Strangeness in Neutron Stars

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What is a Neutron Star?

Watts et al. '16

Crab Nebula · M1 — NASA, ESA, and J. Hester (Arizona State University)
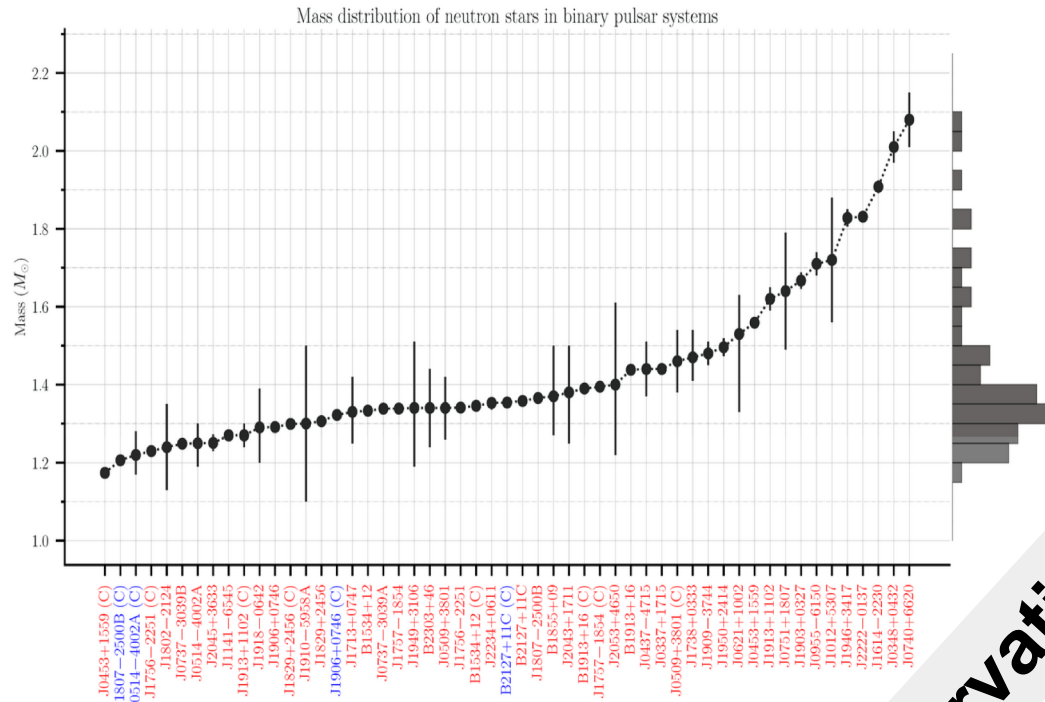

© Mark A. Garlick space-art.co.uk

credit: Watts
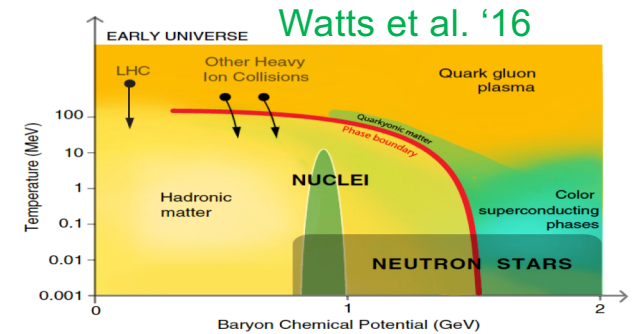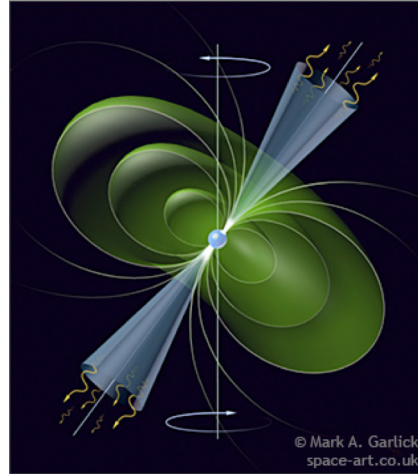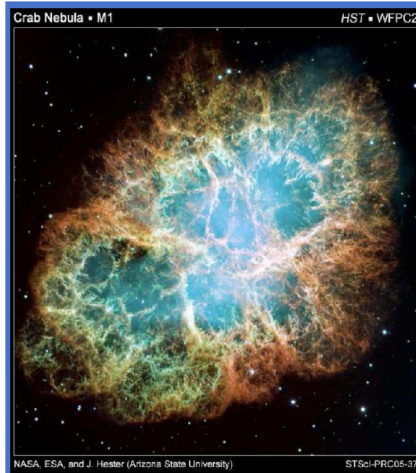
• produced in core collapse supernova explosions, usually observed as pulsars

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

• extreme densities up to 5-10 ρ_0 ($n_0 = 0.16$ fm^{-3} => $\rho_0 = 3 \cdot 10^{14}$ g/cm^3)

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

• temperature: $T \sim 10^{6...11}$ K

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

Masses

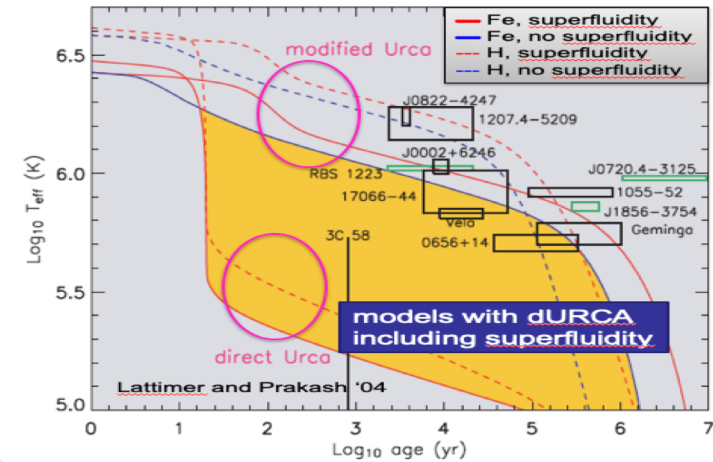Mass distribution of neutron stars in binary pulsar systems

Cooling

modified Urca

models with dURCA
including superfluidity

direct Urca

Lattimer and Prakash '04

GW170817

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

Hanford, Washington (H1) — Livingston, Louisiana (L1)

..also GW190425, GW190814
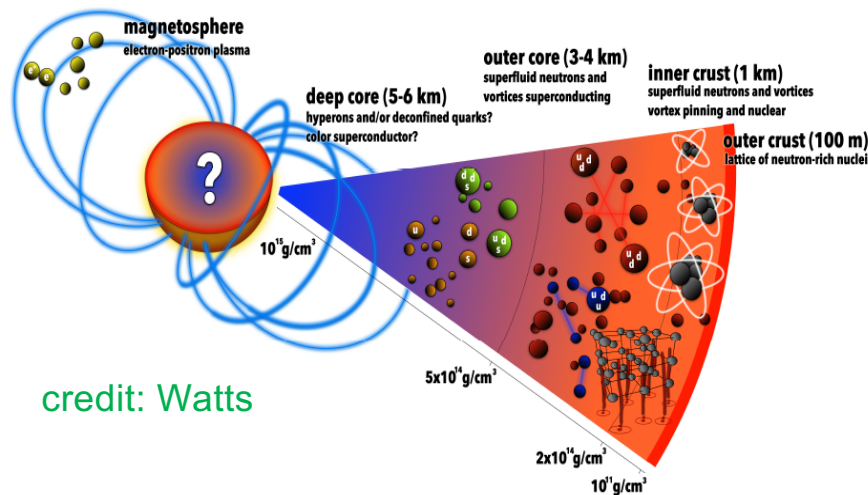
Radius

NICER
PSR J0030+0451

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

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

NICER
PSR J0740+6620

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

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

Observations
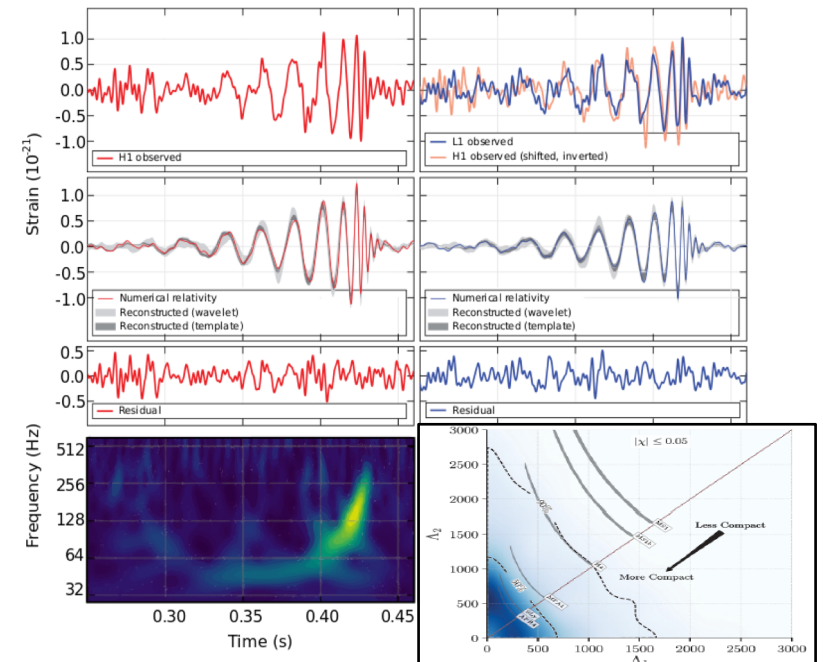
The Structure of Neutron Stars: The Inner Core

magnetosphere
electron-positron plasma

deep core (5-6 km)
hyperons and/or deconfined quarks?
color superconductor?

outer core (3-4 km)
superfluid neutrons and
vortices superconducting

inner crust (1 km)
superfluid neutrons and vortices
vortex pinning and nuclear

outer crust (100 m)
lattice of neutron-rich nuclei

?

10^{15} g/cm^3

5×10^{14} g/cm^3

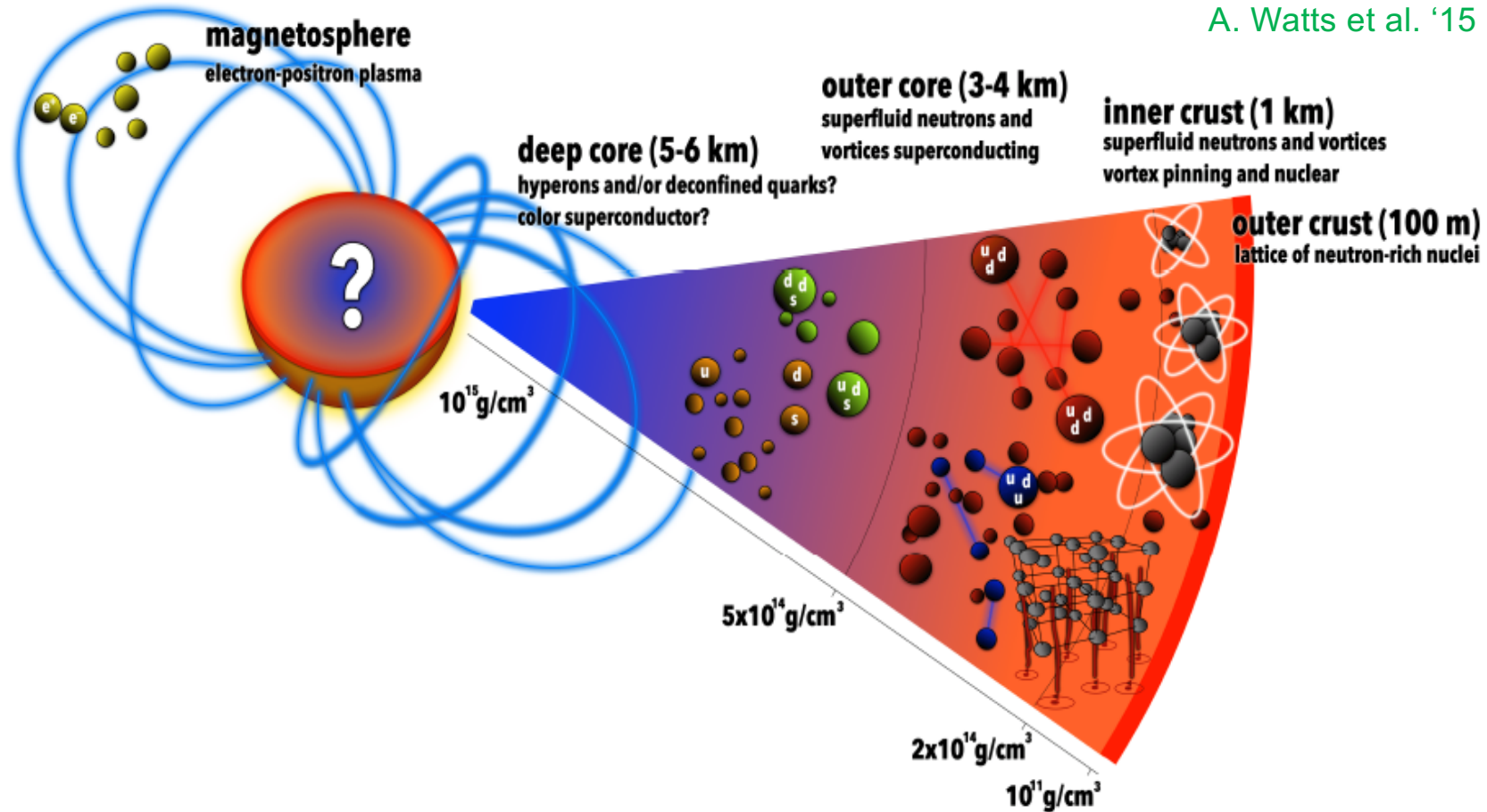2×10^{14} g/cm^3

10^{11} g/cm^3

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).
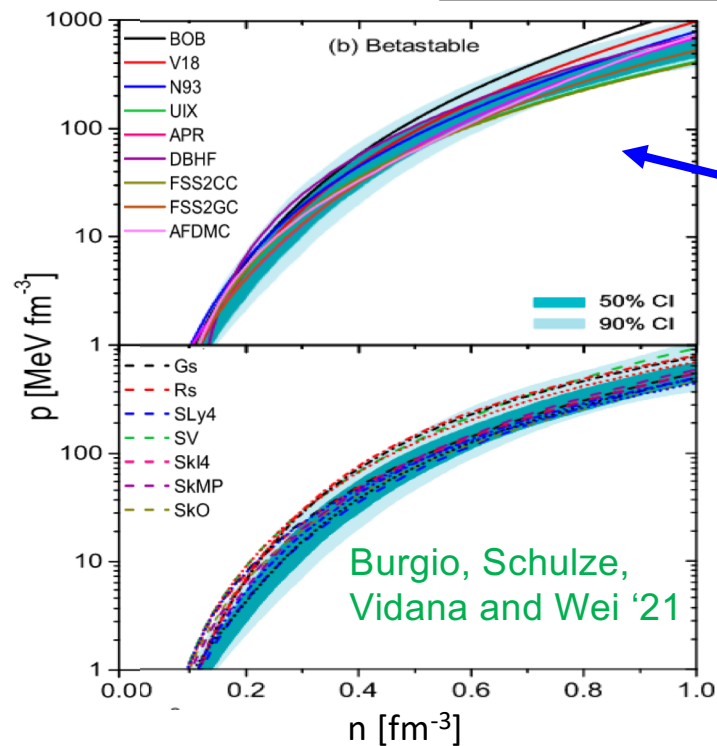
The Inner Core

credit: F. Weber
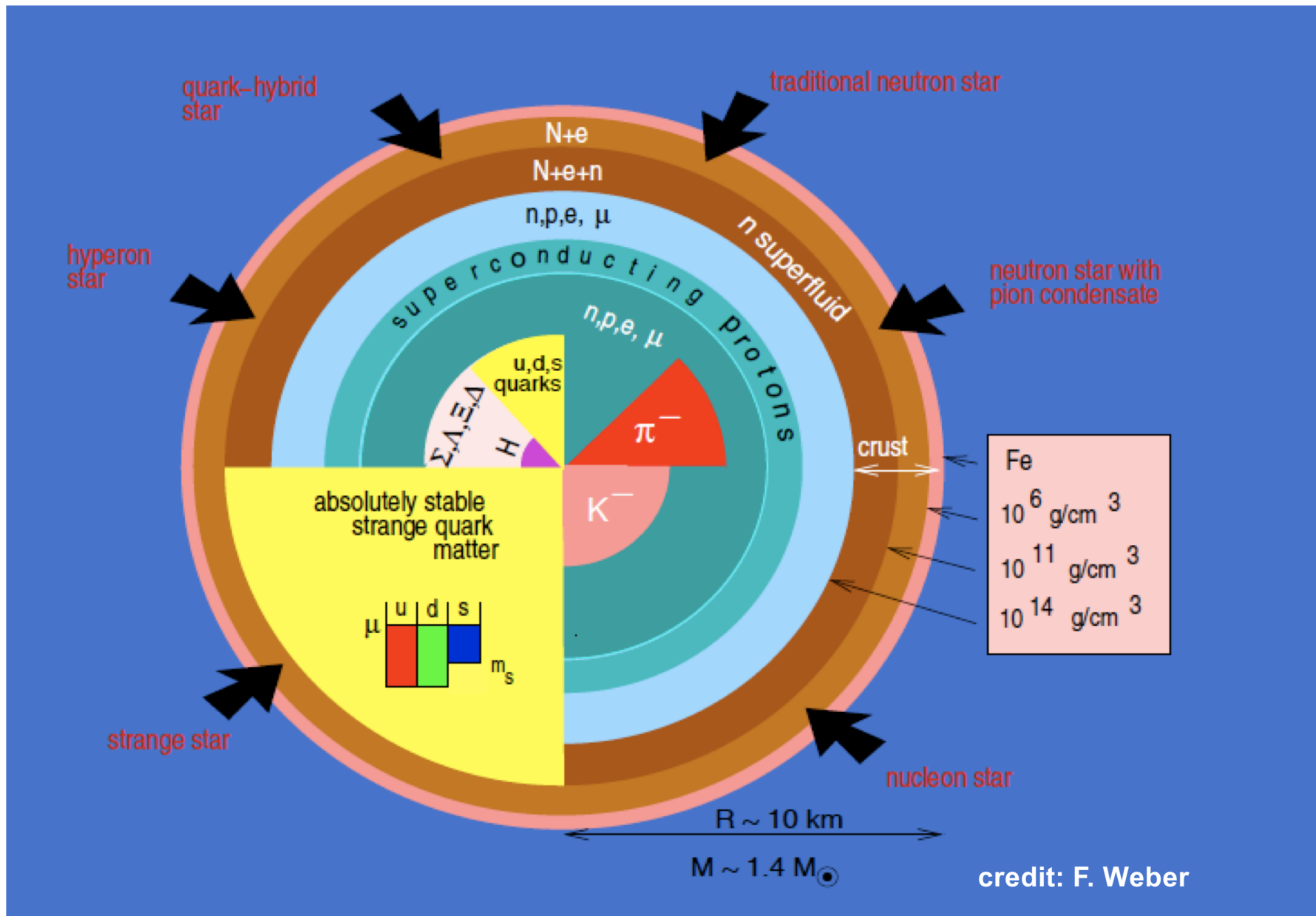
Strange Baryons in the Inner Core

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

credit: F. Weber

Mass-Radius

credit: D. Page

EoS

Burgio, Schulze, Vidana and Wei '21
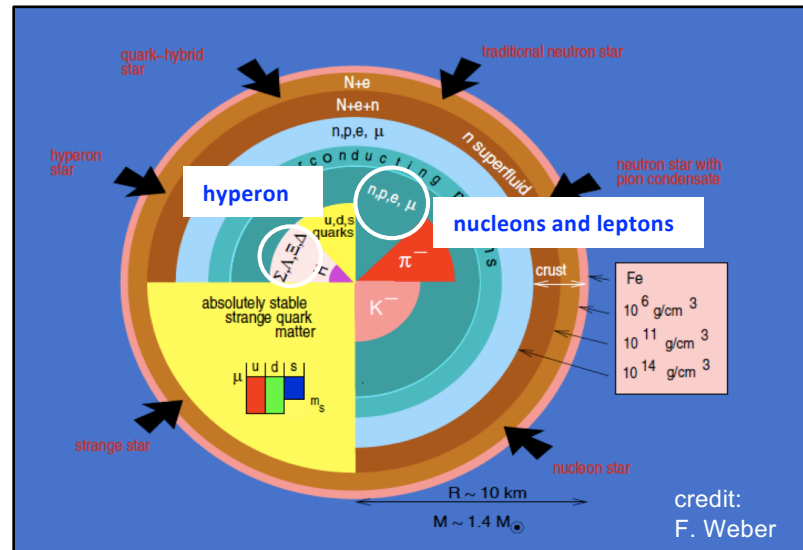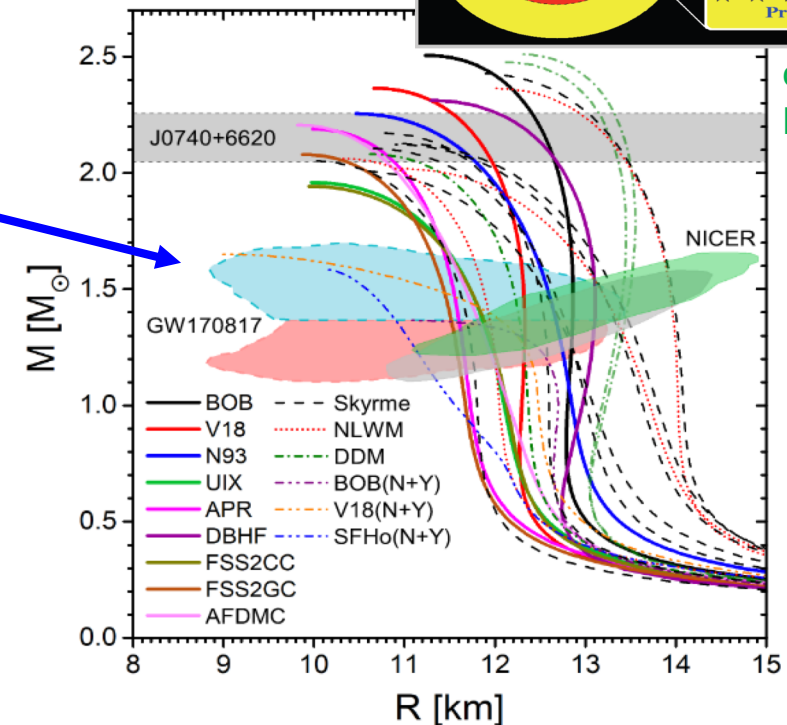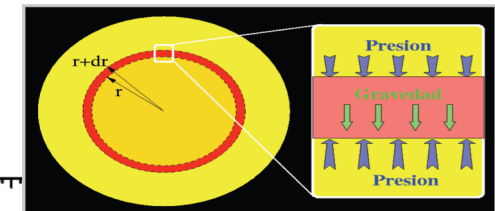
Nucleons and Leptons in the Inner Core

Neutrons, protons and electrons are in β-equilibrium

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

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

This equilibrium can be expressed in terms of the chemical potentials. Since the mean free path of the ν_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

First proposed in 1960 by Ambartsumyan & Saakyan

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

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

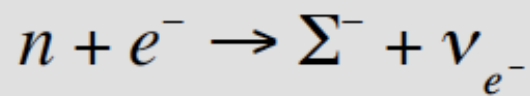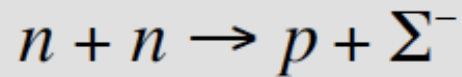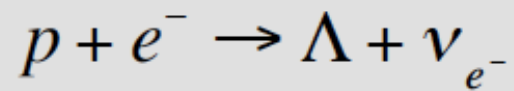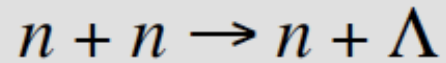$$n \rightarrow p \, e^- \, \bar{\nu}_e$$

$$p \, e^- \rightarrow n \, \nu_e$$
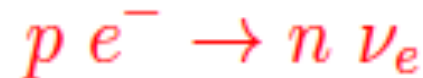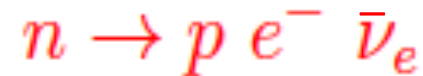
but more exotic degrees of freedom might be expected, such as hyperons, due to:
• high value of density at the center and
• the rapid increase of the nucleon chemical potential with density
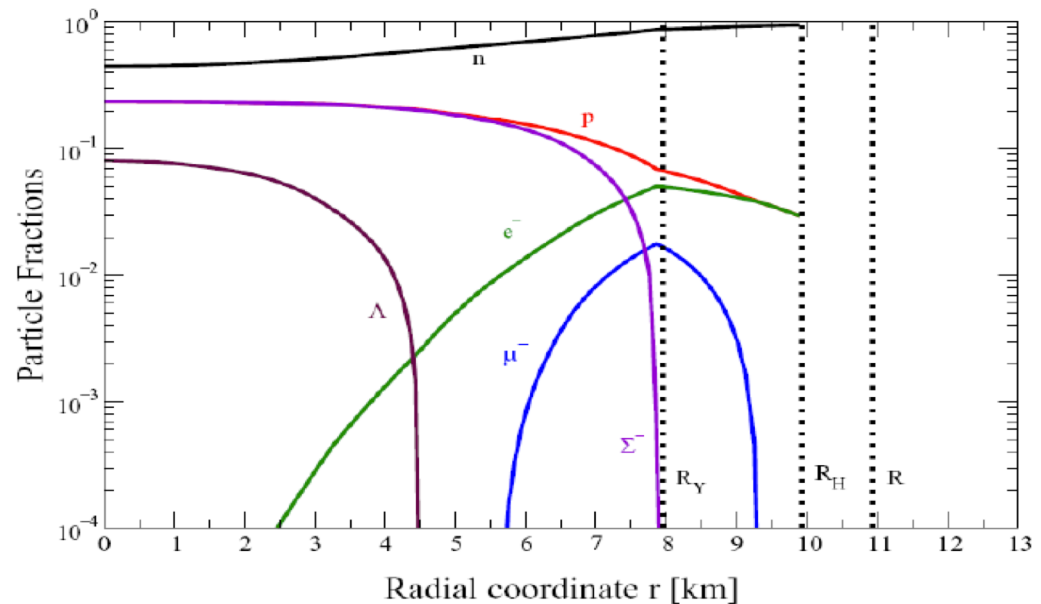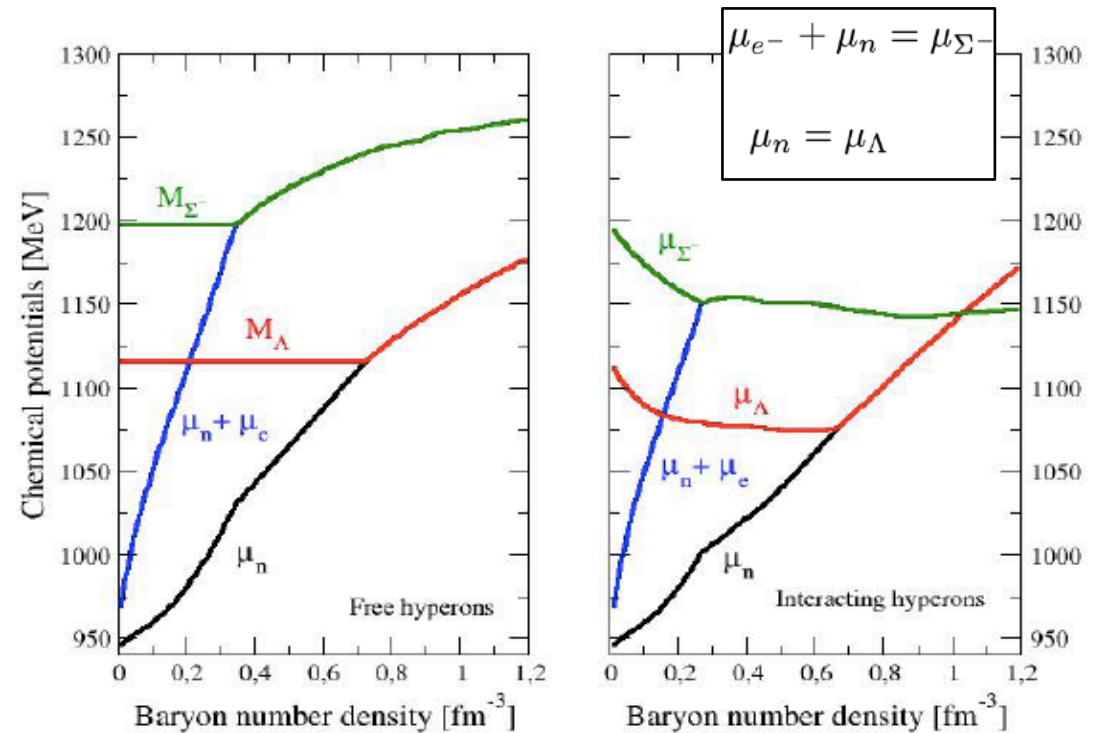
Hyperons might present at n~(2-3)n$_0$!!!

β-stable hyperonic matter

μ_N is large enough to make N->Y favorable

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

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

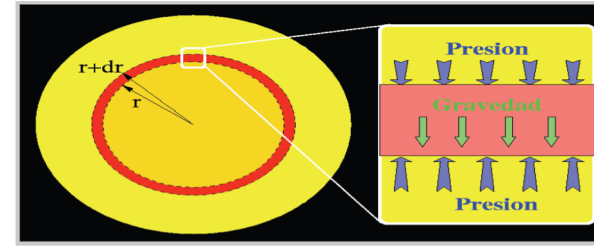$$n + n \rightarrow p + \Sigma^-$$

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

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

$$\sum_i x_i q_i = 0$$

credit: I. Vidana

Inclusion of hyperons....

credit: D. Page

softening of the EoS by the presence of hyperons

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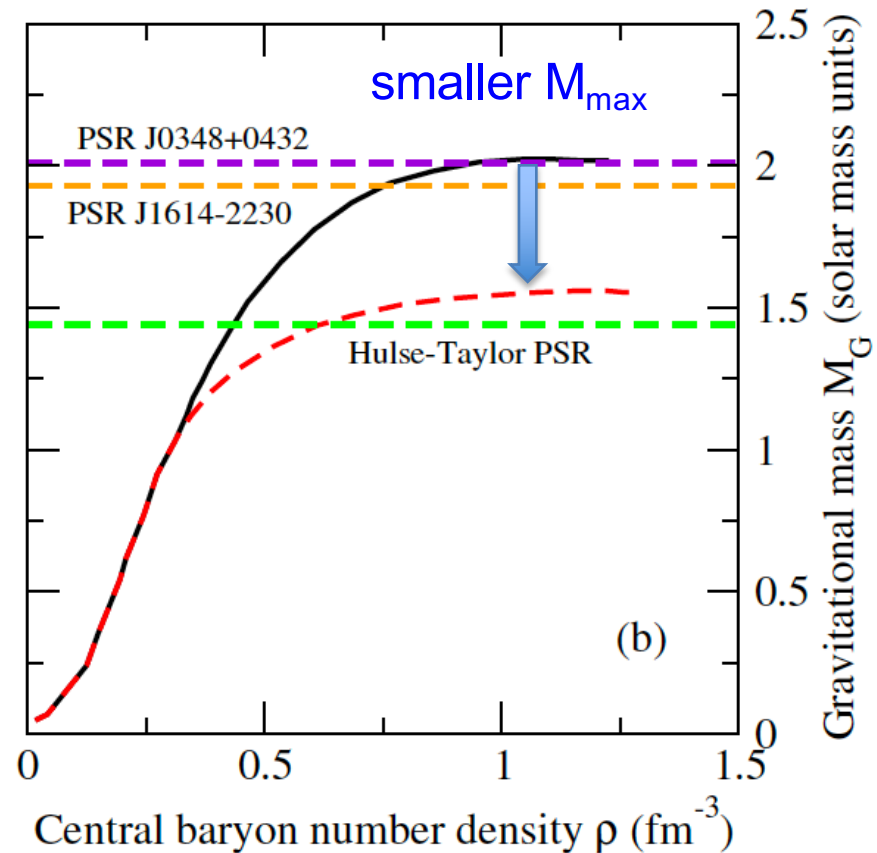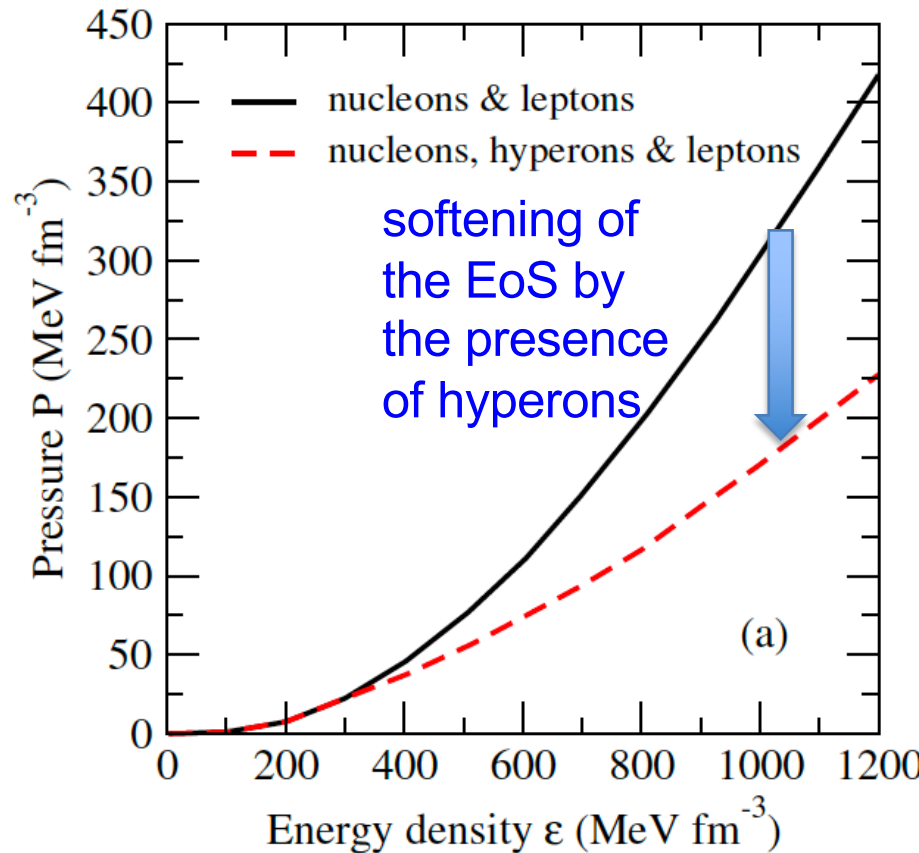
...... induces a strong softening of the EoS that leads to $M_{max} < 2M_\odot$

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

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;
more recently, ΛNN from χ EFT gives enough
repulsion to have Λ in $2M_\odot$ Logoteta et al '19
whereas Λ are unfavoured in NS Gerstung et al '20

Logoteta et al '19
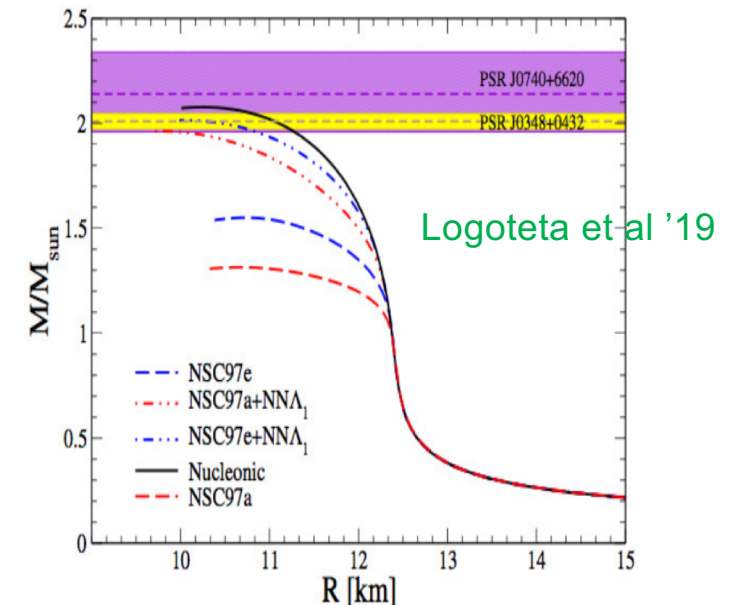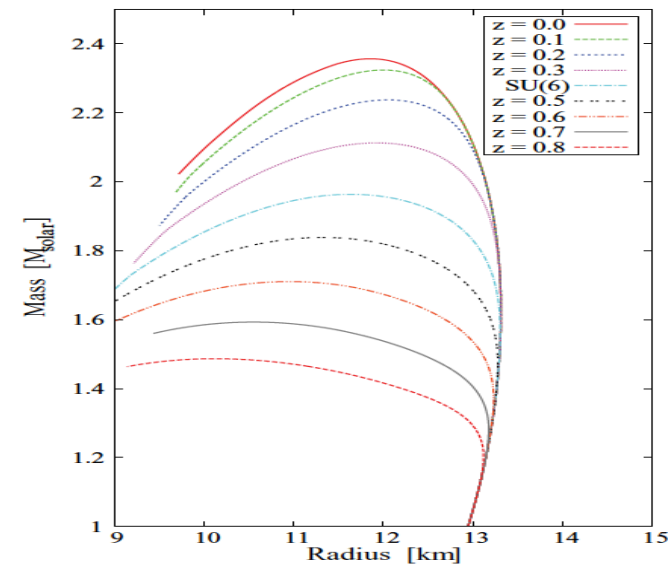
Solutions to the Hyperon Puzzle

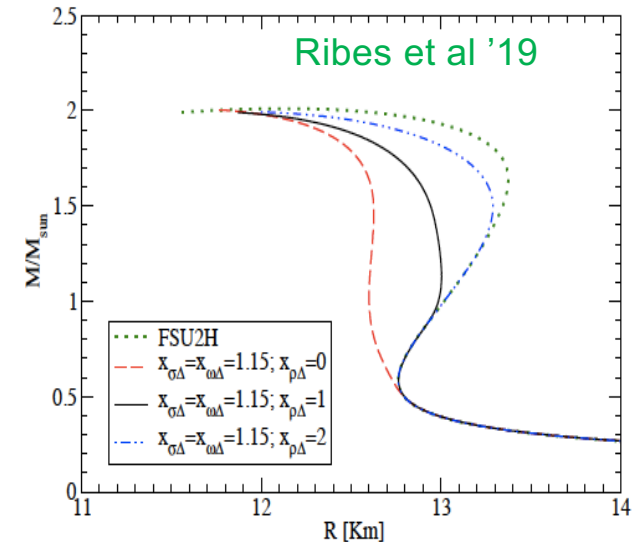## III. Push of Y onset by Δ-isobars or meson condensates

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..

Ribes et al '19

FSU2H
$x_{\sigma\Delta}=x_{\omega\Delta}=1.15; x_{\rho\Delta}=0$
$x_{\sigma\Delta}=x_{\omega\Delta}=1.15; x_{\rho\Delta}=1$
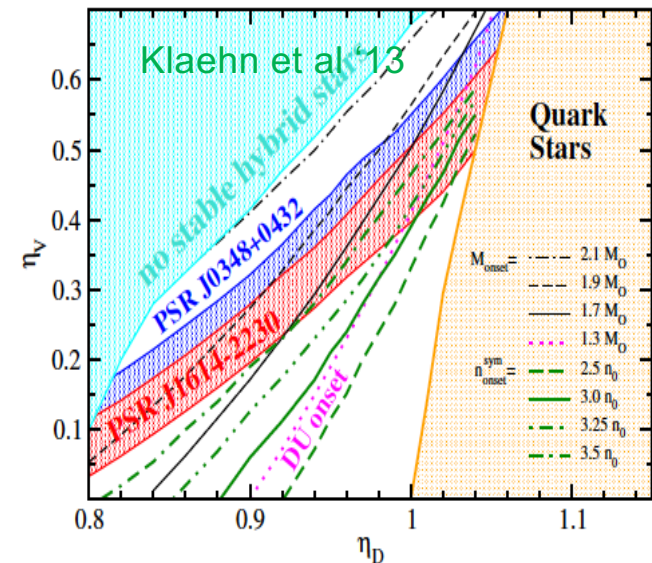$x_{\sigma\Delta}=x_{\omega\Delta}=1.15; x_{\rho\Delta}=2$

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;
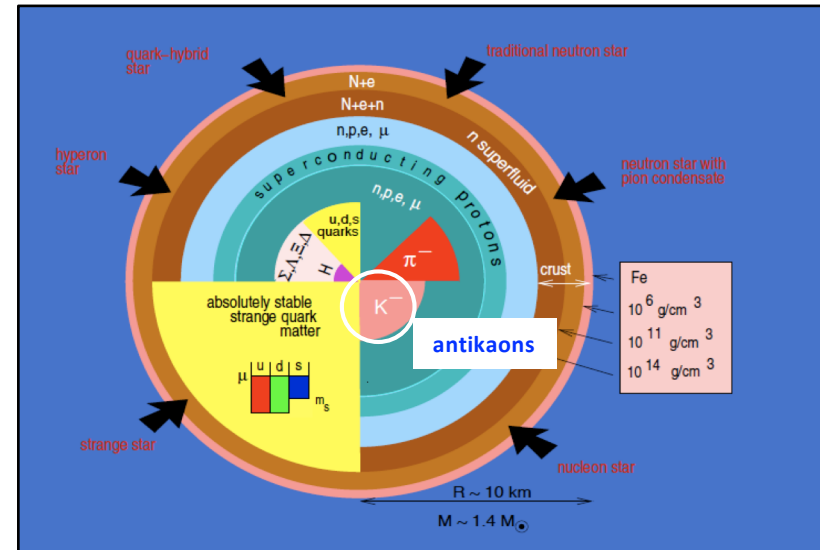Bonanno et al '12; Lastowiecki et al '12, Zdunik and Haensel '12..

V. Others: modified gravity, dark matter..

Klaehn et al '13

no stable hybrid star

PSR J0348+0432

PSR J1614-2230

DU onset

Quark Stars

$M_{onset}=$
2.1 $M_\odot$
1.9 $M_\odot$
1.7 $M_\odot$
1.3 $M_\odot$
$n_{onset}^{sym}=$
2.5 n_0
3.0 n_0
3.25 n_0
3.5 n_0

Strange Mesons in the Inner Core

Kaon condensation in neutron stars

Kaplan and Nelson '86
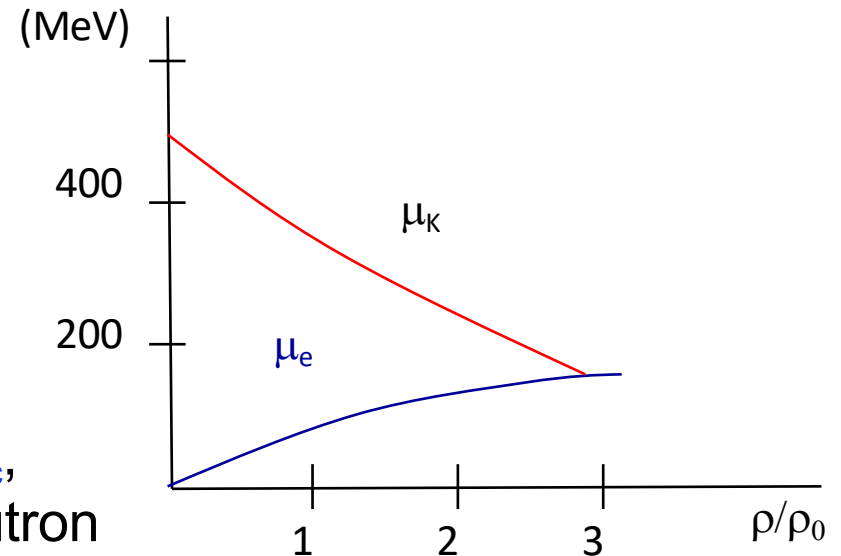Brown and Bethe '94

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
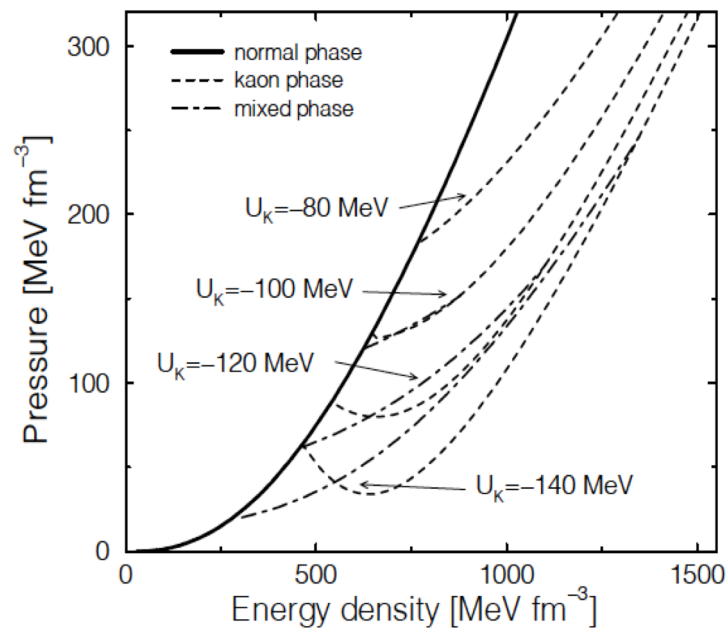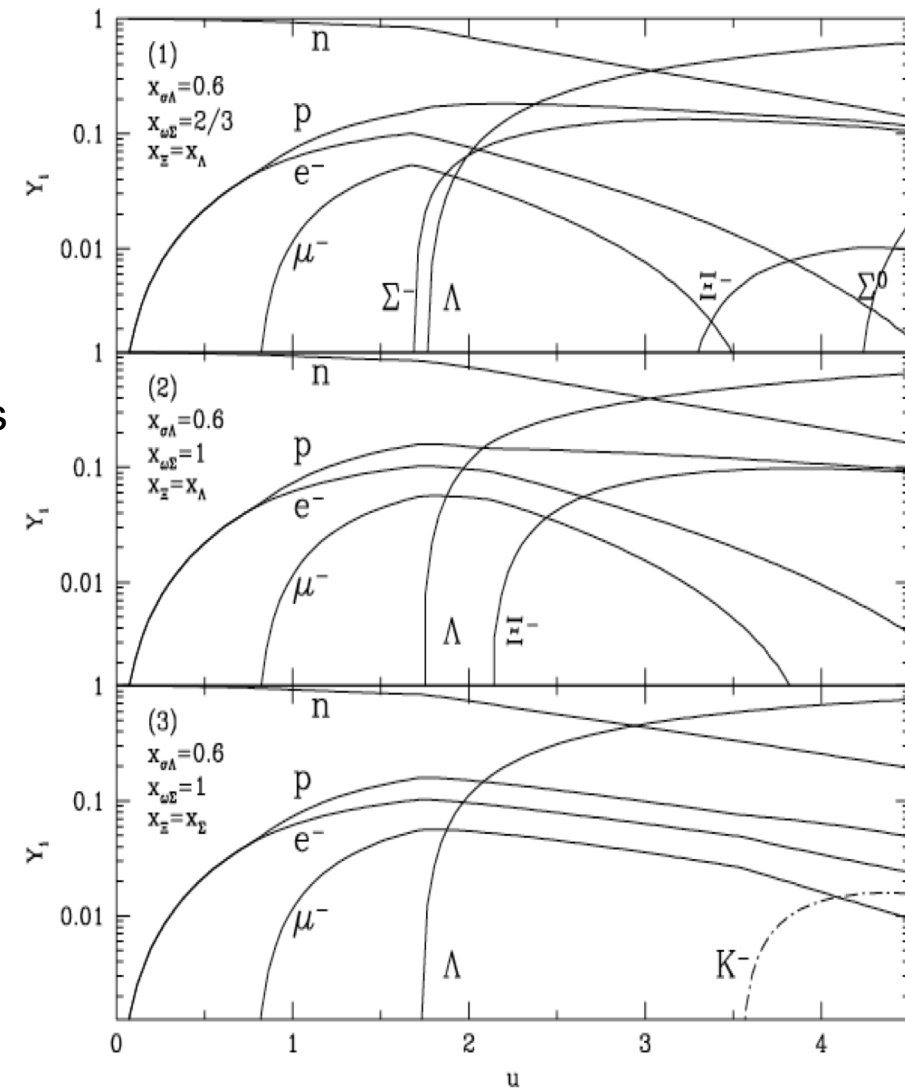

EoS is softened
due to kaon condensation
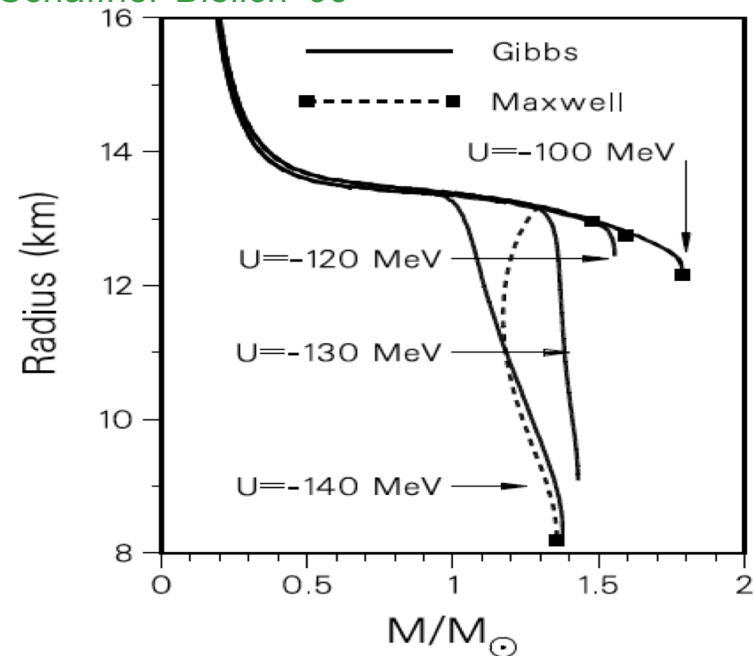
The maximum mass is lowered with
increasing attractive K⁻N potential

Hyperonization on kaon condensation

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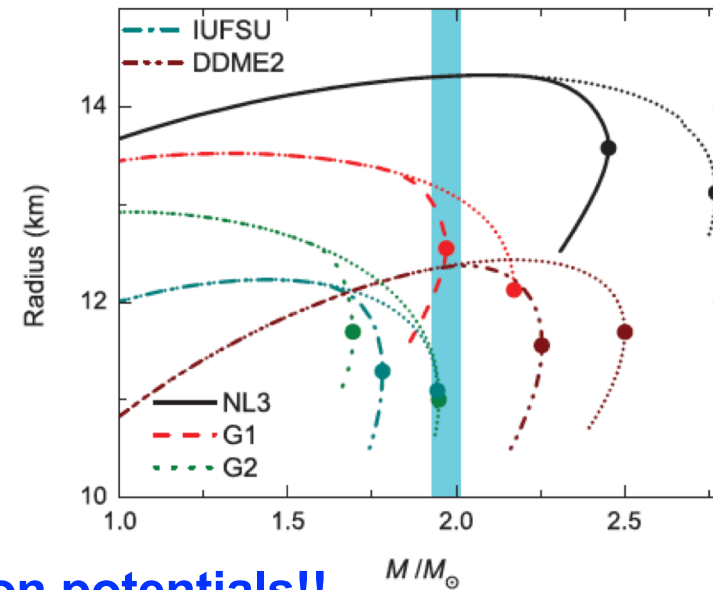

Later on different groups have worked on **improved relativistic-mean field models** to include kaon condensation and to fulfill neutron star properties and to study proto-neutron stars, supernova or neutron star mergers

Banik and Bandyopadhyay '01 '02
Char and Banik '14
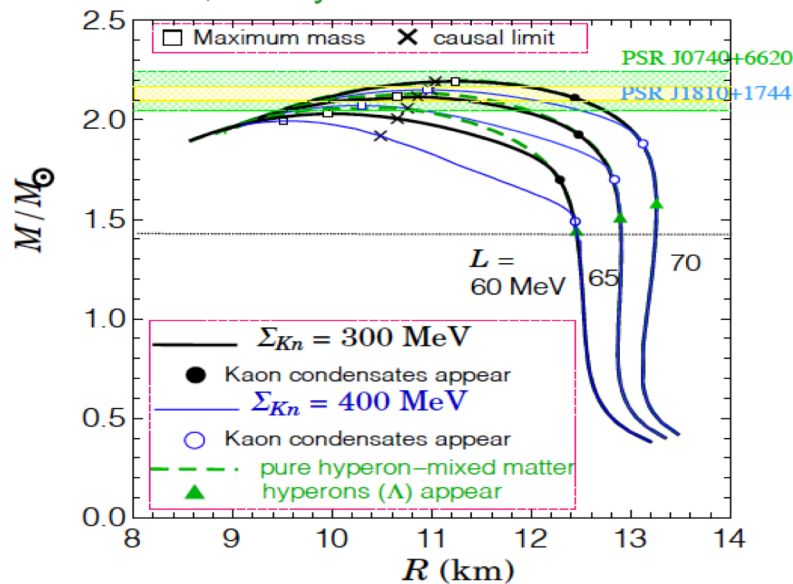Malik, Banik and Bandyopadhyay '20 '21
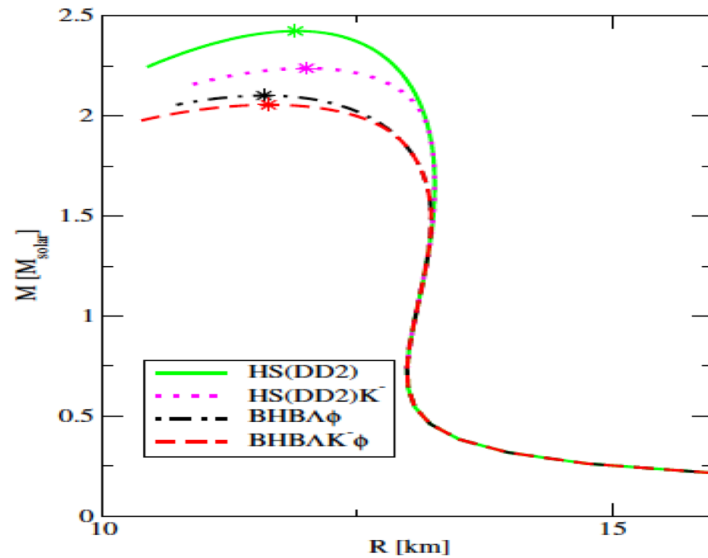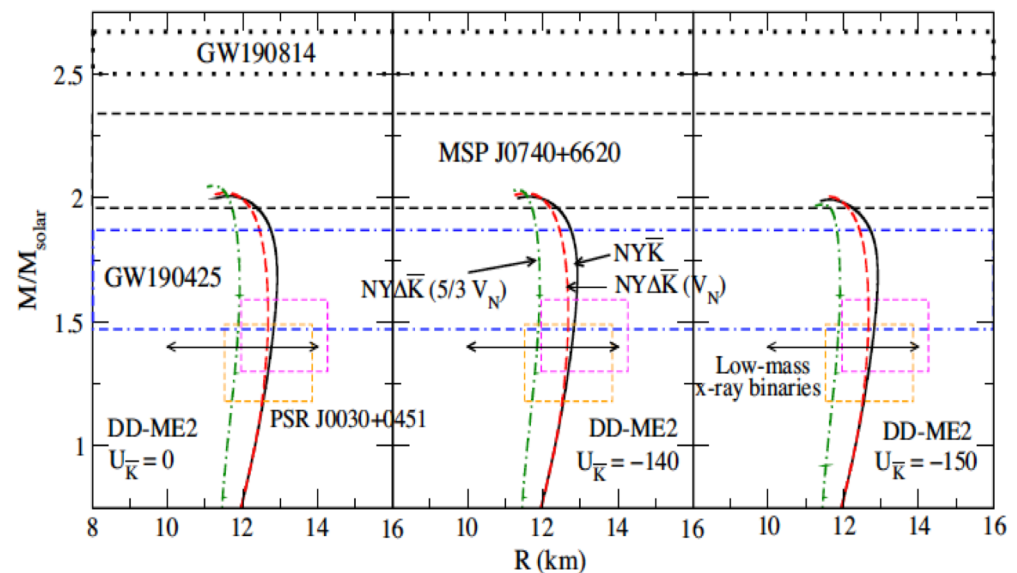
RMF models

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.

$$T_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

Tolos and Fabbietti '20

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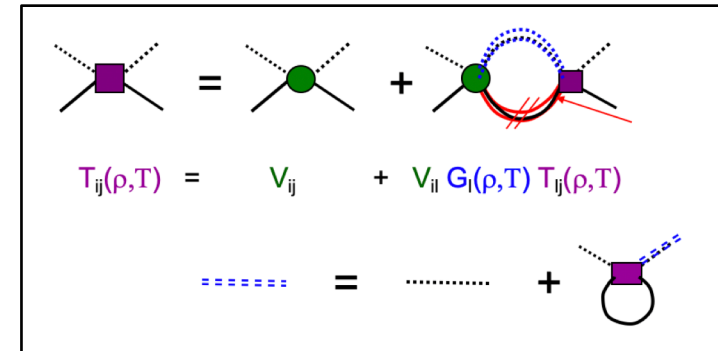chiral Lagrangians predict
a moderate attraction in nuclear matter

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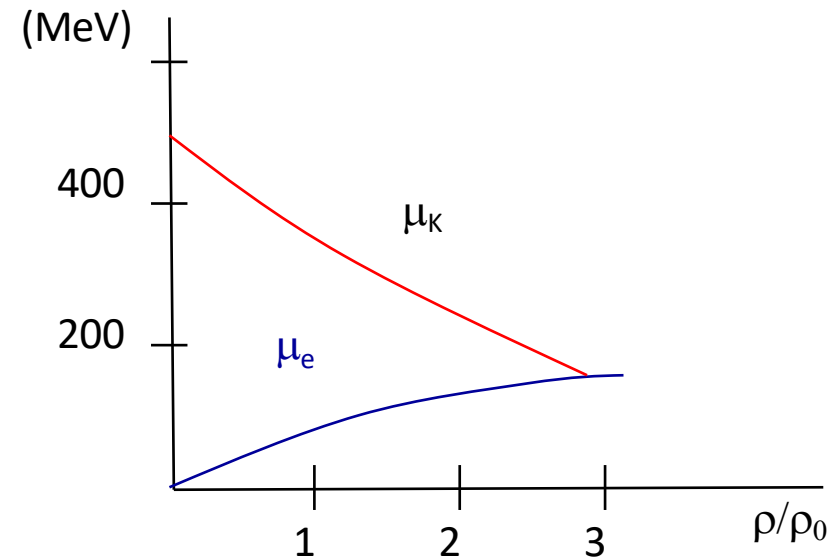Ramos and Oset '00
Tolos, Polls, Ramos '01
Tolos, Ramos and Oset '06
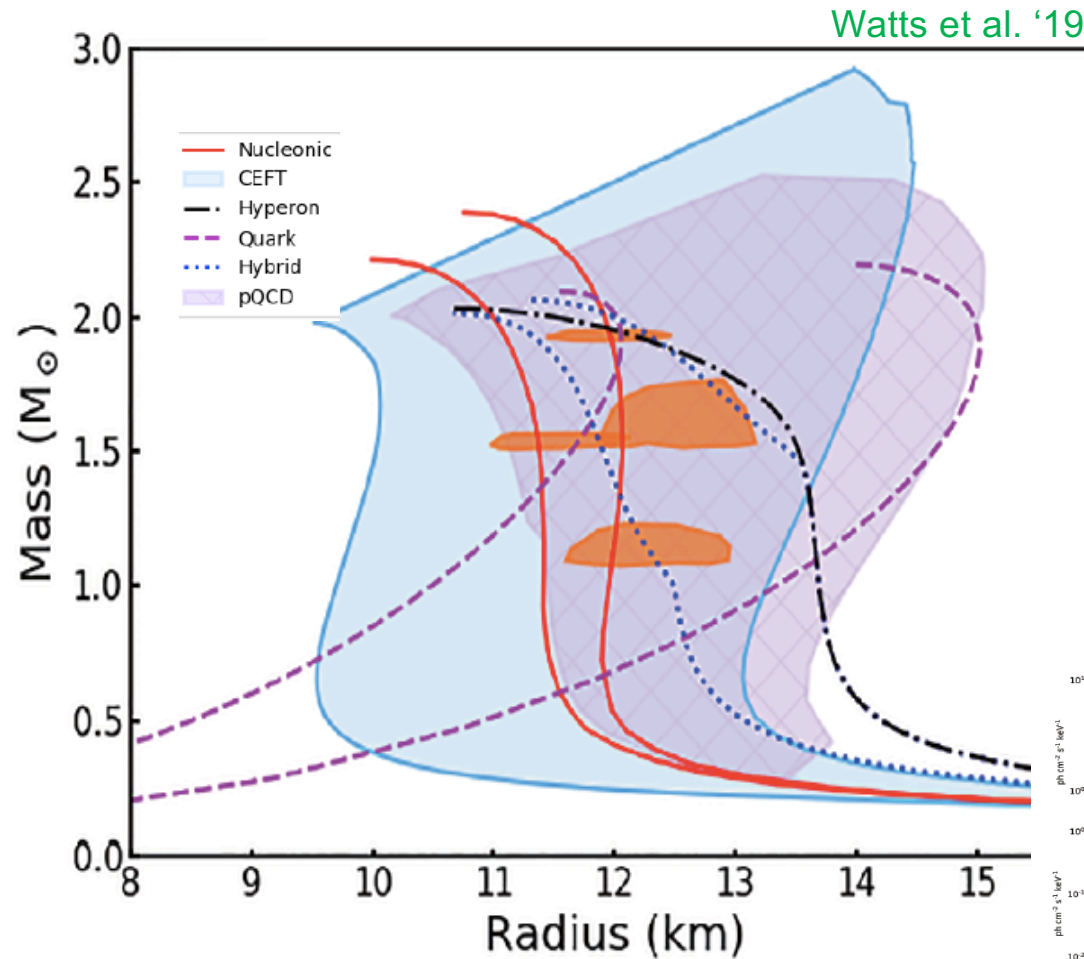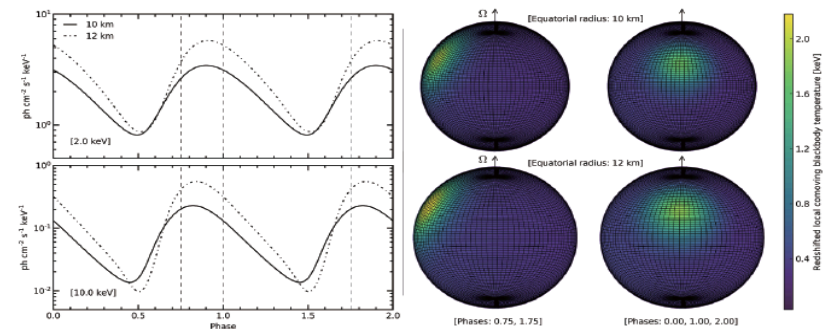Tolos, Cabrera and Ramos '08
Cabrera, Tolos, Aichelin and Bratkovskaya'14…

(MeV)

400

200

μ_K

μ_e

1   2   3 ρ/ρ_0

Kaon condensation seems very unlikely!

Space missions to study NS

Watts et al. '19

NICER/NASA

STROBE-X

eXTP
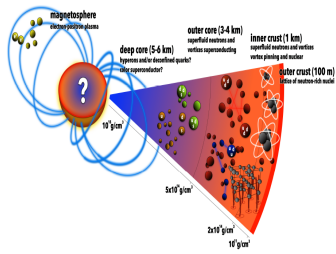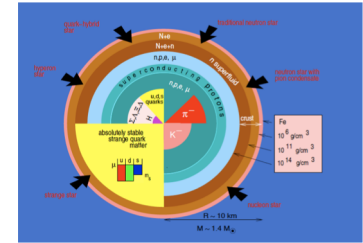enhanced X-ray Timing and Polarimetry Mission
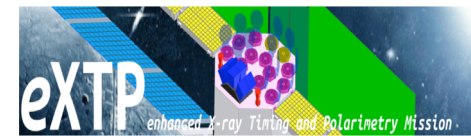
Constraints from pulse profile modelling of
rotation-powered pulsars with eXTP

and multimessenger astronomy!

Present and Future

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

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

Present and future:
NICER, eXTP, STROBE-X…
and GW observations
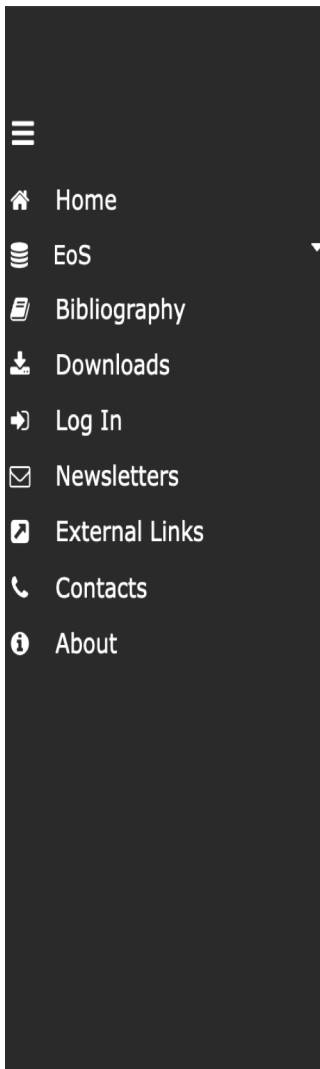
CompOSE

CompStar Online Supernovæ Equations of State

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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