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Constraining neutron star parameters with kilonova spectra and signatures of hyperons

NPAXII, Cluj-Napoca, 10/09/2026

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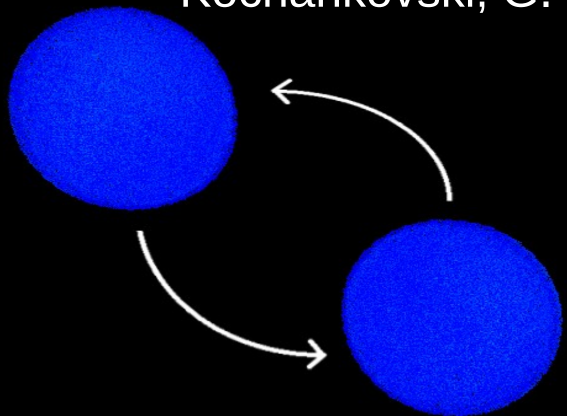
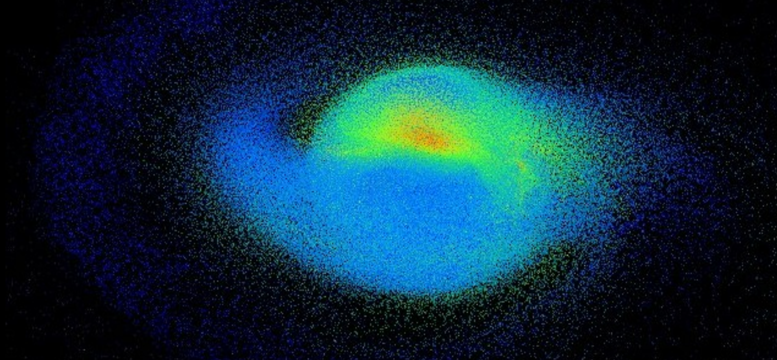
with A. Sneppen, O. Just, R. Damgaard, D. Watson, L. Shingles, C. Collins, S. Sim, Z. Xiong, G. Martinez-Pinedo, T. Soultanis, V.Vijayan, A. Nikolaidis, G. Lioutas, H. Kochankovski, G. Lioutas, P. Char, C. Mondal, M. Oertel, L. Tolos, N. Chamel, S. Goriely, S. Blacker, A. Ramos





Outline

- Intro / Threshold binary mass for EoS constraints

- EoS / NS constraints from a multi-messenger interpretation of GW170817/AT2017gfo

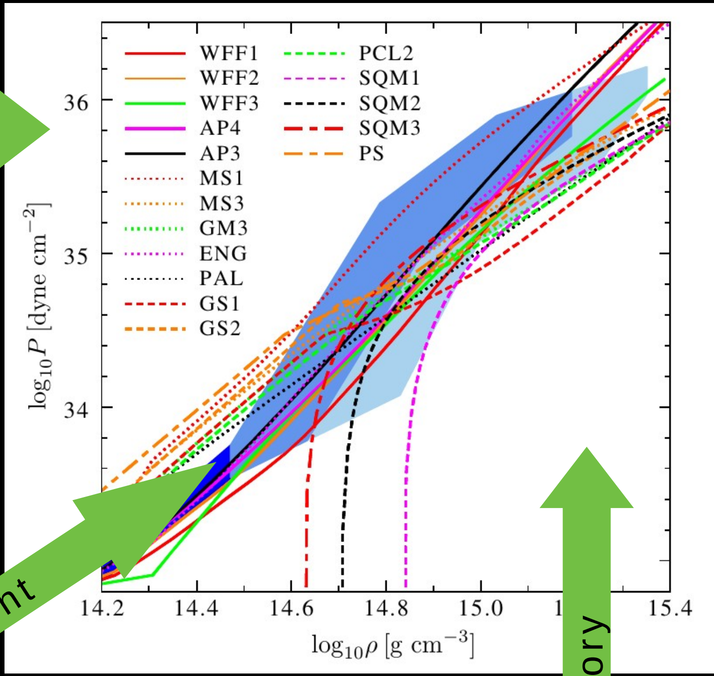
  A. Sneppen, O. Just, A. Bauswein, R. Damgaard, D. Watson, L. Shingles, C. Collins, S. Sim, Z. Xiong, G. Martinez-Pinedo, T. Soultanis, V.Vijayan, PRD 116, 063038 (2026), arxiv:2411.03427

- Characteristic impact of hyperons on mass-radius relations

  A. Bauswein, A. Nikolaidis, G. Lioutas, H. Kochankovski, G. Lioutas, P. Char, C. Mondal, M. Oertel, L. Tolos, N. Chamel, S. Goriely, S. Blacker, A. Ramos, PRR 8, 013253 (2026), arxiv:2507.10372

Different approaches to high density matter

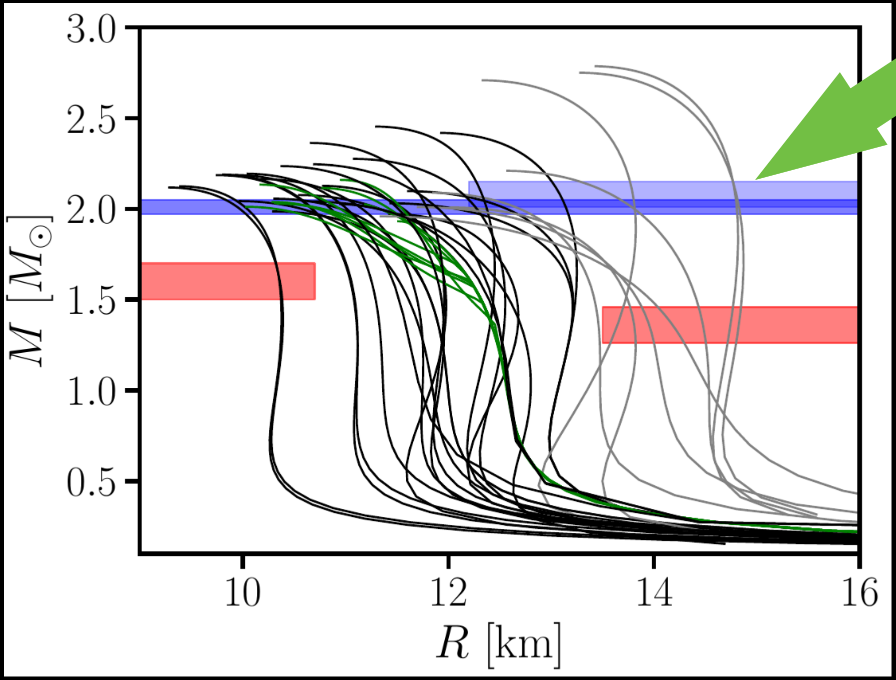
experiment

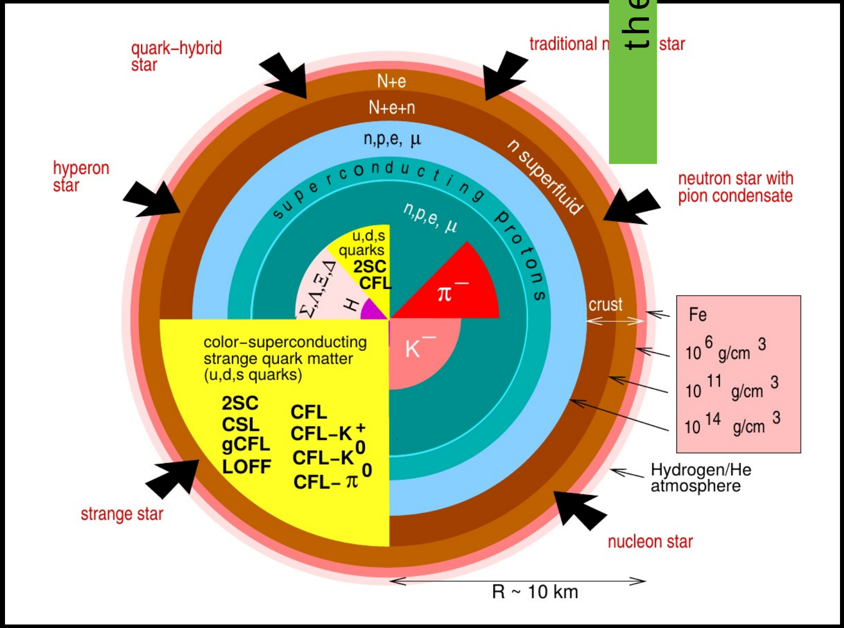


Hebeler & Schwenk 2014

equivalent

theory





Weber 2004

Mergers and EoS/NS constraints

Basic idea: EoS affects structure and dynamics and thus observables

Three complementary strategies:

- Finite-size effects during the inspiral → accelerate inspiral compared to BH-BH

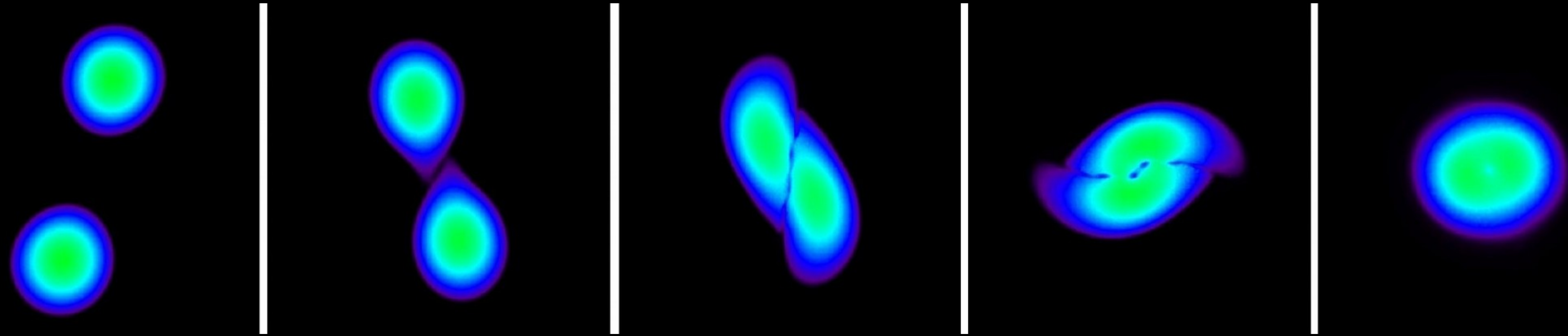
  - GW170817 → R < 13.5 km

- Multi-messenger interpretation: GW → binary masses, Kilonova, GRB

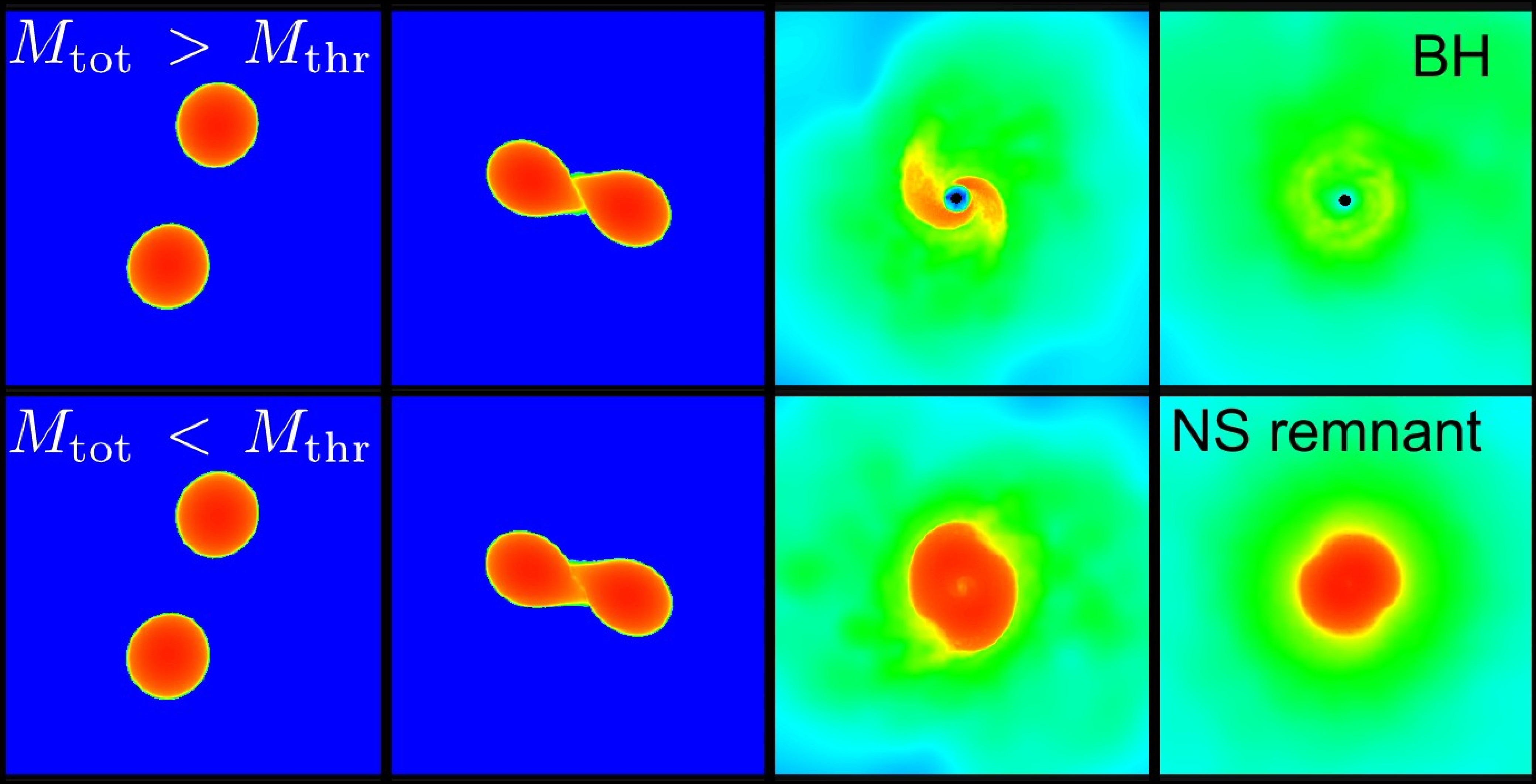
  - many different ideas, can be quite model-dependent

- Oscillations of the postmerger remnant (not yet measured but promising for future)

  - strong EoS impact – weaker signal (at higher frequencies)



Threshold mass for prompt collapse



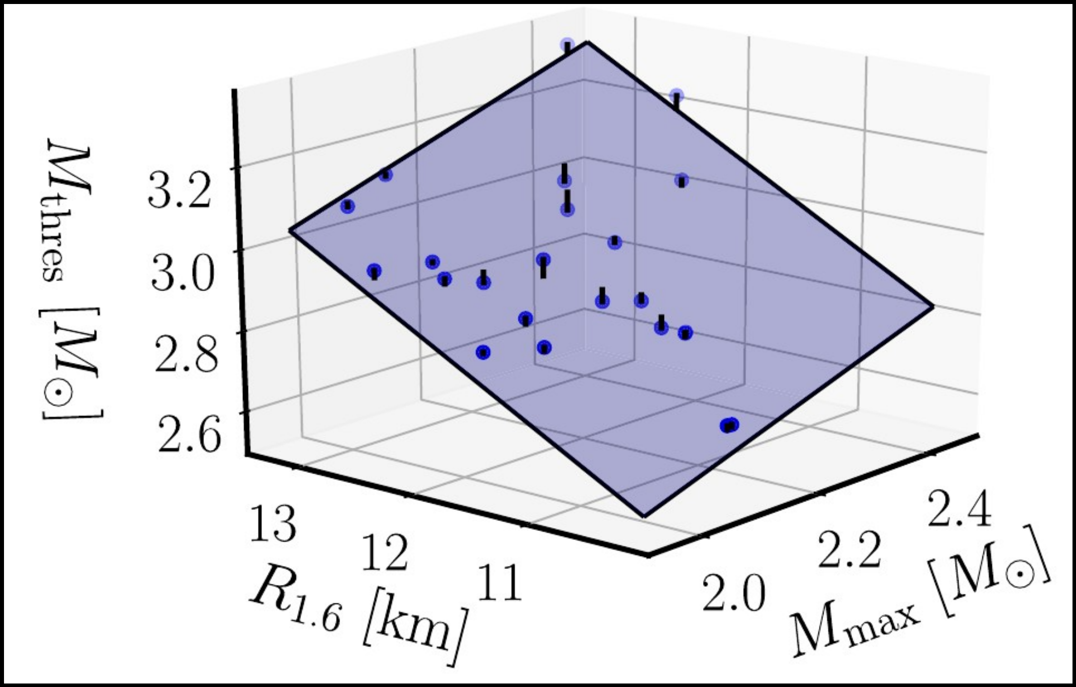
- Essence of ~ 400 relativistic hydrodynamics simualtions
- Relativistic hydrodynamics simulations
- Mostly T-dependent EoSs

Bauswein et al. 2021

EoS	T/B	$M_{\max}$ $(M_\odot)$	$R_{1.6}$ (km)	$\Lambda_{1.4}$	$M_{\rm thres}$ $q=1$ $(M_\odot)$	$\tilde{\Lambda}_{\rm thres}$ $q=1$	$M_{\rm thres}$ $q=0.85$ $(M_\odot)$	$\tilde{\Lambda}_{\rm thres}$ $q=0.85$	$M_{\rm thres}$ $q=0.7$ $(M_\odot)$	$\tilde{\Lambda}_{\rm thres}$ $q=0.7$	sample	Ref.
BHBLP	T	2.100	13.203	696.1	3.125	356.4	3.075	400.9	2.975	516.8	b	[67]
DD2Y	T	2.033	13.182	695.7	3.075	392.2	3.025	440.2	2.875	626.2	b	[68, 69]
DD2	T	2.421	13.258	699.5	3.325	249.7	3.325	255.3	3.275	302.5	b	[70, 71]
DD2F	T	2.079	12.232	426.3	2.925	317.5	2.925	327.4	2.850	430.9	b	[71–73]
APR	B	2.189	11.263	247.5	2.825	233.9	2.862	220.4	2.825	262.1	b	[74]
BSK20	B	2.167	11.658	319.6	2.875	269.5	2.875	276.5	2.875	302.5	b	[75]
eosUU	B	2.191	11.066	229.5	2.825	216.8	2.825	222.3	2.825	242.8	b	[76]
LS220	T	2.043	12.491	541.1	2.975	353.5	2.975	366.7	2.875	523.2	b	[77]
LS375	T	2.711	13.776	957.4	3.575	225.1	3.575	230.4	3.575	250.2	e	[77]
GS2	T	2.091	13.381	722.3	3.175	325.3	3.075	410.8	3.025	491.0	e	[78]
NL3	T	2.789	14.807	1369.4	3.775	230.2	3.812	221.7	3.775	259.7	e	[70, 79]
Sly4	B	2.045	11.533	294.6	2.825	277.4	2.825	285.8	2.775	355.5	b	[81]
SFHO	T	2.058	11.761	333.9	2.875	280.3	2.875	288.2	2.825	355.5	b	[82]
SFHOY	T	1.988	11.758	333.9	2.825	315.0	2.825	323.4	2.725	444.7	b	[68, 69]
SFHX	T	2.129	11.972	395.8	2.975	271.3	2.975	277.0	2.925	330.7	b	[82]
TM1	T	2.212	14.361	1150.8	3.375	337.1	3.325	386.9	3.225	529.1	e	[80, 90]
TMA	T	2.010	13.673	935.3	3.175	400.3	3.125	461.7	2.975	703.6	e	[80, 91]
BSK21	B	2.278	12.552	515.0	3.075	289.2	3.125	266.8	3.075	319.9	b	[75]
GS1	T	2.753	14.877	1402.3	3.775	231.2	3.775	237.7	3.775	262.3	e	[78]
eosAU	B	2.127	10.365	150.9	2.675	201.6	2.712	189.2	2.675	223.7	b	[76]
WFF1	B	2.120	10.370	151.0	2.675	201.6	2.688	199.9	2.675	221.5	b	[76, 87]
WFF2	B	2.188	11.057	223.9	2.825	211.5	2.800	229.5	2.825	236.9	b	[76, 87]
MPA1	B	2.456	12.458	479.1	3.225	203.7	3.225	208.4	3.225	226.1	b	[83, 87]
ALF2	B	1.975	12.628	569.4	2.975	388.2	2.938	428.0	2.875	513.9	b	[84, 87]
H4	B	2.012	13.731	853.2	3.125	407.1	3.025	524.2	2.925	704.9	e	[87, 88]
DD2F-SF-1	T	2.136	12.158	426.3	2.845	383.3	2.845	394.4	2.770	502.0	h	[58, 60–62, 92]
DD2F-SF-2	T	2.162	12.071	426.2	2.925	300.9	2.925	318.4	2.870	402.2	h	[58, 60–62, 92]
DD2F-SF-3	T	2.034	12.205	426.3	2.825	401.9	2.788	451.1	2.720	574.9	h	[58, 60–62, 92]
DD2F-SF-4	T	2.031	12.232	426.3	2.835	392.5	2.797	440.6	2.725	571.2	h	[58, 60–62, 92]
DD2F-SF-5	T	2.040	11.943	426.3	2.815	411.5	2.777	456.8	2.725	543.6	h	[58, 60–62, 92]
DD2F-SF-6	T	2.013	12.231	426.3	2.795	431.4	2.757	483.9	2.675	640.2	h	[58, 60–62, 92]
DD2F-SF-7	T	2.117	12.232	426.3	2.905	332.8	2.868	374.2	2.825	454.6	h	[58, 60–62, 92]
DD2F-SF-8	T	2.026	12.232	426.3	2.915	325.0	2.877	365.6	2.810	471.4	h	[58, 60–62, 92]
VBAG	T	1.932	12.214	422.3	2.885	345.5	2.848	388.4	2.775	505.4	h	[59]
ENG	B	2.238	11.909	370.0	2.975	251.2	2.975	257.6	2.975	281.6	b	[85, 87]
APR3	B	2.365	11.963	367.2	3.075	206.0	3.075	211.0	3.075	229.6	b	[74, 87]
GNH3	B	1.961	13.772	857.8	3.075	436.7	2.975	577.0	2.875	806.1	e	[87, 89]
SAPR	T	2.196	11.474	267.9	2.875	225.5	2.913	213.2	2.875	256.9	b	[86]
SAPRLDP	T	2.247	12.369	449.3	3.025	271.0	3.062	257.4	3.025	309.4	b	[86]
SSkAPR	T	2.028	12.304	442.6	2.950	312.7	2.938	331.6	2.875	420.8	b	[86]

Threshold mass for prompt collapse

- Constraint on M_{thres} → EoS / TOV constraint



Bauswein et al. 2021

$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(R_{1.6}, M_{\mathrm{max}}) = aM_{\mathrm{max}} + bR_{1.6} + c$$

Notes: mild dependence on binary mass ratio q (usually reduction for asymmetric mergers)
Similar relations for other TOV parameters

Threshold mass for prompt collapse

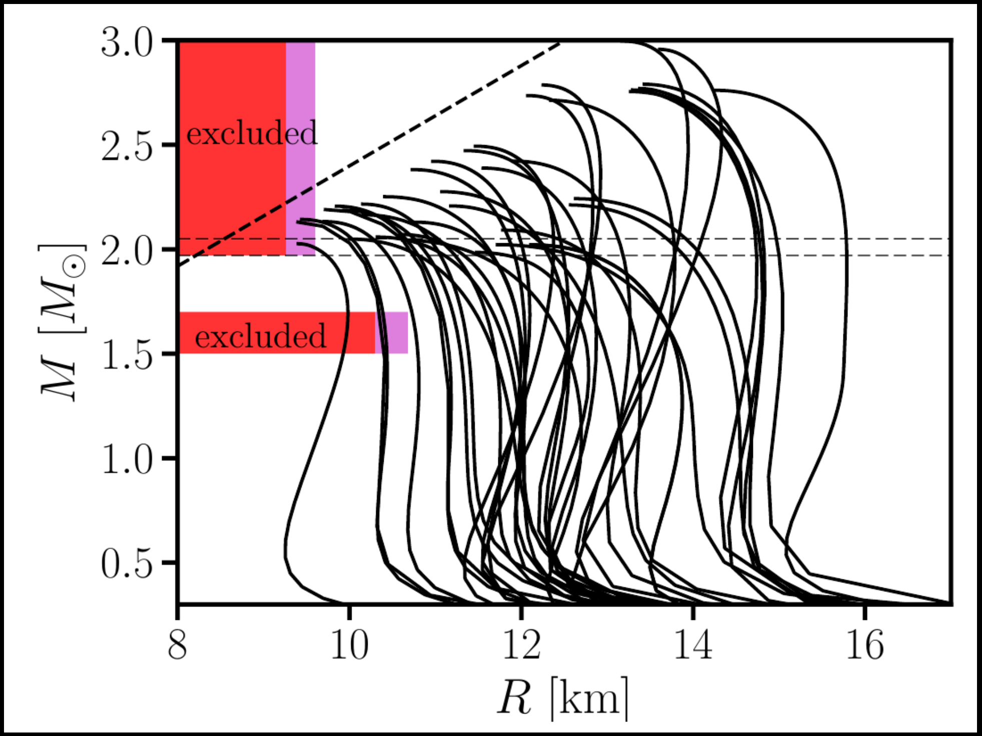
- Example

  - Kilonova of GW170817 very bright

  → no prompt collapse

  → $M_{tot} < M_{thres}$

  → R > 10.7 km



Bauswein et al. 2017

→ to be updated / refined later

Helium

New EoS constraint from GW170817/AT2017gfo

- Exploting so far unused information in 3 major steps

  - Limits on He abundance in ejecta from kilonova spectrum

  - theoretically expected He enrichment from simulations limits lifetime

  - Lifetime limit constrains M_{thres} → EoS/NS constraints

- Notes:

  - Still some open questions but but very powerful and testable predictions

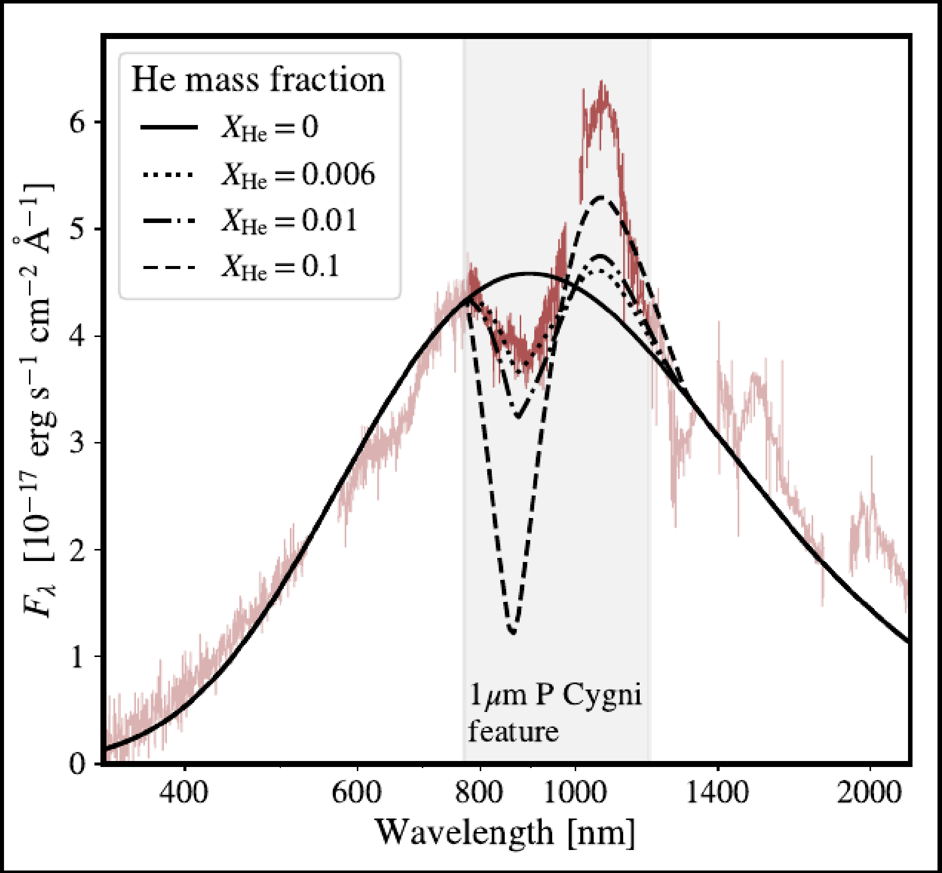
  - Two independent constraints

Sneppen et al., PRD 2026, arXiv:2411.03427

He spectral features in spectrum

- Already tiny amounts of He would produce strong absorption feature

  → mass fraction X(He) < 0.006 … 0.05



Sneppen et al., PRD 2026, arXiv:2411.03427

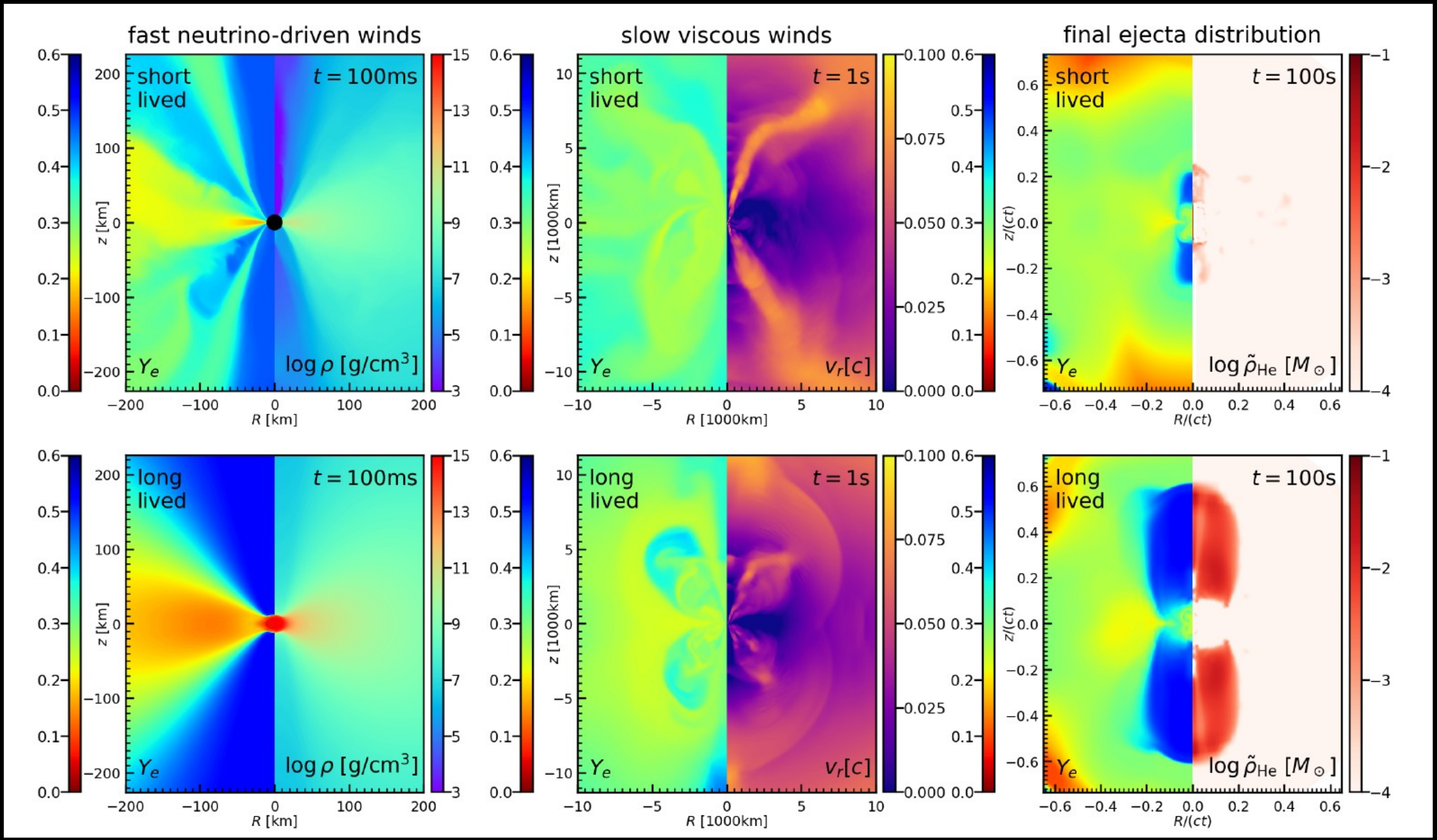
Simulations

- 3d dynamical merger + 2d long-term evolution (cf. Just et al. 2023)

BH formation

@ 10 ms →

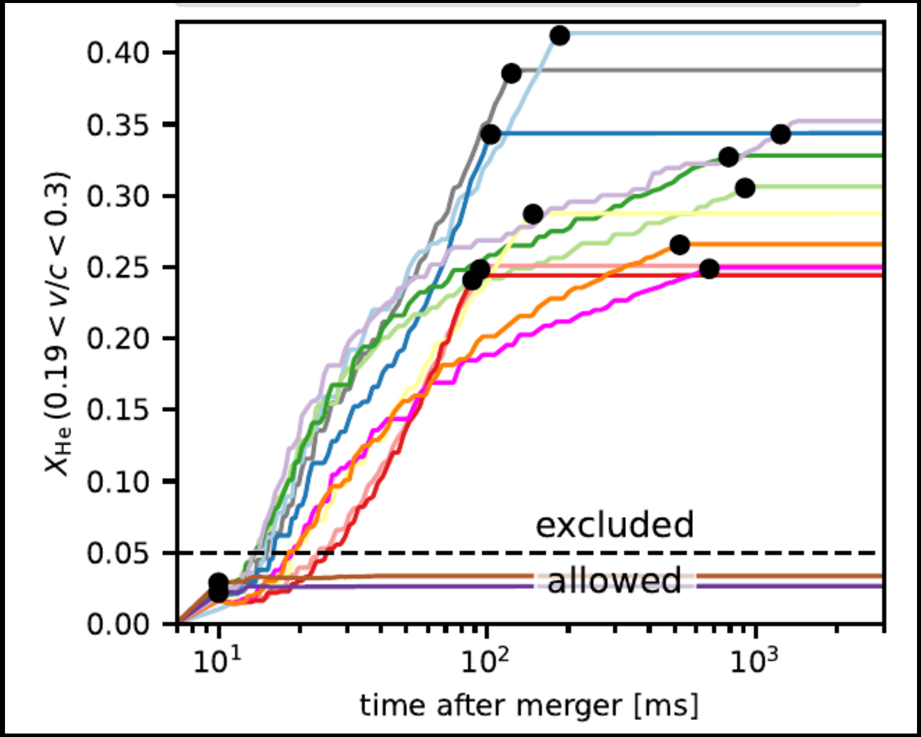
@ 122 ms →

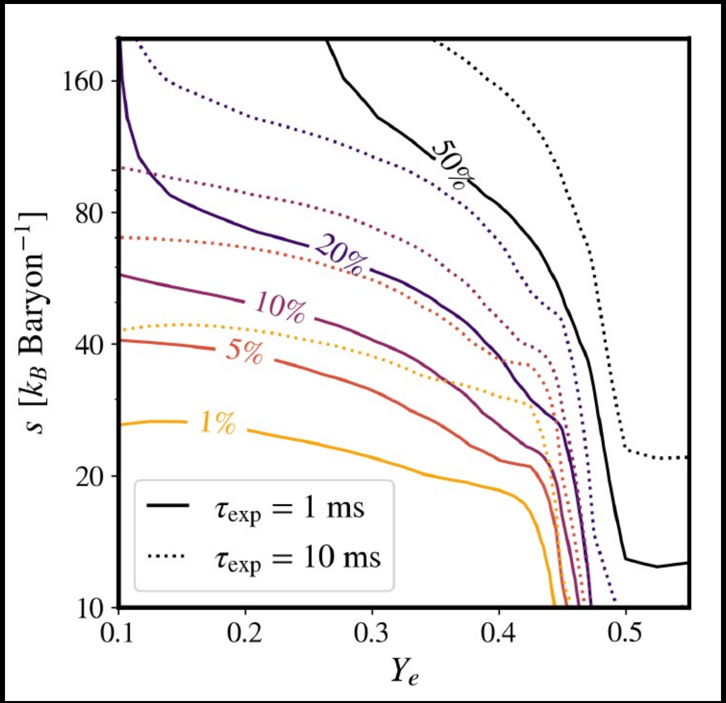


Sneppen et al., PRD 2026, arXiv:2411.03427

He production in merger simuations

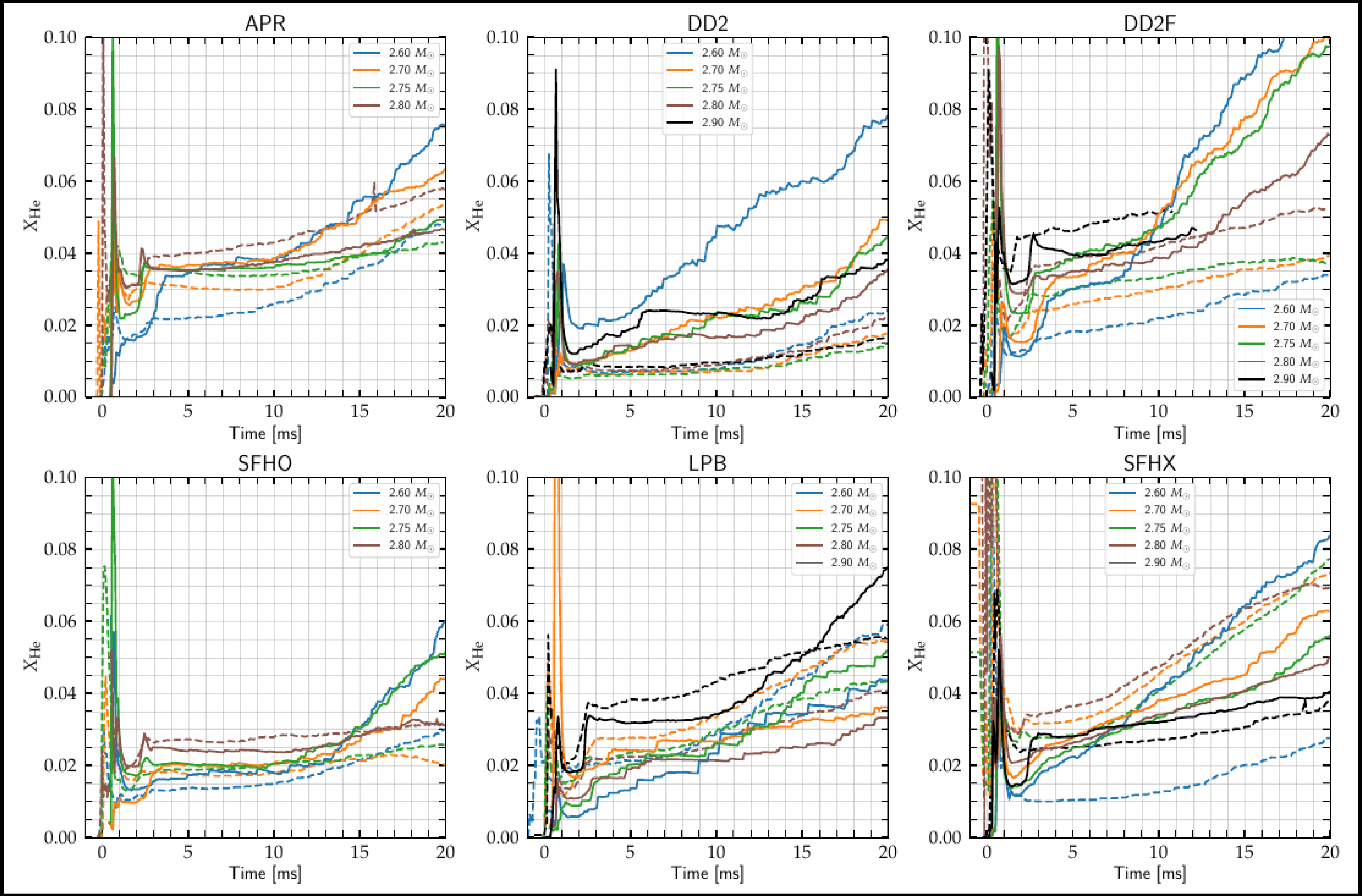
- Efficient He production only by long-lived merger remnants (producing neutrino driven wind with less neutron-rich outflows – after BH formation He production shuts off)
- Low He abundance → remnant in GW170817 collapse latest after 20-30 ms (short-lived)





Sneppen et al., PRD 2026, arXiv:2411.03427

- More models



Vijayan et al, in prep.

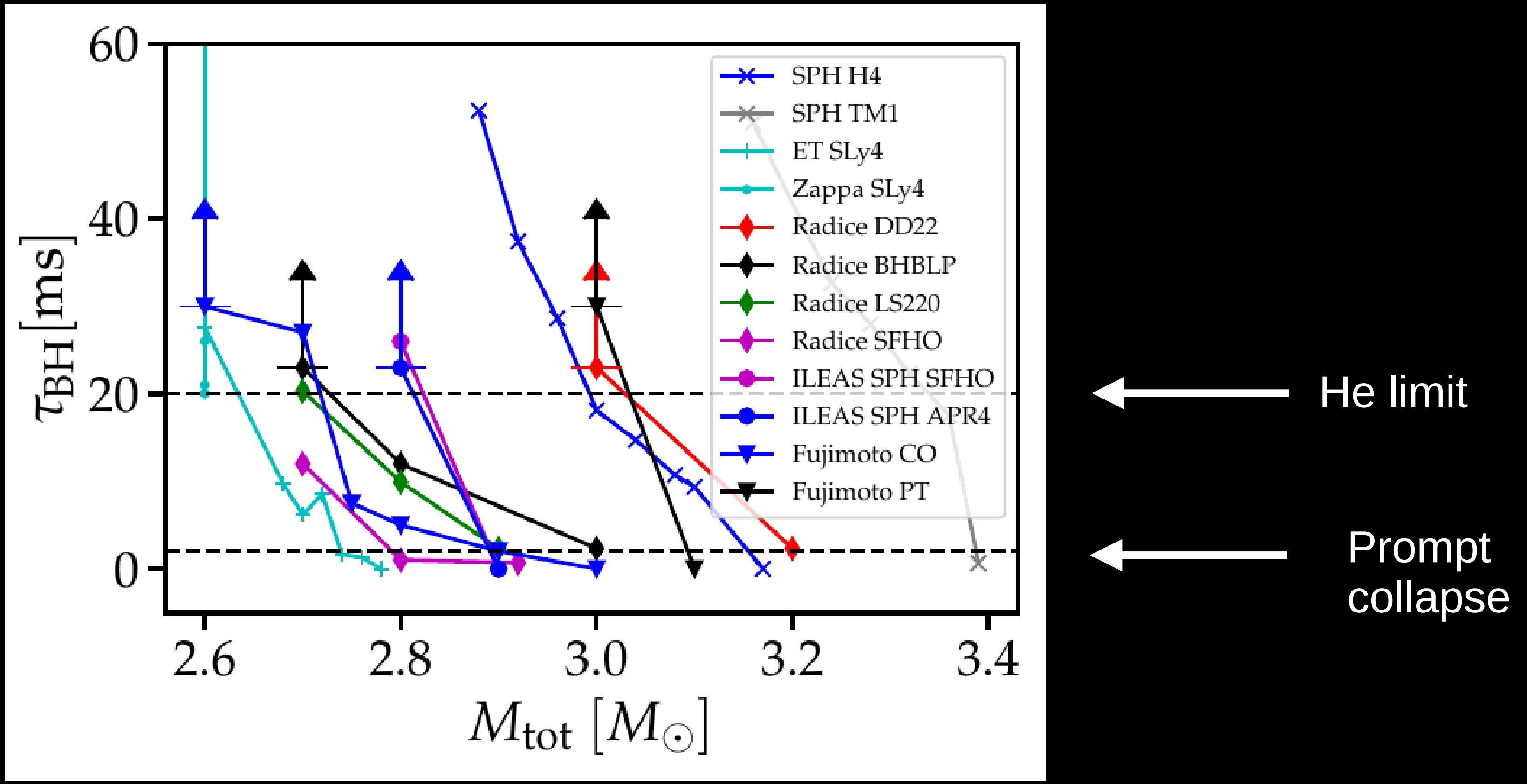
- What does a remnant life time below ~20 ms tell us?

→ "proximity" to M_{thres}

Short-lived remnant constraints M_{thres}

- Lifetime steeply declines with total binary mass reaching ~0 at M_{thres}
- Lifetime of ~20 ms implies that GW170817 was “close” to prompt collapse

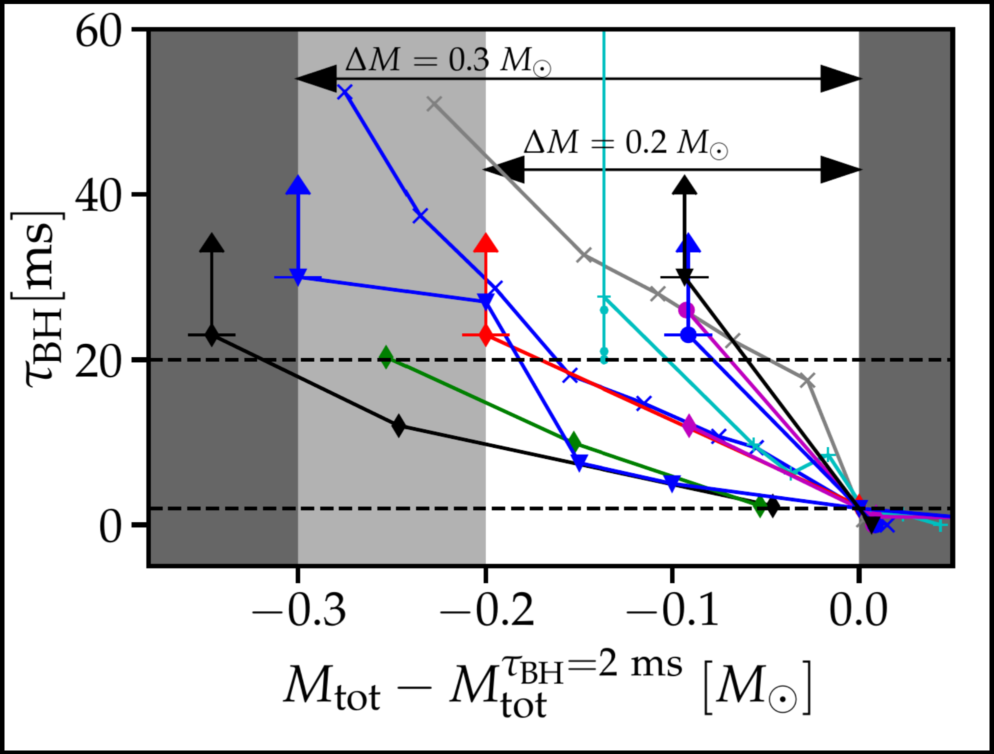
→ M_{tot}=2.73 M_{sun} => M_{thres} < 2.93 M_{sun}



Most studies avoid concrete limits for tau or favor long-lived model – recall GRB after 1700 ms

Sneppen et al., PRD 2026, arXiv:2411.03427

- Condensed in a single number: ΔM <= ~ 0.2 M_{sun}

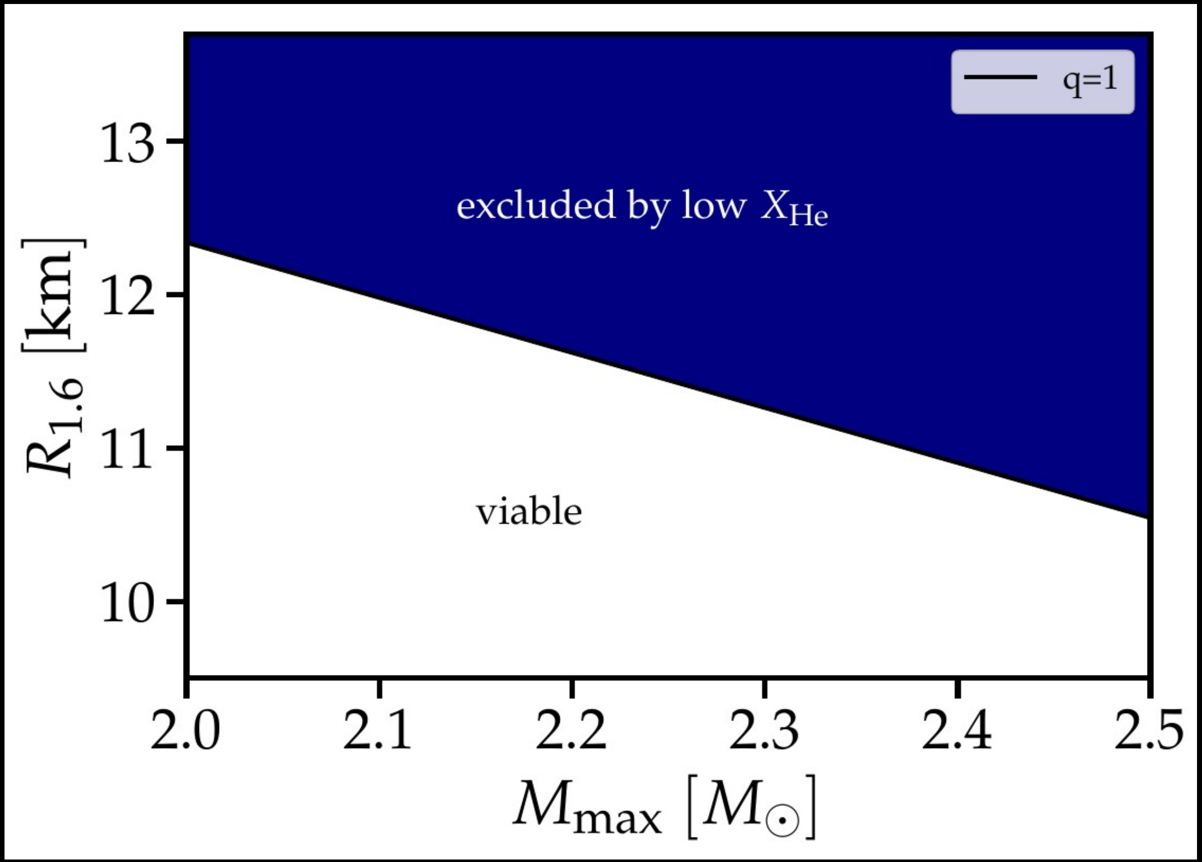


$$M_{\rm tot} + \Delta M > M_{\rm thres} \qquad\qquad \Rightarrow M_{\rm thres} \lesssim 2.9\, M_\odot$$

Sneppen et al., PRD 2026, arXiv:2411.03427

- Rough estimate: $aM_{\mathrm{max}} + bR + c = M_{\mathrm{thres}} \leq 2.9\ M_\odot$

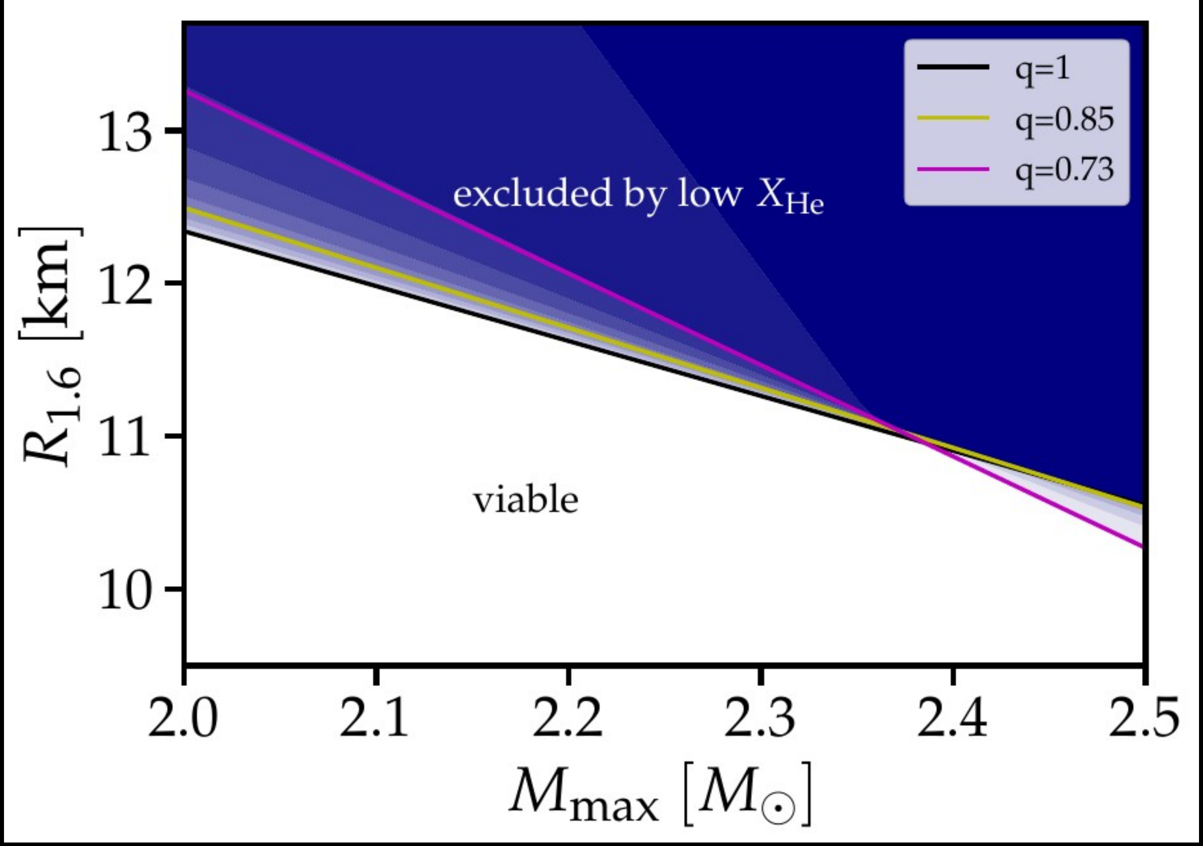
$$\Rightarrow \quad R \leq \frac{2.9\ M_\odot - c - aM_{\mathrm{max}}}{b}$$

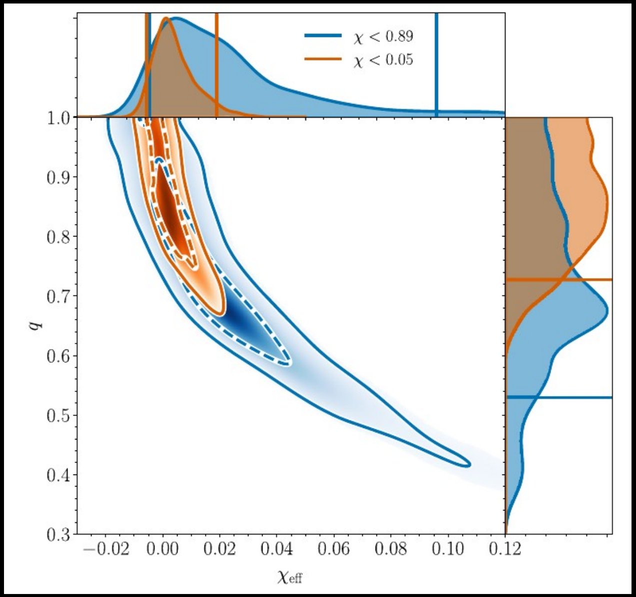


- Binary mass ratio

  → slightly effects M_{thres} (extended fit formula)

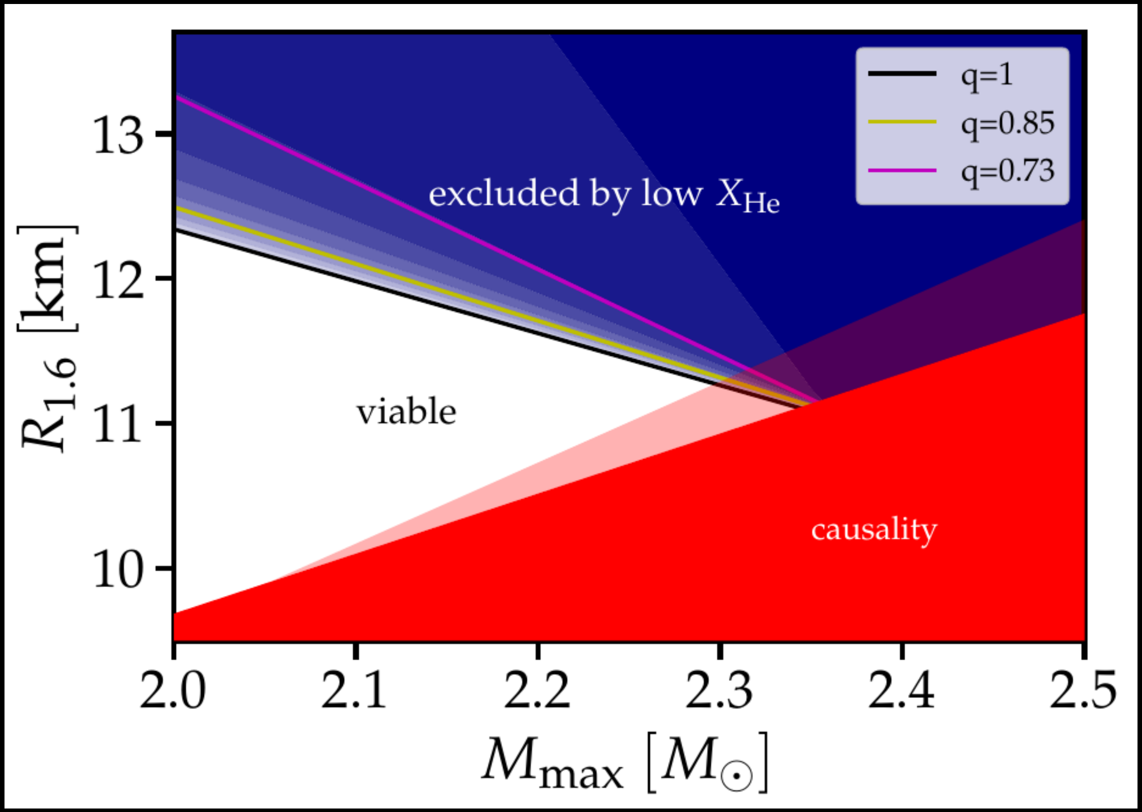
  → not precisely measured in GW170817 → M_{tot} not exactly known



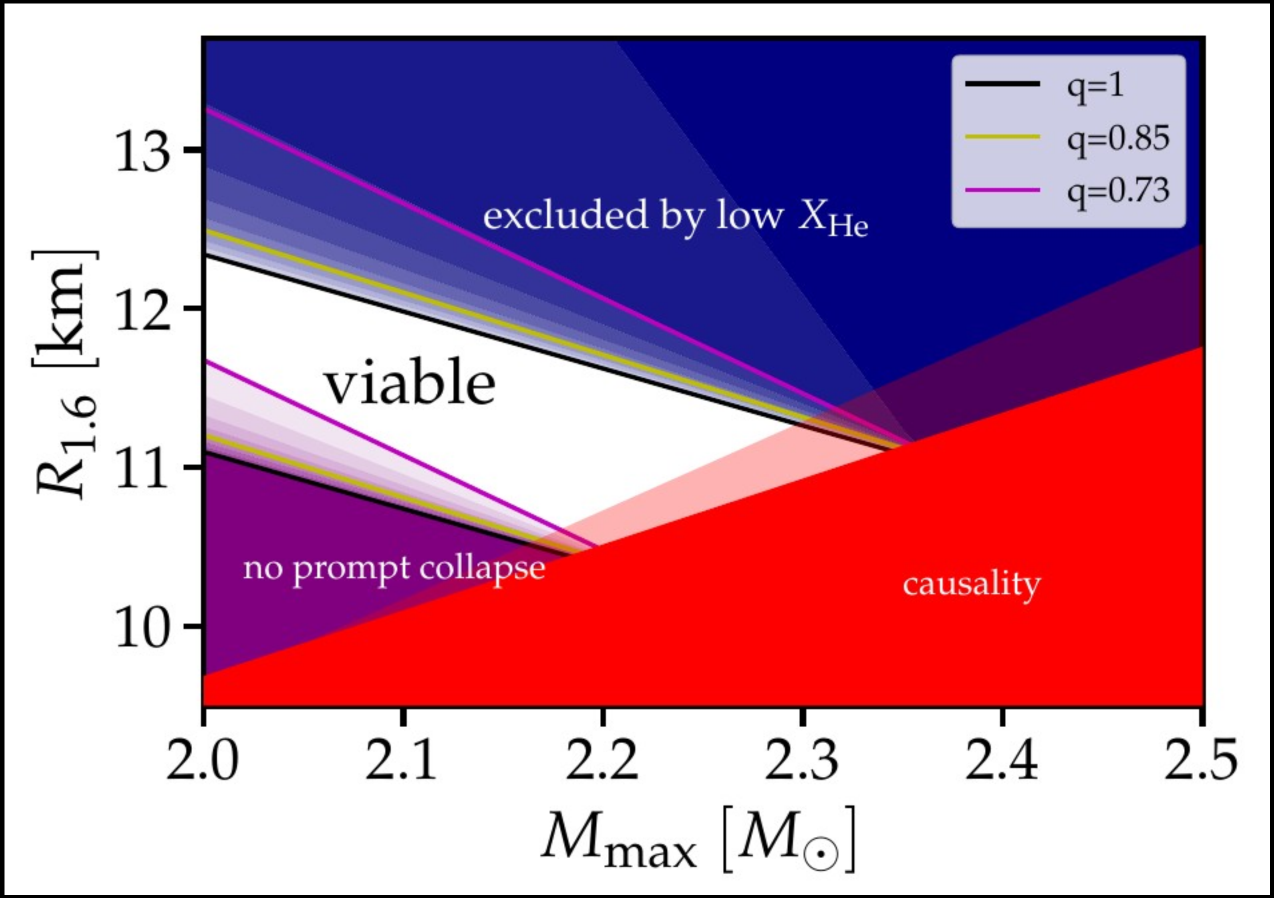


- Causality limits allowed range of TOV properties

→ combination limits M_{max} < 2.3 M_{sun}



- Additional independent constraint: $M_{tot} < M_{thres}$

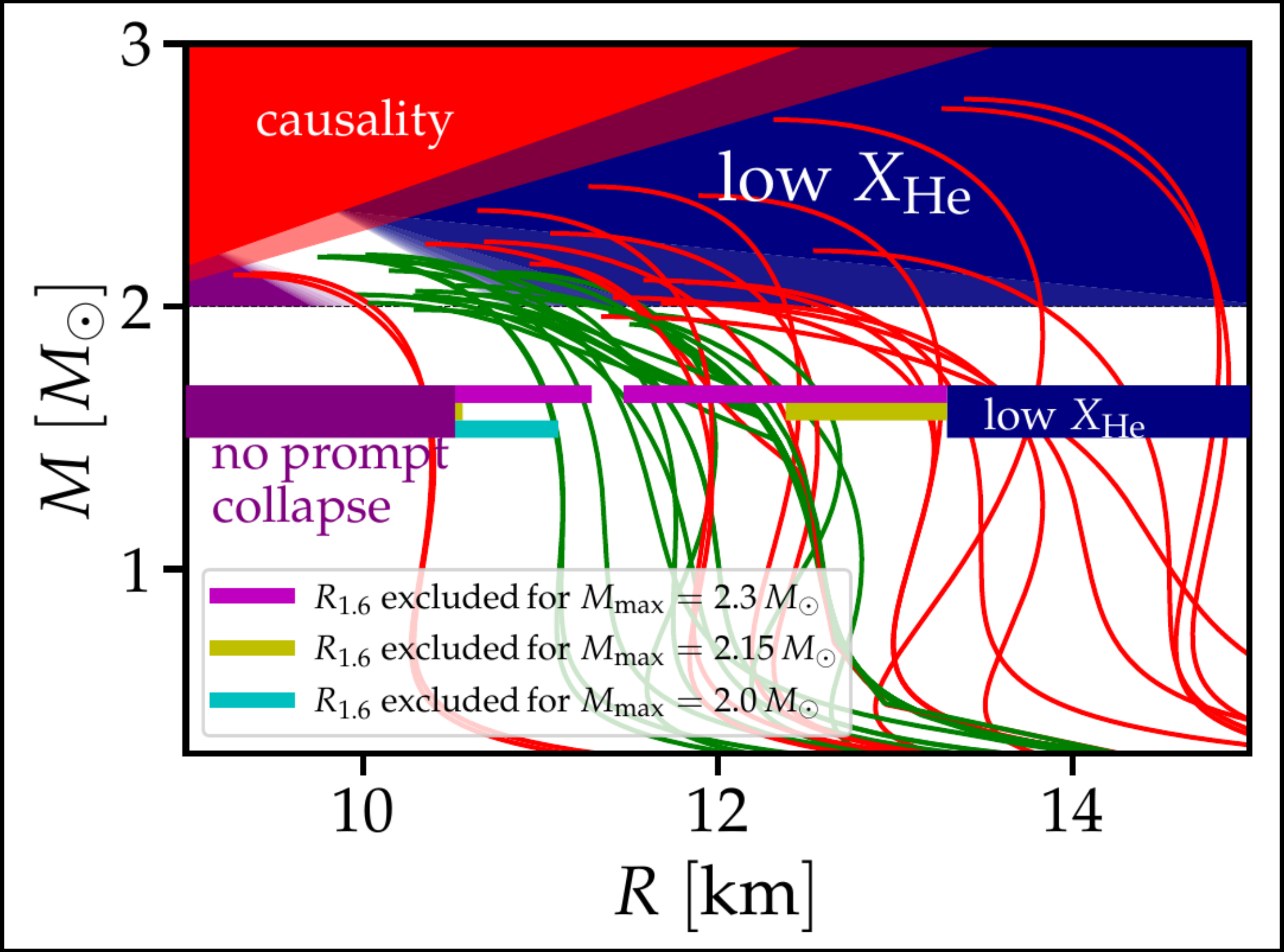


Refined version of the arguments in Bauswein et al. 2017 including M_{max} dependence and q distribution

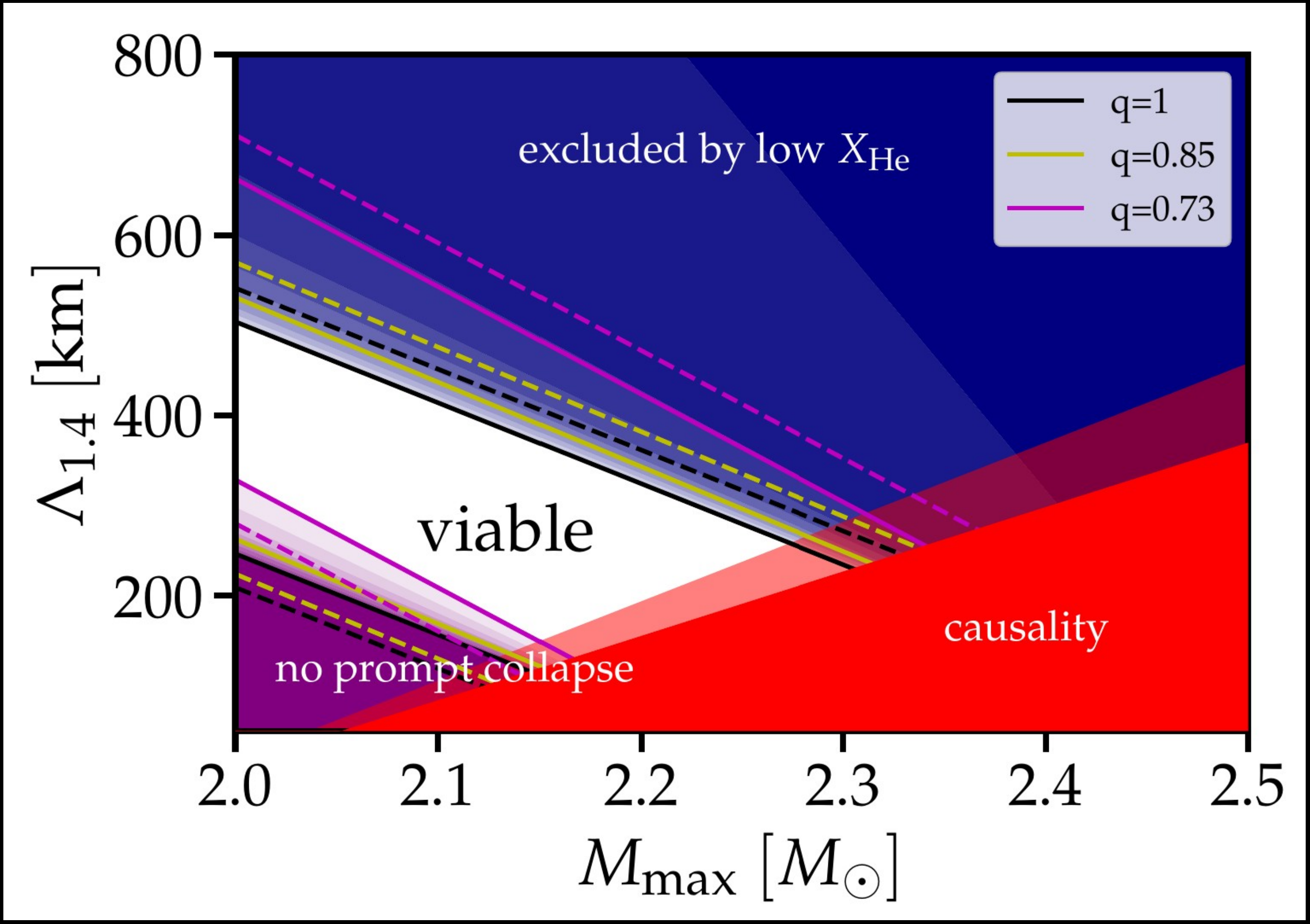
Sneppen et al., PRD 2026, arXiv:2411.03427

Constraints on EoS/NS parameters

- $M_{max} < 2.3\ M_{sun}$
- Radii limited to narrow range (sliding window)
- Rules out a number of current EoS models



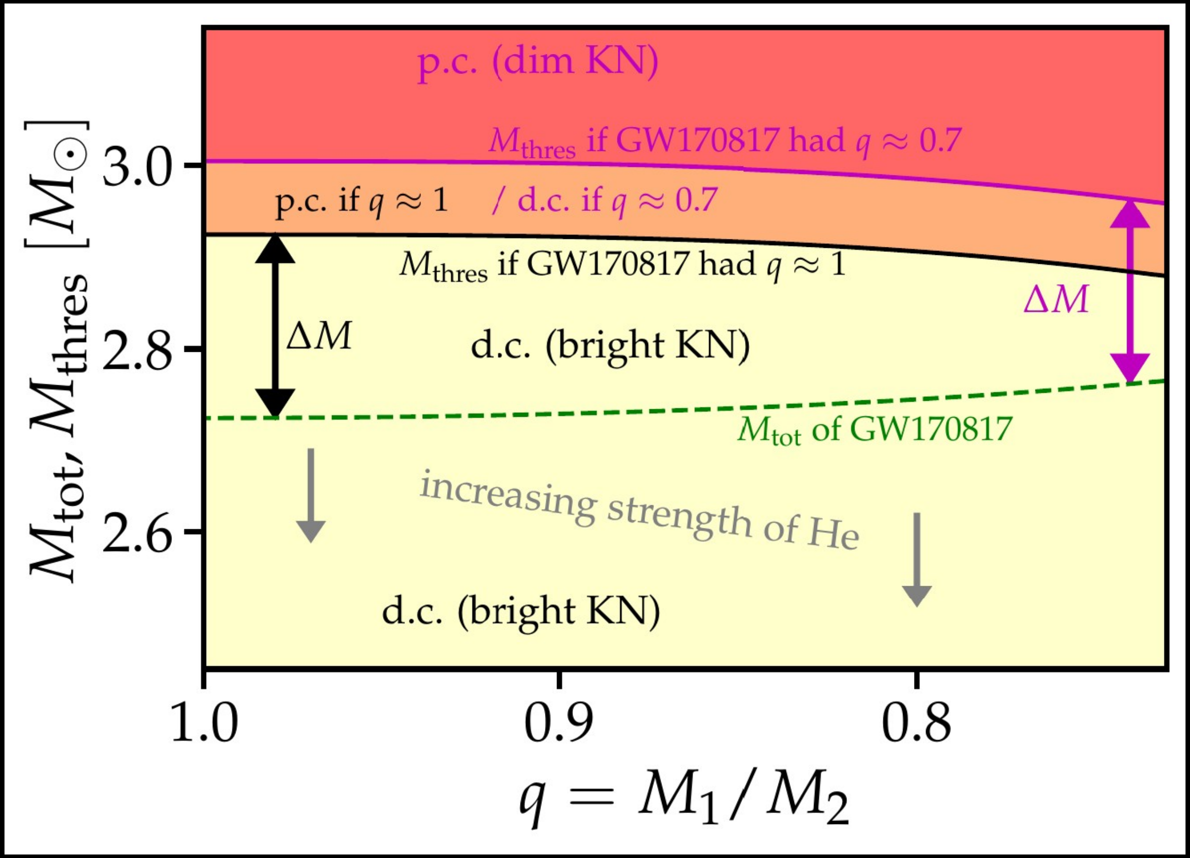
Sneppen et al., PRD 2026, arXiv:2411.03427



Sneppen et al., PRD 2026, arXiv:2411.03427

Predictions

- Increasing strength of He for lower Mtot
- Dim kilonova for somewhat more massive binary
- But we do not know the exact value of ΔM
- Btw, if correct the GRB in 170817 was powered by a BH



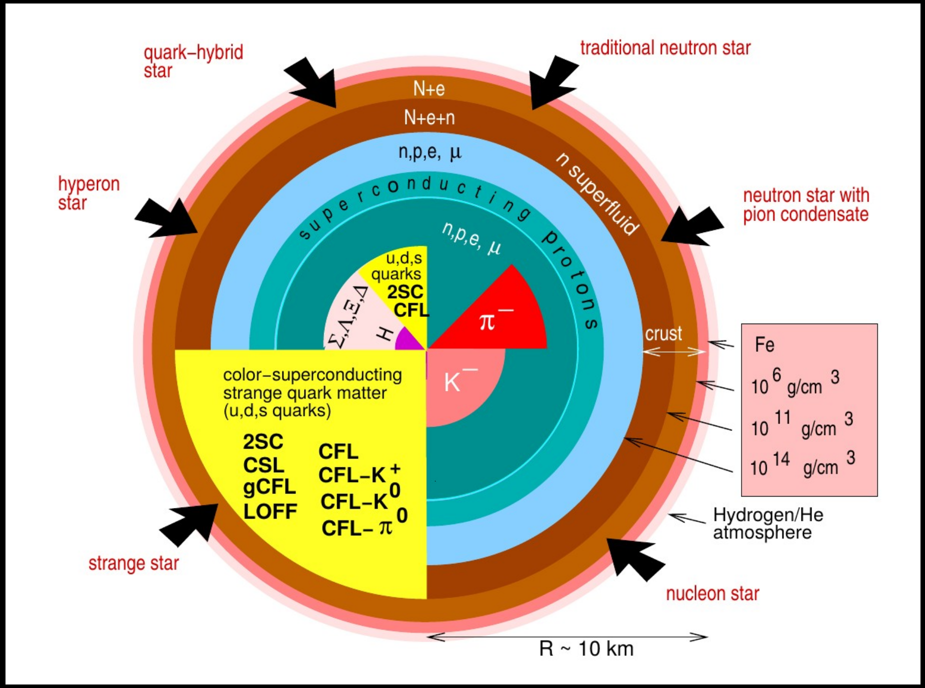
Sneppen et al., PRD 2026, arXiv:2411.03427

Hyperons in neutron stars

Motivation

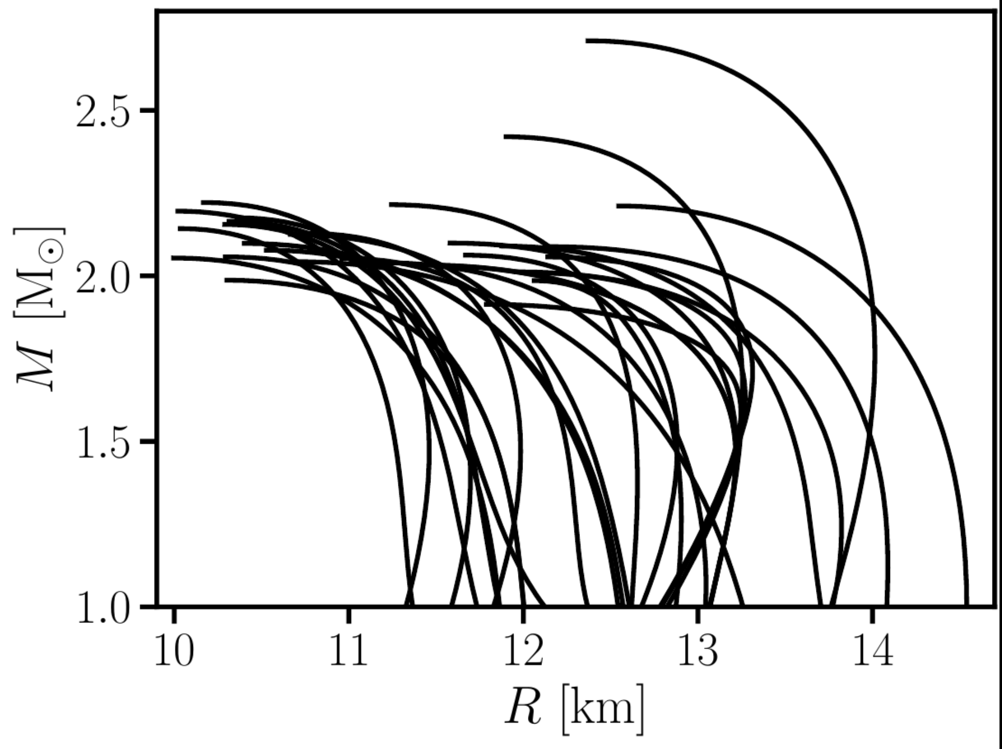
- Are there hyperons in neutron stars ?

  → What can astro observations tell us (one day) ?

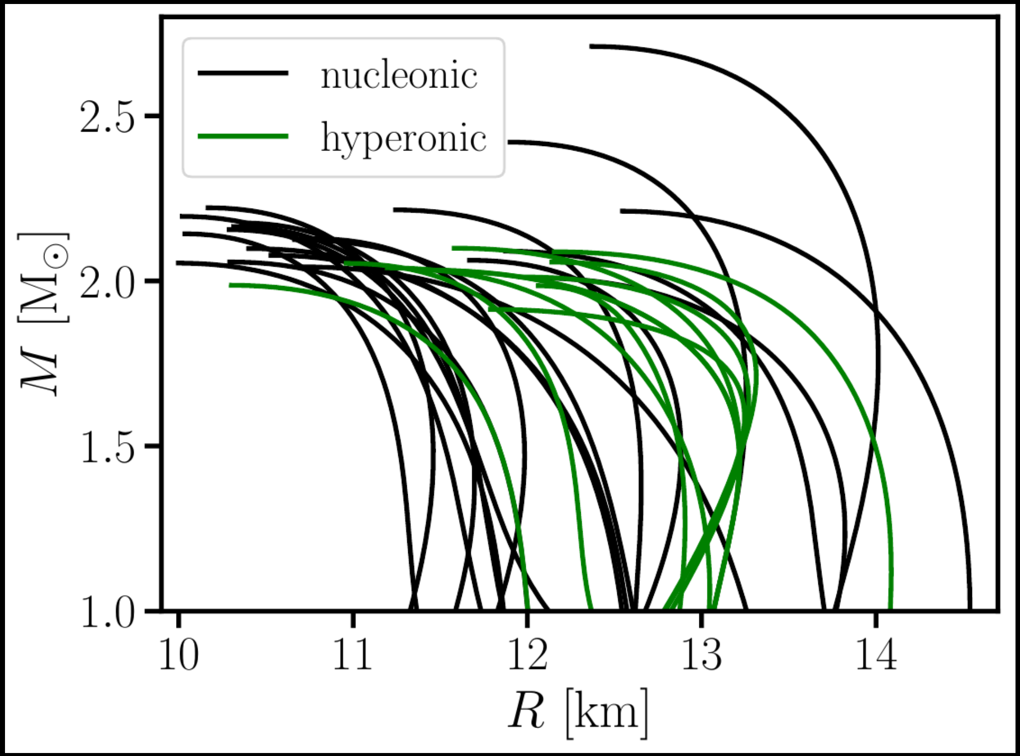


Weber 2004

- One day we will hopefully measure NS radii well enough to get a decent idea about M-R relation
- Which one is hyperonic ?



Blacker et al. 2024



Blacker et al. 2024

- So far there is no quantitative measure known based on which one could infer the presence of hyperons from stellar structure parameters !!

Disclaimer:

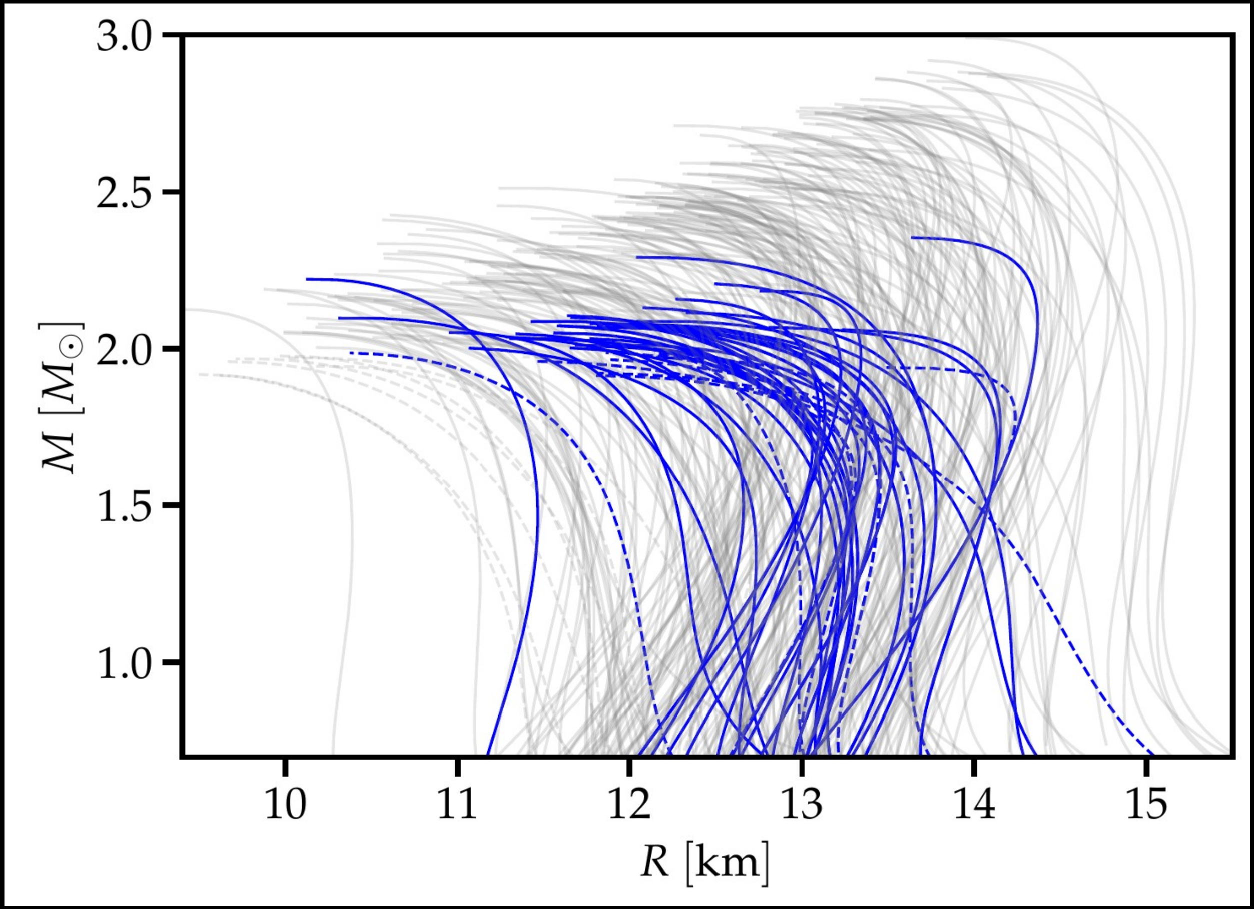
- “measurable” = very challenging but not impossible to measure

- “hyperons” = non-nucleonic degrees of freedom

- There is the tendency that hyperonic models show a stronger “bending”

  - but how to quantify ? (straightforward attempts fail; cf. slope)

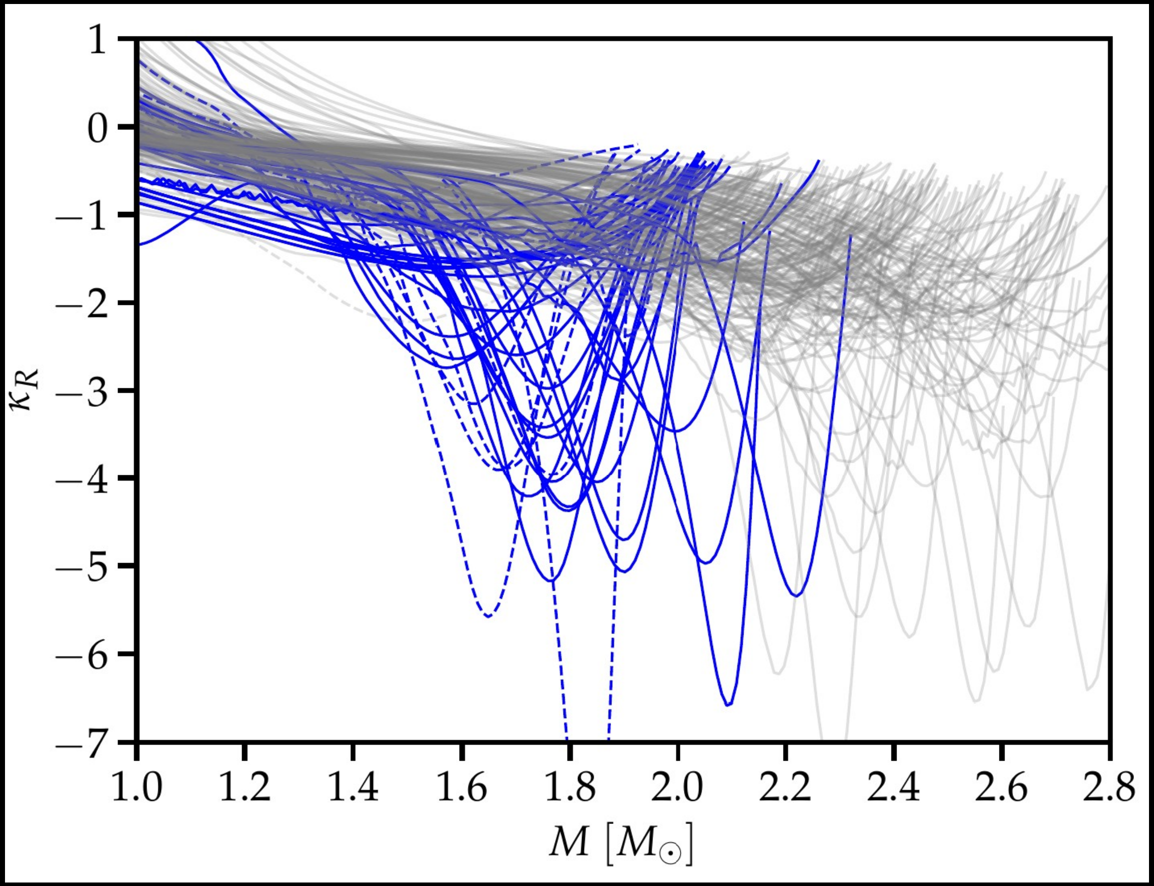
  - btw, related to the study presented by Just (He absence → small M_{max}, larger R)



PRR (2026), arXiv:2507.10372

→ curvature = inverse of curvature radius

$$\kappa_R = \frac{d^2R}{dM^2}\left(1+\left(\frac{dR}{dM}\right)^2\right)^{-3/2}$$



Note 1: Second derivative alone one does not see anything
Note 2: it’s better to use R(M) rather than the usual M(R)

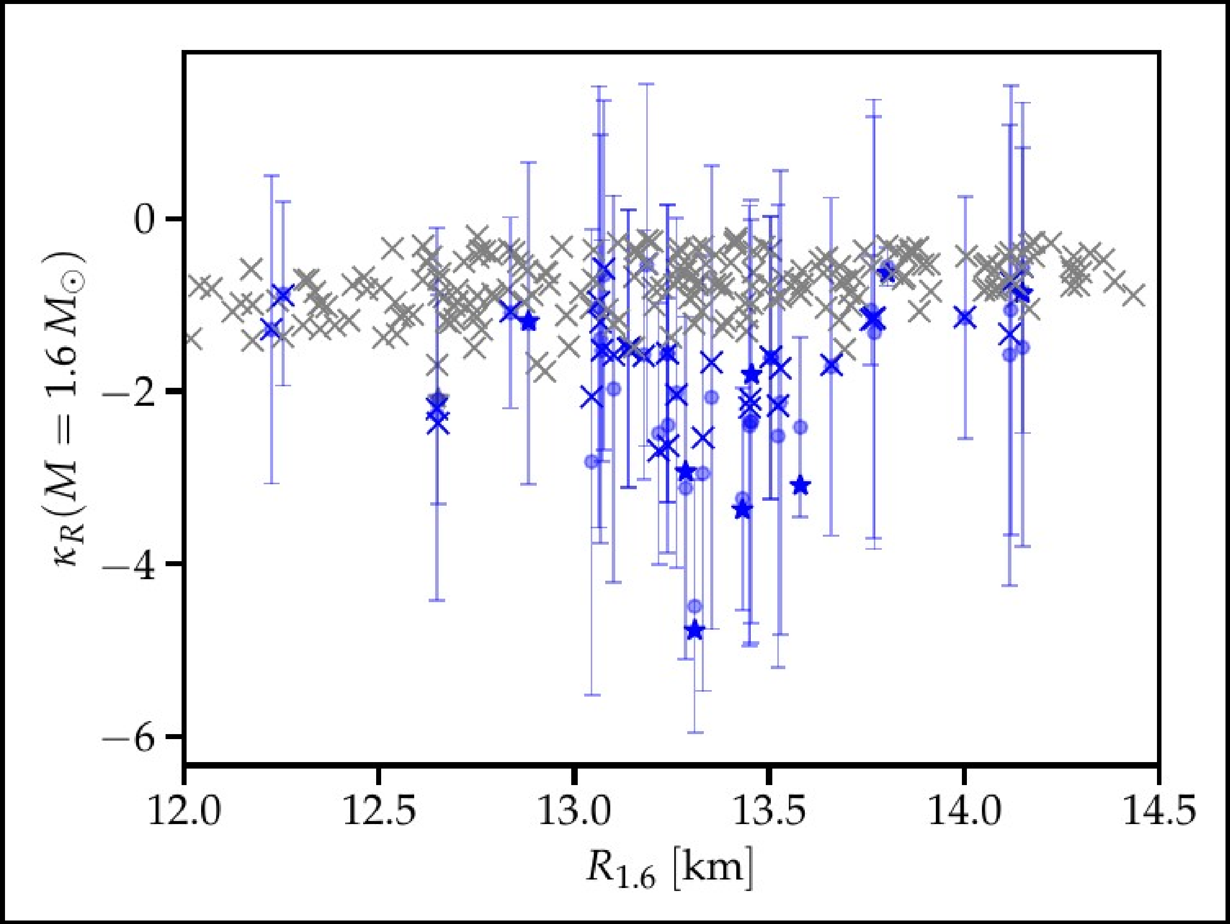
PRR (2026), arXiv:2507.10372

- Derivatives from "finite differening", i.e. R at three different M
- Two sources of error

  - "discretization error" → small for measurements at sufficiently disparate M

  - radius error propagated through finite difference formula

  → for ~100m it gets interesting (challenging but maybe not impossible)



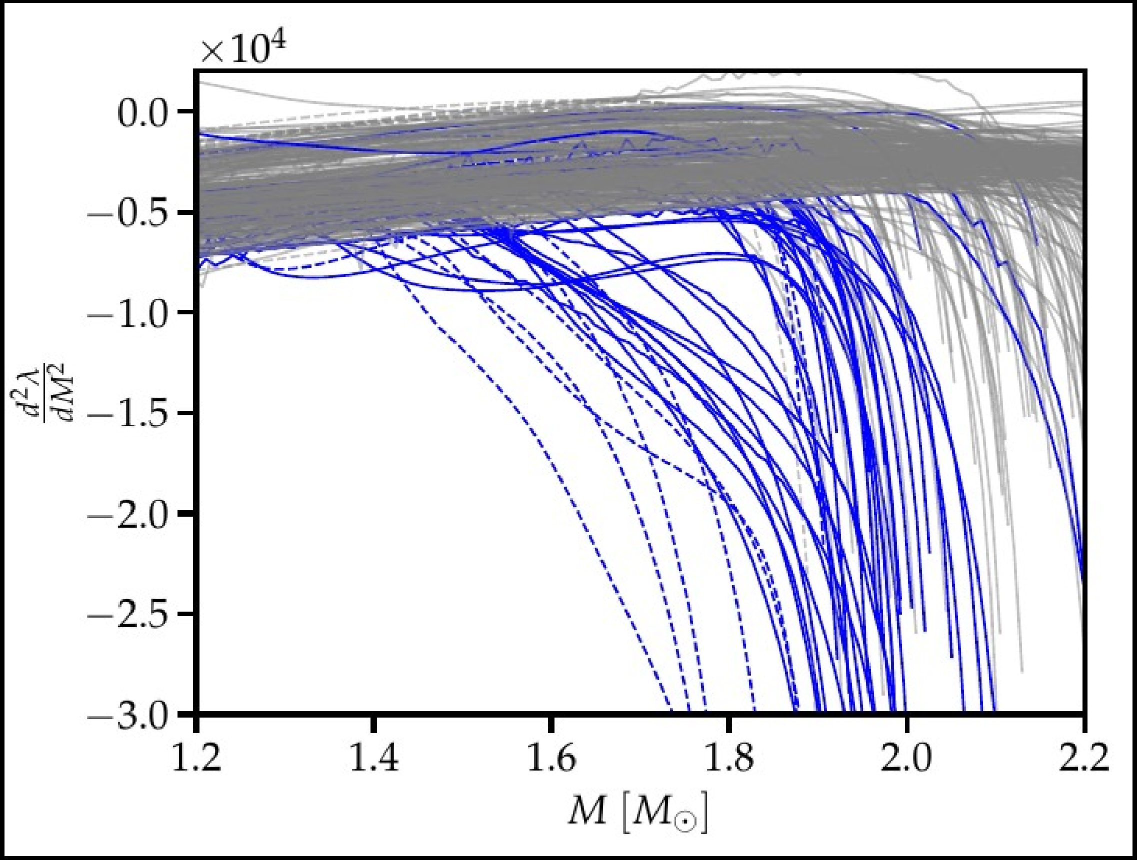
$$\delta R = 100\ m$$

$$\Delta M = 0.25\ M_\odot$$

PRR (2026), arXiv:2507.10372

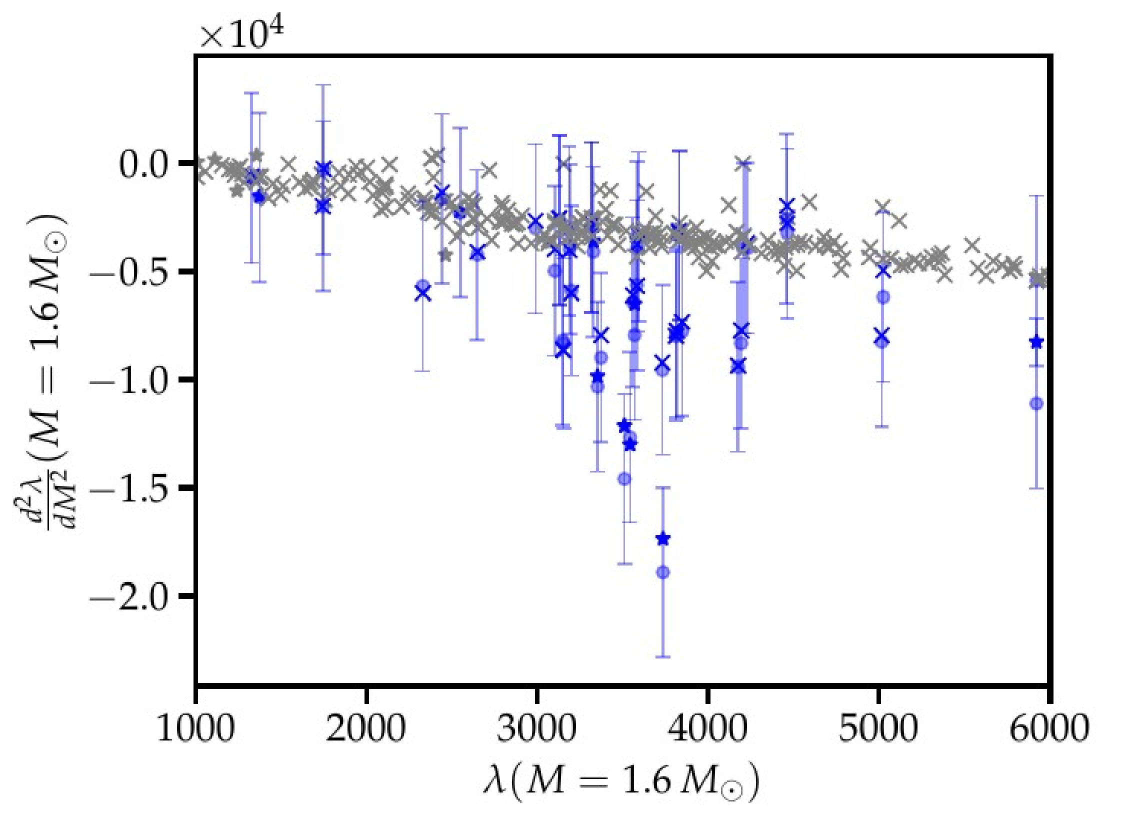
- Tidal deformability potentially easier to measure

  = parameter determining the GW signal of NS merger inspiral $\lambda = \frac{2}{3} k_2 R^5$



PRR (2026), arXiv:2507.10372

- ~10% accuracy in lambda may be sufficient (at three different masses)

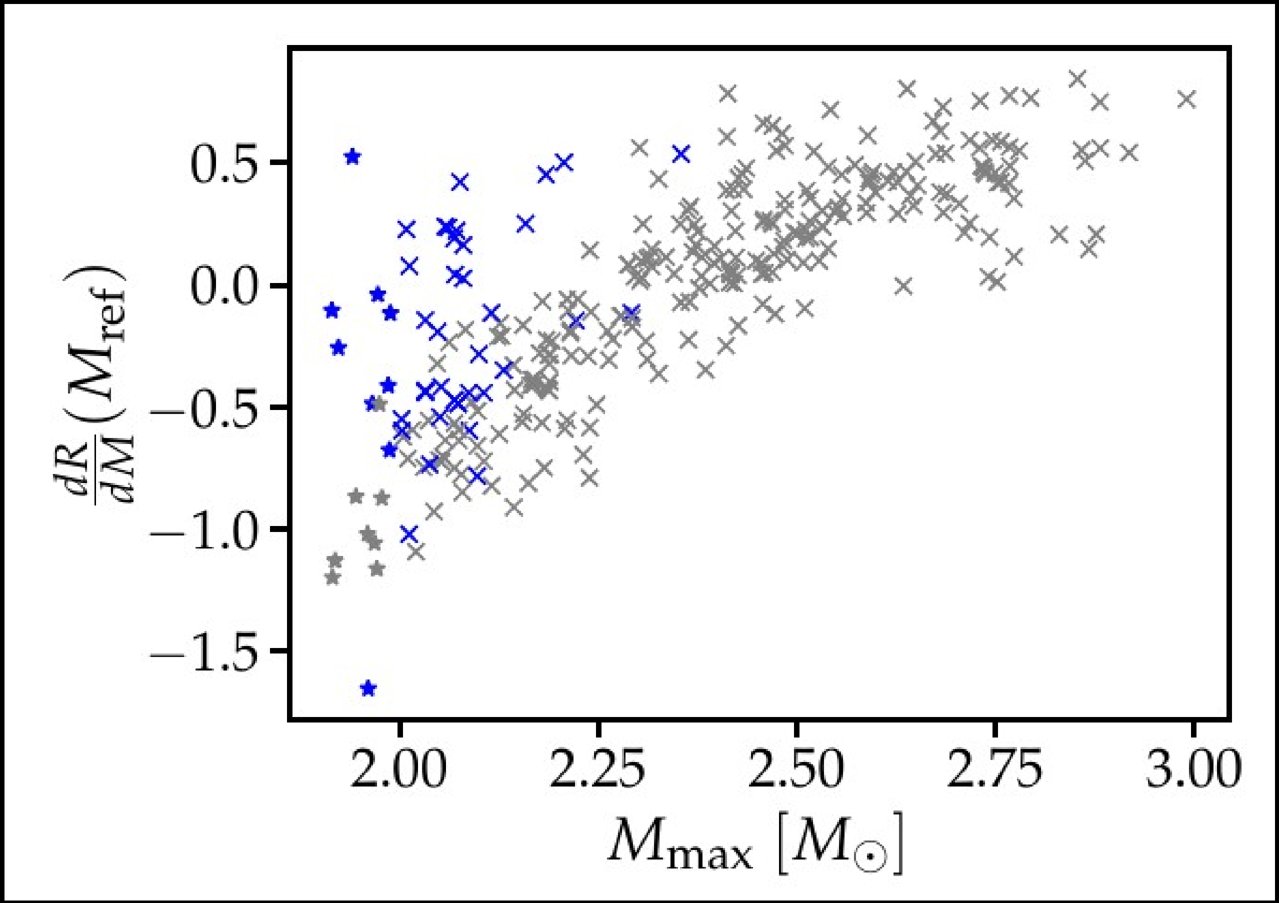


$$\delta\lambda = 100$$

$$\Delta M = 0.25\ M_\odot$$

PRR (2026), arXiv:2507.10372

- Slope (i.e. first derivative) only useful if Mmax is known, otherwise not indicative of hyperons



At 1.6 M_{sun}

PRR (2026), arXiv:2507.10372

cf. Ferreira & Povidencia 2025 for statistical arguments

Summary

- Considering helium in the kilonova seems a decent tracer for remnant life time
- (apparent) absence of helium yields upper limit on M_{thres}

  → upper limit on Radius/ Lambda (Mmax dependent)

  → upper limit on Mmax (<2.3 Msun)

  - significant q dependence

  - predictions what to expect for future events; potential for better NS constraints
- Lower limits on R from kilonova brightness
- Softening of EoS by hyperons modifies stellar parameters characteristically

  → consider curvature

  → per cent measurement of several NSs can yield evidence for non-nucleonic degrees of freedom

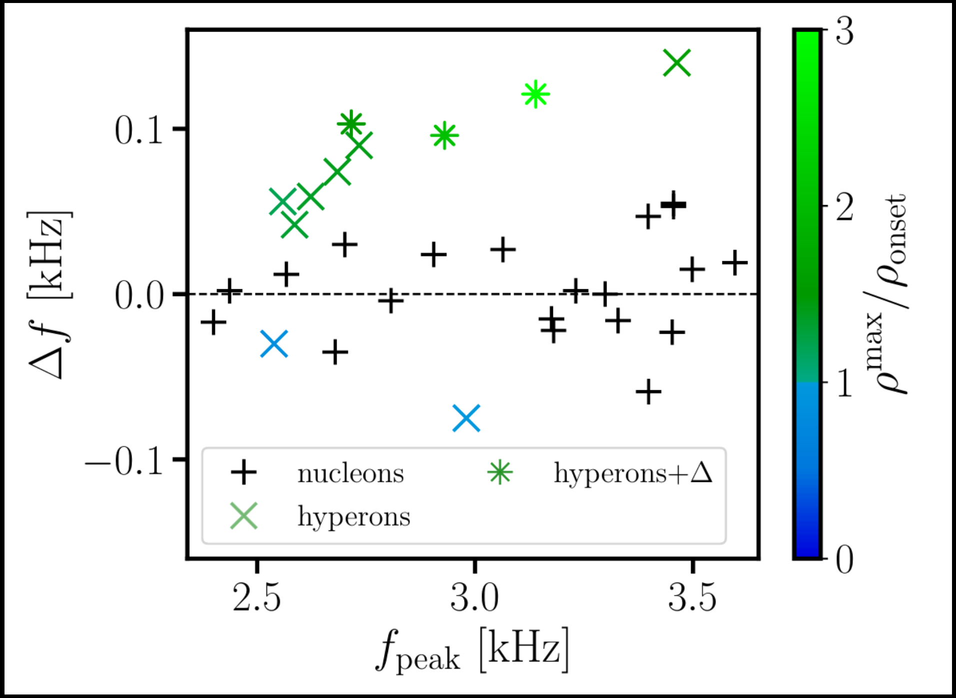
Discussion

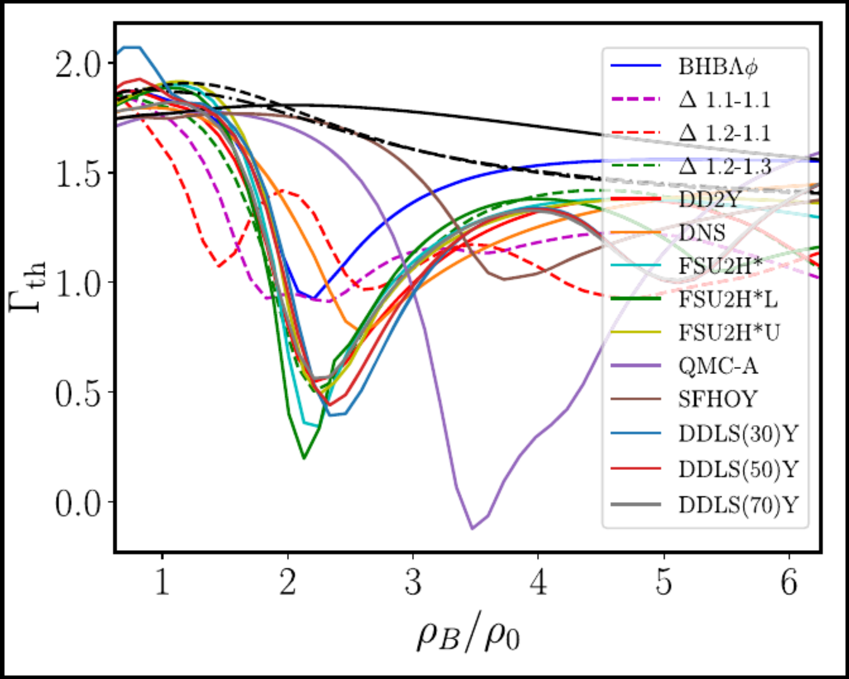
- Certainly challenging to measure – on the other hand the first quantitative feature of hyperons in M-R relation
- Refinements possible, Bayesian analysis
- Curvature may also be high when hyperons are present
- Quark matter may also lead to small curvature – but actually with a kink in the M-R relation (if transition is first order)

Hyperons in mergers

- Hyperons modify the thermal behavior of the EoS – generally small effects

$$\Delta f_{\mathrm{peak}} = f_{\mathrm{peak}} - f_{\mathrm{peak}}^{\Gamma_{\mathrm{th}}=1.75}$$





Comprehensive studies in Blacker et al., PRD 109 (2024), Kochankovski et al., PRD 112 (2025) → GWs, mass ejection, threshold mass, ...