GRMHD Simulations of Neutron Star Binaries

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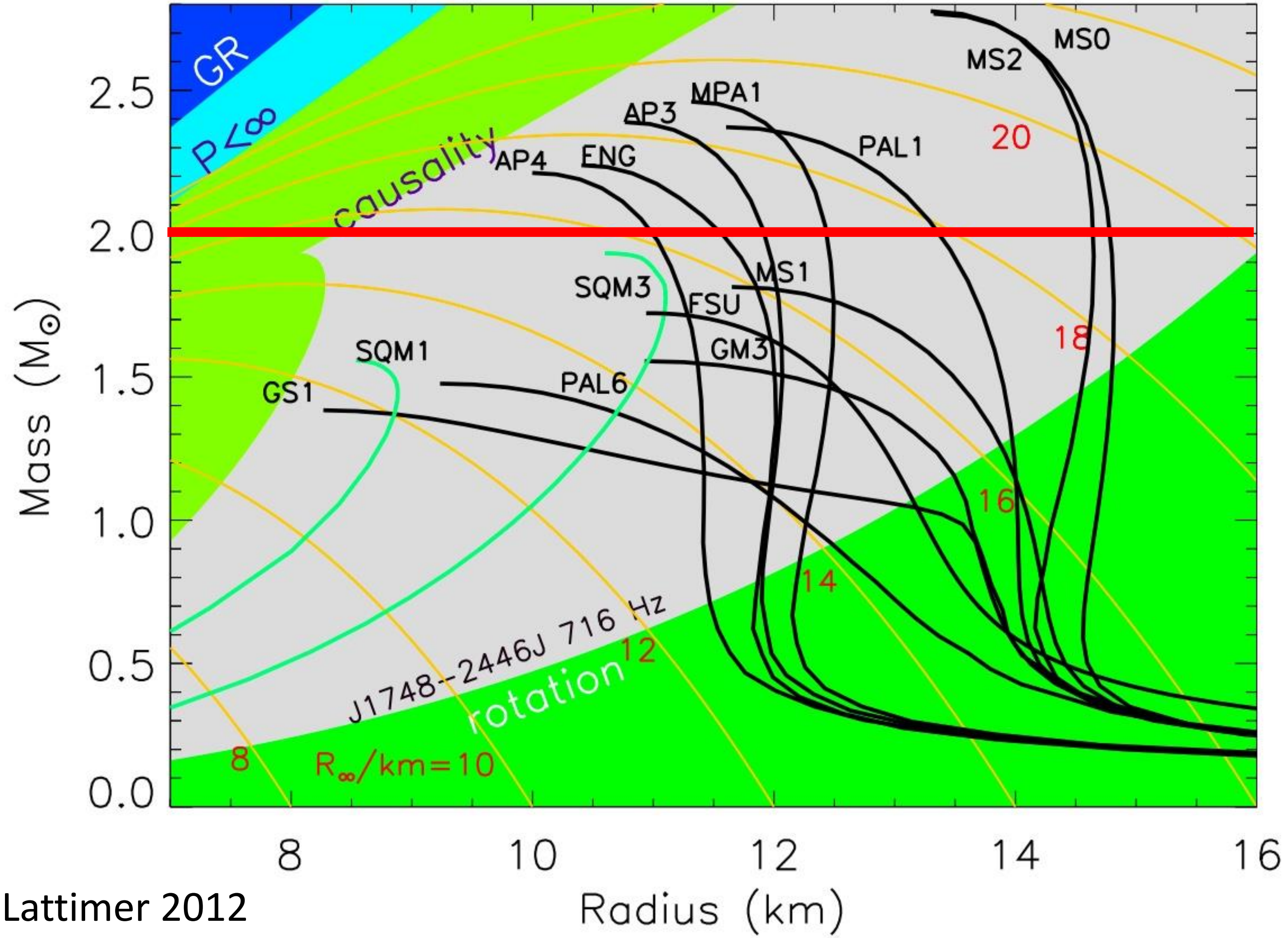
NEUTRON STARS



Lattimer 2012

Photo by Daily Herald Archive/SSPL/Getty Images (23/02/1968)

First NS discovered as a "pulsar" (radio frequencies) in 1967 by PhD student Jocelyn Bell and her supervisor Antony Hewish.

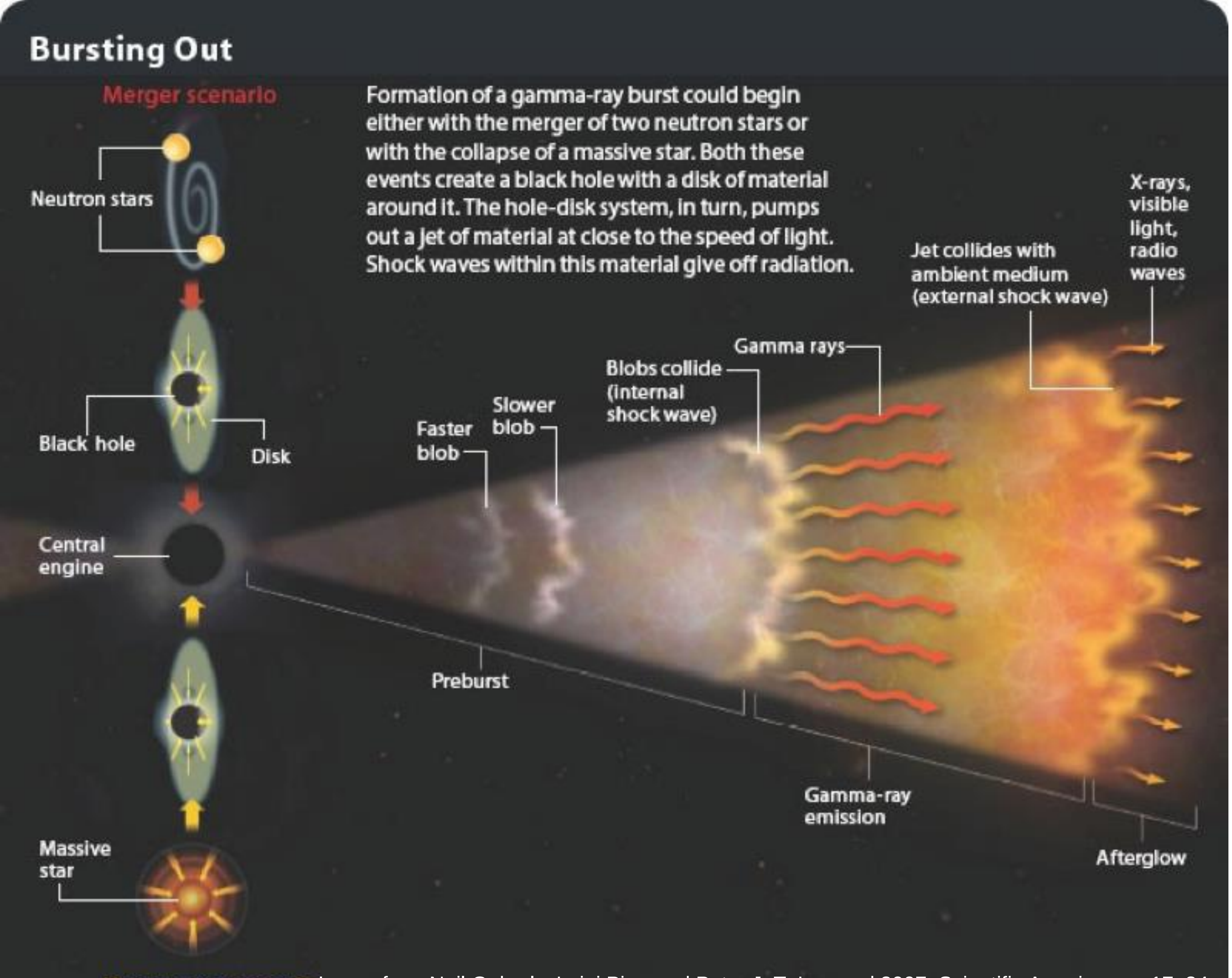


Image from Neil Gehrels, Luigi Piro, and Peter J. T. Leonard 2007, Scientific American sp 17, 34 (CREDIT: JUAN VELASCO)

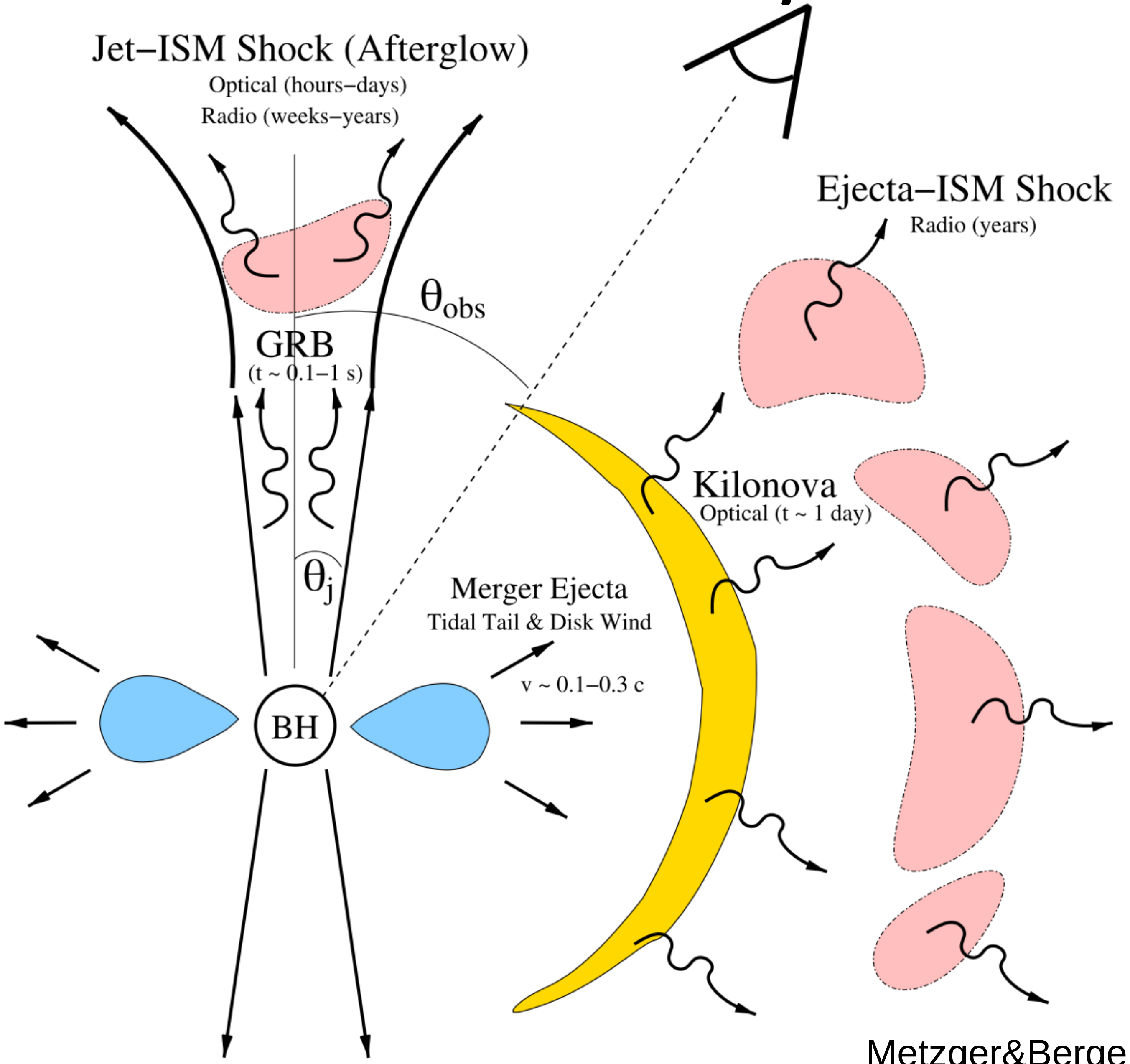
Gamma-Ray Bursts

- Discovered in 1967
- Two types:
  - Short (<2 s)
  - Long (>2 s)

- Long GRBs are due to Supernovae explosions (discovered in 1998)

- Short GRBs have been quite a mystery (but NS-NS/NS-BH were always considered main candidate)

EM emission from NS-NS/NS-BH Mergers

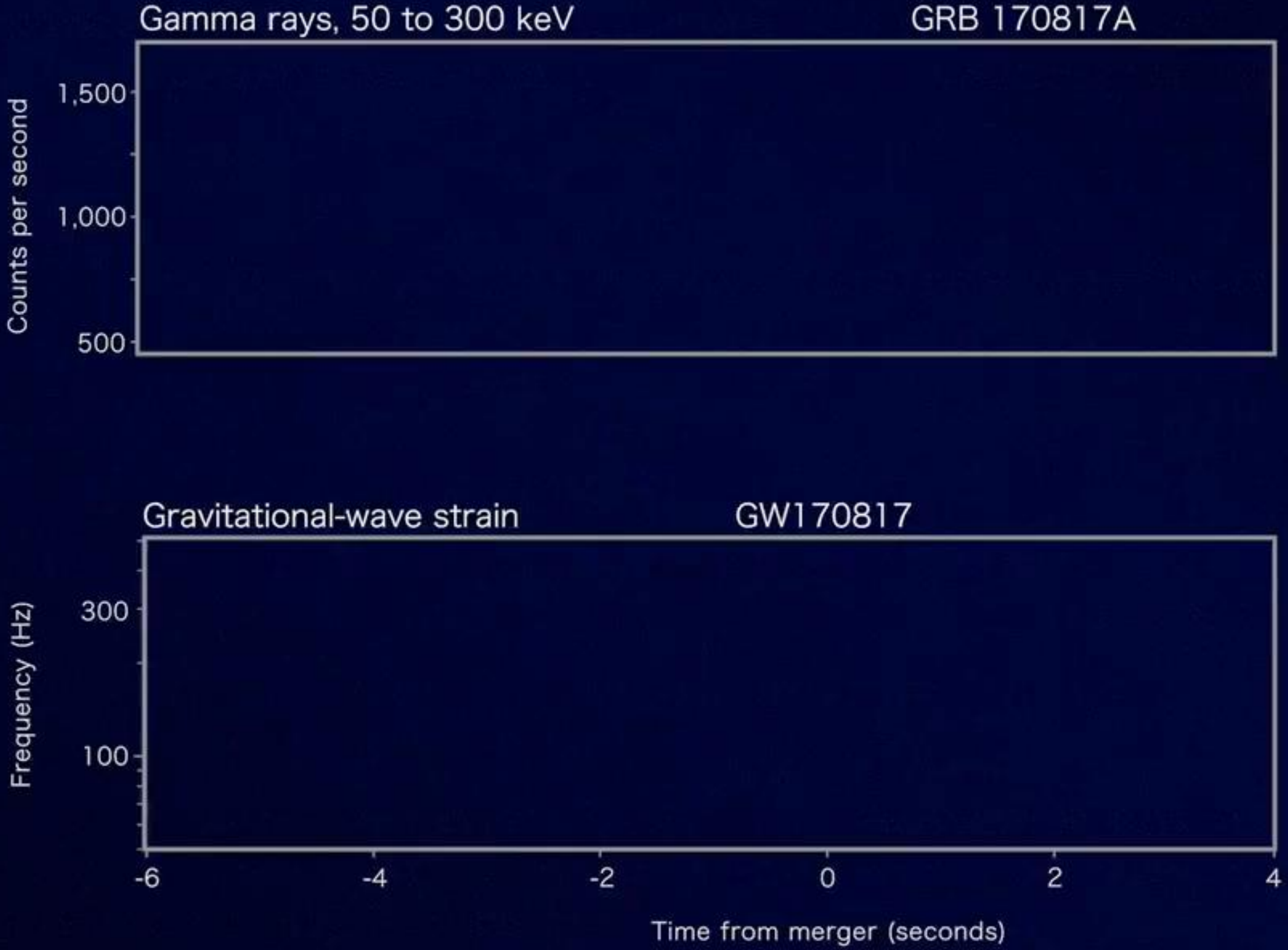


Metzger&Berger 2012

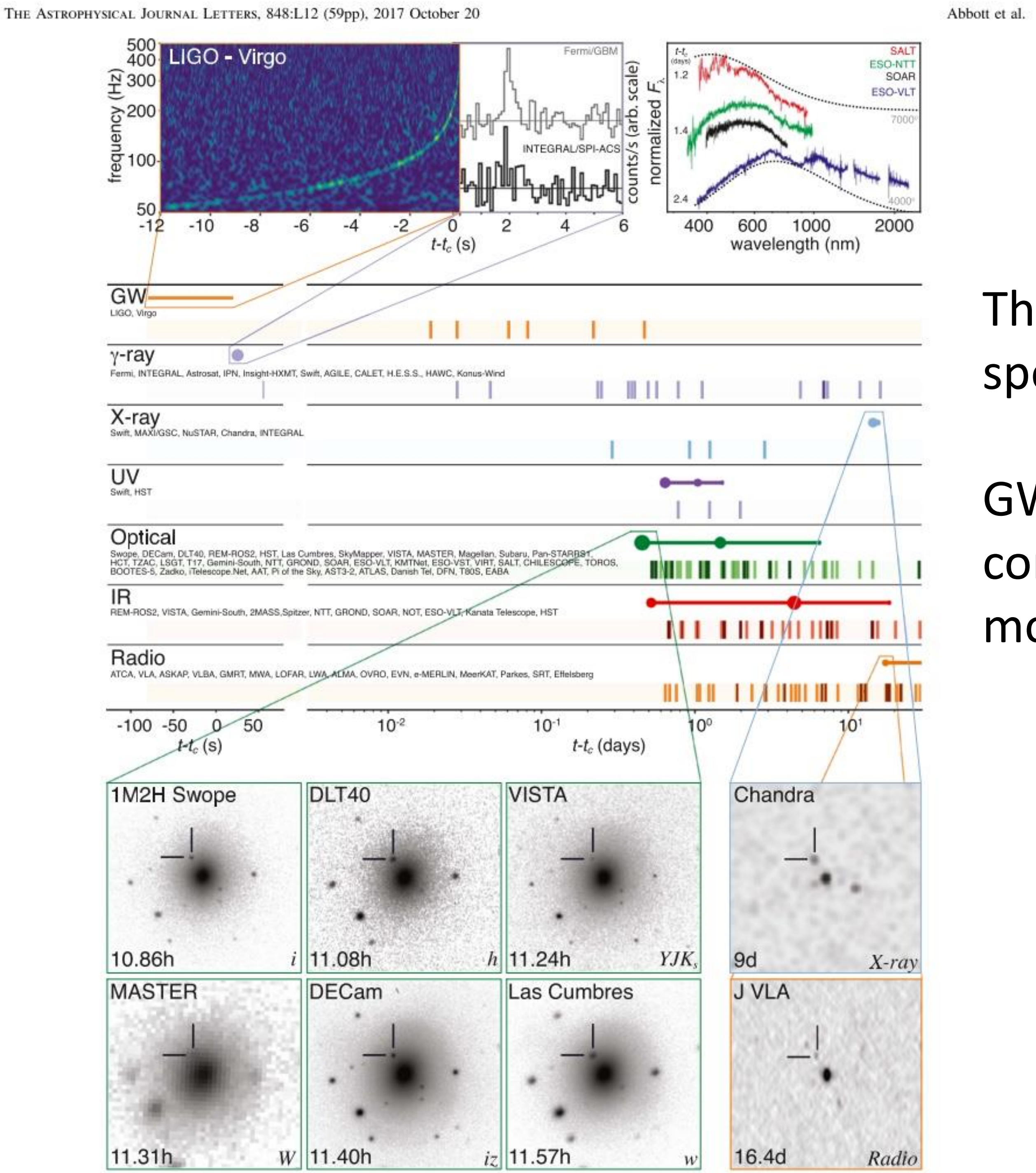
GW170817: the first NS-NS detection

Fermi

LIGO



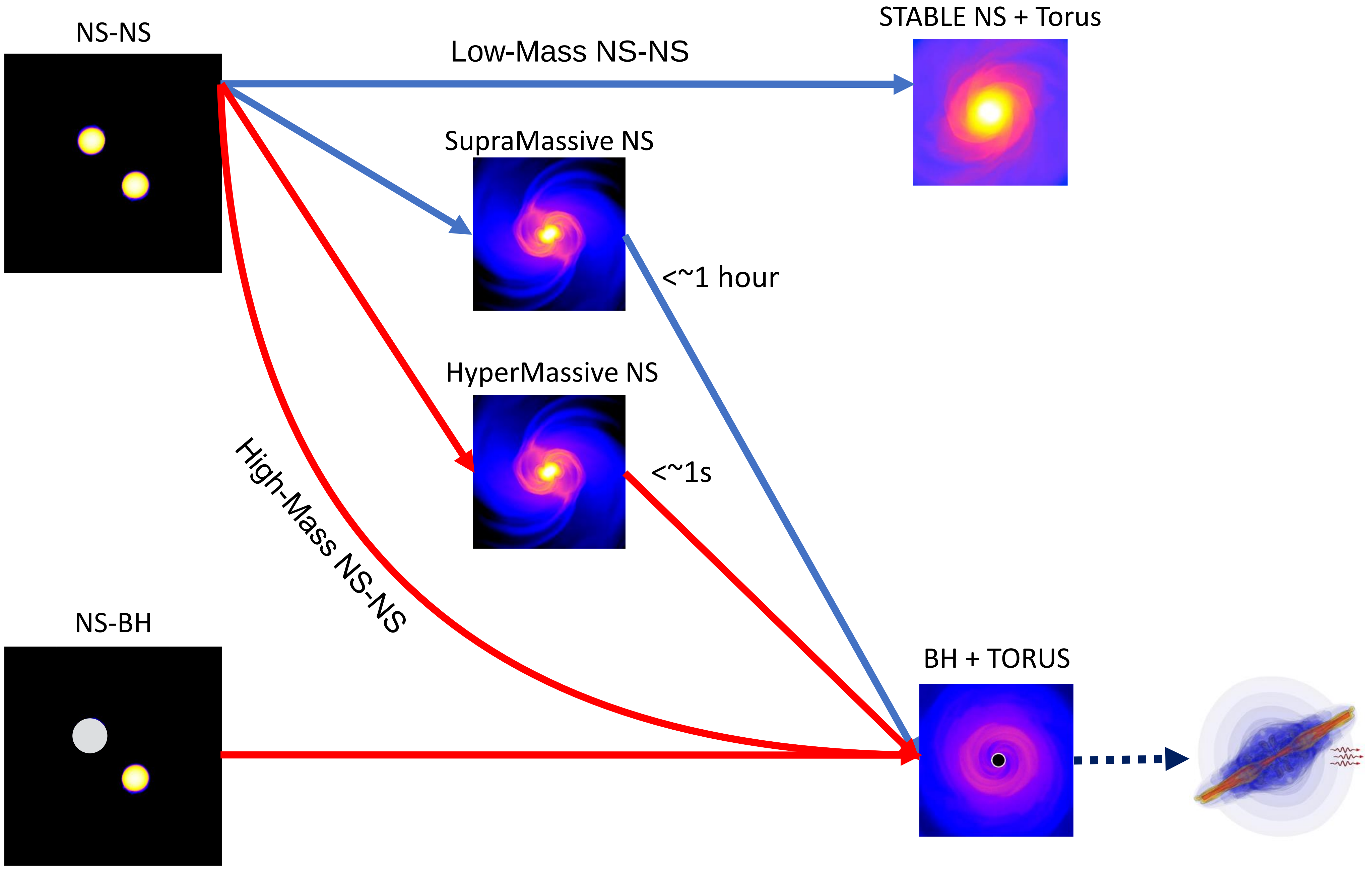
Credit: NASA GSFC & Caltech/MIT/LIGO Lab



The event has been detected in the full EM spectrum from gamma-ray to radio.

GW and EM emission allowed also to put constraints on NS equation of state and SGRB models.

Neutron Star Binary Mergers



BNS Mergers and Short GRBs: Effects of Magnetic Field Orientation, Equation of State, and Mass Ratio

Kawamura, **Giacomazzo**, Kastaun, Ciolfi, Endrizzi, Baiotti, Perna 2016, PRD 94, 064012

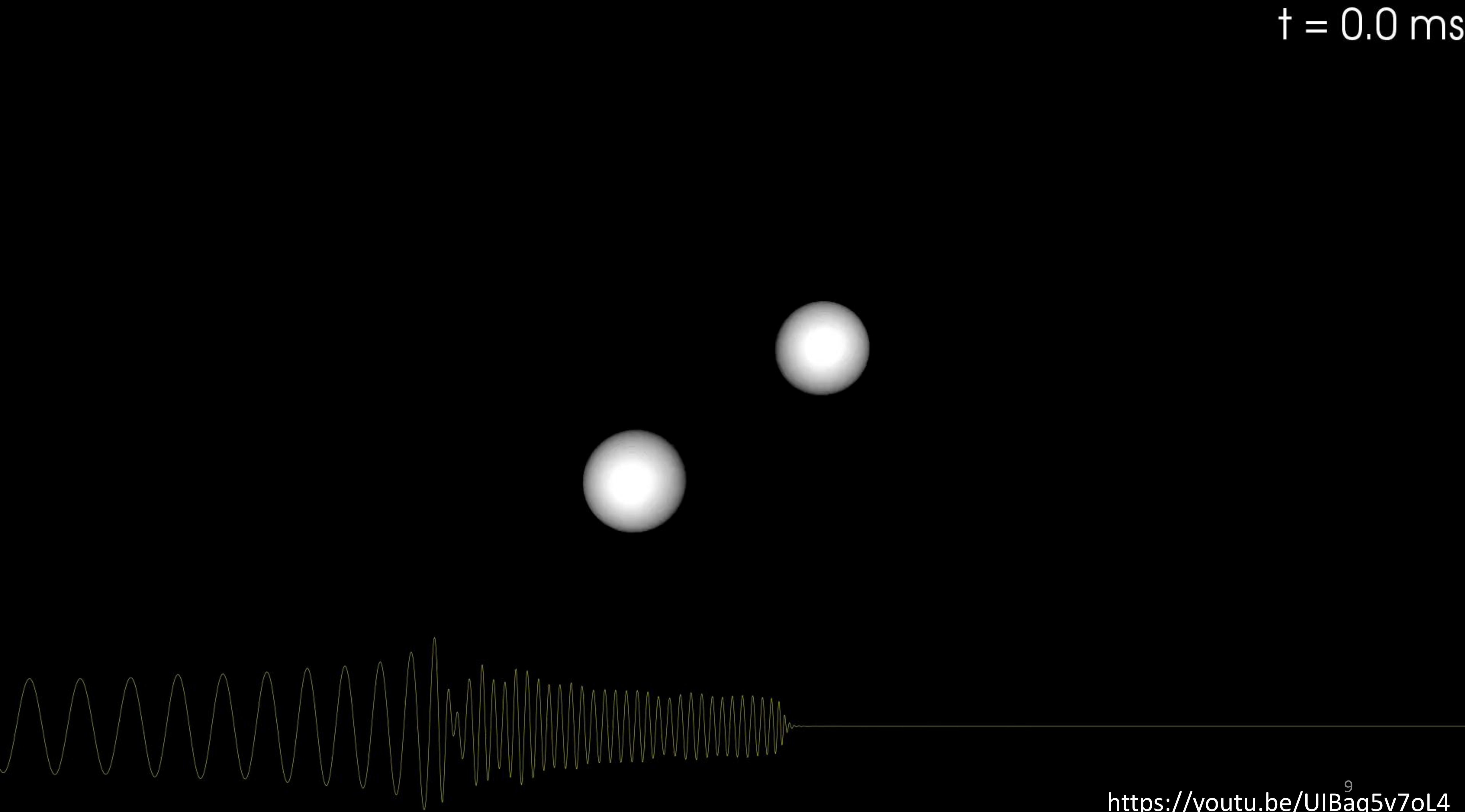
New set of GRMHD simulations of 6 “high-mass” BNSs:

- Ideal-Fluid EOS:
  - Equal-Mass (1.5-1.5) with field alignment UU, UD, DD
  - Unequal-Mass (1.4-1.7)
- H4 EOS:
  - Equal-Mass (1.4-1.4)
  - Unequal-Mass (1.3-1.5)

All models start with an initial magnetic field of ~10^{12} G.

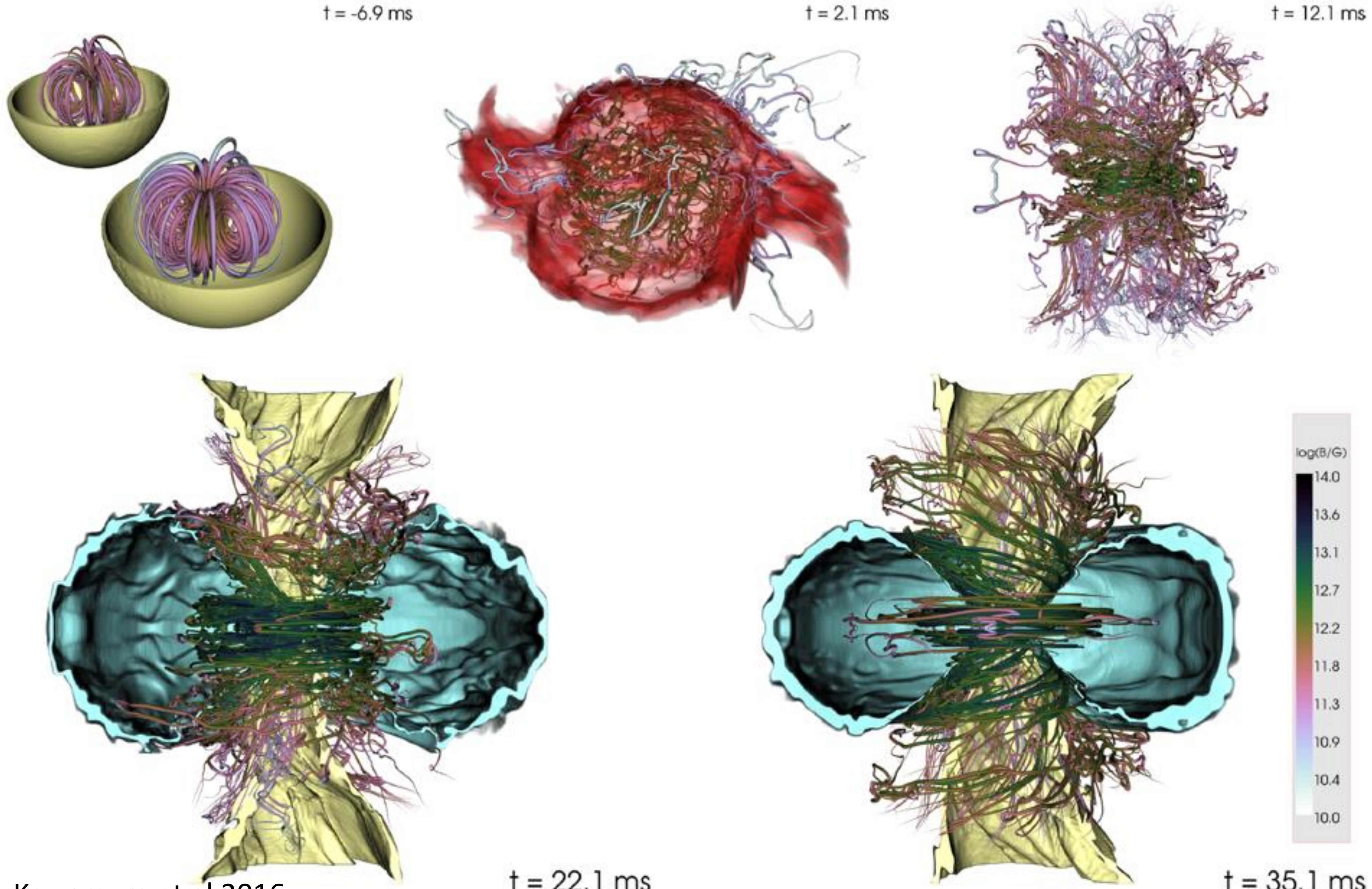
Unequal-mass models studied for the first time.

All simulation performed with WhiskyMHD + EinsteinToolkit.

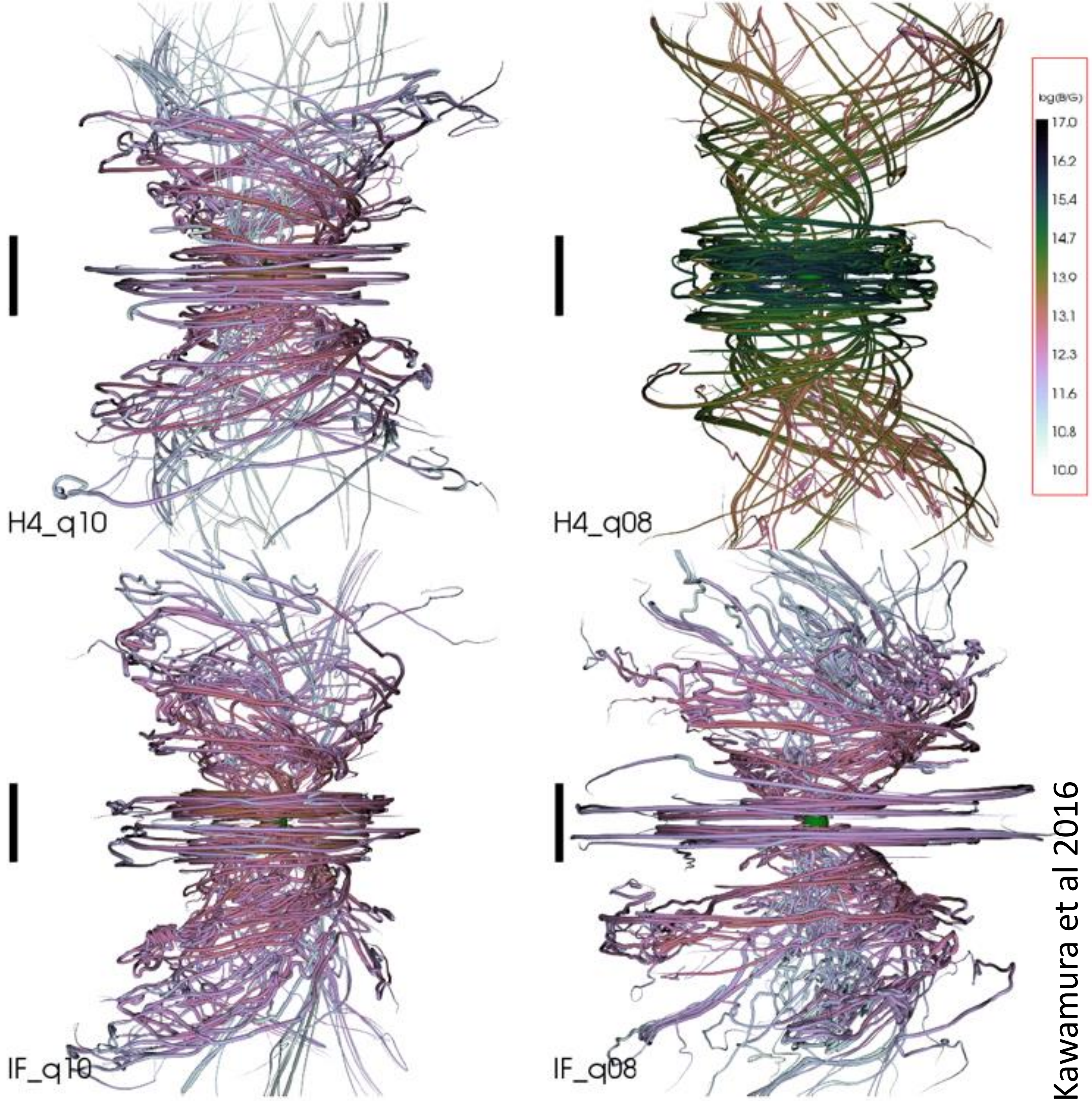


https://youtu.be/UIBaq5v7oL4

Magnetic Field Structure Evolution

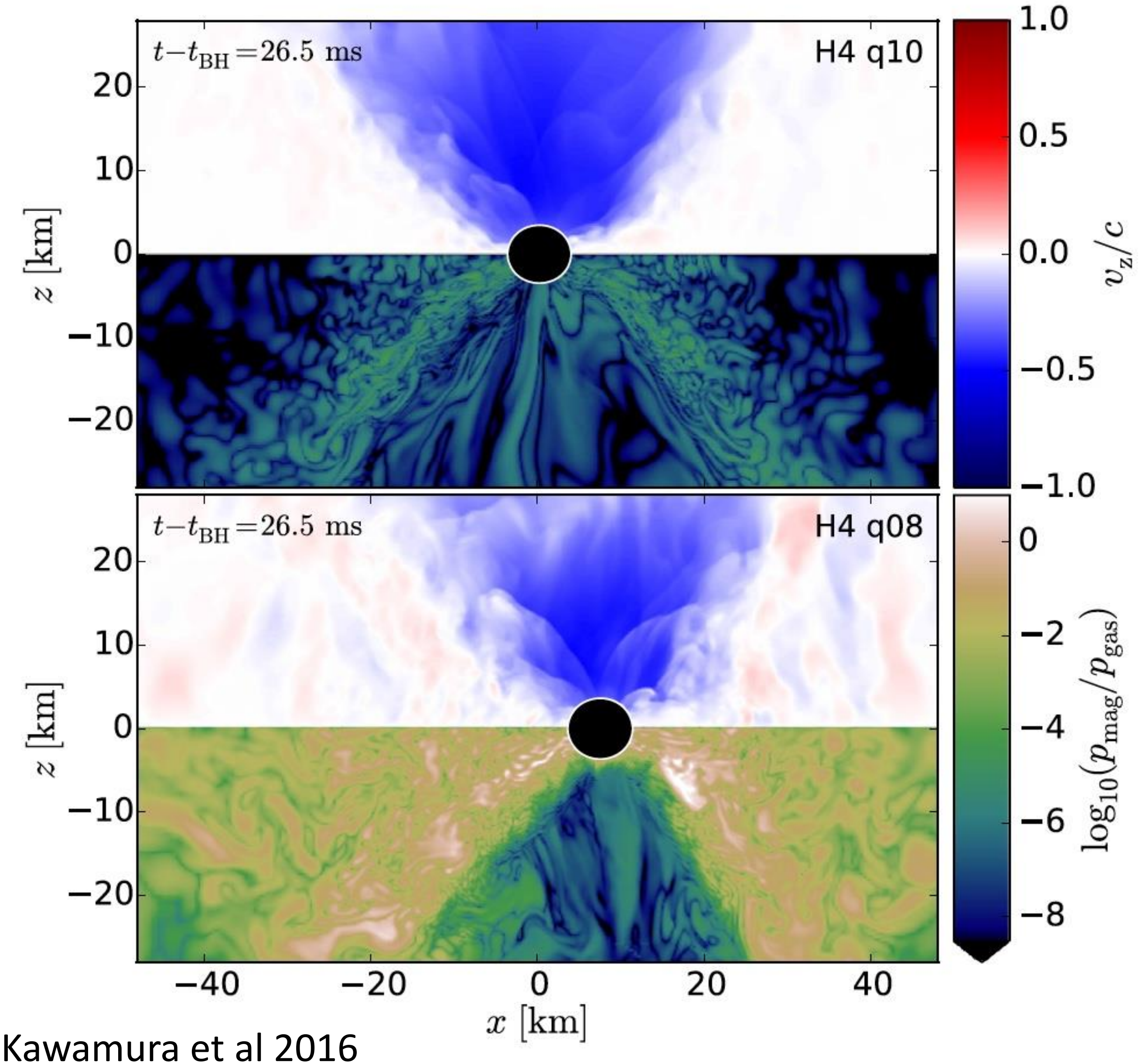


Kawamura et al 2016



Kawamura et al 2016

Same funnel structure independently of EOS and mass ratio.

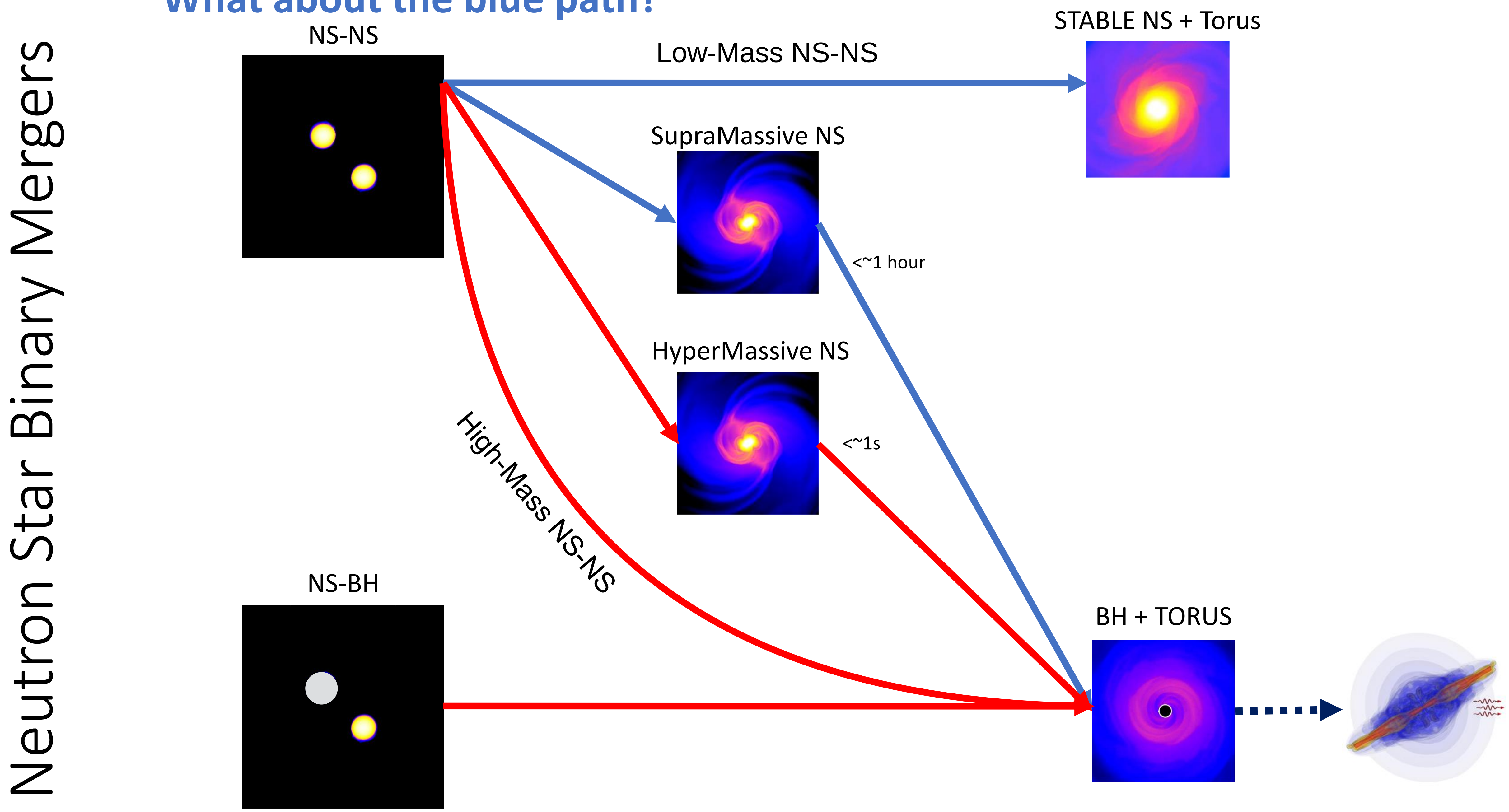


Kawamura et al 2016

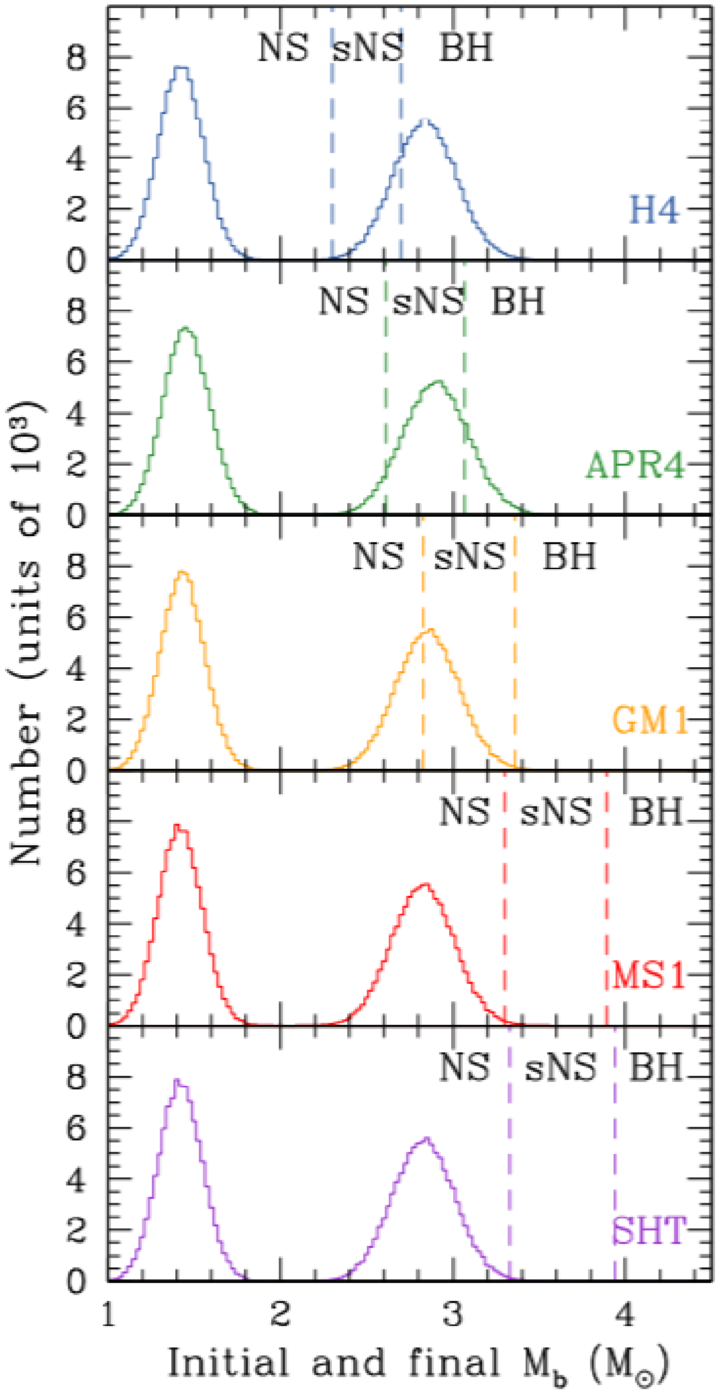
No Jet observed, but it may change with longer evolutions and much higher resolutions (e.g., Kiuchi et al 2015) or by using a subgrid model (e.g., Giacomazzo et al 2015).

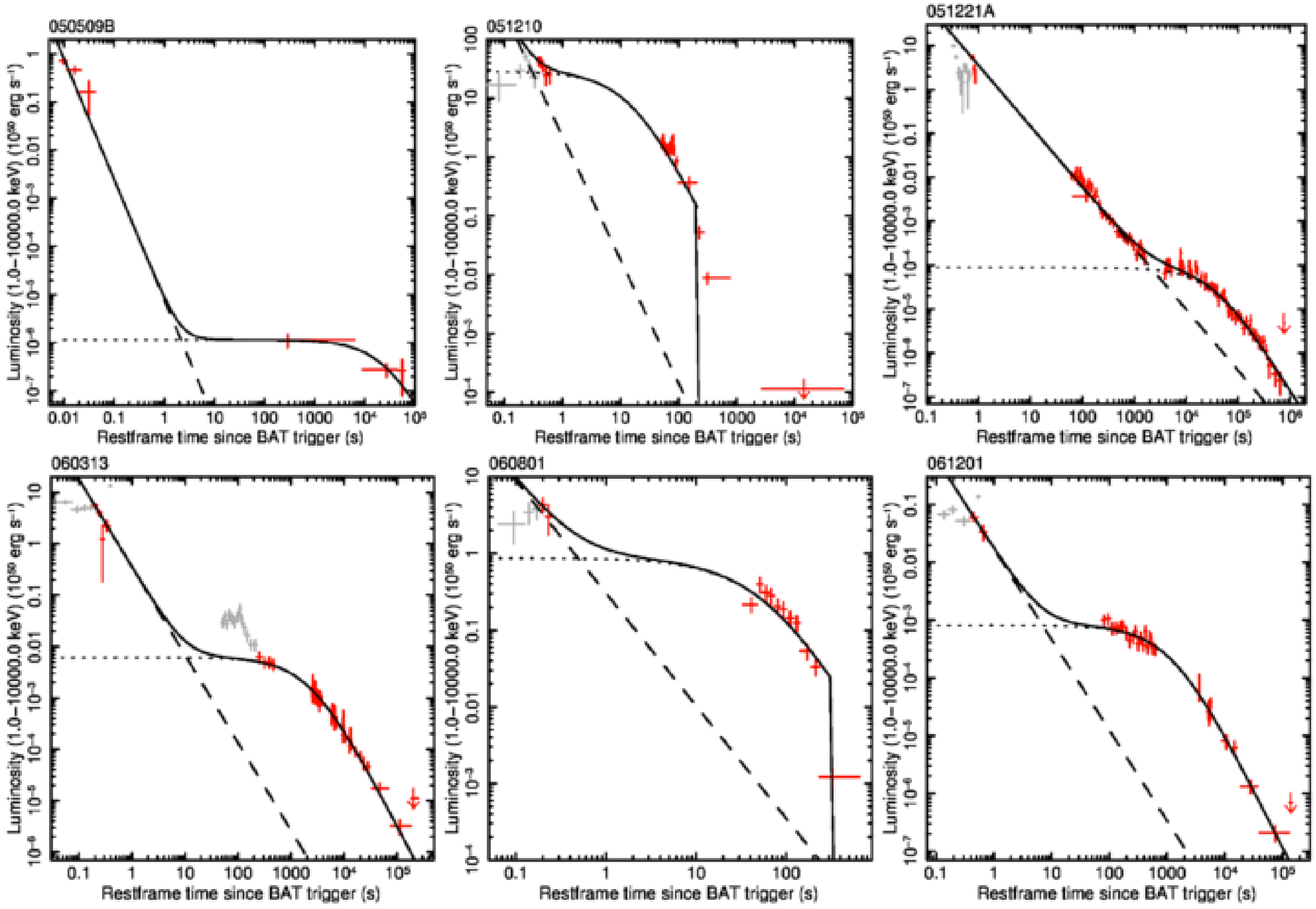
Necessary to have a magnetically dominated funnel to launch a jet (Ruiz et al 2016).

What about the blue path?



Piro, Giacomazzo & Perna 2017





Rowlinson et al 2013

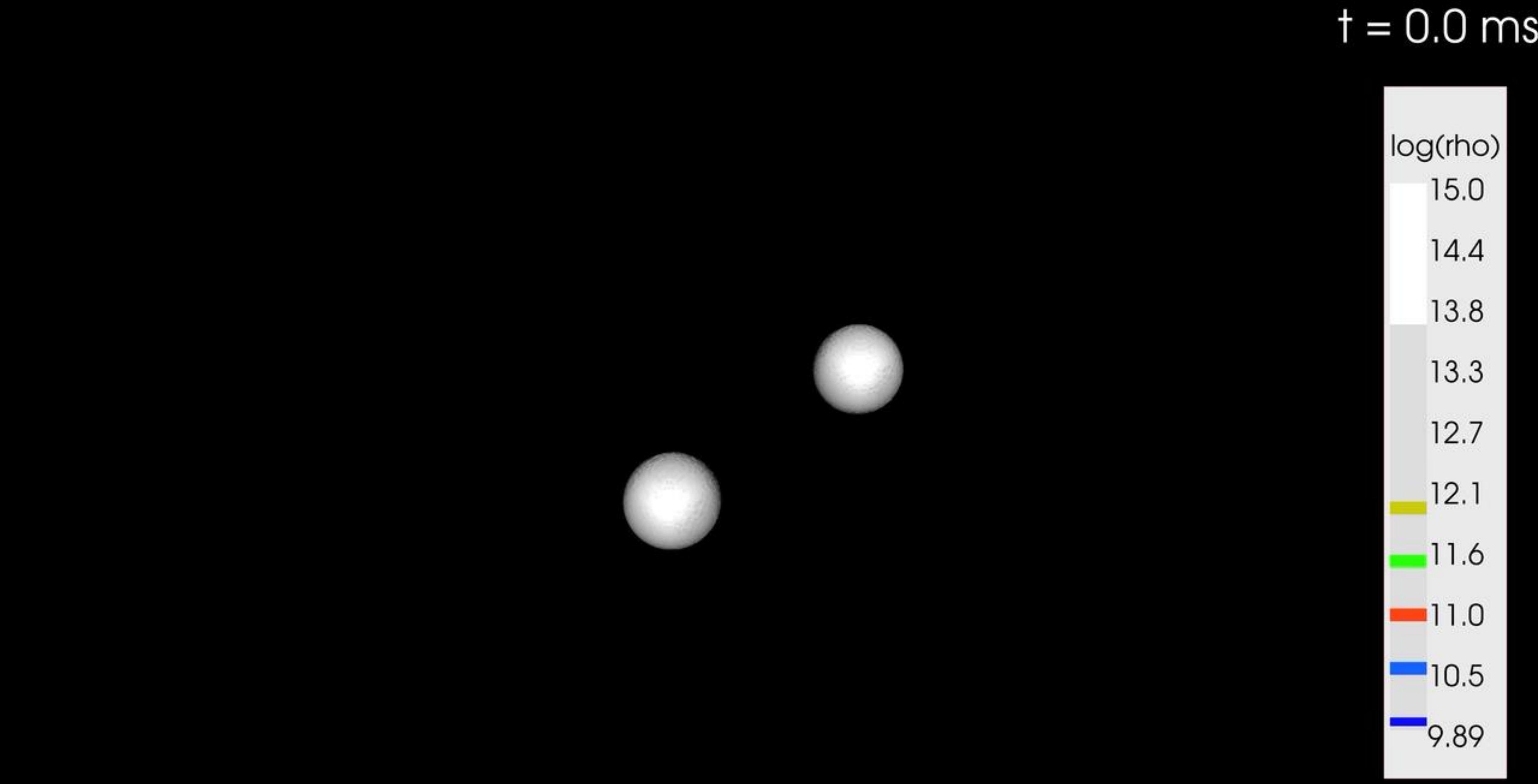
Long-lived NS remnants may form from BNS mergers.

A long-lived magnetar could also explain X-ray plateaus and extended emissions from SGRBs.

GRMHD Simulations of BNS Mergers Forming a Long-lived Neutron Star

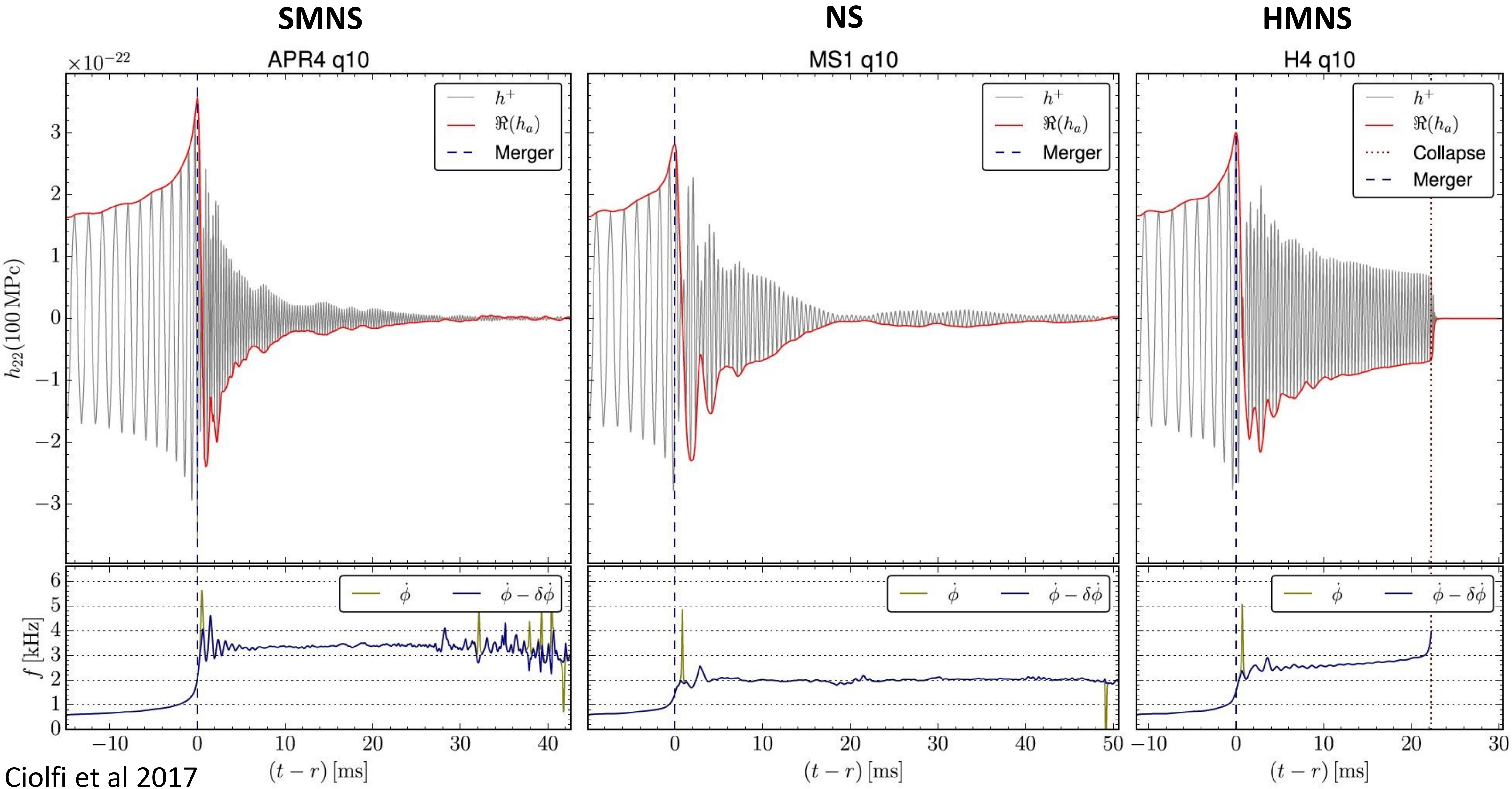
R. Ciolfi, W. Kastaun, **B. Giacomazzo**, A. Endrizzi, D. M. Siegel, R. Perna 2017, PRD 95, 063016

- Set of Simulations investigating "Low-Mass" BNSs
- Considered 6 BNS systems:
  - 2 different mass ratios
  - 3 equations of state (APR4, MS1, H4) with a thermal component (1.8 gamma law)
- All models have the same total gravitational mass at infinity (2.7 $M_\odot$) and the same magnetic energy (initial magnetic field ~10^{15}G)
- 4 models produce a long-lived NS and 2 a HMNS that collapses to BH



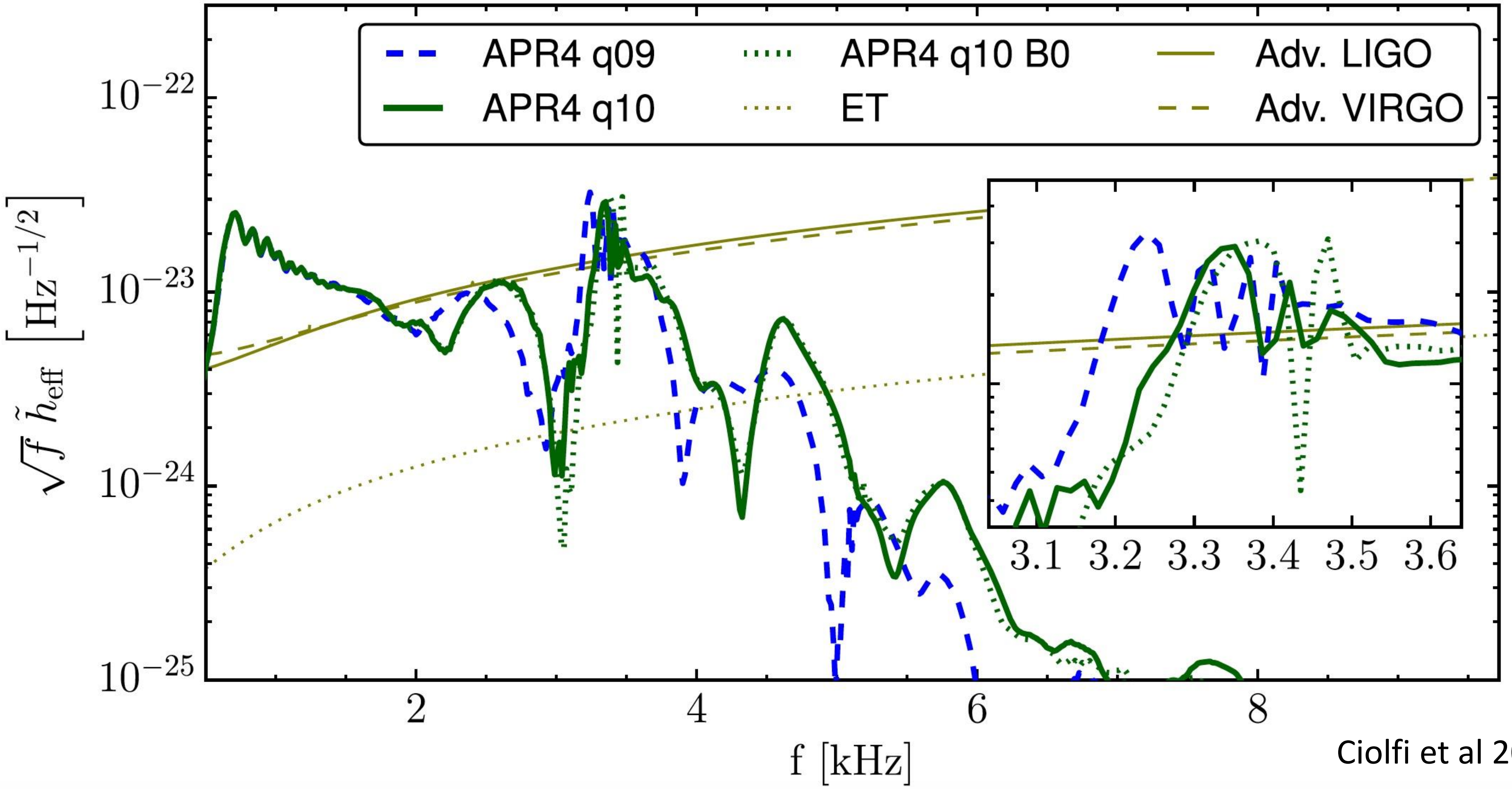
https://youtu.be/00n8uen5xwk

GRAVITATIONAL WAVES



Ciolfi et al 2017

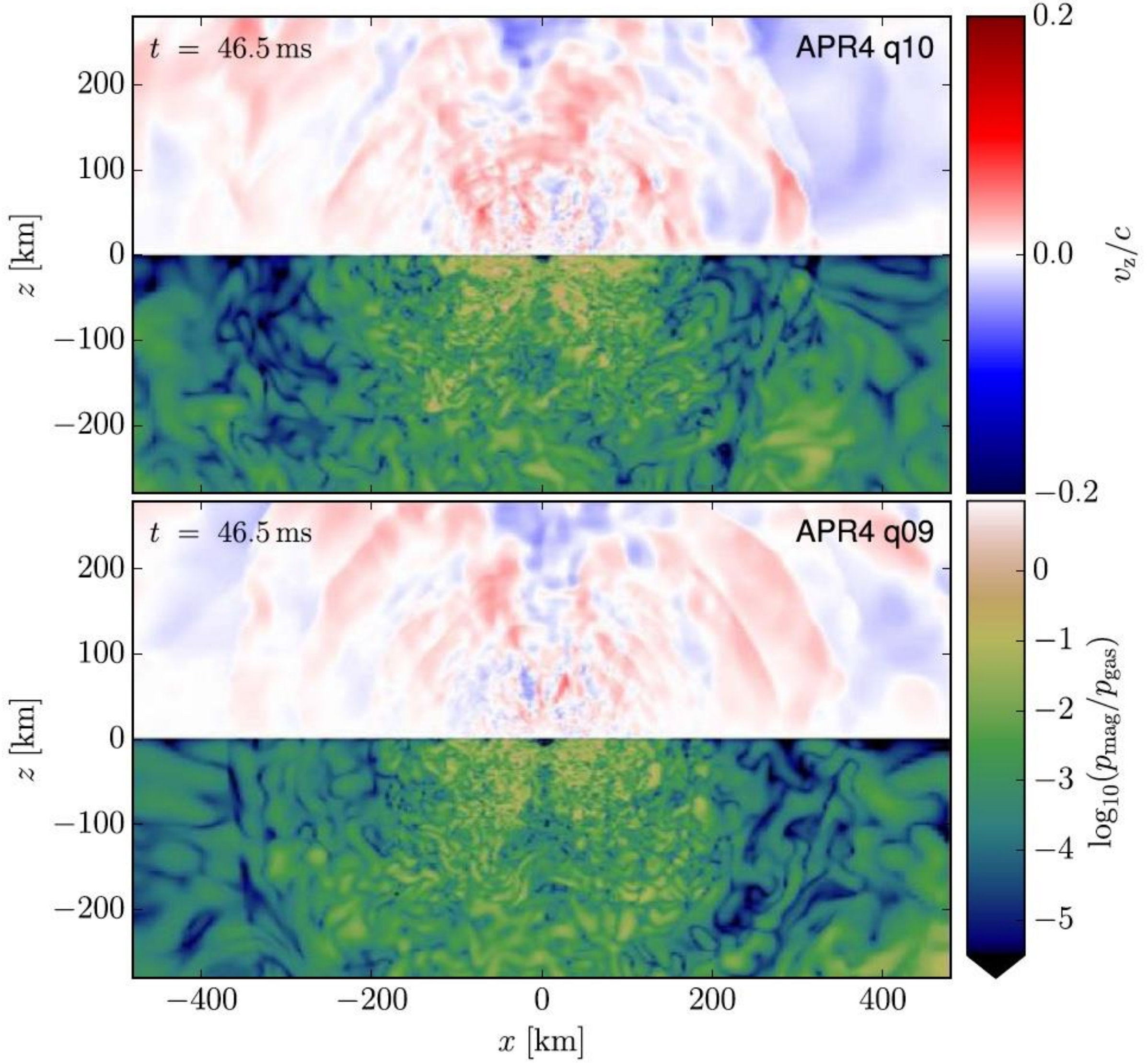
Magnetic Field Effects on Post-Merger GW Emission

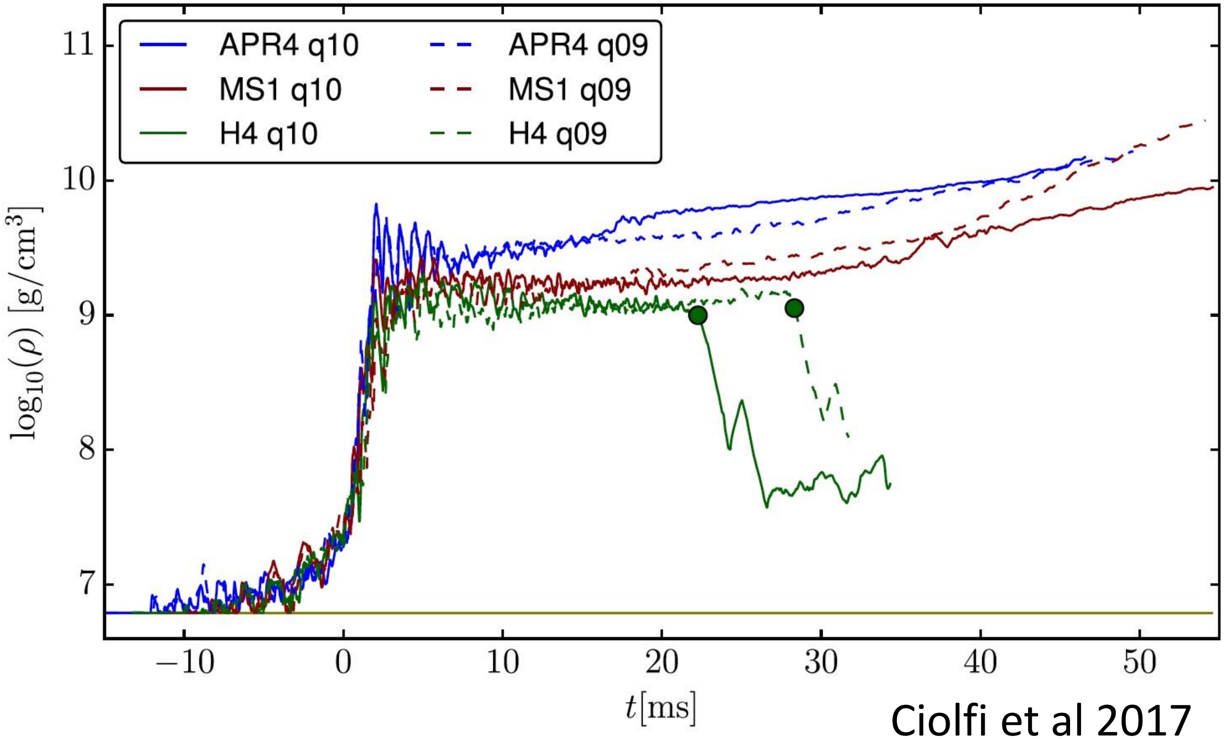


Ciolfi et al 2017

Evolved "low-mass" BNS with high magnetic fields (~10^{15} G during inspiral, ~10^{16} G after merger). Negligible differences in the post-merger peak.

SHORT- OR LONG-LIVED REMNANT?



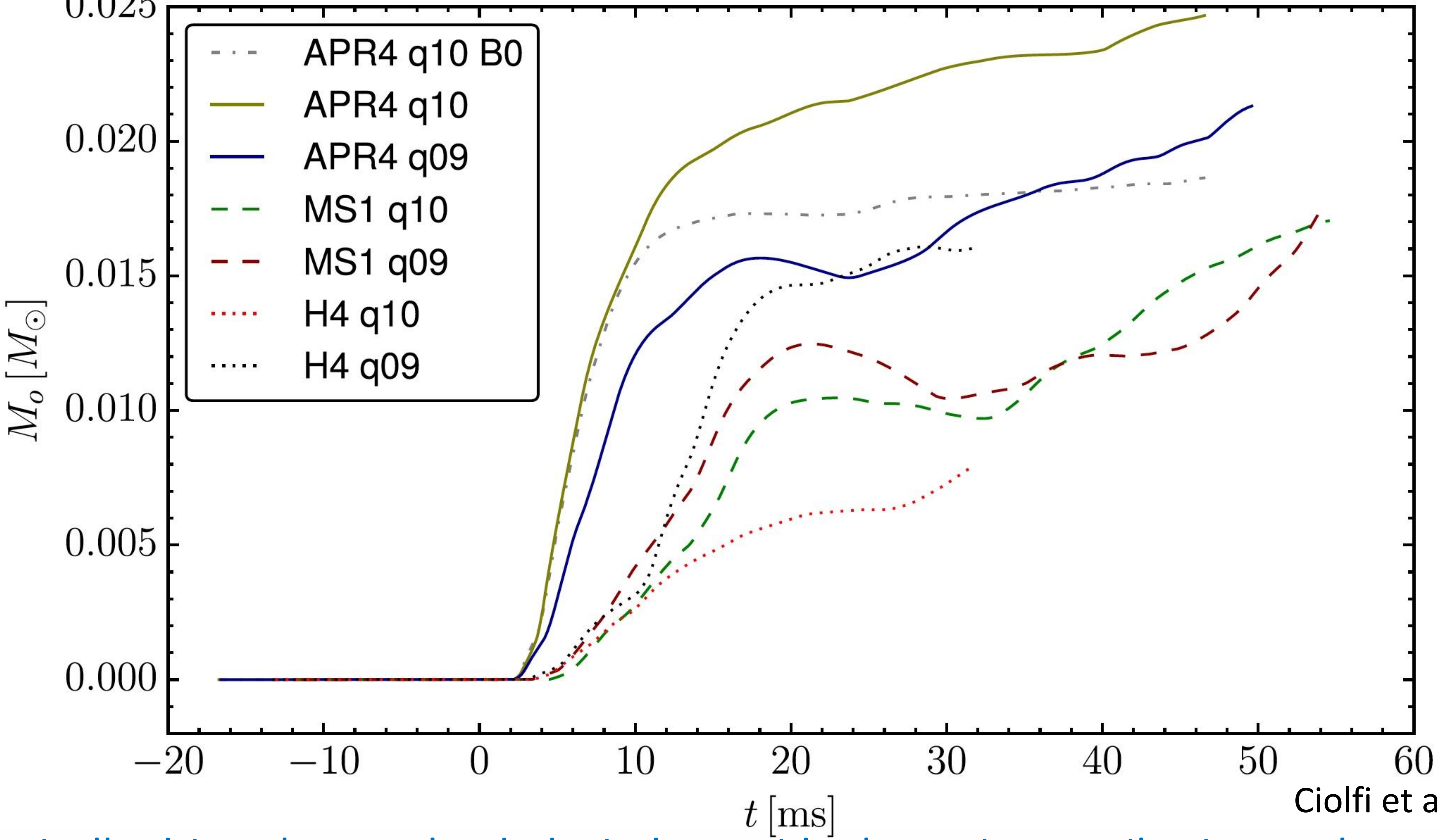


Ciolfi et al 2017

No magnetically dominated funnel.

Baryon pollution problem when a (long-lived) NS is formed instead of a BH.

TOTAL EJECTA



Ciolfi et al 2017

Magnetically-driven baryon-loaded winds provide the main contribution to the steady matter outflows observed towards the end of our simulations (see also Ciolfi et al 2019).

The Spritz Code

https://zenodo.org/record/4350072

1. Cipolletta, Kalinani, **Giacomazzo**, Ciolfi 2020, CQG 37, 135010
2. Cipolletta, Kalinani, Giangrandi, **Giacomazzo**, Ciolfi, Sala, Giudici 2021, CQG 38, 085021

- A new GRMHD code based on WhiskyMHD and on the Einstein Toolkit
- Vector potential formulation with **staggered** vector potential
- Support for several EOSs, including tabulated ones, via EOS_Omni
- It can be used with ZelmaniLeak for neutrino transport
- Tested with several 1D, 2D, and 3D tests

Equations

Einstein Equations

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

Hydro Equations

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu J^\mu = 0$$

$$P = P(\rho, \epsilon)$$

$$J^\mu = \rho u^\mu$$

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

Maxwell Equations

$$\nabla_\nu {}^*F^{\mu\nu} = 0$$

GRMHD equations

The system of equations is written in a conservative form (Valencia formulation, Anton et al 2006):

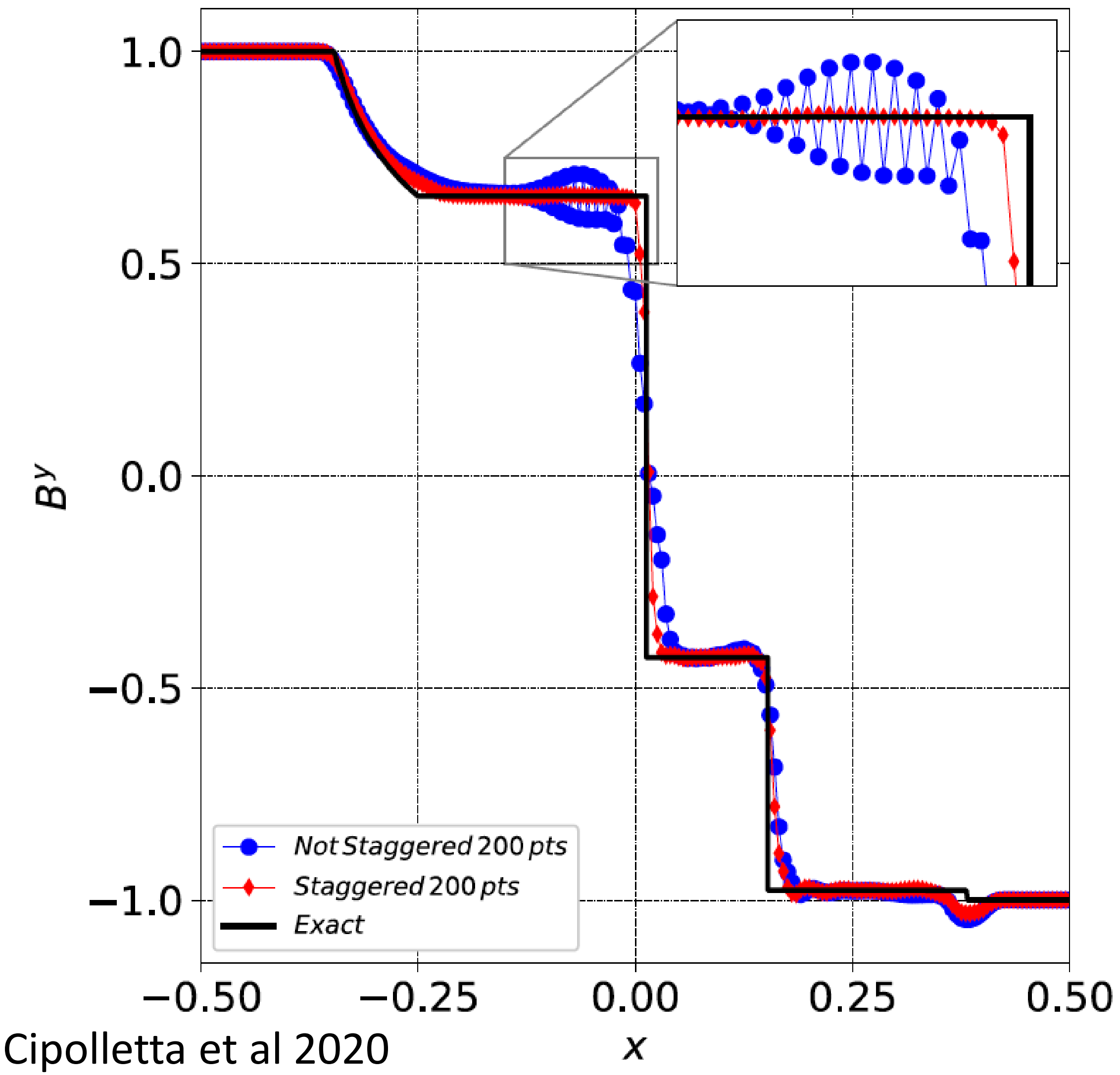
$$\left.\begin{array}{rcl}\nabla_\mu(\rho u^\mu) & = & 0 \\ \nabla_\mu T^{\mu\nu} & = & 0\end{array}\right\} \Rightarrow \frac{1}{\sqrt{-g}}\left(\frac{\partial\sqrt{\gamma}\mathbf{U}}{\partial t} + \frac{\partial\sqrt{-g}\mathbf{F}^i}{\partial x^i}\right) = \mathbf{S}$$

where **U** is the vector of conserved variables, $\mathbf{F^i}$ the fluxes, and **S** the source terms. They can then be solved using HRSC methods using approximate Riemann solvers. The vector potential is evolved (to guarantee $\nabla \cdot B = 0$) using the generalized Lorenz gauge $\nabla_\nu A^\nu = \xi n_\nu A^\nu$:

$$\partial_t A_i = -E_i - \partial_i\left(\alpha\Phi - \beta^j A_j\right)$$

$$\partial_t(\sqrt{\gamma}\Phi) = -\partial_i\left(\alpha\sqrt{\gamma}A^i - \sqrt{\gamma}\beta^i\Phi\right) - \xi\alpha\sqrt{\gamma}\Phi$$

Why a Staggered Vector Potential?



Cipolletta et al 2020

As mentioned in Giacomazzo et al 2011, the centered vector potential formulation may generate oscillations across shocks.

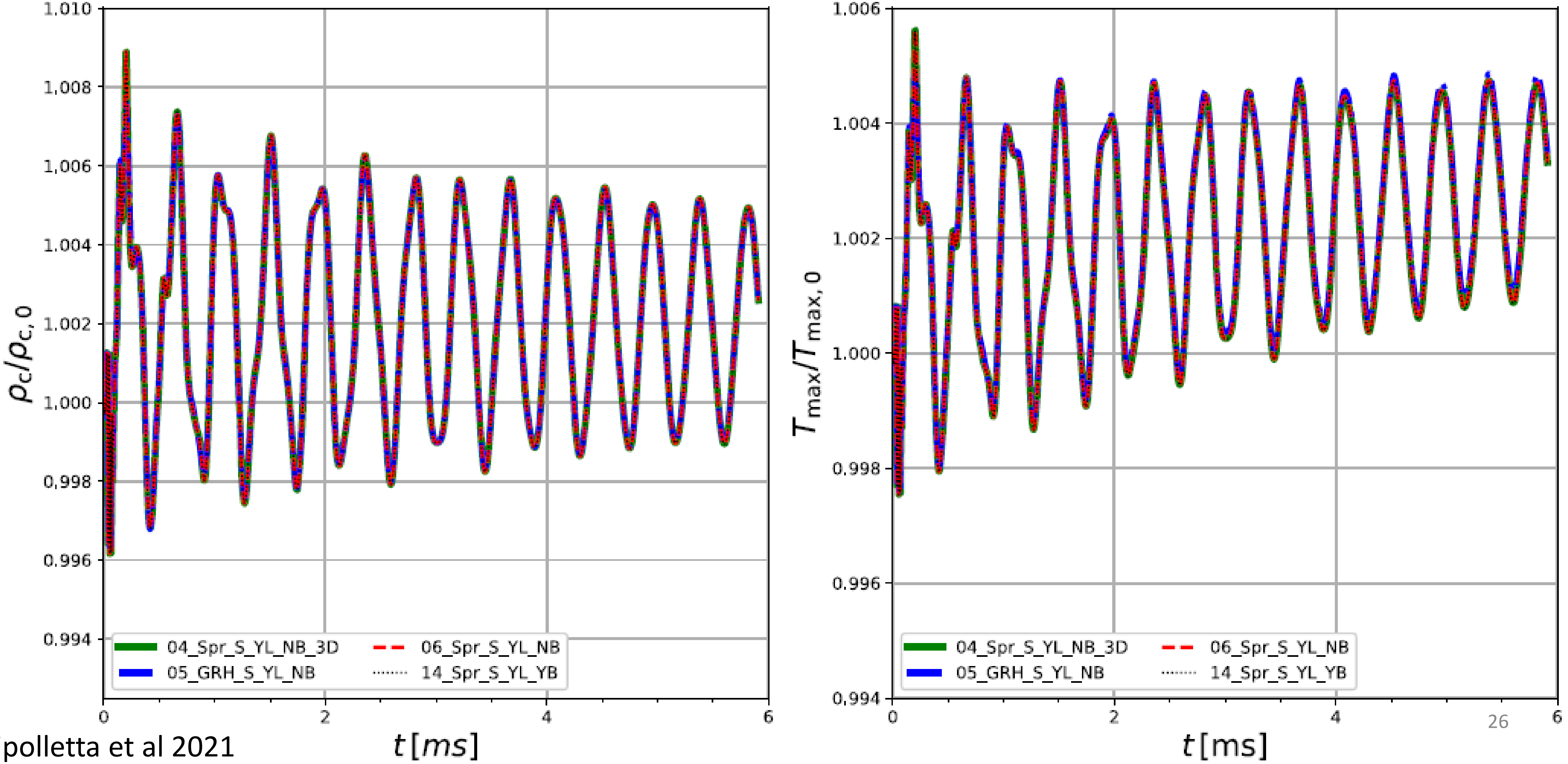
Staggered vector potential does not present this problem.

Staggered vector potential is also identical to the original flux-CT approach of WhiskyMHD (but it works with AMR).

Neutrinos

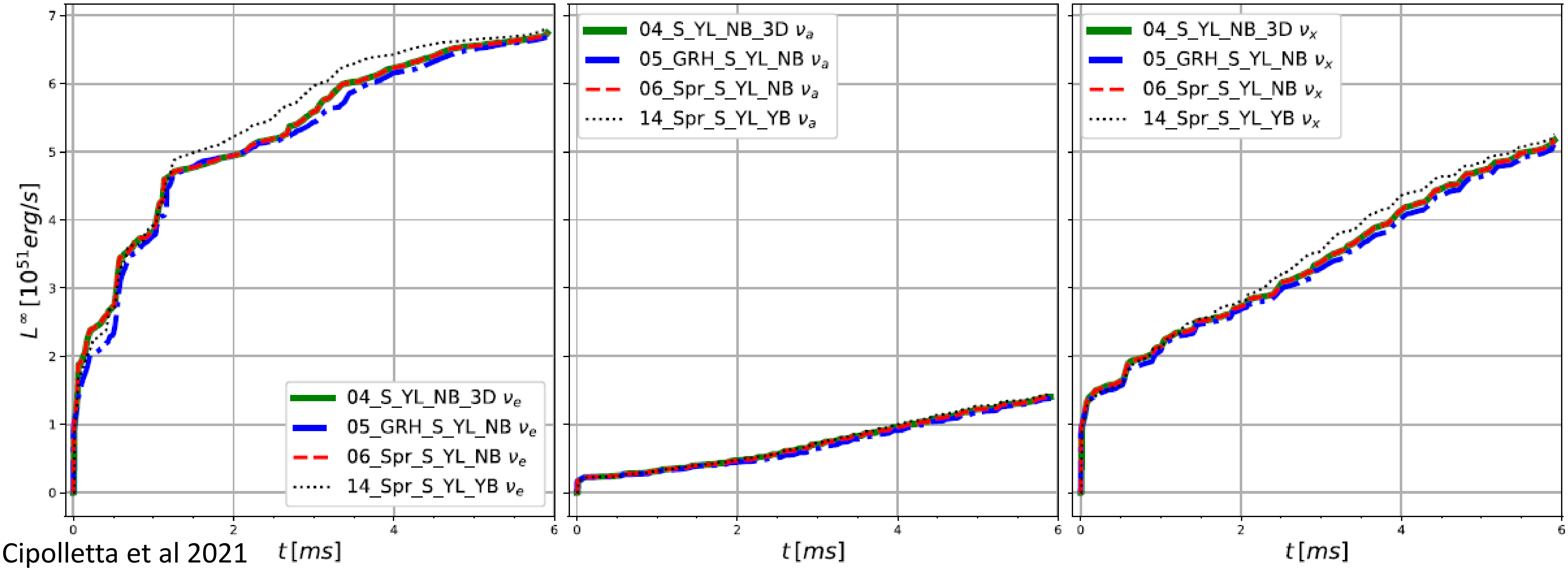
- Spritz uses the ZelmaniLeak code (O'Connor & Ott 2010 and Ott et al 2012): https://stellarcollapse.org/Zelmani
- It implements a leakage scheme with a gray approximation and 3 neutrino species: $\nu_e, \overline{\nu_e}, \nu_x$
- It adds an evolution equation for the electron fraction
- In this case Spritz uses the Con2Prim scheme by Palenzuela et al 2015
- Initial Data are built with LORENE using constant T or S EOS slices and assuming beta equilibrium (using the CompOSE format, https://compose.obspm.fr/)

Tests with neutrino emission



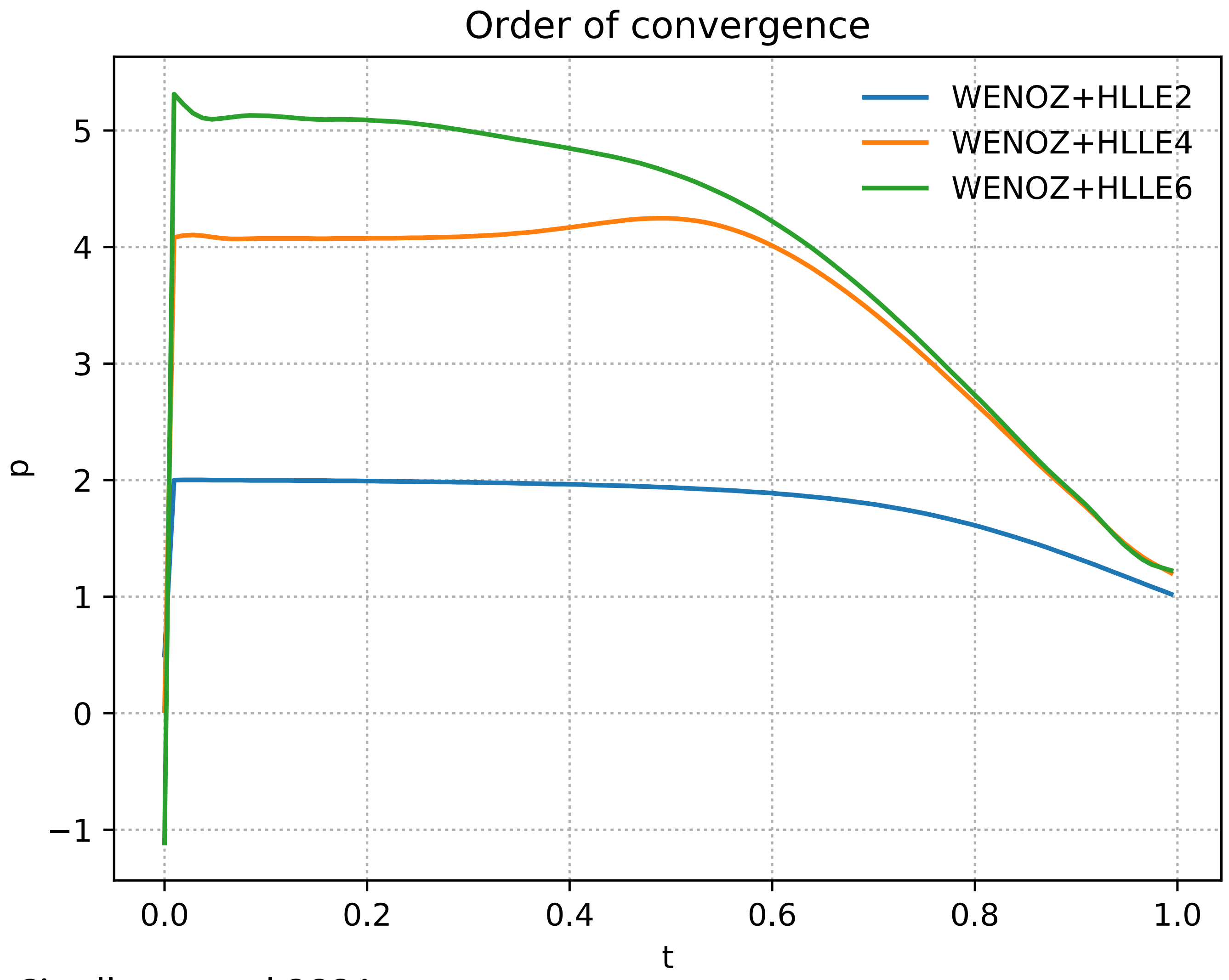
Cipolletta et al 2021

Tests with neutrino emission



Cipolletta et al 2021

WENO-Z 5th order method



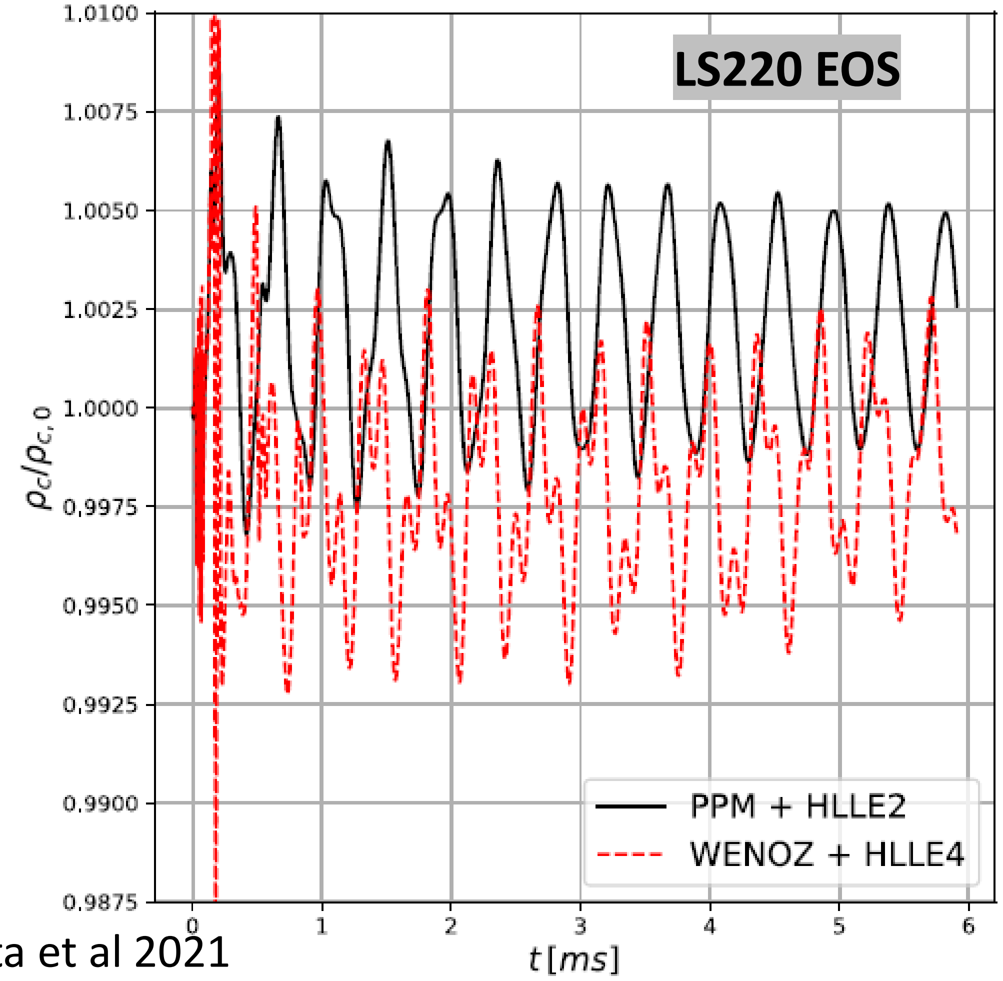
Cipolletta et al 2021

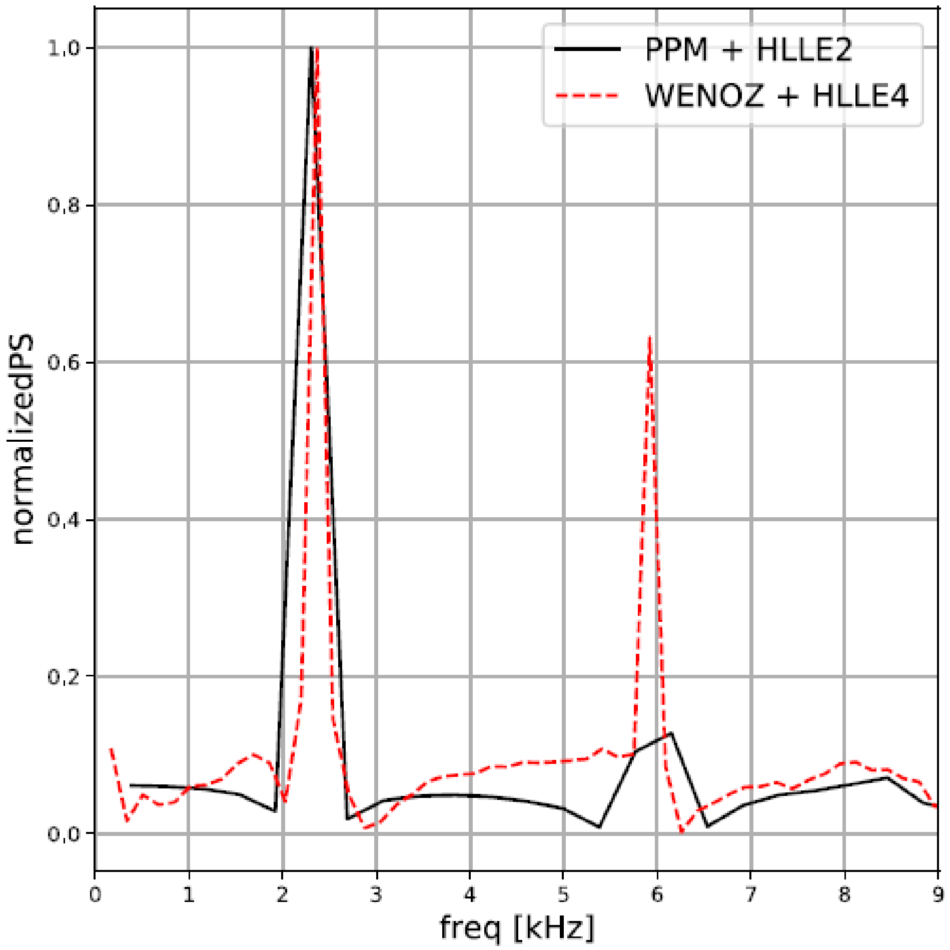
WENO-Z is considered one of the best schemes for BNS simulations (Bernuzzi & Dietrich 2016).

We coupled it with a high-order finite-difference scheme to compute the fluxes (see Most et al 2019, Del Zanna et al 2007).

5-th order convergence recovered for smooth solutions.

WENO-Z 5th order method (TOV test)





Cipolletta et al 2021

The higher order method allows also for a better description of NS oscillations, and it may also be useful in the post-merger evolution of a BNS system.

CONCLUSIONS

- Magnetic fields can play an important role in BNS mergers:
  - **Short GRBs** (launch and collimation of relativistic jets)
  - **Ejected matter** (kilonova and heavy element production)

- Magnetic field effects on GWs seem minimal, but discussion still going on in the community

- For a full description of BNS dynamics it is crucial to account also for temperature effects and neutrino emission

- We therefore developed a new publicly available code (Spritz), that can evolve magnetized NSs with finite temperature equations of state and neutrino emission

- We are currently running BNS simulations with the Spritz code (stay tuned)

Gravitational waves and initial data are available as supplemental material in our papers

Some Advertisement

- Einstein Toolkit online School and Workshop this Summer (possibly July 26 – 30): http://einsteintoolkit.org/

- Rosalba Perna and I edited a special research topic issue on GWs. It is open access and an ebook version should also be released soon: https://www.frontiersin.org/research-topics/11345/gravitational-waves-a-new-window-to-the-universe