NUMERICAL SIMULATIONS IN RELATIVISTIC ASTROPHYSICS

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Plan of Talk

Overview of recent results on:

- Gravitational collapse of differentially rotating neutron stars
- Magneto-elastic oscillations of magnetars
- Asteroseismology of binary neutron star mergers
- Equilibrium and stability of massive tori around black holes

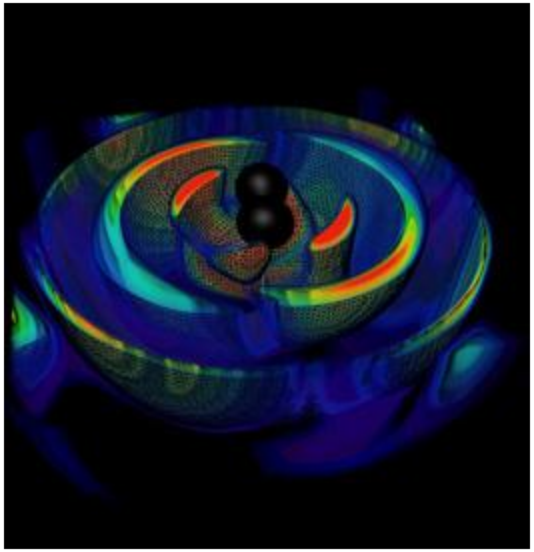
Publications and Collaborators:

- Giacomazzo, B., Rezzolla, L., Stergioulas, N., *Phys. Rev. D*, **84**, 024022 (2011)
- Gabler, M., Cerdá-Durán, P., Font, J. A., Stergioulas, N., *MNRAS*, **410**, L37 (2011)
- Stergioulas, N., Bauswein, A., Zagkouris, K., Janka, H.-T., *MNRAS*, **in press**, (2011)
- Stergioulas, N., *IJMPD*, **20**, 1251 (2011)
- Korobkin, O., Abdikamalov, E., Schnetter, E., Stergioulas, N., Zink, B., *Phys. Rev. D*, **83**, 043007 (2011)

Numerical Relativity

Current status:

- Long-term stable simulations codes in full GR
- Adaptive mesh-refinement
- Accurate gravitational-wave extraction
- General-relativistic magneto-hydrodynamics
- Multi-parameter, realistic equations of state



GRMHD Codes:

• Whisky:	2D/3D	BSSNOK formulation	AEI et al.
• Thor	3D	Gener. harmonic coord.	Tuebingen, LSU
• MCocoa:	2D/3D	CFC approximation	MPA, Valencia et al.

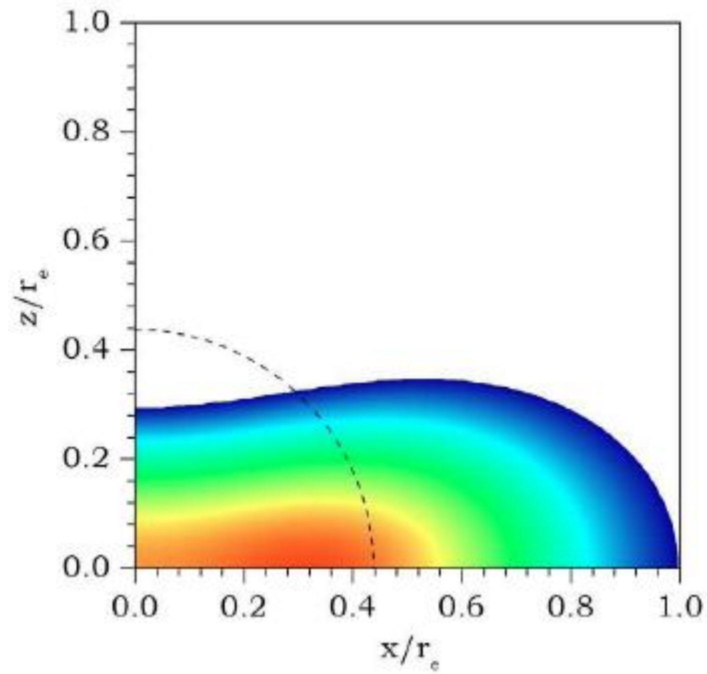
MHD method:

- Valencia formulation (conservative finite volume with shock-capturing).

Initial Data for Simulation Codes

Uniformly rotating neutron stars

- RNS v1.0 (Stergioulas & Friedman, 1995)

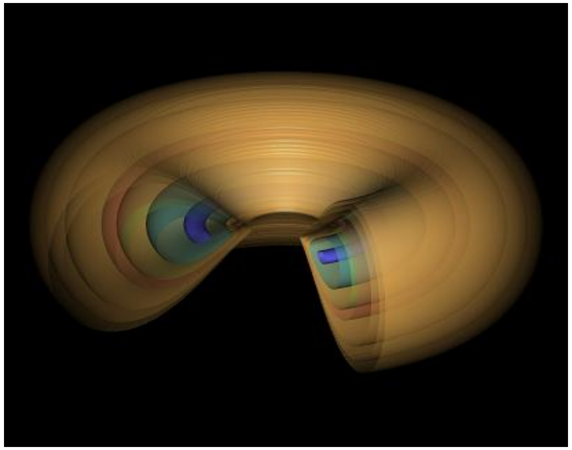


Differentially rotating neutron stars

- RNS v3.0 (Stergioulas, 2003)

Massive accretion tori around black holes with self-gravity

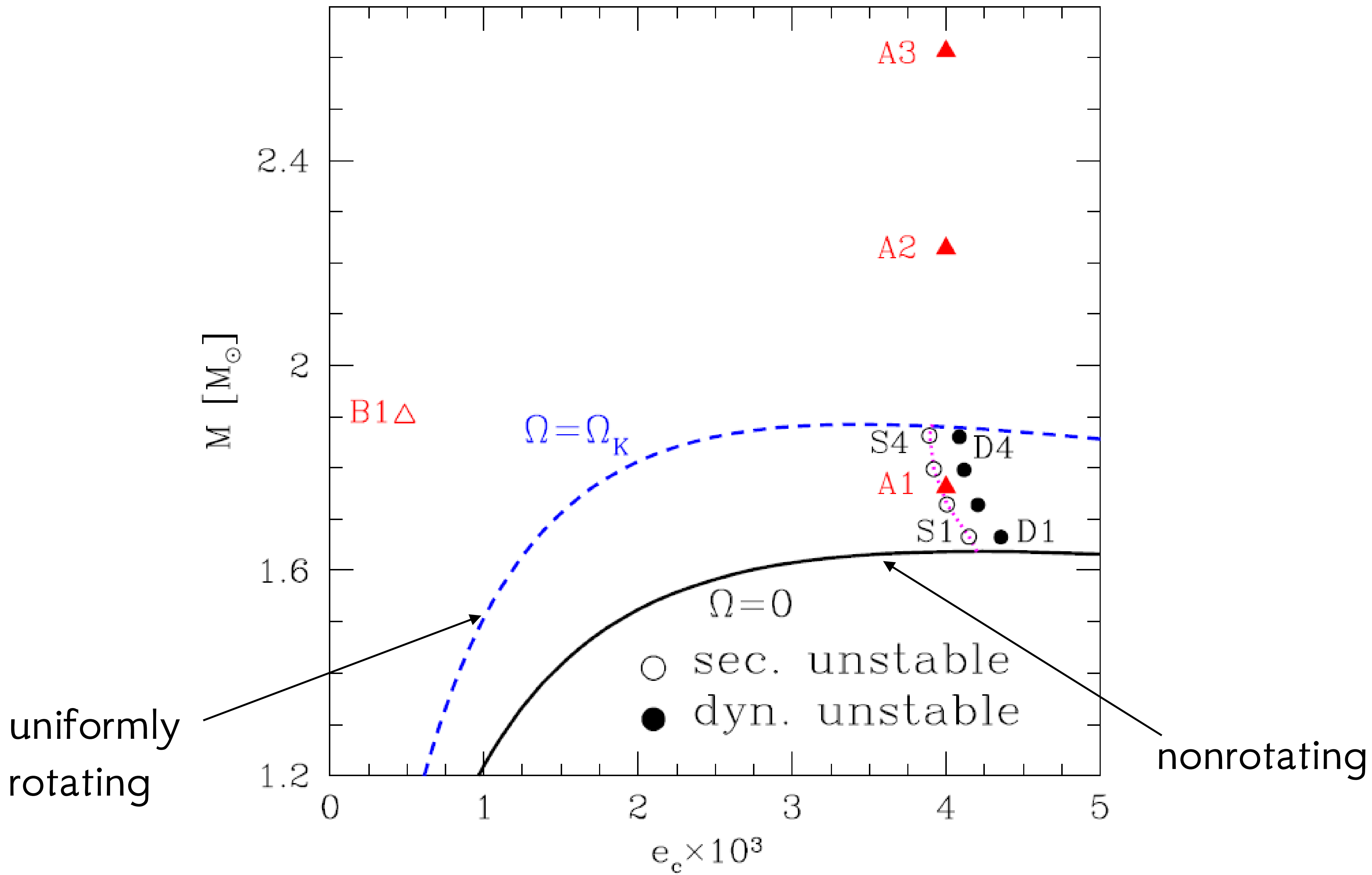
- RNS v4.0 (Stergioulas, 2011)



Gravitational Collapse

Giacomazzo, Rezzolla, NS (2011)

Differentially rotating polytropes (N=1.0)

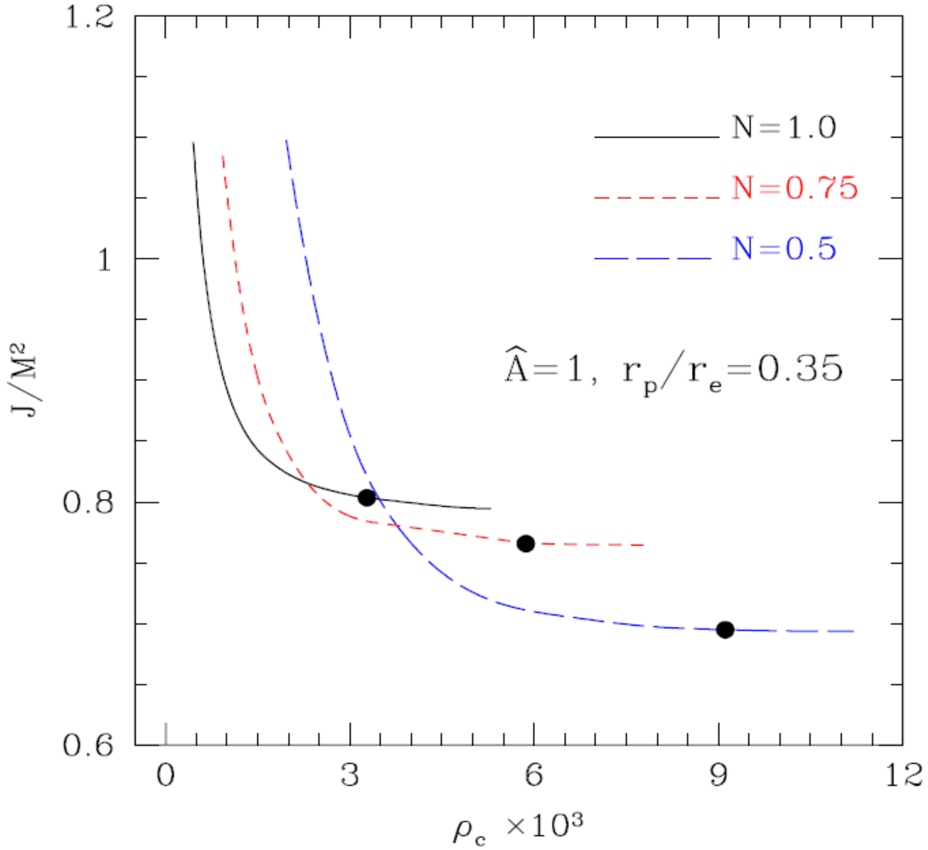


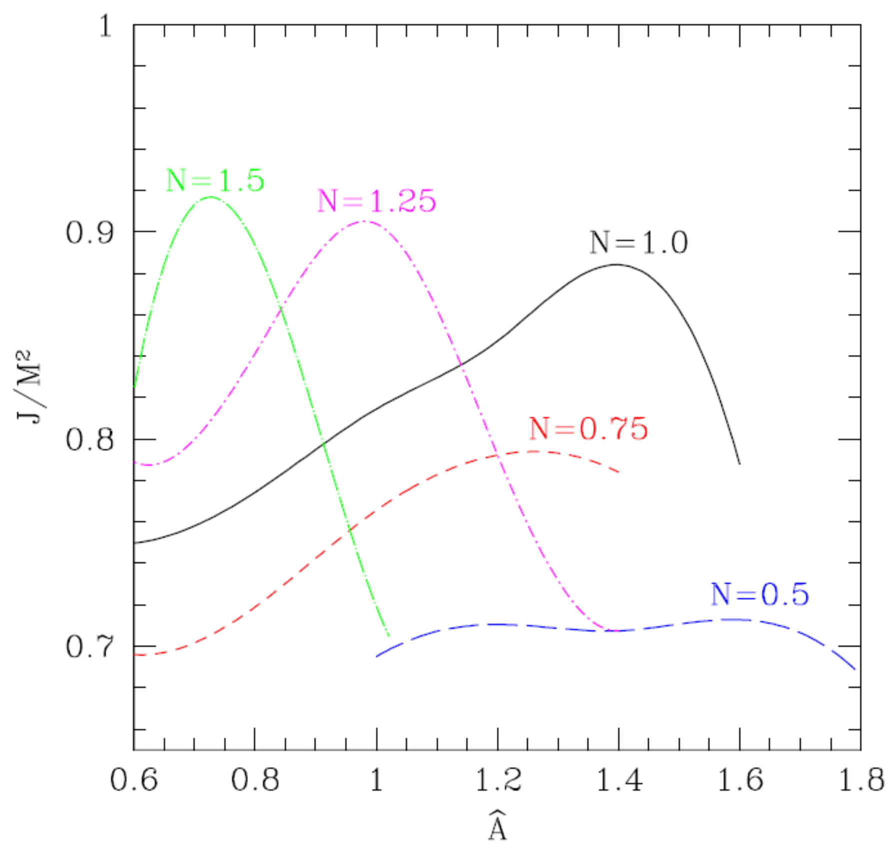
Gravitational Collapse

All unstable polytropic models constructed with RNS: $J/M^2 < 1$

KEH diff. Rotation law: $$A^2(\Omega_c - \Omega) = \frac{(\Omega - \omega)e^{2\psi}}{1 - (\Omega - \omega)e^{2\psi}}$$

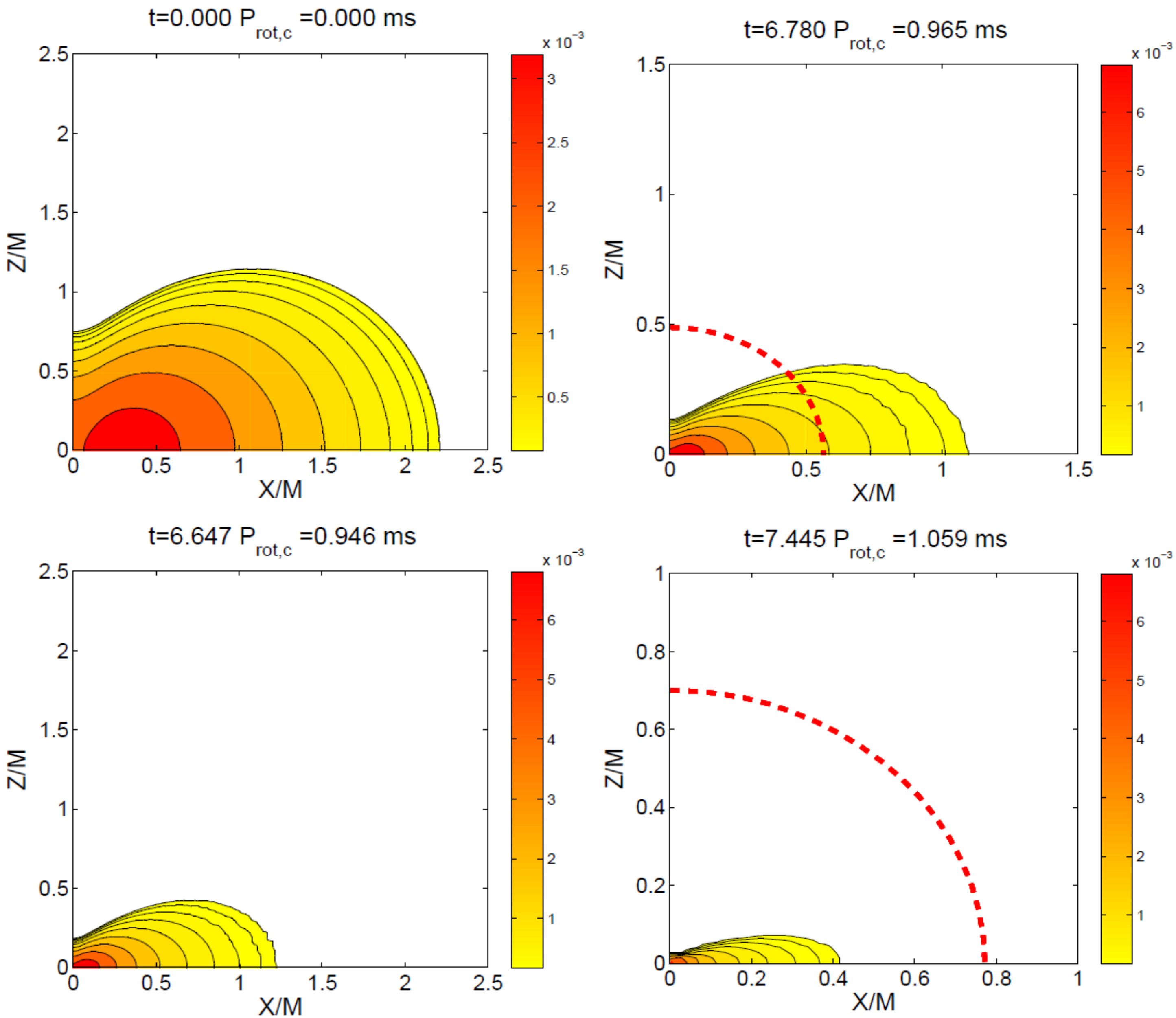
Variation of differential rotation and EOS: still $J/M^2 < 1$ for unstable models.





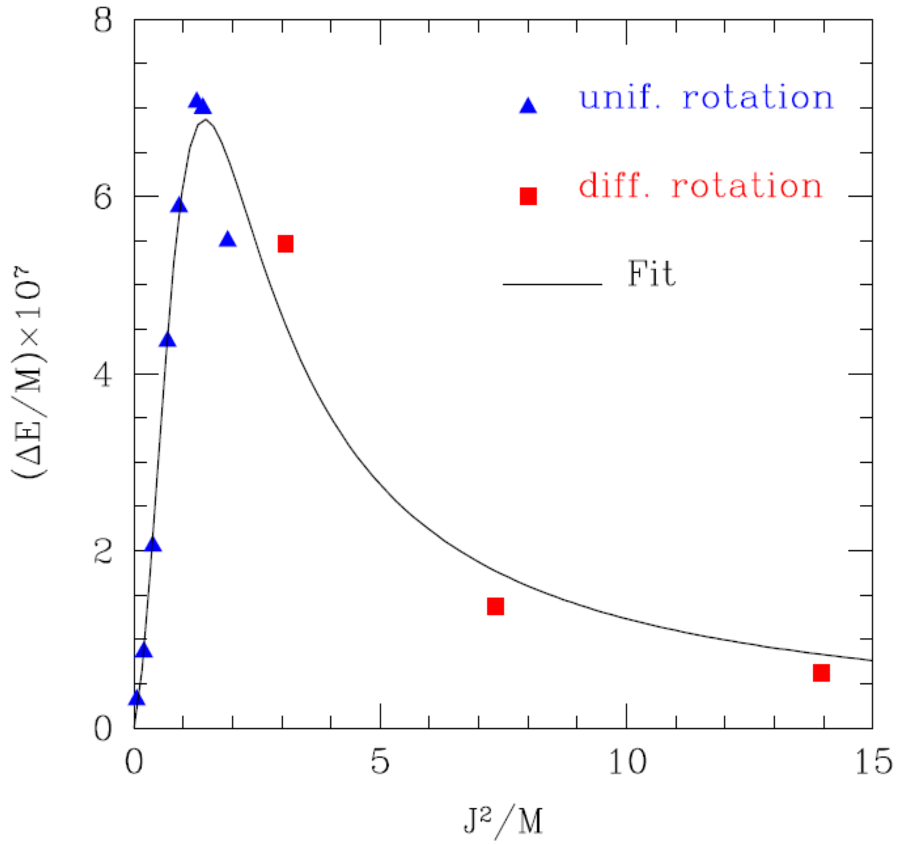
Gravitational Collapse

3-D full GR evolution with Cactus/Whisky code (model A2):



Gravitational Collapse

Energy emitted in gravitational waves:



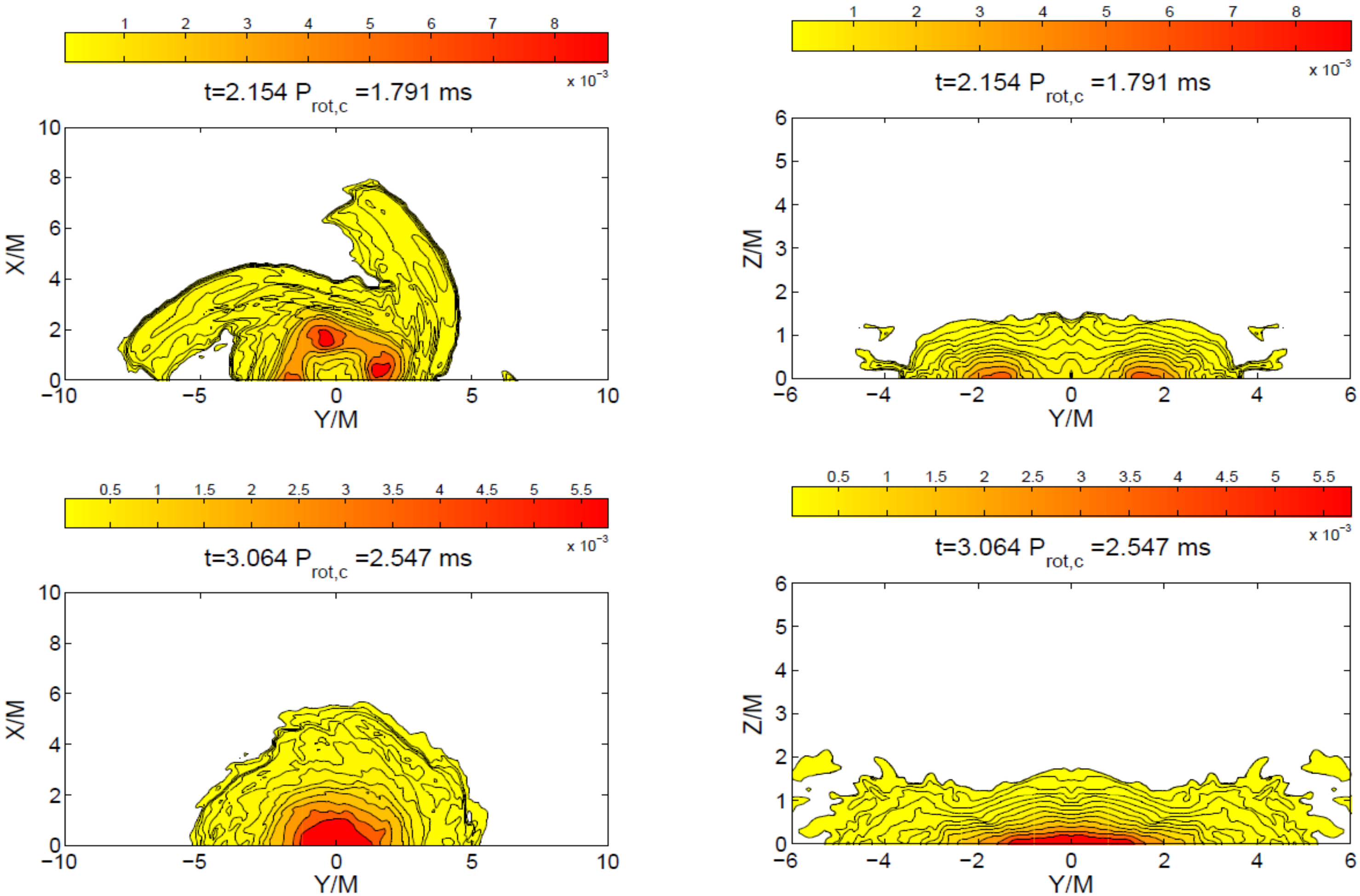
Main result: differential rotation reduces GW efficieny due to centrifugal hangup.

Generalization of classic Stark & Piran (1985) result for uniform rotation.

Gravitational Collapse

Model B1 ($J/M^2 = 1.09$) induce collapse via artificial pressure depletion.

Collapse -> bounce -> m=4, m=2 instabilities

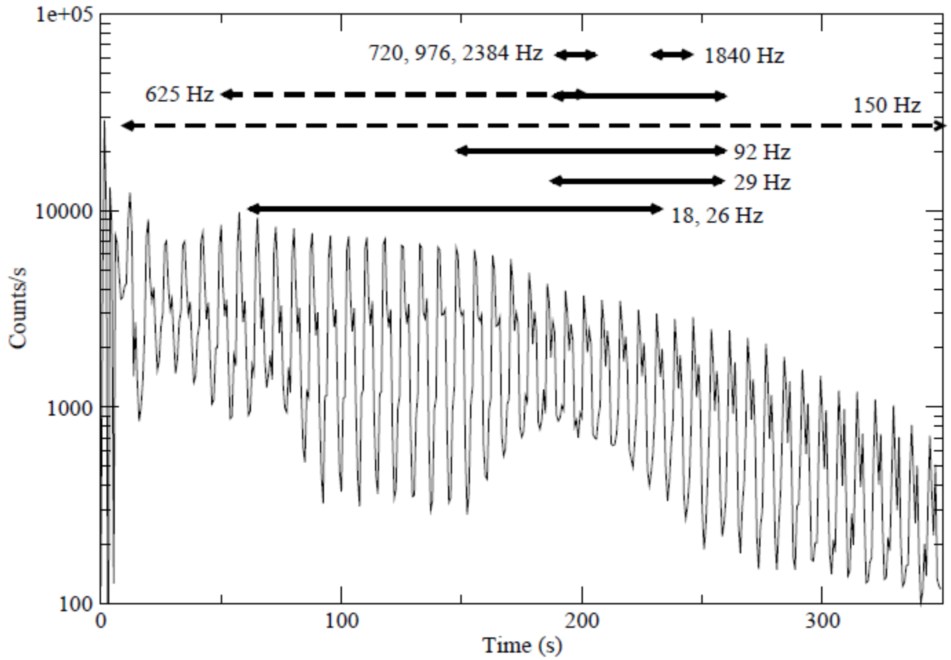


Higher central density, different rotation law, than initial model.

Main result: Confirmation that cosmic censorship holds.

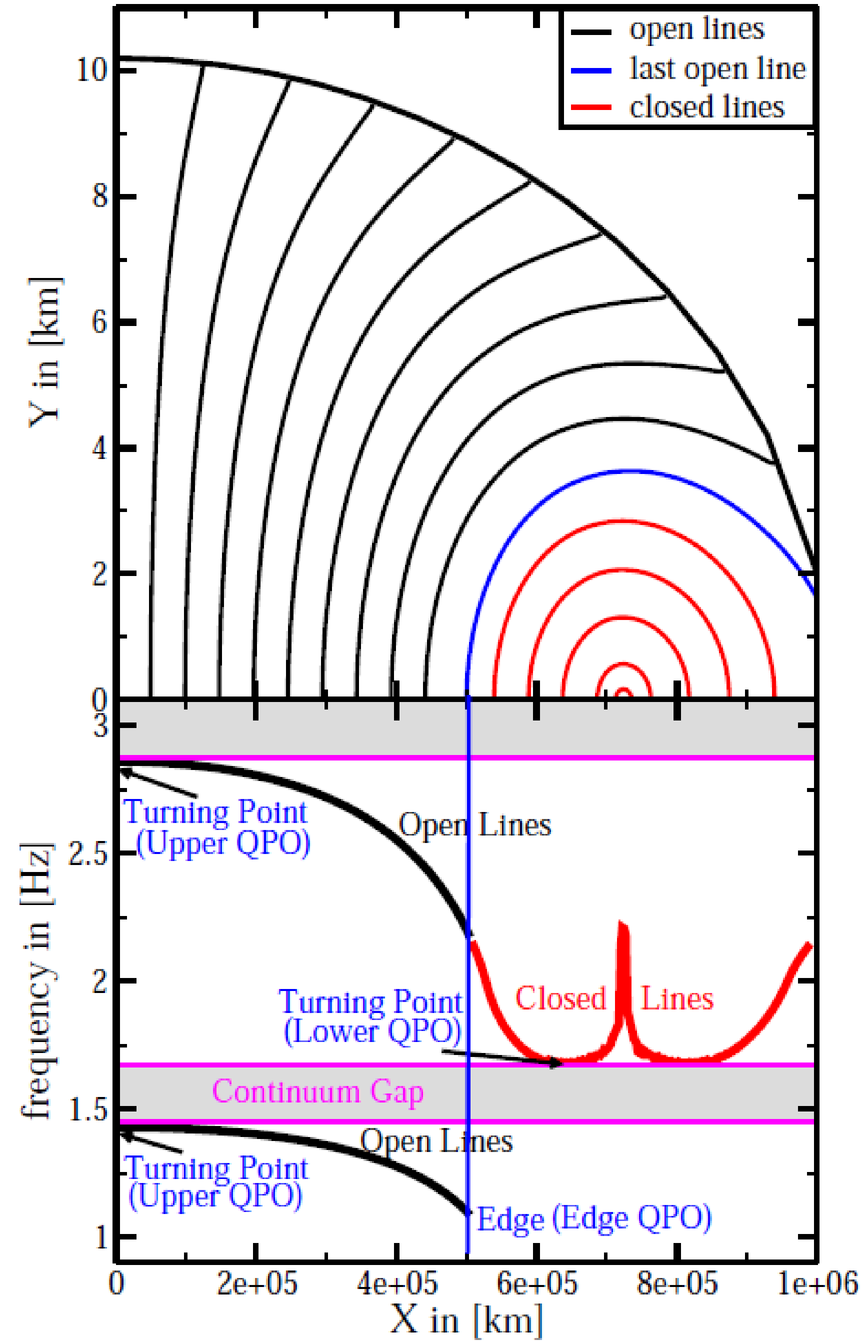
Magnetar Oscillations

QPOs in X-ray tail of giant flares in SGRs, e.g. SGR 1086-20



Crustal shear oscillations?

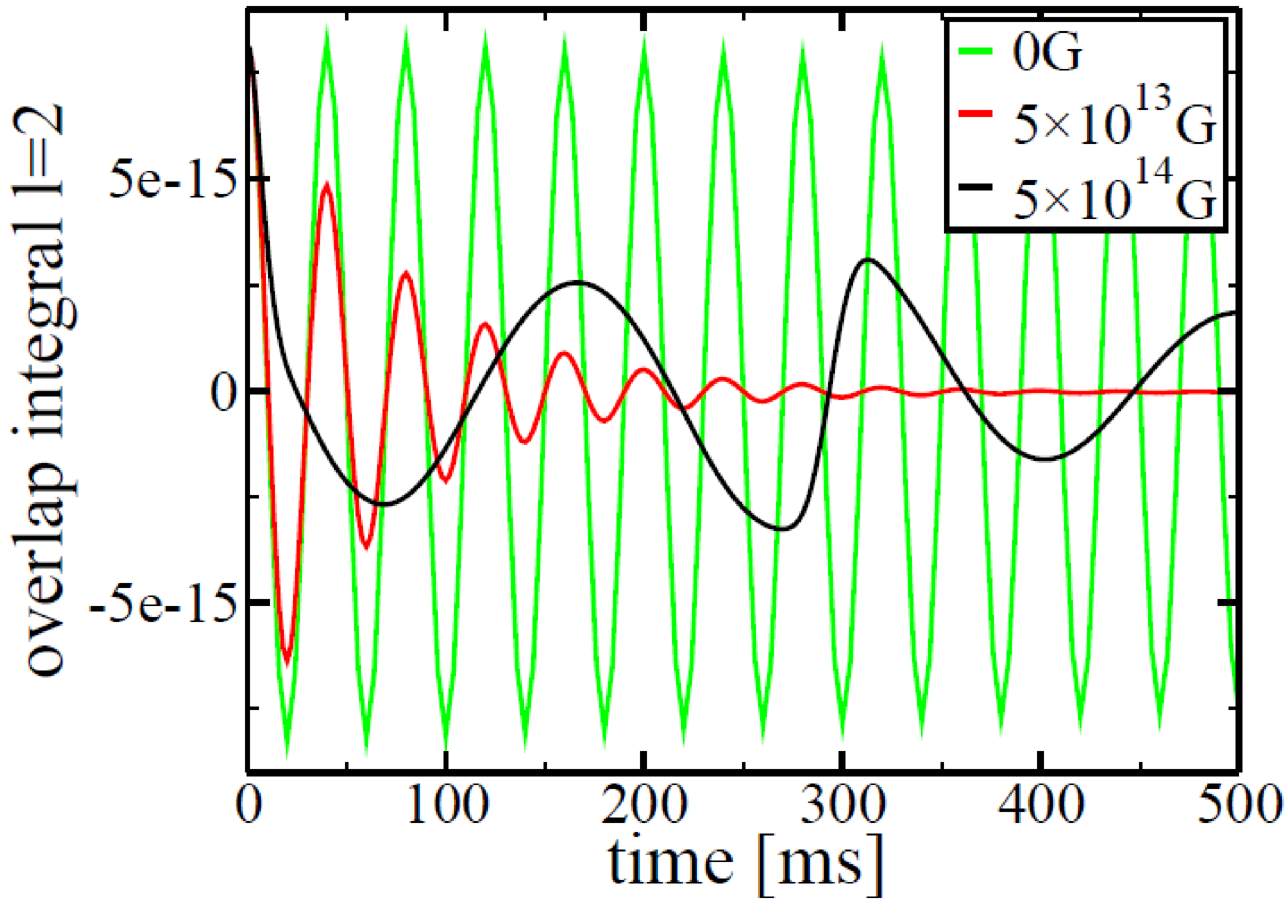
Even though torsional Alfvén waves form a continuous spectrum, there exist QPOS at turning points!



Magnetar Oscillations

Gabler, Cerdá-Durán, Font, Müller, NS (2011)

Coupling to shear tensor in crust: Magneto-elastic oscillations
(2-D McoCoA+shear code)



Crustal shear oscillations are effectively absorbed by the continuum on a timescale of 0.1s even at low magnetic field strenghts:

Main result: crustal shear oscillations not a viable SGR QPO model.

Magnetar Oscillations

Torsional Alfvén QPO frequencies depend only on compactness (M/R) and magnetic field strength B. Construct empirical relations:

$$f_L = 56.8(n+1)\left[1 - 4.55\left(\frac{M}{R}\right) + 6.12\left(\frac{M}{R}\right)^2\right] \times \left(\frac{B}{4\times 10^{15}\mathrm{G}}\right) \quad \mathrm{(Hz)}$$

$$f_U = 48.9(n+1)\left[1 - 4.55\left(\frac{M}{R}\right) + 6.12\left(\frac{M}{R}\right)^2\right] \times \left(\frac{B}{4\times 10^{15}\mathrm{G}}\right) \quad \mathrm{(Hz)}$$

Comparison to observed QPOs

SGR 1086-20: 18, 26, **29**, 92, 150, 626, 1837 Hz

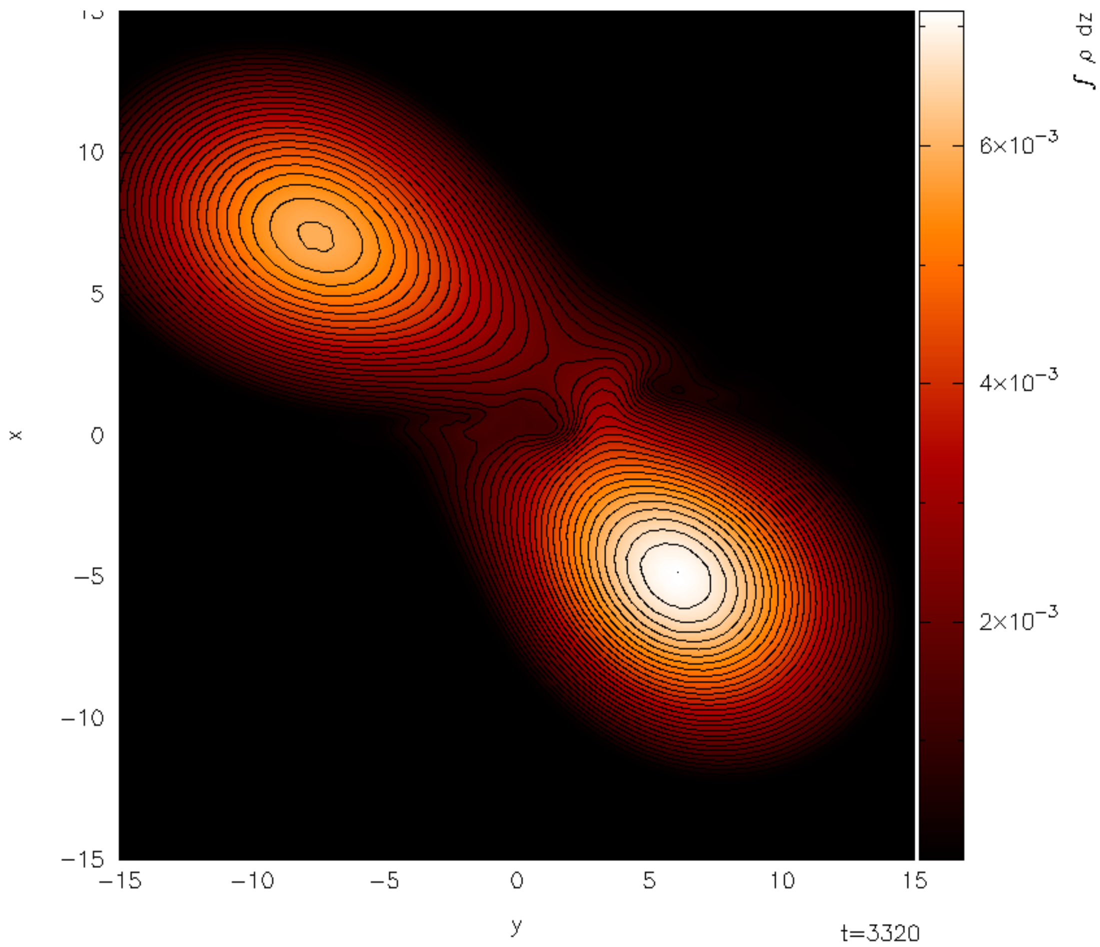
SGR 1900+14: **28**, 53, 84, 155 Hz

Upper limit on mean surface magnetic field **$3 - 8\times10^{15}$** G, independent of EOS or mass of magnetar.

Mergers of Compact Object Binaries

NS, Bauswein, Zagkouris, Janka (2011)

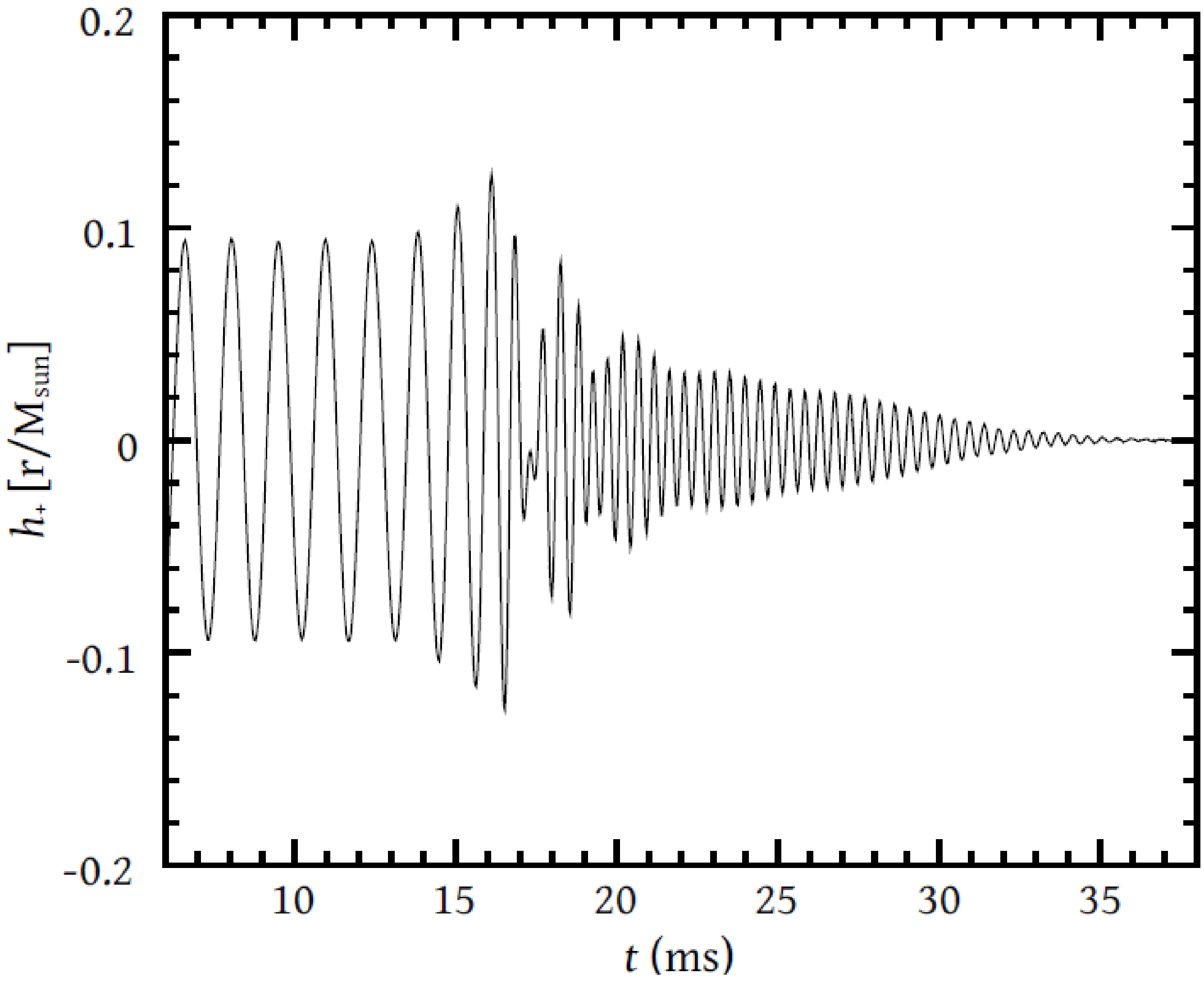
Merger of equal/unequal mass binaries with LS, Shen, MIT60 EOS.
(3-D GR CFC/SPH code)



Shen EOS: 1.2 Msun + 1.35 Msun

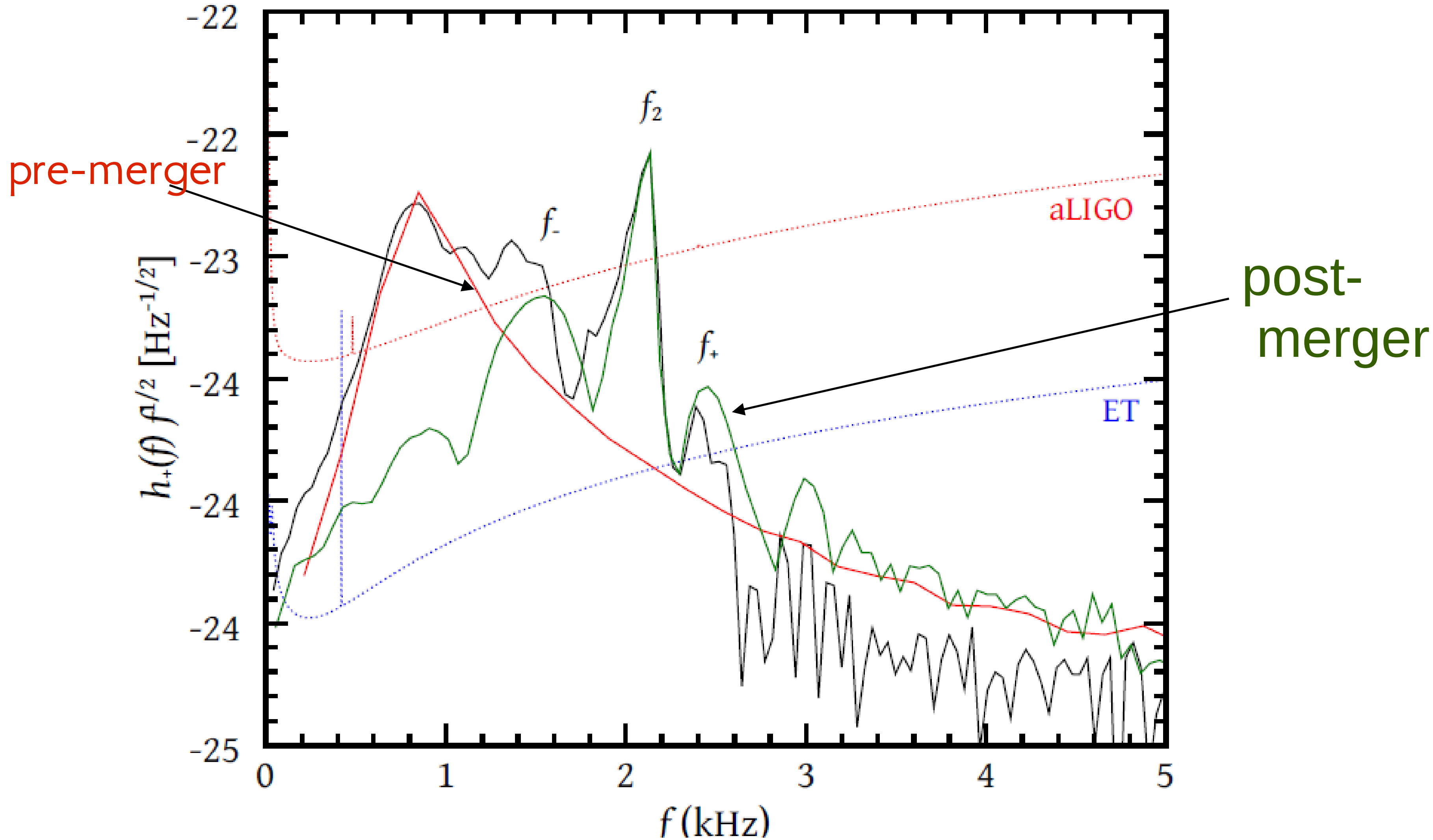
Mergers of Compact Object Binaries

Gravitational waves (via quadrupole formula)



Mergers of Compact Object Binaries

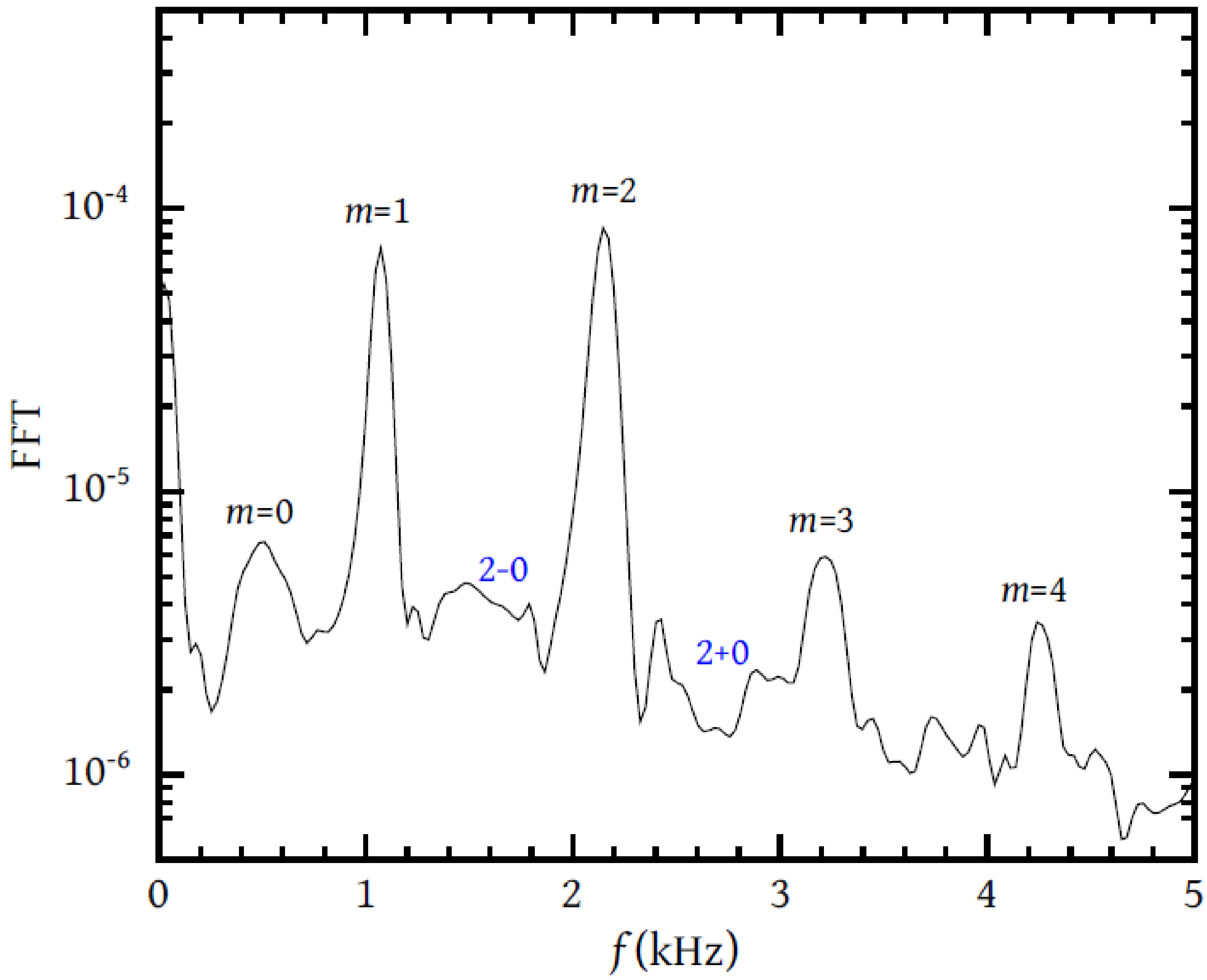
GW scaled power spectral density



Triplet of frequencies: f_- , f_2 , f_+

Mergers of Compact Object Binaries

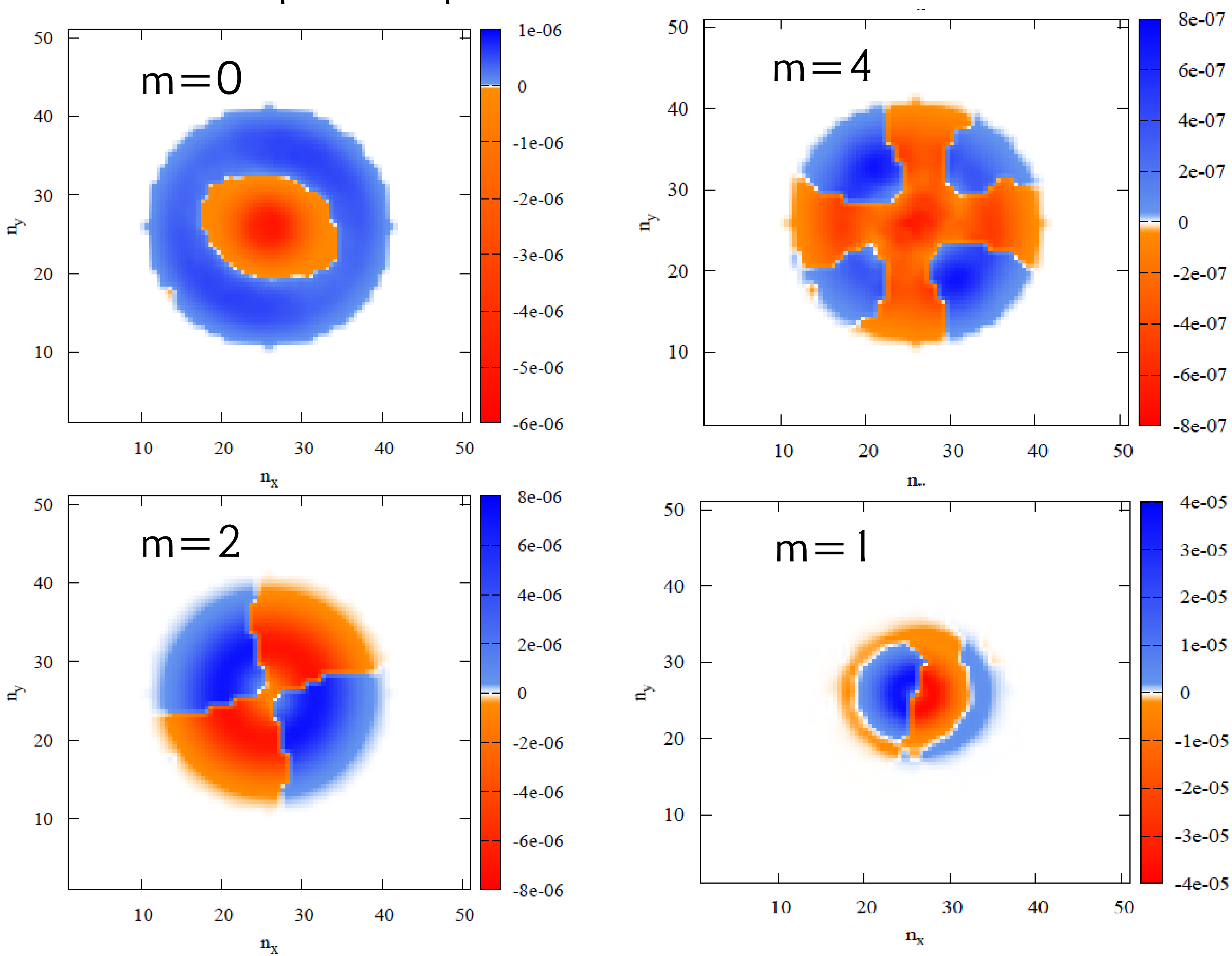
FFT of fluid variables:



Discrete mode frequencies!

Mergers of Compact Object Binaries

Eigenfunctions in equatorial plane



Mergers of Compact Object Binaries

Identification:

f_2 : $m=2$ mode exited after merger

f_- : $(m=2)$ - $(m=0)$ nonlinear combination frequency!

In case of detection: determine both m=0 and m=2 frequencies

Main result: GW gravitational-wave asteroseismology of binary neutron star mergers – can lead to EOS constraints.

Nonaxisymmetric Instabilities in Accretion Tori

Known non-axisymmetric instabilities in Newtonian accretion disks:

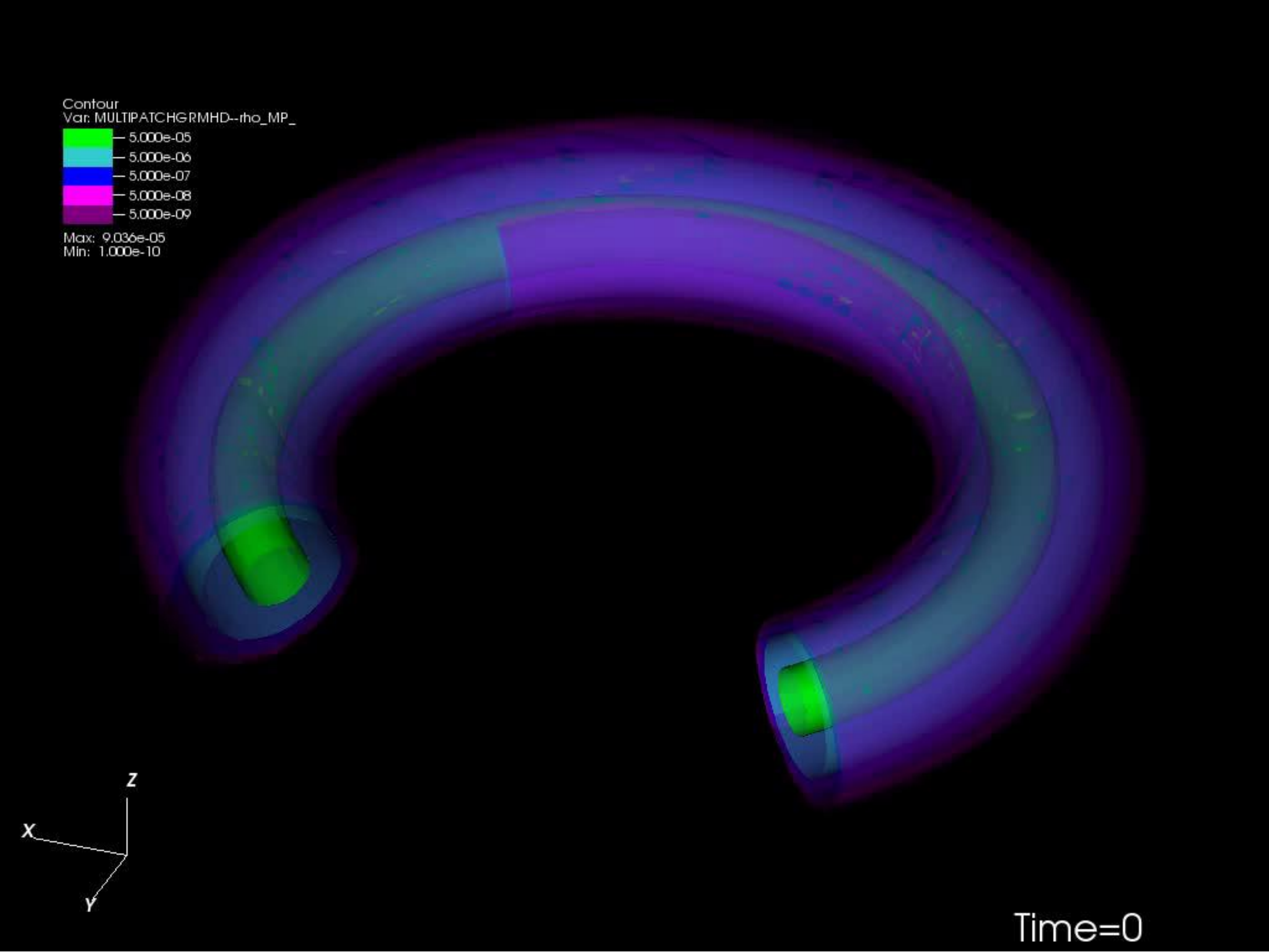
Without self-gravity (Papaloizou-Pringle 1984) :

P-modes due to *corotation resonance* near the density maximum
becomes weaker as self-gravity becomes more important

With self-gravity: two more modes (Goodman & Narayan 1988)

I-modes: elliptic-type deformation
need *moderate degrees* of self-gravity to appear

J-modes: essentially the Jeans instability when self-gravity is *dominant*


Contour
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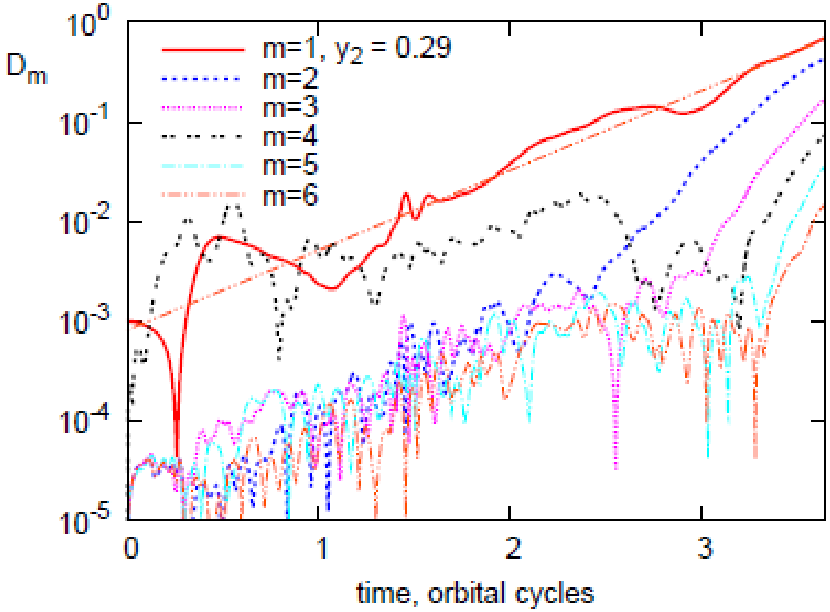
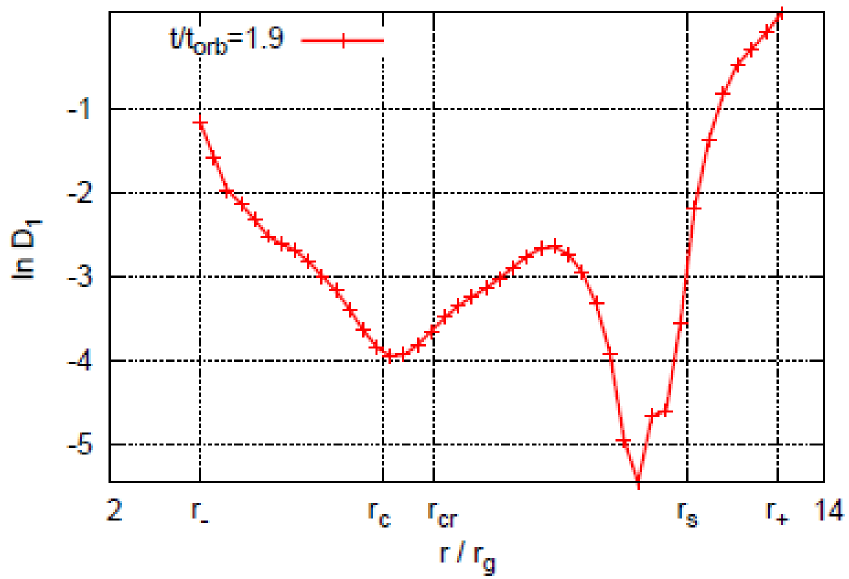
Y
Time=0

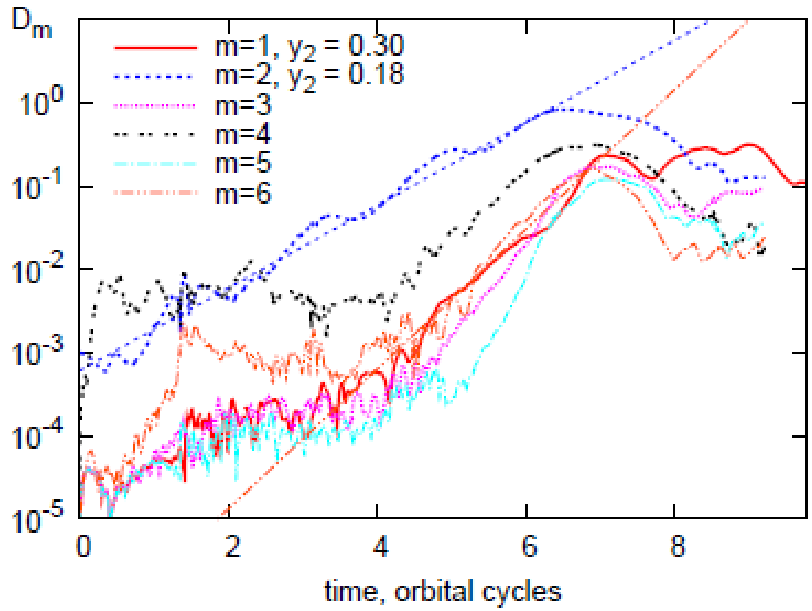
Evolution of Nonaxisymmetric Instabilities

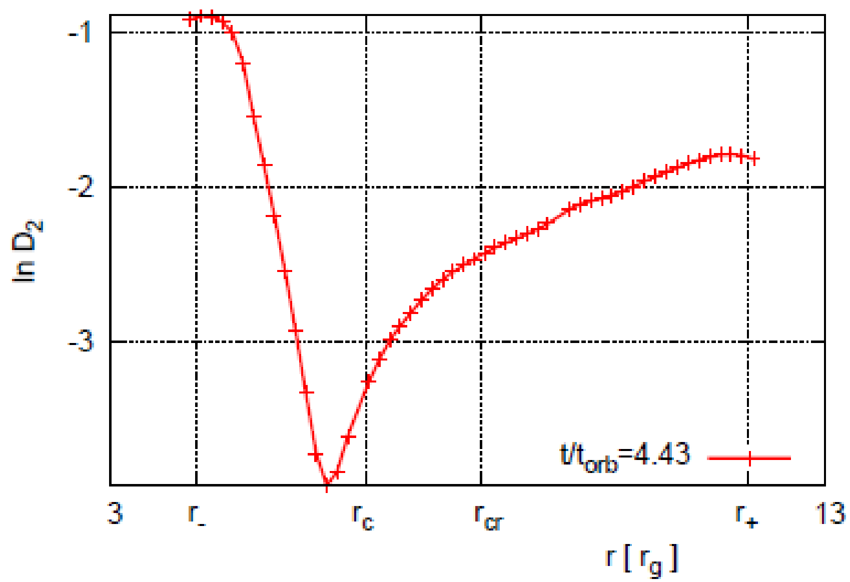
Korobkin, Abdikamalov, Schnetter, NS, Zink (2011)





m=1
P-mode



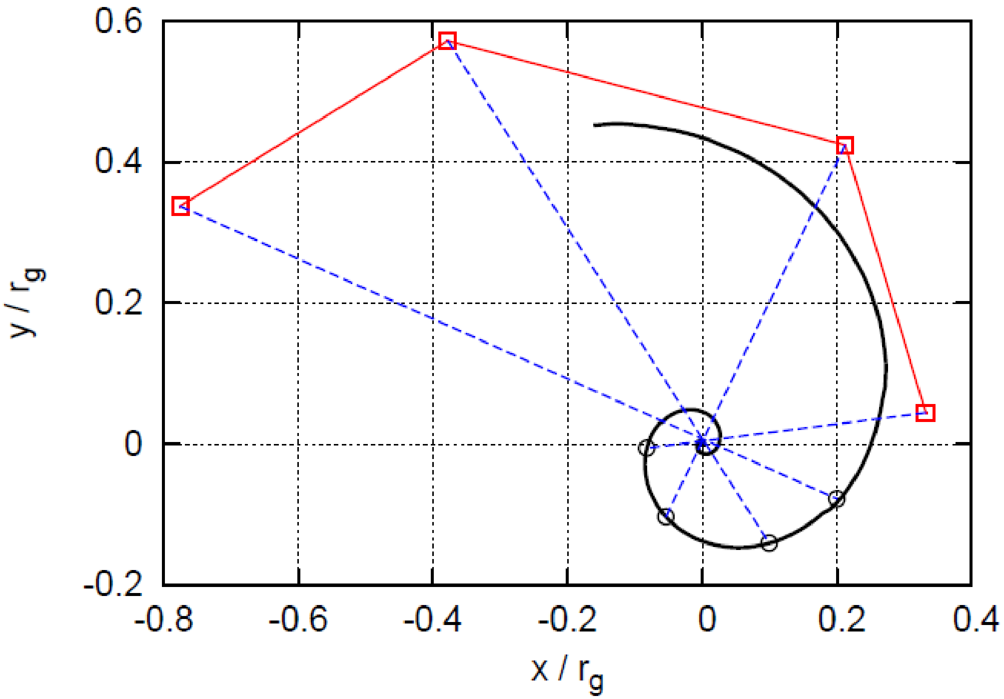


m=2
I-mode

Motion of Black Hole

Black: trajectory of black hole

Red: center of mass of disk



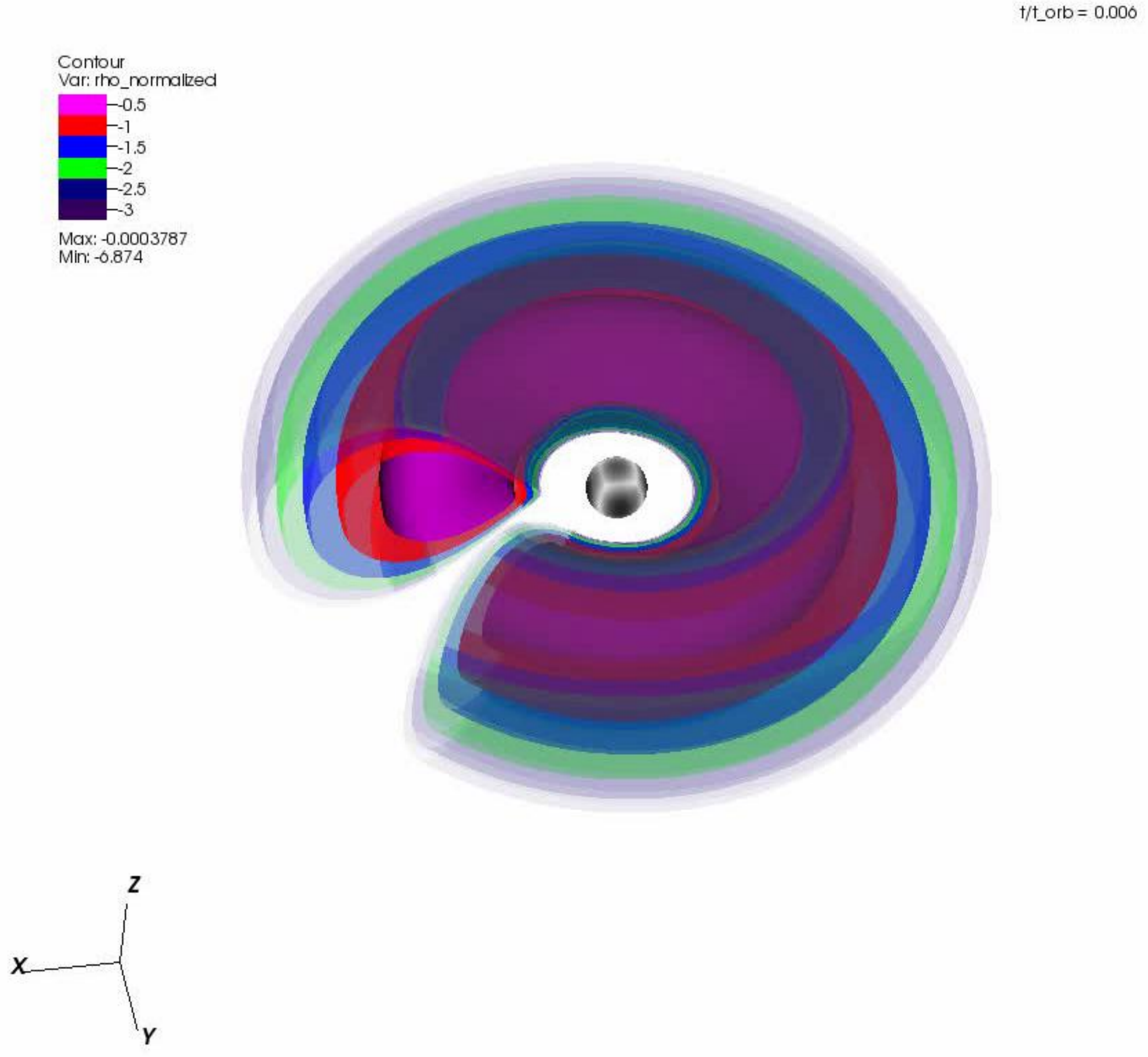
Main results:

- We demonstrated the presence of P-mode and I-mode instabilities in full GR.

- The BH participates in the dynamics of the m=1 instability, so that the center of mass of the BH-torus system is preserved.

- An interesting source of gravitational waves!

Nonaxisymmetric plus Runaway Instabilities



THANK YOU