NP3M

NSF Focus Research Hub
Nuclear Physics from Multi-Messenger Mergers

www.computational-relativity.org

Neutron Star Mergers

David Radice (PSU) — Sept. 2, 2021

arXiv:2002.03863

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

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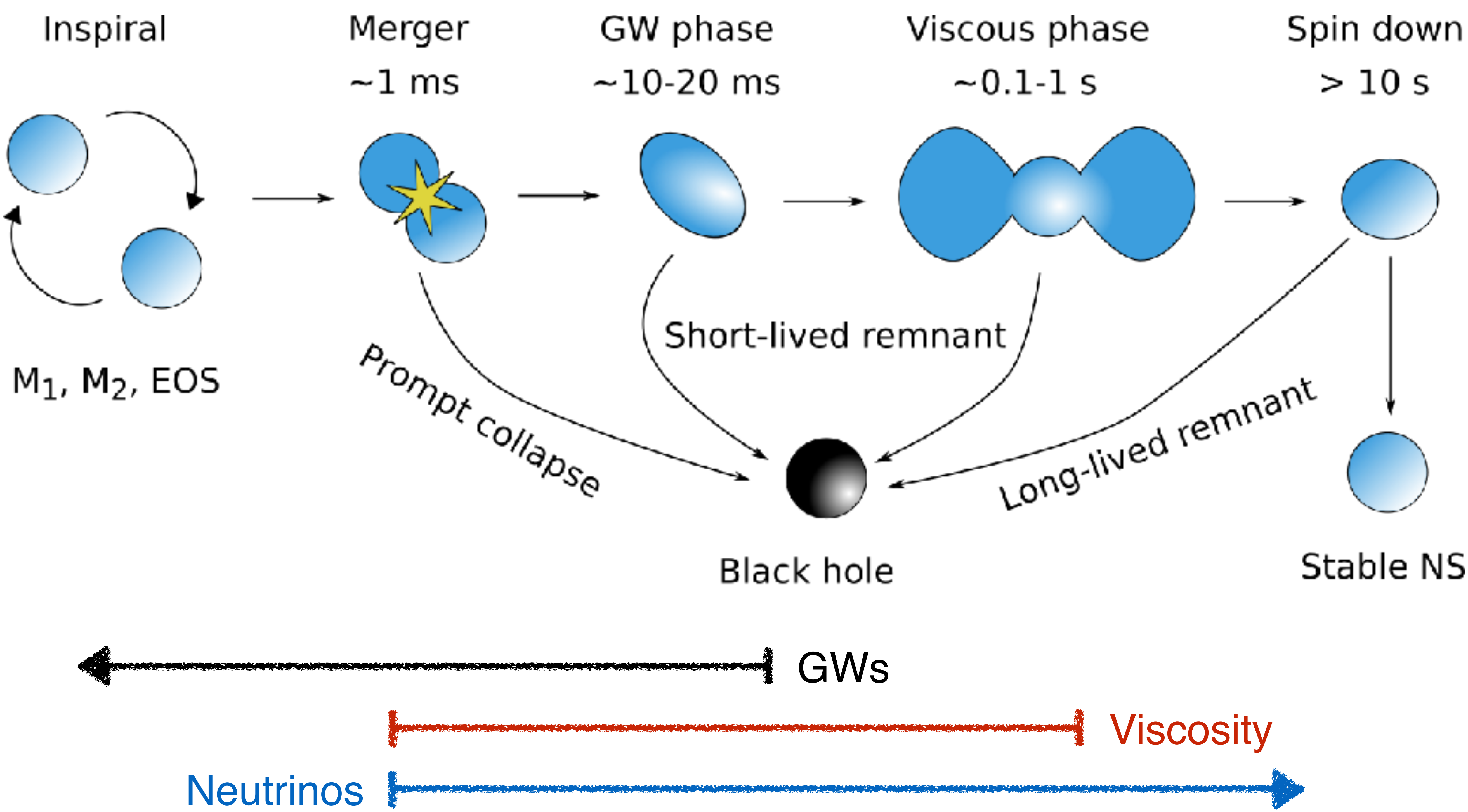
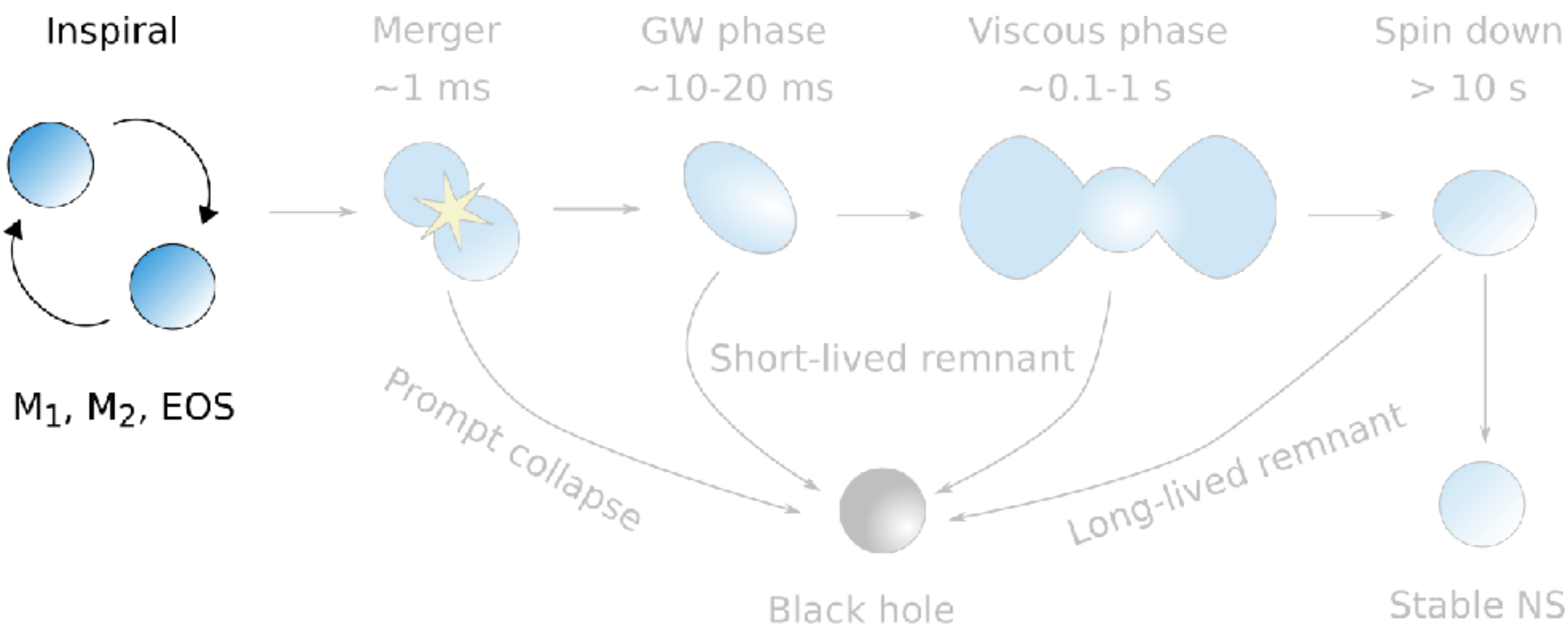
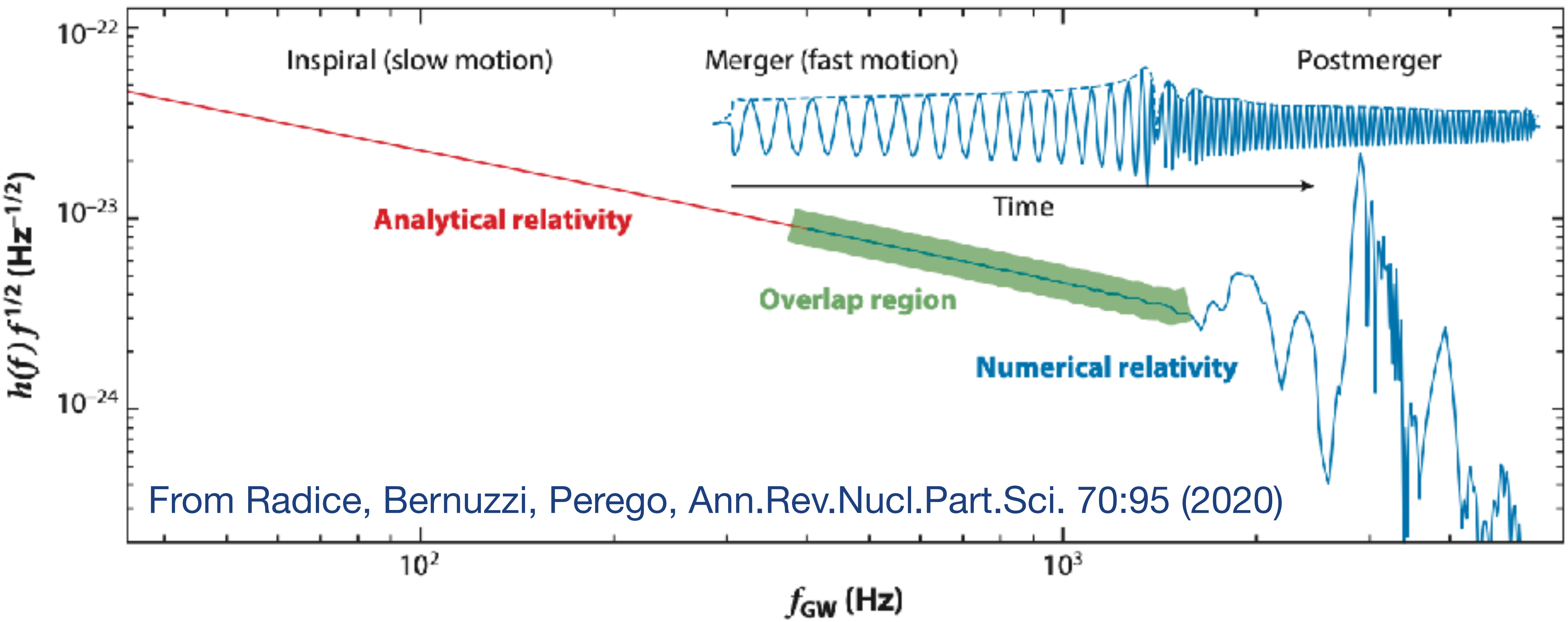
Neutron star merger evolution



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

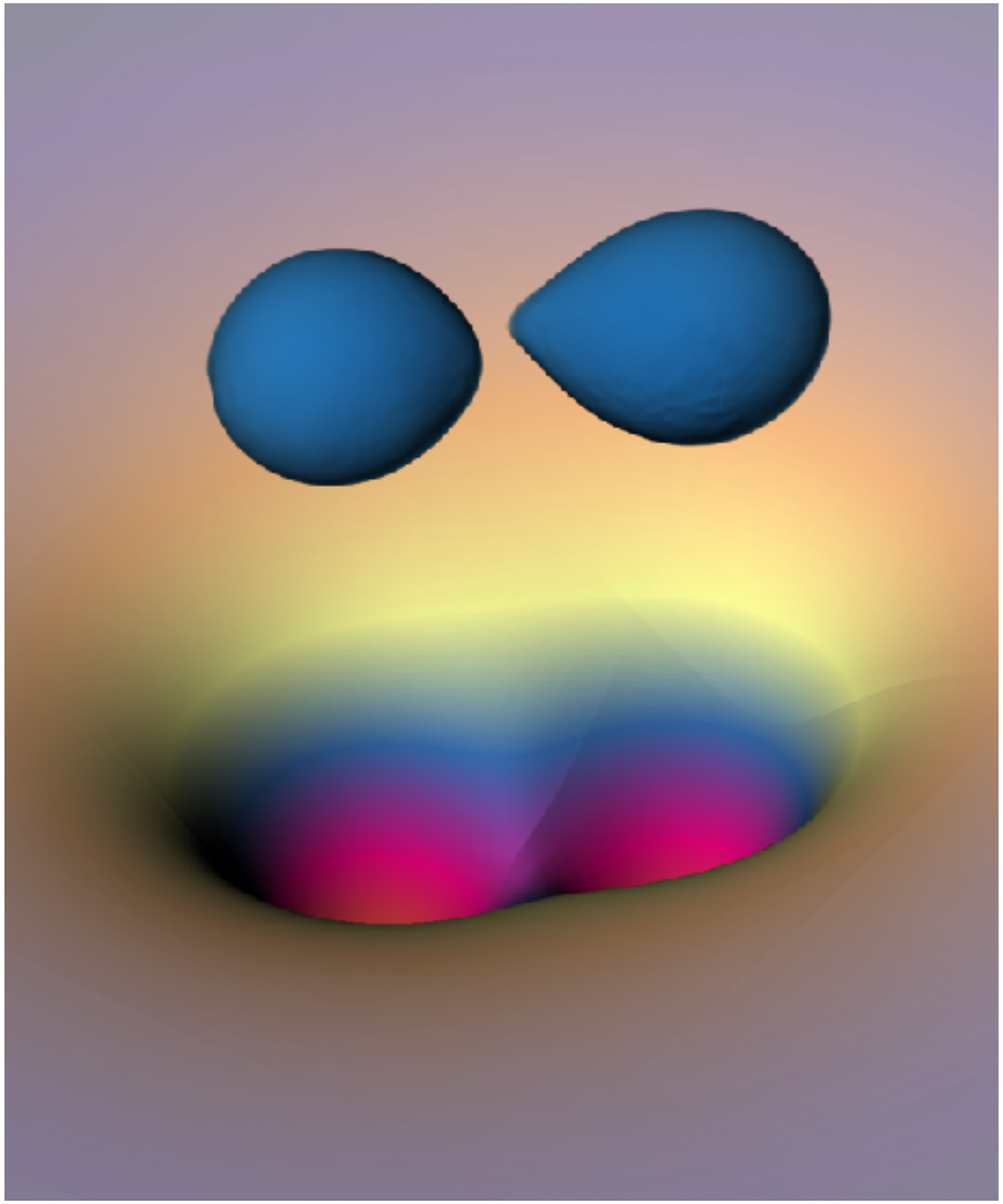
- The impact of tides
    1. The potential is modified and becomes more attractive:

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

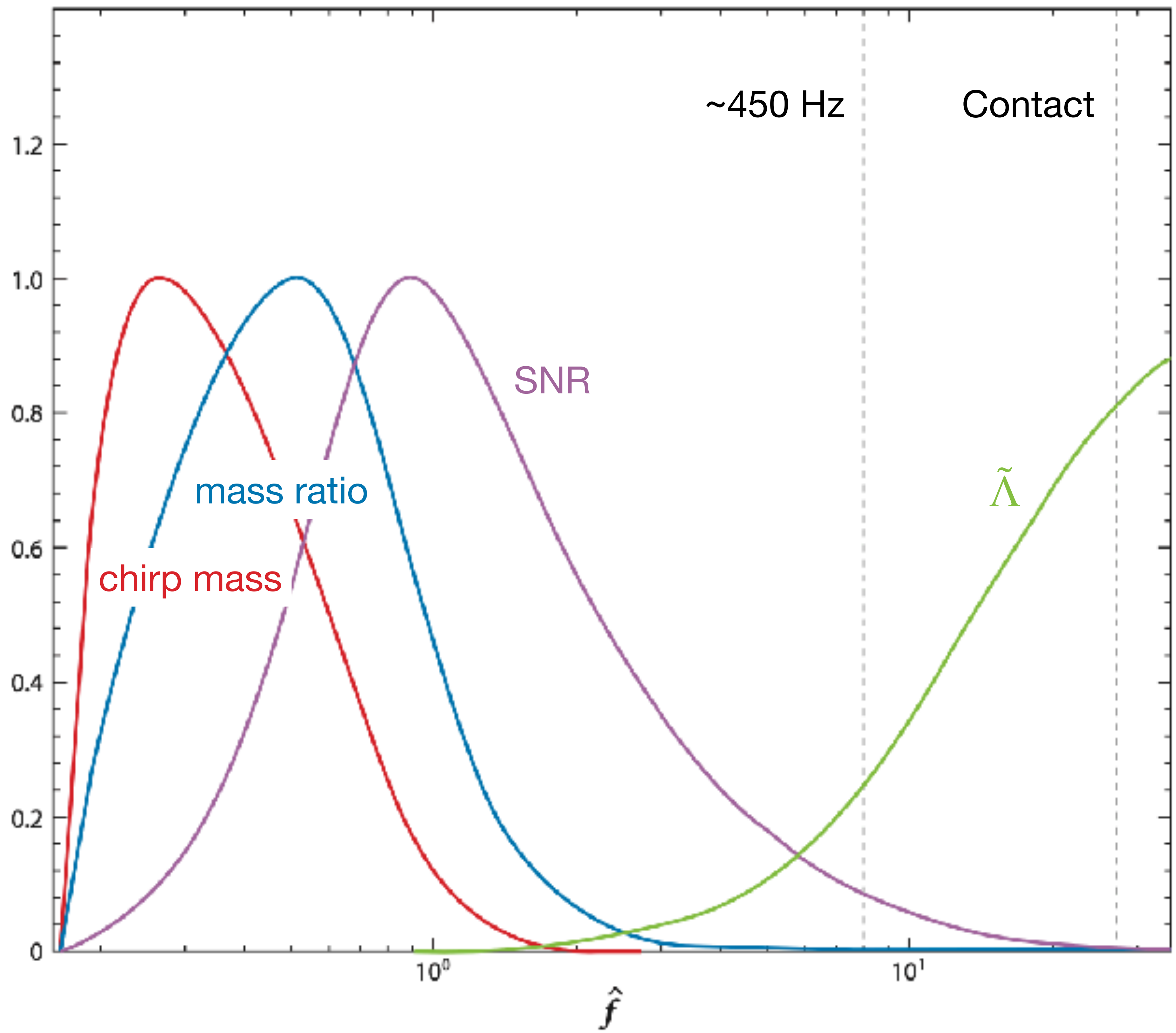
    2. The tidal bulge contribute to the GW emission:

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

- 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

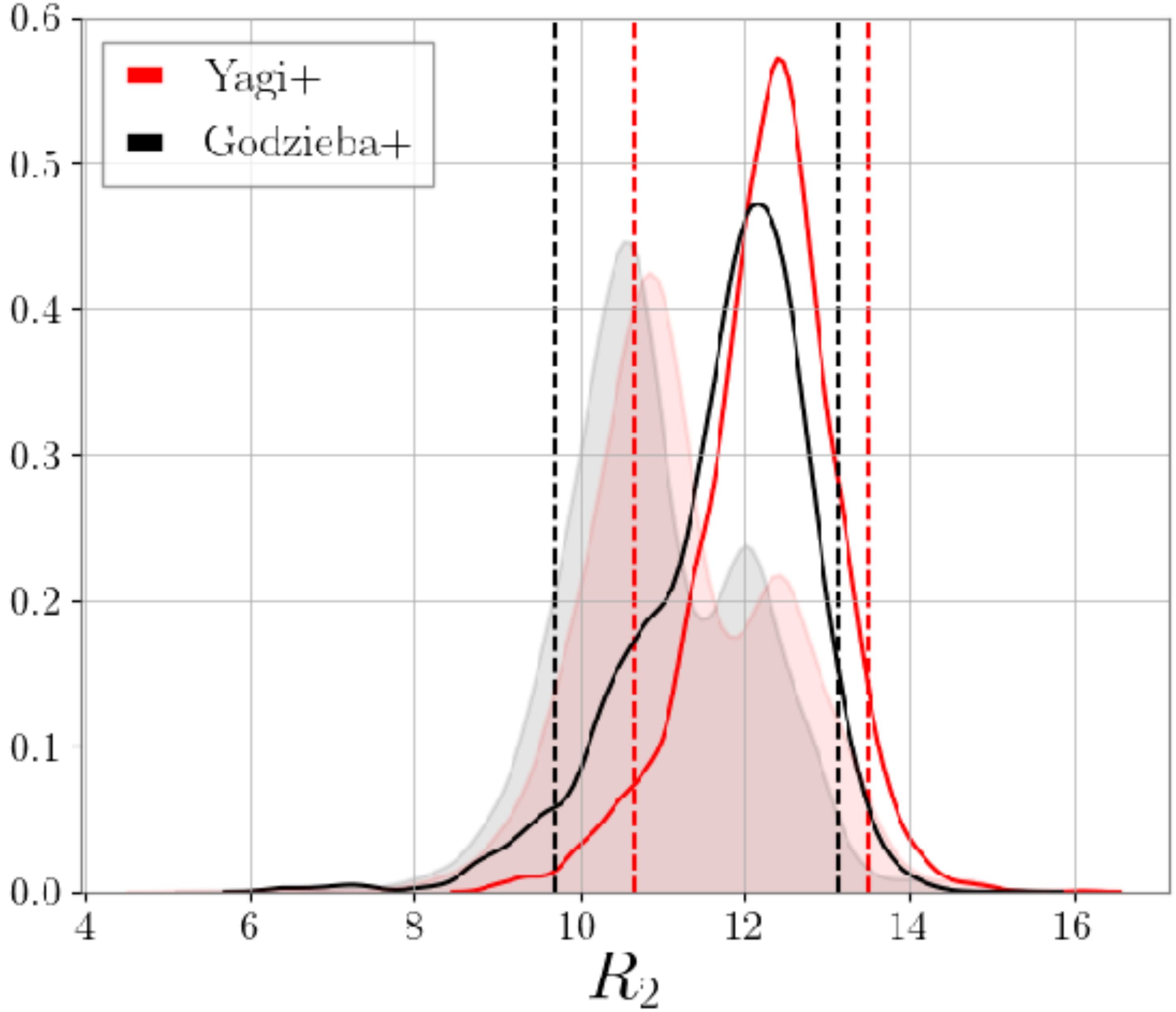


GW parameter estimation



Adapted from Damour & Nagar 2012

GW170817

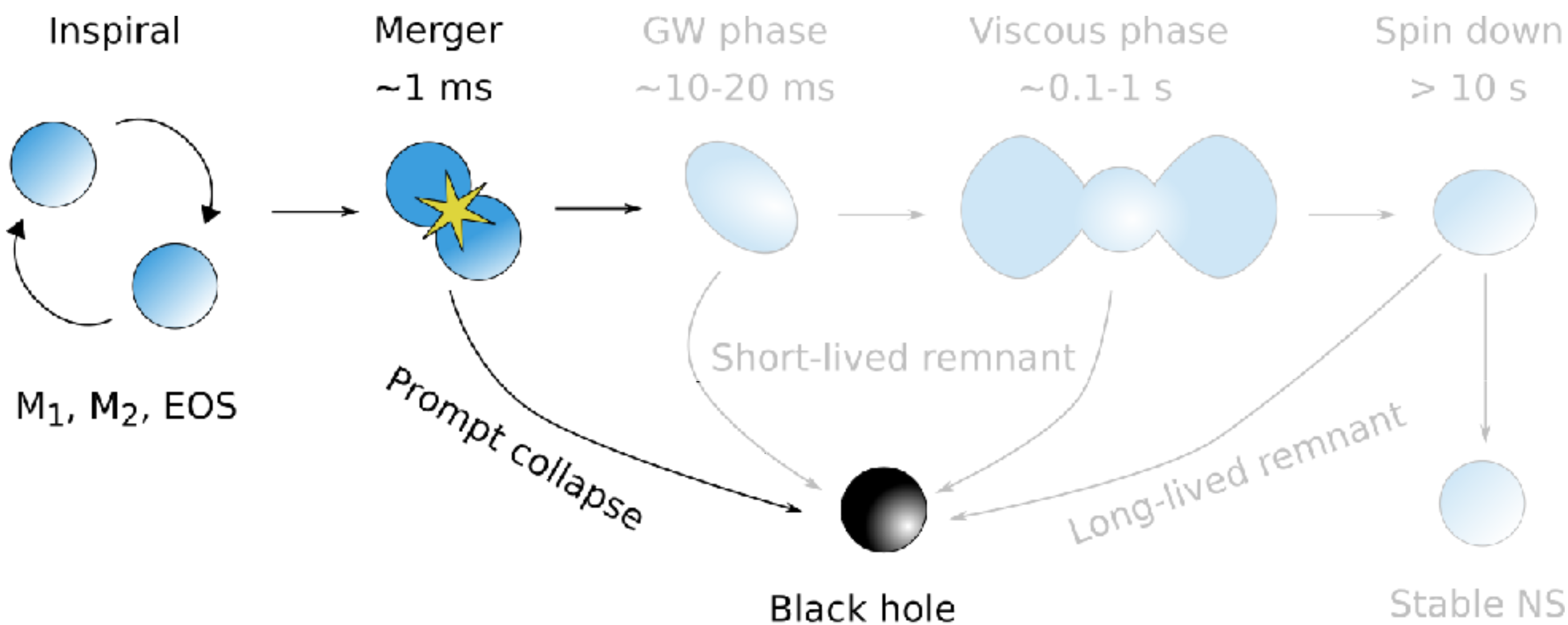


From Godzieba+ Phys. Rev. D 103, 063036 (2021)

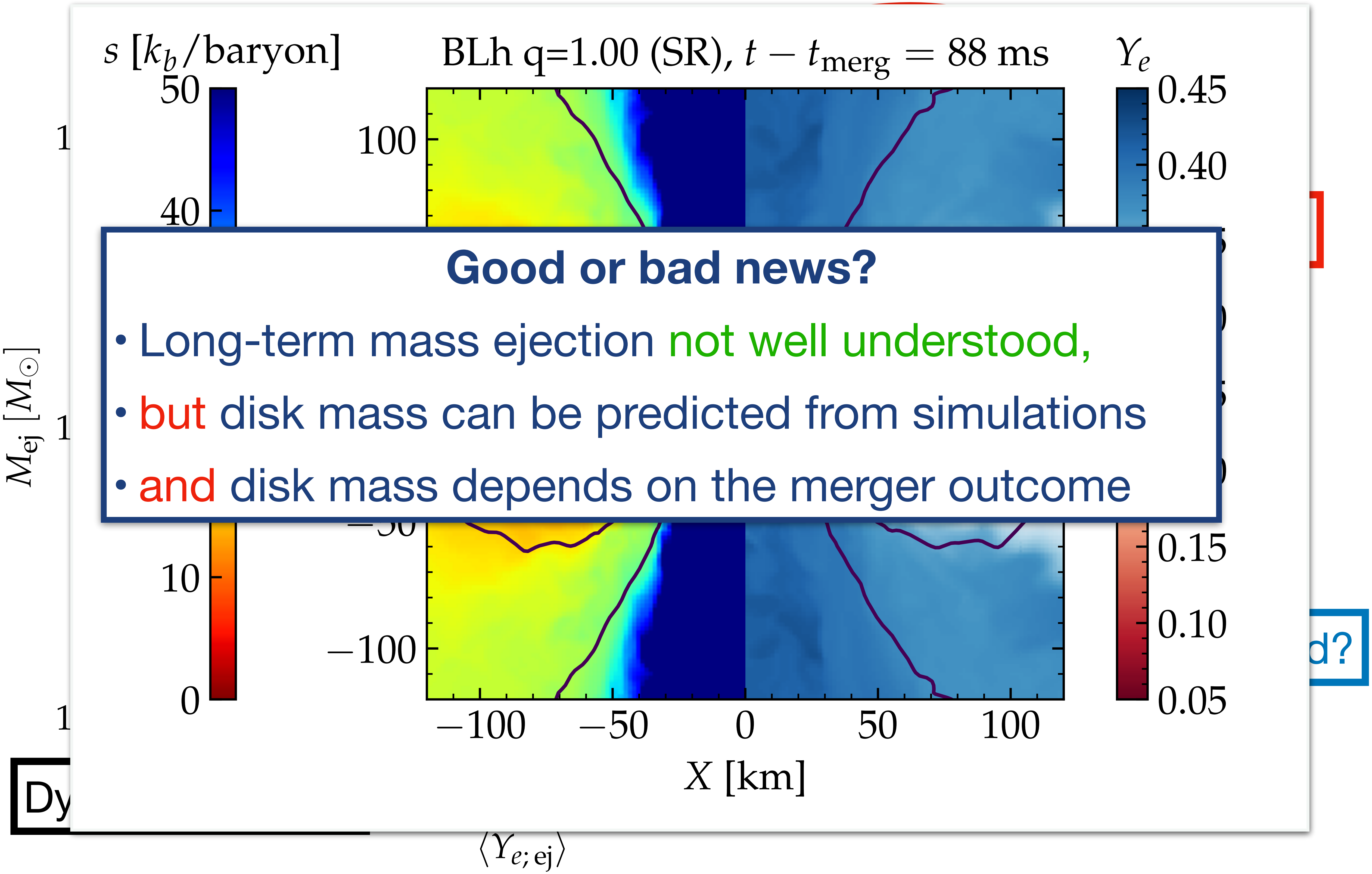
- Robust upper limits $\tilde{\Lambda} < 800$
- Very stiff EOS are ruled out at high confidence
- Lower limits: dependency on details of the analysis, waveform model, etc.
- Probing the EOS on the soft side more challenging: we need multimessenger observations

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

Binary NS merger



Theory vs observations



Good or bad news?

- Long-term mass ejection not well understood,
- but disk mass can be predicted from simulations
- and disk mass depends on the merger outcome

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

GW170817

- Kilonova is powered by the radioactive decay of outflows from the merger and disk winds
- What happens if the stars for a BH promptly? For comparable mass BNS systems prompt-BH implies EM quiet
- Bright kilonova: no prompt BH formation or large mass ratio
- How to distinguish these two cases? Kilonova afterglow? Detailed EM modeling?

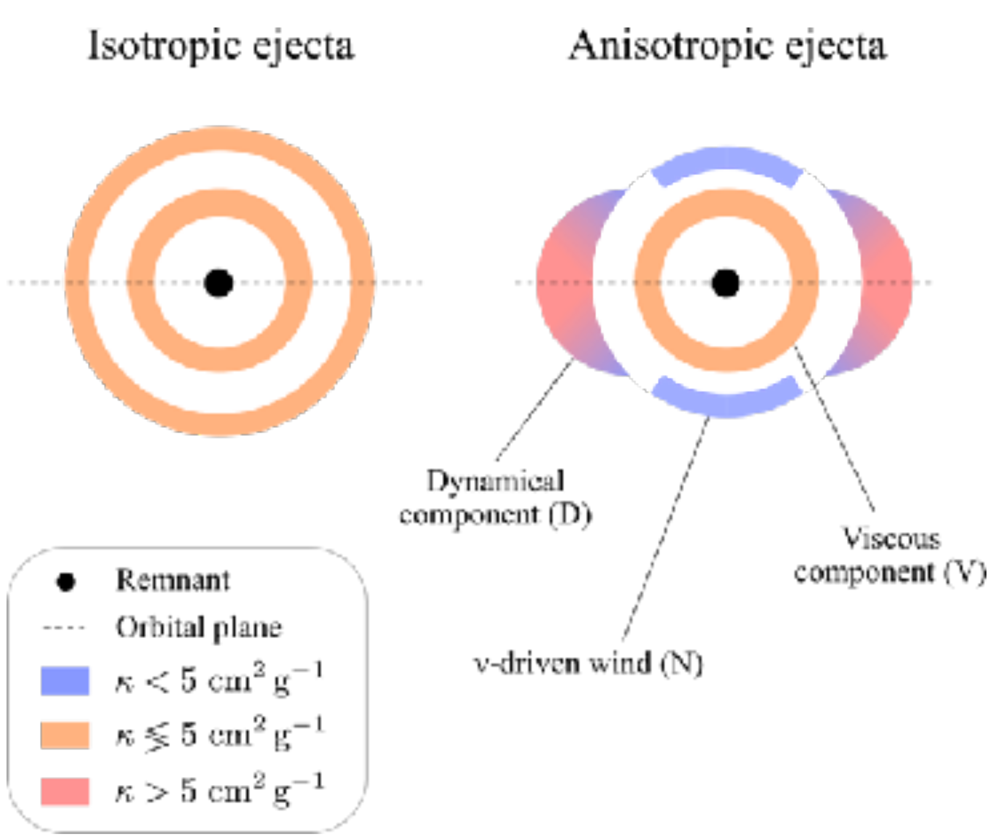
Multimessenger PE

$$P[\theta|d]$$

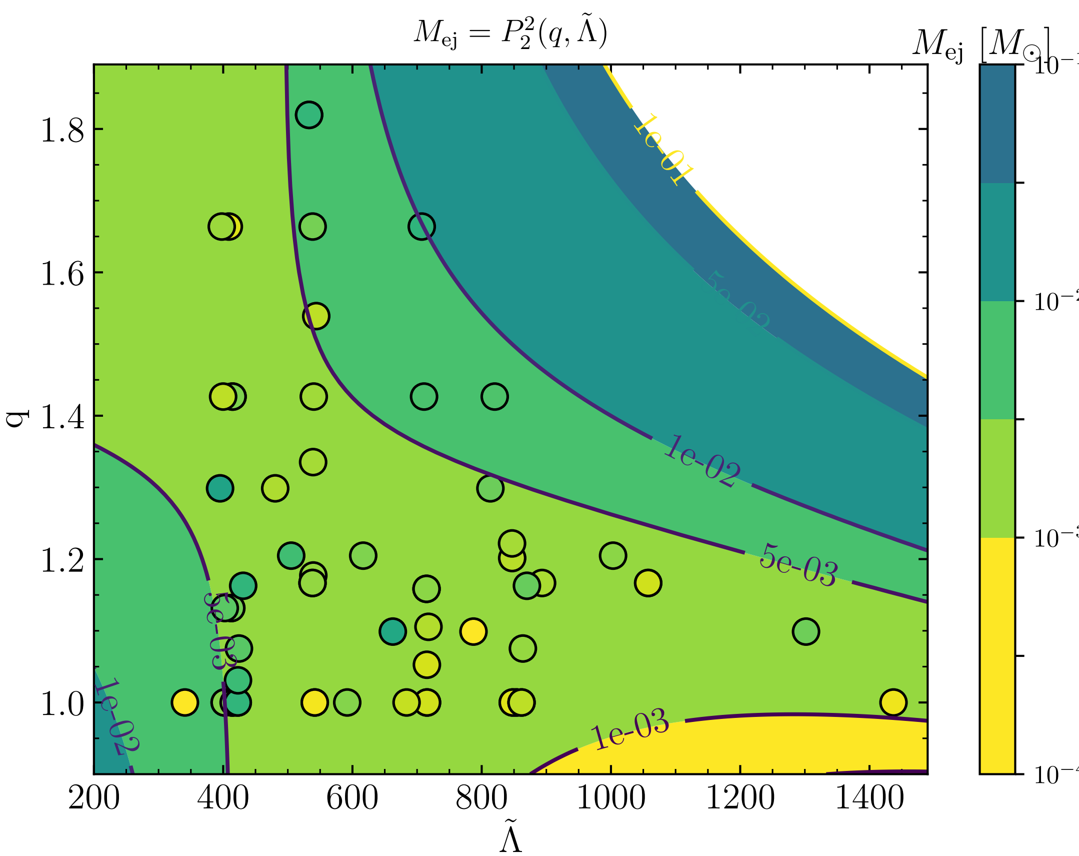
GW modeling and data analysis

kilonova modeling

NR simulations

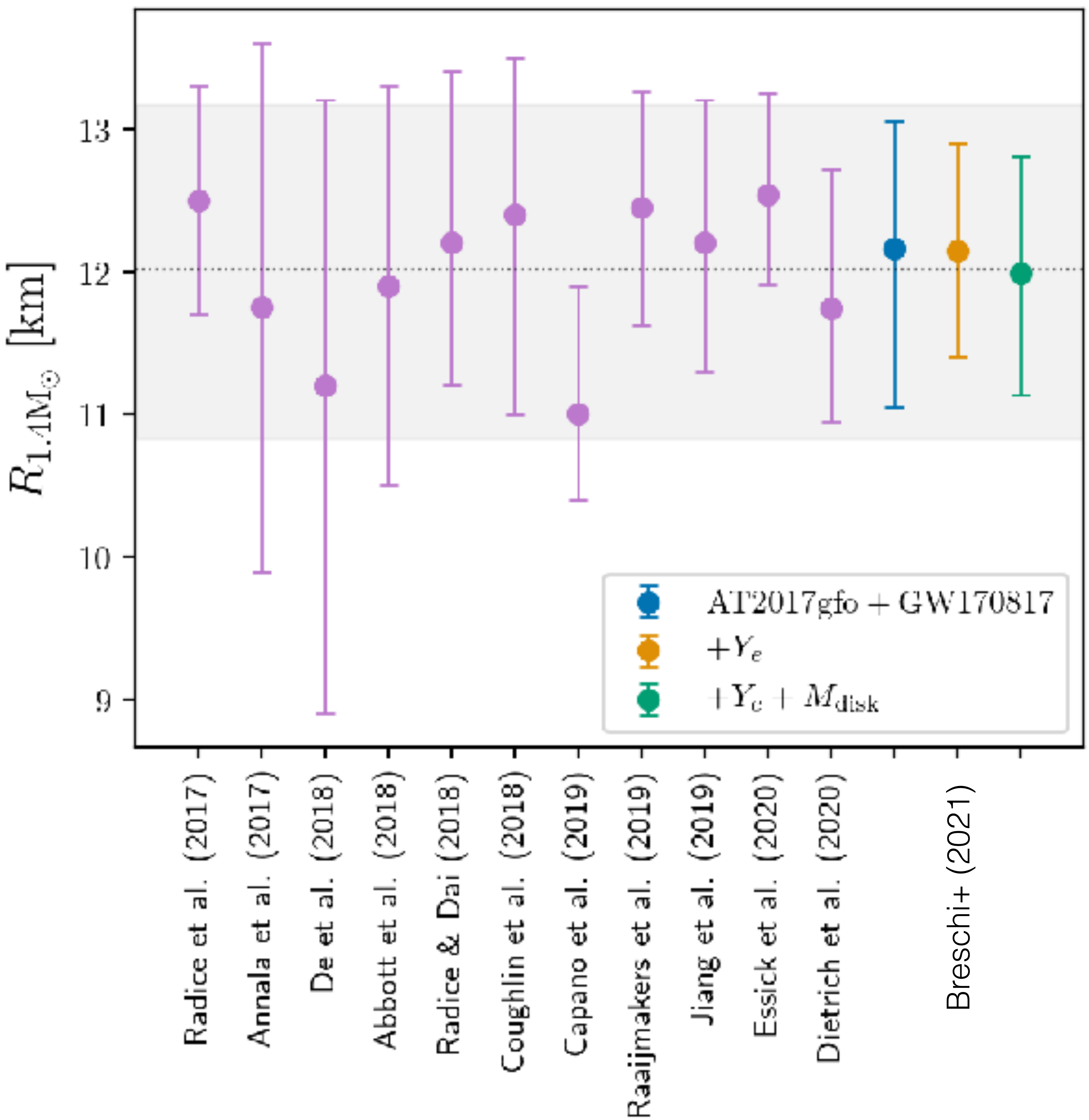


Breschi+ 2021, 2101.01201



Nedora+ 2020, 2011.11110

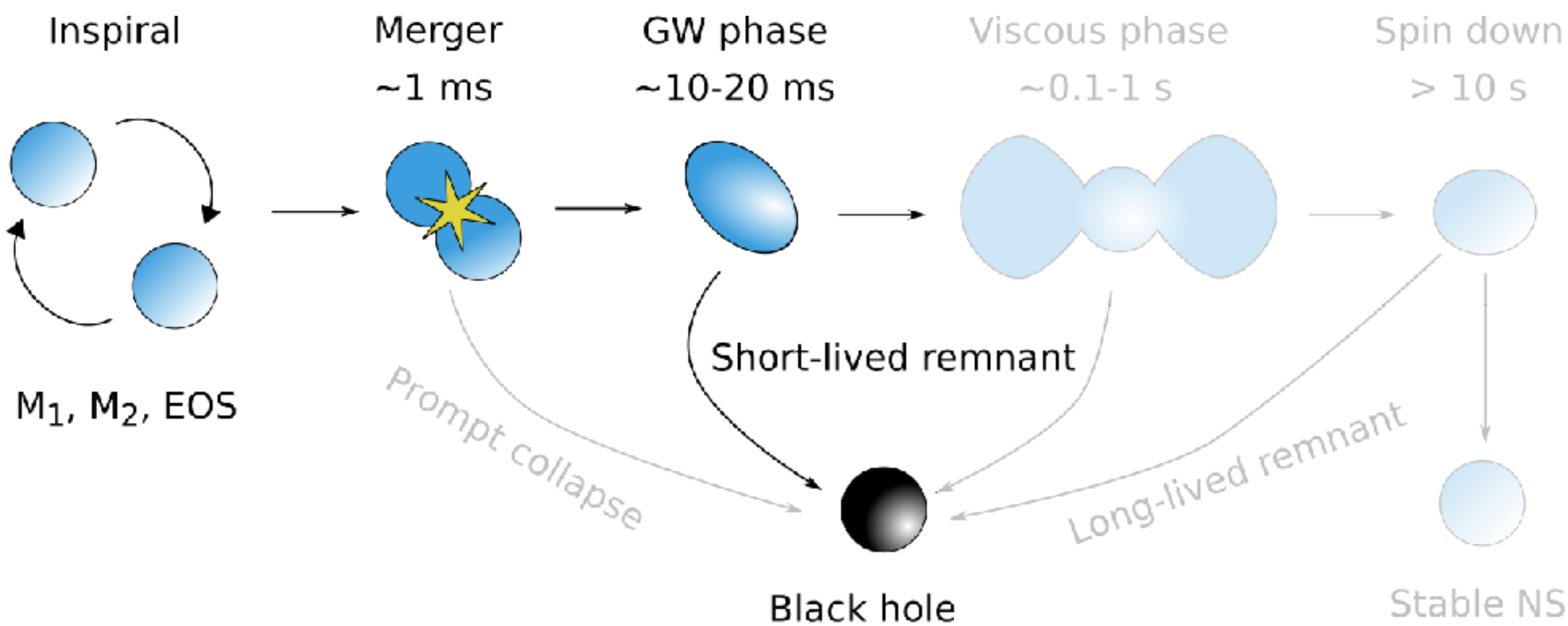
NS radii from GW170817



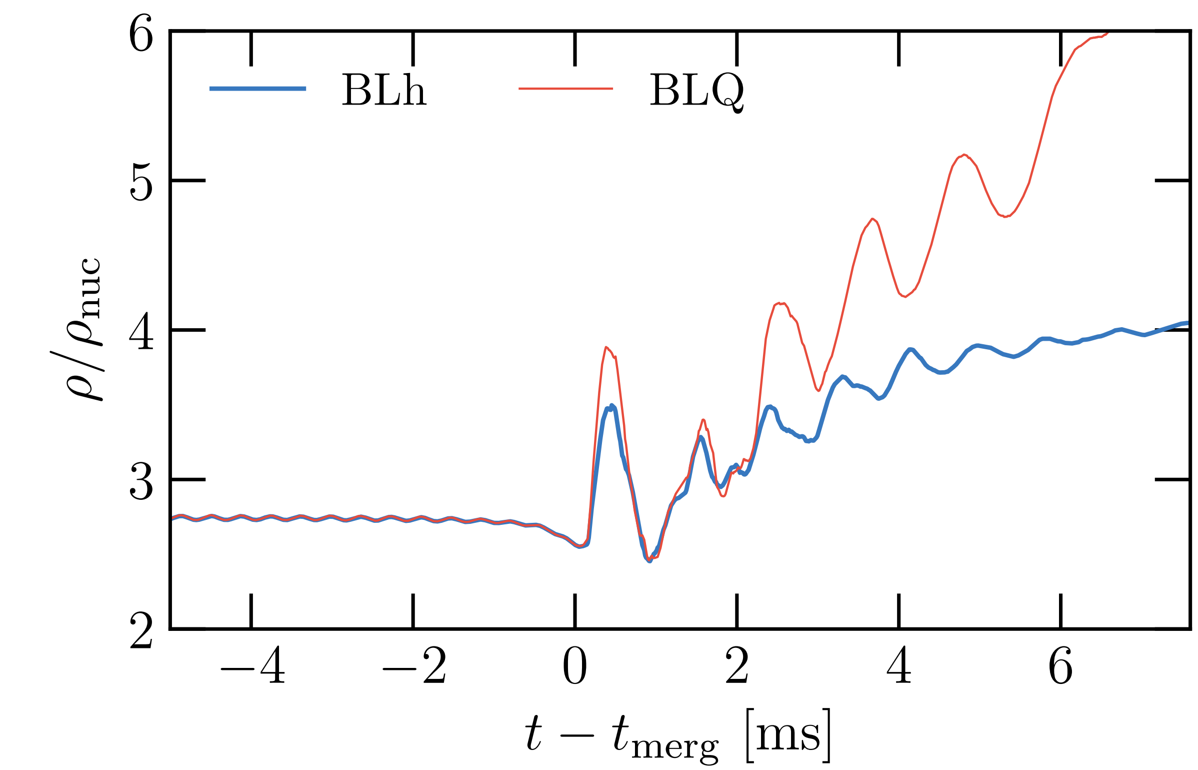
- Potential to constrain the EOS and/or q: the basic physics is understood and included in the simulations
- Modeling uncertainties appear to be under control
- Systematic errors still dominant
- Need to explore the parameter space: EOS, mass ratios, etc.

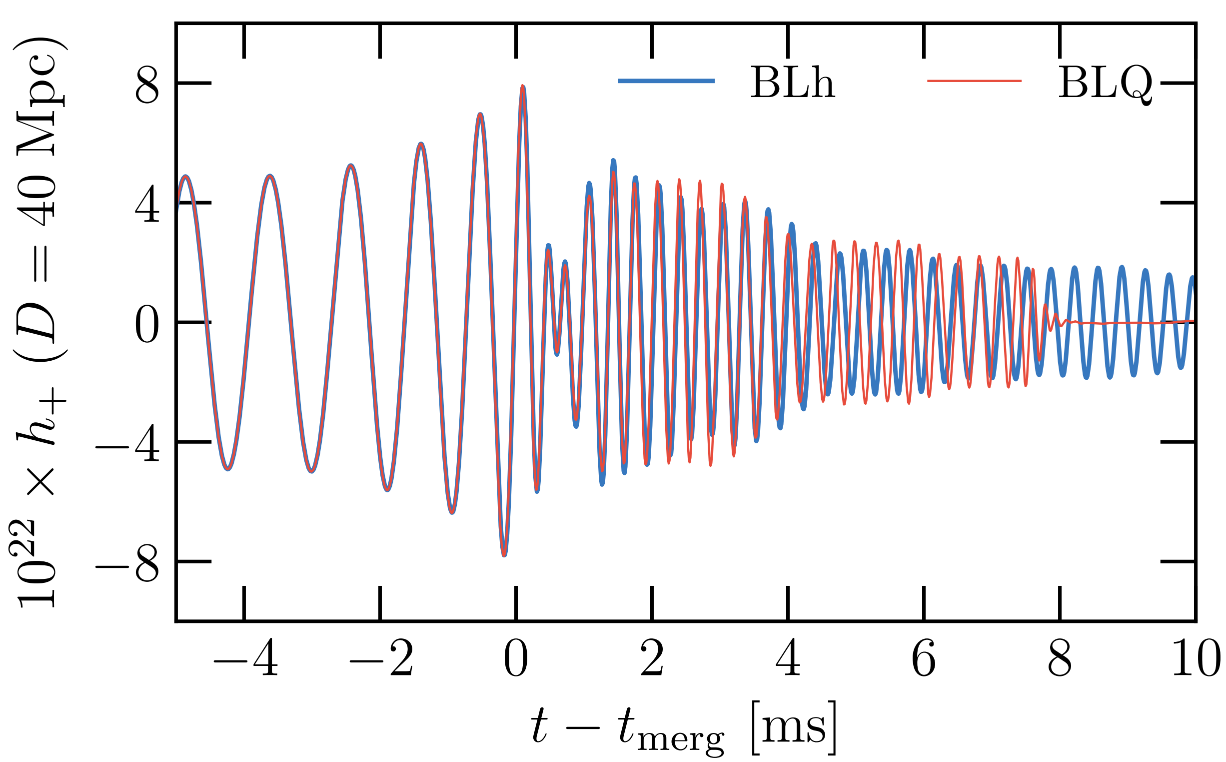
Breschi+ 2021, 2101.01201

BNS postmerger: GW phase



QCD phase transition





BLh: hadronic

BLQ: quarks

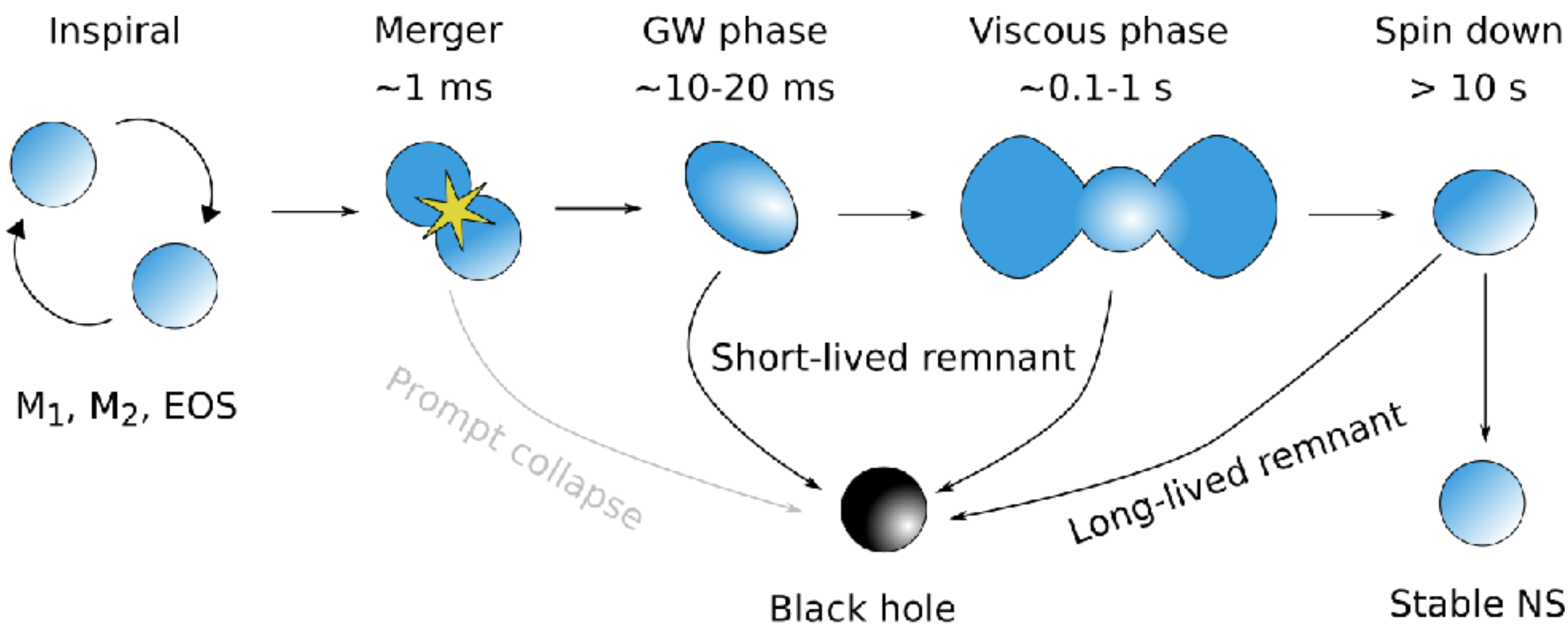
Aviral Prakash (PSU)

- NICER data suggests that if there is a phase transition, then it is at very high density
- Phase transitions cannot be detected with LIGO GW data alone
- Merger shock and postmerger GW data with next gen. detectors could reveal the presence of a phase transition
- Caveat: QCD phase transition potentially degenerate with other physics (e.g., hyperons, kaons, etc.)

See also Most+ 2018; Bauswein+ 2018; Weih+ 2019; …

Prakash, **DR**+, 2106.07885

Long-term 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)

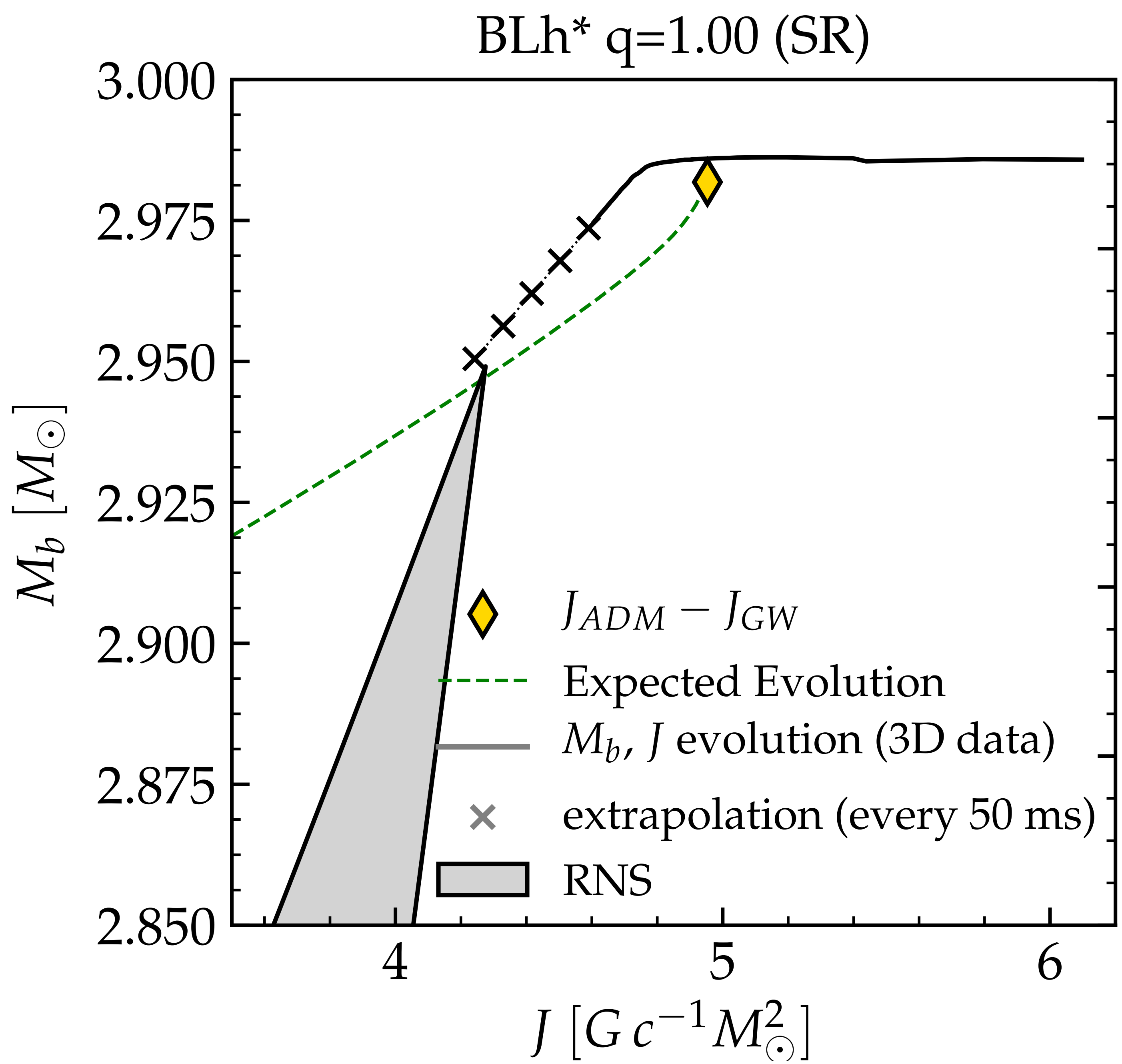
This picture is wrong*!

* or at the very least incomplete

Viscous evolution

Current findings

- Viscosity also drives mass ejection —> stabilizing effect
- Thermal effects lead to softening of the EOS —> destabilizing effect
- Only constrain from GW170817 is no long lived remnant with a strong ordered field. Simulations, find tangled B-field…
- What about phase transitions, pions, viscosity? Much confusion in the literature [see 2108.08649 for a nice review]
- What about the non thermal counterpart? What can that tell us?
- Lots of work to do here



Hot topics

- EOS and binary parameter space explorations
- Microphysics effects in the late inspiral and merger
- Neutrino trapping and weak reactions
- Neutrino irradiation of the ejecta, neutrino oscillations
- MHD effects
- Full-physics, long-term simulations