Fully General Relativistic Simulations of Binary Neutron Stars Mergers

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Albert Einstein Institute, Potsdam, Germany

Plan of the talk

- Introduction
- Numerical Relativity at the AEI
- Binary Neutron Stars mergers
  - The role of the mass
  - The role of the Equation of State
  - Hydrodynamic instabilities
- Summary and conclusions

Why so interesting?

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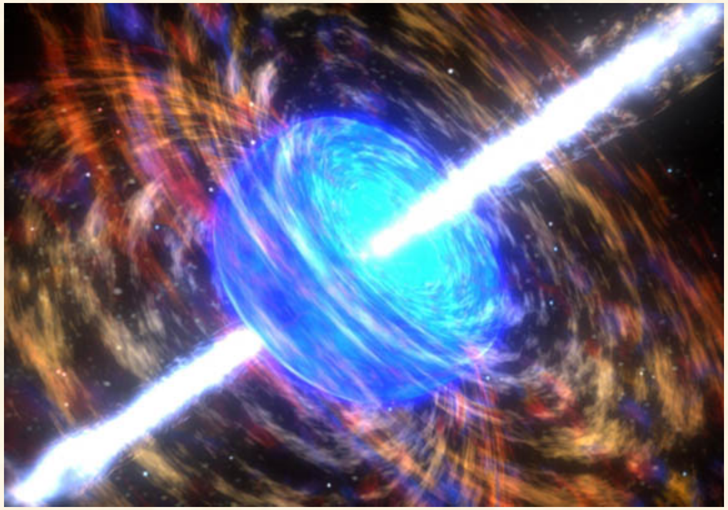

Binary neutron stars mergers are also possible sources for short gamma-ray bursts

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• Like X-ray and γ-ray astronomy they will open a new window on the universe

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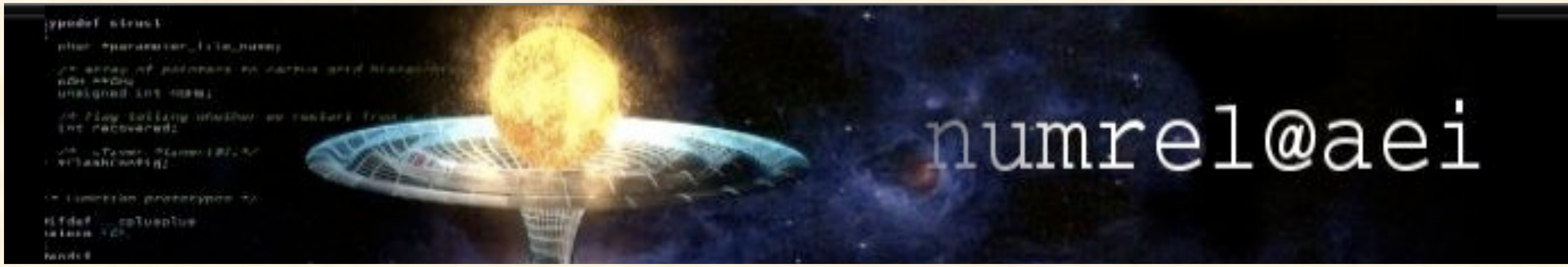
- Numerical relativity can provide templates useful for GW searches (matched filtering techniques)

Numerical Relativity at the AEI



www.numrel.aei.mpg.de

- **Dr. Luca Baiotti** (now in Tokyo)
- **Dr. Cecilia Chirenti**
- Dr. Nils Dorband
- **Filippo Galeazzi**
- **Dr. Bruno Giacomazzo**
- Dr. Sascha Husa
- **Thorsten Kellermann**
- **David Link**
- Philipp Moesta
- **Dr. Carlos Palenzuela**
- Dr. Denis Pollney
- Christian Reisswig
- **Prof. Luciano Rezzolla**
- Lucia Santamaria
- Jennifer Seiler
- Dr. Bela Szilagyi (now at Caltech)
- **Aaryn Tonita**
- **Dr. Shin'ichirou Yoshida**
- Dr. Anil Zenginoglu

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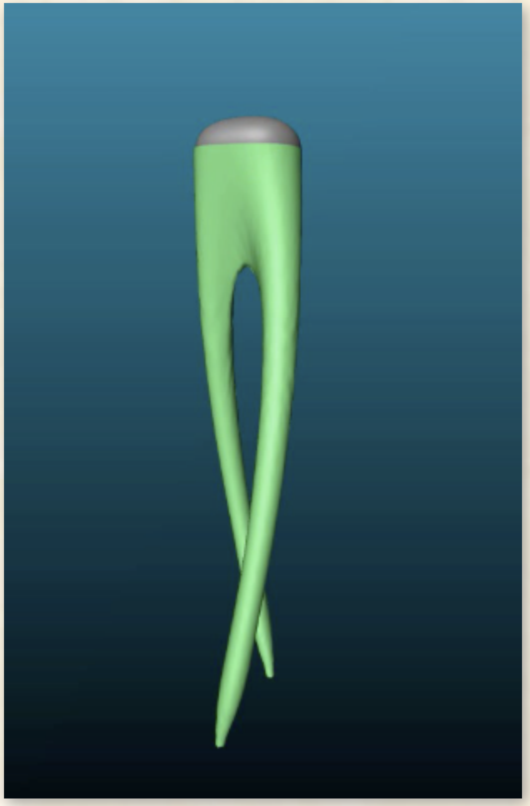
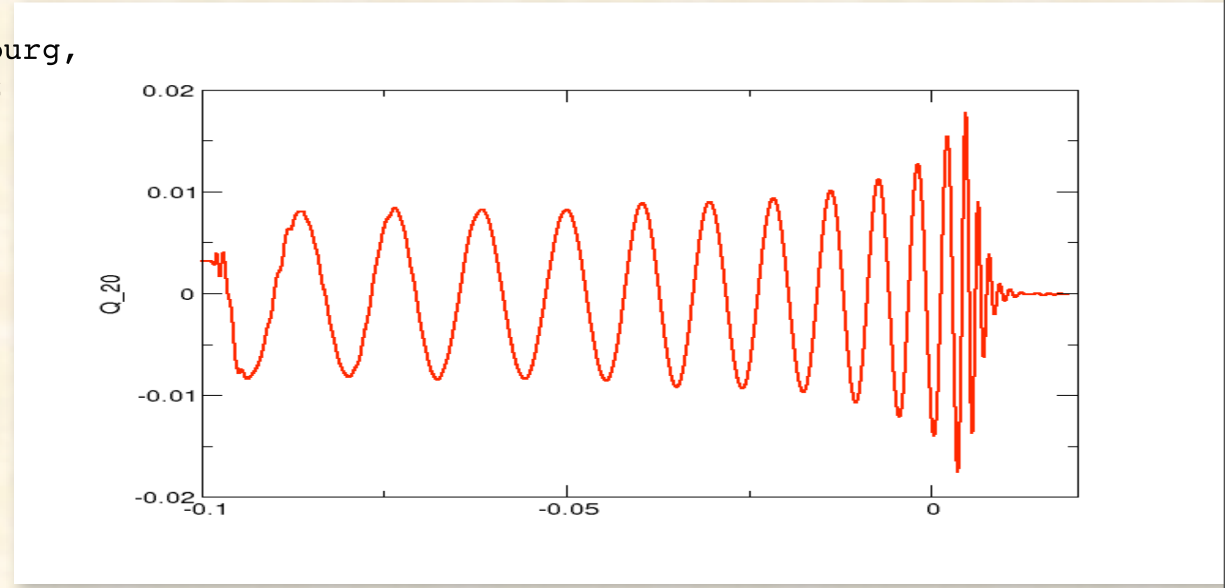
Pollney, Reisswig, Rezzolla, Thornburg, Diener, Schnetter, Seiler, Koppitz





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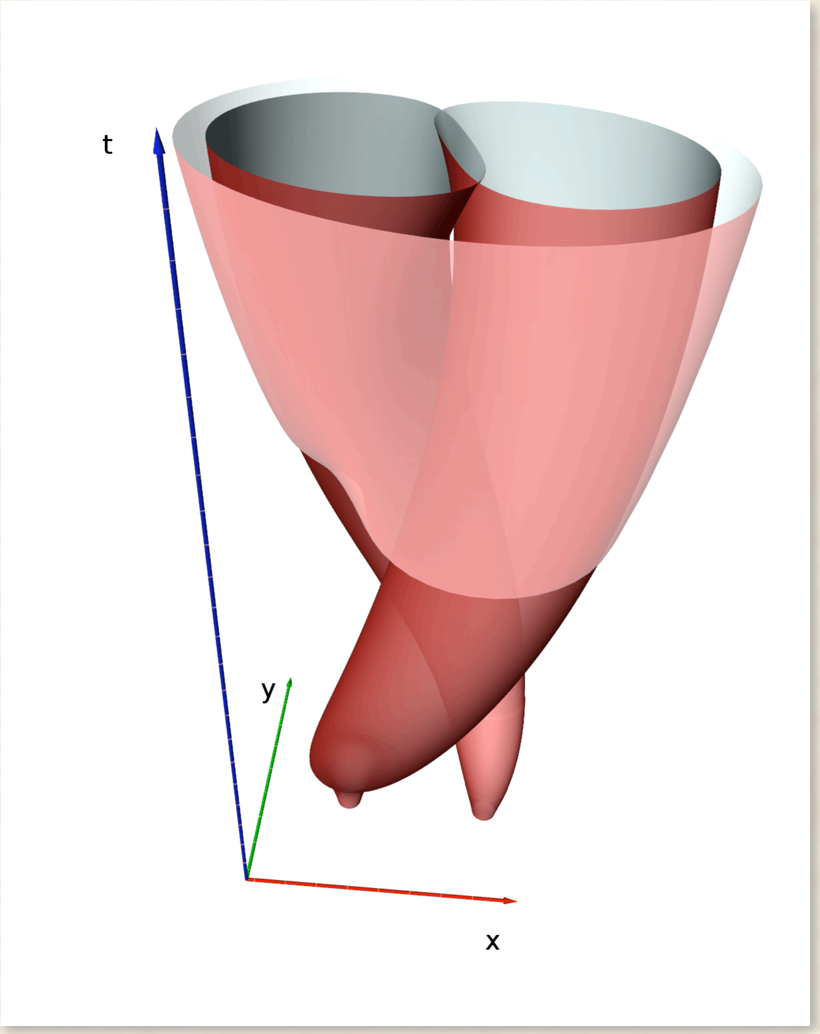

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- A careful investigation of recoil velocity and final spin for asymmetrical binaries

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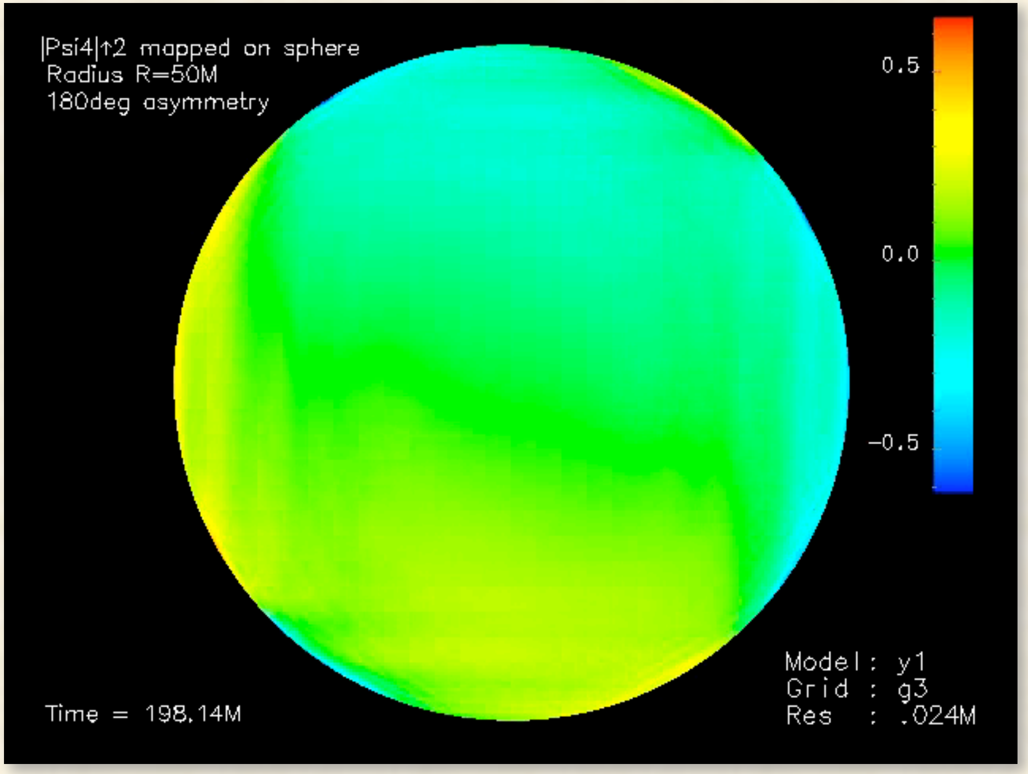

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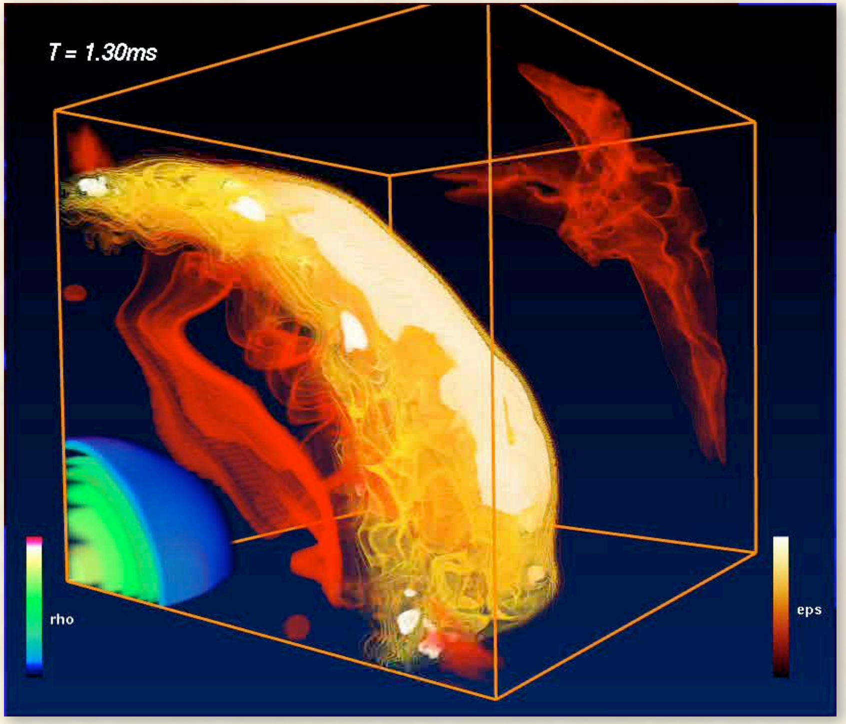

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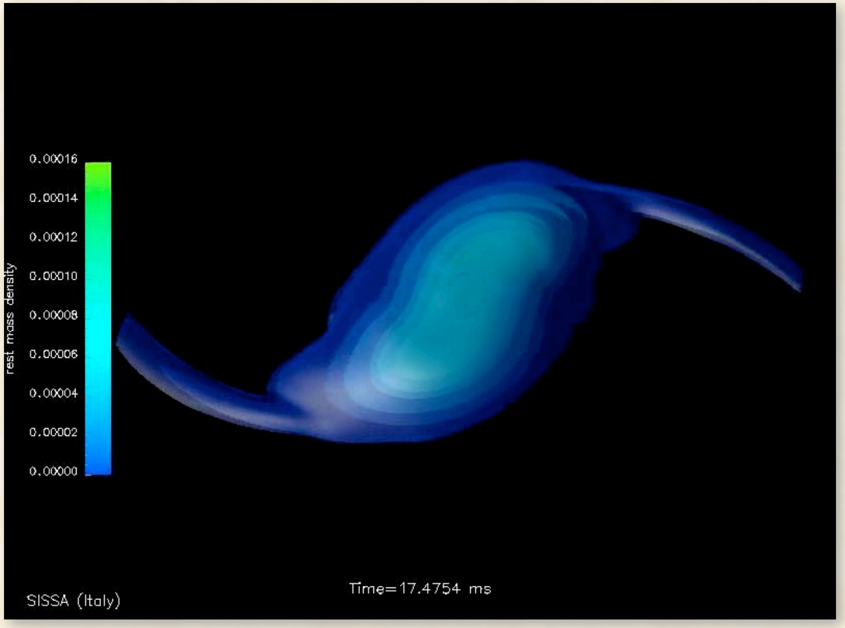

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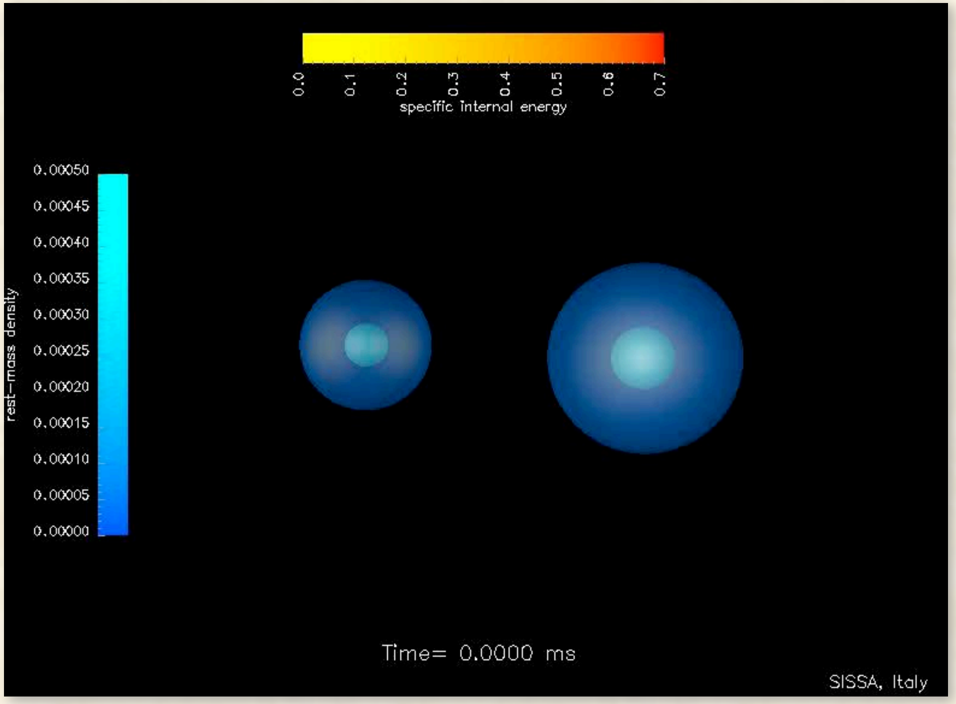

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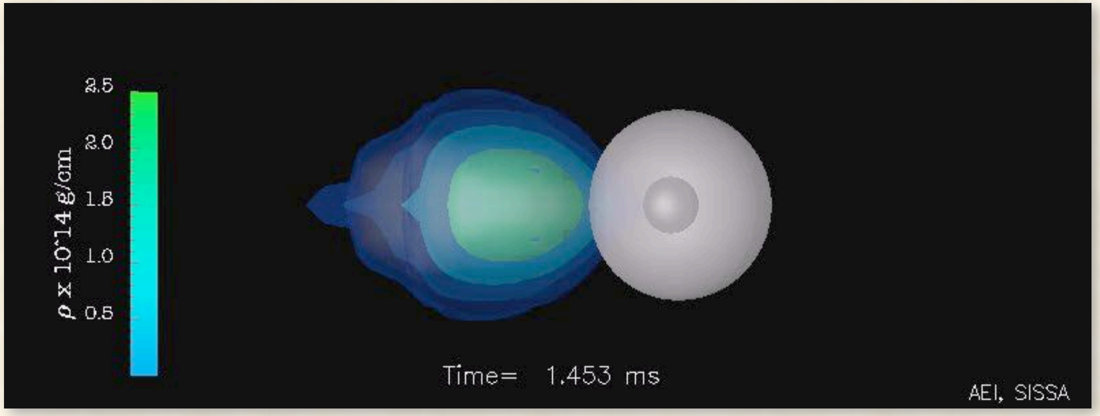

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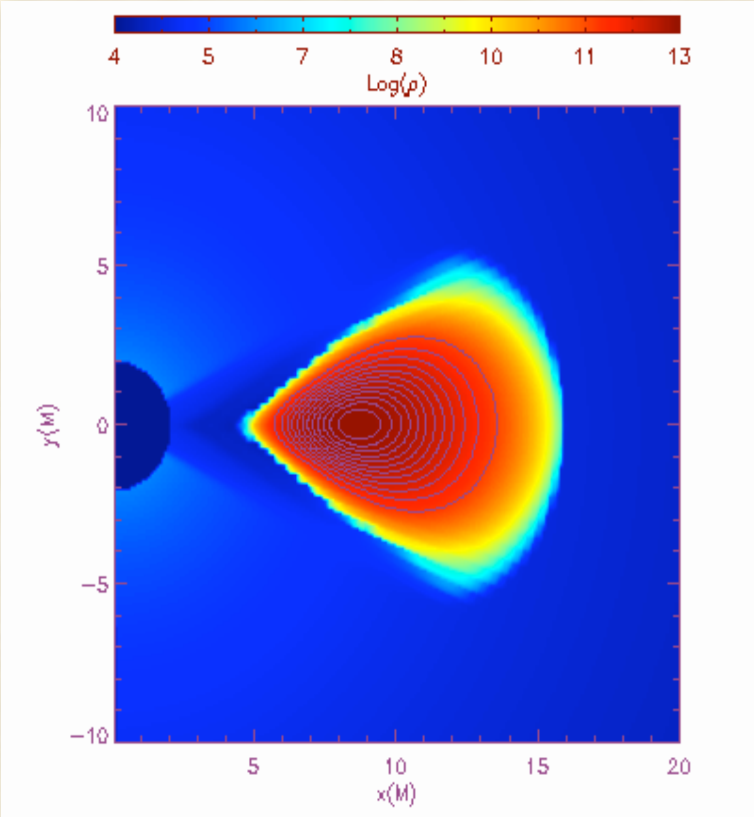

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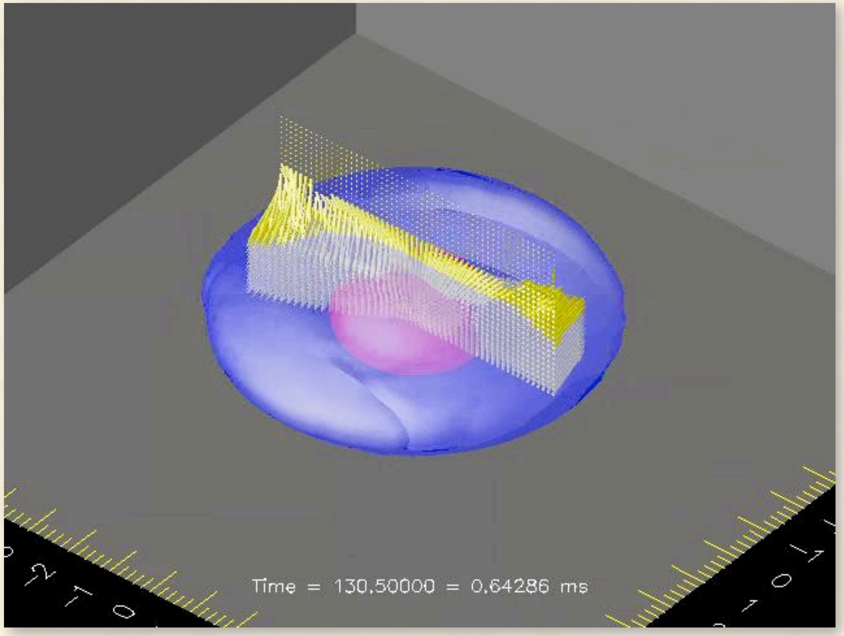
- Rotating collapse to black holes

  Baiotti, Giacomazzo, Hawke, Rezzolla, Schnetter, Stergioulas



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Cactus → $G_{\mu\nu} = 8\pi T_{\mu\nu}$ ← **Whisky**

The Whisky code

- Full GR Magneto-Hydro-Dynamical Code
  - Based on the Cactus framework
  - Solves the HD and MHD equations on dynamical curved background
  - Uses HRSC (High Resolution Shock Capturing) methods
  - Can handle BH formation with or without Excision
  - Implements the Method of Lines
  - Adopts Adaptive Mesh Refinement techniques (Carpet)
  - Implements the Constrained Transport scheme

- It's meant as an "astrophysical laboratory" to study several different sources of gws

Matter field evolution

- The evolution equations of the matter are given as usual by the **conservation of energy-momentum and baryon number**:

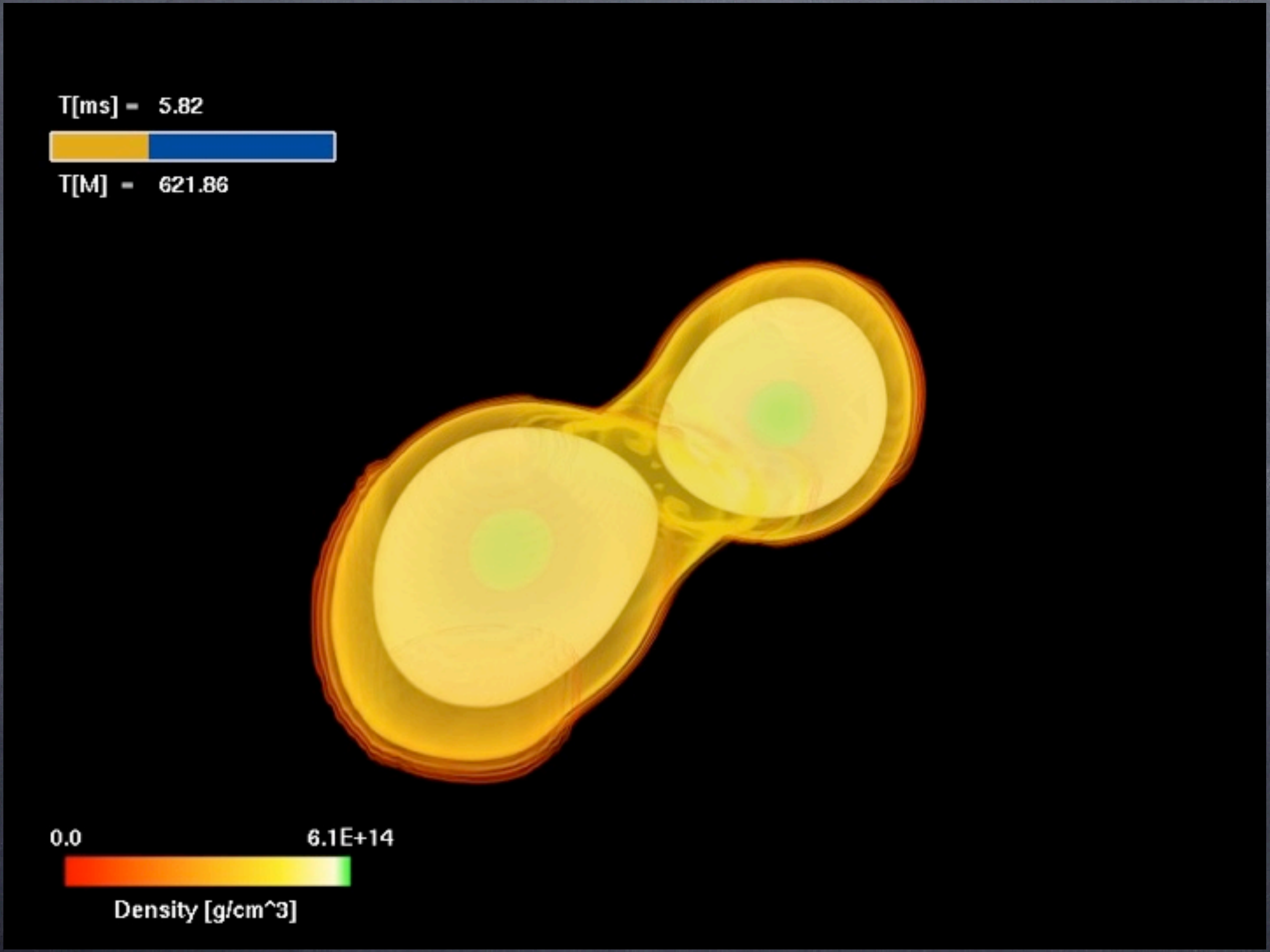
$$\nabla_\mu T^{\mu\nu} = 0$$
$$\nabla_\mu J^{\mu} = 0$$
$$J^{\mu} \equiv \rho u^{\mu}$$

where $T^{\mu\nu} = (\rho + \rho\epsilon + p)u^\mu u^\nu + p g^{\mu\nu}$

plus an **Equation of State P=P(ρ,ϵ)**

- For the simulations presented here we have used during the evolution an ideal-fluid EoS $P = \rho\epsilon(\Gamma - 1)$ or a polytropic EoS $P = \kappa\rho^\Gamma$

Binary Neutron Stars Mergers



- Baiotti, Giacomazzo, Rezzolla 2008, PRD (submitted)

Previous works

Several works in the past by Nakamura, Oohara, Shapiro, Shibata and collaborators. Most recent ones without magnetic field:

- Shibata and Taniguchi 2006, PRD 73, 064027
    - more realistic EOS used
    - fixed uniform grid
    - not able to compute the full signal after BH formation

- Oechslin and Janka 2007, PRL 99, 121102
    - more realistic EOS used
    - SPH, conformally flat approx. to GR, different masses and spins
    - not able to compute the full signal after BH formation

Previous works

Works including also magnetic fields in full GR:

- Anderson et al., PRD 77, 024006 (2007), PRL 100, 191101 (2008)
  - adaptive mesh refinement used
  - initial data built by hand
  - not able to follow the BH formation
  - included magnetic fields (2008 paper); no waves from BH formation

- Liu et al 2008, PRD 78, 024012
  - included magnetic fields
  - no mesh refinement ("fish-eye" coords)
  - consistent (irrotational) initial data
  - only one orbit but follow the BH formation
  - second order reconstruction and low resolution

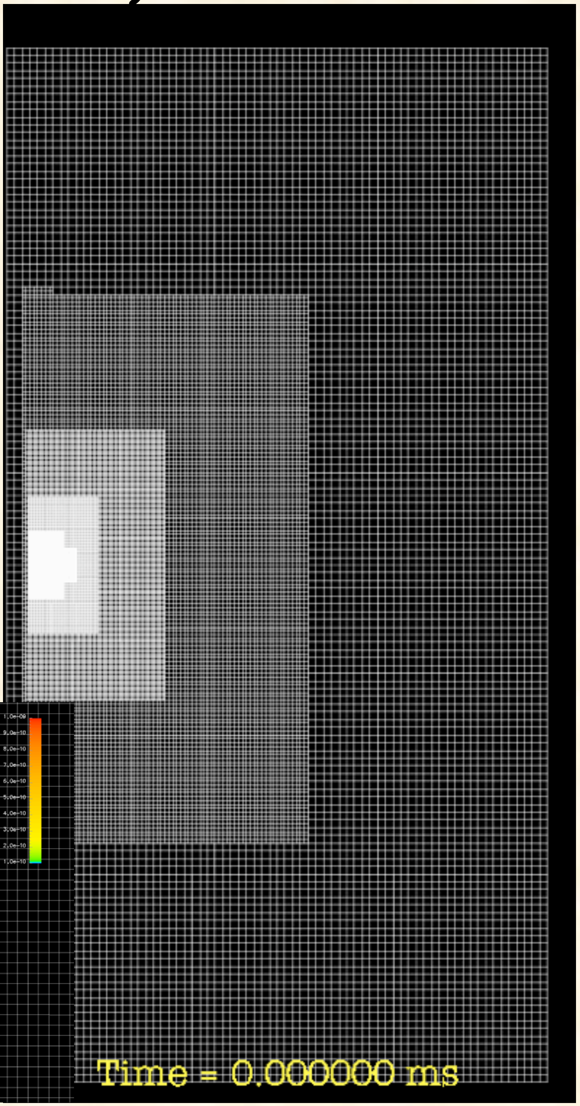
Initial Models

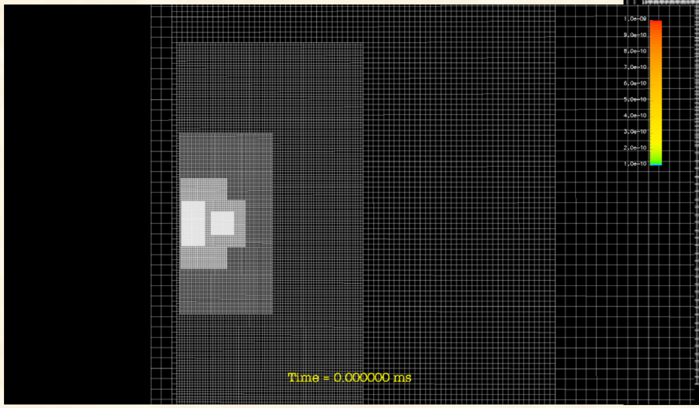
All the initial models are computed using the Lorene code for unmagnetized binary NSs (Bonazzola et al. 1999):

Model	M1,M2	d (km)
low-mass	1.4	45
high-mass	1.6	45

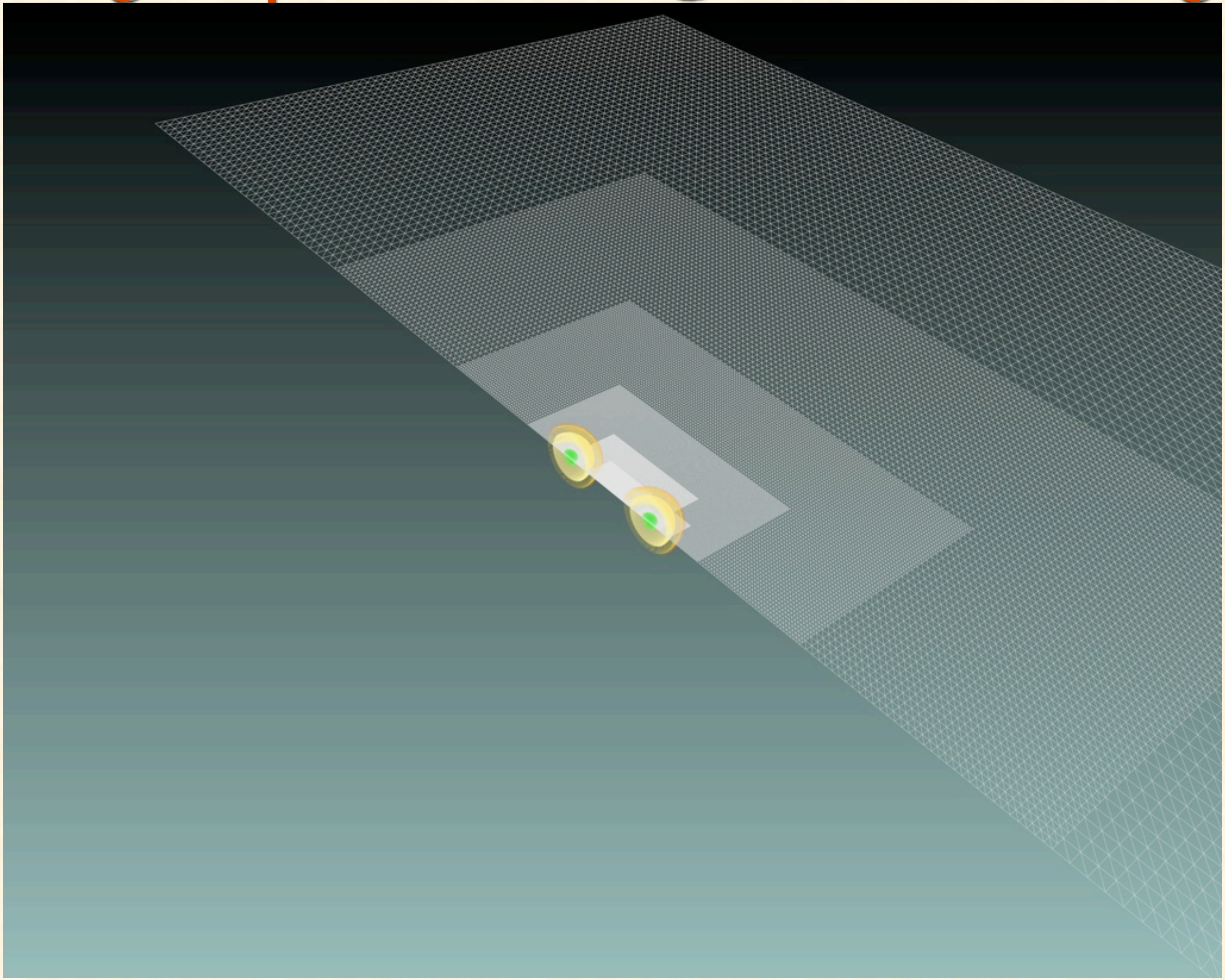
Technical data for the simulations:

- polytropic EOS
- outer boundary: ~370 km
- 8 refinement levels; res. of finest level: ~0.18km
- PPM for the reconstruction
- Marquina flux formula
- Runge Kutta (3rd-order)

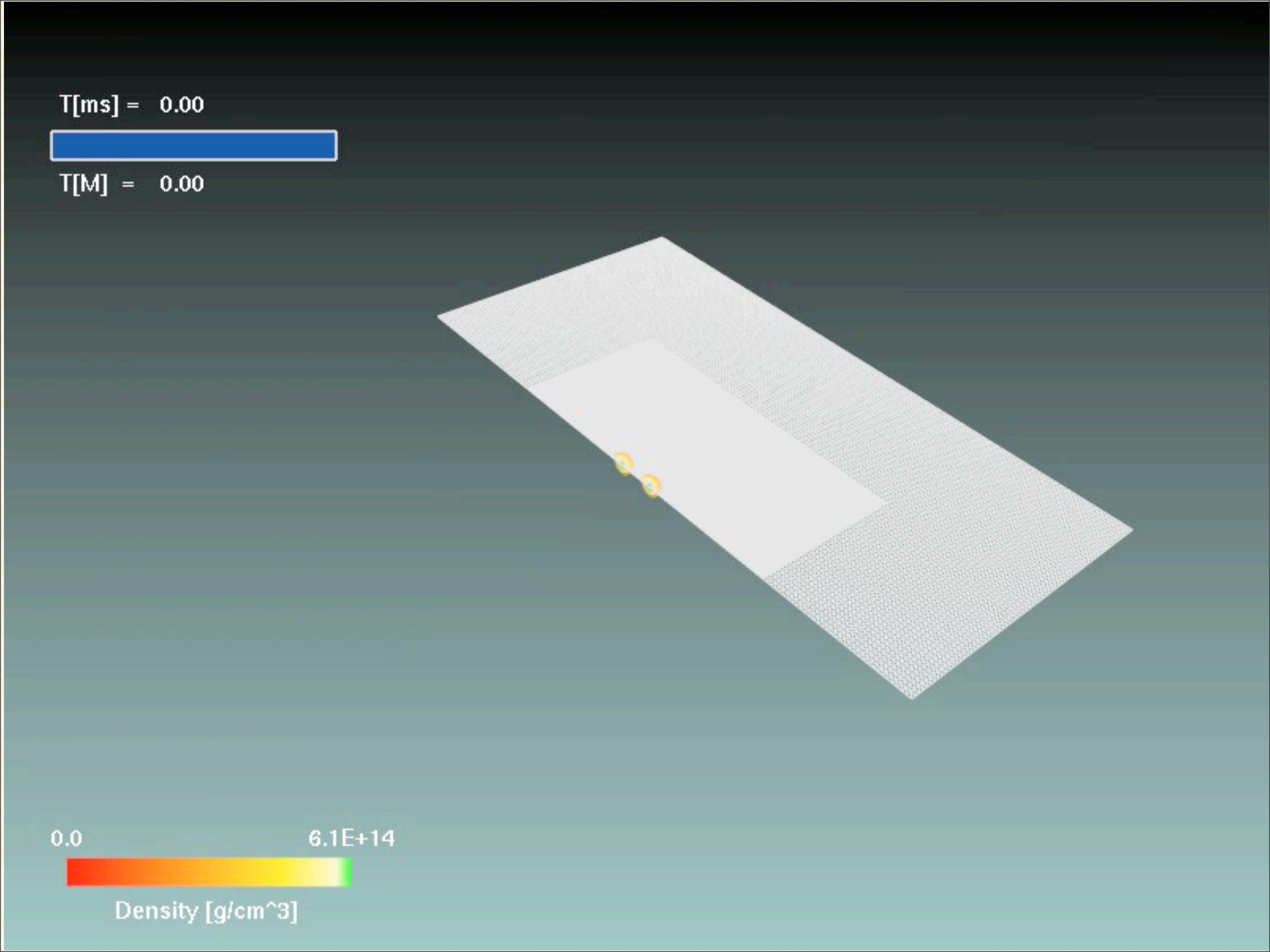




Polytropic EOS: high-mass binary



Visualization by Giacomazzo, Kaehler, Rezzolla


T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]

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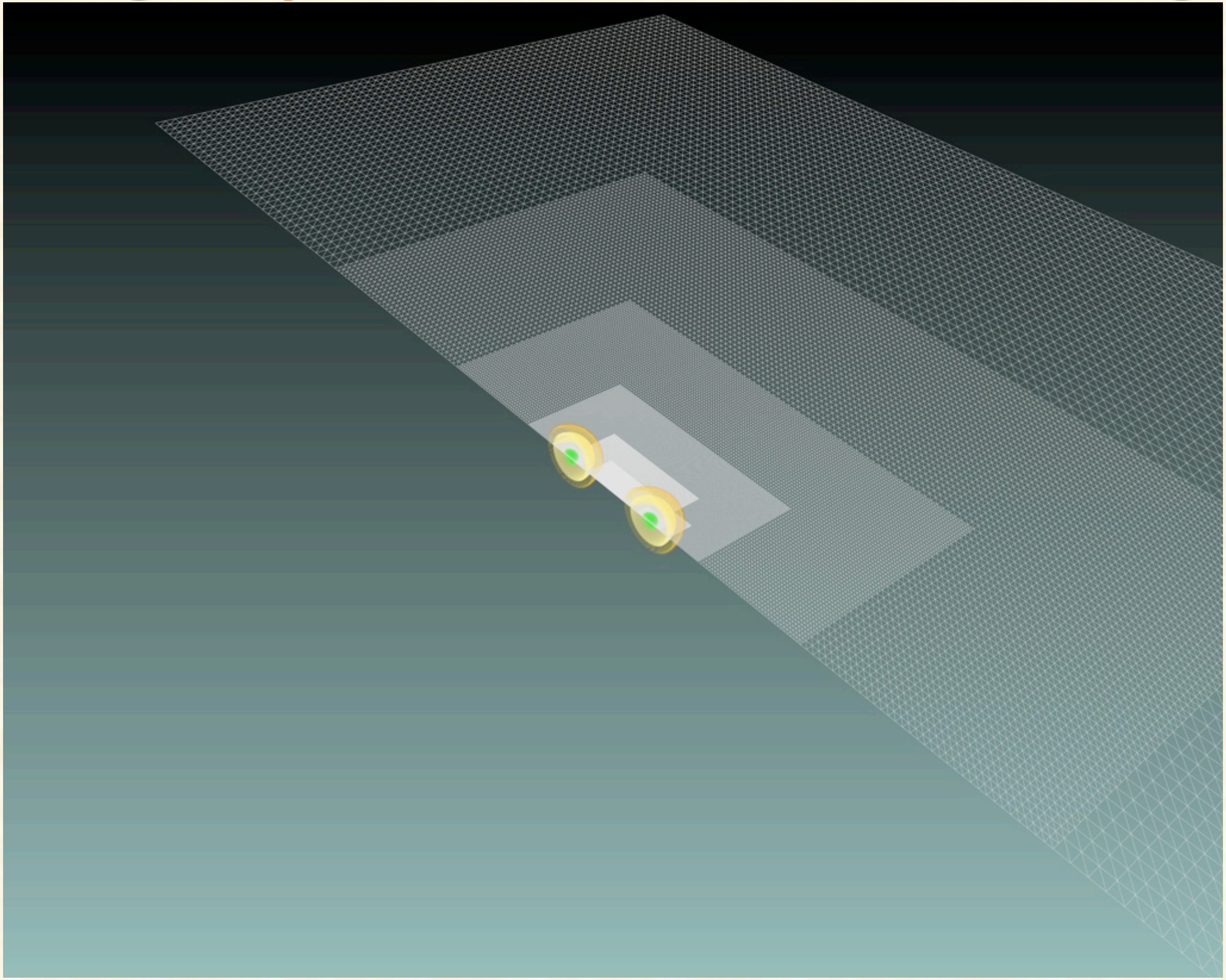
- differences in the EOS for the same mass

  a binary with an EOS with a larger thermal internal energy (ie hotter after merger) will have an increased pressure support and will collapse at a later time

Binary Neutron Stars:
The Role of the Mass

Polytropic EOS: low-mass binary



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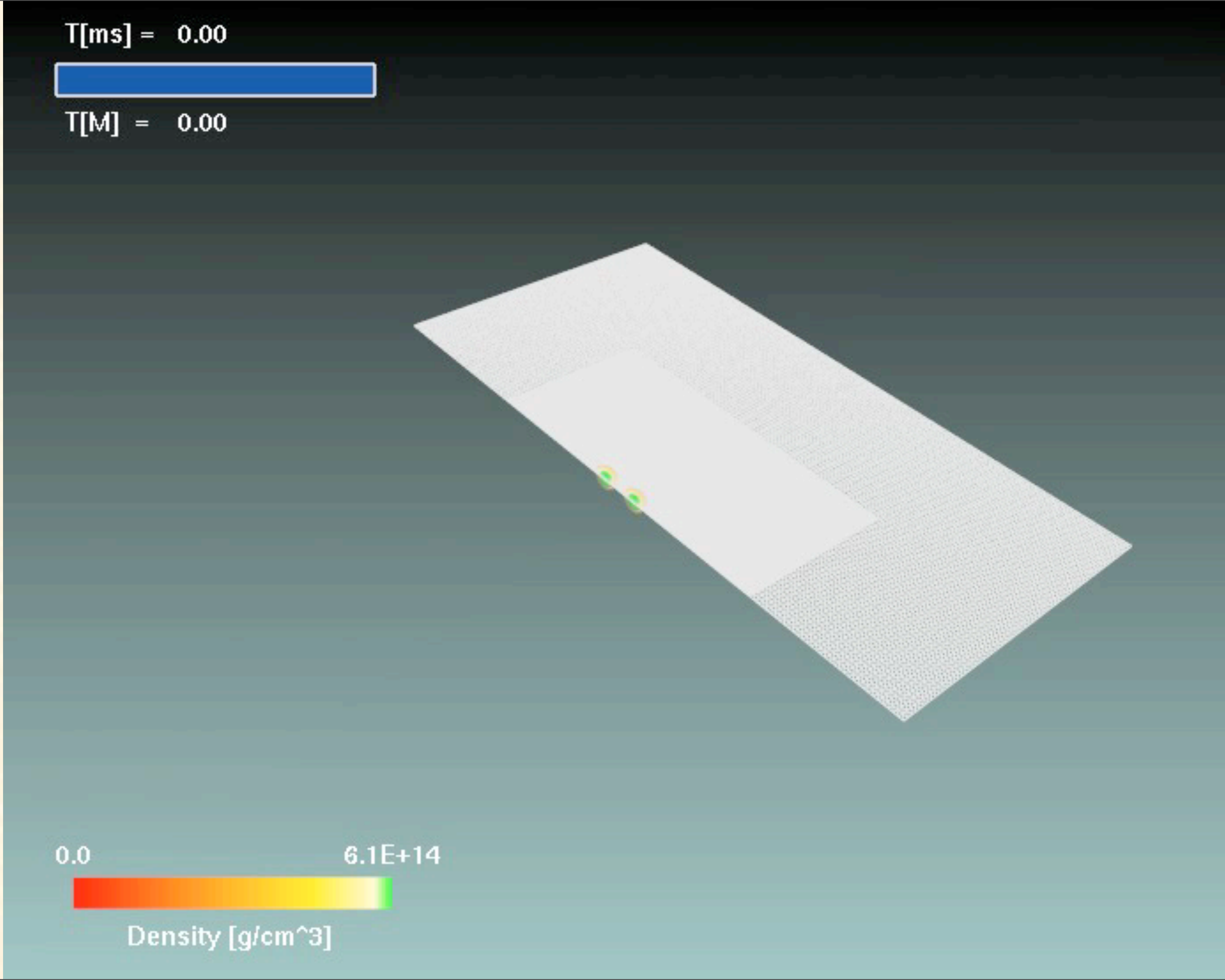

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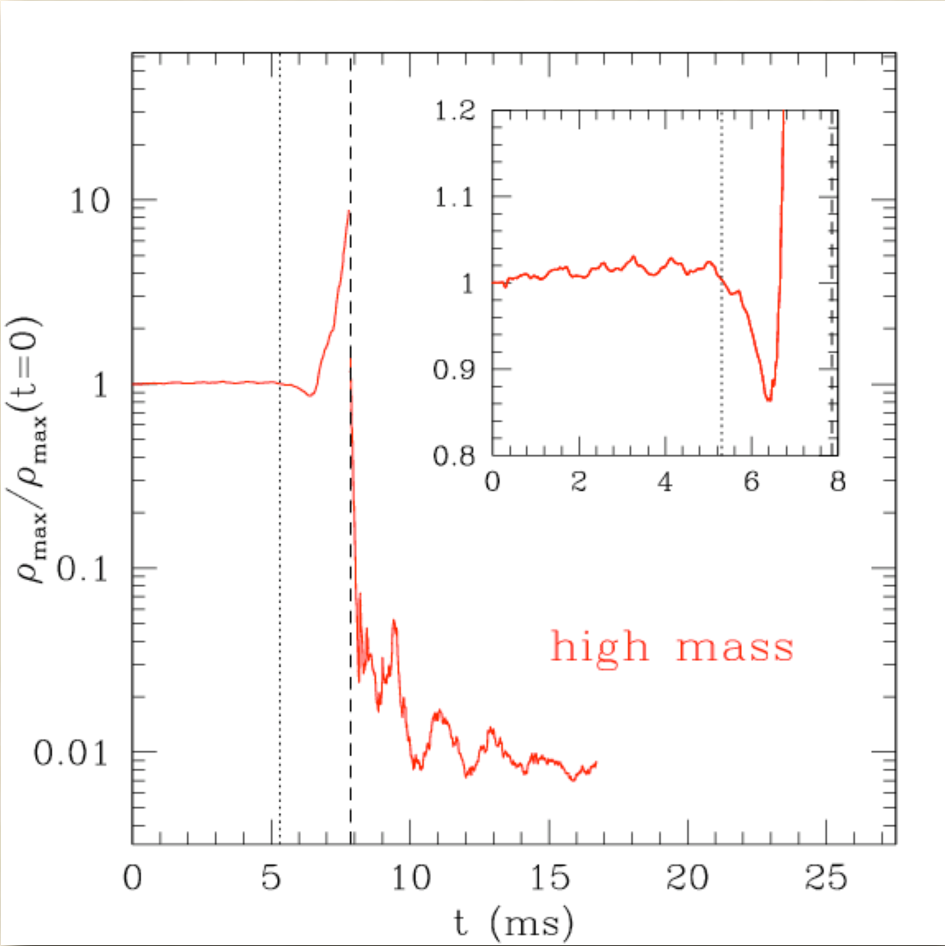
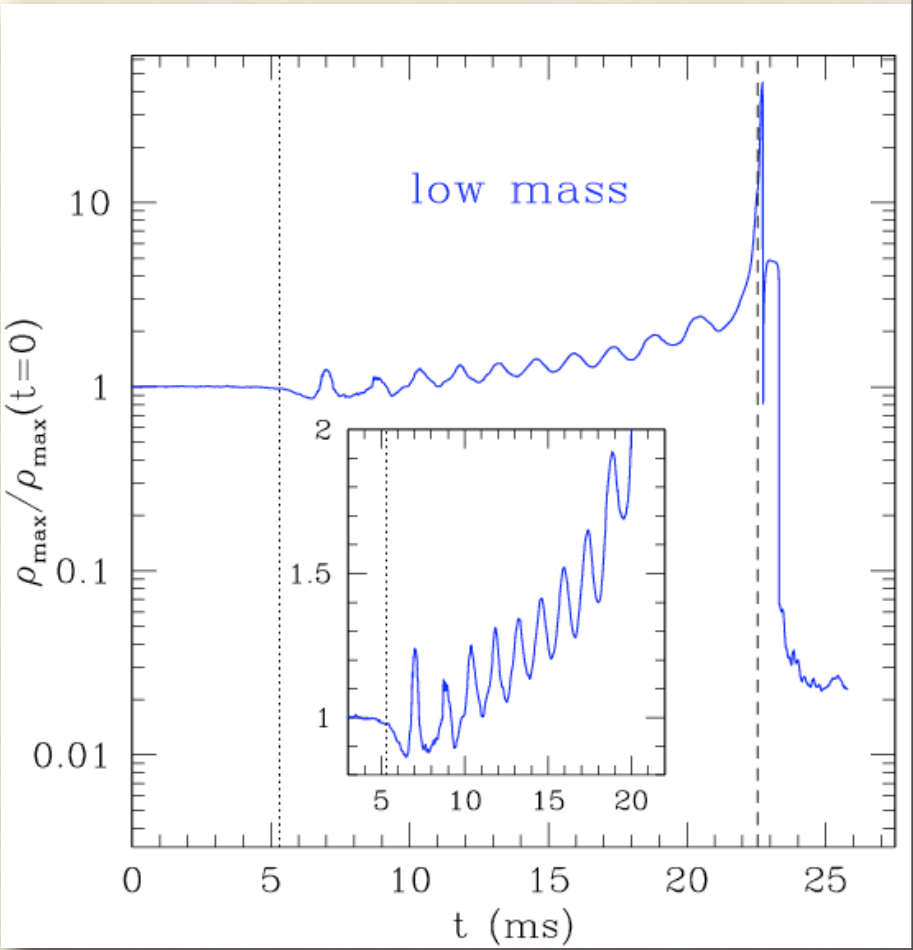
Matter Dynamics

high-mass binary



soon after the merger the torus is formed and undergoes oscillations

low-mass binary

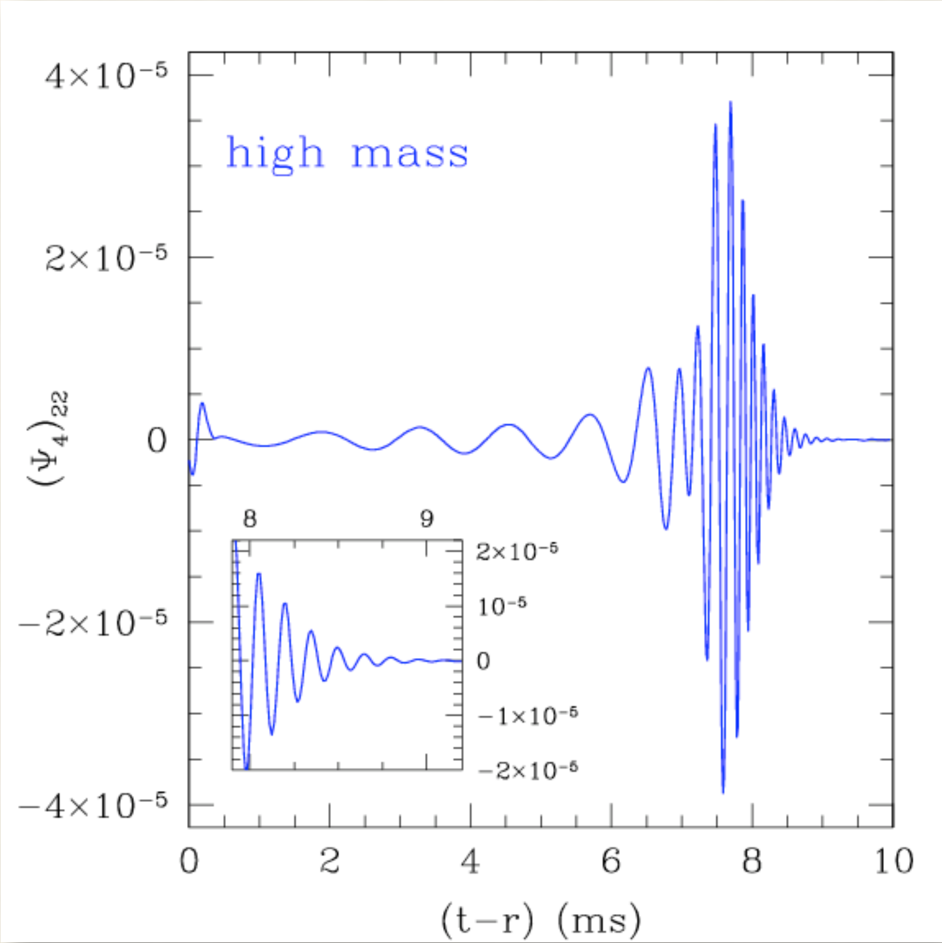


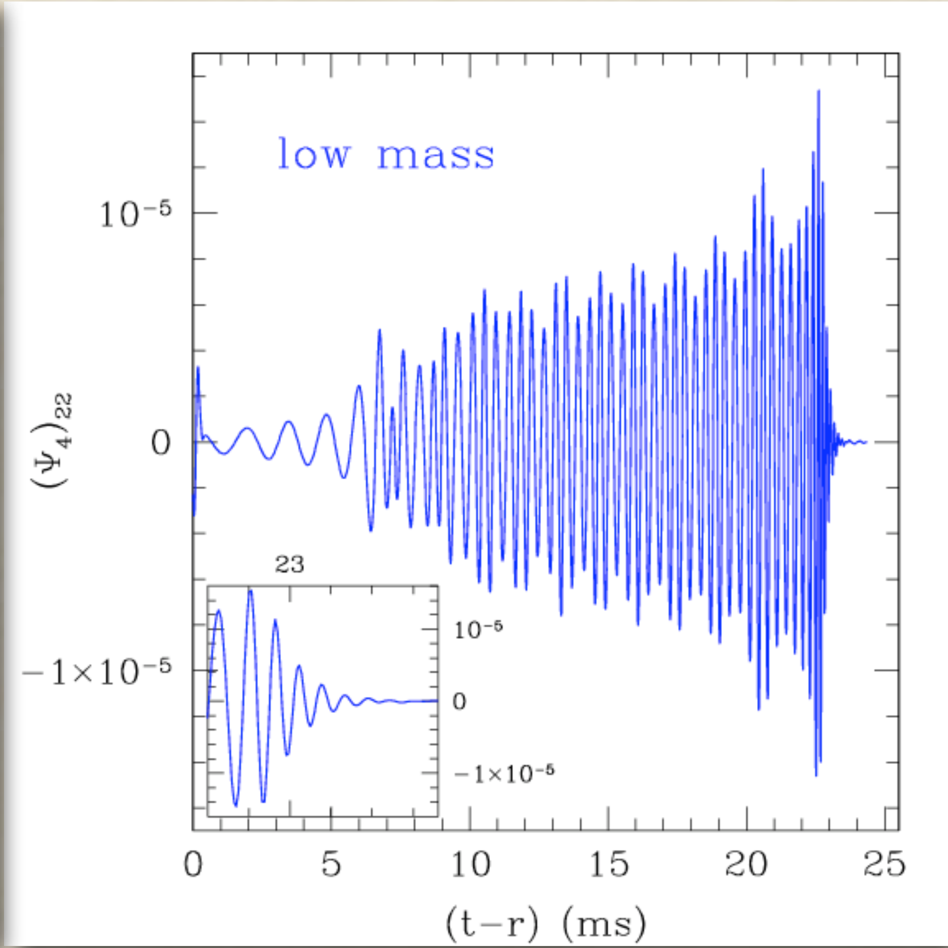
long after the merger a BH is formed surrounded by a torus

Waveforms

high-mass binary

low-mass binary





first time the full signal from the merger to bh has been computed

development of a bar-deformed NS leads to a long gw signal

Binary Neutron Stars:
The Role of the Equation of State

High-mass binary: Polytropic vs Ideal Fluid EOS

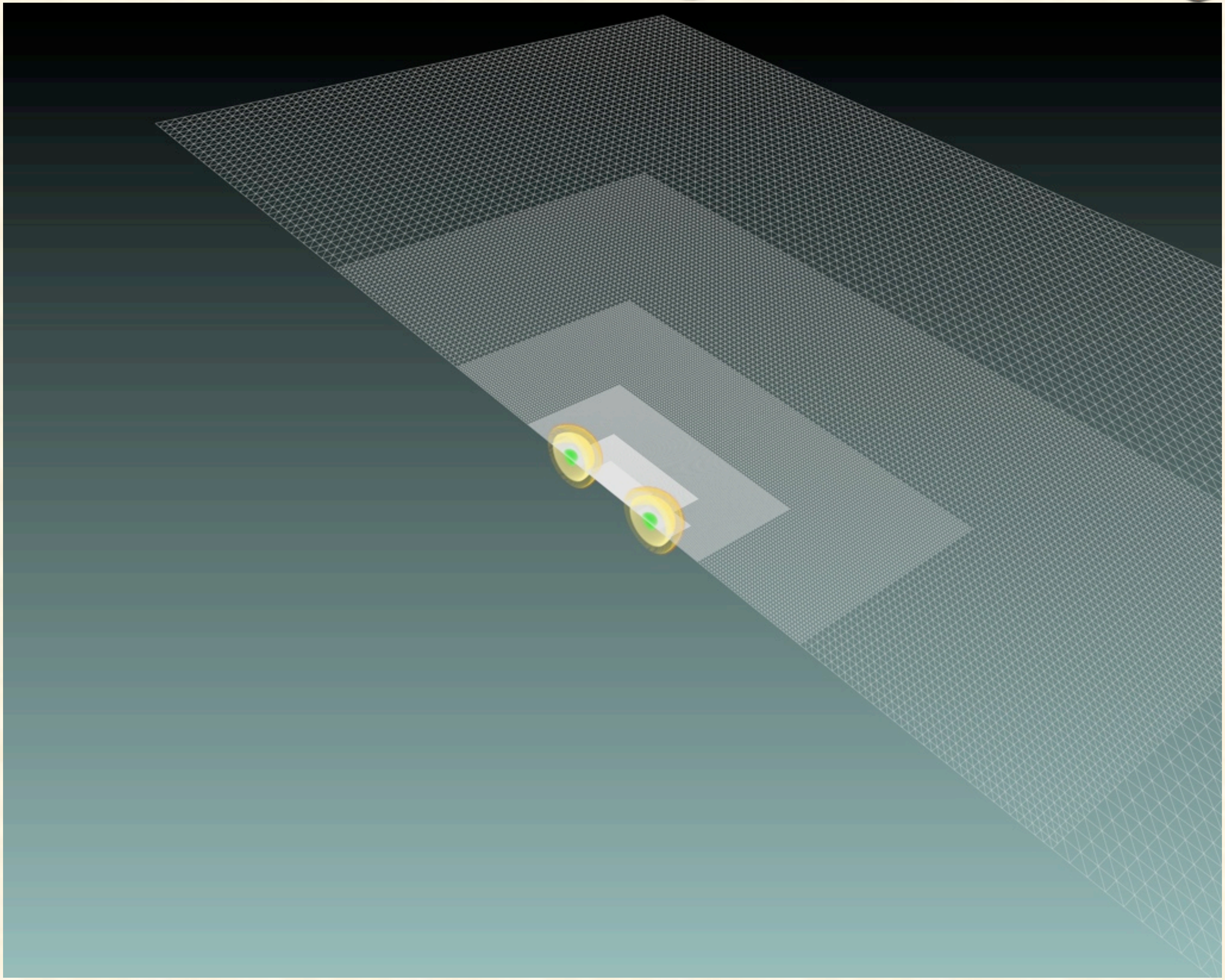
So far considered **polytropic EOS** which is isentropic. Entropy cannot change and the thermal energy cannot increase

$$P = \kappa \rho^{\Gamma}$$

A step forward before implementing realistic EOSs can be made with an **ideal-fluid EOS**, non-isentropic if shocks are present. The thermal energy is expected to increase.

$$P = \rho \epsilon (\Gamma - 1)$$

Ideal Fluid EOS: high-mass binary



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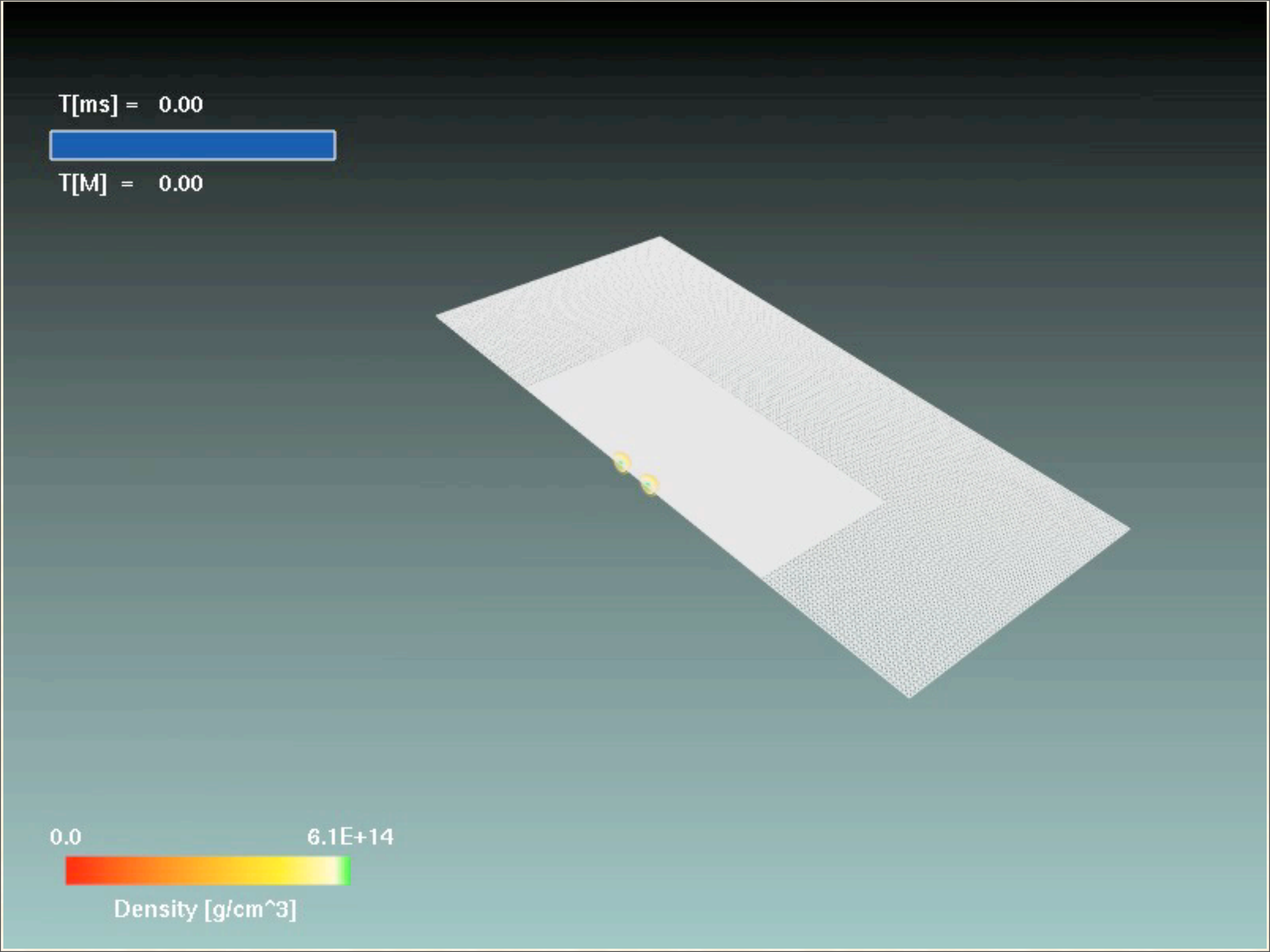
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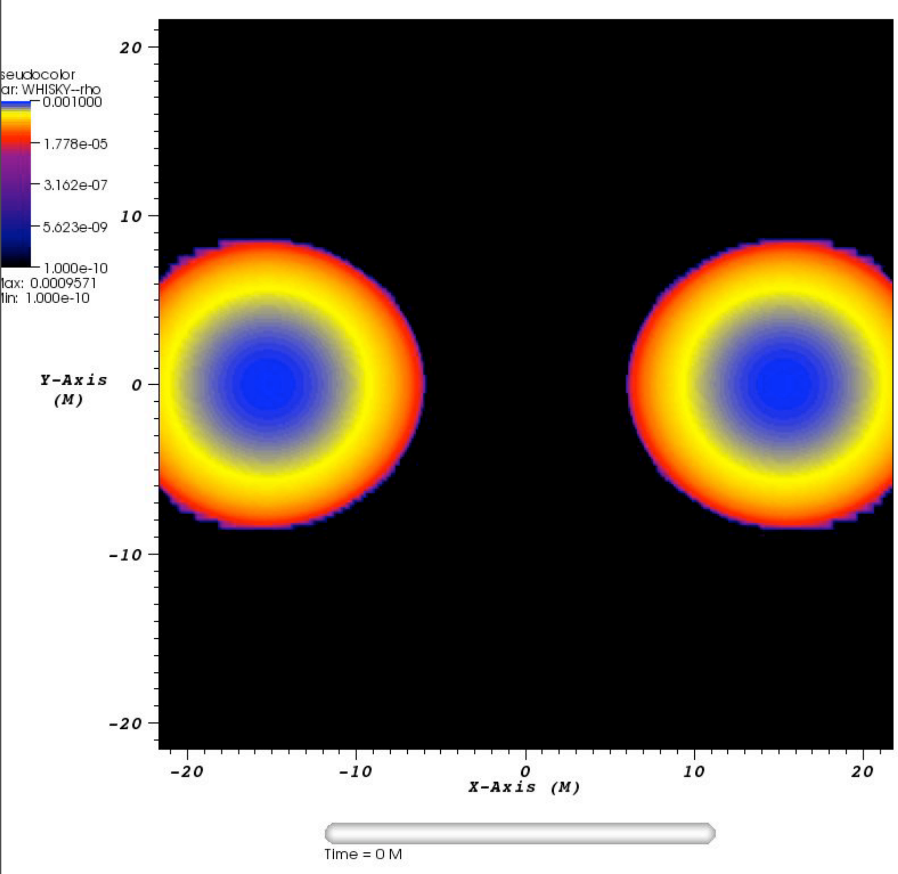
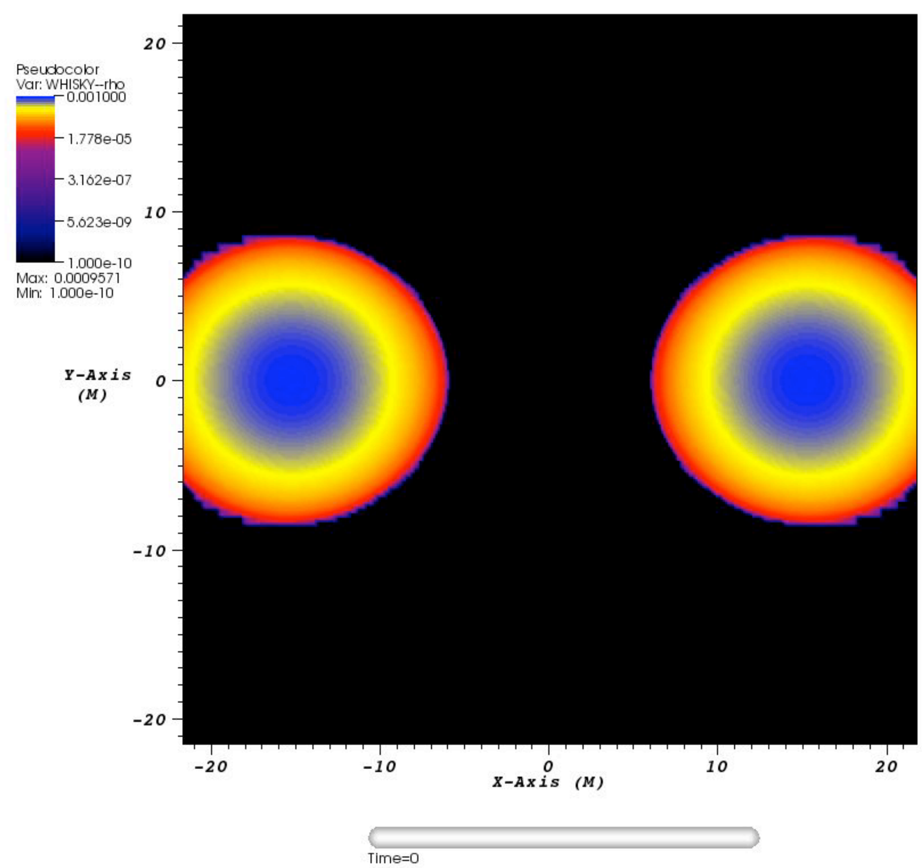




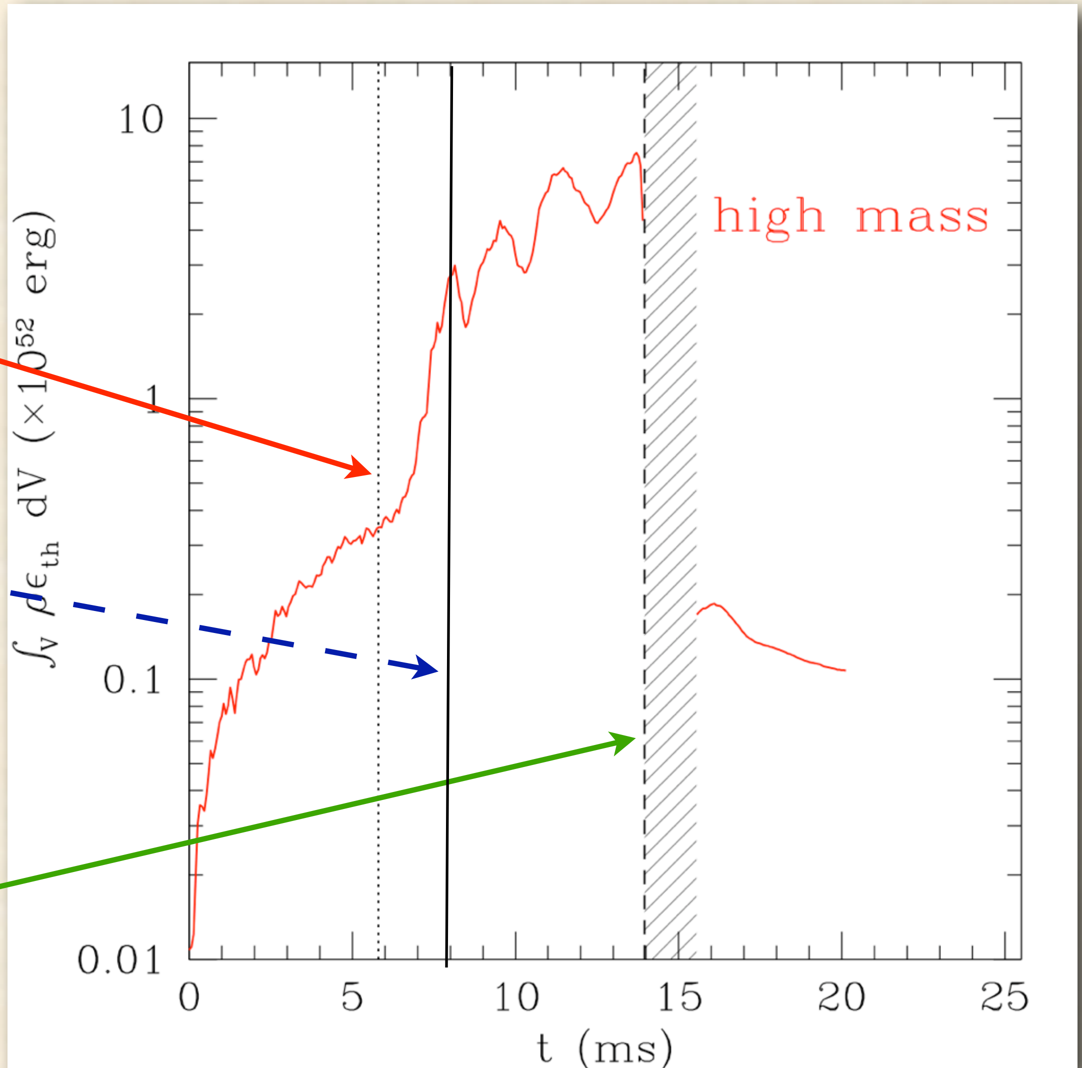
High-mass binary: Ideal Fluid vs Polytropic EOS

The increase in internal energy (produced by the shocks) allows the produced HMNS to resist gravitational collapse.

Coalescence to a single neutron star

Time of collapse for polytropic EOS

Collapse to a rotating BH



Waveforms: Ideal Fluid EOS

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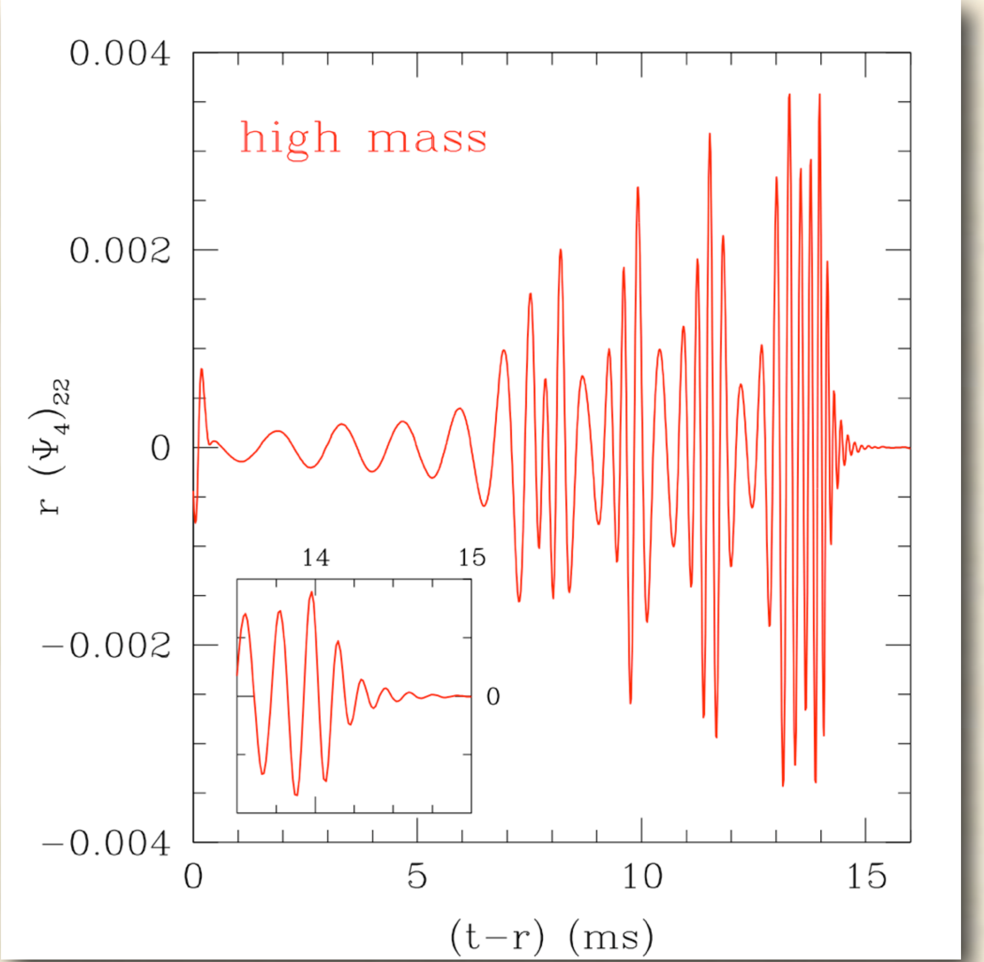
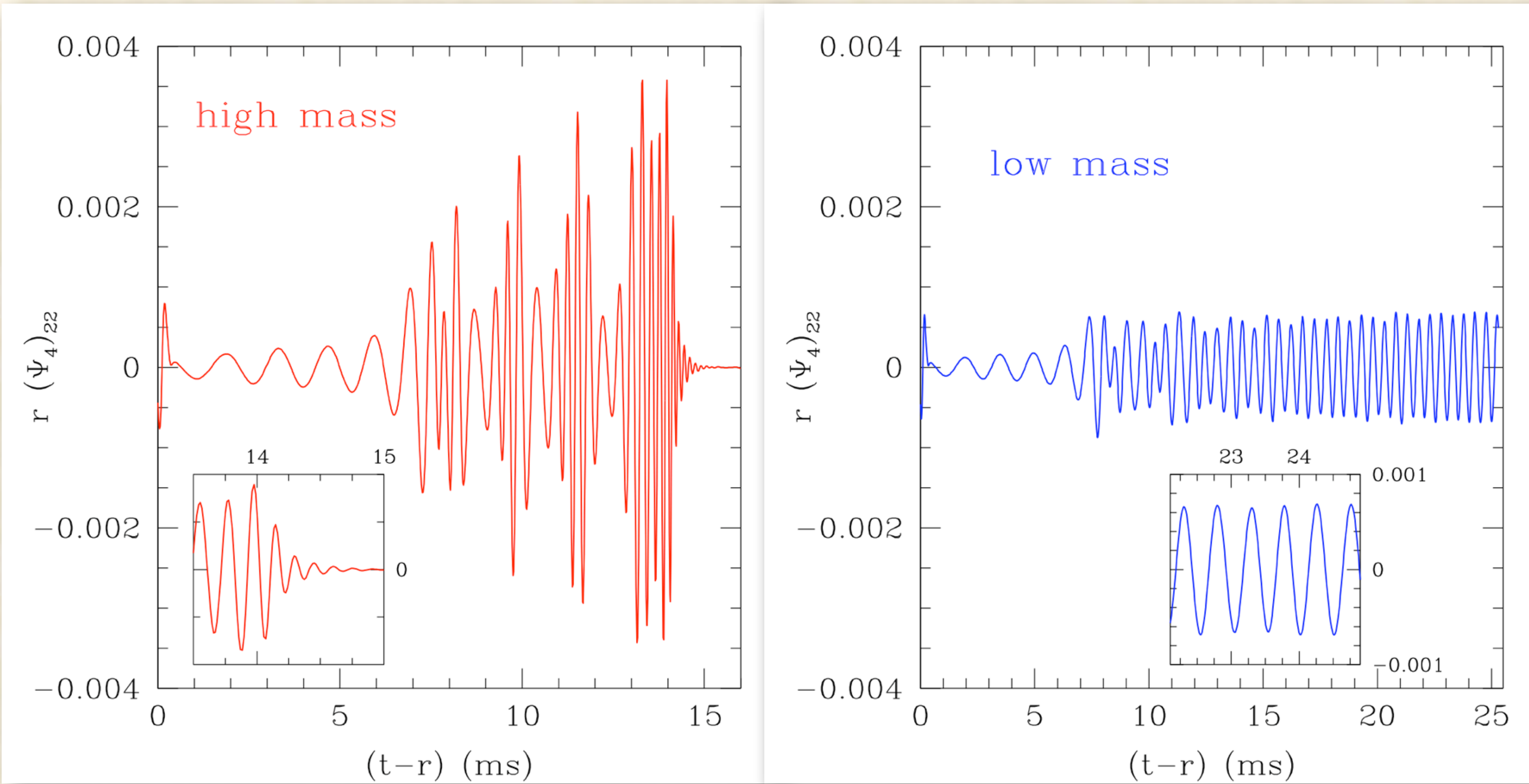
high-mass binary



the high internal energy of the HMNS prevents a prompt collapse

Waveforms: Ideal Fluid EOS

high-mass binary | low-mass binary



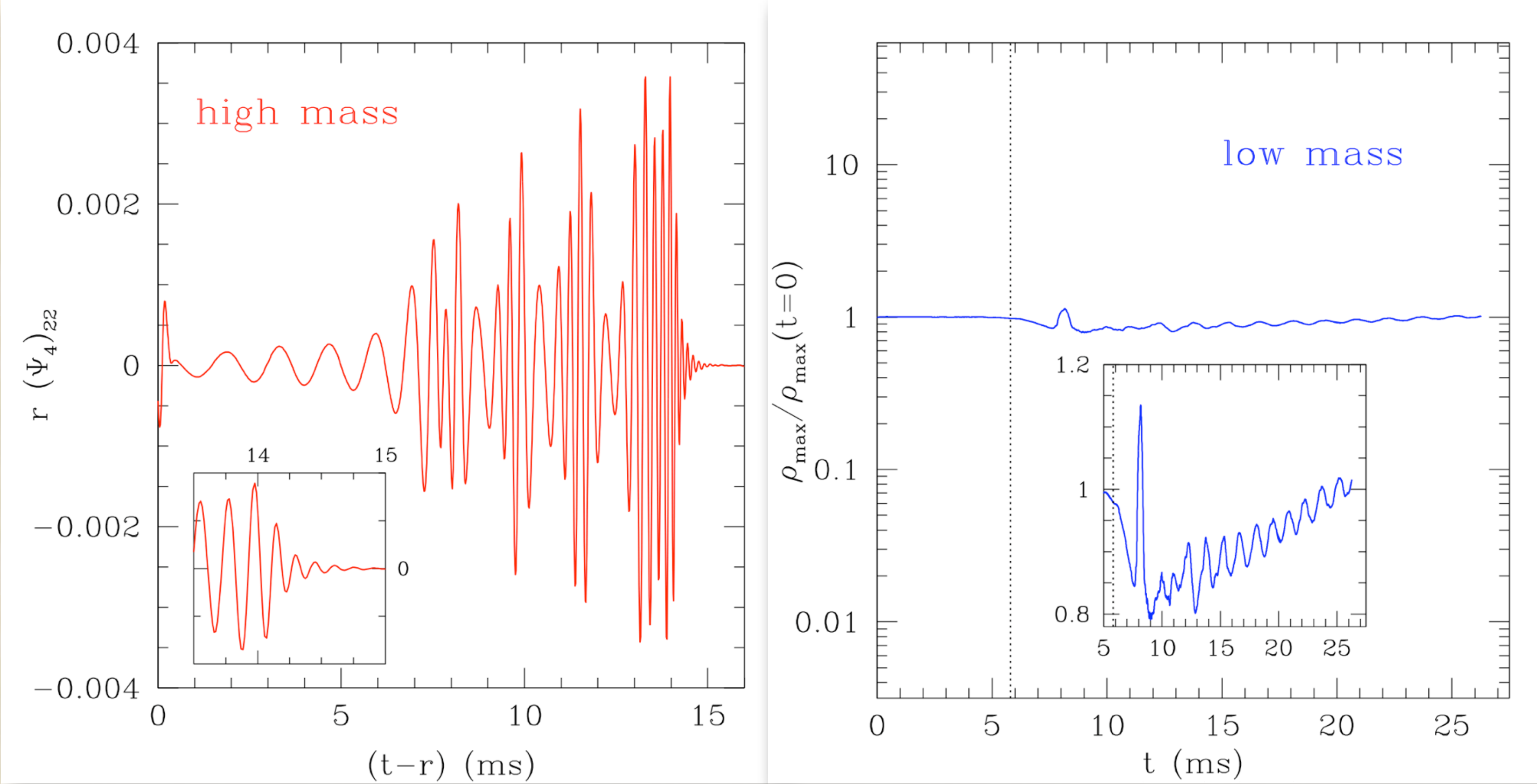
the high internal energy of the HMNS prevents a prompt collapse

the HMNS evolves on a longer timescale

Waveforms: Ideal Fluid EOS

high-mass binary

low-mass binary



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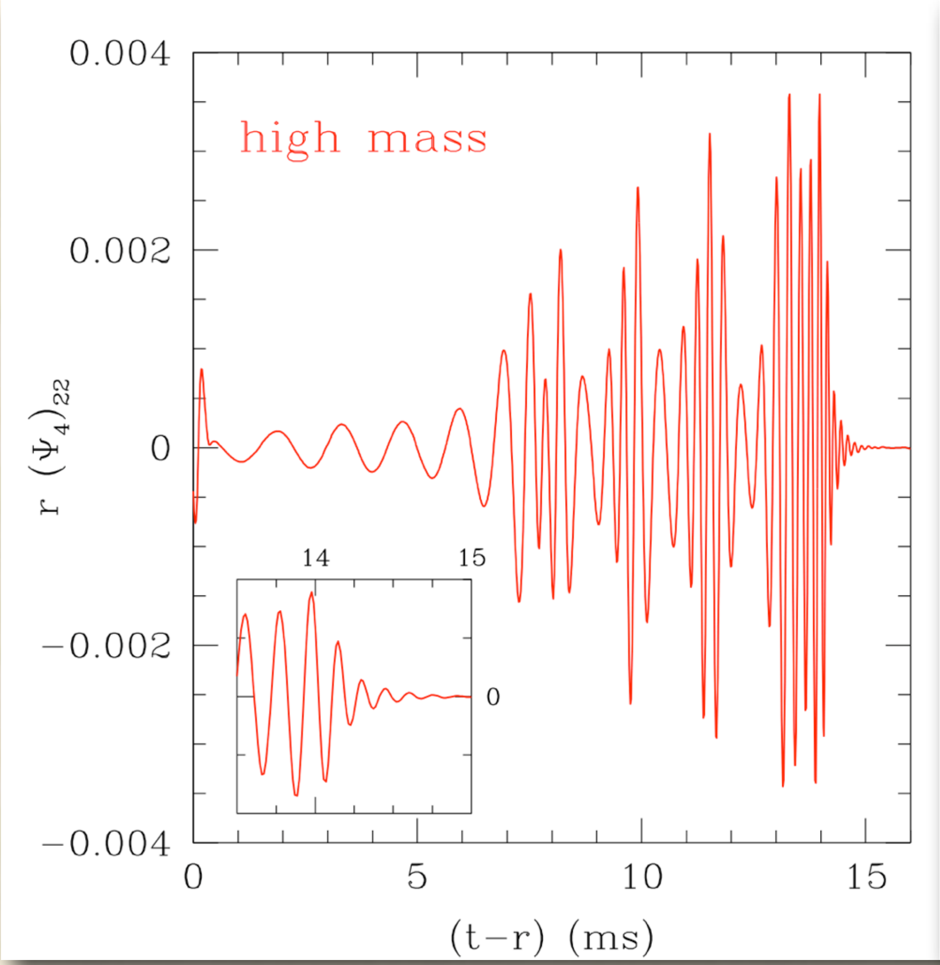
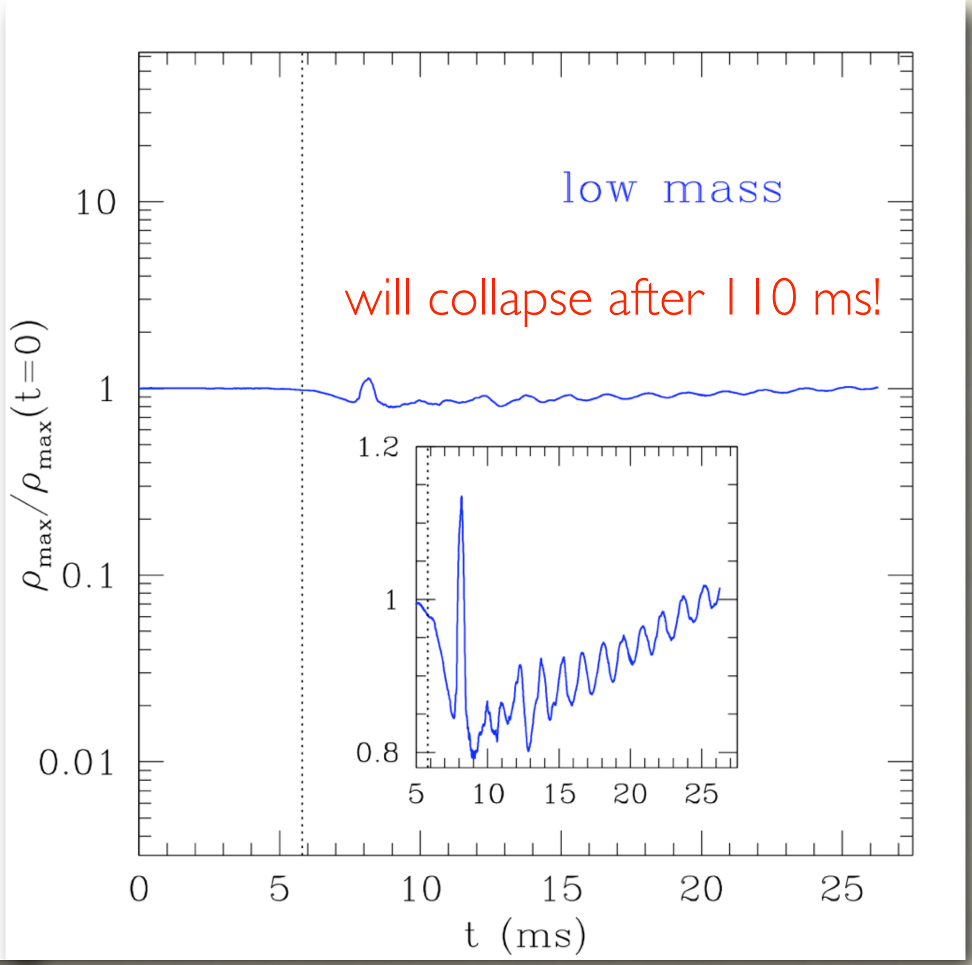
high-mass binary

low-mass binary





the high internal energy of the HMNS prevents a prompt collapse

the HMNS evolves on a longer timescale

Imprint of the EOS: Ideal Fluid vs Polytropic

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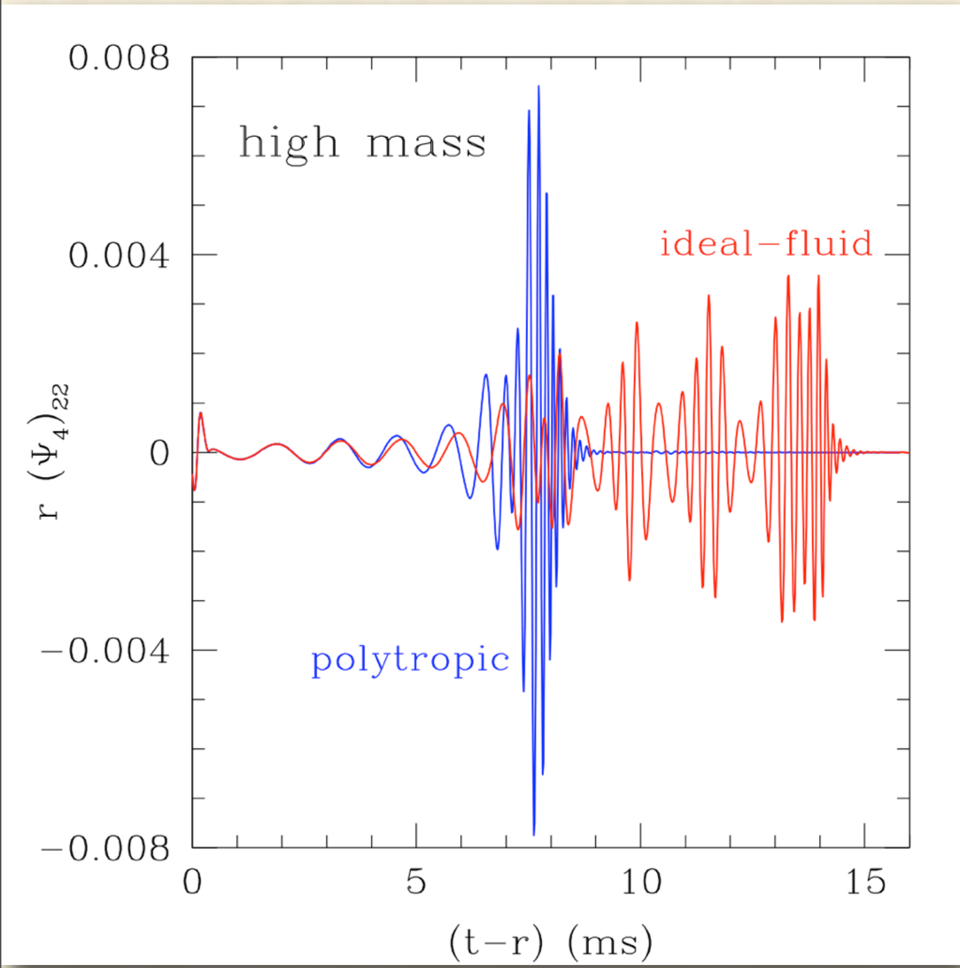

After the merger a BH is produced over a timescale comparable with the dynamical one

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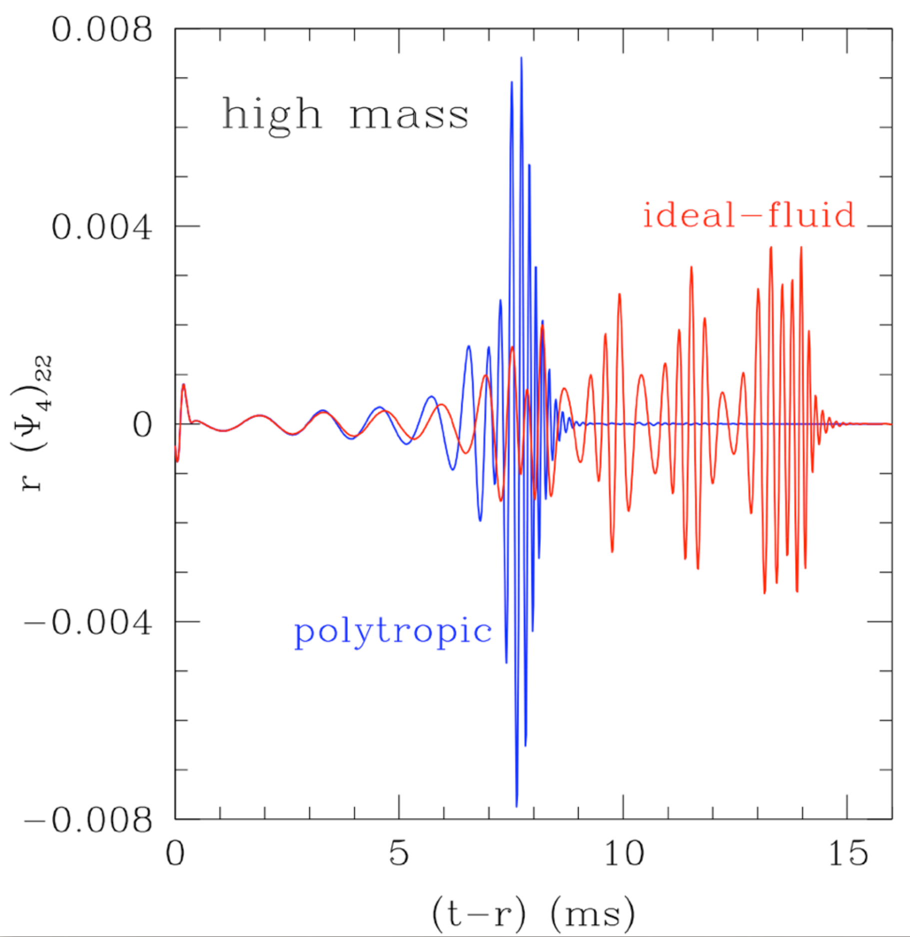

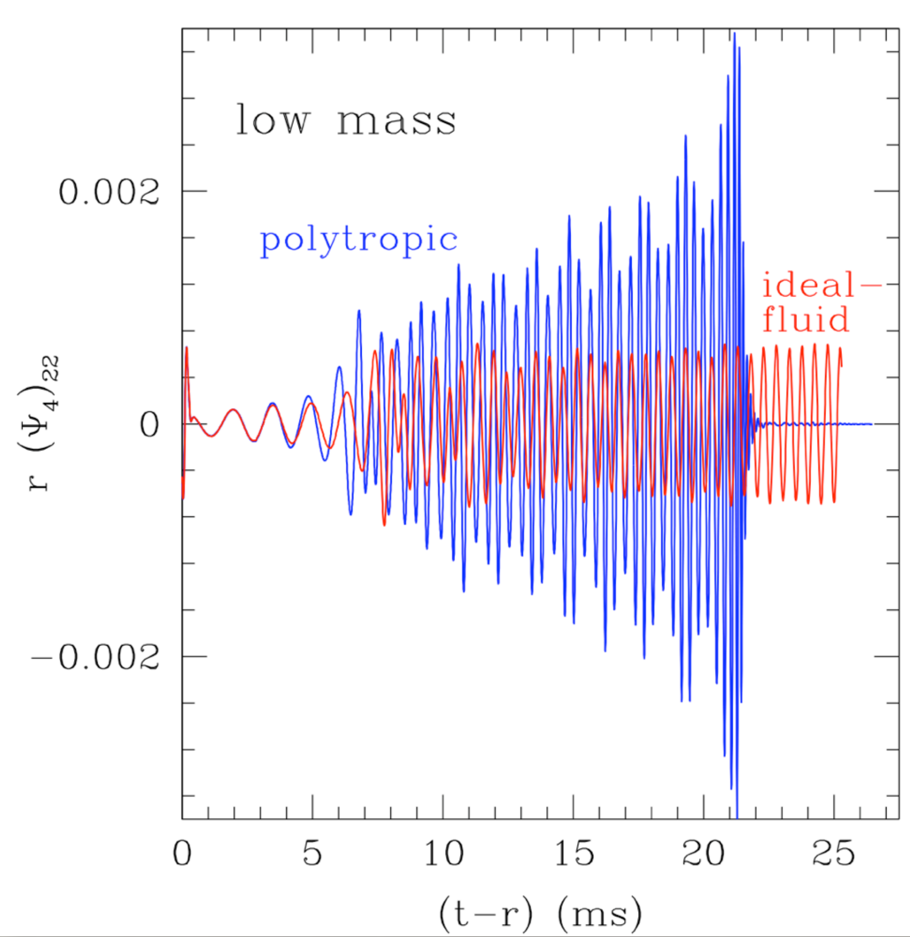

After the merger a BH is produced over a timescale comparable with the dynamical one

After the merger a BH is produced over a timescale larger or much larger than the dynamical one

Binary Neutron Stars:
Hydrodynamics Instabilities

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This can have an important role in the formation of magnetars and short gamma-ray bursts

KH instability: high-mass BNS

Visualization by Giacomazzo, Rezzolla

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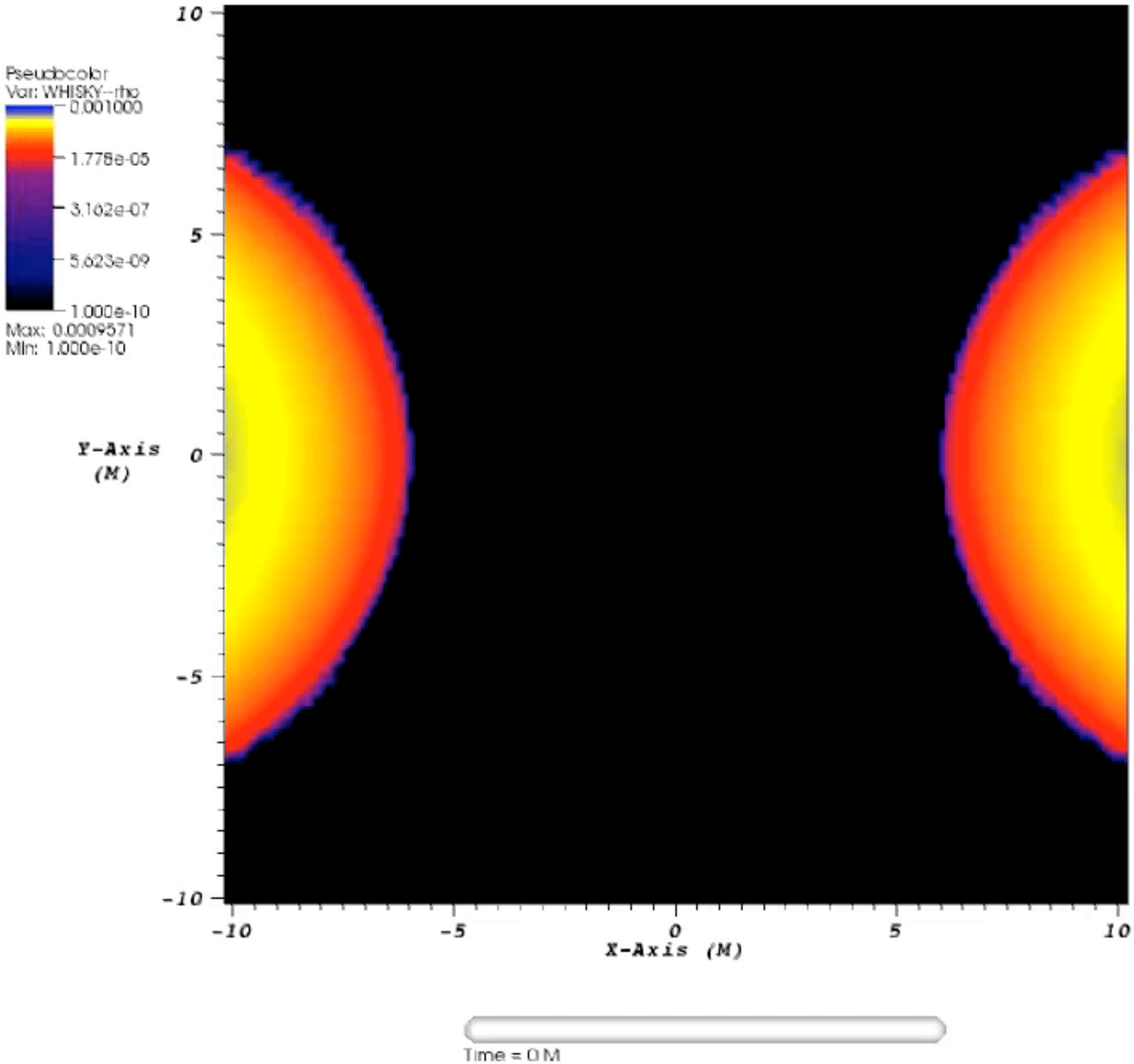

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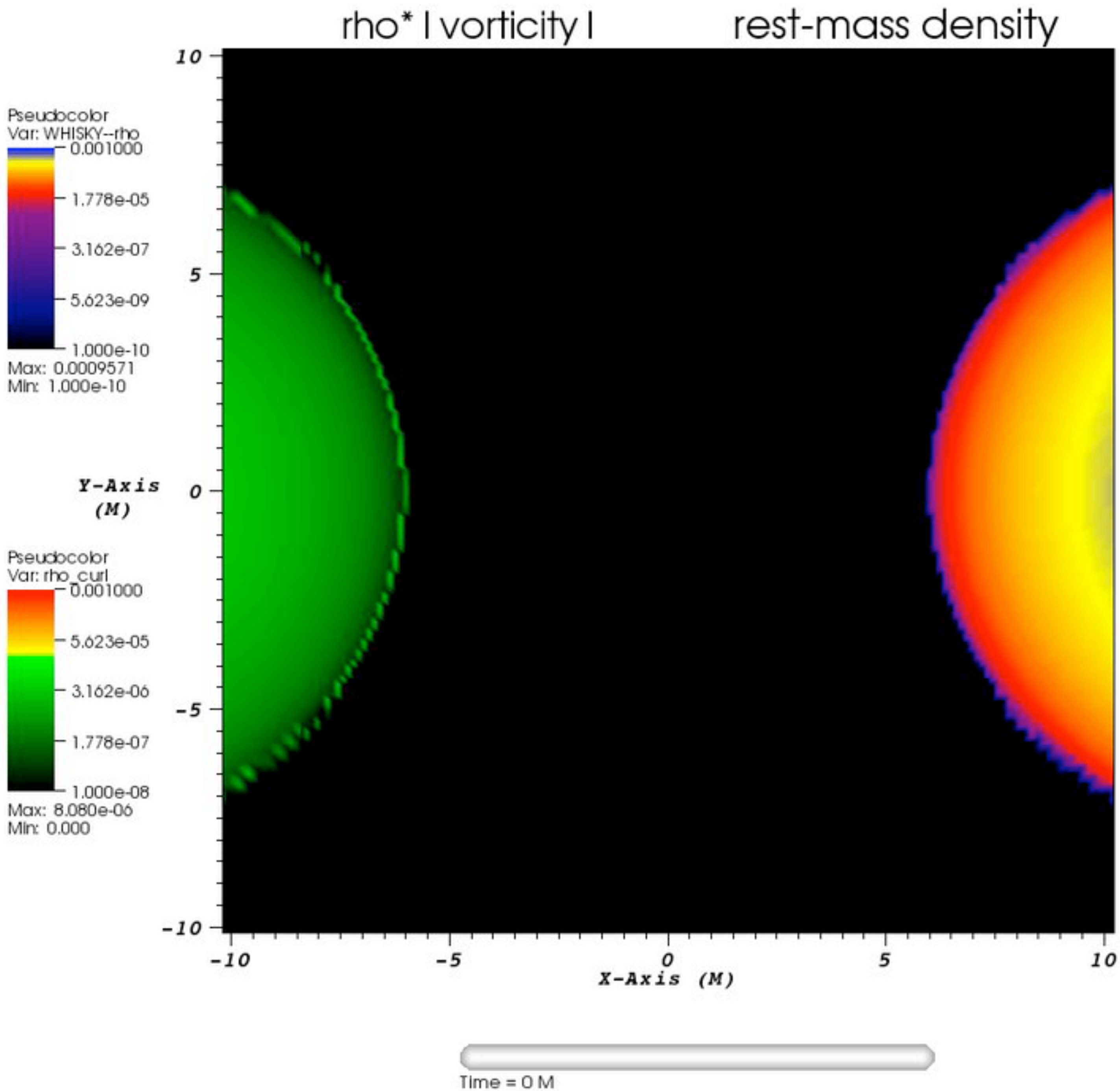

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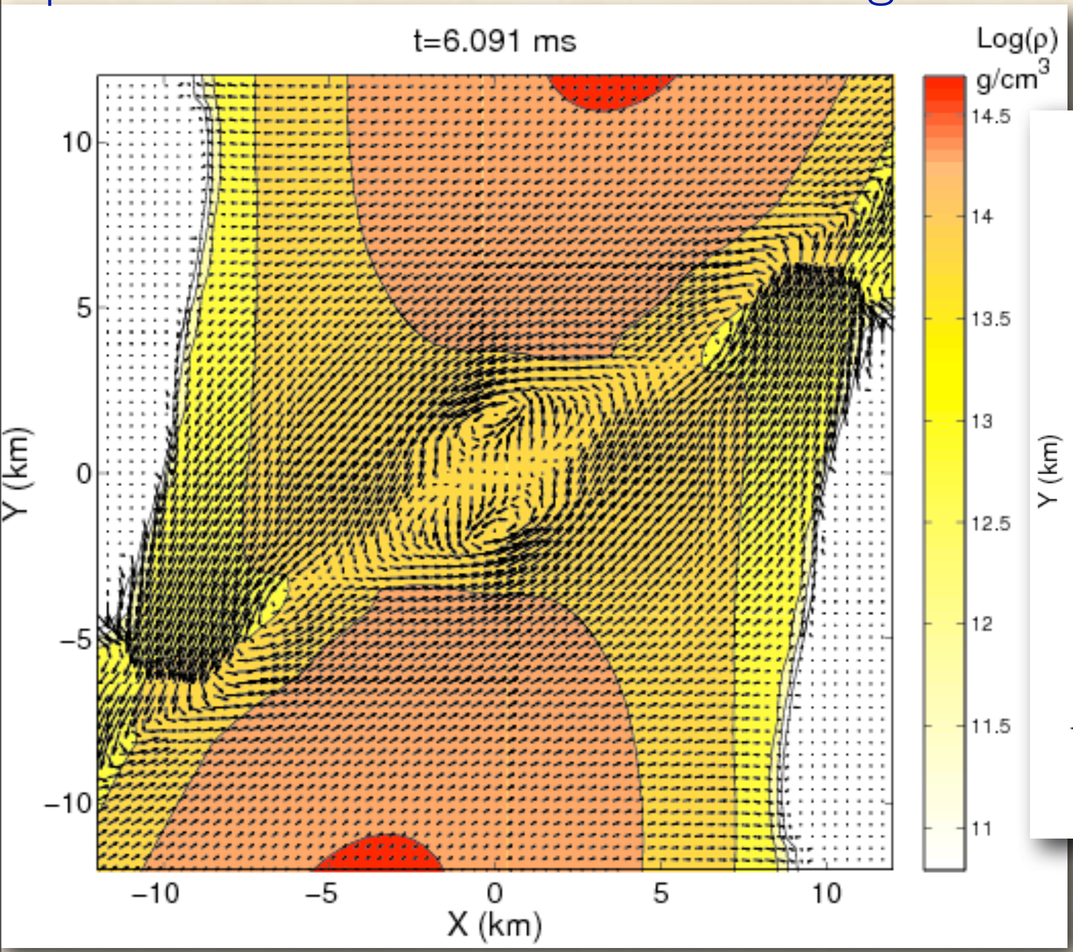
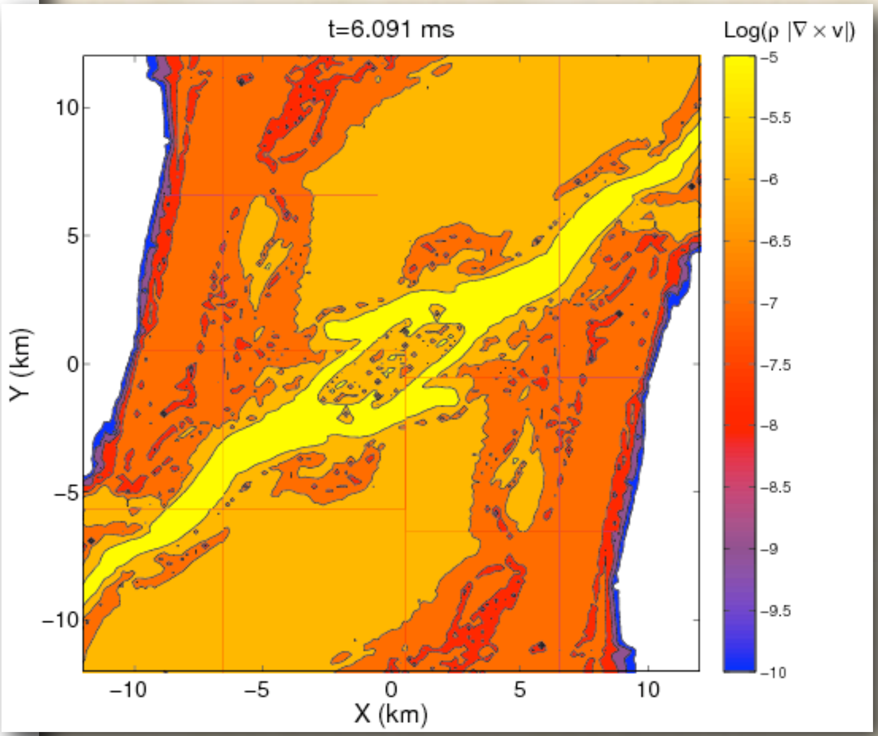
Note the development of vortices in the shear boundary layer produced at the time of the merger



(v^x, v^y) in "corotating" frame

More evident in terms of the weighted vorticity.



$\rho|\nabla \times v|^z$

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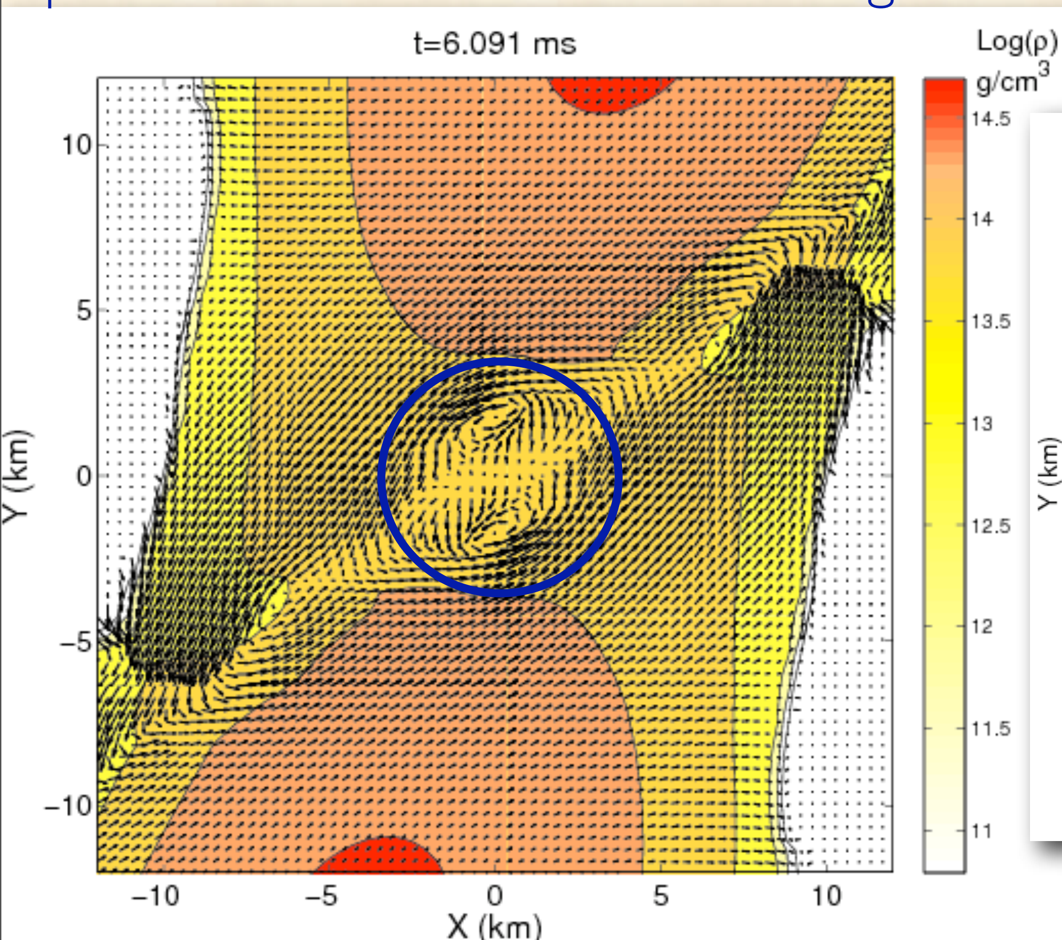

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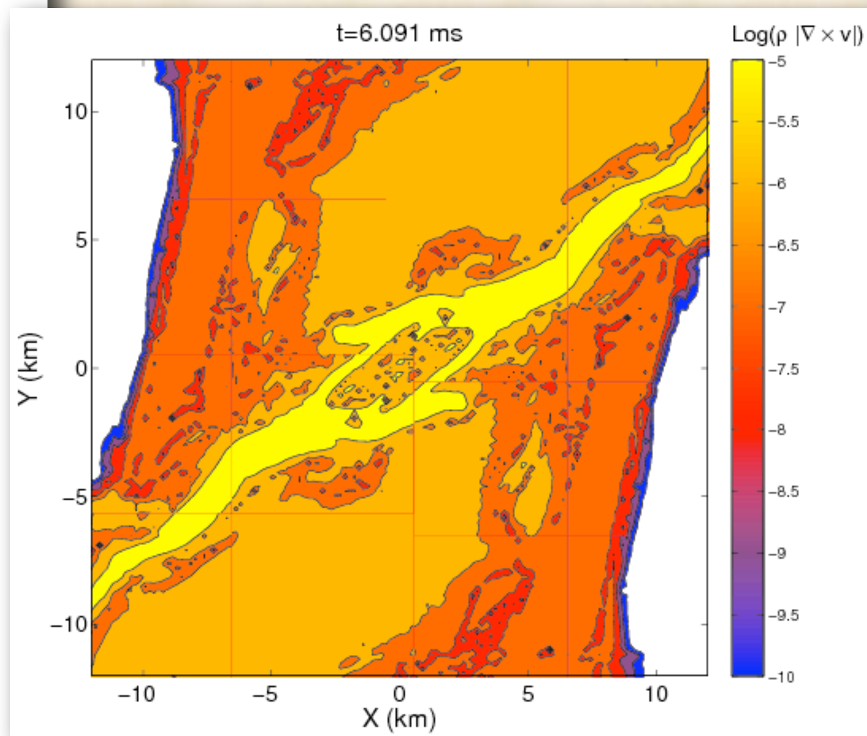

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- Hydrodynamic instabilities coupled with magnetic fields can make these objects sources of short gamma-ray bursts (work in progress...)

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- Our main interest is to study these objects as possible sources of short-GRB and magnetars and extract gws