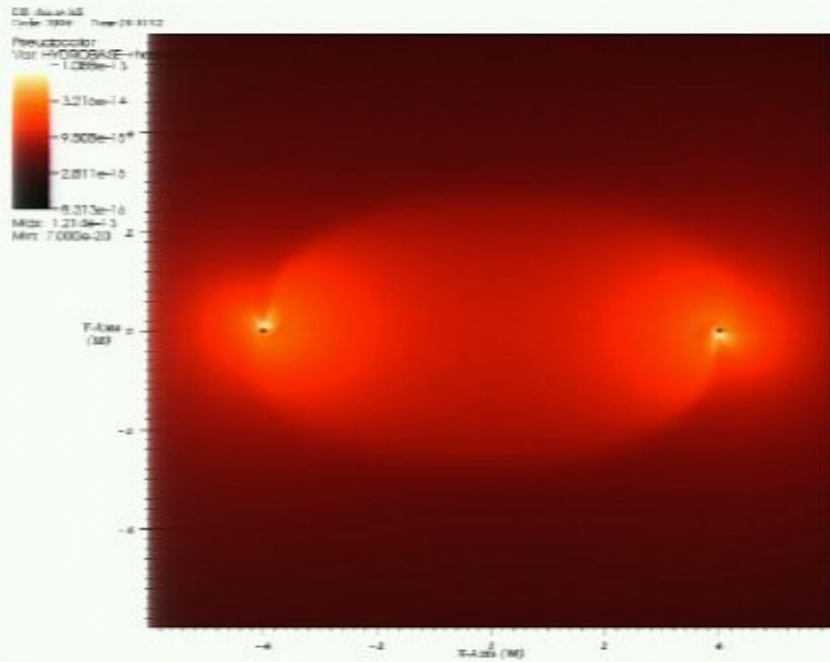


$$s_1/m^2 = s_2/m^2 = 0.6$$

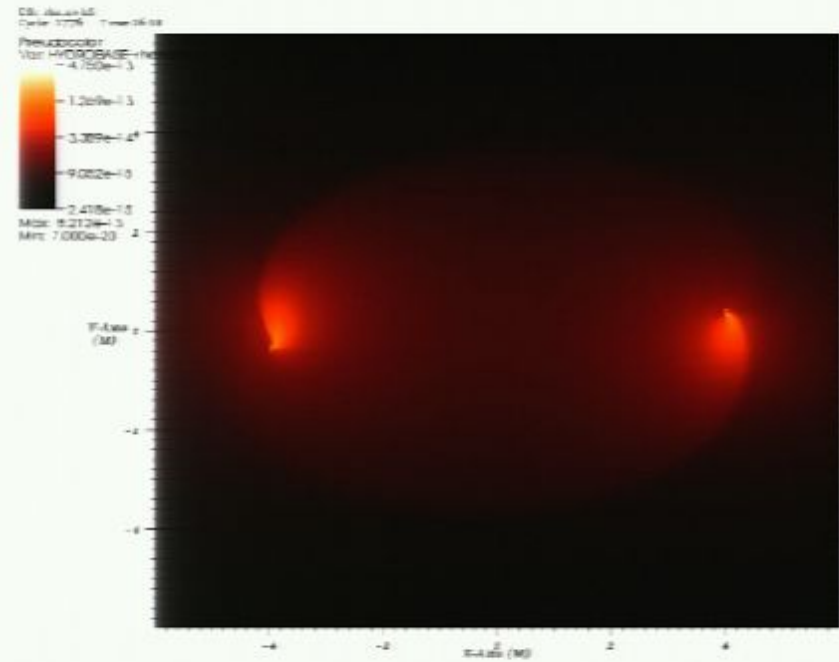


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

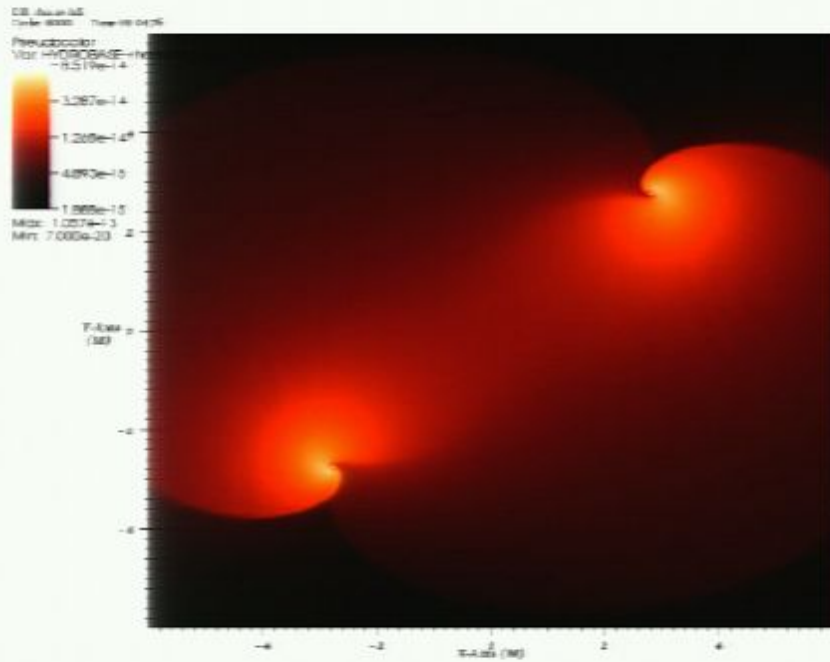


$$s_1/m^2 = s_2/m^2 = 0.6$$

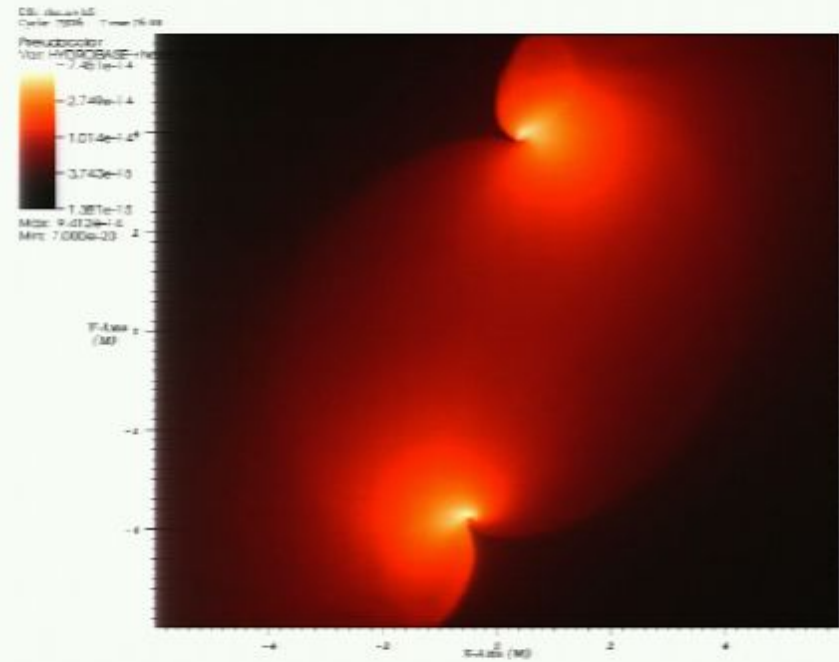


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

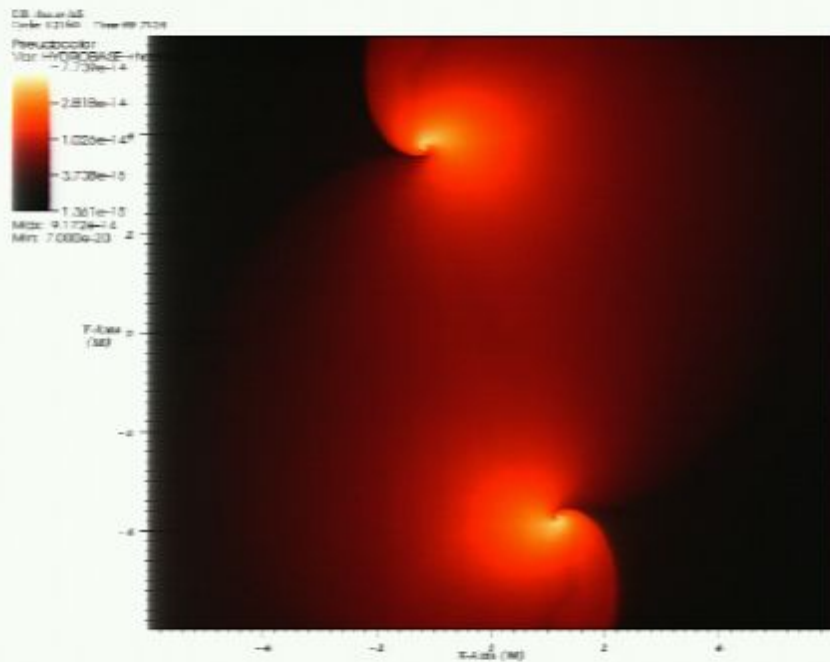


$$s_1/m^2 = s_2/m^2 = 0.6$$

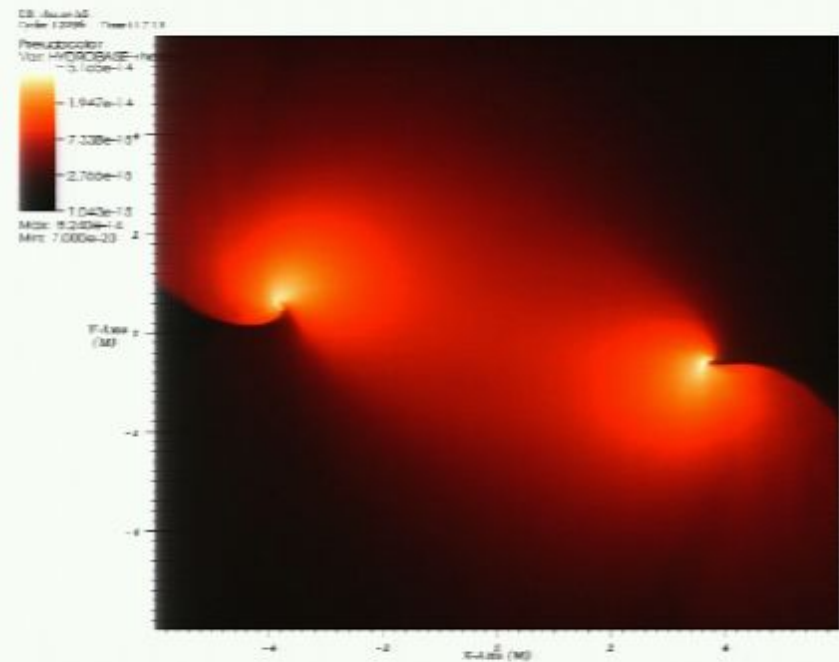


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

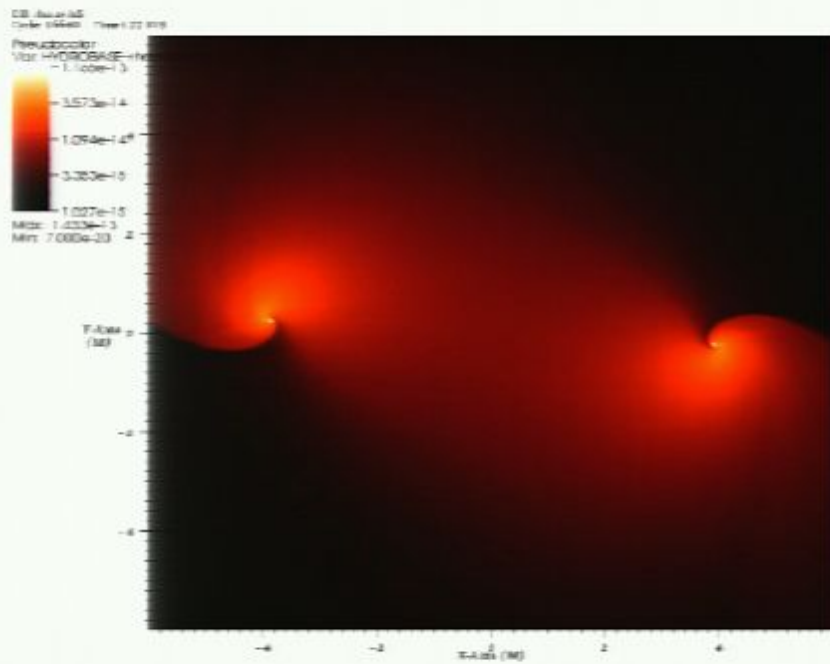


$$s_1/m^2 = s_2/m^2 = 0.6$$

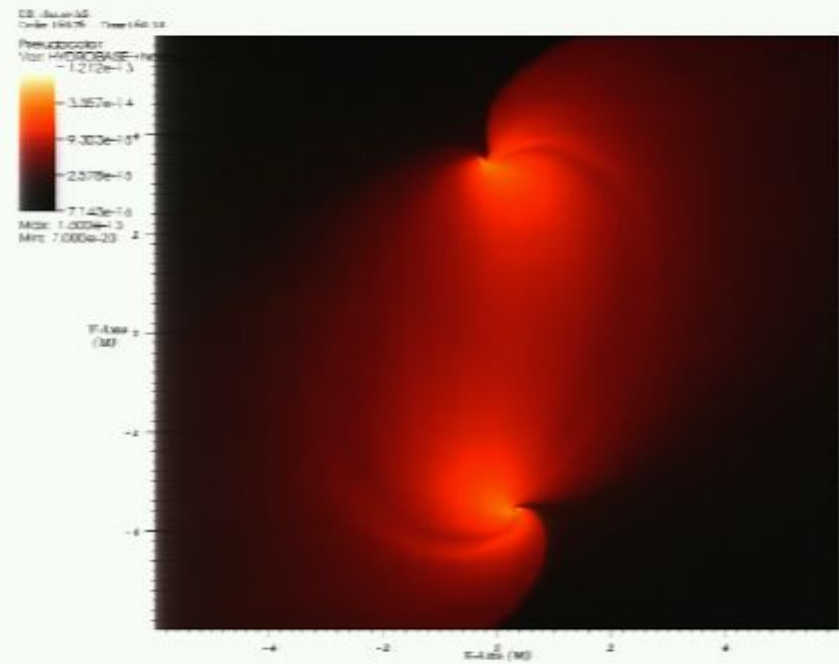


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

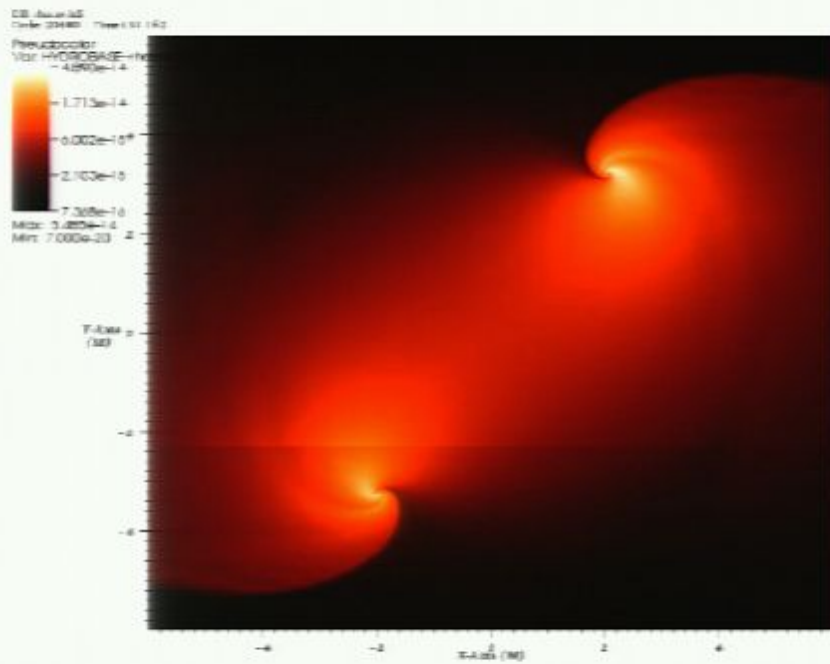


$$s_1/m^2 = s_2/m^2 = 0.6$$

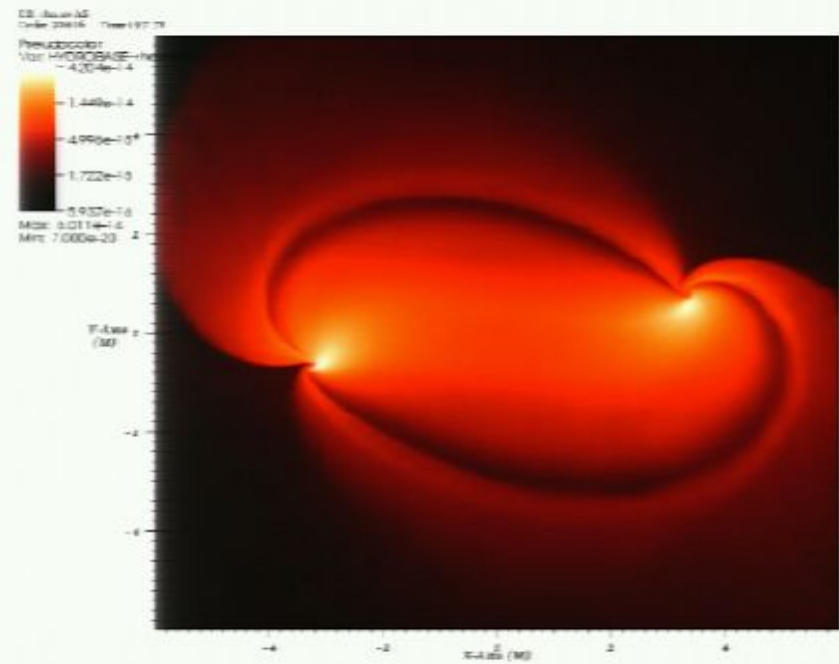


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

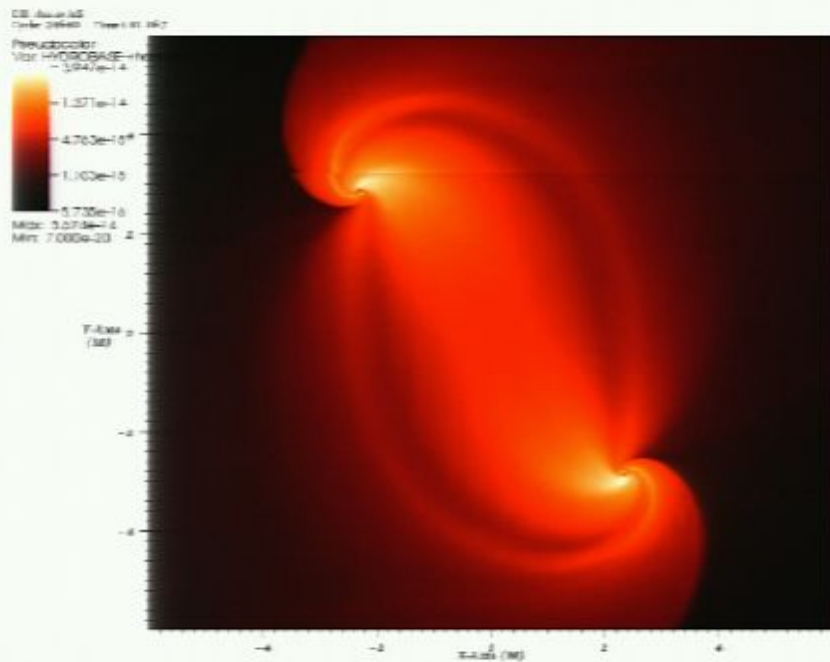


$$s_1/m^2 = s_2/m^2 = 0.6$$

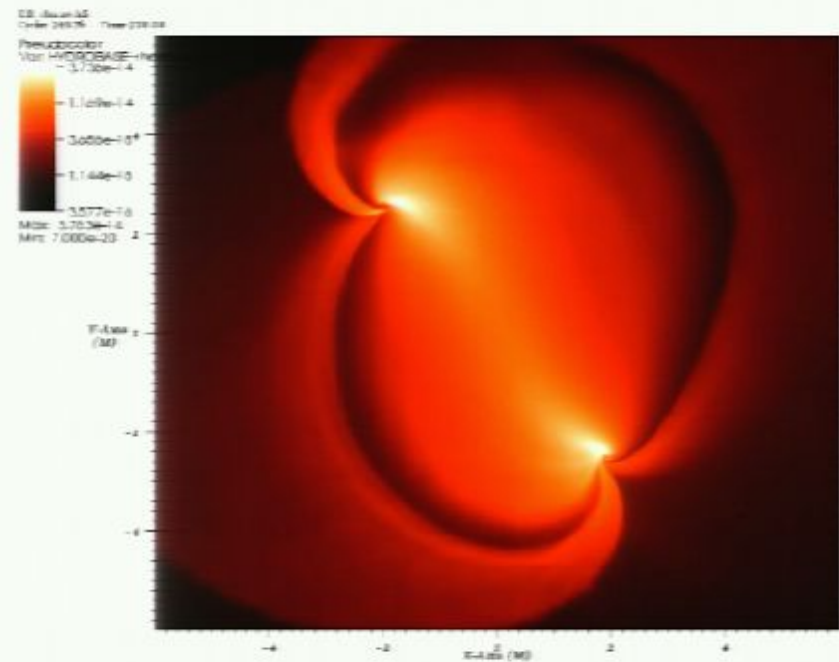


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

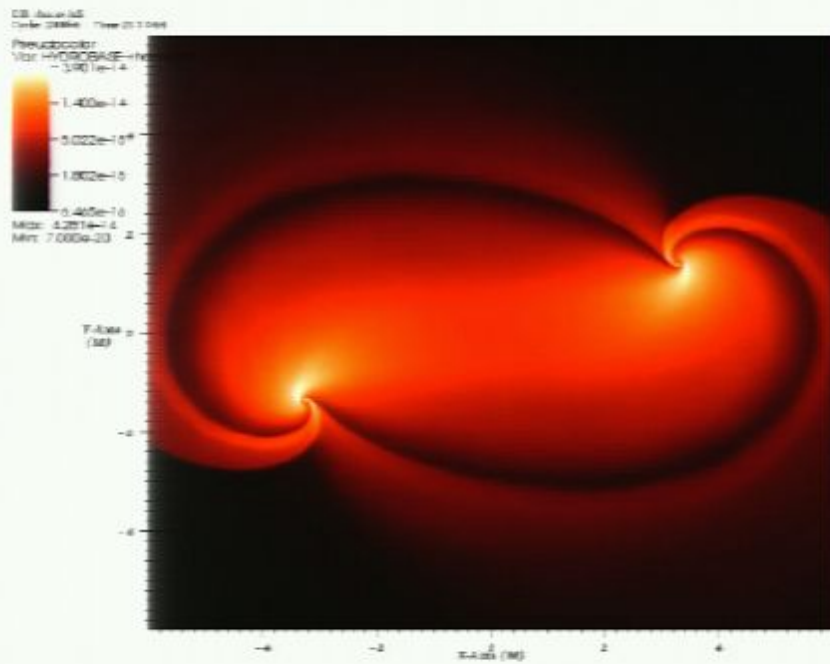


$$s_1/m^2 = s_2/m^2 = 0.6$$

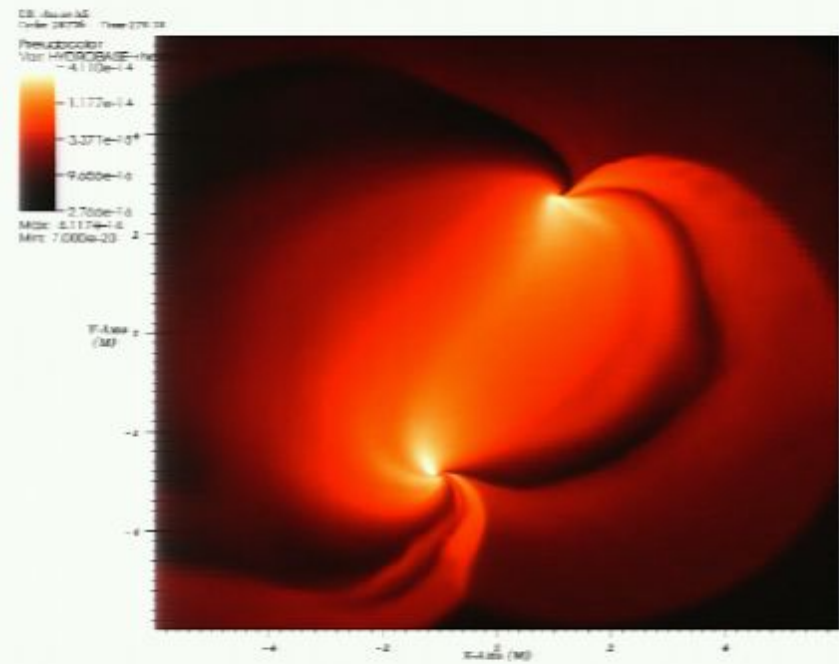


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

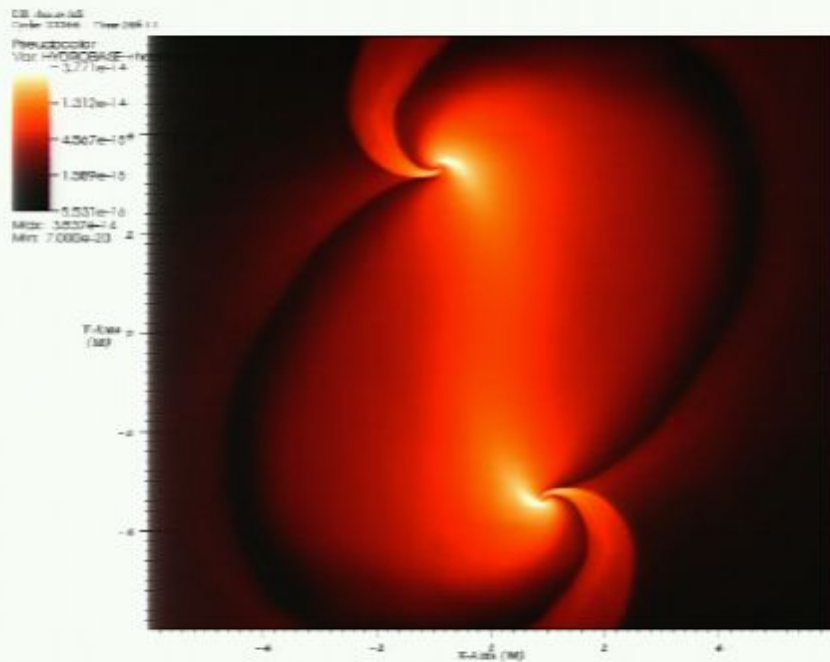


$$s_1/m^2 = s_2/m^2 = 0.6$$

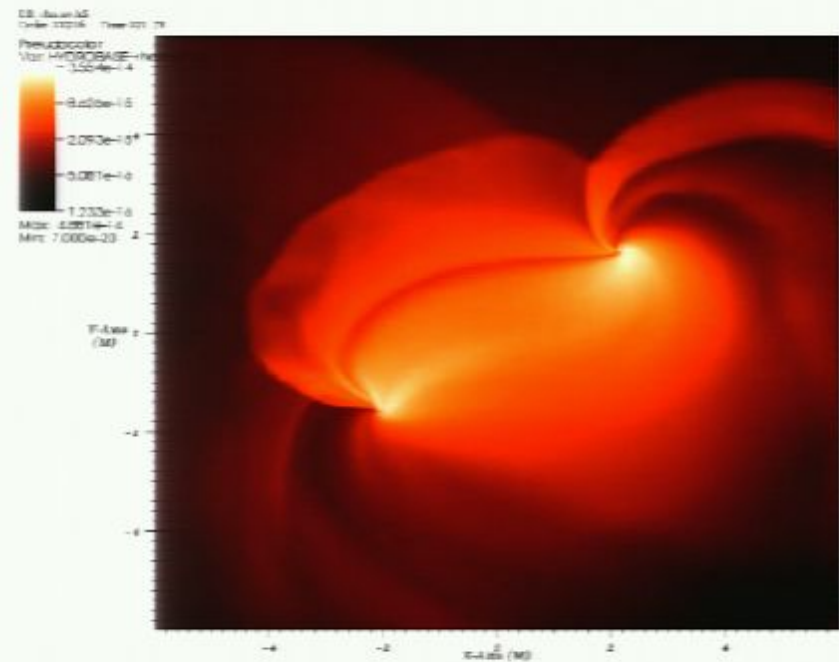


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

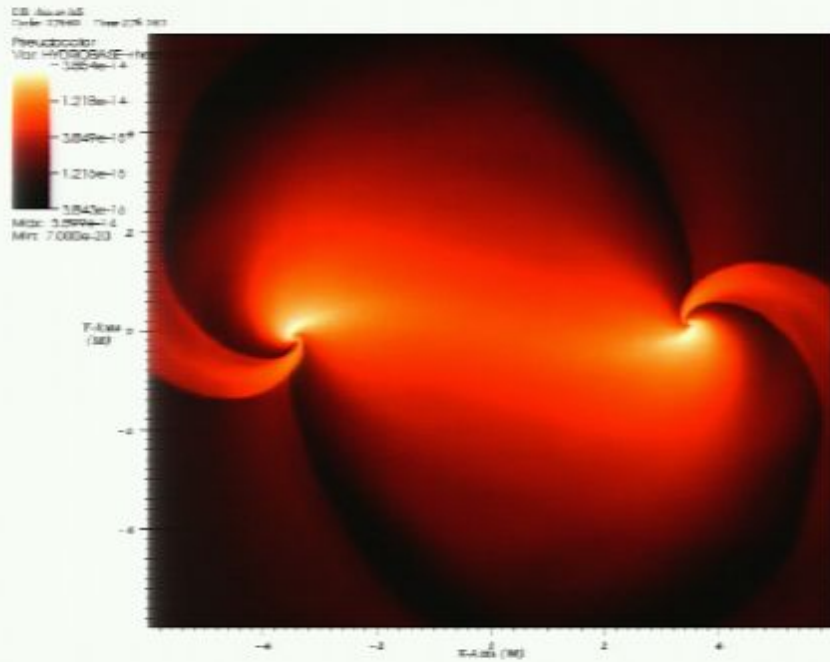


$$s_1/m^2 = s_2/m^2 = 0.6$$

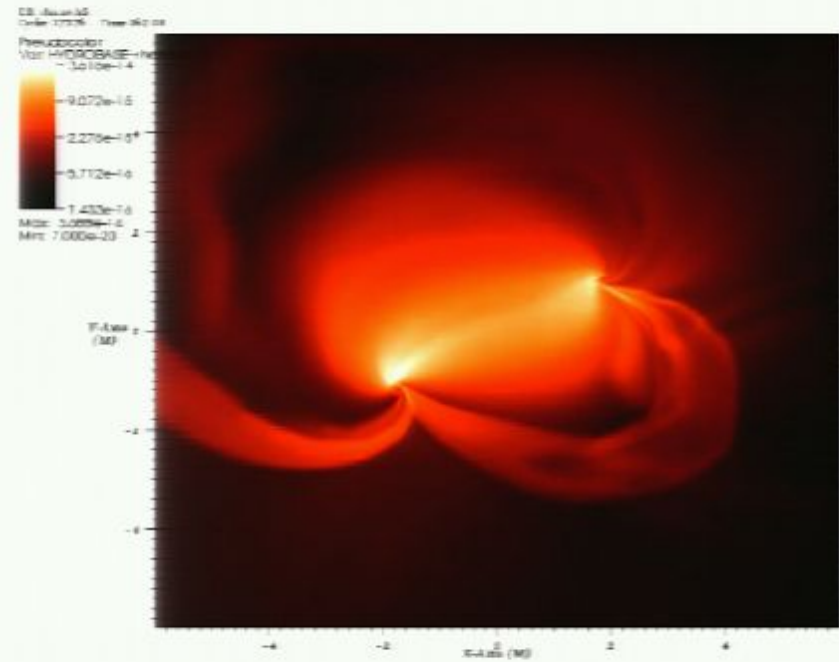


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

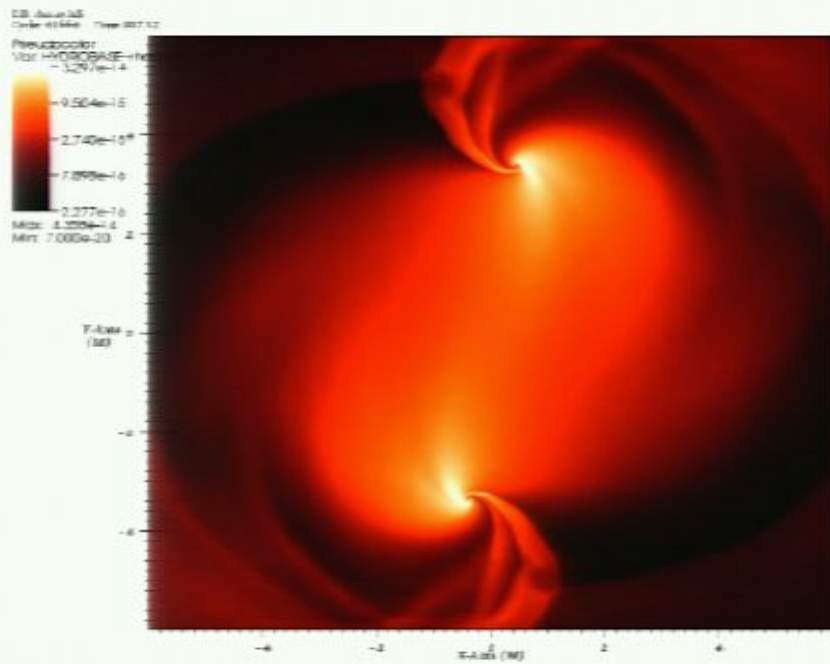


$$s_1/m^2 = s_2/m^2 = 0.6$$

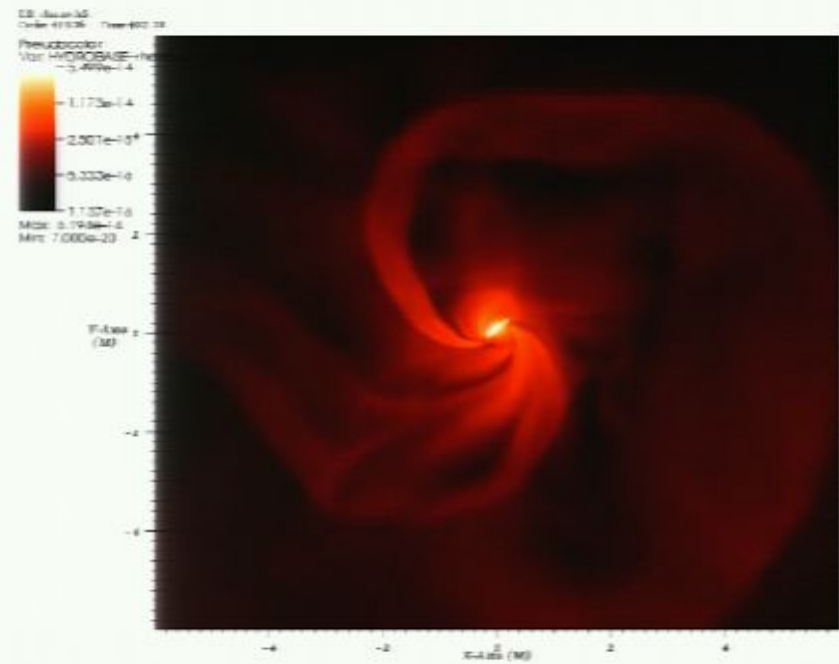


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

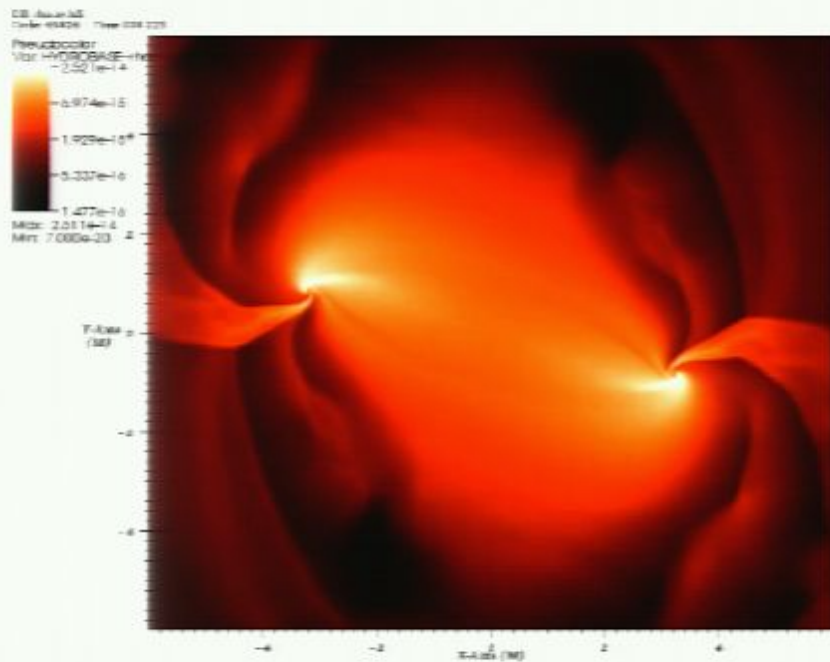


$$s_1/m^2 = s_2/m^2 = 0.6$$

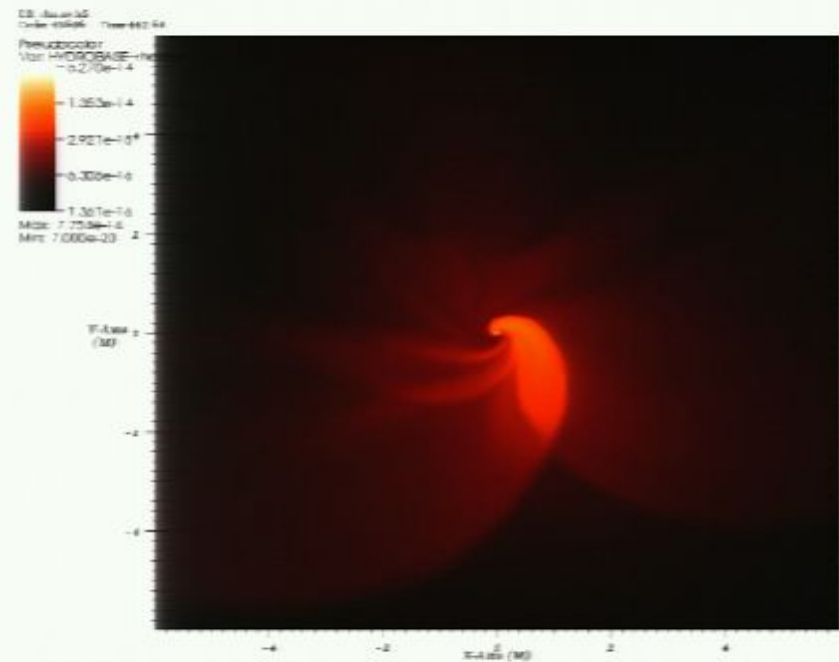


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

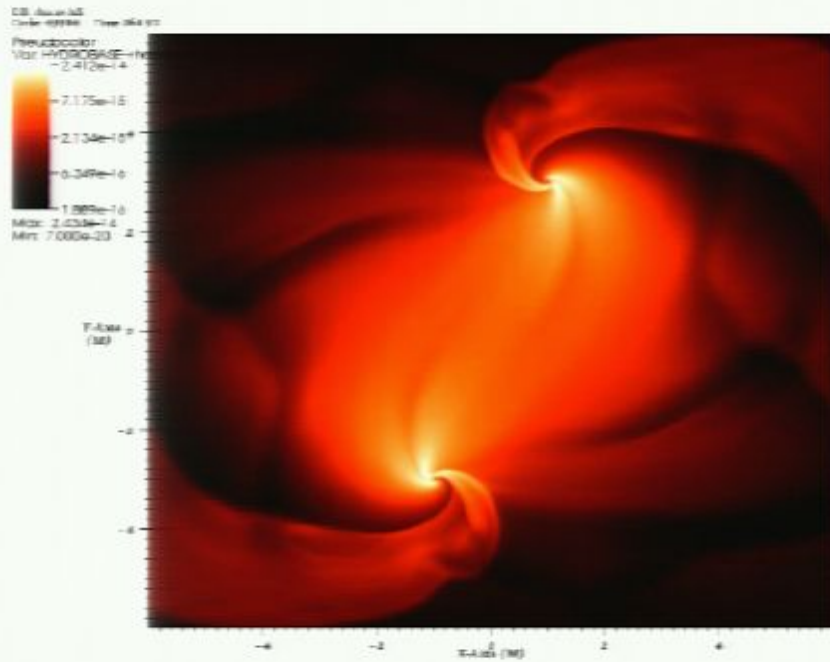


$$s_1/m^2 = s_2/m^2 = 0.6$$

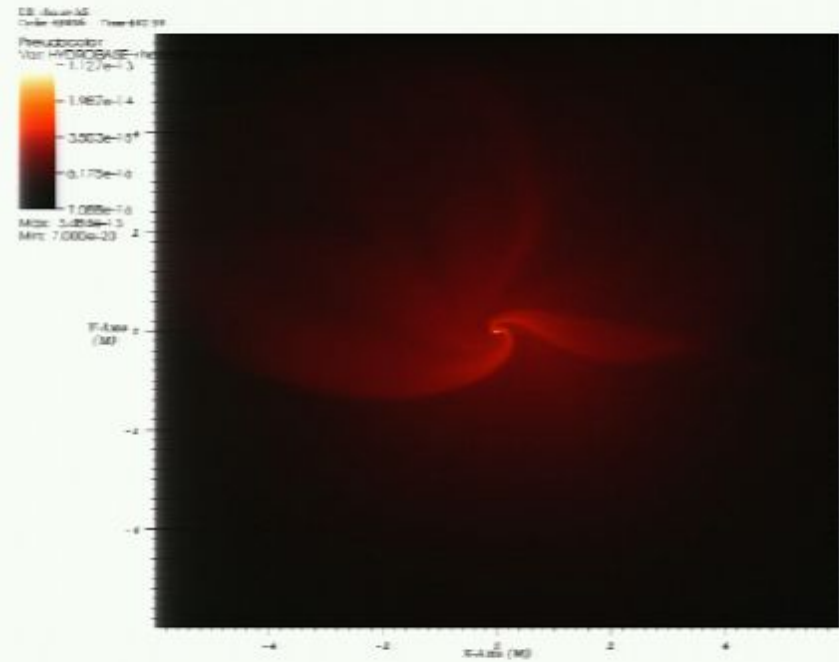


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

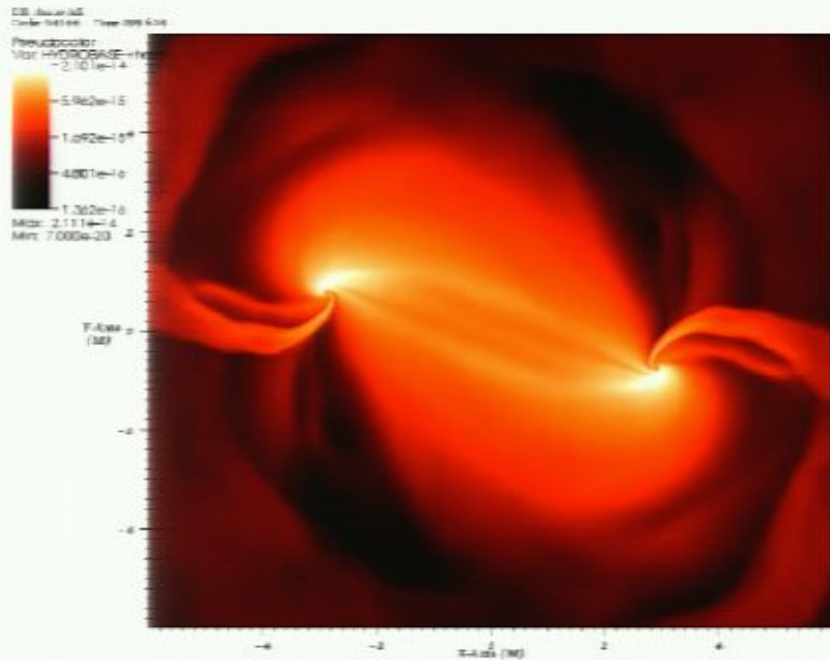


$$s_1/m^2 = s_2/m^2 = 0.6$$

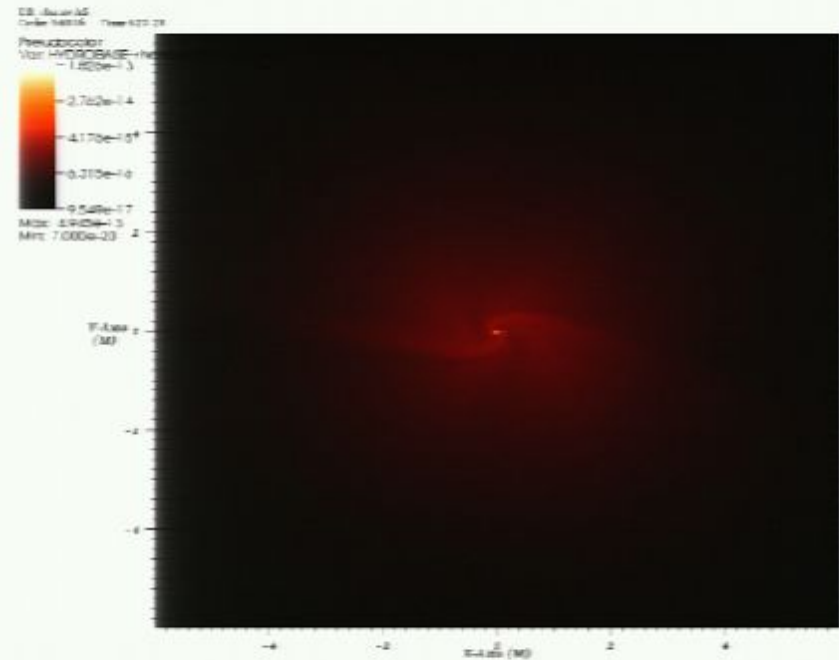


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

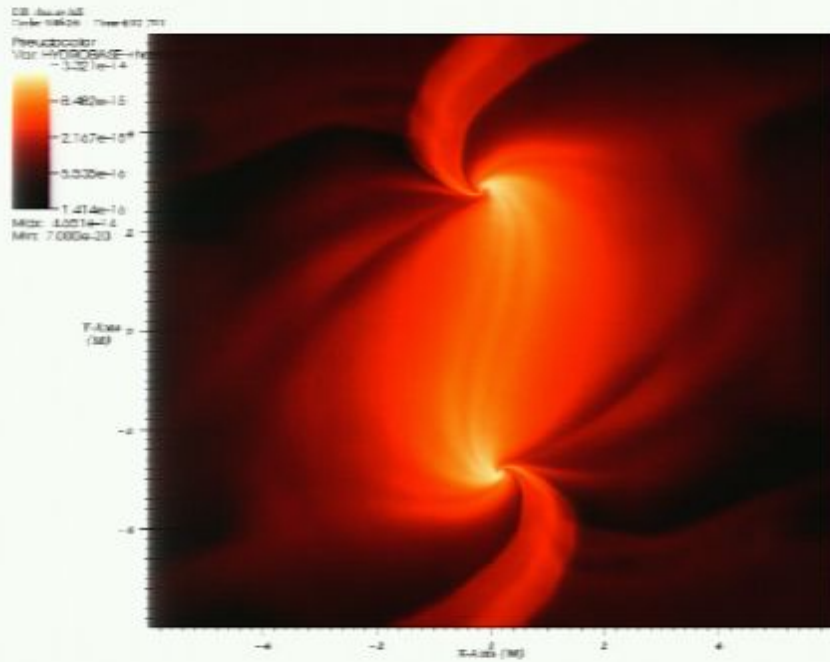


$$s_1/m^2 = s_2/m^2 = 0.6$$

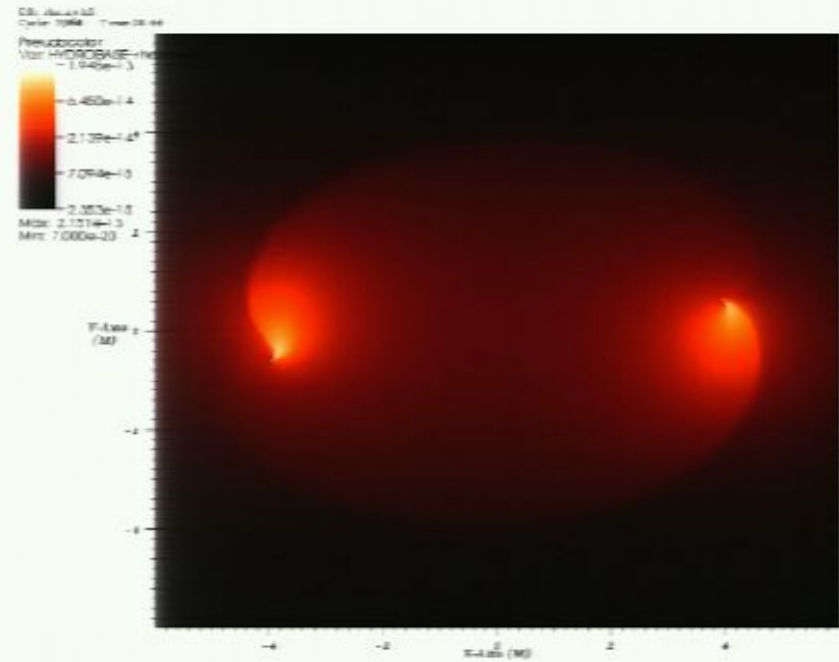


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

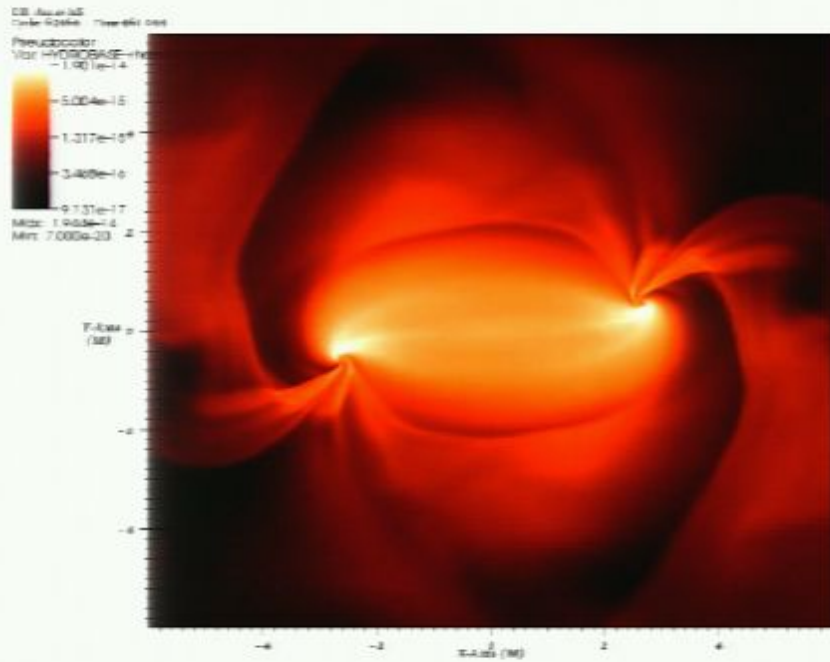


$$s_1/m^2 = s_2/m^2 = 0.6$$

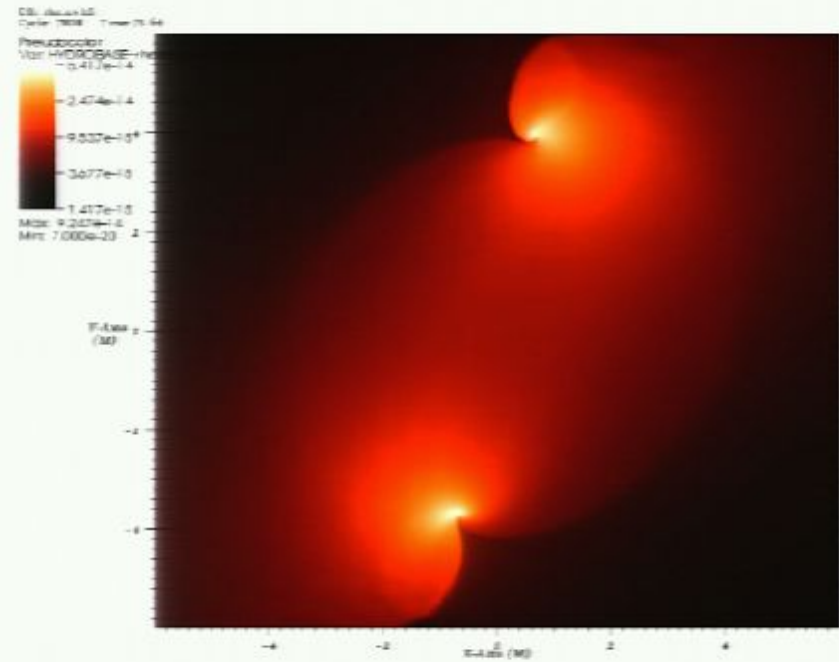


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

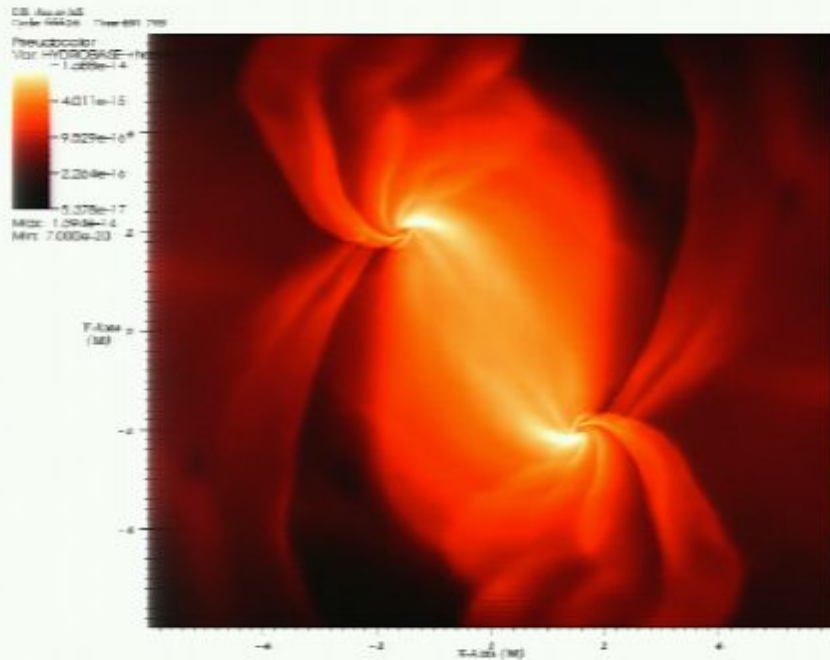


$$s_1/m^2 = s_2/m^2 = 0.6$$

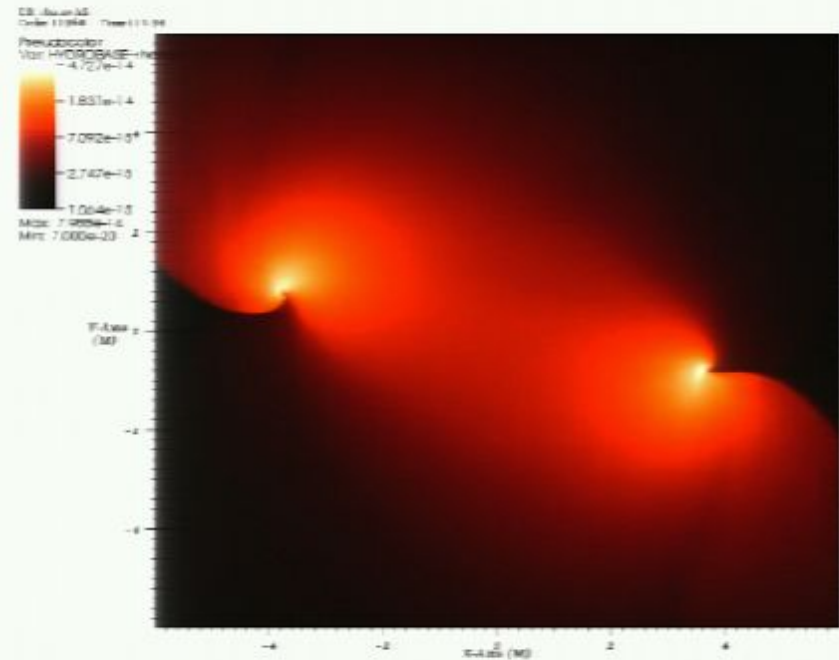


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

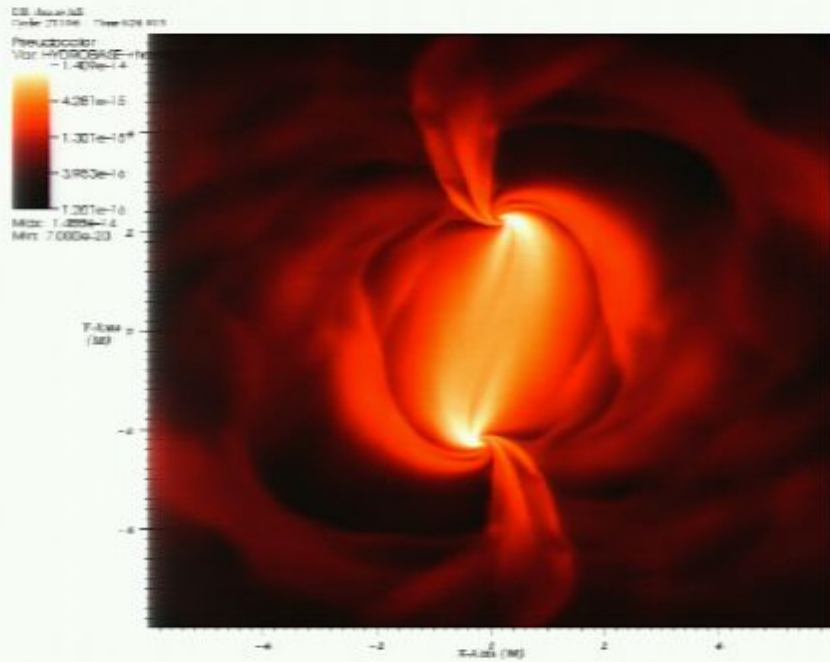


$$s_1/m^2 = s_2/m^2 = 0.6$$

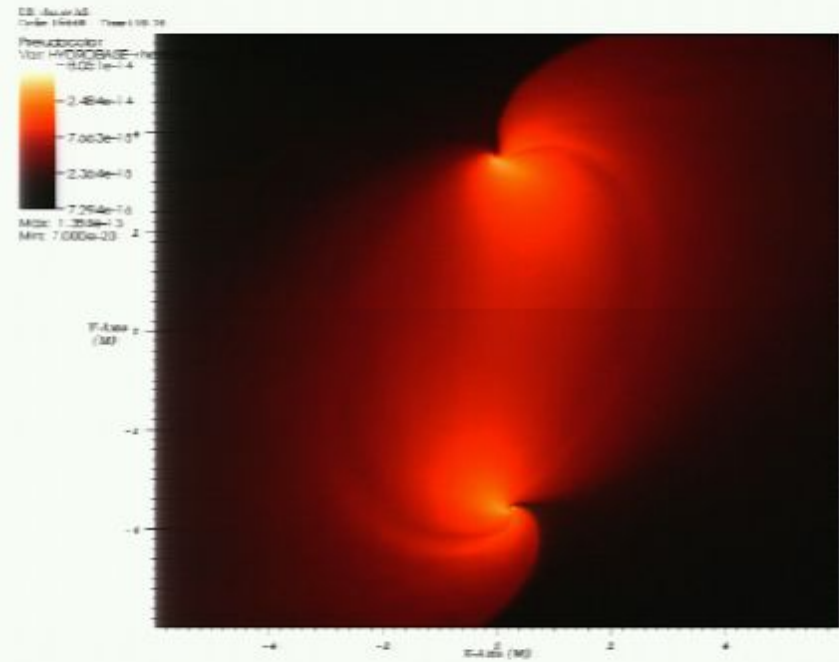


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

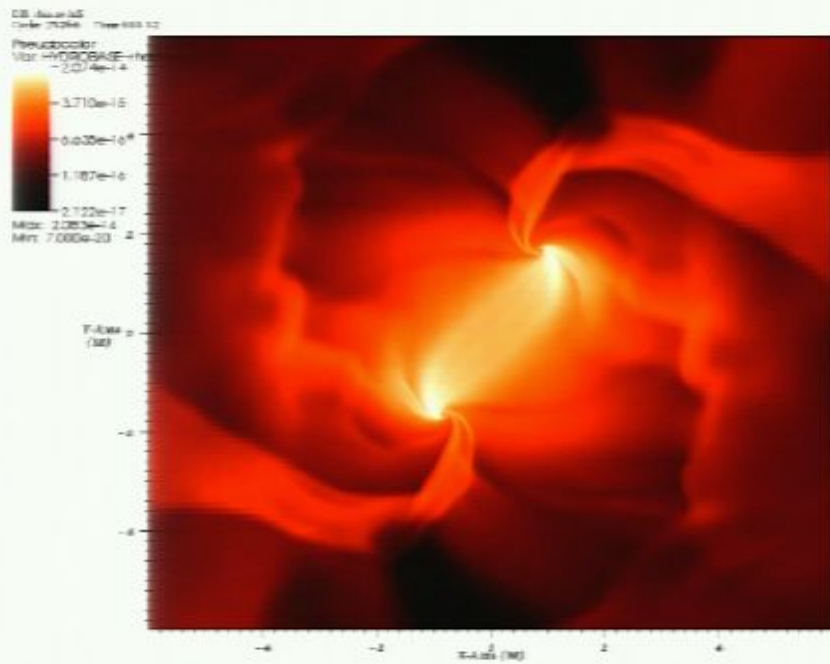


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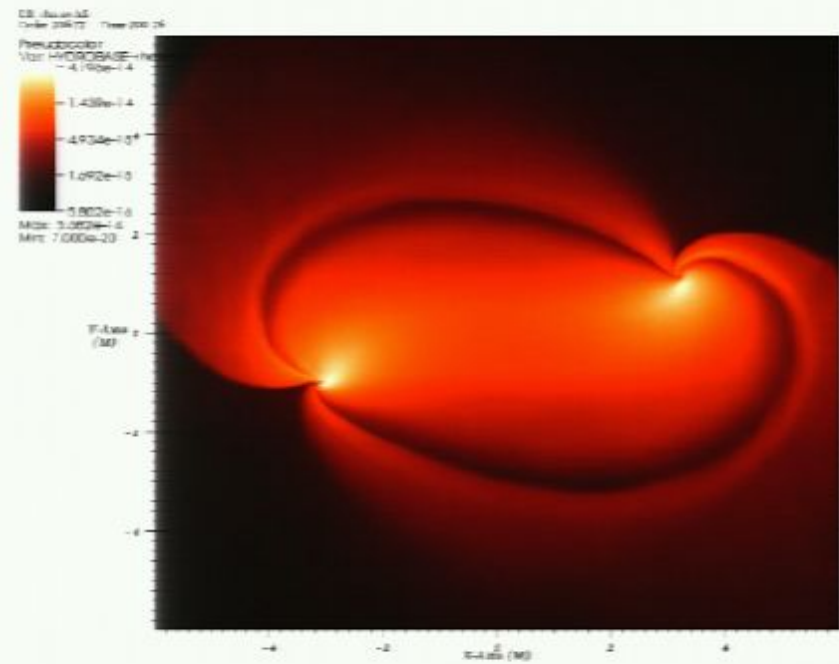


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

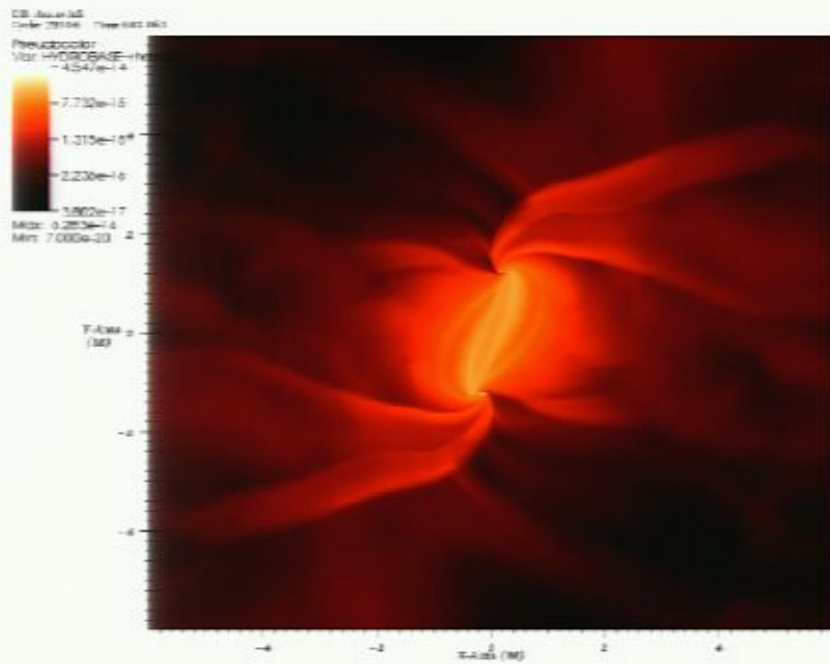


$$s_1/m^2 = s_2/m^2 = 0.6$$

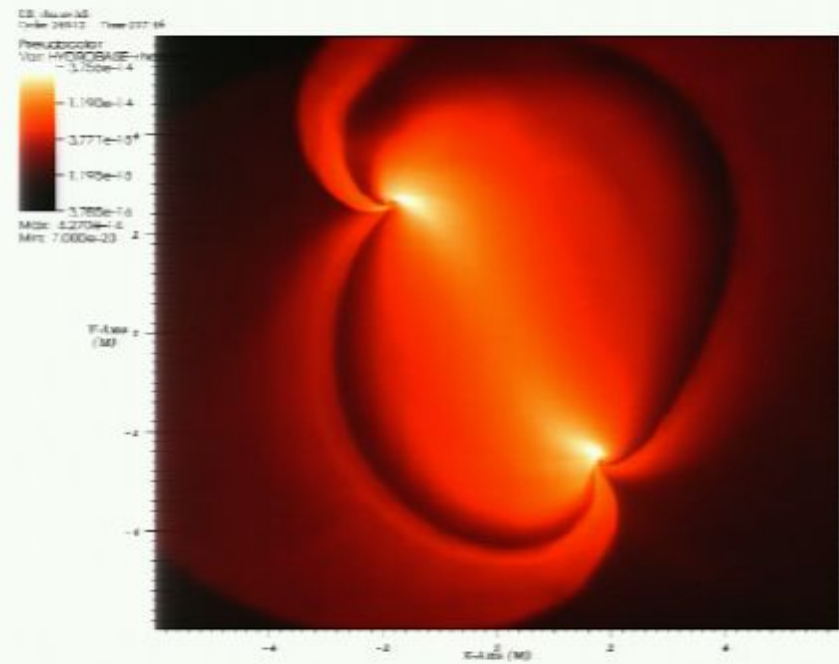


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

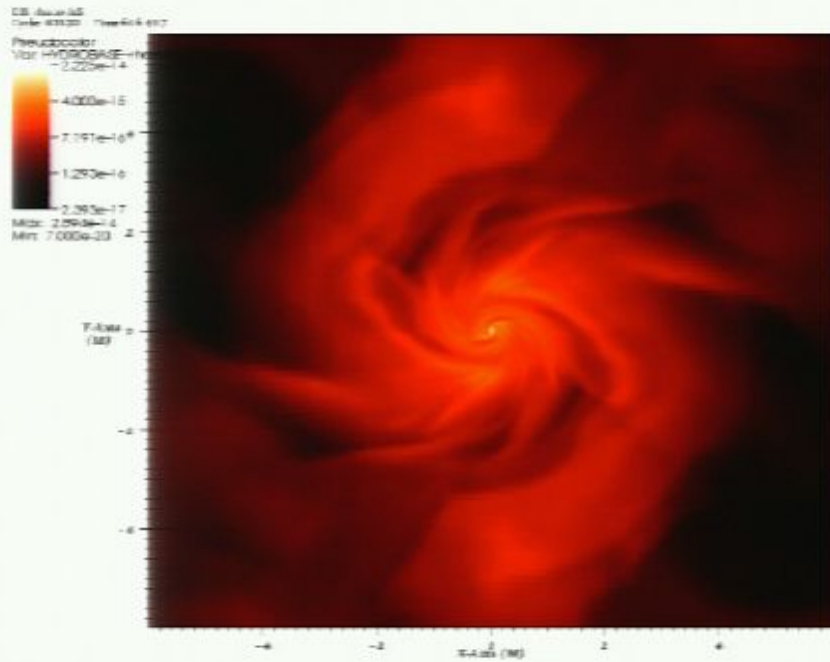


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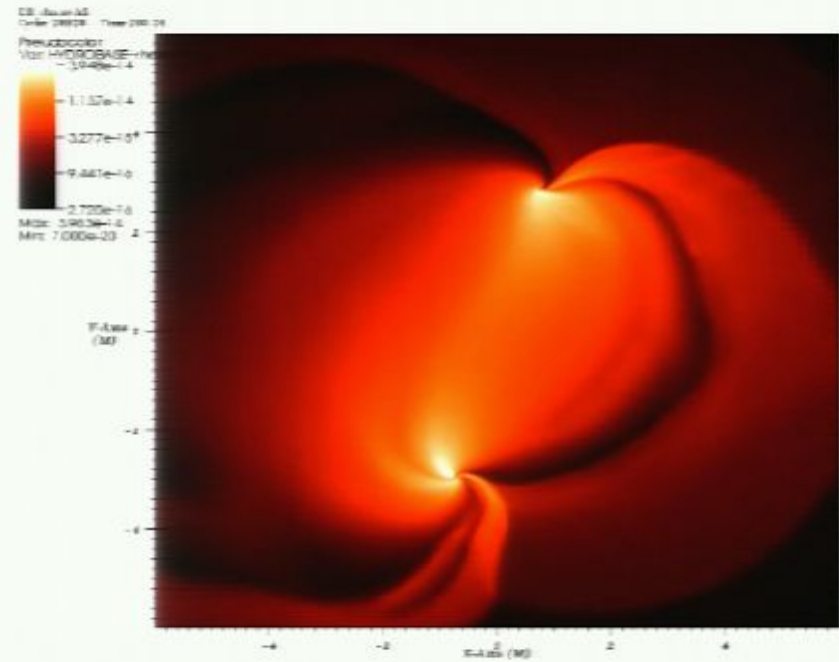


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

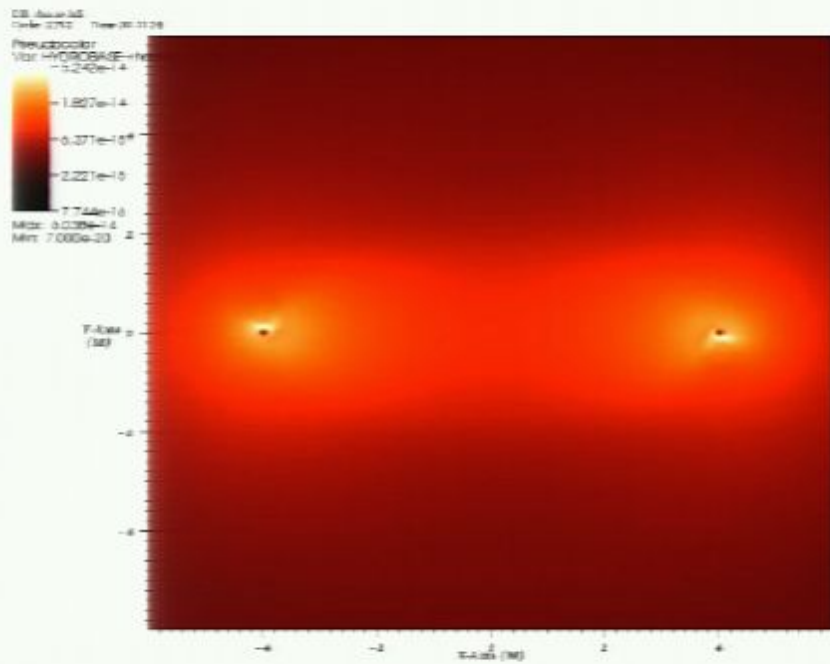


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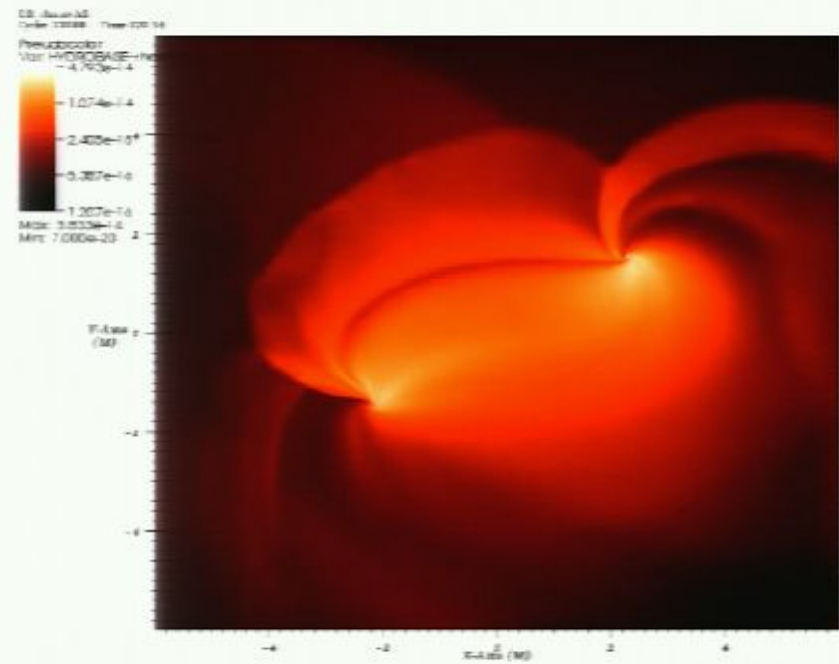


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

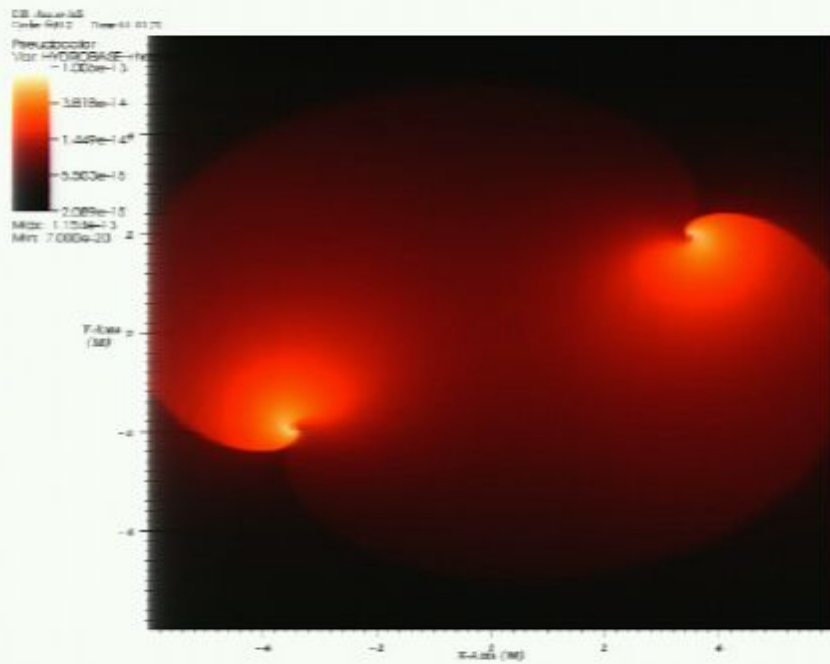


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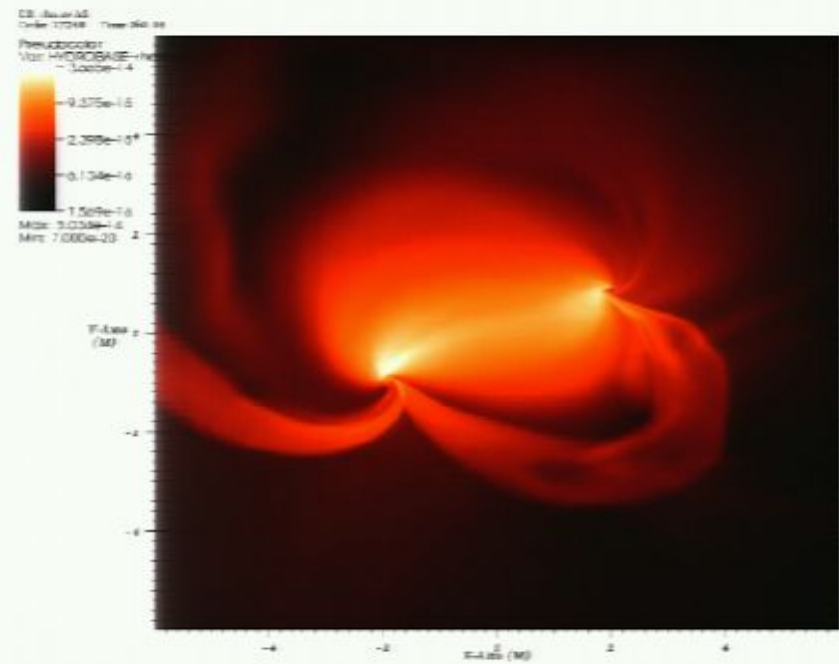


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

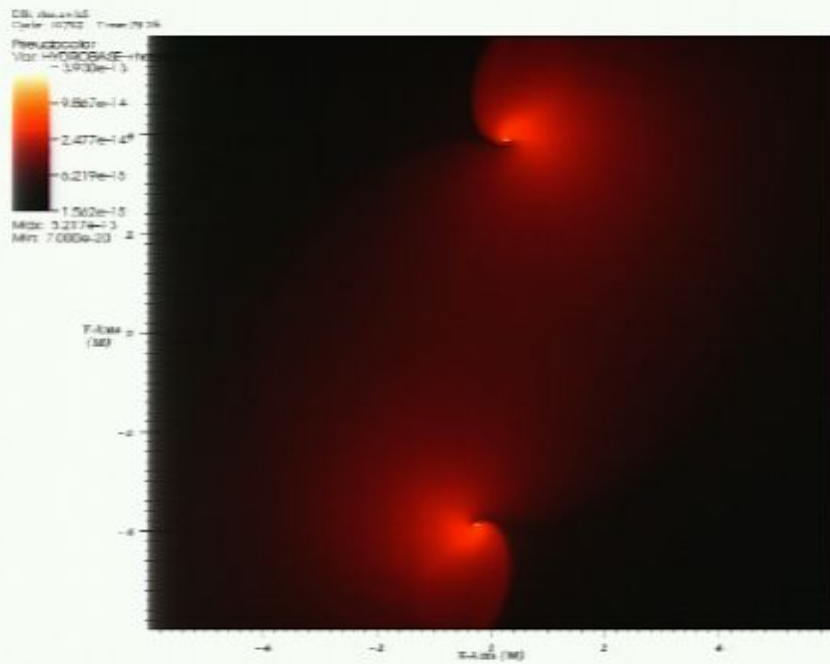


$$s_1/m^2 = s_2/m^2 = 0.6$$

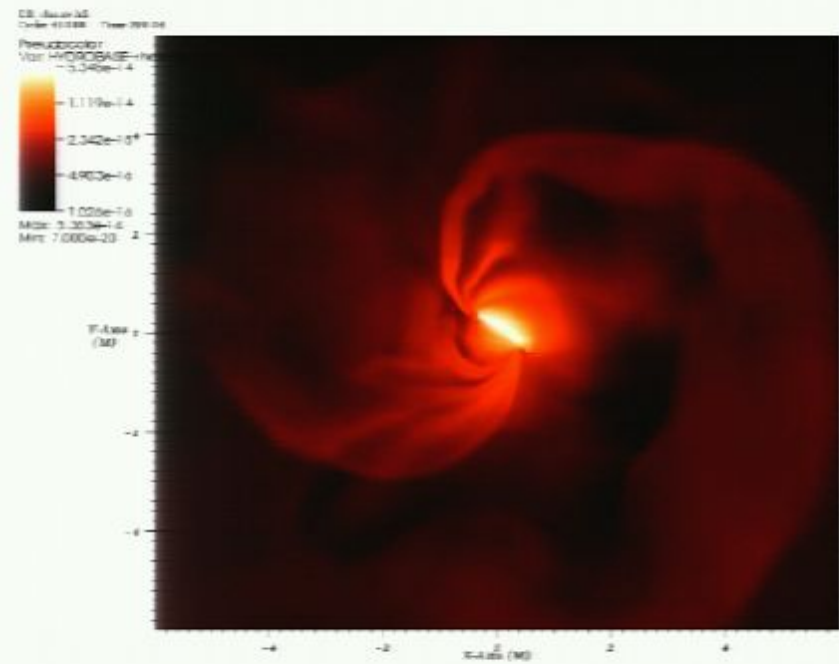


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

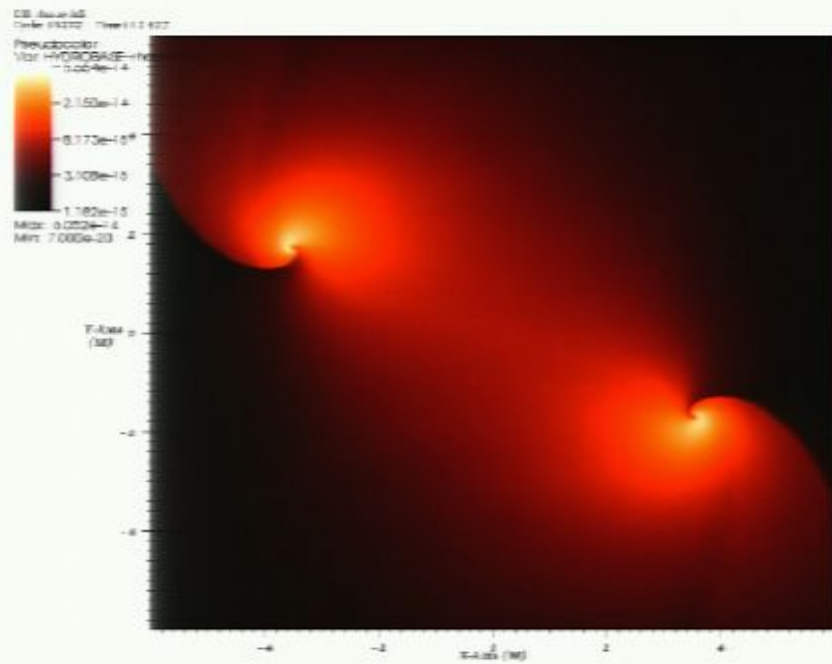


$$s_1/m^2 = s_2/m^2 = 0.6$$

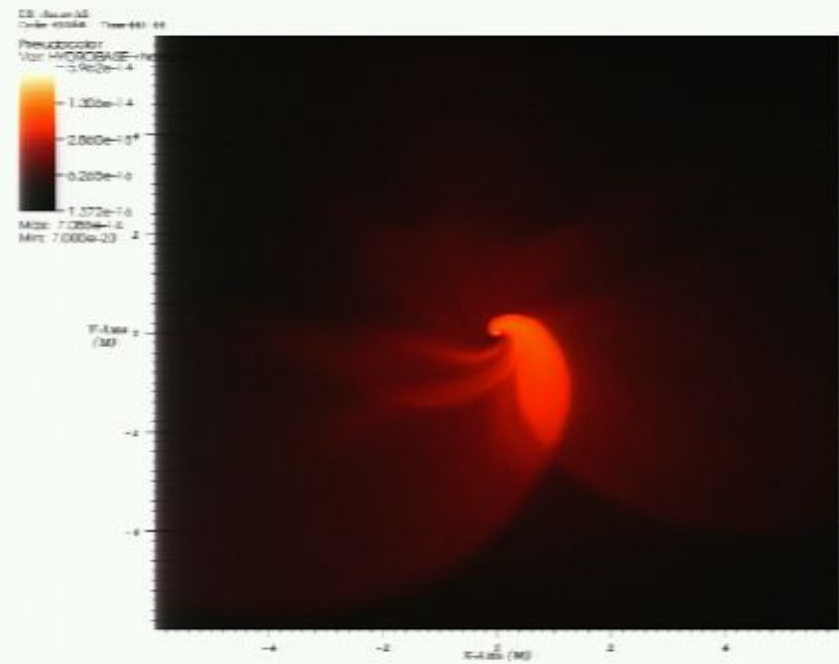


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

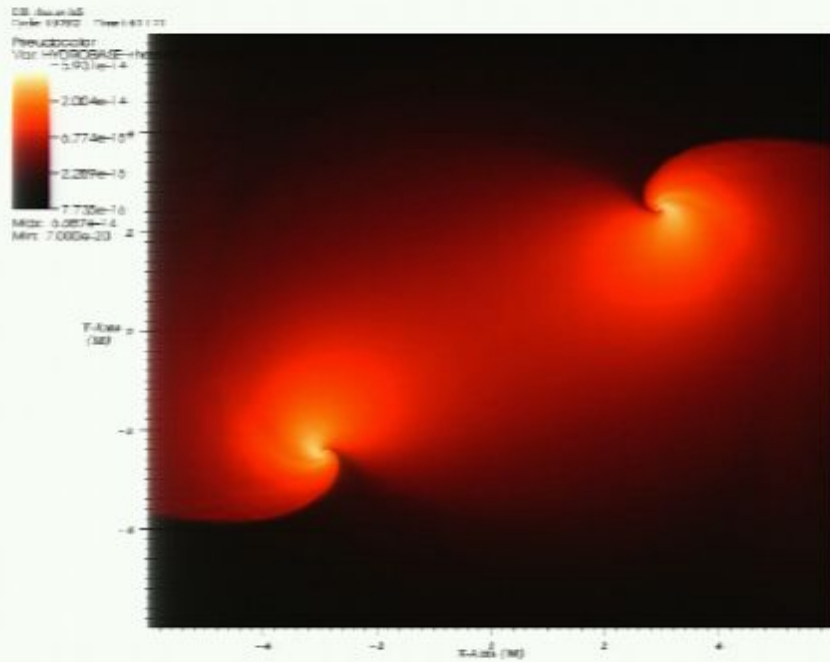


$$s_1/m^2 = s_2/m^2 = 0.6$$

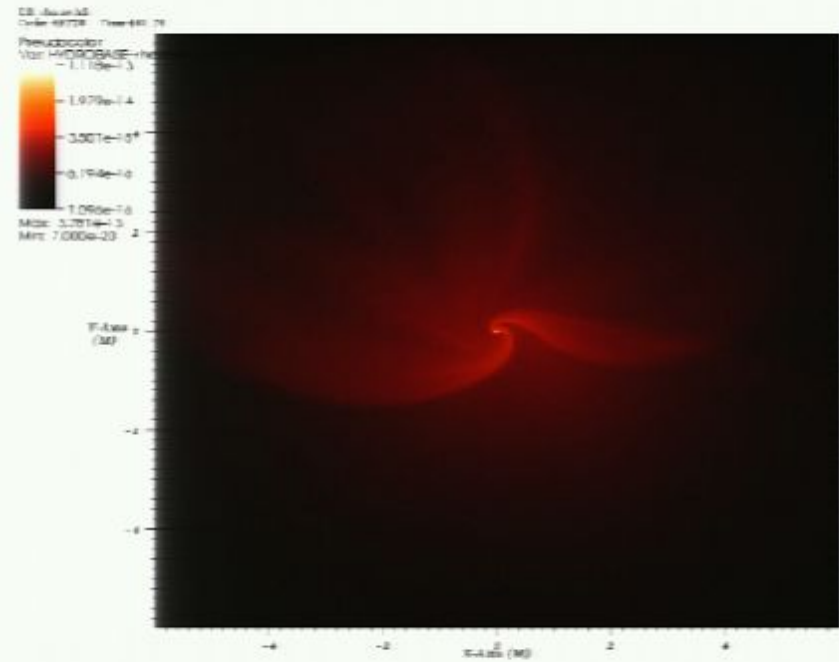


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

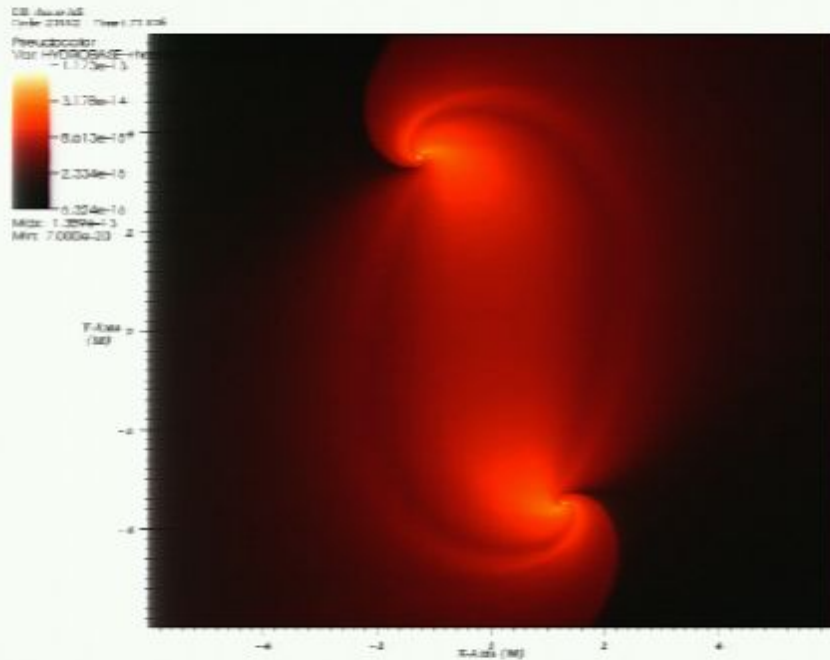


$$s_1/m^2 = s_2/m^2 = 0.6$$

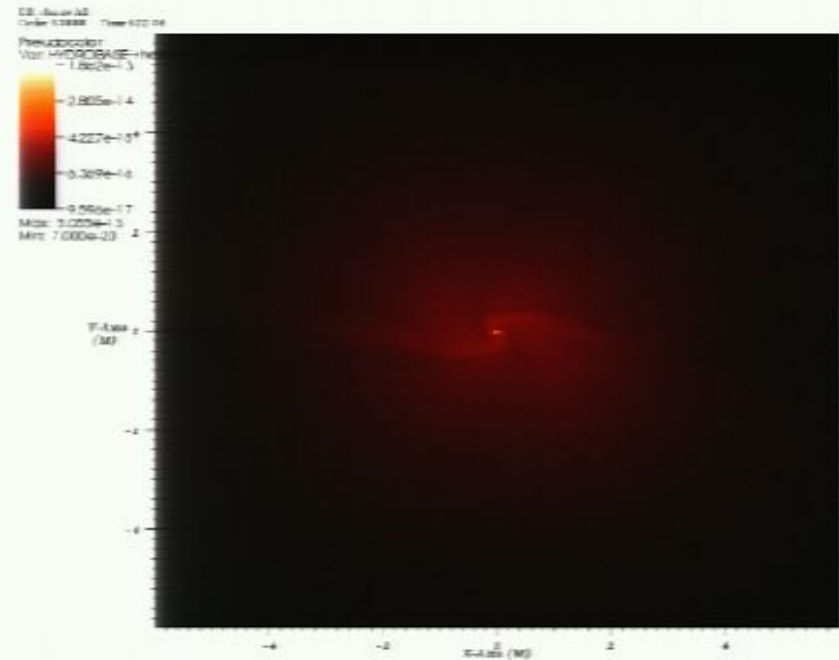


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

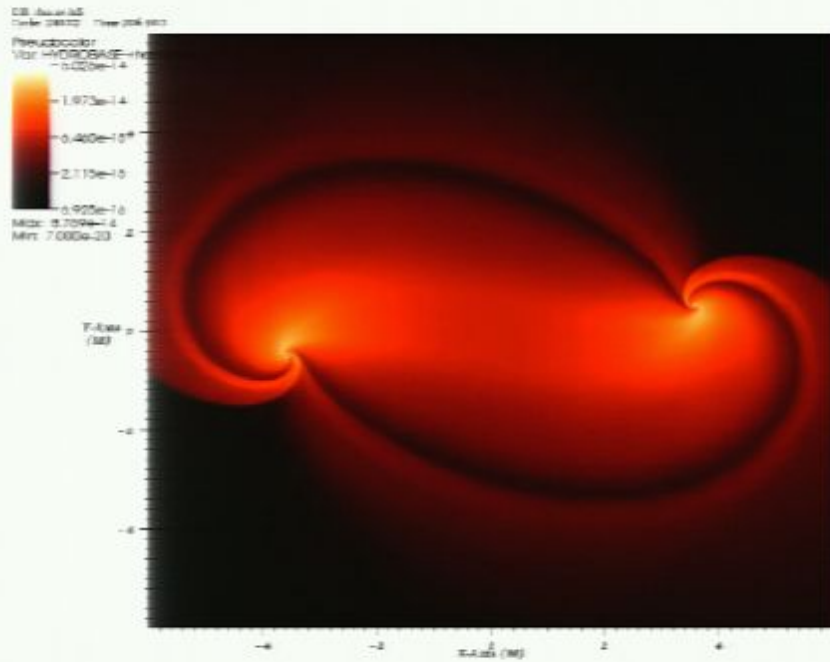


$$s_1/m^2 = s_2/m^2 = 0.6$$

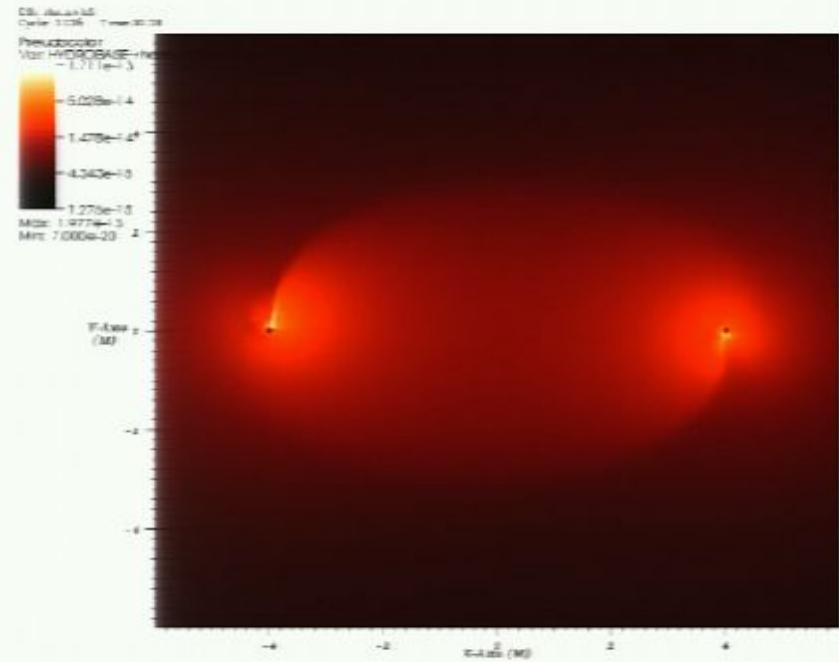


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

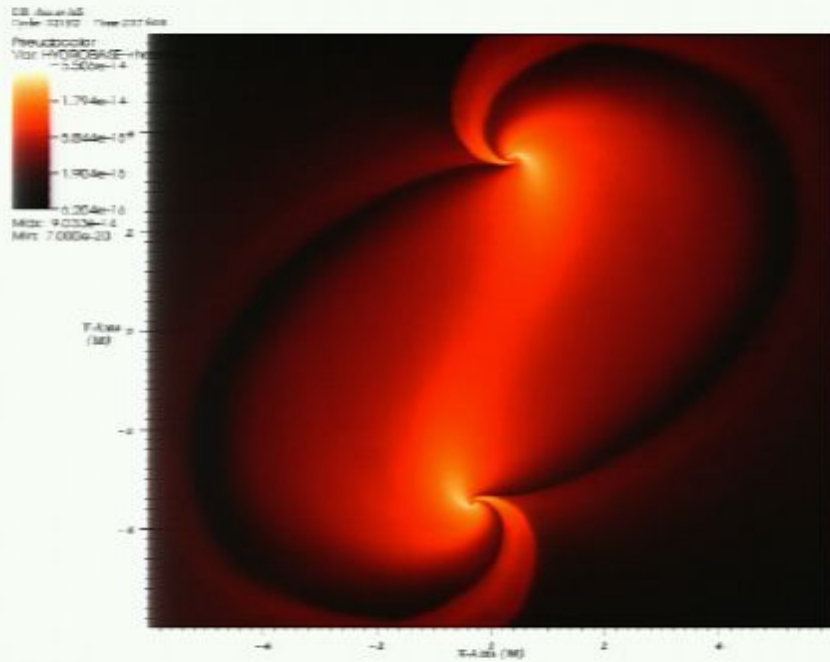


$$s_1/m^2 = s_2/m^2 = 0.6$$

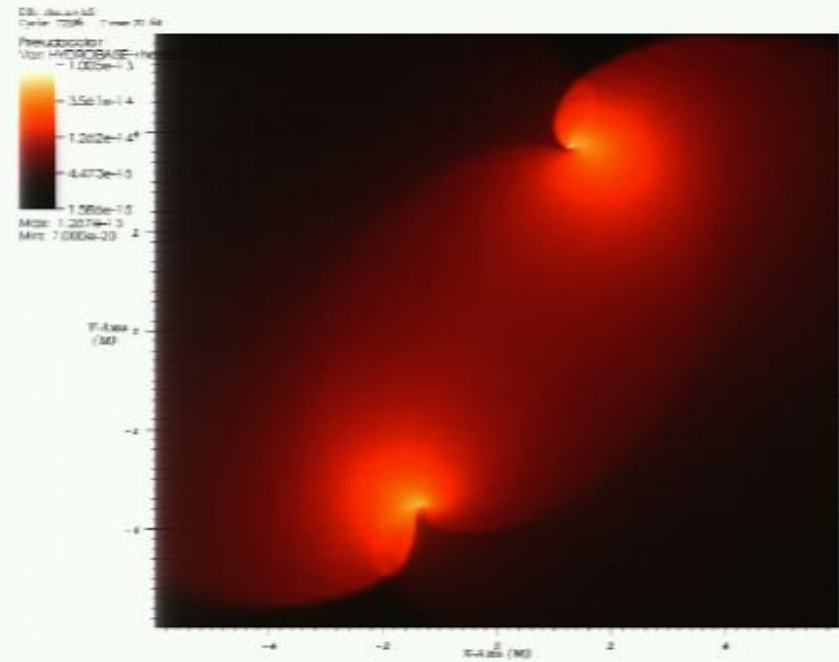


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

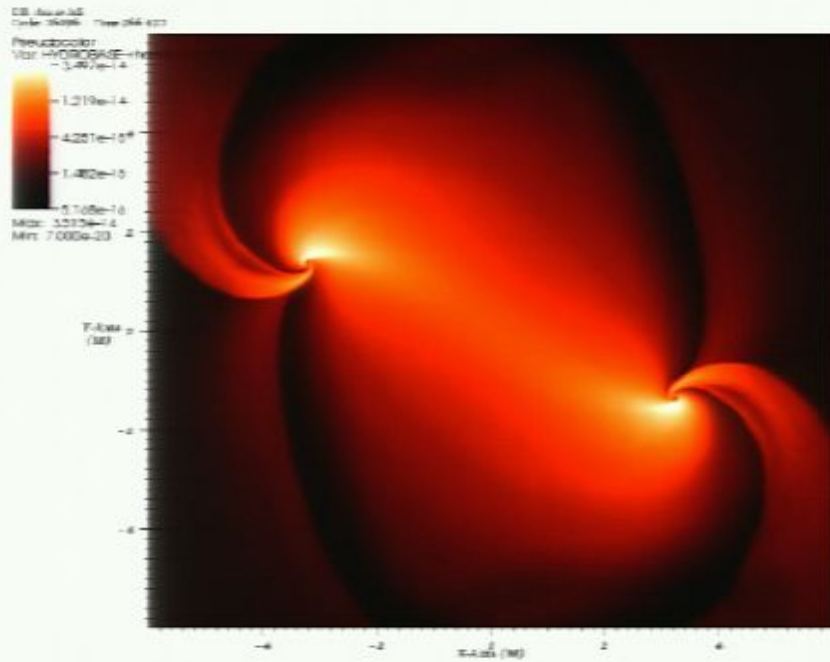


$$s_1/m^2 = s_2/m^2 = 0.6$$

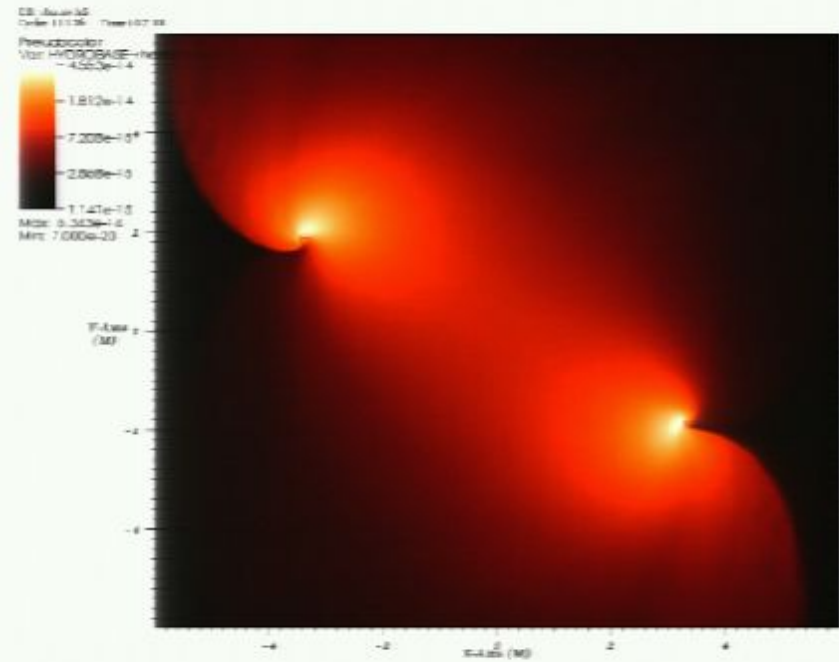


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

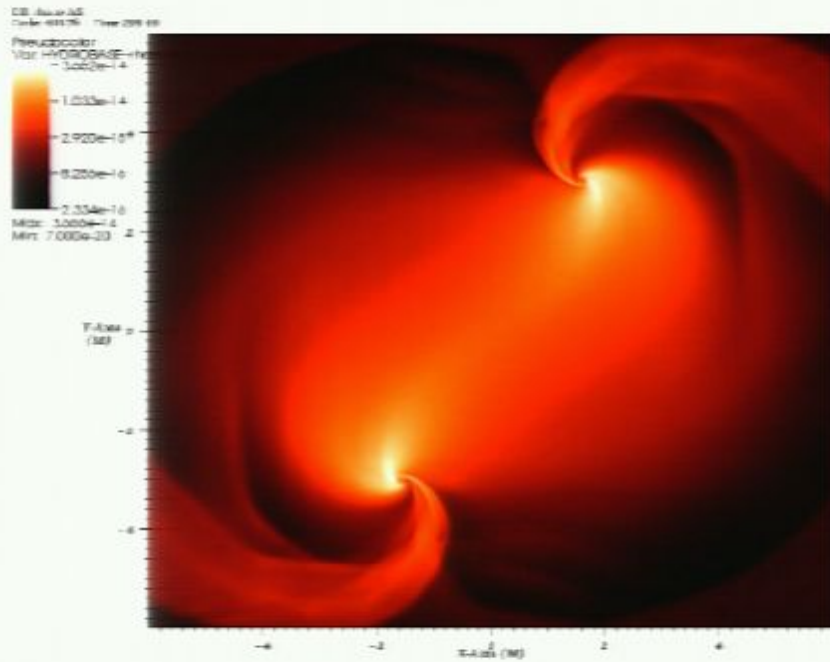


$$s_1/m^2 = s_2/m^2 = 0.6$$

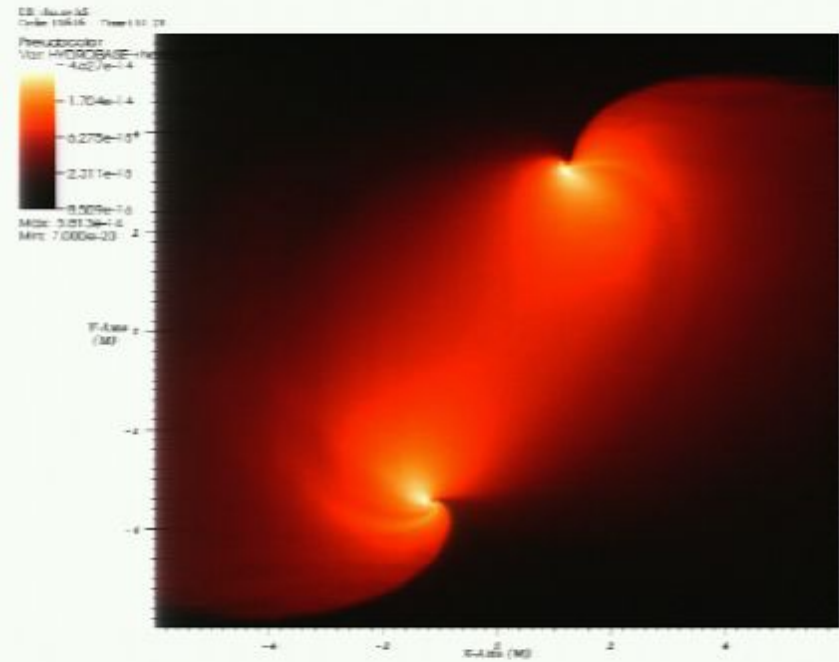


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

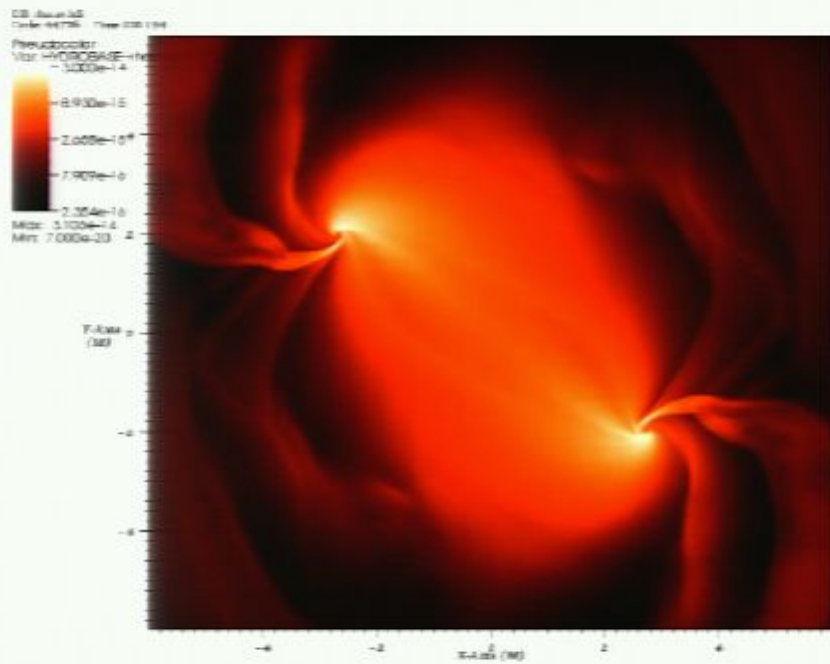


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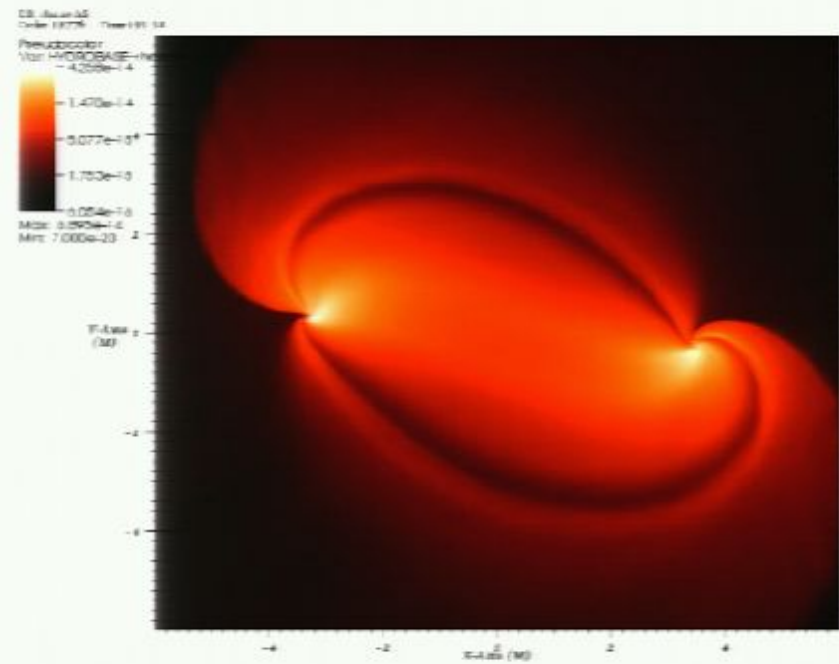


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

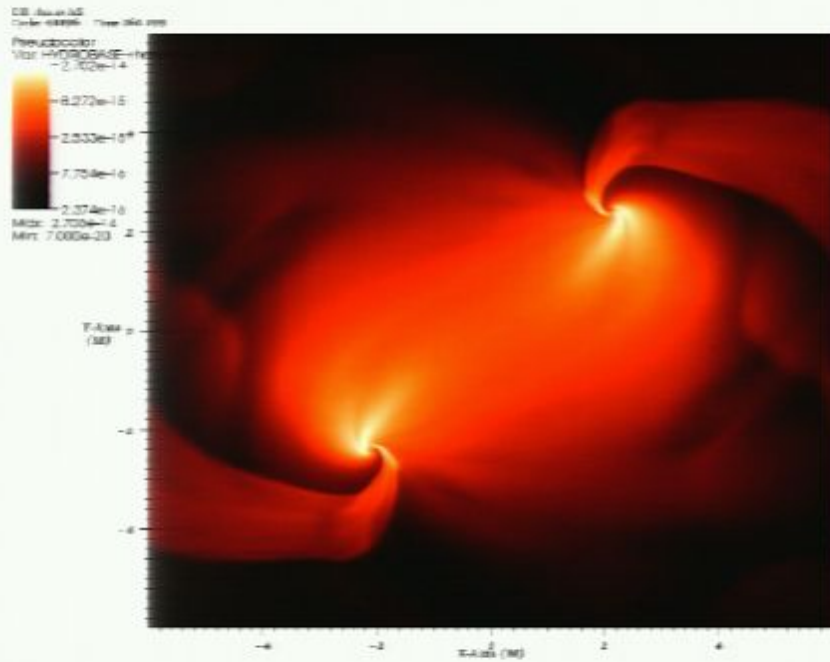


$$s_1/m^2 = s_2/m^2 = 0.6$$

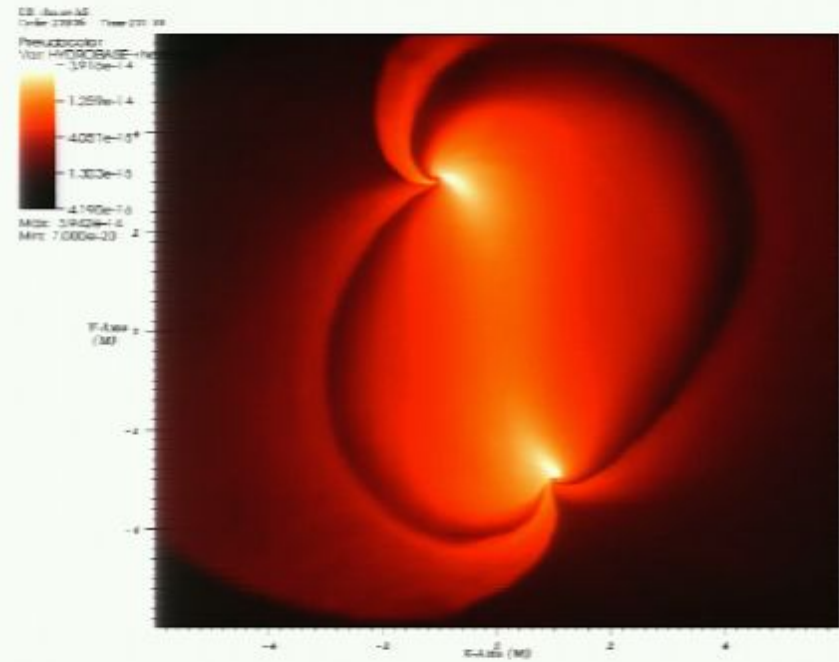


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

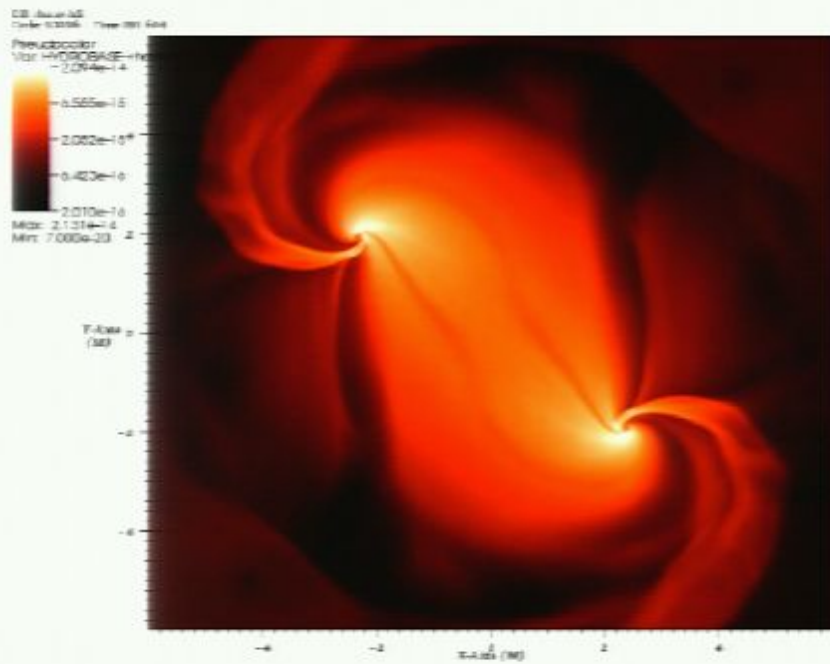


$$s_1/m^2 = s_2/m^2 = 0.6$$

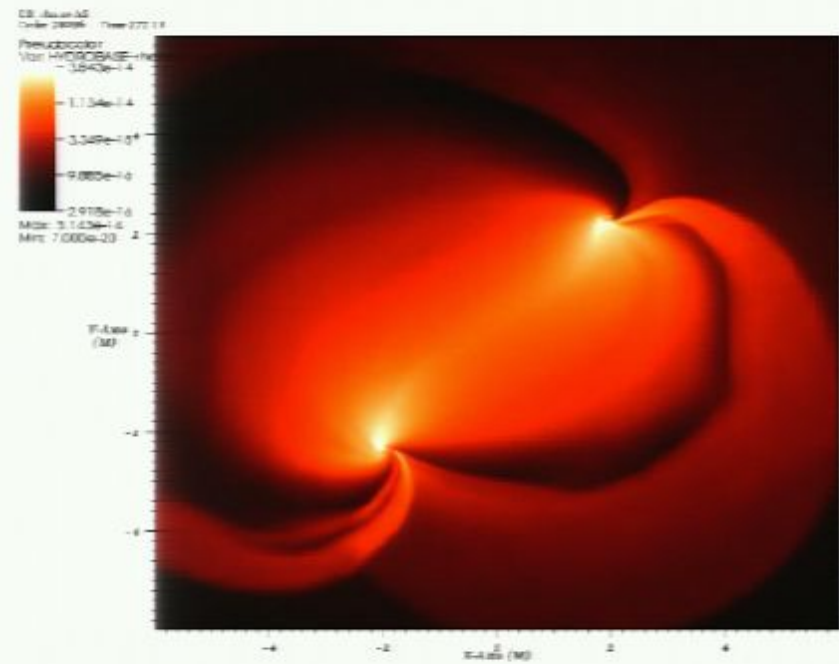


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

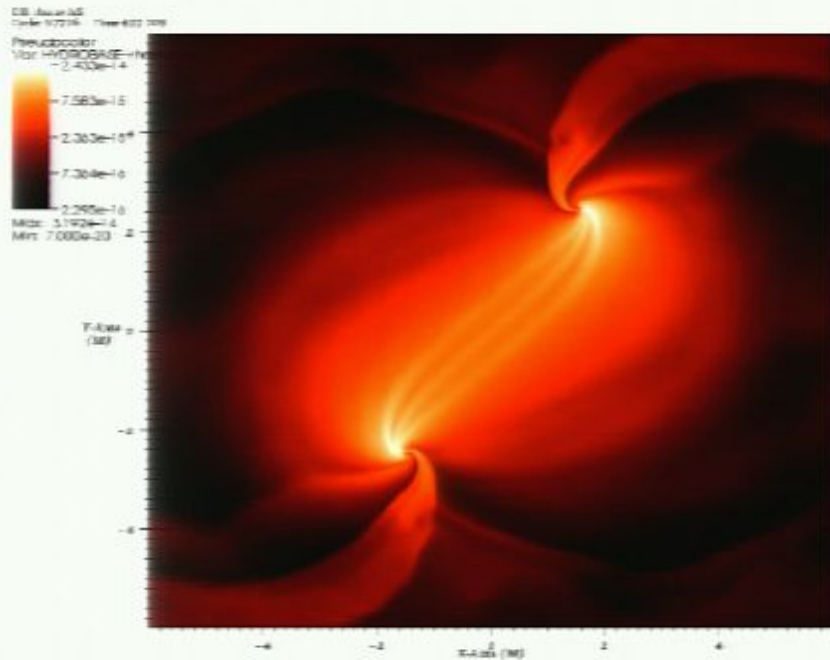


$$s_1/m^2 = s_2/m^2 = 0.6$$

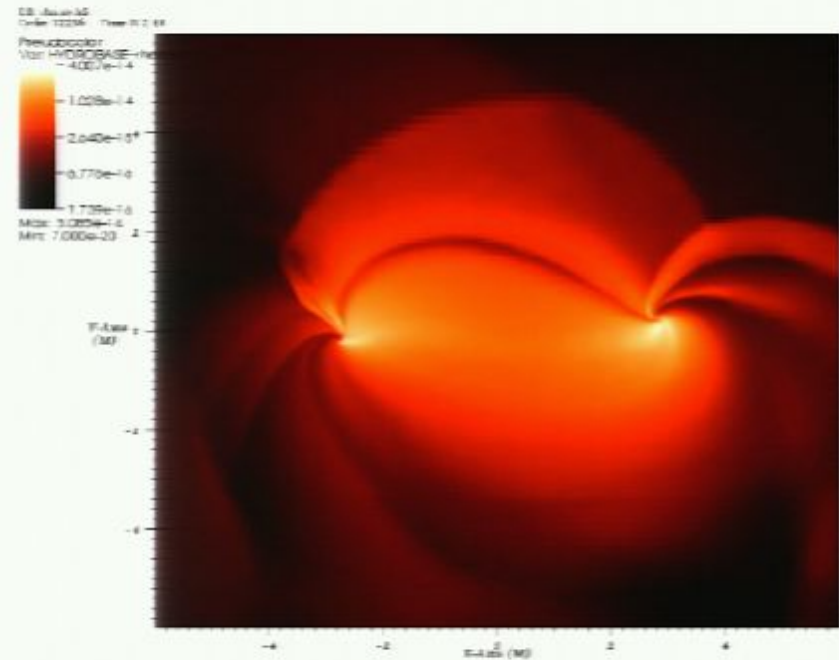


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

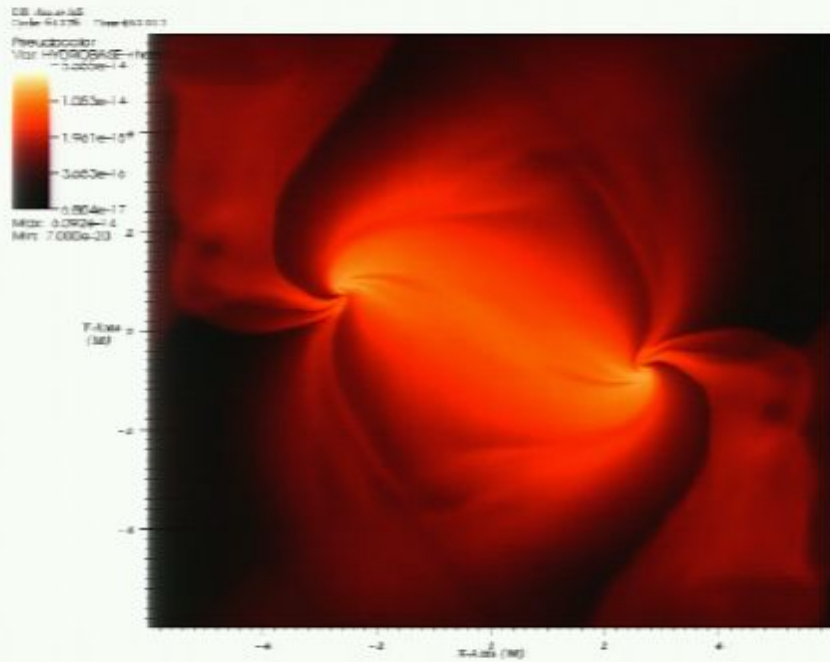


$$s_1/m^2 = s_2/m^2 = 0.6$$

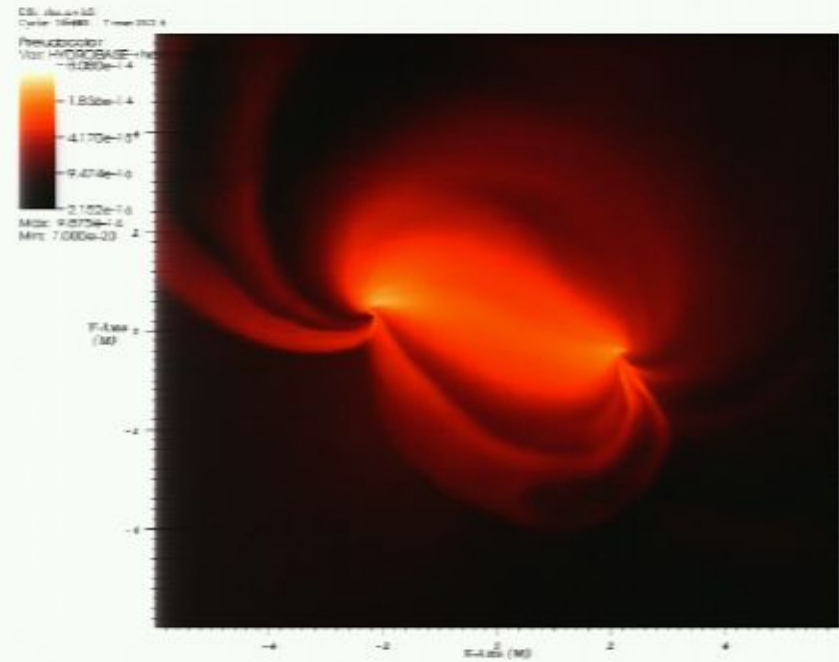


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

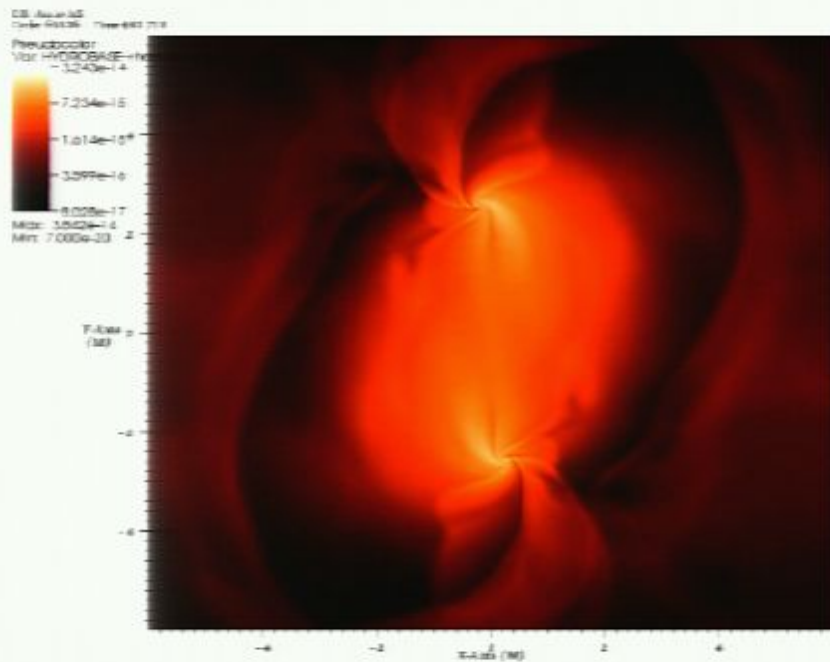


$$s_1/m^2 = s_2/m^2 = 0.6$$

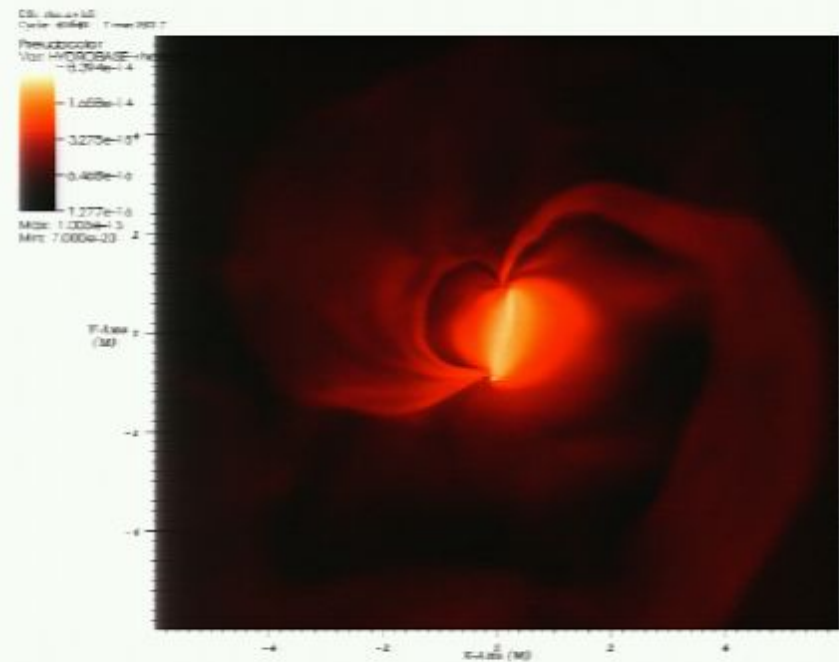


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

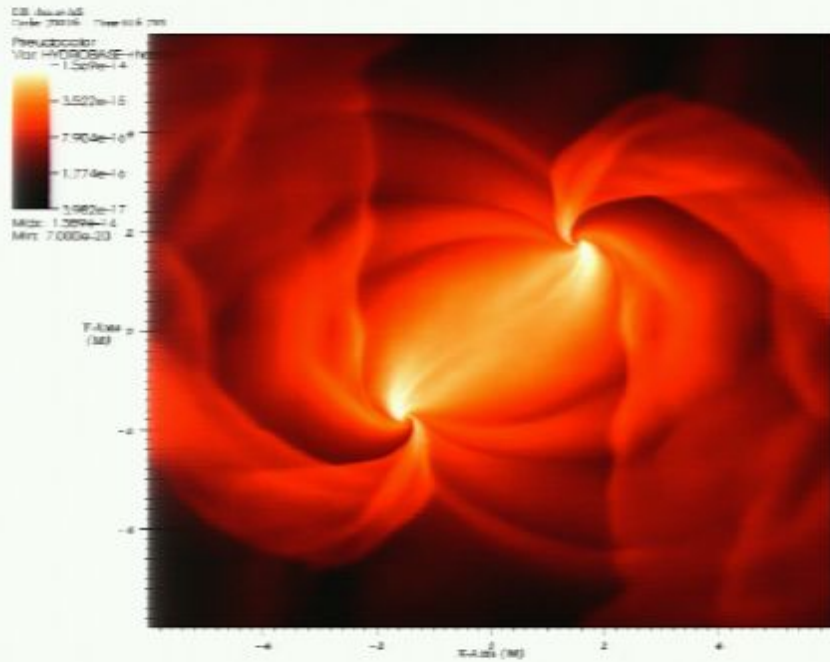


$$s_1/m^2 = s_2/m^2 = 0.6$$

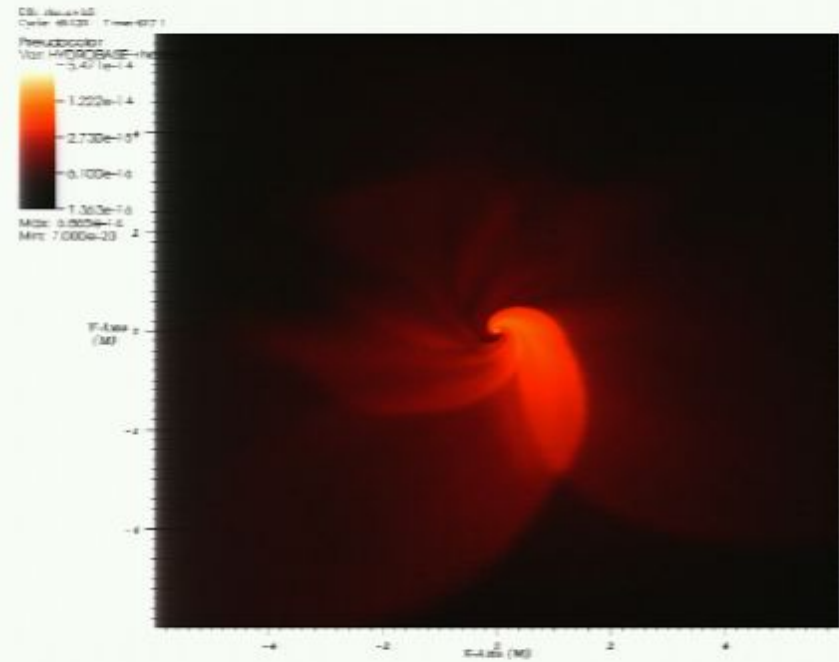


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

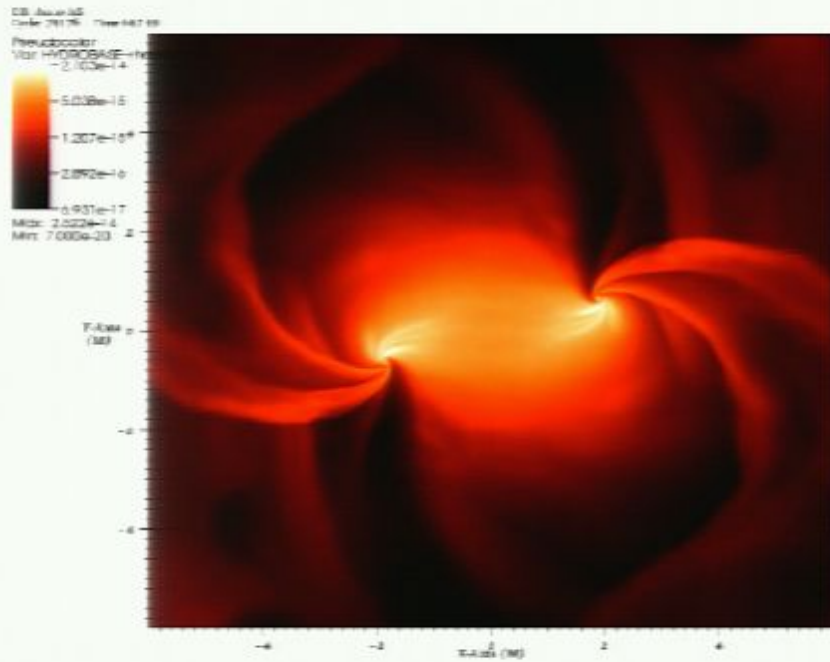


$$s_1/m^2 = s_2/m^2 = 0.6$$

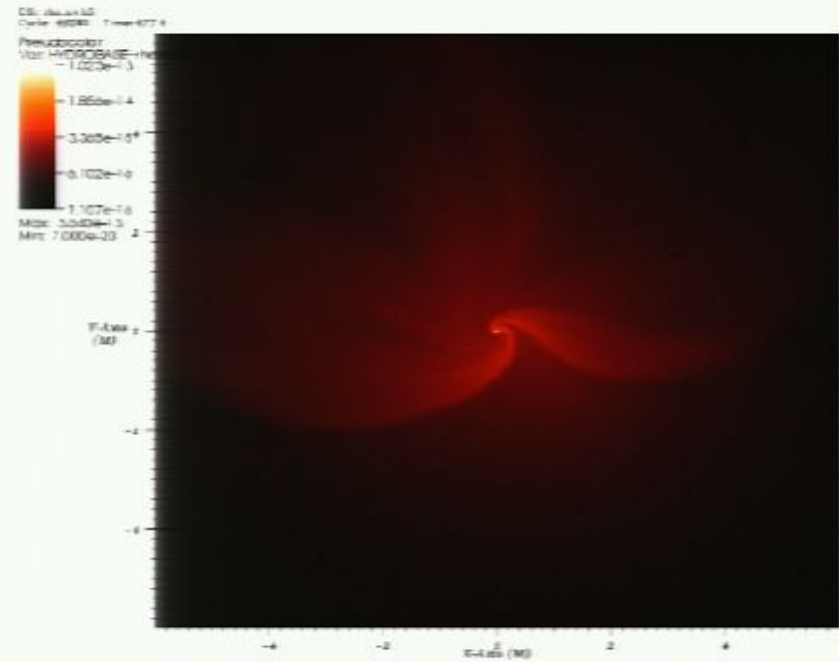


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

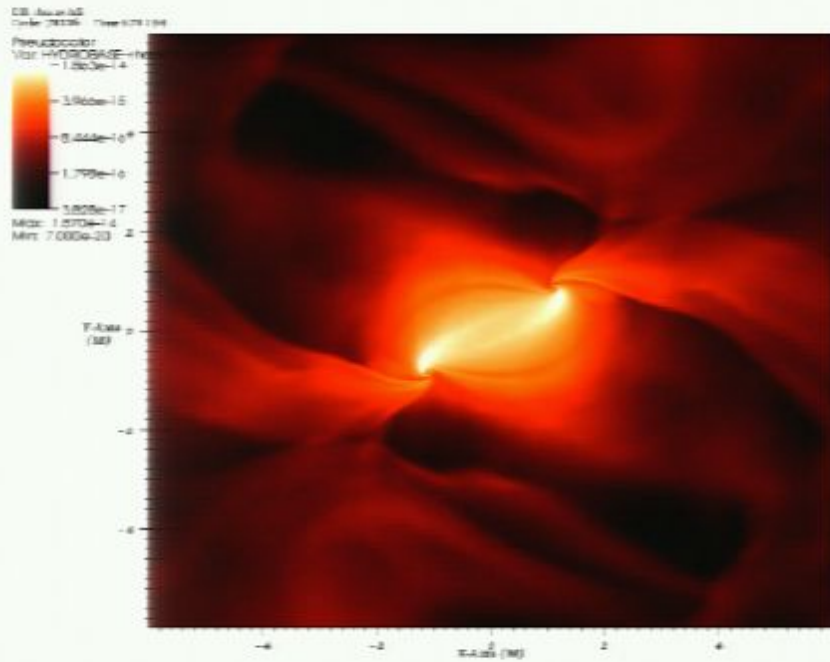


$$s_1/m^2 = s_2/m^2 = 0.6$$

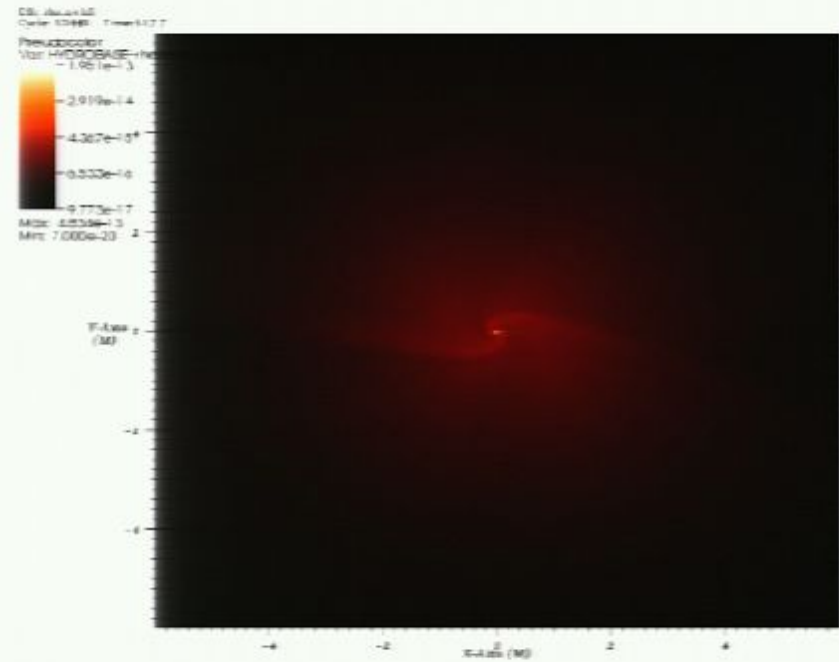


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

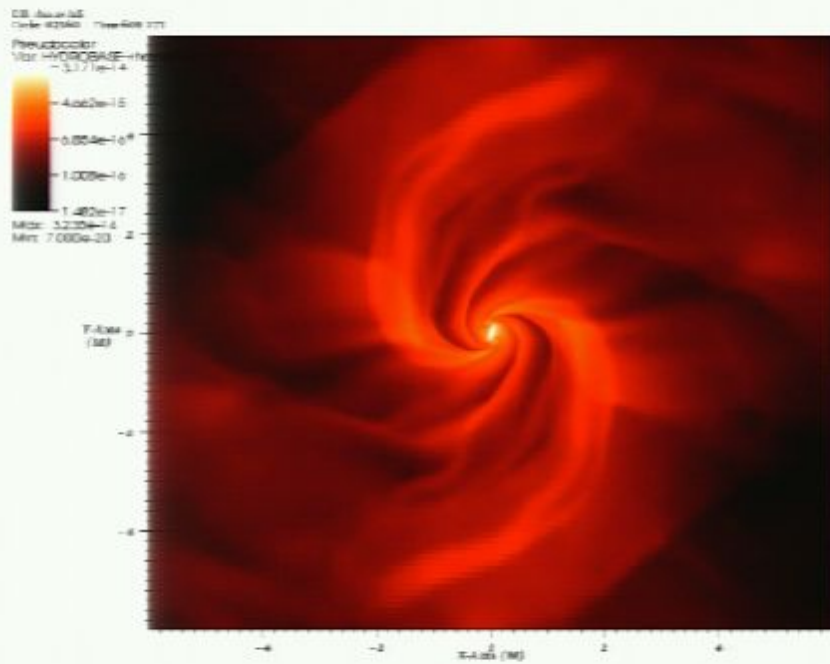


$$s_1/\text{m}^2 = s_2/\text{m}^2 = 0.6$$

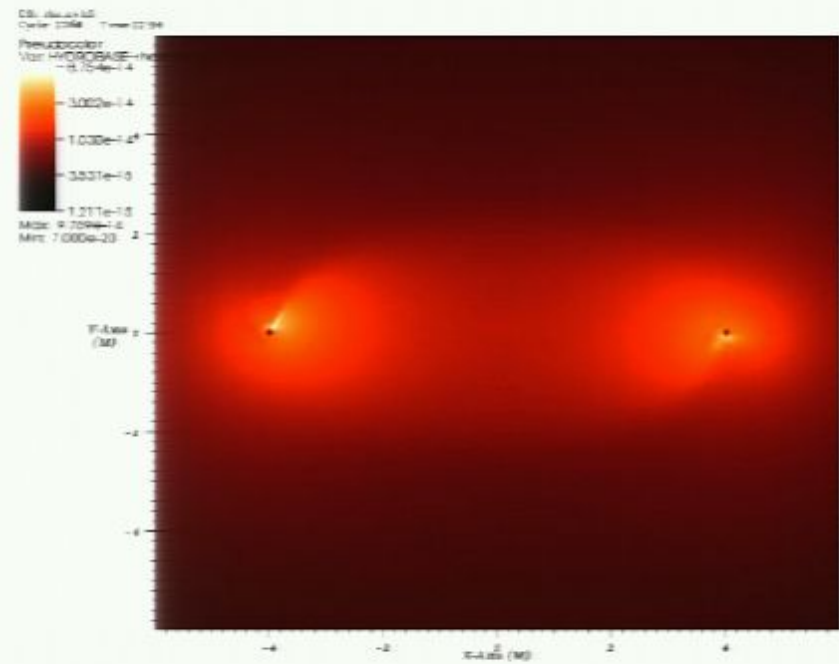


$$s_1/\text{m}^2 = -0.4 \quad s_2/\text{m}^2 = 0.4$$

Gas Density

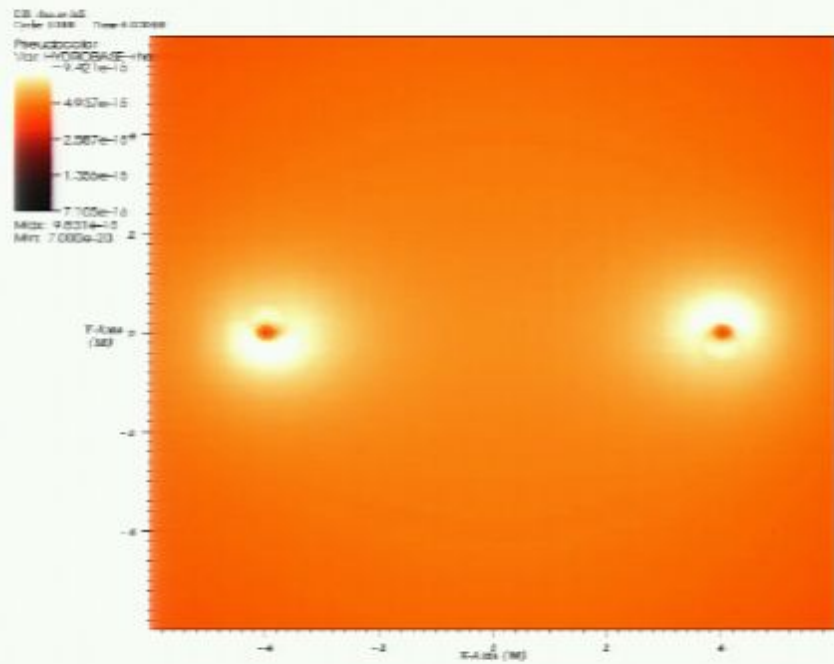


$$s_1/m^2 = s_2/m^2 = 0.6$$

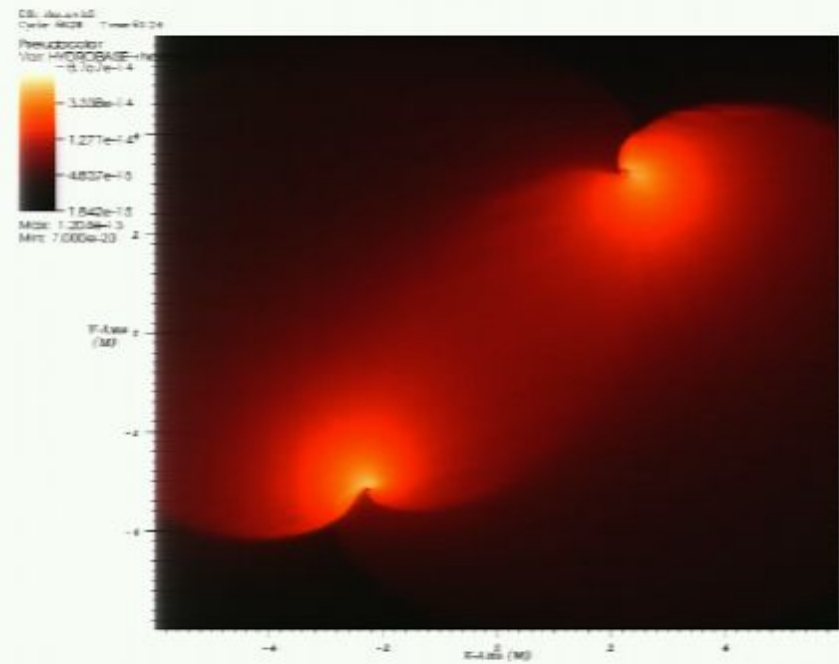


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

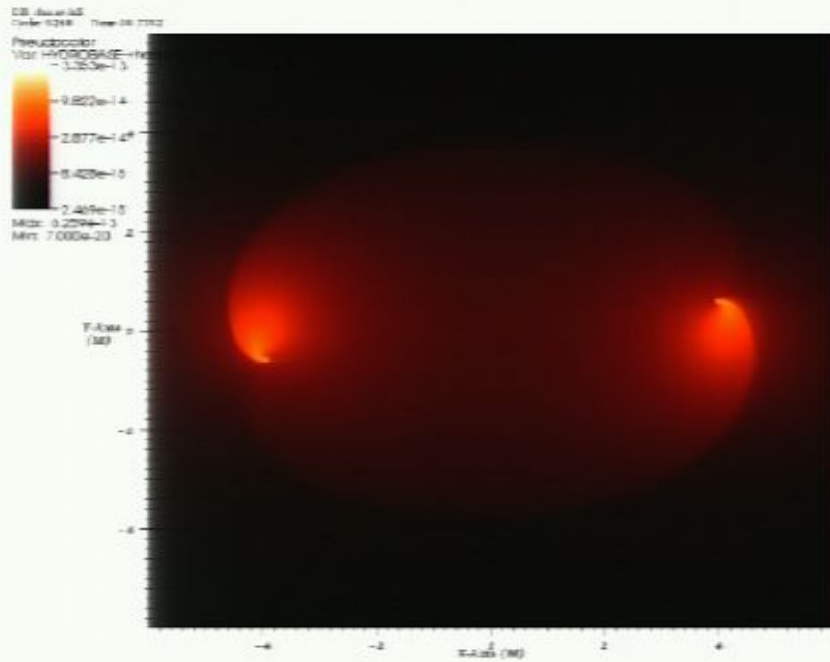


$$s_1/m^2 = s_2/m^2 = 0.6$$

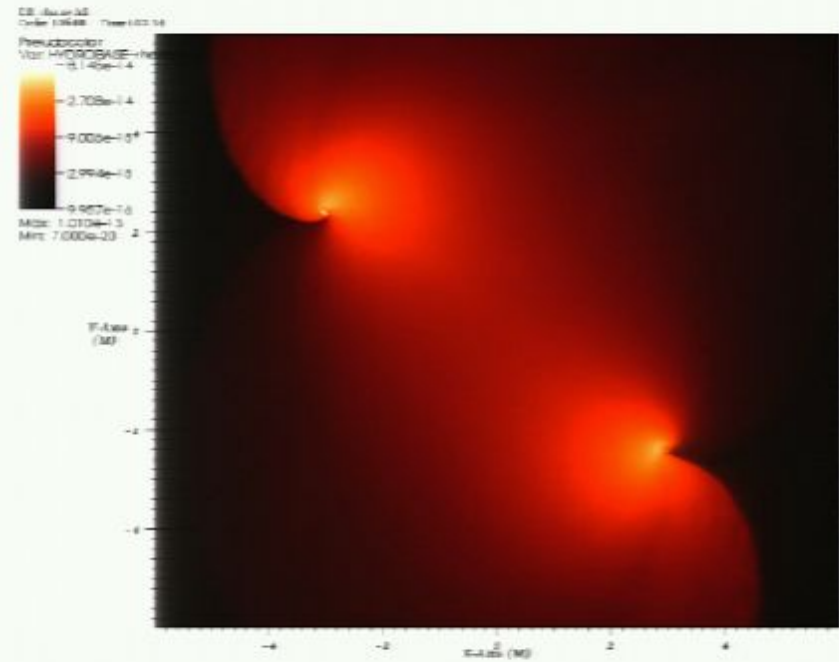


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density



$$s_1/m^2 = s_2/m^2 = 0.6$$

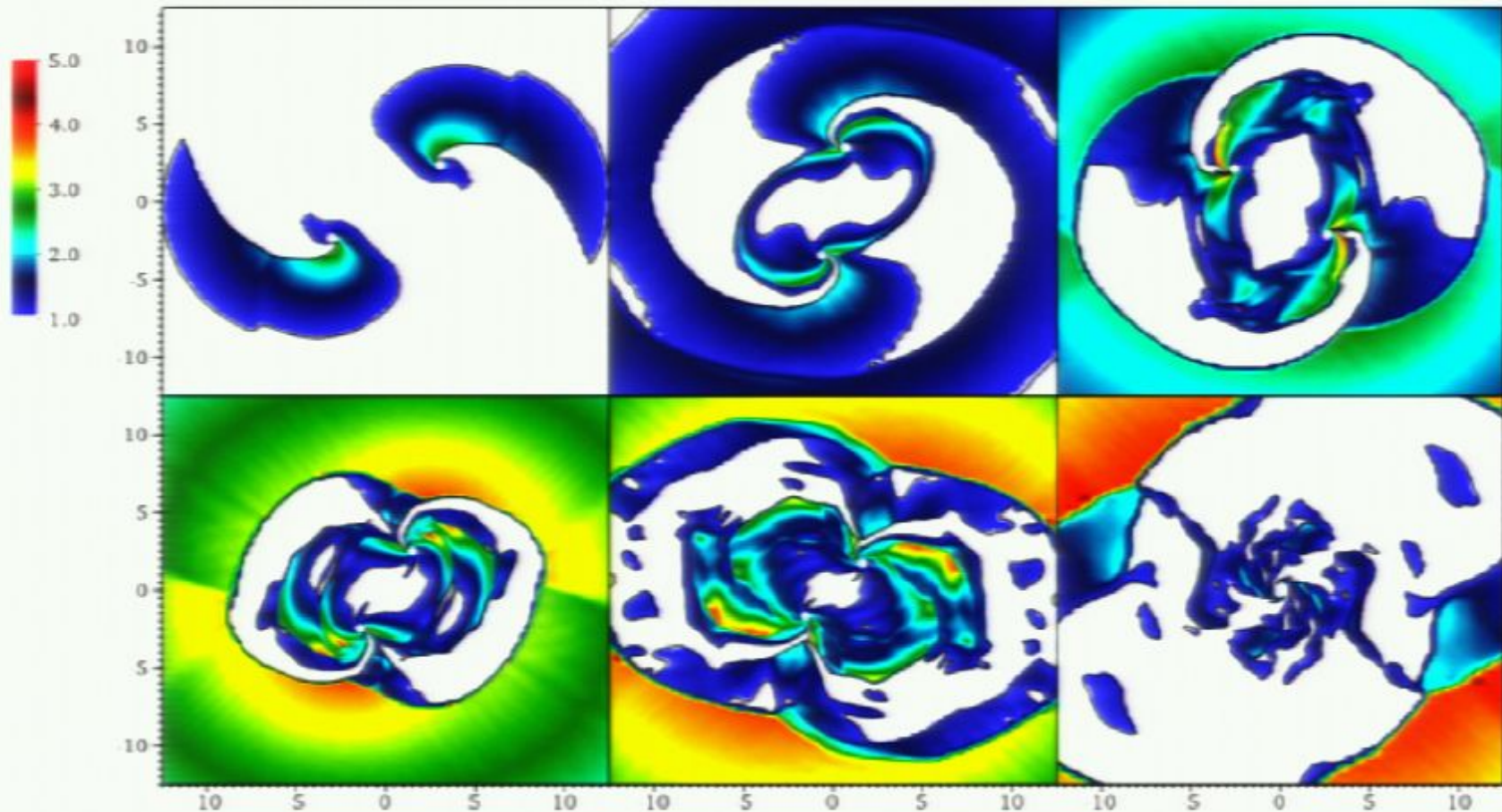


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Shocks triggered by the orbiting BHs

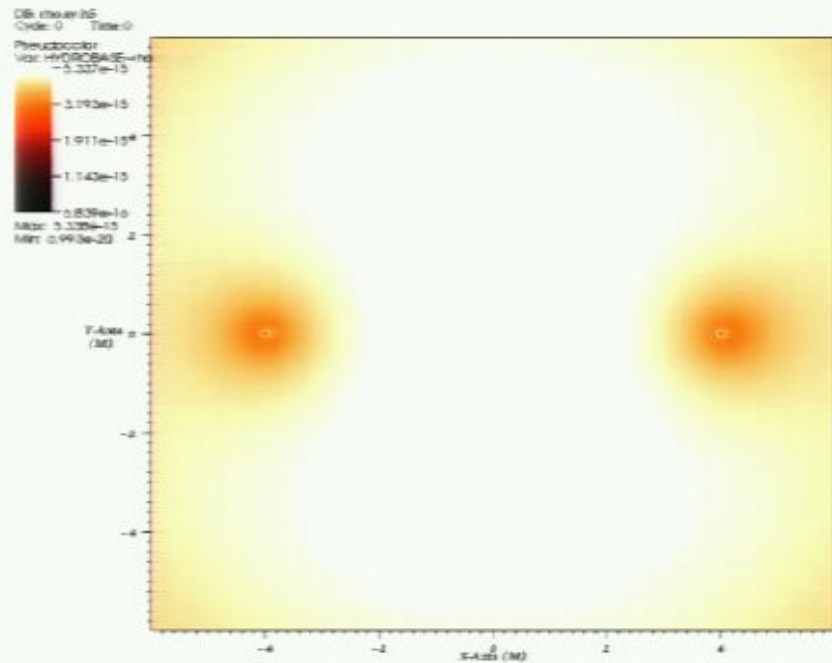
Mach number > 1

$s_1 = s_2 = +0.6$

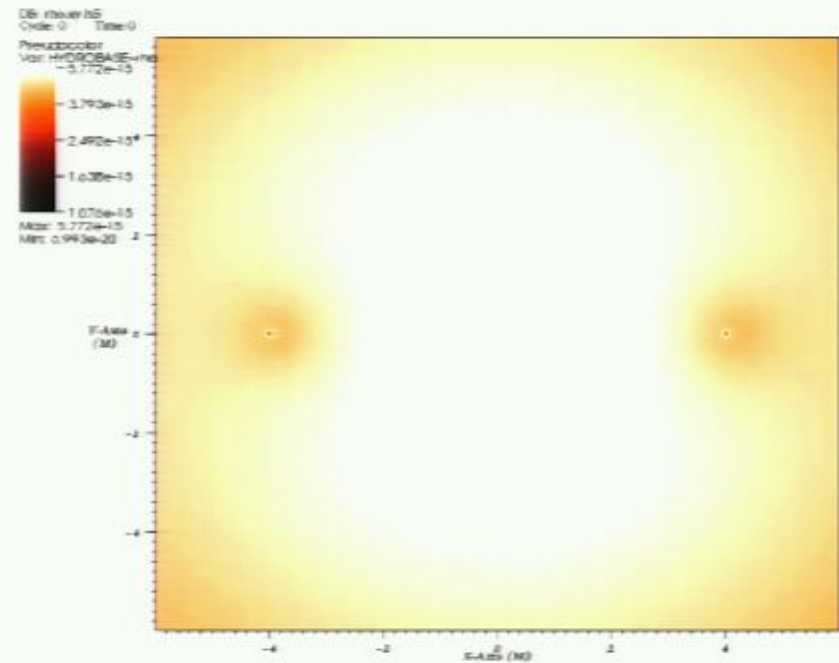


(Bode+ 09)

Gas Density



$$s_1/m^2 = s_2/m^2 = 0.6$$

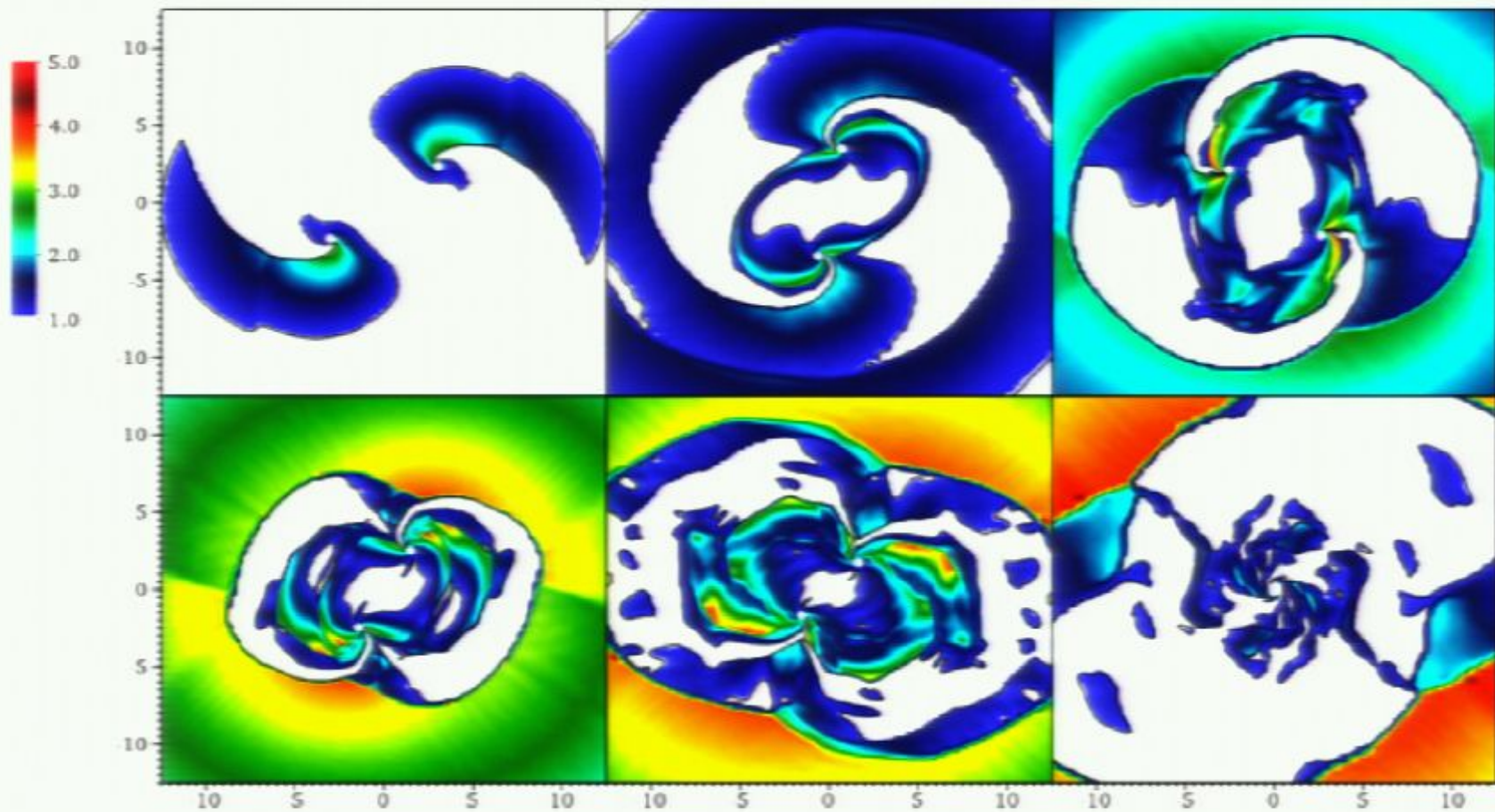


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Shocks triggered by the orbiting BHs

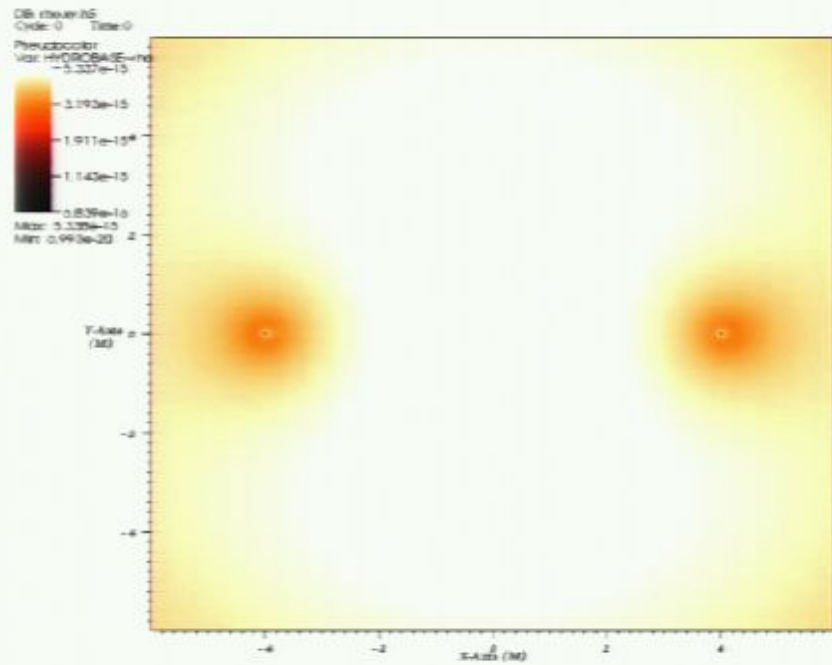
Mach number > 1

$s_1 = s_2 = +0.6$

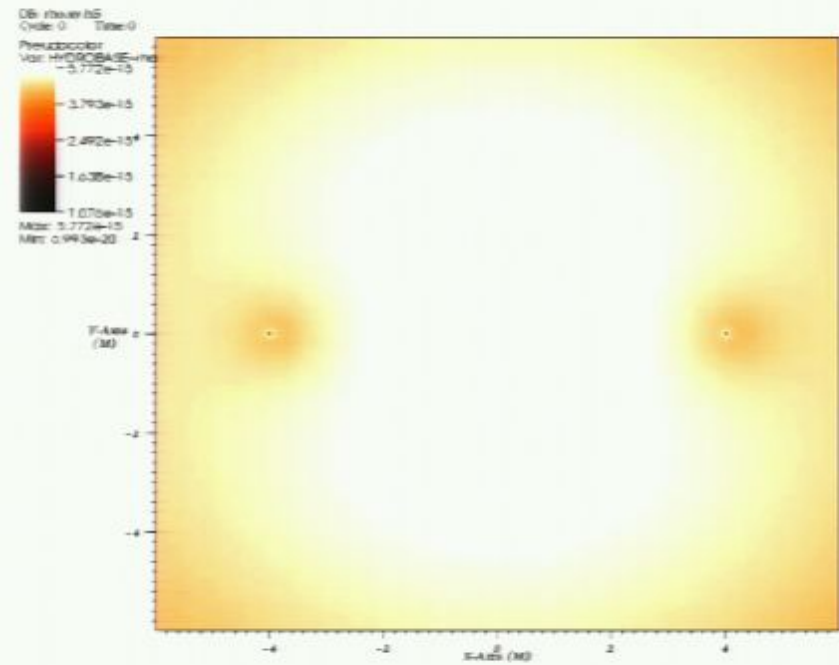


(Bode+ 09)

Gas Density

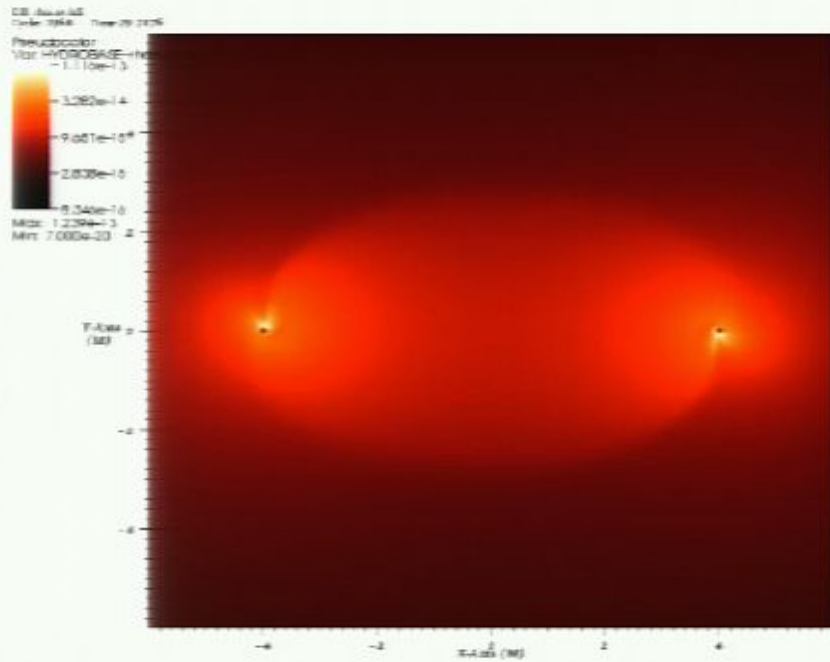


$$s_1/m^2 = s_2/m^2 = 0.6$$

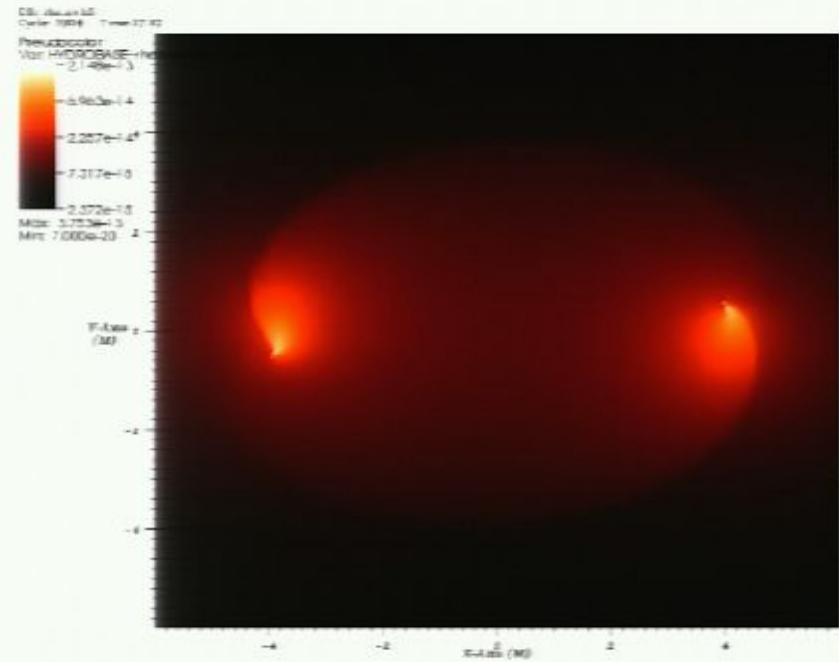


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

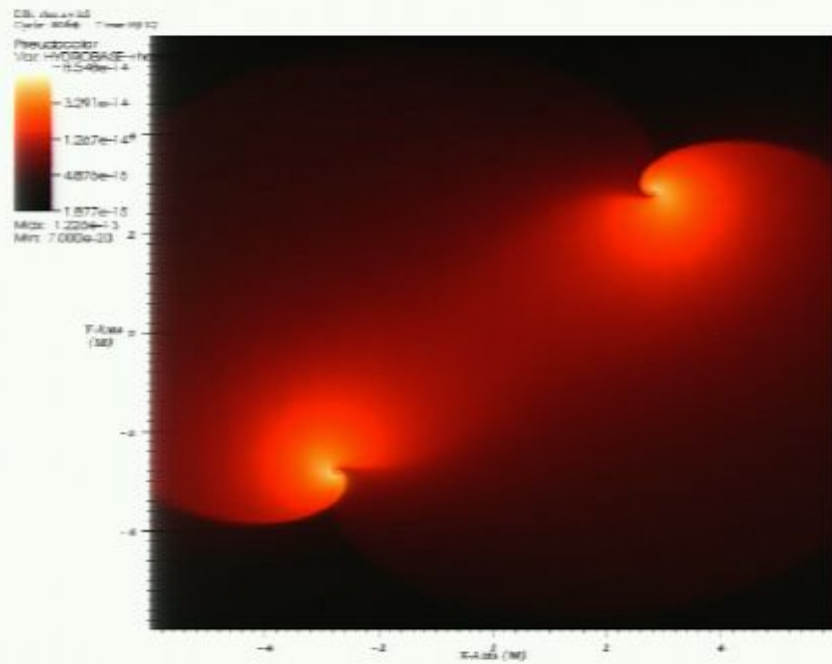


$$s_1/m^2 = s_2/m^2 = 0.6$$

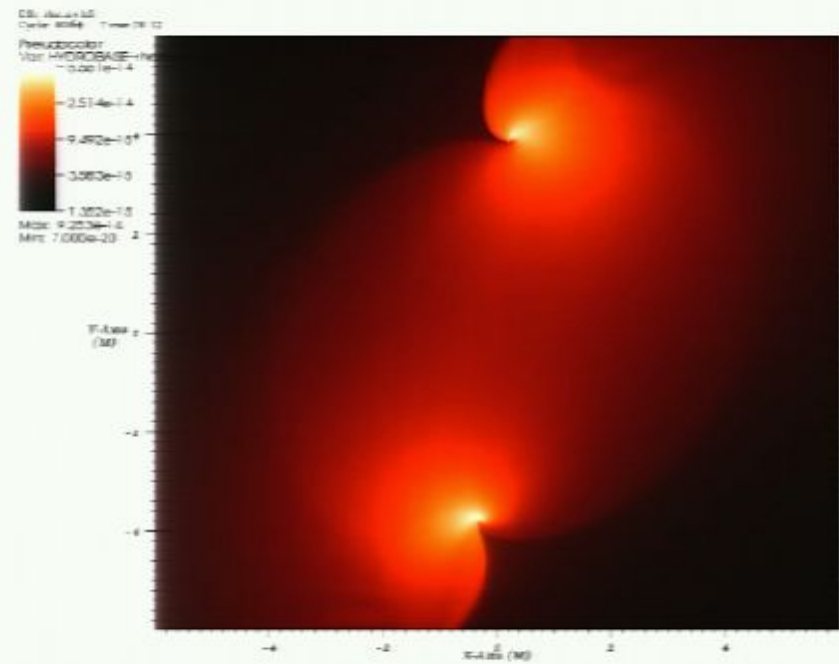


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

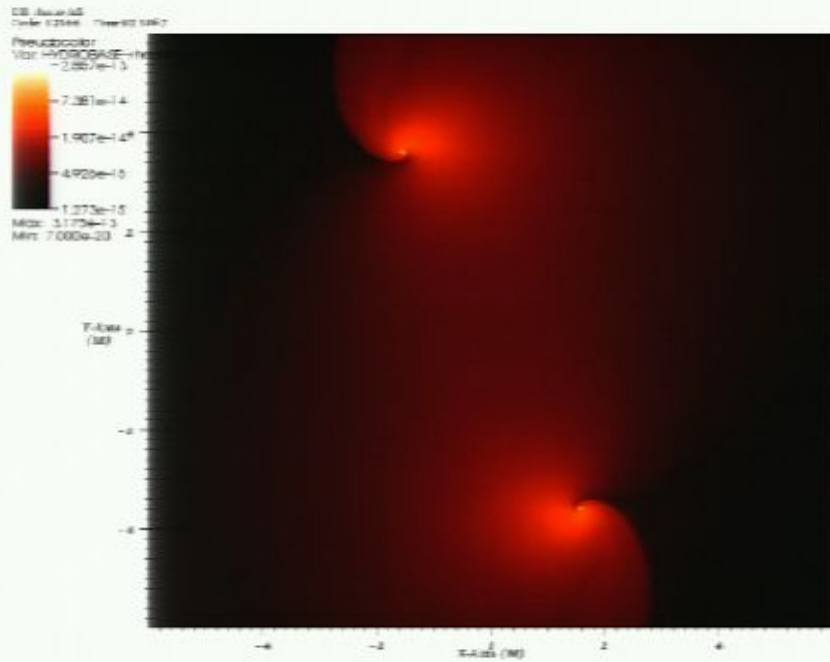


$$s_1/m^2 = s_2/m^2 = 0.6$$

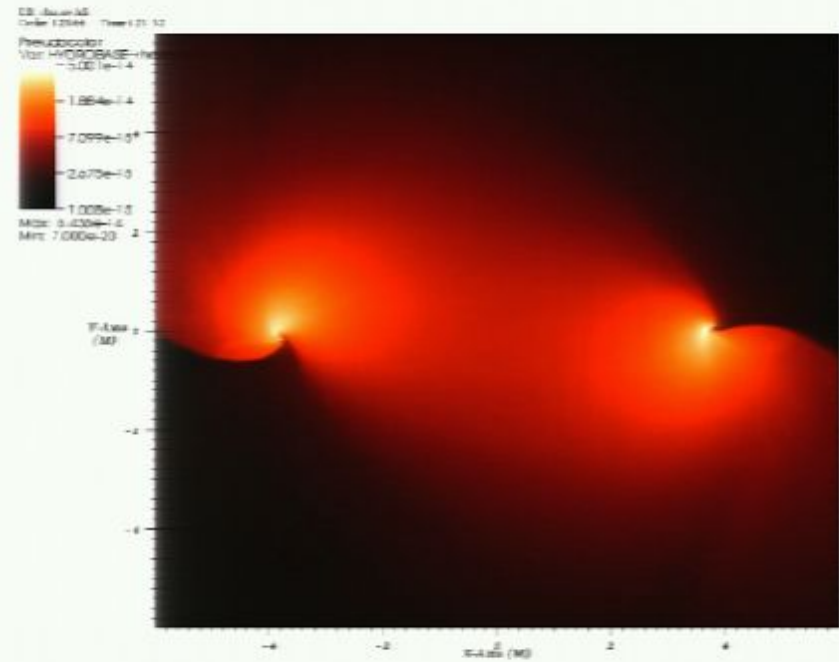


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

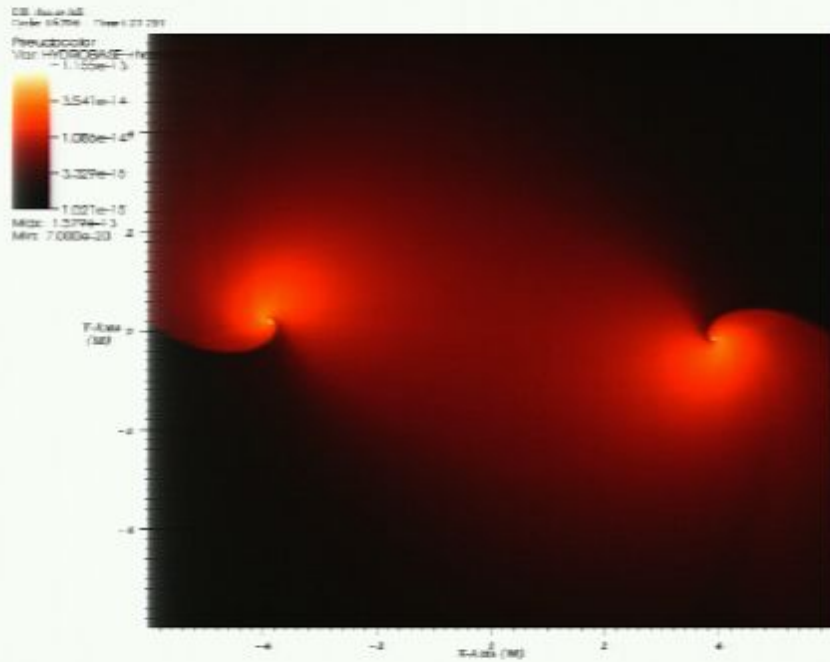


$$s_1/m^2 = s_2/m^2 = 0.6$$

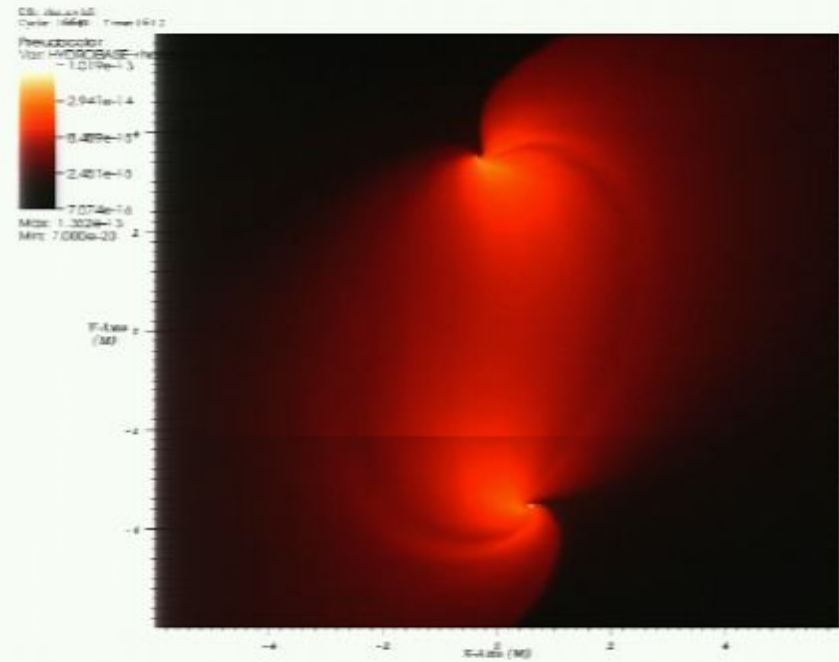


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

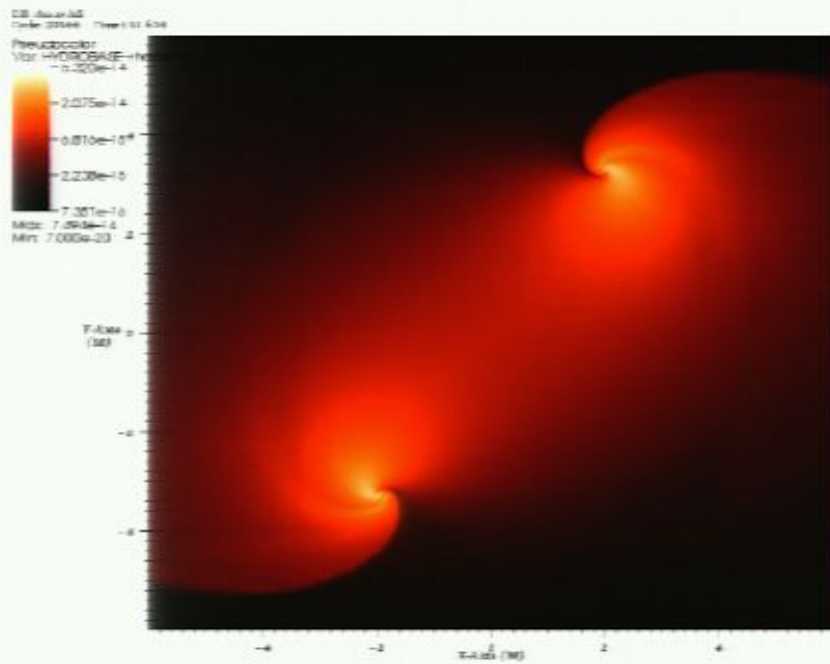


$$s_1/m^2 = s_2/m^2 = 0.6$$

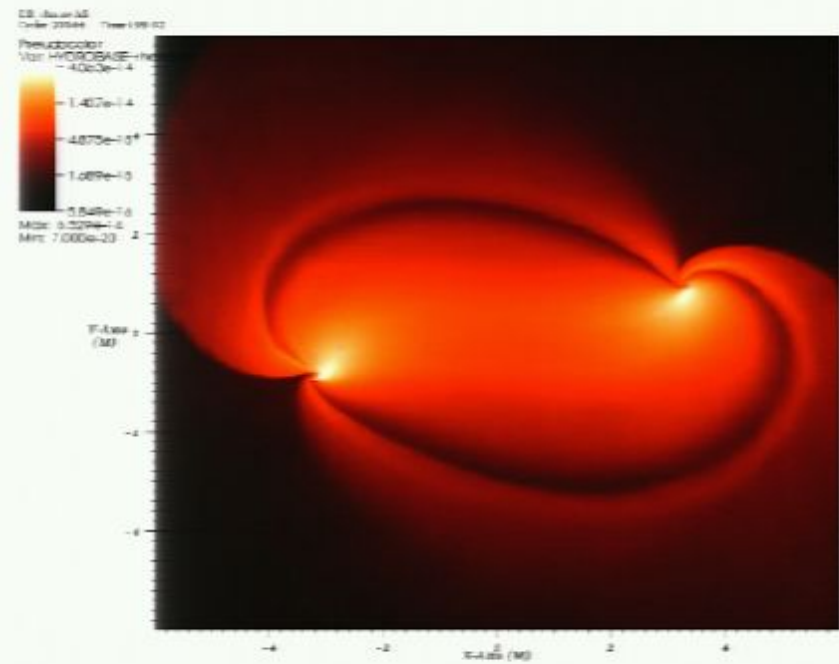


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

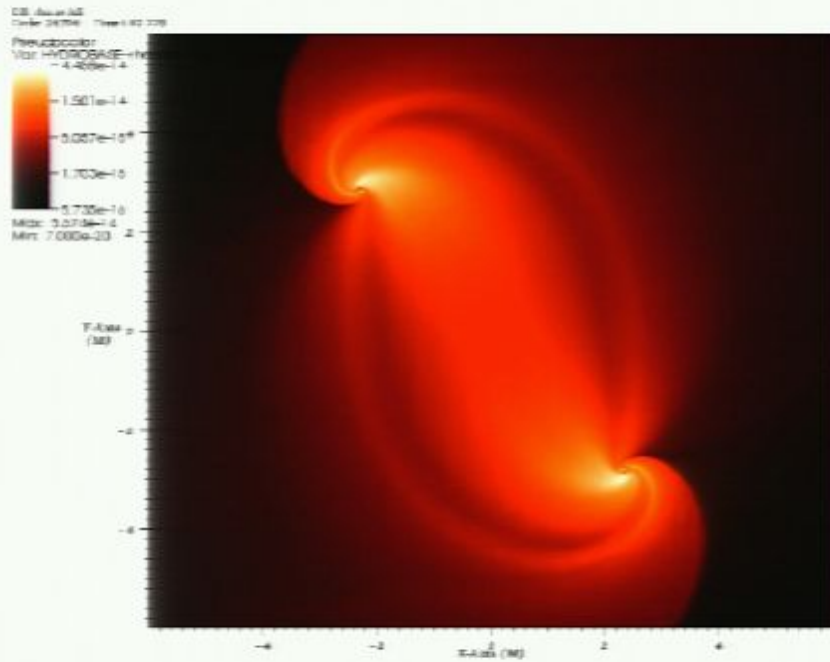


$$s_1/m^2 = s_2/m^2 = 0.6$$

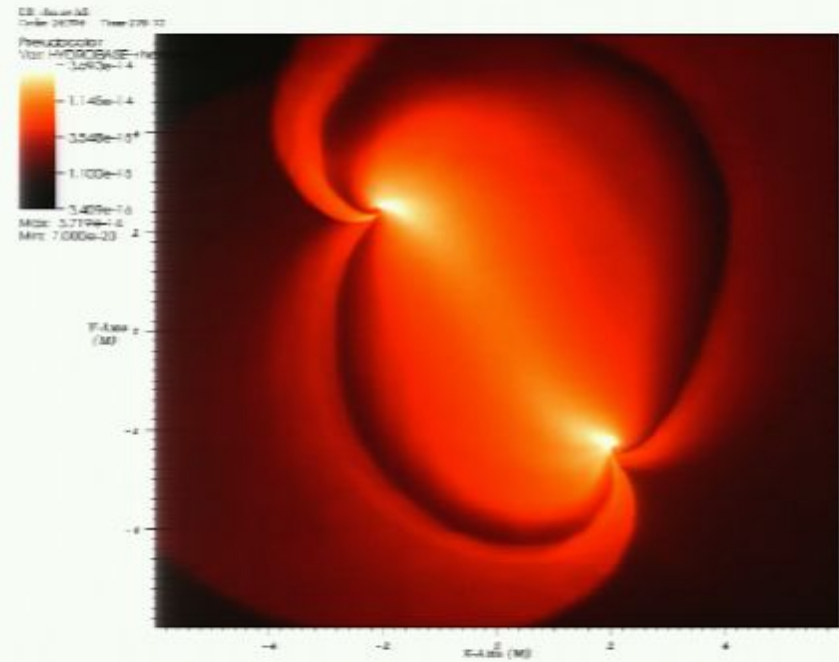


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

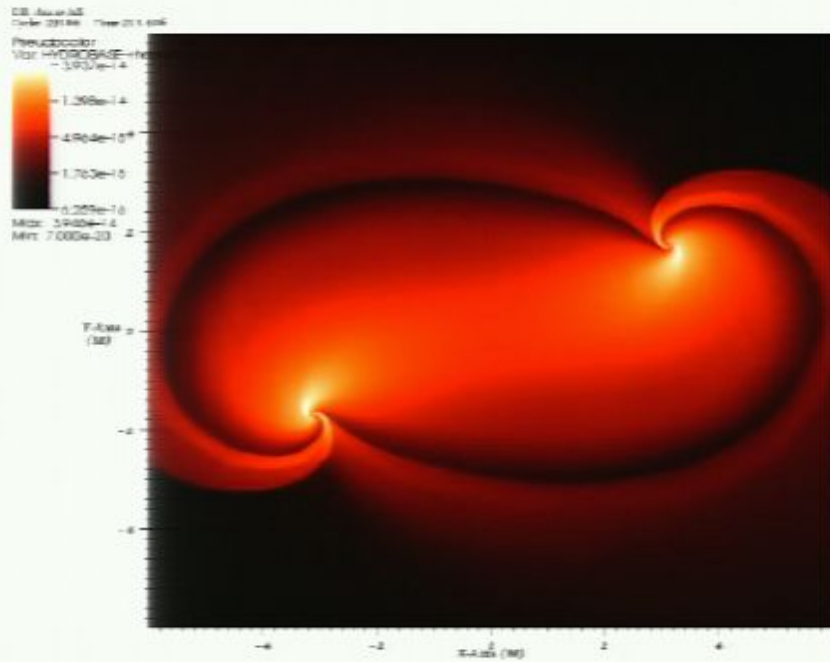


$$s_1/m^2 = s_2/m^2 = 0.6$$

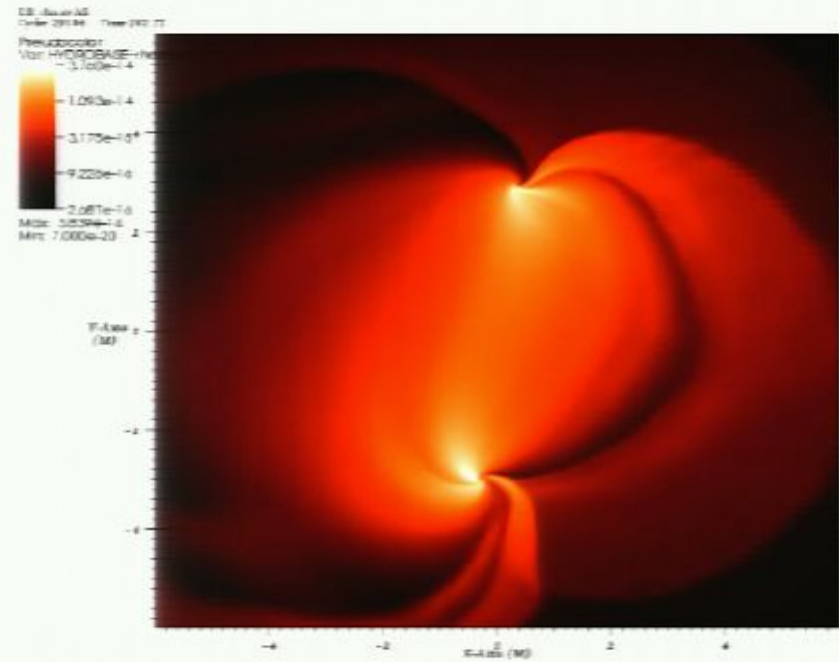


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

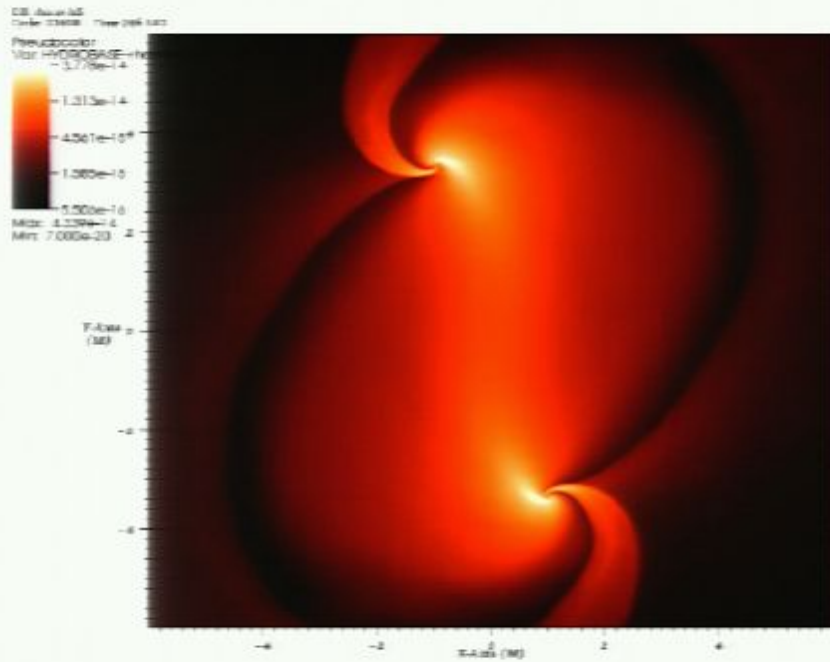


$$s_1/m^2 = s_2/m^2 = 0.6$$

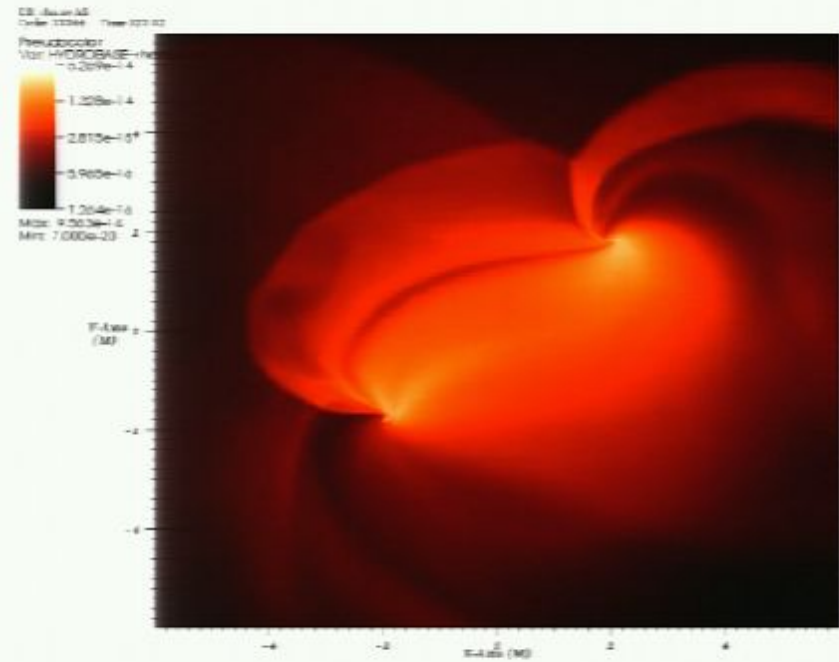


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

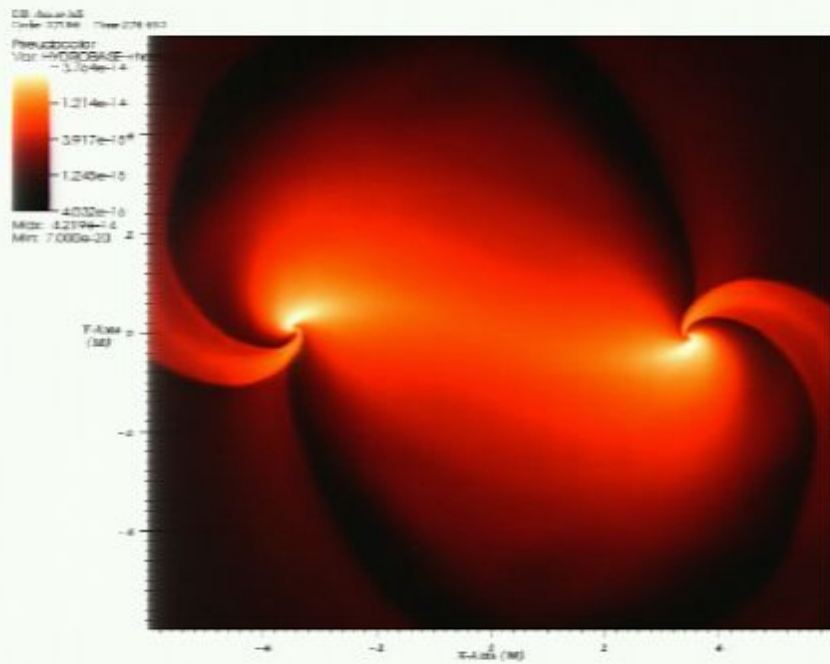


$$s_1/m^2 = s_2/m^2 = 0.6$$

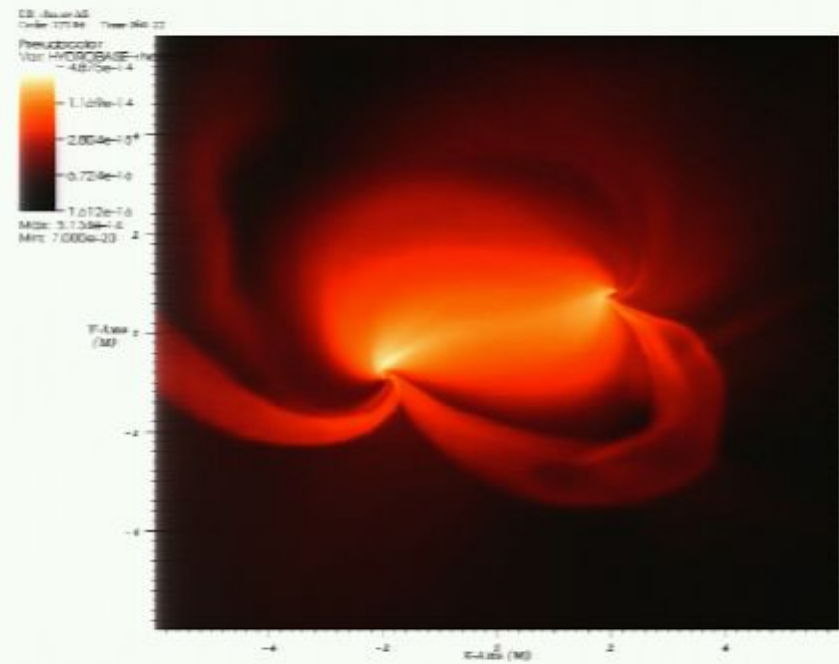


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

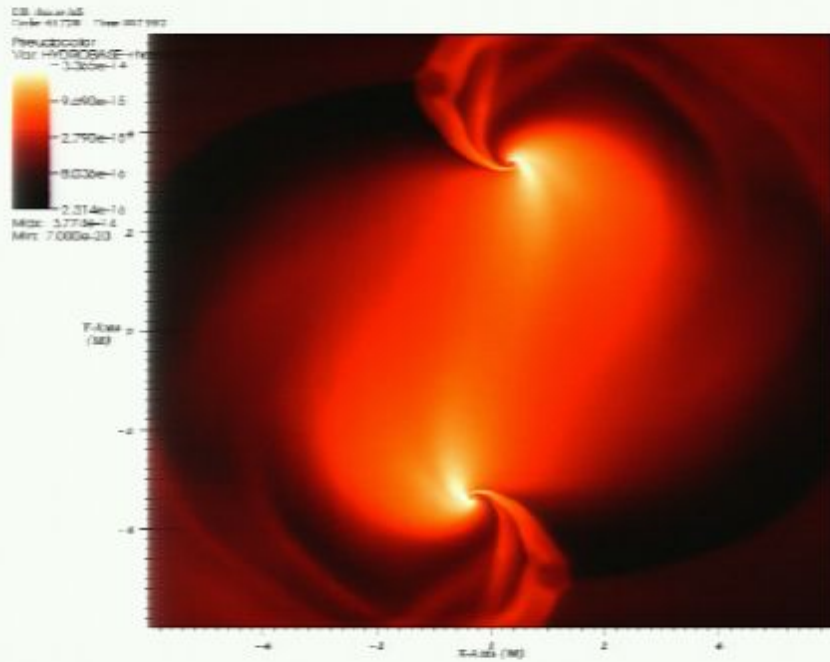


$$s_1/m^2 = s_2/m^2 = 0.6$$

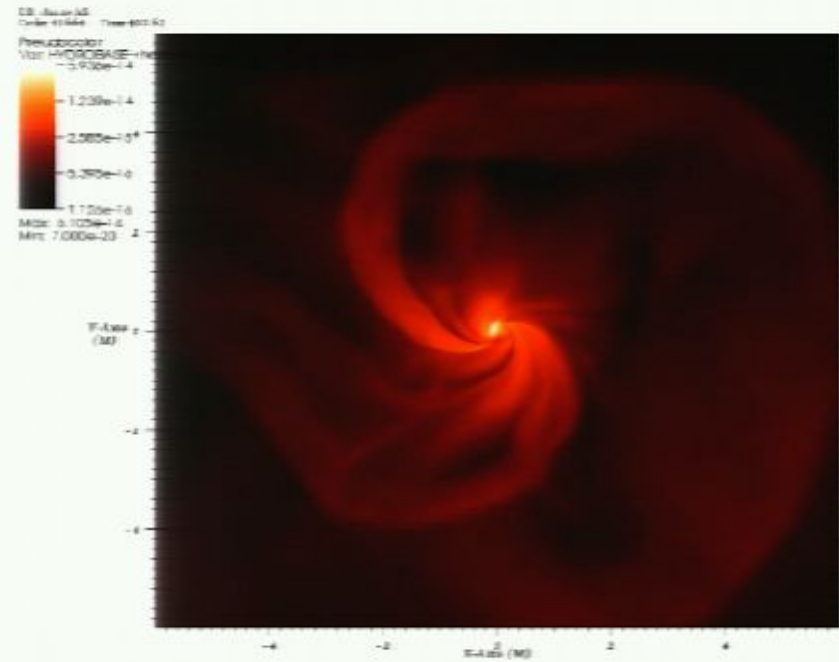


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

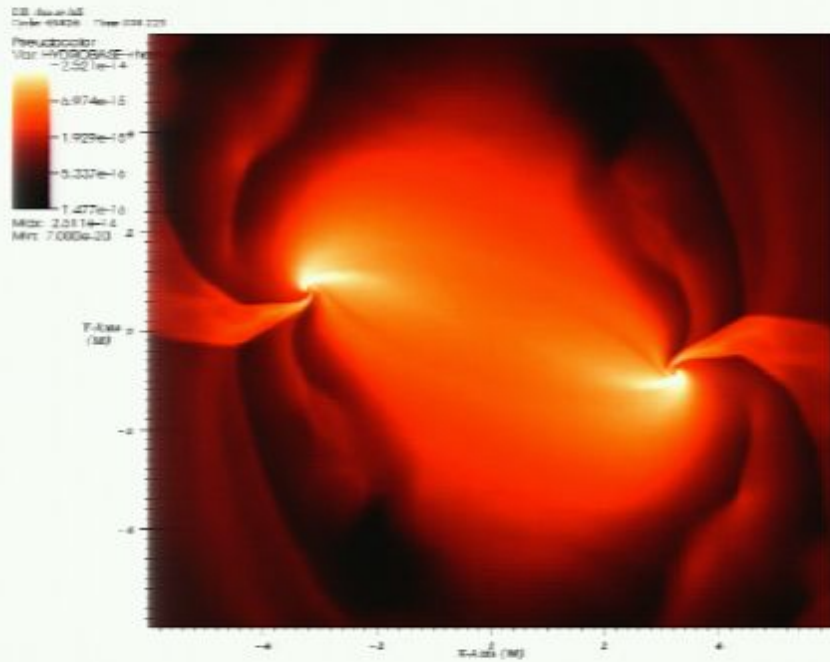


$$s_1/m^2 = s_2/m^2 = 0.6$$

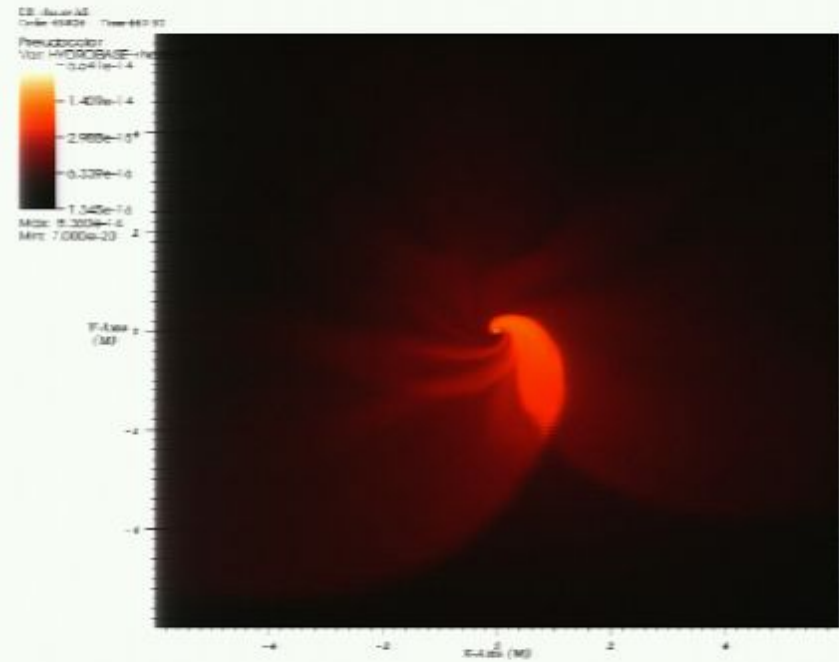


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

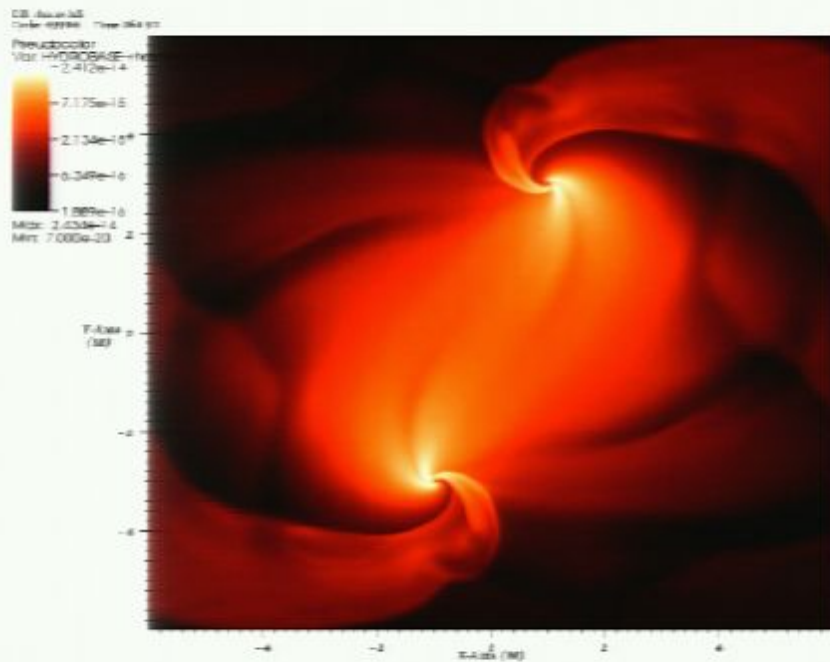


$$s_1/m^2 = s_2/m^2 = 0.6$$

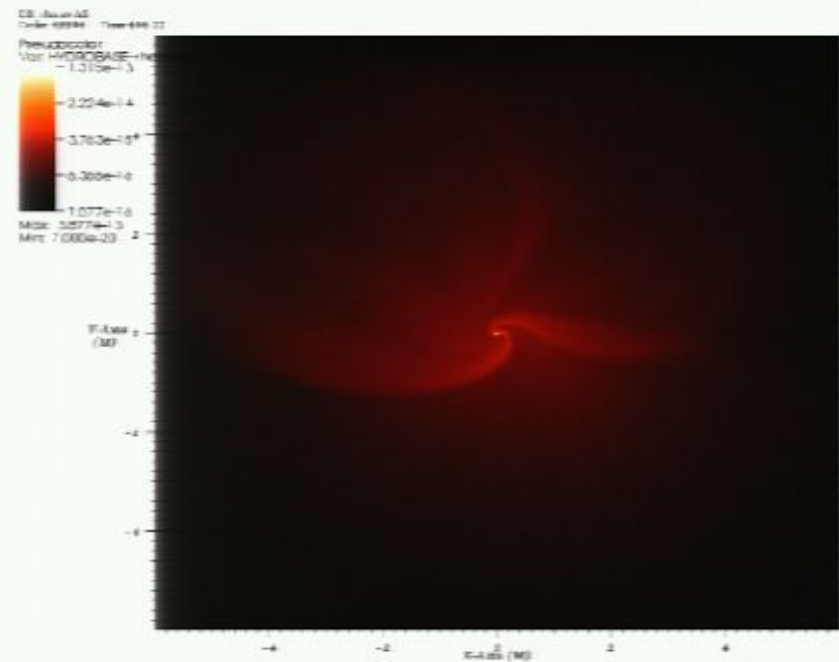


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

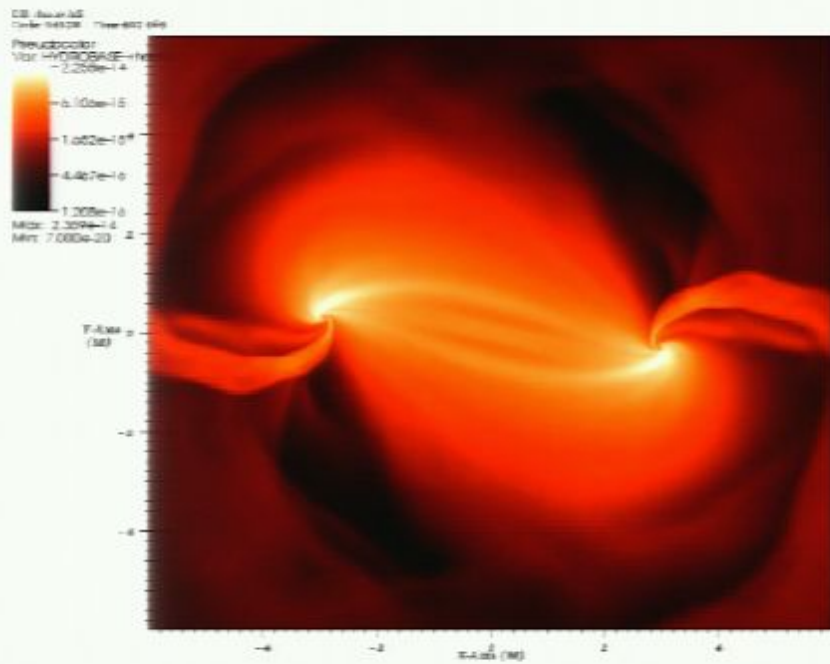


$$s_1/m^2 = s_2/m^2 = 0.6$$

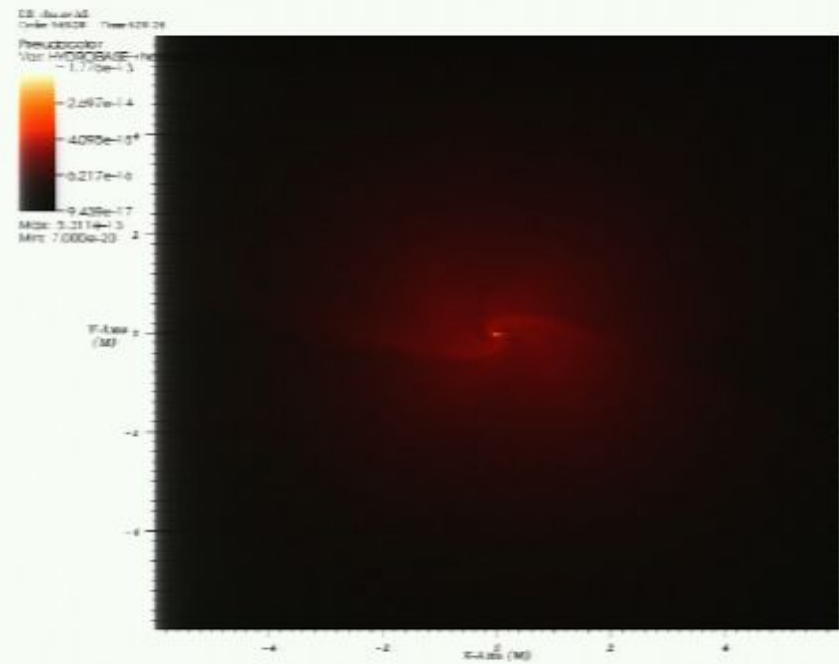


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

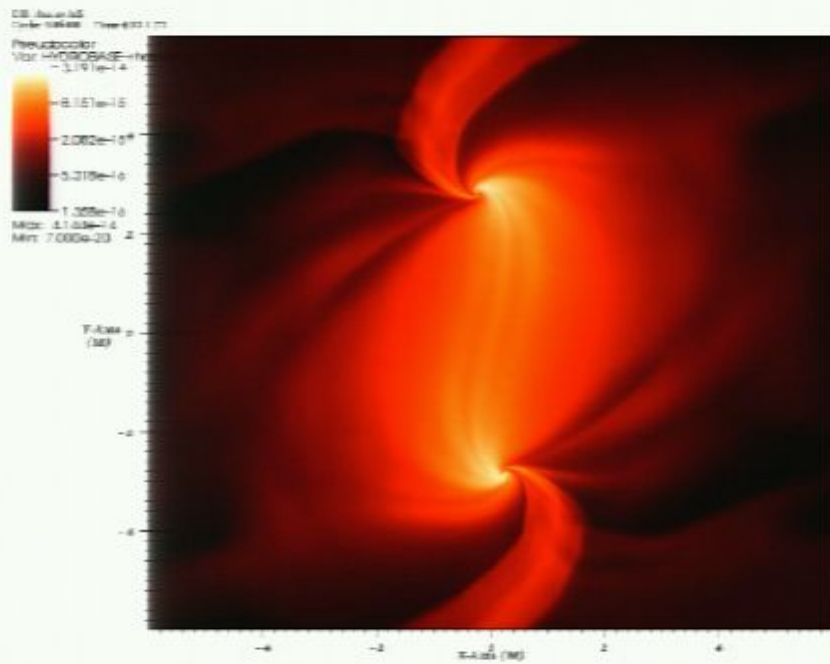


$$s_1/m^2 = s_2/m^2 = 0.6$$

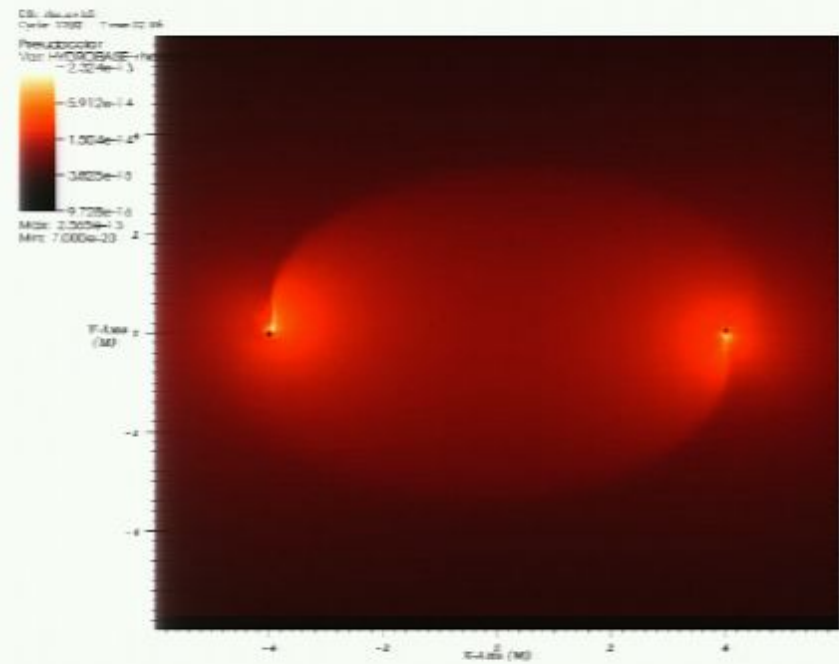


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

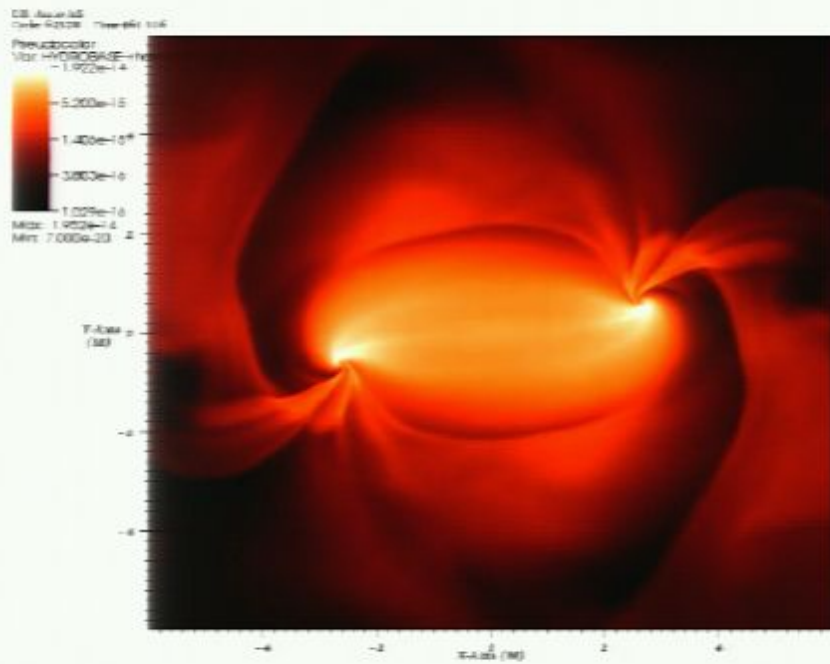


$$s_1/m^2 = s_2/m^2 = 0.6$$

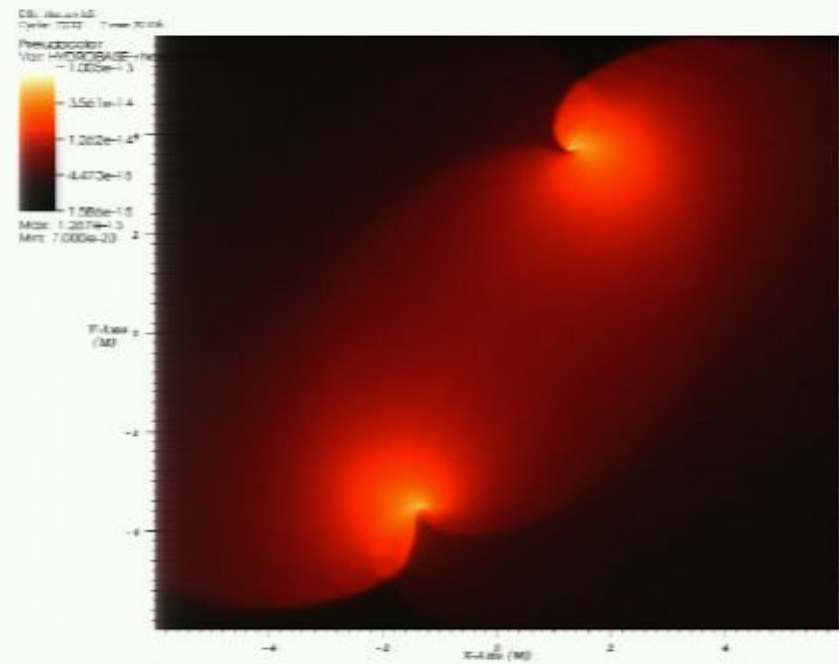


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

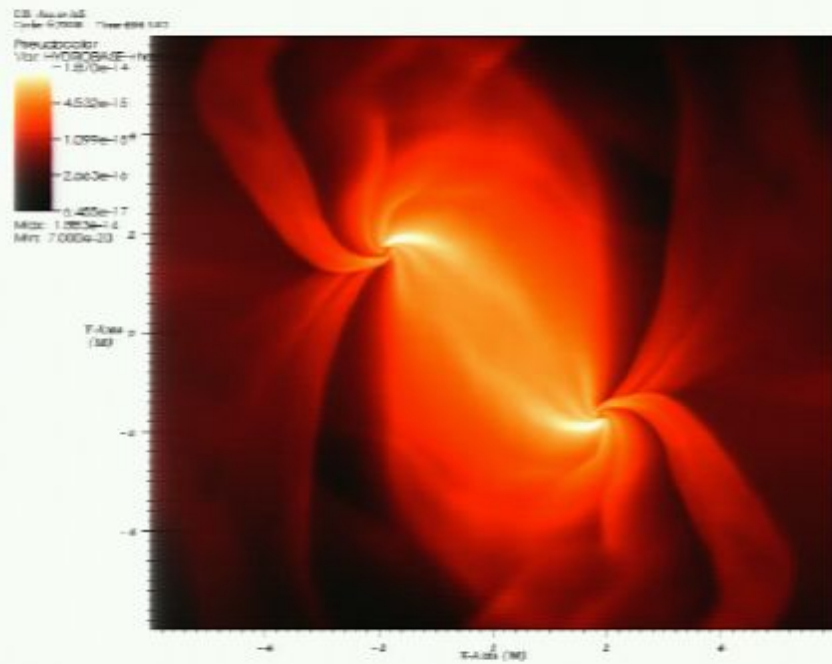


$$s_1/m^2 = s_2/m^2 = 0.6$$

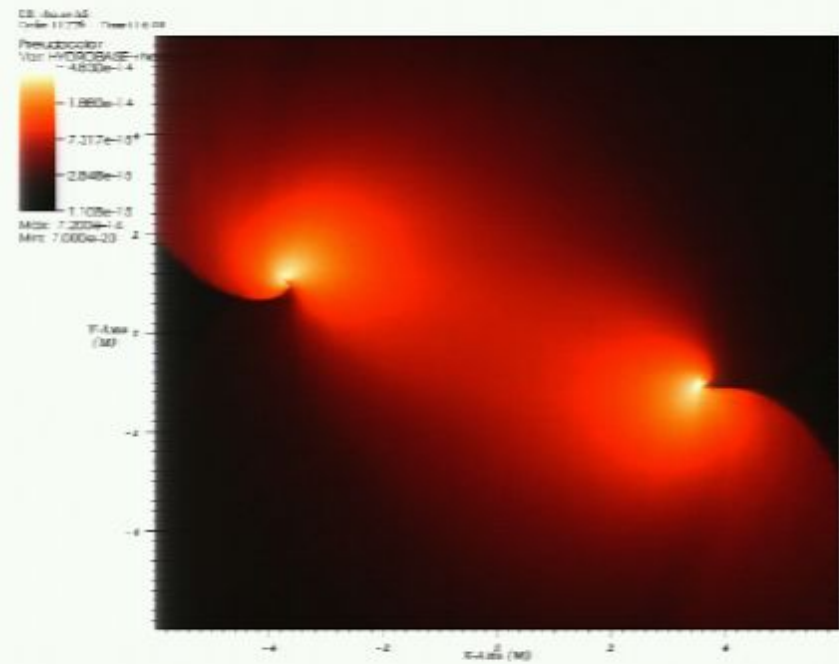


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

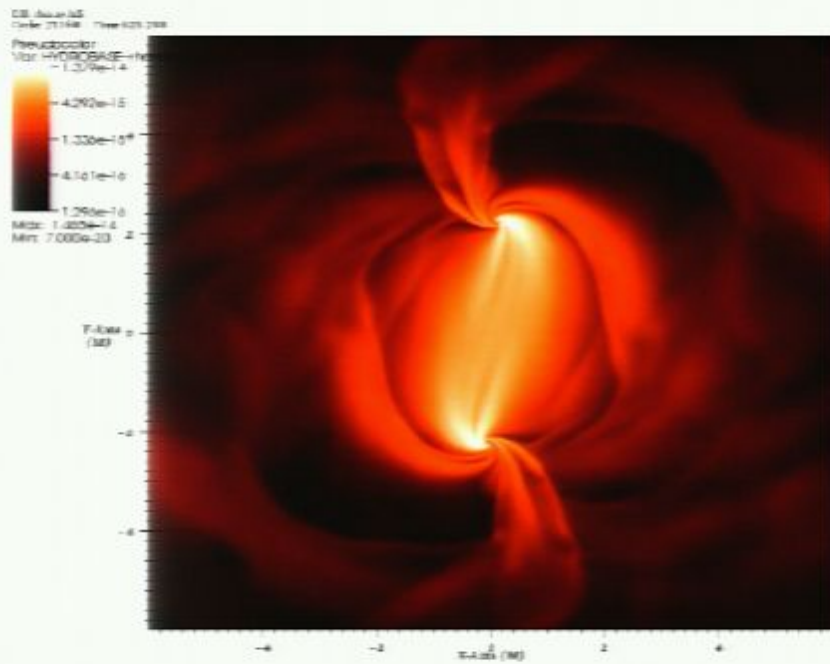


$$s_1/m^2 = s_2/m^2 = 0.6$$

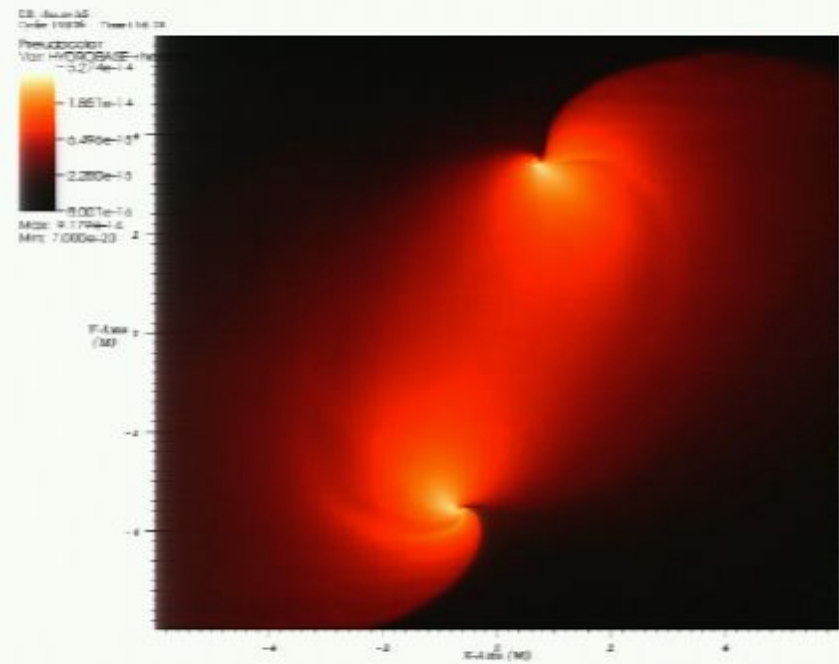


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

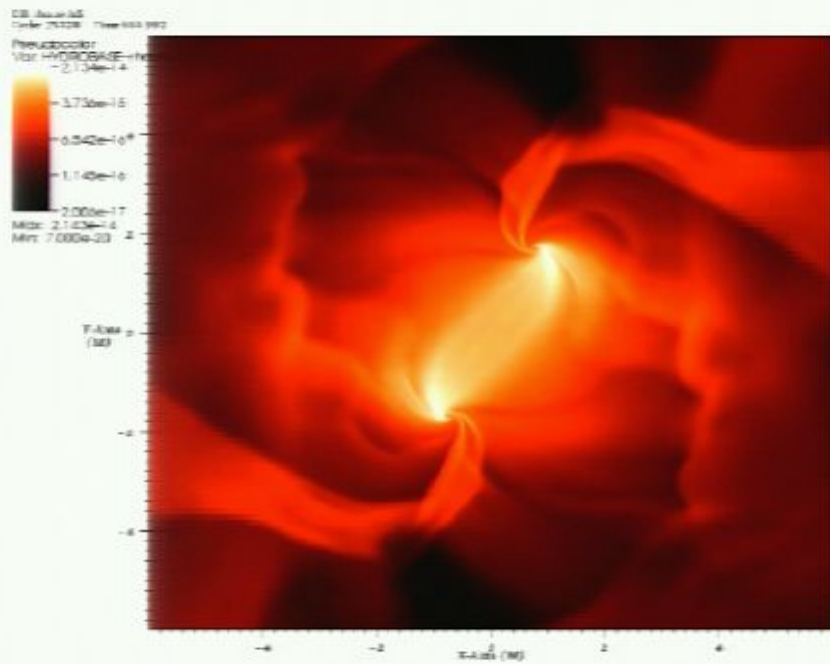


$$s_1/m^2 = s_2/m^2 = 0.6$$

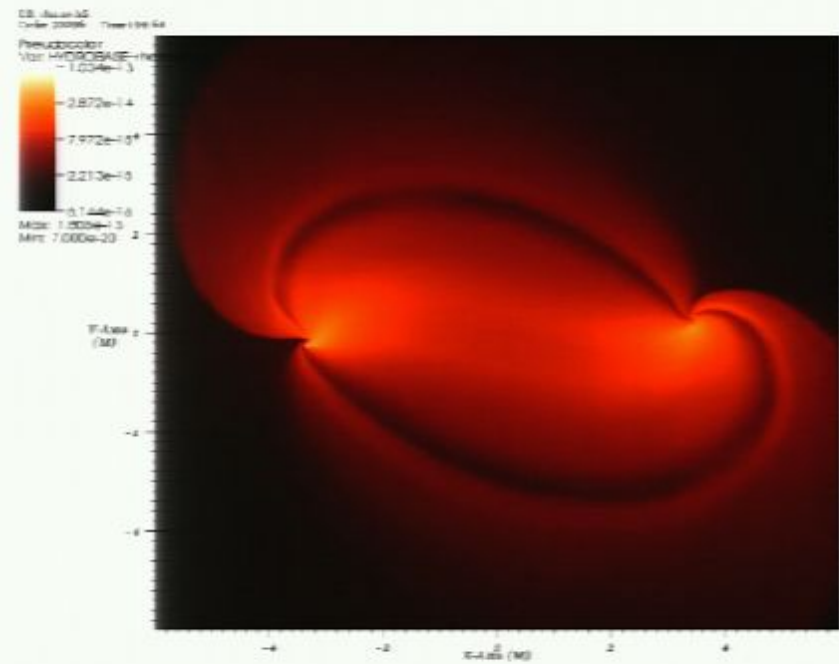


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

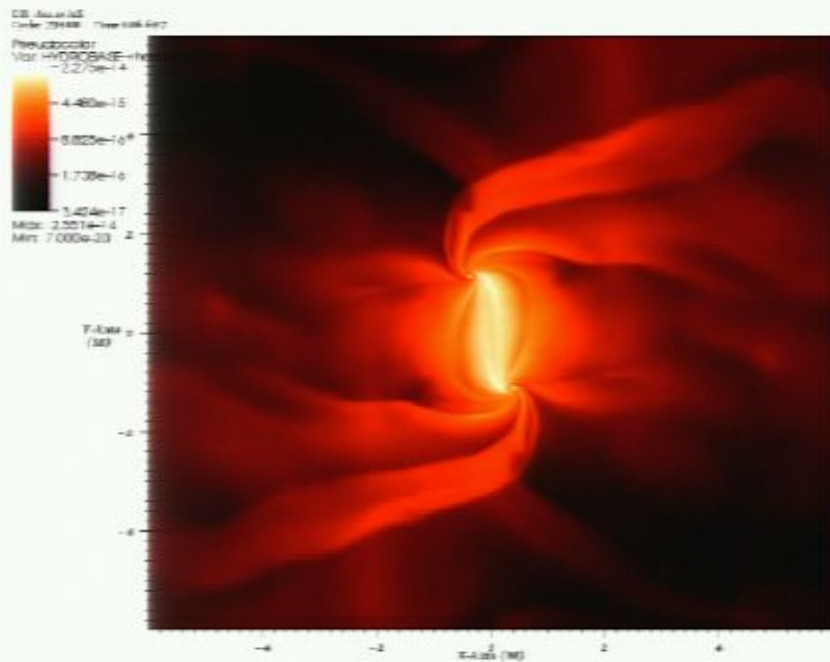


$$s_1/m^2 = s_2/m^2 = 0.6$$

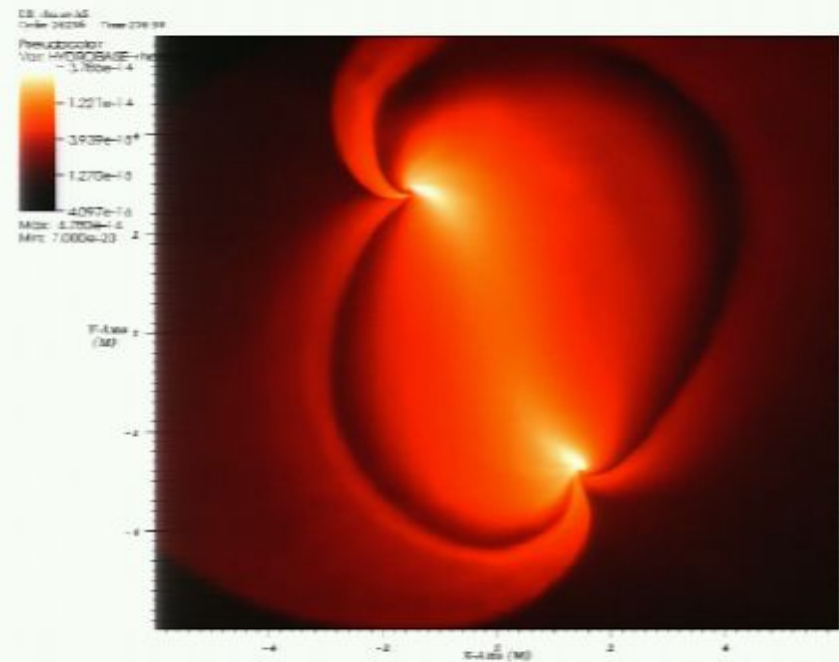


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

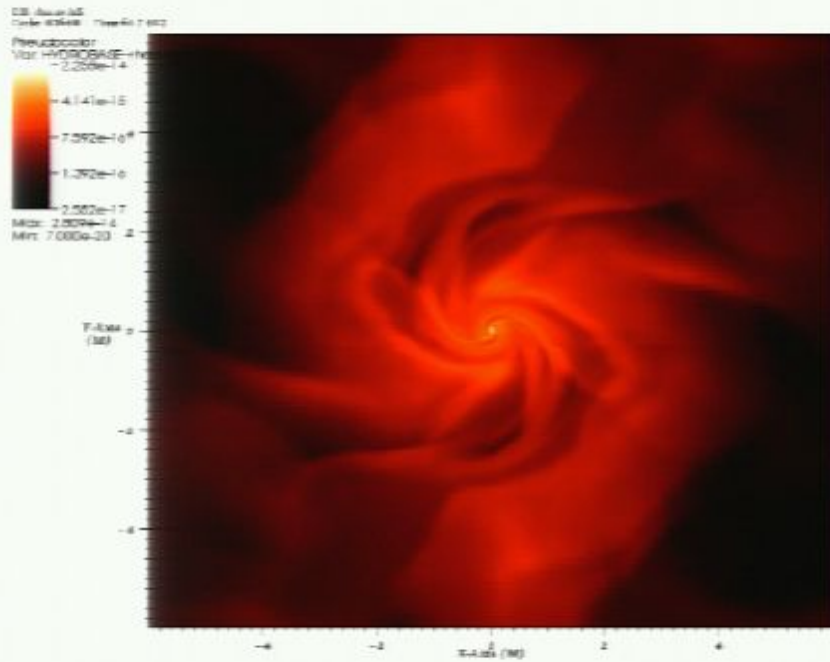


$$s_1/m^2 = s_2/m^2 = 0.6$$

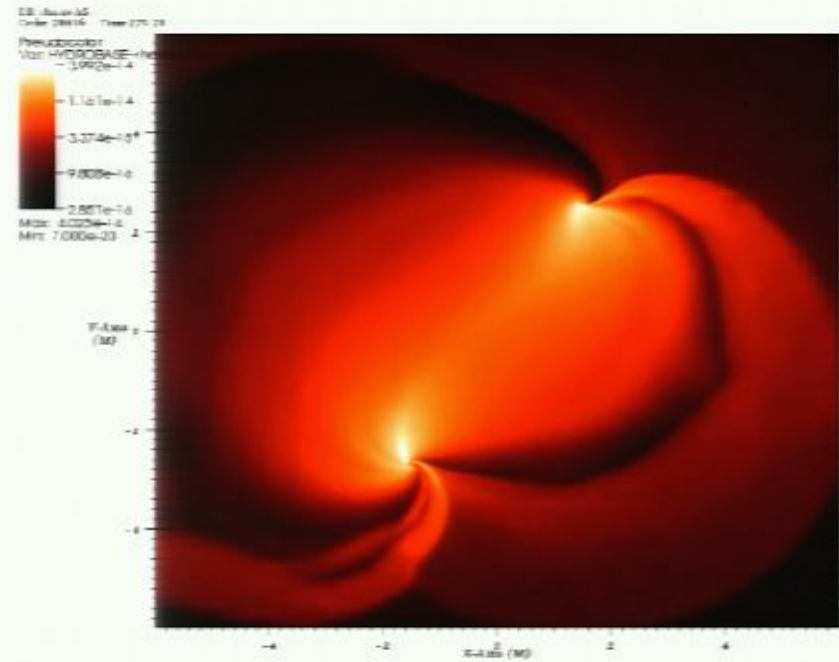


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

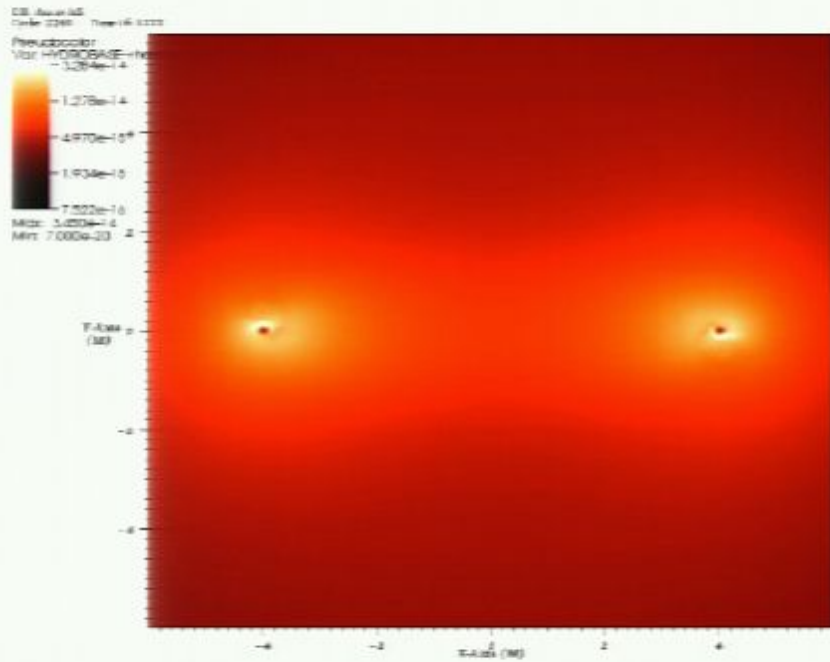


$$s_1/m^2 = s_2/m^2 = 0.6$$

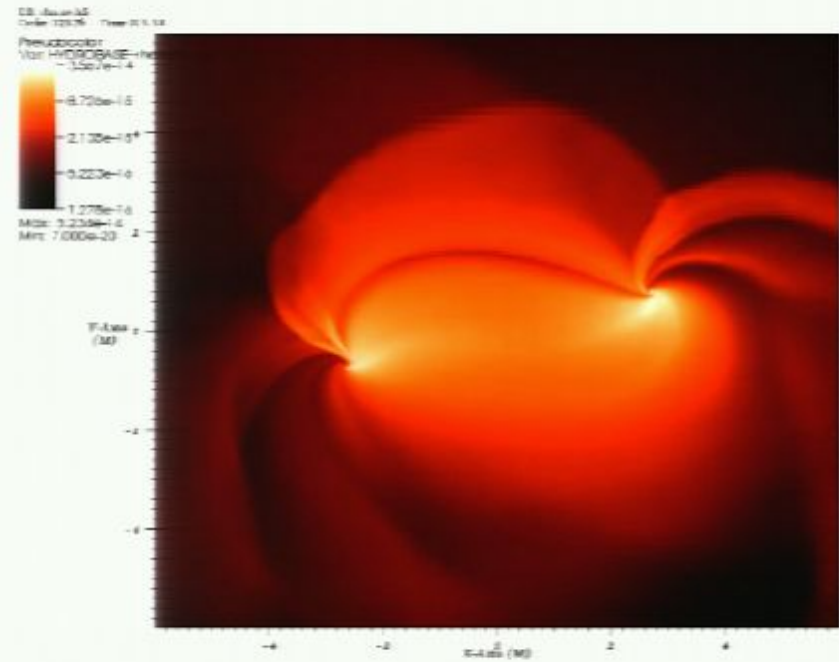


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

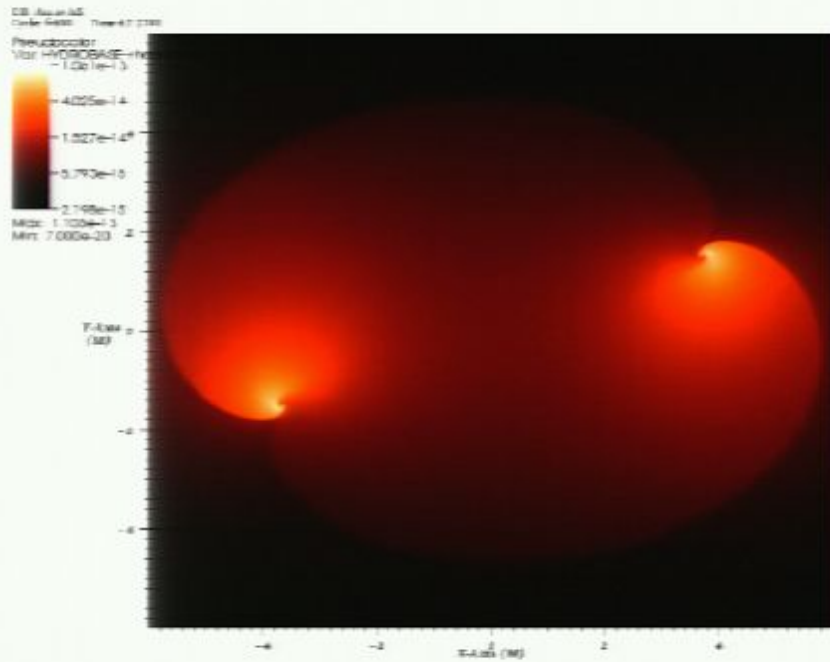


$$s_1/\text{m}^2 = s_2/\text{m}^2 = 0.6$$

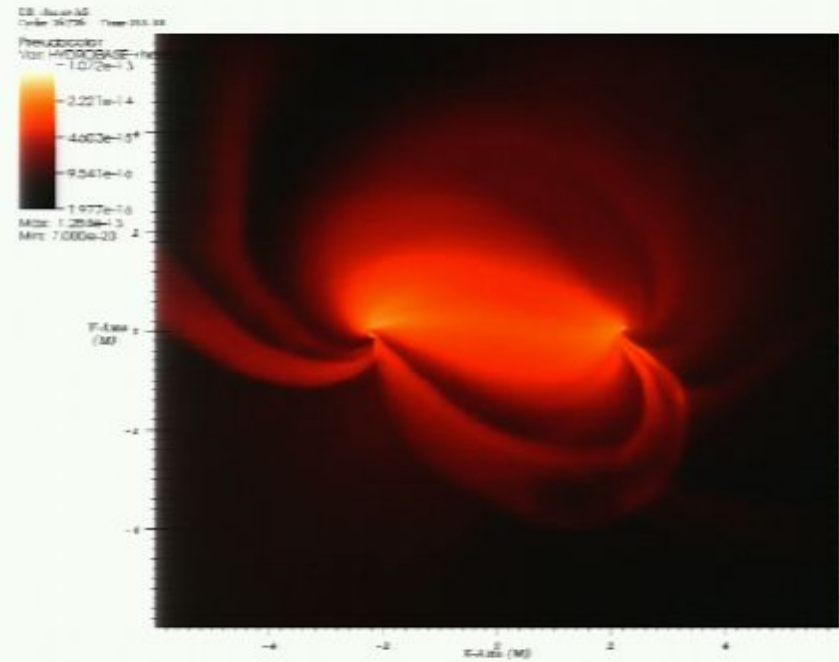


$$s_1/\text{m}^2 = -0.4 \quad s_2/\text{m}^2 = 0.4$$

Gas Density

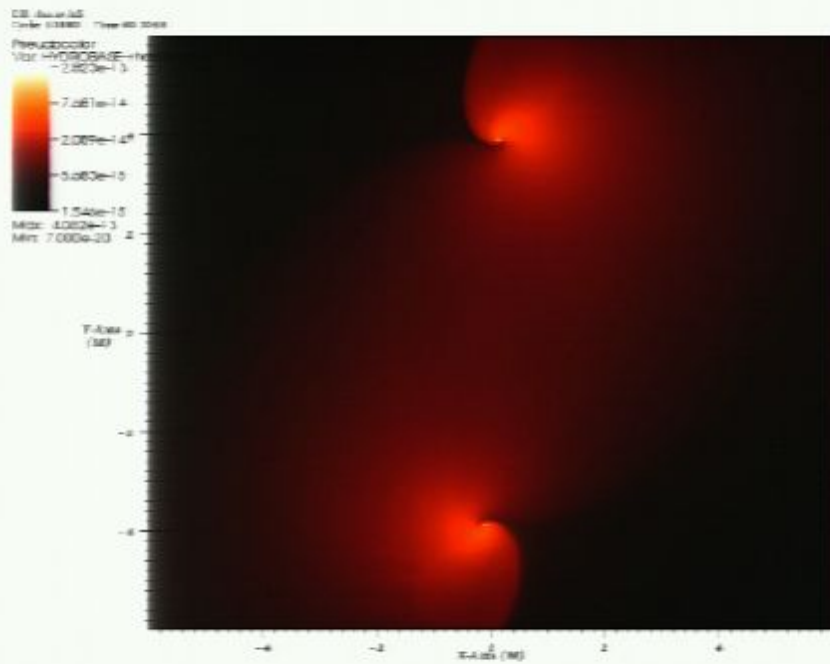


$$s_1/m^2 = s_2/m^2 = 0.6$$

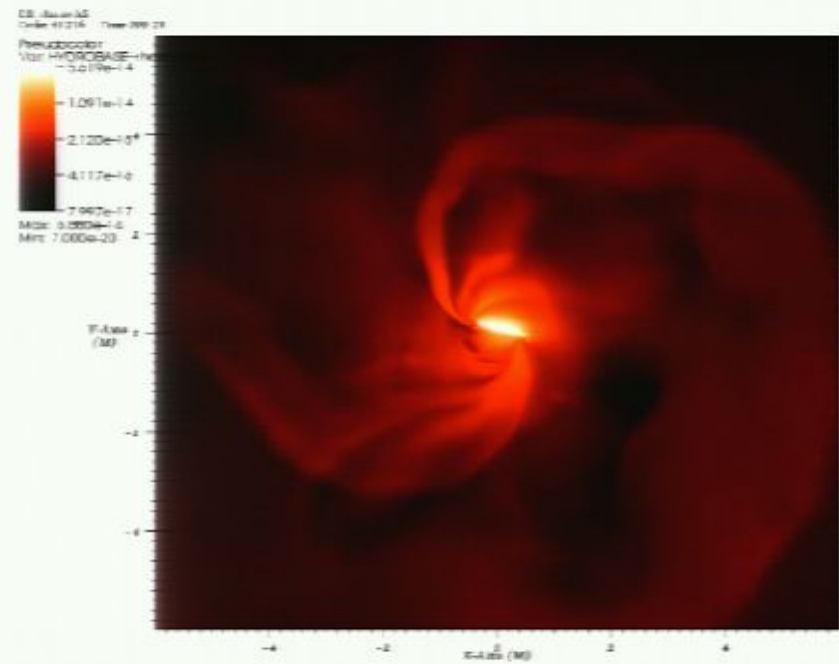


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

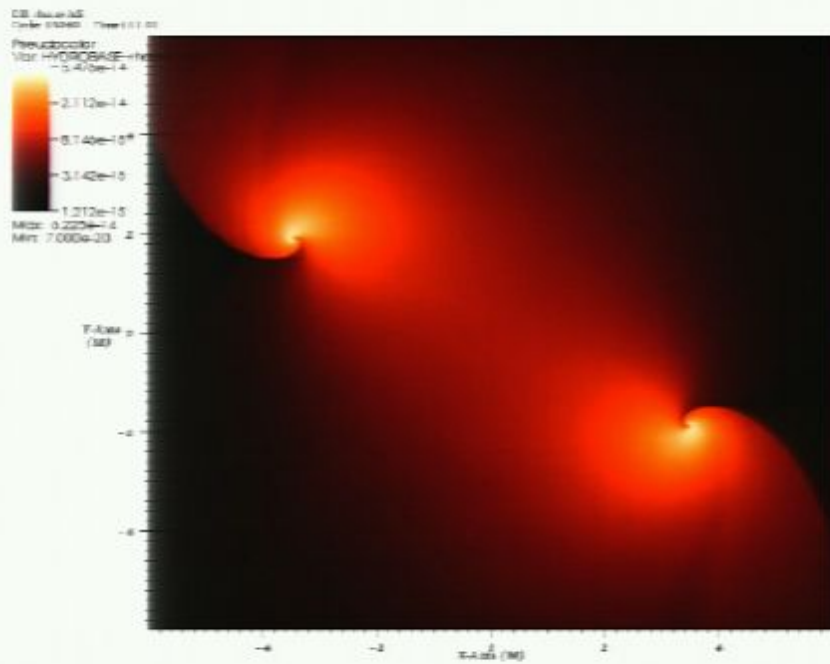


$$s_1/m^2 = s_2/m^2 = 0.6$$

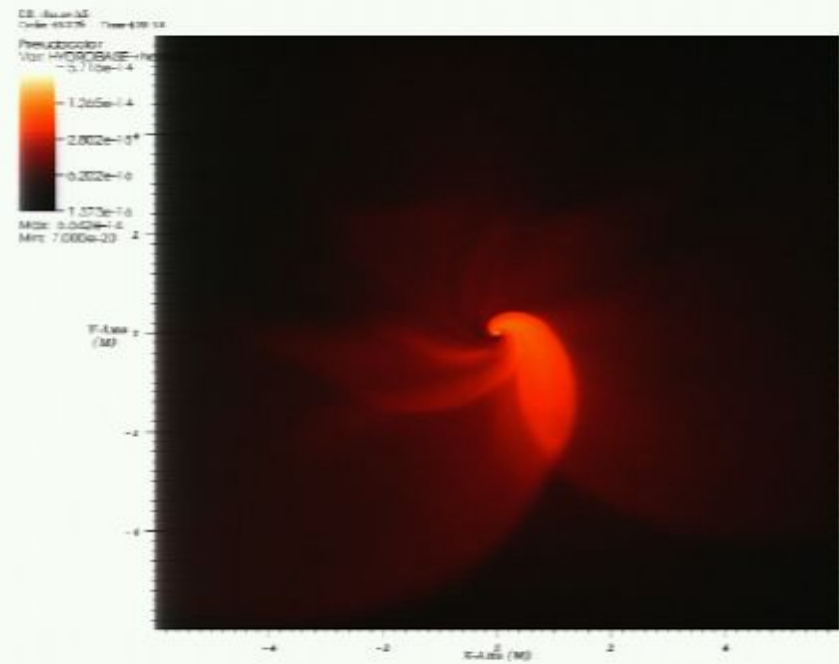


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

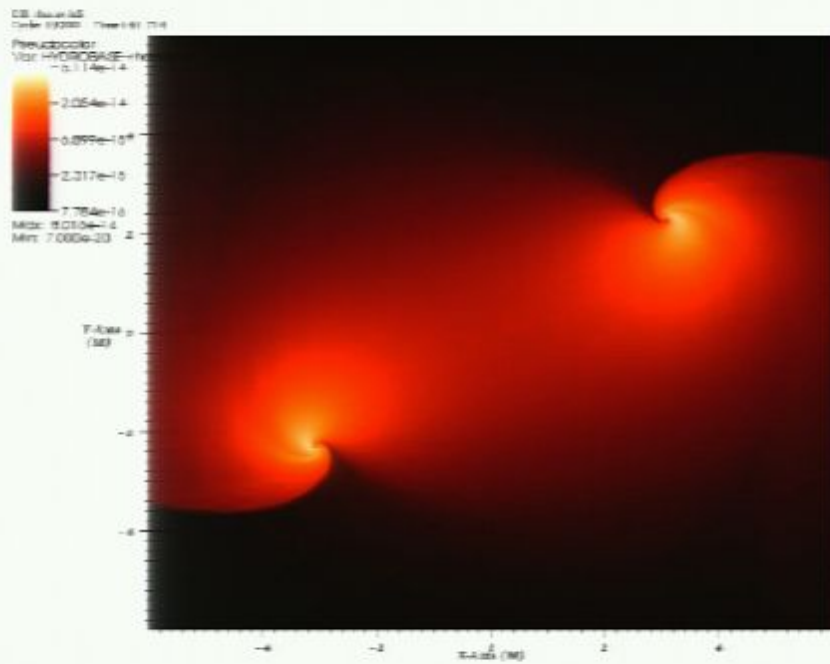


$$s_1/m^2 = s_2/m^2 = 0.6$$

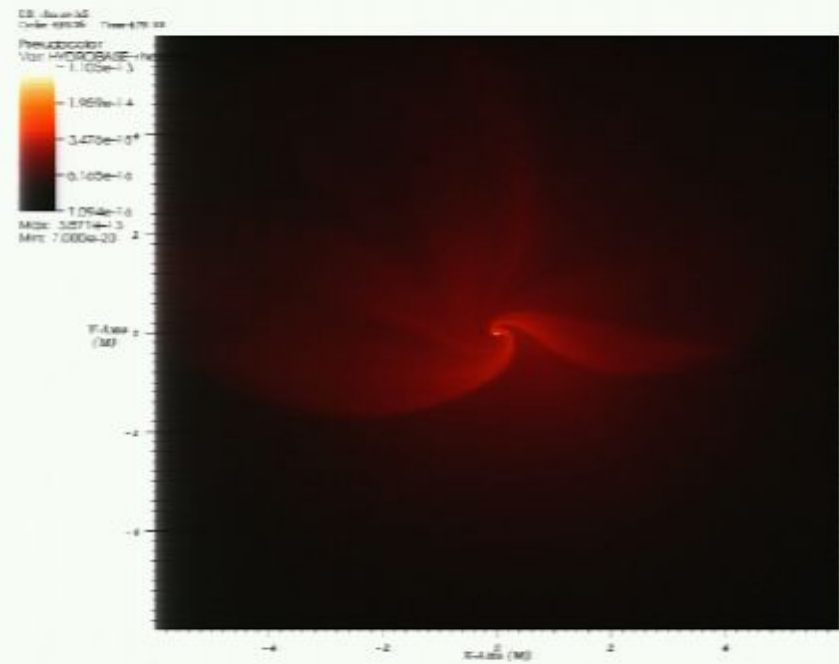


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

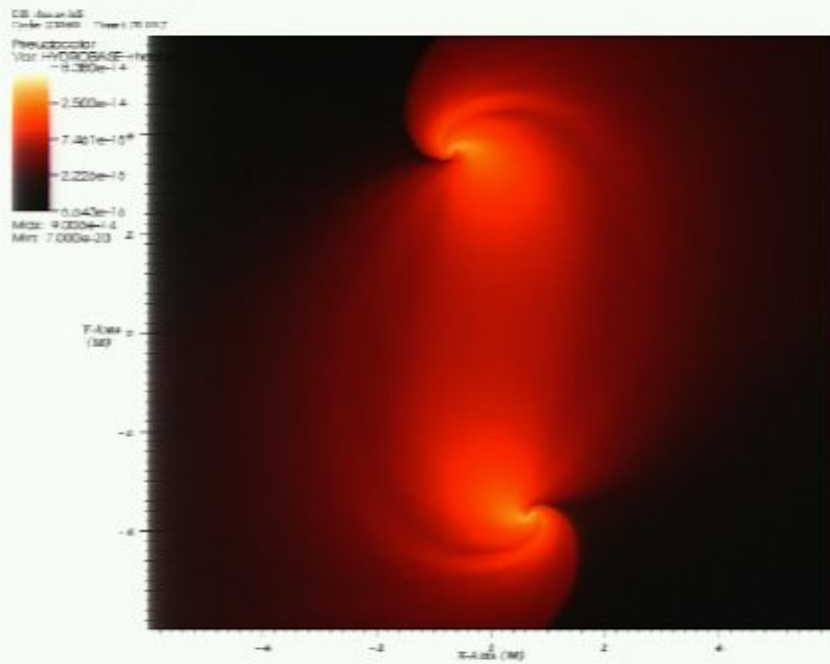


$$s_1/m^2 = s_2/m^2 = 0.6$$

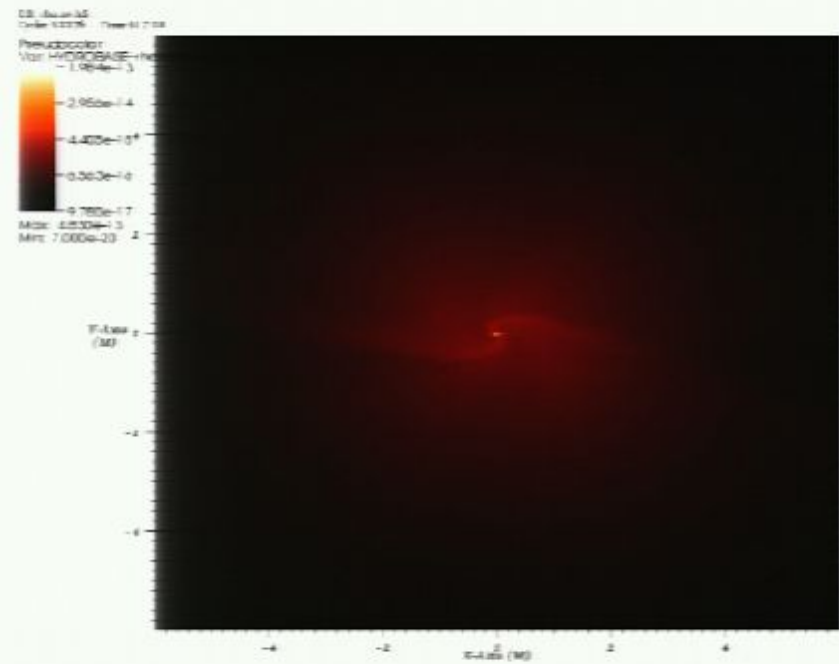


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

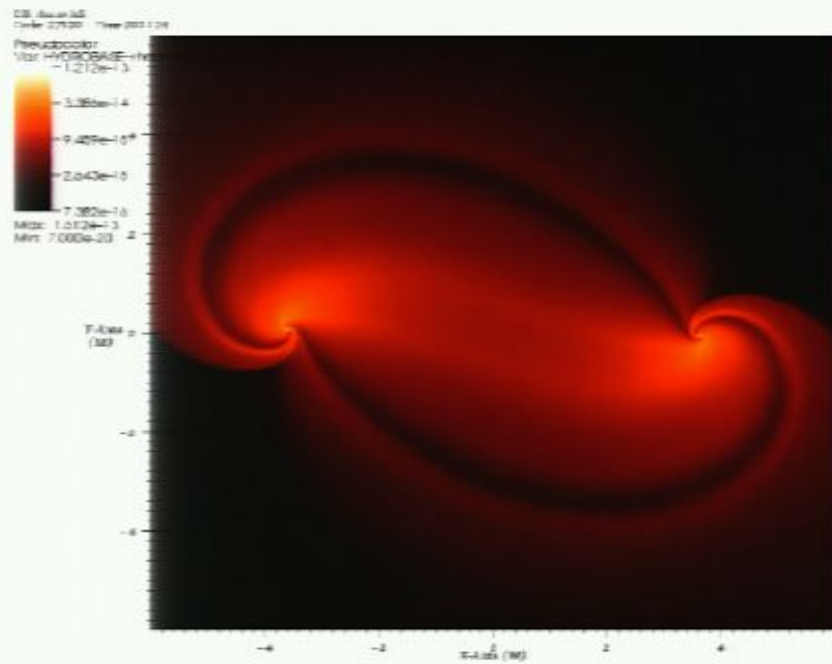


$$s_1/m^2 = s_2/m^2 = 0.6$$

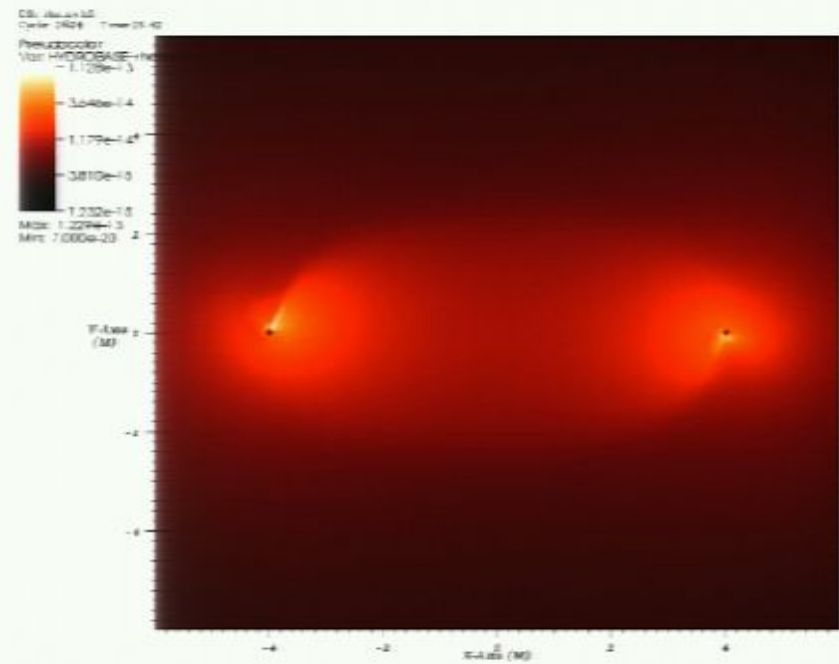


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

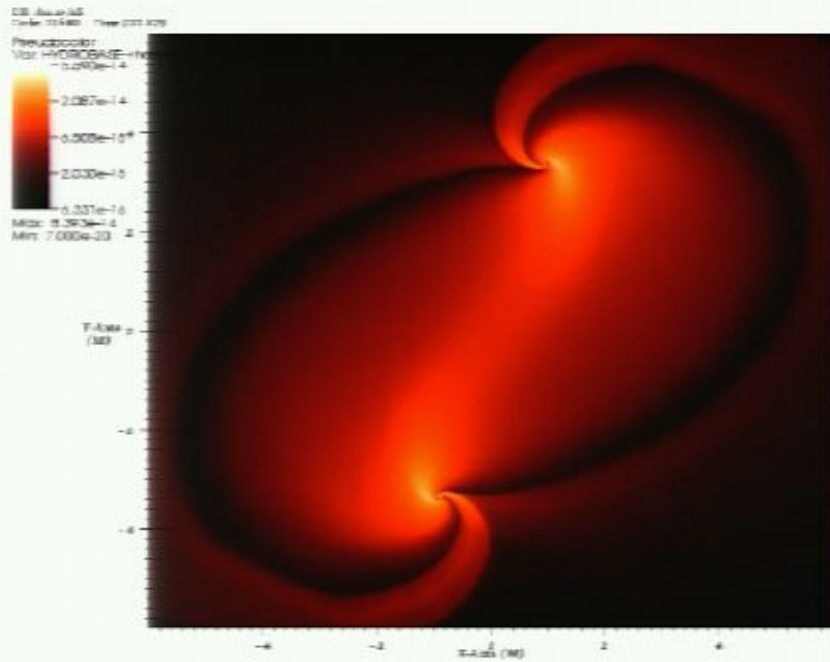


$$s_1/m^2 = s_2/m^2 = 0.6$$

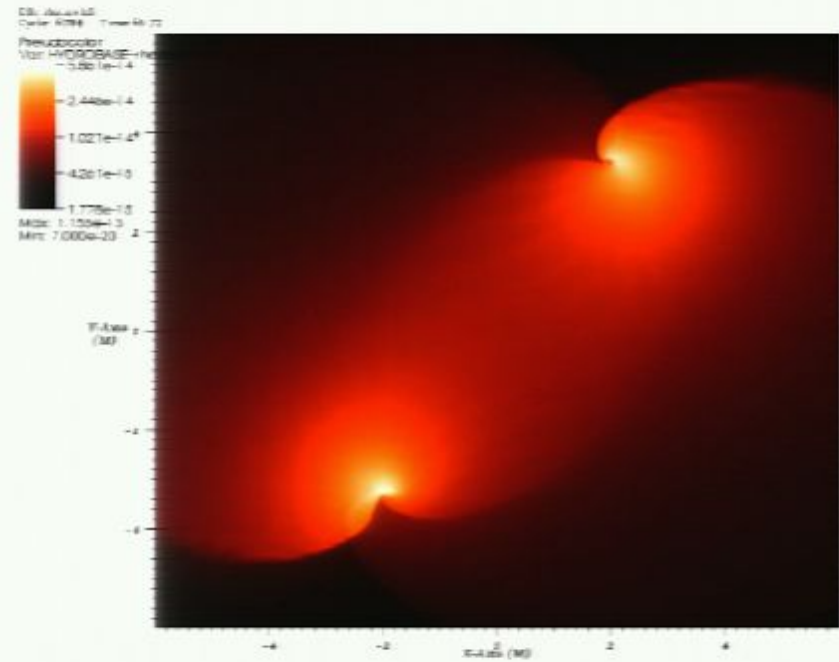


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

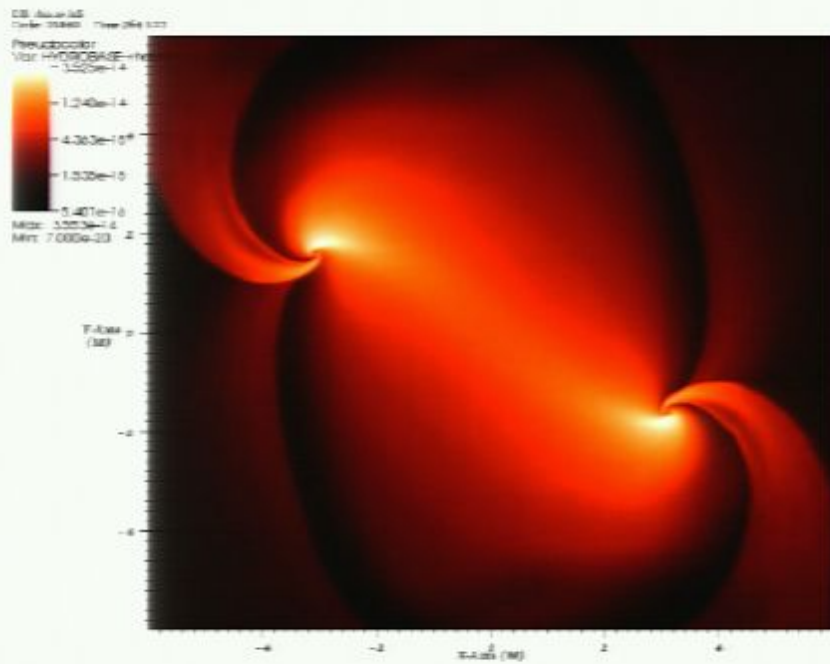


$$s_1/m^2 = s_2/m^2 = 0.6$$

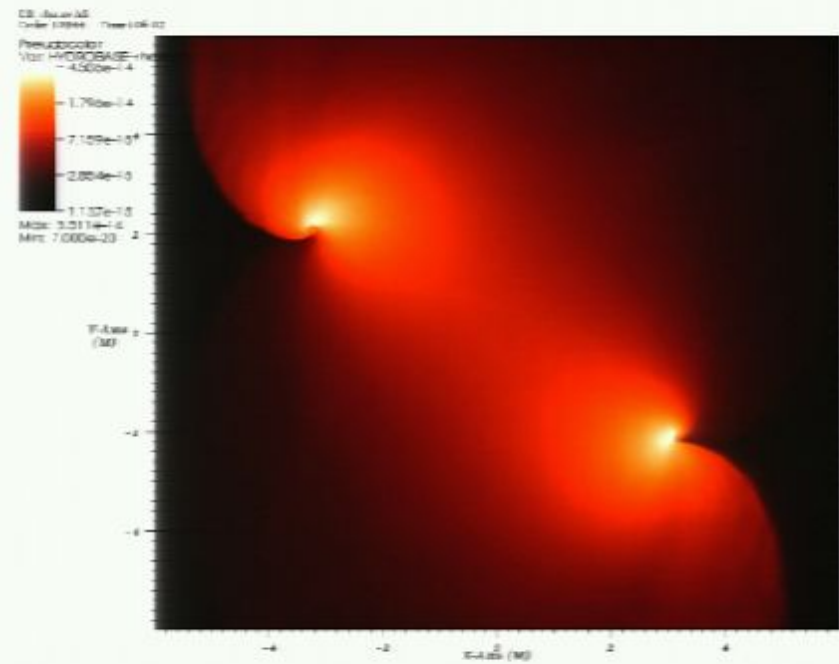


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

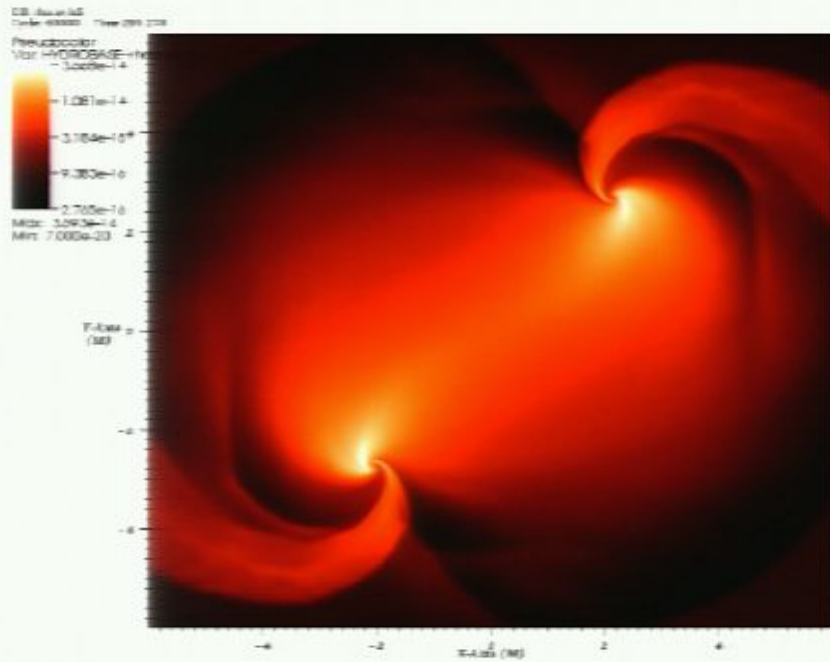


$$s_1/m^2 = s_2/m^2 = 0.6$$

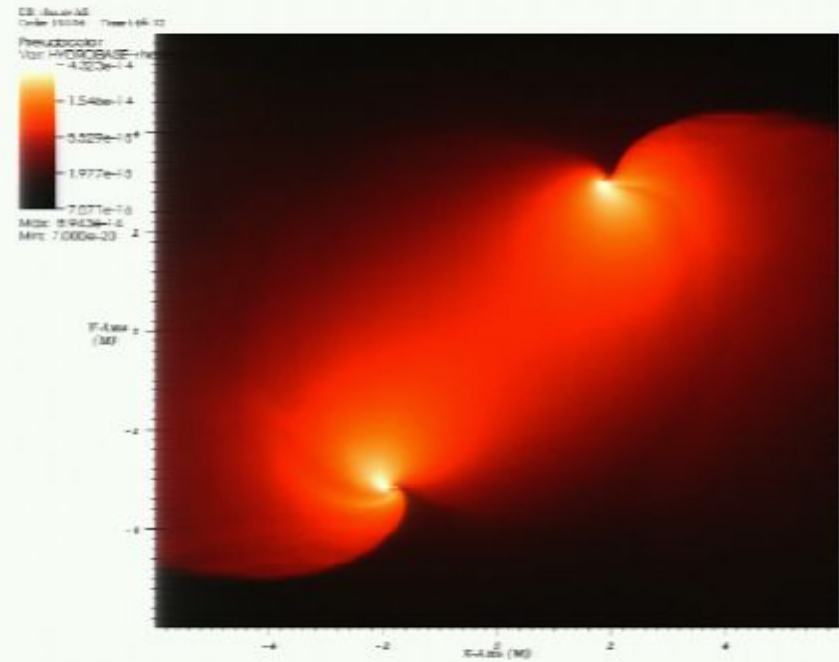


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

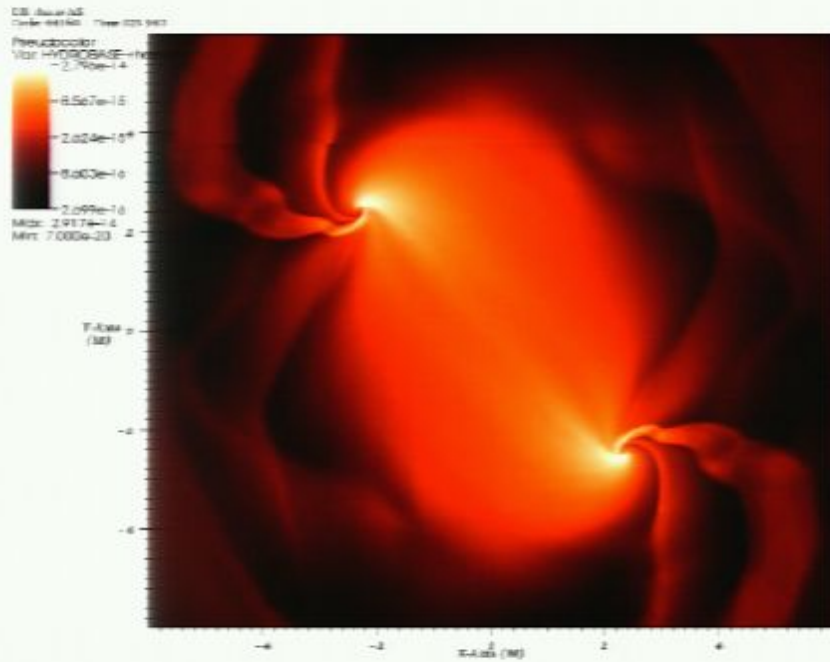


$$s_1/\text{m}^2 = s_2/\text{m}^2 = 0.6$$

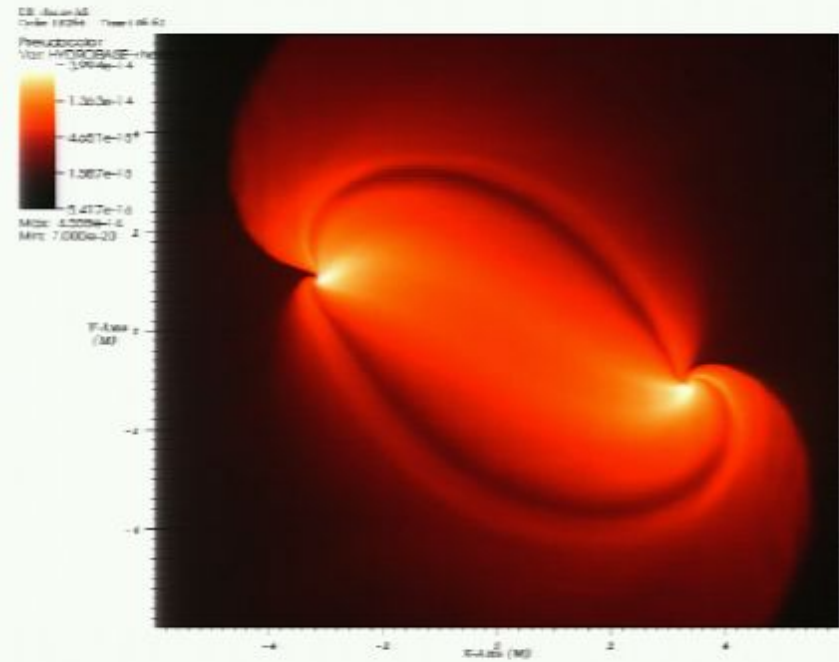


$$s_1/\text{m}^2 = -0.4 \quad s_2/\text{m}^2 = 0.4$$

Gas Density

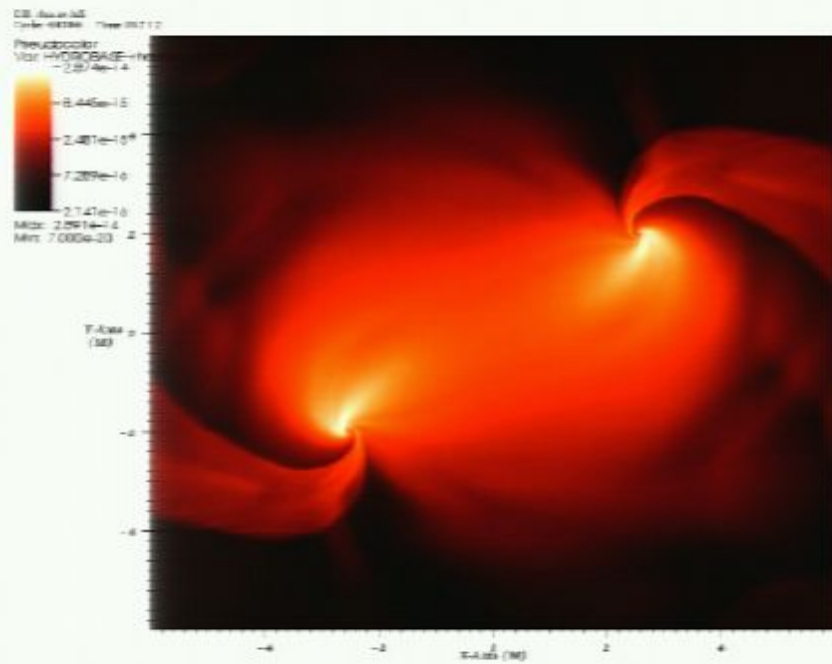


$$s_1/m^2 = s_2/m^2 = 0.6$$

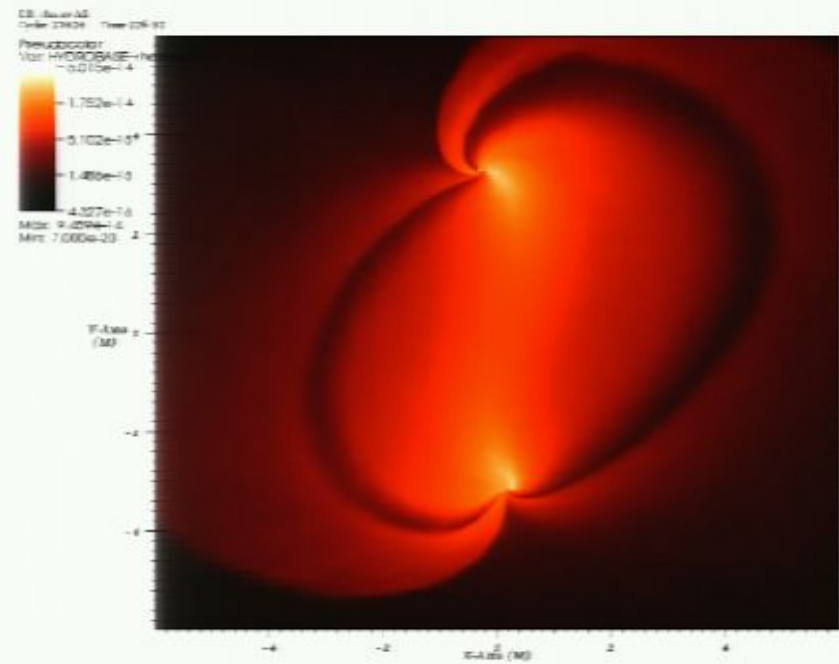


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

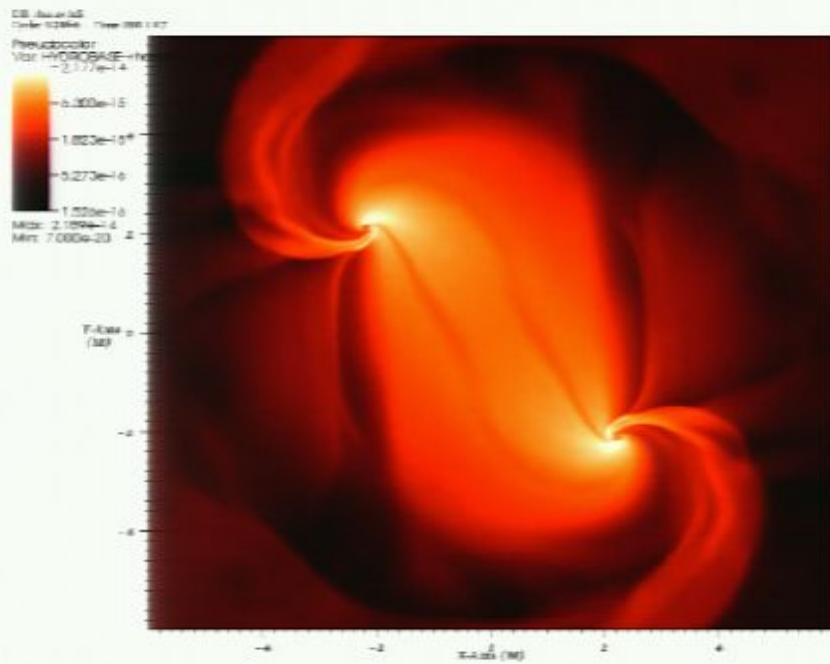


$$s_1/m^2 = s_2/m^2 = 0.6$$

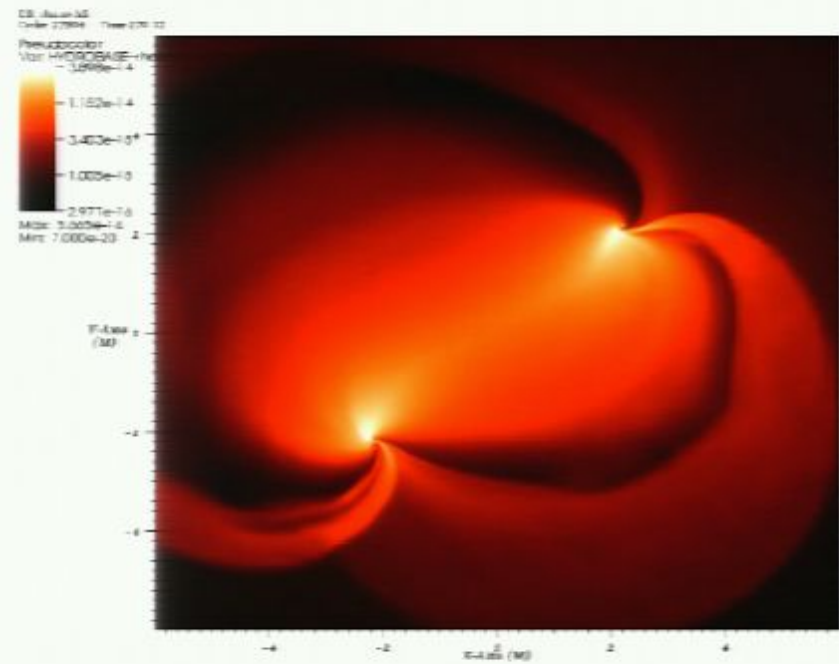


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

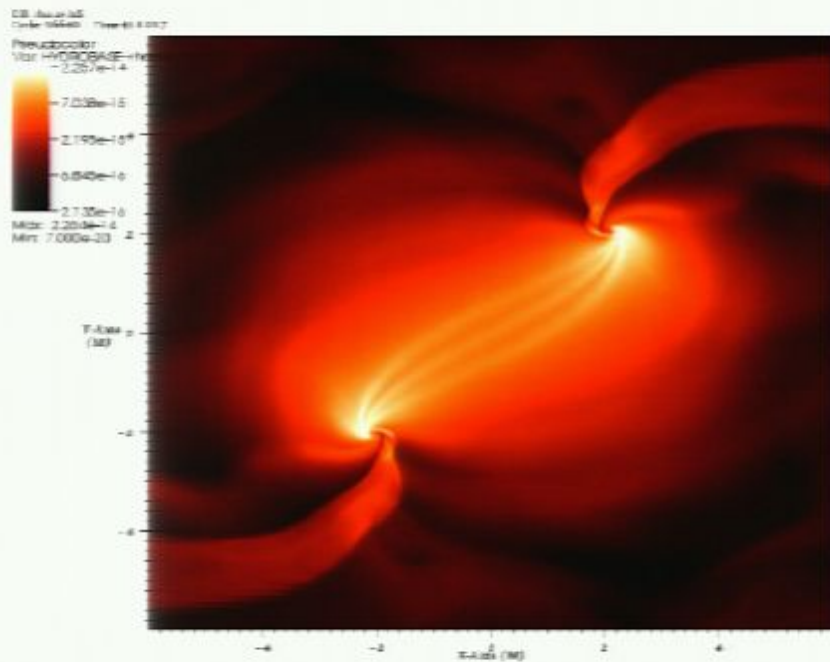


$$s_1/m^2 = s_2/m^2 = 0.6$$

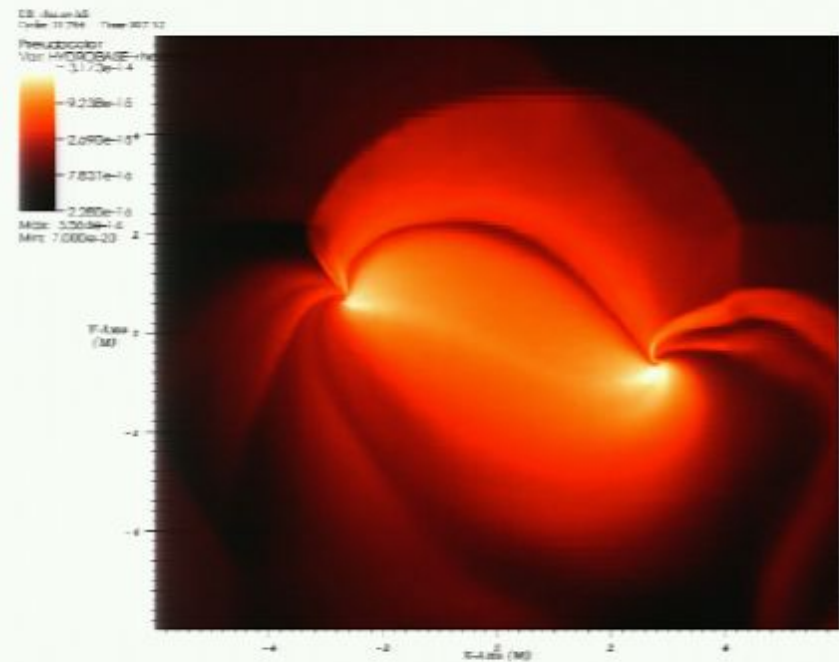


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

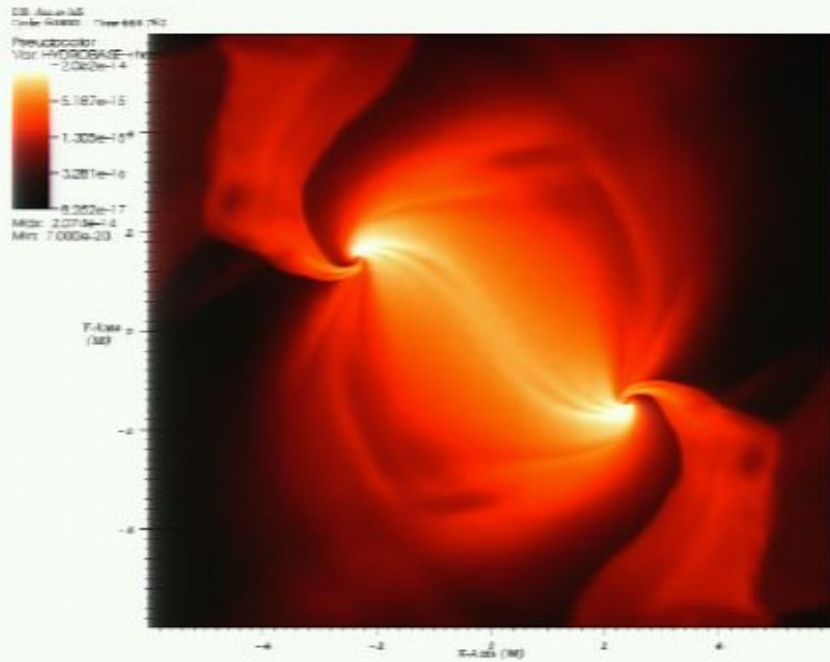


$$s_1/m^2 = s_2/m^2 = 0.6$$

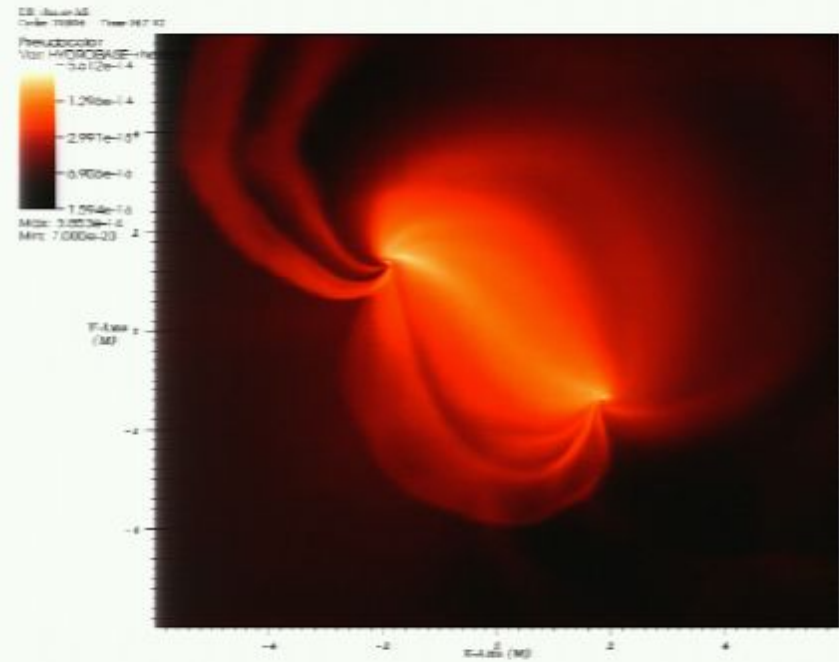


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

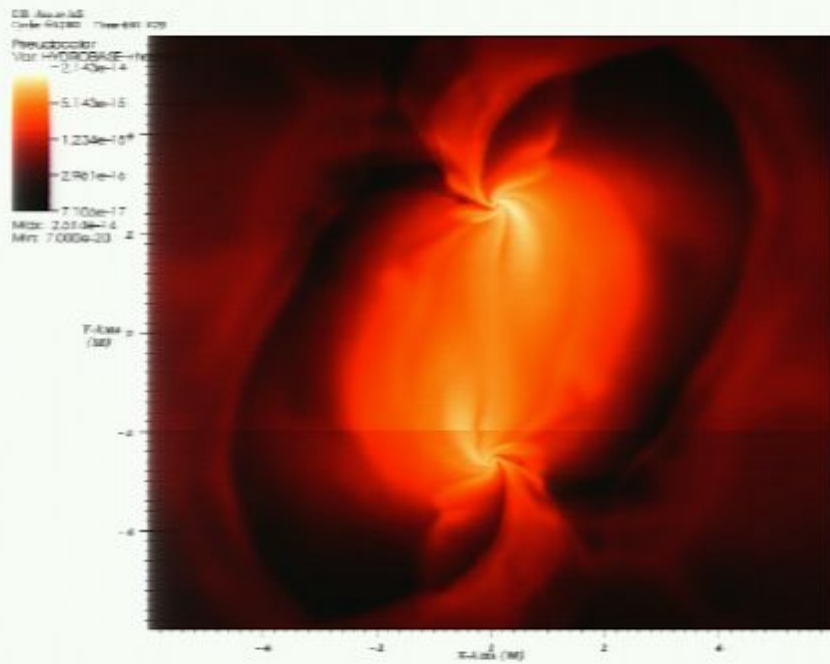


$$s_1/m^2 = s_2/m^2 = 0.6$$

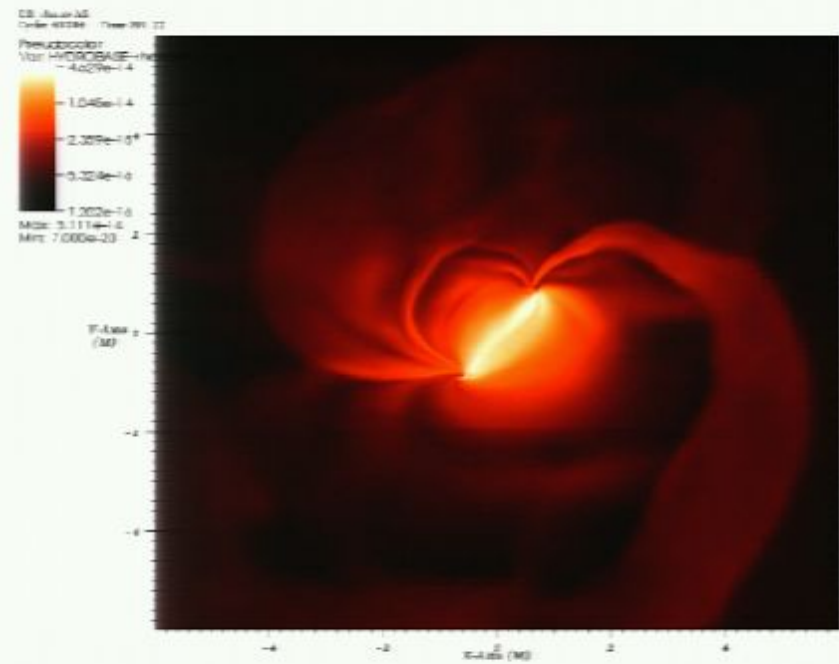


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

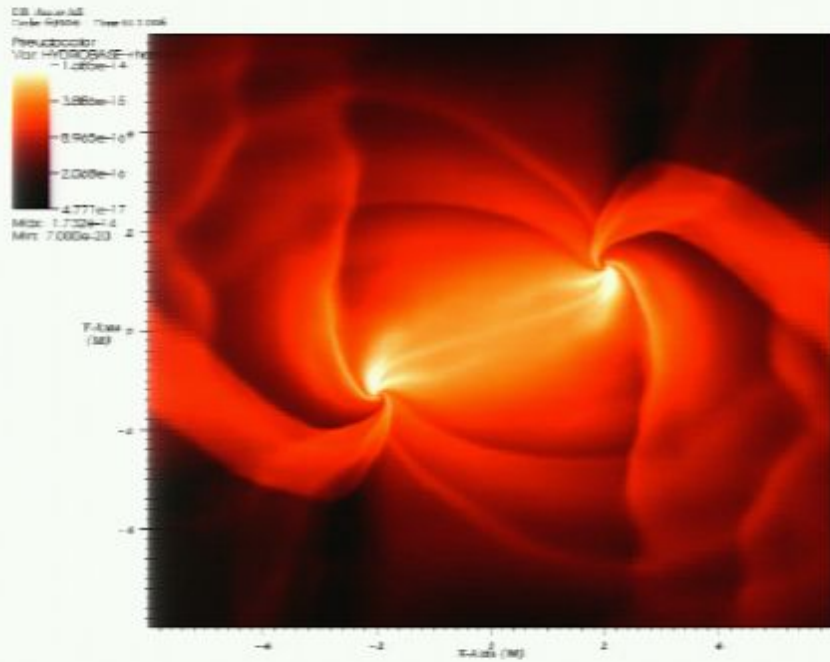


$$s_1/m^2 = s_2/m^2 = 0.6$$

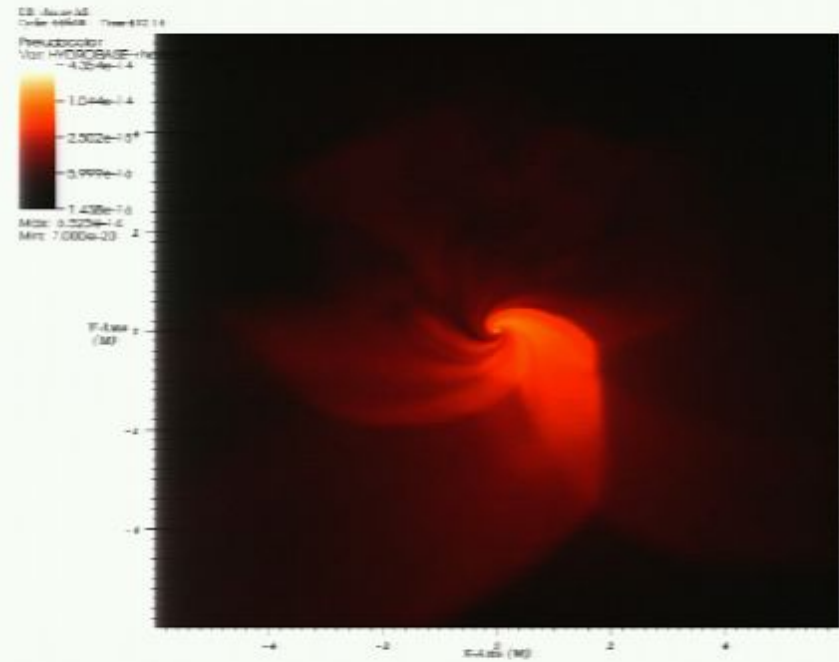


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

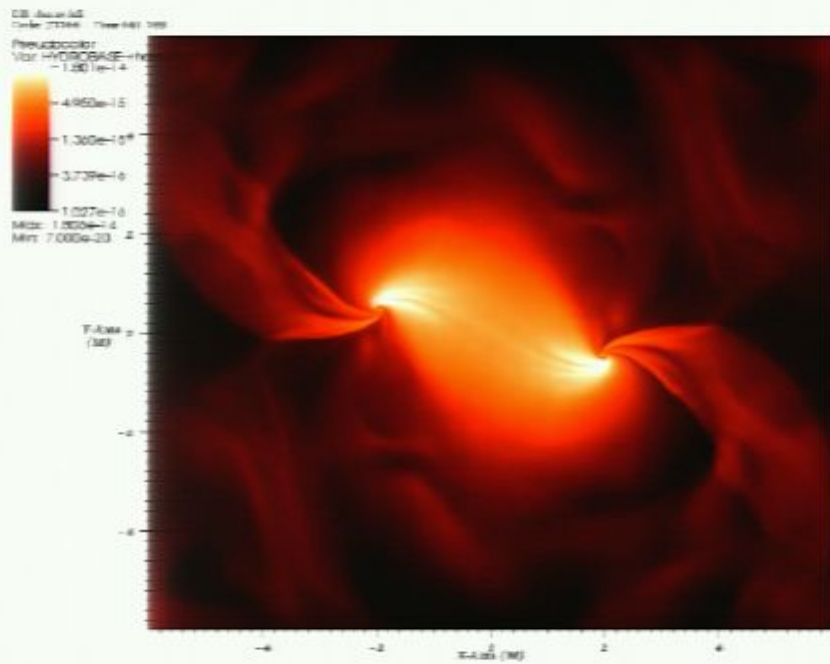


$$s_1/m^2 = s_2/m^2 = 0.6$$

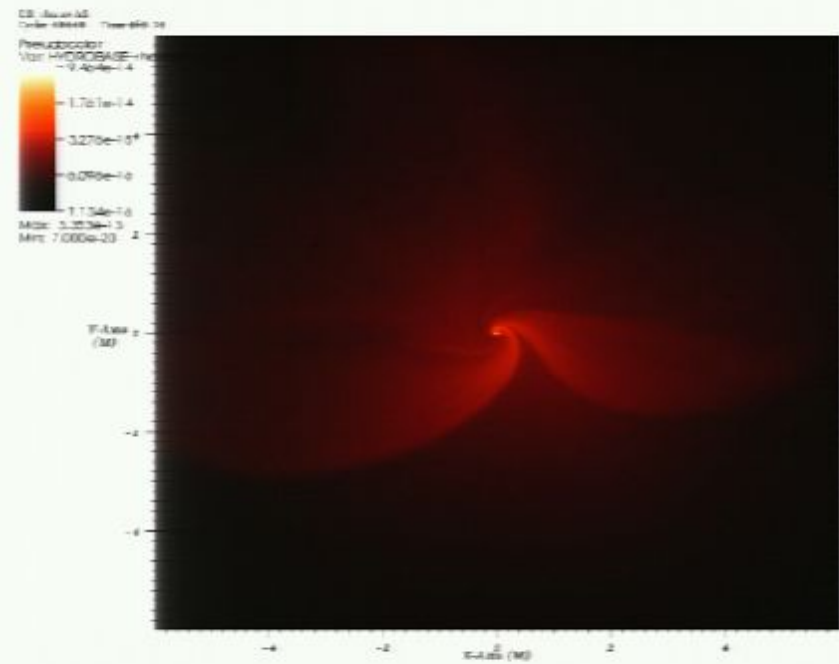


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

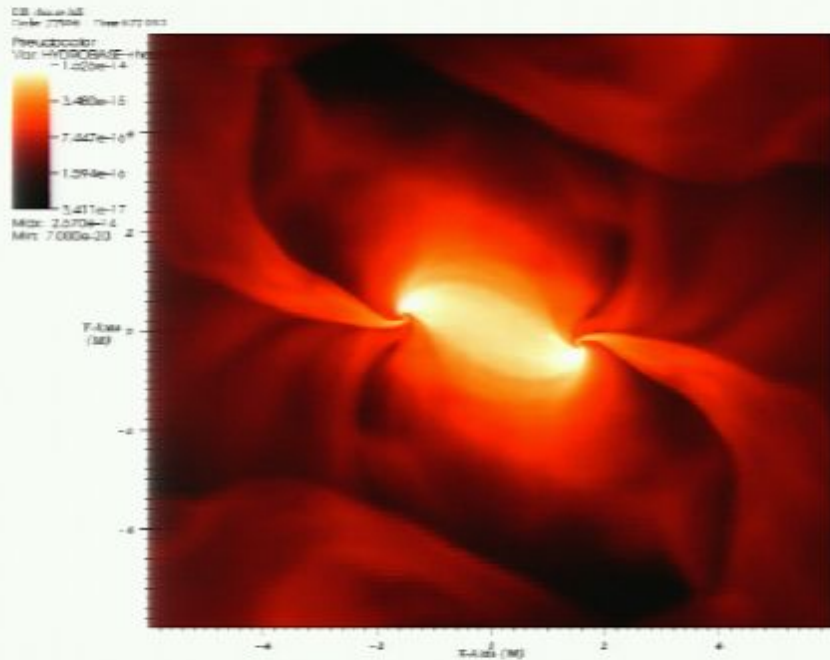


$$s_1/m^2 = s_2/m^2 = 0.6$$

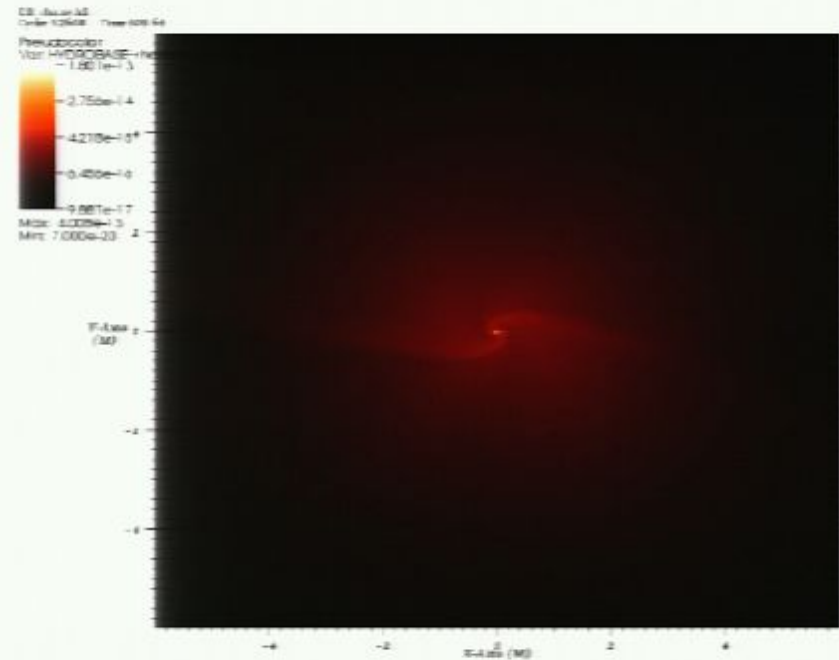


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

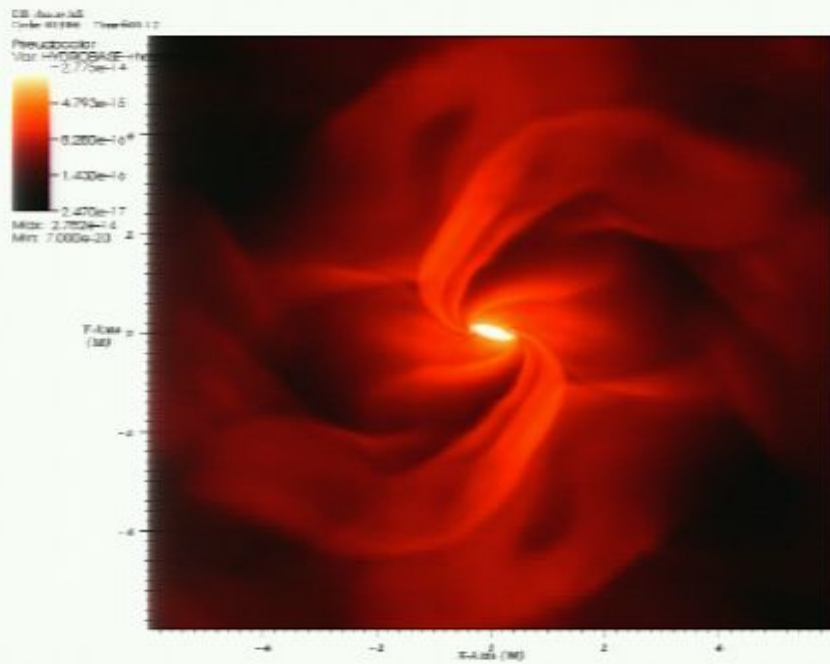


$$s_1/m^2 = s_2/m^2 = 0.6$$

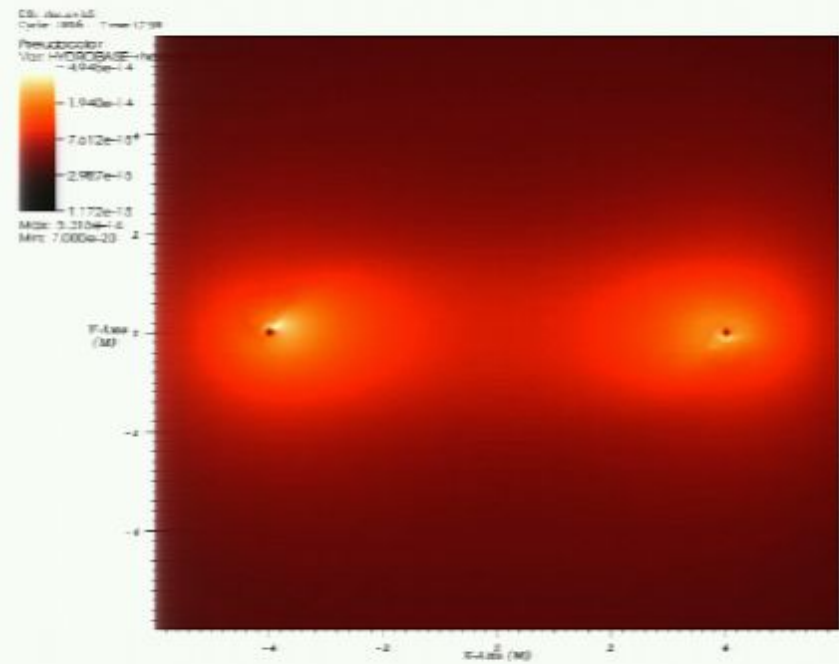


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

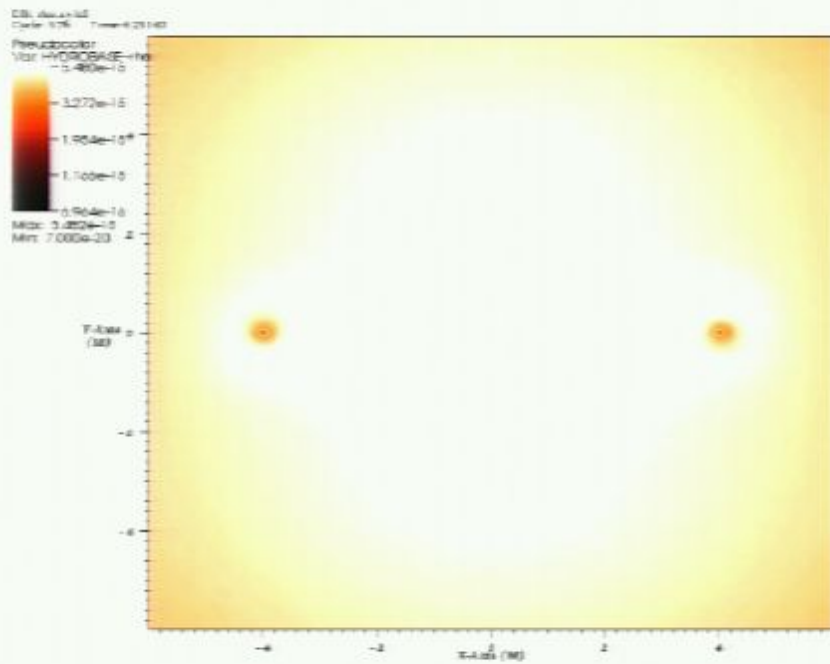


$$s_1/m^2 = s_2/m^2 = 0.6$$

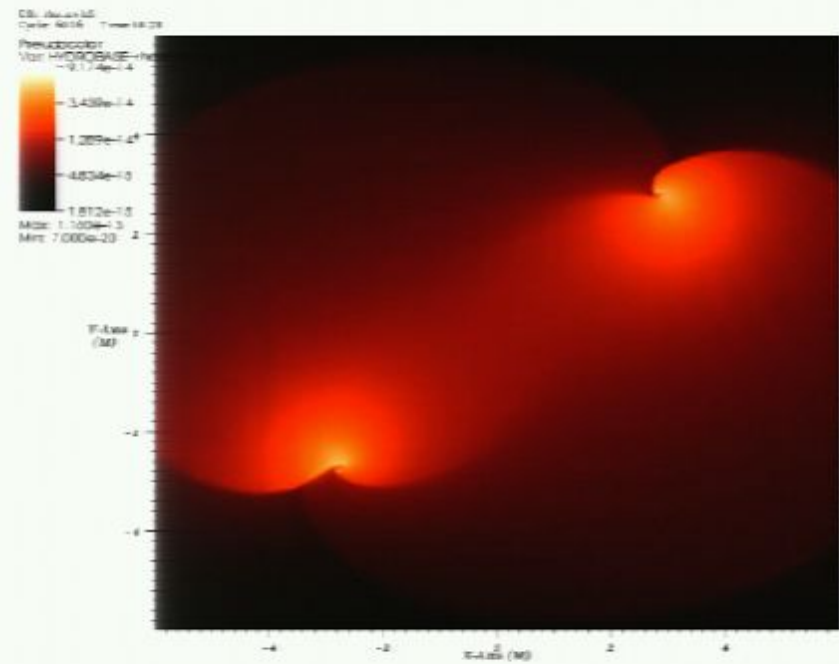


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

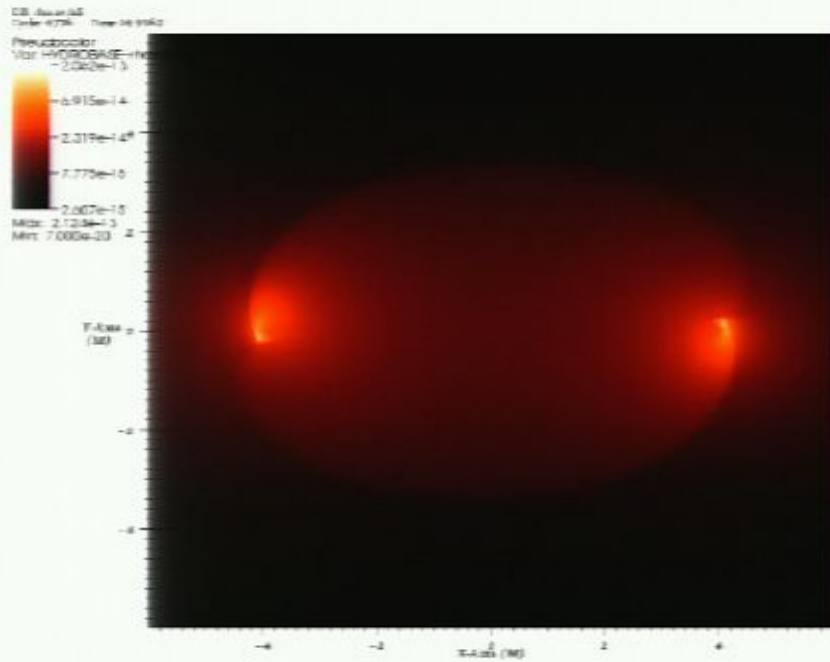


$$s_1/m^2 = s_2/m^2 = 0.6$$

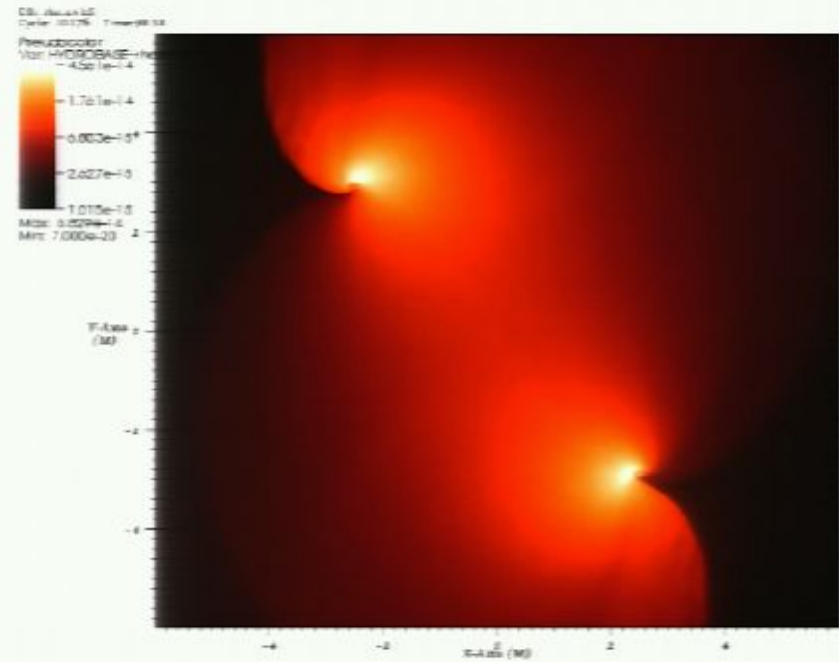


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density



$$s_1/m^2 = s_2/m^2 = 0.6$$

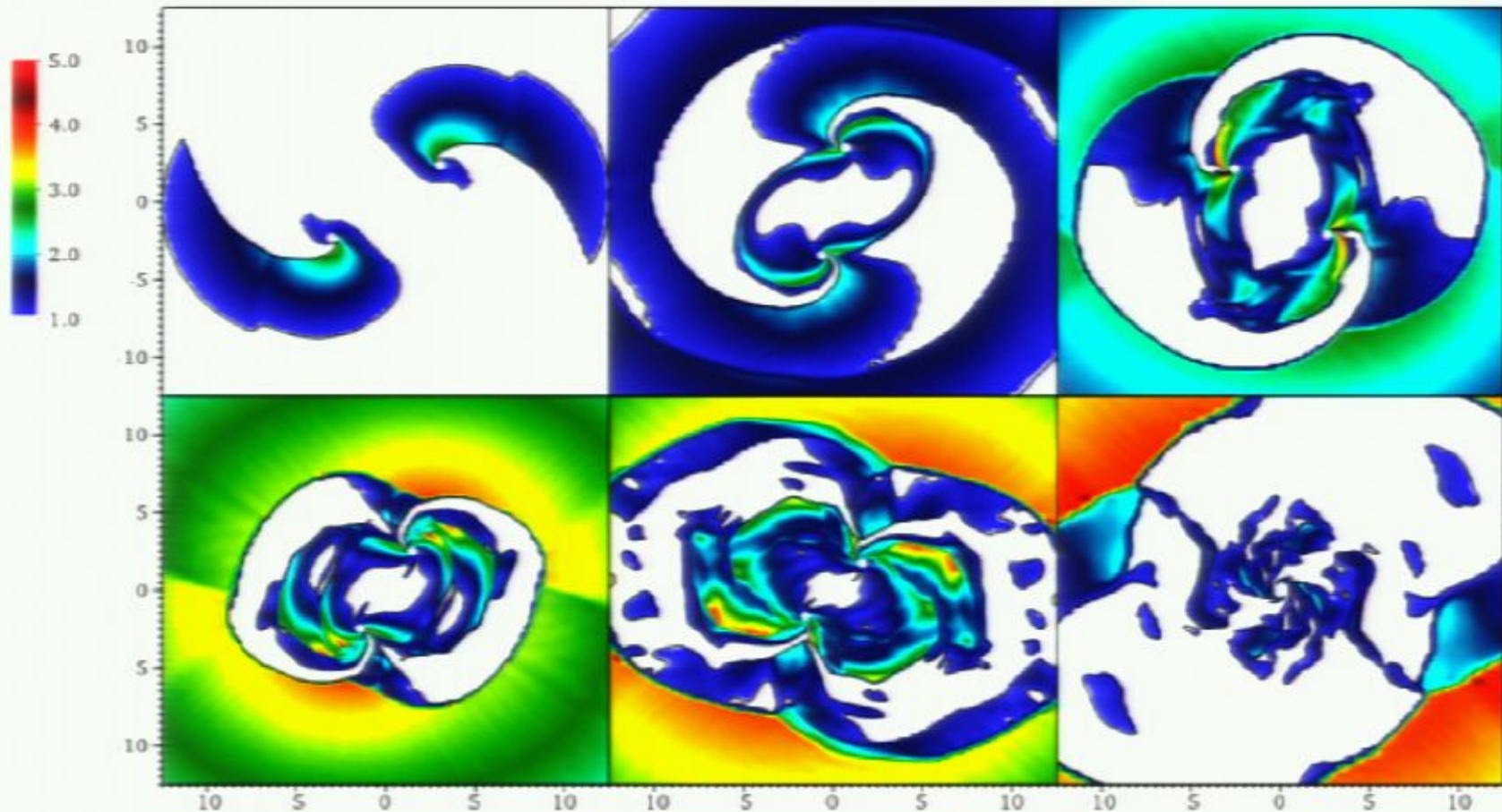


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Shocks triggered by the orbiting BHs

Mach number > 1

$s_1 = s_2 = +0.6$



(Bode+ 09)

Luminosity

Bode+ 09

$$L_{\text{brem}} \approx 4 \times 10^{44} \text{ erg s}^{-1} \left(\frac{\rho}{10^{-11} \text{ g cm}^{-3}} \right)^2 \left(\frac{R}{10M} \right)^3 M_7^3 \left(\frac{T_e}{10^{10} \text{ K}} \right)^{1/2}$$

$$L_{\text{synchro}} \approx 8 \times 10^{36} \text{ erg s}^{-1} \left(\frac{\rho}{10^{-11} \text{ g cm}^{-3}} \right) \left(\frac{R}{10M} \right)^3 M_7^3 \left(\frac{B}{1G} \right)^2$$

Farris+ 09

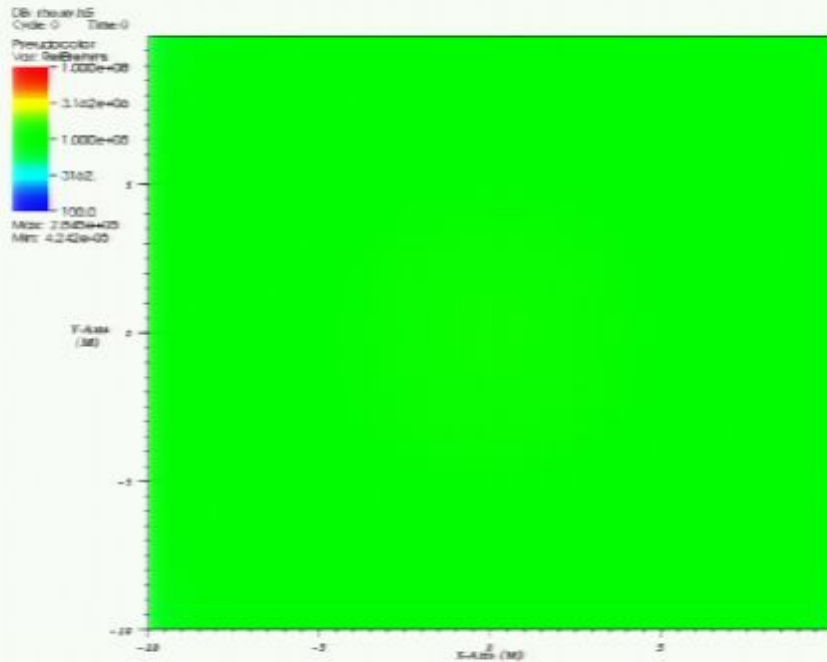
$$L_{\text{synchro}} \approx 8 \times 10^{42} \text{ erg s}^{-1} \left(\frac{\rho}{10^{-11} \text{ g cm}^{-3}} \right) \left(\frac{R}{10M} \right)^3 M_7^3 \left(\frac{B}{10^3 G} \right)^2$$

Optical Depth:

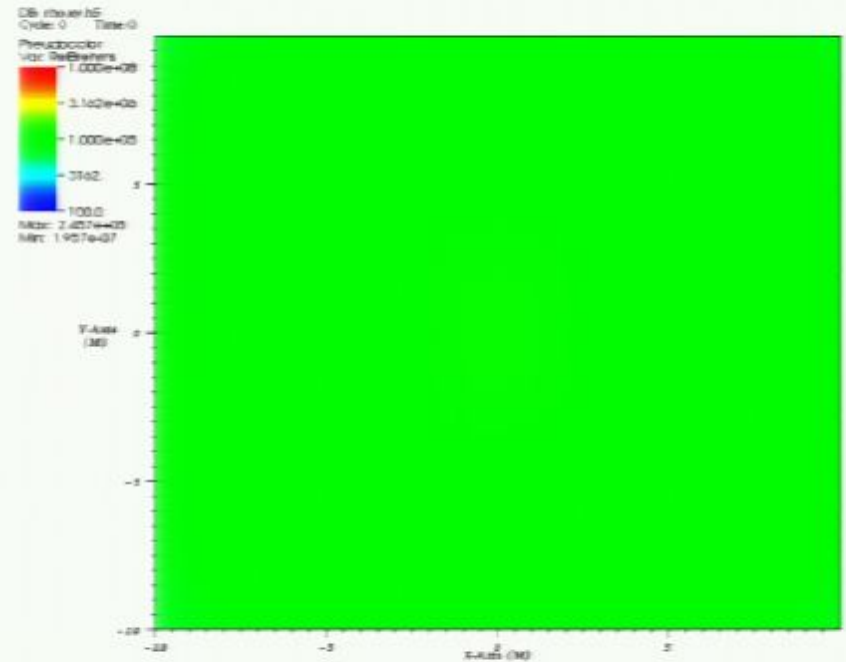
$$\tau \approx n_h \sigma_T R \sim 10^{-1} \left(\frac{n_h}{10^{12} \text{ cm}^{-3}} \right) \left(\frac{R}{10M} \right) M_7$$

Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



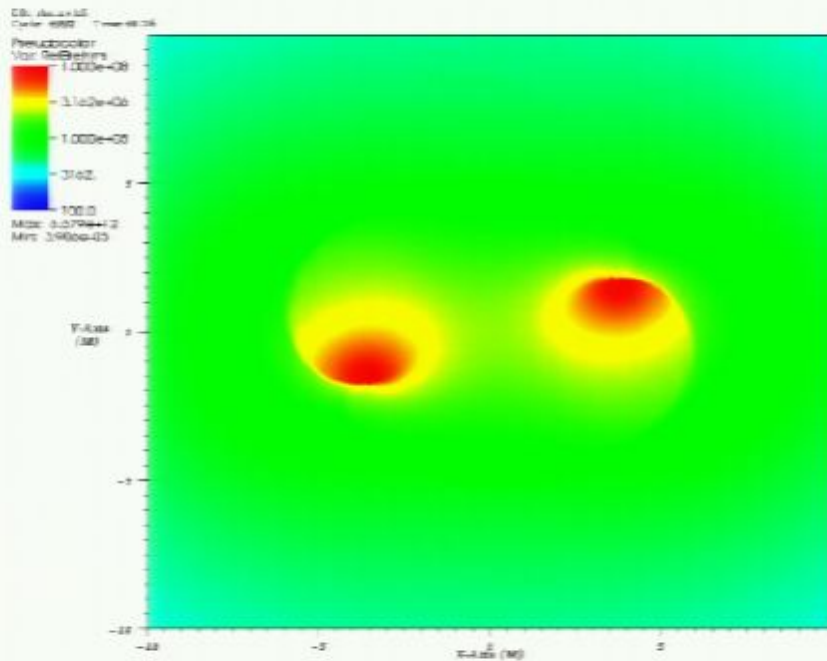
Non-spinning BHs



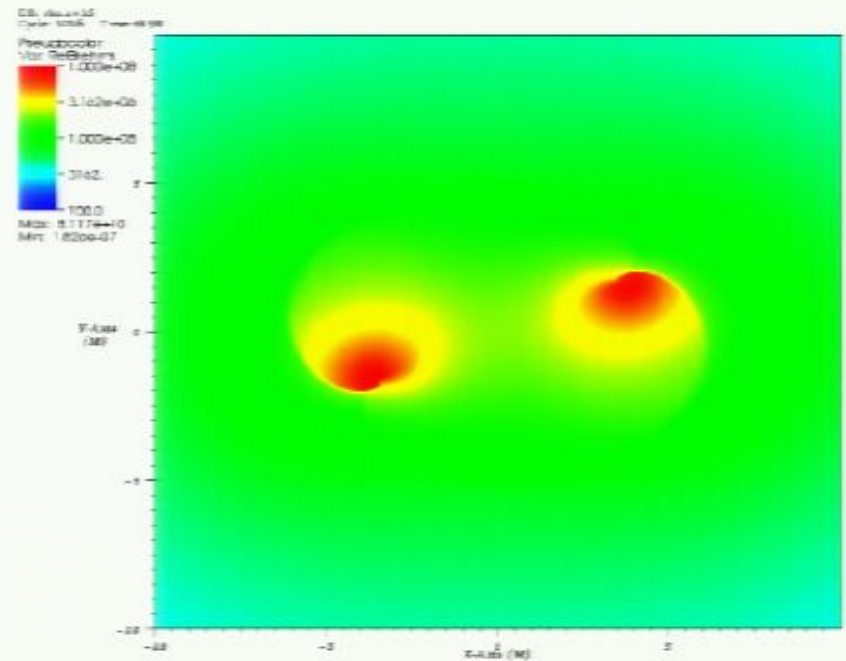
Spinning BHS

Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



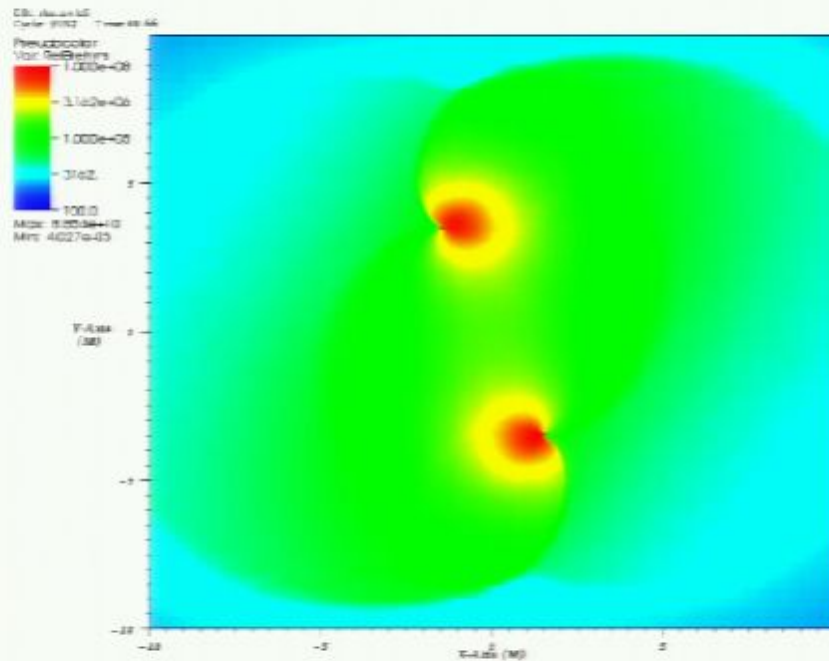
Non-spinning BHs



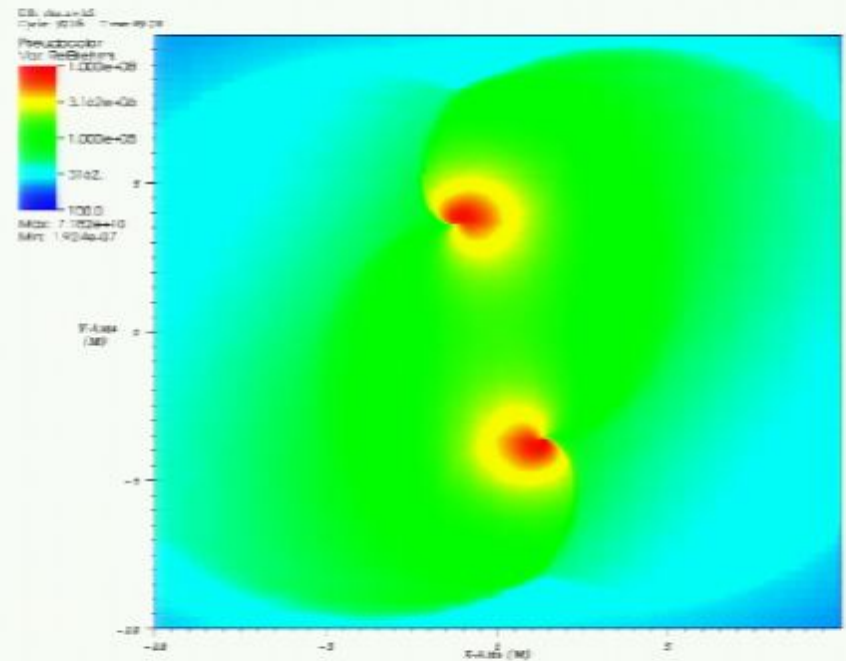
Spinning BHS

Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



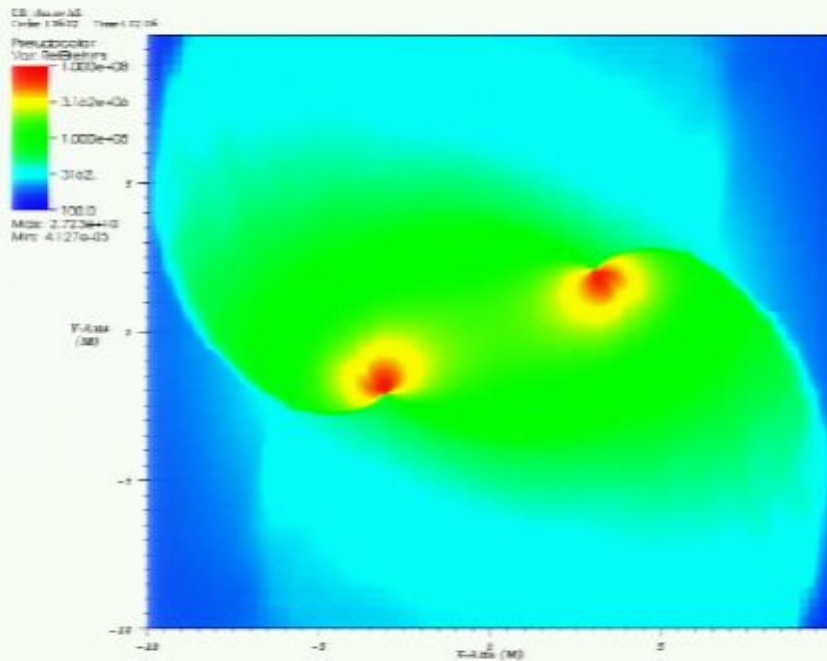
Non-spinning BHs



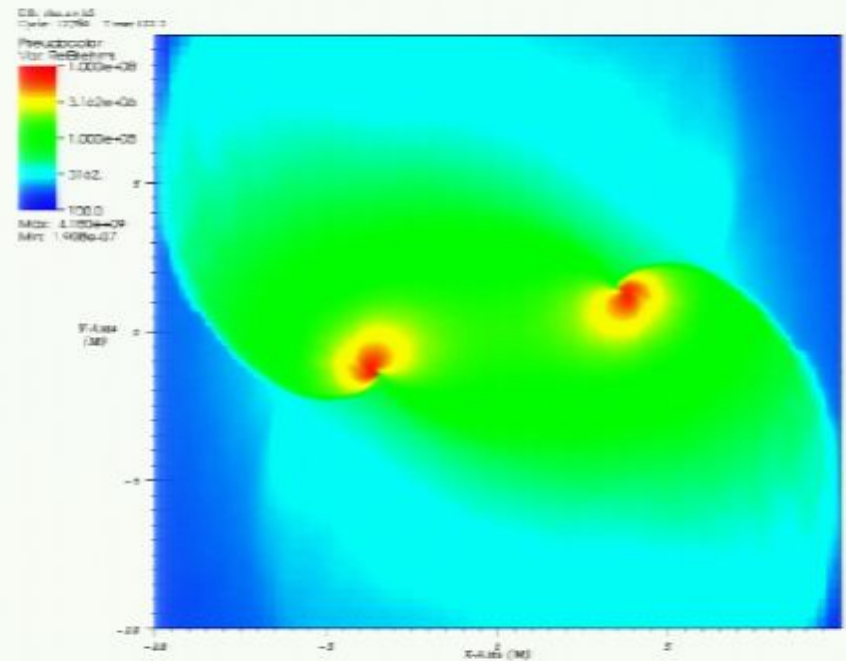
Spinning BHS

Emission from the hot gas

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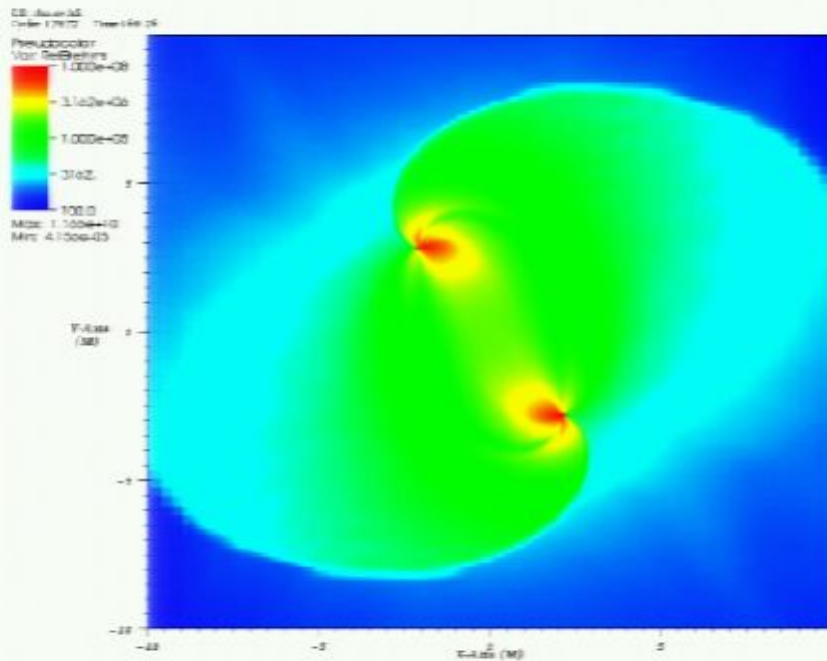
Non-spinning BHs



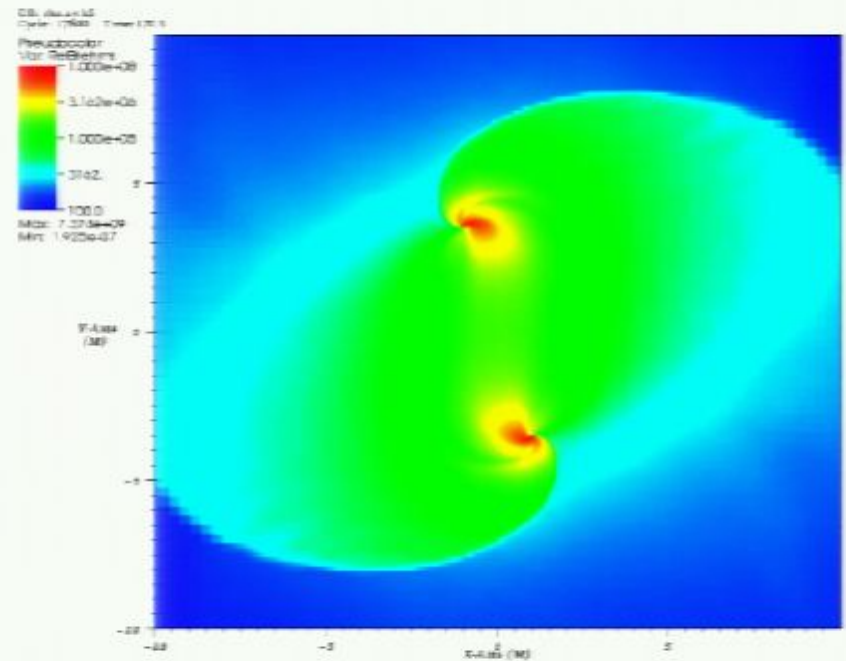
Spinning BHS

Emission from the hot gas

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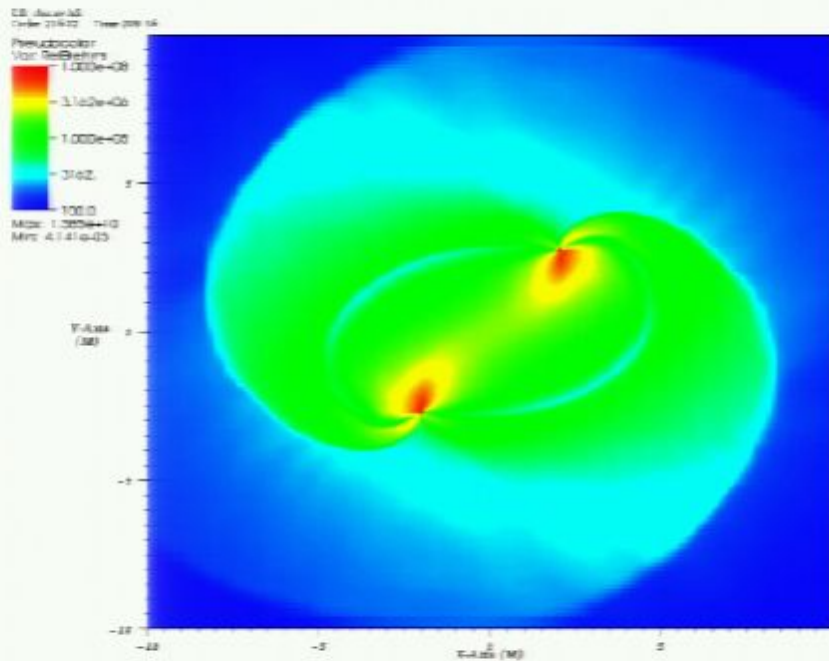
Non-spinning BHs



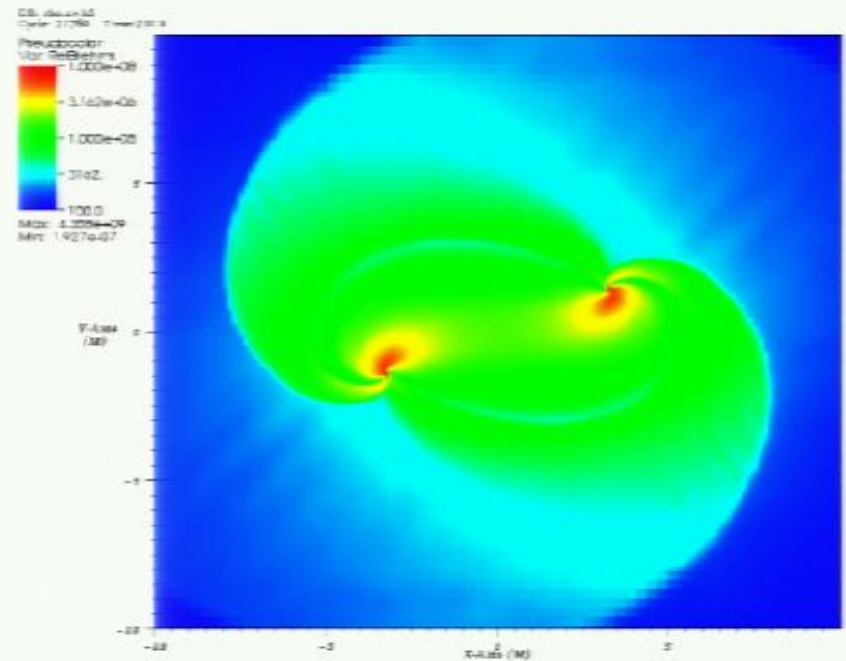
Spinning BHS

Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



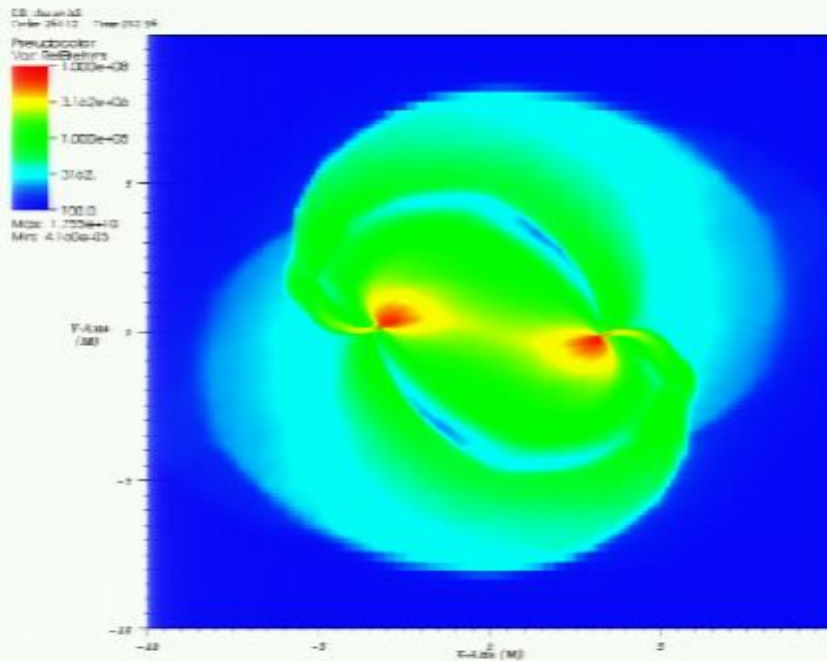
Non-spinning BHs



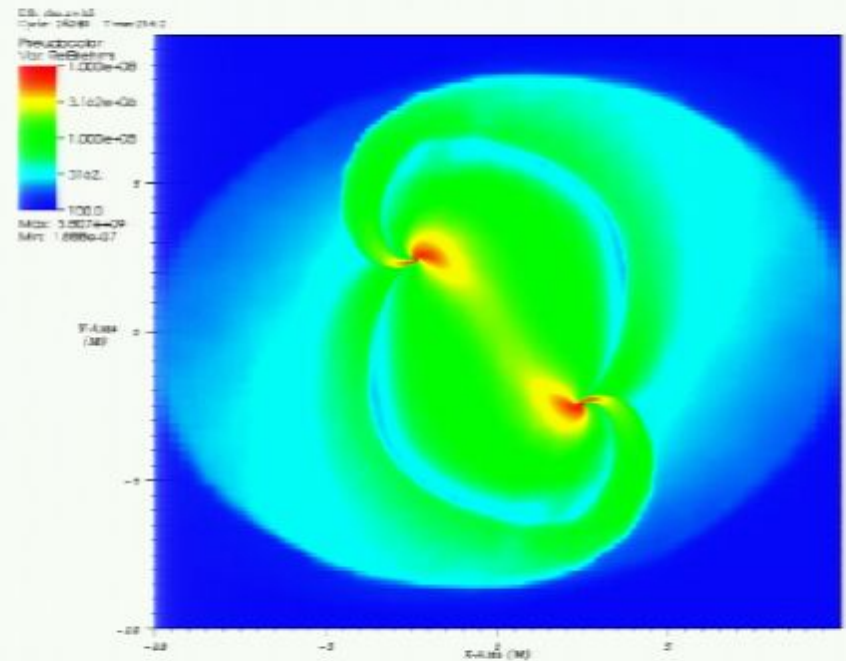
Spinning BHS

Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



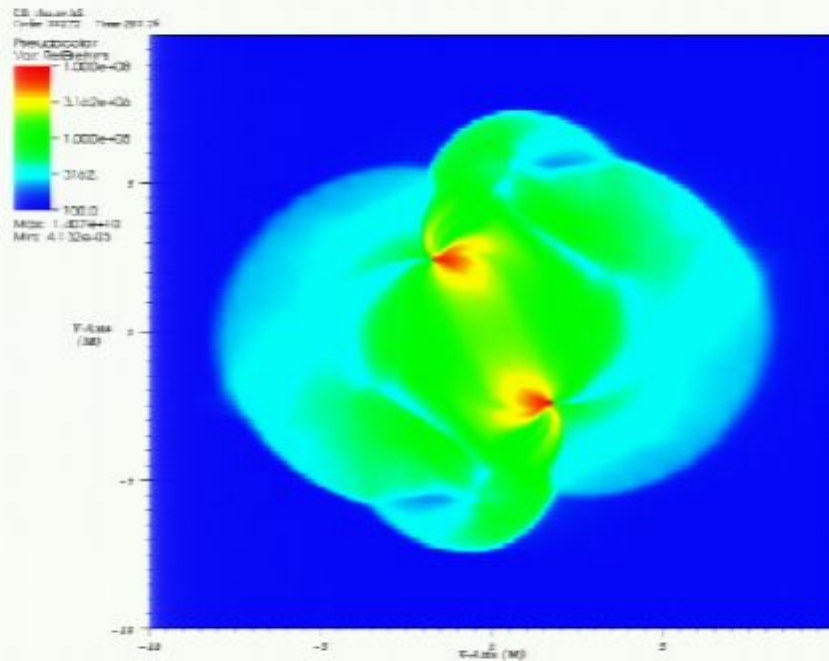
Non-spinning BHs



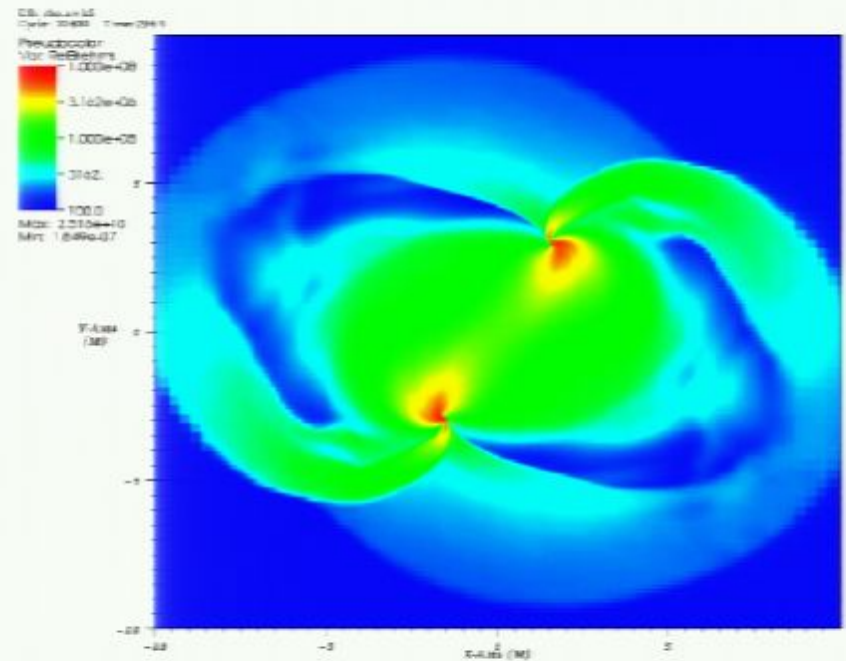
Spinning BHS

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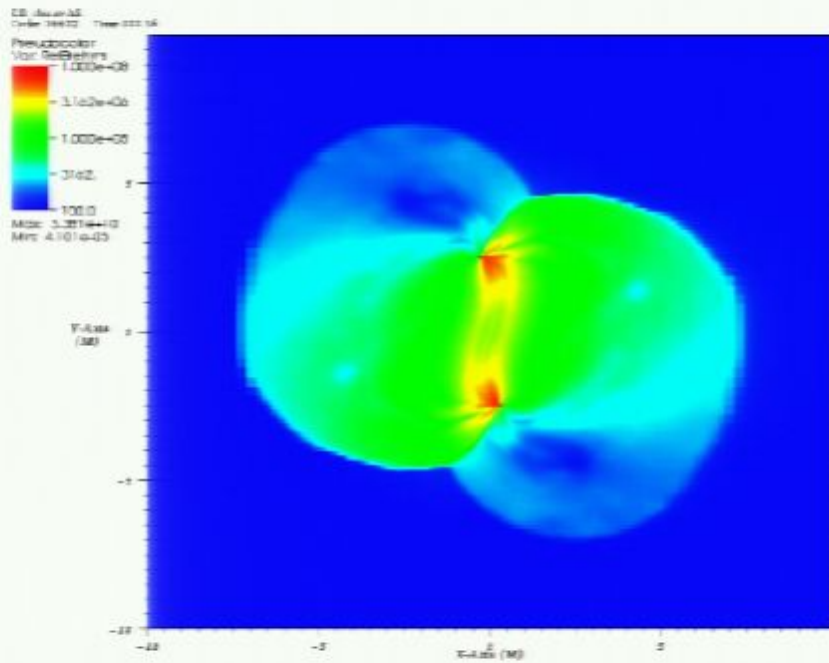
Non-spinning BHs



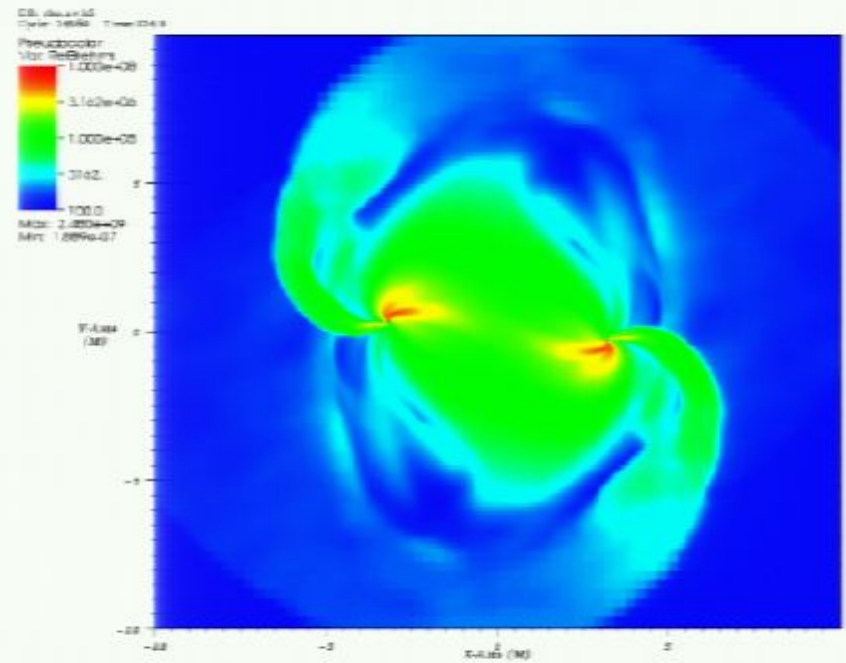
Spinning BHS

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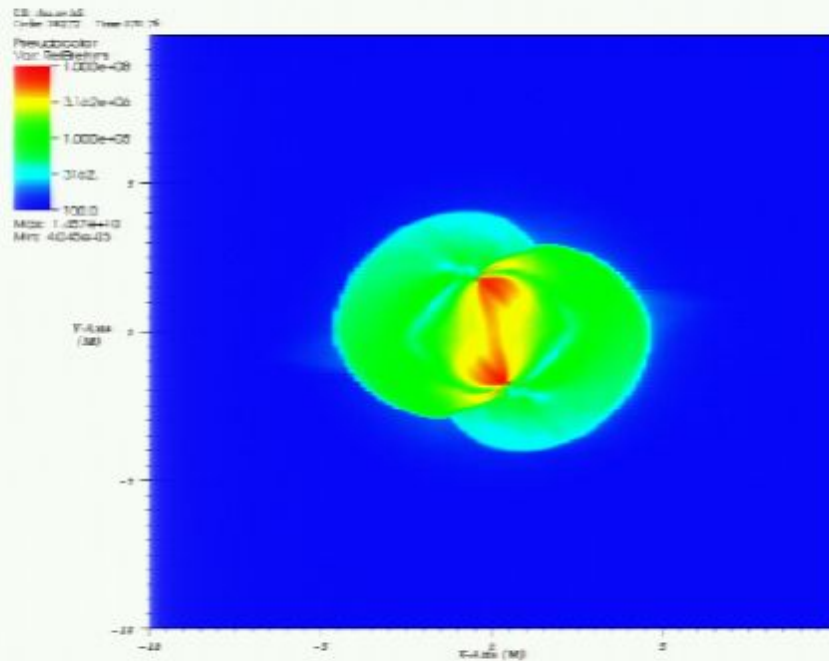
Non-spinning BHs



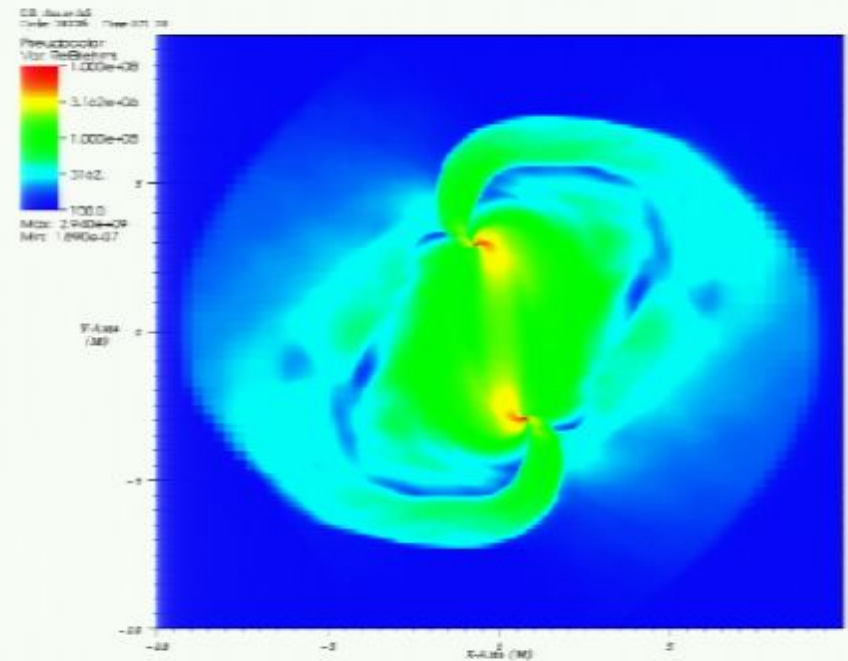
Spinning BHS

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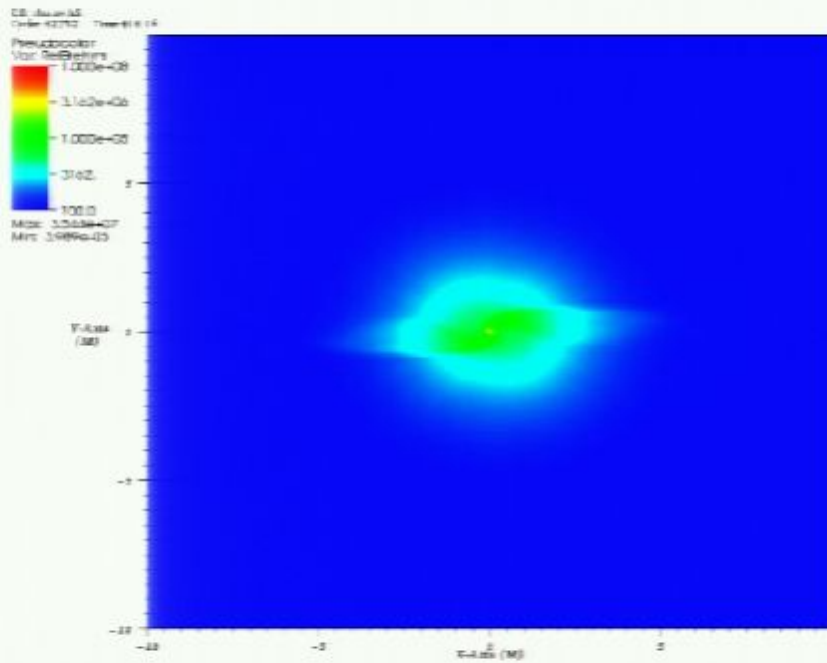
Non-spinning BHs



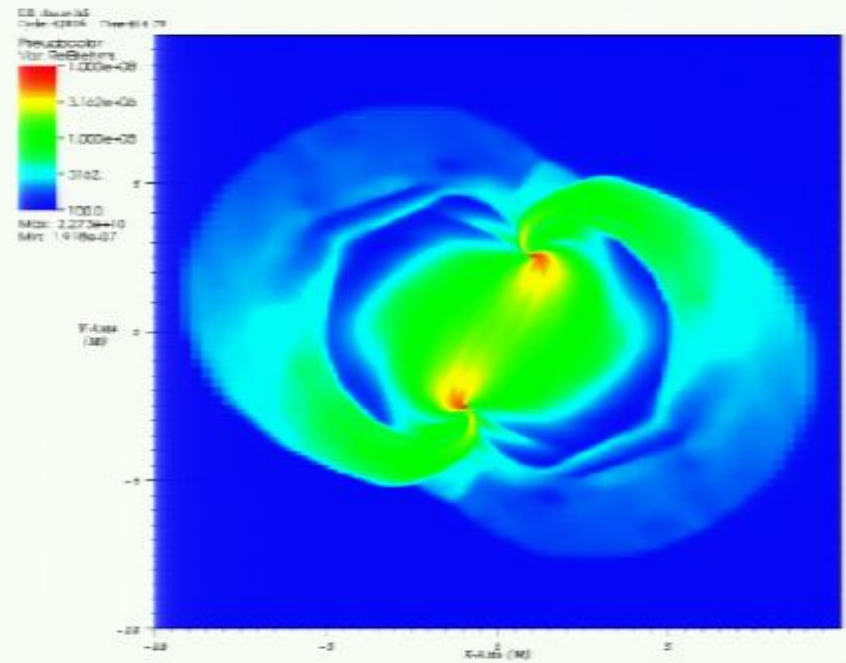
Spinning BHS

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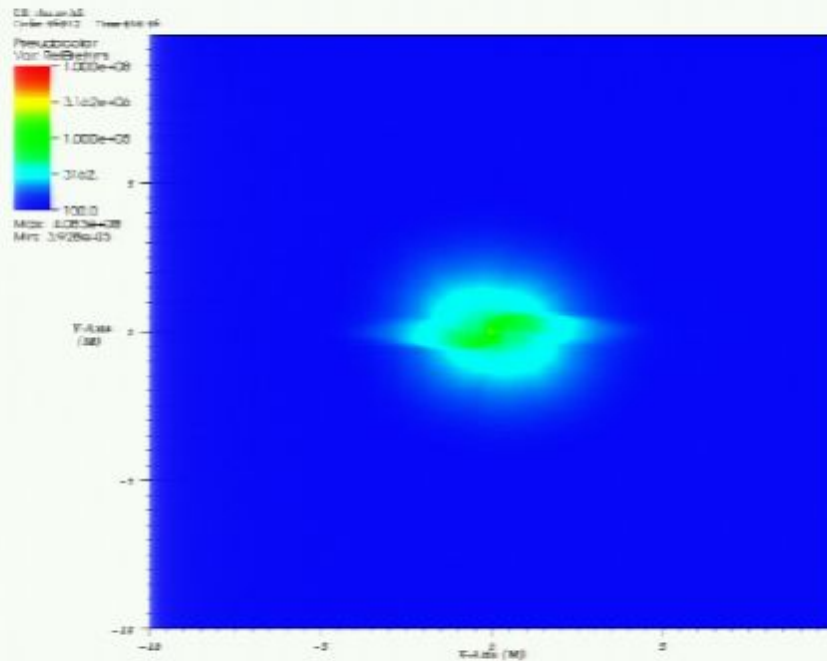
Non-spinning BHs



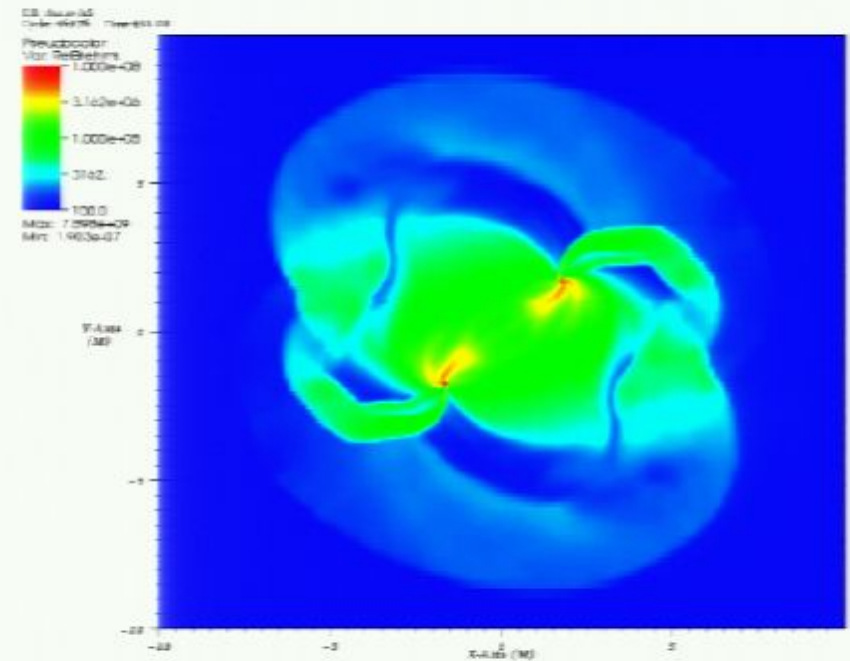
Spinning BHS

Emission from the hot gas

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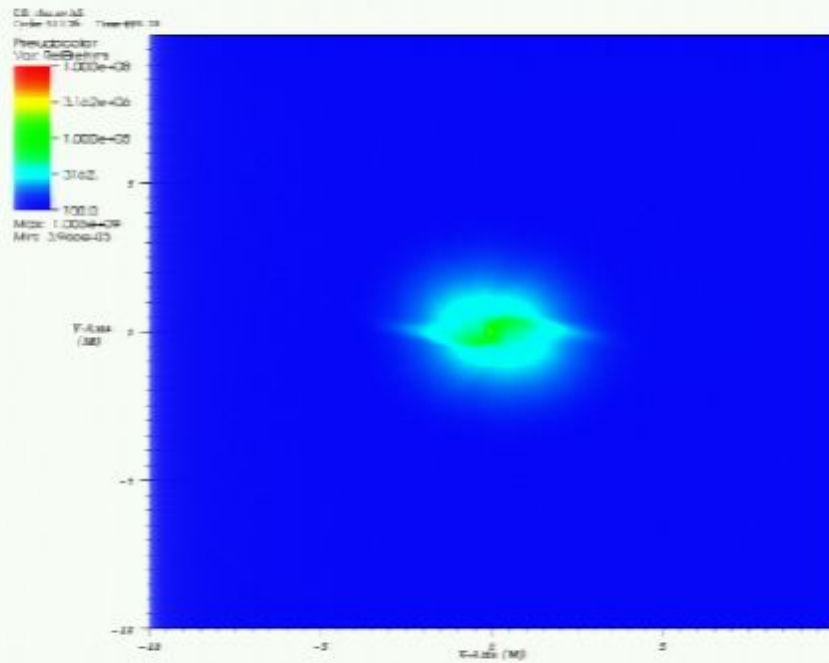
Non-spinning BHs



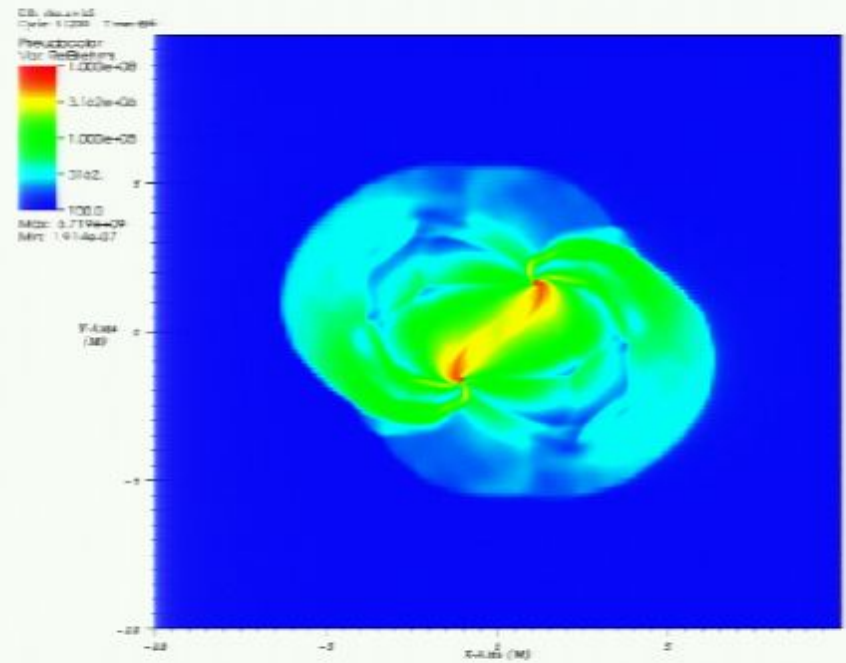
Spinning BHS

Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



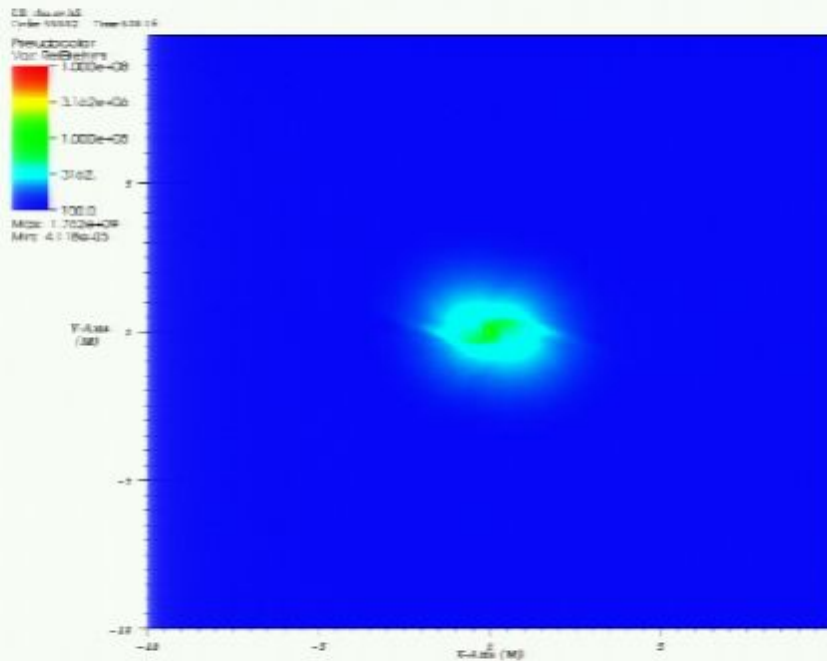
Non-spinning BHs



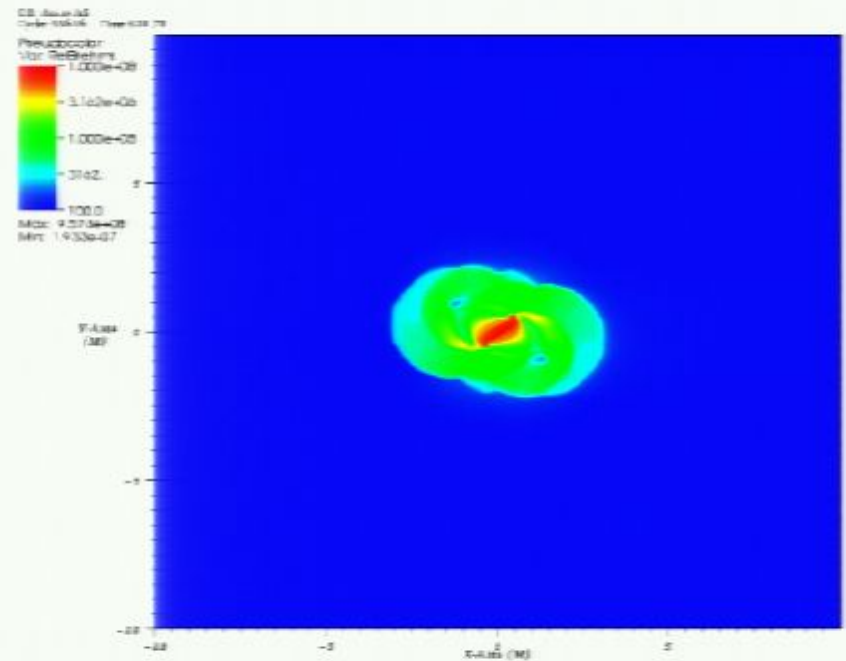
Spinning BHS

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$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



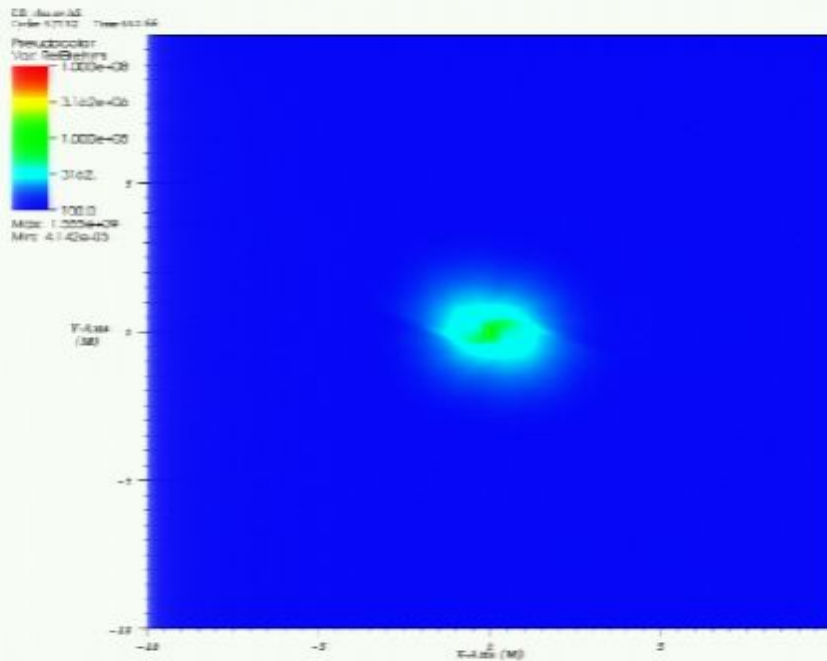
Non-spinning BHs



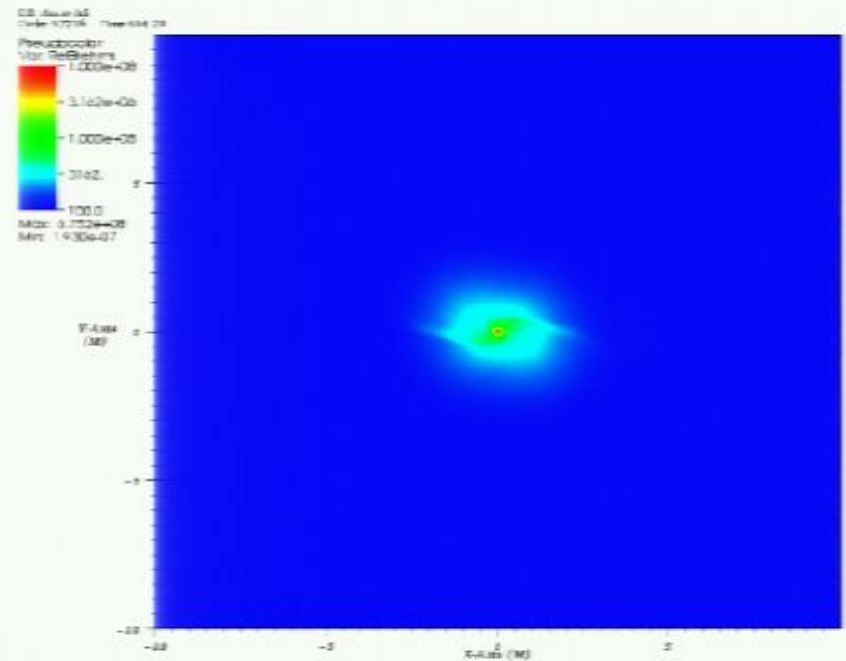
Spinning BHS

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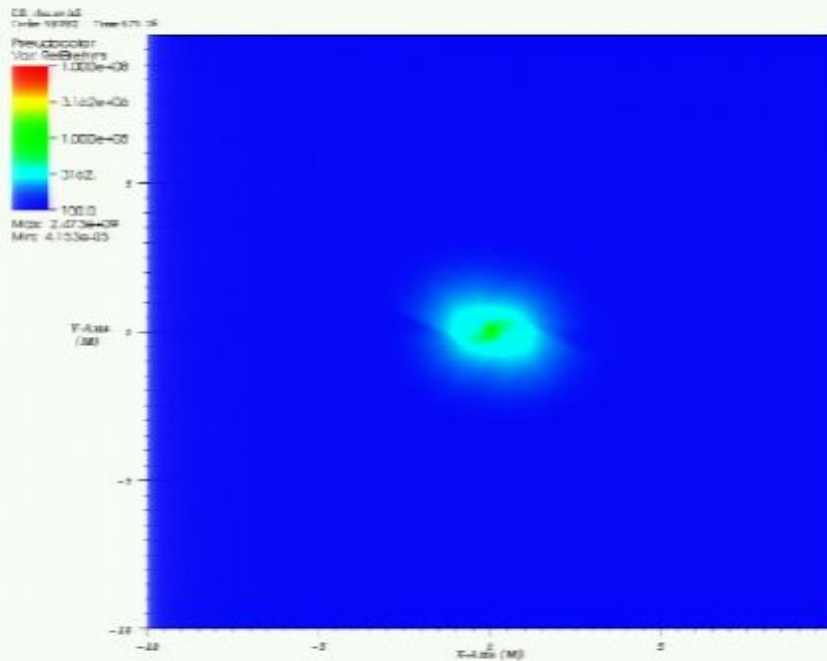
Non-spinning BHs



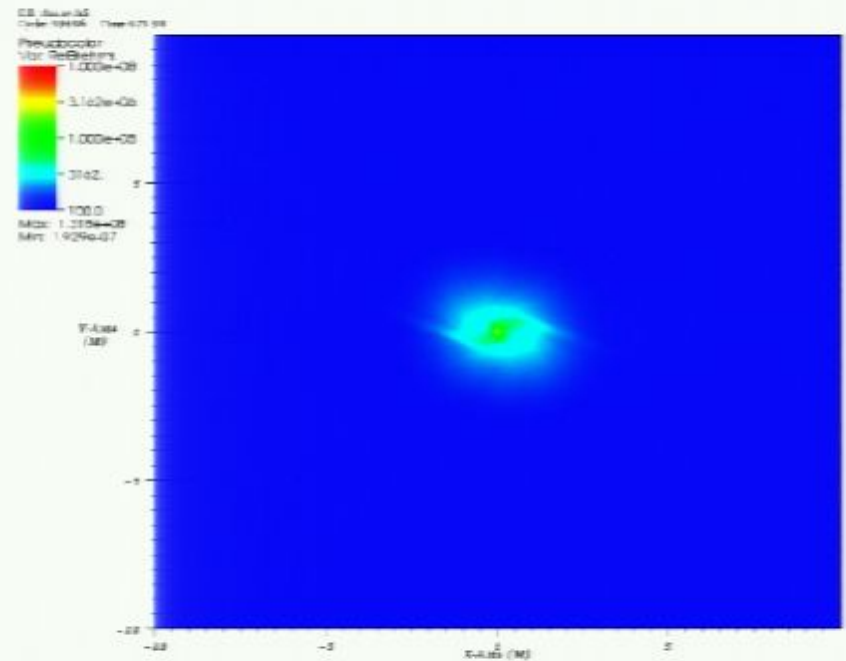
Spinning BHS

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$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$



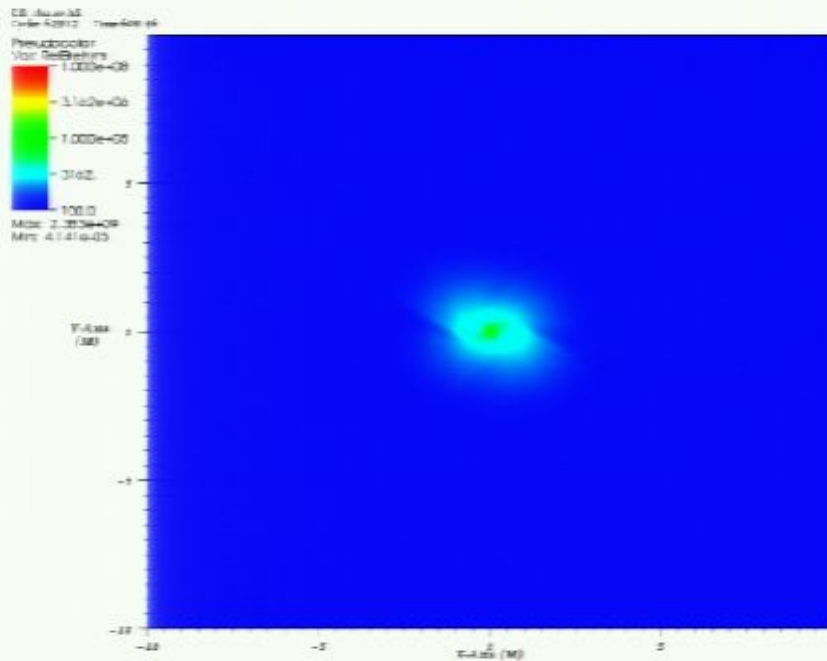
Non-spinning BHs



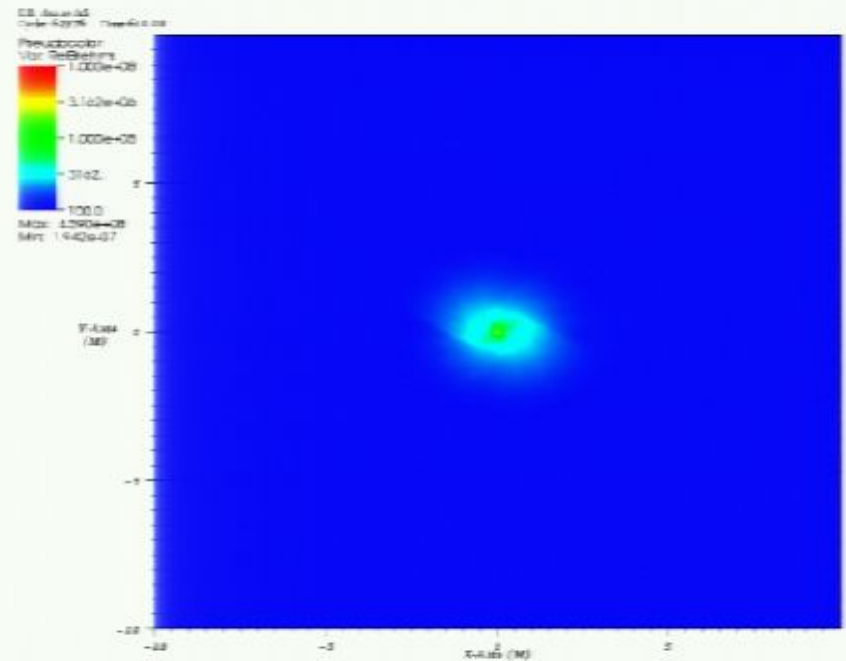
Spinning BHS

Emission from the hot gas

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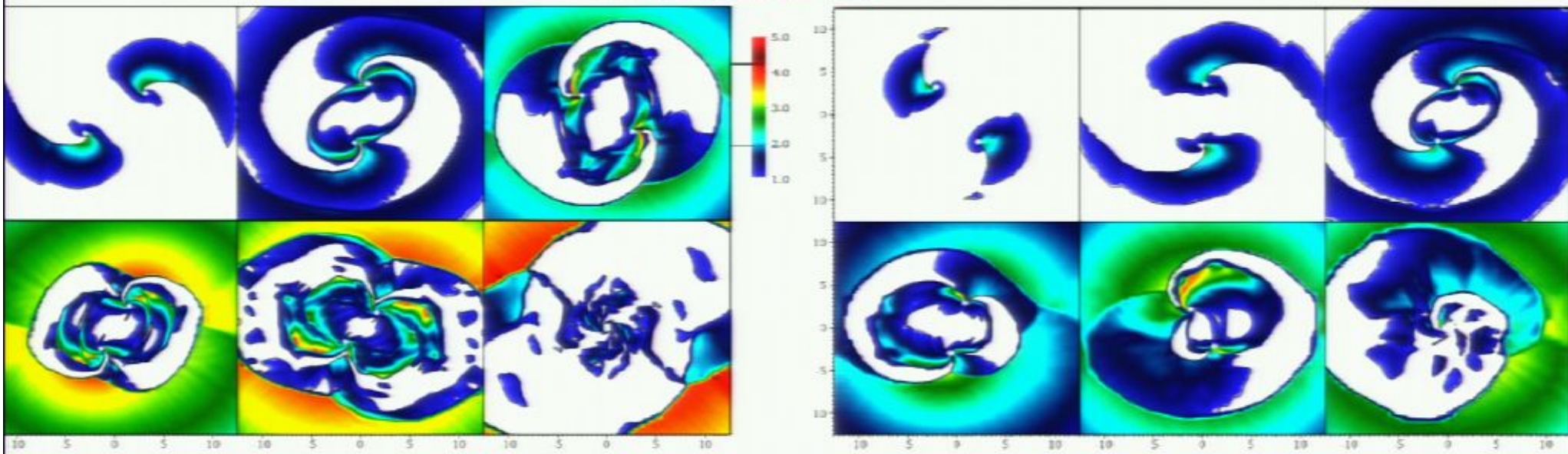


Non-spinning BHs



Spinning BHS

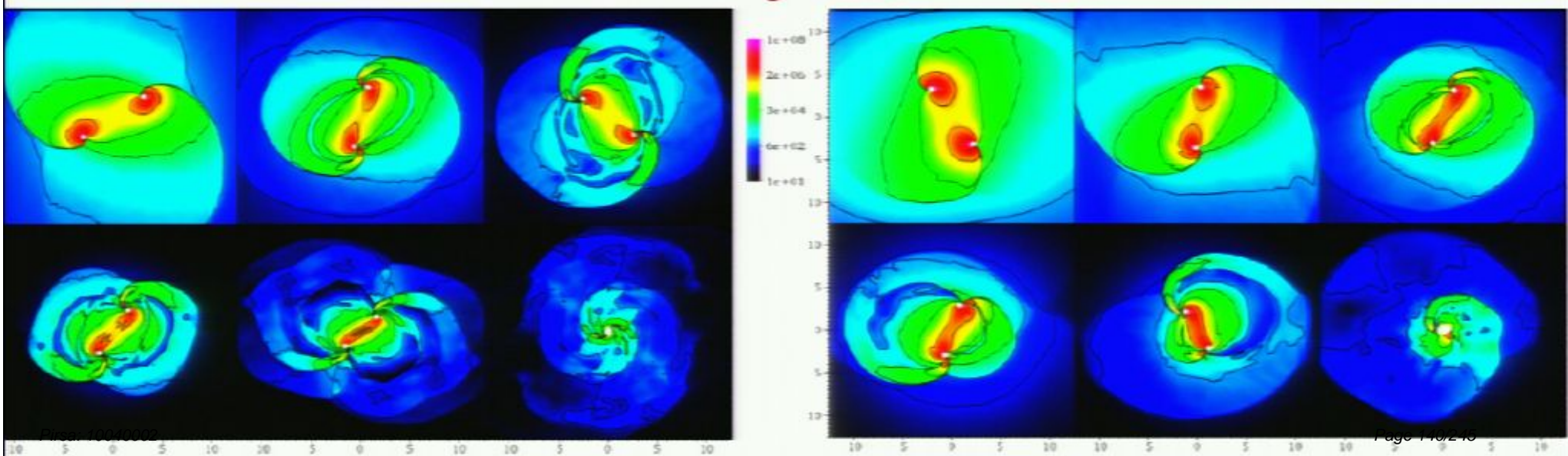
Mach number ≥ 1



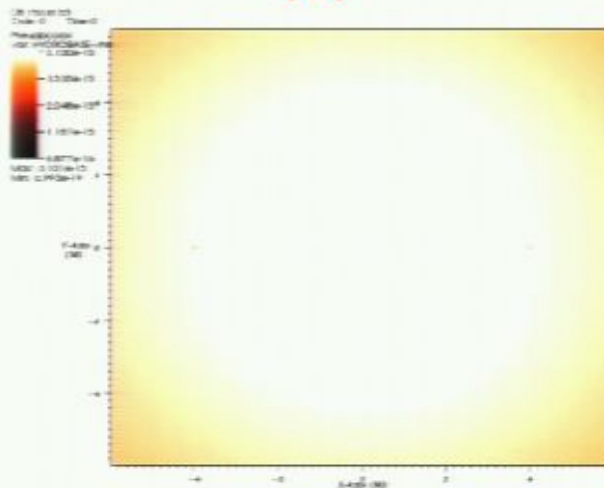
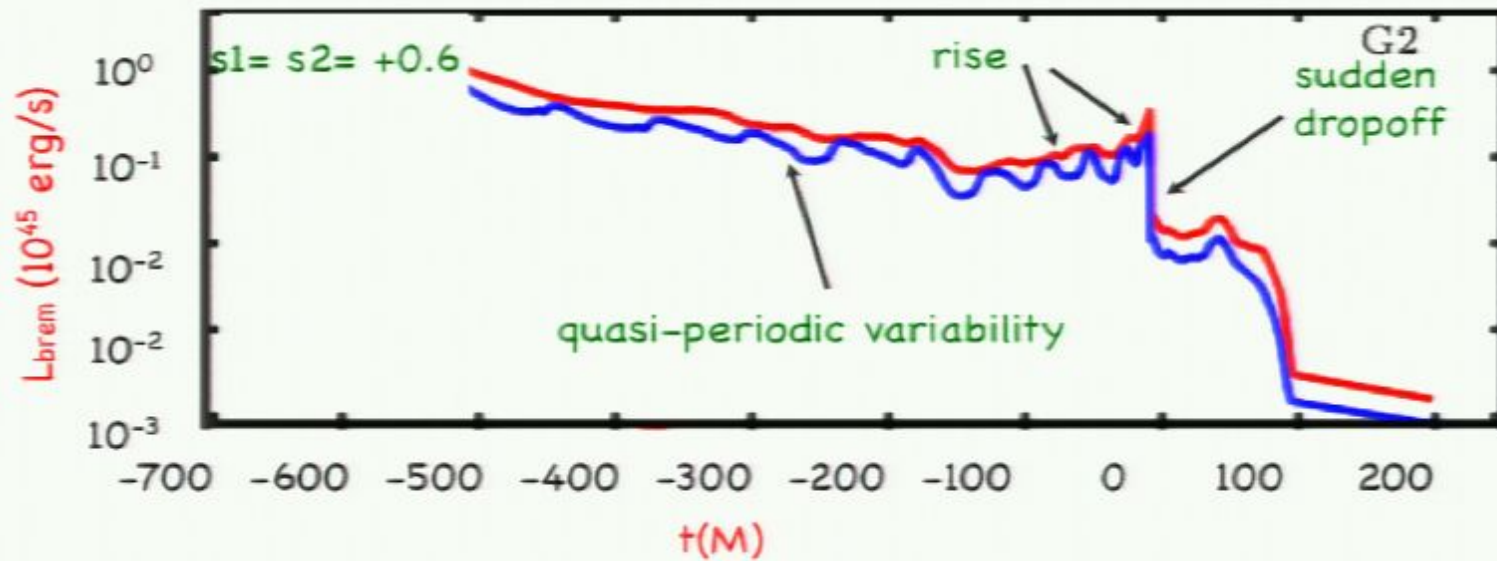
$s_1 = s_2 = +0.6$

Bremsstrahlung emission

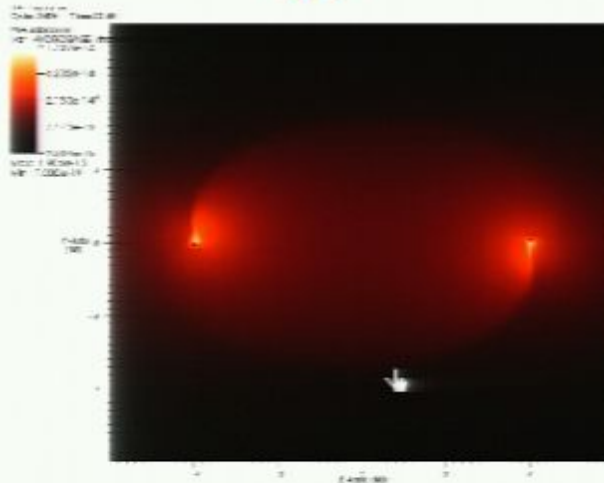
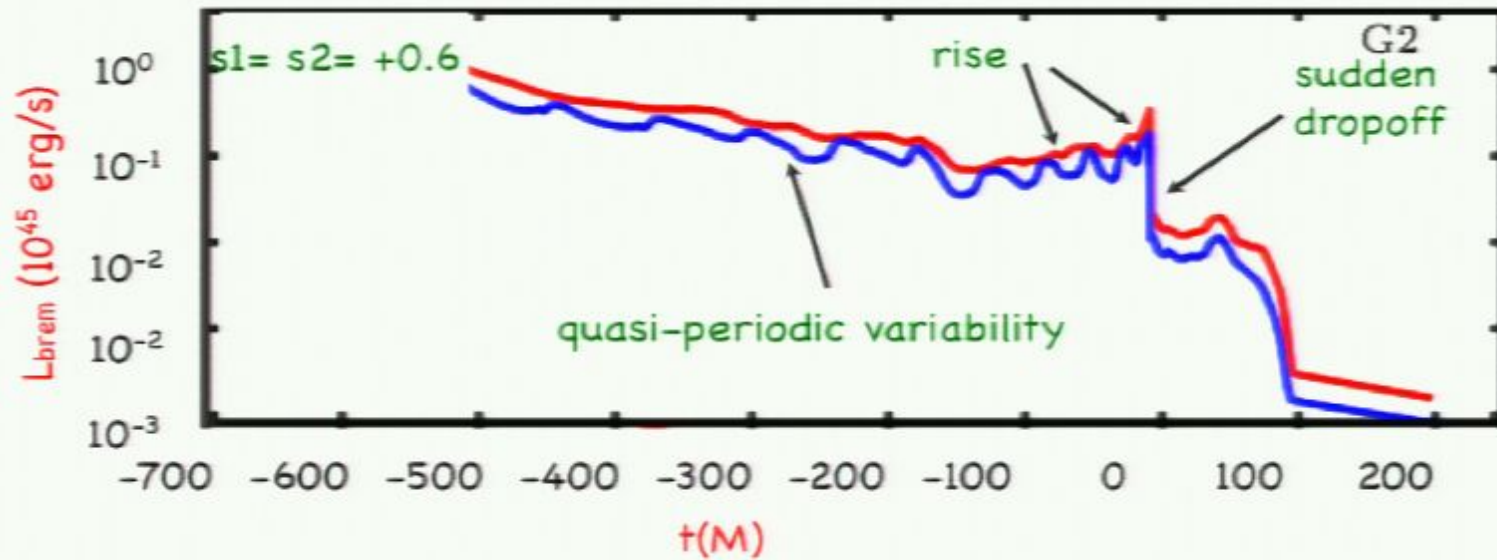
$s_1 = +0.4$ $s_2 = -0.4$



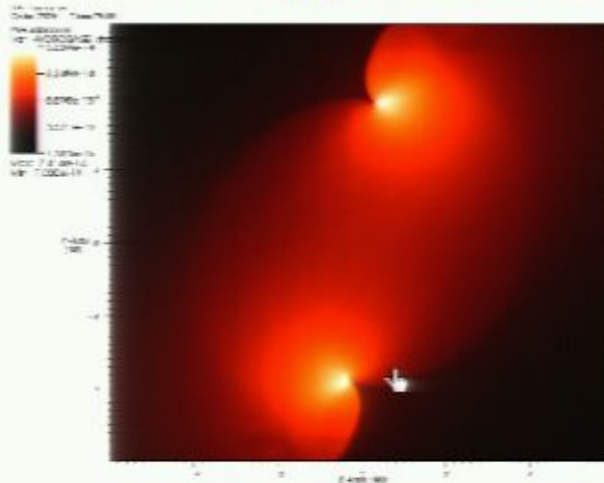
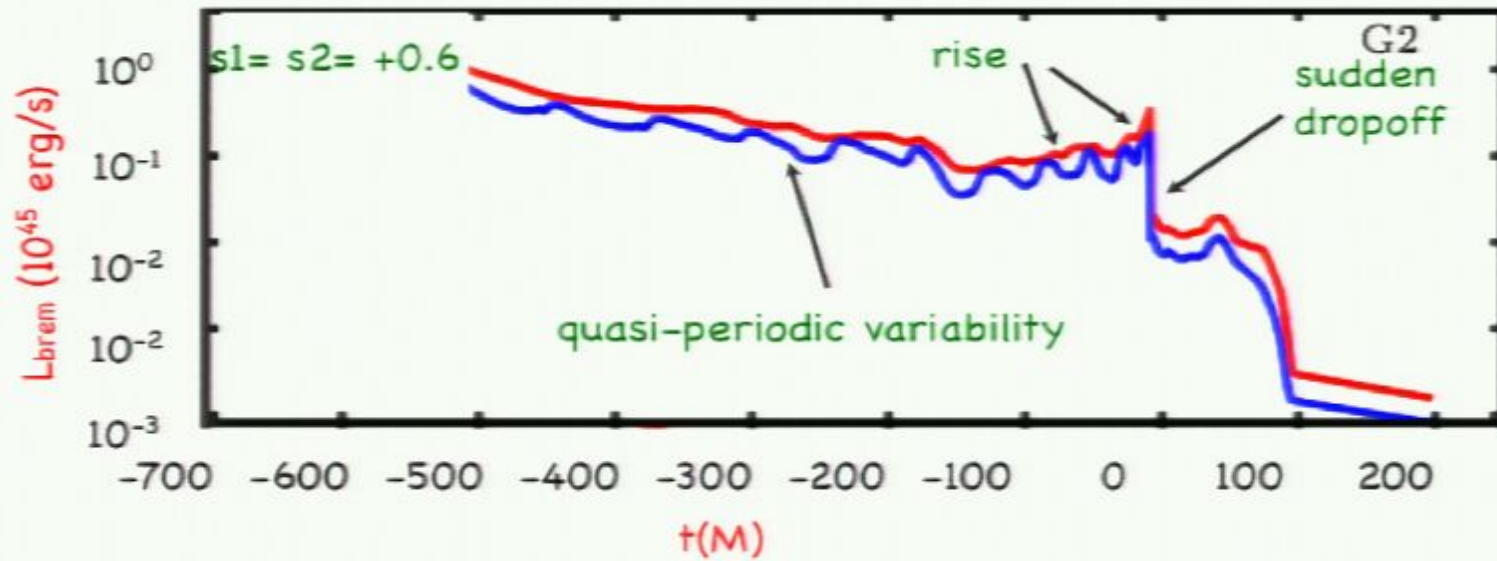
Bremsstrahlung luminosity



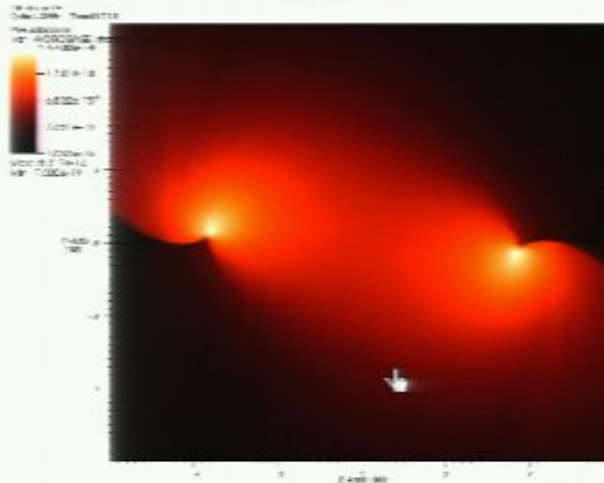
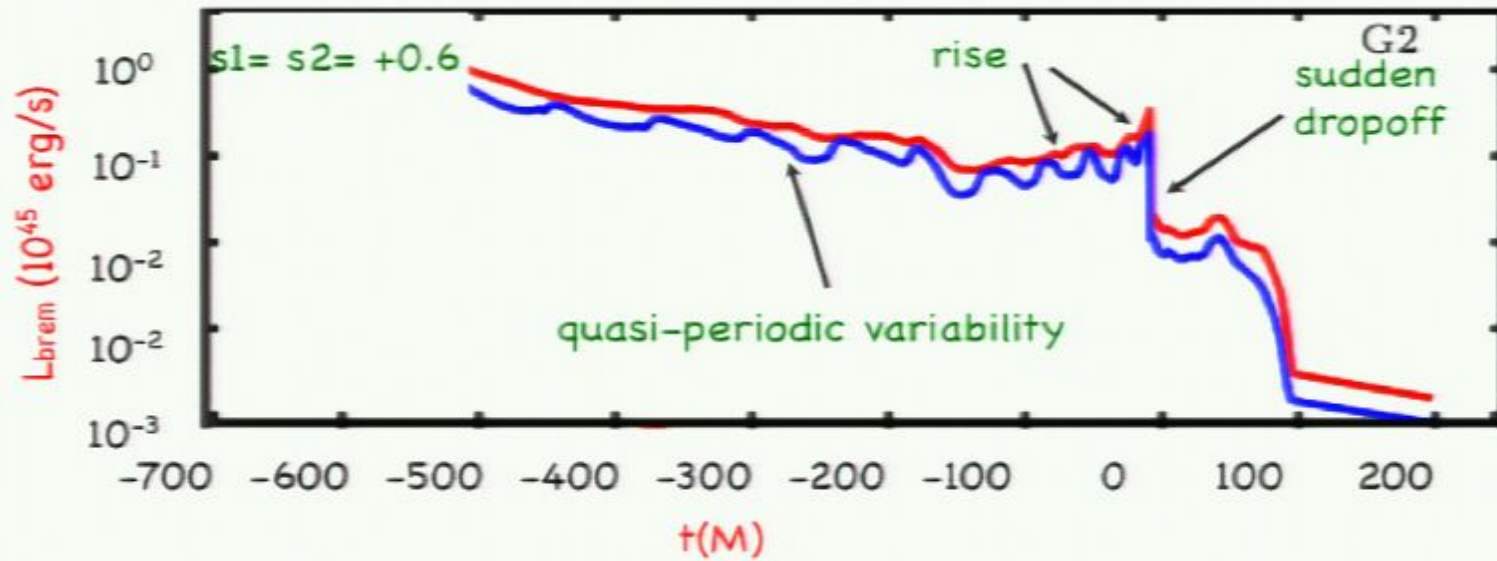
Bremsstrahlung luminosity



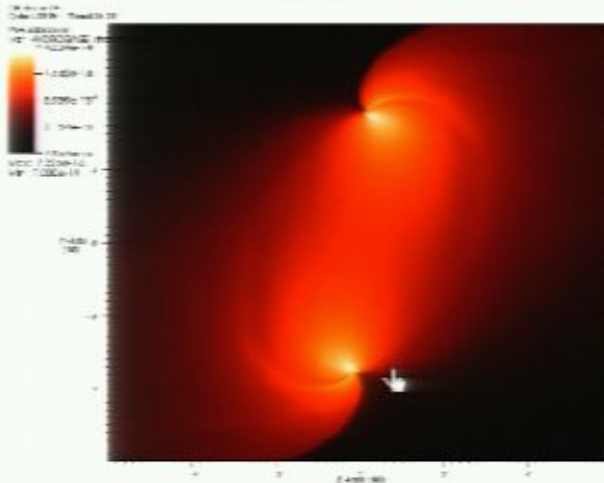
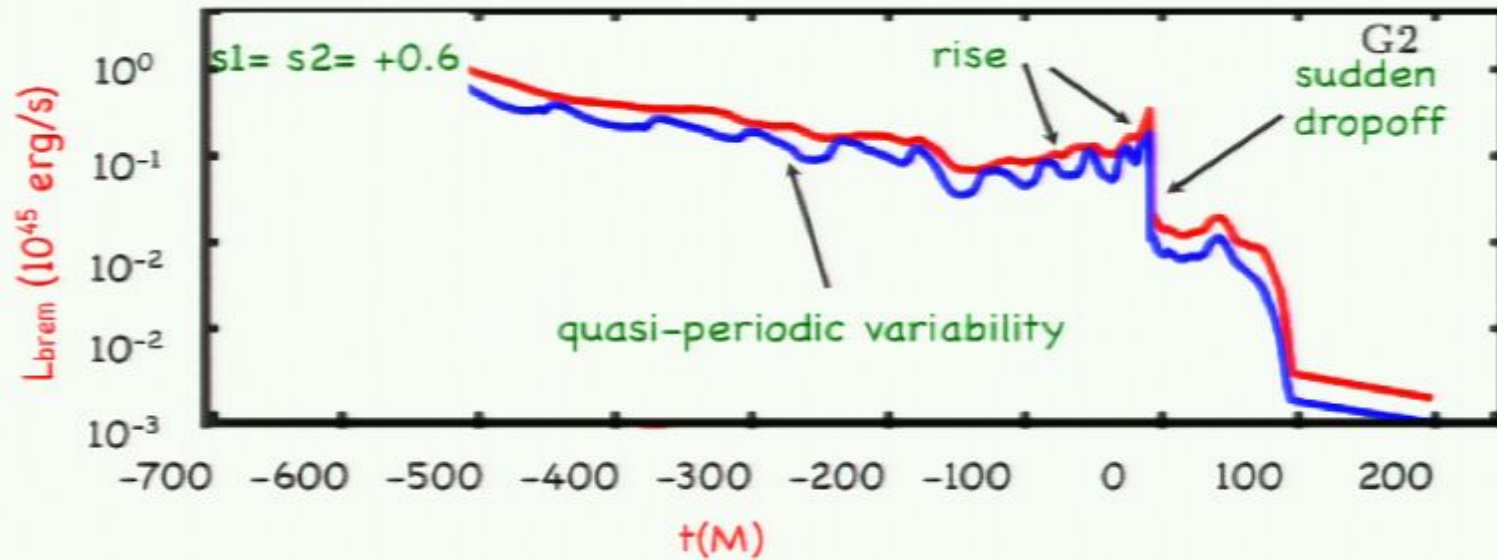
Bremsstrahlung luminosity



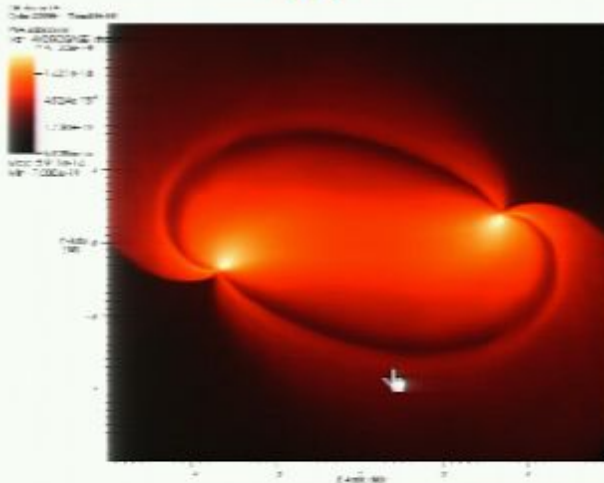
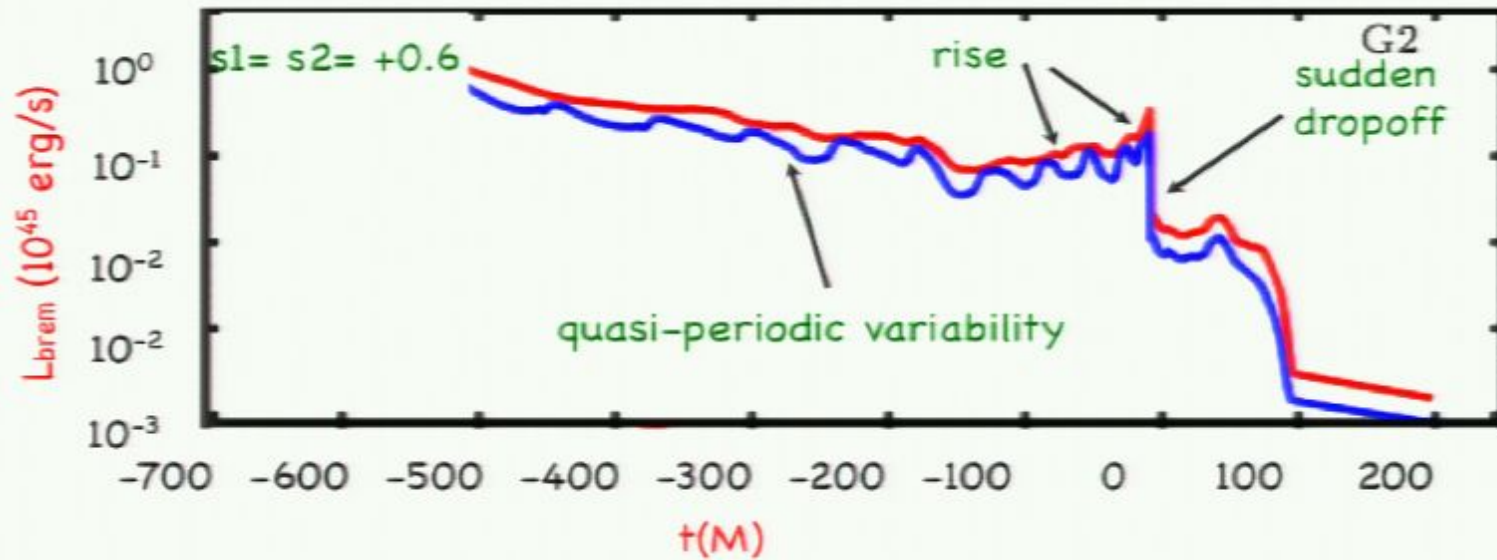
Bremsstrahlung luminosity



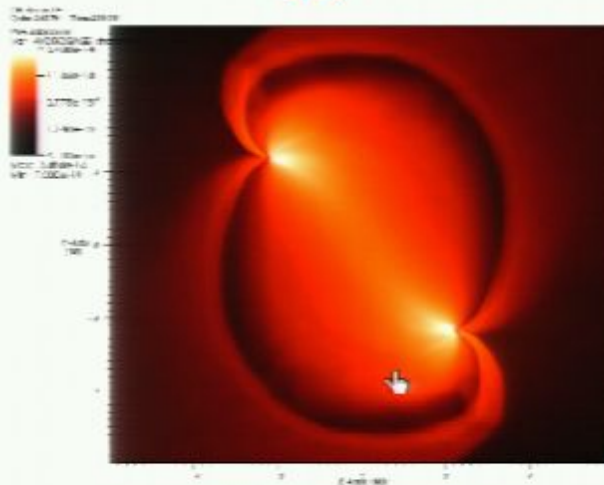
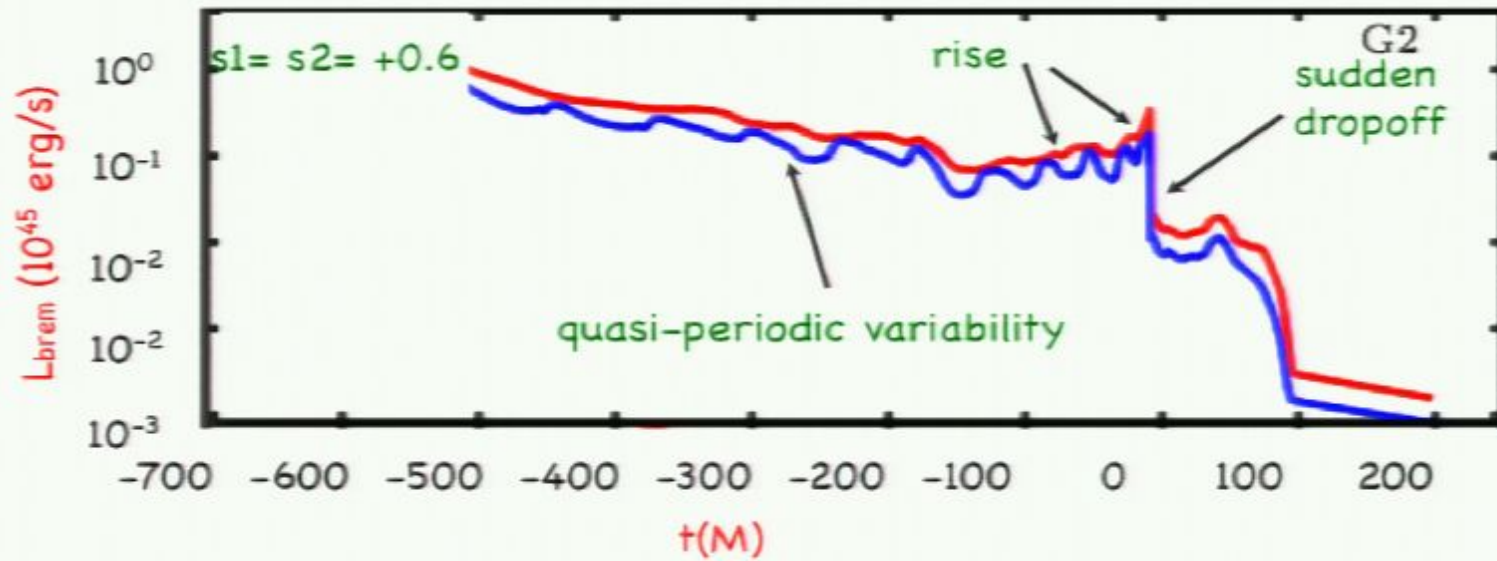
Bremsstrahlung luminosity



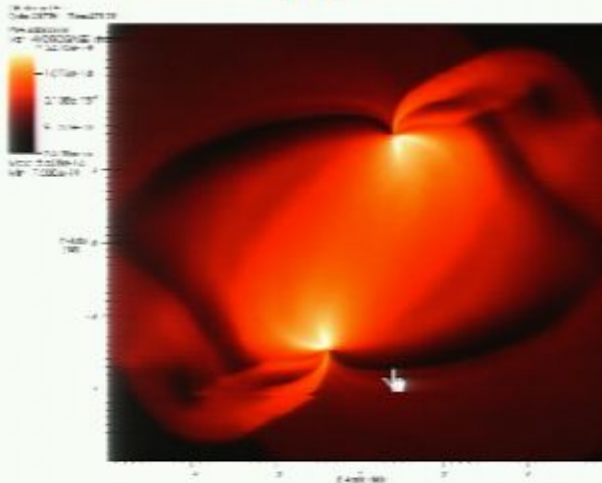
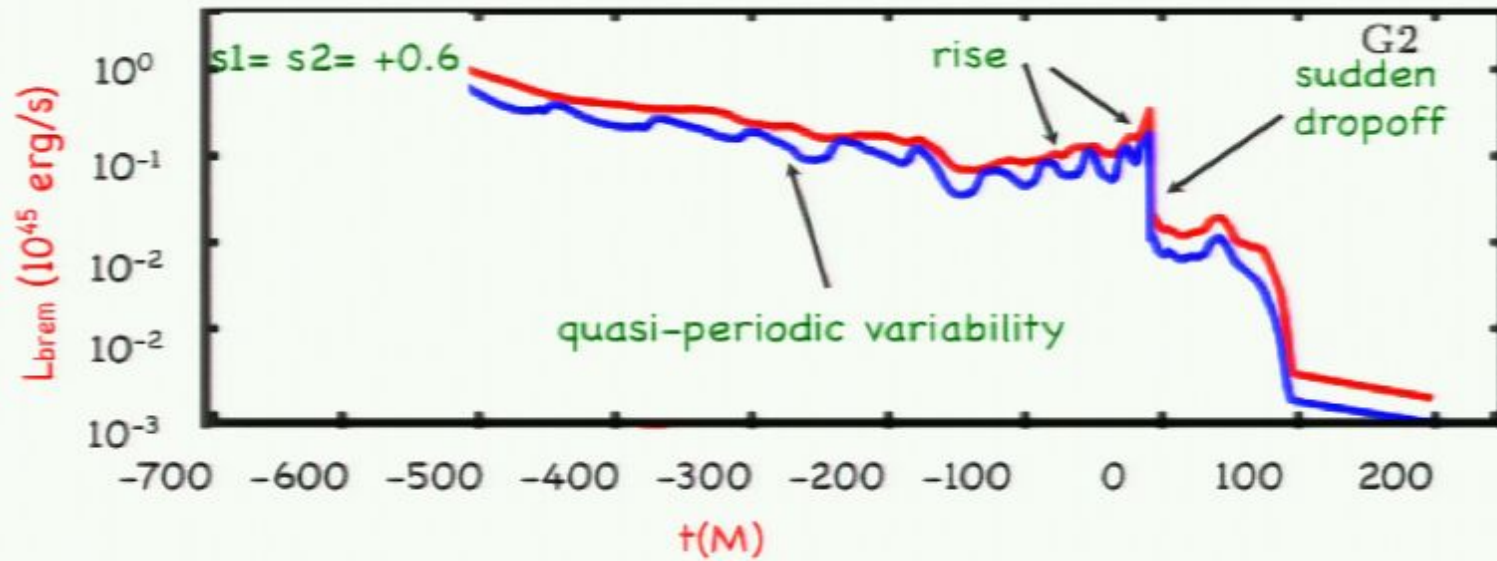
Bremsstrahlung luminosity



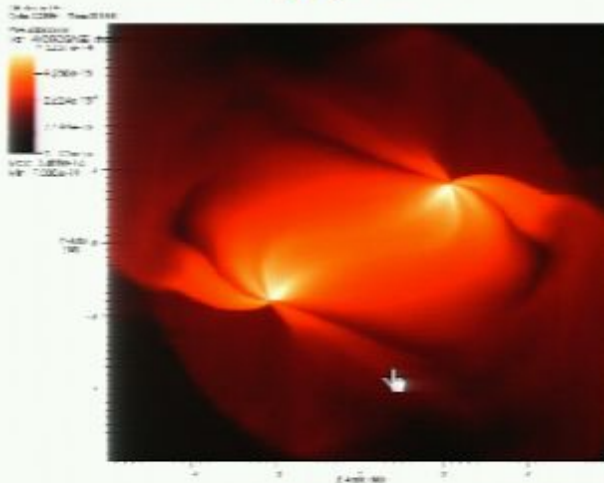
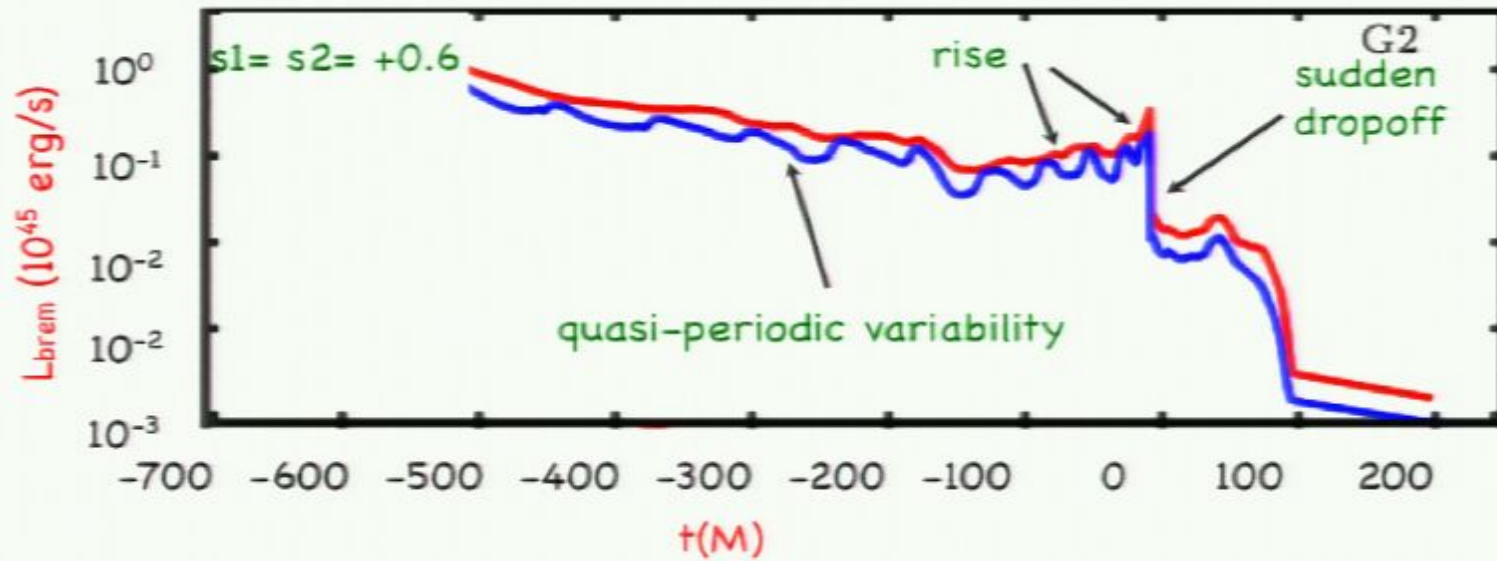
Bremsstrahlung luminosity



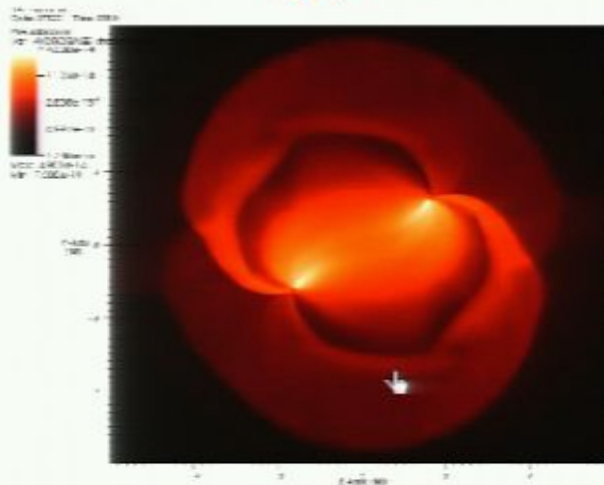
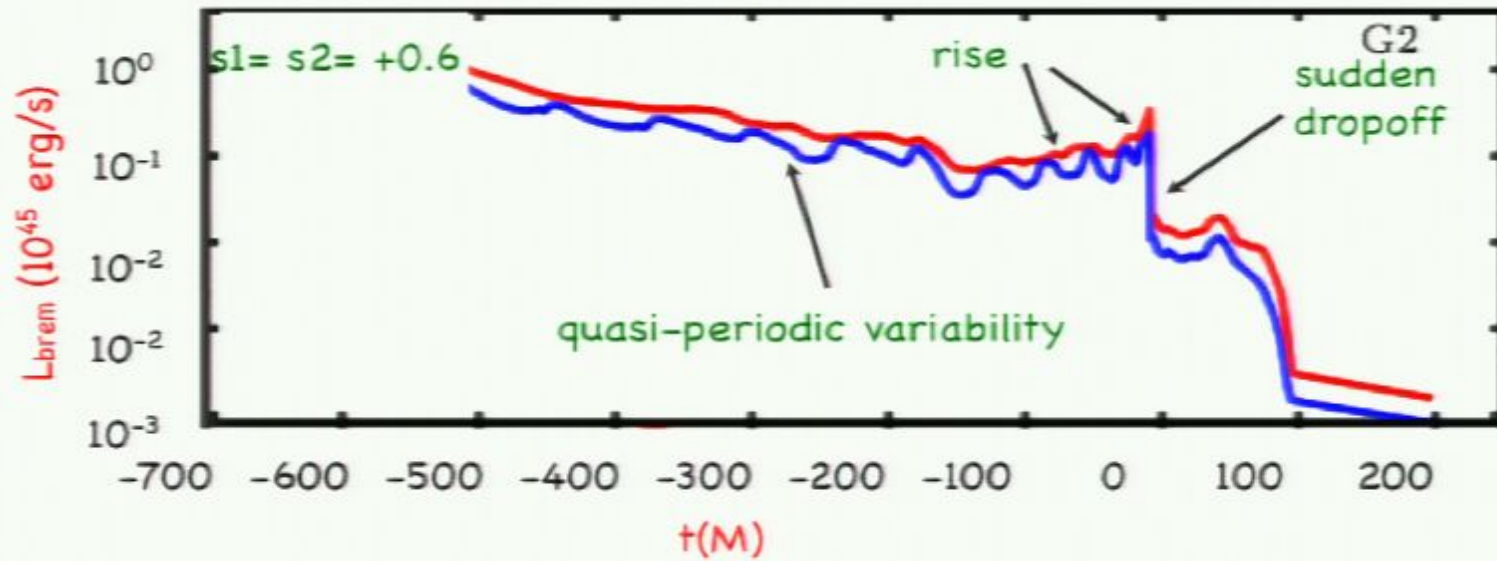
Bremsstrahlung luminosity



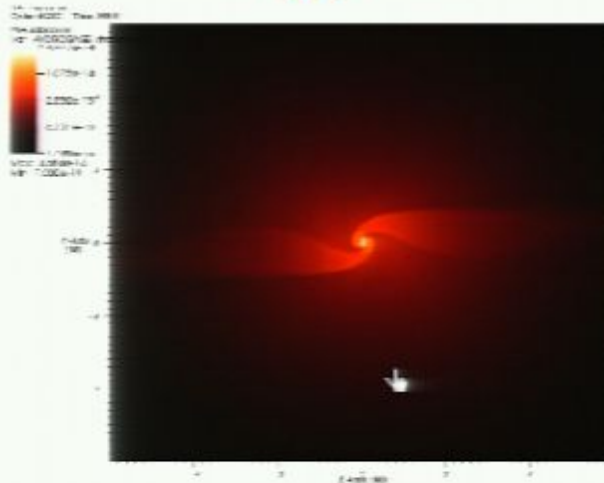
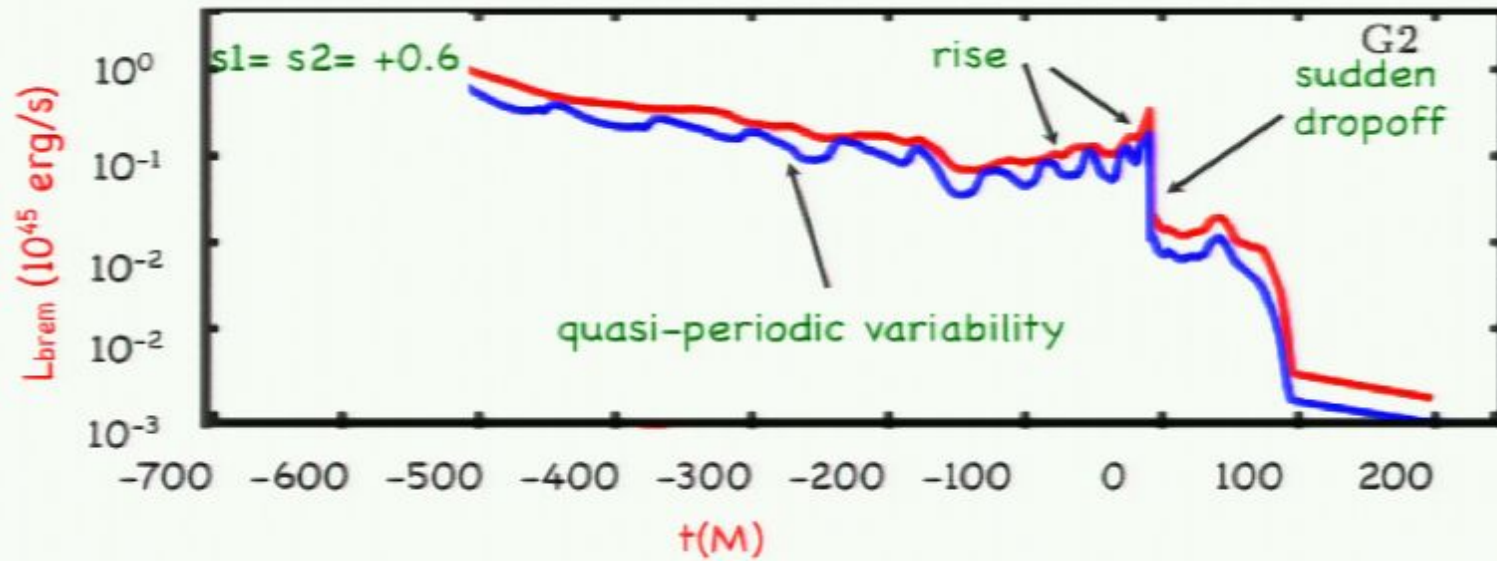
Bremsstrahlung luminosity



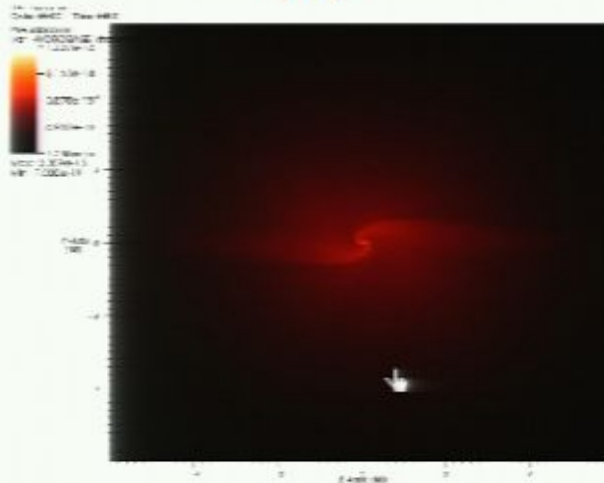
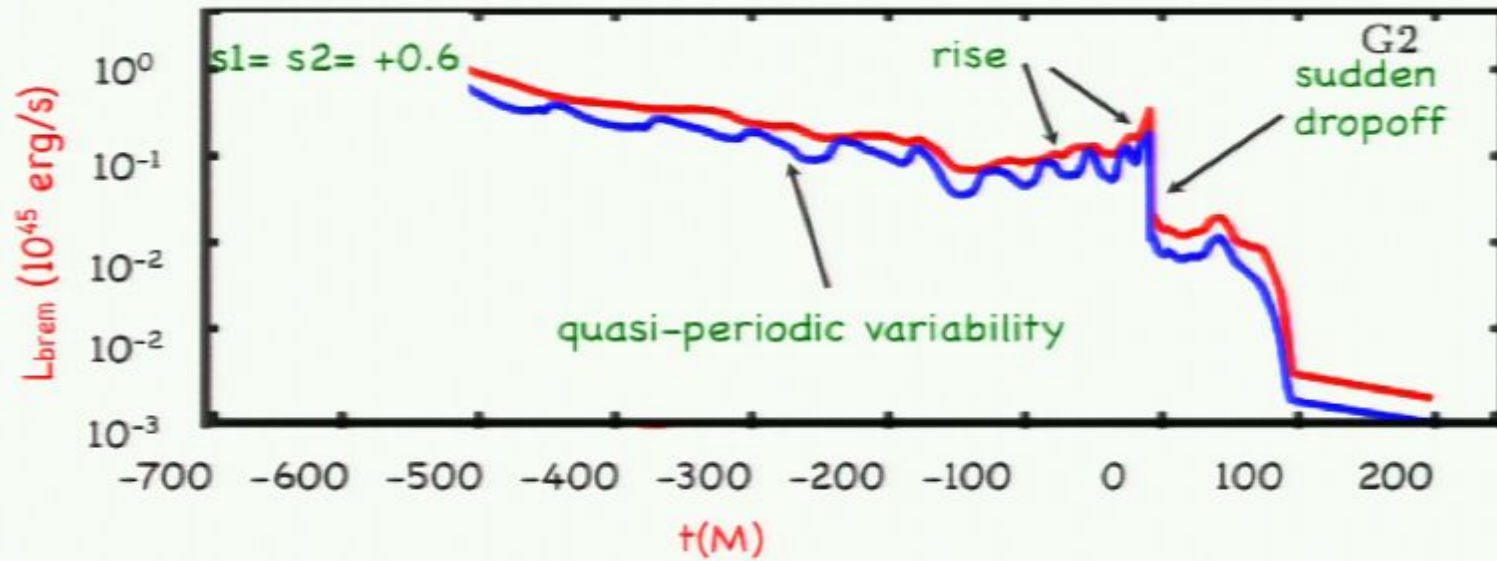
Bremsstrahlung luminosity



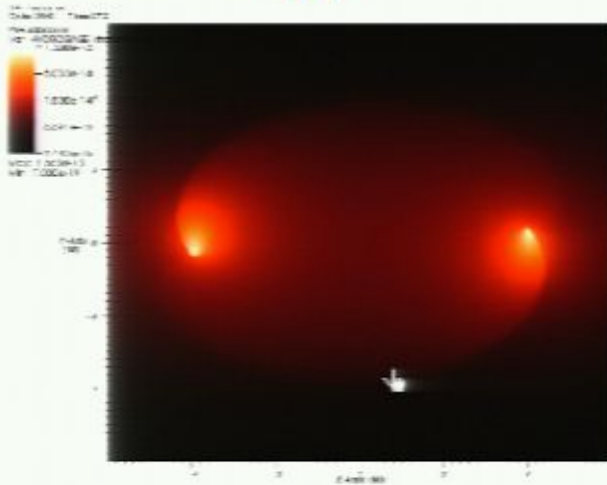
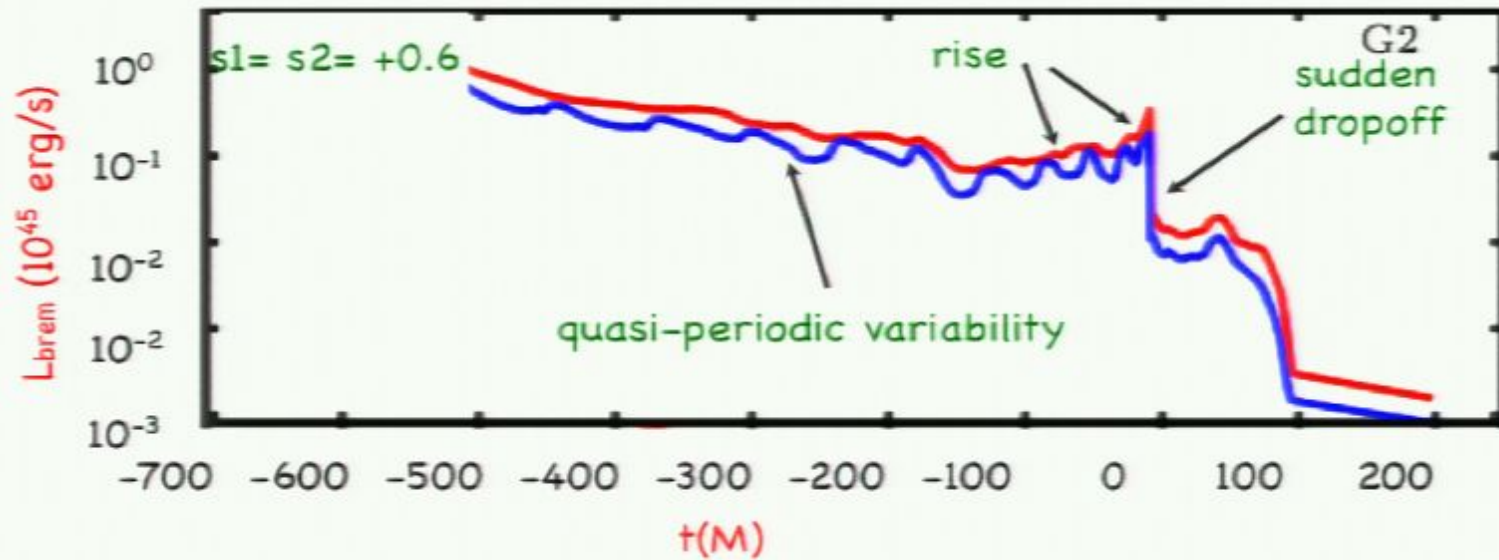
Bremsstrahlung luminosity



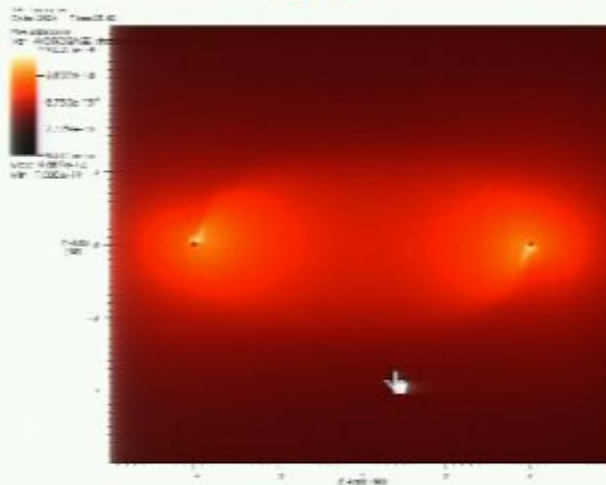
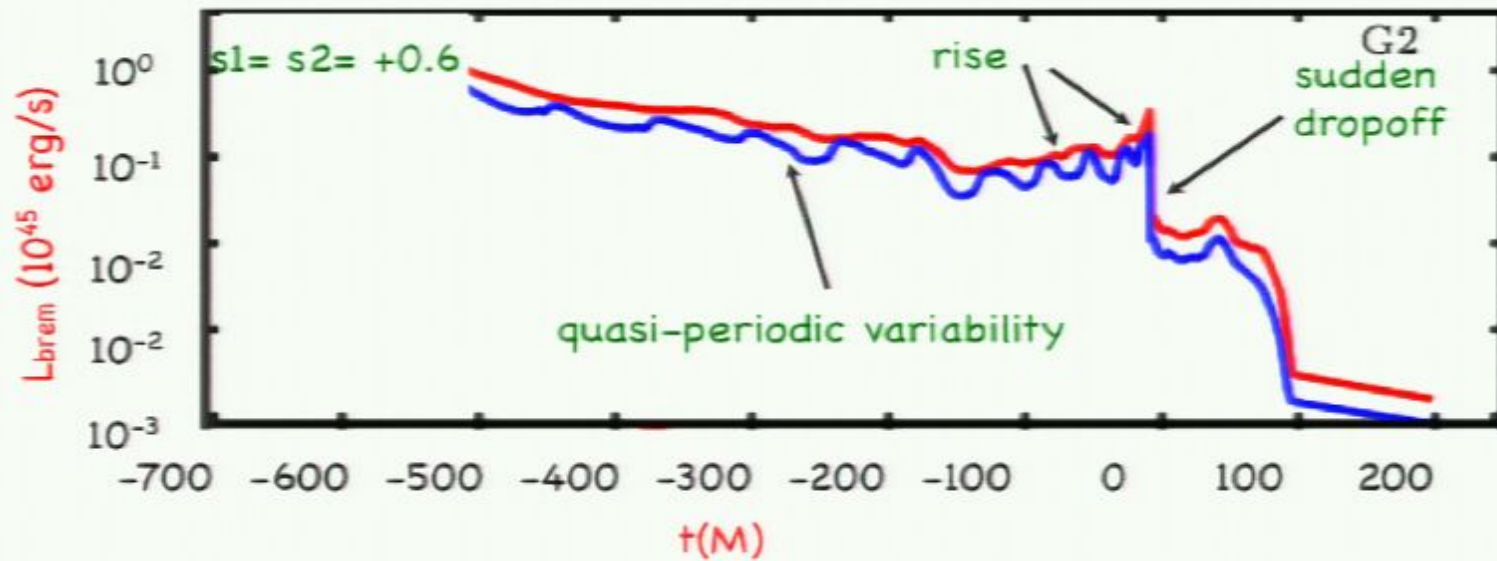
Bremsstrahlung luminosity



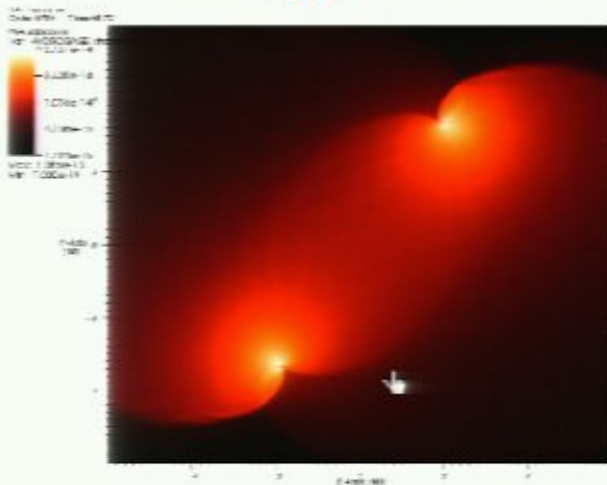
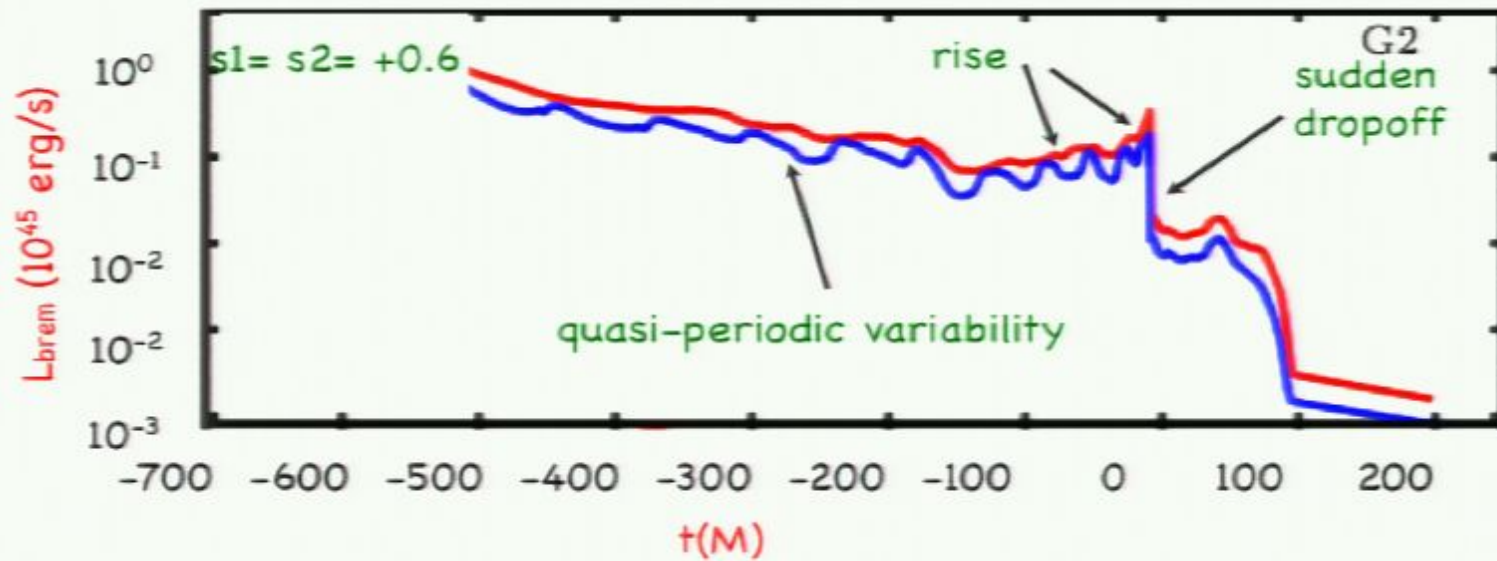
Bremsstrahlung luminosity



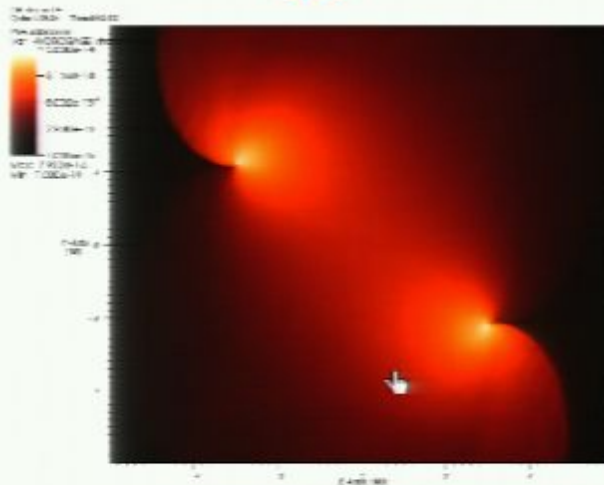
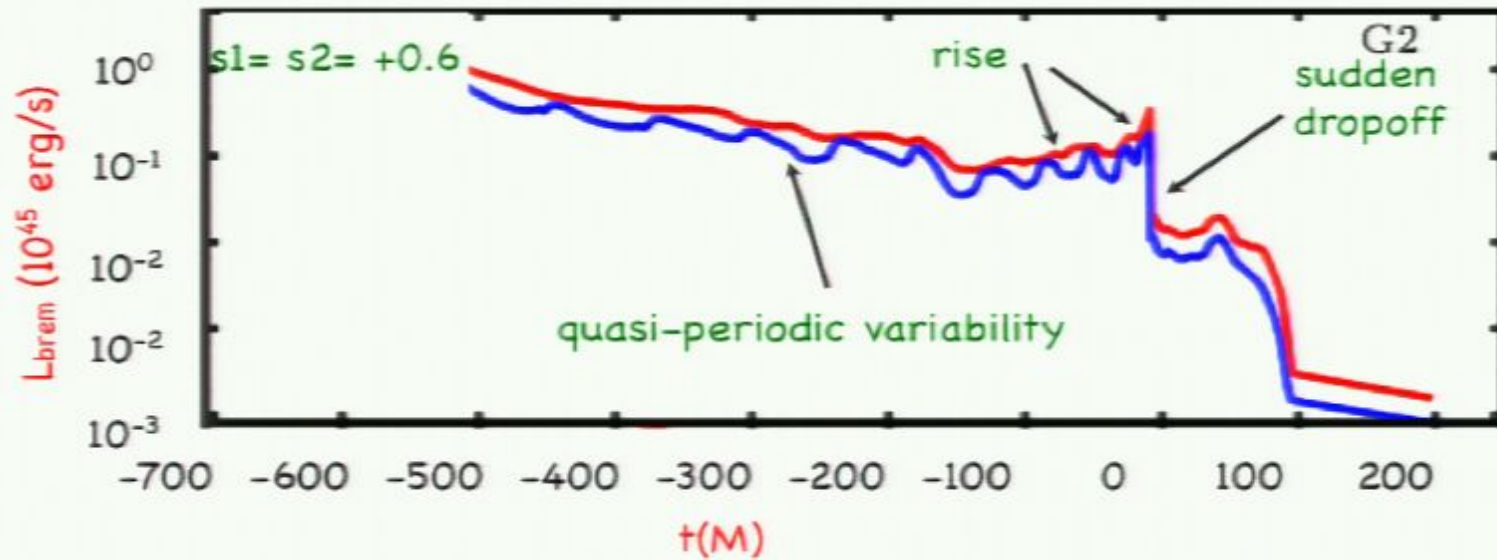
Bremsstrahlung luminosity



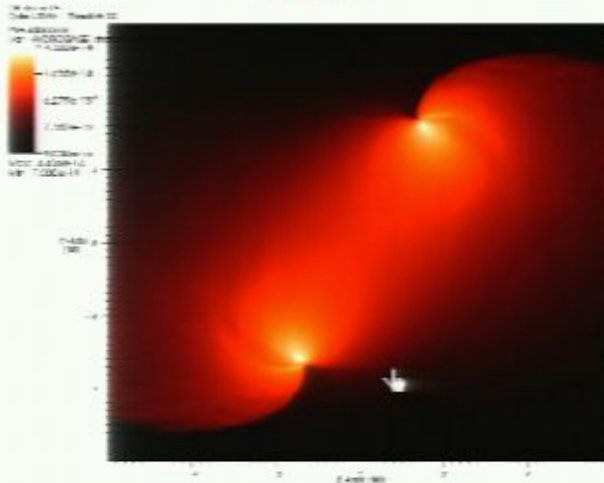
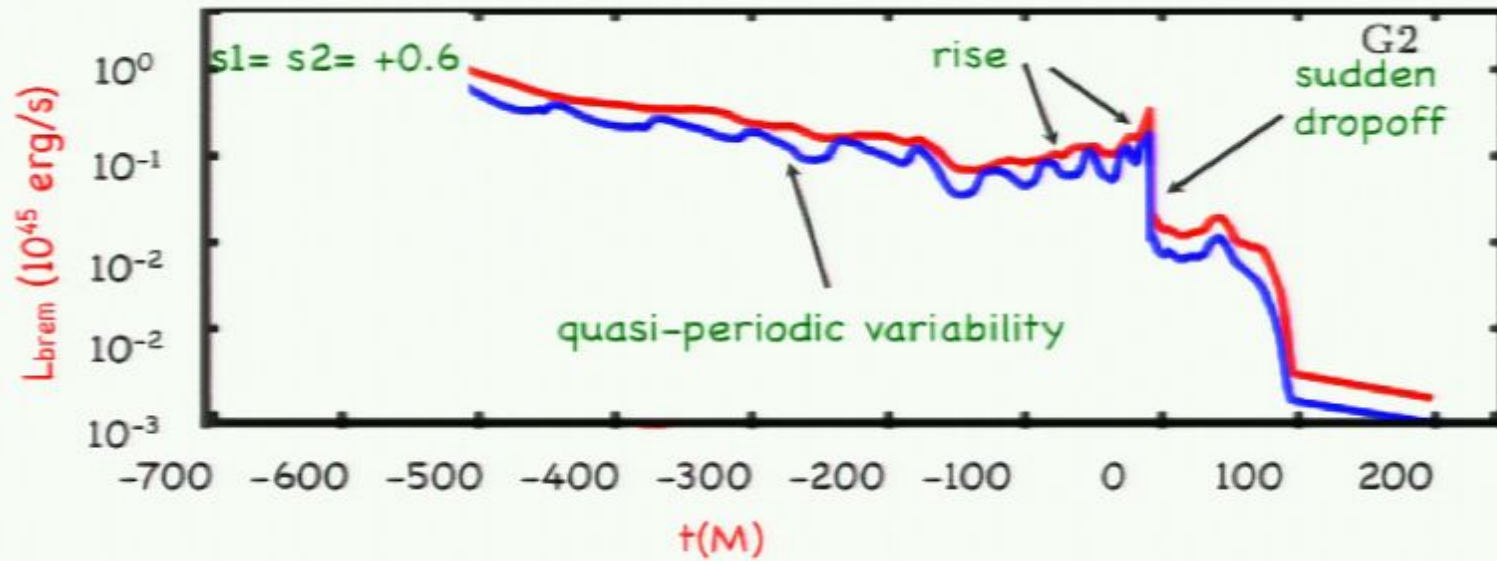
Bremsstrahlung luminosity



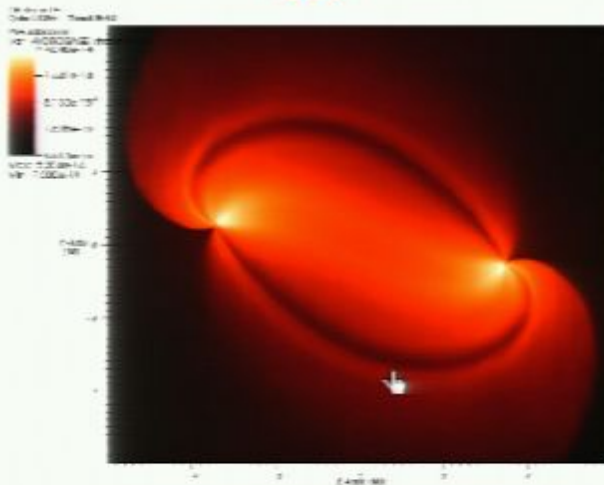
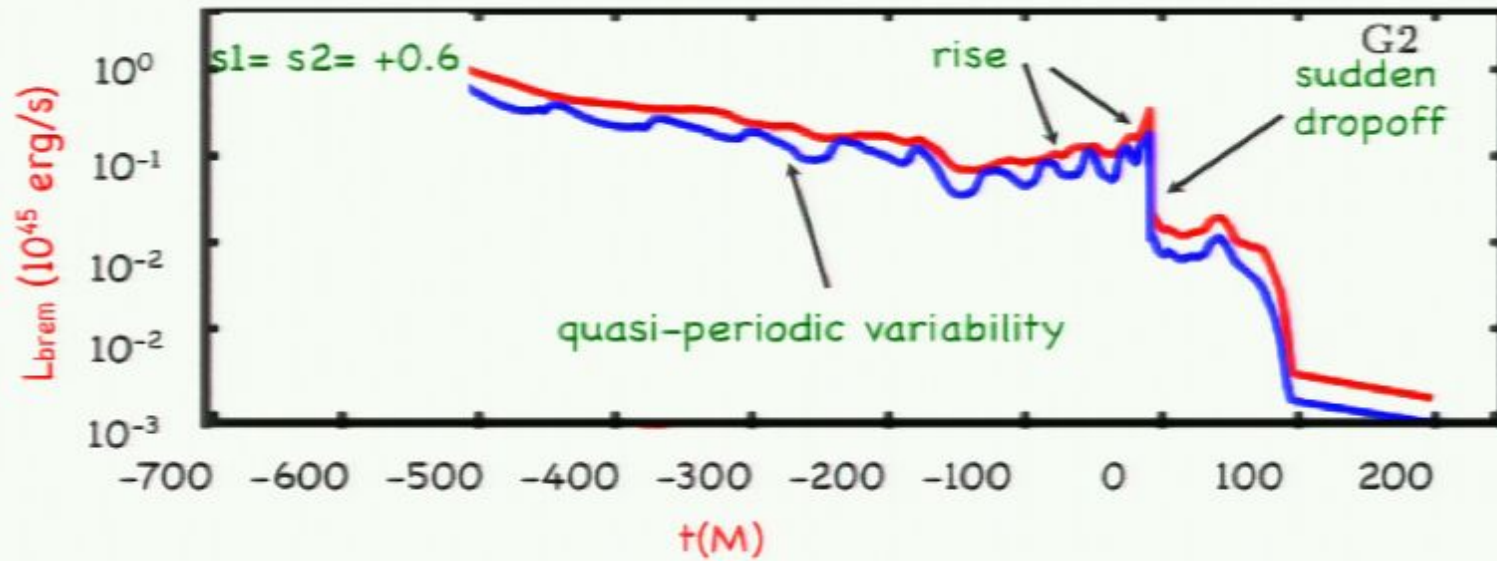
Bremsstrahlung luminosity



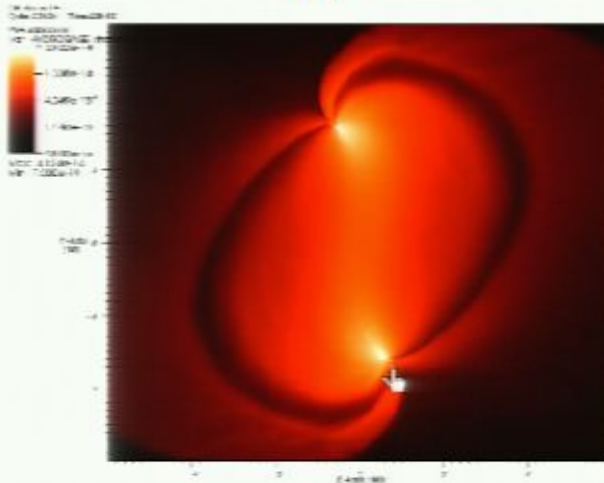
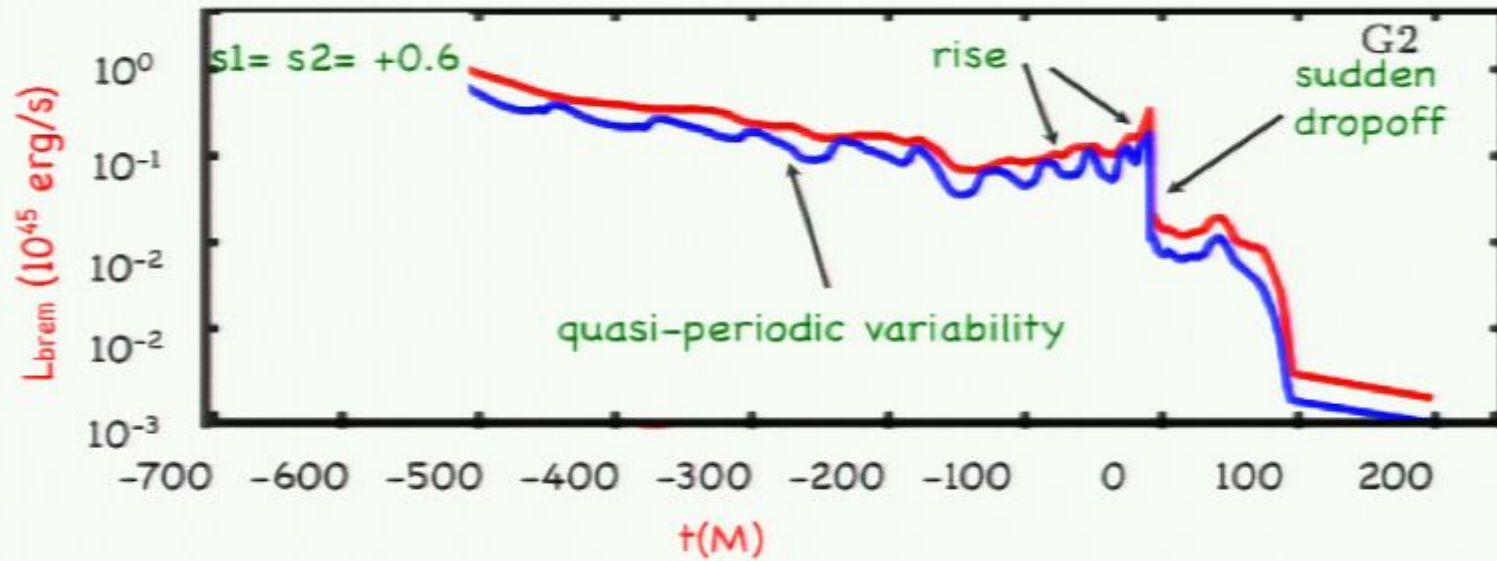
Bremsstrahlung luminosity



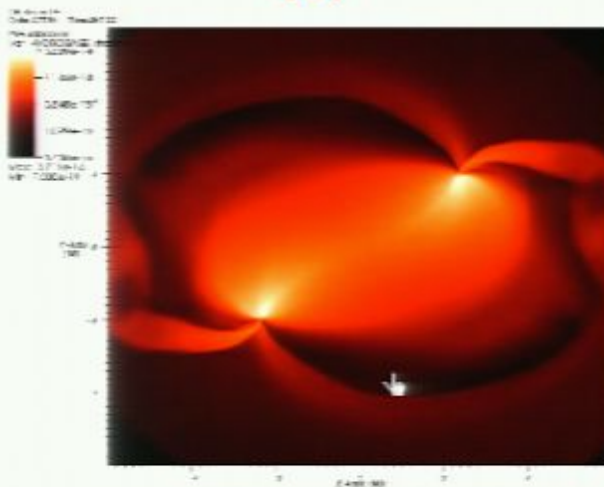
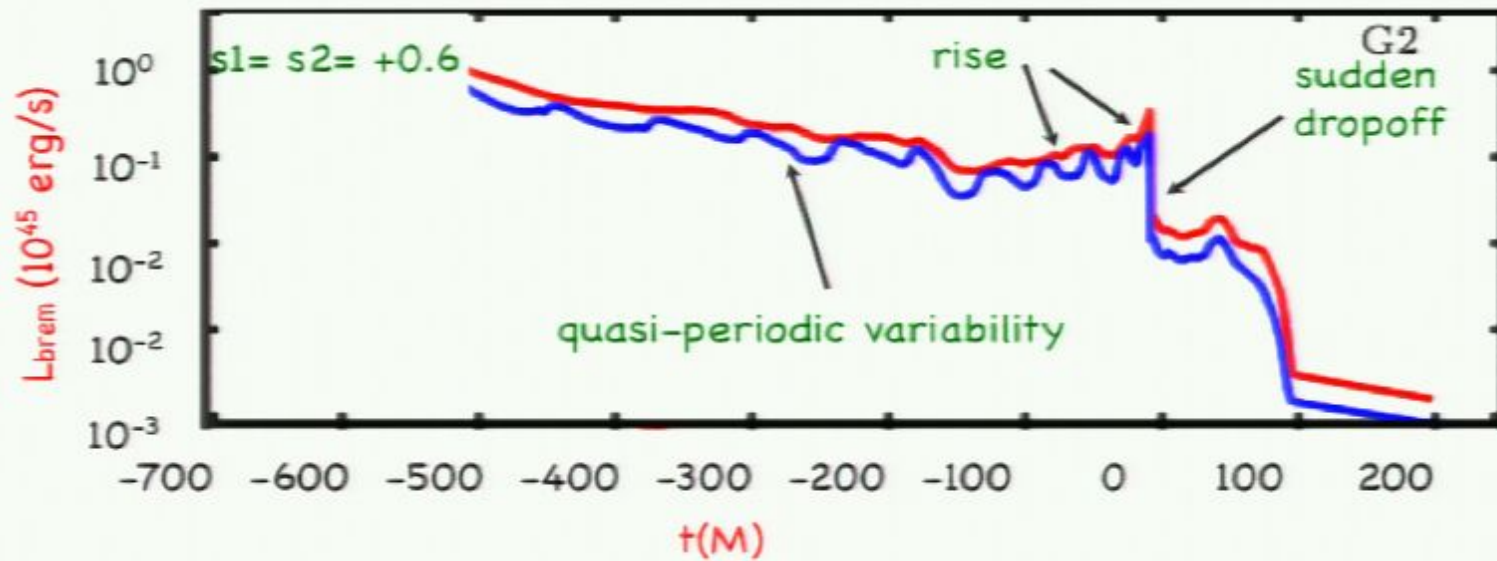
Bremsstrahlung luminosity



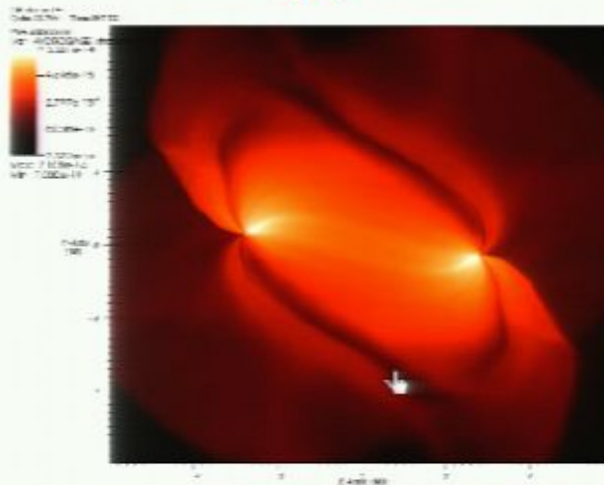
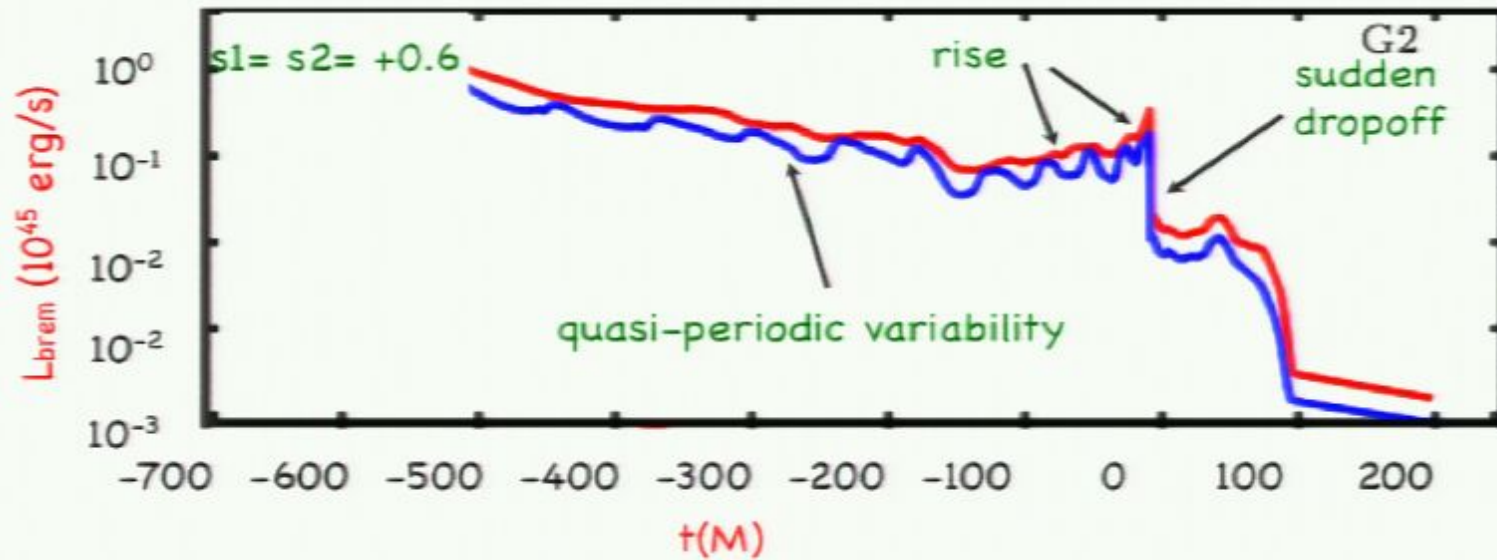
Bremsstrahlung luminosity



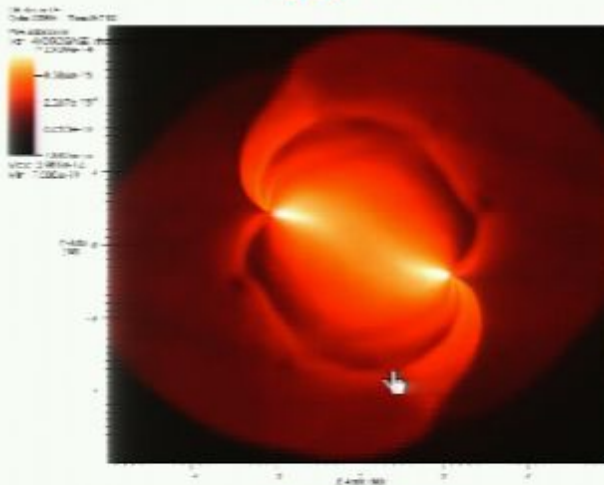
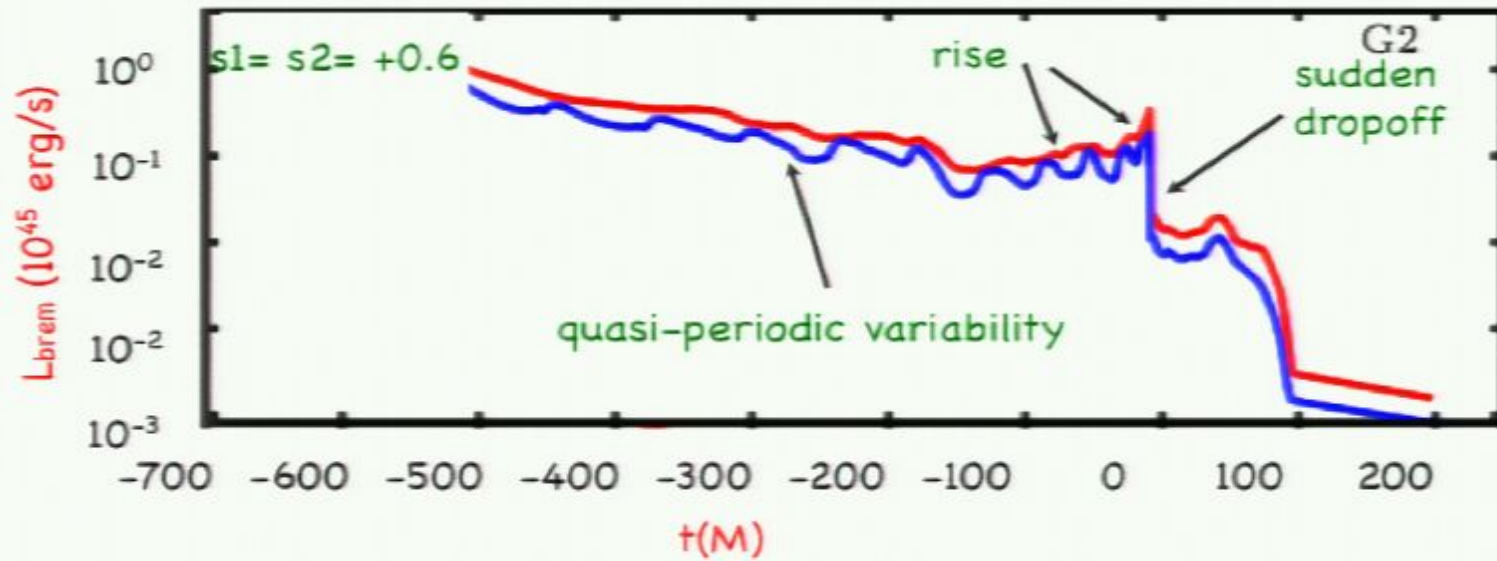
Bremsstrahlung luminosity



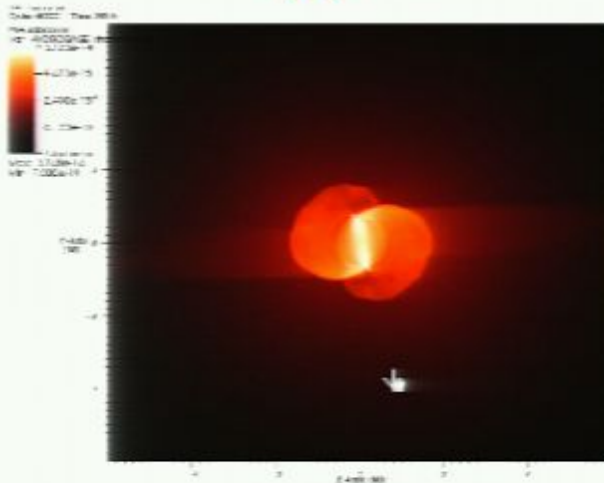
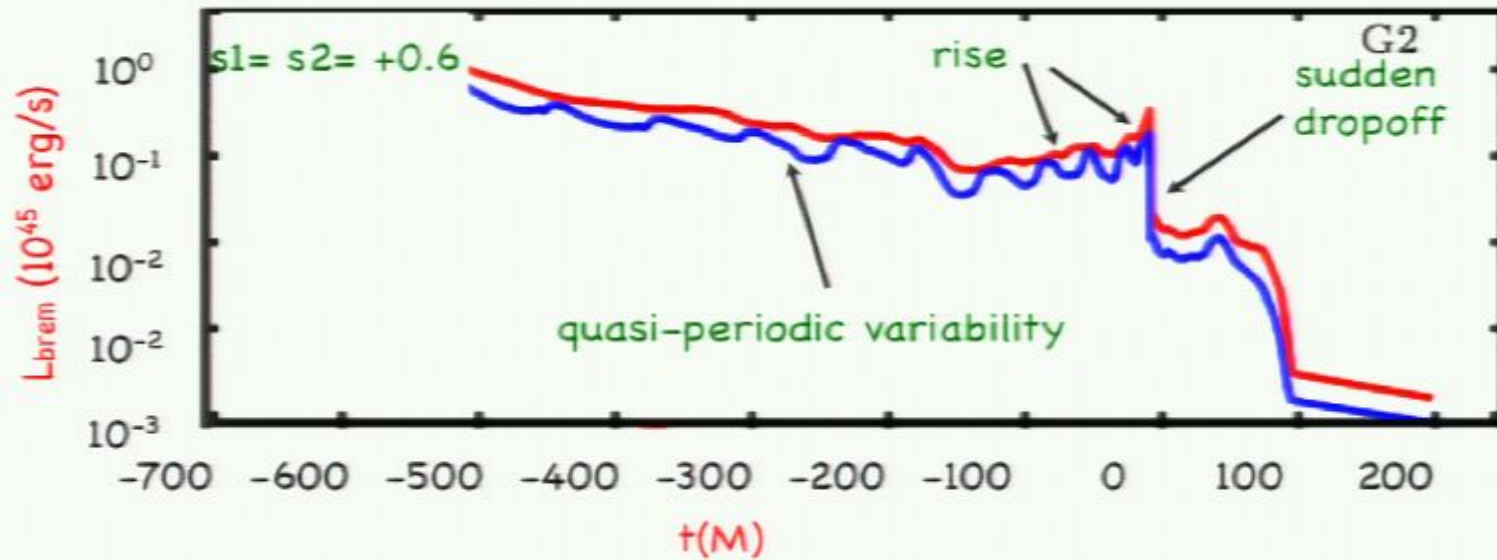
Bremsstrahlung luminosity



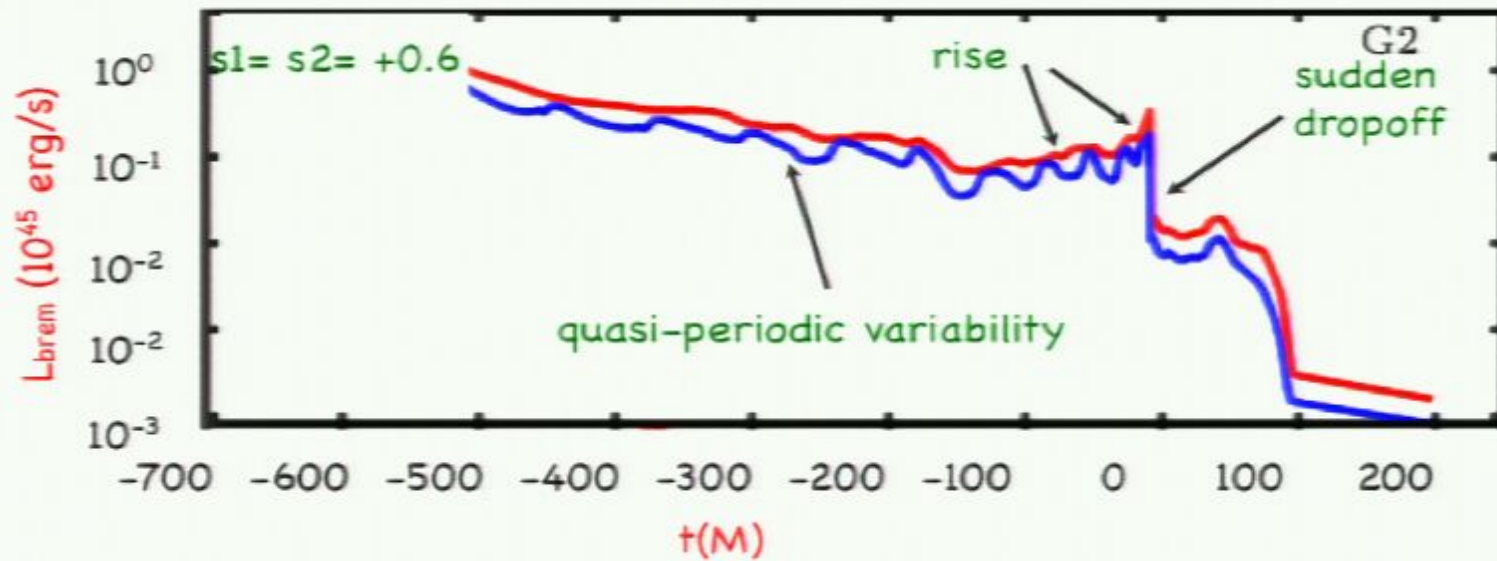
Bremsstrahlung luminosity



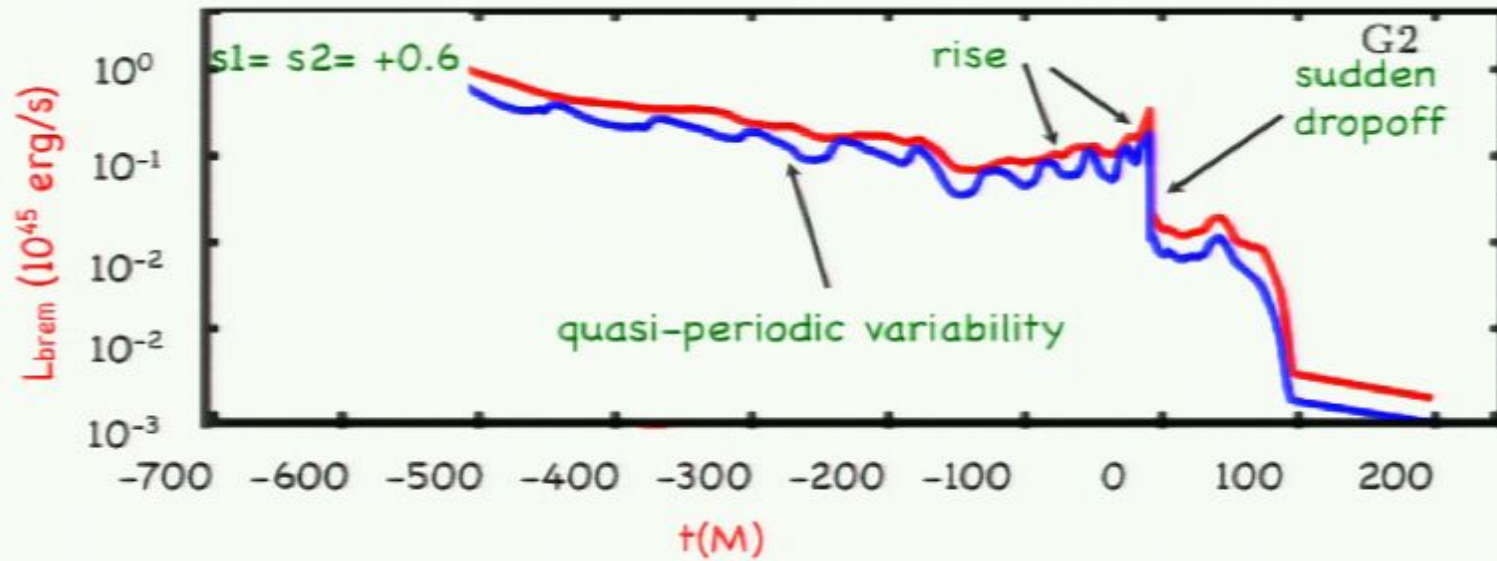
Bremsstrahlung luminosity



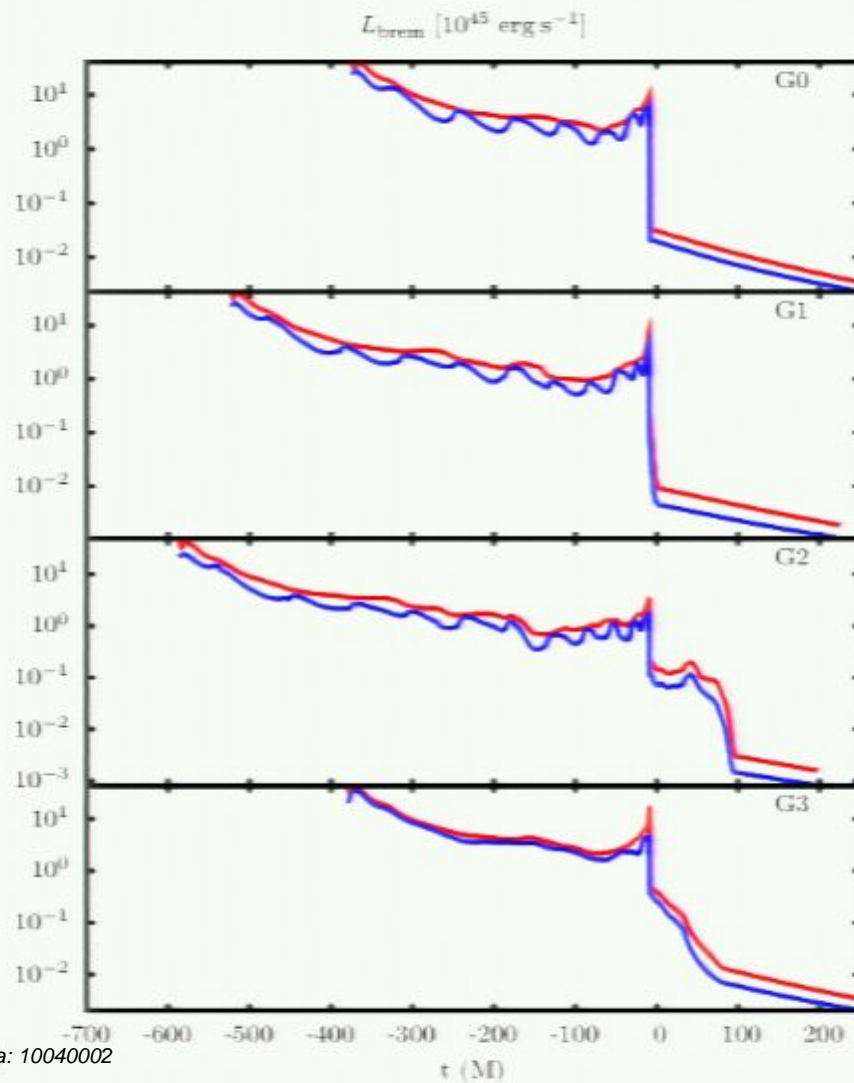
Bremsstrahlung luminosity



Bremsstrahlung luminosity



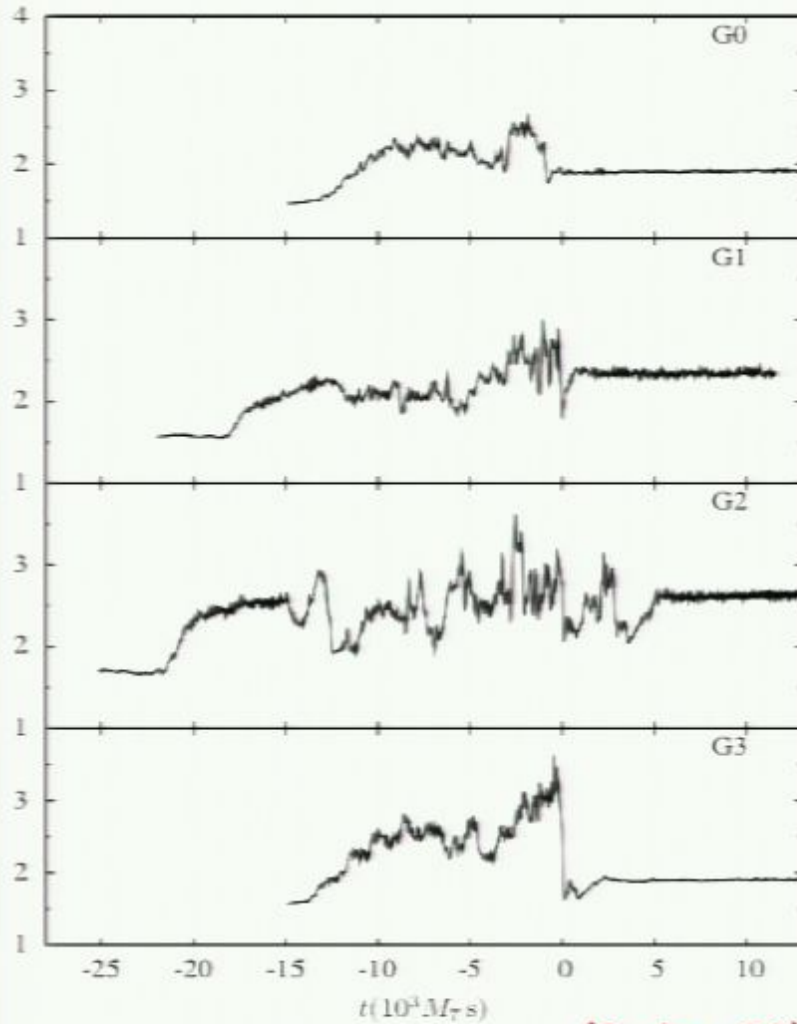
Bremsstrahlung luminosity



runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

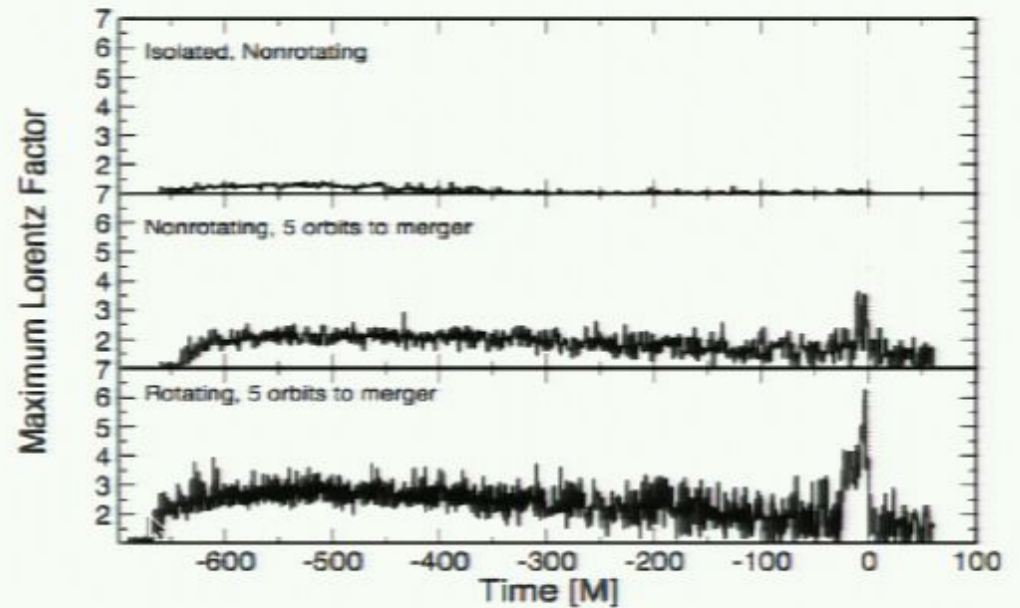
Maximum Lorentz Factor

max(Lorentz Factor)

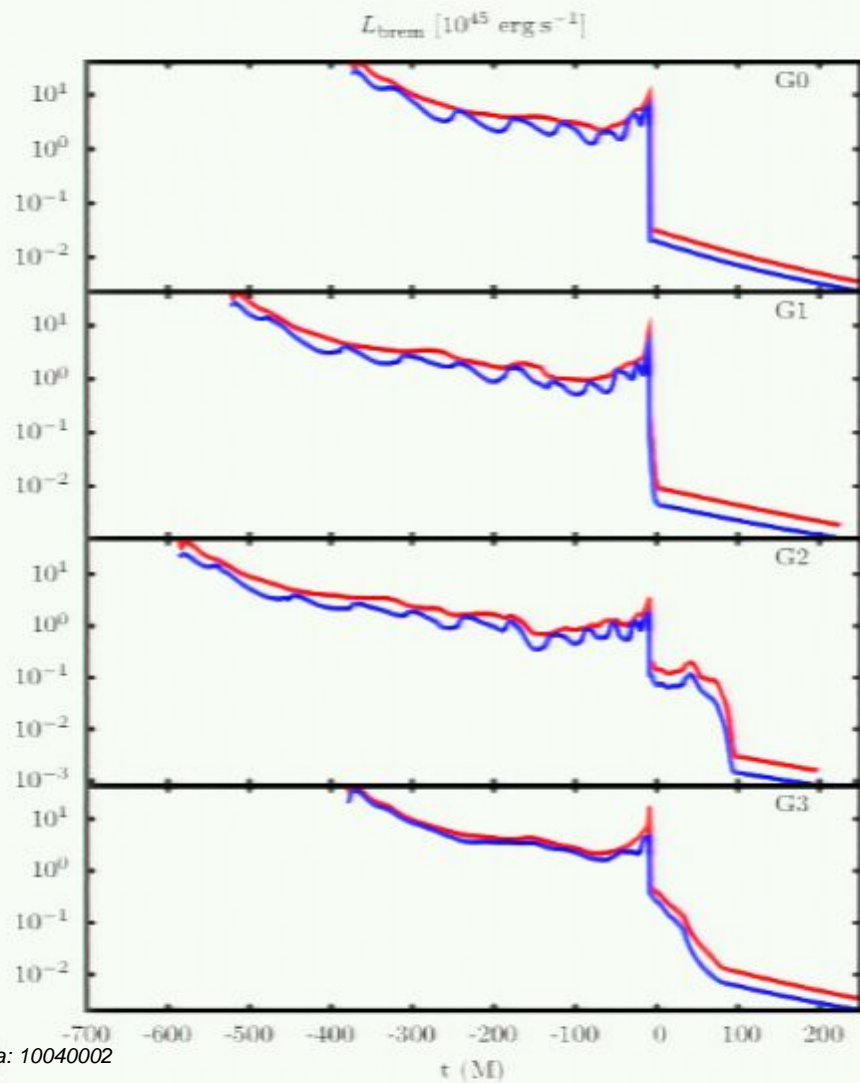


(Bode+ 09)

runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

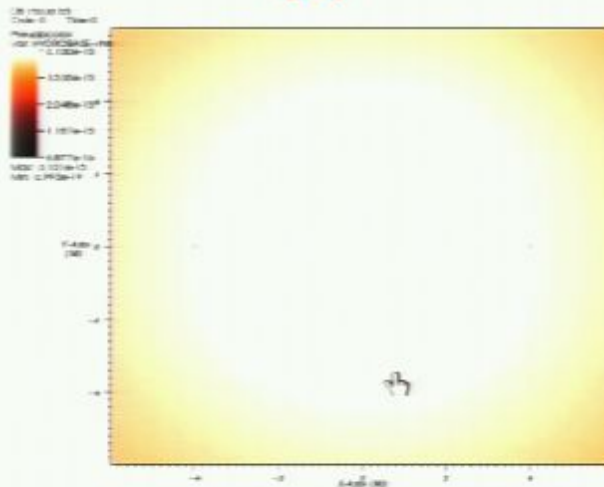
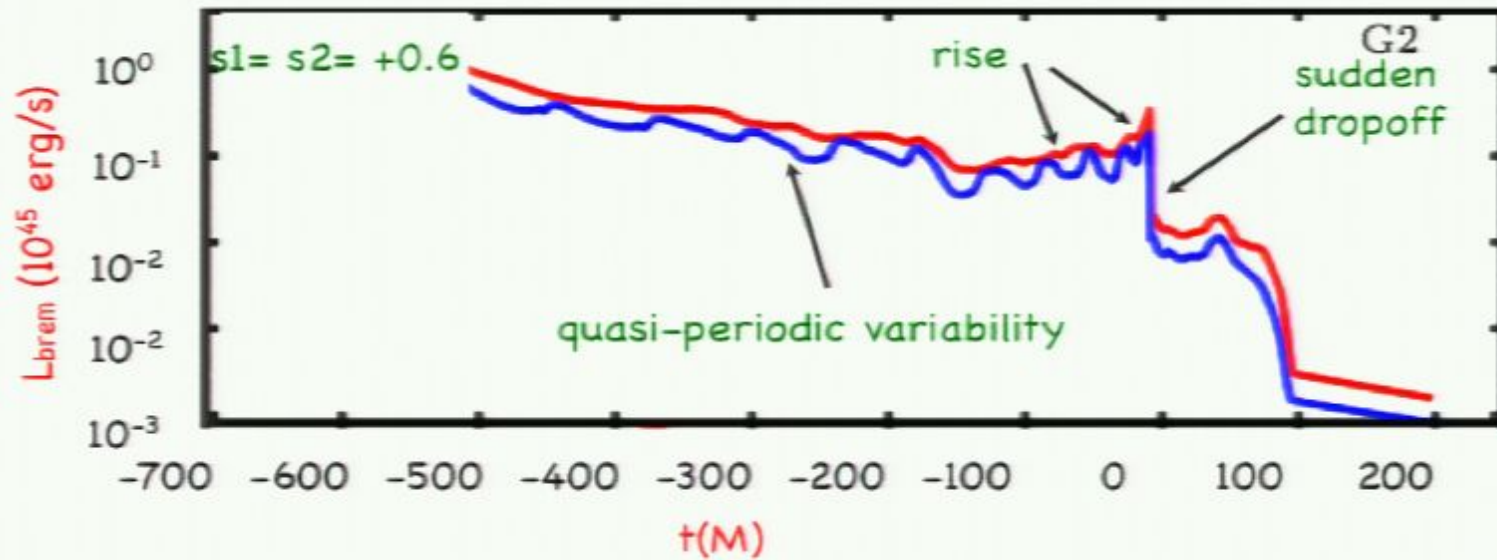


Bremsstrahlung luminosity

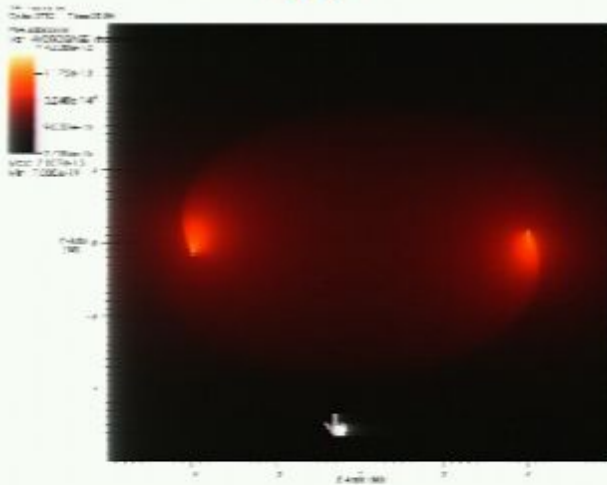
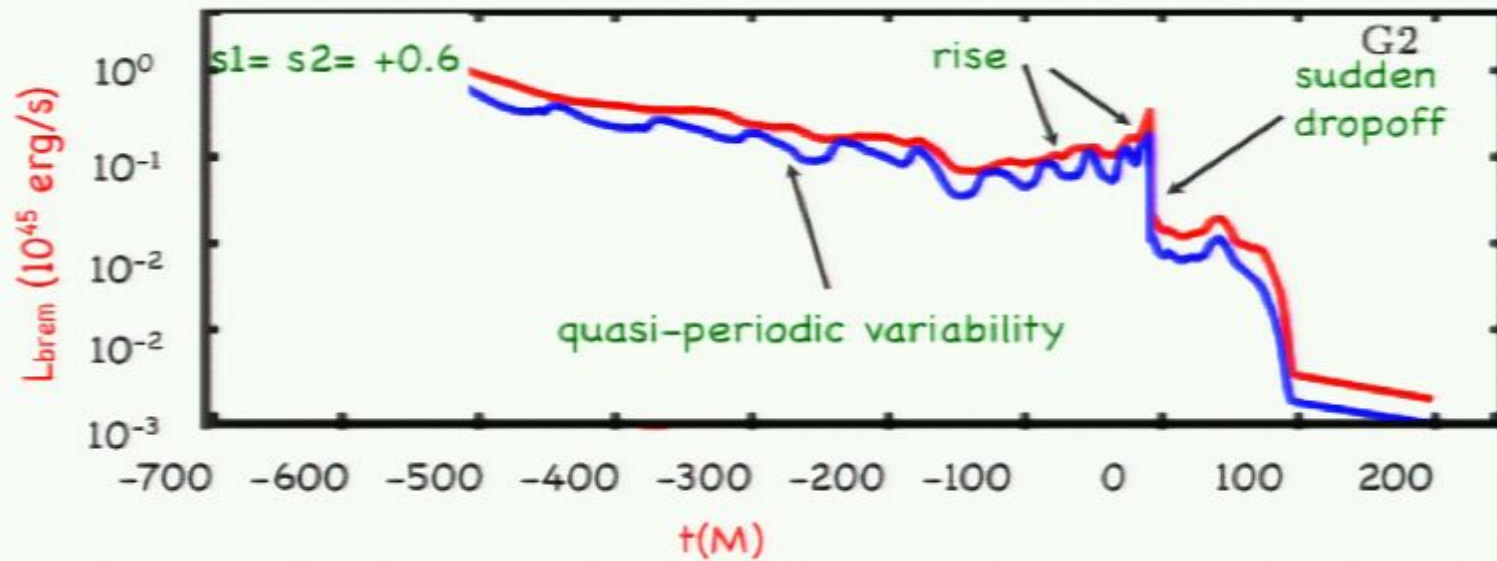


runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

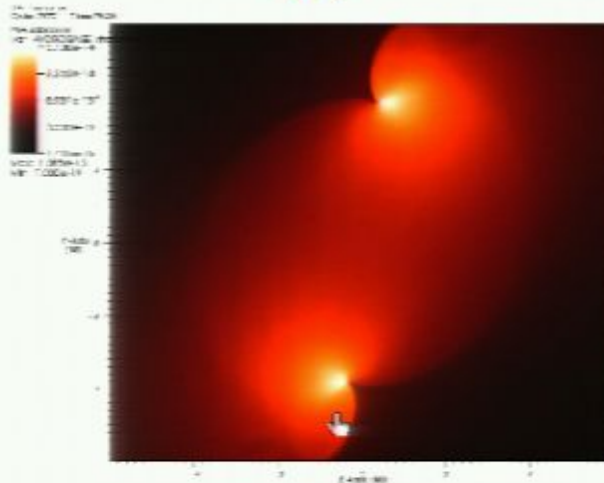
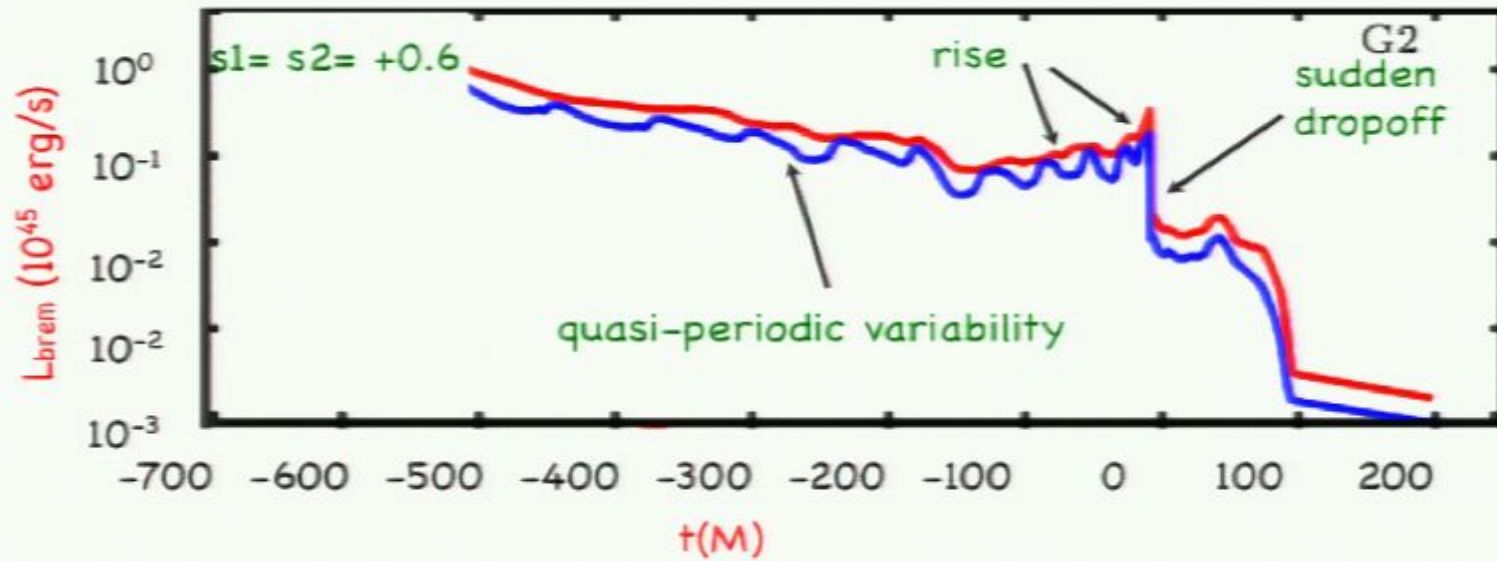
Bremsstrahlung luminosity



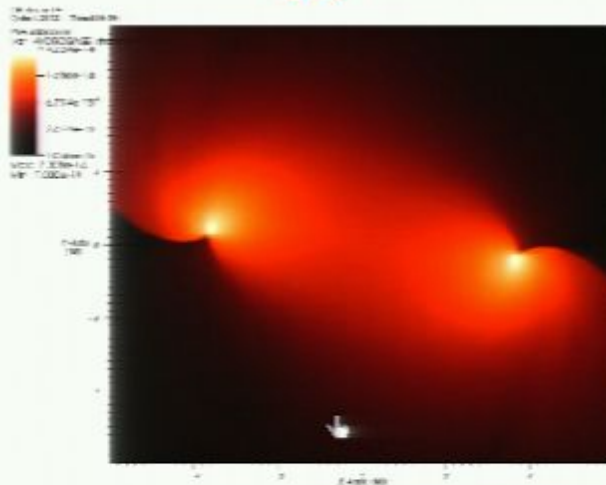
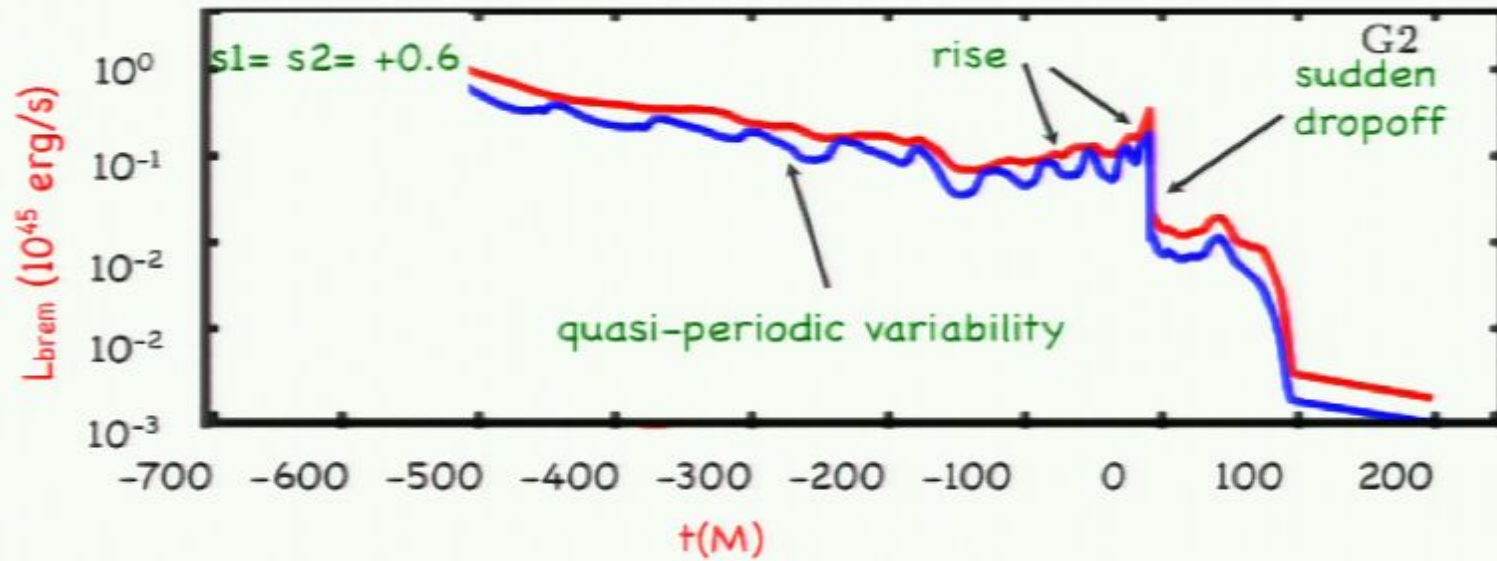
Bremsstrahlung luminosity



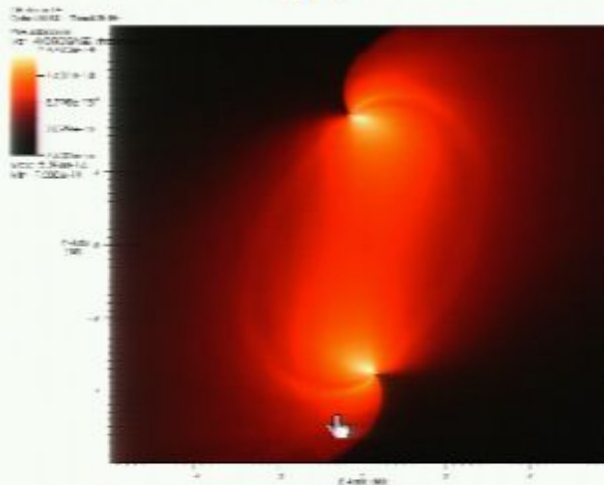
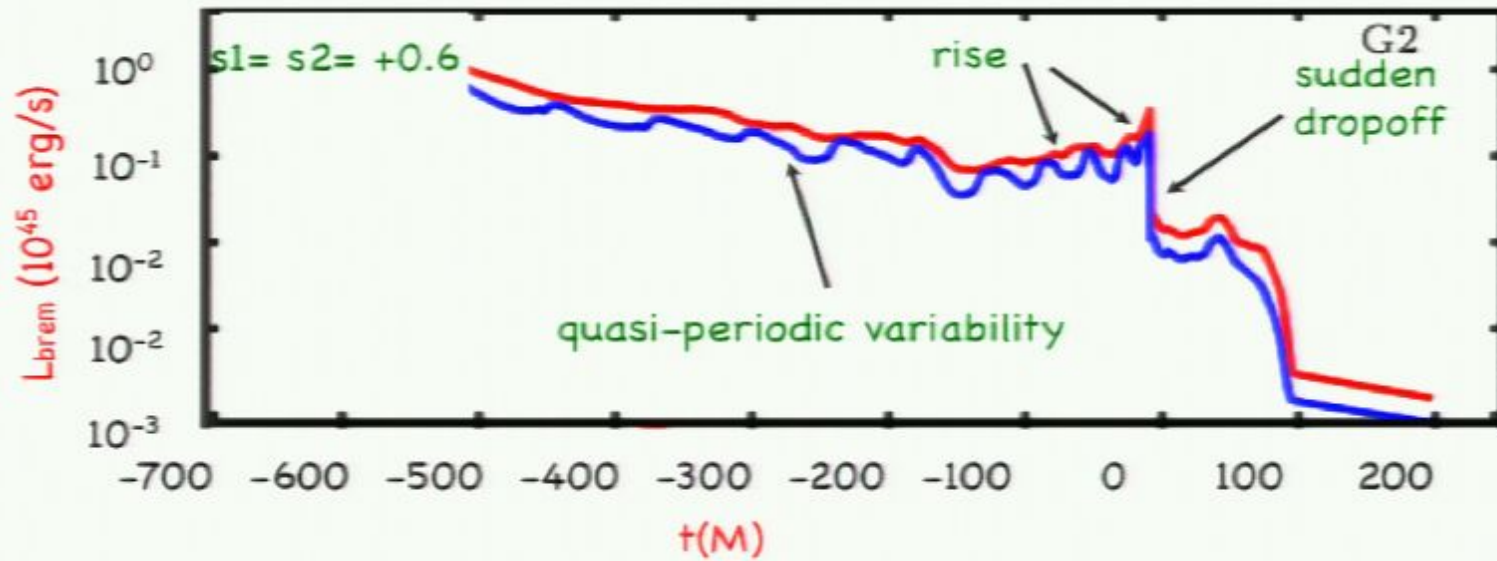
Bremsstrahlung luminosity



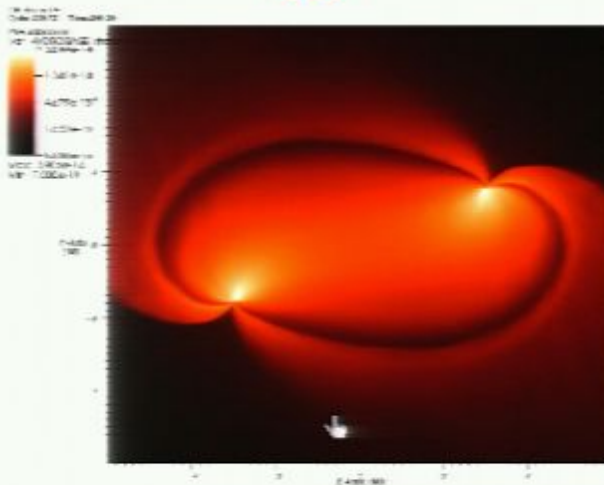
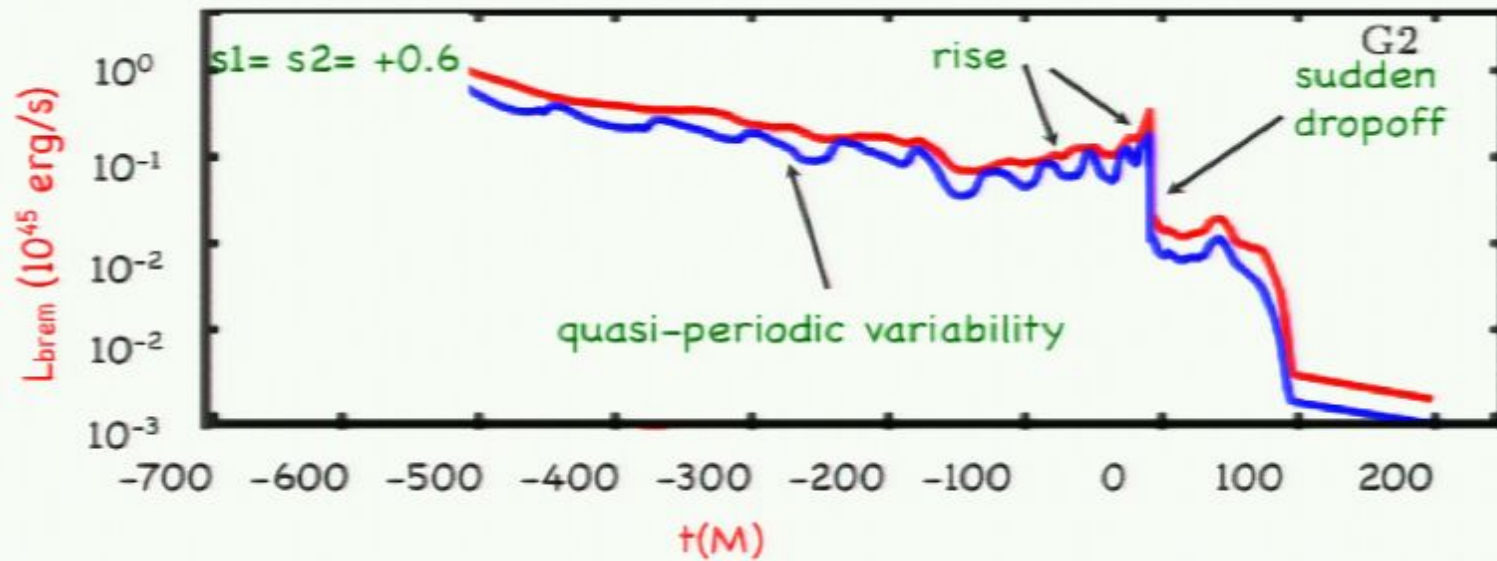
Bremsstrahlung luminosity



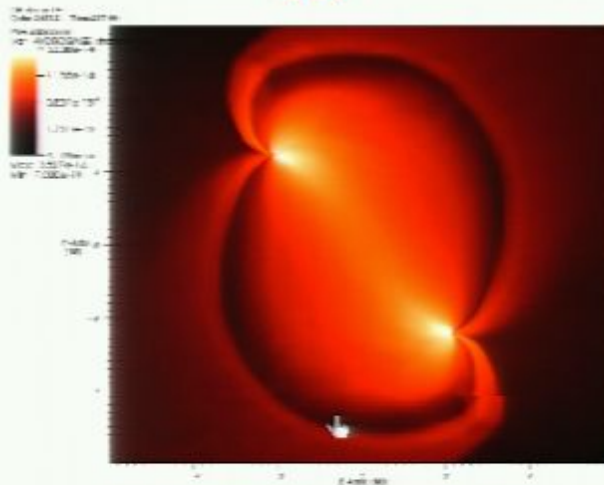
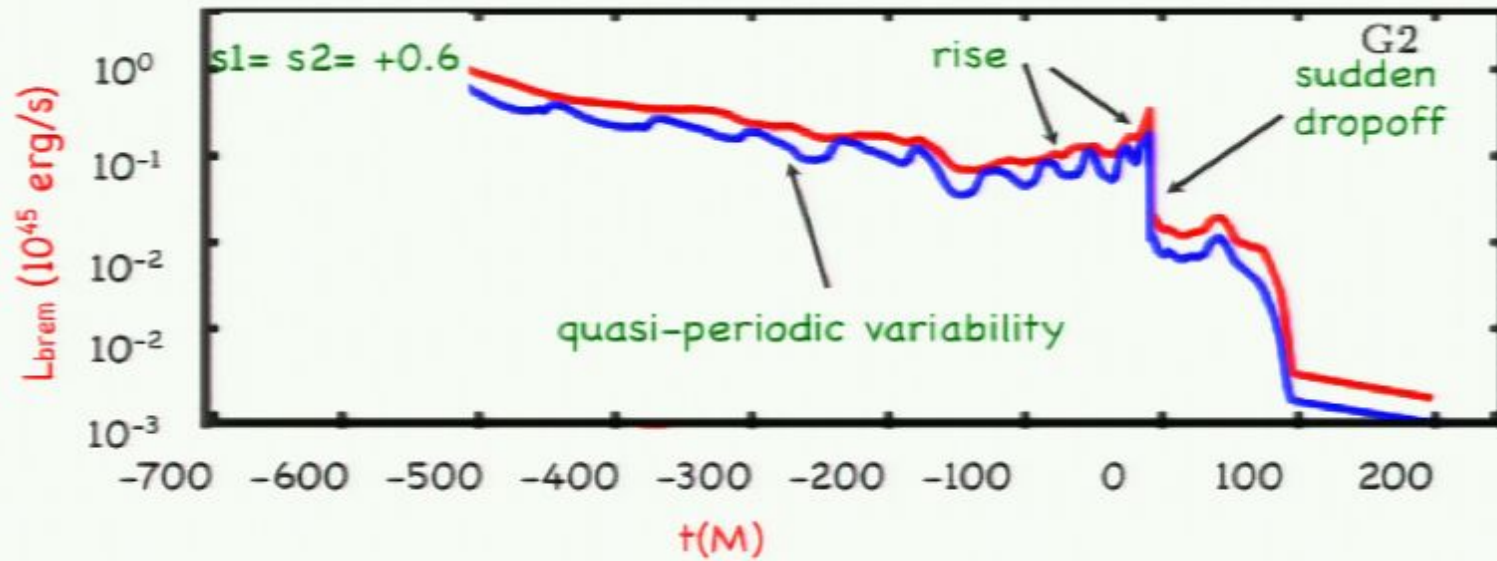
Bremsstrahlung luminosity



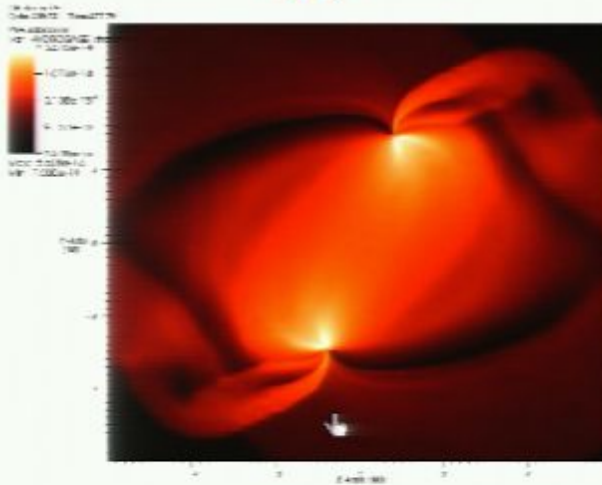
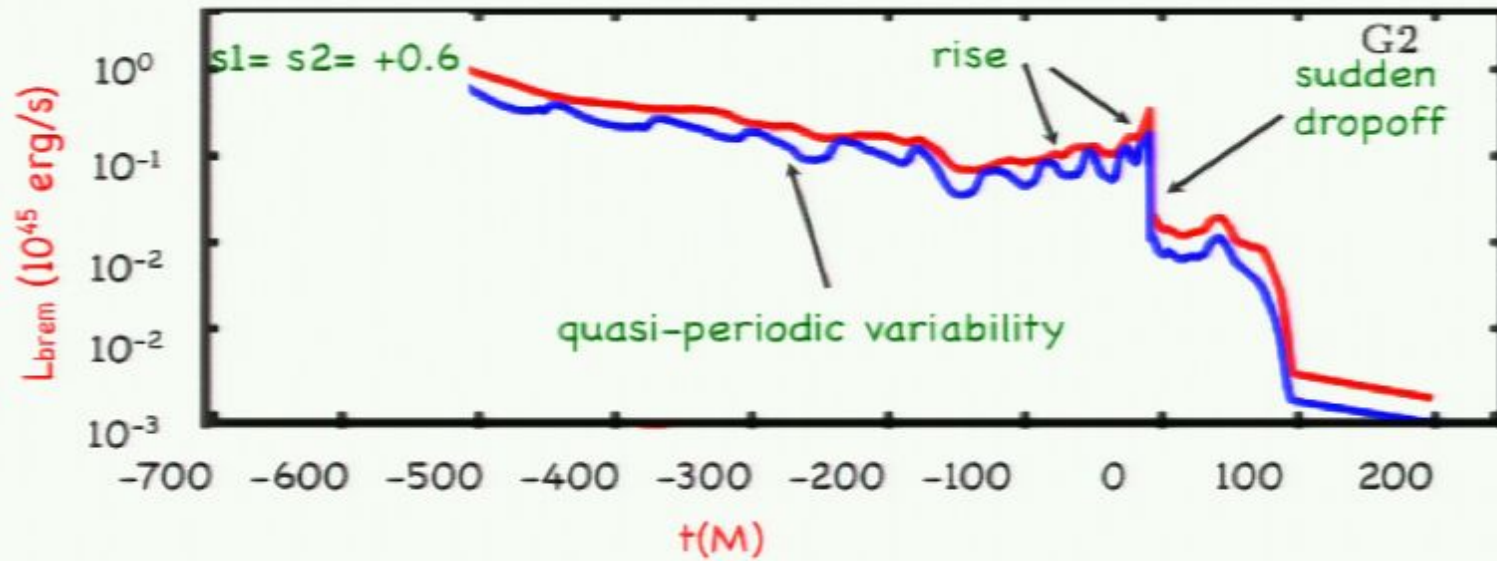
Bremsstrahlung luminosity



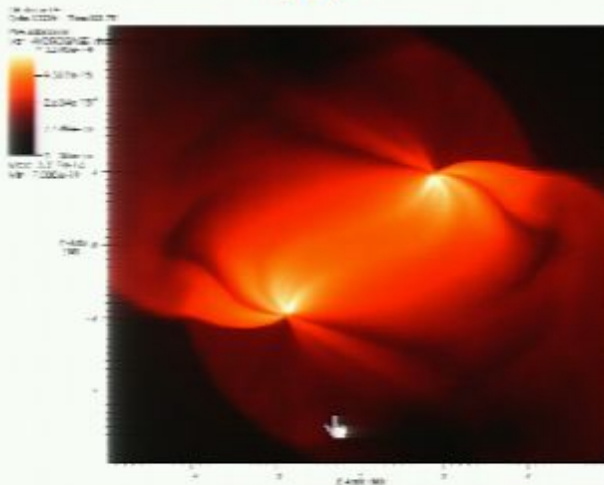
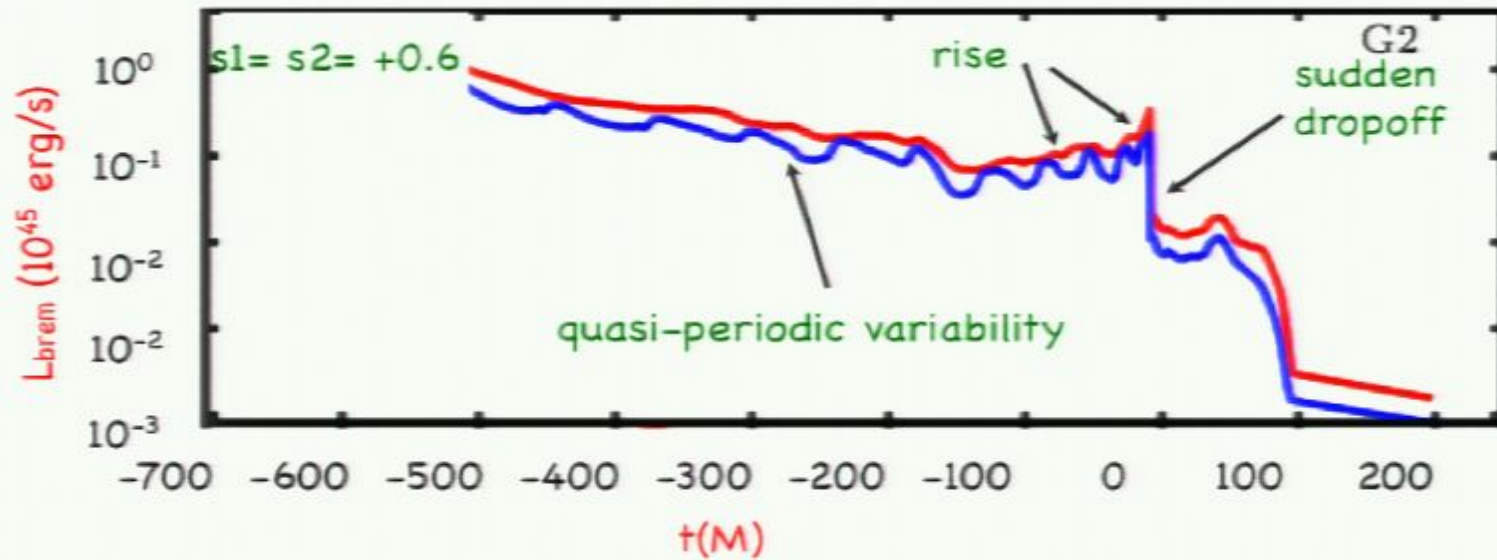
Bremsstrahlung luminosity



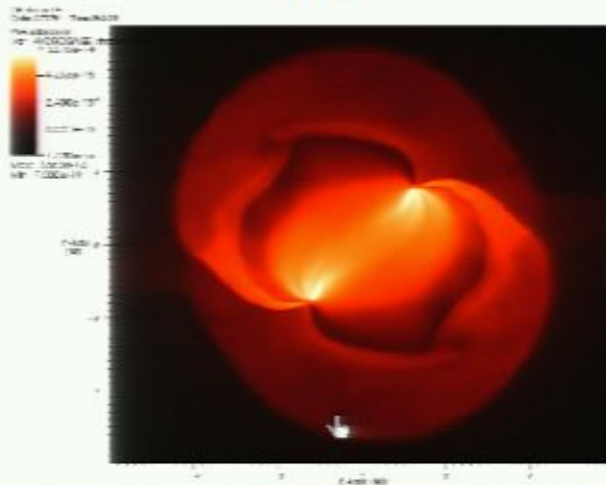
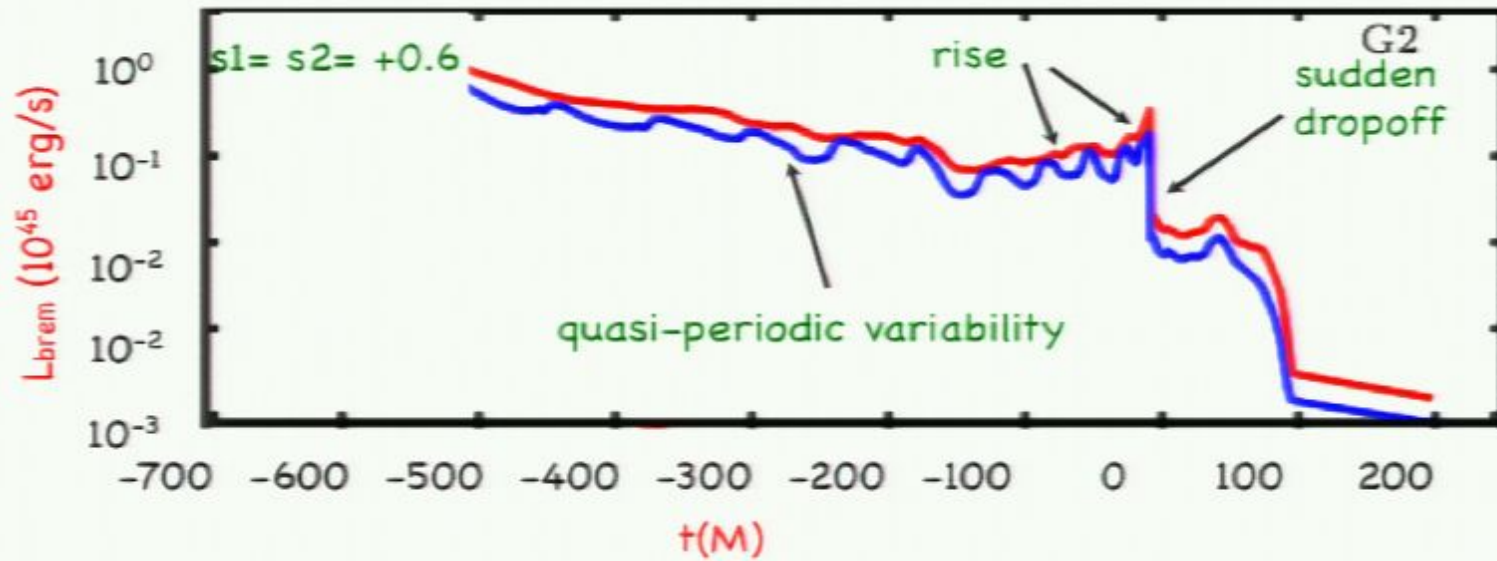
Bremsstrahlung luminosity



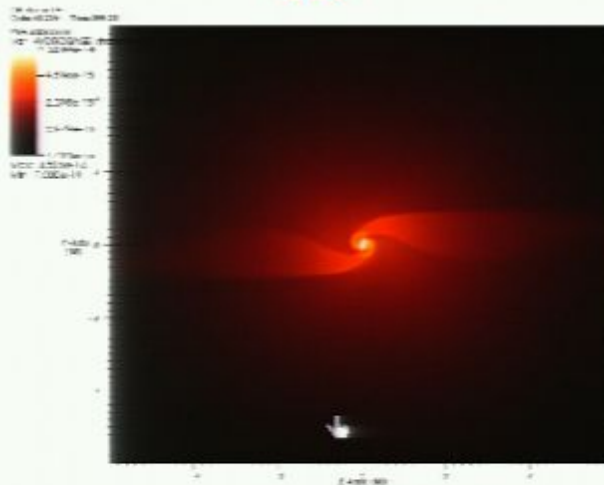
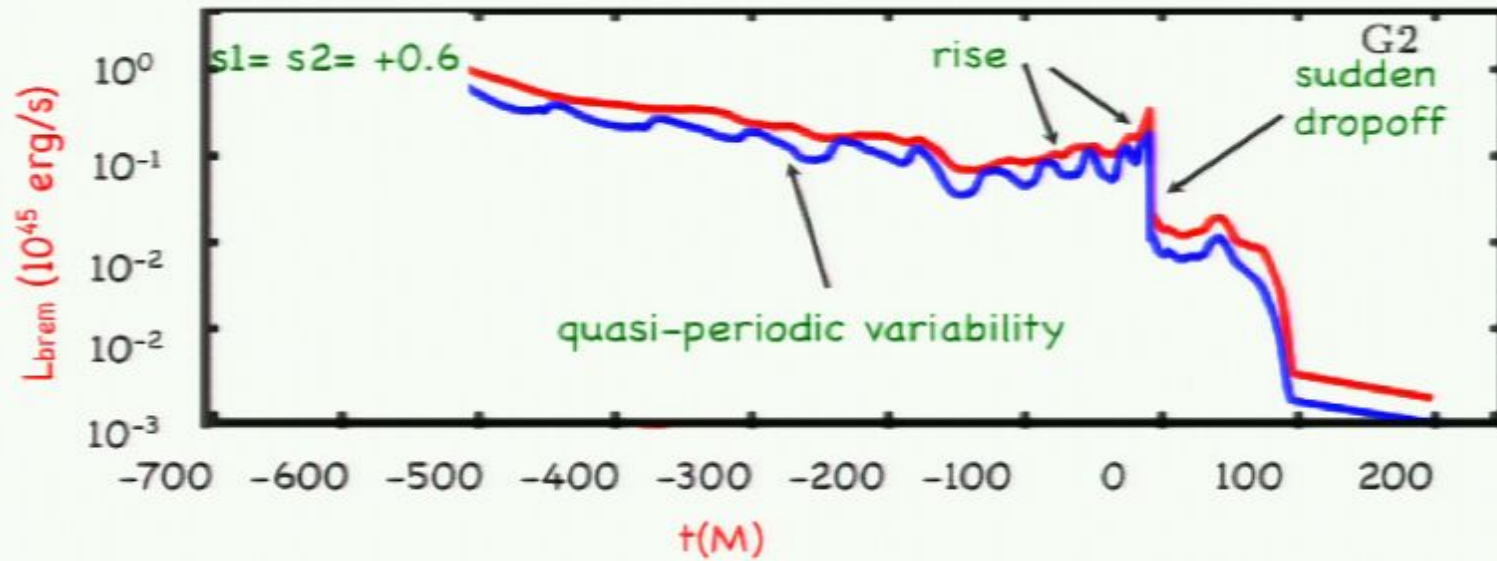
Bremsstrahlung luminosity



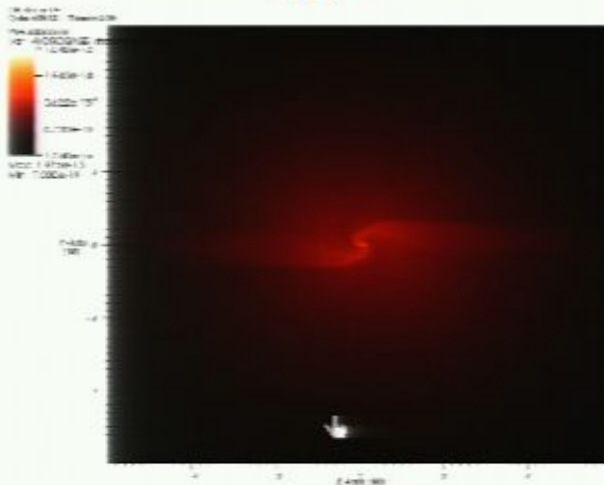
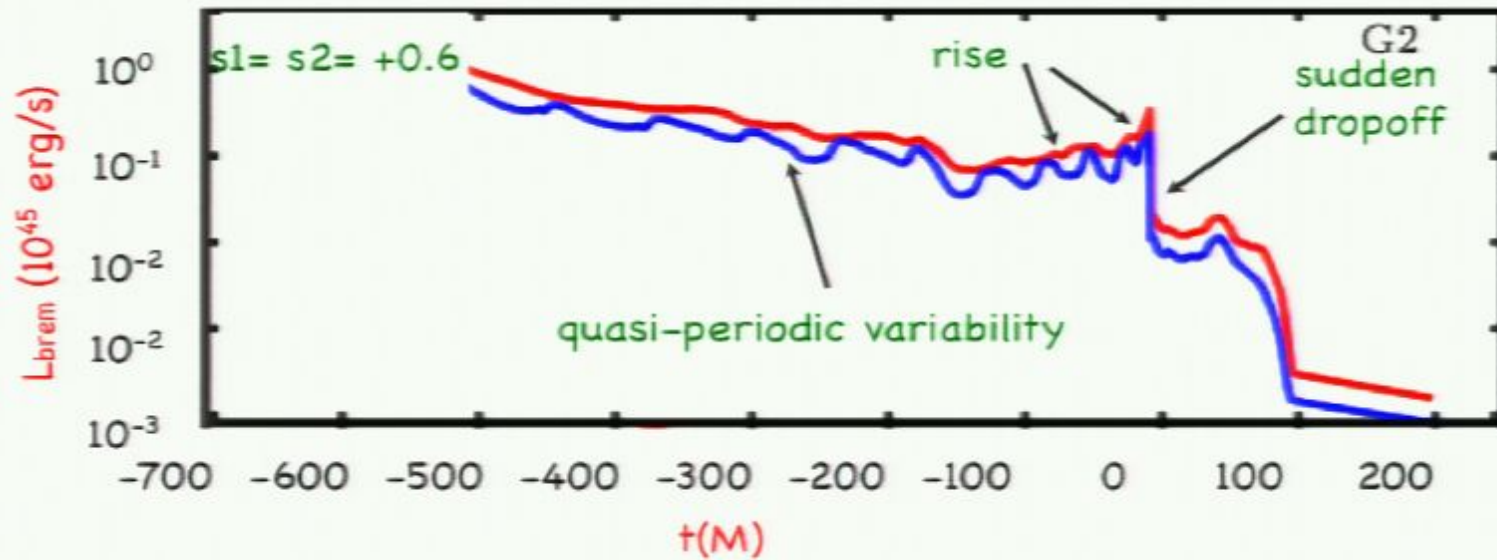
Bremsstrahlung luminosity



Bremsstrahlung luminosity

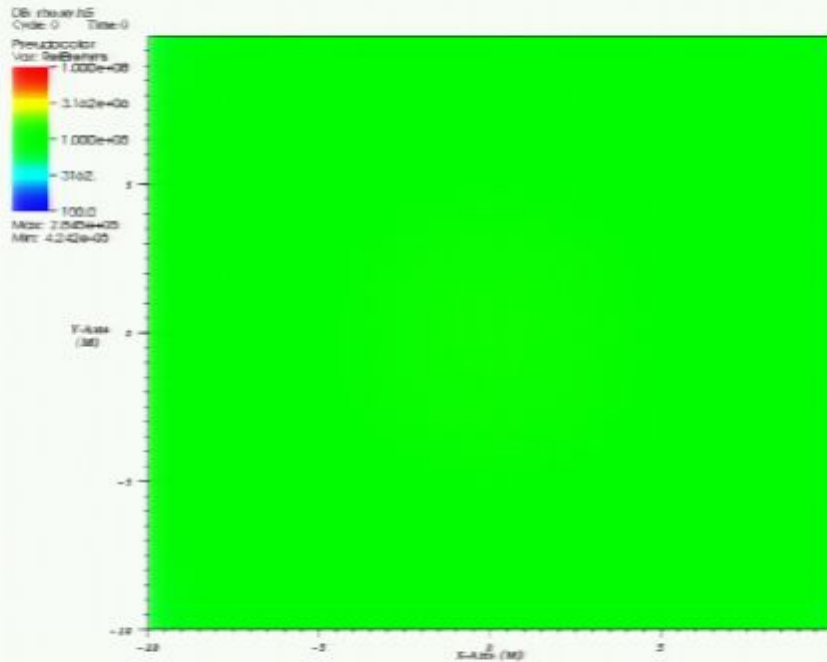


Bremsstrahlung luminosity

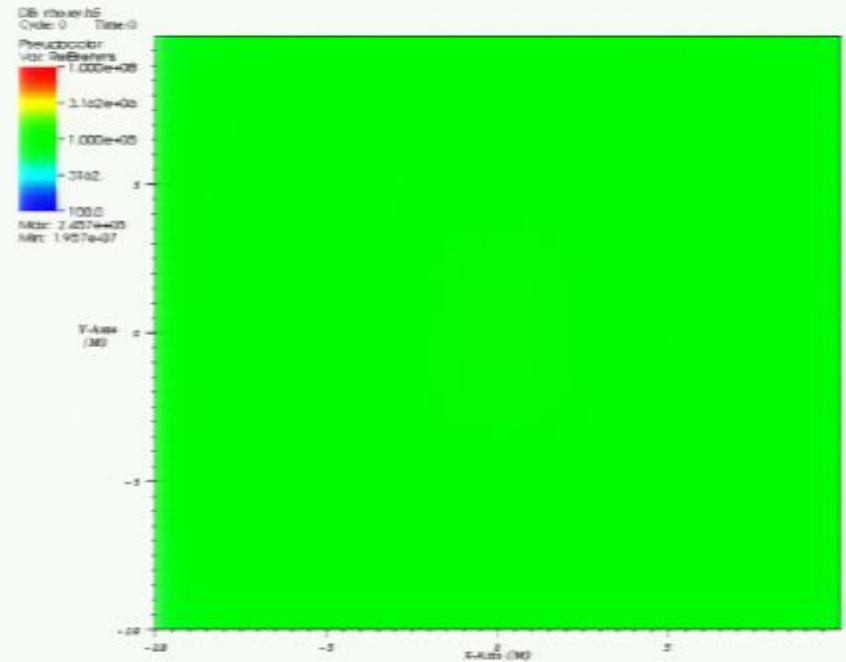


Emission from the hot gas

$$\epsilon \approx 5 \times 10^{33} \epsilon^{1/2} \rho^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$

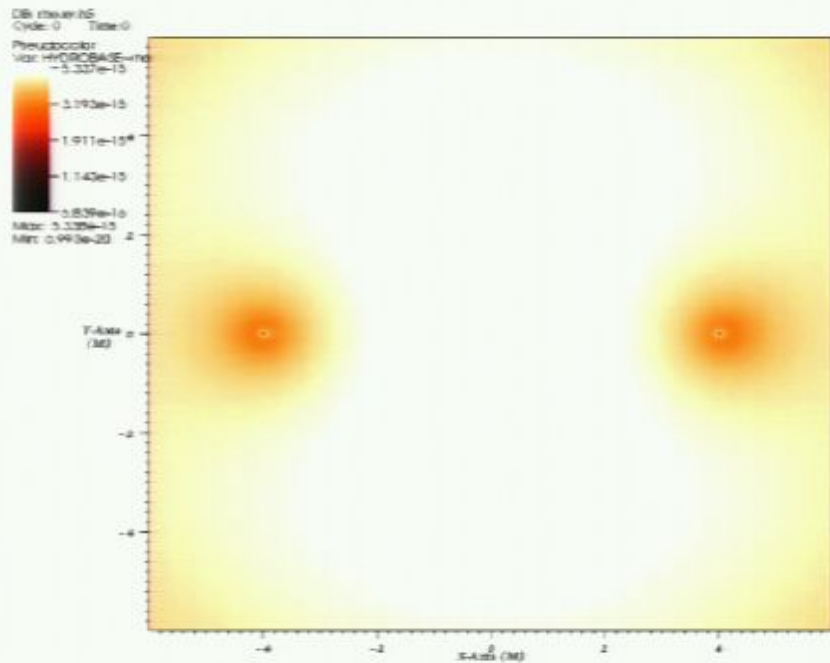


Non-spinning BHs

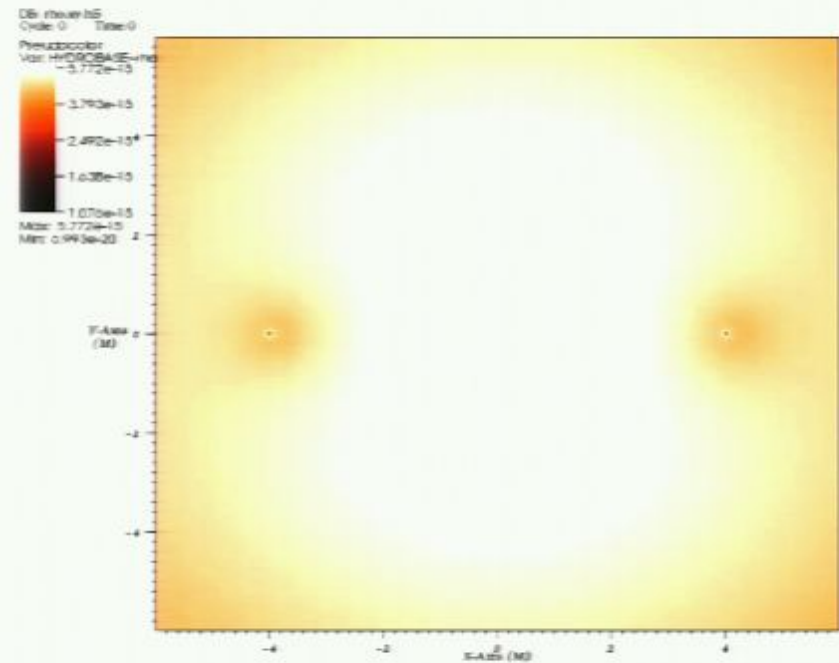


Spinning BHS

Gas Density

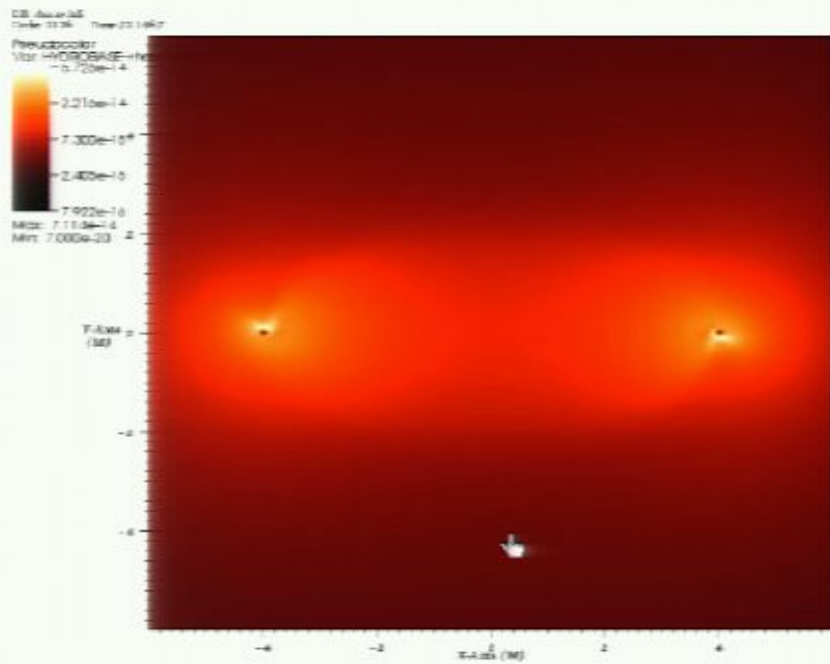


$$s_1/m^2 = s_2/m^2 = 0.6$$

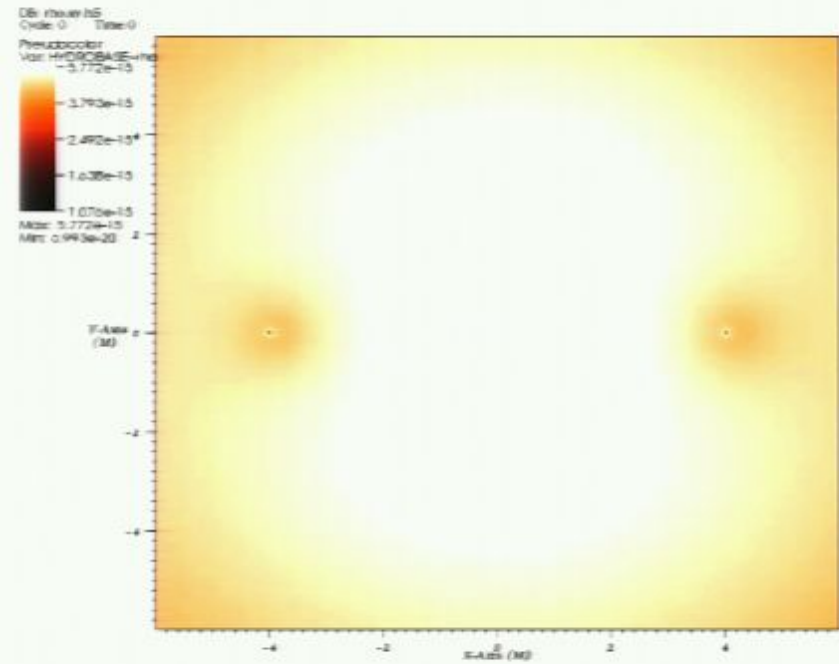


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

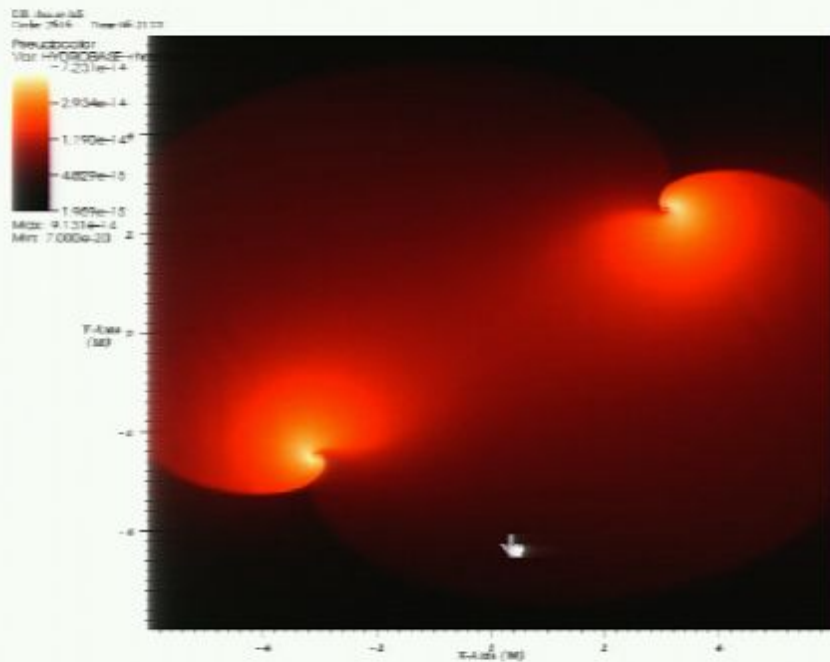


$$s_1/m^2 = s_2/m^2 = 0.6$$

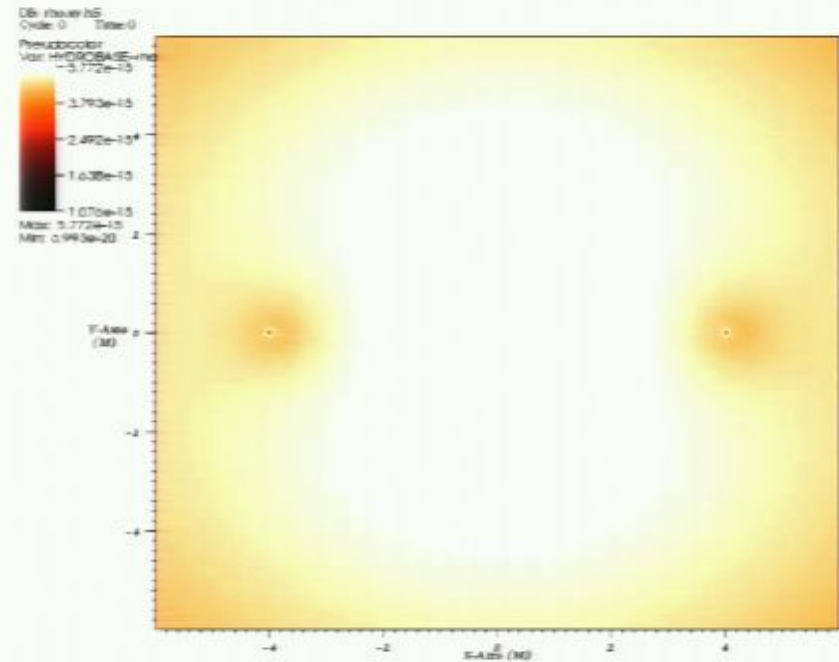


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

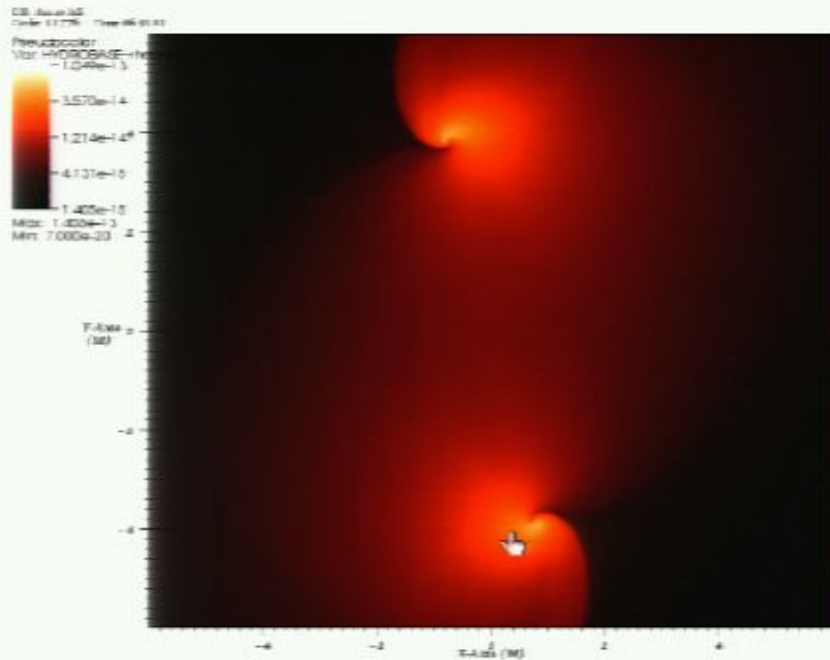


$$s_1/m^2 = s_2/m^2 = 0.6$$

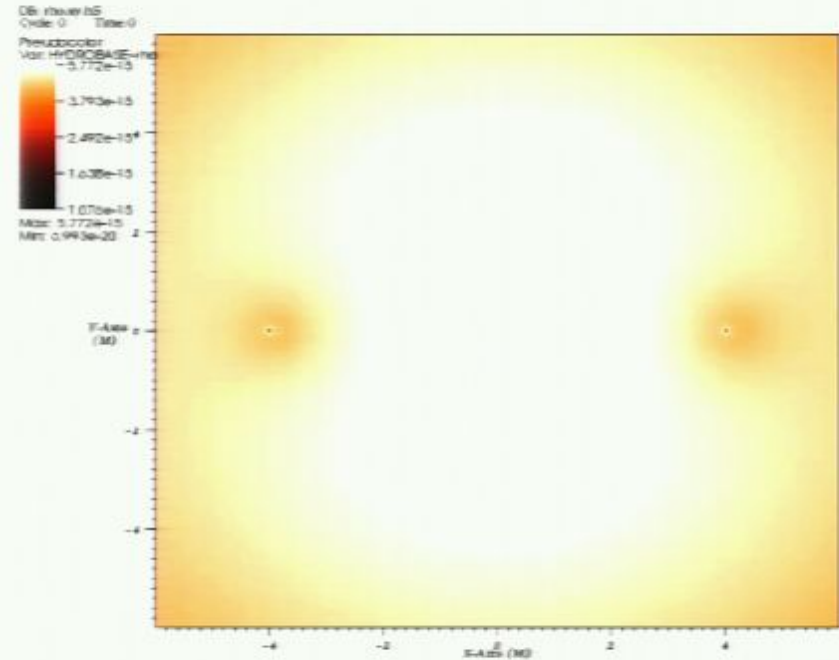


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

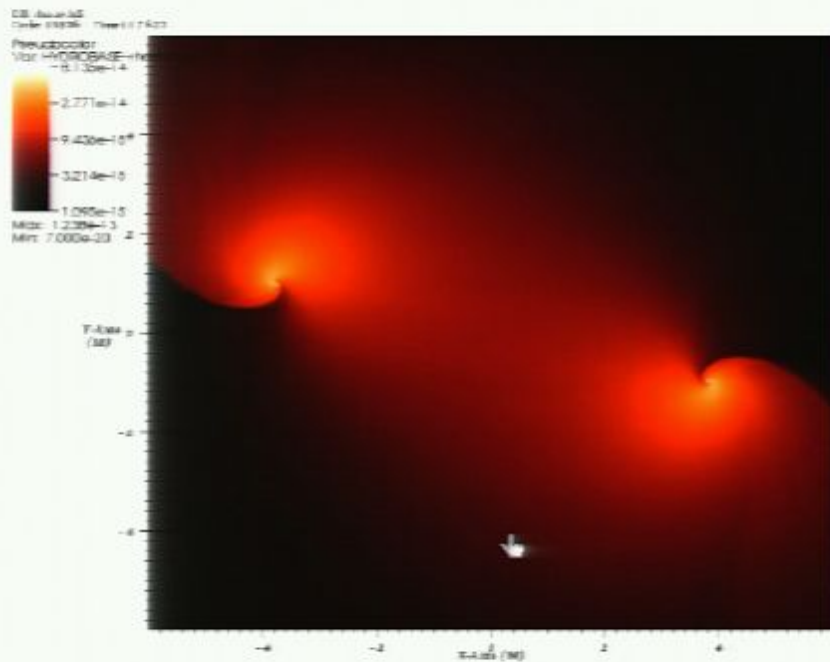


$$s_1/m^2 = s_2/m^2 = 0.6$$

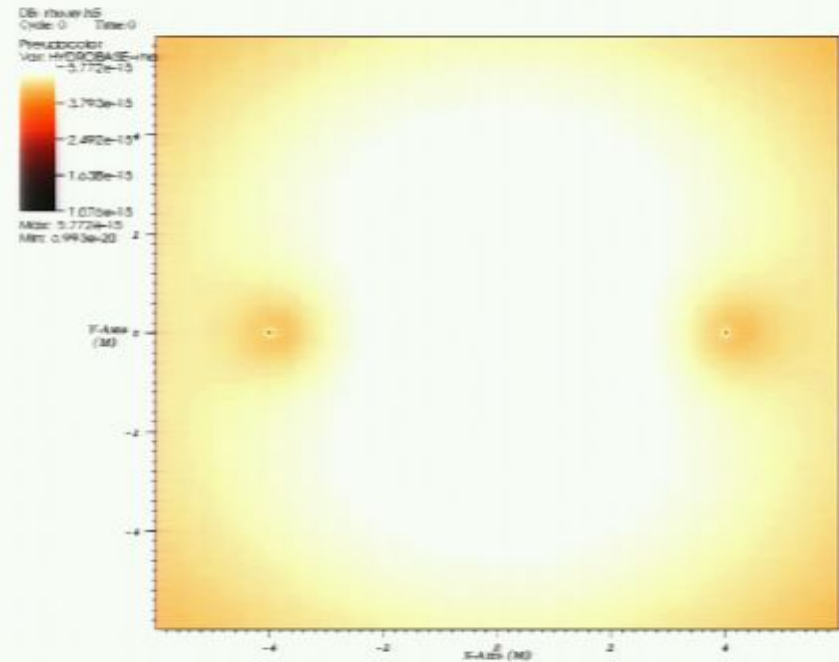


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

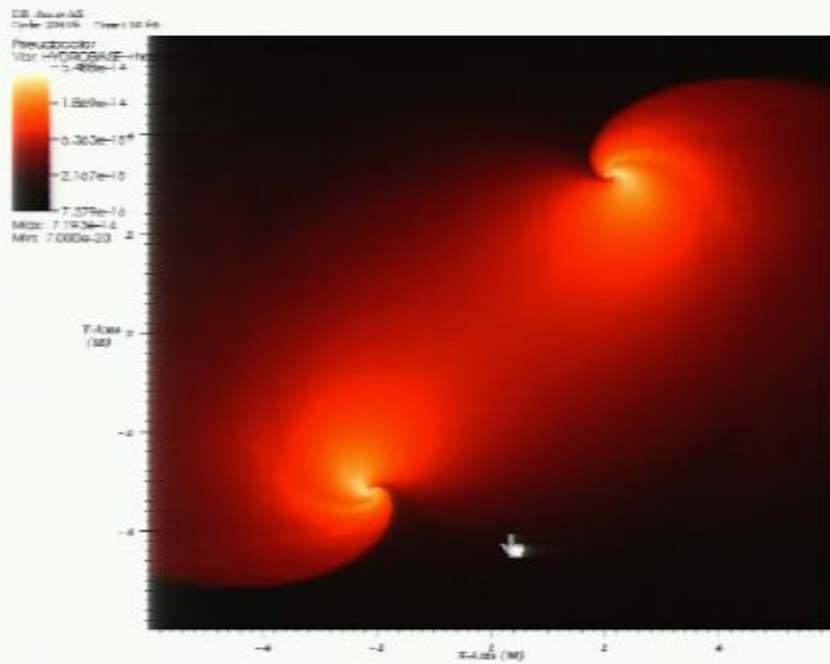


$$s_1/m^2 = s_2/m^2 = 0.6$$

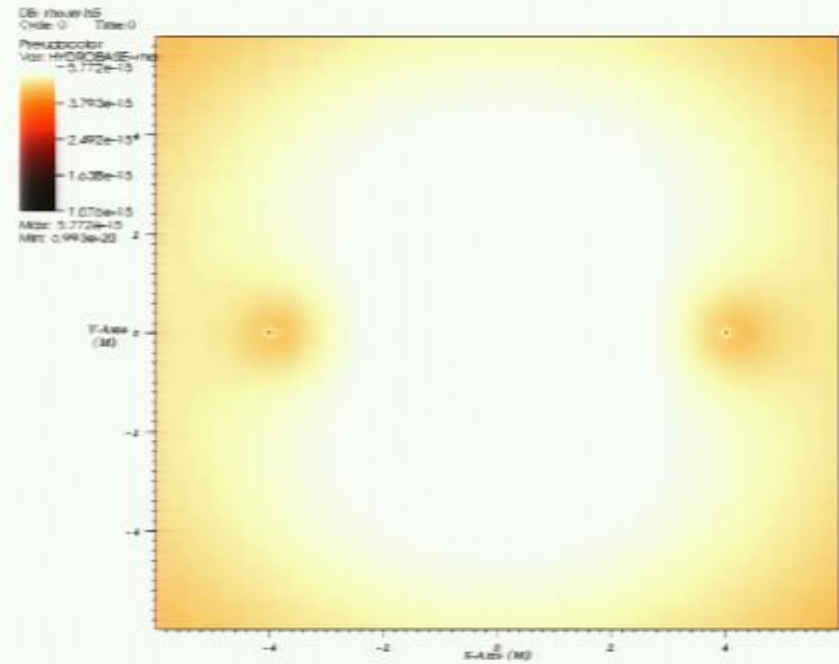


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

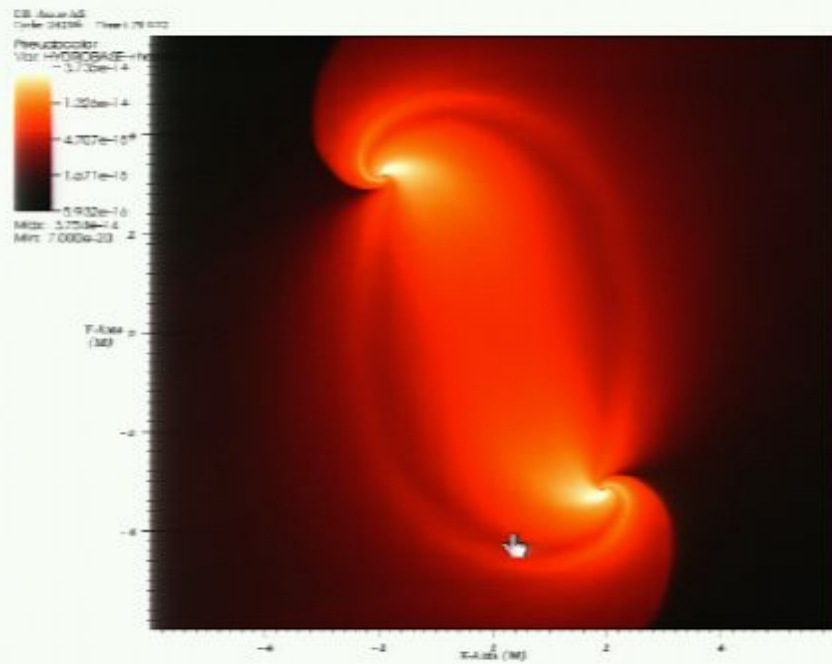


$$s_1/m^2 = s_2/m^2 = 0.6$$

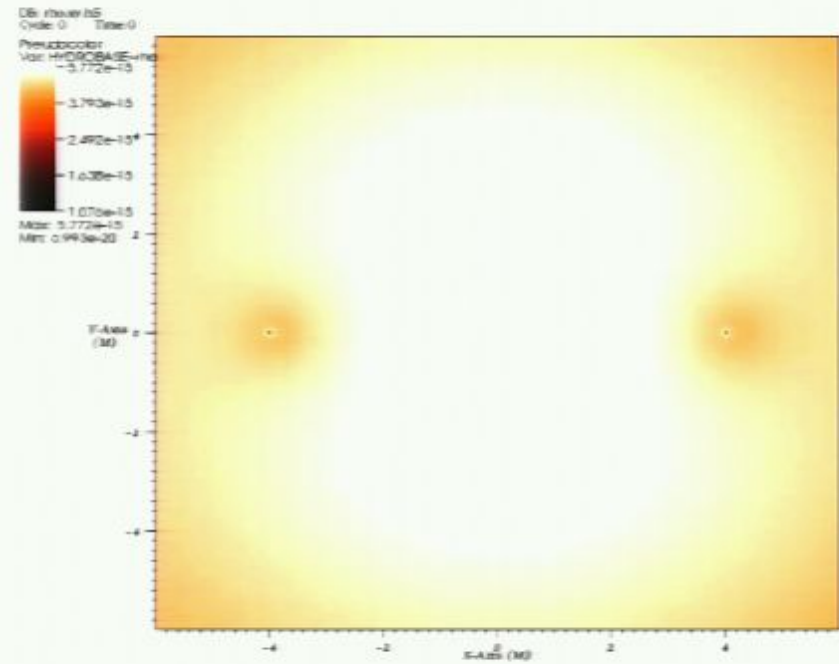


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

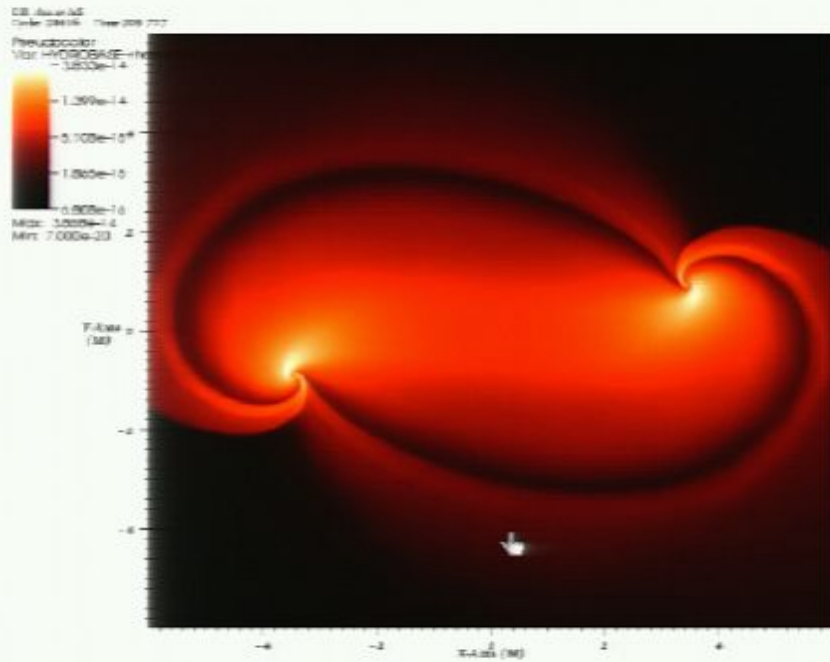


$$s_1/m^2 = s_2/m^2 = 0.6$$

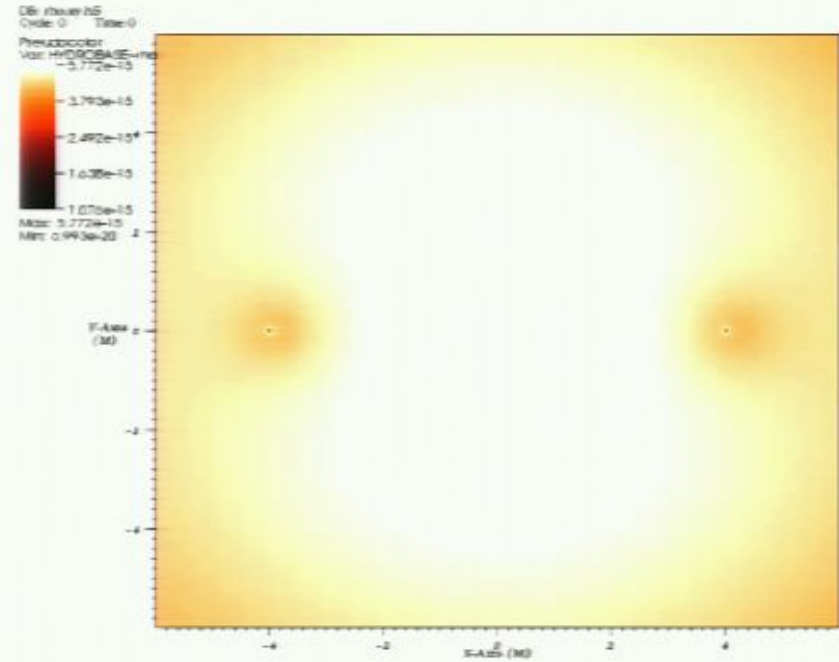


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

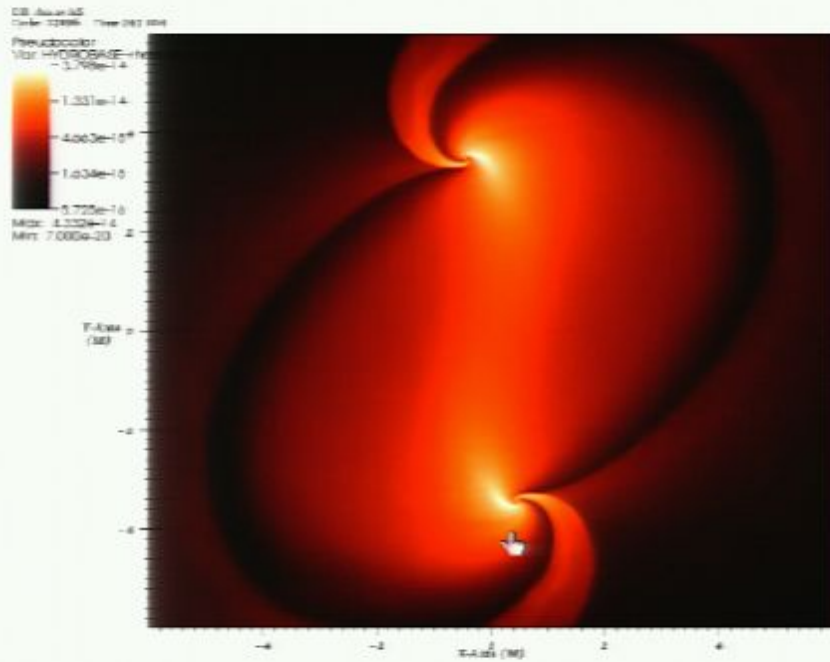


$$s_1/m^2 = s_2/m^2 = 0.6$$

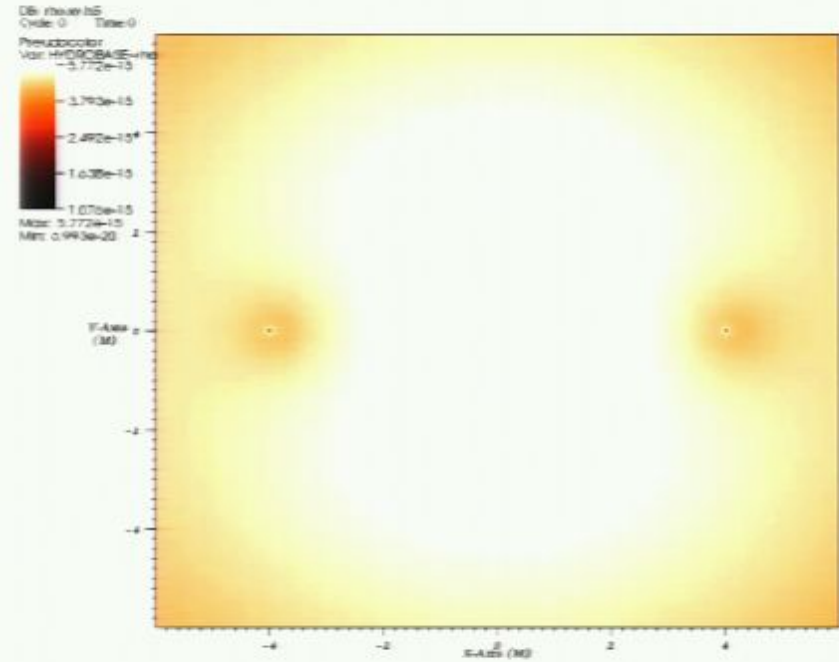


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

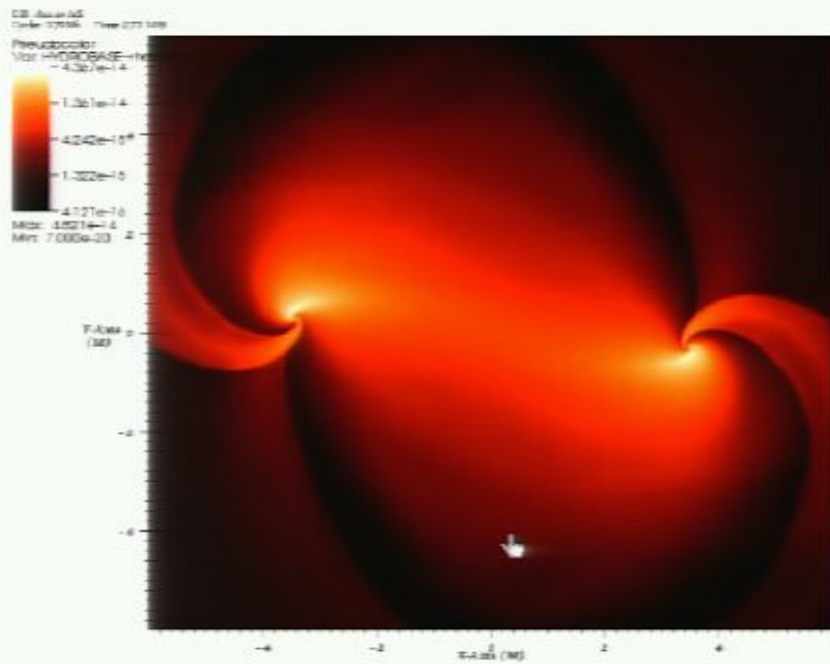


$$s_1/m^2 = s_2/m^2 = 0.6$$

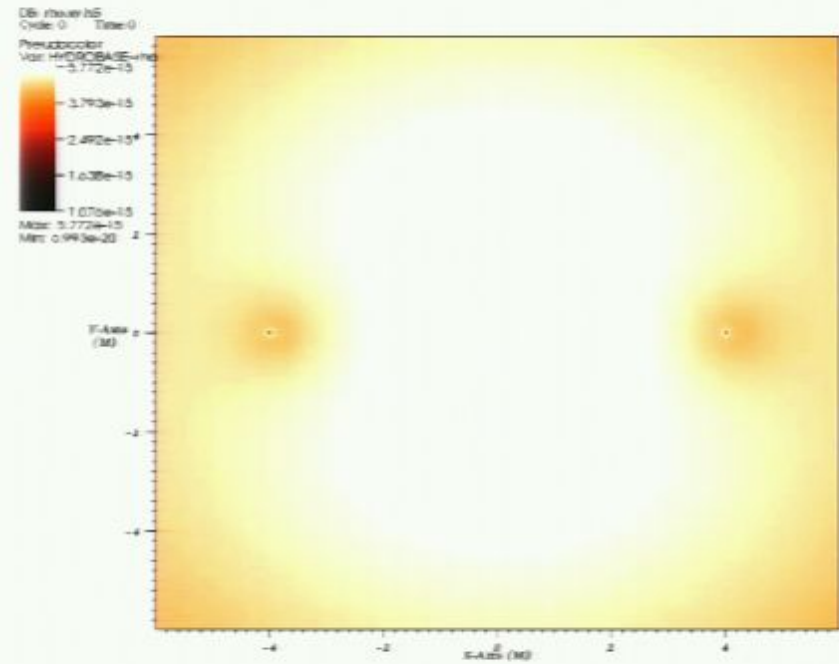


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

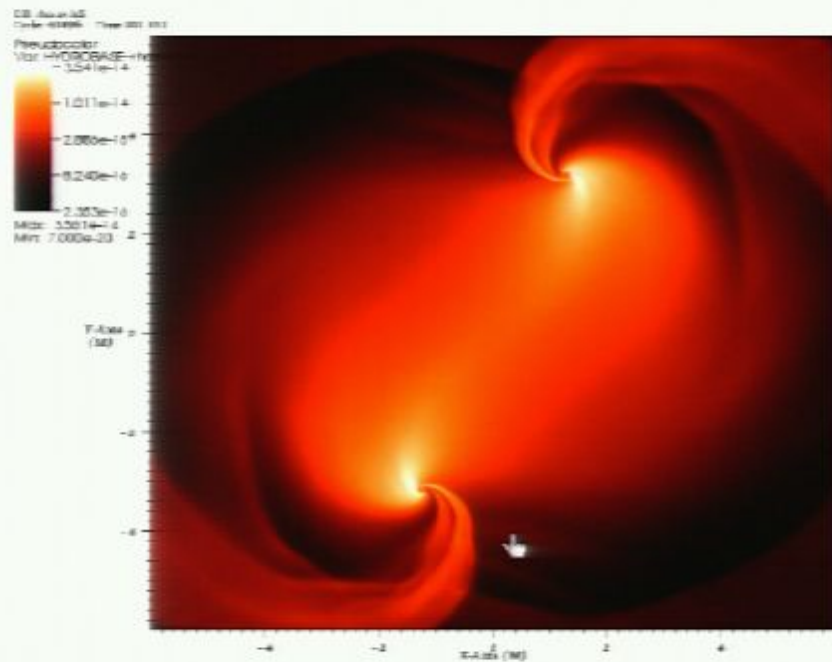


$$s_1/m^2 = s_2/m^2 = 0.6$$

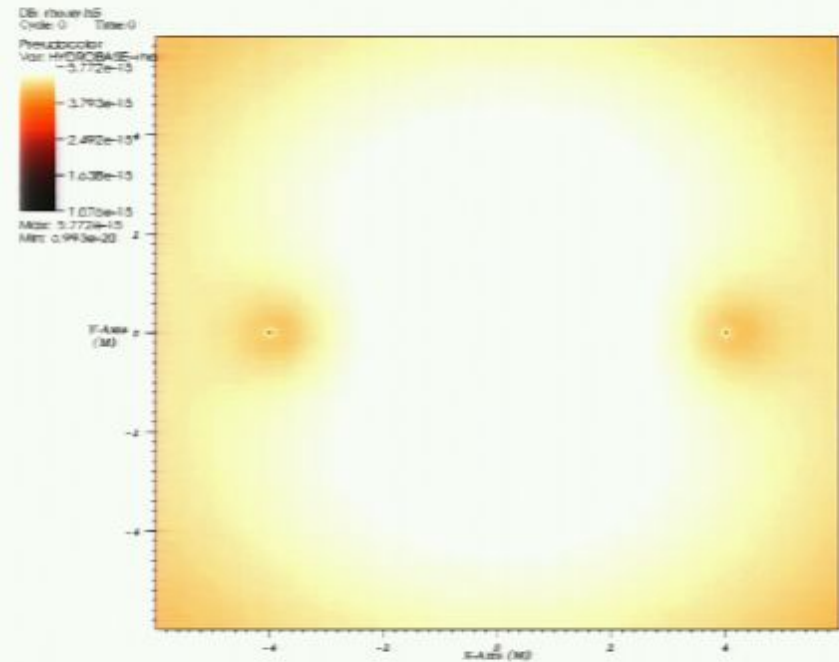


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

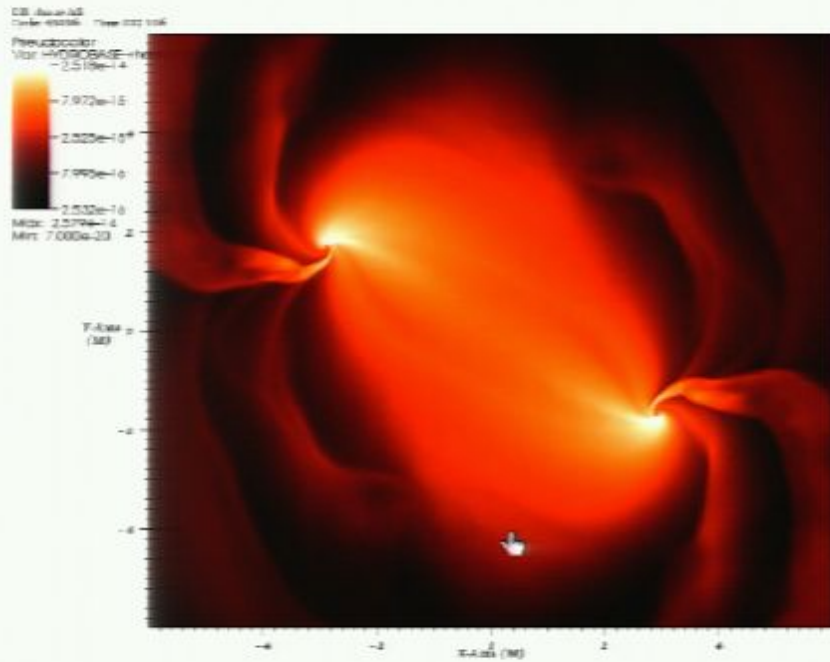


$$s_1/m^2 = s_2/m^2 = 0.6$$

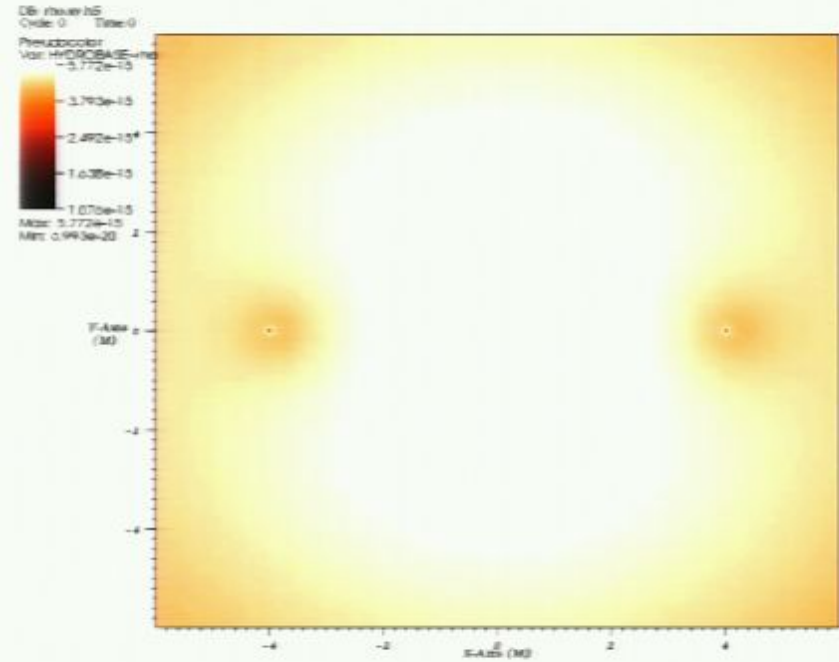


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

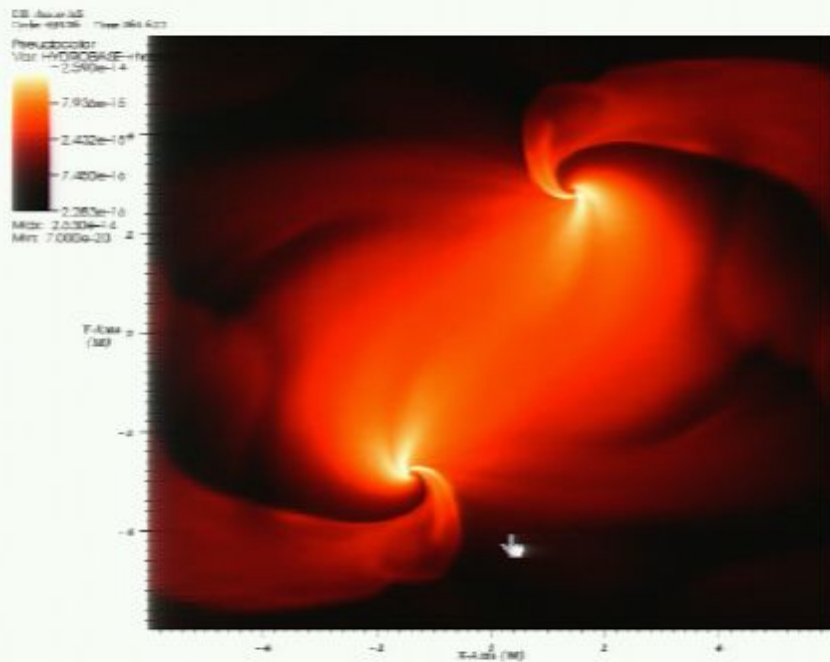


$$s_1/m^2 = s_2/m^2 = 0.6$$

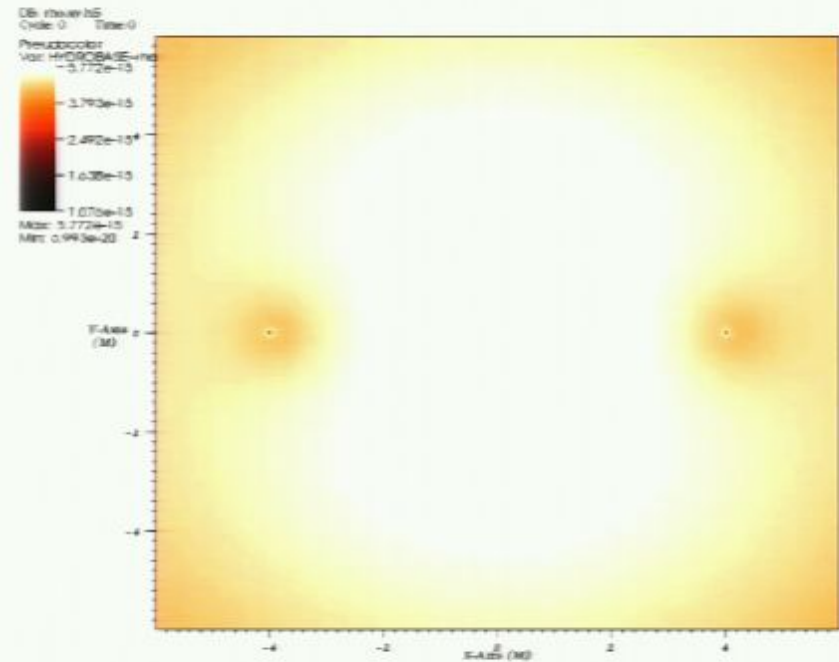


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

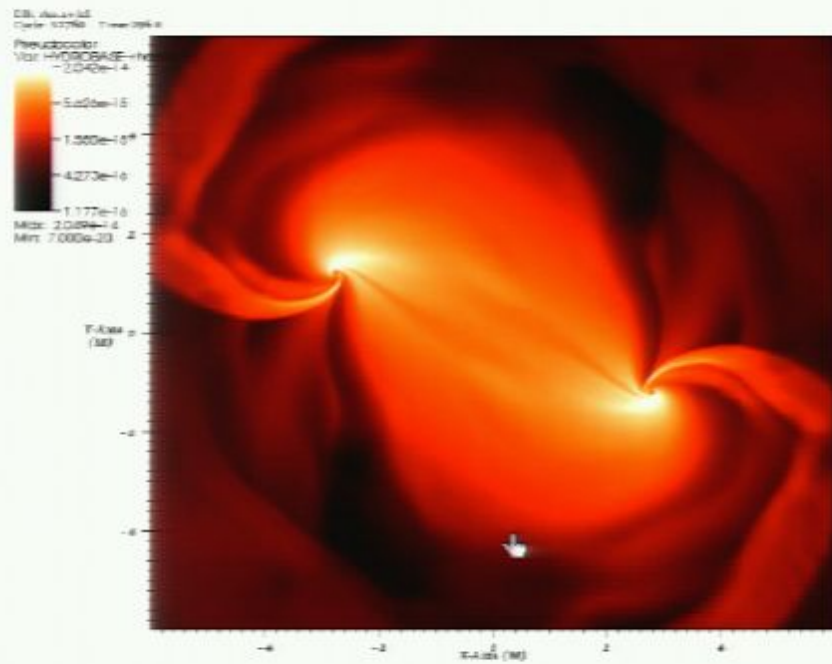


$$s_1/m^2 = s_2/m^2 = 0.6$$

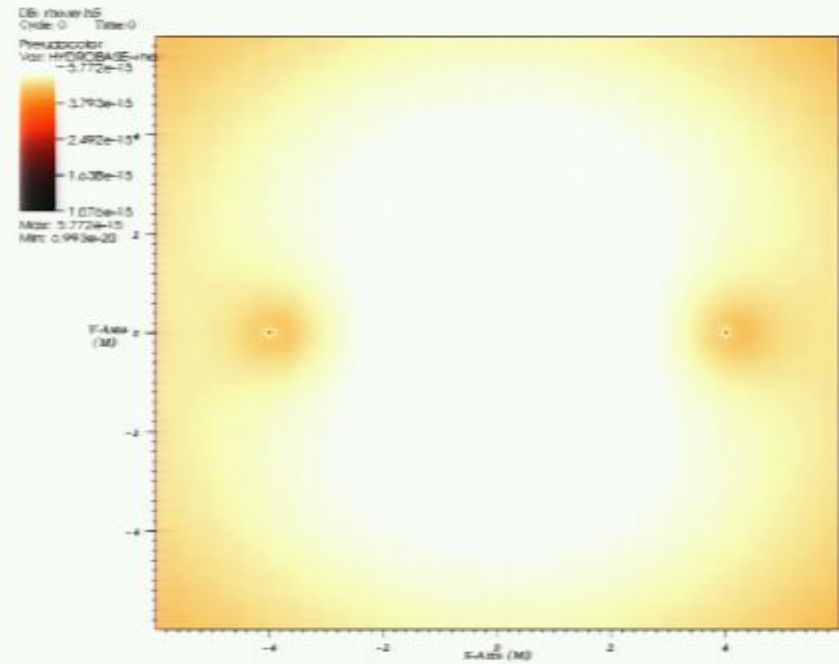


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

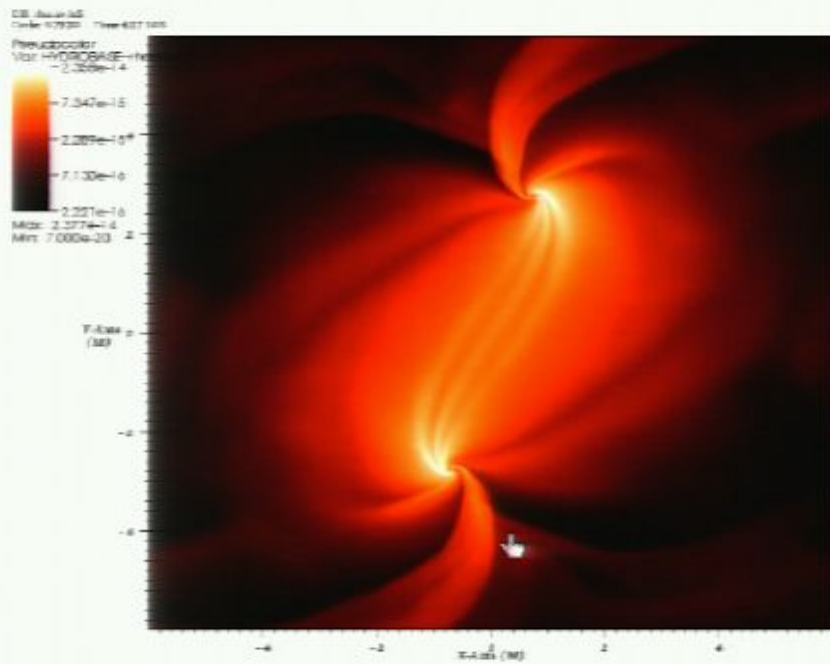


$$s_1/m^2 = s_2/m^2 = 0.6$$

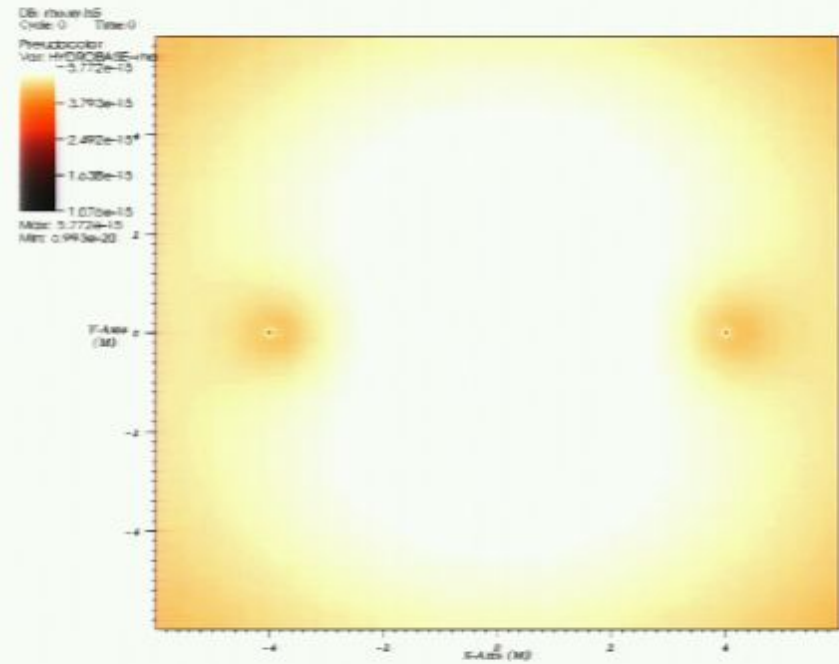


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

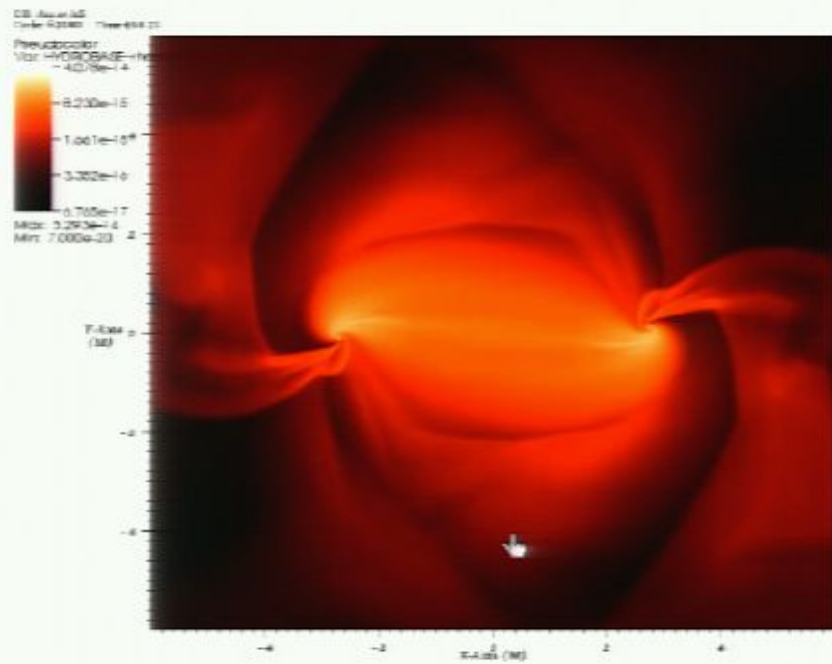


$$s_1/m^2 = s_2/m^2 = 0.6$$

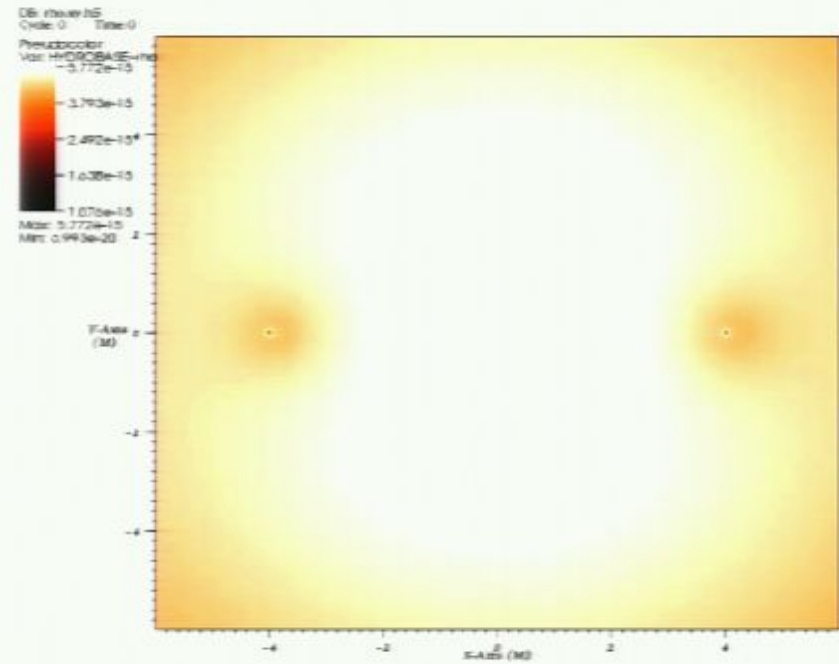


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

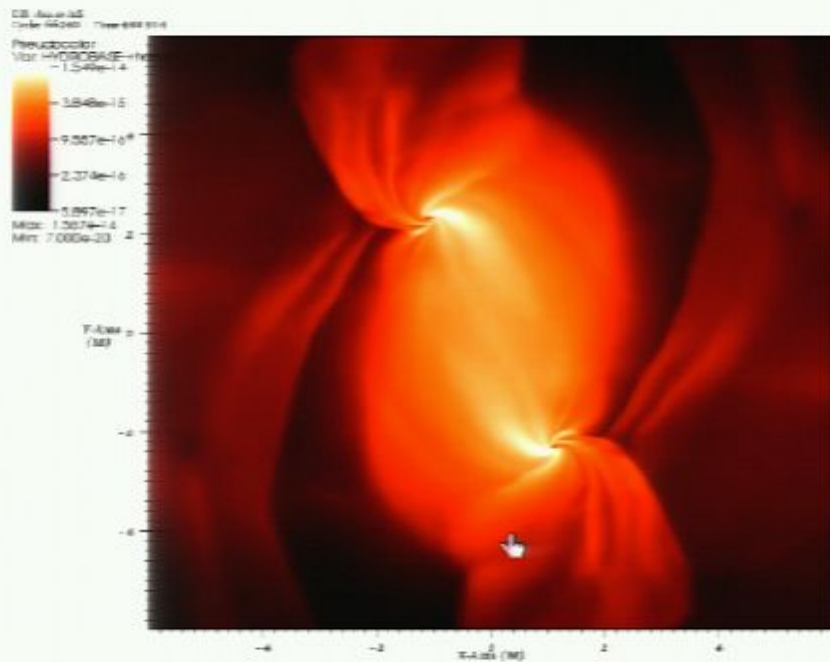


$$s_1/m^2 = s_2/m^2 = 0.6$$

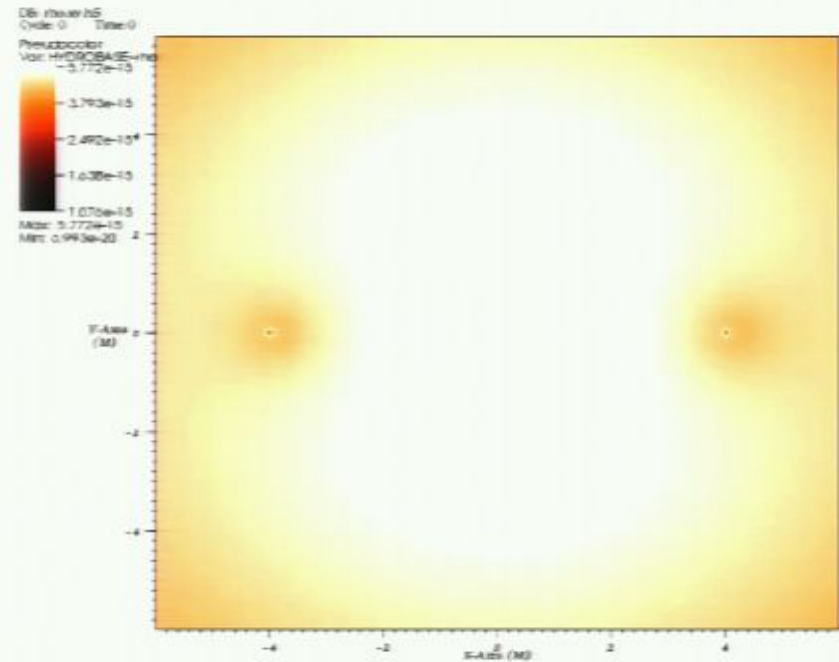


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

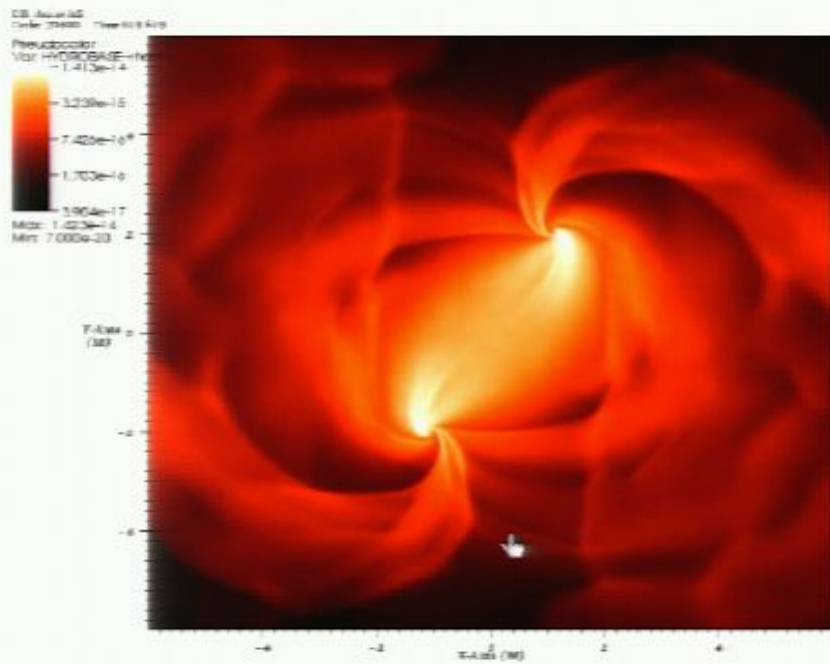


$$s_1/m^2 = s_2/m^2 = 0.6$$

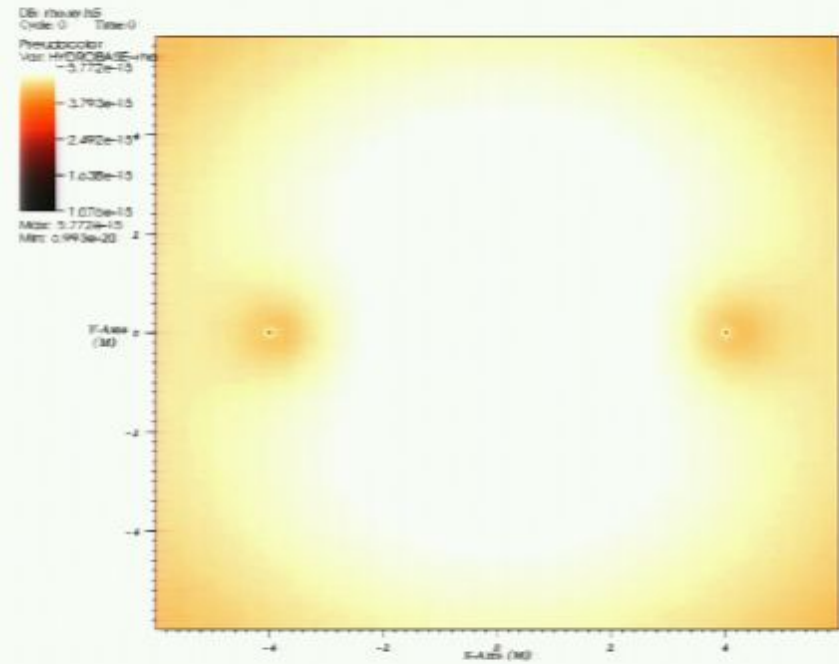


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

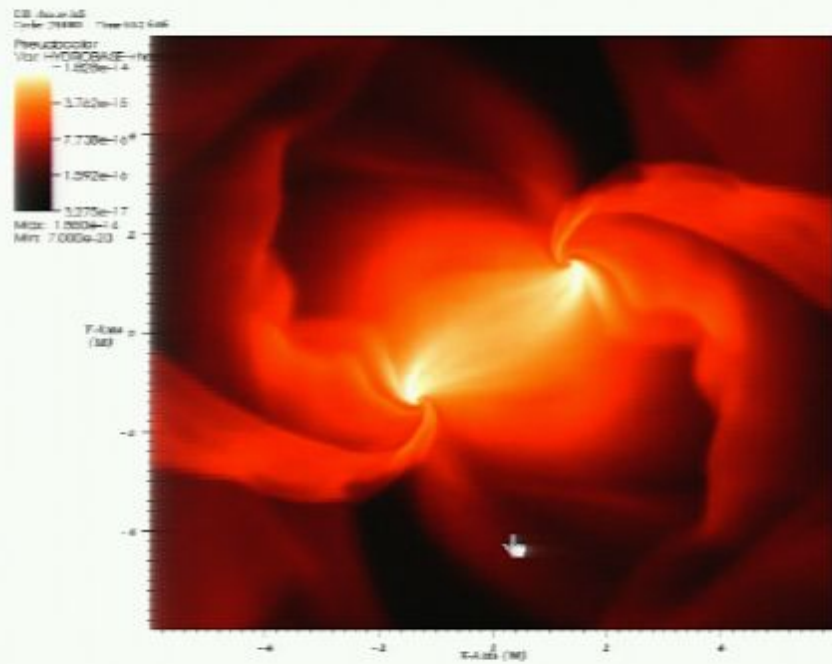


$$s_1/m^2 = s_2/m^2 = 0.6$$

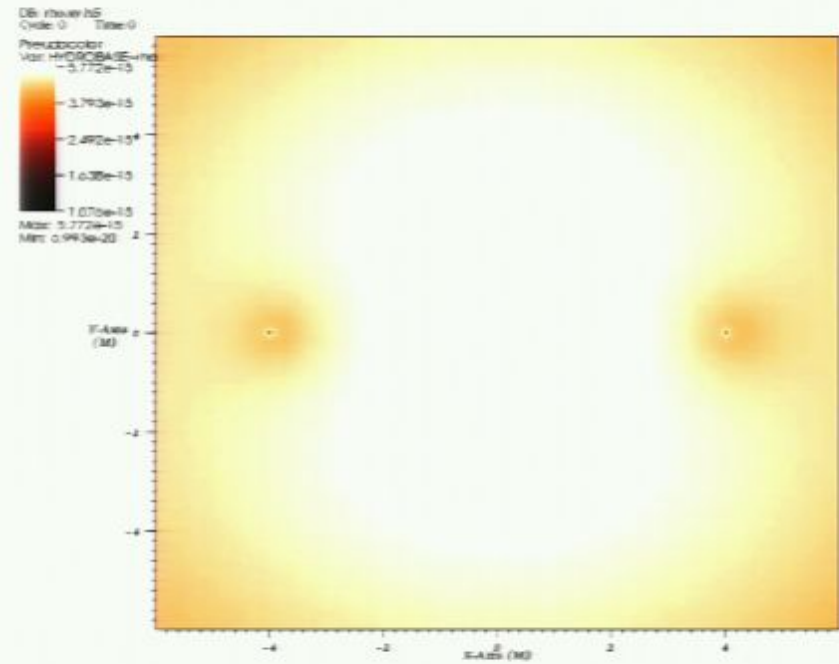


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

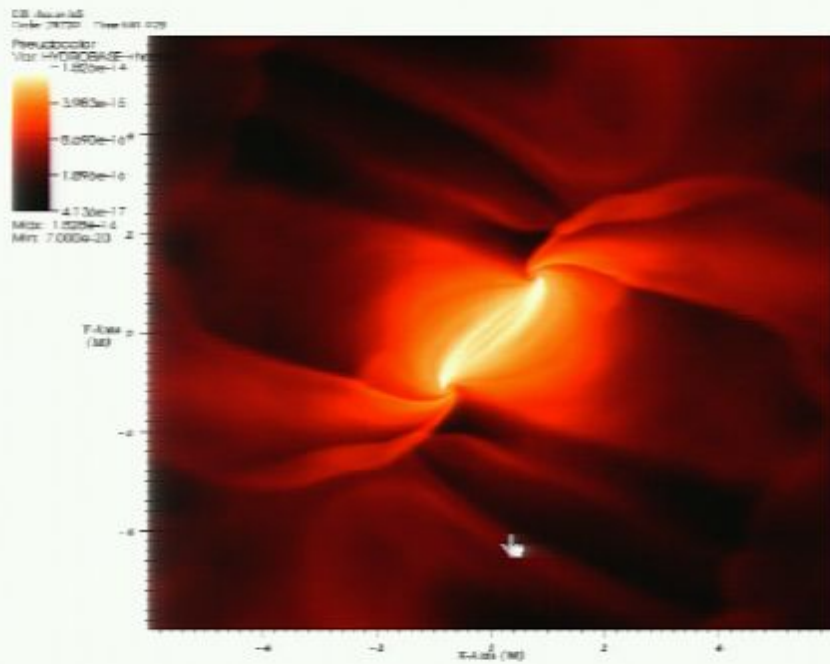


$$s_1/m^2 = s_2/m^2 = 0.6$$

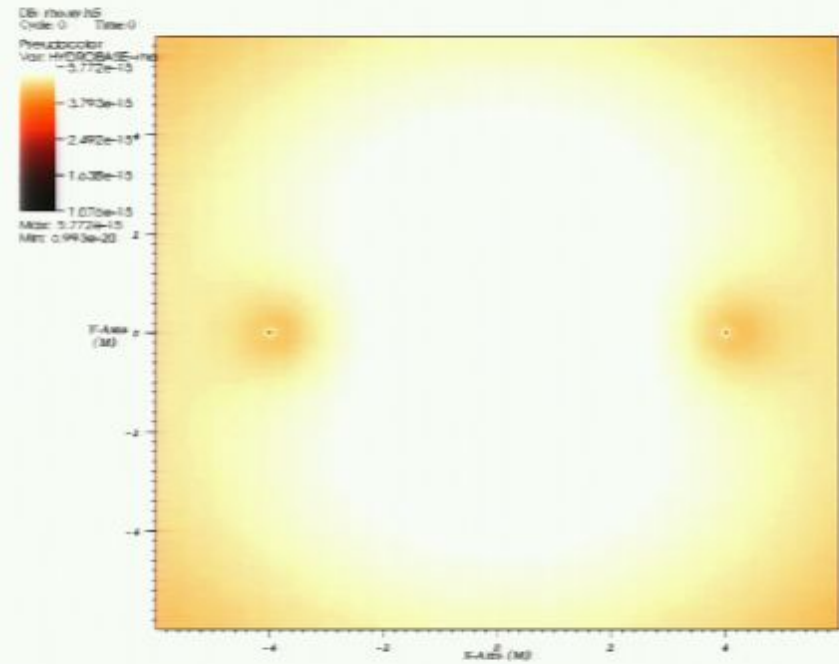


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

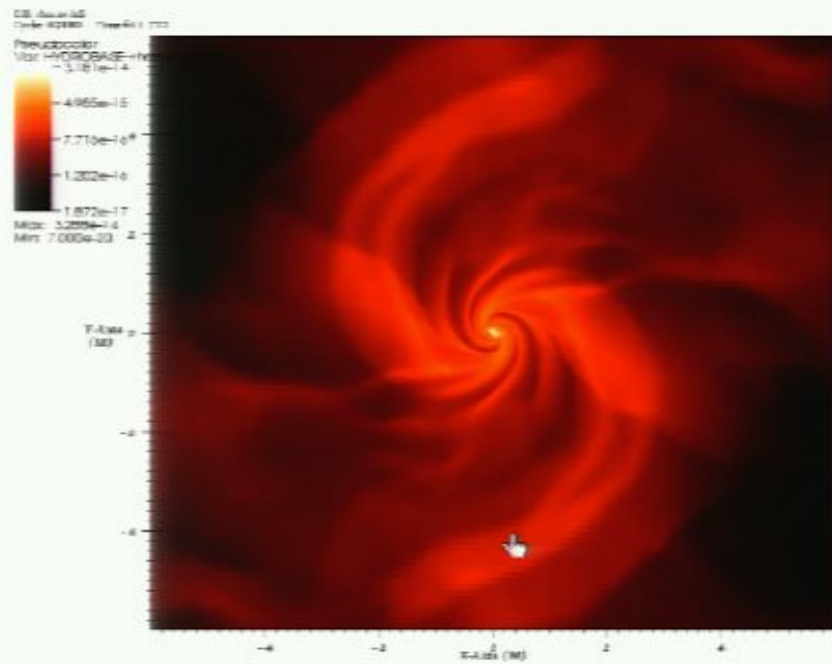


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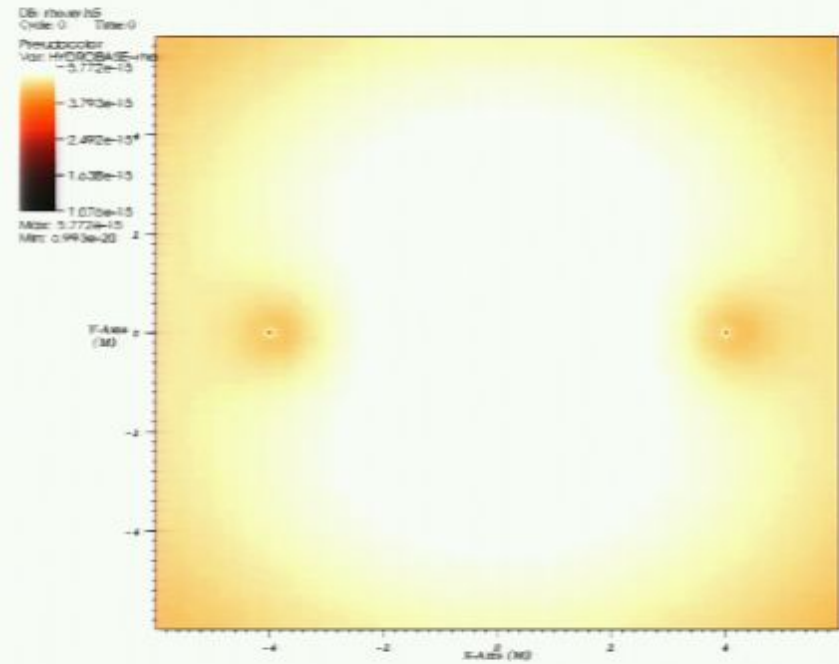


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

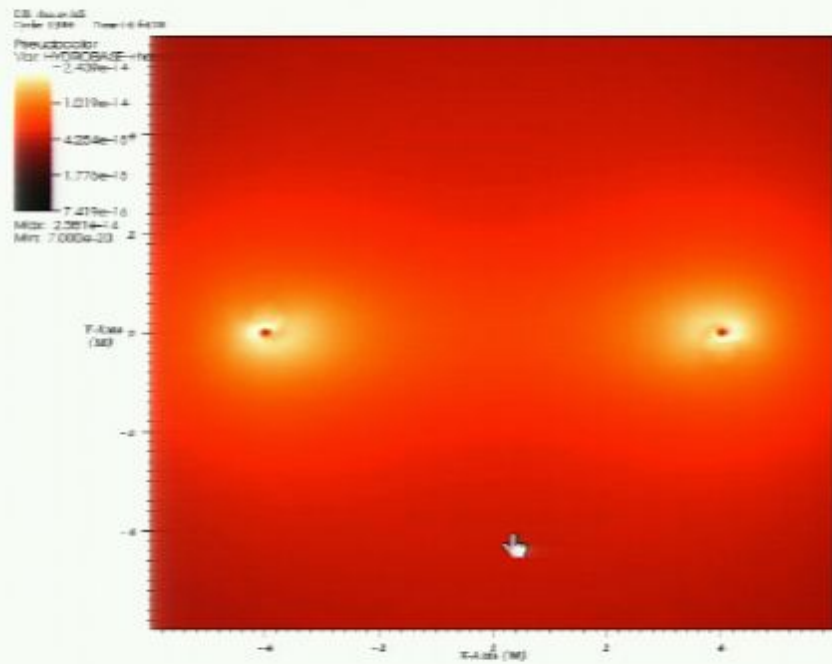


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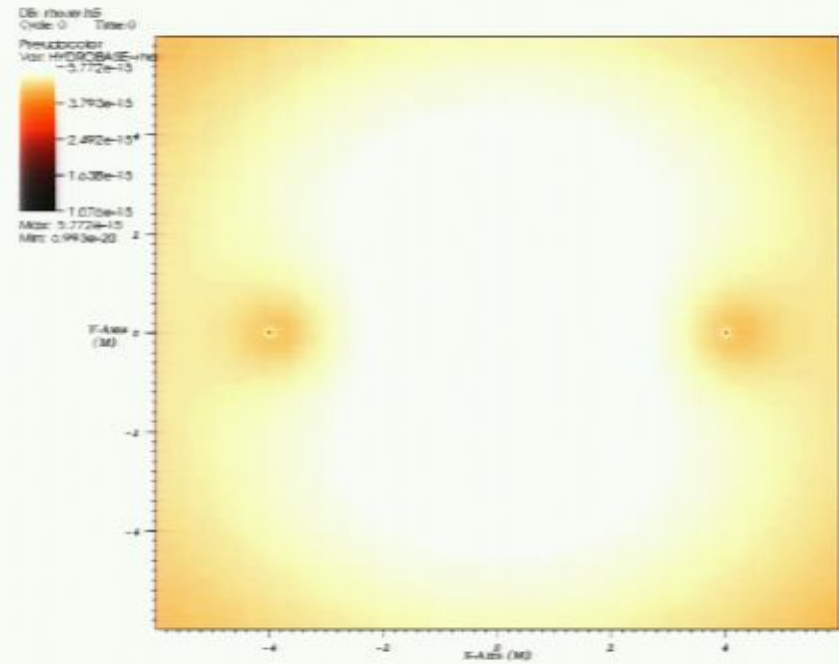


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

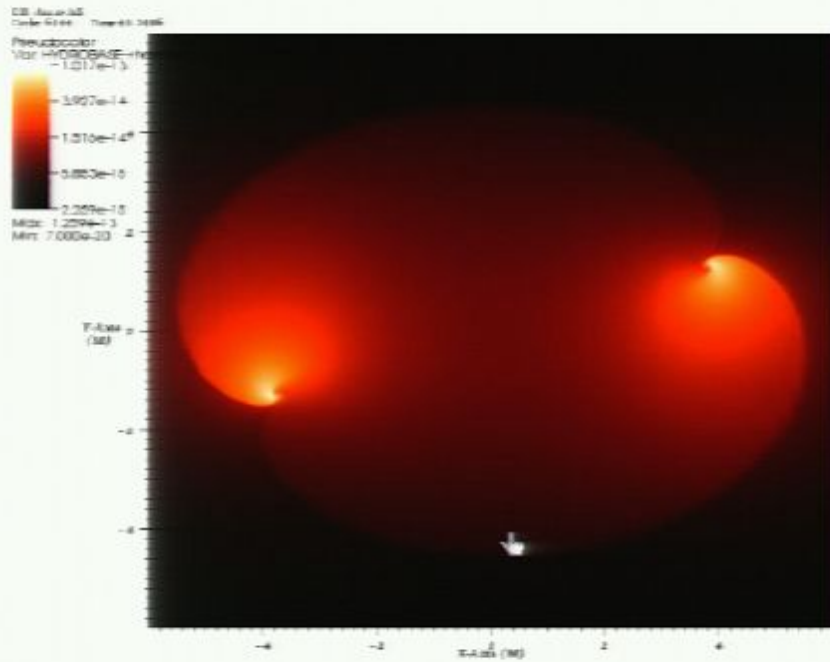


$$s_1/m^2 = s_2/m^2 = 0.6$$

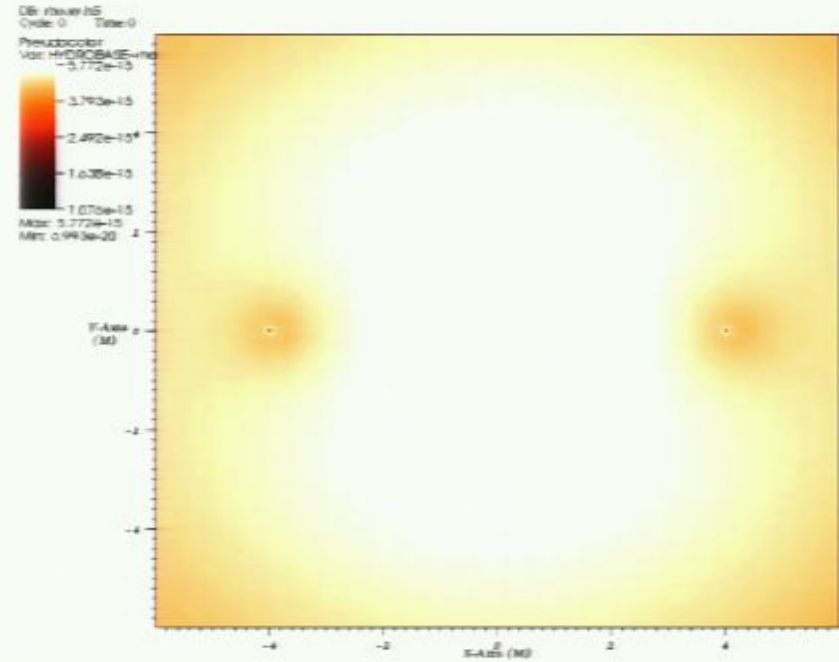


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

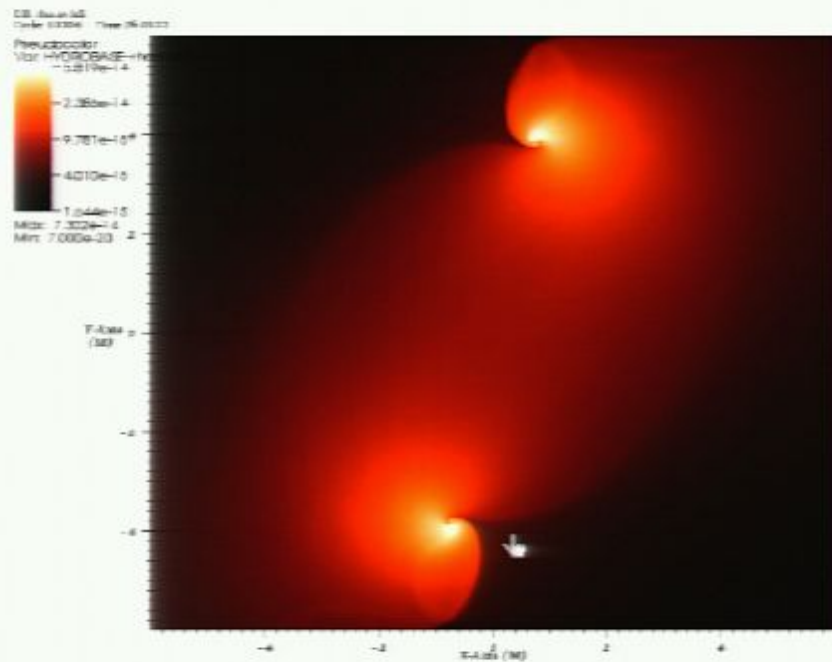


$$s_1/m^2 = s_2/m^2 = 0.6$$

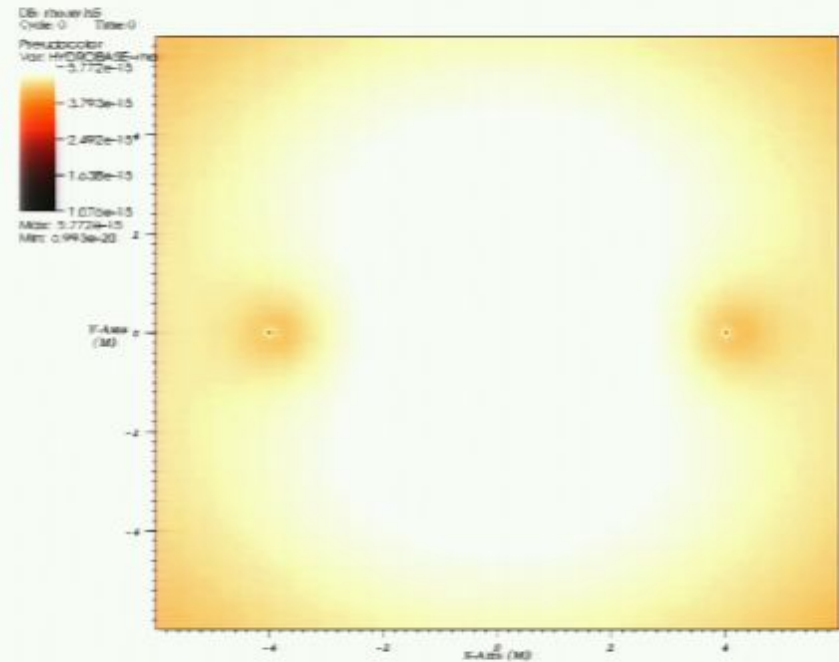


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

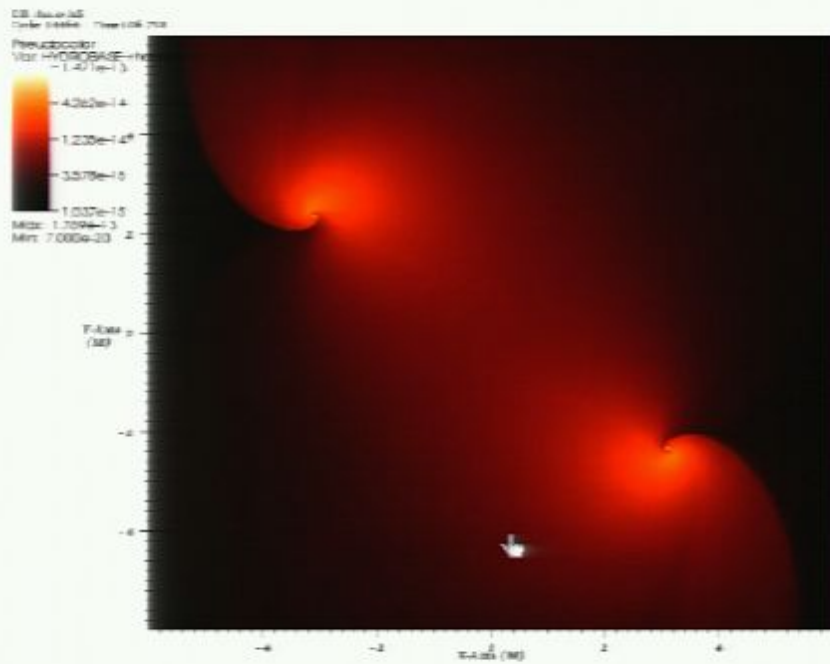


$$s_1/m^2 = s_2/m^2 = 0.6$$

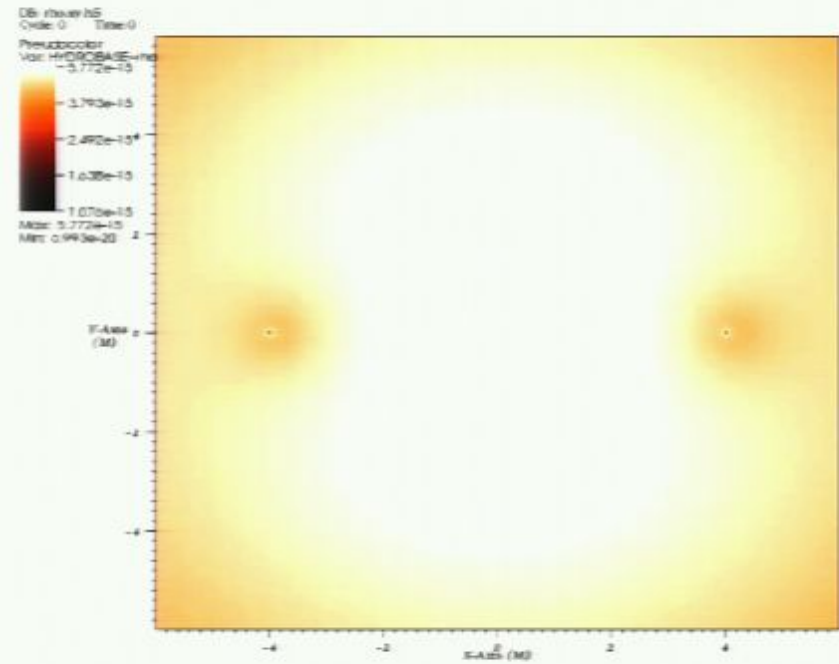


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

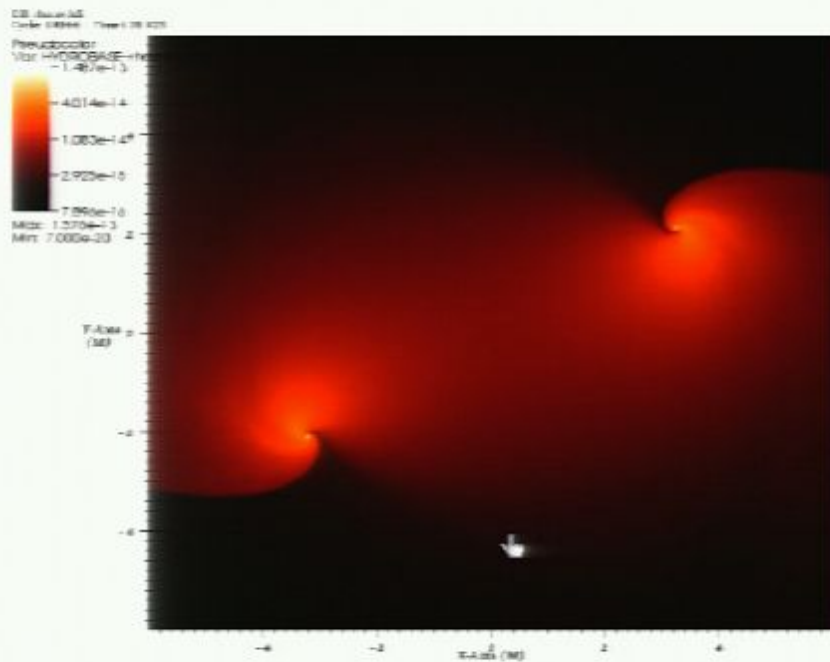


$$s_1/m^2 = s_2/m^2 = 0.6$$

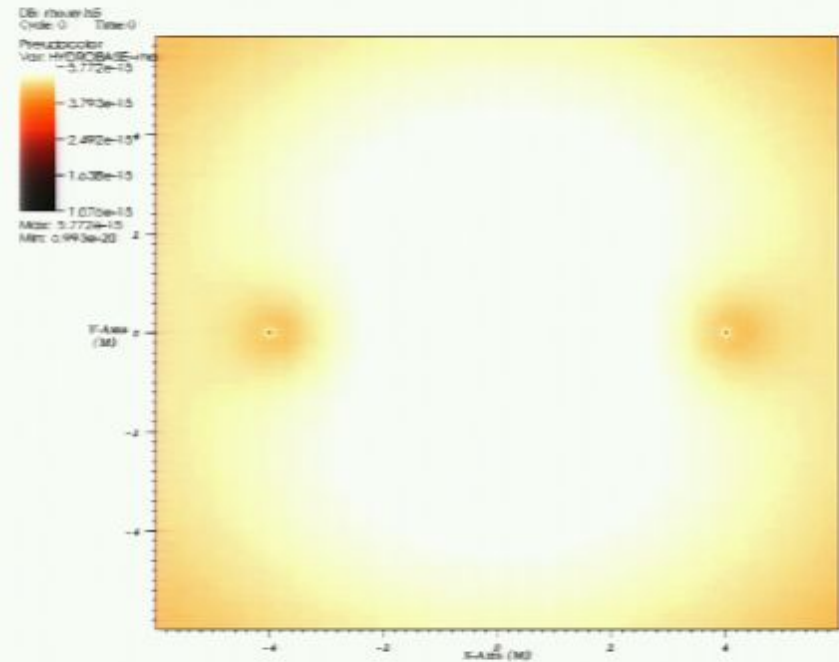


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

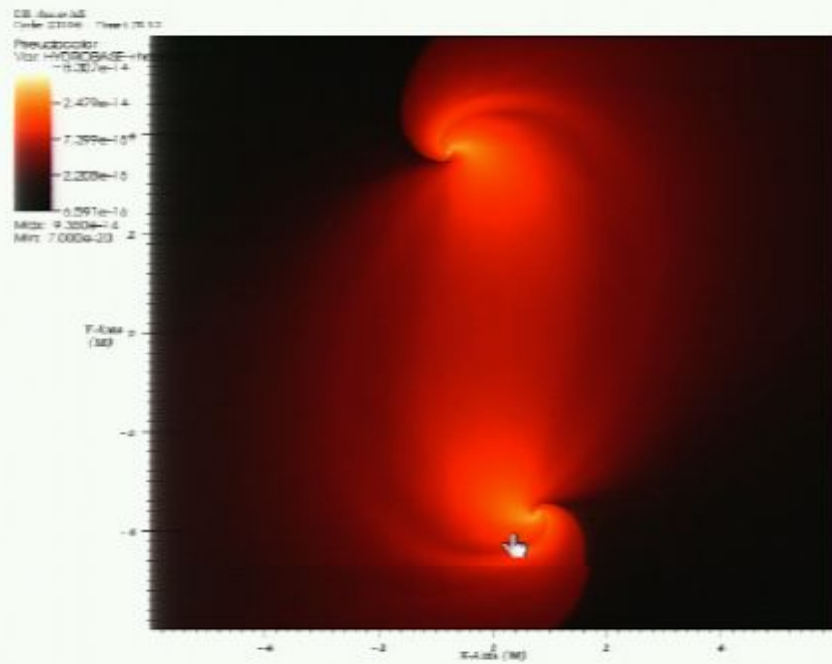


$$s_1/m^2 = s_2/m^2 = 0.6$$

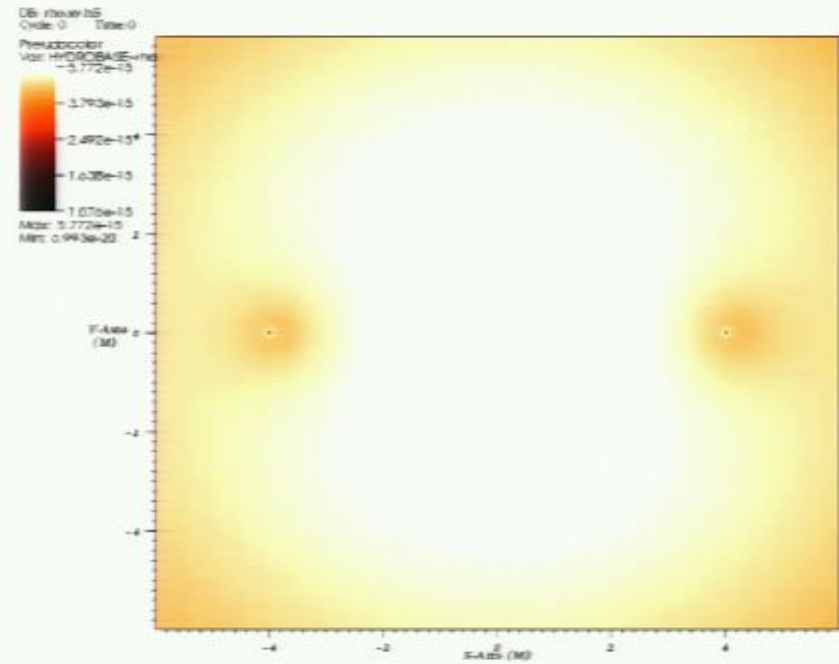


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

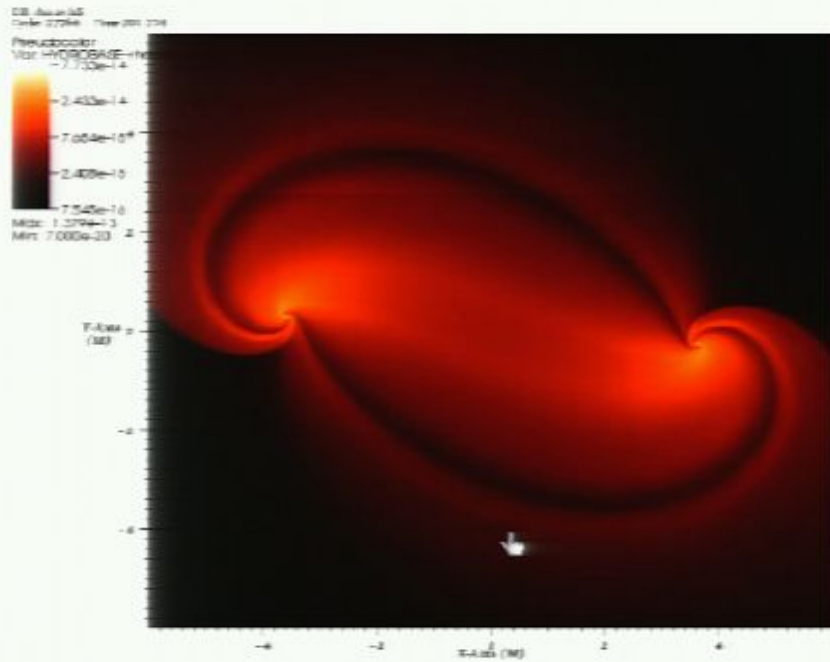


$$s_1/m^2 = s_2/m^2 = 0.6$$

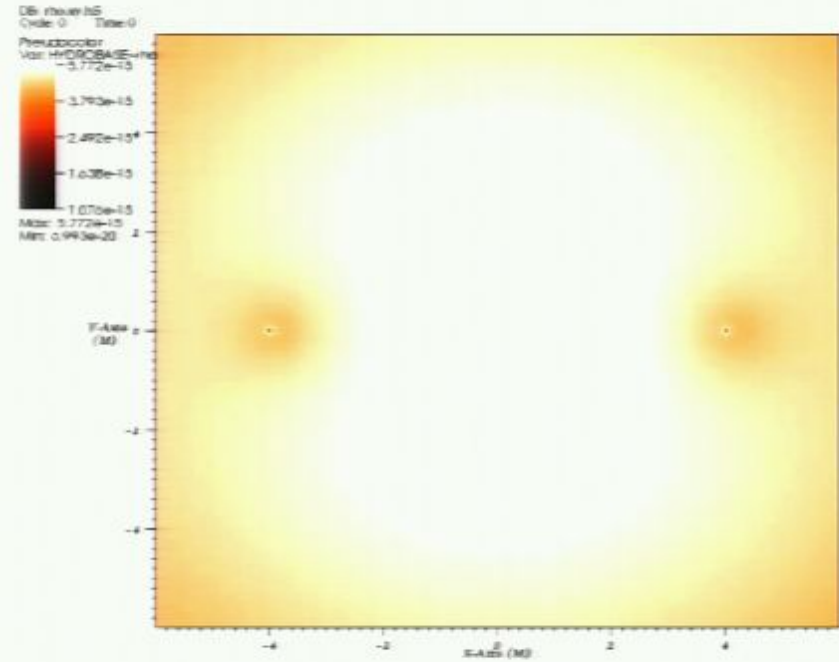


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

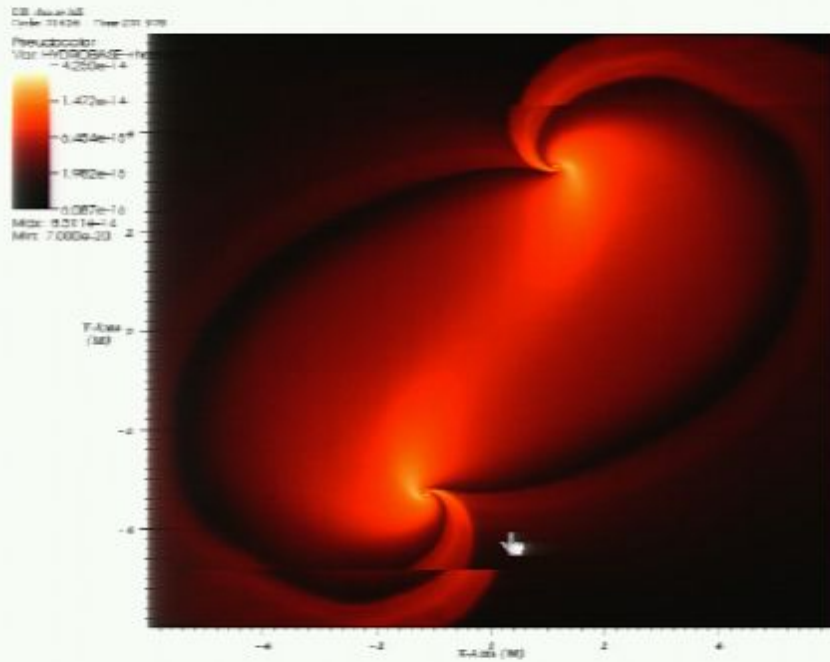


$$s_1/m^2 = s_2/m^2 = 0.6$$

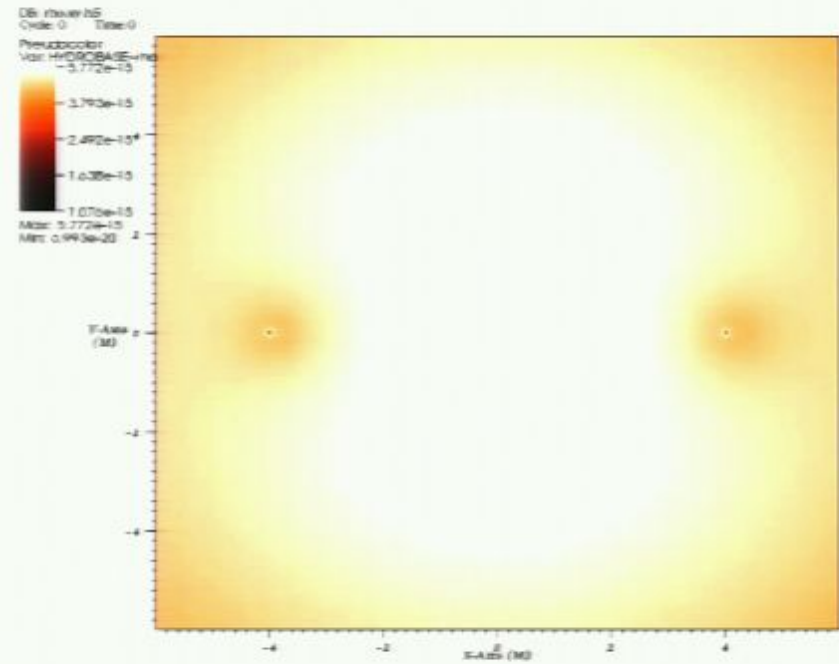


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

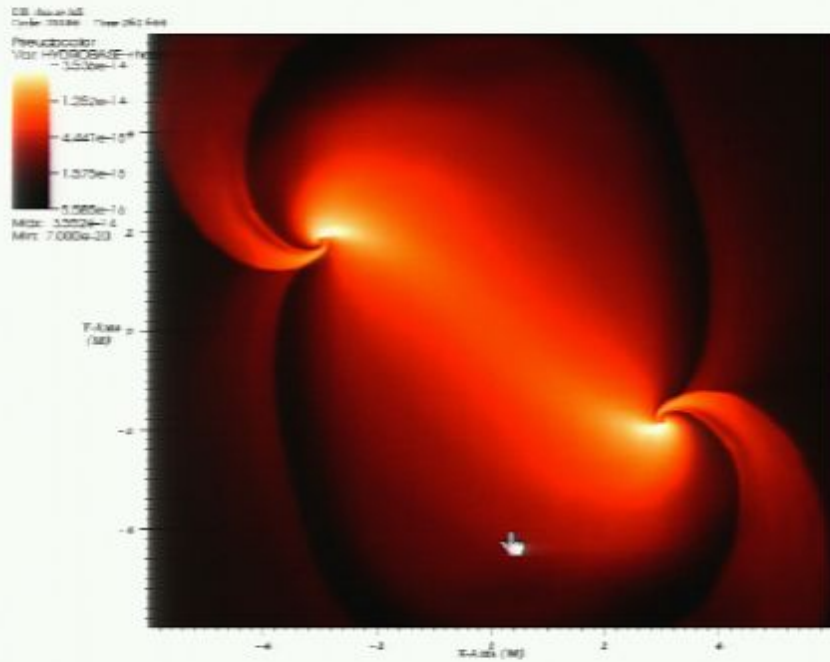


$$s_1/m^2 = s_2/m^2 = 0.6$$

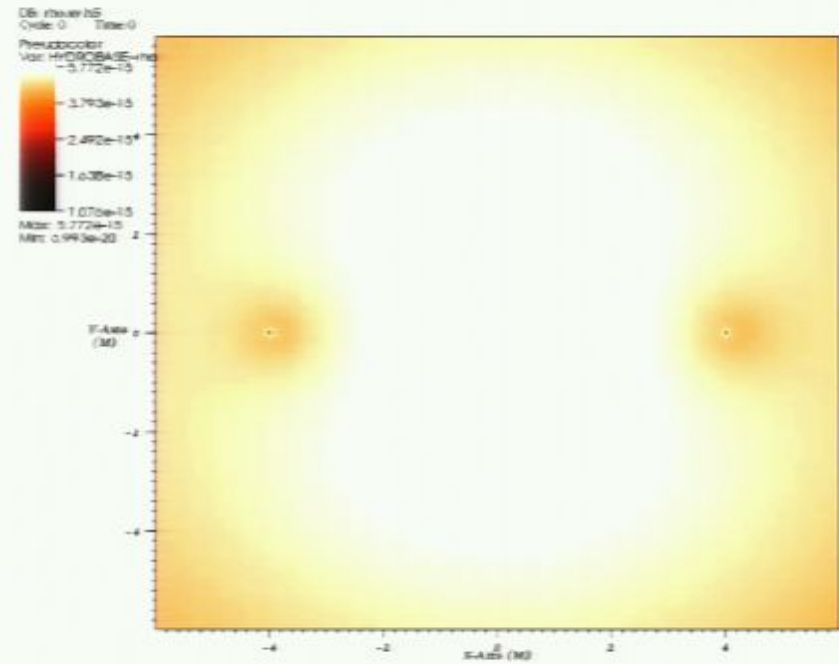


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

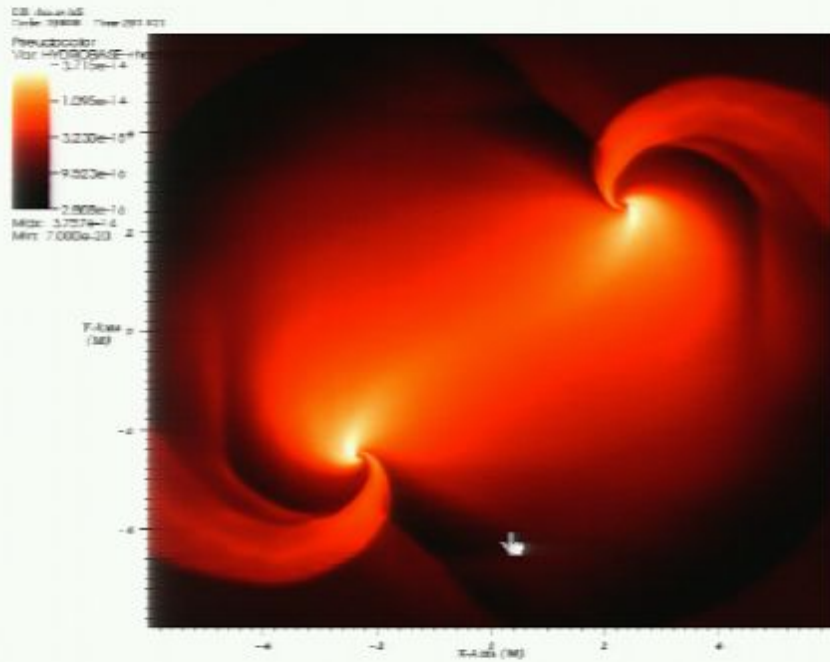


$$s_1/m^2 = s_2/m^2 = 0.6$$

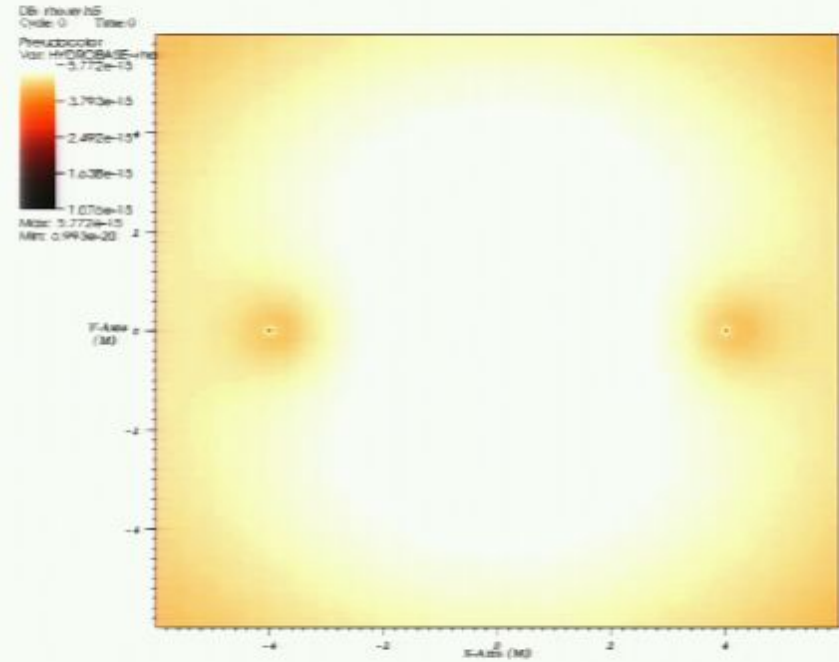


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

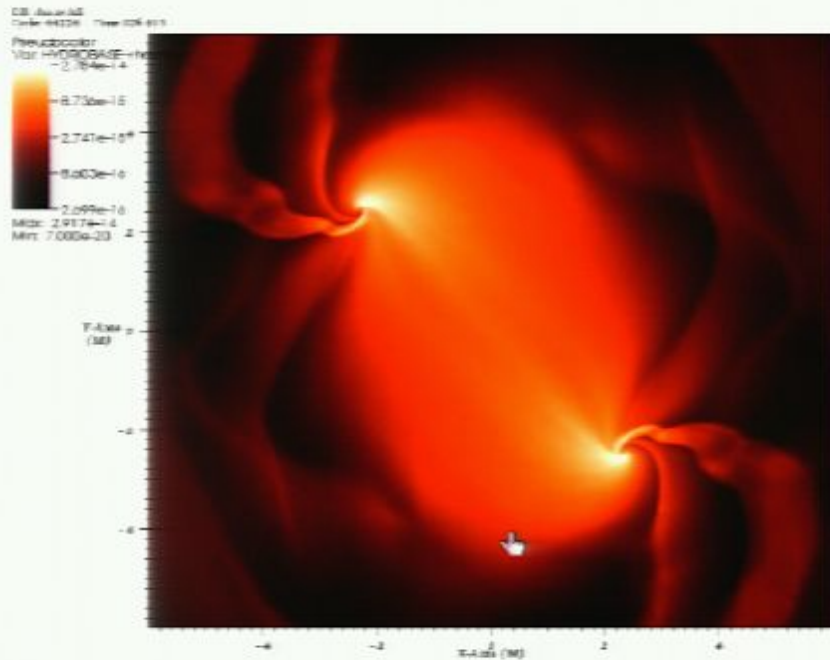


$$s_1/m^2 = s_2/m^2 = 0.6$$

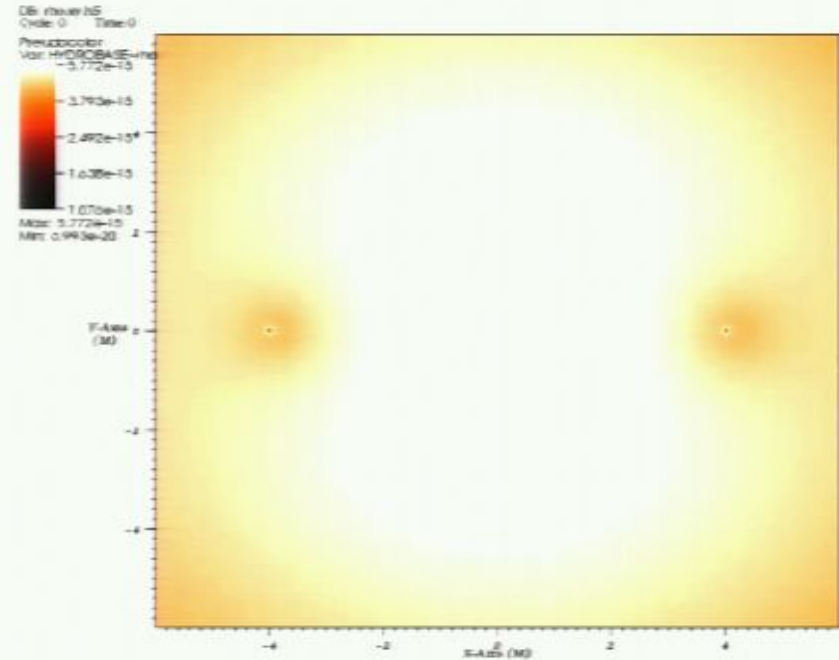


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

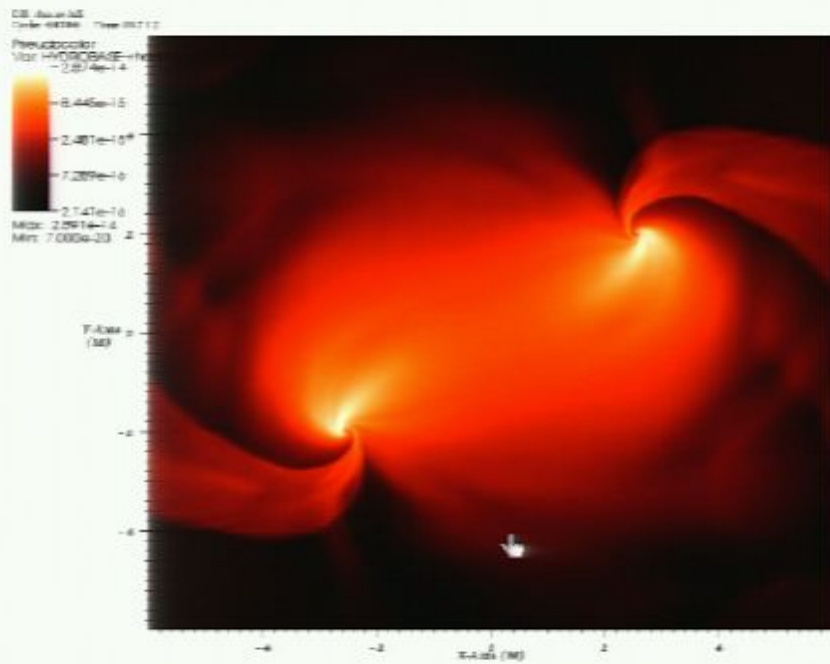


$$s_1/m^2 = s_2/m^2 = 0.6$$

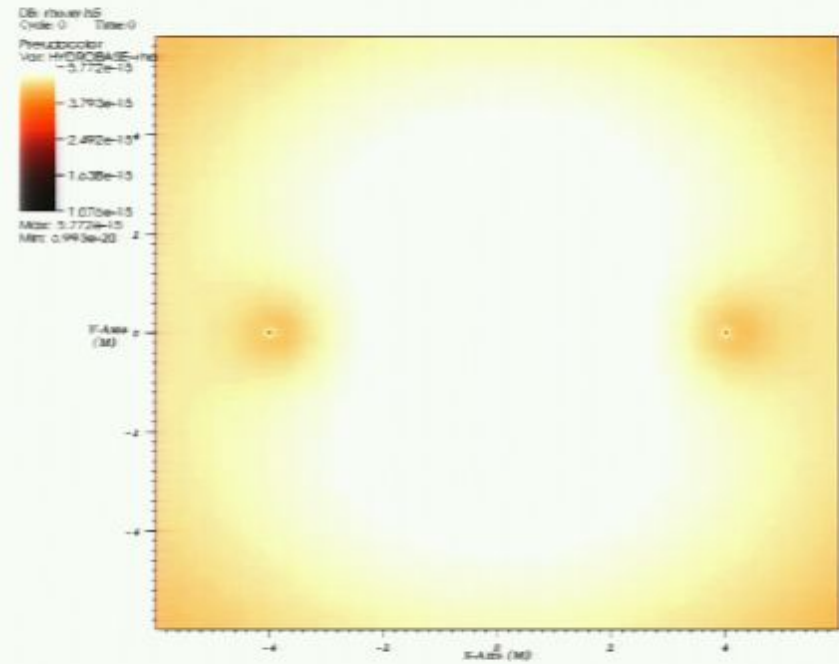


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

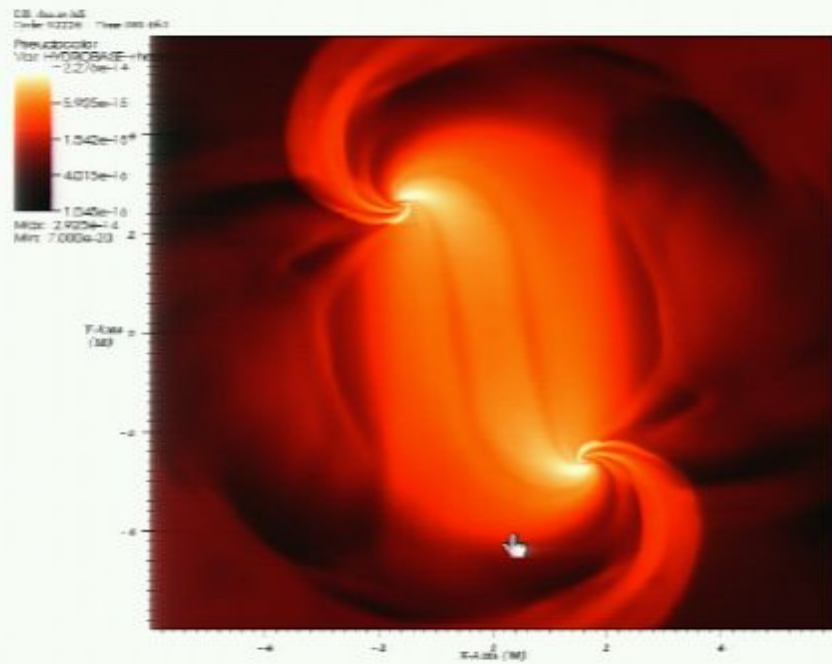


$$s_1/m^2 = s_2/m^2 = 0.6$$

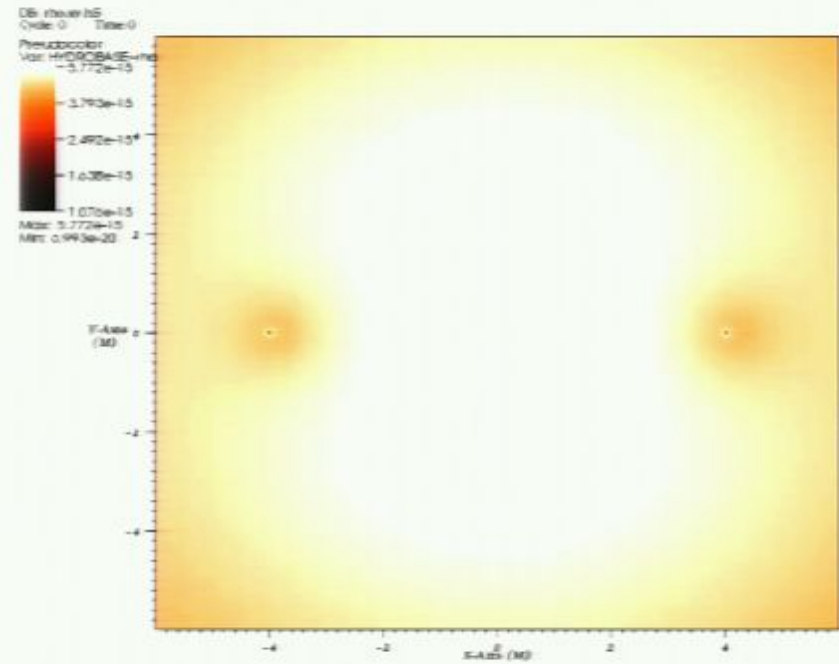


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

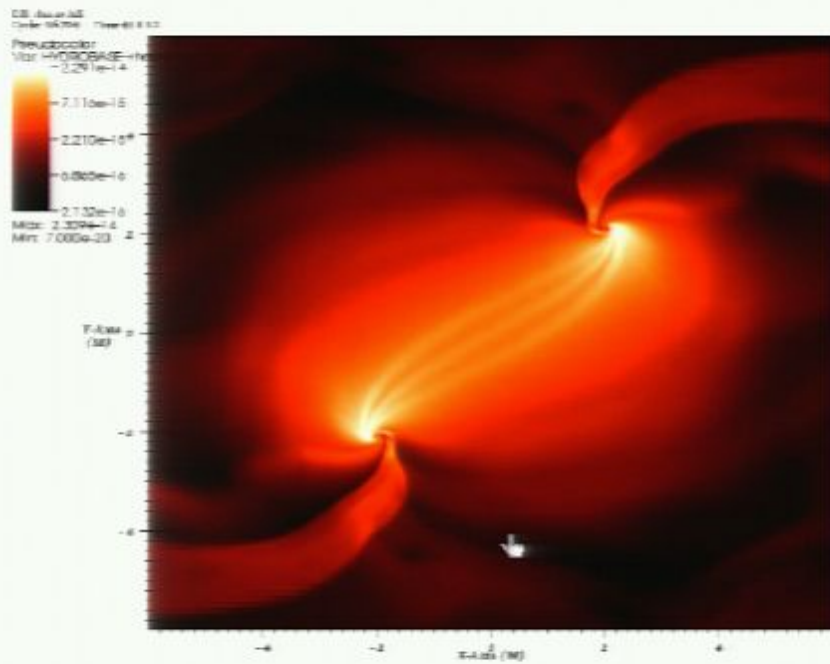


$$s_1/m^2 = s_2/m^2 = 0.6$$

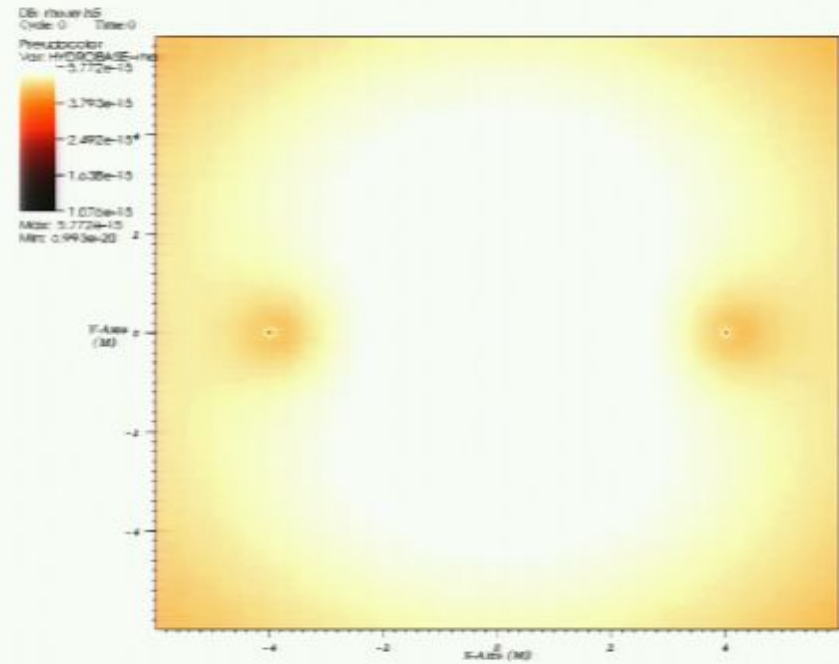


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

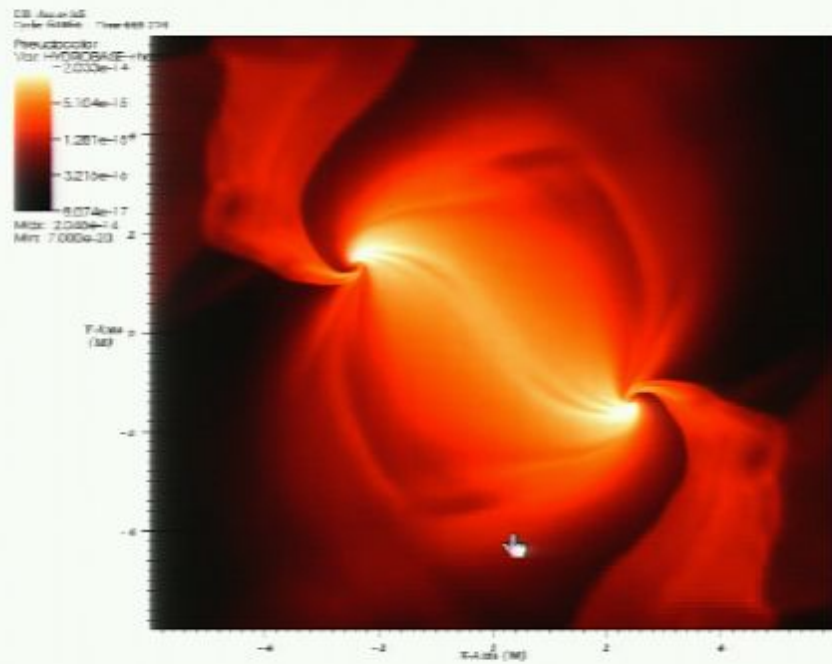


$$s_1/m^2 = s_2/m^2 = 0.6$$

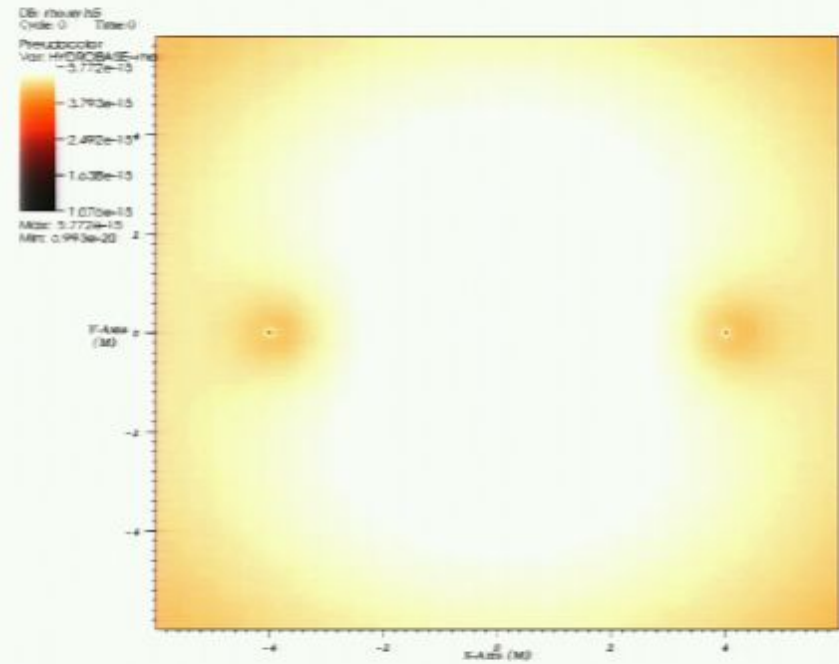


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

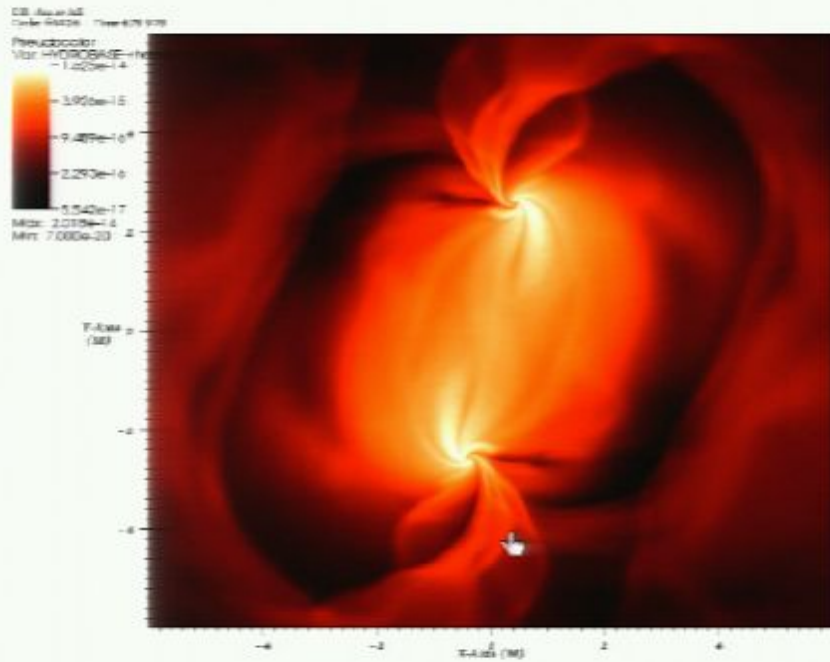


$$s_1/m^2 = s_2/m^2 = 0.6$$

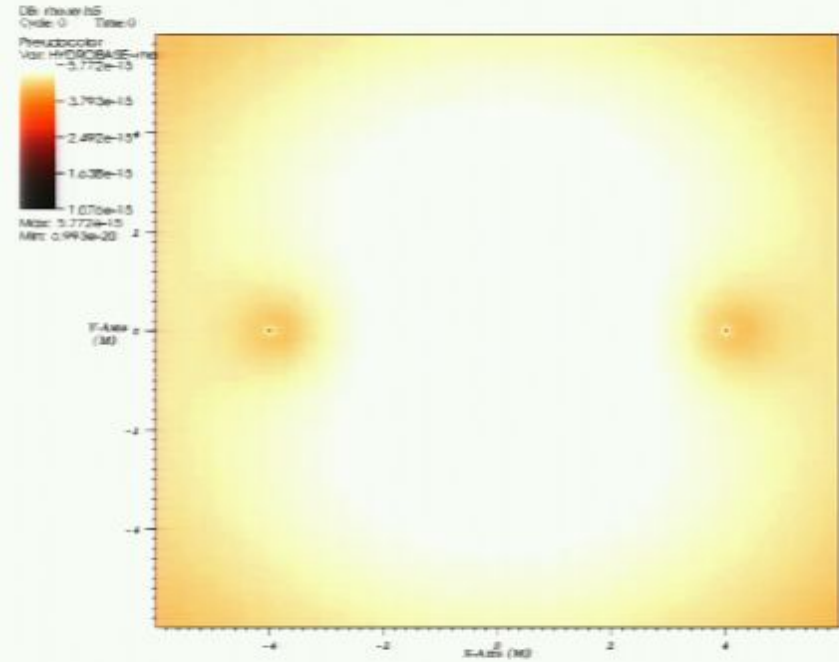


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

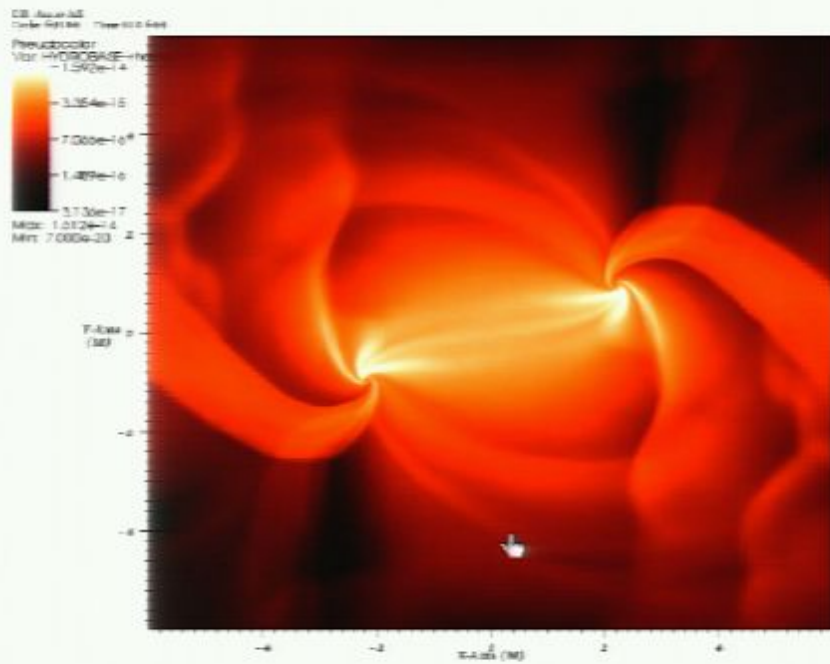


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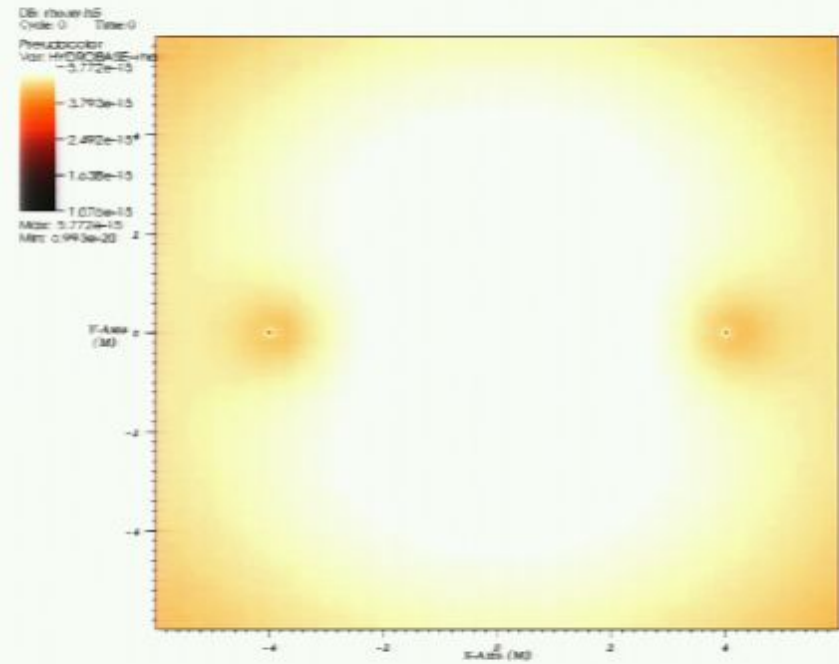


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

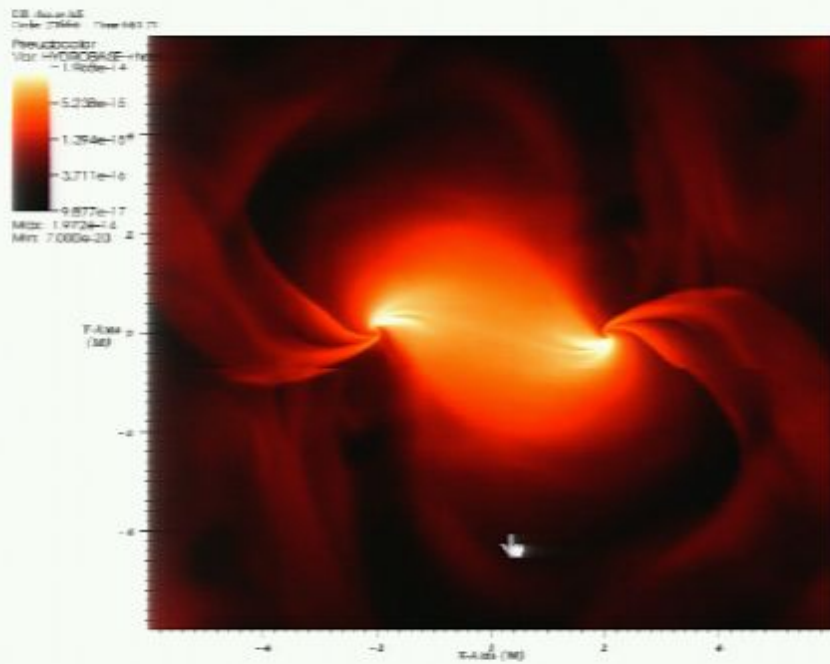


$$s_1/m^2 = s_2/m^2 = 0.6$$

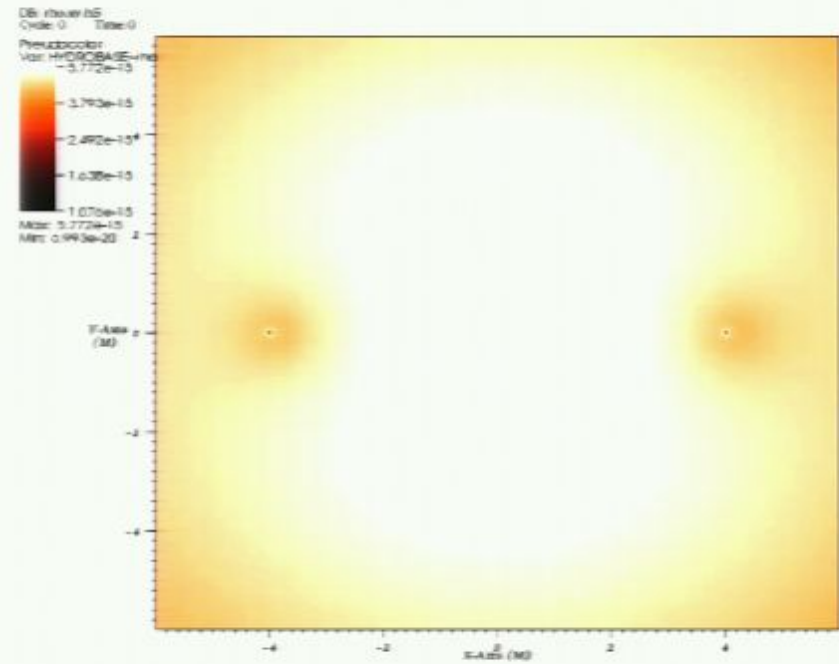


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

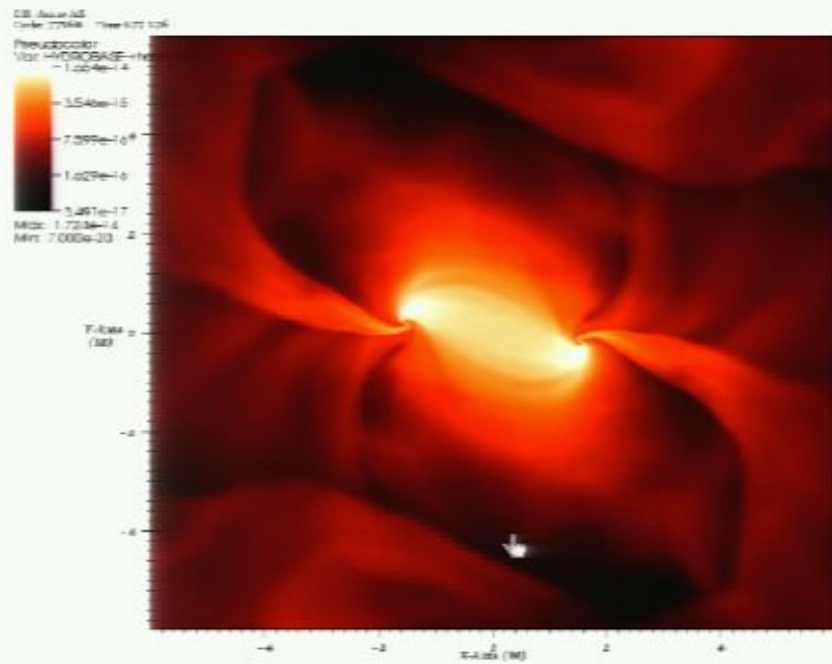


$$s_1/m^2 = s_2/m^2 = 0.6$$

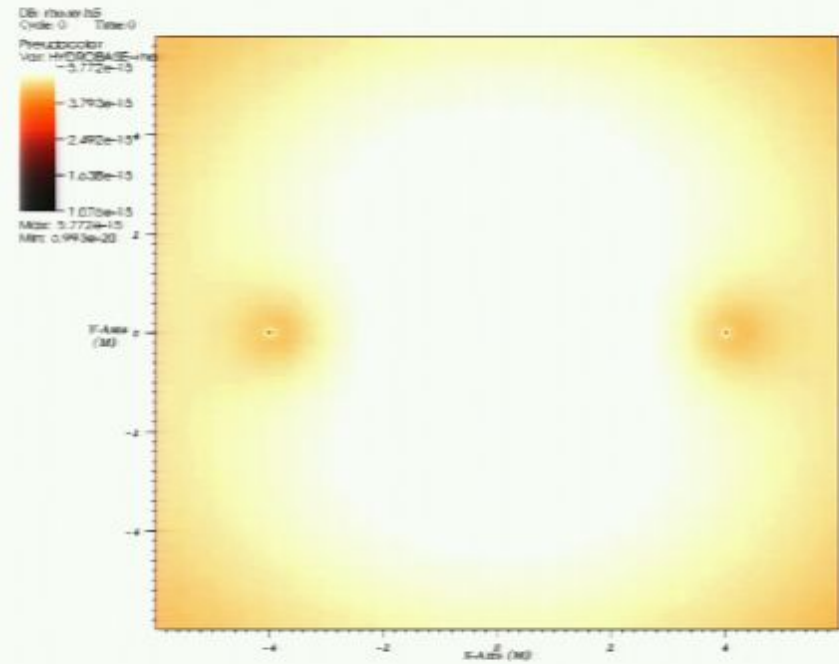


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

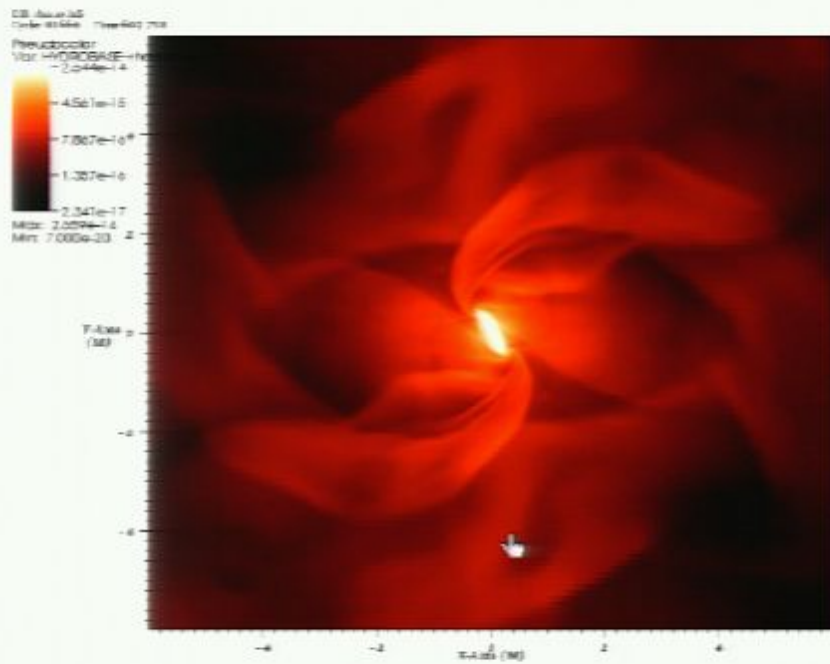


$$s_1/m^2 = s_2/m^2 = 0.6$$

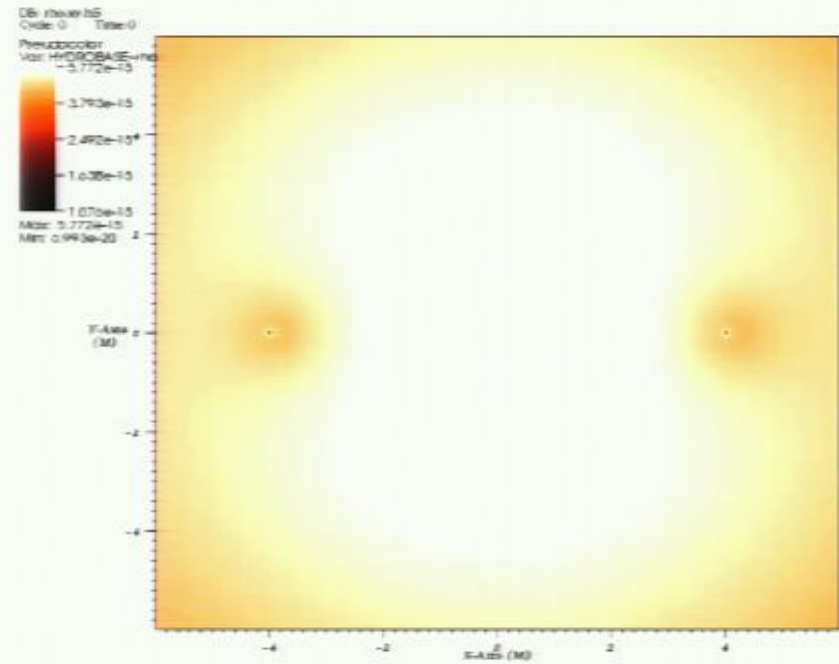


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

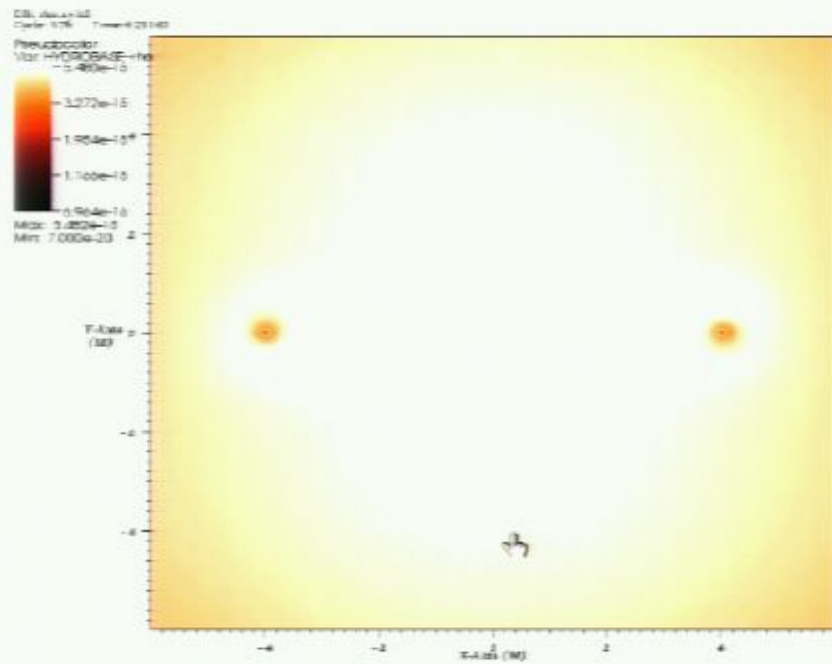


$$s_1/m^2 = s_2/m^2 = 0.6$$

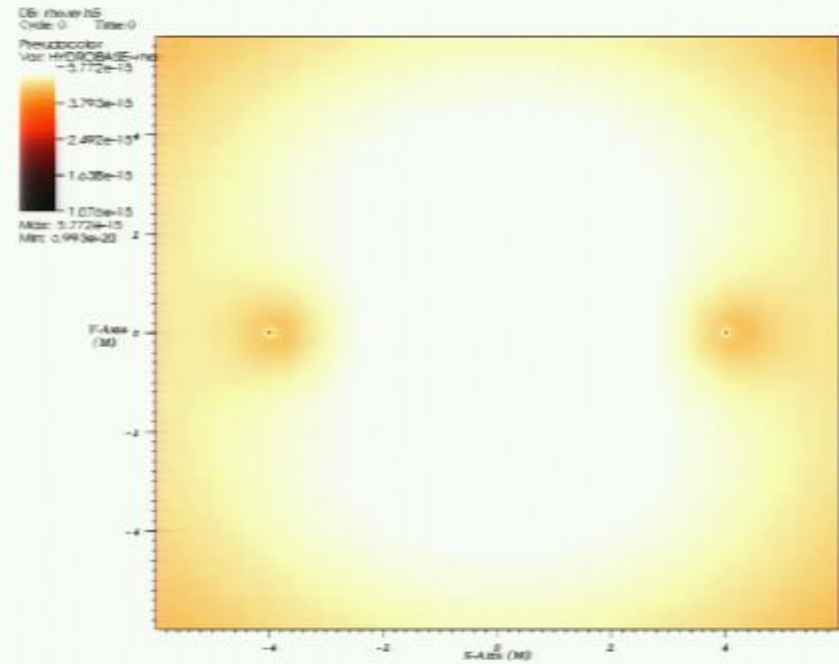


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

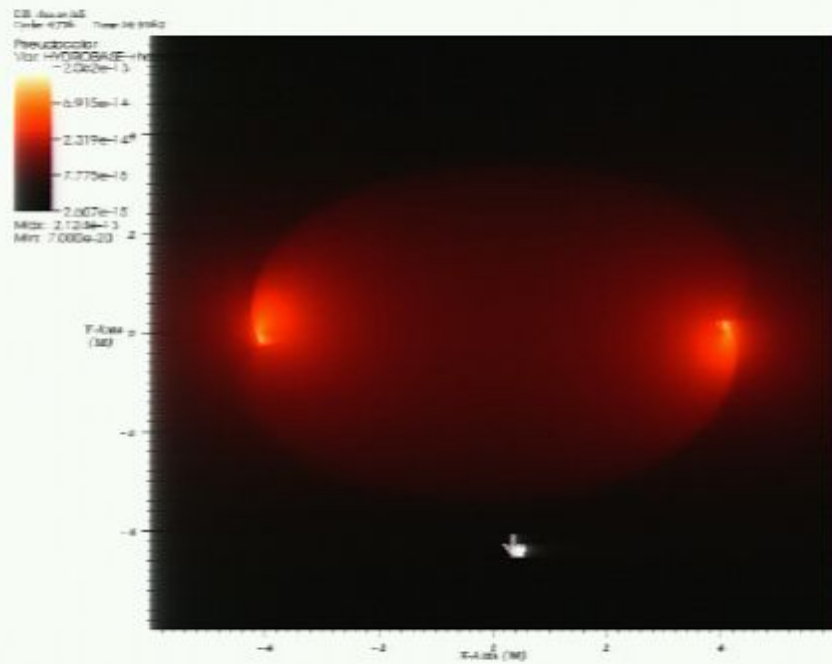


$$s_1/m^2 = s_2/m^2 = 0.6$$

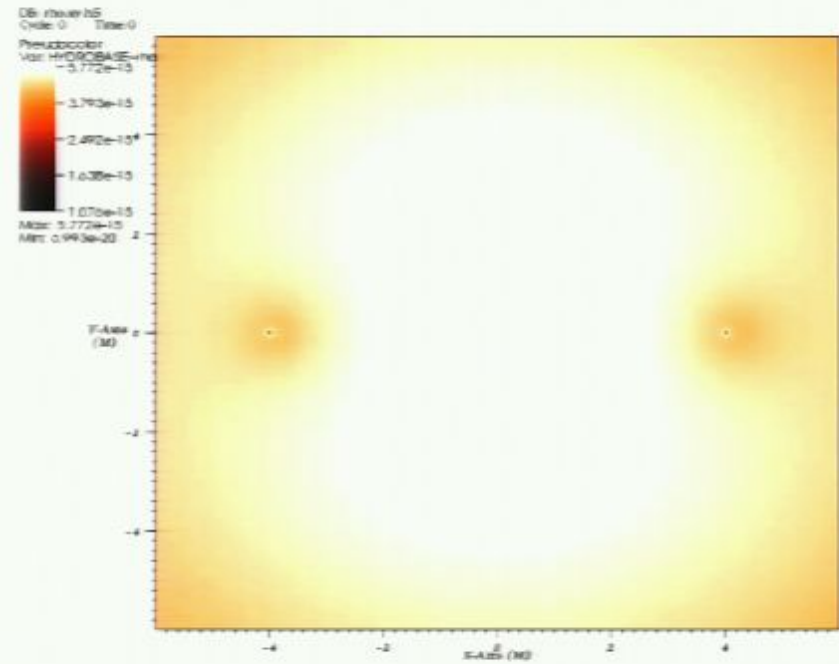


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

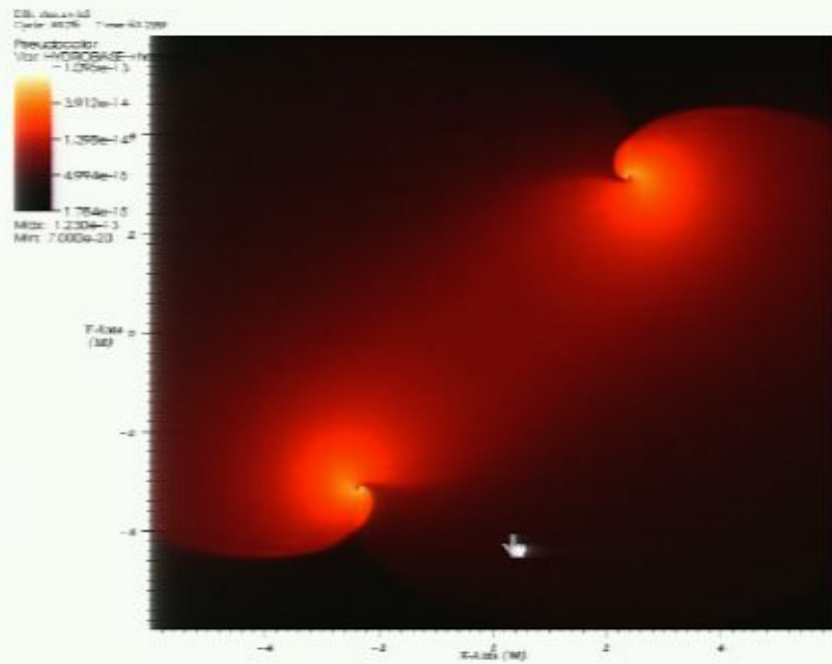


$$s_1/m^2 = s_2/m^2 = 0.6$$

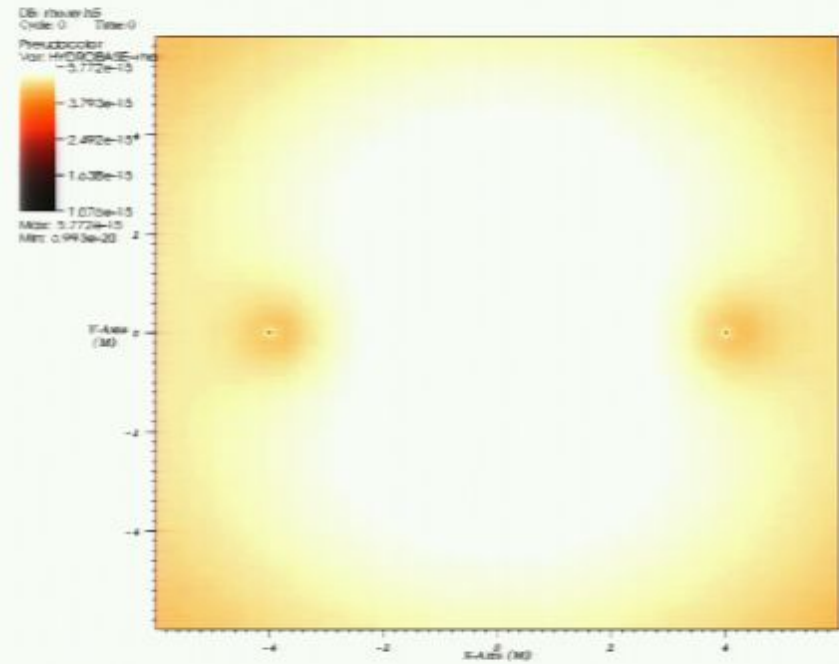


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

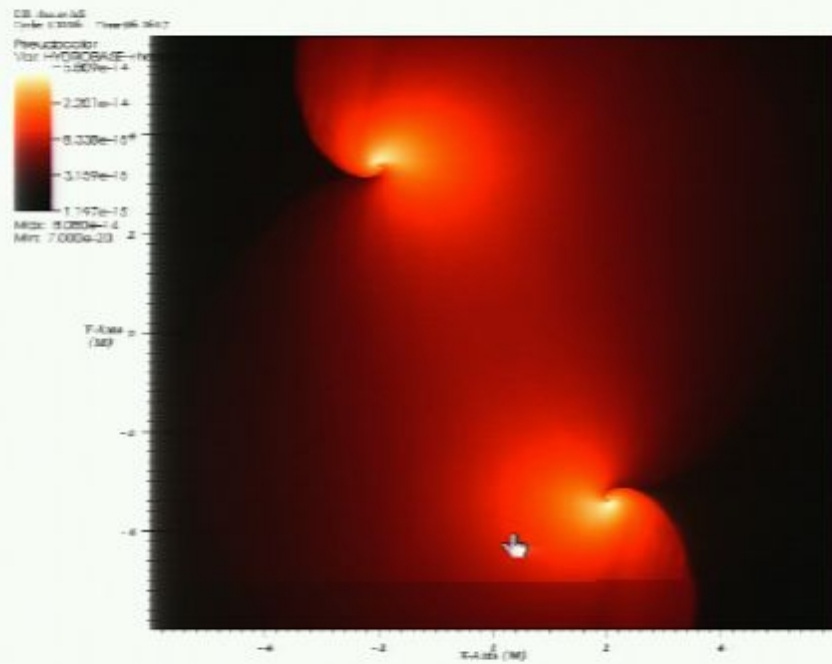


$$s_1/m^2 = s_2/m^2 = 0.6$$

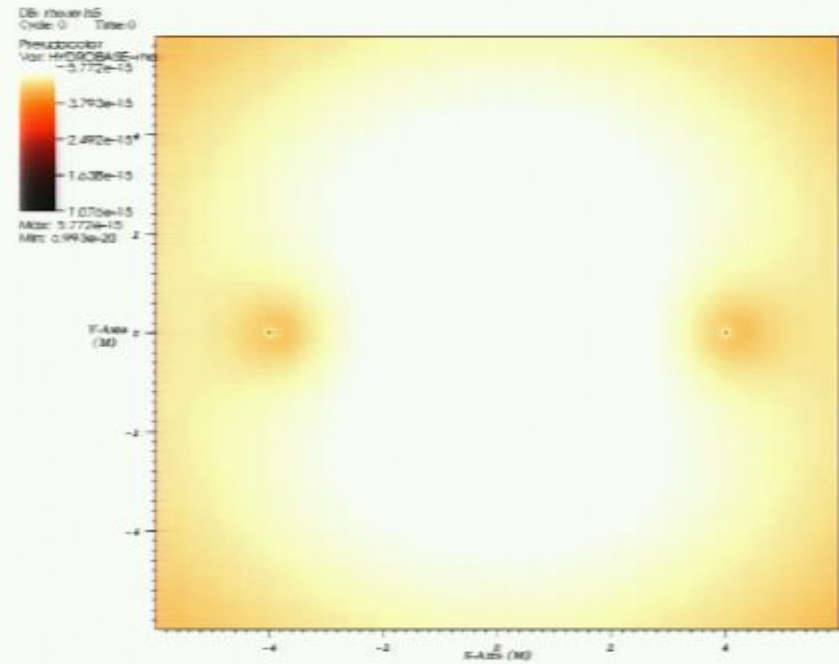


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

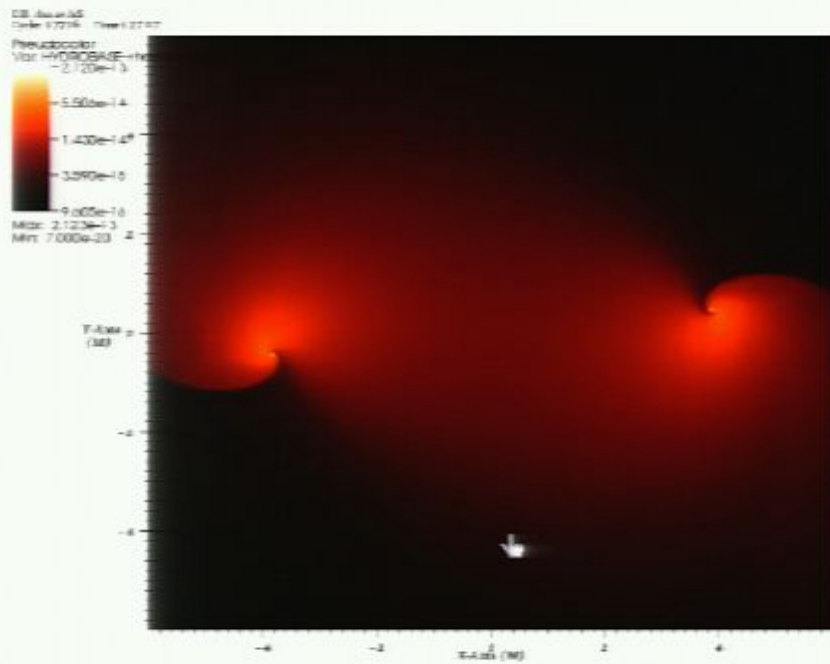


$$s_1/m^2 = s_2/m^2 = 0.6$$

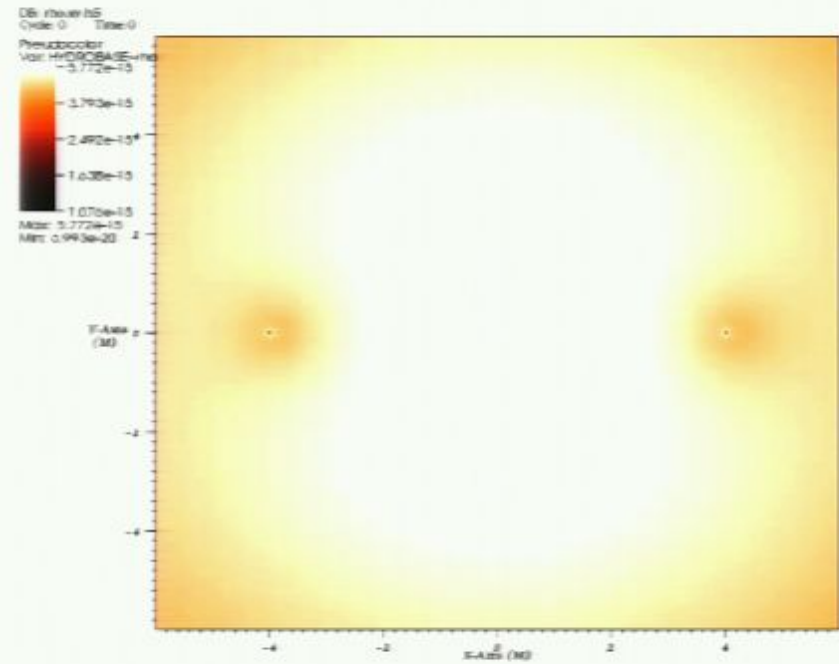


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

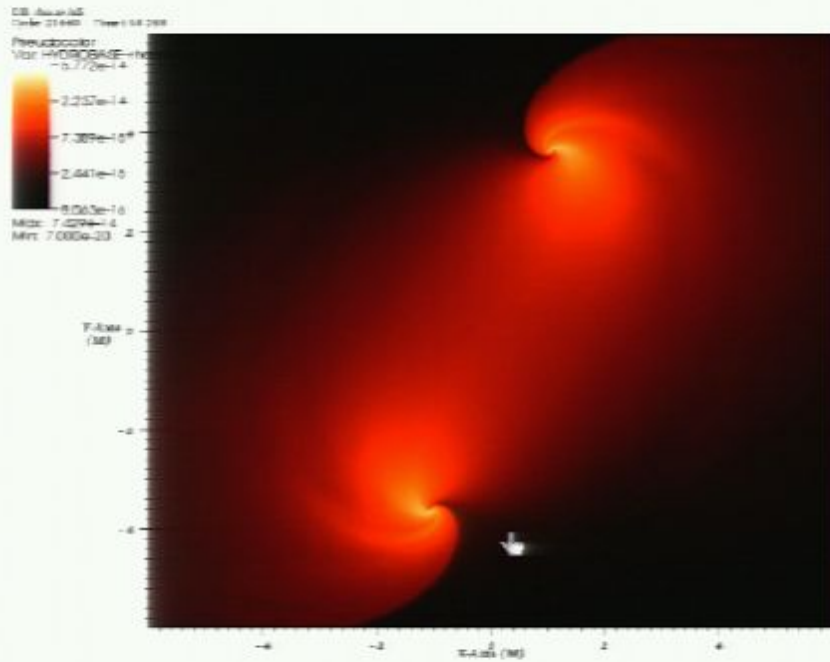


$$s_1/m^2 = s_2/m^2 = 0.6$$

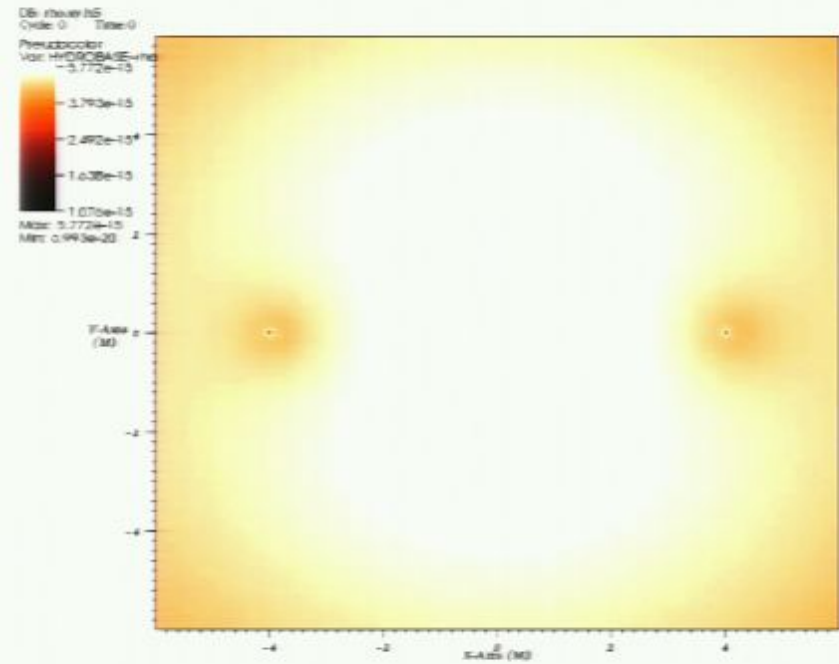


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

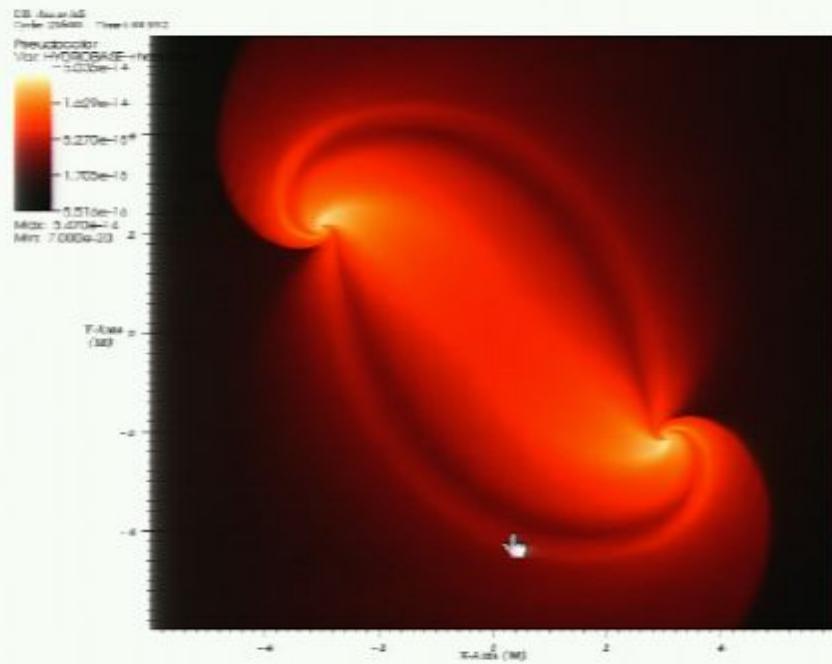


$$s_1/m^2 = s_2/m^2 = 0.6$$

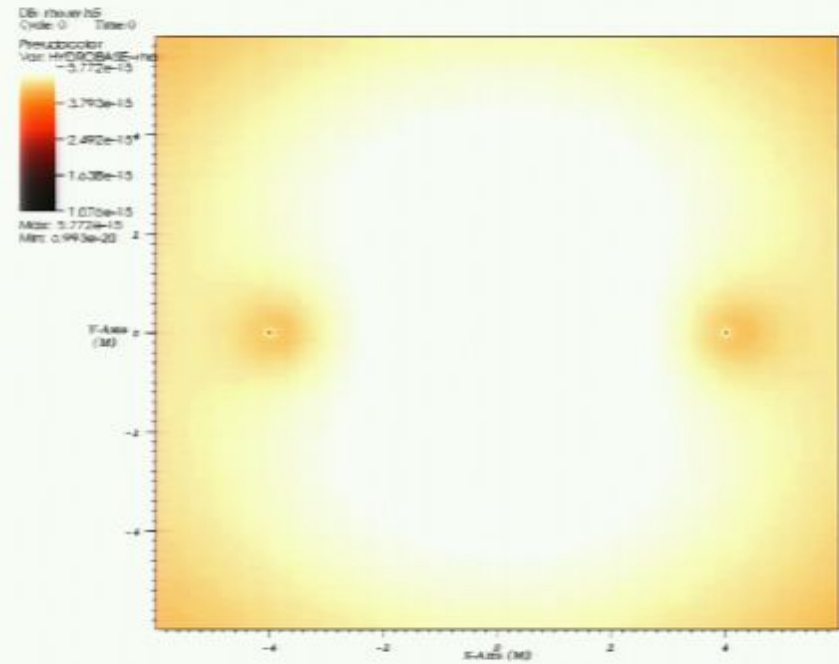


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

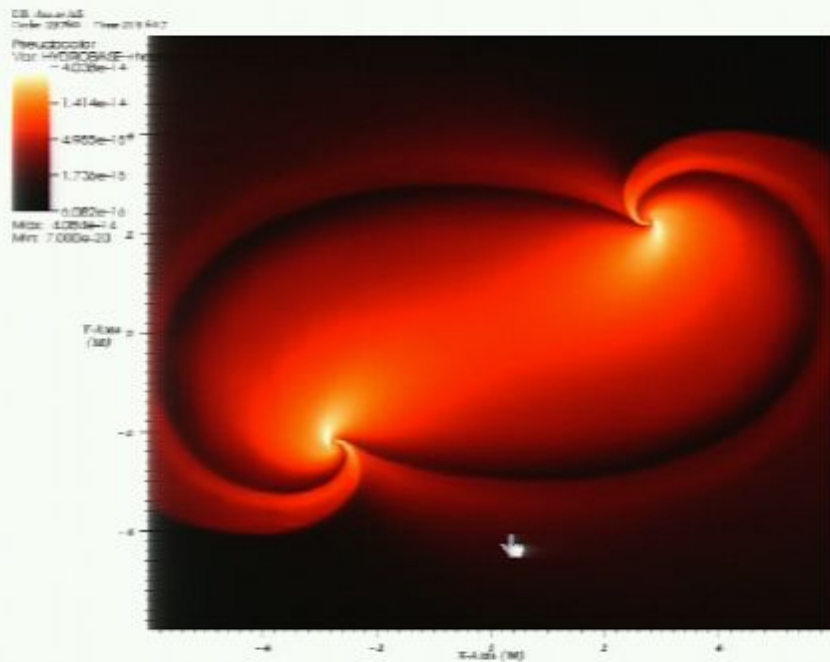


$$s_1/m^2 = s_2/m^2 = 0.6$$

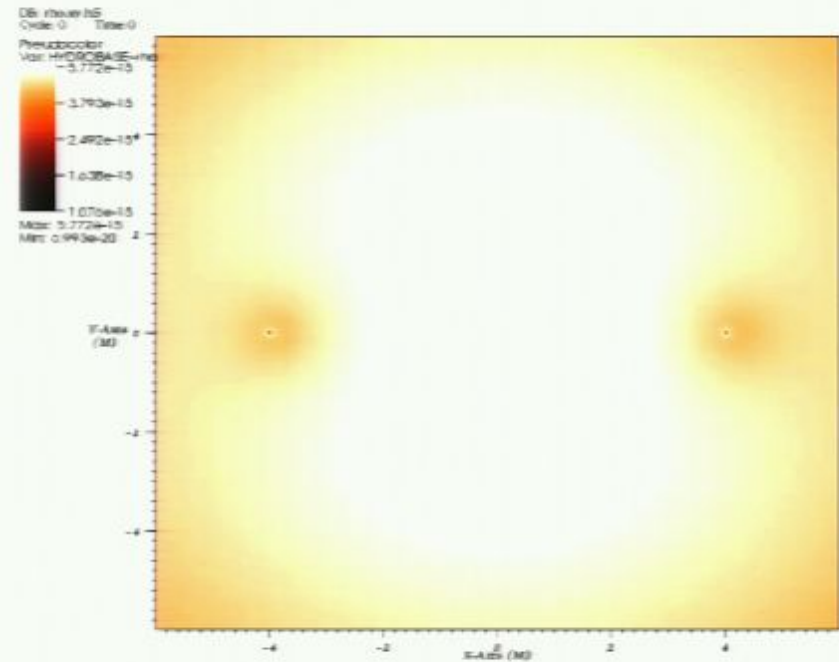


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

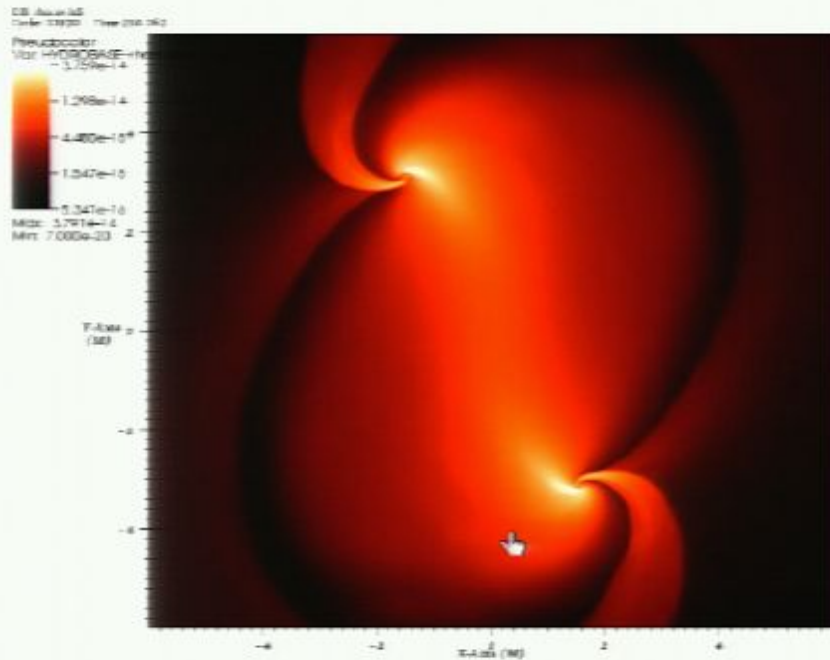


$$s_1/m^2 = s_2/m^2 = 0.6$$

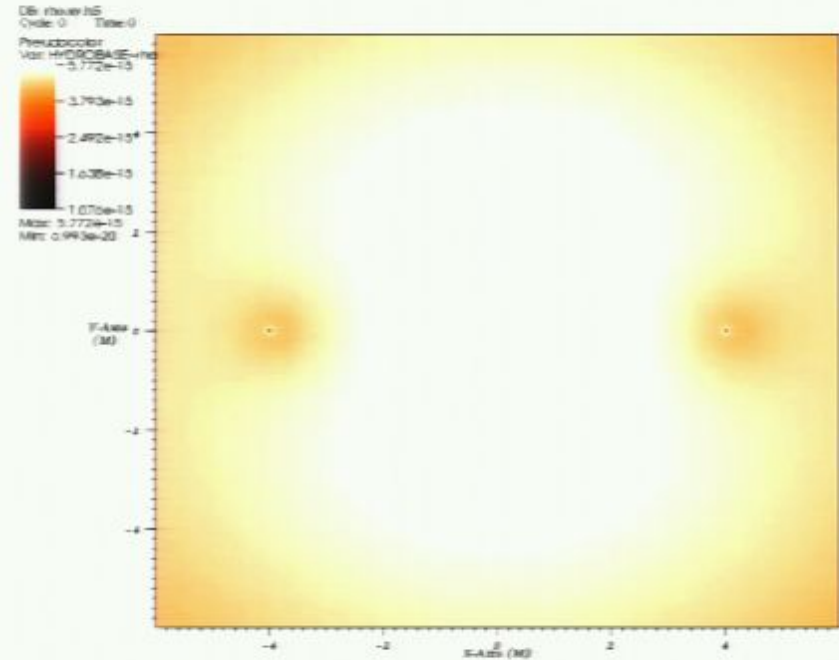


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

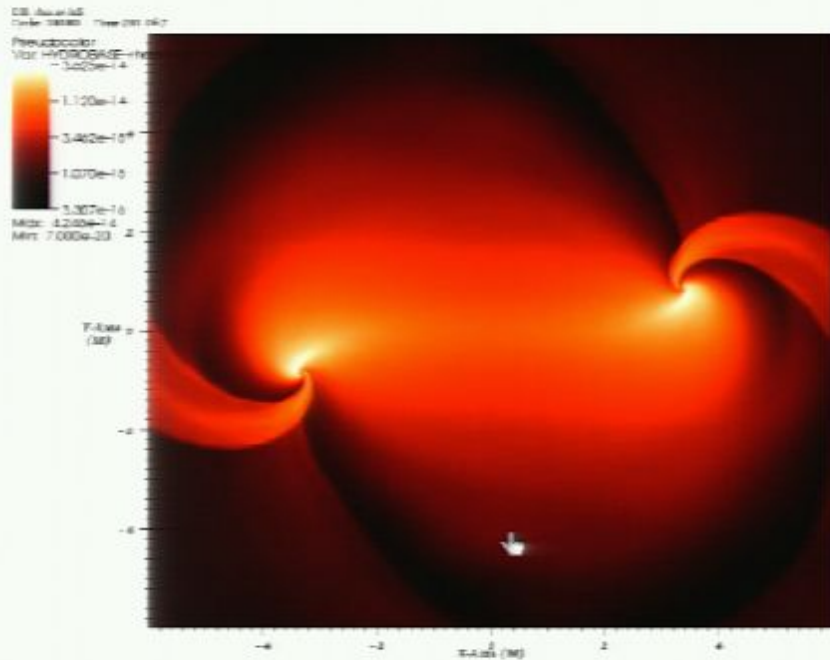


$$s_1/m^2 = s_2/m^2 = 0.6$$

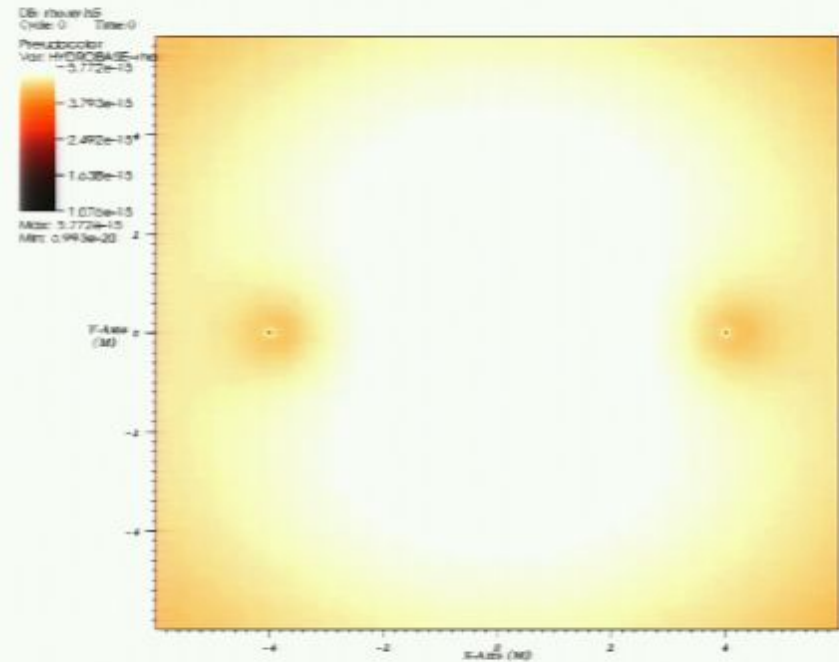


$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

Gas Density

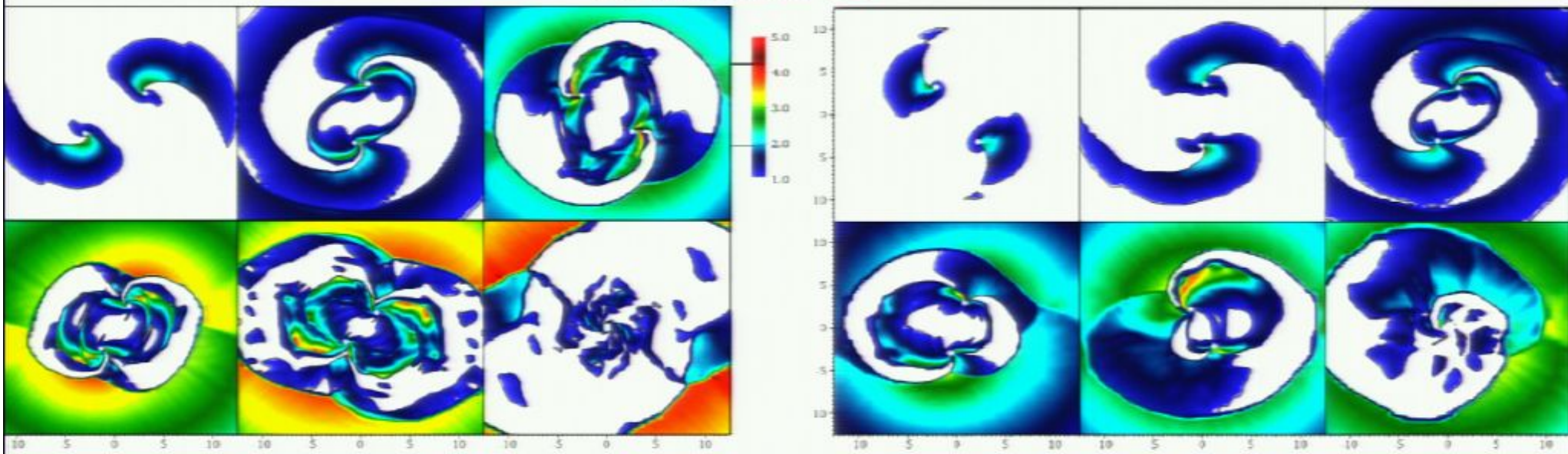


$$s_1/m^2 = s_2/m^2 = 0.6$$



$$s_1/m^2 = -0.4 \quad s_2/m^2 = 0.4$$

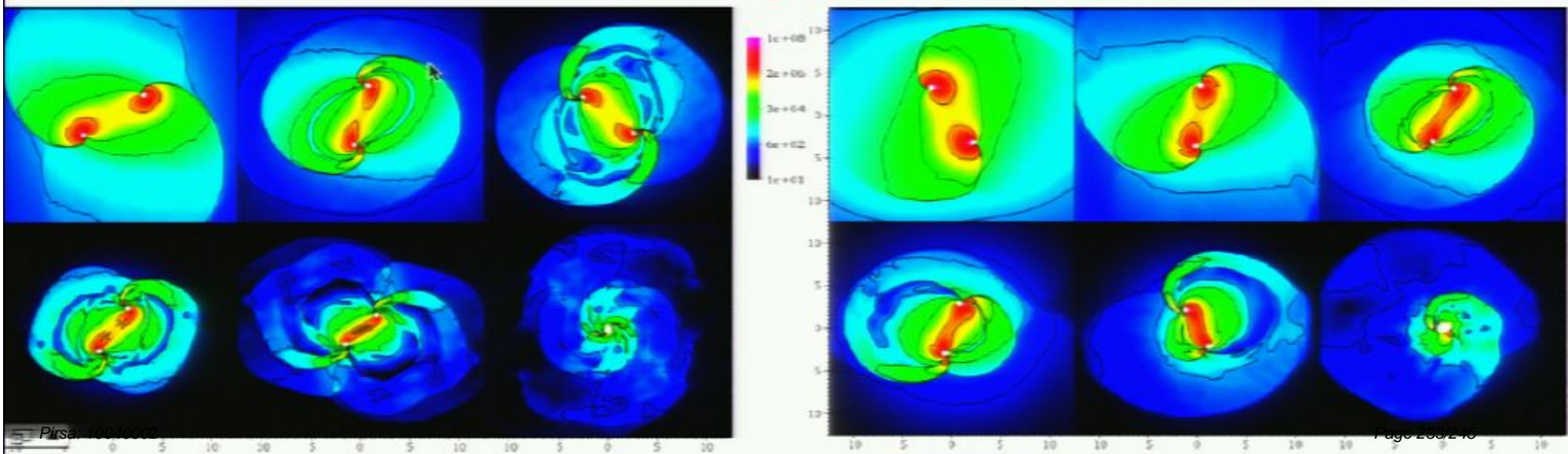
Mach number ≥ 1



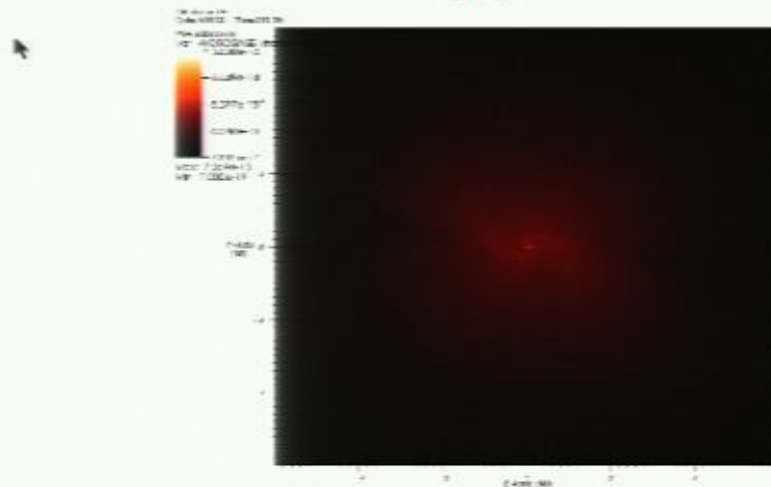
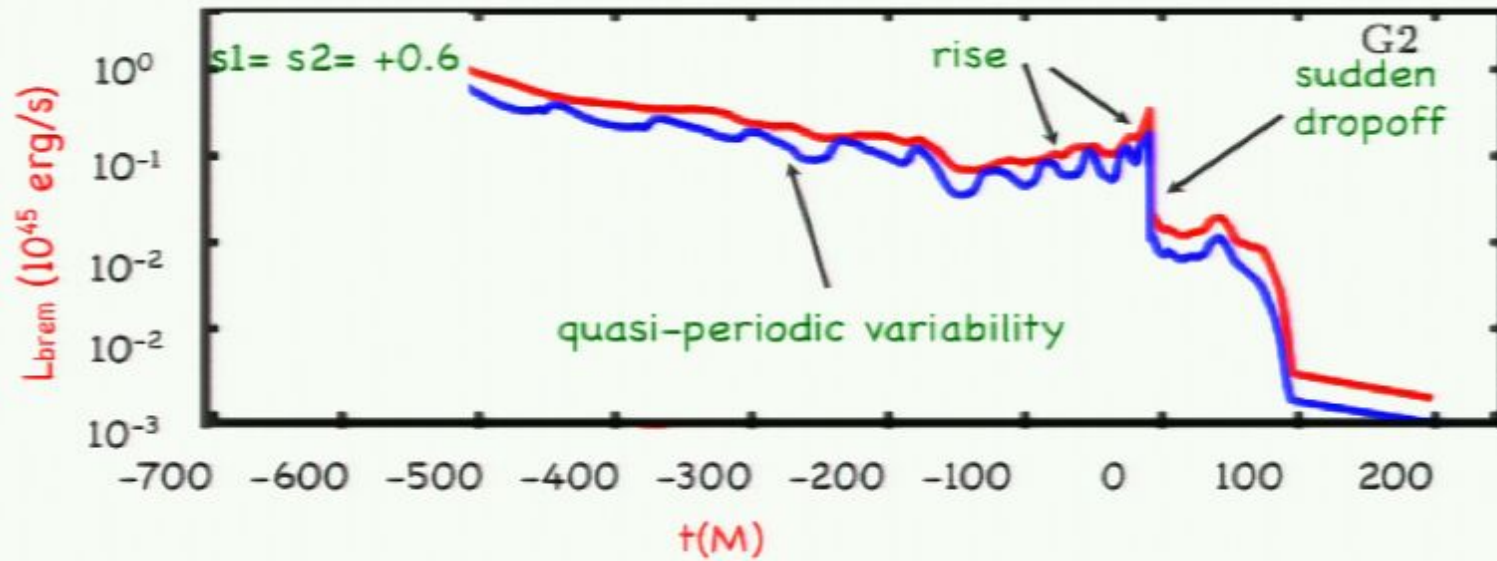
$s1 = s2 = +0.6$

Bremsstrahlung emission

$s1 = +0.4$ $s2 = -0.4$

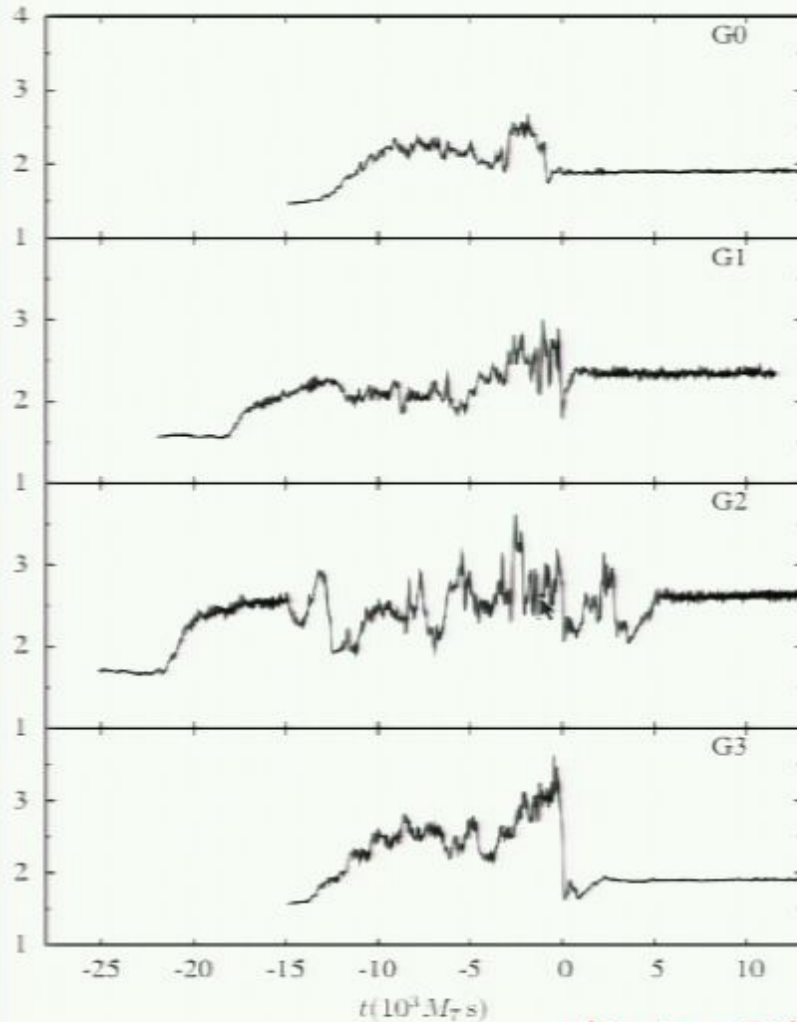


Bremsstrahlung luminosity



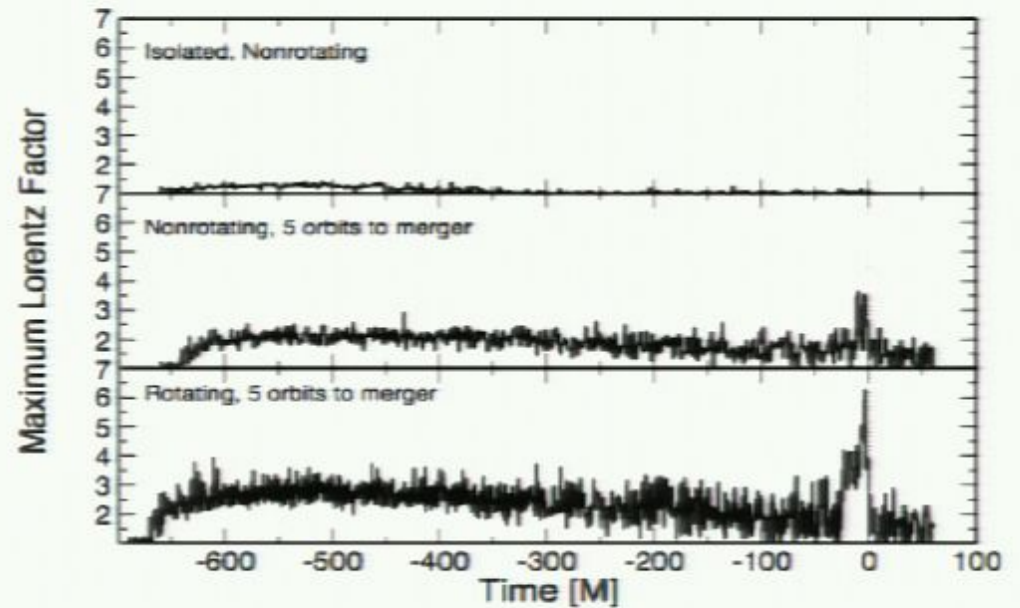
Maximum Lorenz Factor

max(Lorenz Factor)



(Bode+ 09)

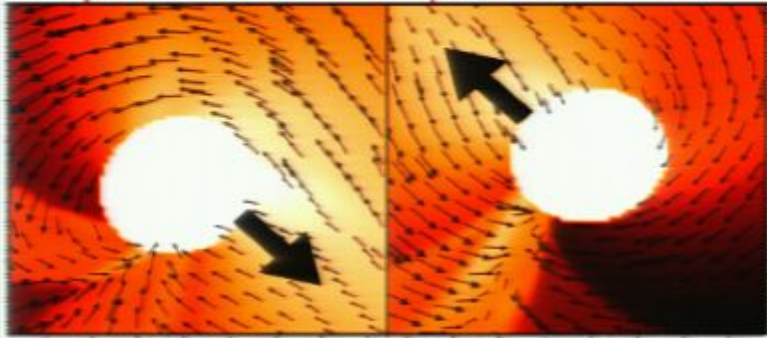
runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4



Accretion onto the BHs

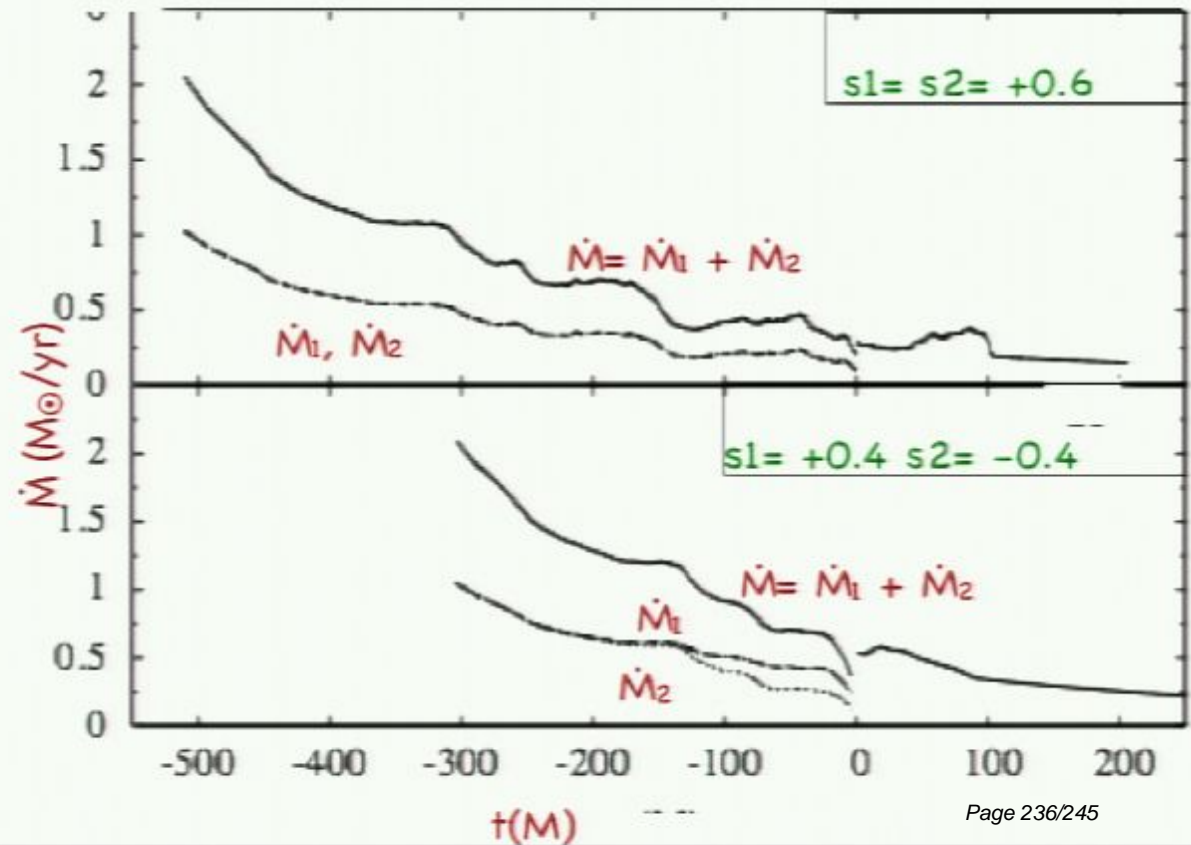
parallel
spin

anti-parallel
spin

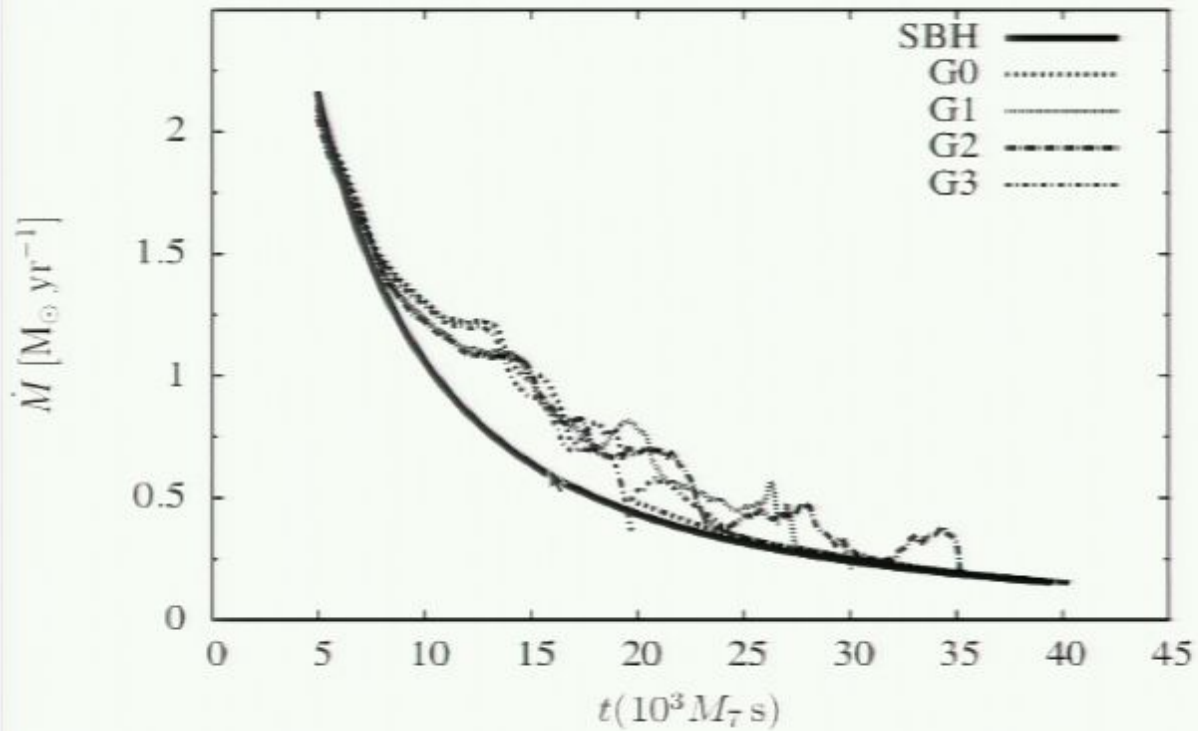


(Bode+ 09)

$$\dot{M}_B \approx 0.84 M_\odot \text{ yr}^{-1} \left(\frac{c_s}{0.3c} \right)^{-3} \left(\frac{\rho}{10^{-11} \text{ g cm}^{-3}} \right) M_7^2$$



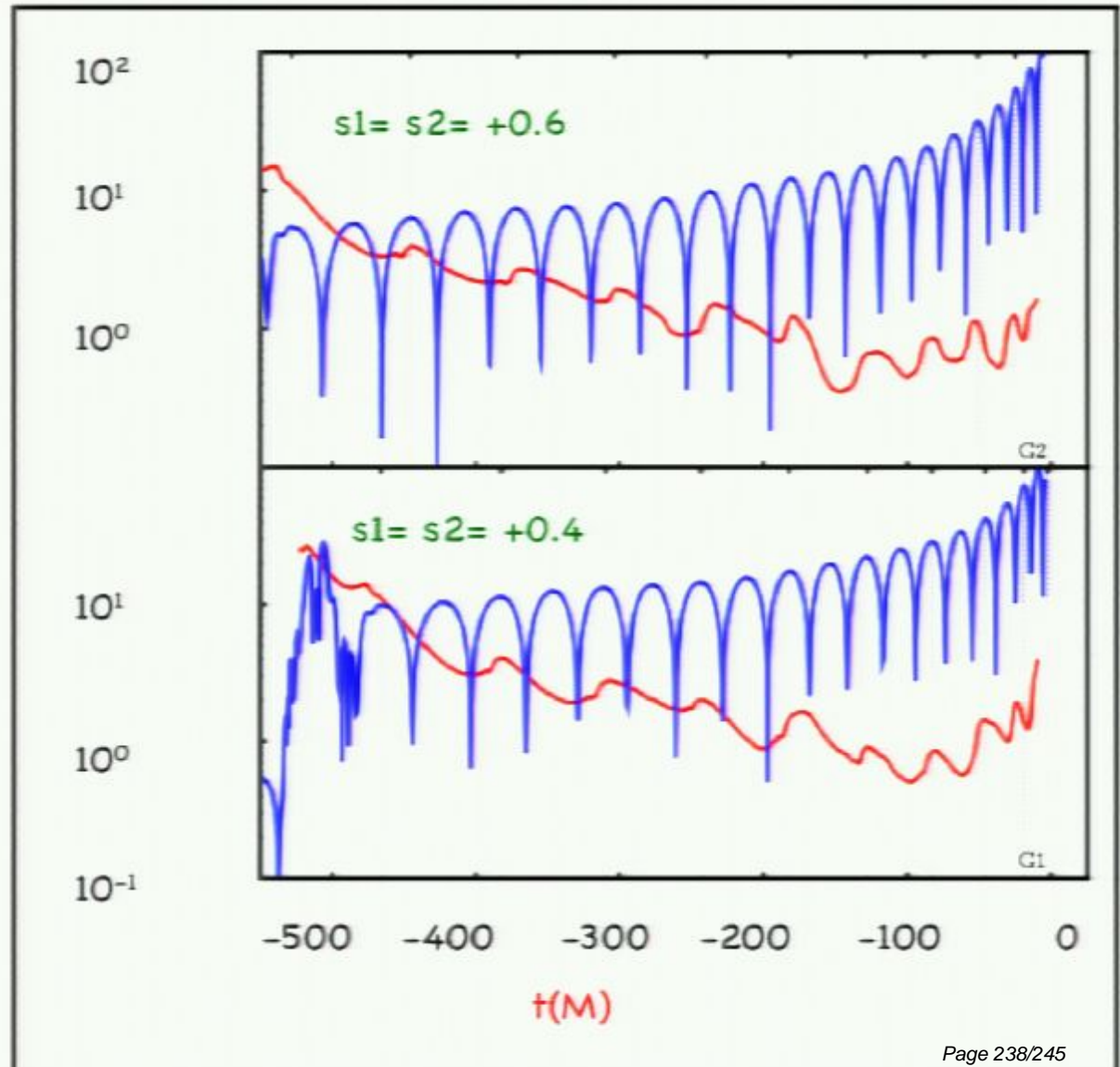
Single BH Test



runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4

EM & GW emission

- Correlated variability can occur due to the effect of relativistic beaming and boosting
- Other characteristic features: rise and sudden drop off of luminosity
- Emission from most massive LISA binaries observable to $z=1$.

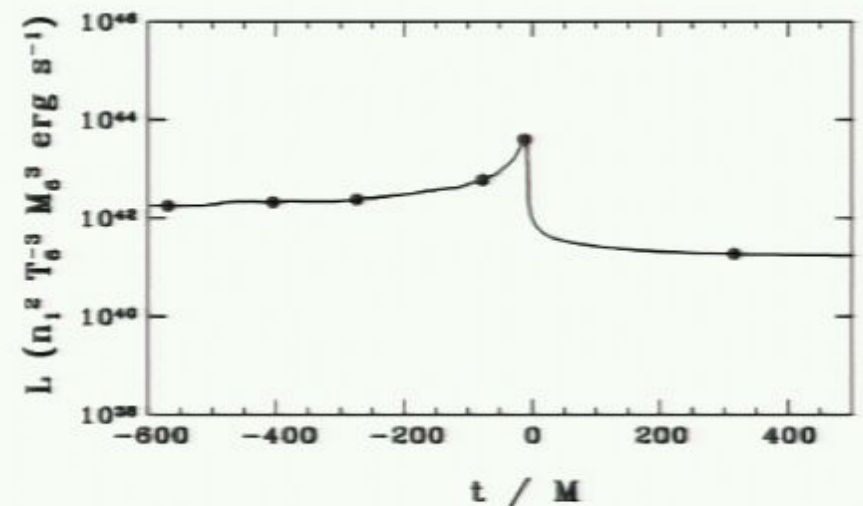
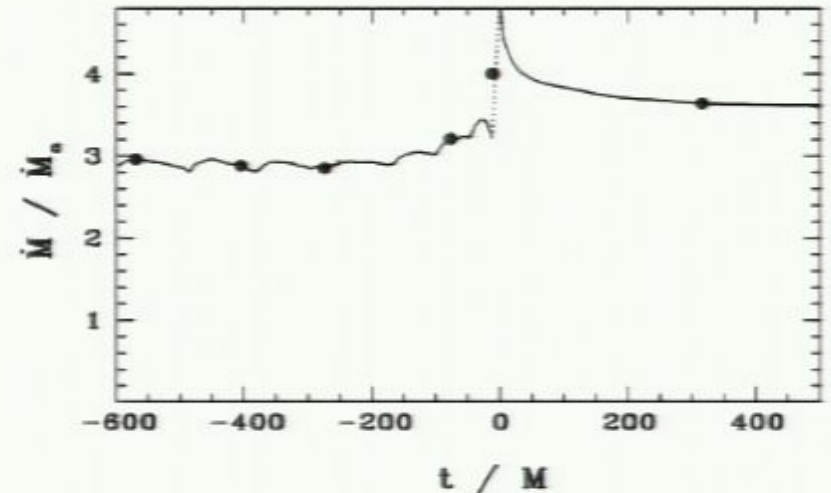


SMBH Mergers in Gaseous Environments

Binary Black Hole Mergers in Gaseous Environments: "Binary Bondi" and "Binary Bondi-Hoyle-Lyttleton" Accretion

Farris, Liu, Shapiro
arXiv:0912.2096

Conclusion: Luminosity should be detectable by LSST for a $10^6 M_{\text{sun}}$ binary in a hot gas cloud of density $n \sim 10^{11} \text{ cm}^{-3}$ and temperature $T \sim 10^6 \text{ K}$ at $z = 1$, reaching a maximum of $L \sim 3 \times 10^{43} \text{ erg s}^{-1}$, with the emission peaking in the visible band.



Conclusions and Prospects

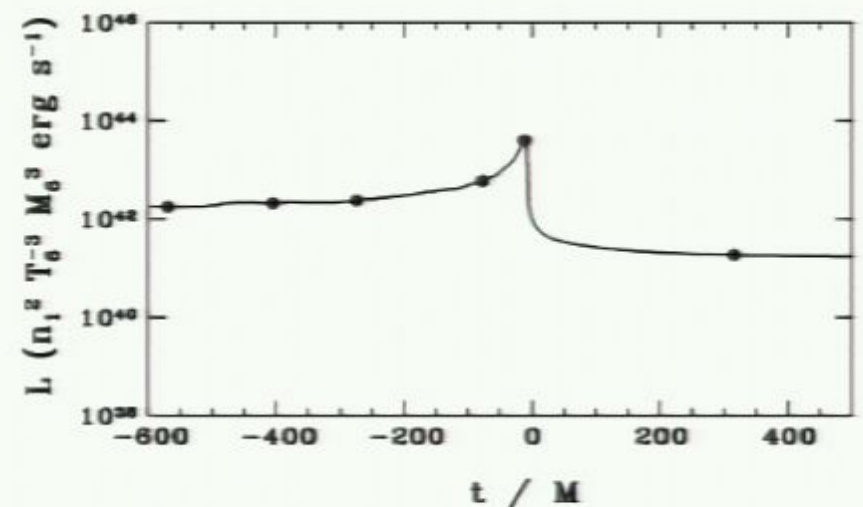
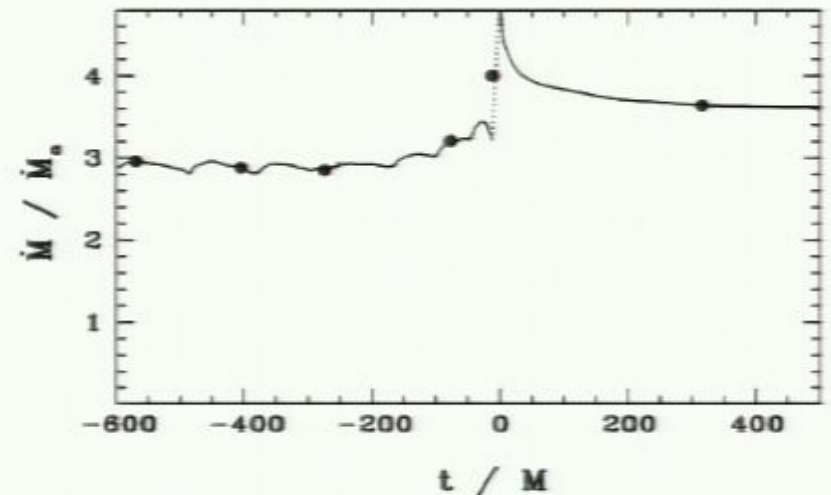
- Binary immersed in hot and turbulent gas cloud with properties similar to accretion flows in low luminosity AGN.
- Correlated variability EM-GW and characteristic features in the EM light can provide convincing evidence for an impending SBH merger.
- Most massive LISA binaries will be EM visible out to $z=1$ while lower mass systems and gas poor systems may be visible only in the local universe.
- These are prototype simulations. More follow-up work is needed in order to explore more astrophysically plausible configurations.
- Steps ahead: GRMHD, cooling, circumbinary ?

SMBH Mergers in Gaseous Environments

Binary Black Hole Mergers in Gaseous Environments: "Binary Bondi" and "Binary Bondi-Hoyle-Lyttleton" Accretion

Farris, Liu, Shapiro
arXiv:0912.2096

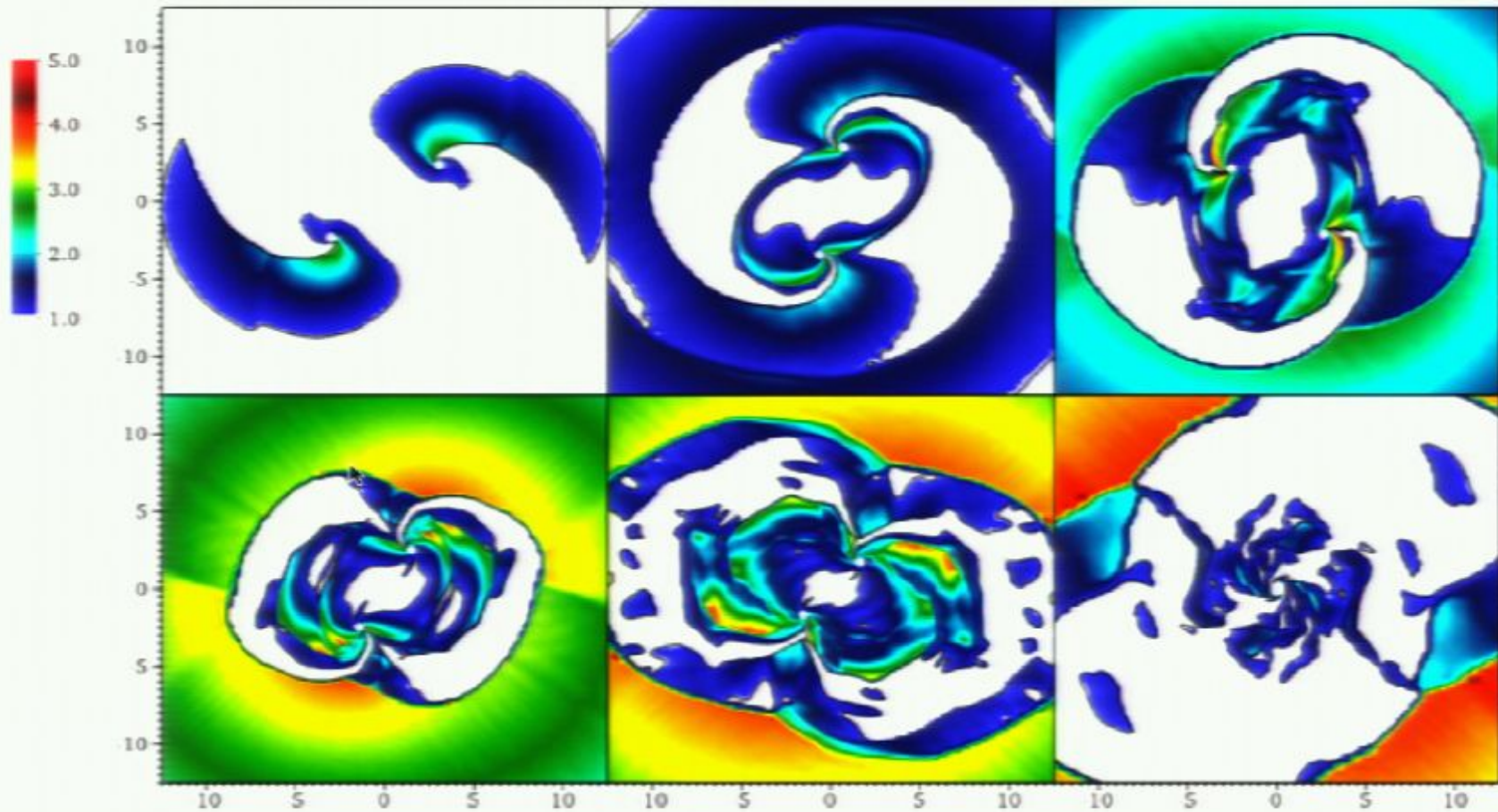
Conclusion: Luminosity should be detectable by LSST for a $10^6 M_{\text{sun}}$ binary in a hot gas cloud of density $n \sim 10^{11} \text{ cm}^{-3}$ and temperature $T \sim 10^6 \text{ K}$ at $z = 1$, reaching a maximum of $L \sim 3 \times 10^{43} \text{ erg s}^{-1}$, with the emission peaking in the visible band.



Shocks triggered by the orbiting BHs

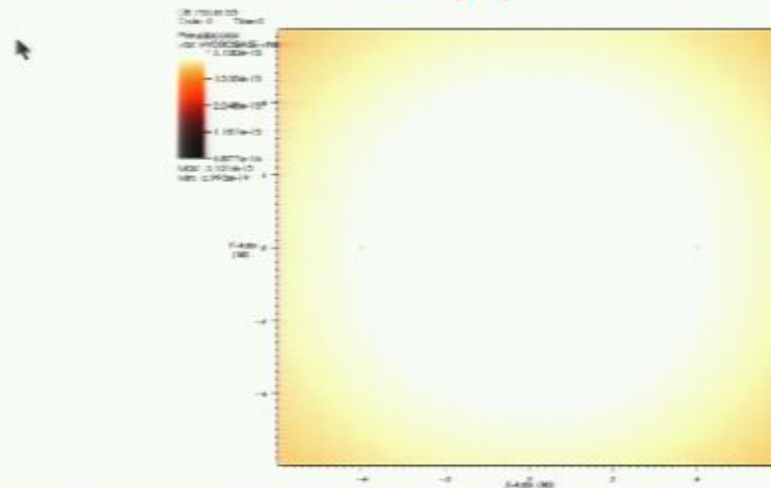
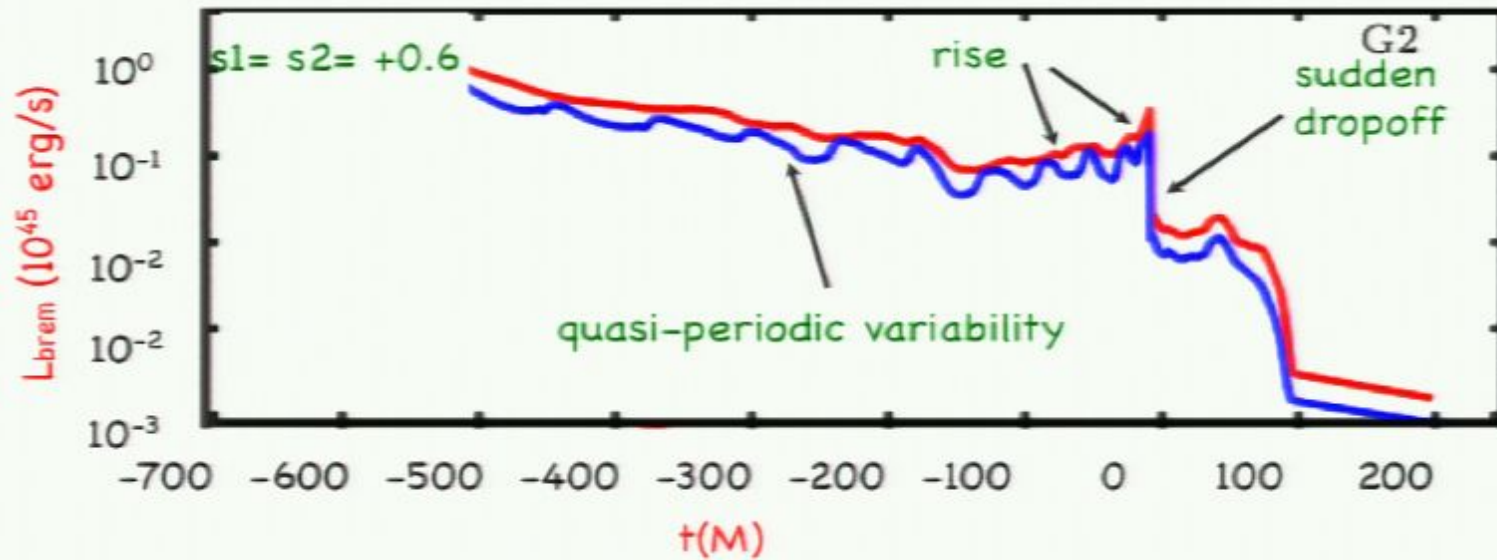
Mach number > 1

$s_1 = s_2 = +0.6$

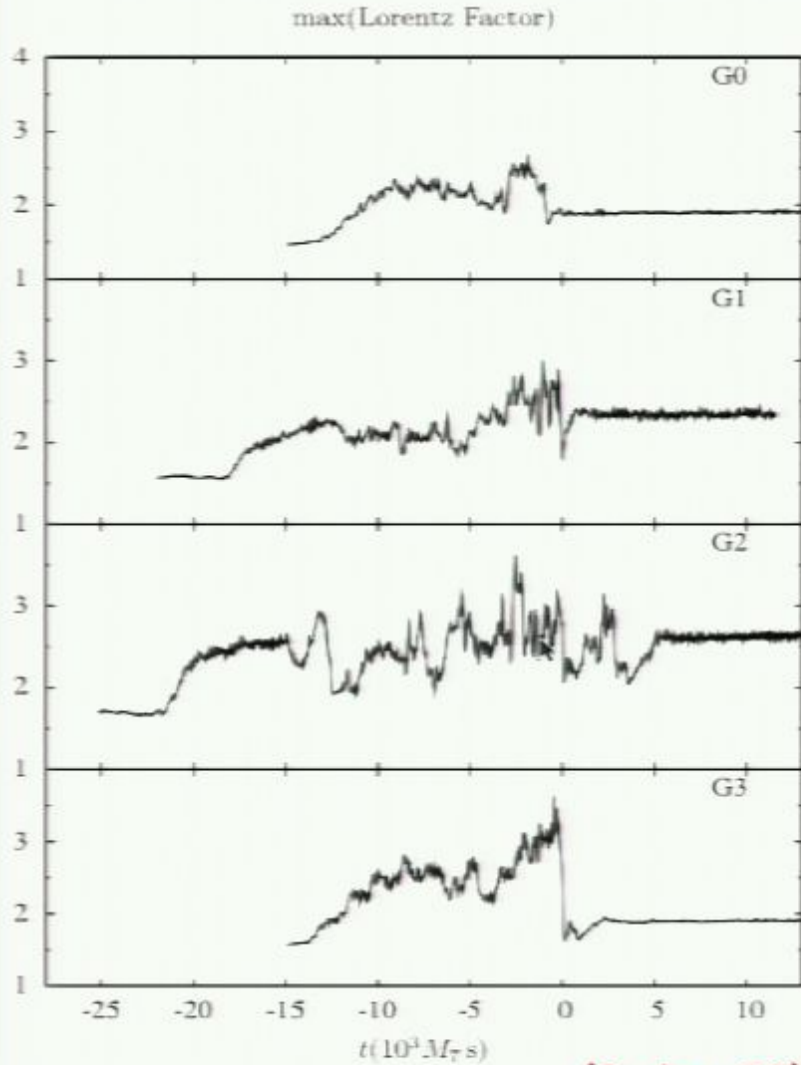


(Bode+ 09)

Bremsstrahlung luminosity

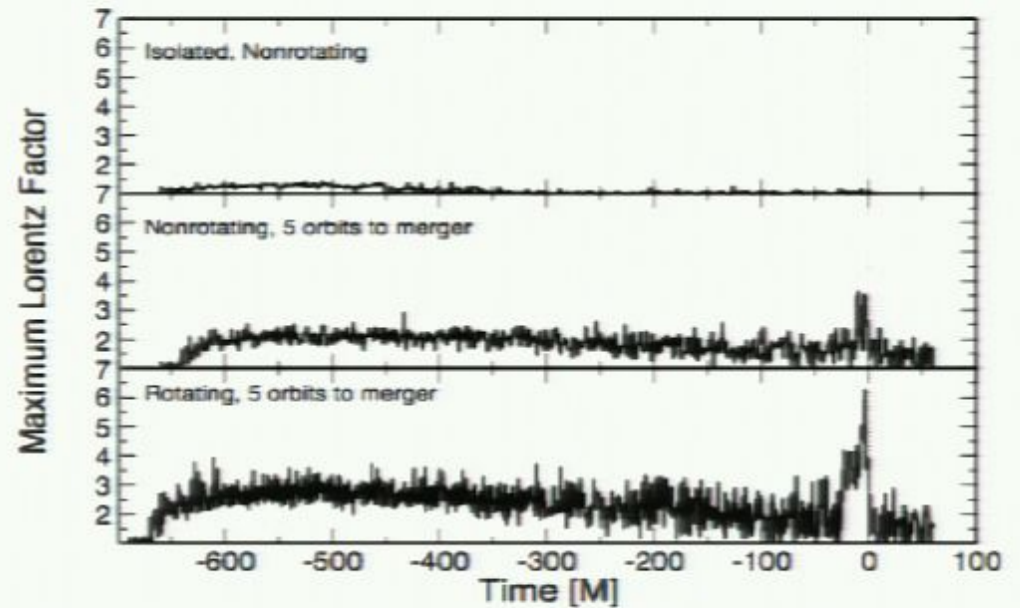


Maximum Lorentz Factor



(Bode+ 09)

runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4



Formatting Palette

Font: Name: Size: Bold Italic Underline Text Color Background Color

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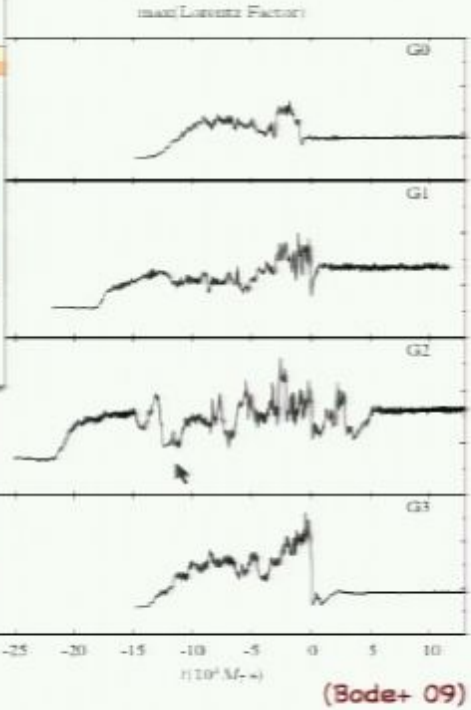
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LightShows.pptx

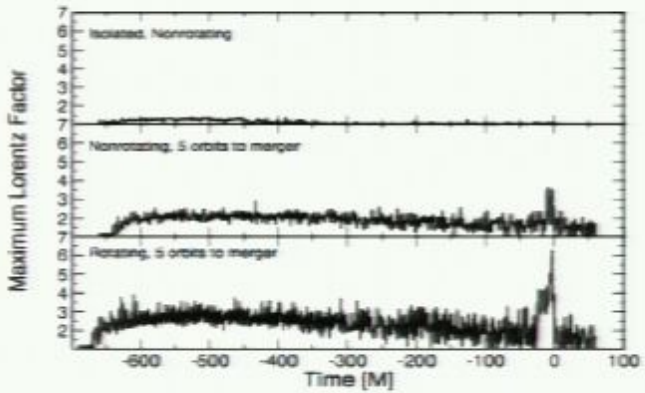
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Maximum Lorenz Factor



runs	S1	S2
G0	0	0
G1	+0.4	+0.4
G2	+0.6	+0.6
G3	+0.4	-0.4



Van Meter et al arxiv:0908.0023

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