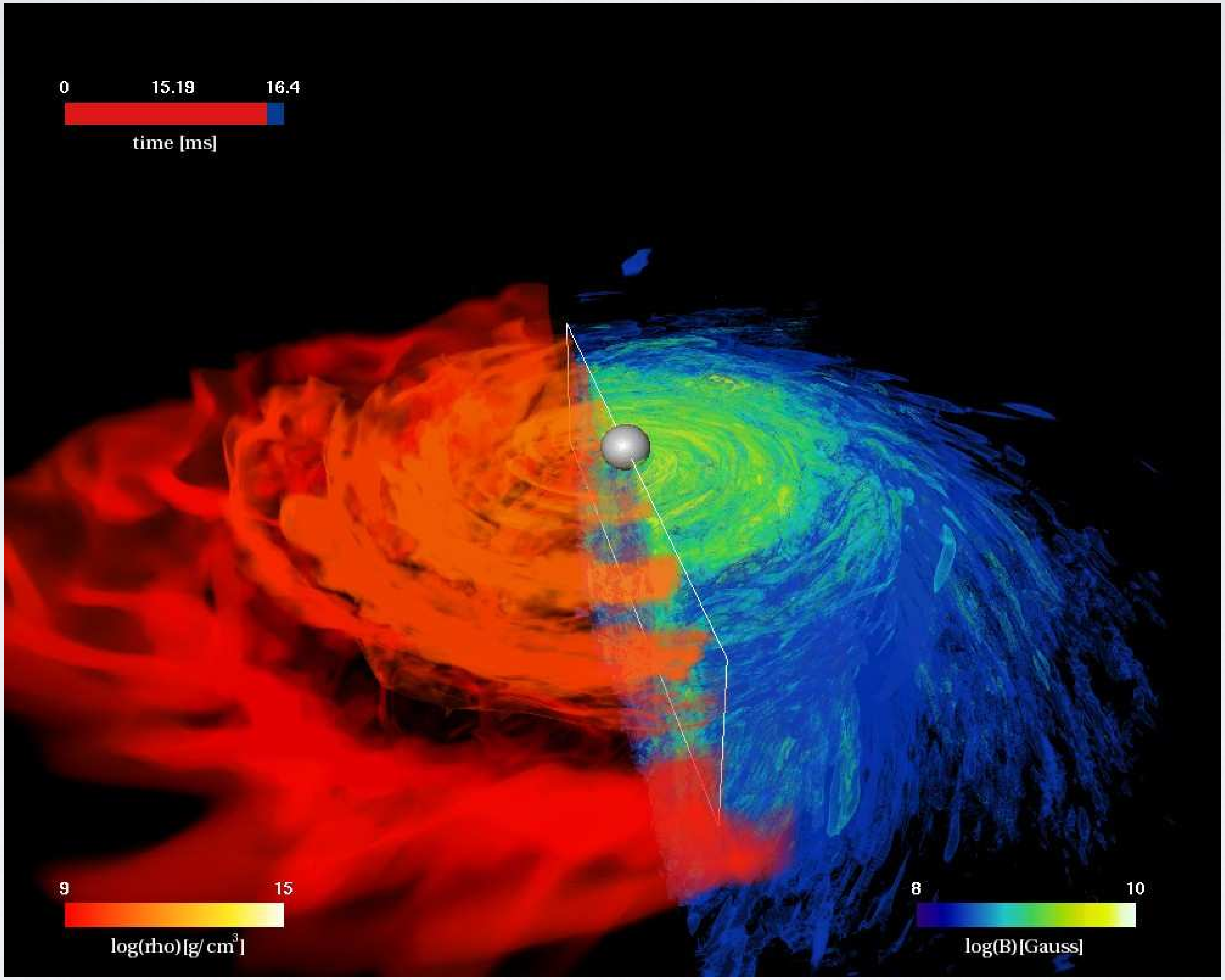
GRMHD SIMULATIONS OF NS-NS MERGERS



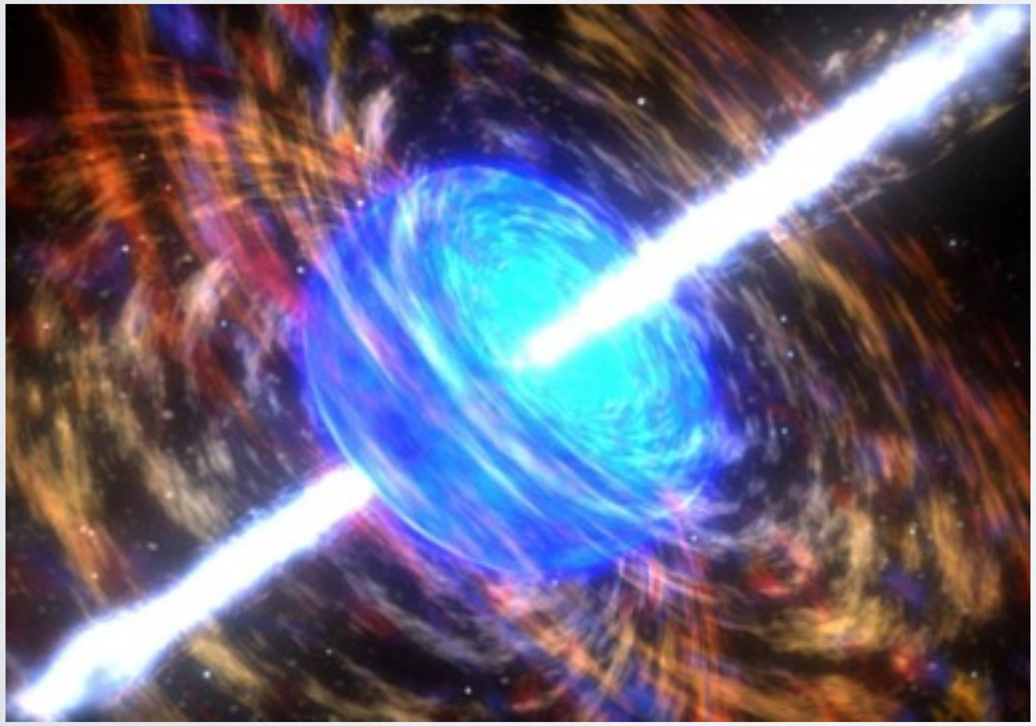
Bruno Giacomazzo

University of Trento and INFN-TIFPA, Italy

WHY SO INTERESTING?

Due to their duration and dynamics, NS-NS and NS-BH binaries are very good sources for gravitational wave detectors such as Virgo (Italy) and Ligo (USA)

Virgo (Pisa, Italy)



Credit: NASA/SkyWorks Digital

They are also possible sources for short gamma-ray bursts.
Tori formed after the merger could power GRBs via neutrino or magnetic fields.

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)
  - Baiotti et al 2008: AMR, ideal-fluid EOS, first complete GWs
  - 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
  - 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
  - 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 2014: EM precursors for arbitrary magnetic field orientations

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 $\longrightarrow G_{\mu\nu} = 8\pi T_{\mu\nu} \longleftarrow$ **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):

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

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

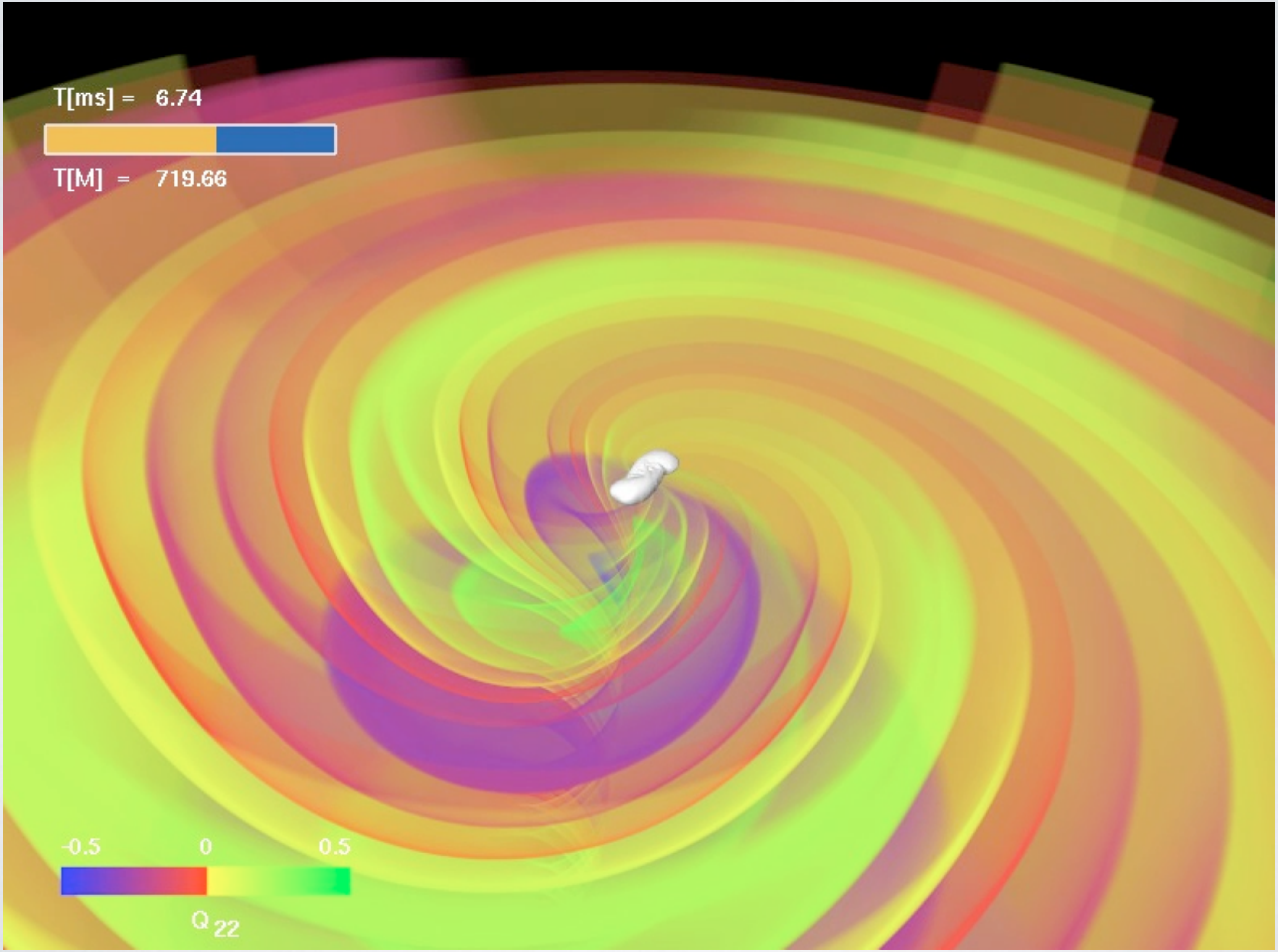
GRMHD EQUATIONS

The evolution equations are then rewritten in a conservative form:

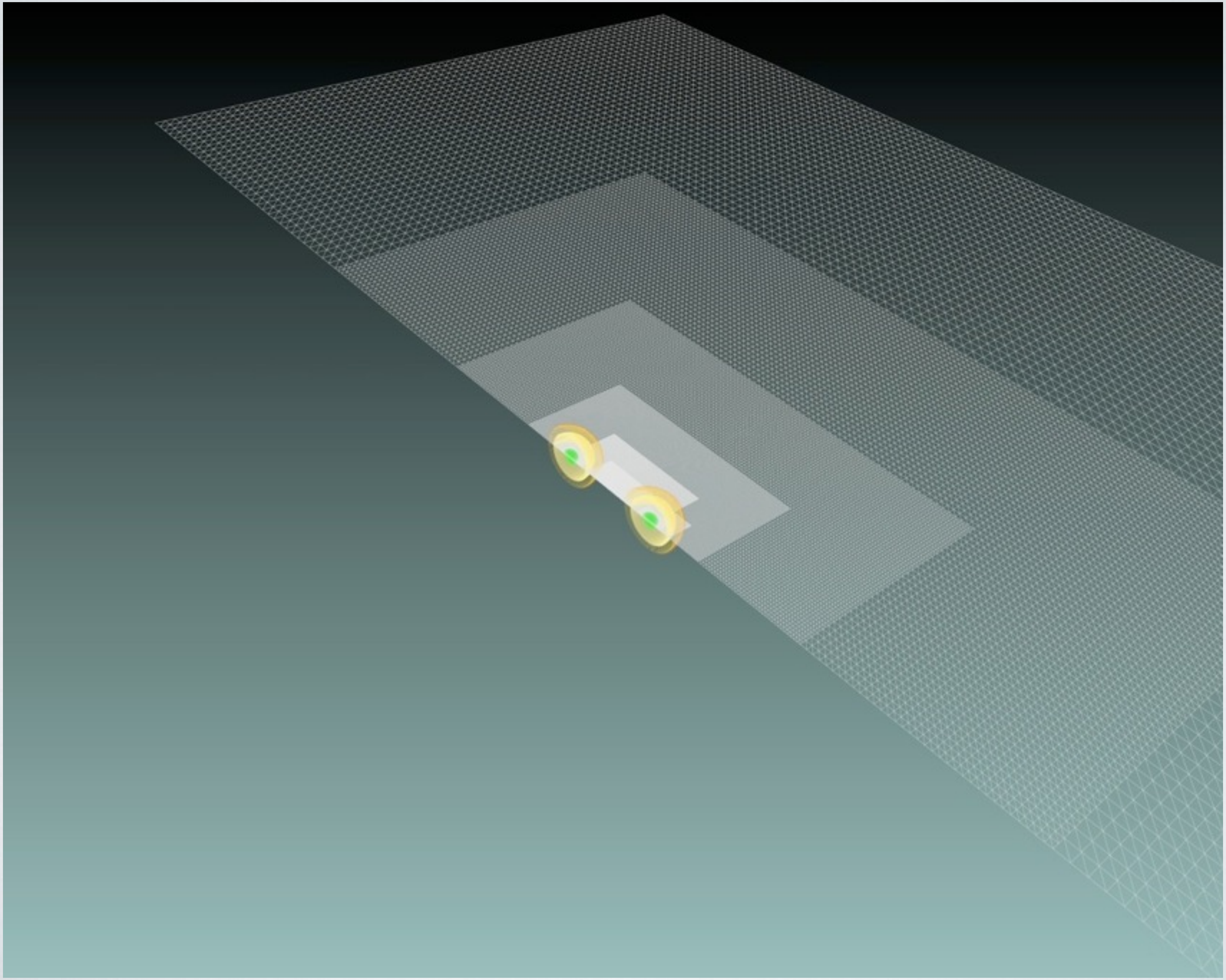
$$\frac{1}{\sqrt{-g}}\left[\partial_t(\sqrt{\gamma}\mathbf{U}) + \partial_i(\sqrt{-g}\mathbf{F}^i)\right] = \mathbf{S}$$

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)

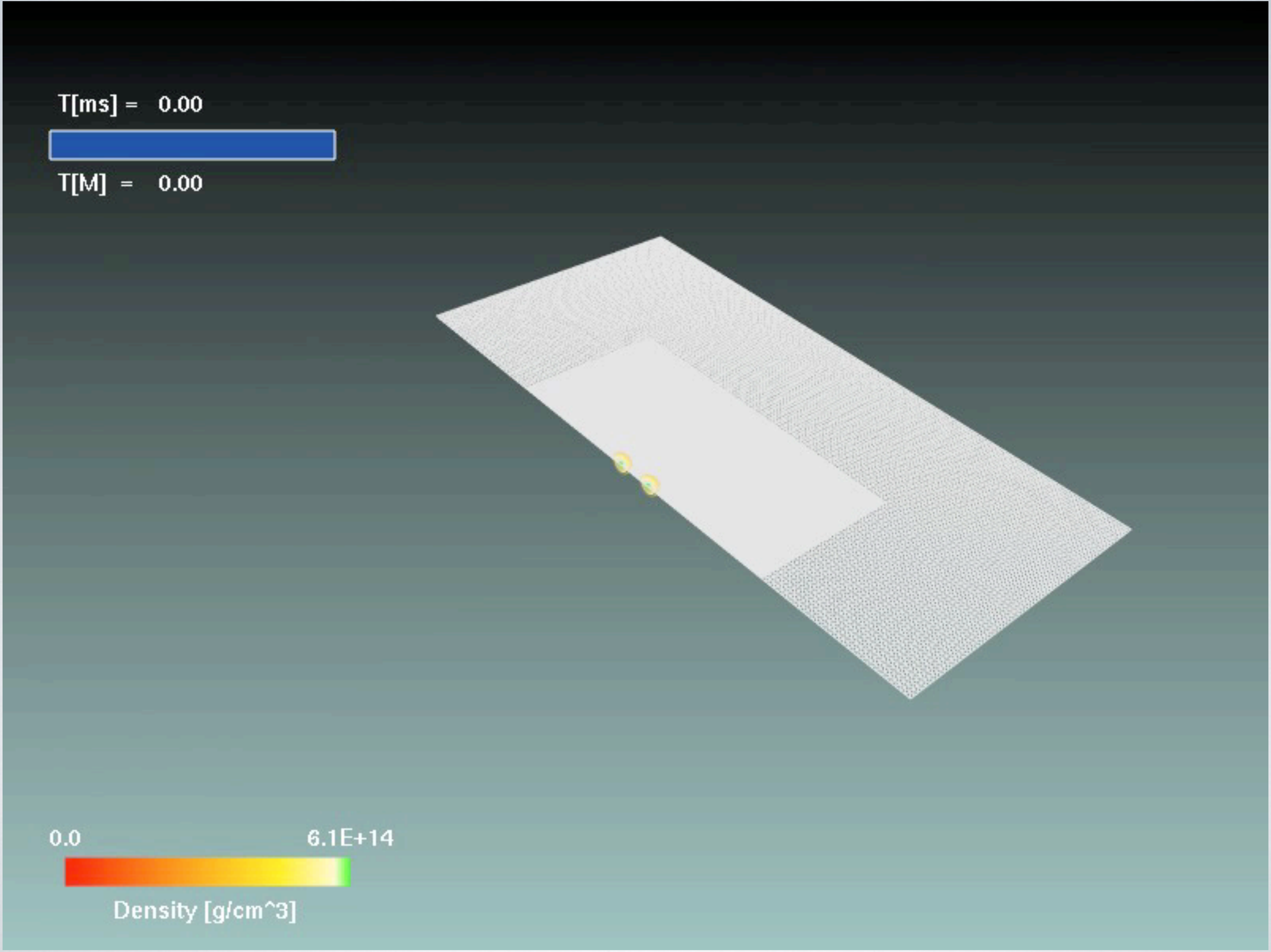
GW EMISSIONS FROM NS-NS MERGERS



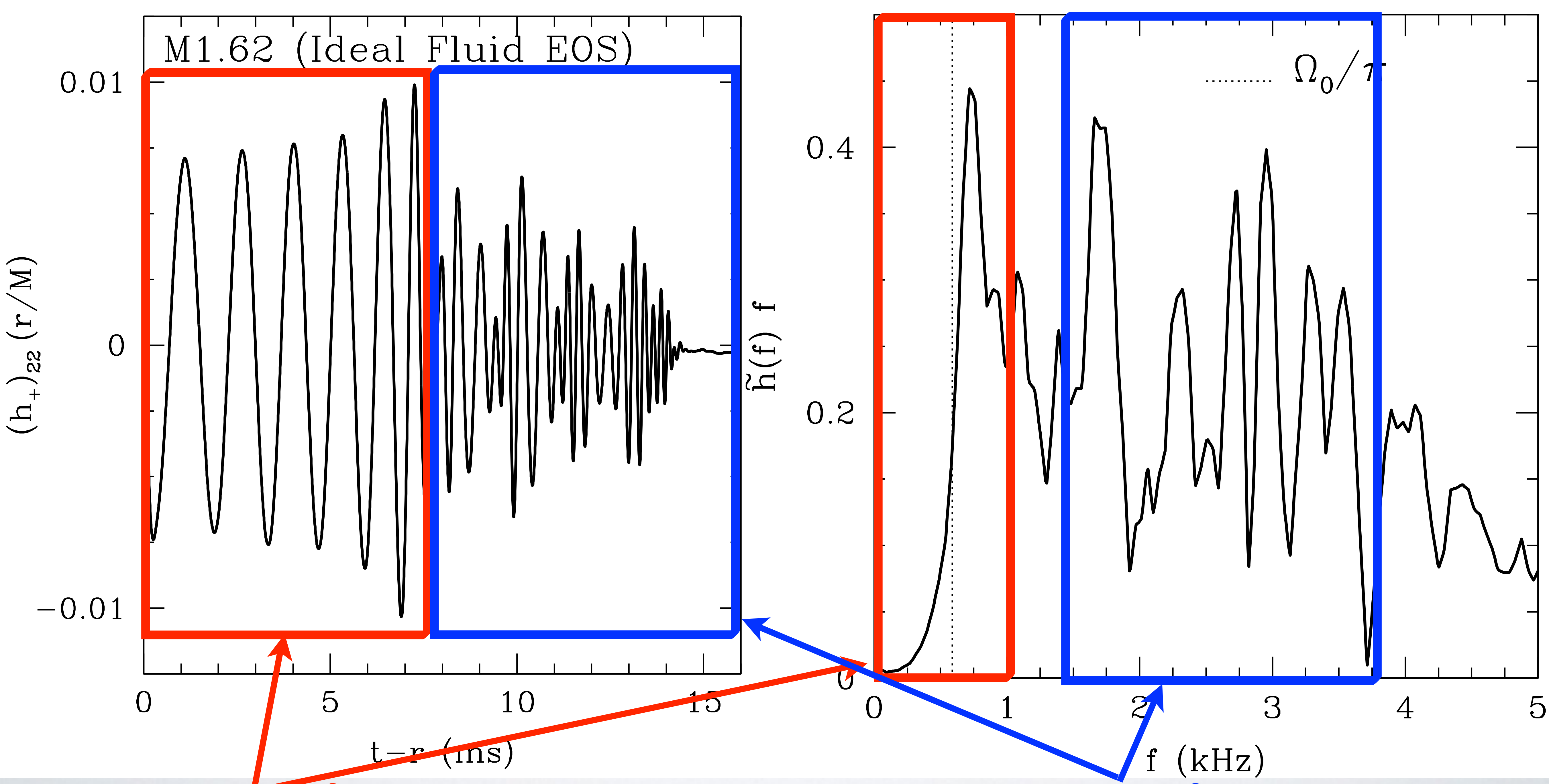
IDEAL-FLUID EOS: HIGH-MASS BINARY



Visualization by Giacomazzo, Kaehler, Rezzolla


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

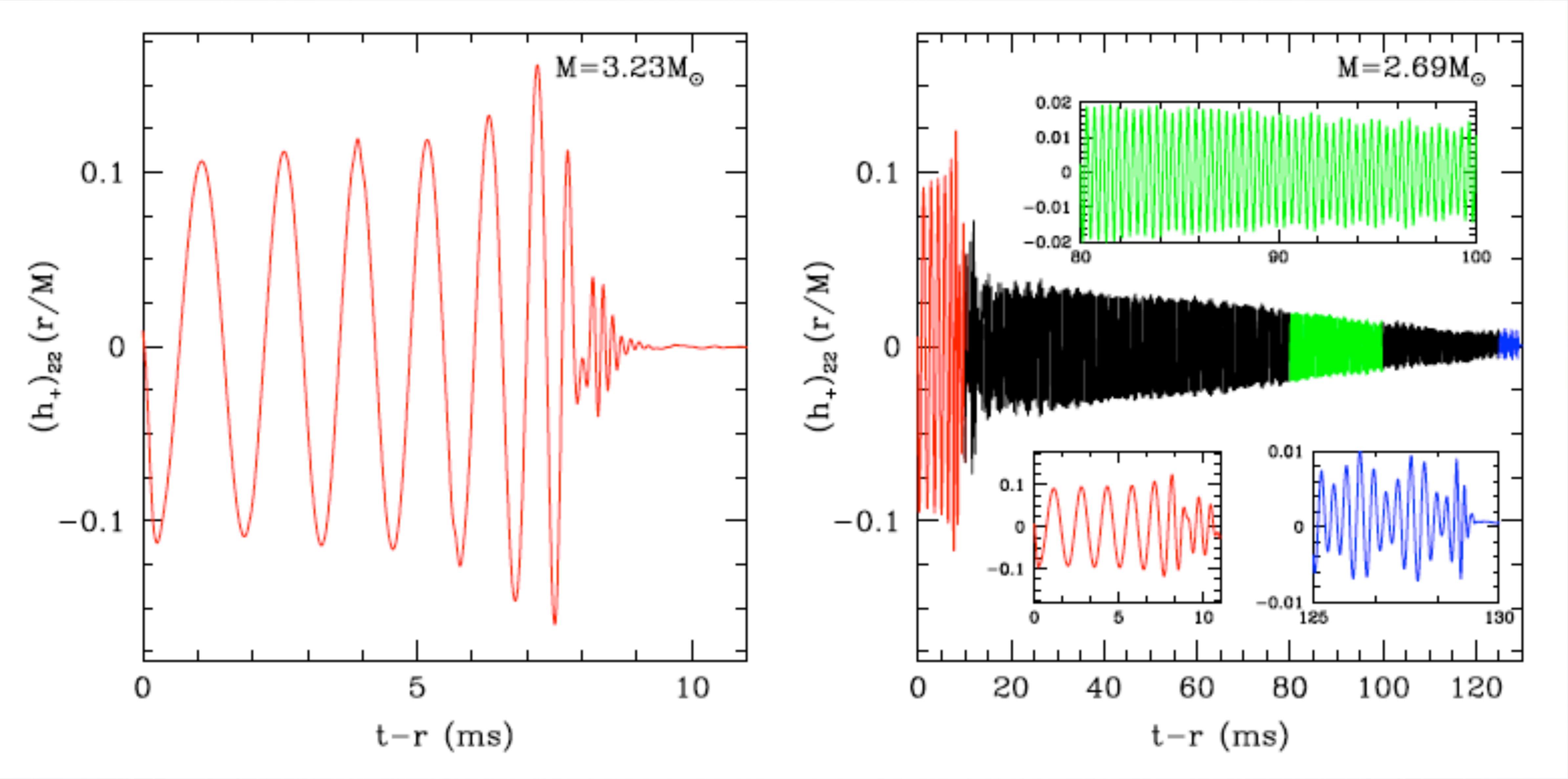
GRAVITATIONAL WAVES FROM BINARY NEUTRON STARS



contribution from the inspiral

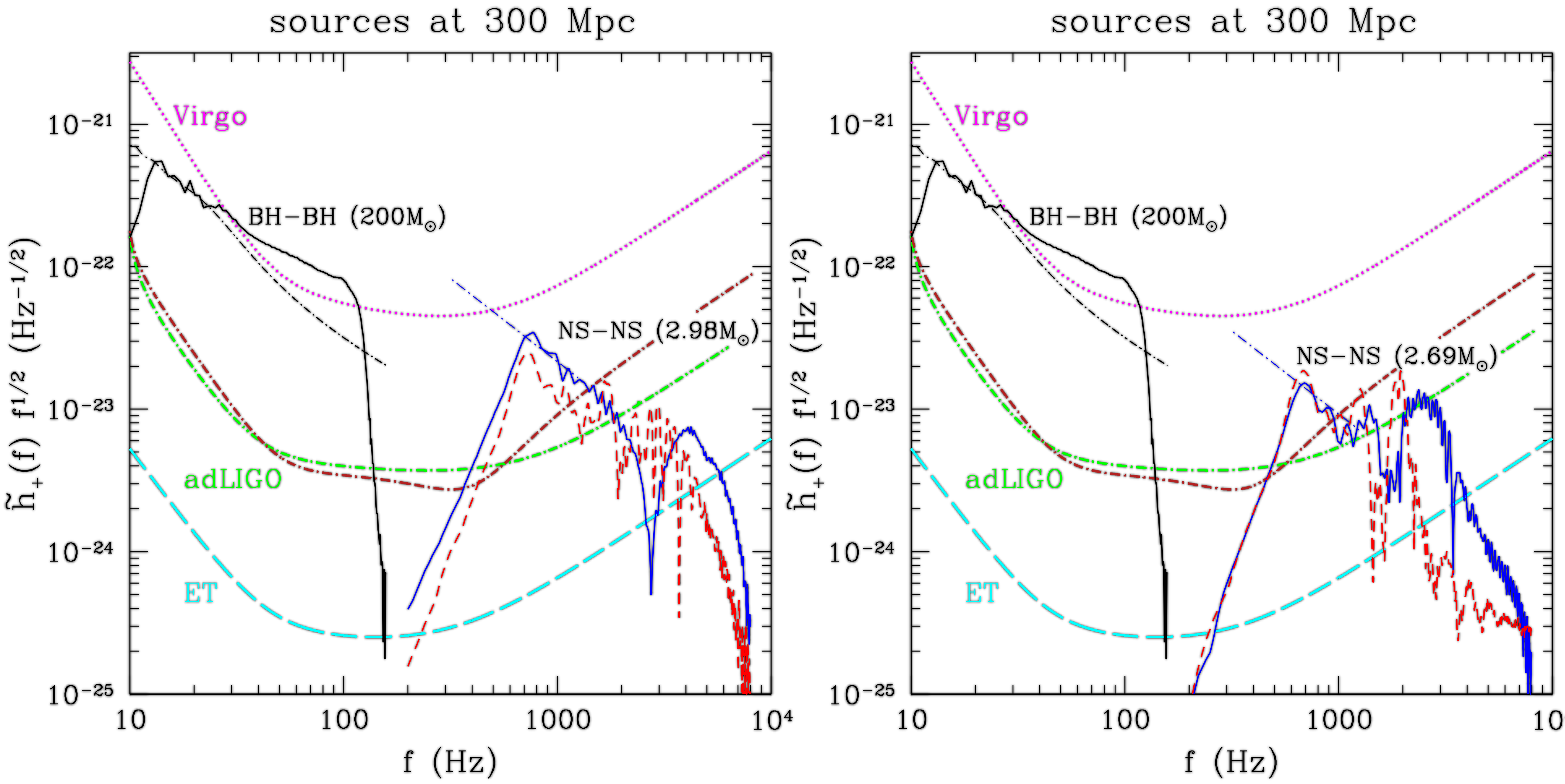
contribution from the HMNS

GW: THE ROLE OF THE MASS



"High Mass" binaries produce a BH promptly after merger
"Low Mass" produce a NS that can be survive for hundreds of ms

GWS: DETECTABILITY



High-mass

Low-mass

Figure by L. Rezzolla (Andersson et al 2009)

Note that in both cases the post-merger phase is almost invisible to current and advanced LIGO/Virgo detectors.

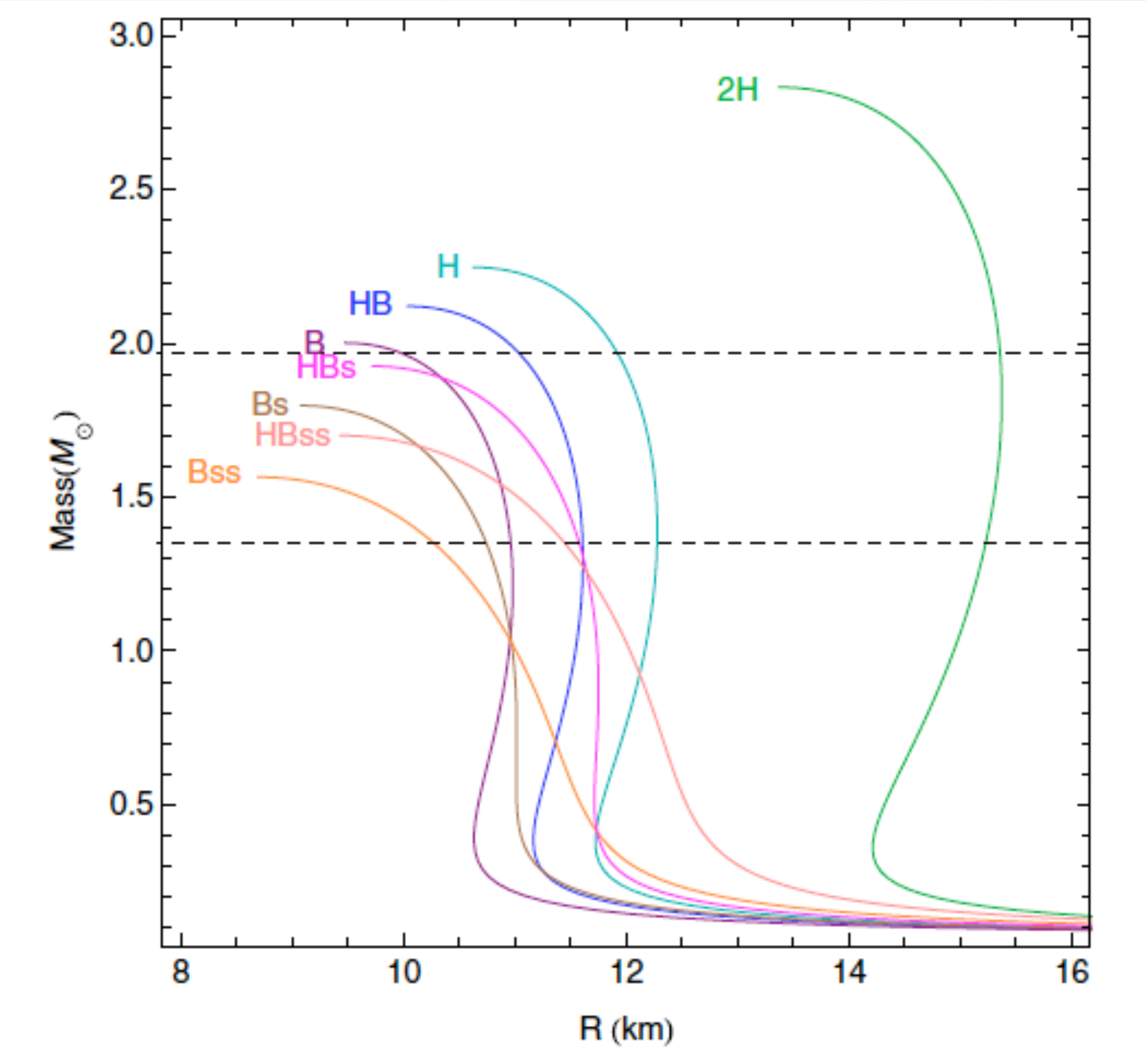
MATTER EFFECTS ON BNS GWs

(Read et al 2013, PRD 88, 044042)

We used the Whisky and SACRA codes to perform the first multi-code study of EOS effects on merger waveforms

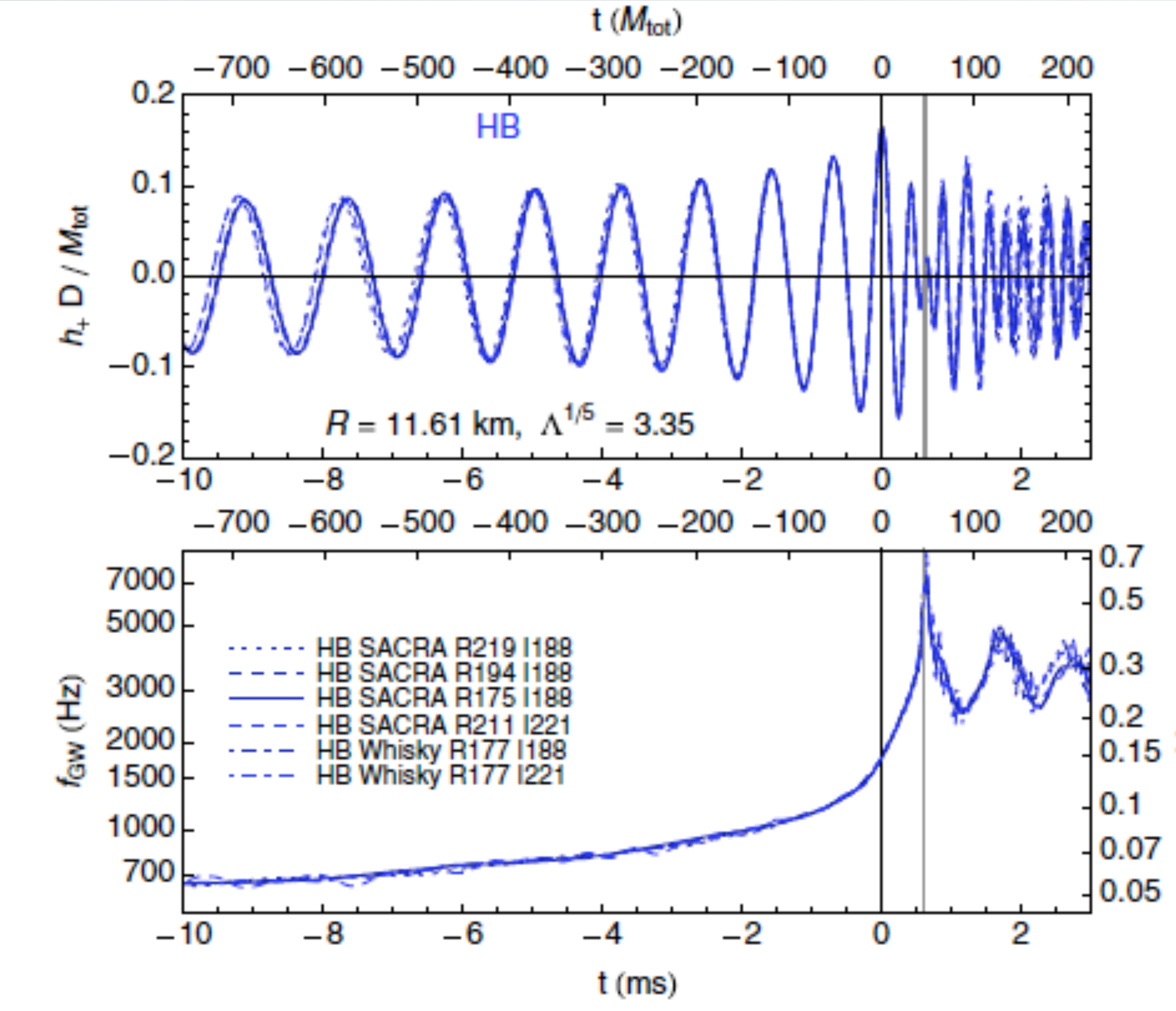
Used an extended set of piecewise polytropic EOSs

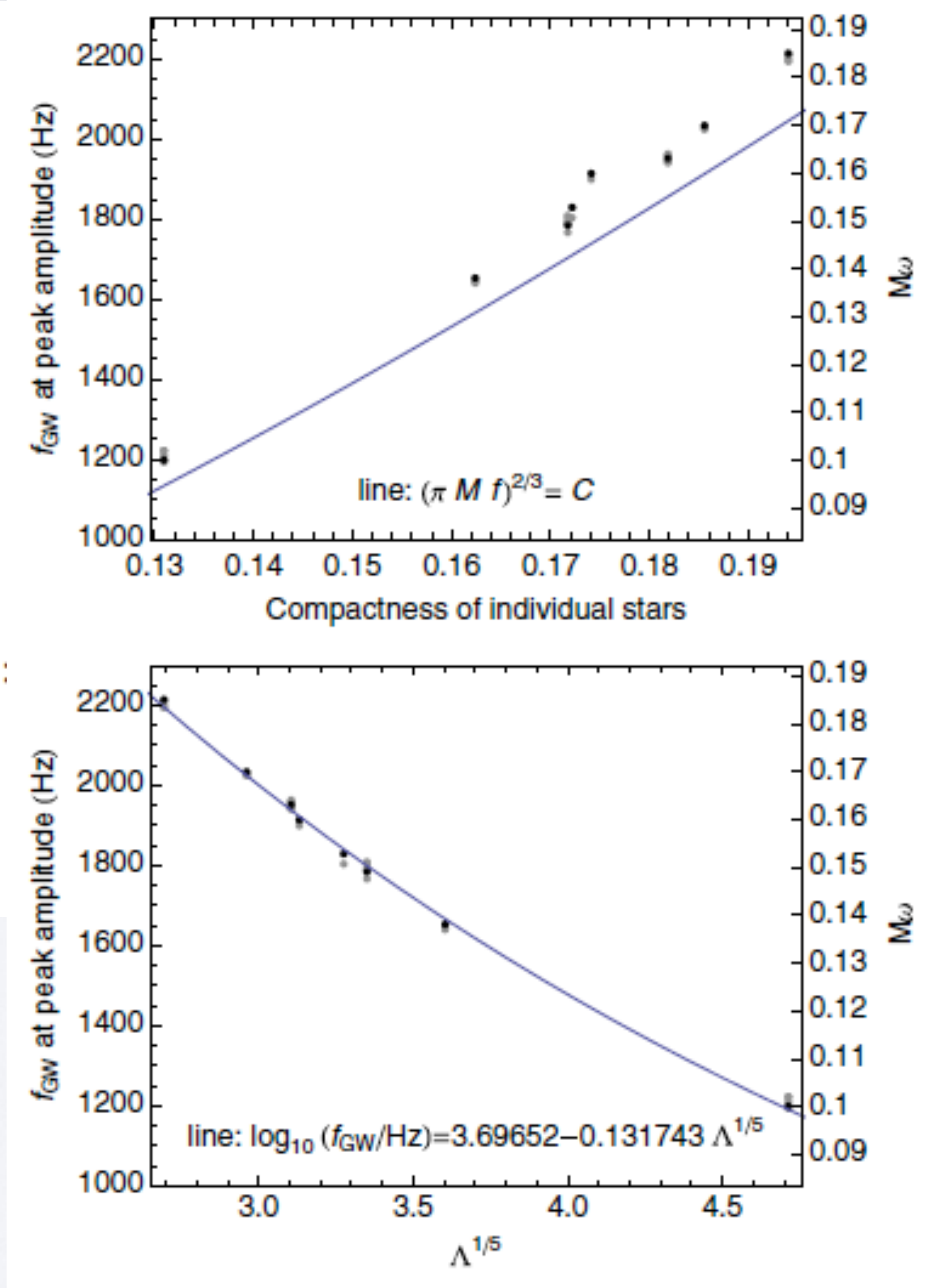
Estimated numerical errors by comparing between the codes and using different resolutions.



MATTER EFFECTS ON BNS GWs

(Read et al 2013, PRD 88, 044042)

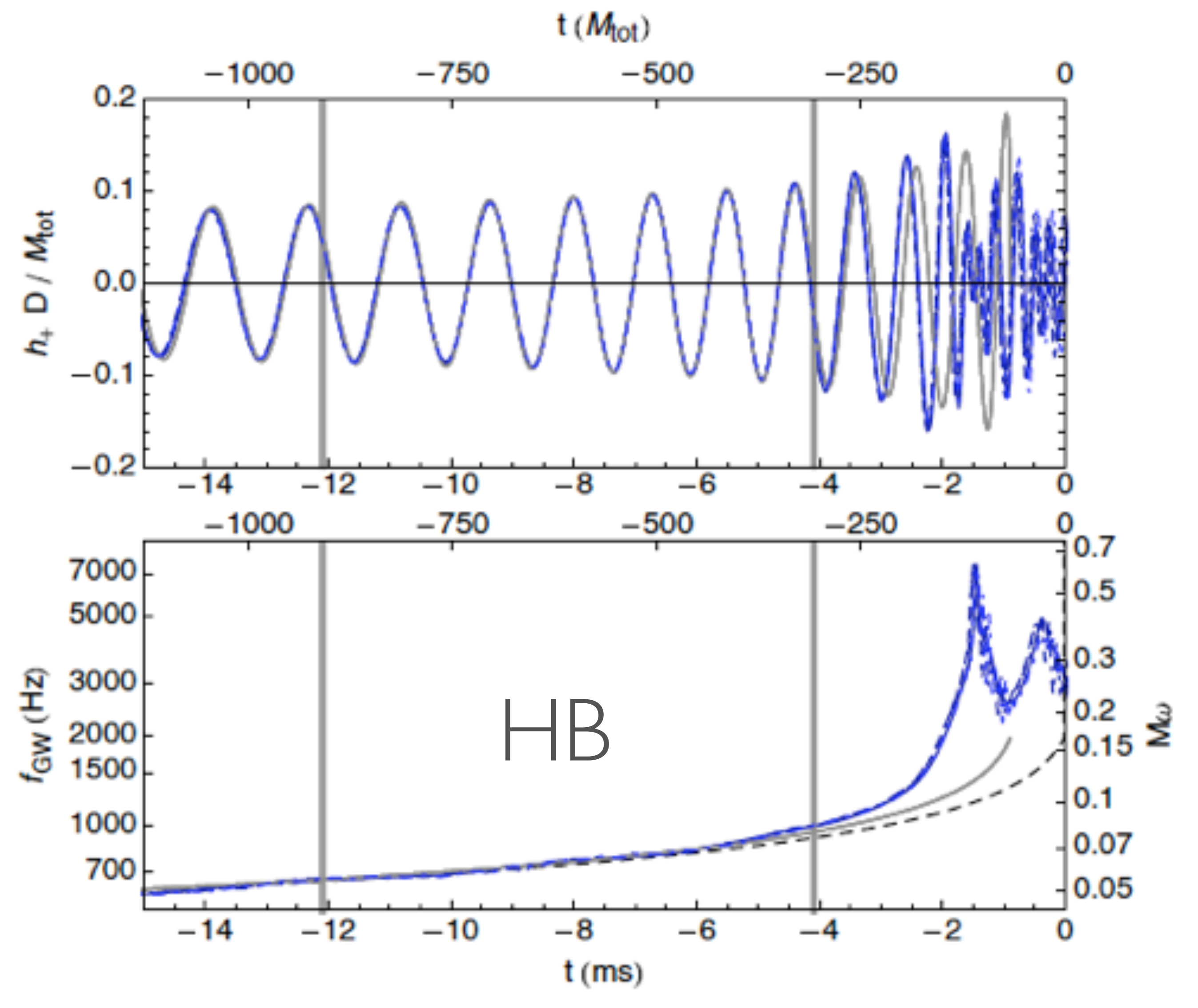


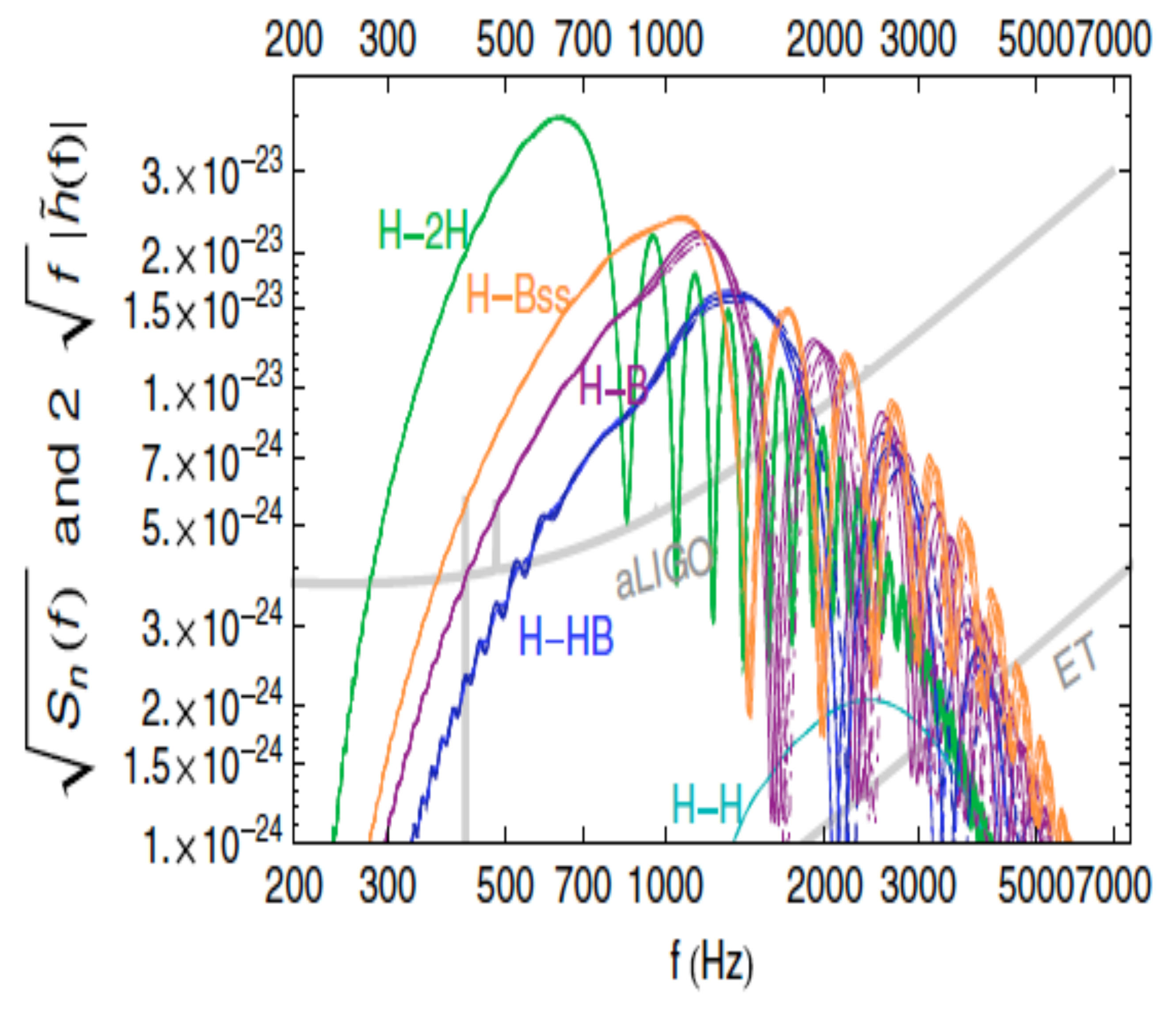


GW frequency at merger is well correlated with tidal deformability (and NS compactness)

MATTER EFFECTS ON BNS GWs

(Read et al 2013, PRD 88, 044042)





Hybrid GWs: EOSs distinguishable at 300 Mpc if NS radii differ of ~1.3km

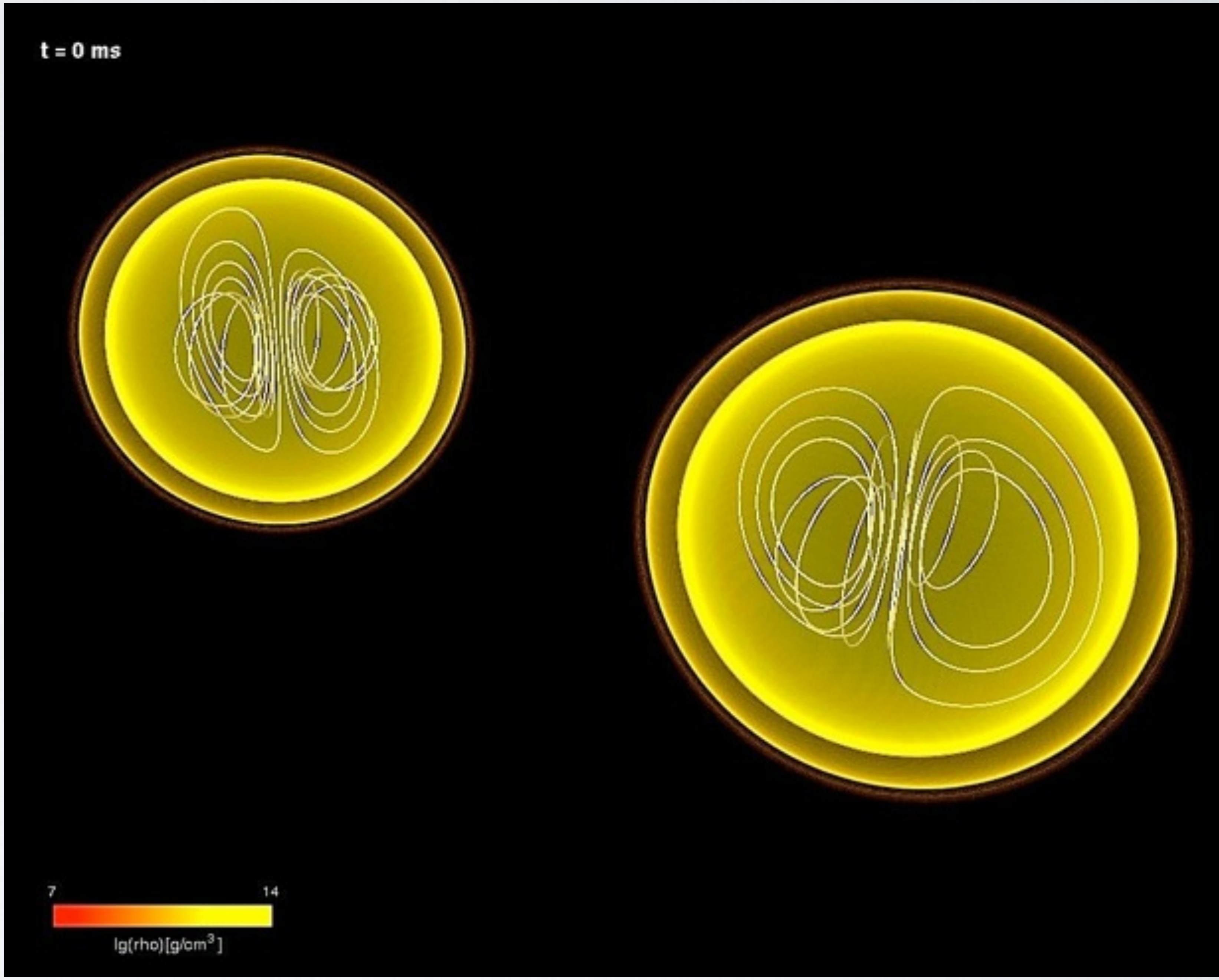
Only numrel GWs: EOSs distinguishable at 100 Mpc if NS radii differ of ~1.3km

POSTMERGER: MAGNETIC FIELD EFFECTS

Giacomazzo, Rezzolla, Baiotti 2011, PRD 83, 044014

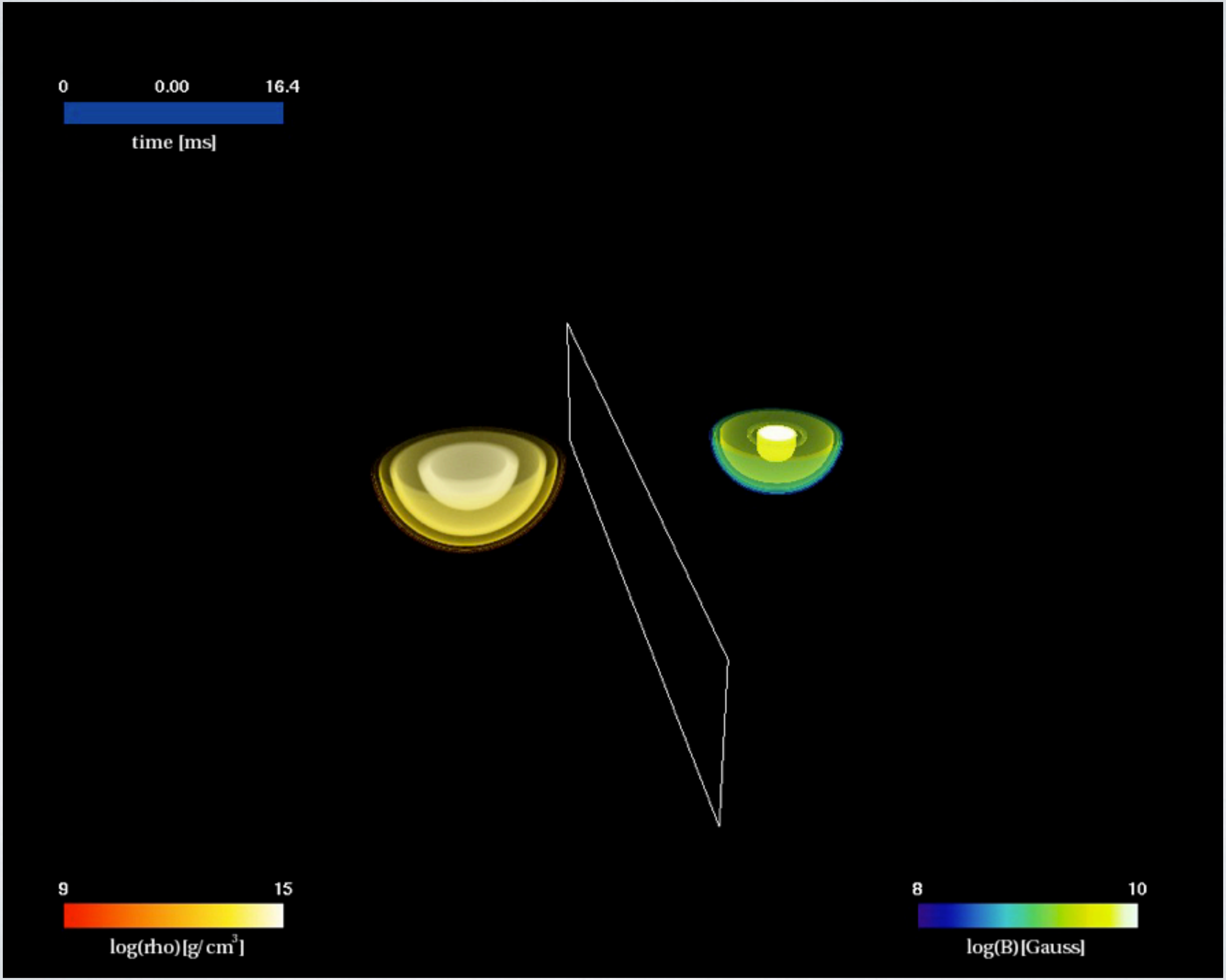
We considered equal-mass BNSs with different masses and with a poloidal magnetic field with different amplitudes (B~10^8-10^{12} G).

- First time this study was done in full GR
- Studied impact on dynamics, disk formation, and GW emission



Highest level of accuracy ever used in GRMHD simulations of BNS

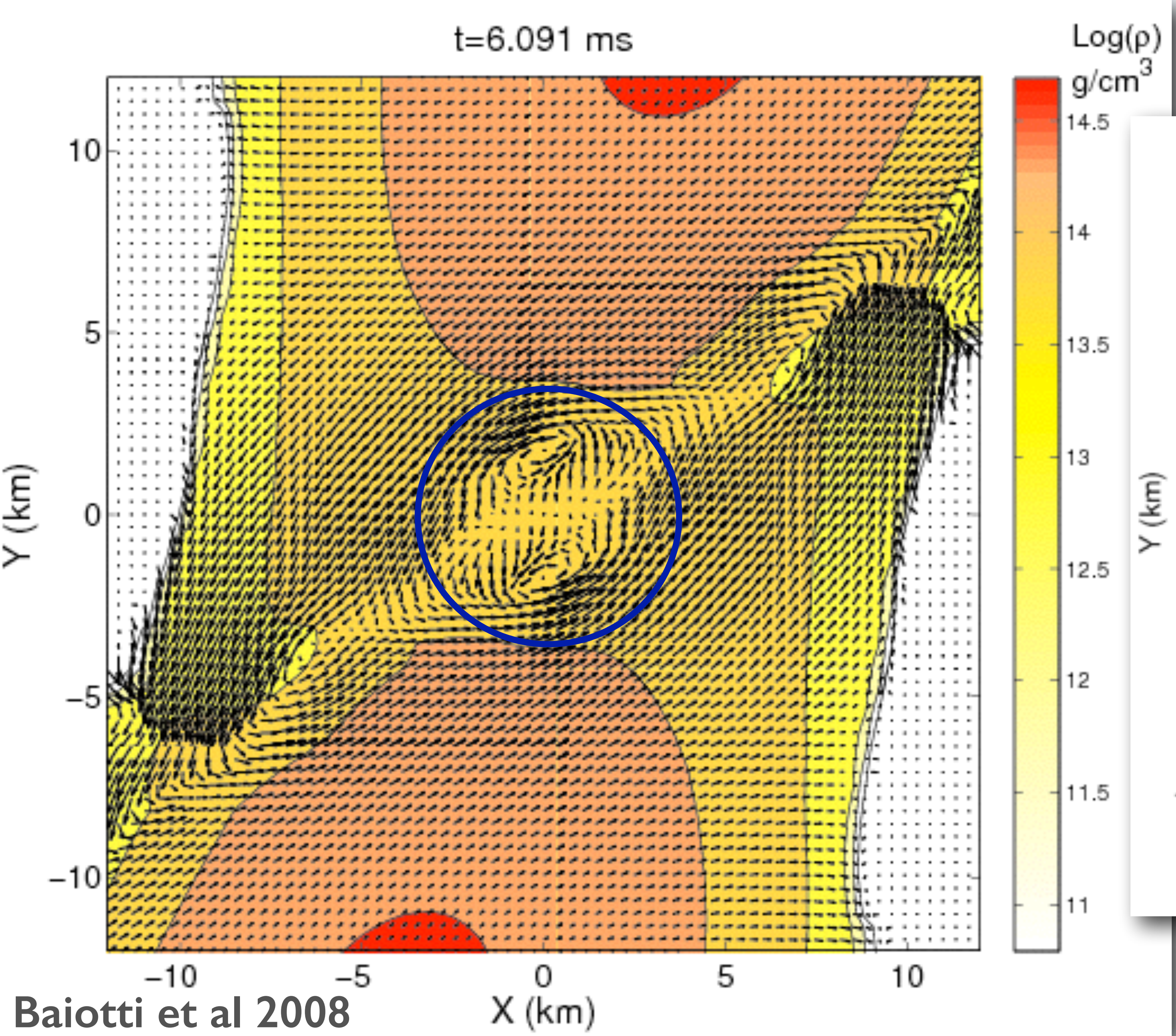
Model M1.62-B10



Visualization by Koppitz, Giacomazzo, Rezzolla

KH INSTABILITY AND MAGNETIC FIELDS

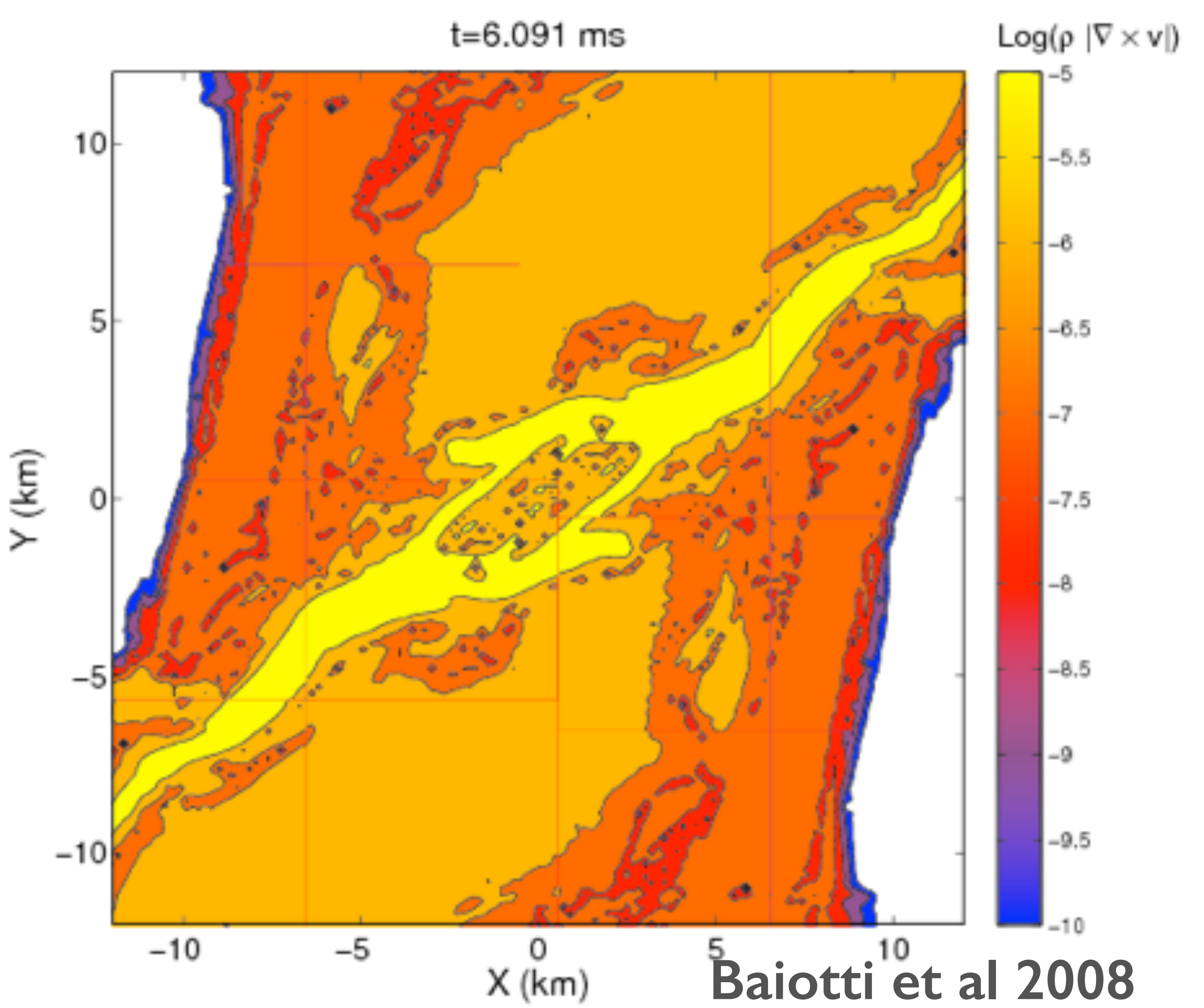
During the merger a shear interface forms and it develops a Kelvin-Helmholtz instability which produces a series of vortices.



Baiotti et al 2008

$$(v^x, v^y)$$

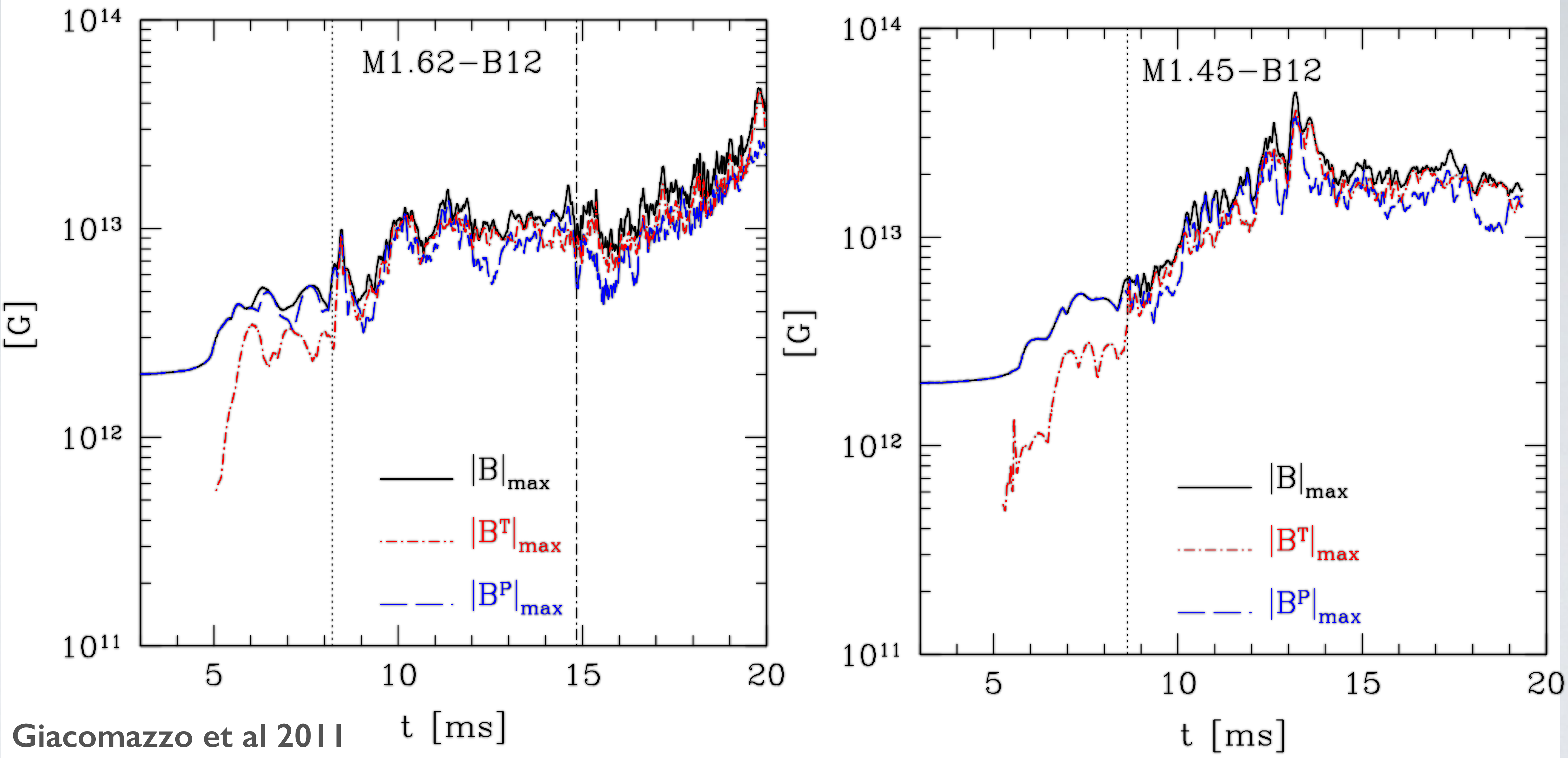
in "corotating" frame



Baiotti et al 2008

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

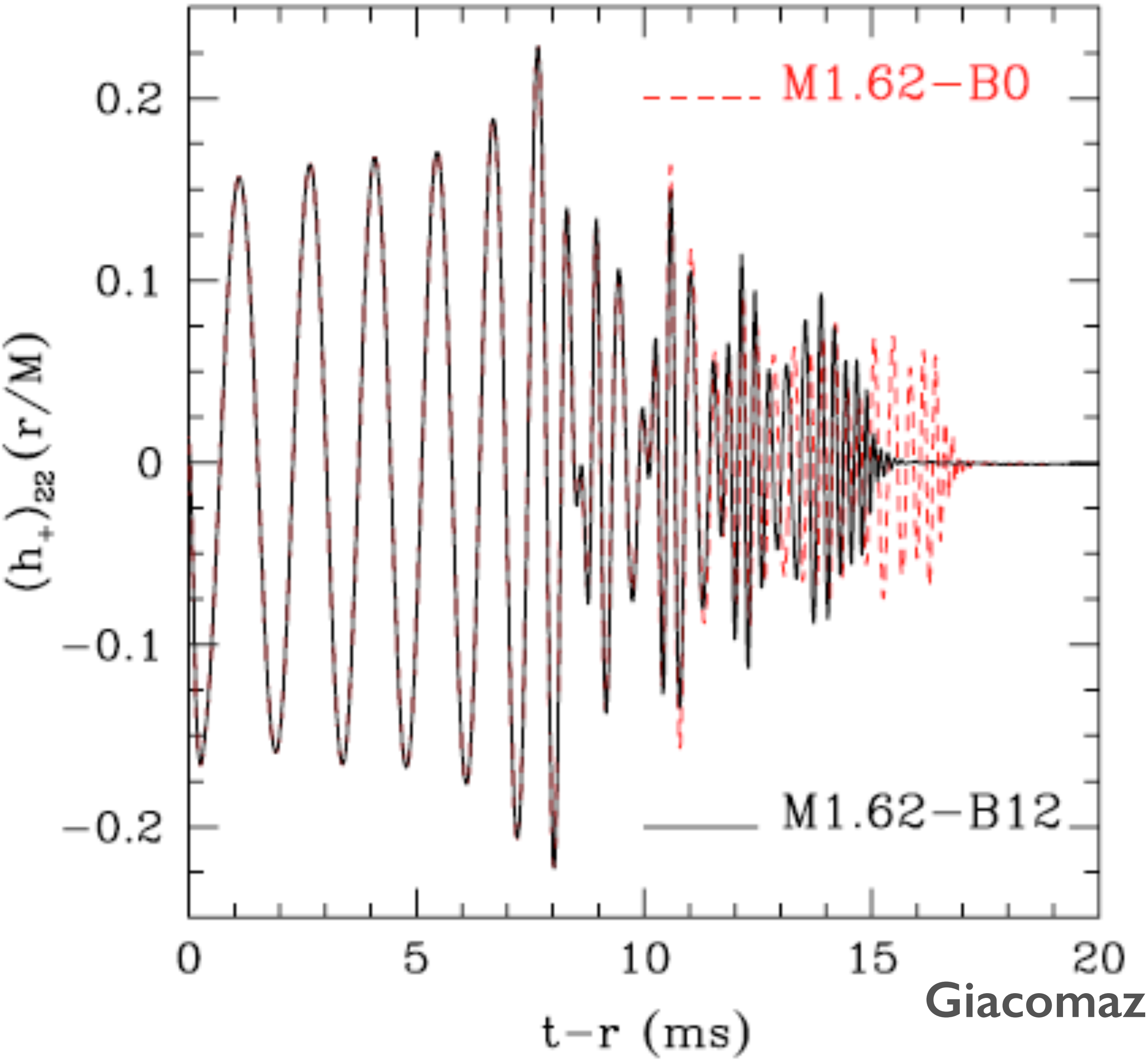
MAGNETIC FIELD AMPLIFICATION

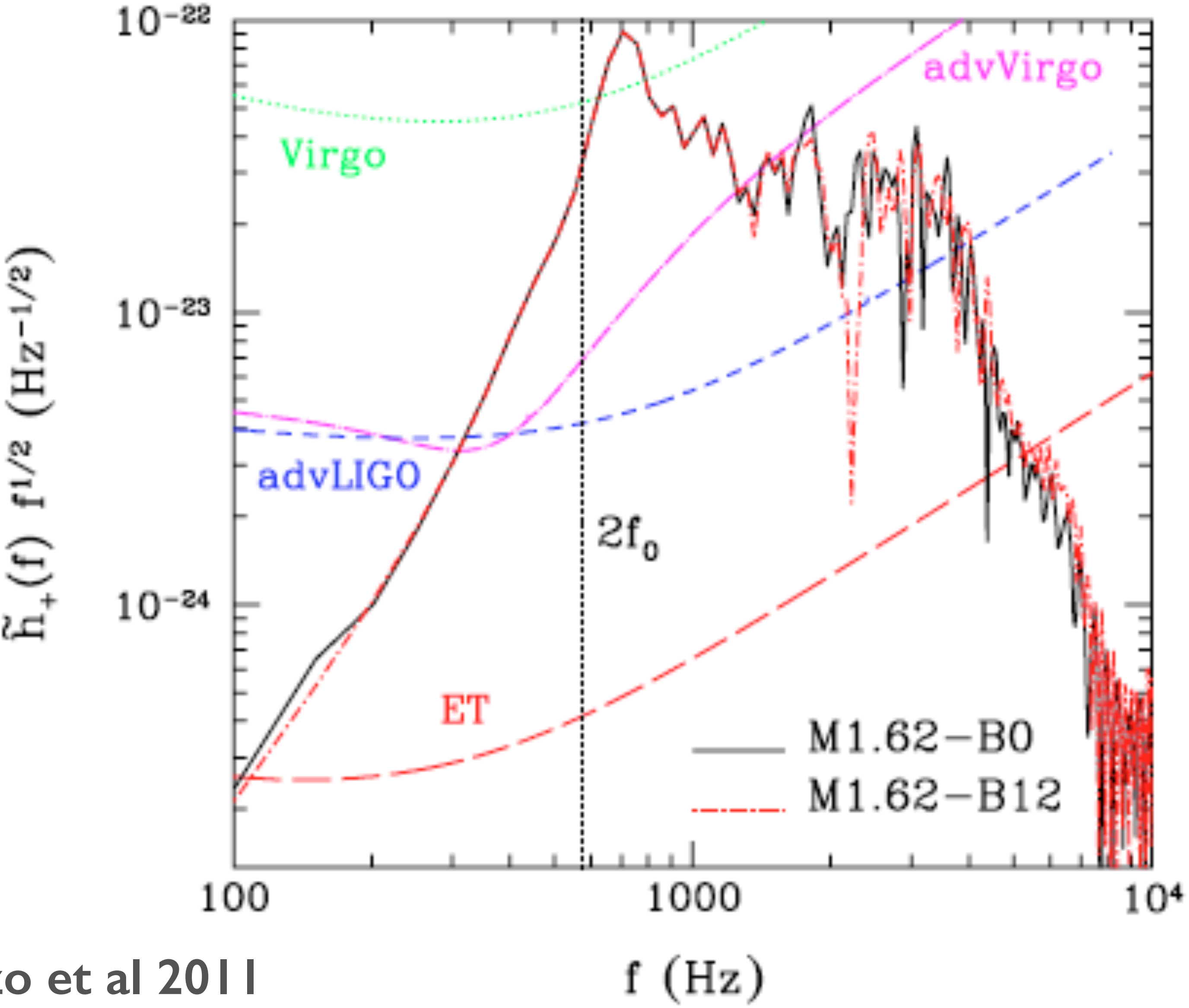


Giacomazzo et al 2011

Due to KH instability the magnetic field grows of ~1 order of magnitude. Local very high-res simulations shows that magnetic fields could be further amplified (Zrake & MacFadyen 2013).

GW: MAGNETIC FIELD EFFECTS IN THE HMNS

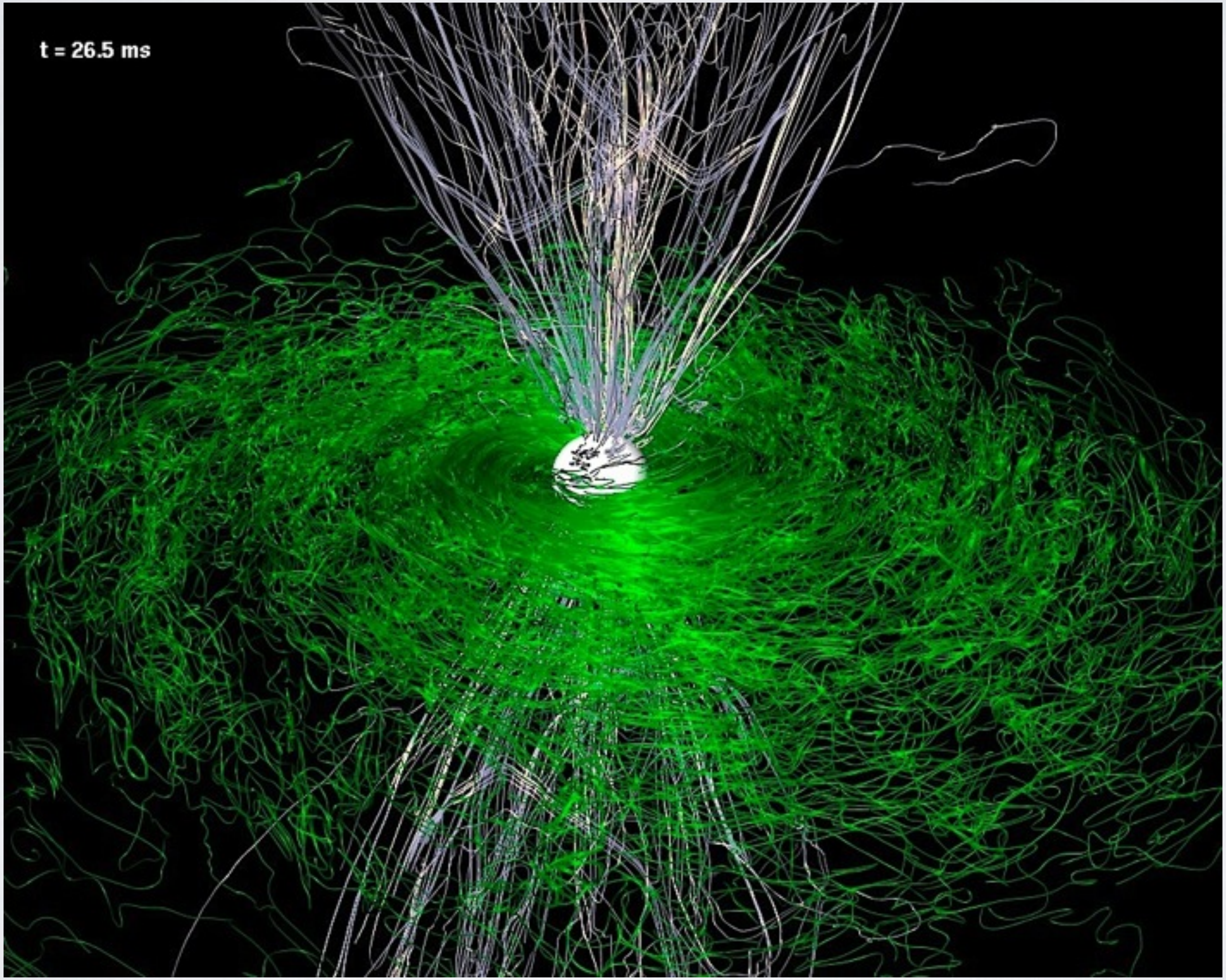




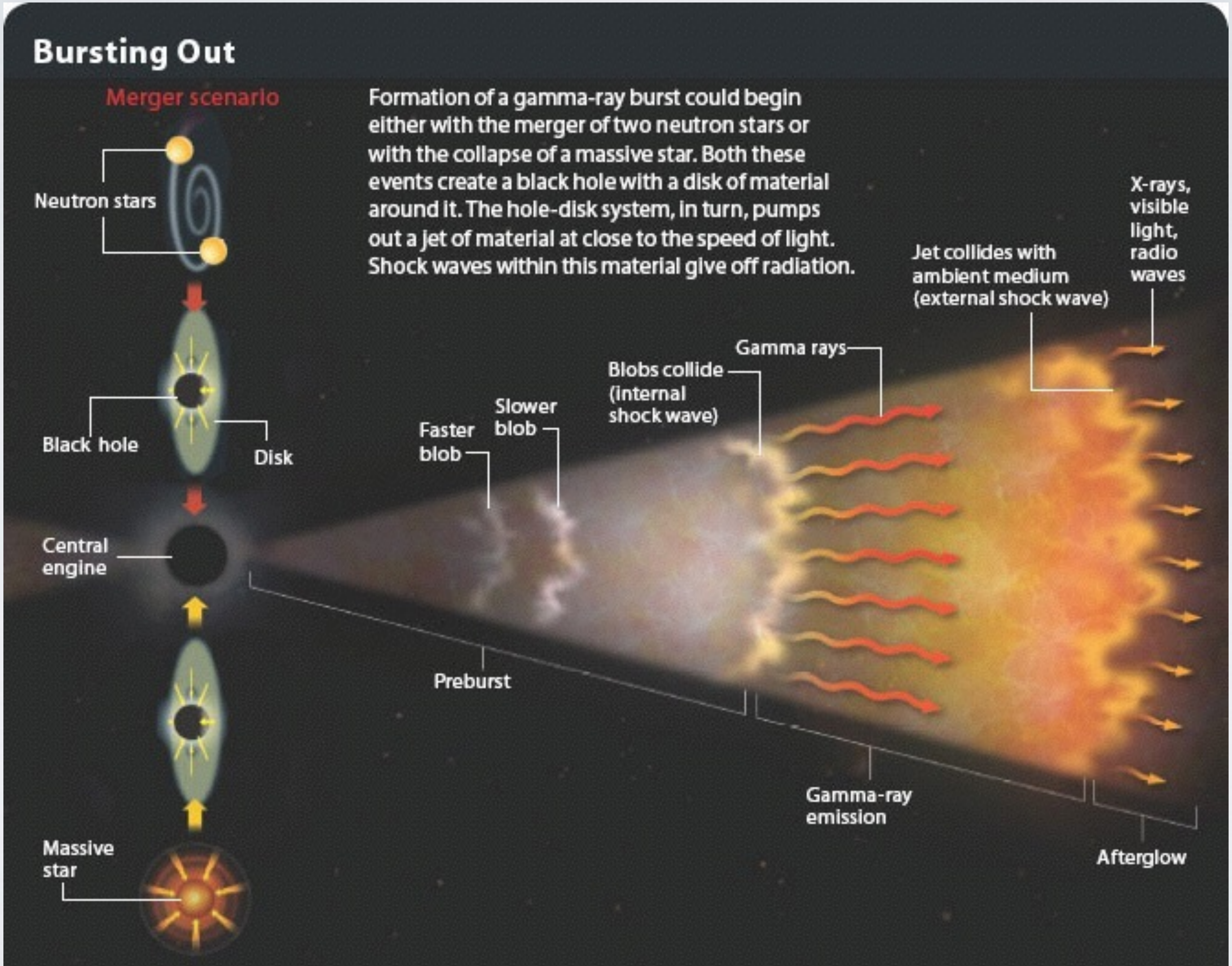
Giacomazzo et al 2011

Magnetic field may have an impact on the post-merger GWs and even accelerate collapse to BH.

BNSs AND THE CENTRAL ENGINE OF SHORT-GRBs



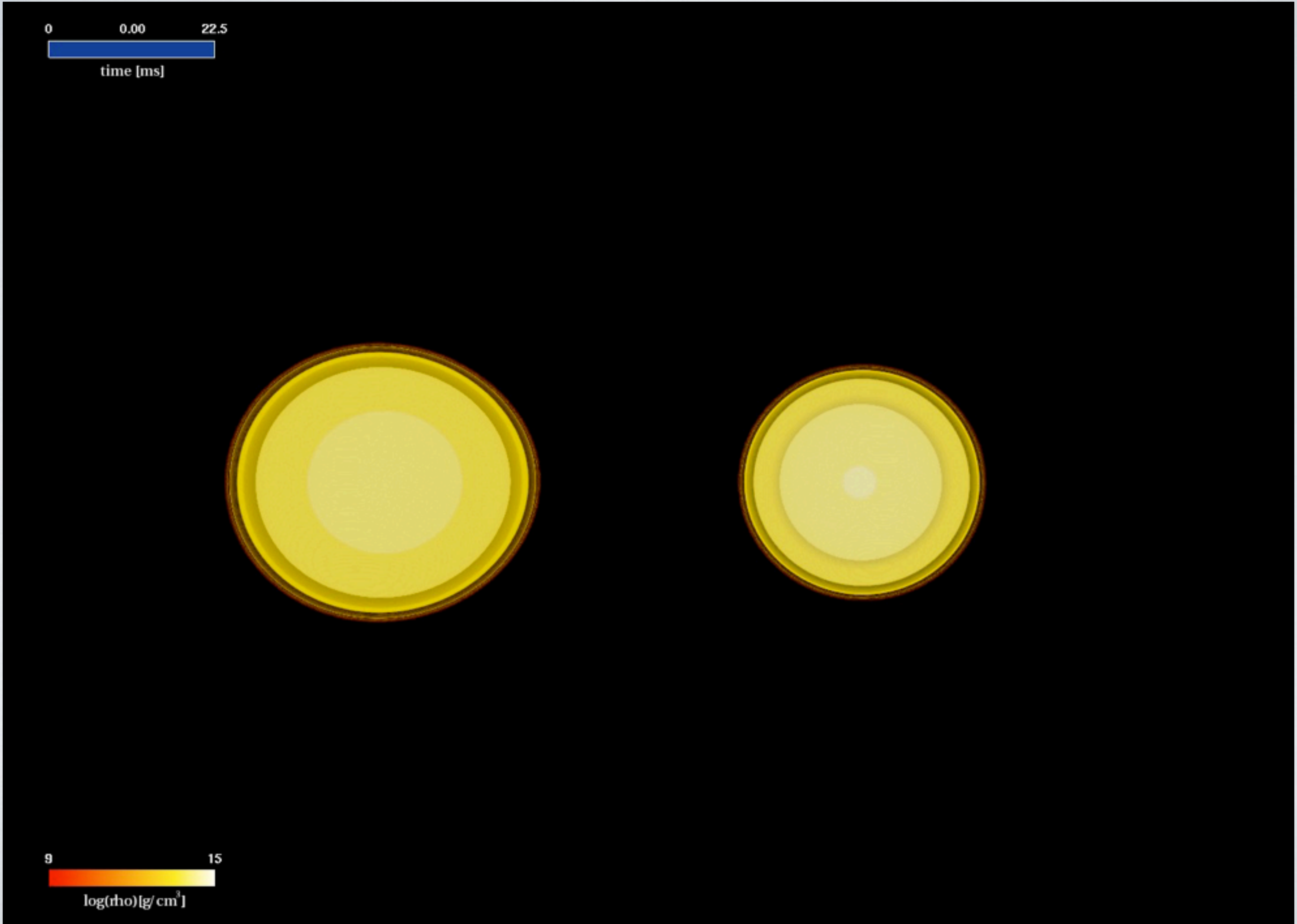
MOST "POPULAR" MODEL FOR SGRB CENTRAL ENGINE



Formation of a gamma-ray burst could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

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

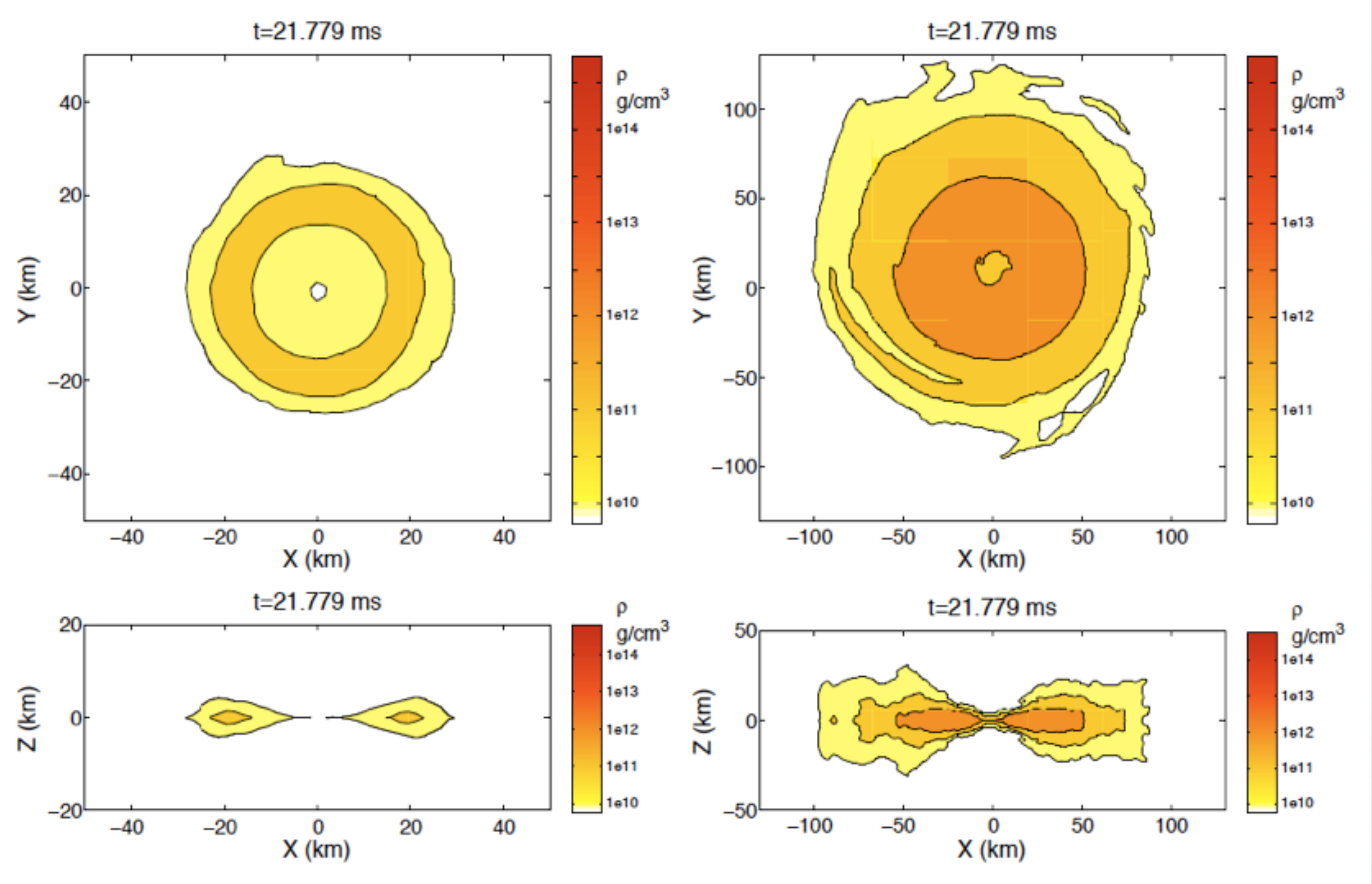
UNEQUAL-MASS BNS: M3.4q0.80



Visualization by Giacomazzo, Koppitz, Rezzolla

TORUS PROPERTIES: UNEQUAL-MASS CASE

M3.6q1.0 M3.4q0.7



Note the different length scales!

JETS FROM BNS MERGERS?

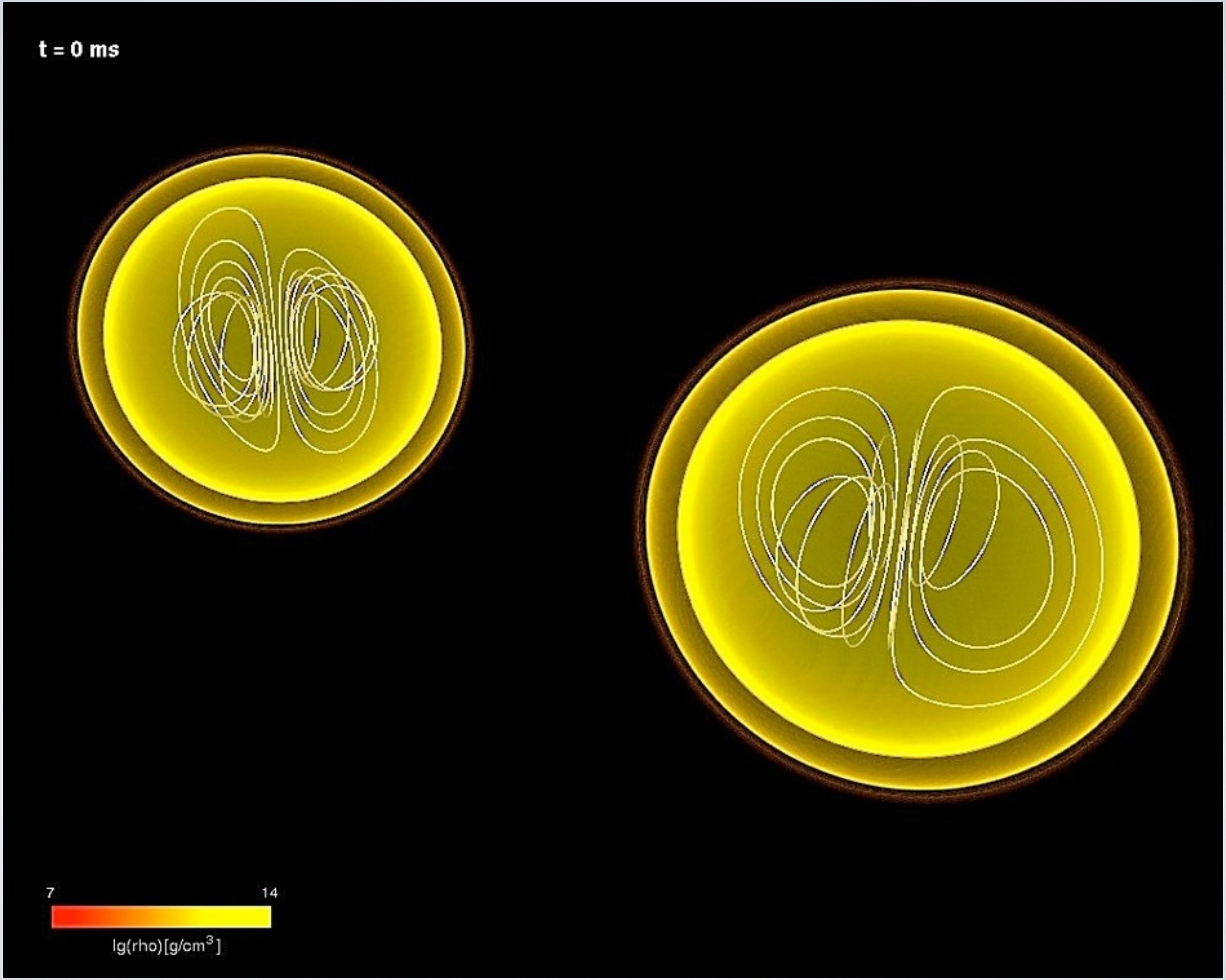
Rezzolla, **Giacomazzo**, Baiotti, Granot, Kouveliotou, Aloy 2011, ApJL 732, L6

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

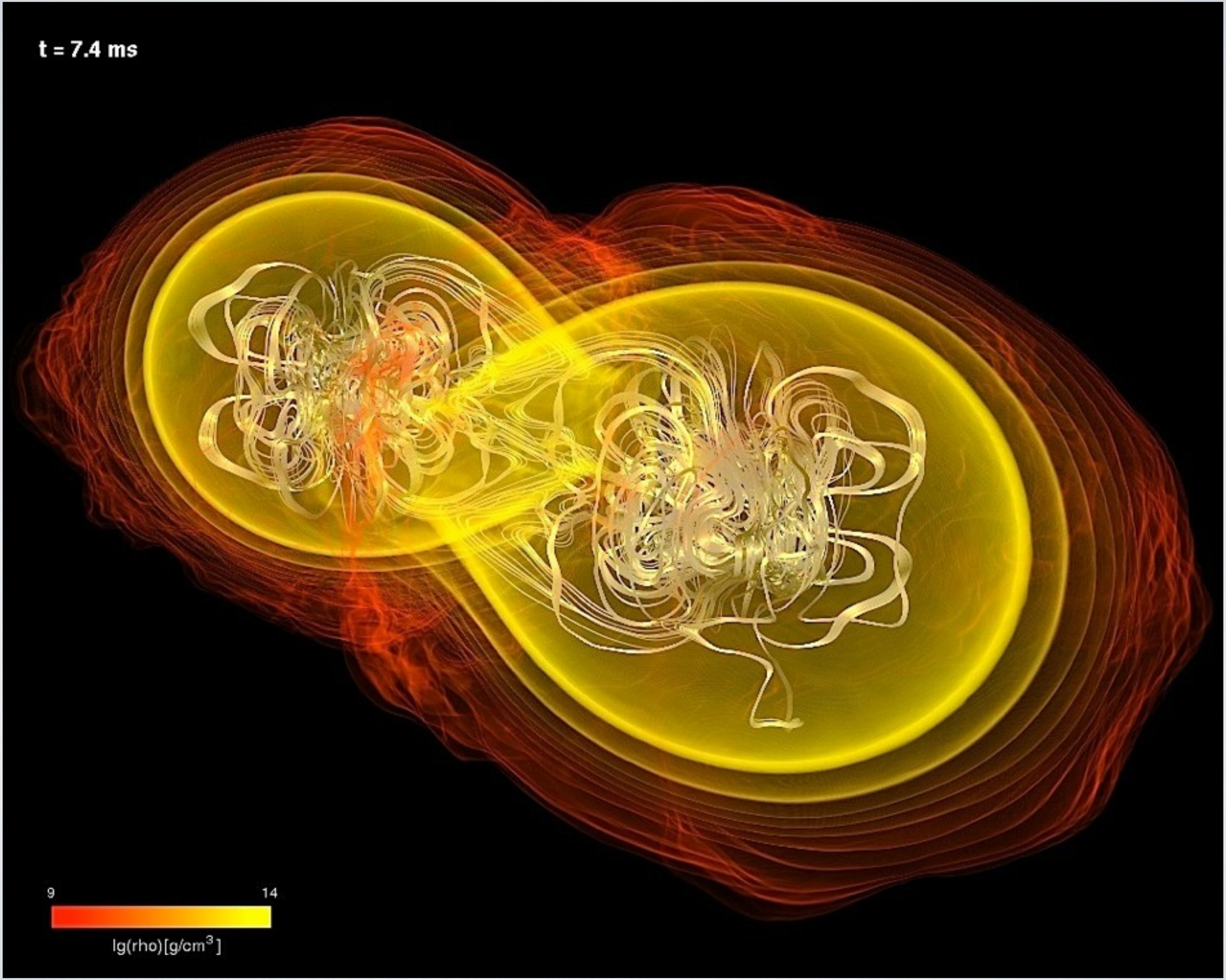
Several numerical studies of tori around spinning BHs, e.g.:

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

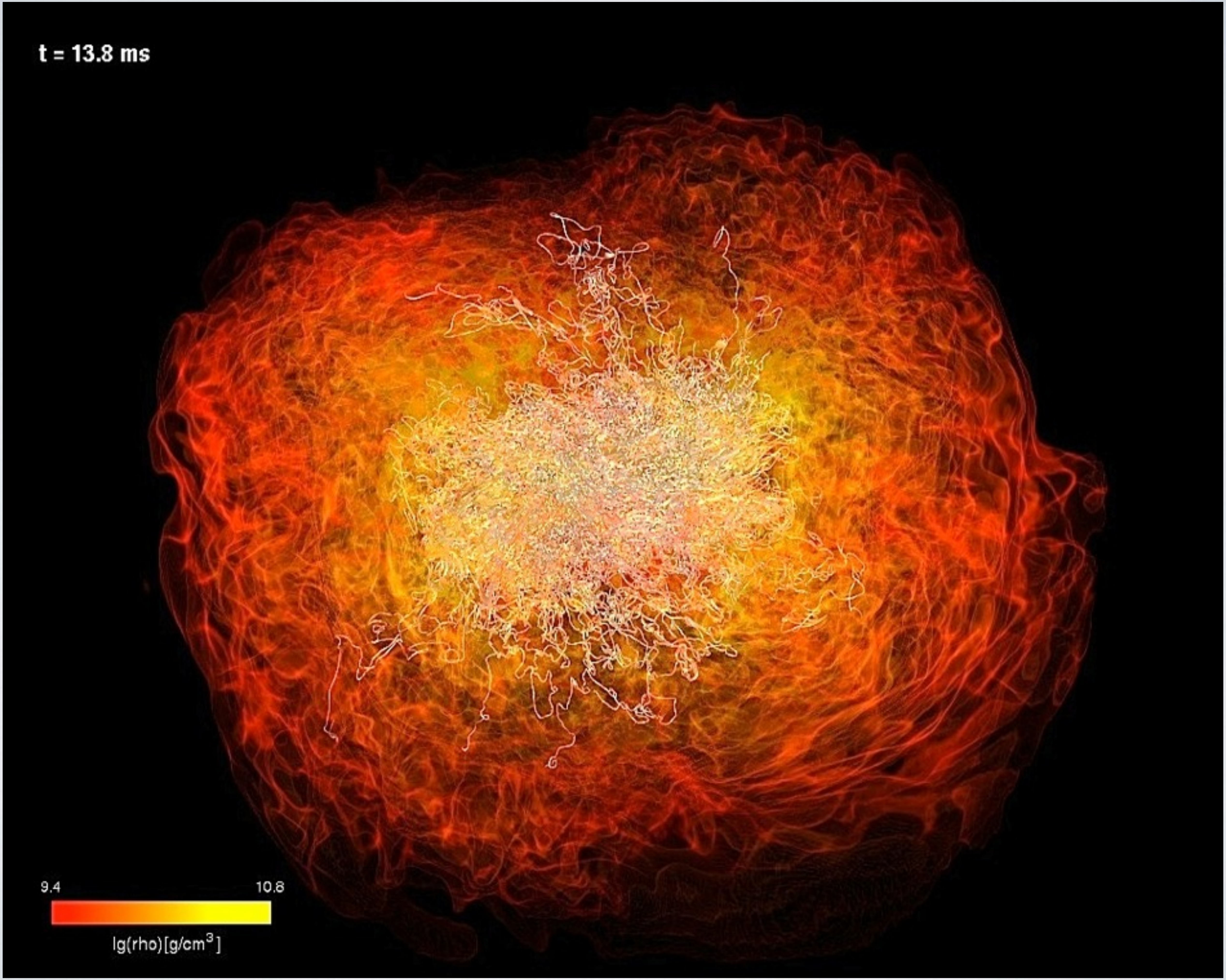
All these studies use as initial conditions specific configurations (such as jet-like structures). Can such configurations be generated by the merger of binary neutron stars?



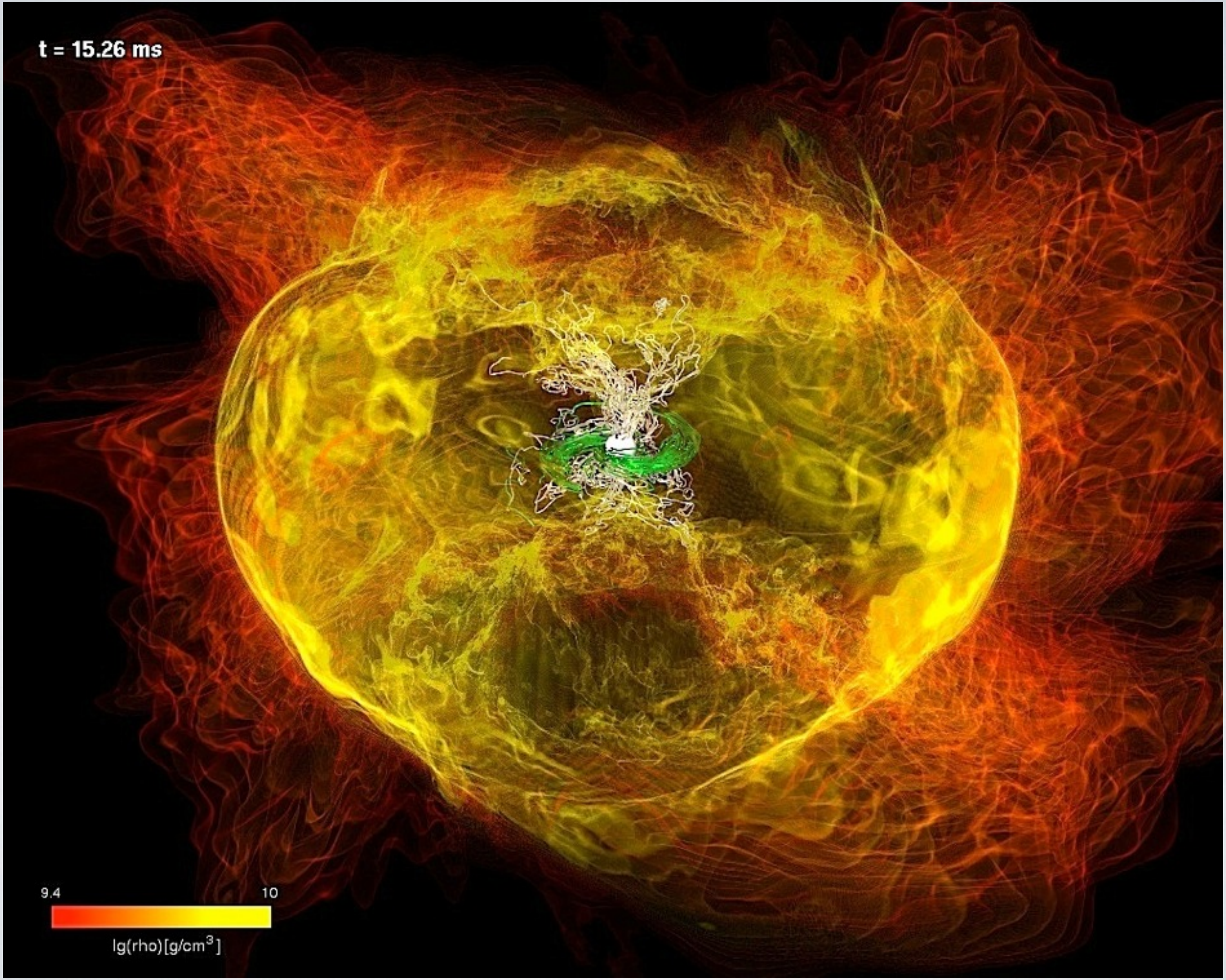
Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti



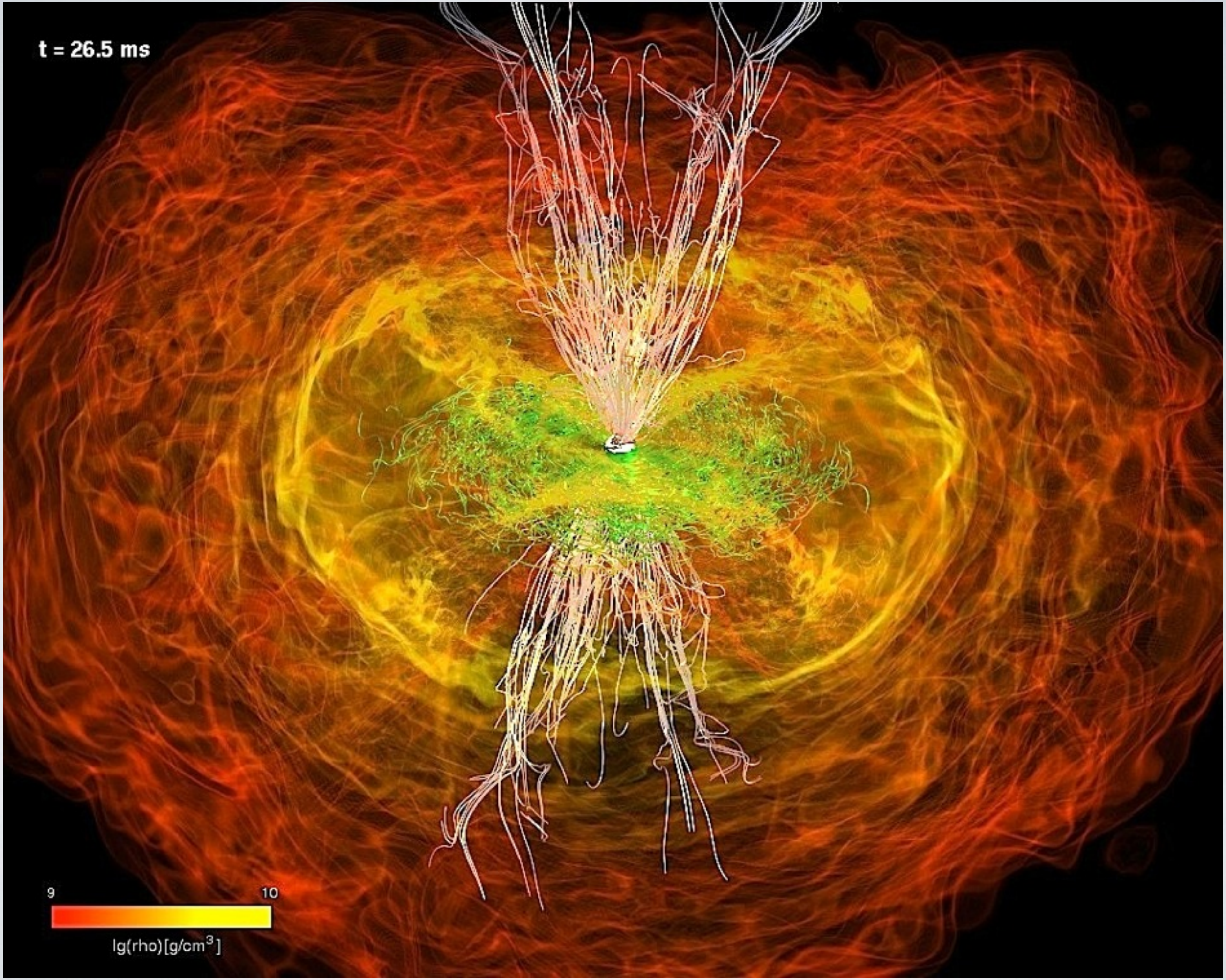
Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti



Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti



Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti



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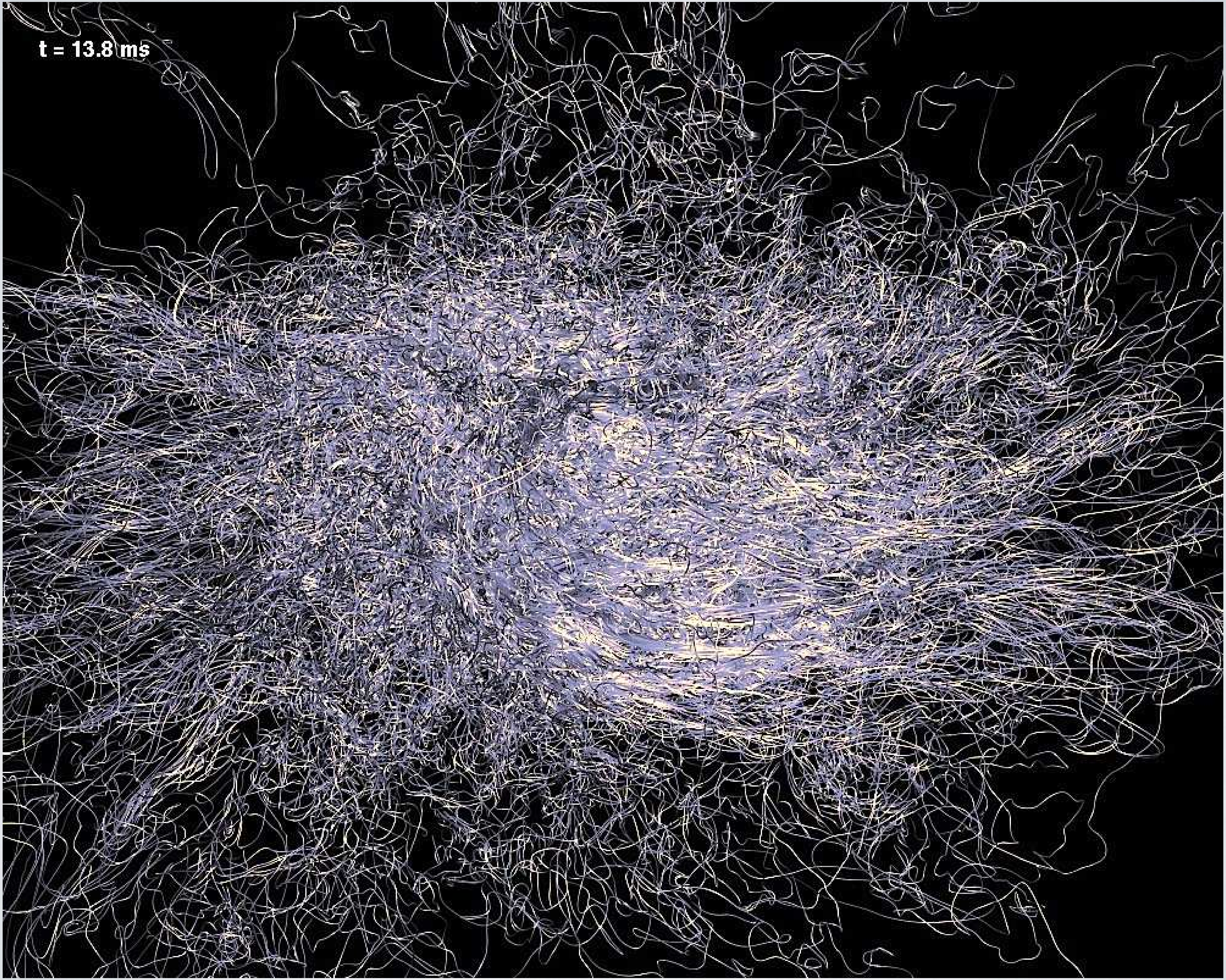

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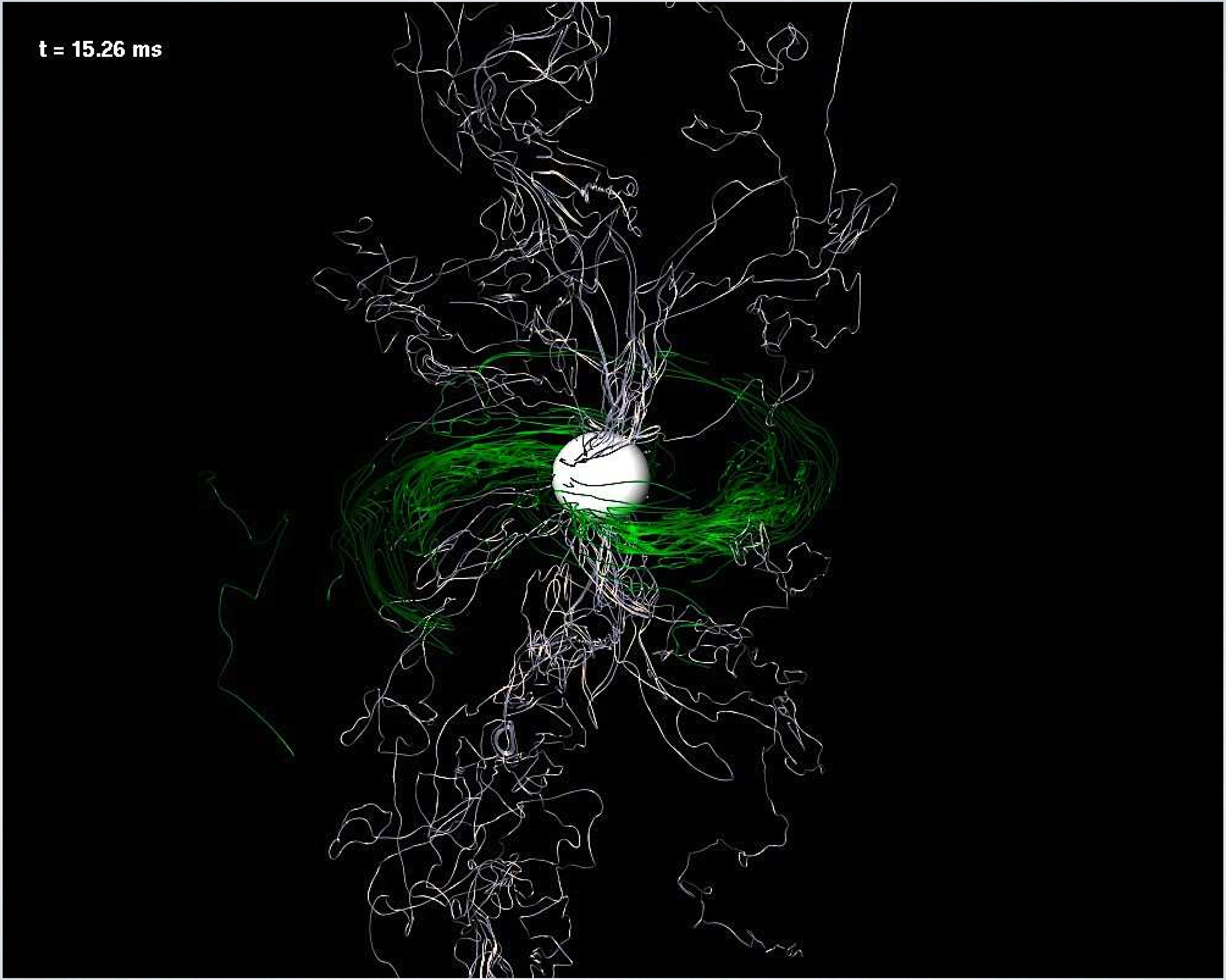

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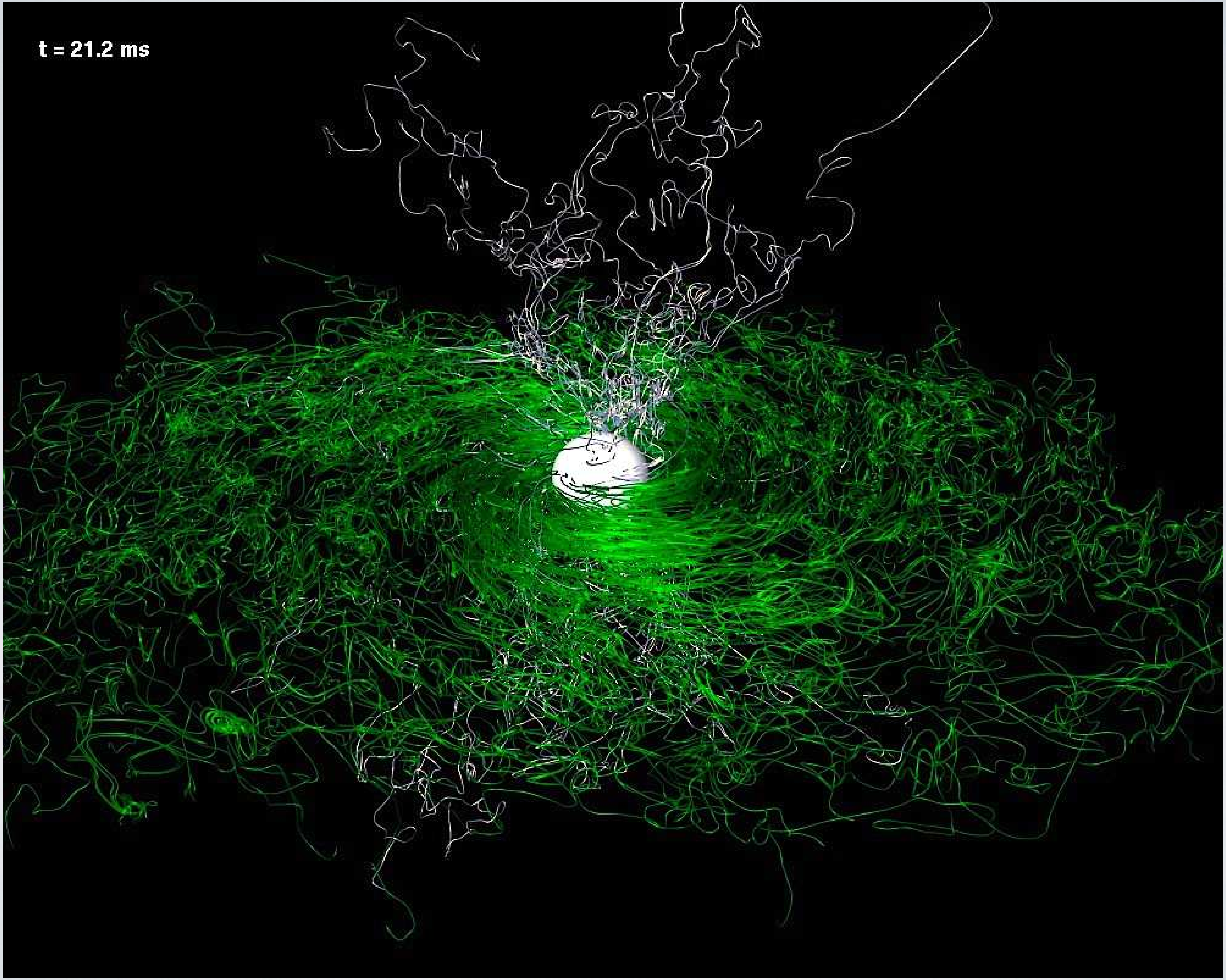
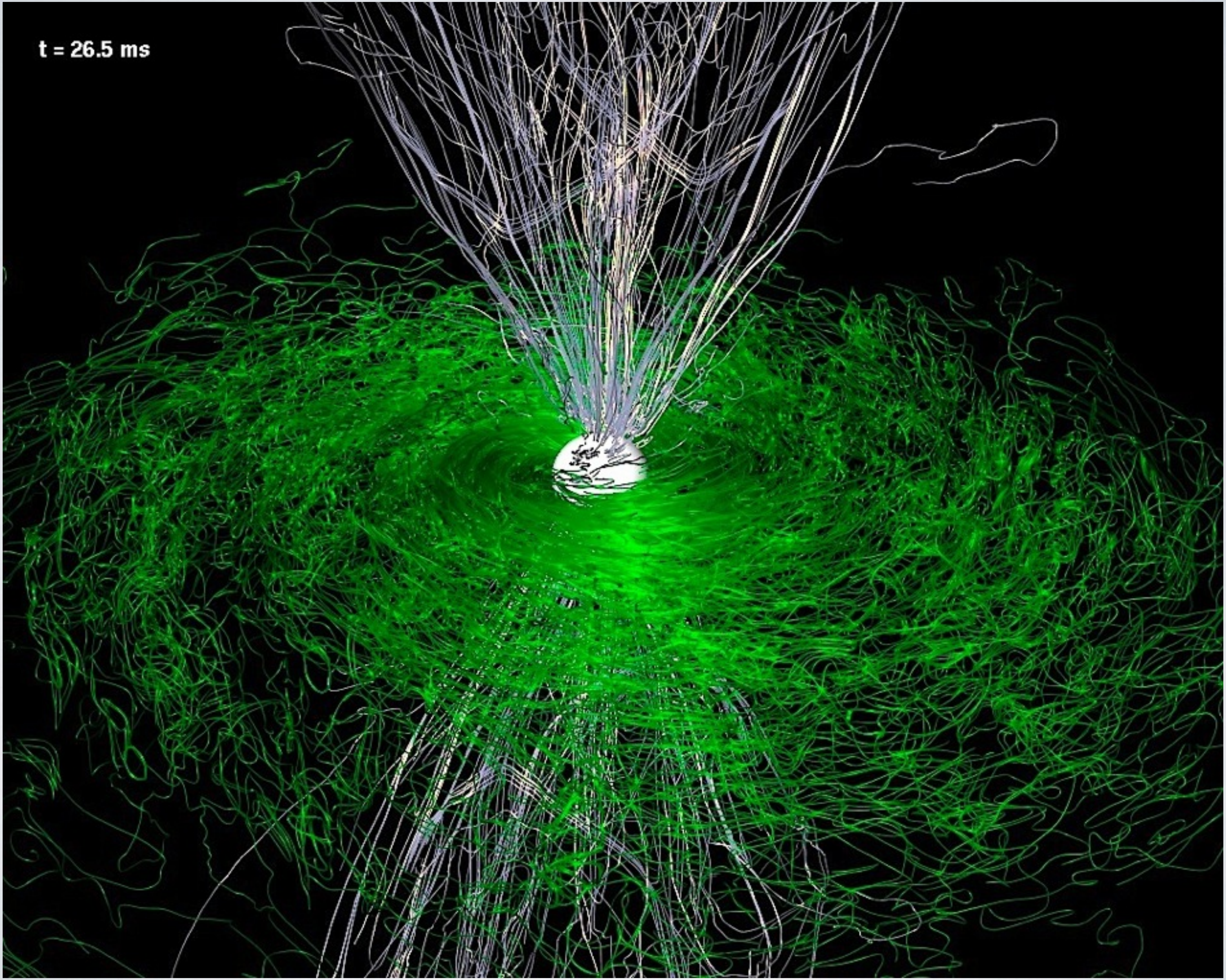
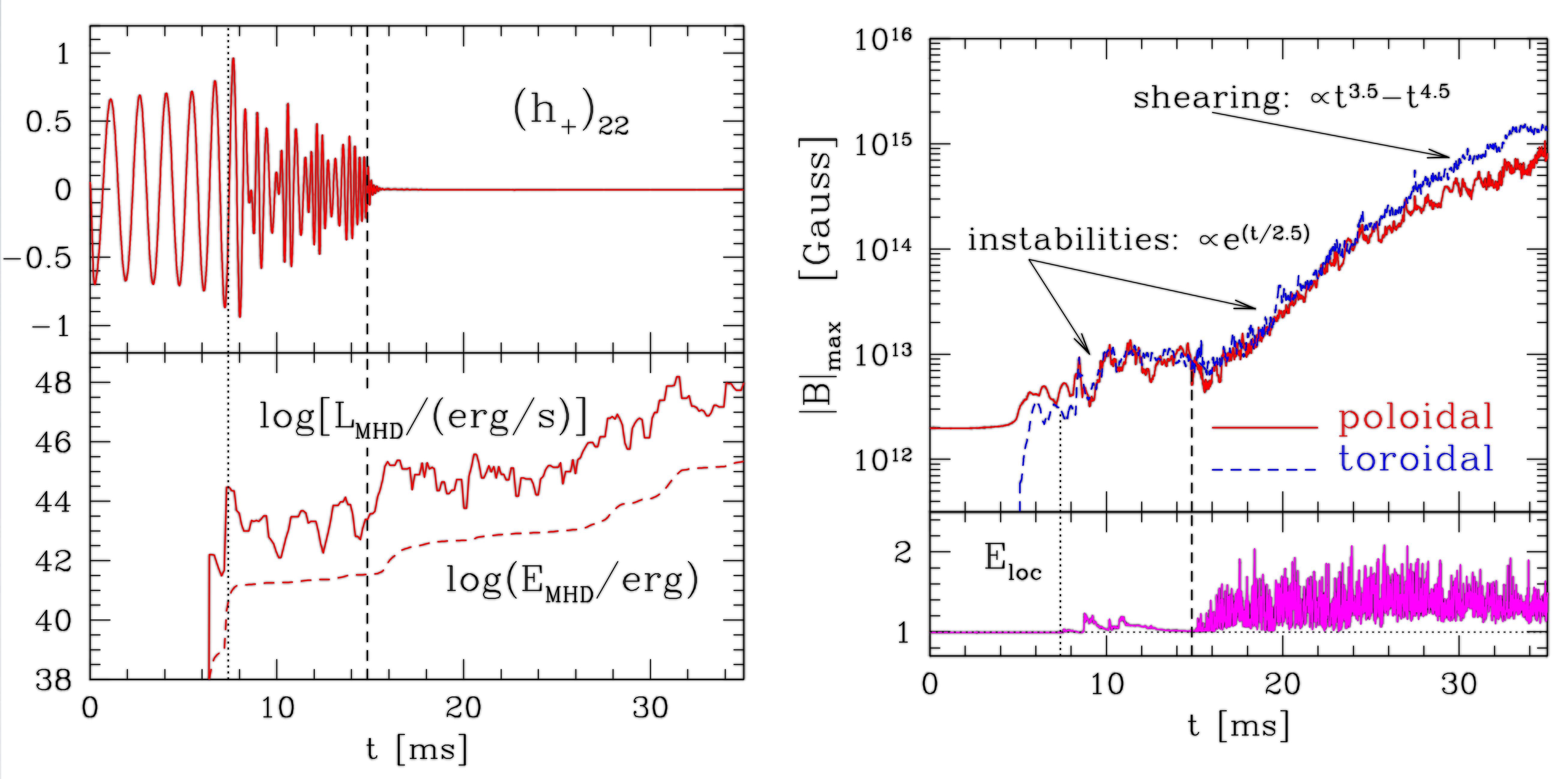


Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti



Visualization by Koppitz, Rezzolla, Giacomazzo, Baiotti

BNSs AND SHORT GRBs



Rezzolla, Giacomazzo et al 2011

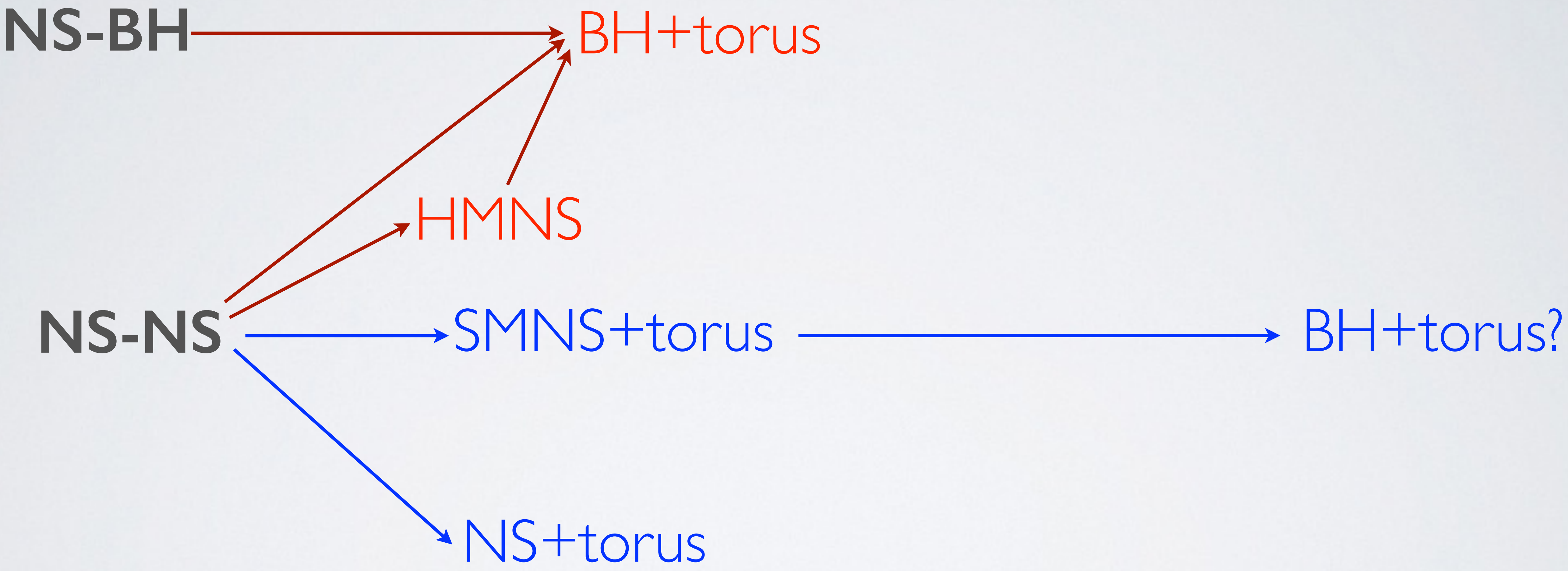
EM signal switches on at the end of GW signal

magnetic field amplified by several order of magnitudes by KH and then MRI instabilities

COMPACT BINARY PROGENITORS OF SHORT GAMMA-RAY BURSTS

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

Depending on mass and EOS several post-merger scenarios:



NS-BH → BH+torus

NS-NS → BH+torus

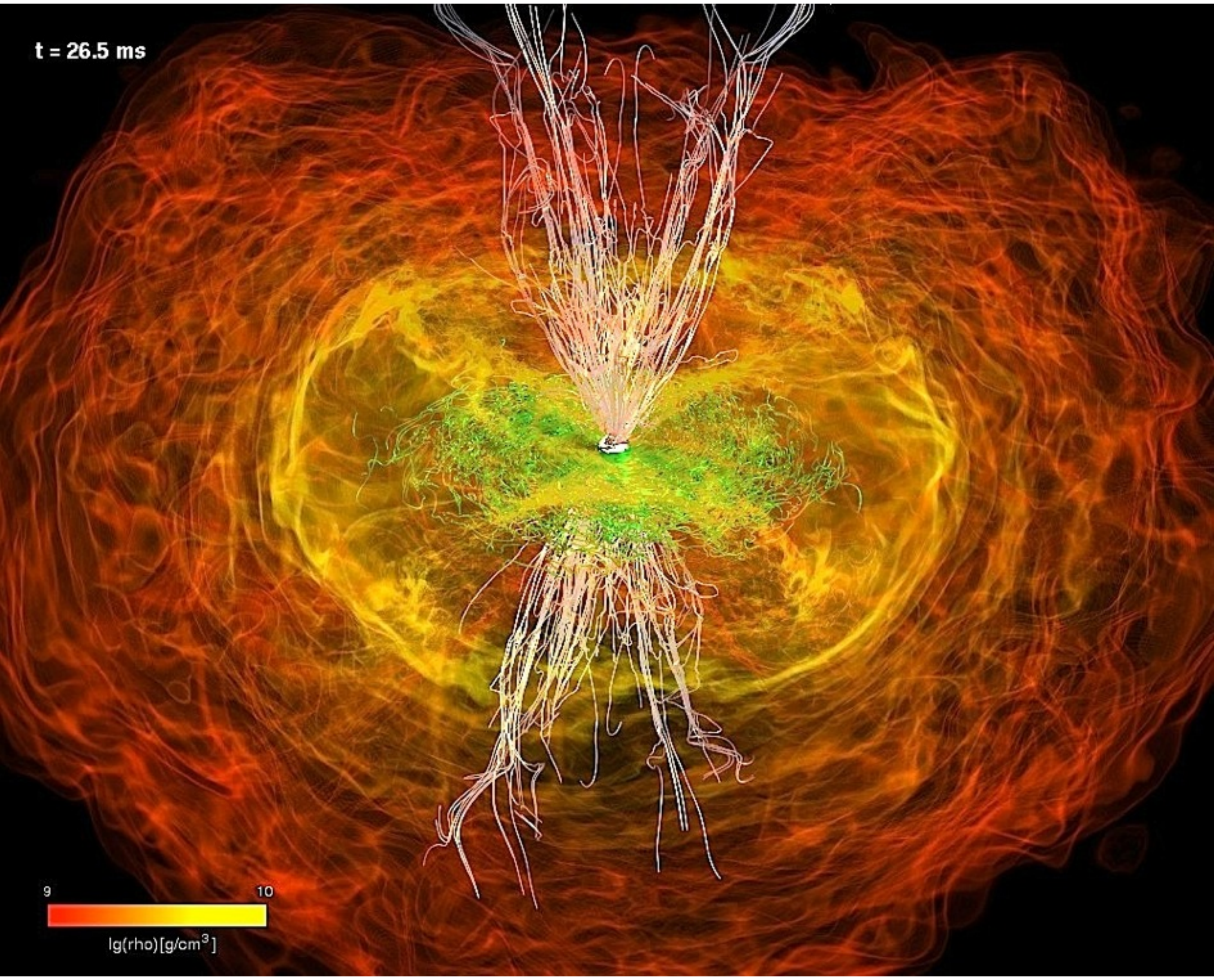
NS-NS → HMNS → BH+torus

NS-NS → SMNS+torus → BH+torus?

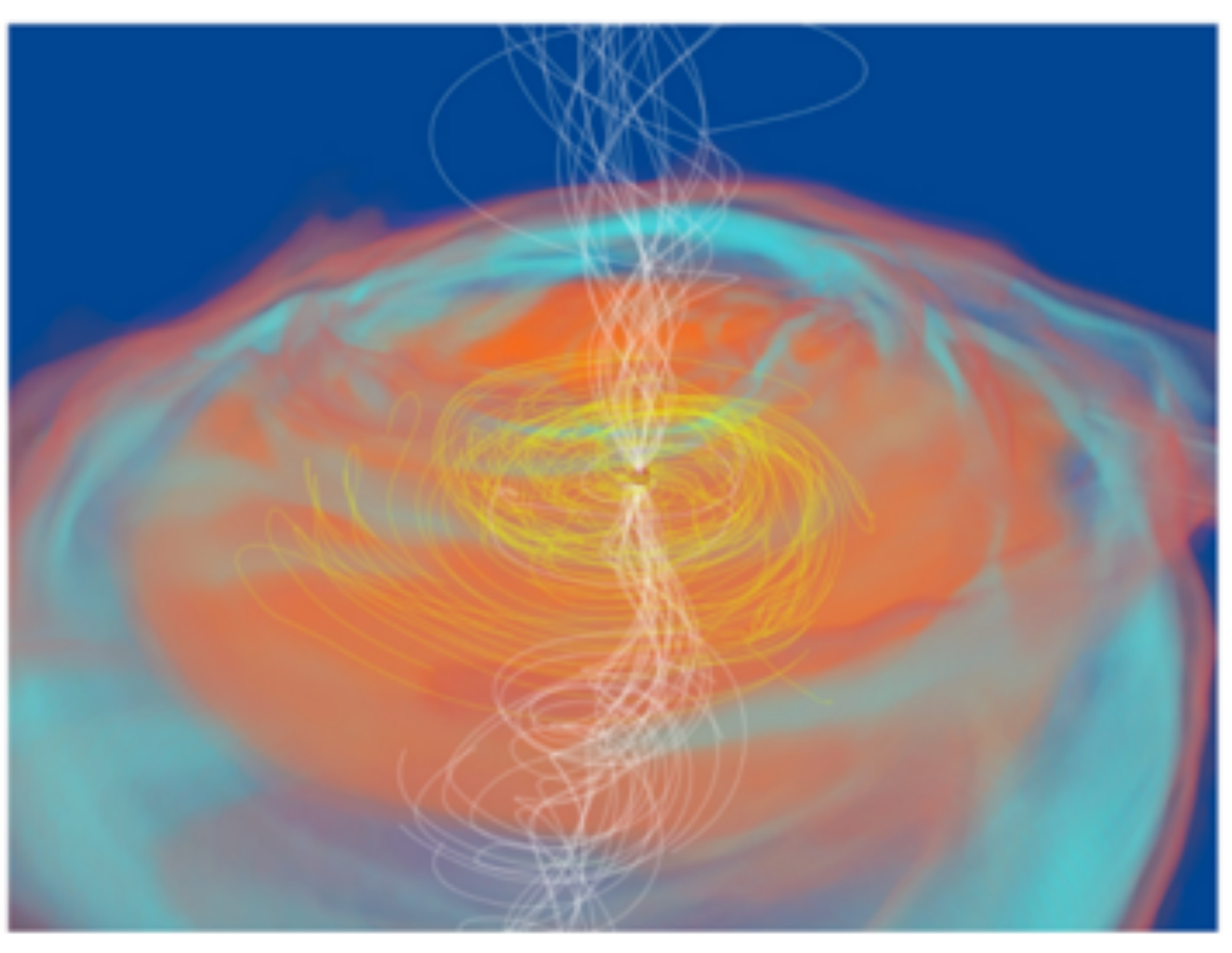
NS-NS → NS+torus

Magnetic fields play fundamental role in post-merger dynamics (jets from BH/NS+torus, NS collapse to BH, ...)

All these scenarios may lead to SGRBs with different properties



Rezzolla et al 2011, ApJL 732, L6



Etienne et al 2012, PRD 86, 084026

BNS and NS-BH can produce tori around spinning BHs.

When NSs are magnetized this can lead to the production of relativistic jets.

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

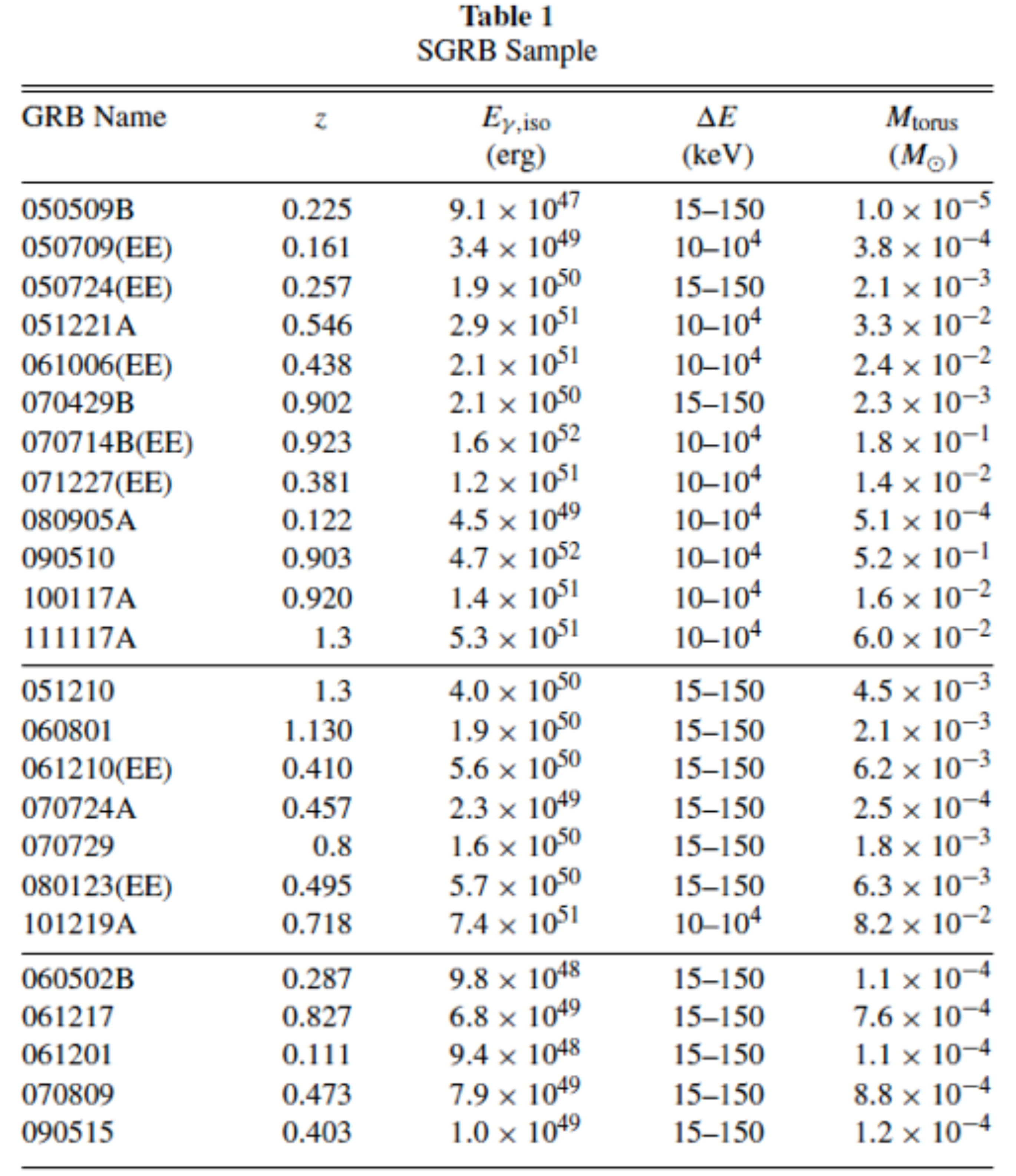


Table 1
SGRB Sample

GRB Name	z	$E_{\gamma,\mathrm{iso}}$ (erg)	ΔE (keV)	M_{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

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

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

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

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

ϵ_{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

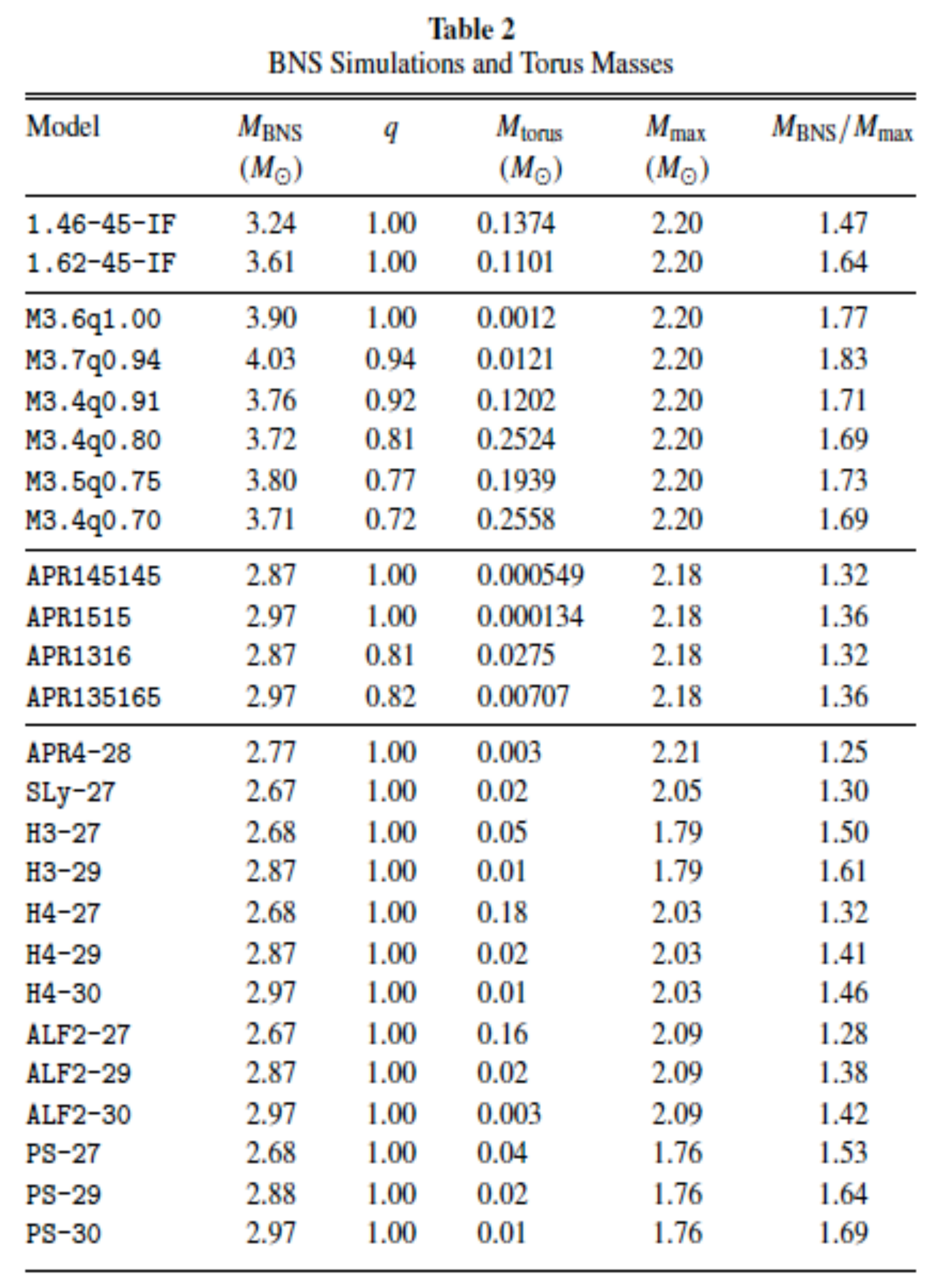
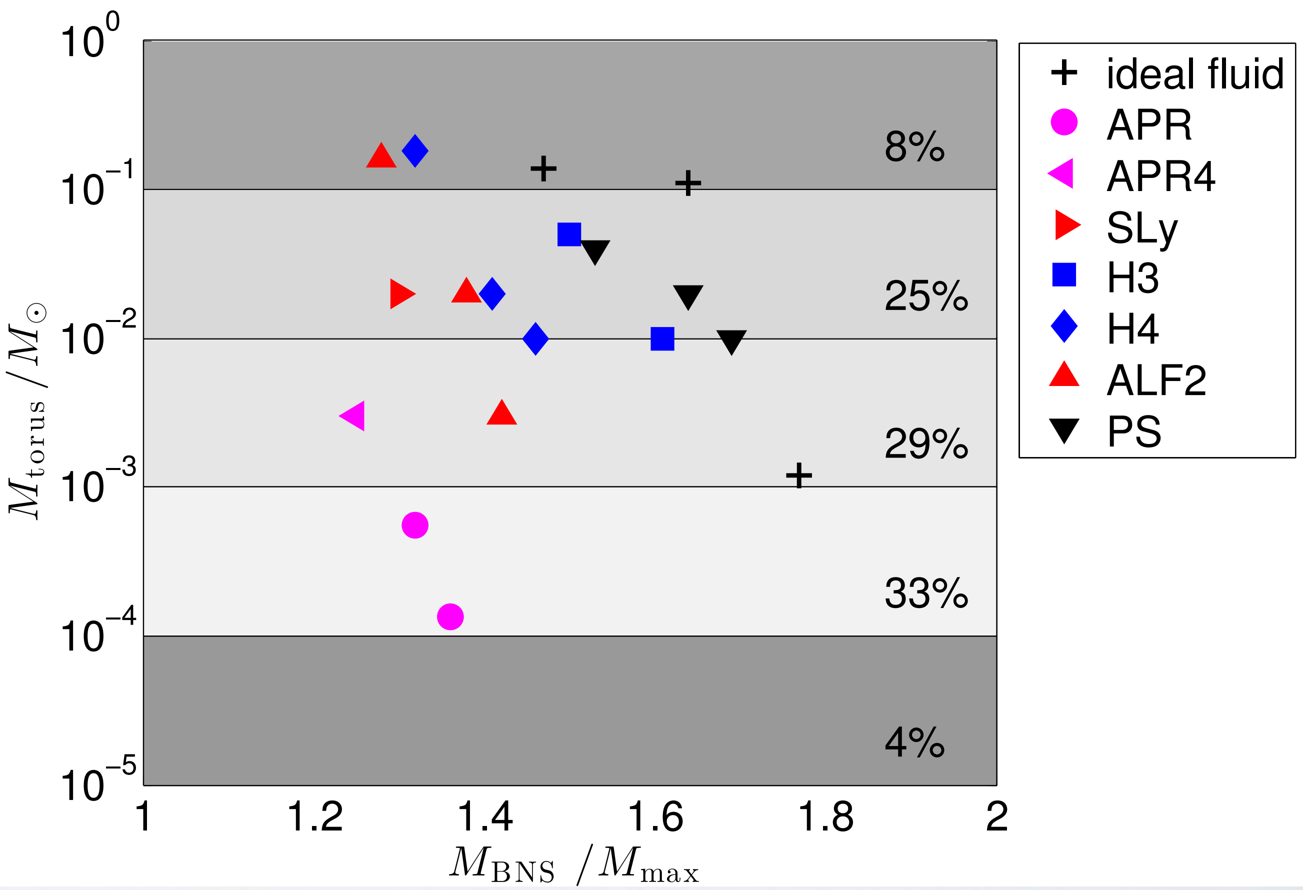


Table 2
BNS Simulations and Torus Masses

Model	$M_{\rm BNS}$ ($M_\odot$)	q	$M_{\rm torus}$ ($M_\odot$)	$M_{\rm max}$ ($M_\odot$)	$M_{\rm BNS}/M_{\rm max}$
`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



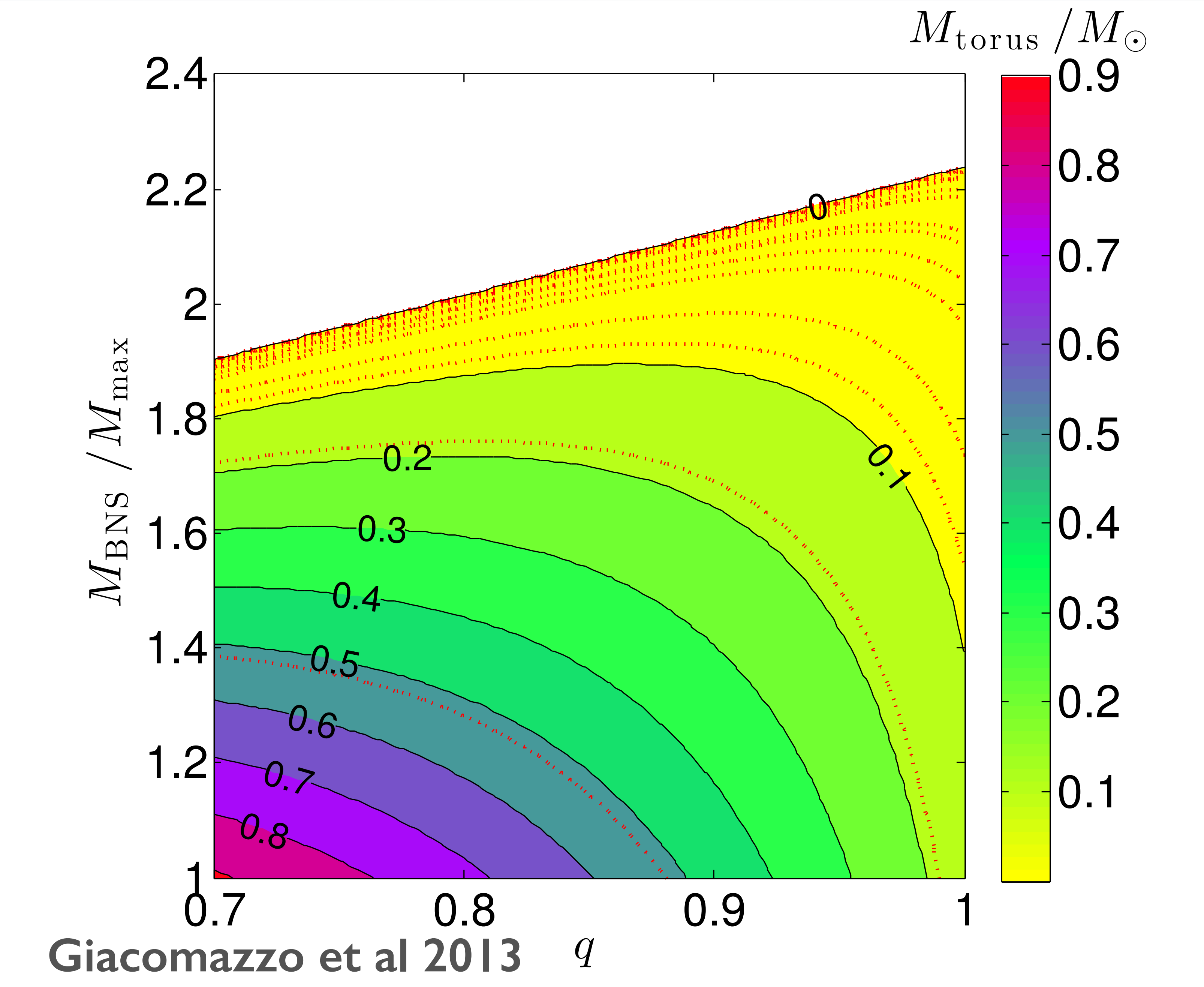
Giacomazzo et al 2013

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

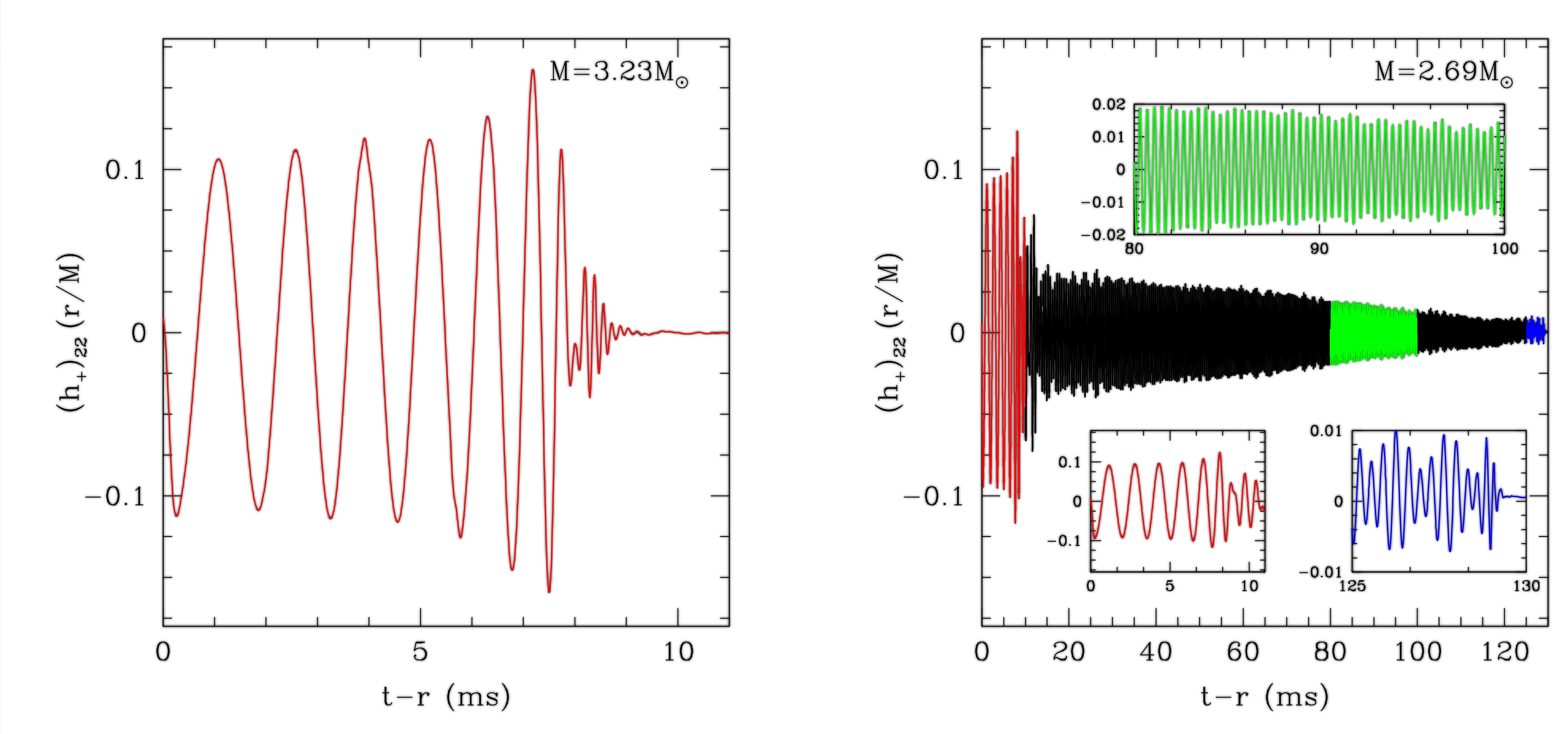
Almost all SGRBs are produced by high-mass BNSs. These BNSs produce an HMNS that survive only few ms before collapse to BH.

"low-energy" SGRBs
(<~1e51 erg)

"high-mass" BNSs

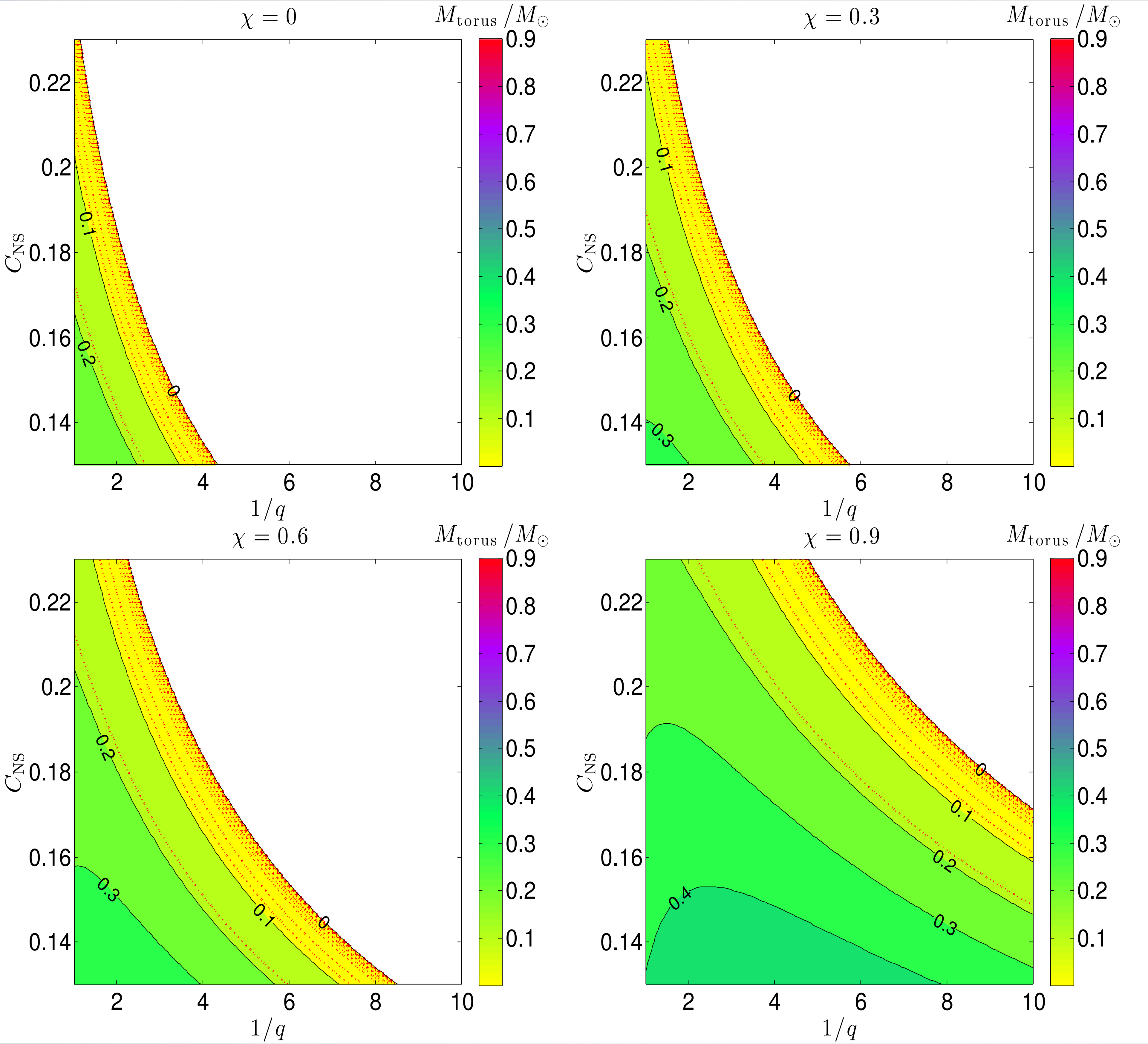
"high-energy" SGRBs
(>~1e51 erg)

"low-mass" BNSs



Simultaneous GW/EM detection will help validate this model

Foucart 2012 derived a similar fit from NS-BH GR simulations

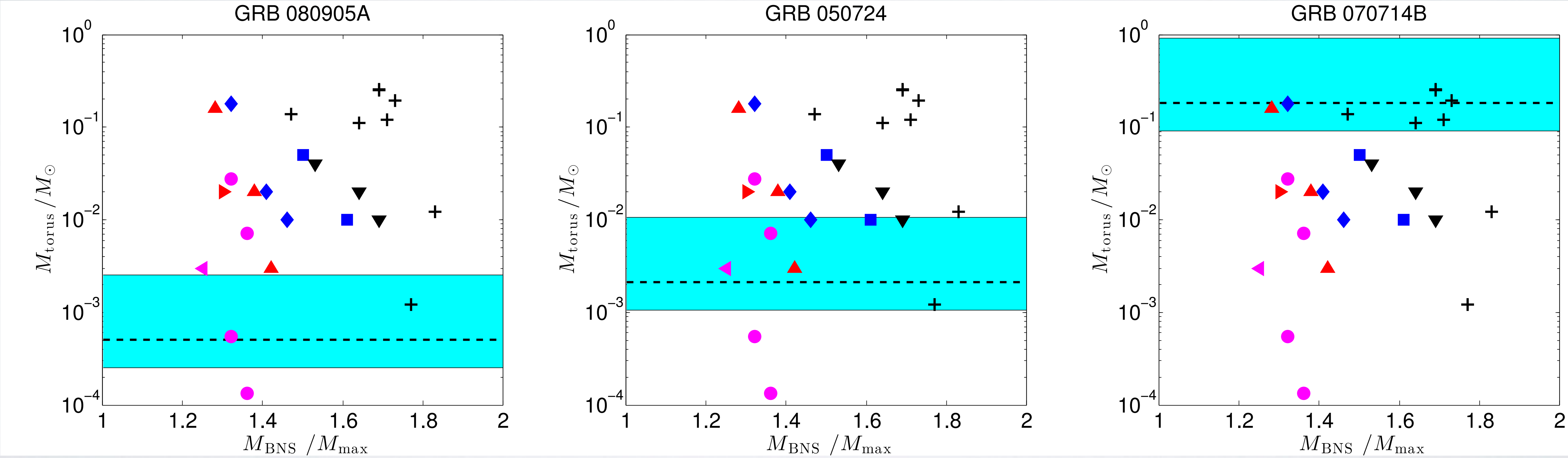


if M_{BH}/M_{NS}>~7 only rapidly spinning BHs (J/M^2>~0.9) may produce SGRBs.

Most energetic bursts cannot be explained with NS-BH mergers.

Giacomazzo et al 2013

What can we learn from a simultaneous GW-SGRB observation?



Giacomazzo et al 2013

- From the GW we can get M_{BNS}
- From the GRB we can get M_{torus}

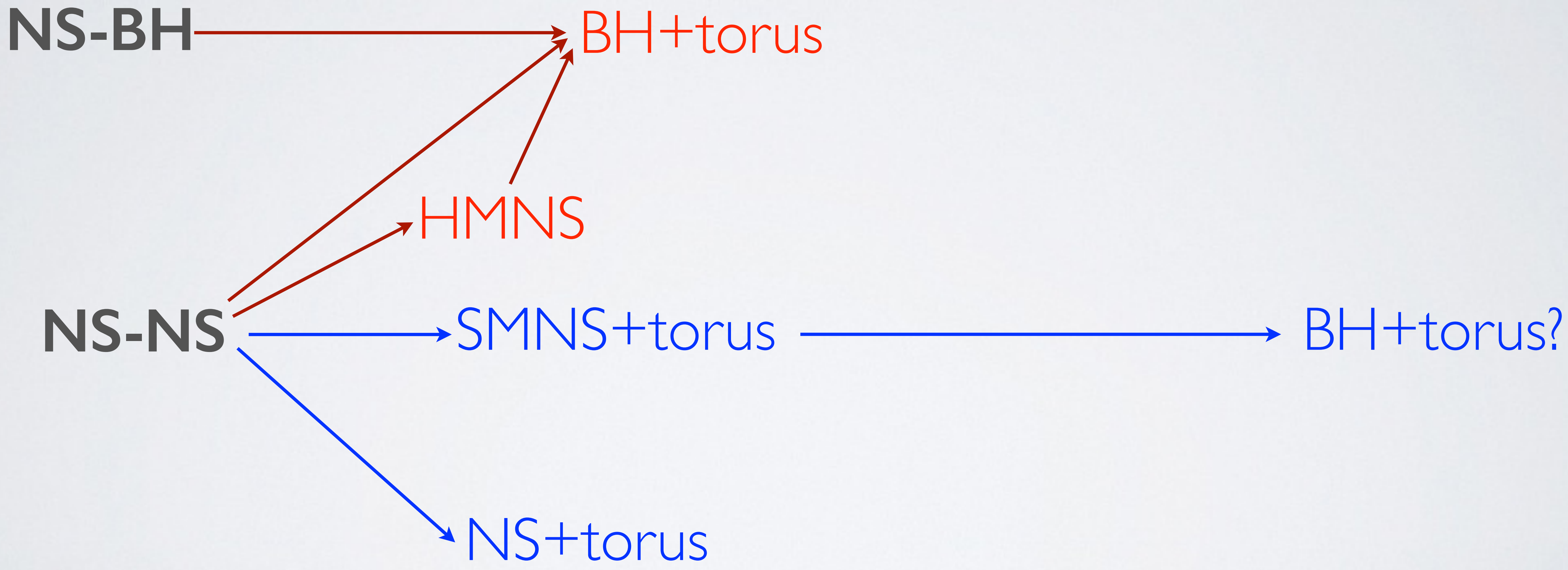
Combining these two informations we may further restrict the BNS parameters (EOS, mass ratio, ...)

The same could be done for NS-BH mergers to infer BH spin and NS compactness.

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26

What about the blue path?



NS-BH

BH+torus

HMNS

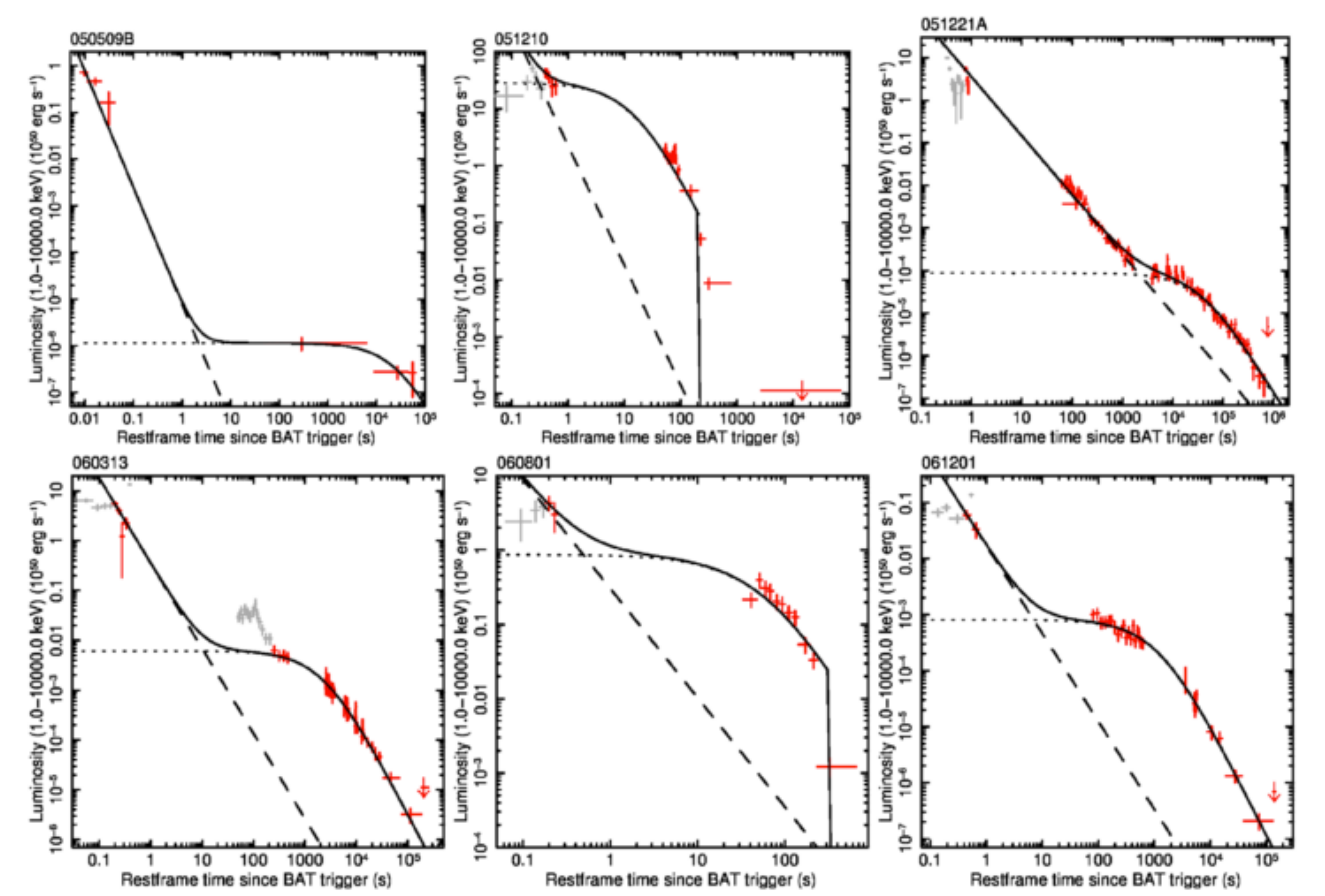
NS-NS

SMNS+torus

BH+torus?

NS+torus

WHY DO WE NEED A MAGNETAR?

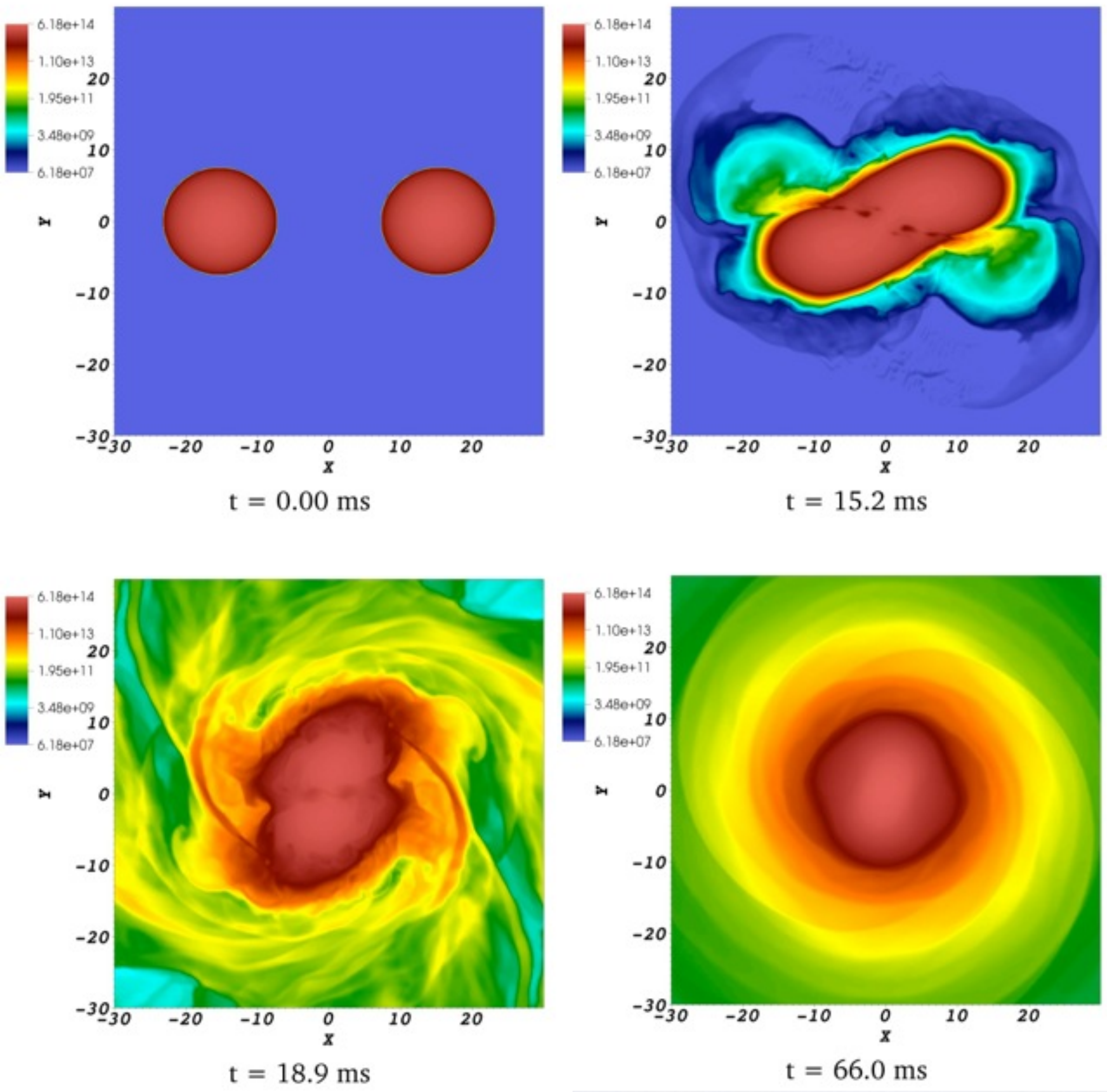


Rowlinson et al 2013

A stable 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



t = 0.00 ms

t = 15.2 ms

t = 18.9 ms

t = 66.0 ms

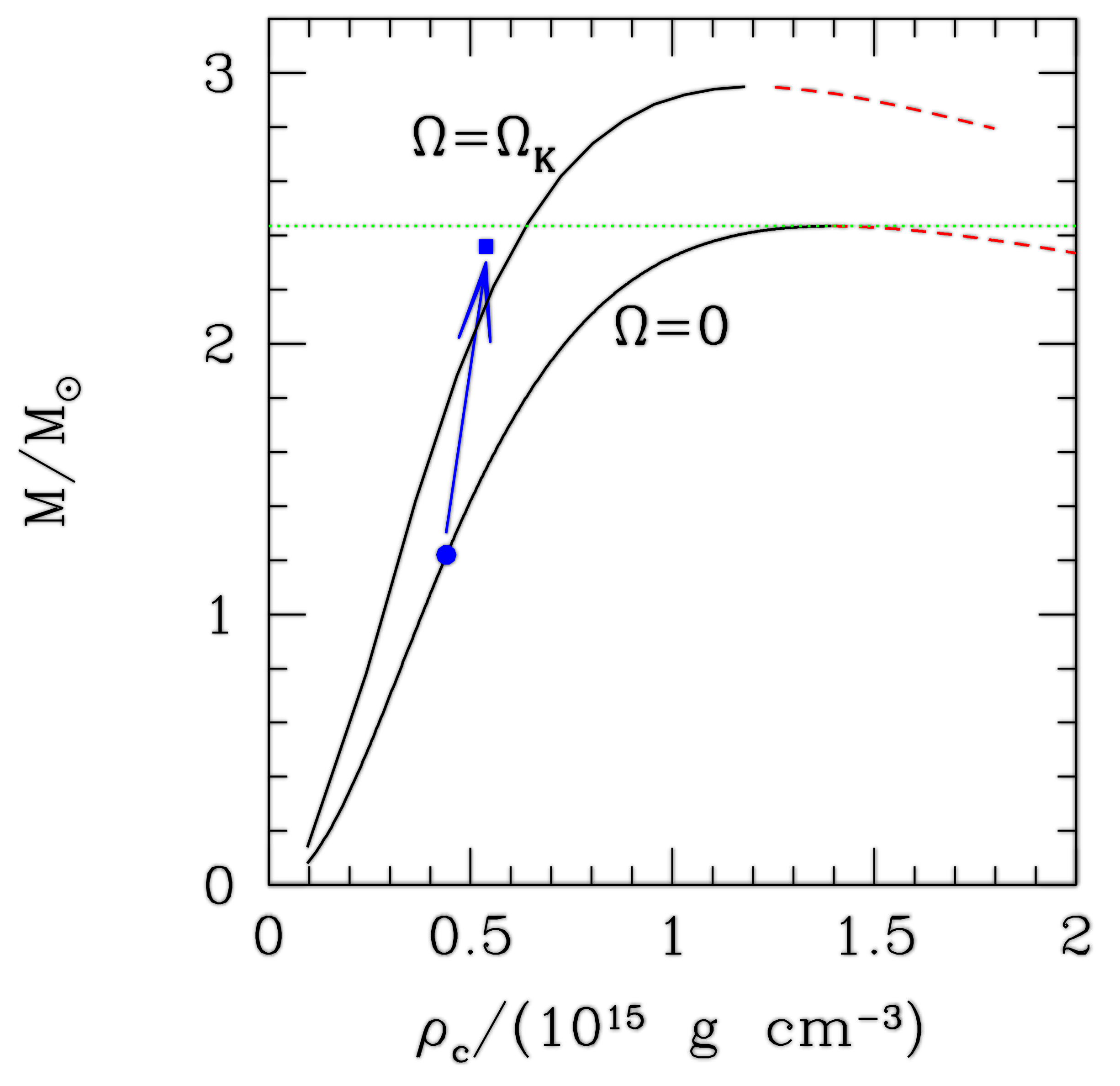
Investigated merger of two 1.2 M⊙ NSs

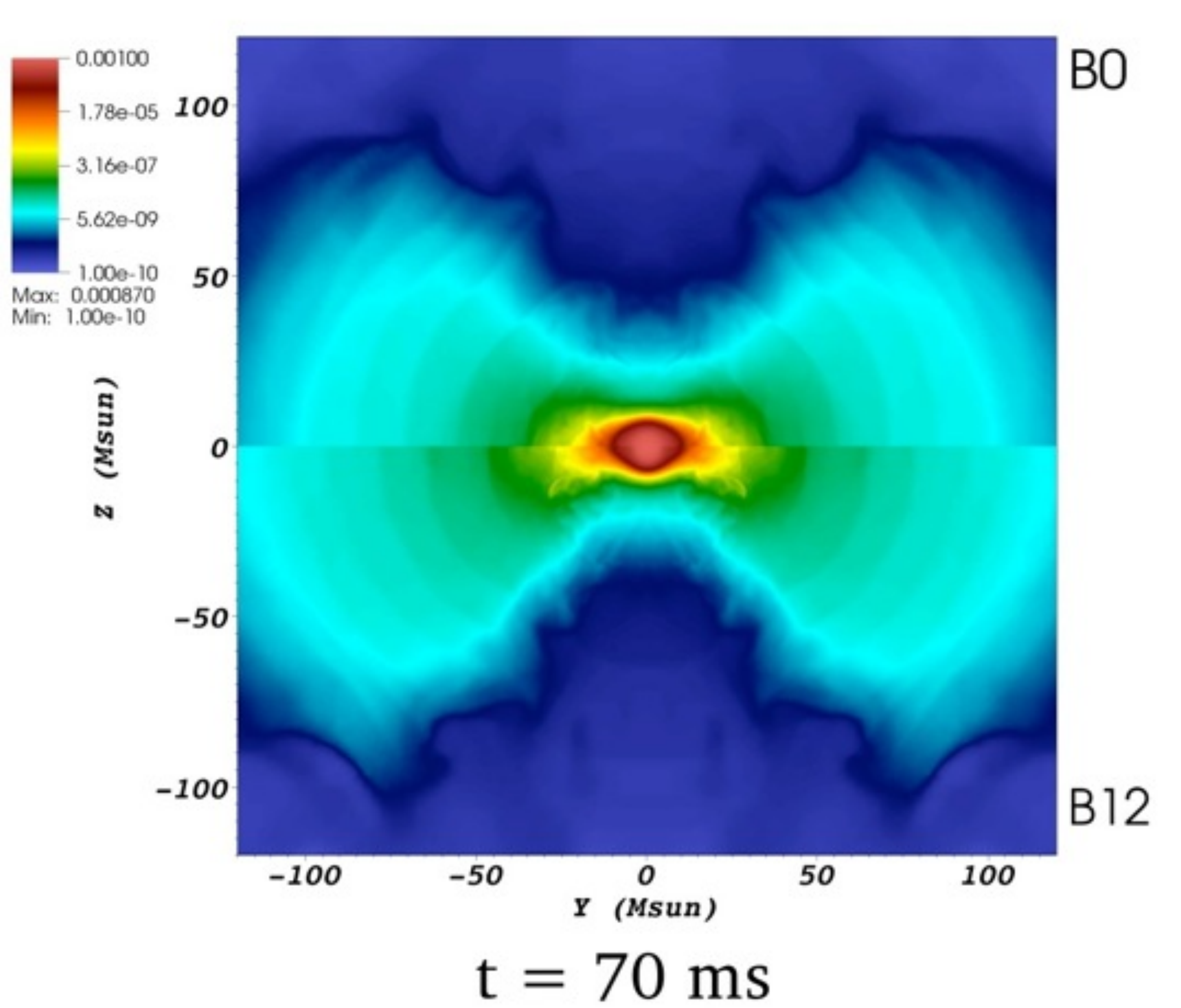
Used Ideal Fluid, Gamma=2.75, k=30000 (Oechslin et al 2007)

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

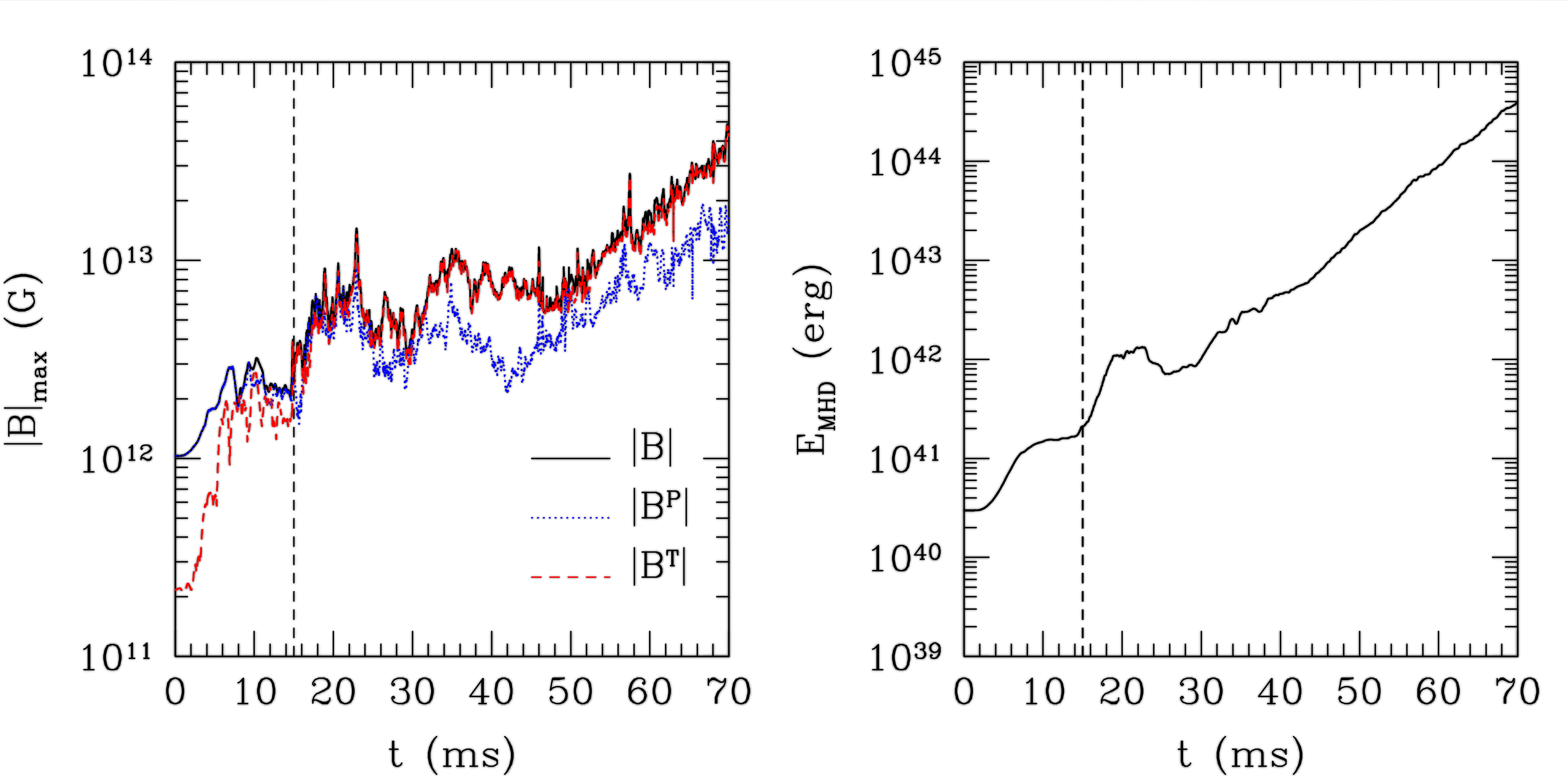




Produced a stable "ultraspinning" NS surrounded by a magnetized disk of ~0.1 M☉

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26

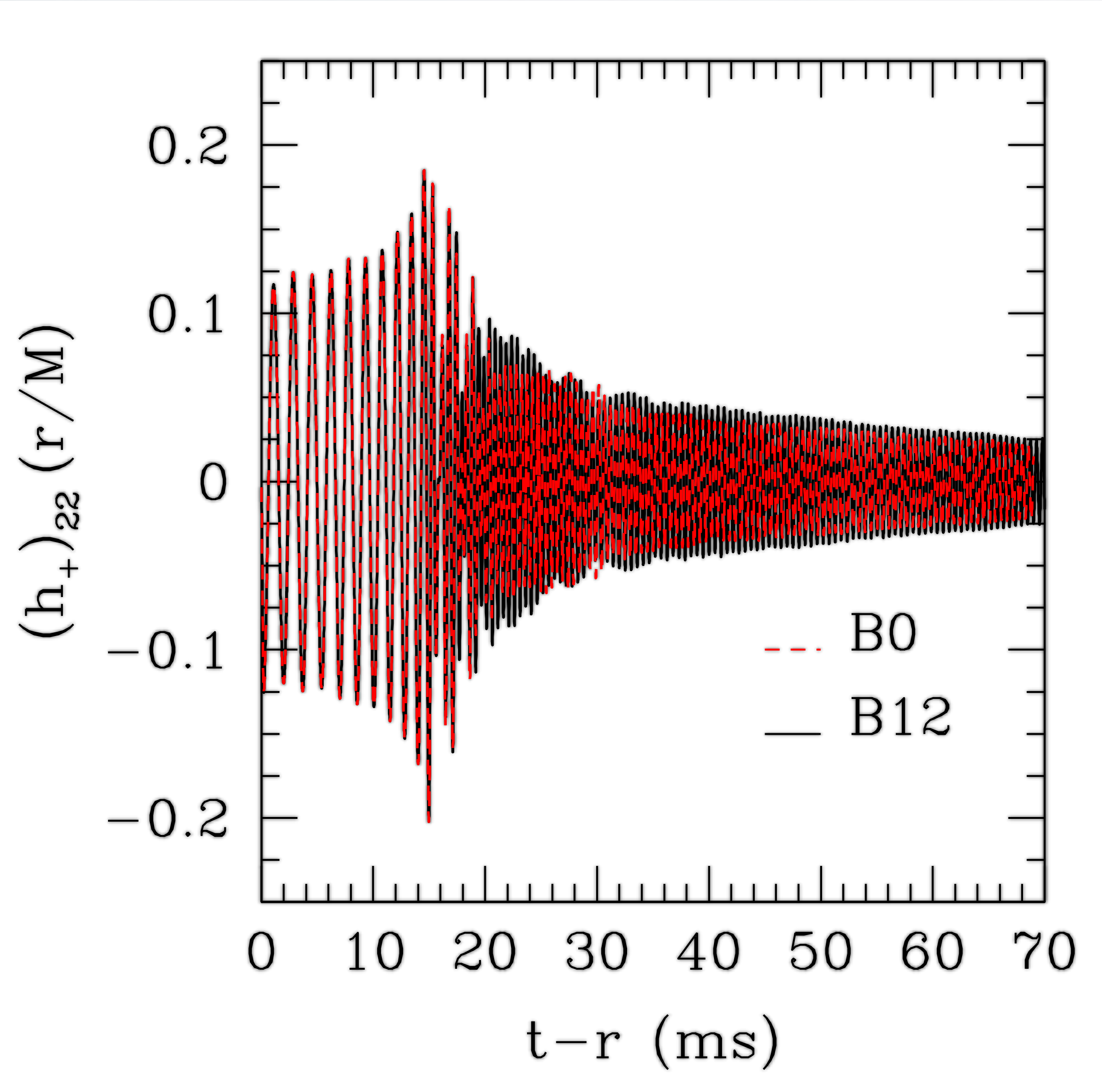


Magnetic field amplified of ~2 orders of magnitude

Larger amplifications possible via longer evolutions and MRI

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26



Difference in the GW signal are small and present only in the post-merger phase

Magnetic fields could emit EM counterparts in radio, optical, X-ray, and gamma rays.

EM signal could be used to confirm magnetar formation.

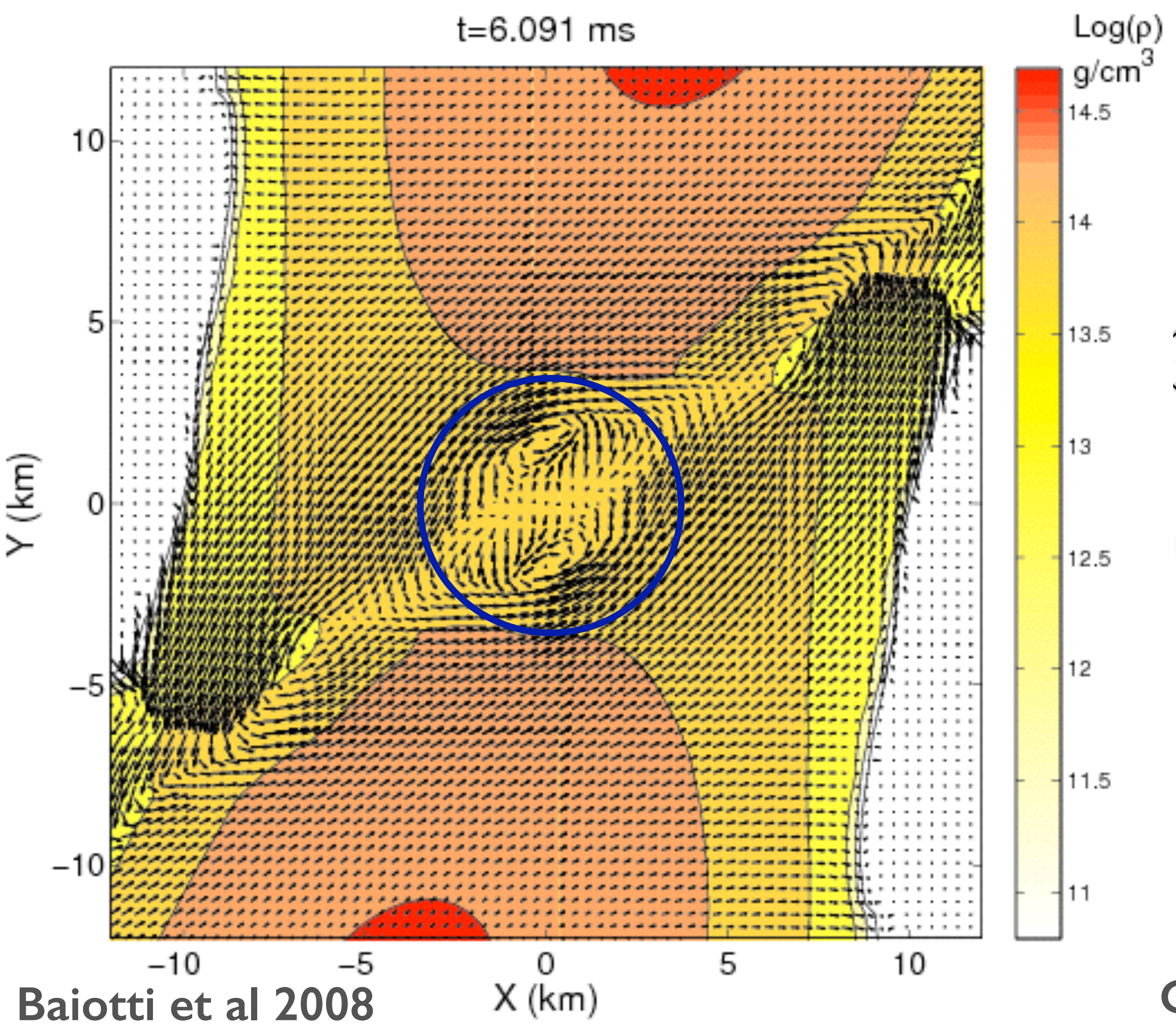
A stable magnetar could be used to explain X-ray plateaus and extended emissions from SGRBs.

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

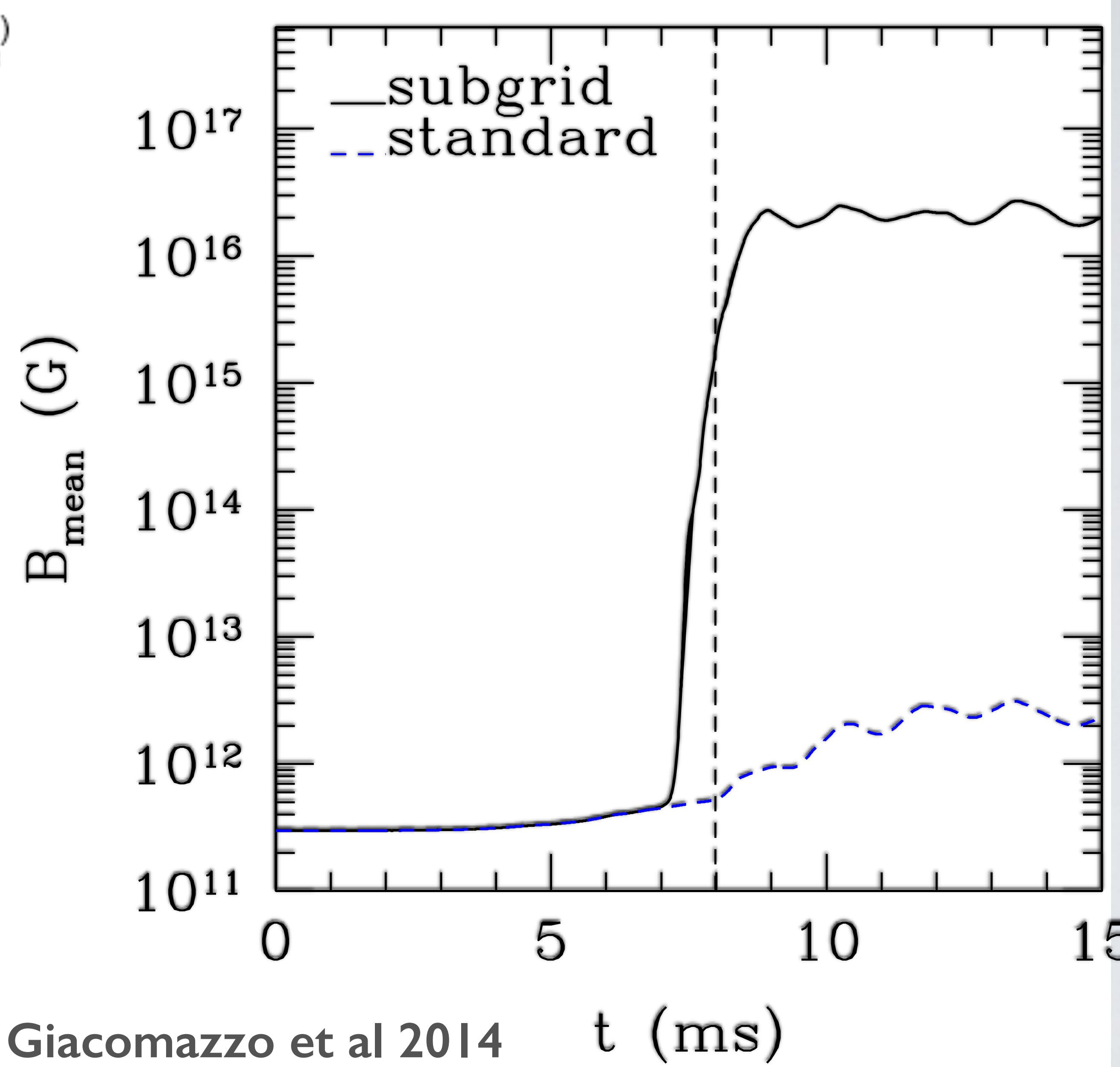
MAGNETAR FORMATION

Giacomazzo, Duffell, MacFadyen, Perna, Zrake, in prep.

Magnetic fields can be strongly amplified via hydrodynamic instabilities at merger, but very difficult to resolve numerically



Baiotti et al 2008



Giacomazzo et al 2014

We developed a sub-grid model and run a set of NS-NS simulations. Magnetar field levels are possible!

CONCLUSIONS

- GRMHD simulations of BNSs now able to study all phases of merger
- Tidal effects at merger may be used to constrain NS EOS
- Magnetized BNSs may produce jets and power SGRBs
- Most SGRBs may be generated by "high-mass" BNSs:
    - less energetic SGRBs are powered by high-mass BNSs
    - more energetic ones by low-mass BNSs
- Possible to form stable magnetar+disk from BNS mergers
- BNS mergers can be used both for the "standard" GRB model and for the magnetar one