Title: Compact Binaries, Disks, and Magnetic Fields

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Abstract:

Compact Binaries, Disks and Magnetic Fields

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MICRA 2011 - Perimeter Institute

Learning to Crawl

- Sources of gravitational waves
  - Compact object binaries (BH-BH, BH-NS, NS-NS)
  - Neutron stars, supernovae, etc.
- Bulk motion of material
- Einstein eqs.---not easy at first, so
- Simple models (vacuum or ideal fluids with simple EOS)

LIGO

Learning to Crawl

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  - Compact object binaries (BH-BH, BH-NS, NS-NS)
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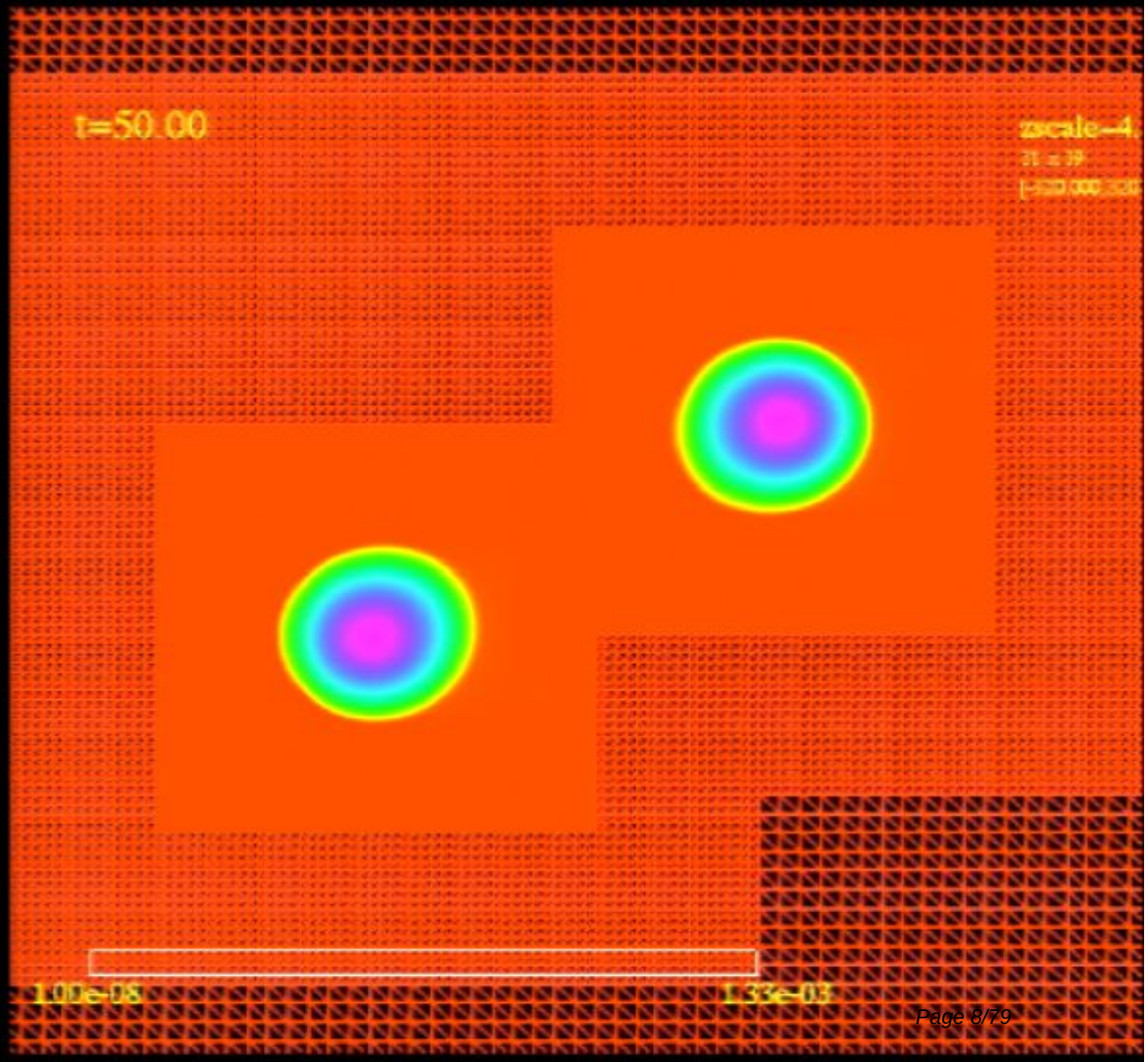
Learning to Stand

- Sources of GWs also strong sources of
  - E&M radiation (Palenzuela)
  - Neutrinos
- Multi-messenger astronomy (O'Shaughnessy)
- Improve physical models
  - EOS (Read & others)
  - (...lots to do...)
- Where we have been, and where to go.

Binary Neutron Stars

HAD

- Berger-Oliger AMR (refine both space & time)
- Truncation error based refinement using shadow hierarchy
- Tapering refinement boundary condition
- FD and FV discretizations
- MPI, strong scaling...



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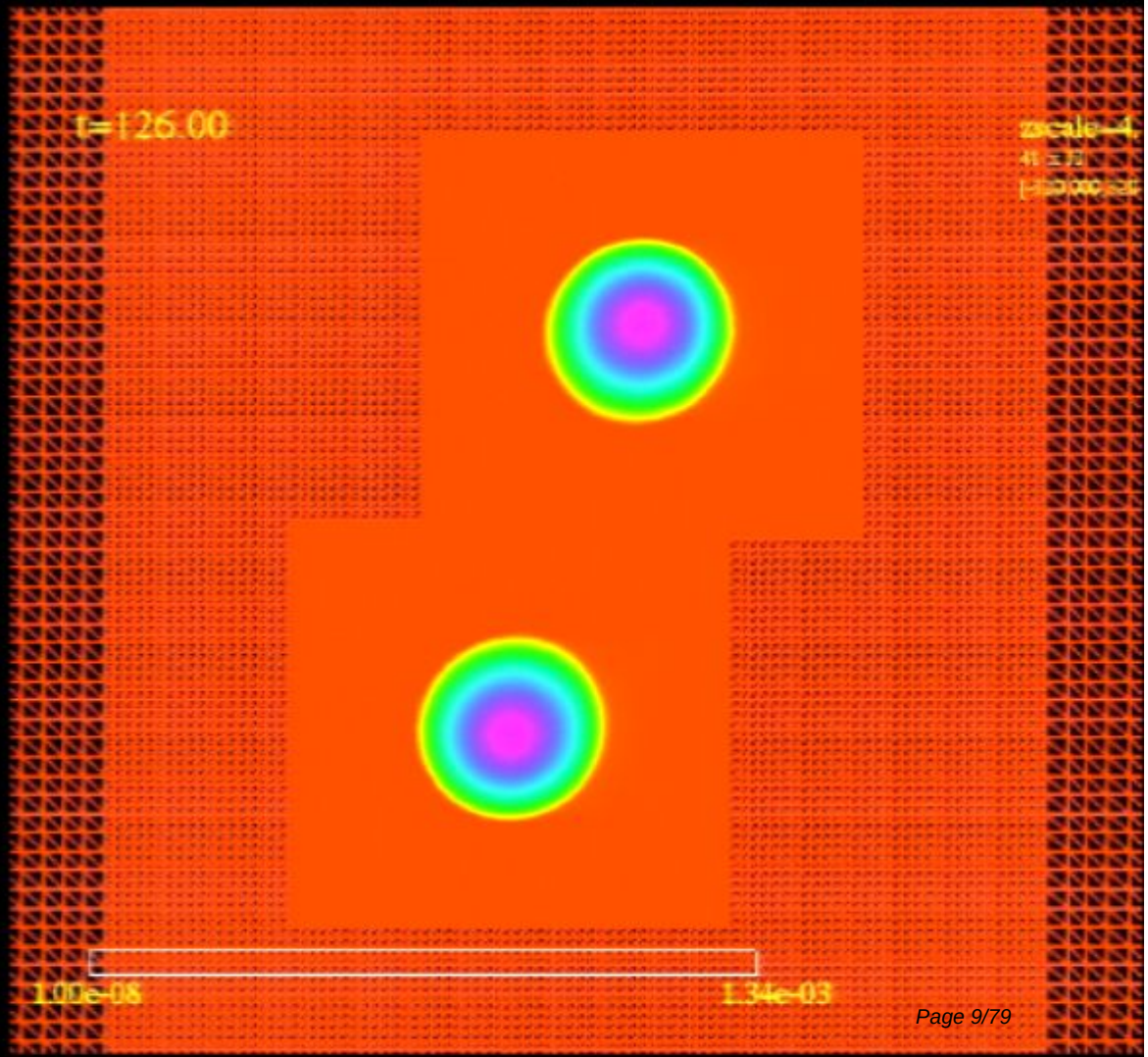

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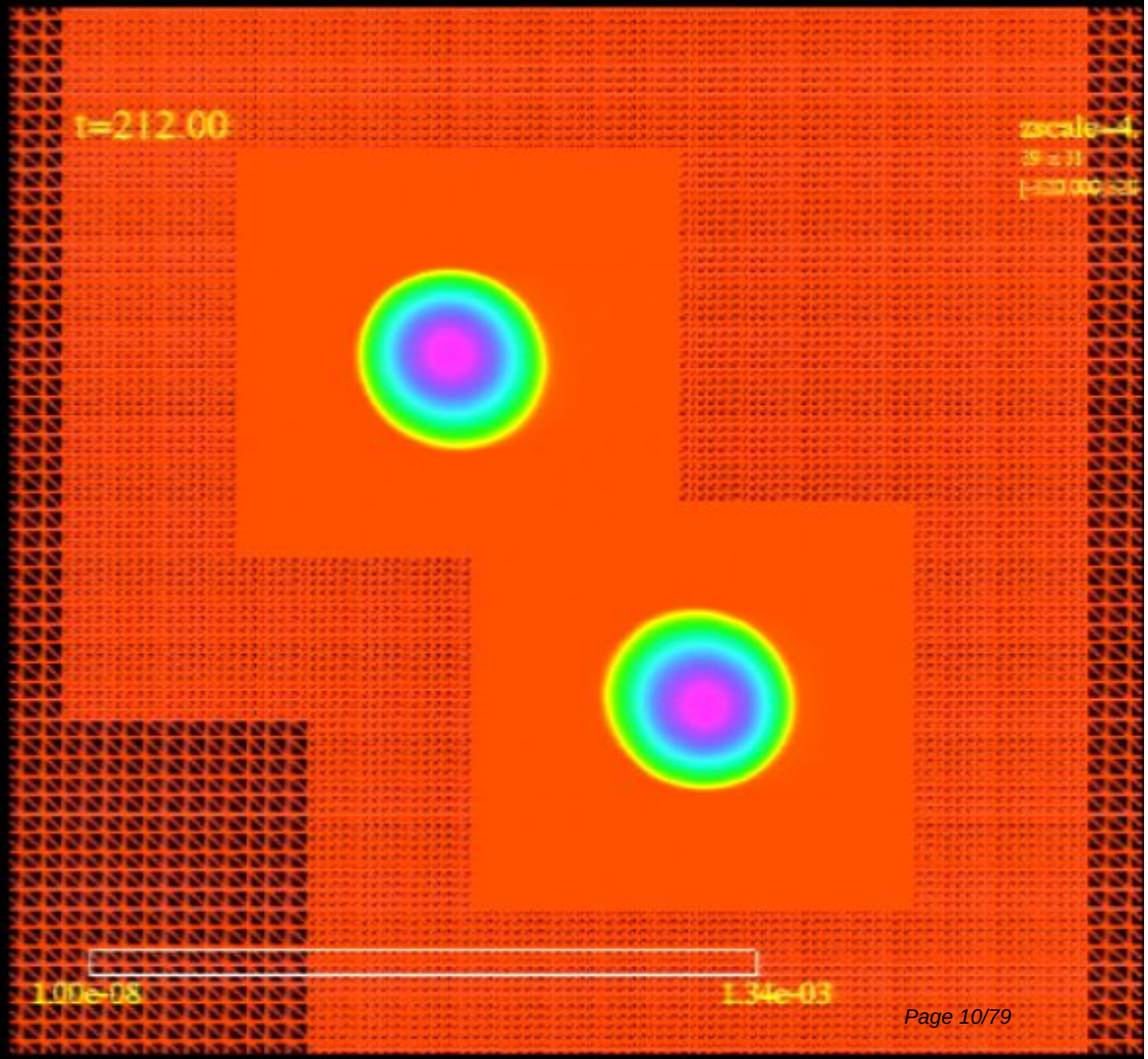

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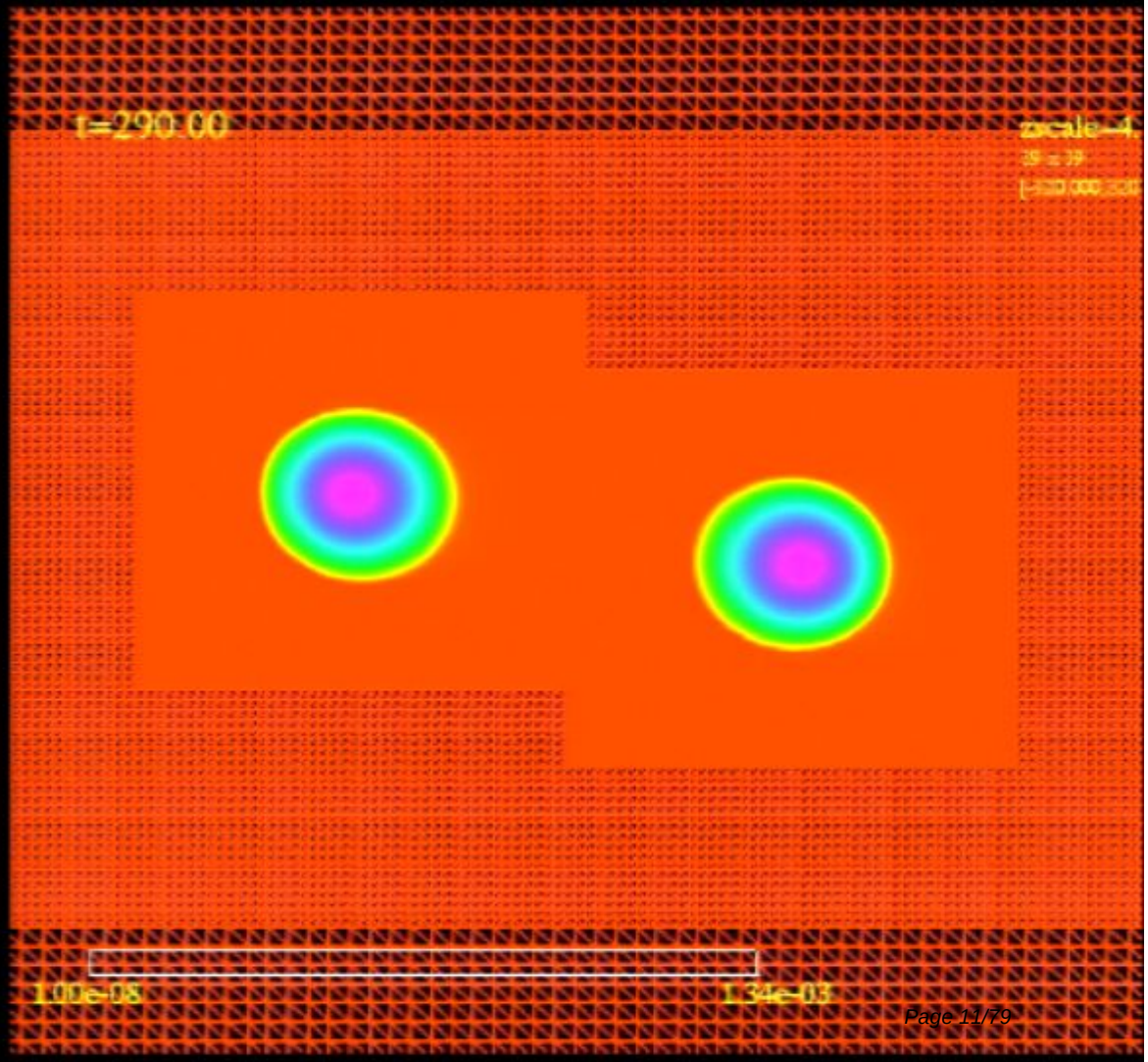

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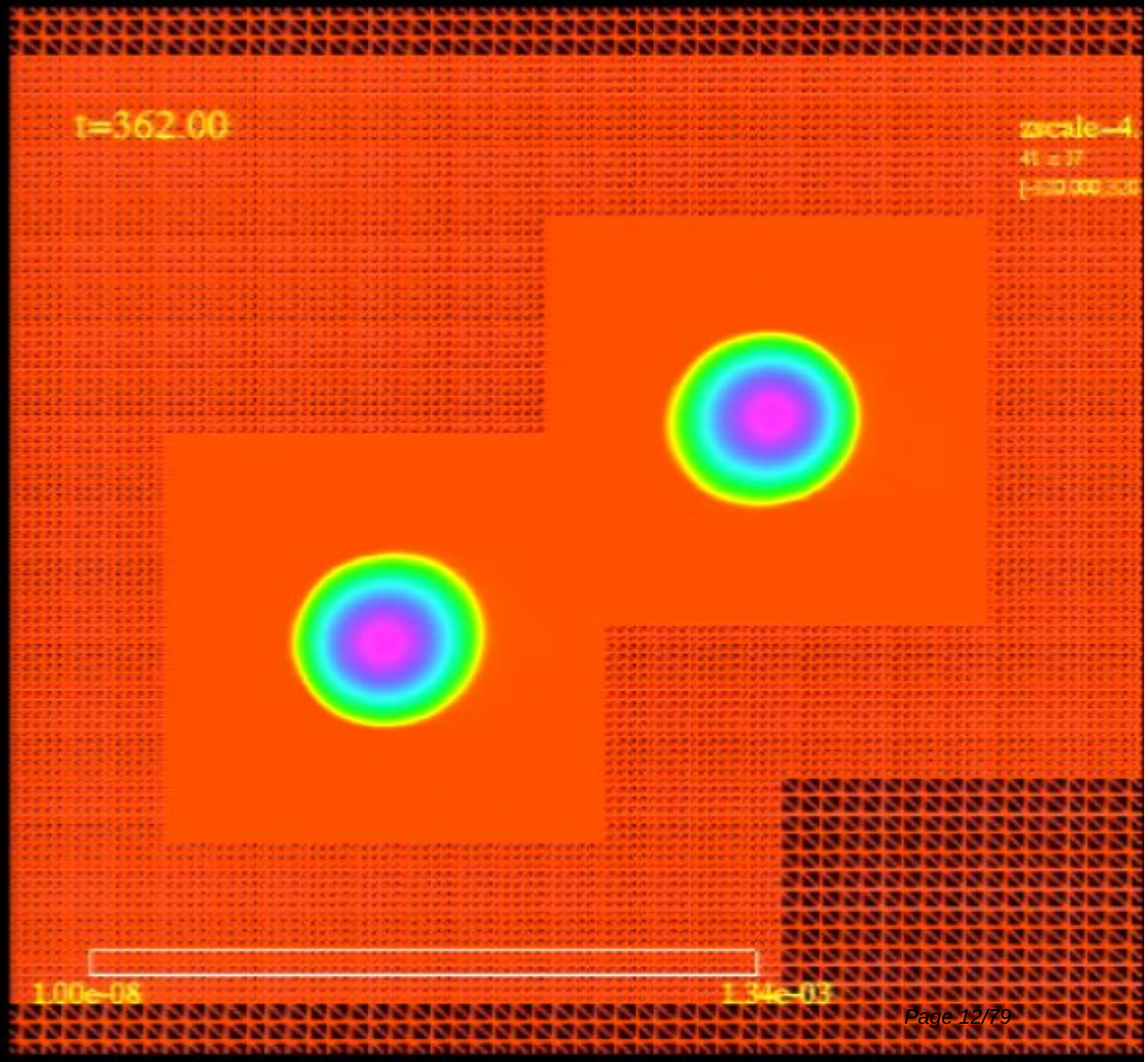

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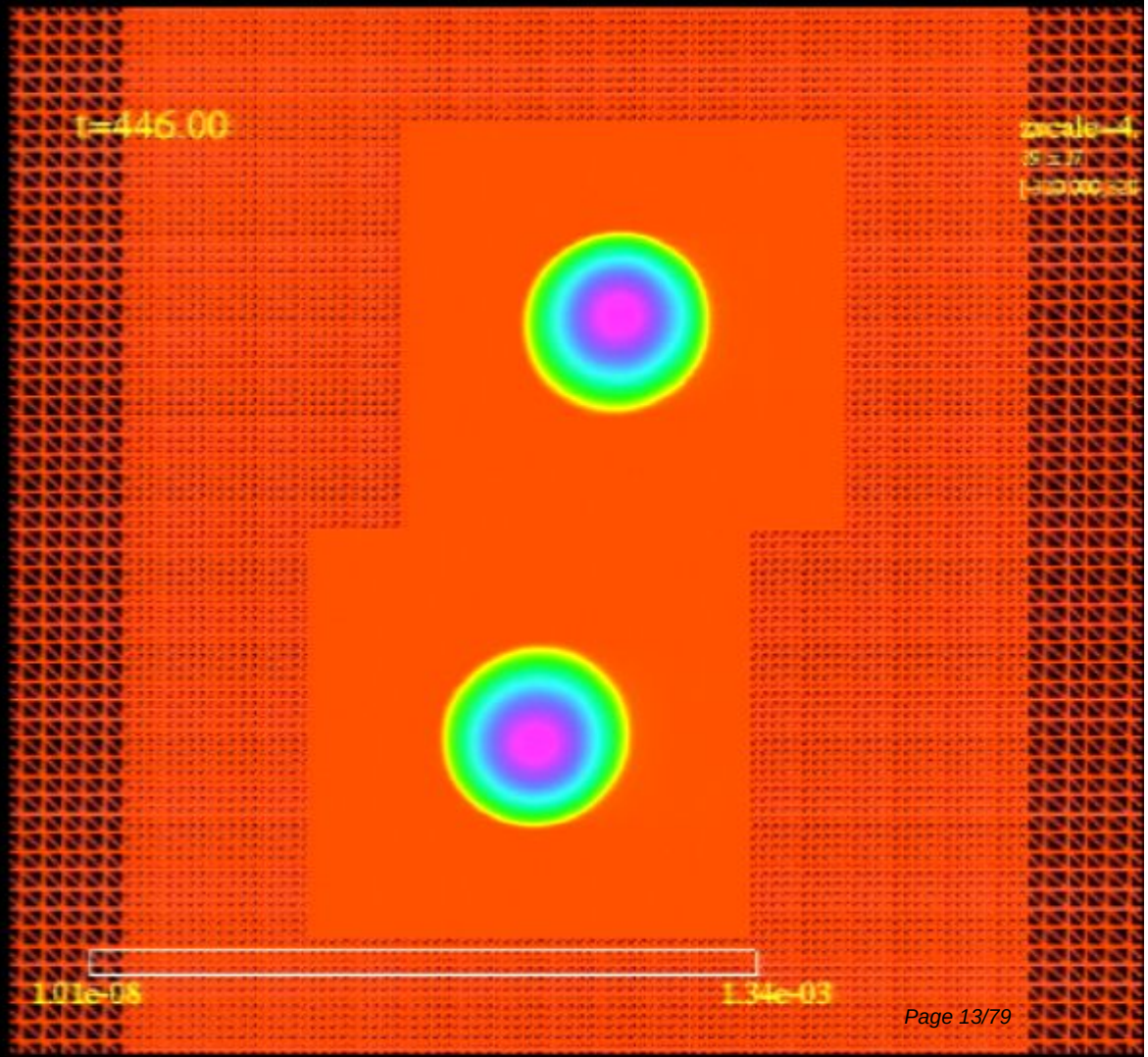

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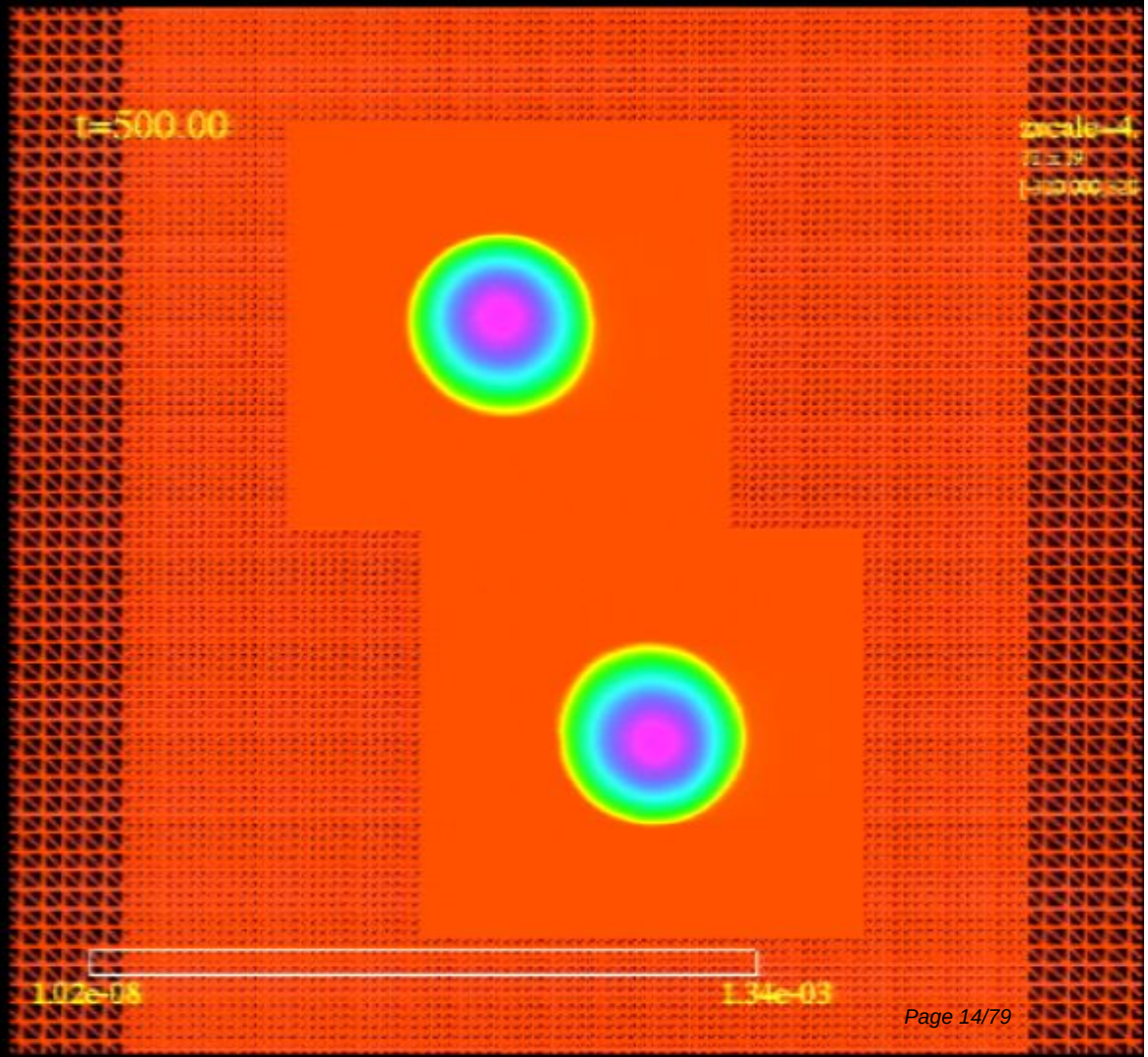


NS-NS with magnetic field

- Superposed, boosted TOV stars (Anderson, et al. PRL 2008)

$$M = 0.89 M_\odot \qquad R = 16.3 \text{ km}$$

- Ideal gas EOS, Gamma=2
- Poloidal magnetic field (extreme magnetar limit)

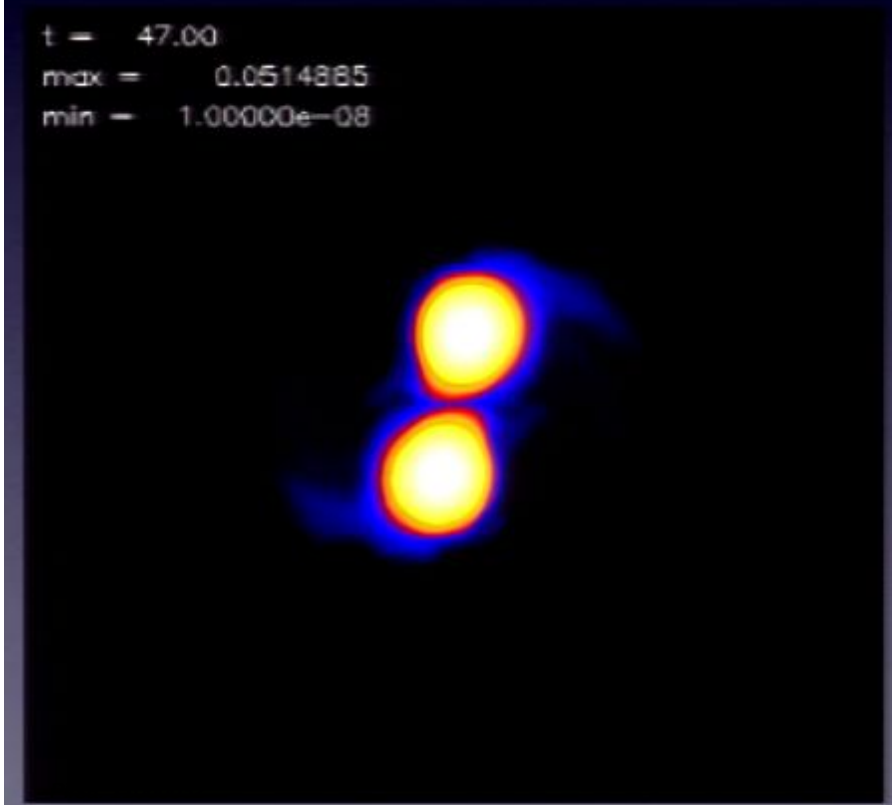
$$B \approx 10^{16} \text{ G} \qquad A_\phi = r^2 \max(P - P_{\rm vac}, 0)$$

- Test case to see what may be there...

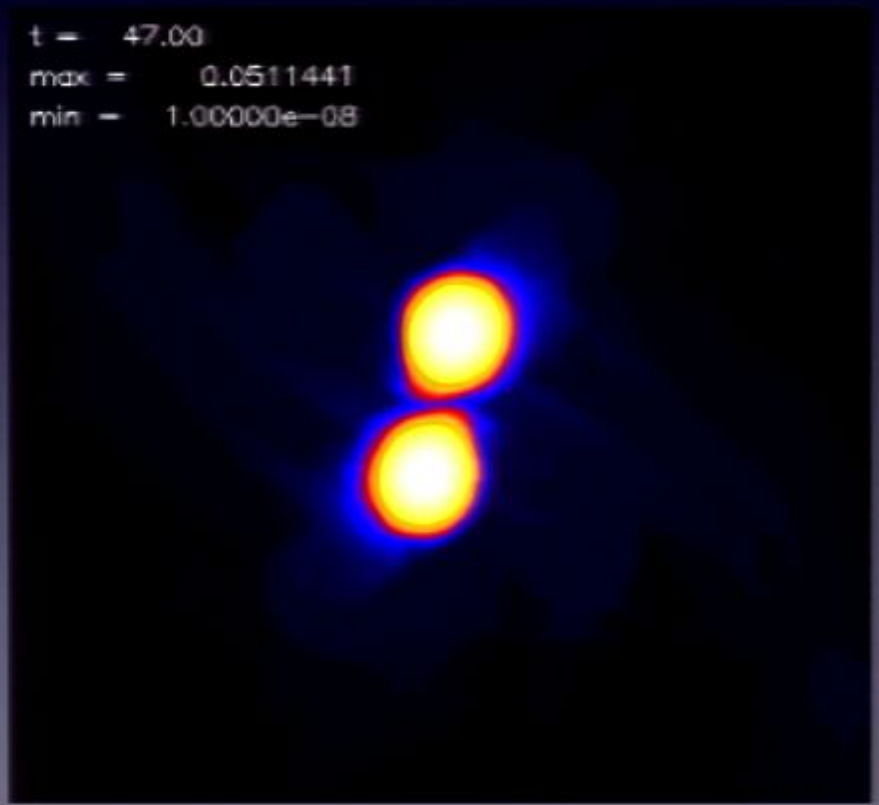
Price & Rosswog, Science (2006)
Liu, Shapiro, Etienne, Taniguchi, PRD (2008),
Giacomazzo, Rezzolla, Biaotti (2009)

Movie Comparison

HD



MHD



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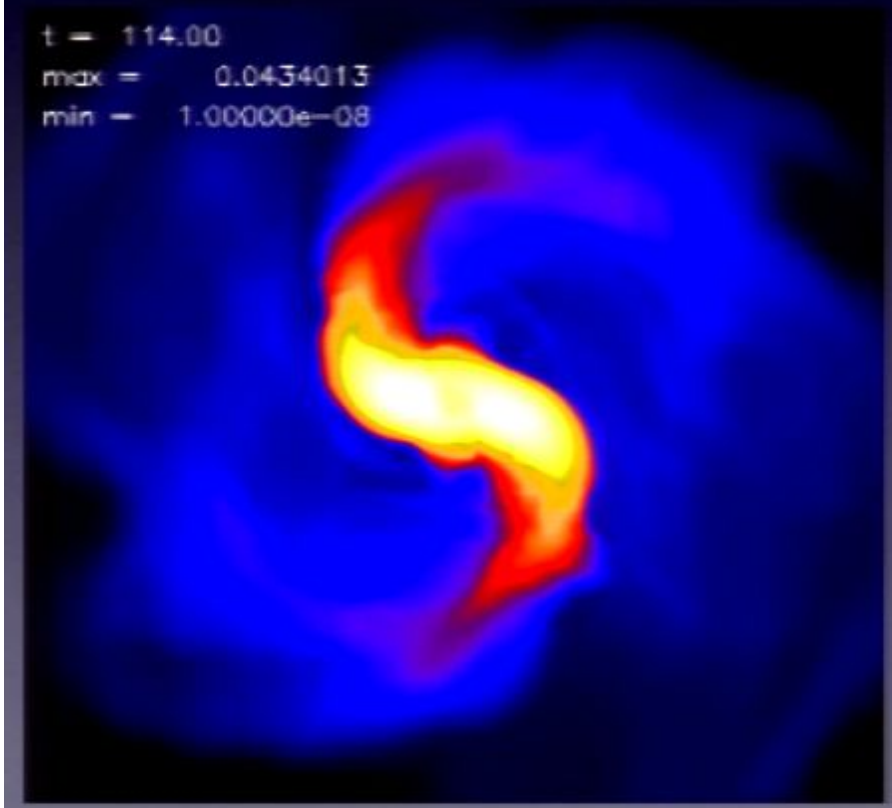

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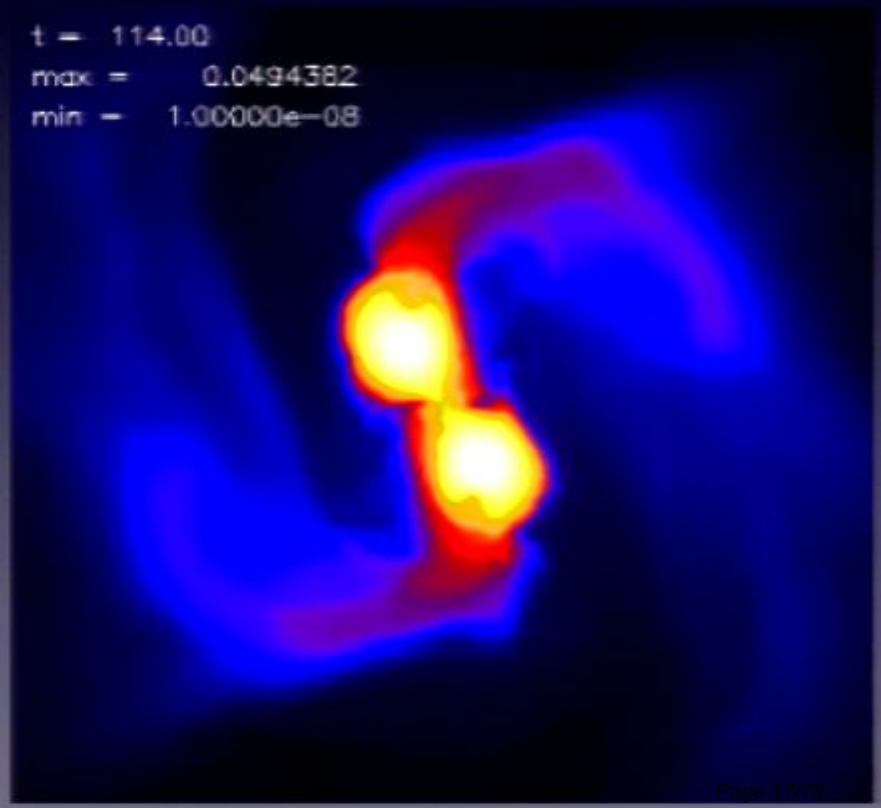

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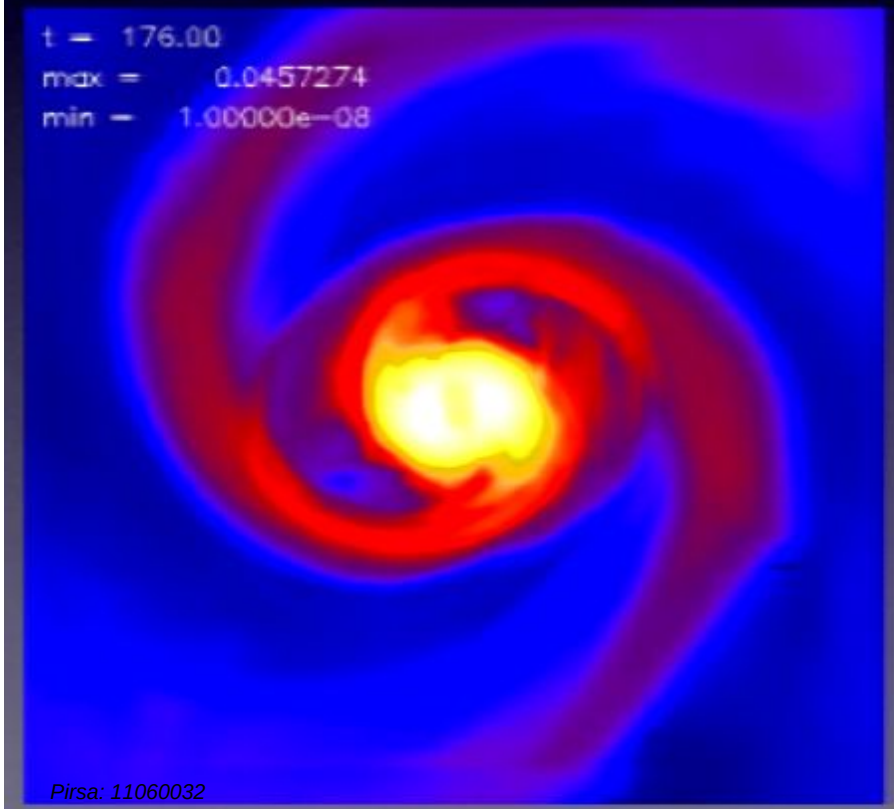

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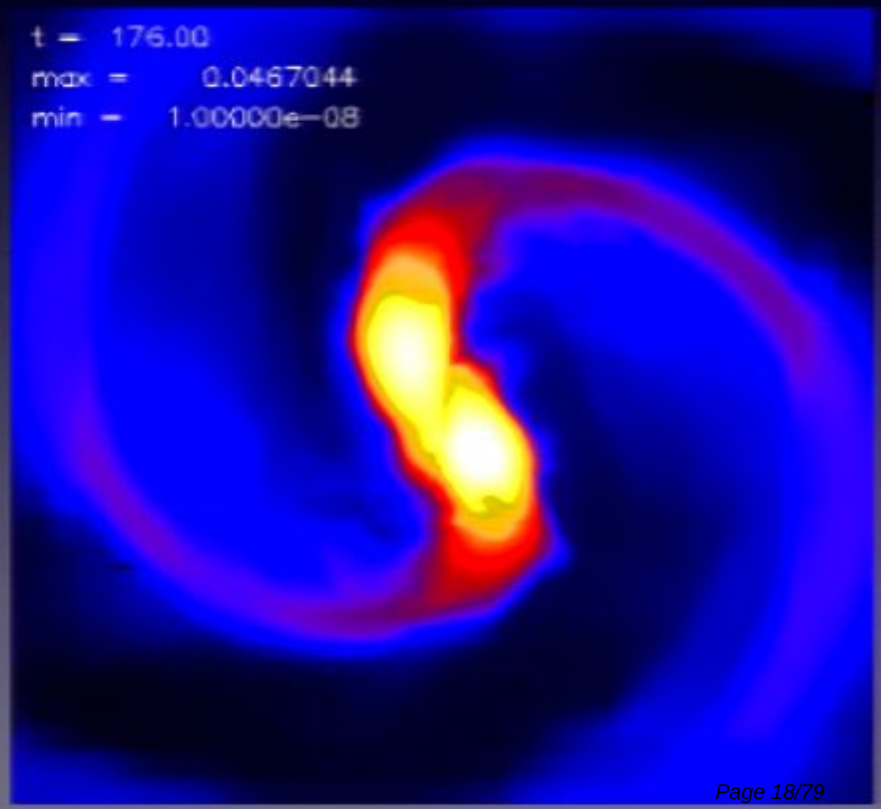

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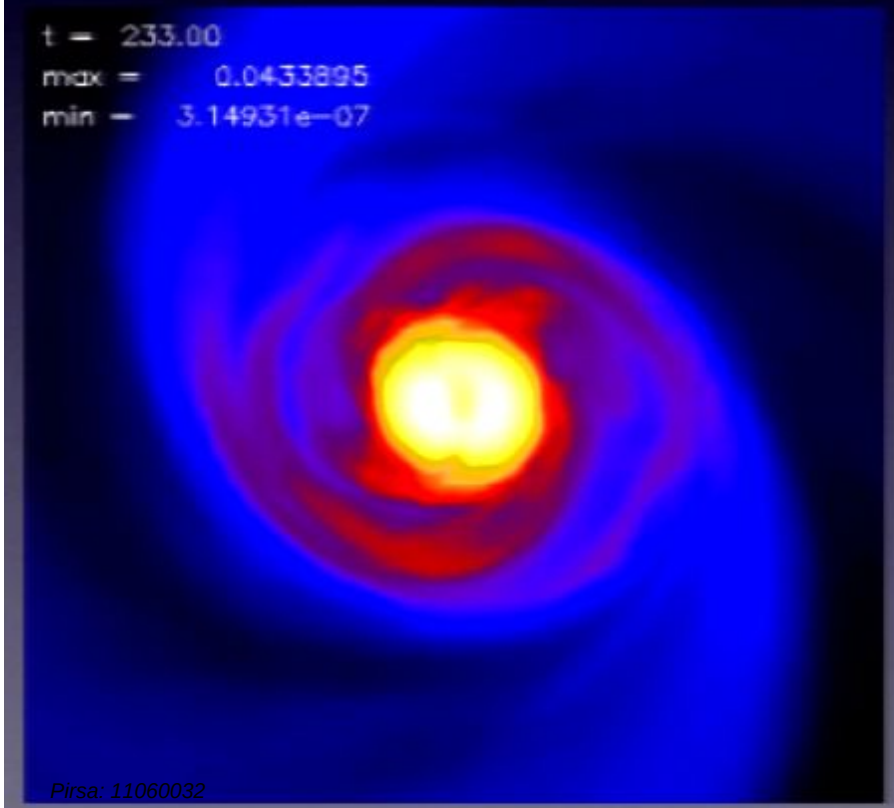

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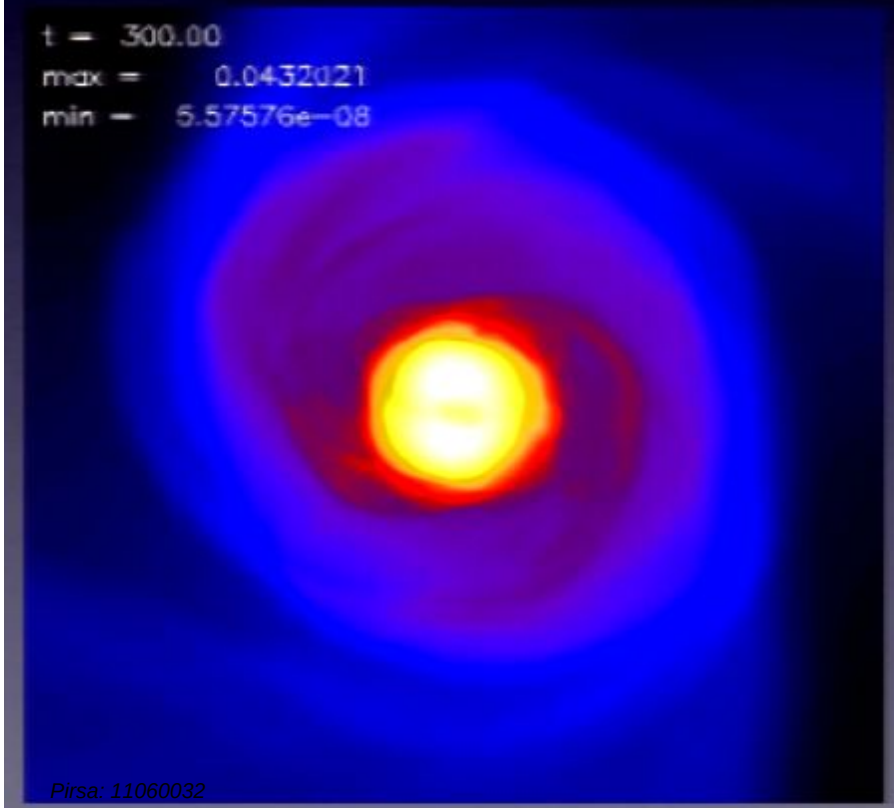

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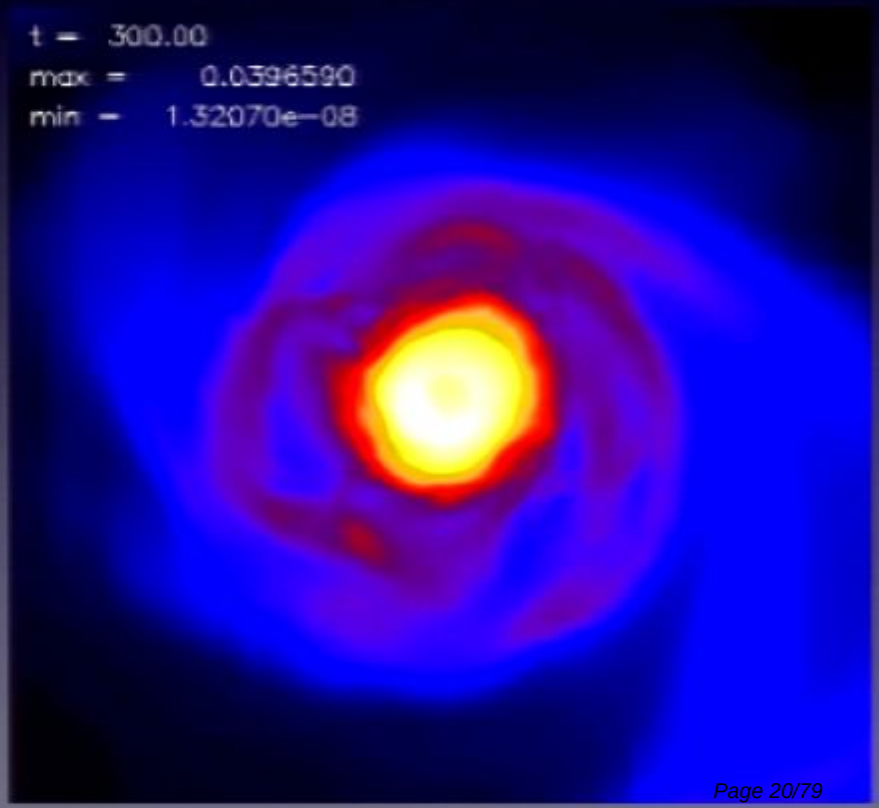

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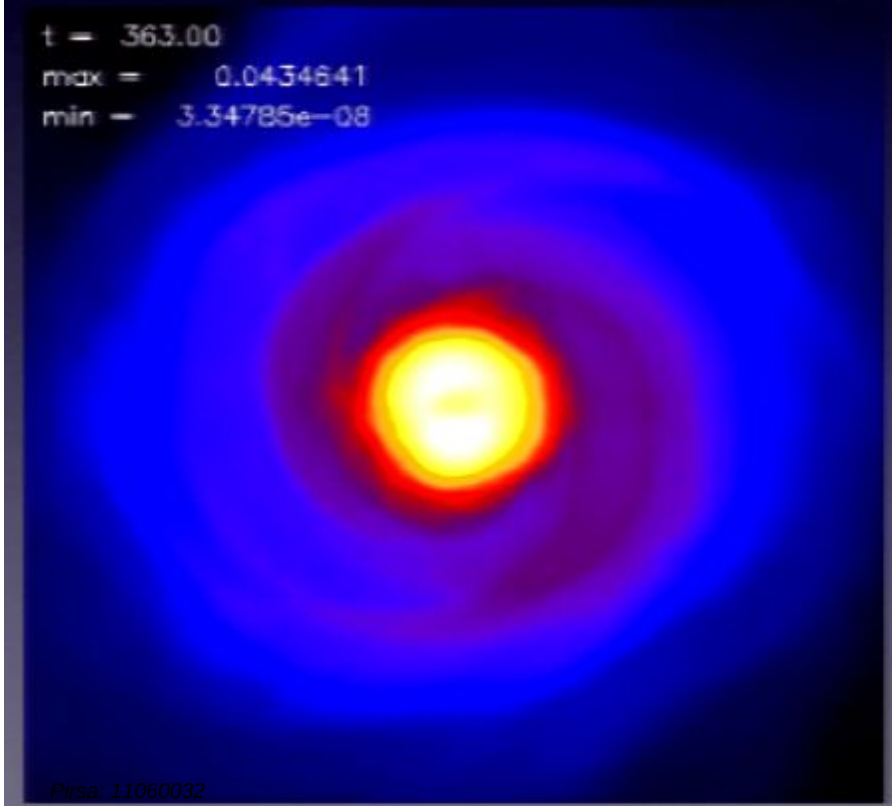

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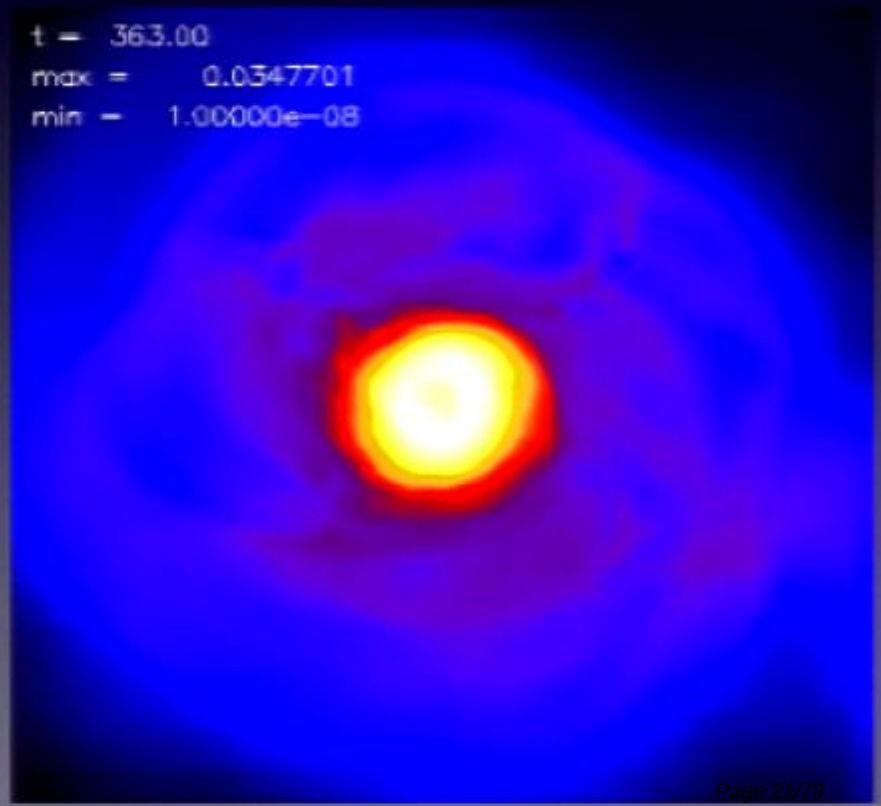

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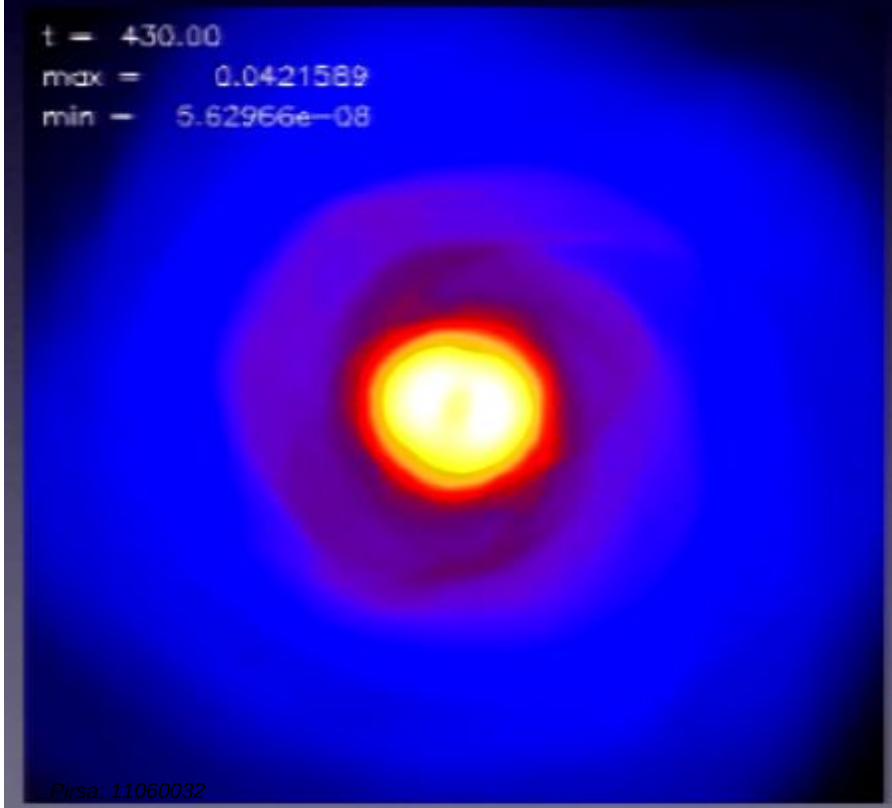

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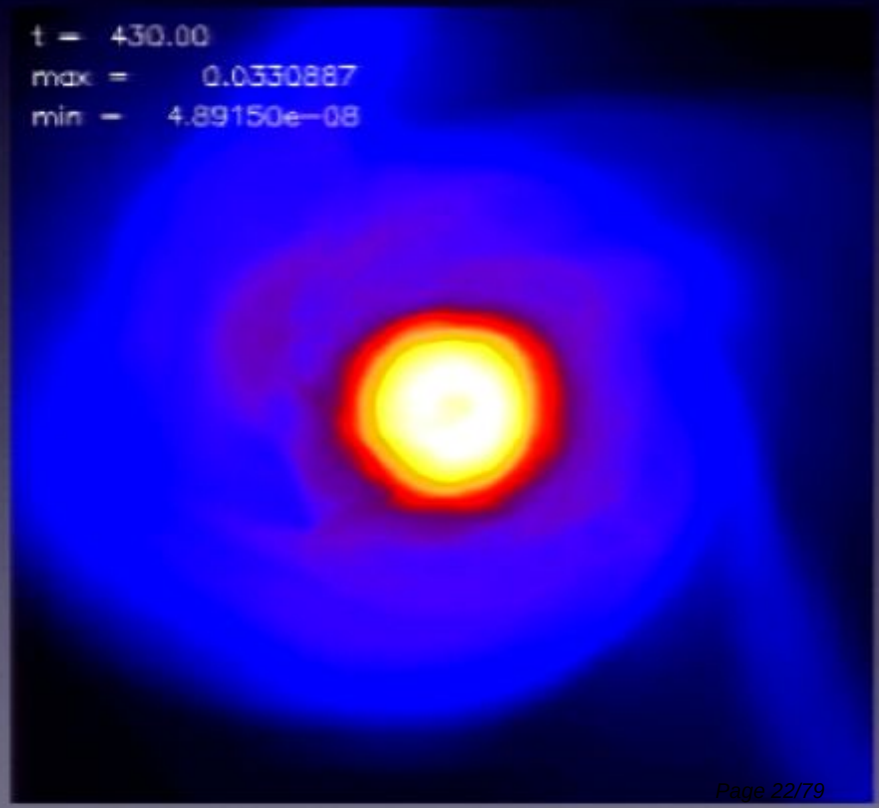

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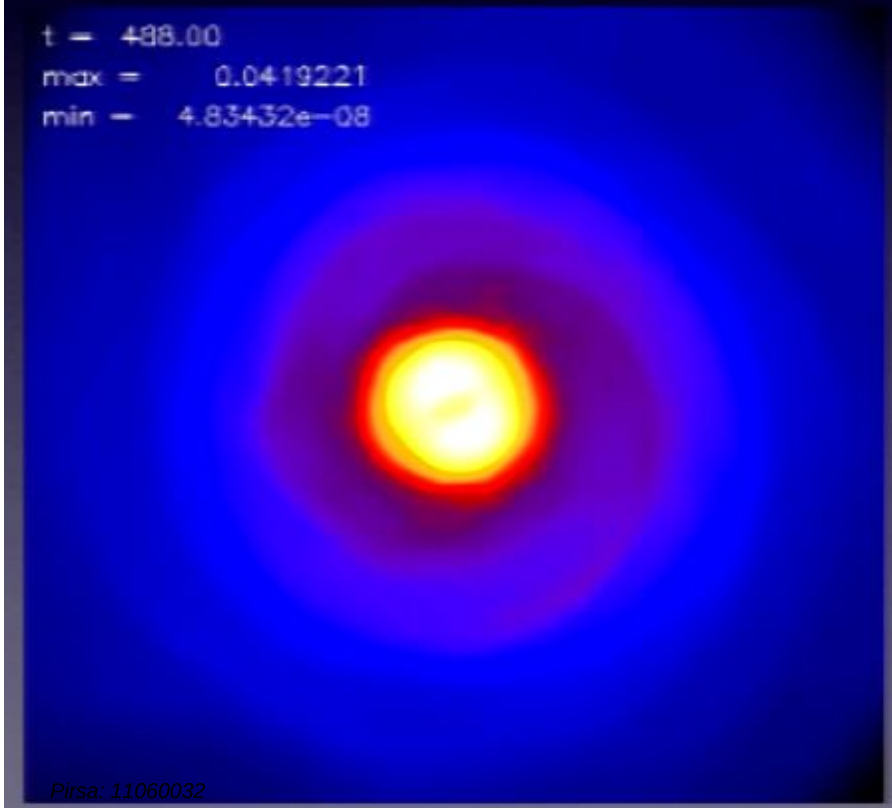

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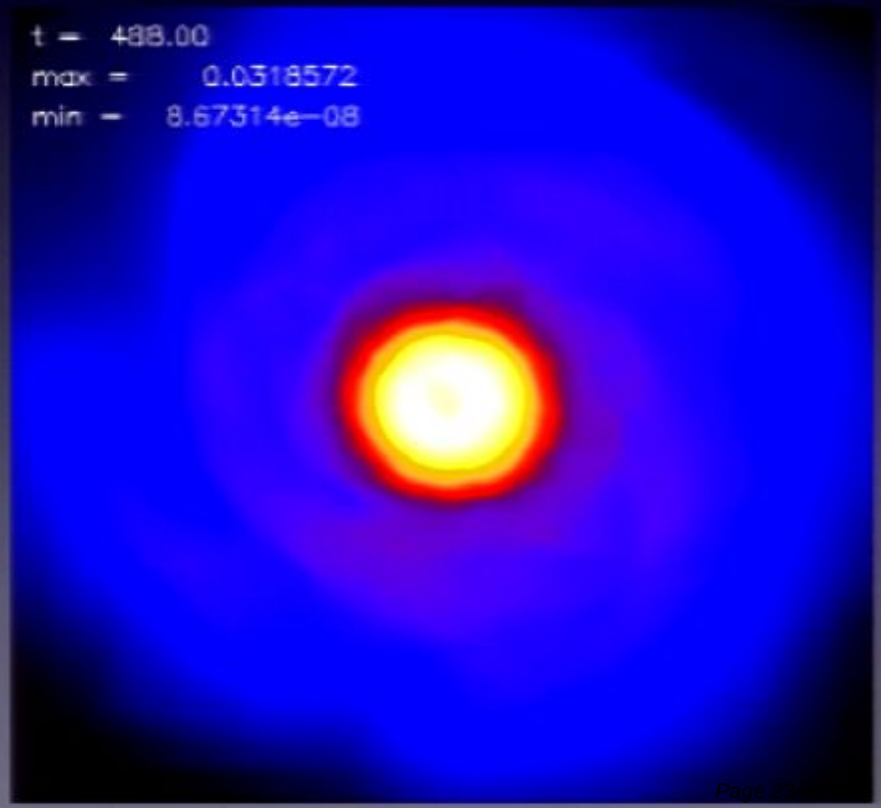
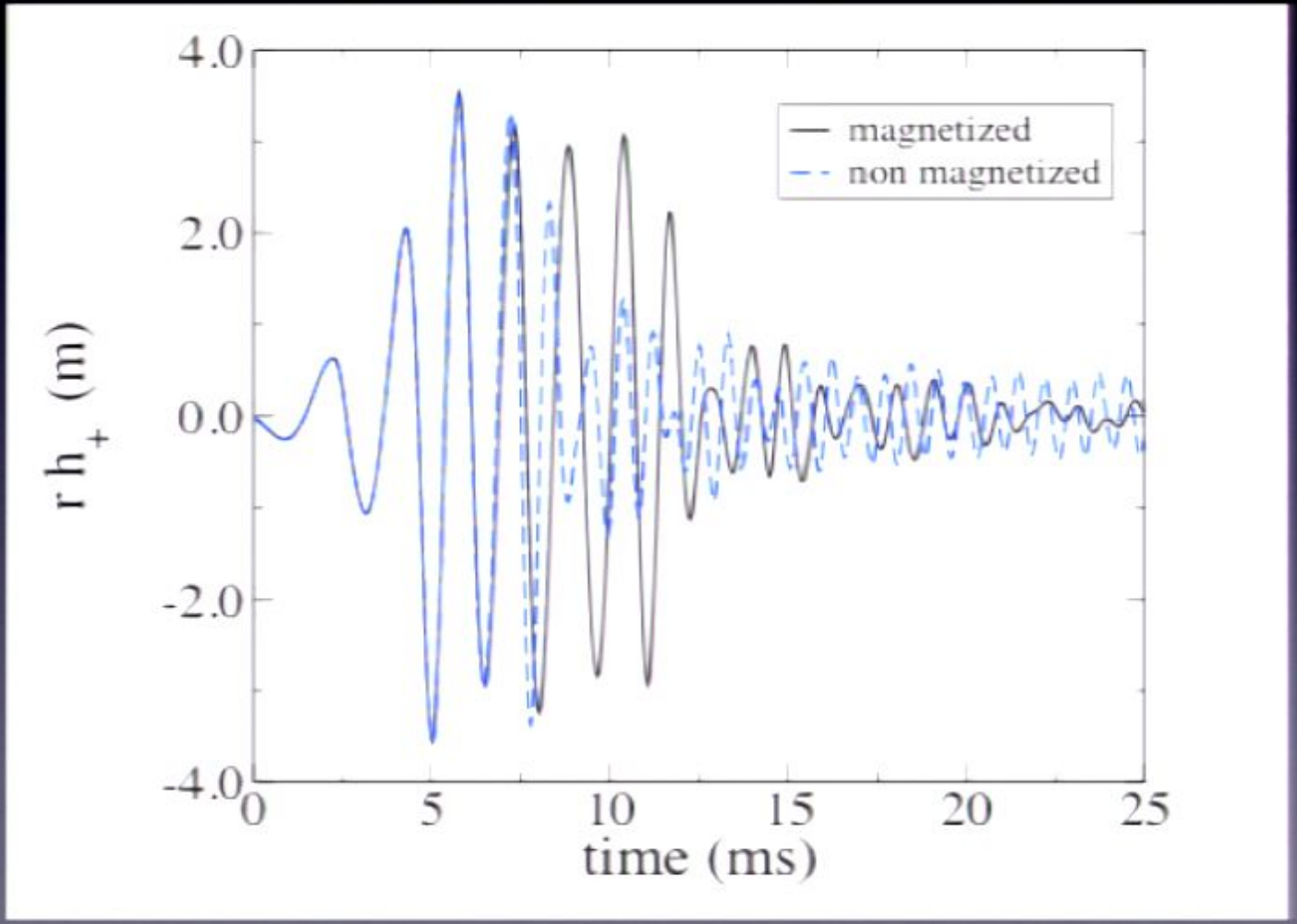
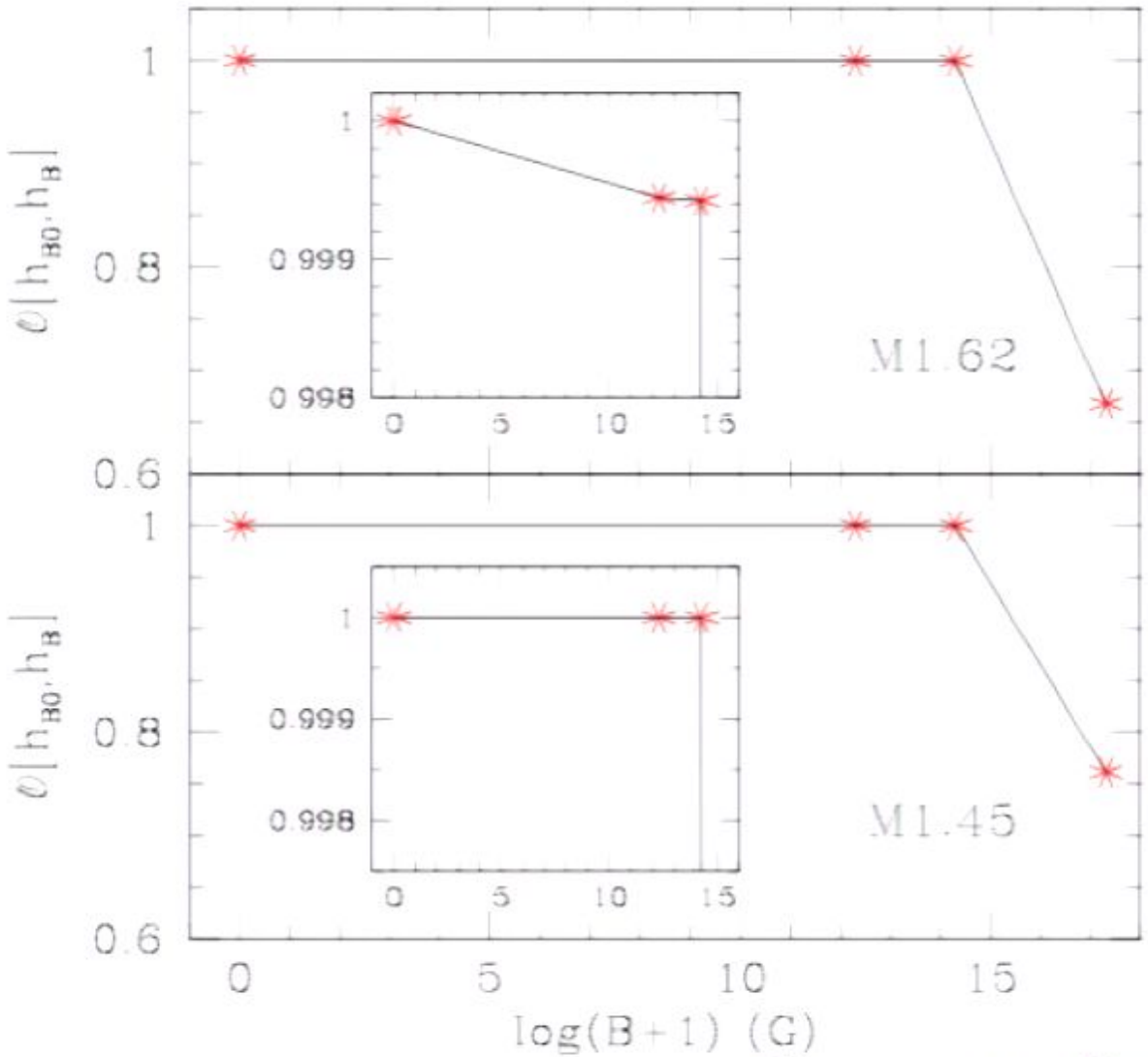


Gravitational wave signal



But...



Giacomazzo, Rezzolla, Baiotti (200

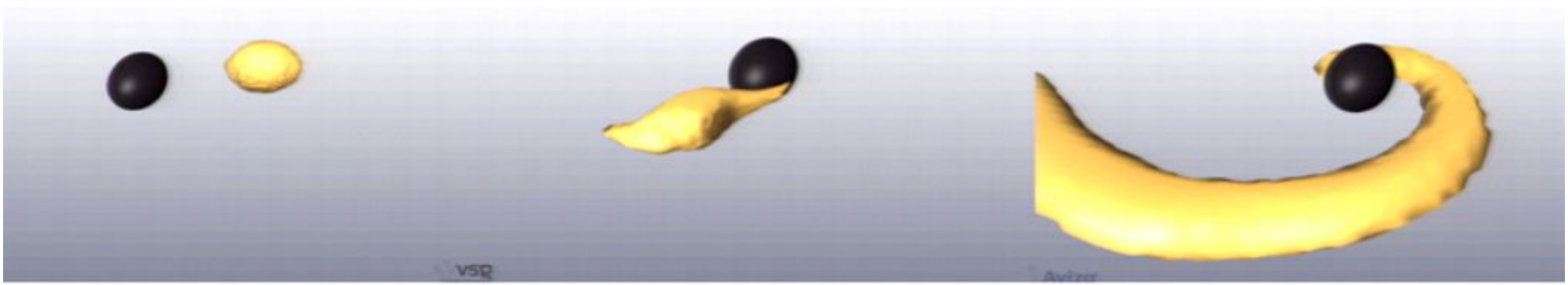
Black Hole-Neutron Star

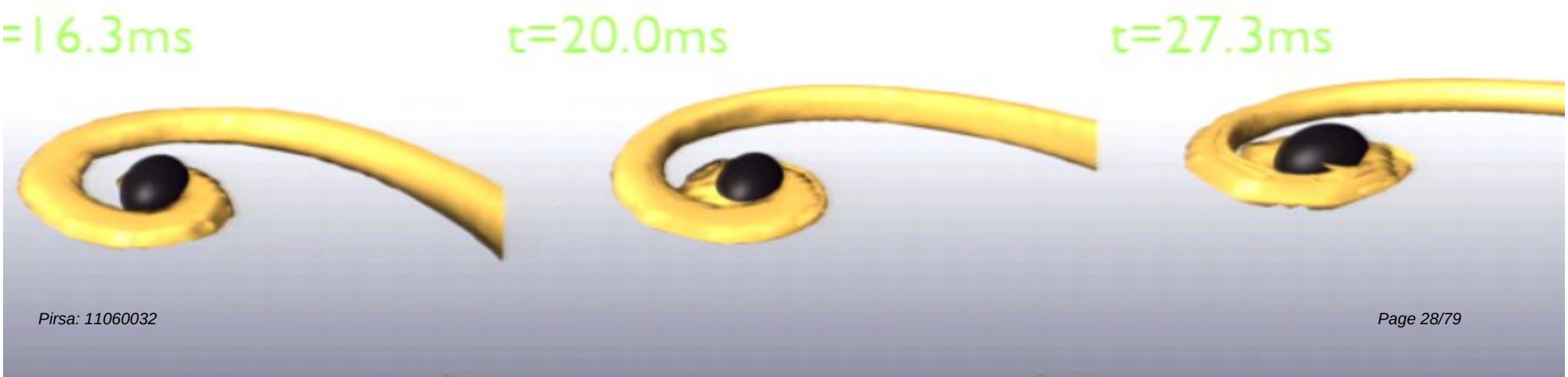
Black Hole-Neutron Star

(Chawla et al., PRL 2010)

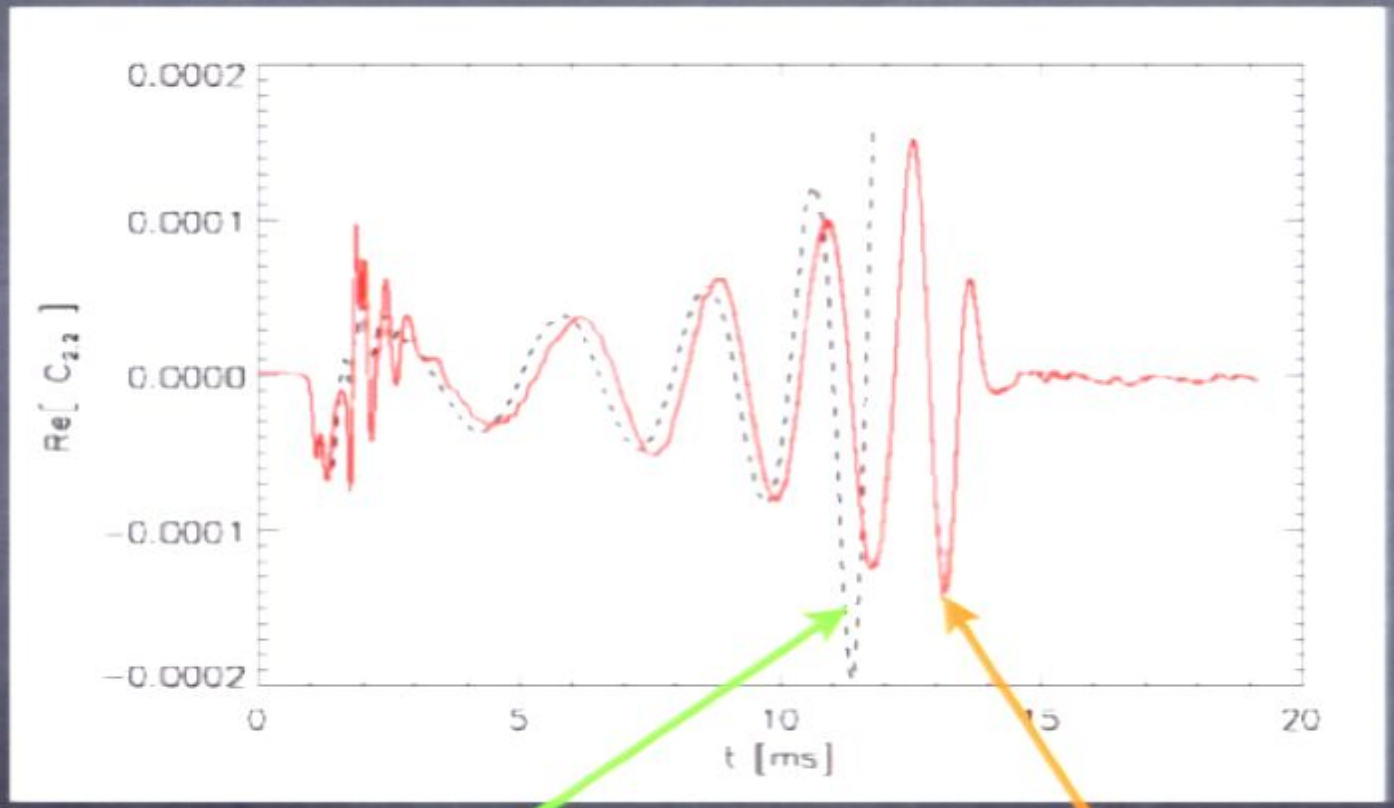
- Black hole
  - Mass $M_{\rm BH} = 7M_\odot$
  - Spinning and non-spinning $a = 0, \quad a = 0.5$
- Neutron Star
  - Mass $M = 1.4M_\odot$
  - Polytrope $R = 15$ km
  - Magnetic field $\Gamma = 2$
- System
  - q=5 and initial separtion 100 km

BH-NS Snapshots





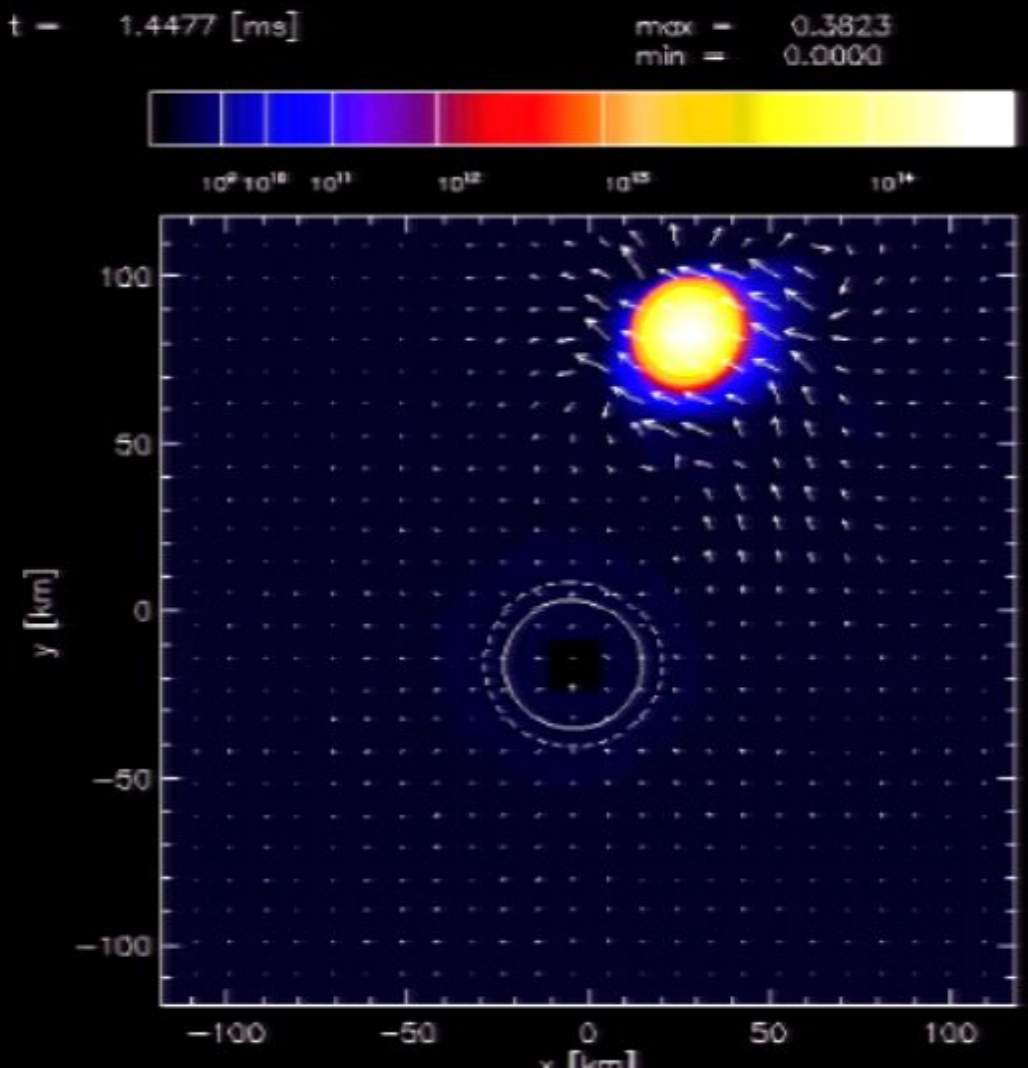
Gravitational Waves



a=0, B=10^{12}

a=0.5, B=0 & B=10^{12}

a=0.5 and B=10^{12} G



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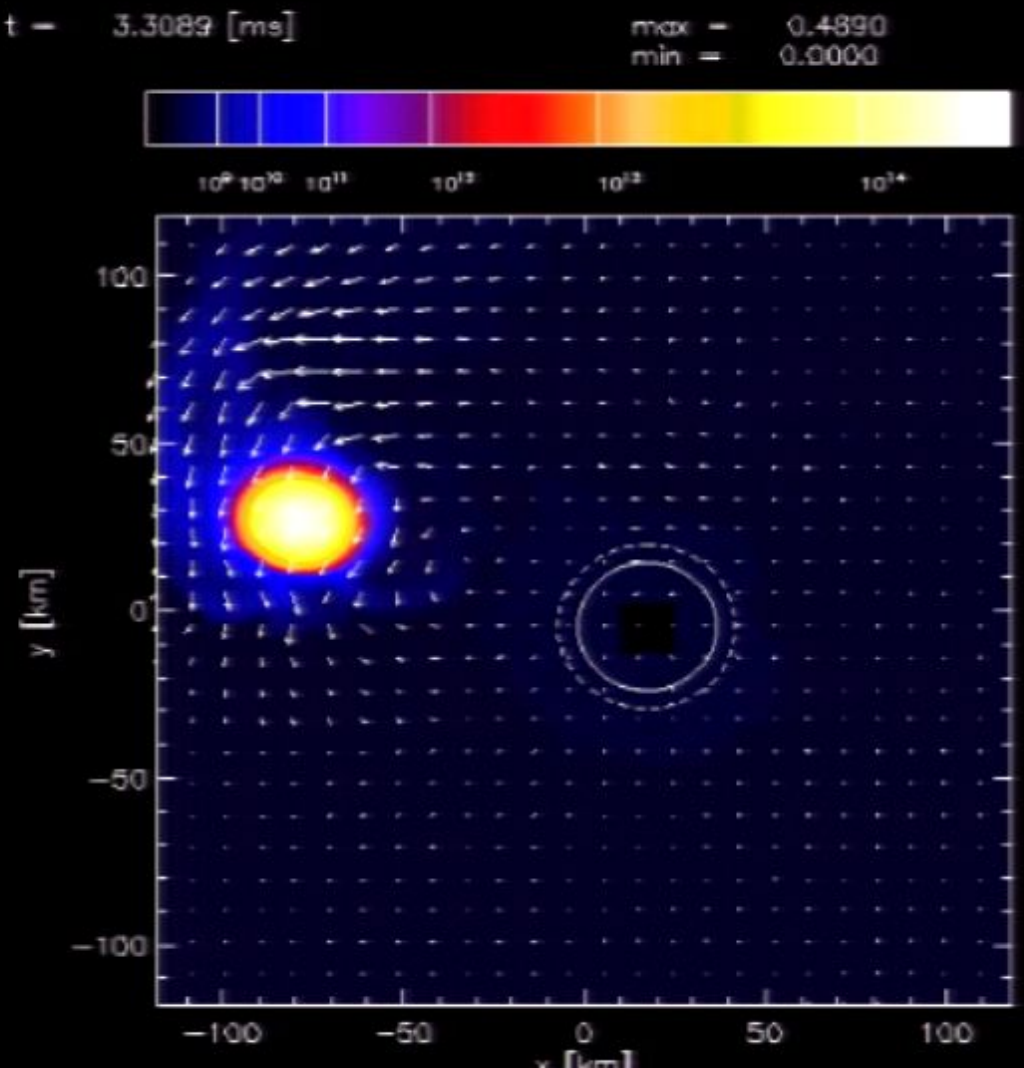

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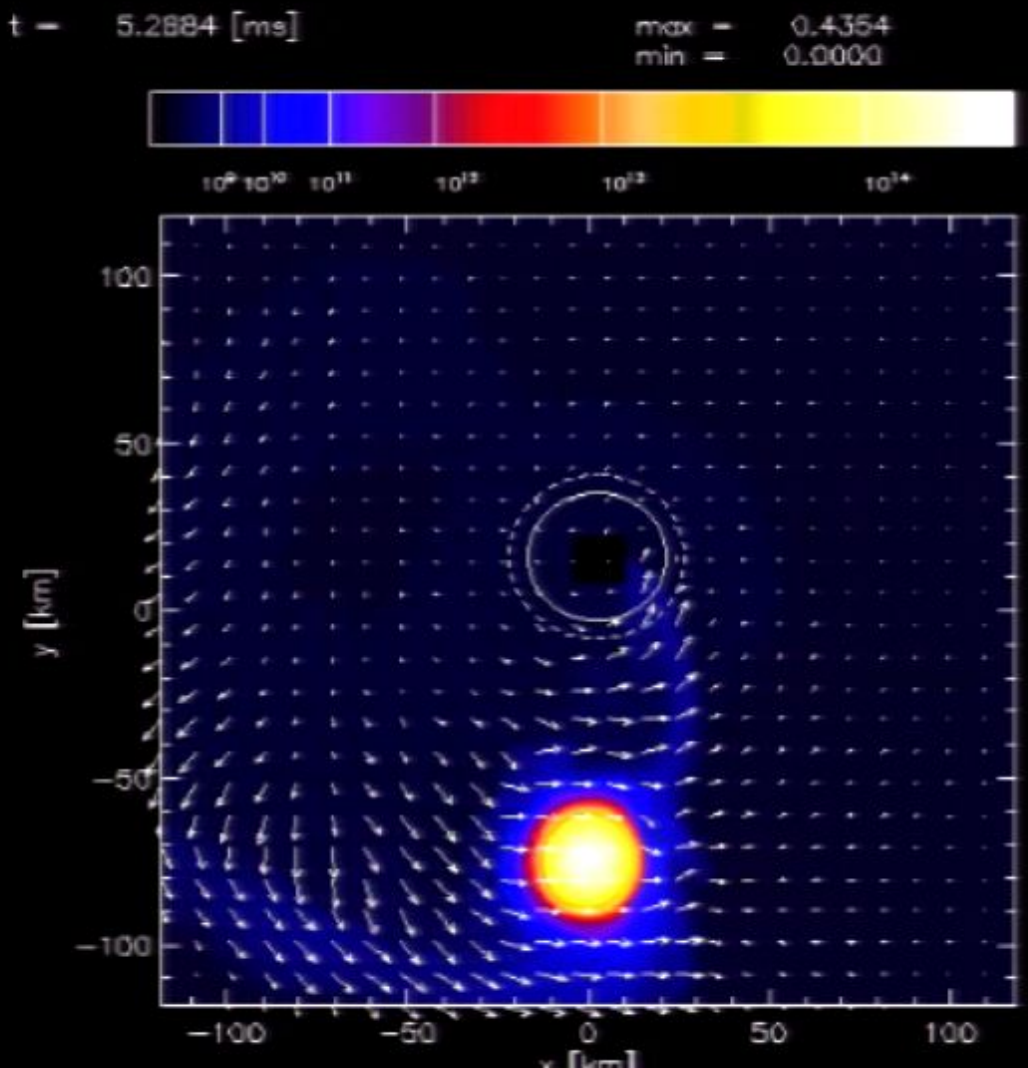

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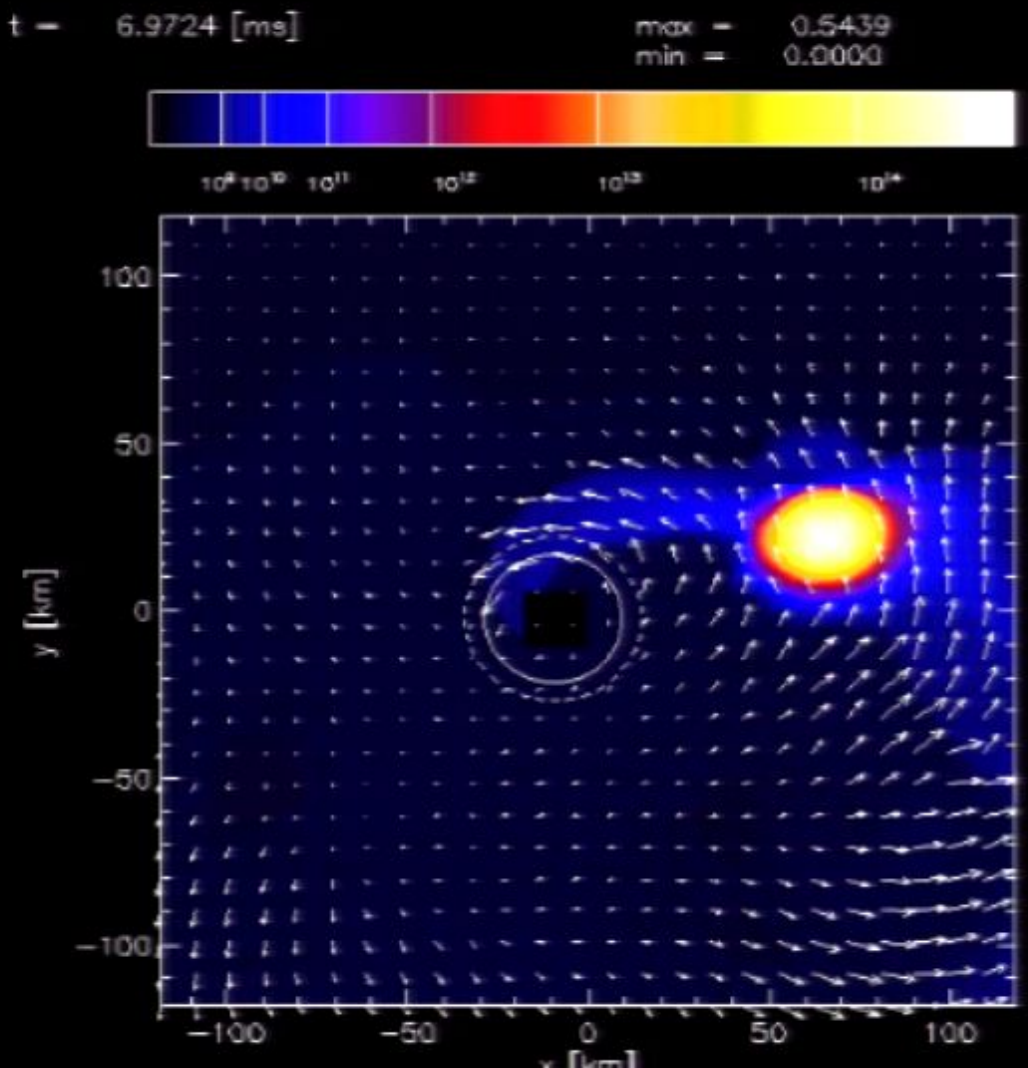

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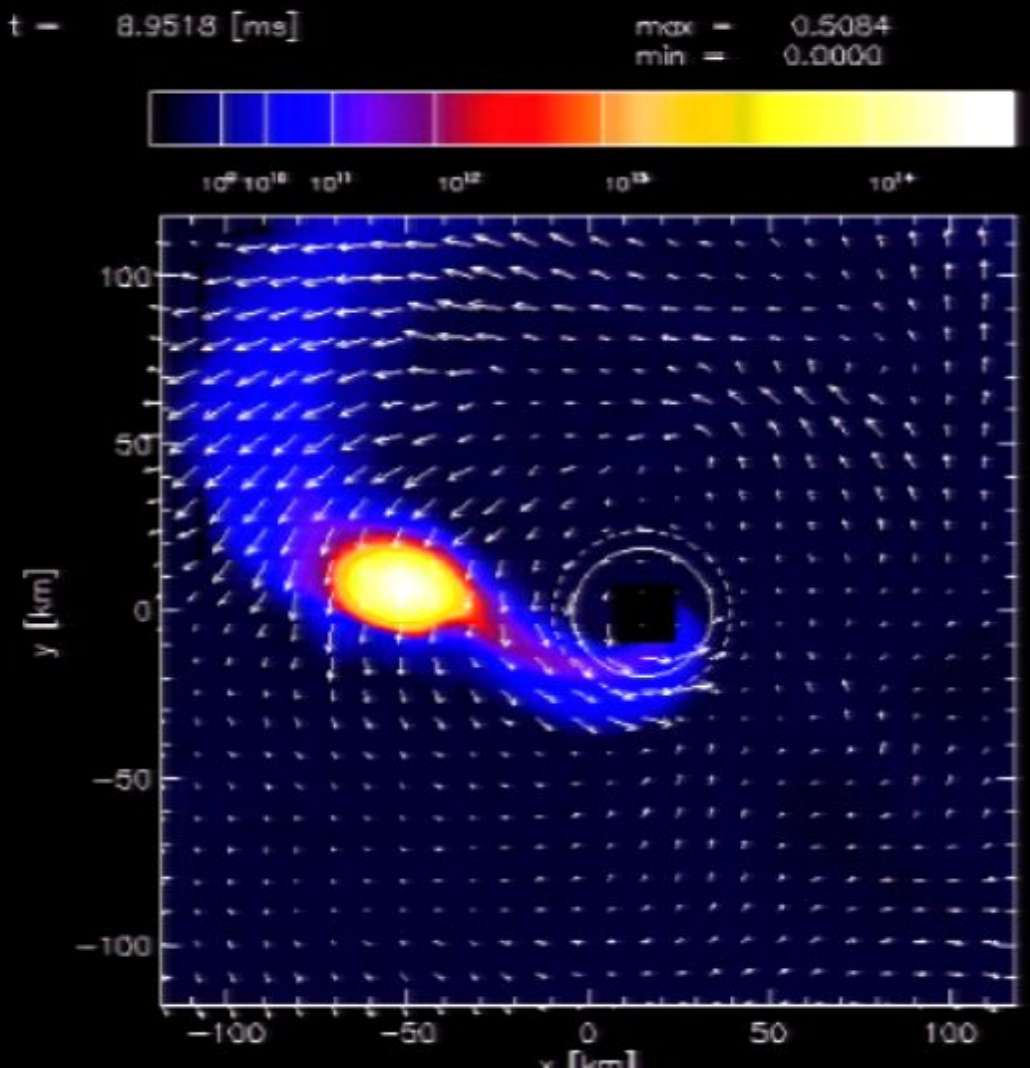

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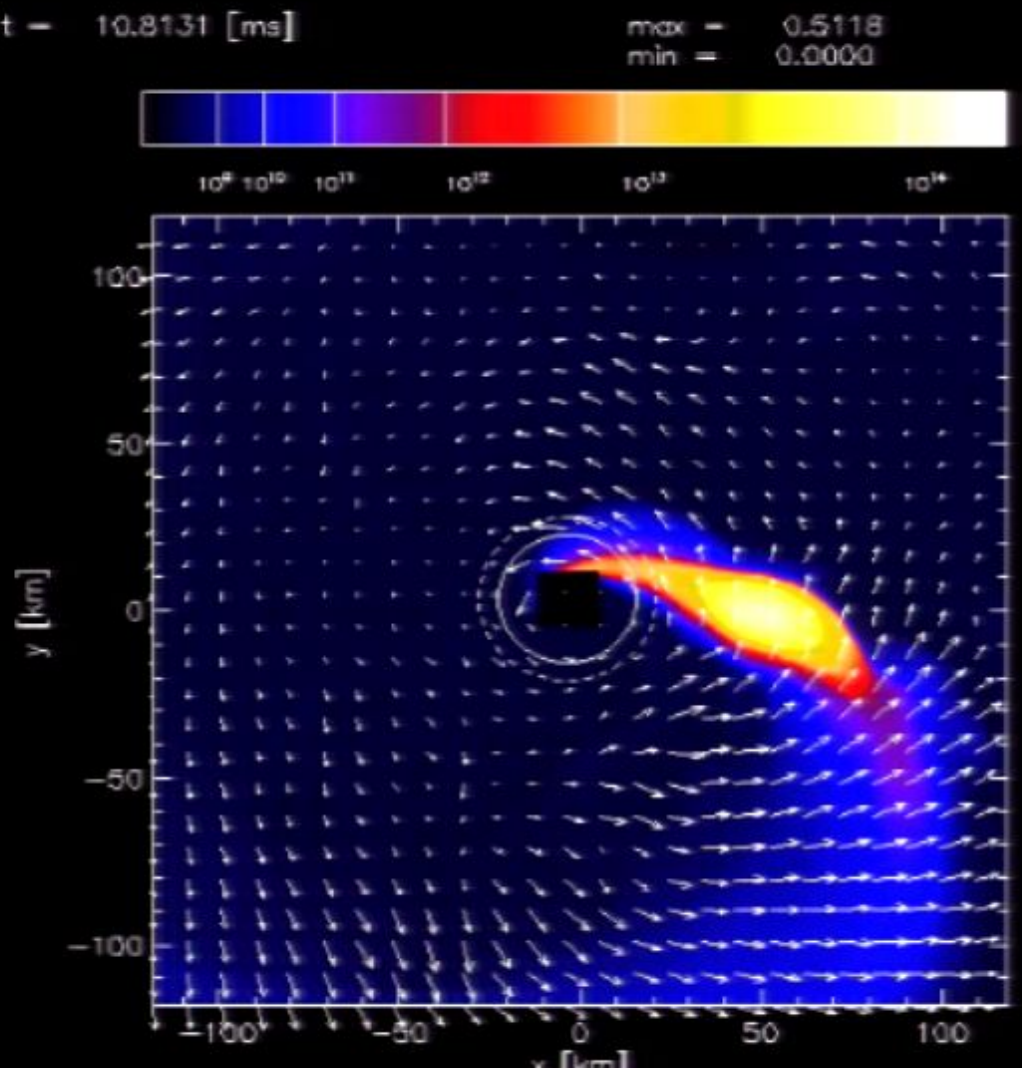

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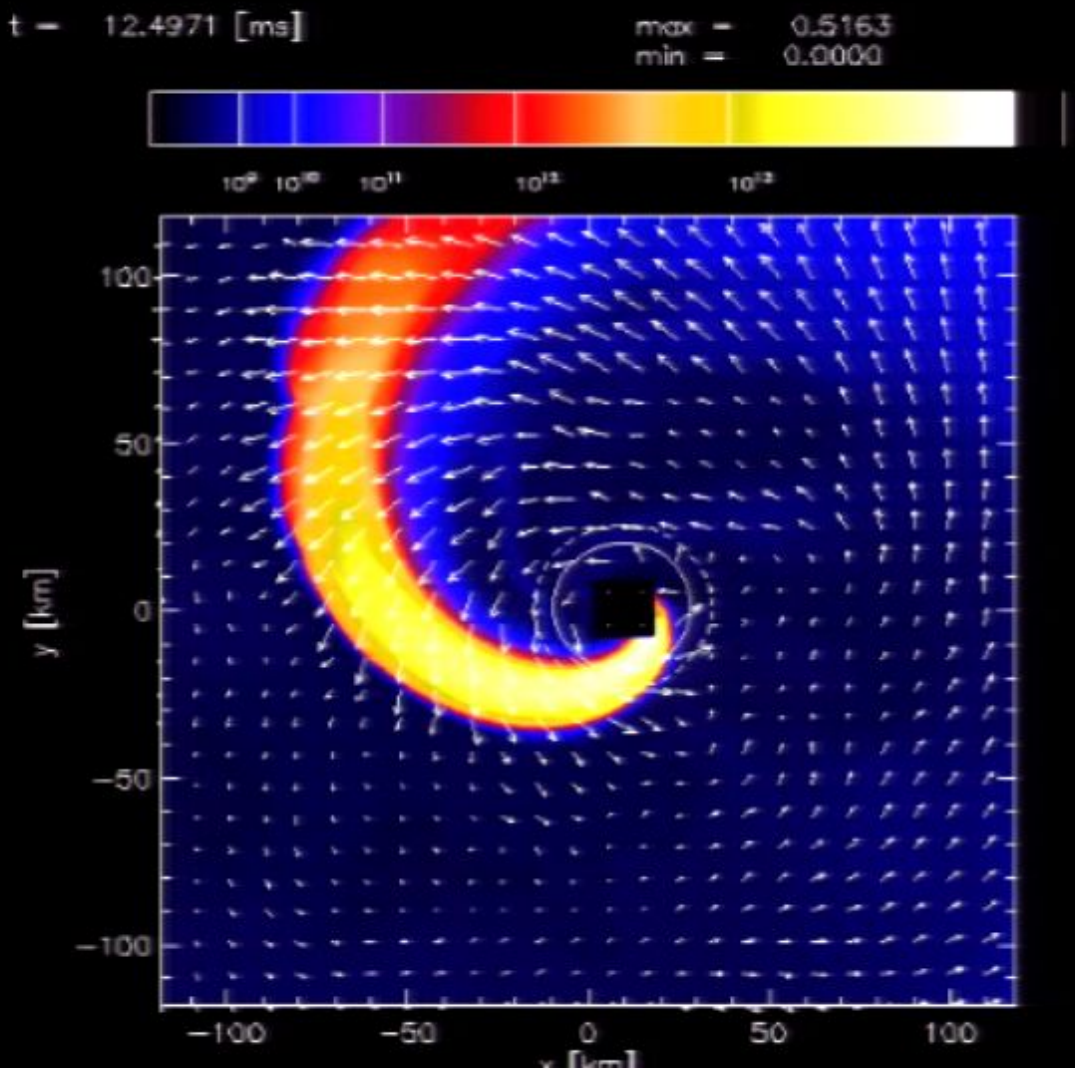

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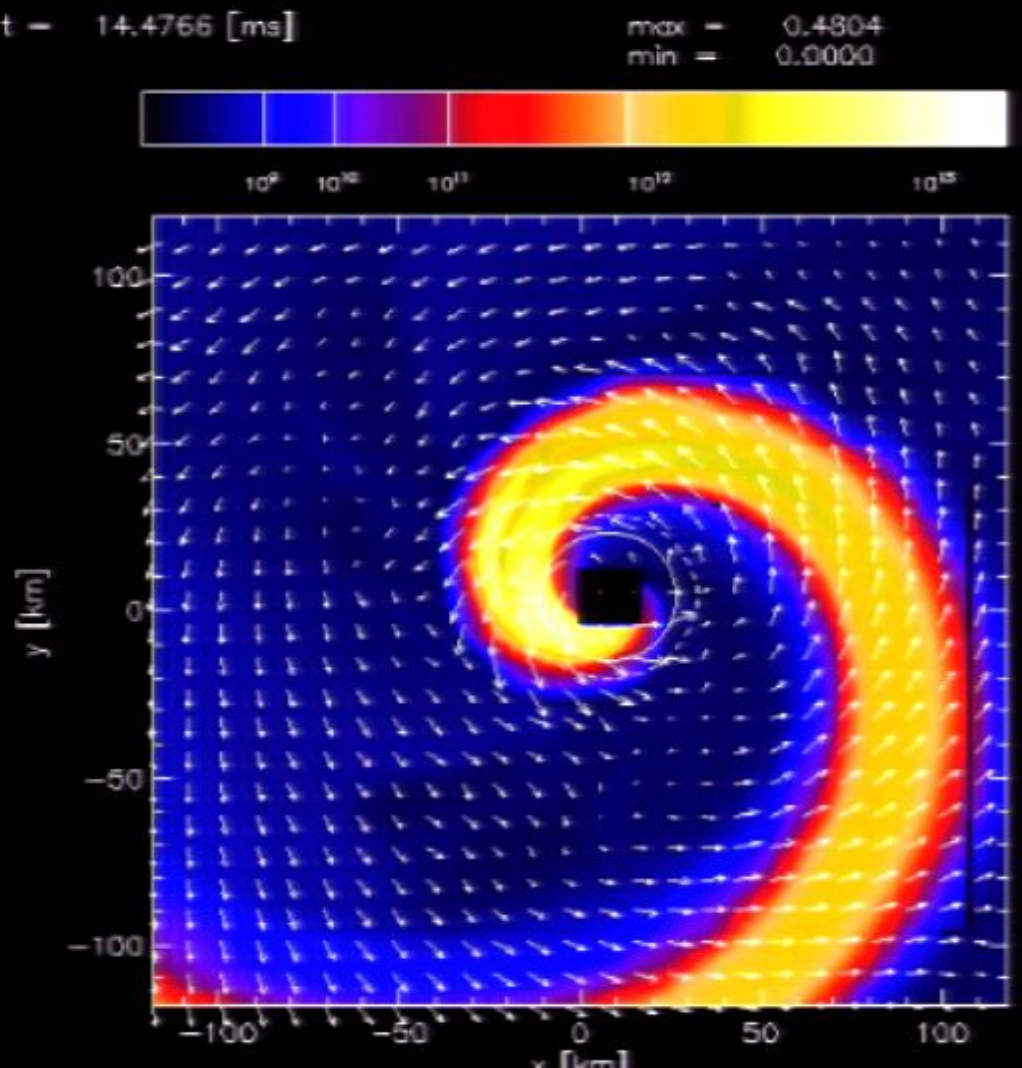

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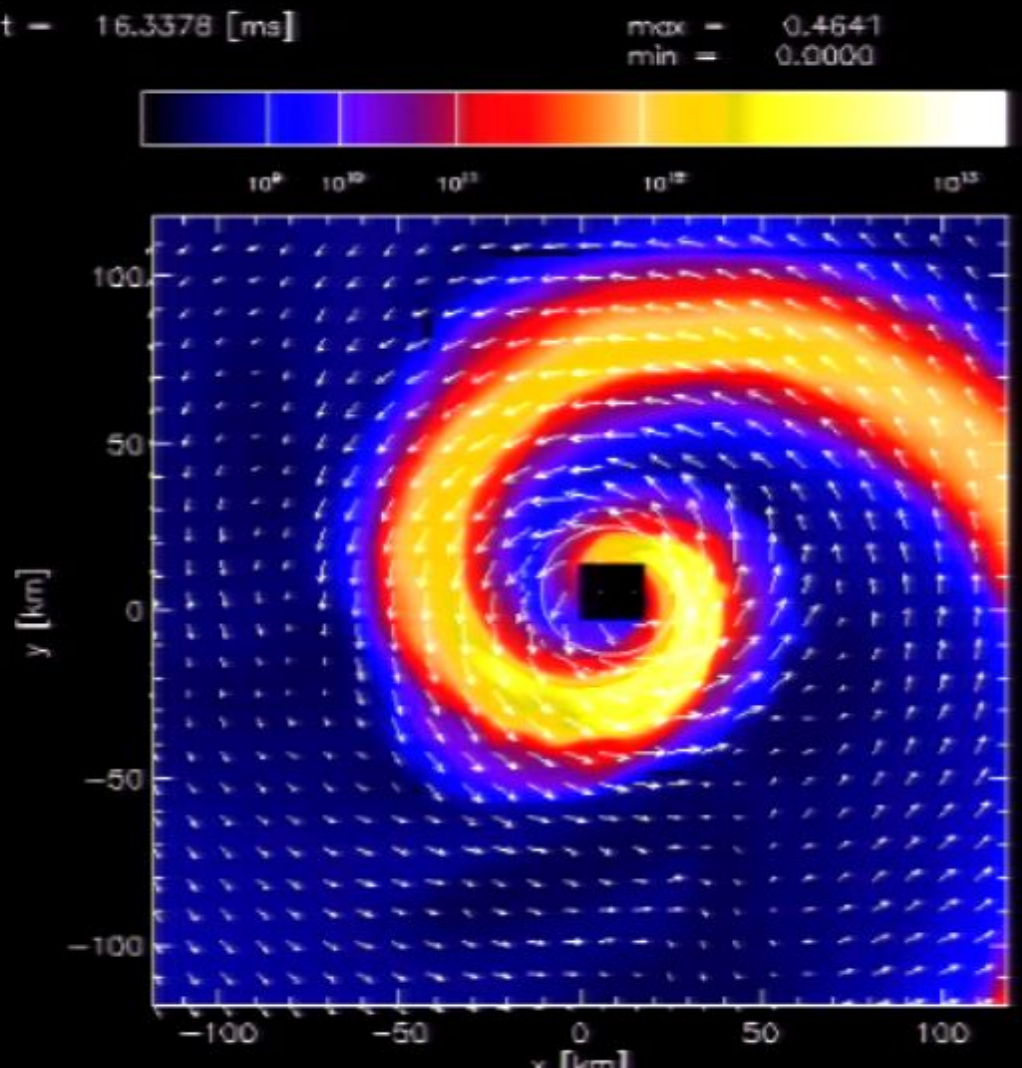

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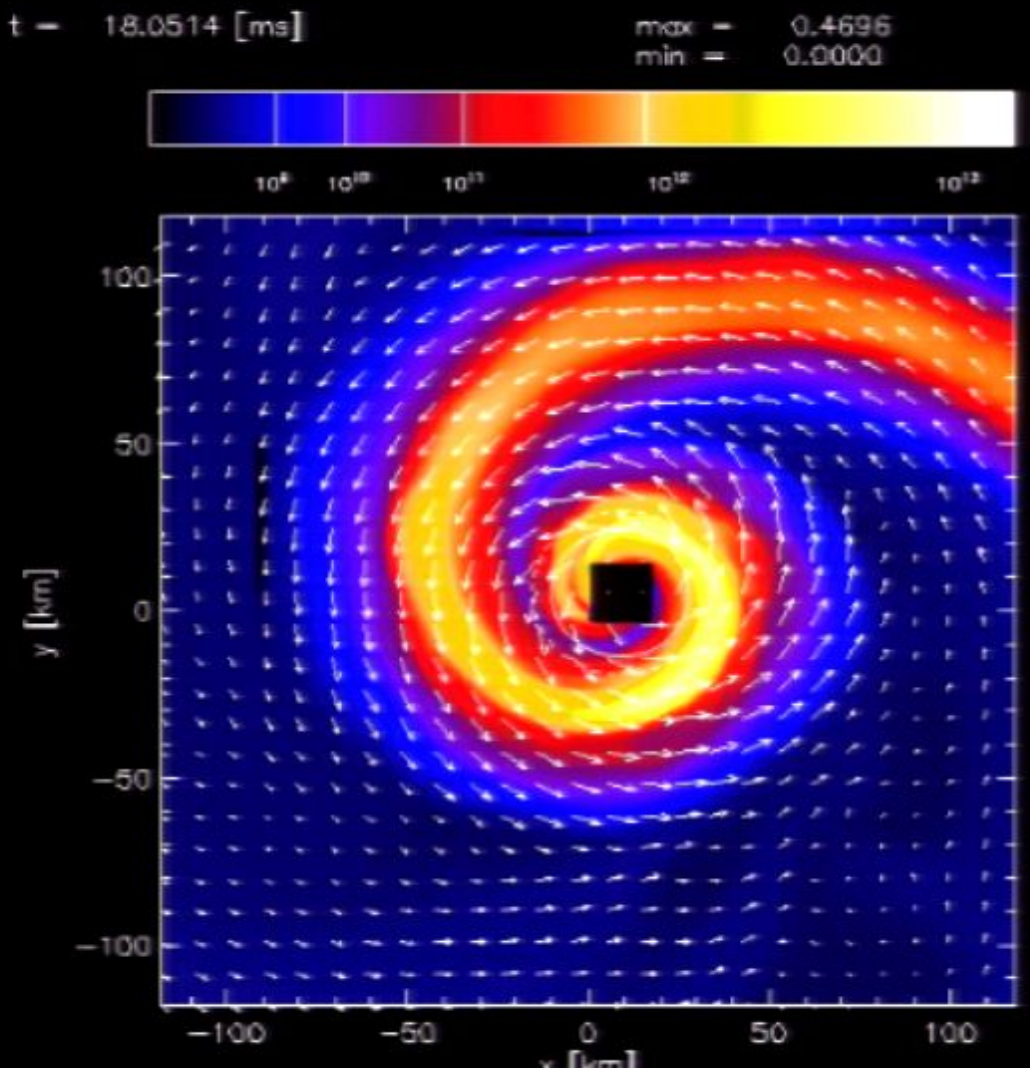

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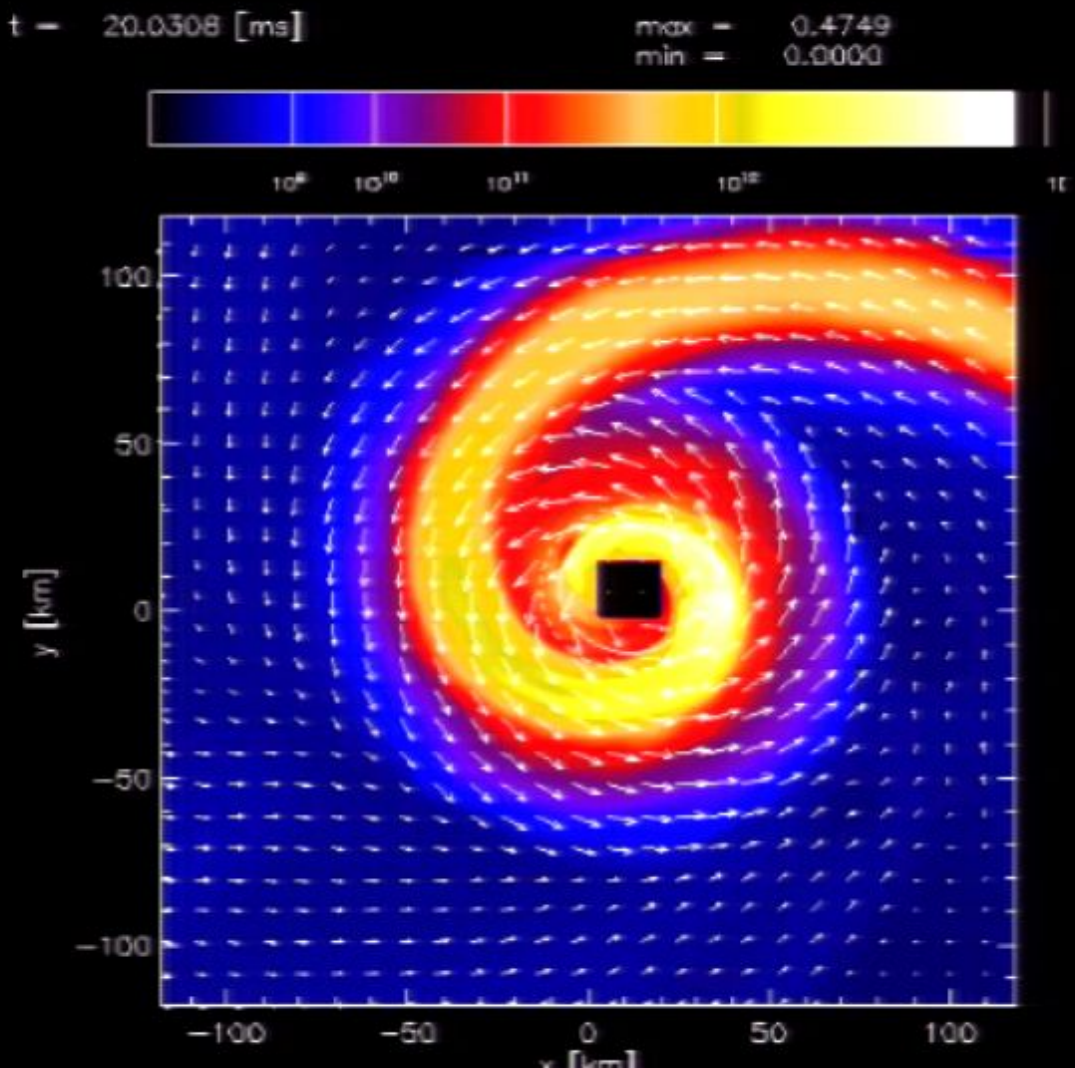

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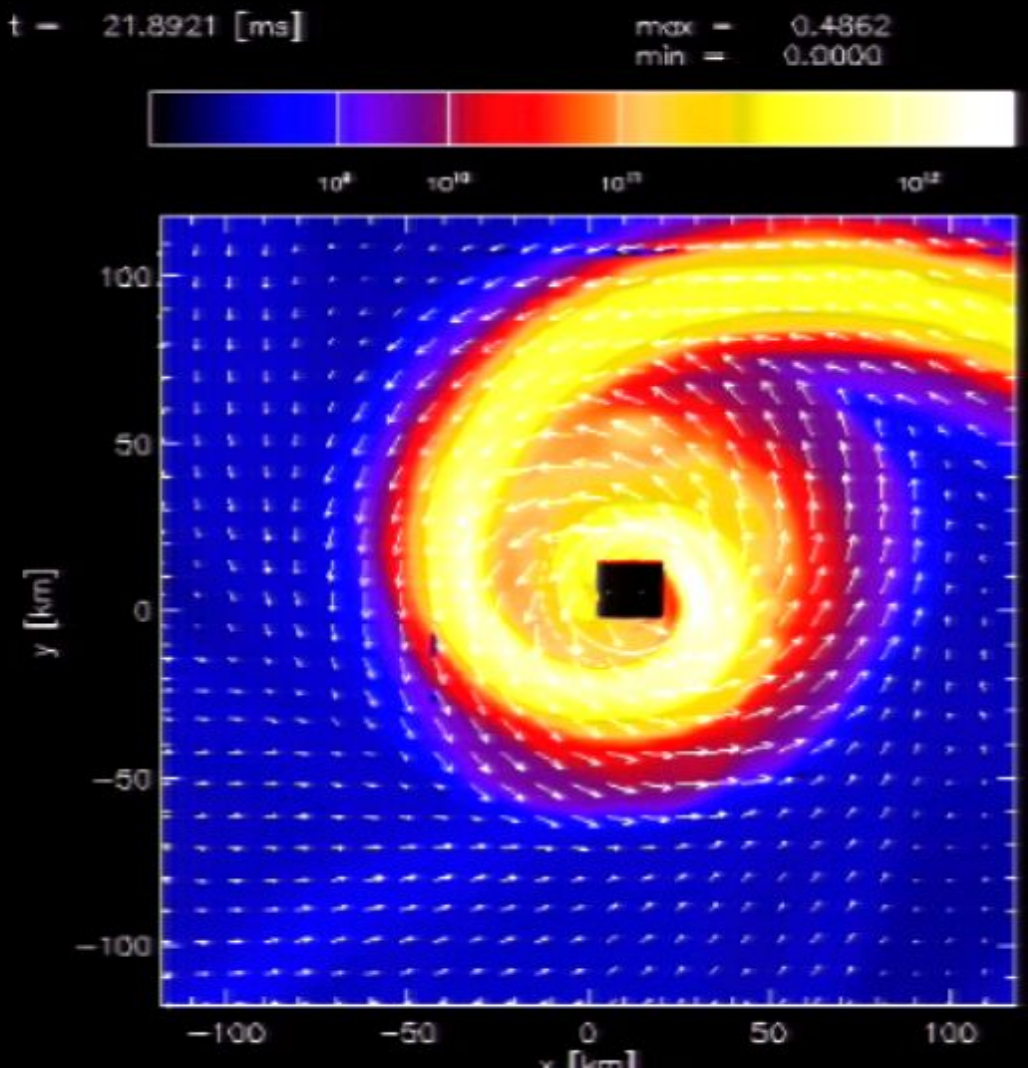

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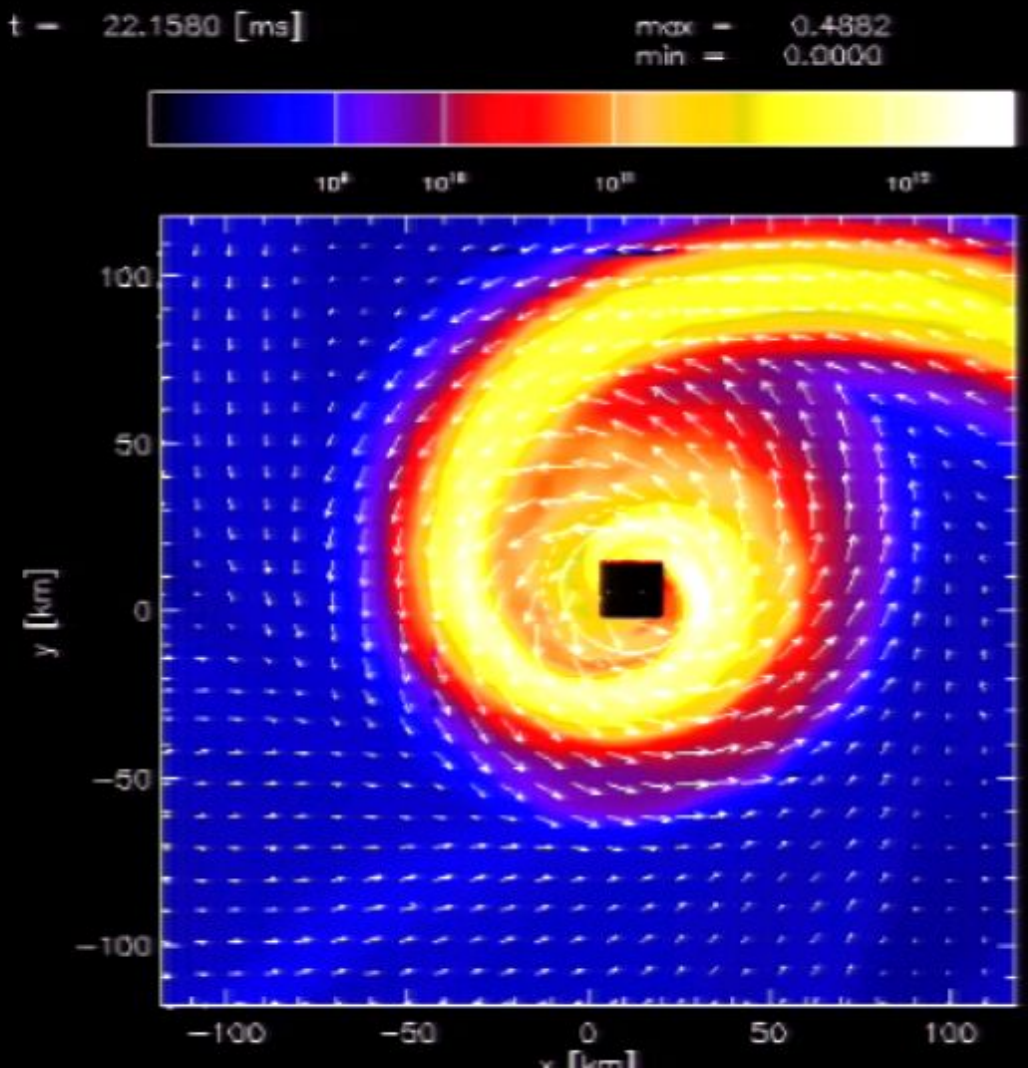
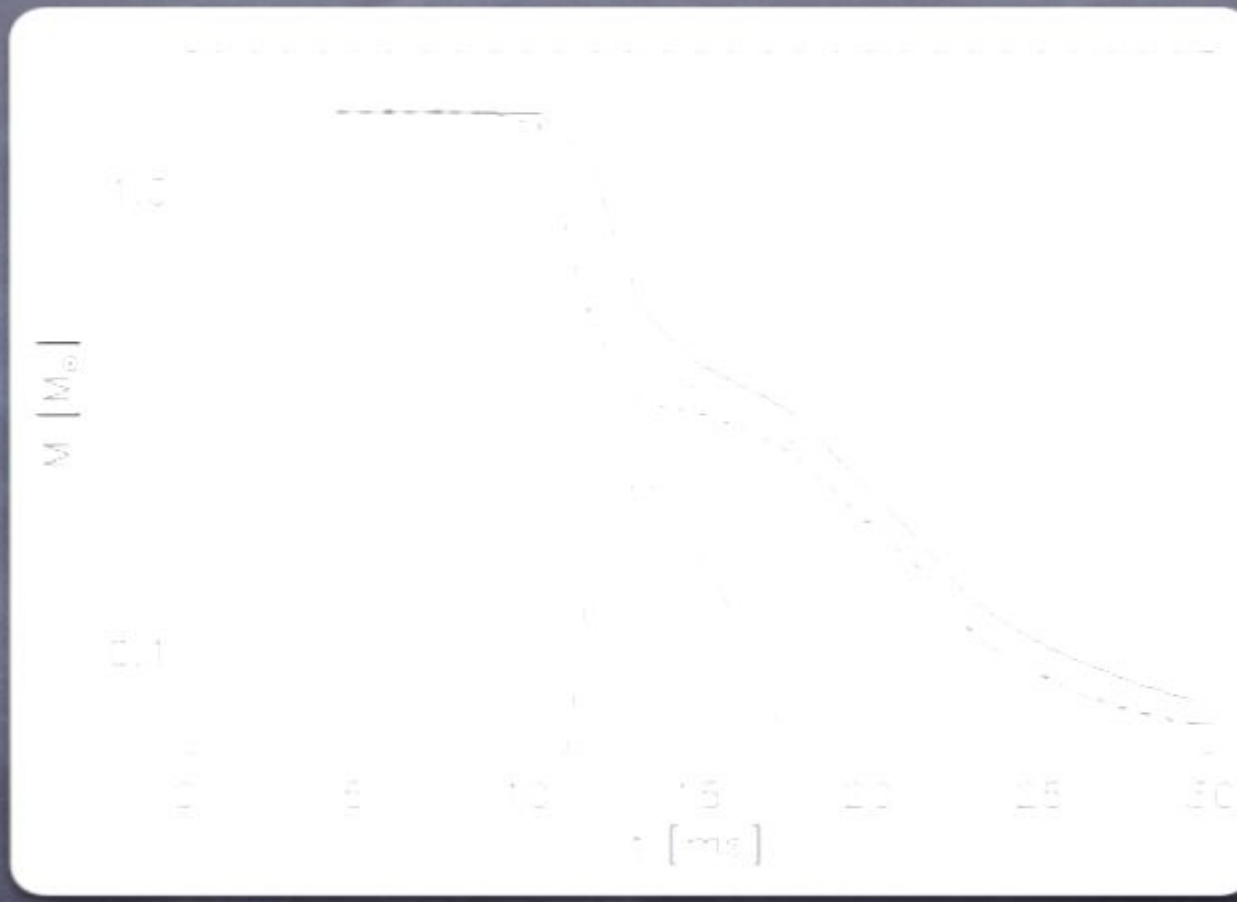


Accretion Disk

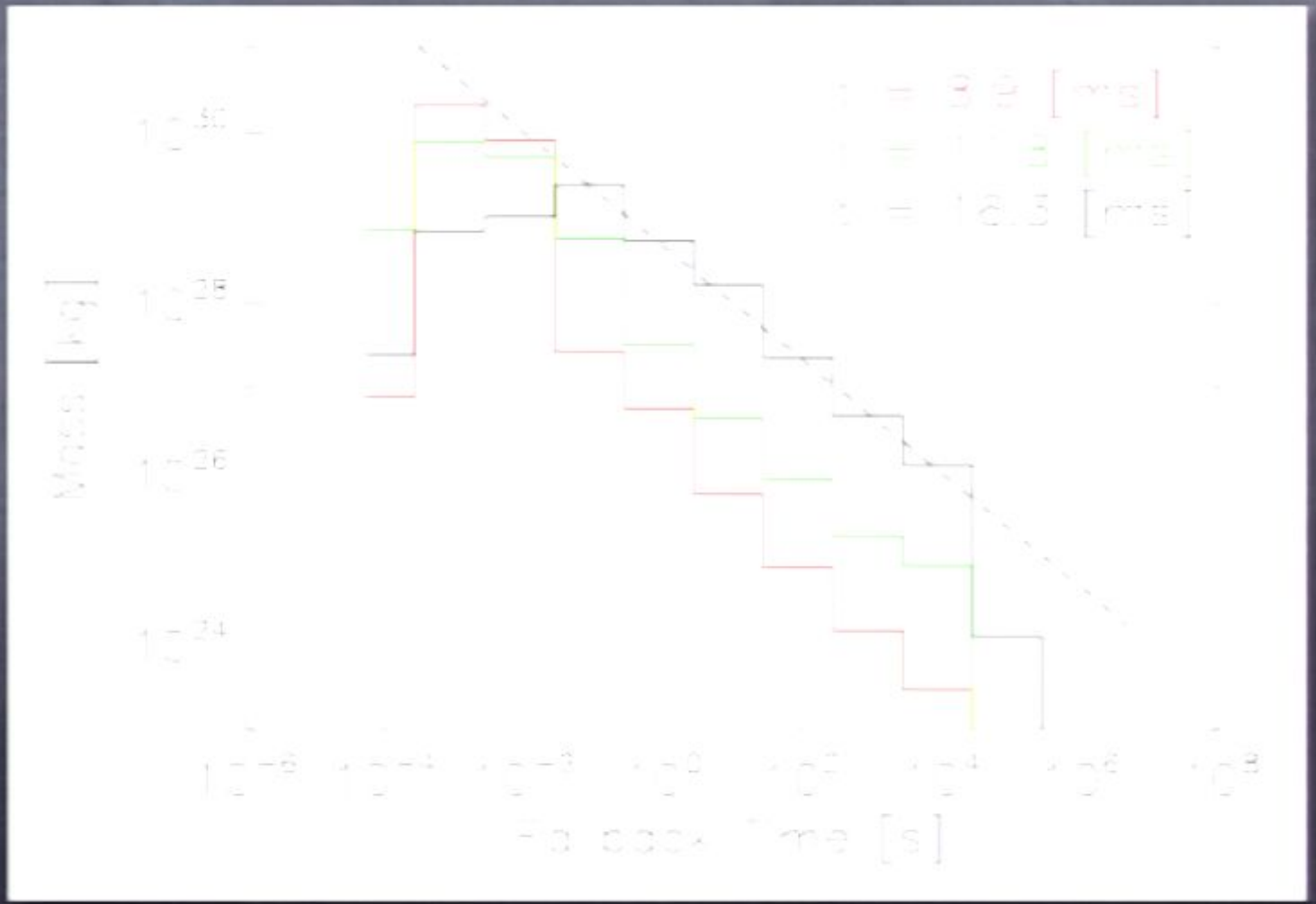
- BH final spin
  $a \approx 0.56$
- Disk mass
  $M_{\rm disk} \approx 1\% M_{\rm NS}$



olid-integrated mass Dash-bound matter
lus-mass outside ISCO Dot-Dash-4*unbound matter

Accretion Power Law

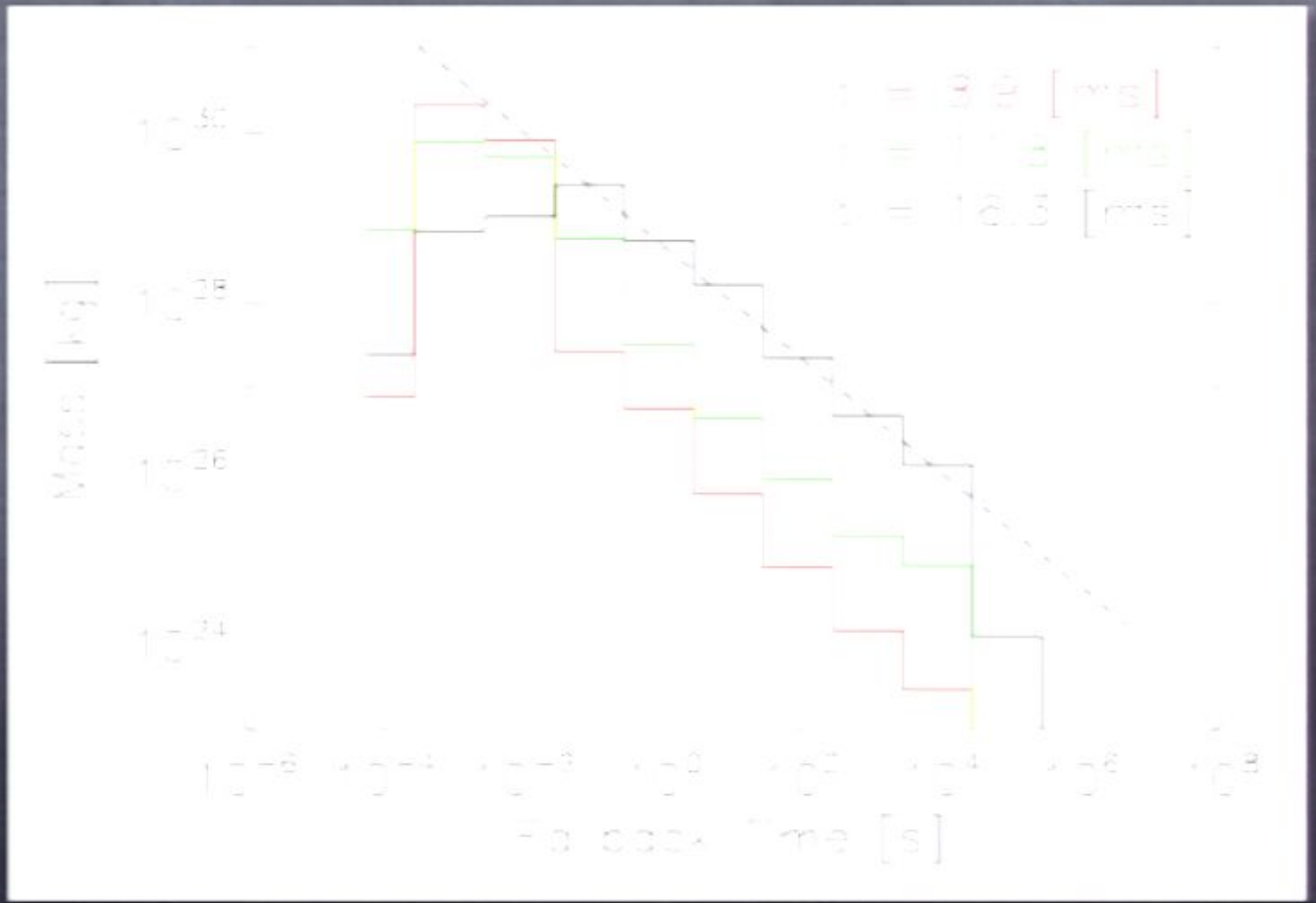
$$\frac{\mathrm{d}M}{\mathrm{d}t} \propto t^{-5/3}$$



Kicked Disk

Accretion Power Law

$$\frac{\mathrm{d}M}{\mathrm{d}t} \propto t^{-5/3}$$



Kicked Disk

Kicked BH + Disk

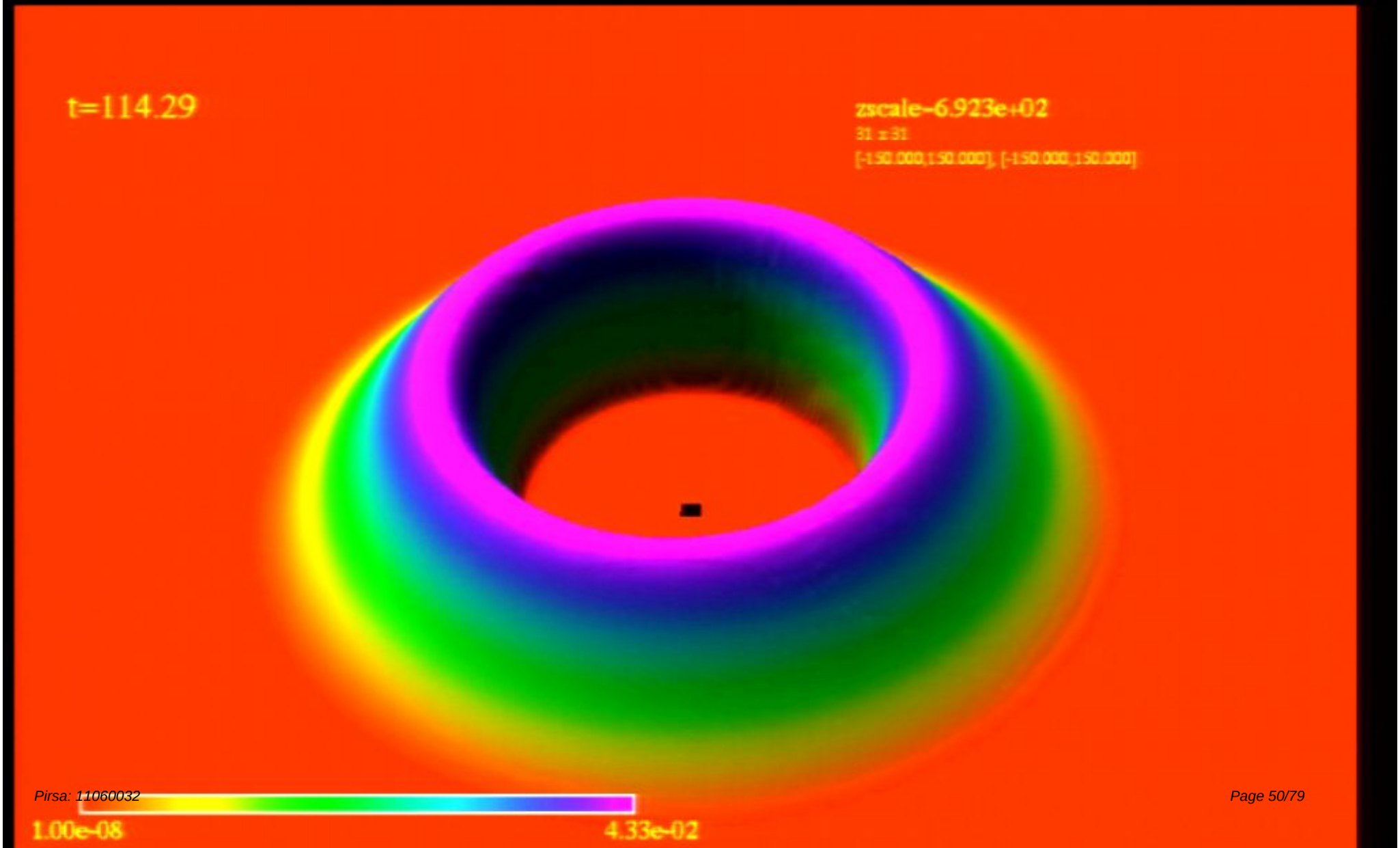
(Megevand et al., PRD 2009
Anderson et al., PRD 2010)

- Single black hole, $M=10^8\ M_{solar}$
- Kick velocity ~3,000 km/s
- "Fat" disk
  - 15 R_S from BH
  - Density 0.01 g/cm3
  - Accretion rate 1 M_{solar} per year
- See also Bode, et al., PRD (2010)

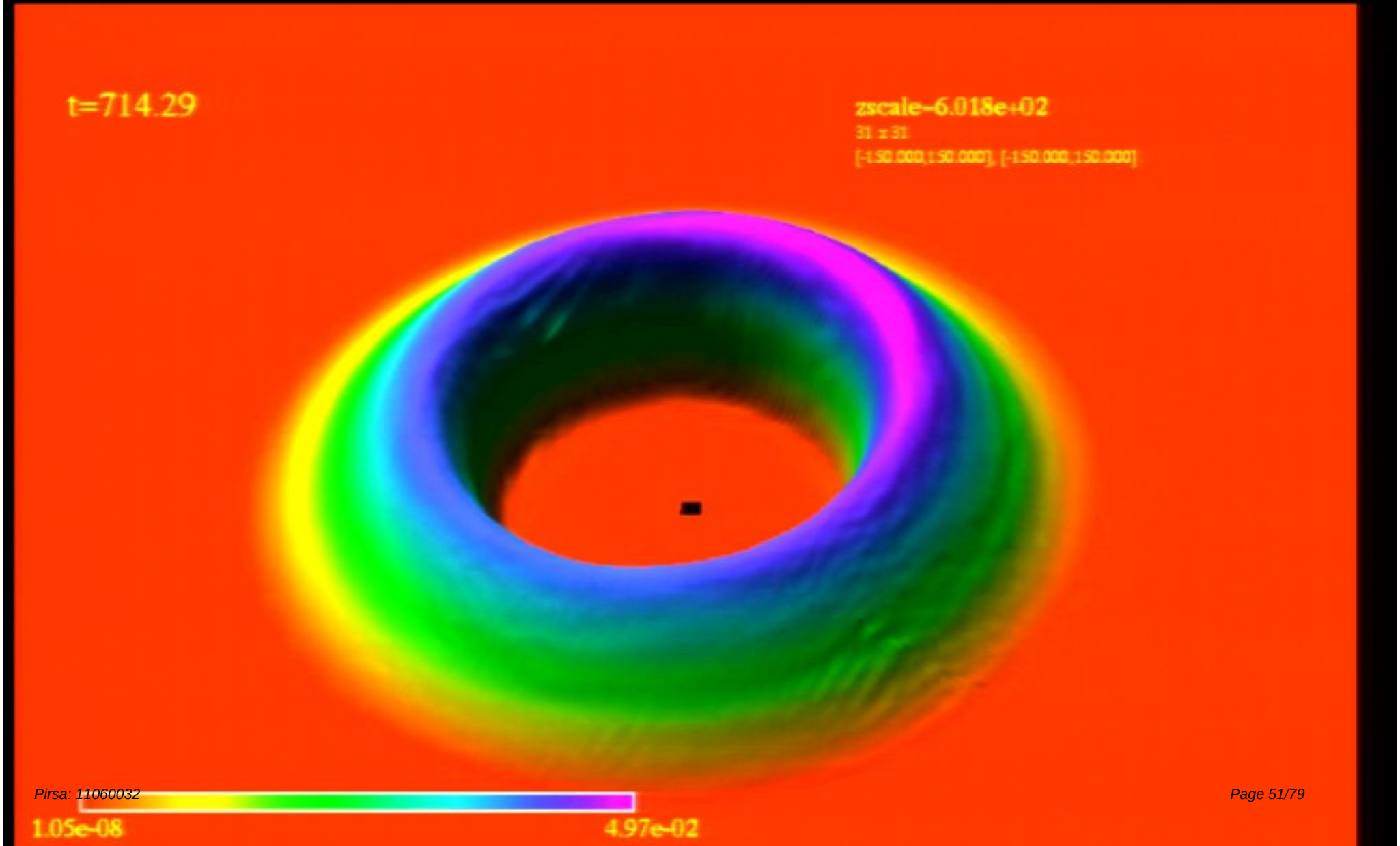
Perturbed disk

PERTURBED DISCS GET SHOCKED

Perturbed disk



Perturbed disk



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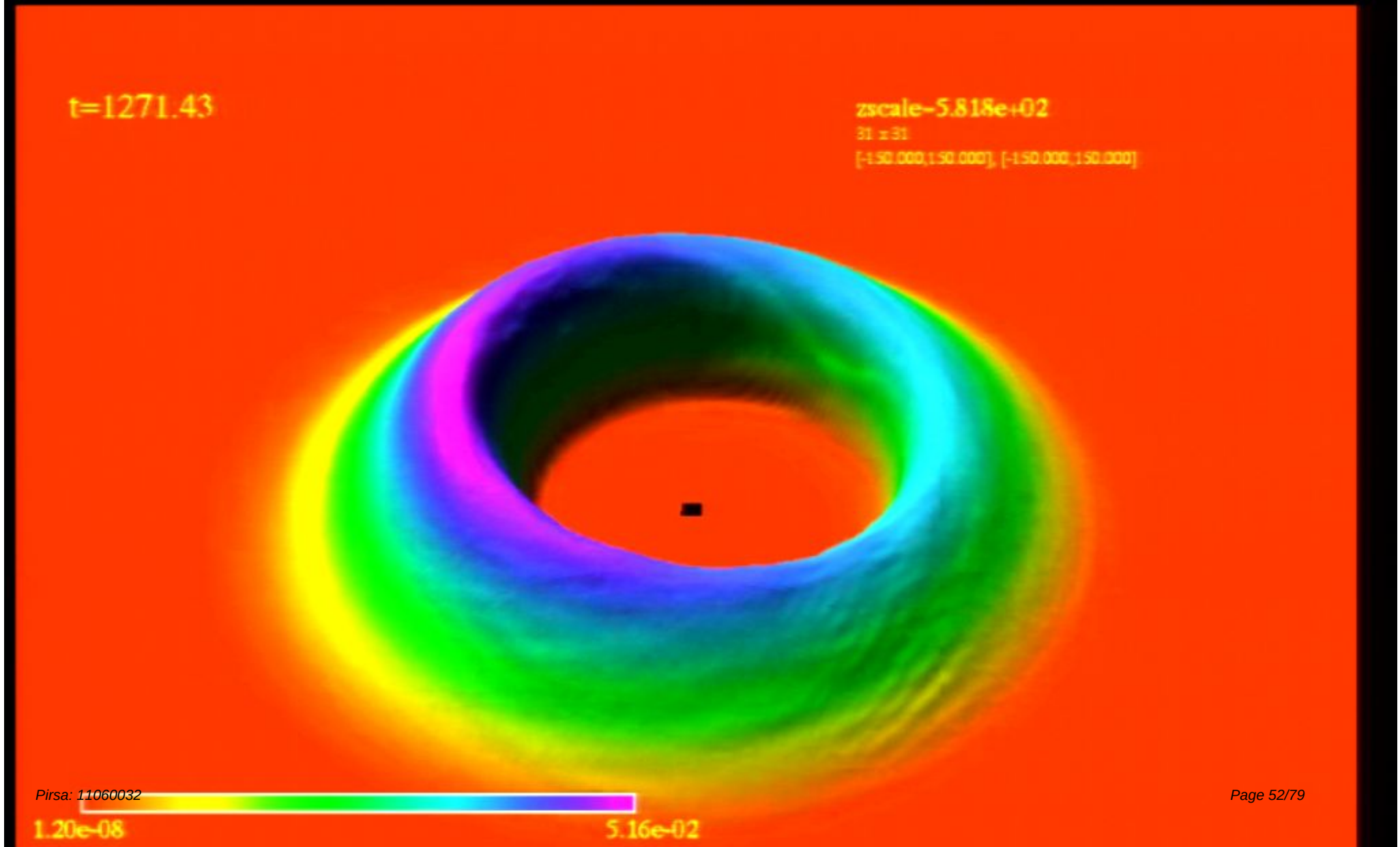

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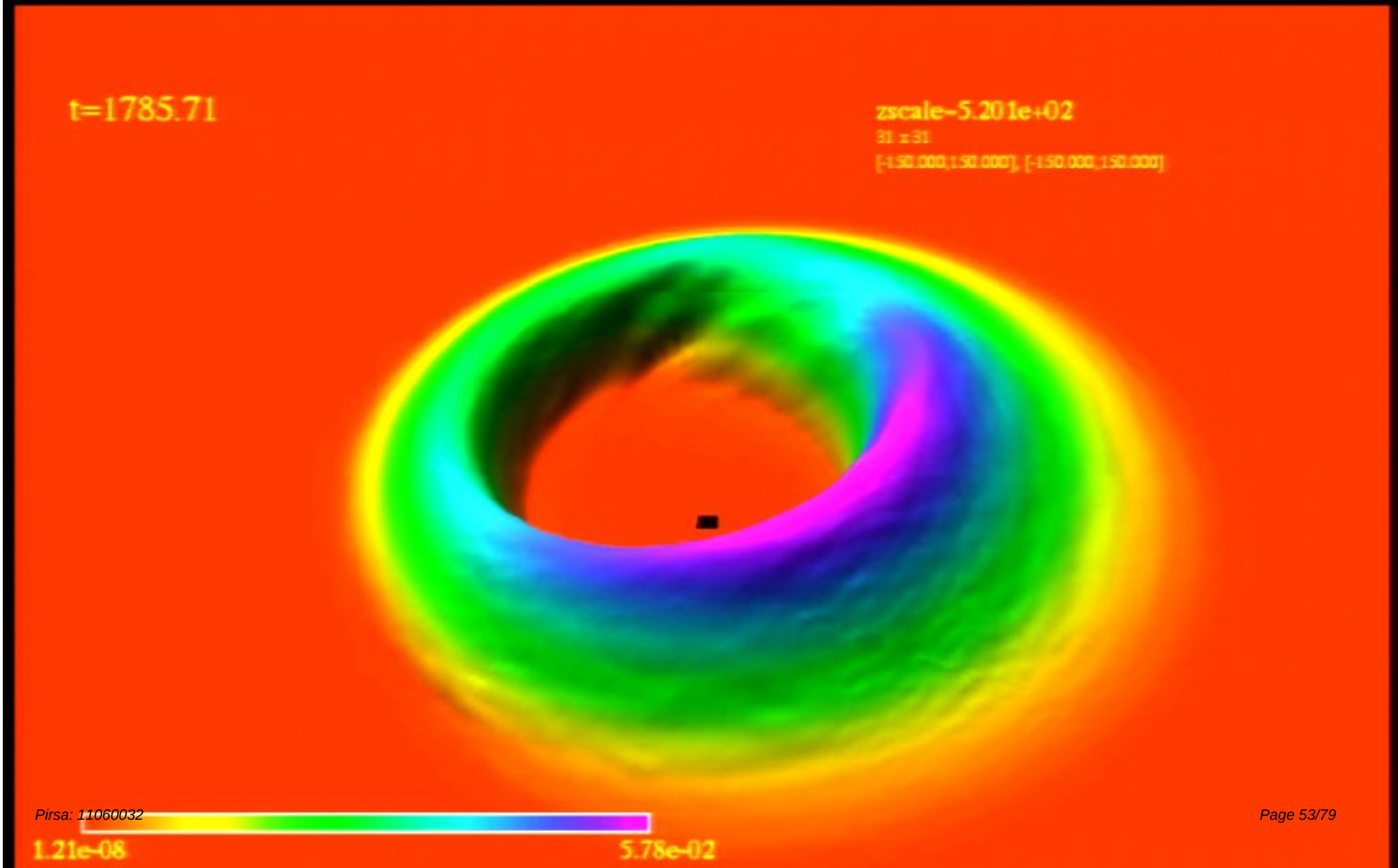

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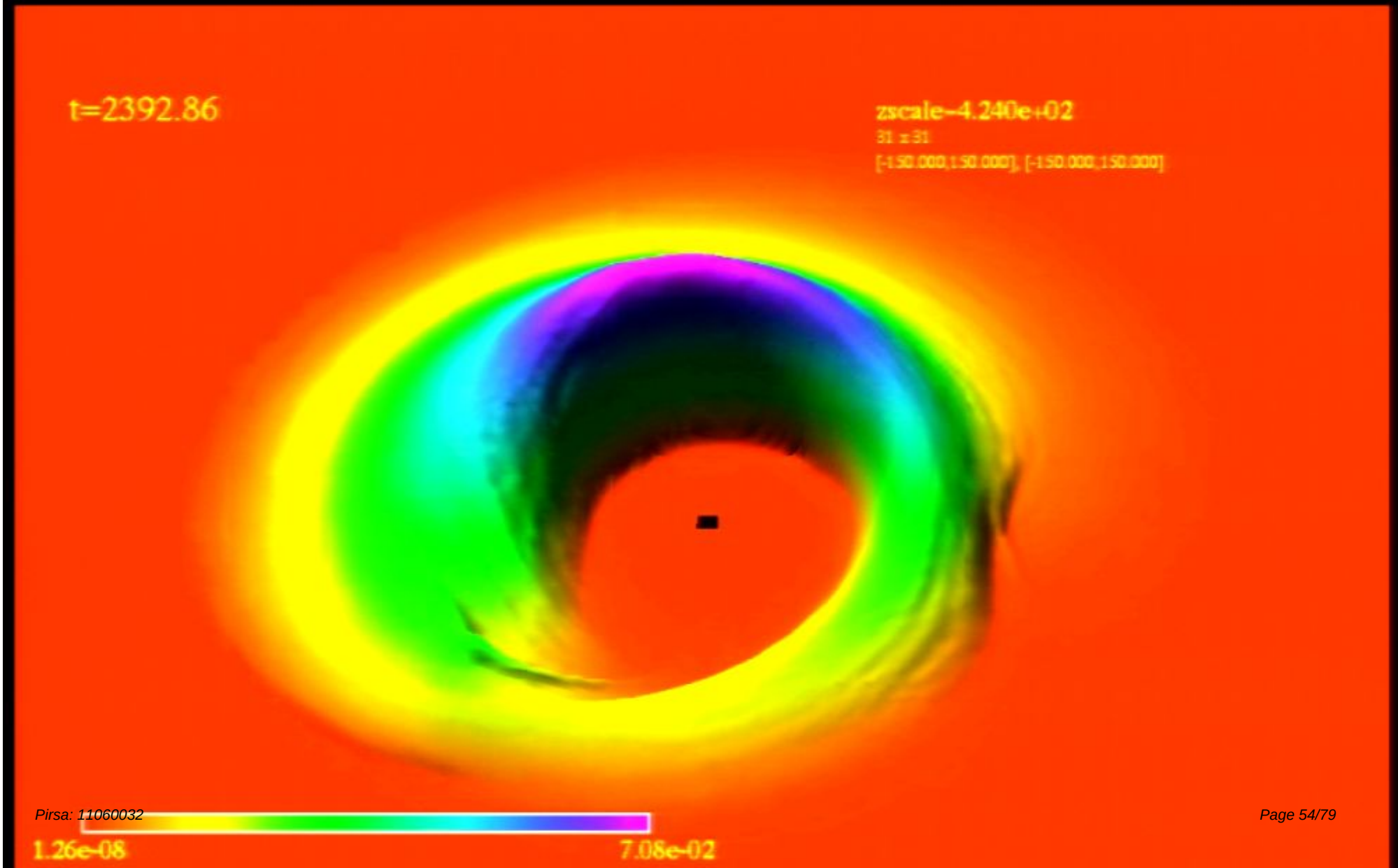

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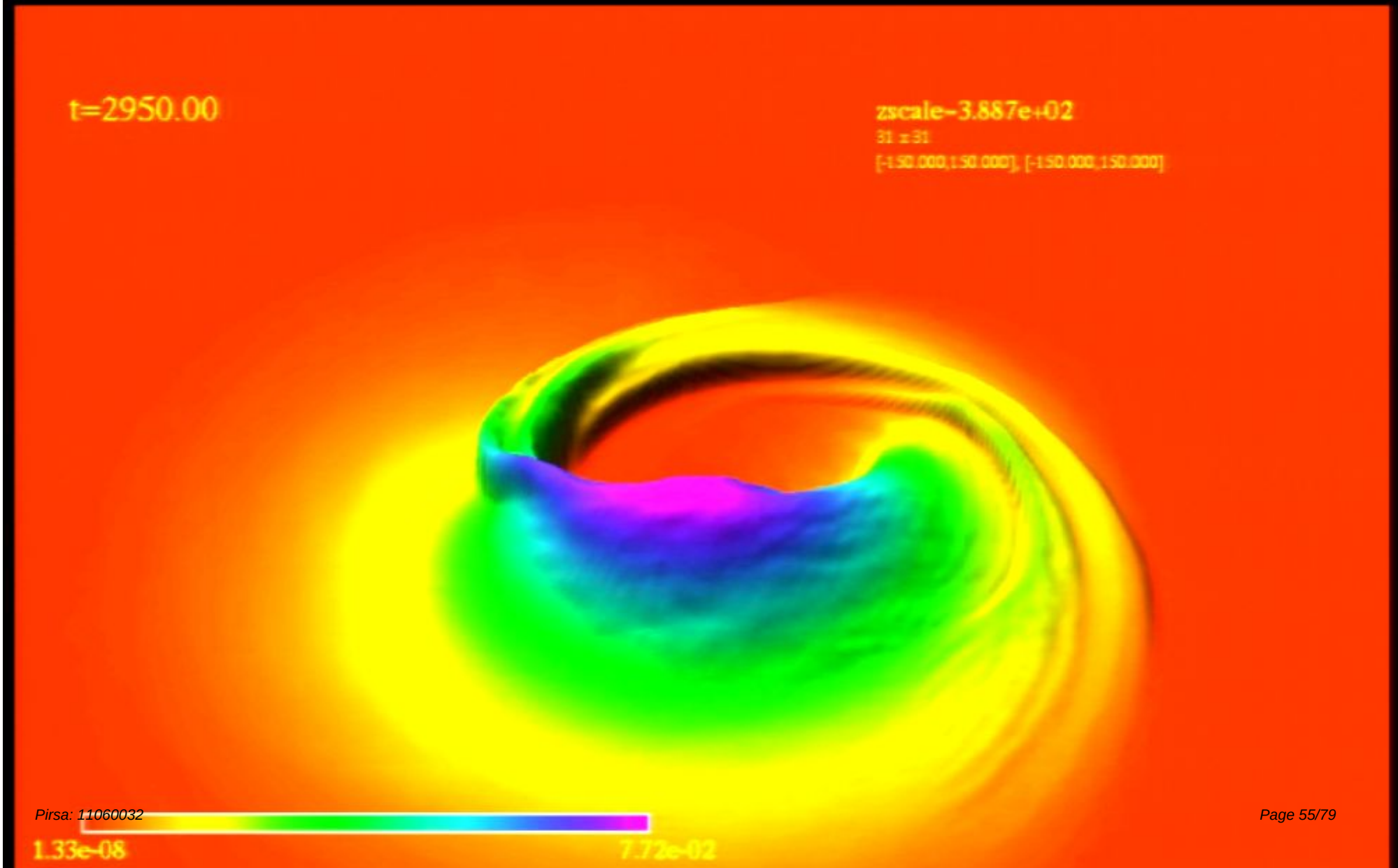
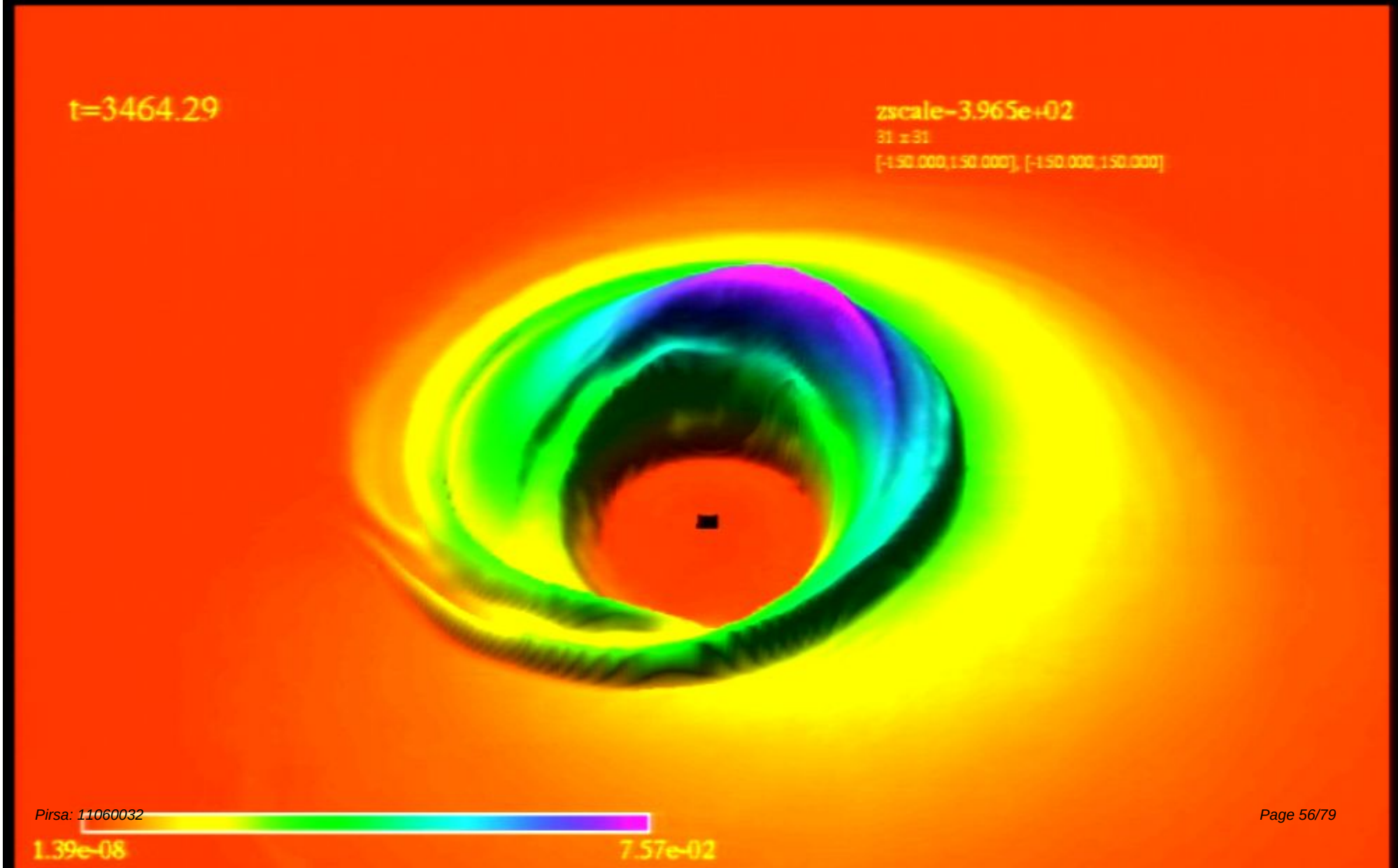
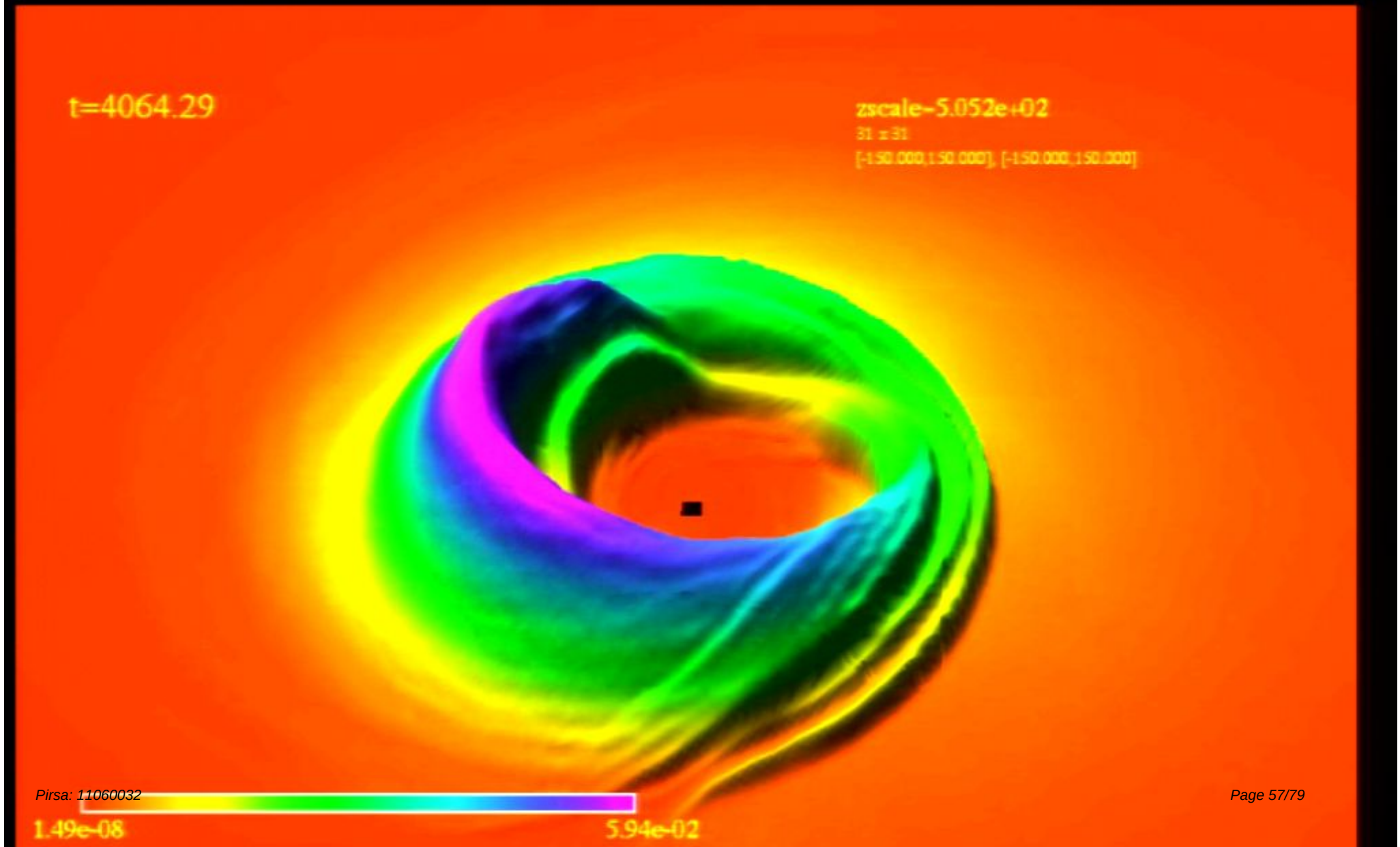


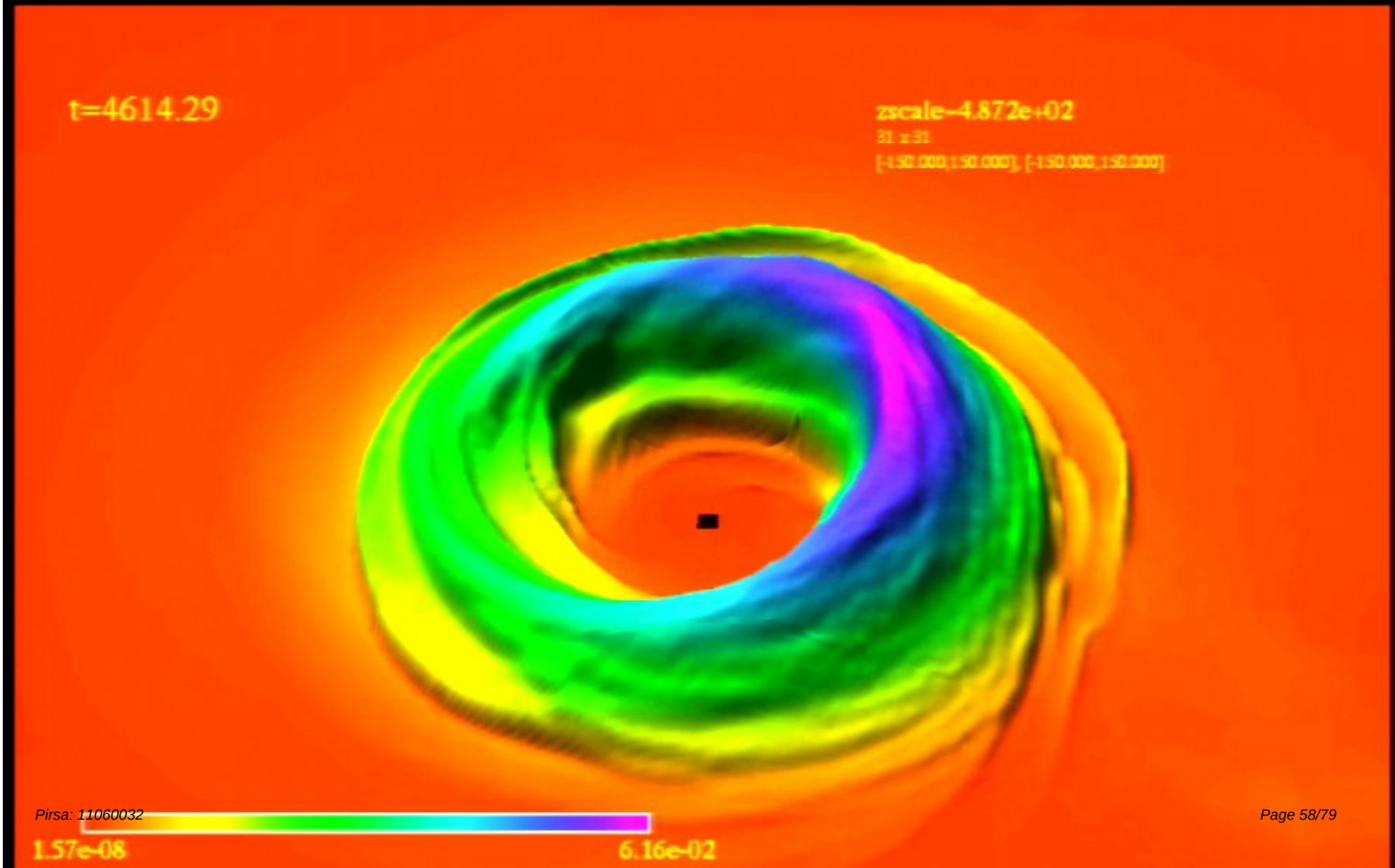
Perturbed disk



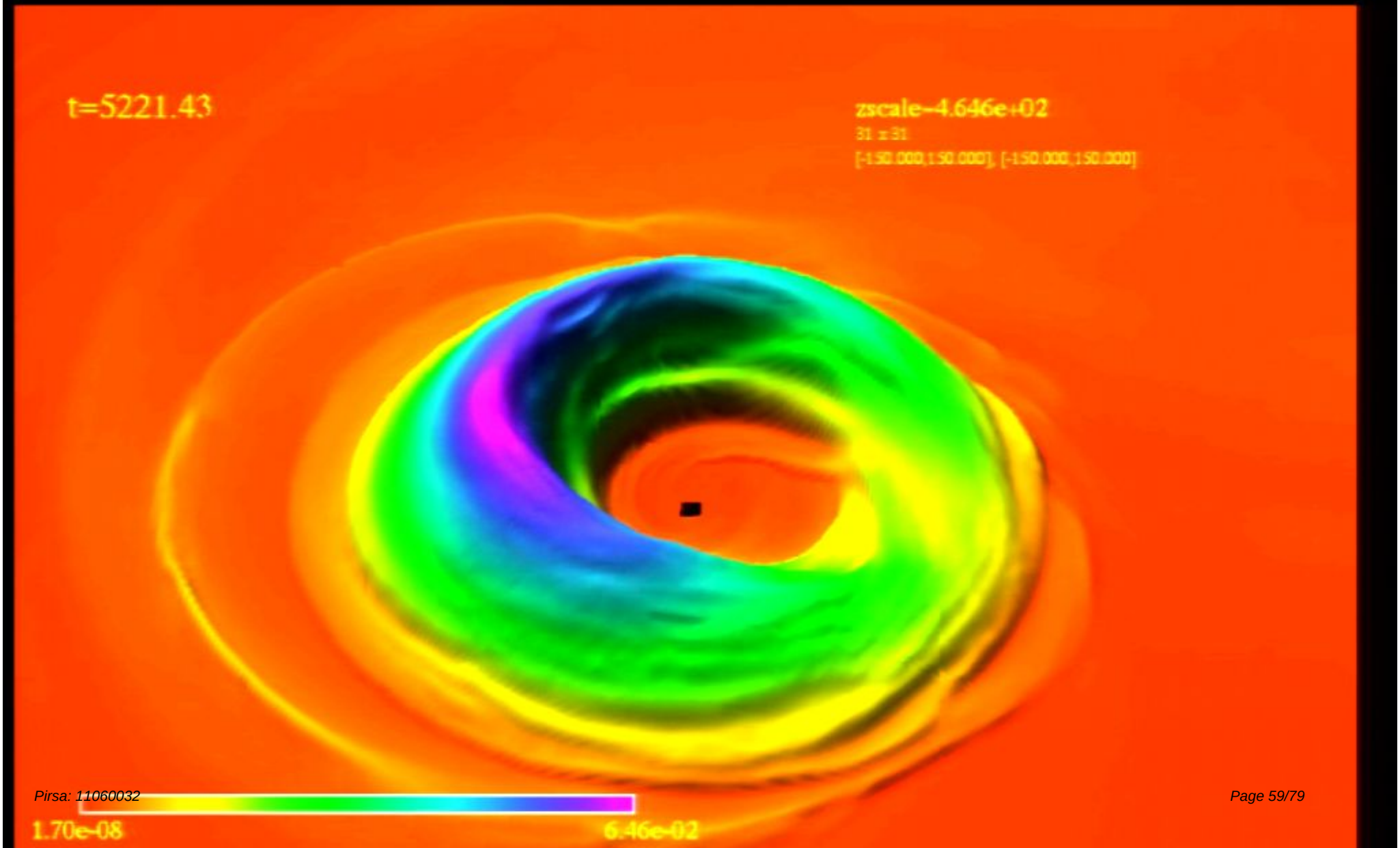
Perturbed disk



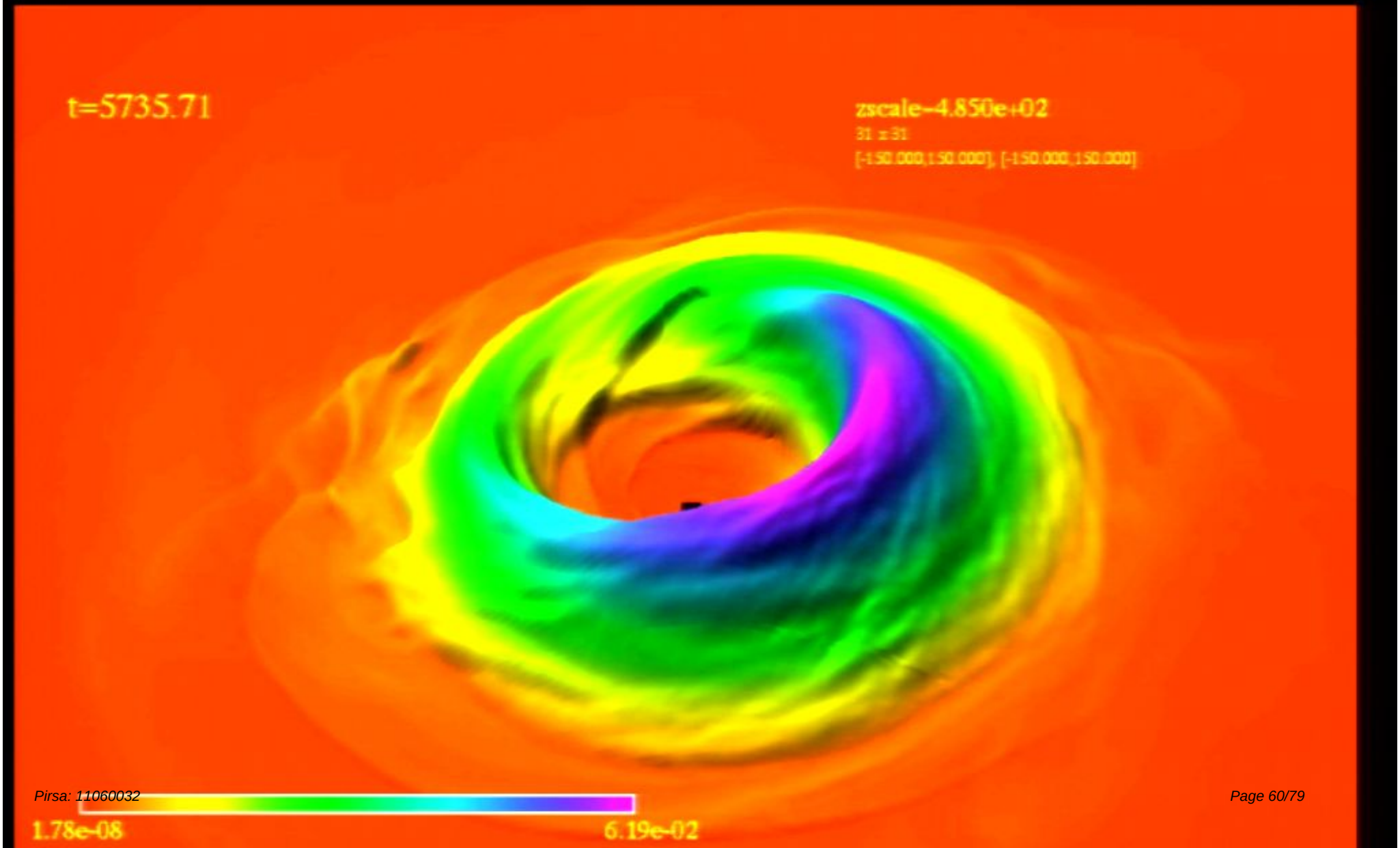
Perturbed disk



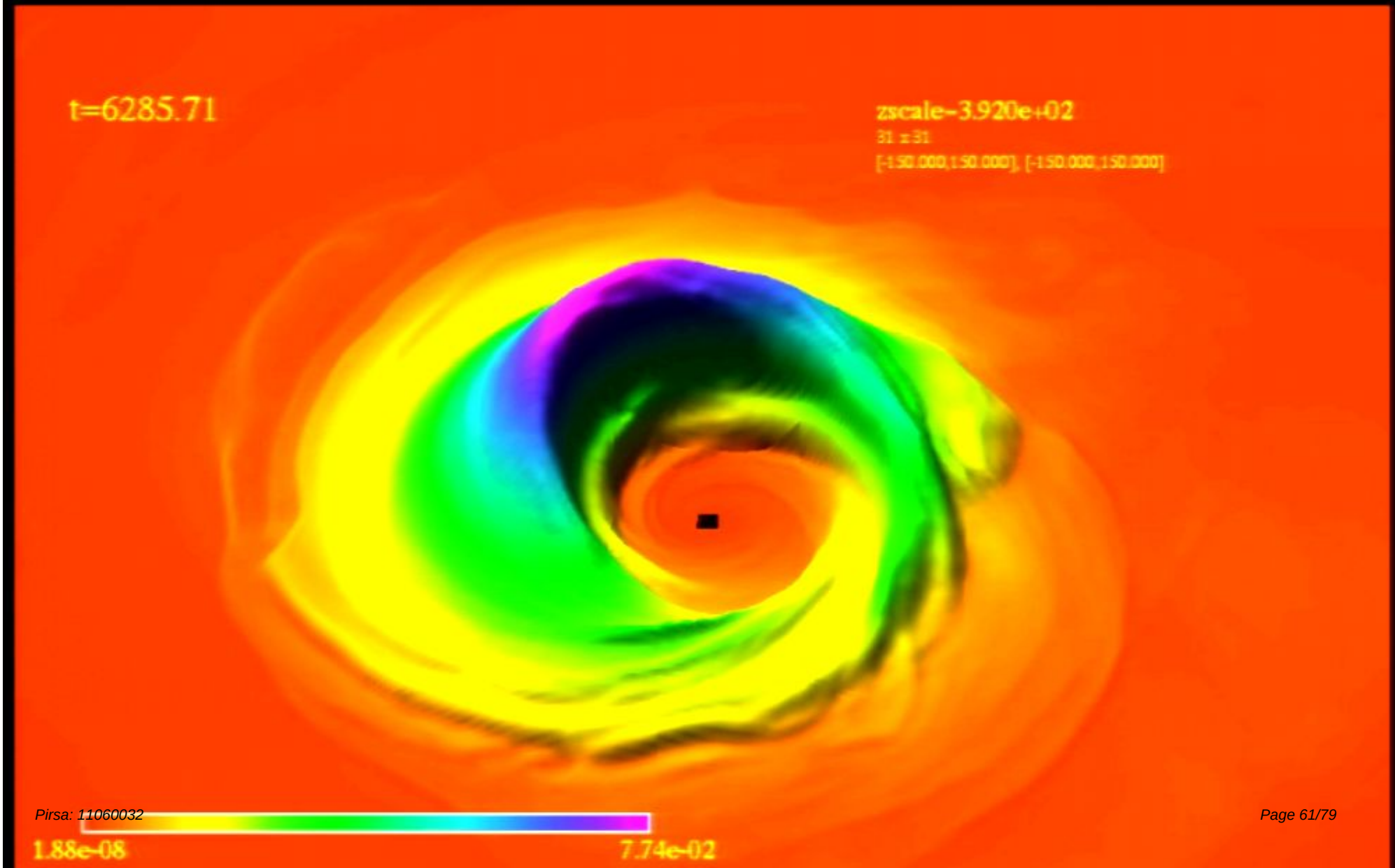
Perturbed disk



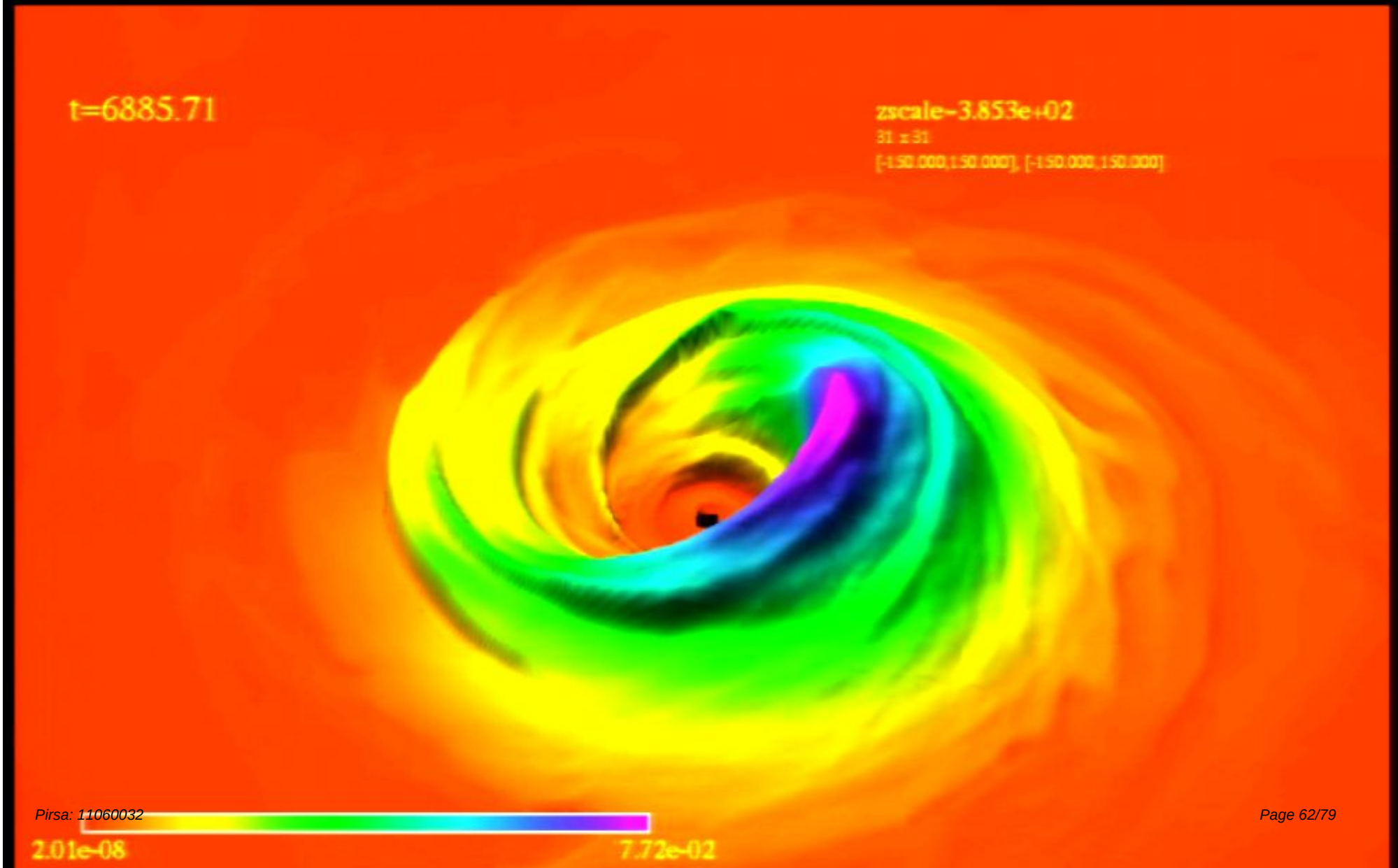
Perturbed disk



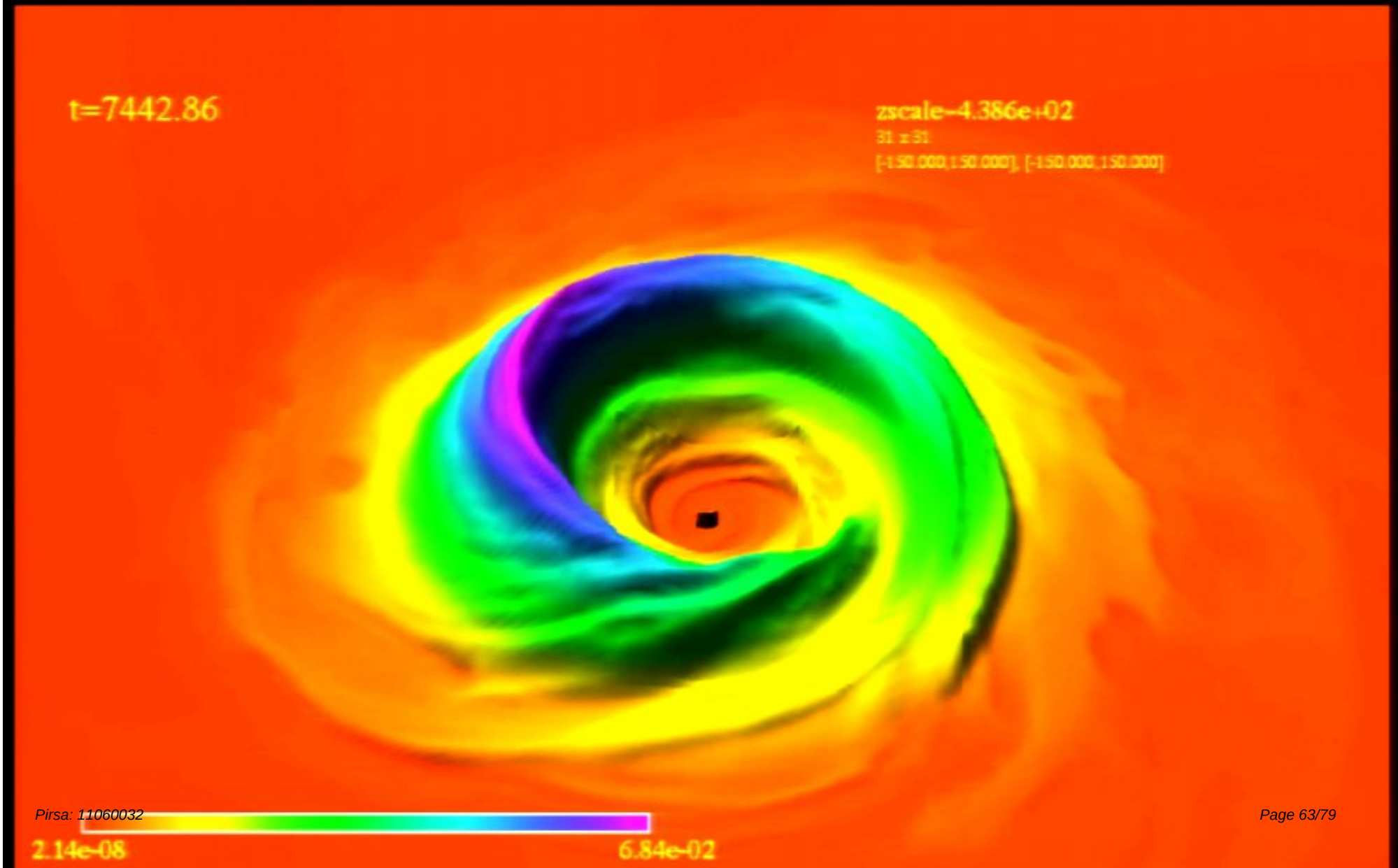
Perturbed disk



Perturbed disk



Perturbed disk



Perturbed disk

SIMULATION:

M. MEGEVAND
M. ANDERSON
J. FRANK
E. W. HIRSCHMANN
L. LEHNER
S. L. LIEBLING
P. M. MOTL
D. NEILSEN

(arXiv:0905.3390)

Movie: A. Gudiel
M. Aufiero

Radiation transfer

- Solve the transfer equation along geodesics

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\lambda} = \eta_0 - \chi_0 I_\nu$$

$$\frac{\mathrm{d}x^a}{\mathrm{d}\lambda} = p^a$$

$$\frac{\mathrm{d}p_a}{\mathrm{d}\lambda} = g^{cb}\Gamma^e{}_{ac}p_b p_e$$

- Post-processing, camera at infinity
- Fluid is adiabatic -> no cooling or heating

Astrophysical Radiation Sources

- Thermal radiation

$$\eta_0 \propto \frac{\nu^3}{e^{h\nu/kT} - 1}$$

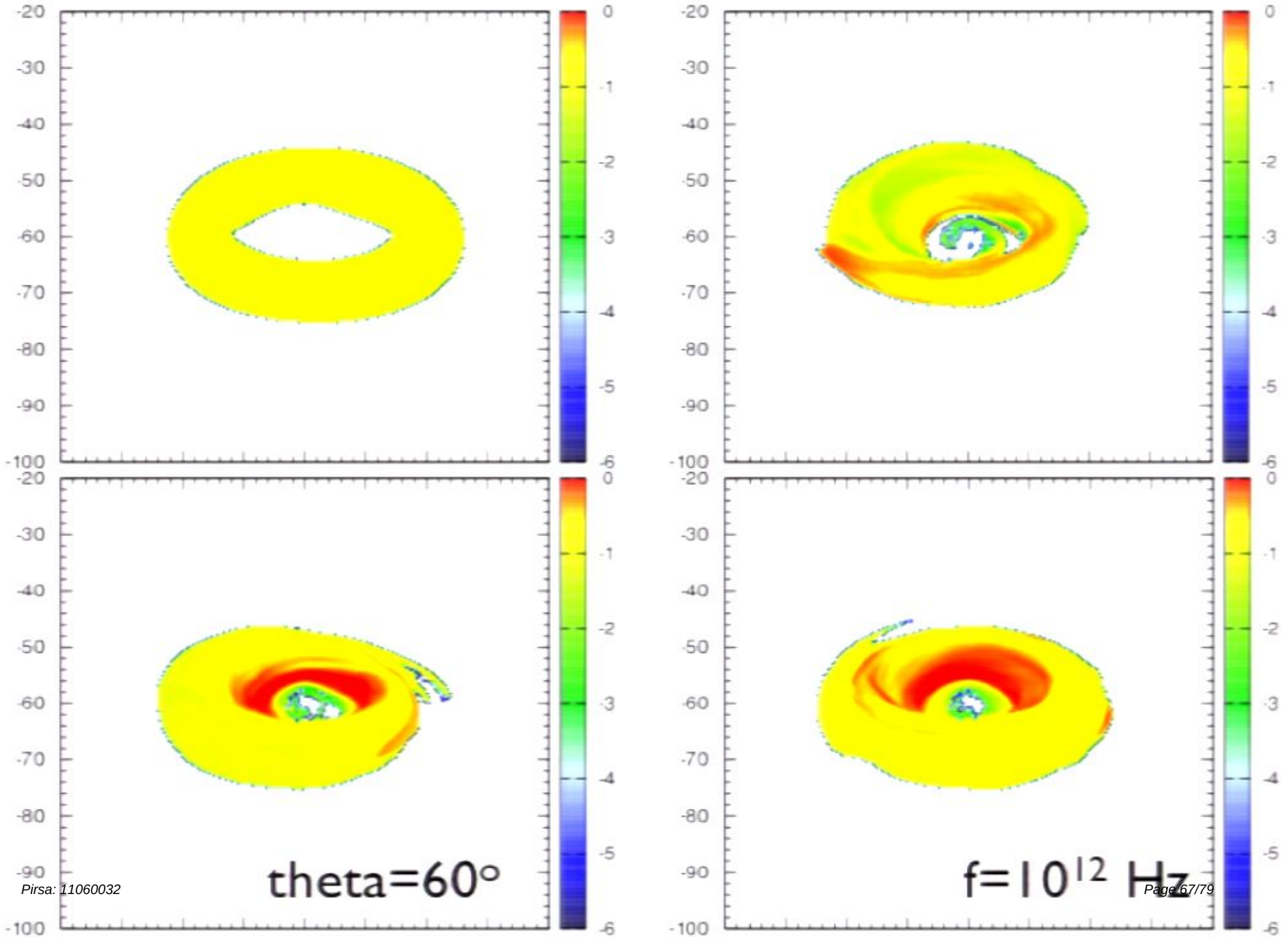
- Bremsstrahlung

$$\eta_0 \propto T^{-1/2} e^{-h\nu/kT}$$

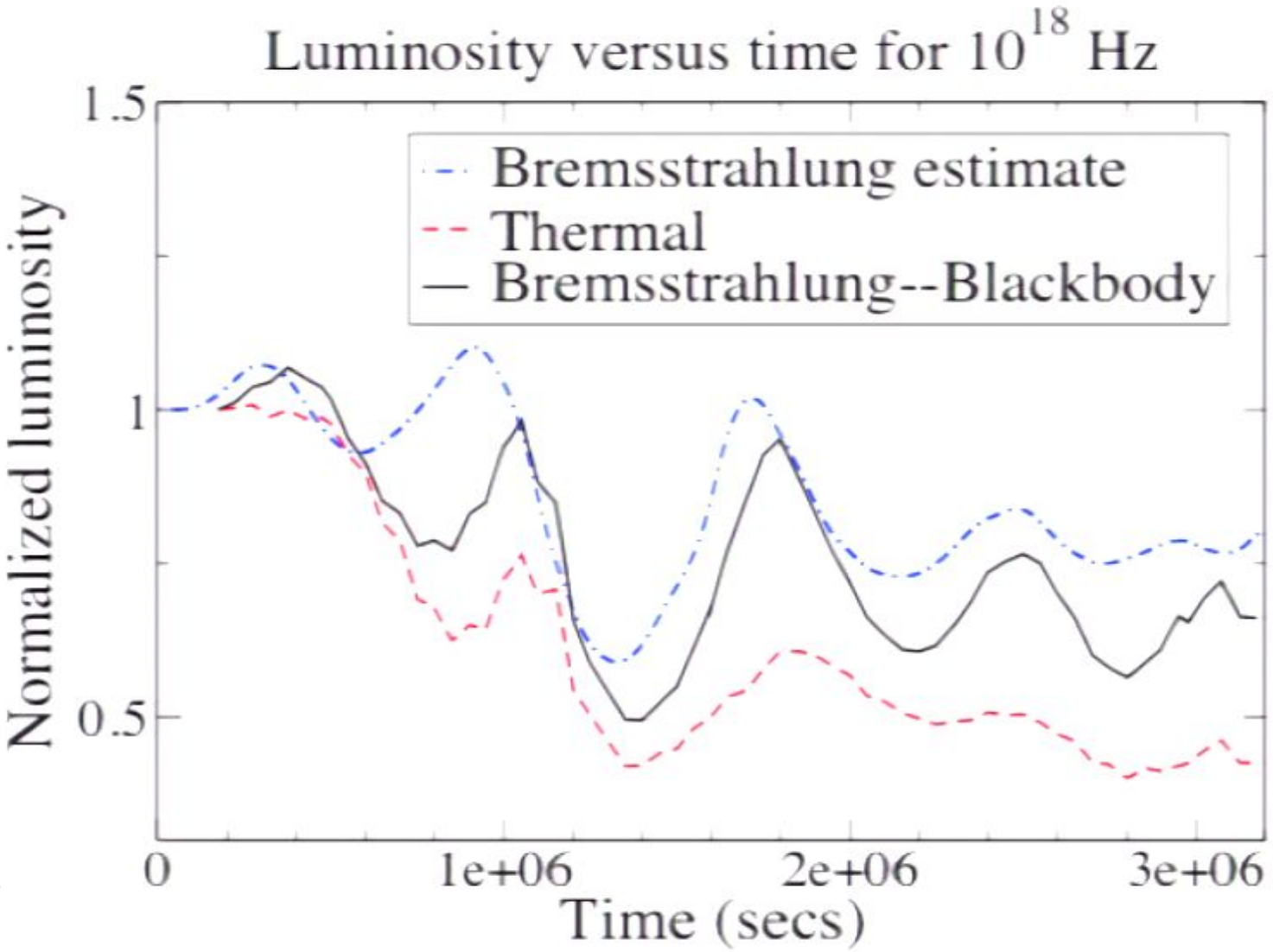
- Synchrotron emission

- Absorption

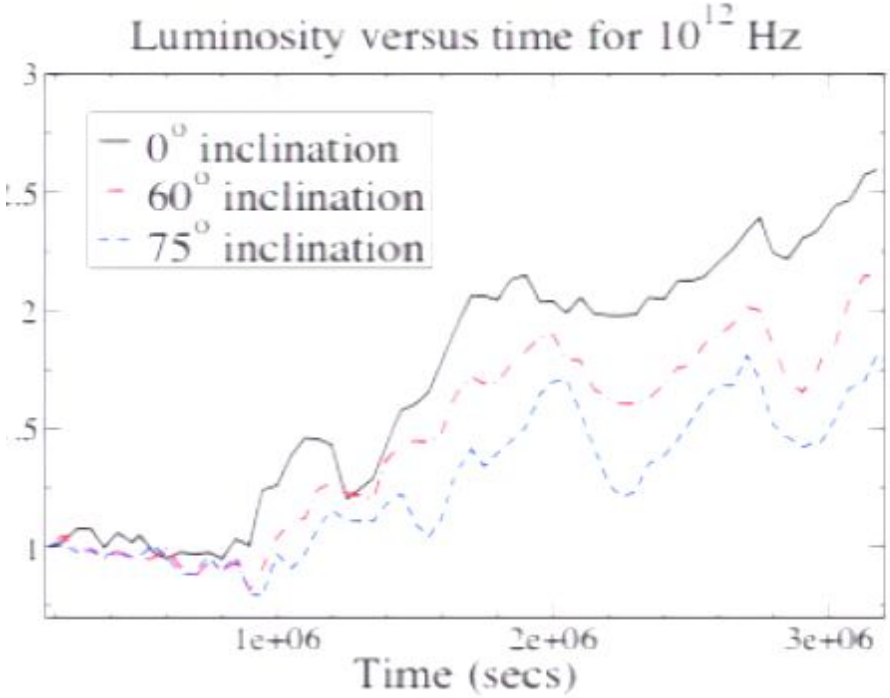
$$\chi_0 \propto \rho^2 T^{-7/2} \left(\frac{1 - e^{-x}}{x^3} \right)$$

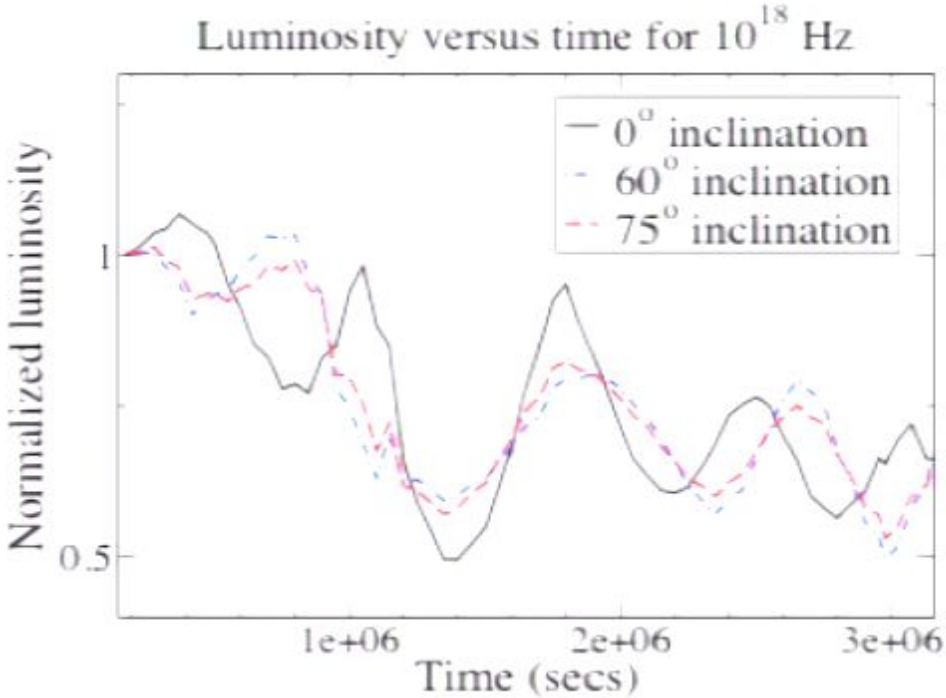

theta=60°
f=10^12 Hz

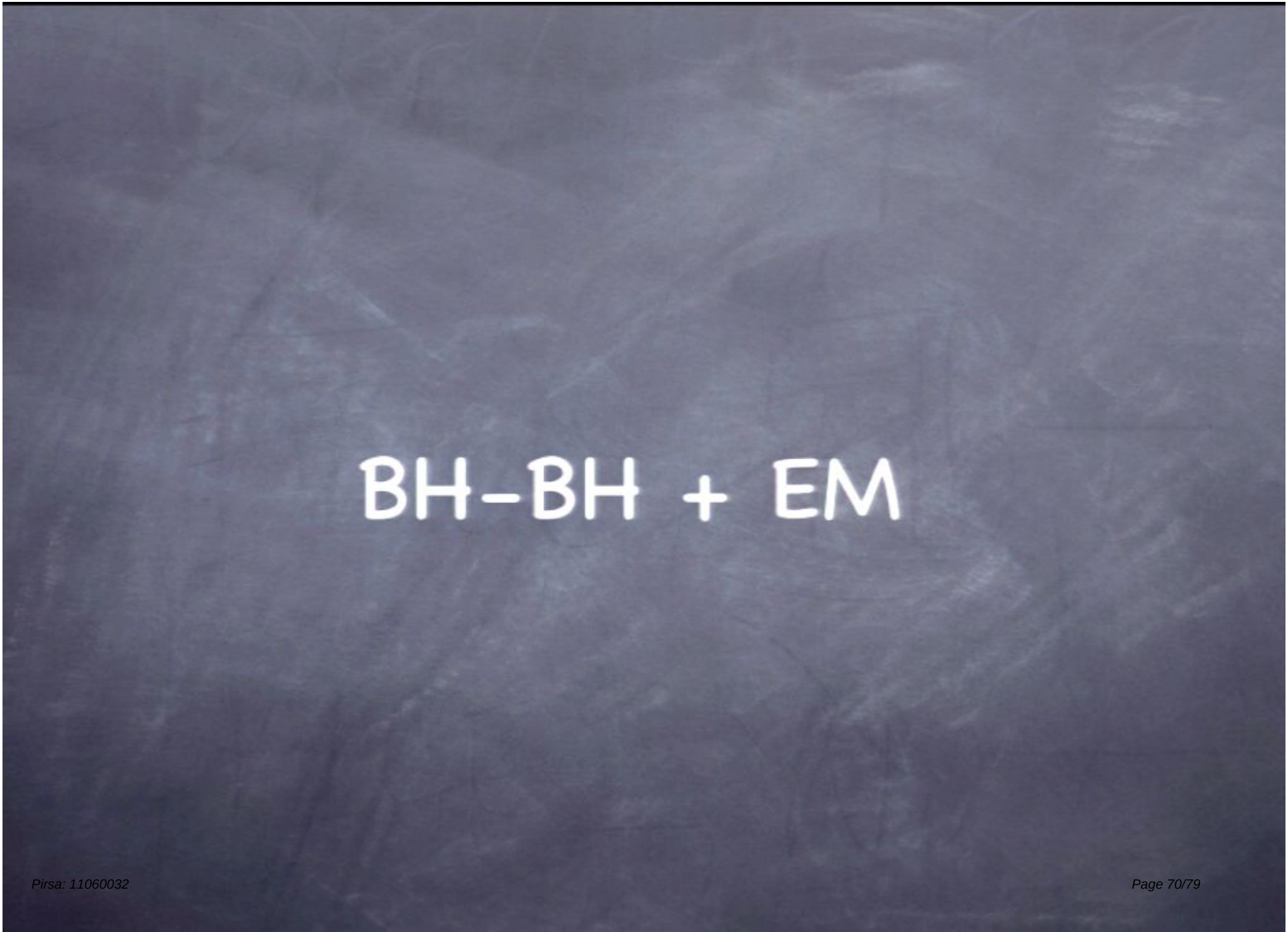
Emission models



Luminosity with inclination

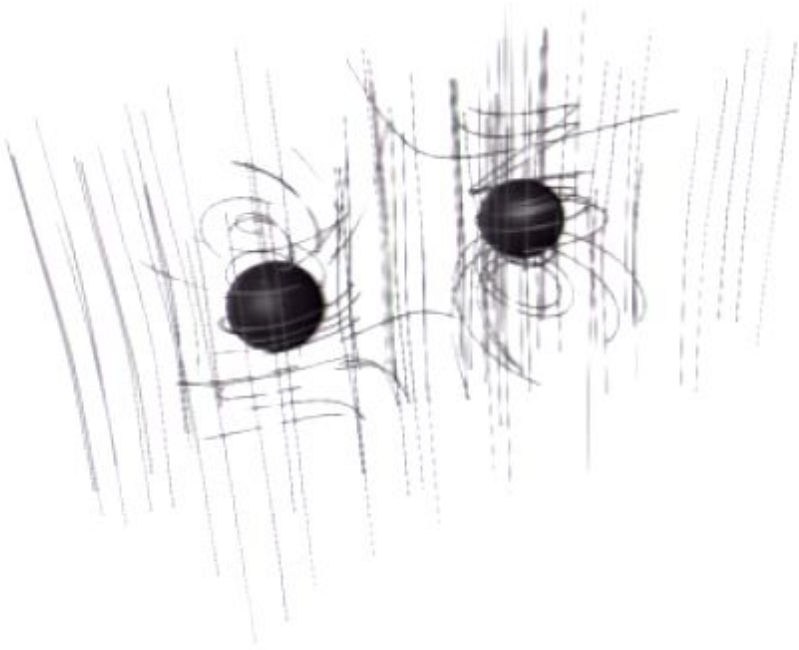




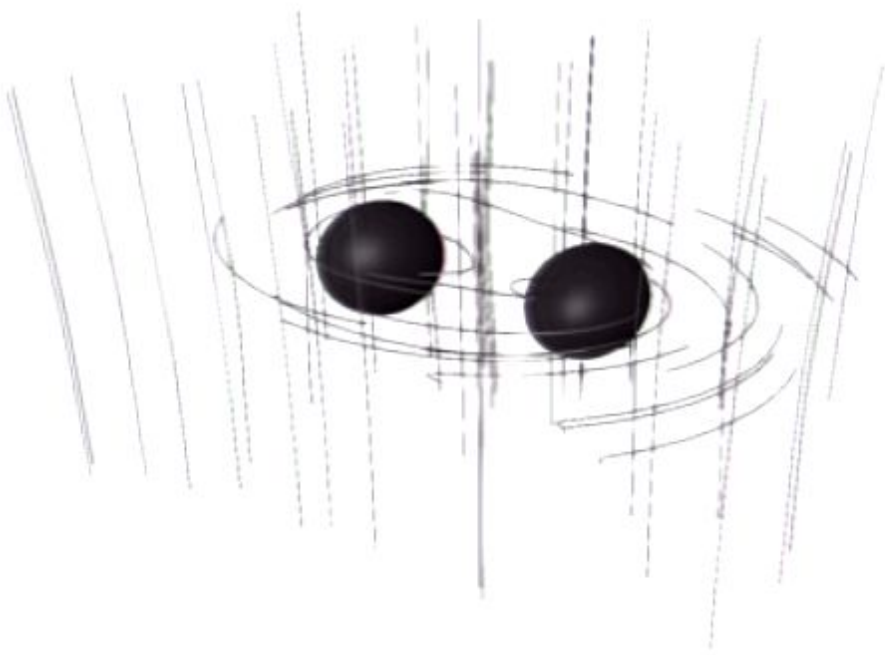

BH-BH + EM

BBH + Maxwell

(Palenzuela et al., PRL 2009)

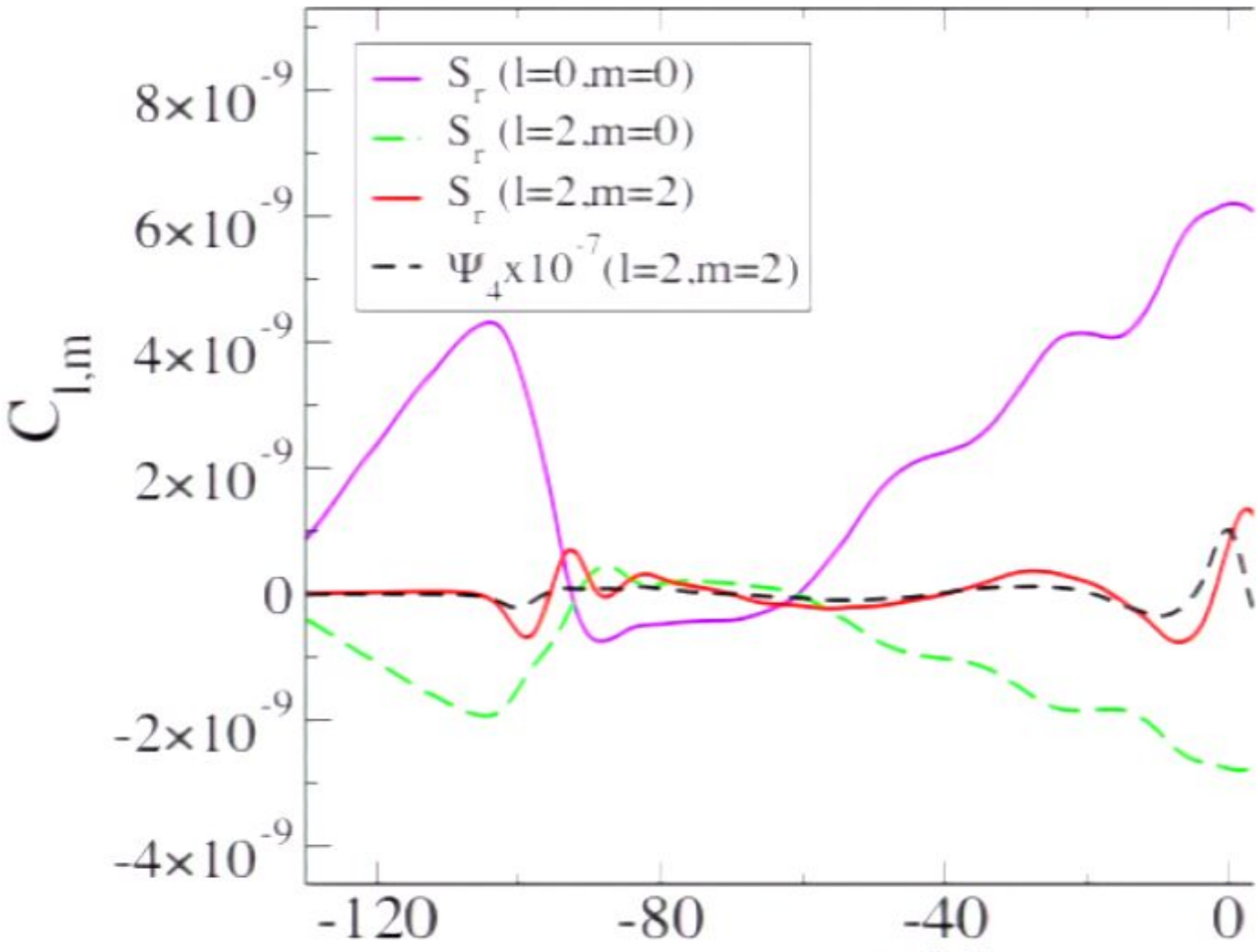


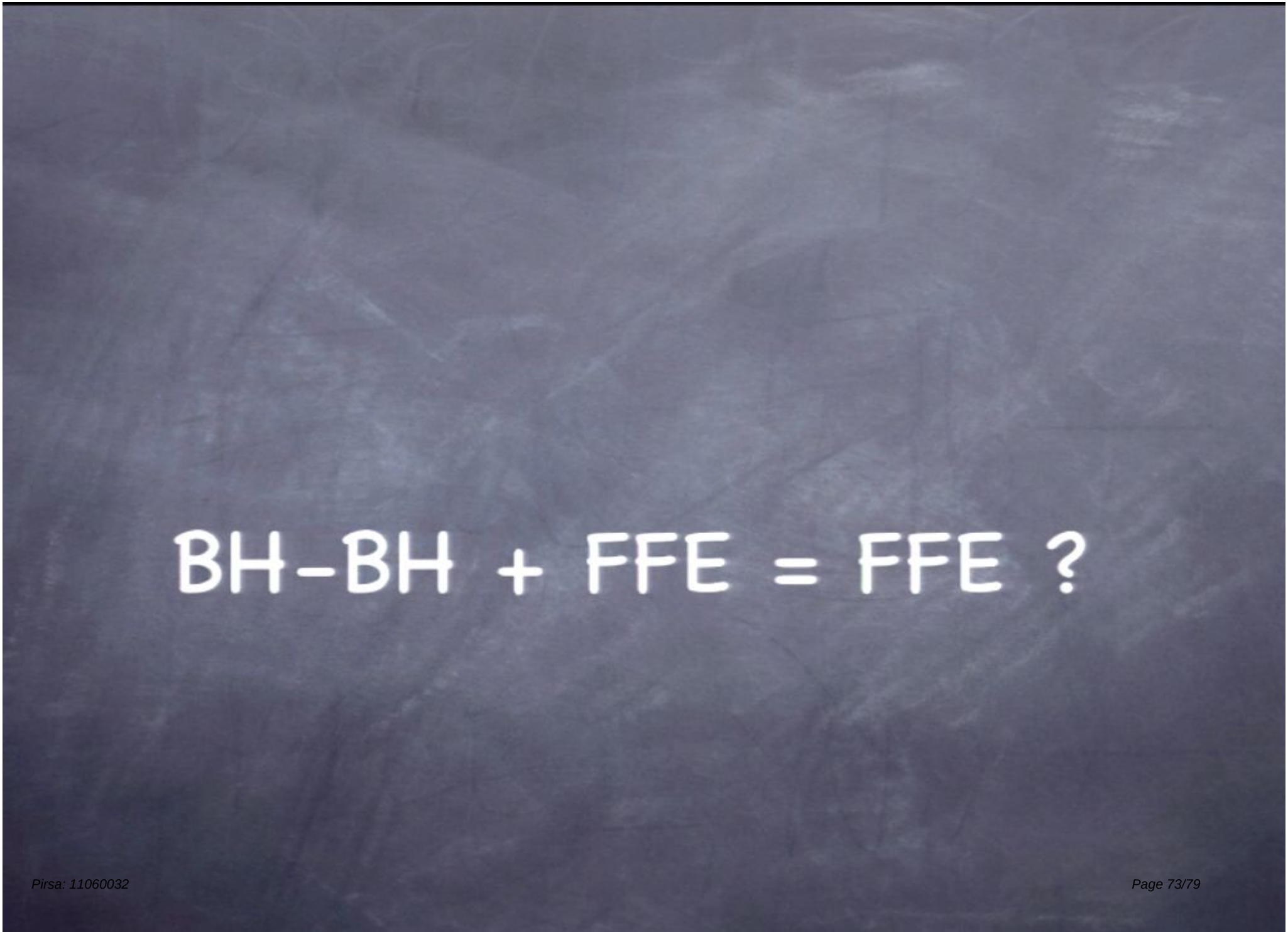
t = -40 M



t = -20 M

EM+GW Modes


S_r (l=0,m=0)
S_r (l=2,m=0)
S_r (l=2,m=2)
$\Psi_4 \times 10^{-7}$ (l=2,m=2)
$C_{l,m}$
8×10^{-9}
6×10^{-9}
4×10^{-9}
2×10^{-9}
0
-2×10^{-9}
-4×10^{-9}
-120
-80
-40
0


BH-BH + FFE = FFE ?

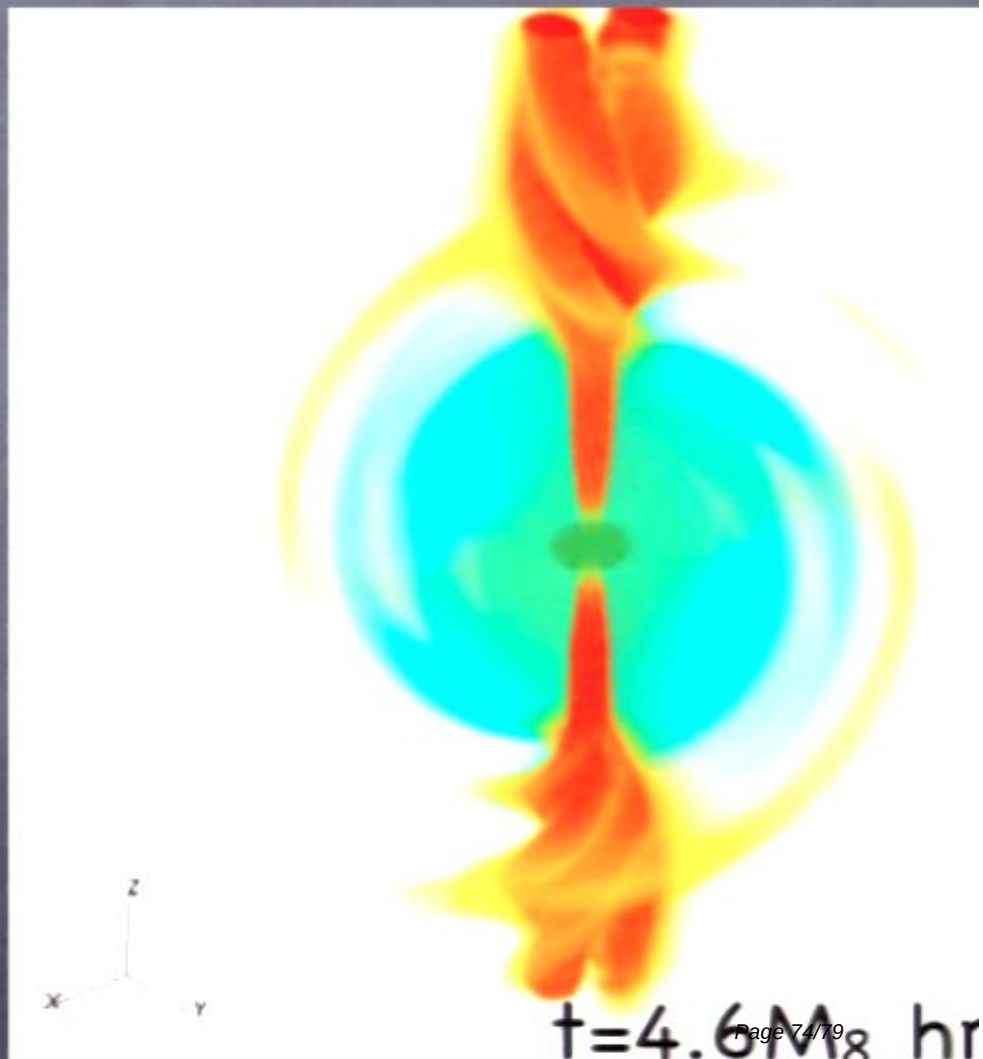
BBH + Magnetosphere

- Einstein+Maxwell
- BBH, M=10^8 M_{solar}
- Force-free condition

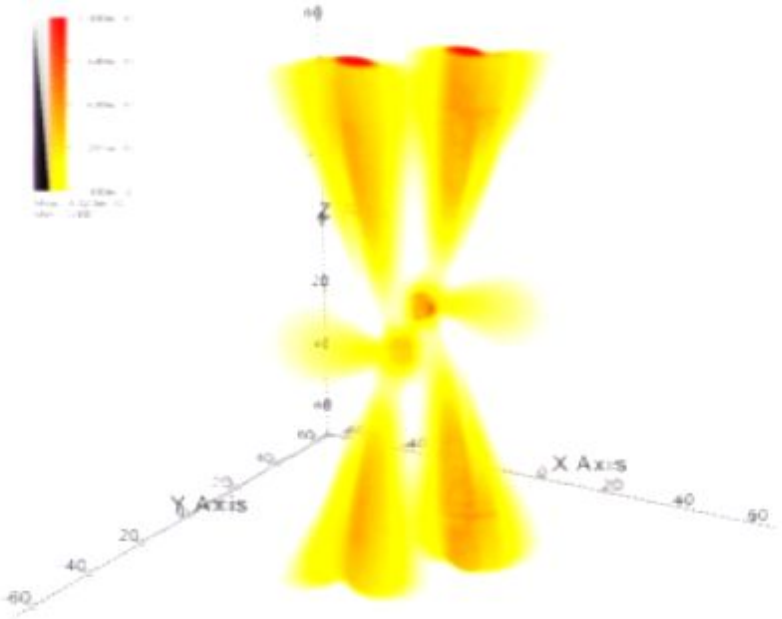
$$E^i B_i = 0$$

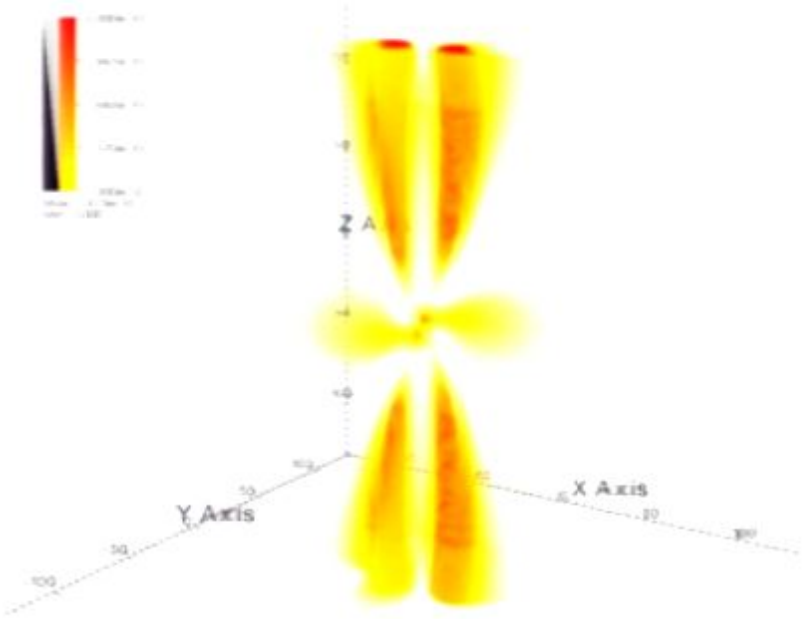
$$J^i = \frac{q}{B^2}\epsilon^{ijk} E_j B_k + J_B \frac{B^i}{B^2}$$

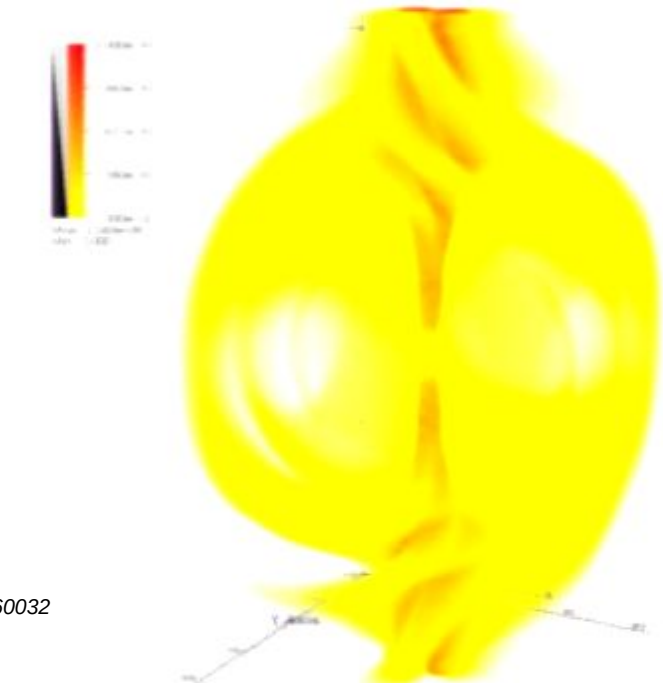
- Circumbinary disk with magnetic field B=10^4 G

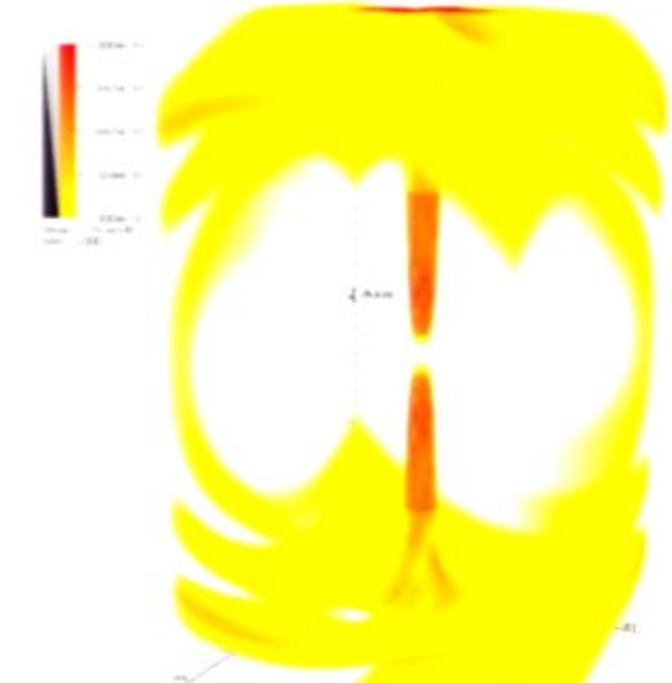


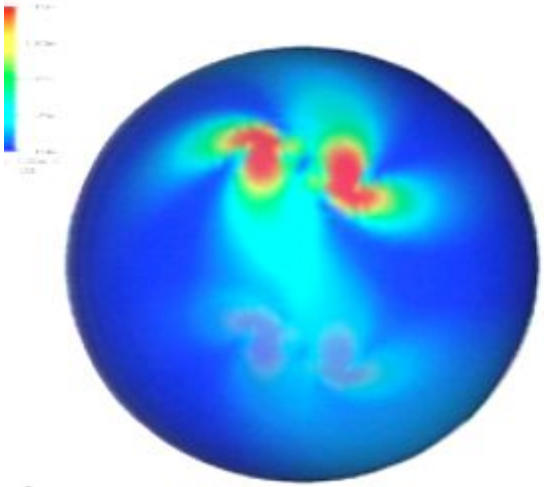
Palenzuela, Lehner, Liebling, Science (2010)


Z
X Axis
Y Axis

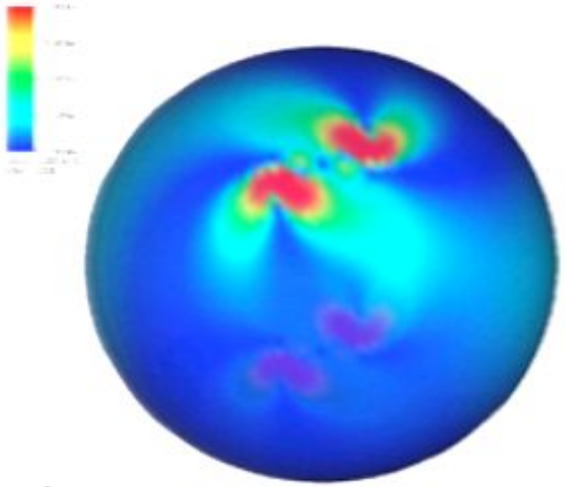

Z
X Axis
Y Axis



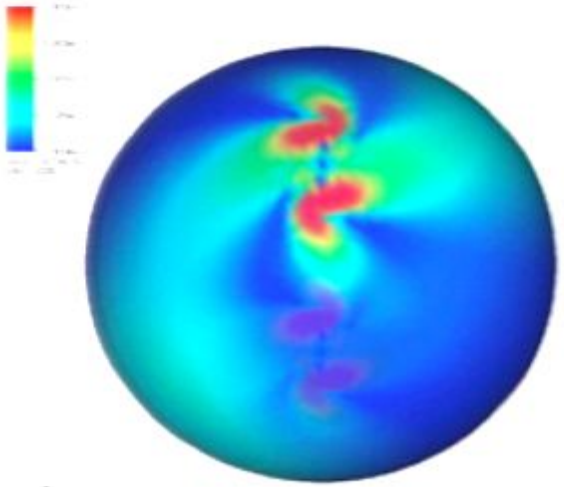




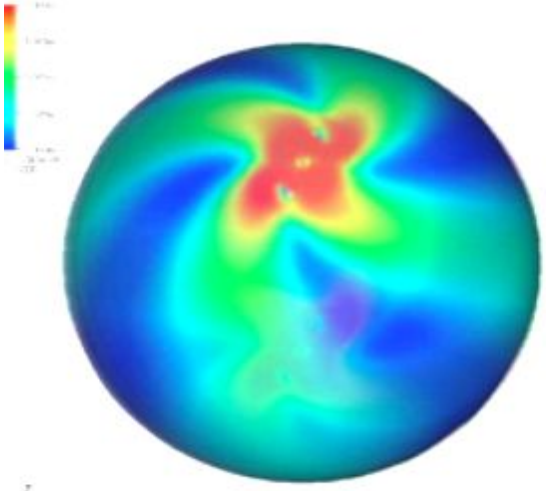
t=-8.2 M_8 hrs



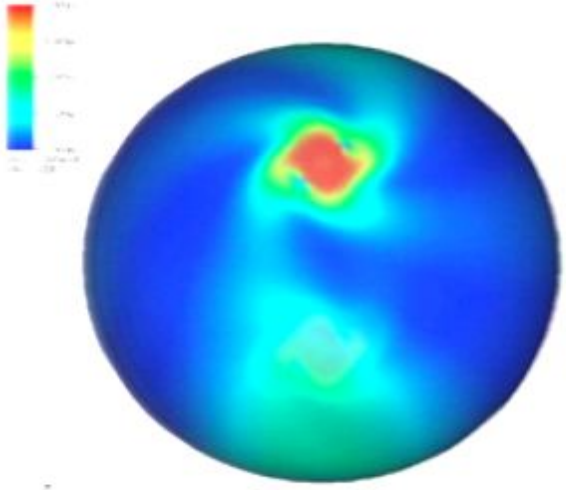
t=-5.5



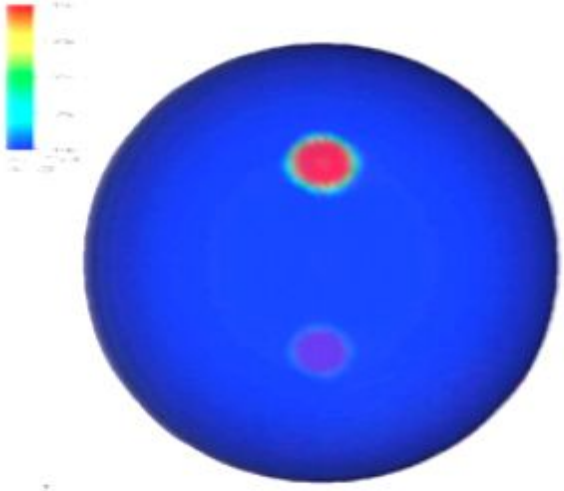
t=-3.0



t=2.0



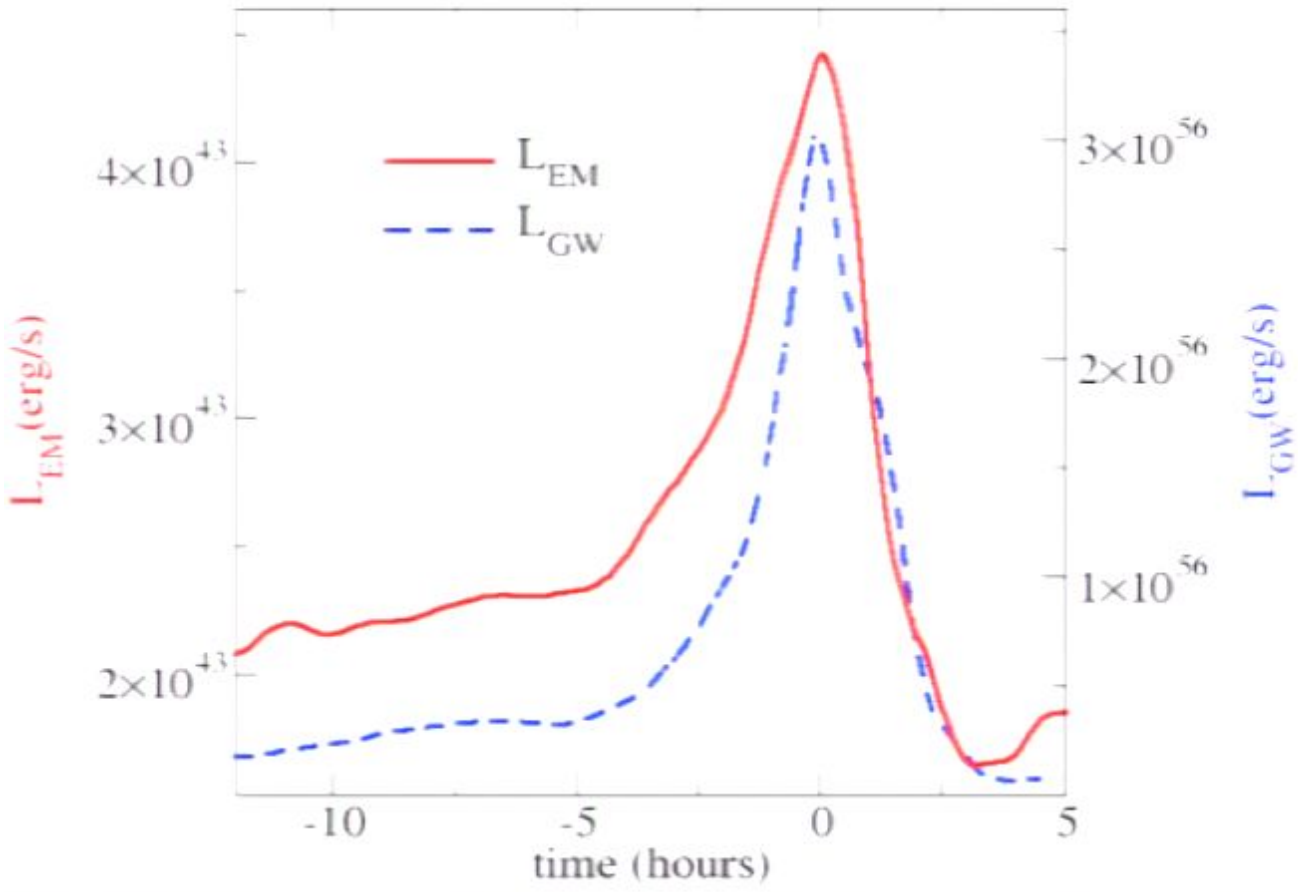
t=4.6



t=6.8

Projection of EM flux on spheres at R=20M

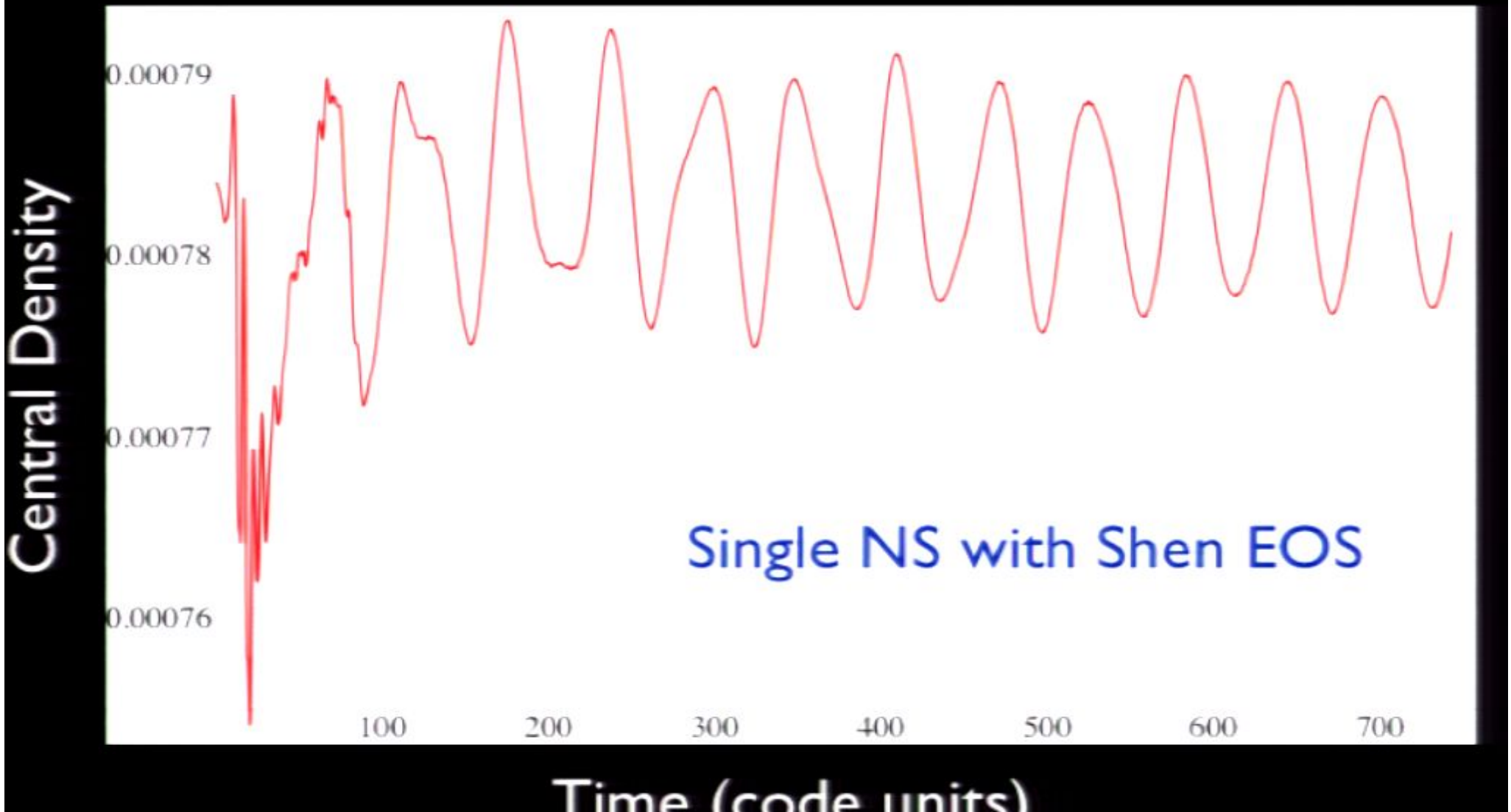
EM & GW fluxes



$$E \propto 10^{-14}(M_8)^2(B_4)$$

$$(R_{\rm orb}\Omega_{\rm orb})^2 B^2$$

First Steps...


Central Density
0.00079
0.00078
0.00077
0.00076
100
200
300
400
500
600
700
Single NS with Shen EOS
Time (code units)

Summary

- Hints of interesting results using simple models
  - NS-NS with magnetic fields
  - BH-NS merger + tidal tails
  - BH-BH with EM
  - BH-BH with FFE
- Need microphysics
  - Finite-temperature EOS
  - Trapped neutrinos
  - Leakage