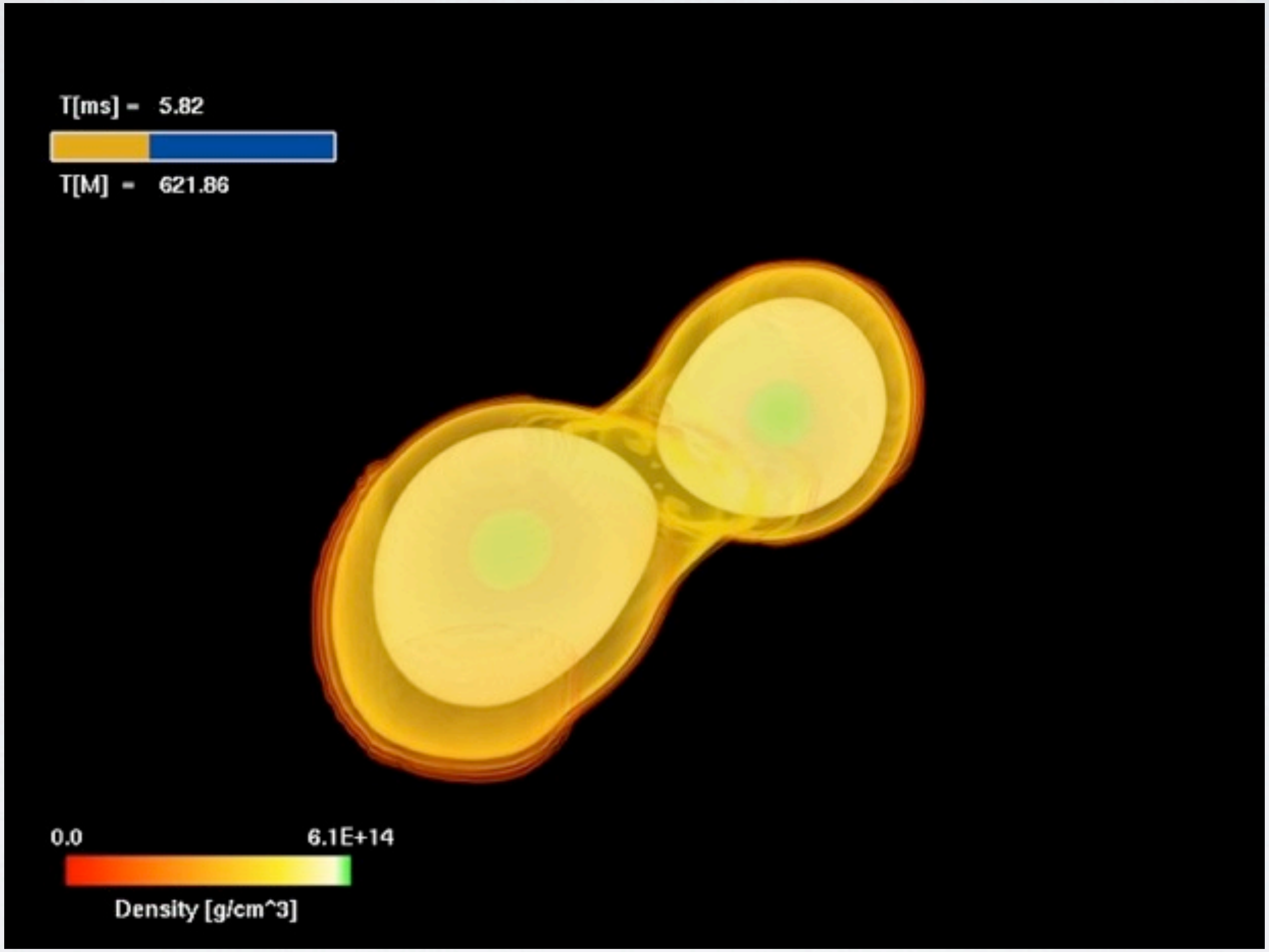
MAGNETIZED BINARY NEUTRON STAR MERGERS



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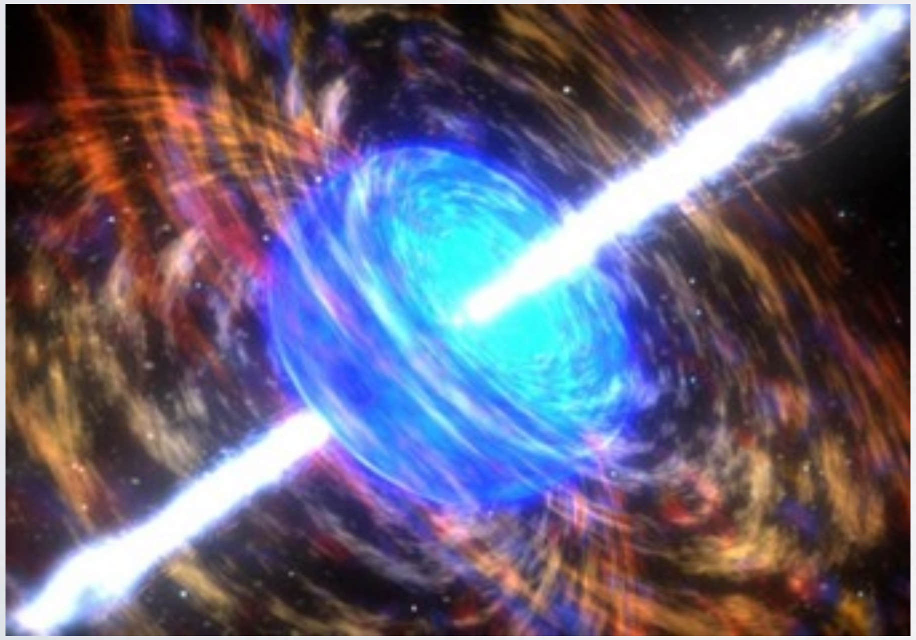
PLAN OF THE TALK

- Introduction
- Magnetized Binary Neutron Star Mergers
  - detectability of magnetic field in the GW signal
  - Hydrodynamic instabilities and magnetic field amplification
  - Jet formation? (work in progress)
- 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

To study these sources we use our fully GRMHD code Whisky

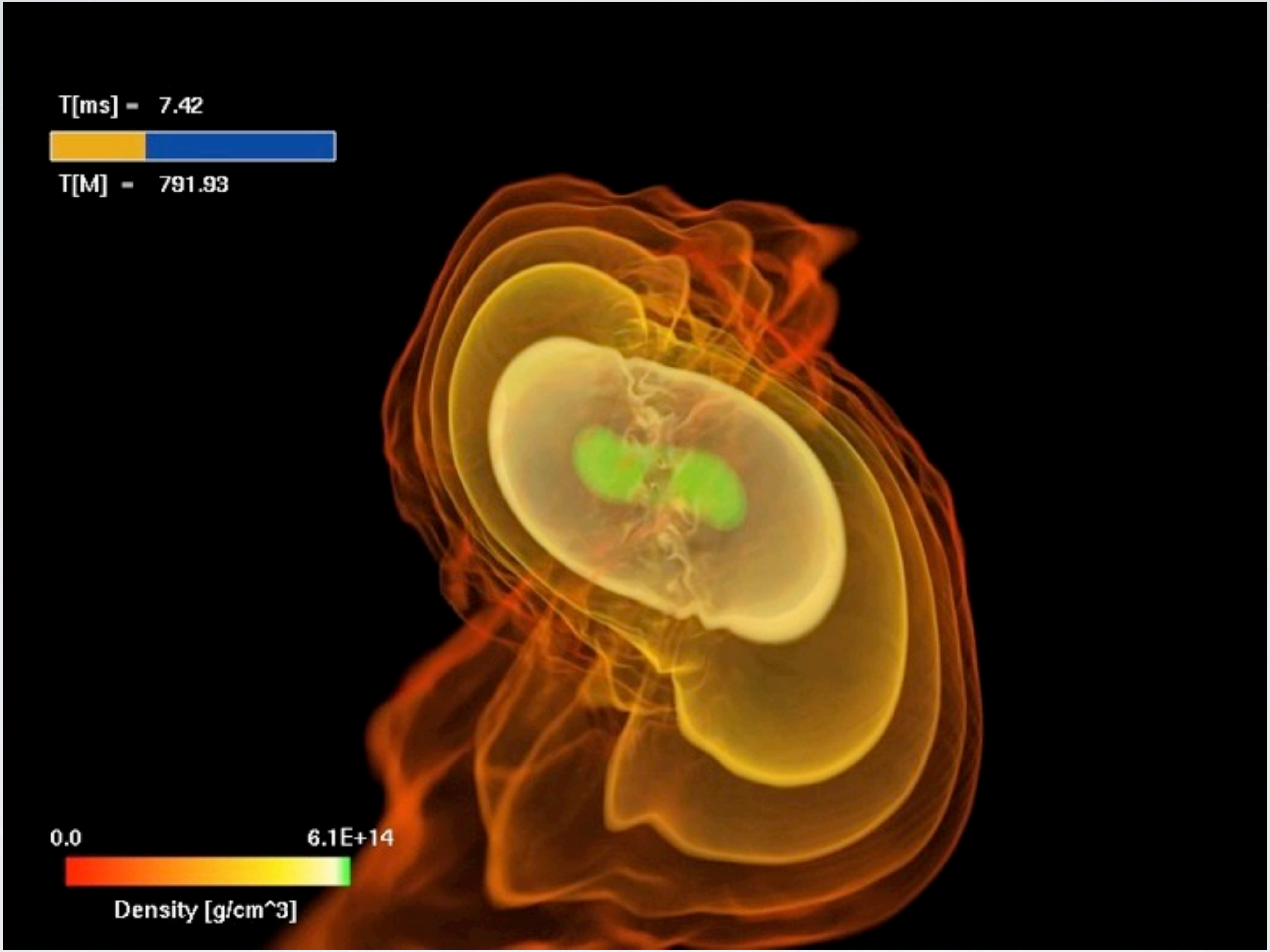
THE WHISKY CODE

www.whiskycode.org

- Full GR Magneto-Hydro-Dynamical Code
  - Based on the Cactus framework
  - Solves the 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

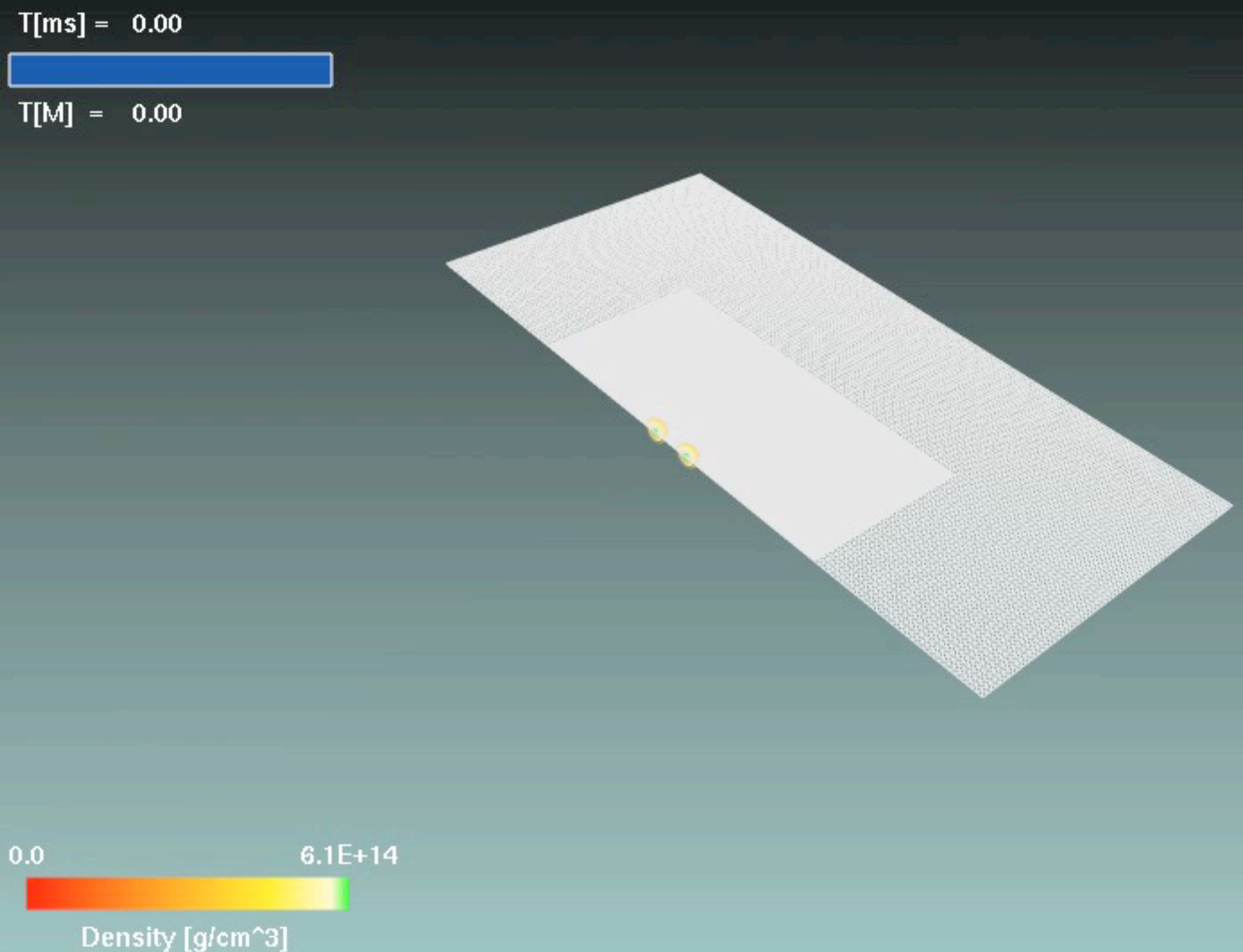
- It's meant as an "astrophysical laboratory" to study several different sources of gws

GWS FROM UNMAGNETIZED BNS

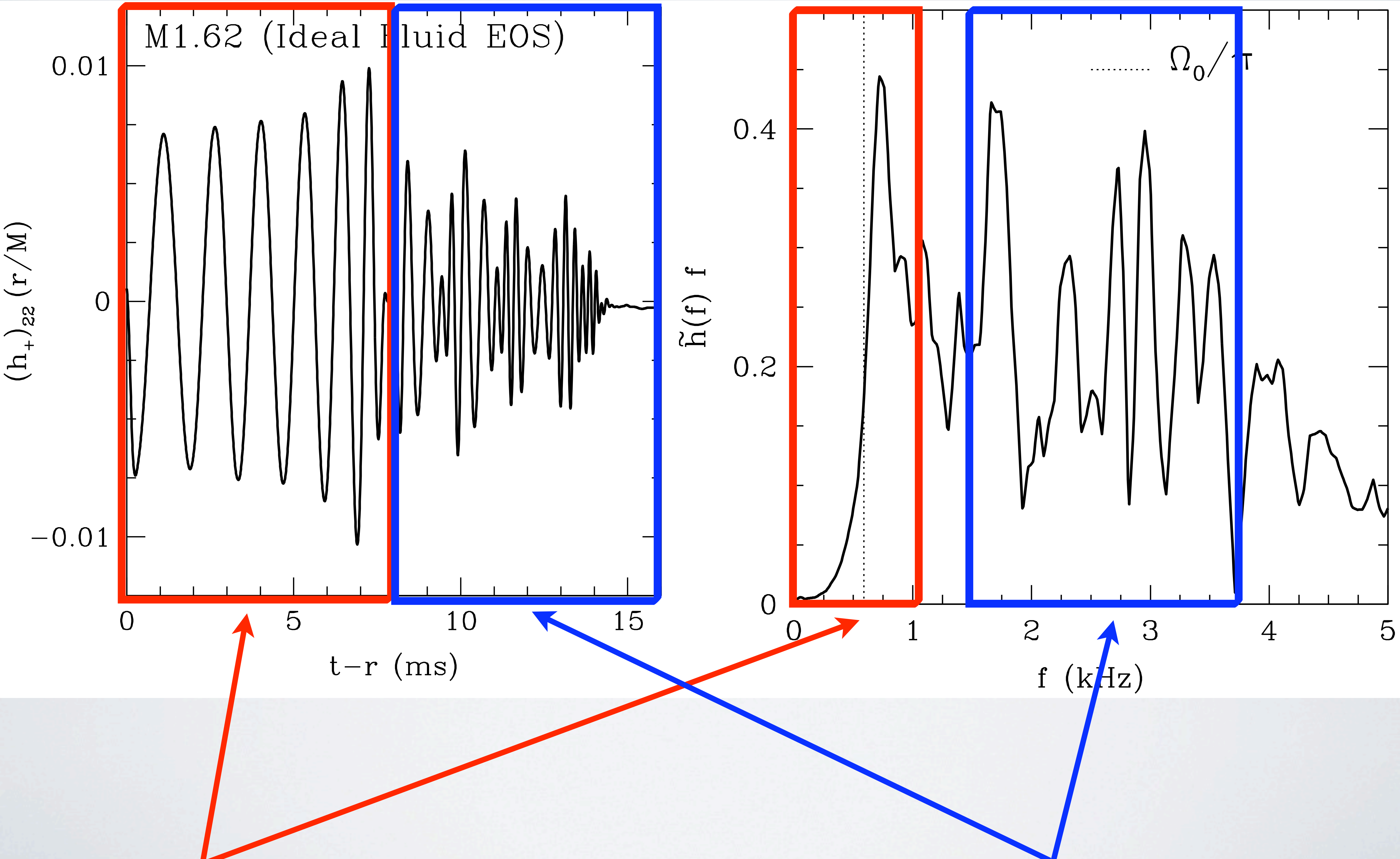


Baiotti, Giacomazzo, Rezzolla 2008, PRD 78, 084033
Baiotti, Giacomazzo, Rezzolla 2009, CQG 26, 114005

Ideal Fluid EOS: High-Mass BNS ($M_1=M_2=1.6$)



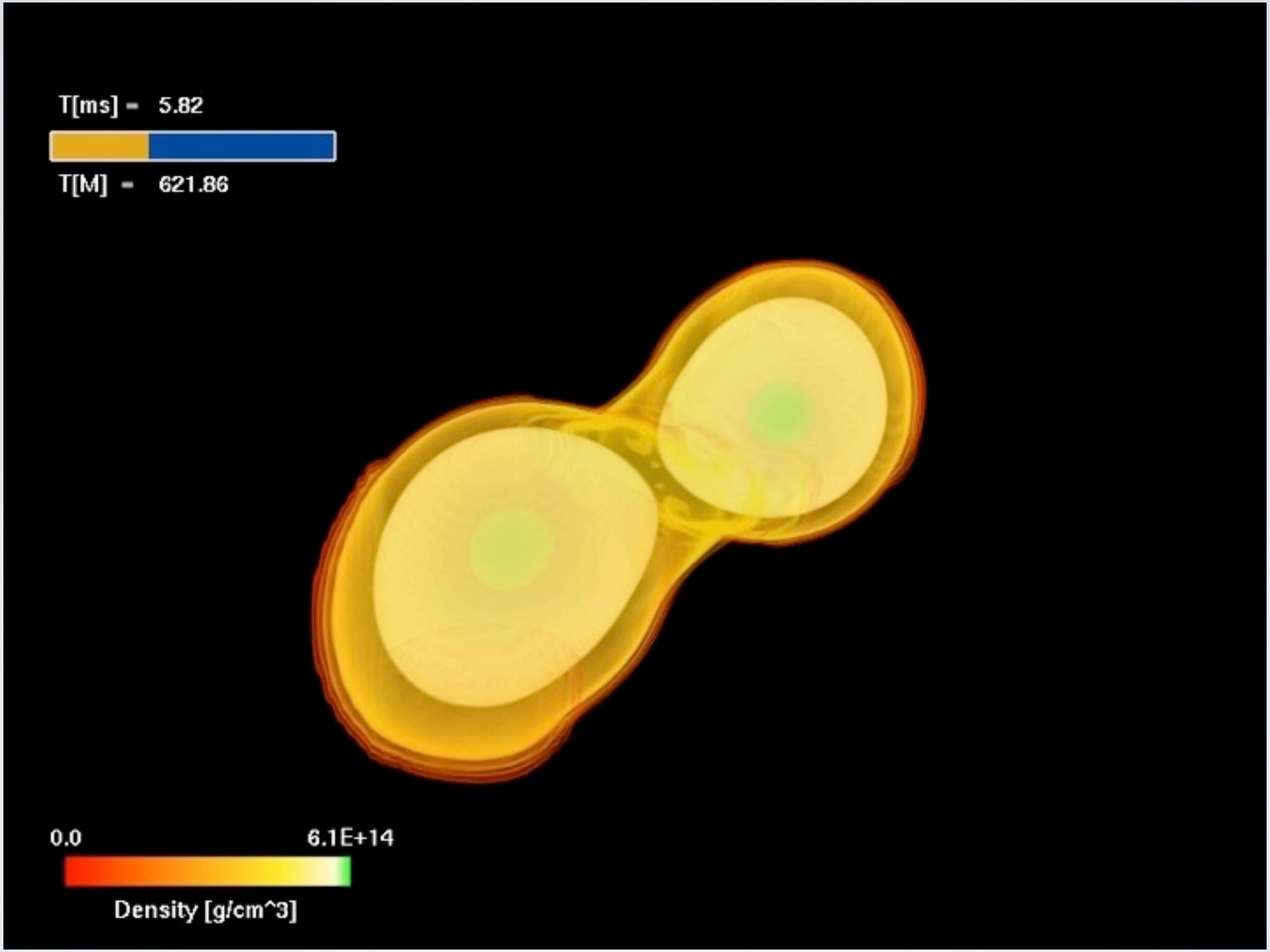
GWS FROM UNMAGNETIZED BNS



contribution from the inspiral

contribution from the HMNS

MAGNETIZED BNS MERGERS



Giacomazzo, Rezzolla, Baiotti 2009, MNRAS, 399, L164-l68

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)

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:

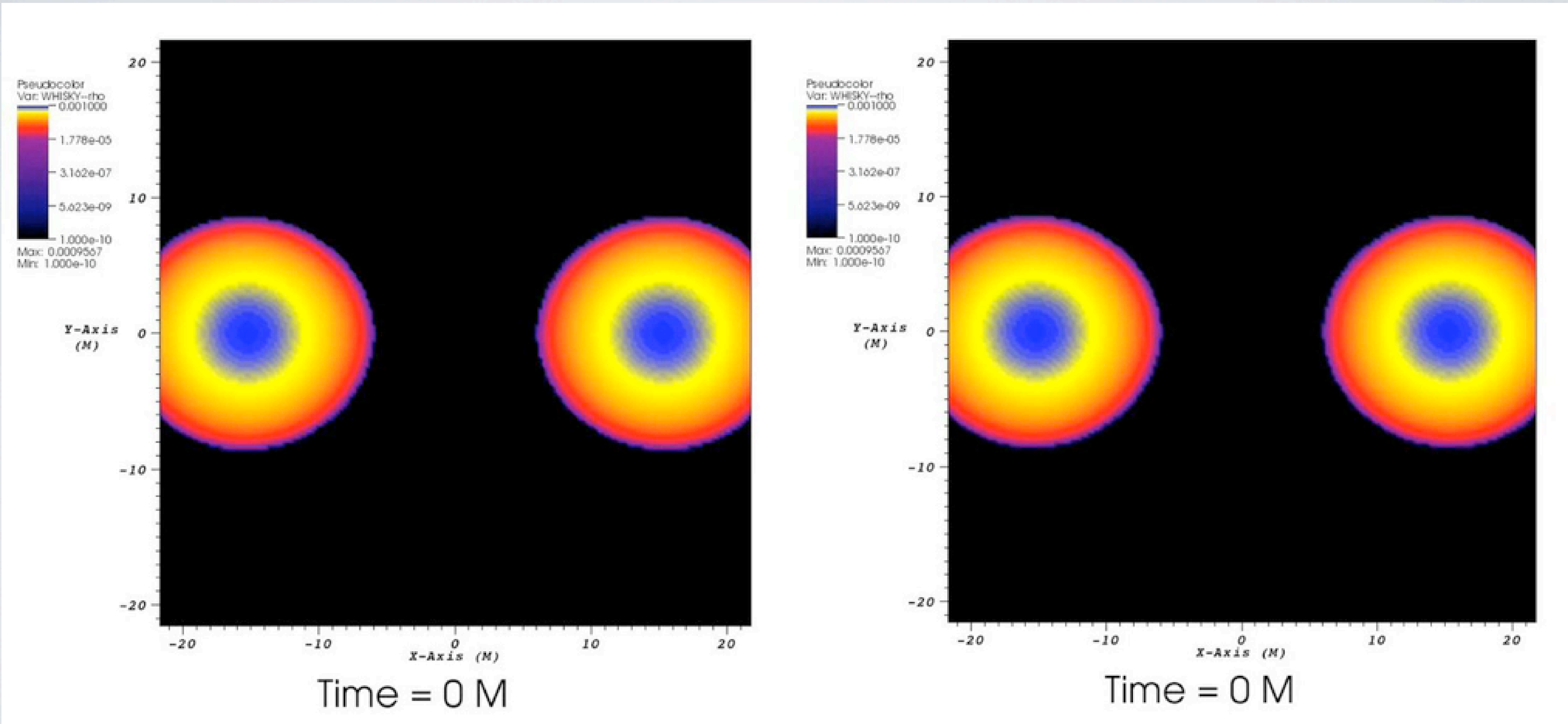
- ideal fluid EOS: $P = \rho\epsilon(\Gamma - 1)$
- outer boundary: ~370 km
- 5 refinement levels; res. on finest level: ~0.36km
- PPM for the reconstruction
- HLLE flux
- Runge Kutta (3rd-order)

We have considered initial magnetic fields from 10^{12} to 10^{17} Gauss
The initial magnetic field is contained inside the star

MHD EFFECTS

high-mass (M_1=M_2=1.62), ideal fluid EOS $P = \rho\epsilon(\Gamma - 1)$

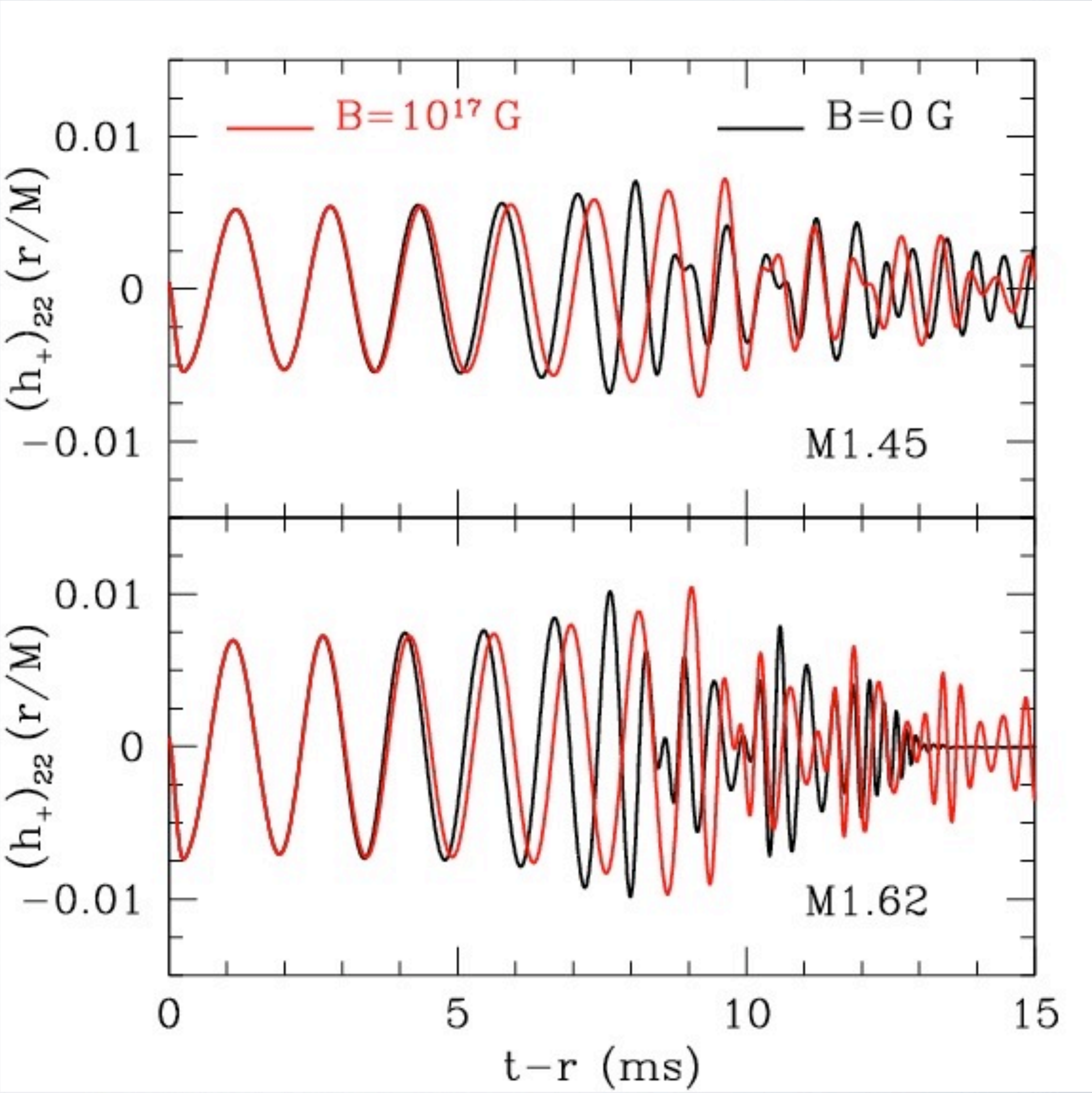
B=0 max(B)~10^{17}G



Very high magnetic fields produce effects both during the inspiral and after the merger

GRAVITATIONAL WAVES

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



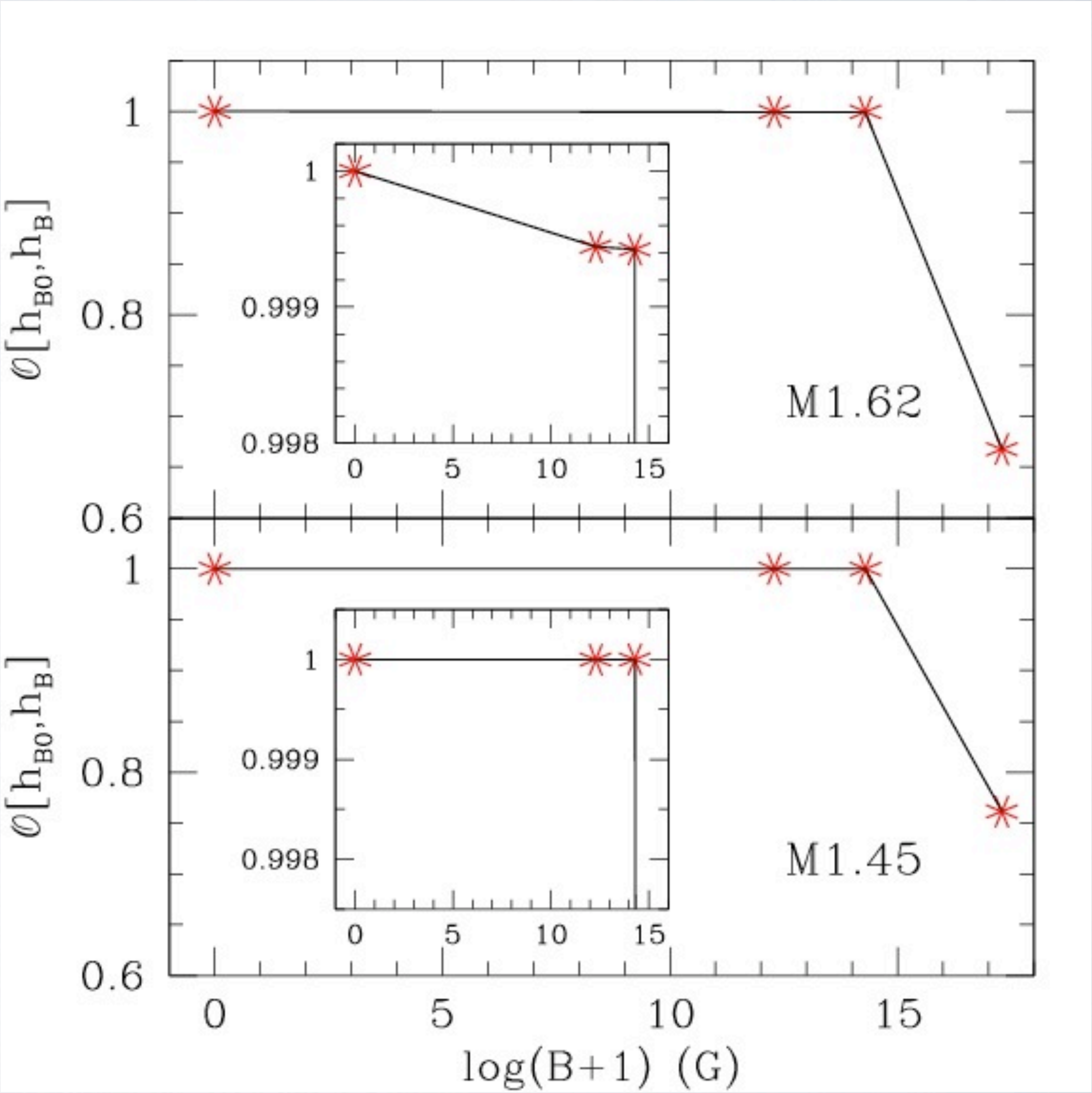
COMPUTING MF EFFECT IN THE GWS

We have computed the overlap between the different waveforms:

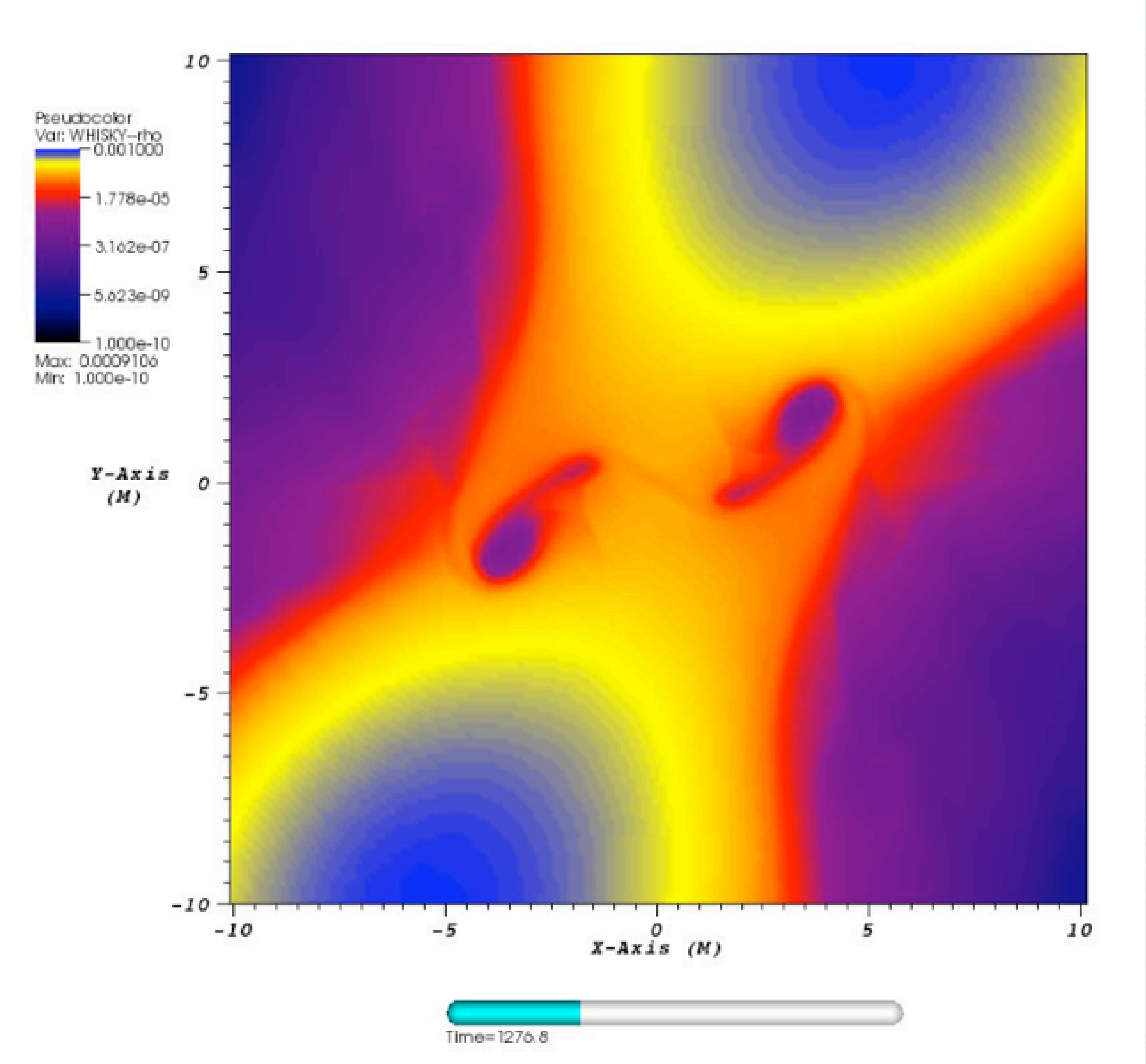
$$\mathcal{O}[h_{B1},h_{B2}] \equiv \frac{\langle h_{B1}|h_{B2}\rangle}{\sqrt{\langle h_{B1}|h_{B1}\rangle\langle h_{B2}|h_{B2}\rangle}}$$

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

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



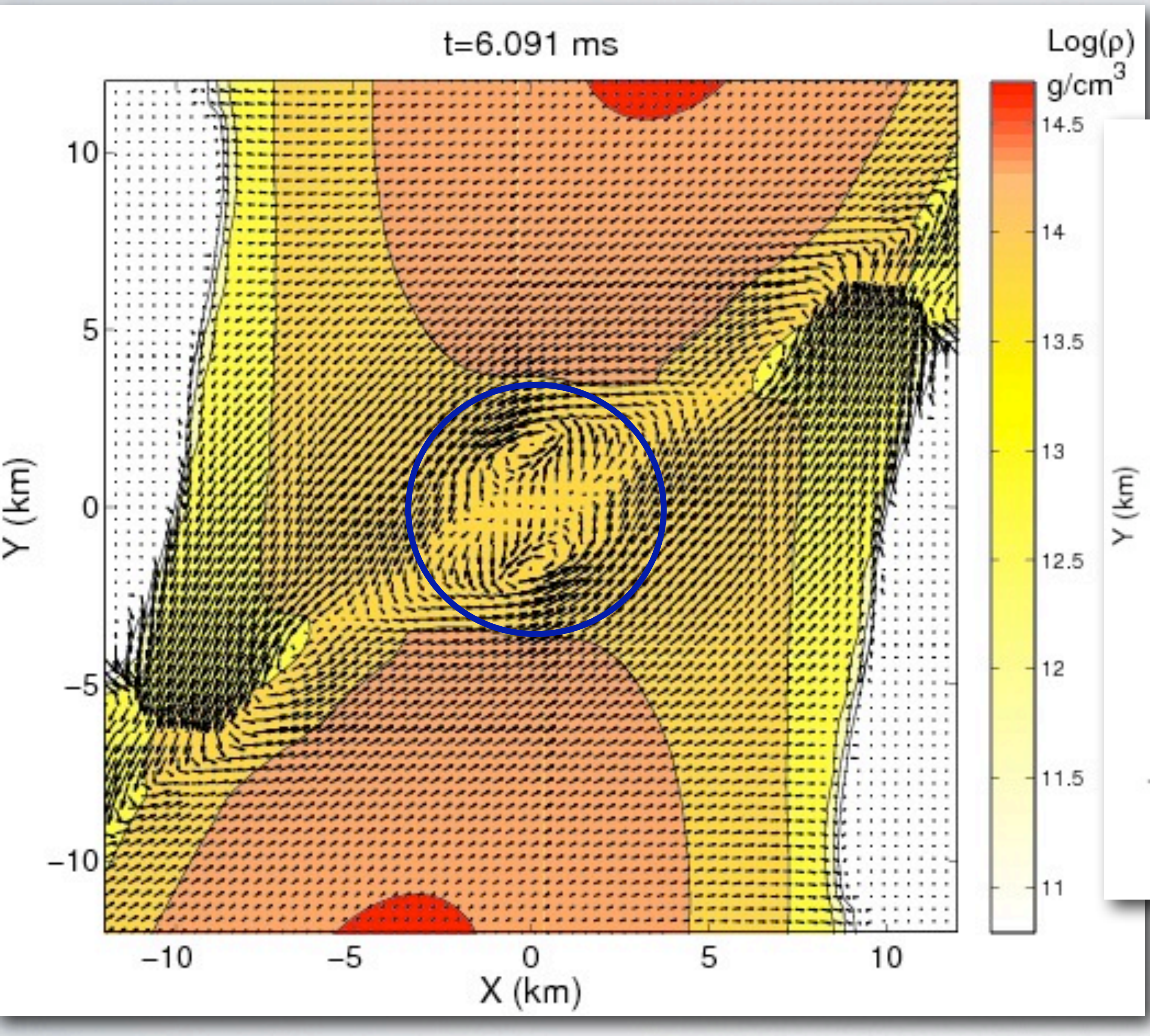
BNS: HD INSTABILITIES AND MAGNETIC FIELD EVOLUTION



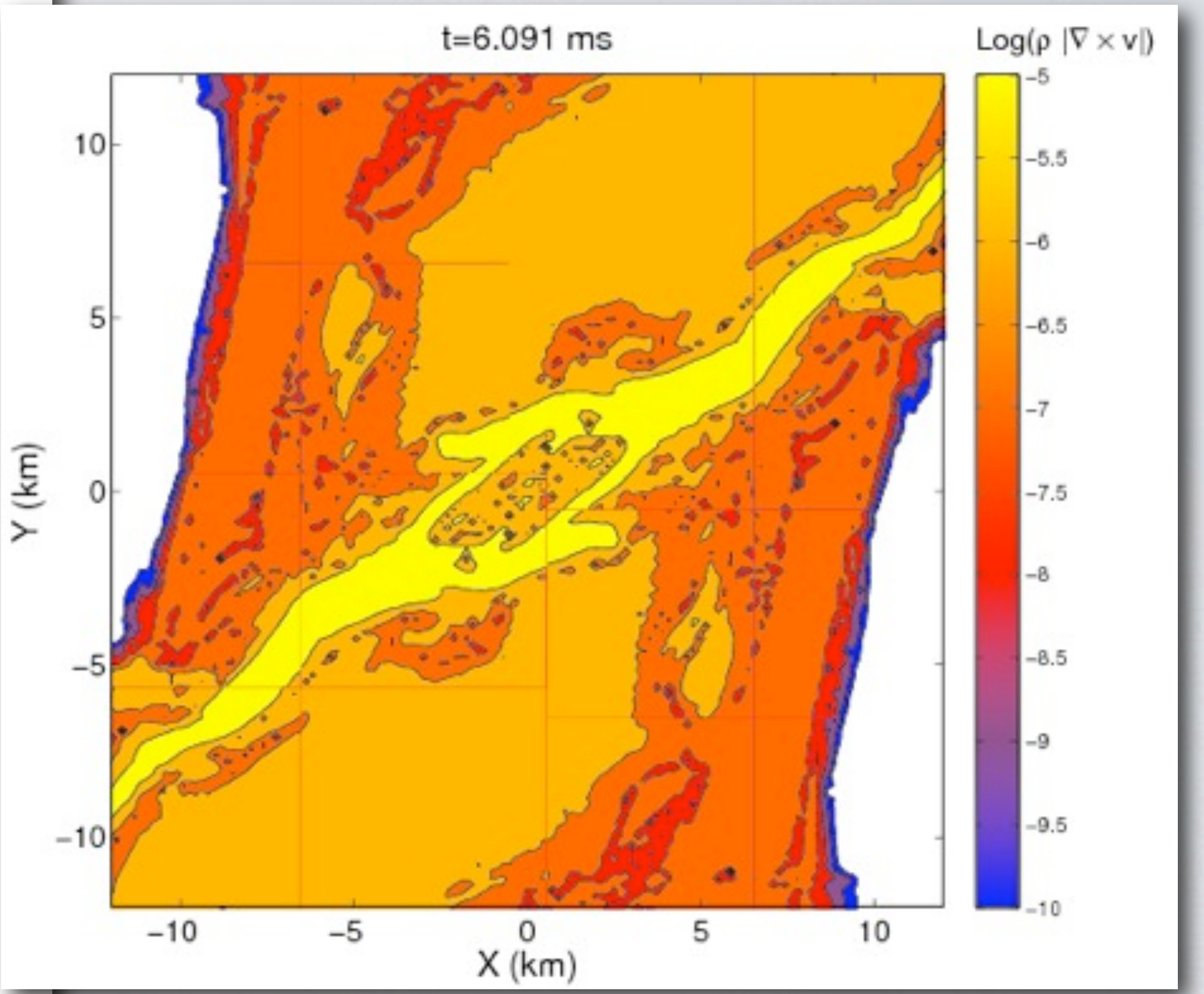
KH INSTABILITY: HIGH-MASS BINARY

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

More evident in terms of the weighted vorticity.



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



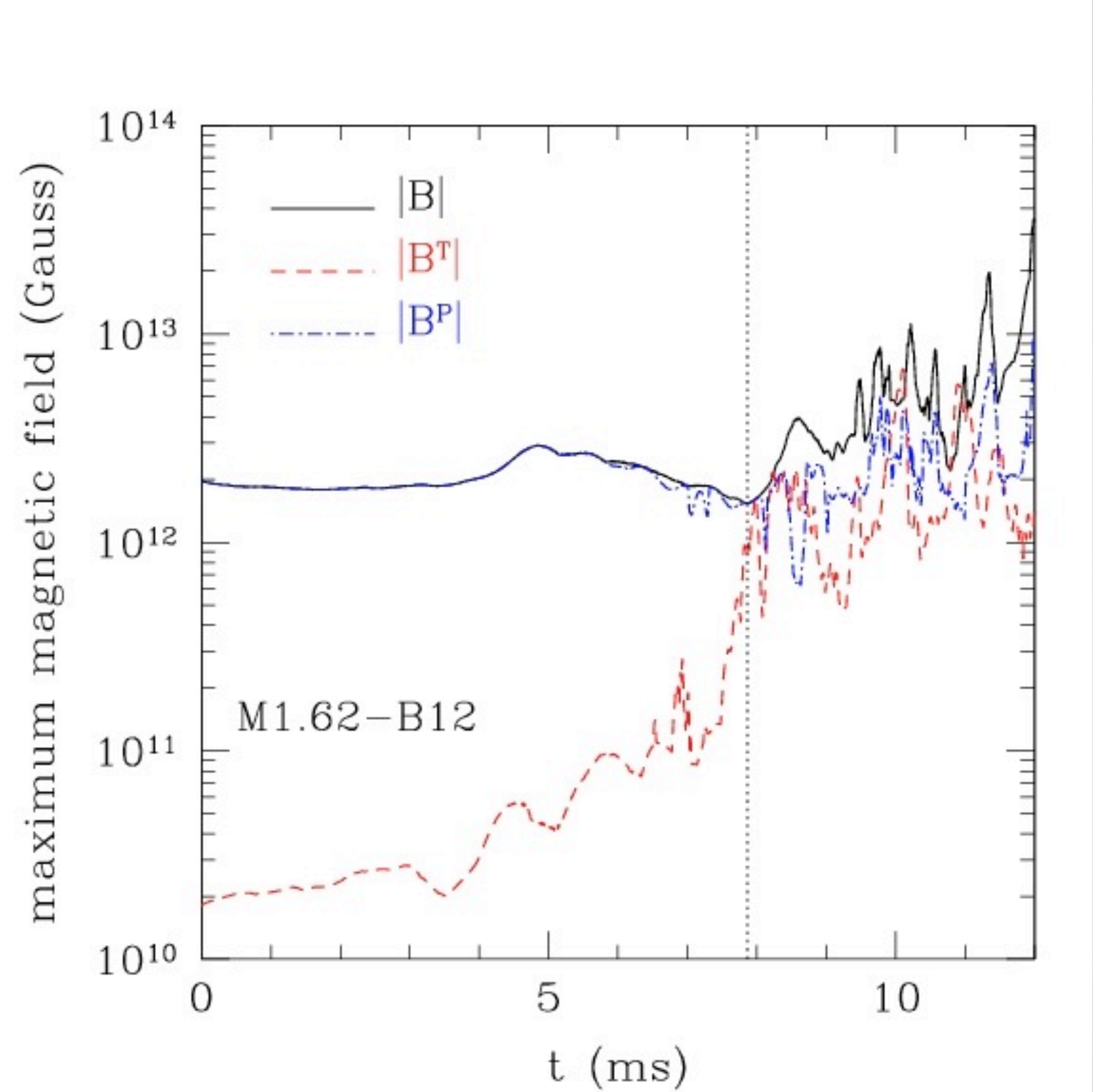
$$\rho|\nabla \times v|^z$$

EFFECTS OF THE KH 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!

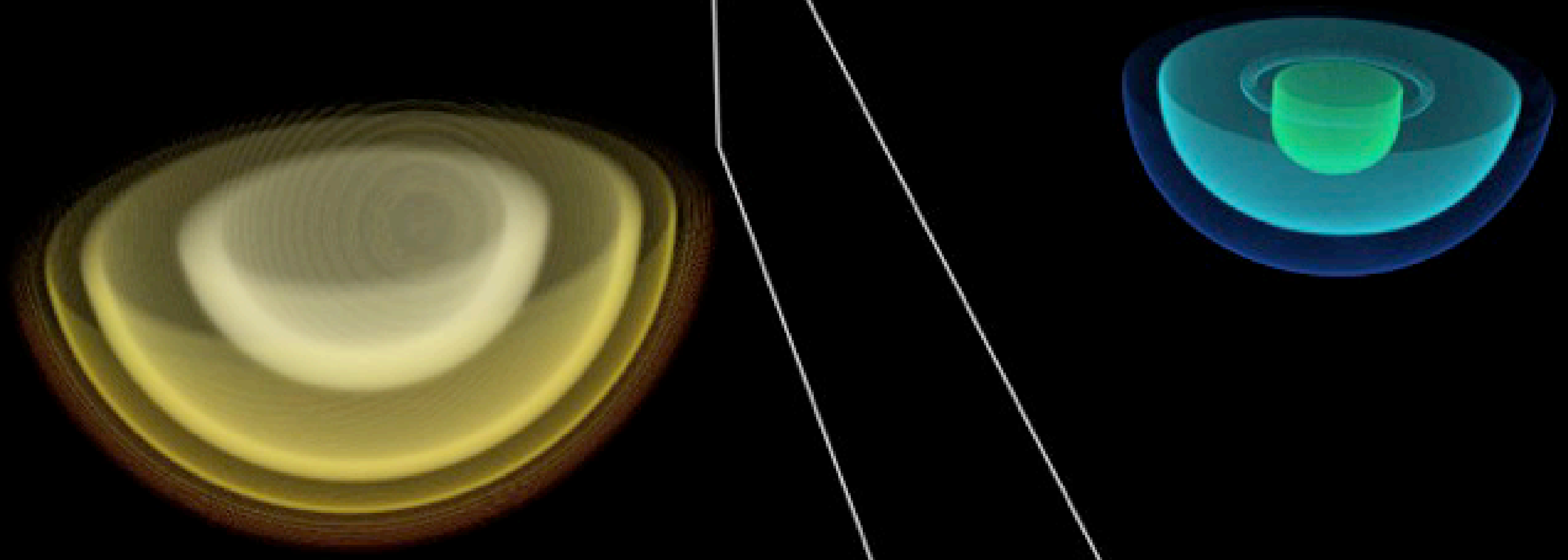
The toroidal component grows up to the value of the poloidal one. This seems to be independet of resolution and initial field value.



MAGNETIZED BNS:
JET FORMATION?

Animations: Koppitz, Giacomazzo, Rezzolla

A large plasma outflow is starting to be launched. The evolution has been stopped because of excessive div(B) violations.



Typical evolution for a magnetized binary

$$\mathrm{Ideal-fluid},\ M = 1.62 M_{\odot},\ B = 10^{12} G$$

SUMMARY

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

- Effects of the magnetic fields in the inspiral are clearly visible in the gws only for high and unrealistic magnetic fields

- Effects of more realistic magnetic fields maybe detectable only after the merger and on high frequencies (f>~2kHz)

- 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 from the merger of equal and unequal mass BNSs with magnetic fields from 10^8 to 10^{12} G

FUTURE DIRECTION

We are currently working to add to Whisky

- **neutrino emission**, in collaboration with:
  - E. Abdikamalov (LSU)
  - J. Barranco (AEI)
  - F. Galeazzi (AEI)
- **more realistic EOSs**, in collaboration with:
  - G. Corvino (AEI)
  - A. Tonita (AEI)
- **resistive MHD**, in collaboration with:
  - D. Alic (AEI)
  - C. Palenzuela (CITA)

For movies and pictures about BNS merger simulations:
http://numrel.aei.mpg.de/Visualisations/index.html