Hyperons and neutron star mergers

In collaboration with:
Georgios Lioutas, Andreas Bauswein, Sebastian Blacker, Angels Ramos and Laura Tolos

Hristijan Kochankovski

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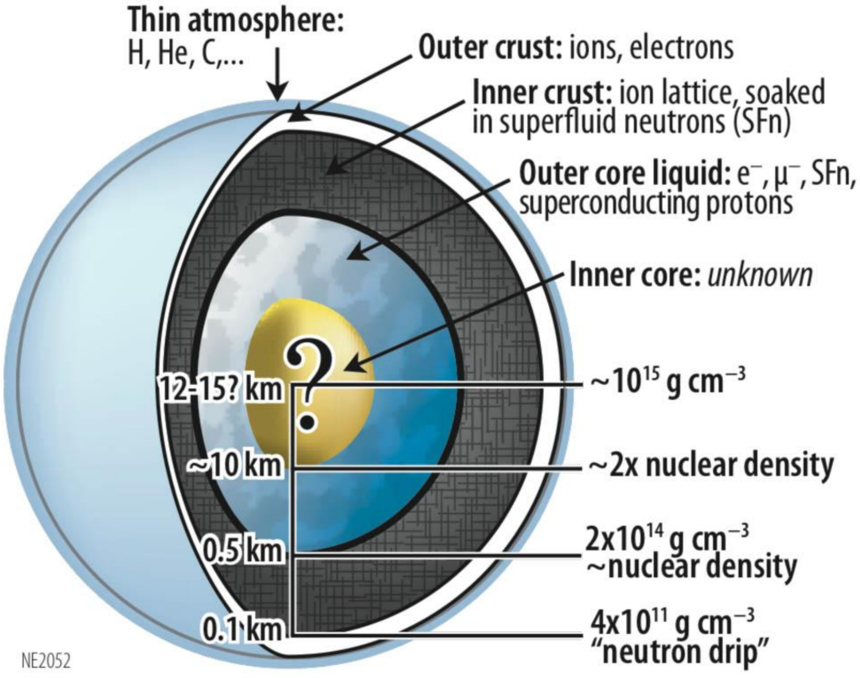
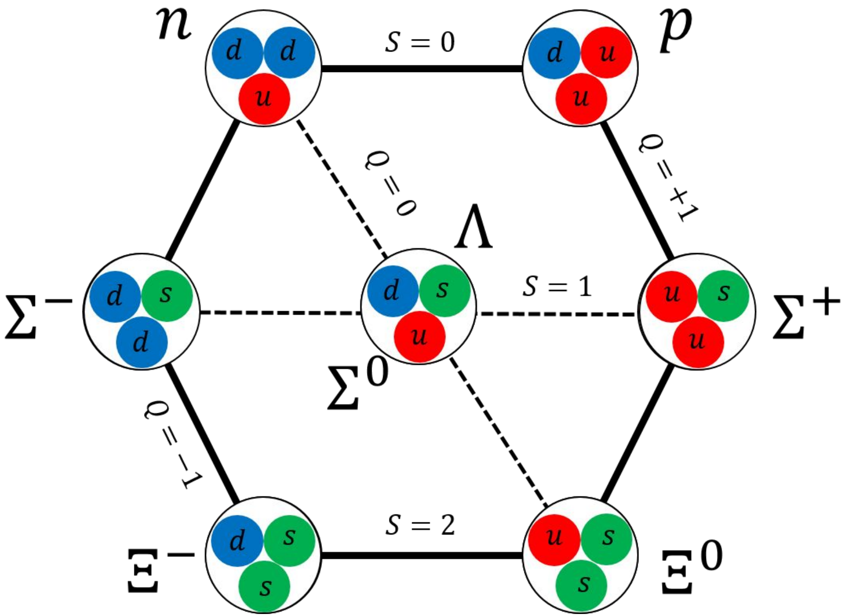
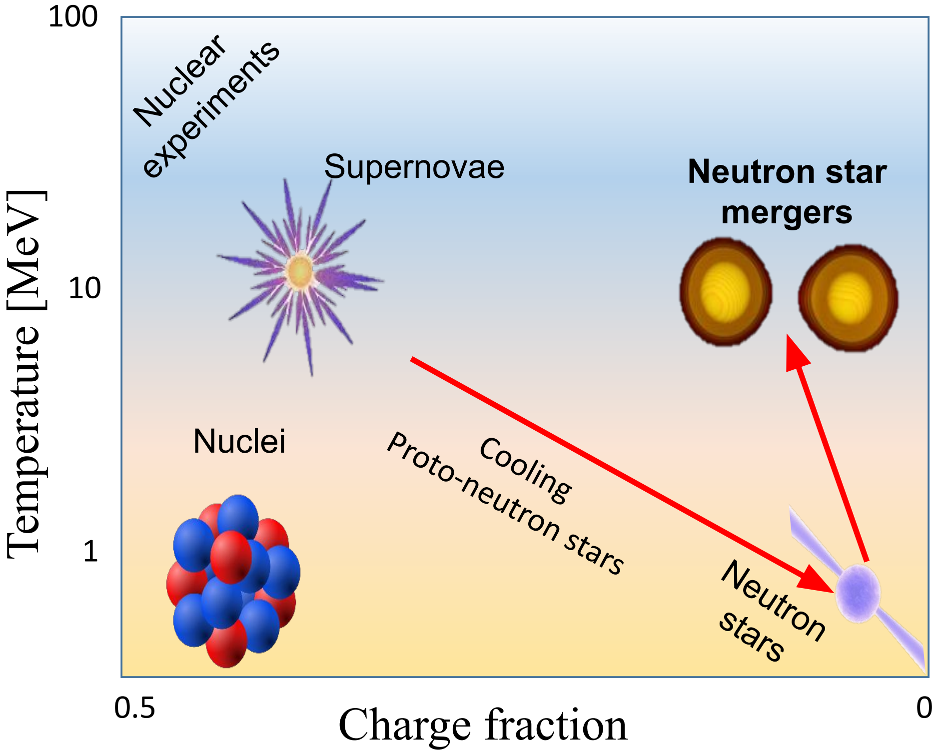
Neutron stars and hyperons

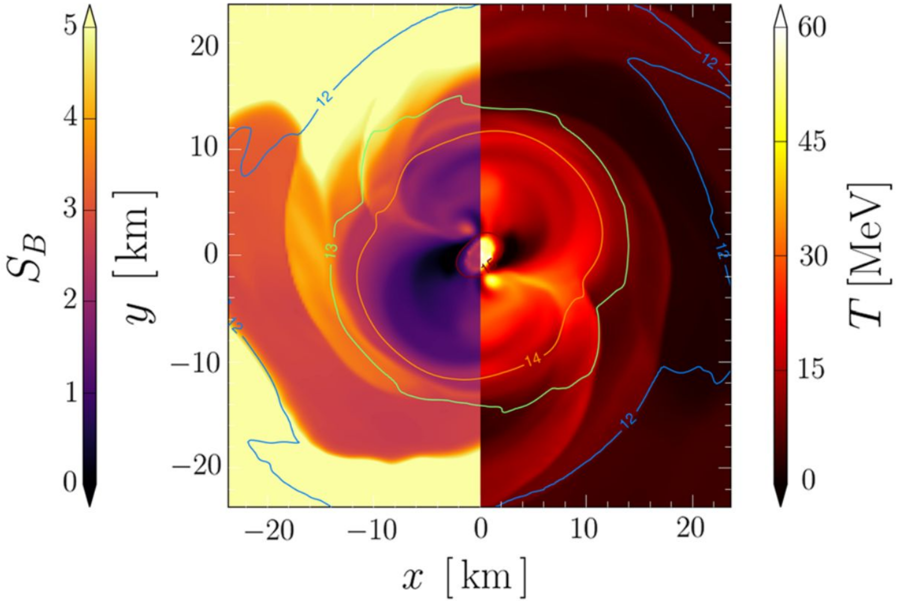


Gendreau et al., SPIE, 2012



Neutron star matter at finite temperature





Most et al. EPJA, 2020

Equation of state (EoS) of dense matter

- The necessary ingredient to predict the properties of NSs is the EoS of dense matter

$$\epsilon = \epsilon(\rho_B)$$

Cold beta-equilibrated EoS

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

Hot EoS, out of beta-equilibrium

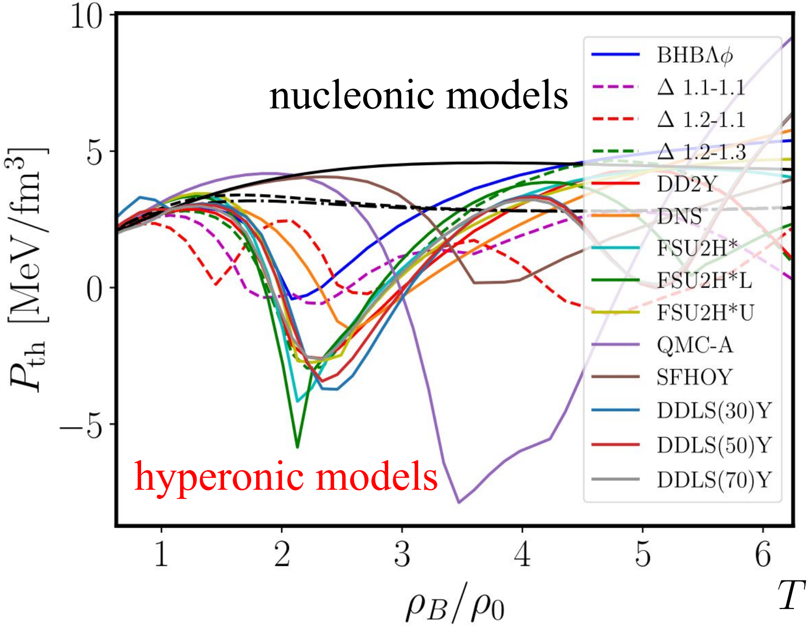
AB INITIO	**PHENOMENOLOGY**
Brueckner–Hartree–Fock	RMF methods
Variational approach	Skyrme potentials
Self-consistent Green Function	Quark-meson coupling method

Does hypernuclear matter have unique properties that are induced by the appearance of hyperons?

Thermal pressure & hyperon excess

Thermal pressure

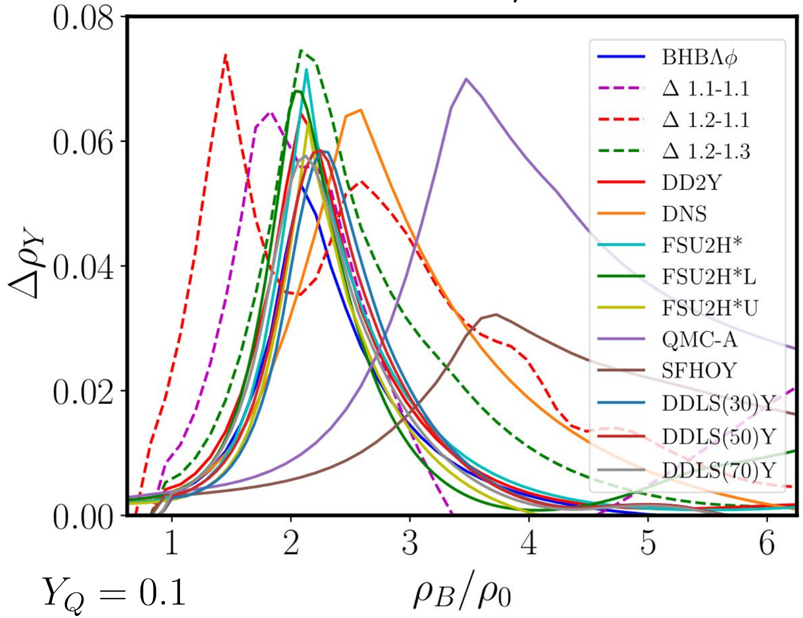
$$P_{\rm th} = P(\rho_B, Y_Q, T) - P(\rho_B, Y_Q, T=0)$$



Kochankovski et al., PRD, 2025

Hyperon excess

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

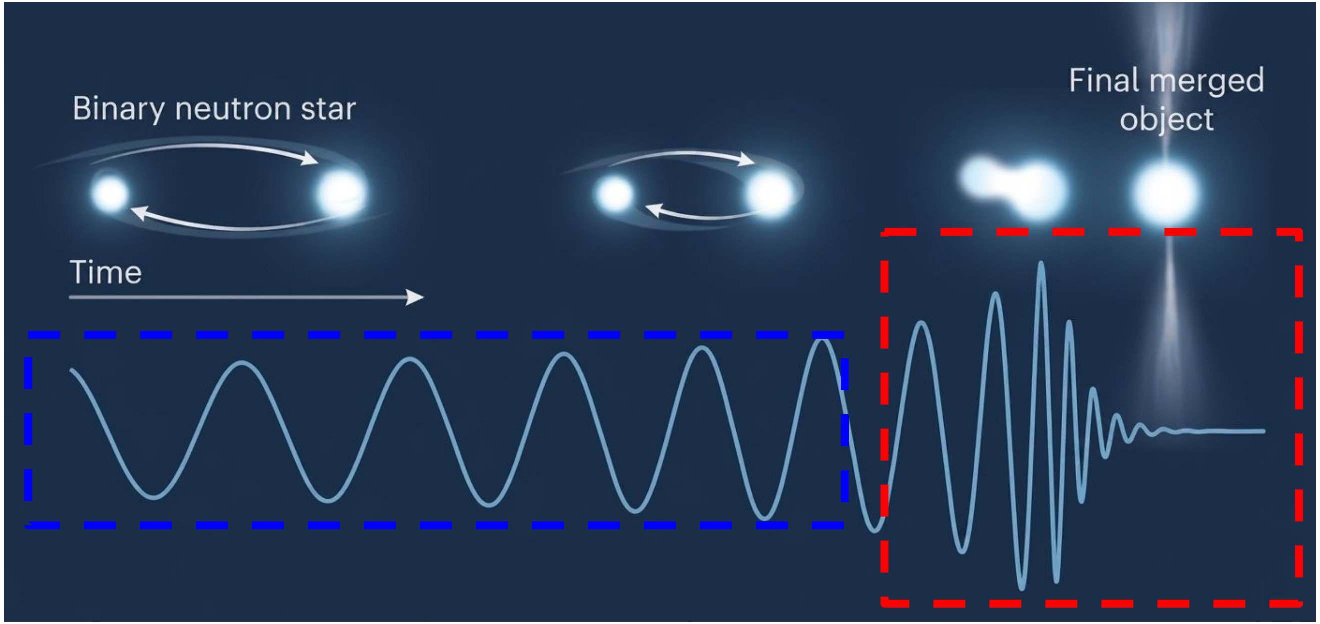


Kochankovski et al., PRD, 2025

$T = 25$ MeV $\quad Y_Q = 0.1$

Can we infer the hyperons' presence in neutron star matter through binary neutron star merger observables?

Scheme of a binary neutron star merger event



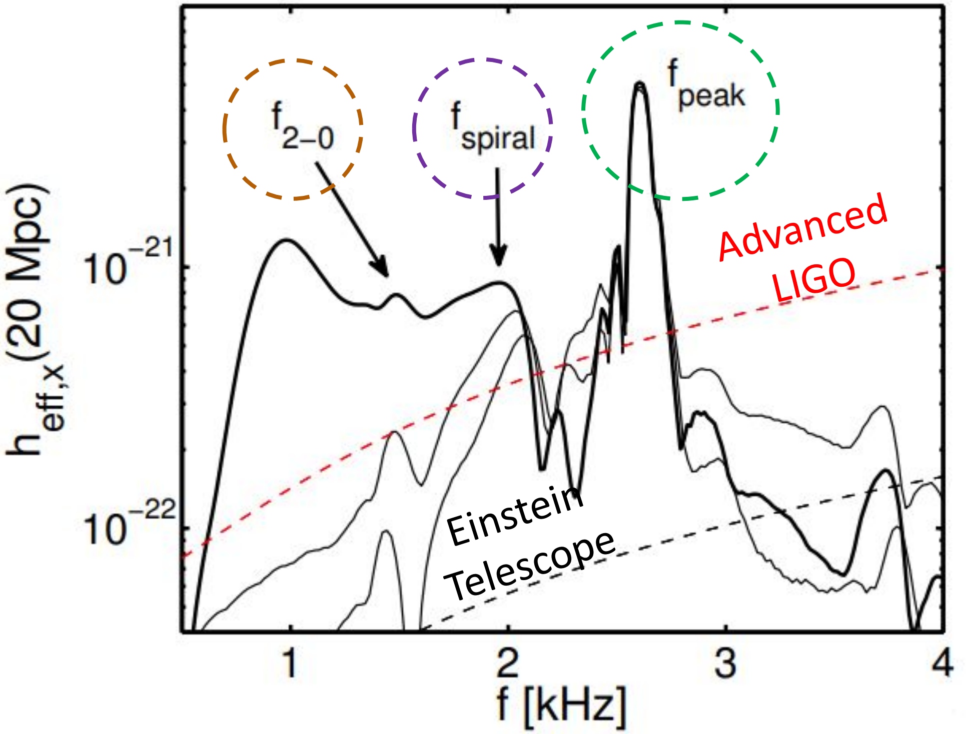
Sensitive to the cold, beta-equilibrated EoS

Λ — Tidal deformability

Sensitive to the hot, out-of-beta-equilibrium EoS

$f_{\rm peak}, M_{\rm ej}, M_{\rm thresh}$

Post-merger gravitational-wave spectrogram



Bauswein et al, J. Phys. G, 2019

Post-merger spectral features are affected by the finite-temperature part of the EoS

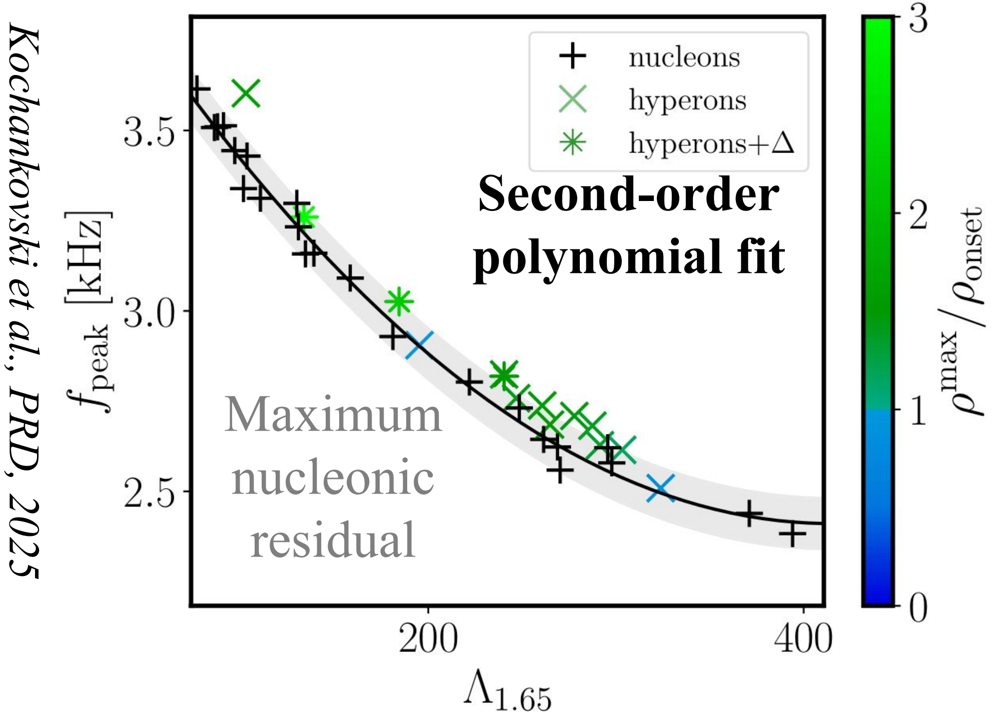
$f_{\rm peak}$ – dominant frequency peak

$f_{\rm spiral}$ – secondary frequency peak

f_{2-0} – secondary frequency peak

Frequency shift and tidal deformability

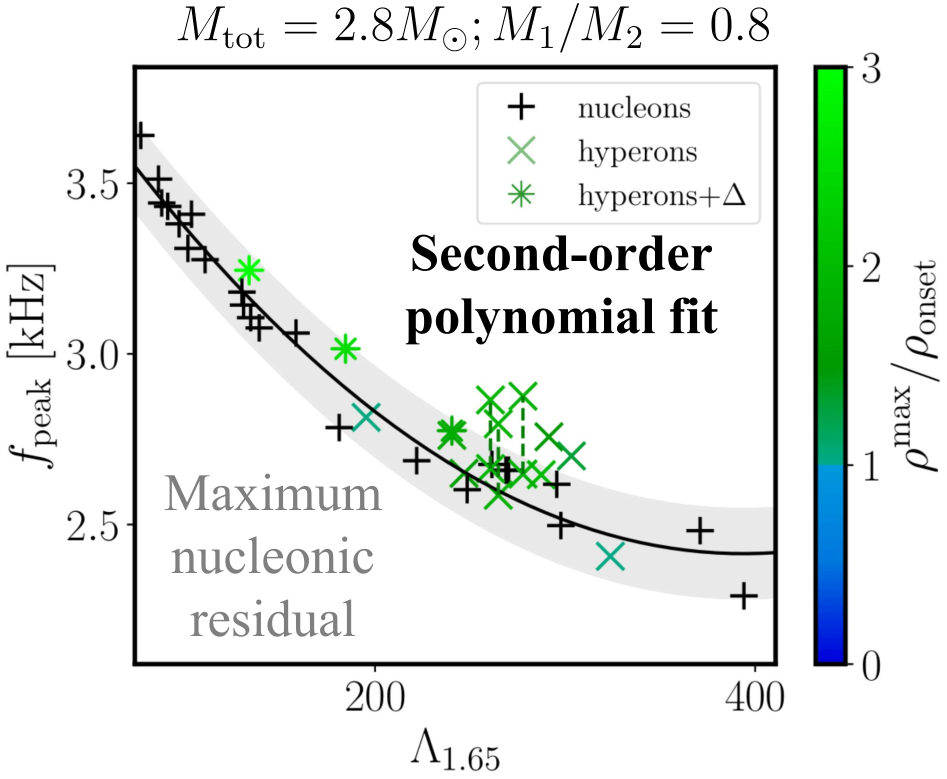
$M_{\mathrm{tot}} = 2.8 M_{\odot}; M_1/M_2 = 1$



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

Frequency shift and tidal deformability

Kochankovski et al., PRD, 2025

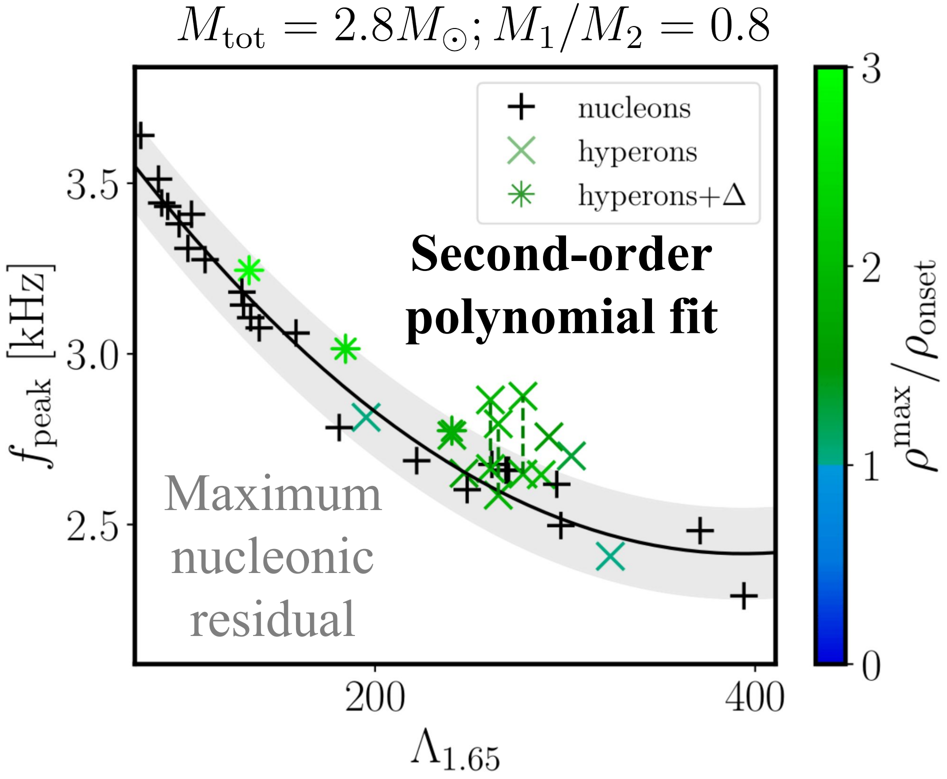


Hyperonic EoSs do not follow the nucleonic $f_{\rm peak} - \Lambda$ relation

Pros:

- Indicates the presence of hyperons
- Valid for any asymmetry between the stars

Frequency shift and tidal deformability



Kochankovski et al., PRD, 2025

Hyperonic EoSs do not follow the nucleonic $f_{\rm peak} - \Lambda$ relation

Pros:

- Indicates the presence of hyperons
- Valid for any asymmetry between the stars

Cons:

- Difficult to be measured
- Can be mimicked by other types of exotic matter

Frequency shift and maximum density

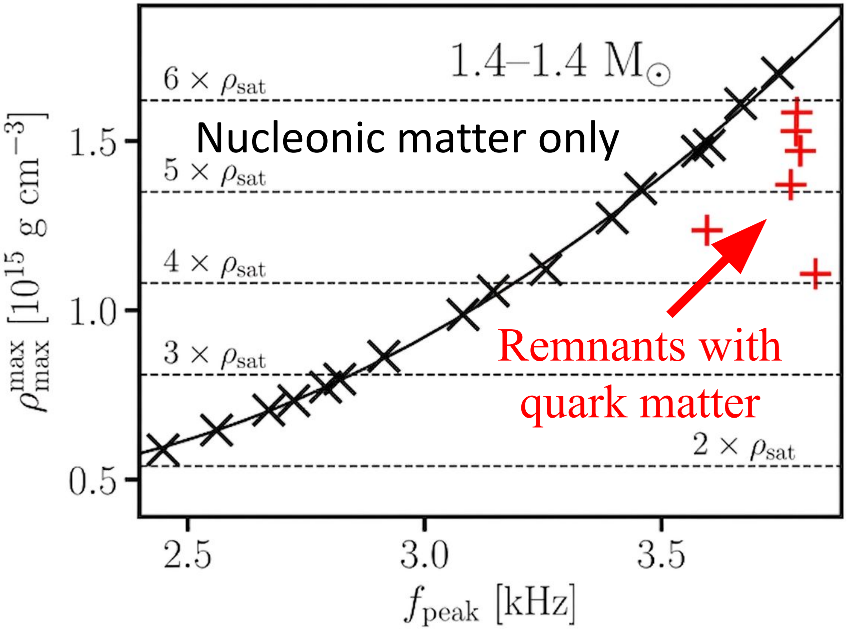
- Past works have found that the empirical relation

$$\rho^{\max} = \rho^{\max}(f_{\text{peak}})$$

holds well in binary neutron star mergers with nucleonic matter

- The relation breaks when quark matter appears in the remnant

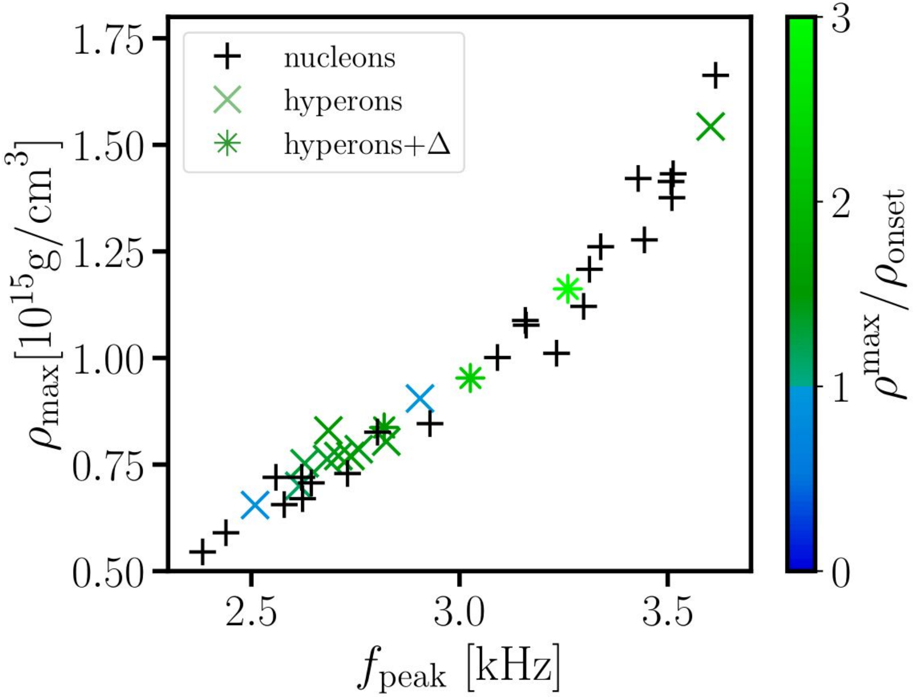
With quark matter



Bauswein et al., PRL, 2019
Blacker et al., PRD, 2020

Frequency shift and maximum density

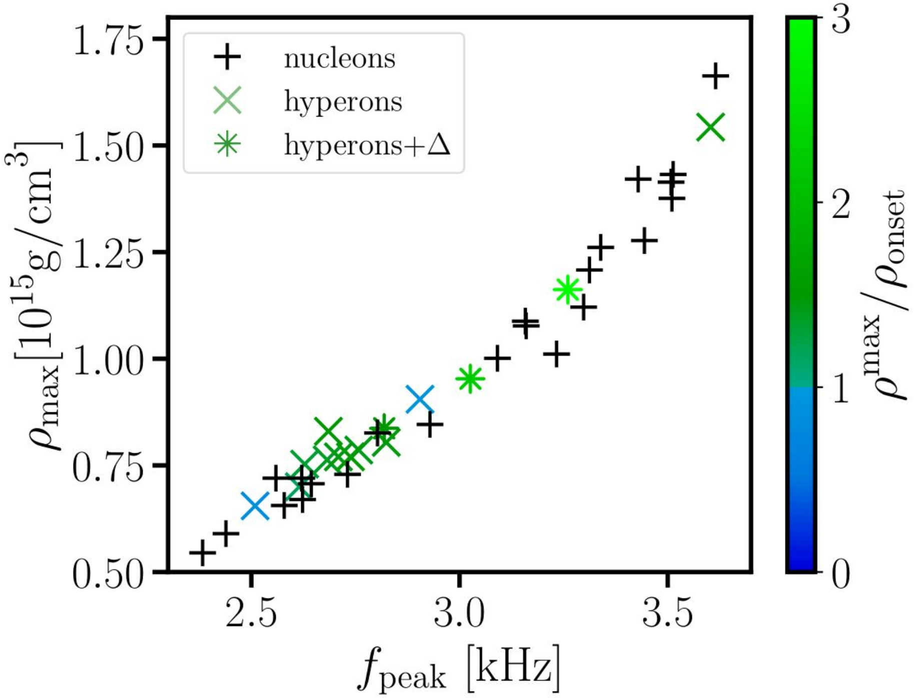
Kochankovski et al., PRD, 2025



The empirical relations can be used even if hyperons are present!

Frequency shift and maximum density

Kochankovski et al. PRD, 2025



The empirical relations can be used even if hyperons are present!

1. The GW measurement suggests that hyperons **appeared** in the dense matter
   → Upper bound on $\rho_{\rm onset}$

2. The GW measurement suggests that hyperons **did not appear** in the dense matter
   → Lower bound on $\rho_{\rm onset}$

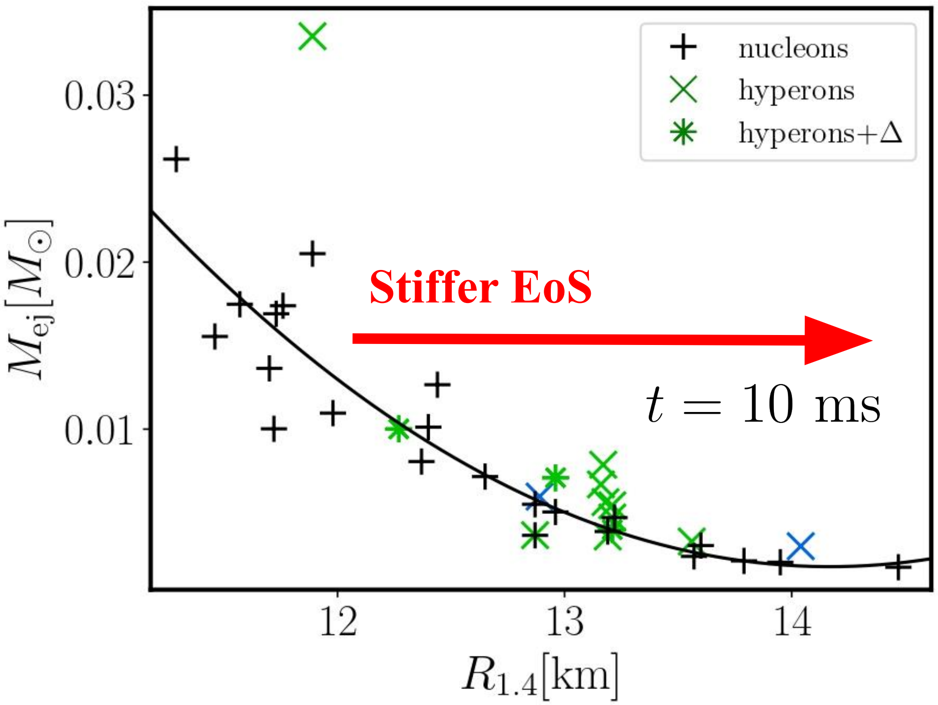
Mass ejecta

- The amount of ejecta mass is connected to the total amount of synthesised elements

- It is related to the stiffness of the underlying EoS

$$M_{\text{ej}} = M_{\text{ej}}(R_{1.4})$$

The appearance of hyperons could increase the amount of mass ejecta



Kochankovski et al., PRD, 2025

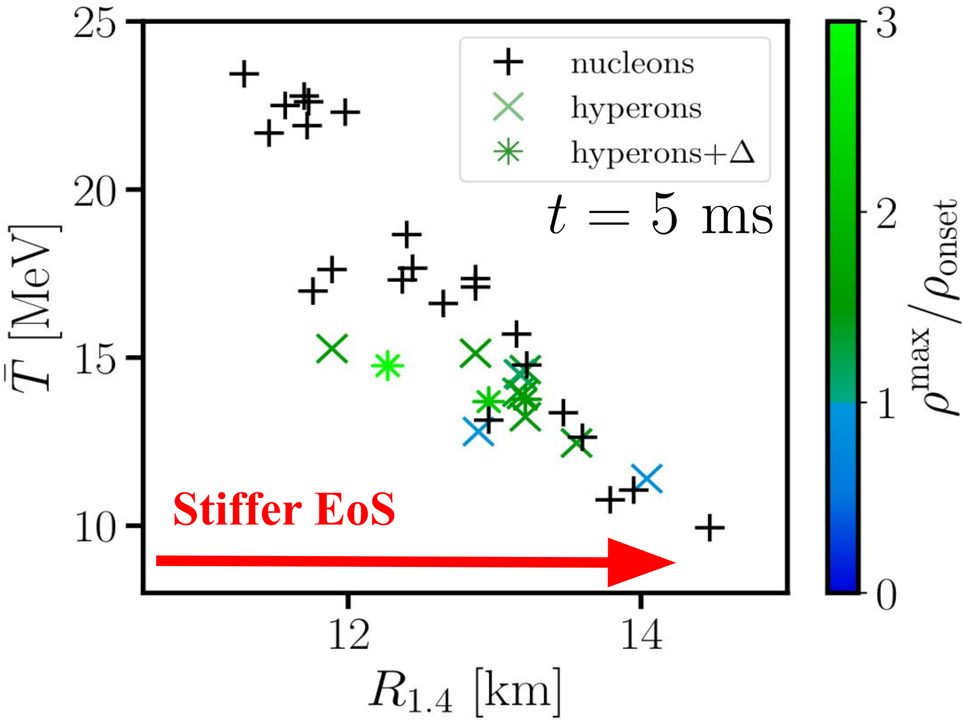
Average temperature

- The average temperature is also related to the stiffness of the underlying EoS

$$\bar{T} = \bar{T}(R_{1.4})$$

- Stiffer EoS induces lower temperature

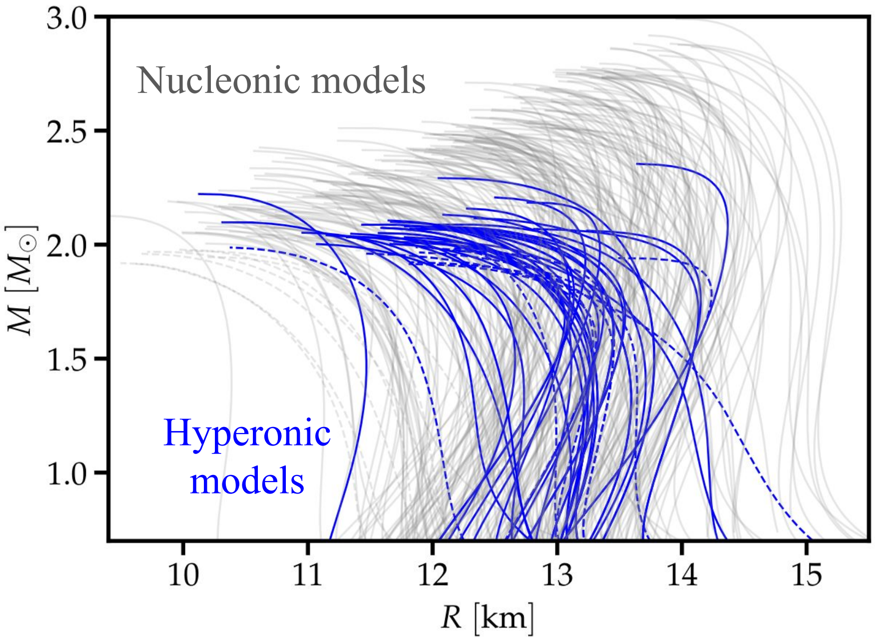
- Hyperonic EoSs yield a lower temperature for a fixed $R_{1.4}$



Kochankovski et al., PRD, 2025

Can we infer the hyperons' presence in neutron star matter through cold star observables?

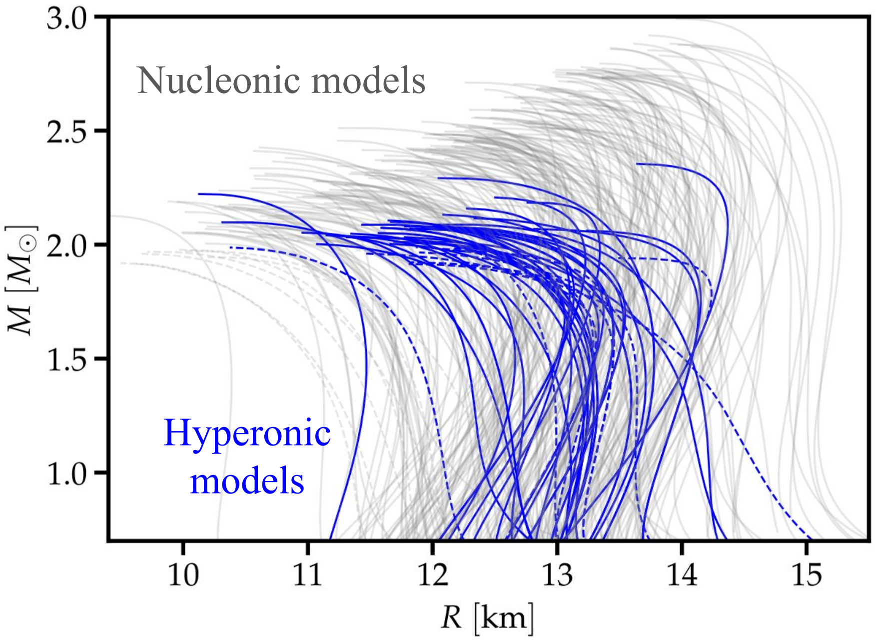
Hyperons' signatures in the cold-star observables



Bauswein et al., PRR, 2026

The mass-radius curves of the two categories are almost indistinguishable

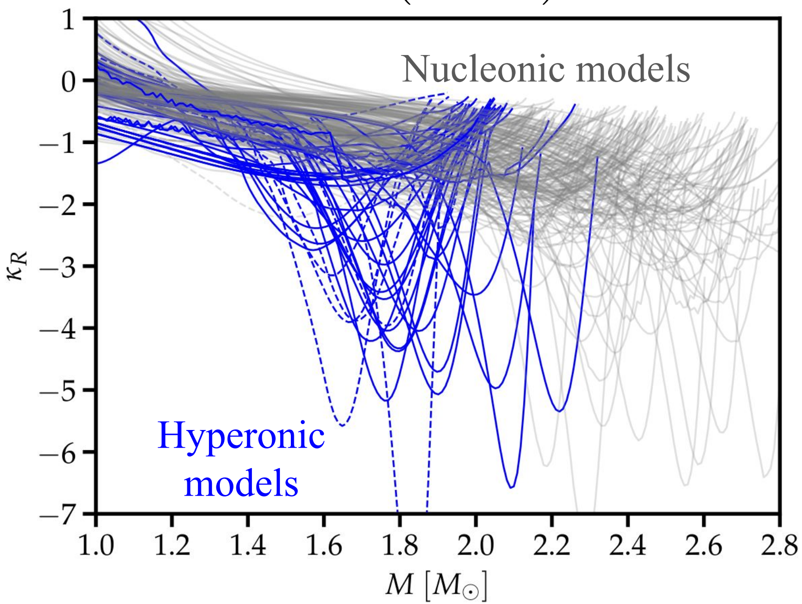
Hyperons' signatures in the cold-star observables



The mass-radius curves of the two categories are almost indistinguishable

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

Bauswein et al., PRR, 2026



The curvature shows a significant drop in the intermediate mass region for hyperonic EoSs

Can we test the conclusions with more complex models?

Conventional RMF models

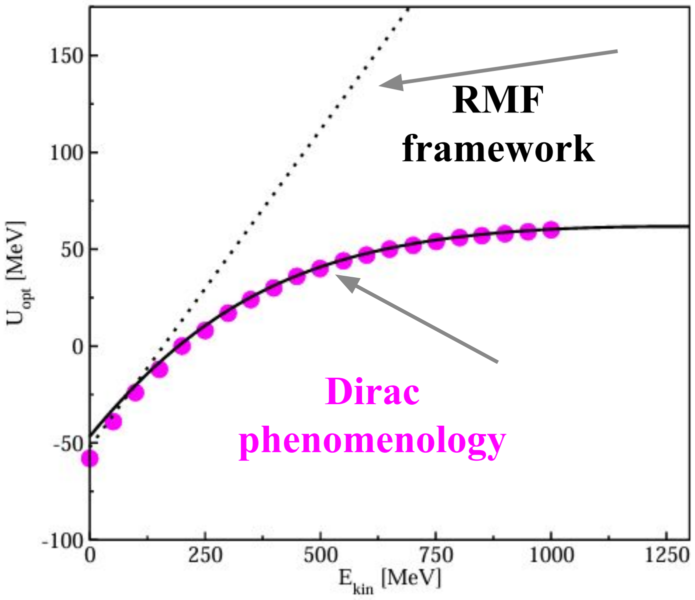
- The conventional RMF models do not have momentum-dependent self-energies

$$S = g_{\sigma N}\sigma$$
$$V = g_{\omega N}\omega + g_{\rho N} I_{3N}\rho$$

- This is reflected in the behavior of the optical potentials

$$U_{\rm opt} = -S + \frac{E}{m}V + \frac{1}{2m}(S^2 - V^2)$$

This is a problem for both nucleonic and hyperonic models



Gaitanos et al, Nuc. Phys. A, 2013

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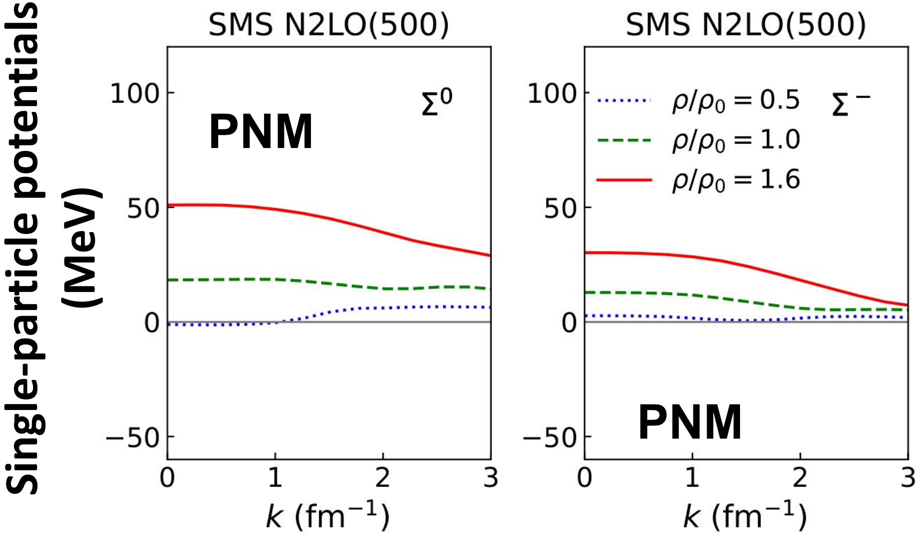

Jinno et al., PRC, 2025

Non-Linear Derivative (NLD) model

- Solution: Introducing a derivative operator, $\vec{D}$, in the Lagrangian

$$
\begin{aligned}
\mathcal{L}_b &= \overline{\Psi}_b(i\gamma_\mu\overrightarrow{\partial^\mu} - i\overleftarrow{\partial^\mu}\gamma_\mu)\Psi_b - m_b\overline{\Psi}_b\Psi_b\,, \\
\mathcal{L}_m &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - b\sigma^3 - c\sigma^4 - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} \\
&+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{1}{4}P^{\mu\nu}P_{\mu\nu}\,, \\
\mathcal{L}_{\text{int}} &= \sum_m\sum_b \frac{g_{mb}}{2}\left(\overline{\Psi}_b\overleftarrow{D}_{mb}\Gamma_m\Psi_b\phi_m + \phi_m\overline{\Psi}_b\Gamma_m\overrightarrow{D}_{mb}\Psi_b\right)
\end{aligned}
$$

$$
\vec{D} = \frac{\Lambda_2^2}{\Lambda_1^2\left[1 + \sum_{j=1}^{4}\left(\frac{v_j^\mu}{\Lambda_1}i\overrightarrow{\partial_\mu}\right)^2\right]}
\qquad
D(p) = \frac{\Lambda_2^2}{\Lambda_1^2 + \vec{p}^2}
$$

Non-Linear Derivative (NLD) model

- Solution: Introducing a derivative operator, $\vec{D}$, in the Lagrangian

$$S(p) = g_{\sigma b}\sigma D_{\sigma b}(p)$$
$$V(p) = g_{\omega b}\omega D_{\omega b}(p) + g_{\rho b} I_{3b}\rho D_{\rho b}(p)$$

$$\begin{aligned}
\mathcal{L}_b &= \overline{\Psi}_b(i\gamma_\mu\overrightarrow{\partial}^\mu - i\overleftarrow{\partial}^\mu\gamma_\mu)\Psi_b - m_b\overline{\Psi}_b\Psi_b \,, \\
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&+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - \frac{1}{4}P^{\mu\nu}P_{\mu\nu} \,, \\
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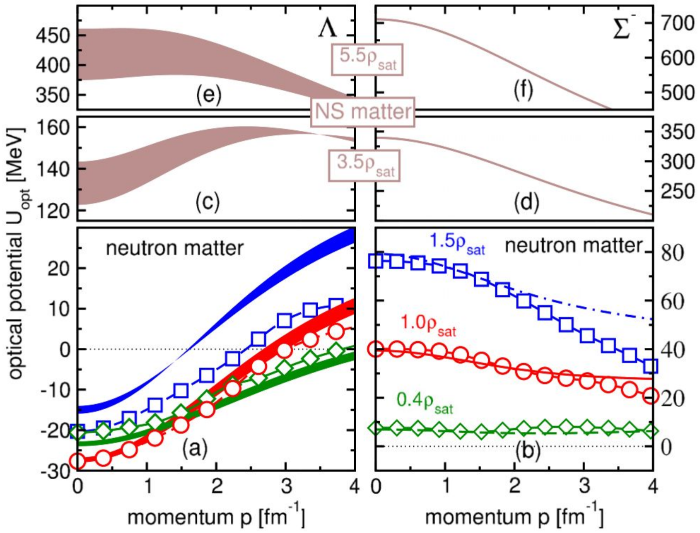
\end{aligned}$$

$$\vec{D} = \frac{\Lambda_2^2}{\Lambda_1^2\left[1 + \sum_{j=1}^{4}\left(\frac{v_j^\mu}{\Lambda_1} i\vec{\partial}_\mu\right)^2\right]}$$

$$D(p) = \frac{\Lambda_2^2}{\Lambda_1^2 + \vec{p}^2}$$

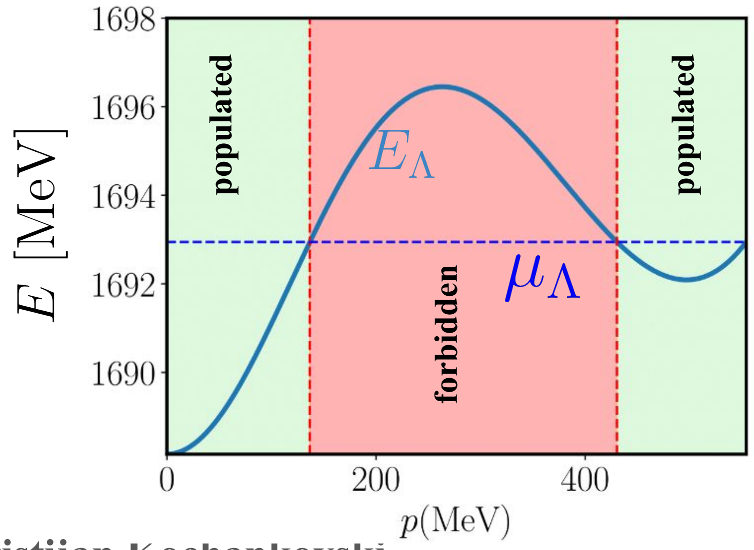


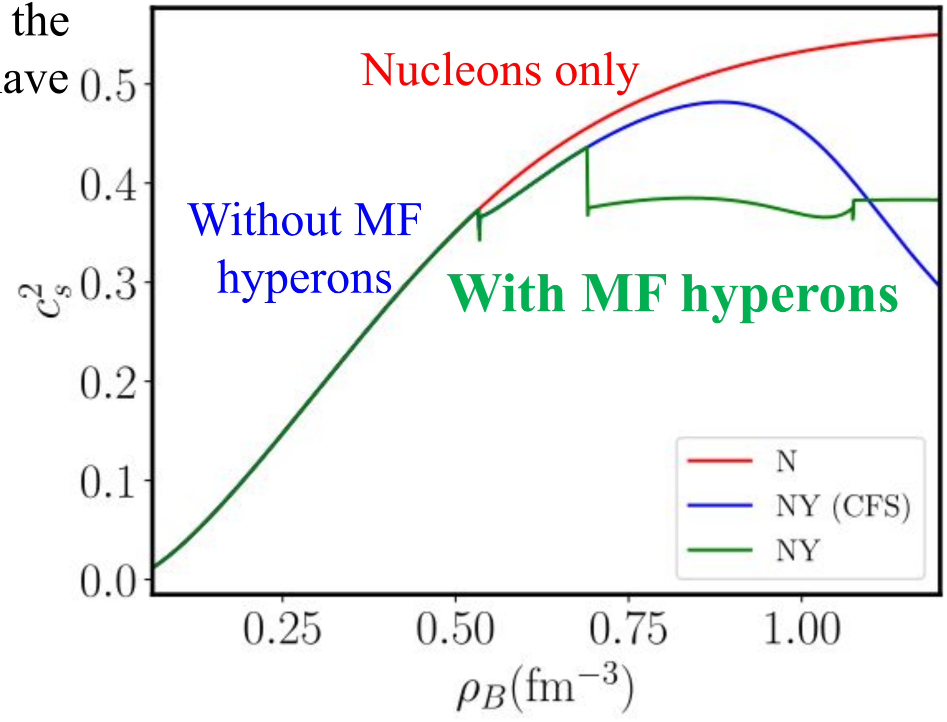
A. Chorozidou et al, PRC, 2024
fitted to the results from χBHF—*S. Petschauer et al., EPJ A, 2016*

Momentum-fragmented (MF) hyperons

- Due to the soft momentum dependence, the in-medium energy of hyperons can have several crossings with the Fermi energy

$$E(p) = \sqrt{m^{*2} + p^2} + V(p)$$





Kochankovski et al., PLB, 2026

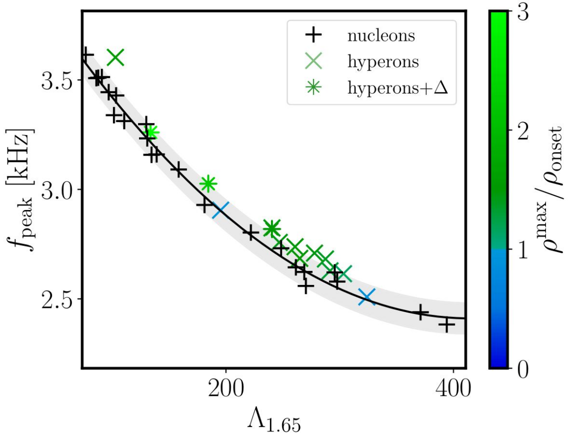
Conclusions and outlook

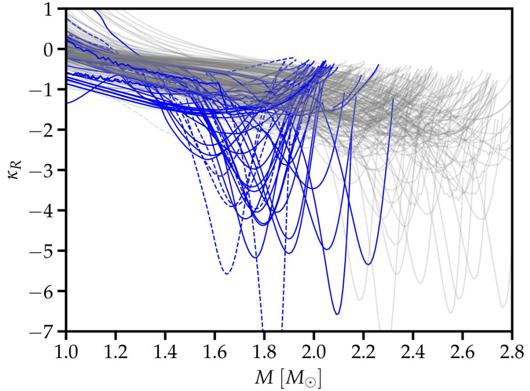
- The appearance of hyperons in dense matter **softens** both **the cold and the hot EoS**

- The **thermal pressure of hypernuclear matter is systematically lower** than that of pure nuclear matter

- The **dominant frequency peak** from the binary neutron star merger event **shows systematically higher values** when hyperons are produced in the remnant

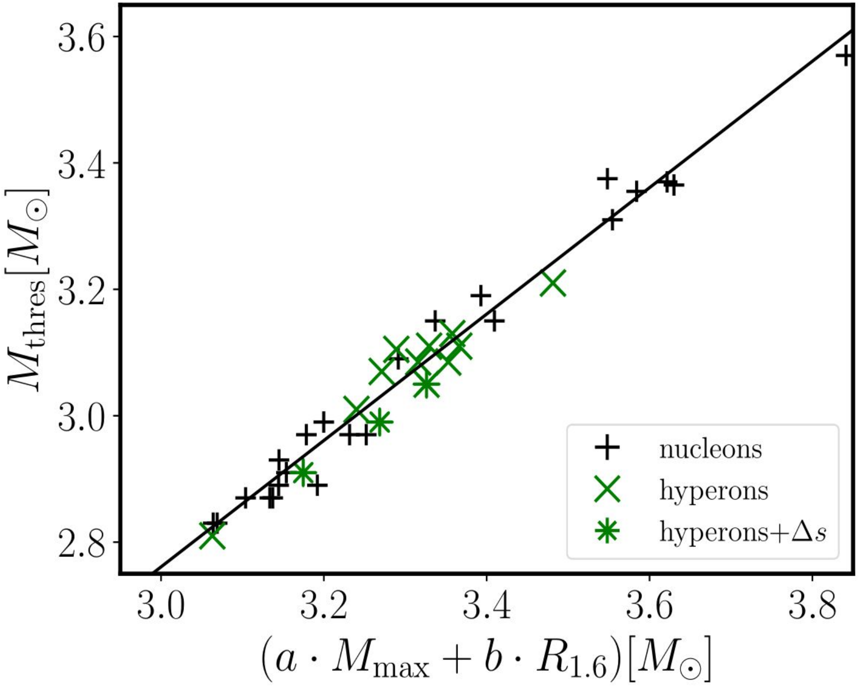
- Future **multimessenger measurements** may finally answer the **composition question of dense matter**



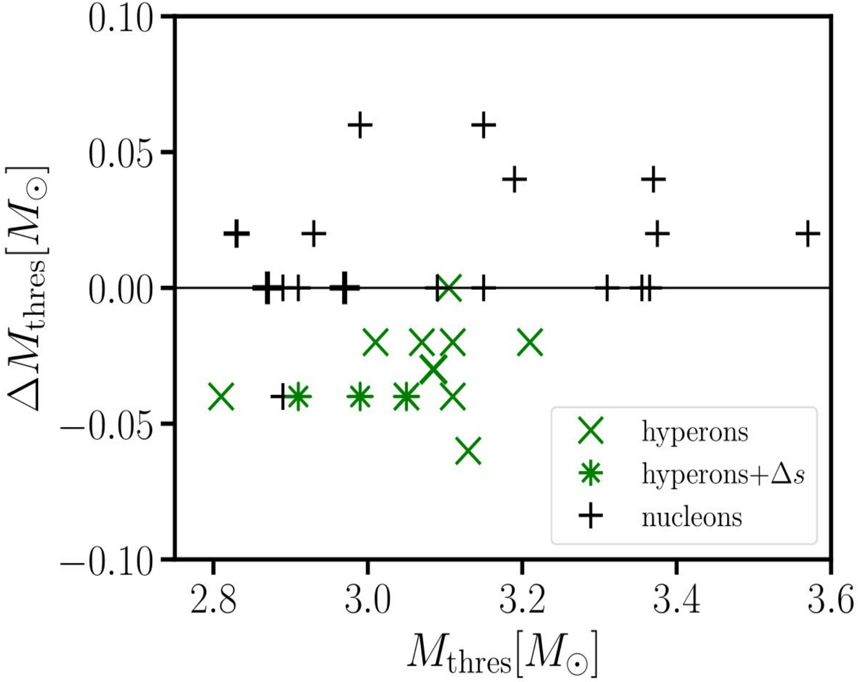


THANK YOU FOR YOUR ATTENTION!

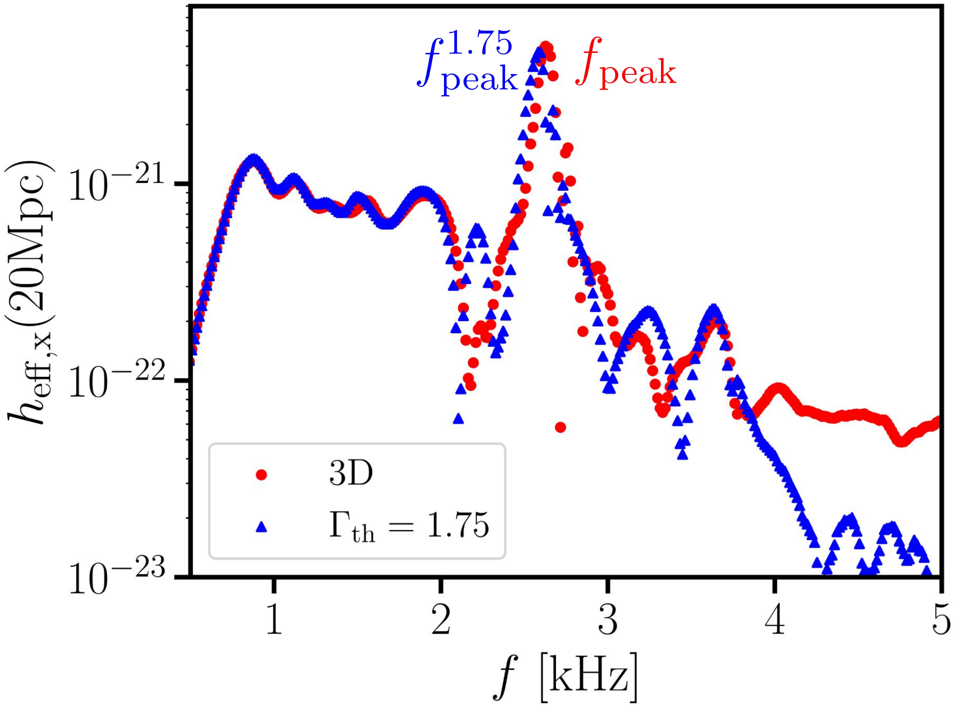
Threshold mass



Hyperonic EoSs are scattered around the nucleonic fit

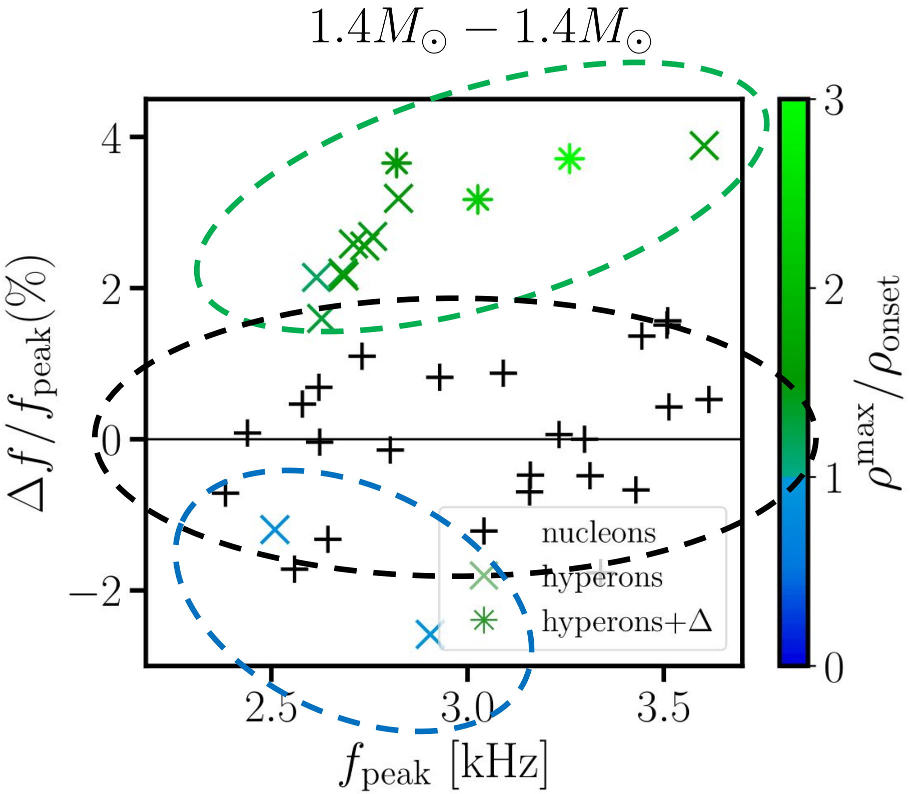


Finite-temperature behavior affects the threshold mass!



Dominant Frequency Peak

Dominant frequency peak shift



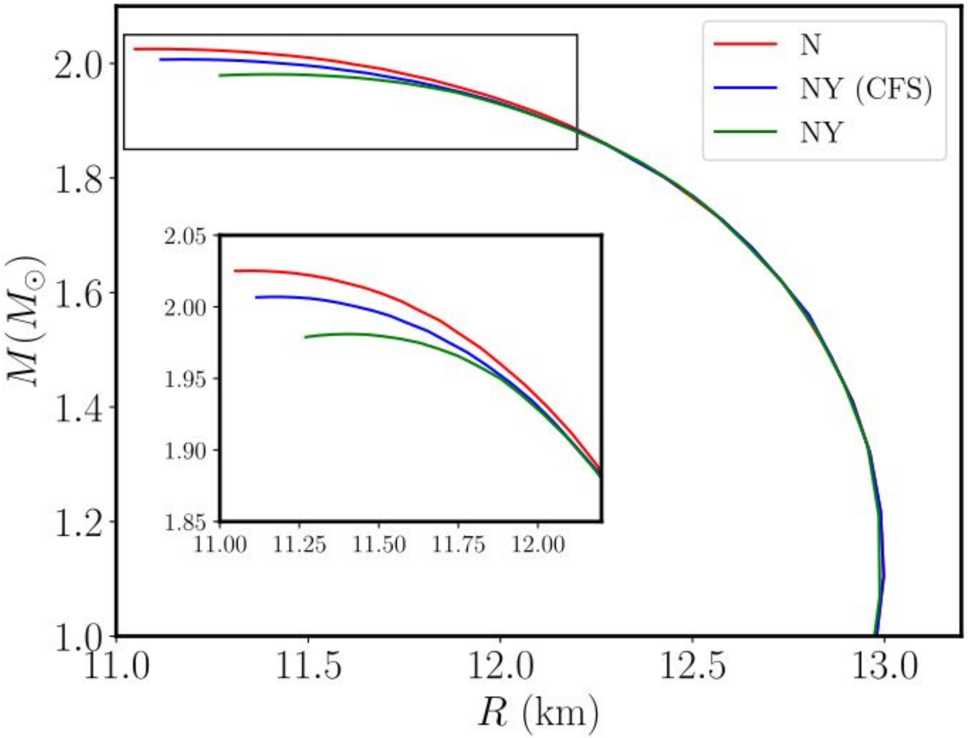
$$\Delta f = f_{\rm peak} - f_{\rm peak}^{1.75}$$

Hyperonic EoSs show a systematic shift towards higher frequencies

Nucleonic models are scattered around the reference values

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

Mass-radius relation in the NLD model



The mass radius curves are insensitive to the different matter composition