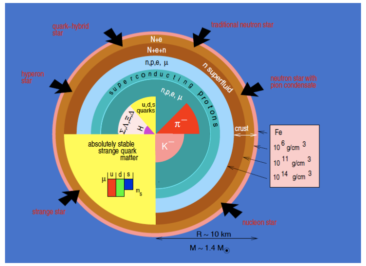
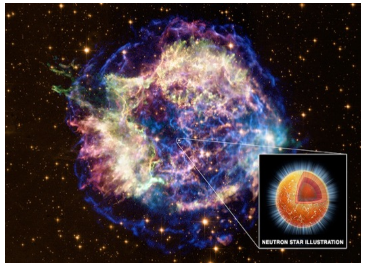


Hyperons in Neutron Stars and Mergers



Institute of Space Sciences
CSIC IEEC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Laura Tolós

FIAS Frankfurt Institute for Advanced Studies

Hristijan Kochankovski, Angels Ramos,
Sebastian Blacker and Andreas Bauswein

SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms
May 13 – 17, 2024
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Outline

- Motivation
- Equation of State and composition of the hot neutron star core: FSU2H* model
- Thermal index of the neutron star core
- Thermal behavior as indicator for hyperons in neutron star mergers
- Summary

Kochankovski, Ramos and LT, MNRAS 517 (2022) 507, 2206.11266 [astro-ph.HE]
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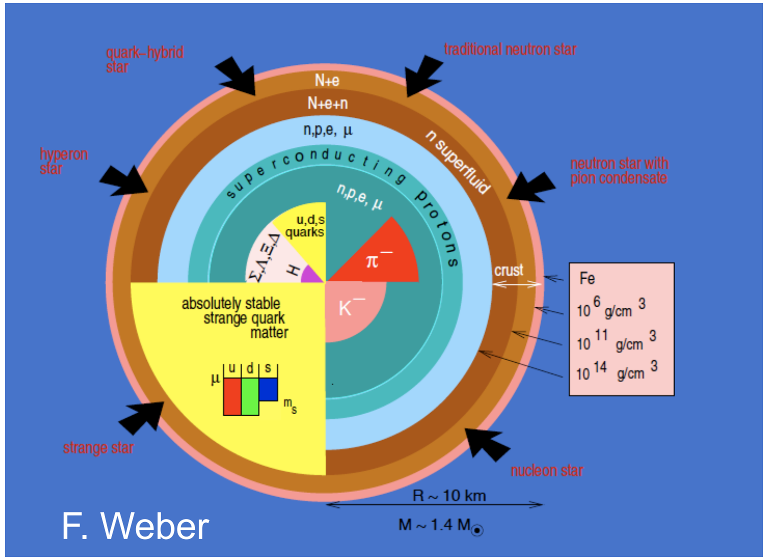
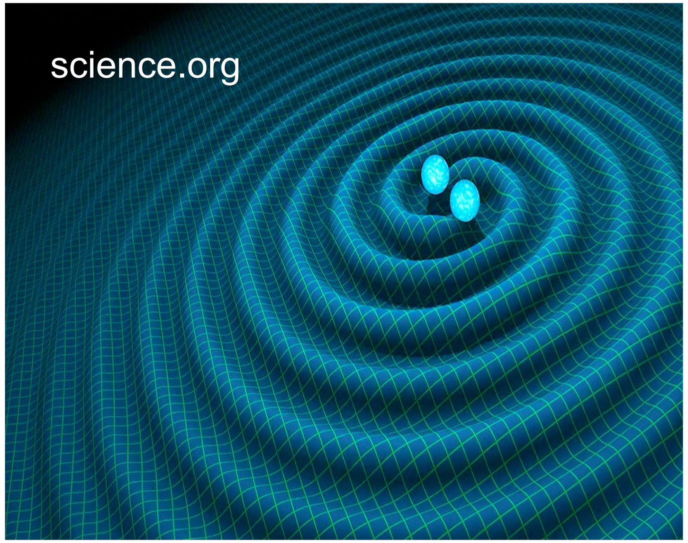
Motivation



F. Weber



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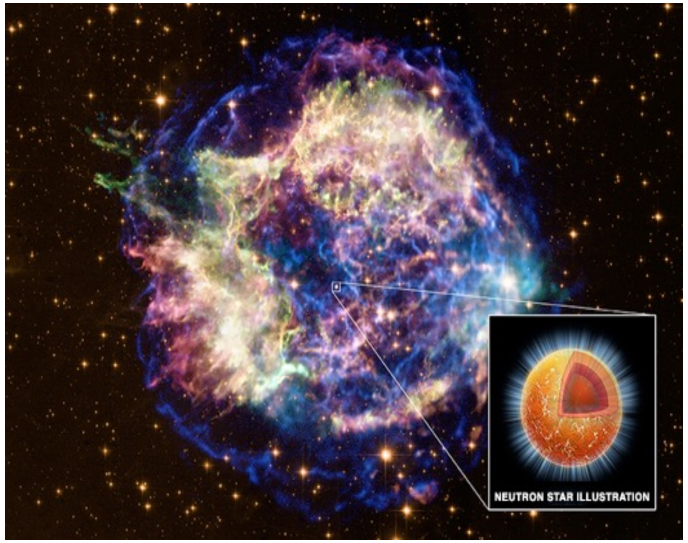


Neutron stars are a natural laboratory for studying matter under extreme conditions

Little is known about the composition of the core. Non-nucleonic components can appear, such as **hyperons**

A finite temperature treatment is necessary in order to understand the evolution of young neutron stars, the collapse of supernovae or the merger of a binary system of neutron stars

Finite temperature EoS depends (ρ_B, T, Y_Q)

$$\mathbf{T = (0 - 100)\ MeV}$$

$$\boldsymbol{\rho_B = (0.5 - 6)\rho_0}$$

$$\boldsymbol{Y_Q = (0 - 0.6)}$$

EoS and composition of the hot NS core: FSU2H* model

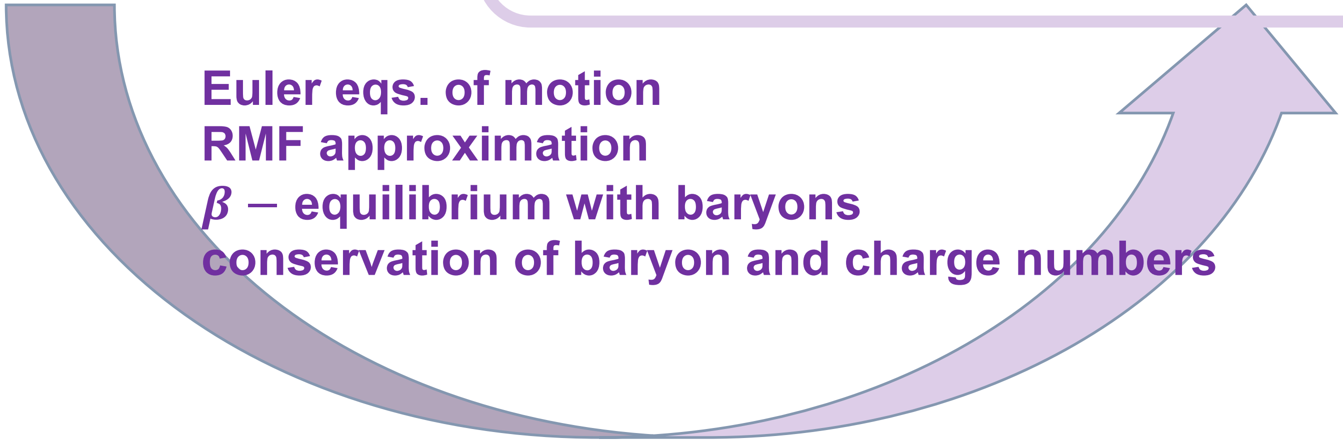
$$
\begin{aligned}
\mathcal{L} &= \sum_b \mathcal{L}_b + \mathcal{L}_m, \\
\mathcal{L}_b &= \bar{\Psi}_b(i\gamma_\mu\partial^\mu - q_b\gamma_\mu A^\mu - m_b + g_{\sigma b}\sigma + g_{\sigma^* b}\sigma^* \\
&- g_{\omega b}\gamma_\mu\omega^\mu - g_{\phi b}\gamma_\mu\phi^\mu - g_{\rho,b}\gamma_\mu\vec{I}_b\cdot\vec{\rho}^{\,\mu})\Psi_b, \\
\mathcal{L}_m &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{\kappa}{3!}(g_{\sigma N}\sigma)^3 - \frac{\lambda}{4!}(g_{\sigma N}\sigma)^4 \\
&+ \frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} \\
&- \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{\zeta}{4!}g_{\omega N}^4(\omega_\mu\omega^\mu)^2 \\
&- \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^{\,\mu} + \Lambda_\omega g_{\rho N}^2\vec{\rho}_\mu\vec{\rho}^{\,\mu}g_{\omega N}^2\omega_\mu\omega^\mu \\
&- \frac{1}{4}P^{\mu\nu}P_{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu},
\end{aligned}
$$

Need of an equation of state (EoS) that depends on temperature (T), baryon density (ρ_B) and charged fraction (Y_Q)
→ construct a relativistic mean-field model (RMF):

FSU2H* model

from the **energy-momentum tensor**
we extract **thermodynamic properties**

$\epsilon_{tot}, \mathbf{P}, \mathbf{s}, \mathbf{f}$



Euler eqs. of motion
RMF approximation
β – equilibrium with baryons
conservation of baryon and charge numbers

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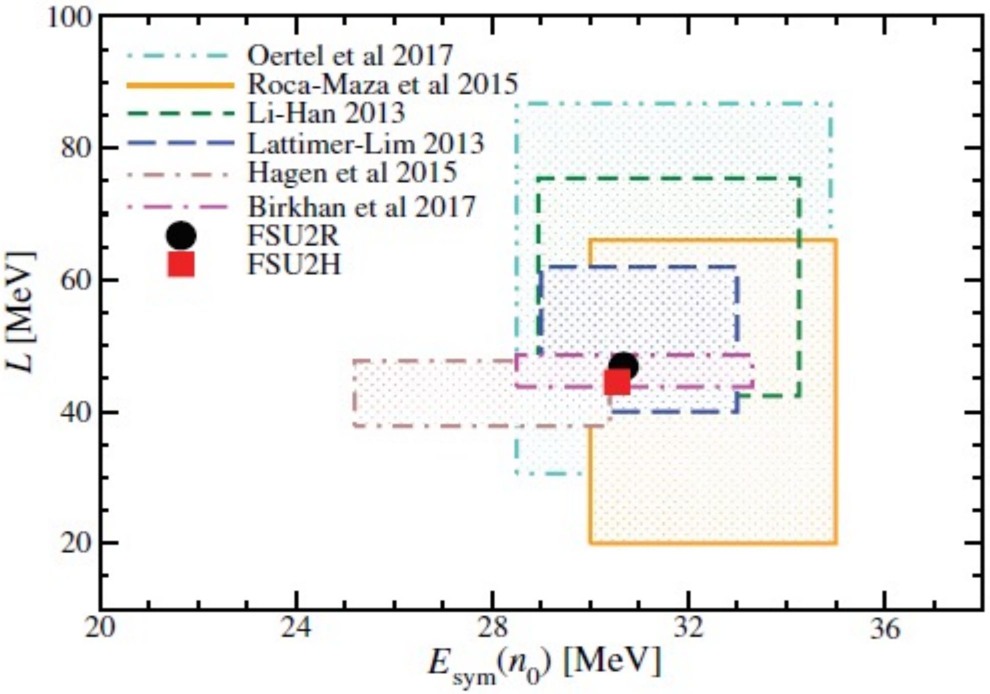
FSU2H* model: nuclear properties

Parameters of the FSU2H*model (nucleon mass m_N=939 MeV)

m_σ (MeV)	m_ω (MeV)	m_ρ (MeV)	m_{σ^*} (MeV)	m_ϕ (MeV)	$g^2_{\sigma N}$	$g^2_{\omega N}$	$g^2_{\rho N}$	κ (MeV)	λ	ζ	Λ_ω
497.479	782.500	763.000	980.000	1020.000	102.72	169.53	197.27	4.00014	-0.0133	0.008	0.045



LT, Centelles and Ramos '17

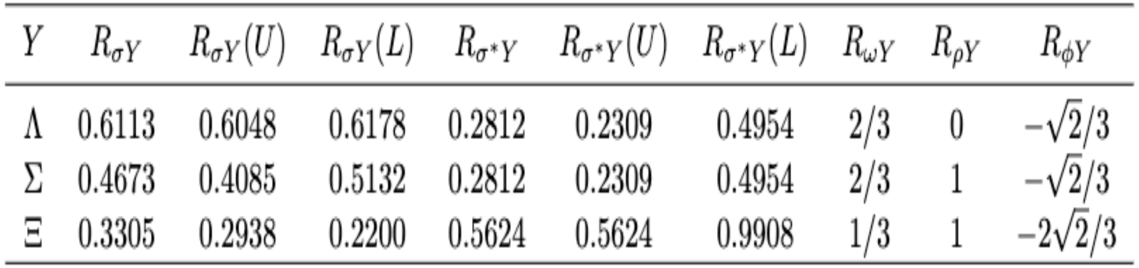
Nuclear properties at T = 0

ρ_0 (fm^{-3})	E/A (MeV)	K (MeV)	$\frac{m_N^*}{m_N}(\rho_0)$	$E_{sym}(\rho_0)$ (MeV)	L (MeV)	K_{sym} (MeV)
0.1505	-16.28	238.0	0.593	30.5	44.5	86.7

EoS fulfills saturation properties of nuclear matter and finite nuclei together with constraints on high-density coming from HiCs

FSU2H*, FSU2H*U, FSU2H*L models: hyperon uncertainties

Parameters of the FSU2H* model
related to hyperons



Y	$R_{\sigma Y}$	$R_{\sigma Y}(U)$	$R_{\sigma Y}(L)$	$R_{\sigma^* Y}$	$R_{\sigma^* Y}(U)$	$R_{\sigma^* Y}(L)$	$R_{\omega Y}$	$R_{\rho Y}$	$R_{\phi Y}$
Λ	0.6113	0.6048	0.6178	0.2812	0.2309	0.4954	2/3	0	$-\sqrt{2}/3$
Σ	0.4673	0.4085	0.5132	0.2812	0.2309	0.4954	2/3	1	$-\sqrt{2}/3$
Ξ	0.3305	0.2938	0.2200	0.5624	0.5624	0.9908	1/3	1	$-2\sqrt{2}/3$

$$R_{iY} = \frac{g_{iY}}{g_{iN}};\, i = (\sigma, \omega, \rho);\ R_{\sigma^* Y} = \frac{g_{\sigma^* Y}}{g_{\sigma Y}};\ R_{\phi Y} = \frac{g_{\phi Y}}{g_{\omega N}}$$

- vector couplings from flavor SU(3) symmetry, the vector dominance model, and ideal mixing for the physical ω and ϕ field
- scalar couplings fitted to hyperon potentials

Potential felt by a hyperon i in j-particle matter:

$$U_i^{(j)}(\rho_j) =$$
$$= -g_{\sigma i}\bar{\sigma}^{(j)} - g_{\sigma^* i}\bar{\sigma}^{*(j)} + g_{\omega i}\bar{\omega}^{(j)} + g_{\rho i} I_{3i}\bar{\rho}^{(j)} + g_{\phi i}\bar{\phi}^{(j)}$$

Hyperon potentials

FSU2H*U

$$U_\Lambda^{(N)}(\rho_0) = (-30, -25)\ \mathrm{MeV}$$

$$U_\Sigma^{(N)}(\rho_0) = (10, 50)\ \mathrm{MeV}$$

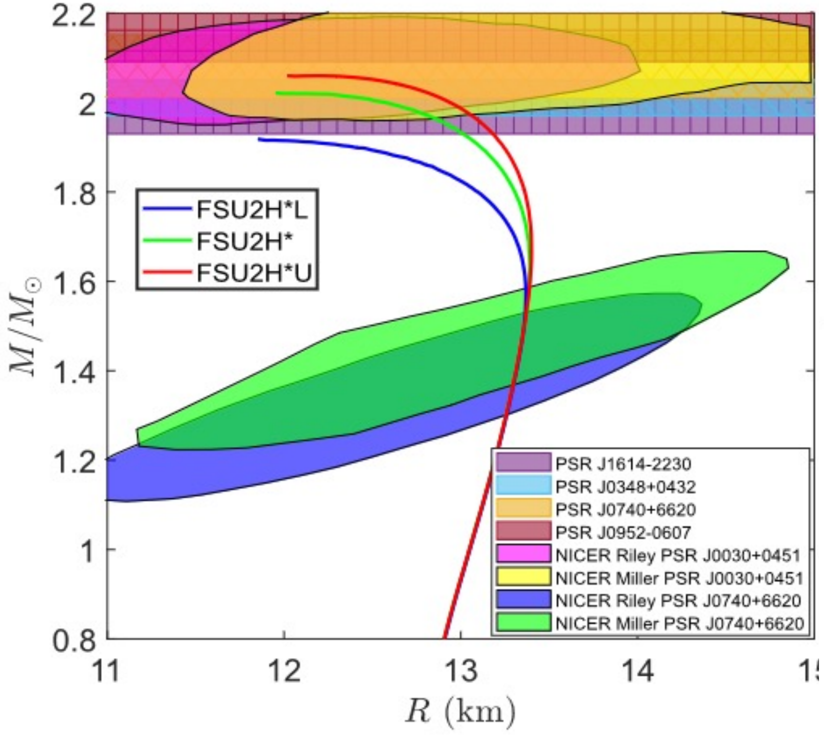
$$U_\Xi^{(N)}(\rho_0) = (-24, -10)\ \mathrm{MeV}$$

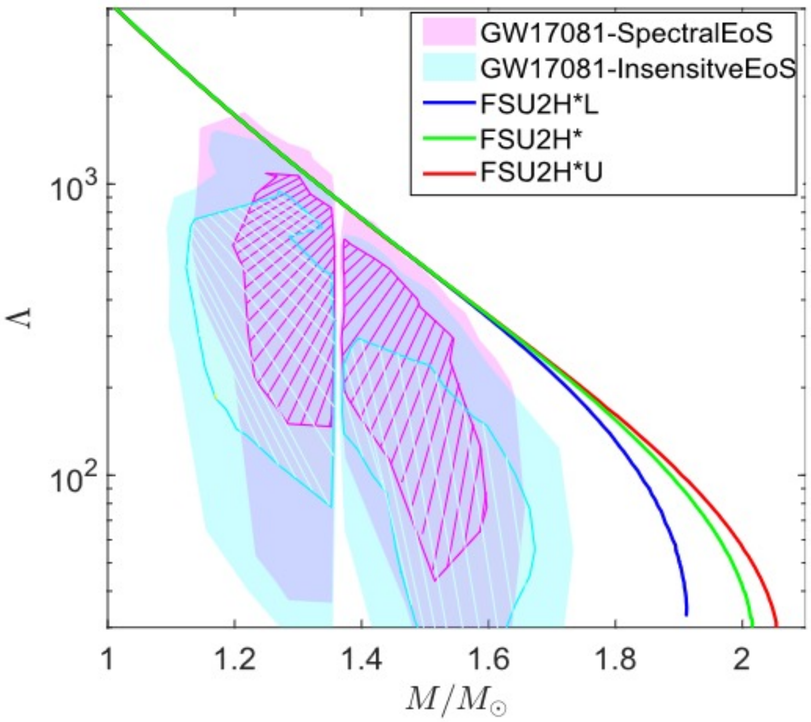
$$U_\Lambda^{(\Lambda)}(\rho_0/5) = (-6{,}0)\ \mathrm{MeV}$$

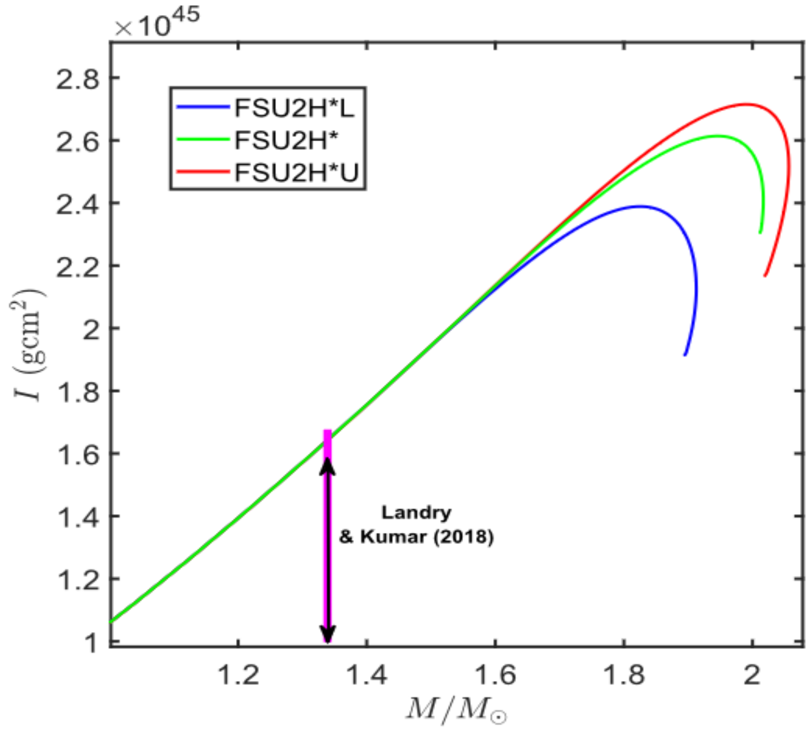
FSU2H*L

variation allowed by nuclear experimental data

T=0: mass-radius, tidal deformability, moment of inertia…



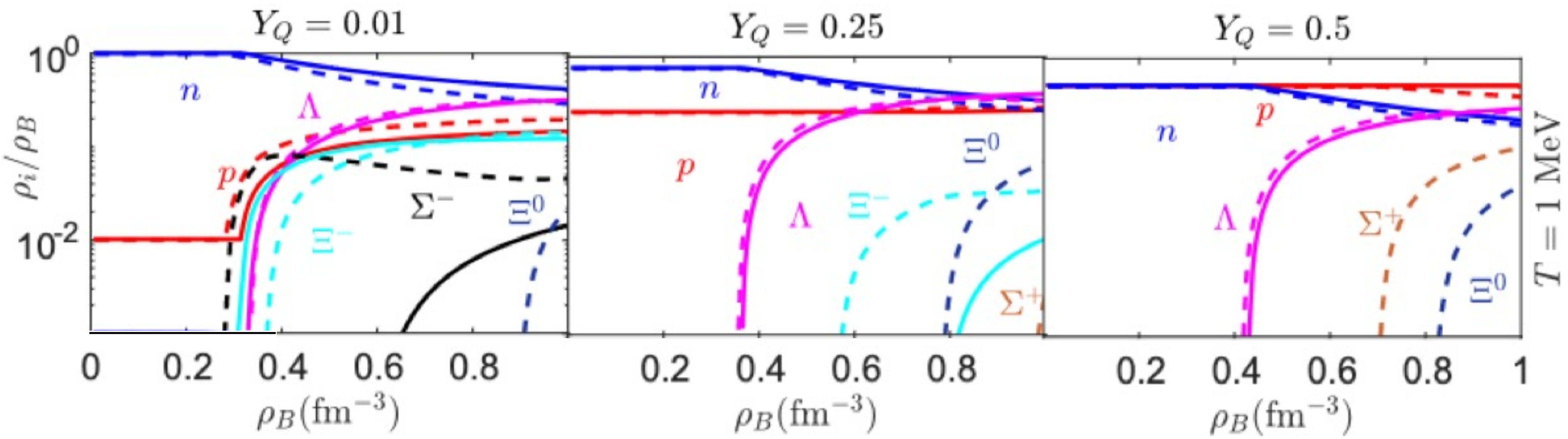




- in agreement with 2 $M_\odot$ observations (except FSU2H*L), with NICER measurements on radii and constraints from GW170817 on tidal deformability
- fulfill less restrictive constraint on moment of inertia (not observed yet!)

EoS and composition: composition at finite temperature (I)

FSU2H*L (dashed lines)
FSU2H*U (solid lines)

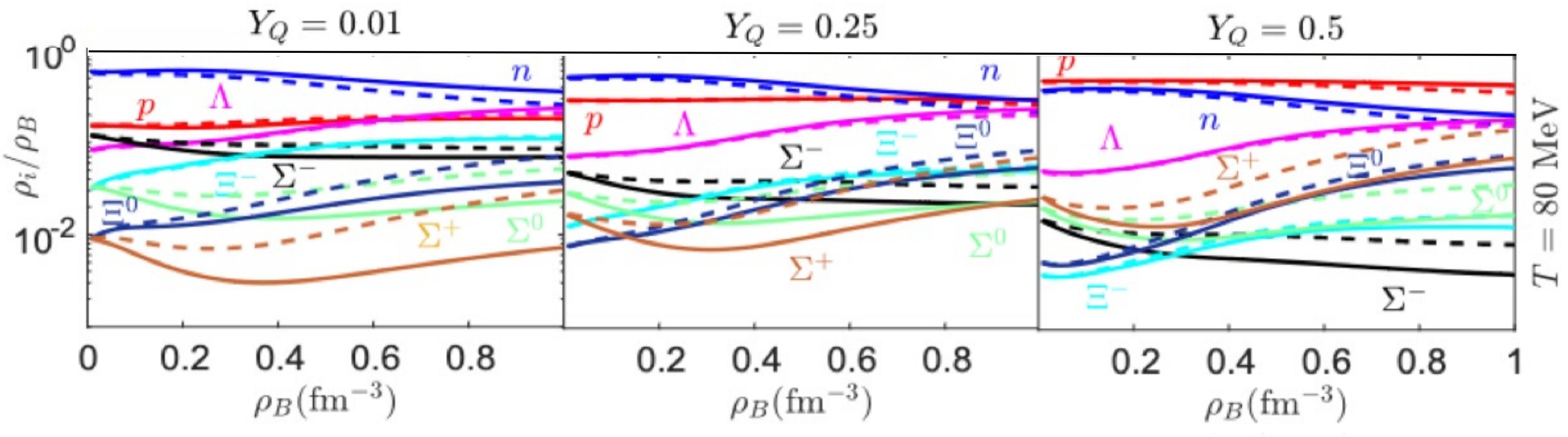


Low T (T=1 MeV)

- appearance of hyperons strongly depends on hyperonic potentials
- proton abundance correlated to negative hyperons (increases @ low Y_Q, no change otherwise)
- @ all Y_Q: abundance of neutrons reduced with density as more Λ appear

EoS and composition: composition at finite temperature (II)

FSU2H*L (dashed lines)
FSU2H*U (solid lines)

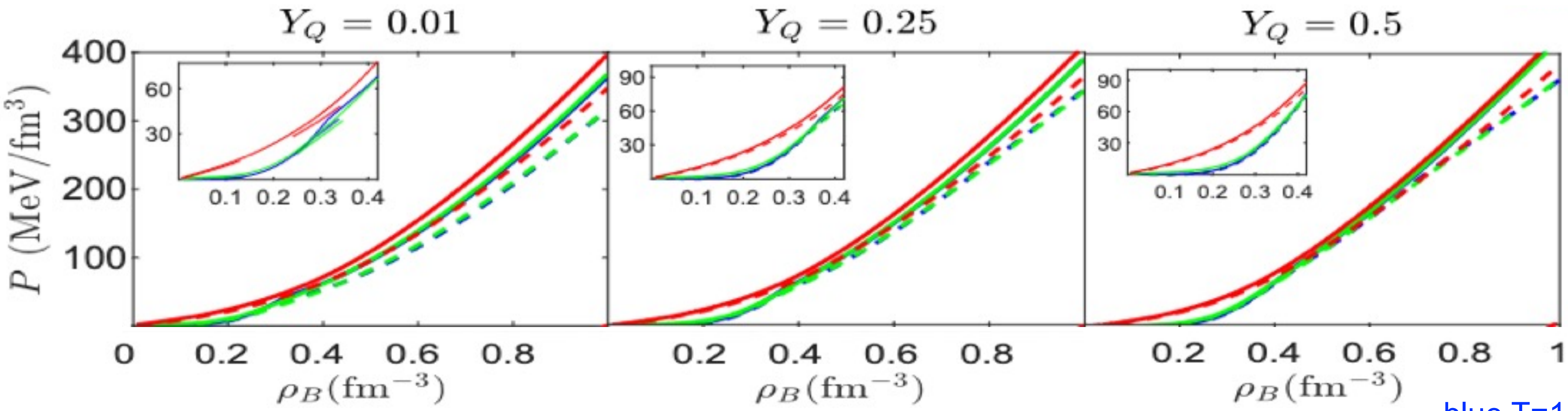


Large T (T=80 MeV)

- appreciable abundance of hyperons at any density
- @ all Y_Q: abundance of neutrons no longer decreasing monotonically
- hyperonic potentials strongly influence Σ appearance, while Σ^+ quite abundant!

EoS and composition: EoS at finite temperature (I)

FSU2H*L (dashed lines)
FSU2H*U (solid lines)



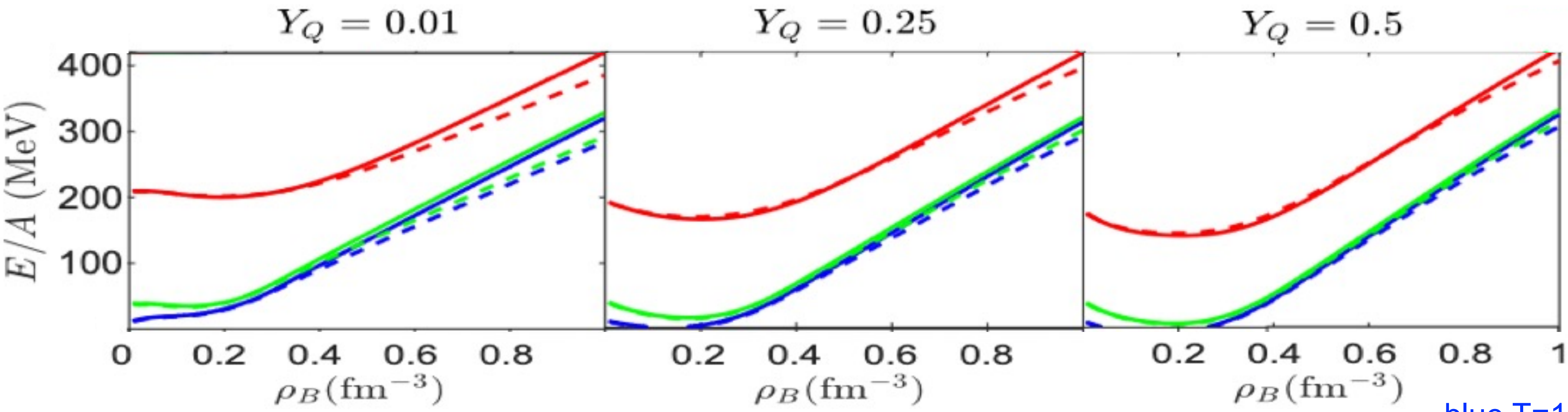
blue T=1 MeV
green T=20 MeV
red T=80 MeV

Pressure

- hyperonic uncertainties quite visible
- at large density hyperonic uncertainties more important than thermal effects

EoS and composition: EoS at finite temperature (II)

FSU2H*L (dashed lines)
FSU2H*U (solid lines)



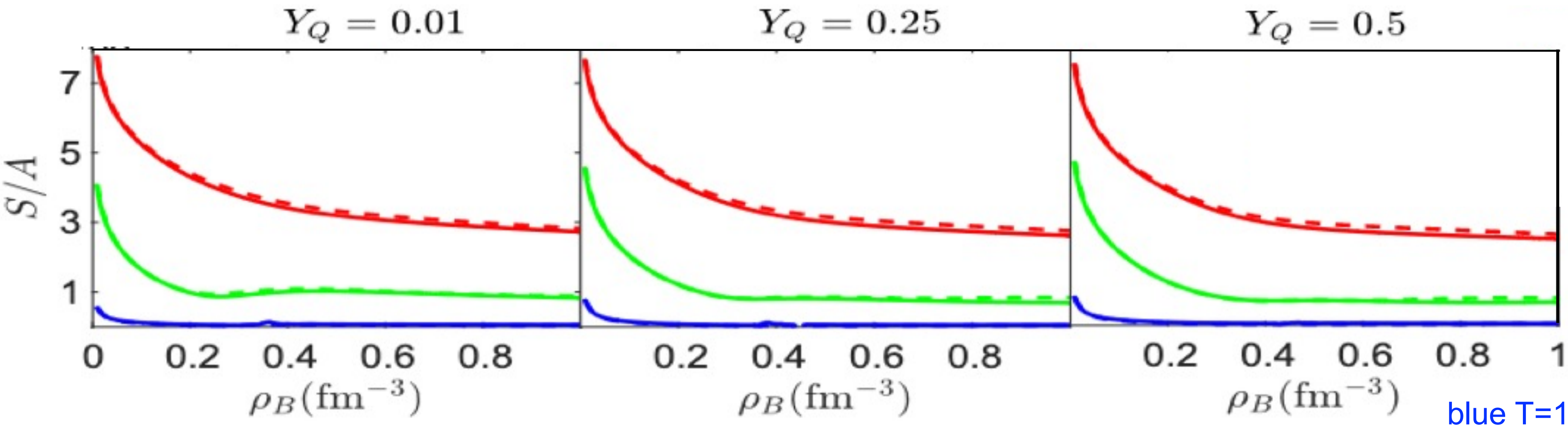
blue T=1 MeV
green T=20 MeV
red T=80 MeV

E/A

- larger differences between models for large densities and temperatures
- @ low Y_Q larger differences between models (more hyperons appear)

EoS and composition: EoS at finite temperature (III)

FSU2H*L (dashed lines)
FSU2H*U (solid lines)



blue T=1 MeV
green T=20 MeV
red T=80 MeV

S/A

- plateau due to appearance of hyperons
- not strong dependence on the model

Thermal index of the NS core

Thermal index

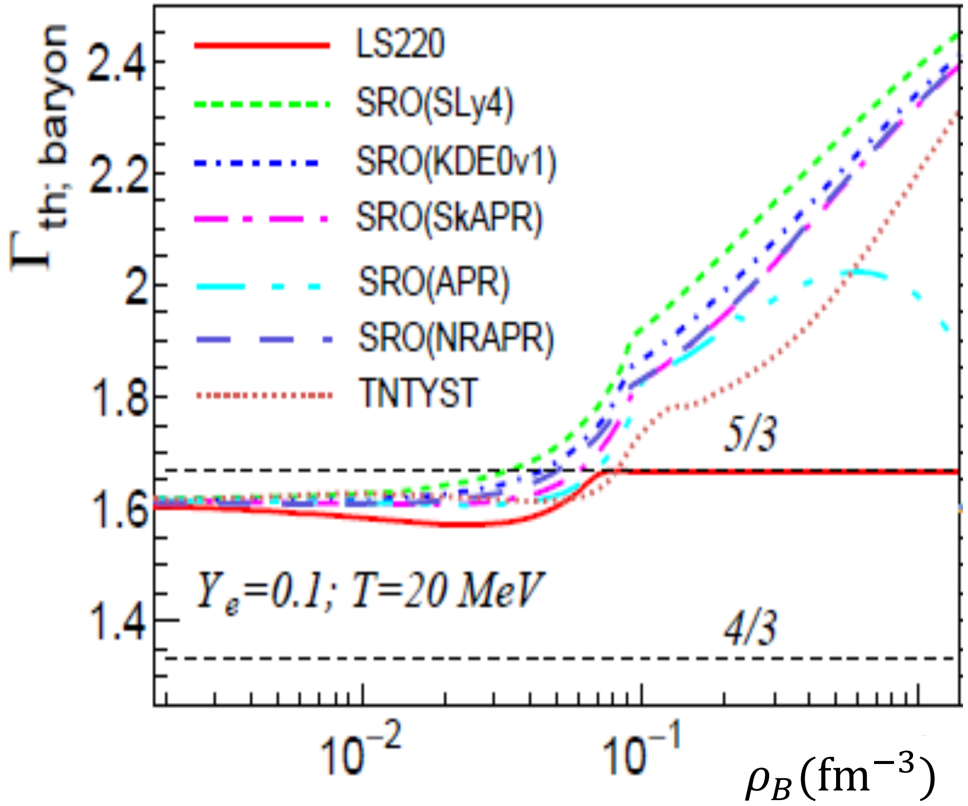
$$\Gamma(\rho_B, T) \equiv 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}}$$

$$\begin{aligned} P_{\rm th} &= P(\rho_B, T) - P(\rho_B, T=0) \\ \epsilon_{\rm th} &= \epsilon(\rho_B, T) - \epsilon(\rho_B, T=0) \end{aligned}$$

Merger simulations usually use a Γ that is constant. However, this procedure can be inaccurate

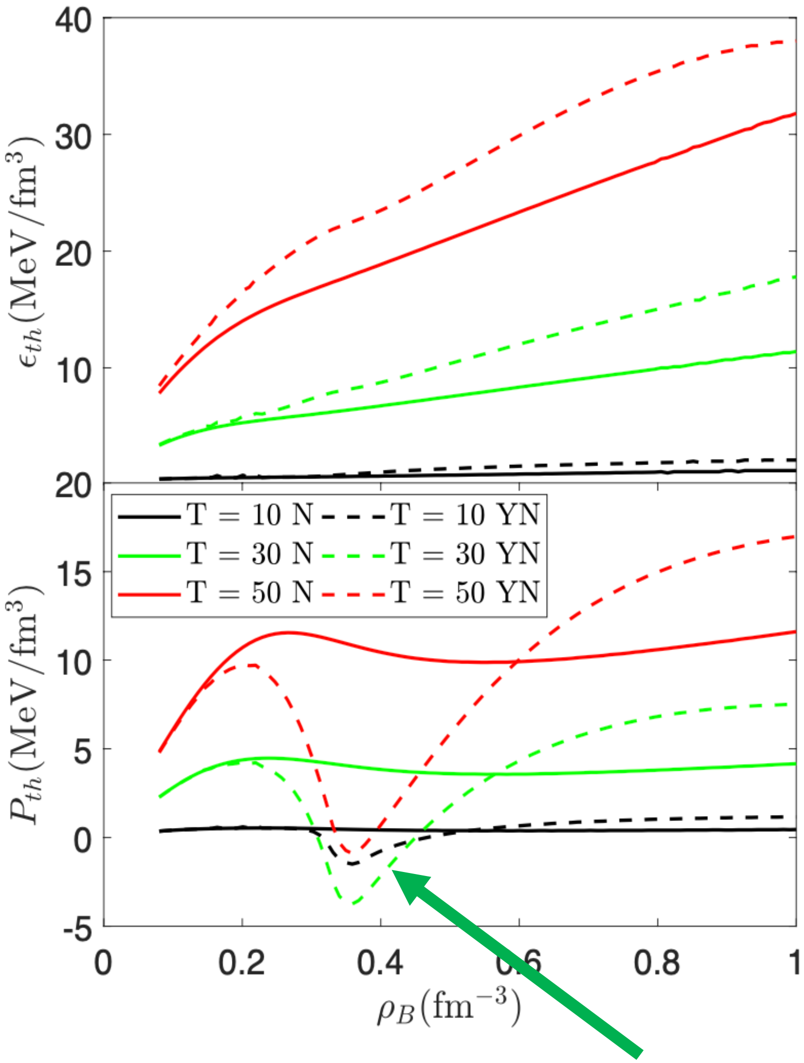
Kochankovski, Ramos and LT, MNRAS 517 (2022) 507, 2206.11266 [astro-ph.HE]

Raduta, Nacu and Oertel '21



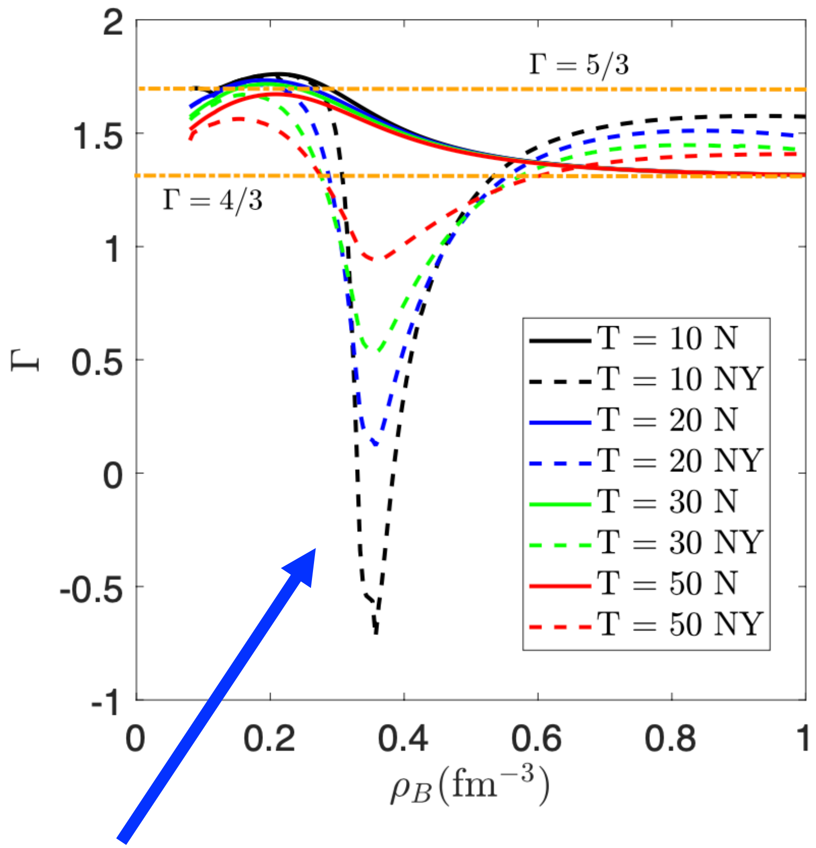
in this case, nucleons are the only baryons considered

Thermal index : β- stable ν free matter with FSU2H* (I)



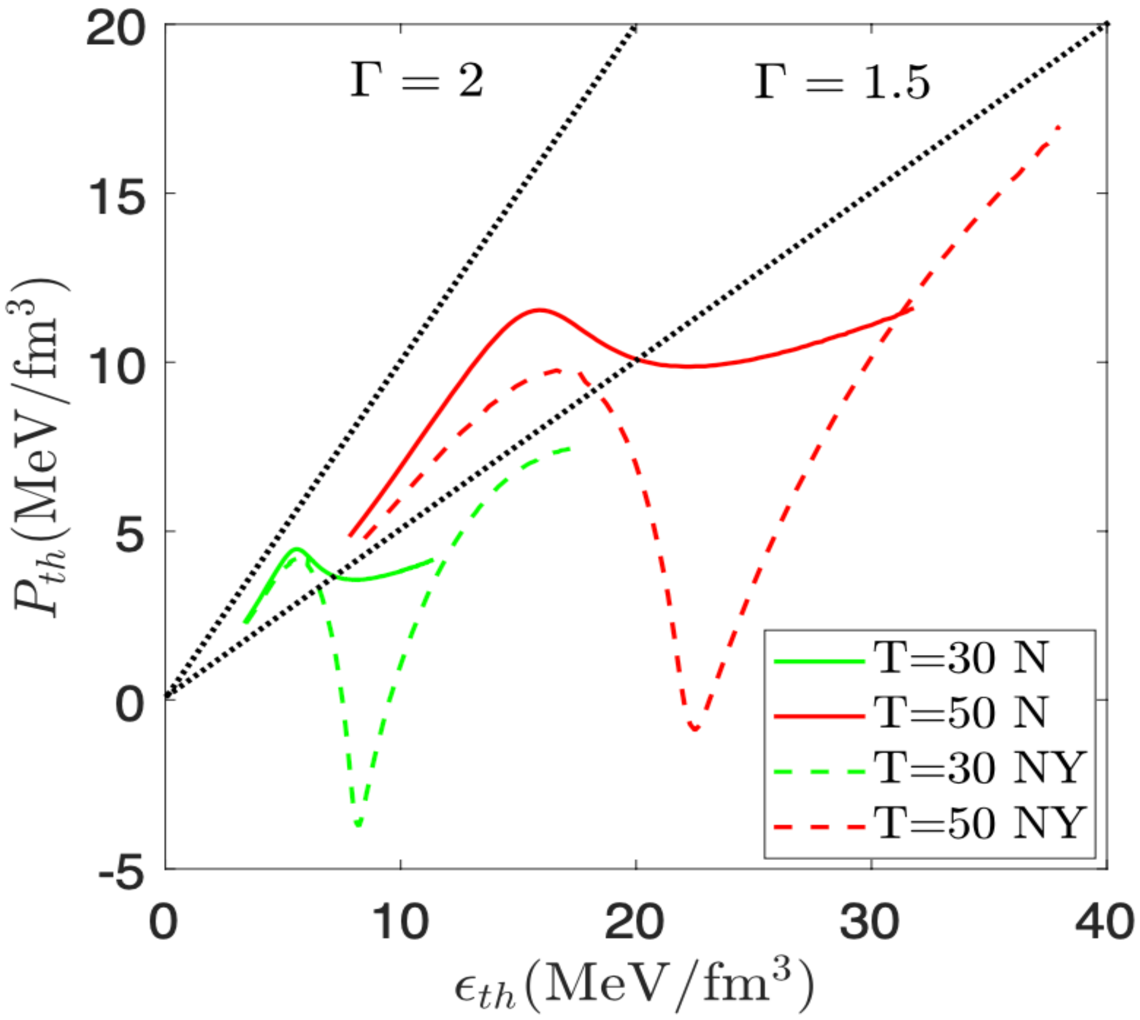
- the thermal pressure experiences a sizable drop when hyperon abundance starts being significant

- the complex behavior of the thermal pressure heavily influences the thermal index



(considering leptons)

Thermal index : β- stable ν free matter with FSU2H* (II)



thermal effects with Γ constant are not accurate, specially when hyperons are present

be aware when using Γ constant in merger simulations!

(considering leptons)

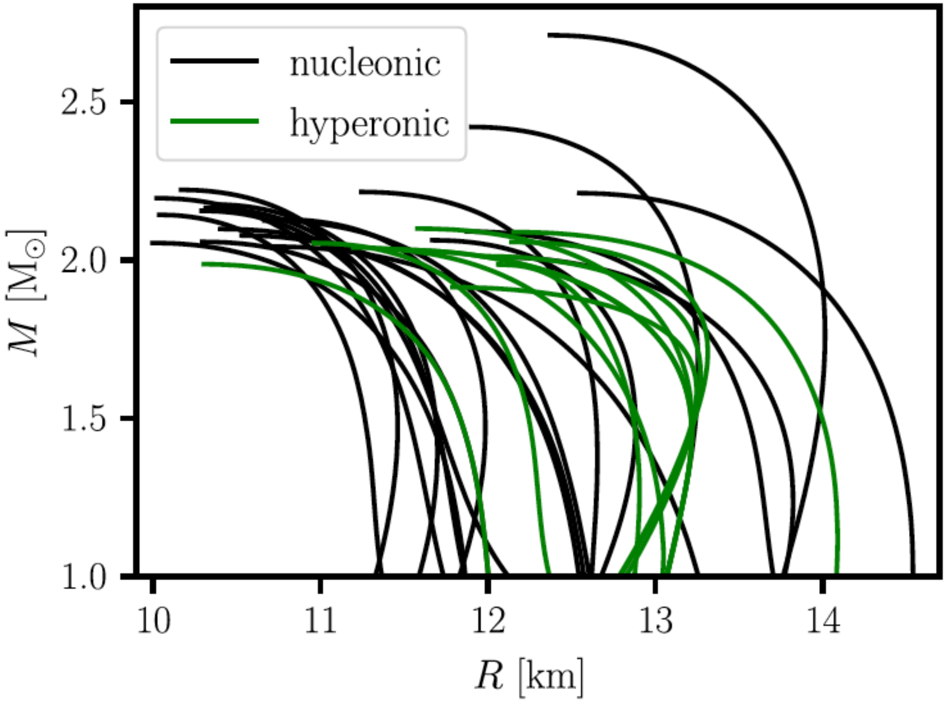
Thermal behavior as indicator for hyperons in NS mergers

is there a clear signal of the presence of hyperons in NS?

Nucleonic models

EOS	$M_{\rm max}$ $[M_\odot]$	$R_{1.4}$ [km]	$\Lambda_{1.4}$	$\Lambda_{1.75}$	$f_{\rm peak}$(3D) [kHz]	$f_{\rm peak}$ $(\Gamma_{\rm th} = 1.75)$ [kHz]	$\bar{\Gamma}_{\rm th}$	$\rho^{\rm max}$ $[10^{15}\ {\rm g/cm^3}]$
APR	2.20	11.57	267.6	54.5	3.51	3.46	1.74	1.41
DD2	2.42	13.22	698.8	178.5	2.64	2.68	1.78	0.71
DD2 $(q = 0.8)$	2.42	13.22	698.8	178.5	2.68	2.69	1.74	0.73
DD2F	2.08	12.40	425.5	79.3	3.30	3.30	1.66	1.12
DSH Fiducial	2.17	11.73	296.3	61.8	3.44	3.40	1.77	1.28
DSH Large Mmax	2.22	12.65	513.9	119.9	2.93	2.91	1.79	0.85
DSH Large SL	2.16	11.76	271.5	55.9	3.51	3.46	1.52	1.38
DSH Large R	2.13	12.44	437.6	87.3	3.16	3.18	1.72	1.08
DSH Small SL	2.18	11.70	335.8	70.3	3.31	3.33	1.76	1.21
DSH Smaller R	2.14	11.29	233.1	48.8	3.62	3.60	1.72	1.66
FSU2R	2.06	12.87	640.8	143.5	2.80	2.81	1.81	0.83
FSU2R $(q = 0.8)$	2.06	12.87	640.8	143.5	2.69	2.70	1.76	0.91
FTNS	2.22	11.46	304.8	65.3	3.34	3.40	1.73	1.26
GS2	2.09	13.60	721.3	160.6	2.73	2.70	1.76	0.73
LPB	2.10	12.37	429.9	79.9	3.23	3.23	1.68	1.01
LS220	2.04	12.96	541.9	94.2	3.09	3.06	1.54	1.00
LS375	2.71	13.95	960.1	257.7	2.44	2.44	1.63	0.59
SFHo	2.06	11.89	333.5	63.5	3.43	3.45	1.62	1.42
SFHx	2.13	11.98	395.1	86.7	3.16	3.18	1.82	1.09
SRO(SLy4)	2.05	11.72	303.7	54.7	3.51	3.50	1.78	1.43
TM1	2.21	14.47	1149.0	257.7	2.38	2.40	1.82	0.55
TMA	2.01	13.79	929.1	184.1	2.58	2.57	1.74	0.66

not straightforward to tell from a measured mass-radius relation if EoS contains hyperons



Hyperonic models

EOS	$M_{\rm max}$ $[M_\odot]$	$R_{1.4}$ [km]	$\Lambda_{1.4}$	$\Lambda_{1.75}$	$\rho_{\rm onset}$ $(T = 0)$ $[10^{15}\ {\rm g/cm^3}]$	$\rho^{\rm max}_{\rm init}$ $[10^{15}\ {\rm g/cm^3}]$	$f_{\rm peak}$ (3D) [kHz]	$f_{\rm peak}$ $(\Gamma_{\rm th} = 1.75)$ [kHz]	$\bar{\Gamma}_{\rm th}$	$\bar{Y}_{\rm hyp}$	$\rho^{\rm max}$ $[10^{15}\ {\rm g/cm^3}]$
BHB$\Lambda\phi$	2.10	13.21	695.2	160.1	0.56	$\underline{0.59}$	2.76	2.68	1.37	0.018	0.79
DD2Y	2.03	13.21	694.8	150.9	0.56	$\underline{0.60}$	2.82	2.73	1.08	0.022	0.80
DD2Y $(q = 0.8)$	2.03	13.21	694.8	150.9	0.56	$\underline{0.68}$	2.76	2.63	1.04	0.050	1.00
DNS	2.09	14.04	957.7	208.3	0.77	0.55	2.51	2.54	1.69	0.003	0.66
FSU2H*	2.01	13.18	778.8	192.1	0.57	0.55	2.63	2.59	1.52	0.012	0.75
FSU2H* $(q = 0.8)$	2.01	13.18	778.8	192.1	0.57	$\underline{0.60}$	2.76	2.69	1.37	0.025	0.87
FSU2H*L	1.91	13.16	784.4	177.6	0.56	0.54	2.68	2.62	1.24	0.018	0.76
FSU2H*U	2.06	13.17	784.4	205.7	0.58	0.54	2.62	2.56	1.51	0.008	0.70
QMC-A	1.99	12.89	574.8	126.0	0.93	0.66	2.91	2.98	1.65	0.003	0.91
R(DD2YDelta)1.1-1.1	2.04	12.96	586.8	114.0	0.46	$\underline{0.69}$	3.03	2.93	1.08	0.083	0.95
R(DD2YDelta)1.2-1.1	2.05	12.27	397.3	85.4	0.37	$\underline{0.77}$	3.26	3.14	1.18	0.185	1.16
R(DD2YDelta)1.2-1.3	2.03	13.21	696.1	150.8	0.56	$\underline{0.60}$	2.82	2.72	0.99	0.029	0.84
SFHOY	1.99	11.89	333.6	61.9	0.97	0.85	3.60	3.46	1.38	0.015	1.54

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PRD 109 (2024) 043015, 2307.03710 [astro-ph.HE]

f_{peak} using finite-temperature nucleonic and hyperonic EoSs

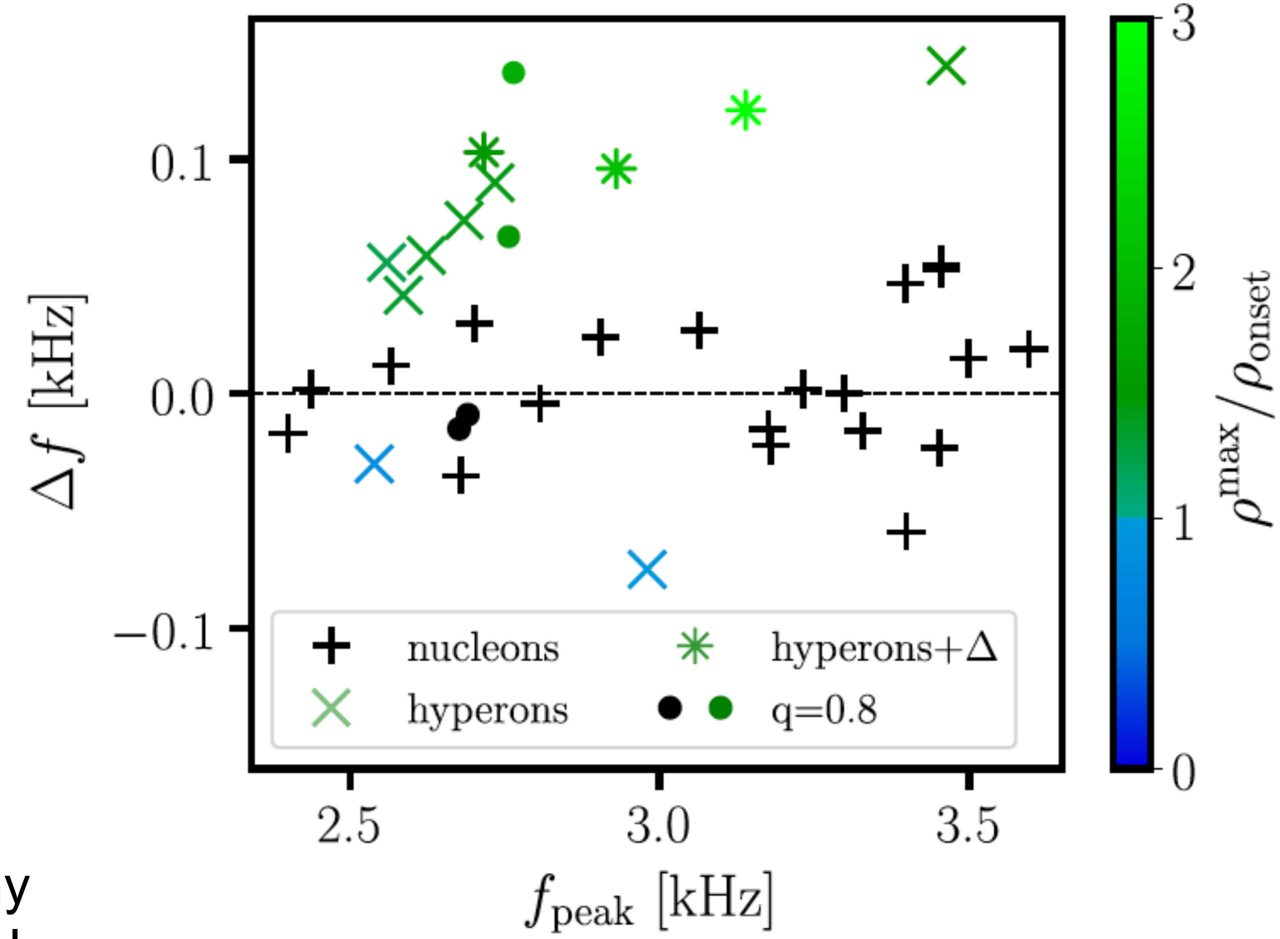
$f_{peak}^{1.75}$ taking these EoSs at T=0 and assume a "nucleonic" thermal behaviour with $\Gamma_{th} = 1.75$

calculate $\mathbf{\Delta f \equiv f_{peak} - f_{peak}^{1.75}}$

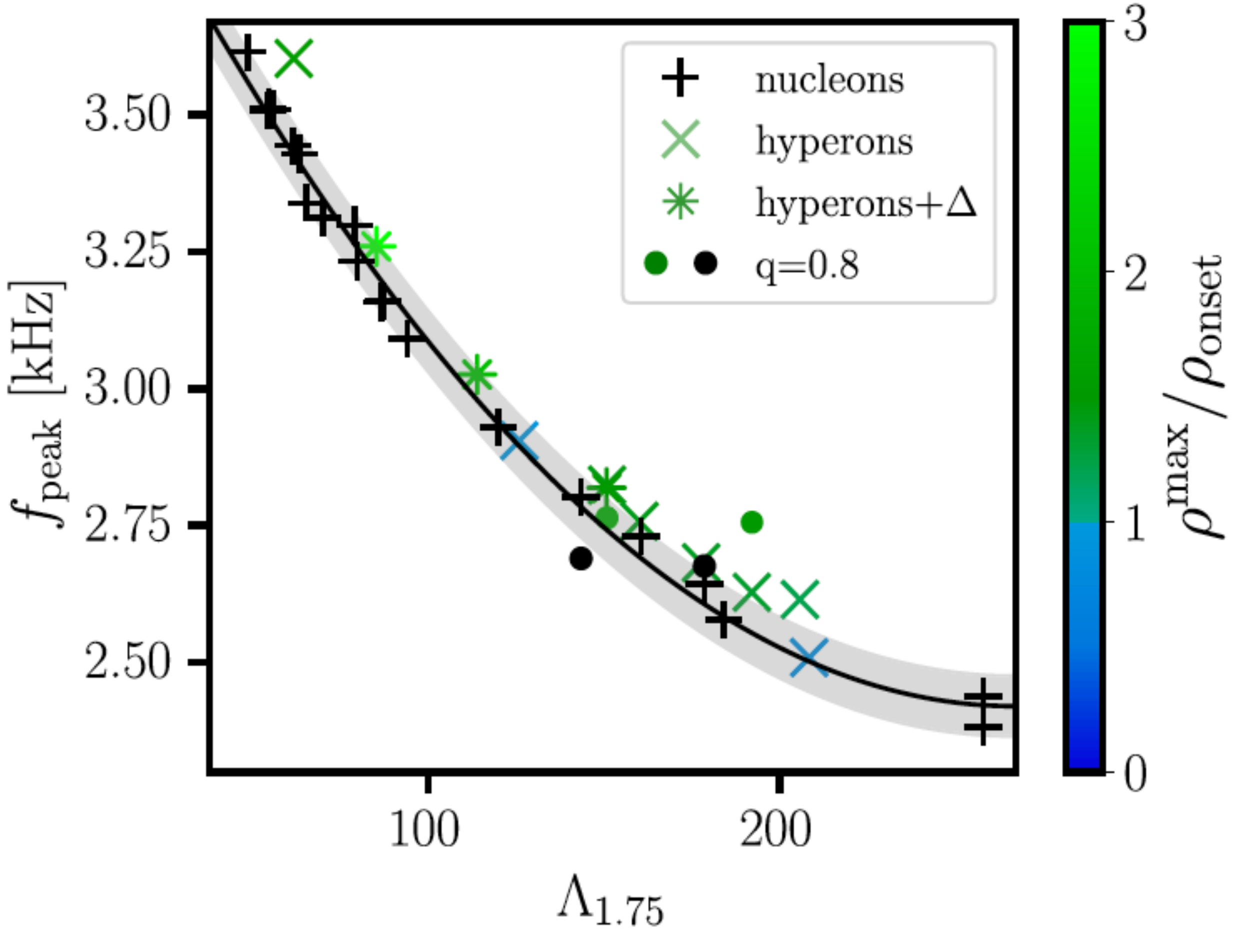
conclusion

hyperonic models lead to systematically higher frequencies with Δf ~ 100 Hz, being small but potentially sizeable

similar behaviour of hyperonic models with a tiny amount of hyperons (in blue) to nucleonic models



presence of hyperons linked to two directly measurable quantities



black line: least-squares quadratic fit
to the purely nucleonic models

$f_{\rm peak}$ vs $\Lambda_{1.75}$

conclusion

the presence of hyperons seems more likely if the postmerger frequency is high compared to the fit

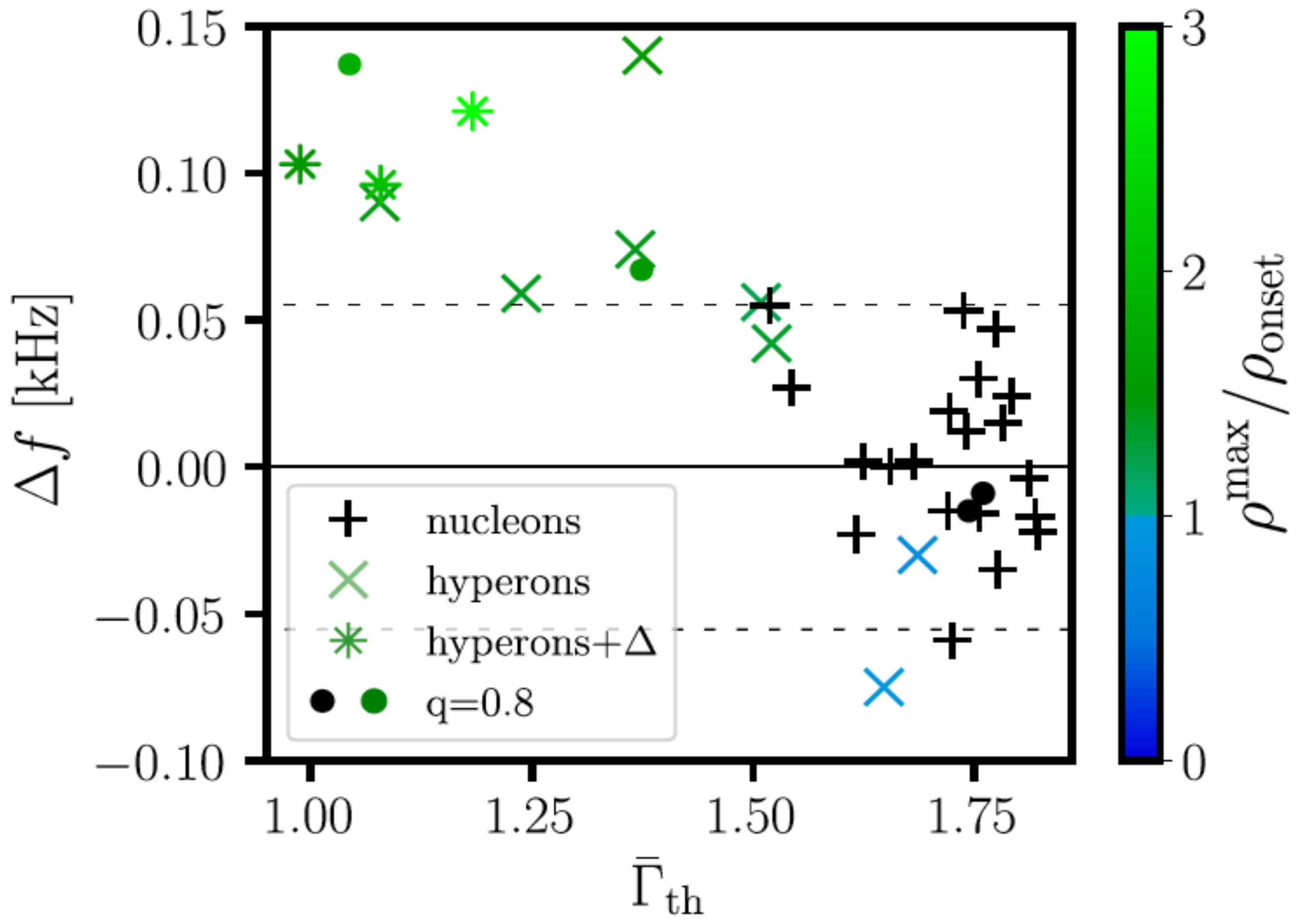
models with tiny amount of hyperons
or hyperonic models with nucleonic $f_{\rm peak}$
in the lower edge do not stick out

also..

Δf vs average thermal index $\bar{\Gamma}_{th}$

conclusions

- hyperons lead to a reduction of the thermal pressure (smaller thermal index) compared to nucleons
- a frequency shift larger for hyperonic models
- Γ_{th} = 1.75 is a good choice for "nucleonic" thermal behavior



some caveats..

- enough statistical power in GW measurements
- T=0 EoS carry information on hyperons
- dependence of our results on abundance of hyperons and hyperon threshold density
- other exotic degrees of freedom softening the EoS and leading to a frequency shift

..and prospects

experimental and theoretical advances on two and three-body interactions with hyperons and nucleons would lead to further constraints for future analyses

Summary

- We have constructed the hyperonic **FSU2H* model** at finite finite temperature including hyperonic uncertainties to be used in early stages of neutron star evolution and in neutron star mergers

- The temperature effects have been analyzed in terms of the **thermal index Γ**, showing that thermal effects with Γ constant when hyperons are present would be inaccurate and should be taken with caution in merger simulations

- We have discussed the **thermal behavior of hyperonic EoSs as an indicator for hyperons in neutron star mergers**. There is a characteristic increase of the dominant postmerger gravitational-wave frequency by $\Delta f \sim 100$ Hz compared to purely nucleonic models. These findings are important as a new route to answer the outstanding question about hyperonic degrees of freedom in high-density matter

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