Neutron-star merger remnants and their potential for equation-of-state constraints

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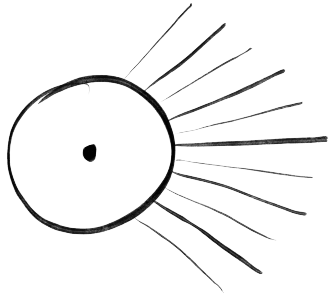
EMMI Workshop, GSI, Nov. 13th, 2025



ERC synergy HeavyMetal

with: A. Bauswein, G. Martinez-Pinedo, S. Goriely, Z. Xiong, V. Vijayan, C. Collins, I. Kullmann, L. Shingles, S. Sim, A. Sneppen, D. Watson, H.-Th. Janka, and more

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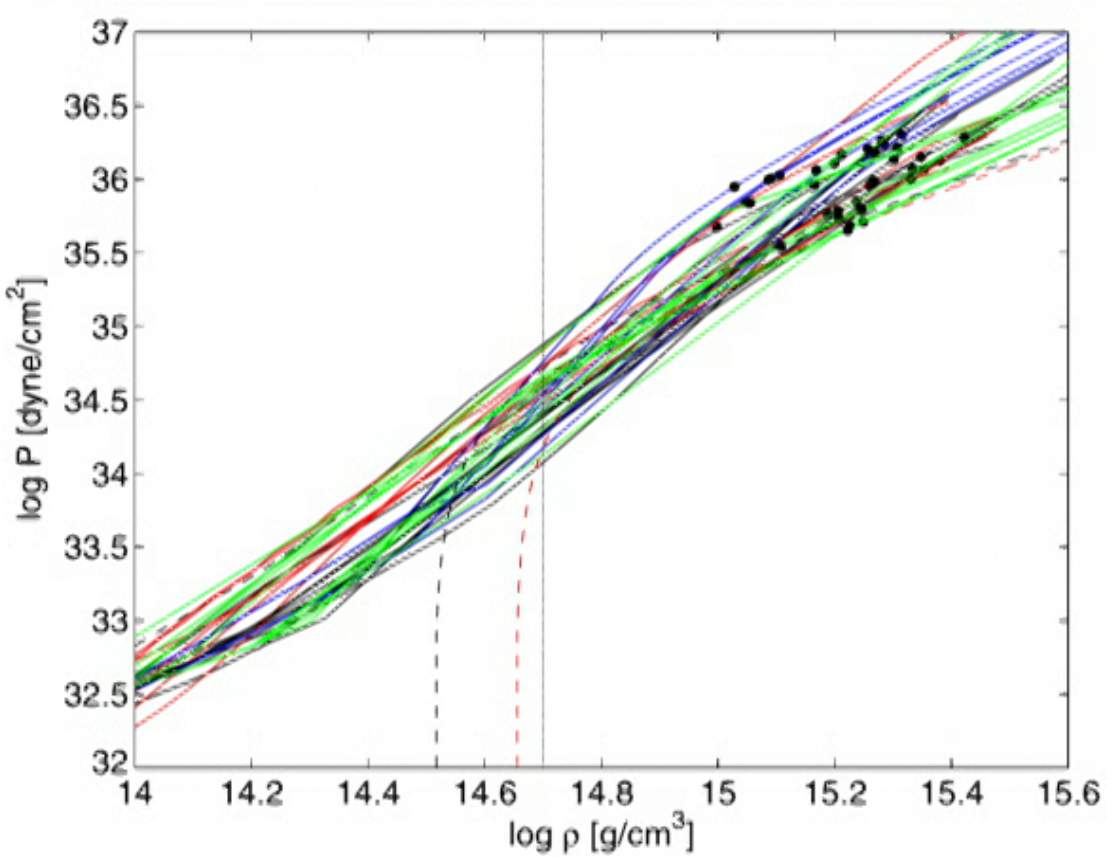
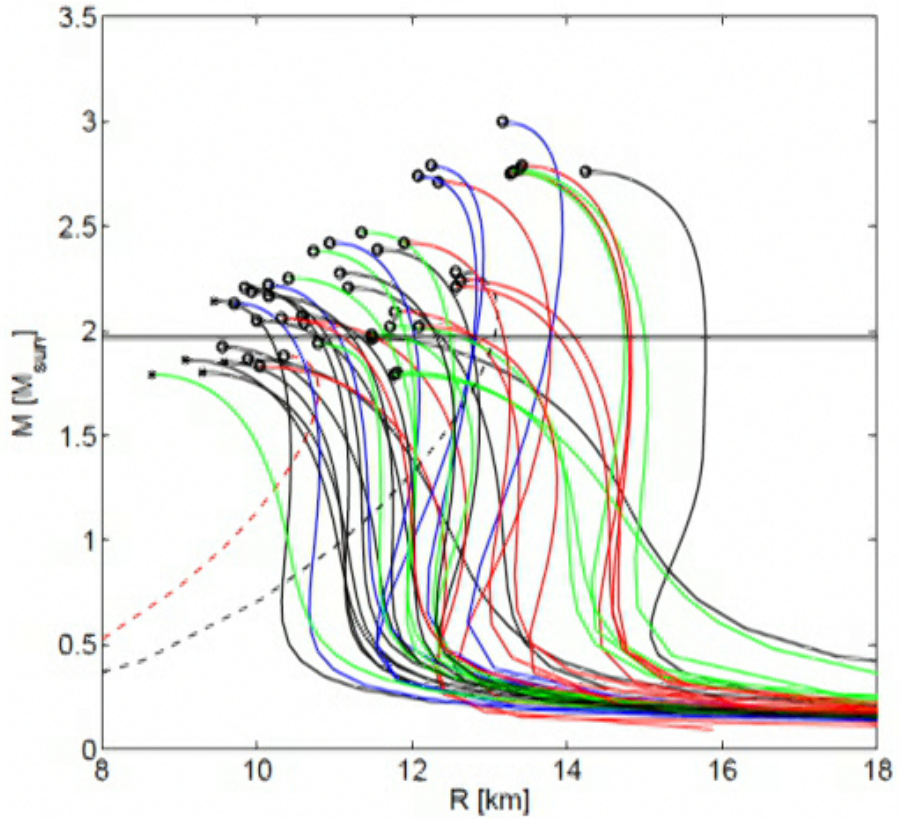
What do NSMs tell us about the nuclear equation of state (EOS)?

possible nuclear equation of states



TOV equations

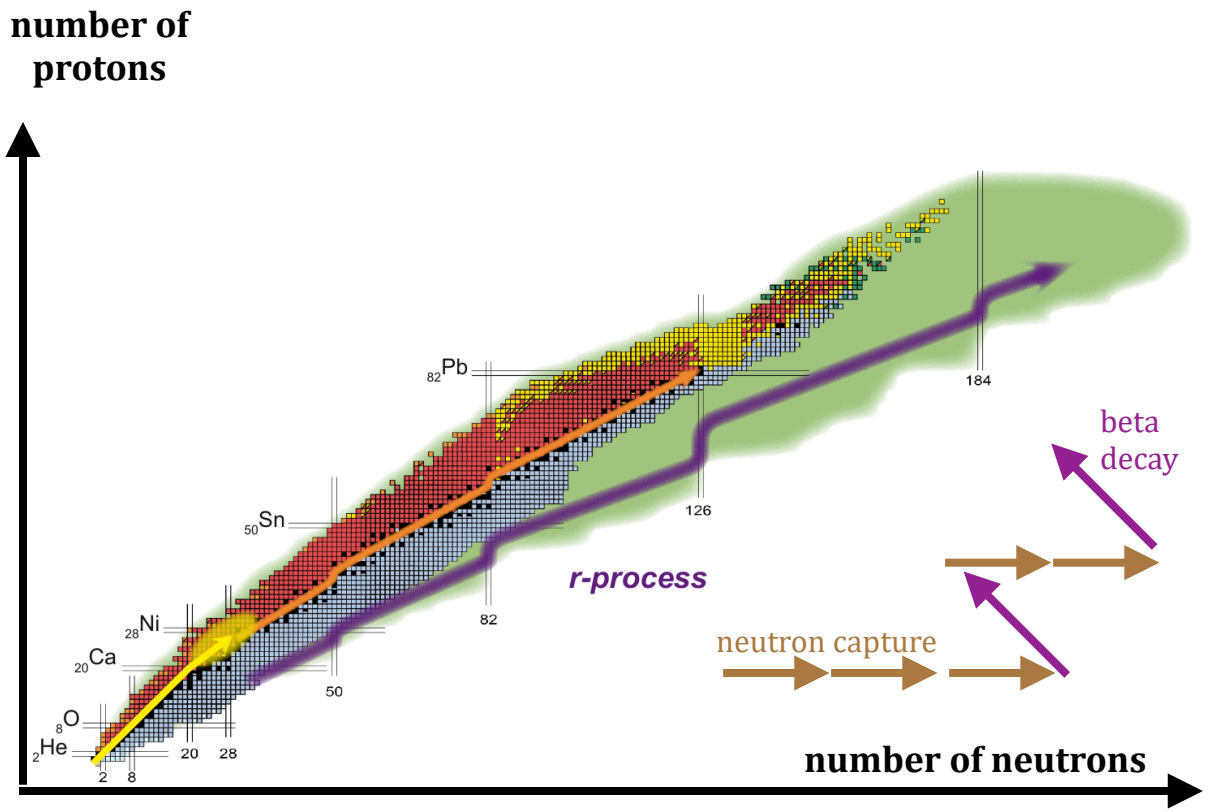
corresponding mass-radius relationships of cold, non-rotating neutron stars



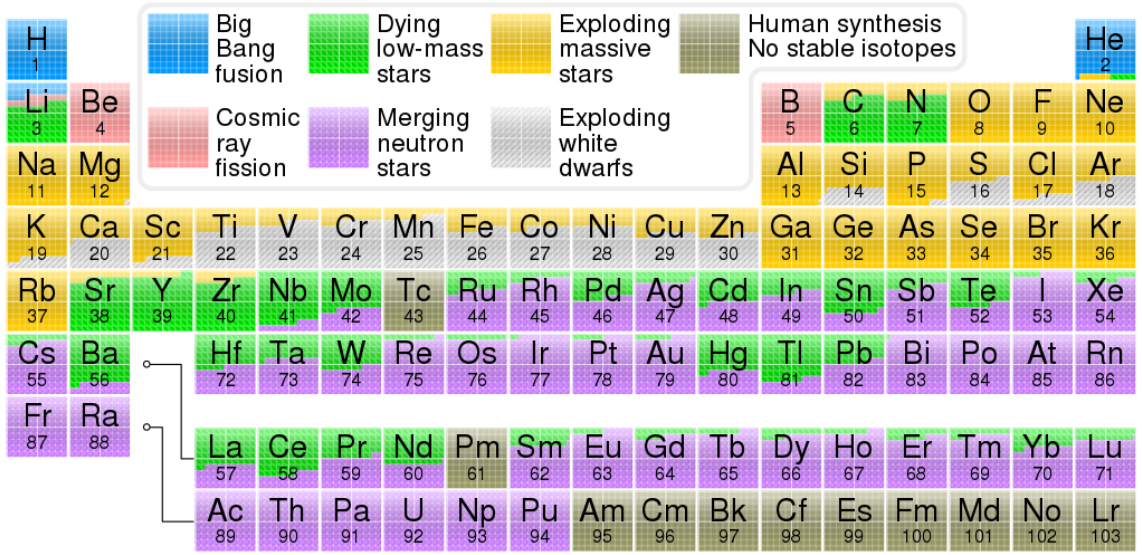
(plots by A. Bauswein)

- softer (stiffer) EOS <=> smaller (larger) neutron star
- softer (stiffer) EOS <=> shorter (longer) lifetime of merger remnant

Are NSMs main sites of the "rapid neutron-capture" (r-) process?



***suggested** sites of origin*



Main condition:

high neutron density = low electron fraction Y_e

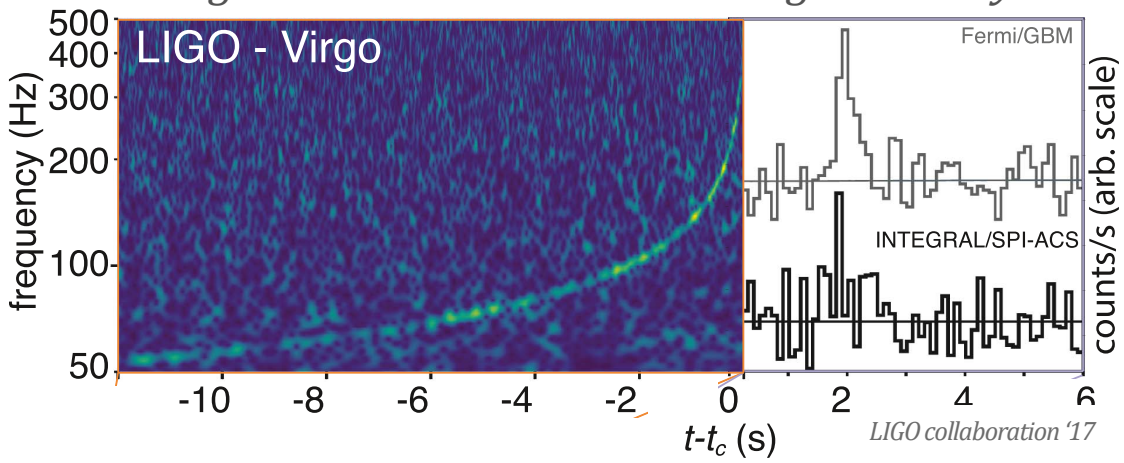
$$Y_e = \frac{n_{\text{proton}}}{n_{\text{neutron}} + n_{\text{proton}}} \overset{!}{<} 0.5$$

- NSMs are the **only confirmed site** so far, but are they main site?
- other suggested sites: core-collapse supernovae, magneto-rotational SNe, collapsars, magnetar giants flares

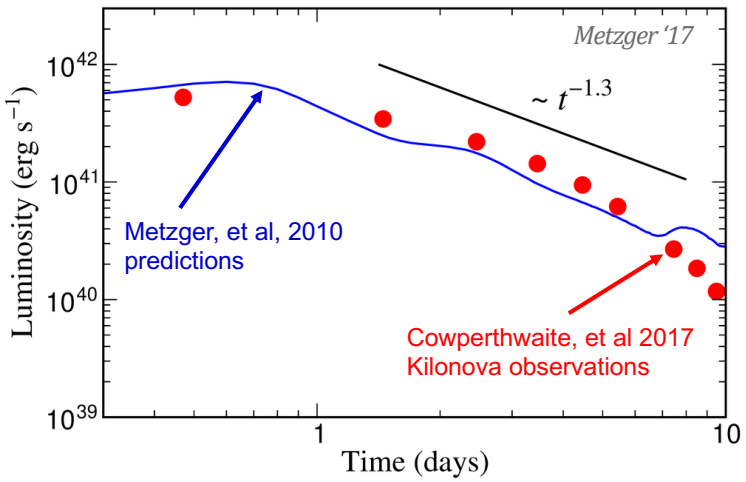
GW170817/AT2017gfo (on August 17th, 2017)
the first multi-messenger observation of a NS merger

- **"Messengers":**
  - gravitational wave (GW) signal
  - gamma-ray burst (GRB)
  - kilonova (light curve + spectra)
- Each messenger can be exploited to learn about EoS
- most existing EoS constraints derived from GW signal and light curve
- **EoS constraints using also spectral information???**

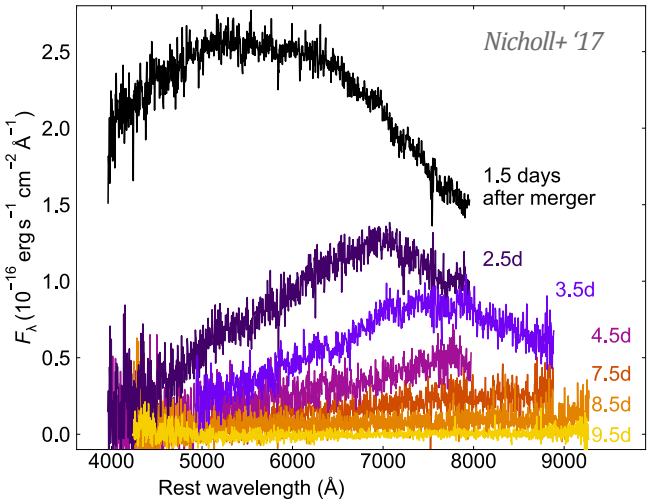
gravitational waves *gamma rays*



light curve



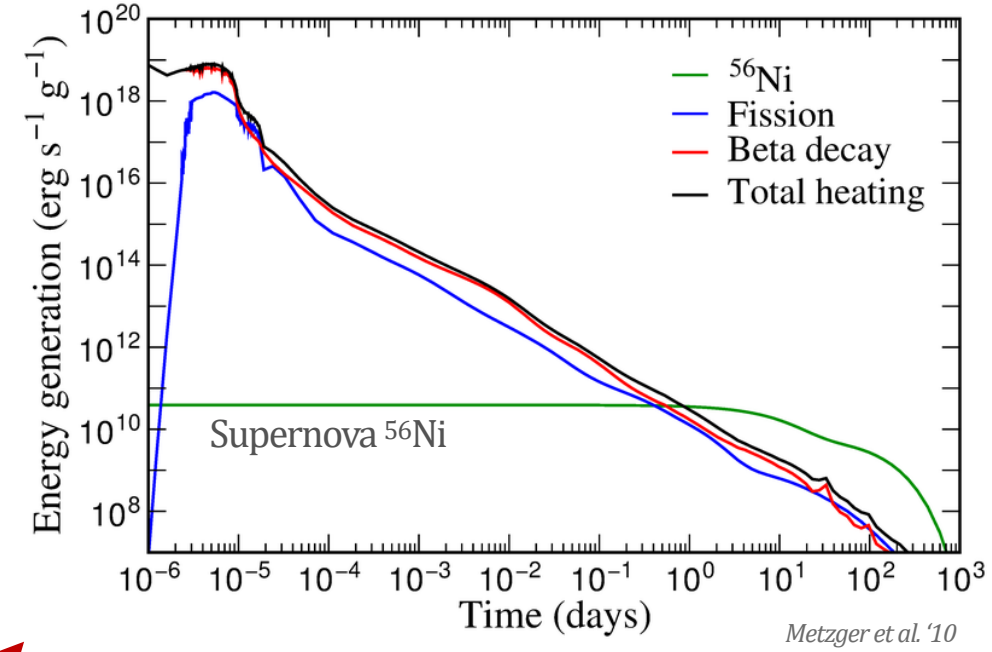
UV+optical+IR spectra



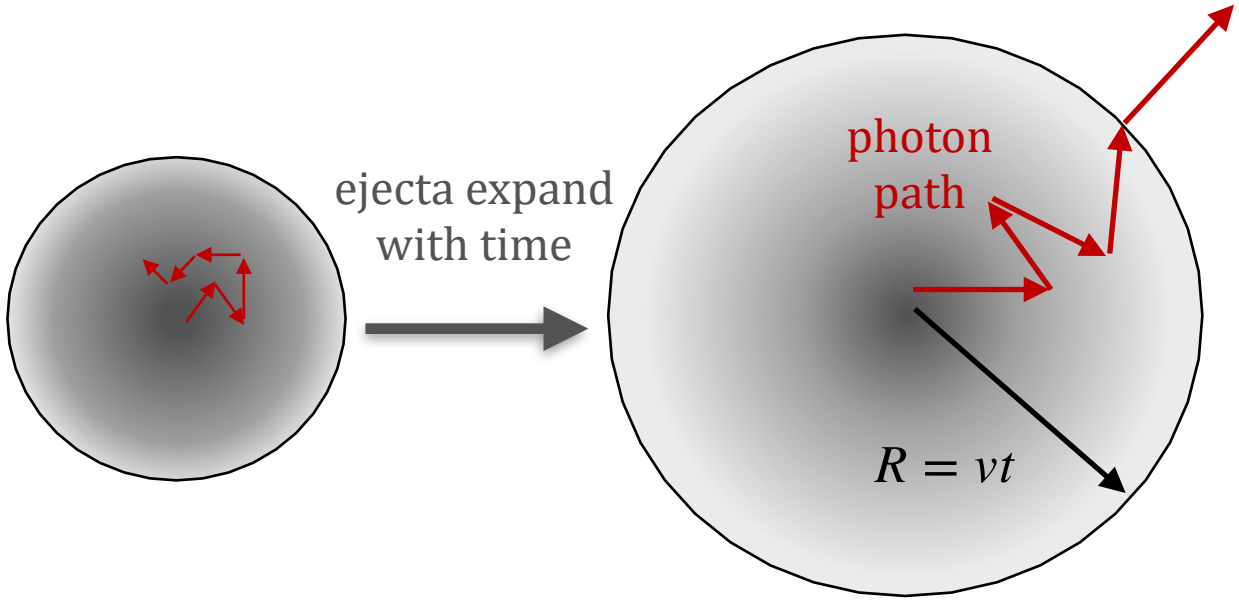
What is a kilonova?

("Kilo" because 1000 times brighter than a nova)

- radioactive decay of freshly synthesized material produces energy (= heat)
- heating rate typically declines as $t^{-1.3}$

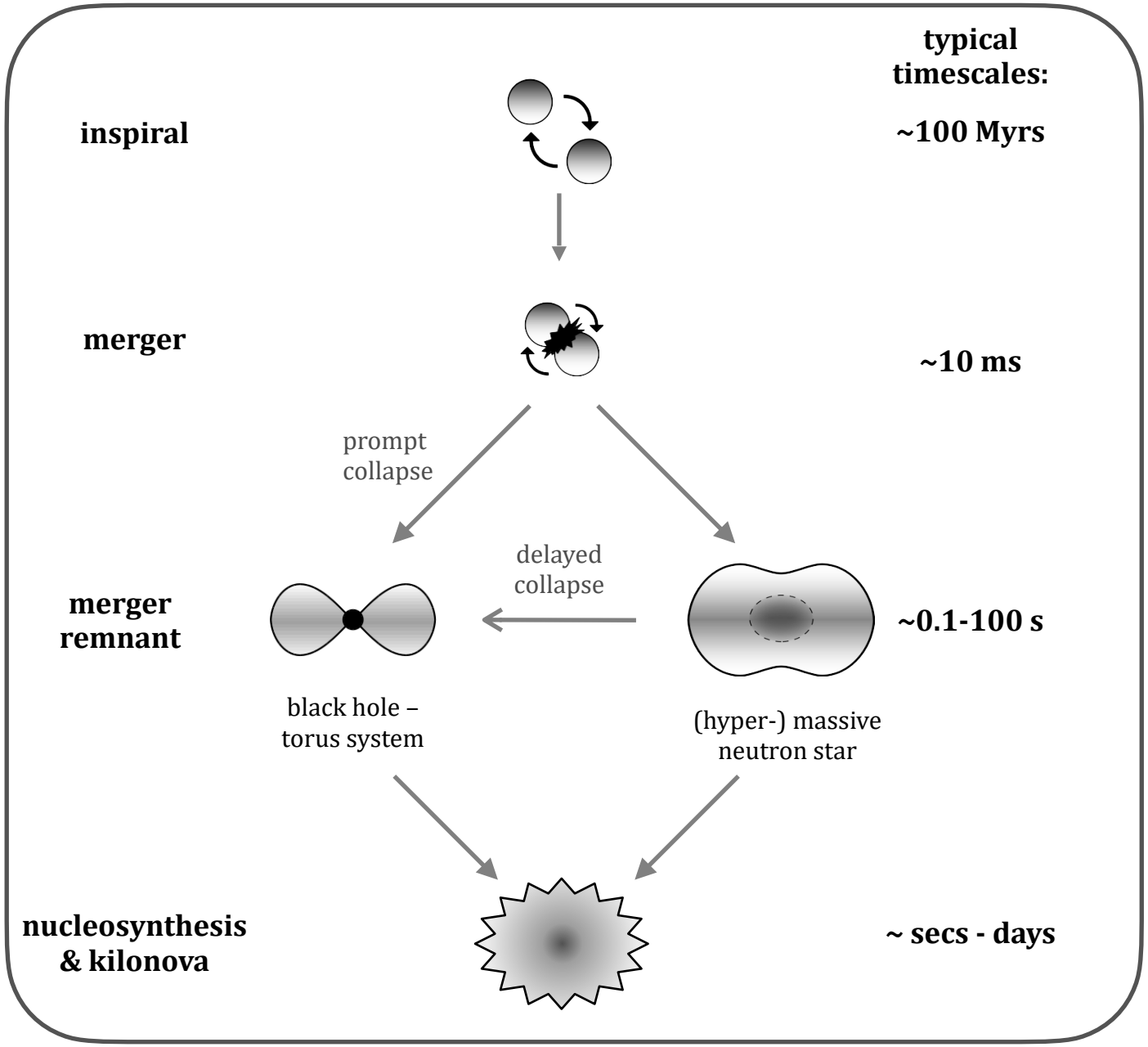


Metzger et al. '10

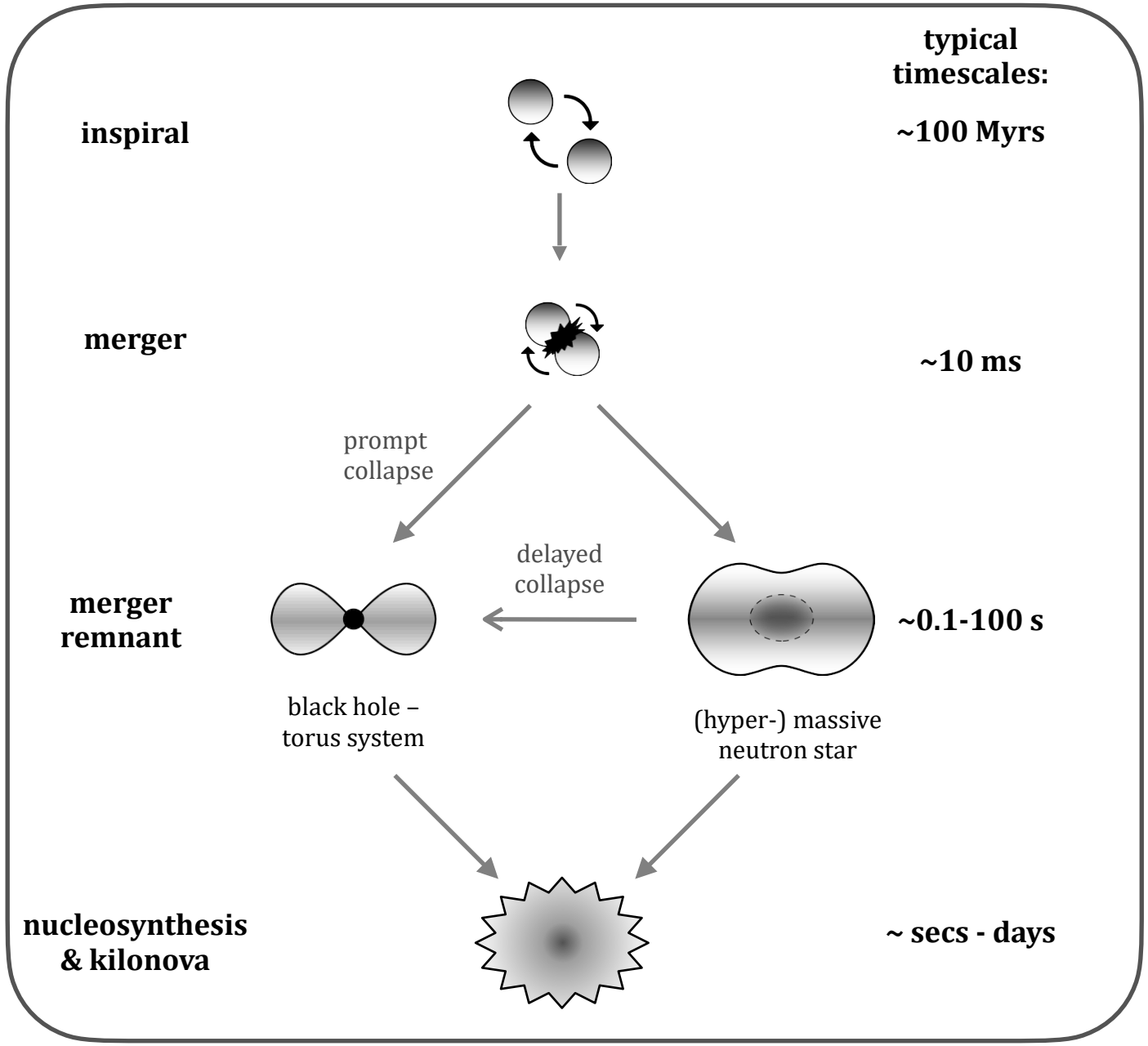


- heating creates photons -> random-walk diffusion through expanding ejecta while density decreases
- emitted light curve encodes information about ejecta mass
- spectrum carries information about ejecta composition

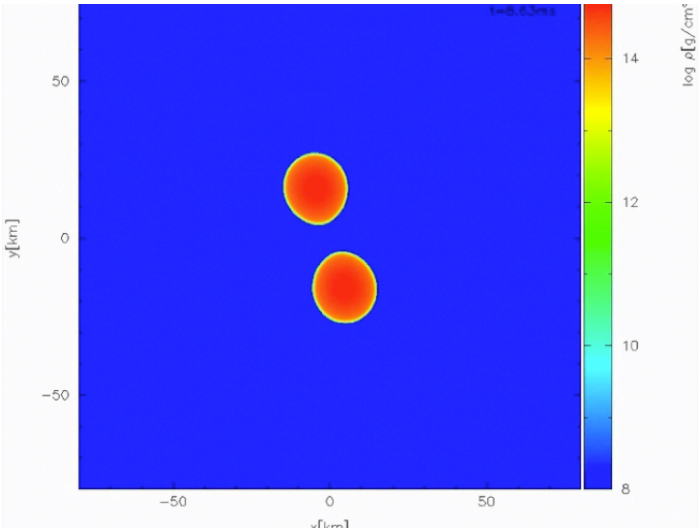
Evolution of NS mergers



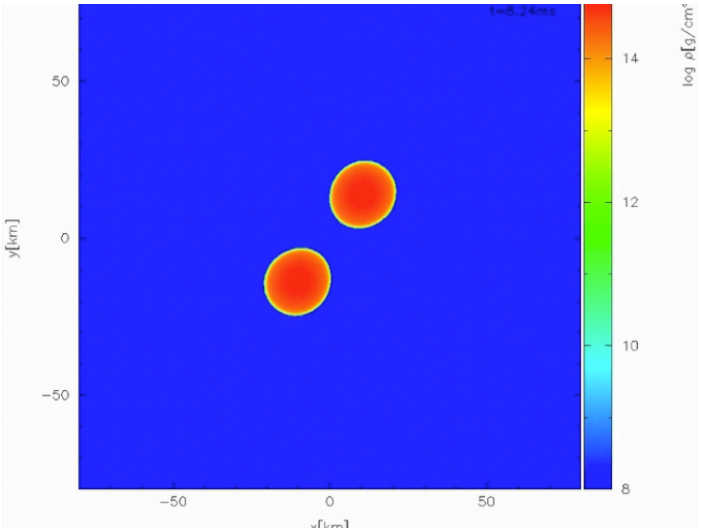
Evolution of NS mergers



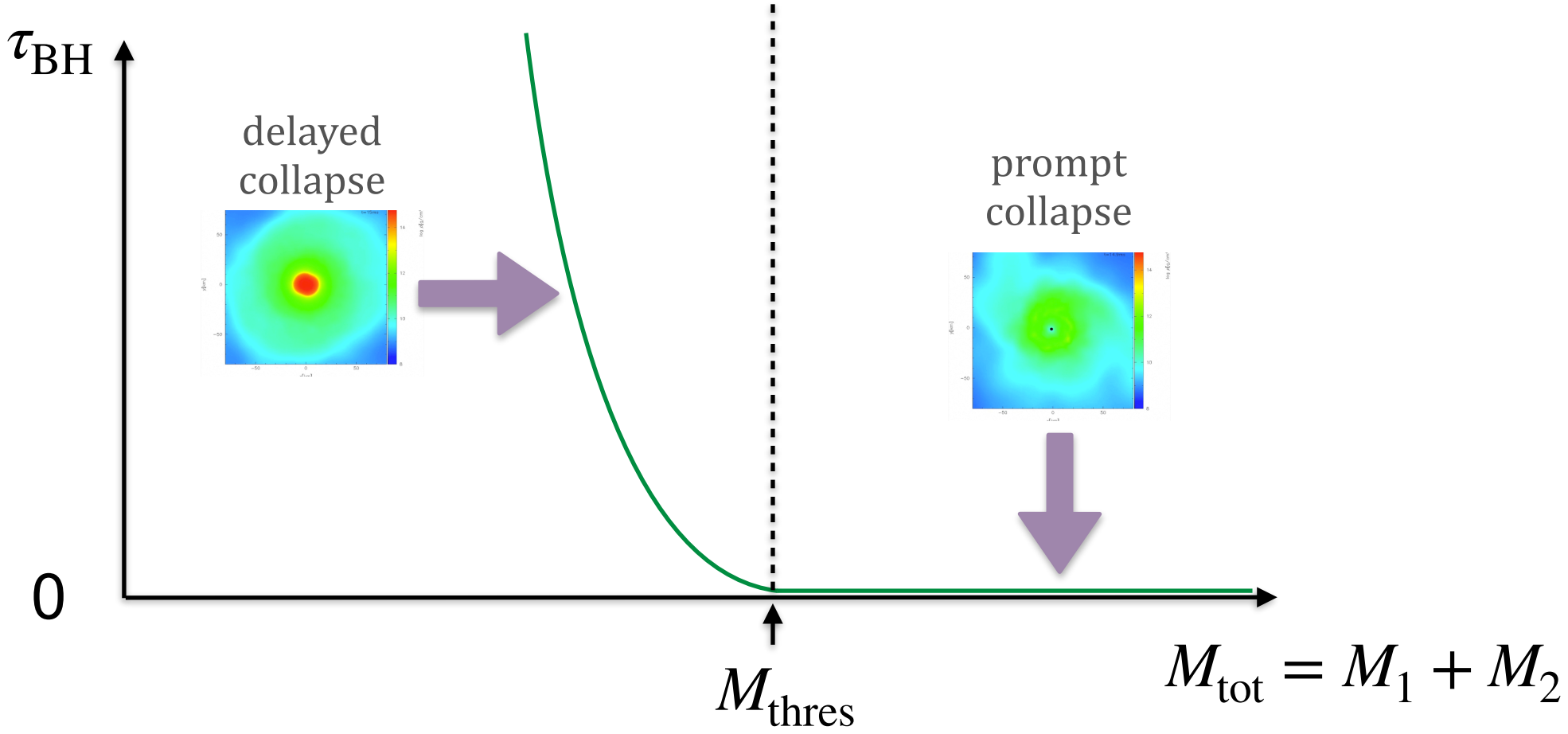
delayed collapse



prompt collapse



Connecting remnant lifetime with the EOS

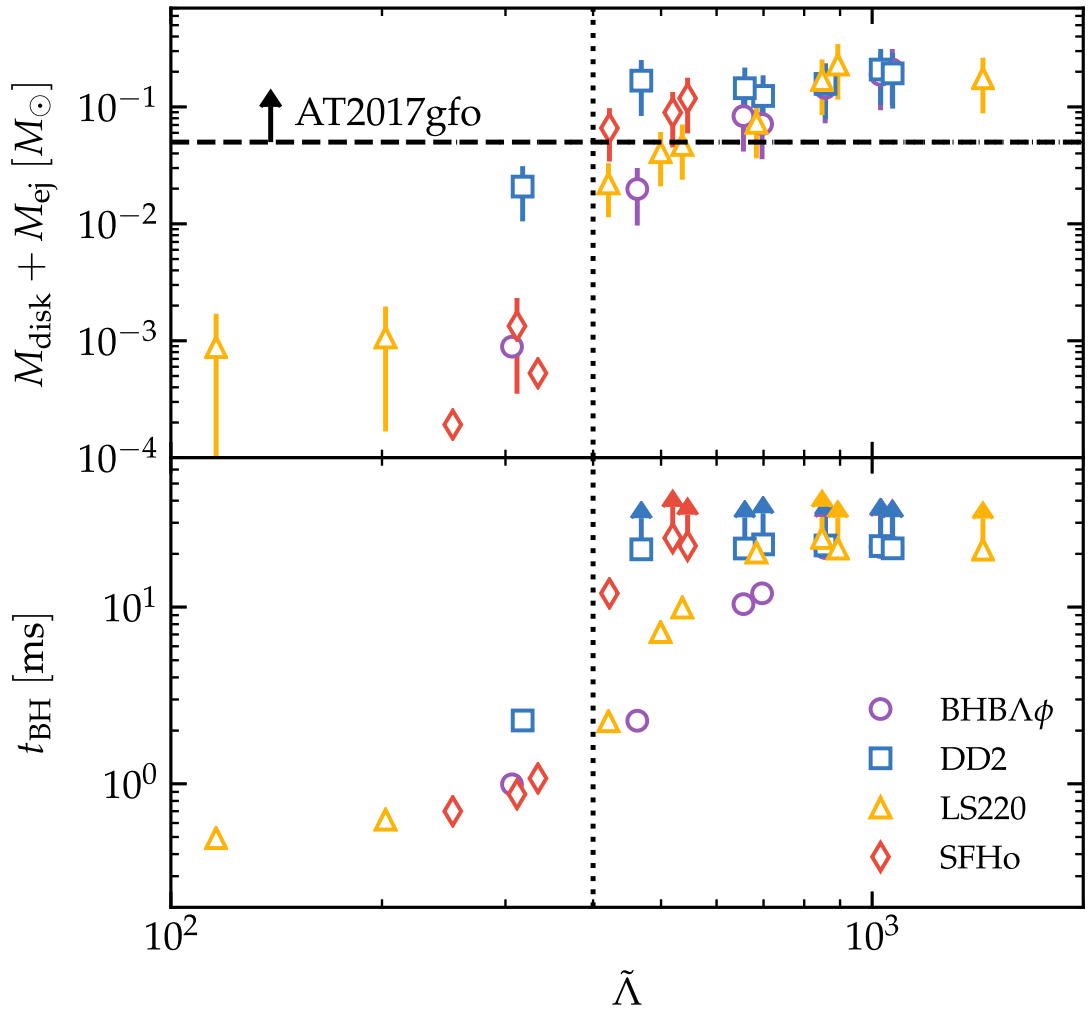


- threshold mass M_{thres} separates prompt-collapse from delayed-collapse cases
- M_{thres} depends only on EOS
- constraint on M_{thres} -> constraint on EOS

Previous EOS constraint based on KN brightness

(Bauswein, OJ, Janka, & Stergioulas 2017, ApJL, 850, L34)

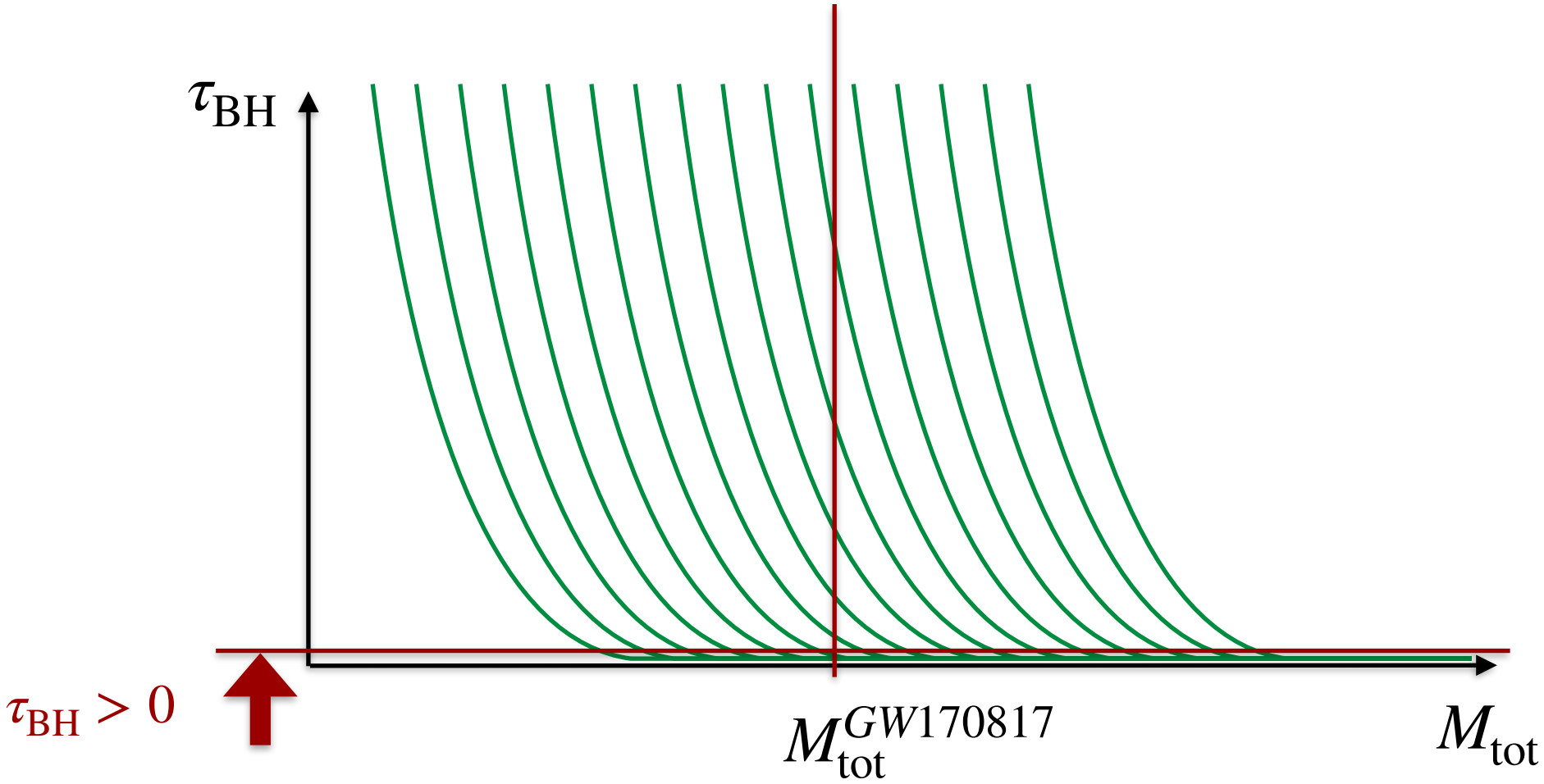
Lower limit on NS remnant lifetime



(plot from Radice et al. 2018)

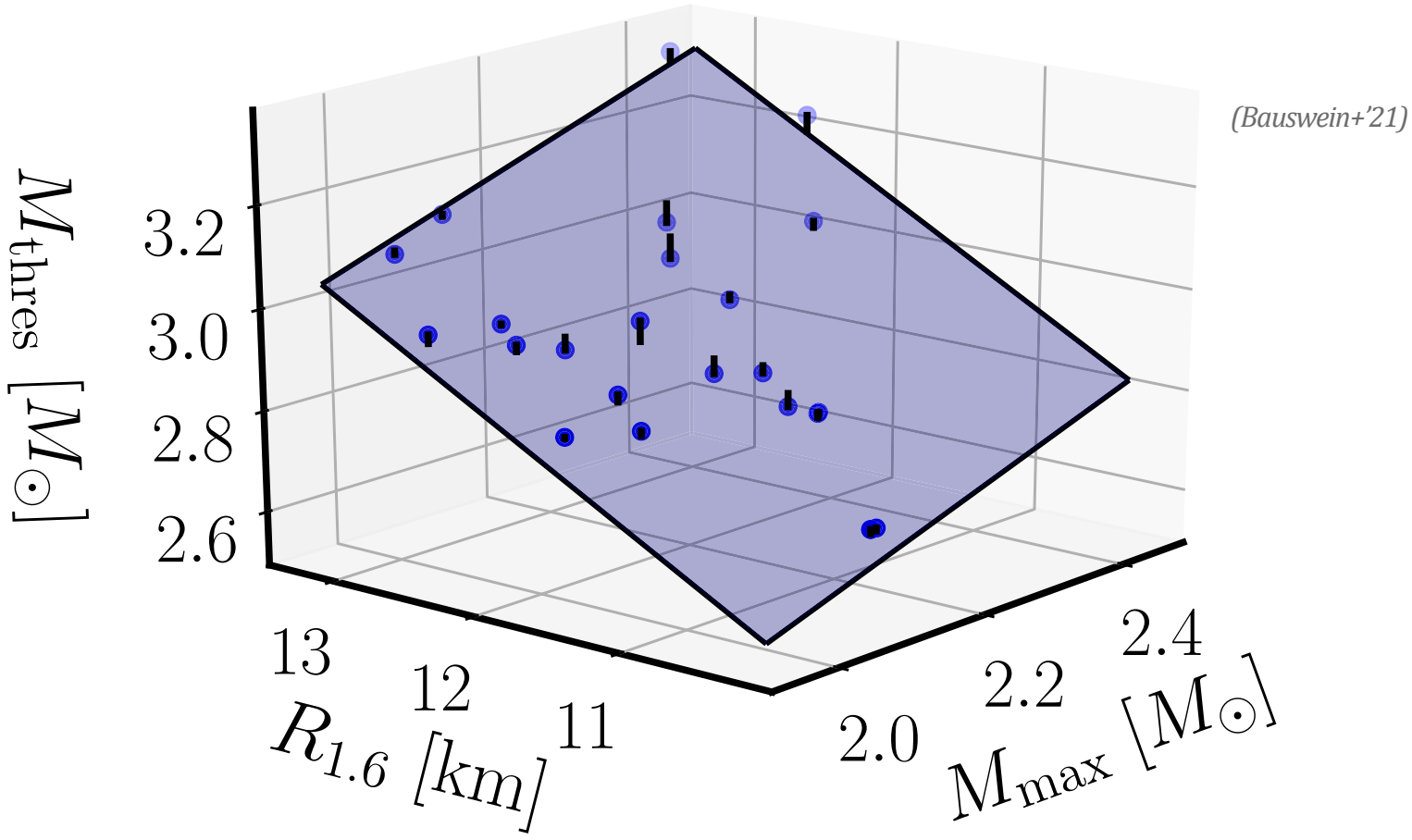
- high brightness of AT2017gfo **strongly disfavors** prompt collapse

Implication of $\tau_{\rm BH} > 0$



$$M_{\rm tot}^{GW170817} < M_{\rm thres}$$

From threshold mass to NS properties

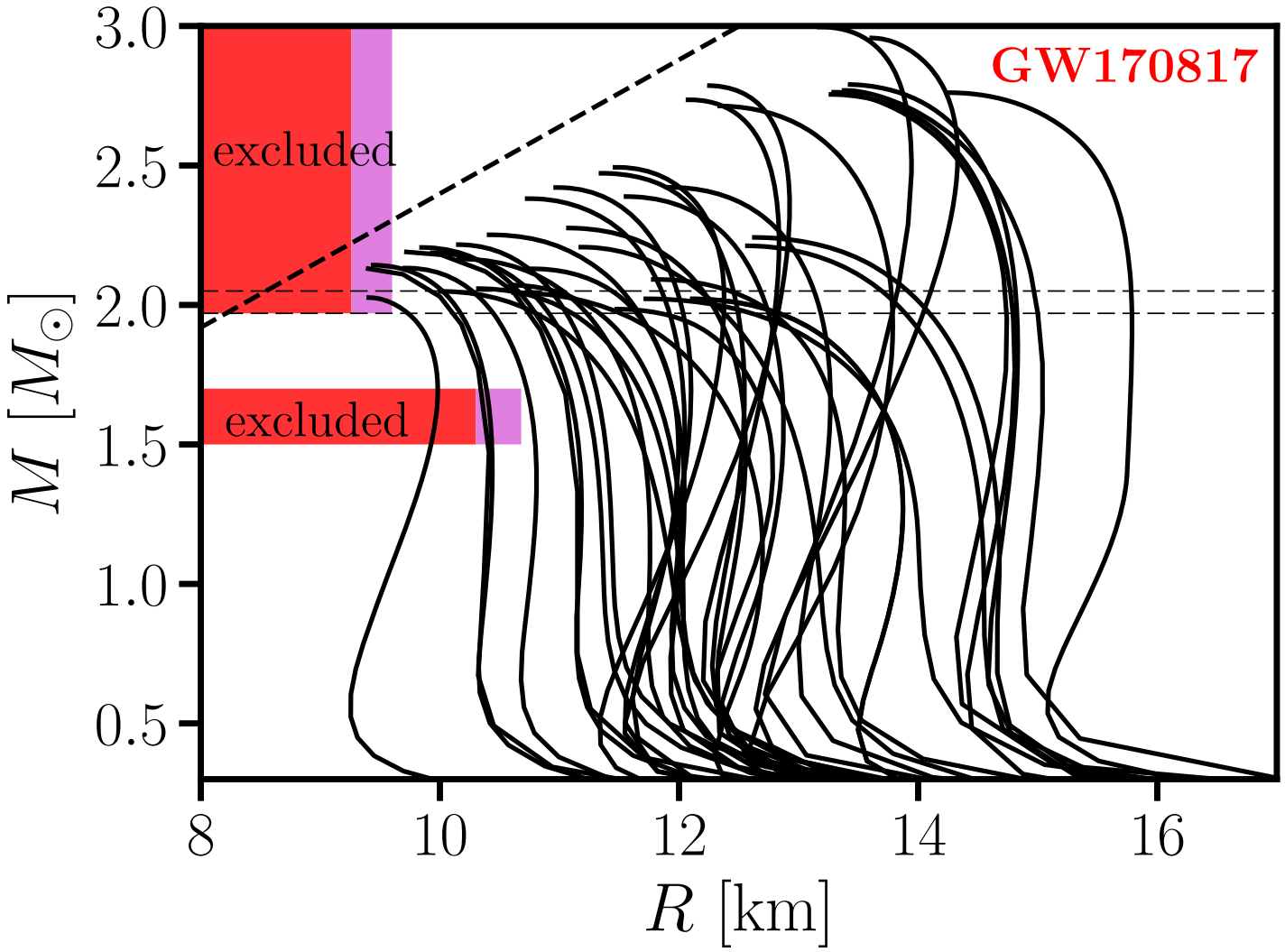


(Bauswein+'21)

- exploit empirical relations (e.g. Bauswein+17,19,21, Kölsch+23):

$$M_{\rm thres}(q, M_{\rm max}, R) = c_1 M_{\rm max} + c_2 R + c_3 + c_4 \delta q^3 M_{\rm max} + c_5 \delta q^3 R$$

Implication of $\tau_{\rm BH} > 0$



- delayed collapse implies: $R_{1.6} \gtrsim 10.7\,\mathrm{km}$

New EOS constraint based on KN spectrum

(Sneppen, OJ, Bauswein, Damgaard, Watson, Shingles, Collins, Sim, Xiong, Martinez-Pinedo, Soultanis, & Vijayan, arxiv:2411.03427)

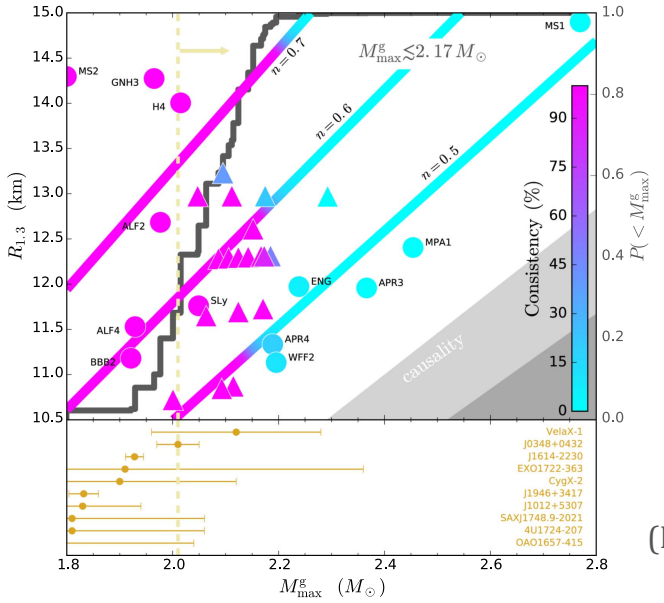
Previous limits on the remnant lifetime $\tau_{\rm BH}$ in GW170817?

- absence of spindown emission (Margalit+17):
  $\tau_{\rm BH} \lesssim$ few seconds

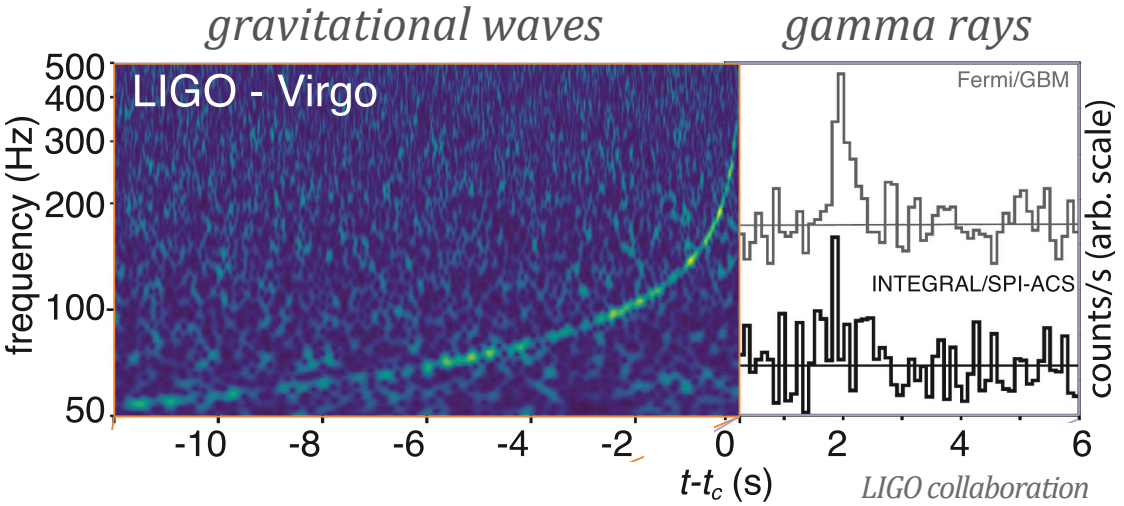
- if gamma-ray burst was produced by BH (Rezzolla+18):
  $\tau_{\rm BH} \lesssim 1.7$ s

- **lifetime of NS remnant largely unconstrained within:**
  $10\,{\rm ms} \lesssim \tau_{\rm BH} \lesssim 1.7$ s

- **tighter upper limit calls for detailed kilonova modeling of the remnant**

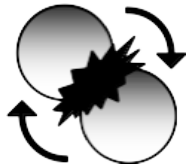


(Margalit+17)



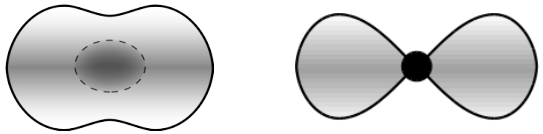
Kilonova modeling pipeline

hydrodynamic modeling of merger + dynamical ejecta



$t \sim \mathcal{O}(10\,\mathrm{ms})$

hydrodynamic modeling of remnant + post-merger ejecta

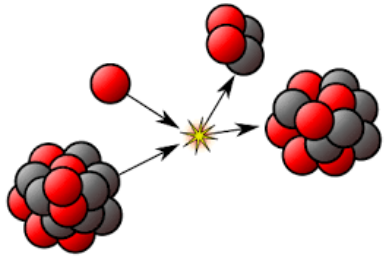


neutron star torus system

black hole torus system

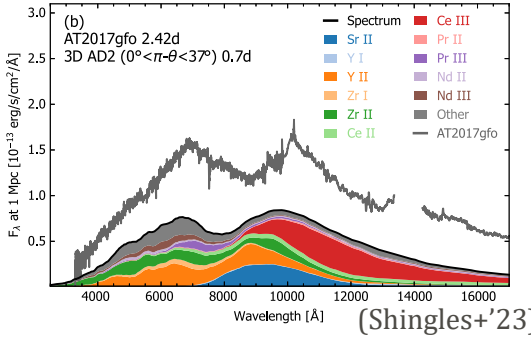
$t \sim \mathcal{O}(10\,\mathrm{s})$

heavy element nucleosynthesis



$t \sim \mathcal{O}(10\,\mathrm{s})$

kilonova radiative transfer



(Shingles+'23)

$t \sim \mathcal{O}(10\,\mathrm{days})$

parameter inference with observations

Kilonova modeling pipeline

hydrodynamic modeling of merger + dynamical ejecta

- 3D smoothed-particle hydro with conformal flatness condition
- ILEAS neutrino scheme

hydrodynamic modeling of remnant + post-merger ejecta

- initial conditions mapped from merger simulations
- 2D axisym. special relativistic with TOV potential
- energy-dependent M1 neutrino transport
- newly developed scheme to parametrize viscosity in the NS indep. of the surrounding disk

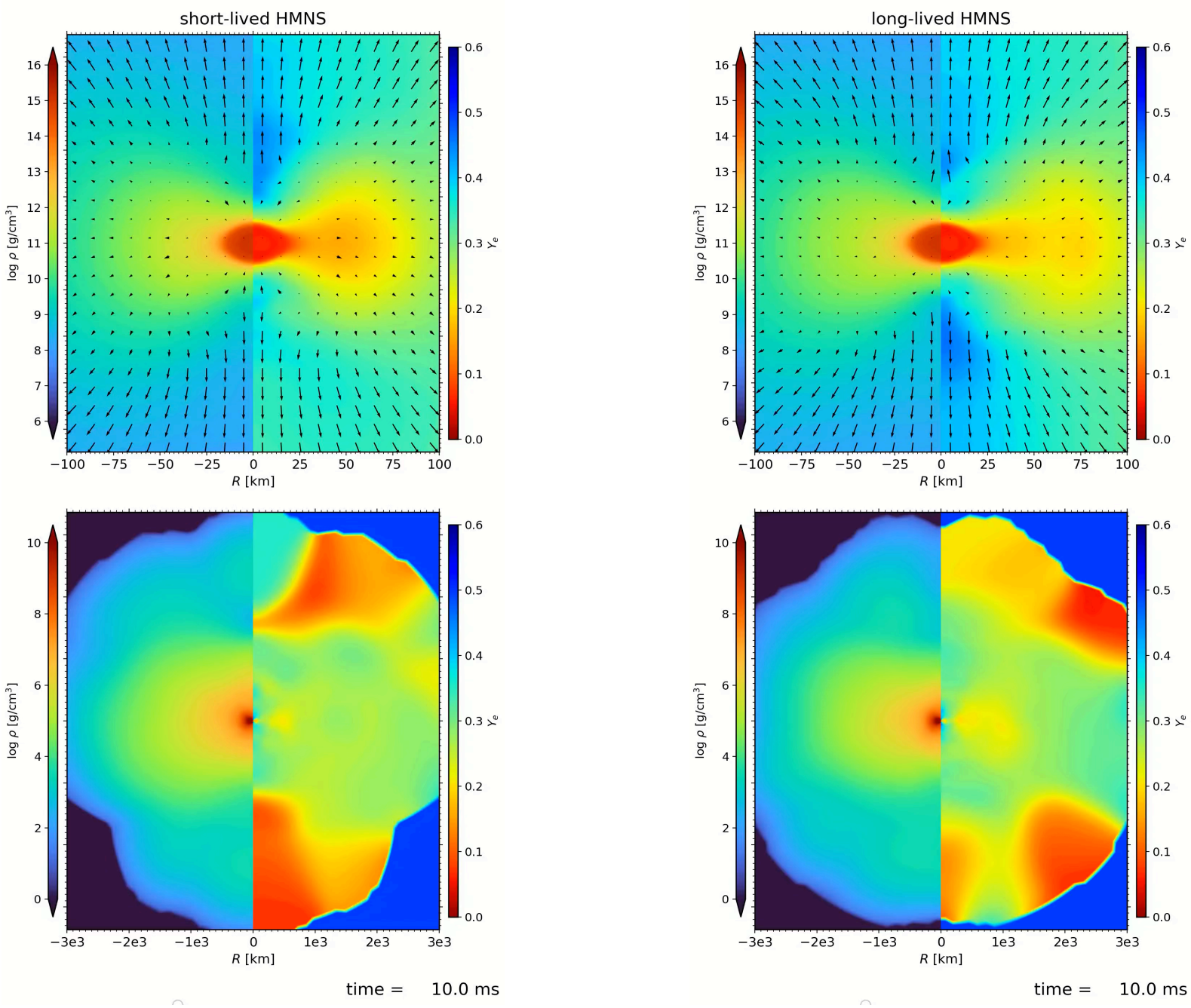
heavy element nucleosynthesis

- extraction of ~5000 outflow tracers per model to sample local hydrodynamic history until 100 s
- post-processed by two nuclear networks (GSI & ULB)

kilonova radiative transfer

- 2D axisymmetric radiative transfer using approximate M1 scheme
- alternatively use ARTIS Monte-Carlo code (with Belfast)
- adopt local time-dependent results from nucleosynthesis calculations

Short-lived vs. long-lived NS remnant



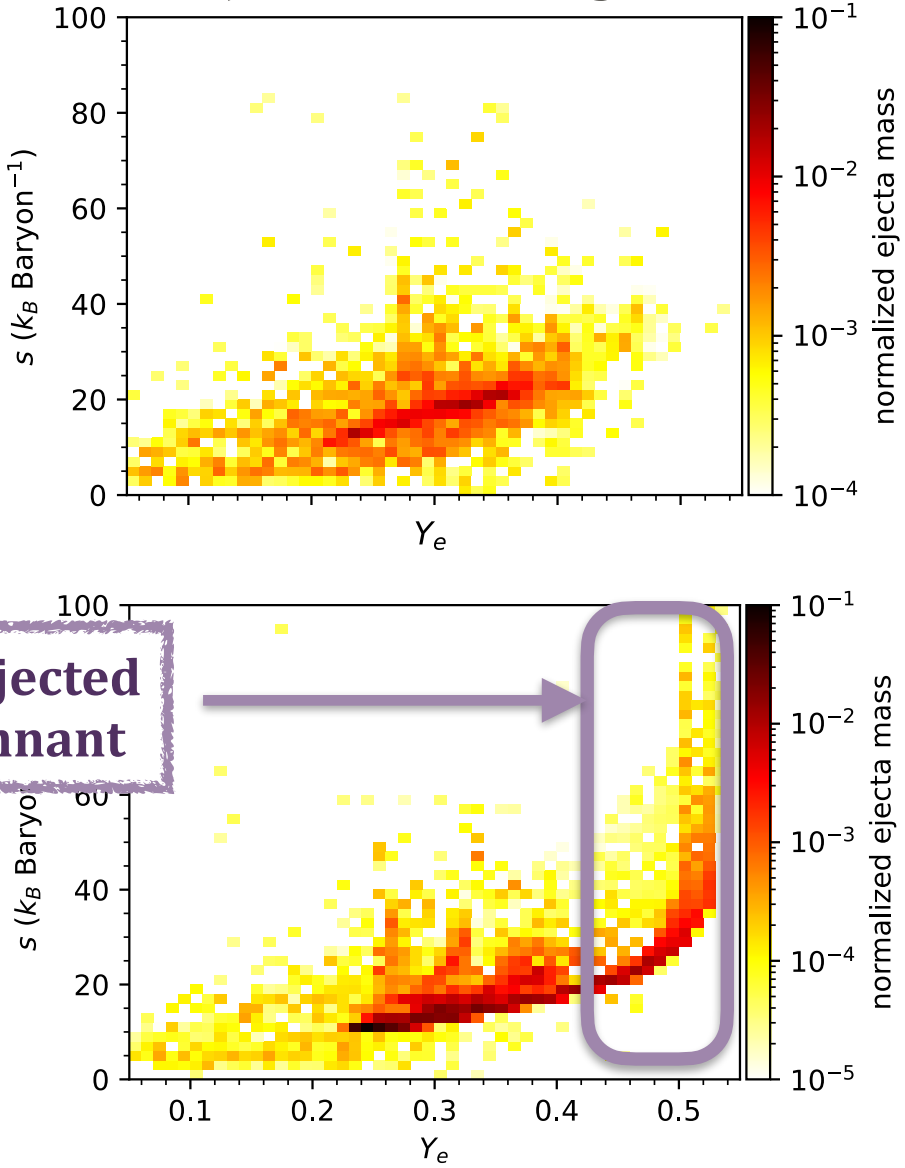
Short-lived vs. long-lived NS remnant

short-lived
($\tau_{\rm BH} = 10\,{\rm ms}$)

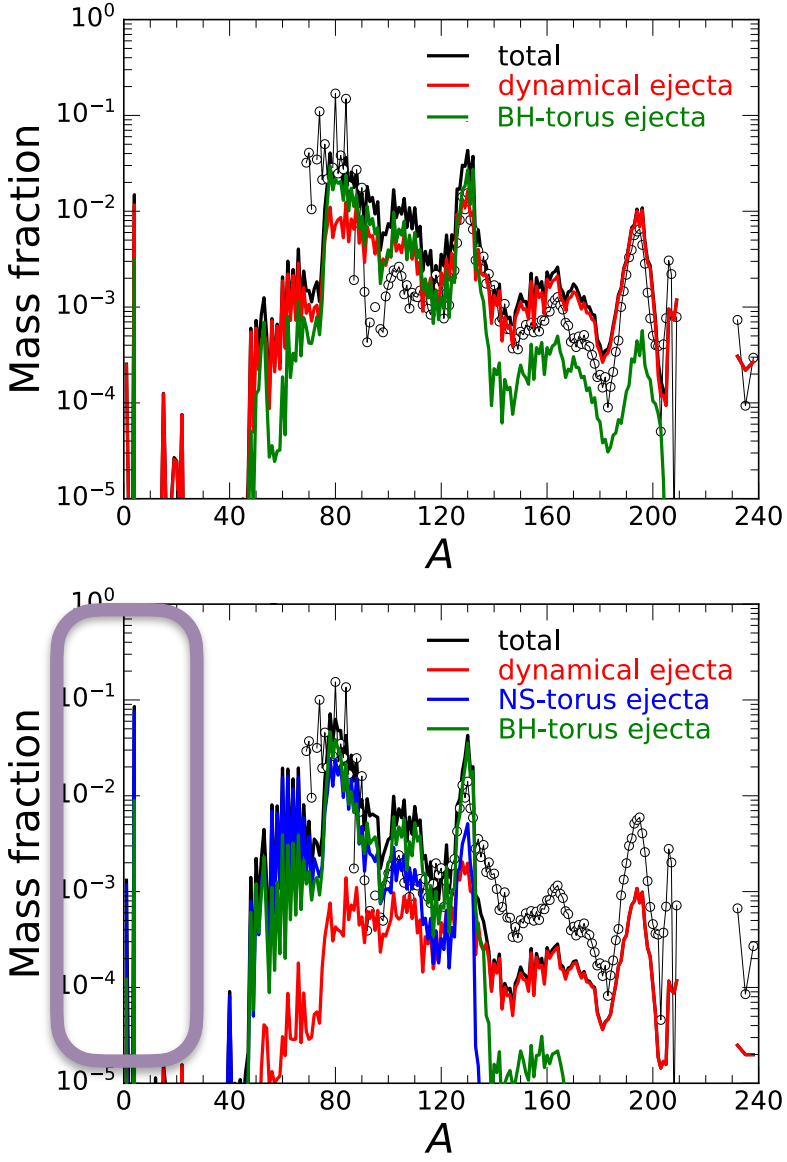
long-lived
($\tau_{\rm BH} = 120\,{\rm ms}$)

mainly helium ejected from the NS remnant

ejecta mass histogram

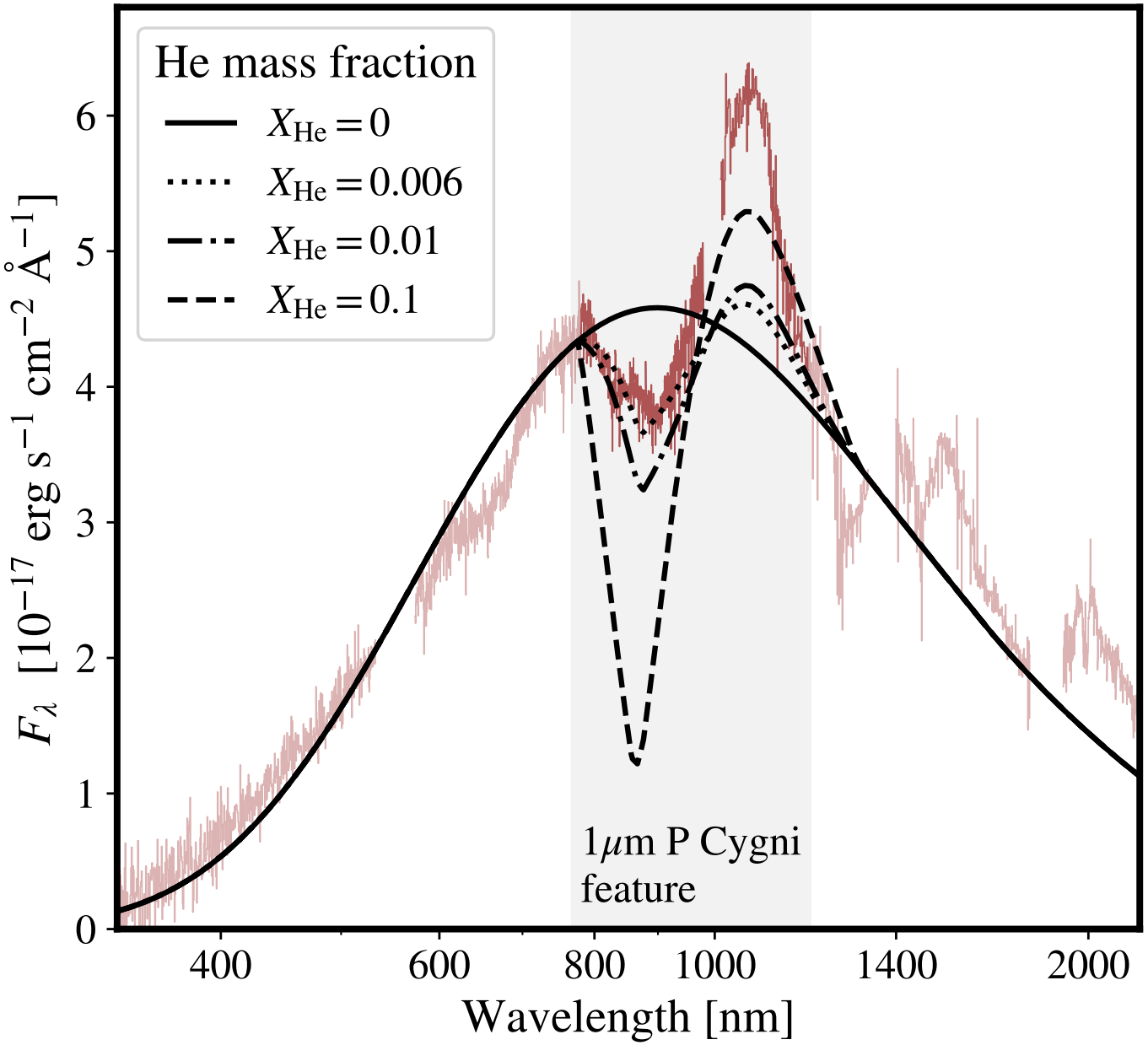


ejecta nucleosynthesis yields



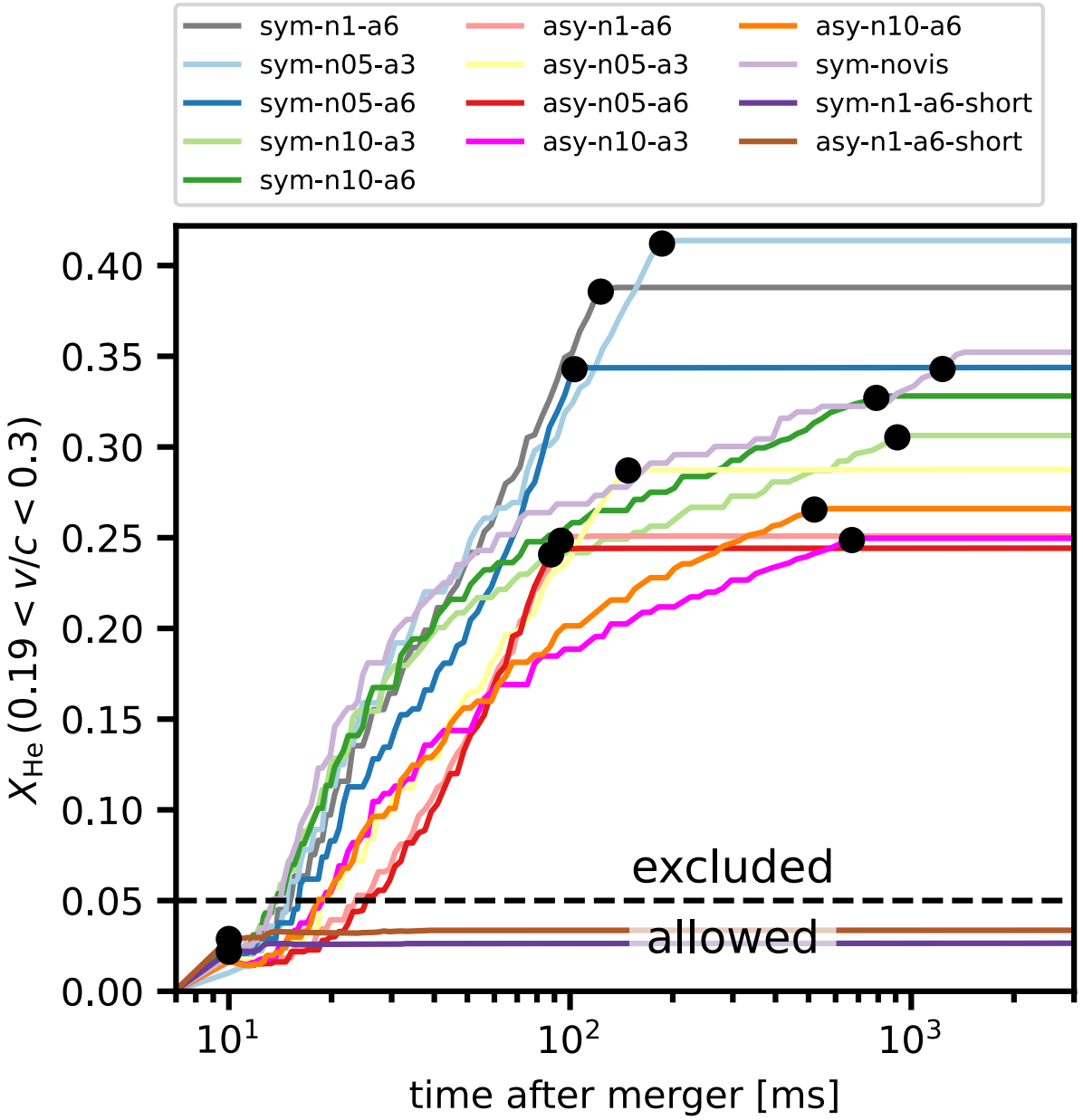
How much helium was produced in AT2017gfo?

- observed spectrum + synthetic spectra assuming different amounts of helium in ejecta
- observed spectrum appears inconsistent with significant $X(\mathrm{He})$
- conservative constraint: $X(\mathrm{He}) \lesssim 0.05$

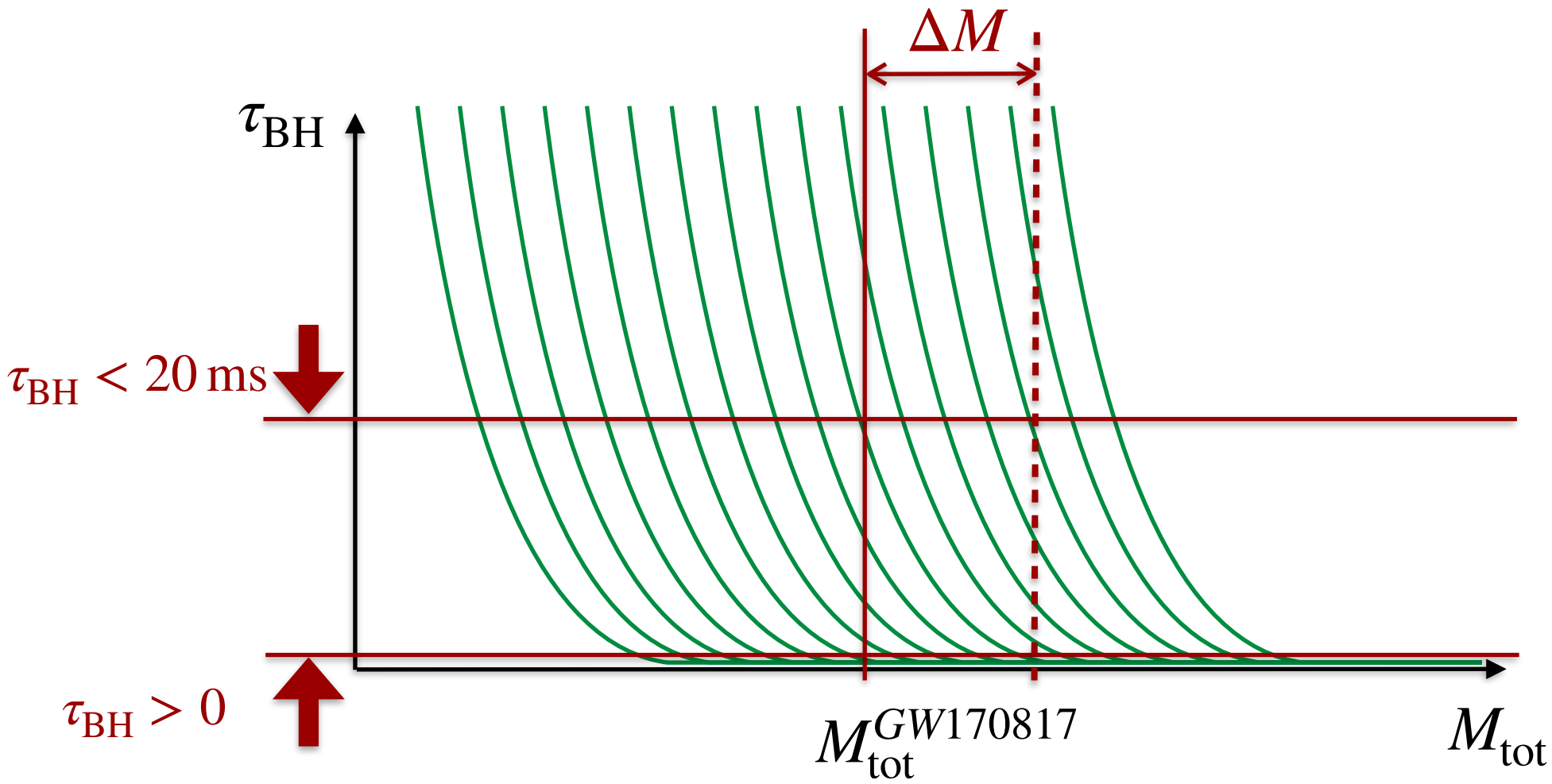


Helium production in NS merger models

- amount of helium grows with NS remnant lifetime
- short lifetime $\tau_{\rm BH} \lesssim 20 - 30\,{\rm ms}$ required to fulfill observational constraint on helium abundance in AT2017gfo

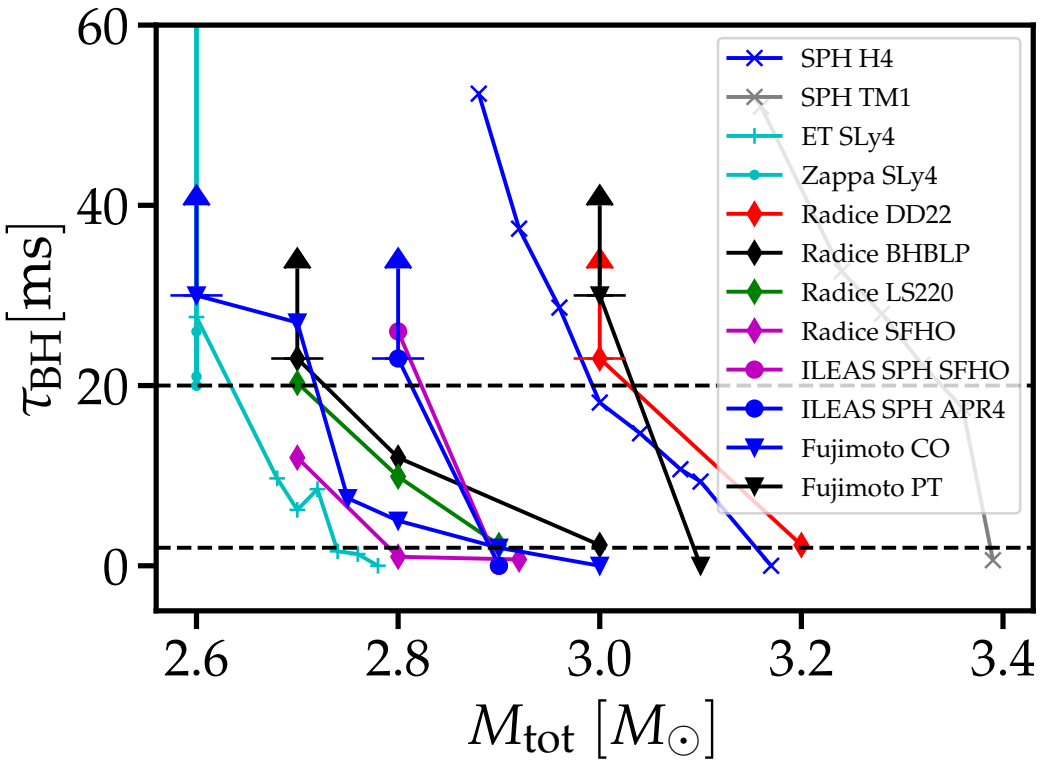


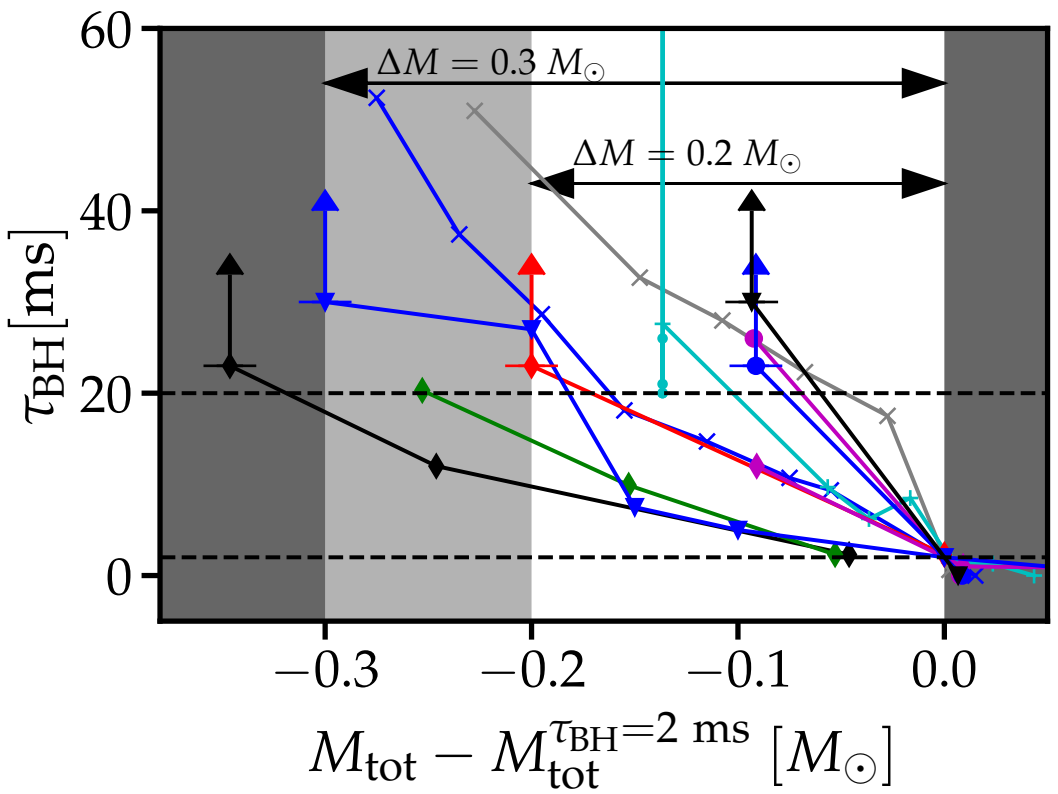
Implications of $\tau_{\rm BH} > 0$ and $\tau_{\rm BH} < 20\,{\rm ms}$



$$M_{\rm thres} - \Delta M < M_{\rm tot}^{GW170817} < M_{\rm thres}$$

Reasonable choice for ΔM?



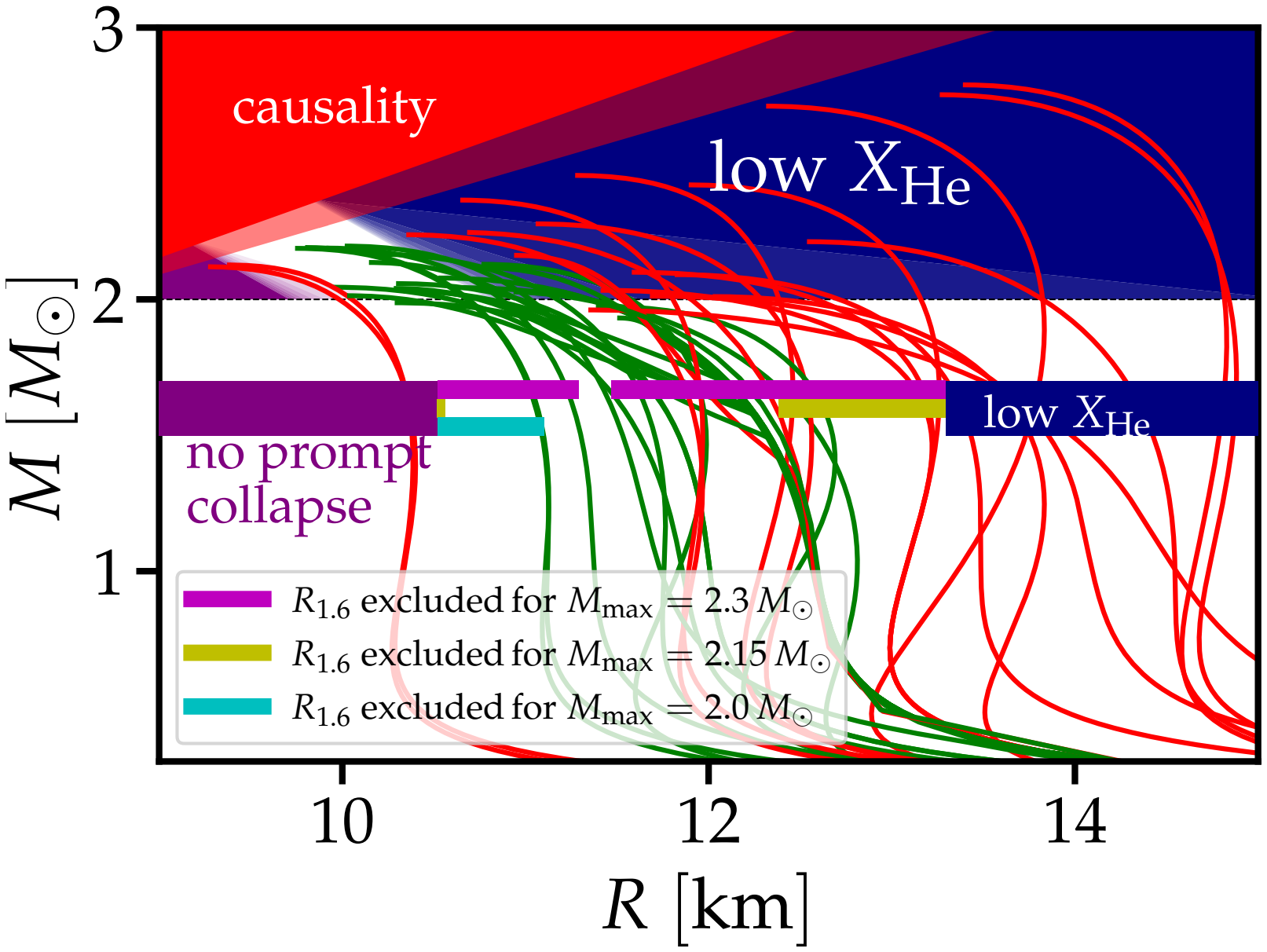


- very challenging to determine $\tau_{\rm BH}(M_{\rm BH})$ because of numerics, physical ingredients, stochasticity, ...
- $\tau_{\rm BH} < 20\,$ms suggests $\Delta M \approx 0.2\,M_\odot$

Implications for NS properties

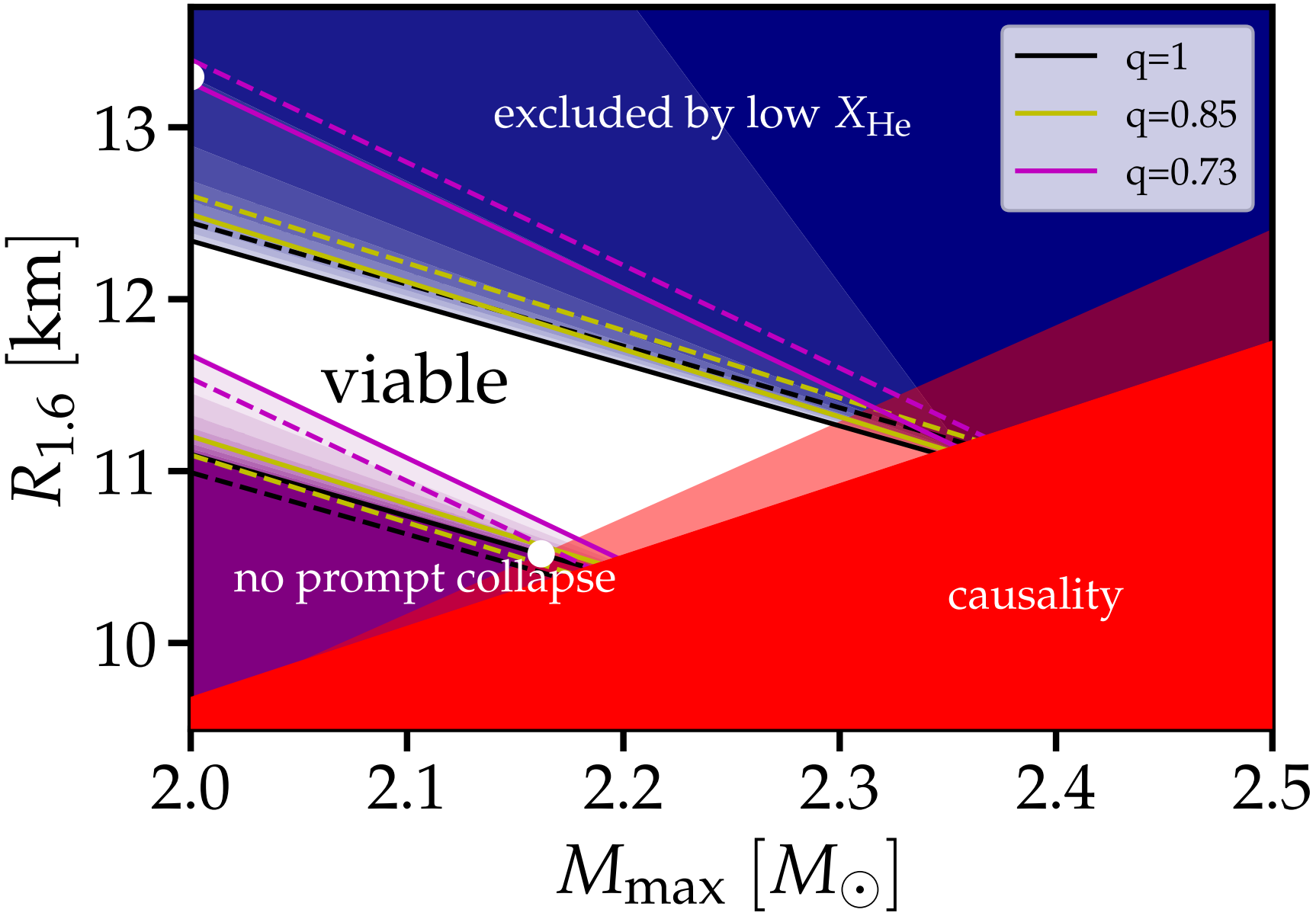
(Sneppen+25, submitted)

- mass-radius relationship for various EOS models
- large number of EOS models excluded (red lines)
- in particular EOS models with simultaneously large $R_{1.6}$ and $M_{\rm max}$



Implications for NS properties

- narrow window of allowed values
- sensitive to mass ratio q that was only poorly constrained in GW170817



Summary

- EOS tightly related to NS remnant lifetime τ_{BH}
- so far poor upper limit on τ_{BH} in GW170817
- new upper limit on τ_{BH} based on absence of helium feature in kilonova spectrum of GW170817
- limit on $X(\mathrm{He})$ -> limit on τ_{BH} -> limit on M_{thres} -> constraints on NS parameters $R_{1.6}$ and M_{max}
- **powerful new possibility to constrain EOS!**
- yet, still potentially significant uncertainties: need to improve He radiative modeling, hydro modeling, $\tau_{\mathrm{BH}} - M_{\mathrm{tot}}$ relation