

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

- Sources of gravitational waves
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- Einstein eqs.---not easy at first, so
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# Learning to Stand

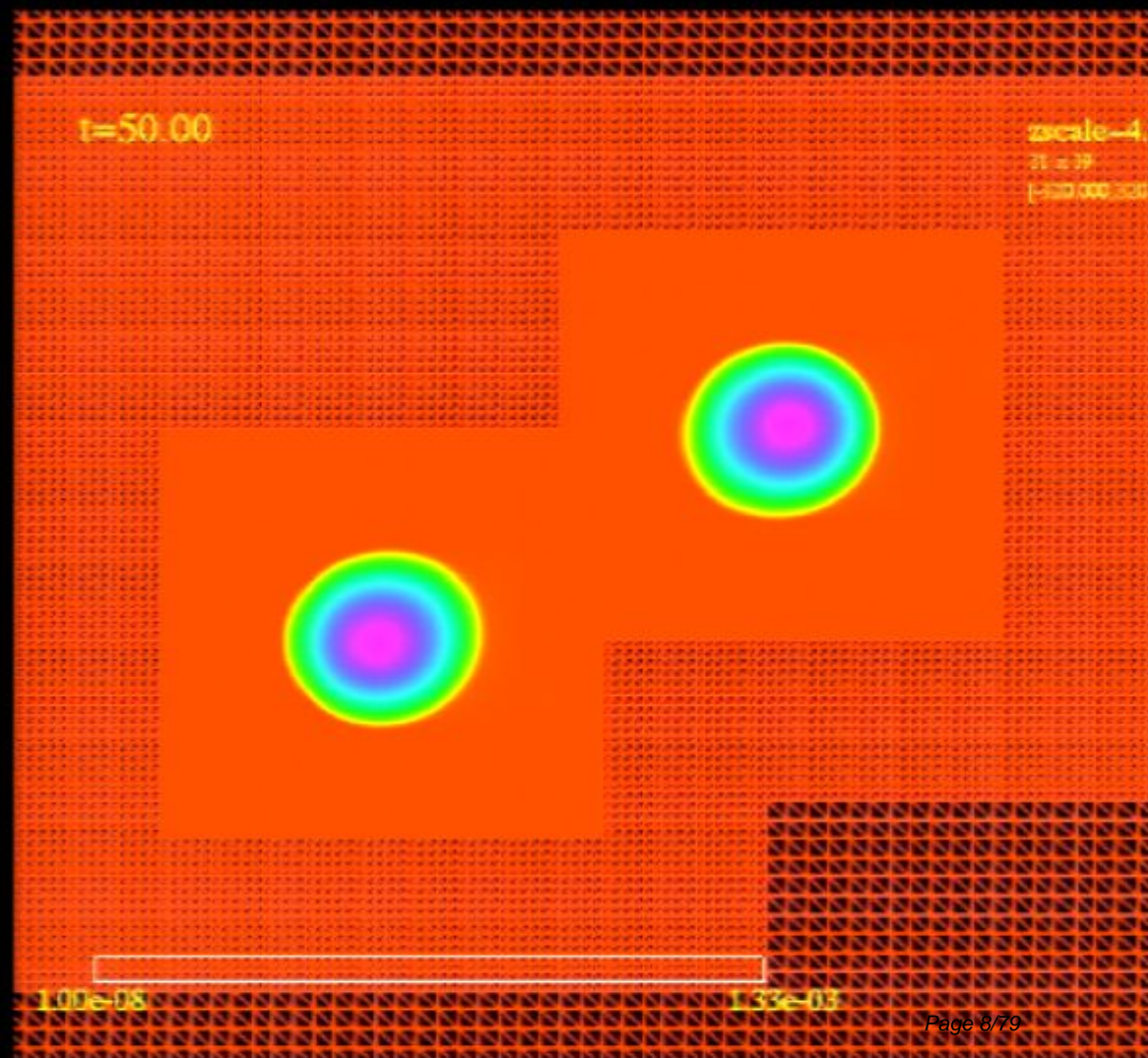
- Sources of GWs also strong sources of
  - E&M radiation (Palenzuela)
  - Neutrinos
- Multi-messenger astronomy (O'Shaughnessy)
- Improve physical models
  - EOS (Read & others)
  - (...lots to do...)
- Where we have been, and where to go.

# Binary Neutron Stars



# HAD

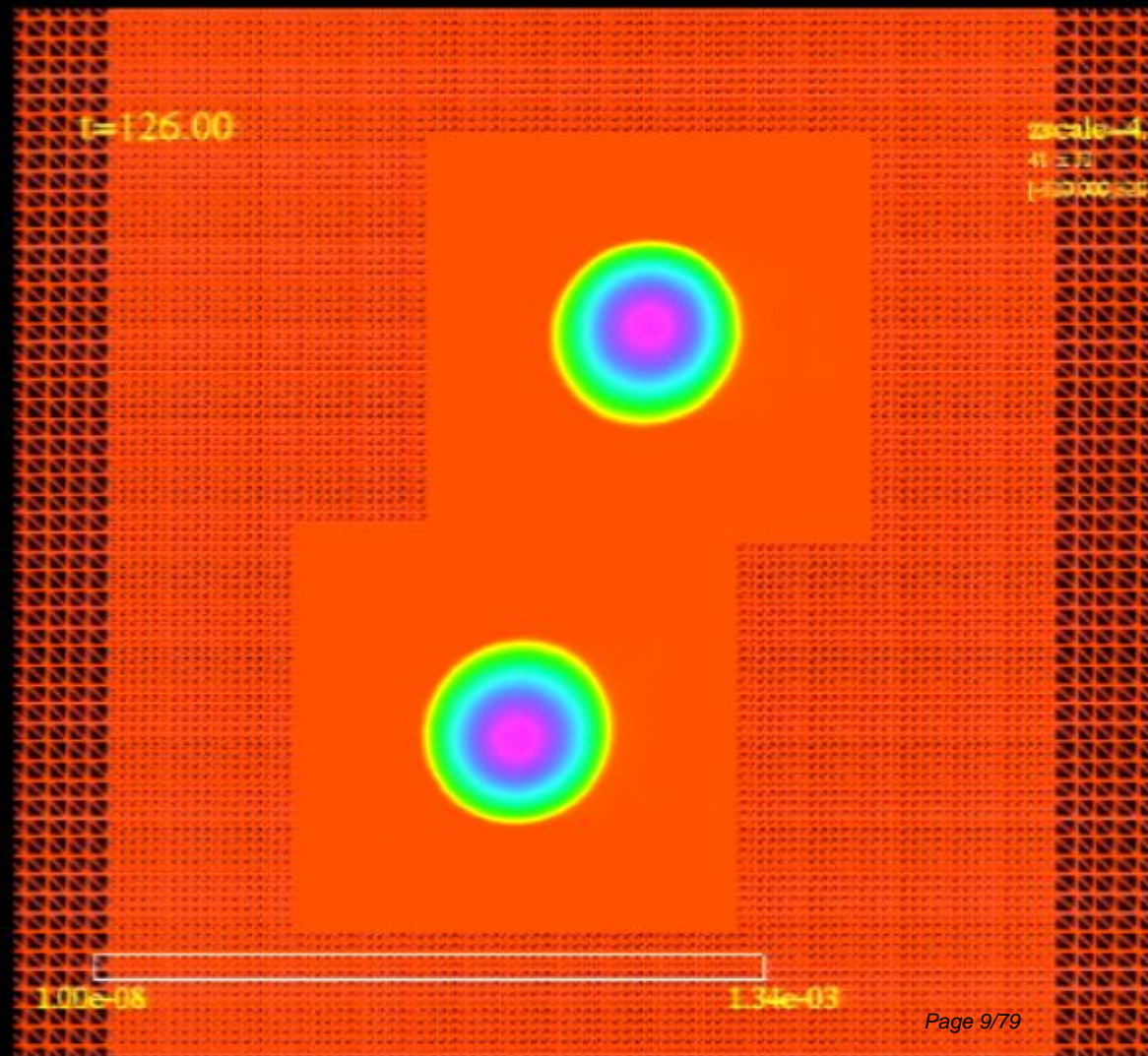
- Berger-Oliger AMR (refine both space & time)
- Truncation error based refinement using shadow hierarchy
- Tapering refinement boundary condition
- FD and FV discretizations
- MPI, strong scaling...





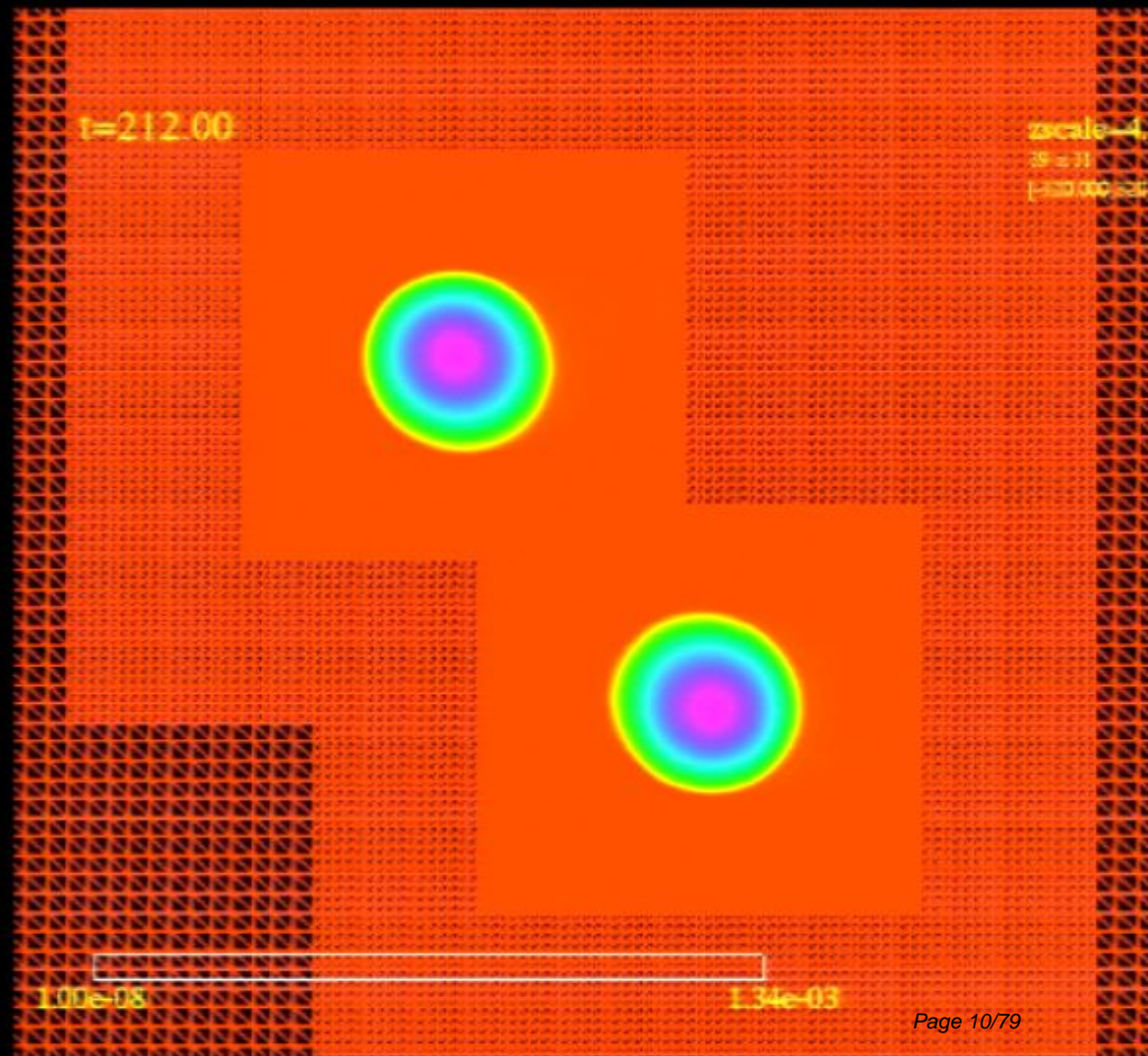
# HAD

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# HAD

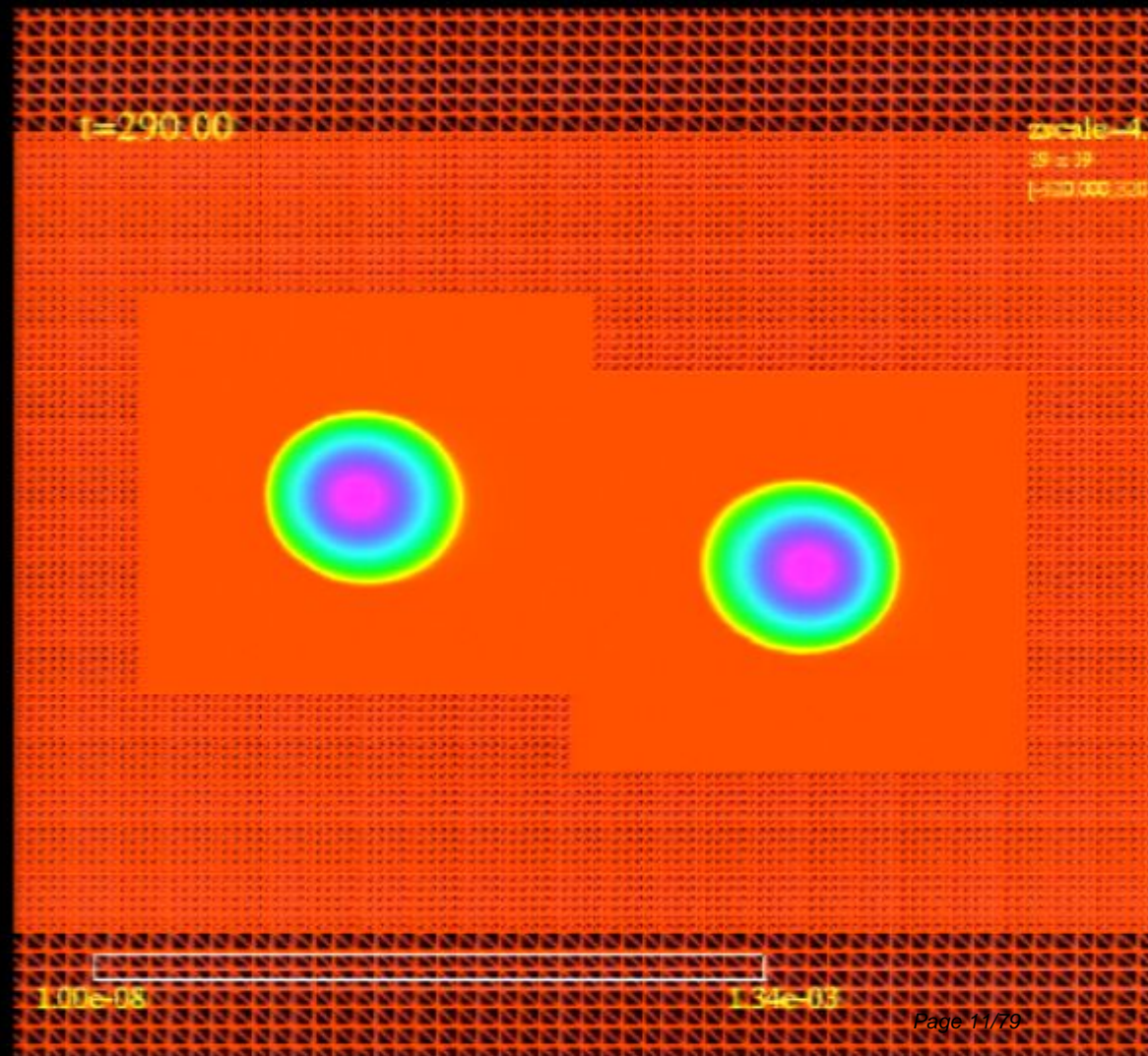
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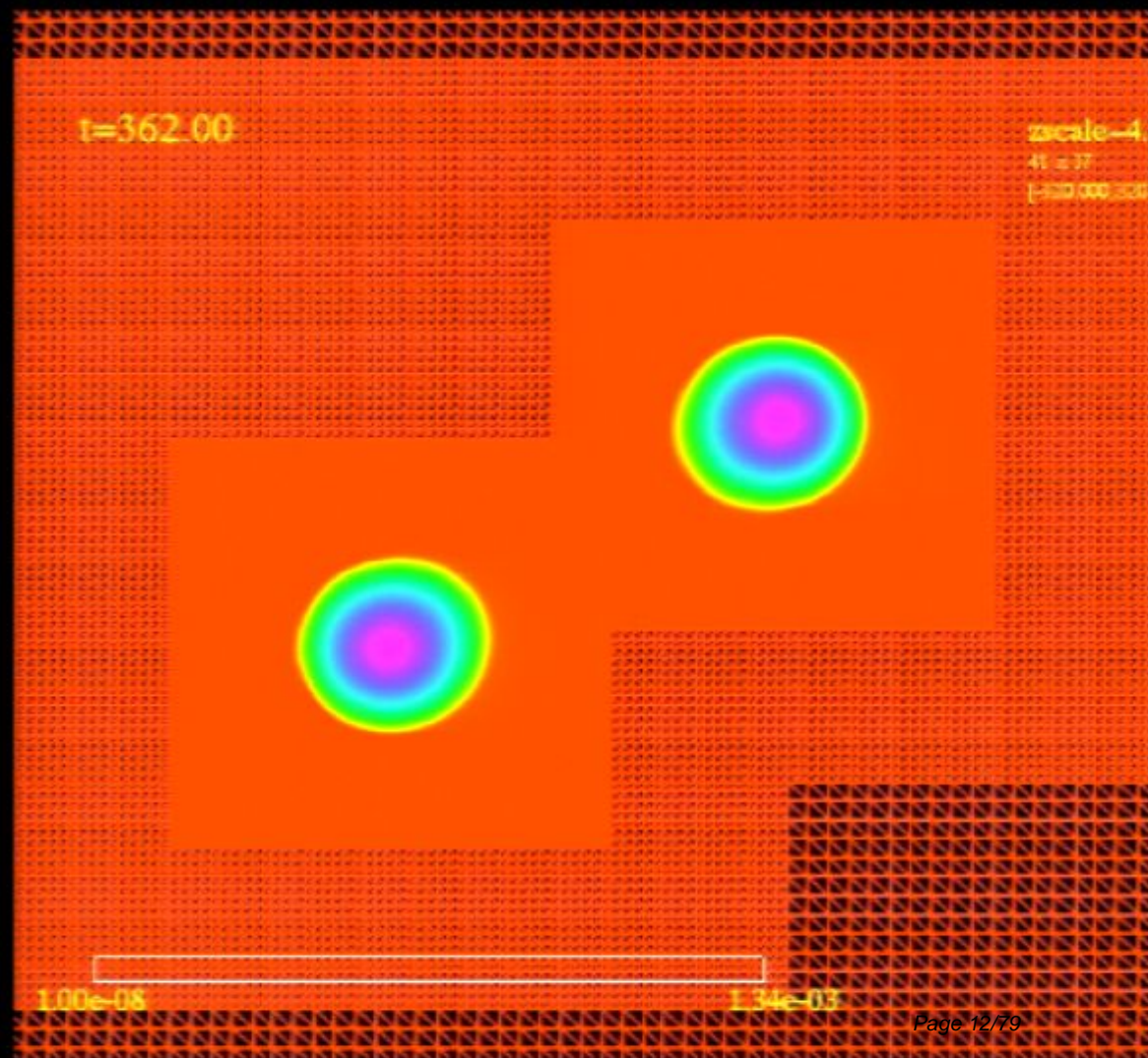
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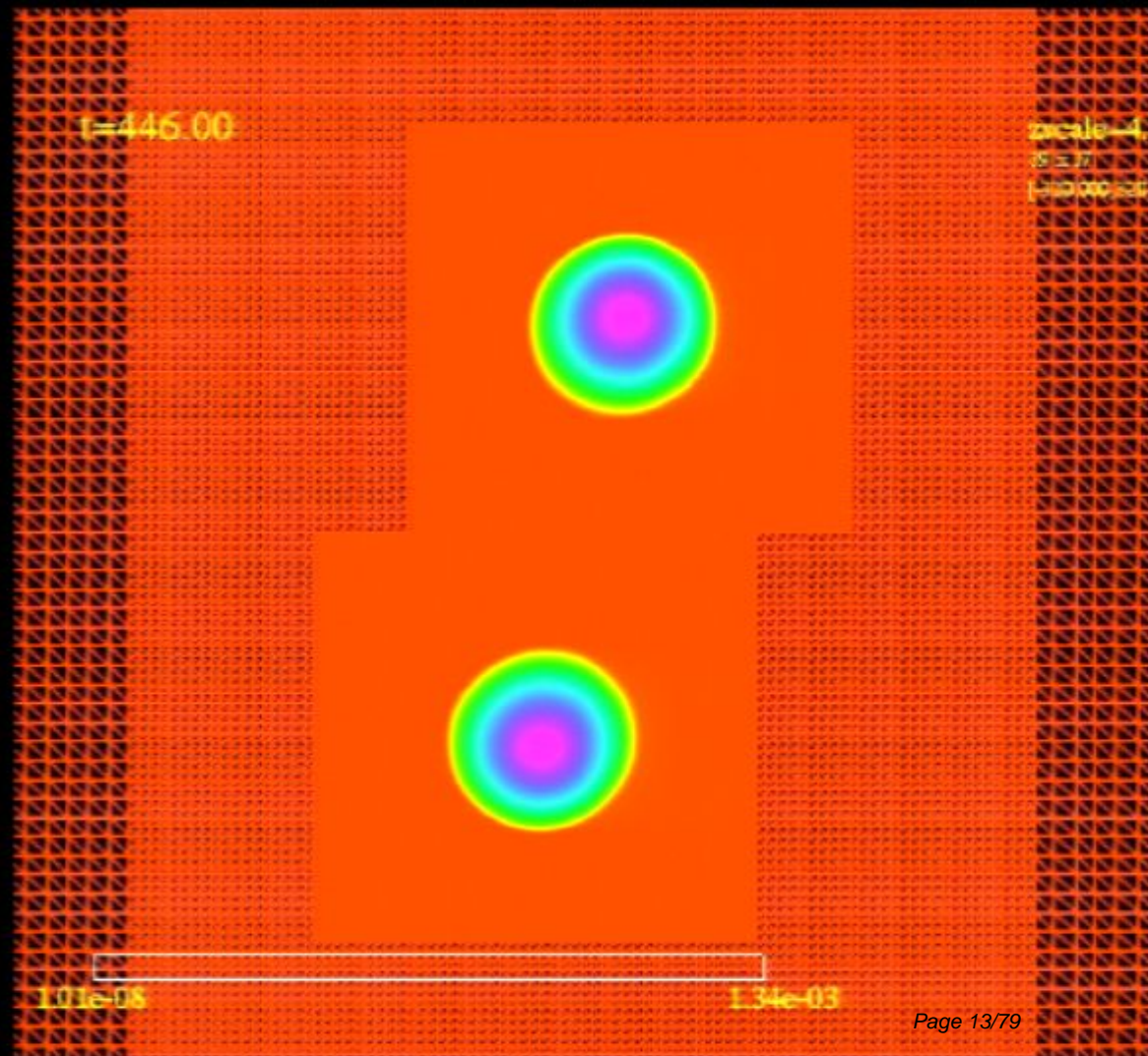
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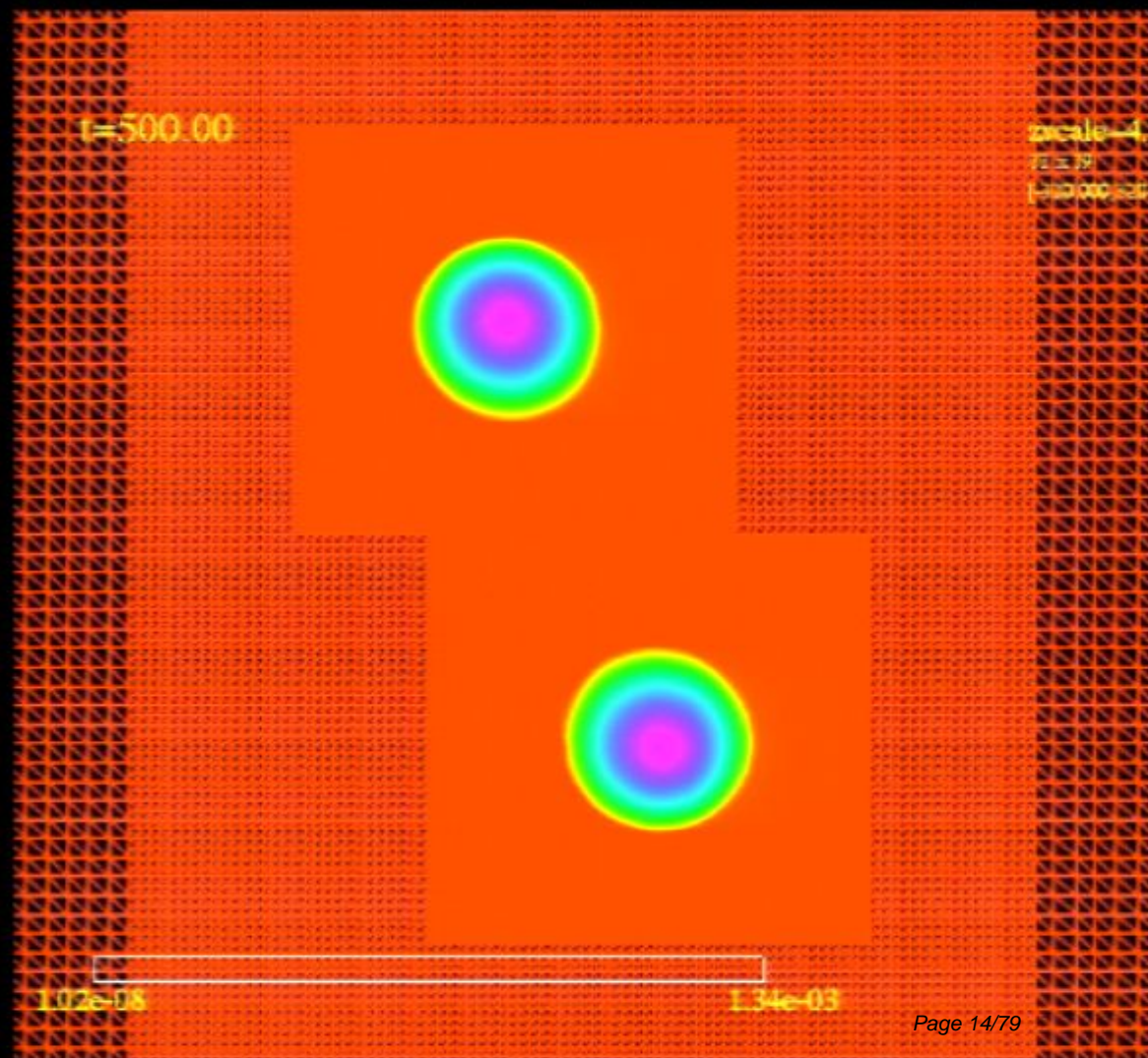
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# NS-NS with magnetic field

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

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

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

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

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

Price & Rosswog, Science (2006)

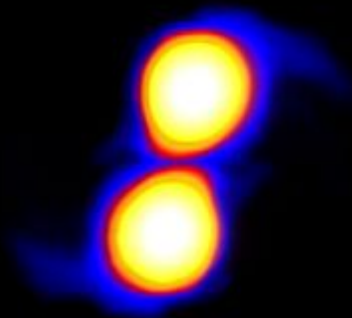
Liu, Shapiro, Etienne, Taniguchi, PRD (2008),

Giacomazzo, Rezzolla, Biaotti (2009)

# Movie Comparison

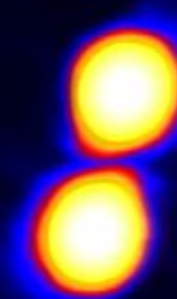
HD

t = 47.00  
max = 0.0514885  
min = 1.00000e-08



MHD

t = 47.00  
max = 0.0511441  
min = 1.00000e-08

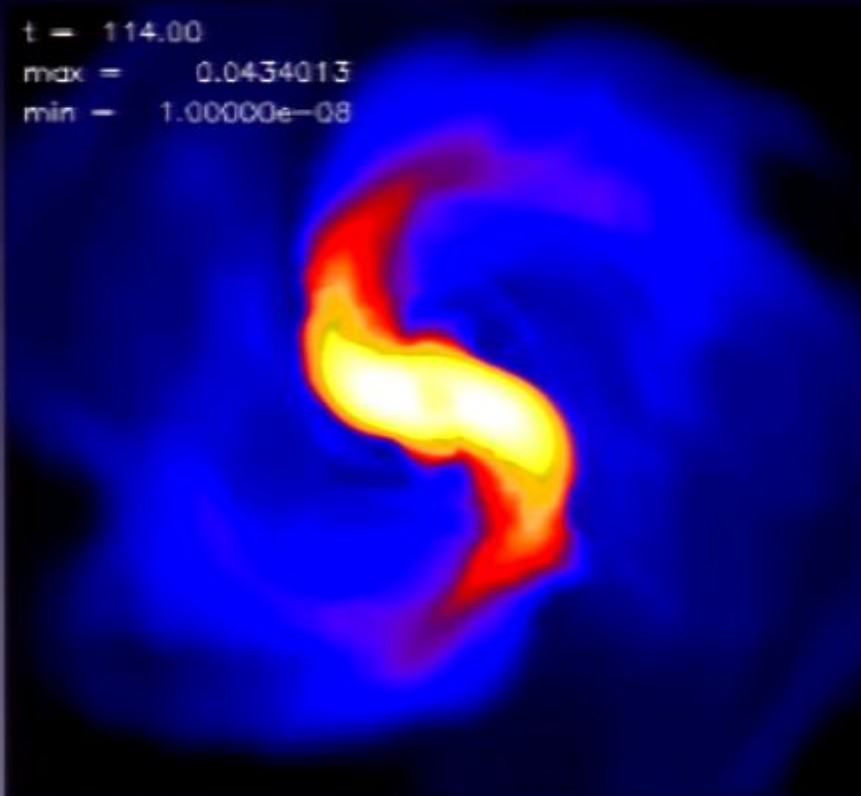




# Movie Comparison

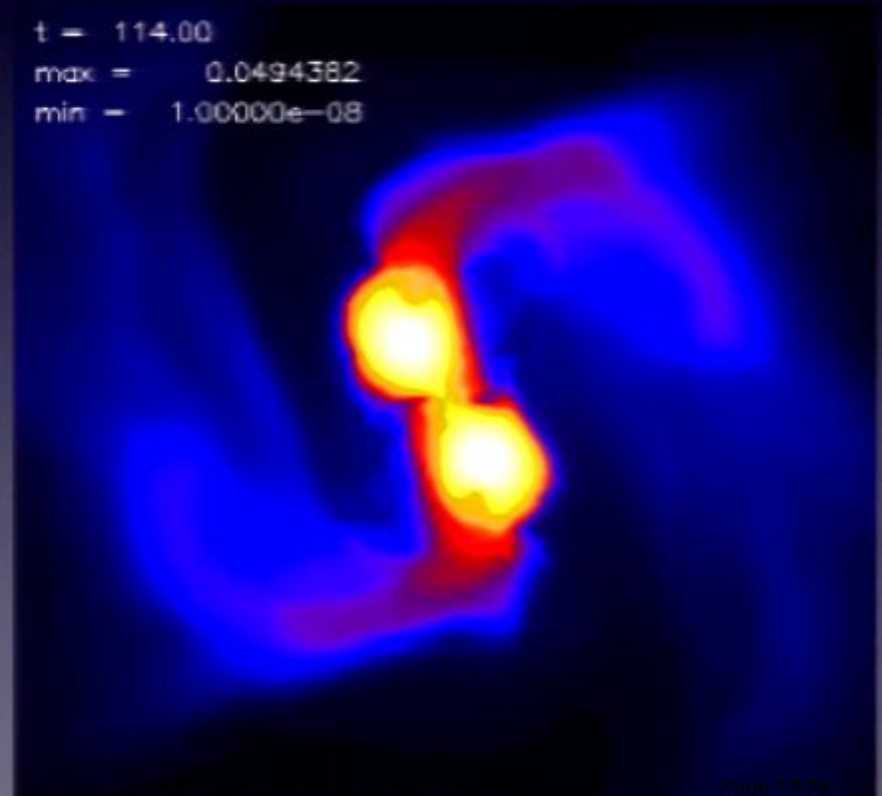
HD

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max = 0.0434013  
min = 1.00000e-08



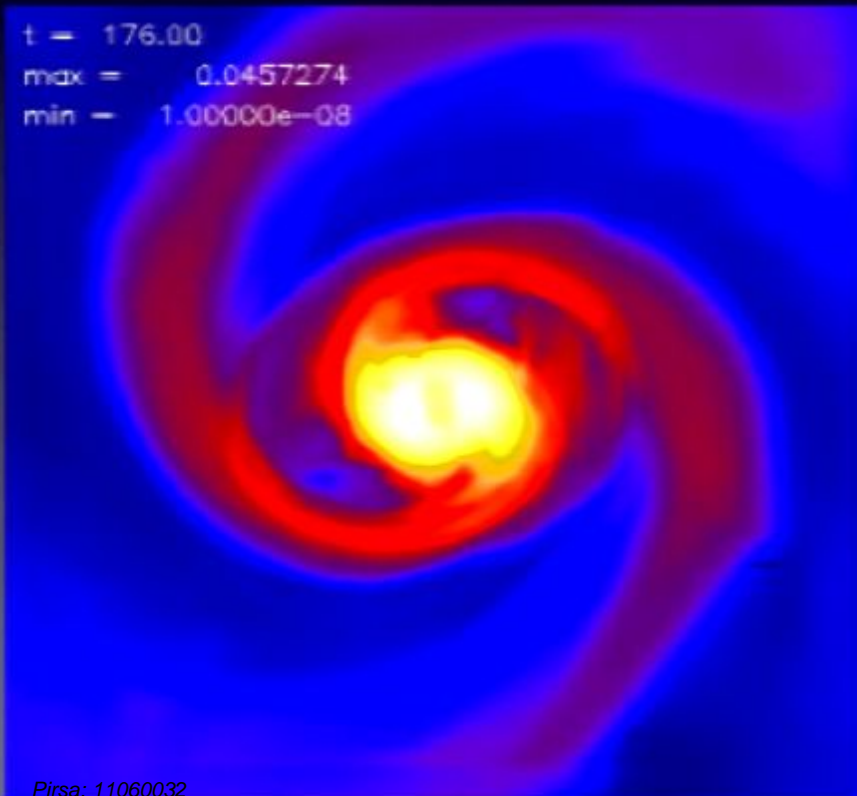
MHD

t = 114.00  
max = 0.0494382  
min = 1.00000e-08



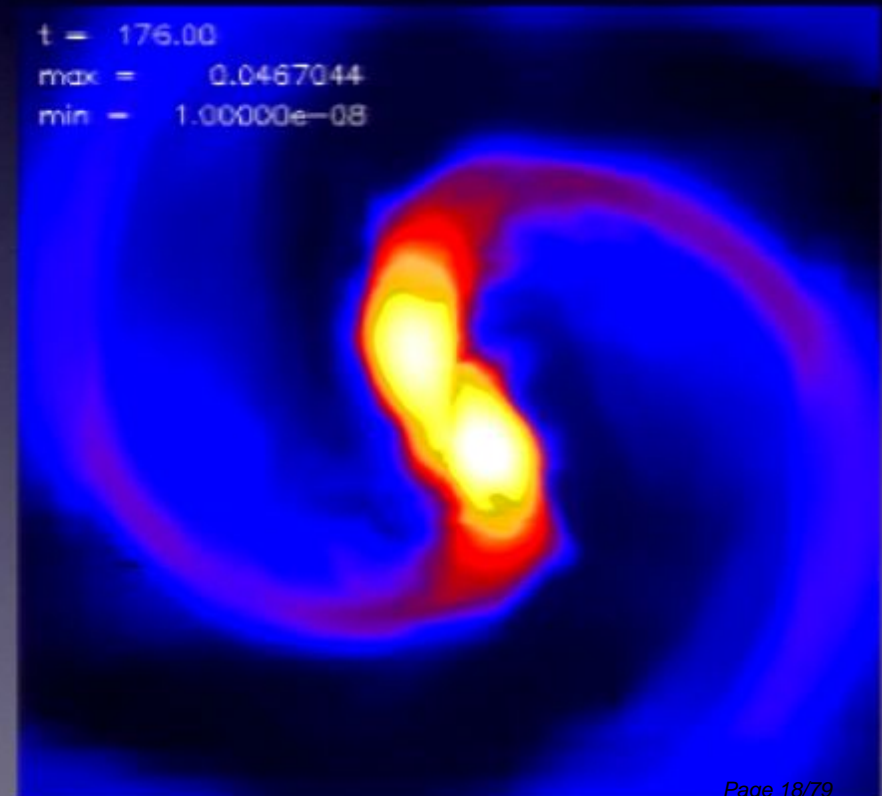
# Movie Comparison

HD



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MHD



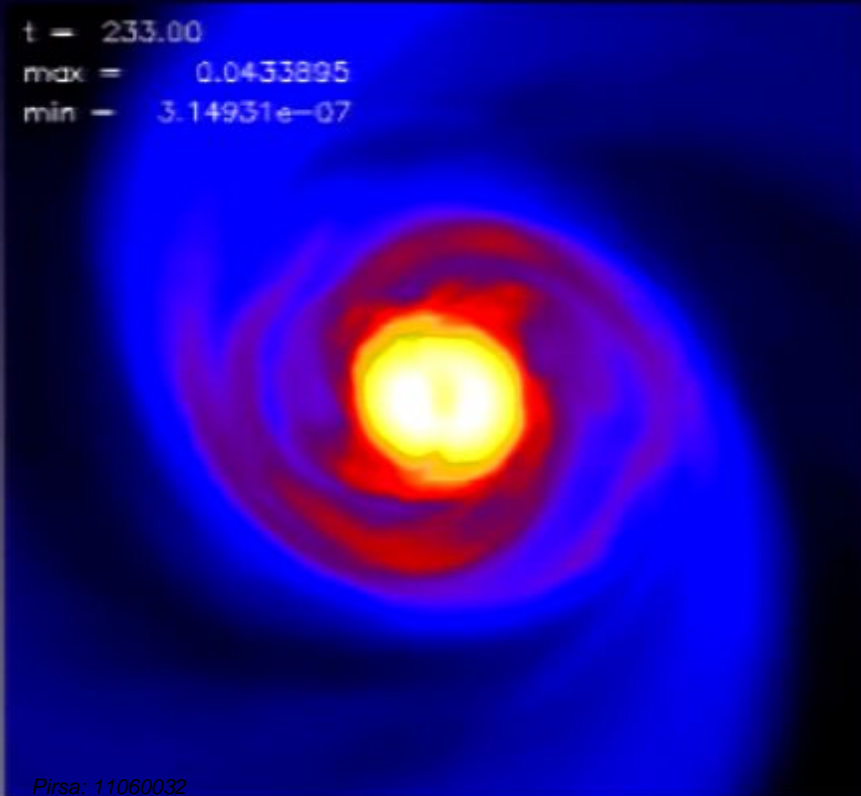
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# Movie Comparison

HD

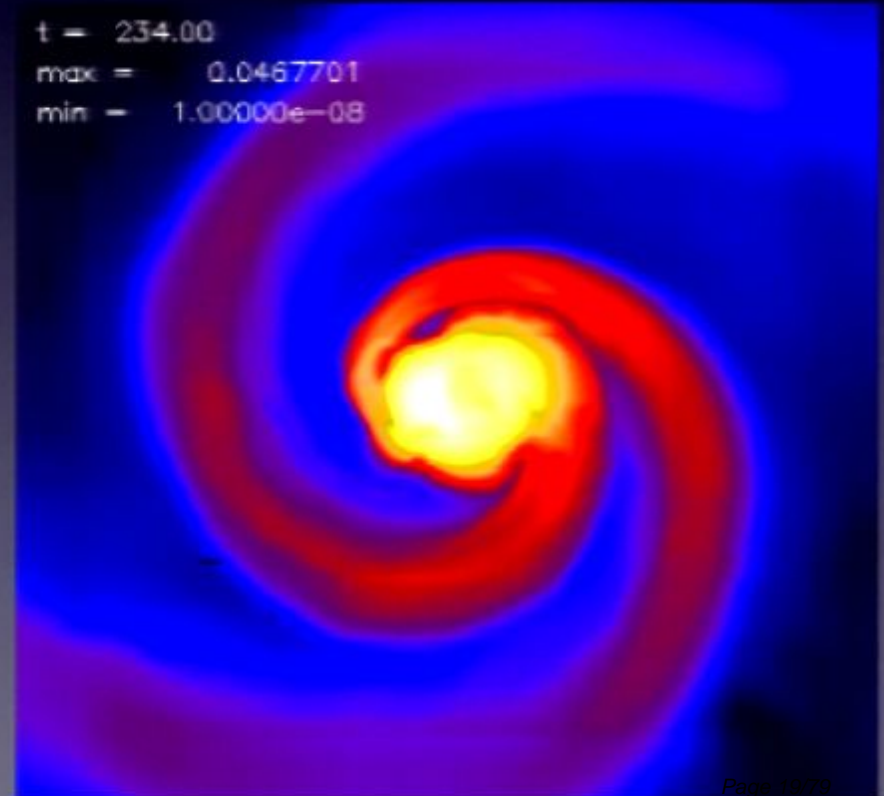
t = 233.00  
max = 0.0433895  
min = 3.14931e-07



Pirsa: 11060032

MHD

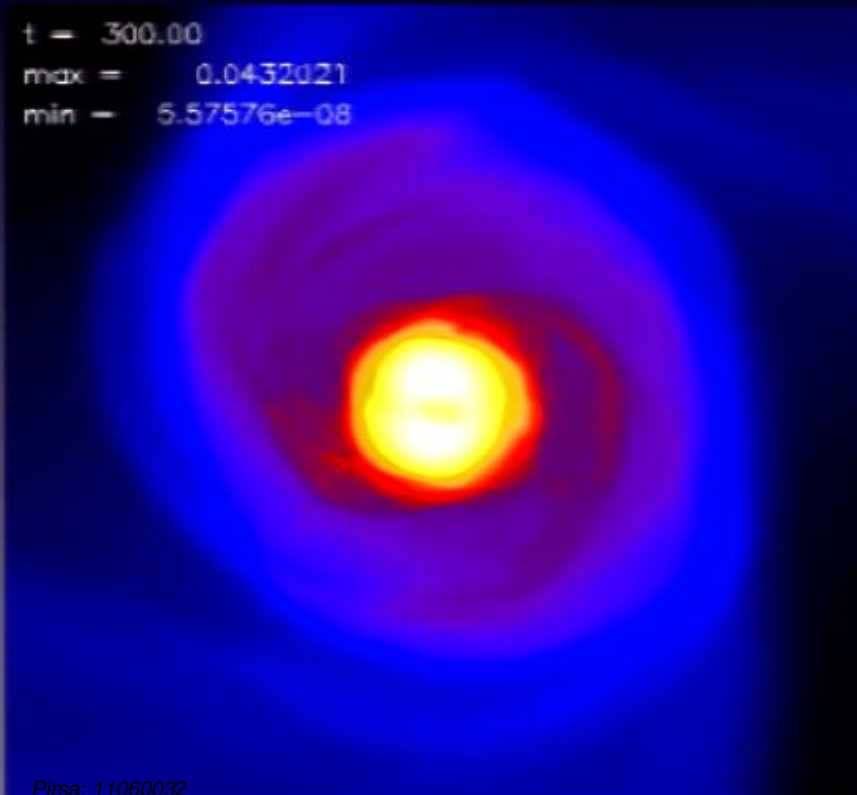
t = 234.00  
max = 0.0467701  
min = 1.00000e-08



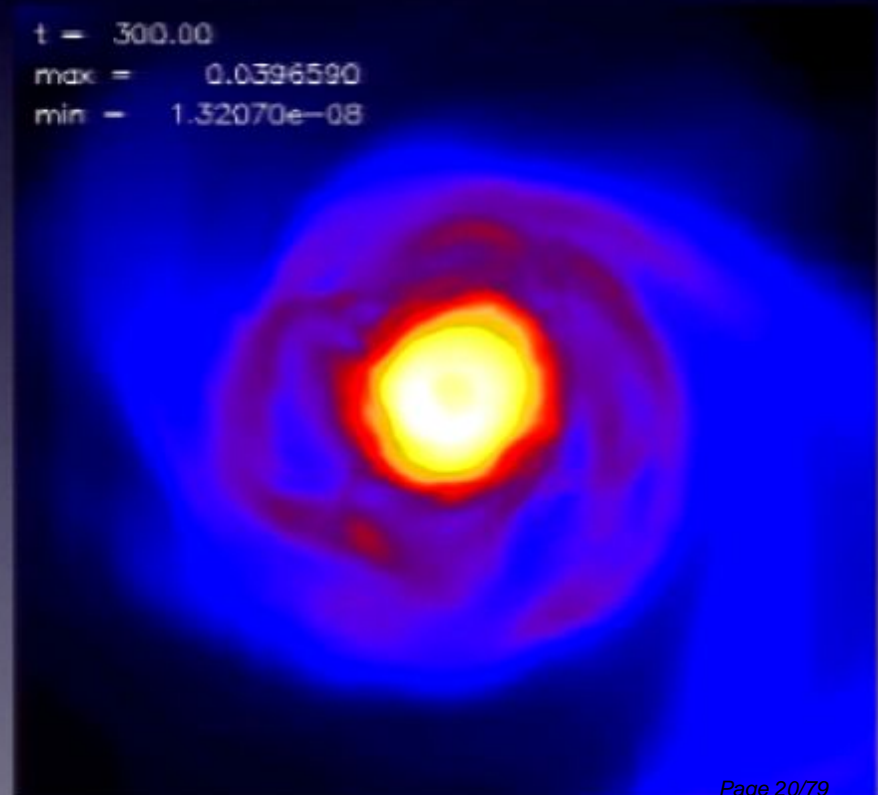
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# Movie Comparison

HD



MHD

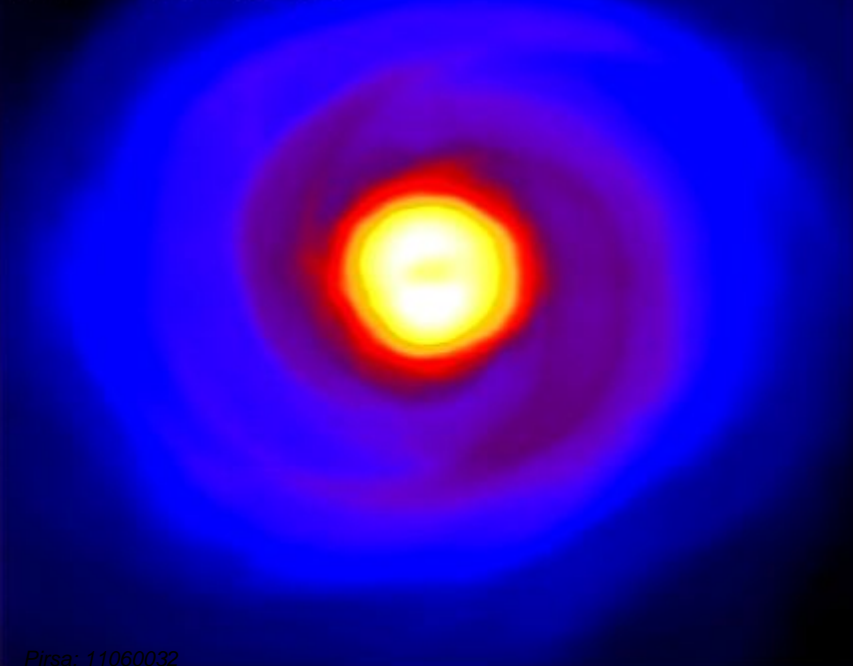




# Movie Comparison

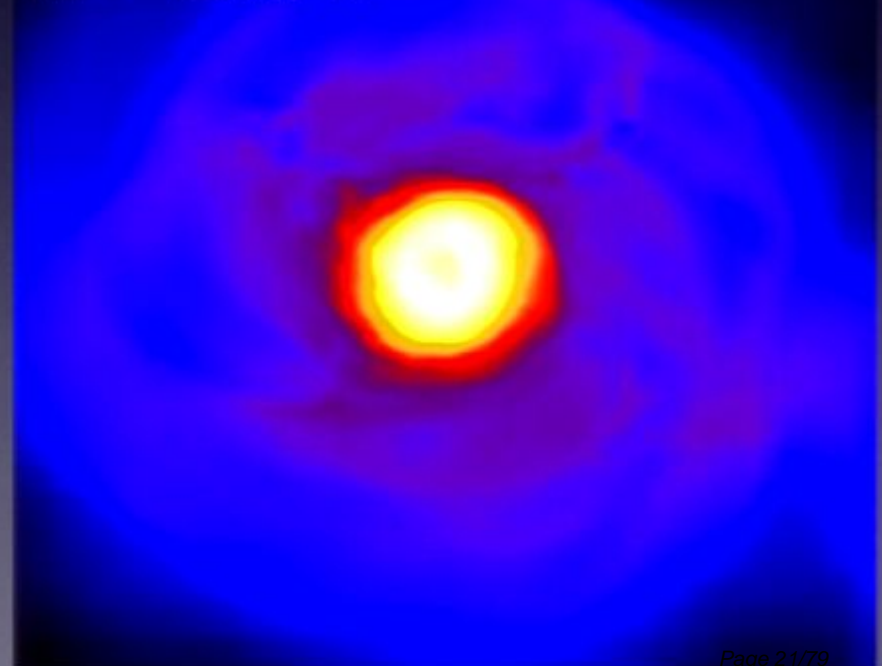
HD

t = 363.00  
max = 0.0434841  
min = 3.34785e-08



MHD

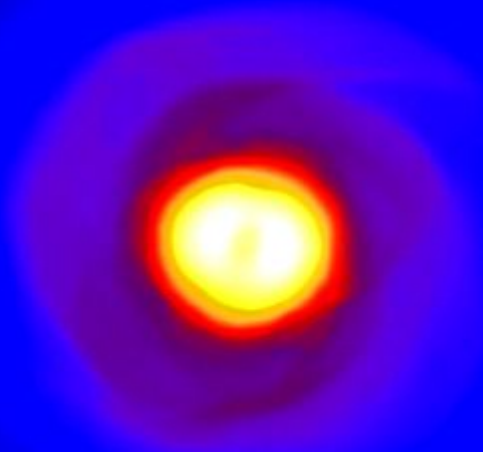
t = 363.00  
max = 0.0347701  
min = 1.00000e-08



# Movie Comparison

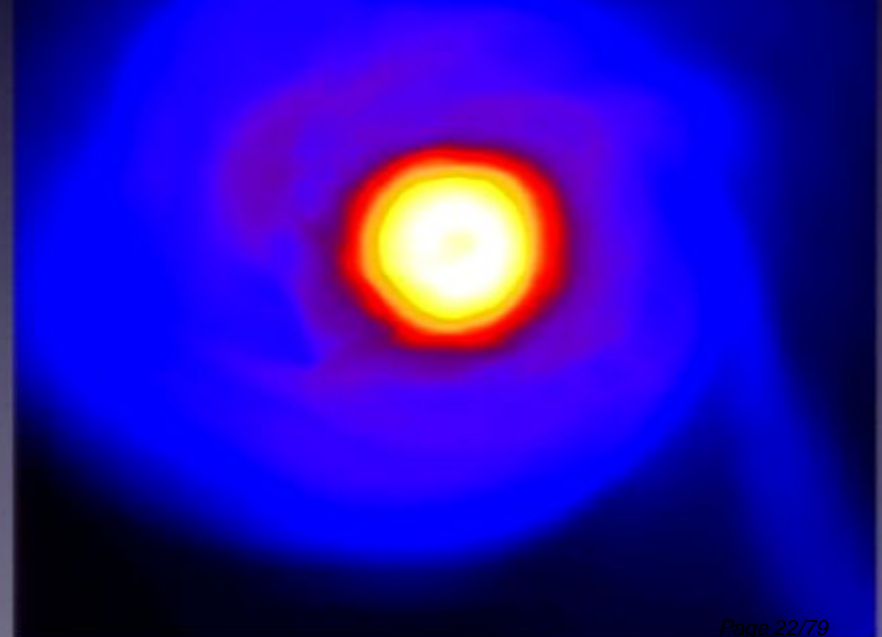
HD

t = 430.00  
max = 0.0421589  
min = 5.62966e-08



MHD

t = 430.00  
max = 0.0330887  
min = 4.89150e-08

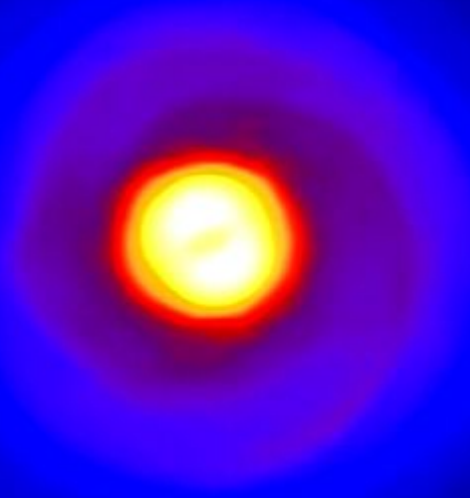




# Movie Comparison

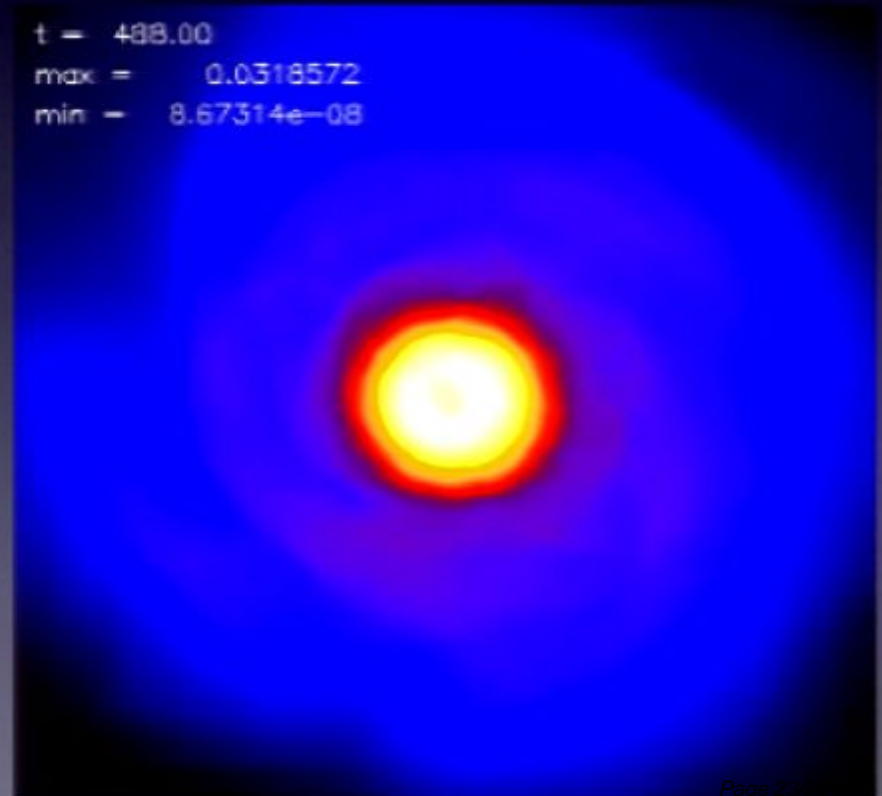
HD

t = 488.00  
max = 0.0419221  
min = 4.83432e-08

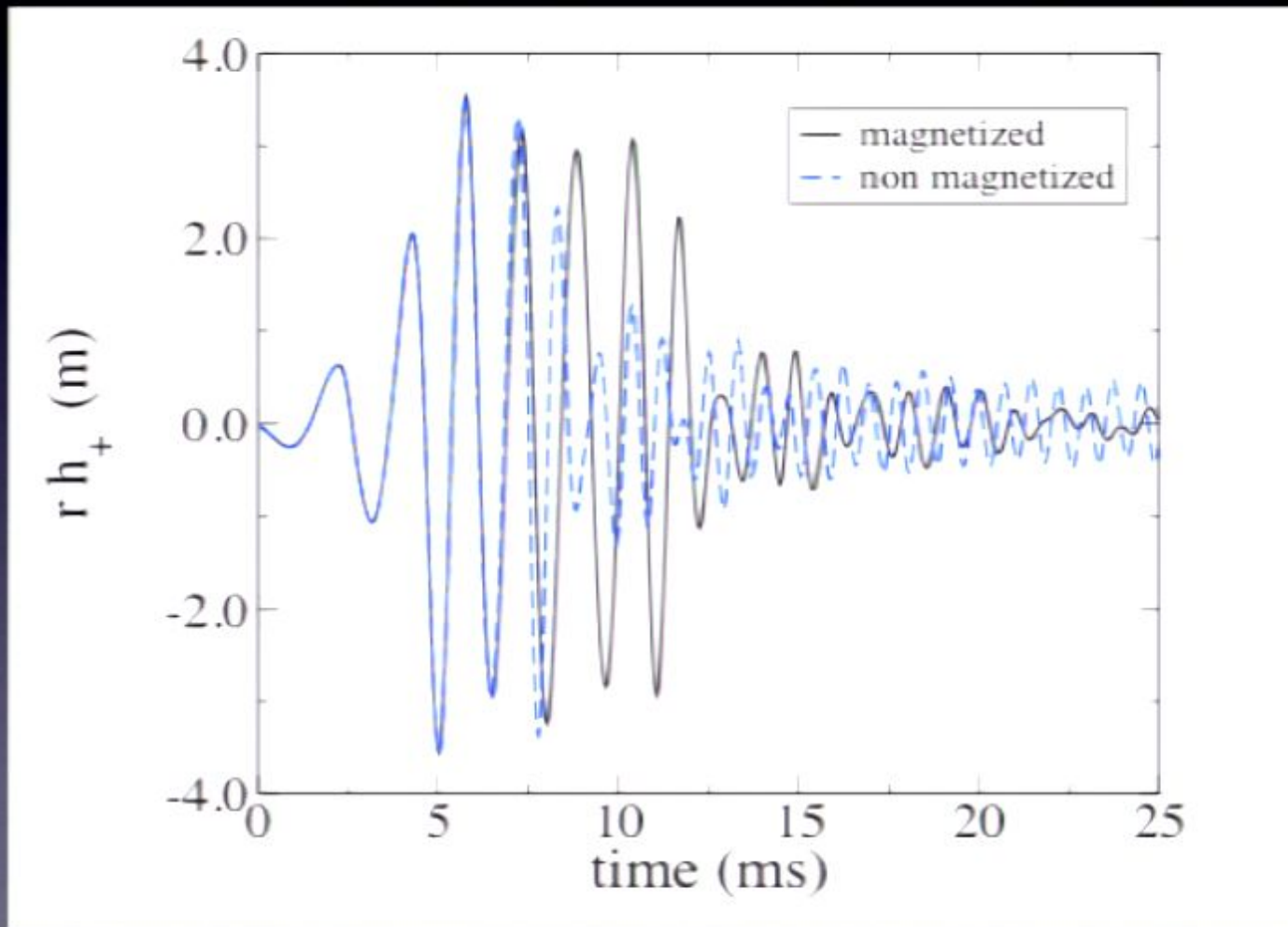


MHD

t = 488.00  
max = 0.0318572  
min = 8.67314e-08

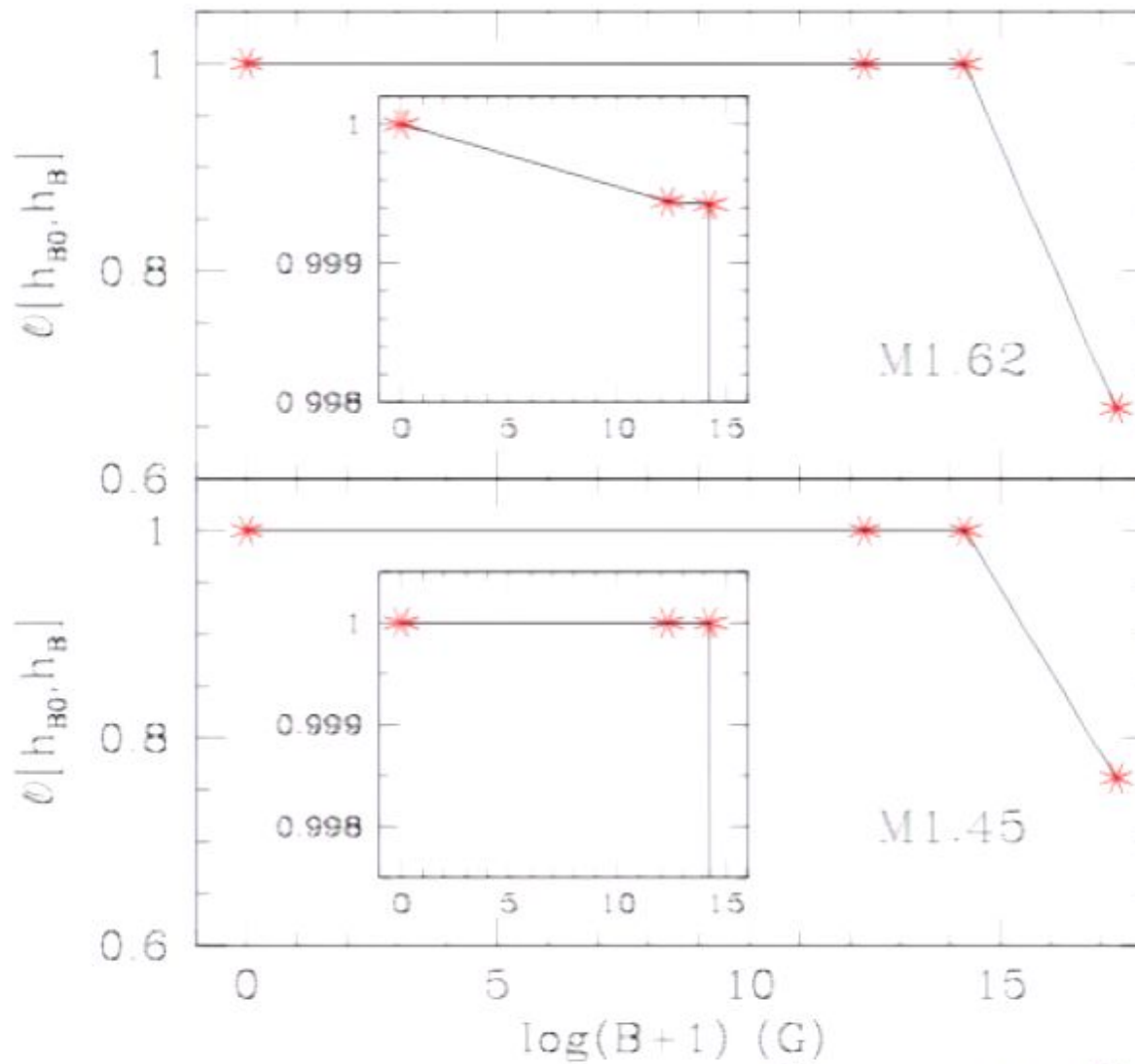


# Gravitational wave signal





# But...



# Black Hole-Neutron Star

# Black Hole-Neutron Star

(Chawla et al., PRL 2010)

- Black hole

- Mass

$$M_{\text{BH}} = 7M_{\odot}$$

- Spinning and non-spinning

$$a = 0, \quad a = 0.5$$

- Neutron Star

- Mass

$$M = 1.4M_{\odot}$$

- Polytrope

$$R = 15 \text{ km}$$

- Magnetic field

$$\Gamma = 2$$

- System

- $q=5$  and initial separation 100 km

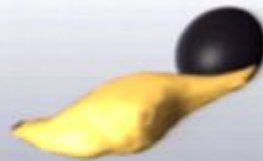


# BH-NS Snapshots

5.9ms



$\tau=8.9\text{ms}$



$\tau=13.3\text{ms}$



$\tau=16.3\text{ms}$



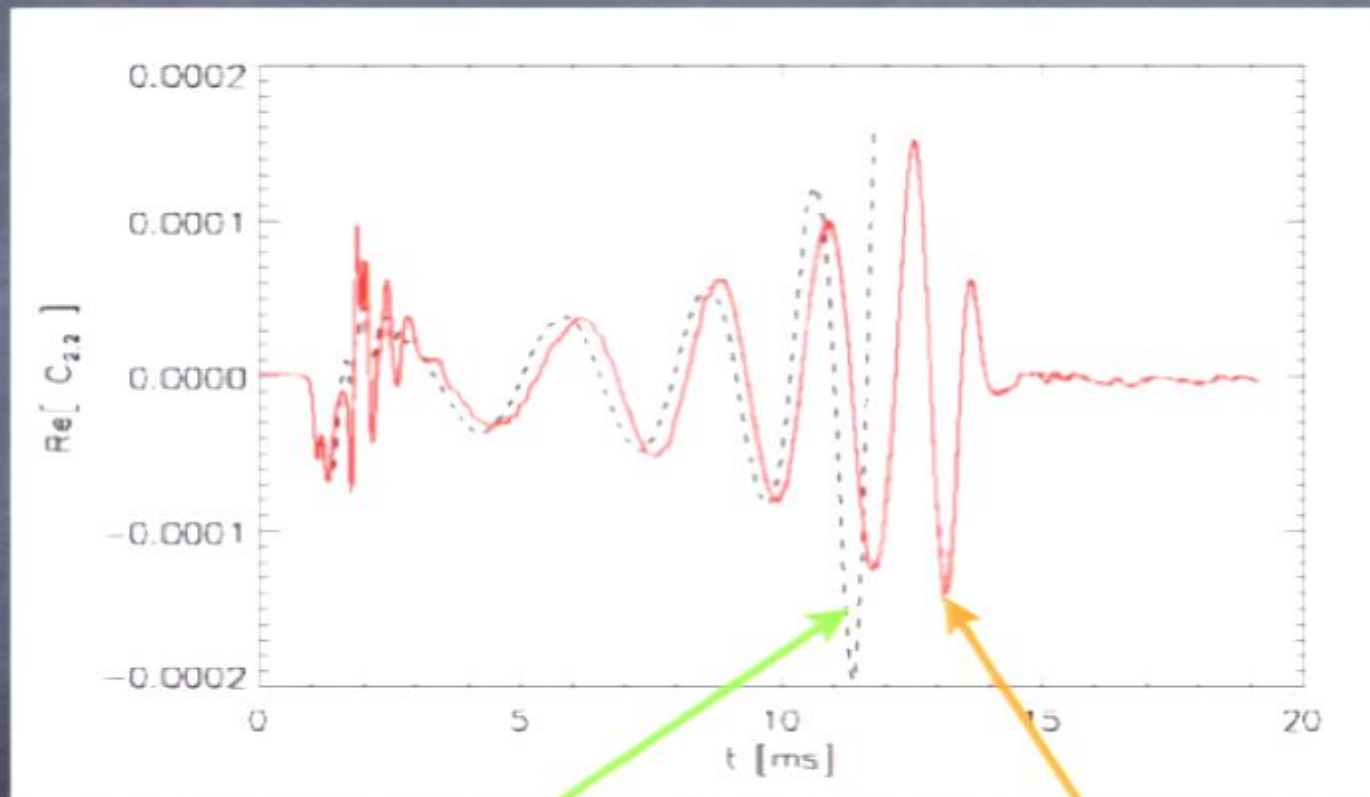
$\tau=20.0\text{ms}$



$\tau=27.3\text{ms}$



# Gravitational Waves



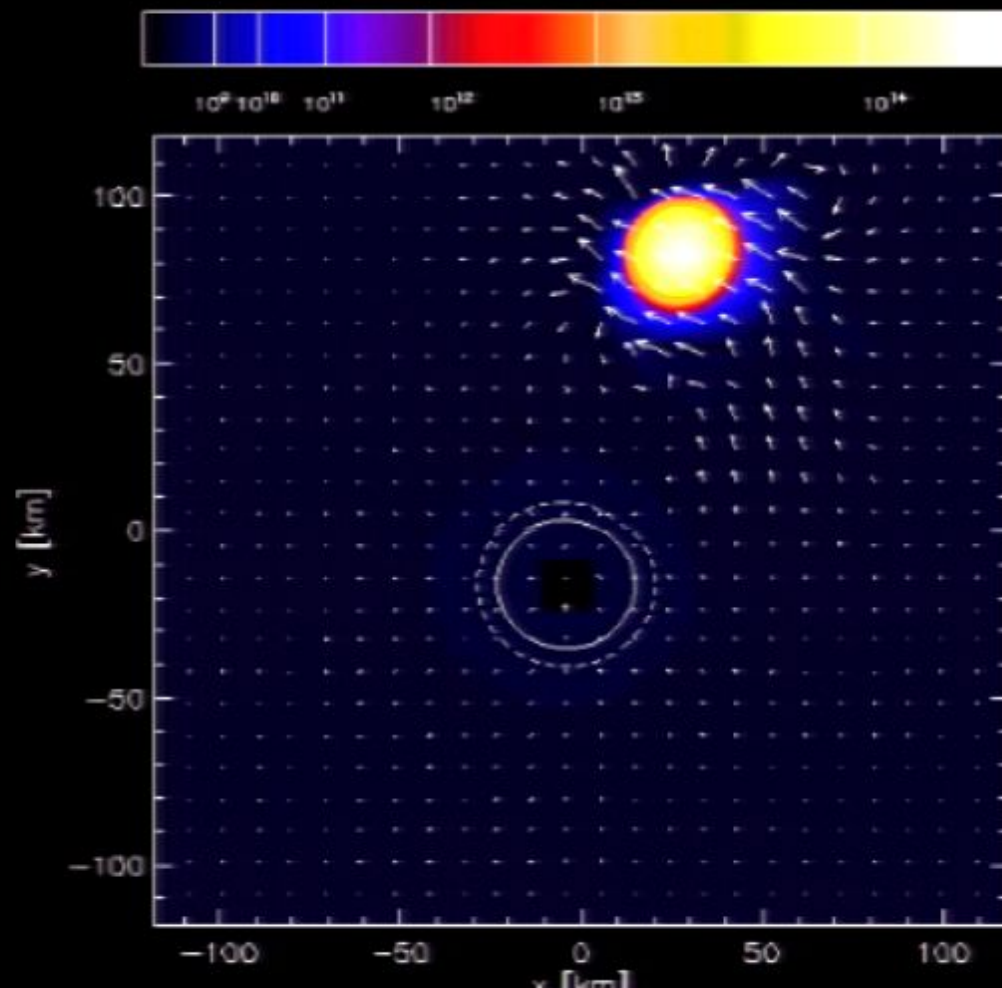
$a=0, B=10^{12}$

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

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

t = 1.4477 [ms]

max = 0.3823  
min = 0.0000

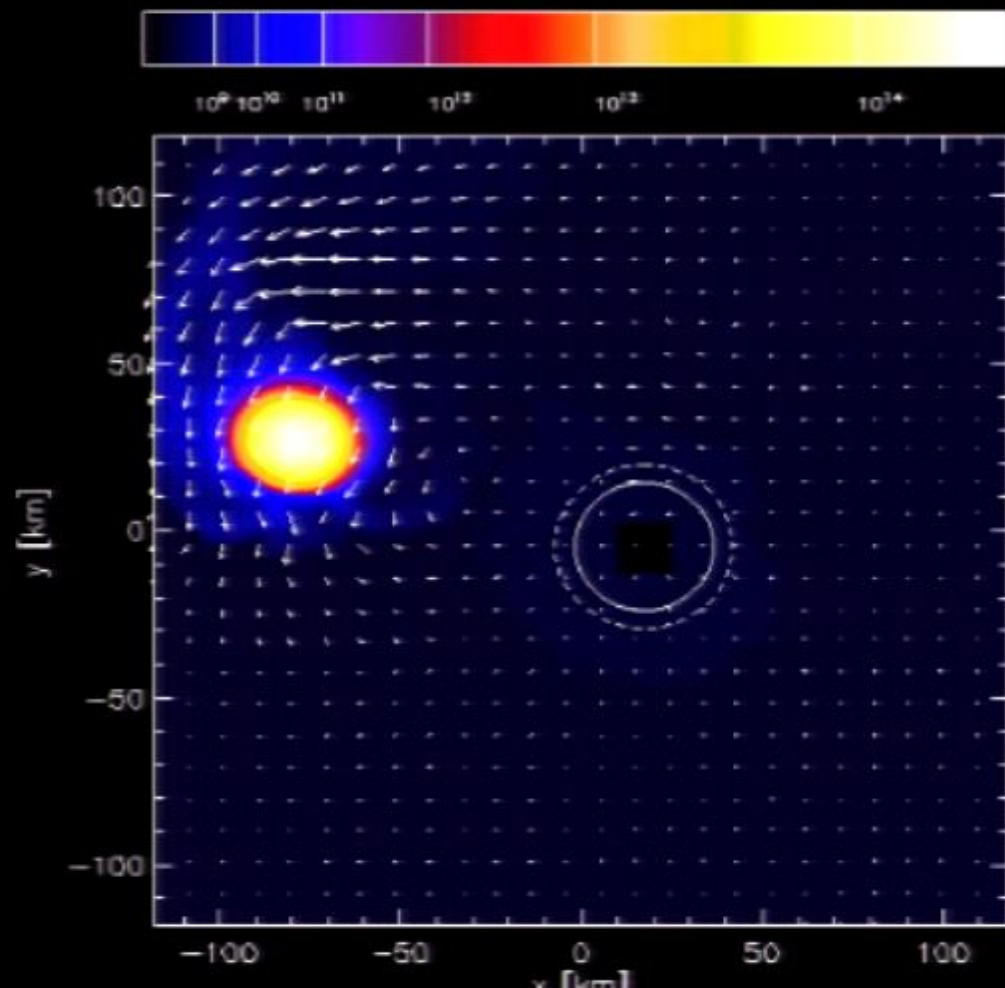




# $a=0.5$ and $B=10^{12}$ G

t = 3.3089 [ms]

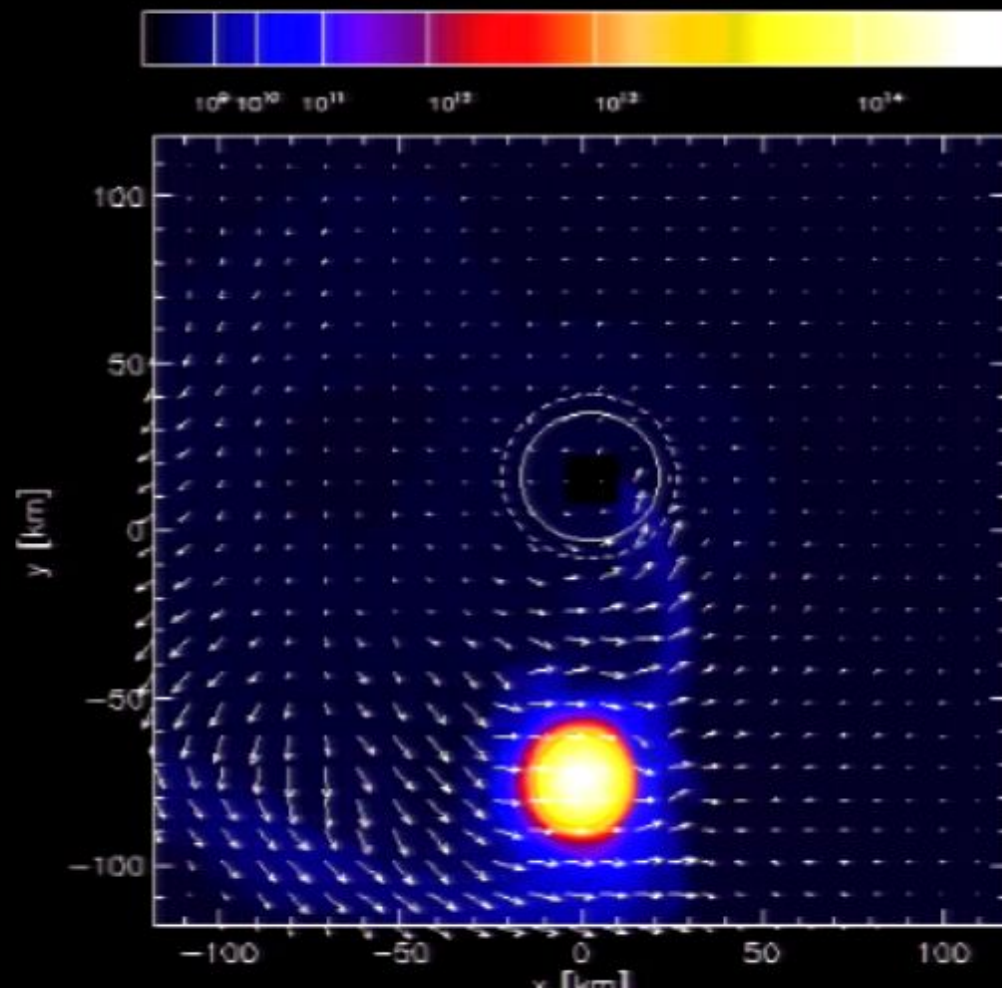
max = 0.4890  
min = 0.0000



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

t = 5.2884 [ms]

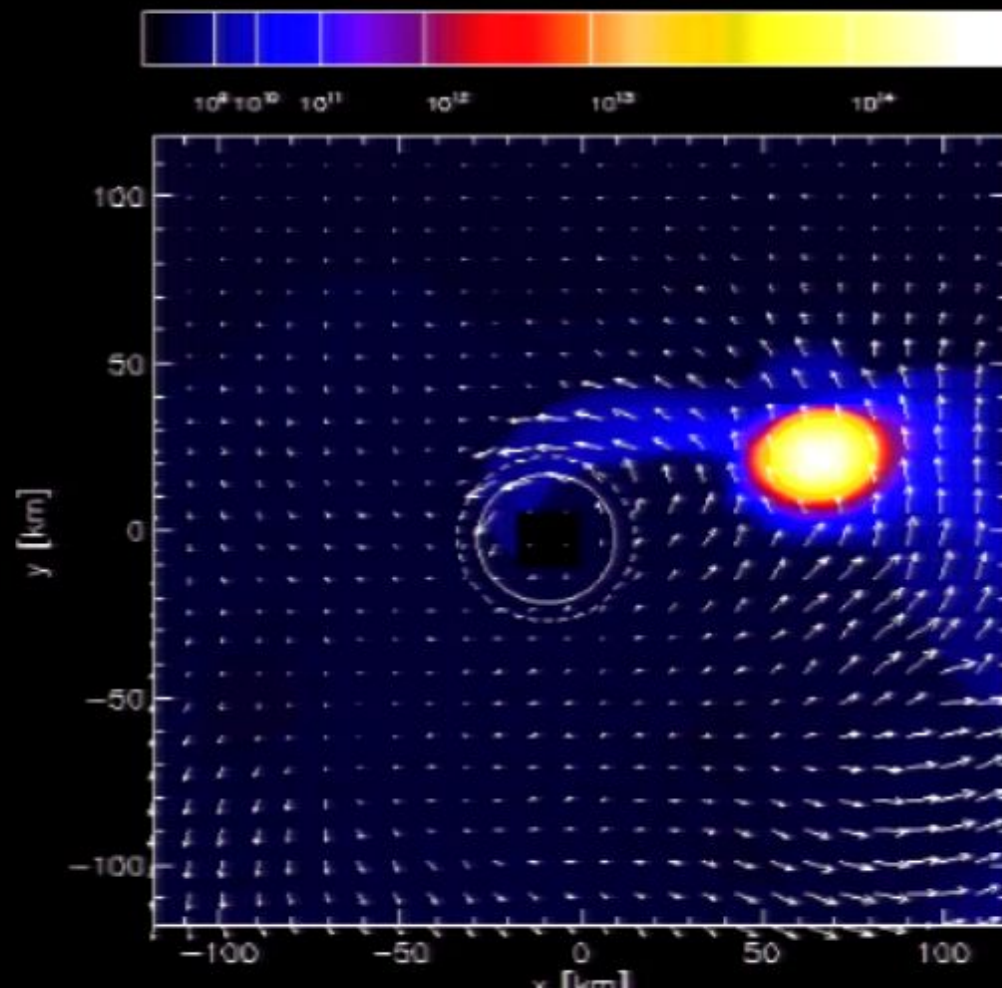
max = 0.4354  
min = 0.0000



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

t = 6.9724 [ms]

max = 0.5439  
min = 0.0000

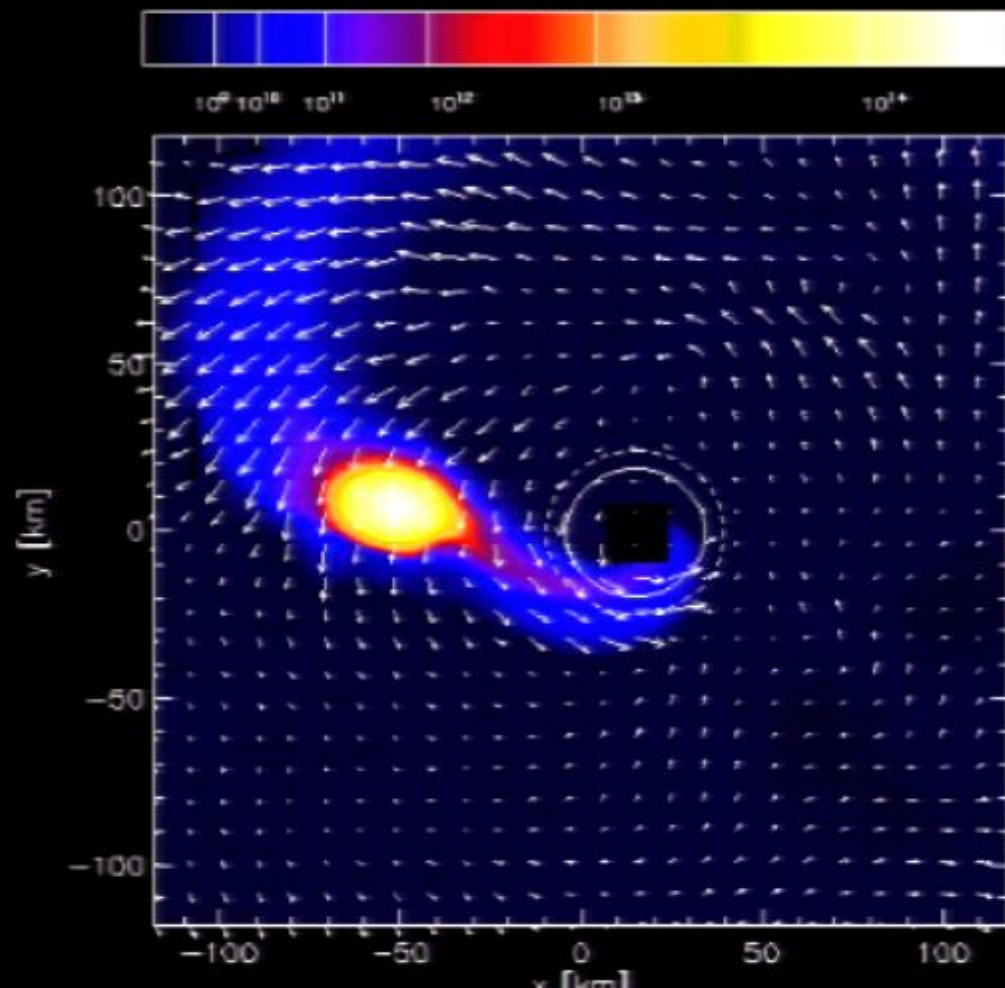




# $a=0.5$ and $B=10^{12}$ G

t = 8.9518 [ms]

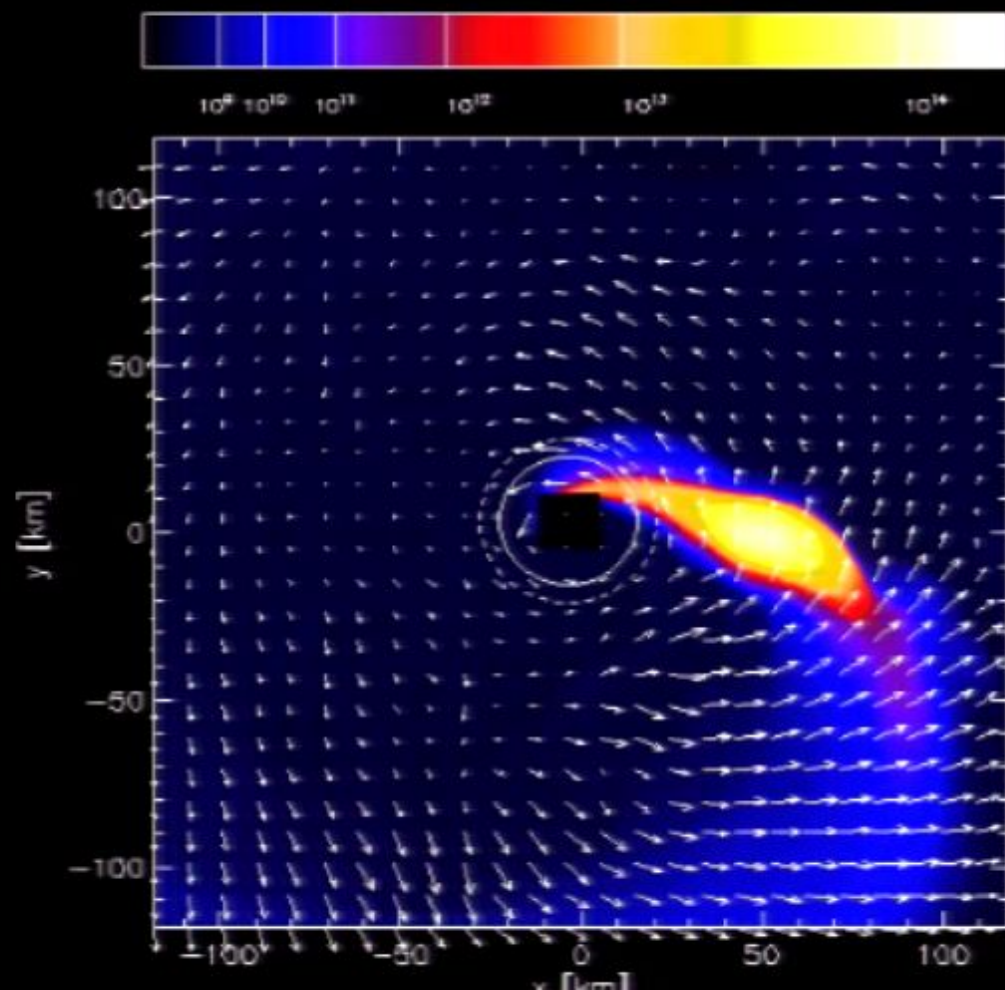
max = 0.5084  
min = 0.0000



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

t = 10.8131 [ms]

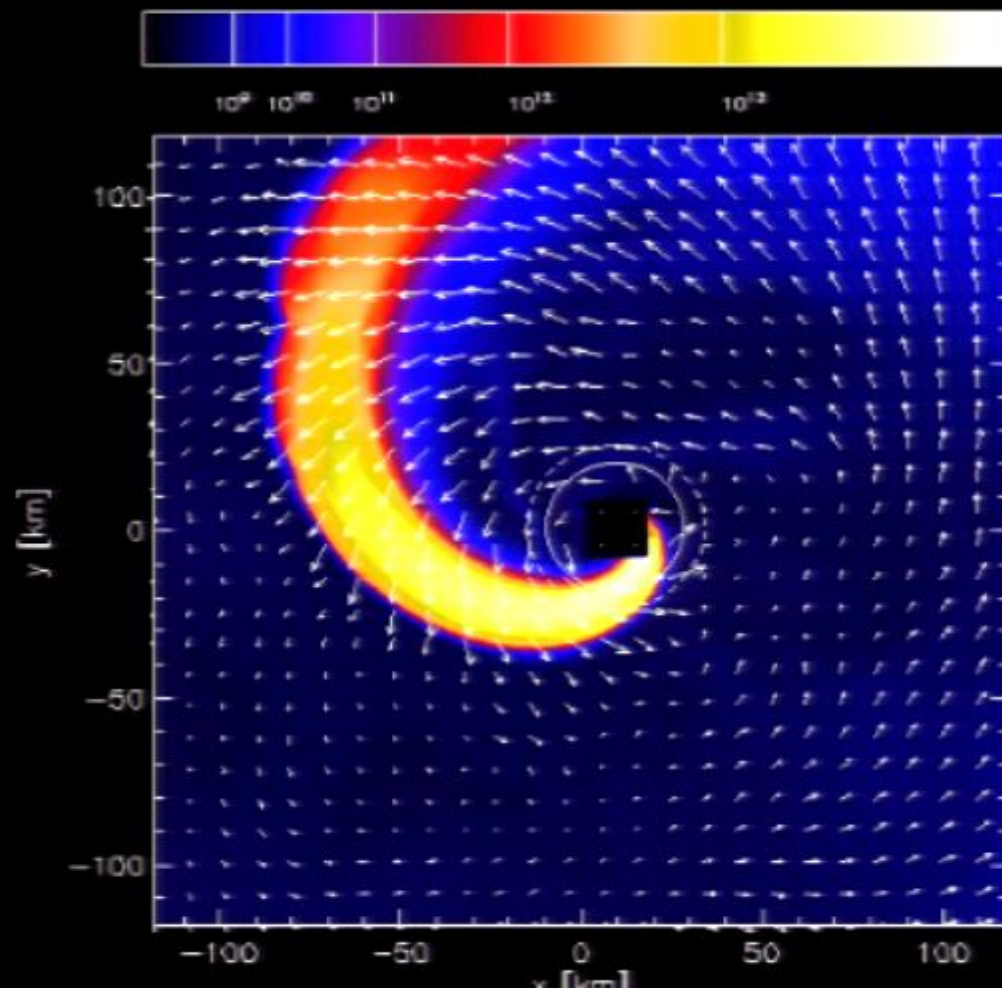
max = 0.5118  
min = 0.0000



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

$t = 12.4971$  [ms]

max = 0.5163  
min = 0.0000

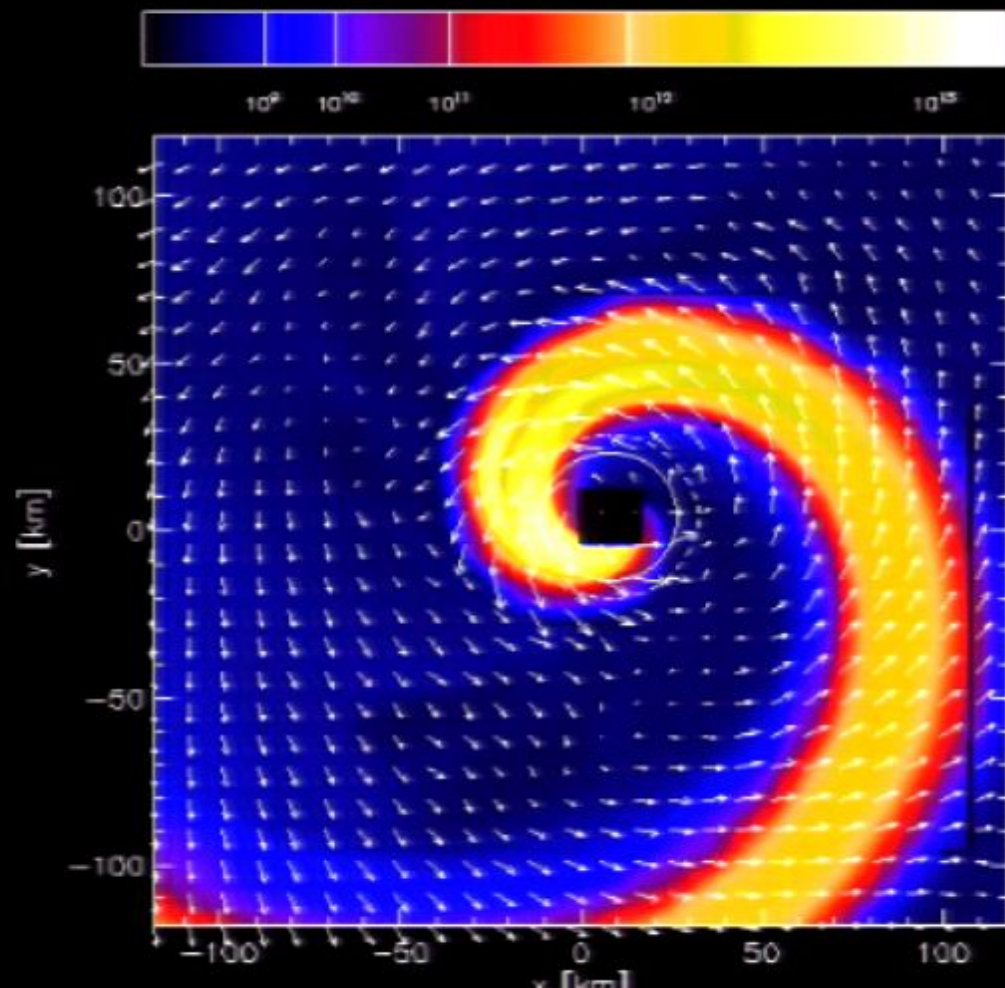




# $a=0.5$ and $B=10^{12}$ G

$t = 14.4766$  [ms]

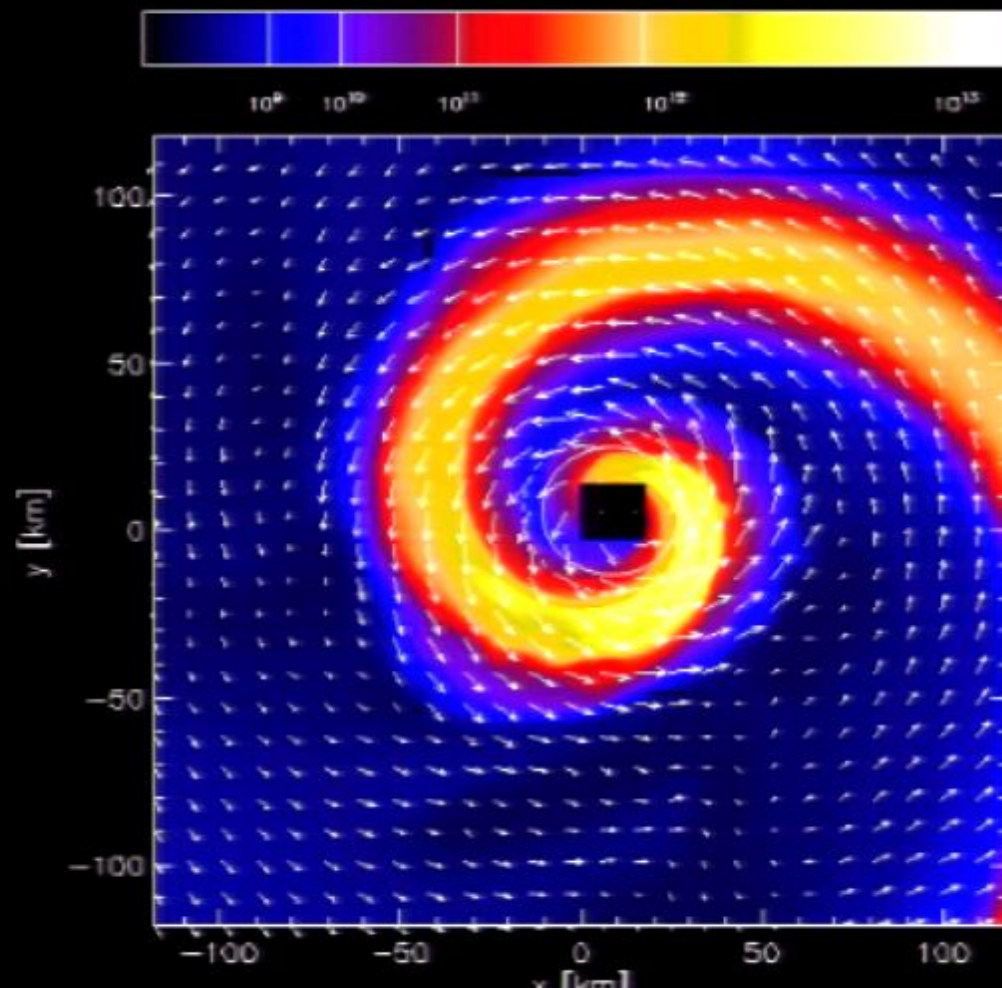
max = 0.4804  
min = 0.0000



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

$t = 16.3378$  [ms]

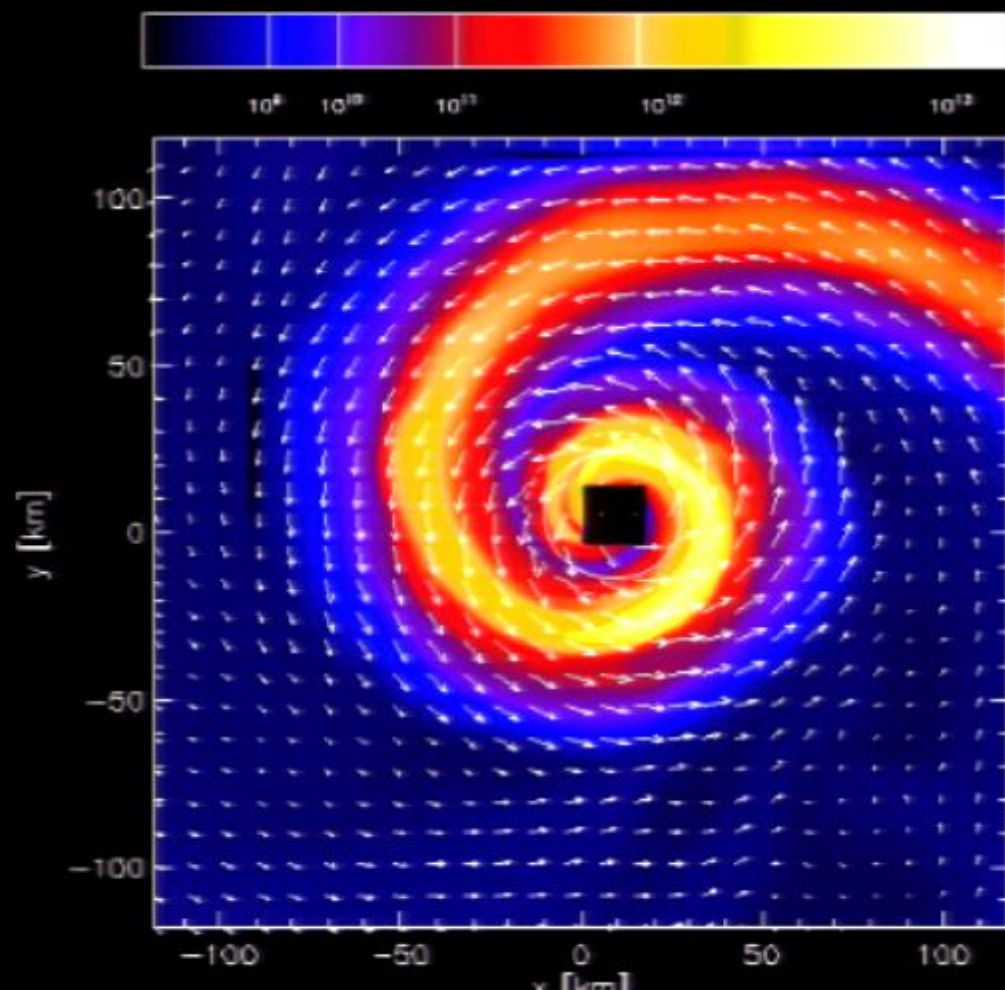
max = 0.4641  
min = 0.0000



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

$t = 18.0514$  [ms]

max = 0.4696  
min = 0.0000

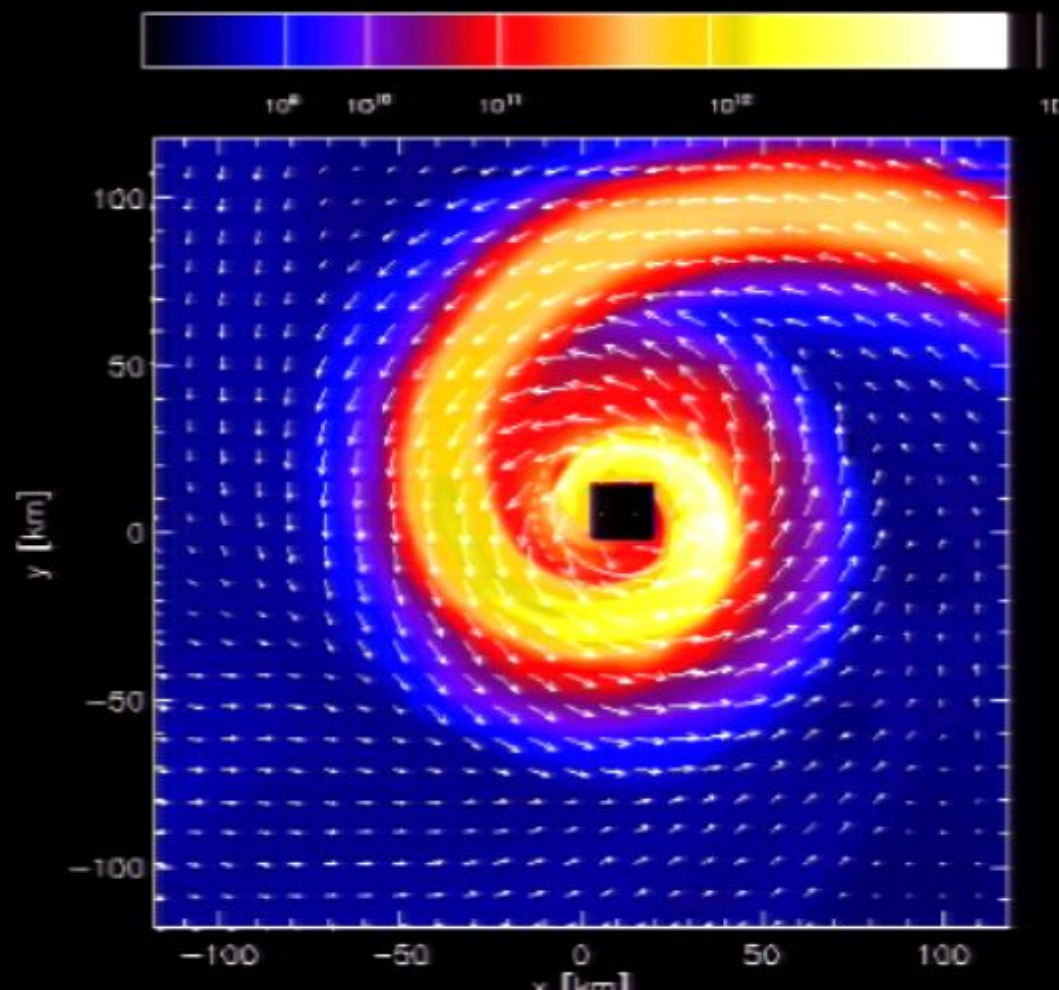




# $a=0.5$ and $B=10^{12}$ G

$t = 20.0308$  [ms]

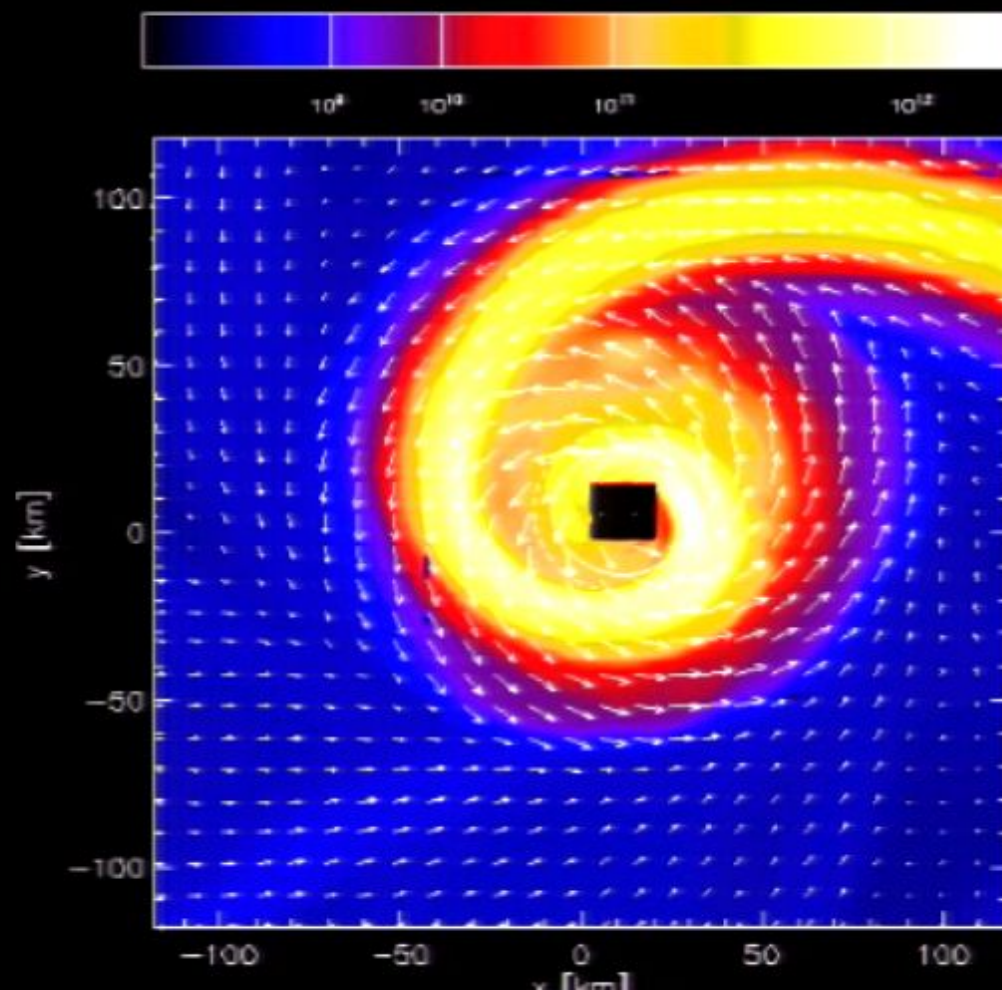
max = 0.4749  
min = 0.0000



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

t = 21.8921 [ms]

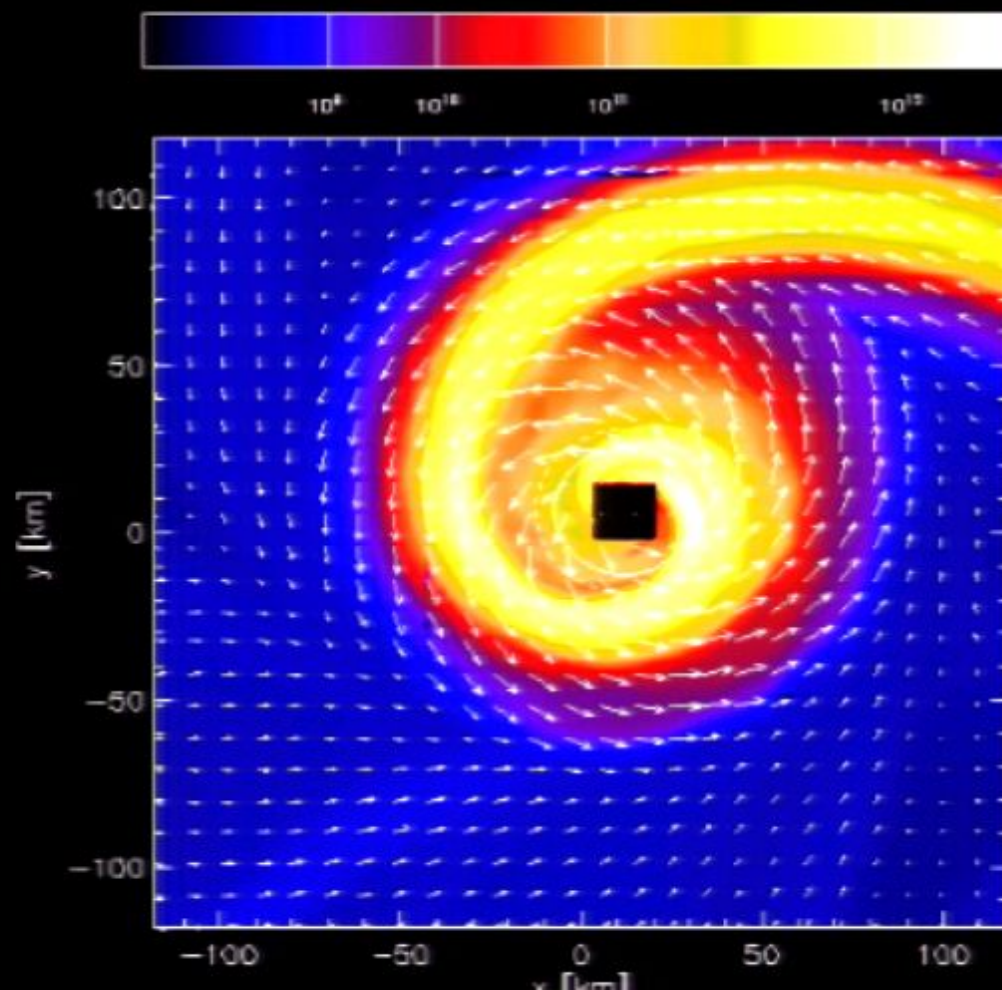
max = 0.4862  
min = 0.0000



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

t = 22.1580 [ms]

max = 0.4882  
min = 0.0000





# Accretion Disk

- BH final spin  
 $a \approx 0.56$

- Disk mass  
 $M_{\text{disk}} \approx 1\% M_{\text{NS}}$

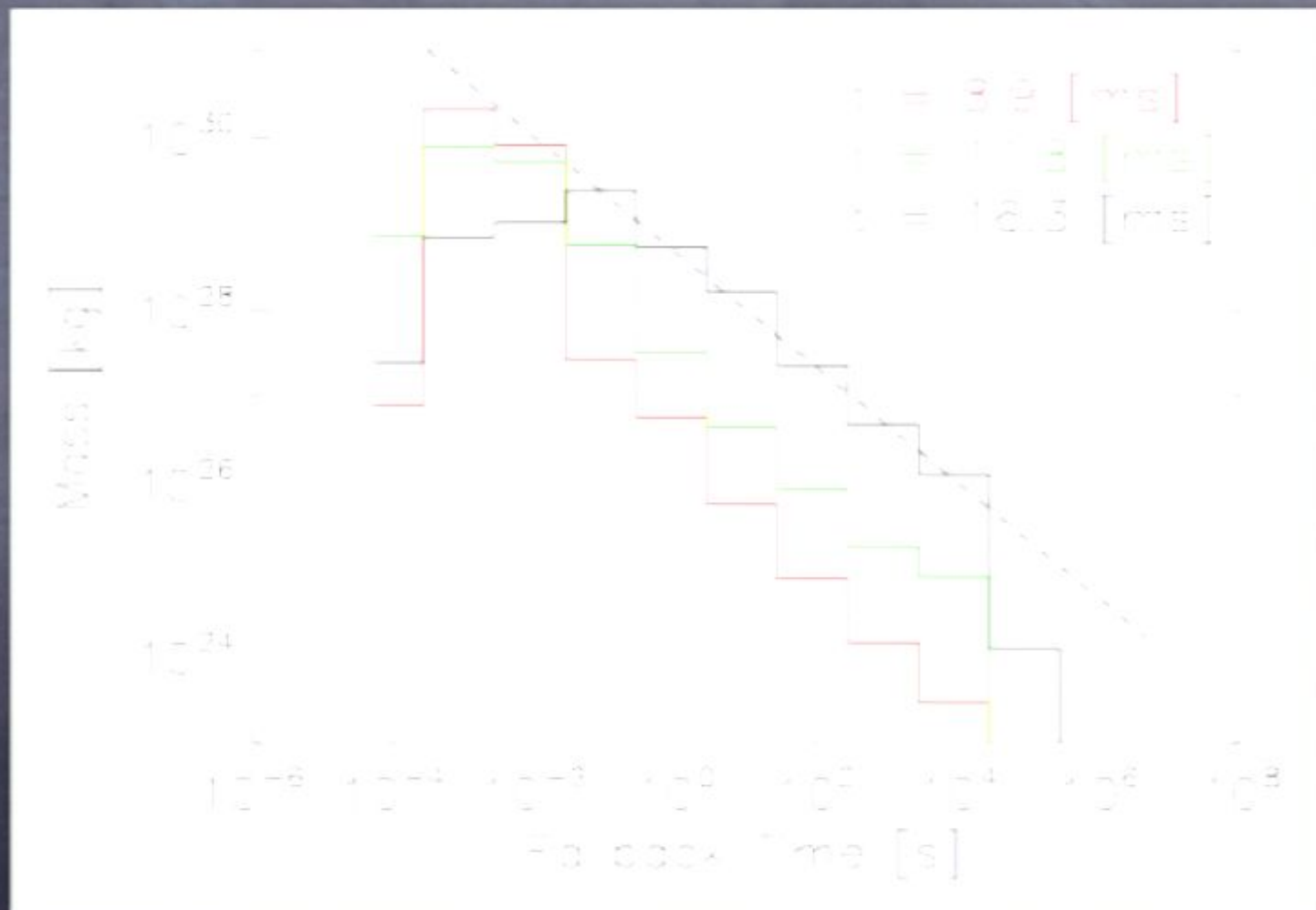


Solid-integrated mass  
plus-mass outside ISCO

Dash-bound matter  
Dot-Dash-4\*unbound matter

# Accretion Power Law

$$\frac{dM}{dt} \propto t^{-5/3}$$

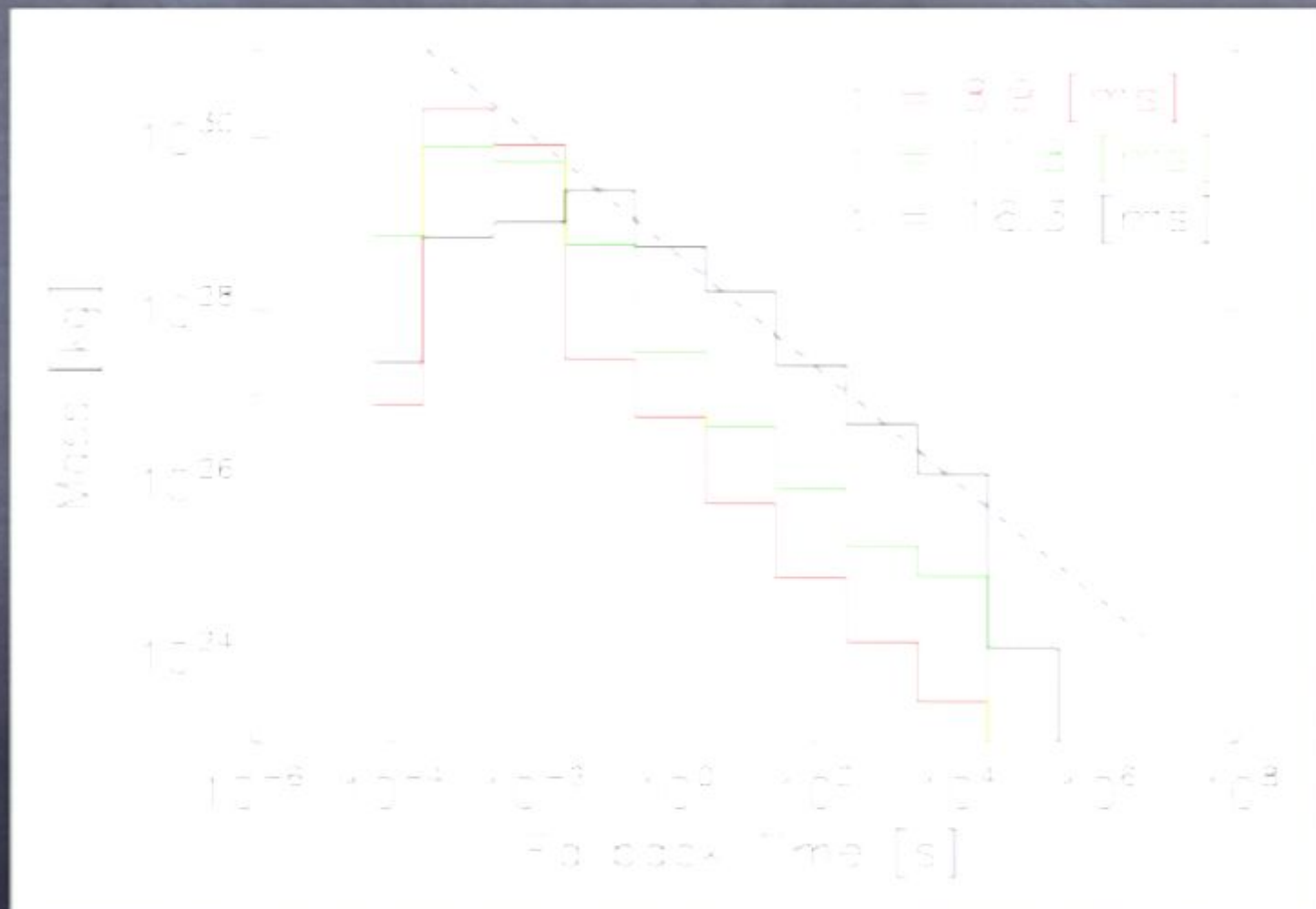


# Kicked Disk



# Accretion Power Law

$$\frac{dM}{dt} \propto t^{-5/3}$$



# Kicked Disk

# Kicked BH + Disk

(Megevand et al., PRD 2009)

Anderson et al., PRD 2010)

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



# Perturbed disk

---

**PERTURBED  
DISCS GET  
SHOCKED**

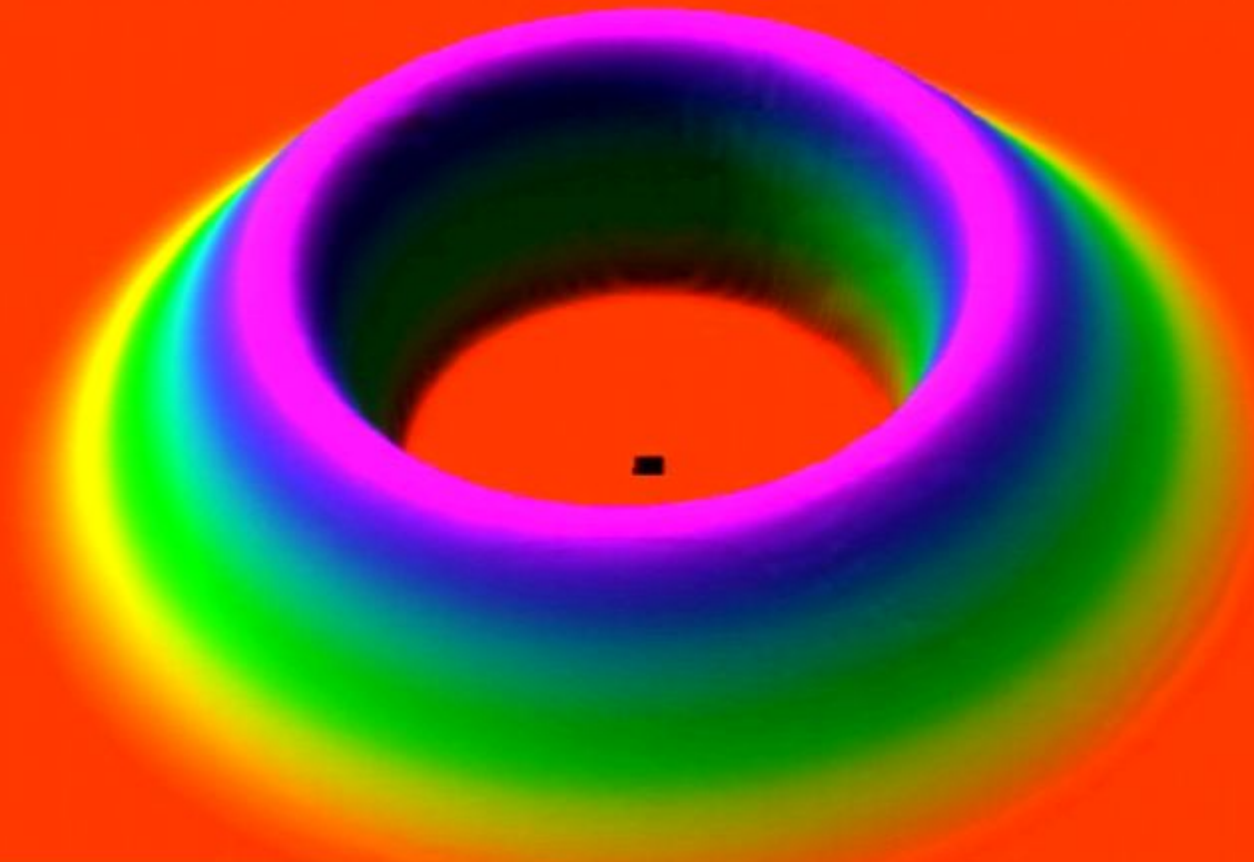
# Perturbed disk

t=114.29

zscale=6.923e+02

31 x 31

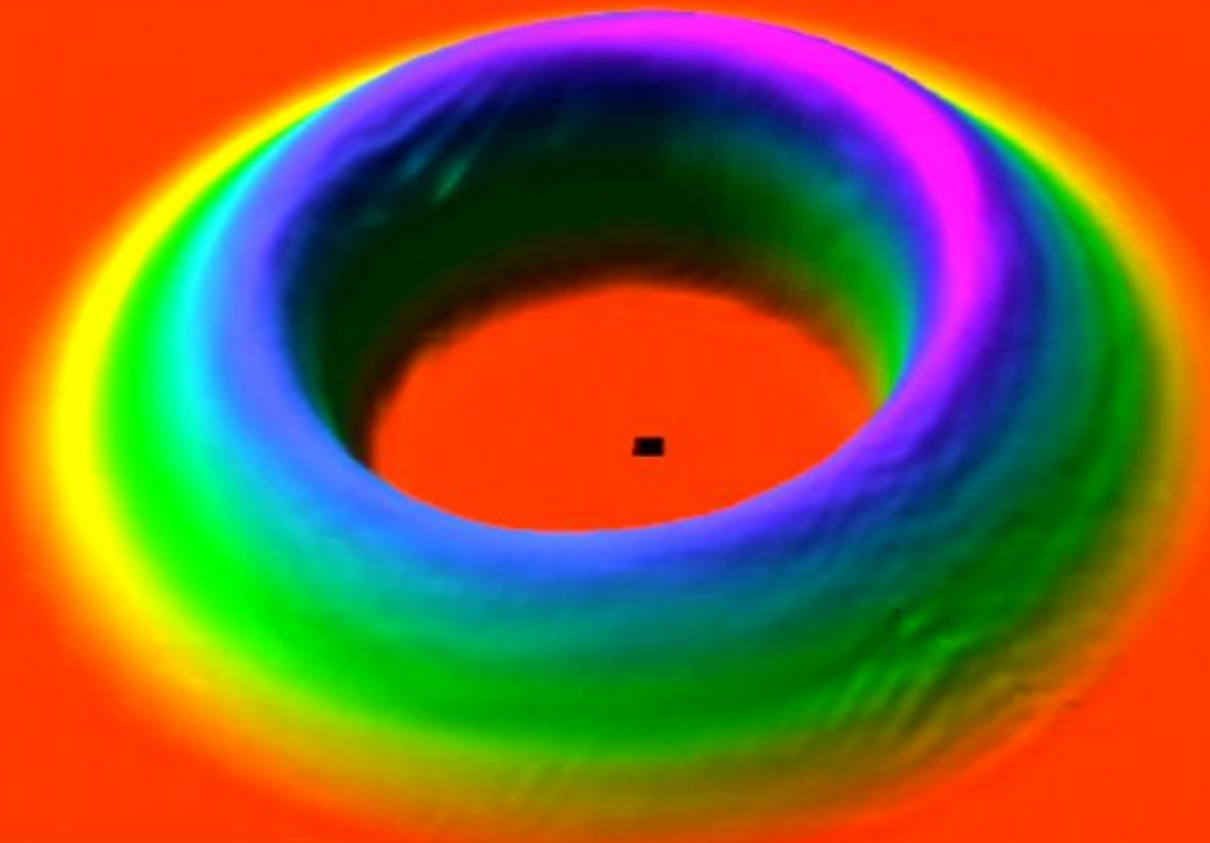
[-150.000,150.000], [-150.000,150.000]



# Perturbed disk

t=714.29

zscale=6.018e+02  
31 x 31  
[-150.000,150.000], [-150.000,150.000]





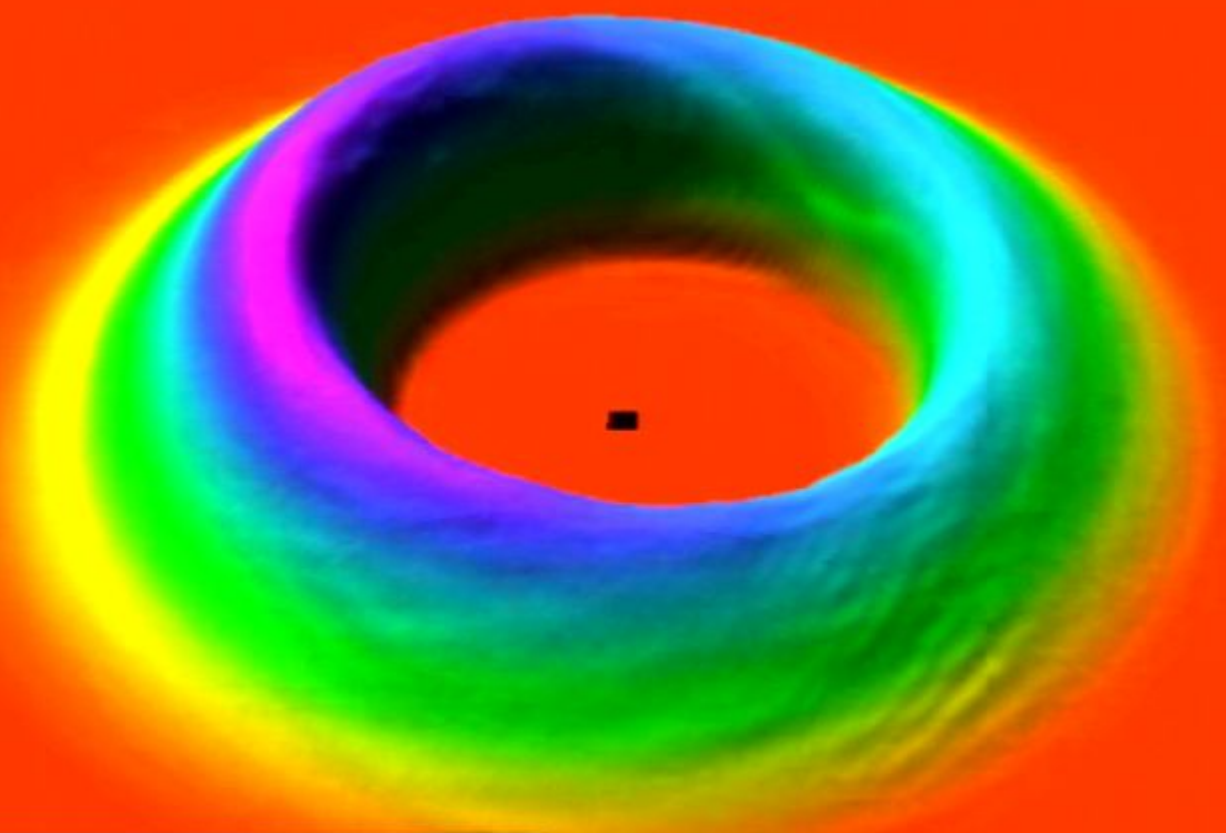
# Perturbed disk

t=1271.43

zscale=5.818e+02

31 x 31

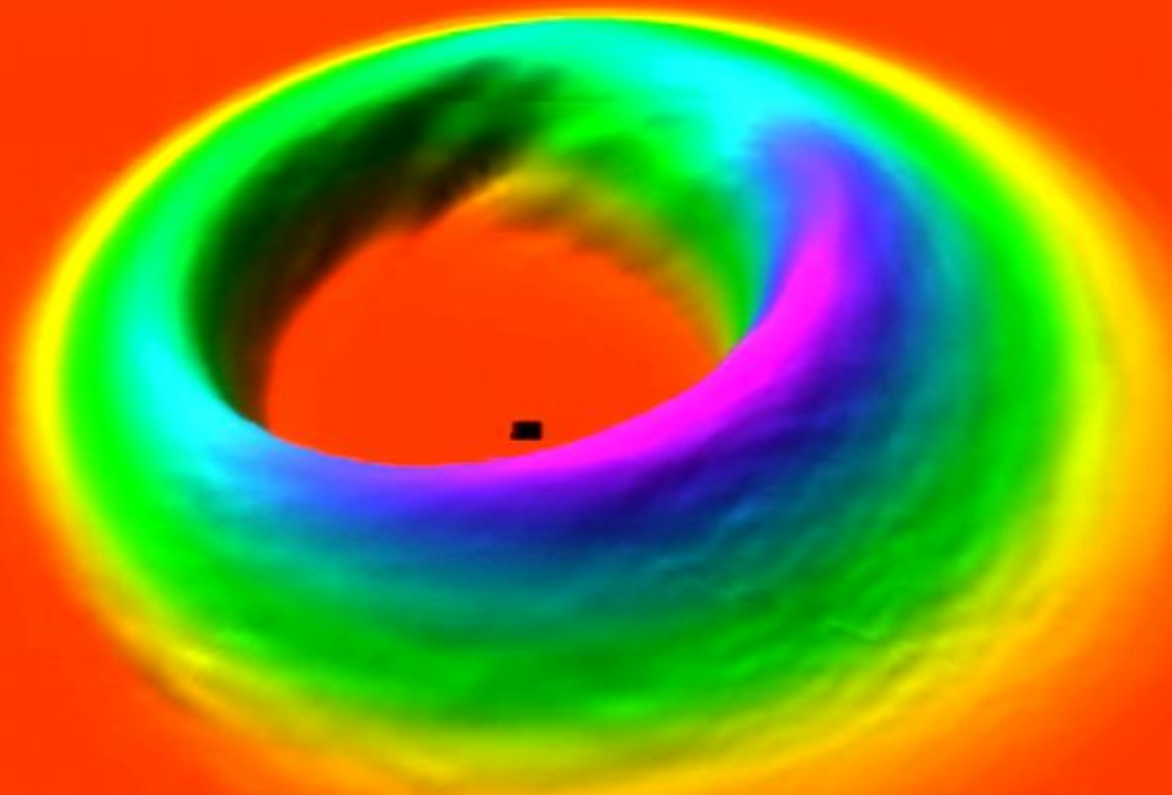
[-150.000,150.000], [-150.000,150.000]



# Perturbed disk

t=1785.71

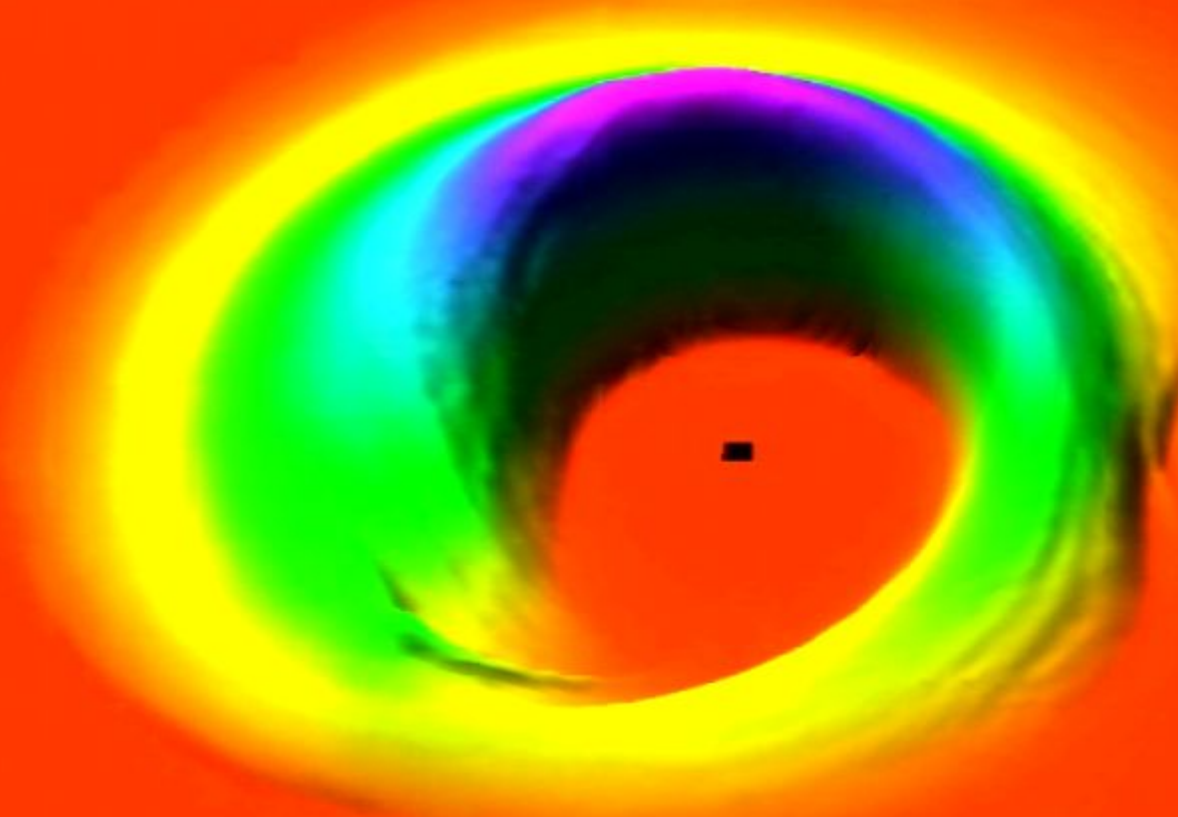
zscale=5.201e+02  
31 x 31  
[-150,000,150,000], [-150,000,150,000]



# Perturbed disk

t=2392.86

zscale=4.240e+02  
31 ± 31  
[-150.000,150.000], [-150.000,150.000]





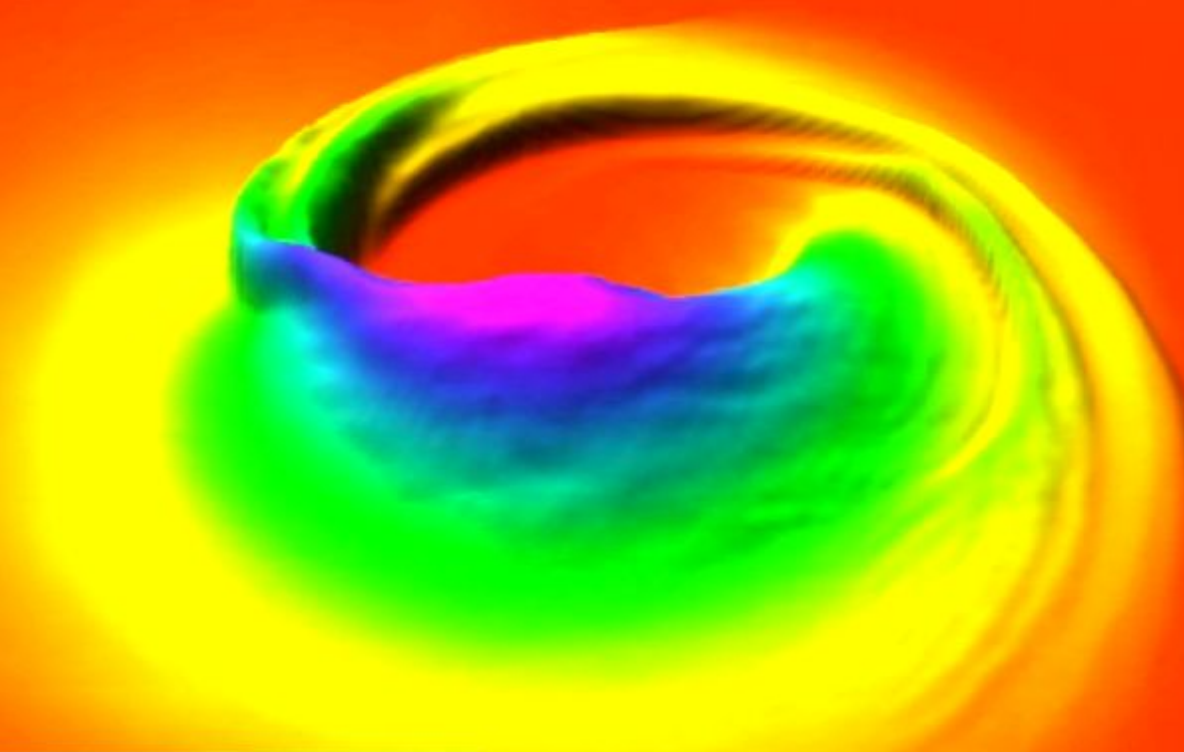
# Perturbed disk

t=2950.00

zscale=3.887e+02

31 x 31

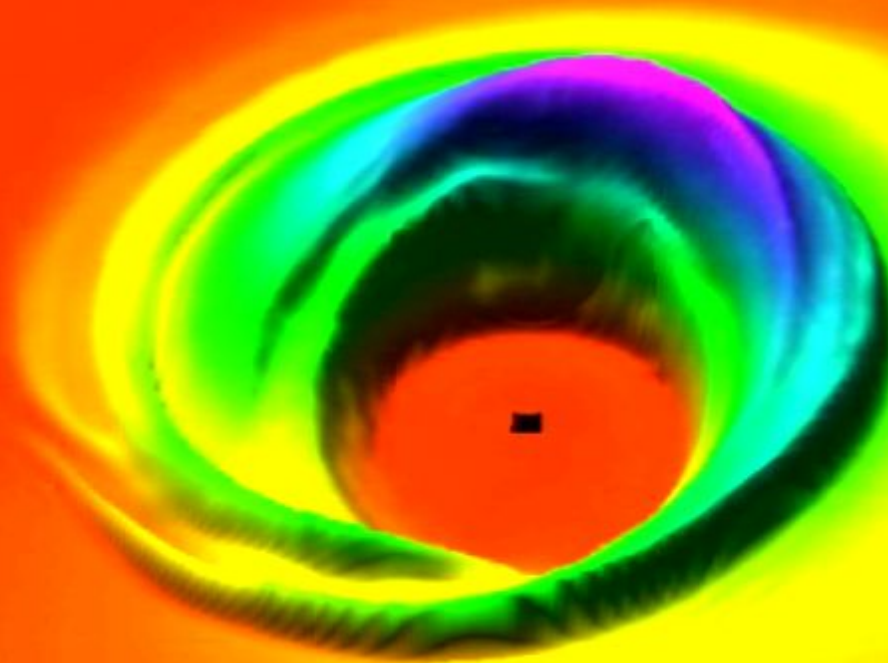
[-150.000,150.000], [-150.000,150.000]



# Perturbed disk

t=3464.29

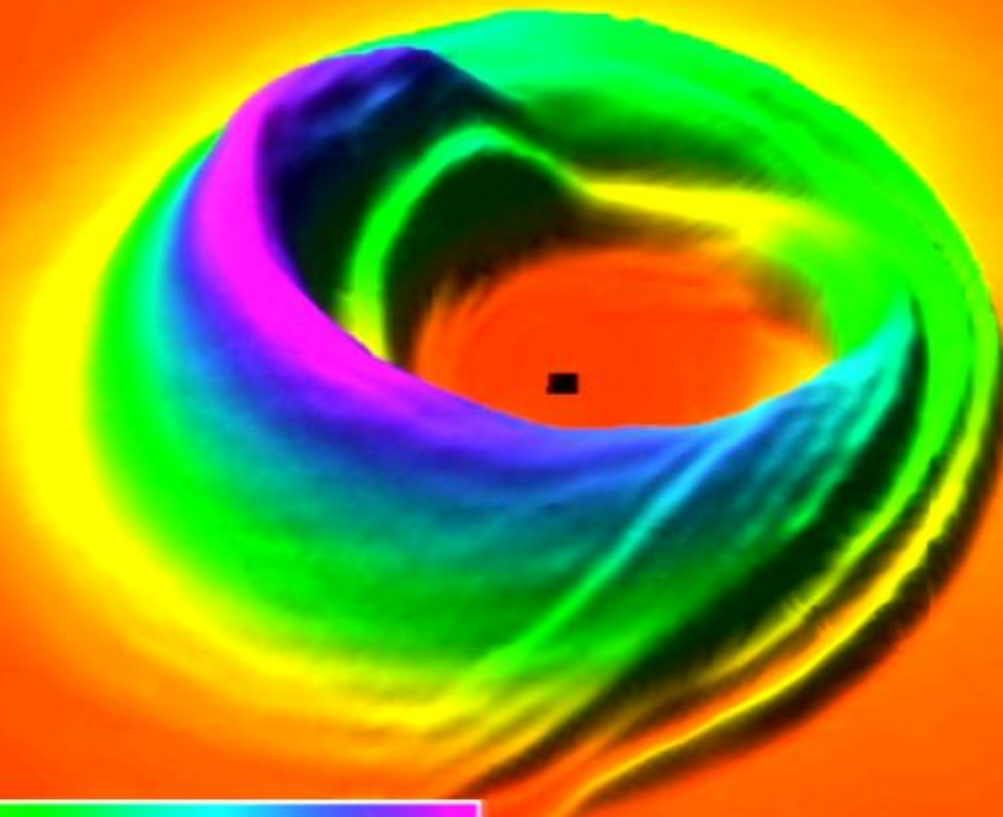
zscale=3.965e+02  
31 x 31  
[-150.000,150.000], [-150.000,150.000]



# Perturbed disk

t=4064.29

zscale=5.052e+02  
31 x 31  
[-150.000,150.000], [-150.000,150.000]

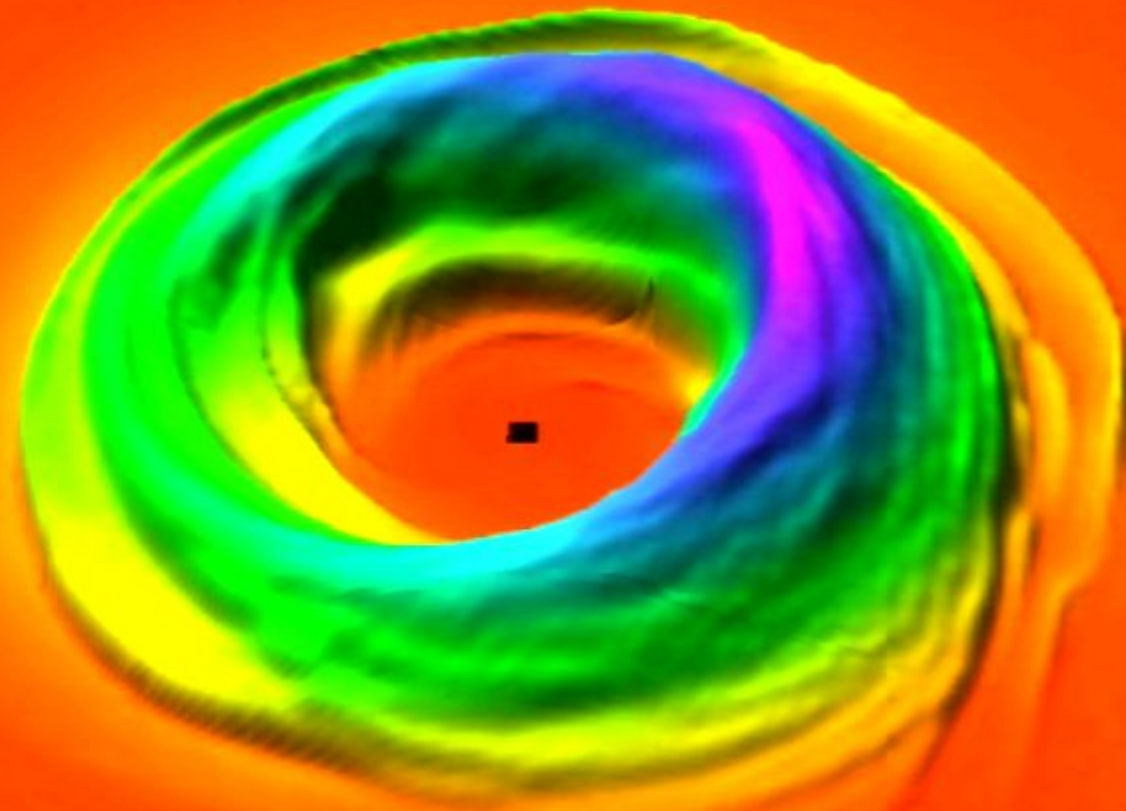




# Perturbed disk

t=4614.29

zscale=4.872e+02  
31 x 31  
[-150.000,150.000], [-150.000,150.000]



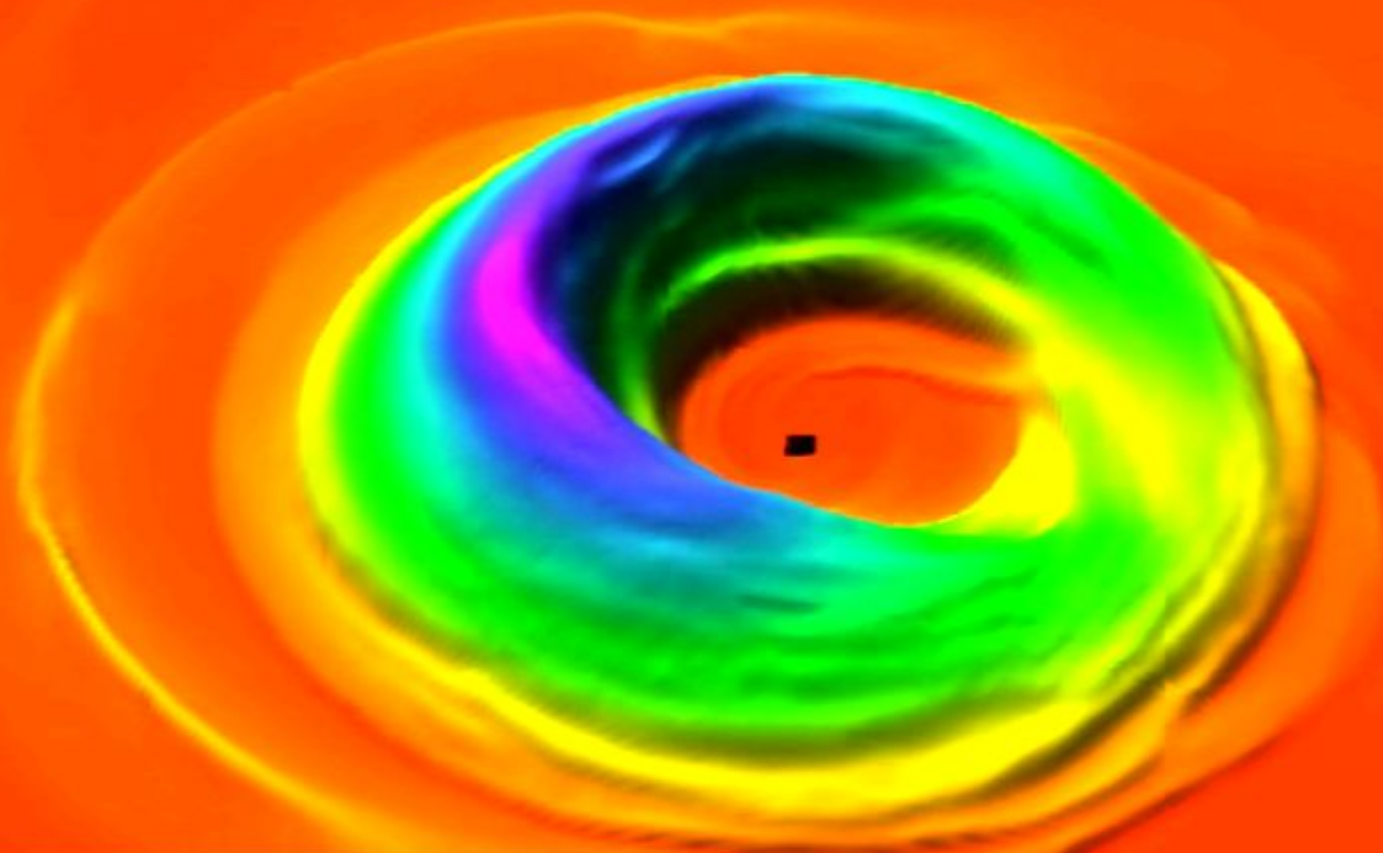
# Perturbed disk

t=5221.43

zscale=4.646e+02

31 x 31

[-150.000,150.000], [-150.000,150.000]



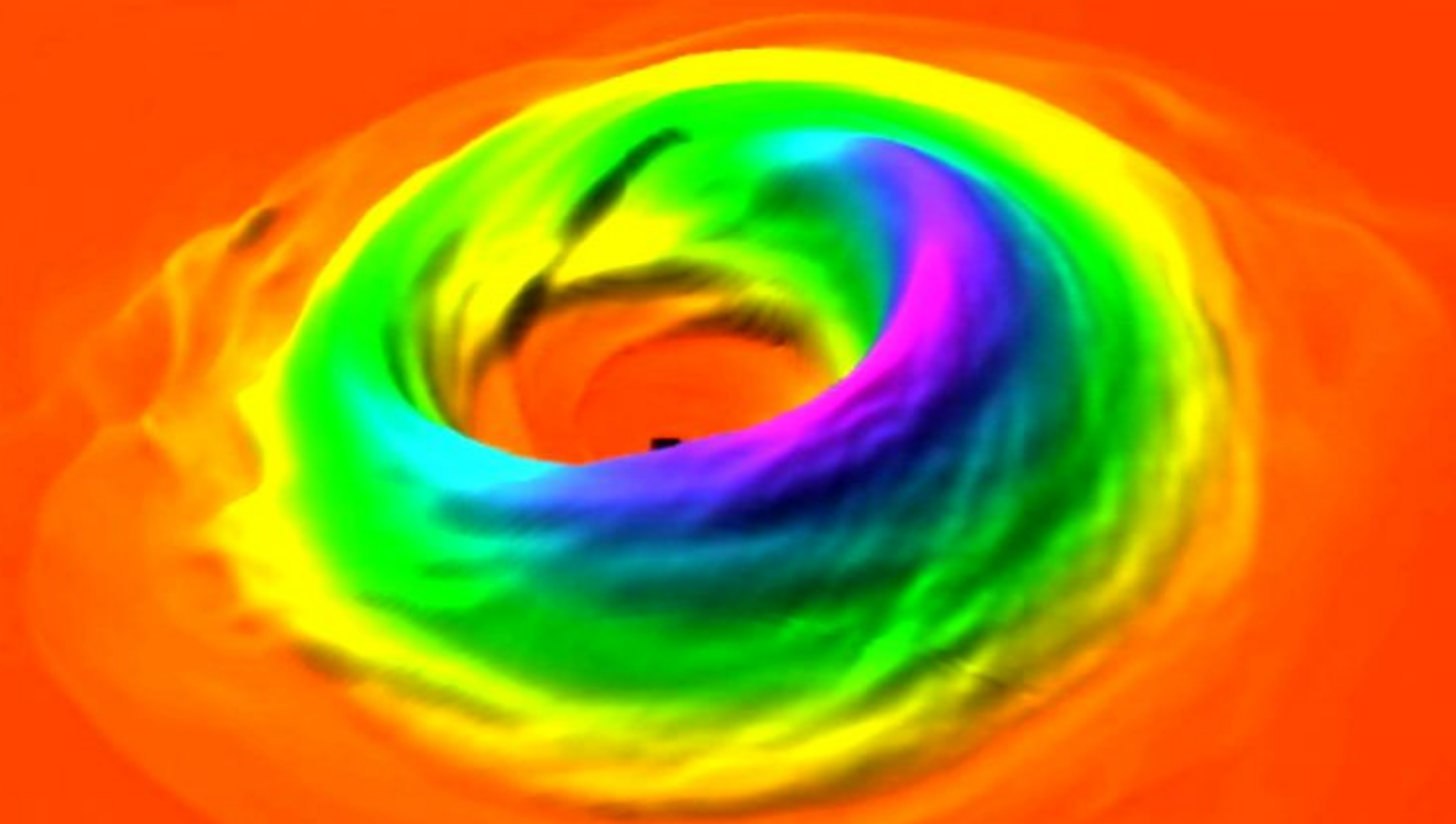
# Perturbed disk

t=5735.71

zscale=4.850e+02

31 x 31

[-150.000,150.000], [-150.000,150.000]





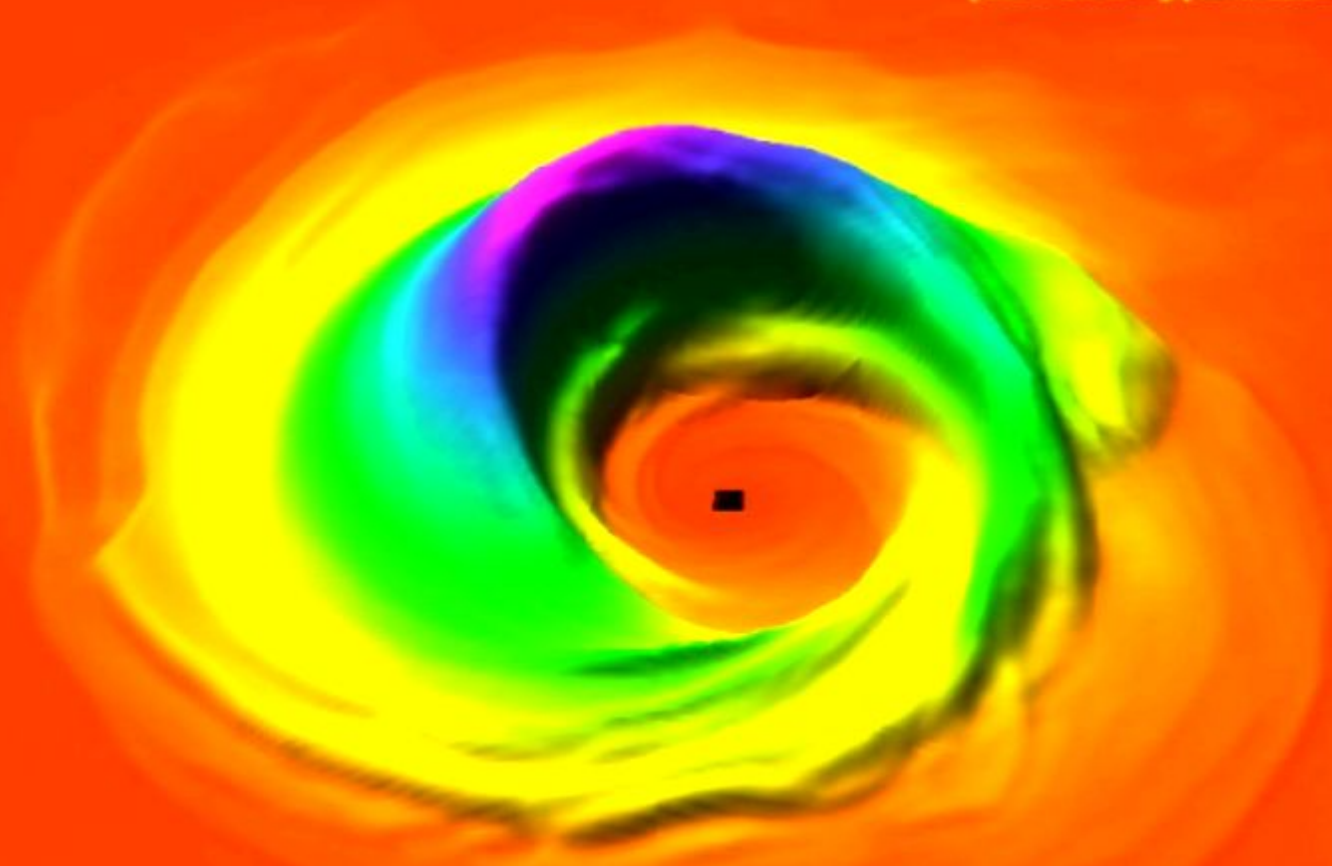
# Perturbed disk

t=6285.71

zscale=3.920e+02

31 x 31

[-150,000,150,000], [-150,000,150,000]



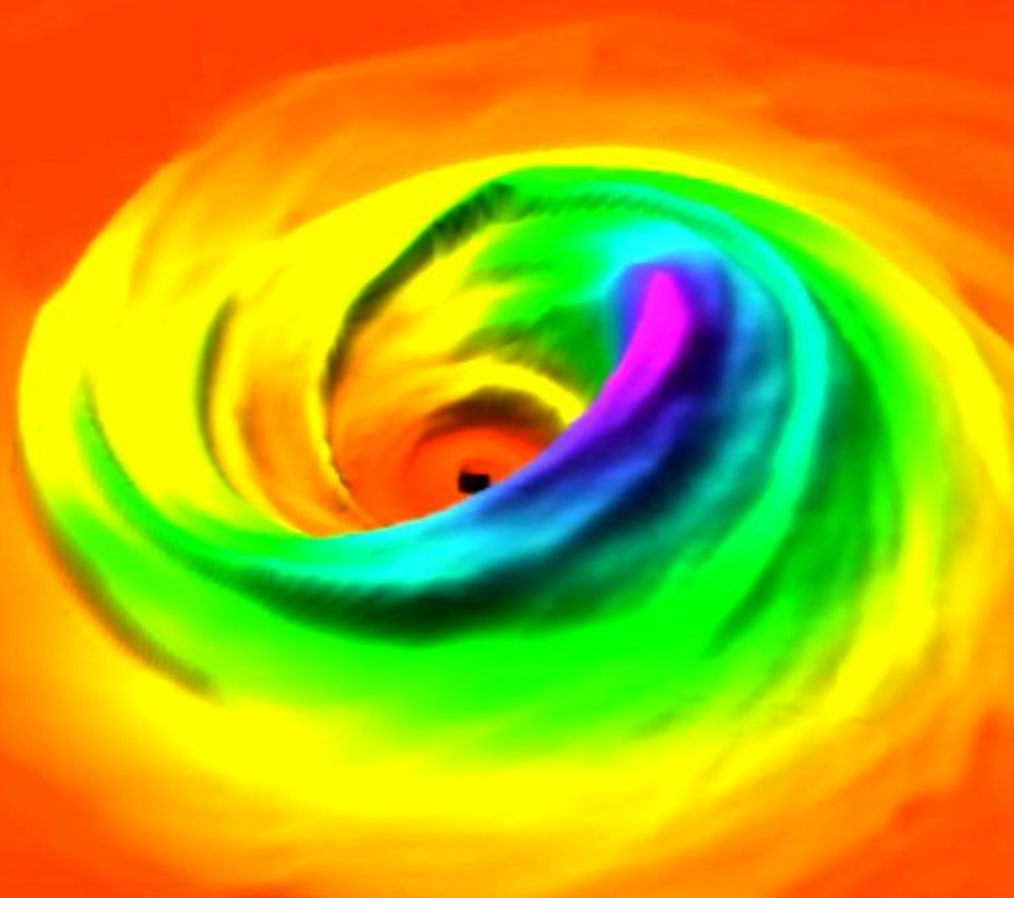
# Perturbed disk

t=6885.71

zscale=3.853e+02

31 x 31

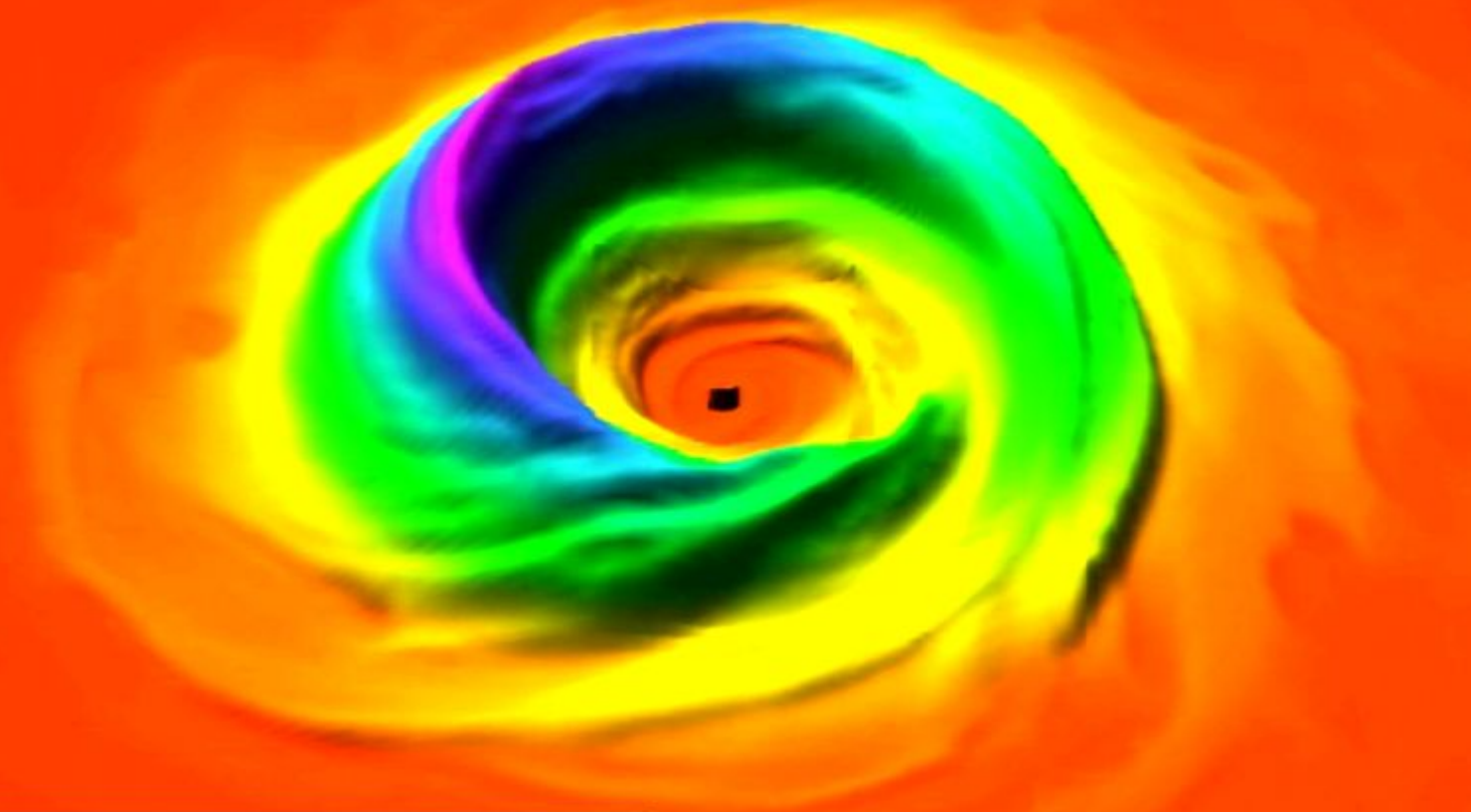
[-150.000,150.000], [-150.000,150.000]



# Perturbed disk

t=7442.86

zscale=4.386e+02  
31 x 31  
[-150,000,150,000], [-150,000,150,000]





# 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

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

$$\frac{dx^a}{d\lambda} = p^a$$

$$\frac{dp_a}{d\lambda} = g^{cb} \Gamma^e_{ac} p_b p_e$$

- Post-processing, camera at infinity
- Fluid is adiabatic  $\rightarrow$  no cooling or heating

# Astrophysical Radiation Sources

- Thermal radiation

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

- Bremsstrahlung

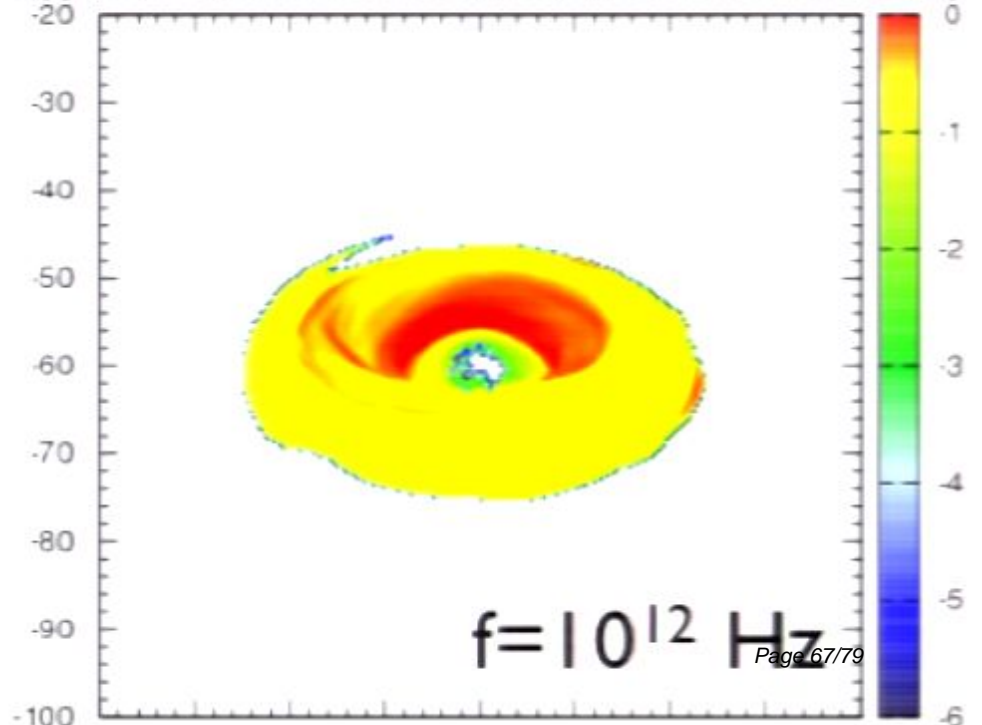
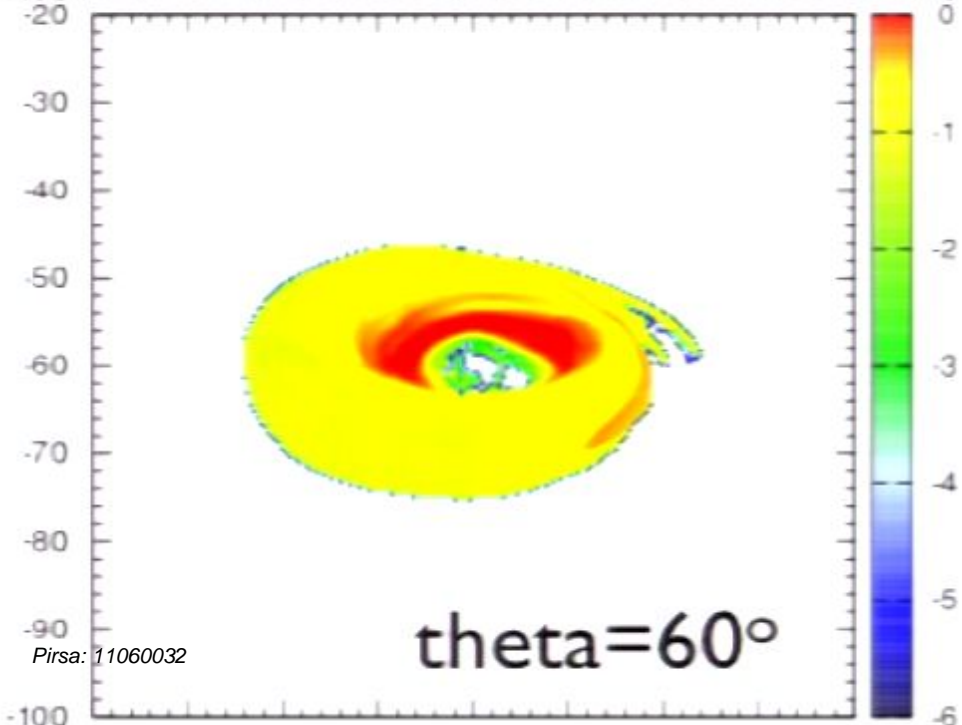
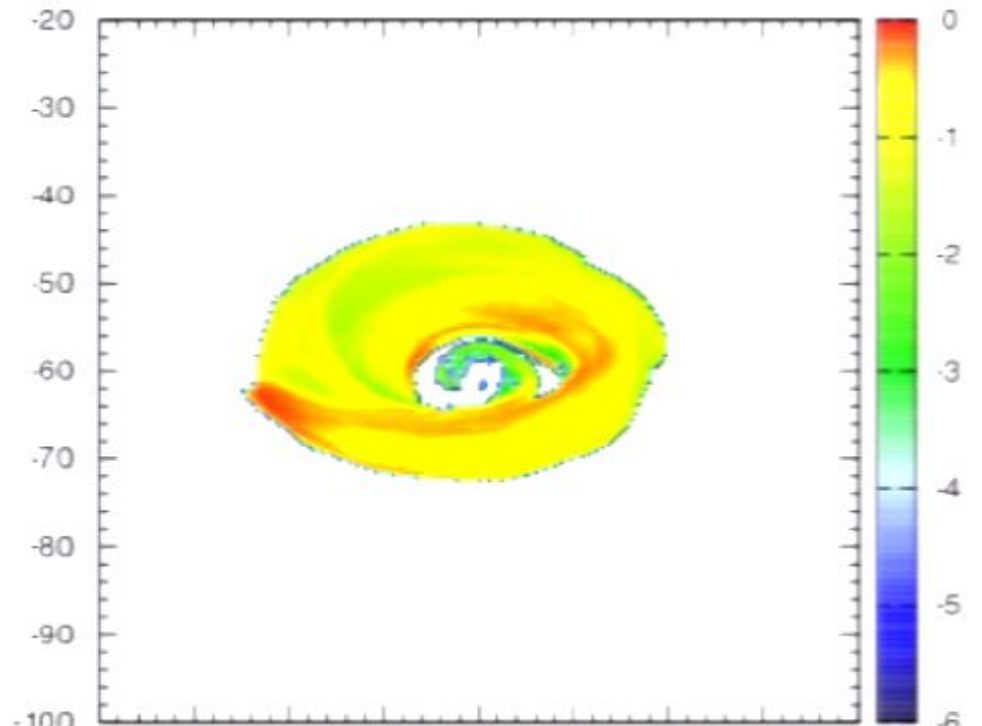
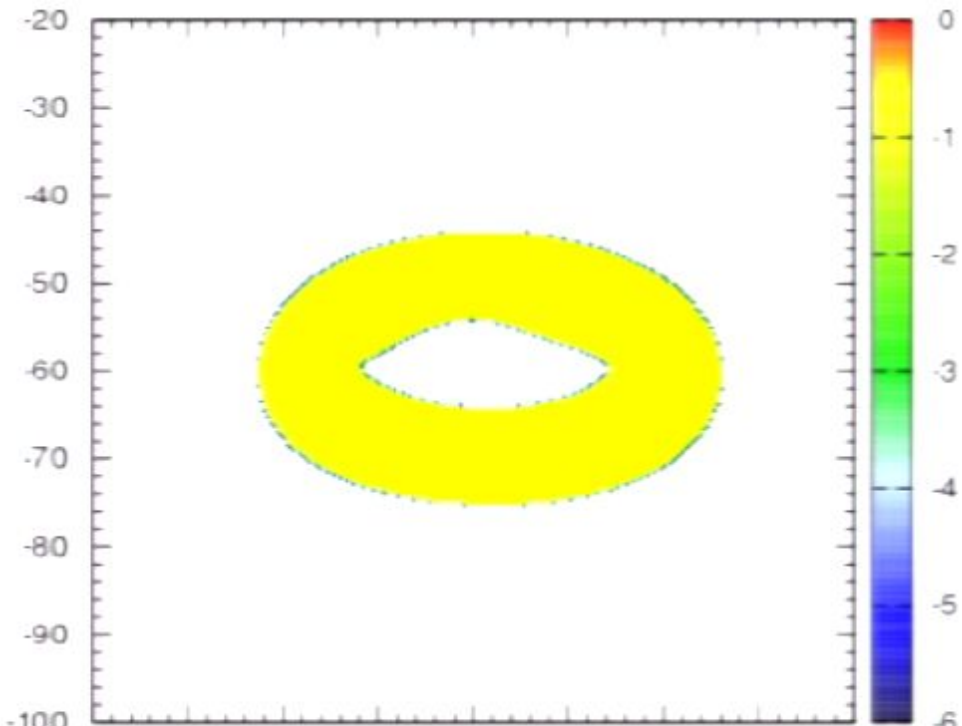
$$\eta_0 \propto T^{-1/2} e^{-h\nu/kT}$$

- Synchrotron emission

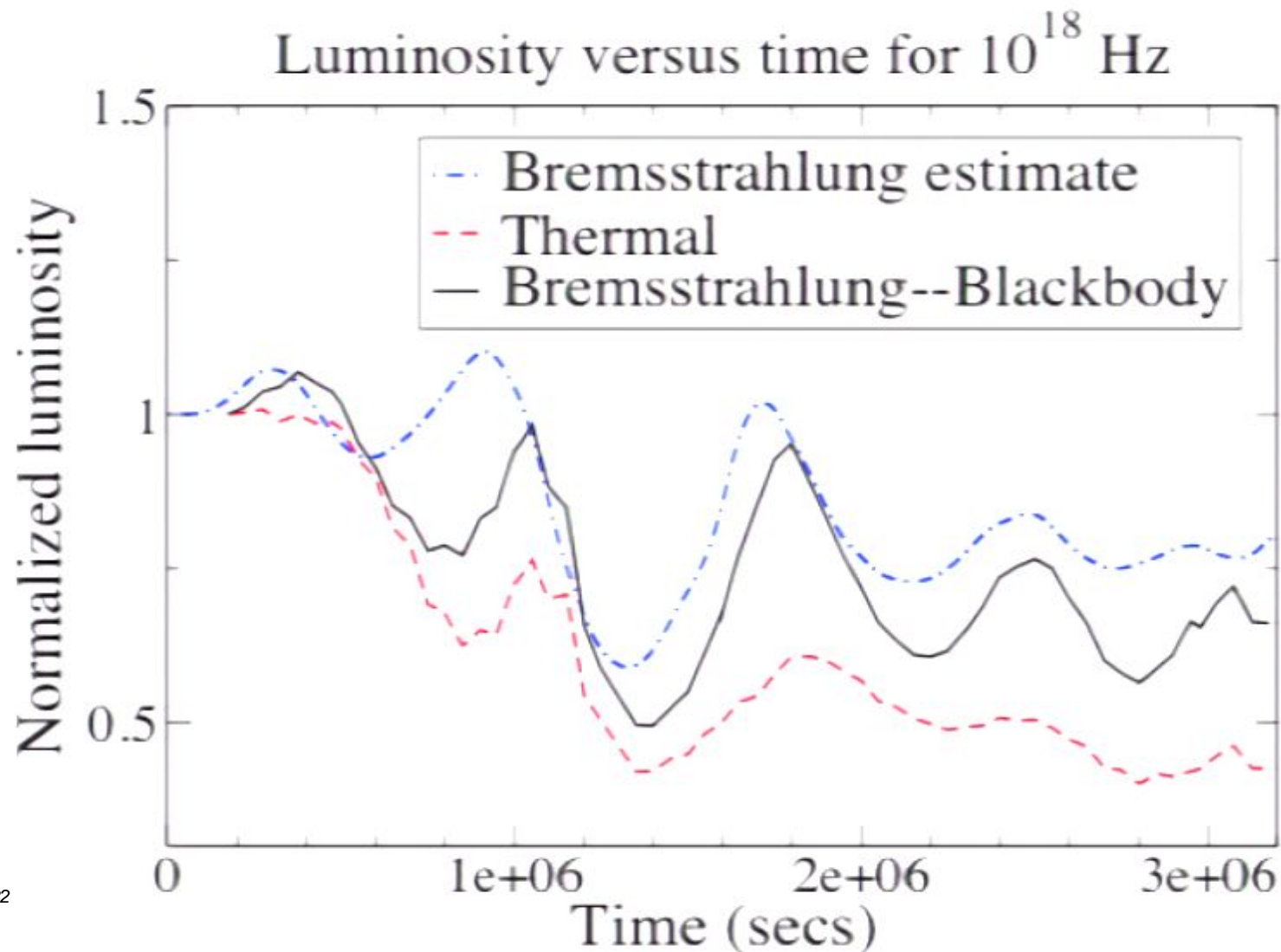
- Absorption

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



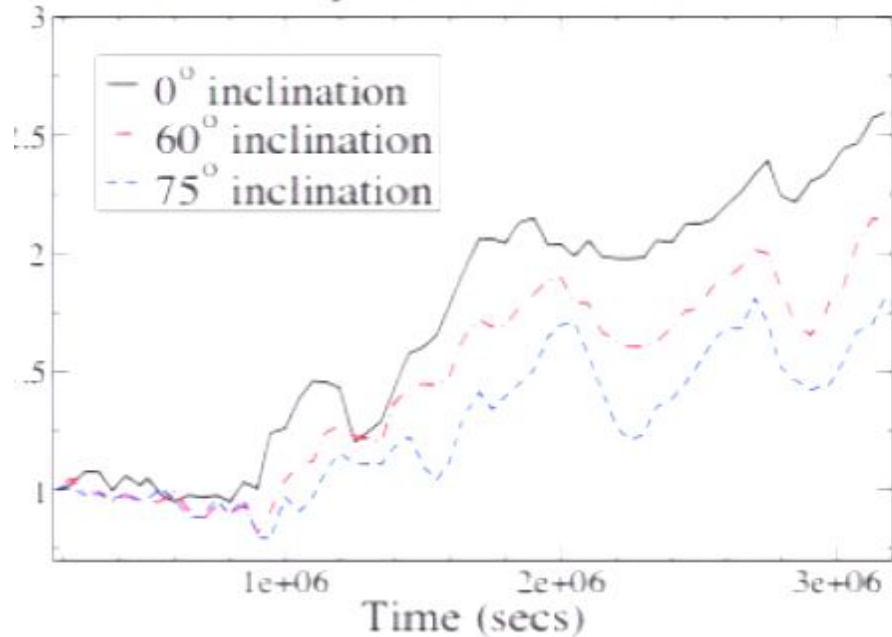


# Emission models

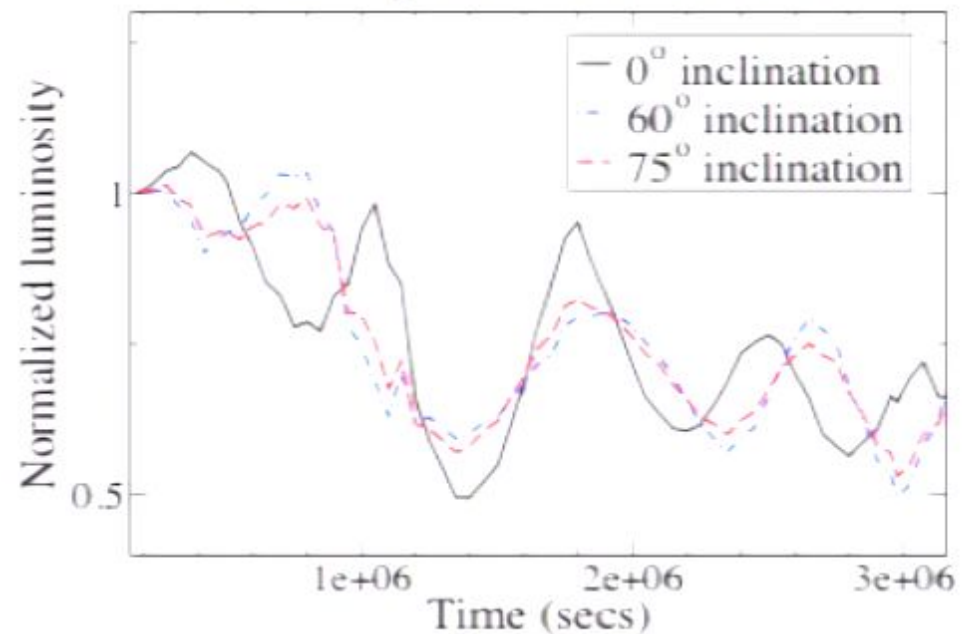


# Luminosity with inclination

Luminosity versus time for  $10^{12}$  Hz



Luminosity versus time for  $10^{18}$  Hz

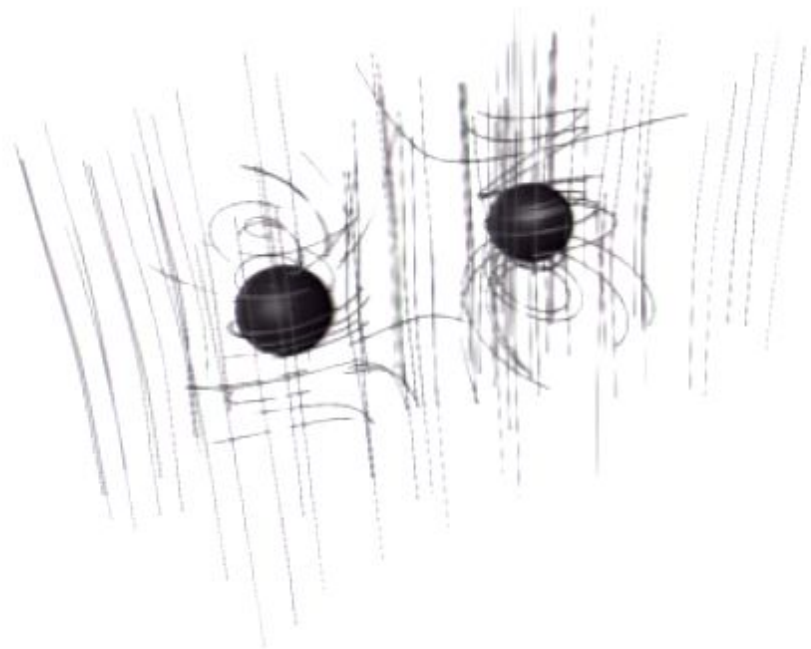




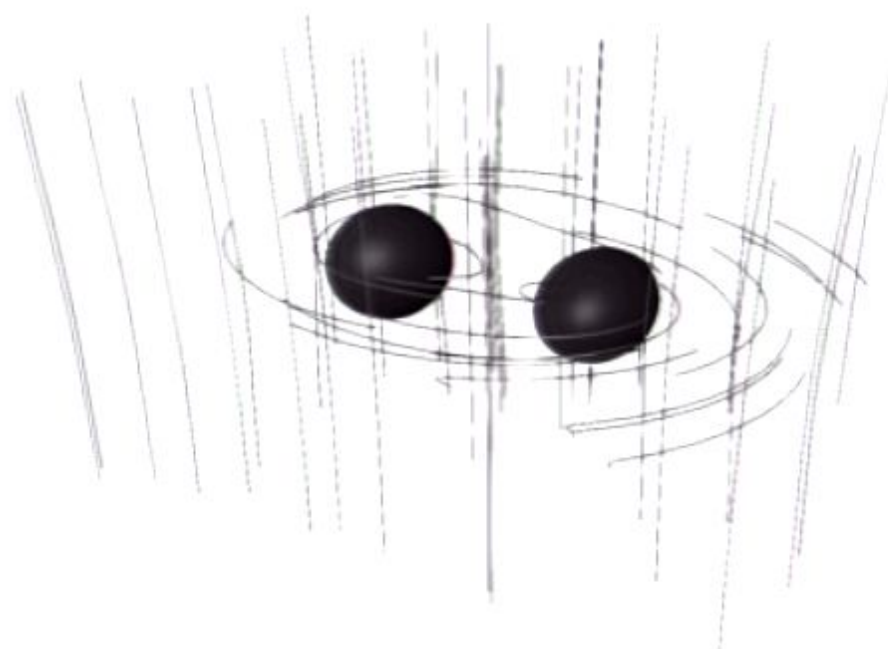
BH-BH + EM

# BBH + Maxwell

(Palenzuela et al., PRL 2009)

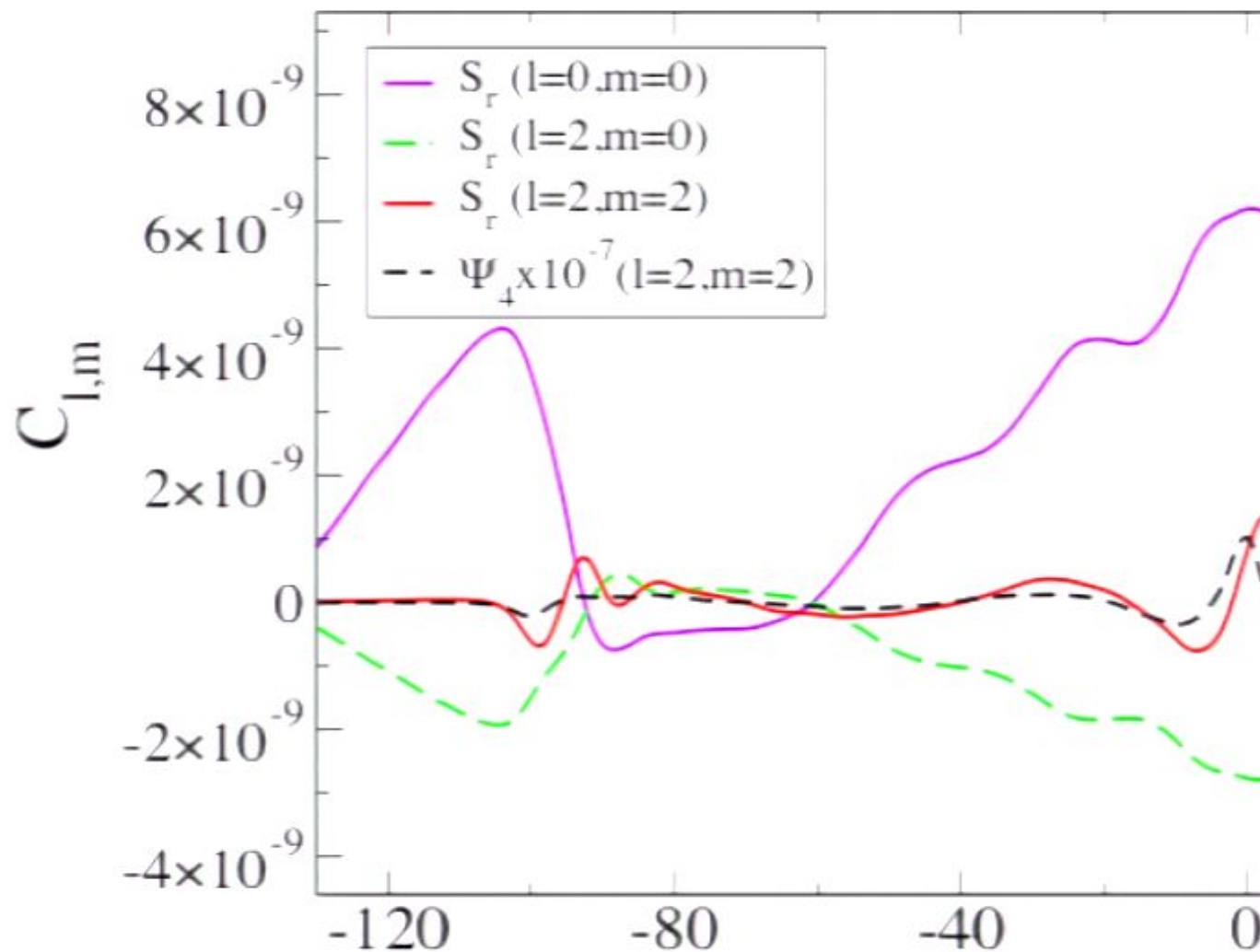


$t = -40 M$



$t = -20 M$

# EM+GW Modes





BH-BH + FFE = FFE ?

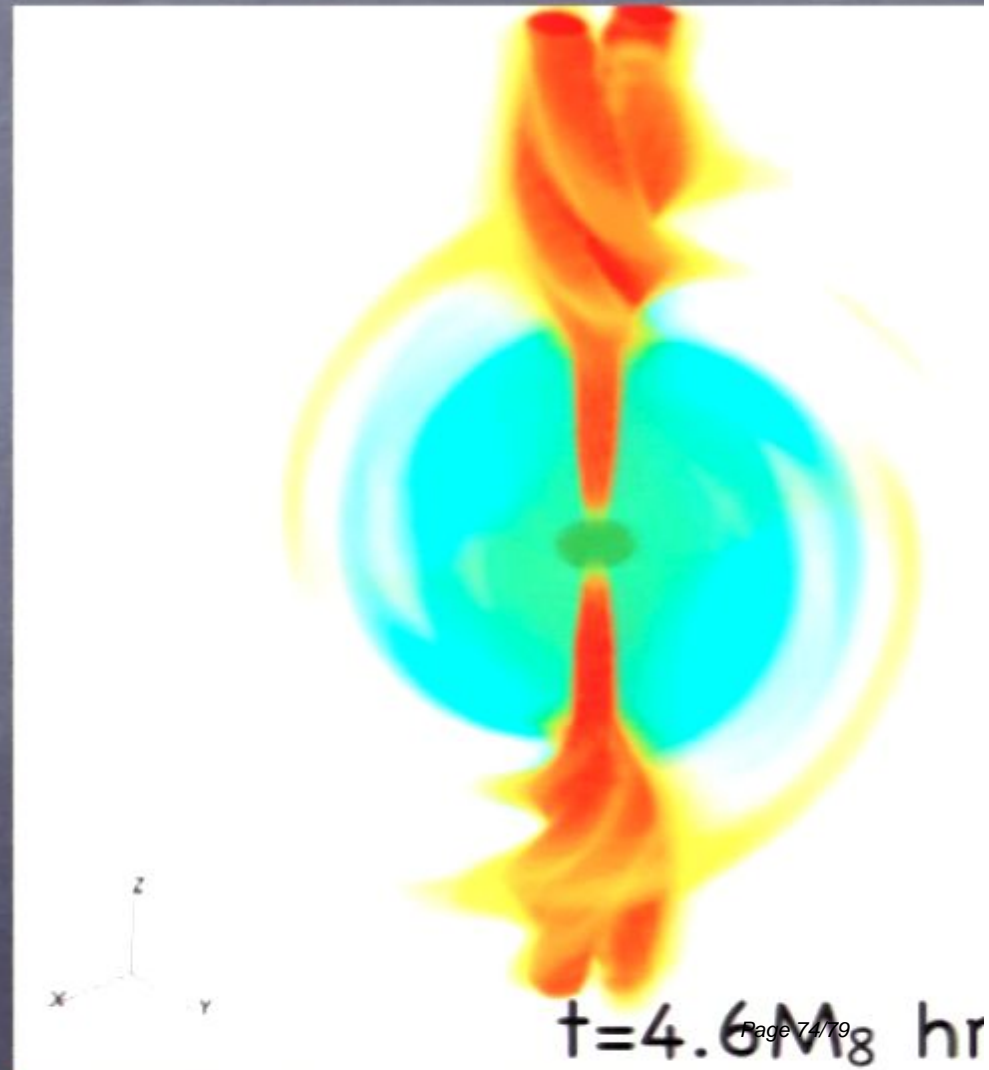
# BBH + Magnetosphere

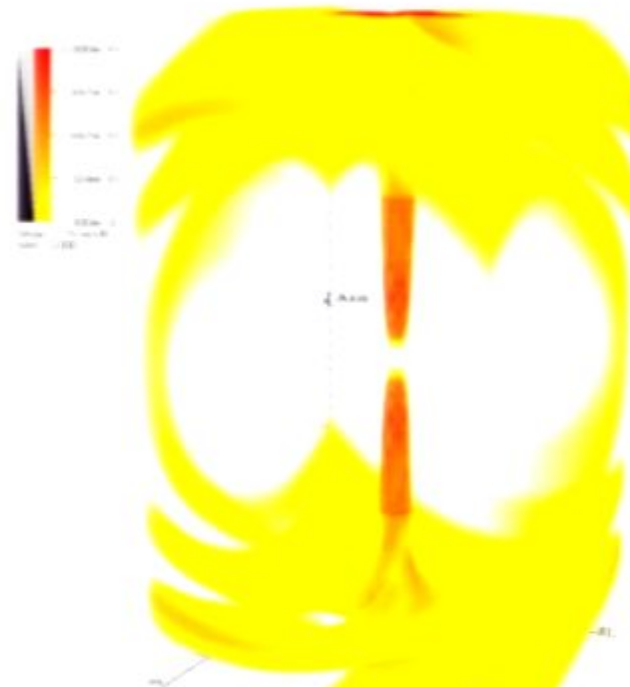
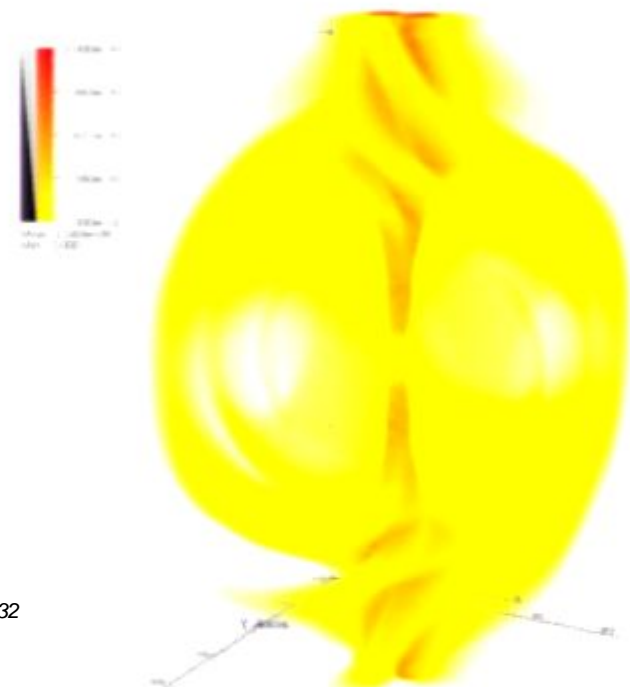
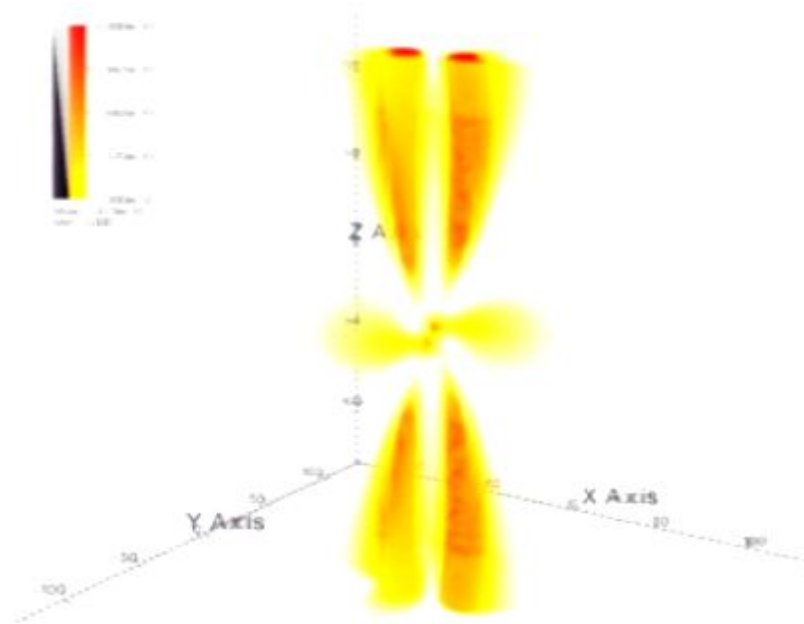
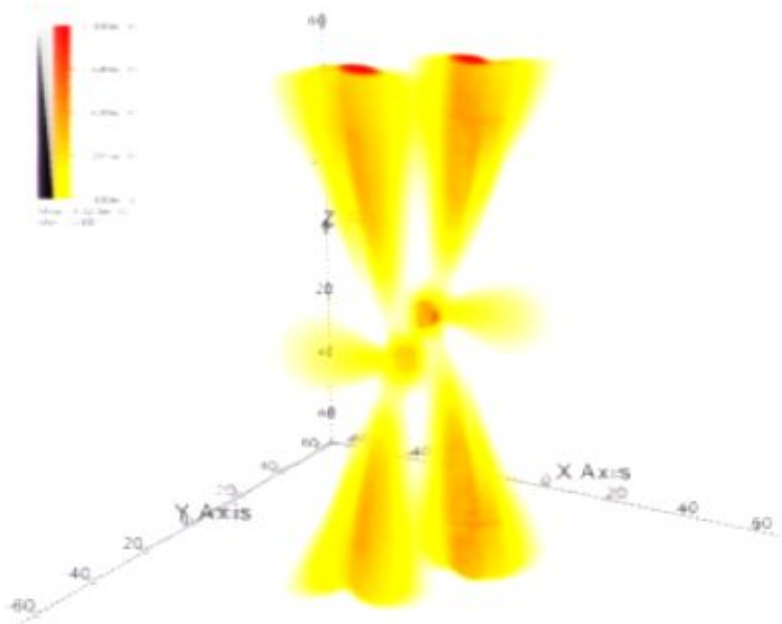
- Einstein+Maxwell
- BBH,  $M=10^8 M_{\text{solar}}$
- Force-free condition

$$E^i B_i = 0$$

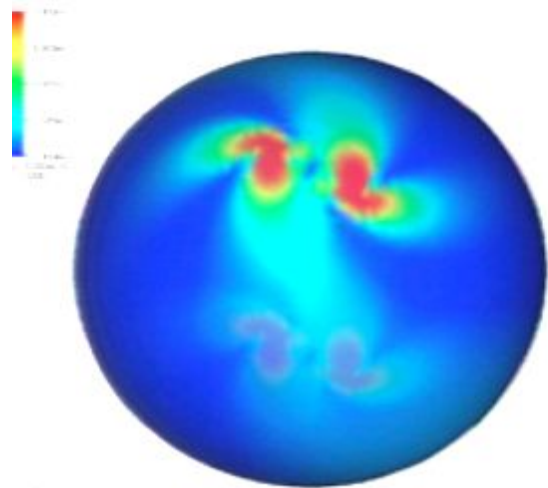
$$J^i = \frac{q}{B^2} \epsilon^{ijk} E_j B_k + J_B \frac{B^i}{B^2}$$

- Circumbinary disk with magnetic field  
 $B=10^4 \text{ G}$

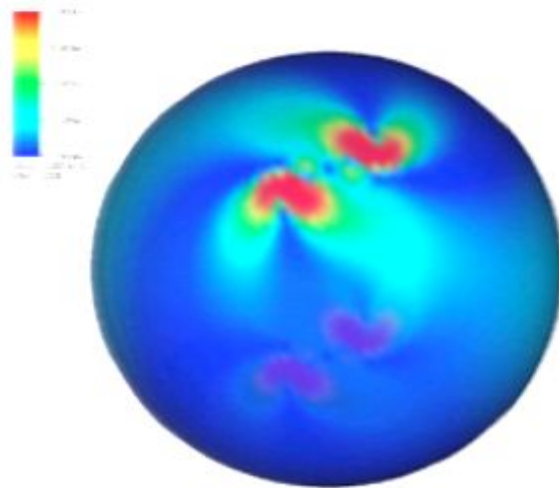




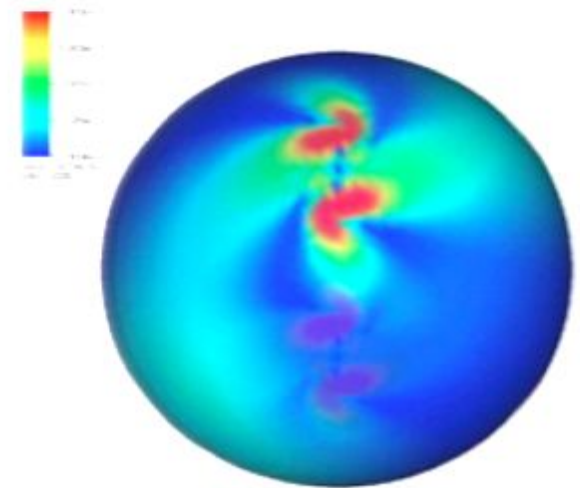




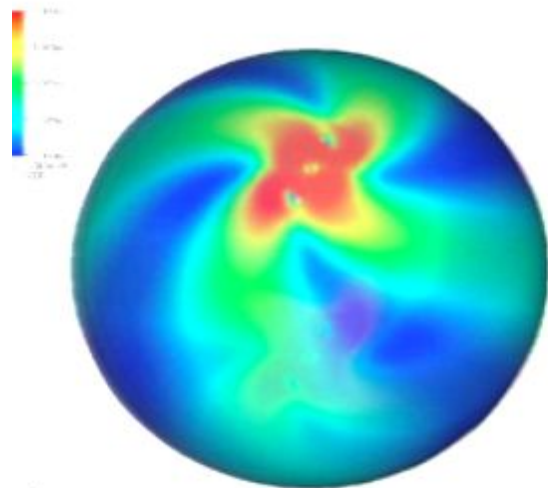
$\tau = -8.2 \text{ M}_8 \text{ hrs}$



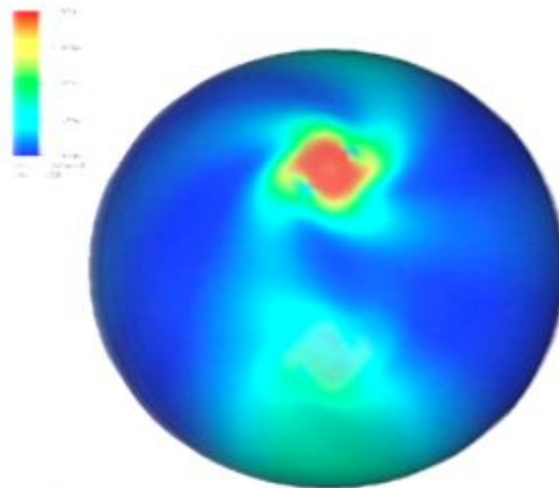
$\tau = -5.5$



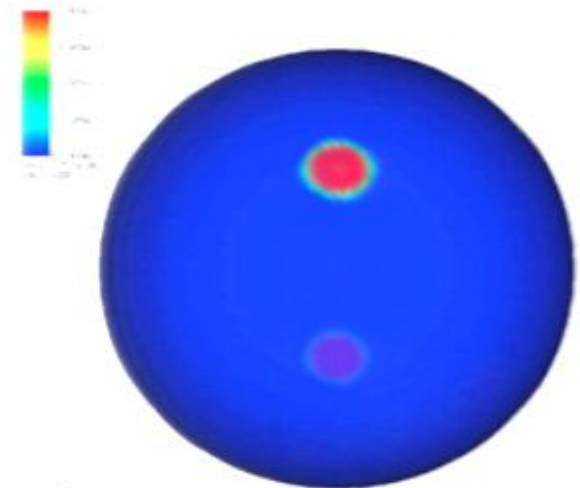
$\tau = -3.0$



$\tau = 2.0$

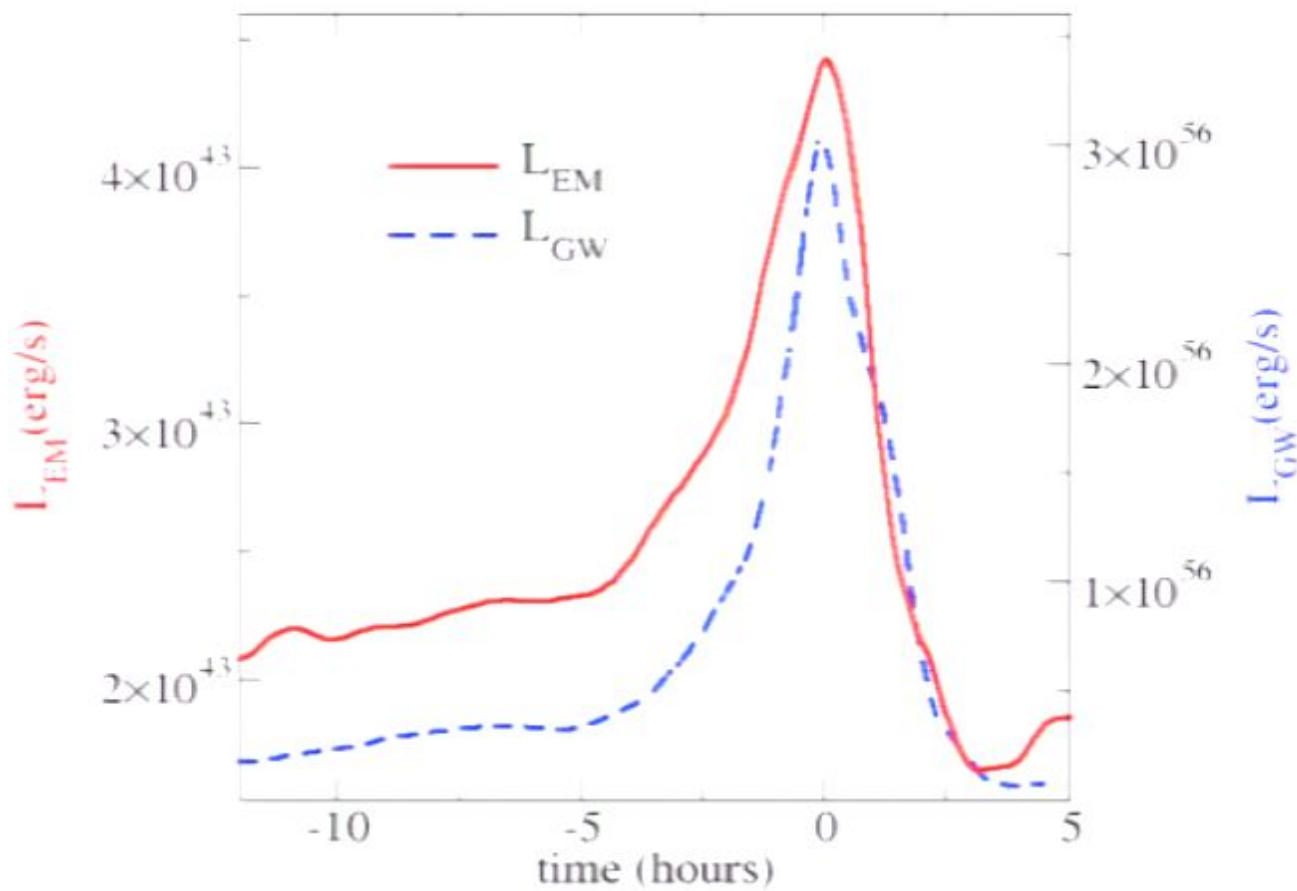


$\tau = 4.6$



$\tau = 6.8$

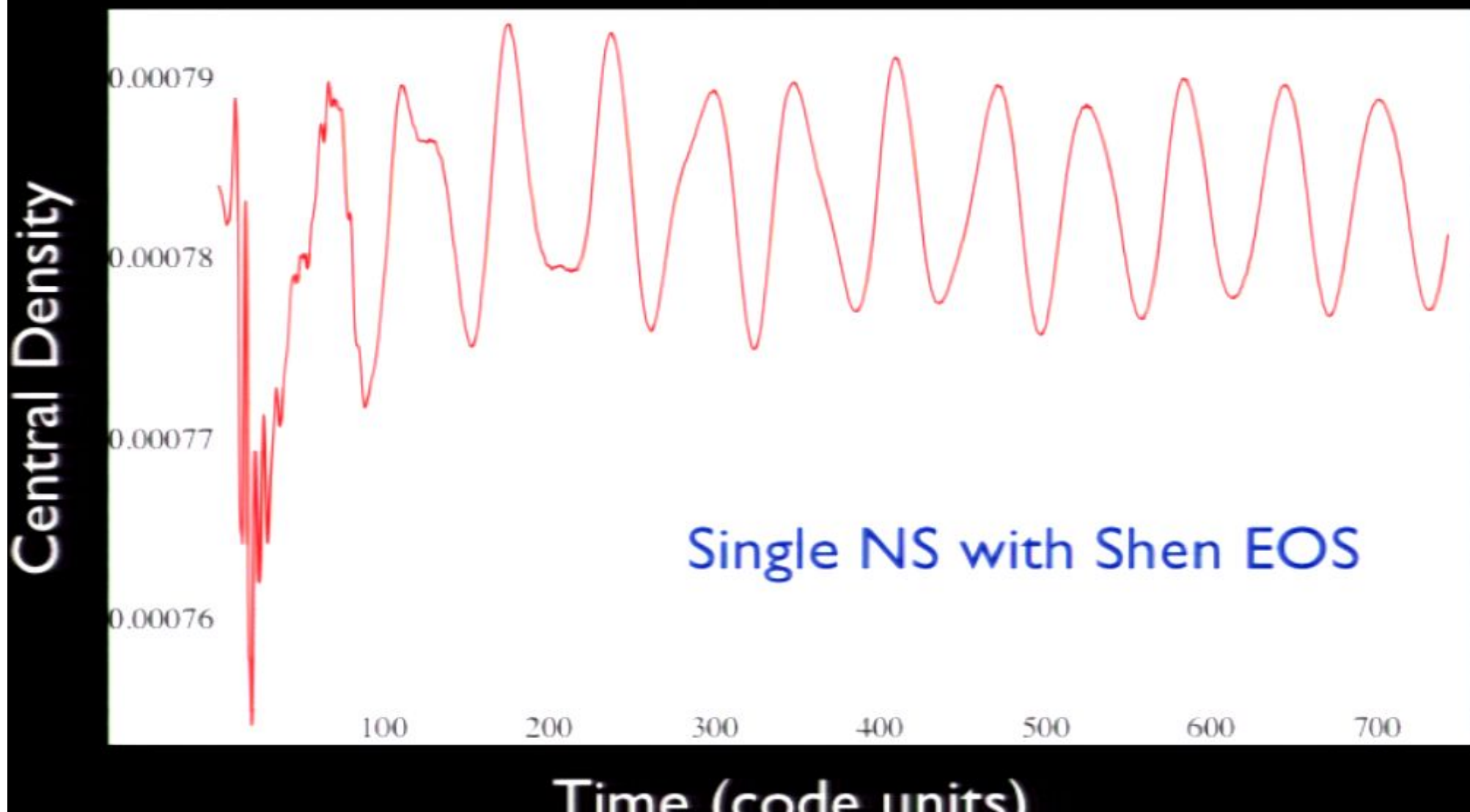
# EM & GW fluxes



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

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

# First Steps...





# 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