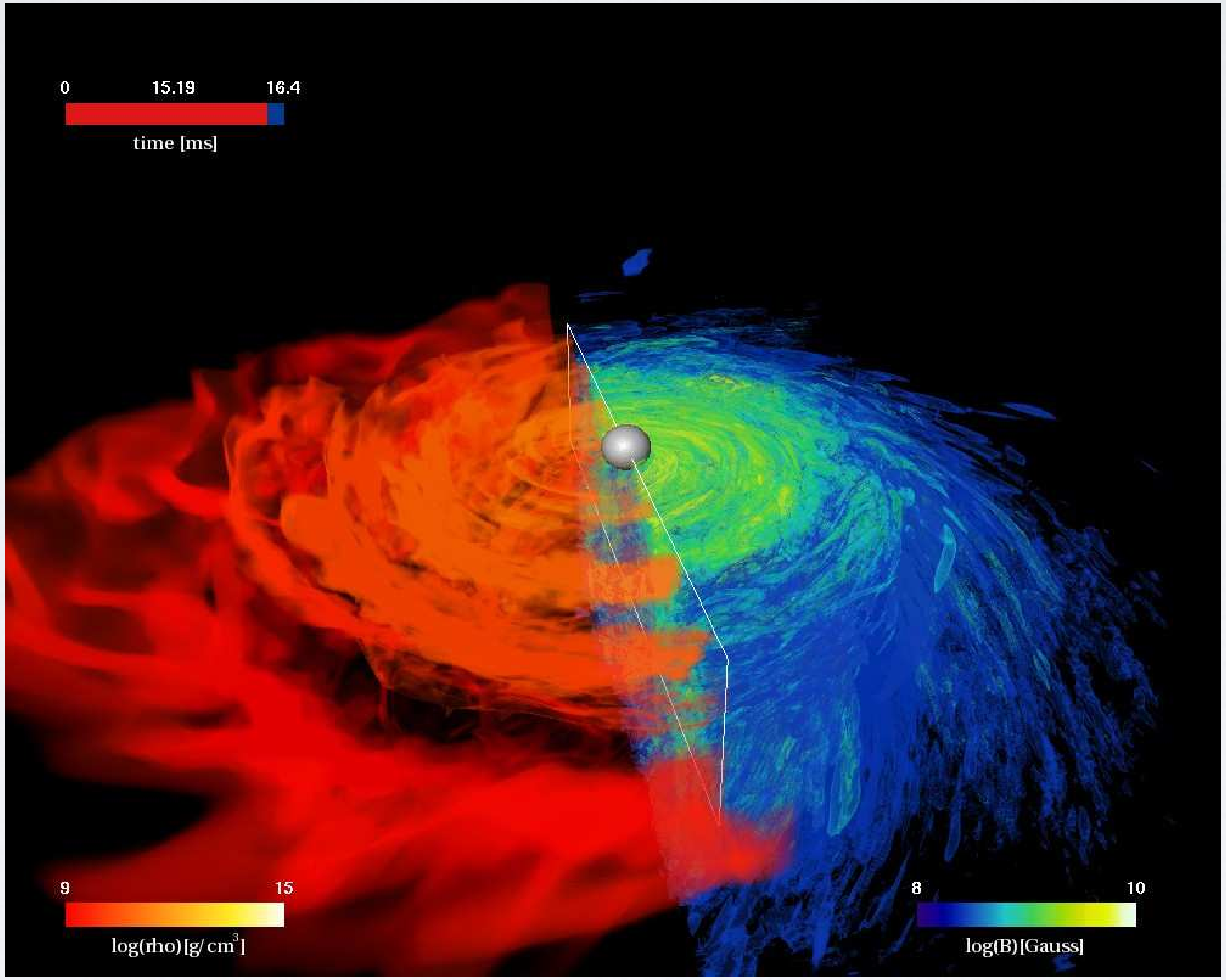
INVESTIGATING THE PROGENITORS OF SHORT GRBs VIA GR SIMULATIONS OF NS MERGERS



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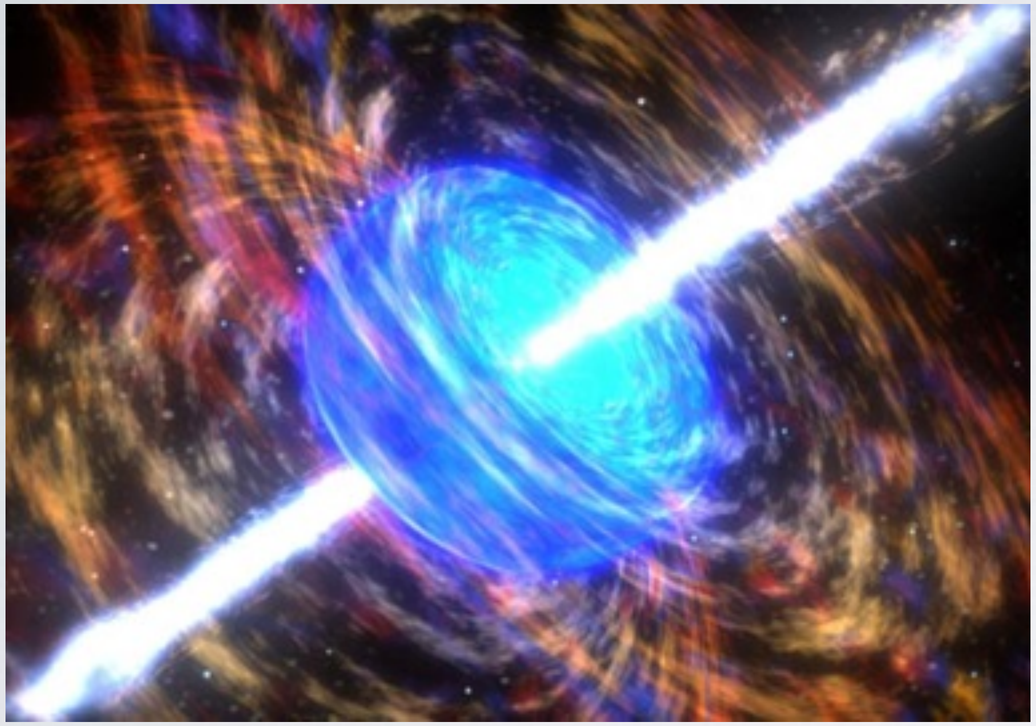
SHORT GAMMA-RAY BURSTS

(for a review, see Berger 2014, Annu. Rev. Astron. Astrophys. 52, 43)



Credit: NASA/SkyWorks Digital

GRB lasting less than 2s (T_{90})

Observed for decades, but engine unknown

Several observational evidences seem to point to NS-NS/BH mergers

NS-NS and NS-BH are also powerful sources of GWs.

Simultaneous detection of an SGRB with a GW could unveil the central engine

Virgo (Pisa, Italy)

"STANDARD" MODEL FOR SGRB CENTRAL ENGINE

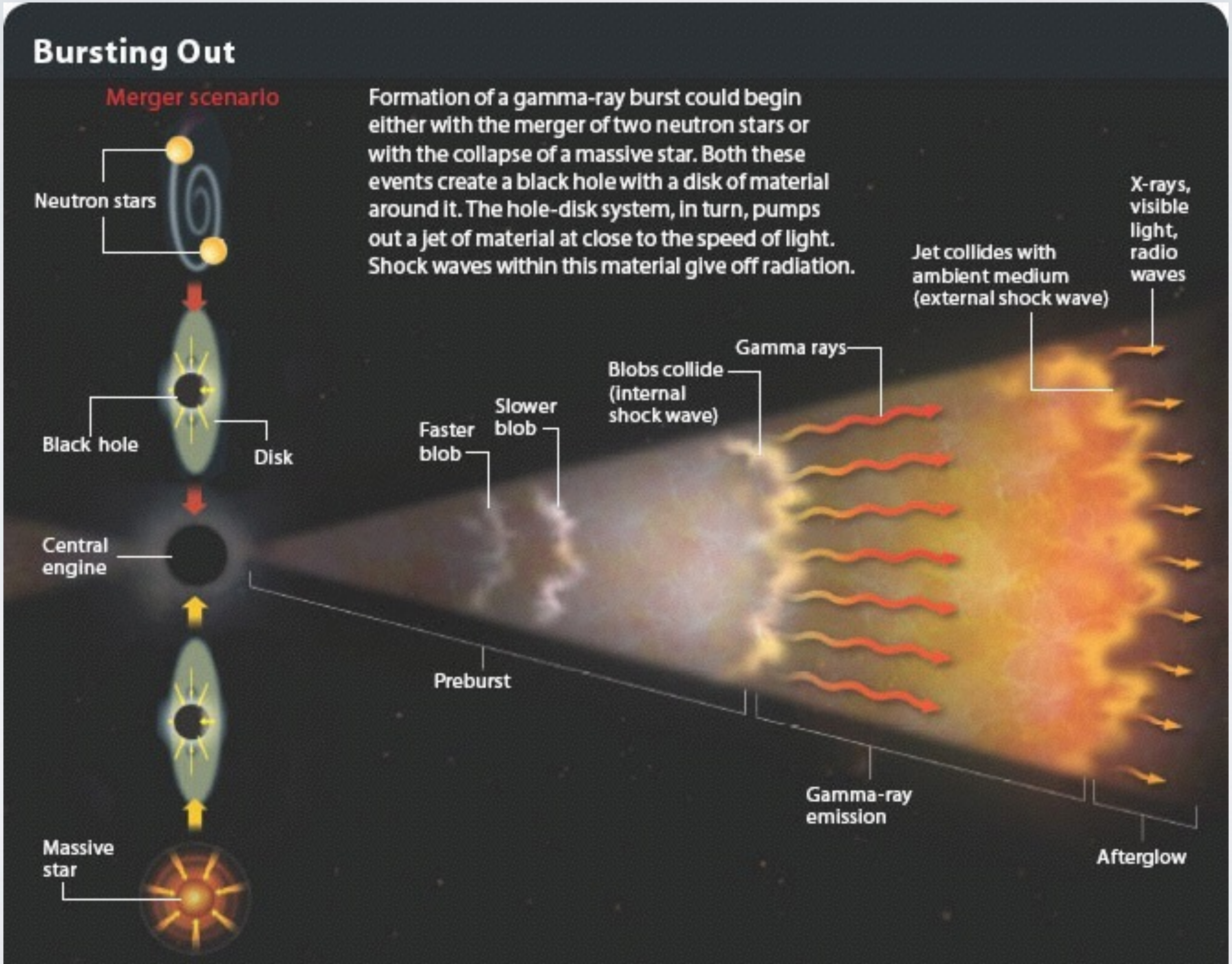
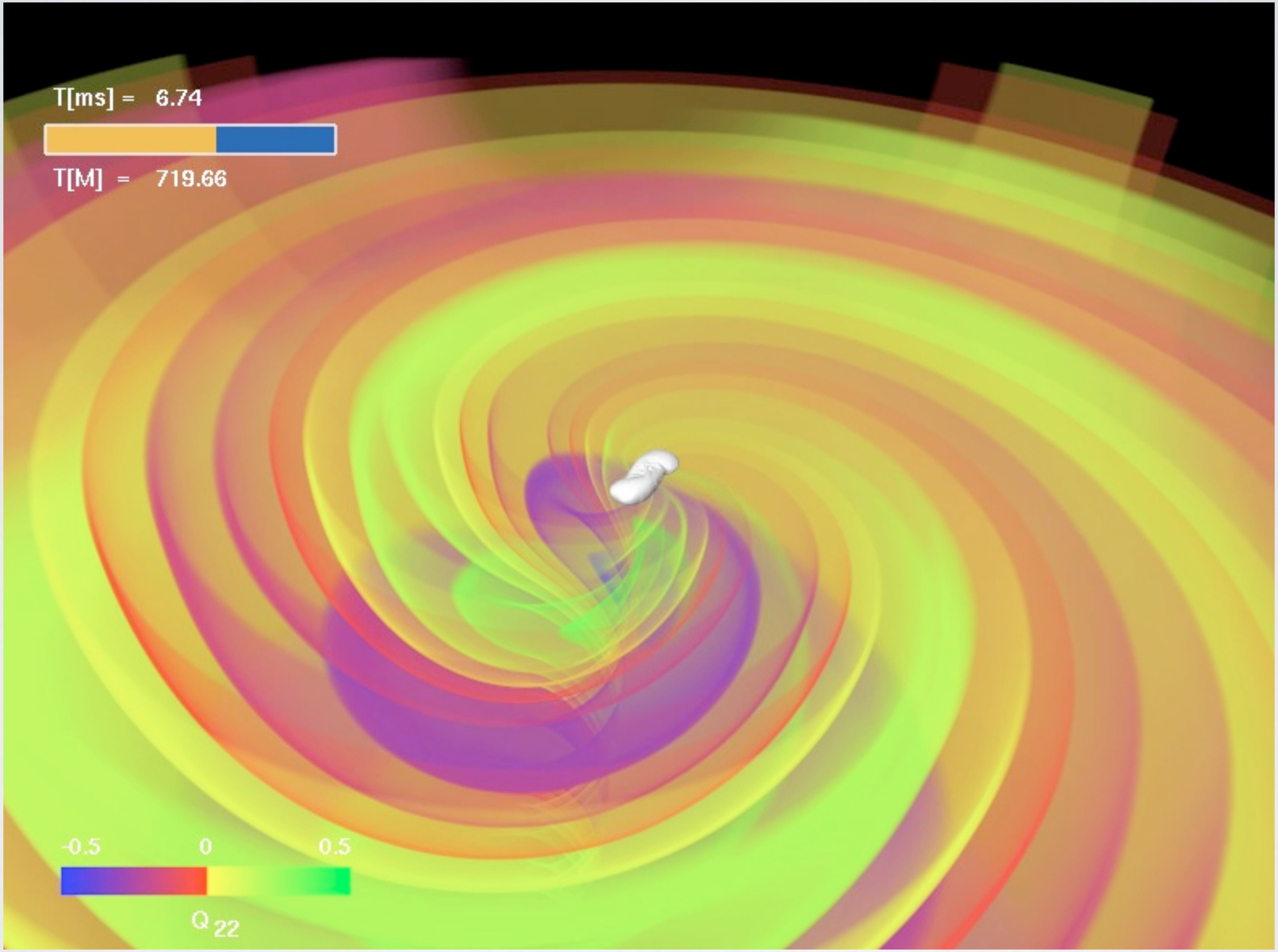


Image from Neil Gehrels, Luigi Piro, and Peter J. T. Leonard 2007, Scientific American sp 17, 34 (CREDIT: JUAN VELASCO)

NS BINARY SIMULATIONS



GR NS-NS SIMULATIONS: STATE OF THE ART

(for a recent review see: Faber & Rasio 2012, arXiv:1204.3858)

- GRHD (only most recent papers listed)
  - Read et al 2009: investigated cold realistic EOS and GW inspiral signals
  - Baiotti et al 2009: first study of the accuracy of GR computed GWs
  - Kiuchi et al 2009: long-term inspiral, APR EOS
  - Rezzolla et al 2010: studied tori and long HMNS evolutions
  - Kiuchi et al 2010: connection between short-GRBs and GWs
  - Baiotti et al 2010, 2011: long-term inspiral and comparison with EOB
  - Sekiguchi et al 2011: first study of neutrino emission in full GR
  - Thierfelder et al 2011: AMR, ideal-fluid EOS, accurate convergence study
  - Gold et al 2012: first study of the merger of eccentric equal-mass neutron stars
  - Bernuzzi et al 2012: study of tidal effects and EOB during inpsiral
  - Barausse et al 2013: BNS mergers in scalar tensor theories of gravity
  - Kastaun et al 2013: study of spin of BH produced by mergers
  - Hotokezaka et al 2013a,b: study of mass ejection and HMNS evolution
  - Read et al 2013: multicode study of EOS effects on GWs
  - Reisswig et al 2013: first BNS merger using multipatch grids
  - Radice et al 2013: first high order simulations of BNS inspiral
  - Bernuzzi et al 2013-2014: BNS simulations with spinning NSs
  - Shibata et al 2014: BNS in scalar tensor theories with spontaneous scalarization
  - Takami et al 2014: relation between post-merger GWs and EOS

GR NS-NS SIMULATIONS: STATE OF THE ART
(for a recent review see: Faber & Rasio 2012, arXiv:1204.3858)

- GRMHD (all the papers listed)
  - Anderson et al 2008: first run of magnetized BNS ($B \sim 10^{16}$G)
  - Liu et al 2008: magnetized BNS ($B \sim 10^{16}$G), followed collapse to BH
  - Giacomazzo et al 2009: first study of amplification of magnetic field
  - Giacomazzo et al 2011: first study of "realistic" configurations ($B \sim 10^8$-10^{12}G)
  - Rezzolla, Giacomazzo et al 2011: first evidence of jet formation
  - Palenzuela et al 2013: study of EM precursors via resistive GRMHD simulations
  - Giacomazzo and Perna 2013: first study of possible magnetar formation
  - Neilsen et al 2014: first GRMHD code including also neutrino emission
  - Ponce et al 2014a: EM precursors for arbitrary magnetic field orientations
  - Kiuchi et al 2014: very high-res simulations (~70 m), no jet observed
  - Ponce et al 2014b: EM outflows in scalar-tensor theories of gravity
  - Giacomazzo et al 2014: magnetic field amplification via a subgrid model

GR NS-BH SIMULATIONS: STATE OF THE ART
(for a recent review see: Shibata & Taniguchi 2011, LRR 14, 6)

- GRHD (only most recent papers listed)
  - Duez et al 2010: effects of piecewise polytropics and tabulated EOSs
  - Kyutoku et al 2010: different piece-wise polytropic EOSs investigated
  - Foucart et al 2011: effect of BH spin orientation
  - Stephens et al 2011: BH-NS mergers on eccentric orbits
  - Kyutoku et al 2011: studied effects of BH spin and EOS
  - Foucart et al 2012: BH-NS merger with a 10 solar mass BH
  - East et al 2012: effects of eccentric orbits, BH spin, and EOS
  - Lackey et al 2012, 2013: EOS effects on NS-BH GWs
  - Deaton et al 2013: first study of neutrino emission
  - Foucart et al 2013: first direct comparison of NS-BH GWs with BH-BH GWs
  - Foucart et al 2014: effect of neutrino emission, finite-temperature EOS, mass-ratio

- GRMHD (all the papers listed)
  - Chawla et al 2010: first GRMHD simulation of NS-BH mergers
  - Etienne et al 2012a: GRMHD simulations of NS-BH and GRB connection
  - Etienne et al 2012b: effect of tilted magnetic fields and jet formation
  - Paschalidis et al 2013: first force-free simulations of the inspiral and EM precursors
  - Paschalidis et al 2014: jet formation

THE **ET** AND **WHISKY** CODES

The Einstein Toolkit (**einsteintoolkit.org**) is a set of open source codes for computational relativity. It provides infrastructures for parallelization, I/O, AMR, space-time evolution routines,...

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

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

GRMHD EQUATIONS

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

$$\begin{aligned}\nabla_\mu T^{\mu\nu} &= 0 \\ \nabla_\mu J^\mu &= 0 \\ J^\mu &\equiv \rho u^\mu\end{aligned}$$

$$T^{\mu\nu} = (\rho + \rho\epsilon + p + b^2)u^\mu u^\nu + \left(p + \frac{1}{2}b^2\right) g^{\mu\nu} - b^\mu b^\nu$$

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

The evolution of the magnetic field obeys Maxwell's equations (assuming infinite conductivity):

$$\frac{\partial}{\partial t}\left(\sqrt{\gamma}\vec{B}\right) = \nabla \times \left[\left(\alpha\vec{v} - \vec{\beta}\right) \times \left(\sqrt{\gamma}\vec{B}\right)\right]$$

$$\nabla \cdot \left(\sqrt{\gamma}\vec{B}\right) = 0$$

GRMHD EQUATIONS

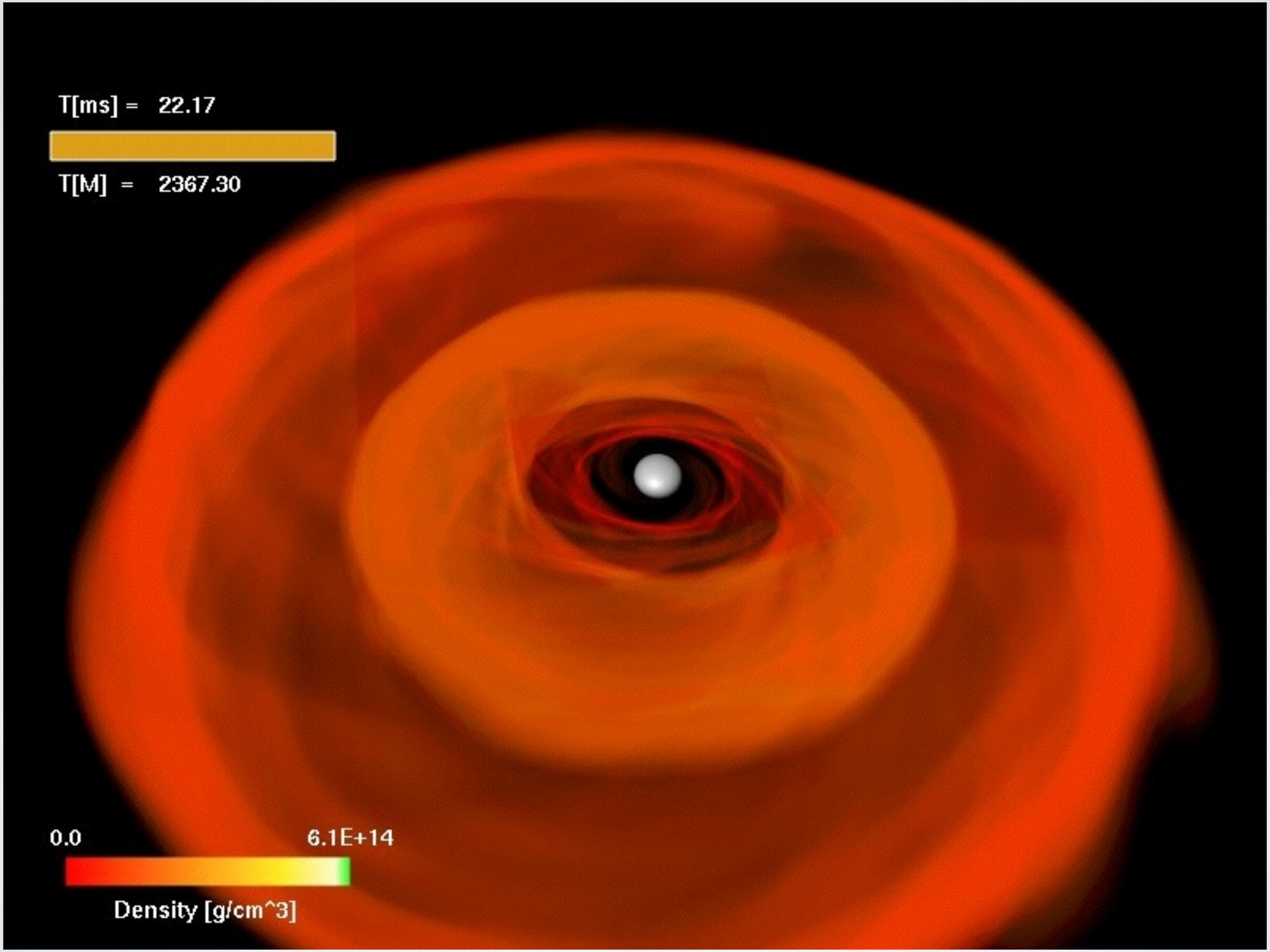
The evolution equations are then rewritten in a conservative form:

$$\frac{1}{\sqrt{-g}}\left[\partial_t(\sqrt{\gamma}\mathbf{U}) + \partial_i(\sqrt{-g}\mathbf{F}^i)\right] = \mathbf{S}$$

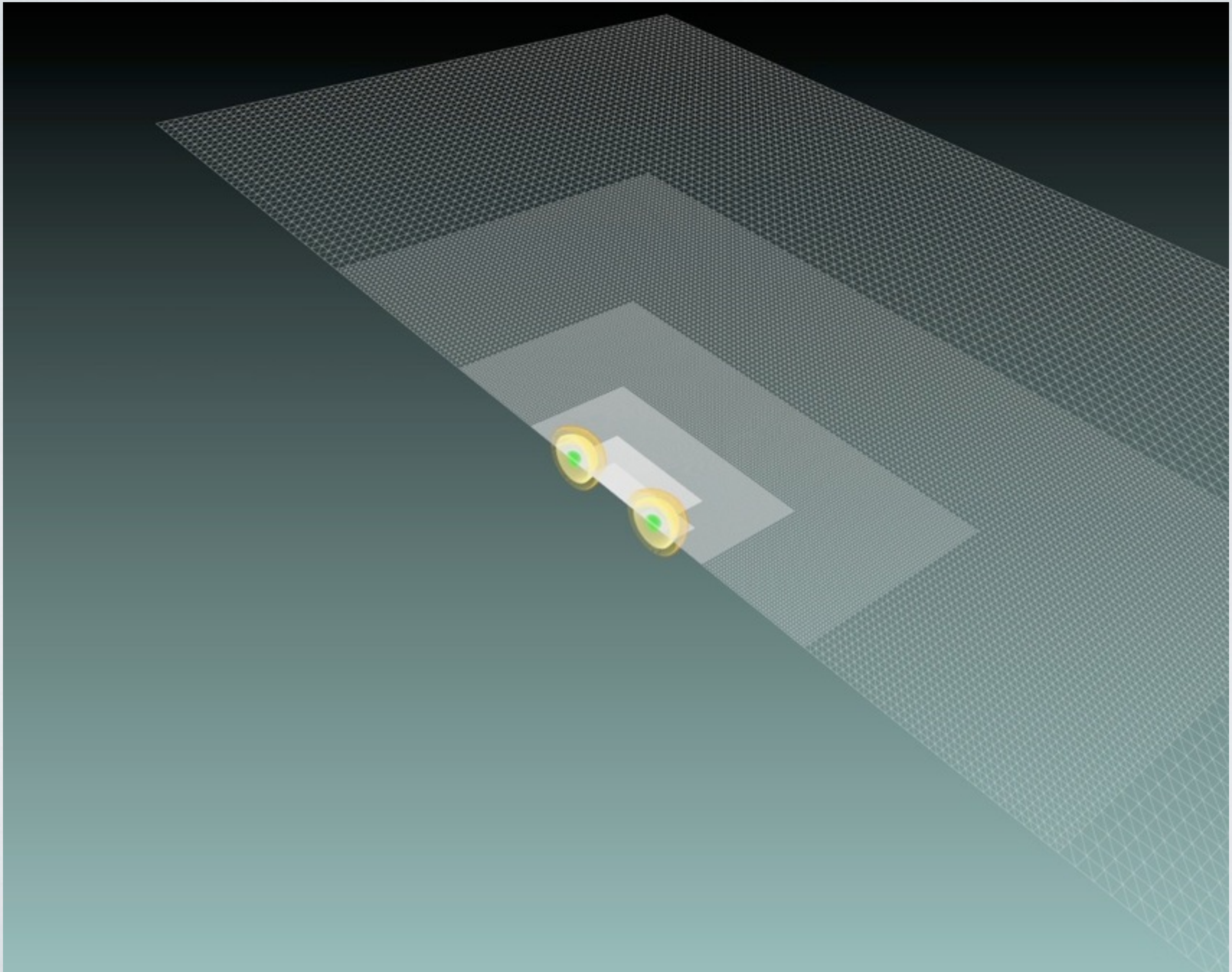
HRSC schemes are used to solve them (HLLE, PPM) and the divergence free character of the magnetic field is guarantee by evolving the vector potential (Giacomazzo and Rezzolla 2007, Giacomazzo et al 2011, Giacomazzo and Perna 2013):

$$\partial_t \vec{A} = -\vec{E}\,, \quad \vec{B} = \frac{1}{\sqrt{\gamma}}\left(\vec{\nabla}\times\vec{A}\right)$$

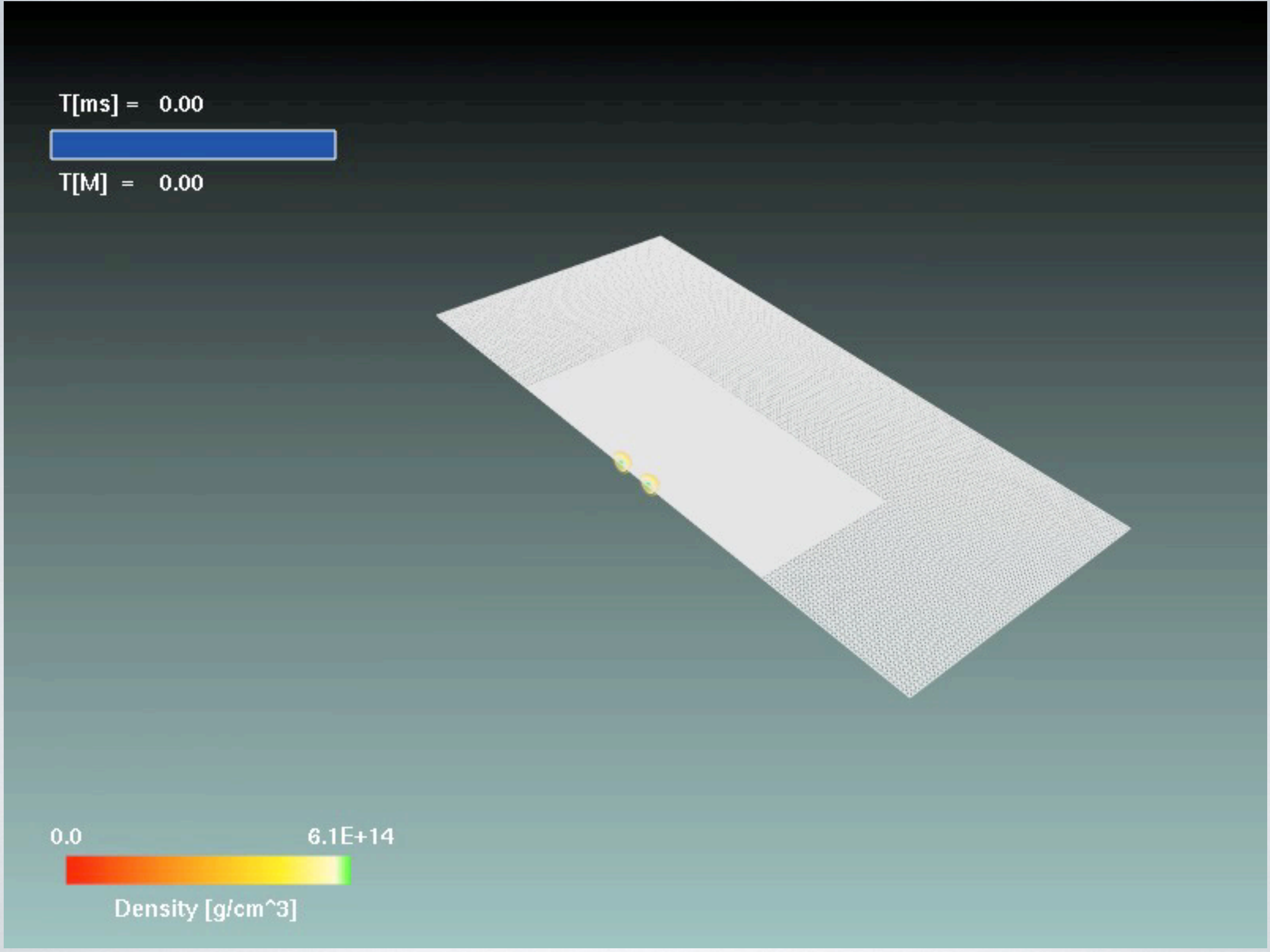
MASSIVE TORI FROM MERGERS?

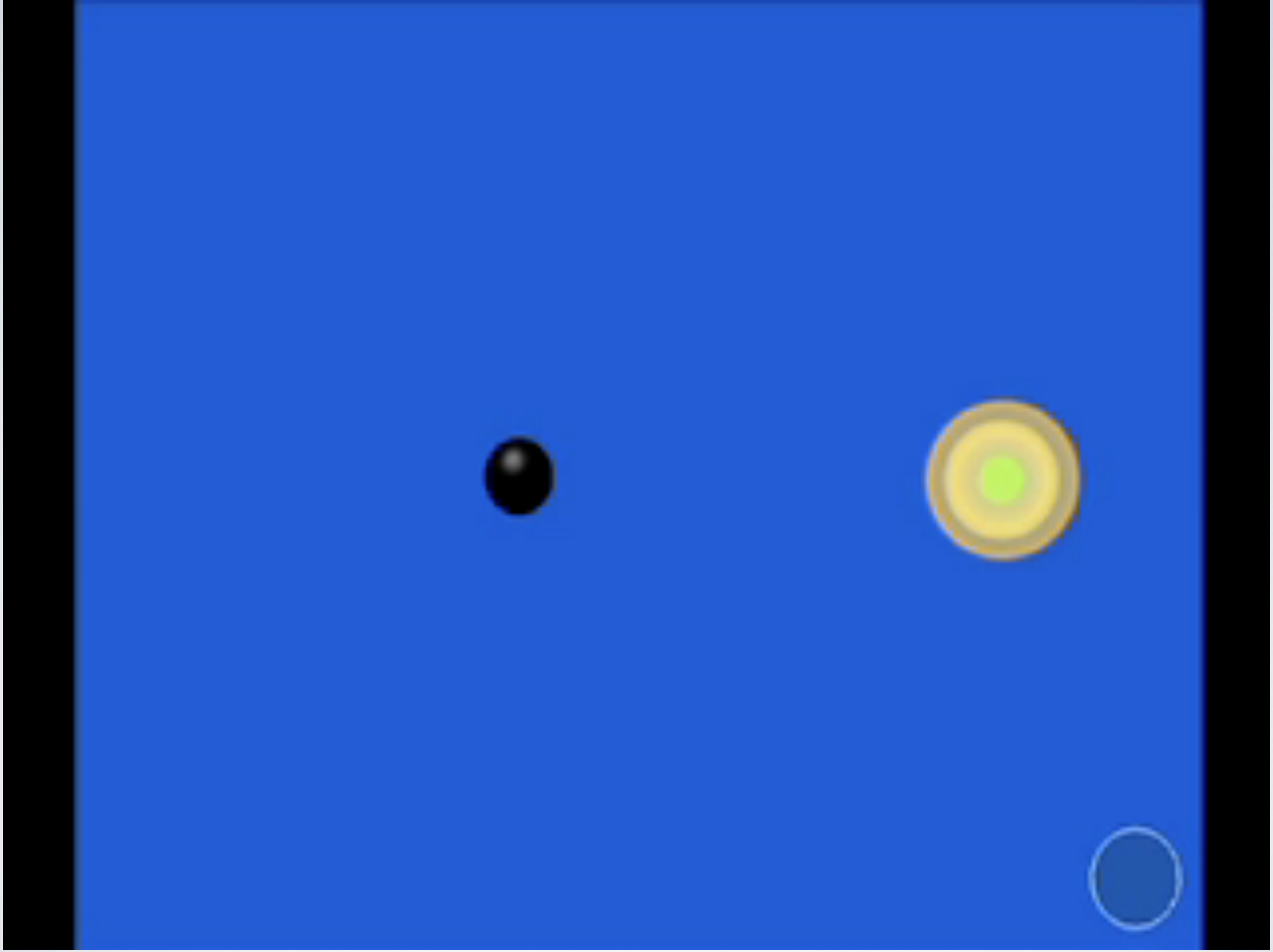


IDEAL-FLUID EOS: HIGH-MASS BINARY



Visualization by Giacomazzo, Kaehler, Rezzolla

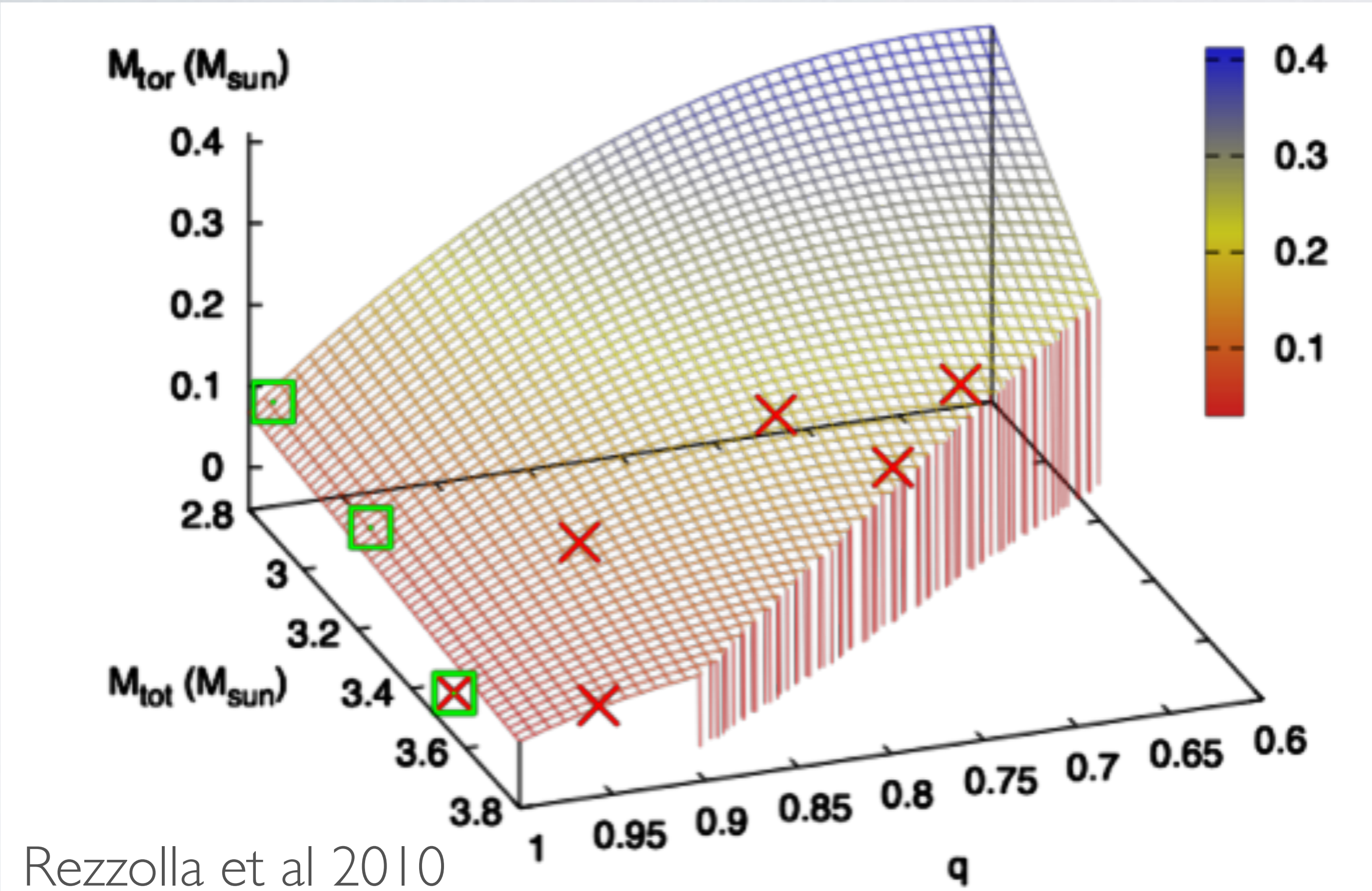

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]



http://research.physics.illinois.edu/cta/movies/cbm/bhns.html

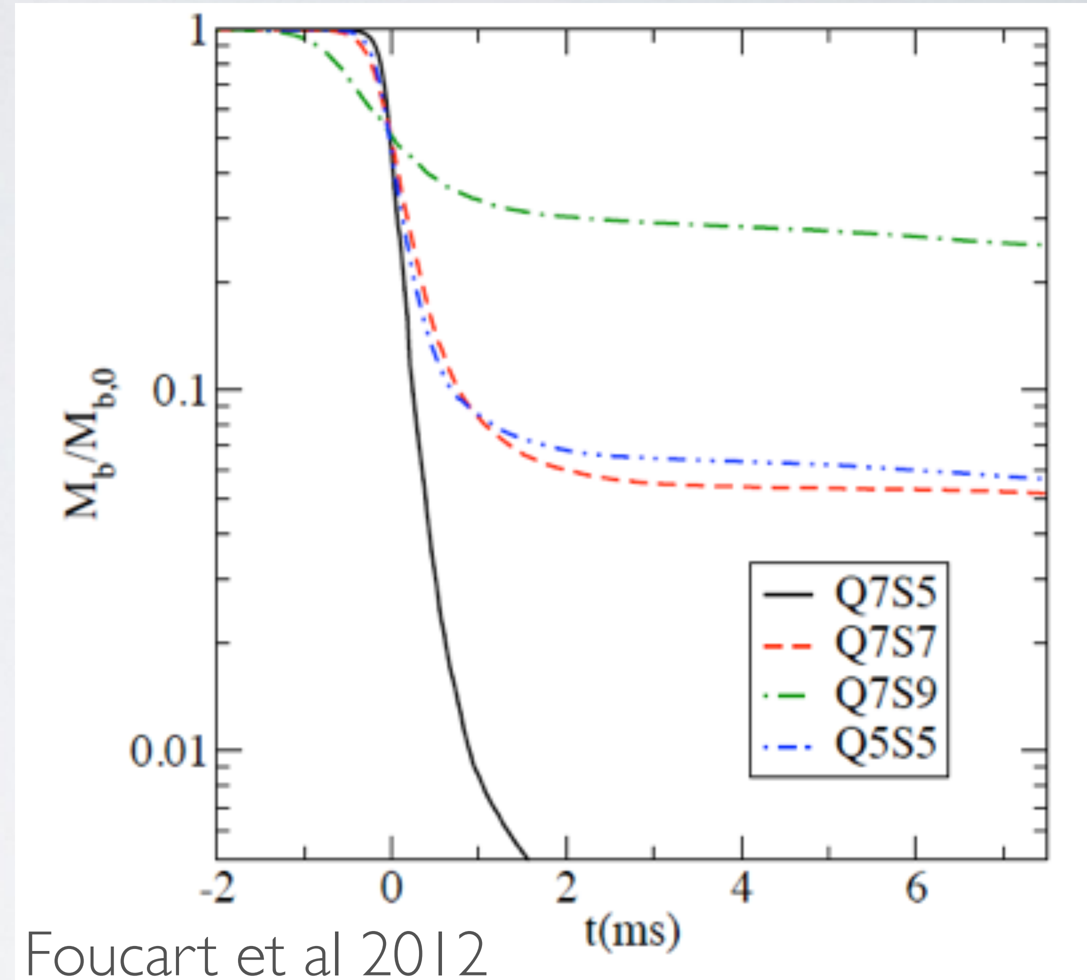
TORI MASSES FROM MERGERS

NS-NS



Rezzolla et al 2010

NS-BH

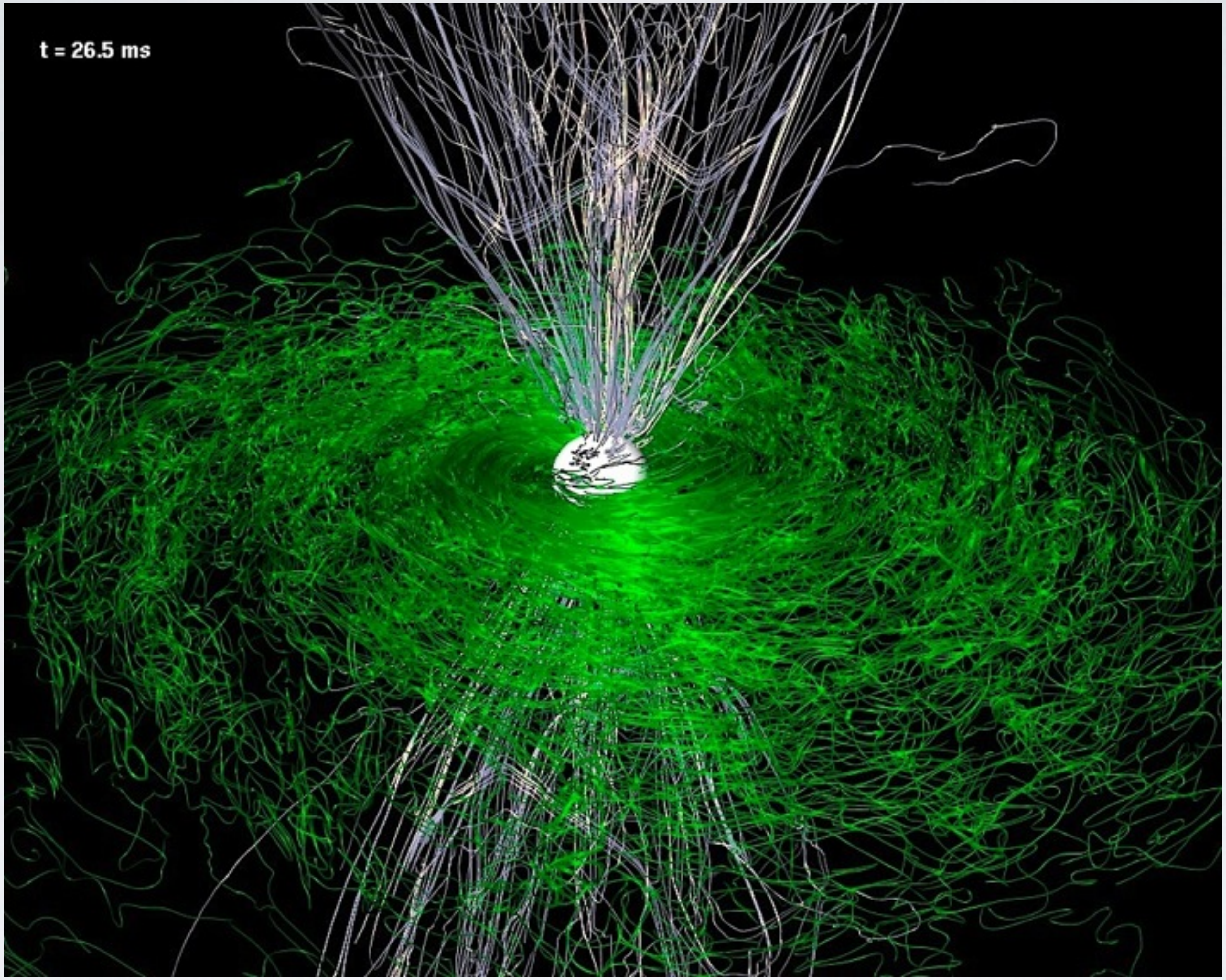


Foucart et al 2012

The torus mass increases with the mass ratio and decreases with the total mass. Possible to form tori up to ~0.3 solar masses.

Even with a 10 Msun BH it is possible to form massive disks if the BH is spinning (a~0.7).

JETS FROM NS BINARIES?



JETS FROM BNS MERGERS?

Rezzolla, **Giacomazzo**, Baiotti, Granot, Kouveliotou, Aloy 2011, ApJL 732, L6

BNS can produce massive tori around spinning BHs, but no evidence of jet formation was provided up to now.

Several numerical studies of tori around spinning BHs, e.g.:

- Aloy et al 2005: neutrino driven jets
- Komissarov et al 2009: magnetically dominated outflows

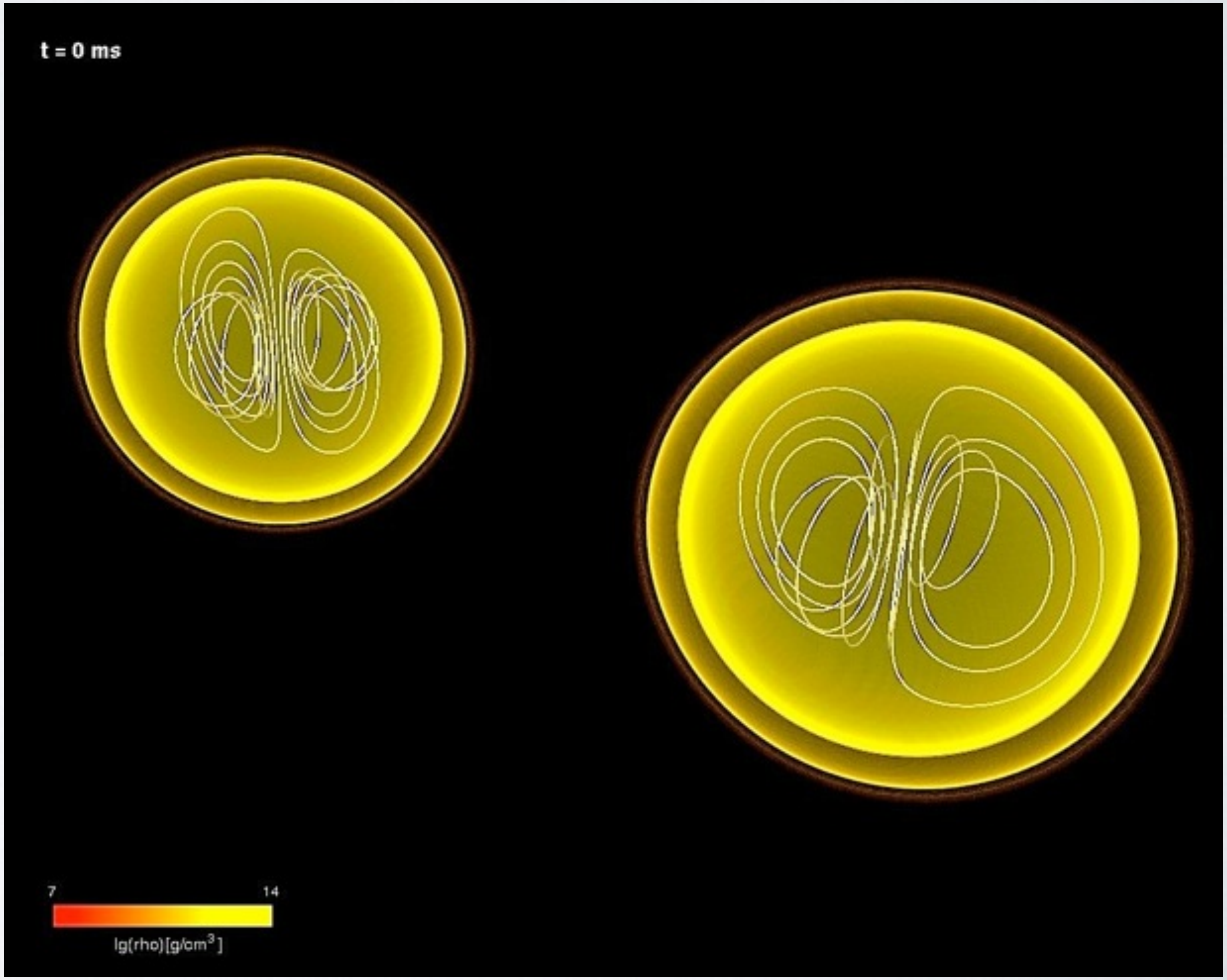
All these studies use as initial conditions specific configurations (such as jet-like structures). Can such configurations be generated by the merger of binary neutron stars?

GRB AS THE RESULT OF BNS MERGERS?

Rezzolla, **Giacomazzo**, Baiotti, Granot, Kouveliotou, Aloy 2011, ApJL 732, L6

We have considered the long evolution of an equal-mass BNS system with $\mathbf{M_1 = M_2 \approx 1.5 M_\odot}$ and with an initial magnetic field of $\mathbf{\sim 10^{12}}$ **Gauss**.

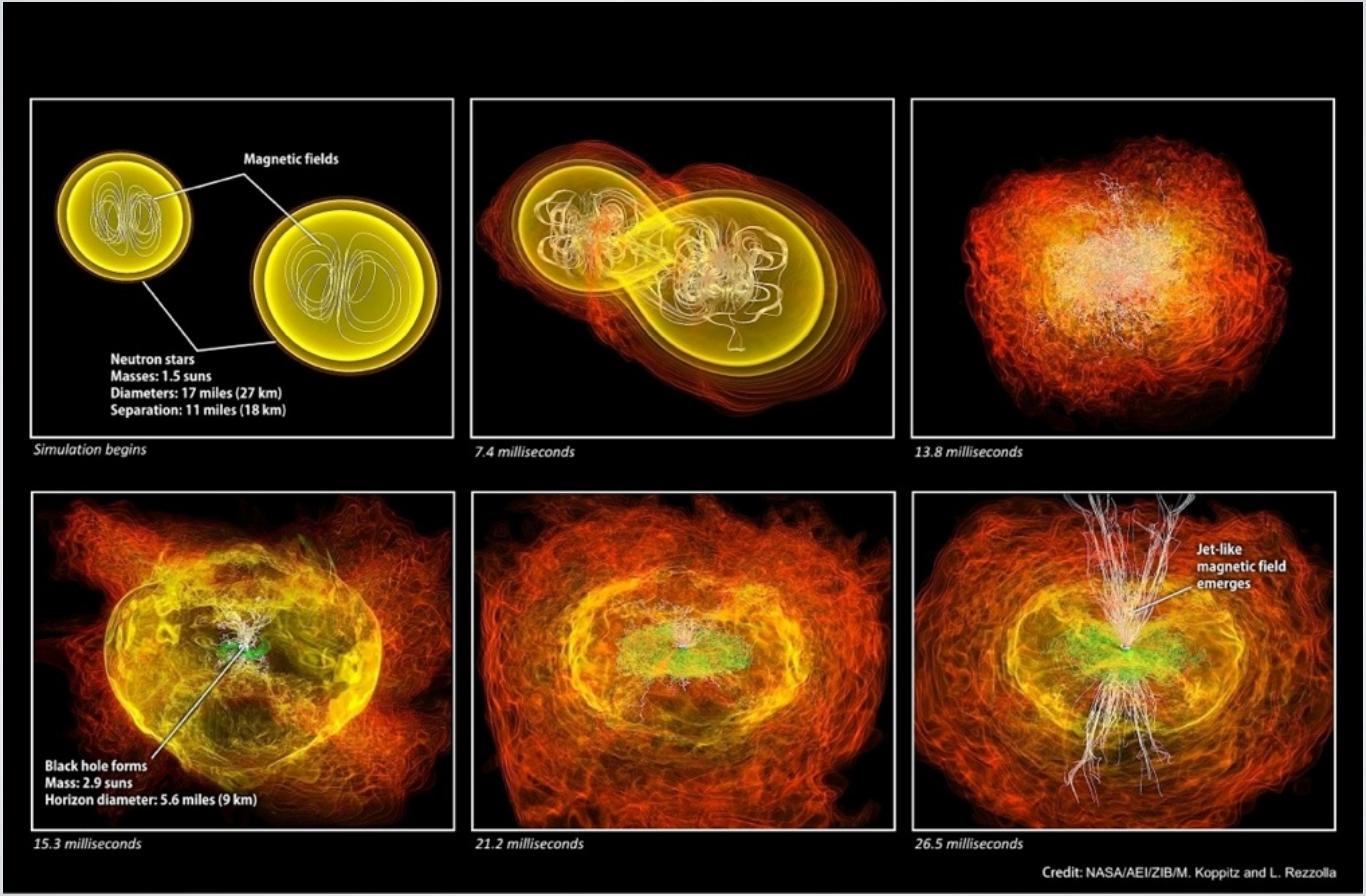
The magnetic field is purely poloidal at the beginning and confined inside the NS



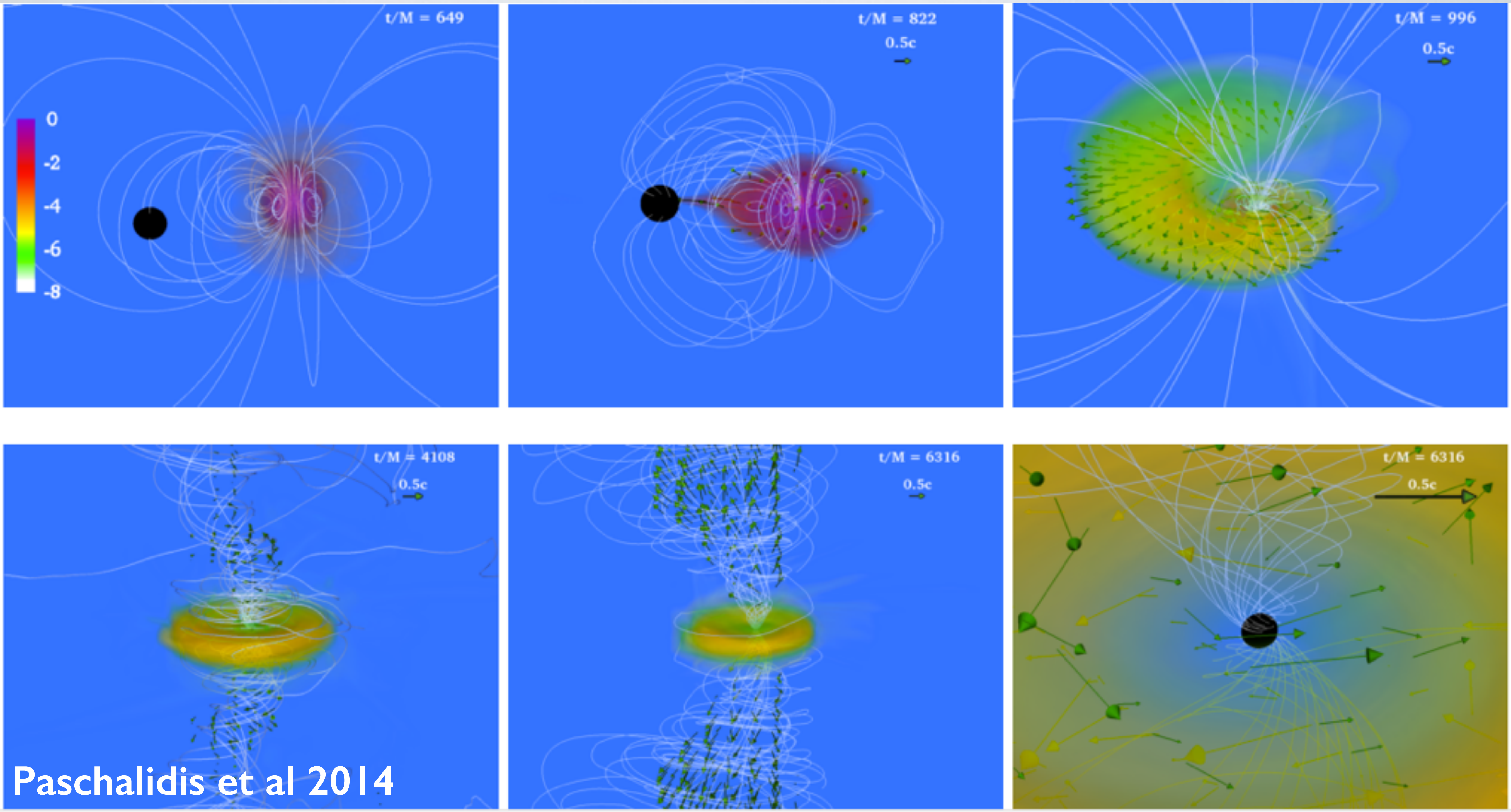
Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti

JETS FROM BNS MERGERS?

Rezzolla, **Giacomazzo**, Baiotti, Granot, Kouveliotou, Aloy 2011, ApJL 732, L6



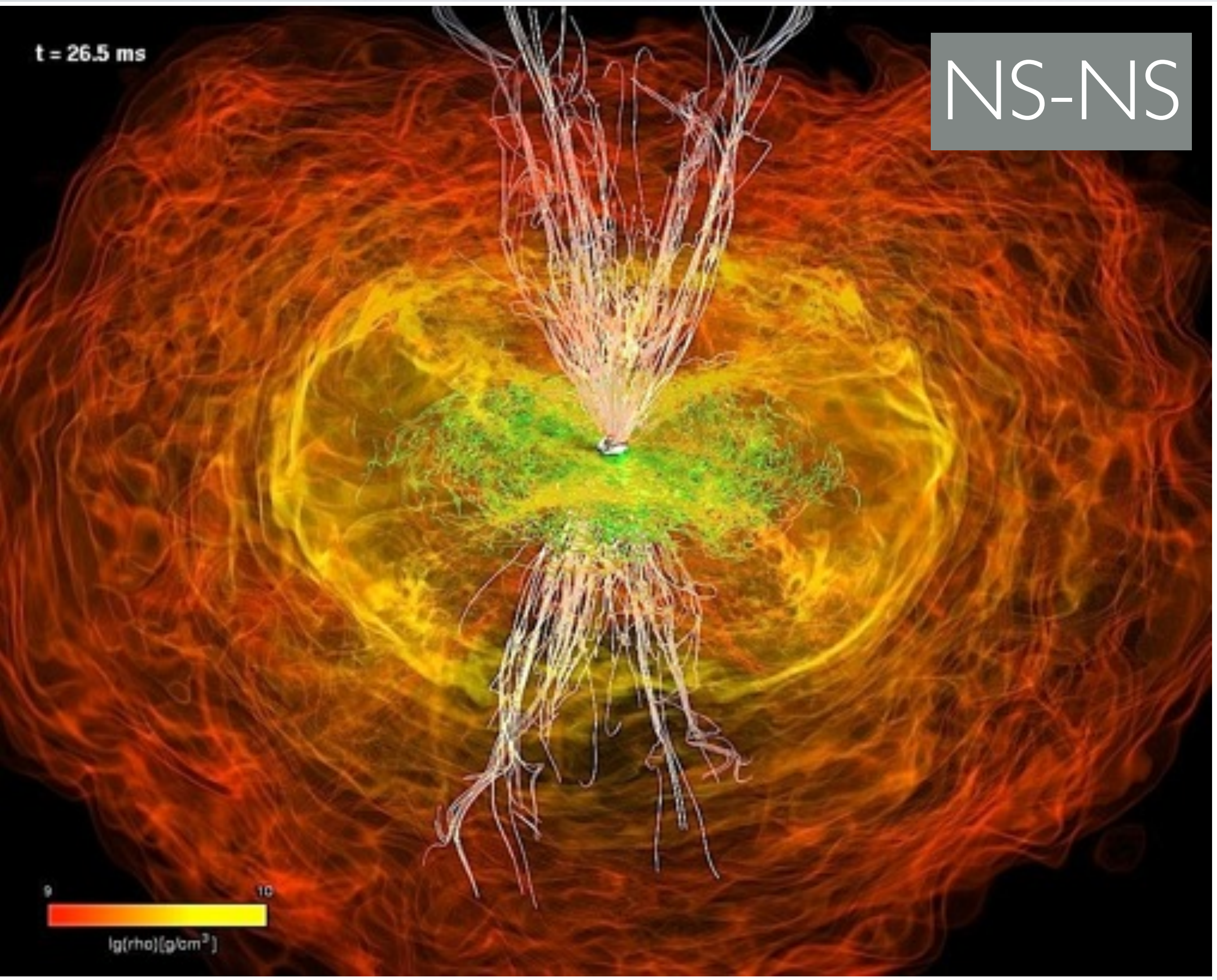
JETS FROM NS-BH MERGERS?



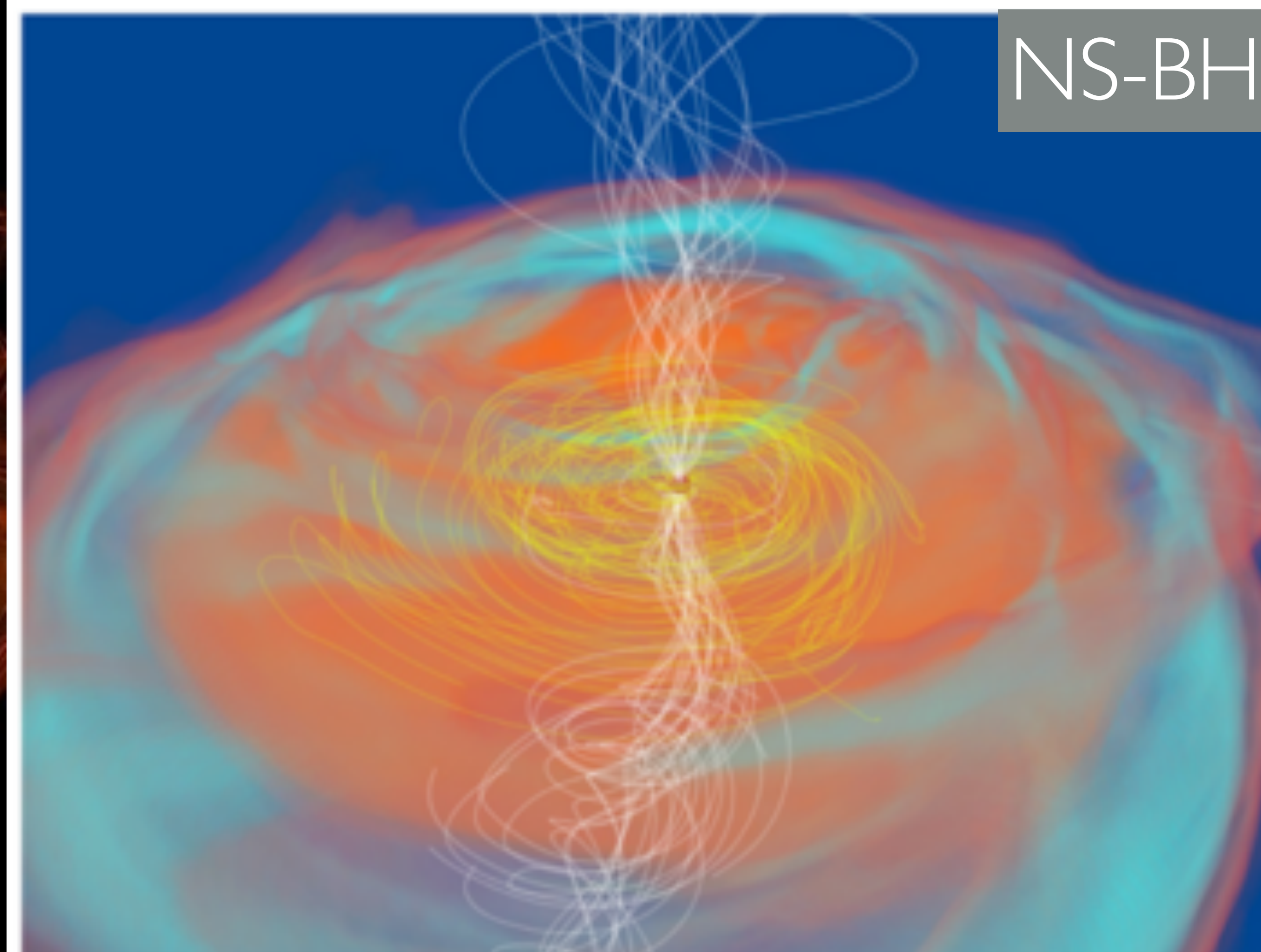
GRMHD simulations of NS-BH have also showed the formation of mildly relativistic jets

COMPACT BINARY PROGENITORS OF SHORT GAMMA-RAY BURSTS

Giacomazzo, Perna, Rezzolla, Troja, Lazzati 2013, ApJL 762, L18



Rezzolla et al 2011, ApJL 732, L6



Etienne et al 2012, PRD 86, 084026

Energy extraction from the disk can power short GRBs.

Can we link SGRBs observations with numerical simulations?

We considered the current sample of SGRBs with measured energies

Table 1
SGRB Sample

GRB Name	z	$E_{\gamma,\rm iso}$ (erg)	ΔE (keV)	$M_{\rm torus}$ ($M_\odot$)
050509B	0.225	9.1×10^{47}	15–150	1.0×10^{-5}
050709(EE)	0.161	3.4×10^{49}	10–10^4	3.8×10^{-4}
050724(EE)	0.257	1.9×10^{50}	15–150	2.1×10^{-3}
051221A	0.546	2.9×10^{51}	10–10^4	3.3×10^{-2}
061006(EE)	0.438	2.1×10^{51}	10–10^4	2.4×10^{-2}
070429B	0.902	2.1×10^{50}	15–150	2.3×10^{-3}
070714B(EE)	0.923	1.6×10^{52}	10–10^4	1.8×10^{-1}
071227(EE)	0.381	1.2×10^{51}	10–10^4	1.4×10^{-2}
080905A	0.122	4.5×10^{49}	10–10^4	5.1×10^{-4}
090510	0.903	4.7×10^{52}	10–10^4	5.2×10^{-1}
100117A	0.920	1.4×10^{51}	10–10^4	1.6×10^{-2}
111117A	1.3	5.3×10^{51}	10–10^4	6.0×10^{-2}
051210	1.3	4.0×10^{50}	15–150	4.5×10^{-3}
060801	1.130	1.9×10^{50}	15–150	2.1×10^{-3}
061210(EE)	0.410	5.6×10^{50}	15–150	6.2×10^{-3}
070724A	0.457	2.3×10^{49}	15–150	2.5×10^{-4}
070729	0.8	1.6×10^{50}	15–150	1.8×10^{-3}
080123(EE)	0.495	5.7×10^{50}	15–150	6.3×10^{-3}
101219A	0.718	7.4×10^{51}	10–10^4	8.2×10^{-2}
060502B	0.287	9.8×10^{48}	15–150	1.1×10^{-4}
061217	0.827	6.8×10^{49}	15–150	7.6×10^{-4}
061201	0.111	9.4×10^{48}	15–150	1.1×10^{-4}
070809	0.473	7.9×10^{49}	15–150	8.8×10^{-4}
090515	0.403	1.0×10^{49}	15–150	1.2×10^{-4}

We made the following assumptions:

- SGRBs are powered via magnetic fields
- SGRBs energy is provided by the disk
- Efficiency is constant

$$E_{\gamma,\rm iso} = \epsilon M_{\rm torus} c^2$$

$$\epsilon \equiv \epsilon_{\rm jet}\epsilon_\gamma$$

$$\epsilon_{\rm jet} = 10\%$$

$$\epsilon_\gamma = 50\%$$

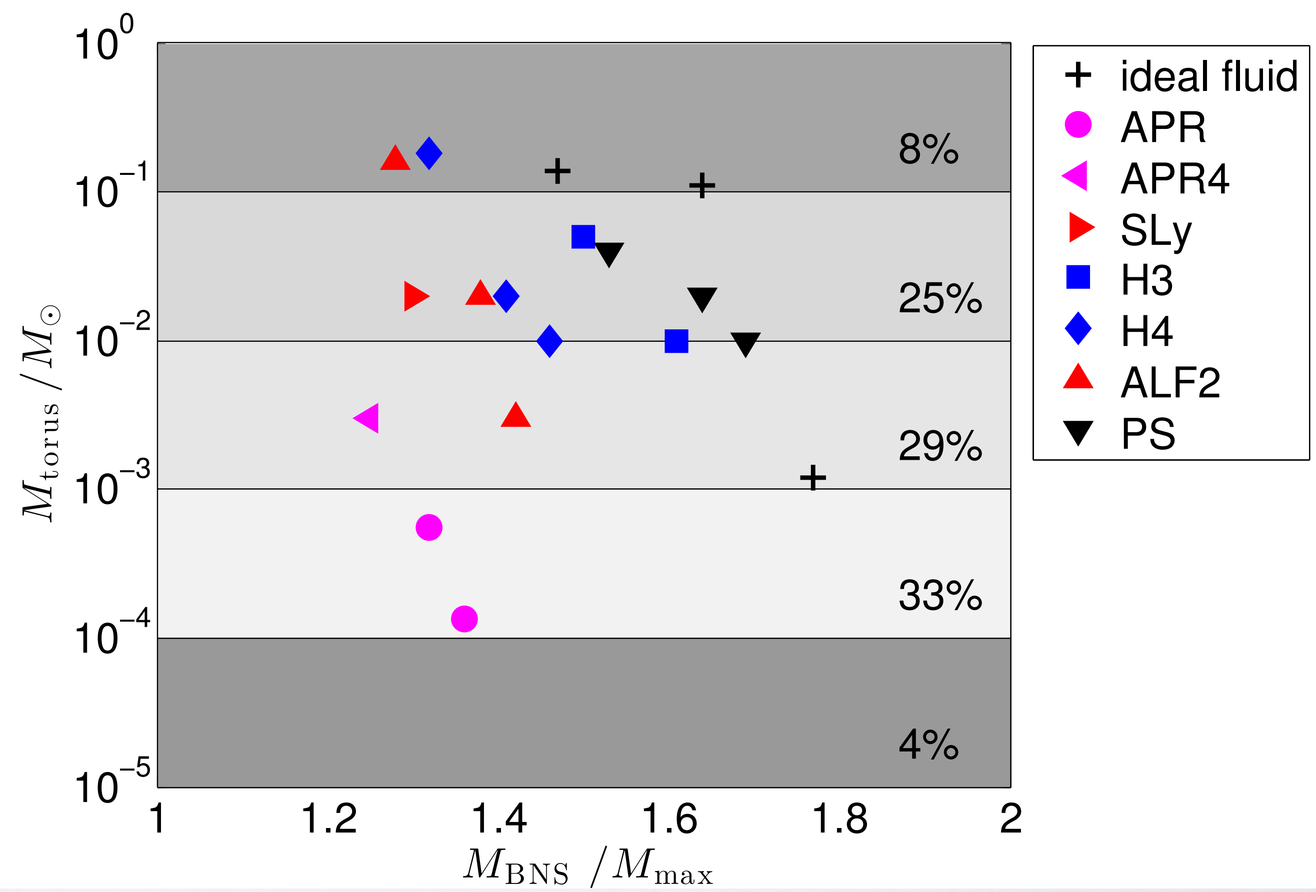
$\varepsilon_{\rm jet}$ is inferred from disk simulations (Fragile, McKinney, Tchekhovskoy, ...)

ε_γ is derived from observations (e.g., Zhang et al 2007)

We then considered a sample of 25 accurate GR BNS simulations

Table 2
BNS Simulations and Torus Masses

Model	M_{BNS} ($M_\odot$)	q	M_{torus} ($M_\odot$)	M_{max} ($M_\odot$)	M_{BNS}/M_{max}
1.46-45-IF	3.24	1.00	0.1374	2.20	1.47
1.62-45-IF	3.61	1.00	0.1101	2.20	1.64
M3.6q1.00	3.90	1.00	0.0012	2.20	1.77
M3.7q0.94	4.03	0.94	0.0121	2.20	1.83
M3.4q0.91	3.76	0.92	0.1202	2.20	1.71
M3.4q0.80	3.72	0.81	0.2524	2.20	1.69
M3.5q0.75	3.80	0.77	0.1939	2.20	1.73
M3.4q0.70	3.71	0.72	0.2558	2.20	1.69
APR145145	2.87	1.00	0.000549	2.18	1.32
APR1515	2.97	1.00	0.000134	2.18	1.36
APR1316	2.87	0.81	0.0275	2.18	1.32
APR135165	2.97	0.82	0.00707	2.18	1.36
APR4-28	2.77	1.00	0.003	2.21	1.25
SLy-27	2.67	1.00	0.02	2.05	1.30
H3-27	2.68	1.00	0.05	1.79	1.50
H3-29	2.87	1.00	0.01	1.79	1.61
H4-27	2.68	1.00	0.18	2.03	1.32
H4-29	2.87	1.00	0.02	2.03	1.41
H4-30	2.97	1.00	0.01	2.03	1.46
ALF2-27	2.67	1.00	0.16	2.09	1.28
ALF2-29	2.87	1.00	0.02	2.09	1.38
ALF2-30	2.97	1.00	0.003	2.09	1.42
PS-27	2.68	1.00	0.04	1.76	1.53
PS-29	2.88	1.00	0.02	1.76	1.64
PS-30	2.97	1.00	0.01	1.76	1.69



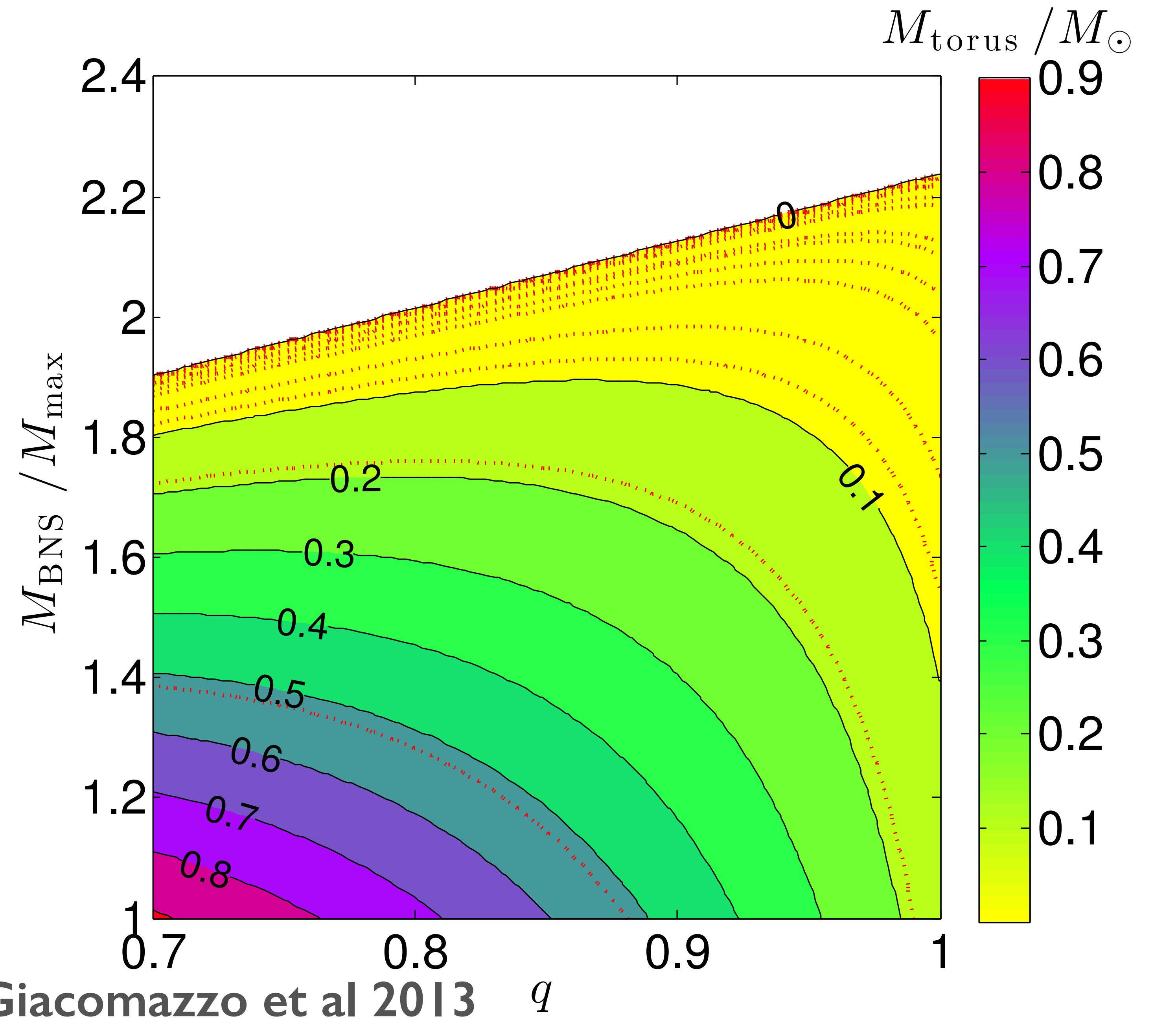
Giacomazzo et al 2013

And we compared their torus masses with the distribution derived from observations

Note that most SGRBs requires tori with masses <~0.1 $M_\odot$

From the BNS simulations we computed a fit to relate the mass of the torus to the NS masses and their mass ratio q:

$$M_{\rm torus} = [c_1(1-q) + c_2][c_3(1+q) - M_{\rm BNS}/M_{\rm max}]$$

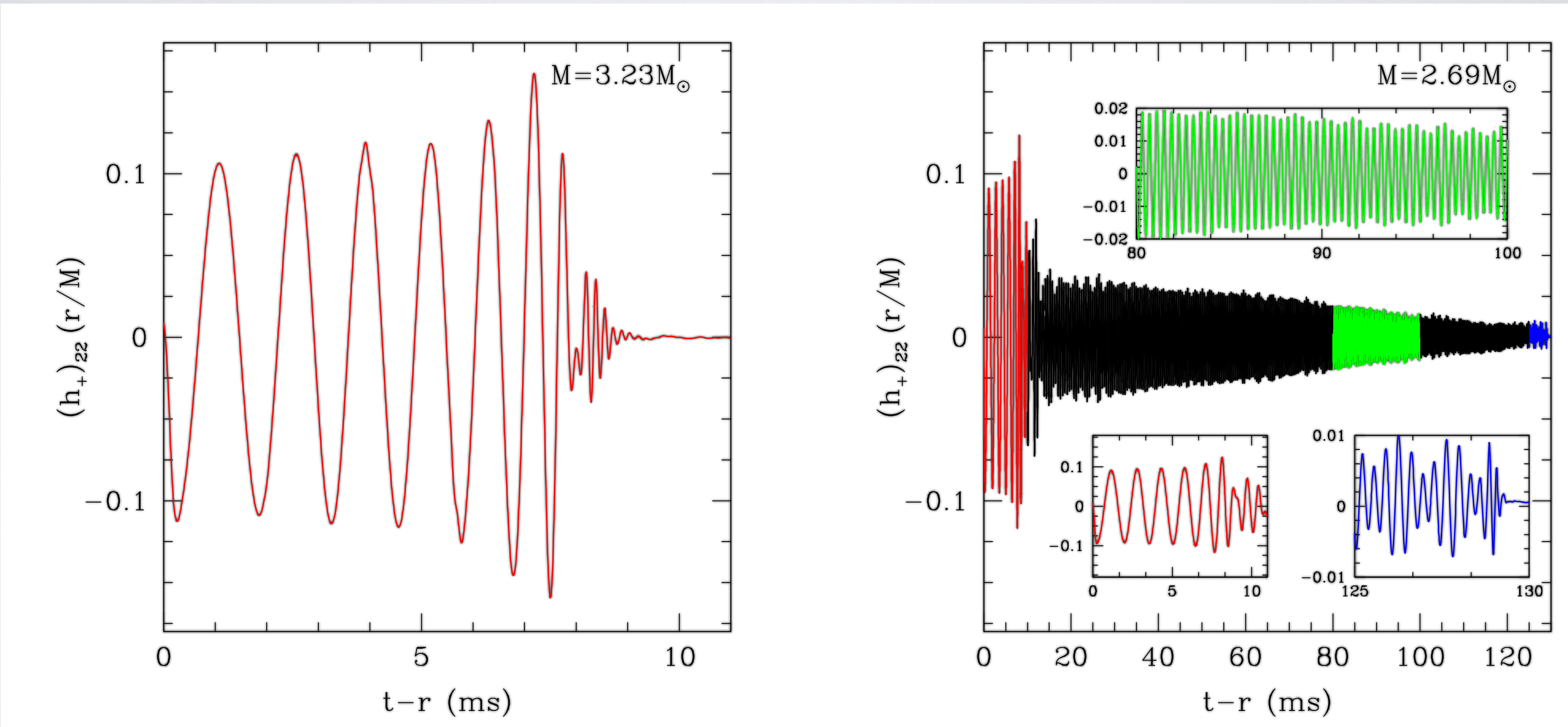


Giacomazzo et al 2013

Almost all SGRBs are produced by high-mass BNSs. These BNSs produce an HMNS that survive only few ms before collapse to BH.

"low-energy" SGRBs
(<~1e51 erg)
↓
"high-mass" BNSs

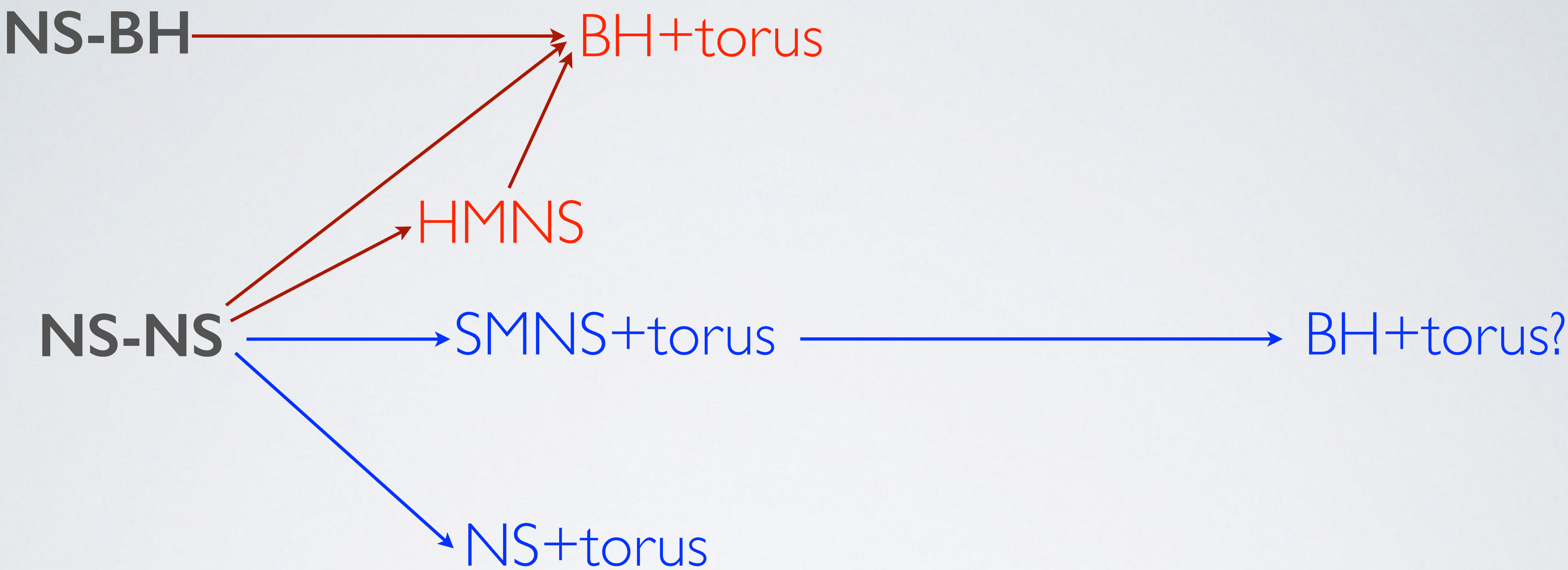
"high-energy" SGRBs
(>~1e51 erg)
↓
"low-mass" BNSs



Simultaneous GW/EM detection will help validate this model

IS THIS THE FULL STORY?

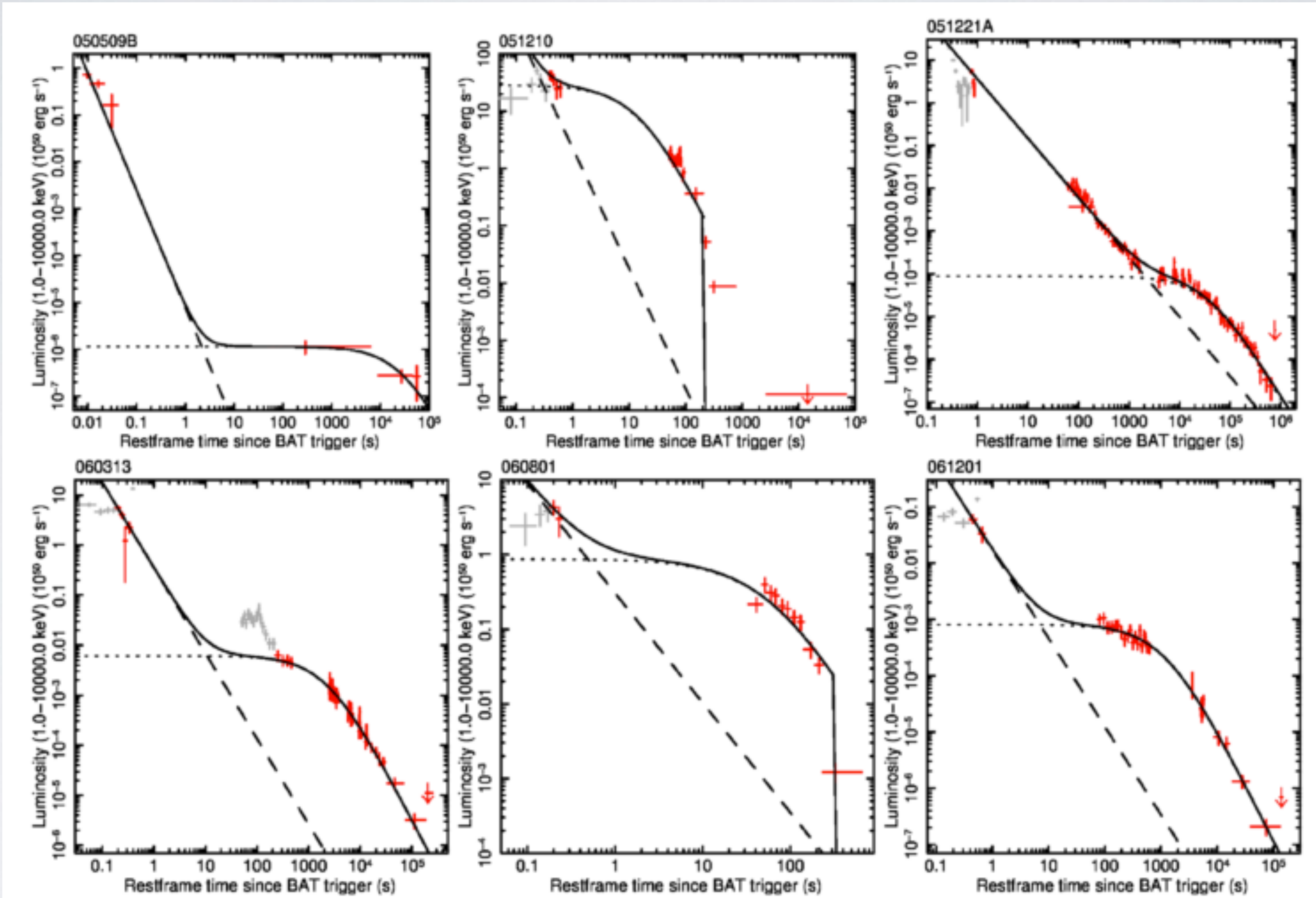
Depending on mass and EOS several post-merger scenarios:



What about the blue path?


Credit: The Matrix (1999)

WHY DO WE NEED A MAGNETAR?

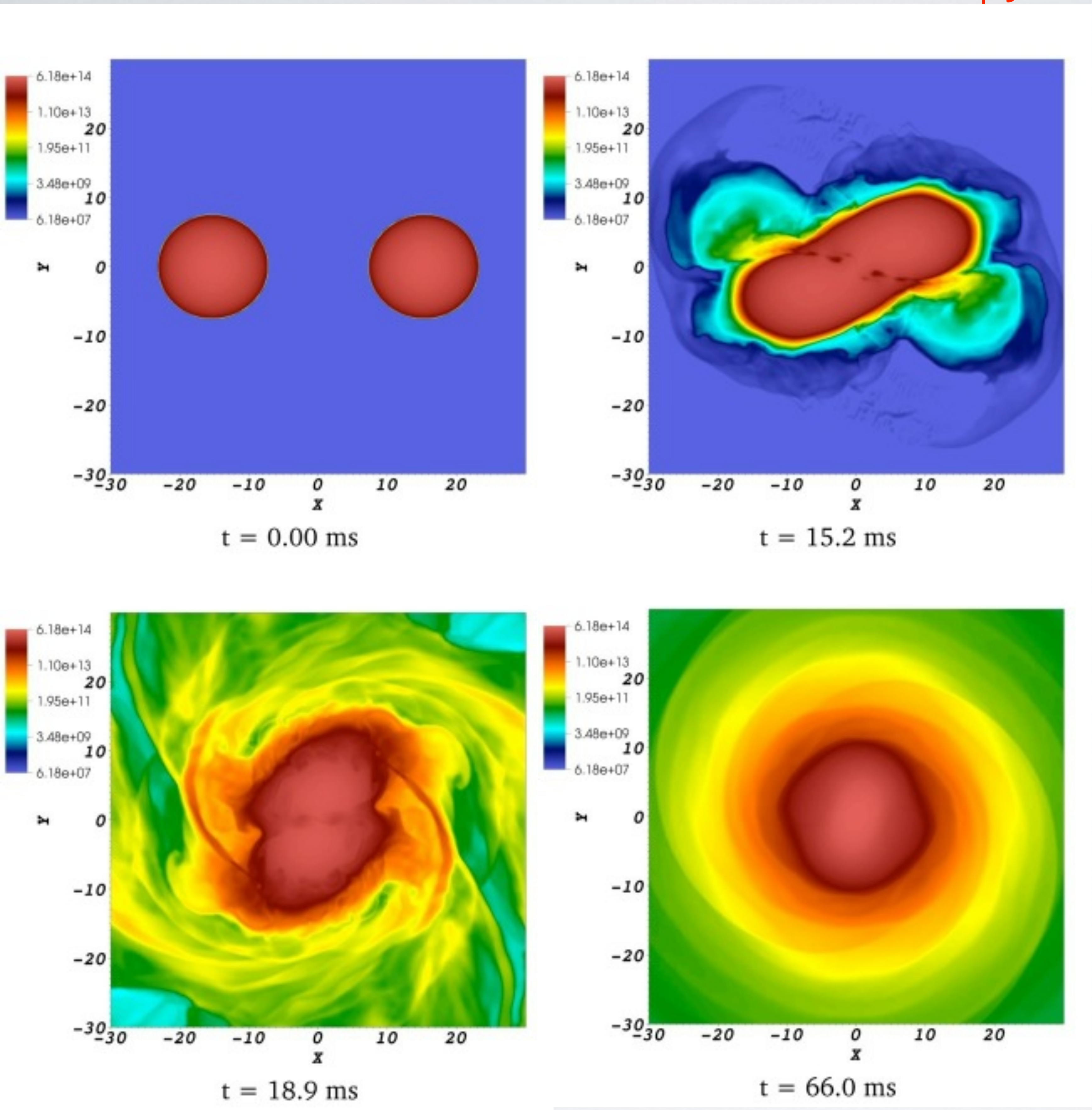


Rowlinson et al 2013

A stable or supramassive magnetar could be used to explain X-ray plateaus and extended emissions from SGRBs (e.g., Rowlinson et al 2013).

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26



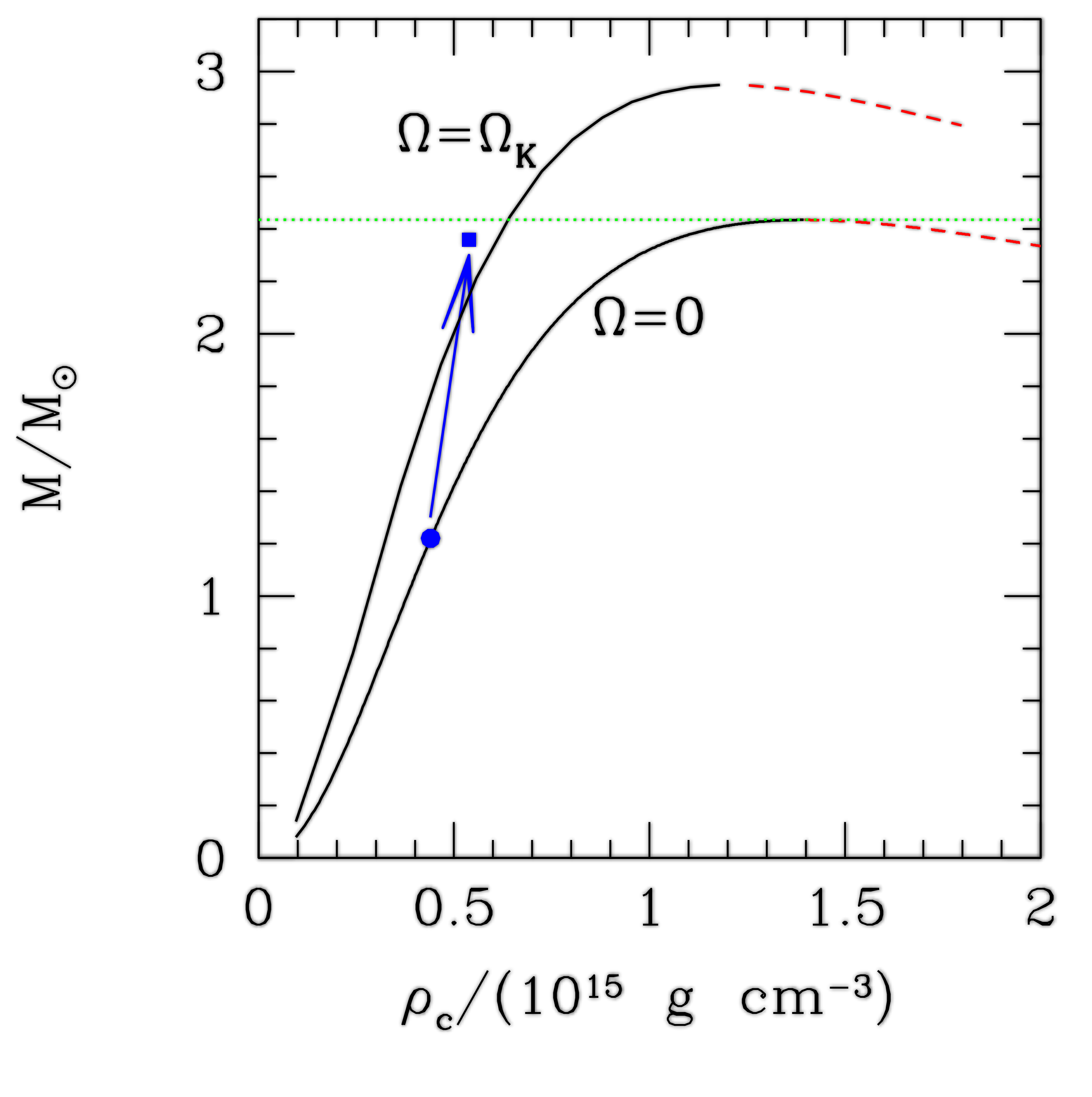
Investigated merger of two 1.2 $M_\odot$ NSs

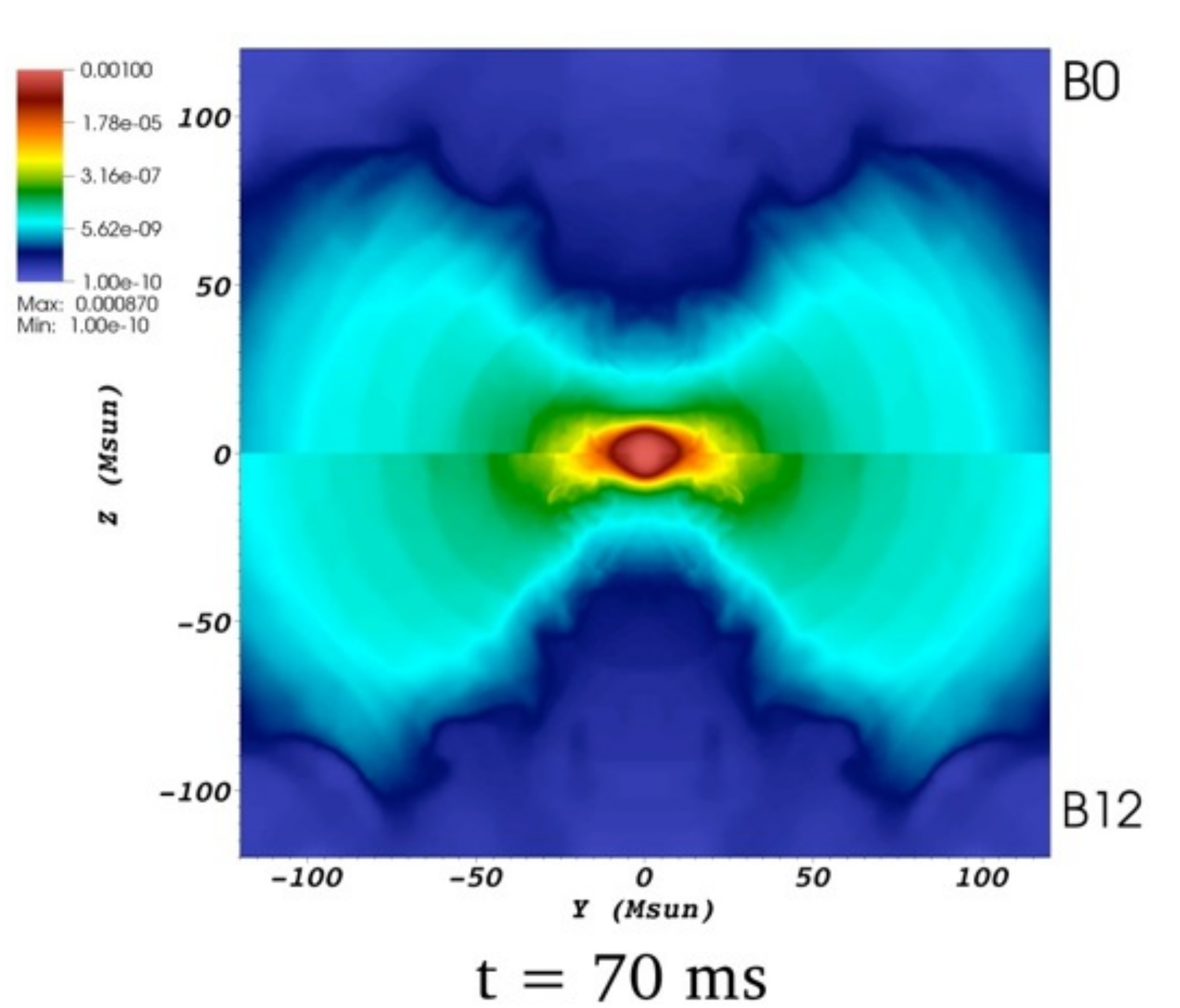
Used Ideal Fluid, Gamma=2.75, k=30000 (Oechslin et al 2007)

Formation of stable magnetar could explain some SGRB features (e.g., Dai et al 2006, Rowlinson et al 2013)

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26

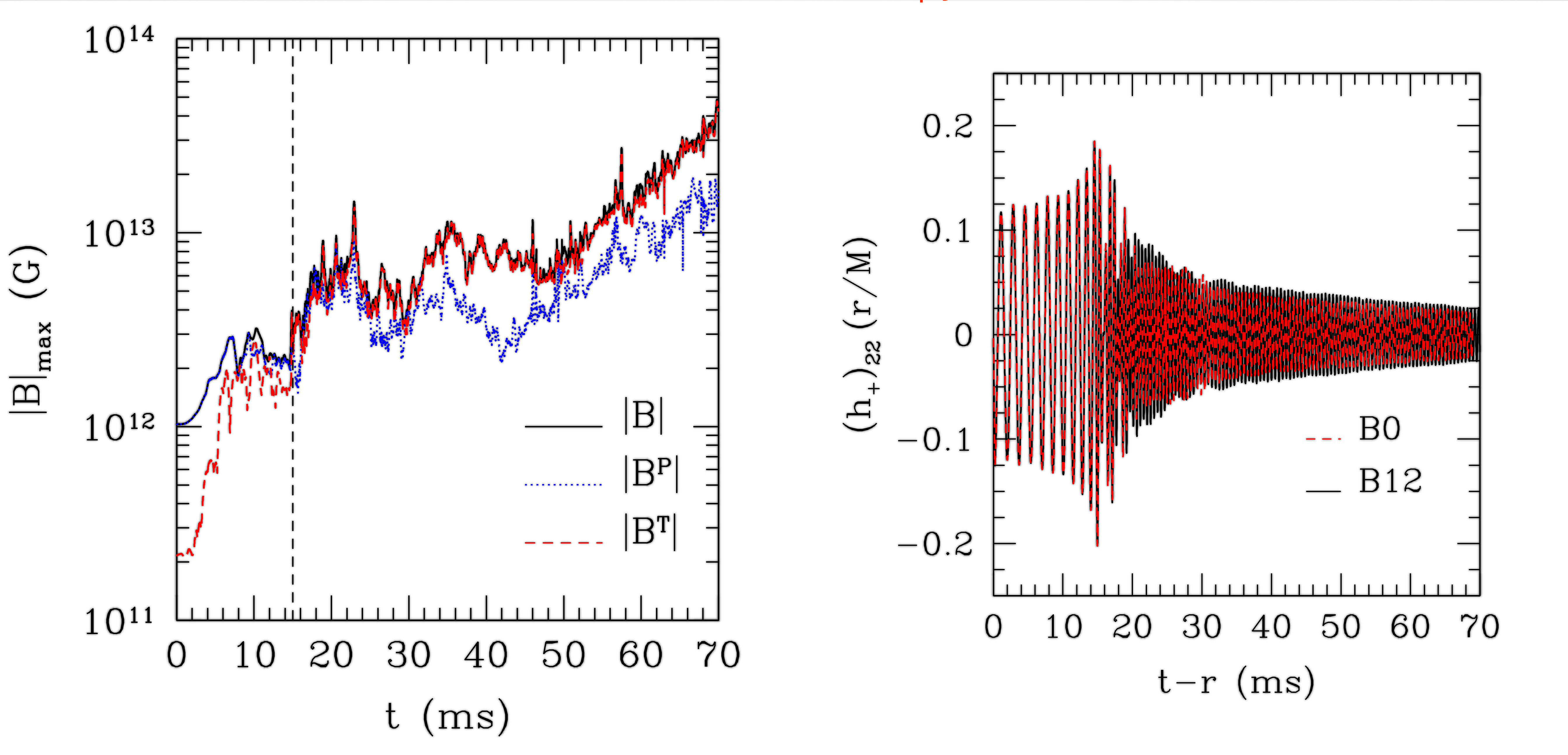




Produced a stable "ultraspinning" NS surrounded by a magnetized disk of ~0.1 $M_\odot$

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26

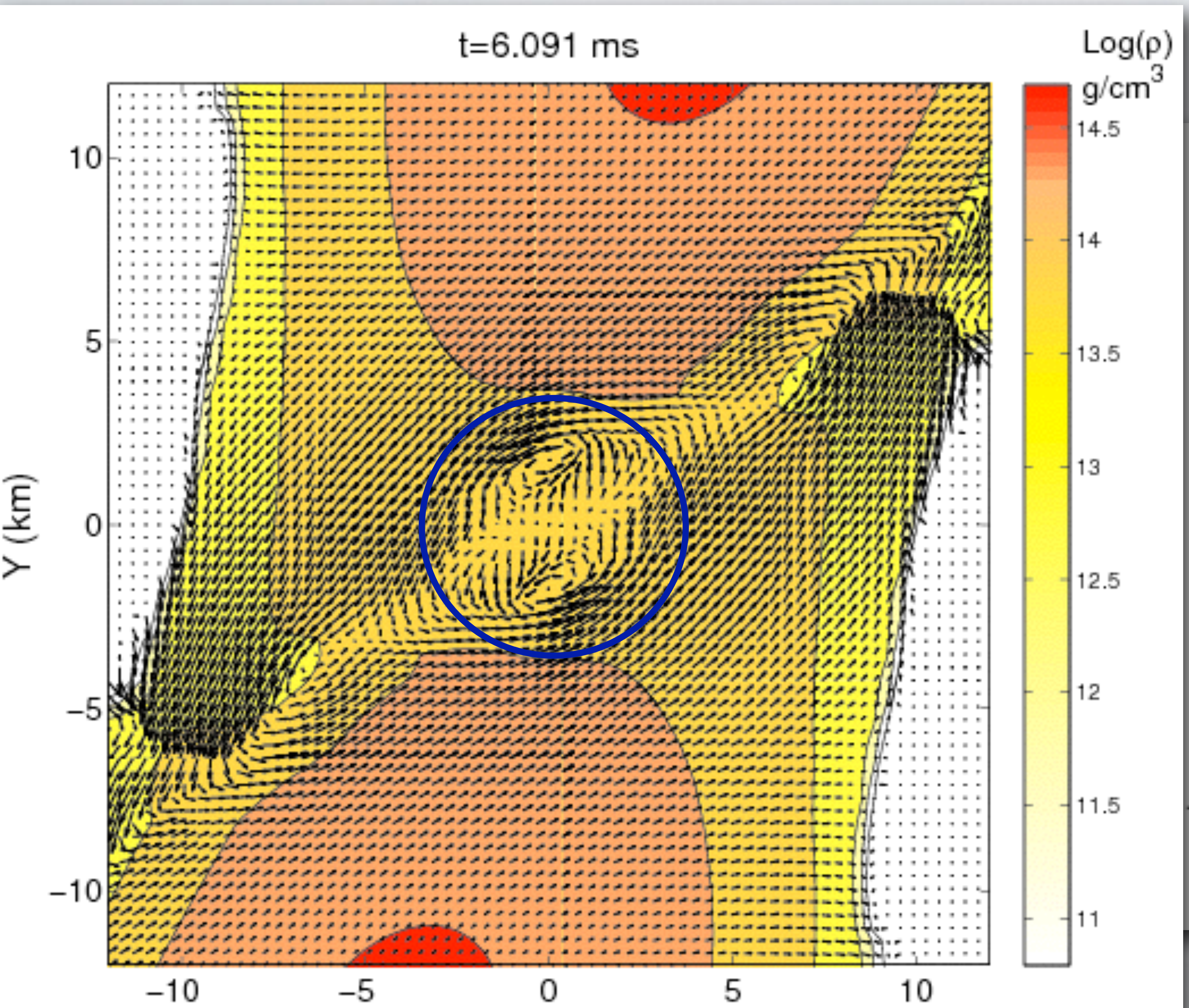


Magnetic field amplified of ~2 orders of magnitude. Difference in the GW signal are small and present only in the post-merger phase.

GWs publicly available for download at www.brunogiacomazzo.org/data.html

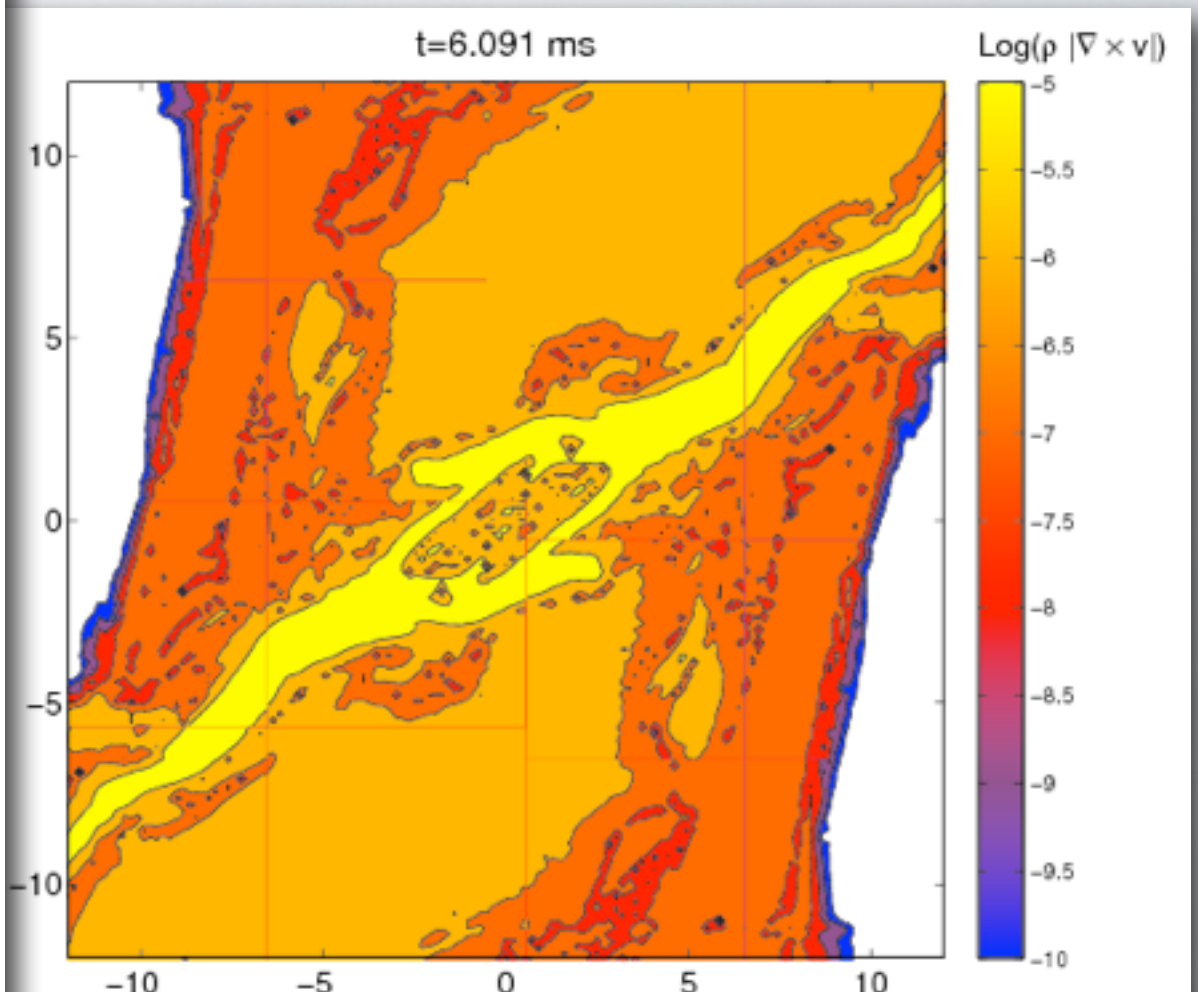
MAGNETIC FIELD AMPLIFICATION AT MERGER

During the merger a shear interface forms and it develops a Kelvin-Helmholtz instability which produces a series of vortices.



Baiotti et al 2008

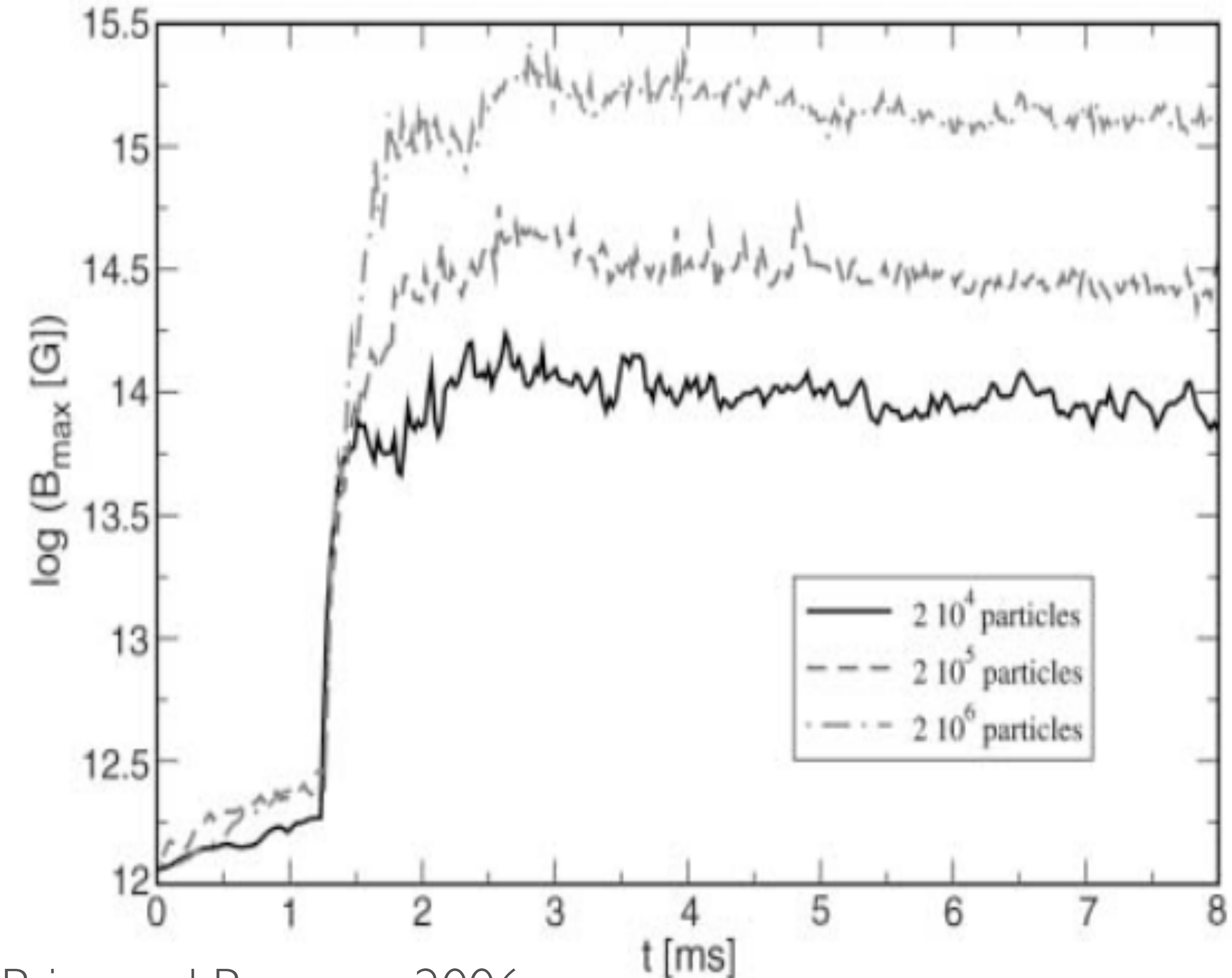
$$(v^x, v^y)$$ in "corotating" frame



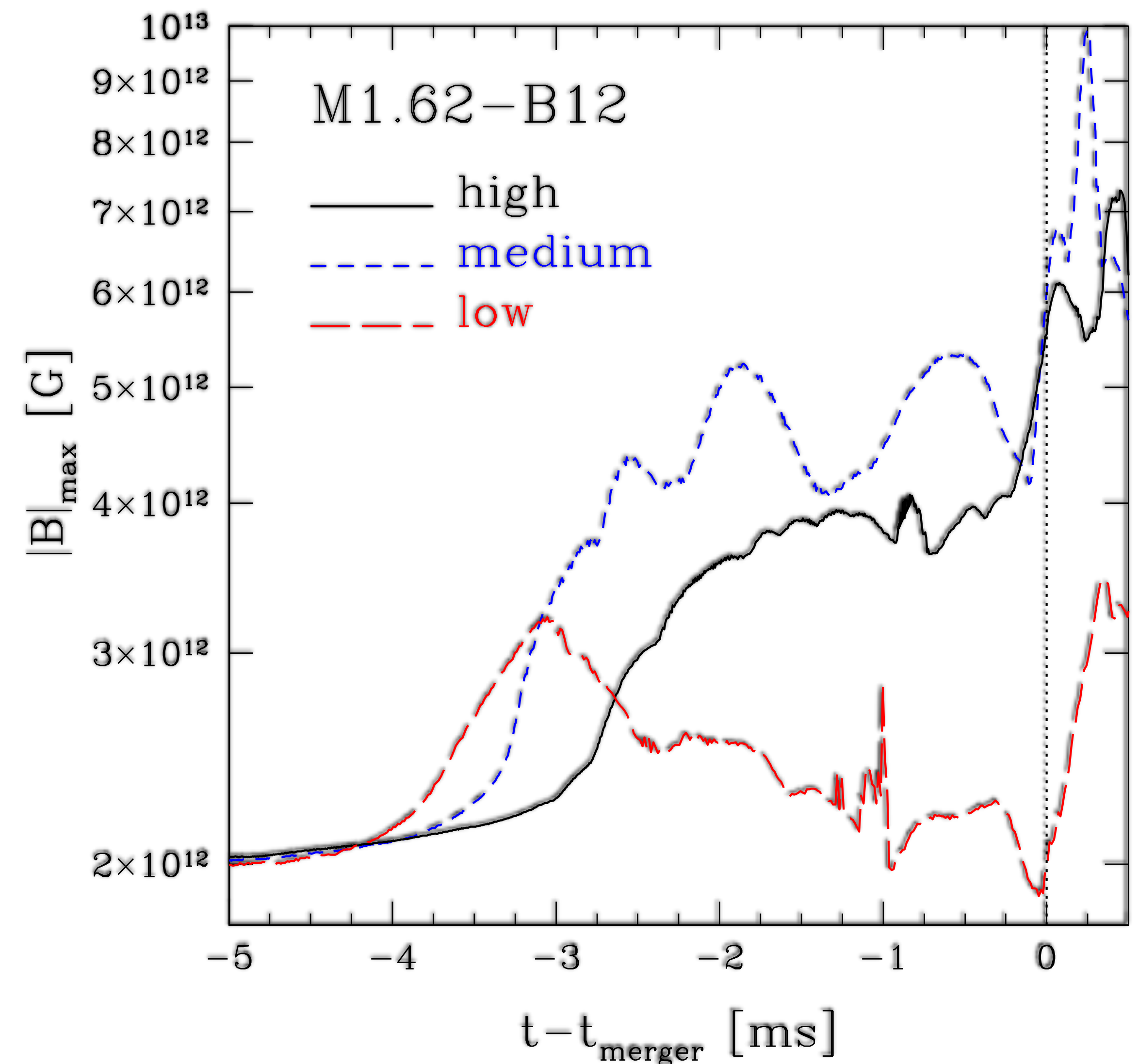
Baiotti et al 2008

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

MAGNETIC FIELD AMPLIFICATION AT MERGER



Price and Rosswog 2006



Giacomazzo et al 2011

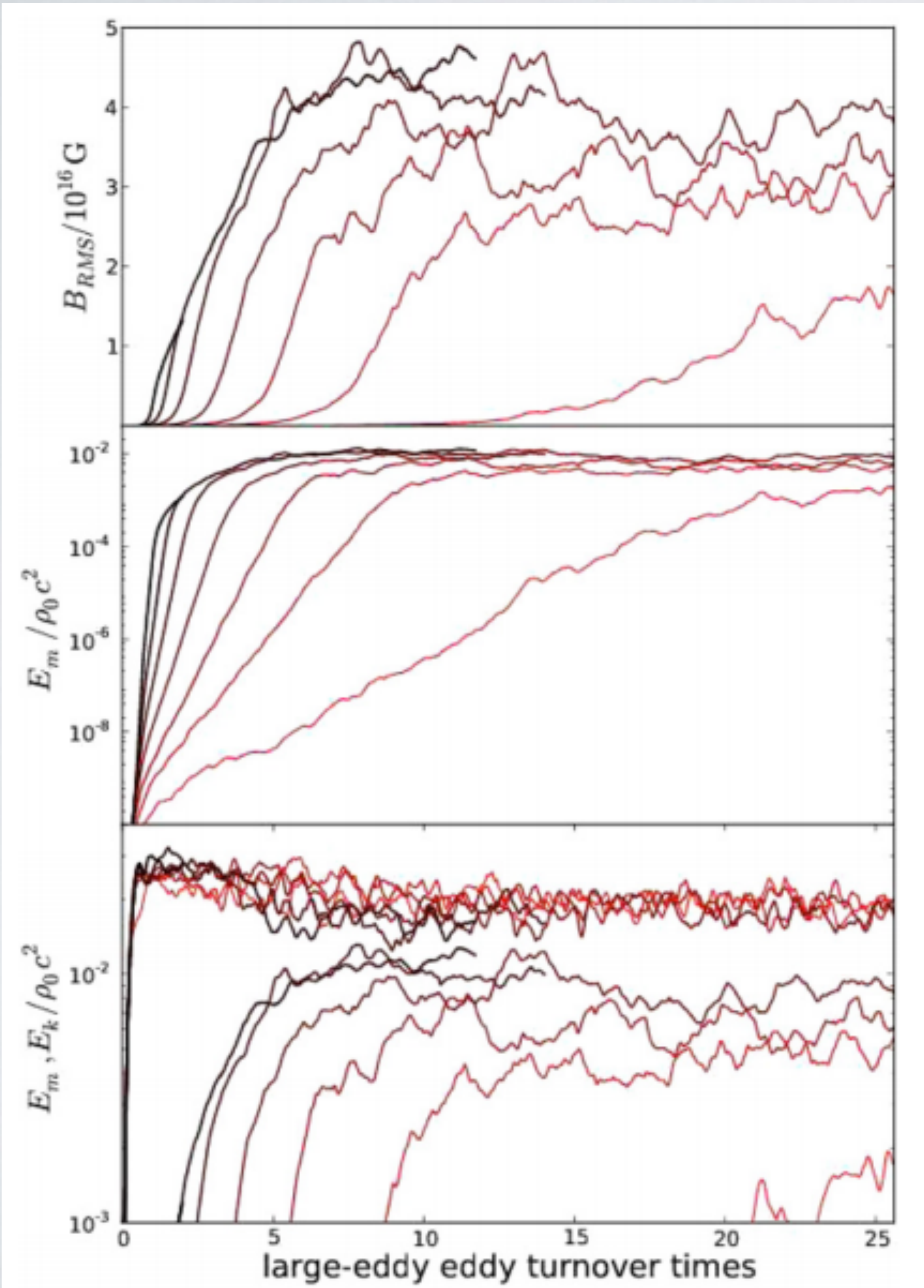
Previous Newtonian simulations by Price and Rosswog showed large magnetic field amplification (but not reproduced by other groups).

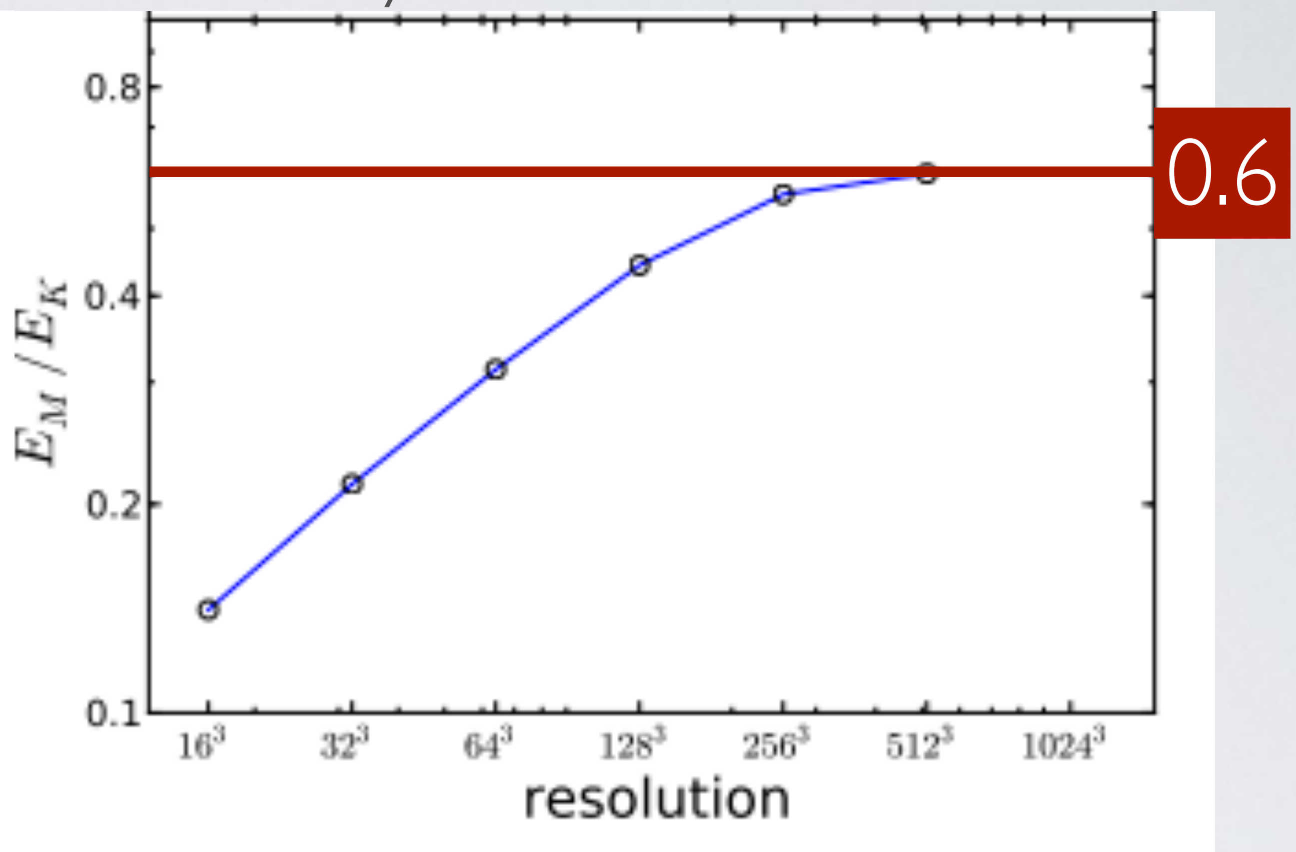
Even with high res we do not observe amplifications of several orders of magnitudes (similar results by other GR groups).

Local very high-res simulations shows that magnetic fields could be strongly amplified (Zrake & MacFadyen 2013), but res unfeasible for global BNS sims!

LOCAL SIMULATIONS

Zrake and MacFadyen 2013





Performed local high-res relativistic MHD simulations of turbulent flows.

Magnetic energy reaches equipartition with kinetic energy

Similar results (in Newtonian MHD) were obtained by Obergaulinger et al 2010

MAGNETIC FIELD AMPLIFICATION AT MERGER

Giacomazzo, Zrake, Duffell, MacFadyen, Perna 2014, submitted

We developed a sub-grid model to account for small scale effects:

$$\partial_t A_i = -E_i + S_{\rm subgrid}\, A_i$$

$$S_{\rm subgrid} \equiv c_1 \max\left(|\nabla \times v| - c_3, 0\right) \times \max\left(1 - c_4 \frac{\rho_{\rm atmo}}{\rho}, 0\right) \times \max\left(1 - \frac{b^2}{c_2 \Delta w}, 0\right)$$

where $w \equiv \rho + \rho\epsilon$ is the energy density and

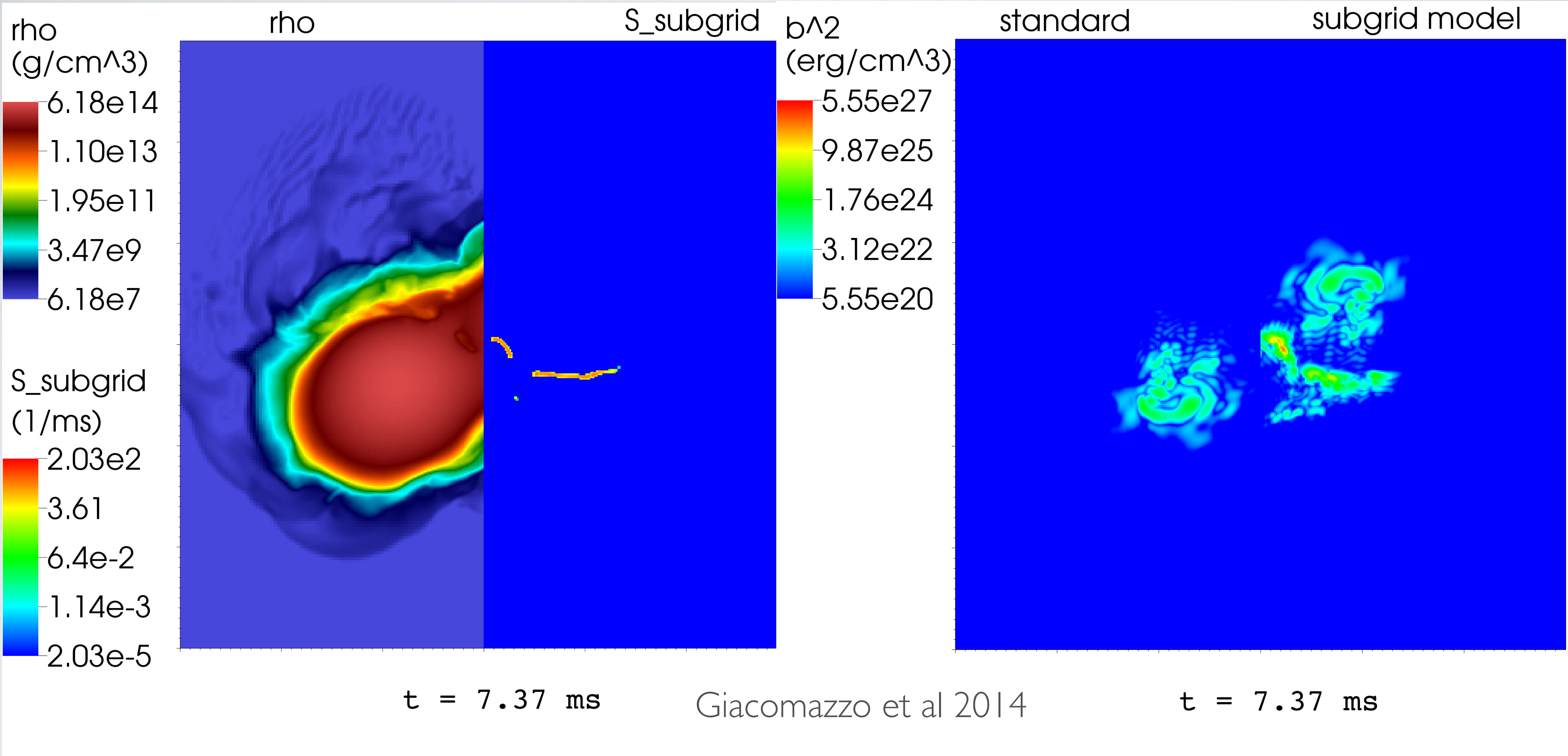
$$\Delta w \equiv <\rho>_{Cons} + <\rho\epsilon>_{Cons} - <\rho>_{Vol} - <\rho\epsilon>_{Vol}$$

which is equal to the turbulent kinetic energy (Duffel and MacFadyen 2013).

This model has four parameters: two need to be fine tuned (c_3 and c_4) and two (c_1 and c_2) are based on local simulations (Zrake & MacFadyen 2013).

MAGNETIC FIELD AMPLIFICATION AT MERGER

Giacomazzo, Zrake, Duffell, MacFadyen, Perna 2014, submitted



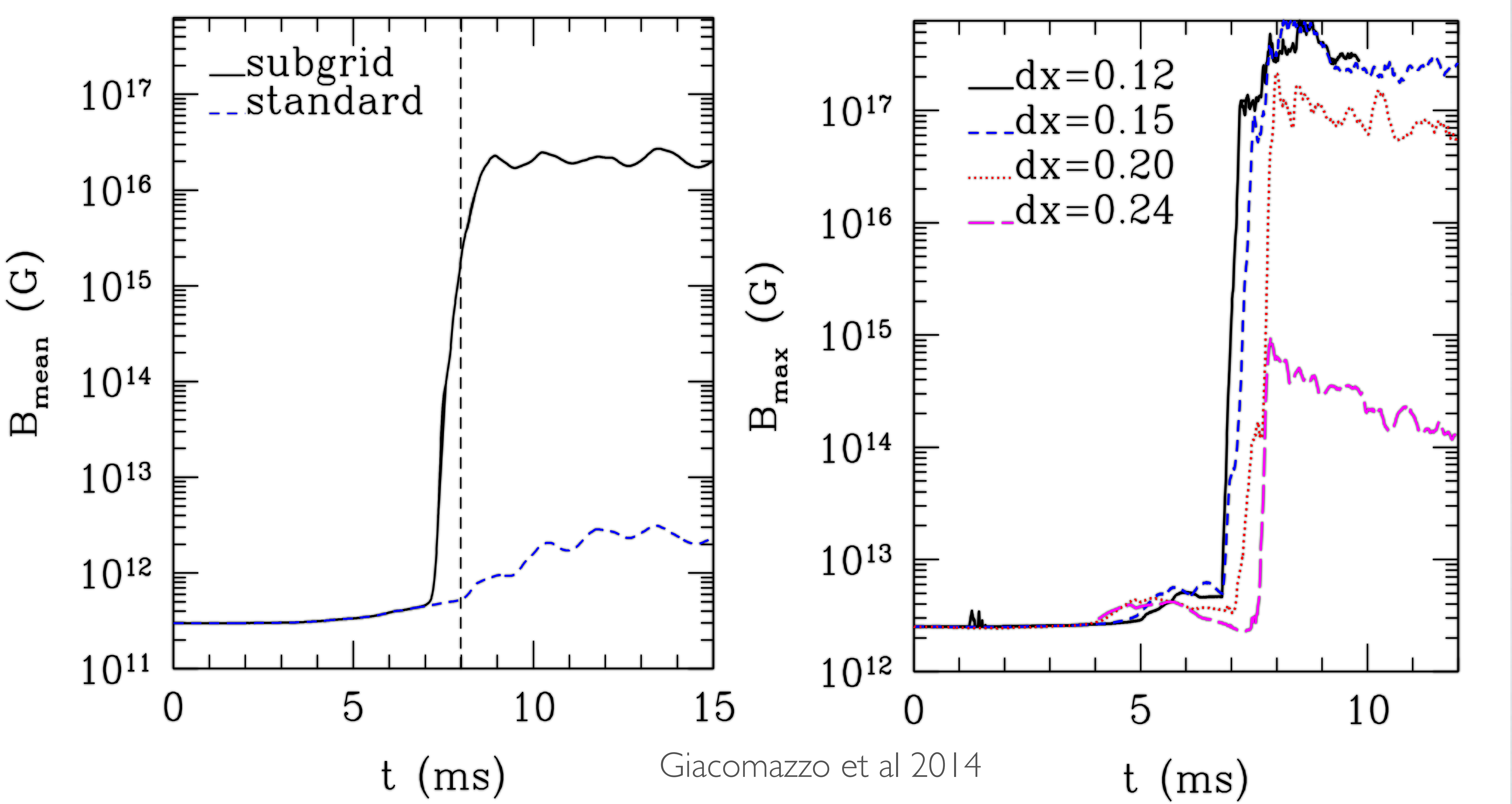
Giacomazzo et al 2014

$S_{\rm subgrid}$ is different from zero only in the central turbulent region.
Magnetic field amplification is larger in the central vortices.

MAGNETIC FIELD AMPLIFICATION AT MERGER

Giacomazzo, Zrake, Duffell, MacFadyen, Perna 2014, submitted

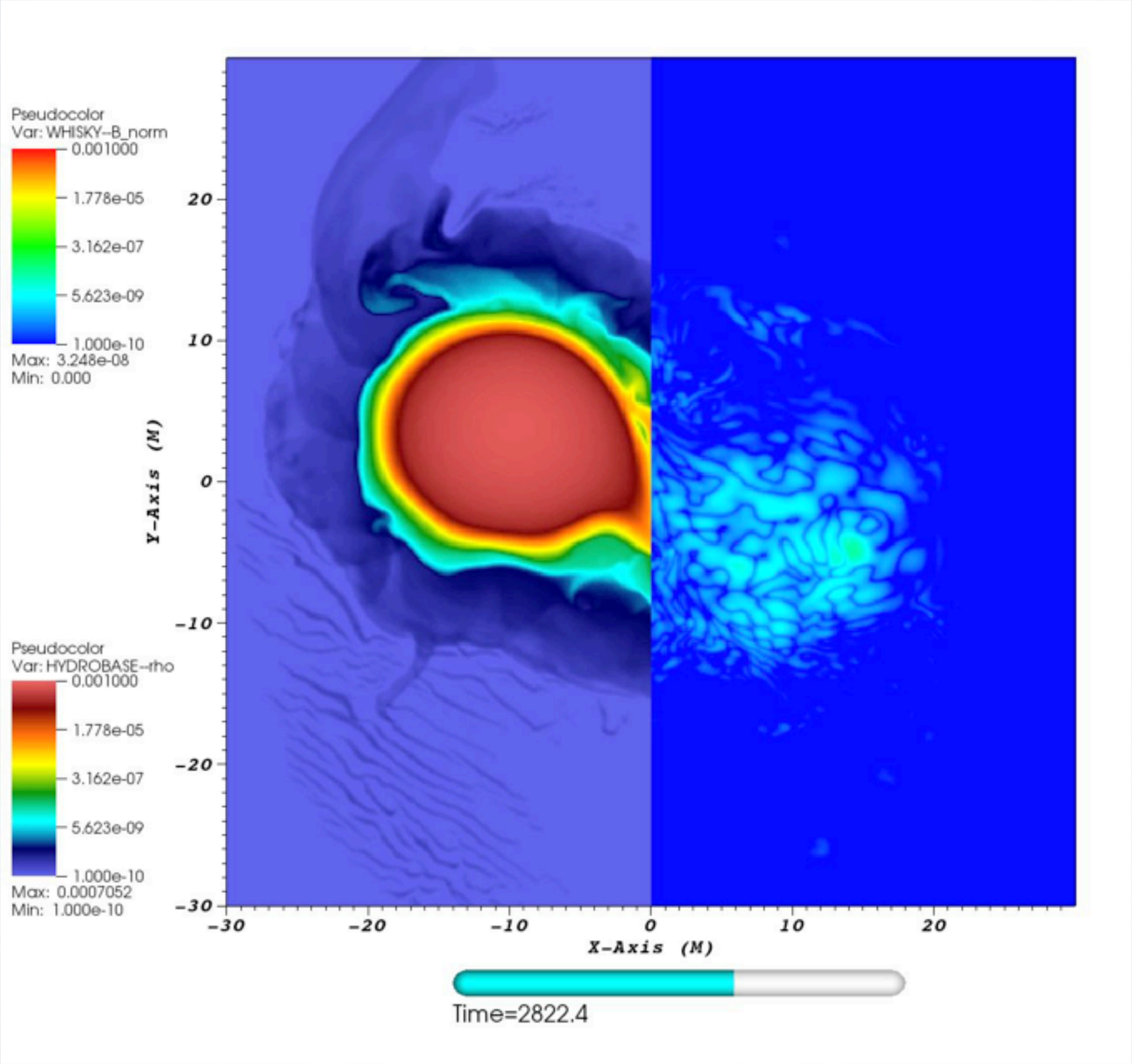
We implemented a sub-grid model in our GRMHD code Whisky and run a set of high-mass NS-NS simulations.



Giacomazzo et al 2014

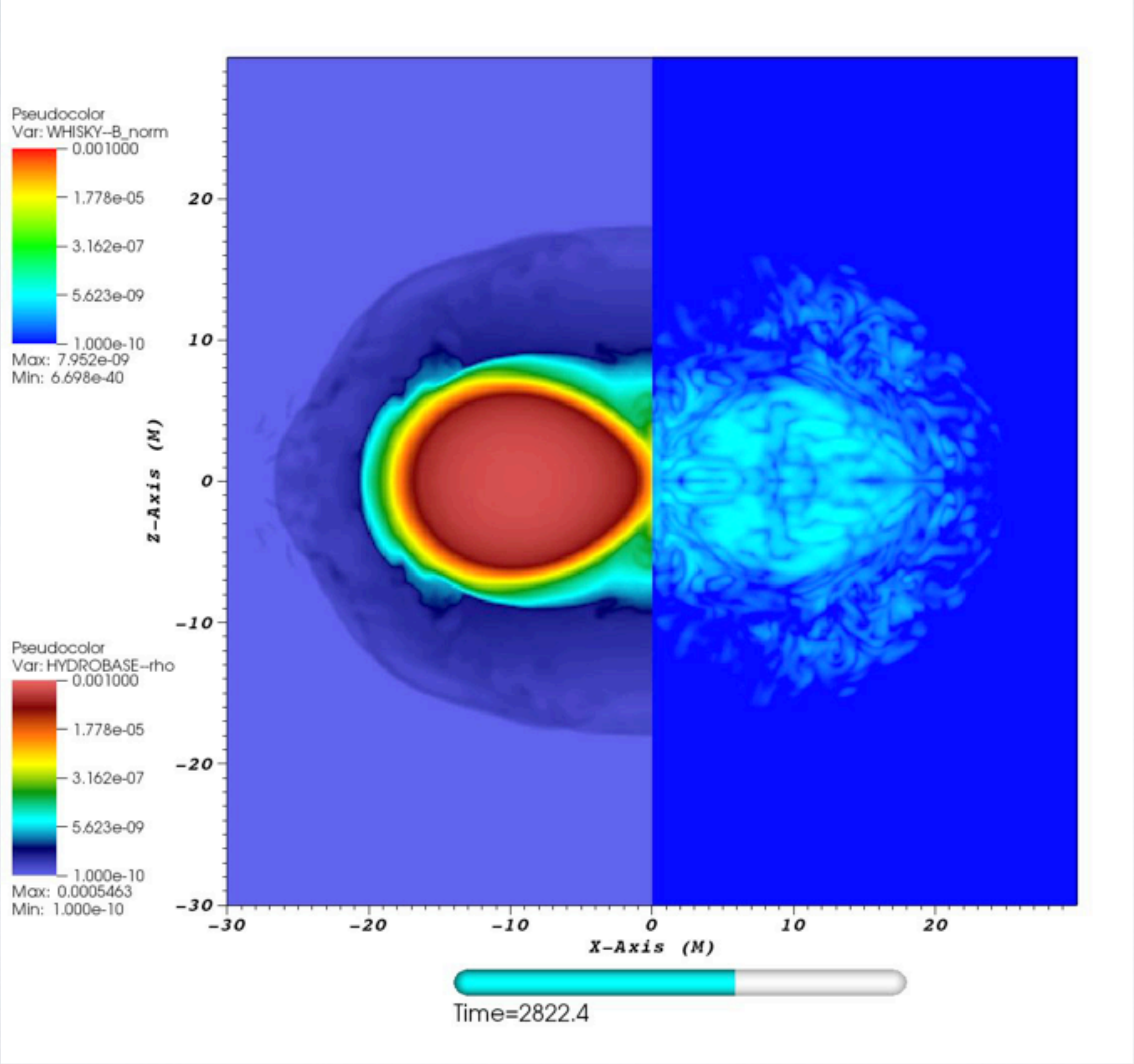
AND FINALLY A MAGNETAR…

Giacomazzo, et al 2015, in preparation



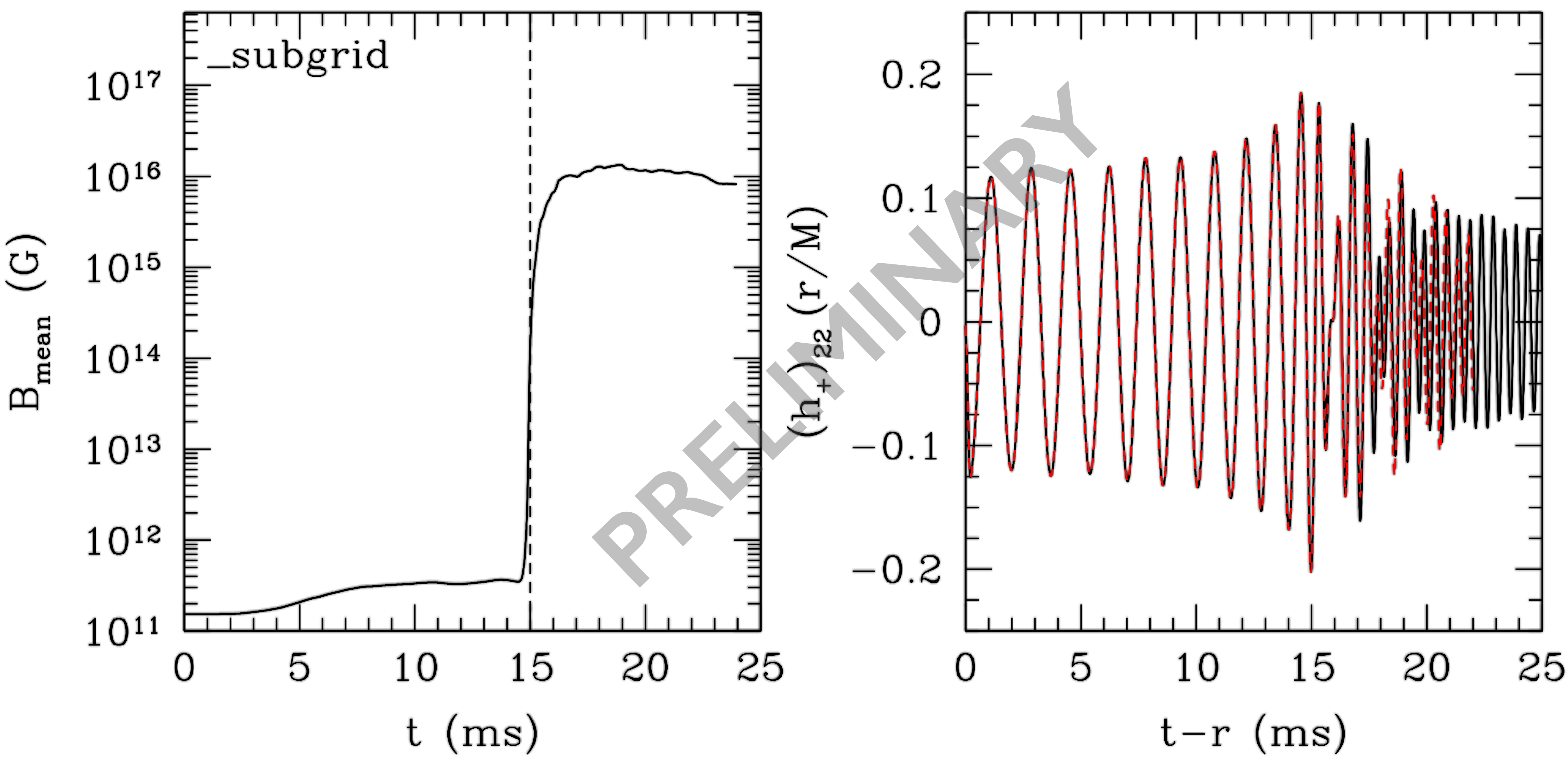
AND FINALLY A MAGNETAR…

Giacomazzo, et al 2015, in preparation



AND FINALLY A MAGNETAR…

Giacomazzo, et al 2015, in preparation



Magnetic field reaches magnetar values, but impact on GWs seems to be still small (but longer sim needed).

CONCLUSIONS

- GRMHD simulations of BNSs now able to study all phases of merger
- Possible to study both the "standard" SGRB and the magnetar models
- in "standard" SGRBs model "high-mass" BNSs are preferred:
  - less energetic SGRBs are powered by high-mass BNSs
  - more energetic ones by low-mass BNSs
- Magnetar model requires accurate magnetic field evolution
- Crucial to resolve small scale turbulence
- EM observations (kilonova) and GW detections may help us to distinguish between the different models