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Hyperons in neutron stars and neutron star mergers

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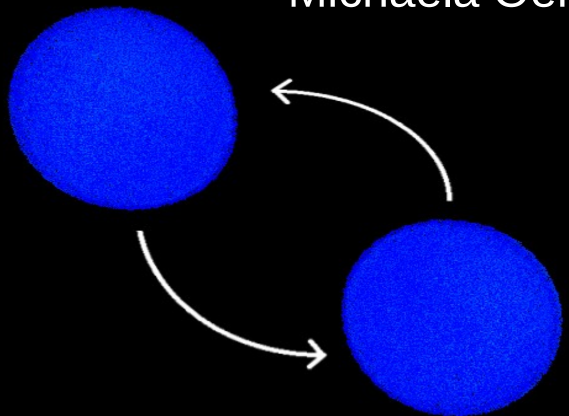
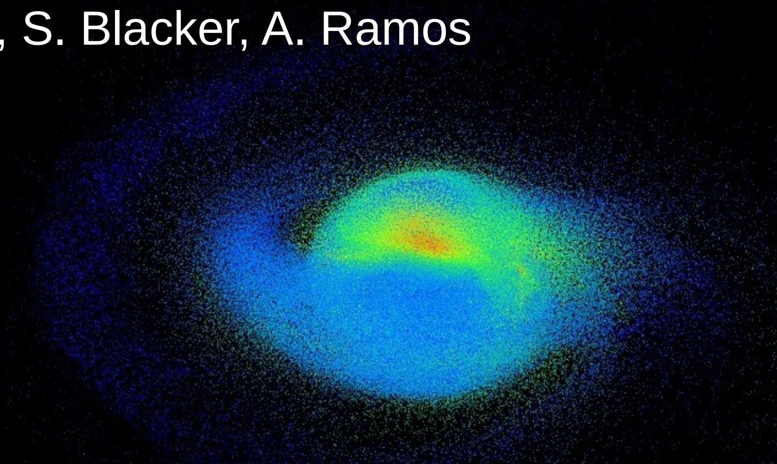




Motivation

- Are there hyperons in neutron stars ?

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

Motivation

Disclaimer:

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

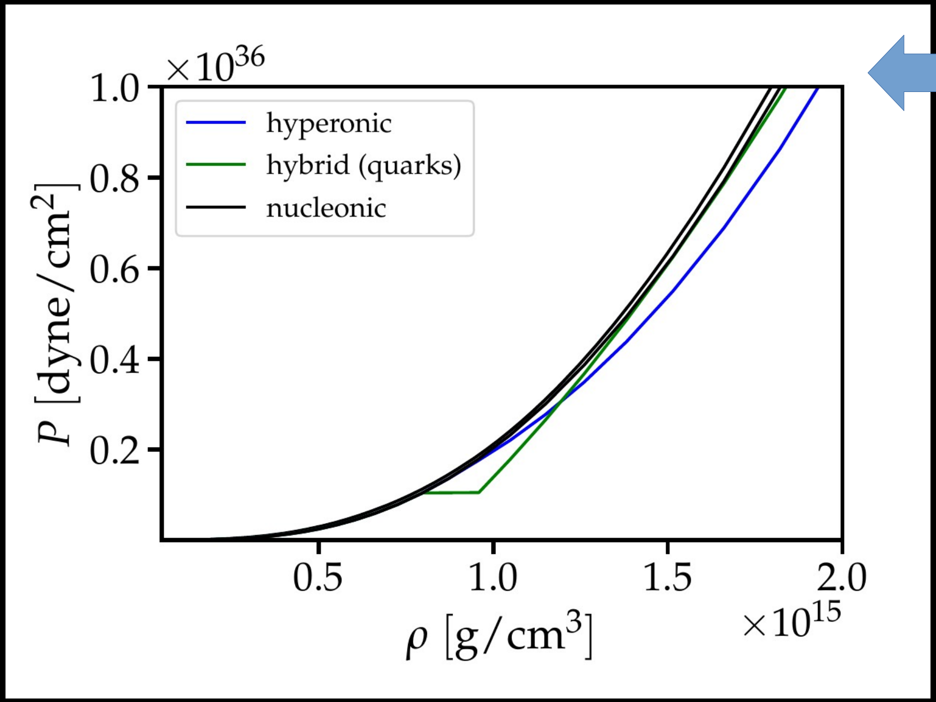
- “hyperons” = non-nucleonic degrees of freedom

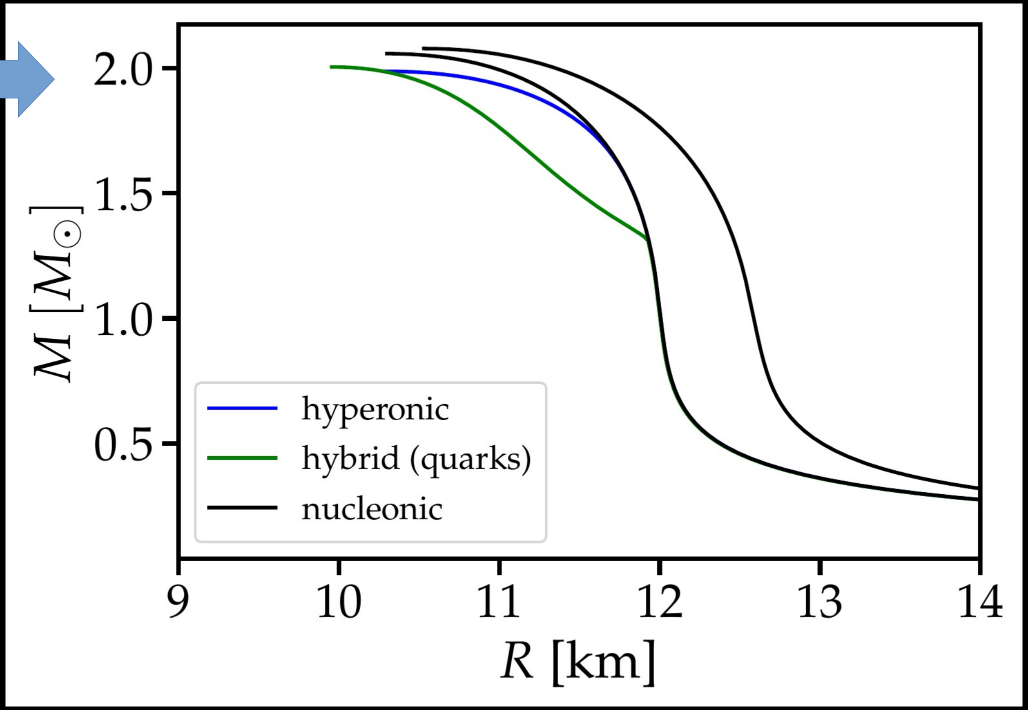
Outline

- Impact of hyperons on stellar structure of isolated neutron stars
- Impact of hyperons in binary neutron star mergers

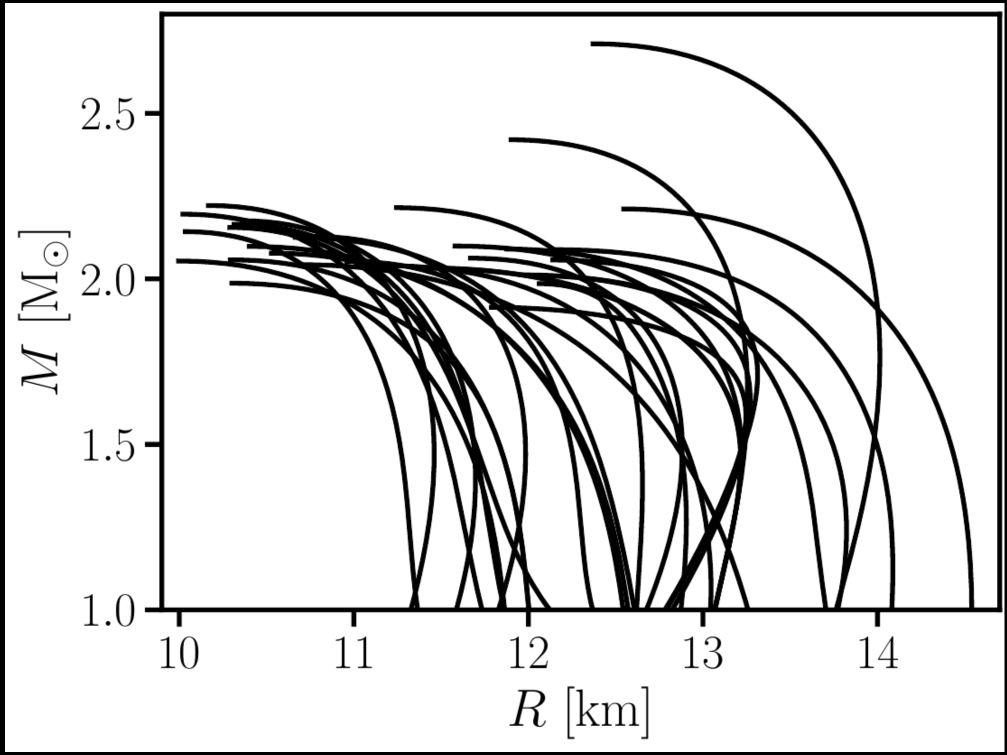
"Hyperon puzzle"

- If hyperons occur, EoS is expected to be softened
- Tension with observations of NS with M~2.0 Msun (which requires a certain stiffness) ?? = "hyperon puzzle"
- Several EoS models exist which contain hyperons and reach 2 Msun

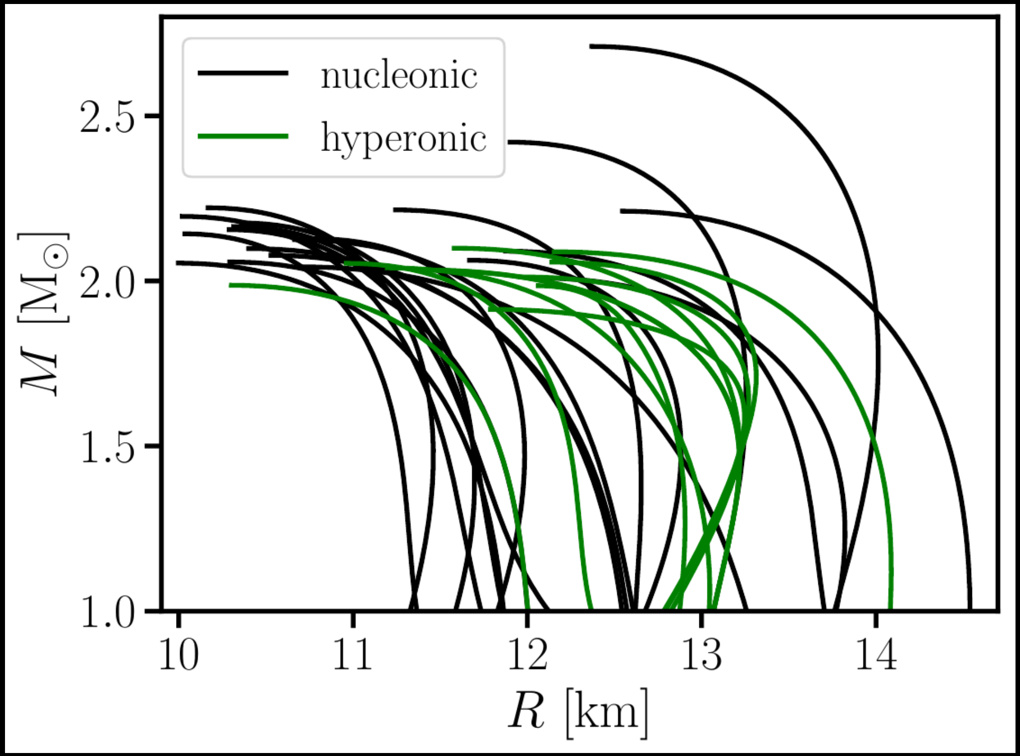




- One day we will hopefully measure NS radii well enough to get a decent idea about M-R relation
- Which one is hyperonic ?



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 !!

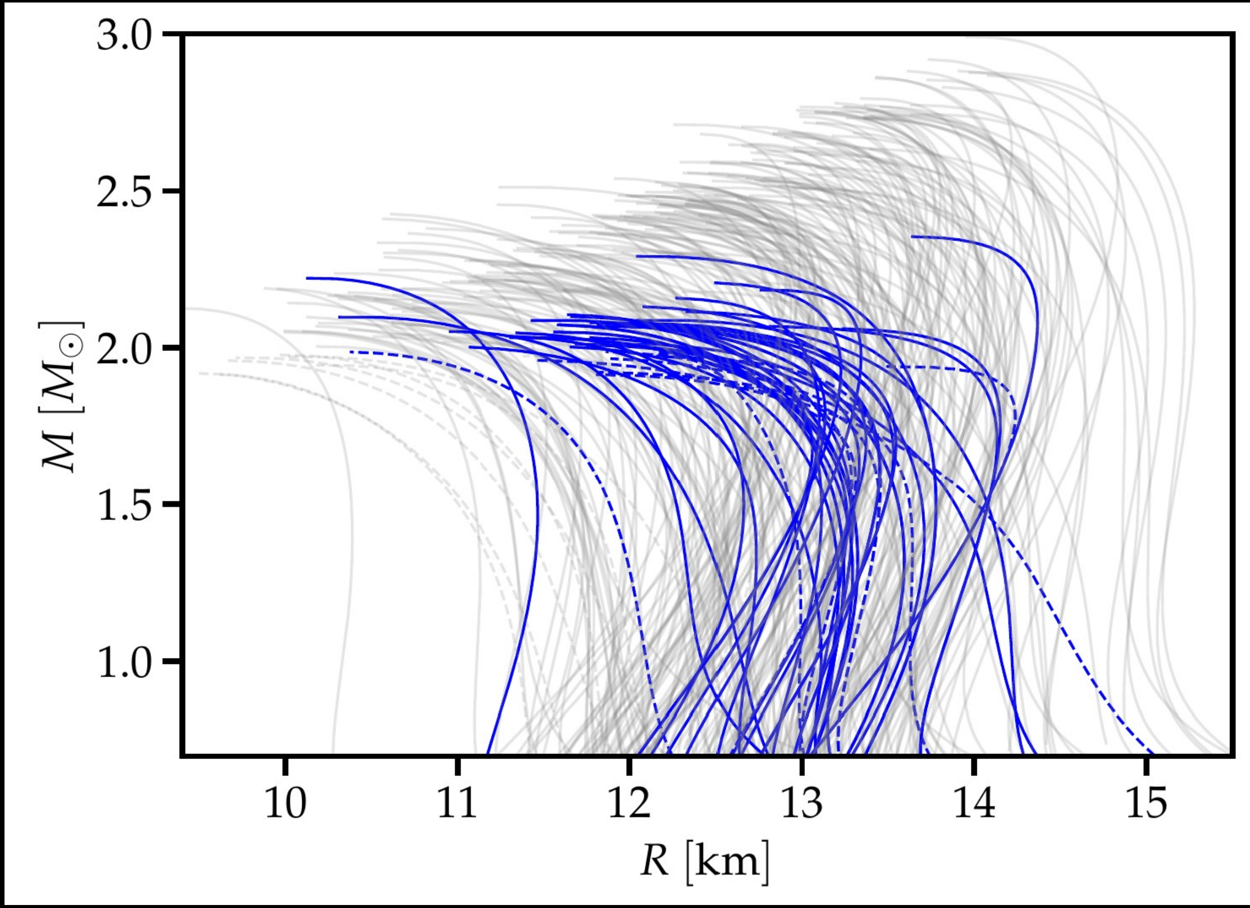
- statistical argument considering slope at lower masses (Ferreira & Povidencia 2025); positive slope a bit counterintuitive because it means stiff

$M/M_\odot$	1.2		1.4		1.8	
$dM/dR\|_M$	-	+	-	+	-	+
hyperonic	95	16,501	193	15,953	16,146	0
nucleonic	13,025	4,511	16,023	1,514	17,537	47

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

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

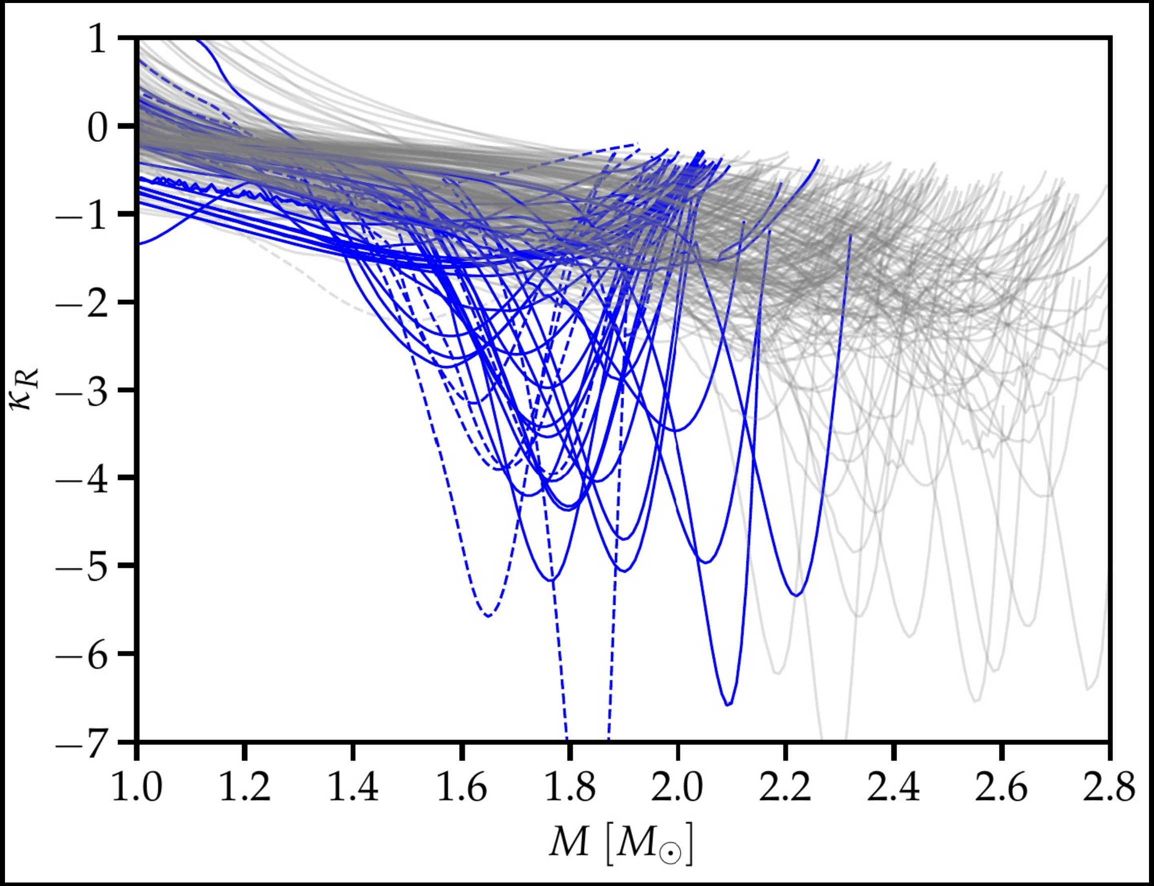
  - btw, related to the study presented by Just (He absence → small Mmax, larger R)



arXiv:2507.10372

→ curvature = inverse of curvature radius

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



arXiv:2507.10372

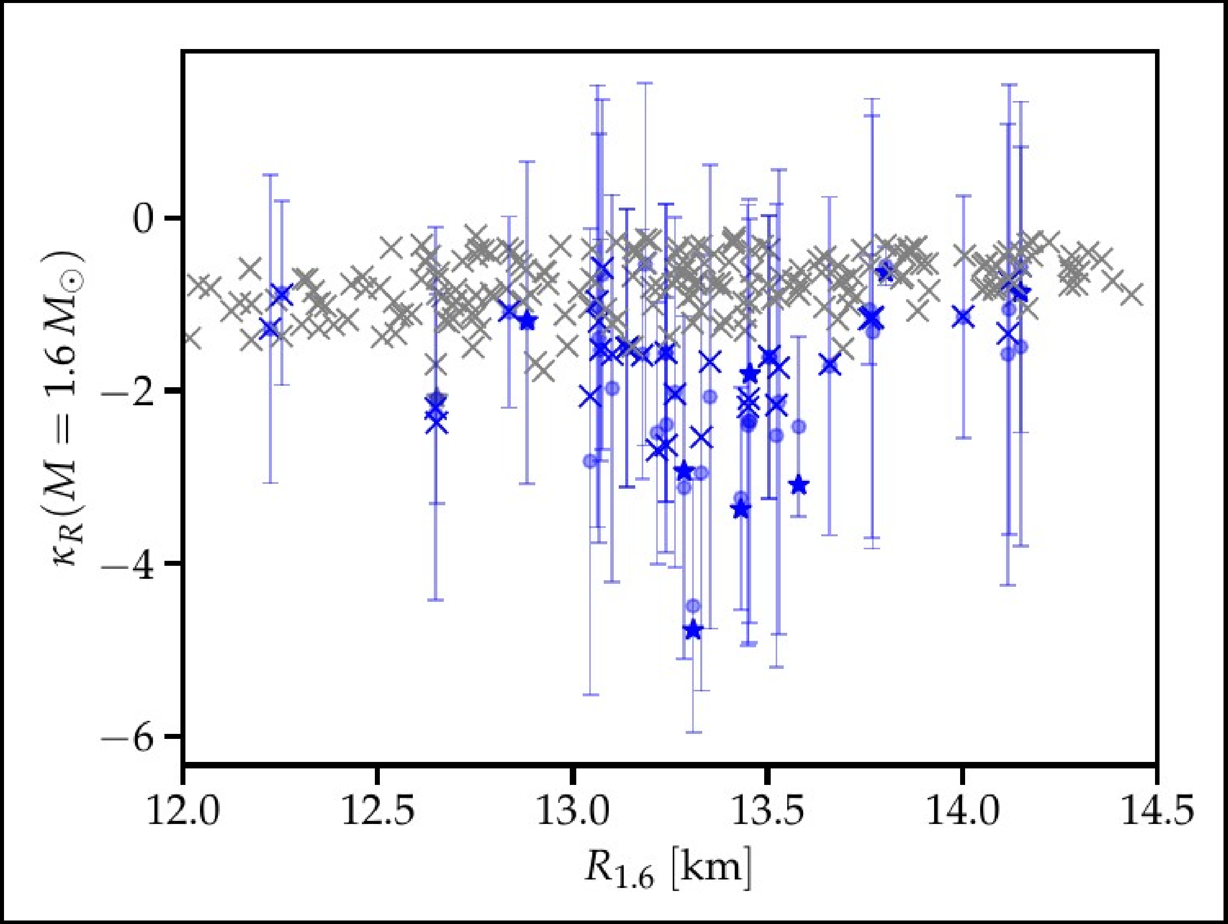
Note 1: Second derivative alone one does not see anything
Note 2: it’s better to use R(M) rather than the usual M(R)

- 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)



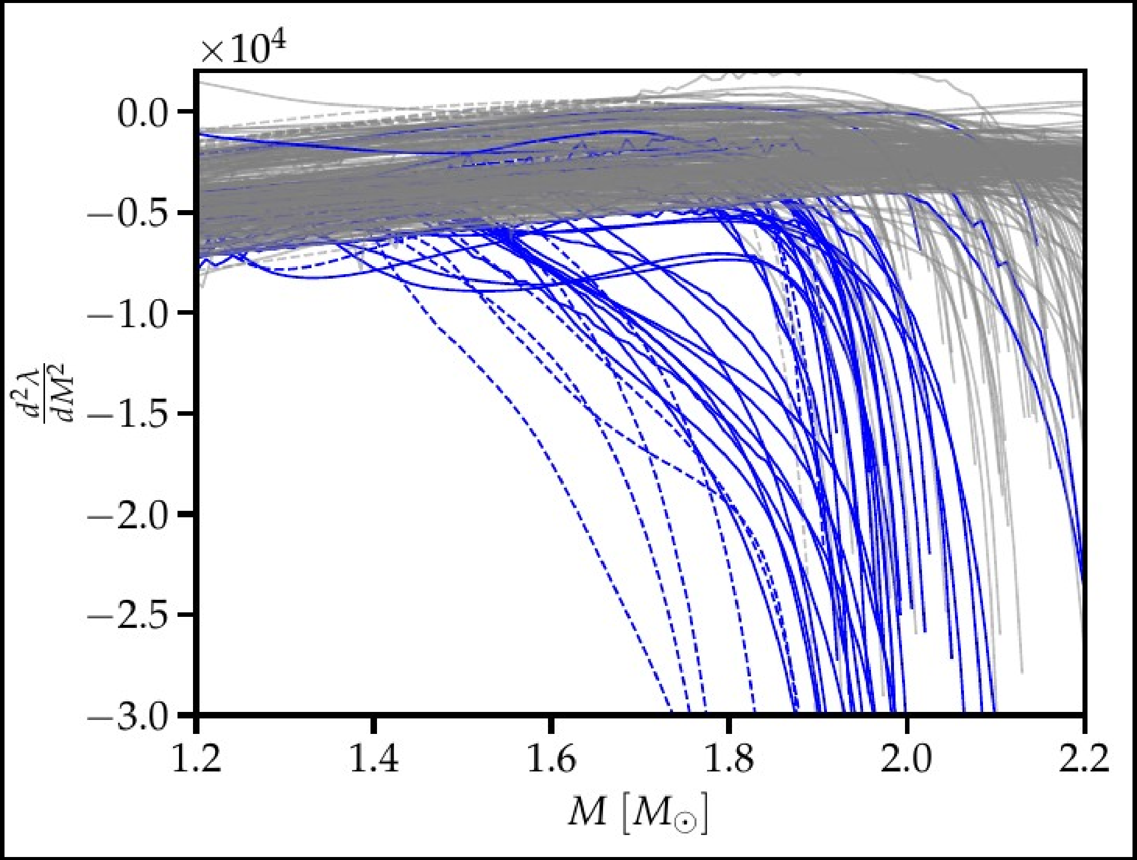
$\delta R = 100\ m$

$\Delta M = 0.25\ M_\odot$

arXiv:2507.10372

- Tidal deformability potentially easier to measure

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



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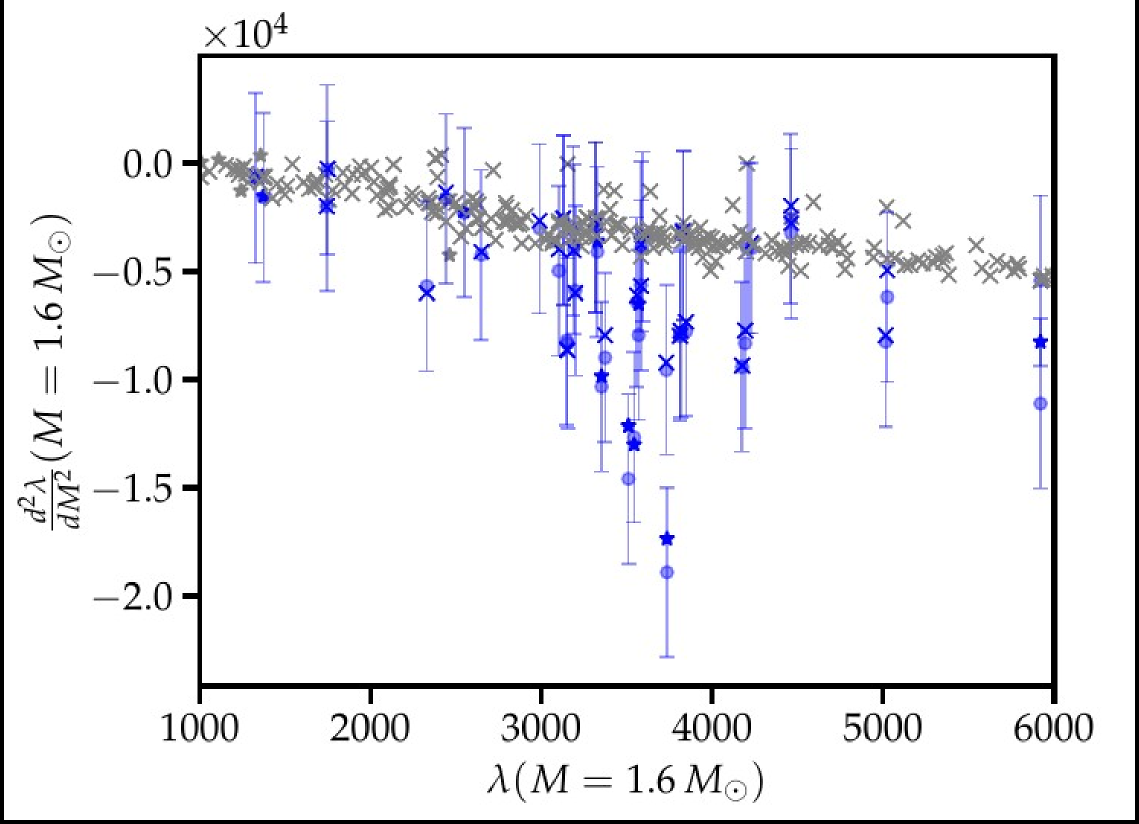
- ~10% accuracy in lambda may be sufficient (at three different masses)

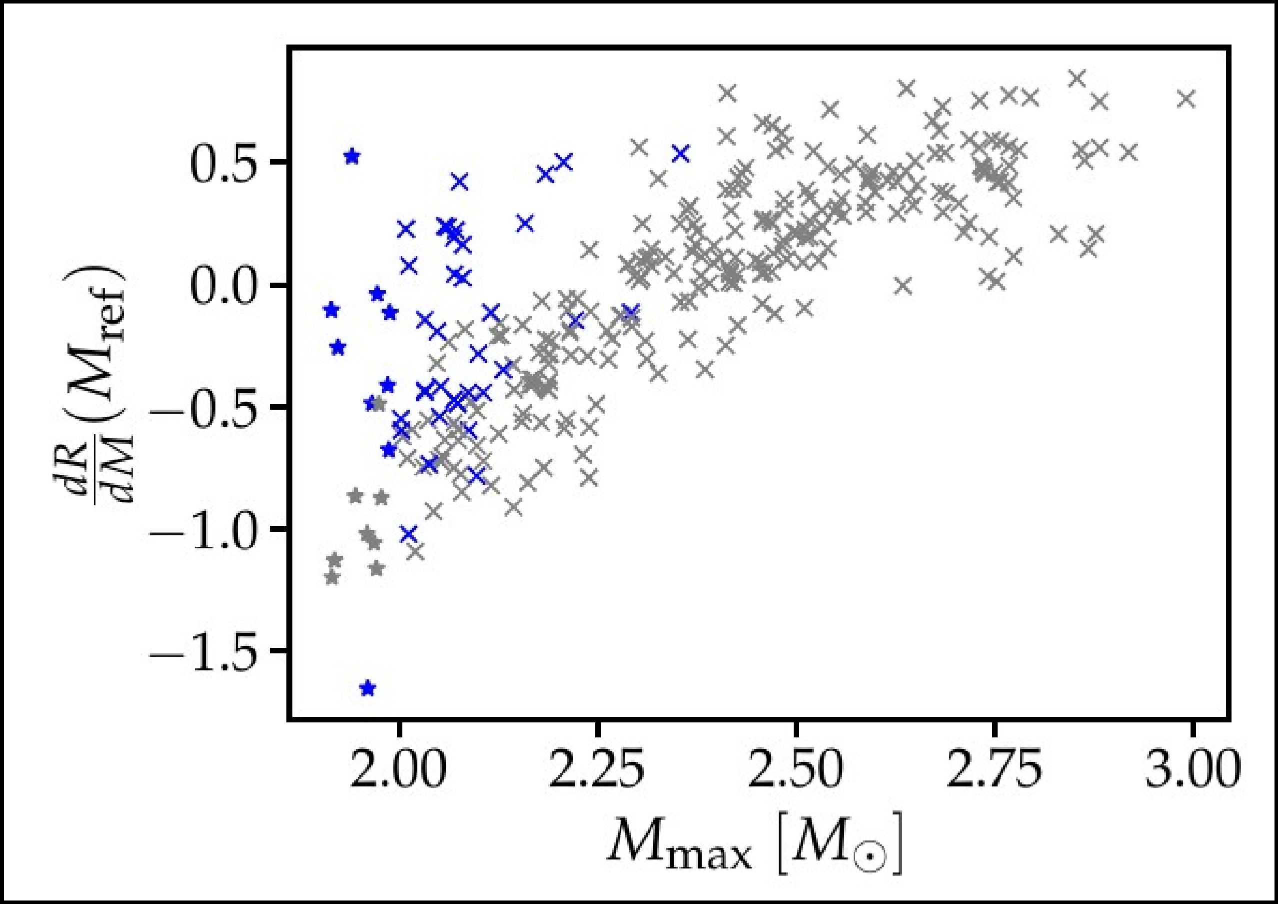


$\delta\lambda = 100$

$\Delta M = 0.25\ m_\odot$

arXiv:2507.10372

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



At 1.6 Msun

arXiv:2507.10372

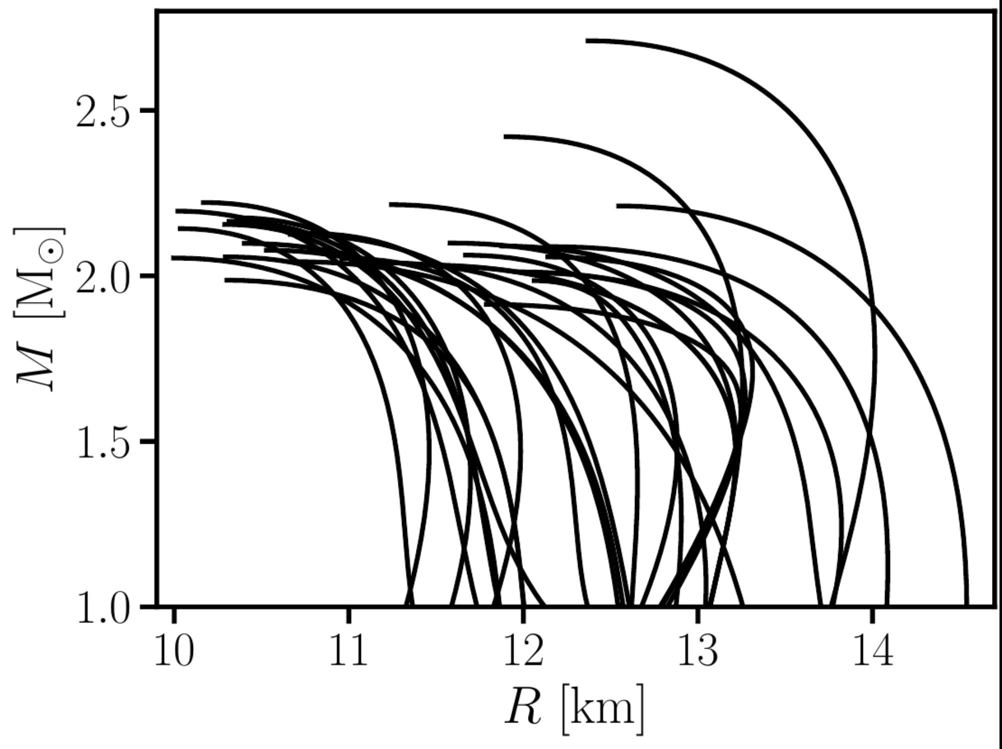
Discussion

- 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 NS mergers

- Which one is hyperonic ?

  → at zero temperature M-R relations / EoS look very similar



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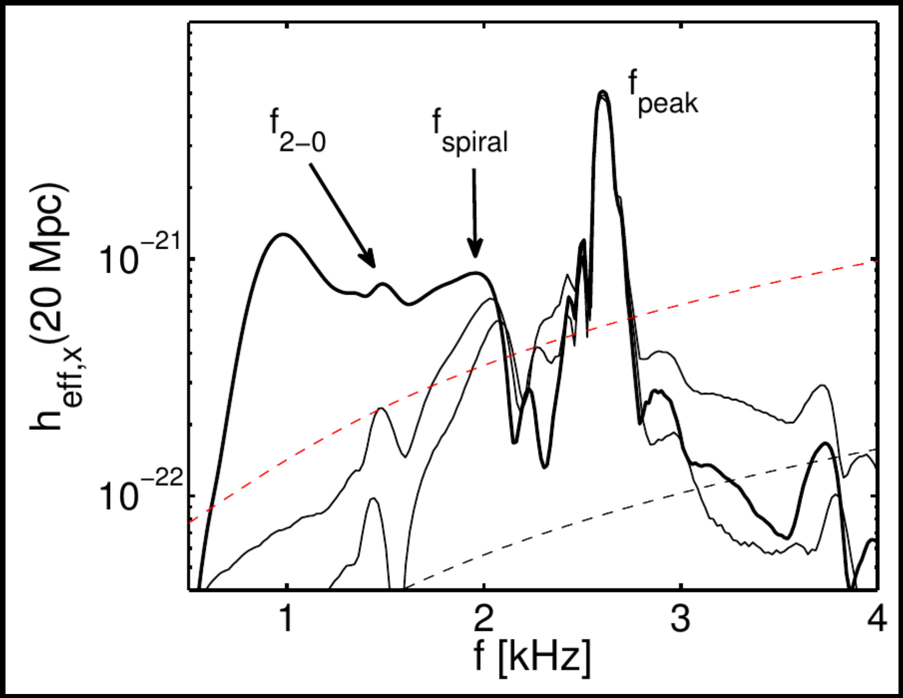
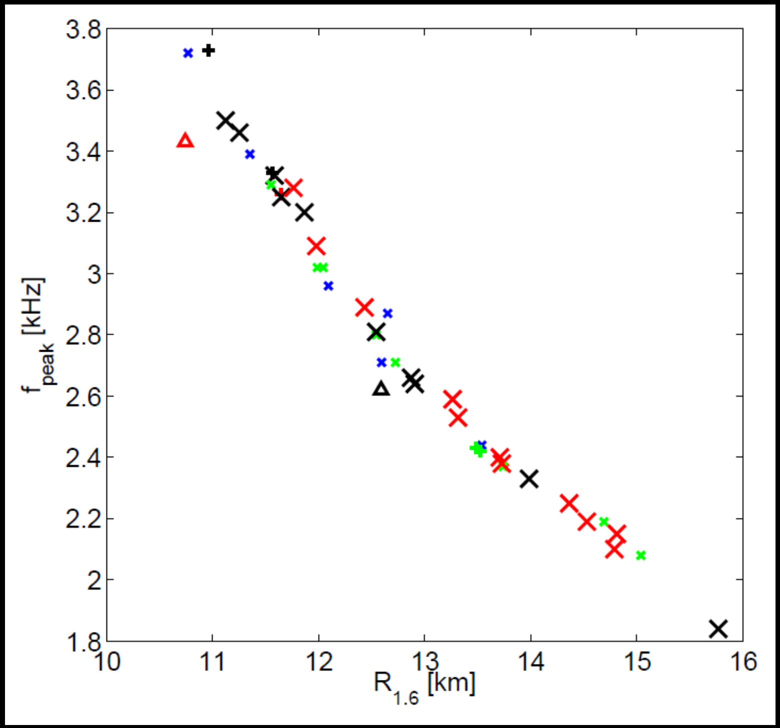
Empirical relations from simulations: Postmerger GWs

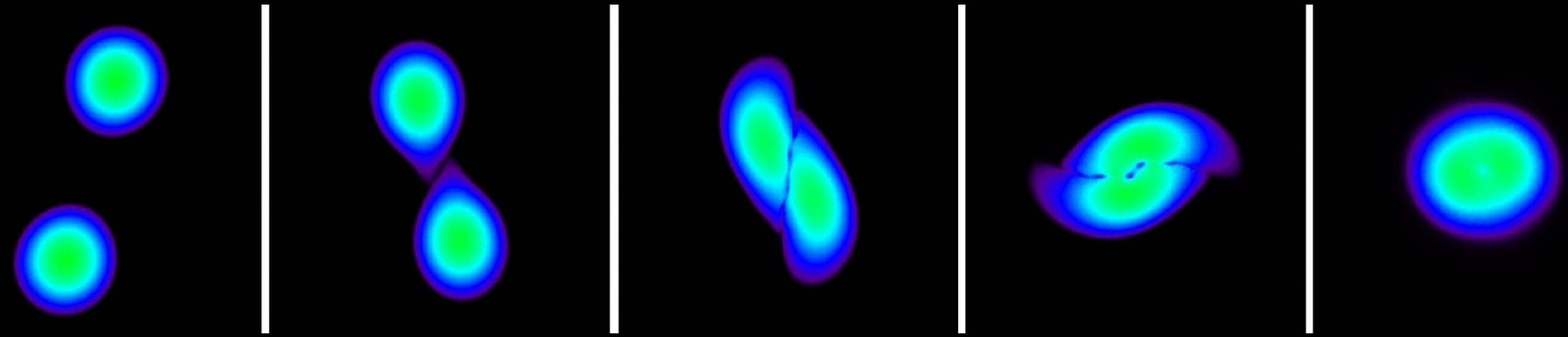
- To determine NS properties and EoS from some merger observable
- For postmerger GW emission, ejecta / kilonova properties, threshold mass for black-hole formation etc.

Bauswein et al. 2016



Bauswein et al. 2012





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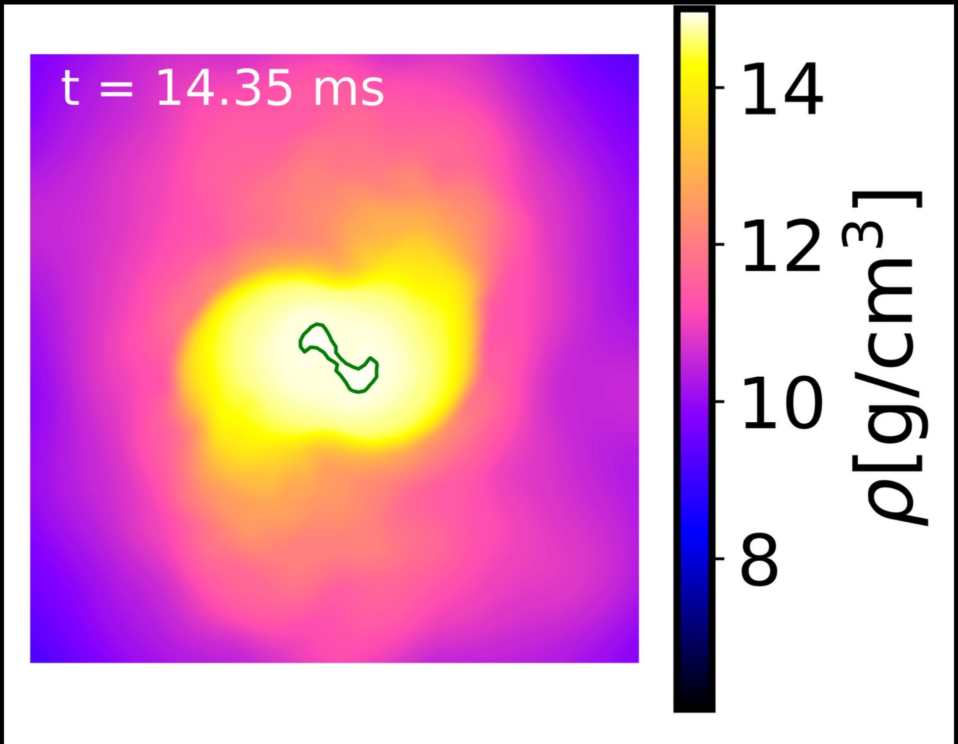
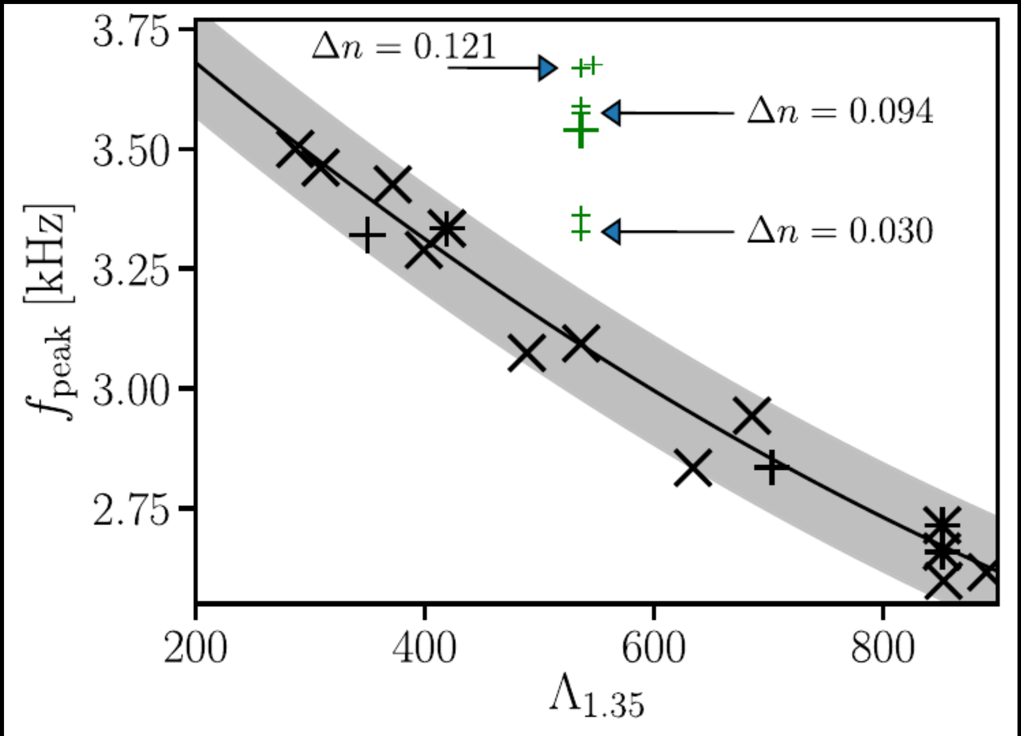
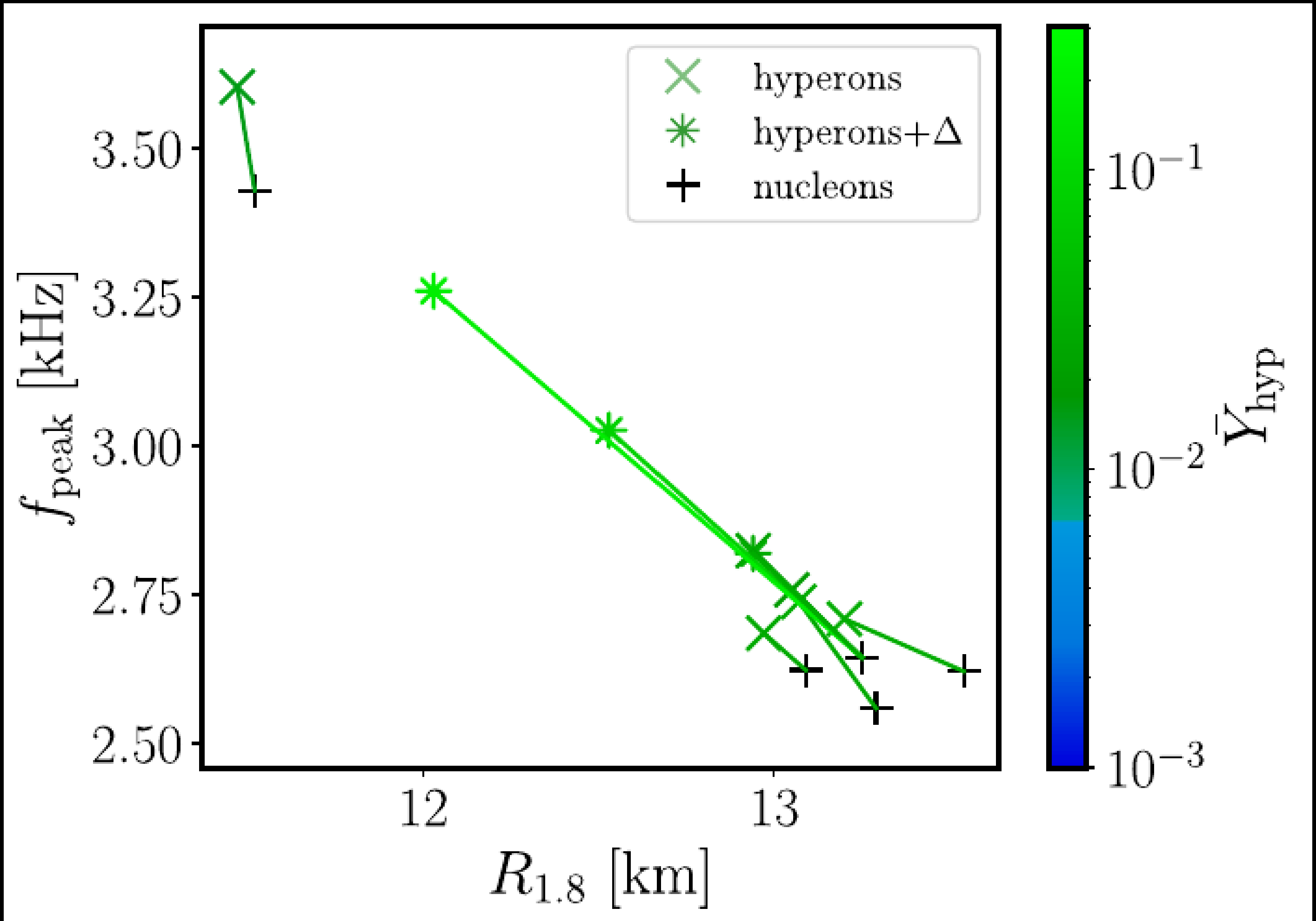




Violations / deviations indicate “new” physics (here quark matter) → what do hyperons do ??

Adding hyperons

- Impact of hyperons - “academic”

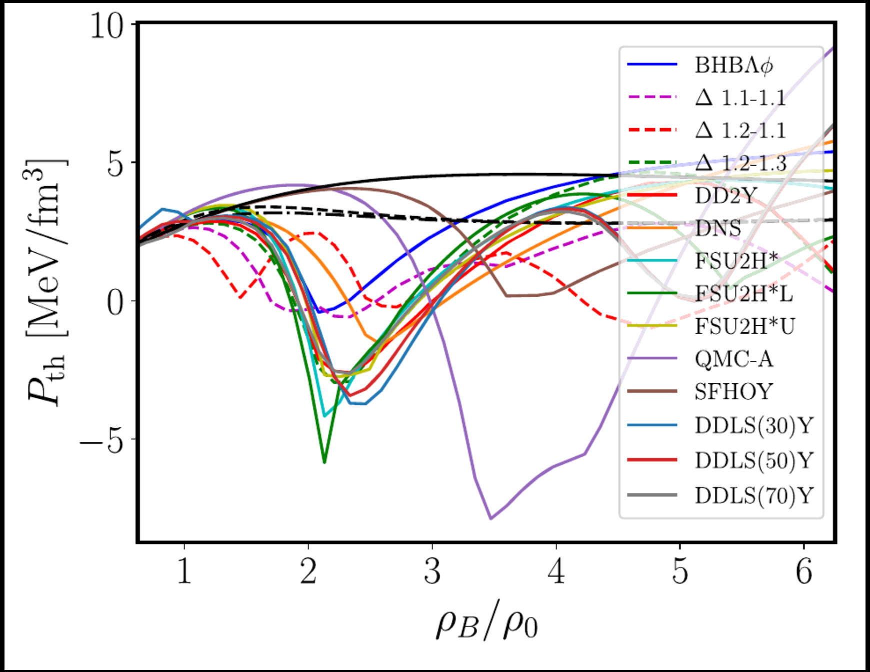


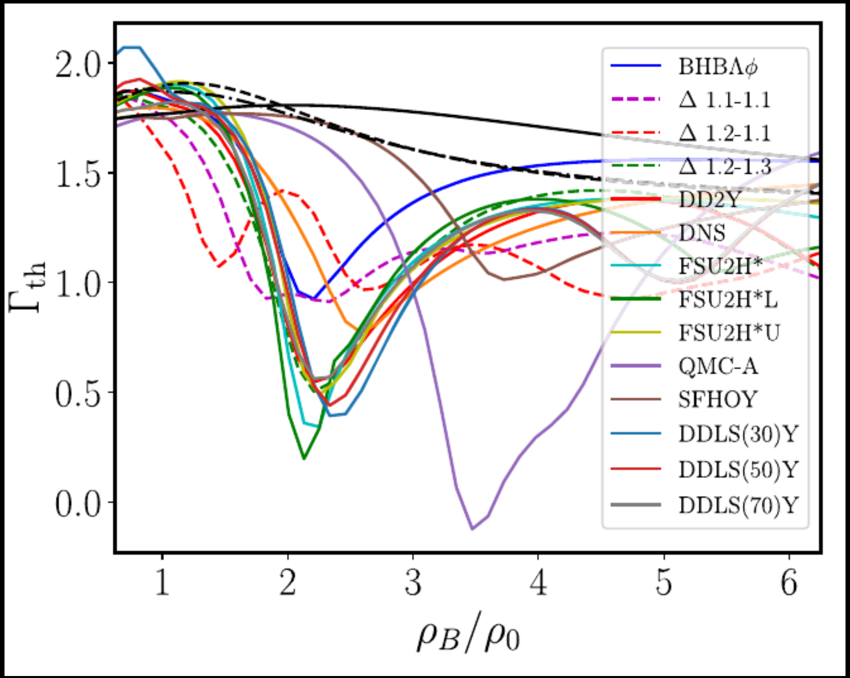
Kochankovski et al. 2025

Thermal properties of EoS with hyperons

- At 20 MeV

$$P = P(\rho, T, Y_e) \qquad P_{th} = (\Gamma_{th} - 1)\epsilon_{th}\rho$$





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Pulrey nucleonic EoSs well approximated by $\Gamma_{th} = 1.75$

Thermal behavior as indicator for hyperons

- A nucleonic EoS could mimic T=0 behavior of any hyperonic EoS ! (but see part 1)

  → Comprehensive study of hyperonic EoSs in NS mergers

- Isolate thermal behavior of hyperons

  - Idea: assume T=0 EoS do not contain any information (in stark contrast to what I claimed before) and adopt hyperonic EoS to be purely nucleonic (obviously incorrect assumption but necessary)

  - supplement with approximate thermal pressure treatment to mimic "nucleonic" thermal behavior

$$P_{th} = (\Gamma_{th} - 1)\epsilon_{th}\rho$$

$\Gamma_{th} = 1.75$ found to reproduce nucleonic EoSs

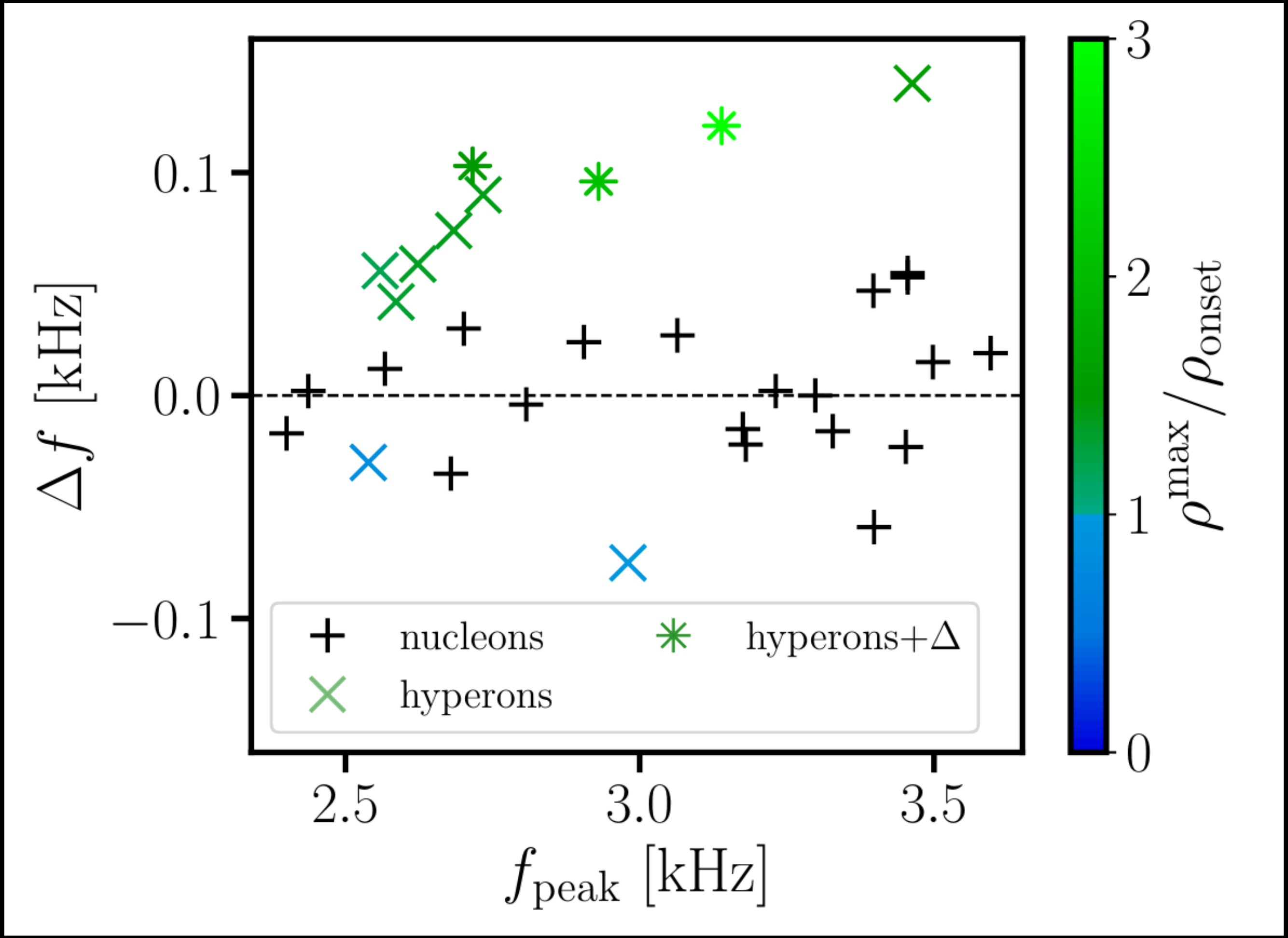
Compare $\Gamma_{th} = 1.75$ runs vs. full T-dependent simulations

→ thermal behavior of hyperons

Thermal behavior as indicator for hyperons

- Delta f describes impact of hyperons on thermal behavior → in principle measurable !!

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



Blacker et al. 2024

Thermal behavior as indicator for hyperons

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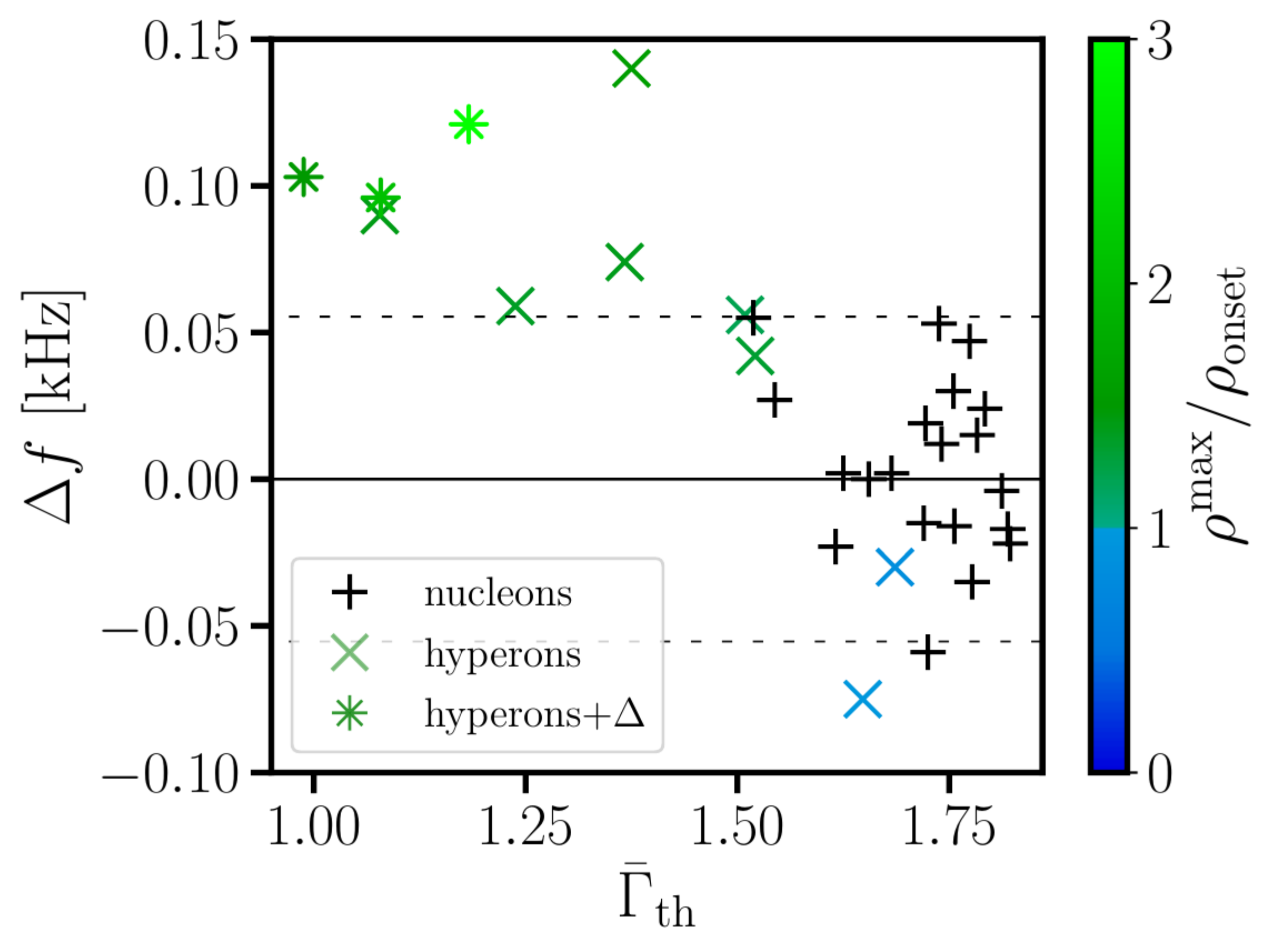

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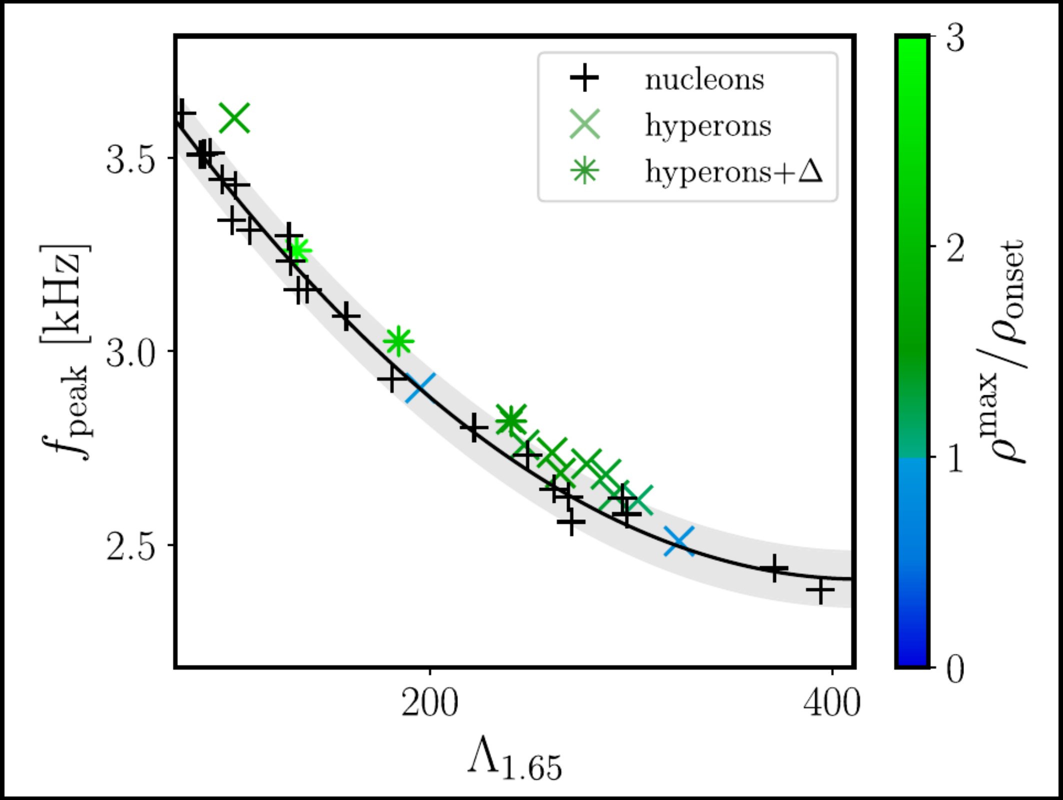
Signature of hyperons

- ~100 Hz effect – challenging to measure



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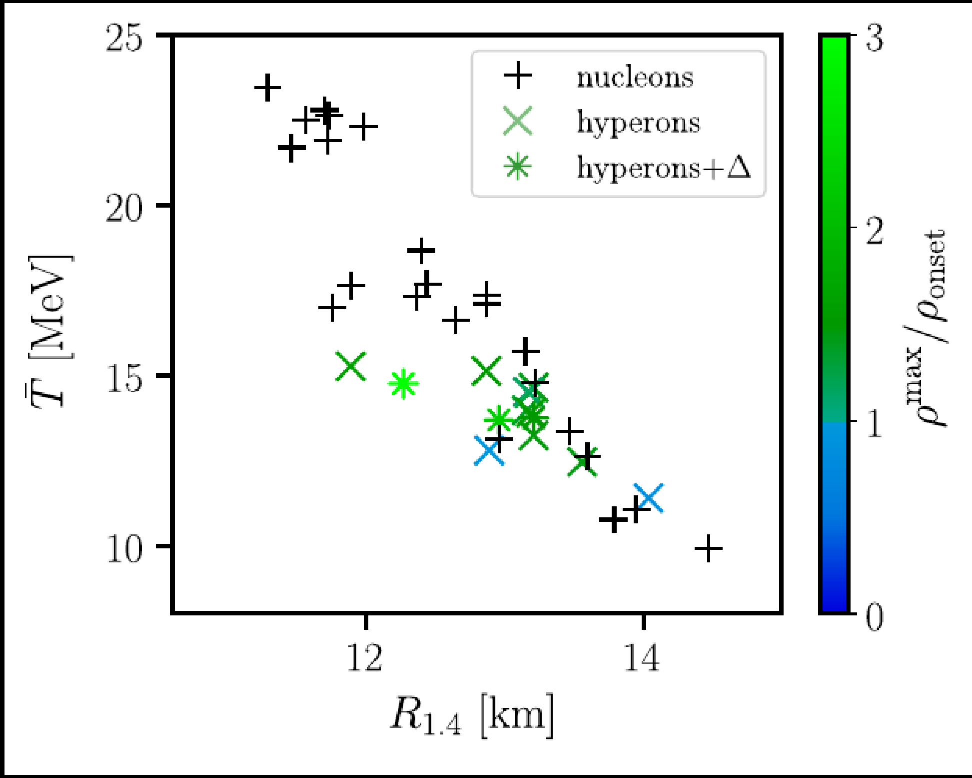
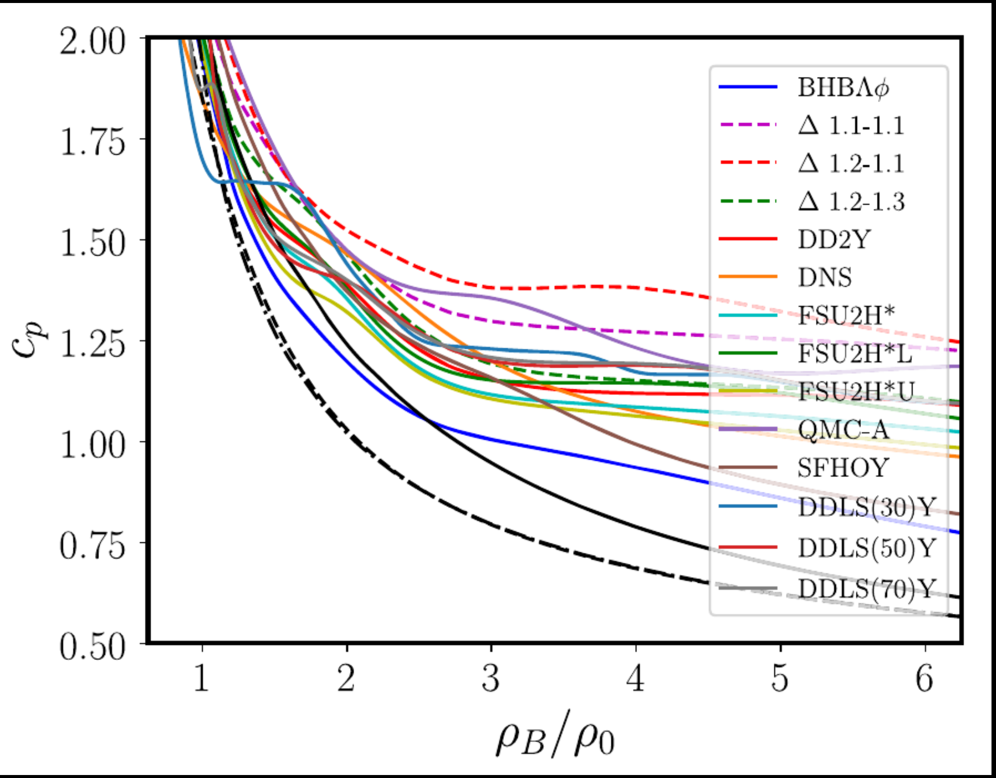
Thermal properties

- 1.4-1.4 Msun





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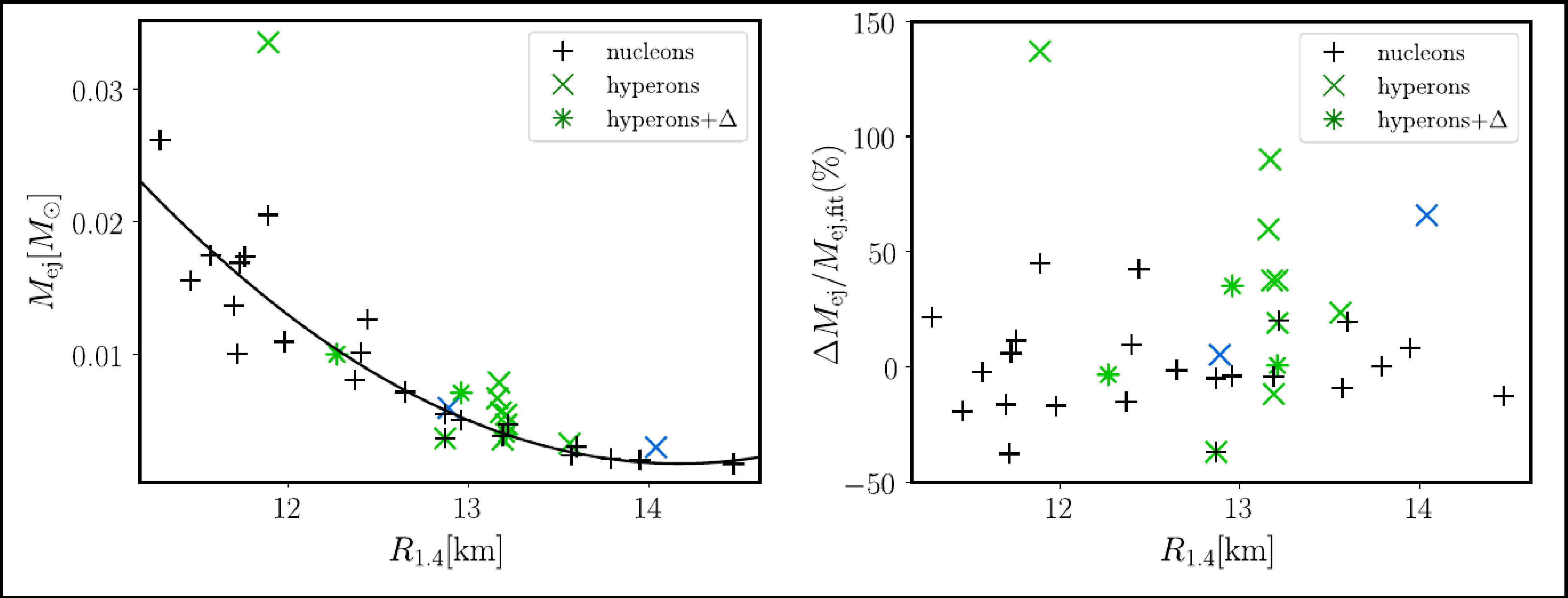
Mass ejection - kilonova

- 1.4-1.4 Msun



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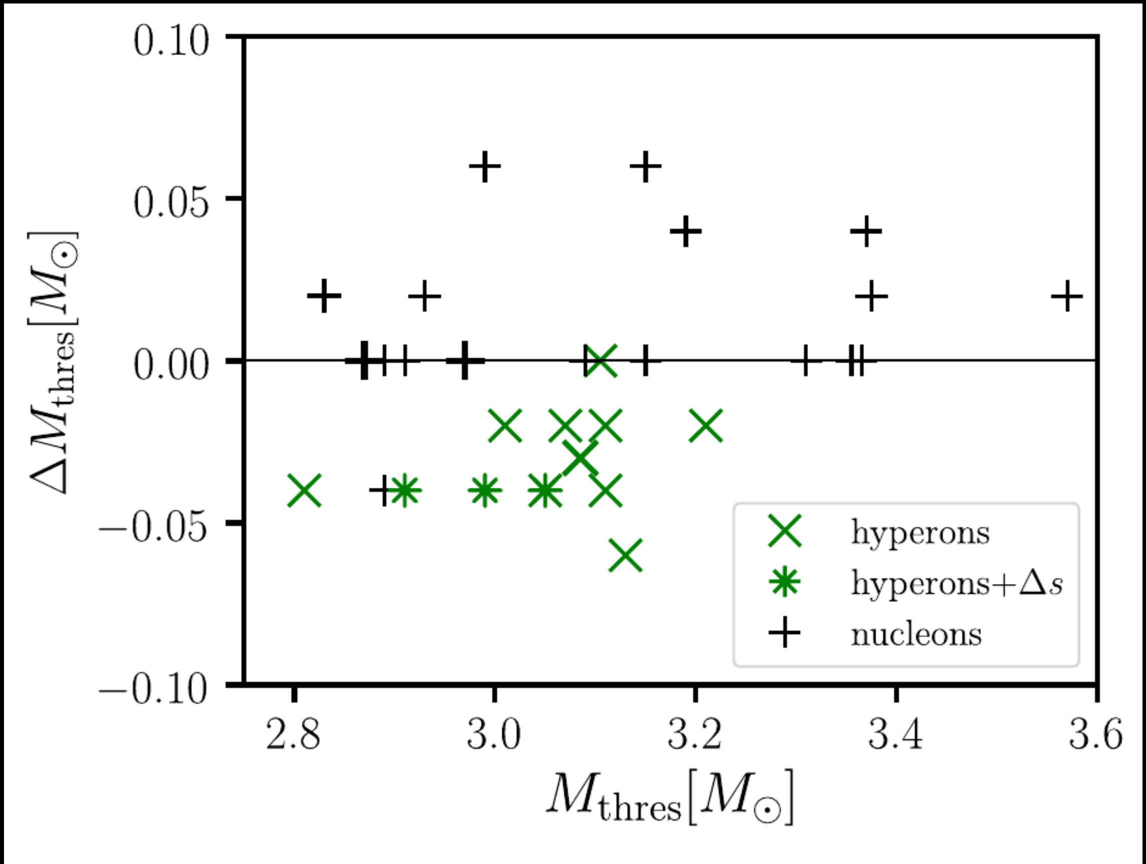
Threshold to prompt collapse

- Hyperons lead to small reduction

$$\Delta M_{thres} = M_{thres} - M_{thres}^{1.75}$$



Kochankovski et al. 2025

Summary

- Cold isolated neutron stars

  → Softening by hyperons increases bending of M-R curves

  → quantifive measure: curvature

  → via measurements at three masses (finite differences; challenging)

  → Several-per-cent measurements of tidal deformability is sufficient to see indications for hyperons

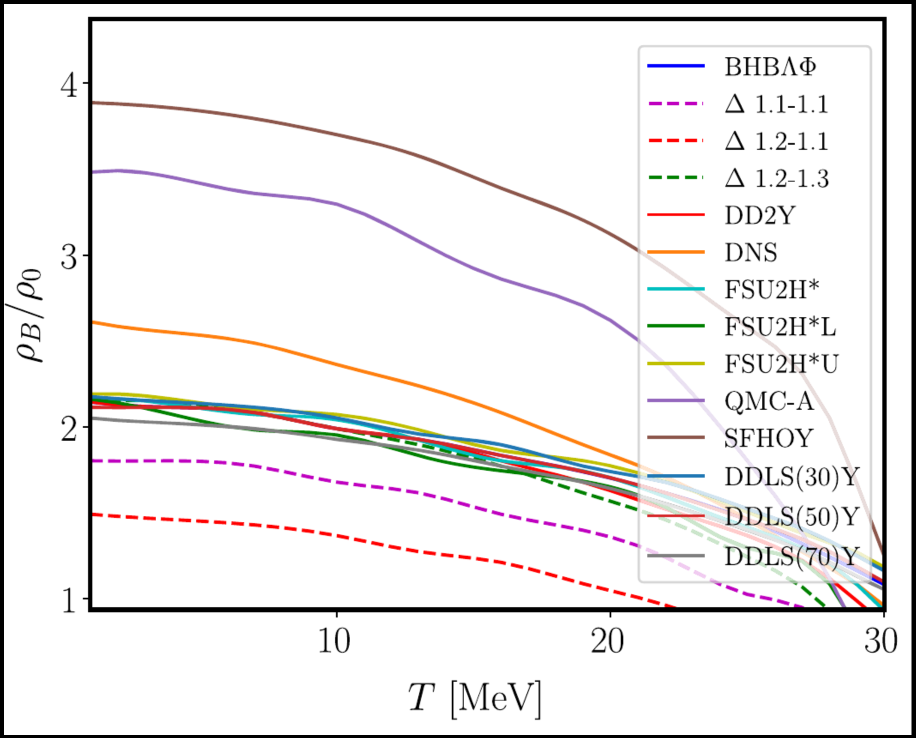
- Mergers – thermal behavior modified by hyperons

  → higher heat capacity, reduced average temperature, thermal pressure significantly reduced compared to purely nucleonic matter

  → small shift of postmerger GW frequency

  → mass ejection possibly increased

  → small effect on threshold mass for collapse



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