Binary Neutron Star Mergers: Numerical Simulations and Observations

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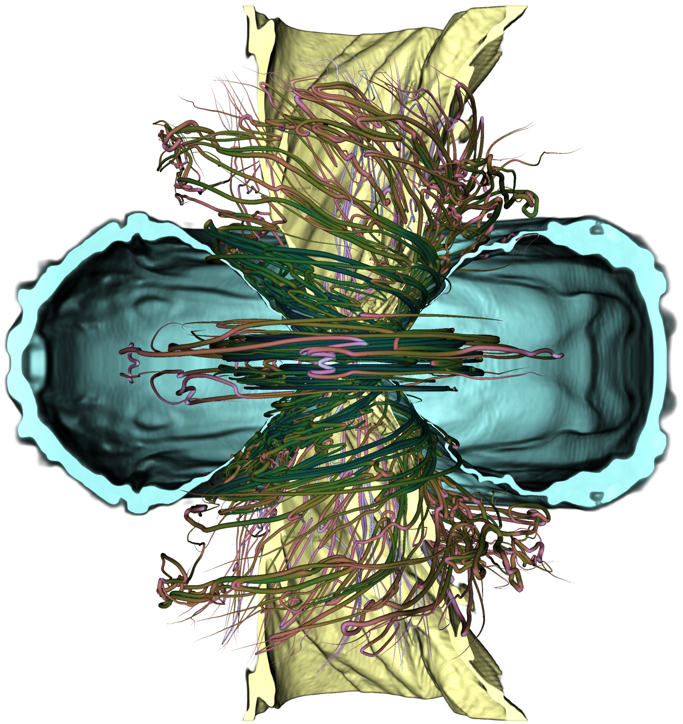
General Relativity and Astrophysics

- Binary Black Hole Mergers
- Binary Neutron Star Mergers
- Neutron Star – Black Hole Mergers
- Supernovae
- Accretion Disks
- Cosmology



Kawamura et al 2016

In all these scenarios general relativity plays a fundamental role.

Developing a code that solves the full set of GR and (Magneto)Hydrodynamic equations is not an easy task.

(a brief) History of Numerical Relativity
(see https://link.springer.com/article/10.1007/lrr-2015-1)

- 1962 Arnowitt, Deser and Misner (ADM) 3+1 formulation
- 1966 May and White first 1D GR simulation of collapse to BH
- 1985 Stark and Piran extract GWs from a simulation of rotating collapse to a BH in NR.
- 1993 Anninos et al. first simulation of head-on collision of two BHs
- 1995-1998 BSSN formulation
- 1996 Brügmann mesh refinement simulation of BHs
- 1997 Cactus 1.0 is released
- 1997 Brandt & Brügmann “puncture” initial data
- 2000 Brandt et al. simulate the first grazing collisions of BHs
- 2000 Shibata and Uryū first NS-NS merger simulation in GR
- 2003 Schnetter et al. “Carpet” driver for Cactus
- 2005 Pretorius first simulation of BH-BH inspiral and merger

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

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

einstein
toolkit

Einstein Toolkit
einsteintoolkit.org

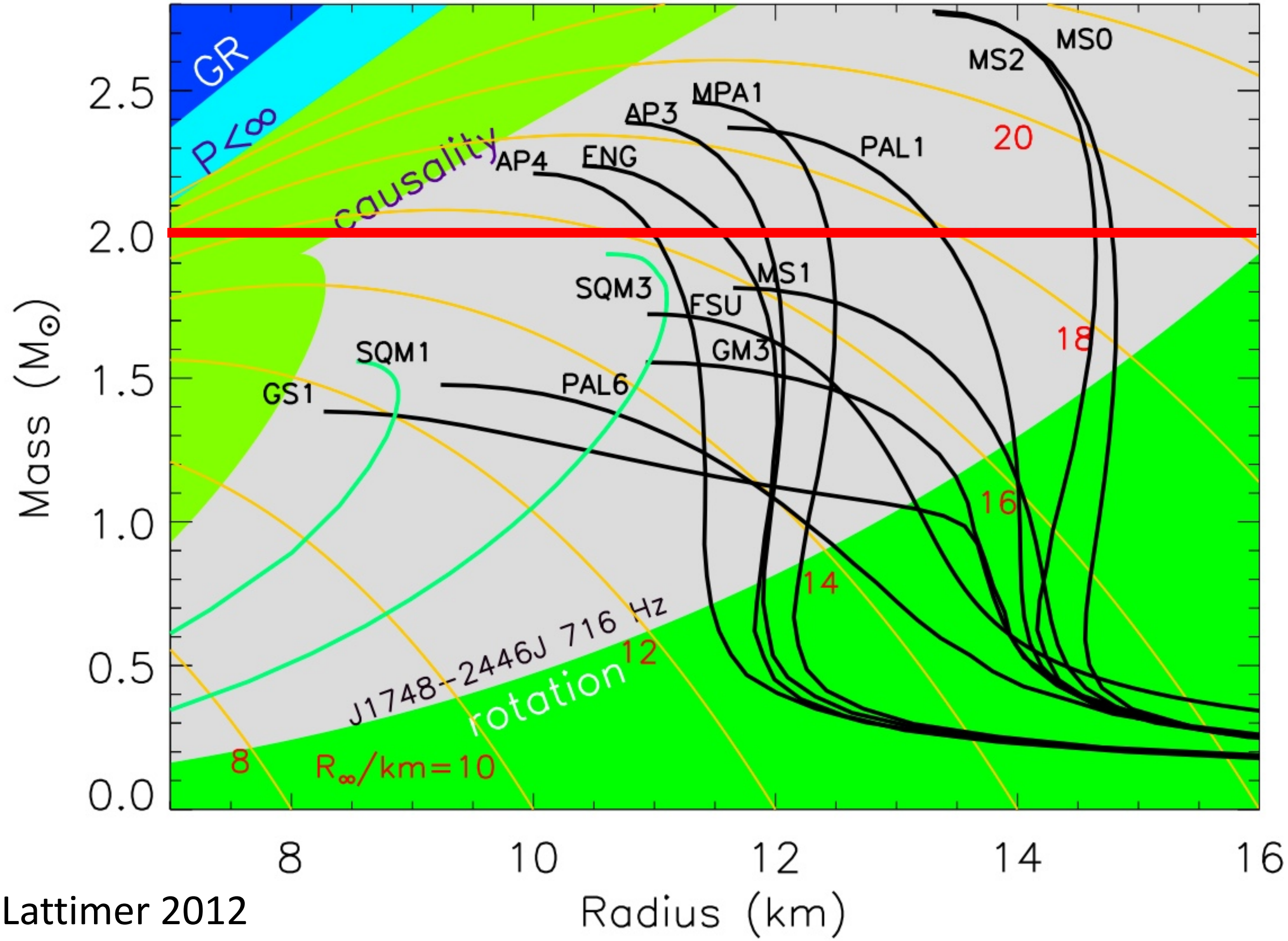
- Set of publicly available tools for relativistic astrophysics
- Latest release on March 29 2019 (codename "Proca")
- More than 150 users on 6 continents
- Tested on several HPC infrastructures around the world
- Includes over 100 Cactus thorns, including:
  - McLachlan (space-time evolution)
  - GRHydro and IllinoisGRMHD (GRMHD equations)
  - Several initial data and analysis routines
- Data can be read and visualized by open source codes (e.g., Visit, PostCactus, yt)

References

- Einstein Toolkit Webpage: http://einsteintoolkit.org
- Main Publications presenting the toolkit:
  - Loeffler et al 2012: http://arxiv.org/abs/1111.3344
  - Moesta et al 2013: http://arxiv.org/abs/1304.5544
  - Zilhao and Loeffler 2013: http://arxiv.org/abs/1305.5299
- Visualization Tools:
  - PostCactus & SimRep: https://bitbucket.org/DrWhat/pycactuset
  - Visit: https://visit.llnl.gov/
  - YT: http://yt-project.org/
- Every year workshops and (sometimes) schools are organized in EU and USA:
  - Rochester, NY, USA, June 2019: https://ccrg.rit.edu/content/events/2019-06-17/north-american-einstein-toolkit-workshop-2019
  - **London, UK, September 2019**: https://sites.google.com/view/eetm2019/home

Binary Neutron Star Mergers

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

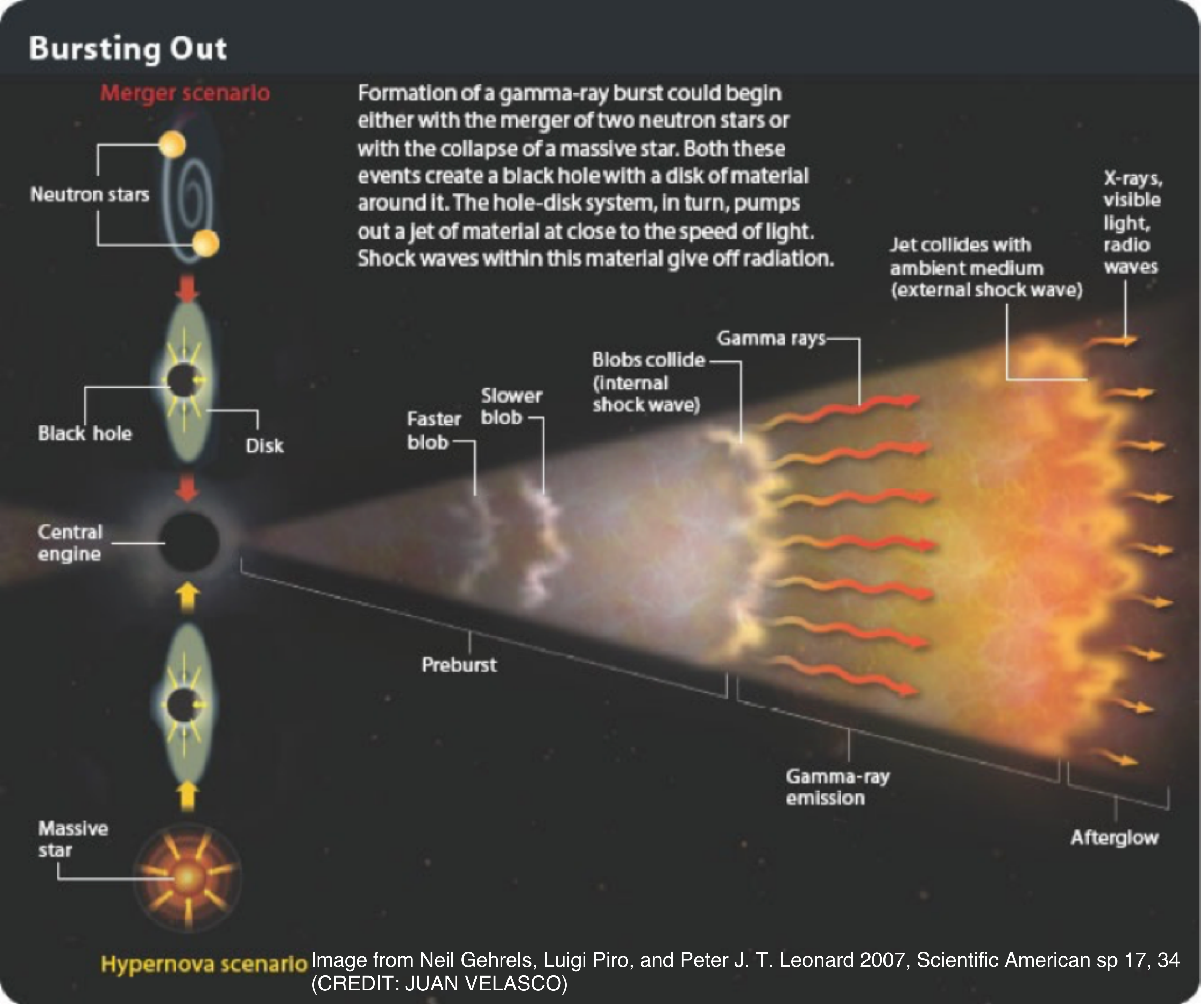
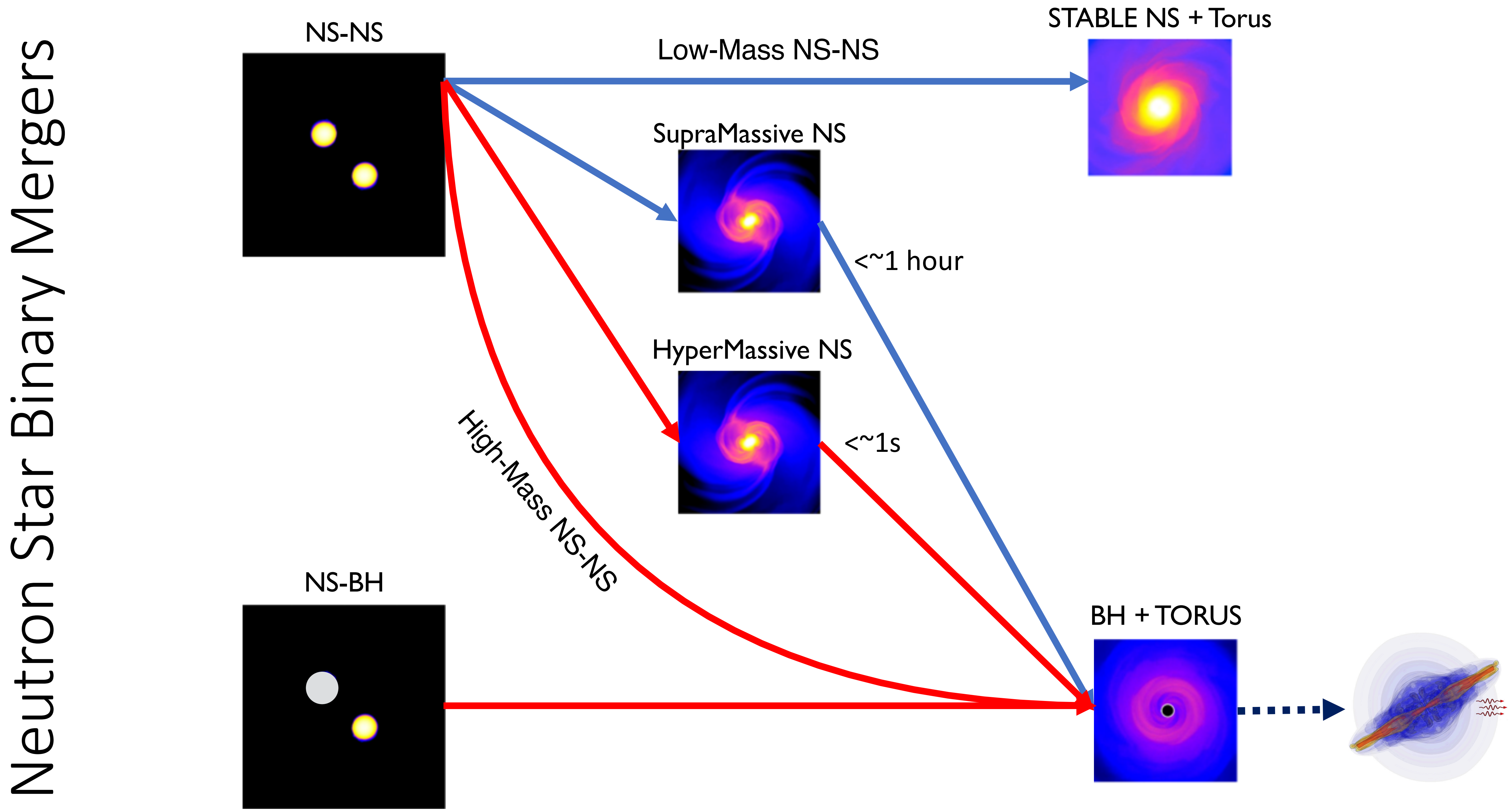


Image from Neil Gehrels, Luigi Piro, and Peter J. T. Leonard 2007, Scientific American sp 17, 34 (CREDIT: JUAN VELASCO)

Gamma-Ray Bursts

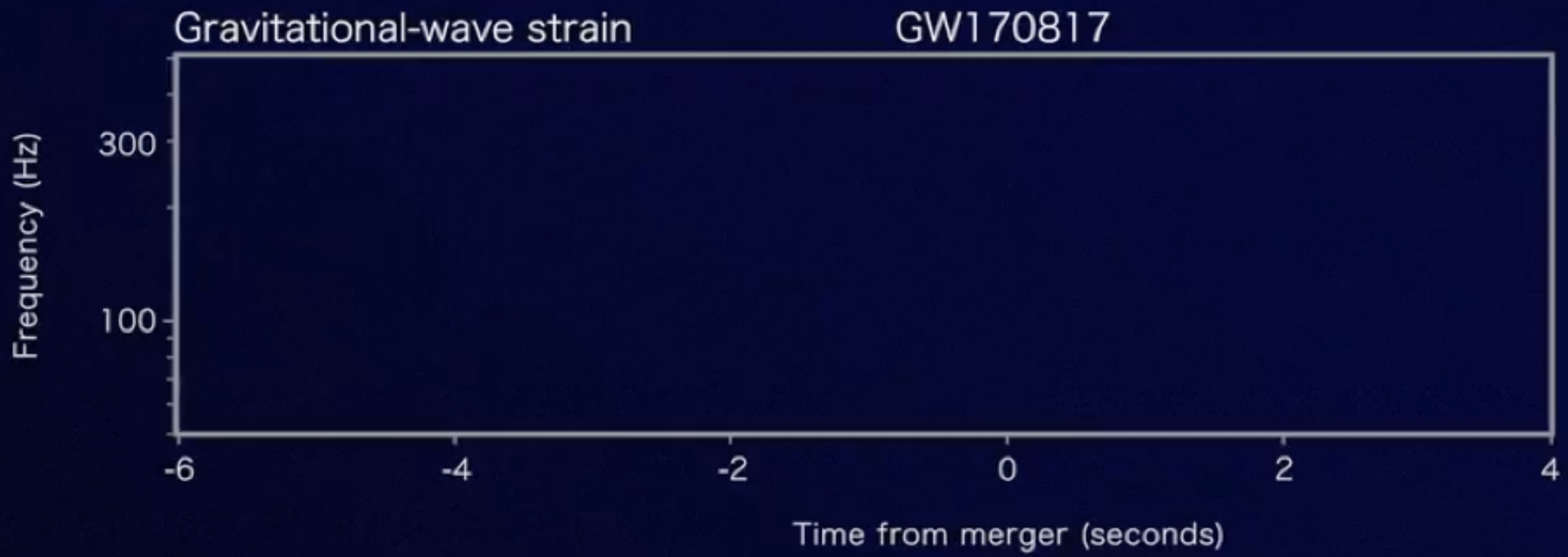
- Discovered in 1967
- Two types:
  - Short (<2 s)
  - Long (>2 s)
- Long GRBs are due to Supernovae explosions (discovered in 1998)
- Short GRBs have been quite a mystery


Neutron Star Binary Mergers
NS-NS
Low-Mass NS-NS
STABLE NS + Torus
SupraMassive NS
<~1 hour
HyperMassive NS
<~1s
High-Mass NS-NS
NS-BH
BH + TORUS

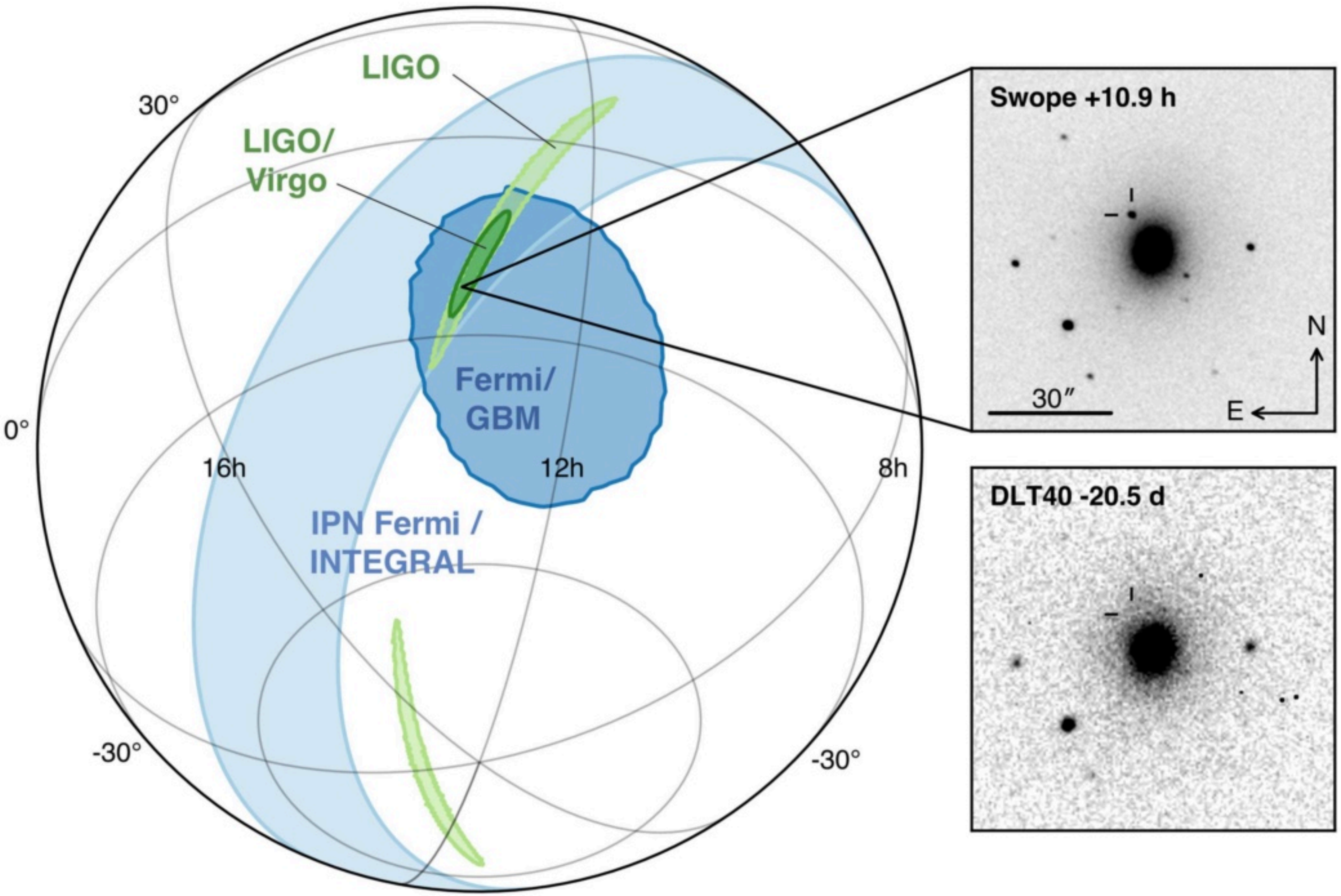
GW170817: the first NS-NS detection

Fermi

LIGO



Credit: NASA GSFC & Caltech/MIT/LIGO Lab


LIGO
LIGO/
Virgo
30°
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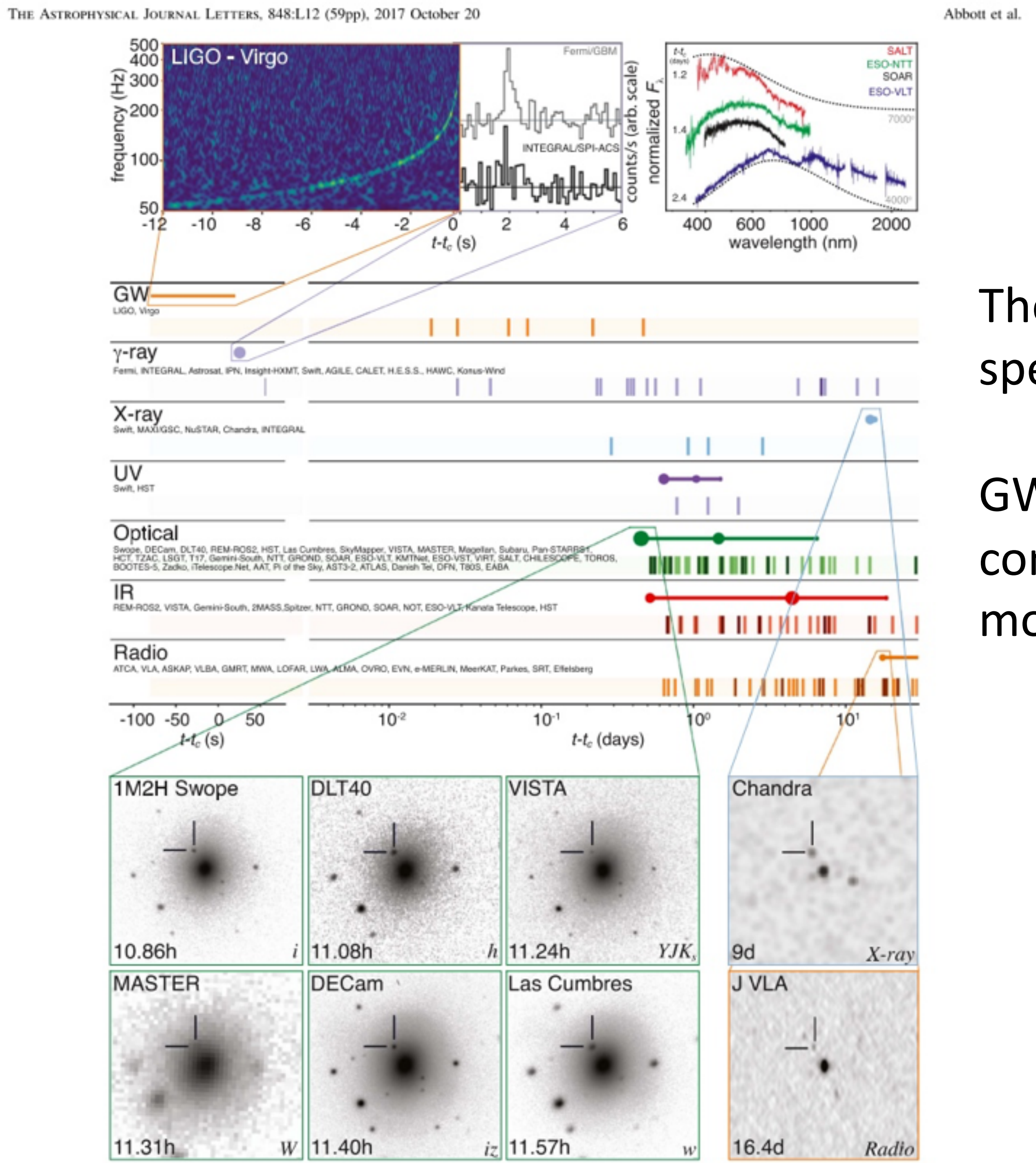
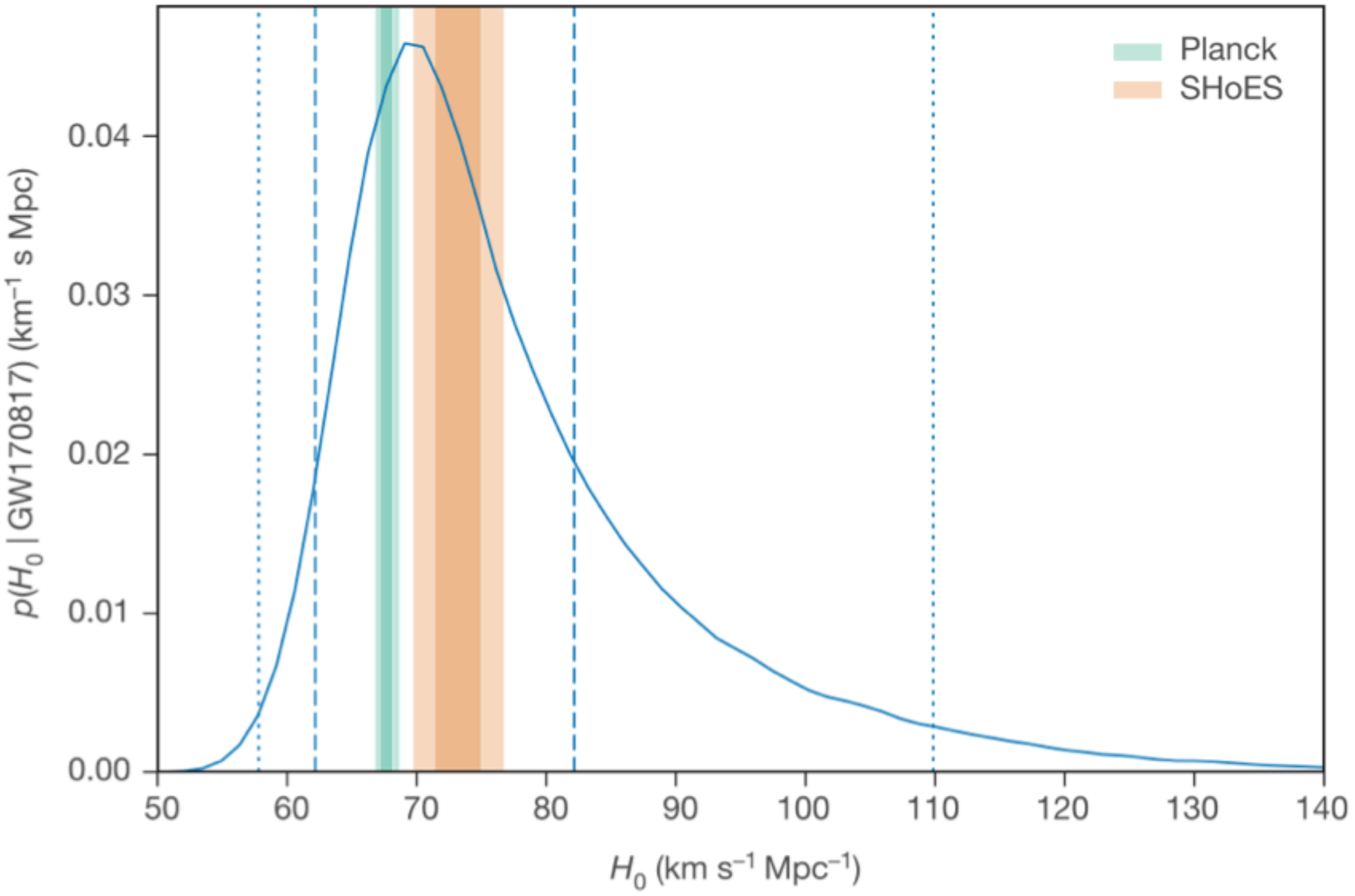


The event has been detected in the full EM spectrum from gamma-ray to radio.

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

Hubble Constant Measure



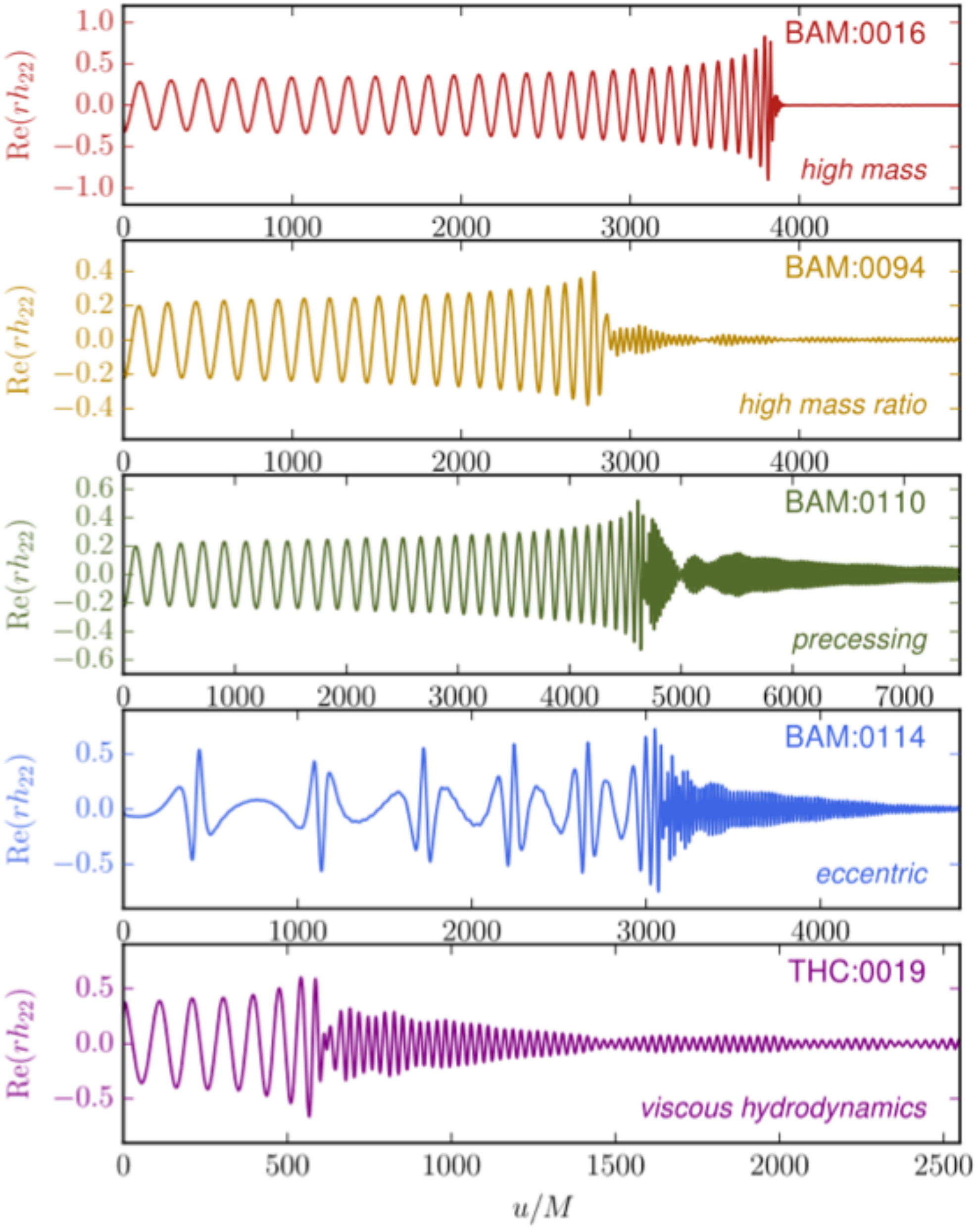
Combination of GW and EM emission allowed for a new measure of the Hubble constant.

The comparison of time of arrival also constrained the speed of gravitational waves to be equal to the speed of light:

$$\frac{\Delta v}{v_{EM}} \approx 10^{-15}$$

http://dx.doi.org/10.1038/nature24471

Equation of State Effects

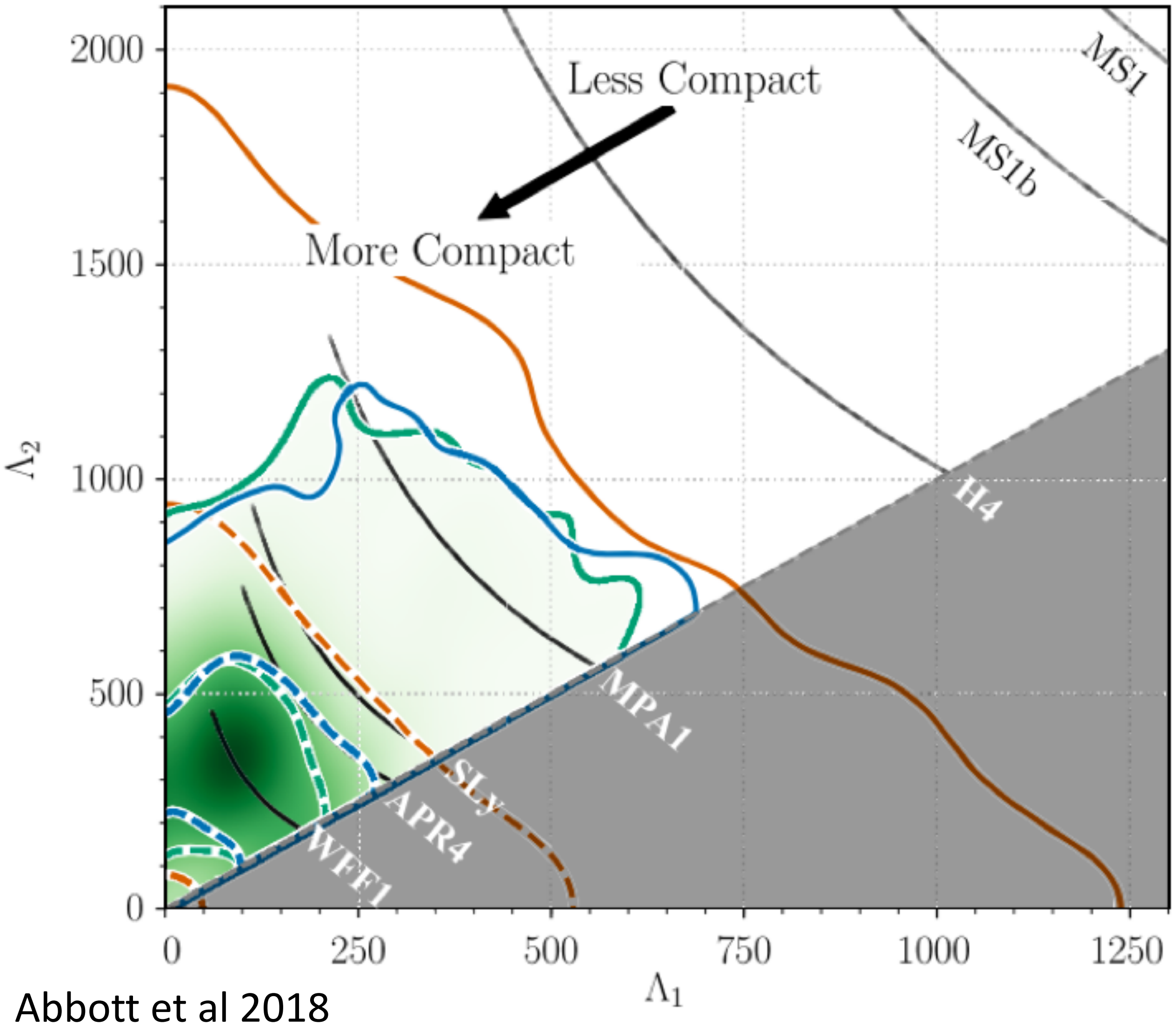


Dietrich et al 2018
http://www.computational-relativity.org/index.html

General relativistic simulations of BNS mergers from different groups now include quite a range of parameters:

- Total mass
- Mass ratio
- Spins (few)
- Cold and (a few) hot EOSs
- Eccentricity (few)
- Viscosity (few)
- Neutrinos (few)
- Magnetic fields (few)

An important quantity that can be measured is the dimensionless tidal deformability $\Lambda = \frac{2}{3} k_2 [(\frac{c^2}{G})(\frac{R}{m})]^5$ where k_2 is the (dimensionless) Love number. One can more easily extract a combination of the tidal deformabilities of the two NSs:



Abbott et al 2018

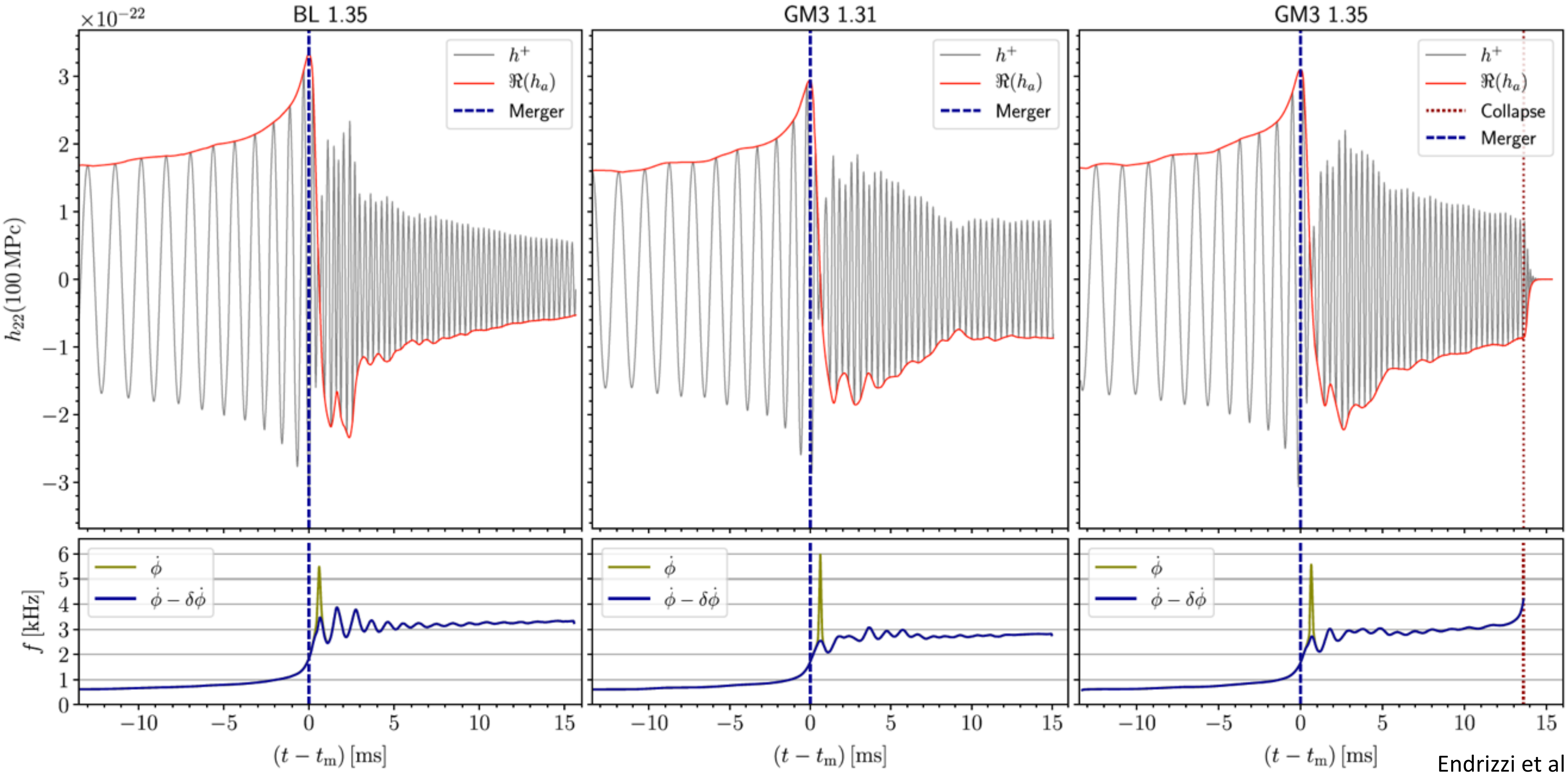
$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2) m_1^4 \Lambda_1 + (m_2 + 12m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

$\tilde{\Lambda} = 300^{+500}_{-190}$ for low spin (<0.05)

$\tilde{\Lambda} = (0, 630)$ for high spin (<0.89)

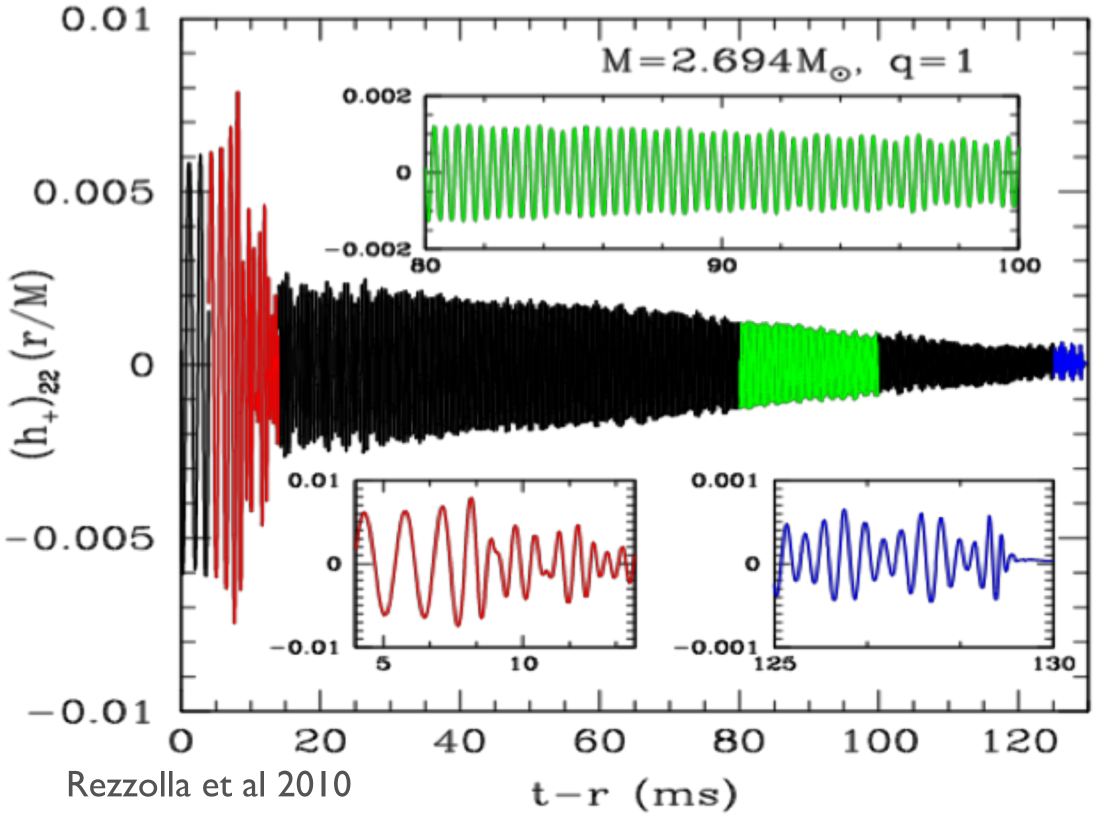
(see Abbott et al 2019)

Post-Merger Effects

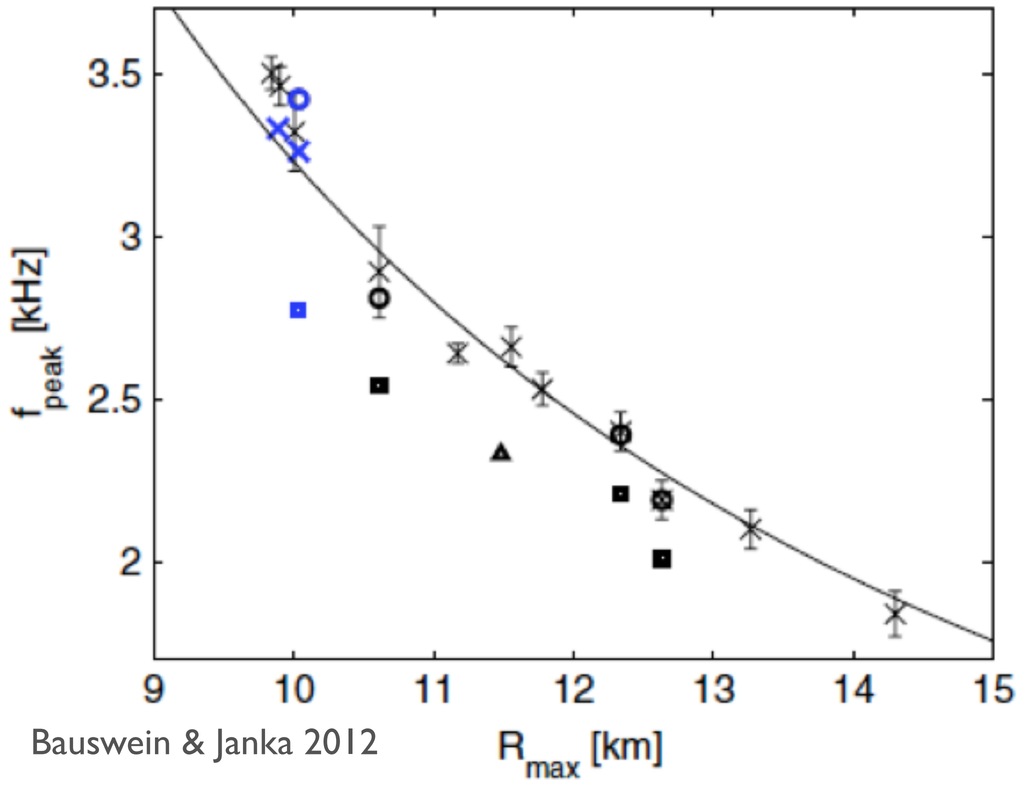


Endrizzi et al 2018

EOS EFFECTS IN THE POSTMERGER



Rezzolla et al 2010

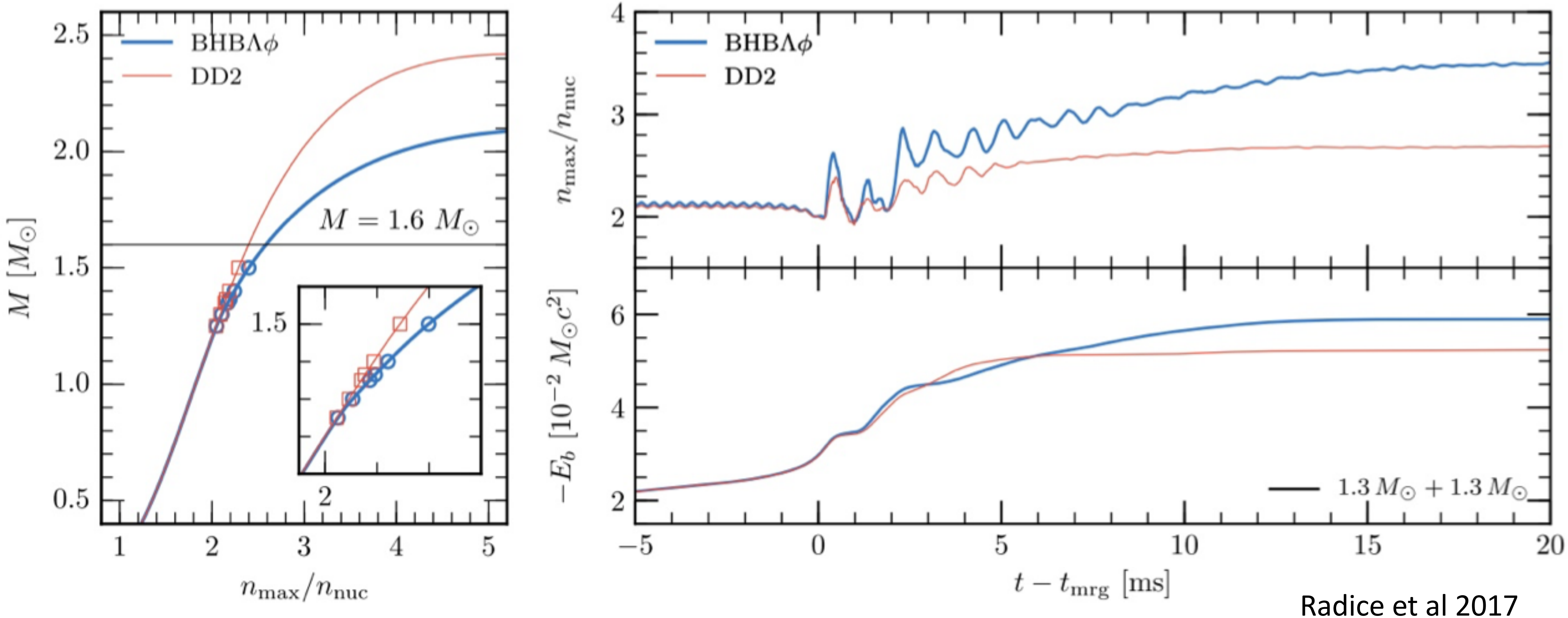


Bauswein & Janka 2012

A significant fraction of NS-NS mergers can produce long-lived NSs (e.g., Piro, Giacomazzo, Perna 2017)

Frequency peak in GWs emitted after merger can constrain EOS at high densities and temperature (and maybe magnetic fields).

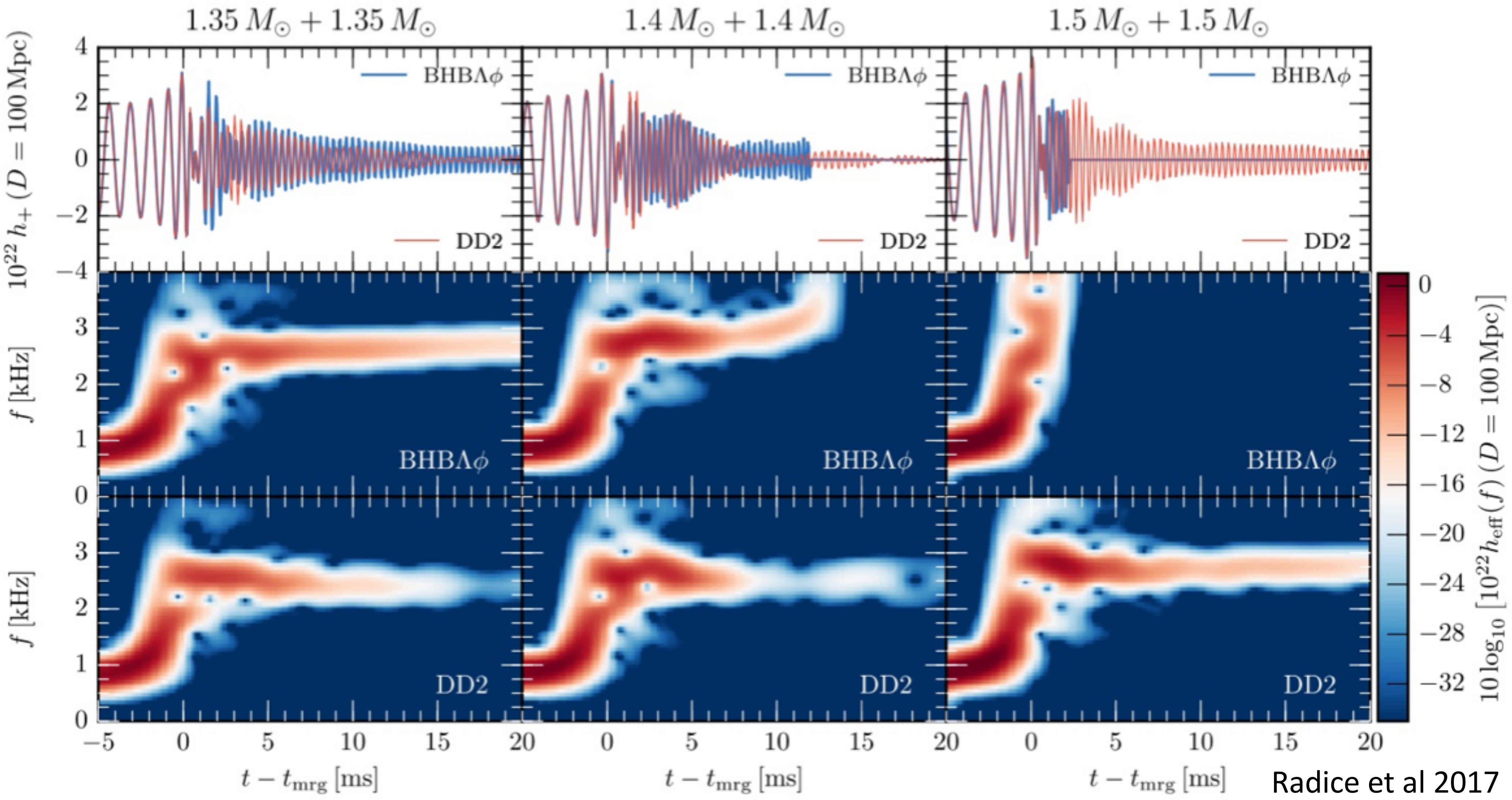
EOS EFFECTS IN THE POSTMERGER



Radice et al 2017

EOS identical at “low” (inspiral) densities, but different at post-merger densities (due to appearance of hyperons).

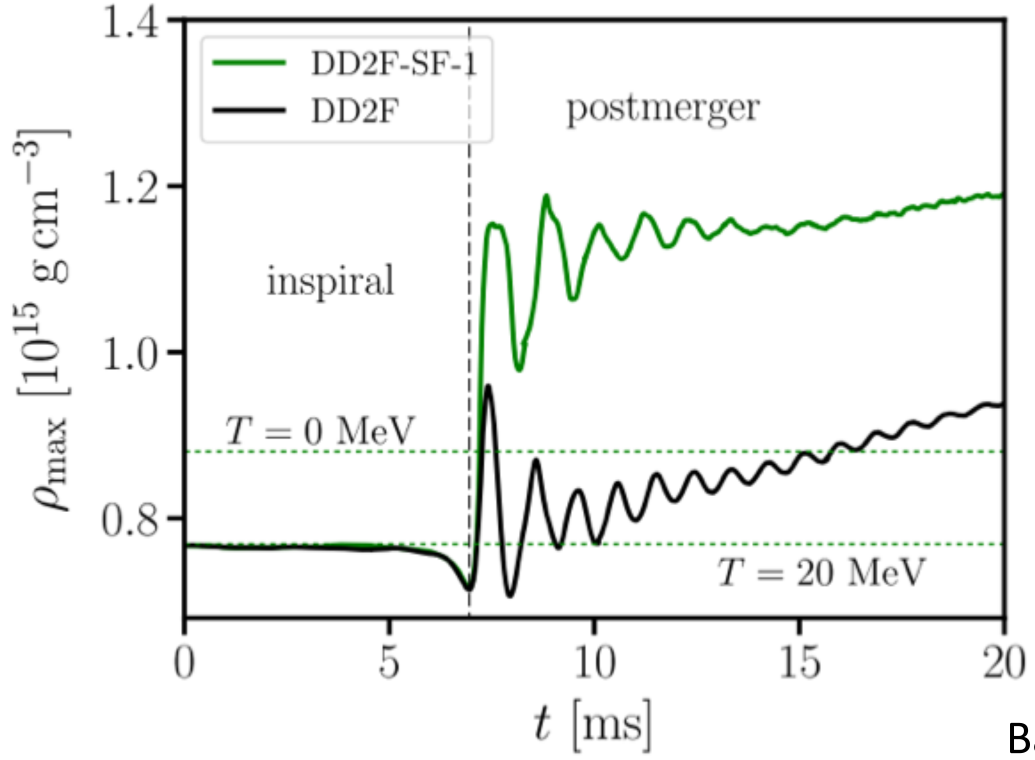
EOS EFFECTS IN THE POSTMERGER

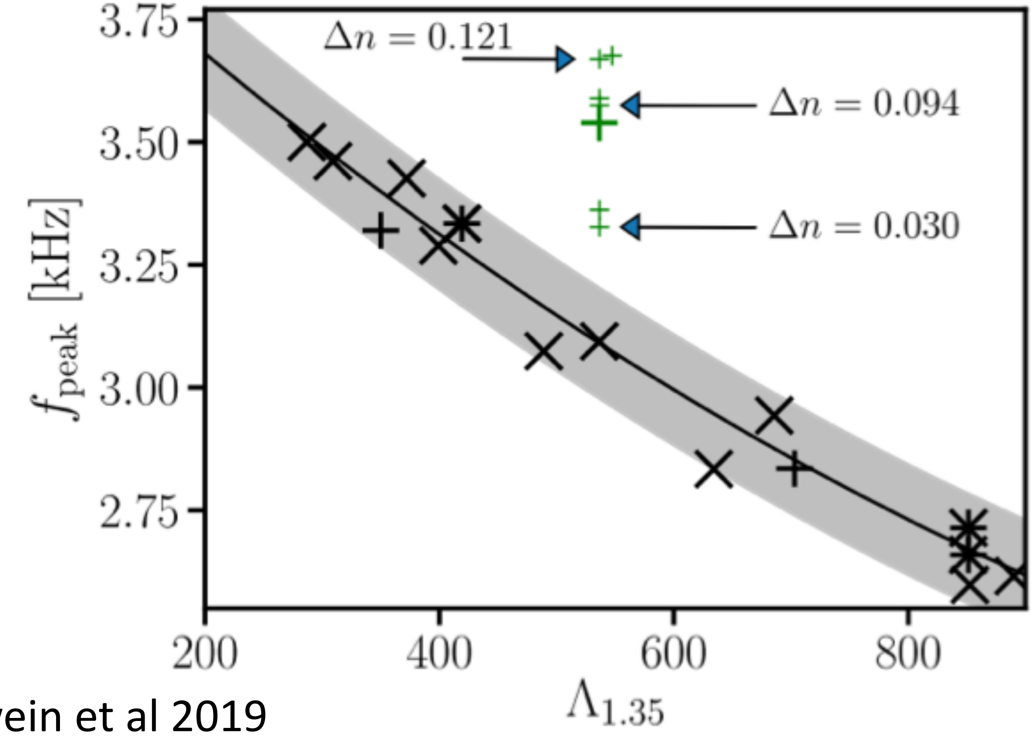


Radice et al 2017

Effects are more evident in post-merger luminosities and phase evolution (see also Bernuzzi et al 2016).

PHASE TRANSITIONS IN THE POST-MERGER

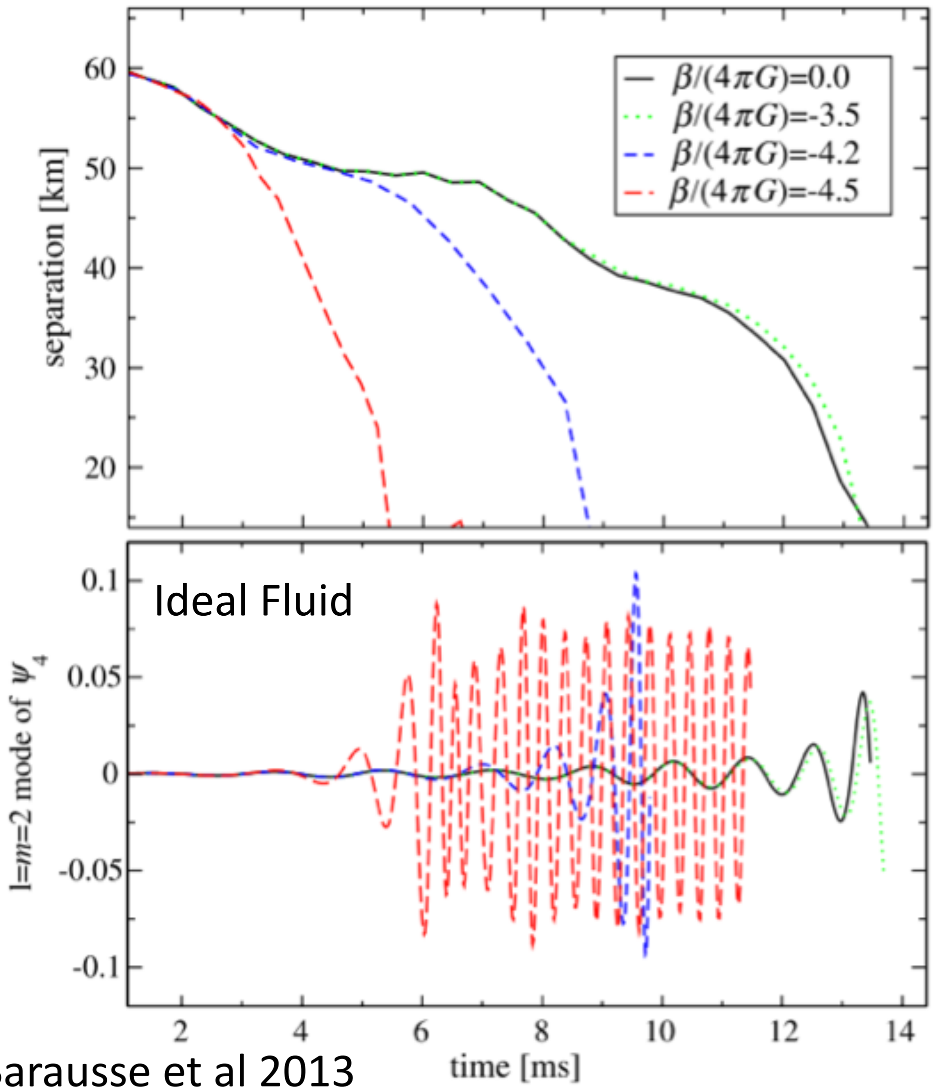




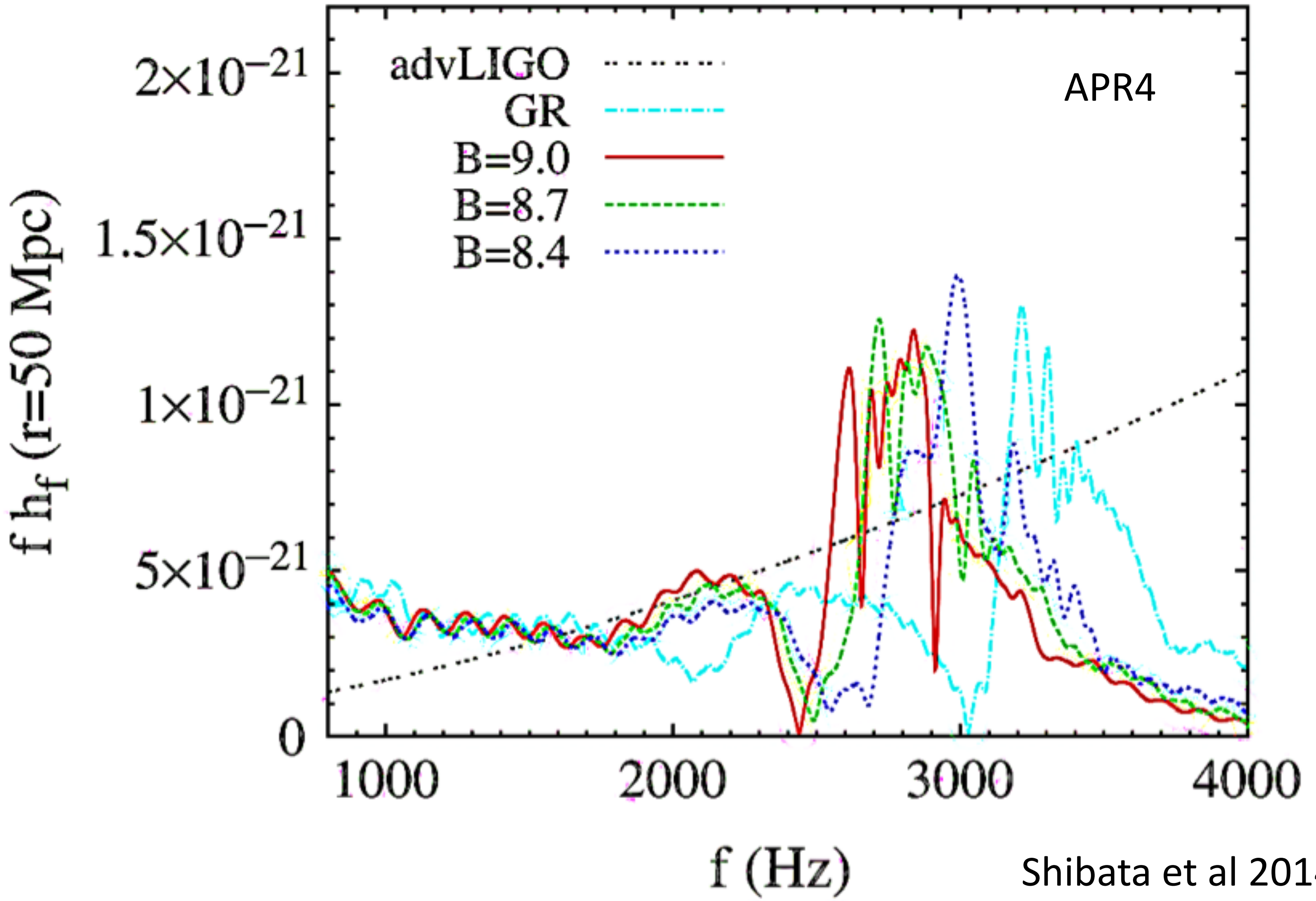
Bauswein et al 2019

A phase transition to a deconfined-quark-matter core affects significantly the post-merger GW peak.

BNS Mergers in Scalar-Tensor Theories



Barausse et al 2013

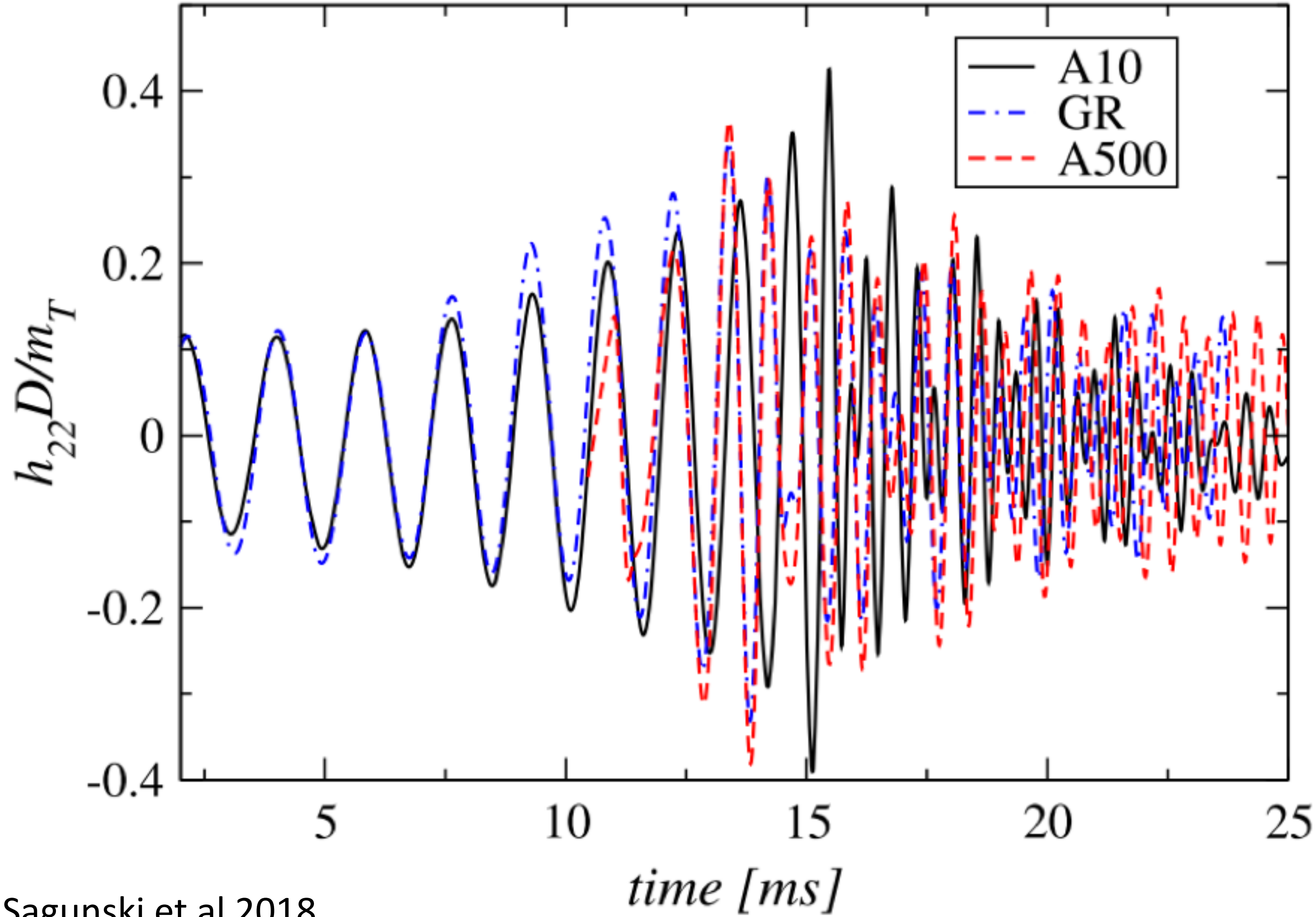


Shibata et al 2014

Spontaneous scalarization may happen during the inspiral or merger and may affect the GW signal.

BNS Mergers in f(R) Theories

Considered $f(R) = R + a_2 R^2$ with $a_2 = 1090.3\ km^2$ (model A500) and $a_2 = 21.8\ km^2$ (A10)



Sagunski et al 2018

The long-range scalar force (A500) produce an earlier merger while the short-range one is similar to GR.

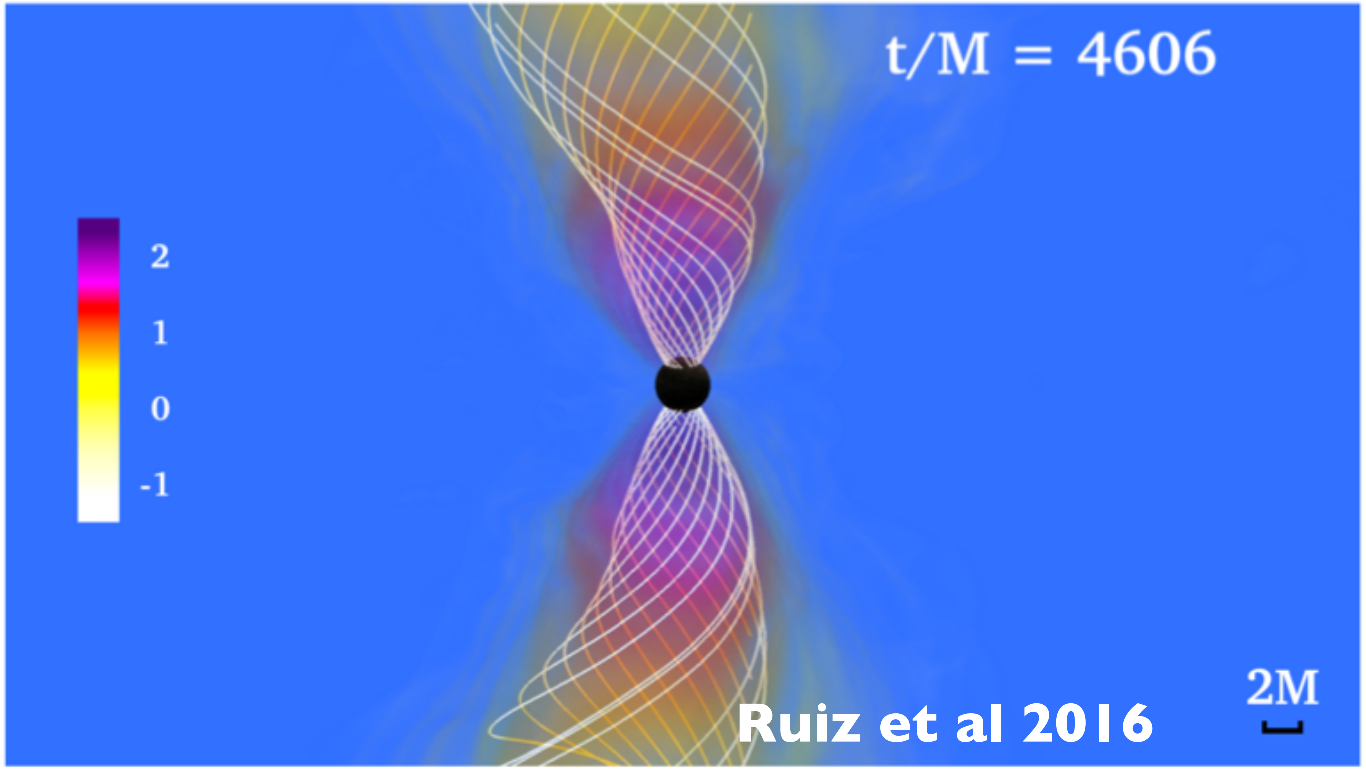
Effects of short-range scalar force are more evident in the post-merger phase, but they may be confused with EOS effects.

Combining EM and GW signals (e.g., Ponce et al 2015) may help (perhaps).

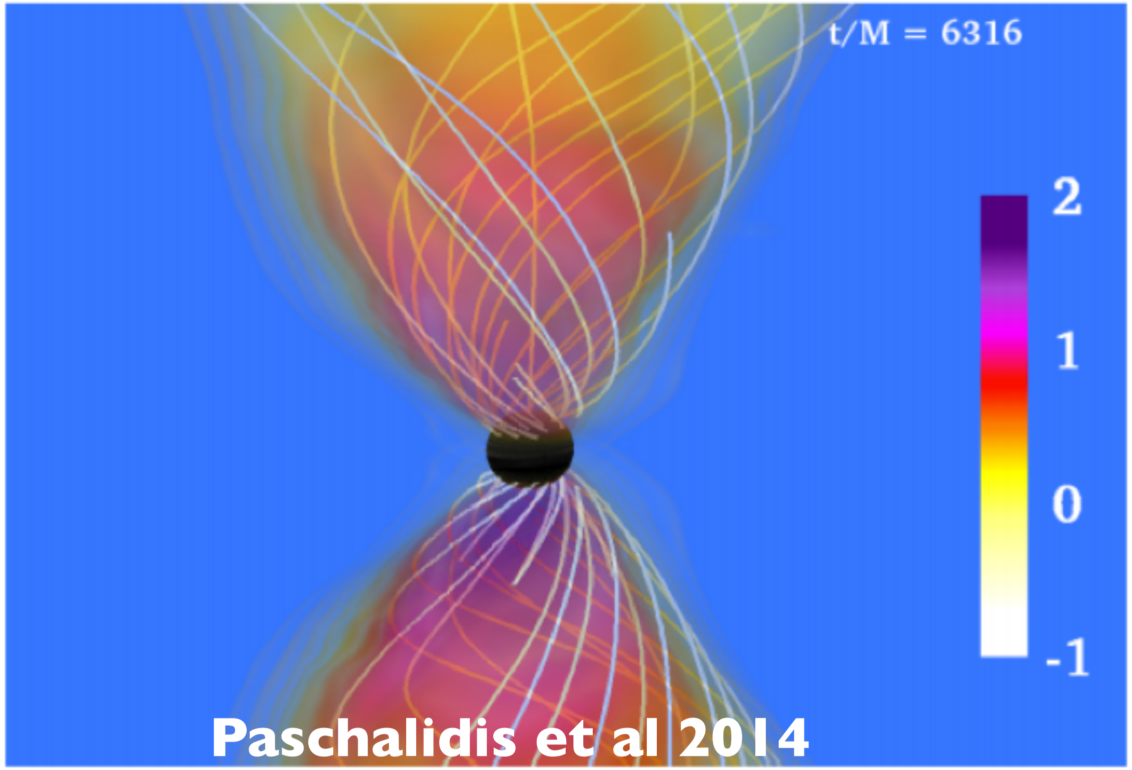
The Role of Magnetic Fields

JETS FROM NS BINARY MERGERS

NS-NS



NS-BH

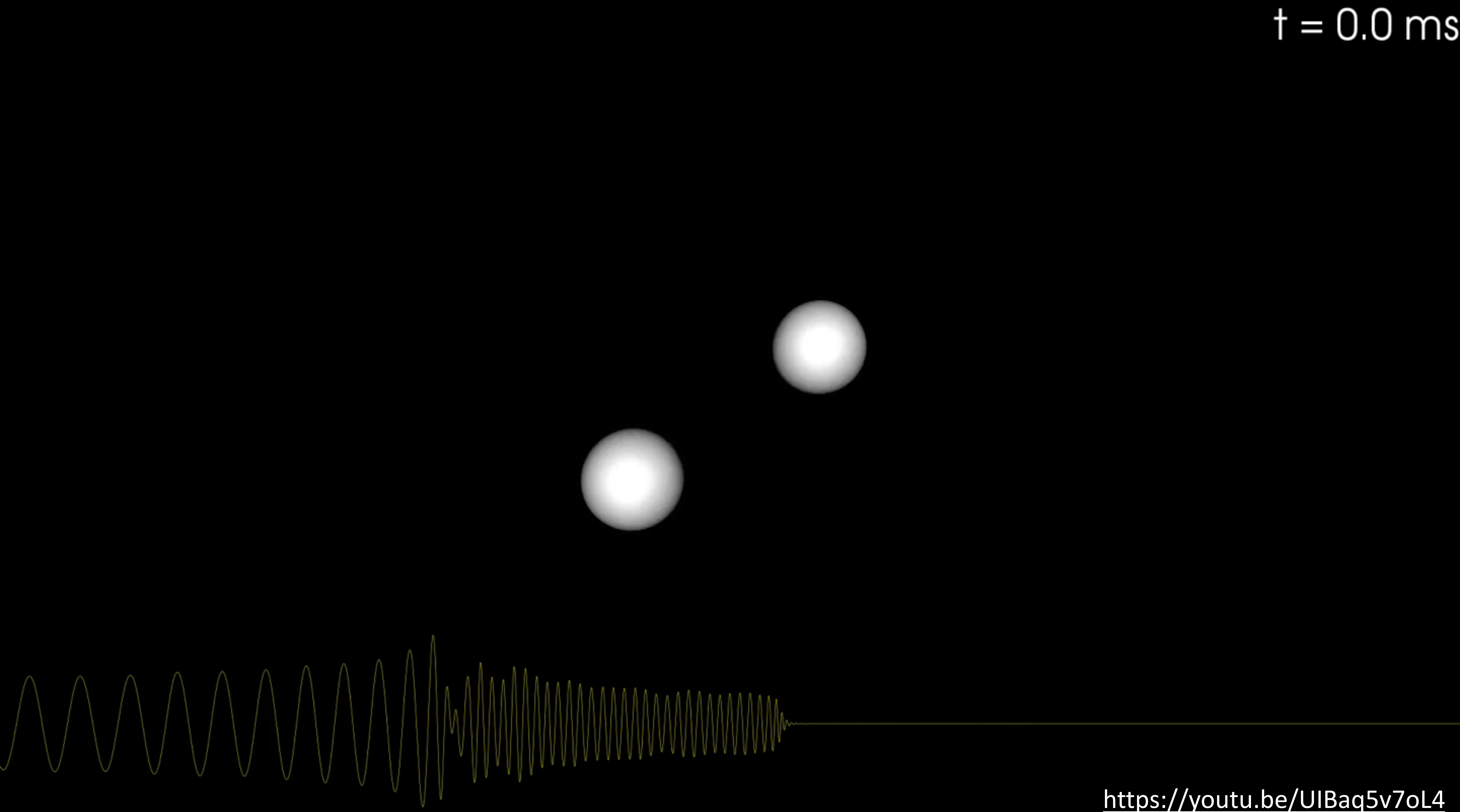


Jet formation observed in Ideal-Fluid simulations with the IllinoisGRMHD code starting with very large (10^{16}G) fields

WHISKYMHD SIMULATIONS OF BNS MERGERS

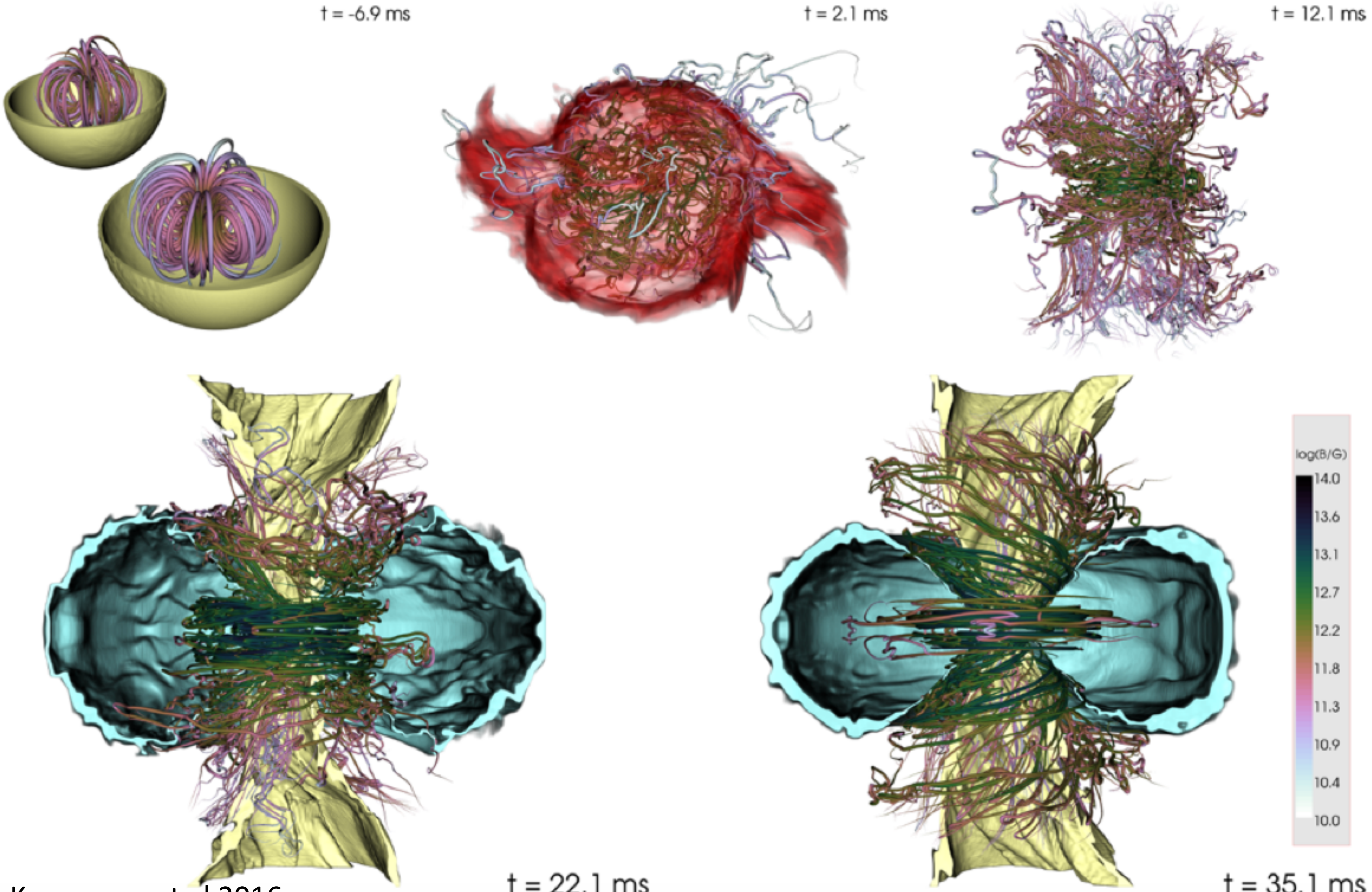
- T. Kawamura, **B. Giacomazzo**, W. Kastaun, R. Ciolfi, A. Endrizzi, L. Baiotti, R. Perna 2016, PRD 94, 064012
  - First study of different "high-mass" models (two EOSs, two mass ratios, different magnetic field orientations)
  - All models started with B~10^{12}G (vs ~10^{16}G of Ruiz et al 2016)
- R. Ciolfi, W. Kastaun, **B. Giacomazzo**, A. Endrizzi, D. M. Siegel, R. Perna 2017, PRD 95, 063016
  - Studied 6 different models with 3 EOSs and 2 mass ratios
  - All models had the same total gravitational mass at infinity (2.7 solar masses) and the same magnetic energy (initial magnetic field ~10^{15}G)

All simulations performed with WhiskyMHD + EinsteinToolkit.

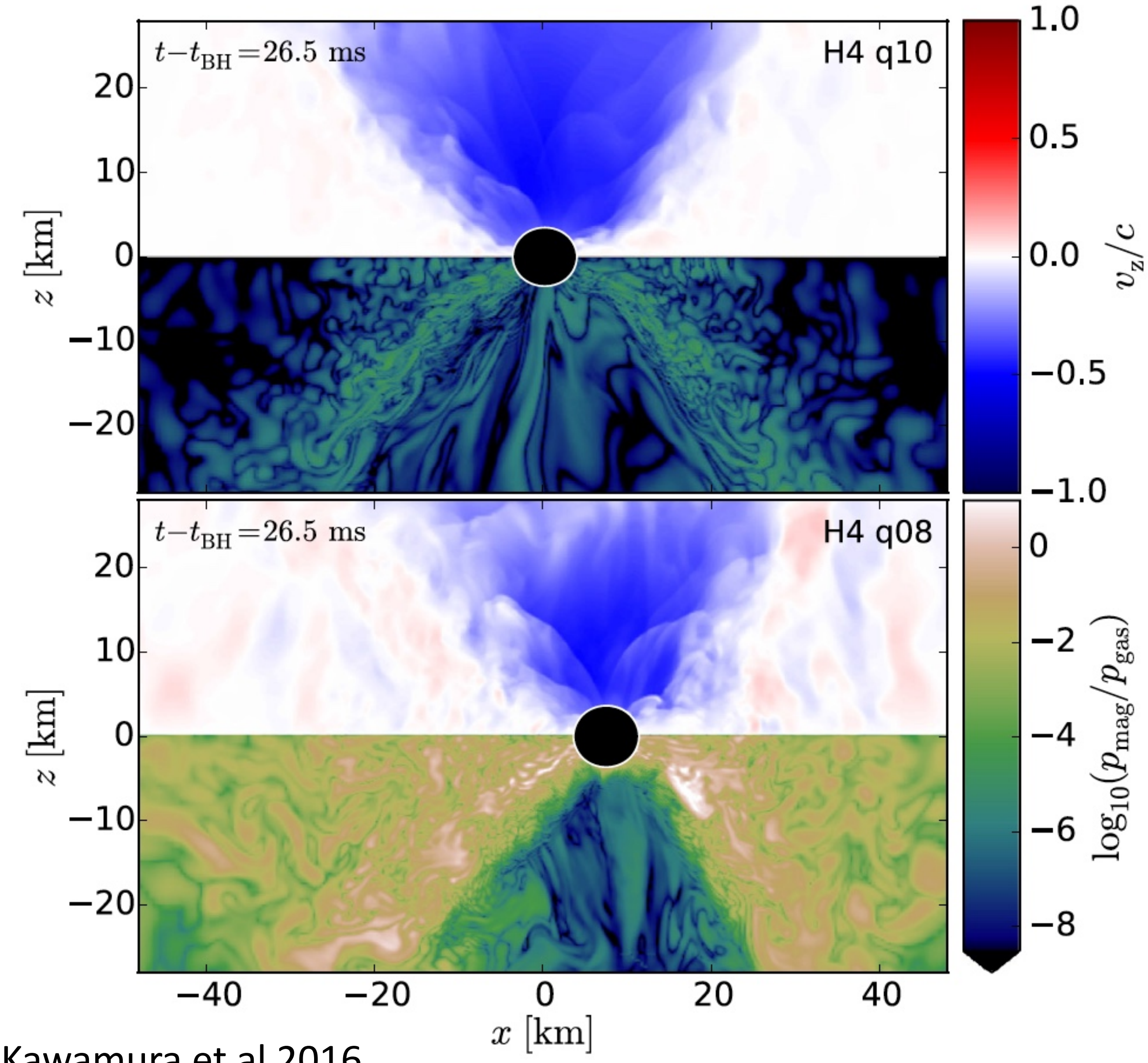


https://youtu.be/UIBaq5v7oL4

Magnetic Field Structure Evolution



Kawamura et al 2016

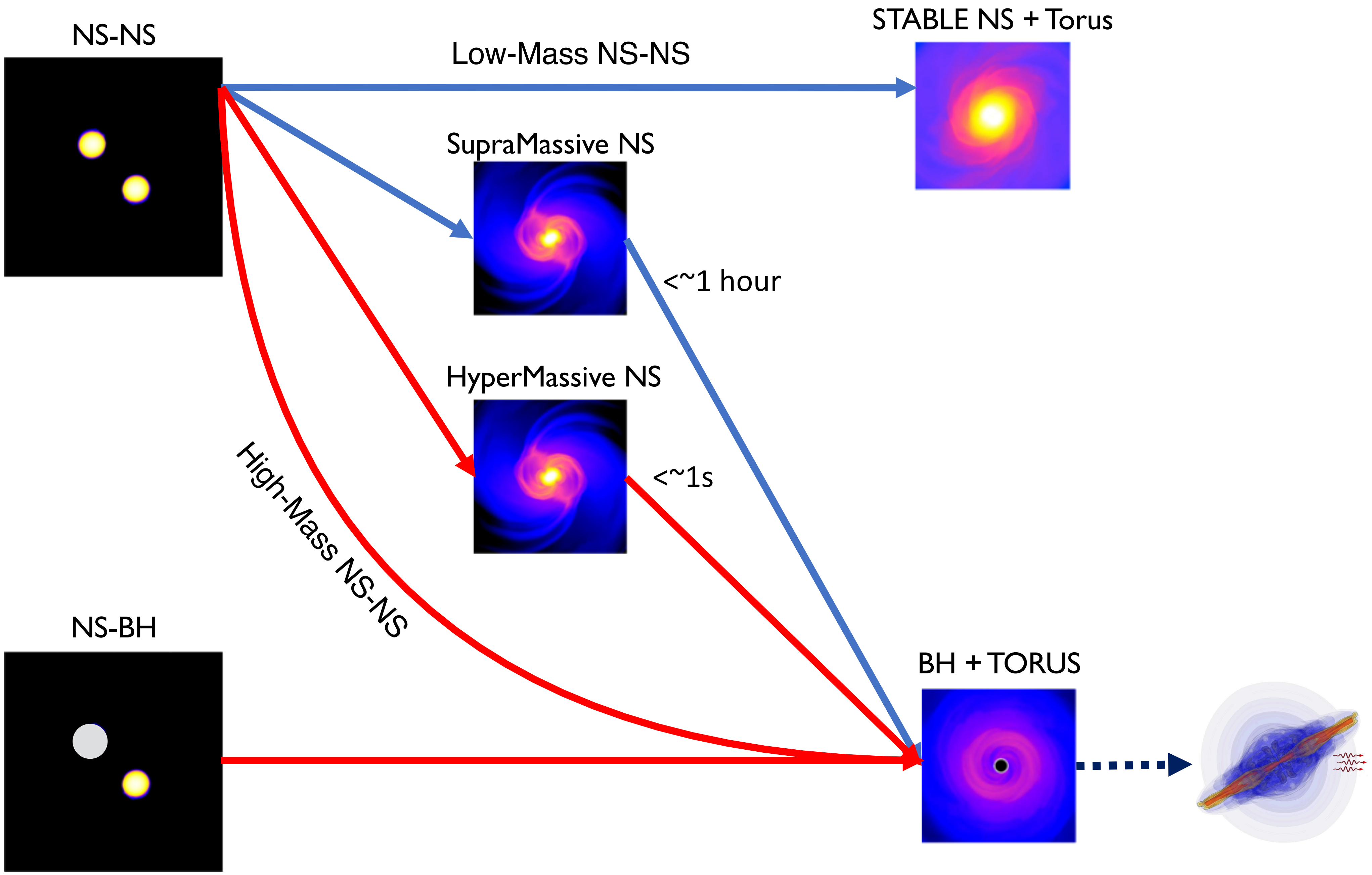


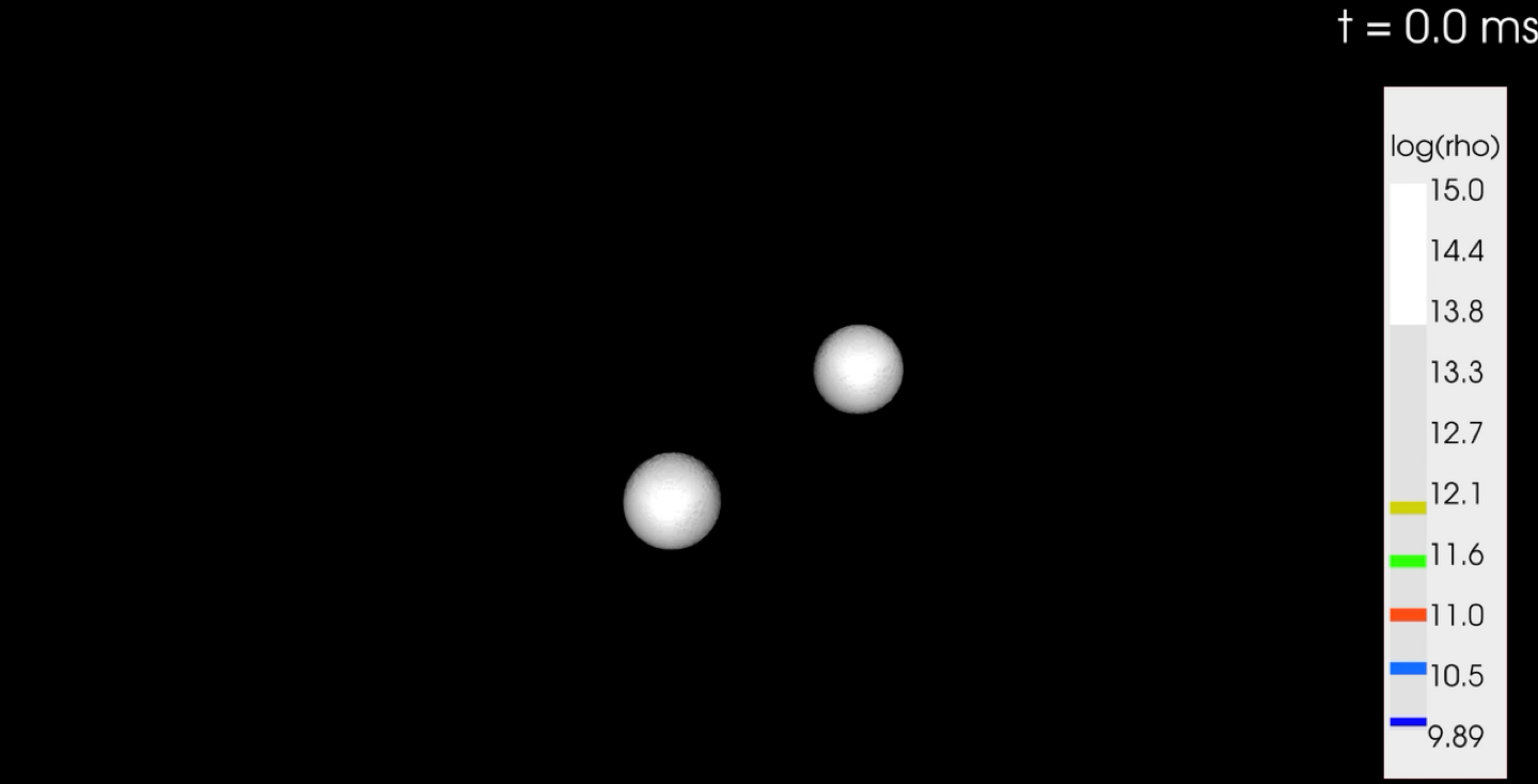
Kawamura et al 2016

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 starts sims with ~10^{16}G).

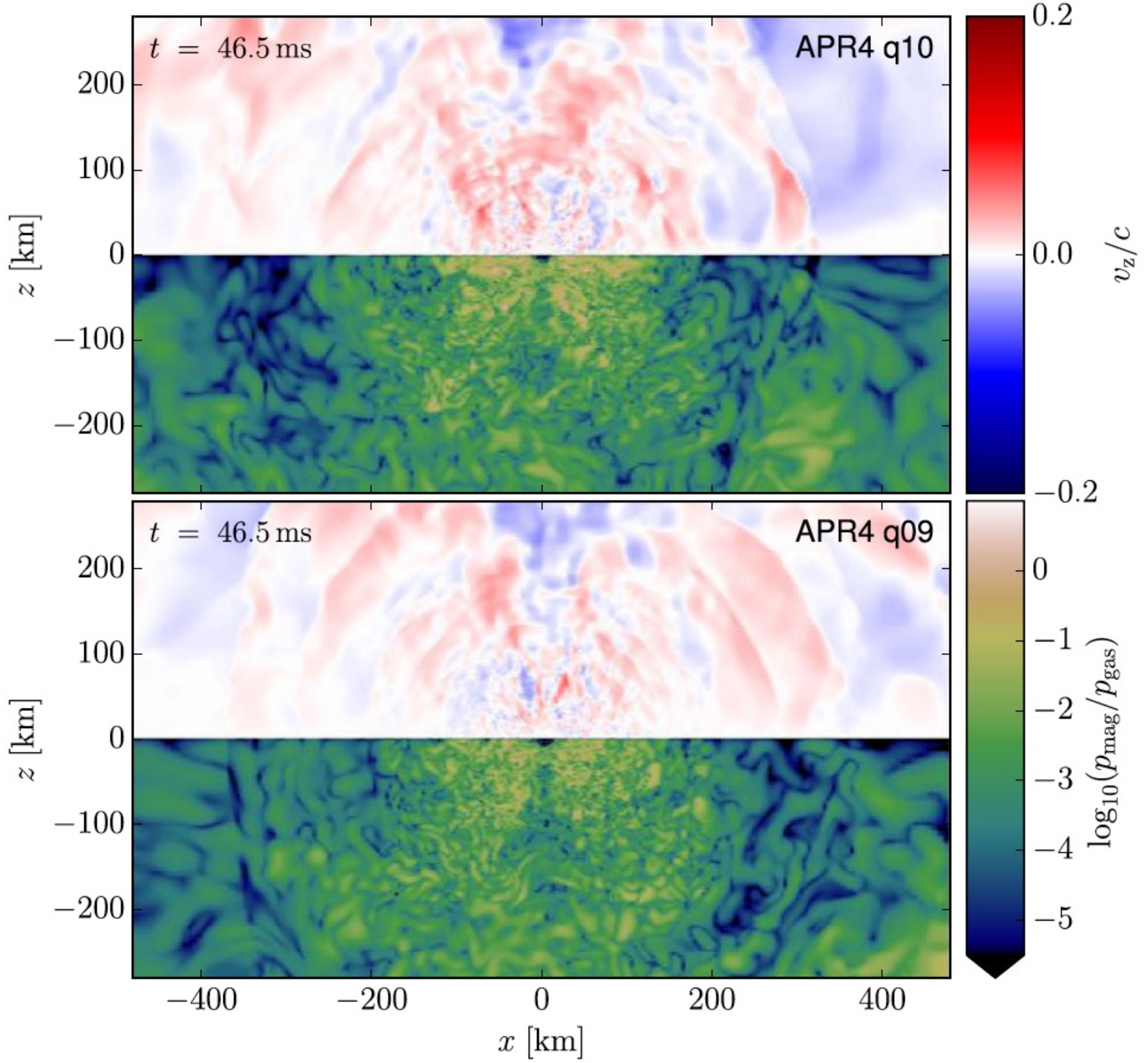
Neutron Star Binary Mergers

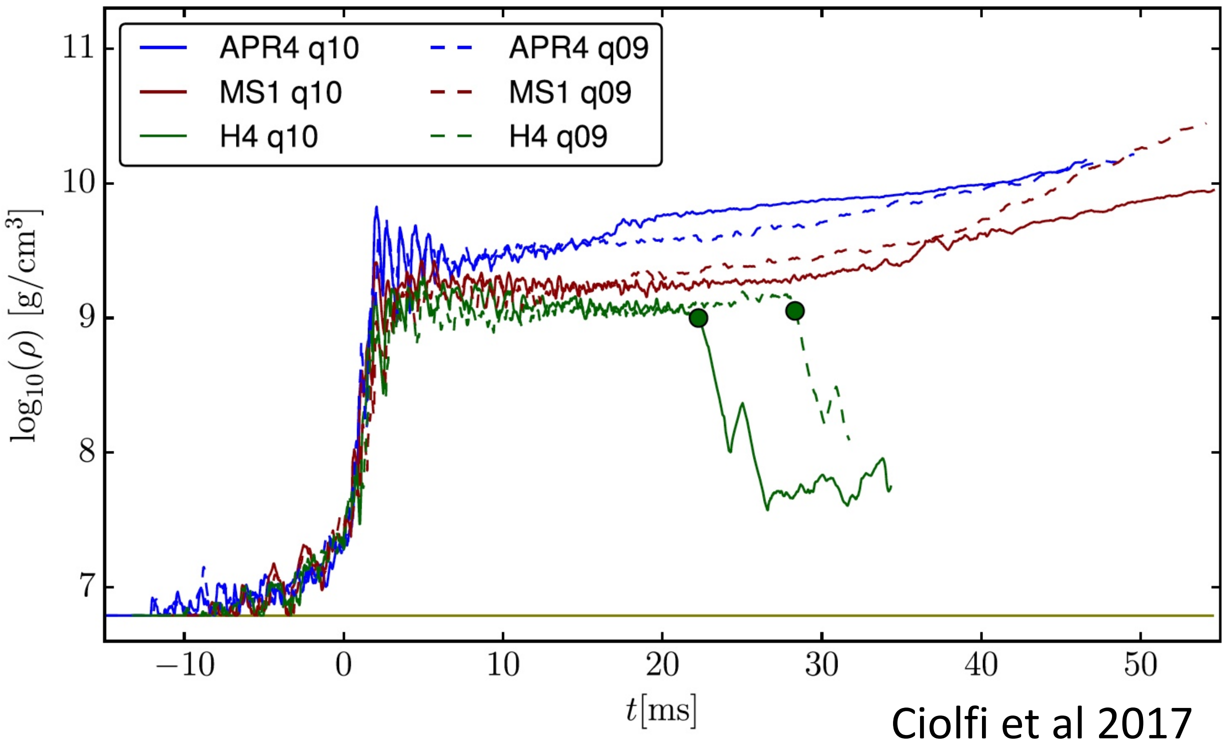




https://youtu.be/00n8uen5xwk

SHORT- OR LONG-LIVED REMNANT?



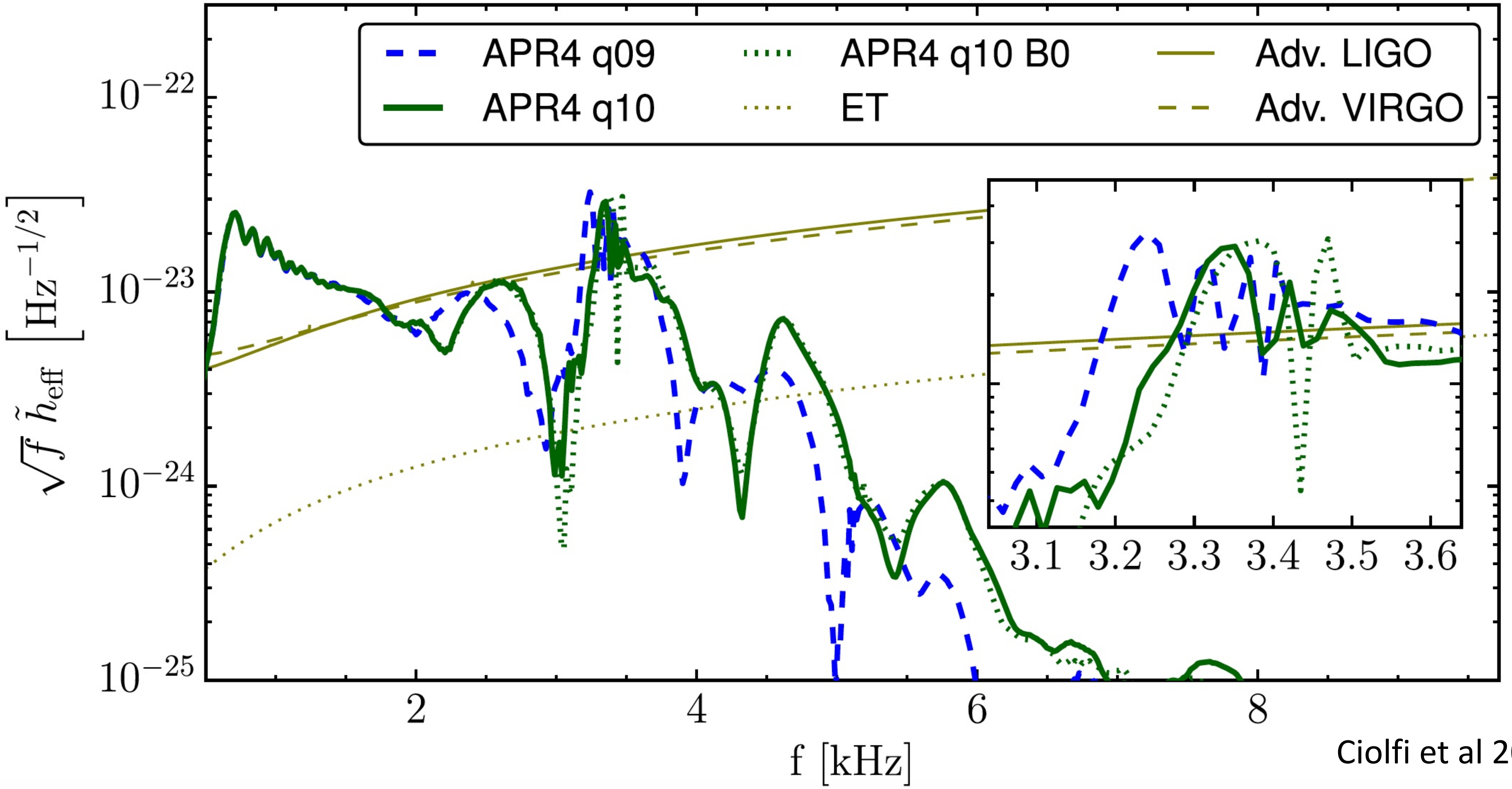


Ciolfi et al 2017

No magnetically dominated funnel.

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

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). Difference in the post-merger peak of less than ~100 Hz.

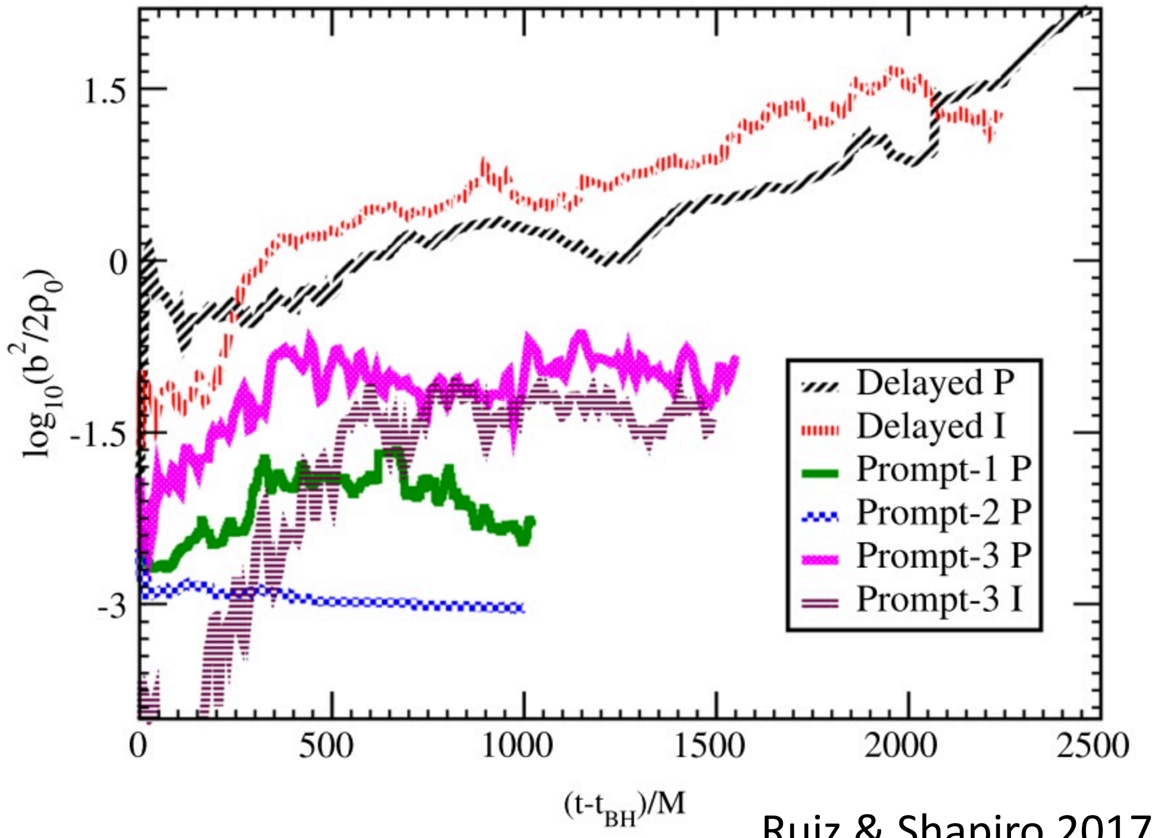
Open Problem: Do all “High-Mass” BNS launch jets?

Ruiz & Shapiro 2017 run a set of 2 equal and 1 unequal-mass BNS mergers with ideal-fluid EOS and large initial magnetic field ($B \sim 10^{16}G$).

Considered models that result in prompt collapse to BH after merger (no HMNS phase).

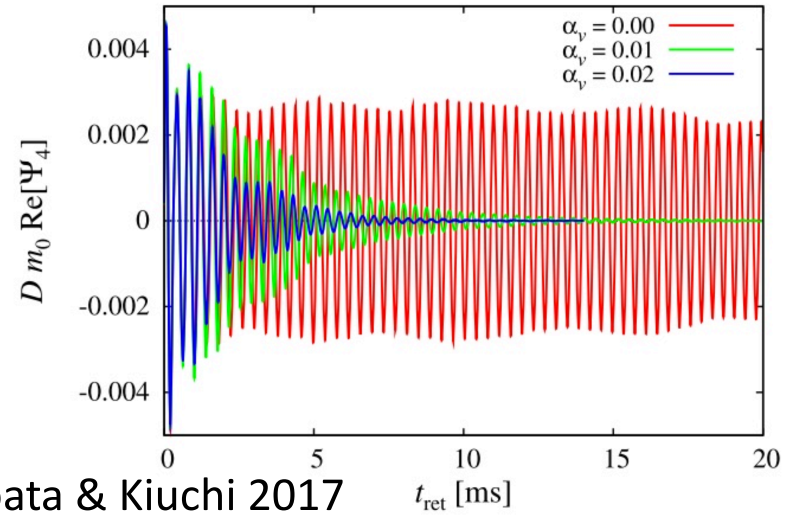
All prompt collapse models do not launch a jet and do not produce a magnetically dominated region.

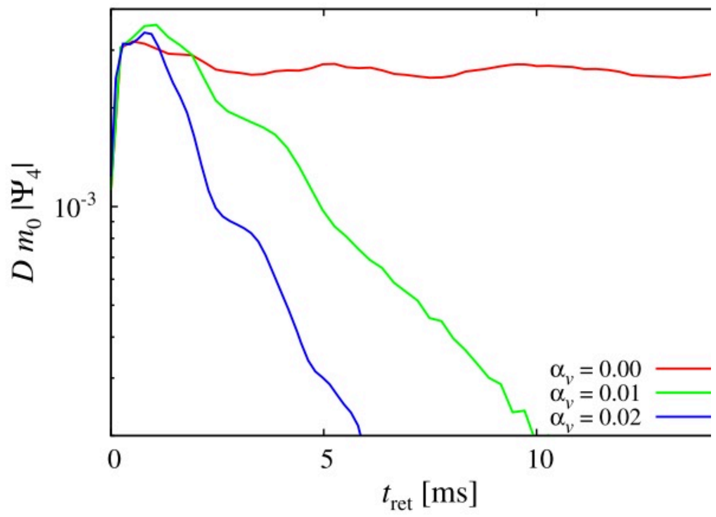
Delayed collapse necessary to produce SGRB?



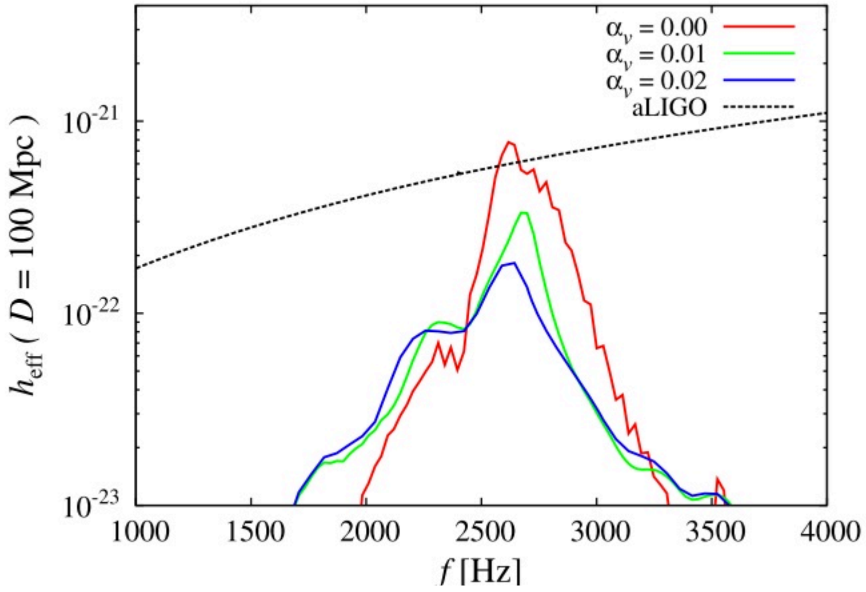
Ruiz & Shapiro 2017

Open Problem: Magnetic Field Effects in the PostMerger

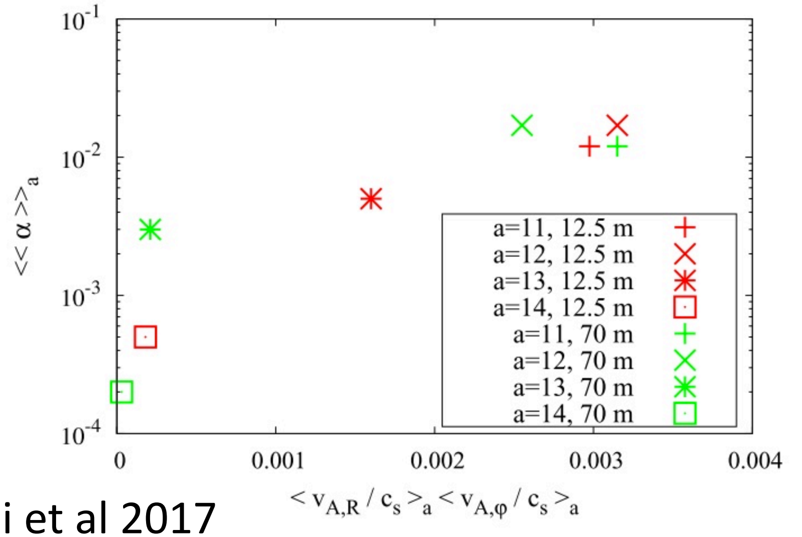




Shibata & Kiuchi 2017



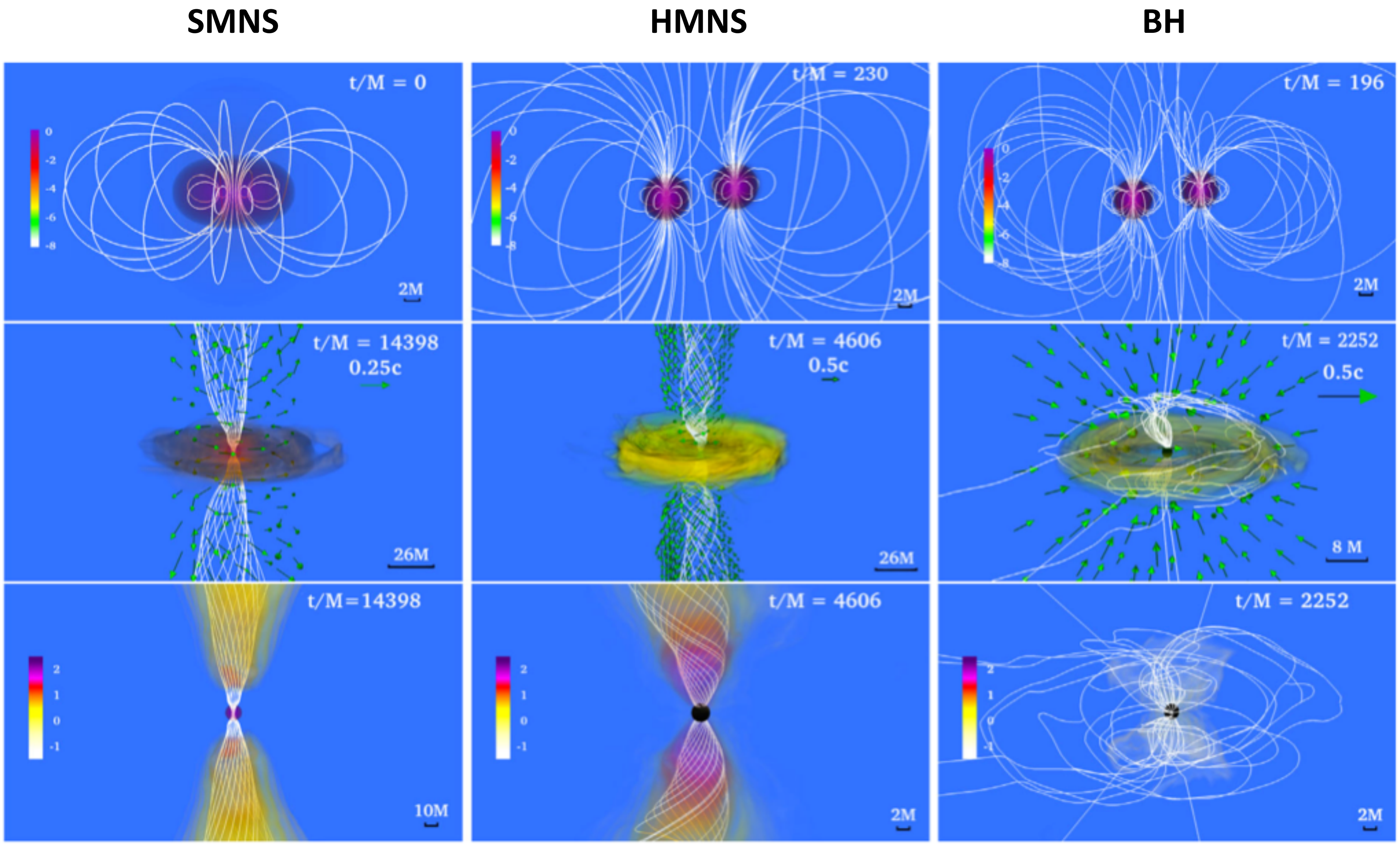
Shibata & Kiuchi 2017 state that strong magnetic fields can damp quickly the GW signal (result obtained using viscosity as a model for magnetic field effects).



Kiuchi et al 2017

Kiuchi et al 2017 performed ultra high resolution (dx=12.5 m) simulation of BNS post-merger remnant with magnetic fields. Magnetic field amplified via KH up to 1% of thermal energy and may act as viscosity with alpha_{max}~0.001-0.02.

Using GW and GRB to Infer Maximum NS Mass



In order to produce a jet it seems necessary to have an HMNS phase followed by BH collapse.

This would constrain the maximum mass to M_{max}~2.15-2.28 in order to explain GW170817 and GRB 170817A

Ruiz, Shapiro, and Tsokaros 2018, PRD 97, 021501(R)

CONCLUSIONS

- Open source codes can be used now to study binary neutron star mergers (Einstein Toolkit)
- Several BNS sims now with piecewise polytropes, cold tabulated EOSs, and a few finite temperature EOSs
- Neutrino effects still poorly studied (very few simulations include absorption by ejecta)
- Magnetic fields are crucial to explain GRBs, but only one code reported jet formation and with a simple Ideal Fluid EOS
- Magnetic field effects on GWs seem minimal, but discussion still going on in the community
- Simulations of BNS mergers in alternative theories of gravity are still limited (due to well-posedness problem)