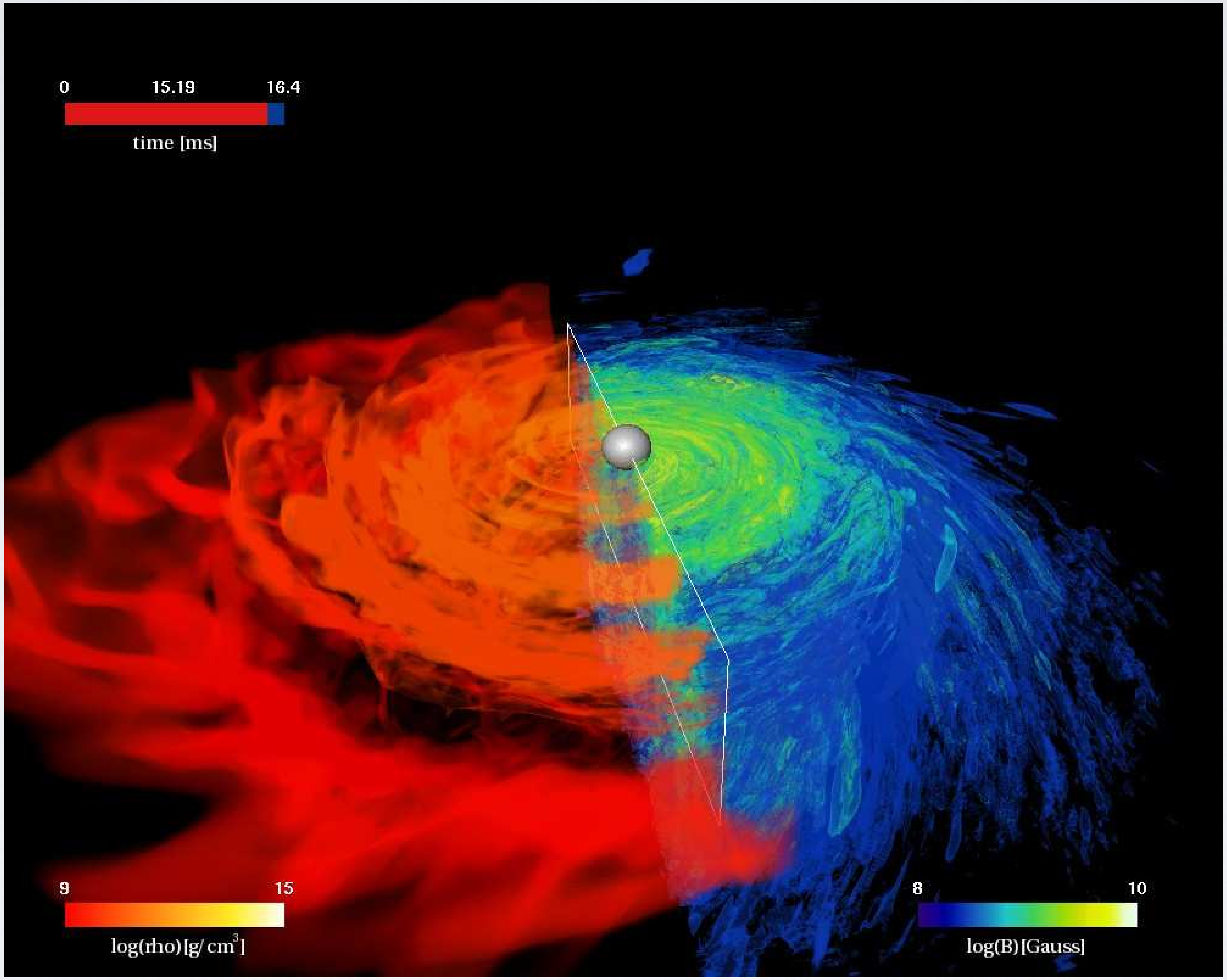
NUMERICAL MODELLING IN BINARY INSPIRAL

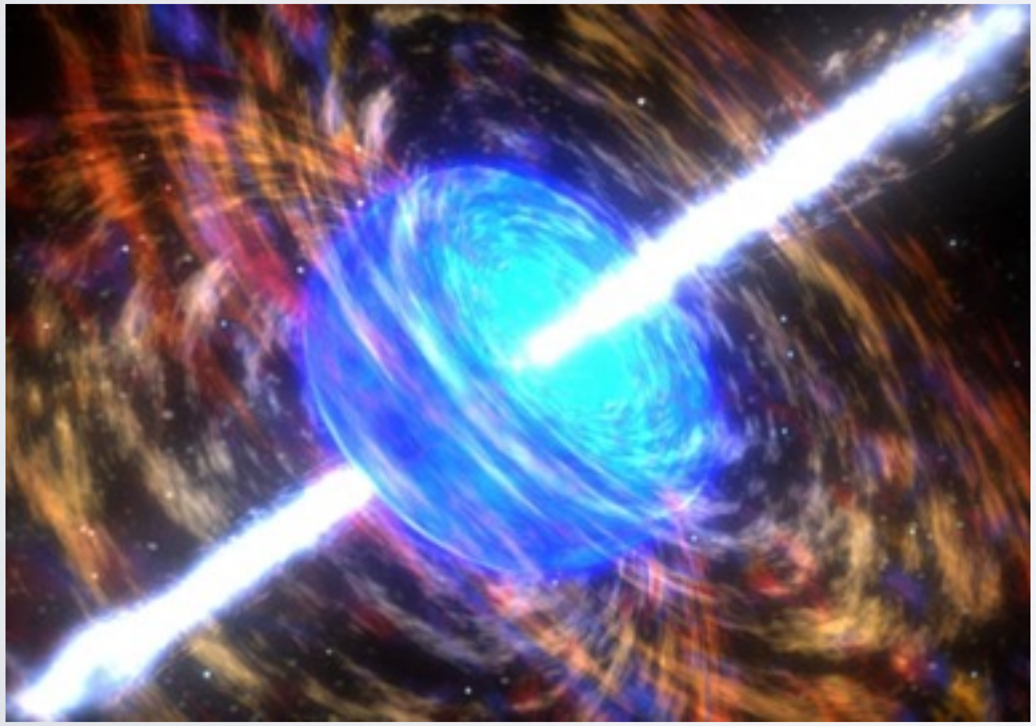


Bruno Giacomazzo
University of Trento and INFN-TIFPA, Italy

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.

FULLY GR NUMERICAL CODES

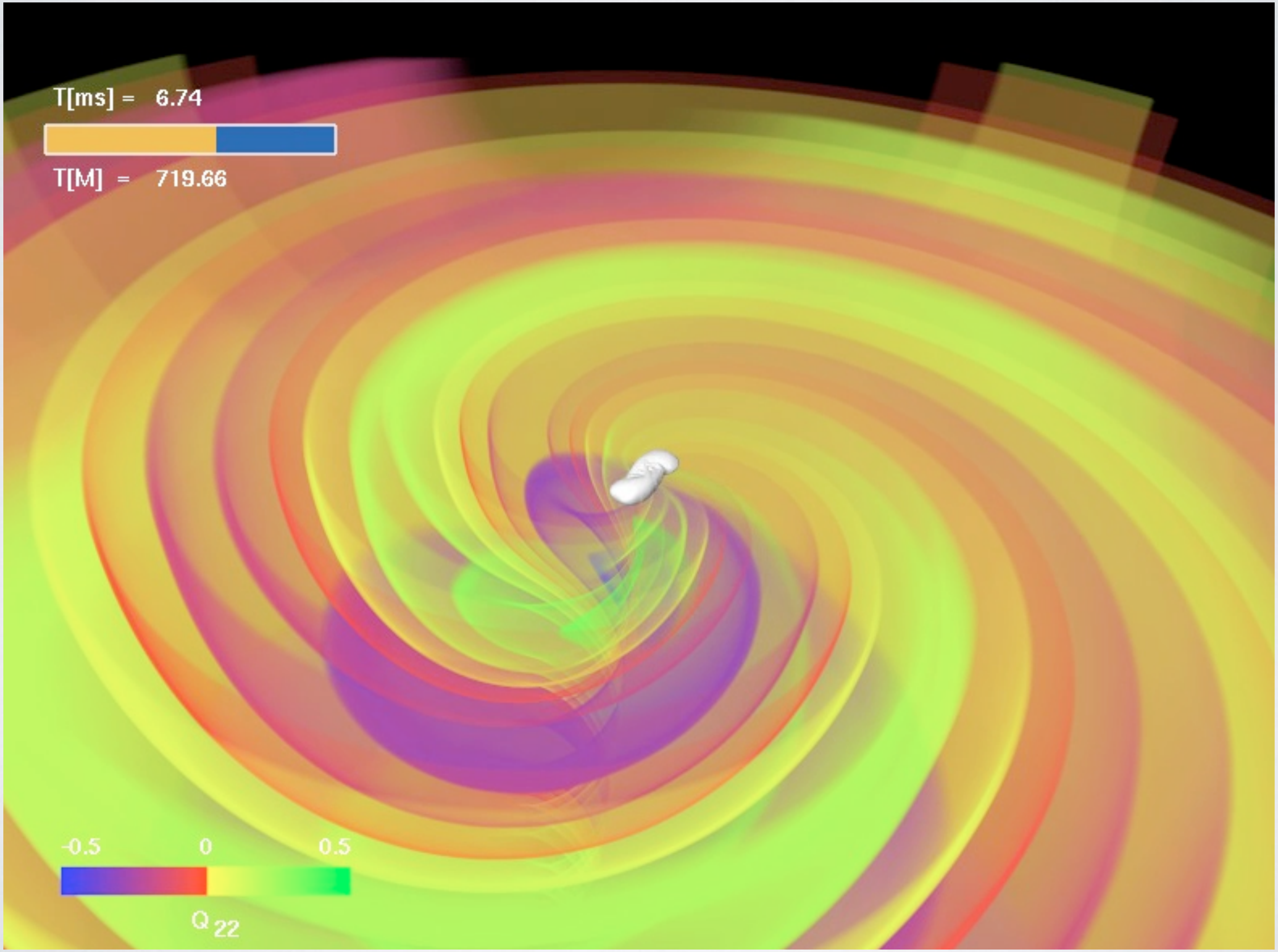
For recent reviews see: Faber & Rasio 2012, arXiv:1204.3858 (NS-NS) and Shibata & Taniguchi 2011, LRR 14, 6 (NS-BH).

- **Publicly Available Codes**:
  - **GRHydro**: HD, MHD (einsteintoolkit.org)
  - **IllinoisGRMHD:** MHD (now also part of einsteintoolkit.org)
  - **Whisky**: HD (www.whiskycode.org)
- **Private Codes**:
  - **BAM**: HD
  - **HAD**: MHD+neutrinos (www.had.liu.edu)
  - **SACRA**: MHD, HD+neutrinos
  - **SPEC**: HD+neutrinos (www.black-holes.org)
  - **Whisky**: MHD, HD+neutrinos (www.whiskycode.org)

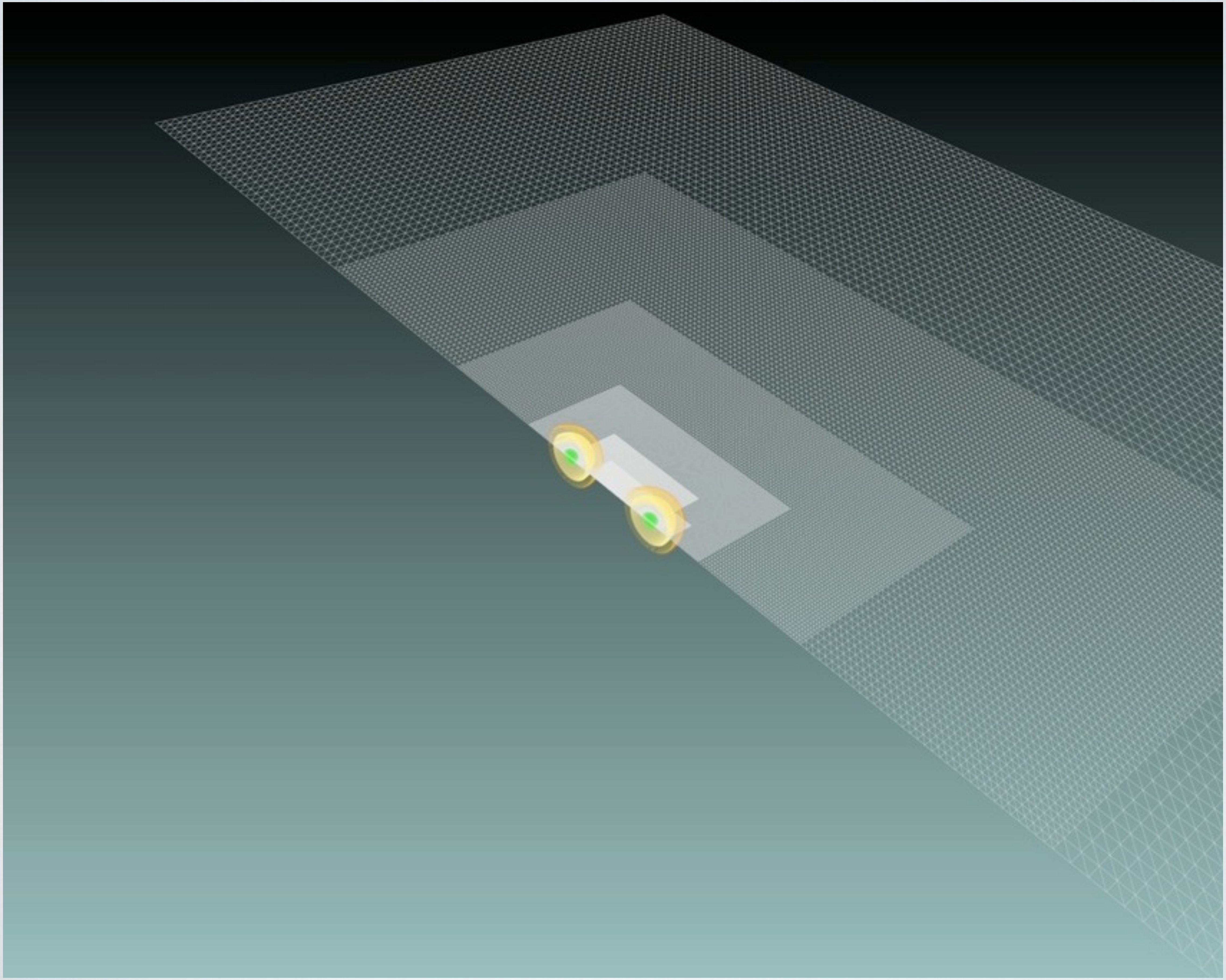
Many other codes in CFC and Newtonian HD/MHD too (see Andreas' talk)

Disclaimer: I'm listing some of the most used codes in fully GR NS binary simulations

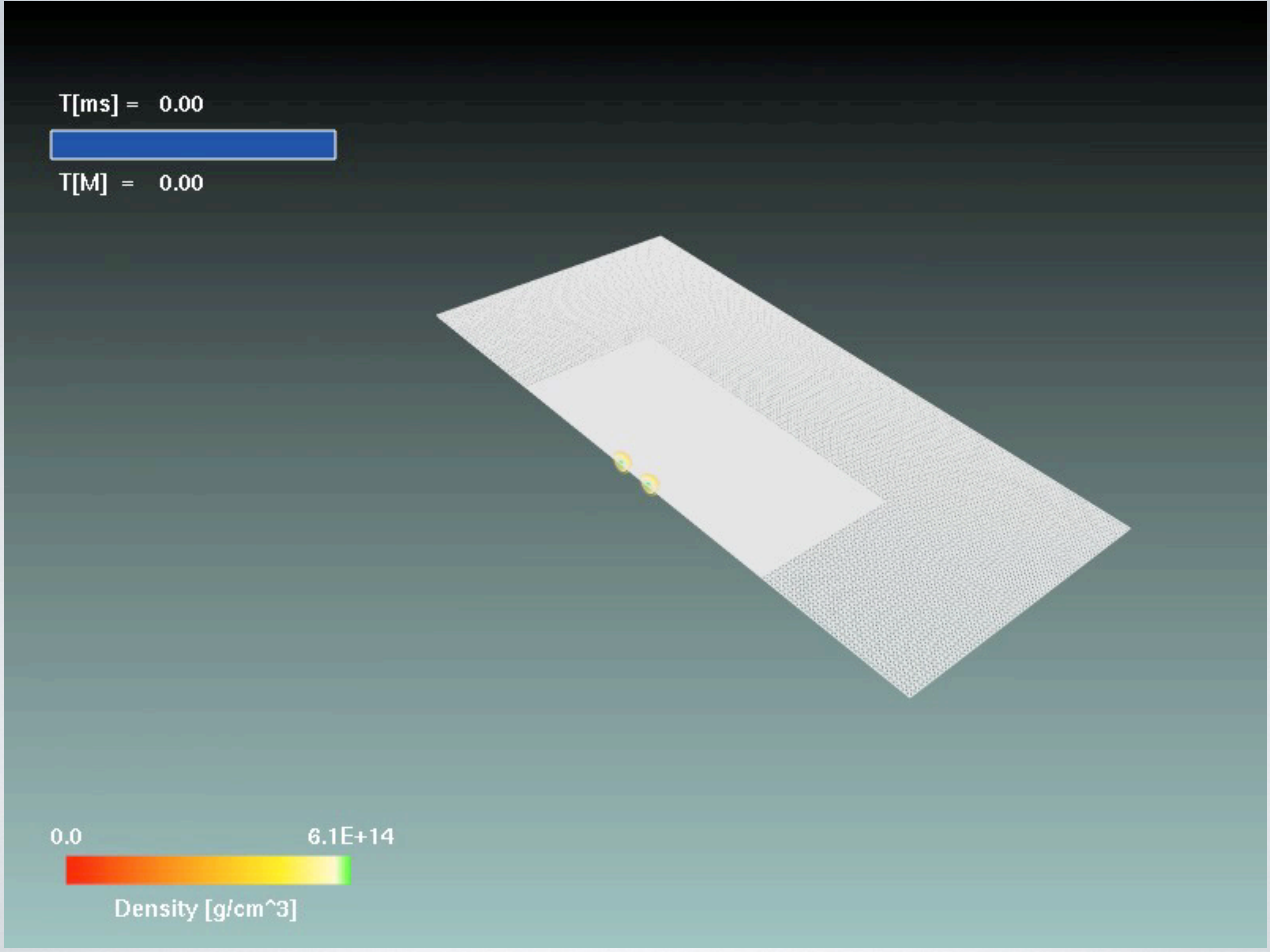
GW EMISSIONS FROM NS-NS AND NS-BH MERGERS



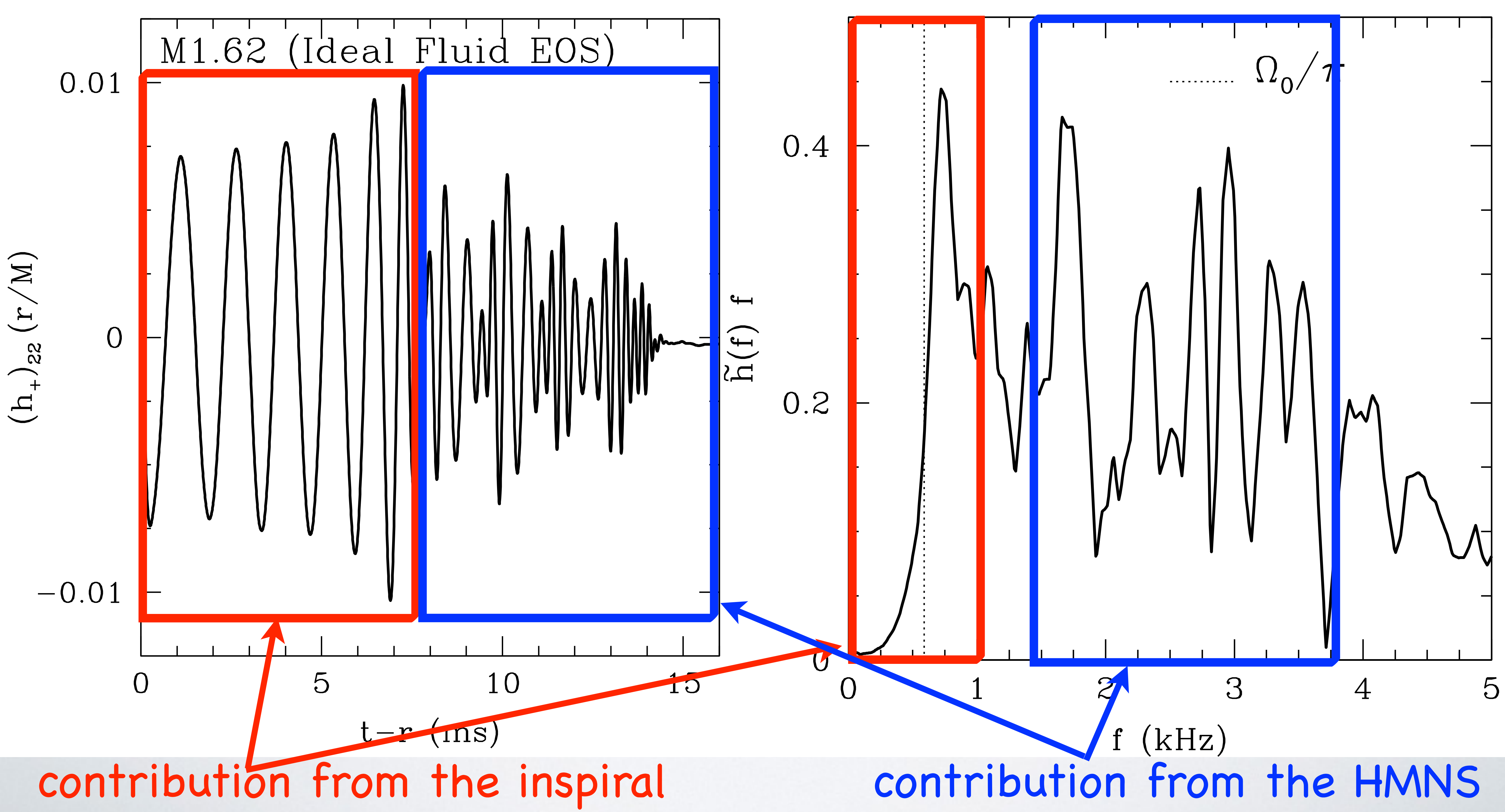
IDEAL-FLUID EOS: HIGH-MASS BINARY



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



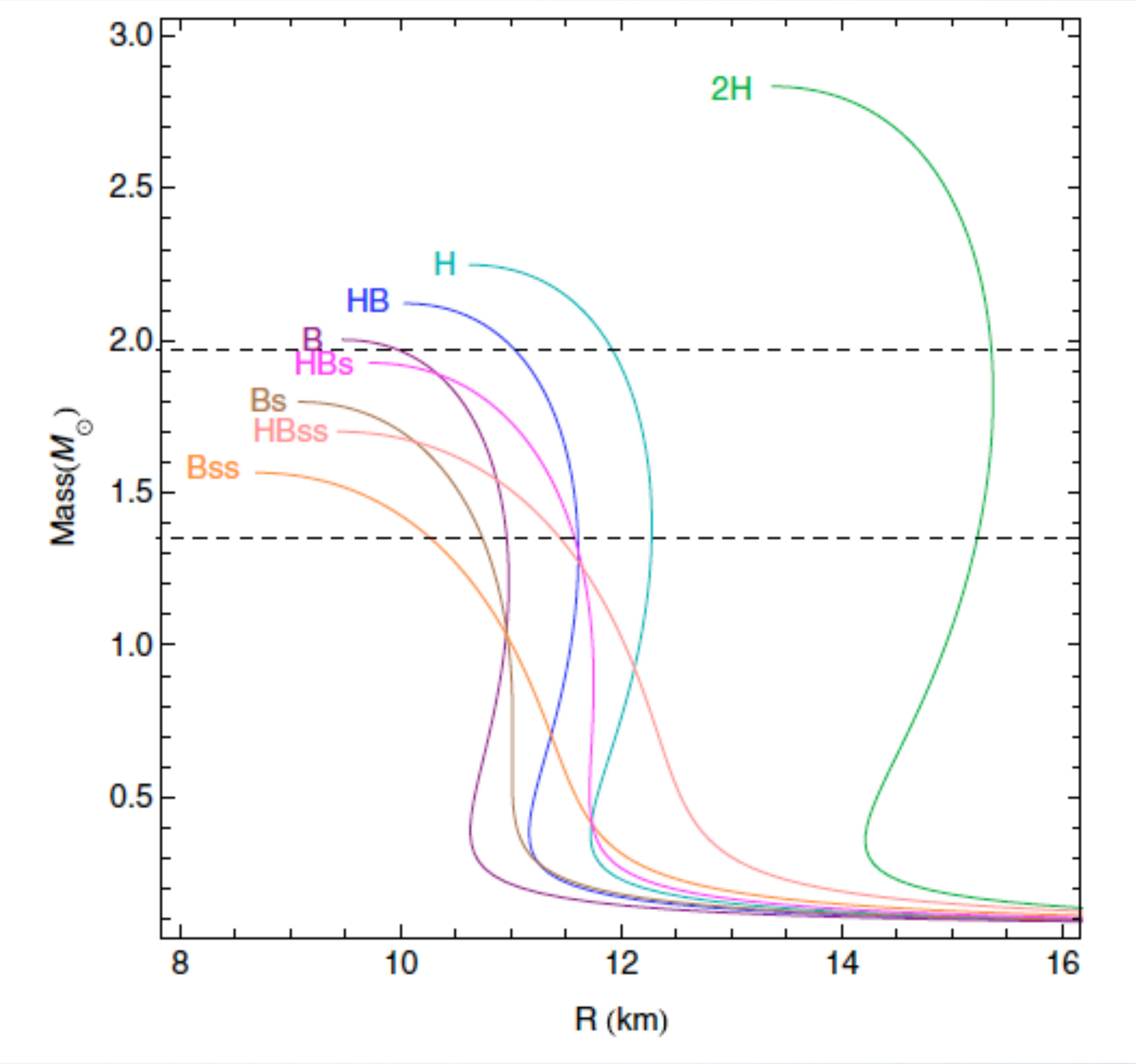
MATTER EFFECTS ON BNS GWs

(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

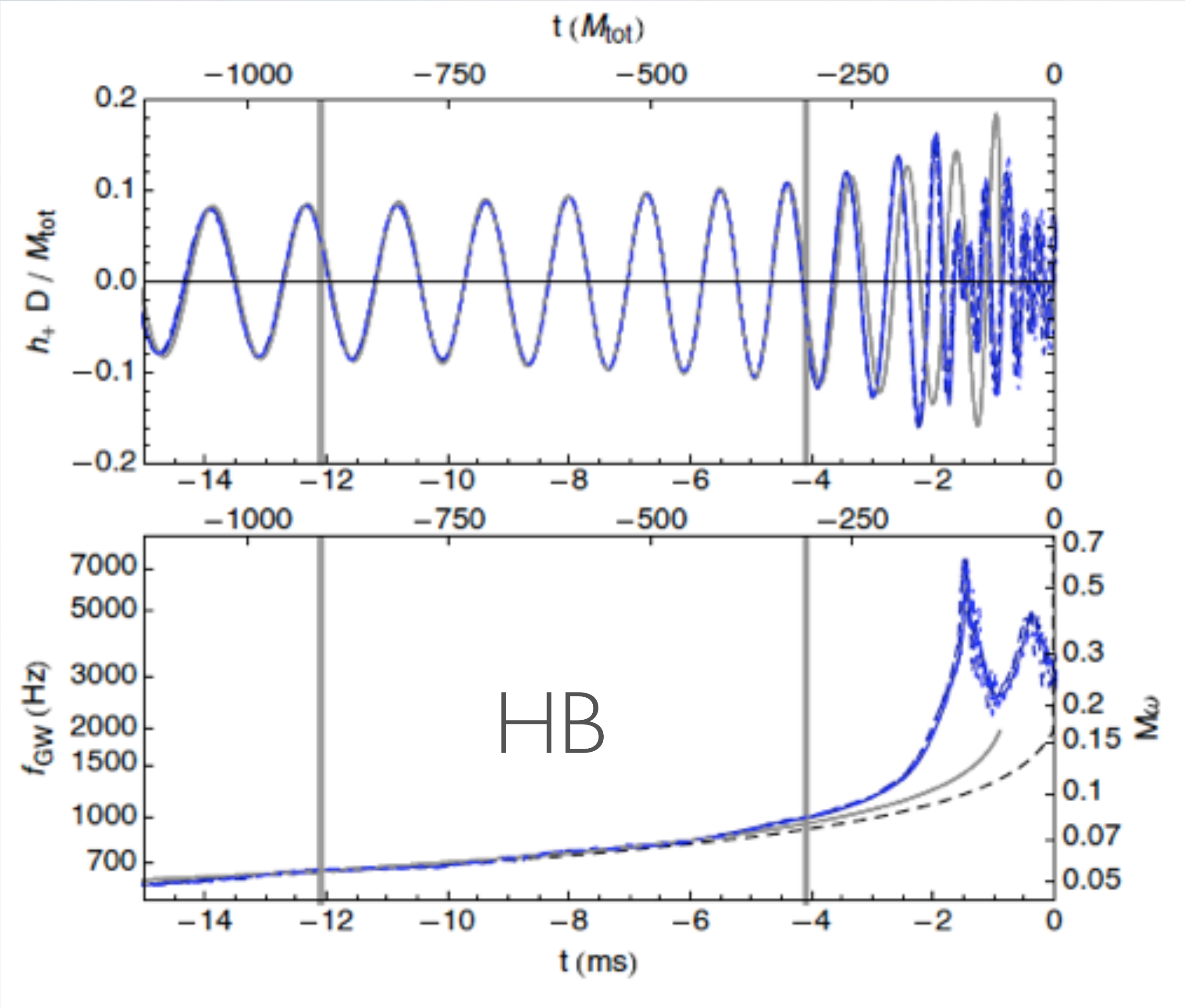
Used an extended set of piecewise polytropic EOSs

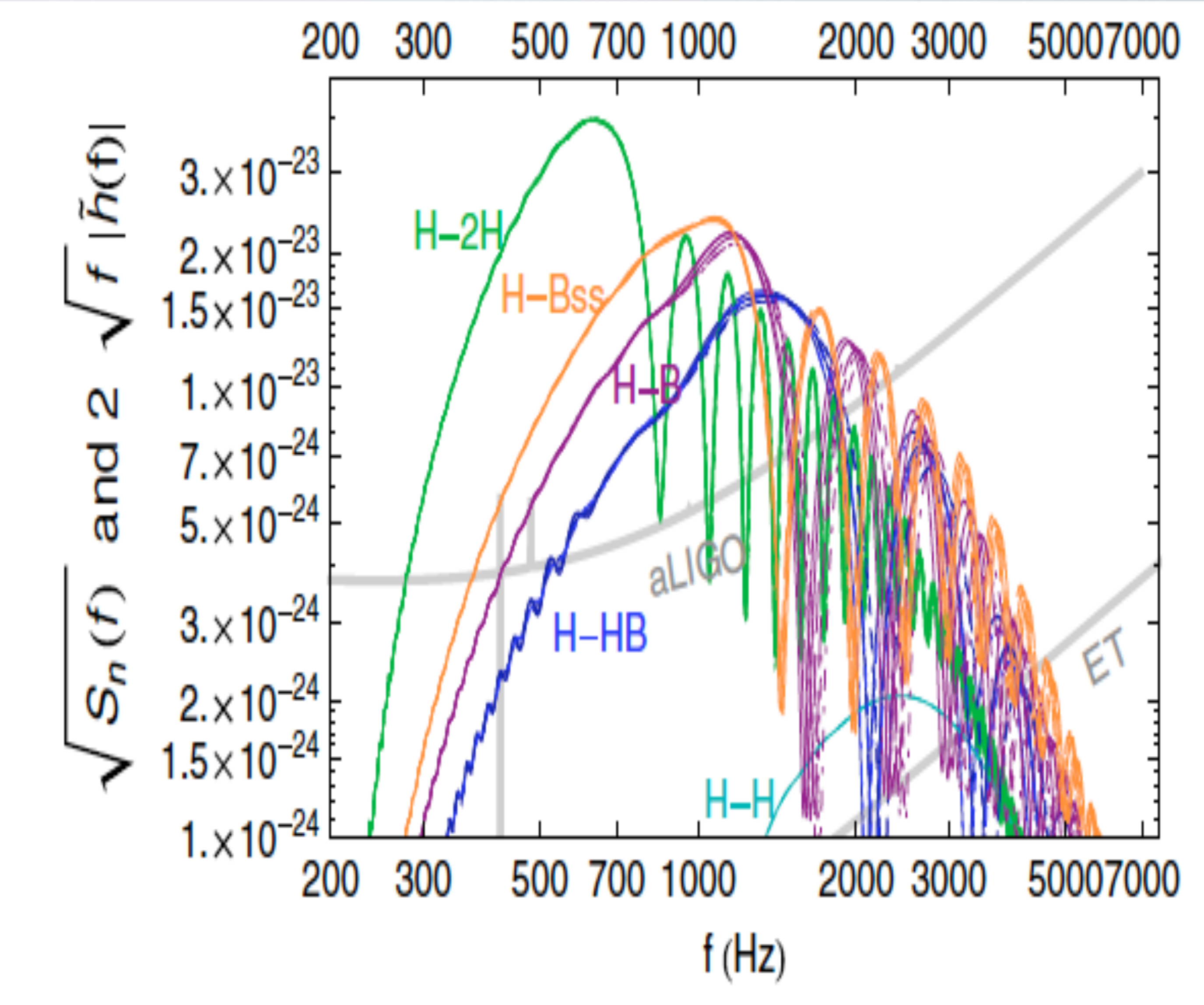
Estimated numerical errors by comparing between the codes and using different resolutions.



MATTER EFFECTS ON BNS GWs

(Read et al 2013, PRD 88, 044042)

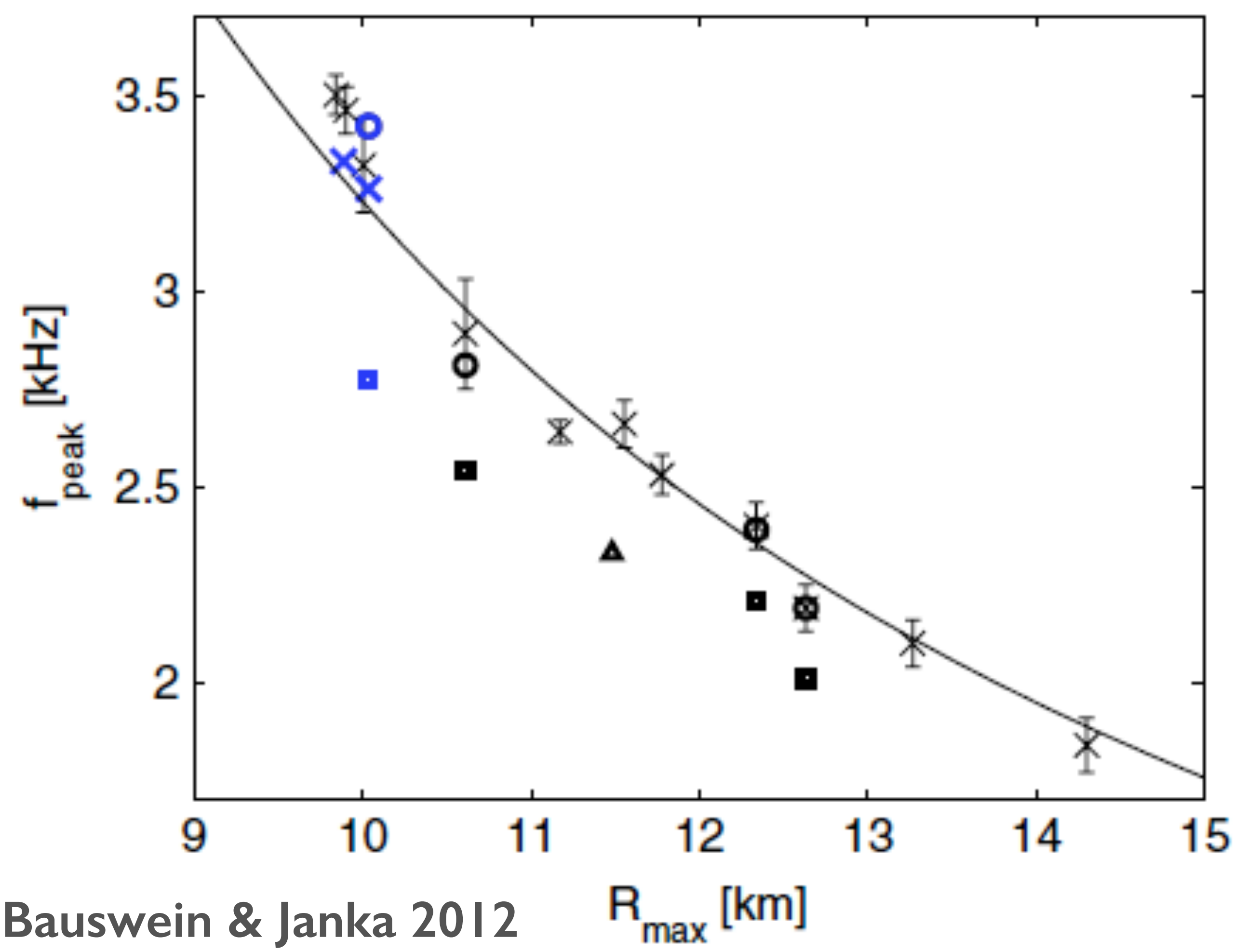




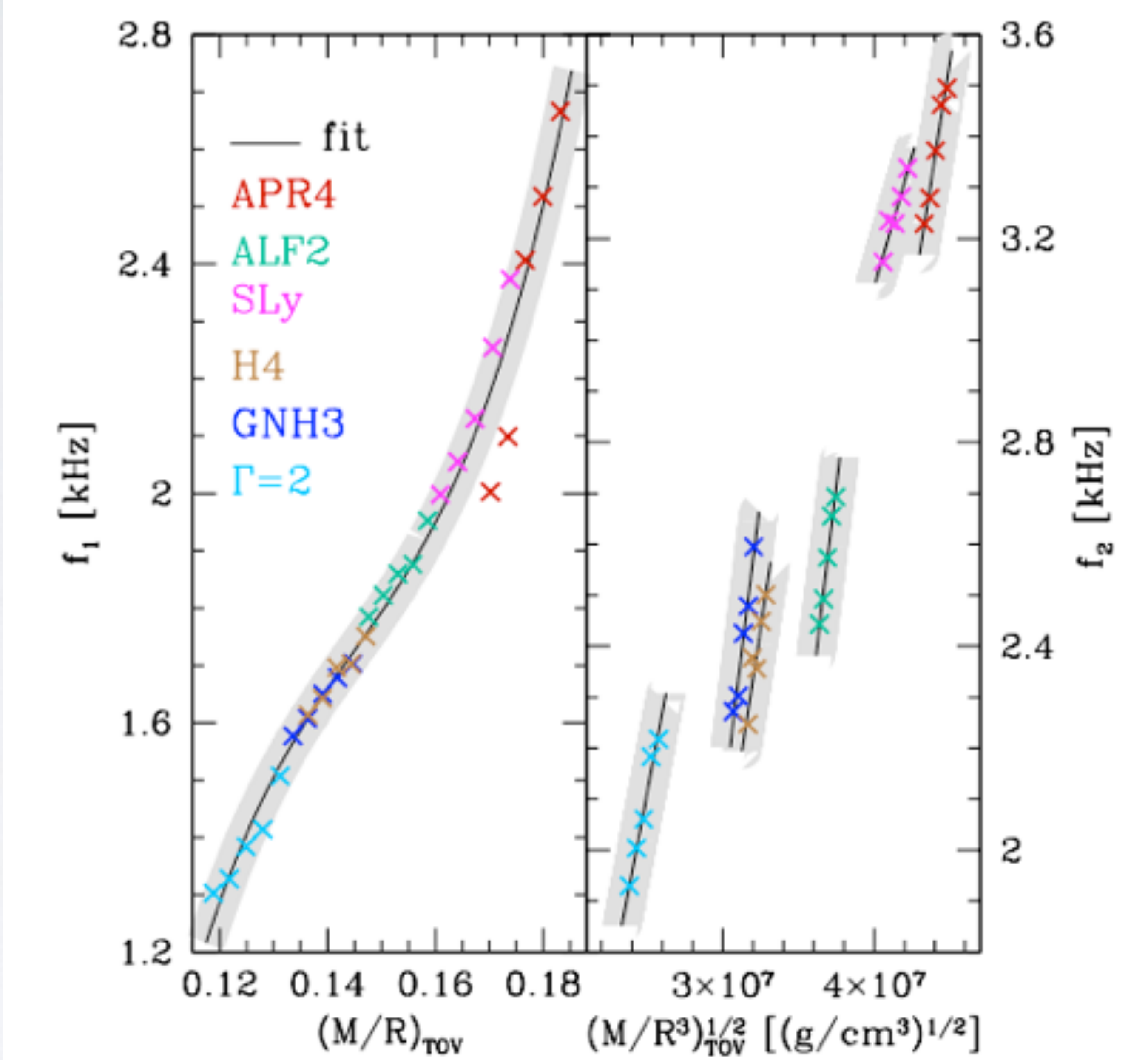
Hybrid GWs: EOSs distinguishable at 300 Mpc if NS radii differ of ~1.3km

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

GW: EOS EFFECTS IN THE POSTMERGER



Bauswein & Janka 2012

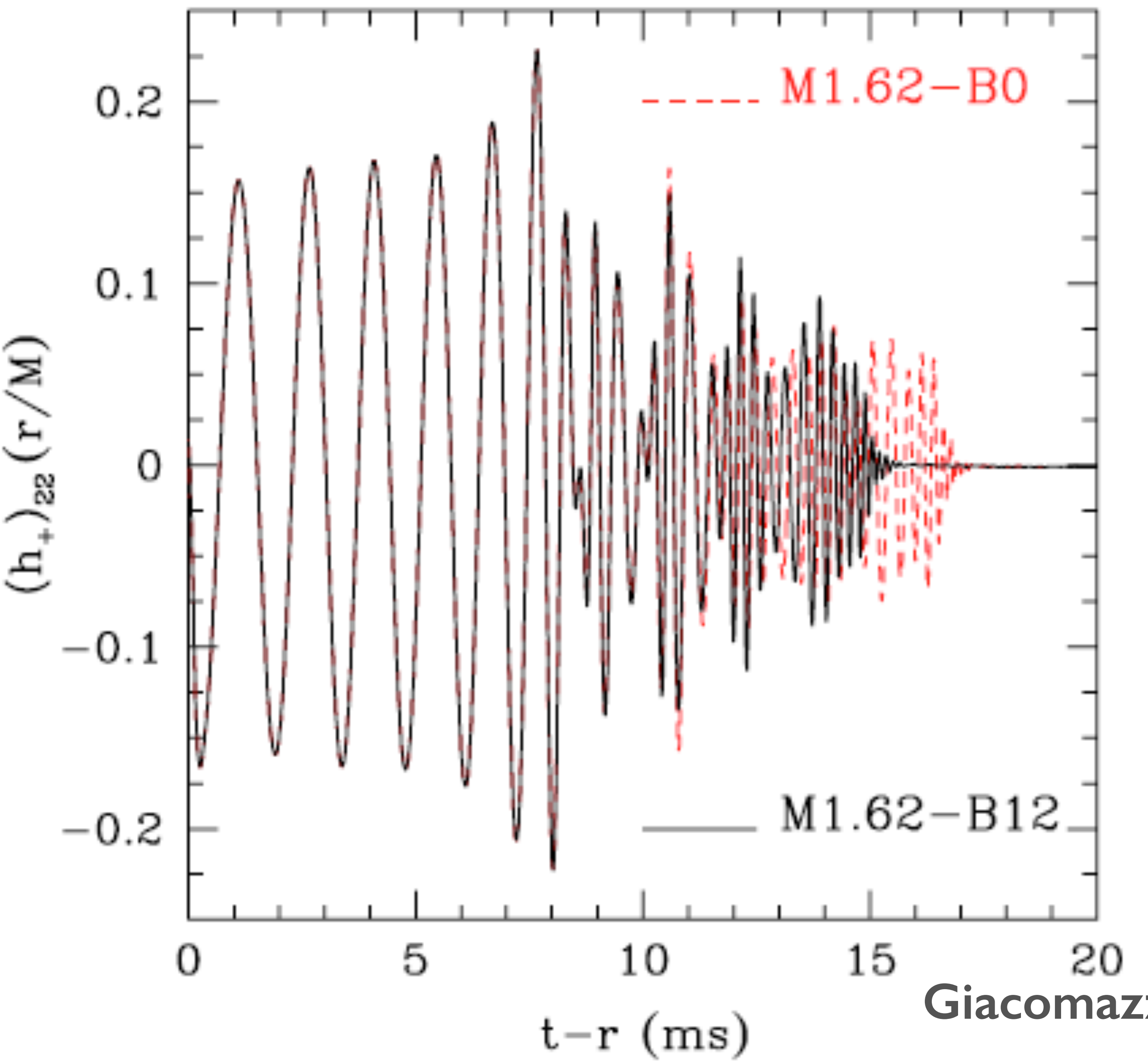


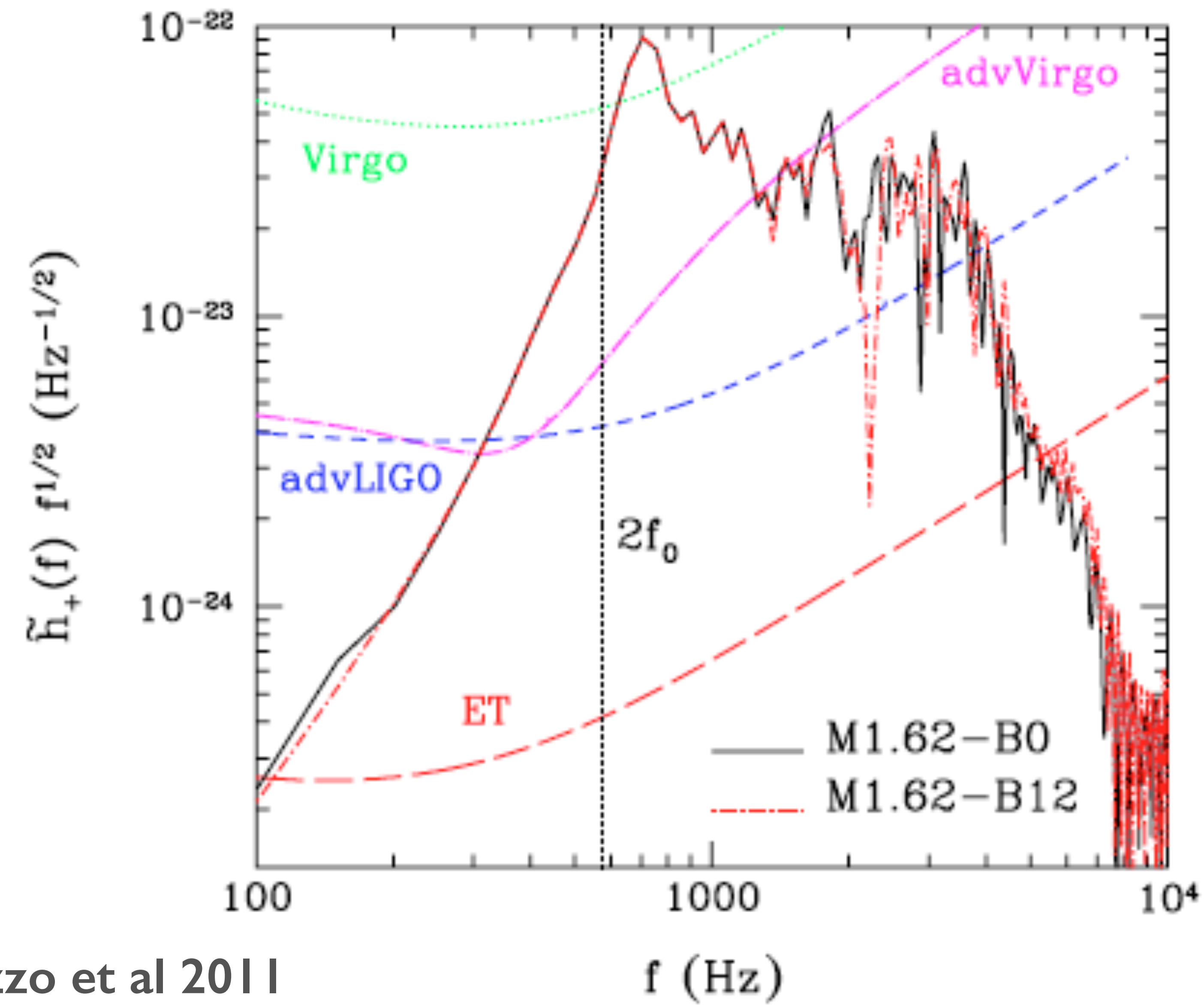
Takami et al 2014

Bauswein et al 2012-2014: frequency peak in GWs emitted after merger can constrain EOS

A recent full GR investigation confirmed the relation between high-frequency peaks in post-merger GWs and NS EOS.

GW: MAGNETIC FIELD EFFECTS IN THE HMNS



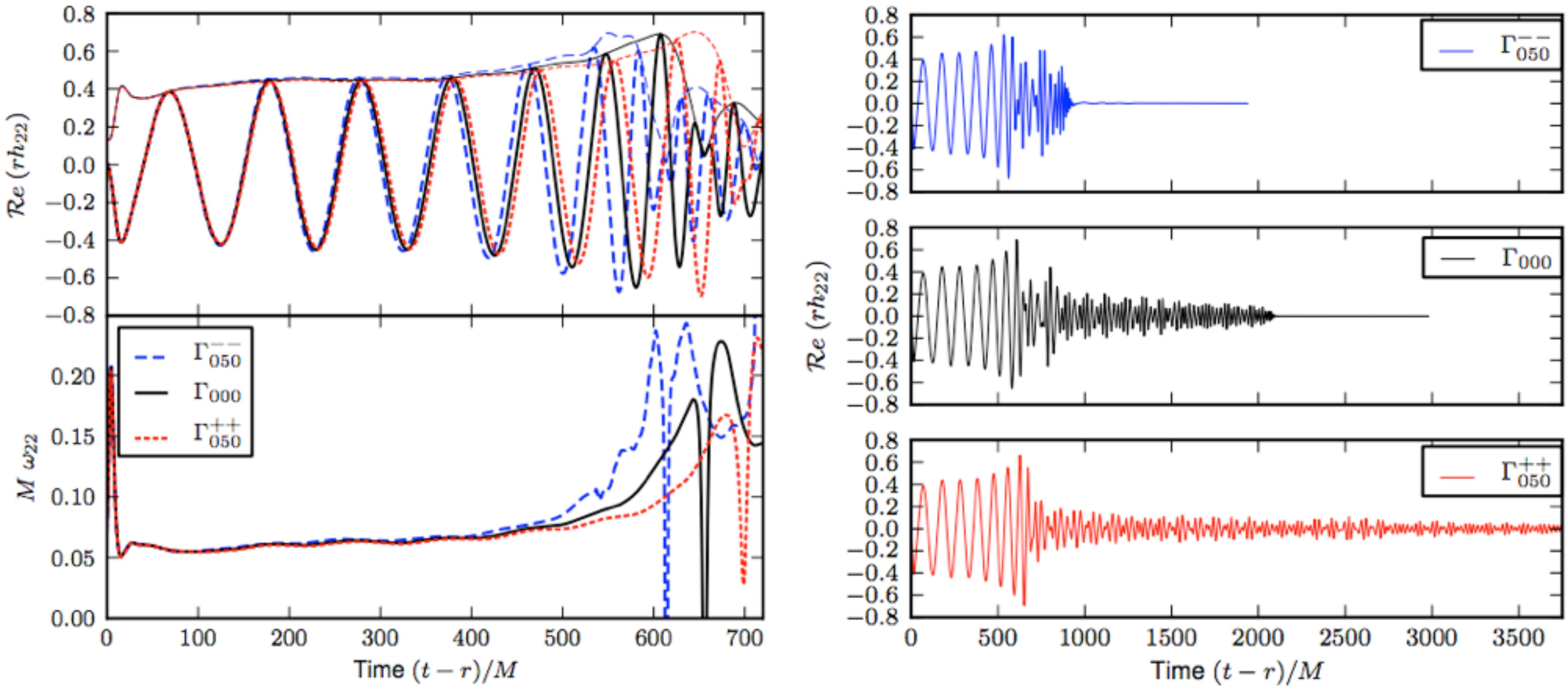


Giacomazzo et al 2011

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

GW: NS SPIN EFFECTS

Bernuzzi et al 2014 PRD 89, 104021



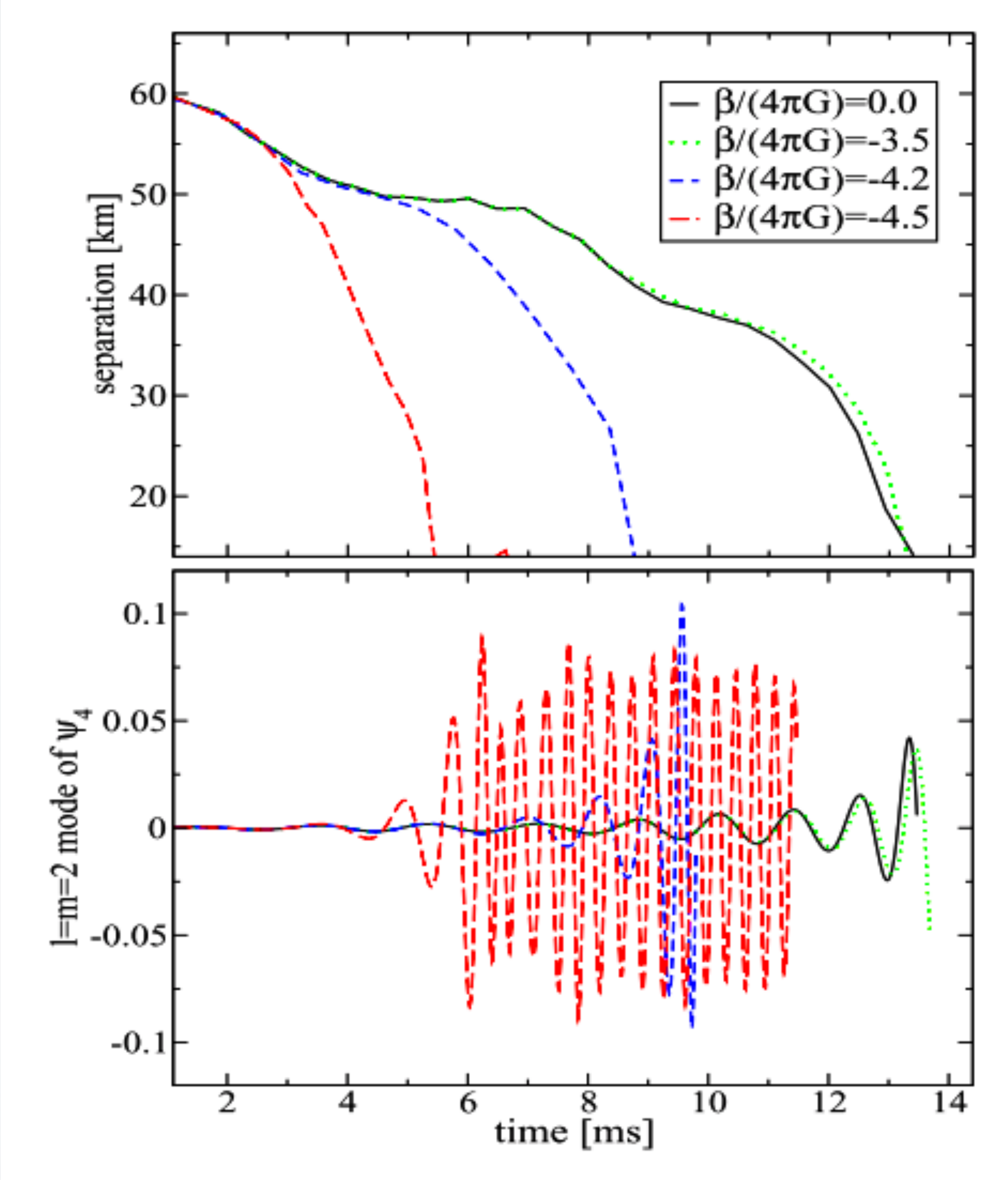
Investigated the effect of NS spins on GWs.

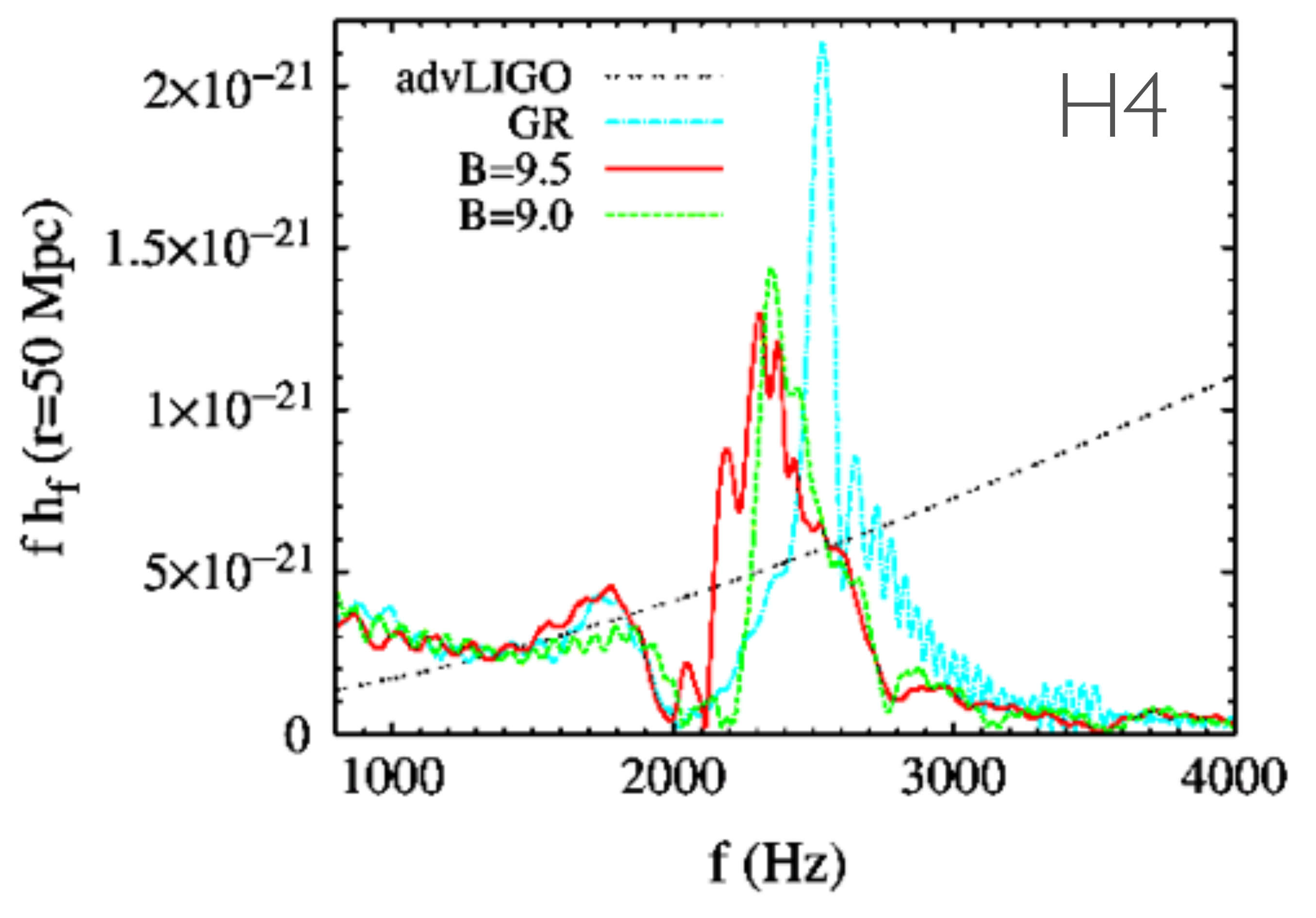
Spin effects relevant if spin ~0.05!

GW peak from HMNS shifted to lower frequencies.

GW: ALTERNATIVE THEORIES OF GRAVITY

(e.g., see Barausse et al 2013, Shibata et al 2014)

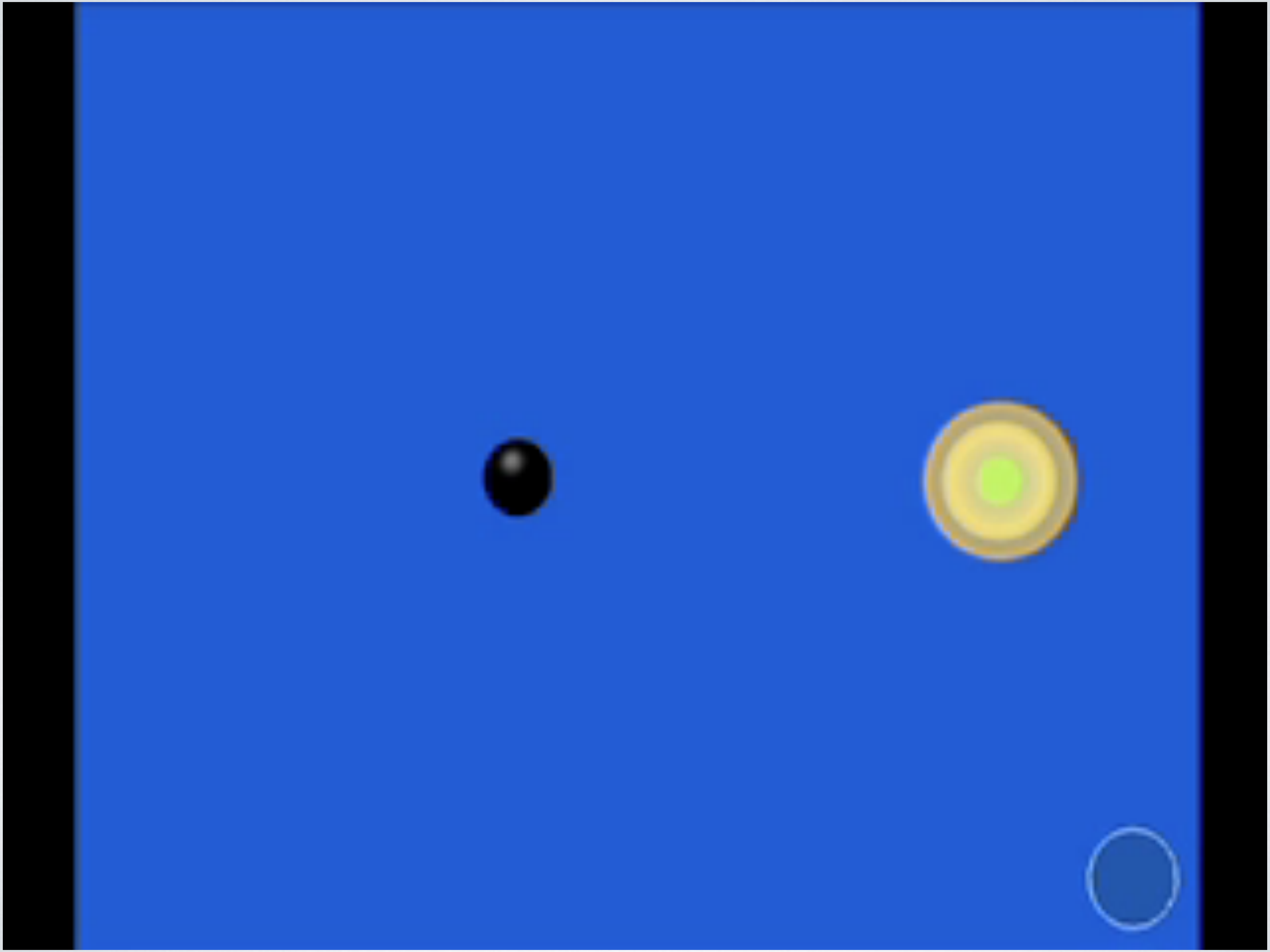




Shibata et al 2014: observed shift in post-merger GW frequency. Deviation from GR in inspiral may be not detectable if B is small.

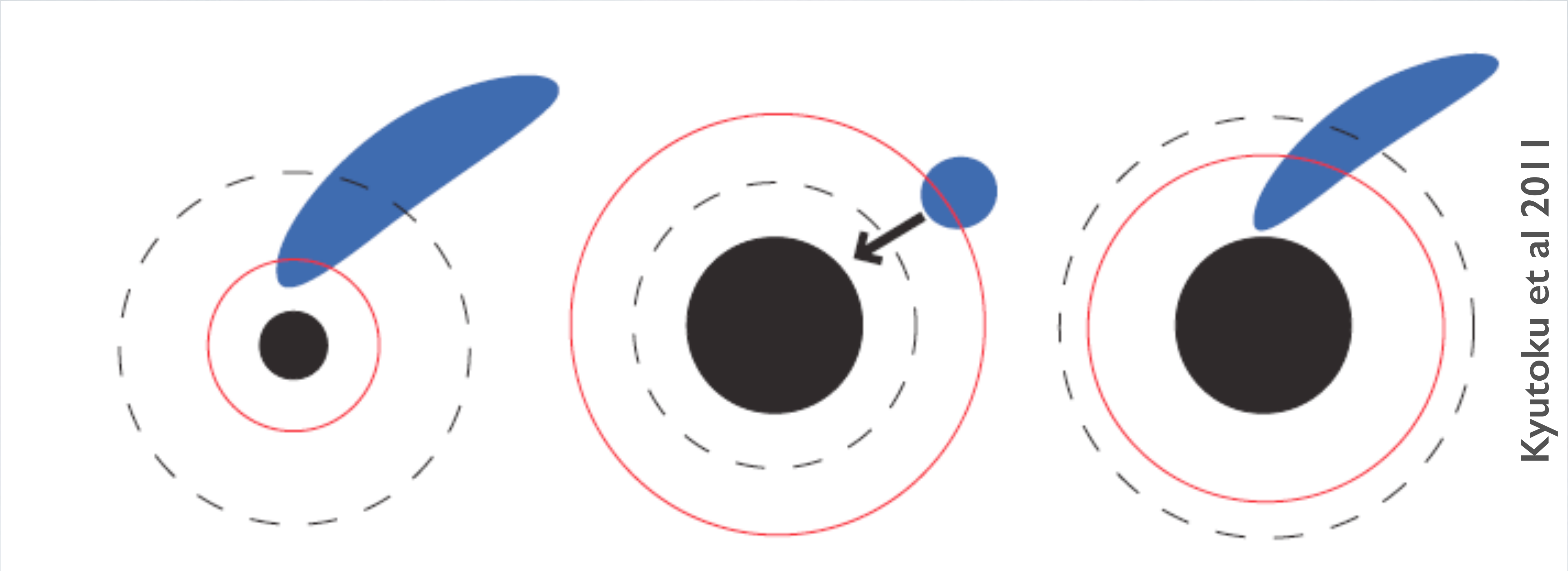
Barausse et al 2013: merger happens at lower frequencies (up to ~600 Hz) and it is detectable in the LIGO/Virgo band.

BH-NS MERGERS



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

BH-NS: CLASSIFICATION OF GWS



type I: NS disrupted outside ISCO. Only inspiral .

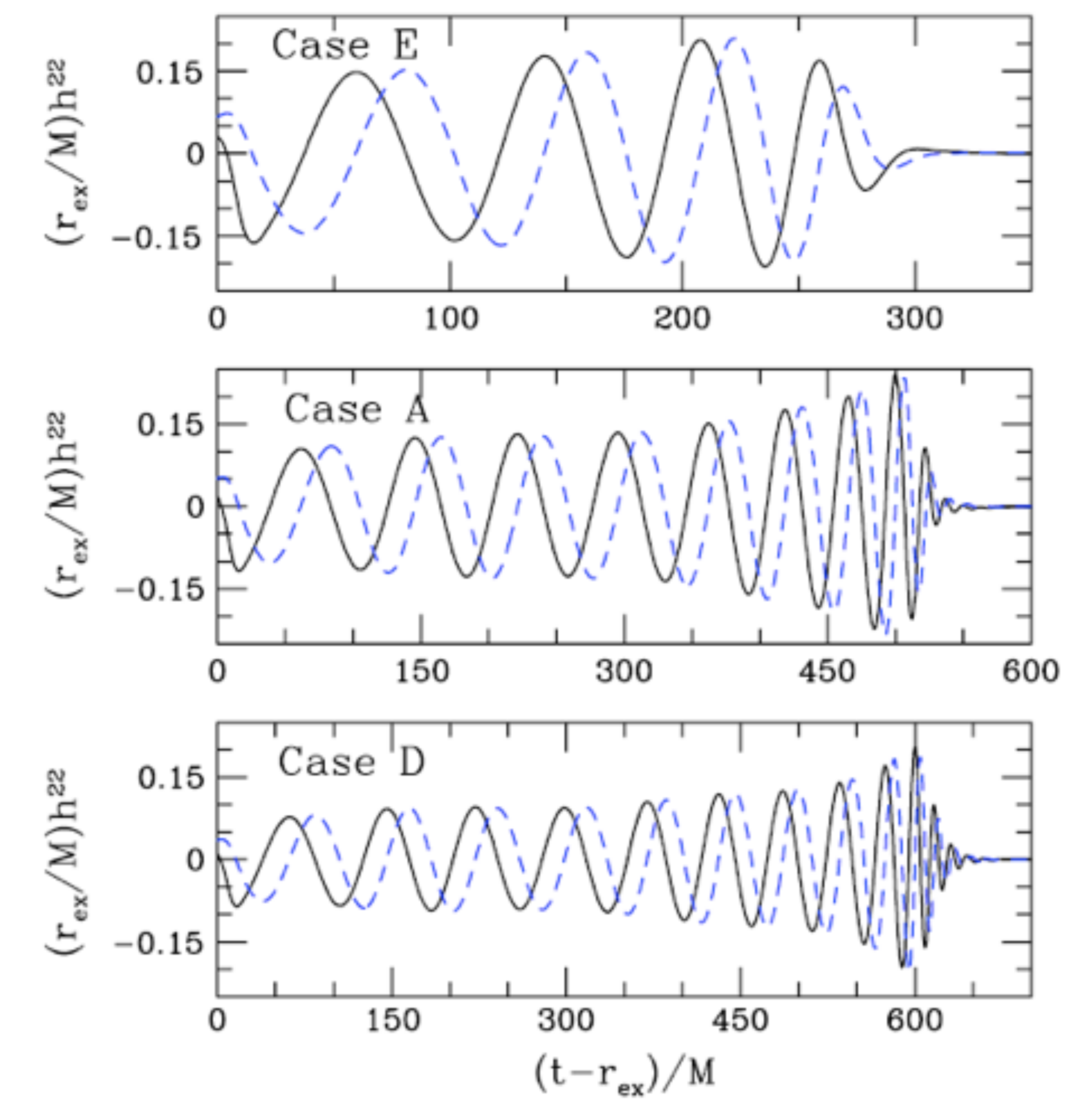
type II: no disruption. GWs very similar to BBH and composed by inspiral, merger, and ringdown (e.g., Foucart et al 2013).

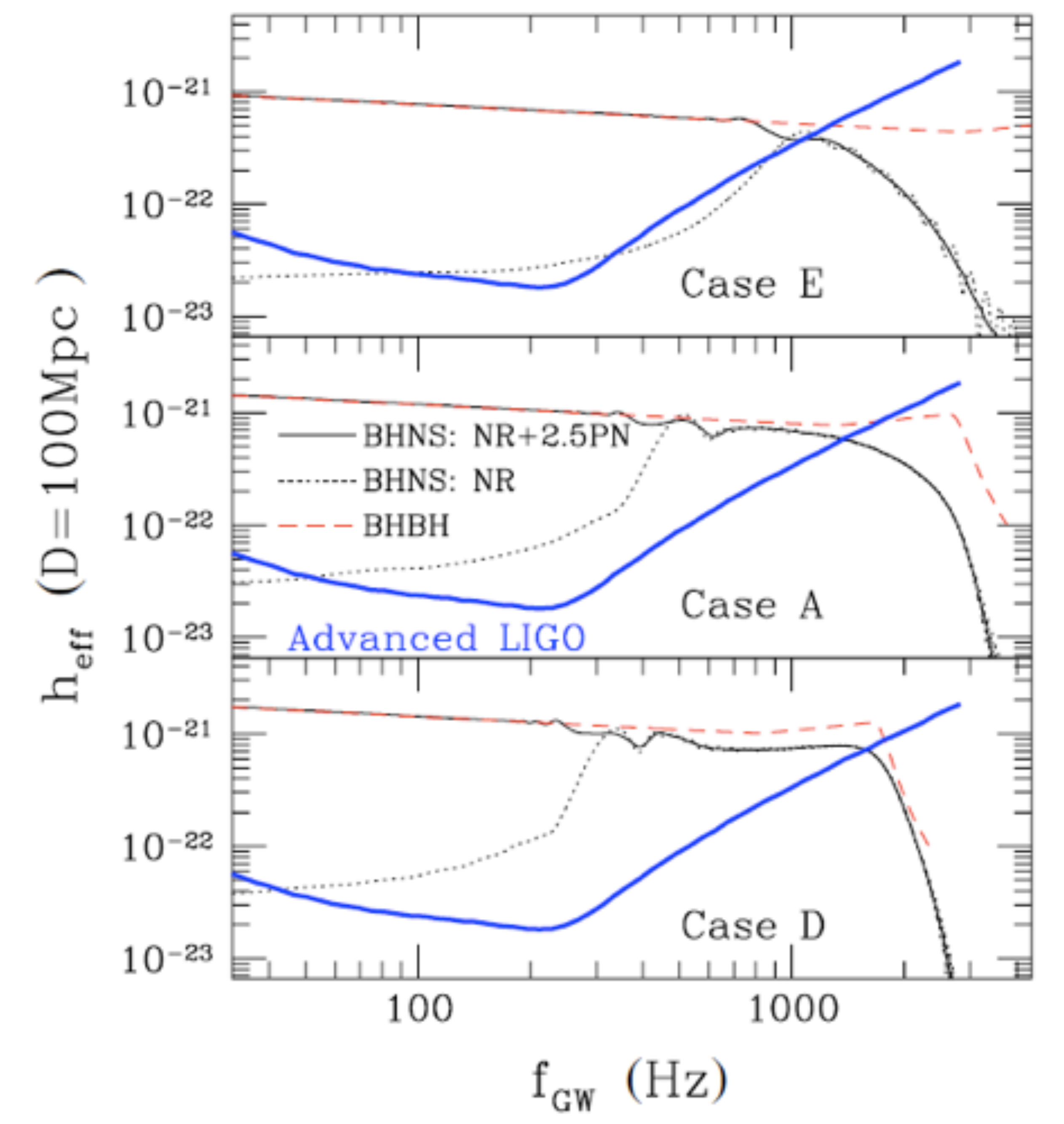
type III: mass transfer near ISCO. Both inspiral and merger are present in the GWs.

Classification depends on mass-ratio, BH spin, and NS compactness

GW FROM BH-NS (NO SPIN)

Etienne et al 2009

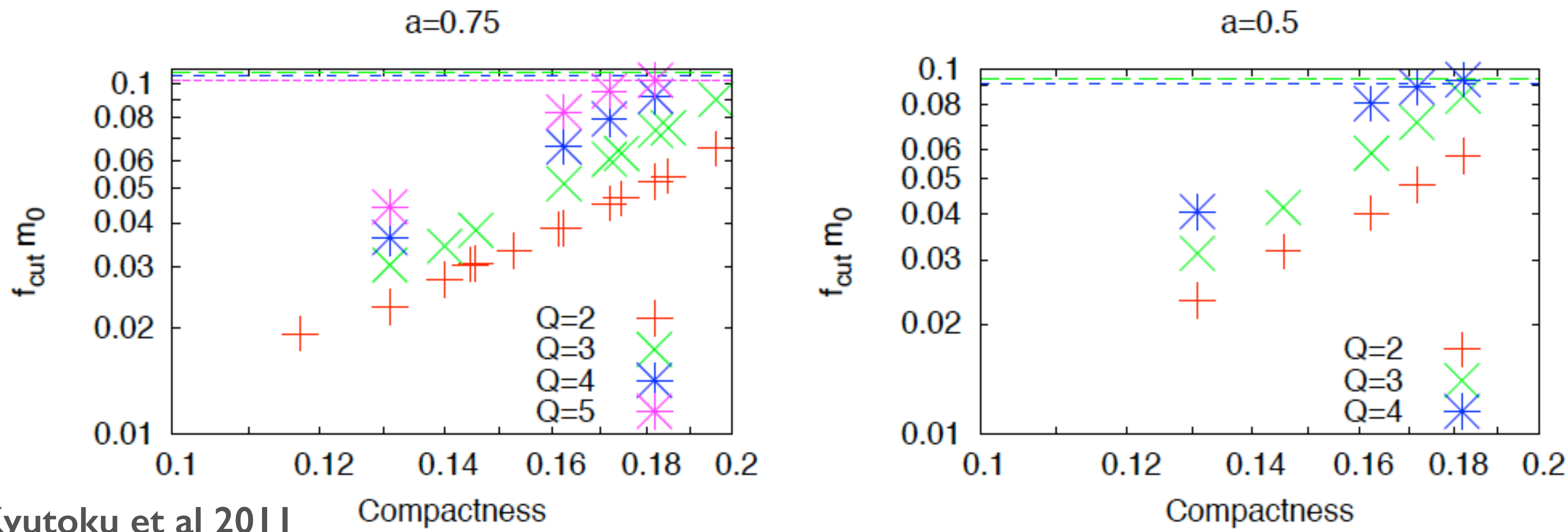




E: Q=1
A: Q=3
D: Q=5

Difficult to detect difference with BBH if low spin and high Q.
Note how when increasing Q the frequency cutoff gets close to the one for BBH.

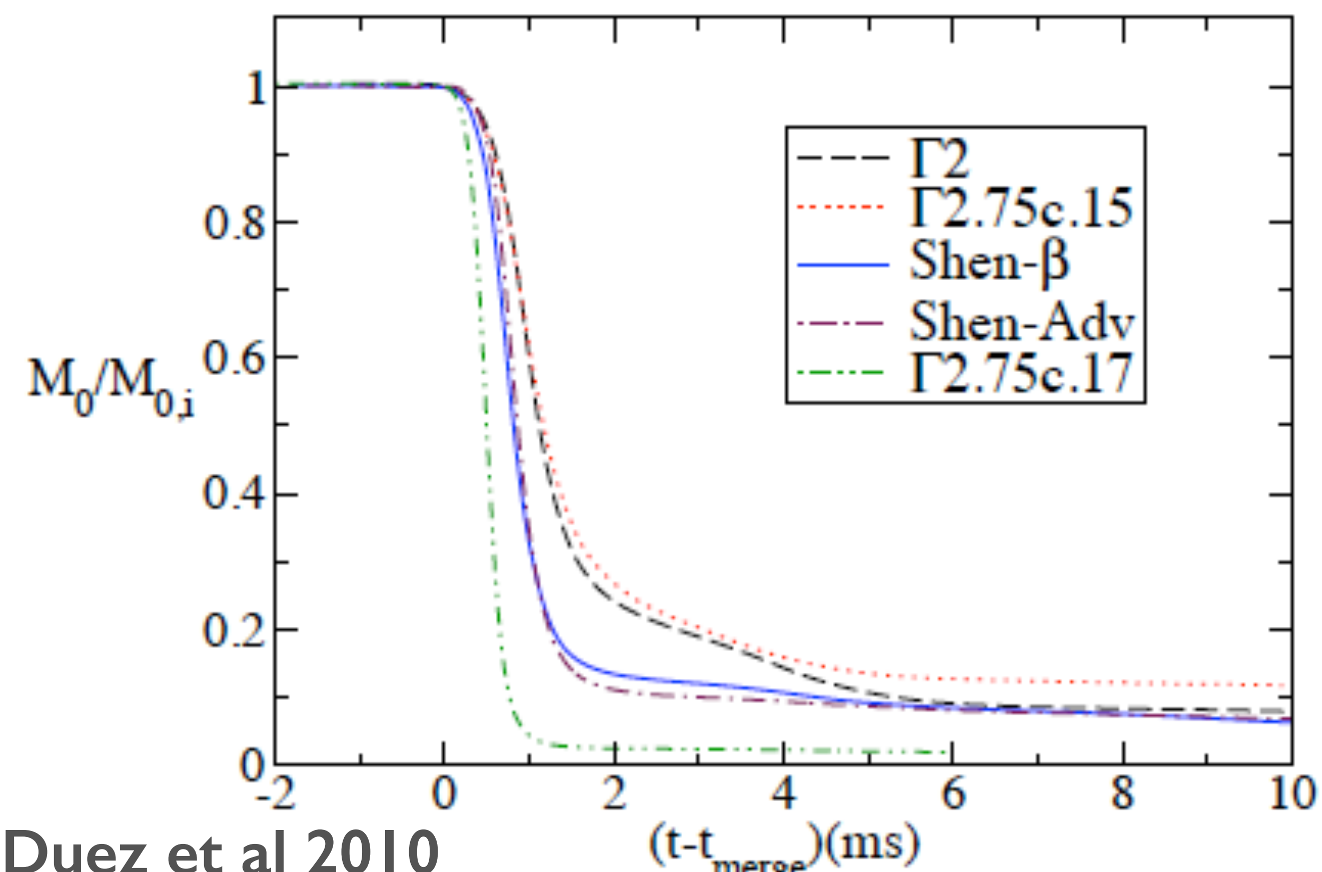
NS-BH: EOS EFFECTS



Kyutoku et al 2011

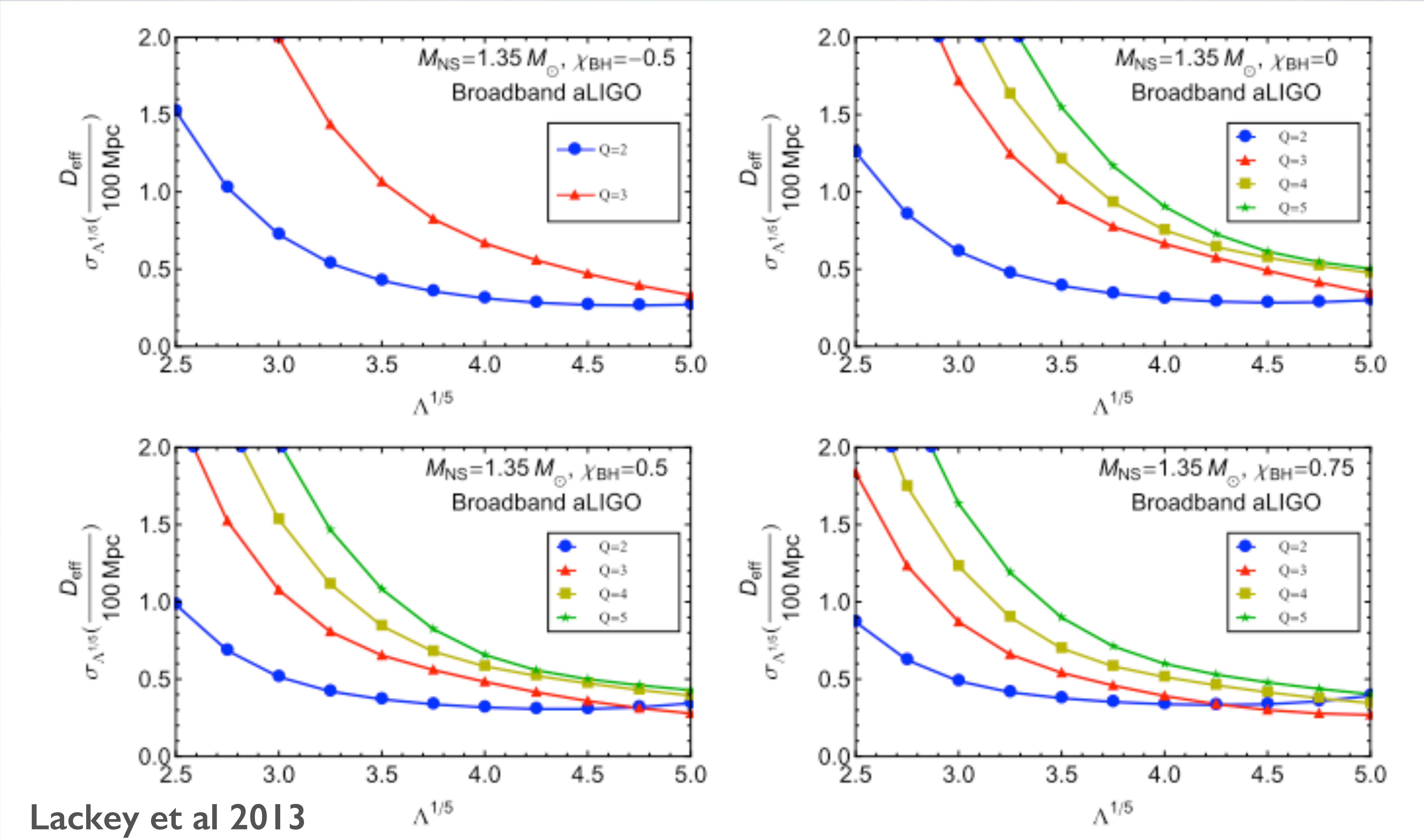
NS compactness influence the GW frequency cutoff

NS EOS influences also the torus mass



Duez et al 2010

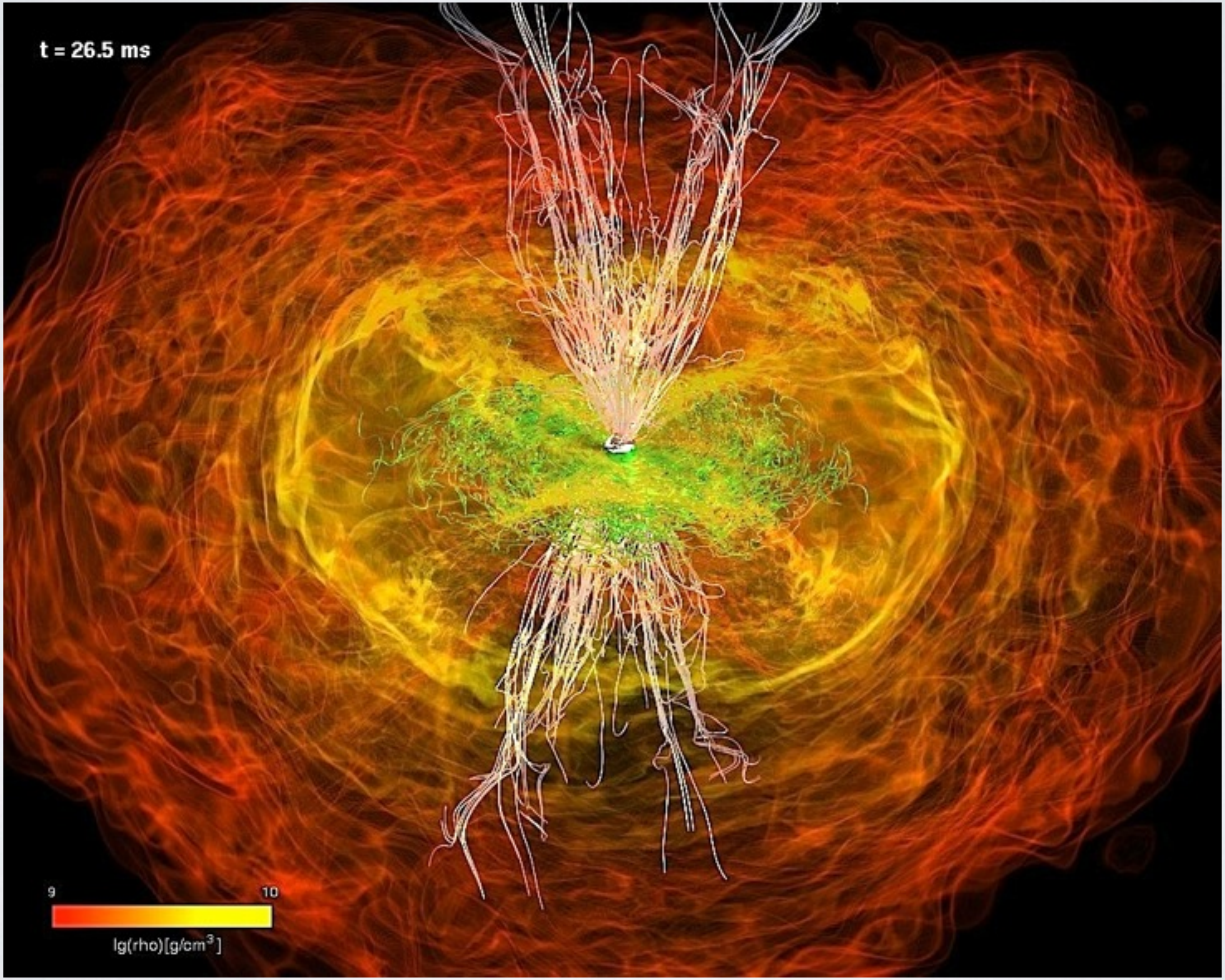
NS-BH: MATTER EFFECTS



Lackey et al 2013

AdvLIGO could measure tidal deformability (R) at 100Mpc with 10%-100% error for Q=[2,5], a=[-0.5, 0.75], M_{NS}=[1.2,1.45].

EM EMISSIONS FROM NS-NS AND NS-BH MERGERS



MOST "POPULAR" MODEL FOR SGRB CENTRAL ENGINE

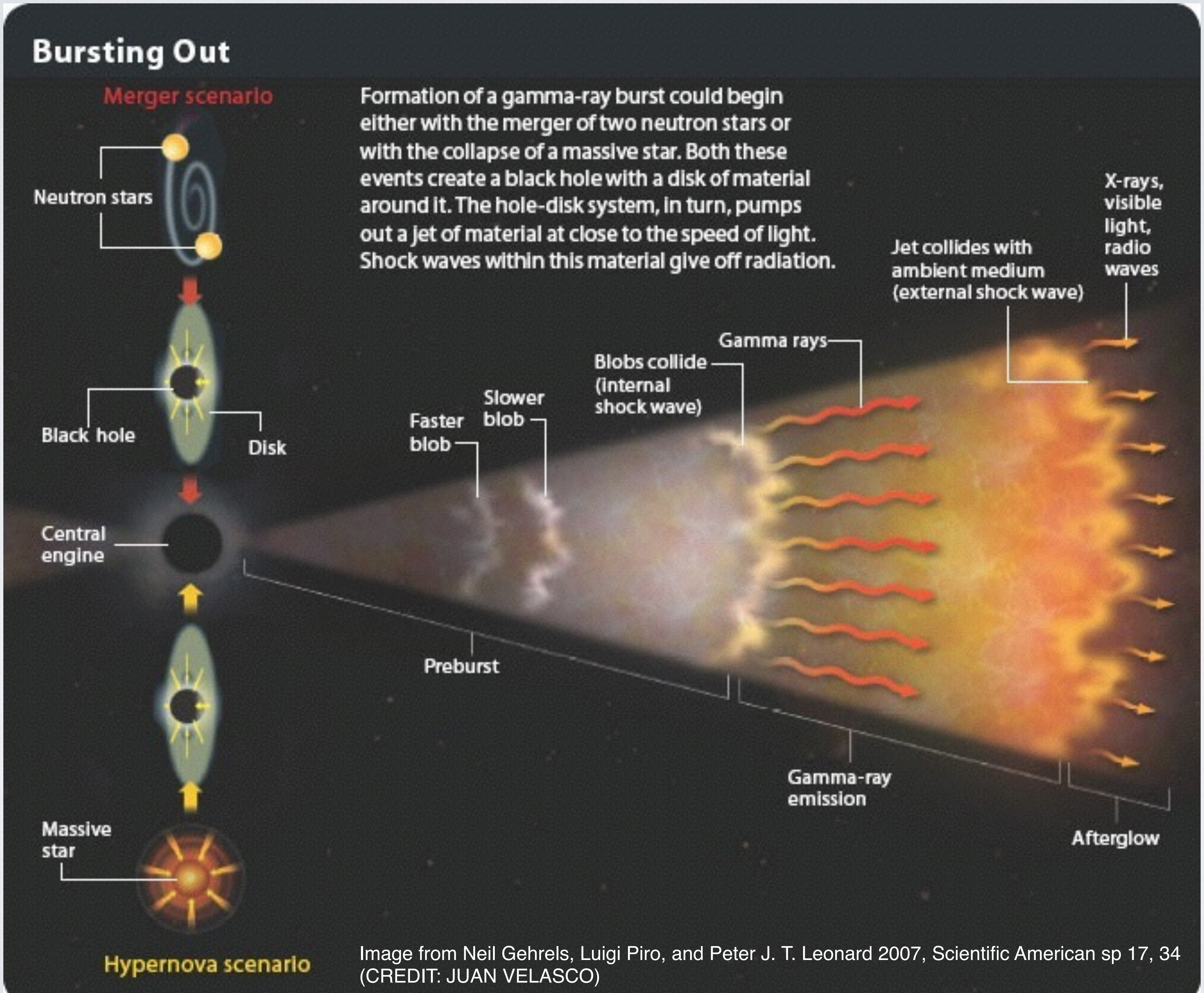
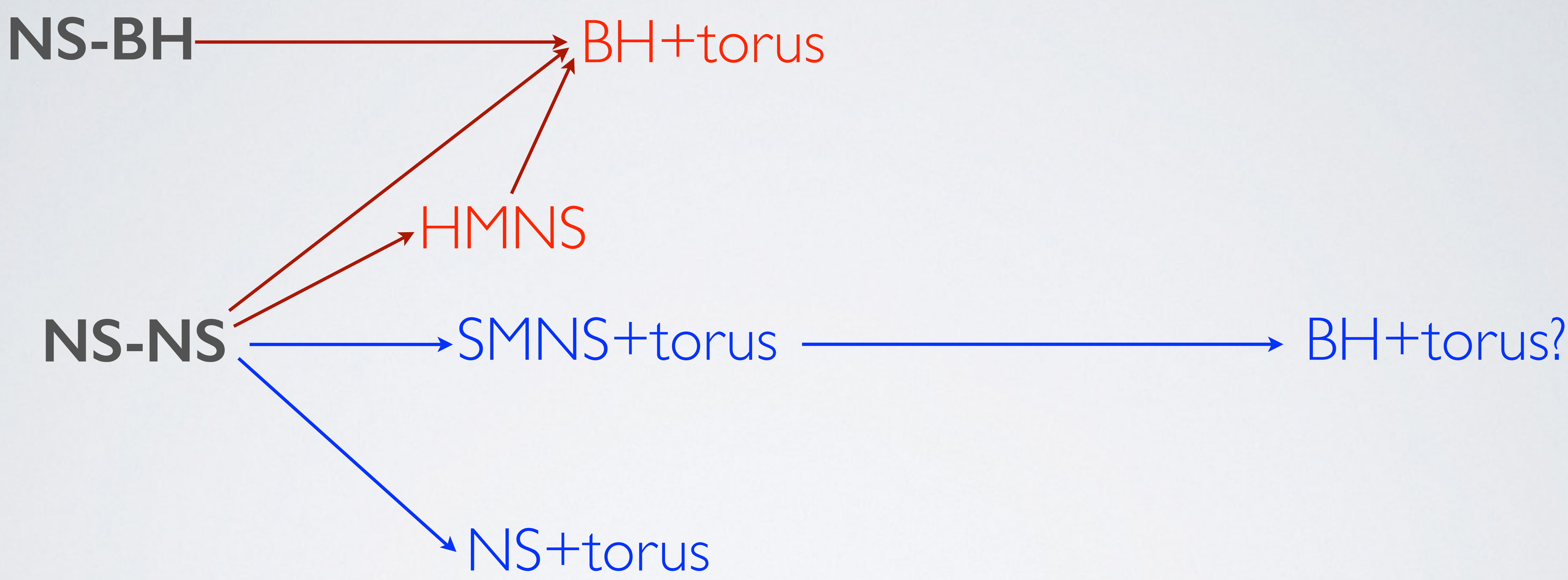


Image from Neil Gehrels, Luigi Piro, and Peter J. T. Leonard 2007, Scientific American sp 17, 34 (CREDIT: JUAN VELASCO)

BNS MERGER OUTCOME

Depending on mass and EOS several postmerger scenarios:

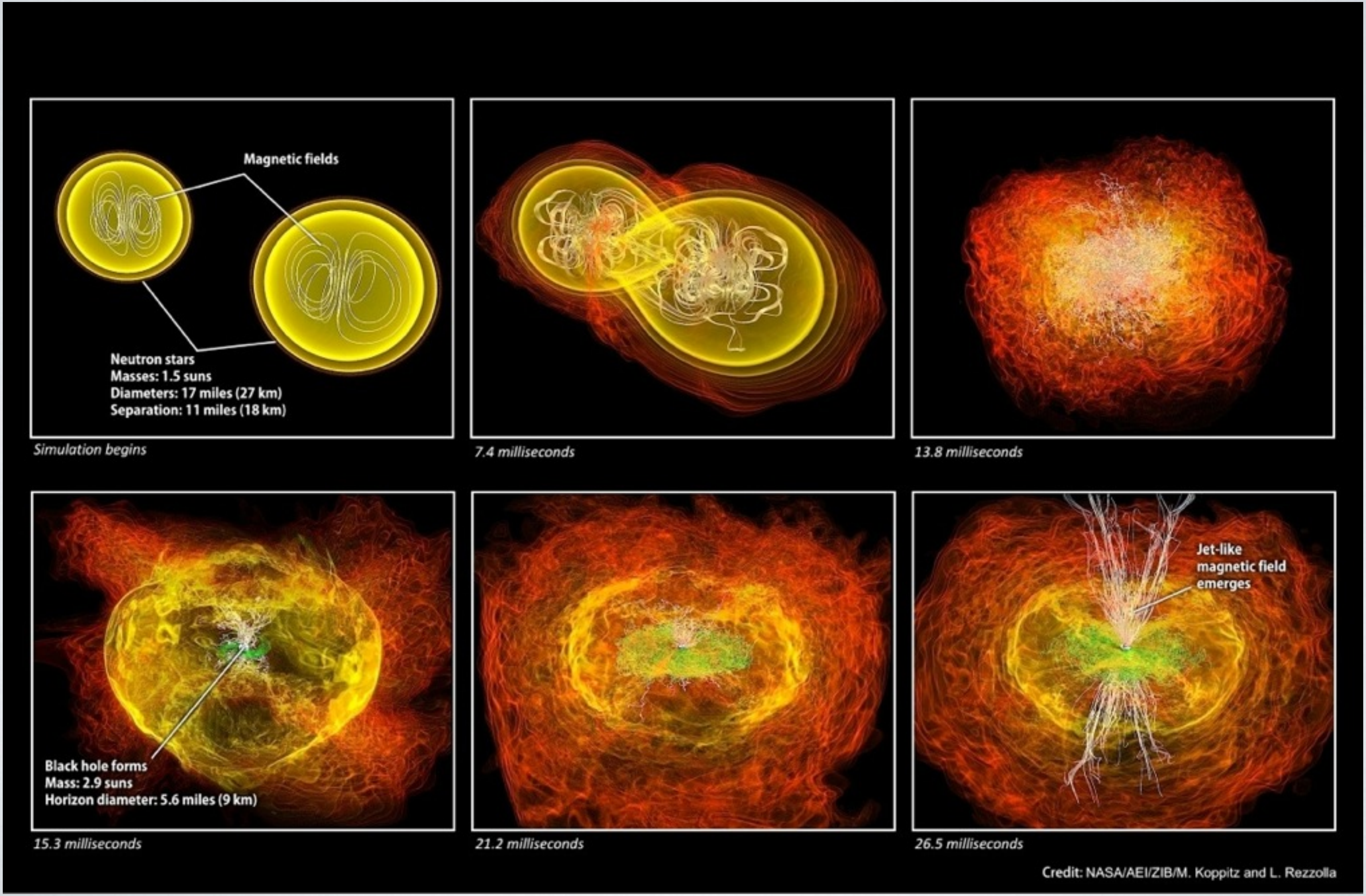


Magnetic fields play fundamental role in post-merger dynamics (jets from BH/NS+torus, NS collapse to BH, ...)

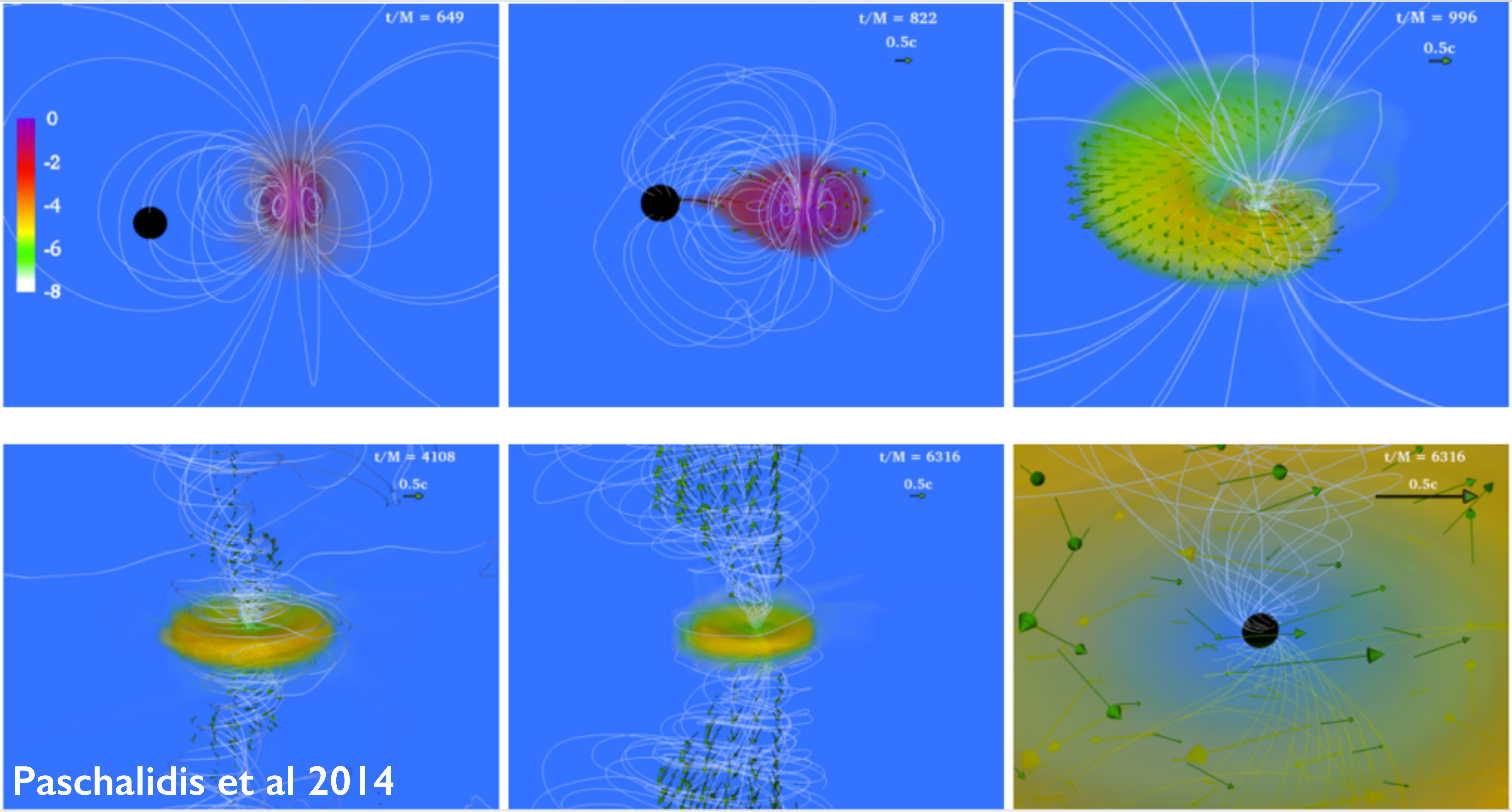
All these scenarios may lead to SGRBs with different properties

JETS FROM BNS MERGERS?

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



JETS FROM NS-BH MERGERS

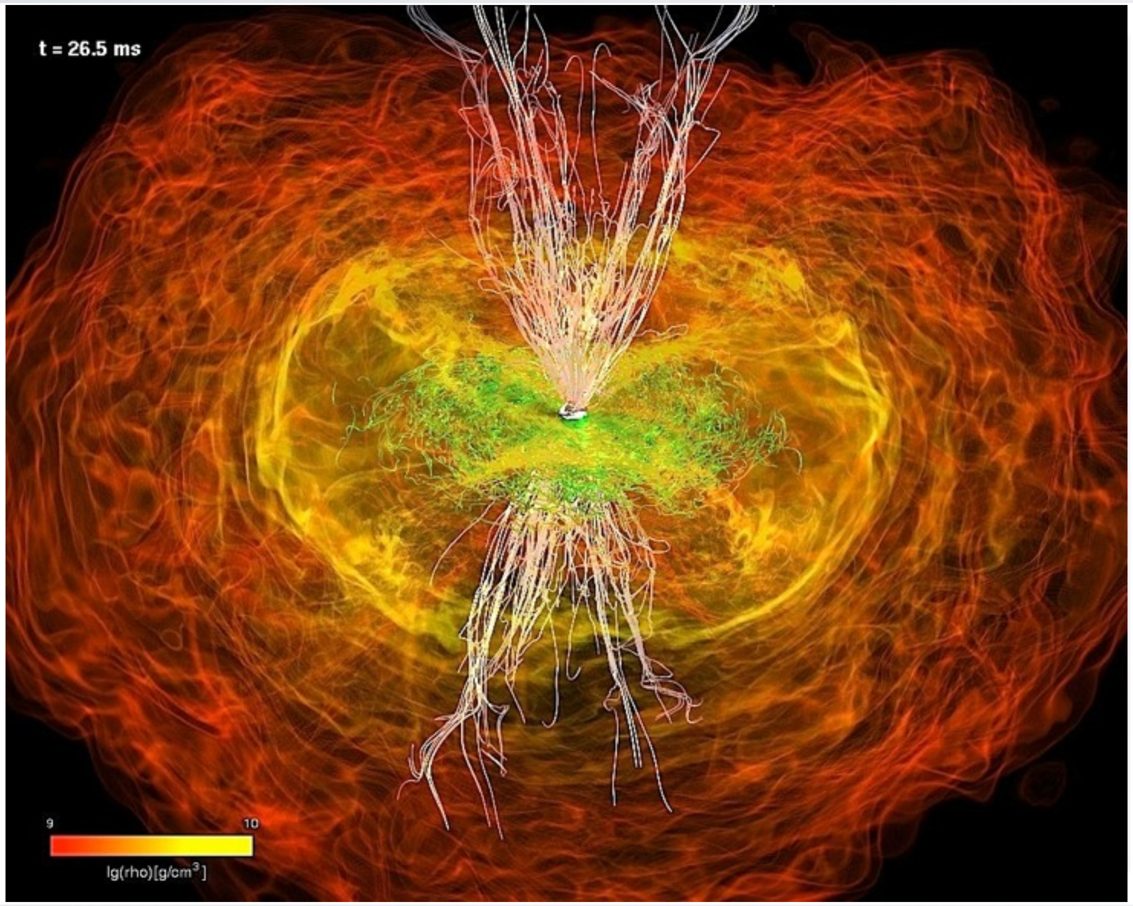


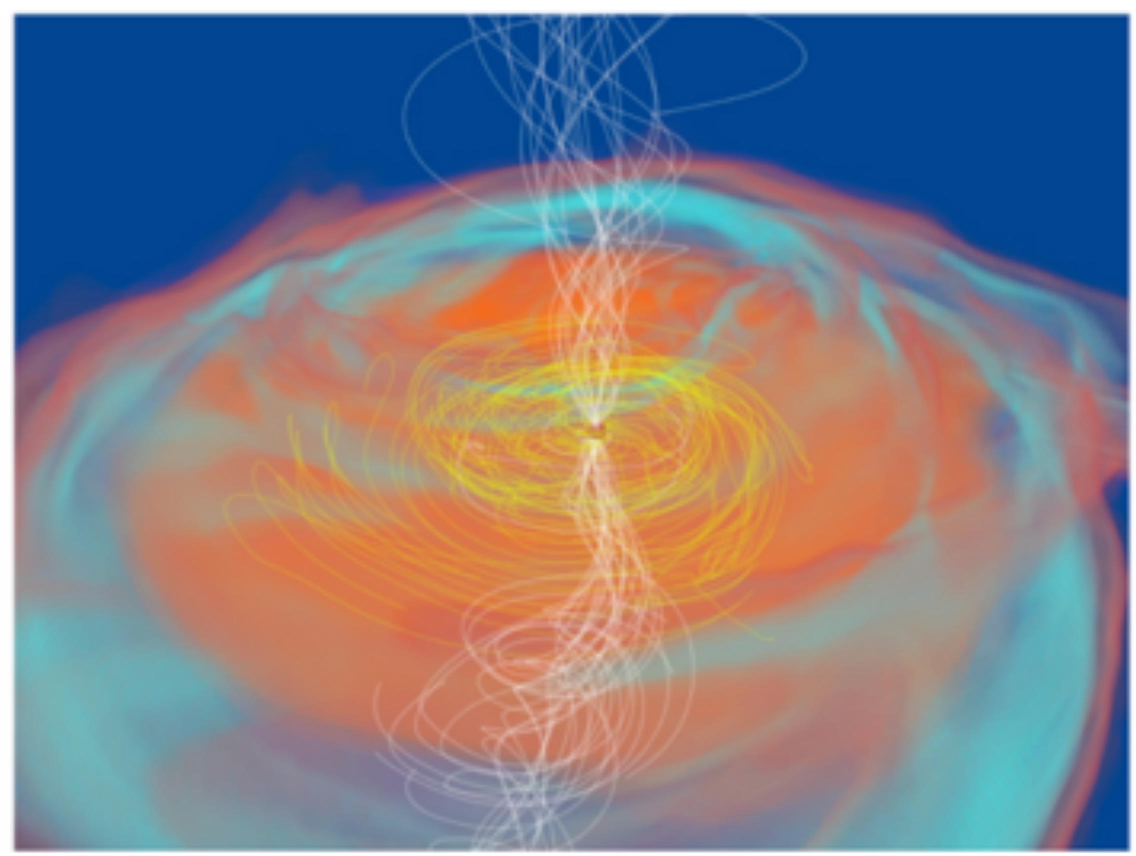
GRMHD simulations of NS-BH have also showed the formation of mildly relativistic jets

COMPACT BINARY PROGENITORS OF SHORT GAMMA-RAY BURSTS

(Giacomazzo et al 2013, ApJL 762, L18)

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

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

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

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

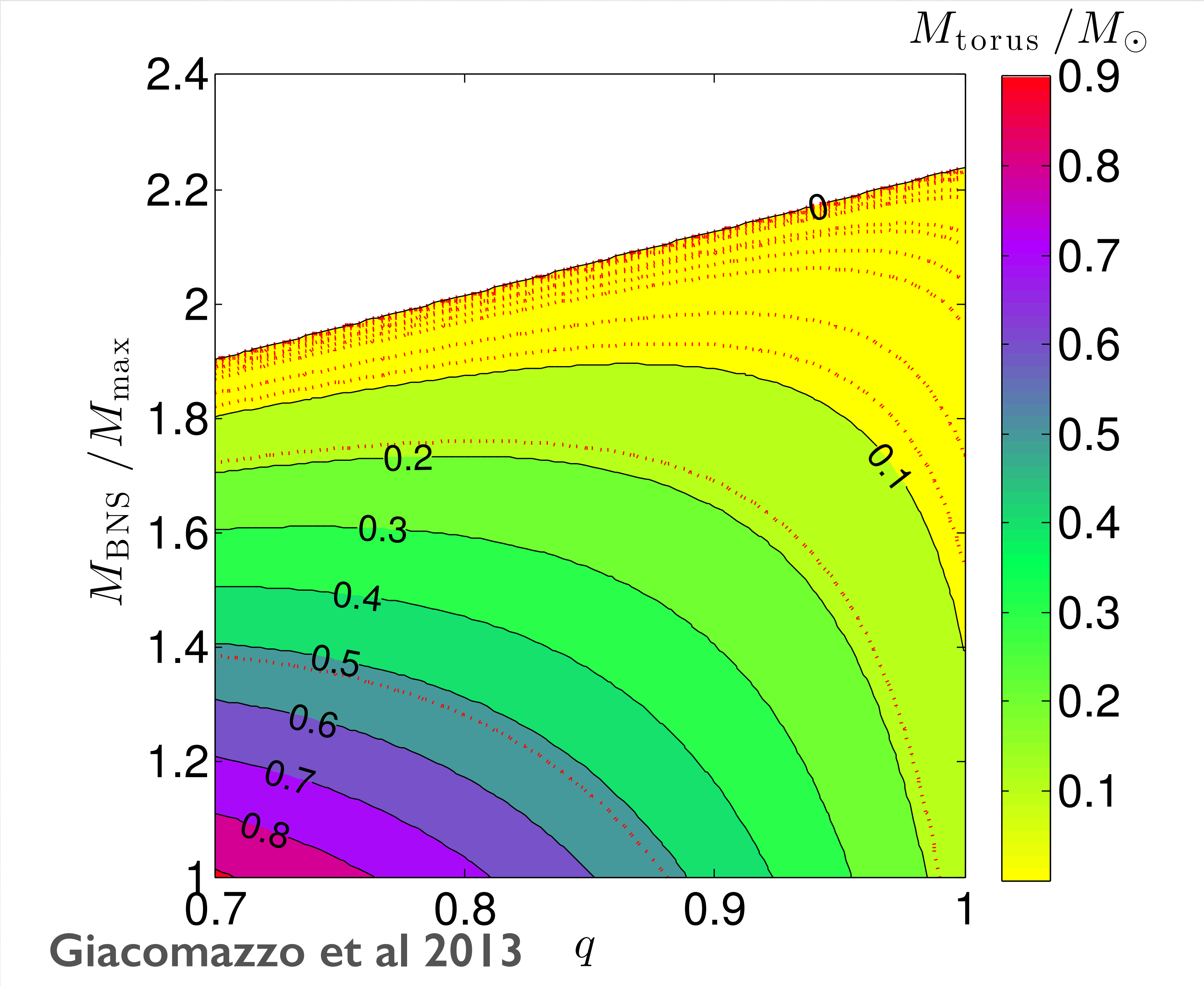
$$\epsilon_\gamma = 50\%$$

ϵ_{jet} is inferred from disk simulations (Fragile, McKinney, Tchekhovskoy, ...)

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

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

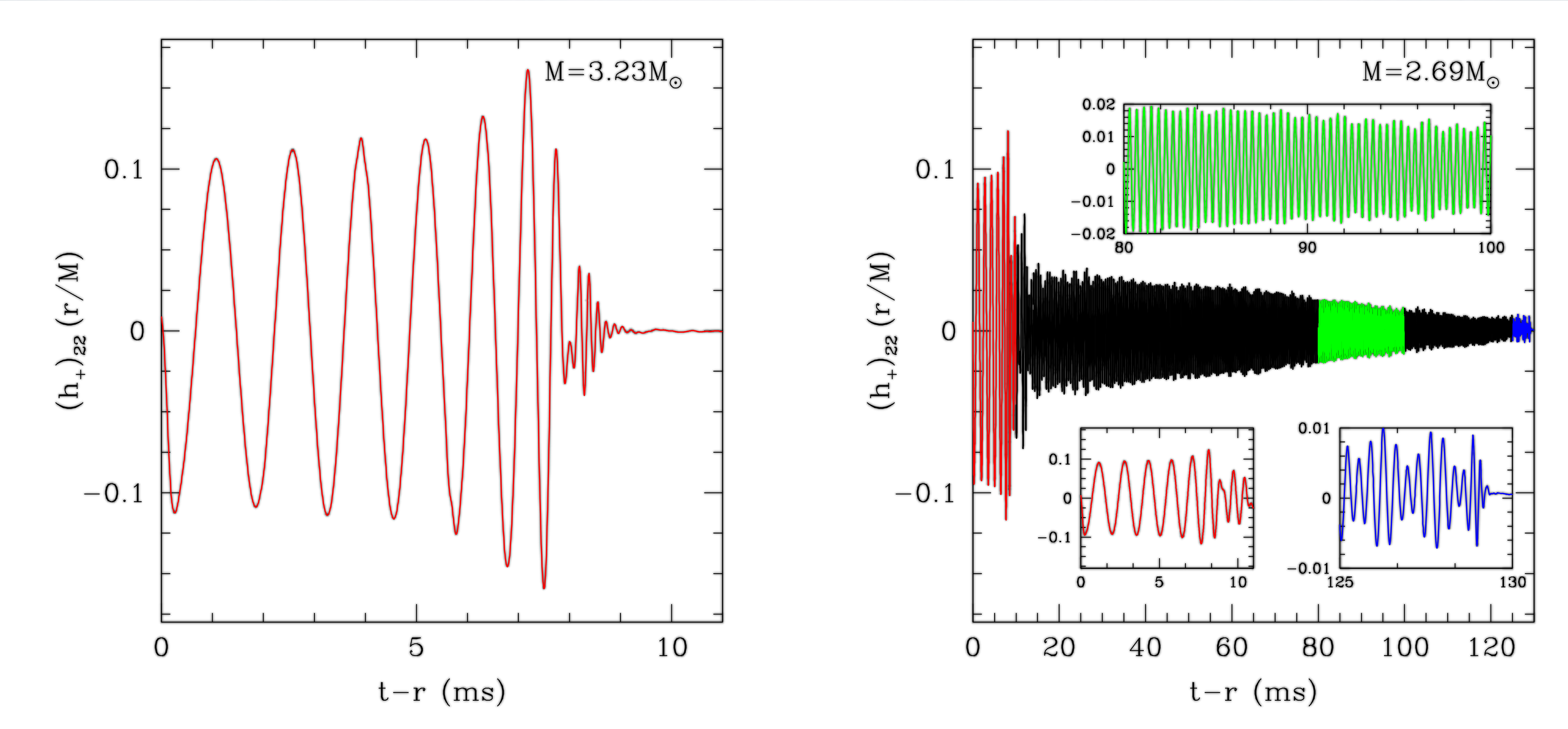
$$M_{\mathrm{torus}} = [c_1(1-q) + c_2][c_3(1+q) - M_{\mathrm{BNS}}/M_{\mathrm{max}}]$$



Almost all SGRBs are produced by high-mass BNSs. These BNSs produce an HMNS that survive only few ms before collapse to BH (consistent with Murguia-Berthier et al 2014).

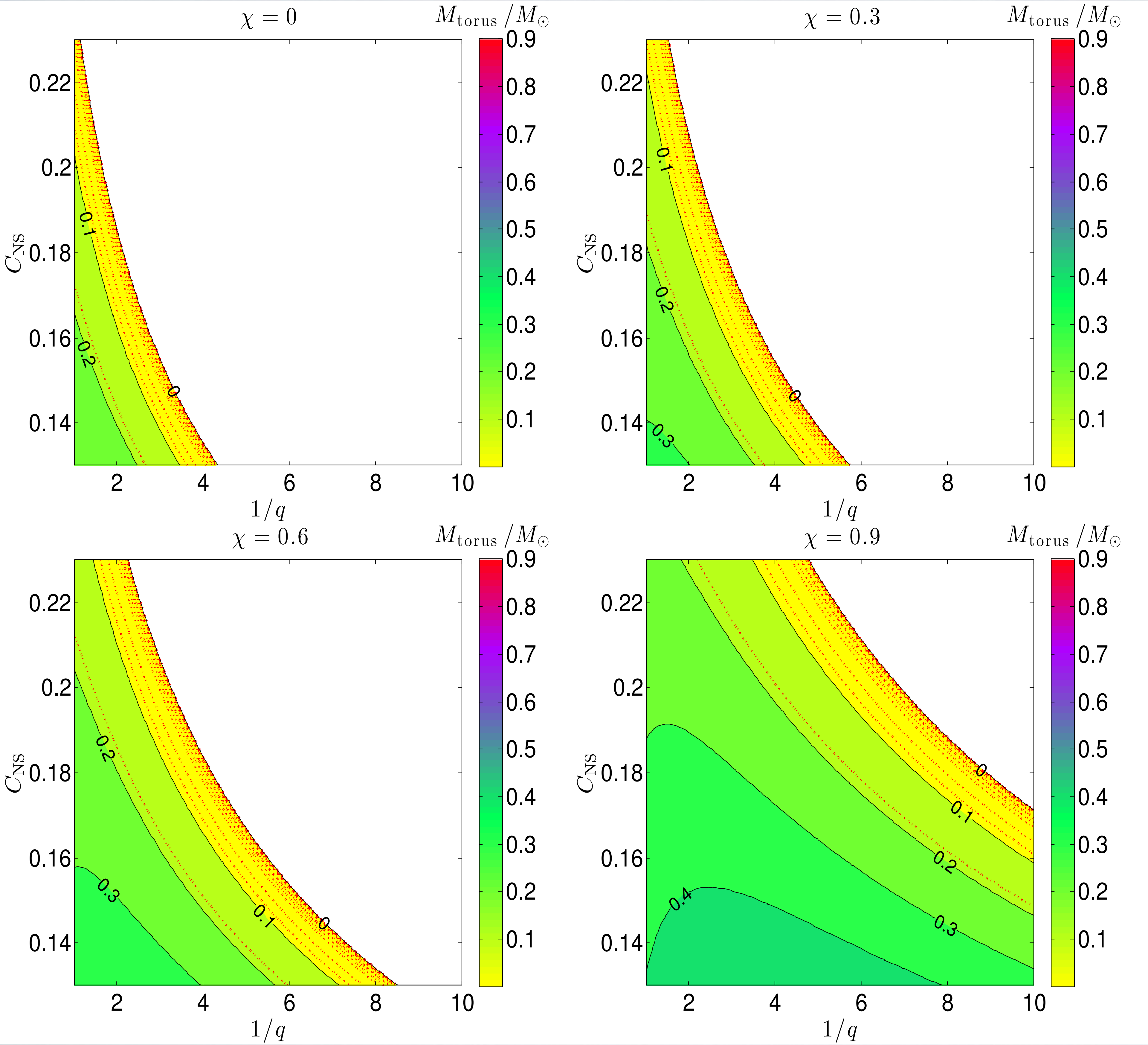
"low-energy" SGRBs
(<~1e51 erg)
↓
"high-mass" BNSs

"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



Giacomazzo et al 2013

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.

NS compactness could be measured (see also Pannarale and Ohme 2014).

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26

What about the blue path?

NS-BH → BH+torus

NS-NS → BH+torus

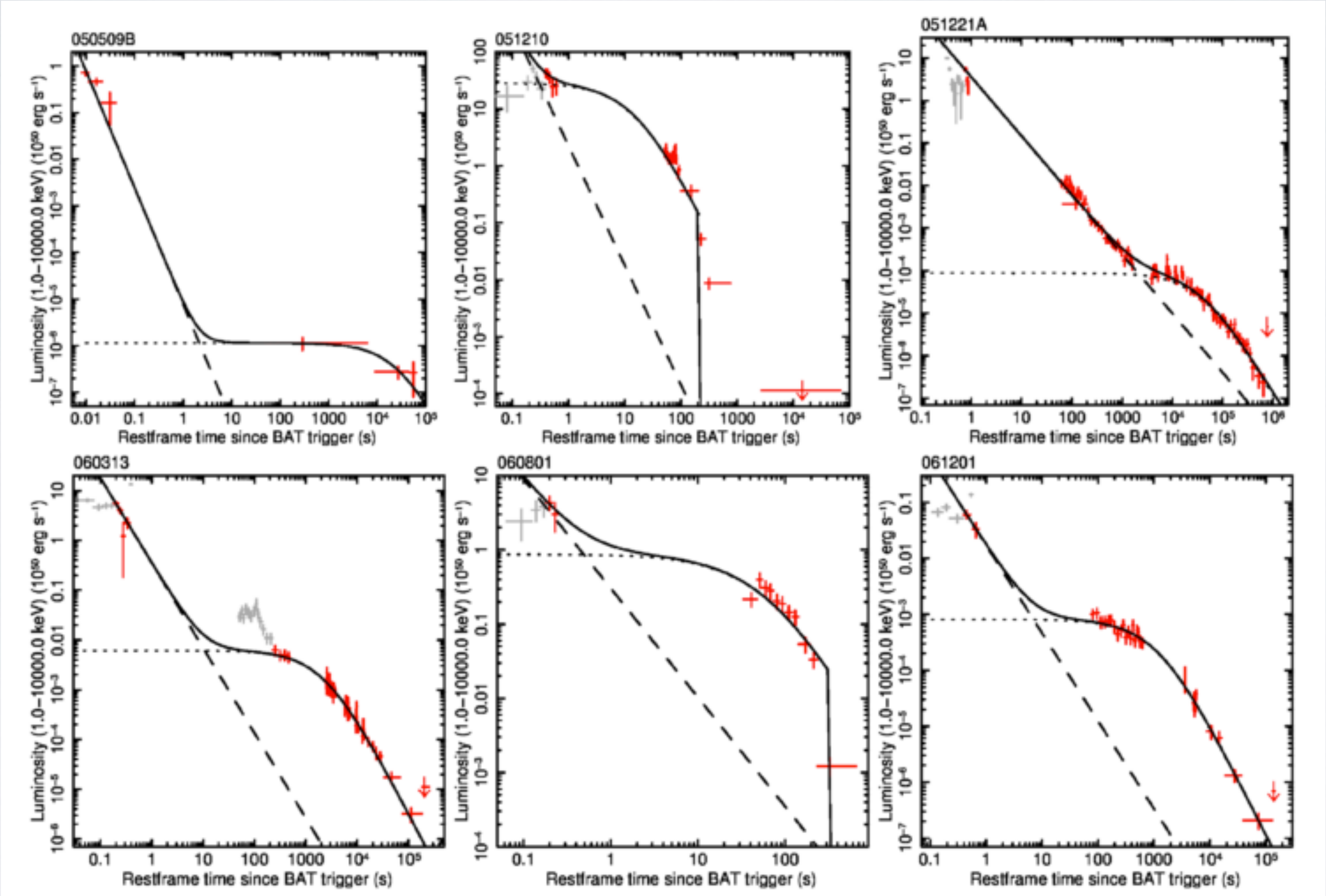
NS-NS → HMNS → BH+torus

NS-NS → SMNS+torus → BH+torus?

NS-NS → NS+torus

Credit: The Matrix (1999)

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).

TIME-REVERSAL SGRB MODEL
(CIOLFI+SIEGEL 2014, REZZOLLA+KUMAR 2014)

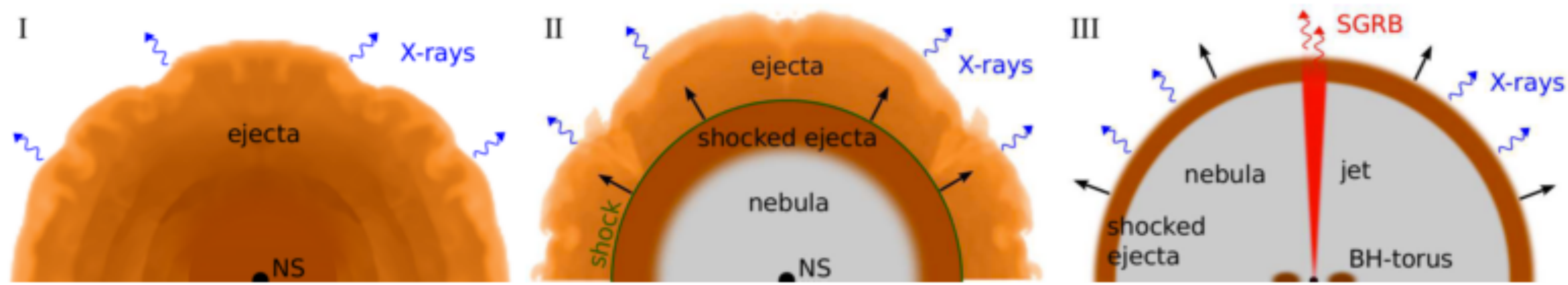


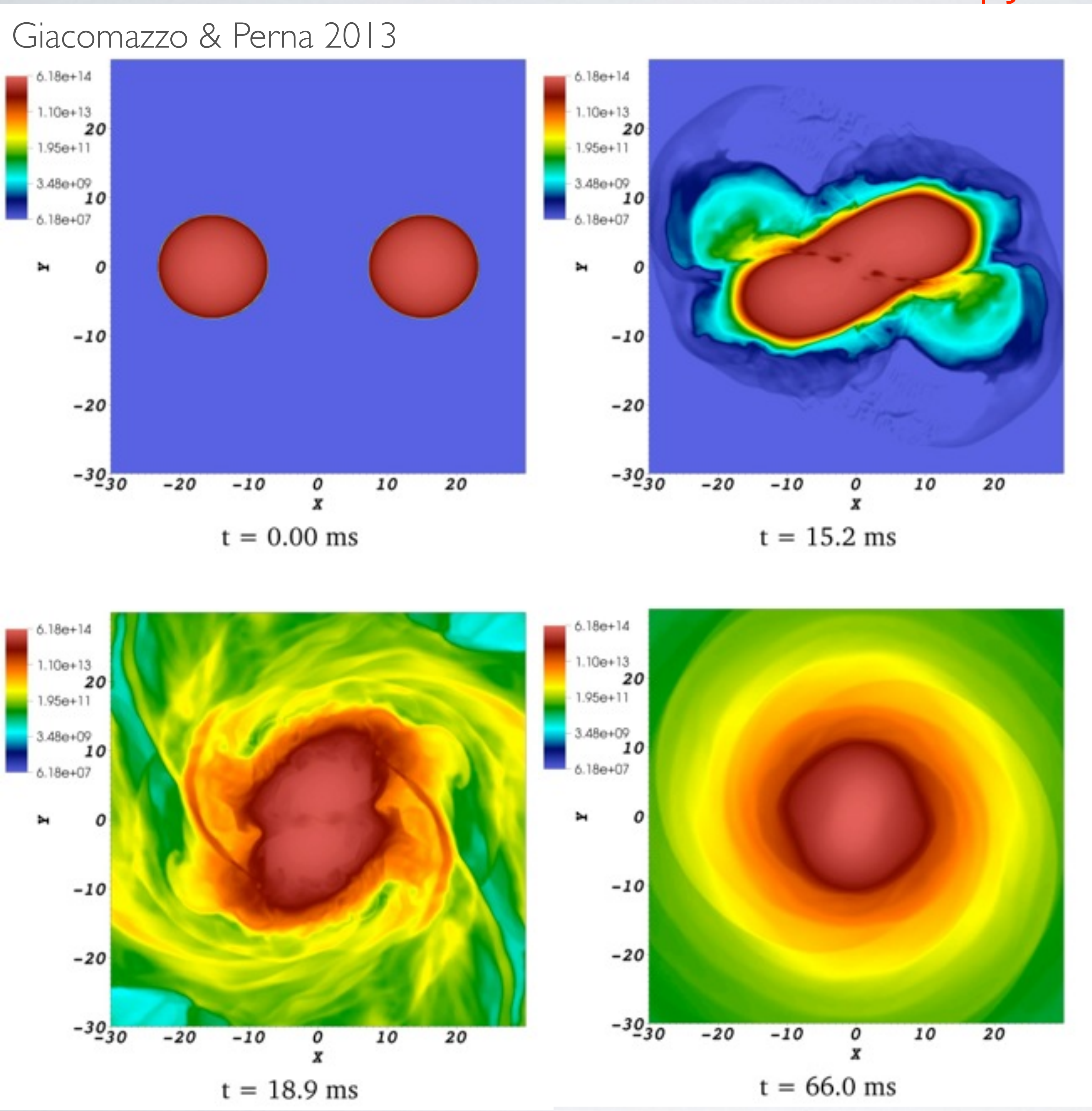
Figure 1. Evolution phases: (I) The differentially rotating supramassive NS ejects a baryon-loaded and highly isotropic wind; (II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta; (III) The NS collapses to a BH, a relativistic jet drills through the nebula and the ejecta shell and produces the prompt SGRB, while spin-down emission diffuses outwards on a much longer timescale.

Ciolfi & Siegel 2014

X-ray afterglow emitted by magnetar
SGRB emitted by BH after magnetar collapse

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26



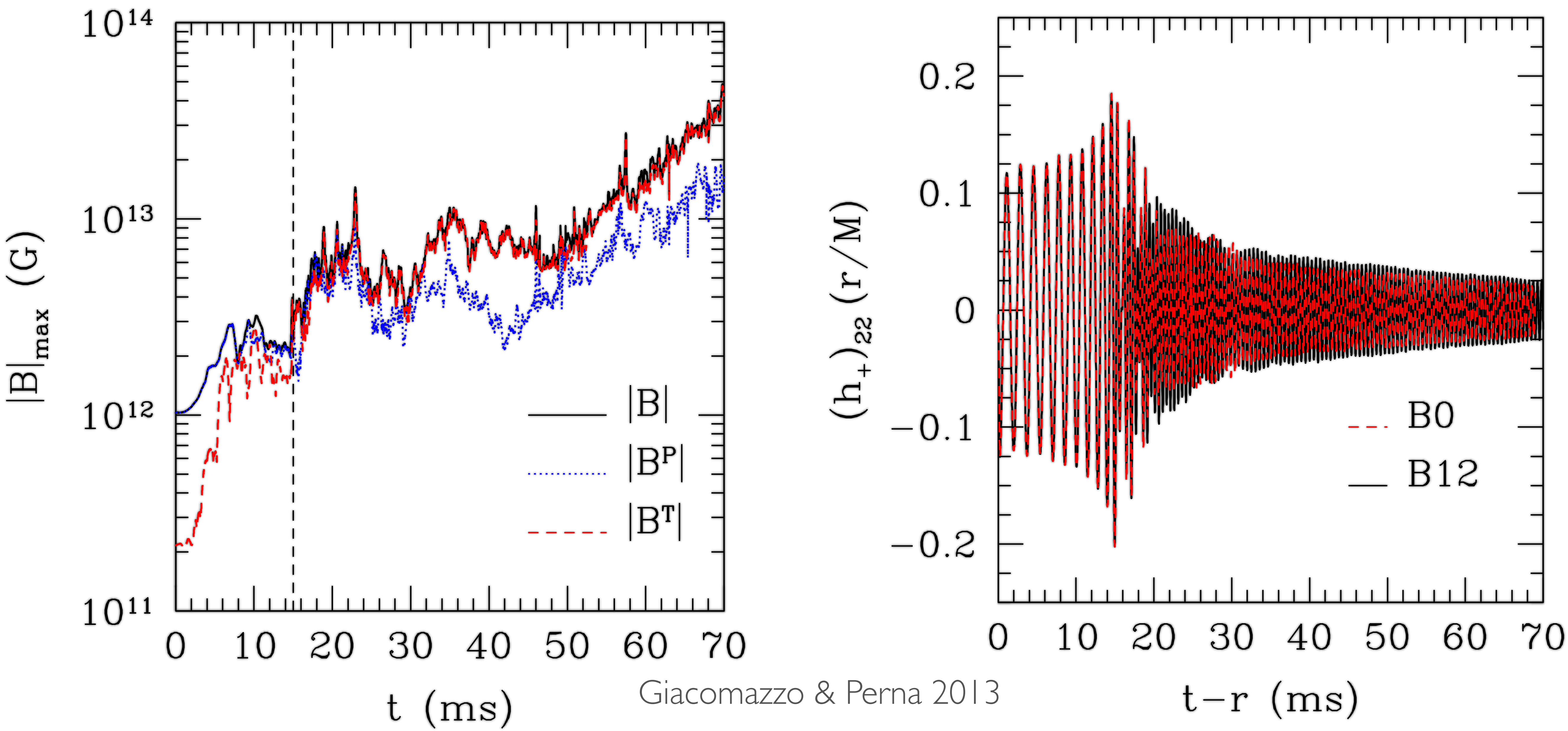
NSs of ~2.0 M⊙ have been observed, hence low-mass BNSs may produce stable NSs.

Investigated merger of two 1.2 M⊙ NSs (with and without magnetic fields). Used Ideal Fluid, Gamma=2.75, k=30000.

Produced a stable "ultraspinning" NS surrounded by a disk of ~0.1 M⊙.

MAGNETAR FORMATION

Giacomazzo & Perna 2013, ApJ Letters, 771, L26



Giacomazzo & Perna 2013

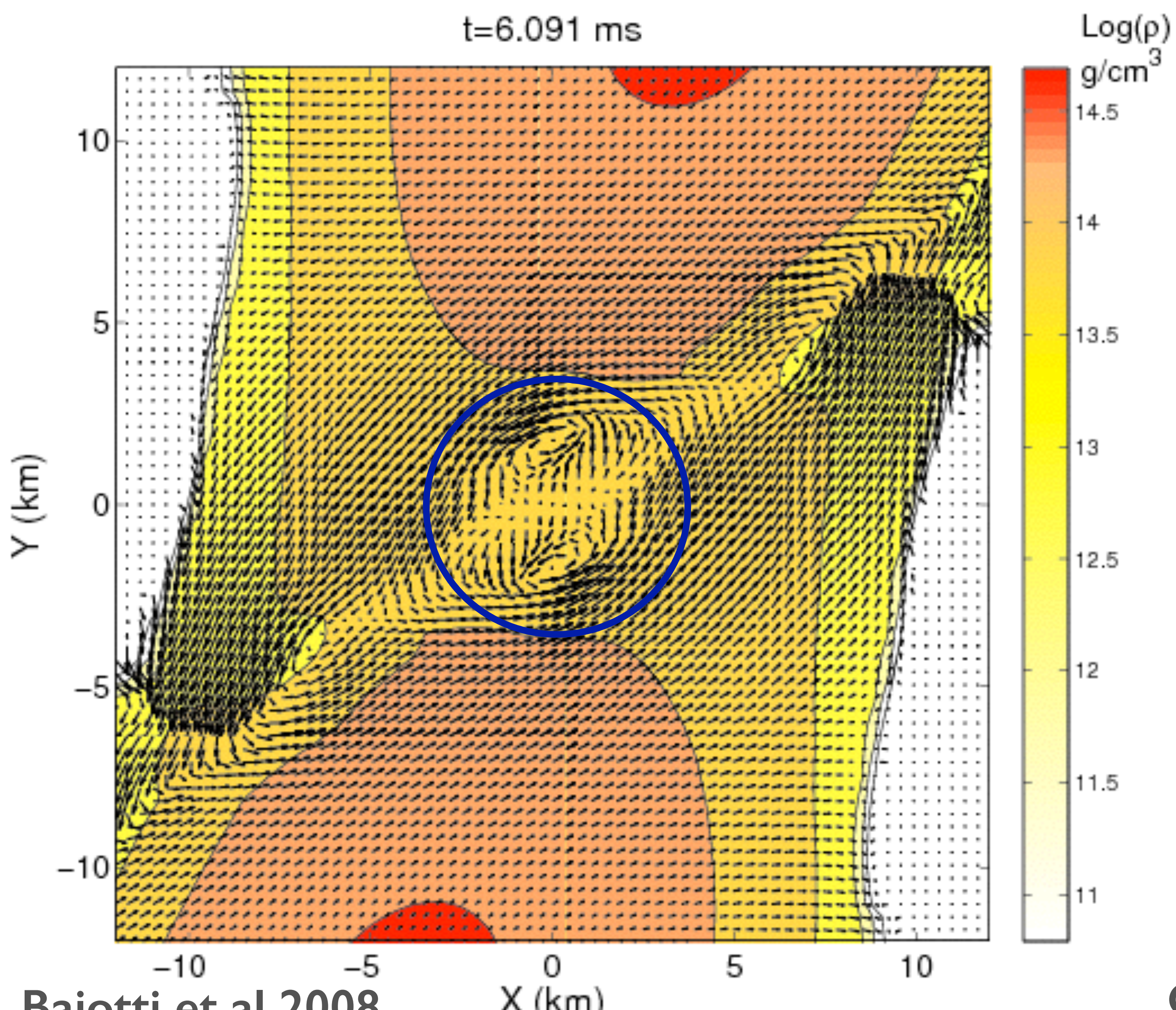
Magnetic field amplified of almost ~2 orders of magnitude. Difference in GWs is small, but EM counterparts could reveal stable NS formation.

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

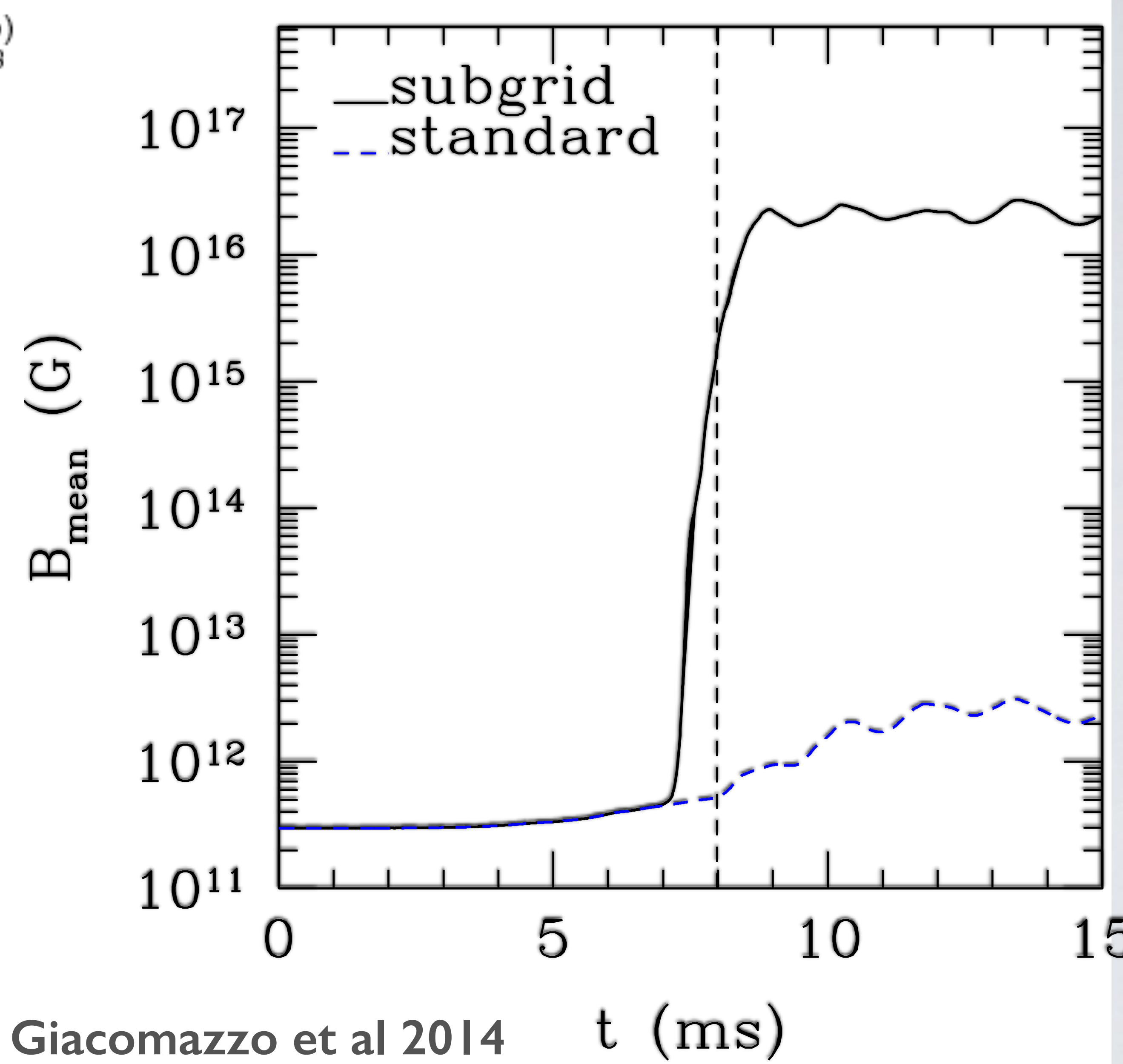
MAGNETAR FORMATION

Giacomazzo, Zrake, Duffell, MacFadyen, Perna, submitted

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



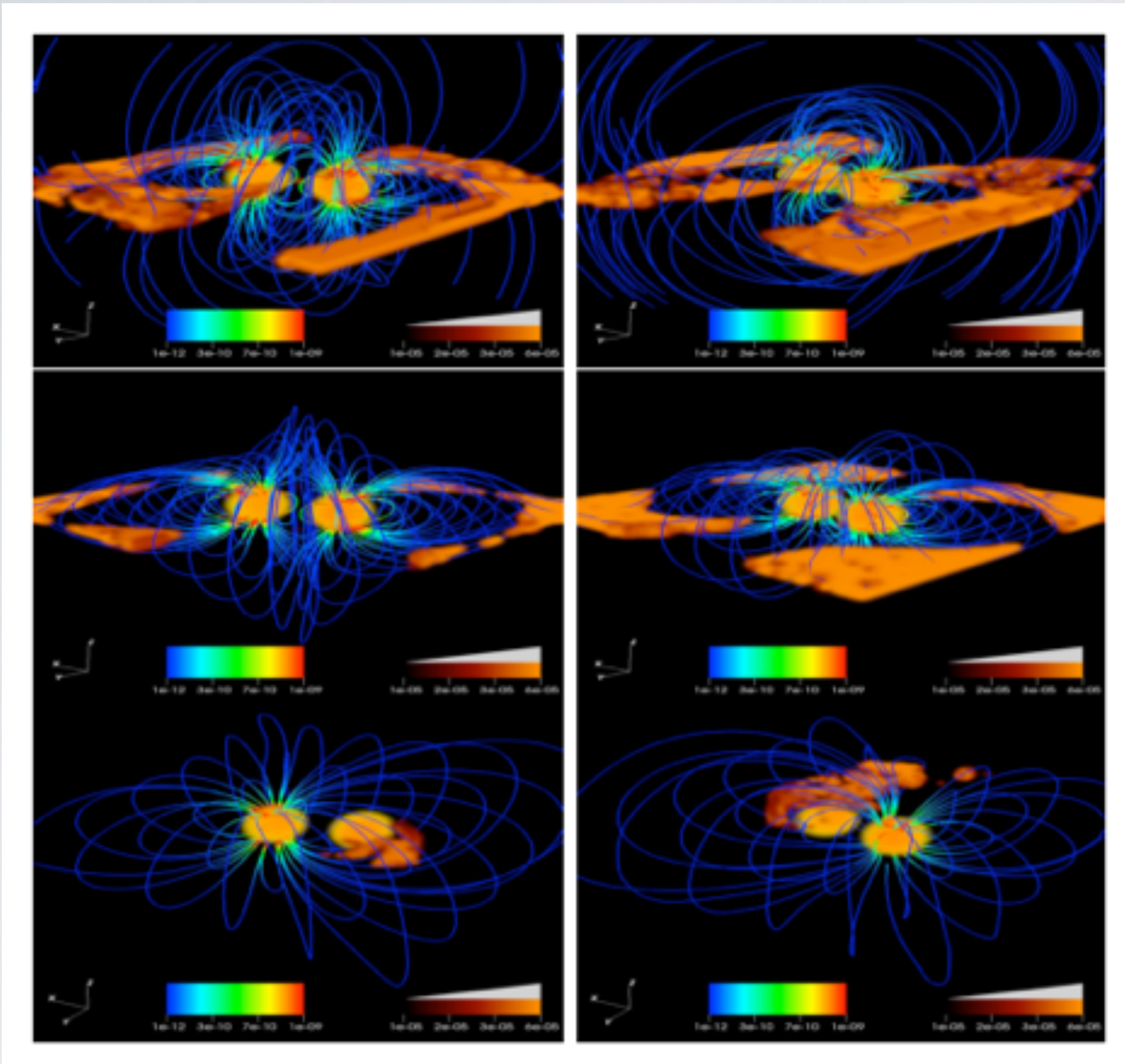
Baiotti et al 2008

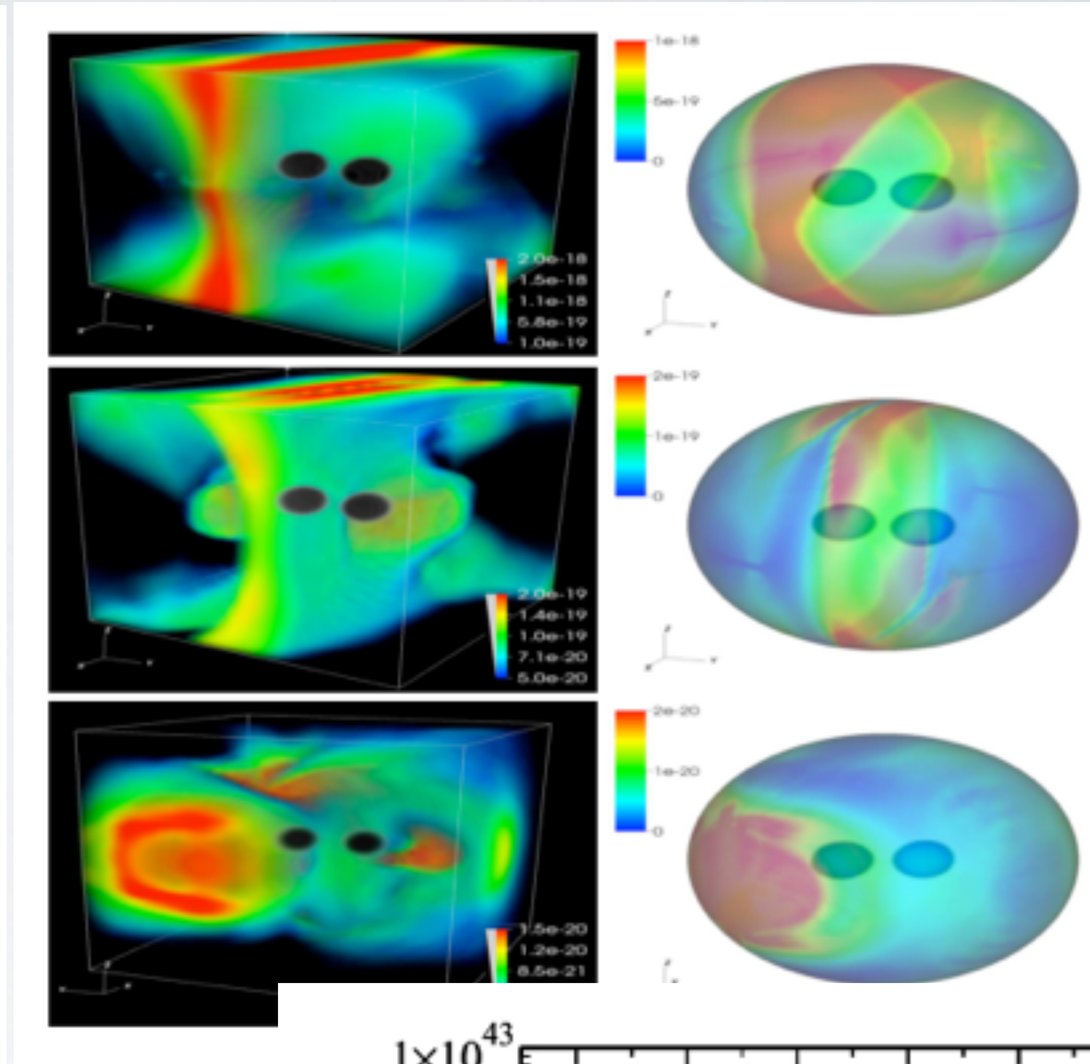


Giacomazzo et al 2014

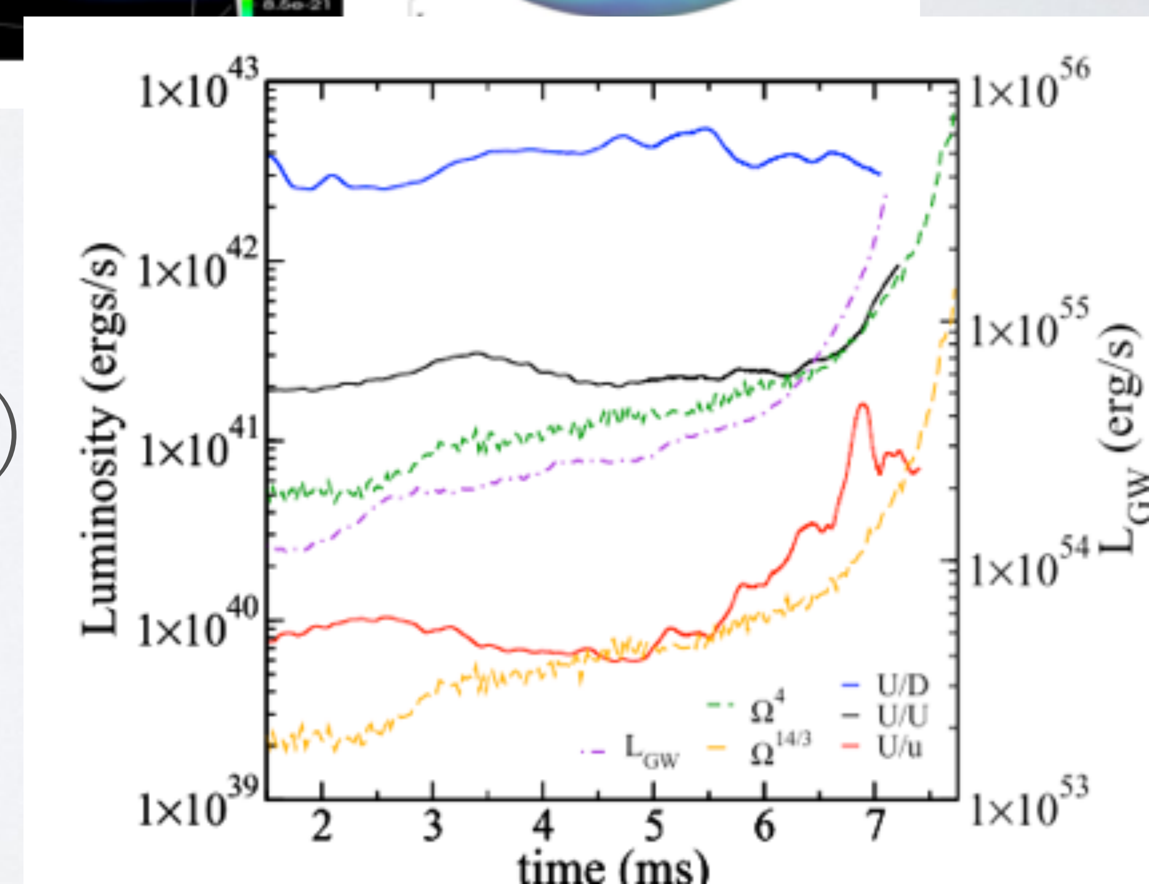
We developed a sub-grid model and run a set of NS-NS simulations. Magnetar field levels are possible!

NS-NS: EM PRECURSORS





Palenzuela et al 2013

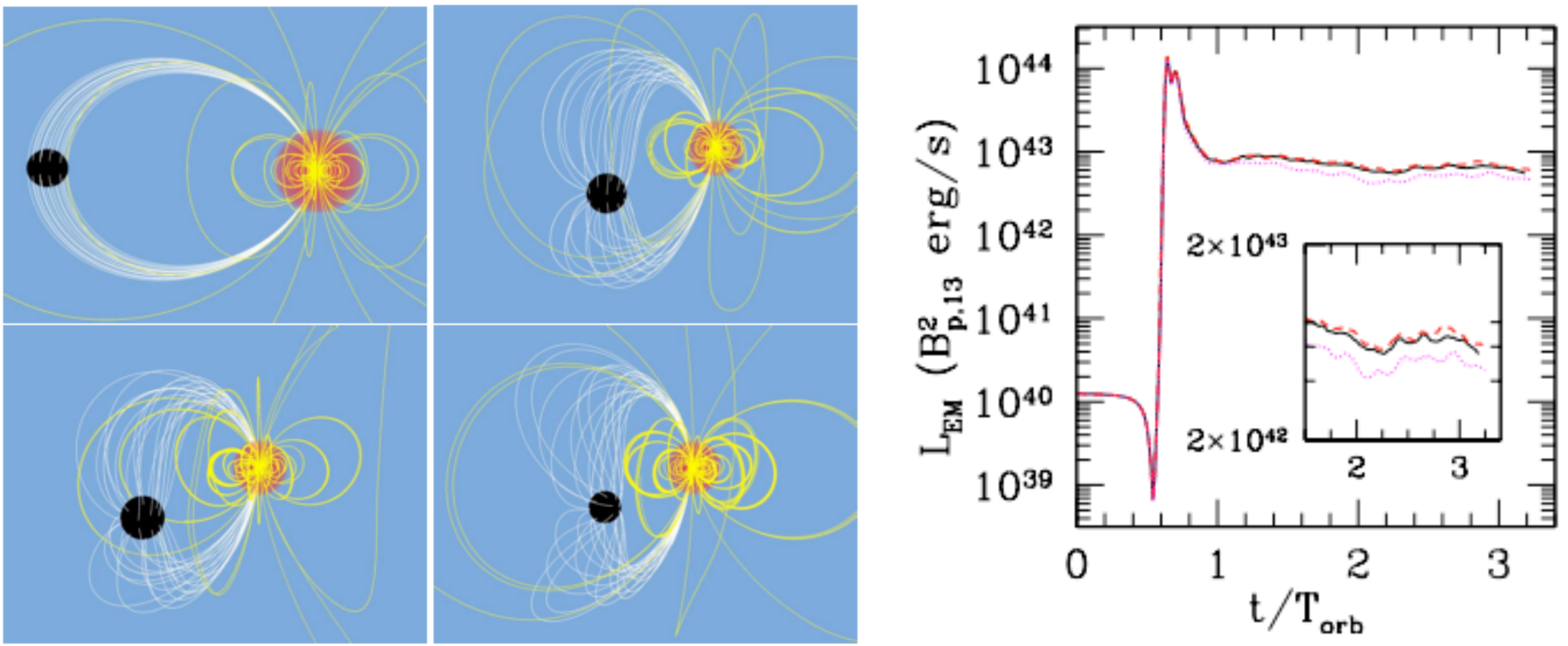


Resistive MHD simulations (full GR)

EM emission during inspiral (~1e43 erg/s)

Emission depends on initial configuration (see also Ponce et al 2014)

NS-BH: EM PRECURSORS



Paschalidis et al 2013

Force Free simulations of NS-BH mergers show also 1e43 erg/s emission (but for larger fields, ~1e13G)

Emission within ~60° from orbital plane (possible lighthouse effect)

CONCLUSIONS

- GR simulations of NS-NS and NS-BH now able to study all phases of inspiral and merger
- Included effects of EOSs, neutrinos, and magnetic fields
- Possible to infer EOS from inspiral GWs (but alternative theories of gravity make life more difficult…)
- Magnetic field role important in all phases (especially post-merger)
- Possible to form stable magnetars+disk from BNS mergers
- Magnetized BNSs and NS-BH may produce jets and power SGRBs
- Highly spinning BH necessary to power SGRBs in NS-BH mergers
- Possible EM precursors during inspiral and EM emission from HMNS

SOME OPEN QUESTIONS

- Are we happy with the numerical accuracy of numrel GWs?
- Which microphysics are we still missing into simulations? Do we need to model the crust? Multifluid approaches?
- Can we detect EM emission from post-merger phase? What about EM precursors? Can we get reliable lightcurves from simulations?
- What about magnetic field amplification and turbulence?
- Neutrino and cooling?
- How important are thermal effects in the post-merger phase?

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