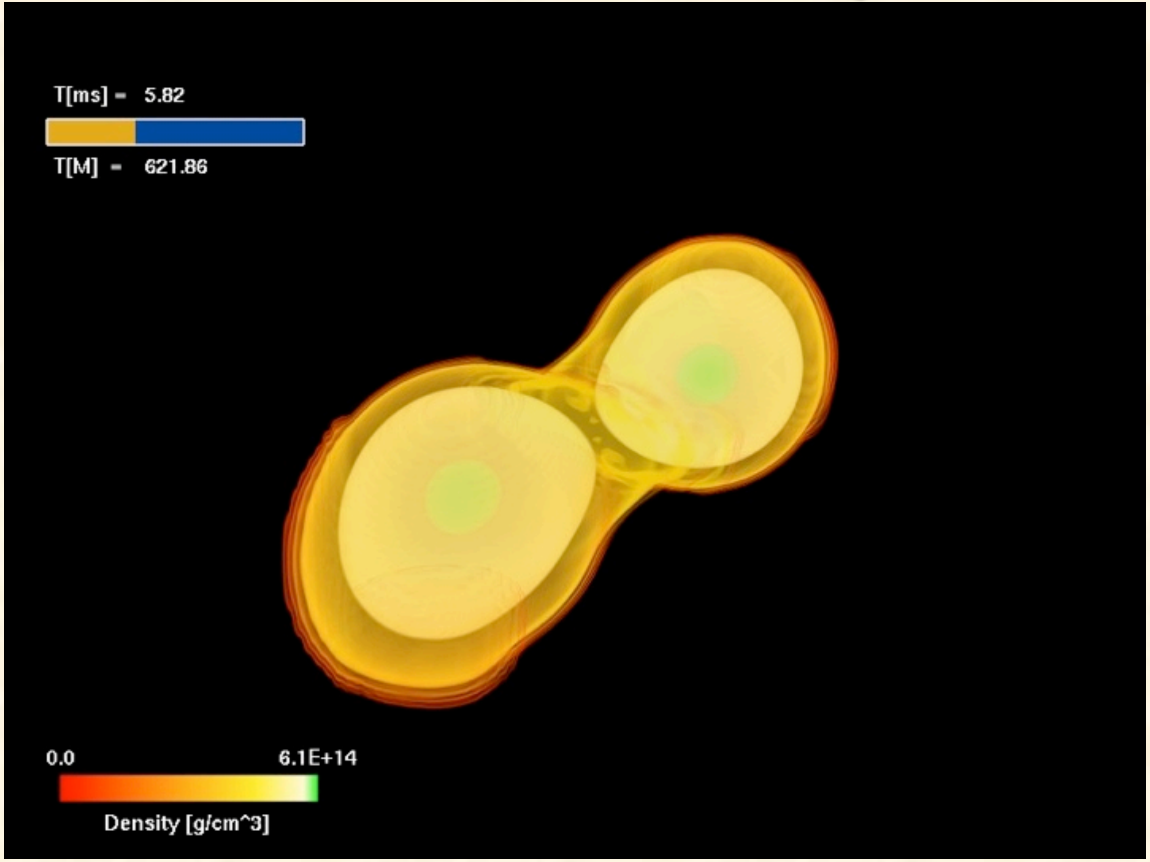
GR Simulations of Binary NSs: GWs and matter dynamics



Bruno Giacomazzo

Albert Einstein Institute, Potsdam, Germany

Plan of the talk

- Introduction

- GWs from unmagnetized binary neutron stars
  - The role of the mass and of the EOS
  - Torus formation and properties

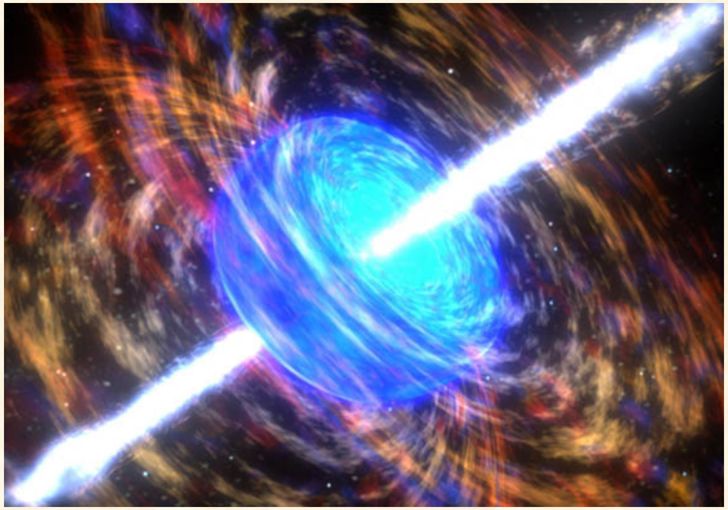
- GWs from magnetized binaries
  - Detectability of magnetic fields
  - Hydrodynamic instabilities and magnetic field evolution

- Summary and conclusions

Why so interesting?

Due to their duration and dynamics, Binary Neutron Stars are very good sources for gravitational wave detectors such as Virgo (Italy) and Ligo (USA)

Virgo (Pisa, Italy)



Credit: NASA/SkyWorks Digital

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

Numerical Relativity at the AEI

Cactus (**www.cactuscode.org**) is a computational "toolkit" developed at the AEI/CCT/LSU over the last 10 years and provides a general infrastructure for the solution in 3D and on parallel computers of PDEs in general and of the Einstein equations in particular.

Whisky (**www.whiskycode.org**) is a more recent code, developed at the AEI and SISSA, for the solution of the general relativistic hydrodynamics and magnetohydrodynamics equations in arbitrary curved spacetimes.

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 ideal MHD equations on dynamical curved background
  - Uses HRSC (High Resolution Shock Capturing) methods
  - Can handle BH formation without Excision
  - Implements the Method of Lines
  - Adopts Adaptive Mesh Refinement techniques (Carpet)
  - Implements the Constrained Transport and Hyperbolic Divergence Cleaning schemes

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

Simulations done at the AEI with Whisky

- Neutron star oscillations: linear/nonlinear; magnetized/not

  Baiotti, Giacomazzo, Rezzolla

- Dynamical (barmode) instability

  Baiotti, De Pietri, Manca, Rezzolla

- Binary neutron stars

  Baiotti, Giacomazzo, Link, Rezzolla

- Mixed Binary systems

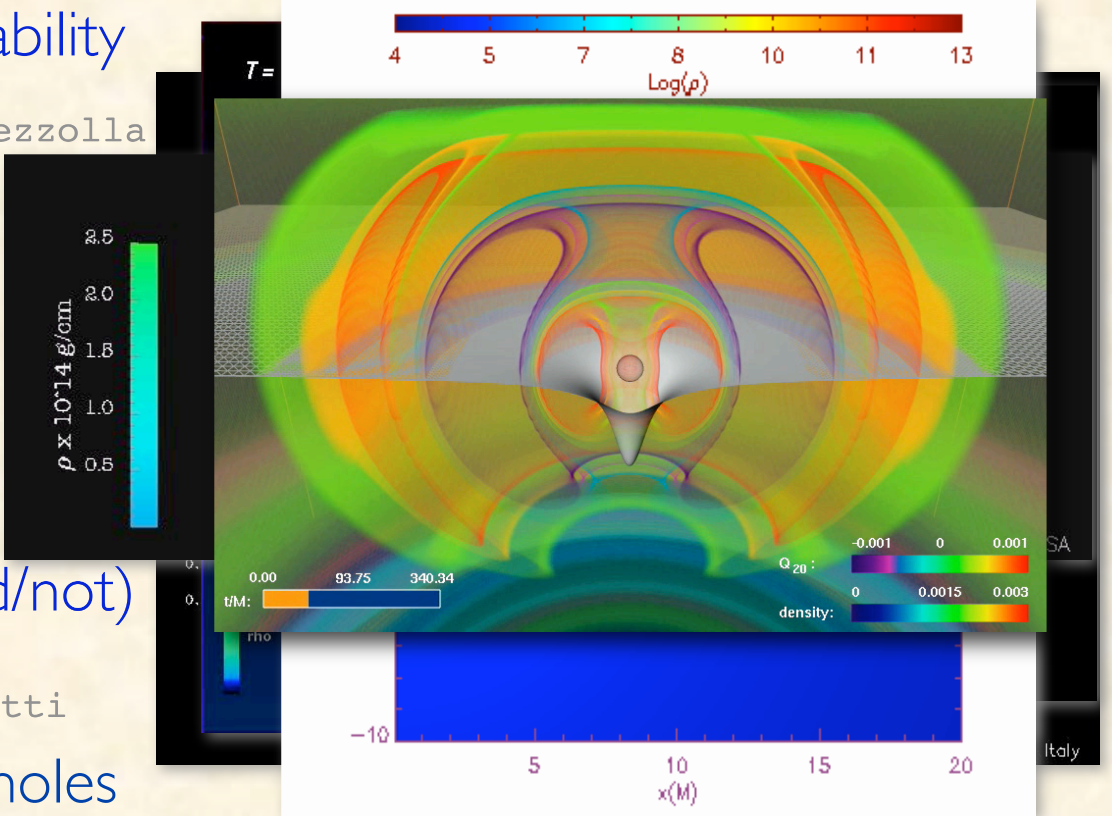
  Ansorg, Giacomazzo, Loeffler, Rezzolla, Tonita

- Accretion torii (magnetized/not)

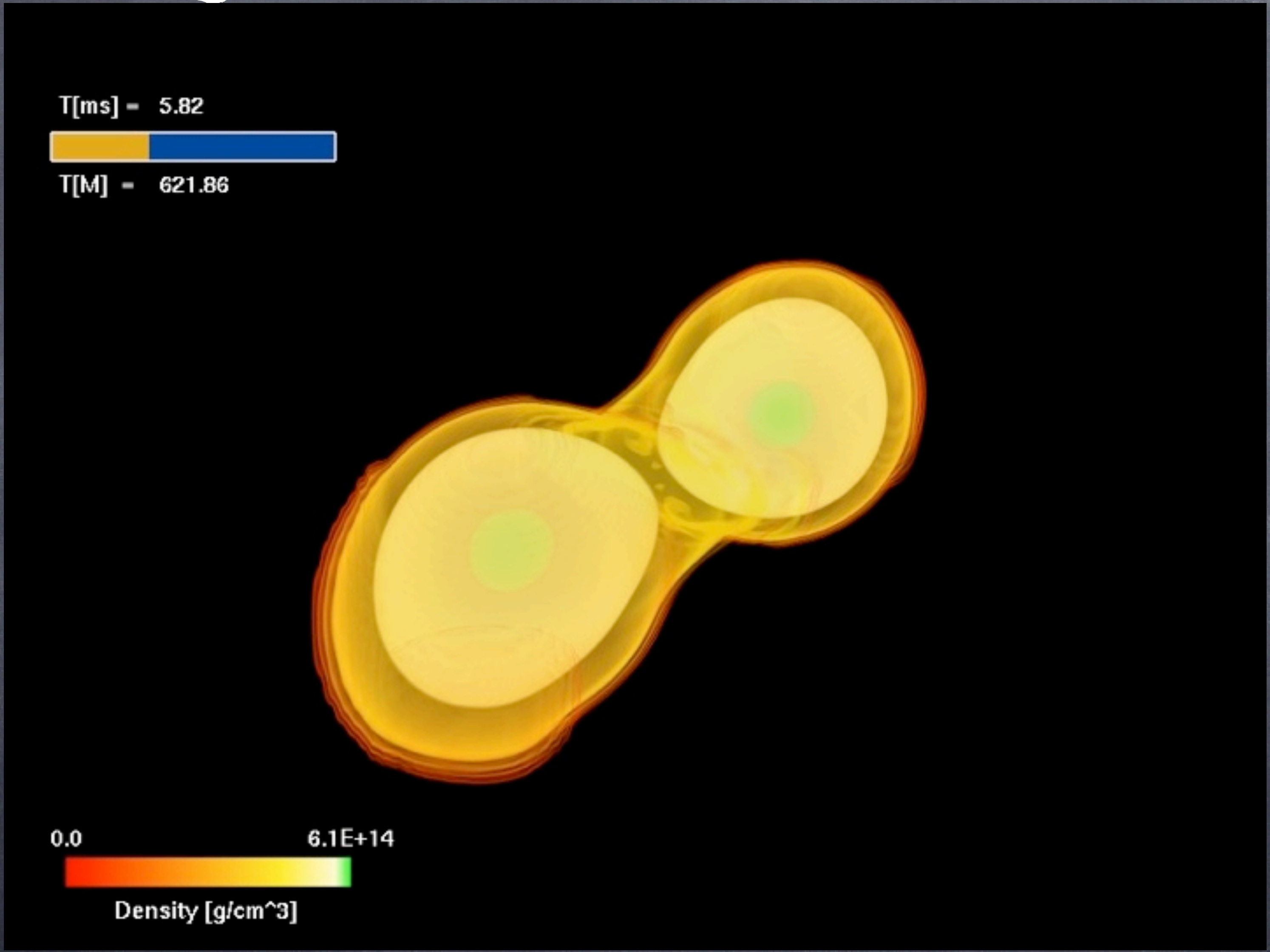
  Font, Montero, Rezzolla, Zanotti

- Rotating collapse to black holes

  Baiotti, Giacomazzo, Hawke, Rezzolla, Schnetter, Stergioulas



Binary Neutron Stars Mergers



- Baiotti, Giacomazzo, Rezzolla 2008, PRD 78, 084033
- Baiotti, Giacomazzo, Rezzolla 2009, CQG 26, 114005

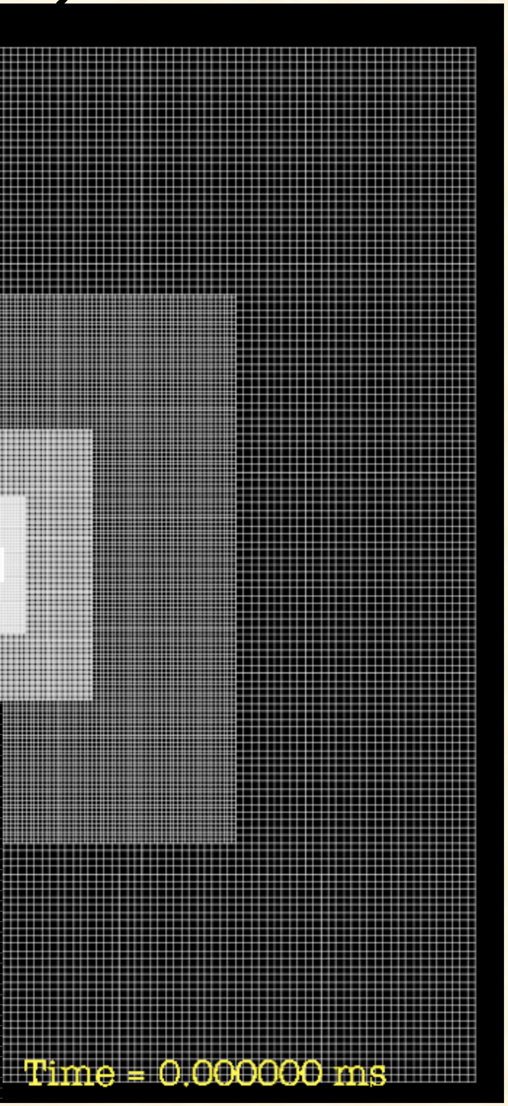
Initial Models

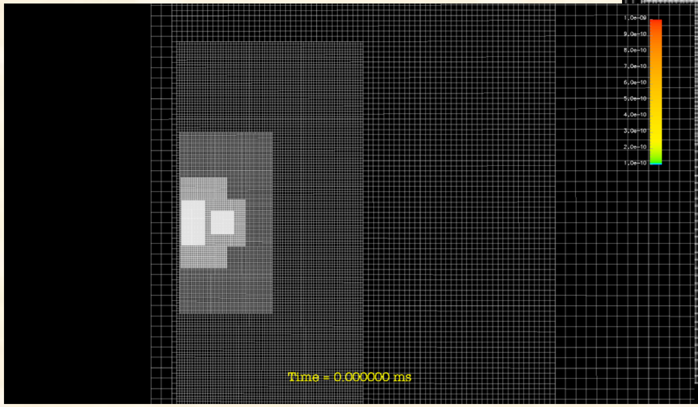
All the initial models are computed using the Lorene code for unmagnetized binary NSs (Bonazzola et al. 1999):

Model	M1,M2	d (km)
low-mass	1.45	45
high-mass	1.62	45

Technical data for the simulations:

- polytropic or ideal-fluid EOS
- outer boundary: ~370 km
- 8 refinement levels; res. of finest level: ~0.2km
- PPM for the reconstruction
- Marquina flux formula
- Runge Kutta (3rd-order)





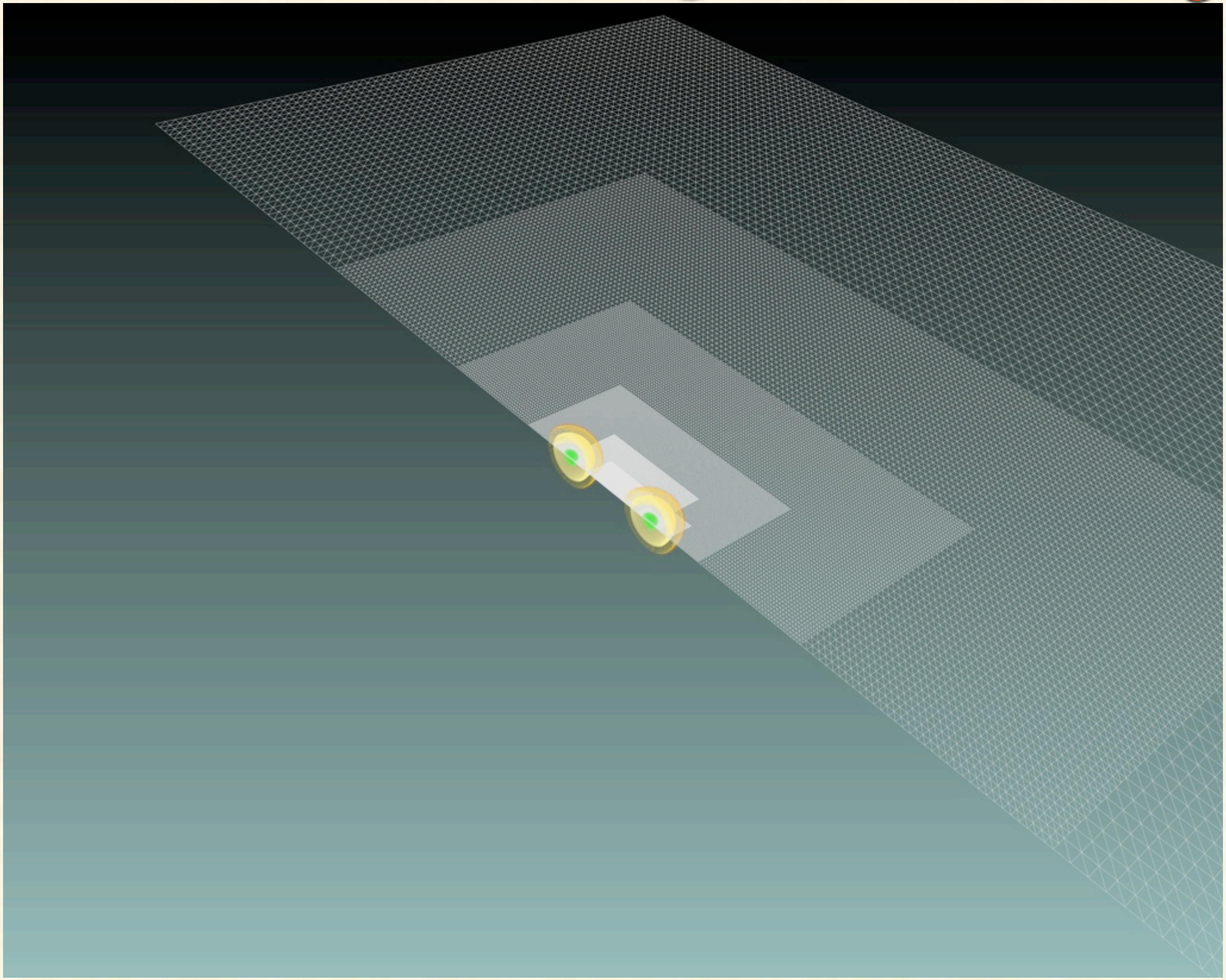
Equation of State

We used in our simulations a cold or a hot EOS:

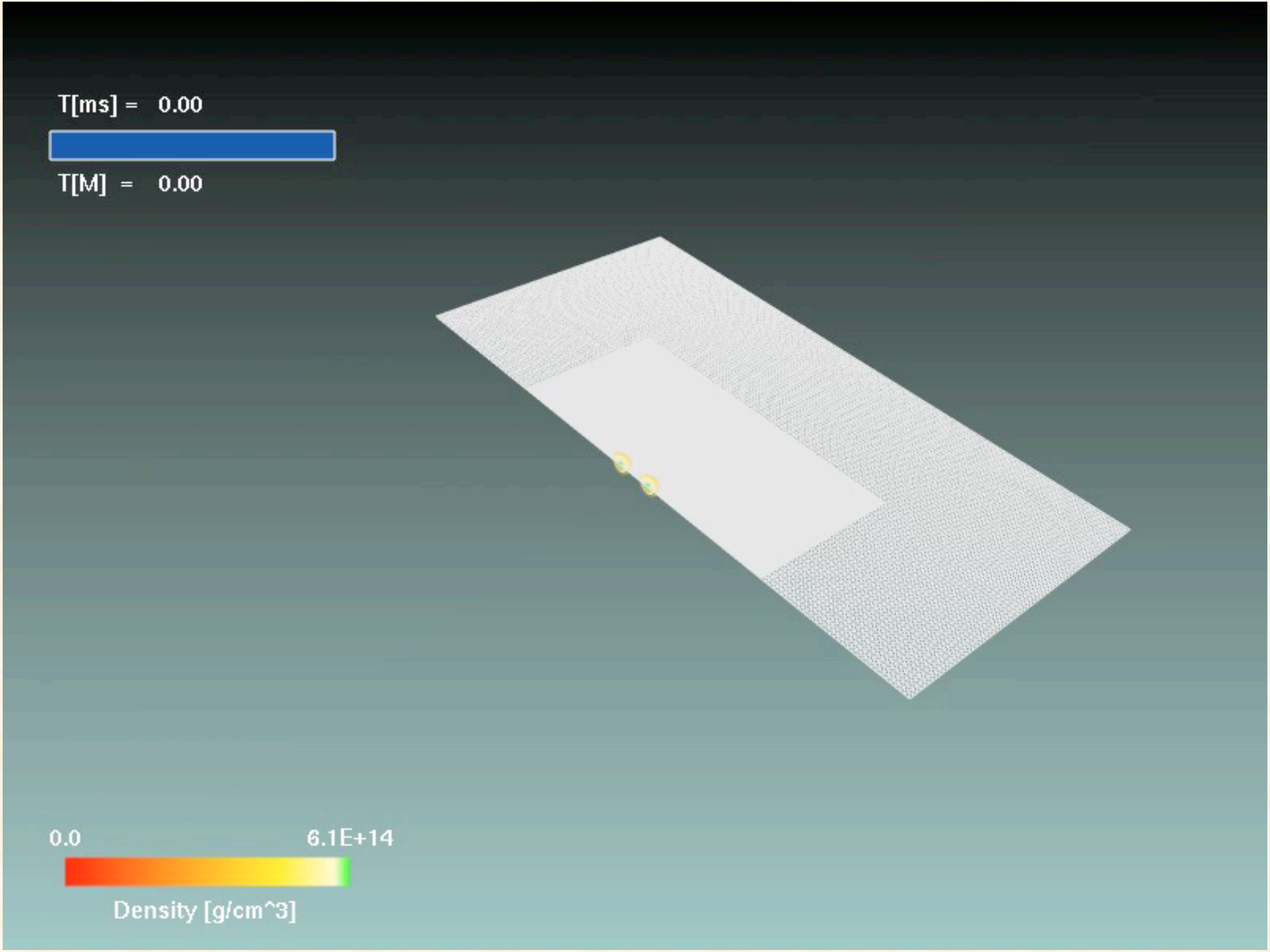
- Cold EOS: we considered a simple polytropic EOS $P = \kappa\rho^\Gamma$
- Hot EOS: we used an ideal fluid EOS $P = \rho\epsilon(\Gamma - 1)$

The polytropic EOS doesn't allow for shock heating. It can be a good simple approximation for the inspiral phase, but it is unrealistic for the post-merger phase.

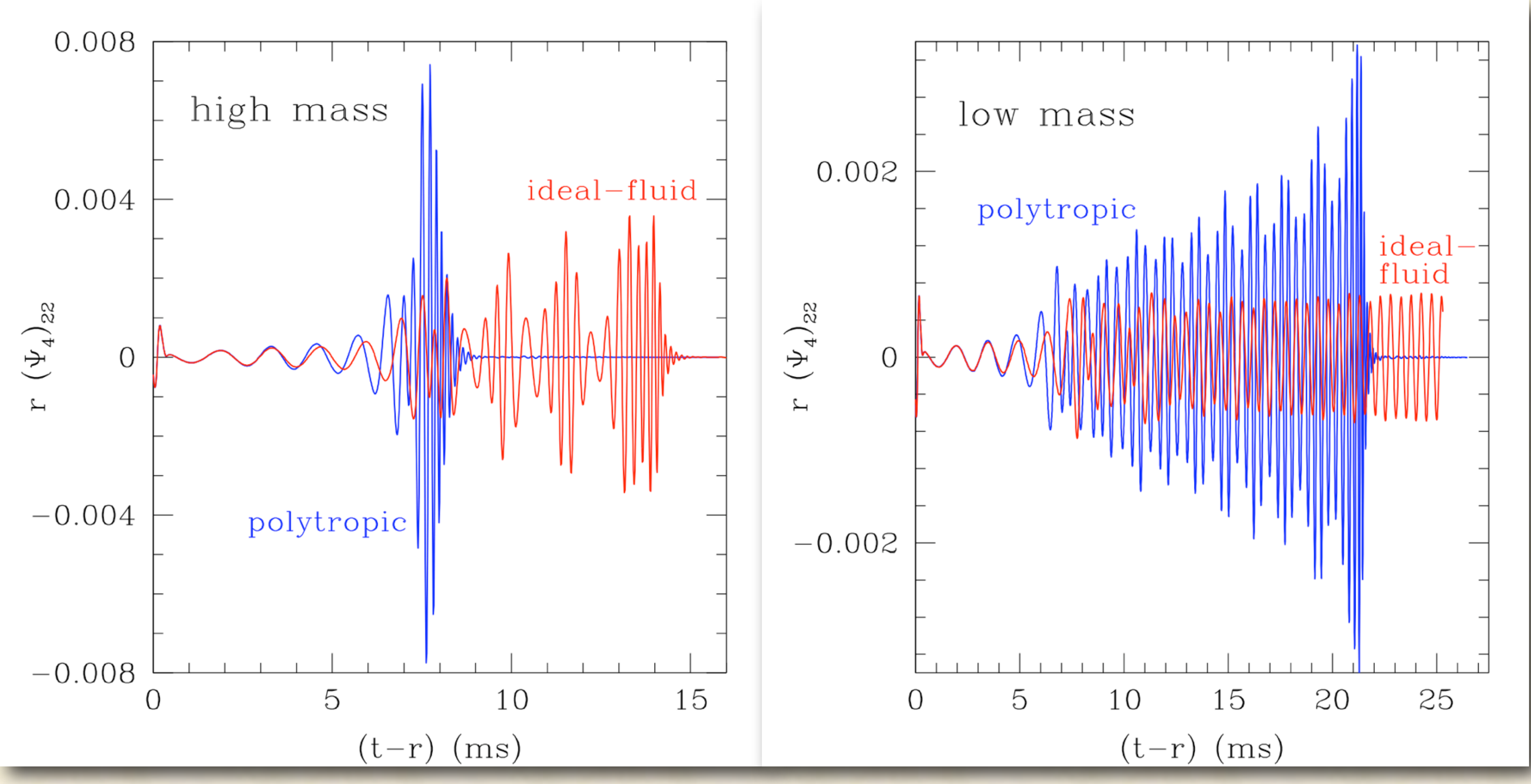
Ideal Fluid EOS: high-mass binary



Visualization by Giacomazzo, Kaehler, Rezzolla


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

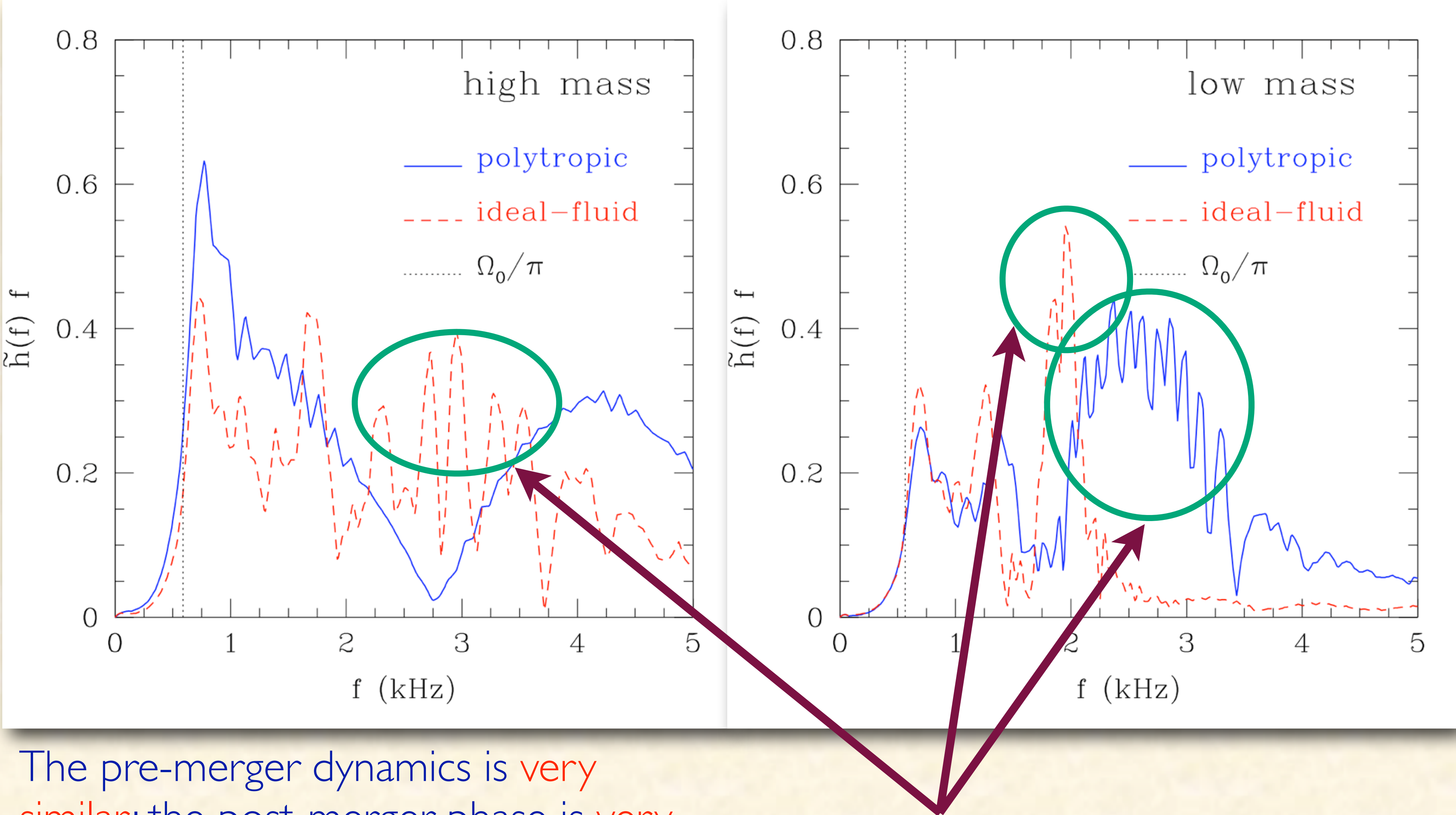
GWs from unmagnetized binaries



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

GWs from unmagnetized binaries



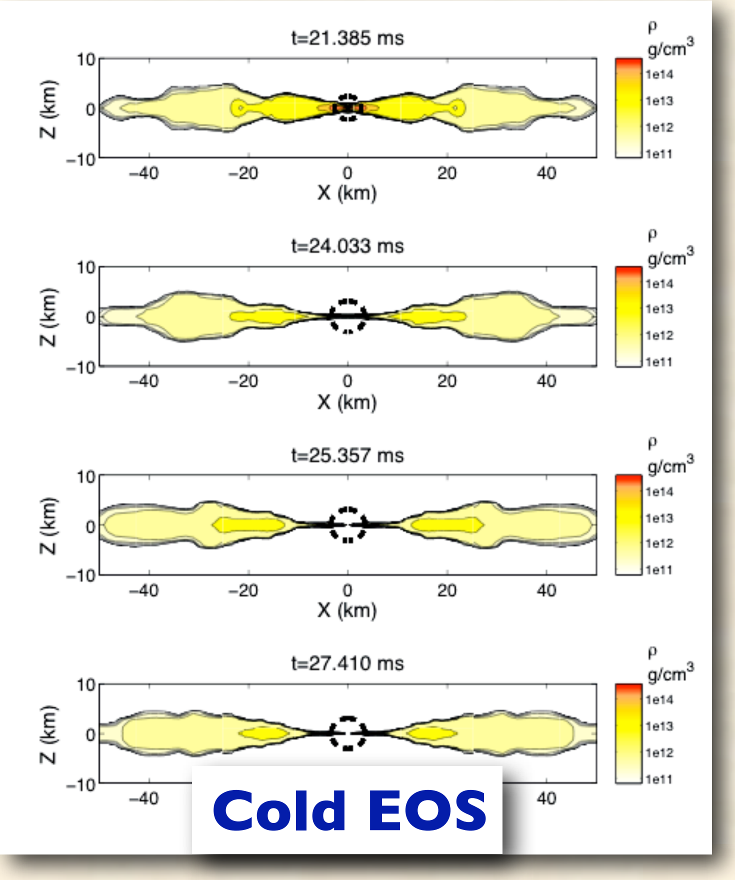
The pre-merger dynamics is very similar; the post-merger phase is very different

Contributions from the bar-deformed HMNS

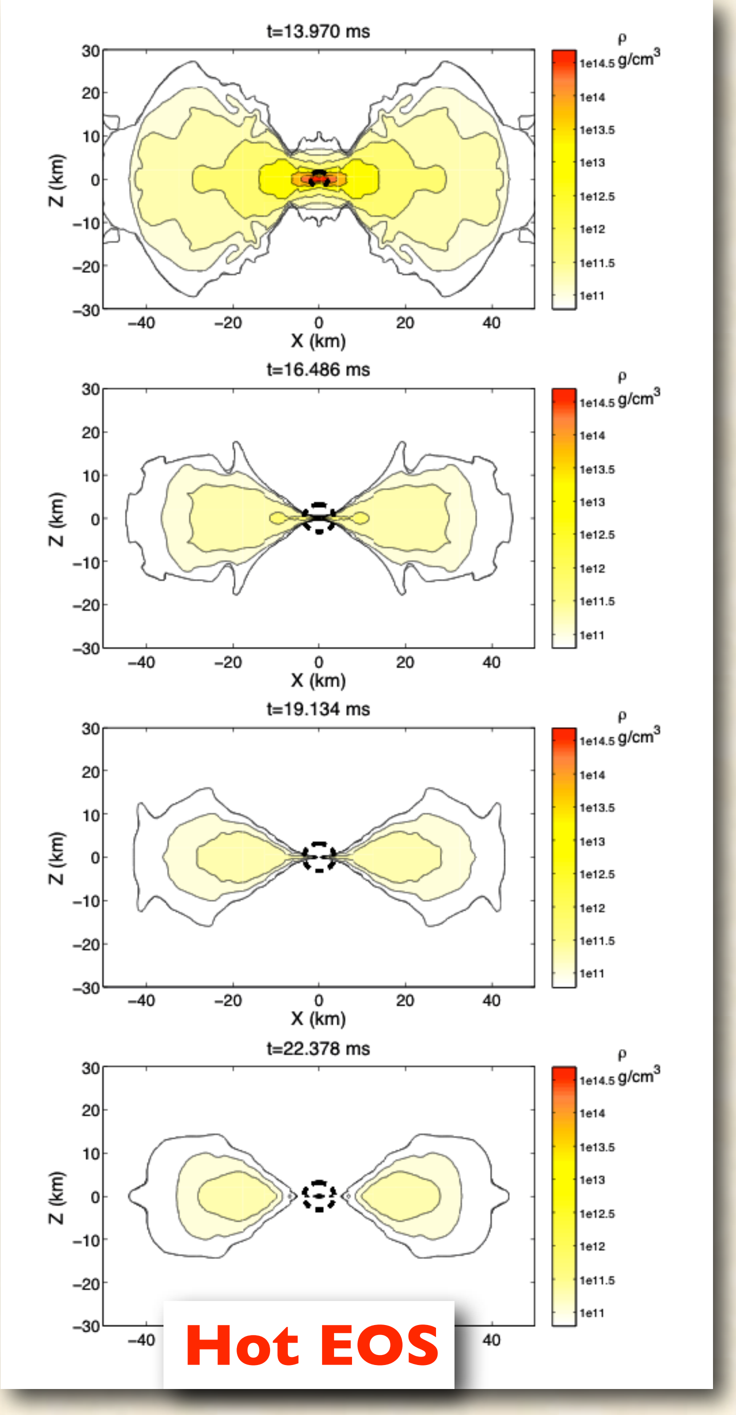
Binary Neutron Stars:
Torus properties

(Link, Rezzolla, Baiotti, Giacomazzo 2009, in preparation)

Torus: ideal-fluid vs polytropic EOS



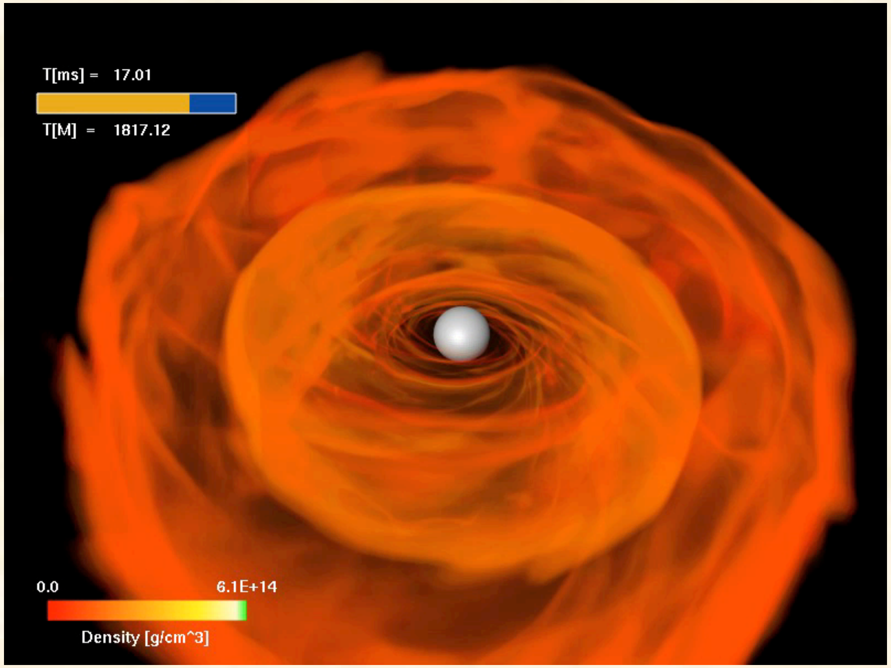
Cold EOS



Hot EOS

The increased internal energy (temperature) via shocks "puffs up" the torus for a hot EOS. This can help in the collimation of a jet within a short GRB scenario

Mass of the Torus and of the BH (equal-mass case)



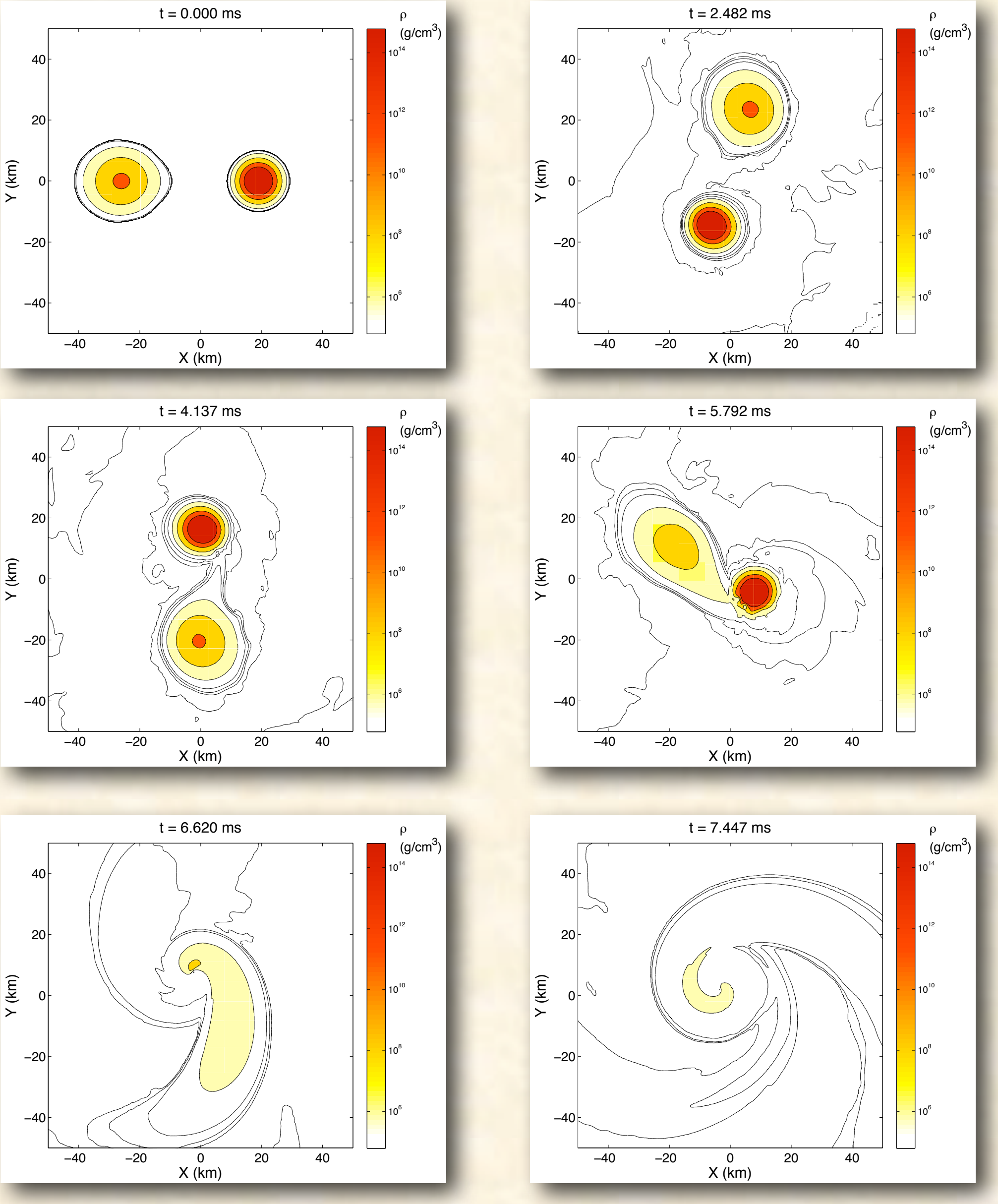
The torus undergoes initial rapid accretion but then settles to be:

Average mass: $<0.1\ M_\odot$
Average size (z-x): 20-40 km
Average density: $\sim 10^{11}$-10^{12} g/cm^3
Average temperature: $\sim 10^{11}$K

BH parameters:
Mass: 2.9 (high-mass case)
J/M^2: 0.8

Torus properties: unequal-mass case

(with David Link)



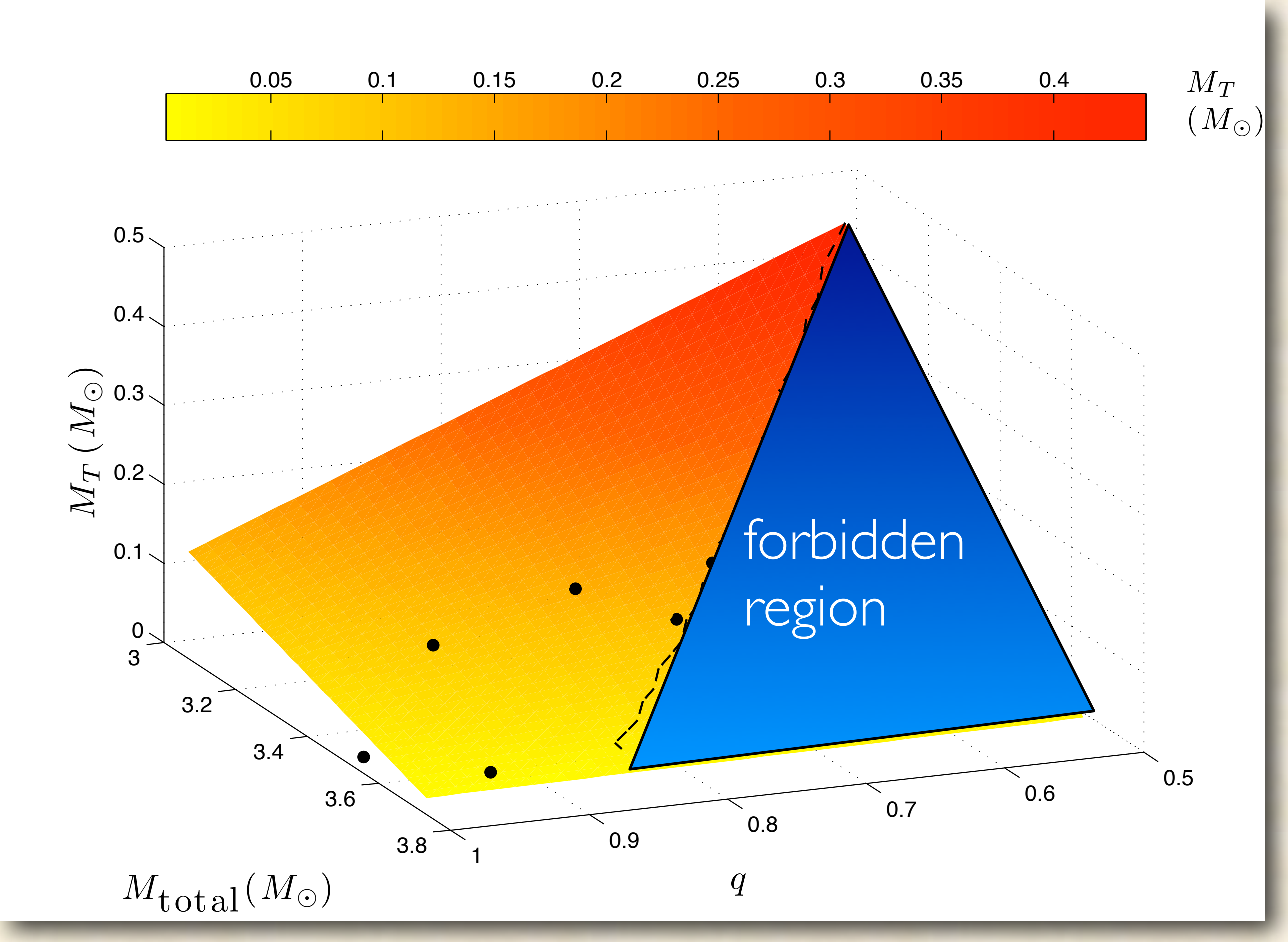
If the masses are not equal the dynamics is somewhat different.

The lower-mass star is larger in size (less compact) and is disrupted by the higher-mass (more compact) one.

As a result a larger and more massive torus can be produced.

Torus properties: unequal-mass case

(with David Link)



A systematic investigation shows that: the torus mass increases with the mass ratio and decreases with the total mass

$$M_T(q, M_{\rm total}) = (1-q)\,(M_{\rm max} - M_{\rm total})$$

GWs from Binary Neutron Stars: The Role of Magnetic Fields

(Giacomazzo, Rezzolla, Baiotti 2009, arXiv:0901.2722)

Previous Works

In Newtonian Physics (SPH)

- Price and Rosswog 2006, *SCIENCE* 312, 719
  - studied the mf amplification after the merger
  - initial mf $B \sim 10^{12}$ Gauss

Fully General Relativistic Simulations:

- Anderson et al. 2008, PRL 100, 191101
  - adaptive mesh refinement used
  - initial data built by hand
  - not able to follow the BH formation
  - initial mf $B \sim 10^{16}$ Gauss (**strong effects** in the waves)
- Liu et al 2008, PRD 78, 024012
  - 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 mf $B \sim 10^{16}$ Gauss (**weak effects** in the waves)

Adding Magnetic Fields

We have considered the same high-mass and low-mass models discussed in the unmagnetized case when an initially poloidal magnetic field is introduced.

The magnetic field is added by hand using the following vector potential:

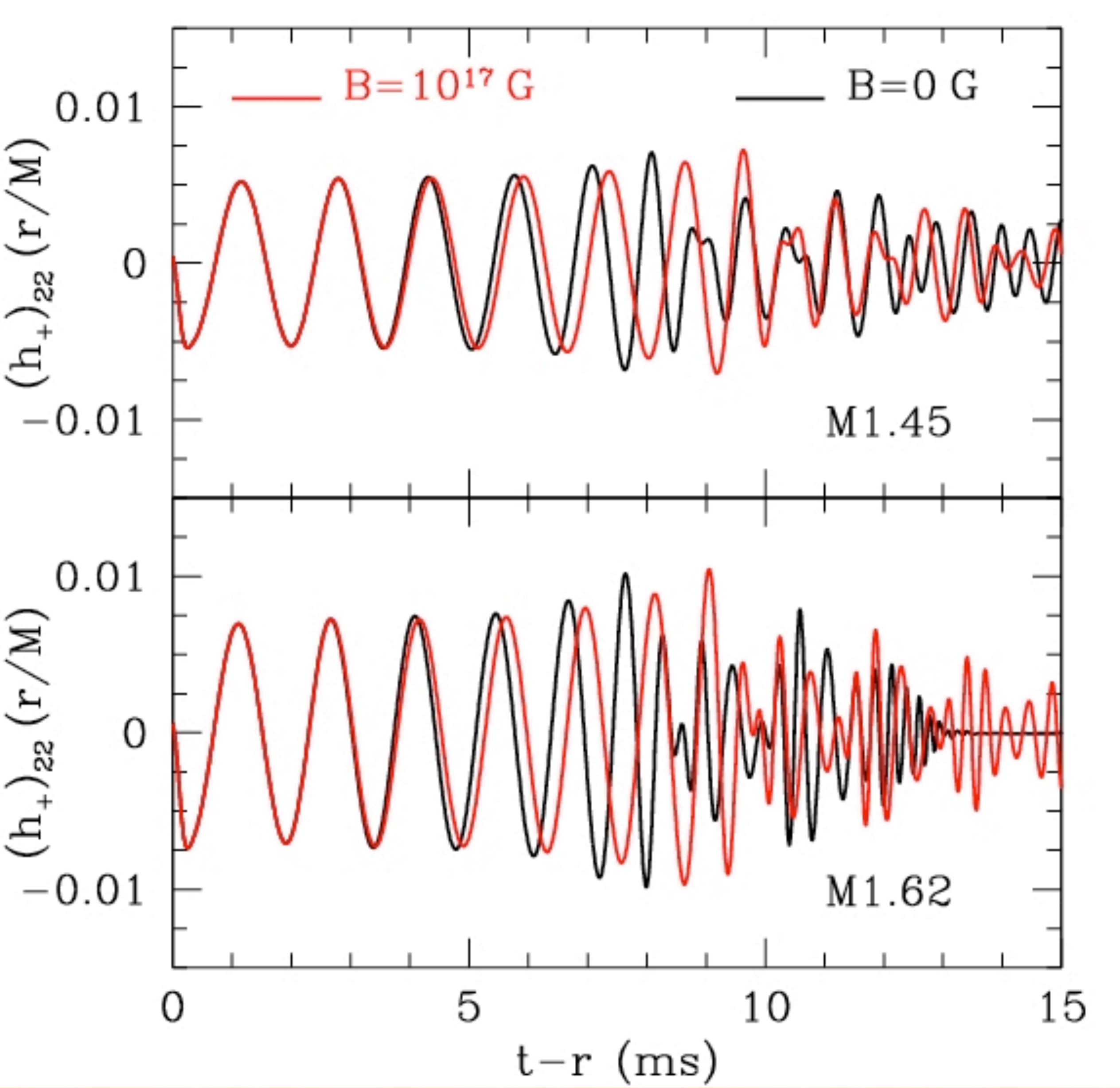
$$A_\phi = A_b r^2 [\max(P - P_{cut}, 0)]^n$$

where A_b and $P_{cut} = 0.04 \times \max(P)$ are two constants defining respectively the strength and the extension of the mf inside the star. n=2 defines the profile of the initial mf.

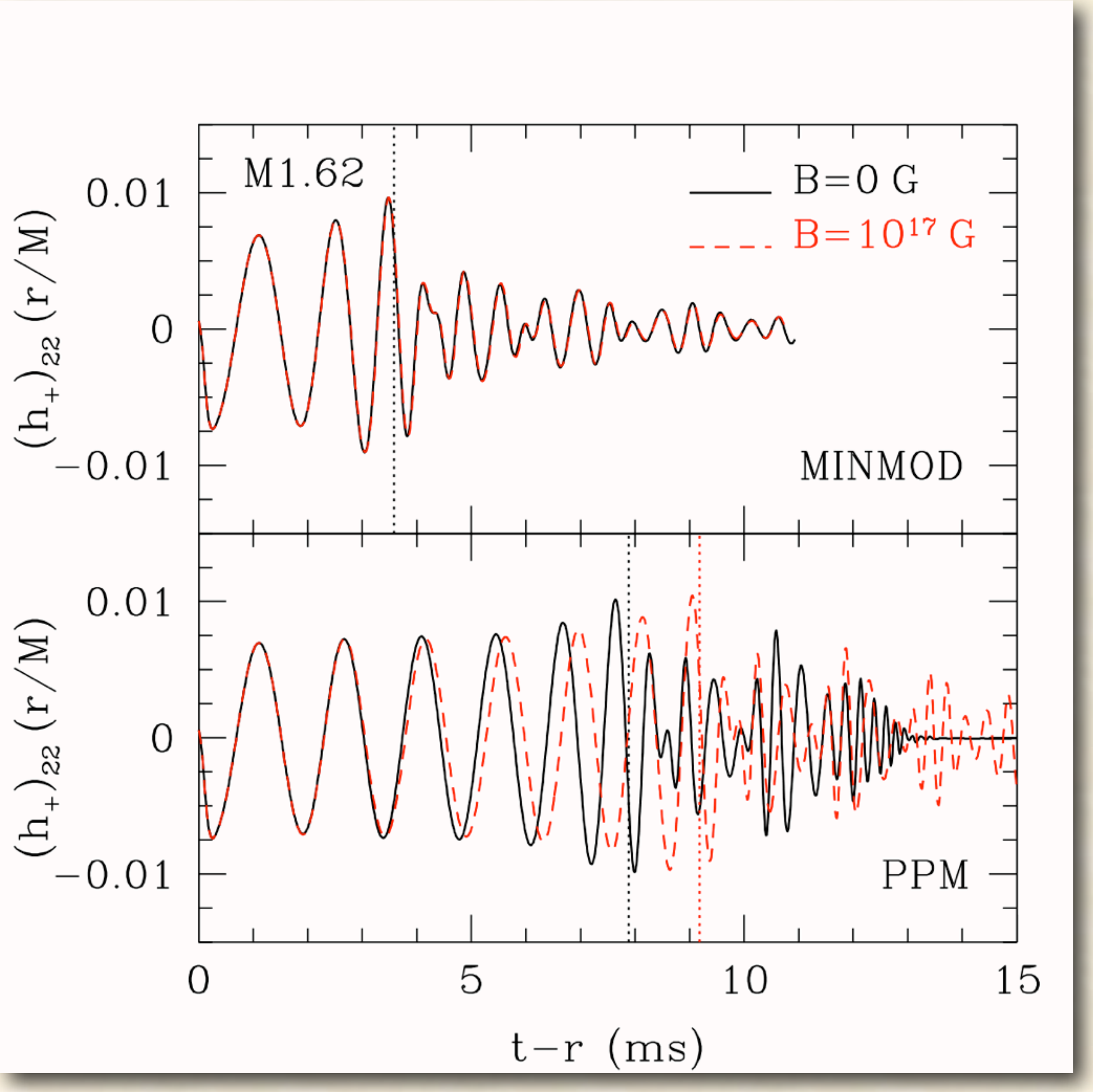
The initial magnetic field is contained inside the star
We have considered initial magnetic fields from 10^{12} to 10^{17} Gauss
In these simulations only the ideal fluid EOS was used

Comparing with the unmagnetized cases

An initial magnetic field of 10^{17} Gauss lead to very different waveforms both in the low-mass and in the high-mass case.



Extreme care is needed!



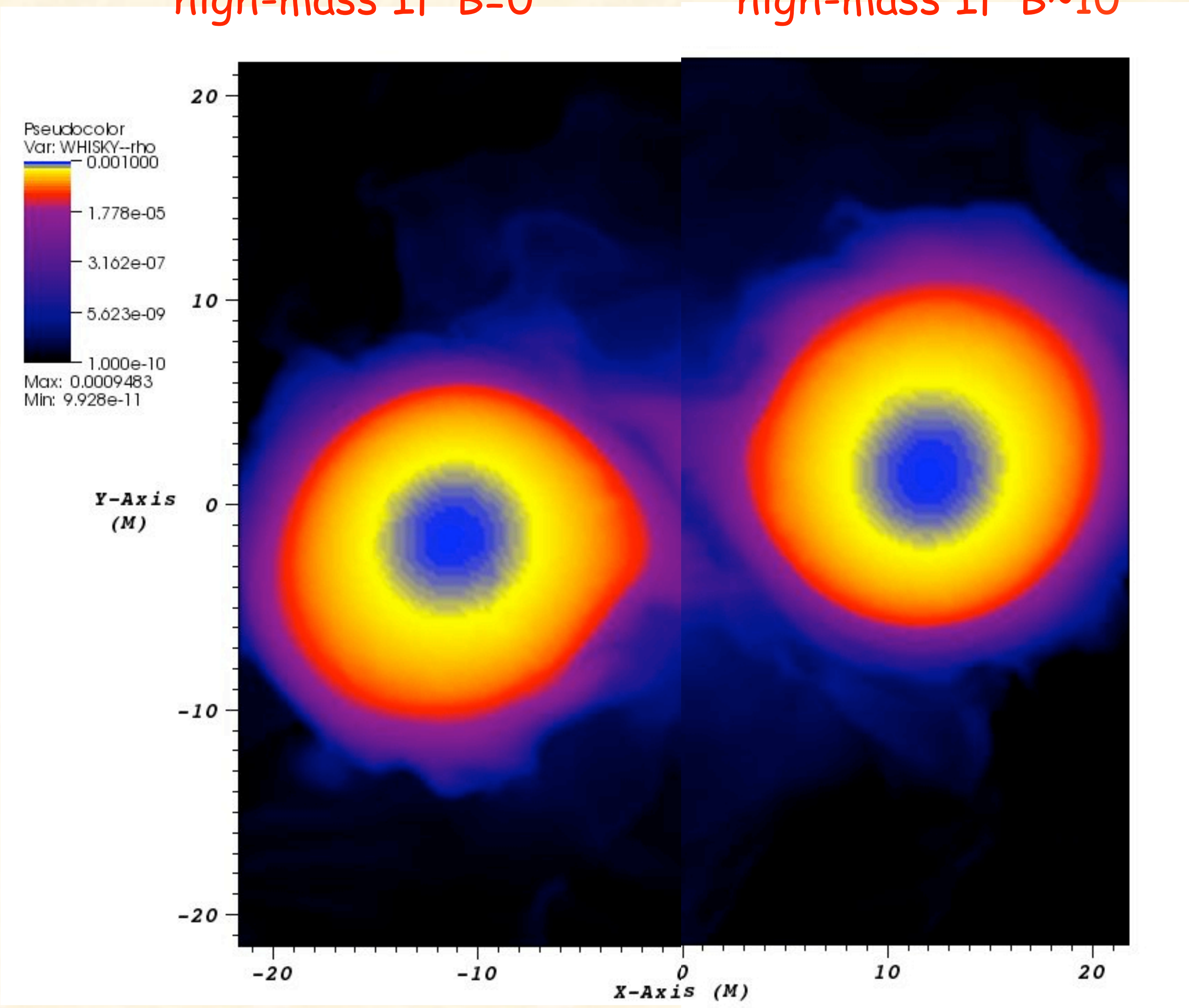
Top panel: results obtained using HLLE Riemann solver and a **"minmod"** reconstruction (2nd-order) similar to Liu et al. 2008 (MC).

Bottom panel: results obtained using HLLE Riemann solver and **PPM** reconstruction (3rd-order) as in Anderson et al. 2008.

For sufficiently large MFs changes can be detected even in the inspiral!

MHD effects during the inspiral

high-mass IF B=0 high-mass IF B~10^{17}



The magnetic field has an effect on the tidal deformations and then on the inspiral

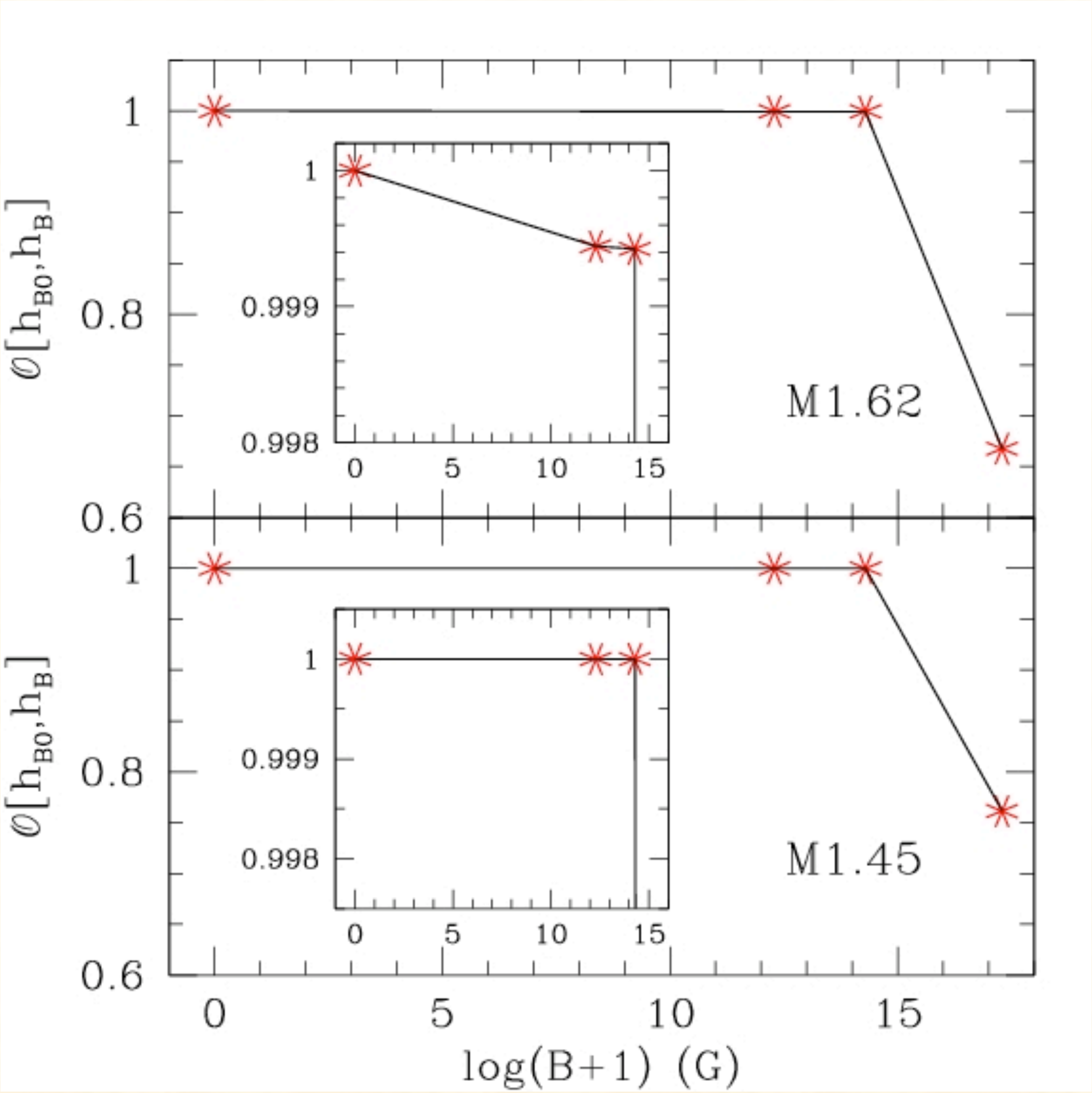
Computing the mf effect during the inspiral

We have computed the overlap between the different waveforms:

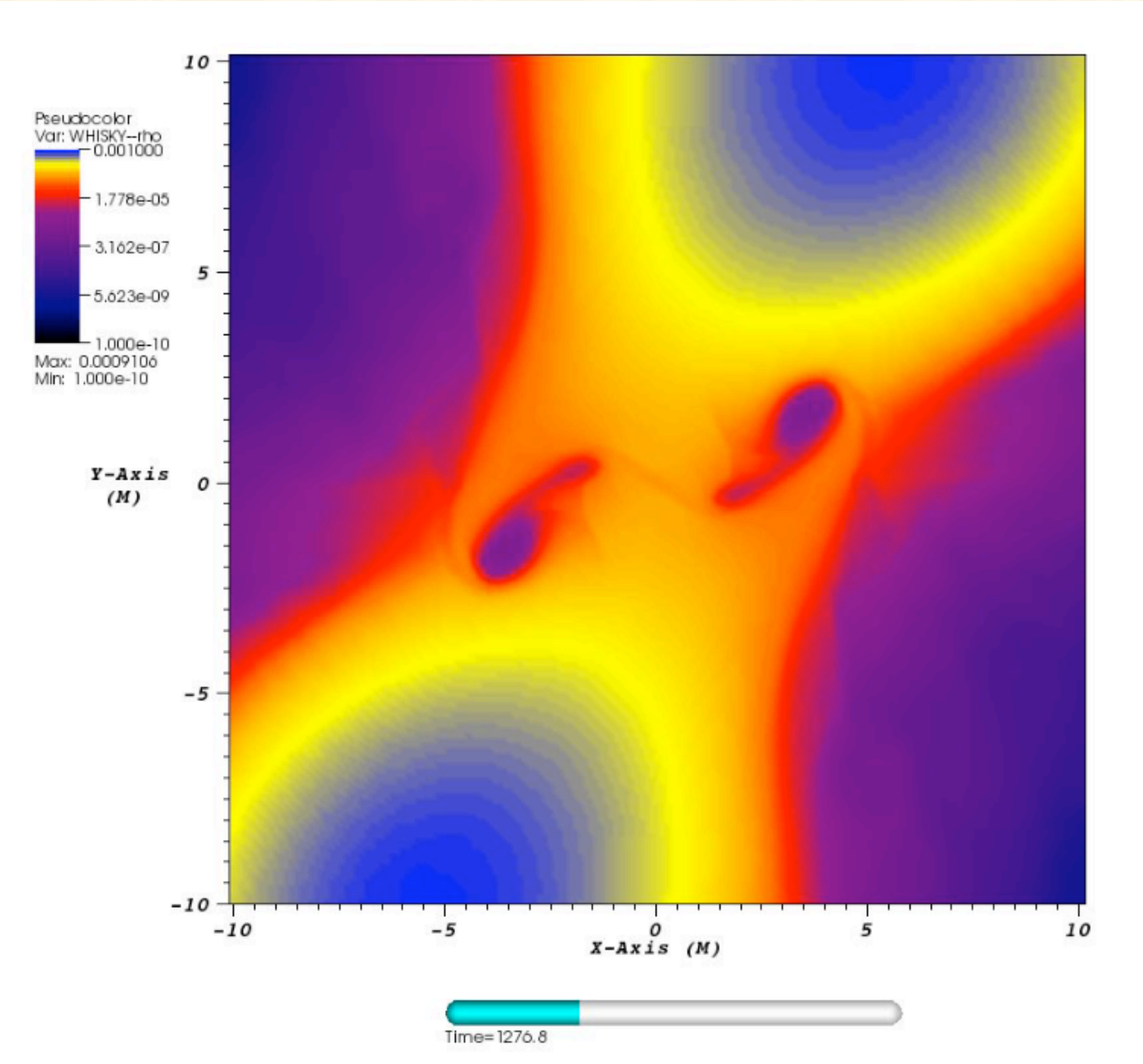
$$\mathcal{O}[h_{B1},h_{B2}] \equiv \frac{\langle h_{B1}|h_{B2}\rangle}{\sqrt{\langle h_{B1}|h_{B1}\rangle\langle h_{B2}|h_{B2}\rangle}}$$

$$\langle h_{B1}|h_{B2}\rangle \equiv 4\Re\int_0^\infty df\,\frac{\tilde{h}_{B1}(f)\tilde{h}^*_{B2}(f)}{S_h(f)}$$

Effects in the inspiral can be detected only for very large unrealistic magnetic fields

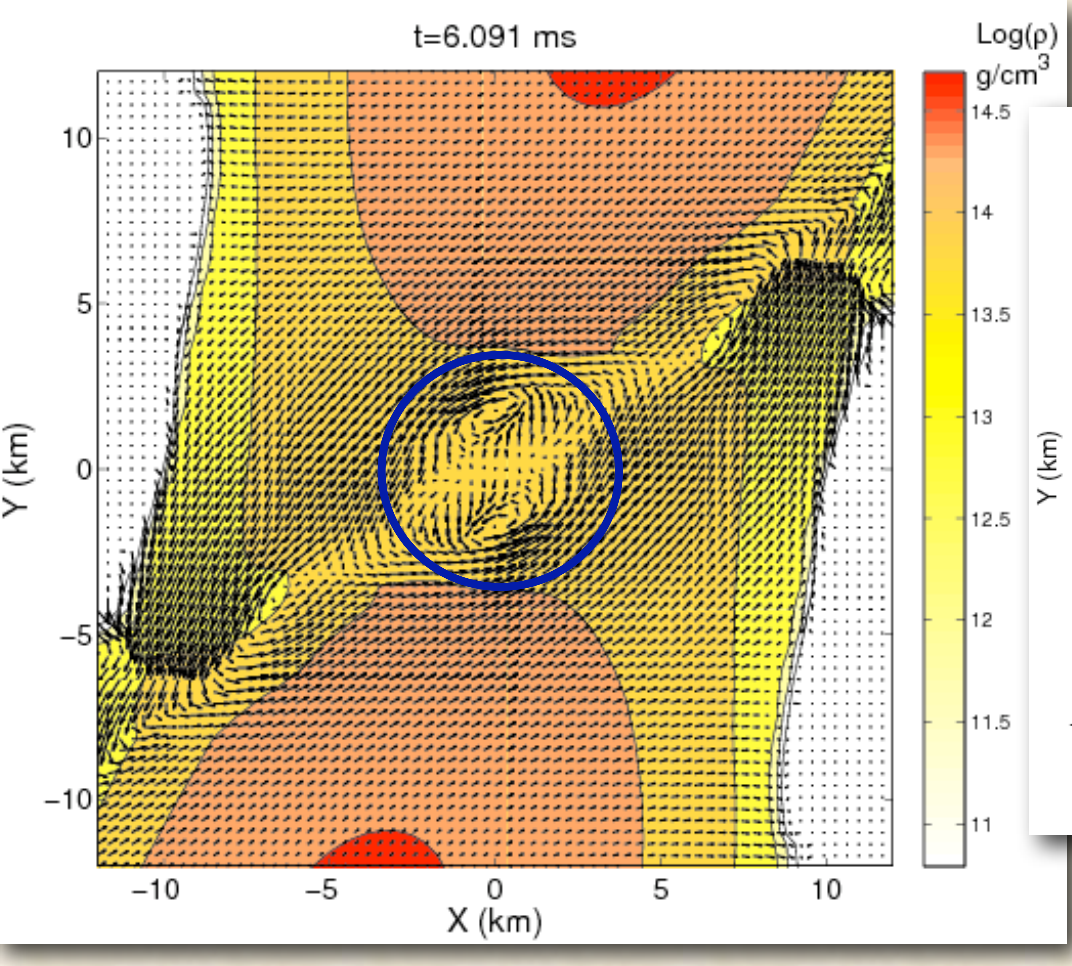


Binary Neutron Stars:
HD instabilities and Magnetic field evolution



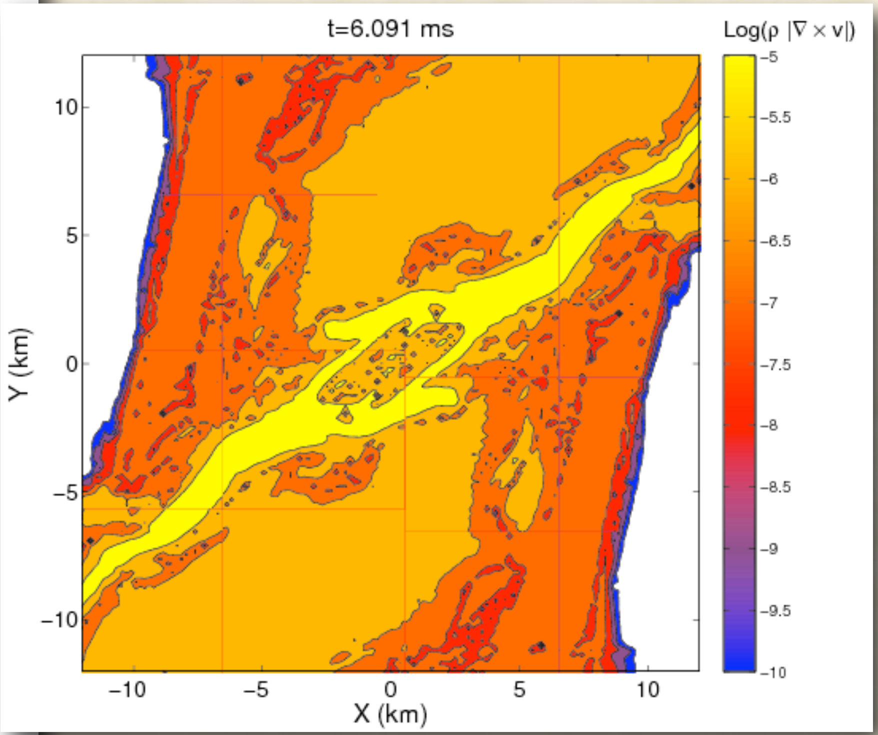
KH instability: high-mass binary

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.

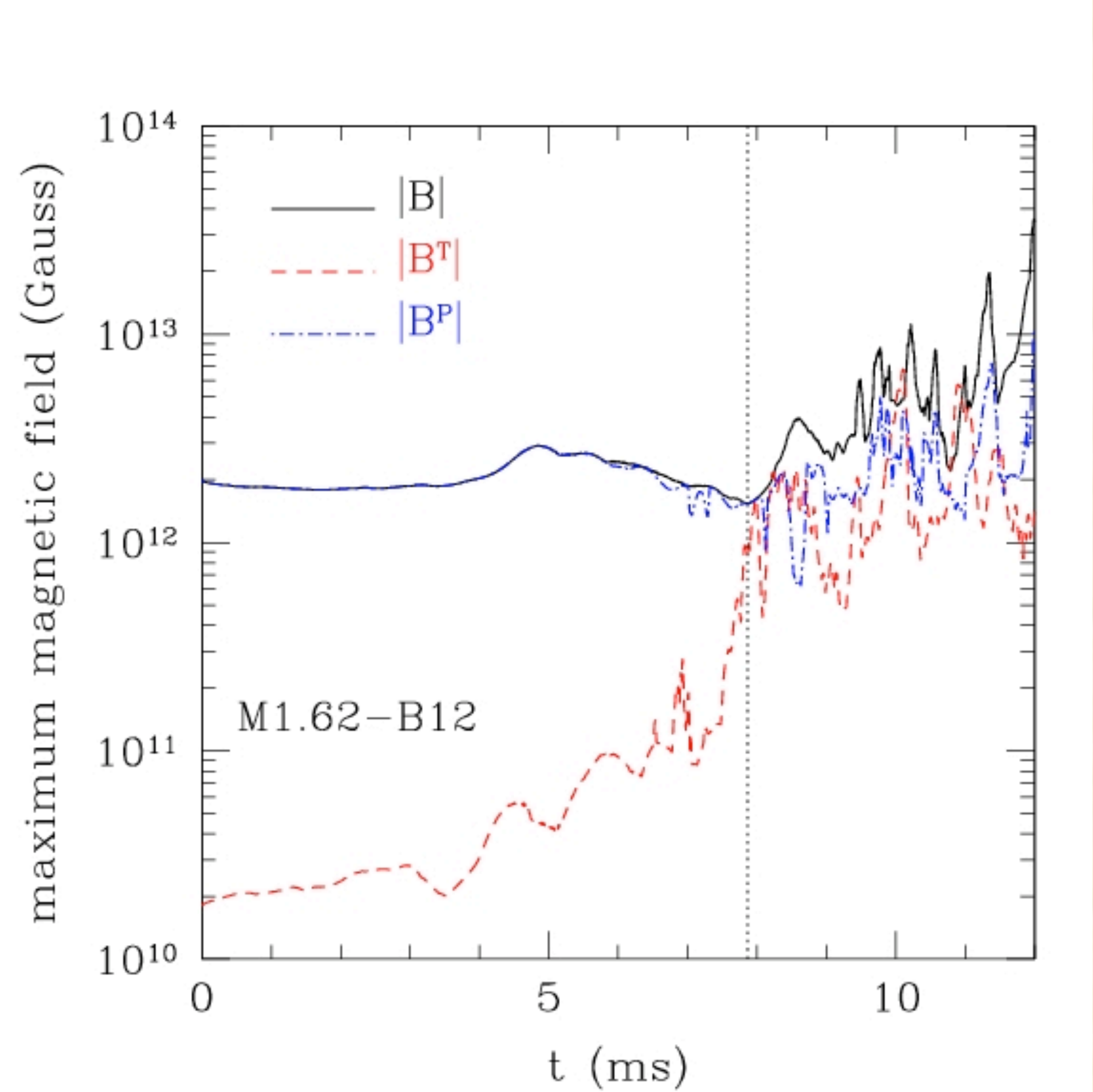


$$\rho|\nabla \times v|^z$$

Effects of Instabilities at the merger

At the merger the toroidal component of the magnetic field grows exponentially of ~1 order of magnitude.

First time that this effect is shown in full General Relativity!



Summary

- Able to perform long and stable simulations of all the phases of BNS inspiral, merger, collapse and torus evolution

- Able to extract the full gw signal (inspiral, merger and ring-down)

- Effects of the magnetic fields in the inspiral are clearly visible in the gws only for high and unrealistic magnetic fields (very important to use high-order reconstruction)

- Effects of more realistic magnetic fields probably detectable only after the merger and on high frequencies (f>1kHz)

- Shown the role that hydrodynamic instabilities have on the amplification of the magnetic field during the merger

- Currently investigating the evolution of HMNS, magnetized tori and jet formation formed after the merger of BNS with magnetic fields from 10^8 to 10^{12} Gauss

Future directions

We are currently working to add to Whisky:

- neutrino emission (in collaboration with F. Galeazzi)
- more realistic EOSs (in collaboration with G. Corvino)
- resistive MHD (in collaboration with C. Palenzuela)

For movies and pictures about BNS and BBH merger simulations:

http://numrel.aei.mpg.de/Visualisations/index.html