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Binary Neutron Star Mergers

David Radice — May 12, 2021

arXiv:2002.03863

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Background

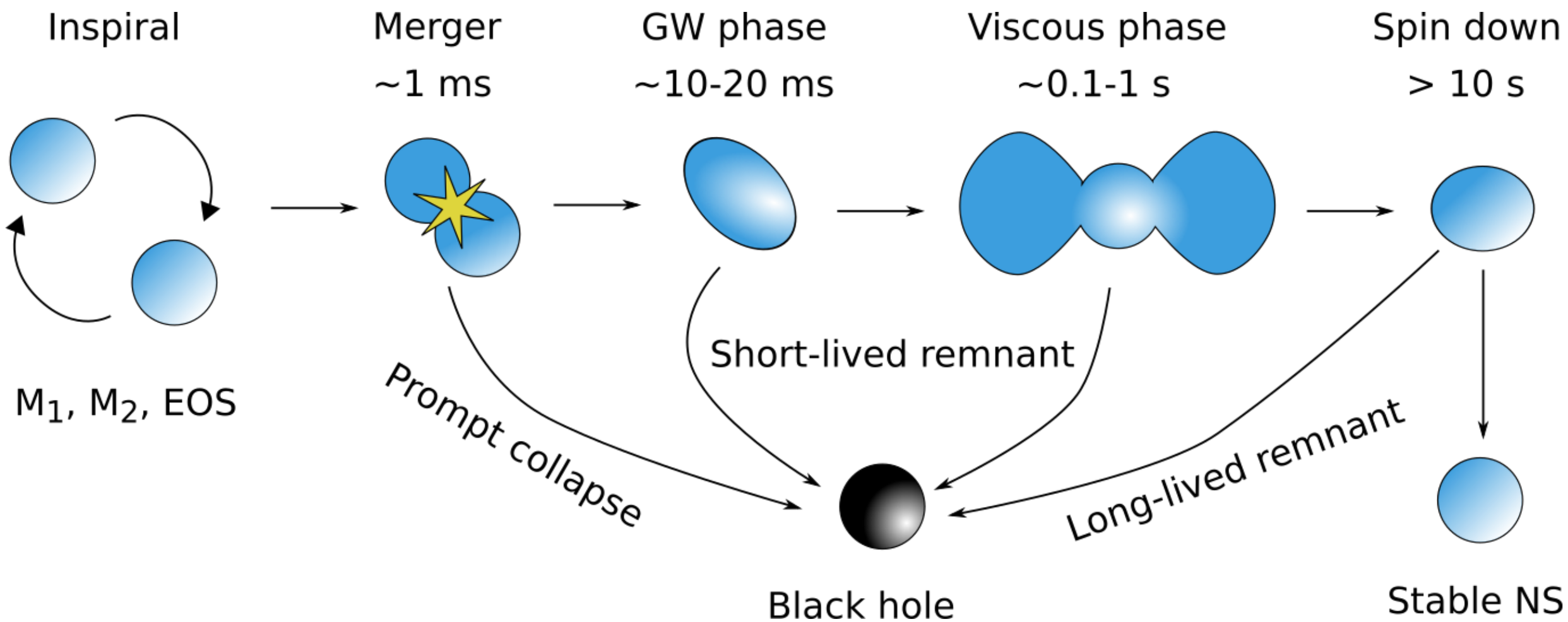
Open problems in nuclear astrophysics

- How did the elements come into existence?
- What makes stars explode as supernovae, novae, or X-ray bursts?
- What is the nature of neutron stars?
- What can neutrinos tell us about stars?

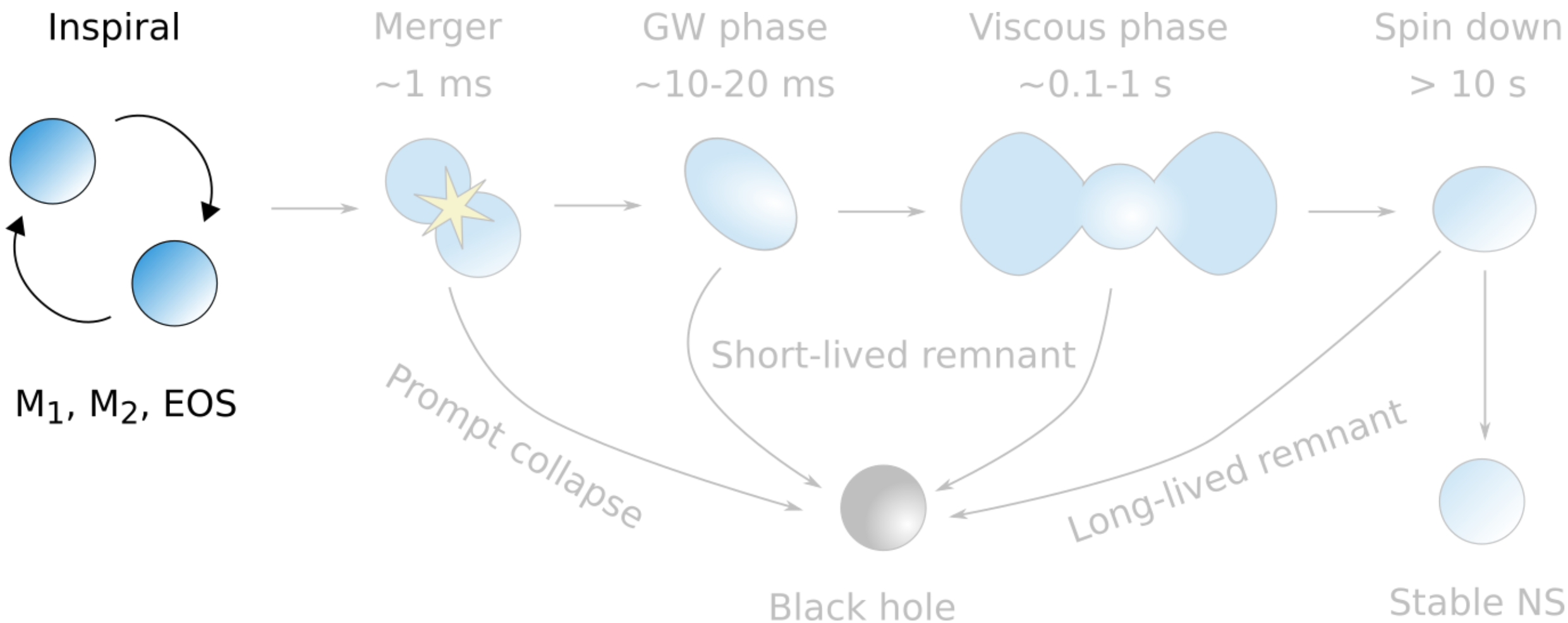
From: National Research Council of the National Academies
"Nuclear Physics — Exploring the Heart of Matter" (2012)

GW observations of NS mergers are key to answer these questions!

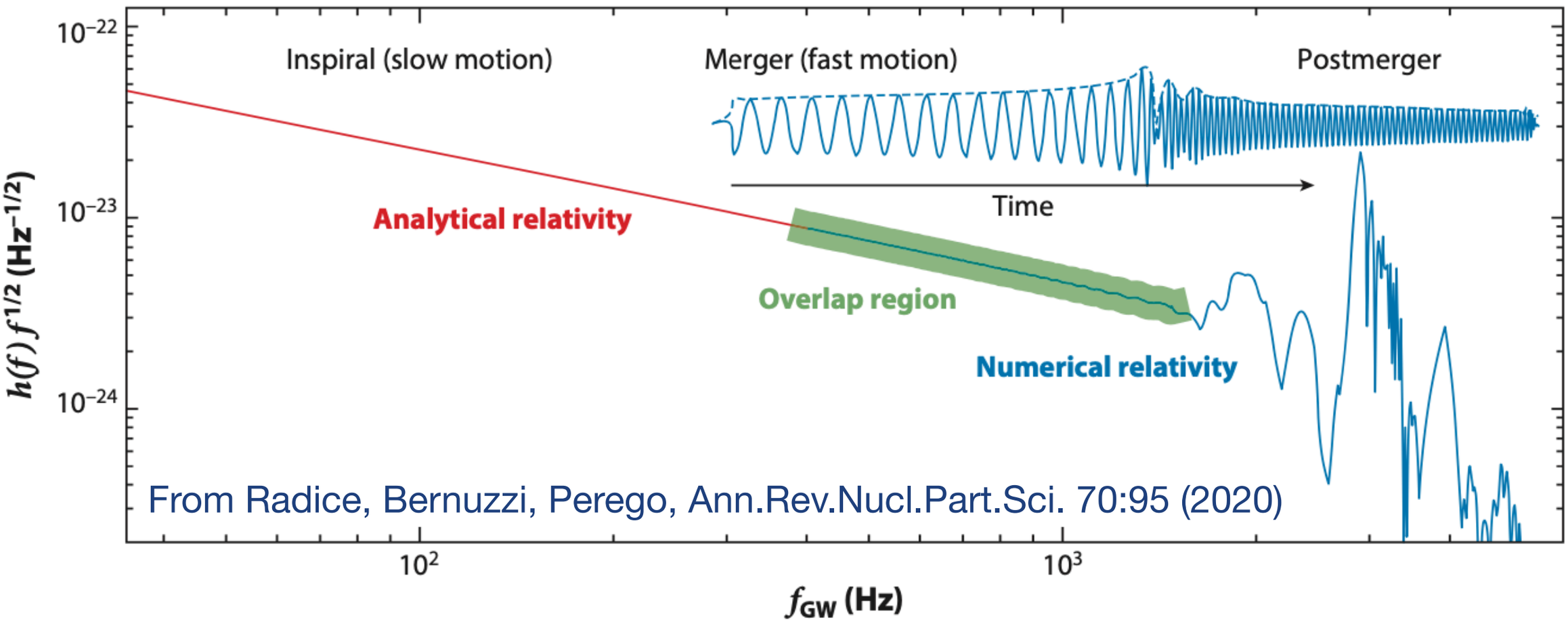
NS merger: our roadmap



Binary NS inspiral



GWs from BNS mergers



From Radice, Bernuzzi, Perego, Ann.Rev.Nucl.Part.Sci. 70:95 (2020)

- Inspiral: 0 - ~1.5 kHz
- Postmerger: 1.5 kHz - 4 kHz
- Most of the SNR is in the inspiral

- Analytical techniques valid at low frequencies
- Last ~10-20 orbits, merger, and postmerger: need NR

Tidally interacting NSs

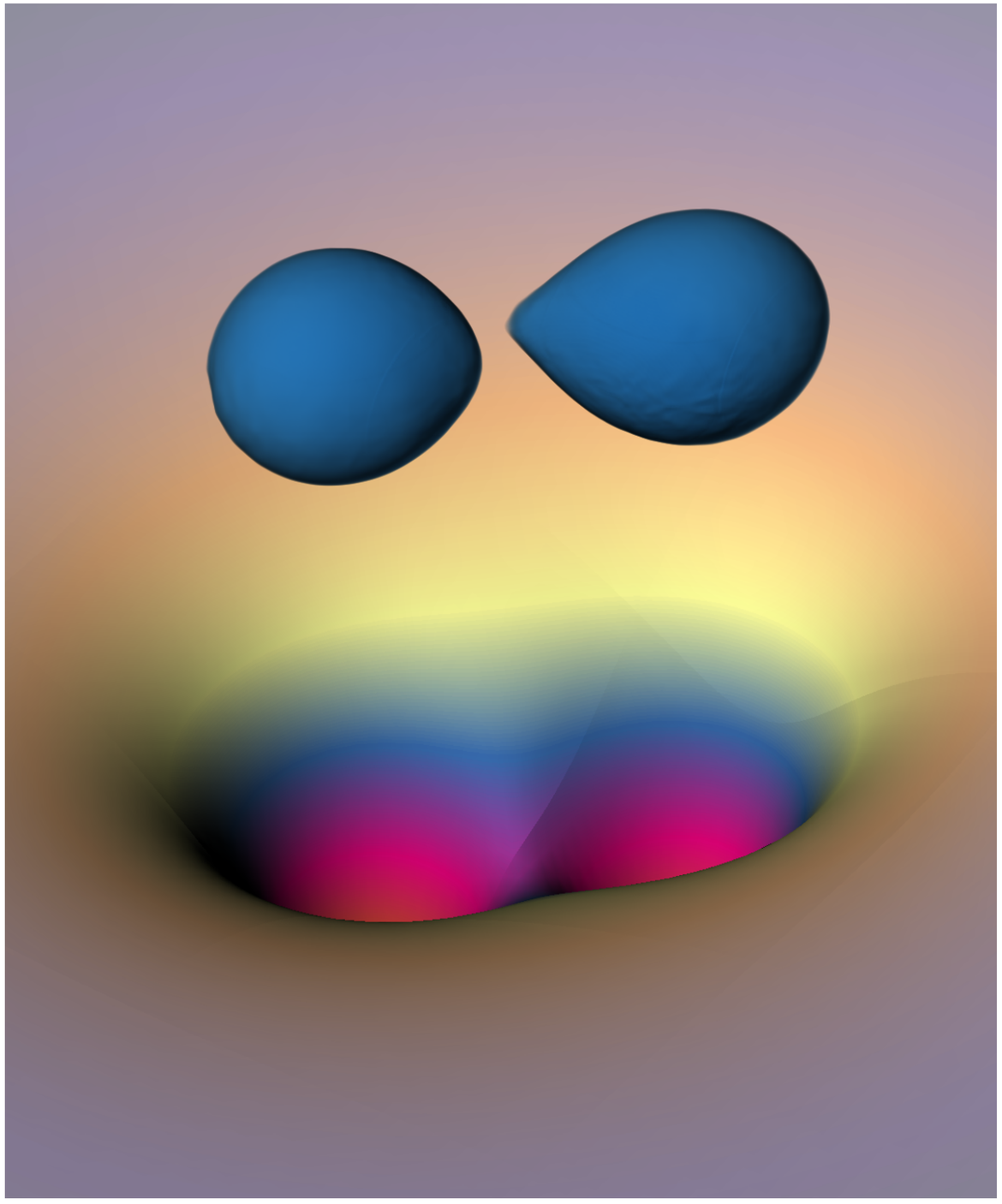
- The impact of tides
  1. The potential is modified and becomes more attractive:

     $$U^T \sim -\frac{\tilde{\Lambda}}{r^6}$$

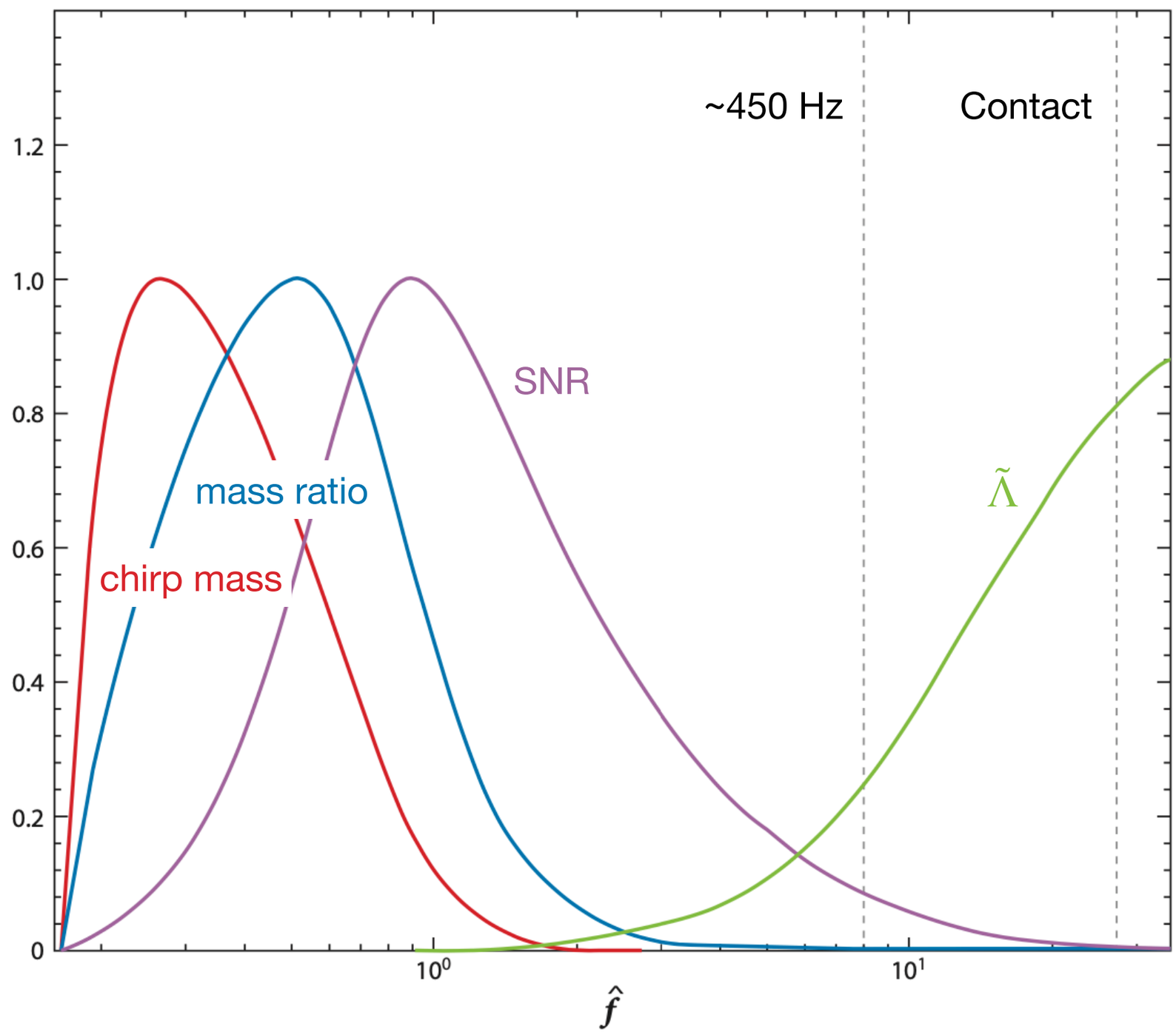
  2. The tidal bulge contribute to the GW emission:

     $$L^T_{\rm GW} = \frac{G}{5c^5}\langle \dddot{Q}^T_{ij}\dddot{Q}^T_{ij}\rangle$$

- The inspiral is accelerated compared to that of two BHs with the same parameters as the BNS
- Read off tidal information from the dephasing of the wave

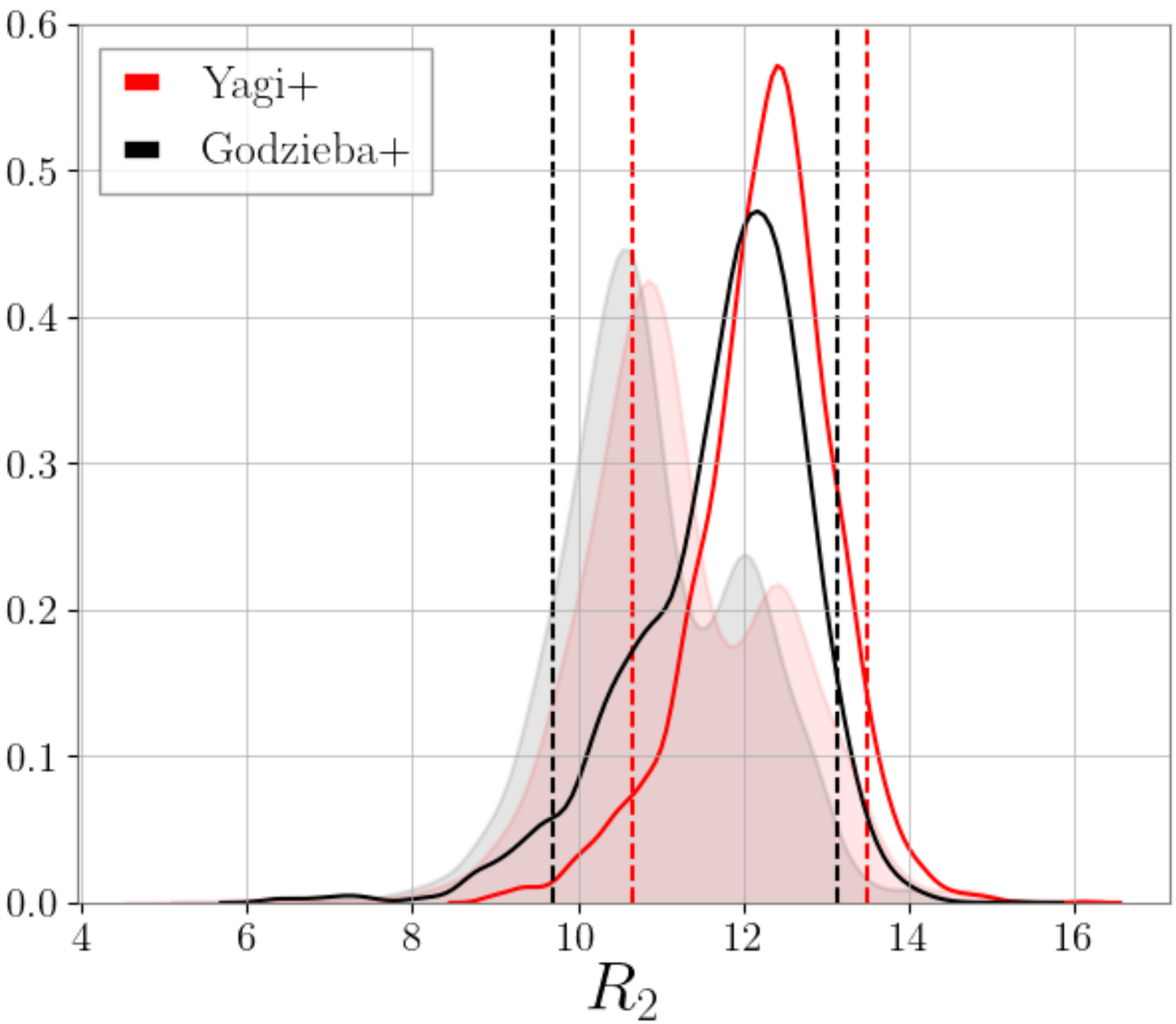


GW parameter estimation



Adapted from Damour & Nagar 2012

GW170817

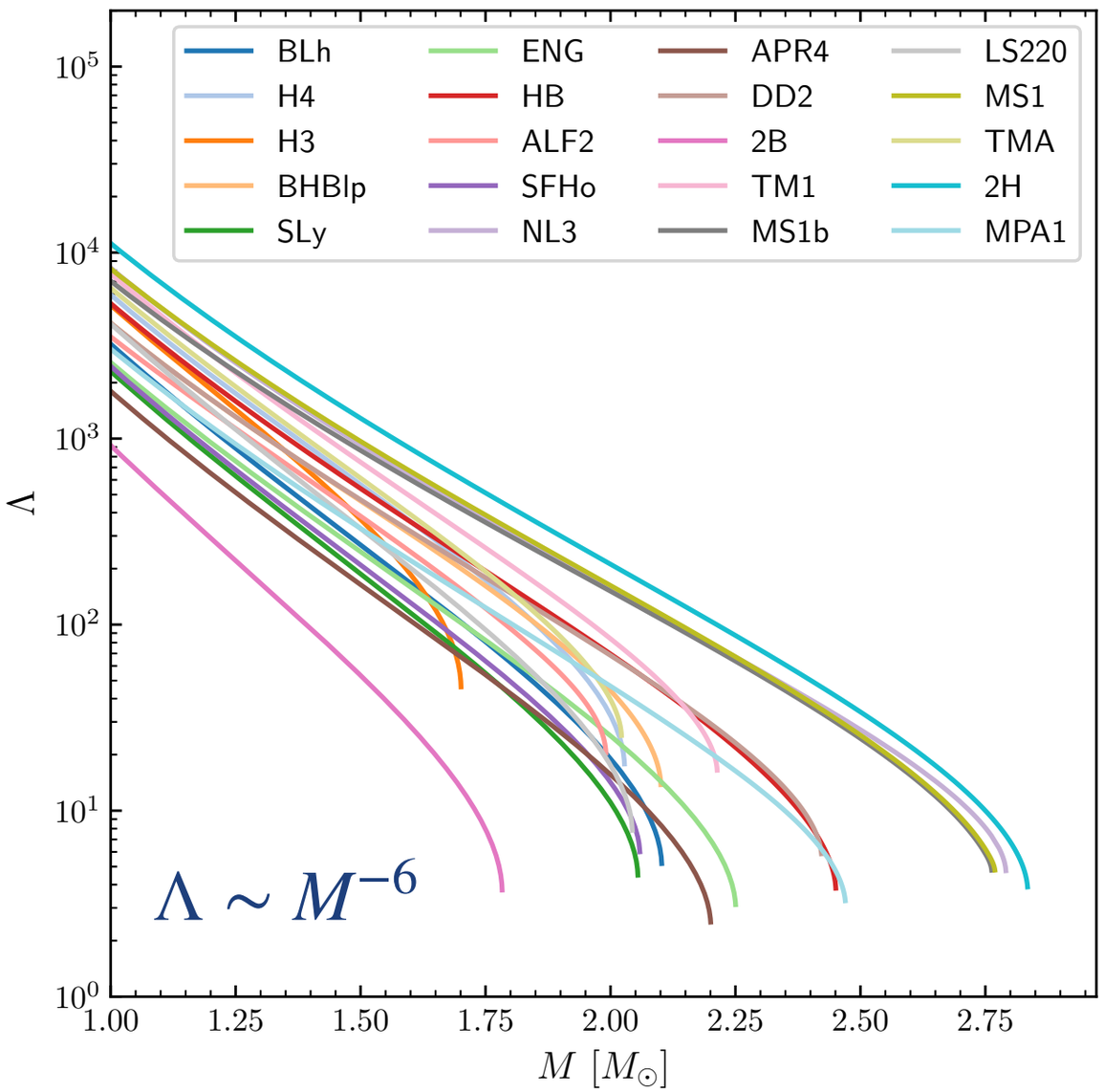


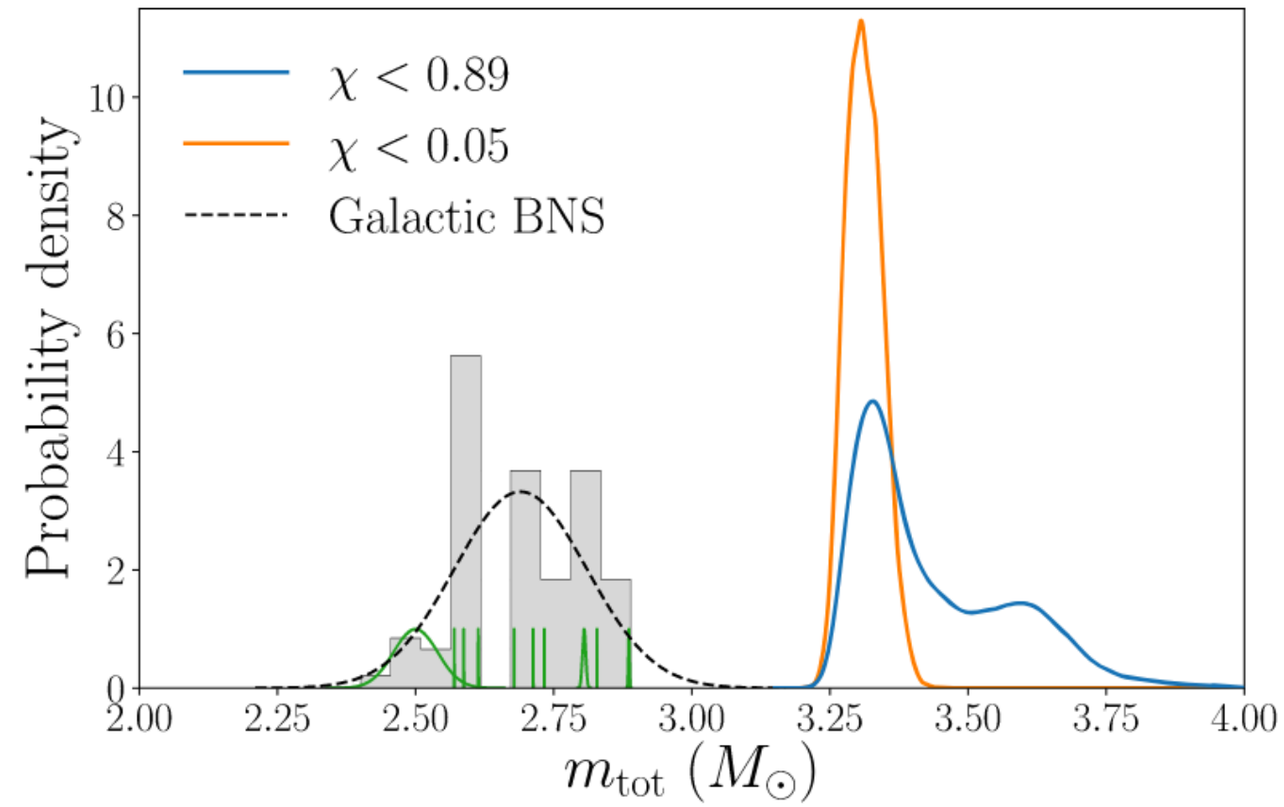
From Godzieba+ Phys. Rev. D 103, 063036 (2021)

- Robust upper limits $\tilde{\Lambda} < 800$
- Very stiff EOS are ruled out at high confidence
- Lower limits: dependency on details of the analysis, waveform model, etc.
- Probing the EOS on the soft side more challenging: we need multimessenger observations

See also: LVC 2017, De+ 2018, LVC 2018, Radice+2018, Capano+ 2019, Gamba+ 2020, …

GW190425





From: LVC 2019, ApJL 892:L3 (2020)

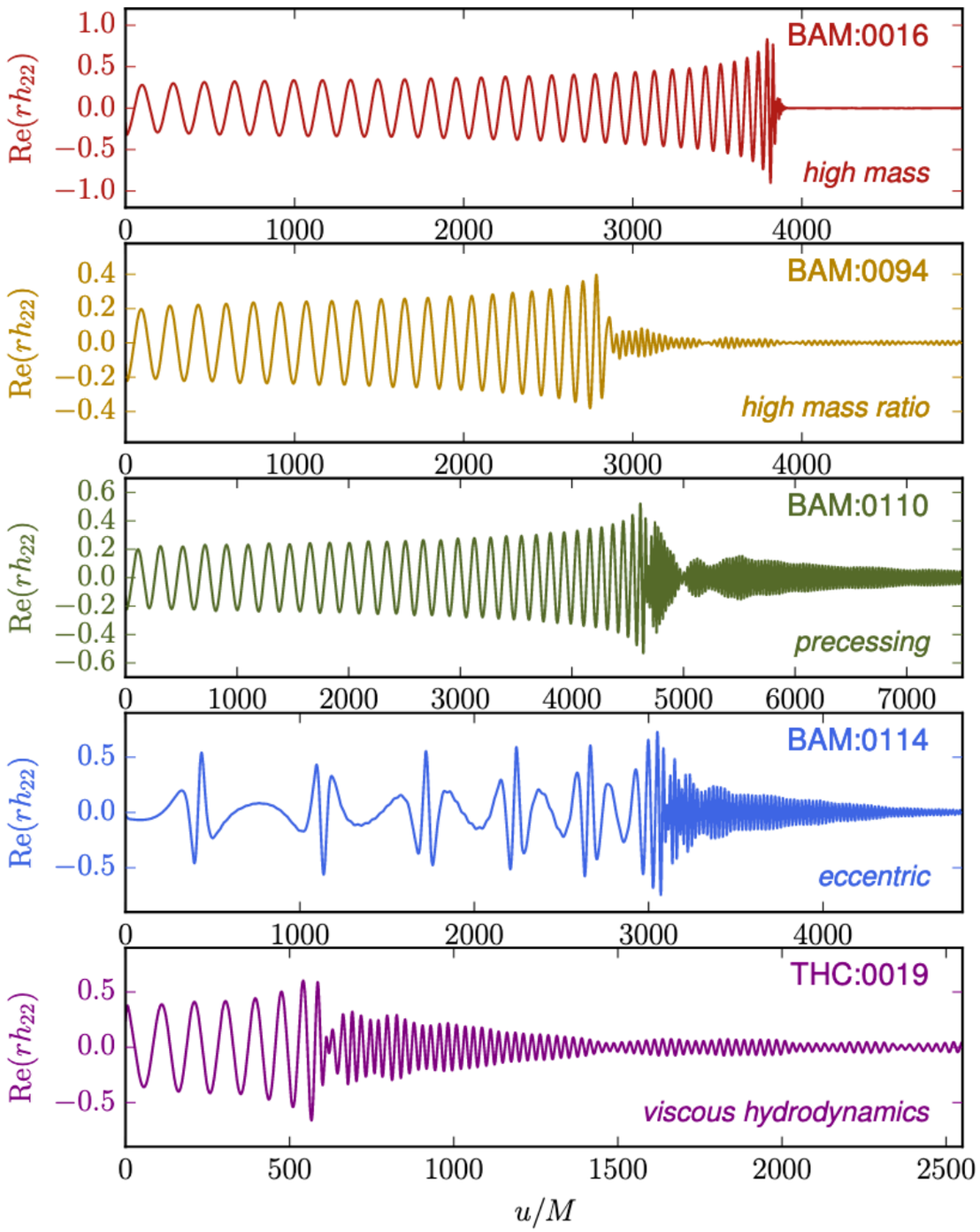
Measuring Λ for massive NSs would provide very strong constrain on the EOS (e.g., probe phase transitions), but challenging measure

Preparing for the next discovery

Much work remains to be done in modeling, data analysis, and experimental techniques

- Waveform systematics will dominate for SNRs $\gtrsim 50$.
- 3G is needed to measure $\Lambda(M)$.
- How do we combine GW and EM data from multiple events?

The CoRe catalog

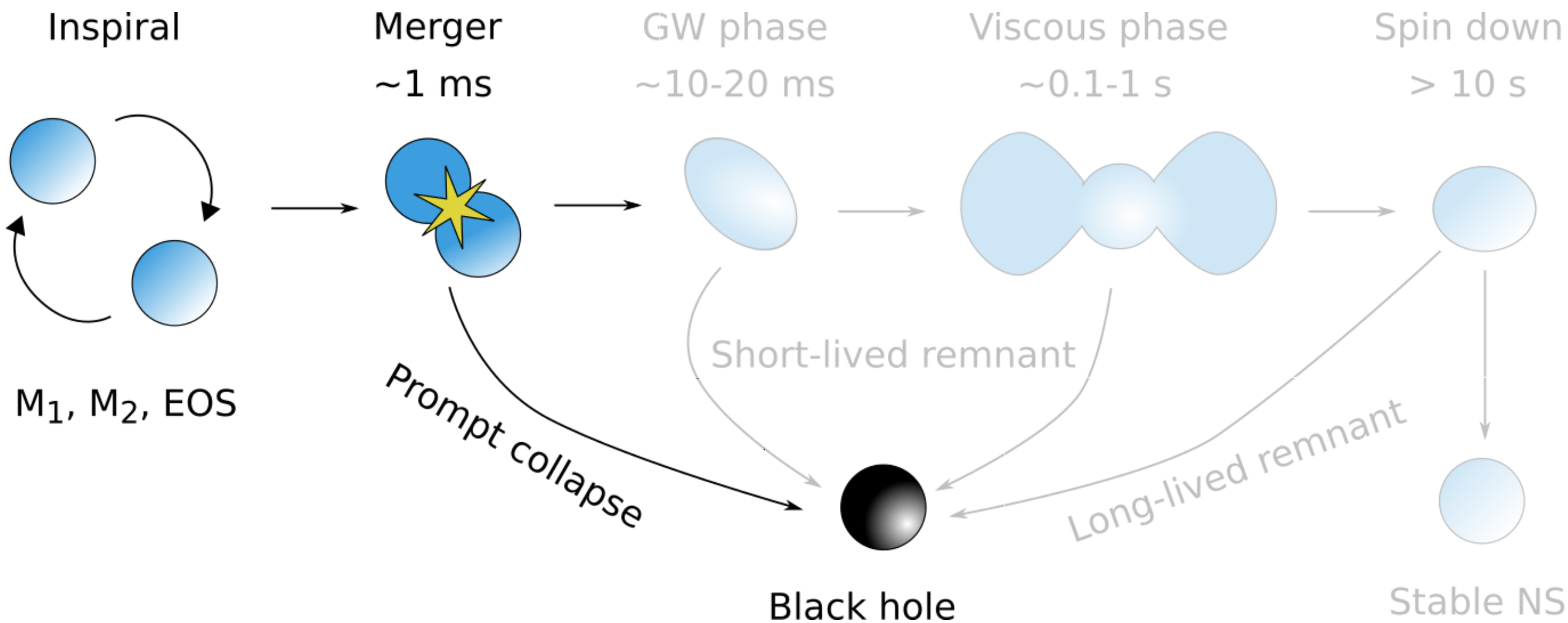


- Largest catalog of NR GW waveforms for BNS systems
- Two independent codes: cross validation
- Used for LVC TidalEOB, NRTides, waveform models calibration and validation
- EM light curves and r-process nucleosynthesis available
- Open source: simulation codes, initial data, EOS tables, parameter files, all available

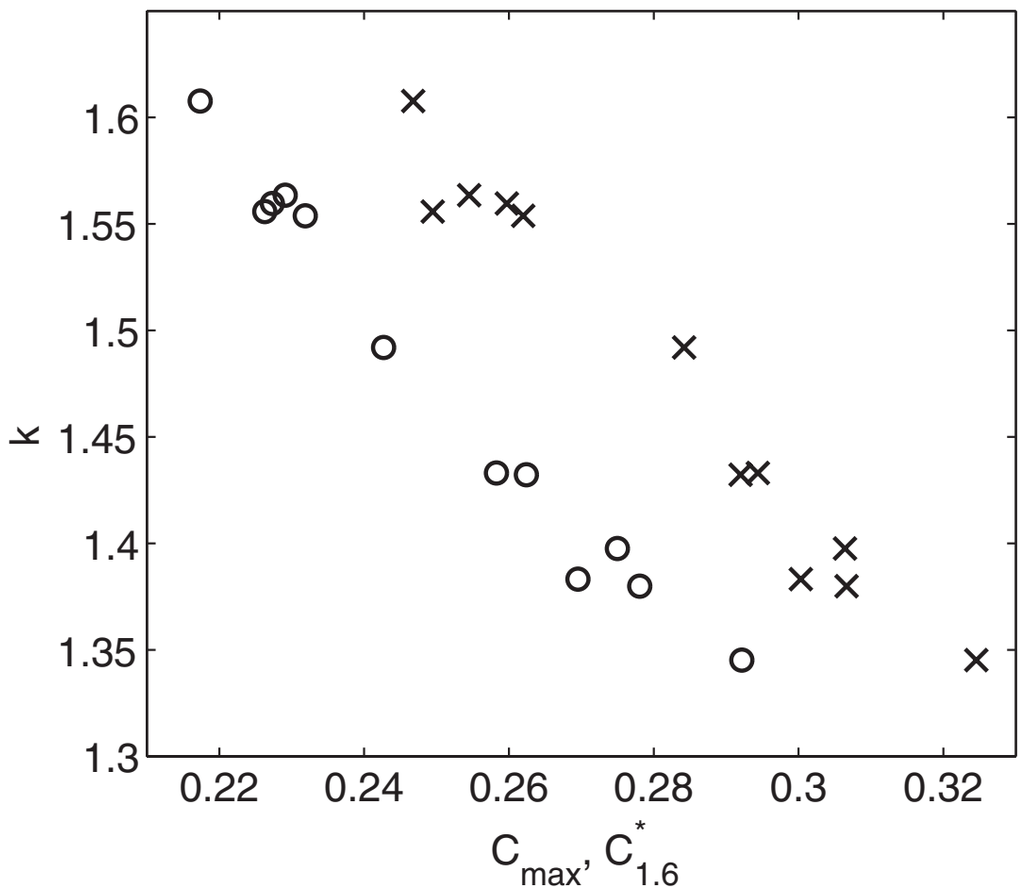
www.computational-relativity.org

Dietrich, **DR**, Bernuzzi+ CQG 35:LT01 (2018)

Binary NS merger

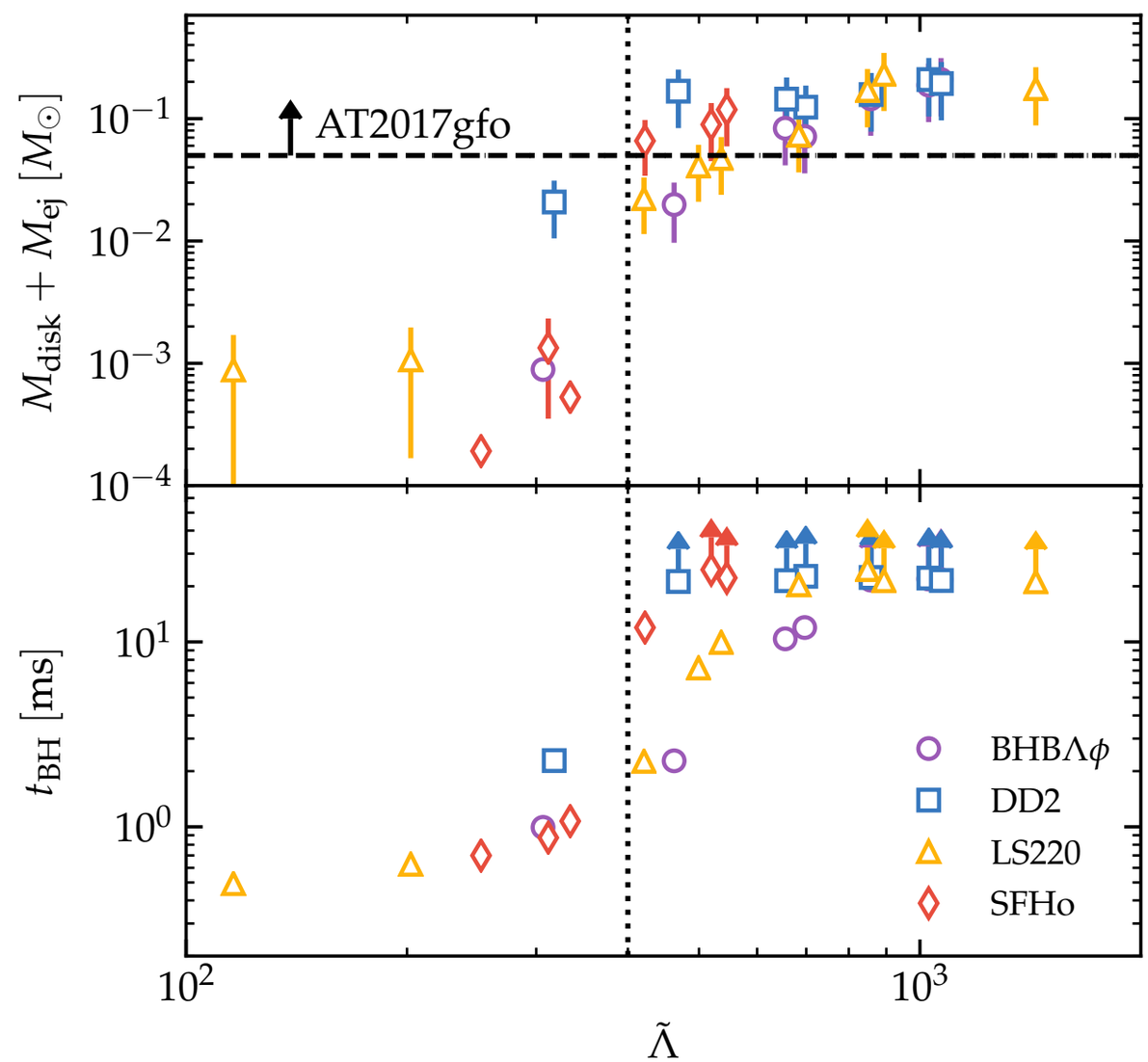


Prompt BH formation: q ~ 1



$$M_{\rm thr} = k_{\rm thr} M_{\rm max}$$

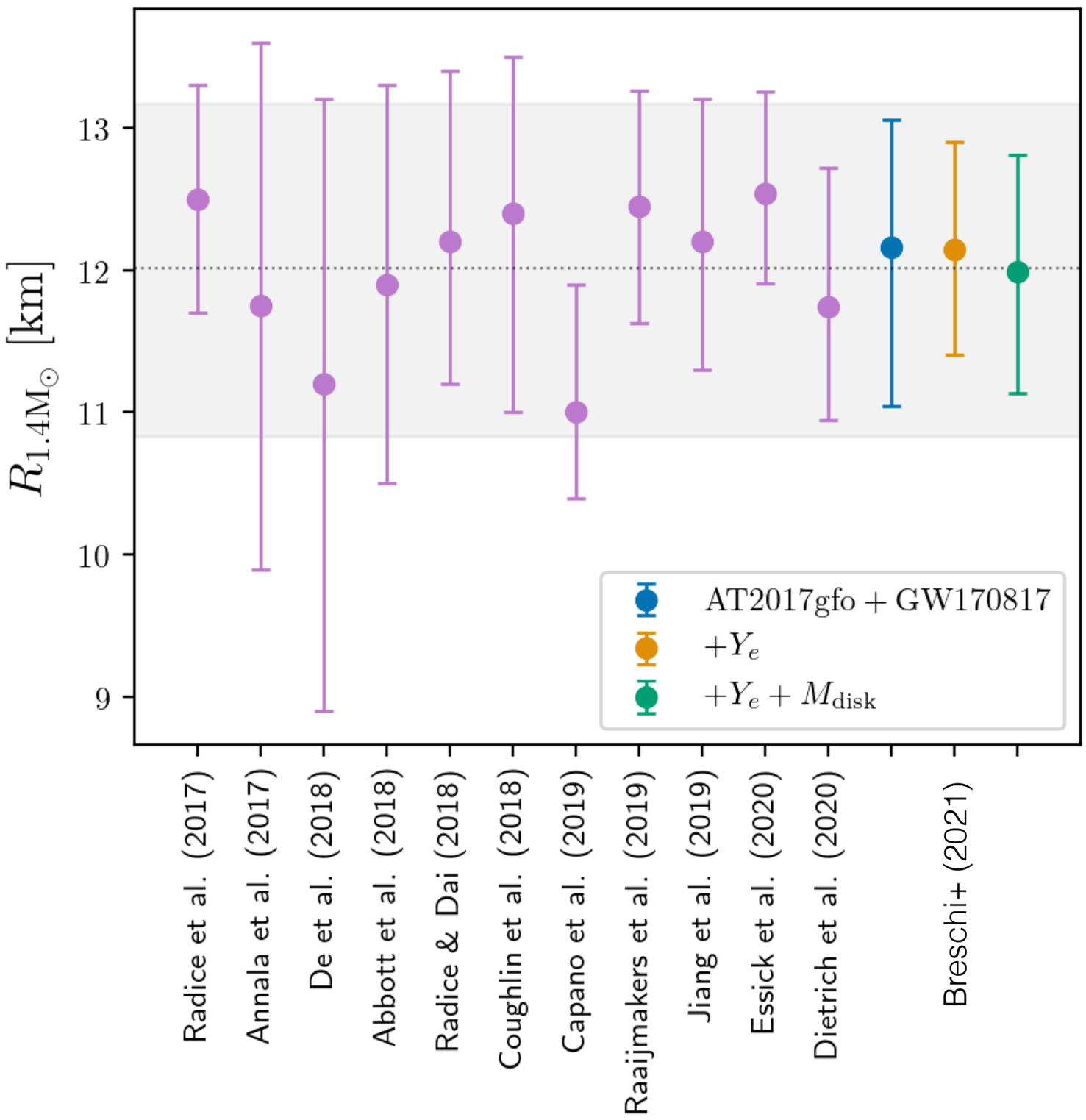
From Bauswein+ 2013



From **DR**, Perego+ ApJL 852:L29 (2018)

See also Bauswein+ 2017, DR+ 2018, Köppel+ 2019, Agathos+ 2019, Bernuzzi+ 2020

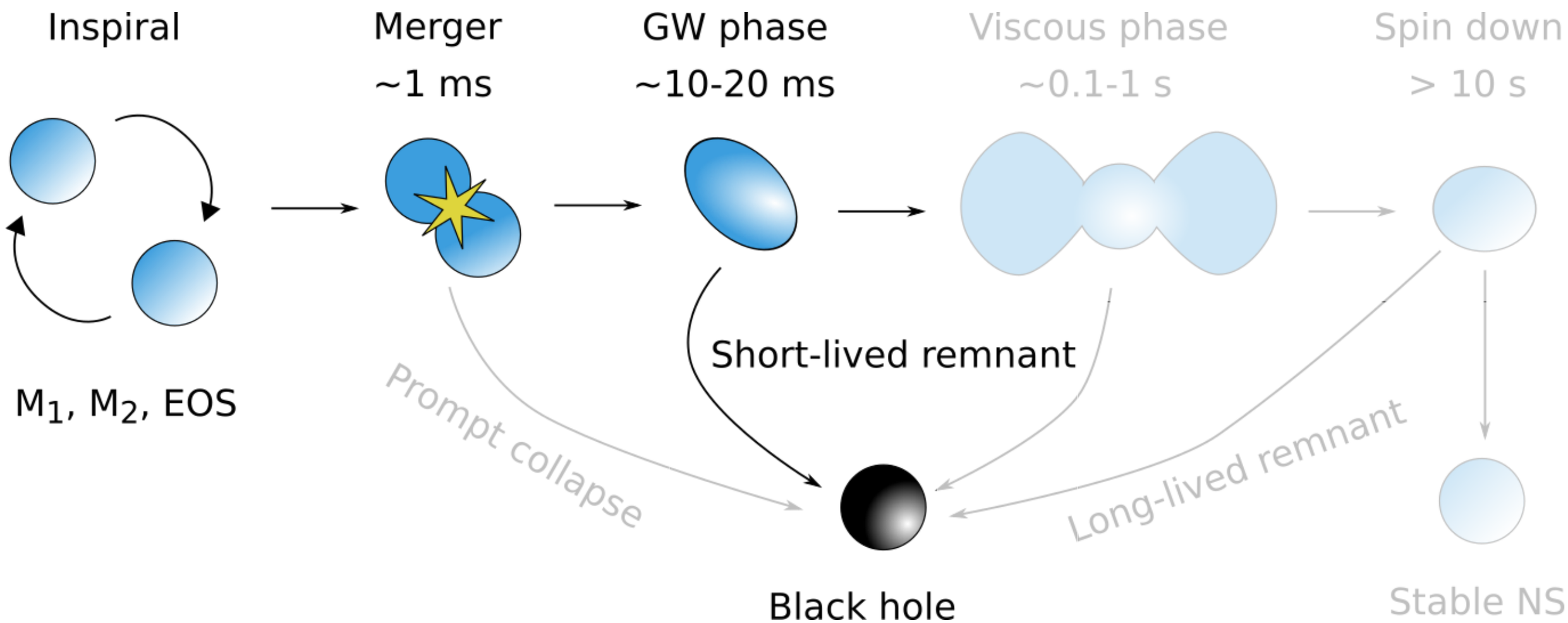
NS radii from GW170817



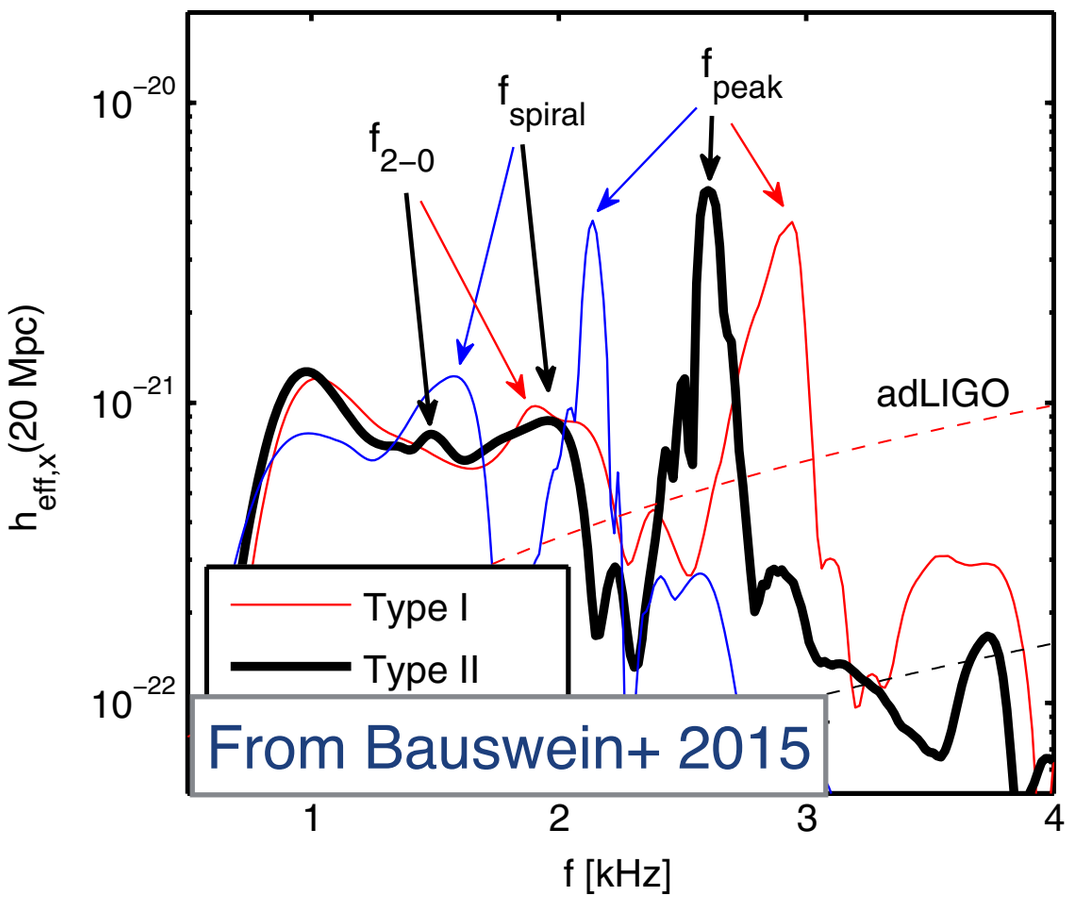
- Potential to constrain the EOS and/or q: the basic physics is understood and included in the simulations
- Modeling uncertainties appear to be under control
- Systematic errors still dominant
- Need to explore the parameter space: EOS, mass ratios, etc.

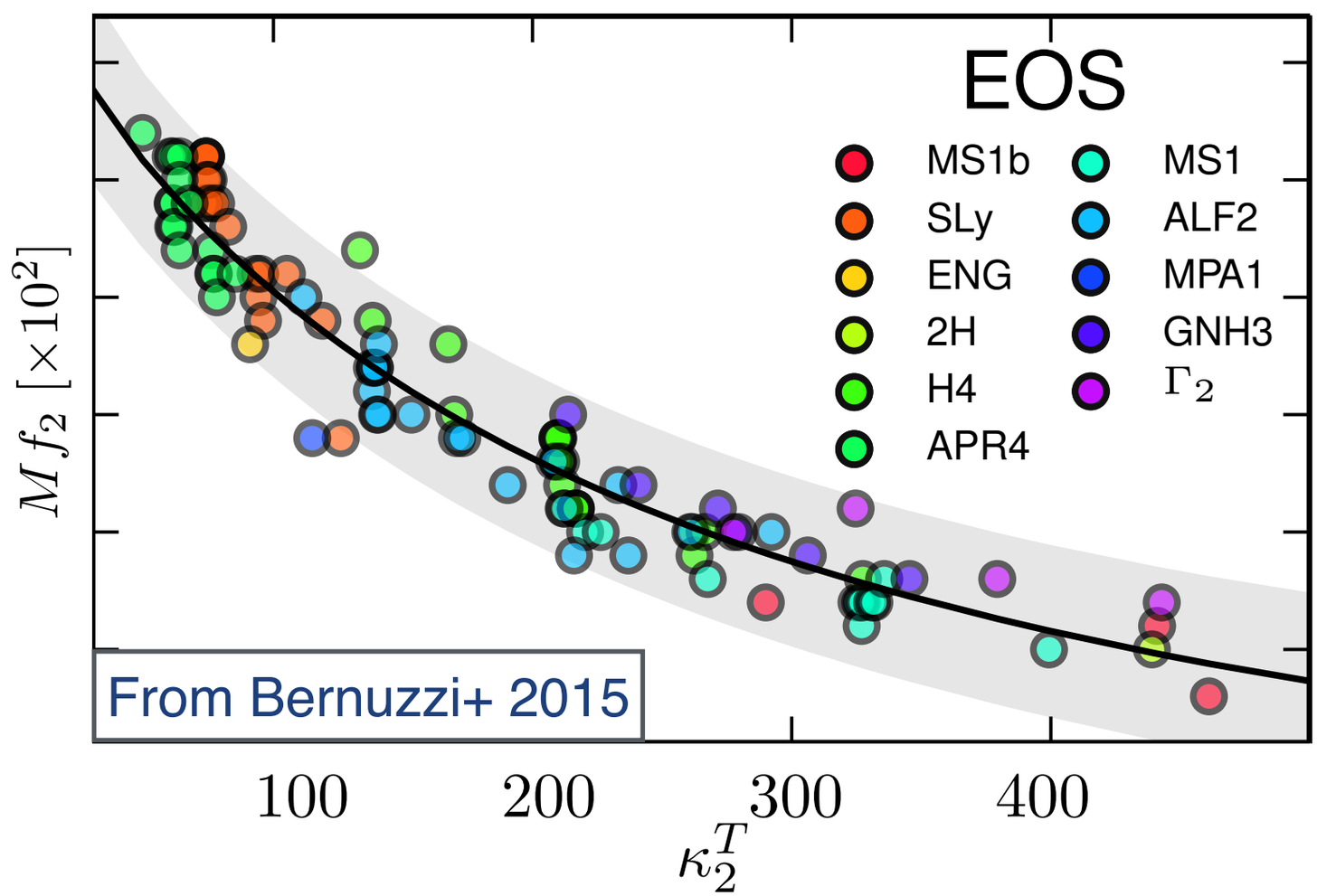
Breschi+ (2021), 2101.01201

BNS postmerger: GW phase



Postmerger GW frequency

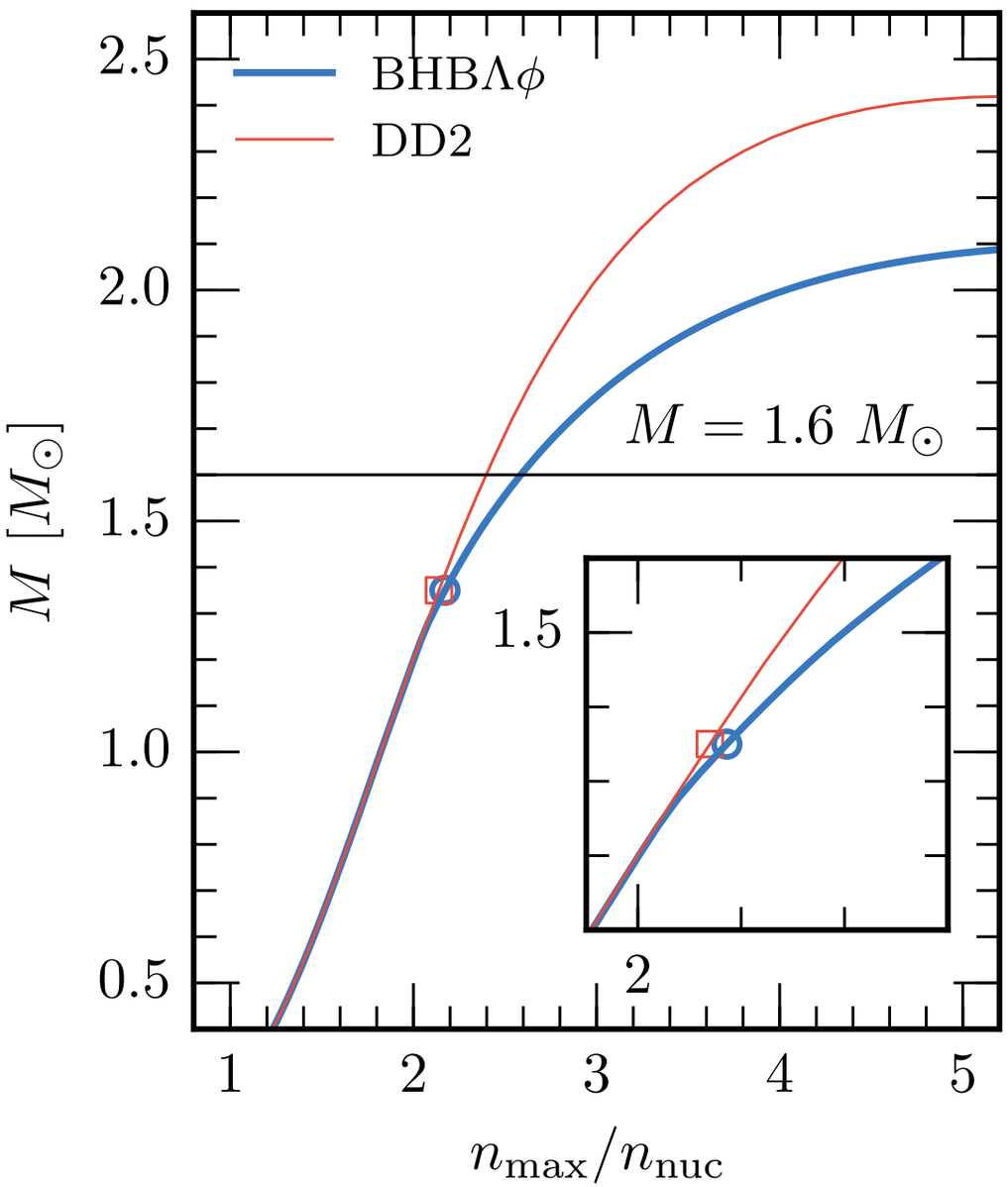


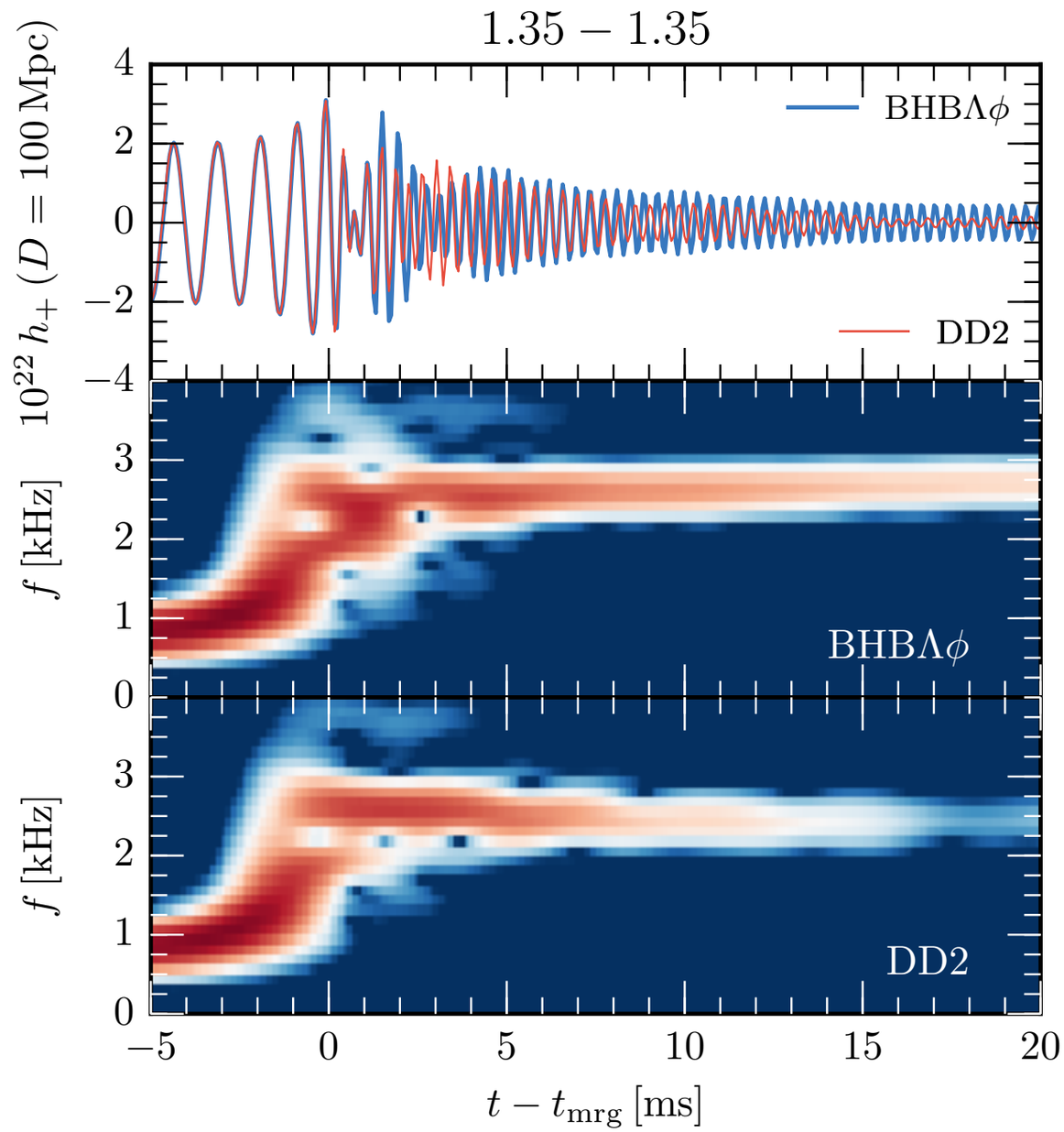


- Post-merger signal has a characteristic peak frequency
- f_{peak} correlates with the NS radius and tidal deformability
- A deviation from the expected correlation would be a signal for a phase transition in the postmerger

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Most+ 2018; Bauswein+ 2018, 2019; …

Postmerger GW amplitude

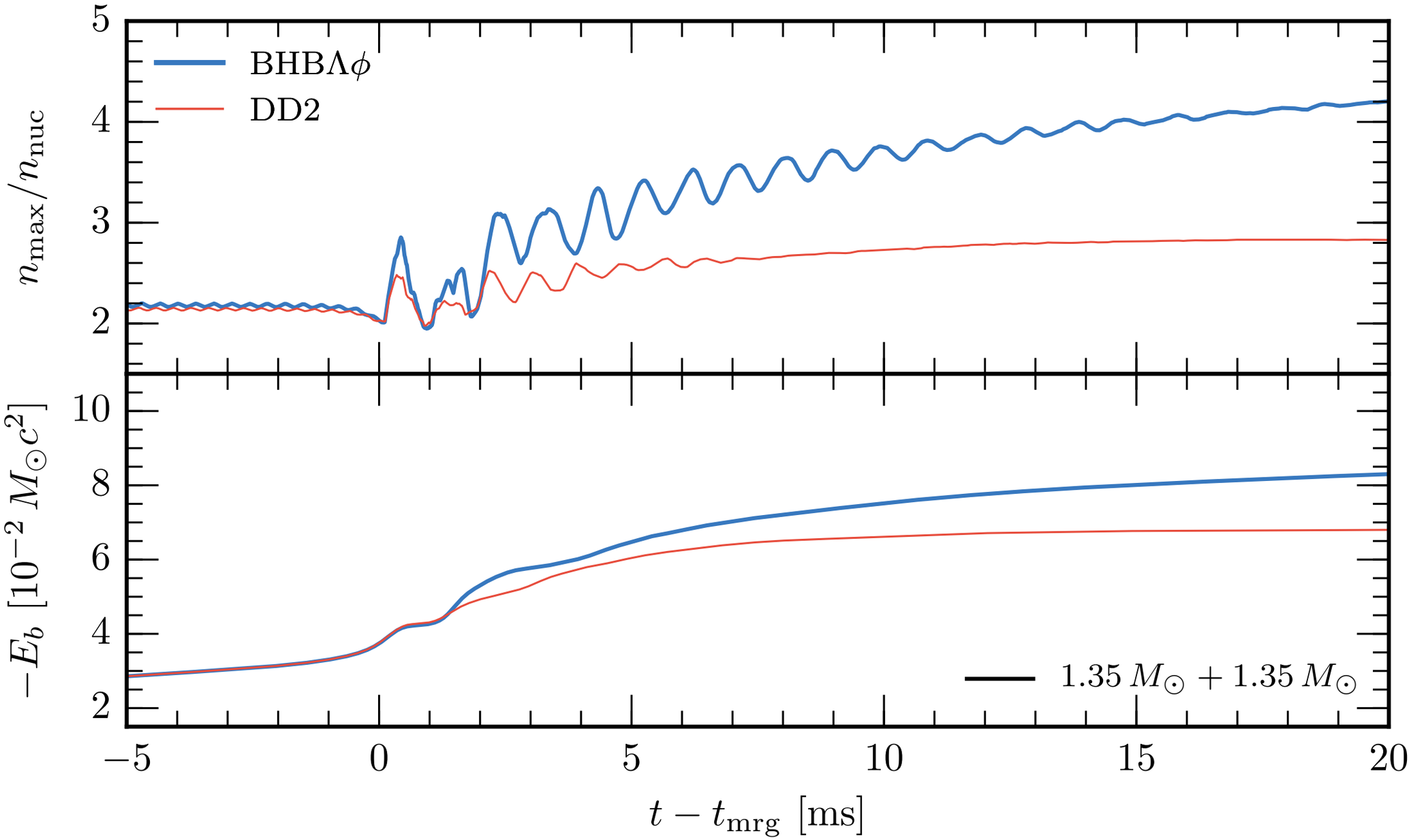




The GW amplitude could reveal the outcome of the merger and constraint the properties of matter at extreme densities.

DR, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

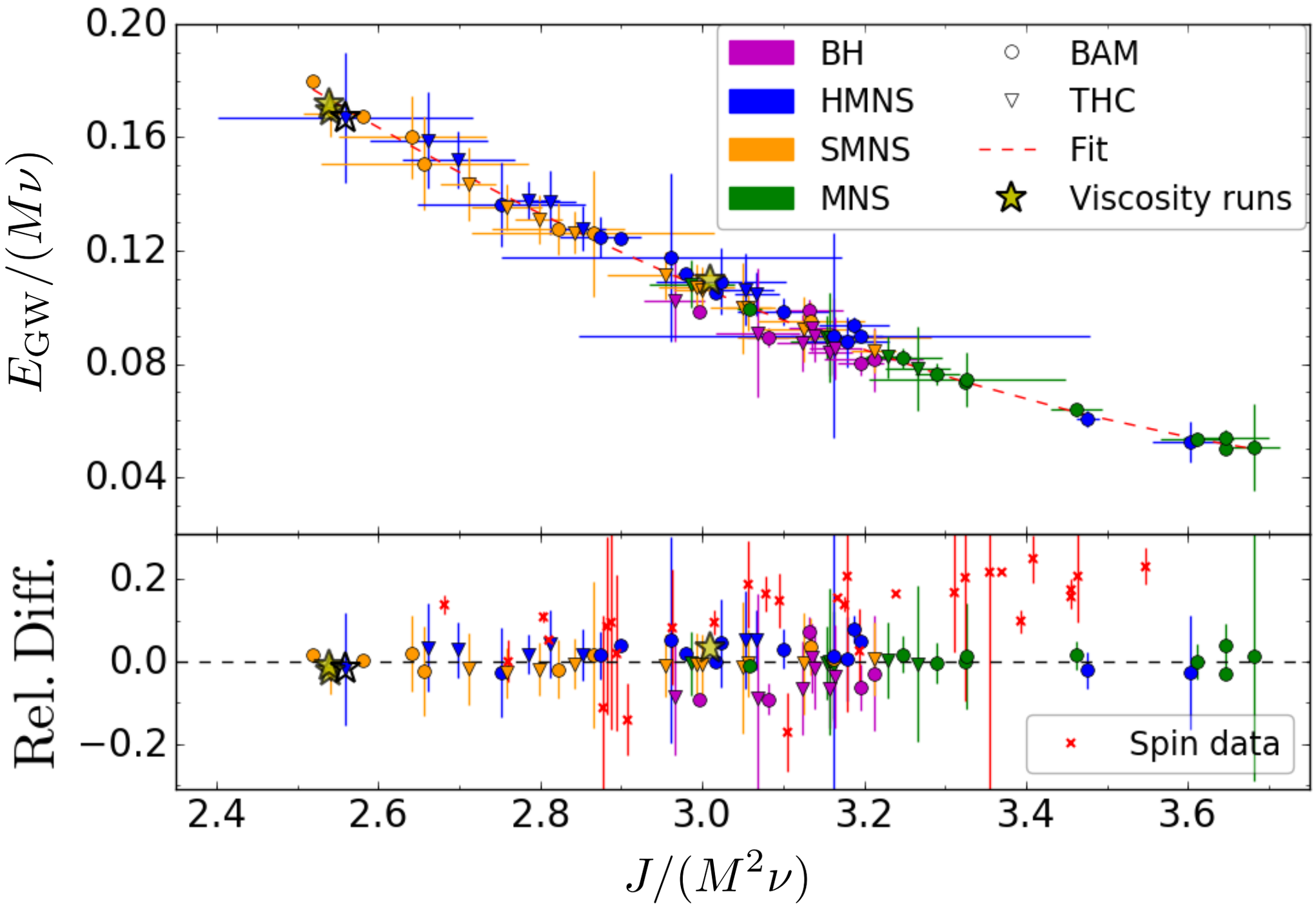
Binding energy



High-density EOS encoded in the binding energy

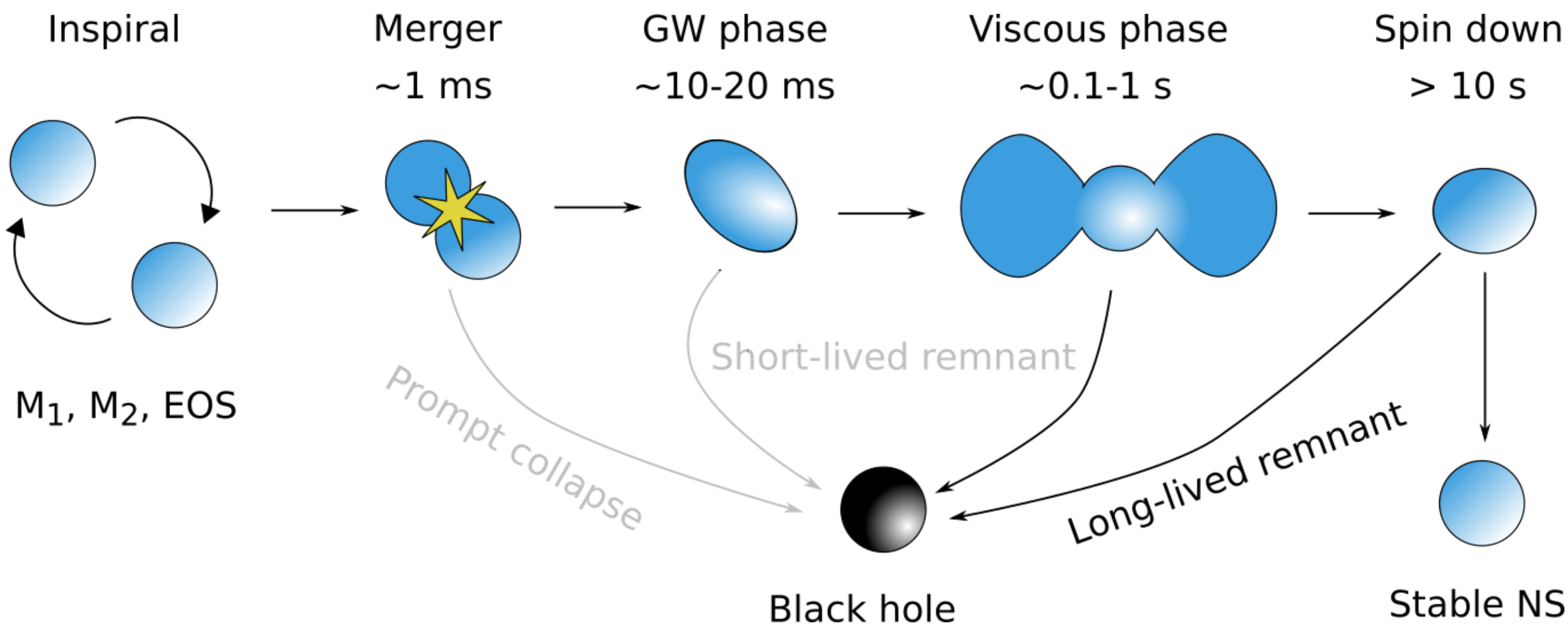
DR, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

End of the GW phase



Zappa, Bernuzzi, **DR**+, Phys. Rev. Lett. 120, 111101 (2018)

Long term postmerger evolution



Viscous evolution

Common wisdom

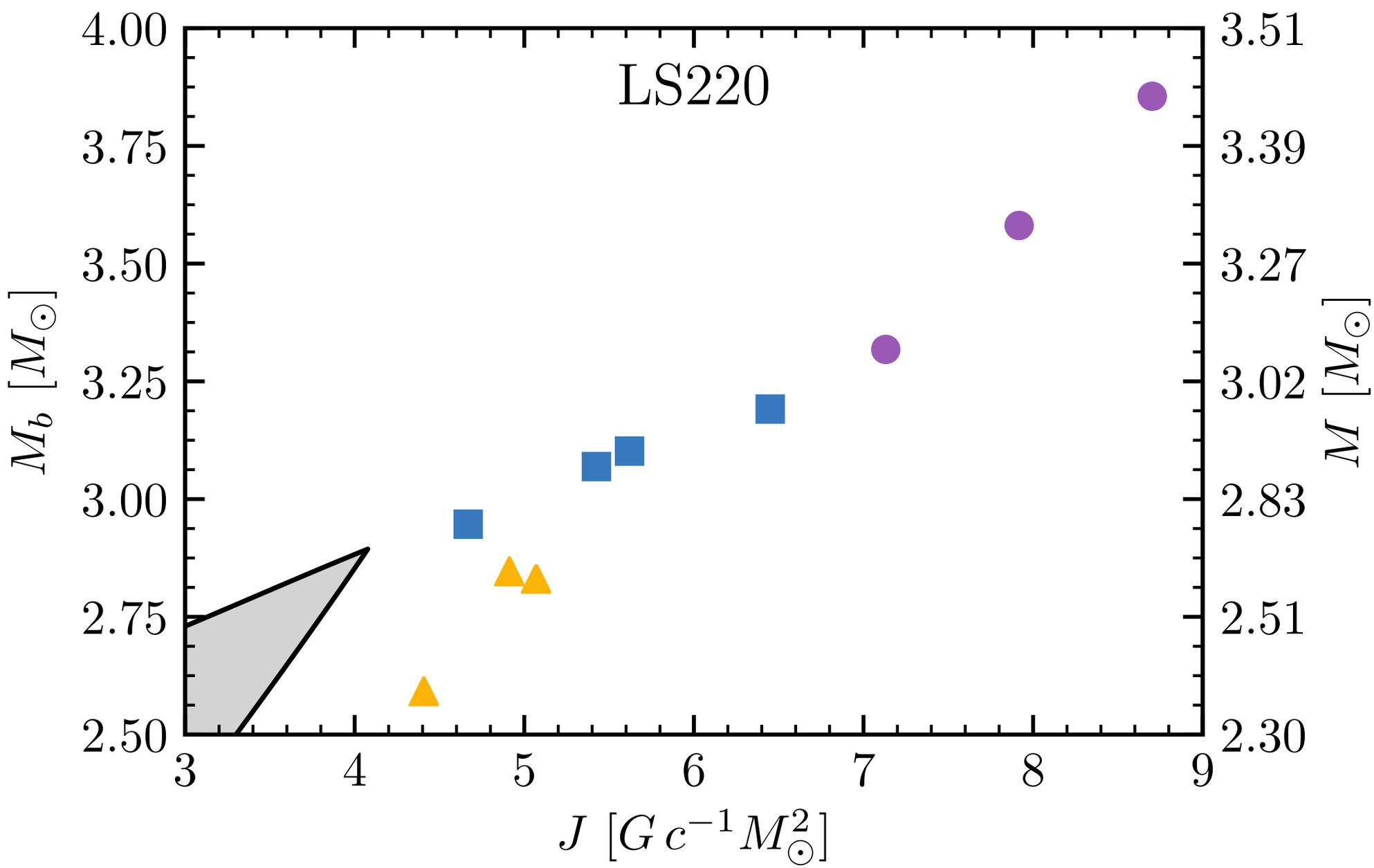
- The remnant is supported by differential rotation
- Viscosity will bring the system to solid body rotation
- If $M > M_{rot}$, then the remnant collapses to BH (HMNS), otherwise the remnant survives for long time (SMNS)

This picture is wrong*!

* or at the very least incomplete

Viscous evolution

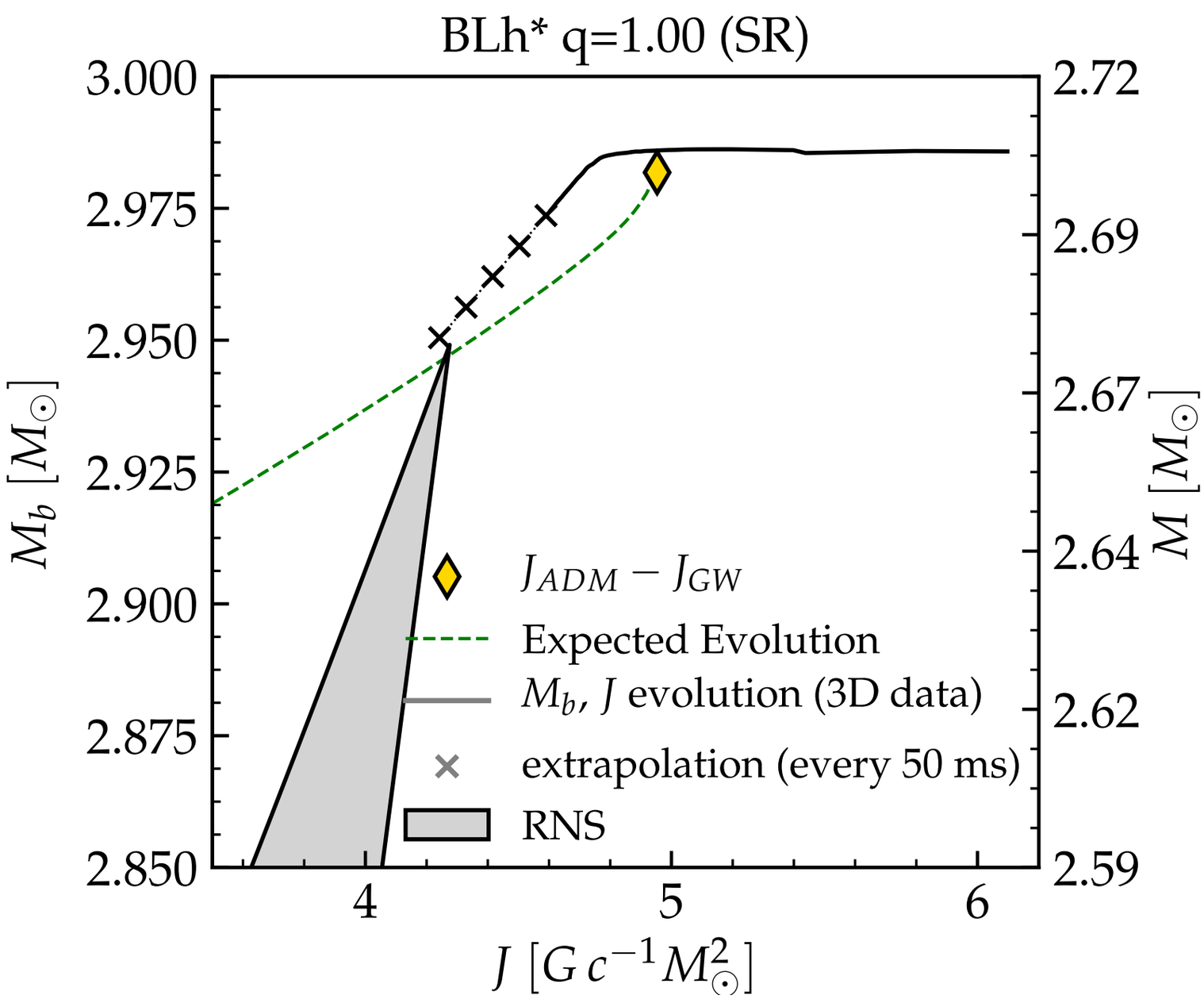
Remnants



DR, Perego, Bernuzzi, Zhang, MNRAS 481:3670 (2018)

Viscous evolution

Simulation results



- Remnants have too much angular momentum to become centrally condensed
- "Viscosity" (really MHD turbulence and neutrinos) drives mass ejection
- Ultimate fate of binaries that survive until this point is difficult to predict
- Necessary physics not yet fully included or resolved in simulations

From Nedora, Bernuzzi, **DR**+, ApJ 906:98 (2021)

Conclusions

- Inspiral physics well understood, but waveform models need to be improved for 3G (or even a very loud signal in O4).
- The merger phase physics is understood. We can already do multimessenger astronomy today! Works remains to be done to explore the BNS parameter space (EOS, mass ratio, spin, etc)
- The postmerger GW signal can probe matter under the most extreme conditions, but works to be done on all fronts.
- The fate of BNS mergers over long timescales is understood only qualitatively.