# Numerical simulations of coalescing neutron star binaries Part II – BNS Simulations

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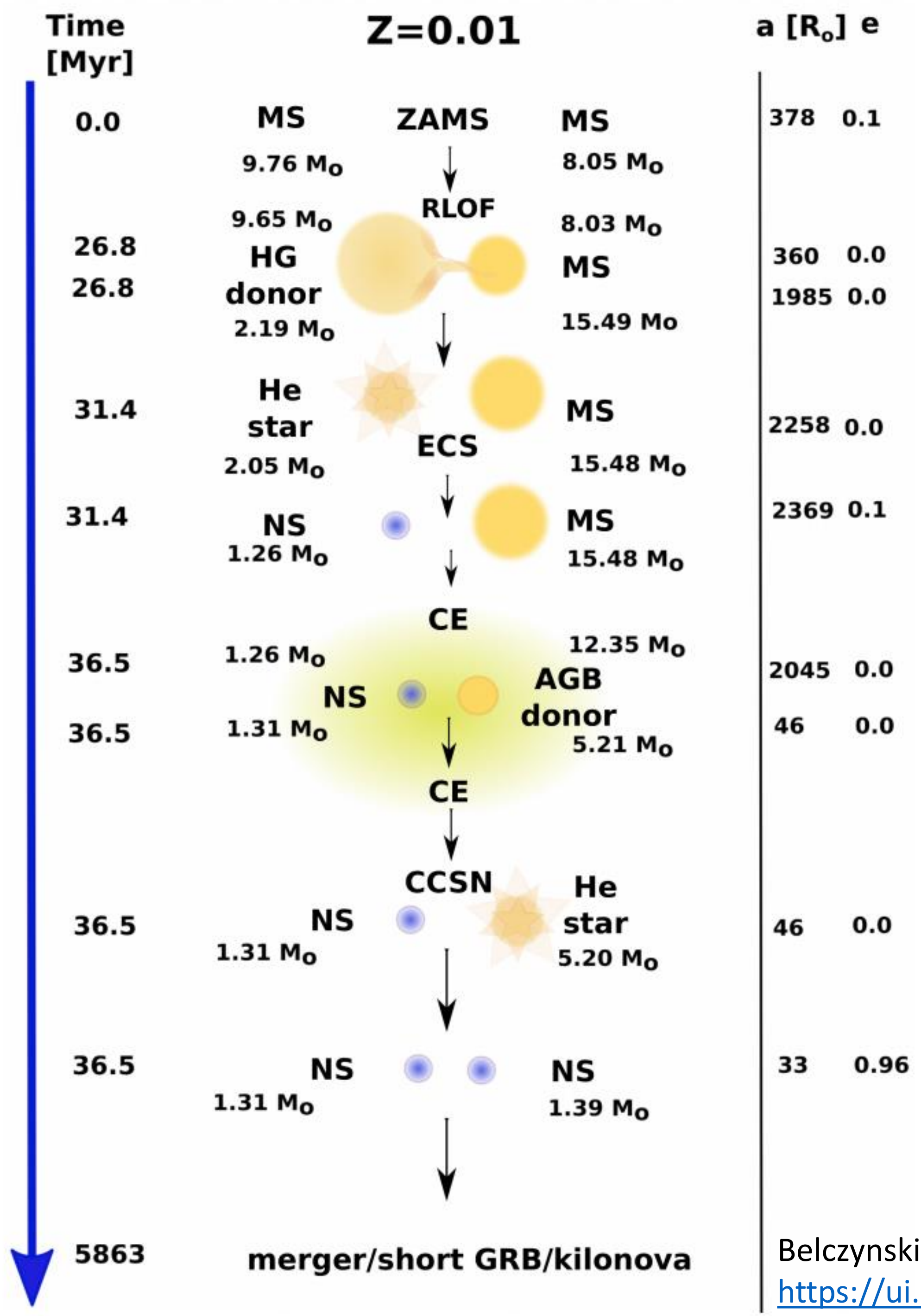
# NS Binary Formation




Several possible formation channels

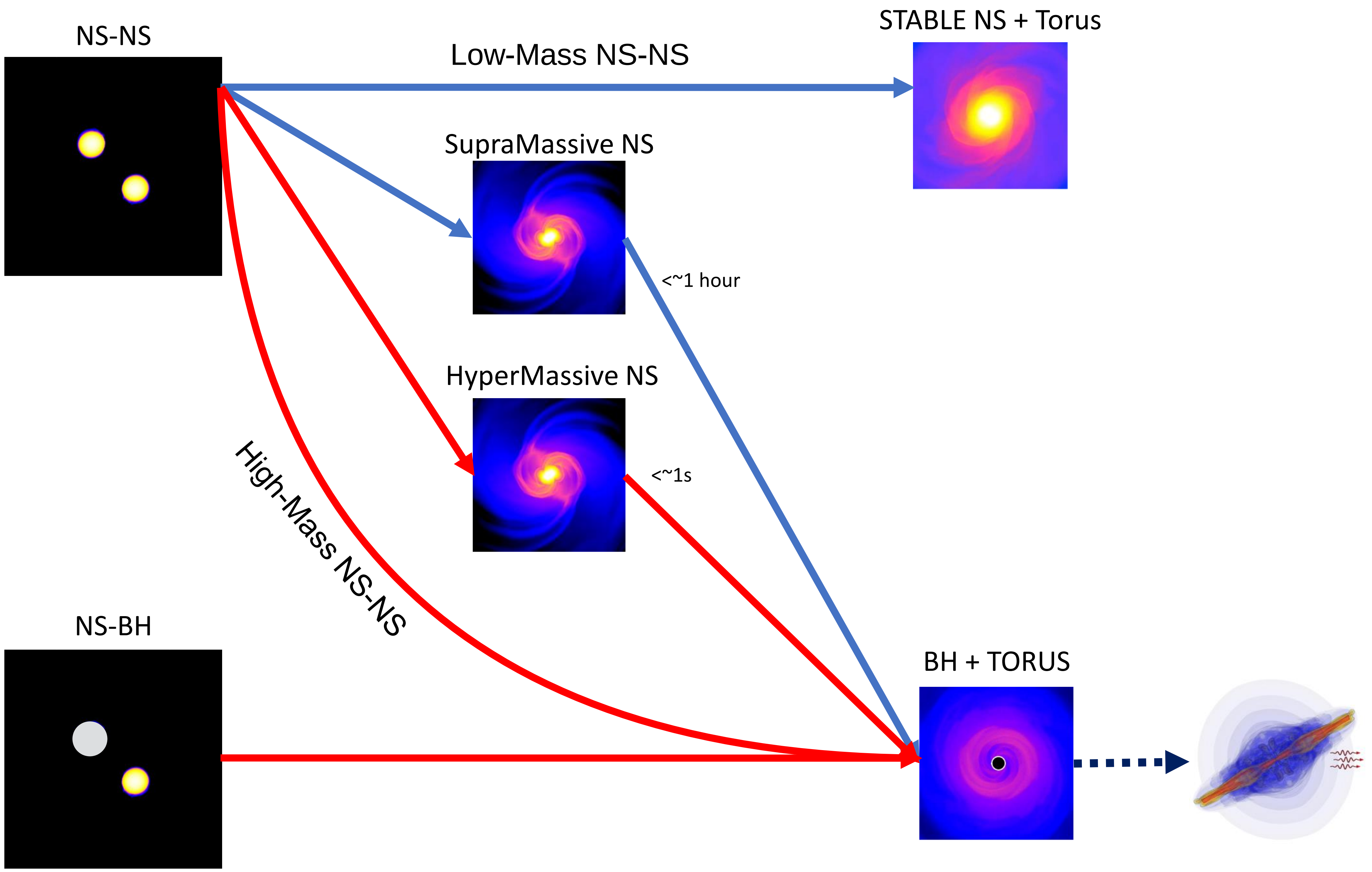
Requires two stars with masses between ~8 and ~20 M$_\odot$

System needs to survive both SN explosions and common envelope phase

Similar evolution (different progenitors) will lead to NS-BH and BH-BH binaries

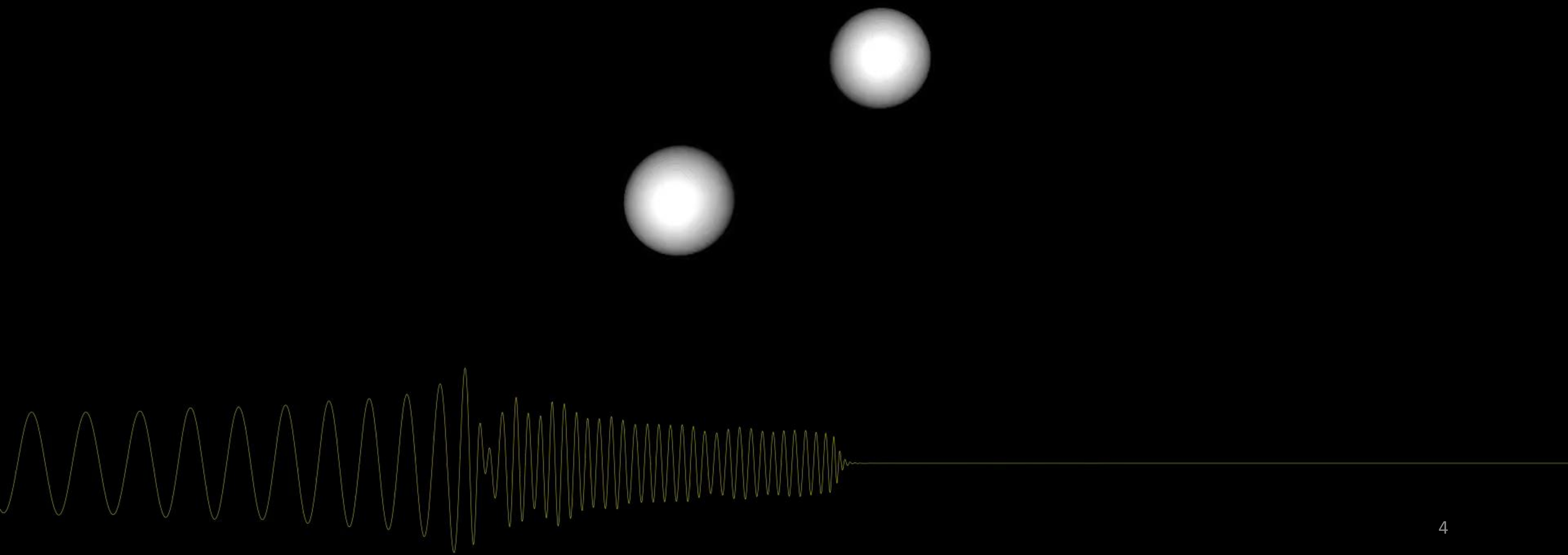
Belczynski et al 2018
https://ui.adsabs.harvard.edu/abs/2018A%26A...615A..91B/abstract

# Neutron Star Binary Mergers



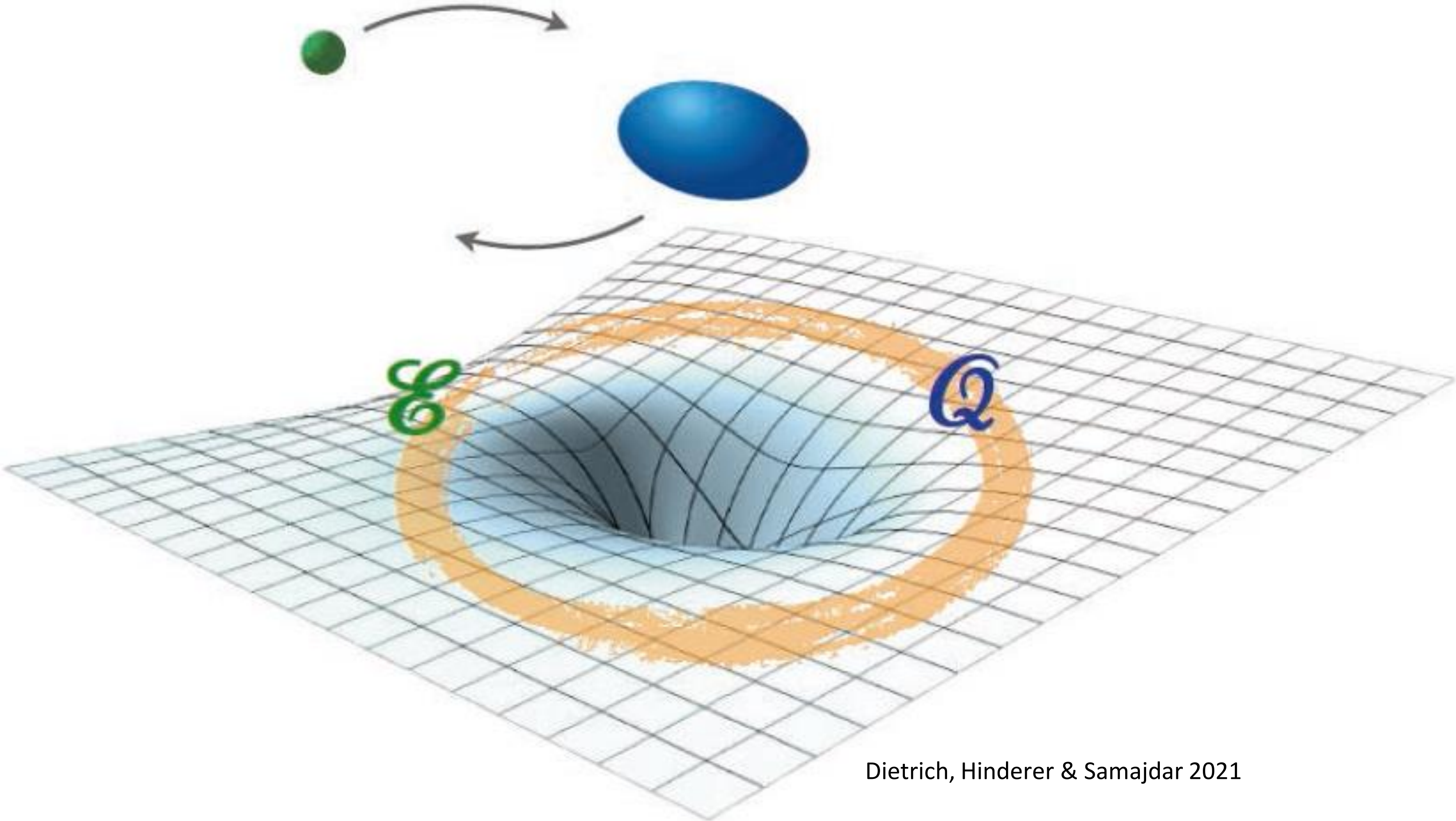
Kawamura et al 2016
Movie by W. Kastaun

t = 0.0 ms



# Matter Effects on BNS GW signals

# Tidal Deformability




Dietrich, Hinderer & Samajdar 2021

For recent reviews, see
Chatziioannou 2020 https://link.springer.com/article/10.1007/s10714-020-02754-3
Dietrich, Hinderer & Samajdar 2021 https://link.springer.com/article/10.1007/s10714-020-02751-6

**Newtonian Theory**:

- external quadrupolar tidal field $\mathcal{E}_{ij} = \frac{\partial^2 \Phi_{ext}}{\partial x^i \partial x^j}$
- induced quadrupole moment $Q_{ij} = \int \delta\rho(\boldsymbol{x}) \left( x_i x_j - \frac{1}{3} r^2 \delta_{ij} \right) d^3x$
- the **dimensionless Love number** $k_2$ is then introduced by $Q_{ij} = -\frac{2}{3G} k_2 R^5 \mathcal{E}_{ij}$
- in general, it needs to be computed numerically
- important  to note that for a rigid body $k_2 = 0$

**General Relativity**:

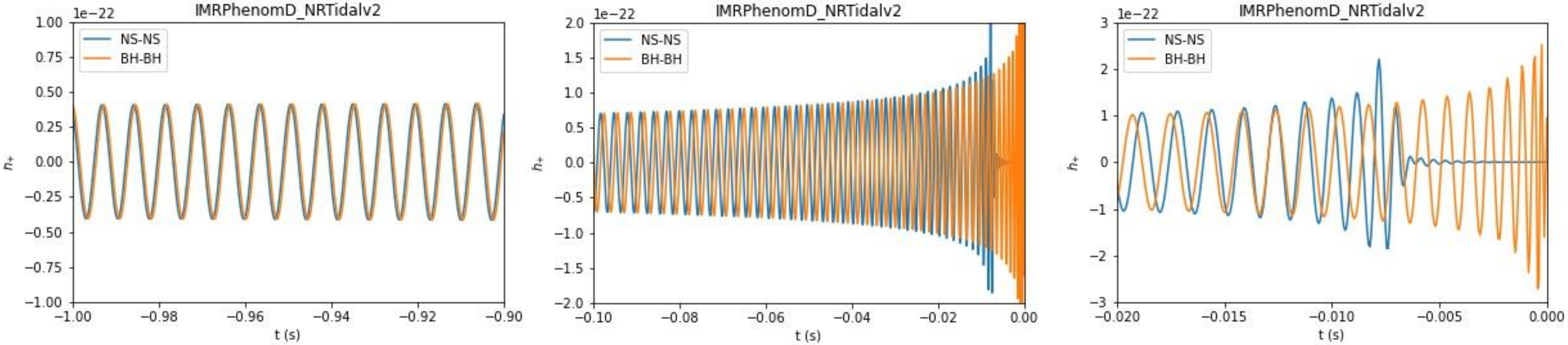
- An important quantity that can be measured is the **dimensionless tidal deformability**:

$$\Lambda = \frac{2}{3} k_2 \left[ \left( \frac{c^2}{G} \right) \left( \frac{R}{m} \right) \right]^5$$

- In BNS systems one can more easily extract a combination of the tidal deformabilities of the two NSs:

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

- $M_1 = M_2 = 1.3717$
- $\Lambda_1 = \Lambda_2 = 1013.4$ (BNS) vs $\Lambda_1 = \Lambda_2 = 0$ (BBH)



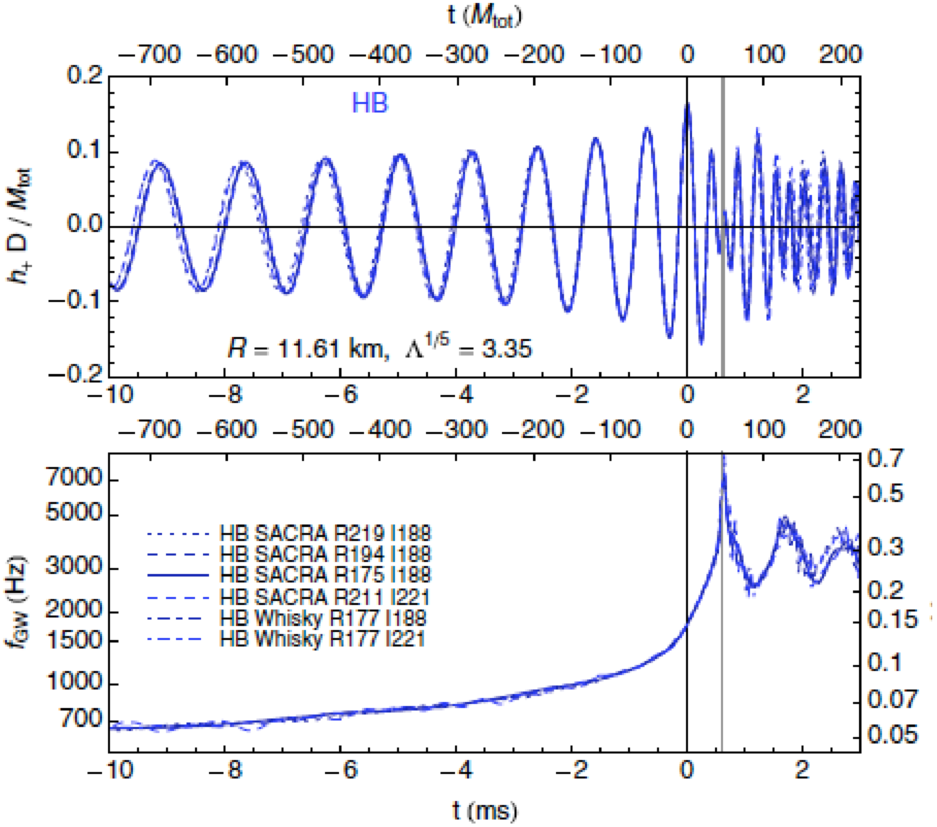
# MATTER EFFECTS ON BNS GWS

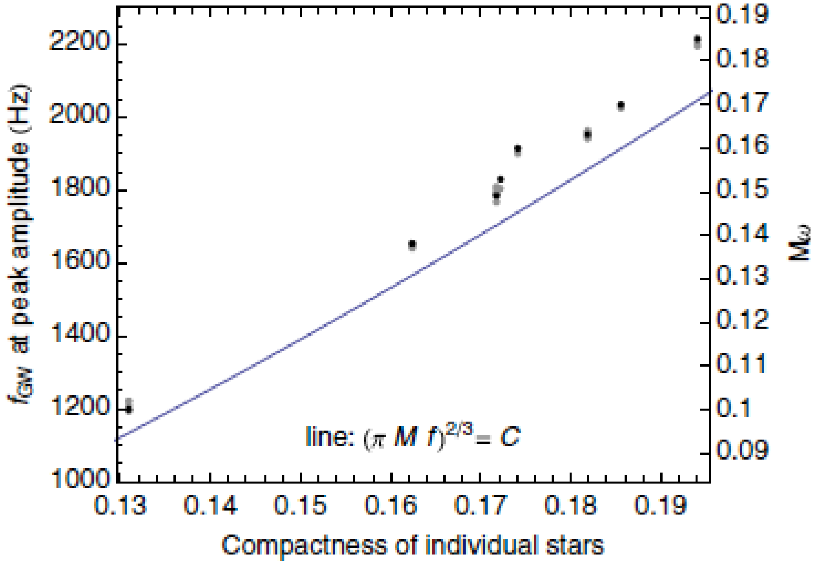
(Read et al 2013, PRD 88, 044042)

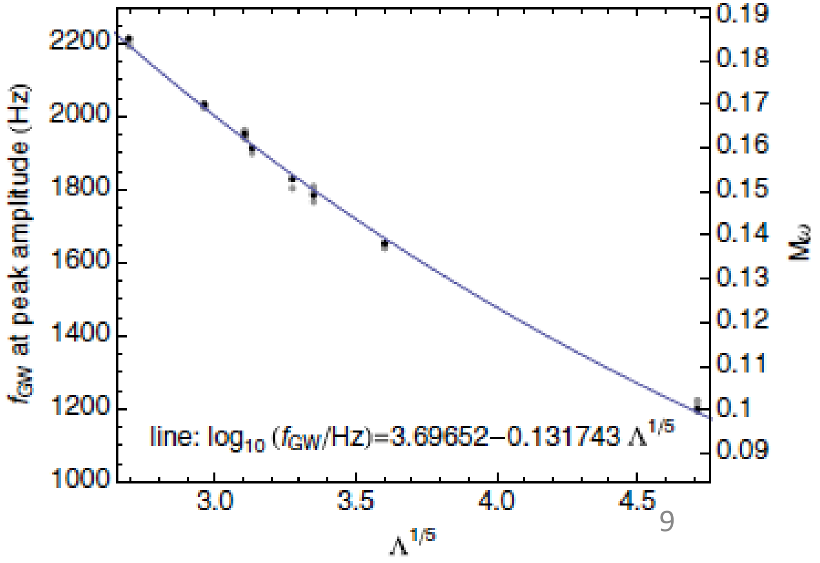
We used the Whisky and SACRA codes to perform the first multi-code study of EOS effects on merger waveforms for equal-mass systems

Used an extended set of EOSs

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

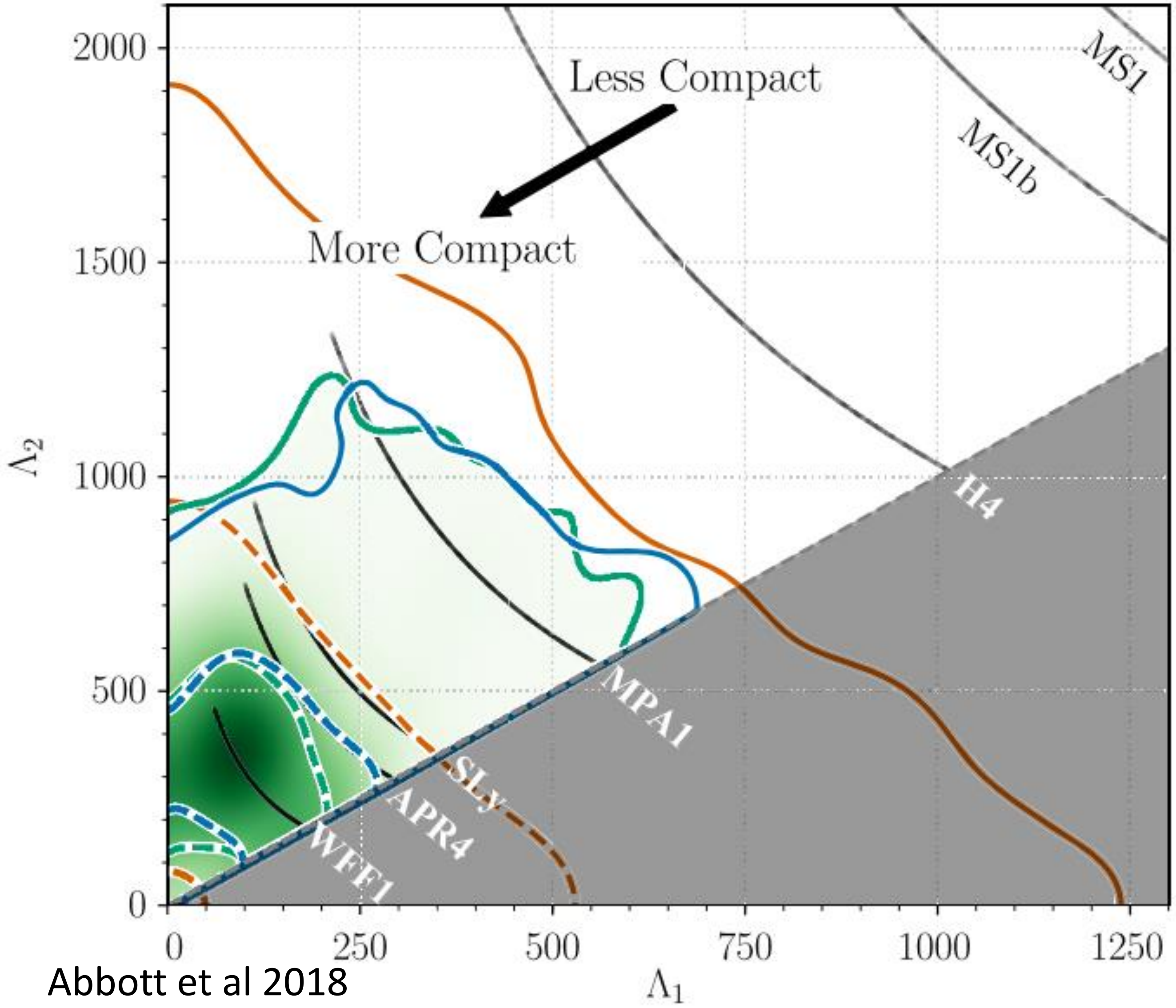


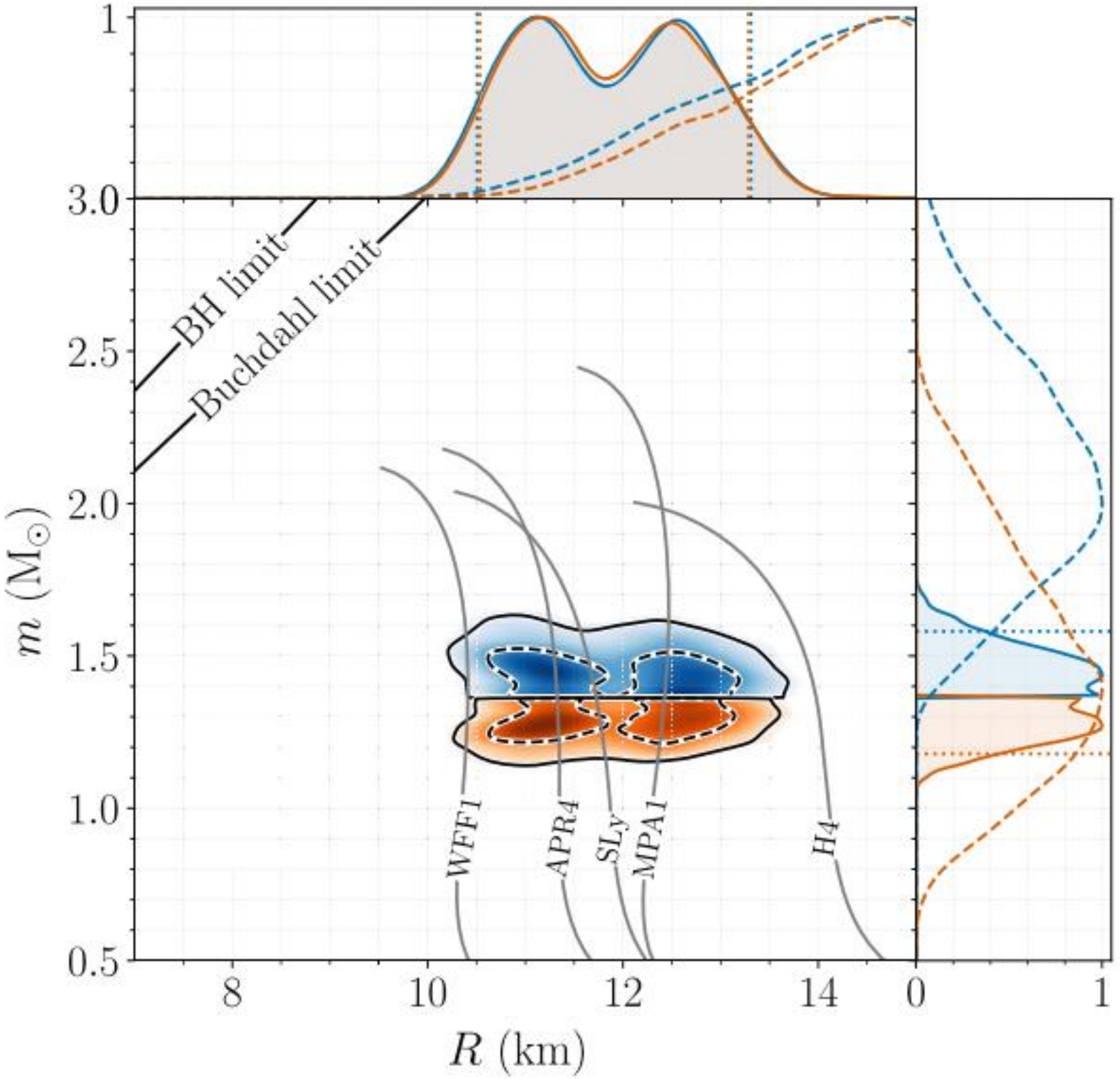




GW frequency at merger is well correlated with tidal deformability and NS compactness.
(see also Bernuzzi et al 2014).

# GW170817: EOS constraints




Abbott et al 2018




First measure of NS EOS (radius) via gravitational waves. Several stiff EOSs now excluded.

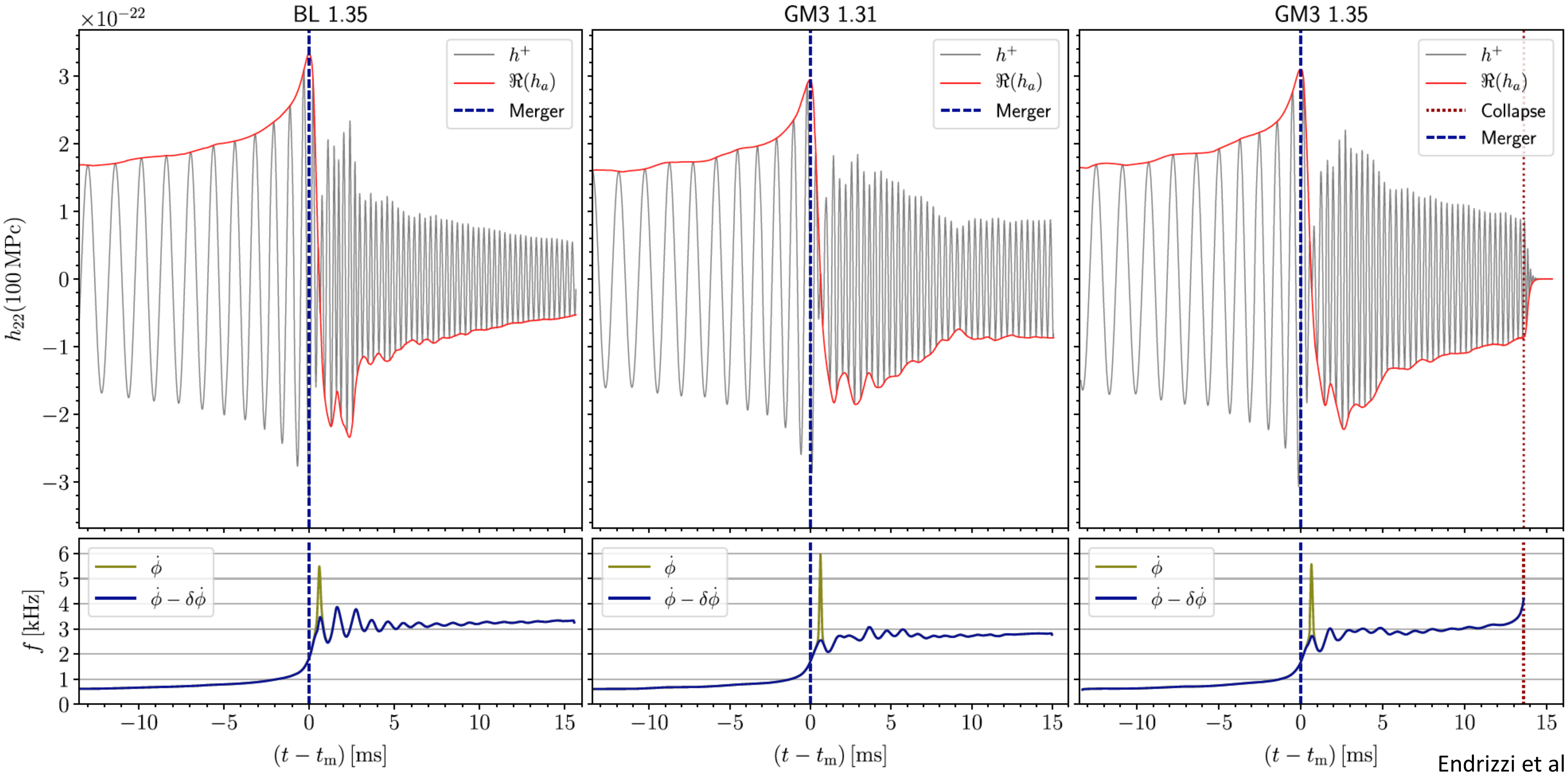
# GWs in the INSPIRAL (Recap)

- Dominant Parameters:
  - Masses and Mass Ratios
  - Equation of State (Tidal Deformability)

- Minor corrections (maybe):
  - Spin (only relevant if $\chi > 0.05$). Fastest spinning NS observed in an NS-NS system (PSR J0737-3039A) has $\chi \sim 0.02$ $(\mathrm{P} \sim 22.7\ ms)$.
  - Eccentricity. This is relevant only for BNS systems formed via dynamical capture in star clusters and globular clusters.

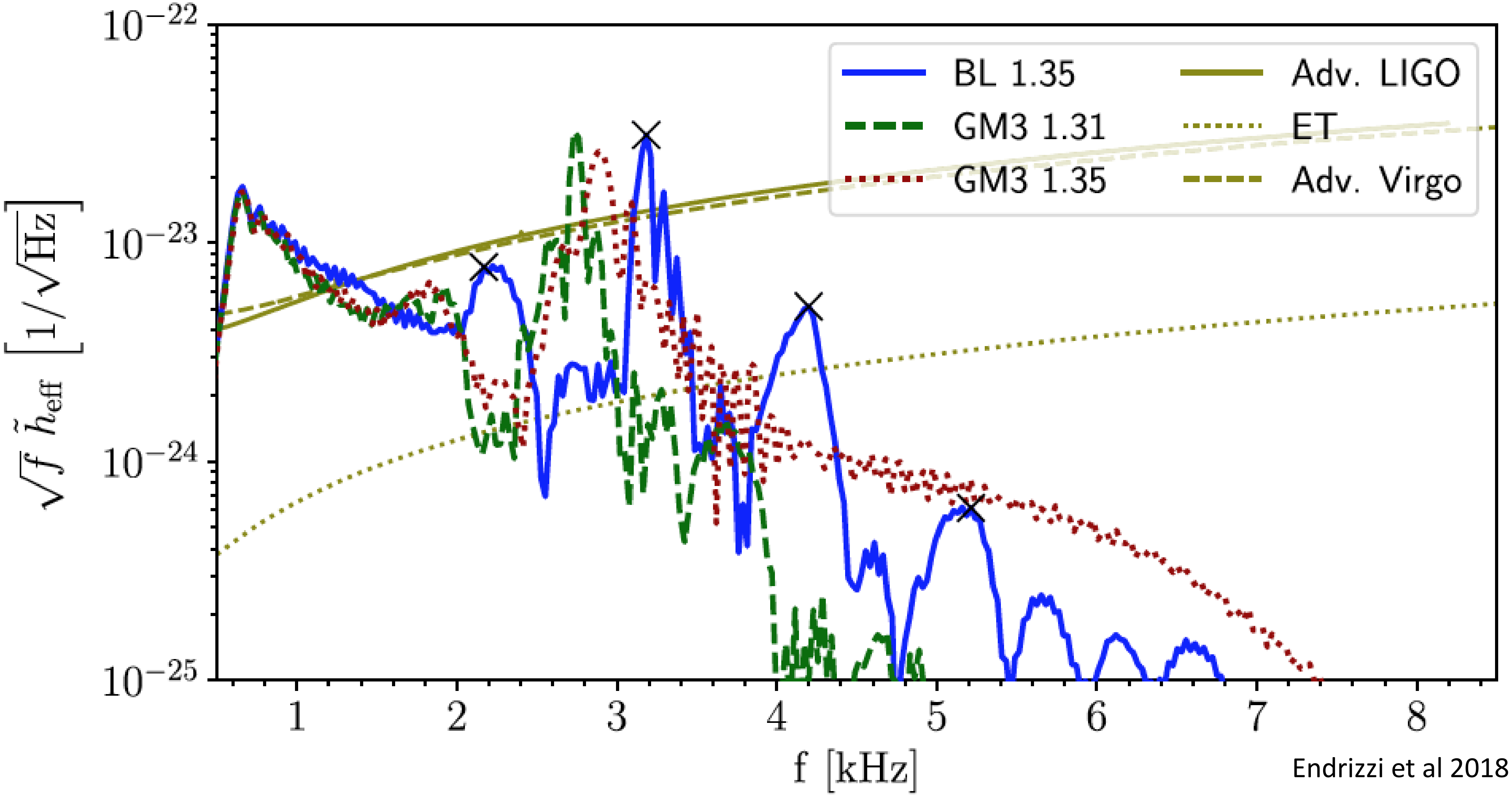
# POST-MERGER GW SIGNAL

# GW: EOS Effects on the Post-Merger Phase



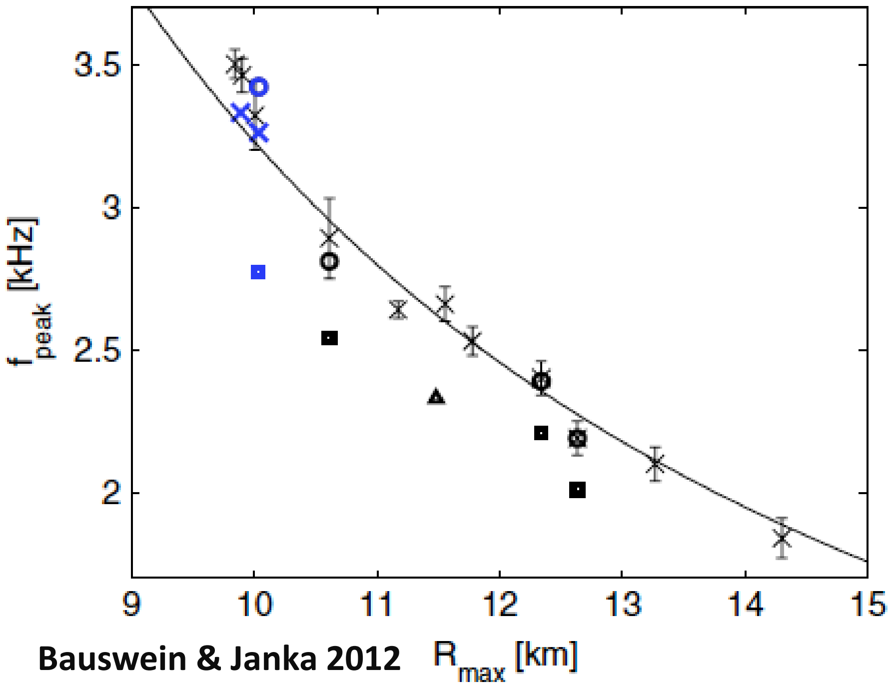

Endrizzi et al 2018

# GW: EOS Effects on the Post-Merger Phase




Endrizzi et al 2018

# GW: EOS Effects on the Post-Merger Phase

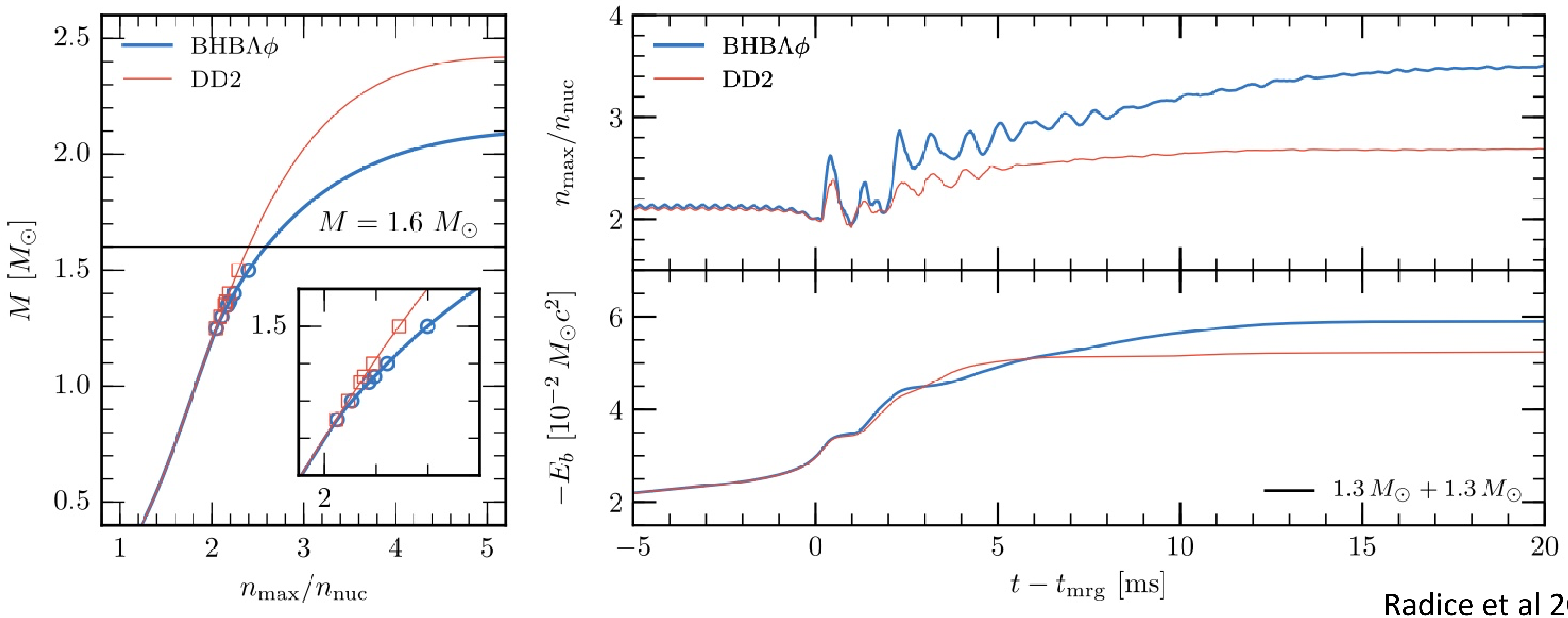



**Bauswein & Janka 2012**

Bauswein & Janka 2012, Hotokezaka et al 2013: frequency peak in GWs emitted after merger can constrain EOS

High sensitivities at f>~1Khz required for post-merge signal!

# GW: EOS Effects on the Post-Merger Phase

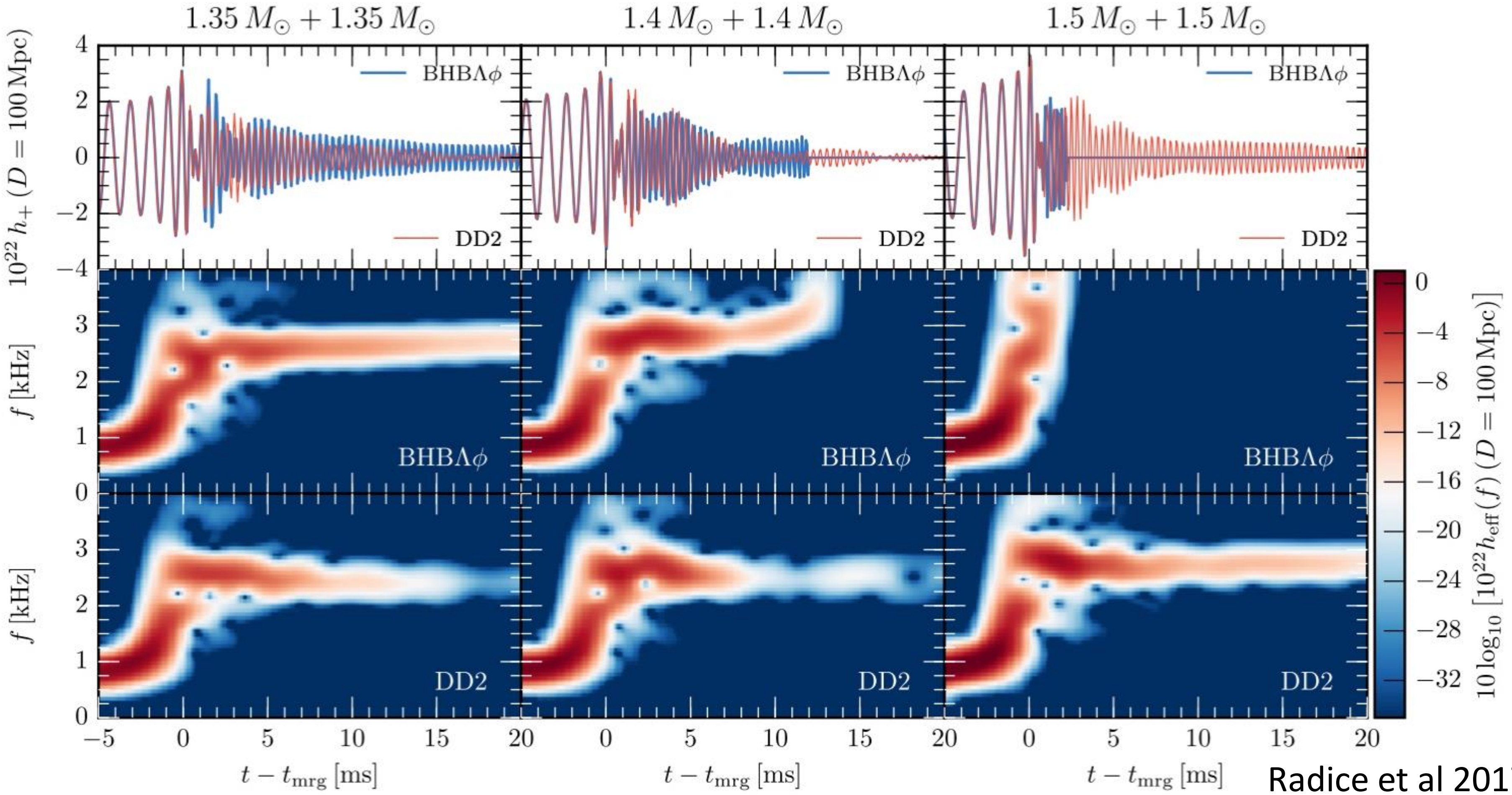



Radice et al 2017

EOS identical at "low" (inspiral) densities, but different at post-merger densities (phase transition effects).

# GW: EOS Effects on the Post-Merger Phase

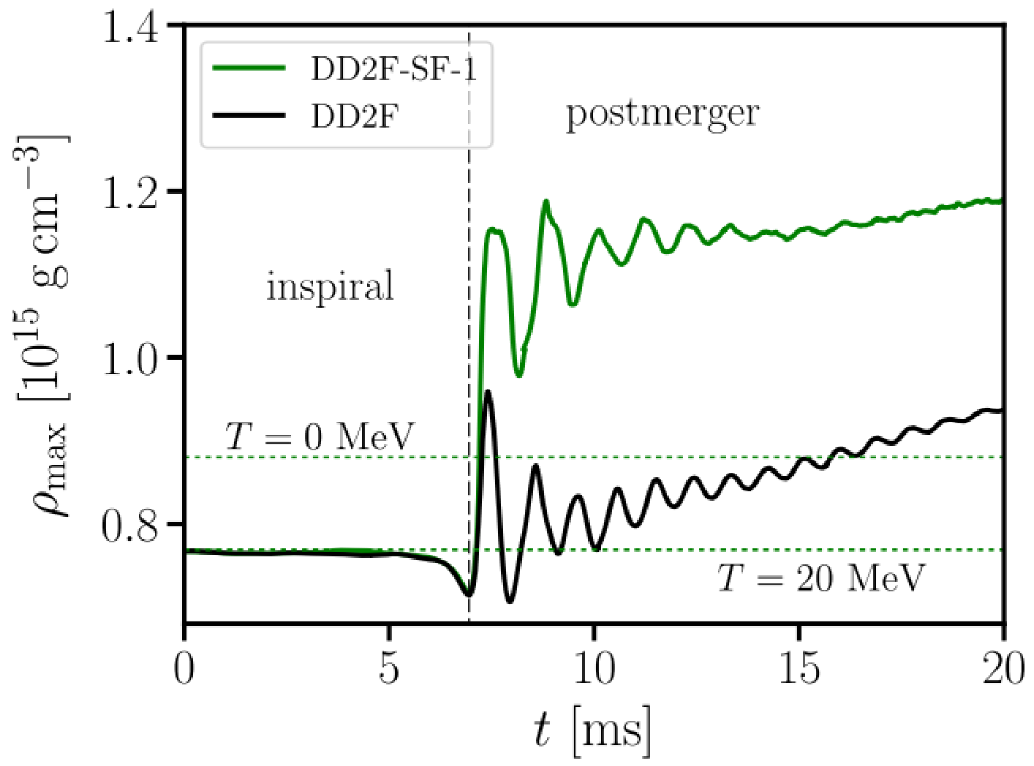
Same post-merger frequencies. Difficult to distinguish between the two, unless collapse to BH is detected.

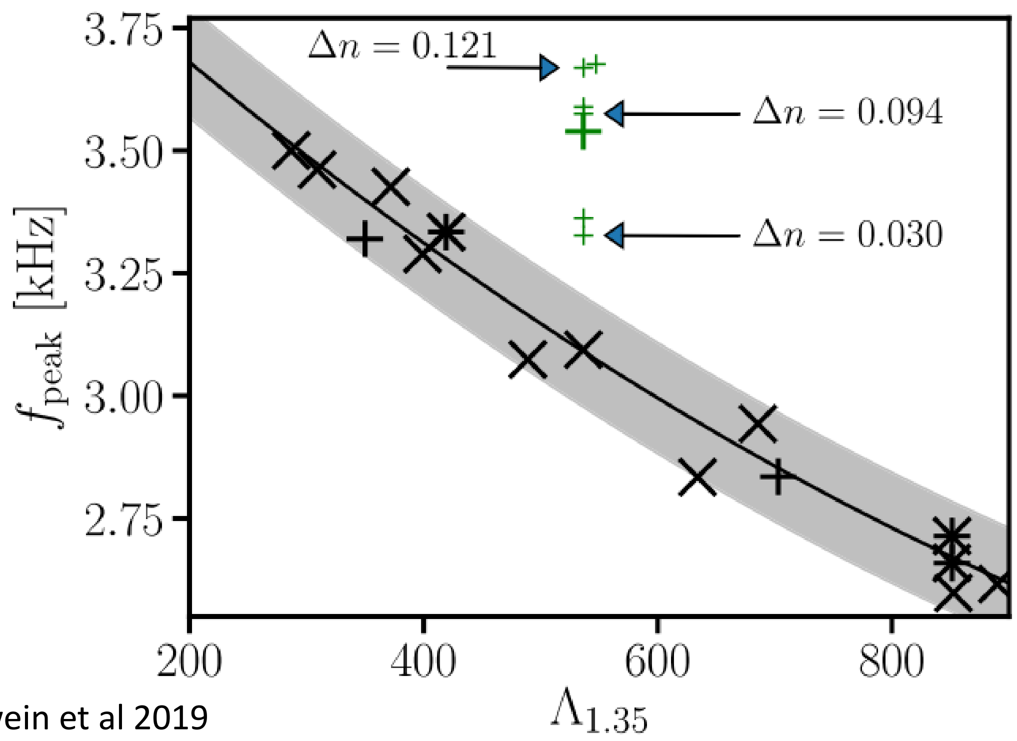



Radice et al 2017

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

# Phase transitions in the post-merger



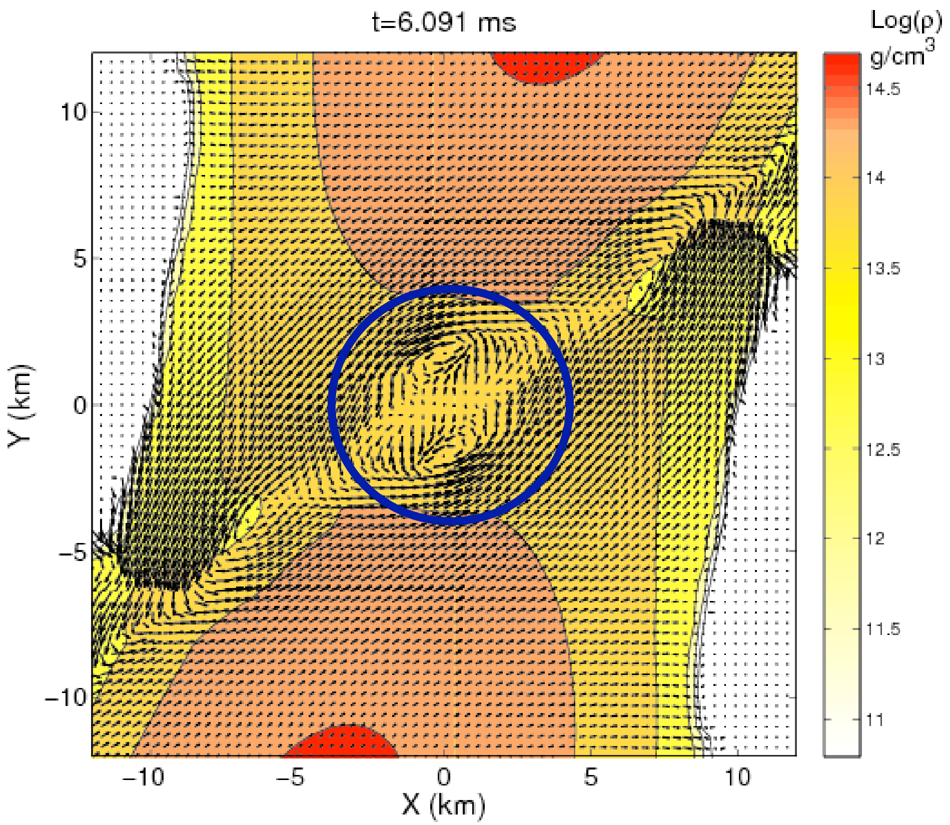




Bauswein et al 2019

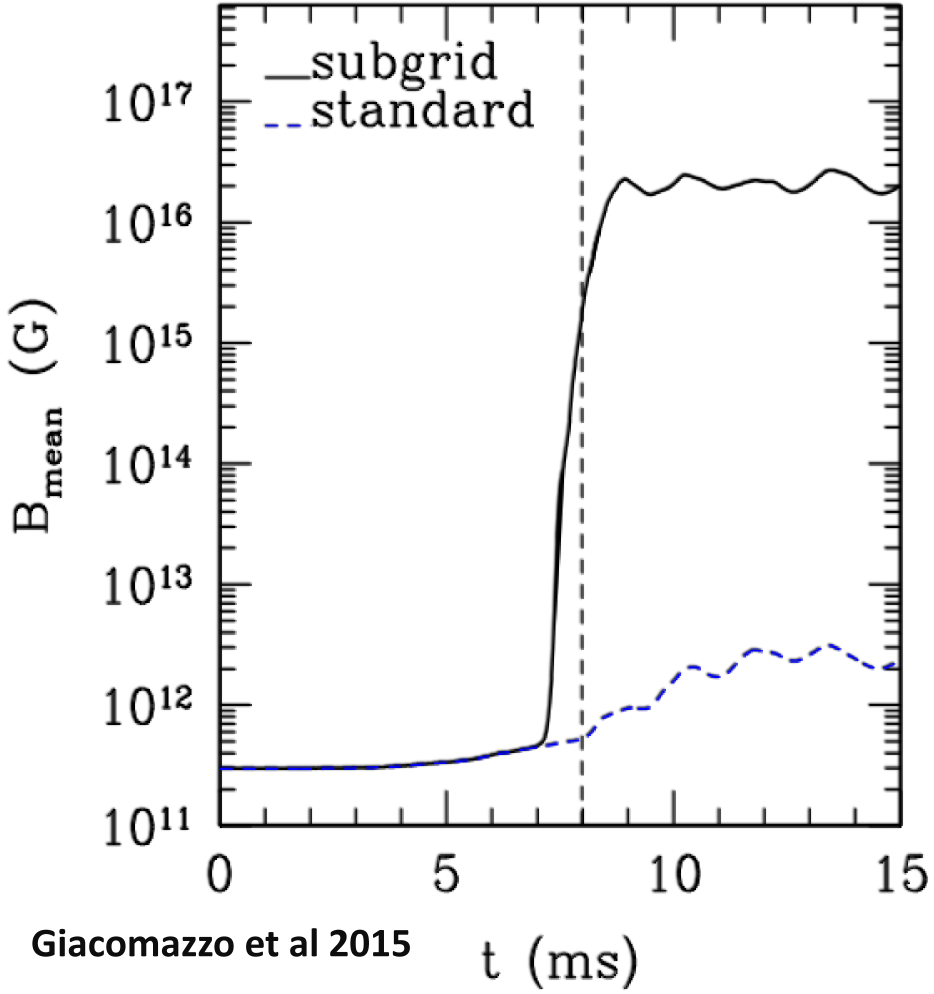
A phase transition to a deconfined-quark-matter core affects significantly the post-merger GW peak.
(see Mondal et al 2023 for an example of PT detection instead in the GW inspiral)

# 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.



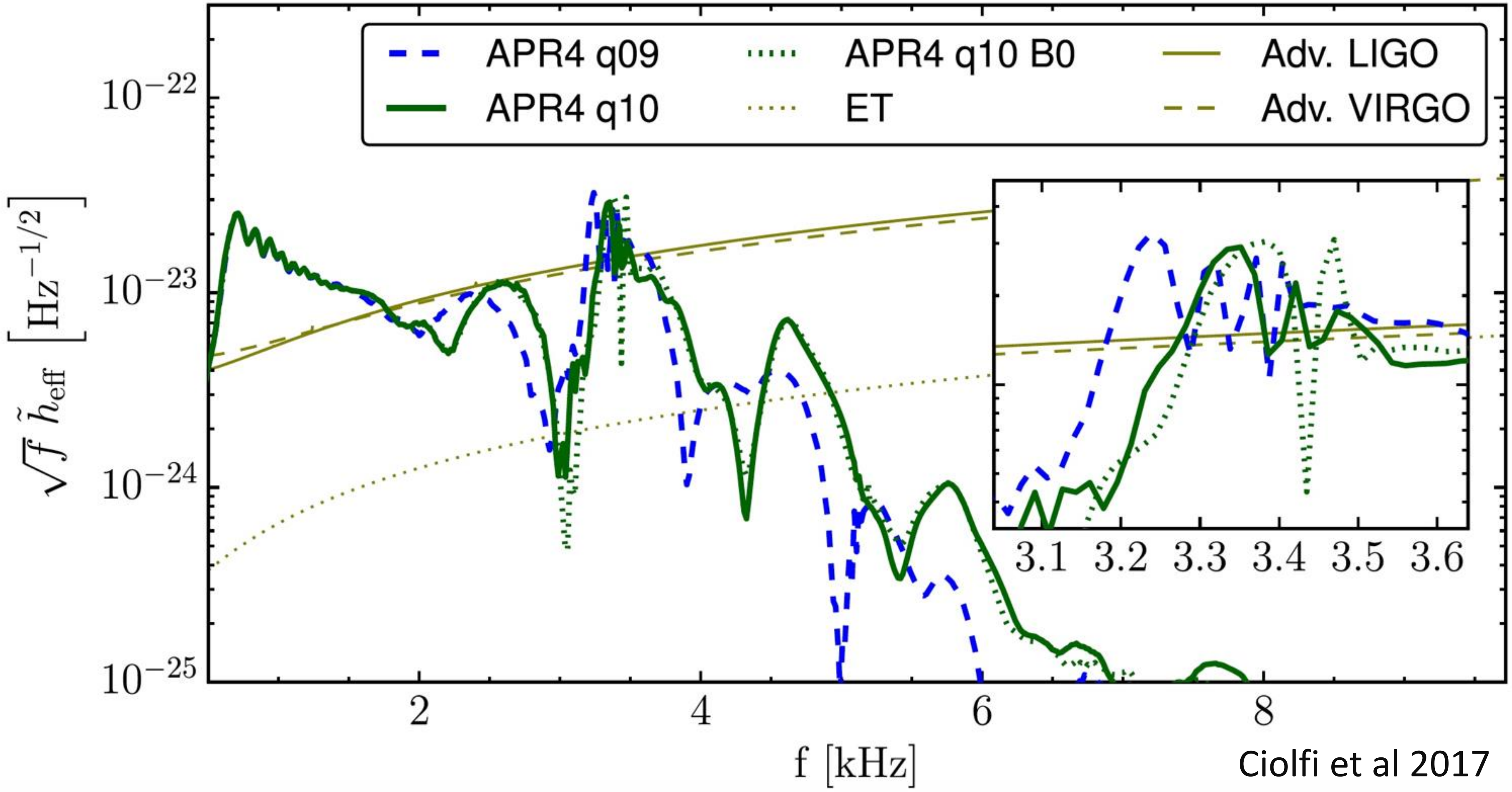

Baiotti et al 2008




Giacomazzo et al 2015

After merger the magnetic field may grow up to equipartition with the kinetic energy of the turbulent fluid ($B \sim 10^{16}$G).

# Magnetic field effects on GWs



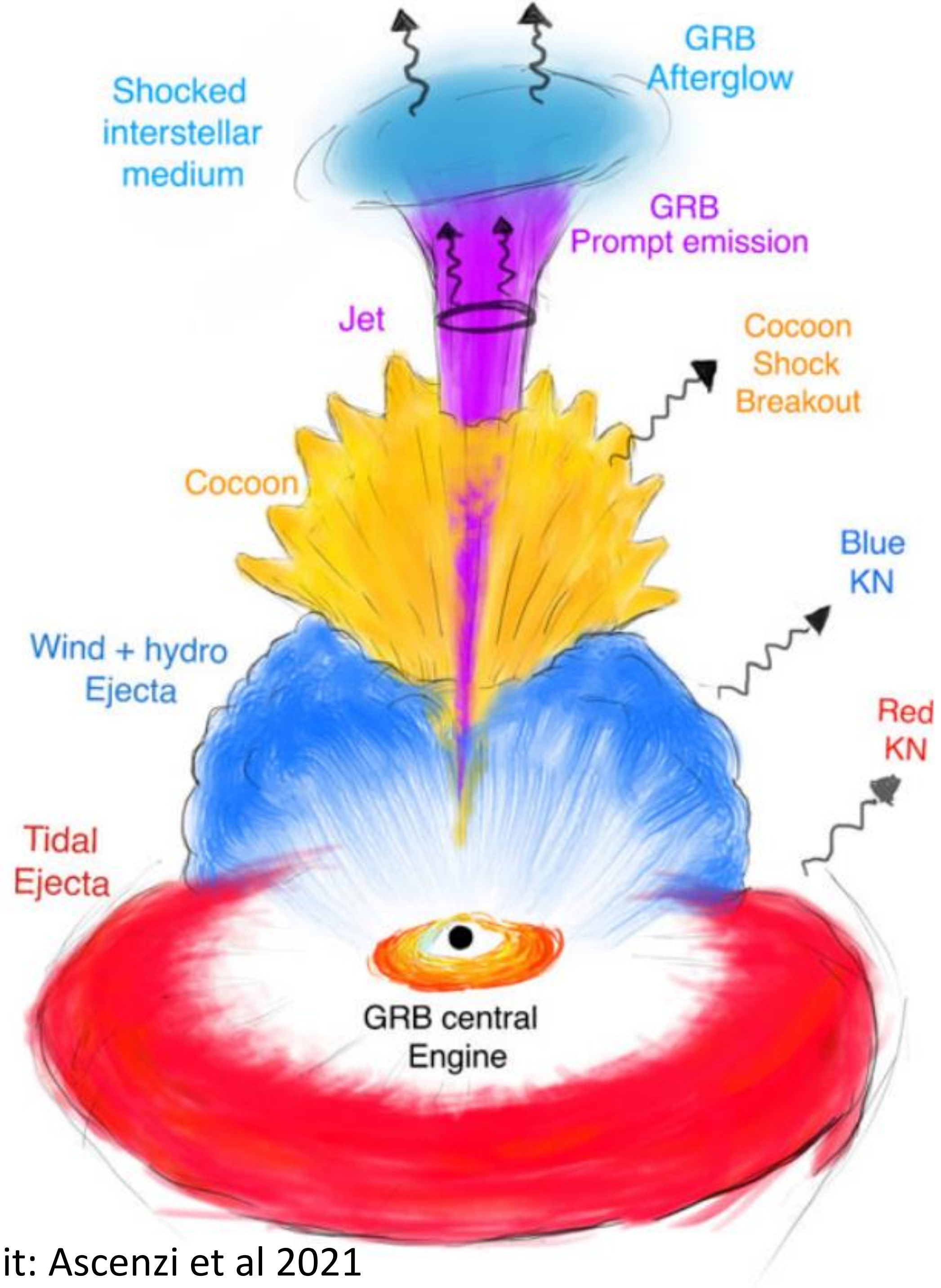

Ciolfi et al 2017

We simulated a BNS merger with high magnetic fields. Difference in the post-merger peak of less than ~100 Hz.

# GWs in the POST-MERGER (Recap)

- Dominant Parameters:
  - Equation of State (high density, high temperature, possible phase transition)

- Minor corrections (maybe):
  - Magnetic field. Even if amplified up to $\sim 10^{16}$ G it does not seem to affect post-merger GW frequency. It may dump down the amplitude of the signal though making it more difficult to detect.



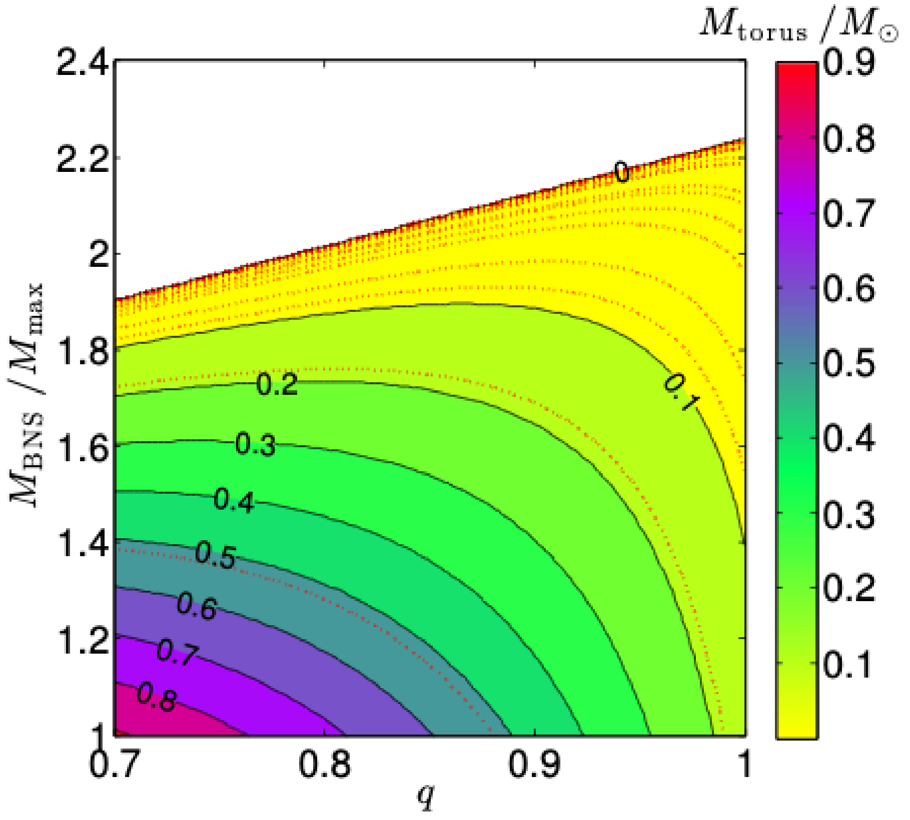

Credit: Ascenzi et al 2021

# Electromagnetic Emission

# SGRB

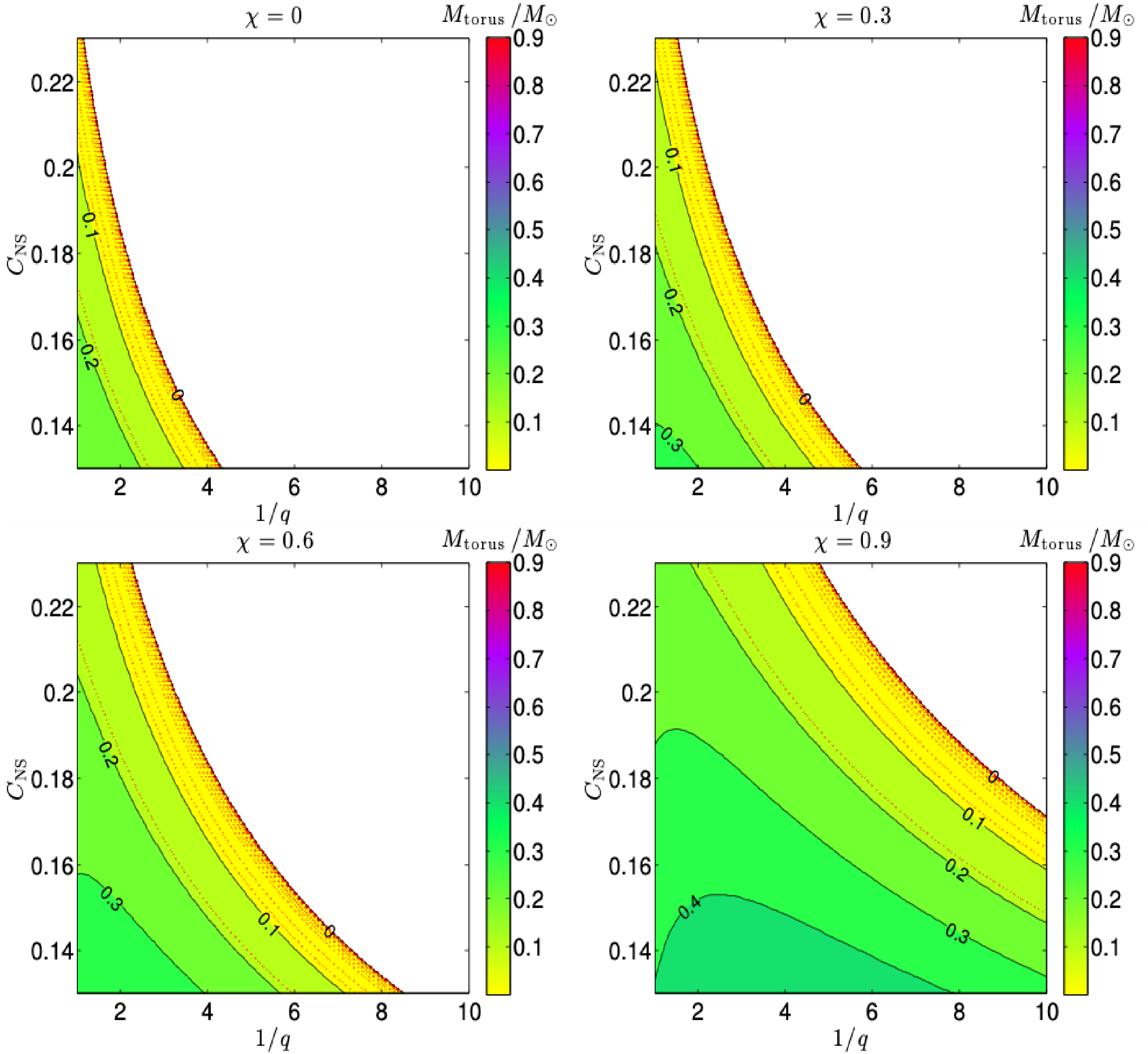
# Torus Masses from Mergers

## NS-NS



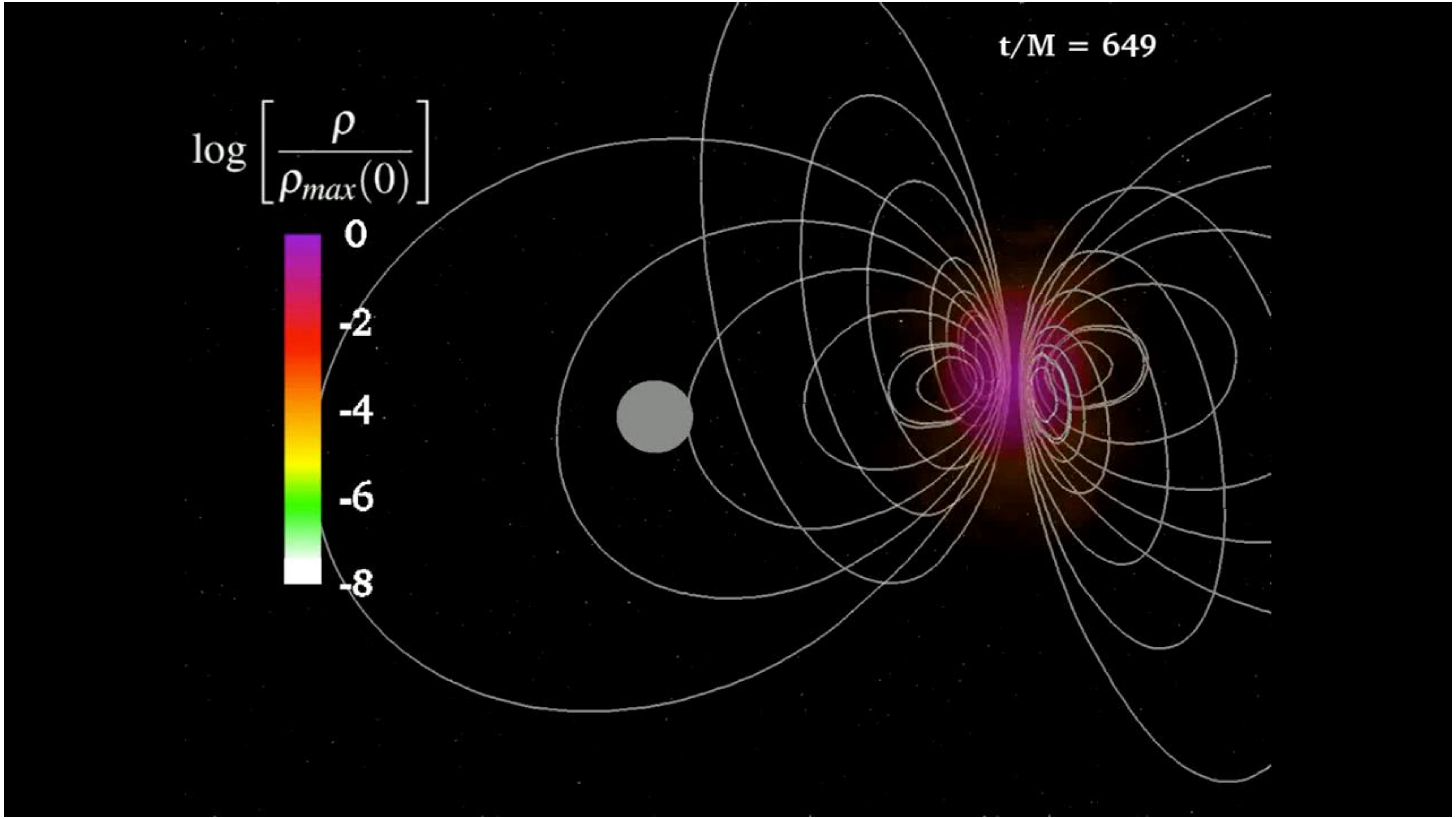

Giacomazzo et al 2013

## NS-BH



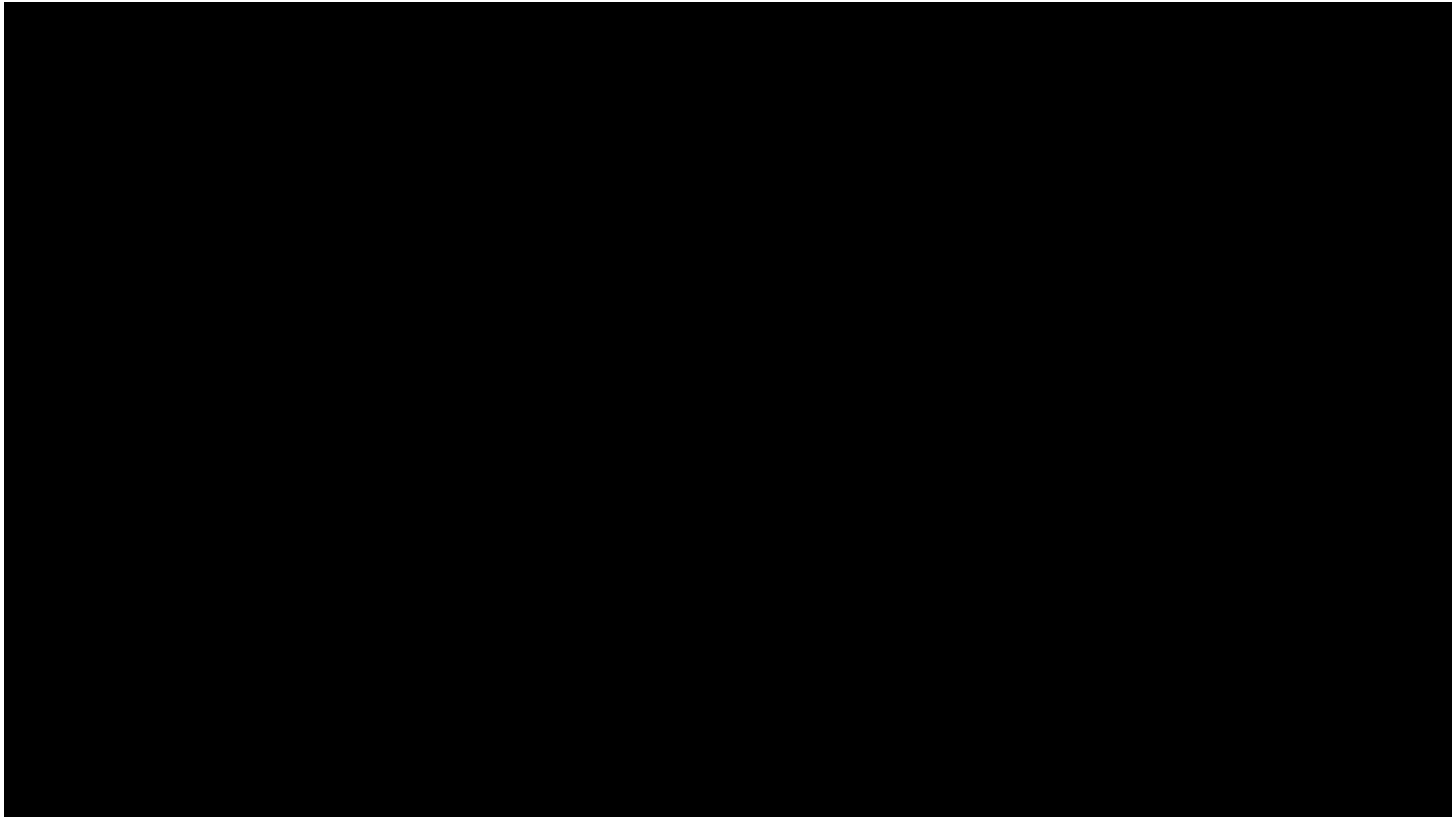

Both NS-NS and NS-BH may produce massive tori.

Paschalidis et al 2014, arXiv:1410.7392



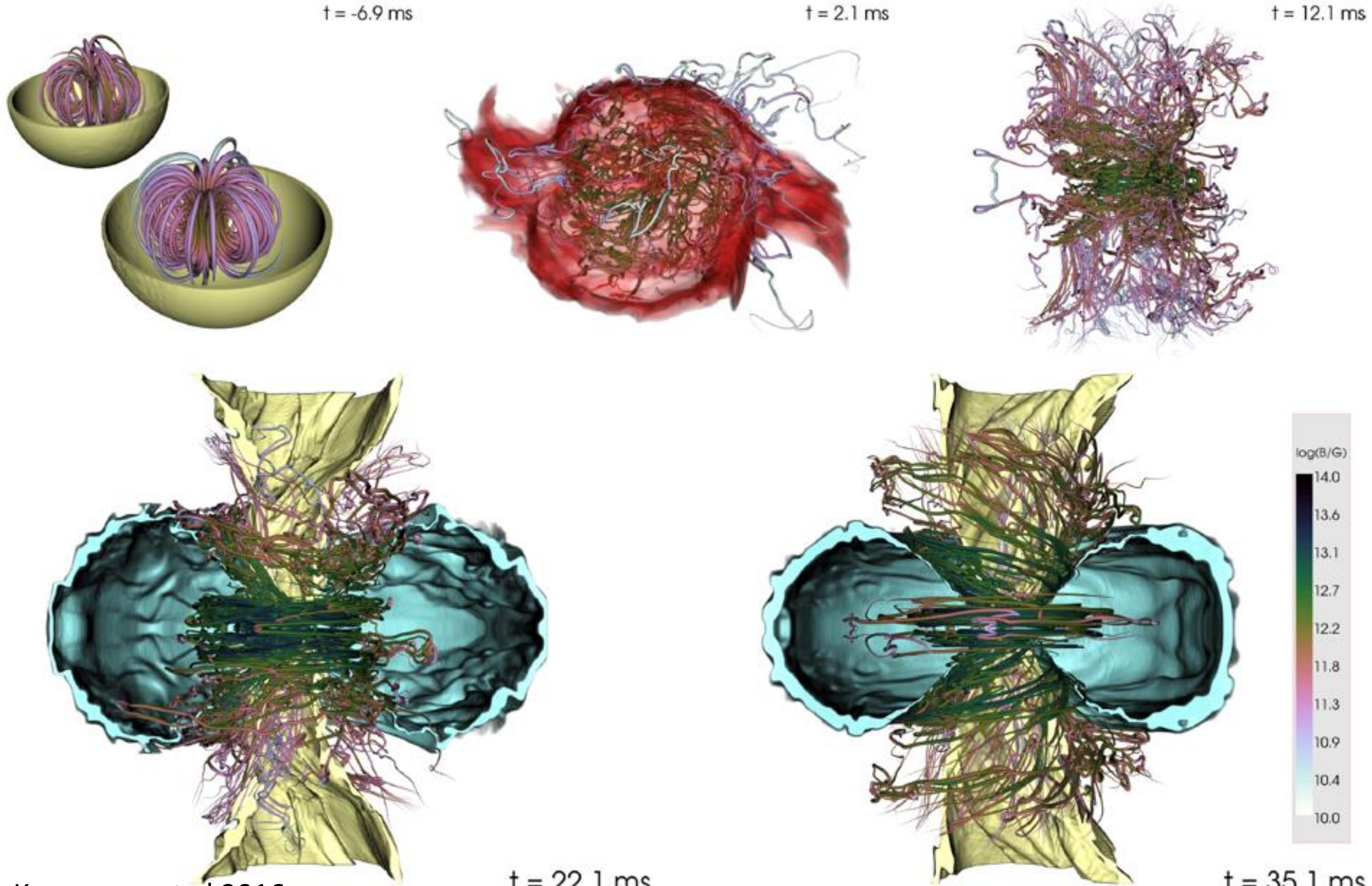

Credits: http://research.physics.illinois.edu/cta/movies/BHNS_jets/

Ruiz et al 2016, arXiv:1604.02455



Credits: http://research.physics.illinois.edu/cta/movies/NSNS_high_res/density_ext.html

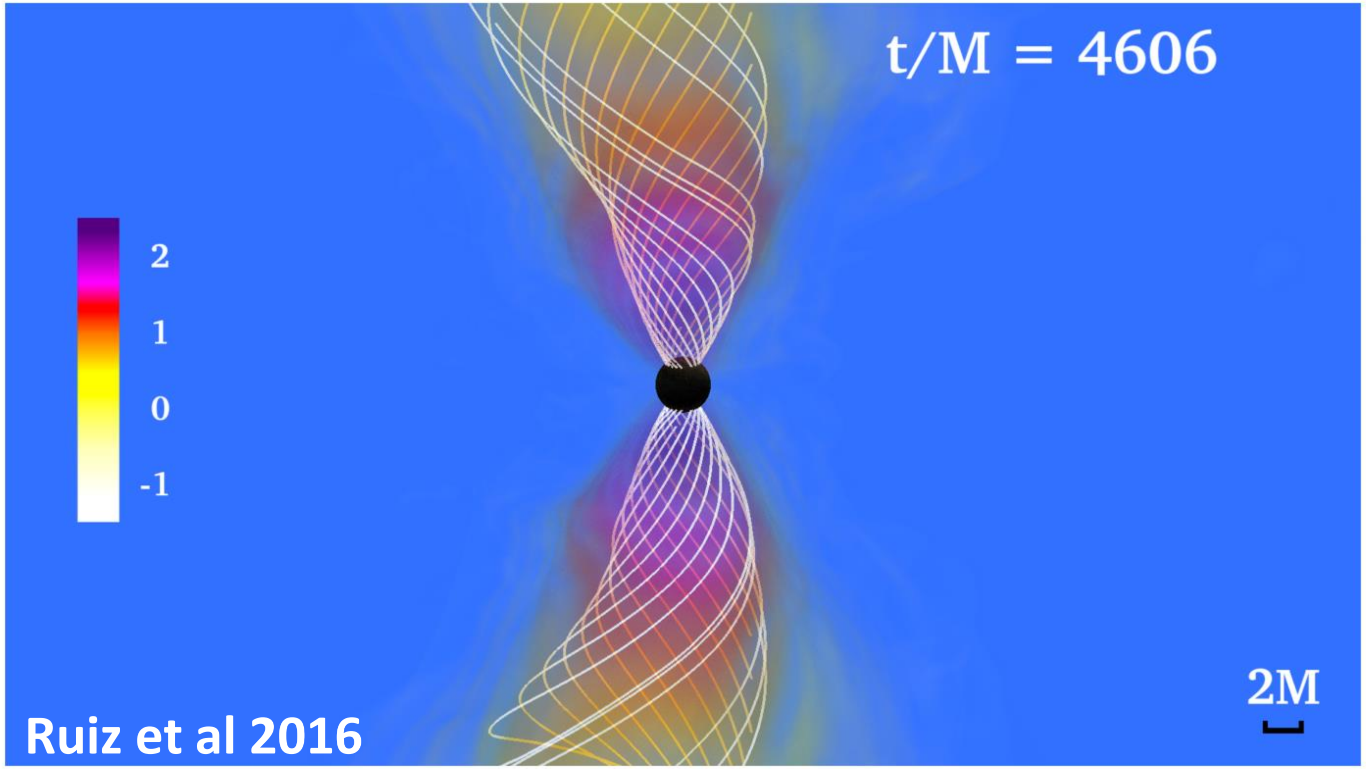
# Magnetic Field Structure Evolution



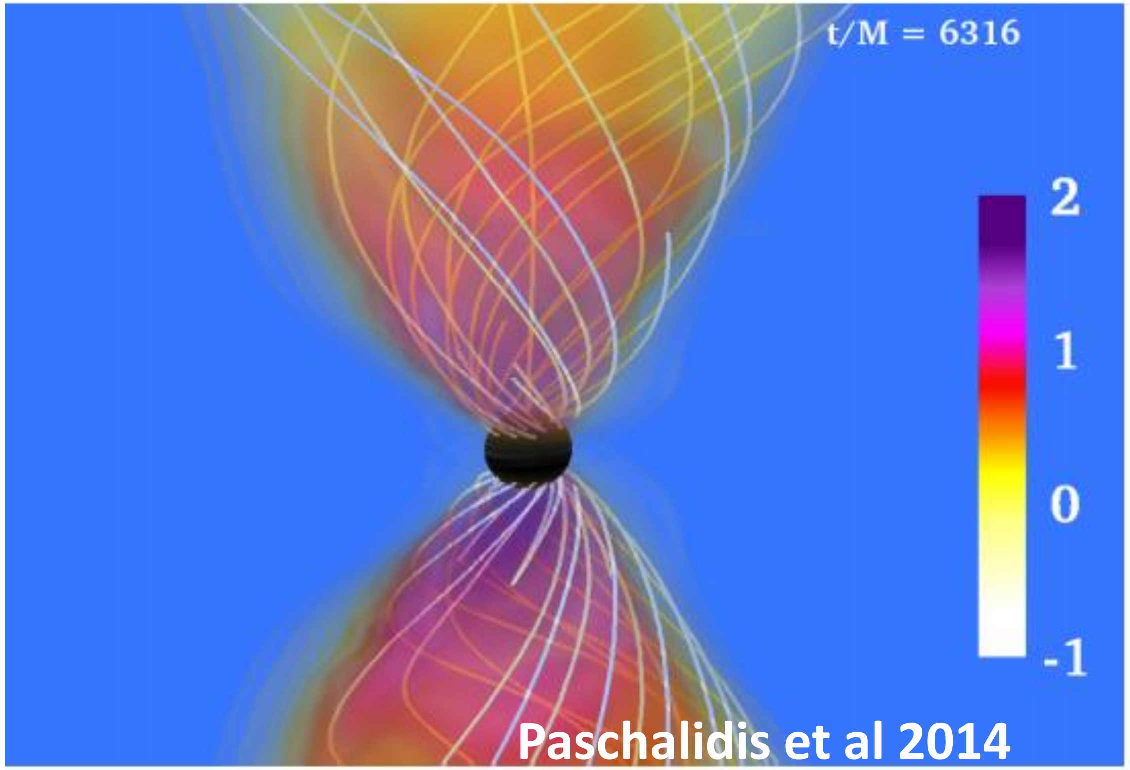

Kawamura et al 2016

# JETS FROM NS BINARY MERGERS

NS-NS




NS-BH



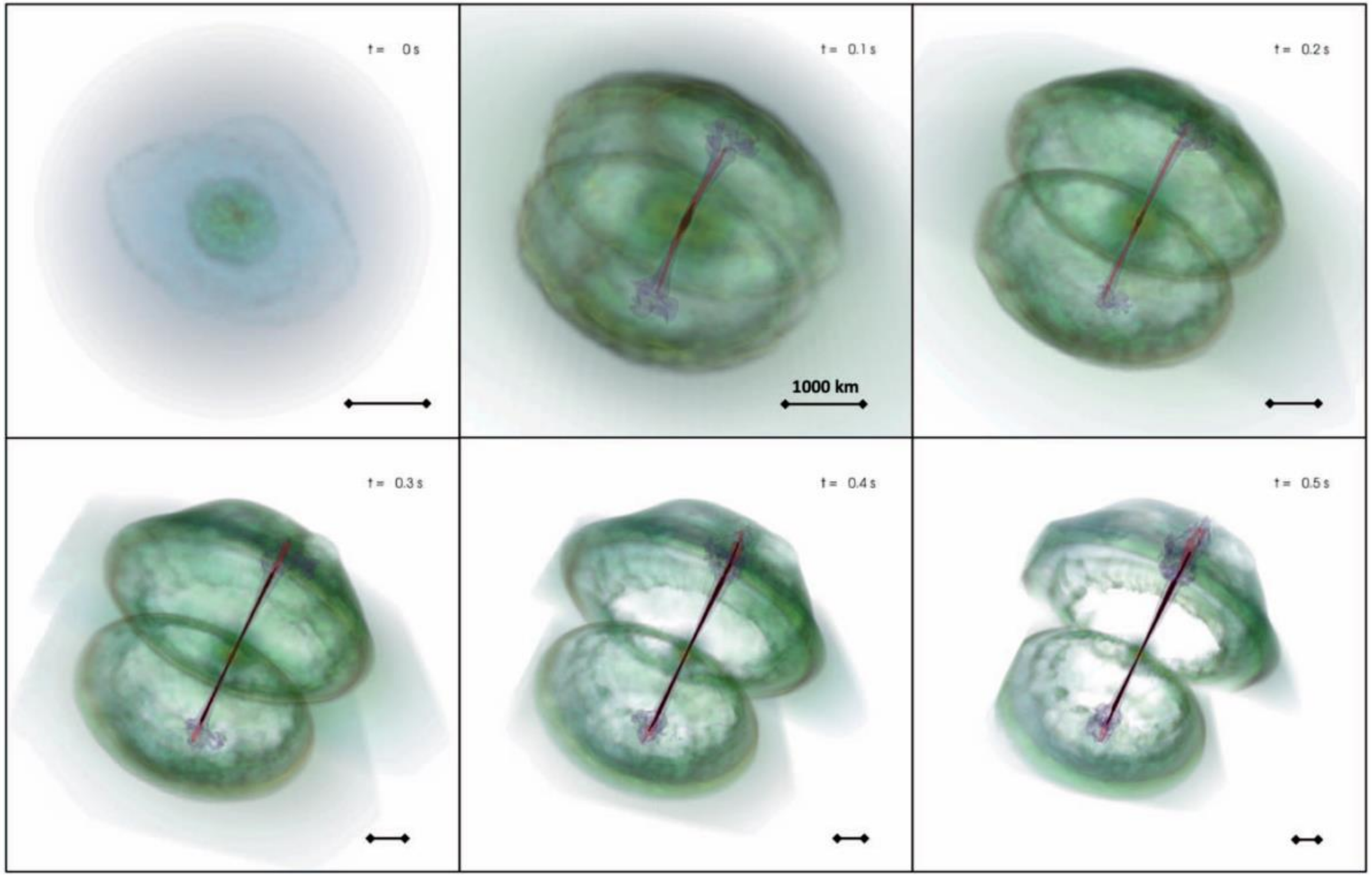

Possible to form jets both in NS-NS and NS-BH binaries

In both cases the emission is due to the Blandford & Znajek (1977) mechanism

# Jet Propagation in BNS Merger Ejecta (Lazzati et al 2021)

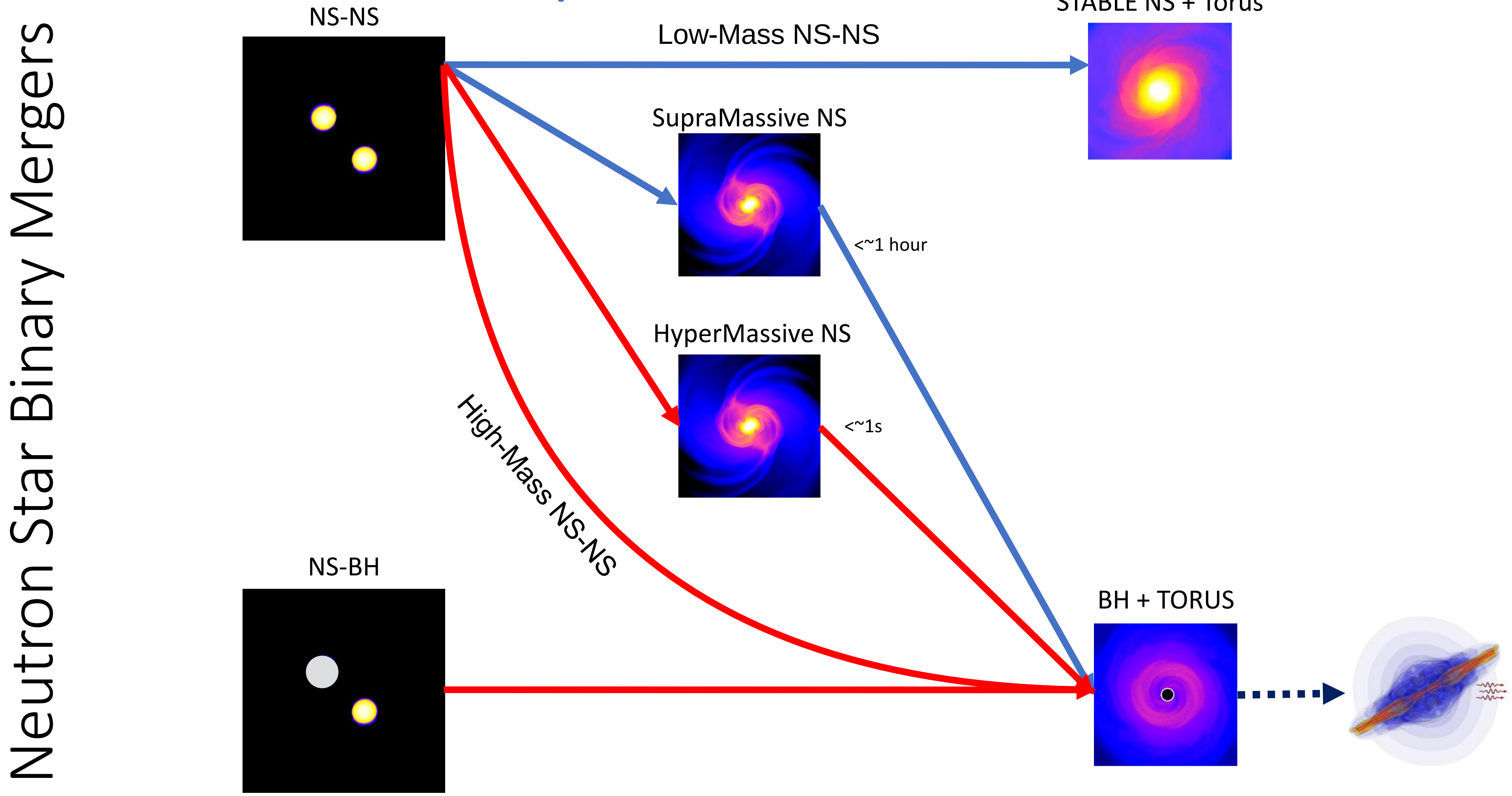
Once a jet is produced, we need to follow its propagation on a long-time scale

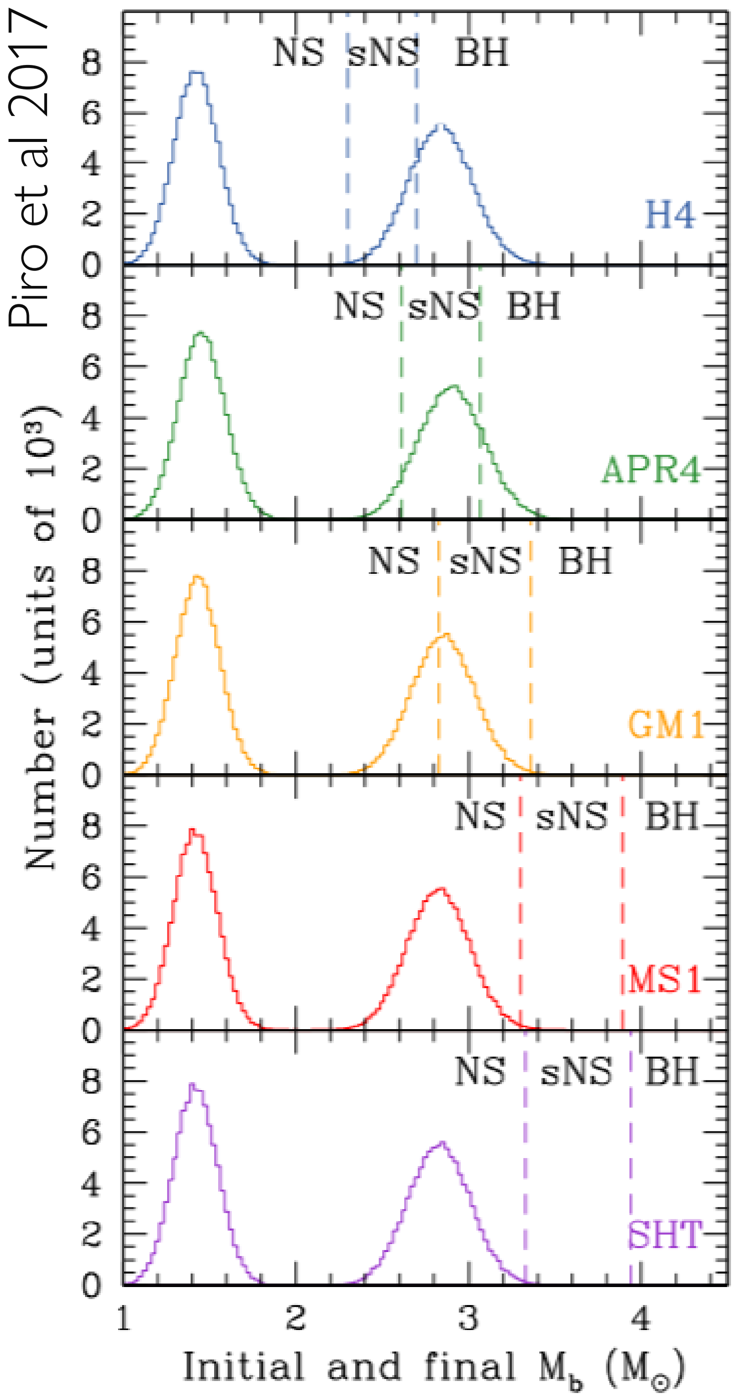
This is not feasible in full GR and most works considered analytical setup for the ejecta.

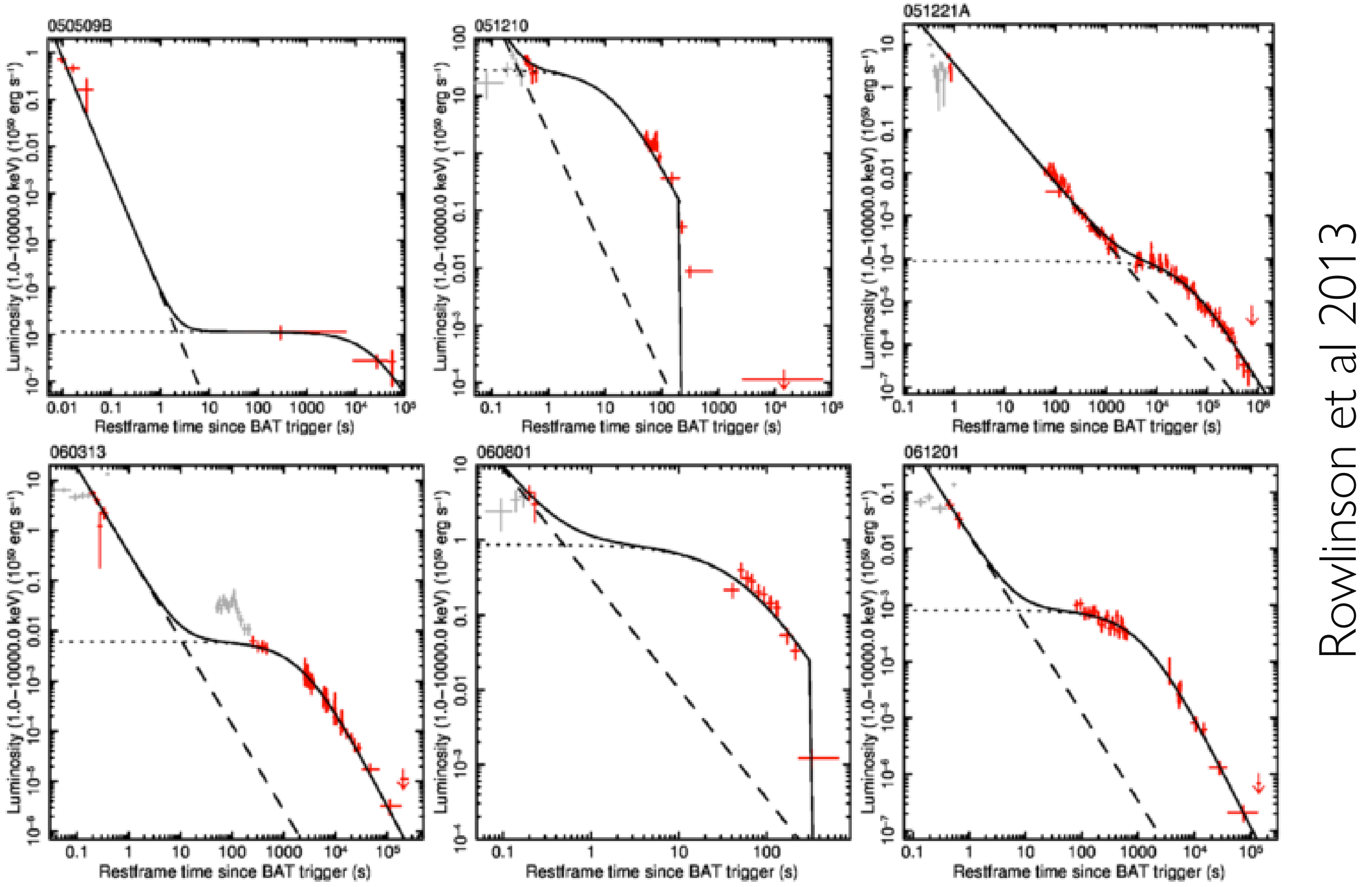



We imported the outcome of a GRMHD simulation into a special relativistic hydrodynamic code. The breakout time is found to be ~0.6 s (see also Pavan et al 2021, Nathanail et al 2021).

# What about the blue path?





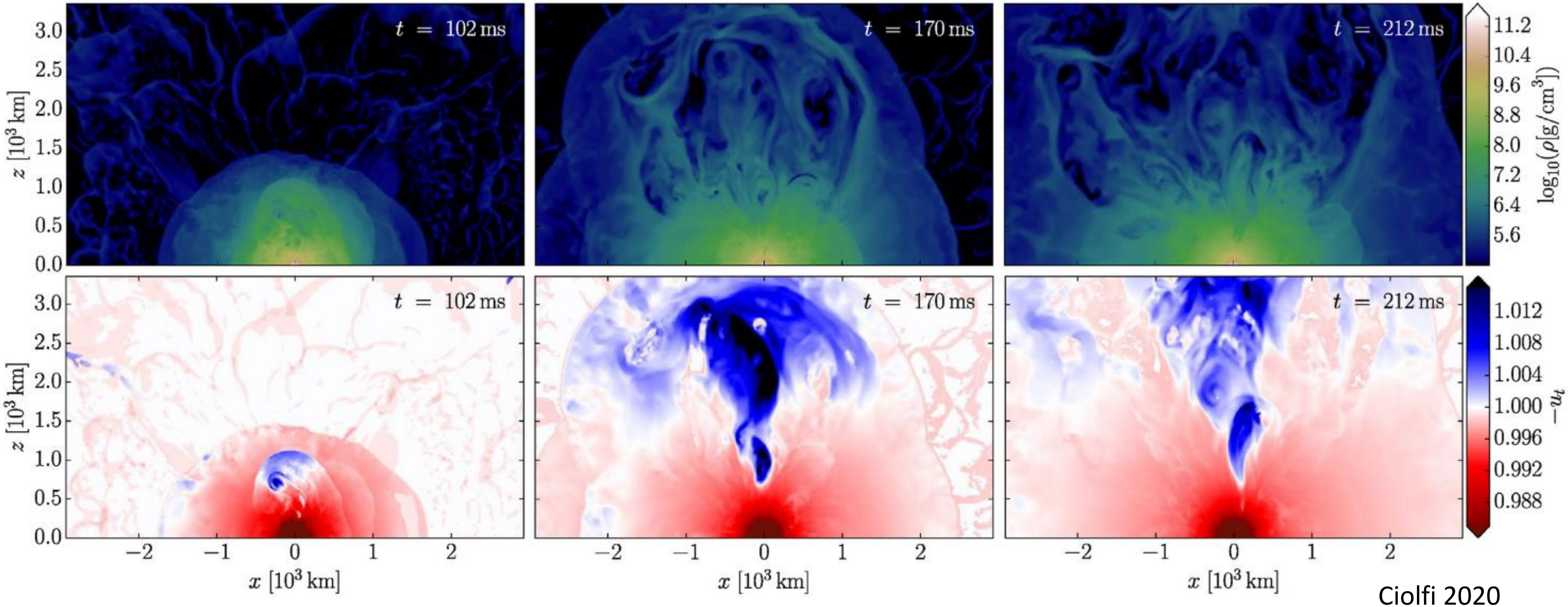




Long-lived NS remnants may form from BNS mergers.

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

First simulation of magnetar formation in BNS merger in Giacomazzo & Perna 2013.

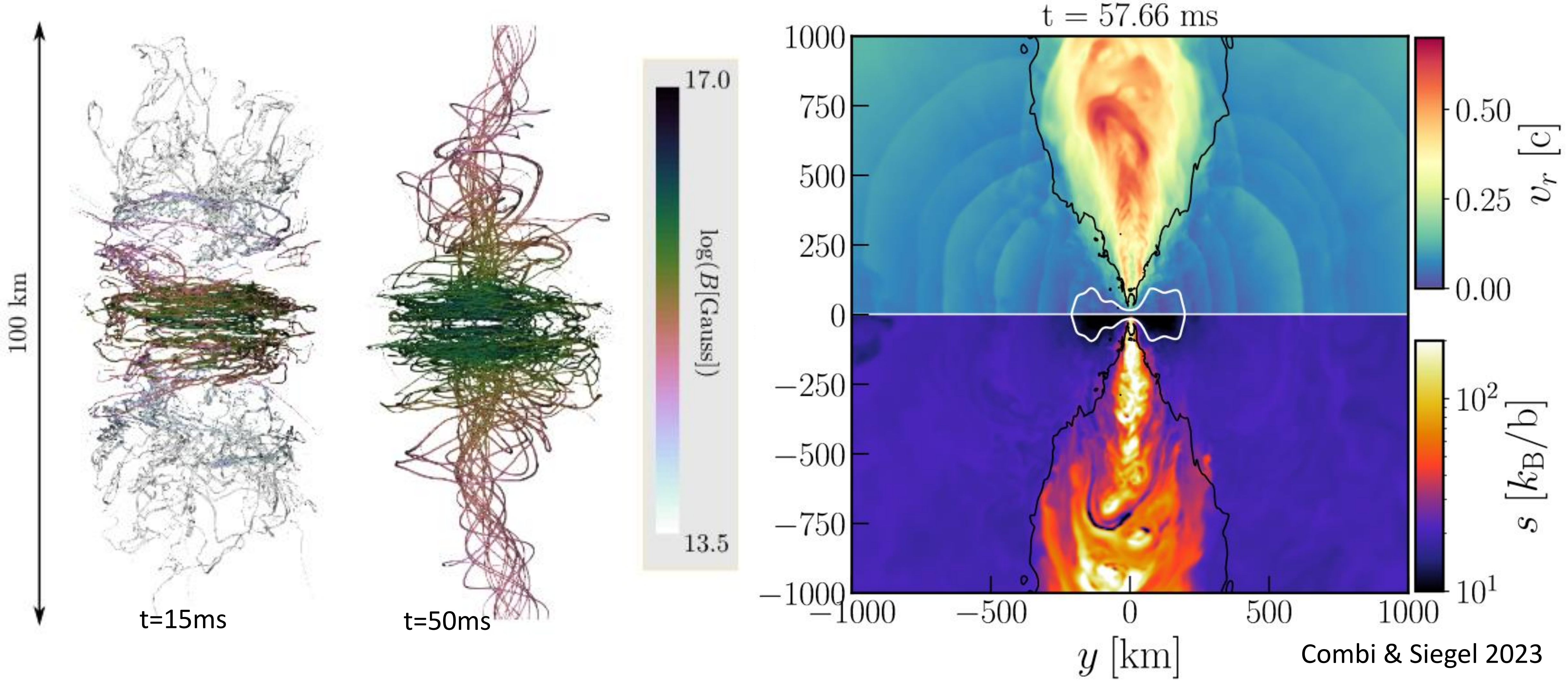
# Collimated outflows from long-lived BNS merger remnants




Ciolfi 2020

Very long post-merger simulation (250 ms), APR4 EOS (1.44-1.29$M_{\odot}$), $B \sim 5 \times 10^{15} G$.
An outflow is produced along the NS spin axis with a half-opening angle of $\sim 15^{o}$.
Lorentz factor (<10) and energy (~$10^{49}$ erg) are not enough to power an SGRB.

# Collimated outflows from long-lived BNS merger remnants

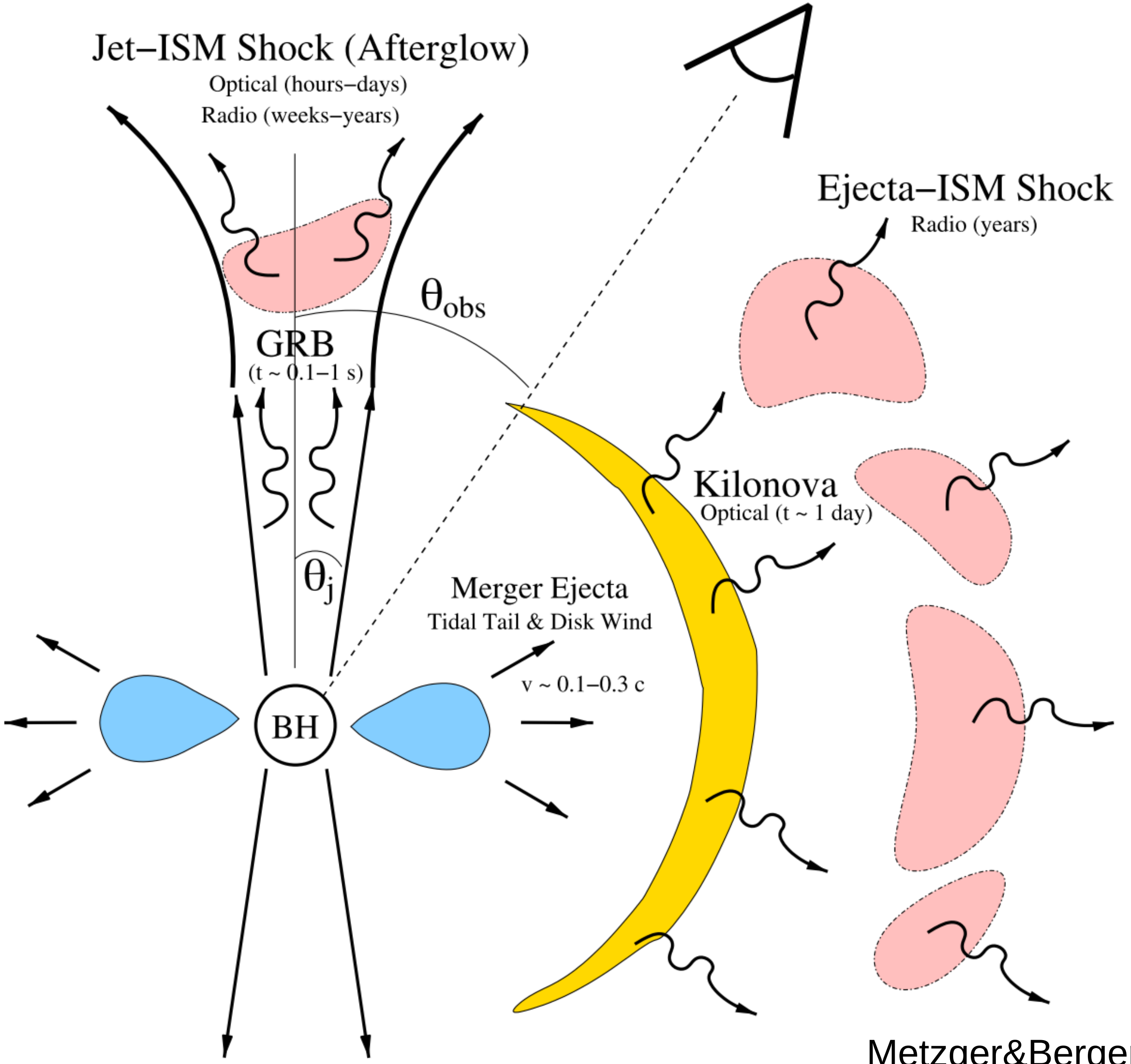



Combi & Siegel 2023

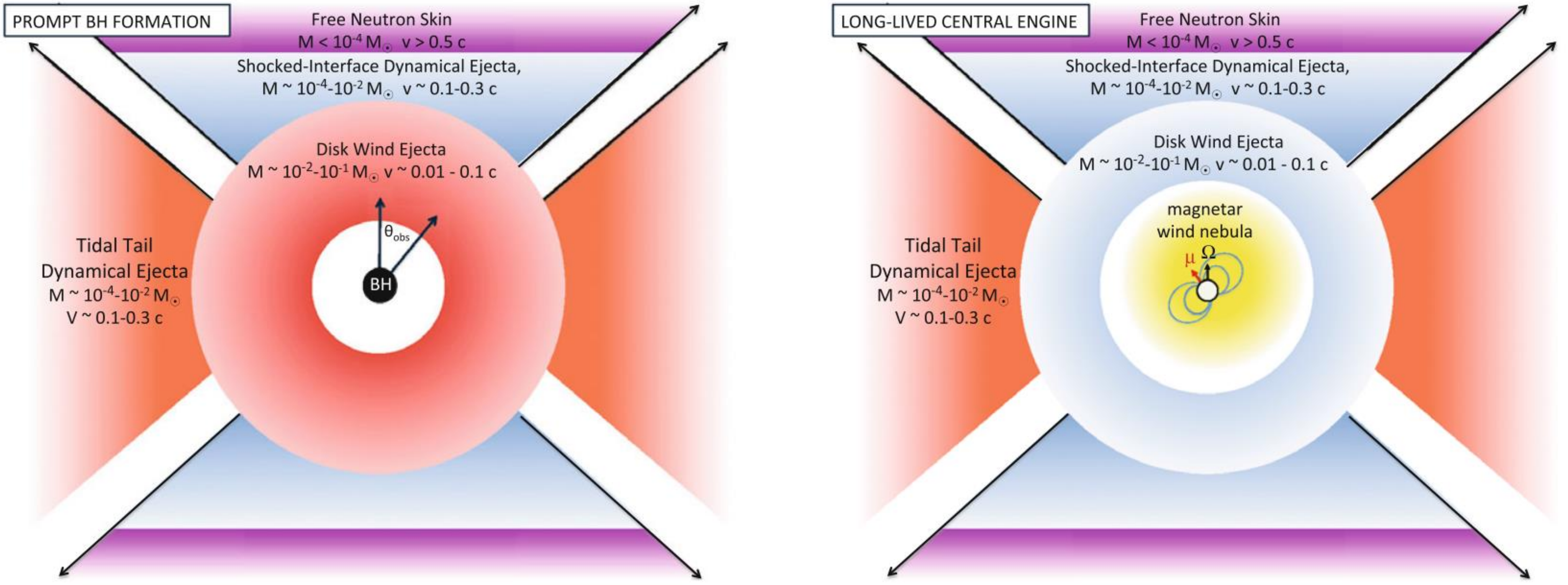
Another very recent GRMHD simulation including neutrino effects shows also the appearance of a collimated jet (asymptotic Lorentz factor ~5-10).

# Kilonova

# kilonova

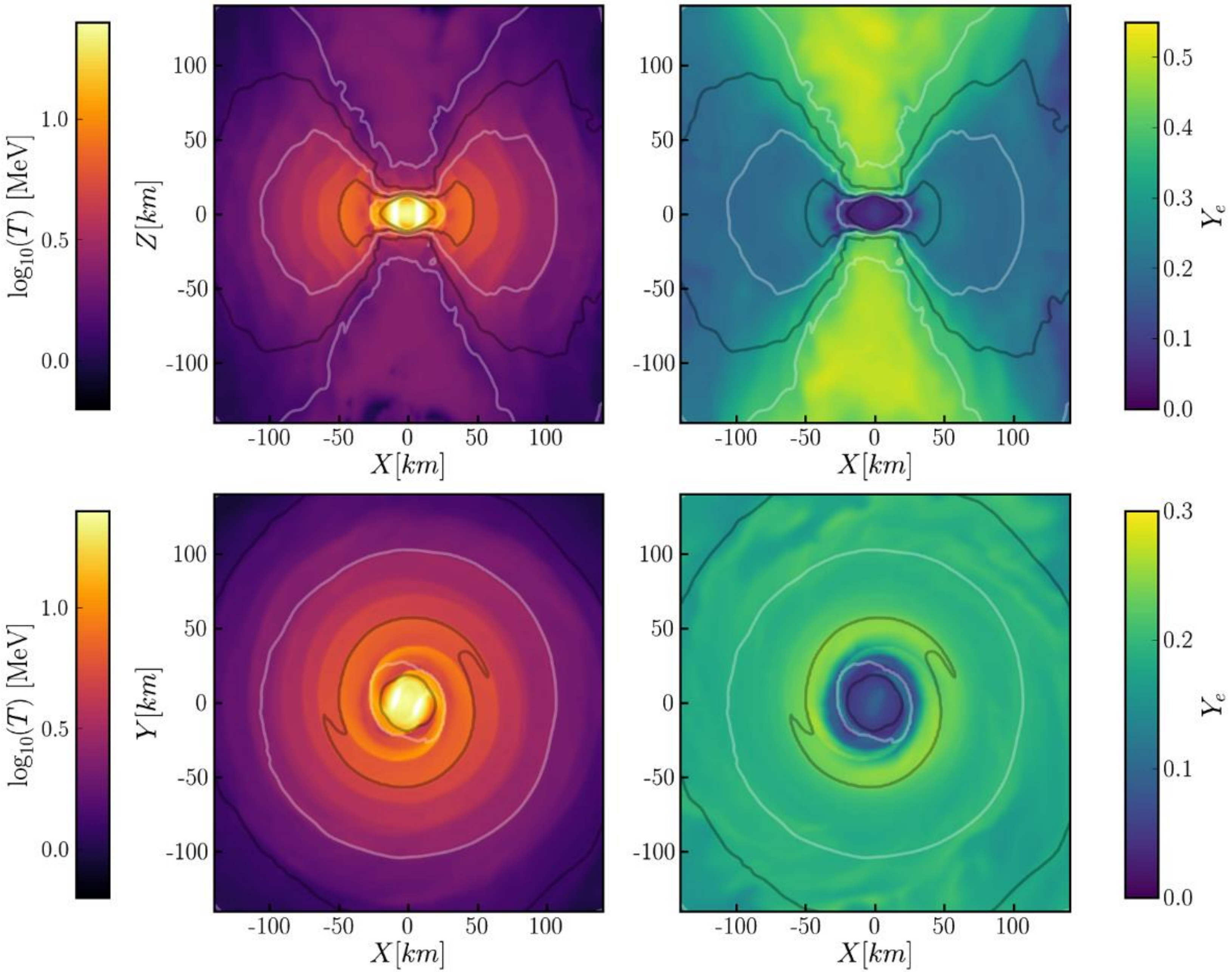



Metzger&Berger 2012



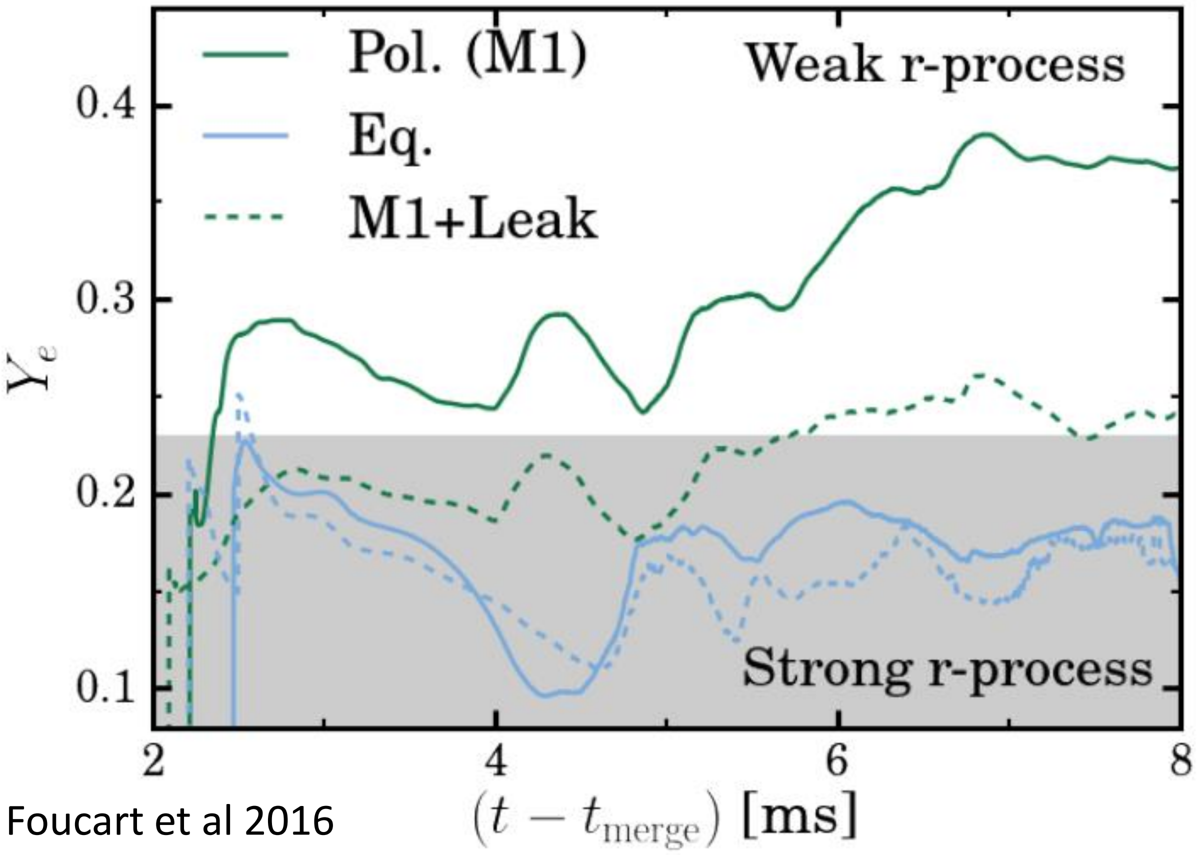

Metzger, B.D. Living Rev Relativ (2017) 20: 3. https://doi.org/10.1007/s41114-017-0006-z

The kilonova has an "early" blue (optical) and a "late" red (infrared) component depending on the mass ejection mechanism and neutrino absorption.



$\log_{10}(T)$ [MeV]
1.0
0.5
0.0
$Z[km]$
100
50
0
-50
-100
$X[km]$
-100
-50
0
50
100
$Y_e$
0.5
0.4
0.3
0.2
0.1
0.0
$\log_{10}(T)$ [MeV]
$Y[km]$
$Y_e$
0.3
0.2
0.1
0.0

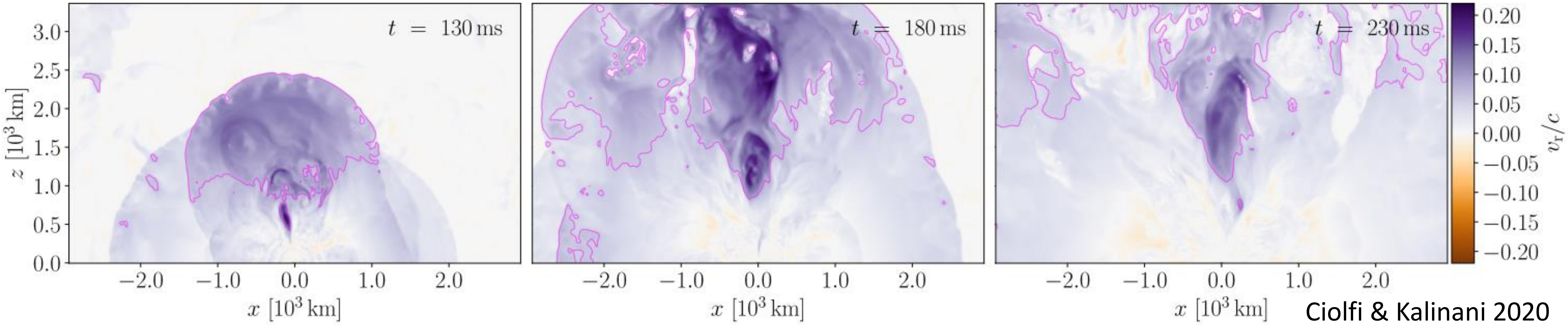
# The Importance of Neutrino Schemes




Foucart et al 2016

The numerical scheme used to evolve neutrinos may have a relevant impact on r-process and kilonova emission (especially in the polar region, see also Foucart et al 2018, Foucart 2023).

# The Importance of Magnetic Fields

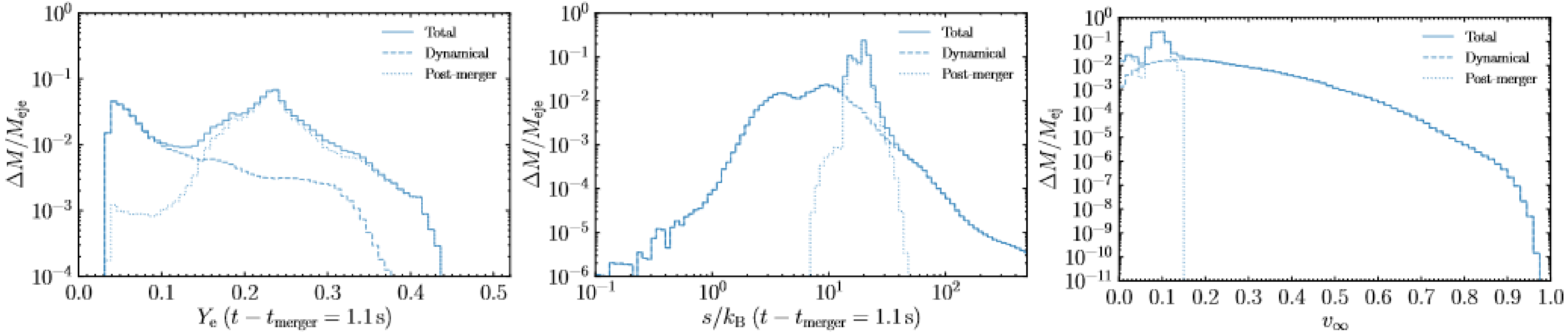



Ciolfi & Kalinani 2020

Strong magnetic fields also contribute to the ejected mass and in particular to the blue kilonova component.

BNS simulation by Ciolfi & Kalinani shows up to $\sim 3 \times 10^{-2} \mathrm{M}_{\odot}$ of ejecta due to magnetic fields. Matter is mainly ejected between ~50 and ~200 ms after merger with a maximum speed of ~0.22 c.

# Second-long GRMHD simulations




Kiuchi et al 2022

- Kiuchi et al 2022: ~1 s long simulation of NS-NS merger (72 million CPU hours with 20,736 cores).
- Hayashi et al 2023: ~3 s long simulations of NS-BH mergers (showing also jet formation)
- Magnetic fields play crucial role in post-merger ejecta

# Some Review Articles

- Shibata & Taniguchi 2011 https://link.springer.com/article/10.12942/lrr-2011-6
- Faber & Rasio 2012 https://link.springer.com/article/10.12942/lrr-2012-8
- Paschalidis 2017 https://ui.adsabs.harvard.edu/abs/2017CQGra..34h4002P/abstract
- The Physics and Astrophysics of Neutron Stars (2018) https://link.springer.com/book/10.1007/978-3-319-97616-7
- Dietrich, Hinderer & Samajdar 2021 https://ui.adsabs.harvard.edu/abs/2021GReGr..53...27D/abstract

# Some Review Articles

- GR Simulations of Compact Binary Mergers as Engines for Short GRBs
  https://doi.org/10.1088/1361-6382/aa61ce
- Gravitational Waves: A New Window to the Universe
  https://www.frontiersin.org/research-topics/11345/gravitational-waves-a-new-window-to-the-universe
- Neutron star mergers and how to study them
  https://link.springer.com/article/10.1007%2Fs41114-020-00028-7
- Kilonovae
  https://link.springer.com/article/10.1007/s41114-019-0024-0
- Binary Neutron Star mergers
  https://link.springer.com/collections/jgeicbdiig

# Waveform Catalogues

- CoRe database: http://www.computational-relativity.org/gwdb/
- SACRA Gravitational Waveform Data Bank: https://www2.yukawa.kyoto-u.ac.jp/~nr_kyoto/SACRA_PUB/catalog.html
- Riccardo Ciolfi's BNS GW database: https://bitbucket.org/ciolfir/bns-waveforms/src/master/
- SXS Gravitational Waveform Database: https://data.black-holes.org/waveforms/index.html