Impact of hyperons on neutron star mergers

(Kochankovski et al., PRD, 2025)

In collaboration with G. Lioutas, S. Blacker, A. Bauswein, A. Ramos and L. Tolos

Hristijan Kochankovski

HYP 2025

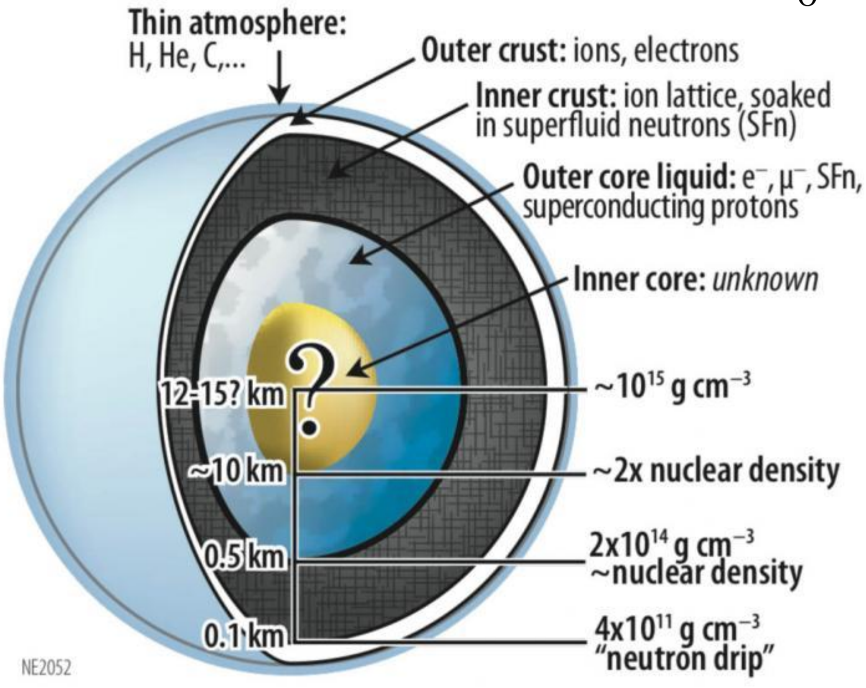
Tokyo, 29/09-03/10/2025

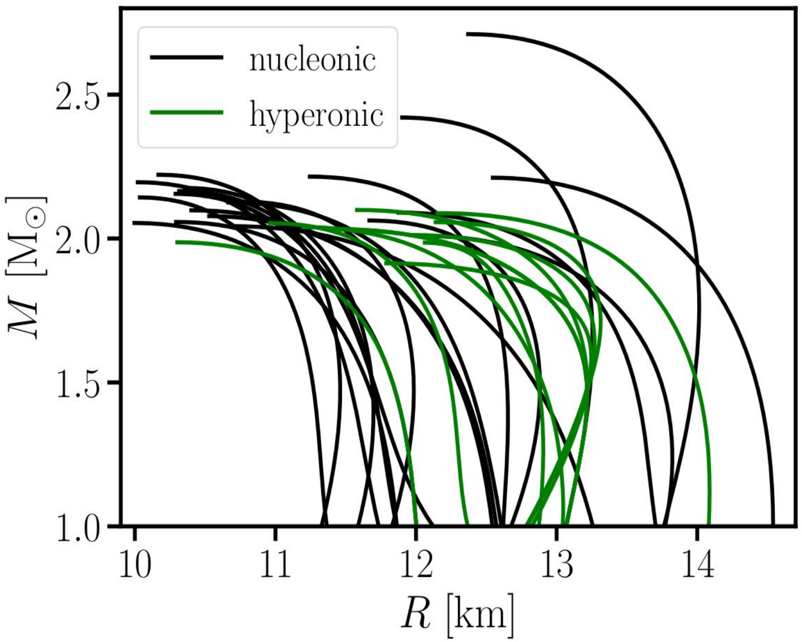
Introduction

$$P_0 = P_0(\rho_B)$$

Nucleonic – nucleons as only baryons

Hyperonic – hyperons and nucleons as baryons





K.C. Gendreau et al., SPIE, 2012

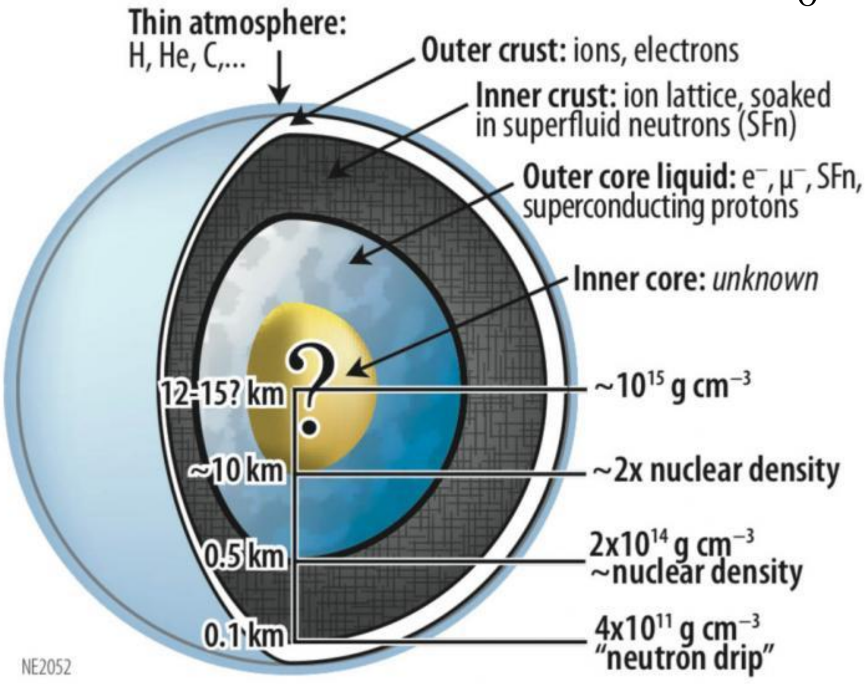
Blacker et al., PRD, 2024

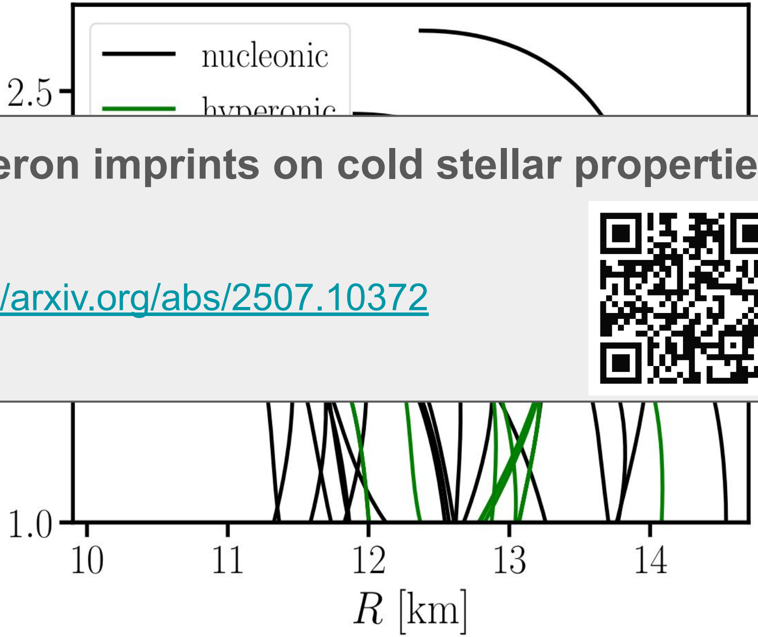
Introduction

$$P_0 = P_0(\rho_B)$$

Nucleonic – nucleons as only baryons

Hyperonic – hyperons and nucleons as baryons





Hyperon imprints on cold stellar properties:

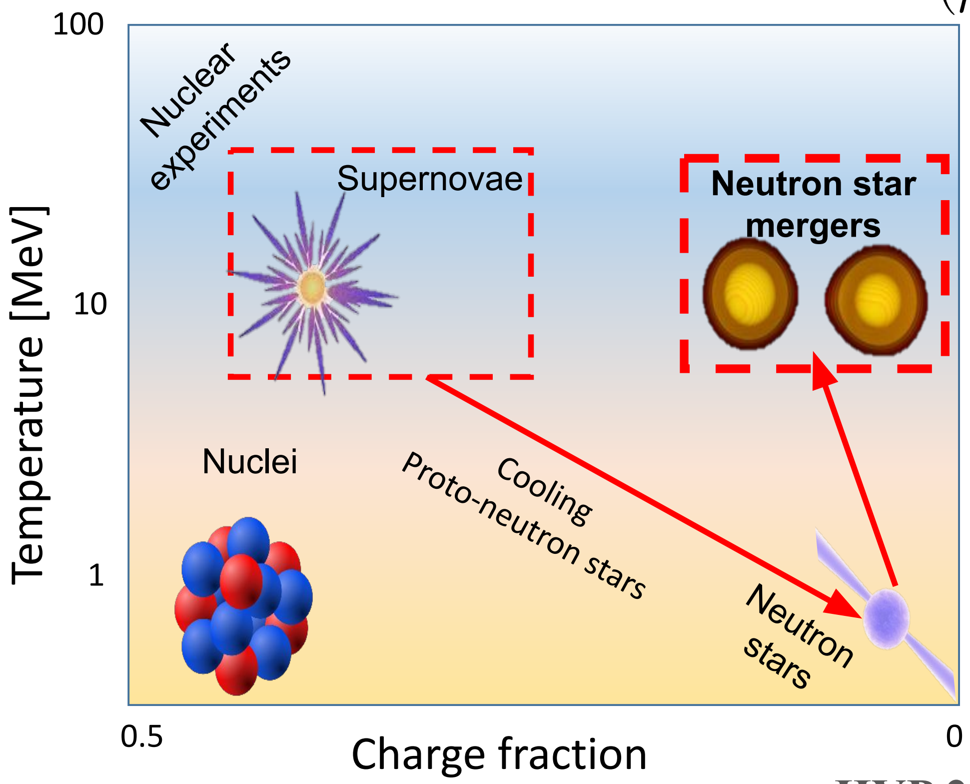
https://arxiv.org/abs/2507.10372

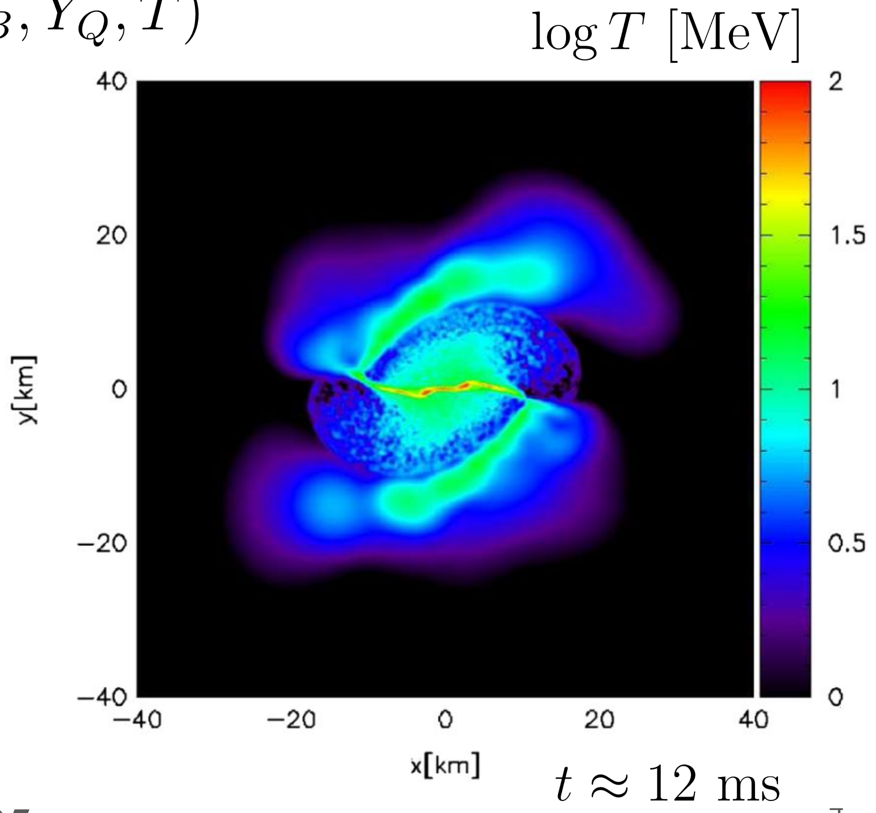
K.C. Gendreau et al., SPIE, 2012

Blacker et al., PRD, 2024

Introduction

$$P = P(\rho_B, Y_Q, T)$$





Bauswein et al., PRD, 2010

Introduction

THE GOAL

Identify clear imprints of hyperon appearance in dense matter on the binary neutron star merger observables.

THE STRATEGY

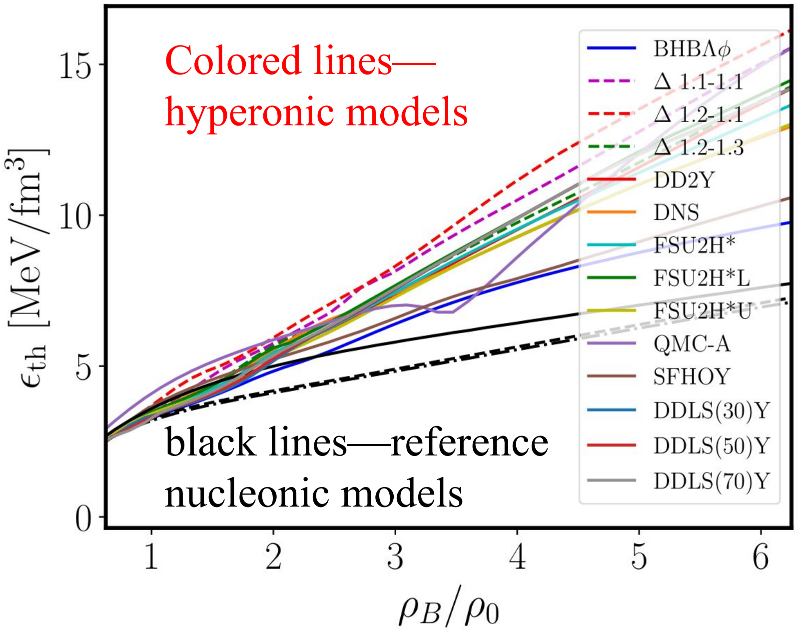
Inspect the unique properties of hypernuclear matter at finite temperature with as many equations of state (EoSs) as possible.

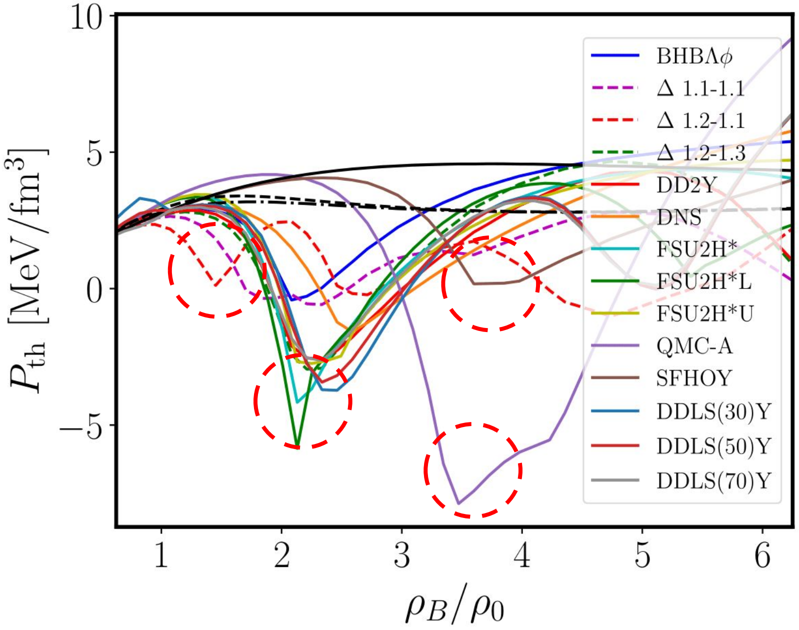
Investigate how the properties translate to signatures in the observables and quantities obtained from binary neutron star mergers by performing numerical simulations with many nucleonic and hyperonic models.

Thermal properties of hot hypernuclear matter

$$X_{\rm th}(\rho_B, Y_Q, T) = X(\rho_B, Y_Q, T) - X(\rho_B, Y_Q, 0)$$

$Y_Q = 0.1; T = 25$ MeV

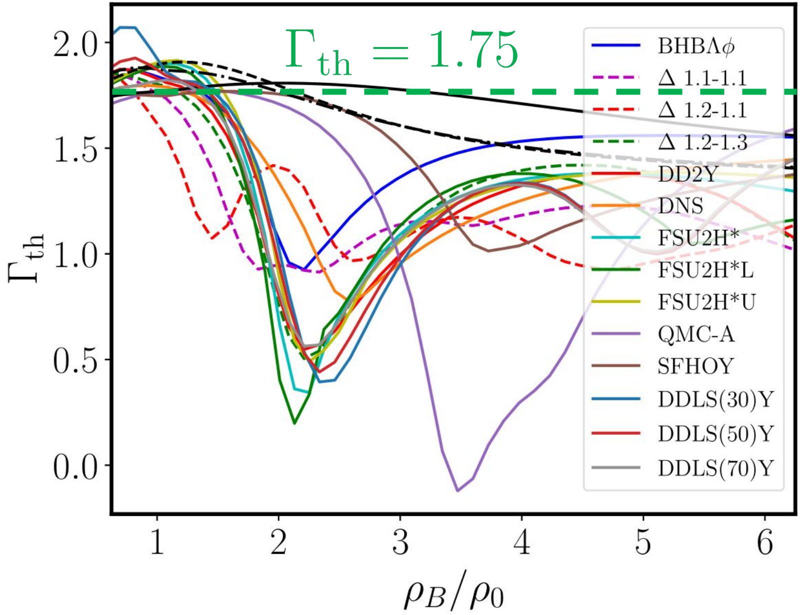




Thermal properties of hot hypernuclear matter

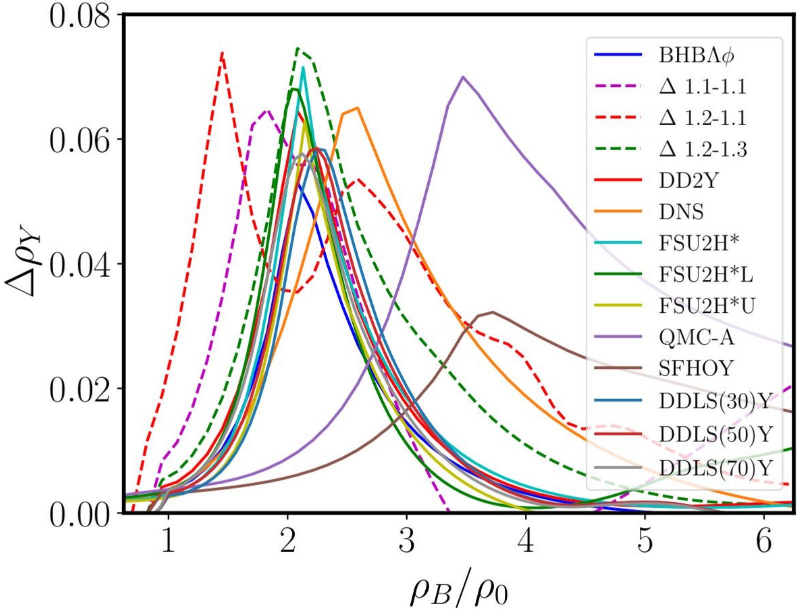
Thermal index

$$\Gamma_{\rm th}(\rho_B, Y_Q, T) = 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}}$$



Hyperon excess

$$\Delta\rho_Y = \frac{\rho_Y(\rho_B, Y_Q, T) - \rho_Y(\rho_B, Y_Q, 0)}{\rho_B}$$



Thermal properties of hot hypernuclear matter

- Let's assume that we have a zero-temperature EoS. That means that we know the relations

$$P_0 = P_0(T=0, \rho_B), \epsilon_0 = \epsilon_0(T=0, \rho_B) \quad P_0 = P_0(T=0, \epsilon_0)$$

- If we want to construct a finite-temperature EoS, based on our zero-temperature EoS, we can start from the thermal index equation:

$$\Gamma_{\rm th} = 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}} \longrightarrow P(T, \rho_B) - P_0 = (\Gamma_{\rm th} - 1)(\epsilon(T, \rho_B) - \epsilon_0)$$

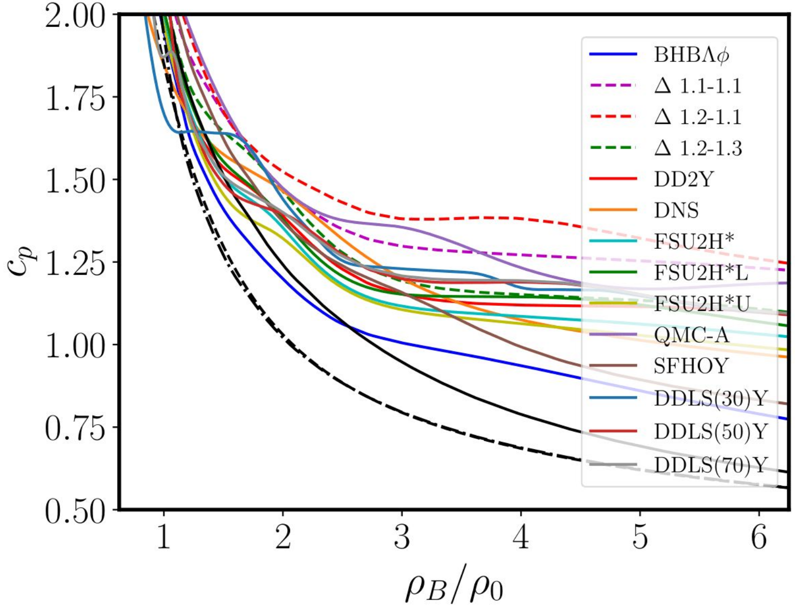
- If $\epsilon_{\rm th} = \epsilon - \epsilon_0$ is an independent quantity, and if one assumes that the thermal index has a constant value independent of the conditions (motivated by the ideal gas behavior)

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

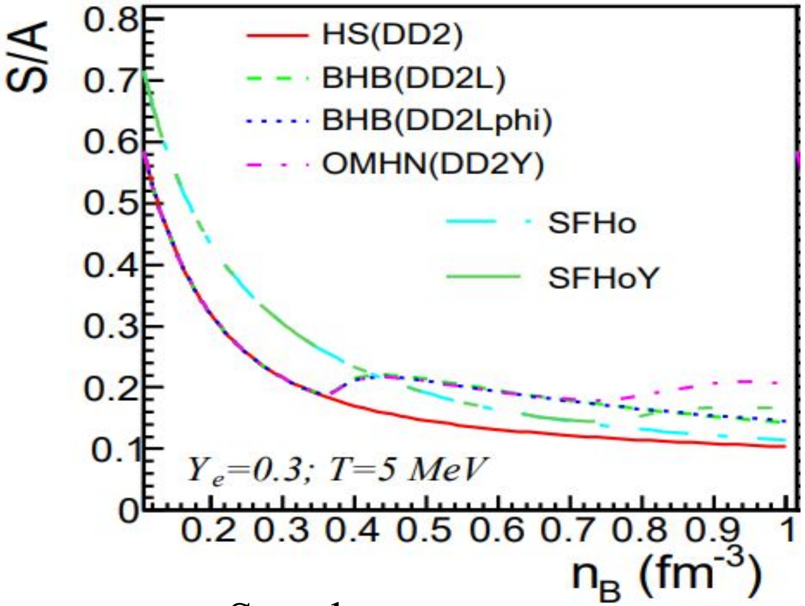
Thermal properties of hot hypernuclear matter

Specific heat

$$c_P = T \frac{\partial S/A}{\partial T}\Big|_{P,A,Y_Q}$$



Raduta et al., EPJA, 2022



See also

Drago et al., EJPA, 2016

Kochankovski et al., MNRAS, 2022

Impact of hyperons on the merger observables and quantities

THE GOAL

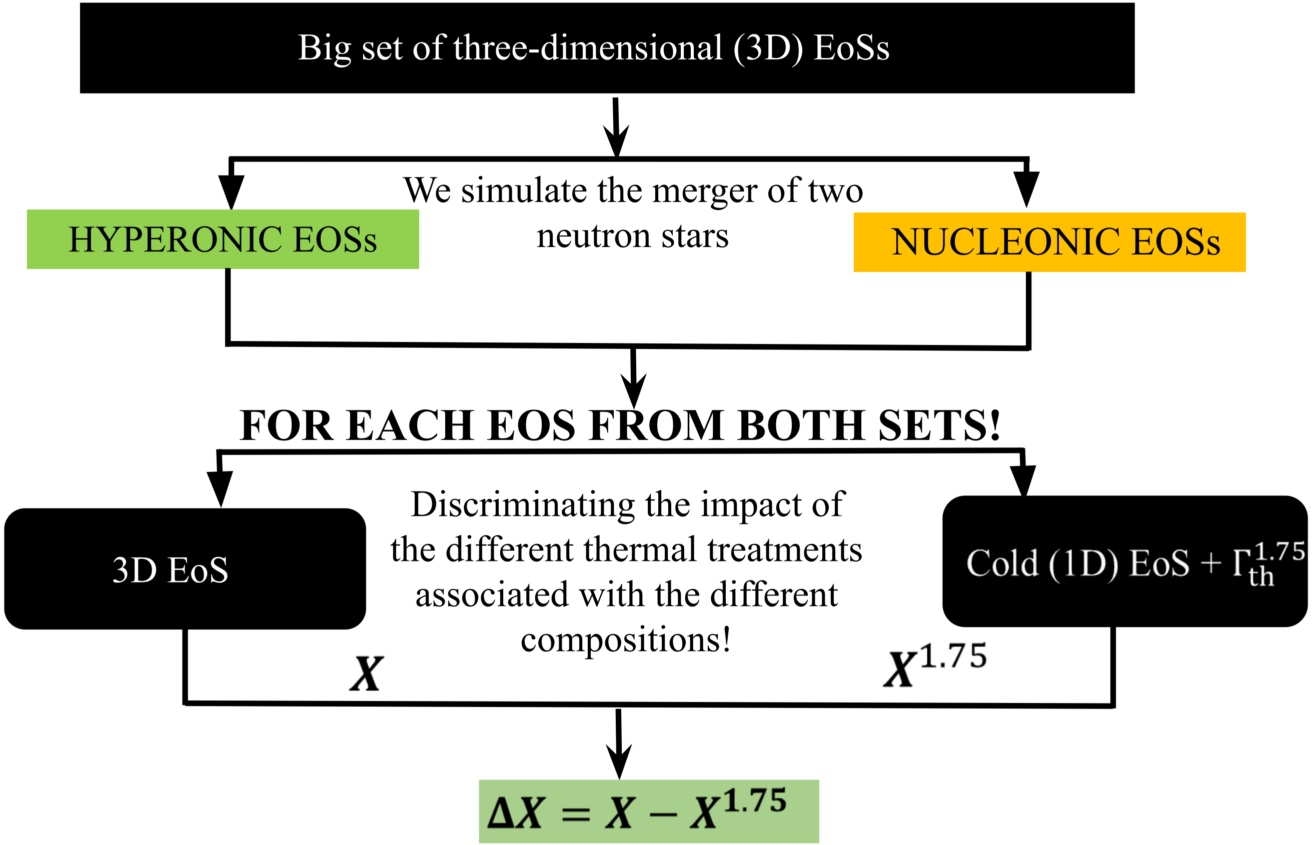
Identify clear imprints of hyperon appearance in dense matter on the binary neutron star merger observables

THE STRATEGY

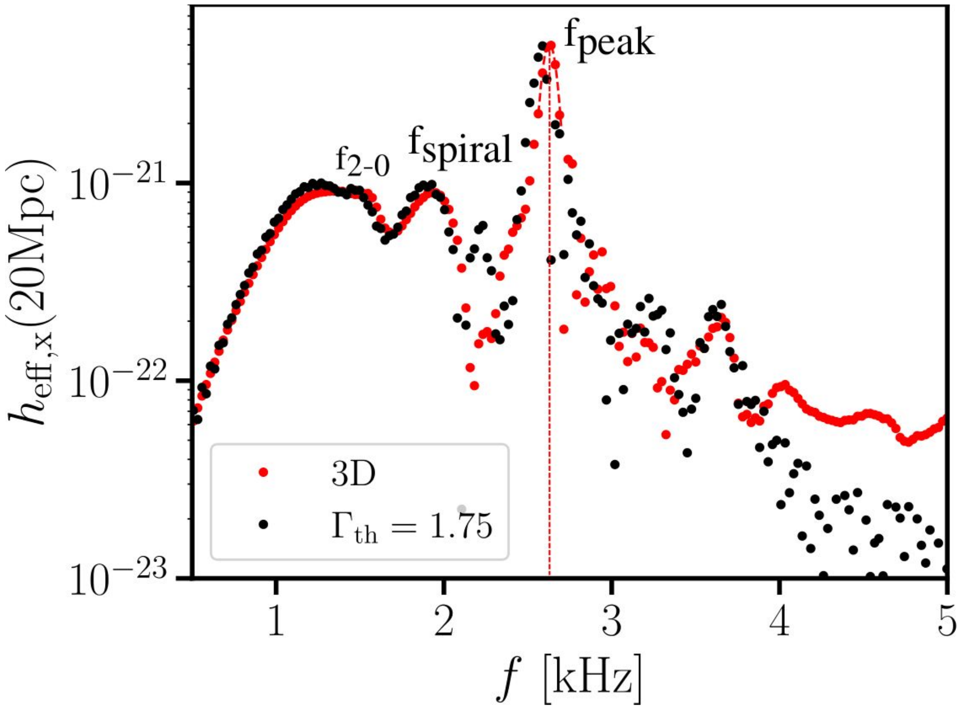
Inspect the unique properties of hypernuclear matter at finite temperature with as many models as possible.

Investigate how the properties translate to signatures in the observables and quantities obtained from binary neutron star mergers by performing numerical simulations with many nucleonic and hyperonic models.

Impact of hyperons on the merger observables and quantities



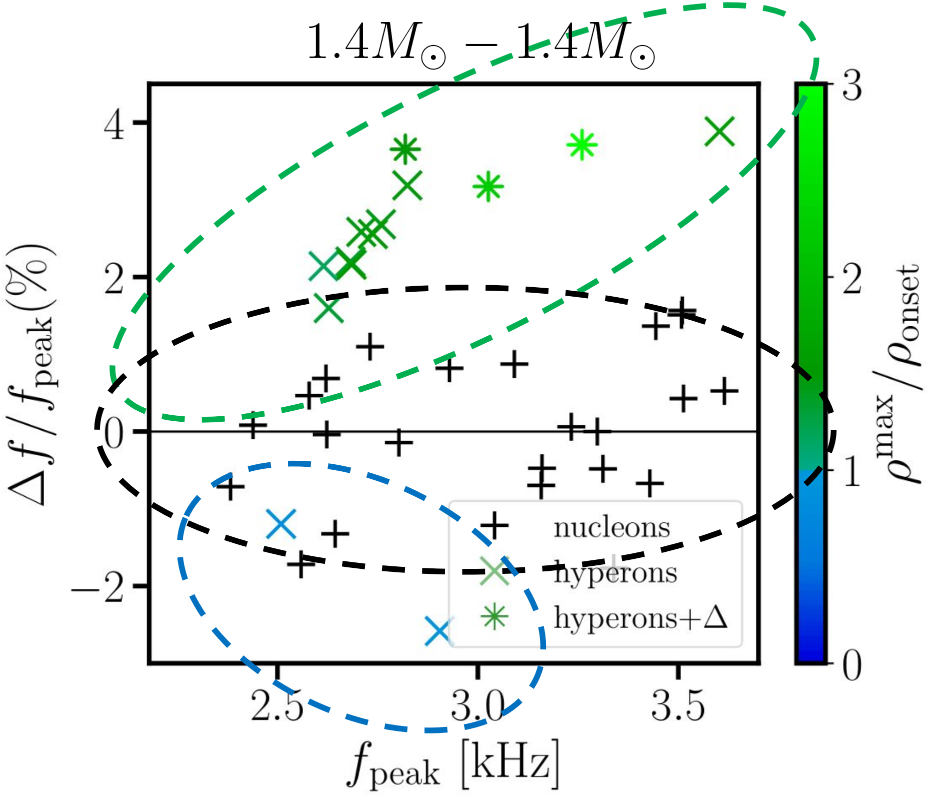
Impact of hyperons on the merger observables and quantities



- The dominant post-merger gravitational wave frequency is the strongest feature in the gravitational-wave spectrum emitted after the two neutron stars merge.

- It corresponds to the fundamental quadrupole oscillation mode of the remnant neutron star.

Impact of hyperons on the merger observables and quantities



$$\Delta f = f_{\rm peak} - f^{1.75}_{\rm peak}$$

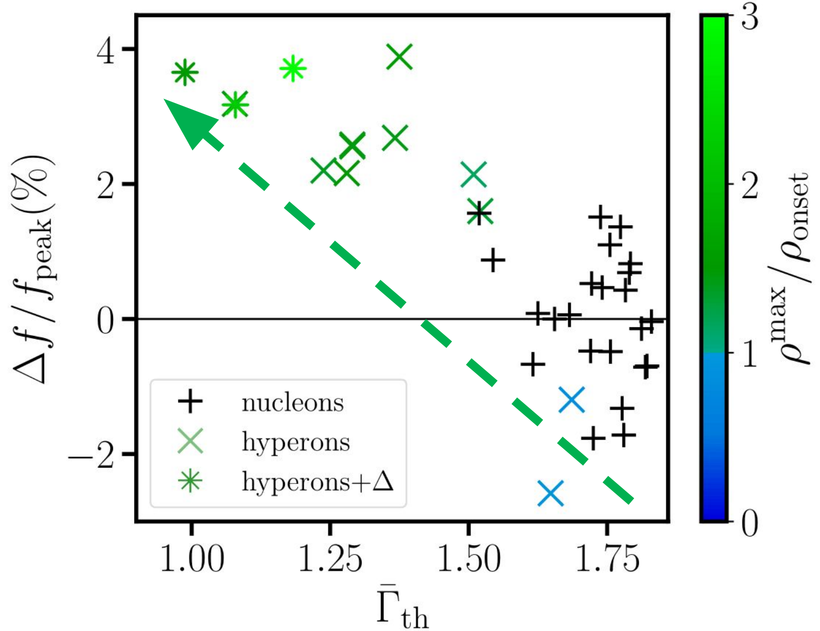
Hyperonic EoSs show a systematic shift toward higher frequencies.

Nucleonic models are scattered around the reference values.

If the hyperons are present in matter only in very small quantities, the corresponding EoSs behave like nucleonic ones.

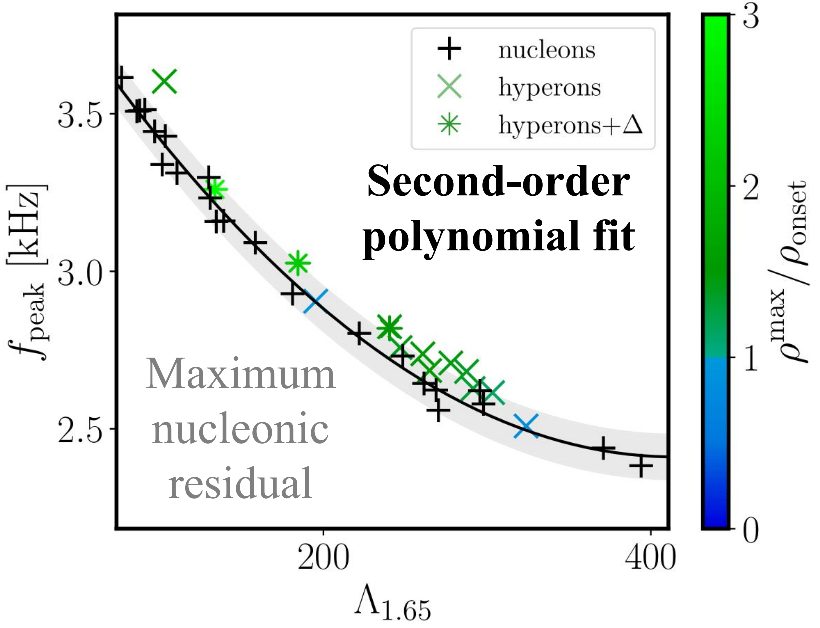
see also: *Blacker et al., PRD, 2024*

Impact of hyperons on the merger observables and quantities



(average thermal index)

Strong correlation between Δf and $\bar{\Gamma}_{\mathrm{th}}$

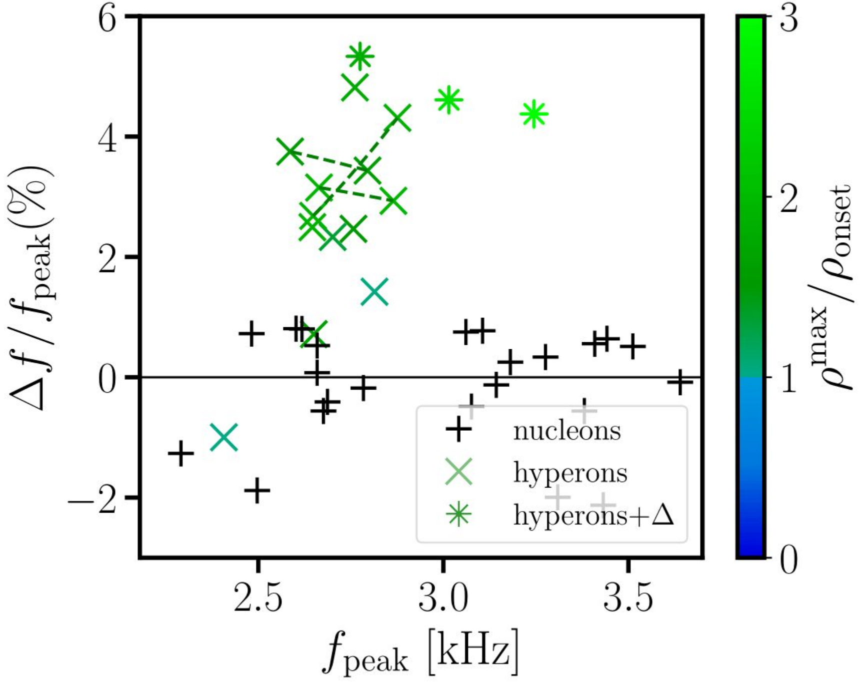


Hyperonic EoS do not follow the nucleonic $f_{\mathrm{peak}} - \Lambda$ relation

Impact of hyperons on the merger observables and quantities

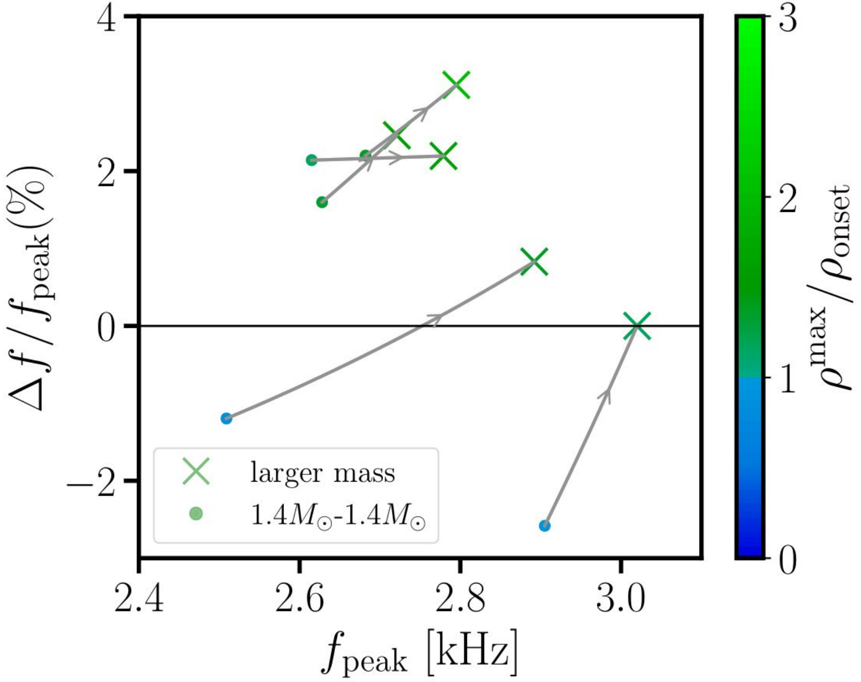
Asymmetric binaries

$M_1/M_2 = 0.8; M_{\rm tot} = 2.8M_\odot$

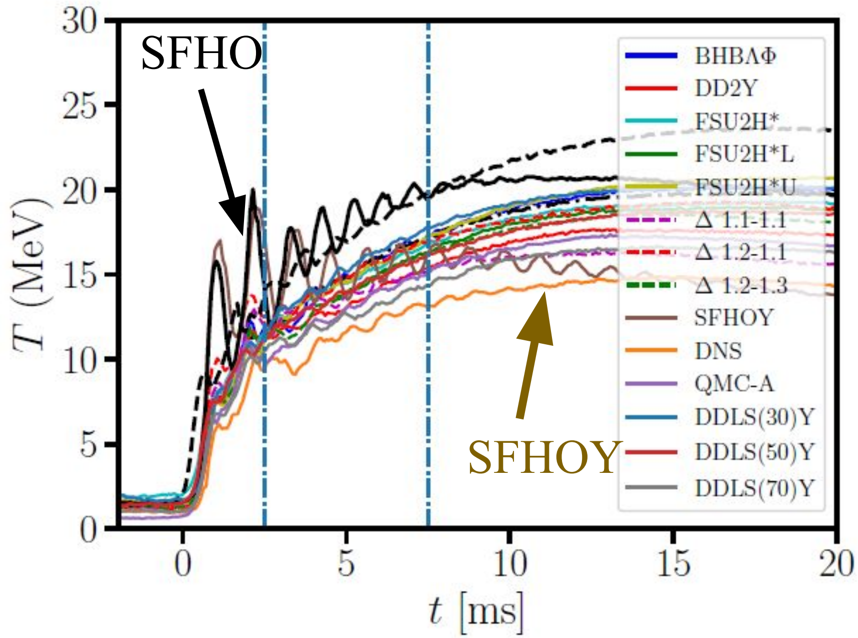


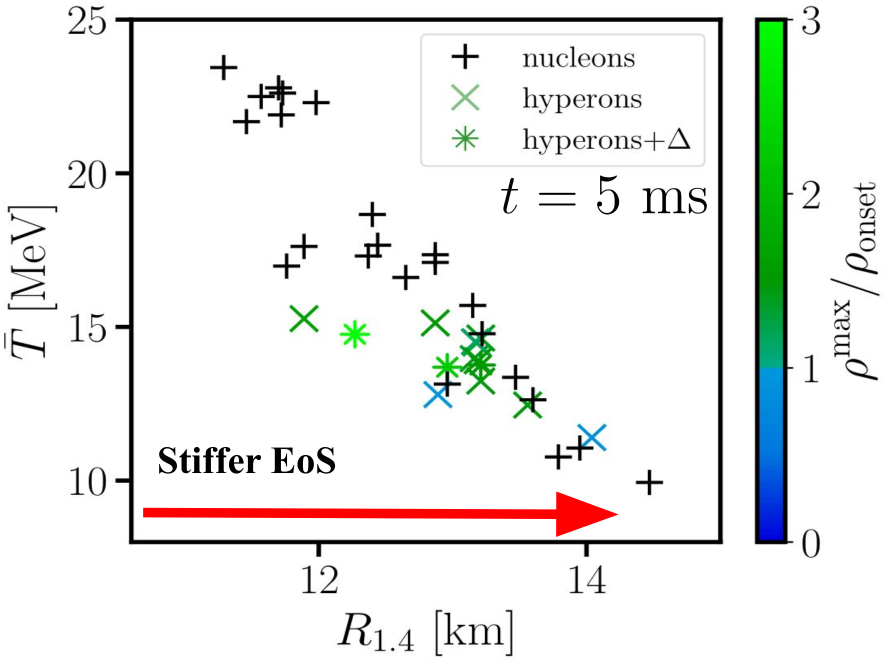
More massive binaries

$M_1 = M_2; M_{\rm tot} > 2.8M_\odot$



Impact of hyperons on the merger observables and quantities





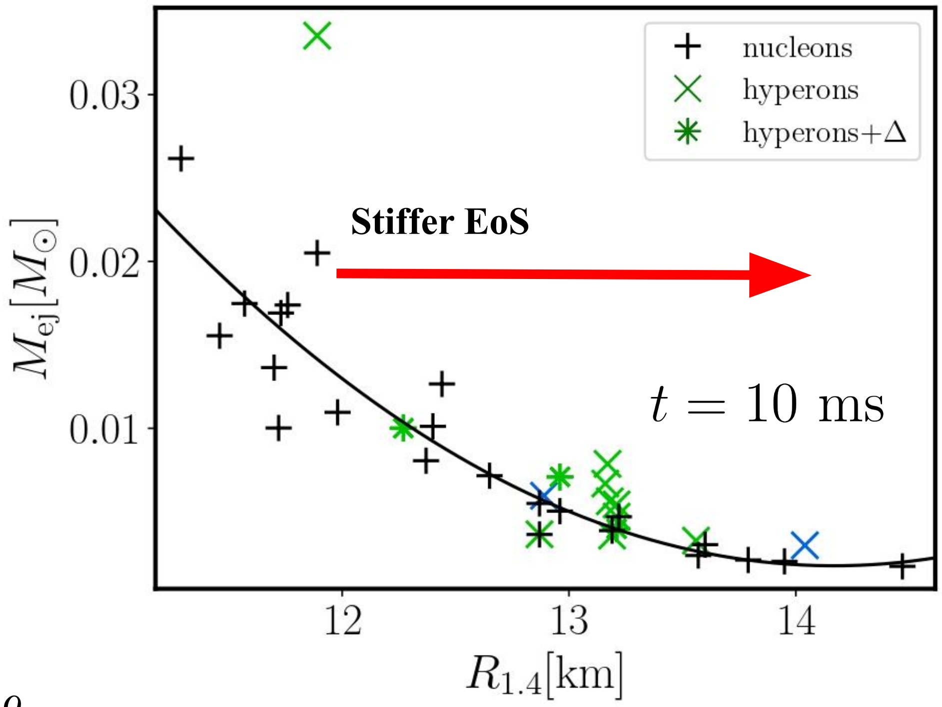
Remnants with hyperons have smaller temperature than their nucleonic counterparts

Hyperonic EoSs yield lower temperature for a fixed $R_{1.4}$

Impact of hyperons on the merger observables and quantities

- **Mass ejecta**—unbound matter from the remnant that undergoes rapid neutron capture.
- The amount of ejecta mass is related to the total amount of synthesized elements.
- We focus on the dynamical (early) ejecta that can be affected by the appearance of hyperons.

Baiotti et al, Rept. Prog. Phys, 2017
Shibata et al, Annu. Rev. Nucl. Part. Sci., 2019



Impact of hyperons on the merger observables and quantities

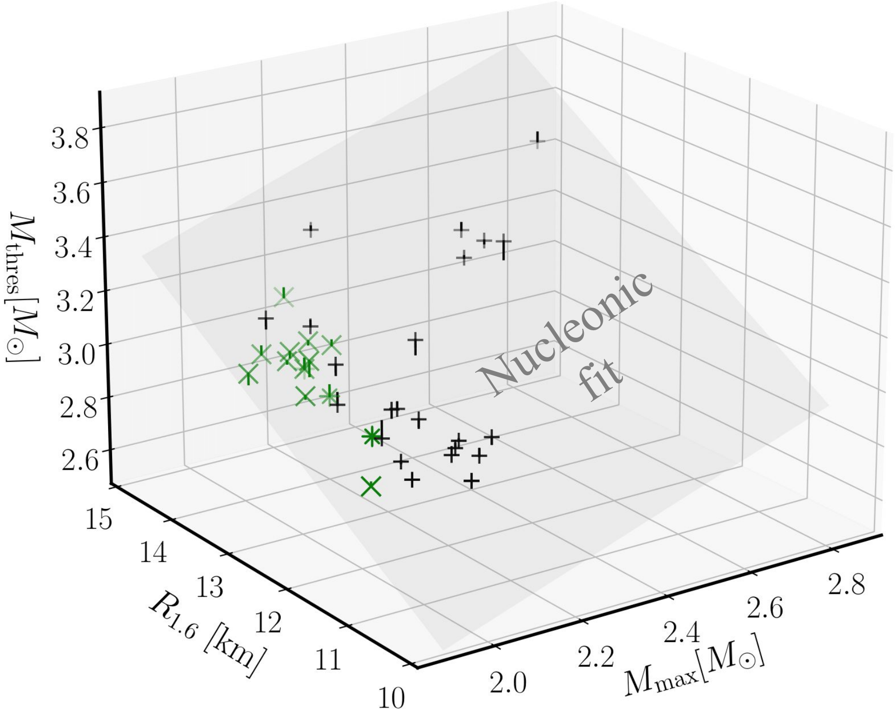
- **Threshold mass**—maximum initial mass at which the remnant does not go to prompt collapse

$$M_{\rm thres} = \frac{M_{\rm unstable} + M_{\rm stable}}{2}$$

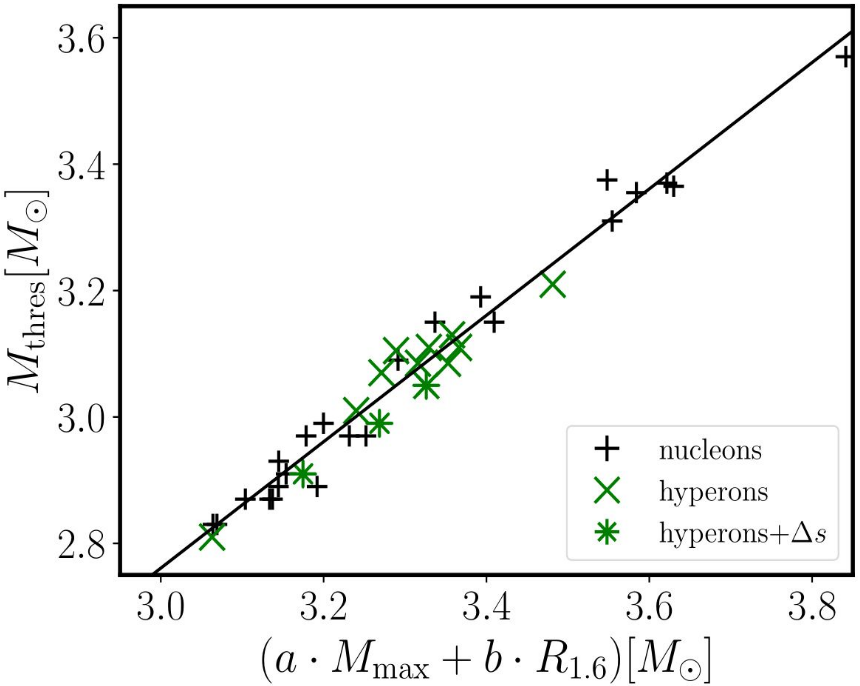
- It has been found that the threshold mass correlates with the cold mass star parameters

$$M_{\rm thres} \approx a M_{\rm max} + b R_{1.6} + c$$

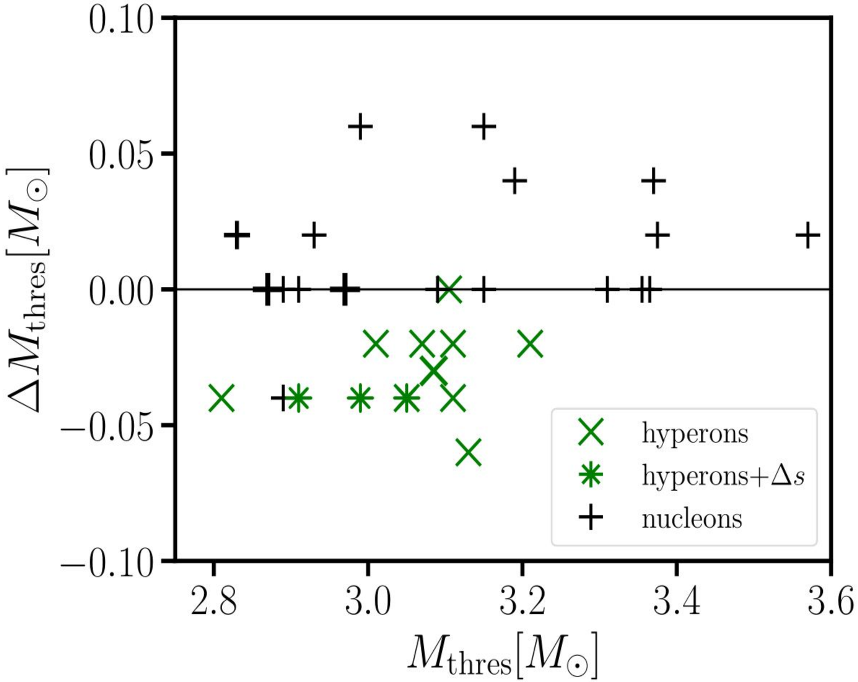
Bauswein et al, PRD, 2021



Impact of hyperons on the merger observables and quantities



Hyperonic EoSs are scattered around the nucleonic mean



Finite temperature behavior has an effect on the threshold mass too!

Conclusions

- Hyperons influence the finite-temperature behavior of the EoS. The thermal index is especially affected.
- The dominant frequency peak shows systematically higher values (up to 6%) in remnants where hyperons are produced.
- The temperature in the remnants is lower if hyperons are present because of the higher specific heat of matter.
- The mass ejecta and the threshold mass are also affected by the appearance of hyperons.
- Our conclusions are general (do not depend on the initial configuration of the stars)


THANK YOU FOR YOUR ATTENTION