Strangeness in Astrophysics

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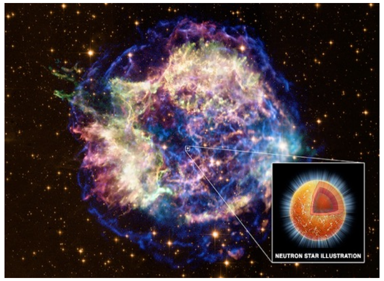
SQM2024
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Strangeness in Neutron Stars and Mergers



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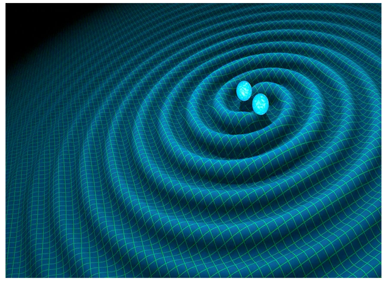

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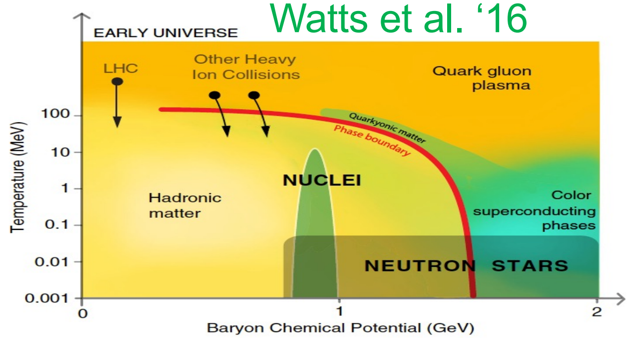
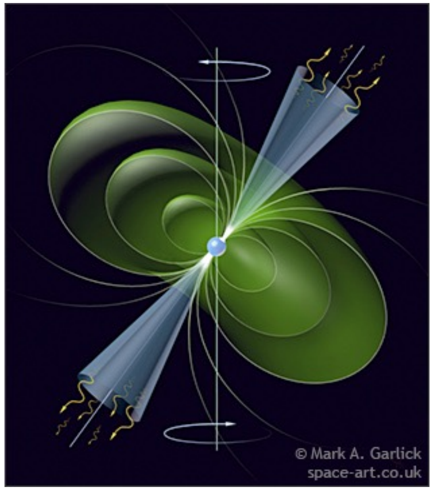
What is a Neutron Star?

Watts et al. '16





- produced in core collapse supernova explosions, usually observed as pulsars

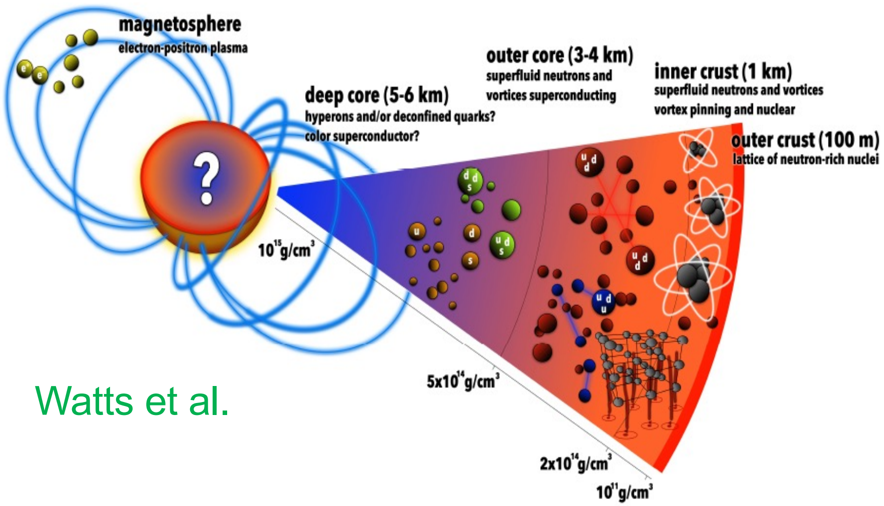
- usually refer to compact objects with $M \approx 1\text{-}2\ M_\odot$ and $R \approx 10\text{-}12$ Km

- extreme densities up to $5\text{-}10\ \rho_0$ ($n_0 = 0.16\ \text{fm}^{-3} \Rightarrow \rho_0 = 3 \bullet 10^{14}\ \text{g/cm}^3$)

- magnetic field : $B \sim 10^{8..16}$ G

- temperature: $T \sim 10^{6\ldots11}$ K

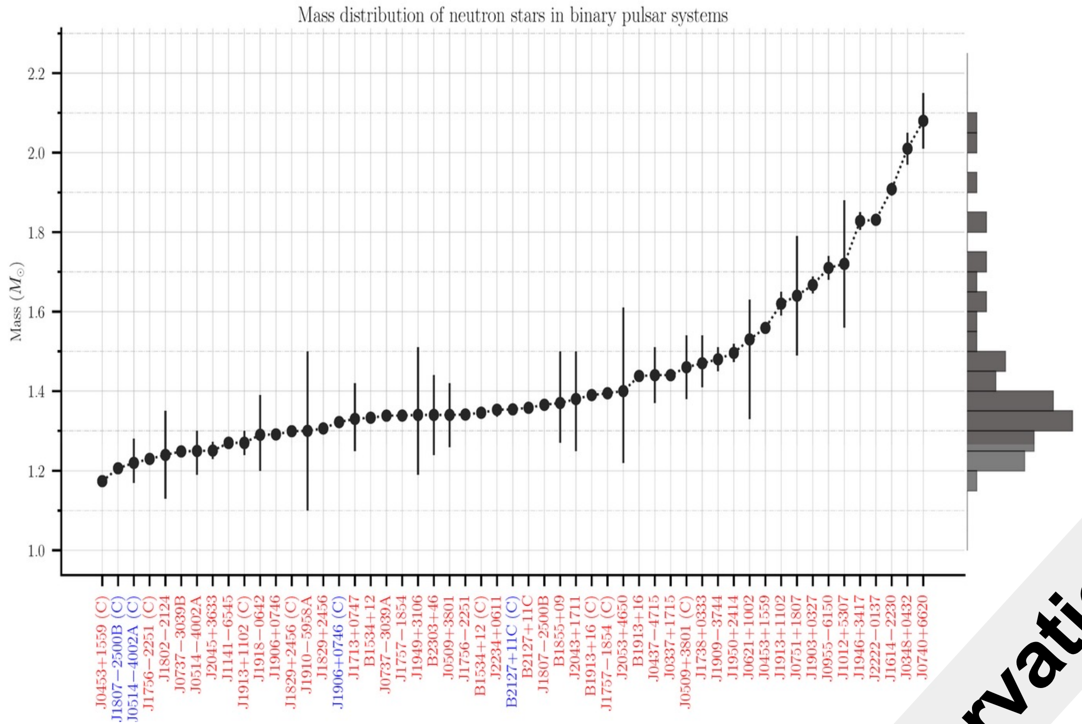
- observations: masses, radius, gravitational waves, cooling…



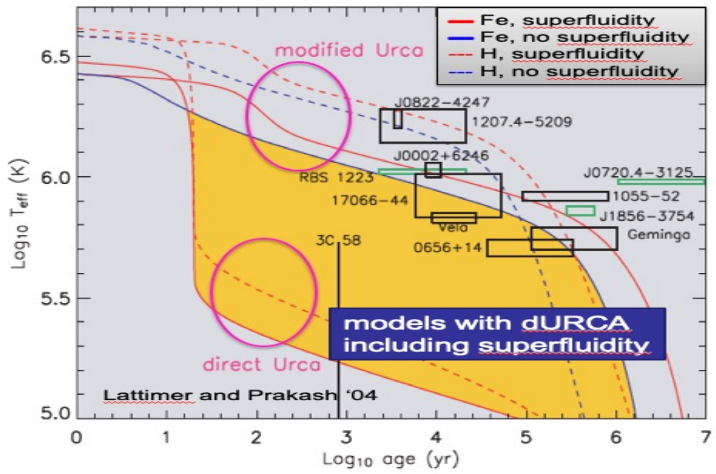
Watts et al.

Masses

credit: P. Freire



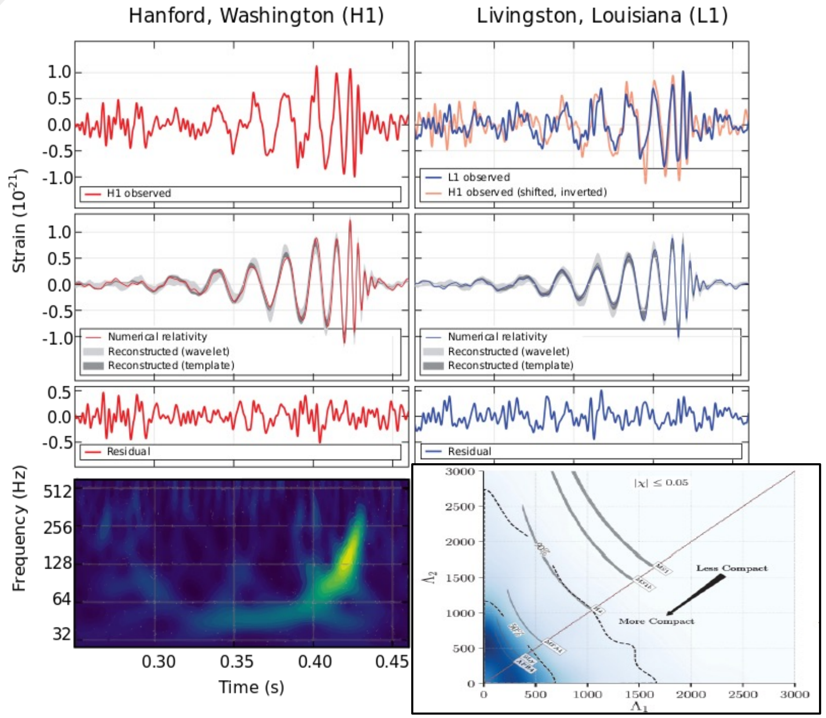
Cooling



Observations

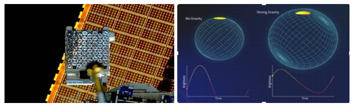
GW170817

Abbot et al. (LIGO-VIRGO) '17 '18



..also GW190425, GW190814

Radius



NICER
PSR J0030+0451

$R_{eq} = 13.02_{-1.06}^{+1.24}$ km
$M = 1.44_{-0.14}^{+0.15}\ M_\odot$
Miller et al. '19

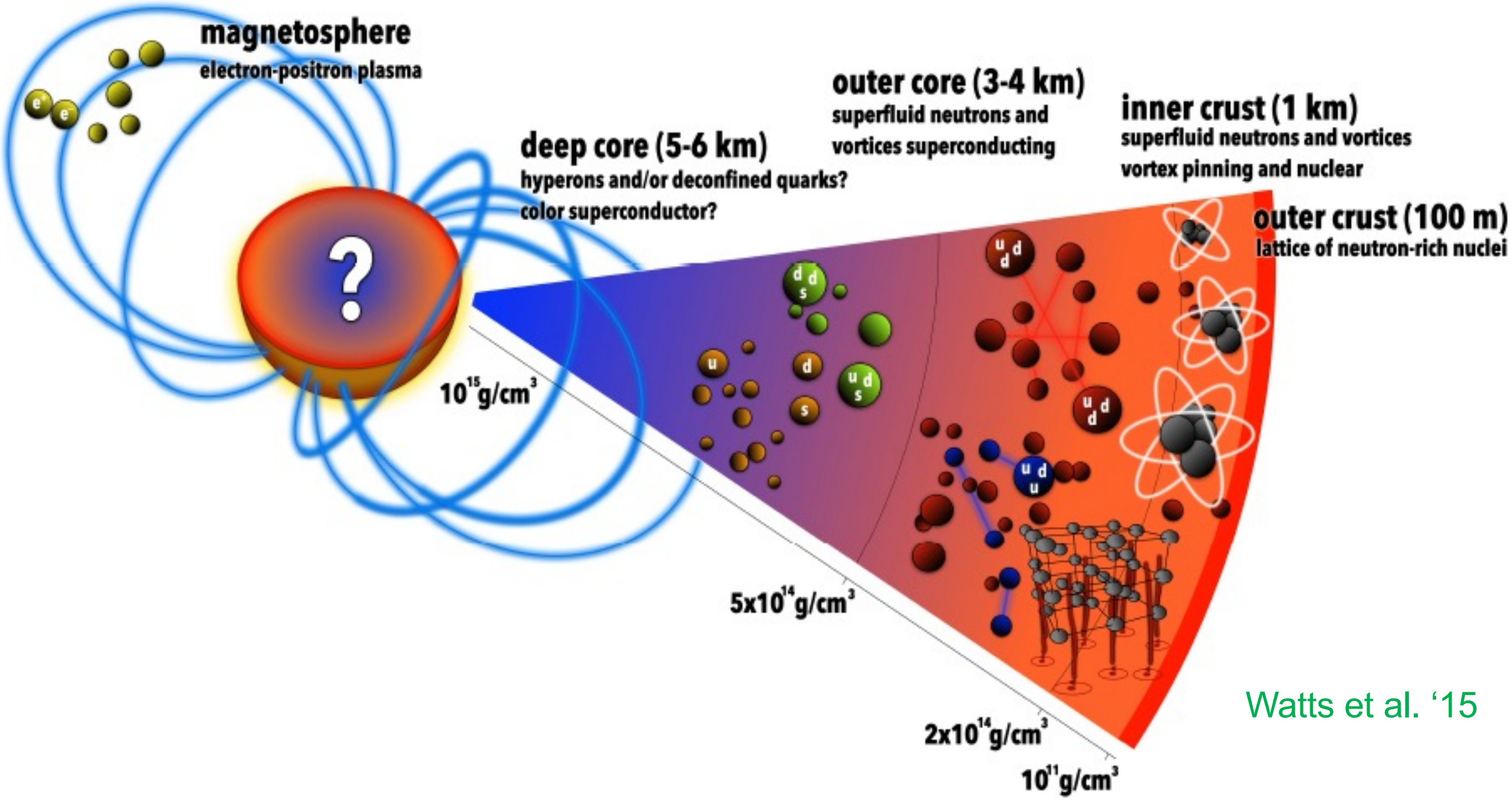
$R_{eq} = 12.71_{-1.19}^{+1.14}$ km
$M = 1.34_{-0.16}^{+0.15}\ M_\odot$
Riley et al. '19

NICER
PSR J0740+6620

$R_{eq} = 13.71_{-1.5}^{+2.6}$ km
$M = 2.08_{-0.07}^{+0.07}\ M_\odot$
Miller et al. '21

$R_{eq} = 12.39_{-0.98}^{+1.30}$ km
$M = 2.072_{-0.066}^{+0.067}\ M_\odot$
Riley et al. '21

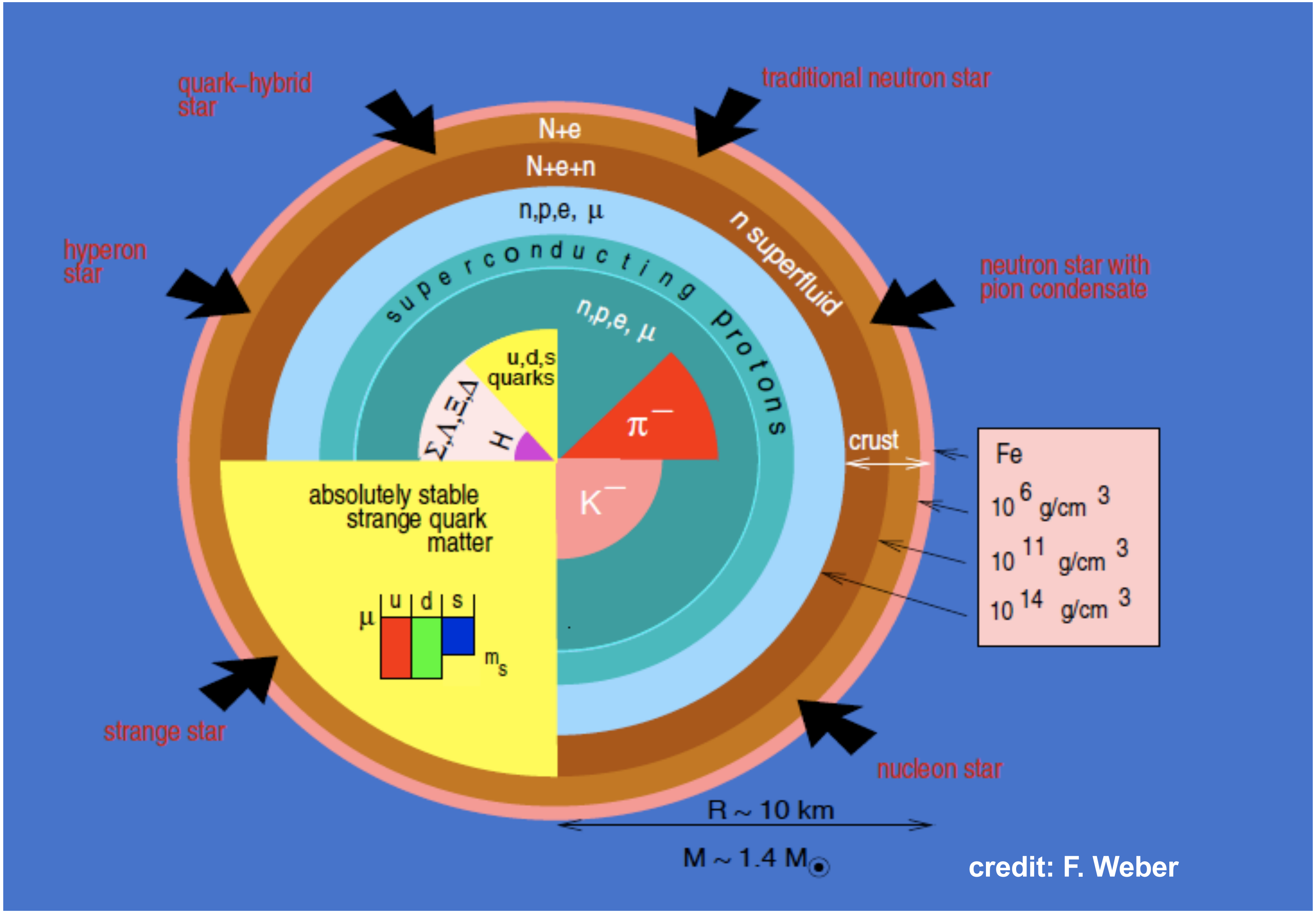
The Structure of Neutron Stars: The Inner Core



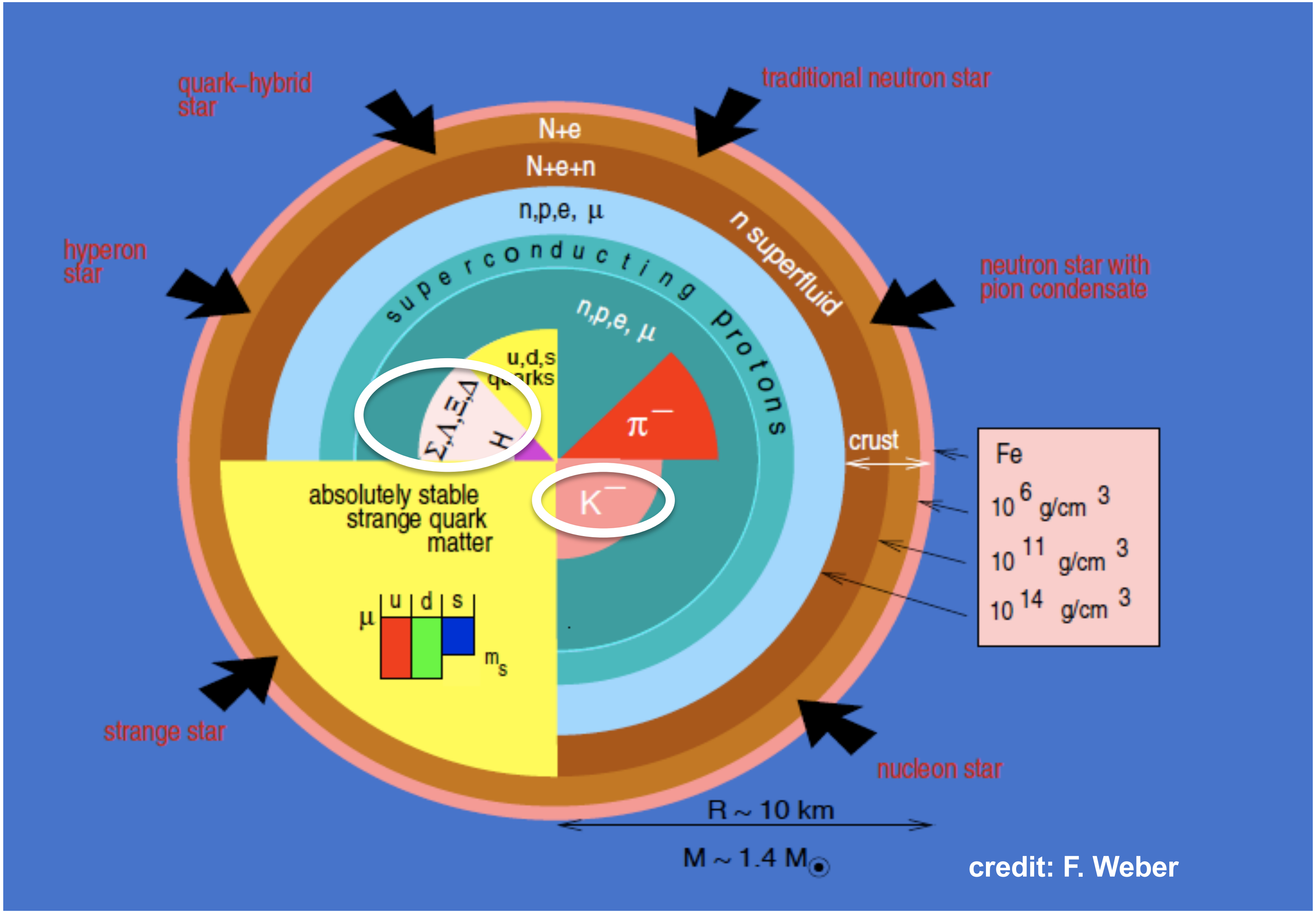
Watts et al. '15

Figure 1: Schematic structure of a NS. The outer layer is a solid ionic crust supported by electron degeneracy pressure. Neutrons begin to leak out of nuclei at densities $\sim 4 \times 10^{11}$ g/cm^3 (the neutron drip line, which separates inner and outer crust), where neutron degeneracy also starts to play a role. At densities $\sim 2 \times 10^{14}$ g/cm^3, the crust-core boundary, nuclei dissolve completely. In the core, densities may reach up to ten times the nuclear saturation density $\rho_{\text{sat}} = 2.8 \times 10^{14}$ g/cm^3 (the density in normal atomic nuclei).

The Inner Core

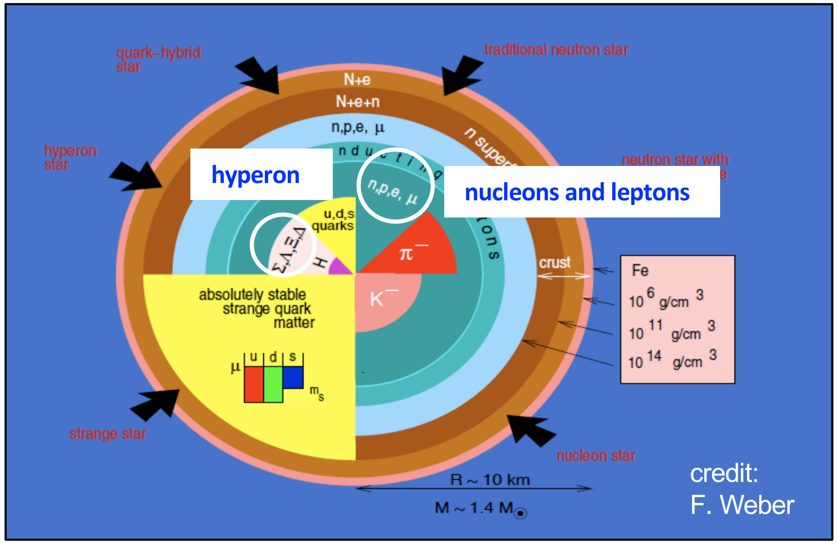


The Inner Core

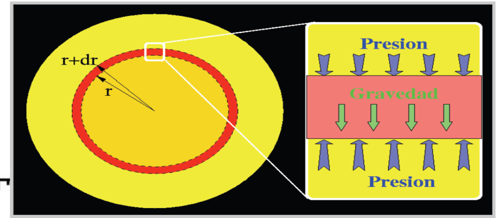


Strange Baryons in the Inner Core

Watts et al. ’16; Burgio and Fantina ’18; Tolos and Fabbietti ’20; Burgio, Schulze, Vidana and Wei ‘21

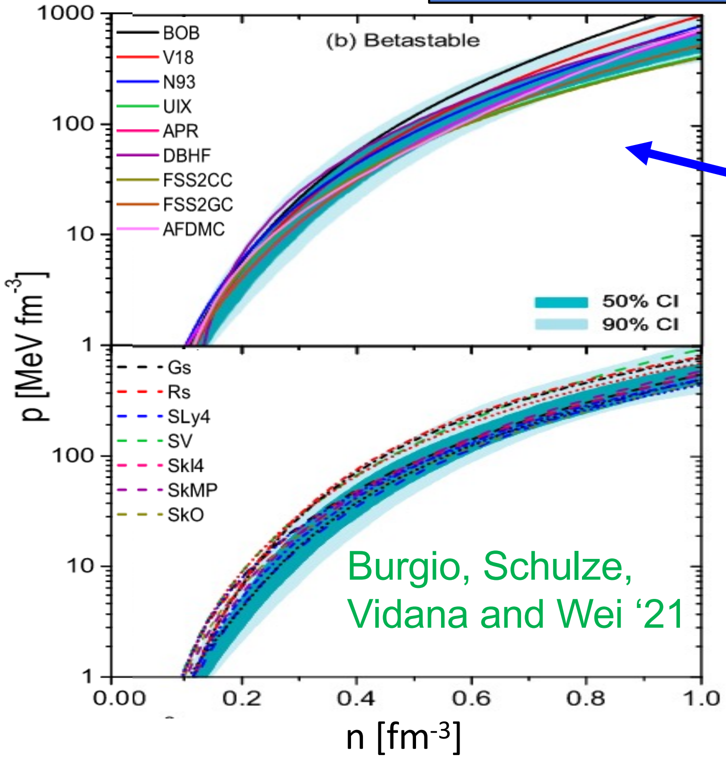


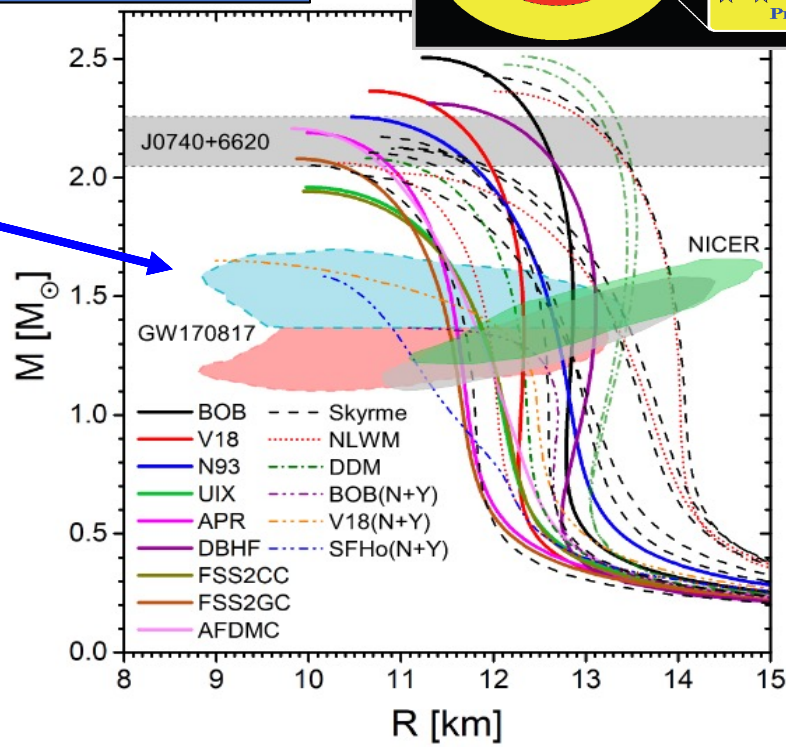
Mass-Radius



credit:
D. Page

EoS





Nucleons and Leptons in the Inner Core

Neutrons, protons and electrons are in β-equilibrium

$$n \rightarrow p\, e^- \, \bar{\nu}_e$$
$$p\, e^- \rightarrow n\, \nu_e$$

This equilibrium can be expressed in terms of the chemical potentials.
Since the mean free path of the v_e is >> 10 Km, neutrinos freely escape

$$\mu_n = \mu_p + \mu_e$$

Charge neutrality is also ensured by demanding

$$n_p = n_e$$

Note that baryon number is conserved too: $n = n_n + n_p$

Theoretical Approaches to nuclear EoS

The Equation of State (EoS) is a relation between thermodynamic variables describing the state of matter

Microscopic Ab-initio Approaches:
based on solving the many-body problem starting from two- and three-body interactions

- *Variational method: APR, CBF,..*
- *Quantum Montecarlo: AFDMC..*
- *Coupled cluster expansion*
- *Diagrammatic: BBG (BHF), SCGF..*
- *Relativistic DBHF*
- *RG methods: SRG from χEFT..*
- *Lattice methods*

Advantage: systematic addition of higher-order contributions
Disadvantage: applicable up to?
(SRG from χEFT ~ 1-2 n_0)

Phenomenological Approaches:
based on density-dependent interactions adjusted to nuclear observables and neutron star observations

- *Non-relativistic EDF: Skyrme..*
- *Relativistic Mean-Field (RMF) and Relativistic Hartree-Fock (RHF)*
- *Liquid Drop Model: BPS, BBP,..*
- *Thomas-Fermi model: Shen*
- *Statistical Model: HWN,RG,HS..*

Advantage: applicable to high densities beyond n_0
Disadvantage: not systematic

What about Hyperons?

A hyperon is a baryon containing one or more strange quarks

Hyperon	Mass (MeV/c^2)
Λ	1115.57 ± 0.06
Σ^+	1189.37 ± 0.06
Σ^0	1192.55 ± 0.10
Σ^-	1197.50 ± 0.05
Ξ^0	1314.80 ± 0.8
Ξ^-	1321.34 ± 0.14
Ω^-	1672.43 ± 0.14

First proposed in 1960 by Ambartsumyan & Saakyan

Traditionally neutron stars were modeled by a uniform fluid of neutron rich matter in β-equilibrium

$$n \rightarrow p\, e^- \, \bar{\nu}_e$$

$$p\, e^- \rightarrow n\, \nu_e$$

but more exotic degrees of freedom might be expected, such as hyperons, due to:

- high value of density at the center and
- the rapid increase of the nucleon chemical potential with density

Hyperons might be present at $n \sim (2\text{-}3)n_0$!!!

β-stable hyperonic matter

μ_N is large enough to make N->Y favorable

$$n + n \rightarrow n + \Lambda$$

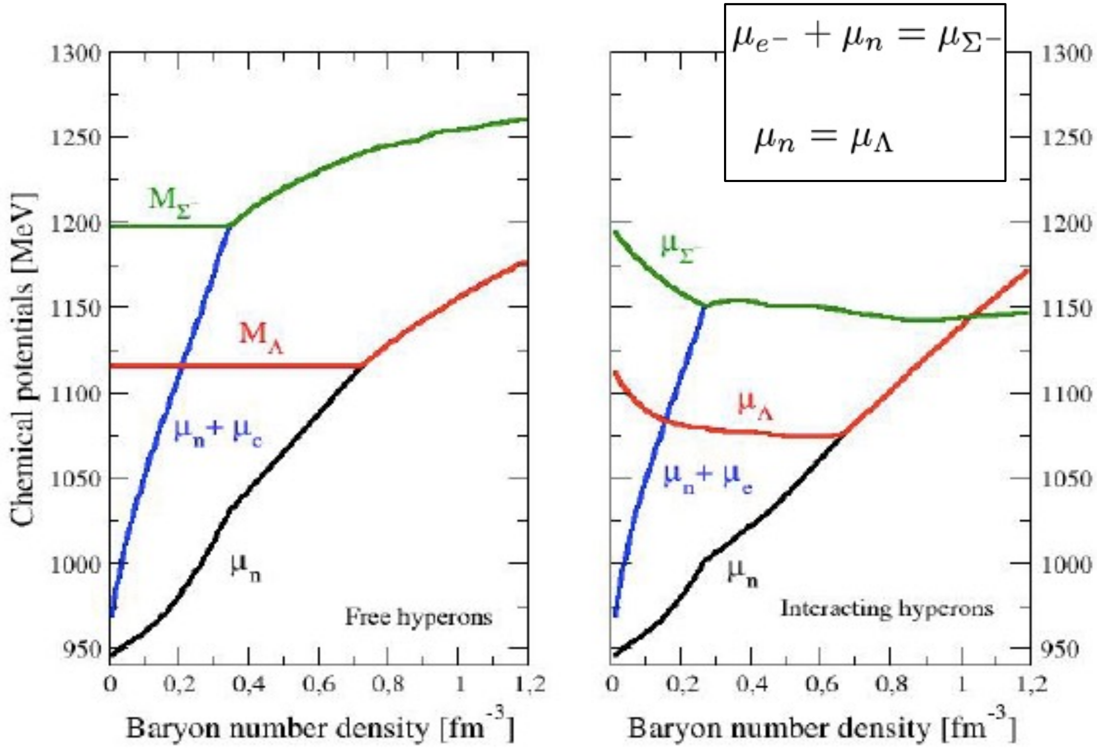
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

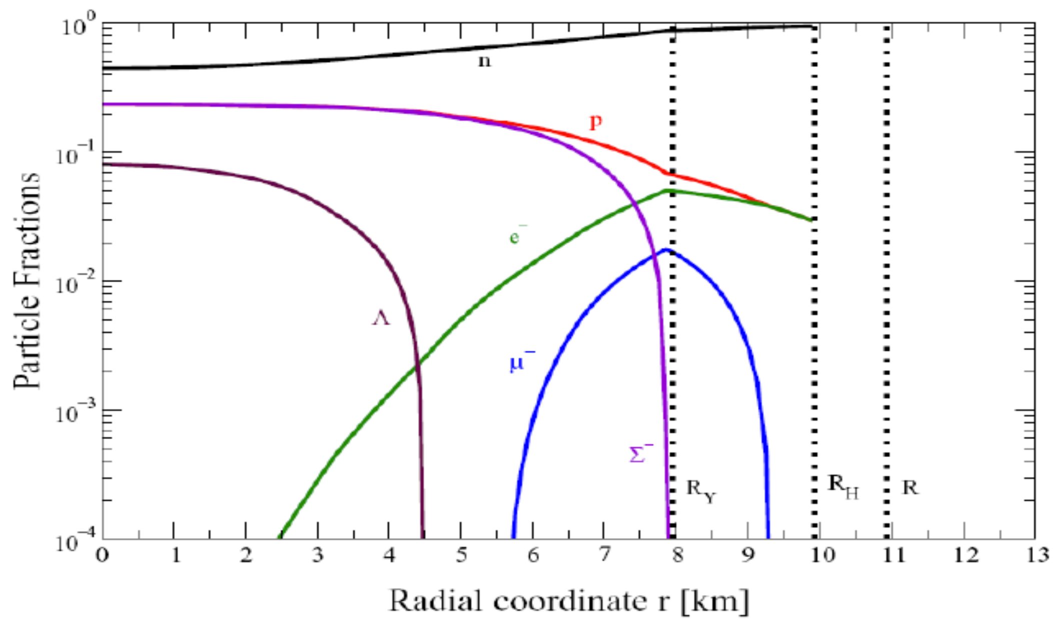
$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

$$\mu_i = b_i \mu_n - q_i \mu_e$$

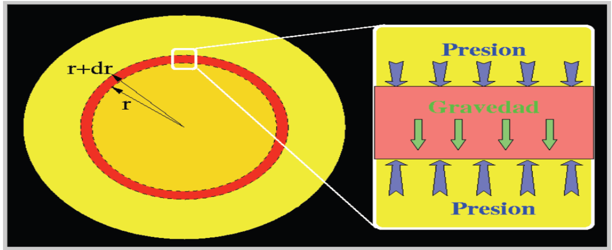
$$\sum_i x_i q_i = 0$$



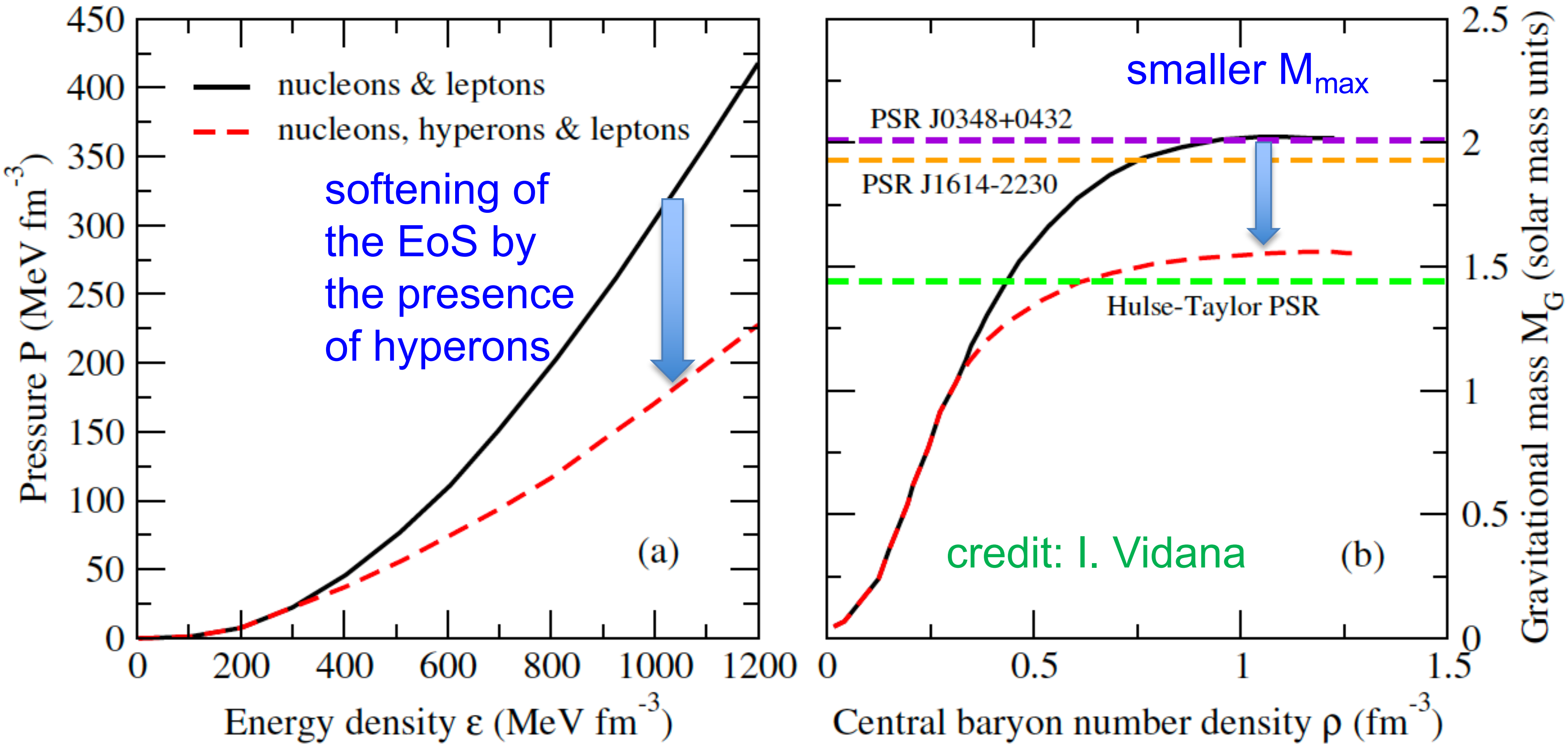


credit: I. Vidana

Inclusion of hyperons….



credit:
D. Page



….. induces a strong softening of the EoS that leads to $\mathbf{M_{max} < 2M_\odot}$

Chatterjee and Vidana ‘16
Vidana ‘18

The Hyperon Puzzle

The Hyperon Puzzle

Experimental information is increasing, but still less than desirable:

- data from several single Λ- and few Ξ- hypernuclei, and few ΛΛ-hypernuclei

- few YN scattering data (~ 50 points) due to difficulties in preparing hyperon beams and no hyperon targets available

- YN data from femtoscopy

The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to **maximum neutron star masses < $2M_{\odot}$**

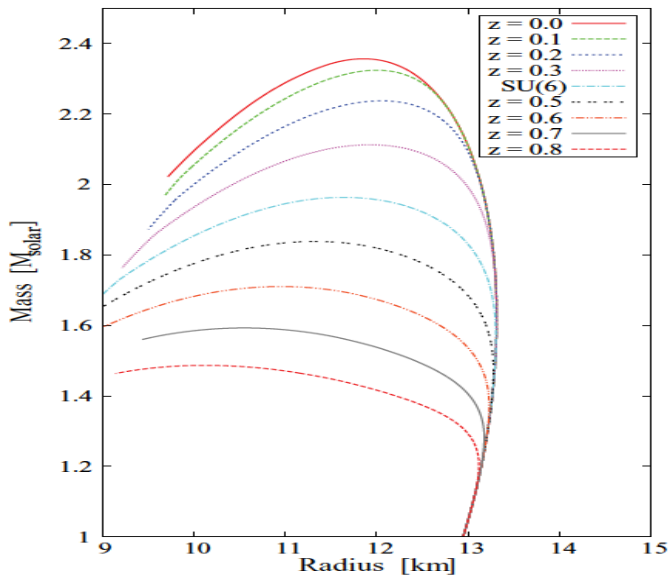
Solution?

- ➢ stiffer YN and YY interactions
- ➢ hyperonic 3-body forces
- ➢ push of Y onset by Δ-isobars or meson condensates
- ➢ quark matter below Y onset
- ➢ dark matter, modified gravity theories…

Solutions to the Hyperon Puzzle

I. Stiffer YN and YY interactions

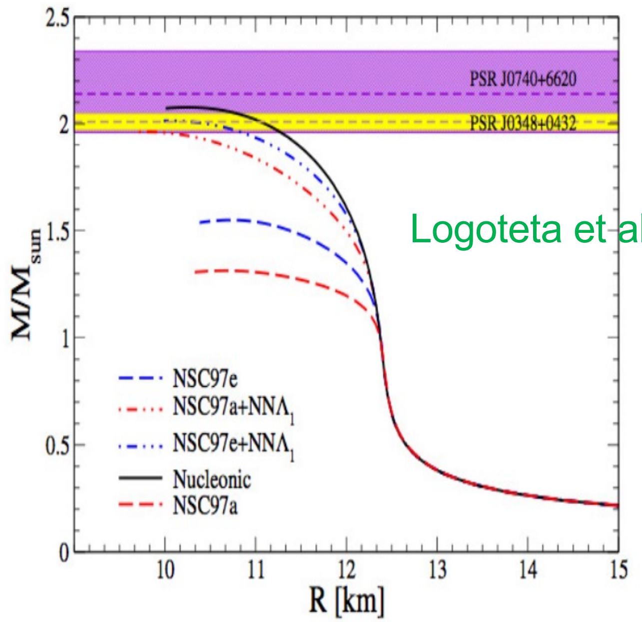
Weissenborn et al ’12



mainly explored in RMF models:
coupling of ϕ to hyperons to shift the onset of hyperons to higher densities
Bednarek et al ‘12; Weissenborn et al ’12; Oerte et al ‘15; Maslov et al ’15..

results still compatible with $\Delta B_{\Lambda\Lambda}(^6He_{\Lambda\Lambda})$
Fortin et al ‘17

II. Hyperonic 3-body forces



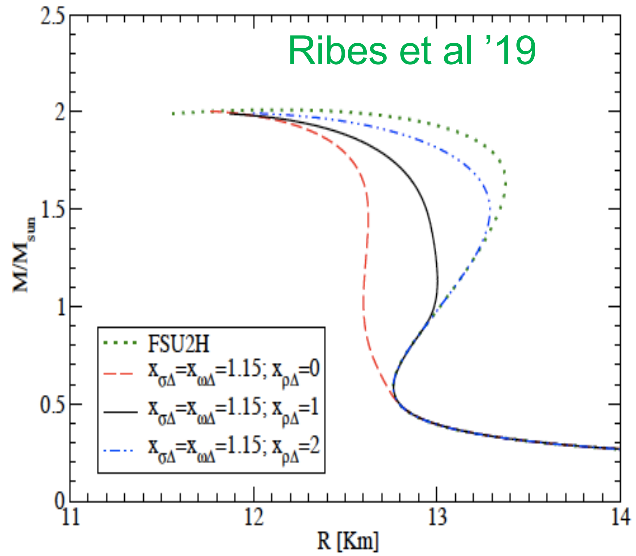
Logoteta et al ’19

not yet a general consensus:
for some models $2M_\odot$ are reached
Taktasuka et al ‘02 ’08; Yamamoto et al ‘13 ’14;
for others M_{max} is $1.6M_\odot$ Vidana et al ’11;
while Lonardoni et al ’15 shows no a conclusive outcome due to the strong dependence on ΛNN;
recently, ΛNN from χEFT gives enough repulsion to $2M_\odot$ Logoteta et al ’19 (or ΛNN and ΛΛN Tong et al ’24) ,
whereas Λ are unfavoured in NS Gerstung et al ’20

Solutions to the Hyperon Puzzle

III. Push of Y onset by Δ-isobars or meson condensates

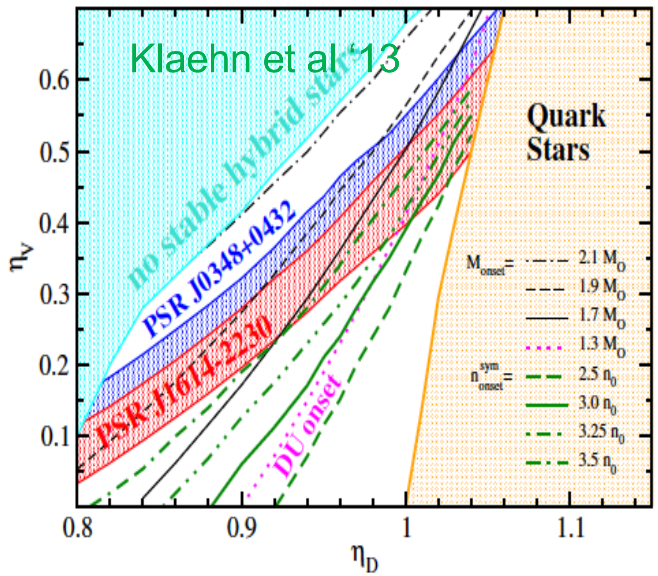
appearance of another degree of freedom
that push Y onset to higher densities.
It might (or not) reach $2M_{\odot}$



Δ
Drago et al '14 '15, Jie Li et al '19 ; Ribes et al '19…
K condensate
Kaplan et al' 86, Brown et al '94; Thorsson et al '94;
Lee '96; Glendenning et al '98..

IV. Quark matter below Y onset

early transition to quark matter below Y onset,
with quarks providing enough repulsion to
reach $2M_{\odot}$
Weissenborn et al '11; Klaehn et al '13;
Bonanno et al '12; Lastowiecki et al '12, Zdunik and Haensel '12..

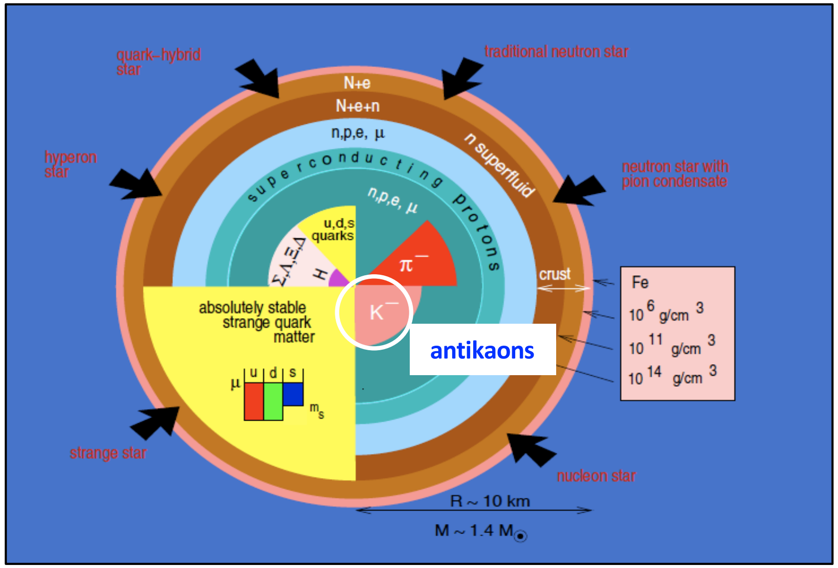


V. Others: modified gravity, dark matter..

Strange Mesons in the Inner Core

Kaon condensation in neutron stars

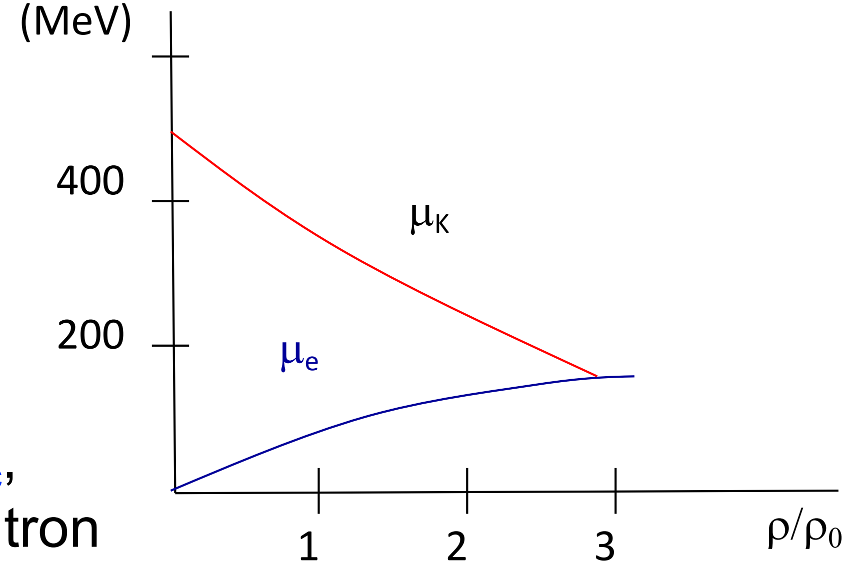
Kaplan and Nelson '86
Brown and Bethe '94



K^- feels attraction in the medium
→ Kaon condensation in neutron stars?

$$n \leftrightarrow p\, e^-\, \bar{\nu}_e \quad \rightarrow \quad \mu_n = \mu_p + \mu_{e^-}$$

$$n \leftrightarrow p\, K^- \quad \rightarrow \quad \mu_n = \mu_p + \mu_{K^-}$$



Antikaons are bosons. If $\mu_{K^-} \leq \mu_{e^-}$ for $\rho \geq \rho_c$, with ρ_c being a feasible density within neutron stars, antikaons will condensate

Glendenning '85

Kaon condensation irrelevant as (anti)kaons have to lower their mass drastically

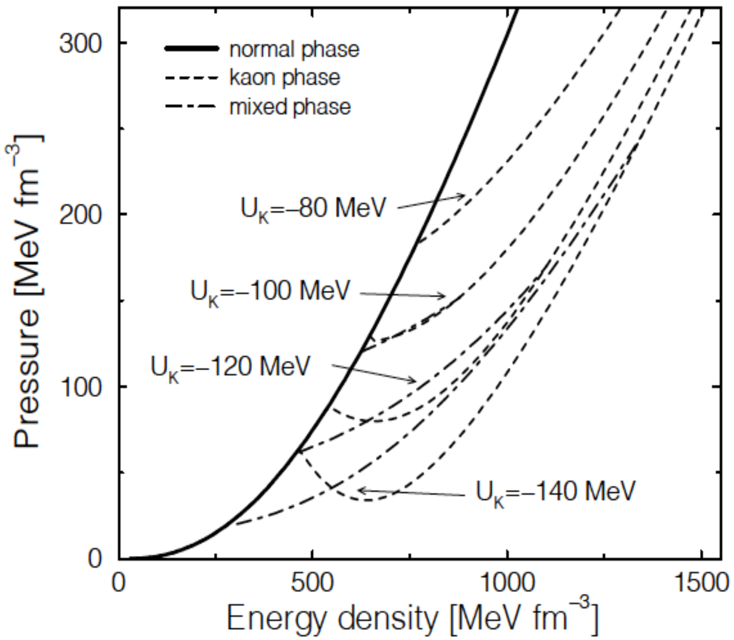
Kaplan and Nelson '86

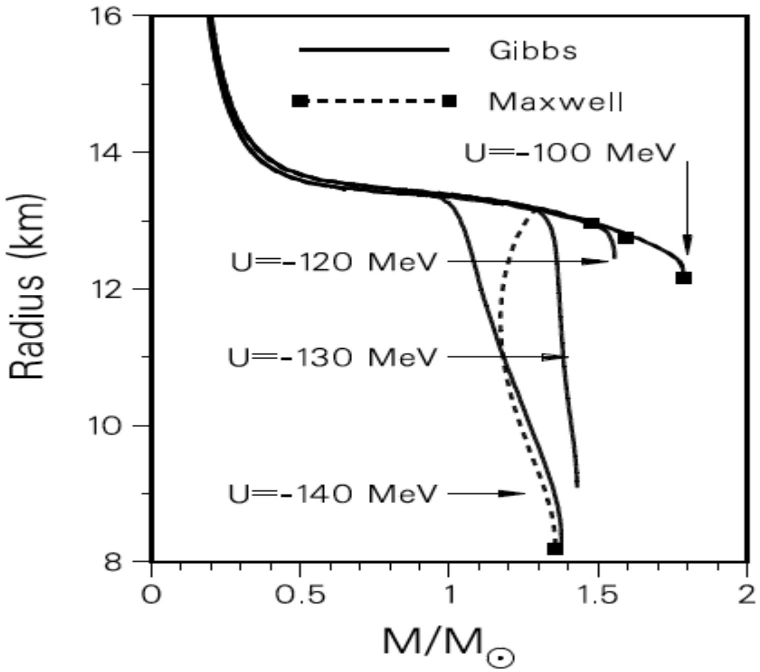
Medium effects on (anti)kaons can be important: kaon condensation is possible!

Brown, Kubodera, Rho and Thorsson'92; Thorsson, Prakash and Lattimer '94; Fujii, Maruyama, Muto and Tatsumi '96; Li, Lee and Brown '97; Knorren, Prakash and Ellis '95; Schaffner and Mishustin '96; Glendenning and Schaffner-Bielich '98 '99

Renewed interest on antikaon-nucleon interaction

Glendenning and Schaffner-Bielich '99





EoS is softened
due to kaon condensation

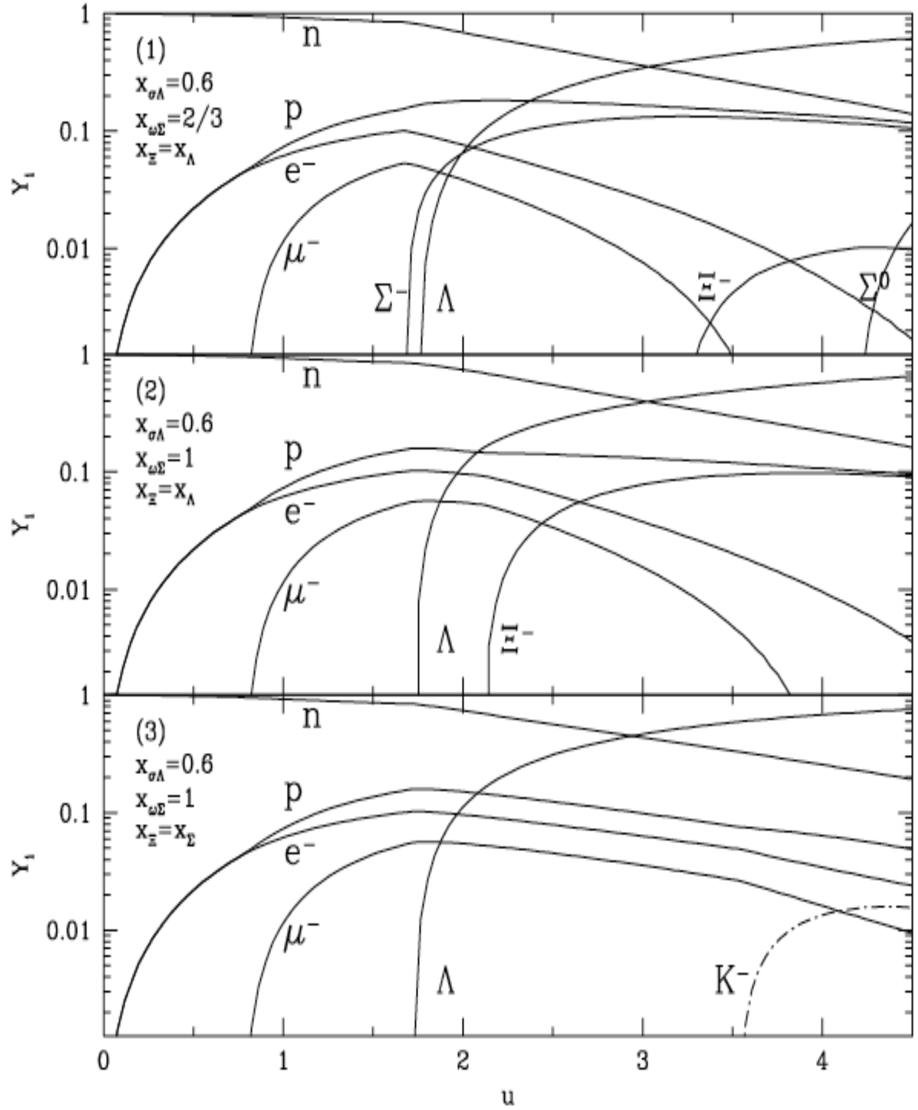
The maximum mass is lowered with increasing attractive K^-N potential

Knorren, Prakash and Ellis ’95

Hyperonization on kaon condensation

Knorren, Prakash and Ellis ’95

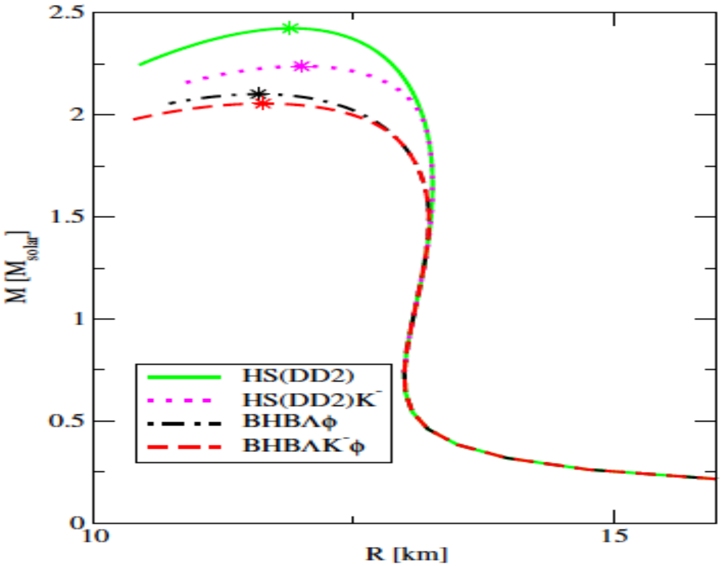
electron fraction decreases once hyperons appear, thus, the presence of hyperons increases the critical density for kaon condensation



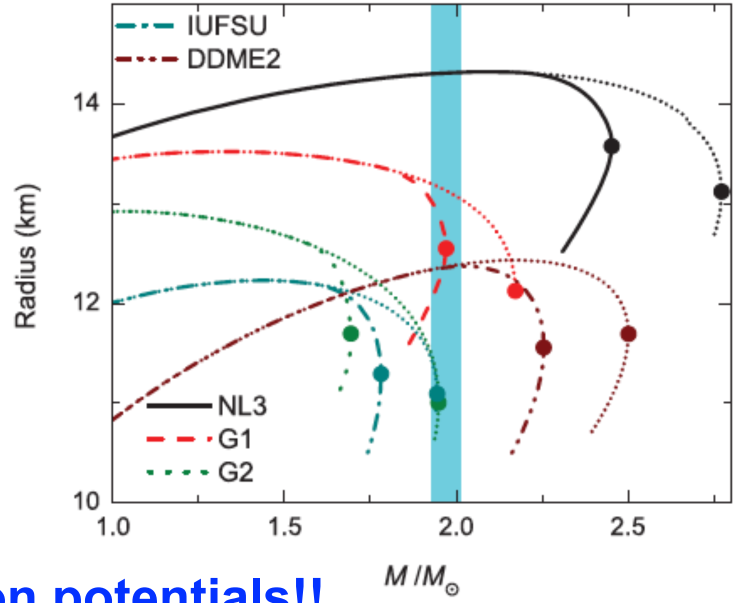
Later on different groups have worked on **improved relativistic-mean field models** to include kaon condensation and to fulfill neutron star properties and to study proto-neutron stars, supernova or neutron star mergers

within RMF models

Banik and Bandyopadhyay ’01 ‘02
Char and Banik ‘14
Malik, Banik and Bandyopadhyay ’20 ‘21

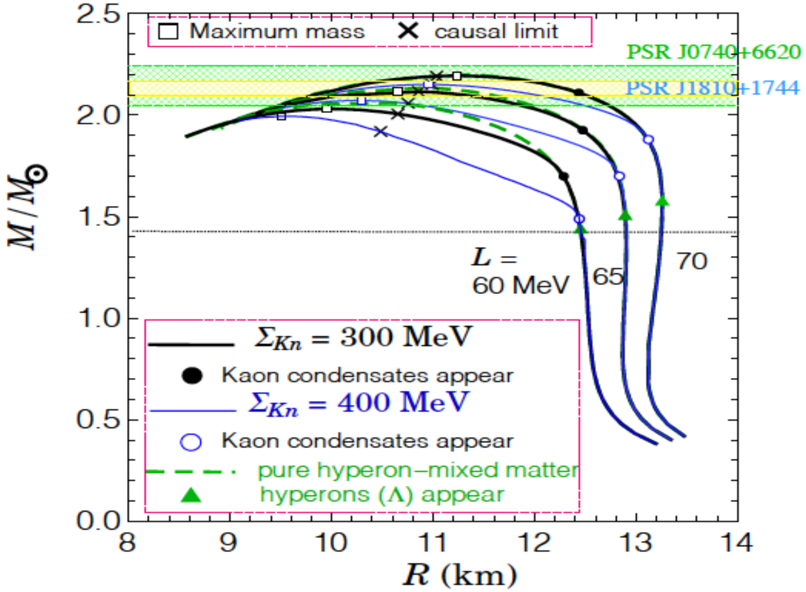


Gupta and Arumugam ‘12 ‘13

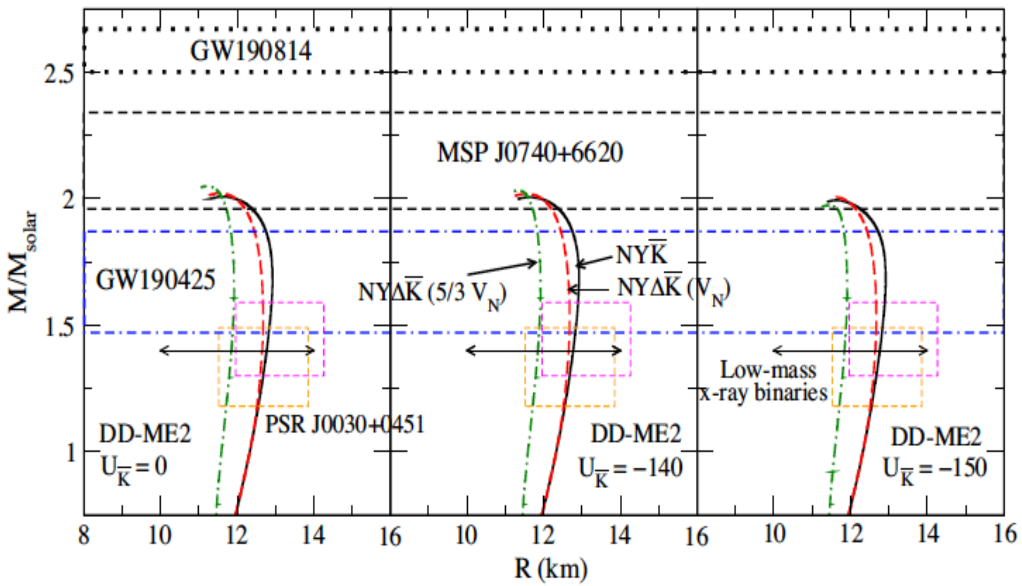


Need of large antikaon potentials!!

Muto ‘08
Muto, Maruyama, Tatsumi and Takatsuka ’19
Muto, Maruyama and Tatsumi ’21

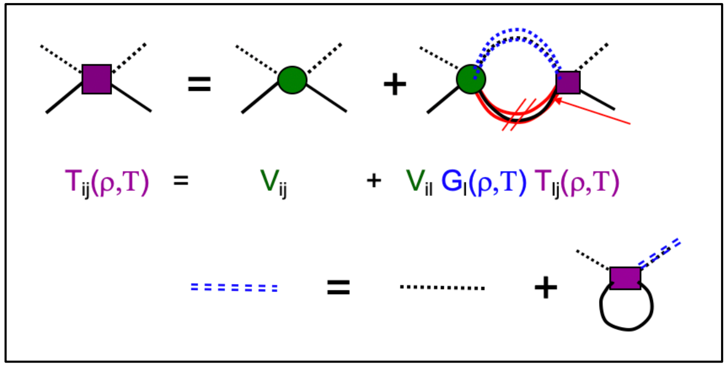


Thapa and Sinha ‘20
Thapa, Sinha, Li and Sedrakian ‘21



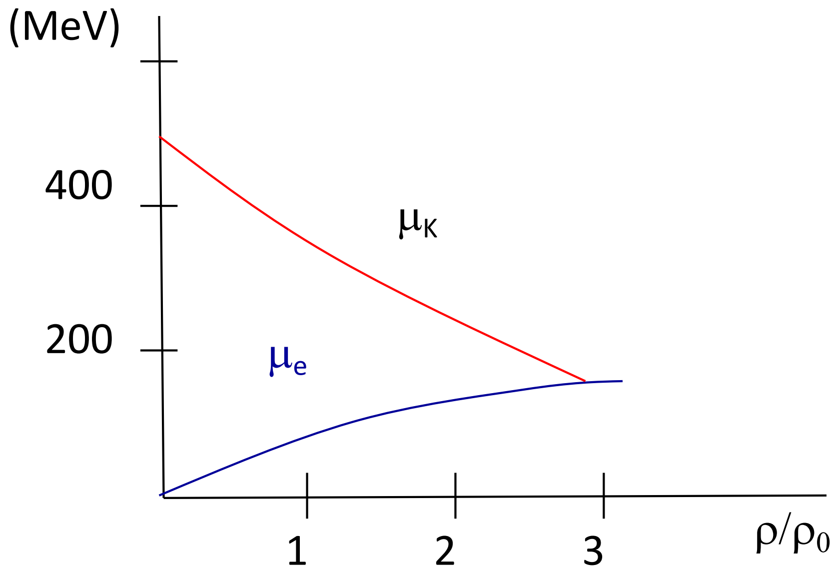
Using microscopic unitarized schemes…

The condition $\mu_{e-} \geq m^*_{K-}$ for a given ρ_c implies that $m_{K-} - m^*_{K-}(\rho_c) \approx 200, 300$ MeV.



However, unitarized schemes based on meson-exchange models or chiral Lagrangians predict a moderate attraction in nuclear matter

Tolos and Fabbietti '20



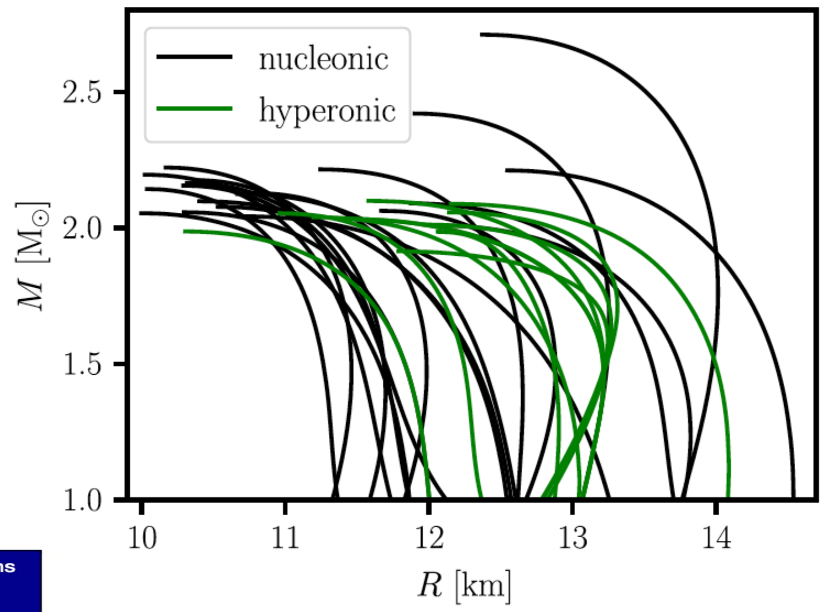
Lutz '98
Ramos and Oset '00
Tolos, Polls, Ramos '01
Tolos, Ramos and Oset '06
Tolos, Cabrera and Ramos '08
Cabrera, Tolos, Aichelin and Bratkovskaya'14…

Kaon condensation seems very unlikely!

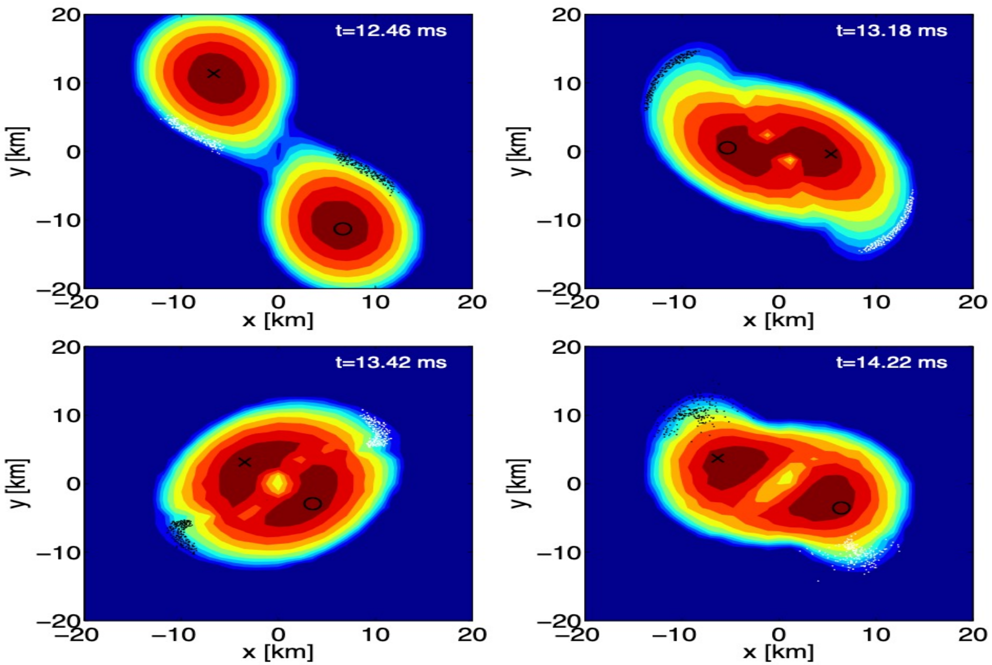
Neutron Star Mergers

is there a clear signal of the presence of hyperons in neutron stars?

Blacker, Kochankovski, Bauswein, Ramos and LT '24



Bauswein and Stergioulas '15



need of new venues to search for strangeness

what about mergers?

Sekiguchi, Kiuchi, Kyutoku and Shibata '11
Radice, Bernuzzi, Del Pozzo, Robert and Ott '17

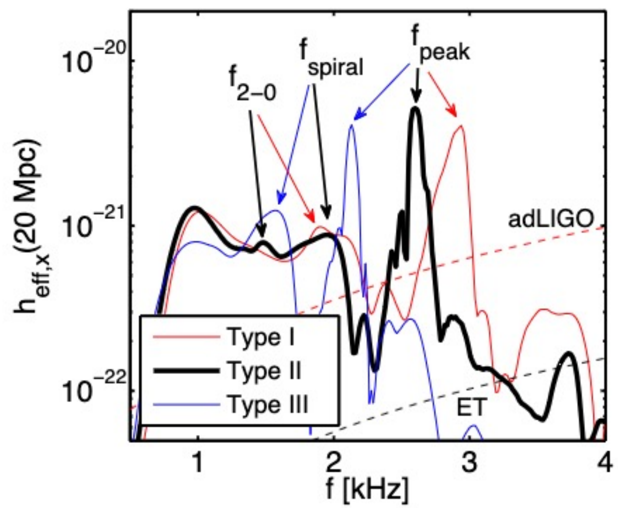
Bauswein and Stergioulas ‘15

check the thermal behaviour!!!

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 Γ_{th} = 1.75

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

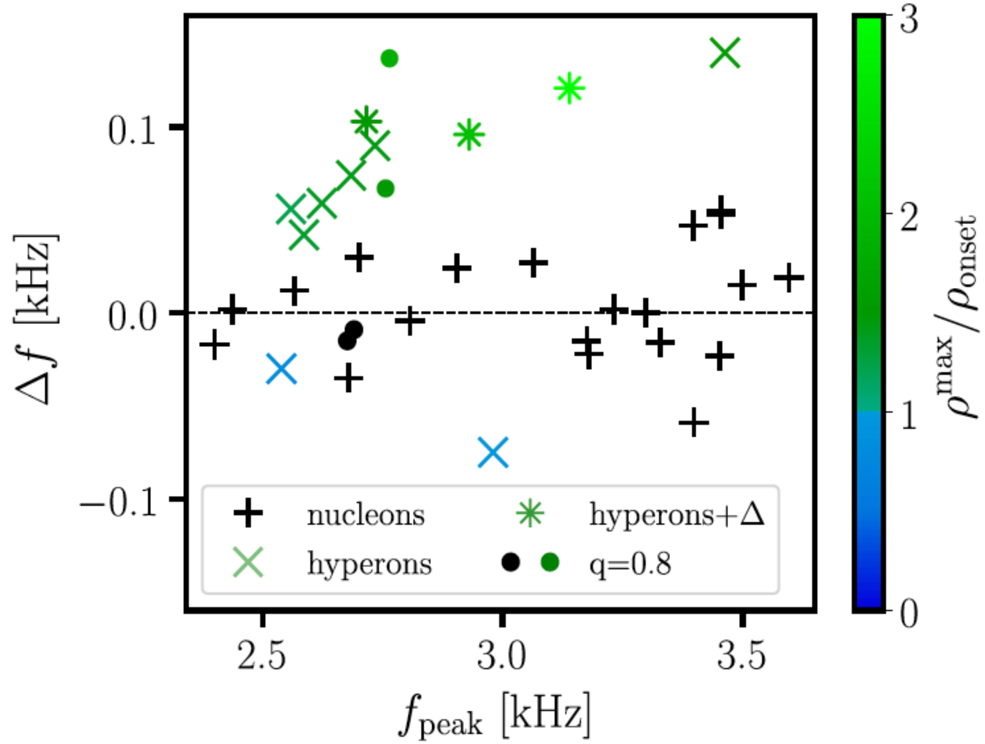


Blacker, Kochankovski, Bauswein, Ramos and LT ‘24

conclusion

hyperonic models lead to systematically higher frequencies by up to Δf ~ 150 Hz, being small but potentially sizeable

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



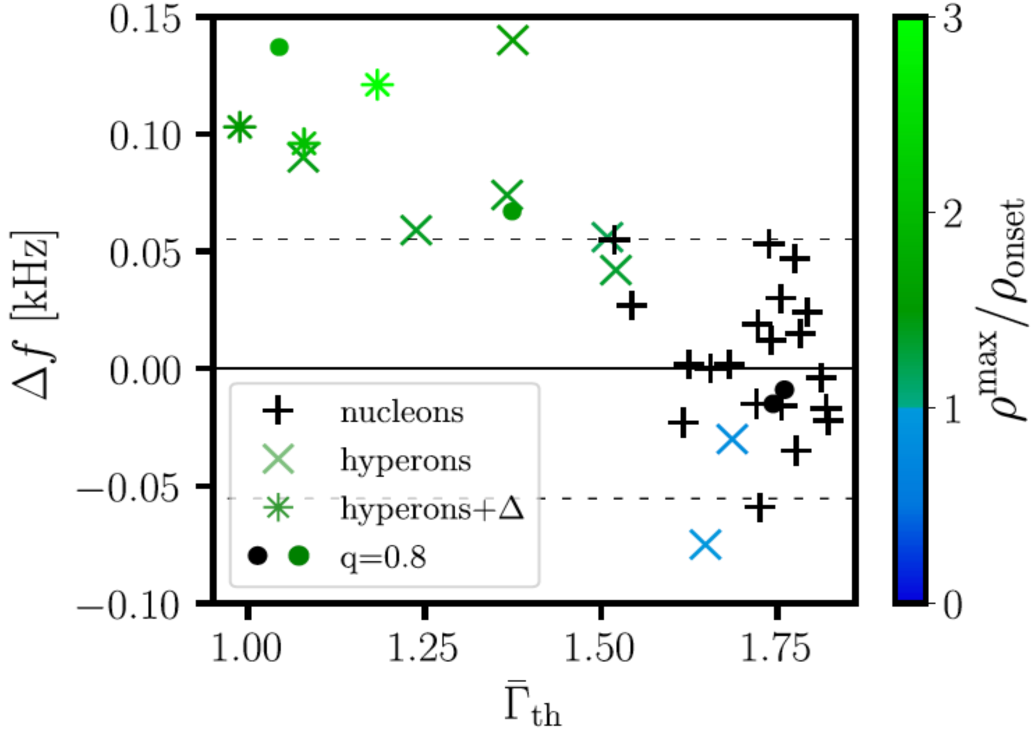
Δf vs $\bar{\Gamma}_{th}$ (average thermal index)

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

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

$$\epsilon_{th} = \epsilon(\rho_B, T) - \epsilon(\rho_B, T=0)$$

Blacker, Kochankovski, Bauswein, Ramos and LT '24

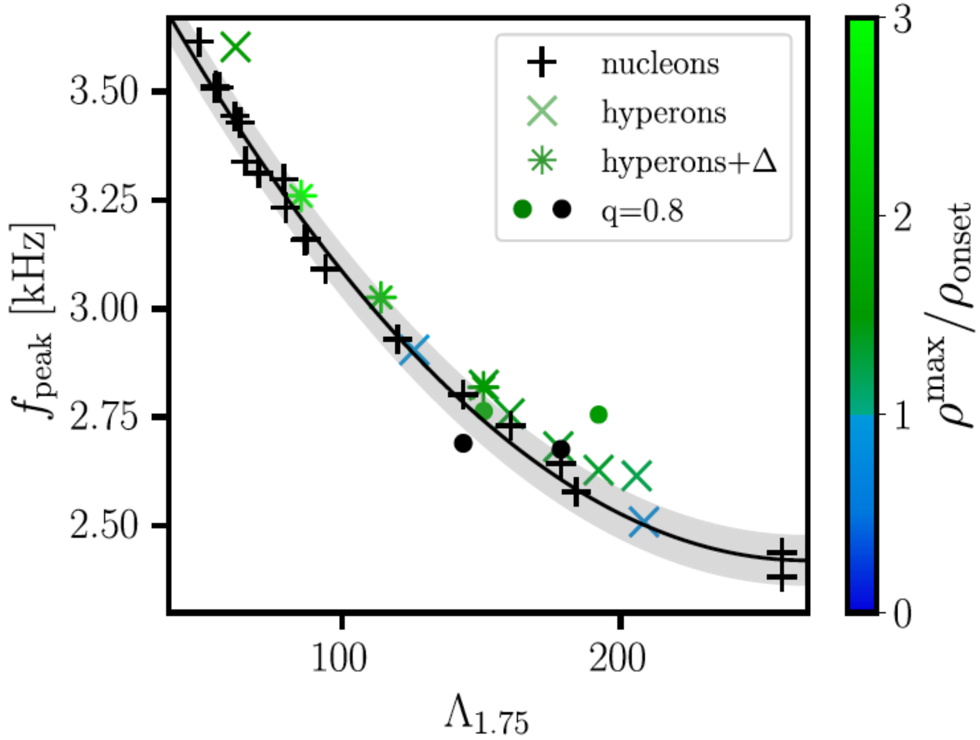


conclusions

- hyperons lead to a smaller thermal index compared to nucleons
- a frequency shift larger for hyperonic models
- $\bar{\Gamma}_{th}$ = 1.75 is a good choice for "nucleonic" thermal behavior

presence of hyperons linked to two directly measurable quantities

Blacker, Kochankovski, Bauswein, Ramos and LT ‘24



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

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

conclusion

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

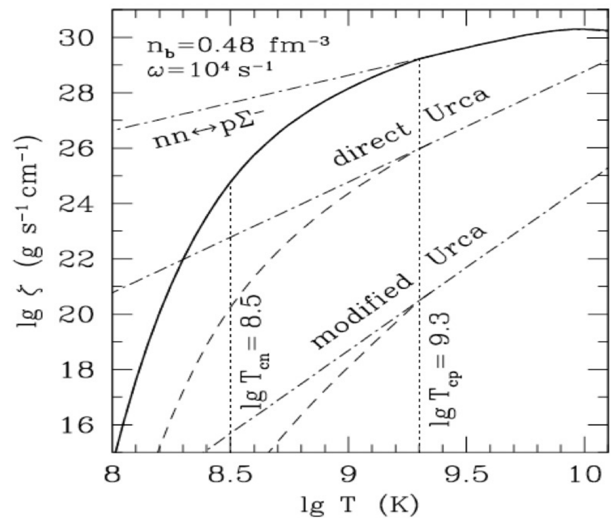
some caveats..

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

Disclaimer:

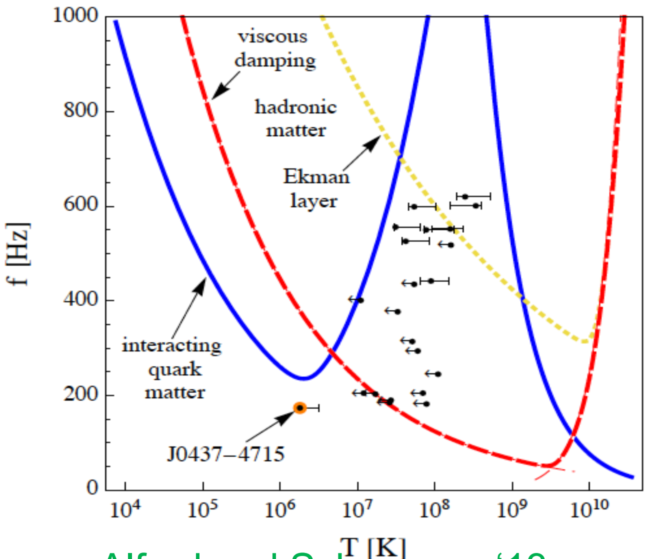
this talk has been focused on EoS but viscous processes important for dynamics of neutron stars and mergers, such as bulk viscosity

Jones '71 '01, Lindblom & Owen '02, Haensel, Levenfish & Yakovlev '02, van Dalen and Dieperink '04, Chatterjee & Bandyopadhyay '07, Gusakov and Kantor '08, Haskell and Andersson '10, Ofengeim, Gusakov, Haensel and Fortin '19, Alford & Haber '21…



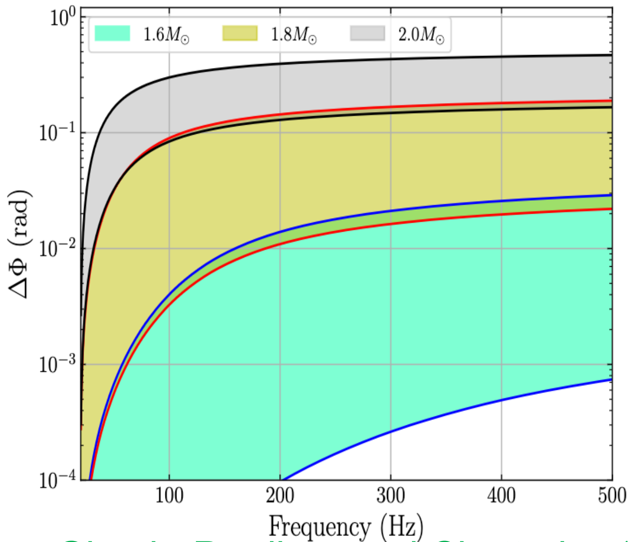
Haensel, Levenfish and Yakovlev '02

r-modes in neutron stars



Alford and Schwenzer '13

tidal heating in mergers

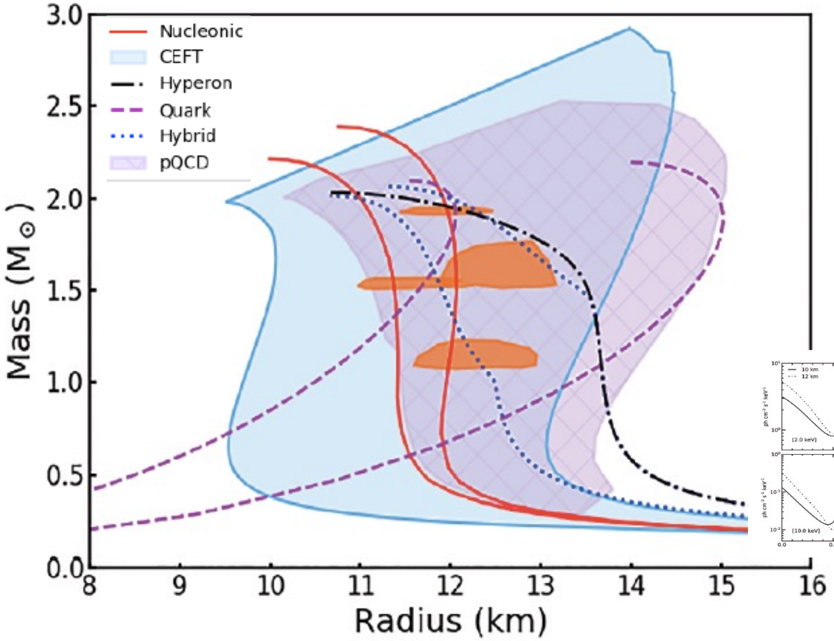


Ghosh, Pradhan and Chatterjee '24

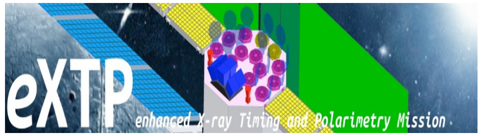
Viscous processes including strangeness for another talk!

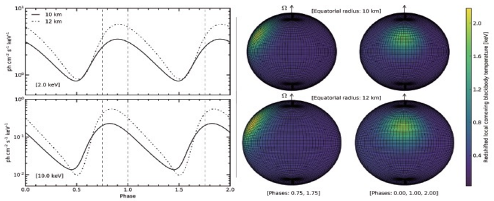
Space missions

Watts et al. '19

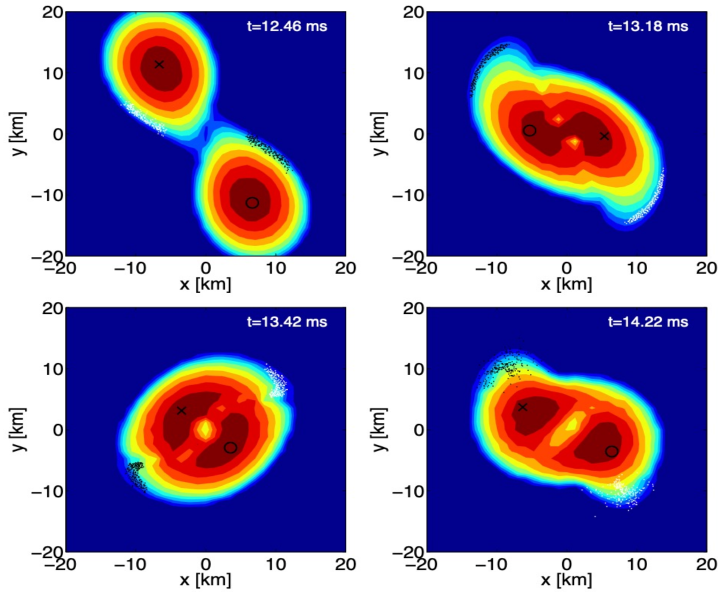


STROBE-X



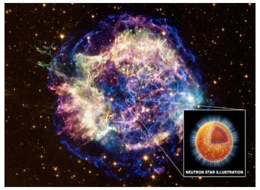


Bauswein and Stergioulas '15

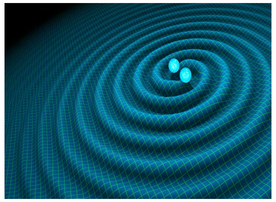


and multimessenger astronomy

in search for strangeness



Present and Future



A lot of observational and theoretical effort has been invested in studying the role of strangeness in neutron stars and mergers

The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to maximum neutron star masses < $2M_{\odot}$ .This is known as The Hyperon Puzzle

The presence of (anti-)kaons in neutron stars is controversial

Need of new routes to search for strangeness in mergers

Present and future:
NICER, eXTP, STROBE-X…
and multimessenger astronomy

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CompOSE

CompStar Online Supernovæ Equations of State

comp star

The online service CompOSE provides data tables for different state of the art equations of state (EoS) ready for further usage in astrophysical applications, nuclear physics and beyond.

The cold neutron star EoS tables can be used directly within LORENE to obtain models of (rotating/magnetised) neutron stars, see the eos_compose class.

If you make use of the tables provided in CompOSE, please cite the publications describing the respective EoS models (available on the CompOSE web pages for each the model) together with a reference to the CompOSE website (https://compose.obspm.fr) and/or the original CompOSE publications :

[**TOK_2015**] S. Typel, M. Oertel, T. Klähn, Phys.Part.Nucl. 46, 633
[**OHKT_2017**] M. Oertel, M. Hempel, T. Klähn, S. Typel, Rev. Mod. Phys. 89, 015007
[**TOK_2022**] S. Typel, M. Oertel, T. Klähn et al, arxiv:2203.03209

Data tables, associated software and the manual can be freely downloaded. Log in is required if you wish to use further utilities, such as graphics and online computations. Please contact "develop.compose(at)obspm.fr" if you wish to have an account.

S. Typel, M. Oertel, T. Klaehn, D. Chatterjee, V. Dexheimer, C. Ishizuka, M. Mancini, J. Novak, H. Pais, C.Providencia, A. Raduta, M. Servillat and L. Tolos CompOSE Reference Manual, Eur. Phys. J. A 58 (2022) 11, 221