Hirschegg Meeting January 20th

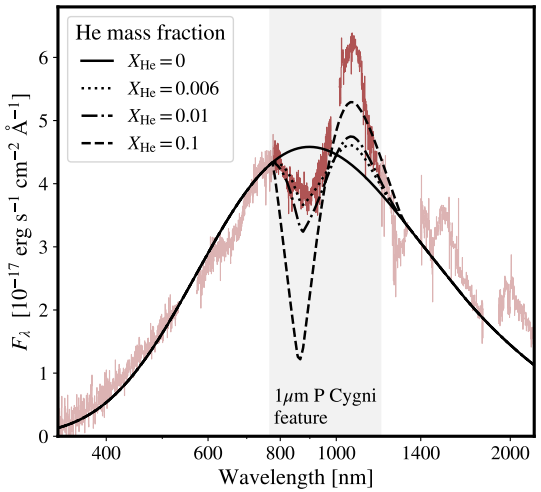
(arXiv: 2411.03427)

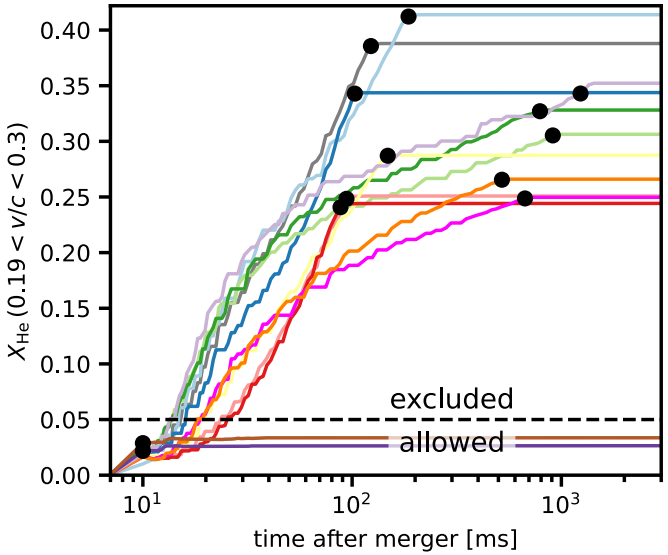
Helium as an Indicator of the Neutron-Star Merger Remnant Lifetime and its Potential for Equation of State Constraints

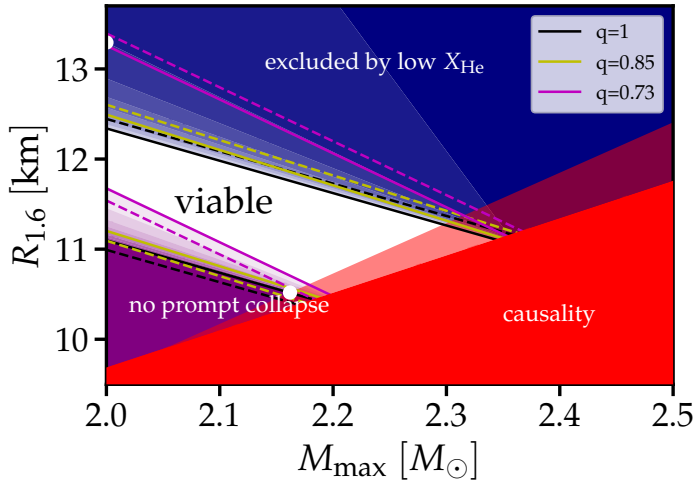
PART 2: Implications on helium limit on lifetime and EOS

(PART 1: talk by Rasmus Damgaard on Friday)

Albert Sneppen,[1,2] Oliver Just,[3,4] Andreas Bauswein,[3,5] Rasmus Damgaard,[1,2] Darach Watson,[1,2] Luke J. Shingles,[3] Christine E. Collins,[6] Stuart A. Sim,[7,1,2] Zewei Xiong,[3] Gabriel Martínez-Pinedo,[3,8,5] Theodoros Soultanis,[3] and Vimal Vijayan[3]





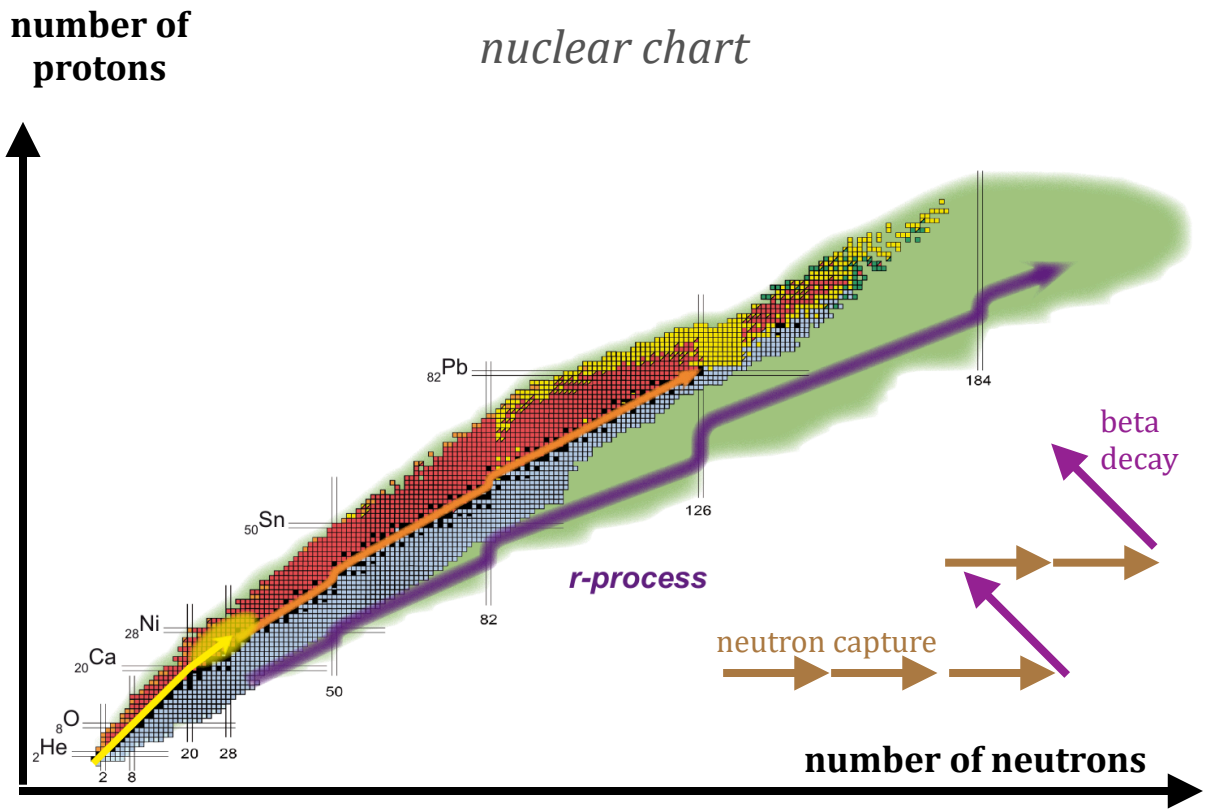


Oliver Just

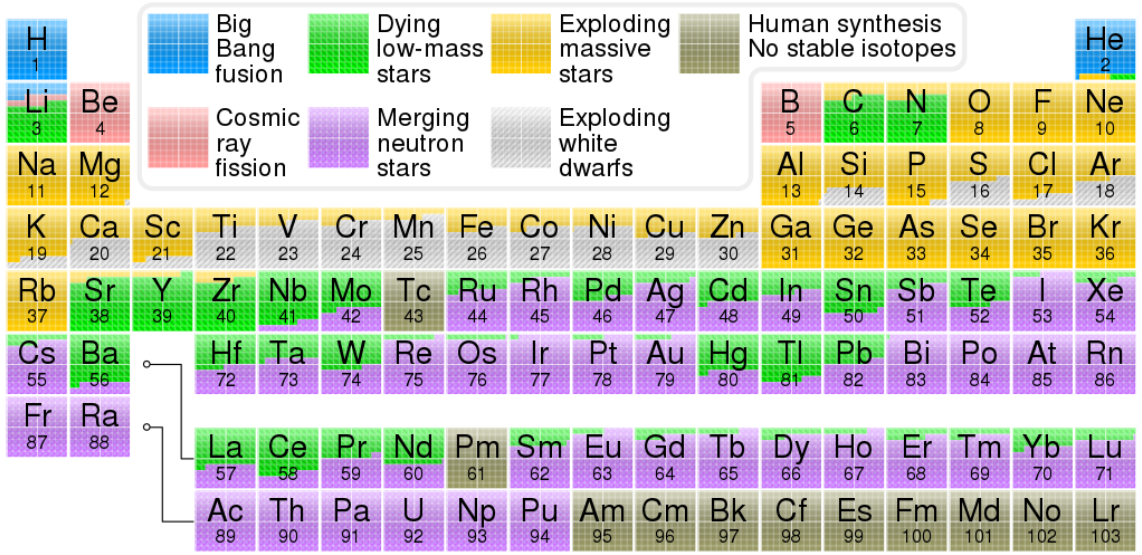
Relativistic Astrophysics Group, GSI

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

nuclear chart



*periodic system with **suggested** site of origin*



Main condition:

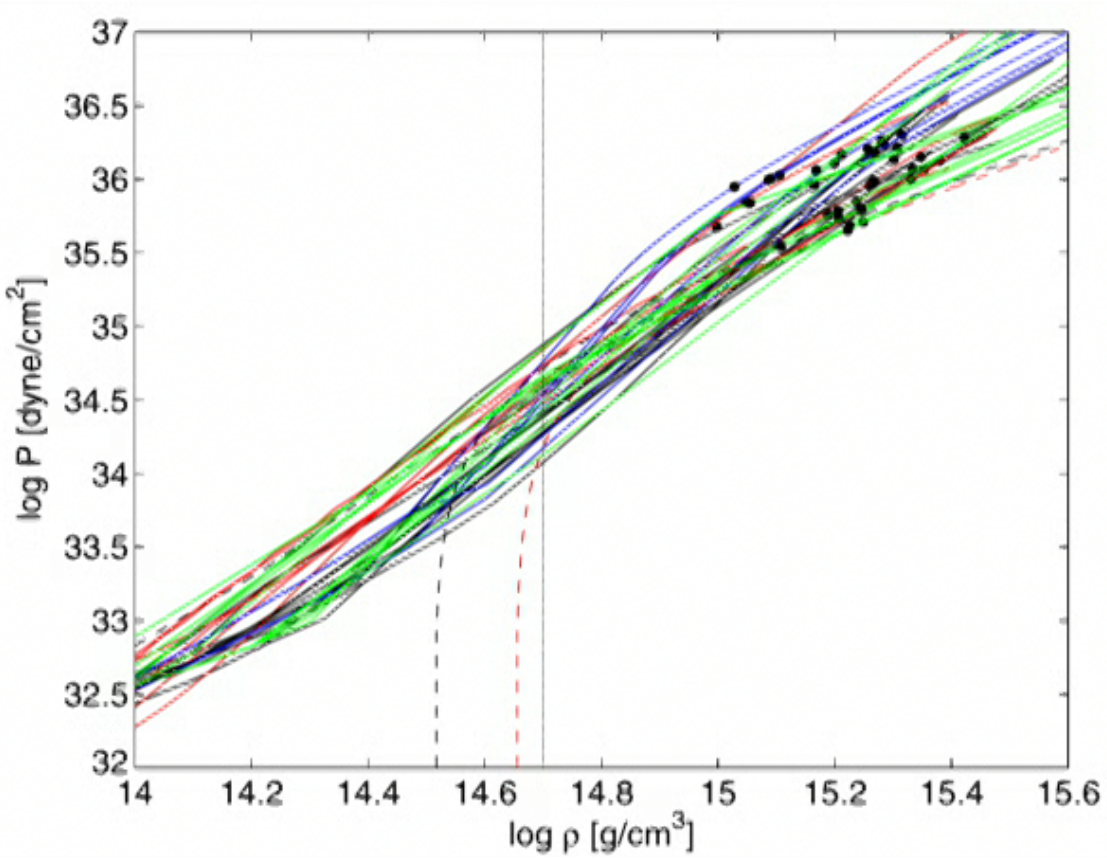
high neutron density = low electron fraction Y_e

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

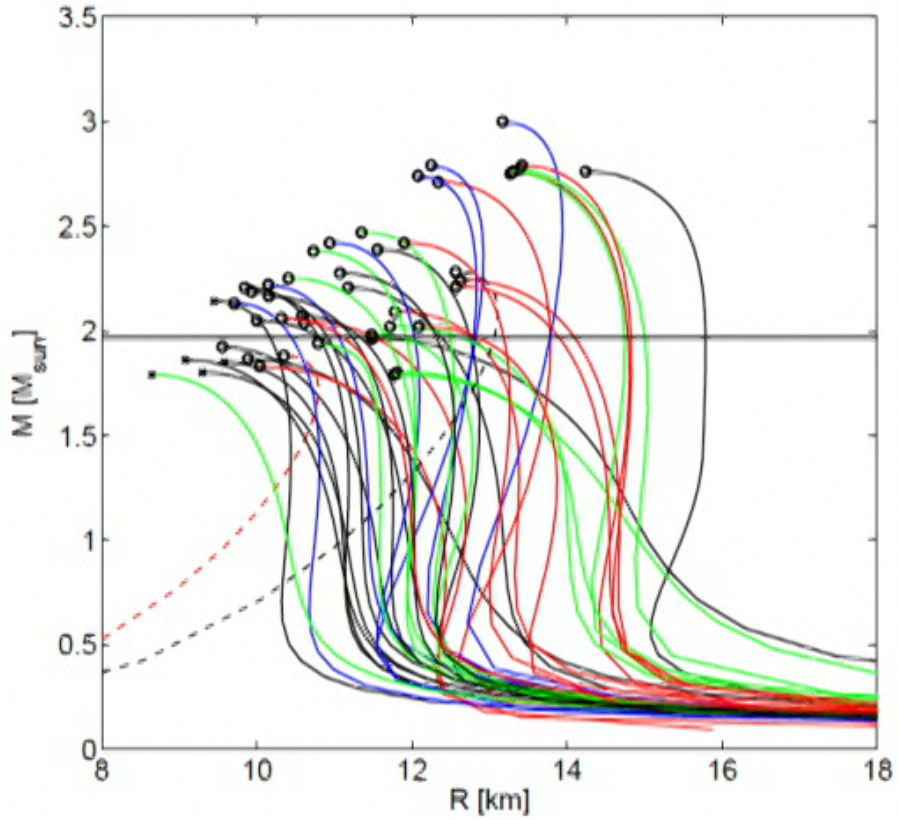
- other suggested sites: core-collapse supernovae, magneto-rotational SNe, collapsars
- NSMs are **only confirmed site** so far
- NSMs probed with multi-messenger astronomy: **Kilonovae, gravitational waves, GRBs**

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

possible nuclear equation of states



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

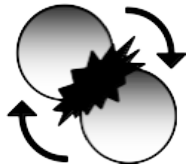


(plots by A. Bauswein)

- softer (stiffer) EOS <=> smaller (larger) neutron star

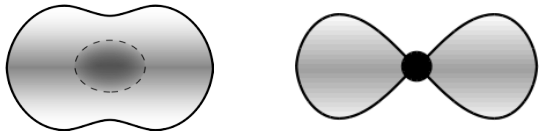
Kilonova modeling pipeline

hydrodynamic modeling of merger + dynamical ejecta



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

hydrodynamic modeling of remnant + post-merger ejecta

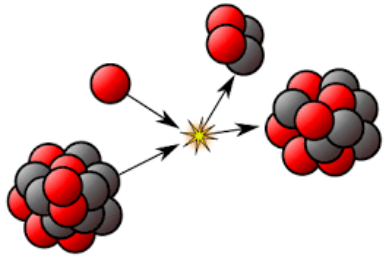


neutron star torus system

black hole torus system

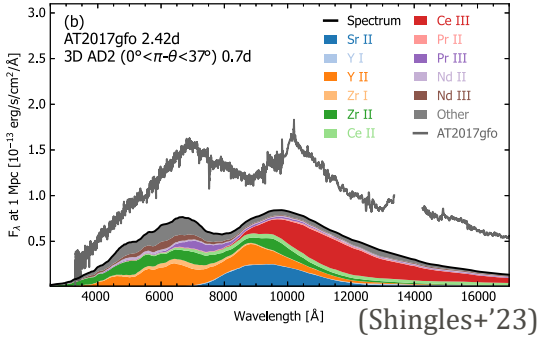
$t \sim \mathcal{O}(10\,\mathrm{s})$

heavy element nucleosynthesis



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

kilonova radiative transfer

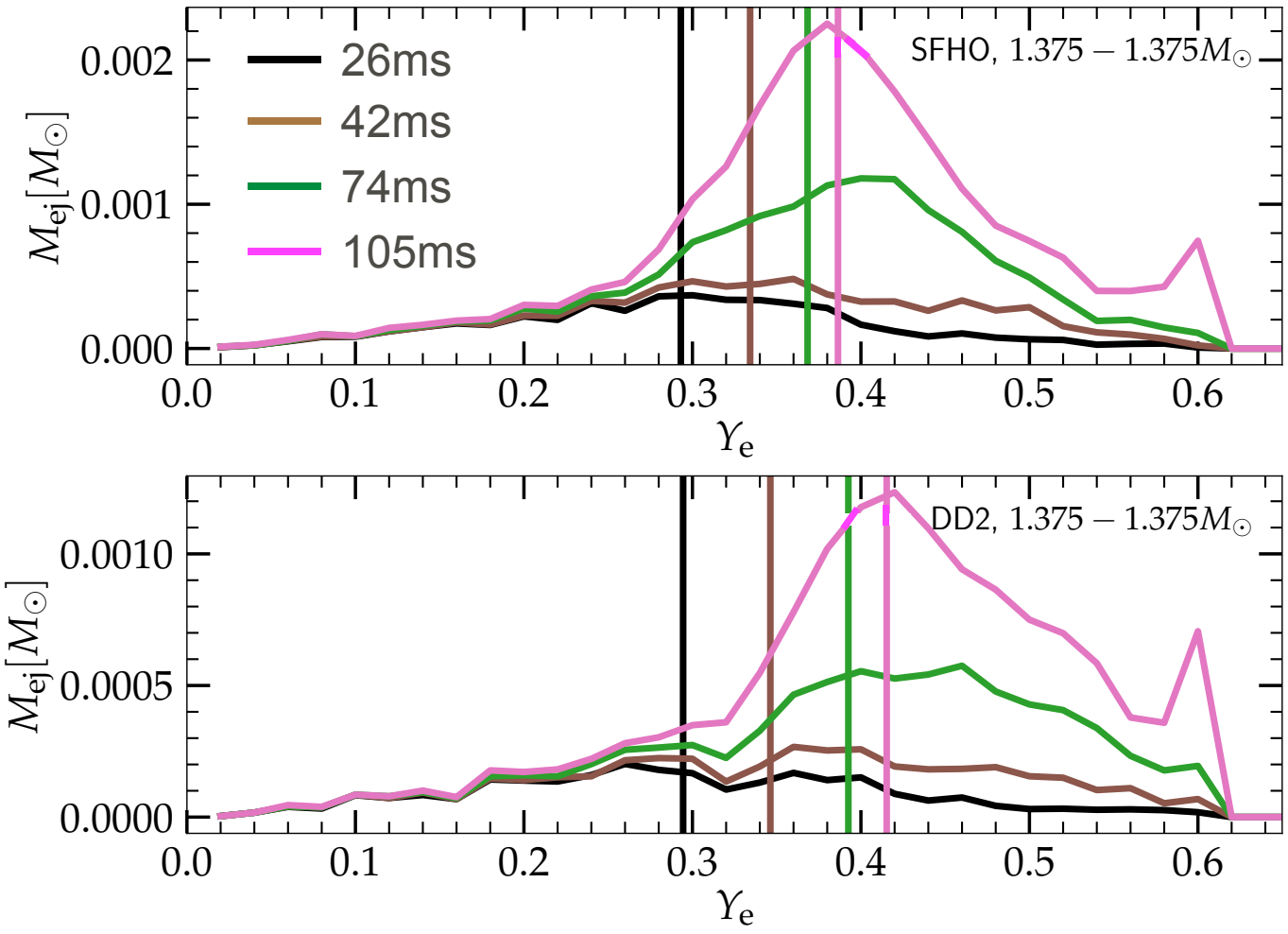


(Shingles+'23)

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

parameter inference with observations

Challenge of post-merger evolution



(simulation by V. Vijayan, SPH,CFC-GR,ILEAS)

- required ingredients:
  - *neutrino transport*
  - *MHD and turbulent viscosity*
  - *general relativity*
- extremely expensive to resolve all relevant length-scales in 3D
- approximations necessary for efficient long-term evolution

Setup of our “end-to-end” models

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

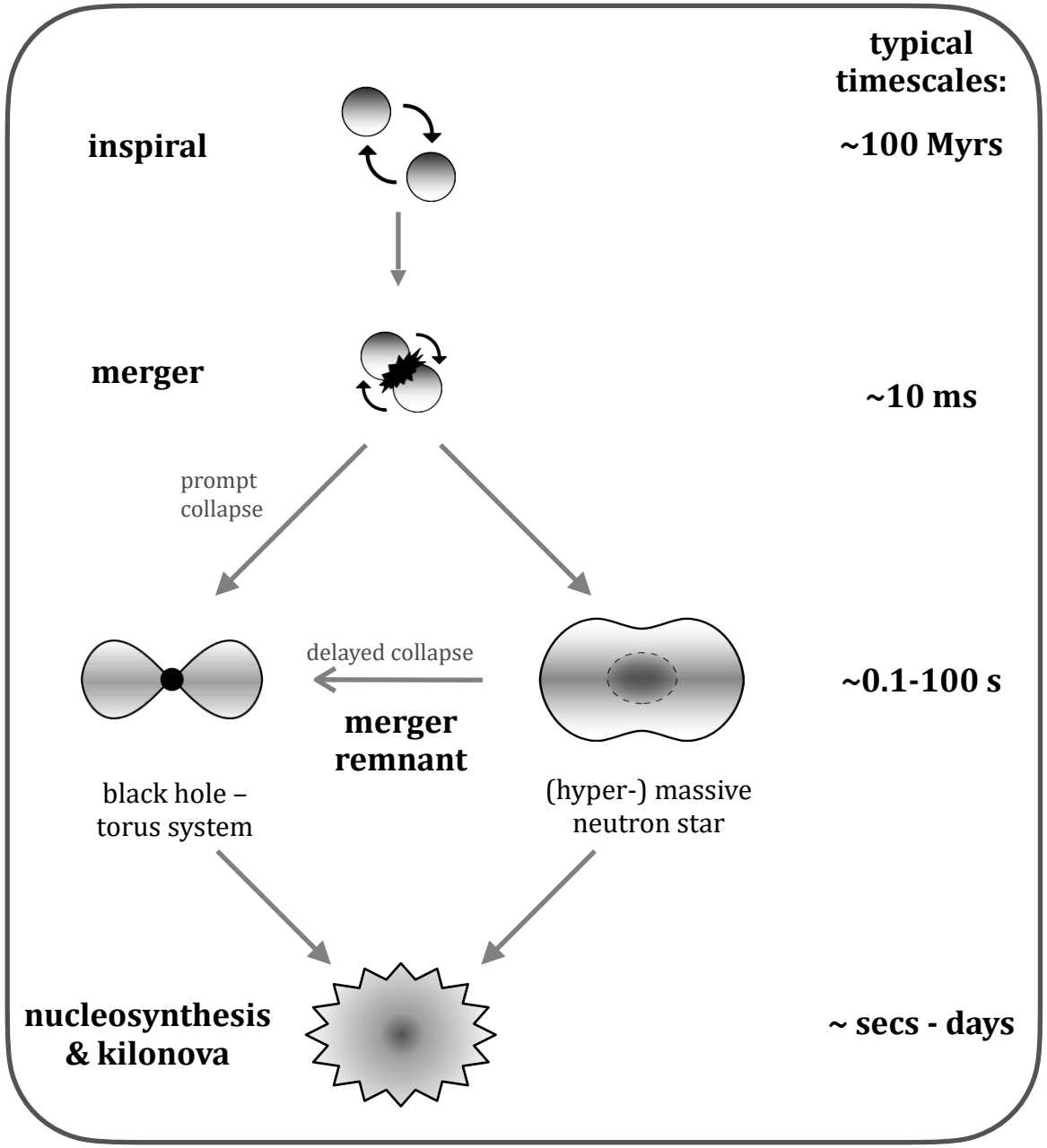
- extraction of ~5000 outflow tracers per model to sample local hydrodynamic history until 100 s
- post-processed by two nuclear networks (GSI & ULB)

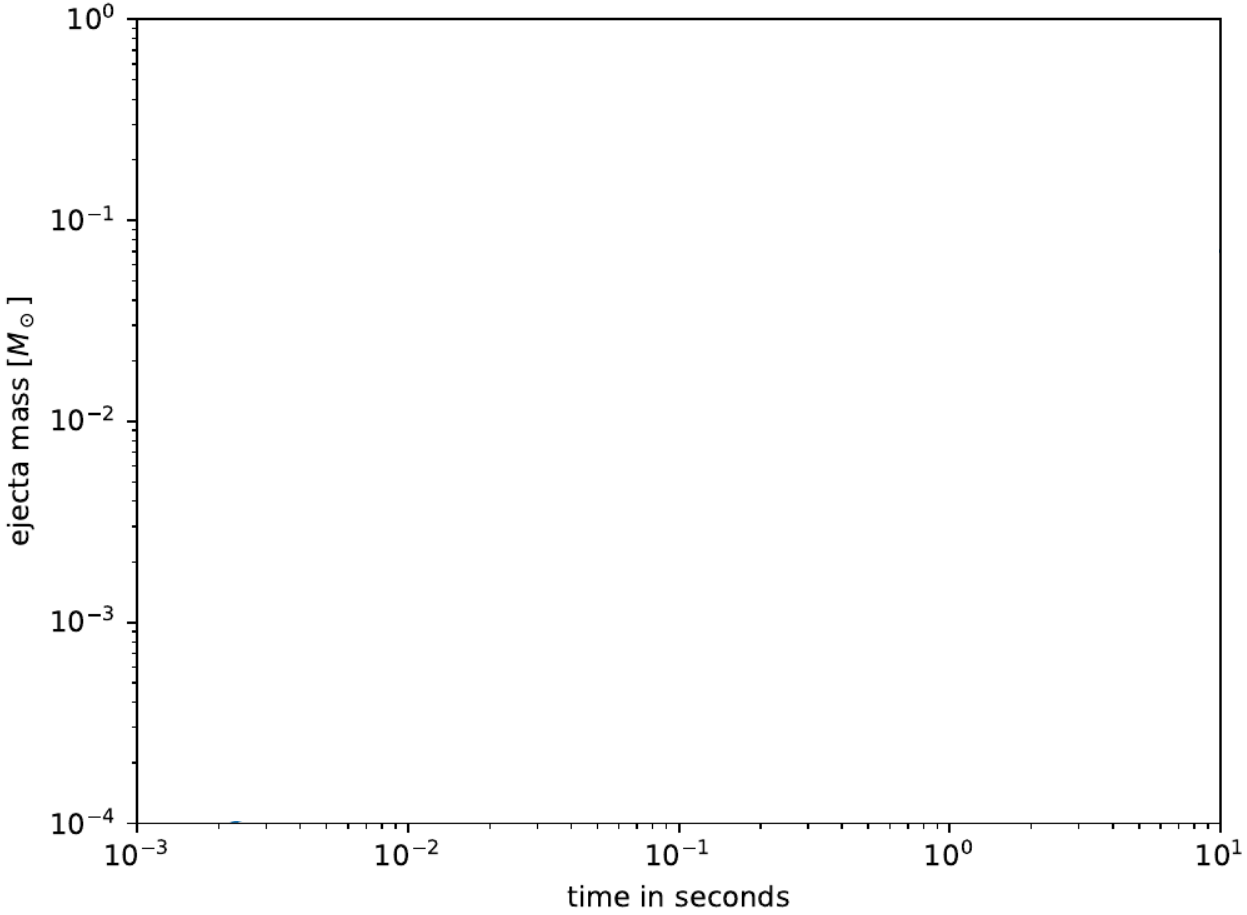
kilonova radiative transfer

- 2D axisymmetric radiative transfer using approximate M1 scheme
- using local time-dependent results from nucleosynthesis calculations

(details in Just et al., ApJL 951, L12, 2023)

Phases of matter ejection





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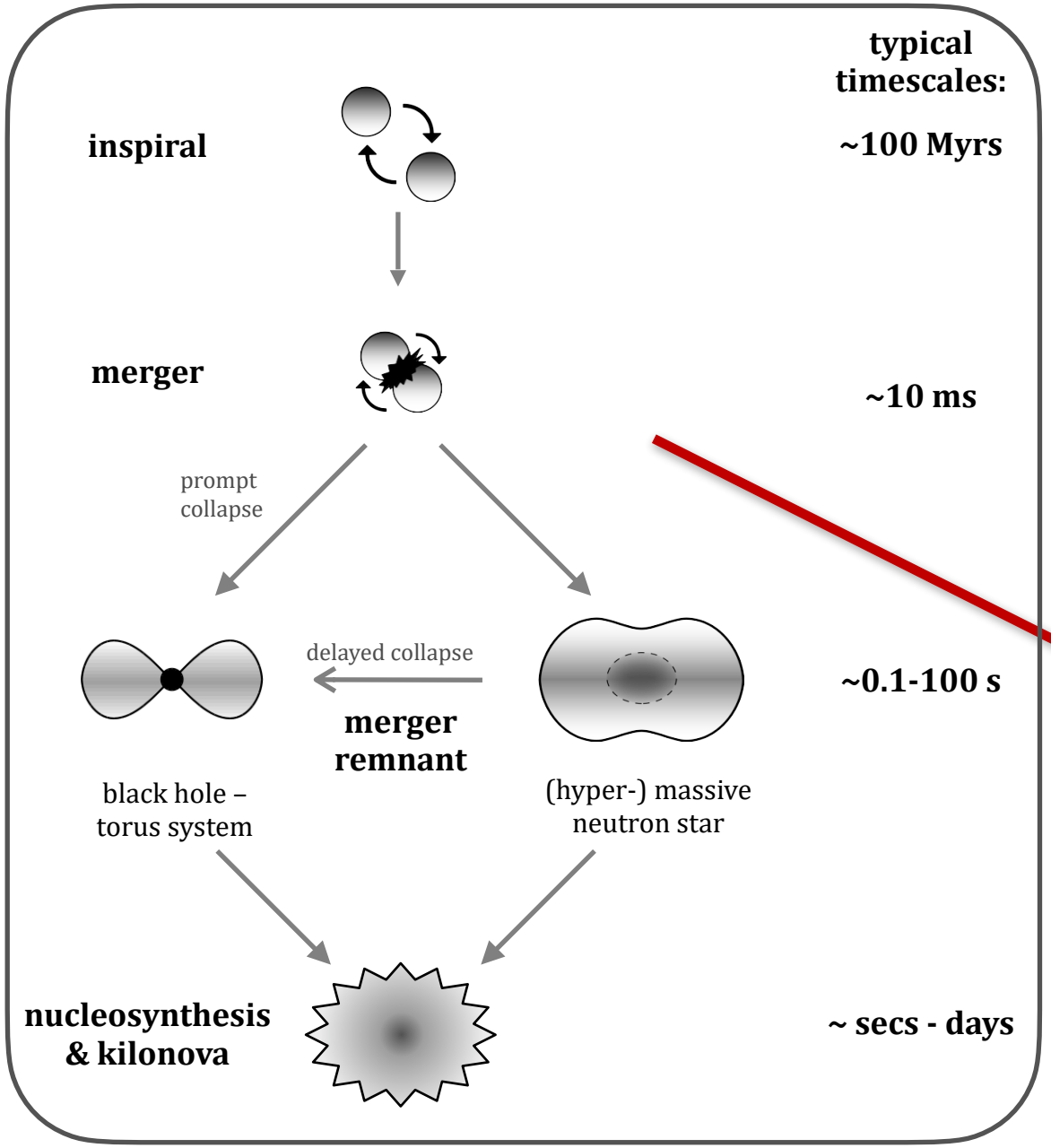
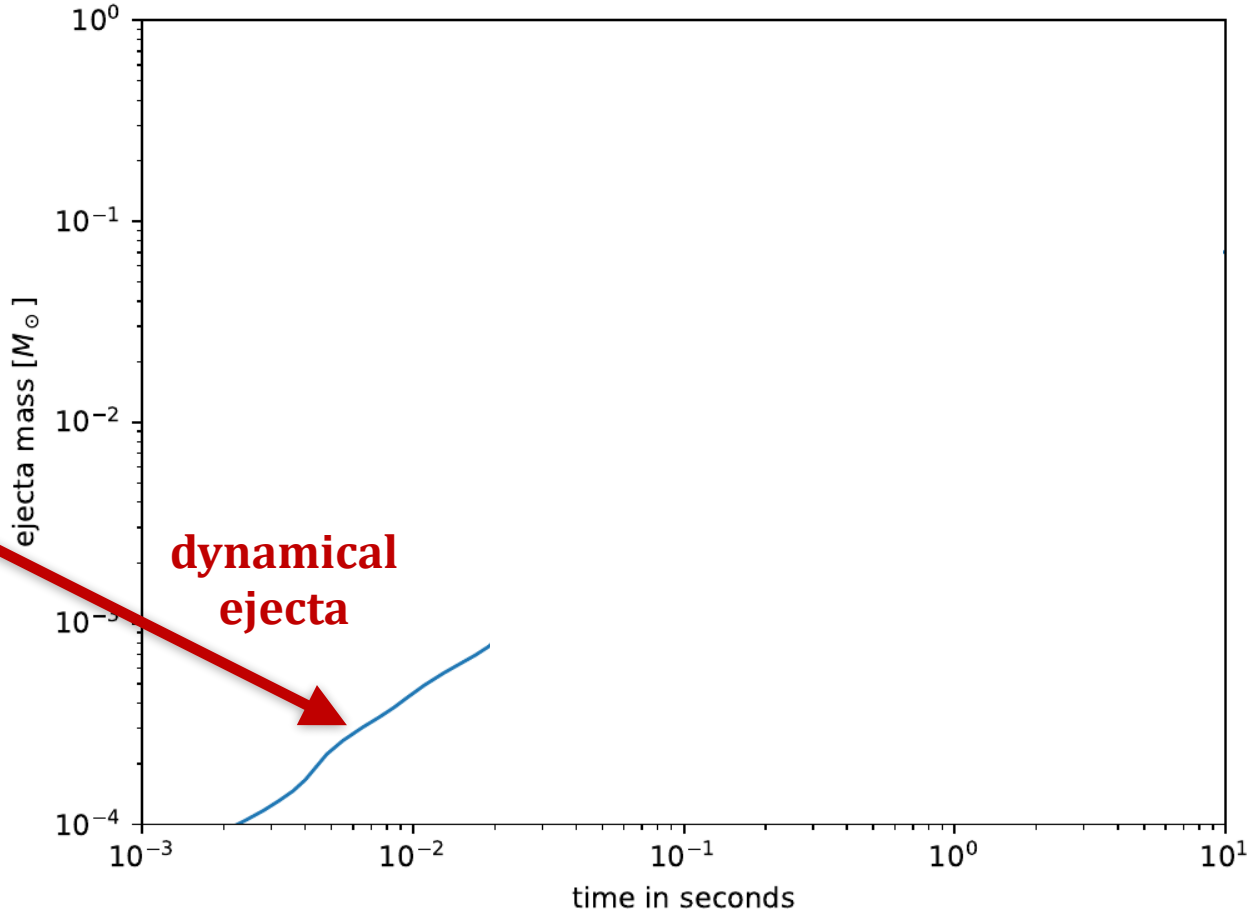




Phases of matter ejection

typical timescales:

inspiral

~100 Myrs

merger

~10 ms

prompt collapse

delayed collapse

merger remnant

black hole – torus system

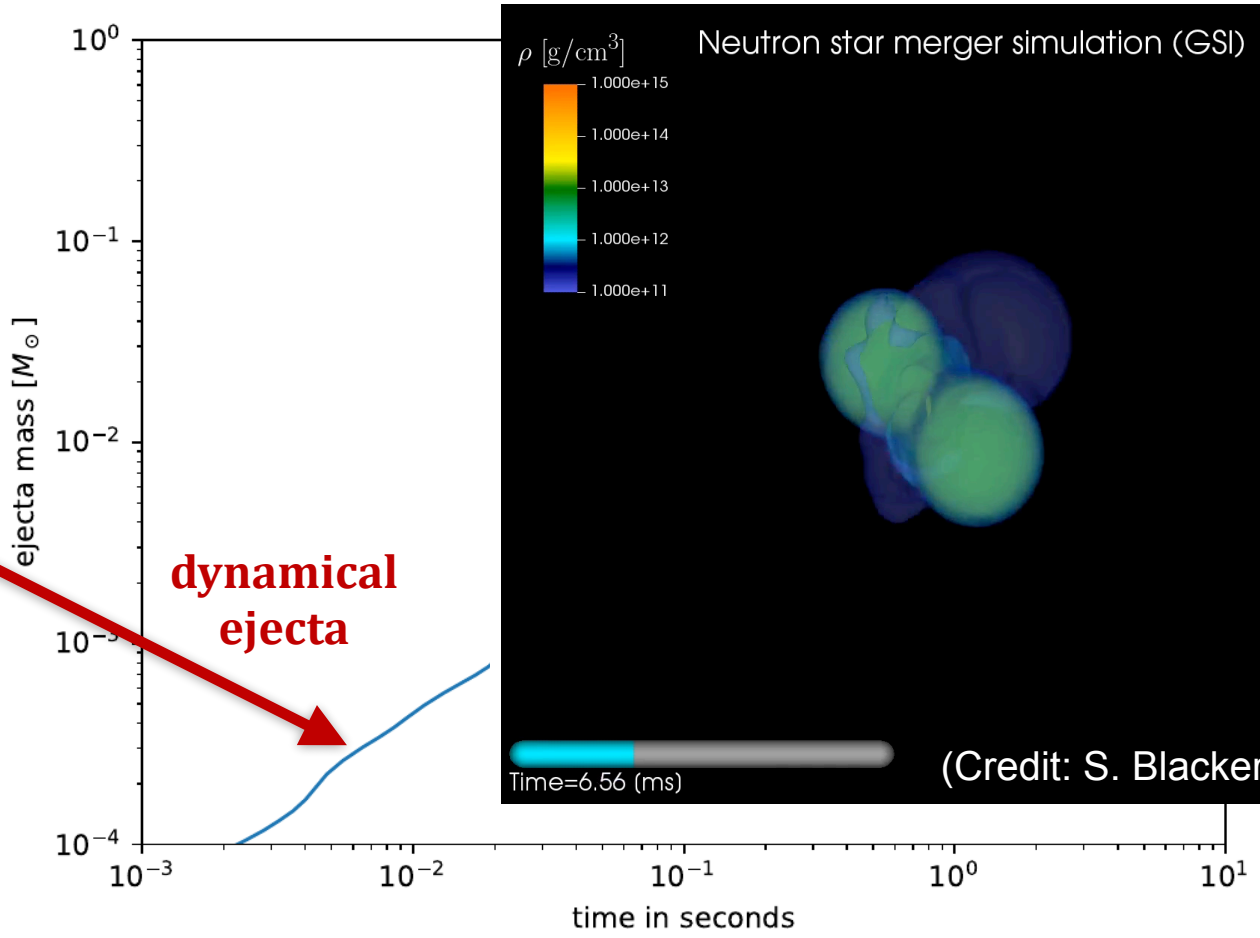
(hyper-) massive neutron star

~0.1-100 s

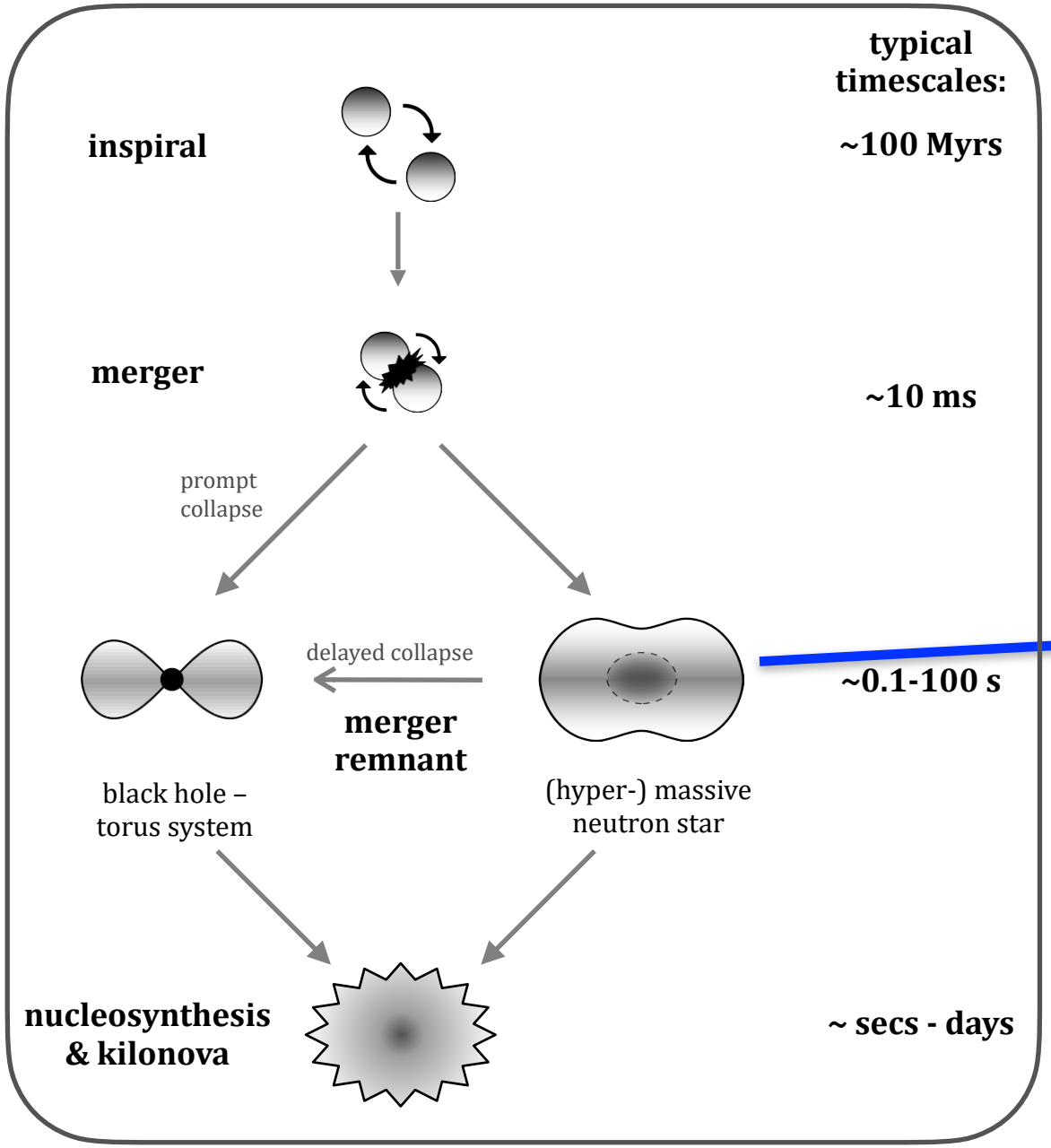
nucleosynthesis & kilonova

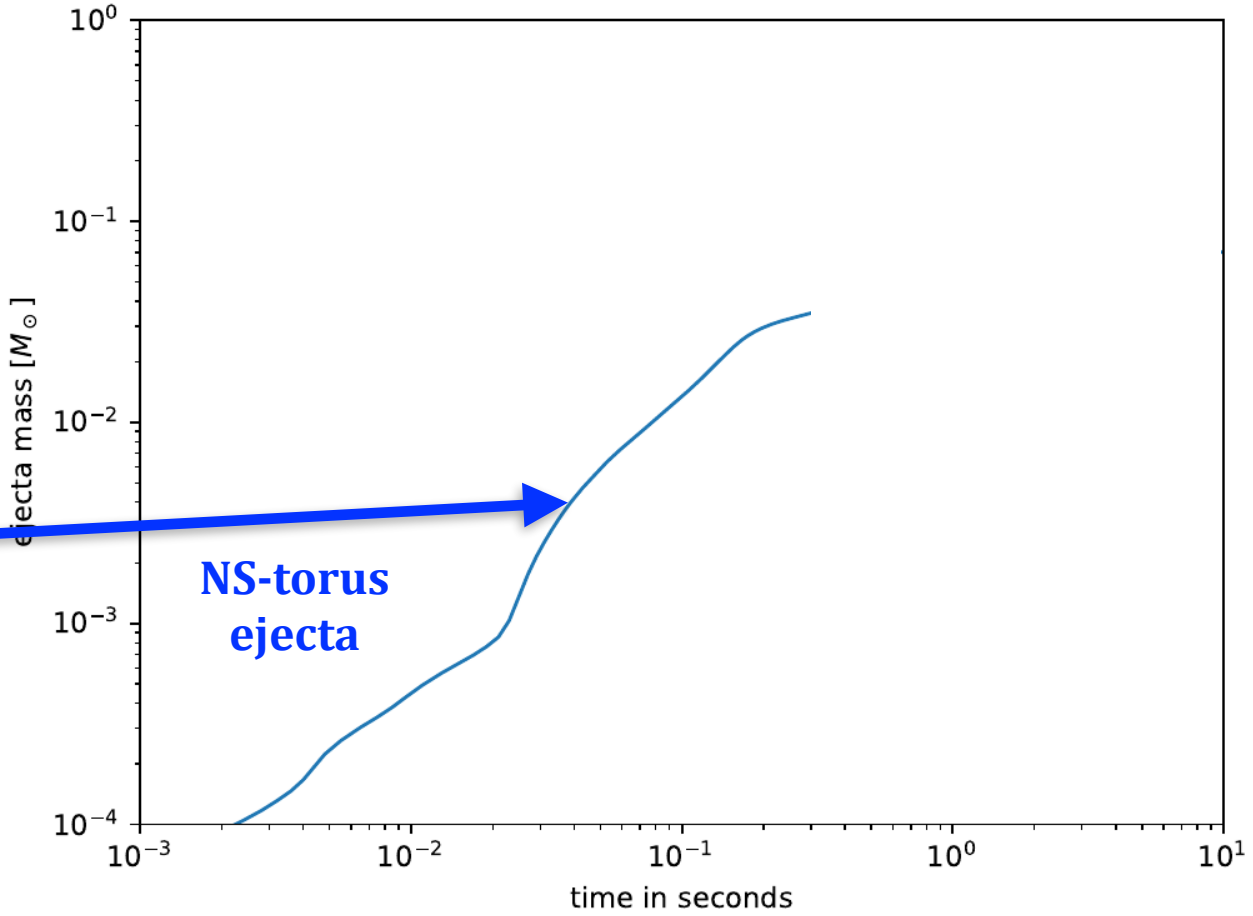
~ secs - days

dynamical ejecta



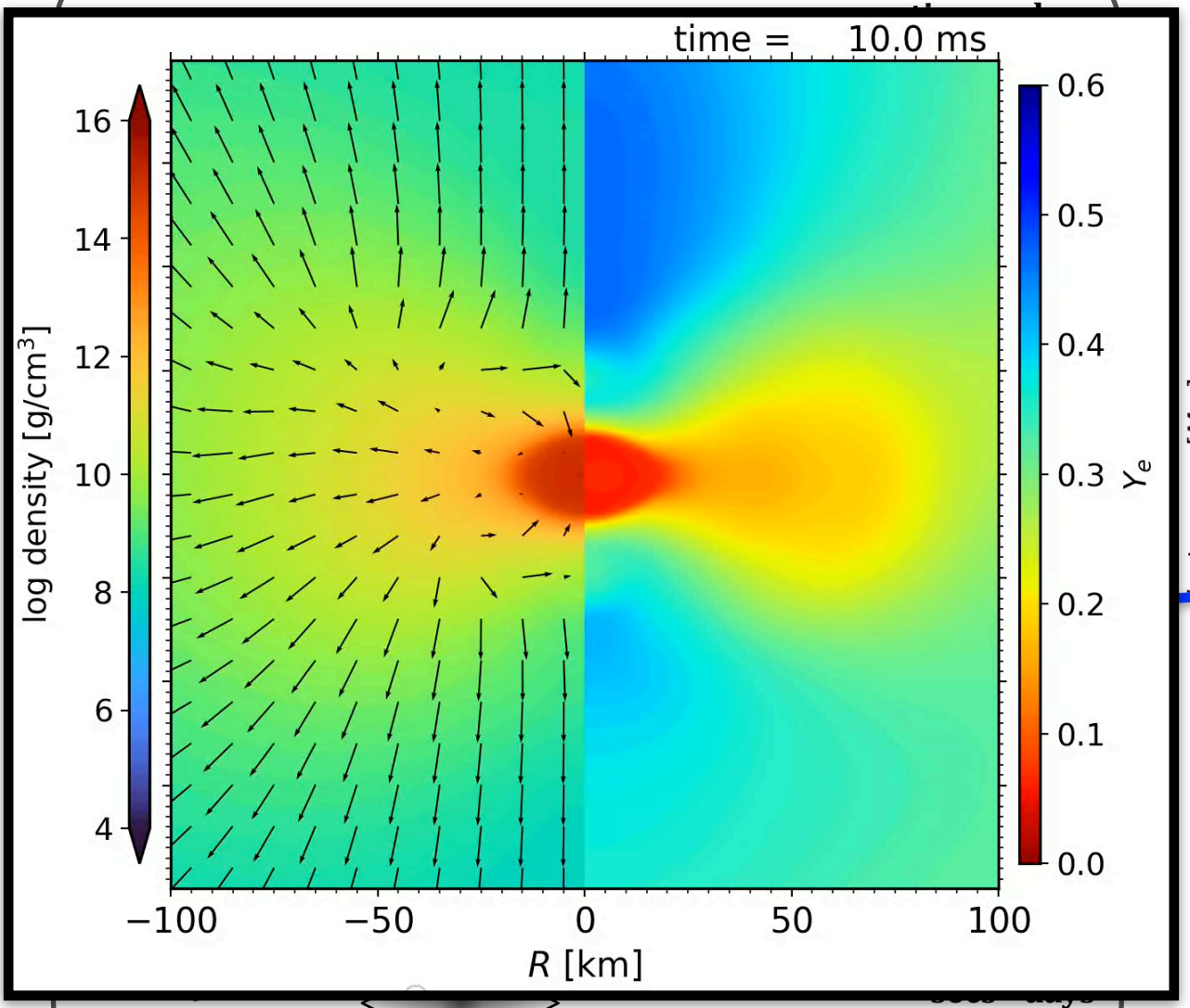
Phases of matter ejection



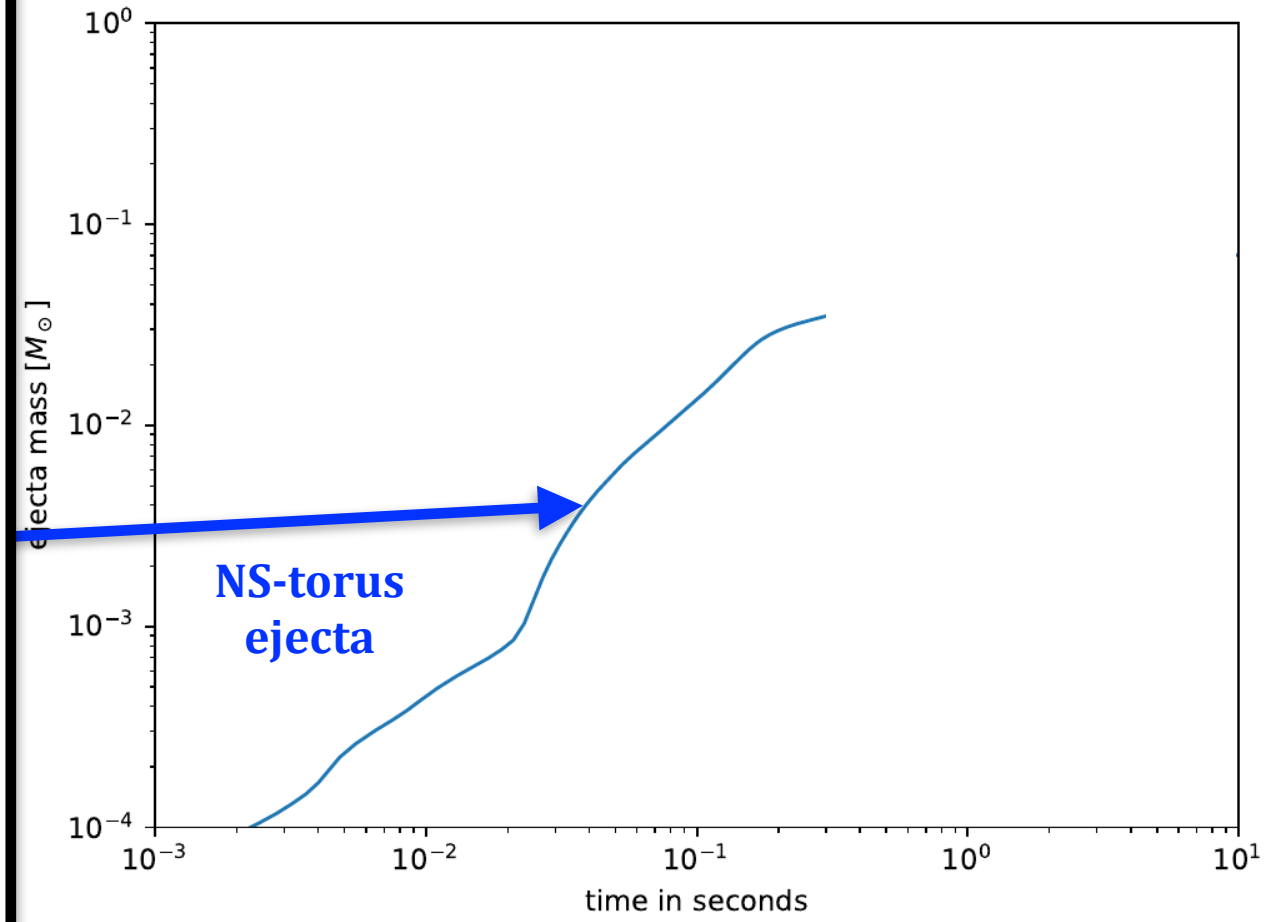


Phases of matter ejection

typical



& kilonova



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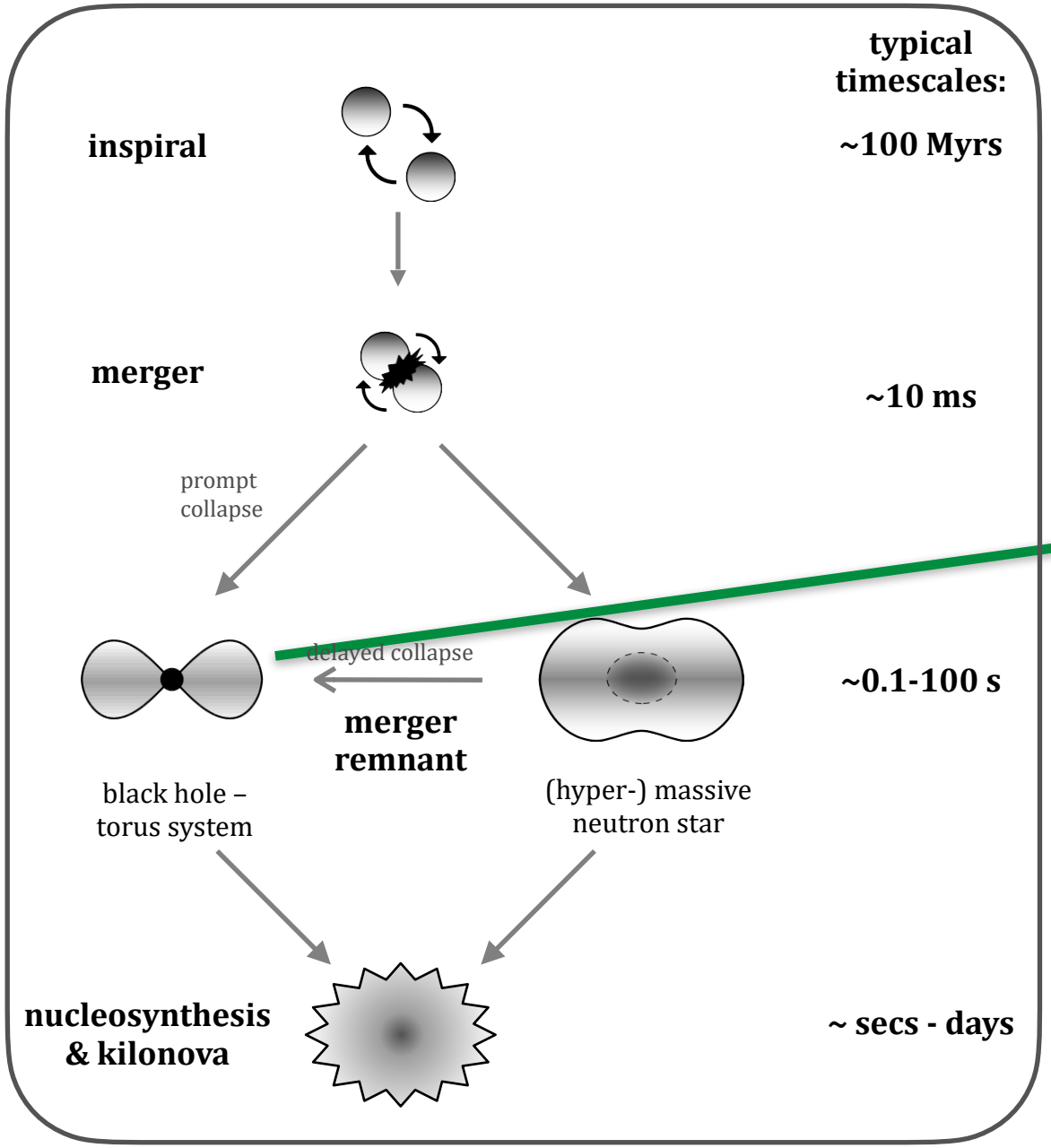
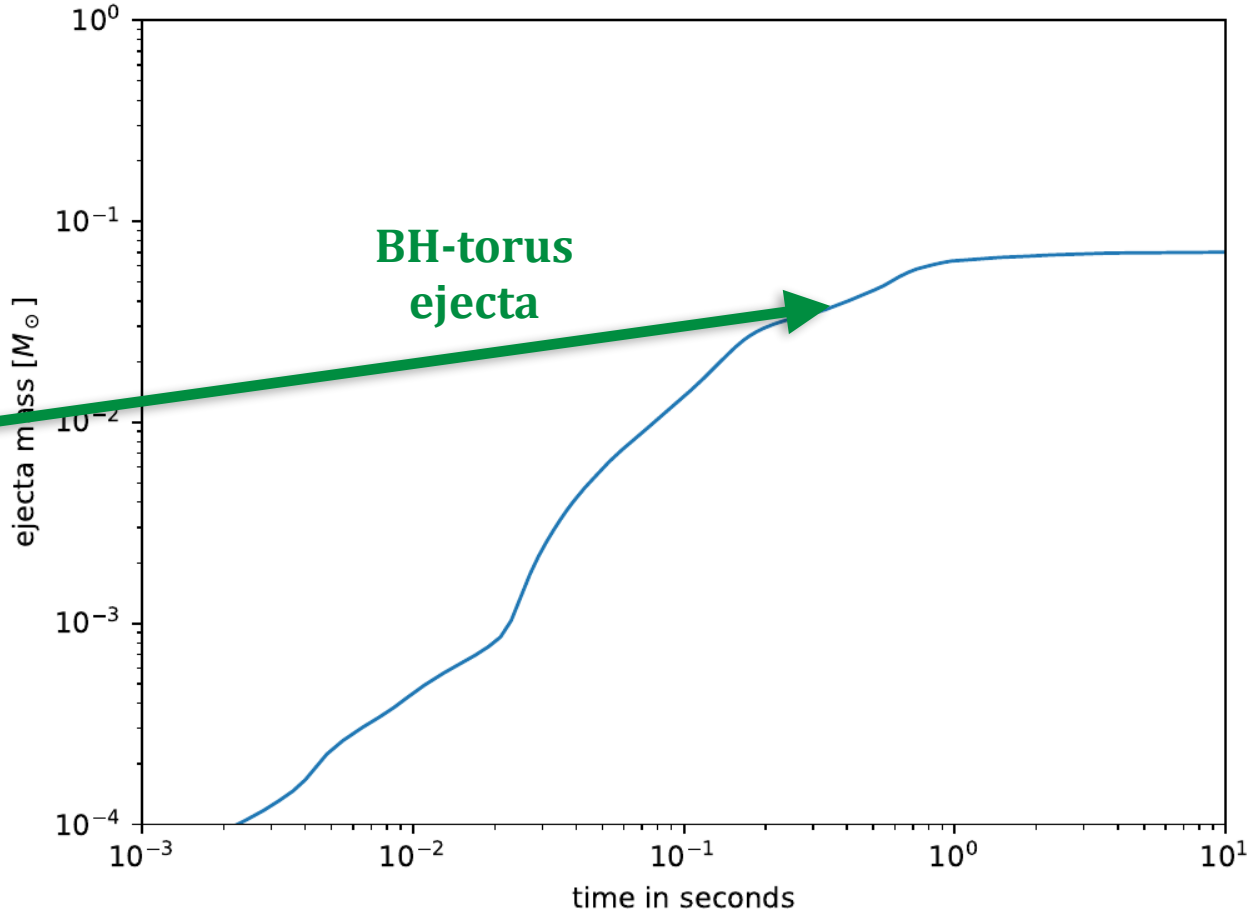
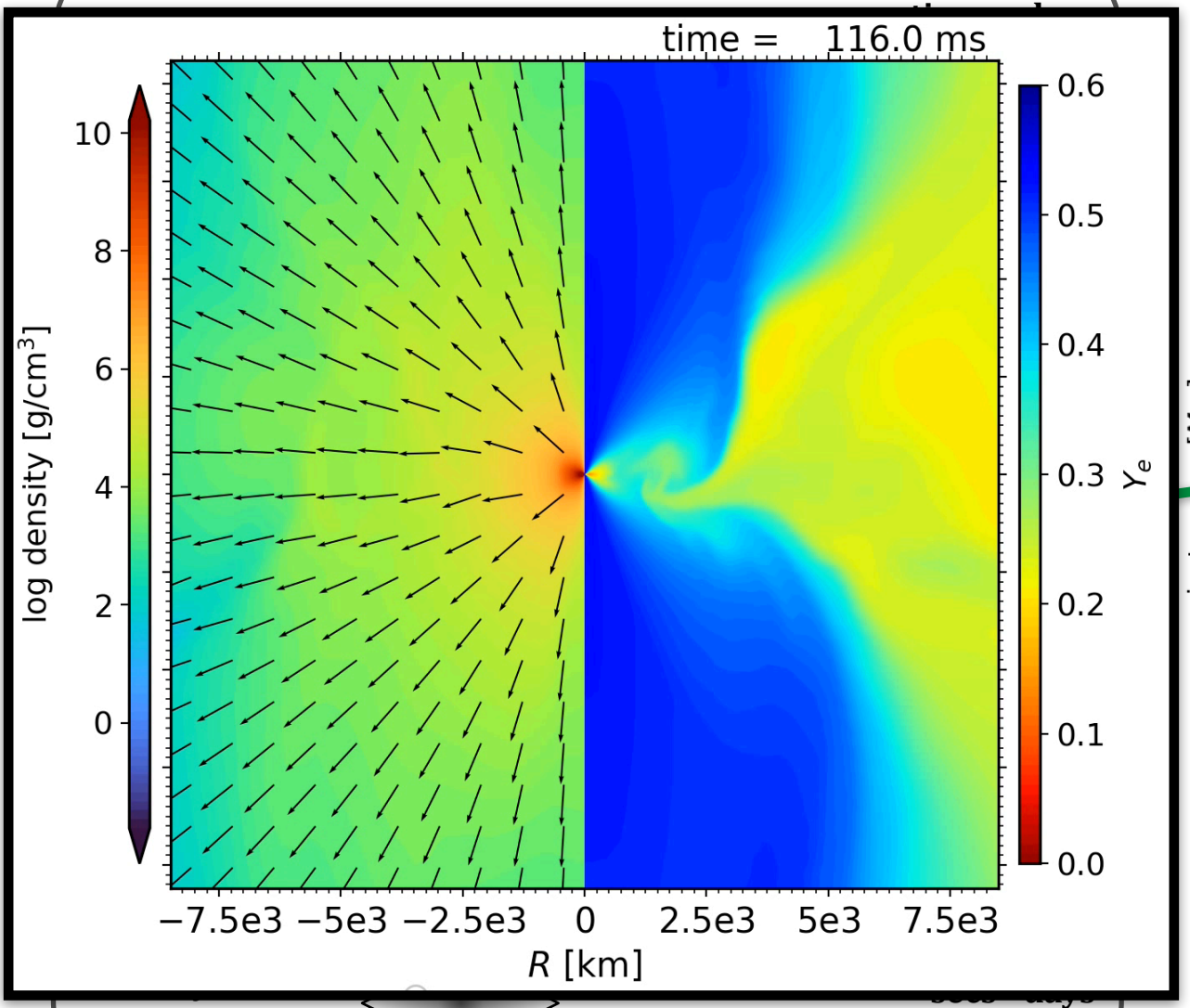




Phases of matter ejection

typical



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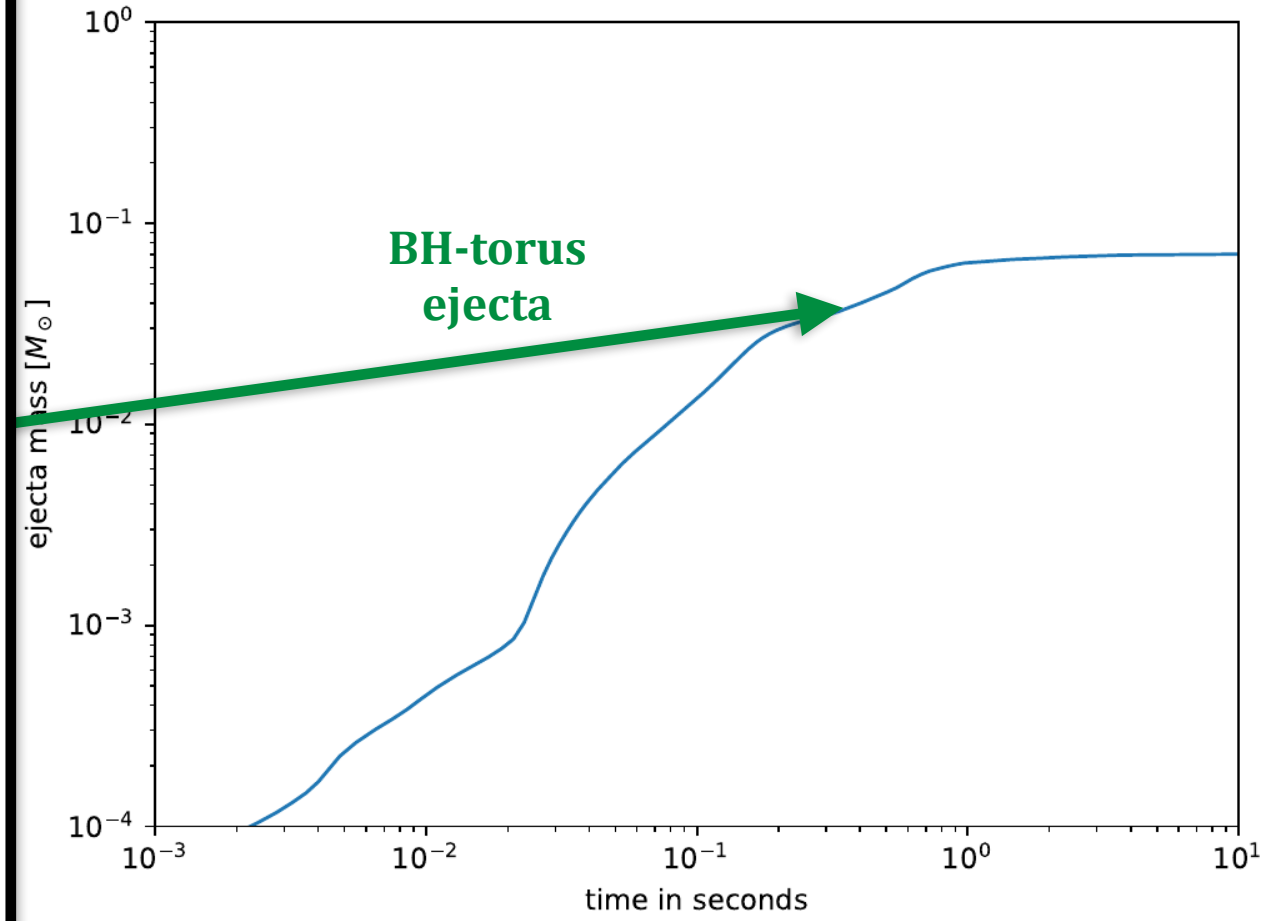
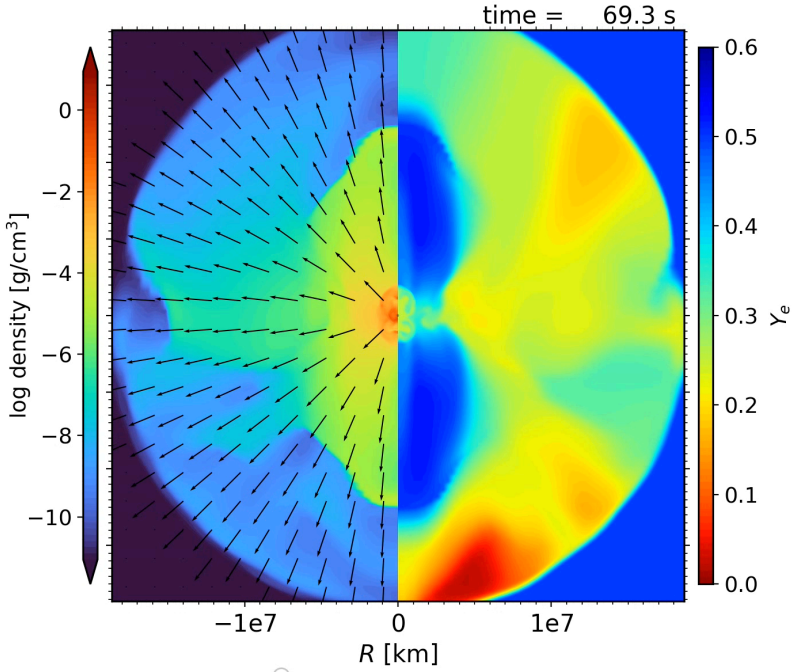
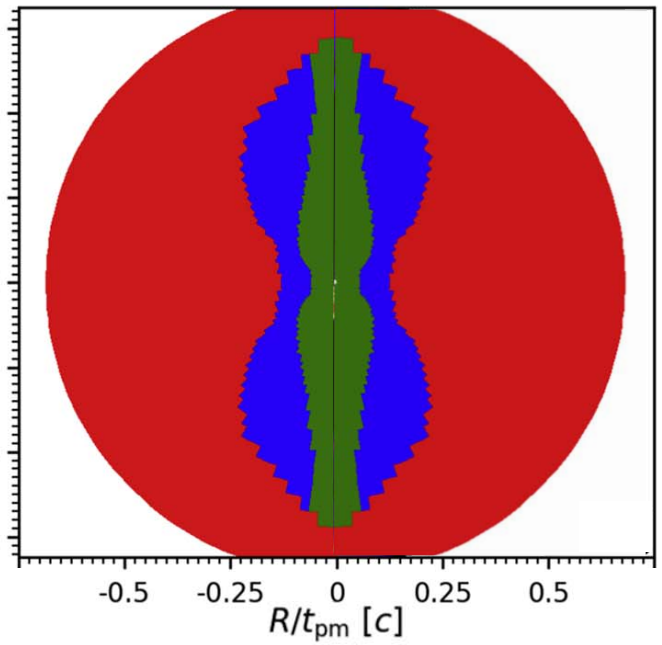
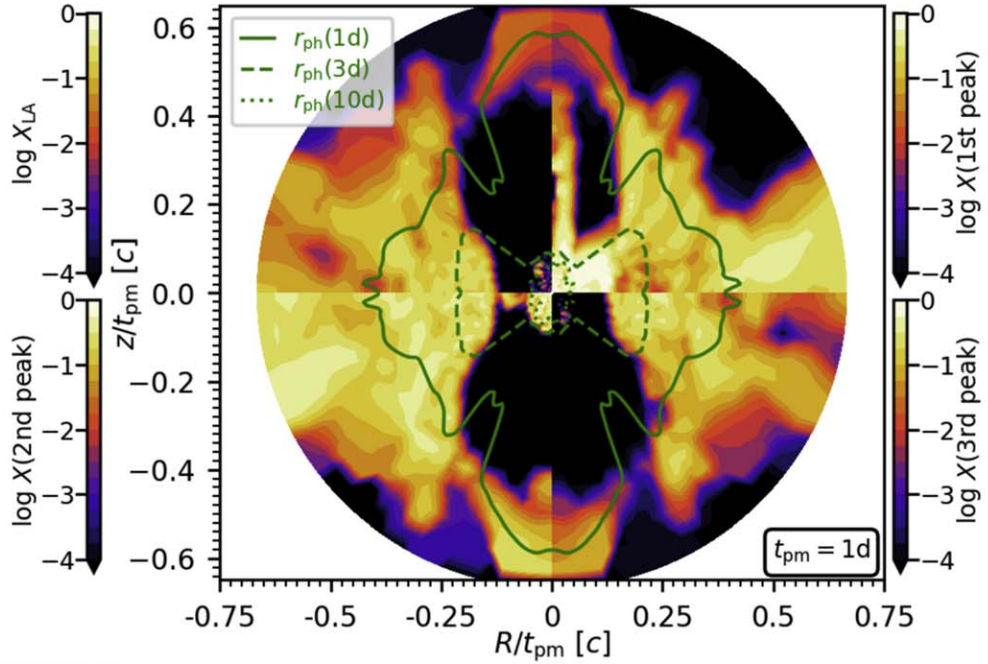


Final ejecta distribution (τ_{BH} ~ 120ms model)







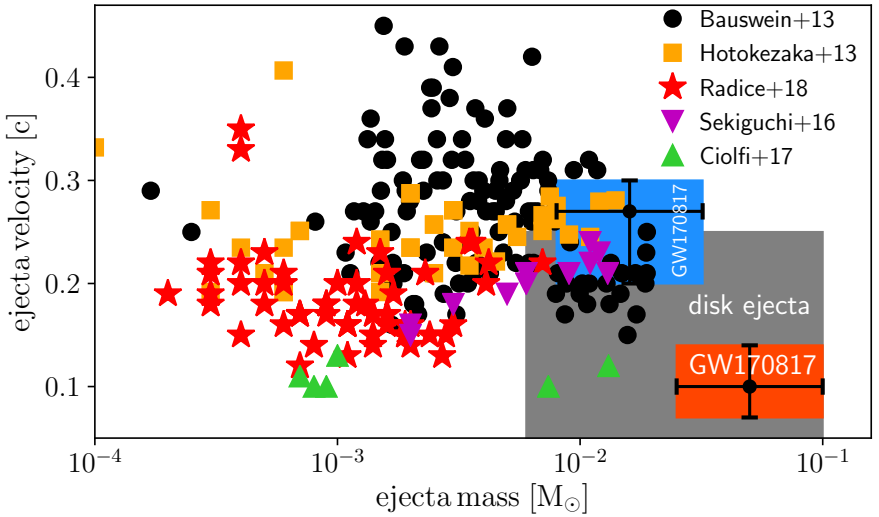
BH-torus ejecta **dynamical ejecta** **NS-torus ejecta**

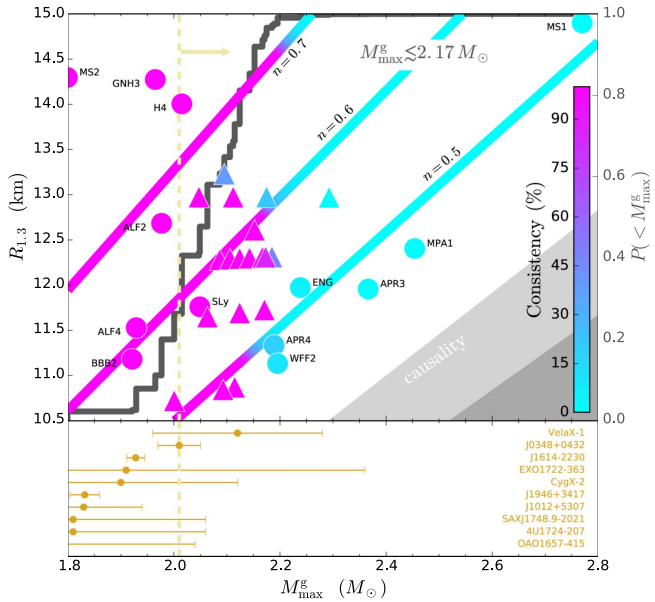
- polar high-Y_e neutrino-driven wind "bubble" surrounded by dynamical ejecta
- slow viscous ejecta
- strongly anisotropic yield distribution

What was the lifetime $\tau_{\rm BH}$ of the NS remnant in GW170817?

(compilation by Siegel '19)

- prompt collapse scenario ($\tau_{\rm BH} = 0$) almost certainly excluded because of bright KN <=> high ejecta masses (see, however, Kiuchi '19)
- absence of spindown emission (Margalit+17) + observed sGRB signal (Rezzolla+18) => $\tau_{\rm BH} \lesssim 1$ sec
- **lifetime of NS remnant remains largely unconstrained within** $10\,{\rm ms} \lesssim \tau_{\rm BH} \lesssim 1.7\,{\rm s}$

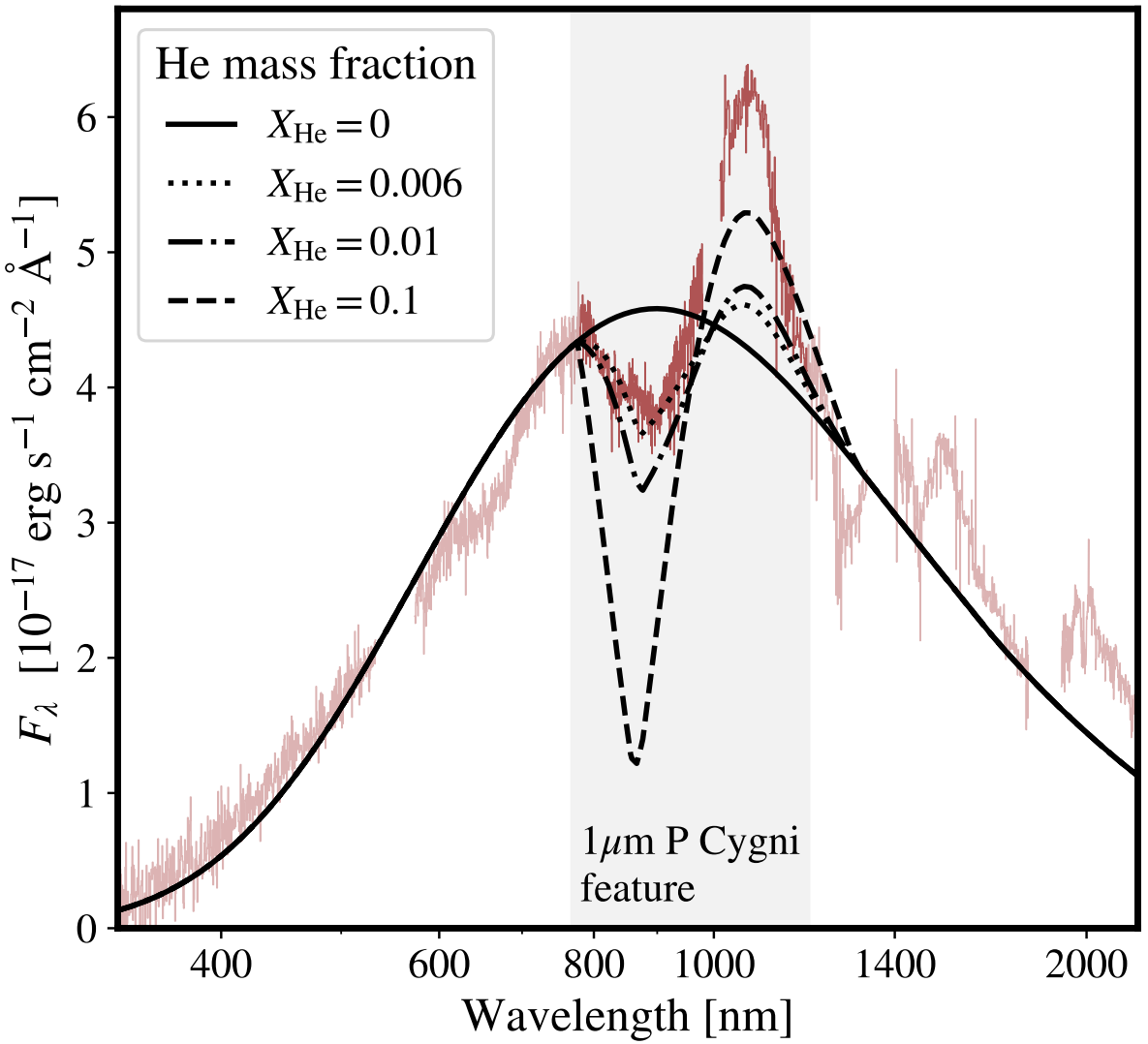




(Margalit+17)

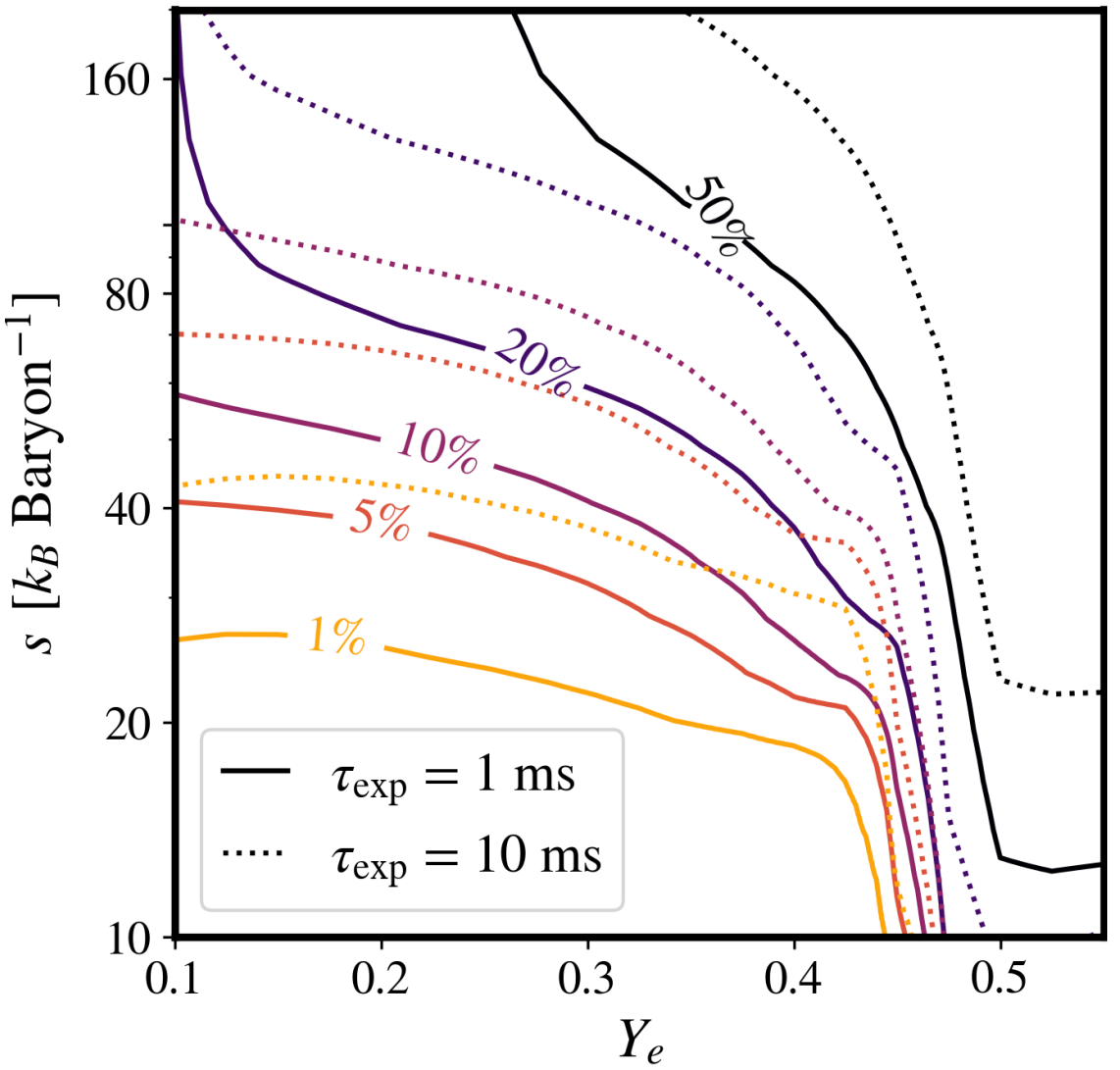
Helium abundance from observed spectrum of AT2017gfo

- observed spectrum (at 4.4 days) appears inconsistent with significant helium mass fractions
- resulting constraint $X(\mathrm{He}) \lesssim 0.05$
- **see talk by Rasmus on Friday for more details!**

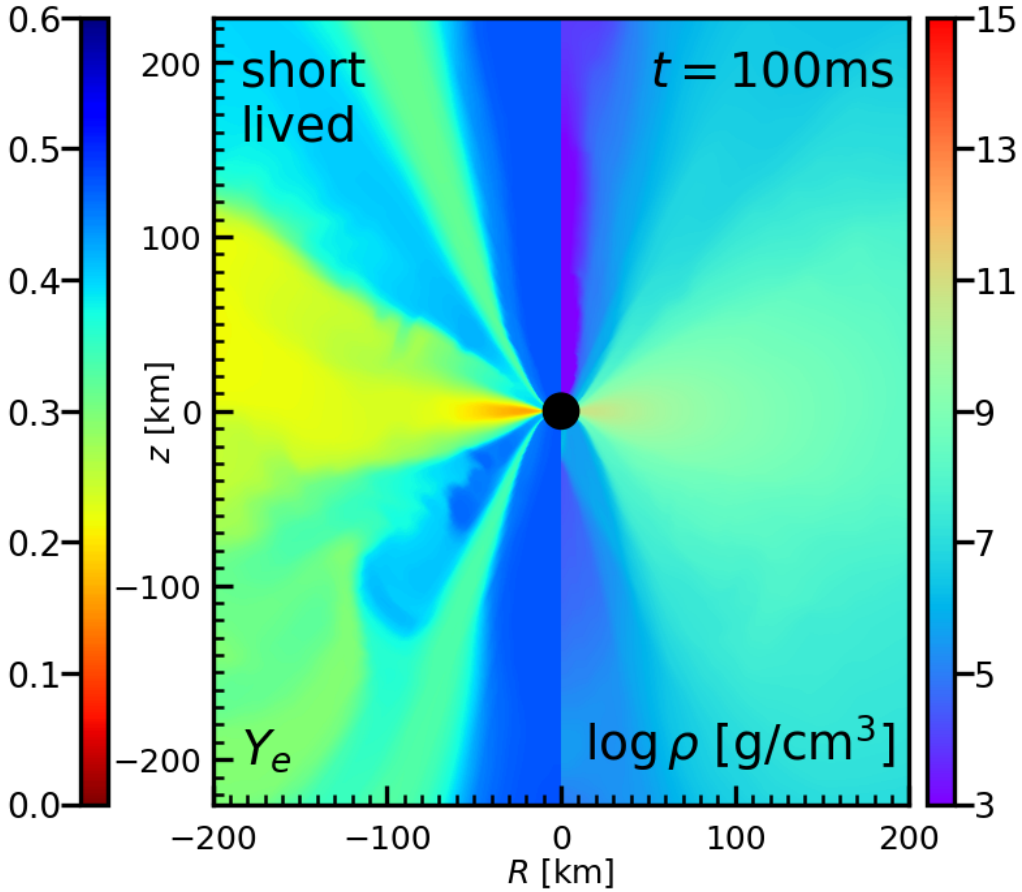


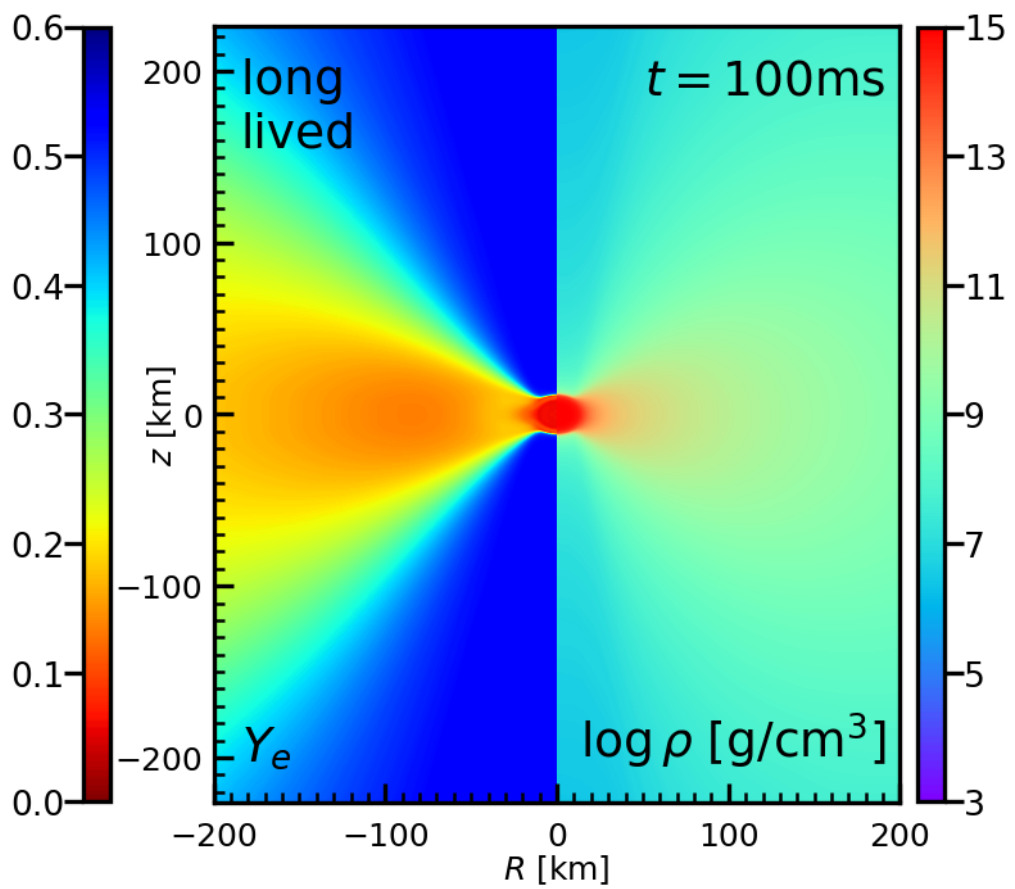
Nucleosynthesis conditions for helium production

- nucleosynthetic production of helium requires high electron fraction Y_e and/or high entropy s



Helium production mainly in neutrino-driven winds

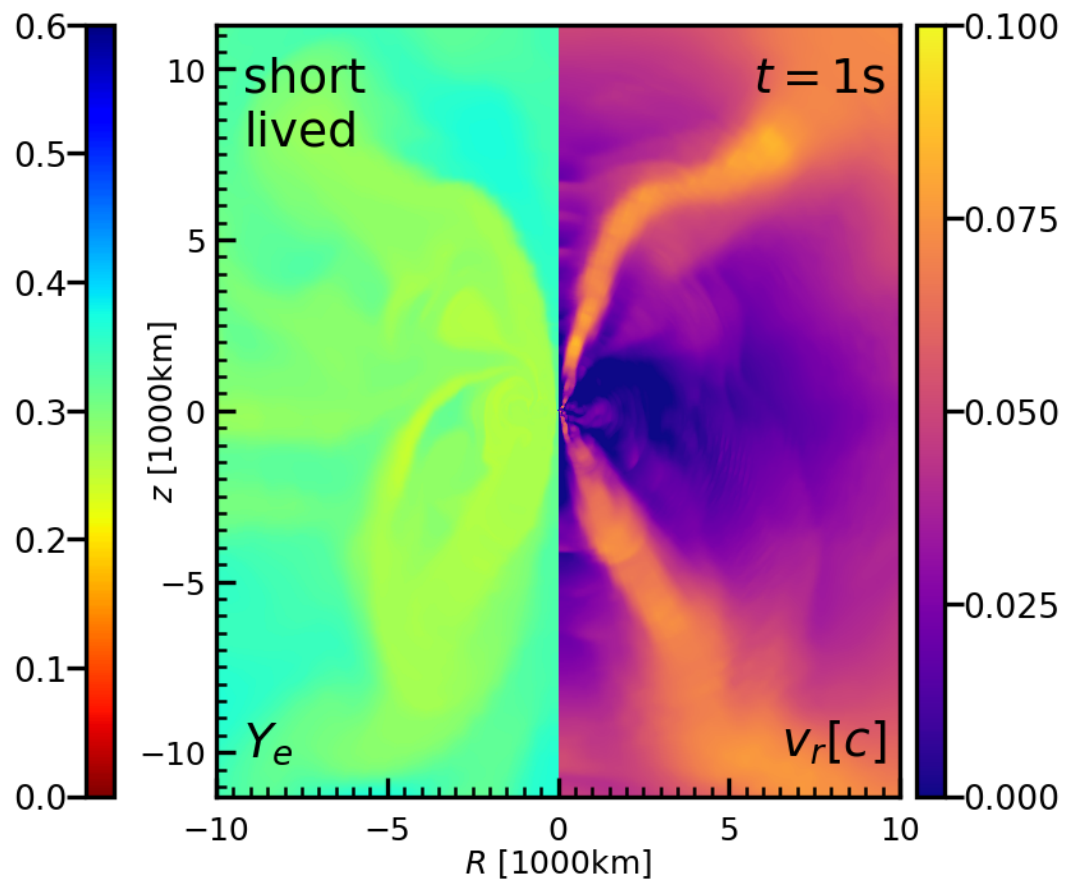


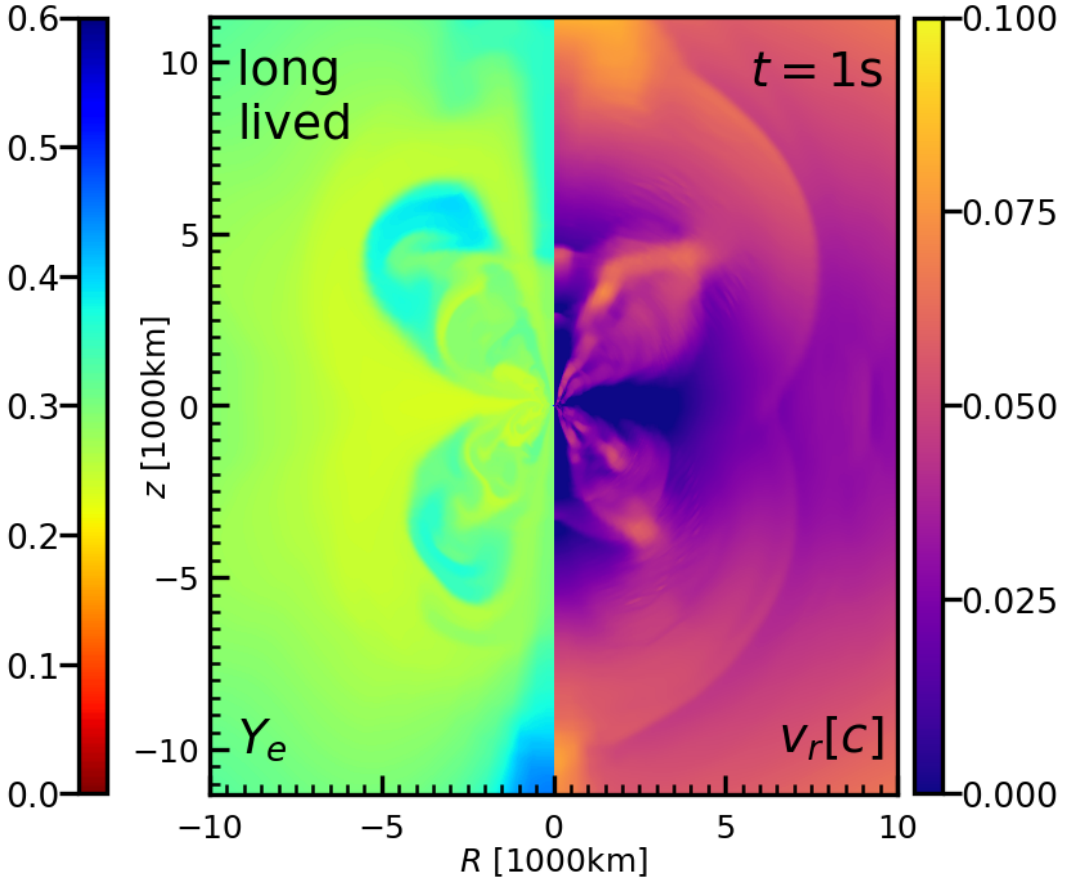


- driven through absorption of neutrinos on free nucleons
- estimate of Y_e:

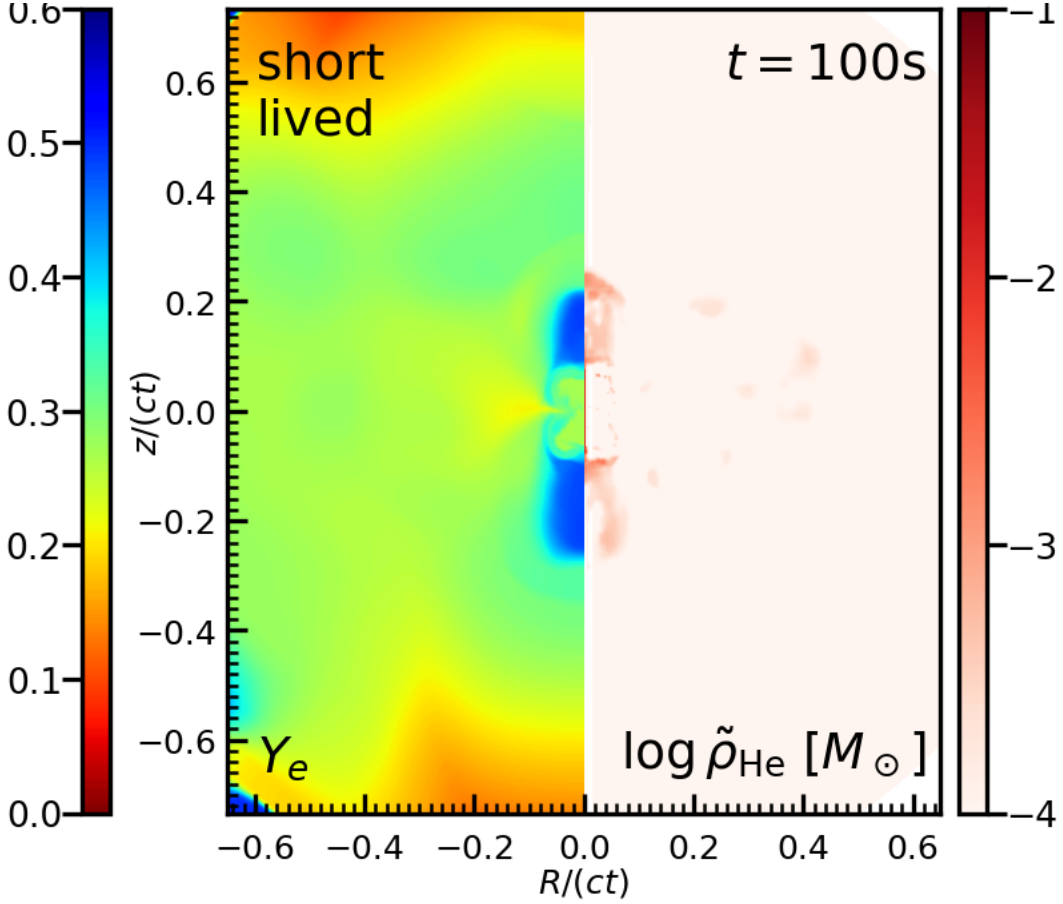
$$Y_e^{\mathrm{eq,abs}} \simeq \frac{1}{1 + \frac{\langle \epsilon^2_{\bar{\nu}_e} \rangle L_{N,\bar{\nu}_e}}{\langle \epsilon^2_{\nu_e} \rangle L_{N,\nu_e}}}$$

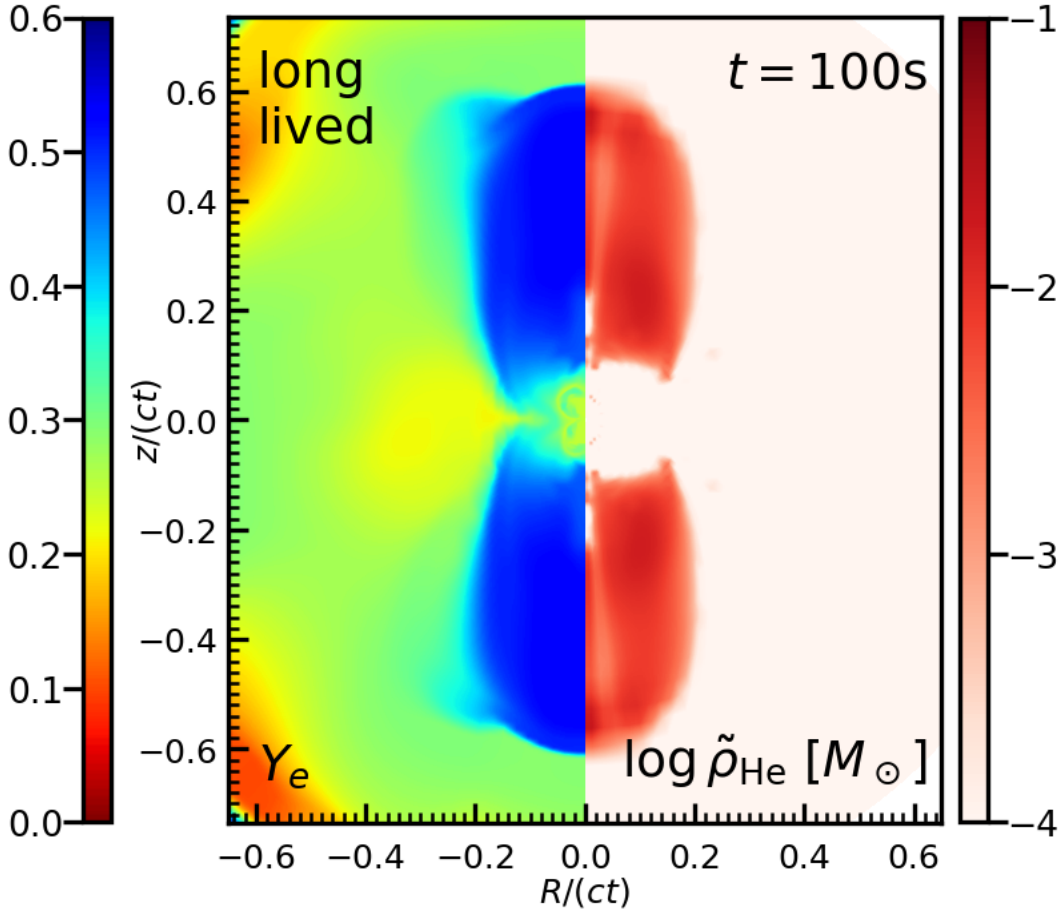
Little helium production in subsequent viscous outflows





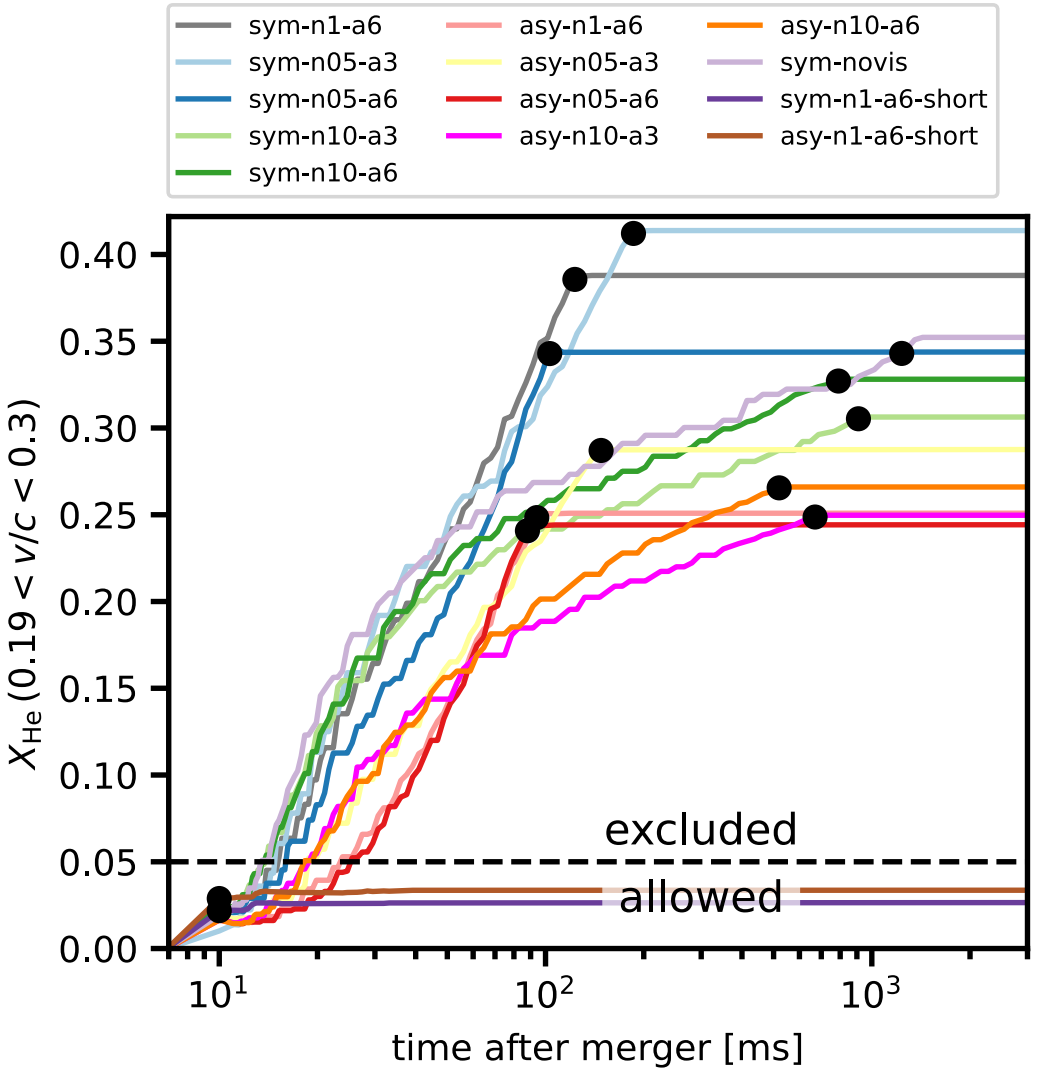
Final (homologous) distribution of helium



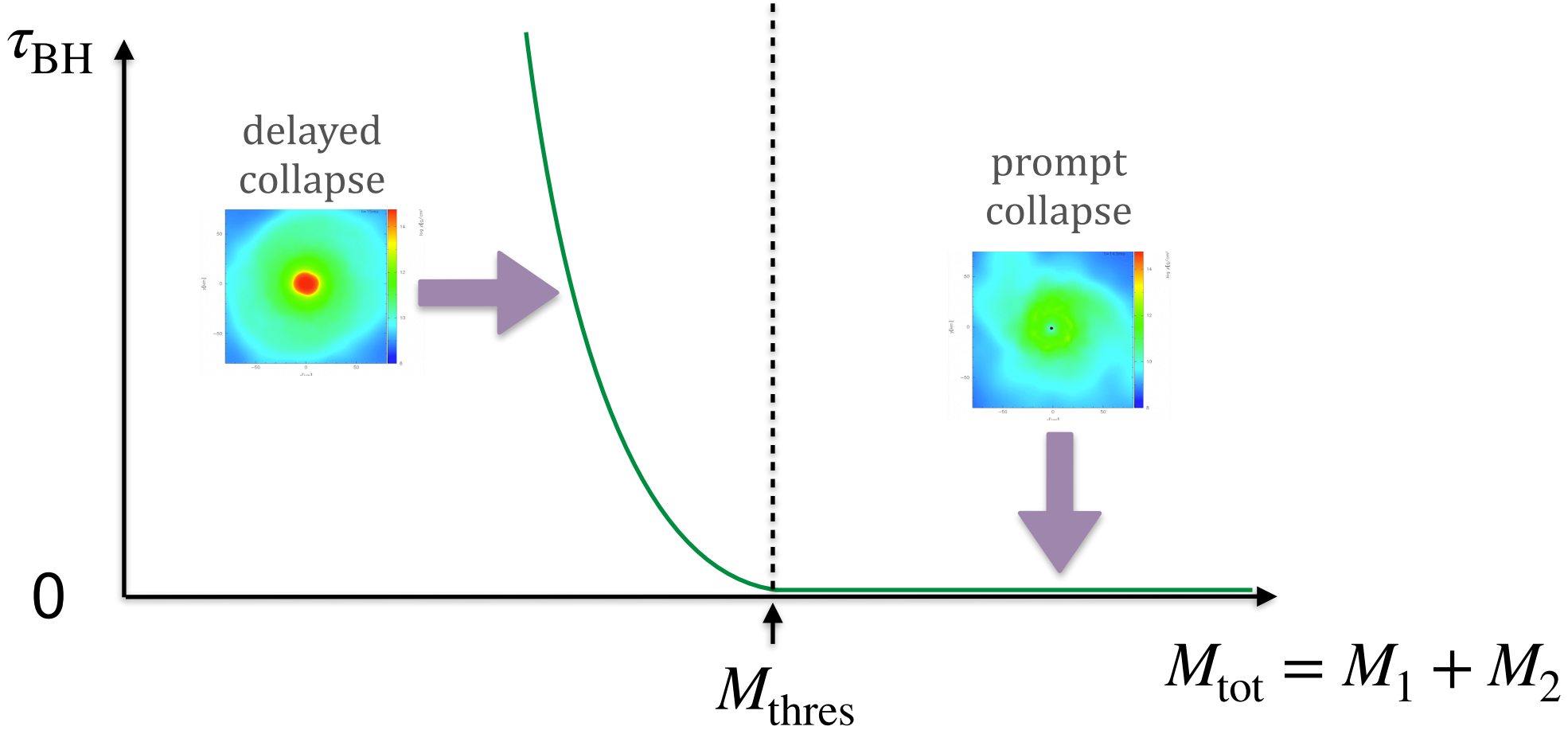


Helium production in NS merger models

- more helium with longer lifetime
- short lifetime $\tau_{\rm BH} \lesssim 20 - 30\,{\rm ms}$ required to fulfill observational constraint on helium abundance in AT2017gfo

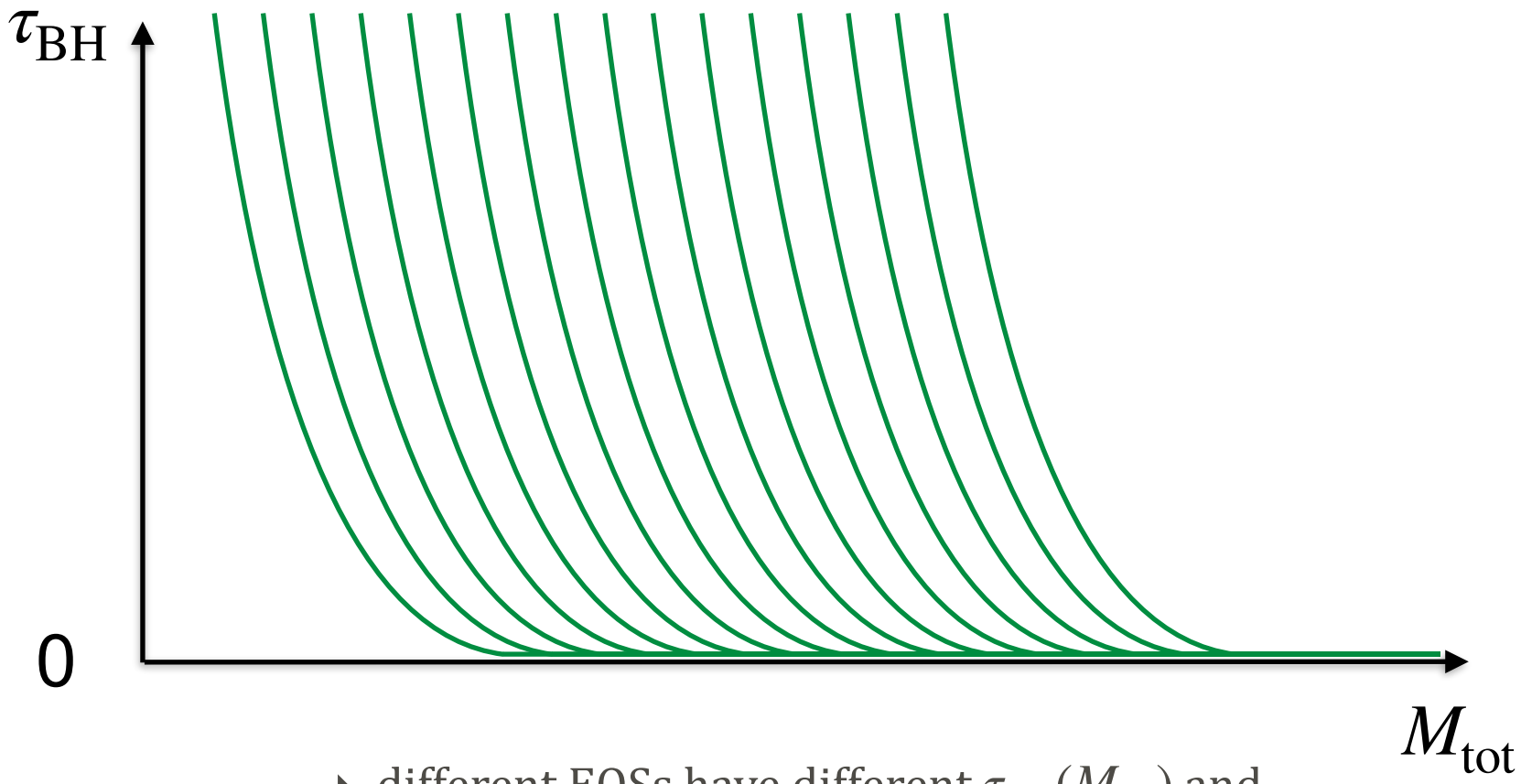


Connecting remnant lifetime with the EOS: The $\tau_{\mathrm{BH}} - M_{\mathrm{tot}}$ relationship



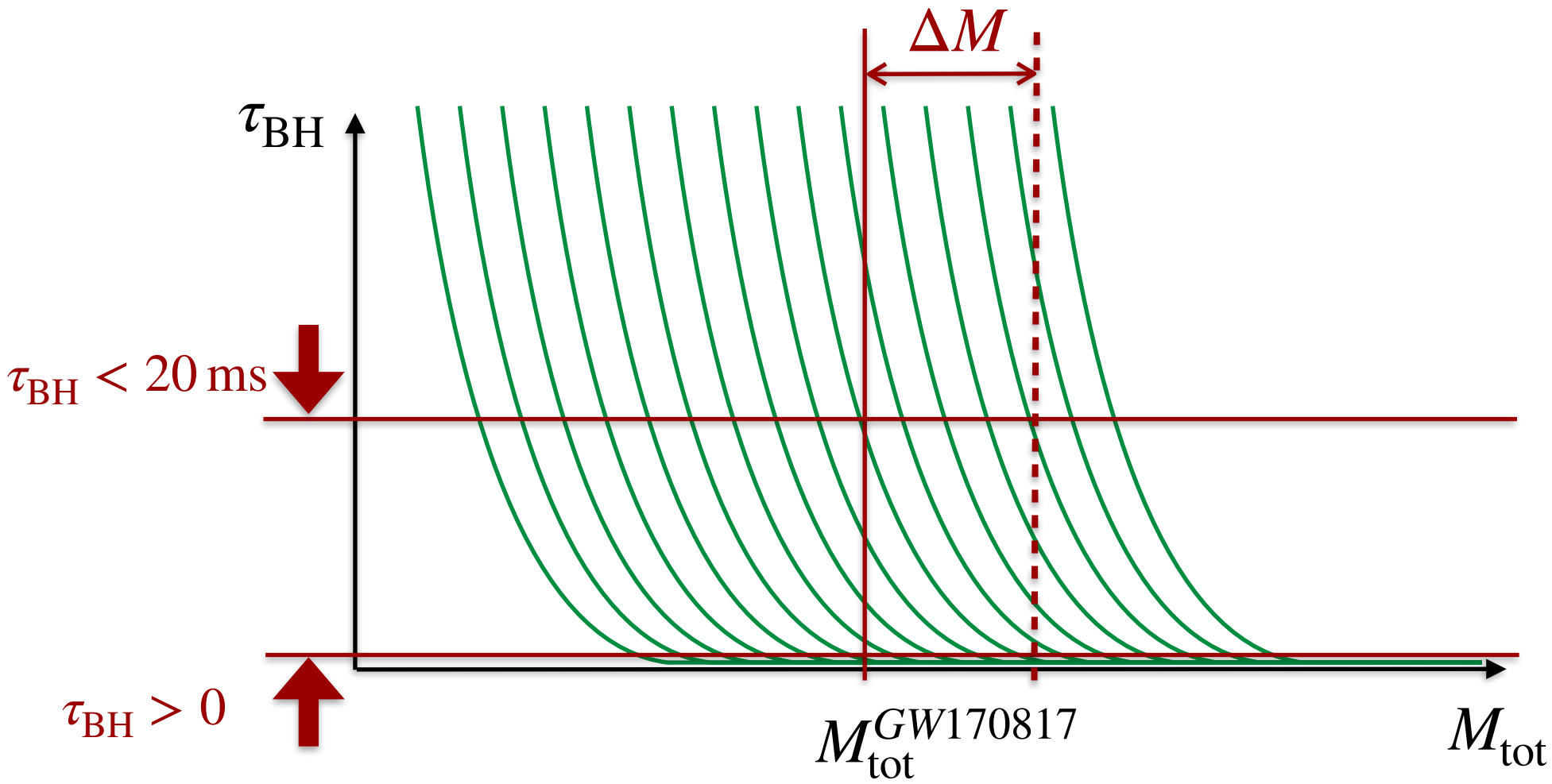
- threshold mass M_{thres} separates prompt-collapse from delayed-collapse cases

Connecting remnant lifetime with the EOS: The $\tau_{\rm BH} - M_{\rm tot}$ relationship



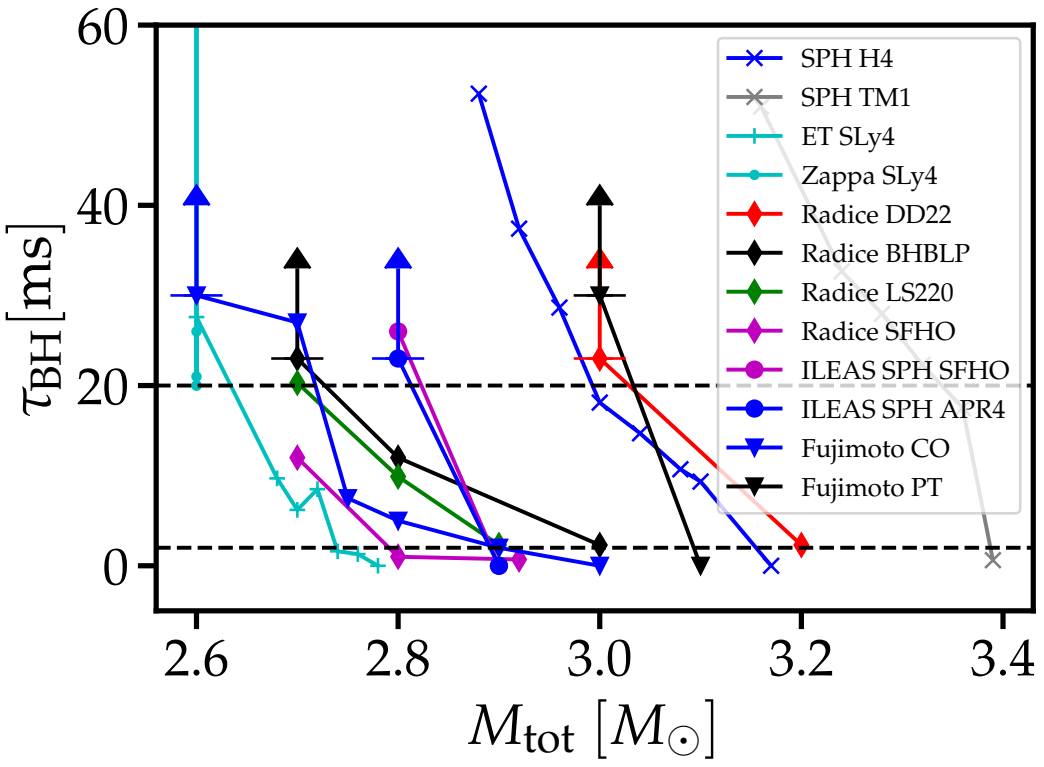
- different EOSs have different $\tau_{\rm BH}(M_{\rm tot})$ and different $M_{\rm thres}$

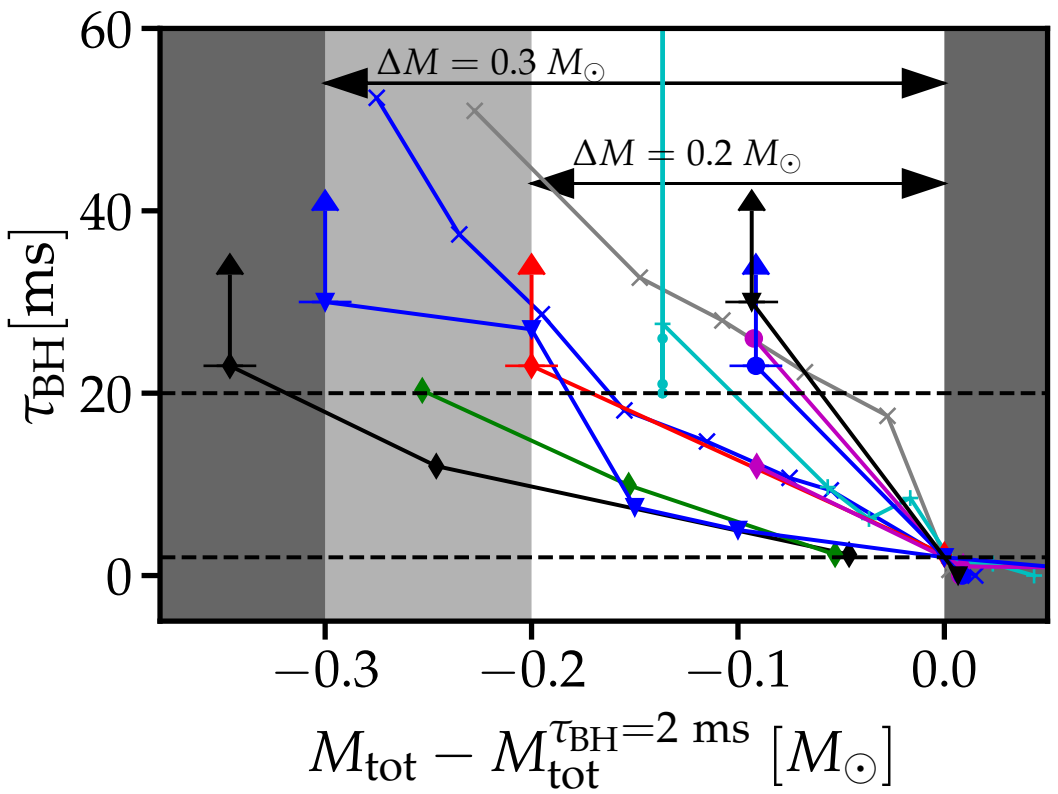
Implications of $\tau_{\rm BH} > 0$ and $\tau_{\rm BH} < 20\,{\rm ms}$



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

Reasonable choice for ΔM?





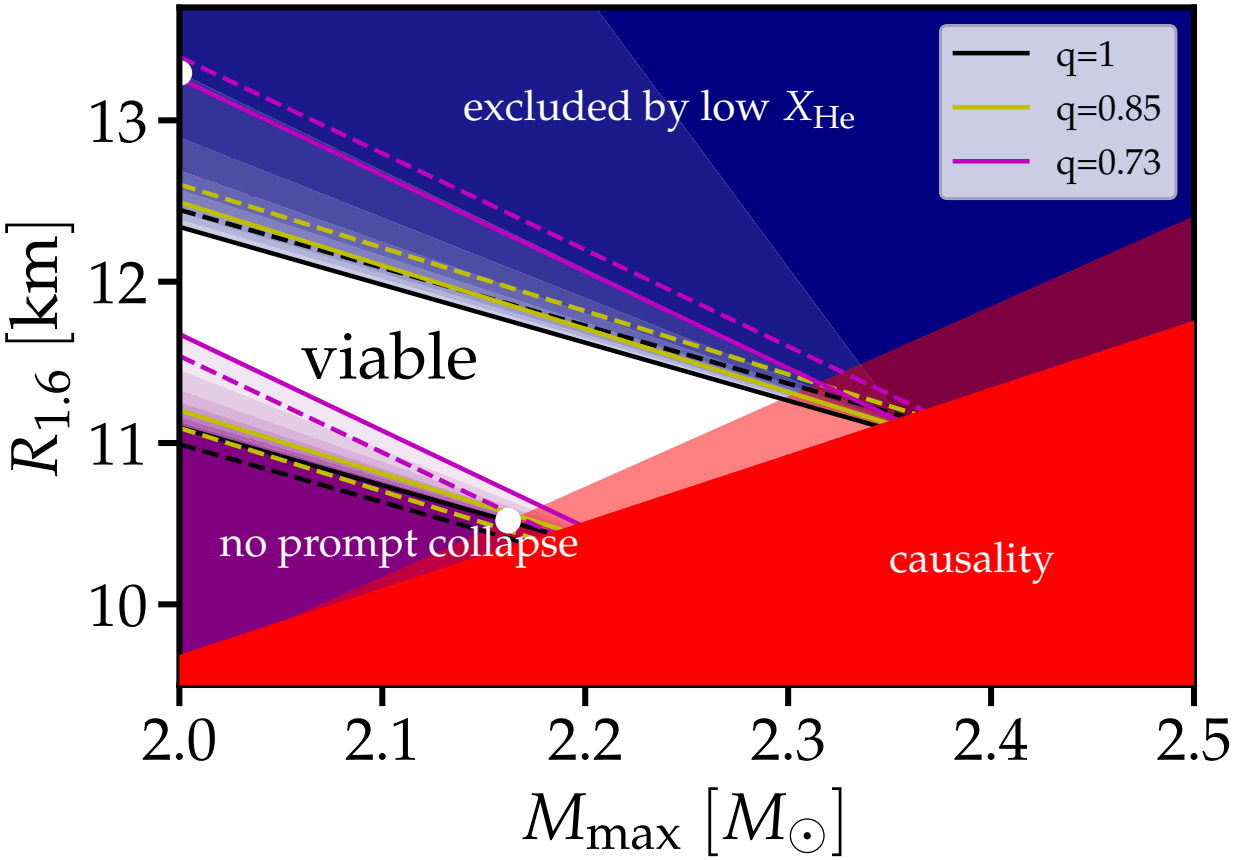
- very challenging to determine $\tau_{\rm BH}(M_{\rm BH})$ because: numerics, physical ingredients, stochasticity, ...
- $\tau_{\rm BH} < 20\,$ms suggests $\Delta M \approx 0.2\,M_\odot$

Implications for NS properties

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

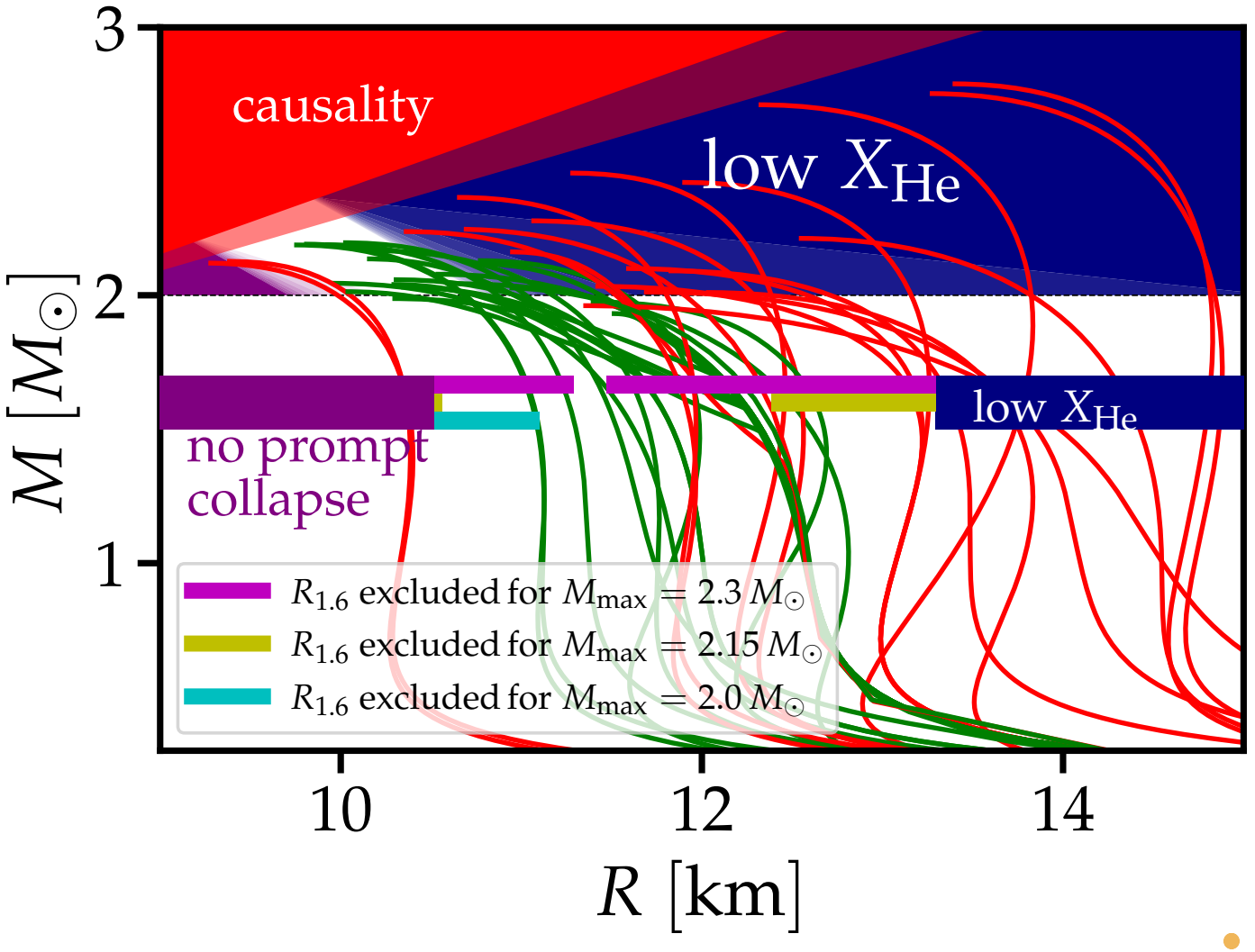
$$M_{\rm thres}(q, M_{\rm max}, R) = c_1 M_{\rm max} + c_2 R + c_3 + c_4 \delta q^3 M_{\rm max} + c_5 \delta q^3 R$$

- strong upper limit on NS radius for given maximum TOV mass
- lower limits from bright KN (delayed collapse) and causality ($c_{\rm sound} < c$)
- radius: $10.7 \lesssim R_{1.6}[\rm km] \lesssim 12.3$
- maximum mass: $M_{\rm max} < 2.3\, M_\odot$
- uncertainties due to poorly constraint mass ratio



Implications for NS properties

- 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 $M_{\max}$



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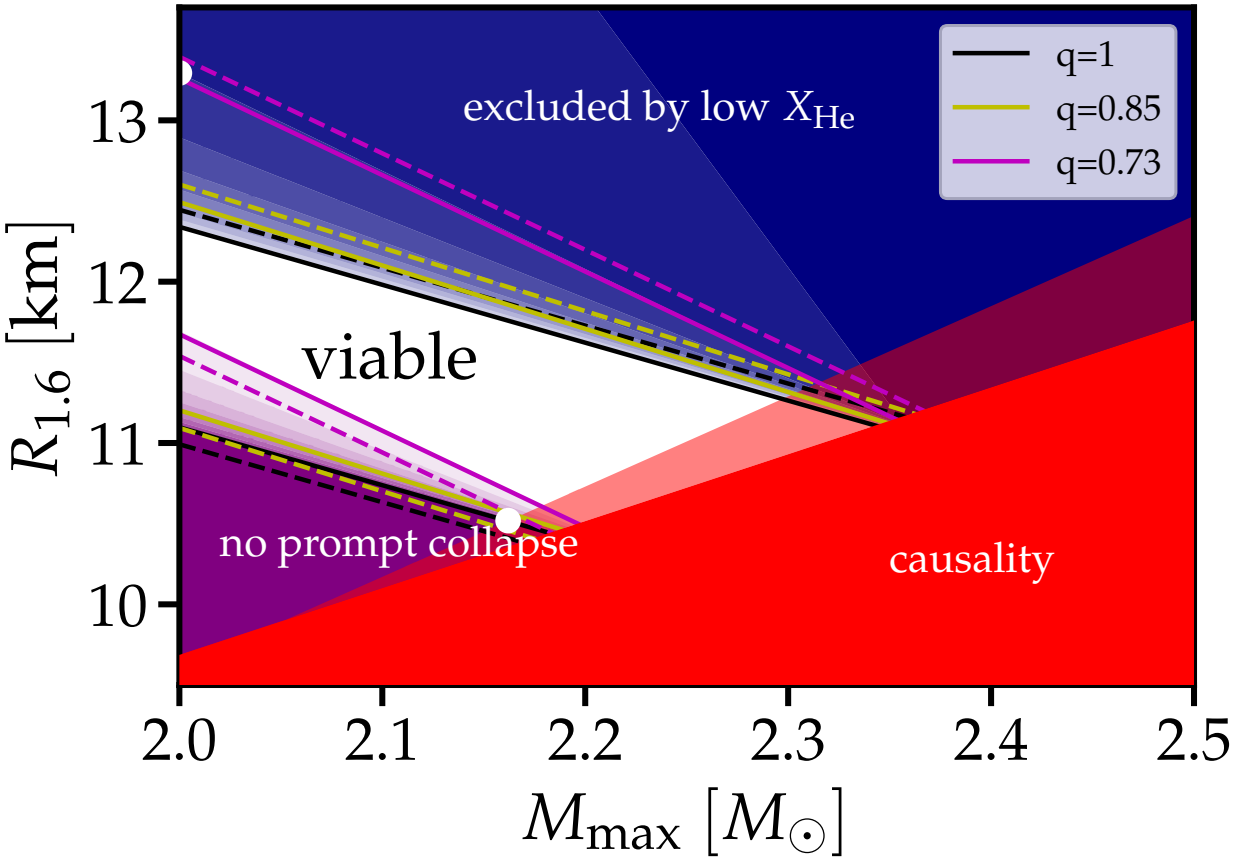
- strong upper limit on NS radius for given maximum TOV mass

- lower limits from bright KN (delayed collapse) and causality ($c_{\mathrm{sound}} < c$)



Conclusions

- neutrino-driven winds appear to enrich NSM ejecta with significant amounts of helium
- observational limit on $X(\mathrm{He})$ can be used to constrain NS lifetime
- use empirical relations for threshold mass to translate to NS properties
- **promising new possibility to constrain nuclear EOS!**

- **Further implications:**
  - GRB170817 probably not from a magnetar
  - secondary component of GW190814 with $M_2 \approx 2.5 - 2.67 M_\odot$ was a BH (not NS!)

- **Caveats:**
  - He radiative modeling, He production modeling, $\tau_{\mathrm{BH}} - M_{\mathrm{tot}}$ relation

Thank you for your attention!

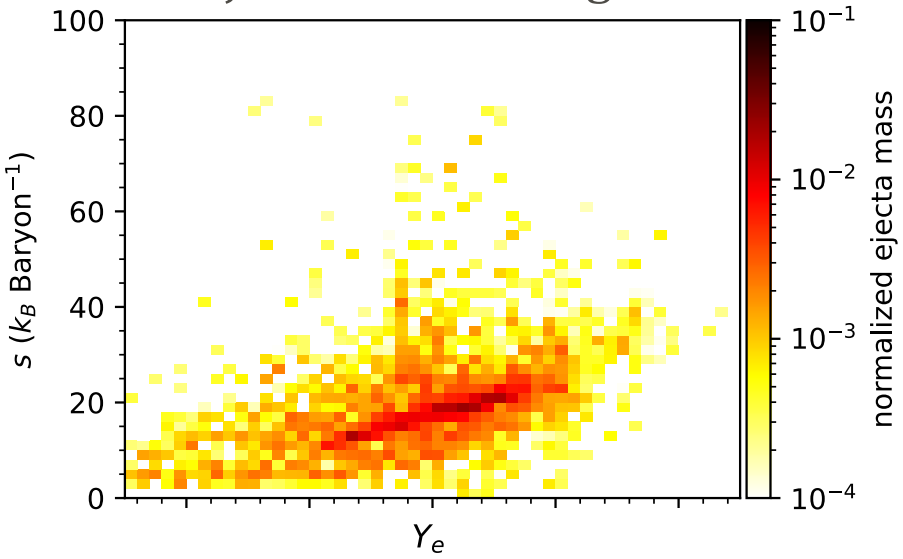
Backup slides

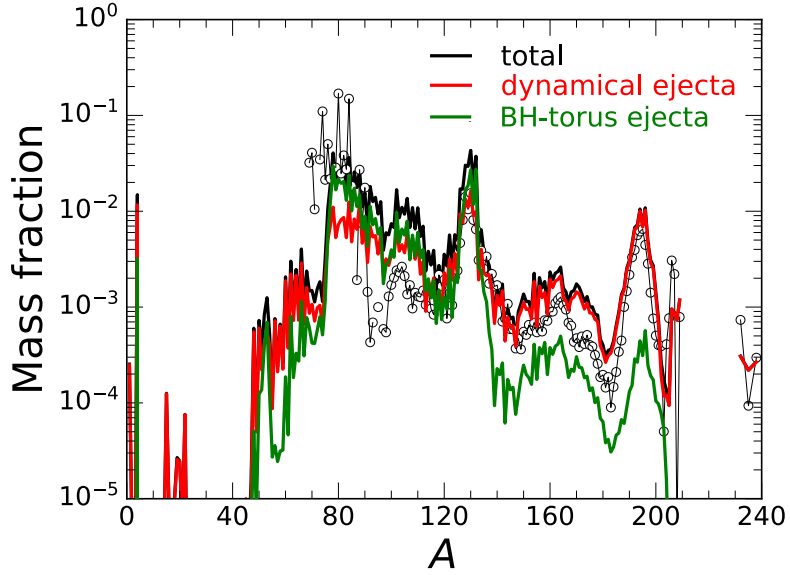
Short vs. long lived NS remnant

ejecta mass histogram

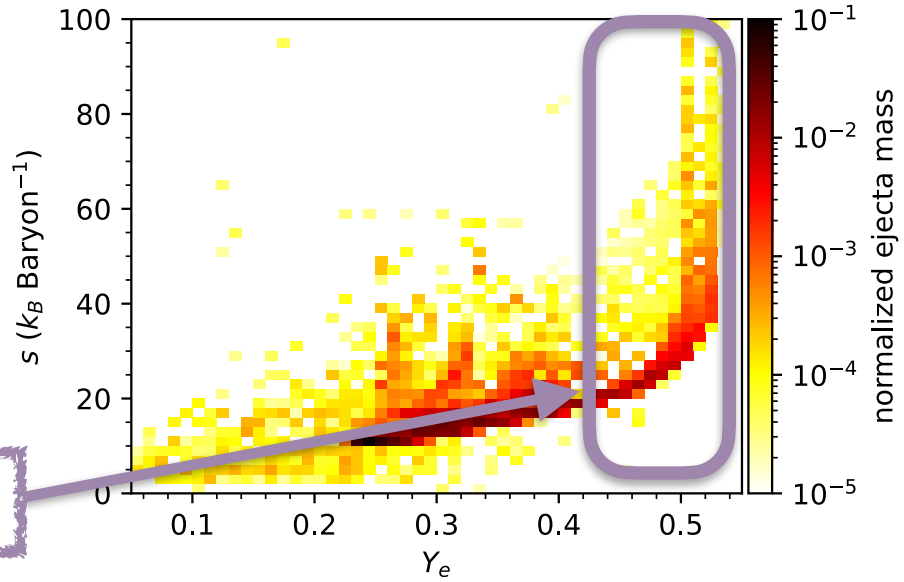
ejecta nucleosynthesis yields

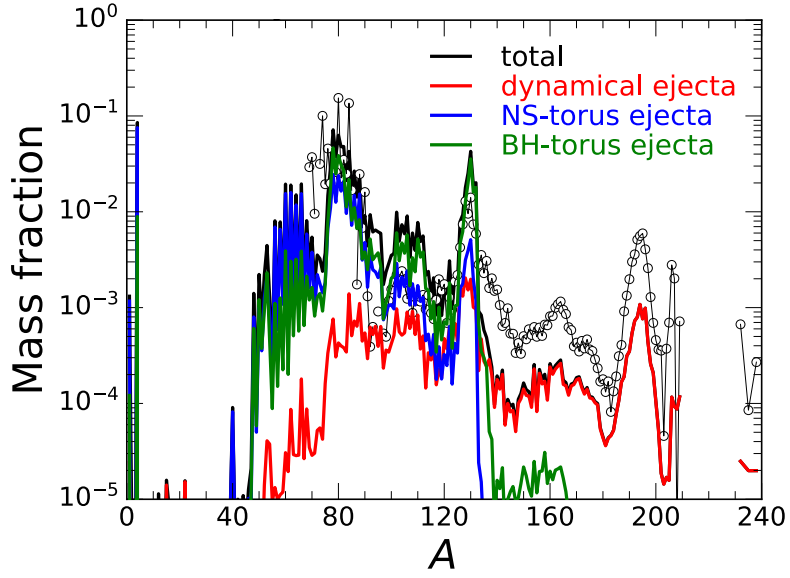
short-lived
(10ms)





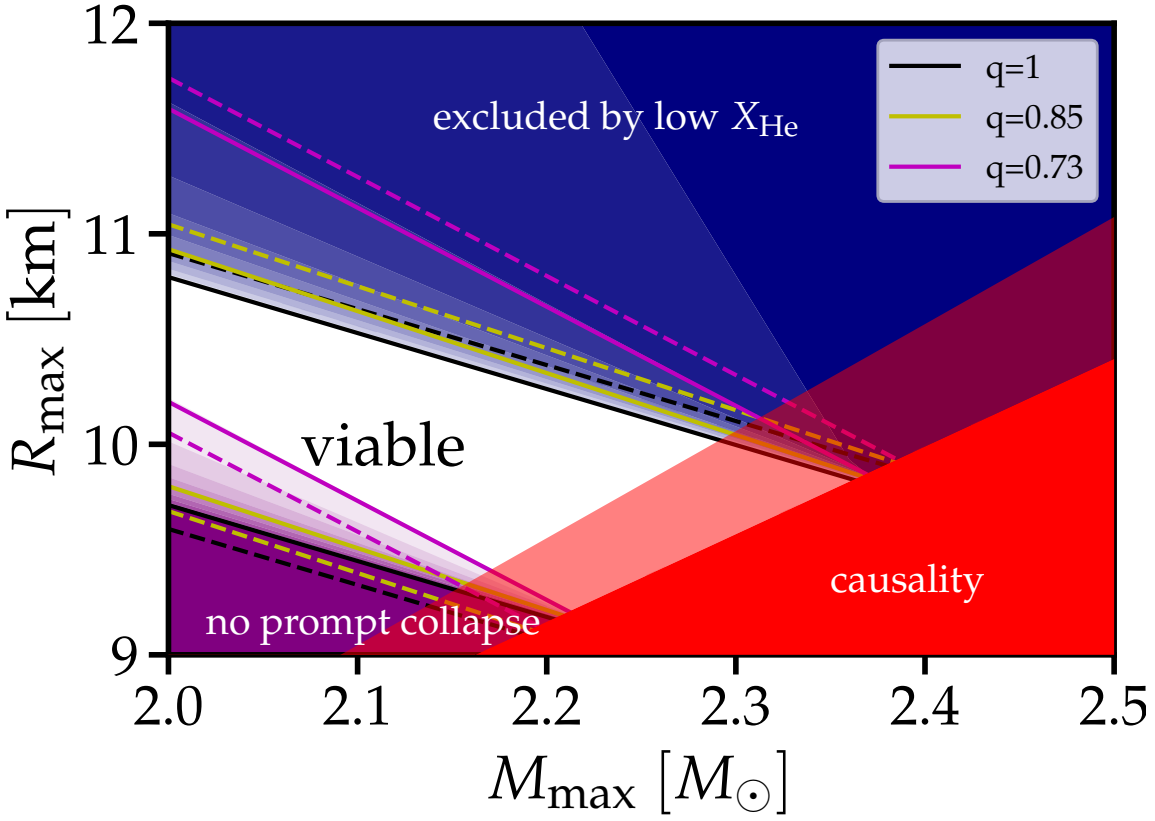
long-lived
(120ms)

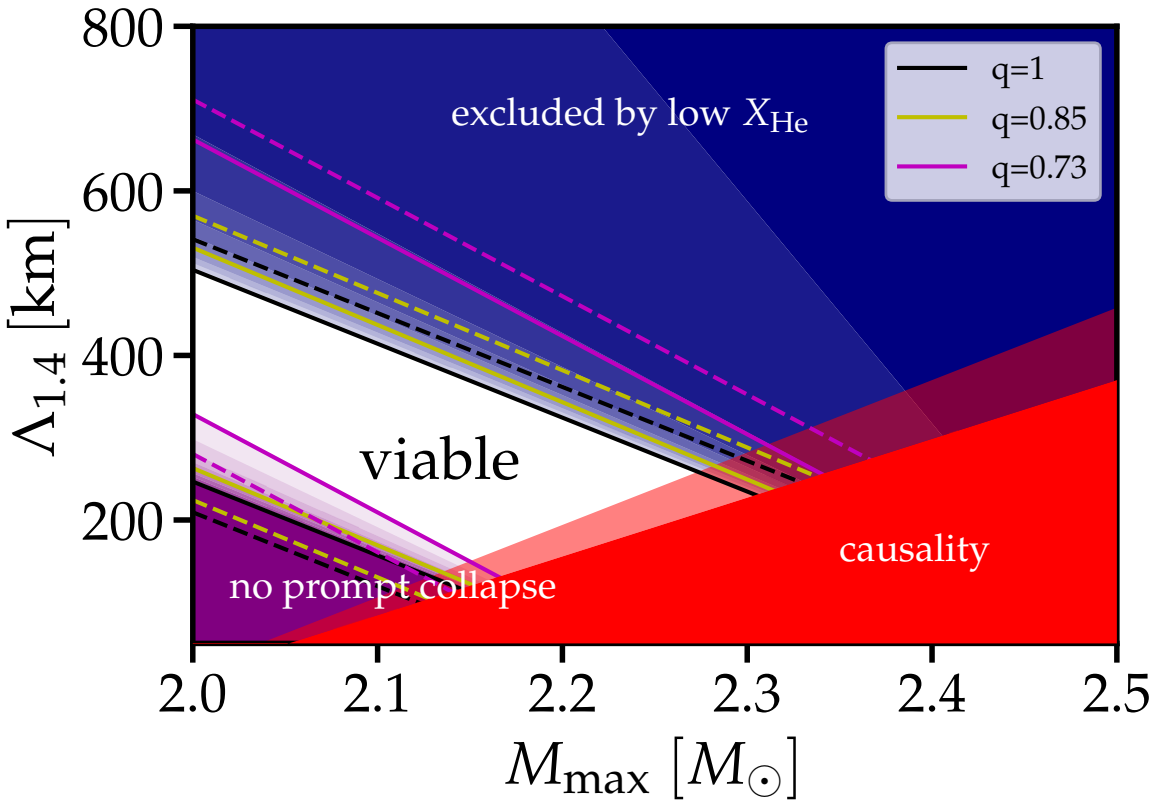




main source of He

Constraints for other NS properties





Relaxing value of ΔM