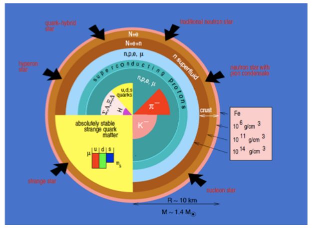
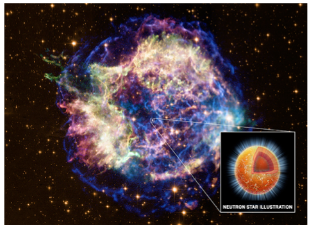


Hyperonic Equation of State for Neutron Stars and Neutron Star Mergers



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FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Strongly interacting matter in extreme magnetic fields

Sep 25 – 29, 2023
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MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

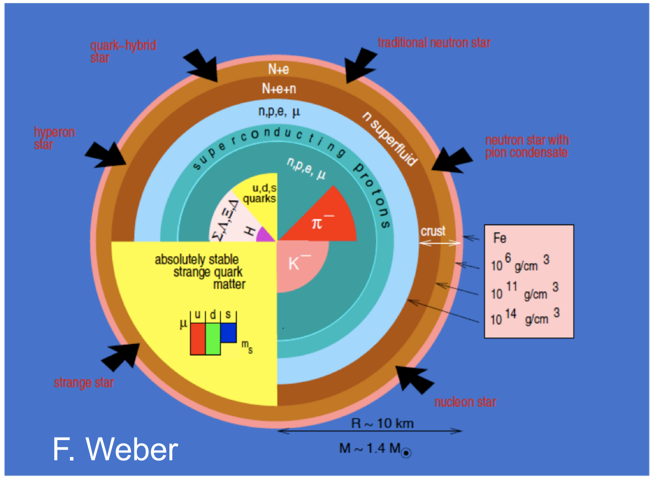
STRONG 2020

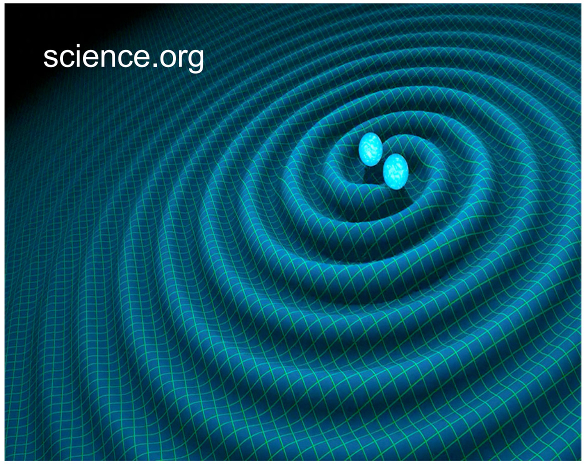
Outline

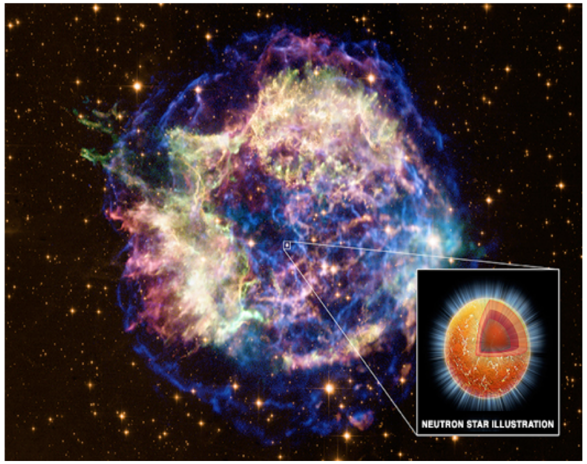
- Motivation
- Equation of State and composition of the hot neutron star core: FSU2H* model
- Thermal index of the neutron star core
- Thermal behavior as indicator for hyperons in neutron star mergers
- Summary

H. Kochankovski, A. Ramos and L. Tolos, Mon. Not. Roy. Astron.Soc 517 (2022) 507, 2206.11266 [astro-ph.HE]
S. Blacker, H. Kochankovski, S. Blacker, A. Ramos and L. Tolos, 2307.03710 [astro-ph.HE]
H. Kochankovski, A. Ramos and L. Tolos, 2309.14879 [astro-ph.HE]

Motivation







Neutron stars are a natural laboratory for studying matter under extreme conditions of density, temperature, isospin, magnetic fields..

Little is known about the composition of the core. Not only nucleons but more exotic 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

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

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**

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

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

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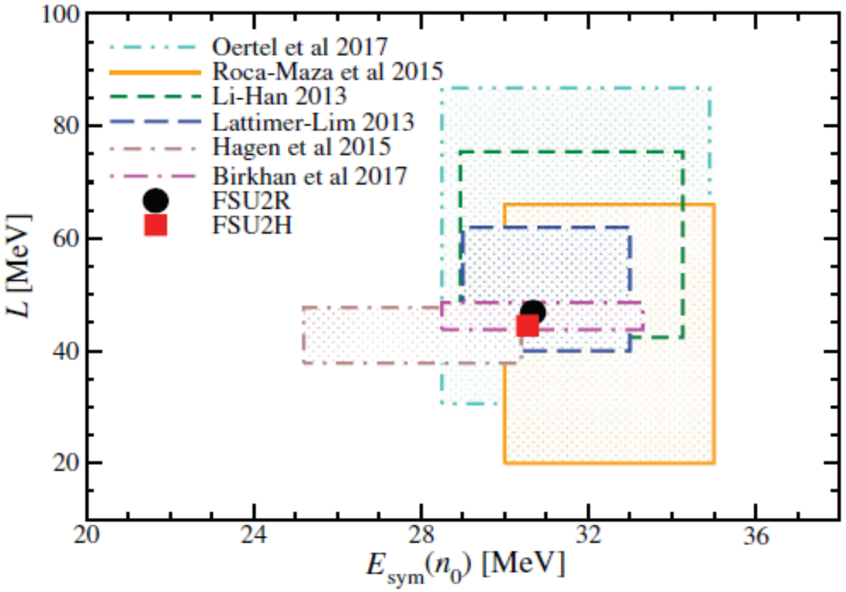
FSU2H* model: nuclear properties

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



Tolos, Centelles and Ramos '17

Nuclear properties at T = 0

ρ_0 (fm^{-3})	E/A (MeV)	K (MeV)	m^*_N/m_N (ρ_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	$-2\sqrt{2}/3$

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

Obtained assuming flavour SU(3) symmetry, the vector dominance model, and ideal mixing for the physical ω and ϕ field

Potential felt by a hyperon *i* in *j*-particle matter is given by

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

Hyperon potentials

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

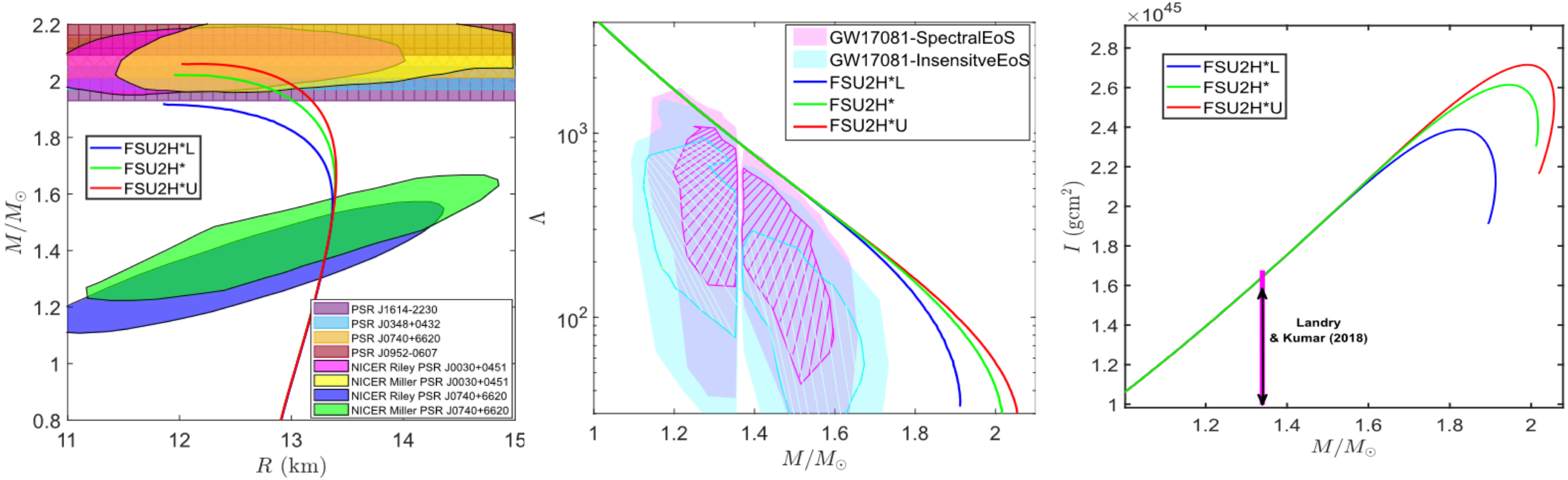
$$U_\Sigma^{(N)}(\rho_0) = (10, 50)\ \text{MeV}$$

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

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

variation allowed by nuclear experimental data

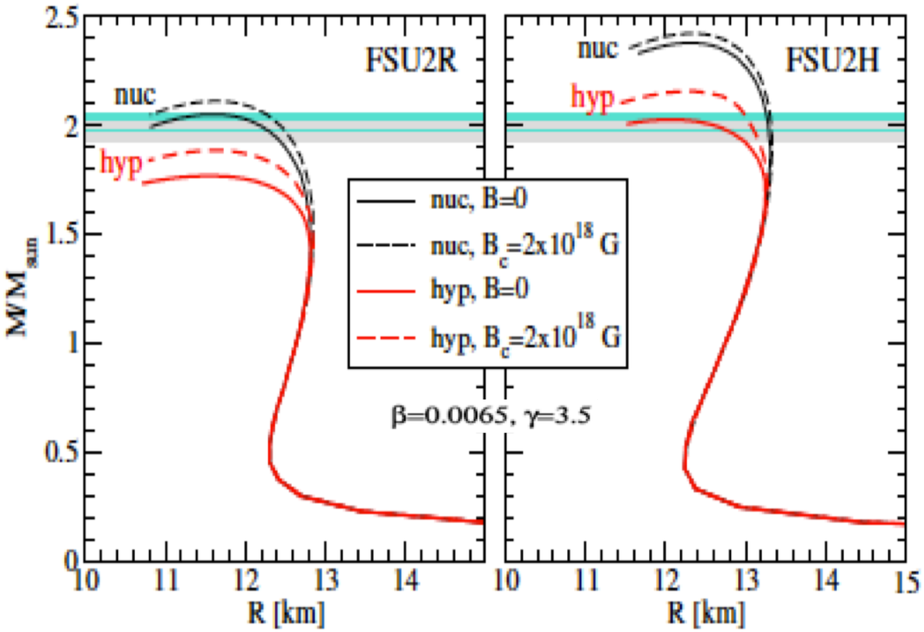
T=0: mass-radius, tidal deformability, moment of inertia…



- 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!)

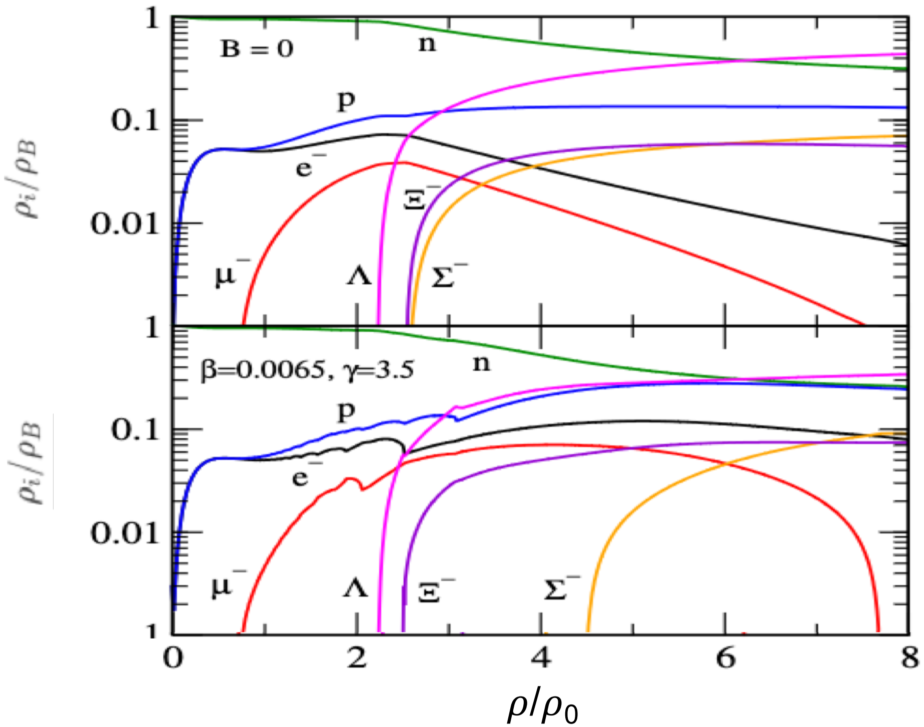
T=0: …magnetic fields (FSU2H)

Chakrabarty et al ‘97
$B(n)=B_s+B_c(1-\exp[-\beta(\rho/\rho_0)^\gamma])$
$B_c \sim 2\times10^{18}$ G, $B_s \sim 10^{15}$ G



- magnetic fields produce larger M_{max} than B=0 case
- larger effects on hyperonic stars due to de-hyperonization in magnetic fields

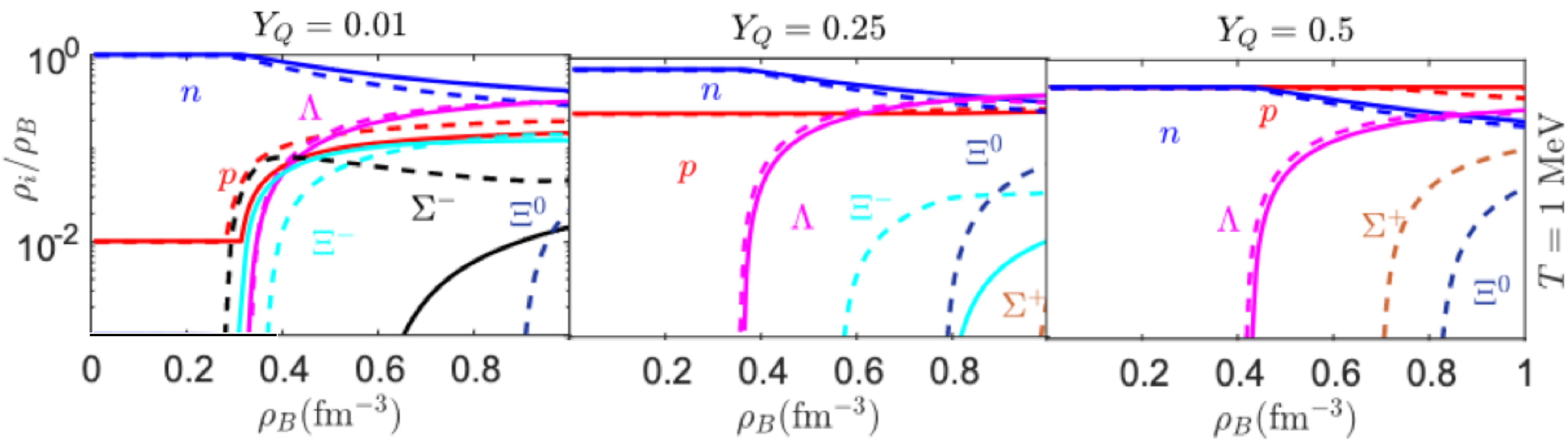
Need of general relativistic treatment of strongly magnetised NSs Chatterjee et al ‘15



Landau oscillations at small densities:
small B-fields accommodate more Landau levels
- hyperonic magnetars re-leptonize and de-hyperonize
- proton abundance increases substantially
--> facilitate direct Urca processes (cooling changed!)

EoS and composition: composition at finite temperature

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

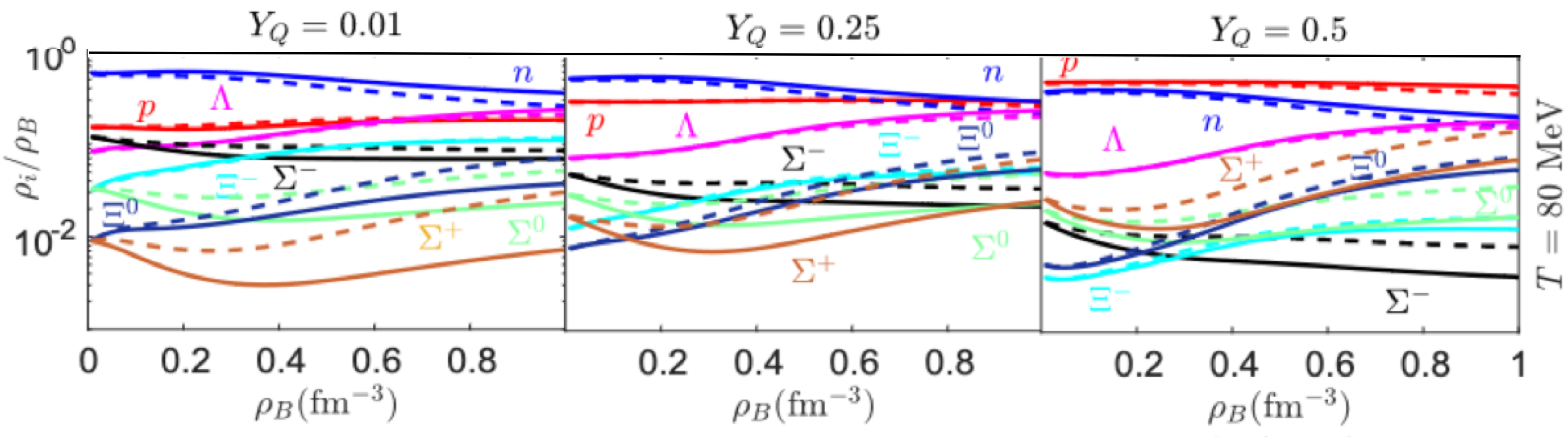


Low T (T=1 MeV)

- 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

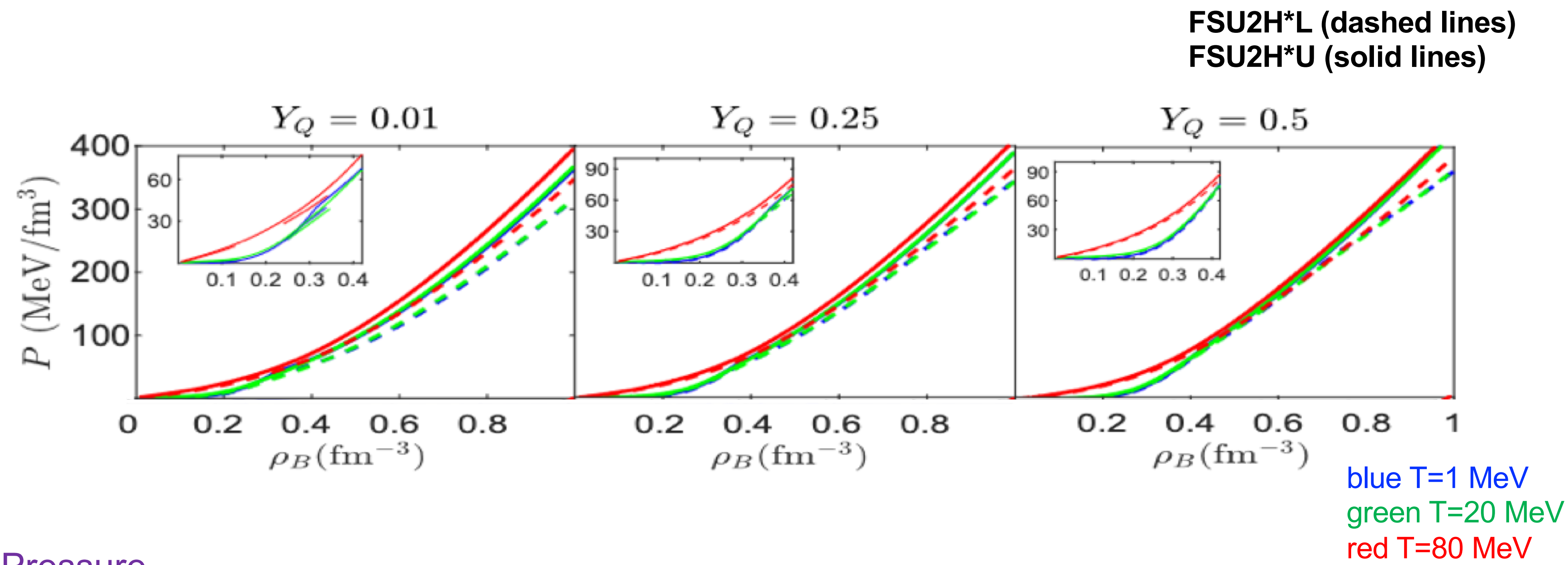
FSU2H*L (dashed lines)
FSU2H*U (solid lines)



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

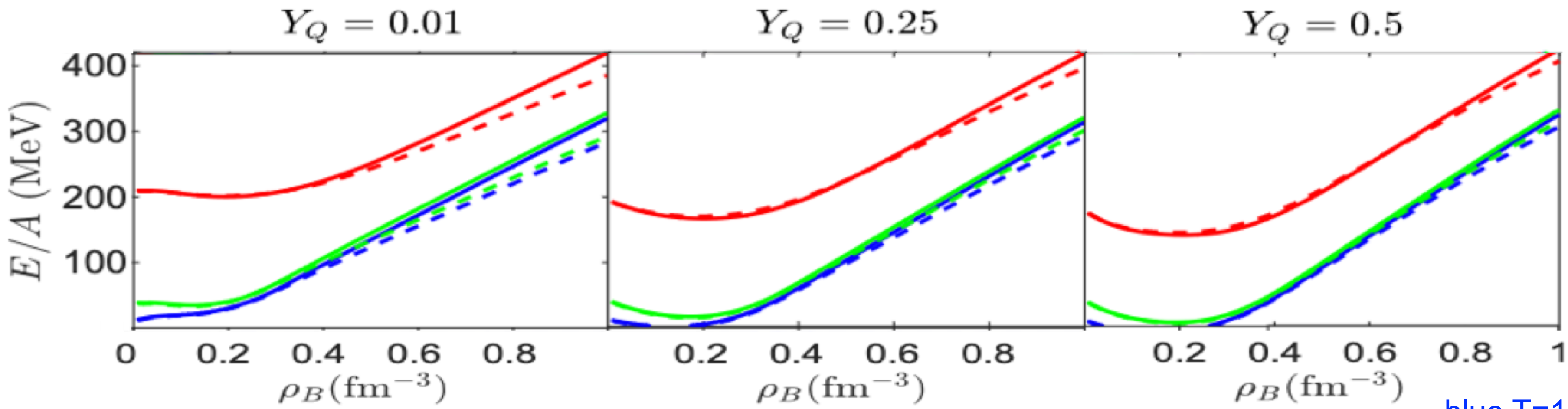


Pressure

- hyperonic uncertainties quite visible
- at large density more important hyperonic uncertainties than thermal effects
- matter @ large Y_Q for FSU2H*L less degenerate than for FSU2H*U, so different T curves visible

EoS and composition: EoS at finite temperature

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



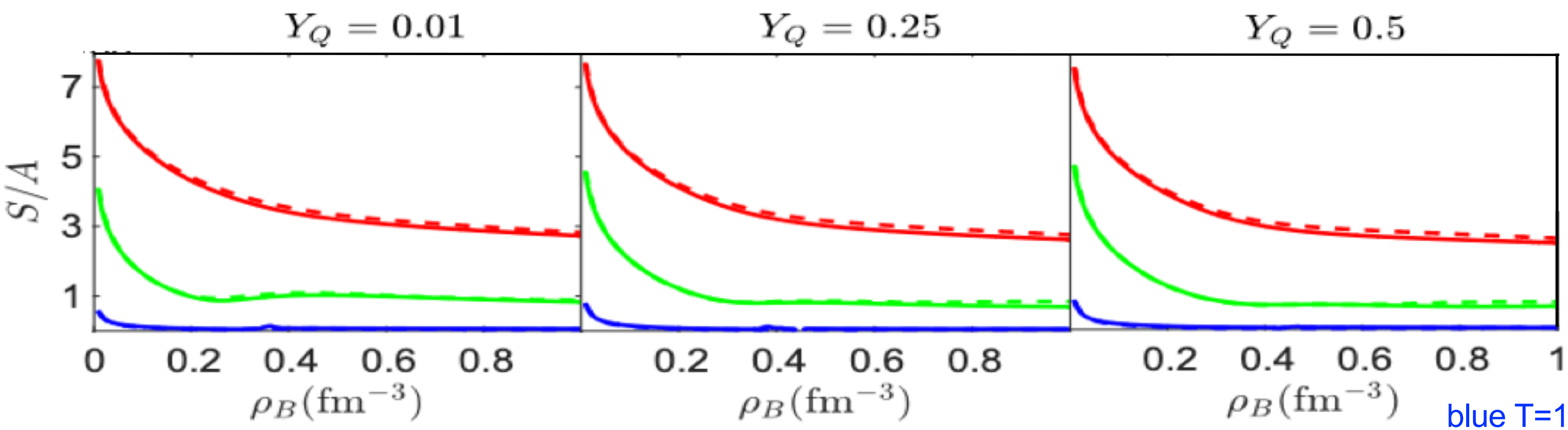
blue T=1 MeV
green T=20 MeV
red T=80 MeV

E/A

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

EoS and composition: EoS at finite temperature

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

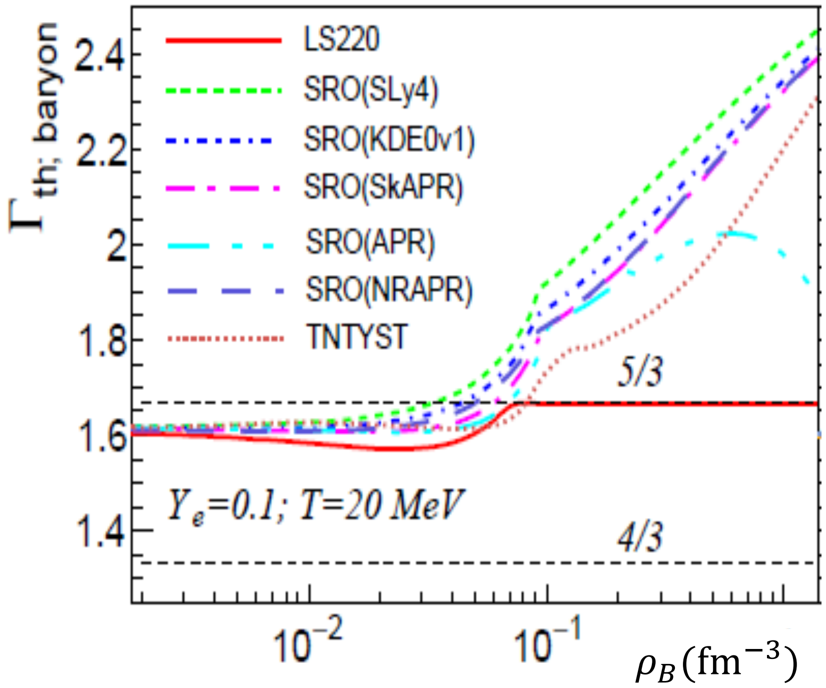
$$\Gamma(\rho_B, T) \equiv 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}}$$

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

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

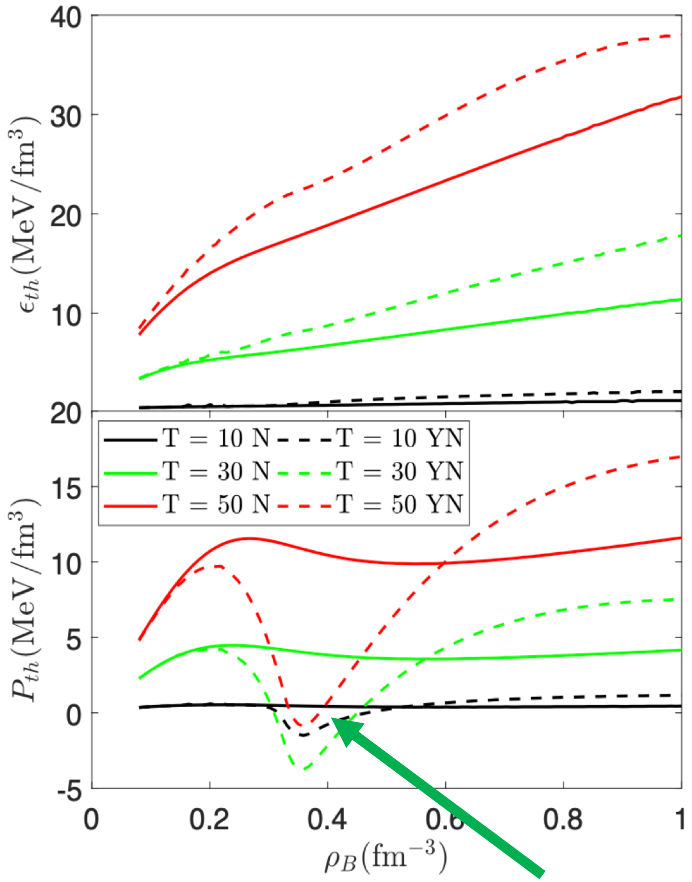
H. Kochankovski, A. Ramos and LT,
Mon. Not. Roy. Astron.Soc 517 (2022) 507, 2206.11266 [astro-ph.HE]

Raduta, Nacu and Oertel '21

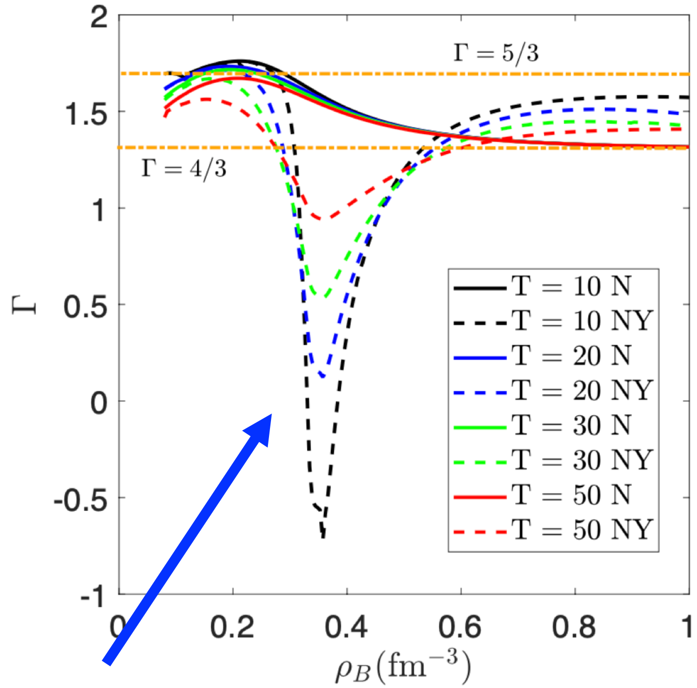


In this case, nucleons are the only baryons considered

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

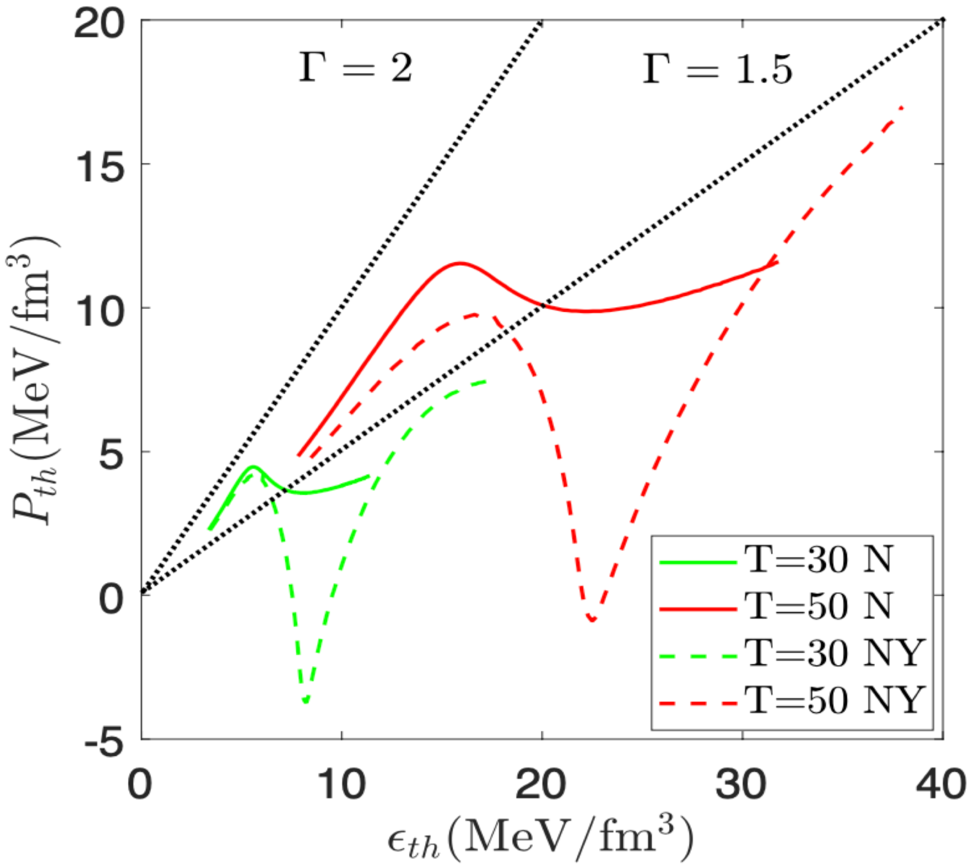


- the thermal pressure experiences a sizable drop when hyperon abundance starts being significant
- the complex behavior of the thermal pressure heavily influences the thermal index



(considering leptons)

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



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?

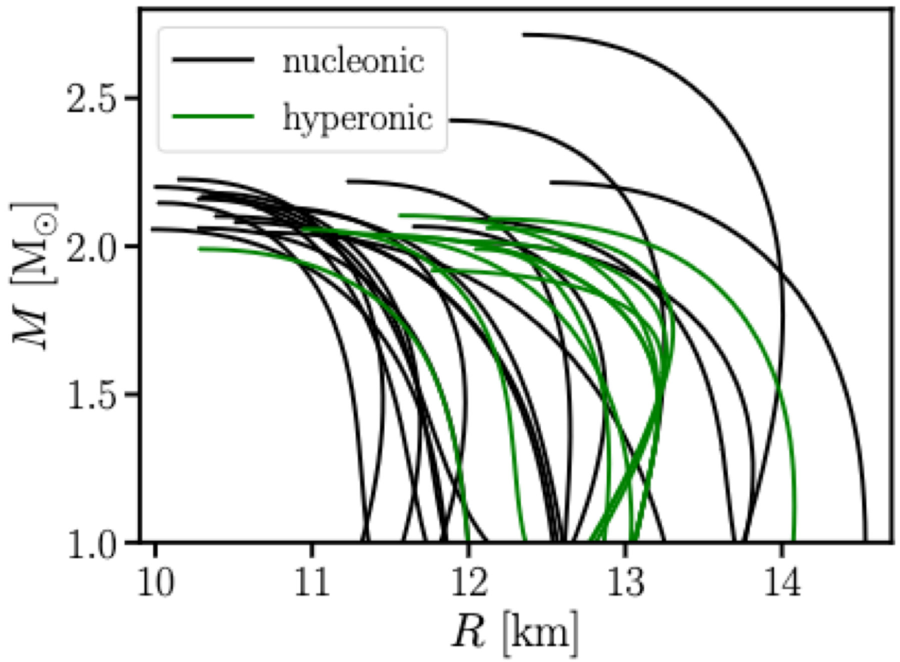
Nucleonic models

EoS	M_{max} $[M_\odot]$	$R_{1.4}$ [km]	$\Lambda_{1.4}$	$\Lambda_{1.75}$	$f_{peak}(3D)$ [kHz]	$f_{peak}(\Gamma_{th}=1.75)$ [kHz]	$\bar{\Gamma}_{th}$	ρ^{max} $[10^{15}$ g/cm$^3]$	Ref.
APR	2.20	11.57	267.6	54.5	3.51	3.46	1.74	1.41	[15, 16]
DD2	2.42	13.22	698.8	178.5	2.64	2.68	1.78	0.71	[17, 18]
DD2F	2.08	12.40	425.5	79.3	3.30	3.30	1.66	1.12	[17, 19]
DSH Fiducial	2.17	11.73	296.3	61.8	3.44	3.40	1.77	1.28	[20]
DSH Large Mmax	2.22	12.65	513.9	119.9	2.93	2.91	1.79	0.85	[20]
DSH Large SL	2.16	11.76	271.5	55.9	3.51	3.46	1.52	1.38	[20]
DSH Large R	2.13	12.44	437.6	87.3	3.16	3.18	1.72	1.08	[20]
DSH Small SL	2.18	11.70	335.8	70.3	3.31	3.33	1.76	1.21	[20]
DSH Smaller R	2.14	11.29	233.1	48.8	3.62	3.60	1.72	1.66	[20]
FSU2R	2.06	12.87	640.8	143.5	2.80	2.81	1.81	0.83	[21]
FTNS	2.22	11.46	304.8	65.3	3.34	3.40	1.73	1.26	[22, 23]
GS2	2.09	13.60	721.3	160.6	2.73	2.70	1.76	0.73	[24]
LPB	2.10	12.37	429.9	79.9	3.23	3.23	1.68	1.01	[25, 26]
LS220	2.04	12.96	541.9	94.2	3.09	3.06	1.54	1.00	[27]
LS375	2.71	13.95	960.1	257.7	2.44	2.44	1.63	0.59	[27]
SFHo	2.06	11.89	333.5	63.5	3.43	3.45	1.62	1.42	[18, 28]
SFHx	2.13	11.98	395.1	86.7	3.16	3.18	1.82	1.09	[18, 28]
SRO(SLy4)	2.05	11.72	303.7	54.7	3.51	3.50	1.78	1.43	[29]
TM1	2.21	14.47	1149.0	257.7	2.38	2.40	1.82	0.55	[30, 31]
TMA	2.01	13.79	929.1	184.1	2.58	2.57	1.74	0.66	[18, 32]

Hyperonic models

EoS	M_{max} $[M_\odot]$	$R_{1.4}$ [km]	$\Lambda_{1.4}$	$\Lambda_{1.75}$	ρ_{onset} $(T=0)$ $[10^{15}$ g/cm$^3]$	$f_{peak}(3D)$ [kHz]	$f_{peak}(\Gamma_{th}=1.75)$ [kHz]	$\bar{\Gamma}_{th}$	$\bar{Y}_{hyp}$	ρ^{max} $[10^{15}$ g/cm$^3]$	Ref.
BHB$\Lambda\phi$	2.10	13.21	695.2	160.1	0.56	2.76	2.68	1.37	0.018	0.79	[8]
DD2Y	2.03	13.21	694.8	150.9	0.56	2.82	2.73	1.08	0.022	0.80	[9]
DNS	2.09	14.04	957.7	208.3	0.77	2.51	2.54	1.69	0.003	0.66	[10]
FSU2H*	2.01	13.18	778.8	192.1	0.57	2.63	2.59	1.52	0.012	0.75	[11]
FSU2H*L	1.91	13.16	784.4	177.6	0.56	2.68	2.62	1.24	0.018	0.76	[11]
FSU2H*U	2.06	13.17	784.4	205.7	0.58	2.62	2.56	1.51	0.008	0.70	[11]
QMC-A	1.99	12.89	574.8	126.0	0.93	2.91	2.98	1.65	0.003	0.91	[12]
R(DD2YDelta)1.1-1.1	2.04	12.96	586.8	114.0	0.46	3.03	2.93	1.08	0.083	0.95	[13]
R(DD2YDelta)1.2-1.1	2.05	12.27	397.3	85.4	0.37	3.26	3.14	1.18	0.185	1.16	[13]
R(DD2YDelta)1.2-1.3	2.03	13.21	696.1	150.8	0.56	2.82	2.72	0.99	0.029	0.84	[13]
SFHOY	1.99	11.89	333.6	61.9	0.97	3.60	3.46	1.54	0.015	1.54	[14]

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



S. Blacker, H. Kochankovski, S. Blacker, A. Ramos and LT, 2307.03710 [astro-ph.HE] first calculate f_{peak} using finite-temperature nucleonic and hyperonic EoSs

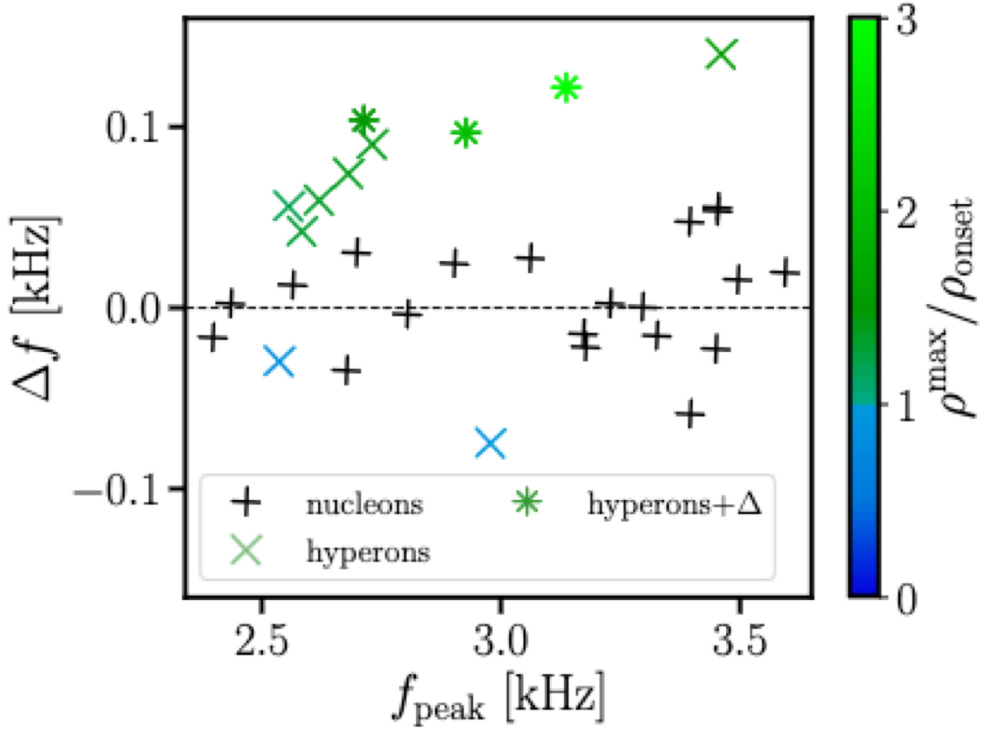
then take these EoSs at T=0 and assume that these EoSs would result from purely nucleonic matter, and supplement them with the ideal-gas treatment of thermal pressure with Γ_{th} = 1.75 ("nucleonic" thermal behaviour), obtaining $f_{peak}^{1.75}$

$\Delta f \equiv f_{peak} - f_{peak}^{1.75}$ measures deviation from "nucleonic" thermal behavior

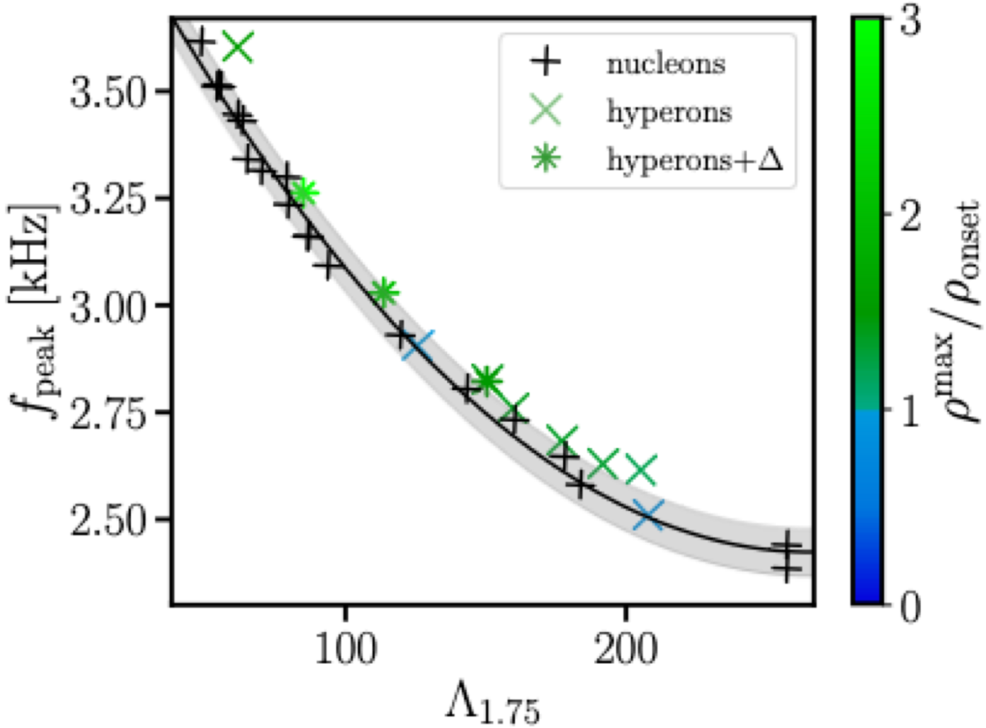
conclusion

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

note that hyperonic models that contain a tiny amount of hyperons (in blue) are similar to nucleonic models



another possible observable..



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

f_{peak} versus $\Lambda_{1.75}$

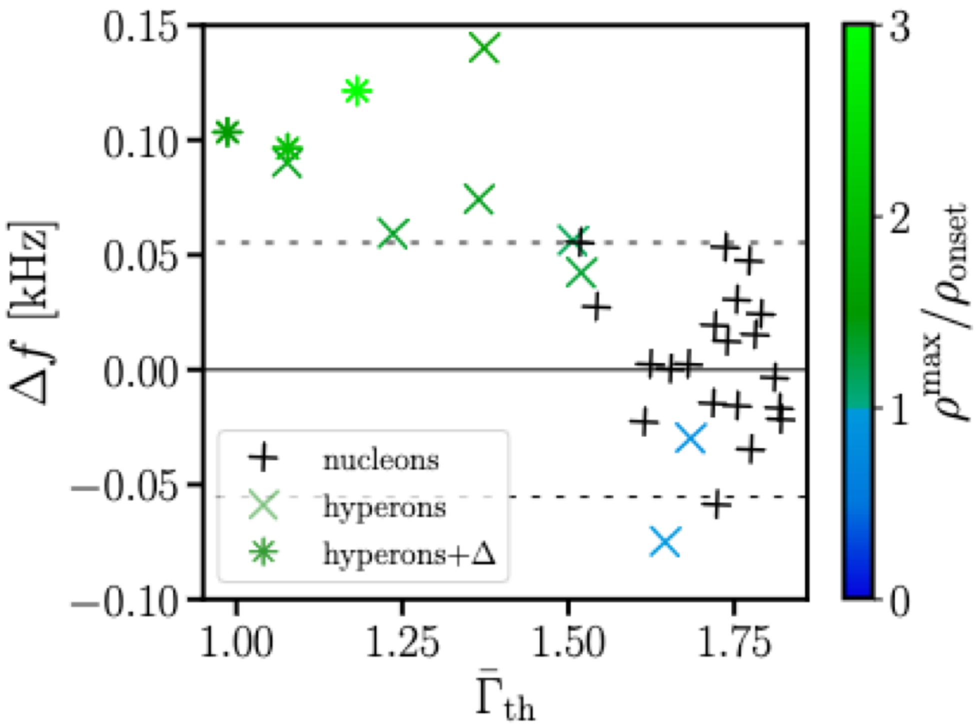
conclusion

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

note that models with tiny amount of hyperons or hyperonic models where the nucleonic counterparts produce f_{peak} in the lower edge do not stick out

since the magnitude of the frequency shift of hyperonic models is generally small…
….show the intrinsic scatter of f_{peak}

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



conclusions

- the presence of hyperons leads to a reduction of the thermal pressure compared to nucleonic models
- hyperonic models feature a frequency shift larger than fit from nucleonic models, with Γ_{th} = 1.75 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 advances on two and three-body interactions with hyperons and nucleons, and corresponding theoretical progress 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