# From Whisky to Spritz: Simulating Magnetized Binary Neutron Star Mergers

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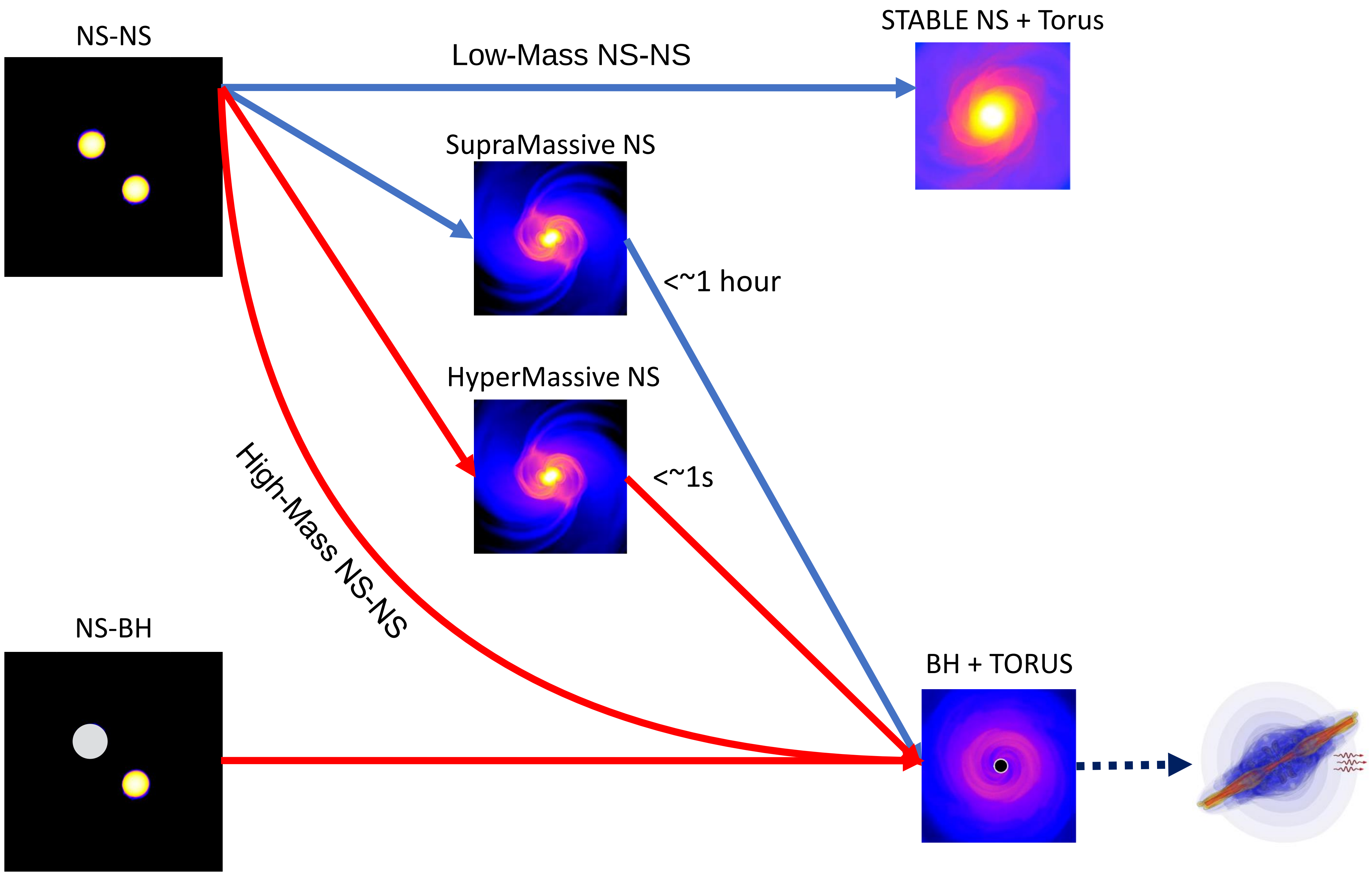
# Neutron Star Binary Mergers



# 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

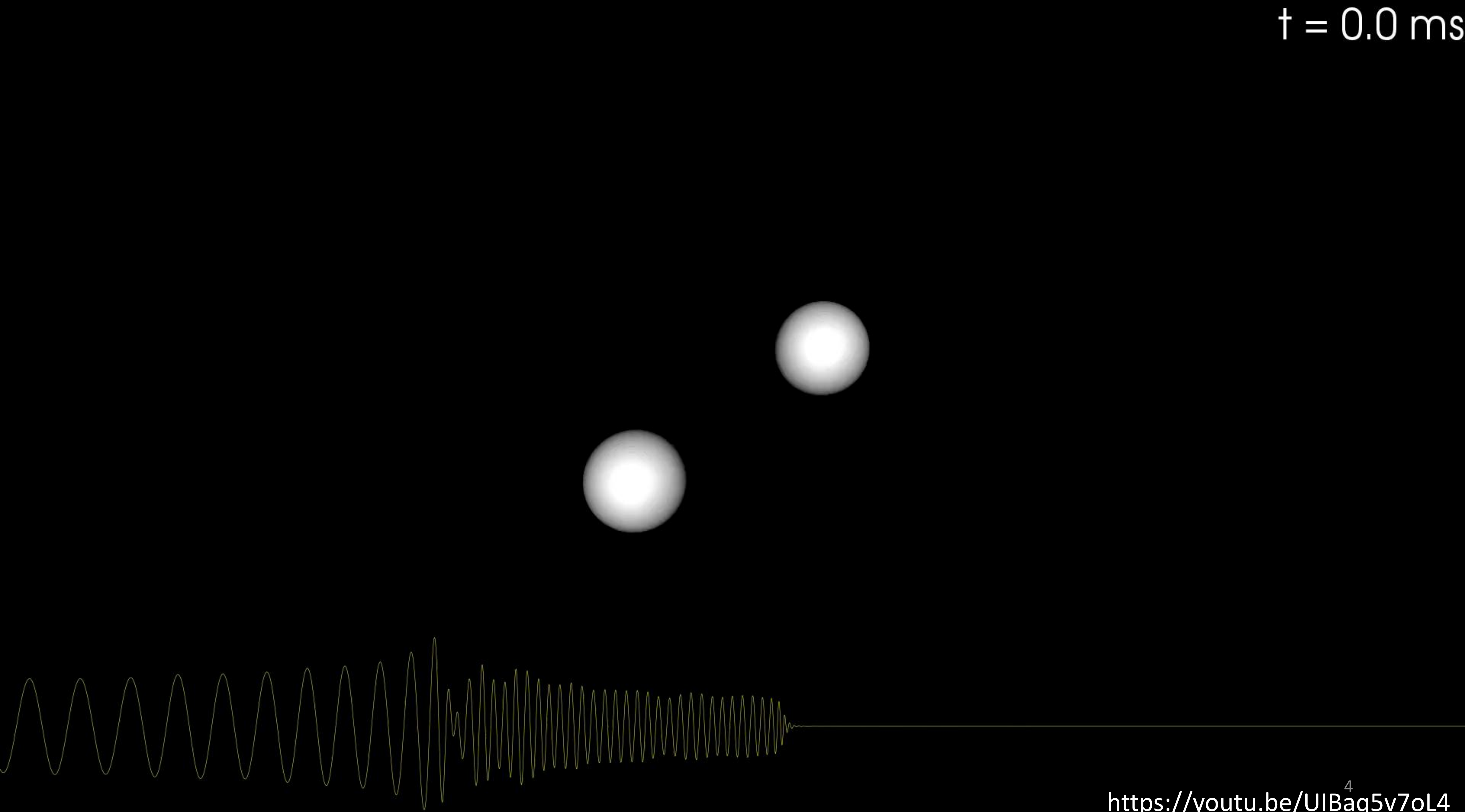
GRMHD simulations of 6 “high-mass” BNSs:

- 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**.

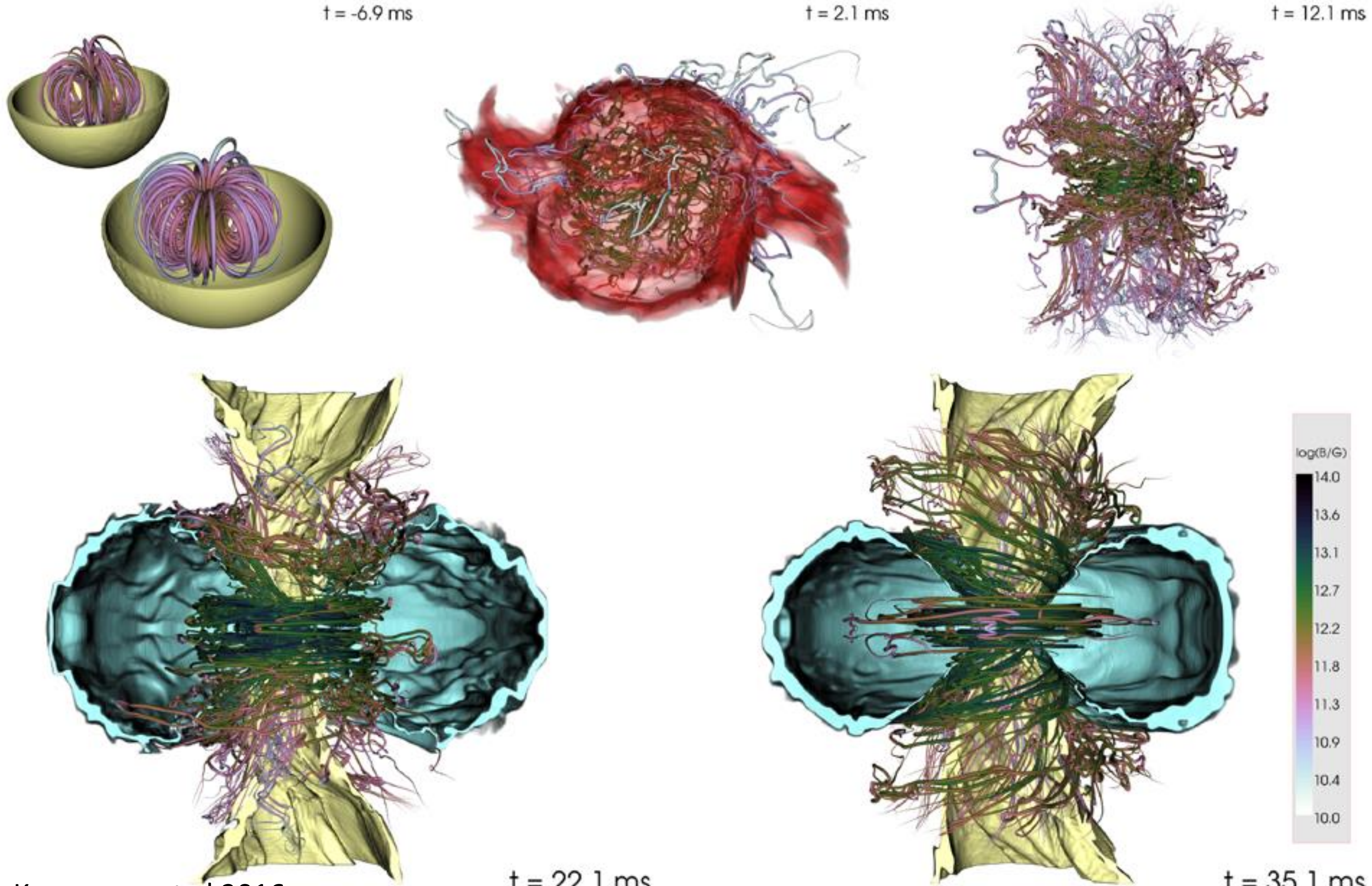
Unequal-mass models studied here for the first time.

All simulation performed with WhiskyMHD + EinsteinToolkit.

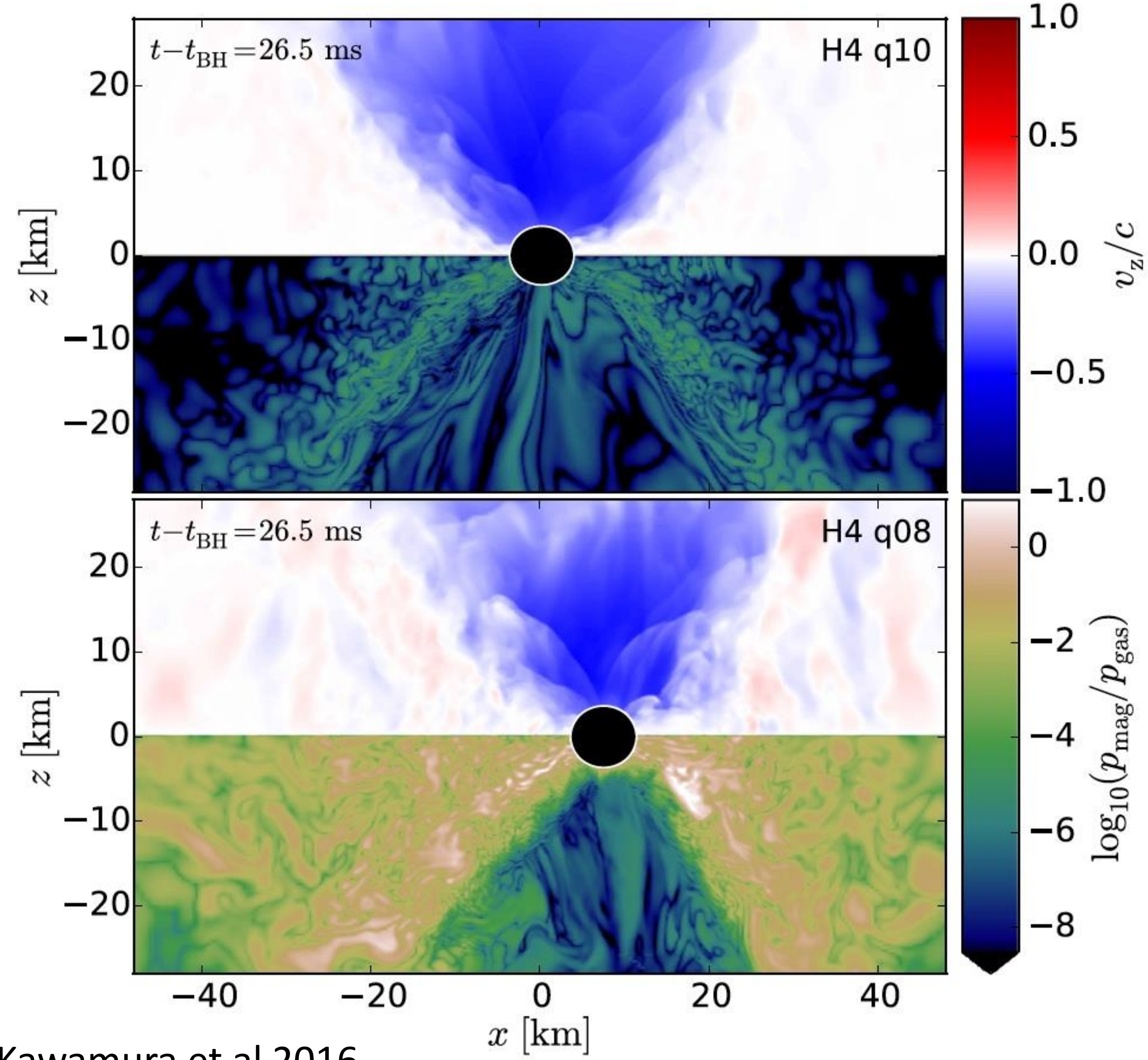



https://youtu.be/UIBaq5v7oL4

# Magnetic Field Structure Evolution




Kawamura et al 2016

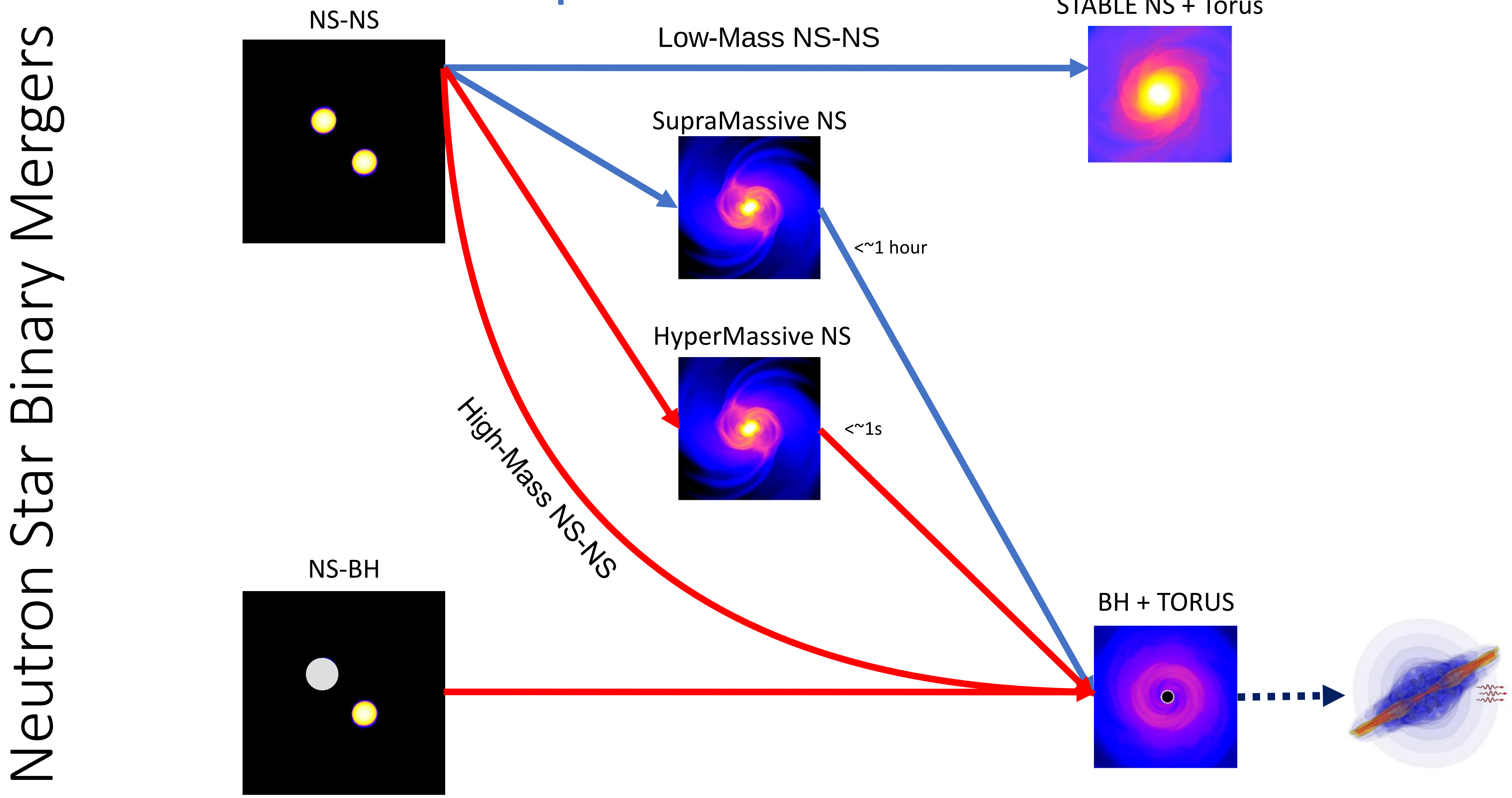



Kawamura et al 2016

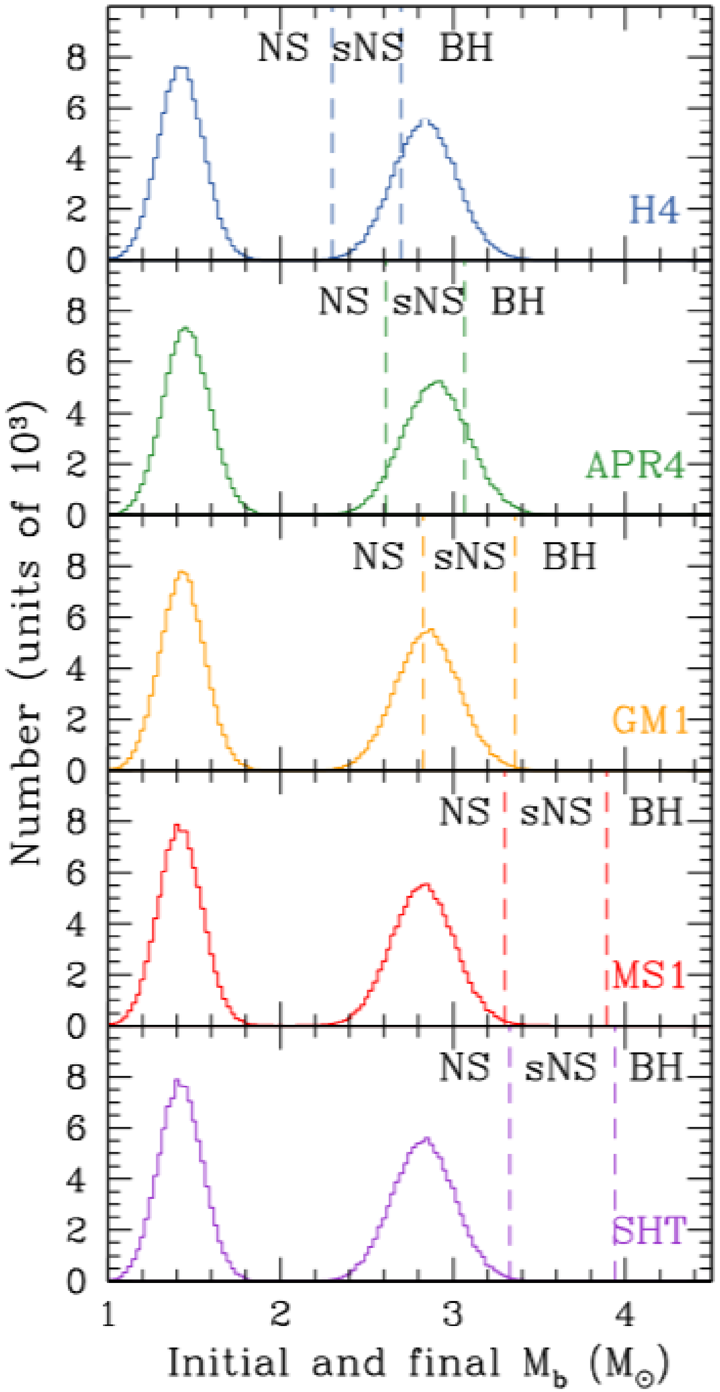
No Jet observed, but it may change with longer evolutions and much higher resolutions (e.g., Kiuchi et al 2015) or by using a subgrid model (e.g., Giacomazzo et al 2015).

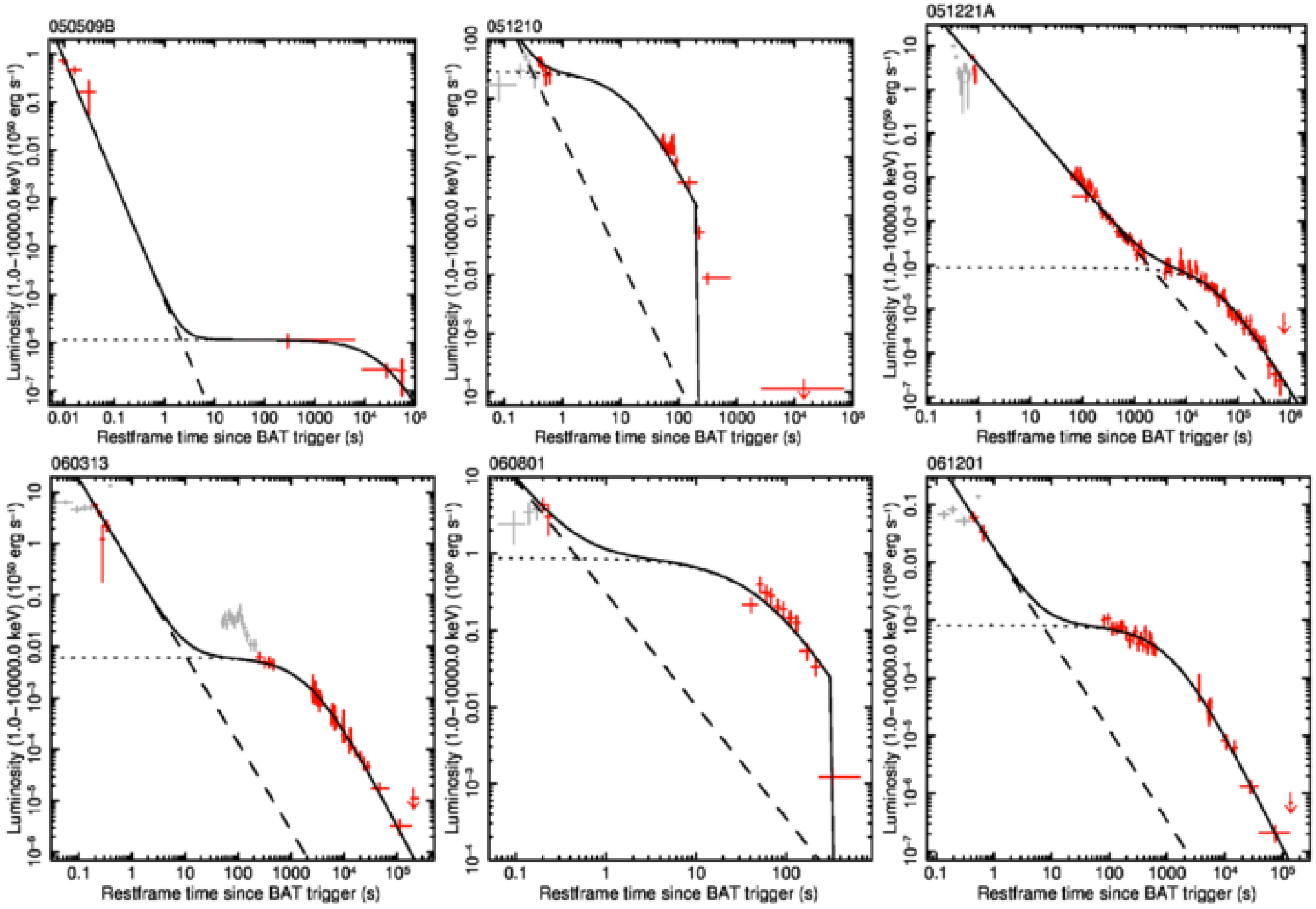
Necessary to have a magnetically dominated funnel to launch a jet (Ruiz et al 2016).

# What about the blue path?



Piro. Giacomazzo & Perna 2017




Rowlinson et al 2013

Long-lived NS remnants may form from BNS mergers.

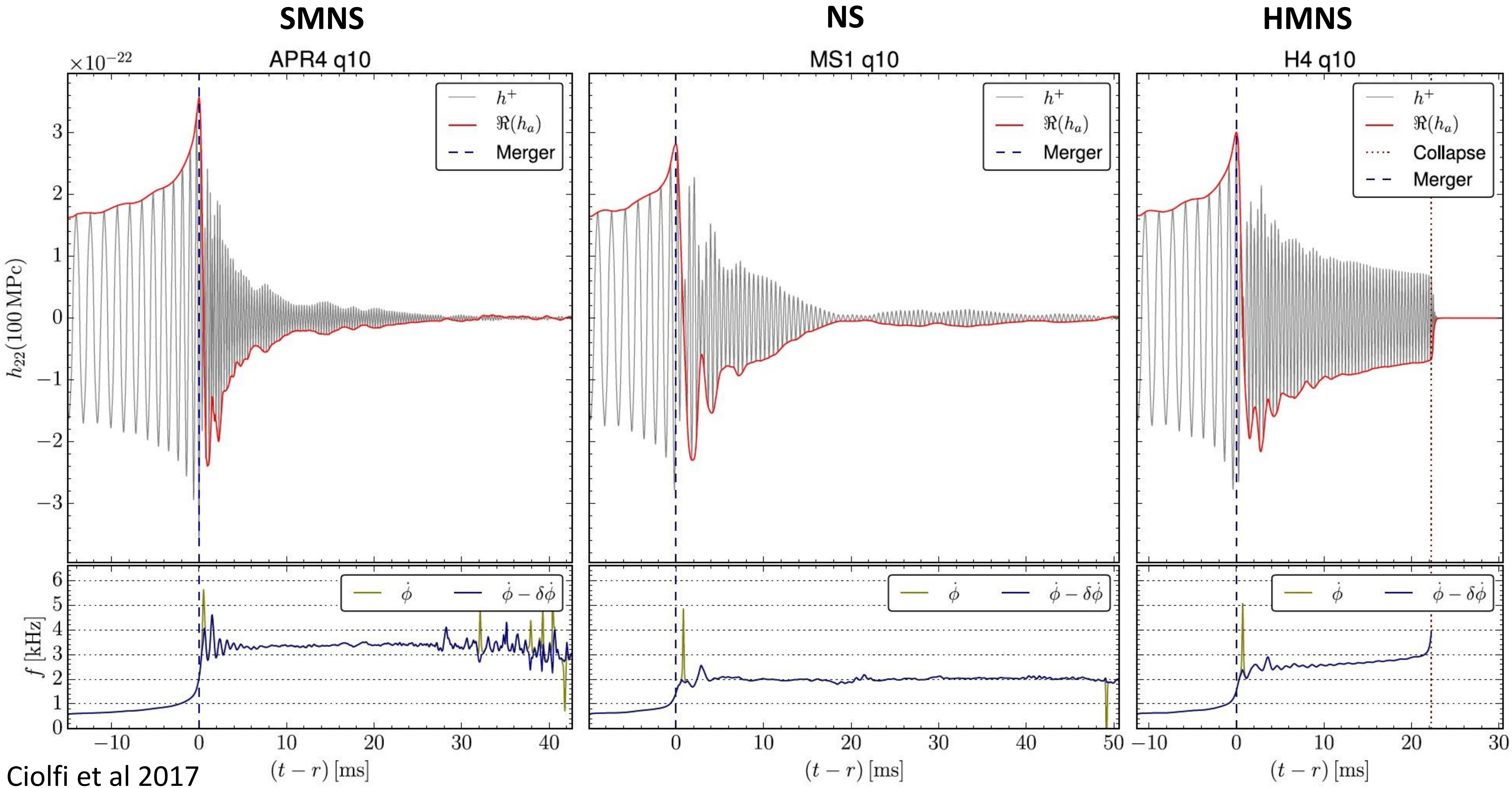
A long-lived magnetar could also explain X-ray plateaus and extended emissions from SGRBs.

# 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

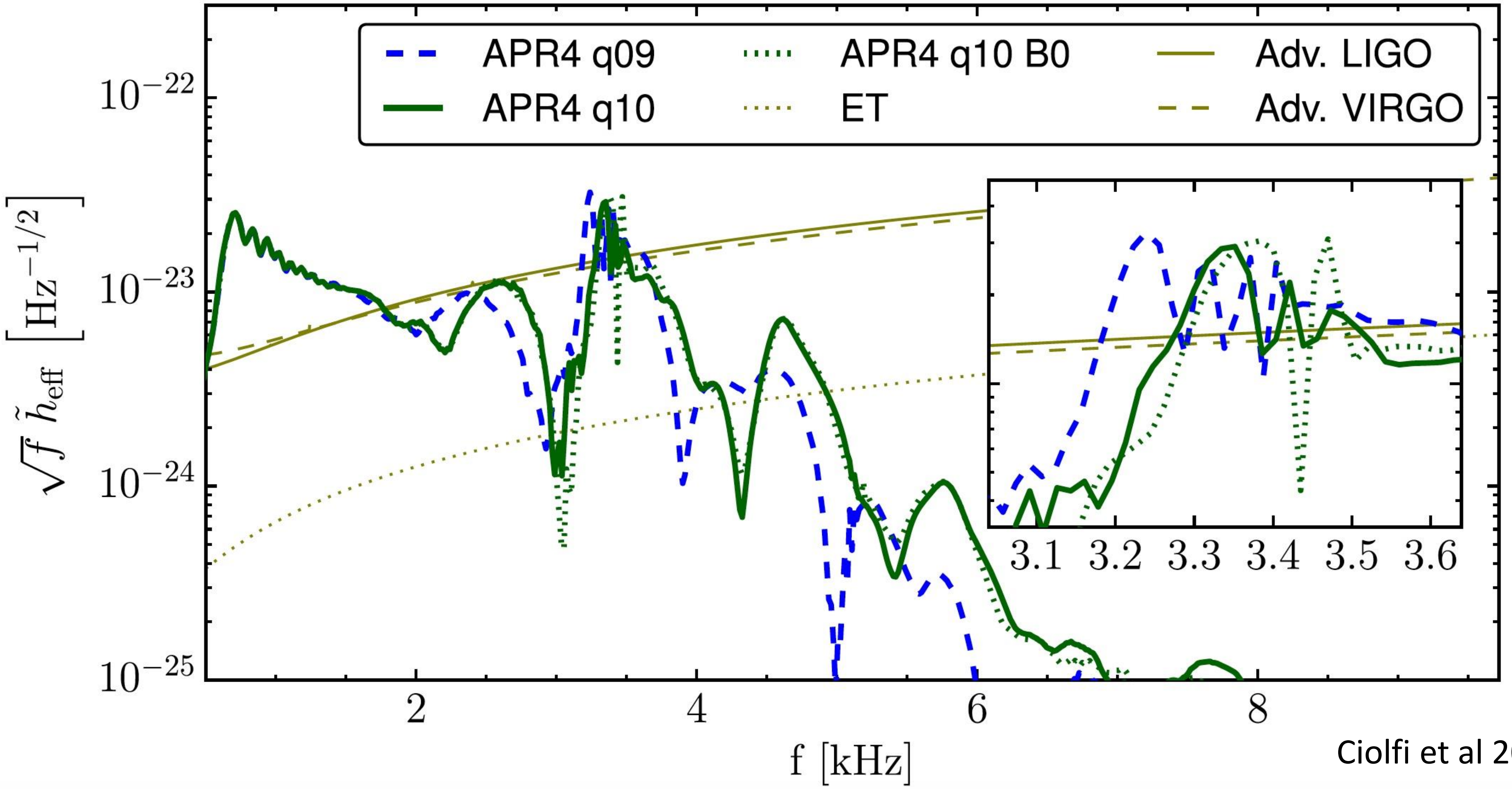
- Set of Simulations investigating "Low-Mass" BNSs
- Considered 6 BNS systems:
  - 2 different mass ratios
  - 3 equations of state (APR4, MS1, H4) with a thermal component (1.8 gamma law)
- All models have the same total gravitational mass at infinity (2.7 $M_{\odot}$) and the same magnetic energy (initial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

# GRAVITATIONAL WAVES




Ciolfi et al 2017

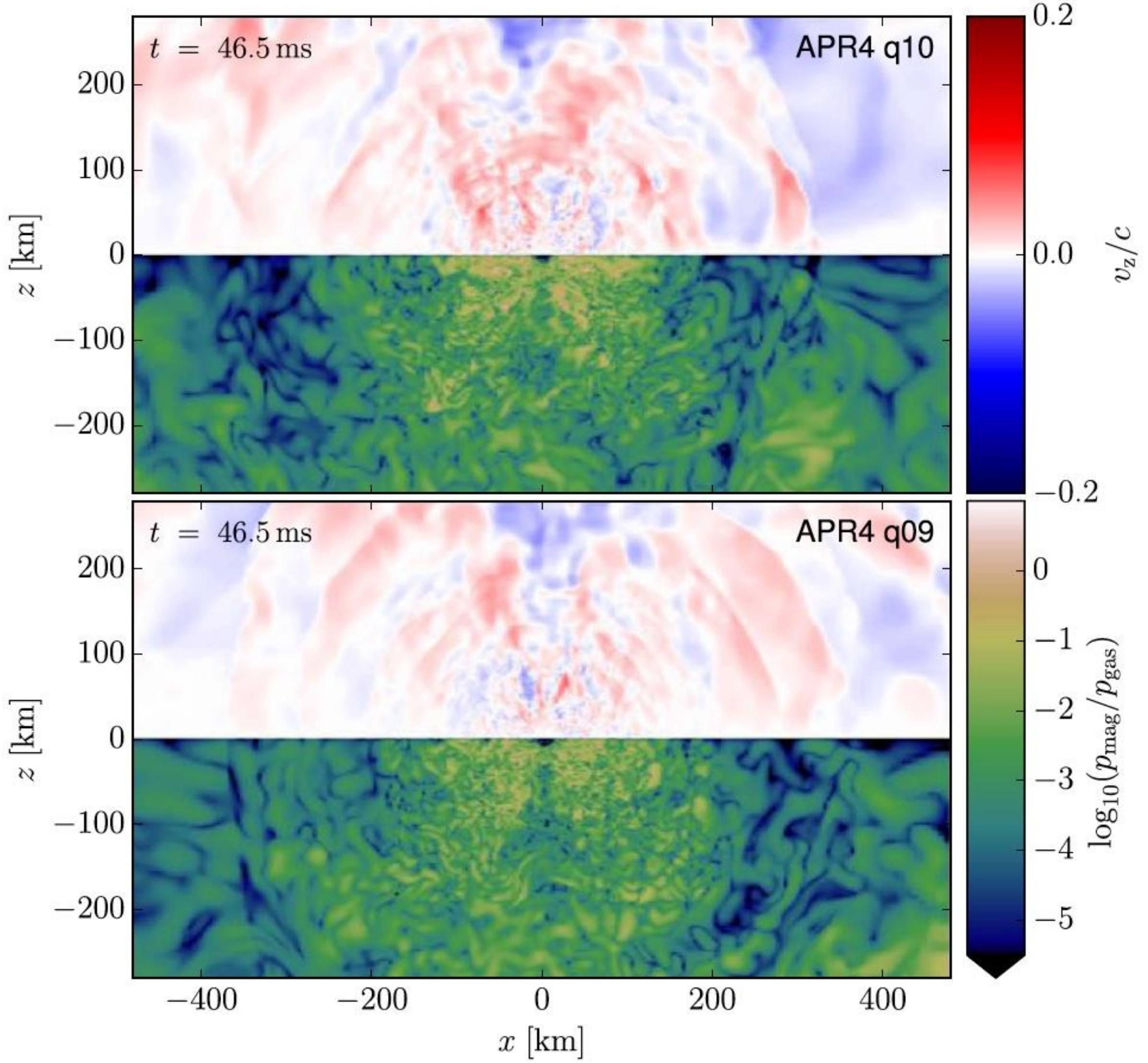
# Magnetic Field Effects on Post-Merger GW Emission

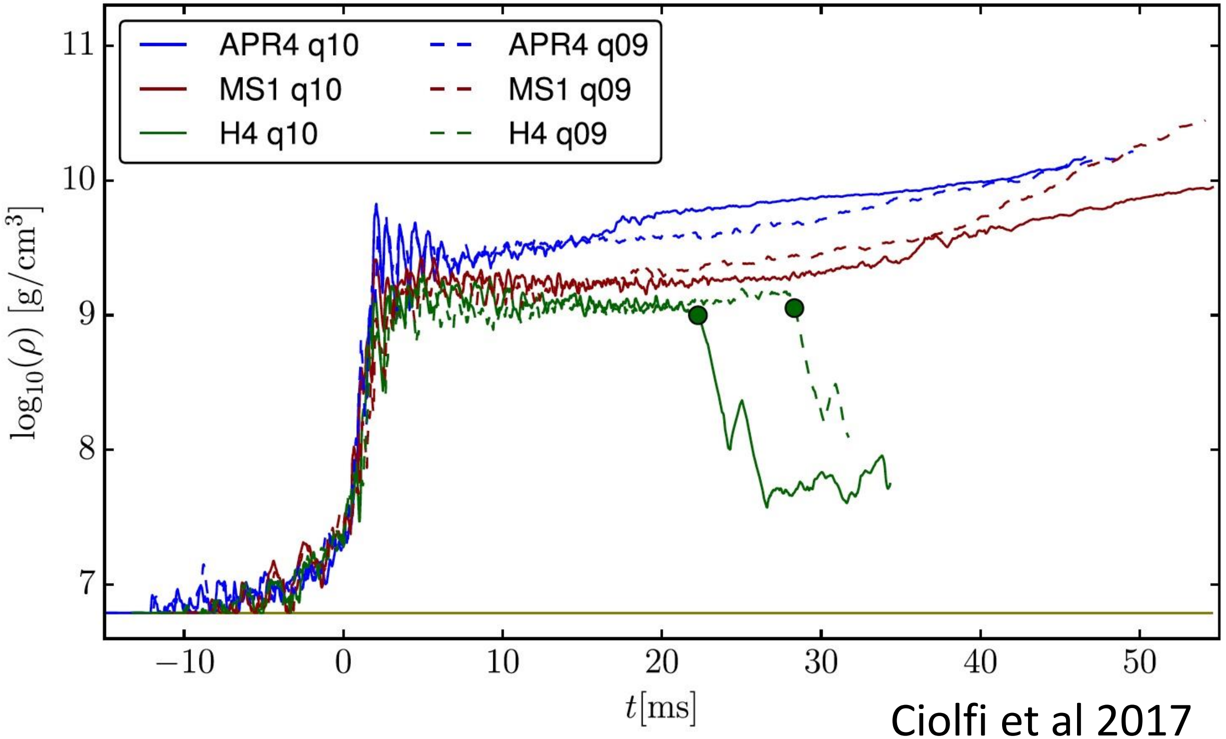



Ciolfi et al 2017

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?

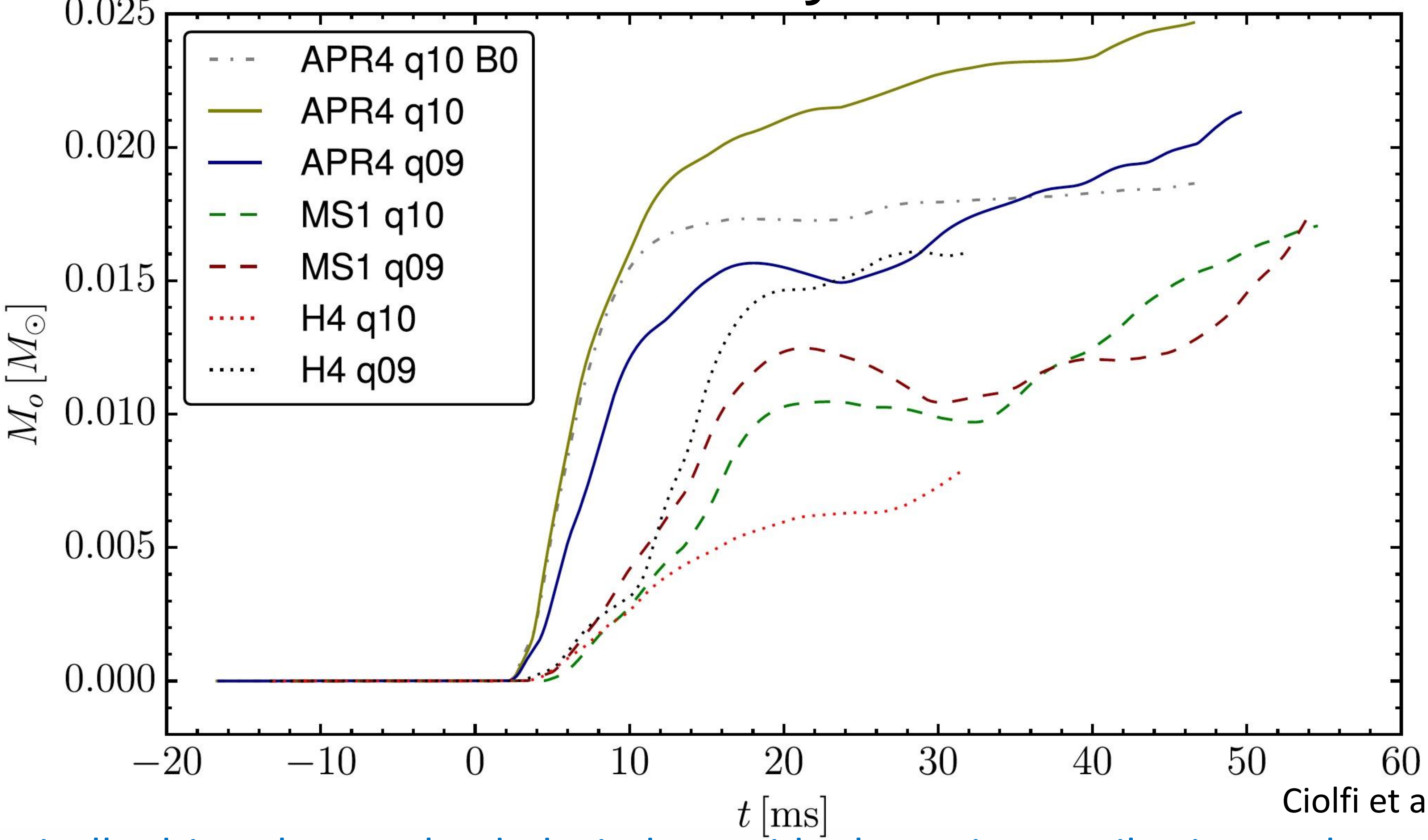



Ciolfi et al 2017

No magnetically dominated funnel.
Baryon pollution problem when a (long-lived) NS is formed instead of a BH (see also Ciolfi et al 2019 and Ciolfi 2020).

# 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

Cipolletta, Kalinani, **Giacomazzo***, Ciolfi 2020, CQG 37, 135010

Cipolletta, Kalinani, **Giangrandi, Giacomazzo***, Ciolfi, **Sala, Giudici** 2021, CQG 38, 085021

BNS sims require to account for magnetic fields, but also for EOS and neutrino emission. No public code was available that included all these effects.

We therefore developed a new General Relativistic GRMHD code named Spritz:

- Publicly available on Zenodo
- Based on the Einstein Toolkit Infrastructure
- Staggered vector potential formulation to evolve the magnetic field
- Support for several Equations Of State, including tabulated ones
- Neutrino transport via a leakage scheme with a grey approximation and 3 neutrino species: $\nu_e, \bar{\nu}_e, \nu_x$
- 5-th order WENO-Z scheme for hydro
- Currently used for NS-NS and NS-BH simulations

# 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 $\nabla_\nu A^\nu = \xi n_\nu A^\nu$ or the algebraic gauge $\Phi = \frac{1}{\alpha}\beta^j A_j$:

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

# 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/)

# 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 (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 is also available: https://www.frontiersin.org/research-topics/11345/gravitational-waves-a-new-window-to-the-universe