Simulations of neutron star mergers: Status and prospects

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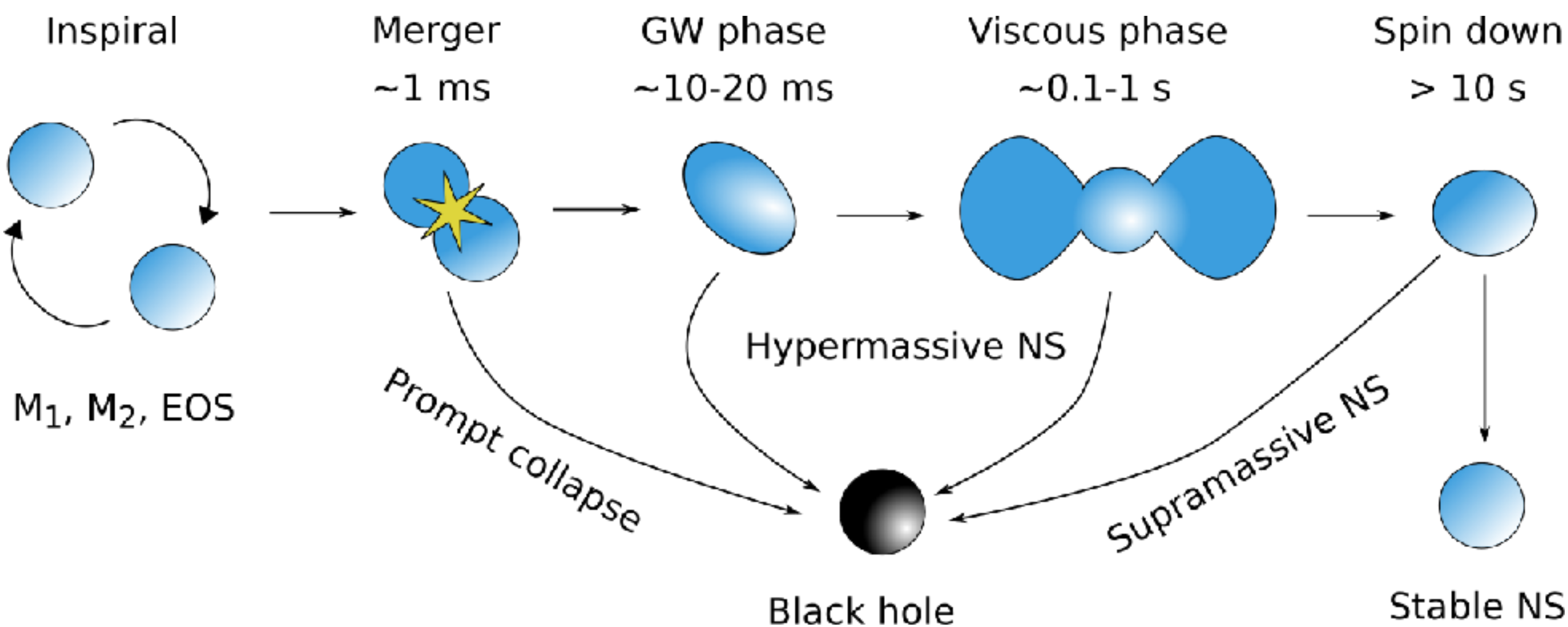
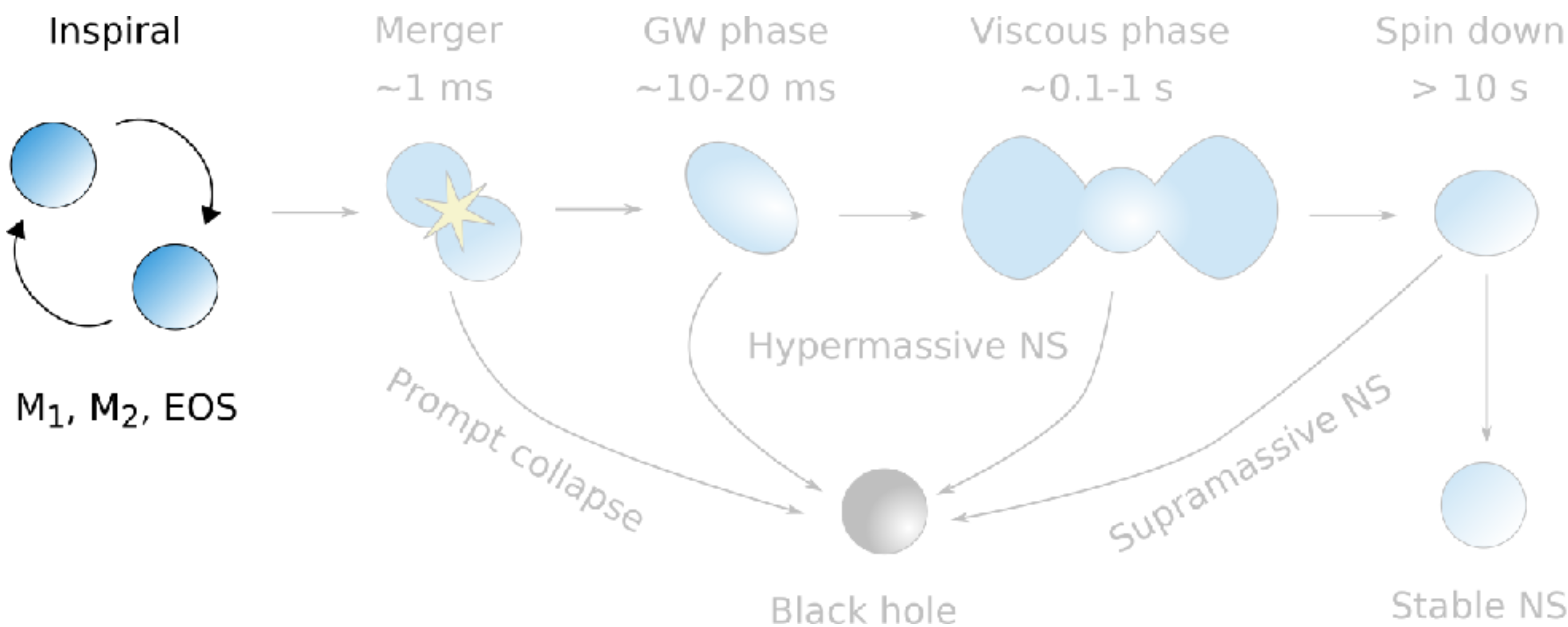
First multi-messenger observations of a neutron star merger
and its implications for nuclear physics — INT 18-72R — March 13, 2018

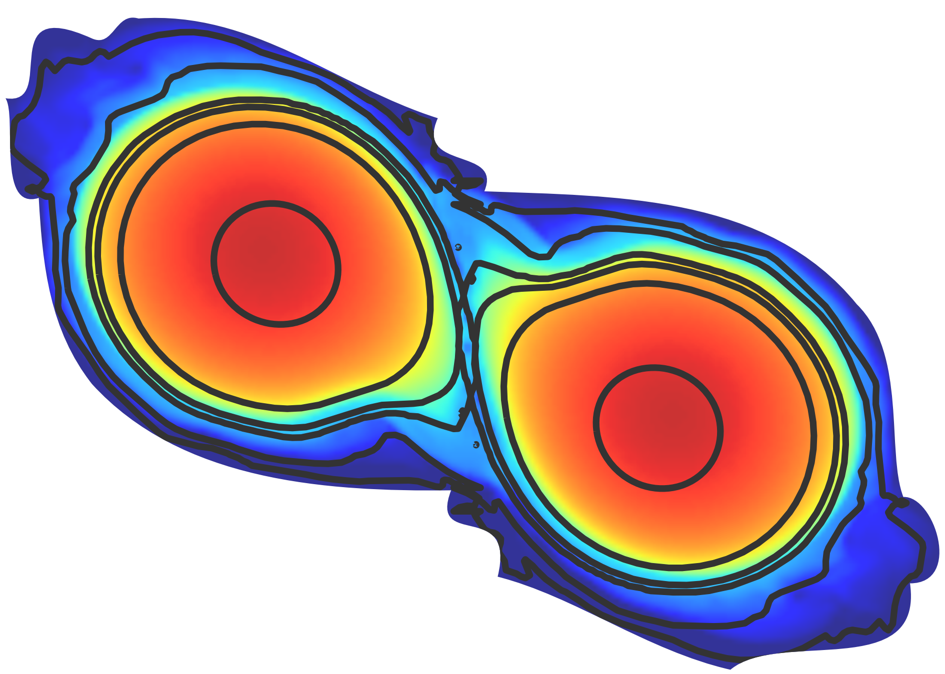
NS merger: roadmap



Binary NS inspiral



Tidal effects in NS mergers

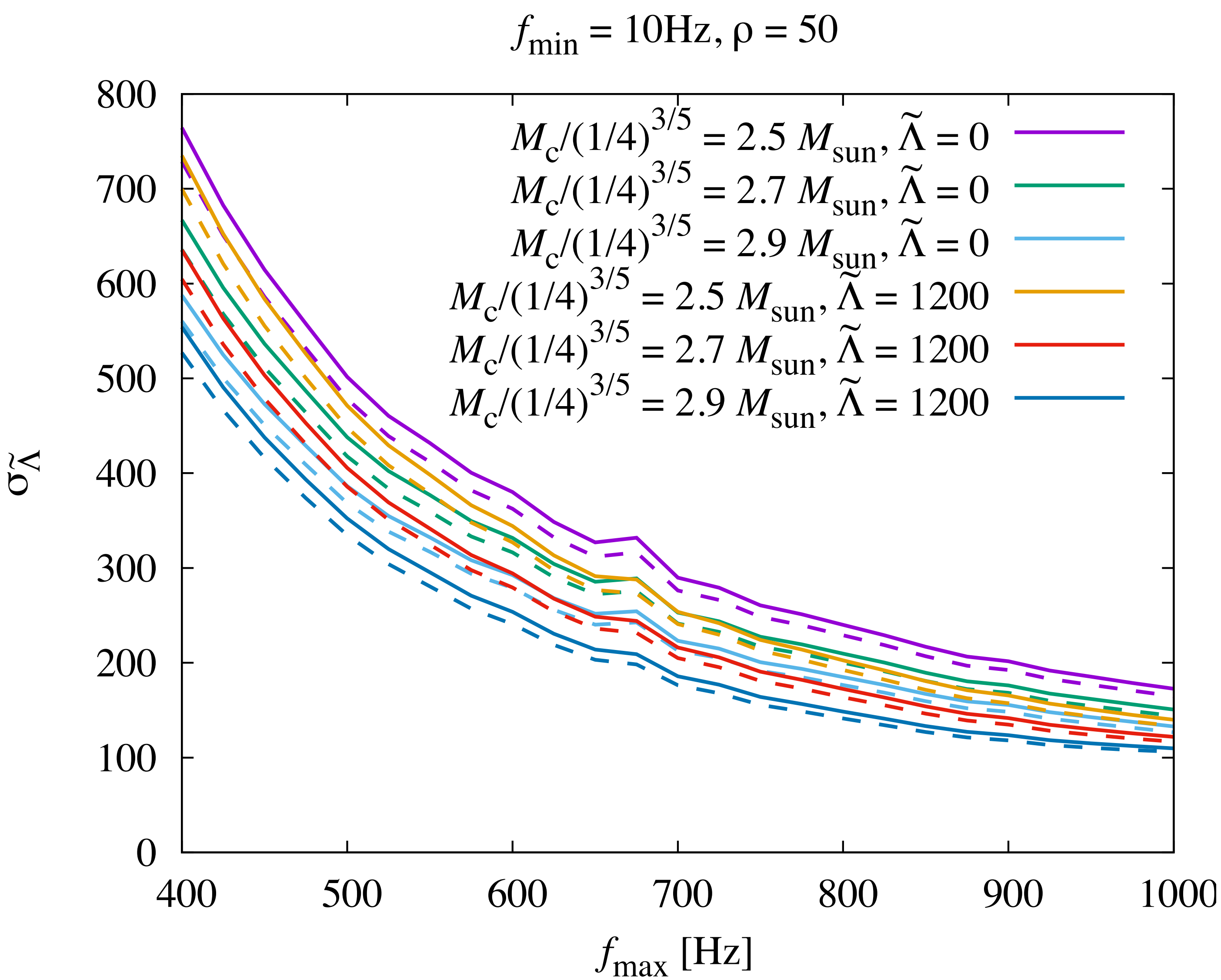


$$Q_{ij} = -\Lambda_2 \mathcal{E}_{ij}$$

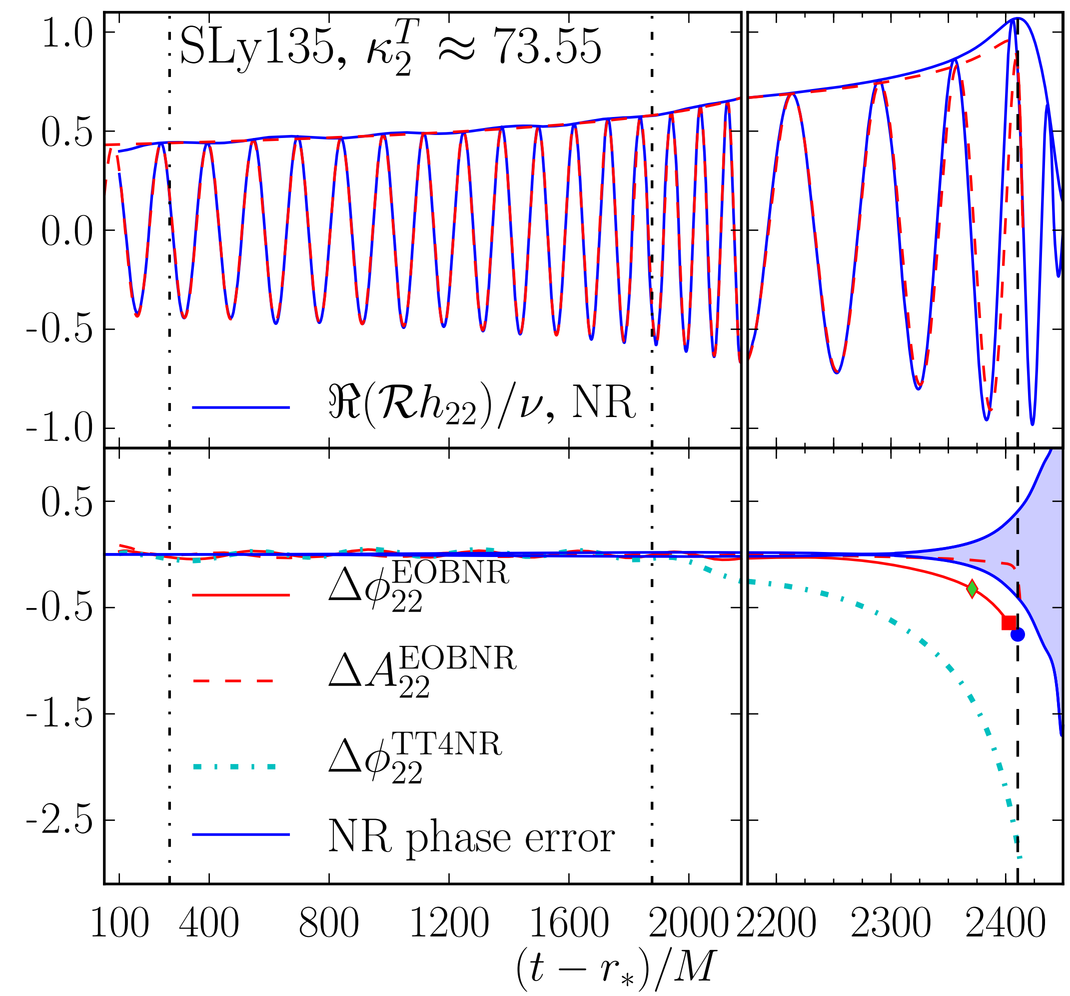
- Part of the orbital energy goes into tidal deformation
- Accelerated inspiral
- Imprinted on the gravitational waves
- Constrains dimensionless tidal parameter

$$\tilde{\Lambda}_2 = \frac{\Lambda_2}{M^5} \sim \frac{R^5}{M^5}$$

Inspiral modeling



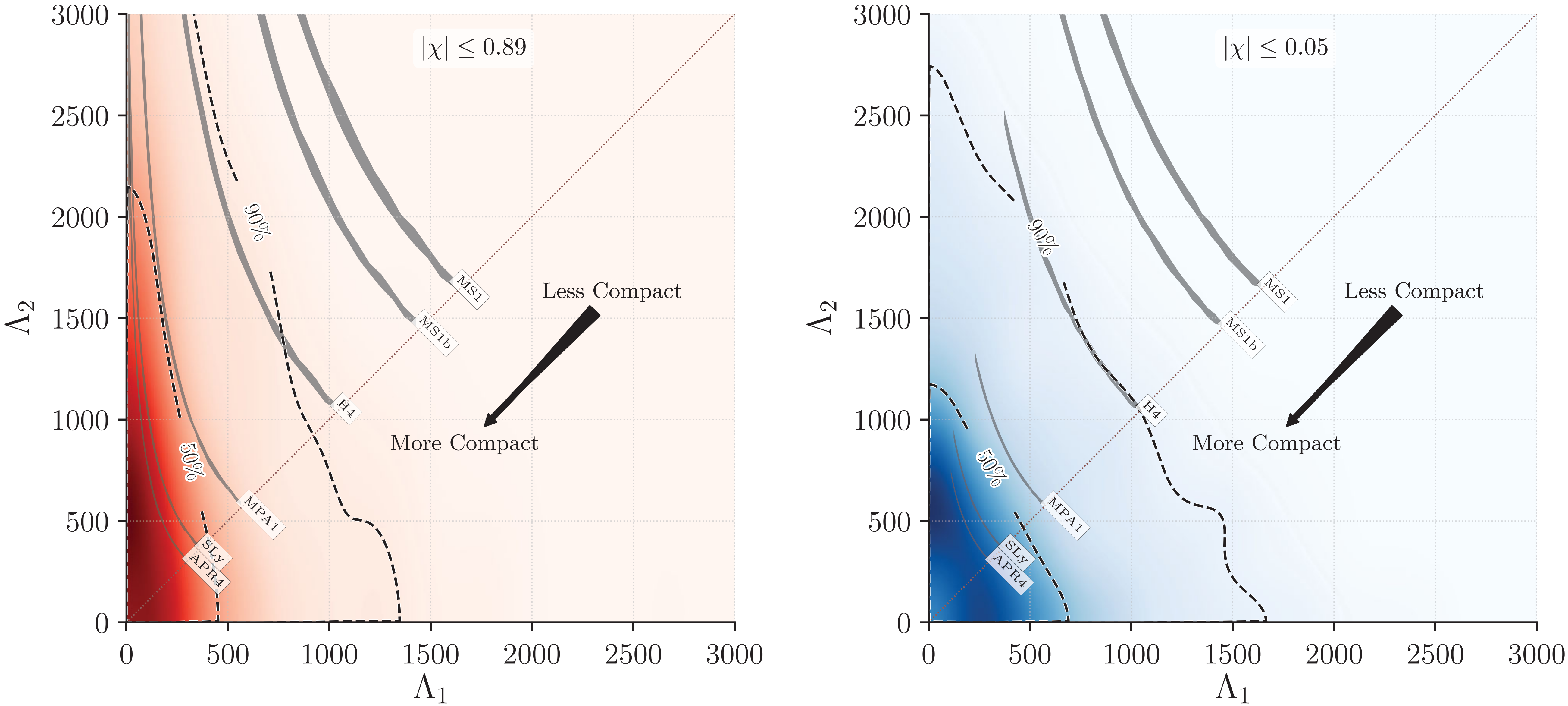
From Kawaguchi, Kiuchi+ (2017)



From Bernuzzi+ (2015)

- Precision modeling over many orbits, see also Hinderer+ (2016), Dietrich+ (2017), Kiuchi+ (2017)
- Open issues: spin, last GW cycles before merger

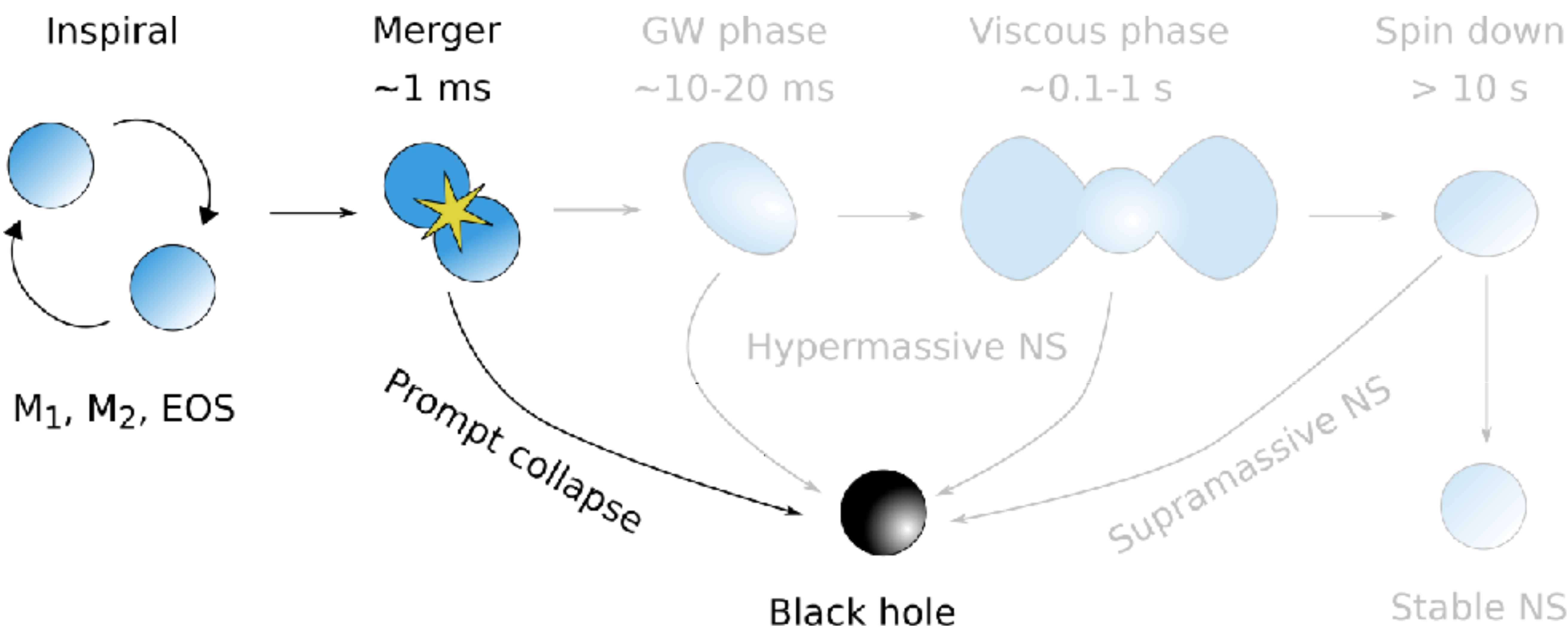
Constraints from GW170817



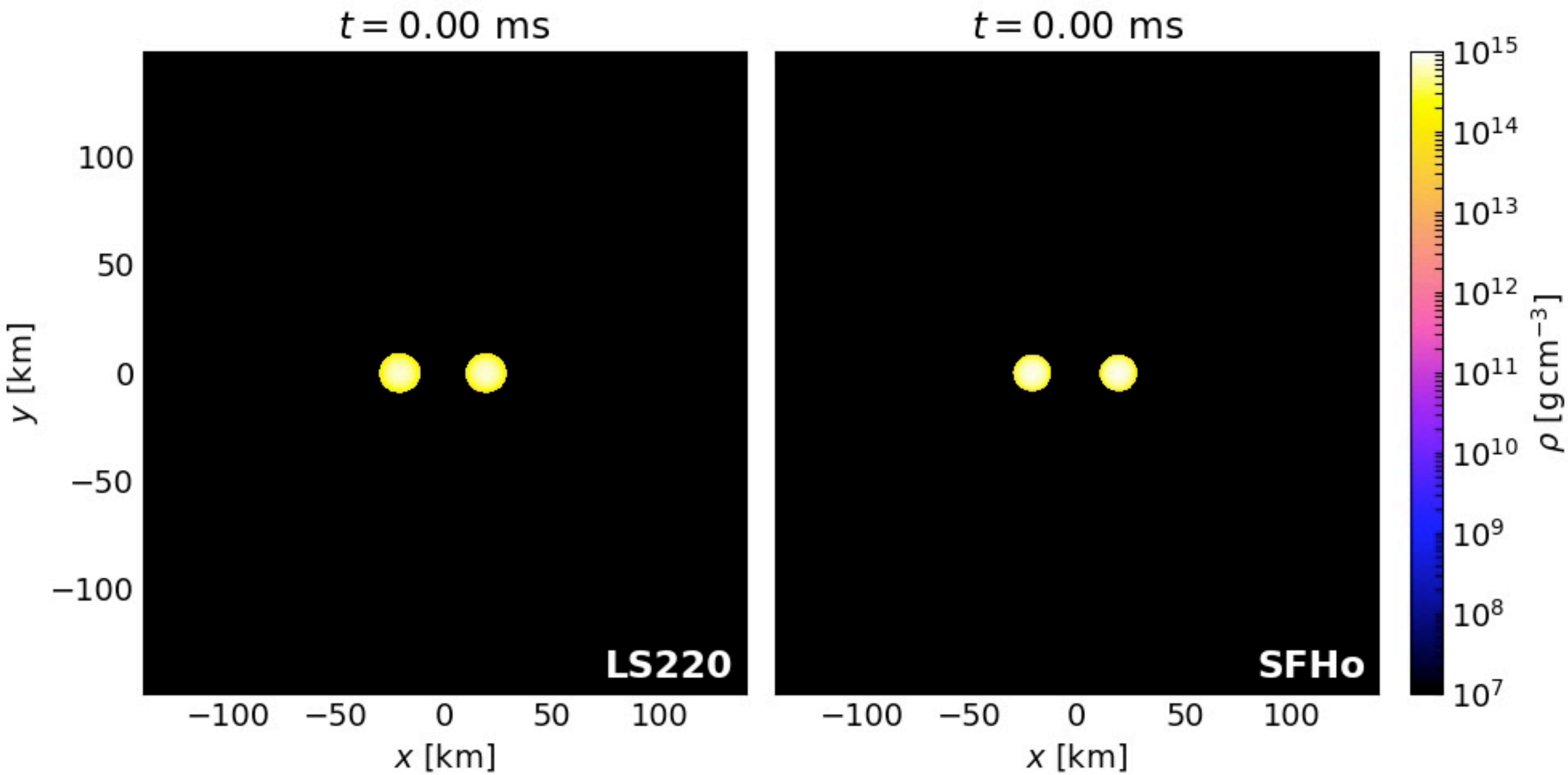
$$\frac{\bar{R}^5}{\bar{M}^5} \sim \tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right] \leq 800$$

From LIGO/Virgo collaboration, PRL 119, 161101 (2017)

Prompt-BH formation



Simulation results



$(1.44 + 1.39)\ M_\odot$ — B1913 + 13

DR, Perego, Zappa, ApJL 852:L29 (2018)

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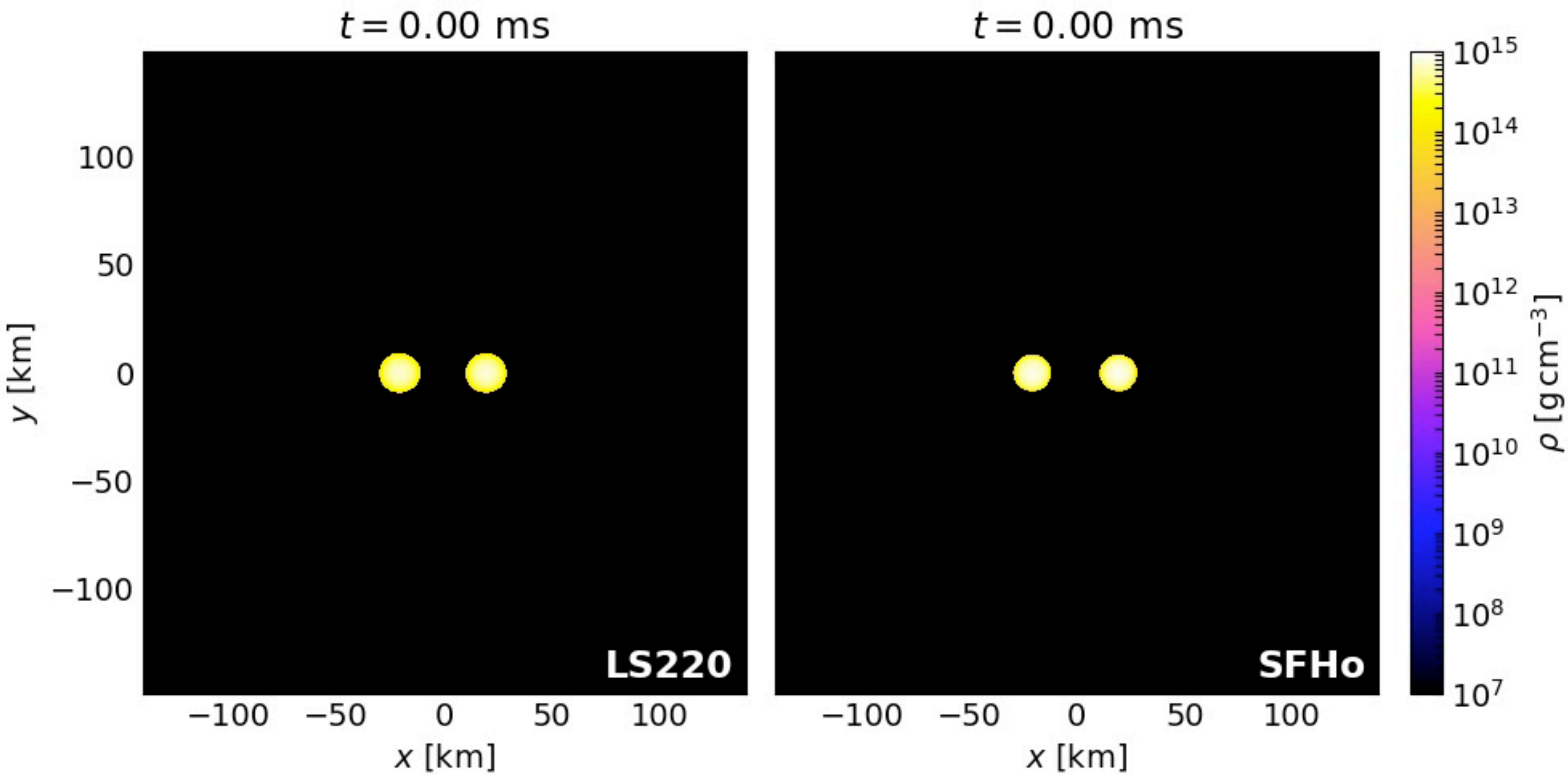

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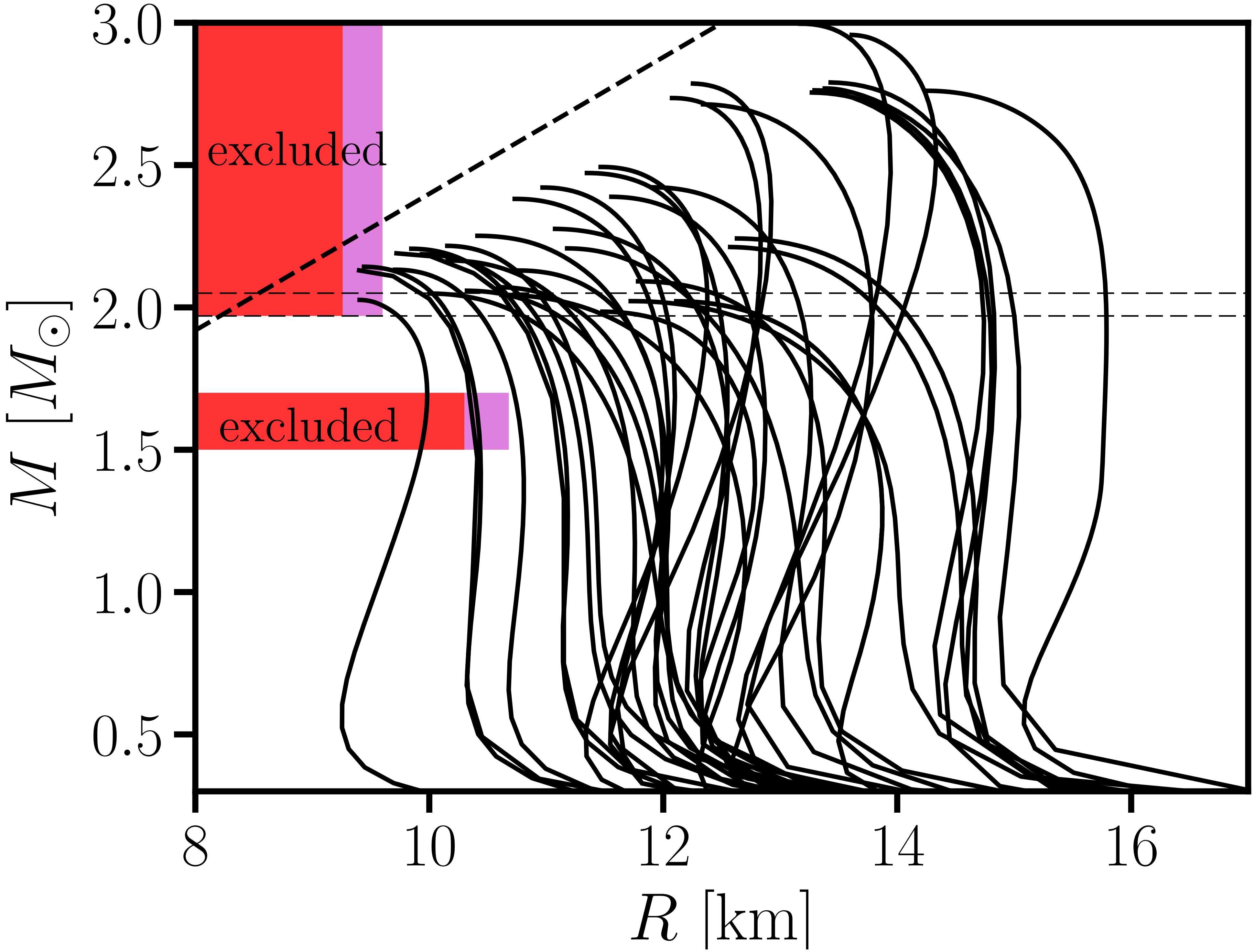
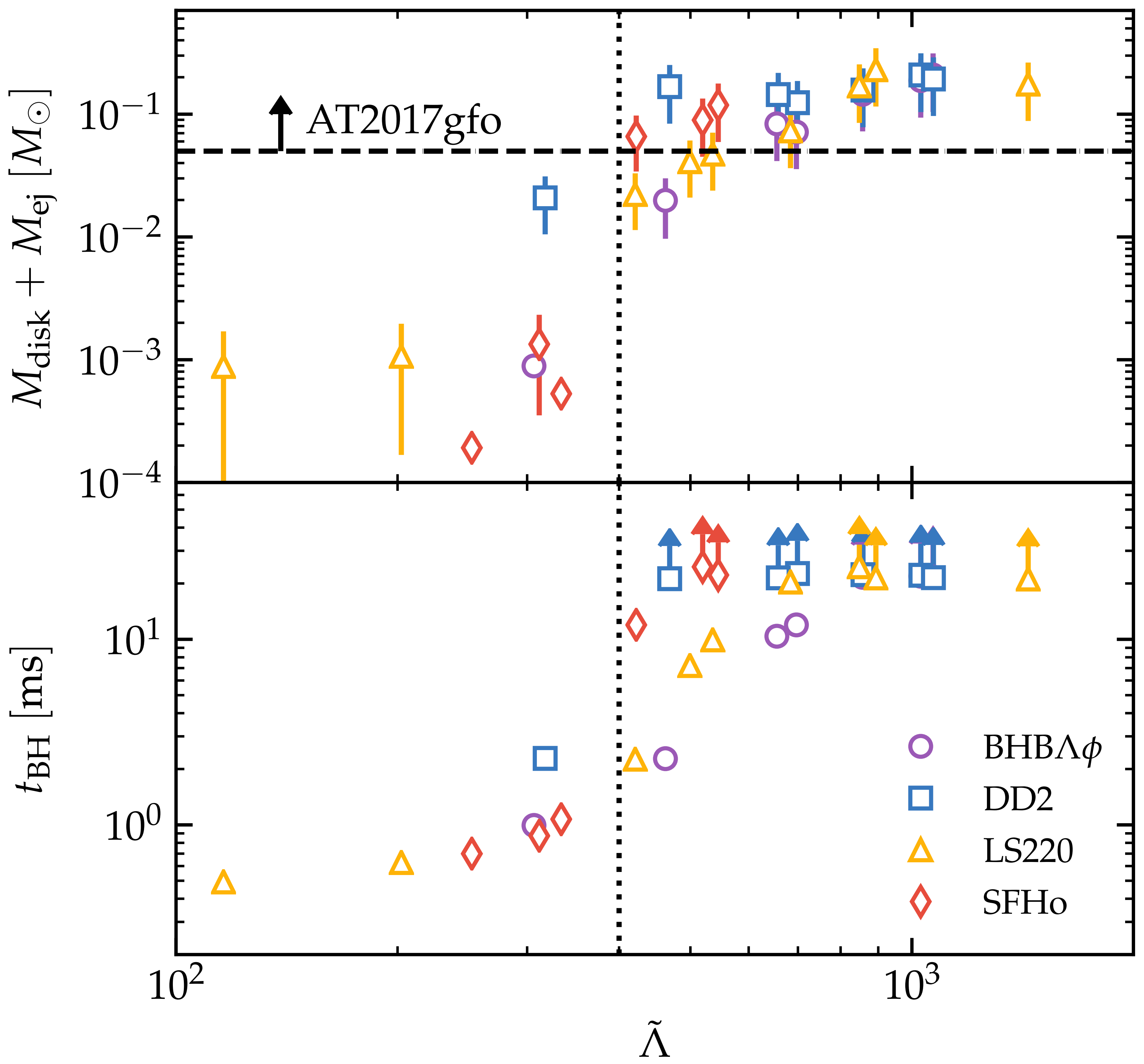
EOS constraints (I)



From Bauswein, Just+ (2017)

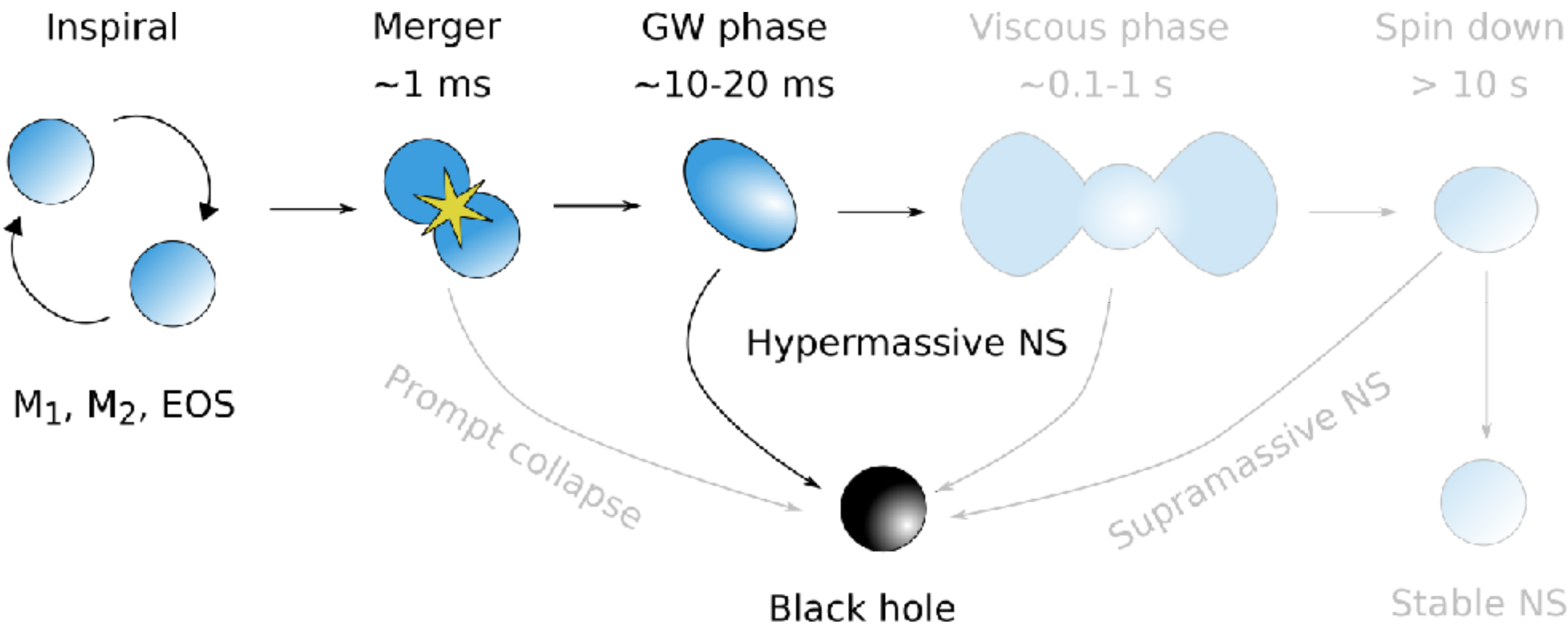
EOS constraints (II)



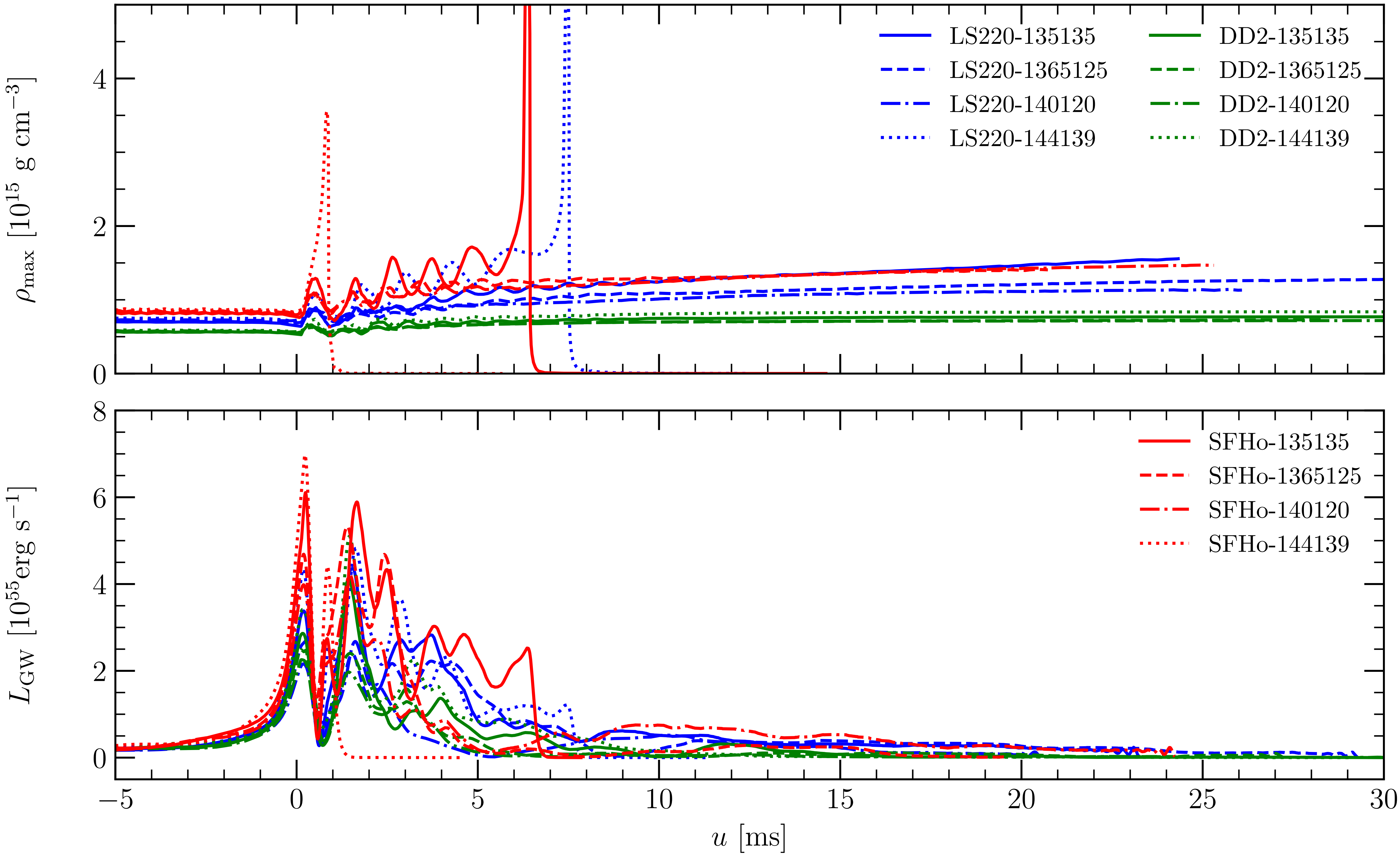
See also Bauswein+ 2017 ApJL 850:L34

DR, Perego, Zappa, ApJL 852:L29 (2018)

Hypermassive NSs

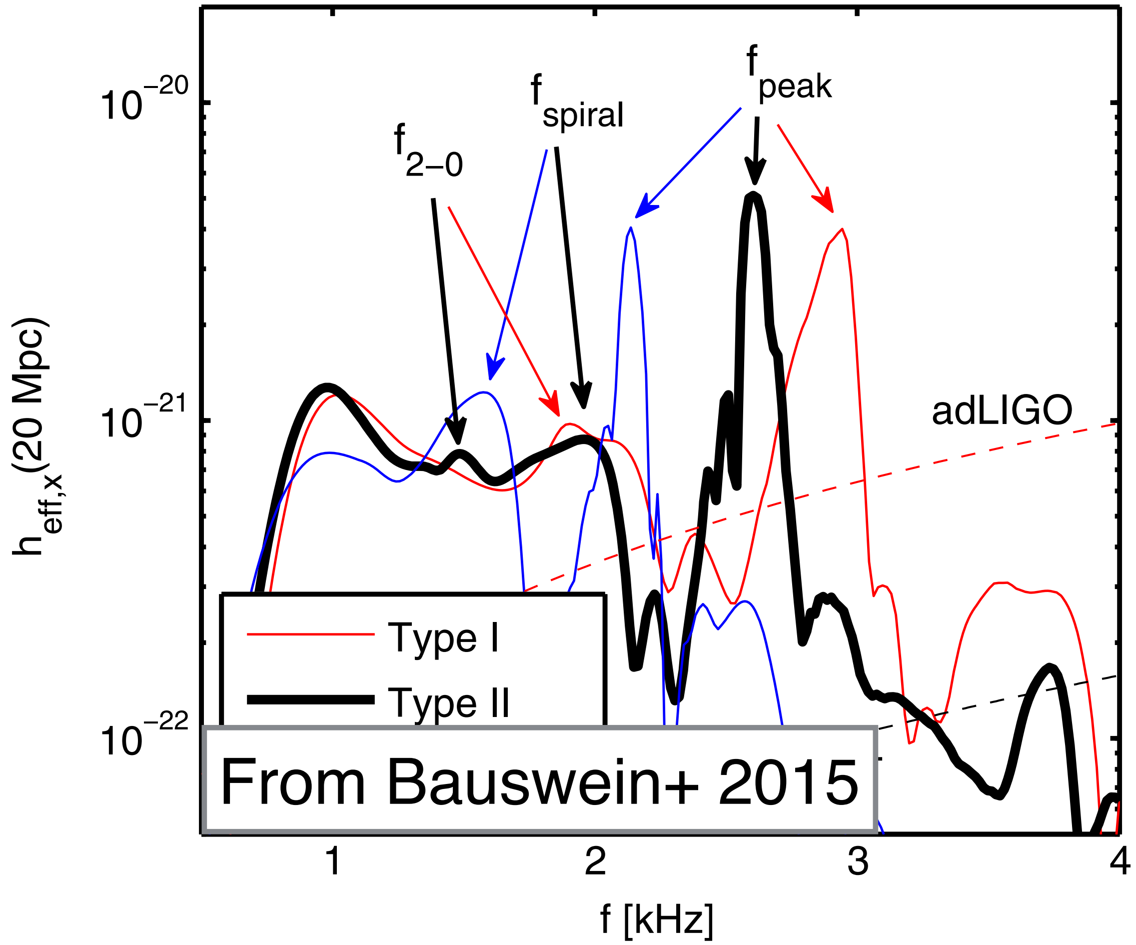


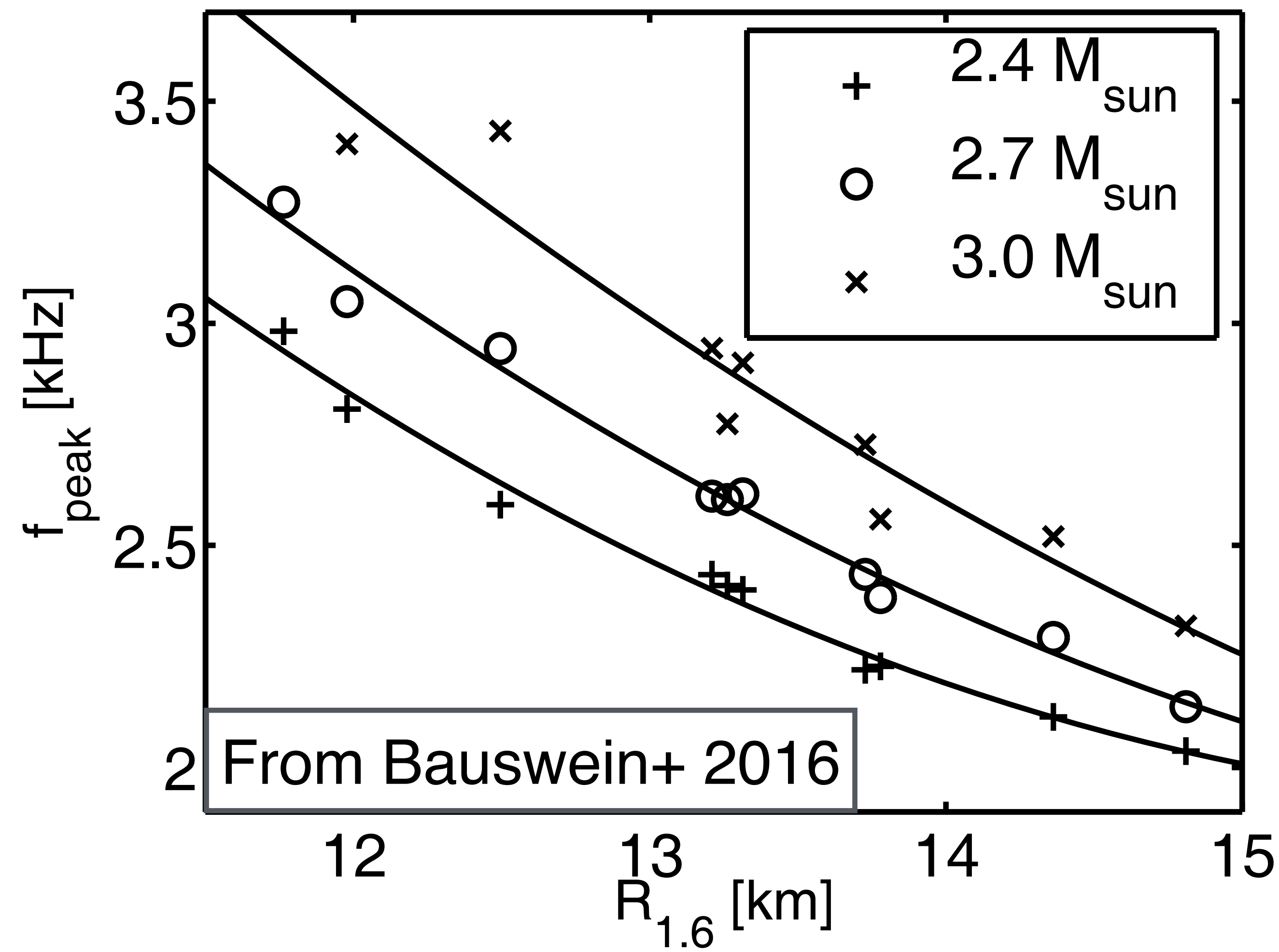
GW-driven phase



Bernuzzi, **DR+**, PRD 94: 024023 (2016)

Postmerger peak frequency

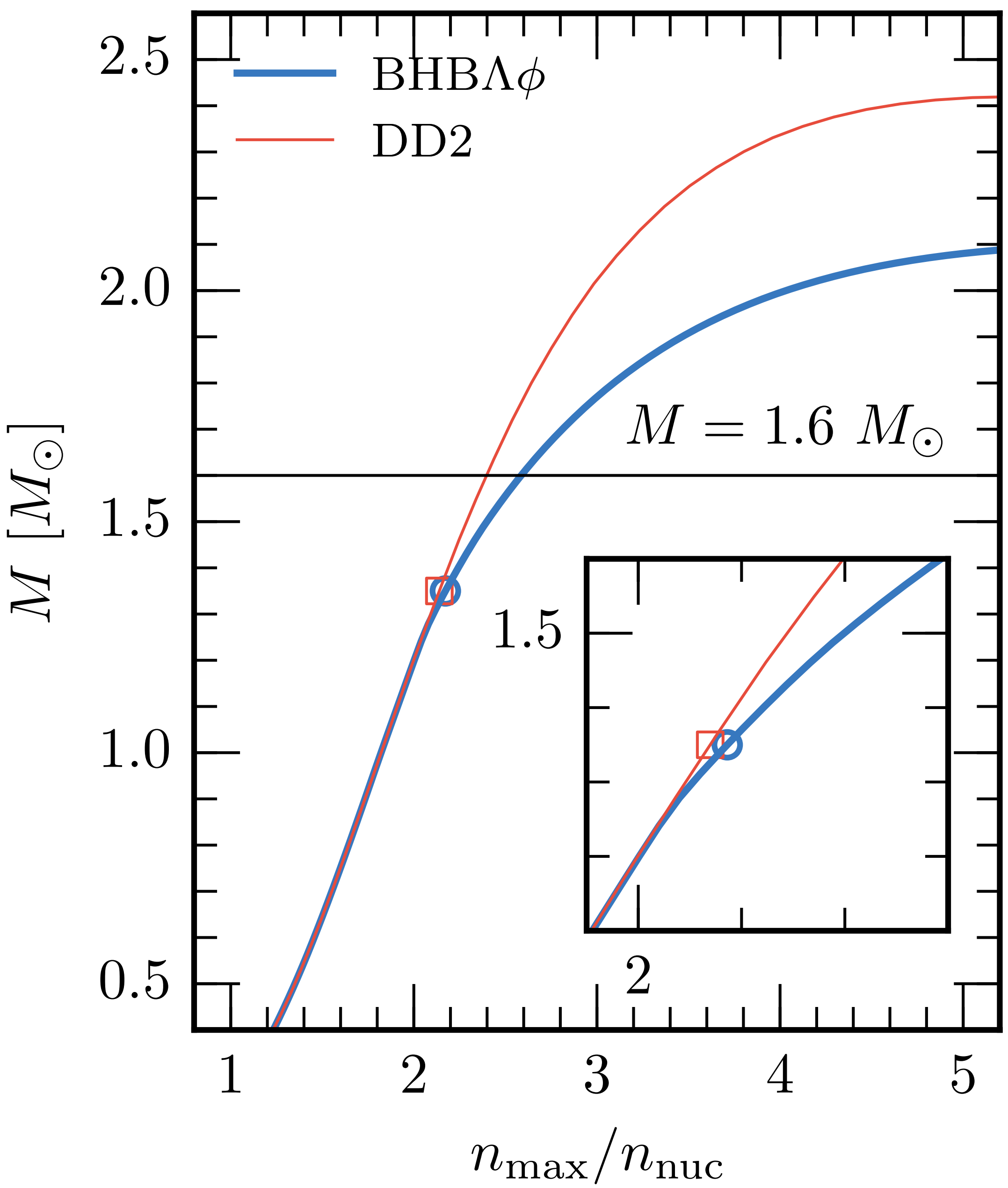




- Post-merger signal has a characteristic peak frequency
- f_{peak} correlates with the NS radius
- Small statistical uncertainty, systematics not understood yet

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bose+ 2017

Extreme-density physics

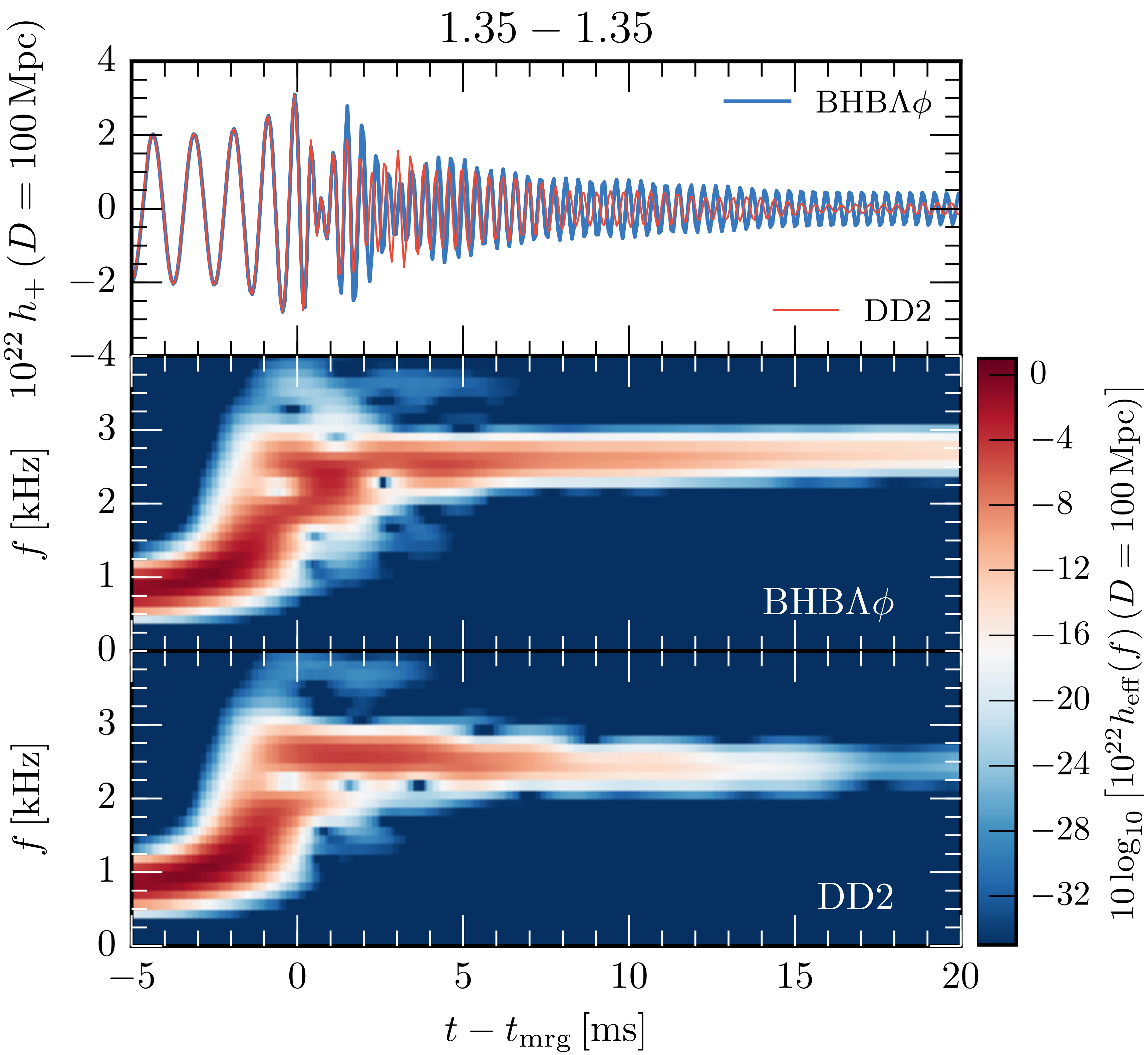


- Neutron stars in binaries have masses clustered around ~1.35 $M_\odot$
- Phase transition at high-density not constrained by the inspiral
- Can we probe the equation of state of nuclear matter at the highest densities?
- Yes, with the postmerger signal

See also Bauswein+ 2011, 2013, 2015, Read+ 2013, Hotokezaka+ 2013, Takami+ 2014, Bernuzzi+ 2015, Clark+ 2014, 2016, Bose+ 2017, Chatziioannou 2017, …

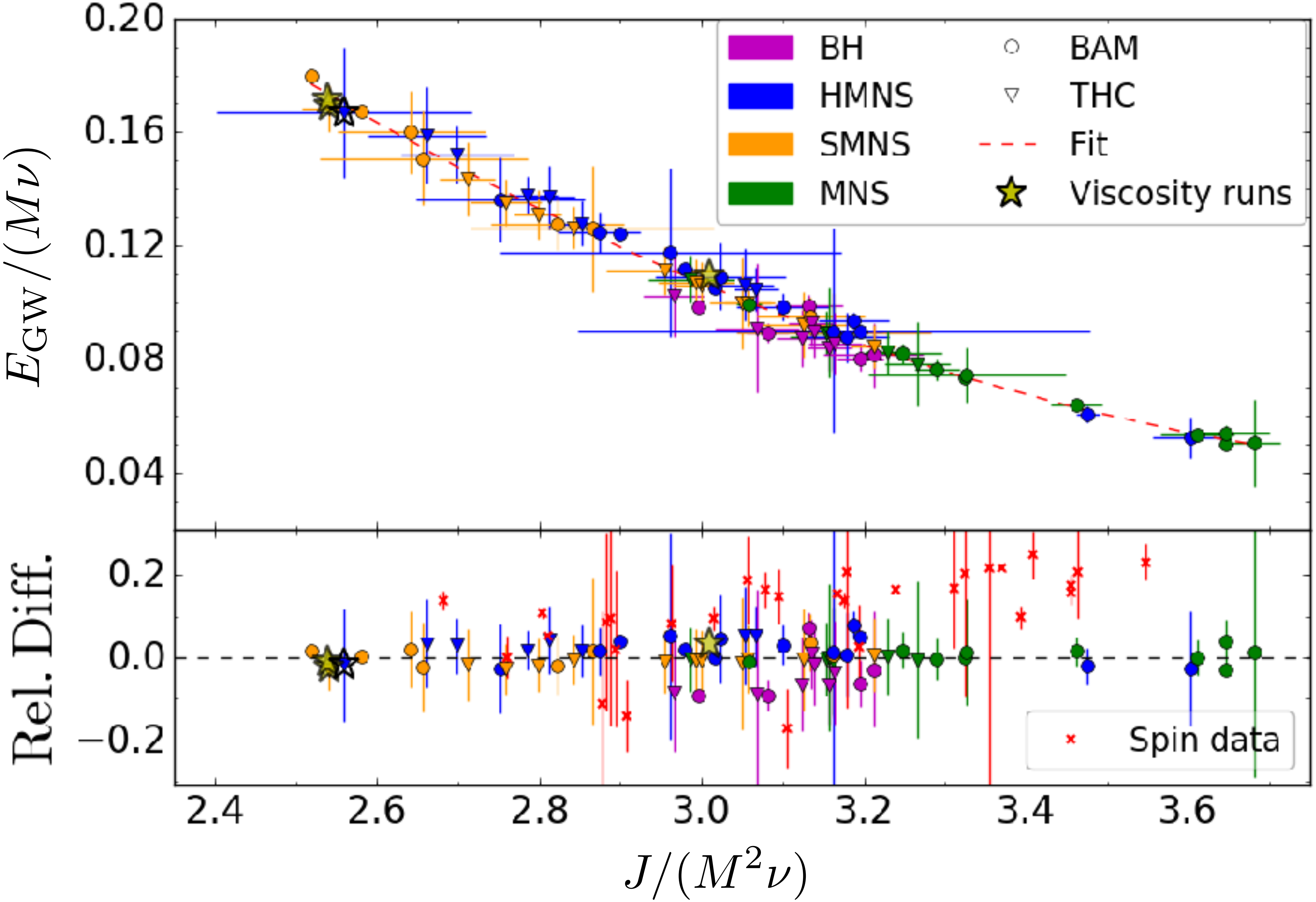
DR, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

Gravitational waveform



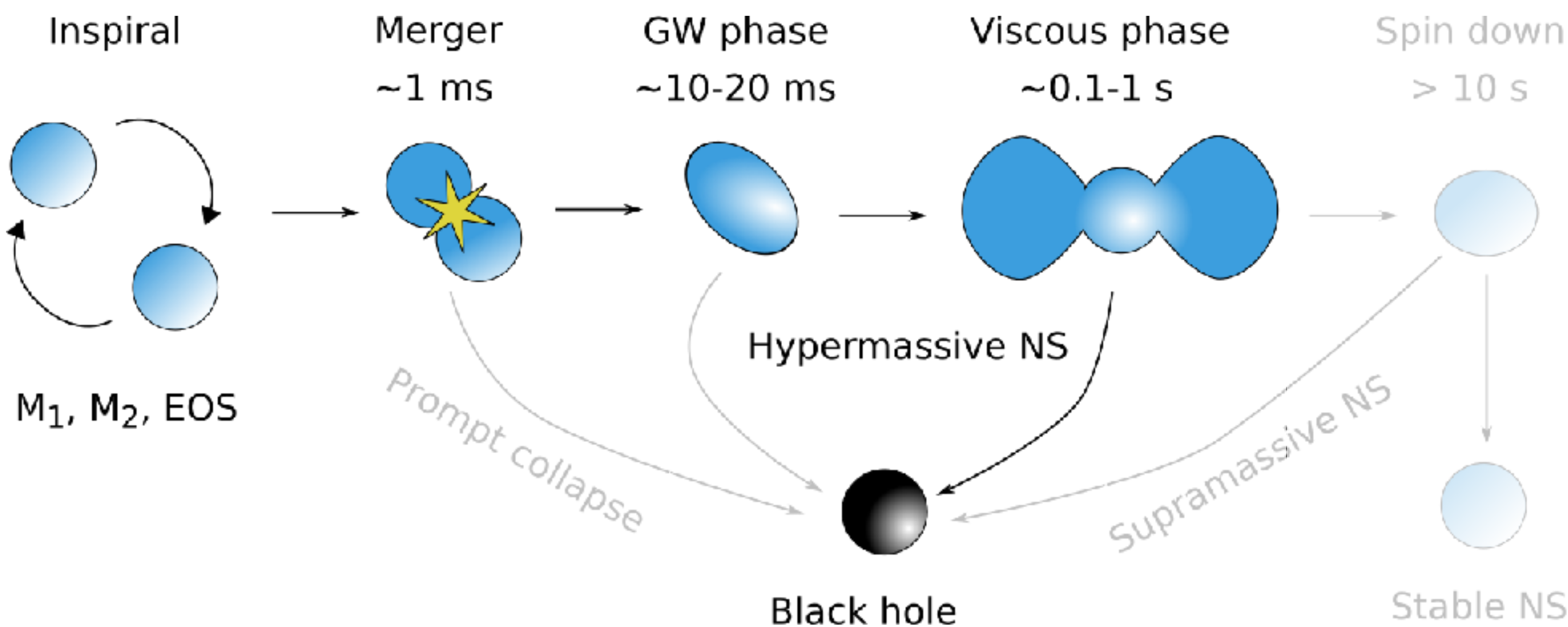
DR, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

End of GW-driven phase



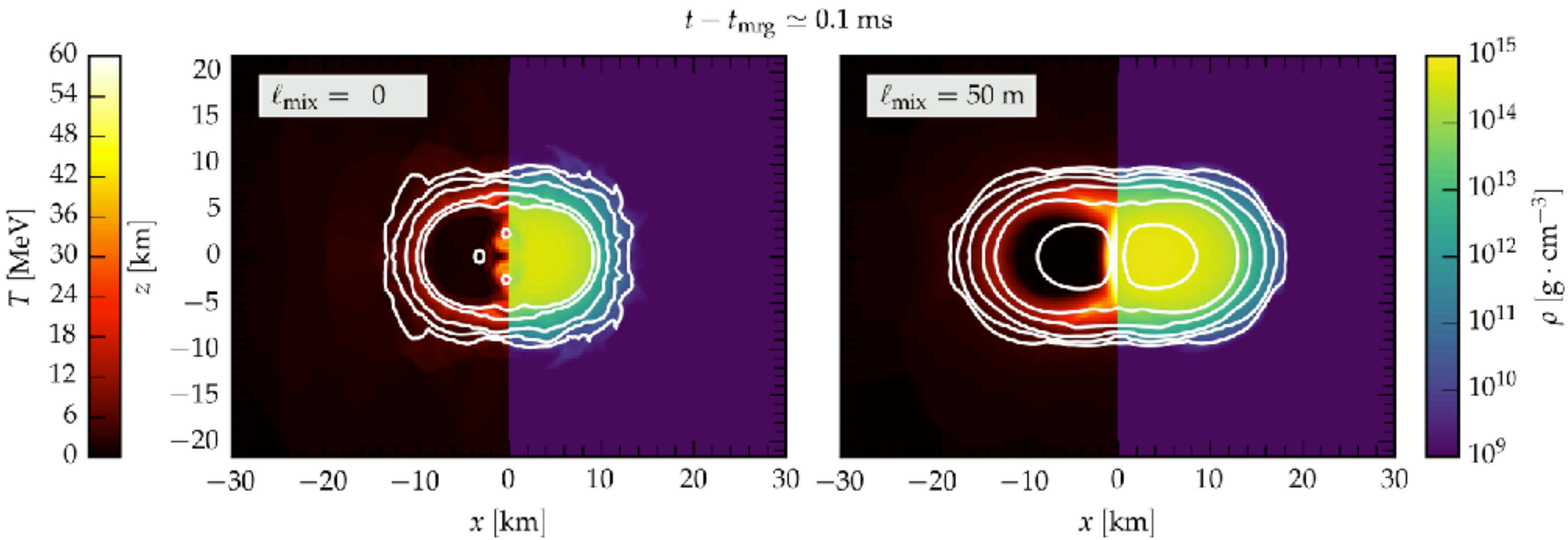
Zappa, Bernuzzi, **DR**+, PRL in press (2018)

Viscous evolution to collapse



Angular momentum transport

$t_{\mathrm{visc}} = \infty$ $t_{\mathrm{visc}} \sim 15\,\mathrm{ms}$



See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

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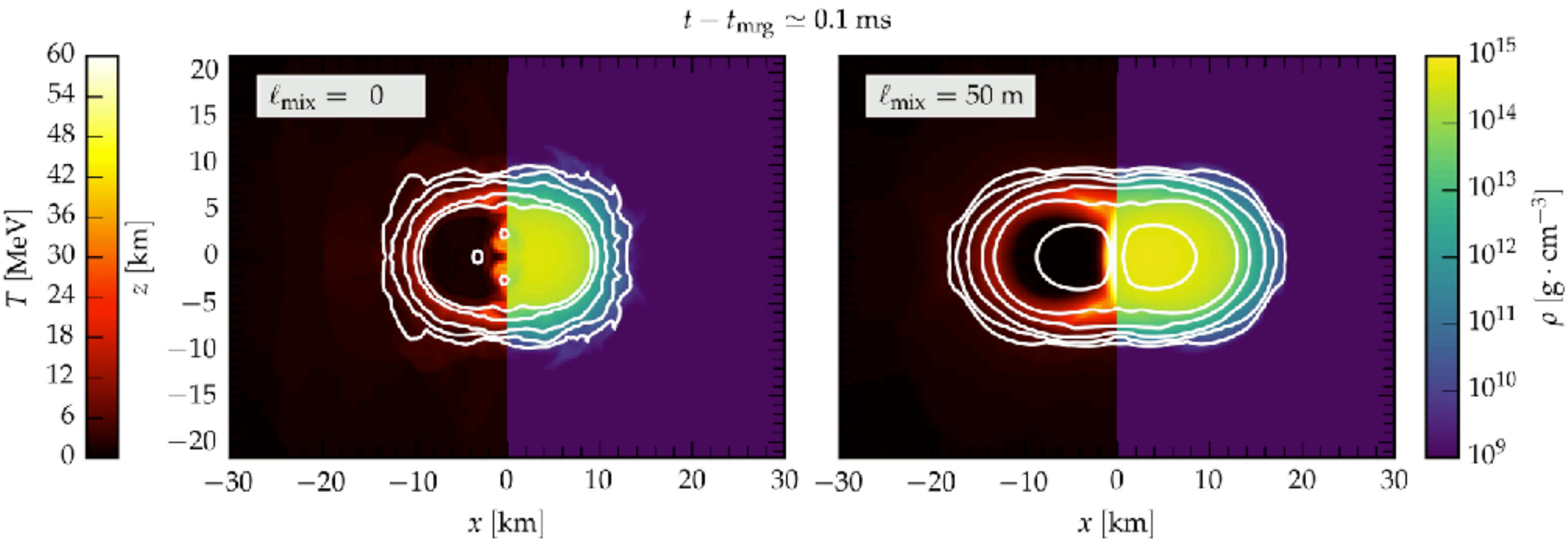

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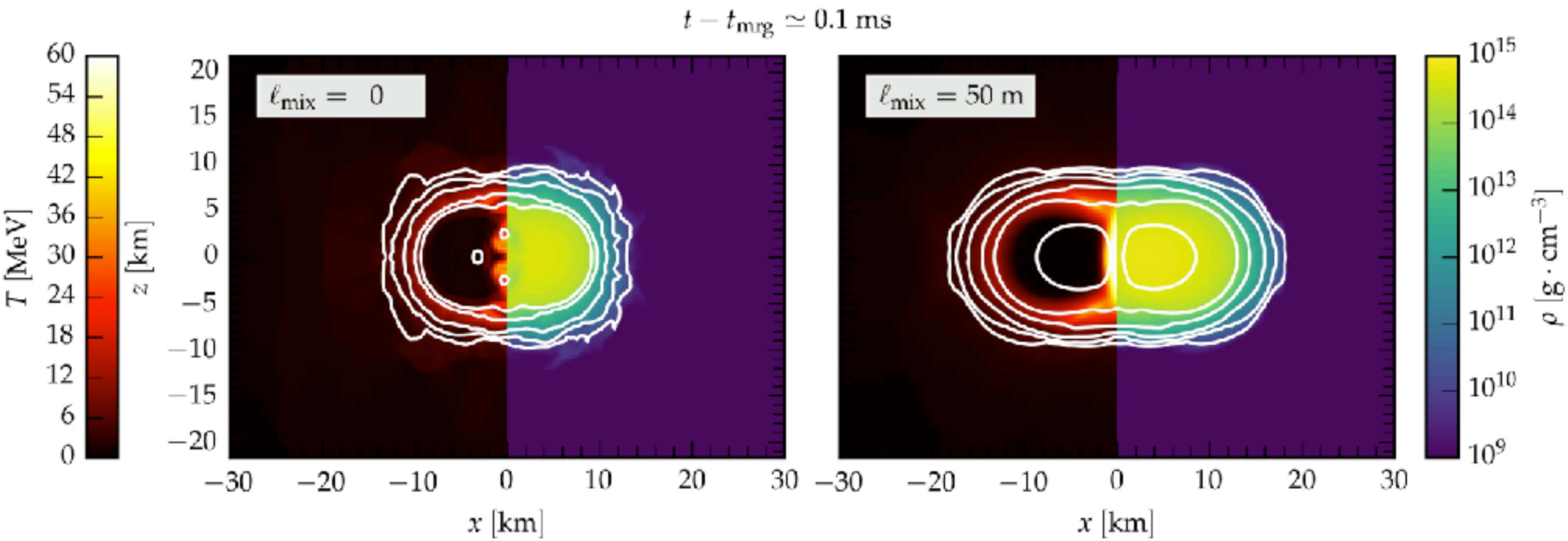
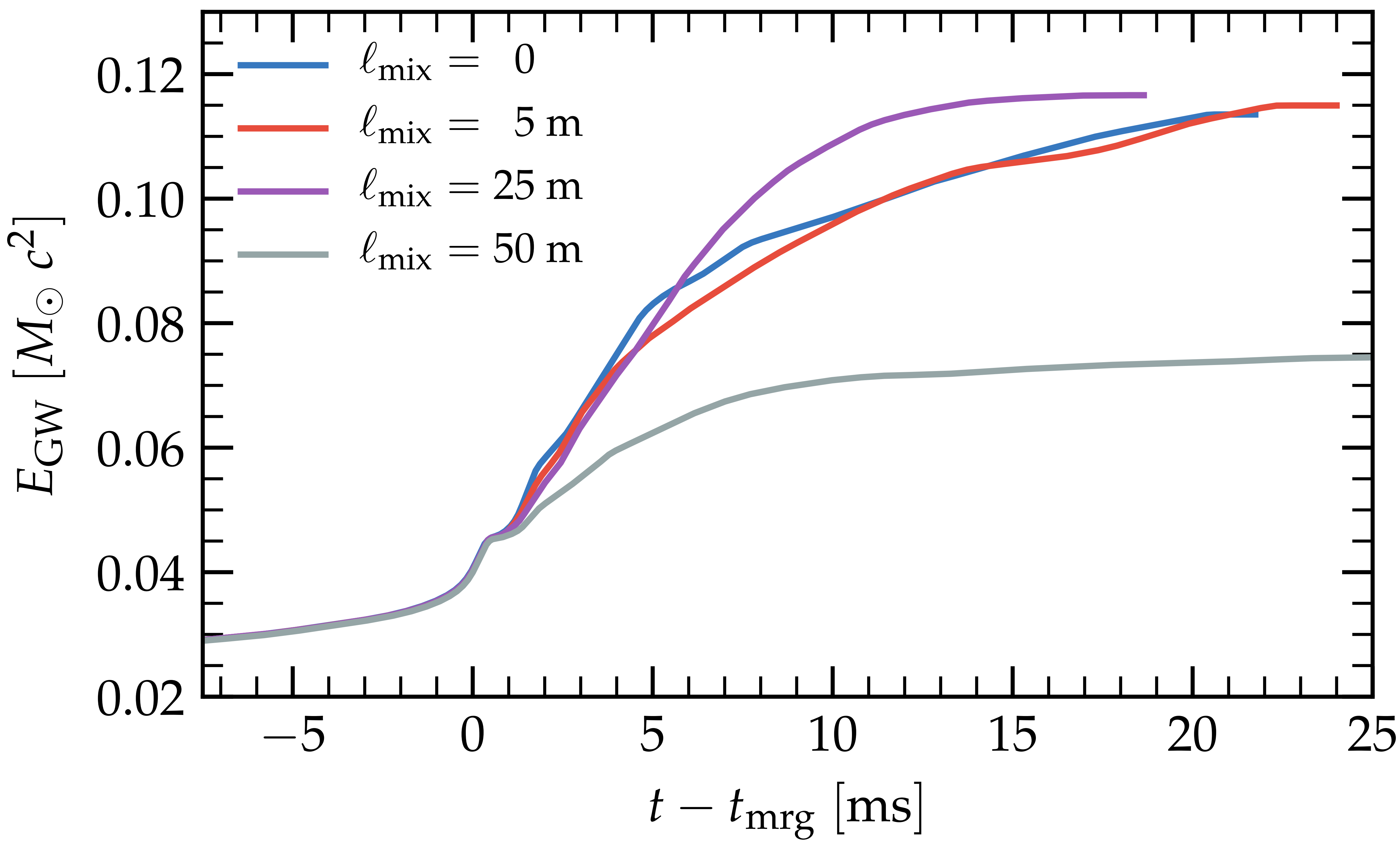


Delayed collapse!

See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

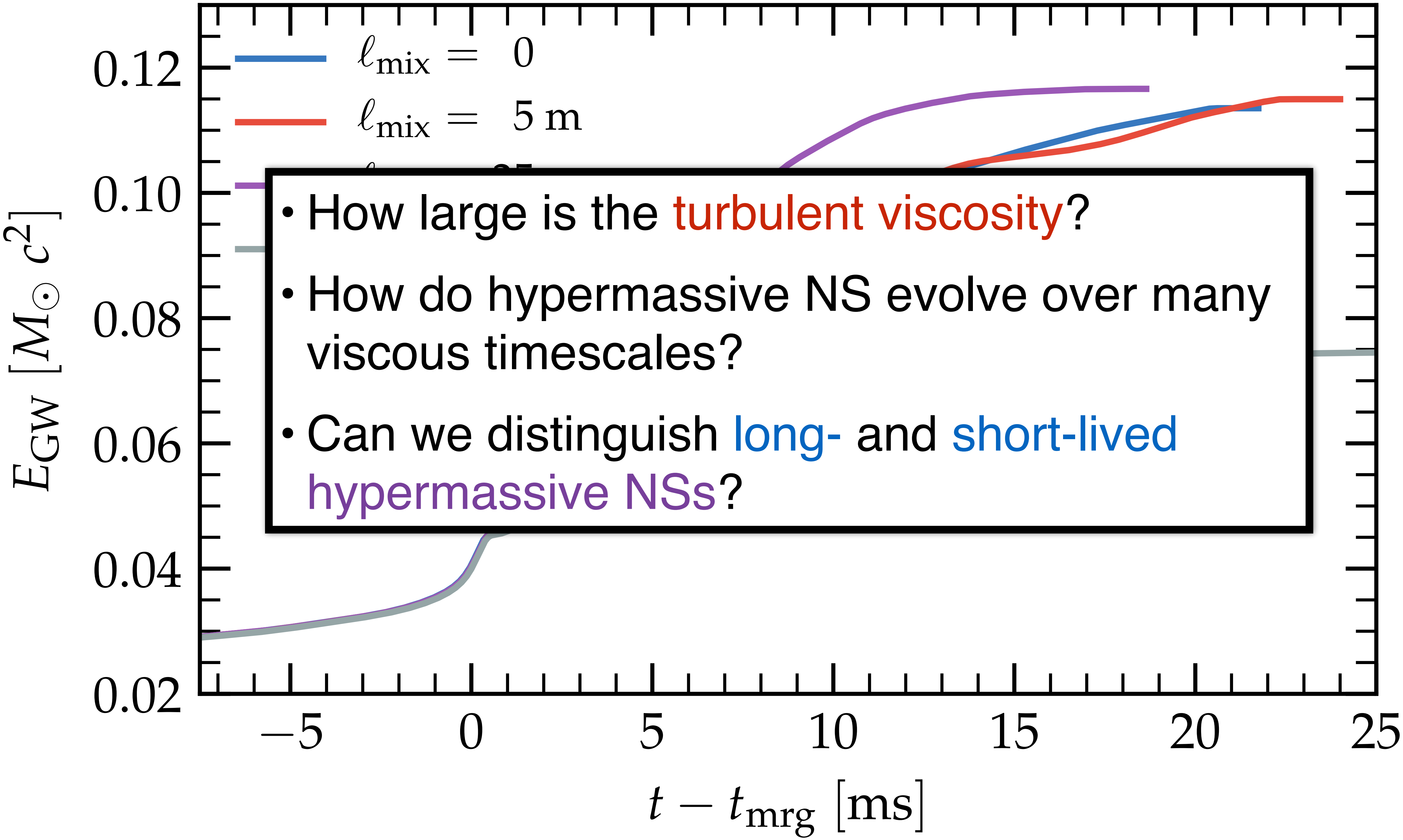
Gravitational waves



See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

Gravitational waves

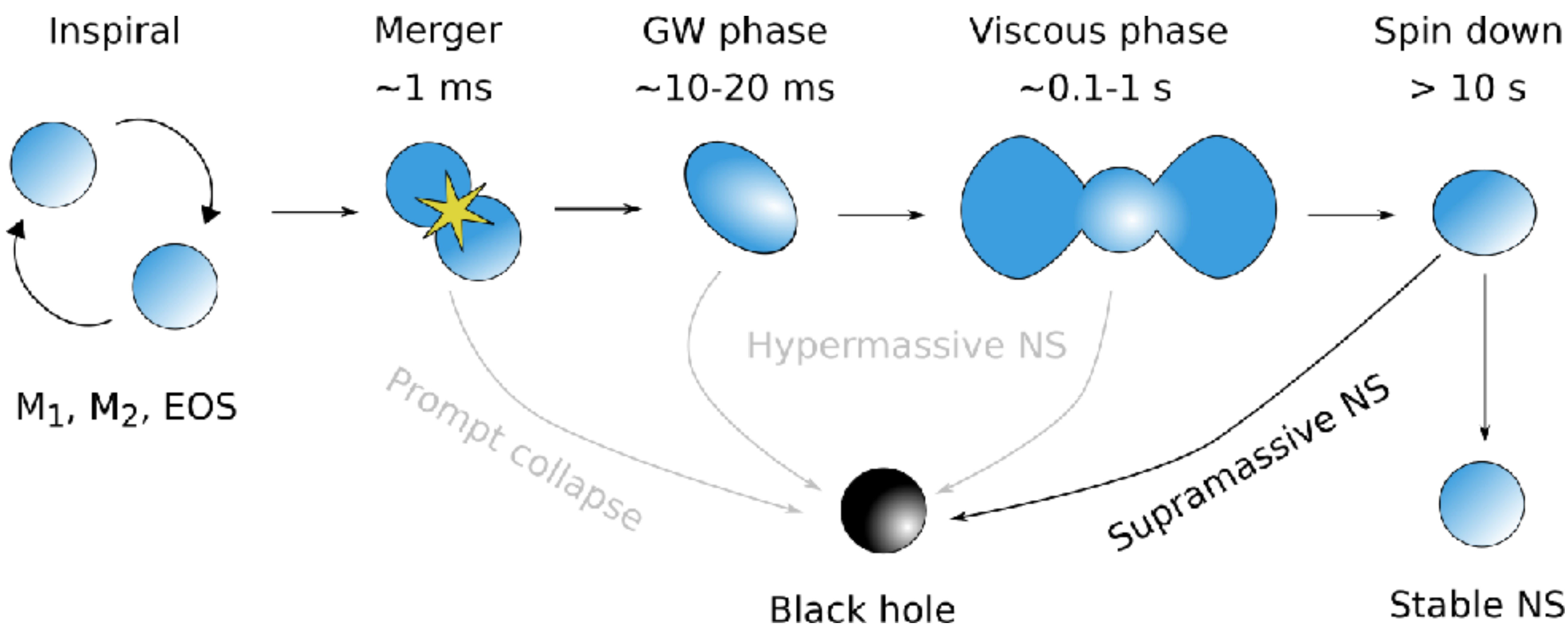


- How large is the turbulent viscosity?
- How do hypermassive NS evolve over many viscous timescales?
- Can we distinguish long- and short-lived hypermassive NSs?

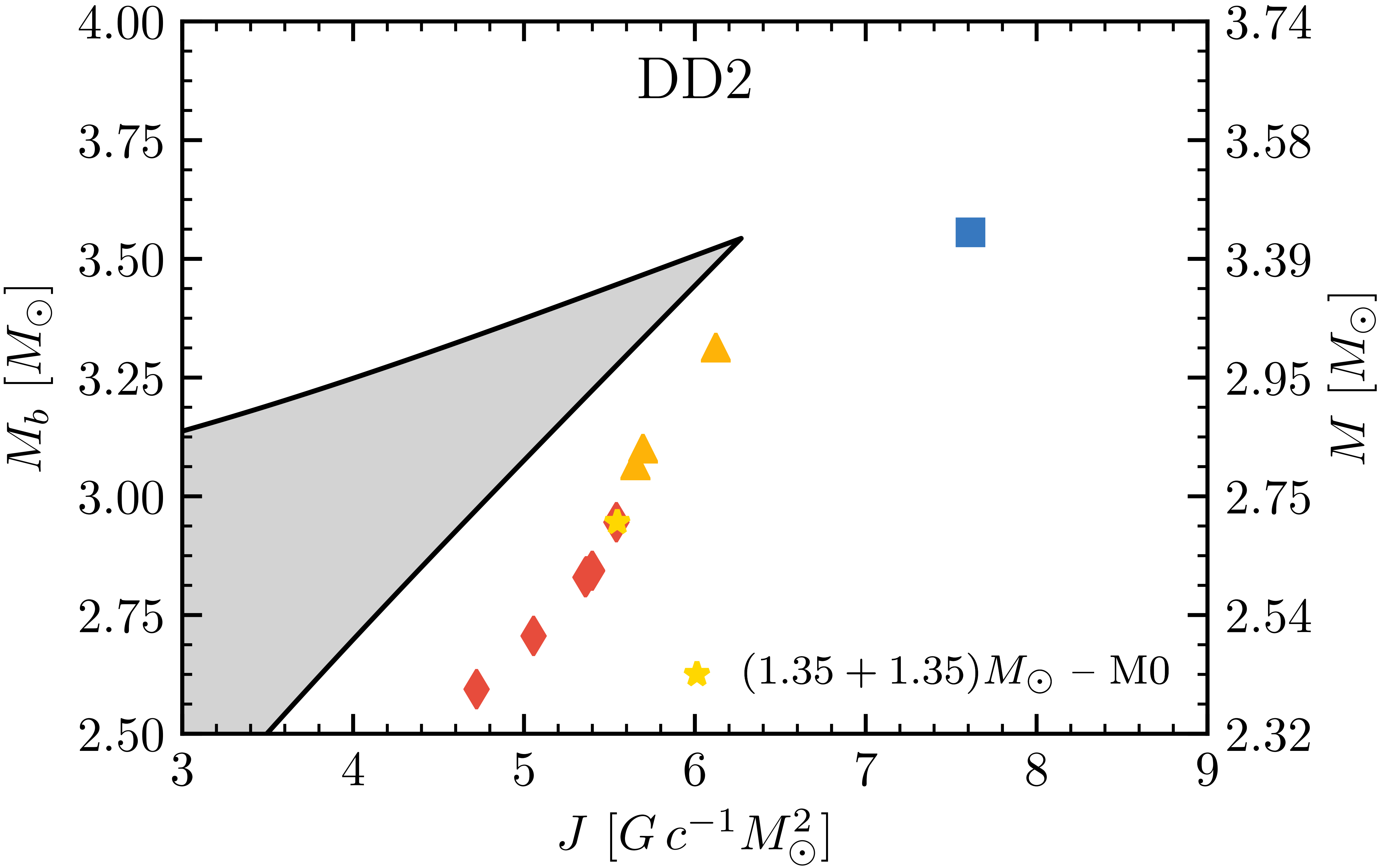
See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

Viscous evolution to equilibrium

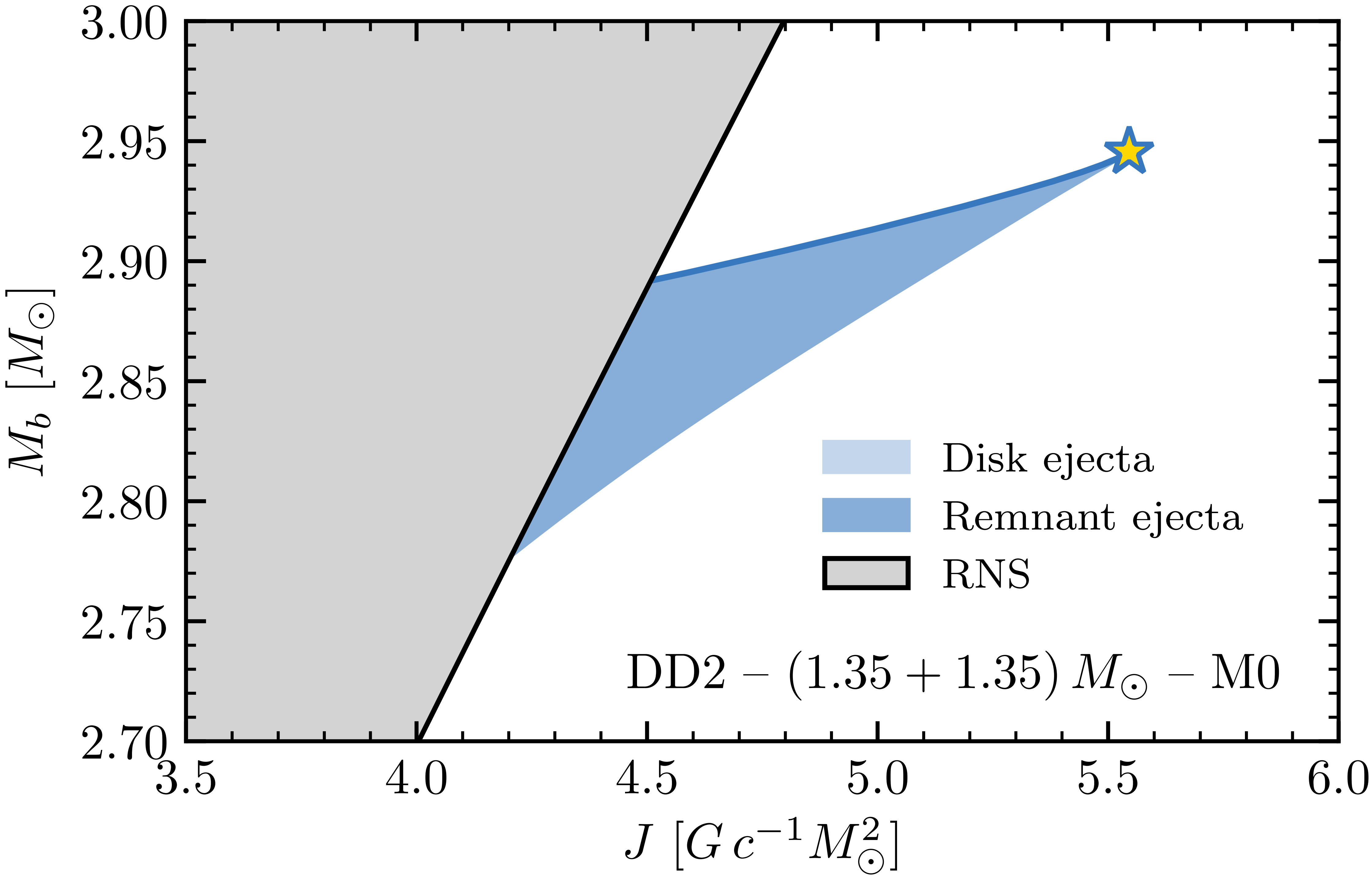


Long-lived remnants



DR, Perego, Bernuzzi, Zhang, in prep.

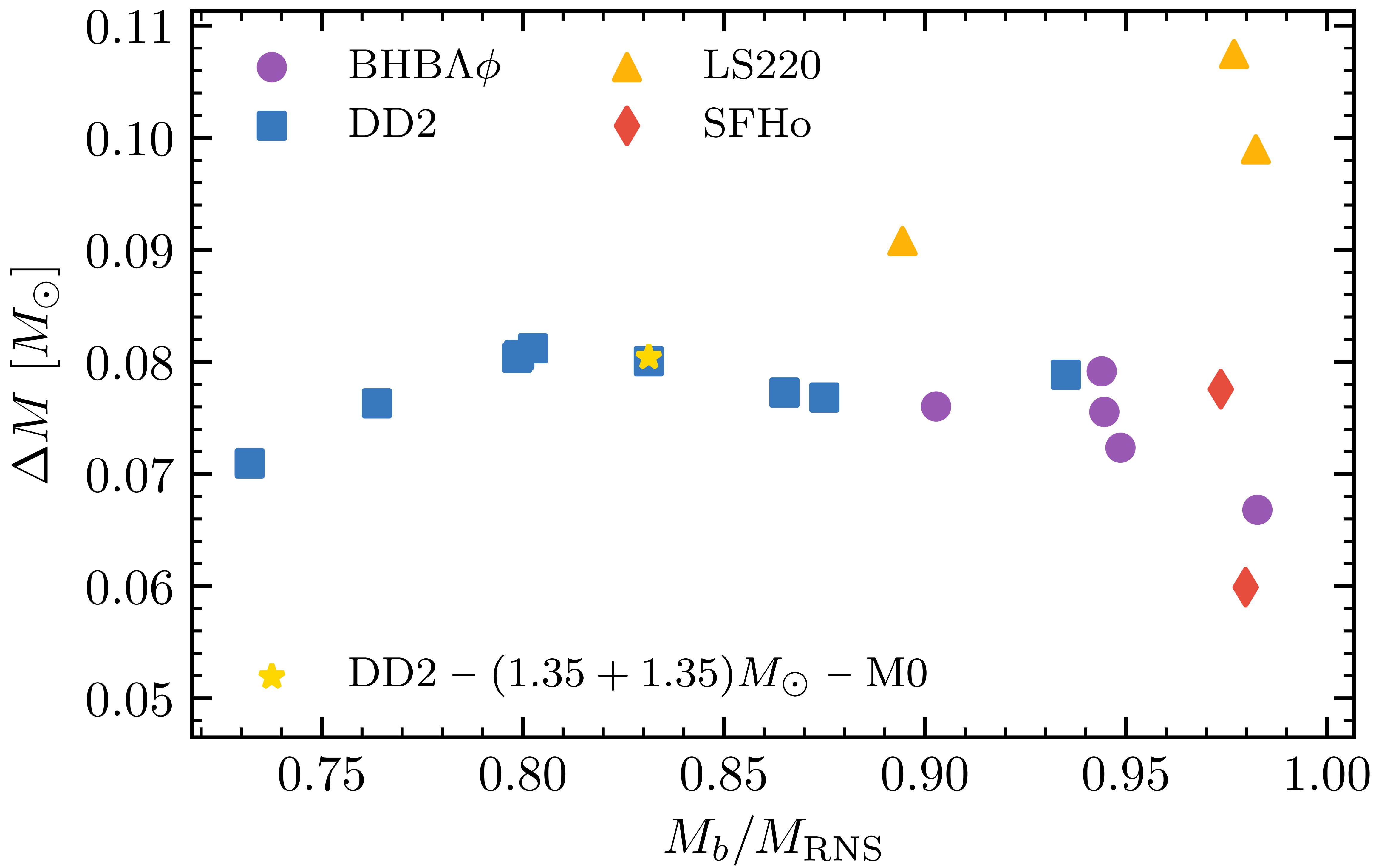
Viscous evolution



See also Fujibayashi, Kiuchi+ (2017)

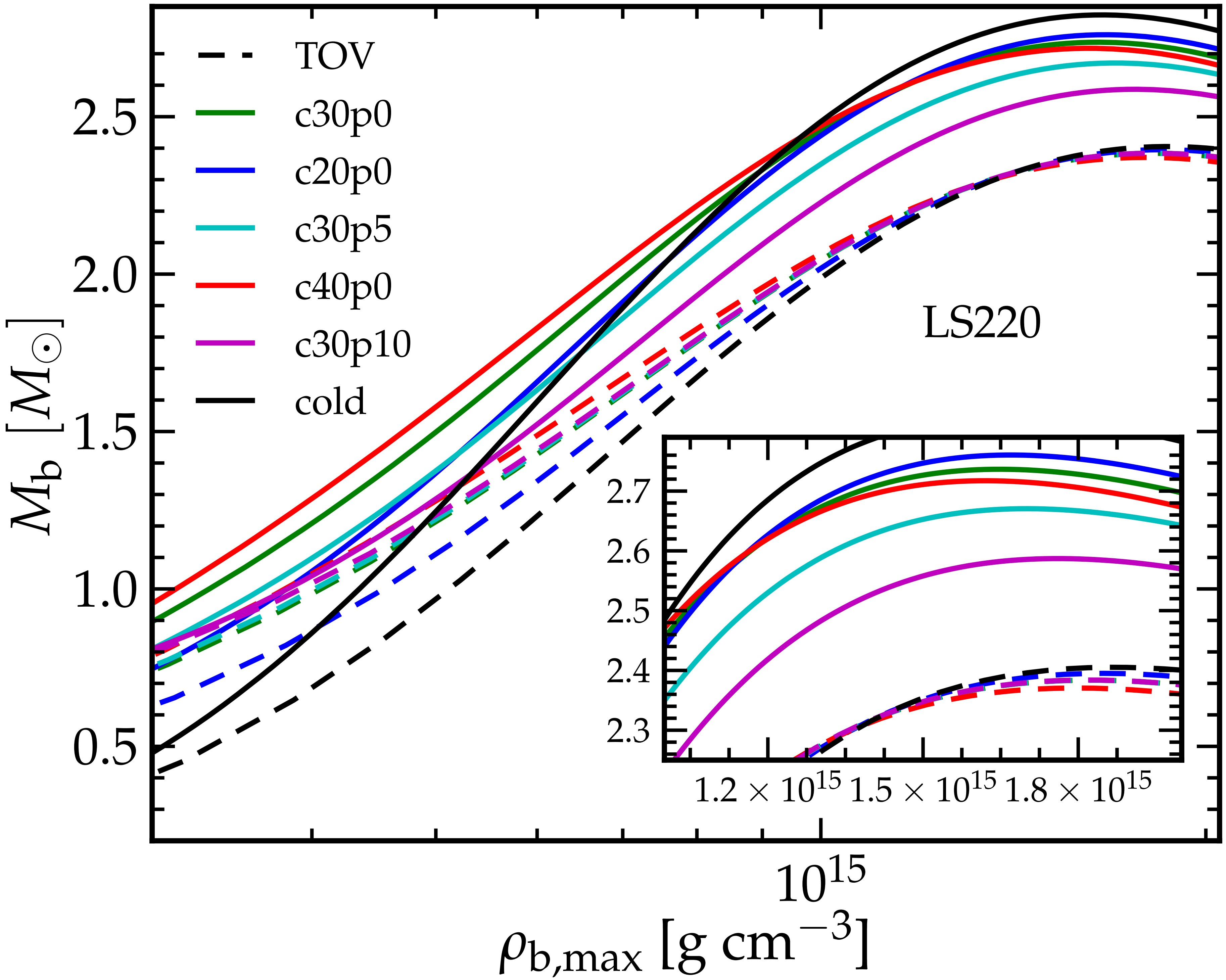
DR, Perego, Bernuzzi, Zhang, in prep.

Excess gravitational mass



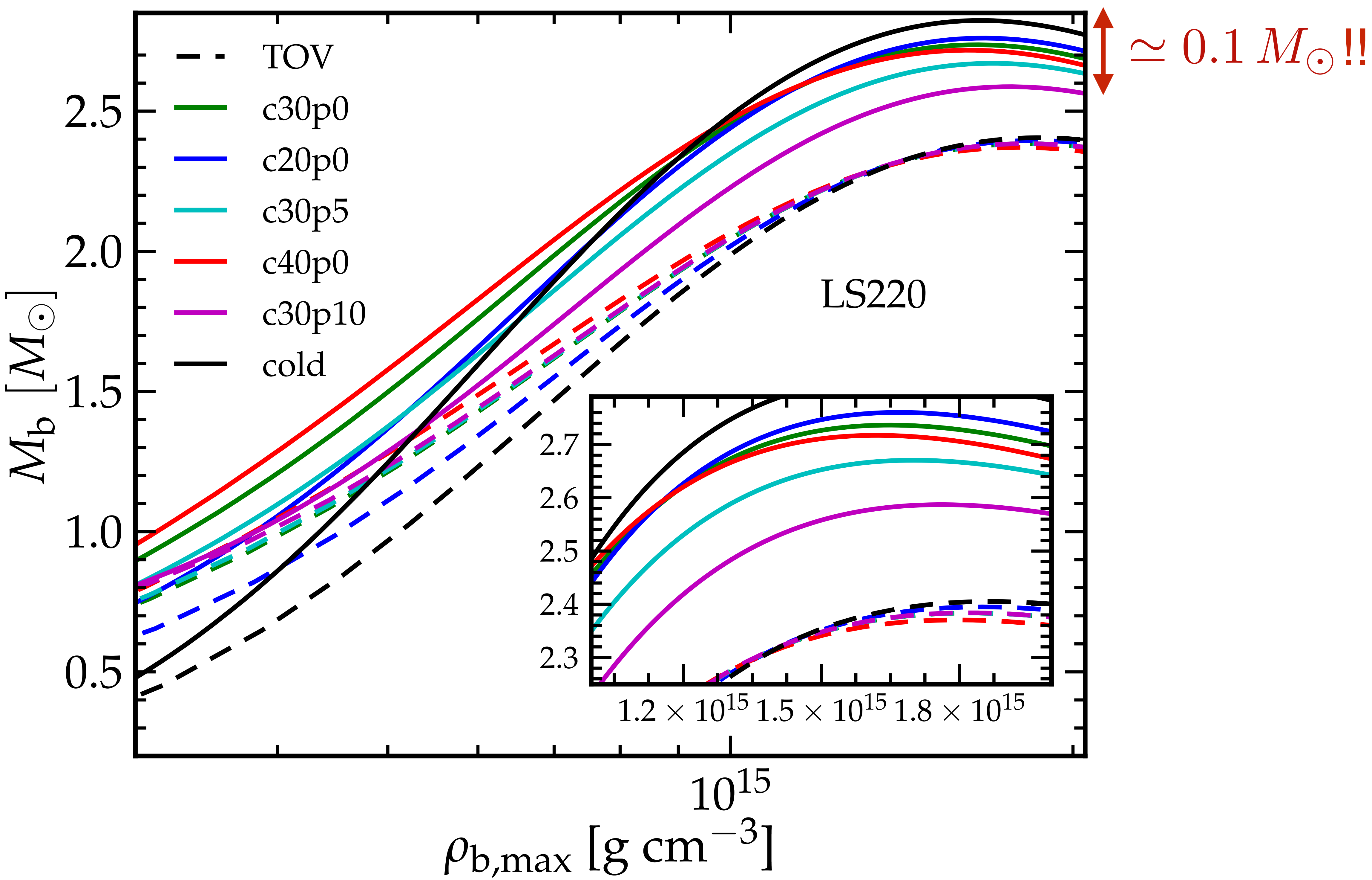
DR, Perego, Bernuzzi, Zhang, in prep.

Stable or unstable?



From Kaplan, Ott, O'Connor+ (2014)

Stable or unstable?



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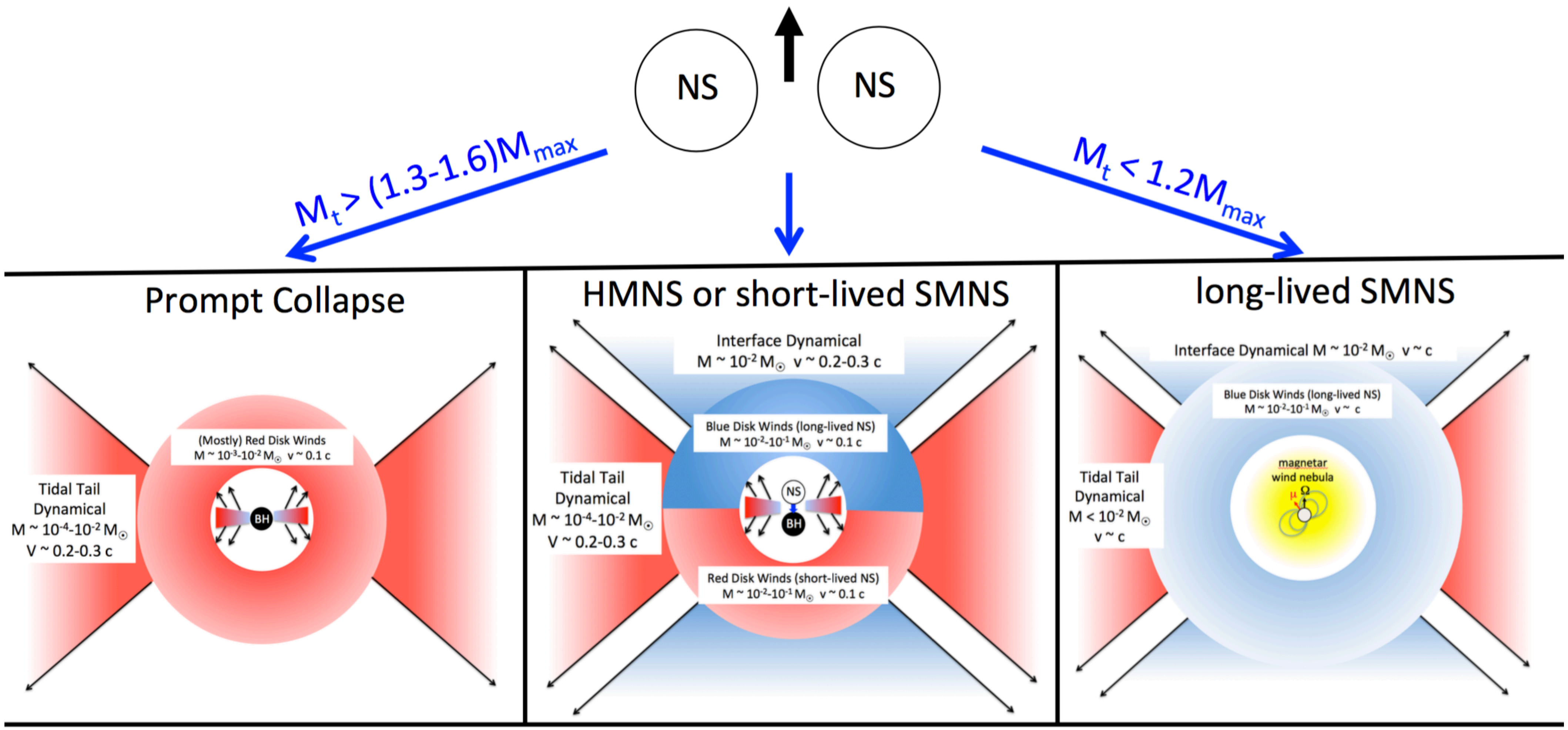
The remnant of GW170817

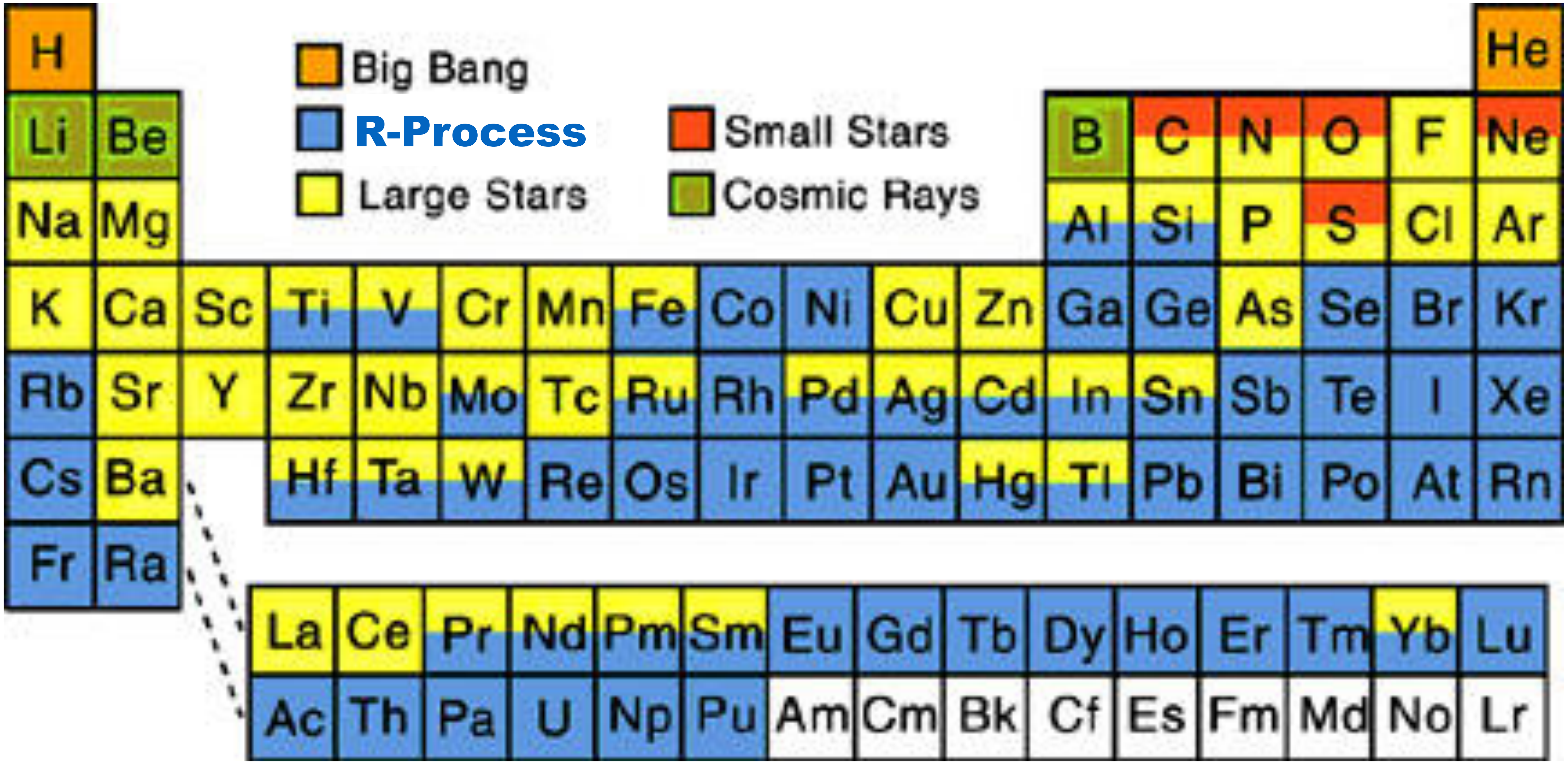


From Margalit & Metzger 2017

Long-lived SMNS unlikely —> limit on the maximum NS mass

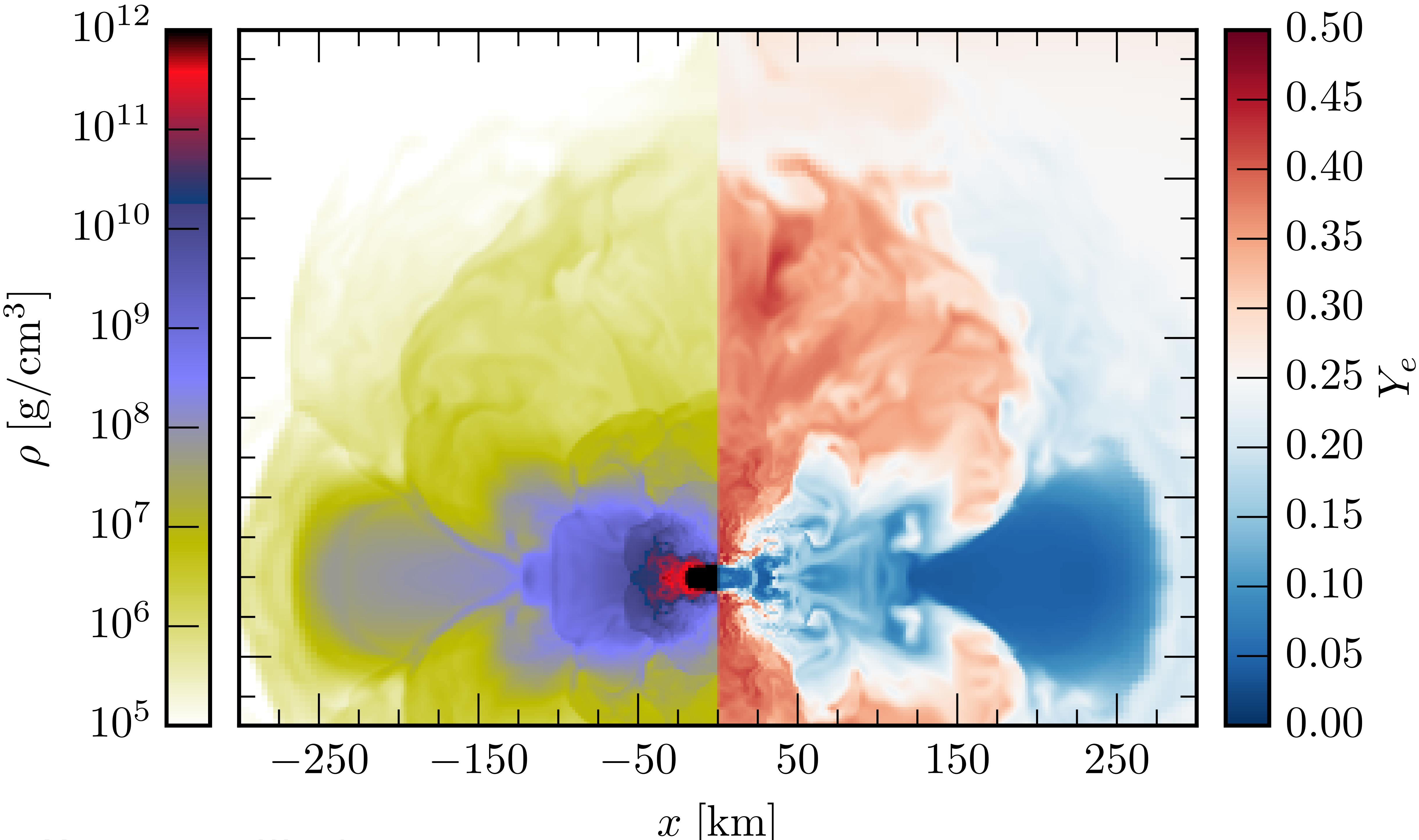
See also Rezzolla+, Shibata+, Ruiz+ (2017)

The origin of the elements



Are neutron star mergers the site of the r-process?

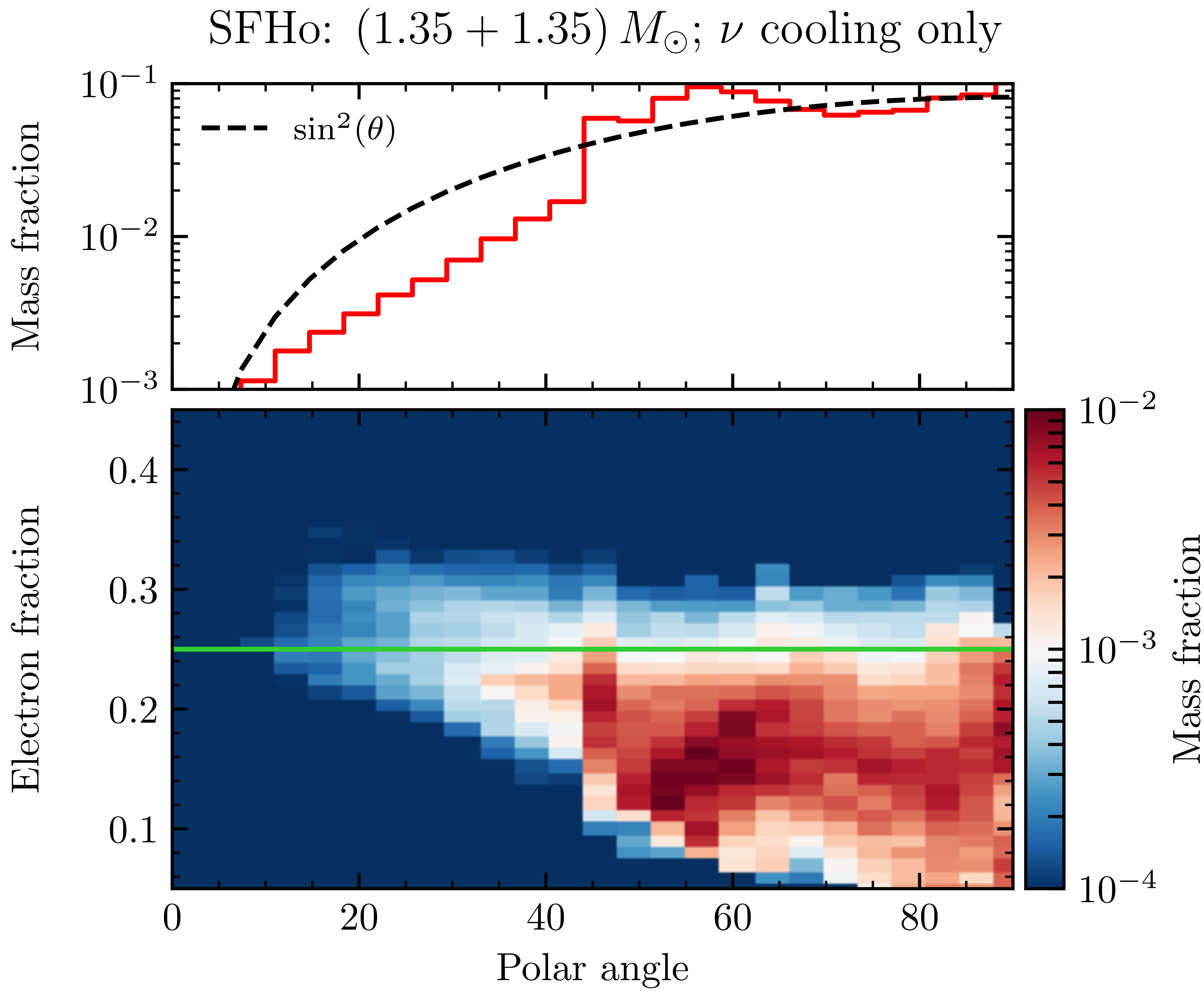
Ejection mechanisms



See also Metzger+2008; Wanajo+2014; Fernandez+2014; Metzger+2014; Perego+2014; Martin+2015; Sekiguchi+2015,2016; Foucart+2016; Siegel+2017

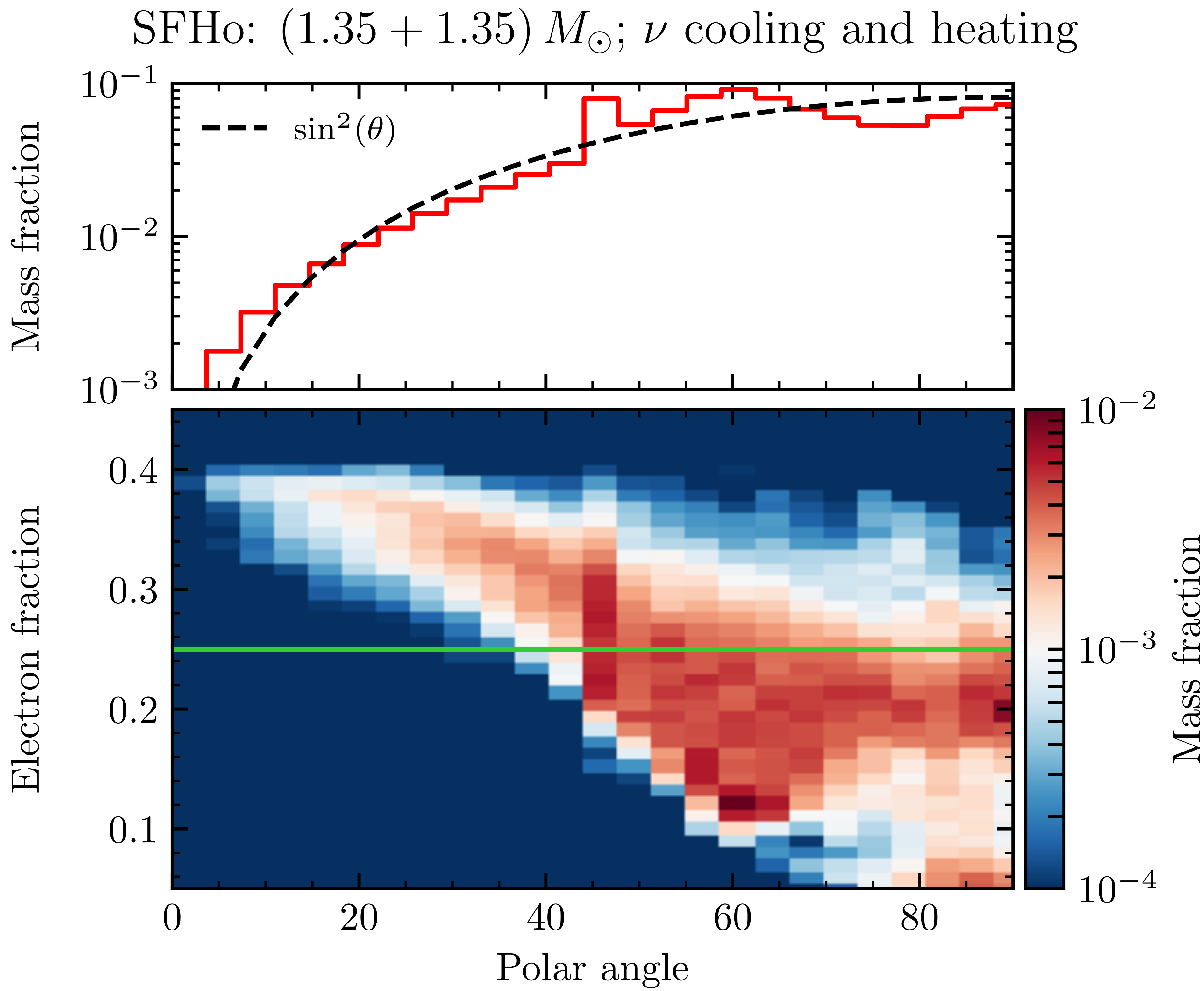
DR, Galeazzi+ MRAS 460:3255 (2016)

Dynamic ejecta: role of neutrinos



Perego, **DR**, Bernuzzi, ApJL:850 L37

Dynamic ejecta: role of neutrinos



Perego, **DR**, Bernuzzi, ApJL:850 L37

Conclusions

- Numerical relativity is essential in the age of multimessenger astronomy
- Do we really understand the outcome of NS mergers?
- Neutrinos play a crucial role for nucleosynthesis and EM counterparts

Thank you!