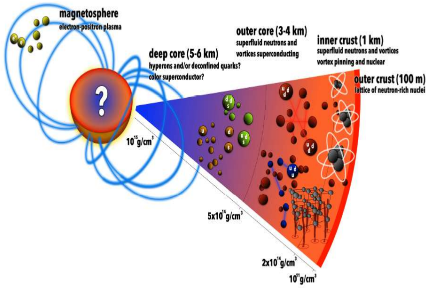

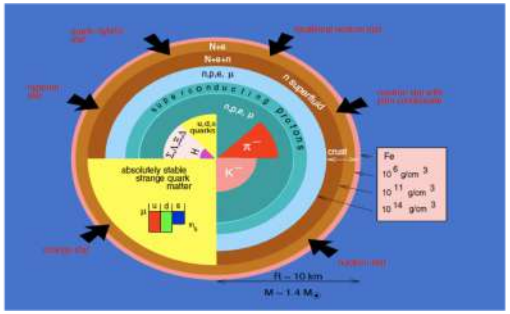

Dense Hadronic Matter in Neutron Stars

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FIAS Frankfurt Institute for Advanced Studies

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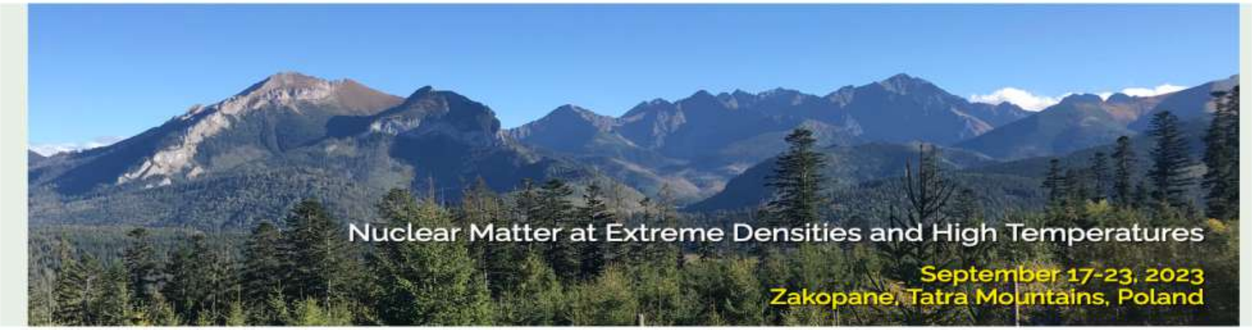

Outline

- What is a Neutron Star?
- The Structure of Neutron Stars..
  ..The Inner Core
- Nucleons
- Strange Baryons - Hyperons
- Strange Mesons - Antikaons
- Present and Future

Outline

- **What is a Neutron Star?**
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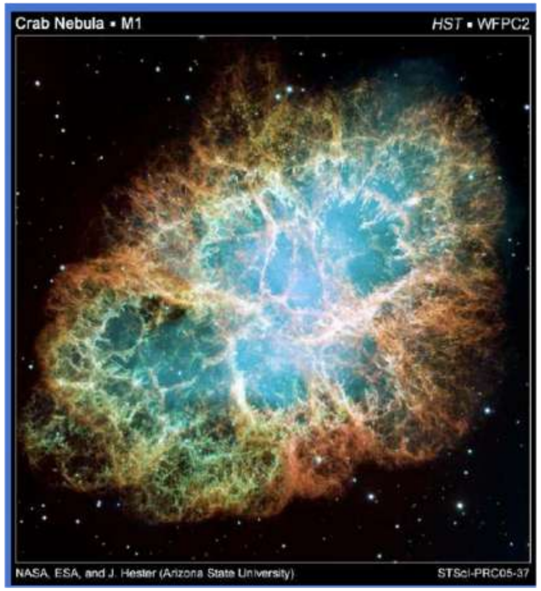
- Strange Mesons - Antikaons
- Present and Future

What is a Neutron Star?



Stellar compact remnant from gravitational collapse of a massive star ($8\,M_\odot < M < 25\,M_\odot$) **in a supernova event,** observed as **pulsars**

Mass: $M \sim 1\text{-}2\,M_\odot$

Radius: $R \sim 10\text{-}12$ km

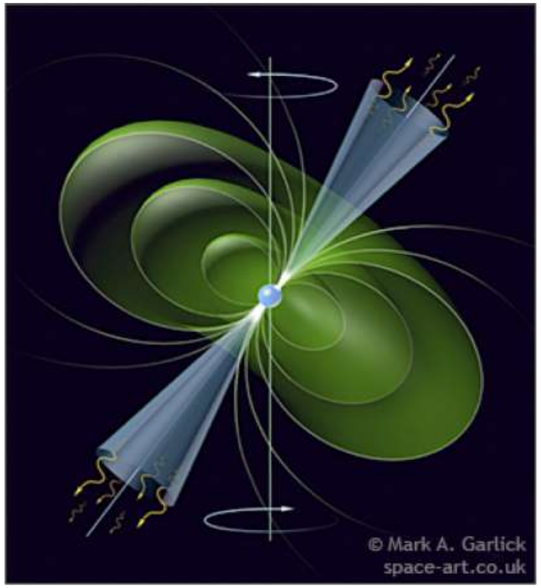
Density:

$n \sim 10^{14}\text{-}10^{15}$ g/cm^3

$n_{universe} \sim 10^{-30}$ g/cm^3

$n_{sun} \sim 1.4$ g/cm^3

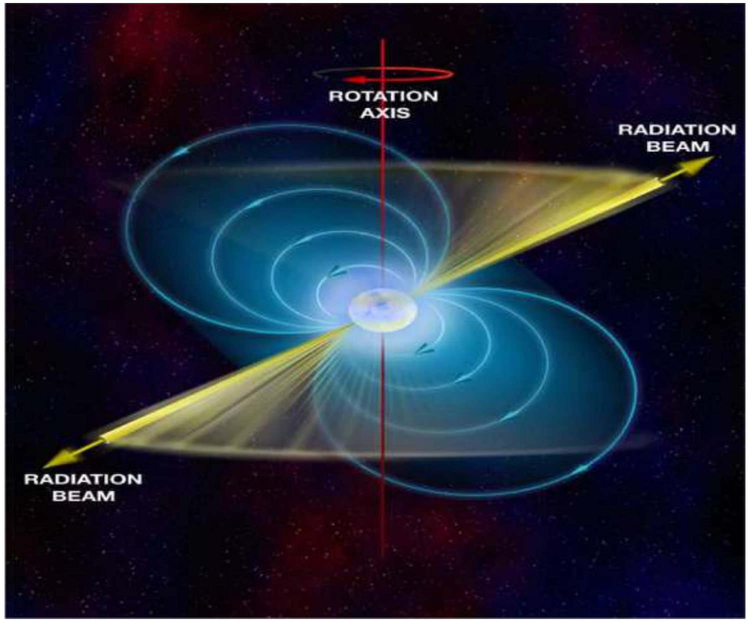
$n_{earth} \sim 5.5$ g/cm^3



Magnetic field: $B \sim 10^{8\ldots16}$ G ($10^{4\ldots12}$ T)

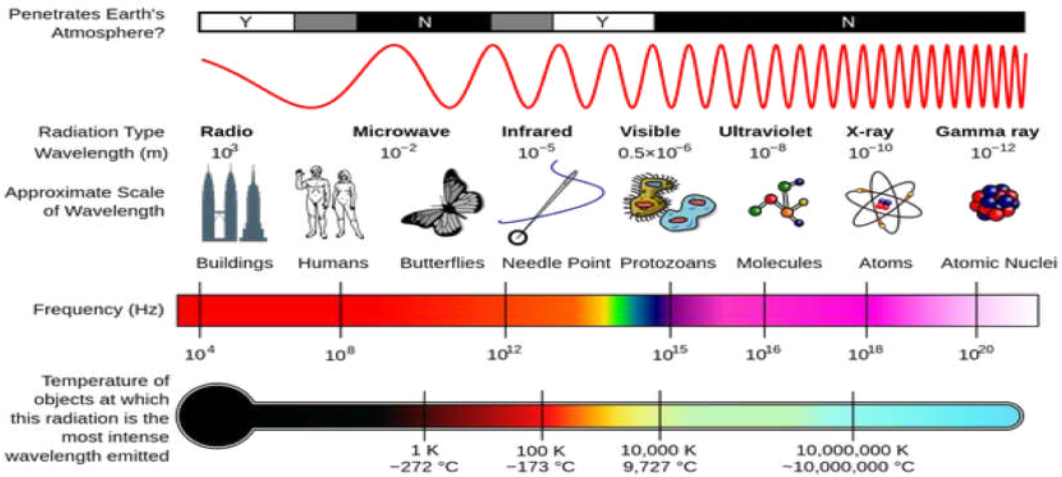
Temperature: $T \sim 10^{6\ldots11}$ K

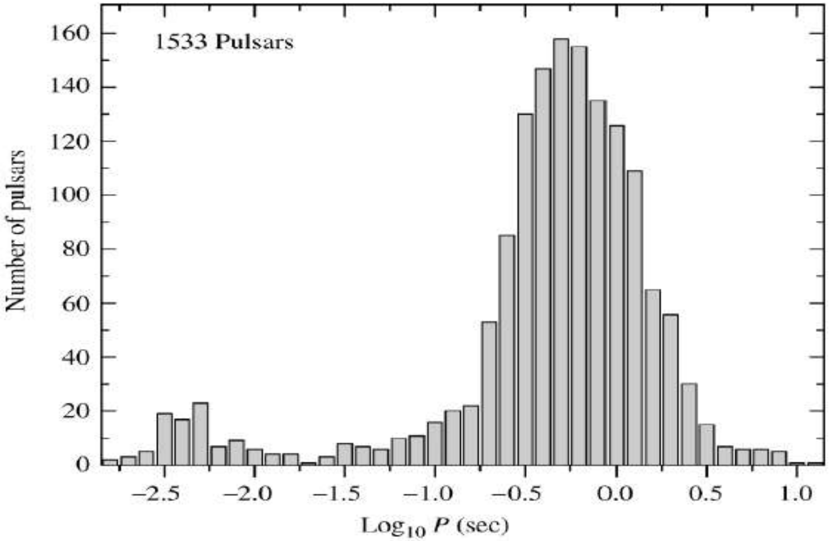
Rotational periods: P ~ ms … s



Pulsars are magnetized rotating neutron stars emitting a highly focused beam of electromagnetic radiation oriented long the magnetic axis. The misalignment between the magnetic axis and the spin axis leads to the lighthouse effect

Since 1967, ~ 2500 pulsars have been discovered.
http://www.atnf.csiro.au/research/pulsar/psrcat/





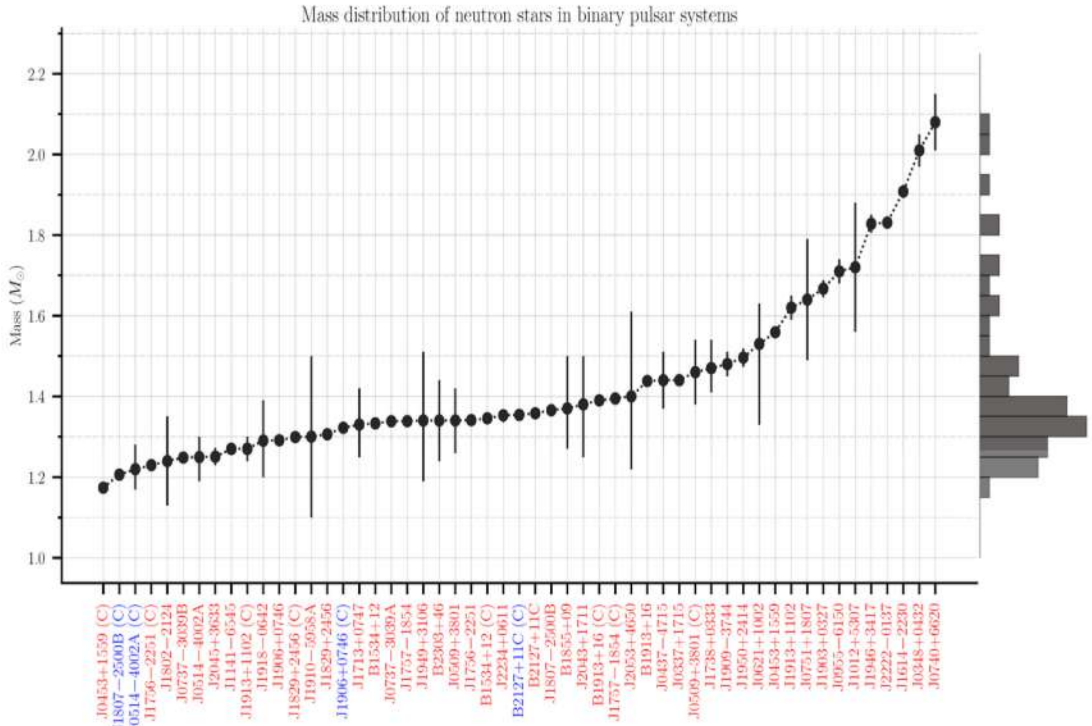
Mostly detected as radio pulsars, but also observed in X-rays and an increasingly large number detected in gamma rays.

Their period P ranges from 1.396 ms for PSRJ1748−2446ad up to 8.5 s for PSR J2144−3933

Observations

Masses

credit: P. Freire



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

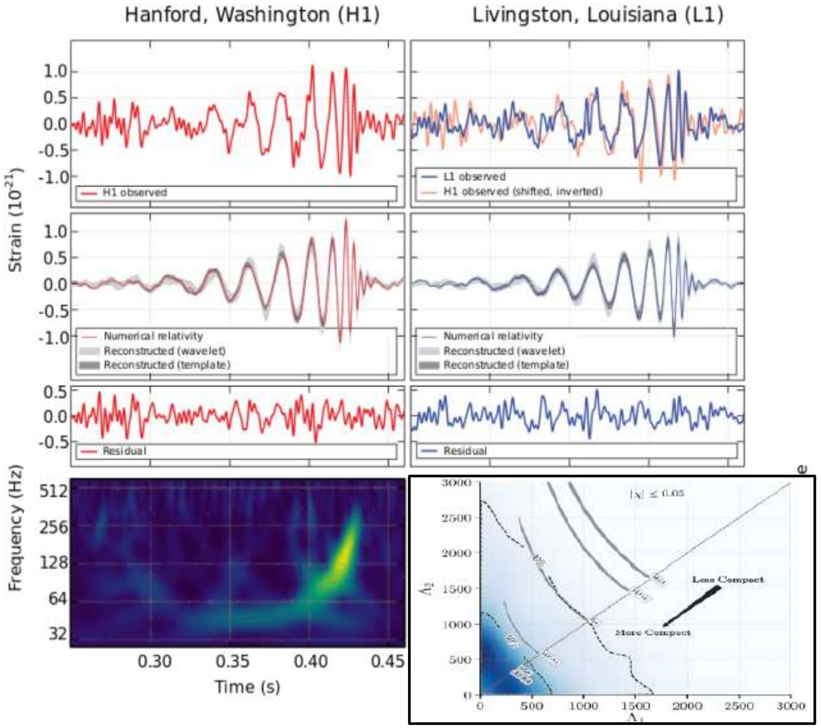
NICER
PSR J0740+6620

$R_{eq} = 13.71_{-1.5}^{+2.6}$ 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

GW170817

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

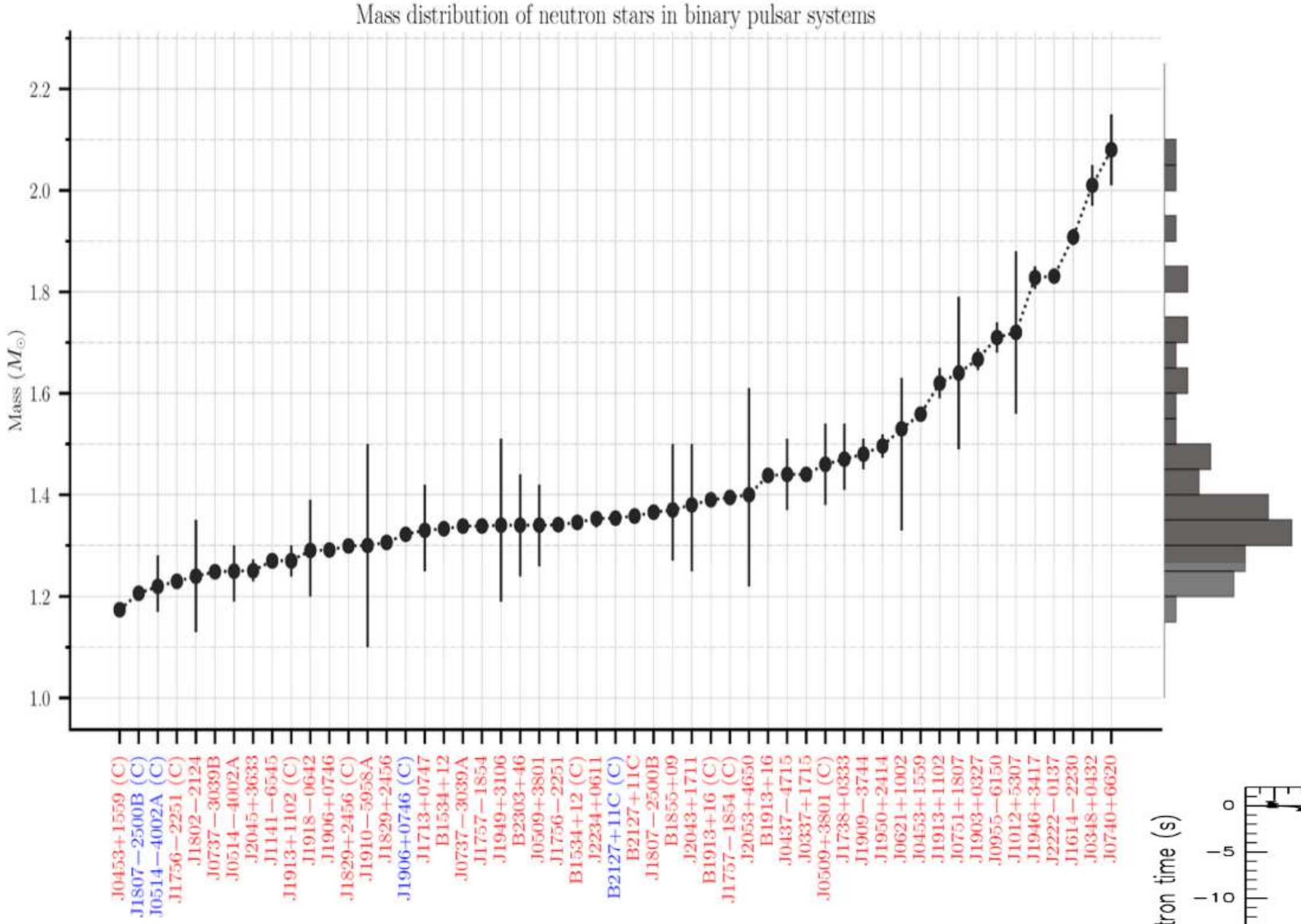


..also GW190425, GW190814

(see S. Bernuzzi lectures)

Observations: **Masses**

credit: P. Freire

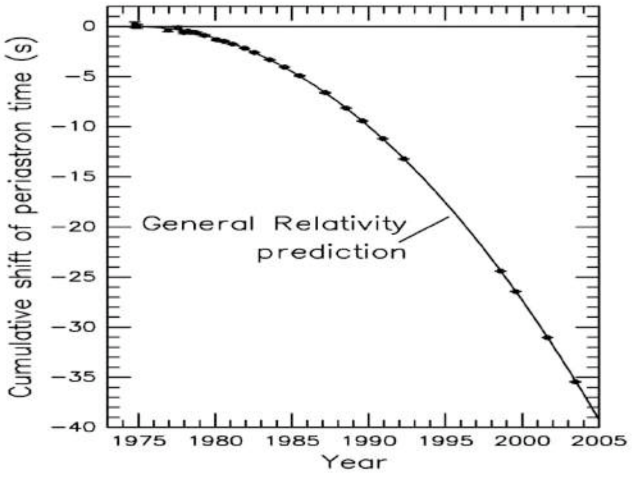


One of the best determined masses:

Hulse-Taylor pulsar

$M = 1.4414 \pm 0.0002\ M_\odot$

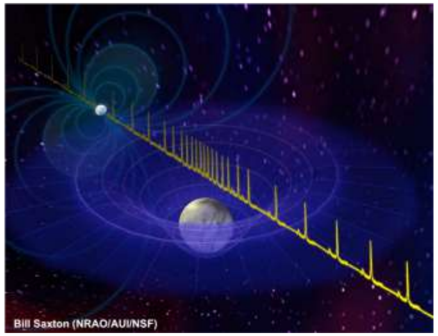
Hulse-Taylor Nobel Prize '94



Measurements of Neutron Stars with Large Masses

Since 2010 neutron stars with 2 $M_\odot$ have been observed by measuring Post-Keplerian parameters of their orbits:

- Advance of the periastron $\dot{\omega}$
- Shapiro delay (range *s* and shape *r*)
- Orbital decay $\dot{P}_b$
- Gravitational redshift and time dilation γ


Bill Saxton (NRAO/AUI/NSF)

PSR J1614-2230
Demorest et al. '10;
Arzoumanian et '15;
Fonseca et al. '16

$M=1.928 \pm 0.017\ M_\odot$

PSR J0348+0432
Antoniadis et al. '13

$M=(2.01 \pm 0.04)\ M_\odot$

MSP J0740+6620
Cromartie et al. '20
Fonseca et al. '21

$M=(2.08 \pm 0.07)\ M_\odot$

Observations: Radius

adapted from Fortin's talk @ NewCompstar Annual Meeting '16; Fortin, Zdunik, Haensel and Bejger '15

analysis of X-ray spectra from NS atmosphere

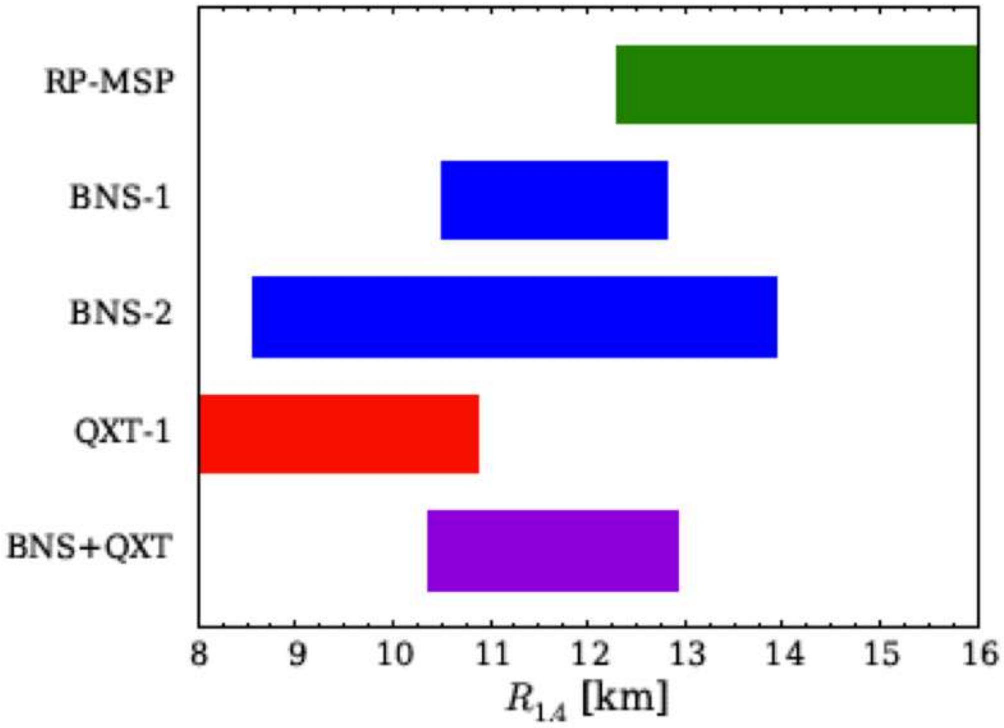
difficult task due to its size, its distance to the source, its magnetic field and the composition of its atmosphere

- RP-MSP: rotation-powered radio millisecond pulsars
- BNS: bursting NSs
- QXT: quiescent thermal emission of accreting NSs

theory + pulsar observations:
$R_{1.4M}$~11-13 Km Lattimer and Prakash '16

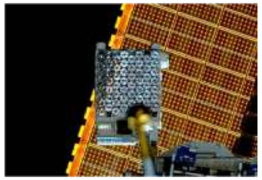
Fortin et al '15

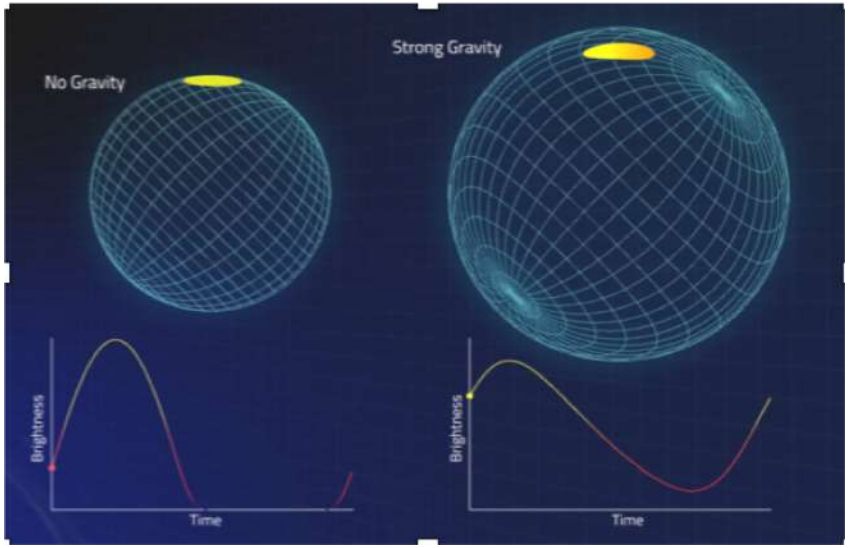
- RP-MSP: Bodganov '13
- BNS-1: Nattila et al '16
- BNS-2: Guver & Ozel '13
- QXT-1: Guillot & Rutledge '14
- BNS+QXT: Steiner et al '13



Conclusion????

NICER: Neutron Star Interior Composition Explorer





Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

To measure the NS radius by tracking the X-ray emission from hot spots on the star's surface as the star rotates.

M/R is extracted by modeling the pulse profile of the hot spots

PSR J0030+0451

$R_{eq} = 13.02_{-1.06}^{+1.24}$ km
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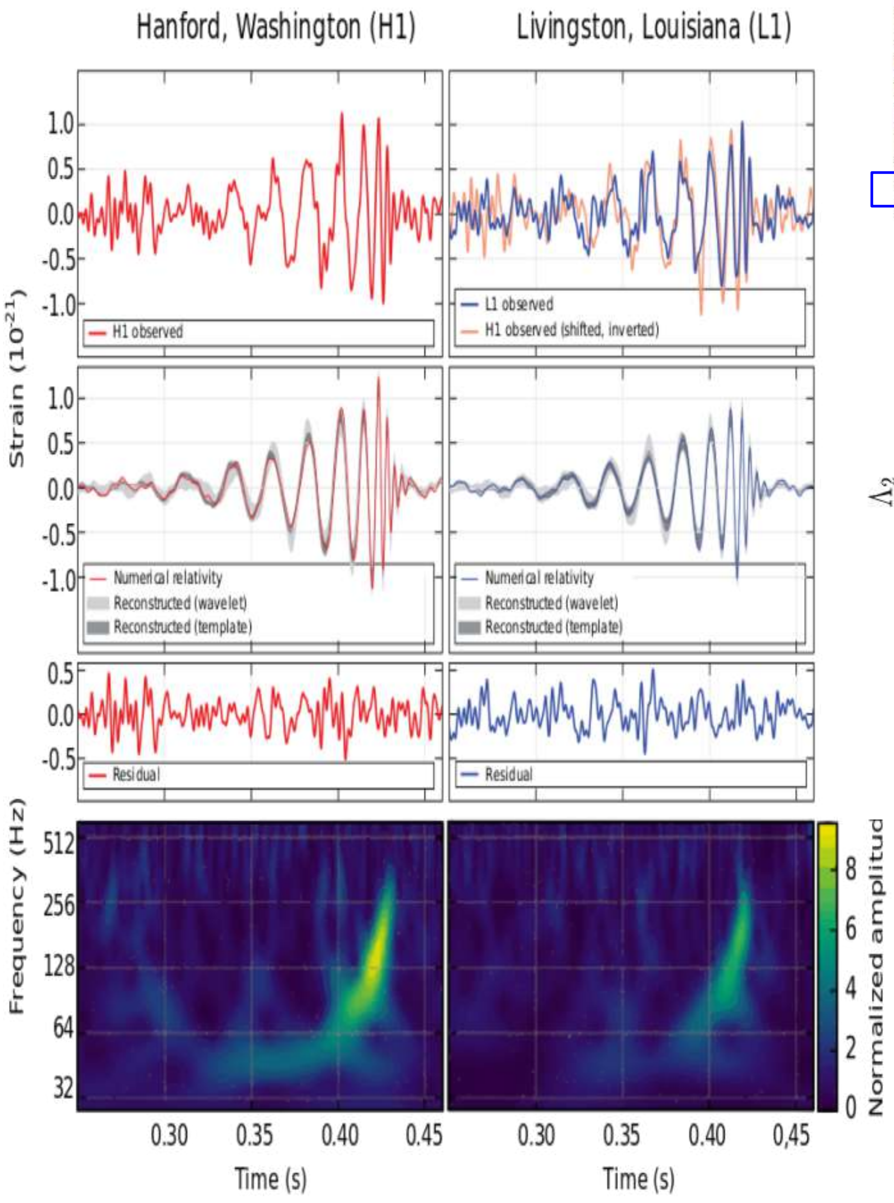
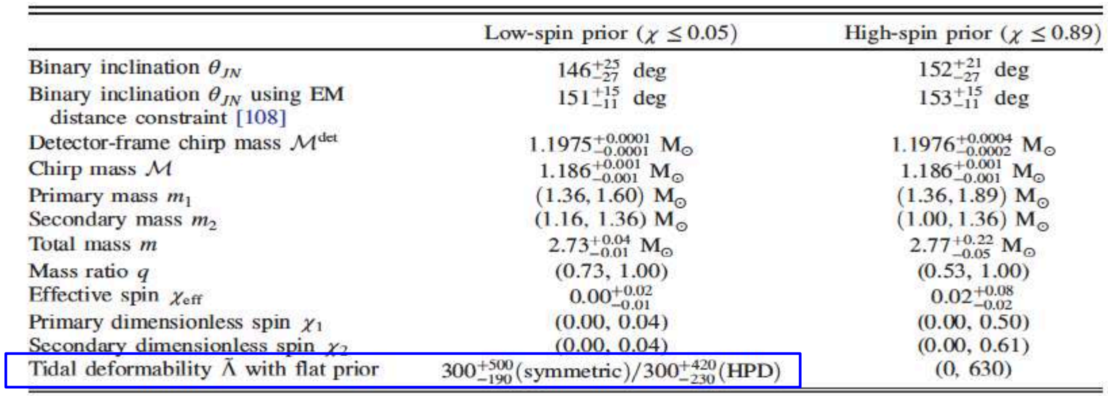
Observations:
GW170817

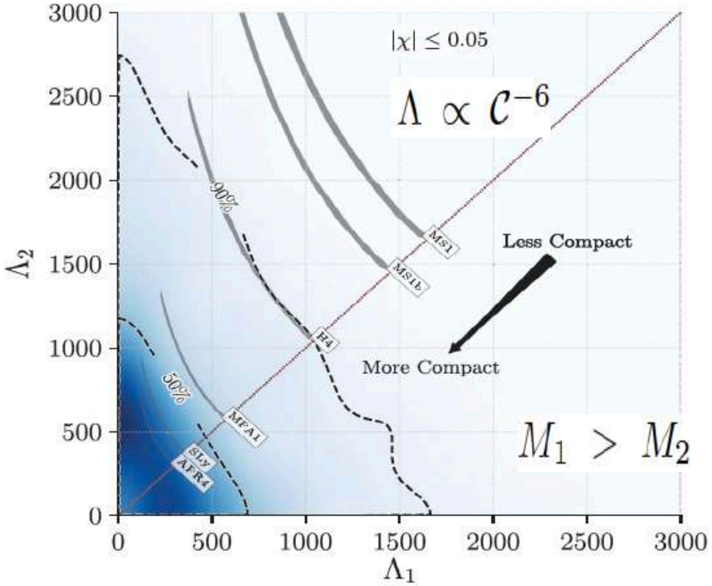


Abbot et al. (LIGO-VIRGO) '17

Abbot et al. (LIGO-VIRGO) '18



	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001}$ $M_\odot$	$1.1976^{+0.0004}_{-0.0002}$ $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$	$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$	(1.36, 1.89) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$	(1.00, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $M_\odot$	$2.77^{+0.22}_{-0.05}$ $M_\odot$
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	(0.00, 0.04)	(0.00, 0.50)
Secondary dimensionless spin χ_2	(0.00, 0.04)	(0.00, 0.61)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/300^{+420}_{-230}(HPD)	(0, 630)



$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

tidal deformability

$$k_2 = \frac{3}{2}\lambda R^{-5}$$

$$\Lambda = \frac{2k_2}{3C^5}\,;\, C = \frac{M}{R}$$

dimensionless tidal deformability

using tidal deformability sets constraints on

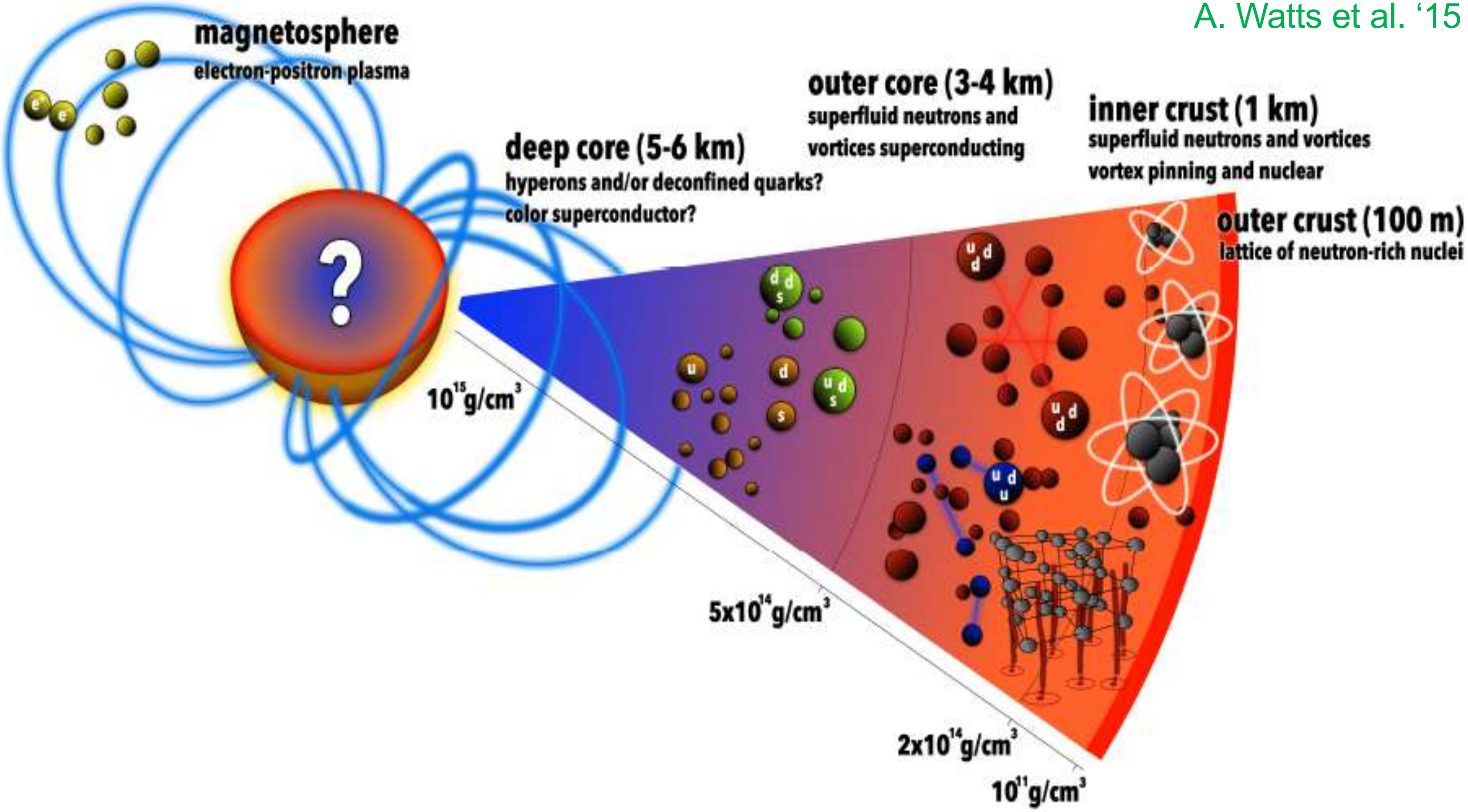
$M_{\rm max} \lesssim 2.2\ M_\odot$

Margalit and Metzger '17, Rezzolla, Most and Weih '18,..

9-10 Km $\lesssim R_{1.4M_\odot} \lesssim$ 13 Km

Annala et al '18, Kumar et al '18, Abbott et al '18, Fattoyev et al '18, Most et al '18, Lim et al '18, Raithel et al '18, Burgio et al '18, Tews et al '18, De et al '18, Abbott et al '18, Malik et al '18, ..

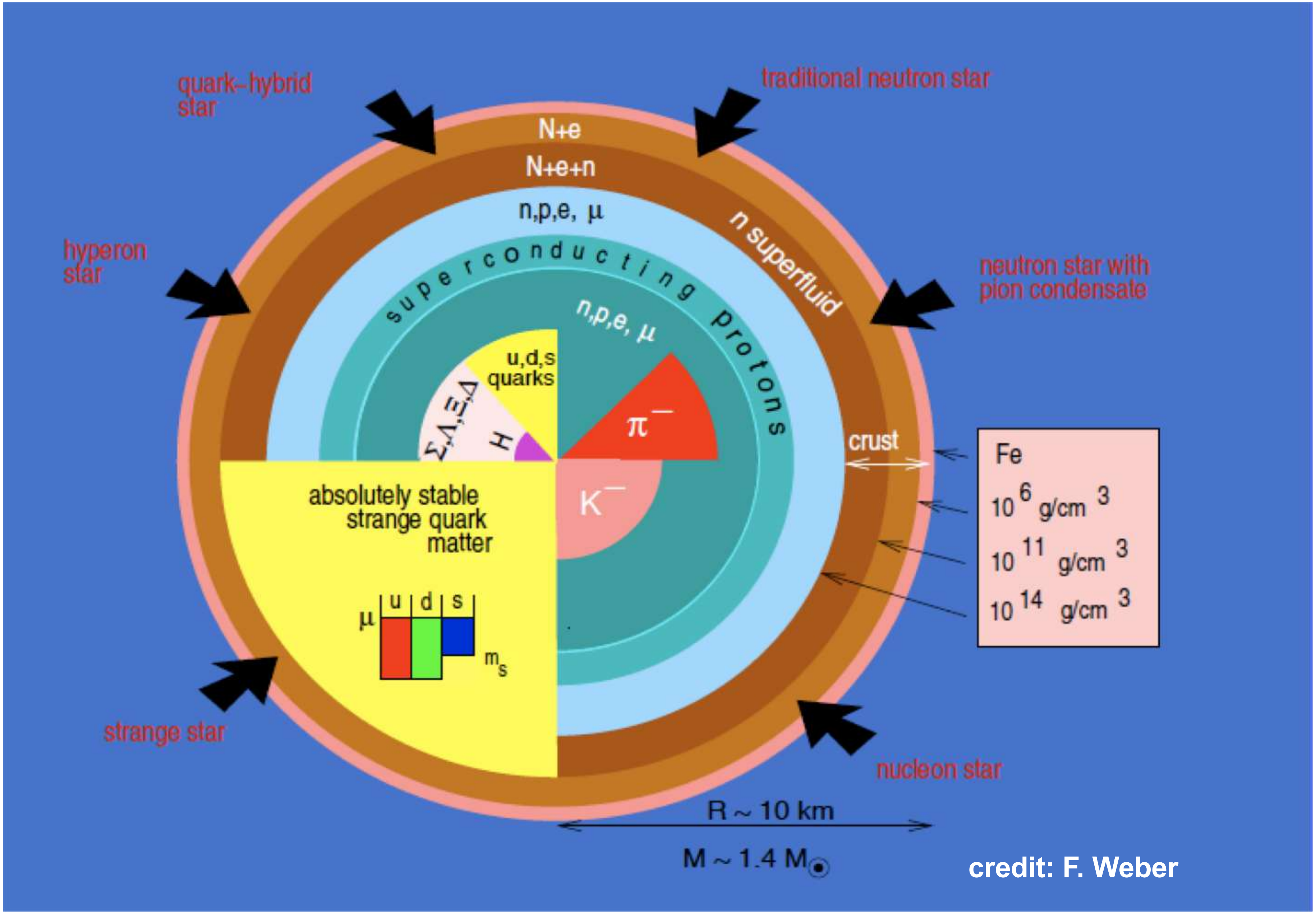
The Structure of Neutron Stars..



A. Watts et al. ‘15

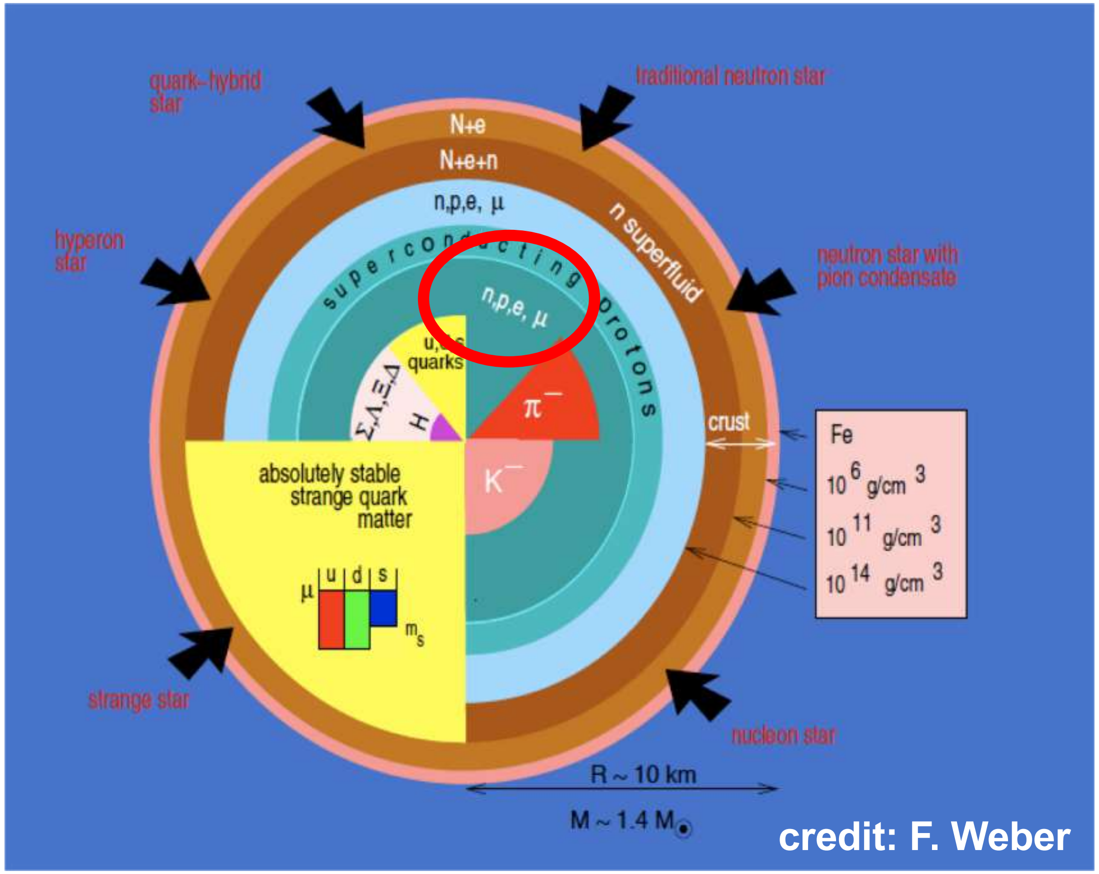
Figure 1: Schematic structure of a NS. The outer layer is a solid ionic crust supported by electron degeneracy pressure. Neutrons begin to leak out of nuclei at densities $\sim 4\times10^{11}$ g/cm^3 (the neutron drip line, which separates inner and outer crust), where neutron degeneracy also starts to play a role. At densities $\sim 2\times10^{14}$ g/cm^3, the crust-core boundary, nuclei dissolve completely. In the core, densities may reach up to ten times the nuclear saturation density $\rho_{\rm sat} = 2.8\times10^{14}$ g/cm^3 (the density in normal atomic nuclei).

..The Inner Core



credit: F. Weber

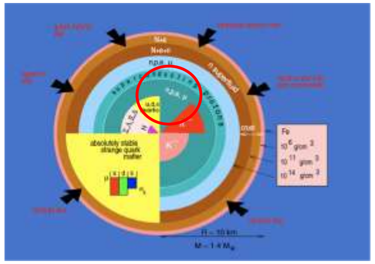
Nucleons in the Inner Core



credit: F. Weber

- Why n,p,e,μ?
- The Nuclear EoS
- Constraints on the Nuclear EoS
- Ab-initio versus Phenomenological Nuclear Models
- Connecting Observations with Theory

Why n,p,e,μ?



A Fermi gas model for only neutrons inside neutron stars is unrealistic

- real neutron star consists **not just of neutrons**, but contains **a small fraction of protons and electrons** - to inhibit the neutrons from decaying into protons and electrons by their weak interactions!

- the Fermi gas model ignores **nuclear interactions**, which give important contributions to the energy density

The Nuclear Equation of State

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 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: $n = n_n + n_p$

The Nuclear Equation of State (EoS) is a relation between thermodynamic variables describing the state of nuclear matter.
At T=0, we can make an expansion...

$$E(n_B,\delta) = E(n_B,0) + S(n_B)\delta^2 + ..$$

baryon density

with

$$\delta = (N-Z)/A$$
$$A = N+Z$$

neutron number

proton number

mass number

energy of symmetric nuclear matter

$$E(n_B,0) = E(n_0) + \frac{1}{18}K_0\,\varepsilon^2 + ..$$

$$\varepsilon = (n_B - n_0)/n_0$$

symmetry energy

$$S(n_B) = S_0 + \frac{1}{3}L\varepsilon + \frac{1}{18}K_{\rm sym}\varepsilon^2 + ..$$

$$E(n_0)/A \equiv E_0/A$$
$$n_0 = 0.16 \pm 0.01 \ \ {\rm fm}^{-3}$$
$$E_0/A = -16.0 \pm 1.0 \ \ {\rm MeV}$$

binding energy per nucleon at saturation density n_0

$$K_0 \equiv 9n_0^2\left(\frac{\partial^2 E}{\partial n_B^2}\right)_{n_B=n_0,\delta=0}$$

incompressibility at n_0

$$S_0 \equiv \frac{1}{2}\left(\frac{\partial^2 E}{\partial \delta^2}\right)_{n_B=n_0,\delta=0}$$

symmetry energy at n_0

$$L \equiv 3n_0\left(\frac{\partial S(n_B)}{\partial n_B}\right)_{n_B=n_0}$$

$$K_{\rm sym} \equiv 9n_0^2\left(\frac{\partial^2 S(n_B)}{\partial n_B^2}\right)_{n_B=n_0}$$

Constraints on the Nuclear Equation of State

Constraints from Nuclear Physics Experiments

- E/A from experimentally measured nuclear masses

$$n_0 = 0.16 \pm 0.01 \text{ fm}^{-3}$$
$$E_0/A = -16.0 \pm 1.0 \text{ MeV}$$

- K_0 from isoscalar giant monopole resonances in heavy nuclei and HiCs (difficult experimentally)

? 180 MeV < K_0 < 270 MeV ?

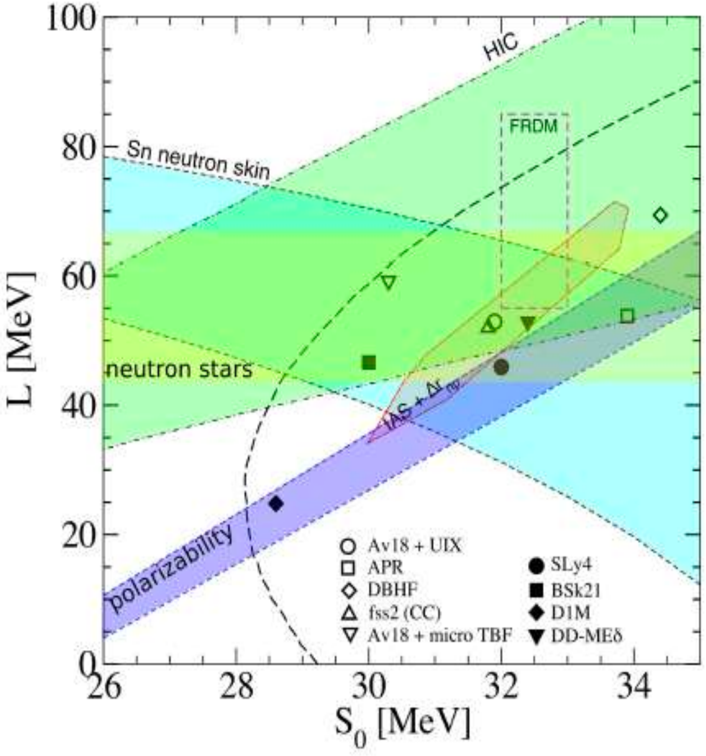
- S_0 from nuclear masses, isobaric analog state phenomenology, neutron skin thickness and HiCs; aditionally from NS data (fairly well constrained)

S_0 ~ 30-32 MeV

- L from dipole resonances, electric dipole polarizability and neutron skin thickness (very uncertain)

- Other higher order coefficients are very uncertain, such as K_{sym}

Burgio and Fantina '18



constraints close to saturation density !!!

Constraints on Nuclear Equation of State

Constraints from Astrophysical Observations

- NS masses

  precise values for NSs in binary system with ~2$M_\odot$

- NS radii

  - precise estimations of NS radii were very difficult because observations were indirect up to recently
  - recent simultaneous NICER M/R measurements
  - future: NICER, eXTP, STROBE-X..

- NS cooling

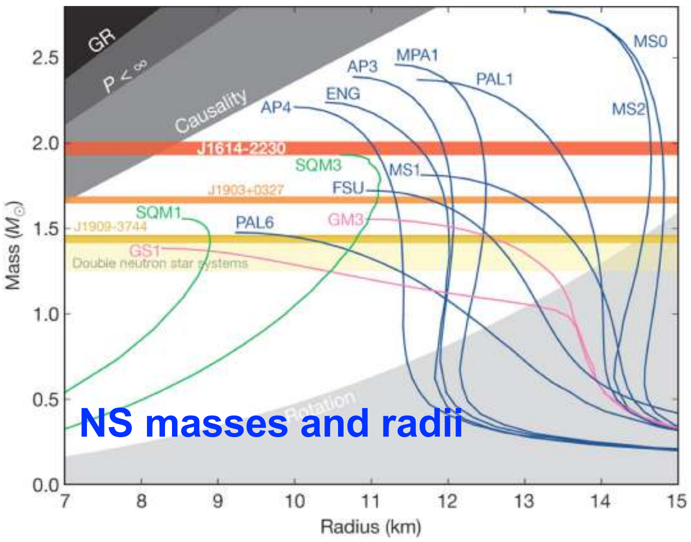
  depends on composition and on occurrence of superfluidity, thus giving complementary information on EoS

- NS moment of inertia

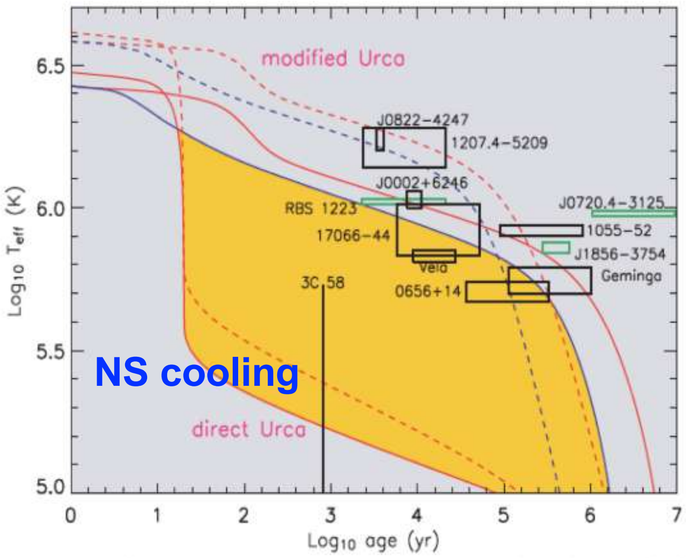
  mass and radius constrained by determination of moment of inertia, but not measured yet

- Gravitational waves and quasi-periodic oscillations

Ozel et al ‘16



Lattimer and Prakash’ 04



Ab-initio versus Phenomenological Models

Microscopic Ab-initio Approaches

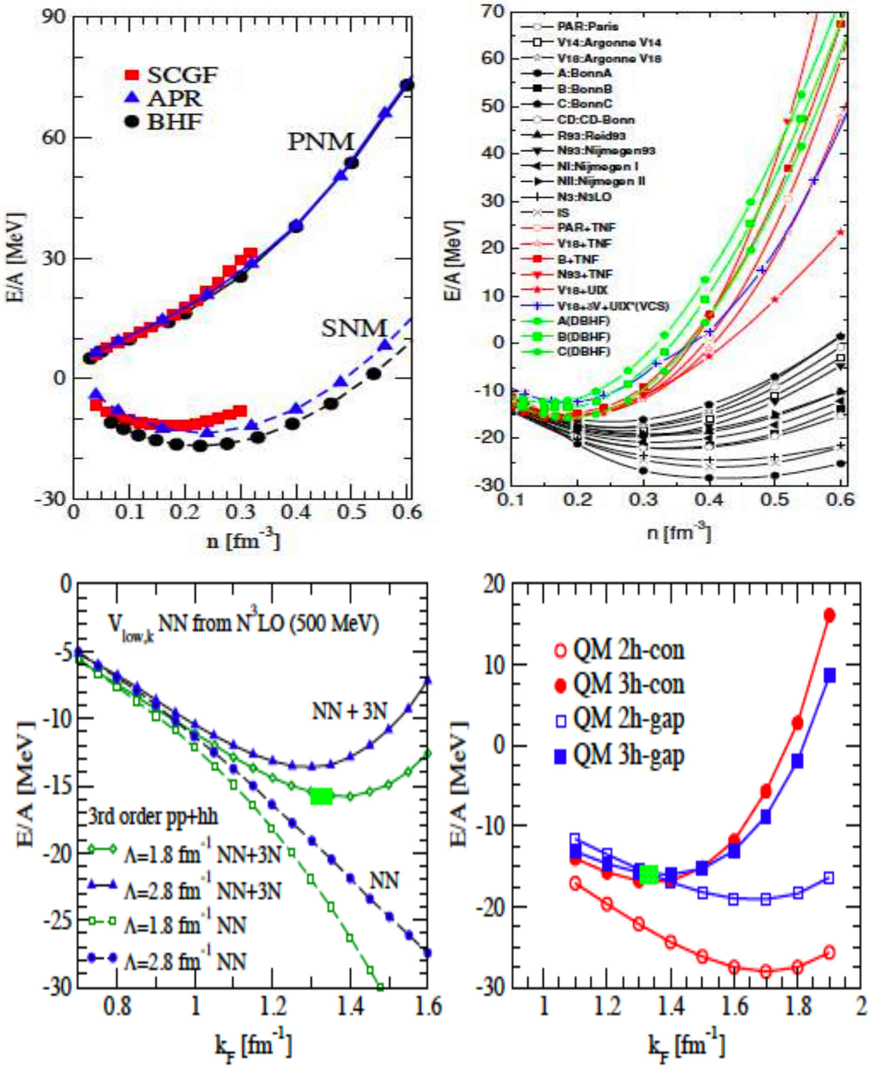
Based on solving the many-body problem starting from two- and three-body interactions

- *Variational method: APR, CBF,..*
- *Quantum Montecarlo : VMC, AFDMC, GFDMC..*
- *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)

Burgio and Fantina ‘18



Ab-initio versus Phenomenological Models

Phenomenological Models

Based on density-dependent interactions adjusted to nuclear observables and neutron star observations

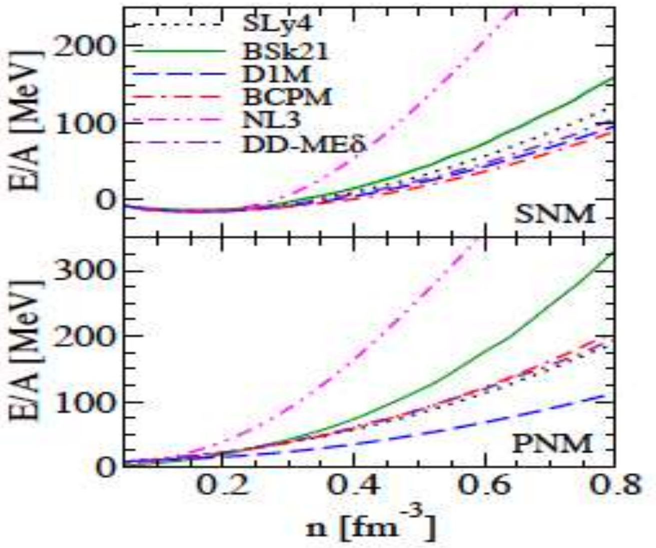
- *Non-relativistic EDF: Gogny, Skyrme..*
- *Relativistic Mean-Field (RMF) and Relativistic Hartree-Fock (RHF)*
- *Liquid Drop Model: BPS, BBP,..*
- *Thomas-Fermi model: Shen*
- *Statistical Model: HWN,RG,HS..*

crust

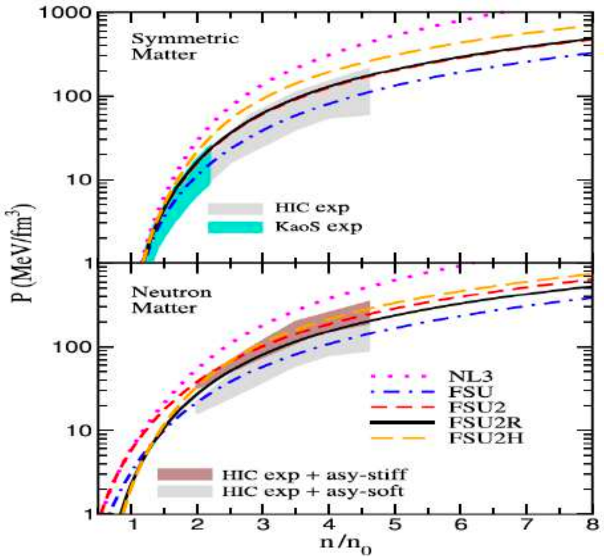
Advantage: applicable to high densities beyond n_0

Disadvantage: not systematic

Burgio and Fantina ‘18

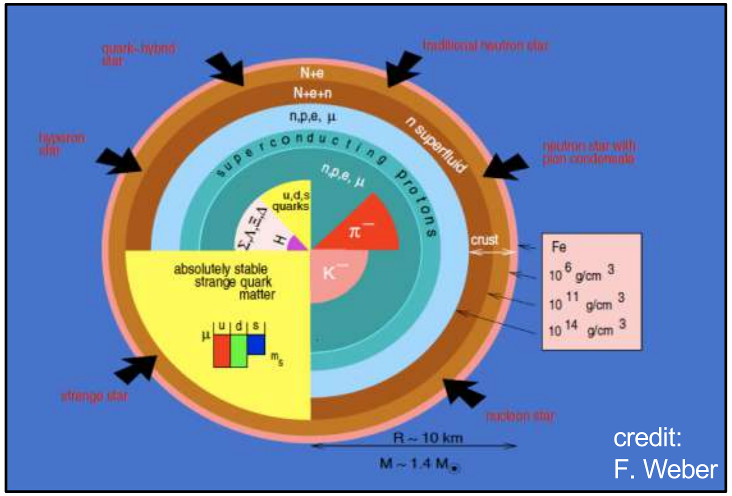


LT, Centelles and Ramos ‘17



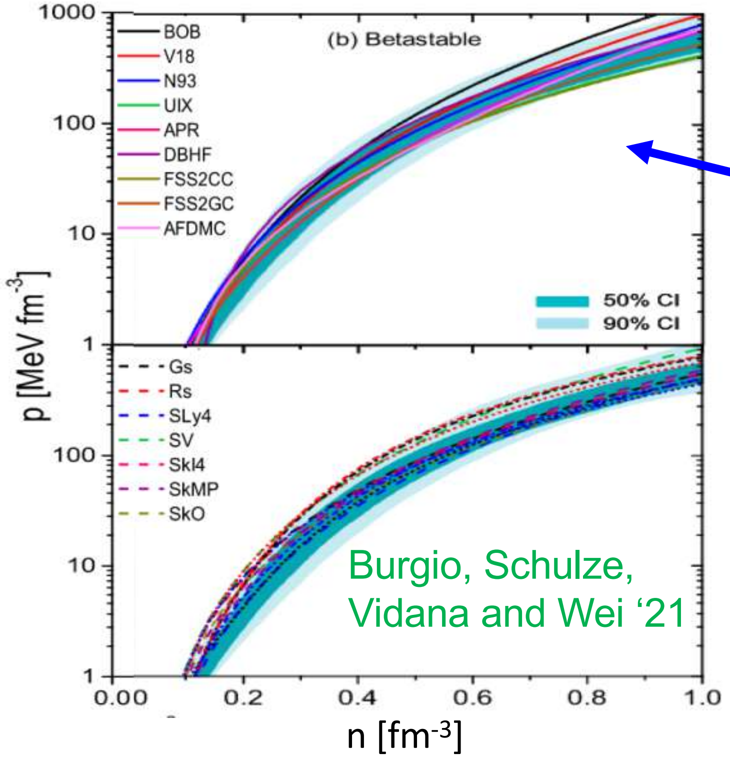
Connecting Observations with Theory

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



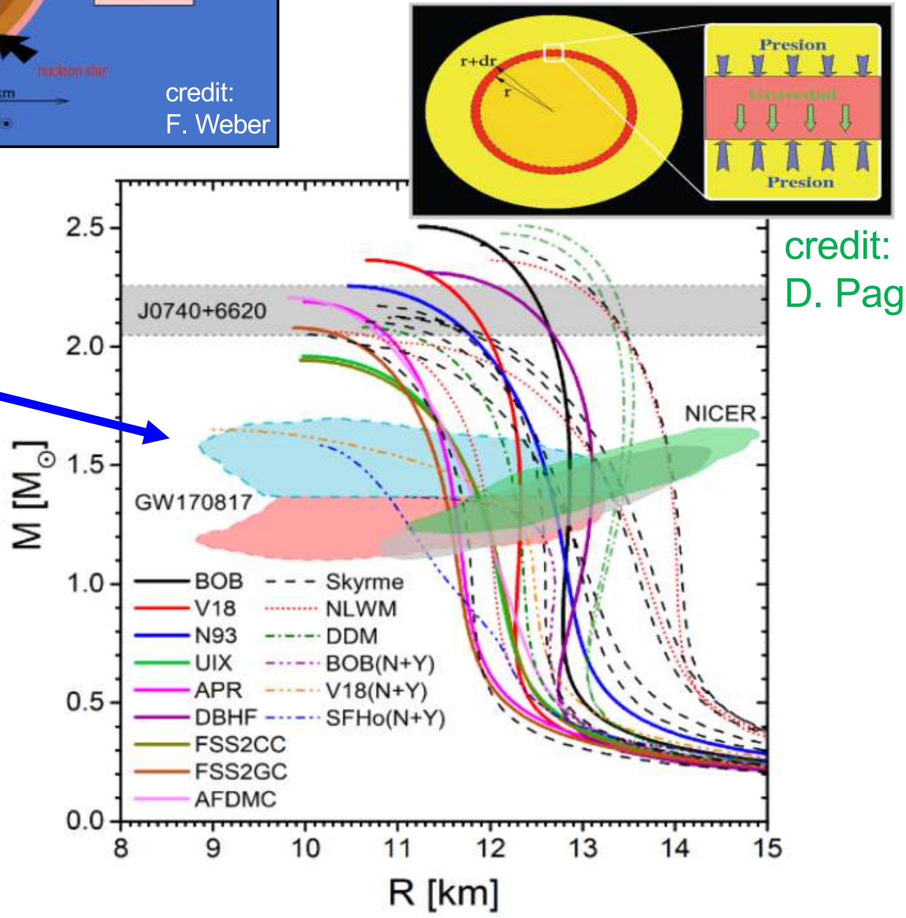
credit:
F. Weber

EoS



Burgio, Schulze, Vidana and Wei ‘21

Mass-Radius



credit:
D. Page

Structure Equations for Neutron Stars

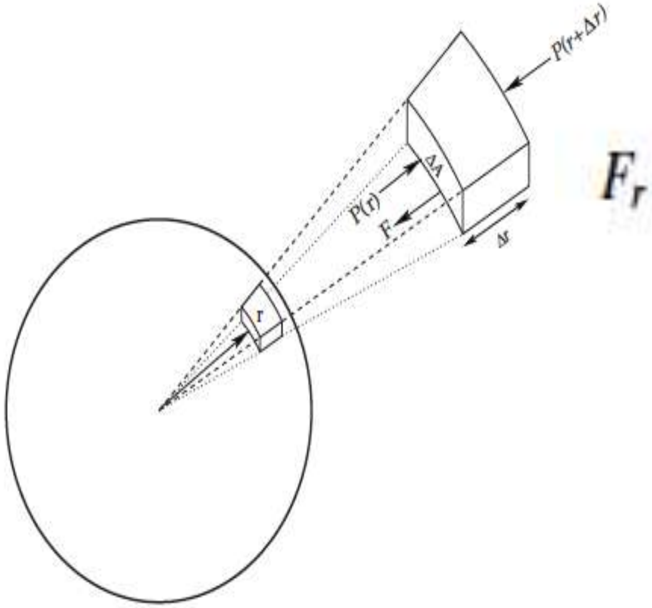


Figure 1. The radial force acting on a small mass element a distance *r* from the centre of the star.

$$F_r = -\frac{GM(r)\Delta m}{r^2} - P(r+\Delta r)\Delta A + P(r)\Delta A = \Delta m \frac{d^2 r}{dt^2}$$

dividing by
ΔV = ΔA Δr ➔

$$-\frac{GM(r)\rho(r)}{r^2} - \frac{dP}{dr} \underset{\uparrow}{=} \bar{\rho}(r)\frac{d^2 r}{dt^2} = 0$$

hydrostatic equilibrium $(\ddot{r} = \dot{r} \equiv 0)$

$\bar{\rho}(r)$: matter density!!!!

$$\boxed{\begin{aligned} \frac{dP}{dr} &= -\frac{GM(r)\bar{\rho}(r)}{r^2}, \qquad & P(r=0) &\equiv P_c; \\ \frac{dM}{dr} &= +4\pi r^2 \bar{\rho}(r), \qquad & M(r=0) &\equiv 0, \end{aligned}}$$

Newtonian formulation

General Relativity Corrections

Since neutron stars have masses M ~1-2 $M_\odot$ and radii R ~ 10-12 Km, the value of the gravitational potential on the neutron star surface is ~ 1

$$\frac{\frac{GM^2}{R}}{Mc^2} \sim 1$$

gravitational binding energy

gravitational mass

with escape velocities of order c/2

Therefore, general relativistic effects become very important!!!

We have to solve Einstein's field equations, $G^{\mu\nu}$, with the energy-density tensor of the stellar matter, $T^{\mu\nu}(\varepsilon,P(\varepsilon))$:

$$G^{\mu\nu} = 8\pi T^{\mu\nu}(\epsilon, P(\epsilon))$$

$$\epsilon = \bar{\rho}c^2$$

For spherically symmetric non-rotating star, the Einstein's equations reduce to the Tolman-Oppenheimer-Volkoff (TOV) equations:

$$\frac{dP}{dr} = -\frac{Gm\epsilon}{c^2r^2}\left(1+\frac{P}{\epsilon}\right)\left(1+\frac{4\pi r^3 P}{c^2 m}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = \frac{4\pi r^2 \epsilon}{c^2}$$

$$P(r=0) = P(\epsilon_c) \qquad m(r=0) = 0$$

$$P(r=R) = 0 \qquad m(r=R) = M$$

R/M constraints

for M=1.4 $M_\odot$ ➔ $GM/c^2 \sim 2$ km

The radius R for a given mass M must fulfill some constraints coming from:

1) General relativity arguments
(neutron stars are not black holes)

$$R > \frac{2GM}{c^2}$$

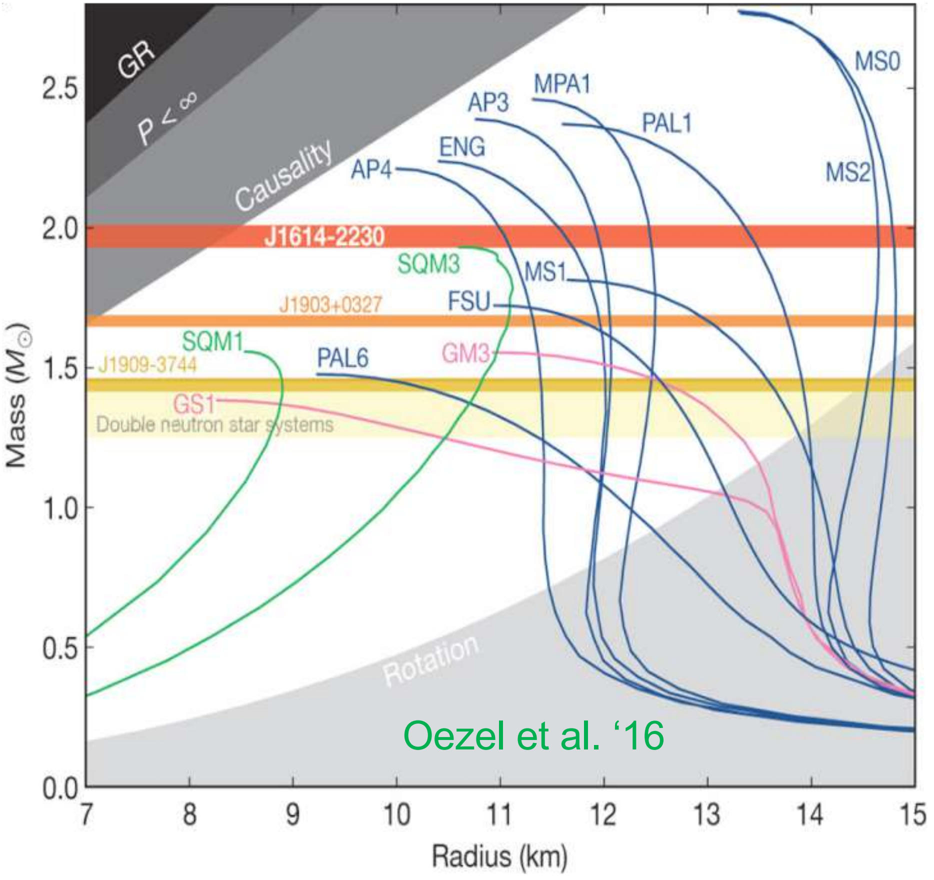
2) Compressibility (stability) of matter

$$R > \frac{9}{4}\frac{GM}{c^2}$$

3) Causality constraint
($c_s < c$)

$$R > 2.9\frac{GM}{c^2}$$

before NICER



Oezel et al. '16

4) Rotation must not pull the star apart

$$\nu < \nu_K = \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}} \longrightarrow R < \left(\frac{GM}{2\pi}\right)^{1/3}\frac{1}{\nu^{2/3}}$$

5) 2M$_\odot$ observations, NICER and GW constraints on R

“Recipe” for neutron star structure calculation

- Energy density $\epsilon(\rho, x_e, x_p, x_{\mathrm{n}}, ..); x_i = \frac{\rho_i}{\rho}$
- Chemical potentials $\mu_i = \frac{\partial \epsilon}{\partial \rho_i}$
- β equilibrium and charge neutrality $\mu_i = b_i \mu_n - q_i \mu_e$ $\sum_i x_i q_i = 0$
- Composition and EoS $x_i(\rho)\ ;\ P(\rho)$
- TOV equations

$$\frac{dP}{dr} = -\frac{Gm\epsilon}{c^2 r^2}\left(1+\frac{P}{\epsilon}\right)\left(1+\frac{4\pi r^3 P}{c^2 m}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

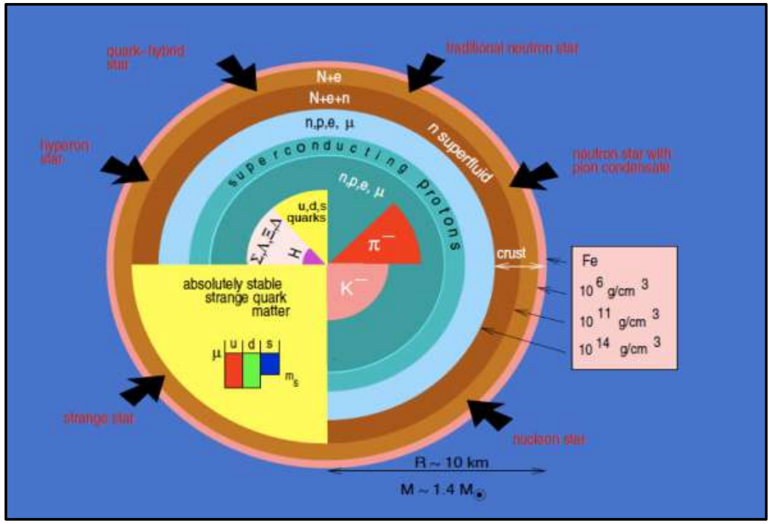
$$\frac{dm}{dr} = \frac{4\pi r^2 \epsilon}{c^2}$$

$$m(r=0)=0 \quad P(r=0)=P(\epsilon_c)$$

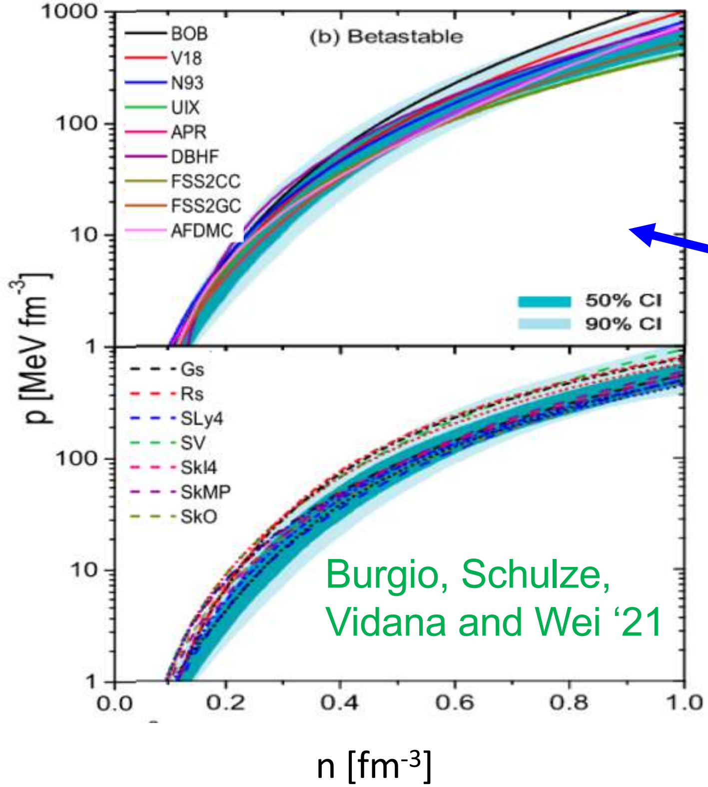
$$m(r=R)=M \quad P(r=R)=0$$

- Structure of the neutron star $\rho(r), M(R), ..$

Shulze@Compstar07

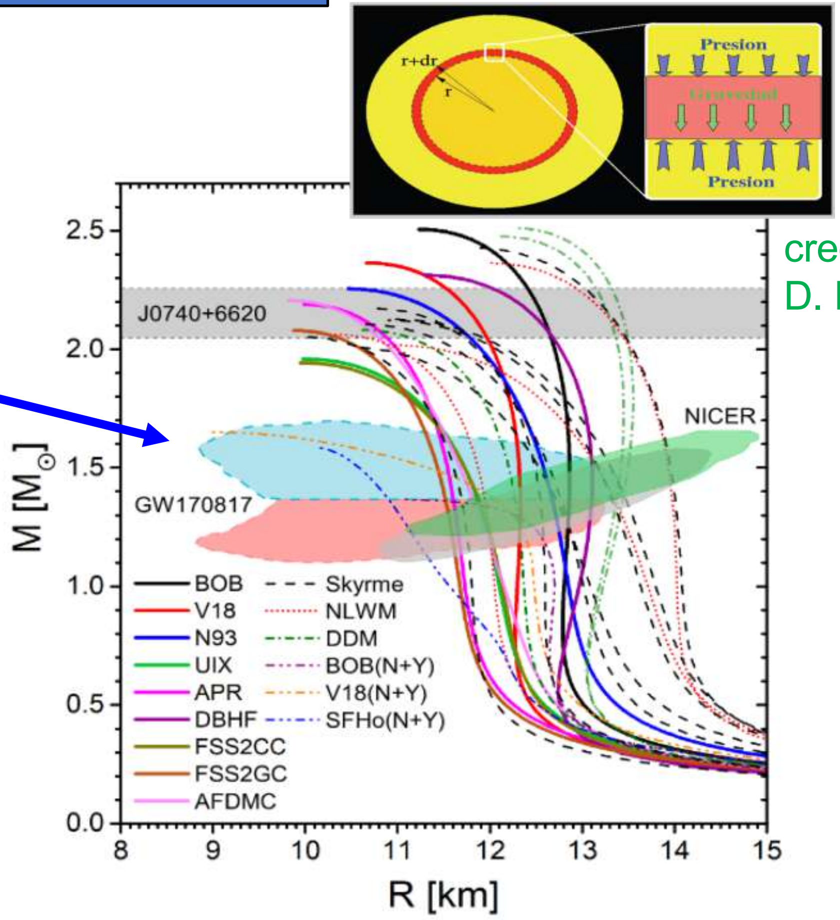


EoS



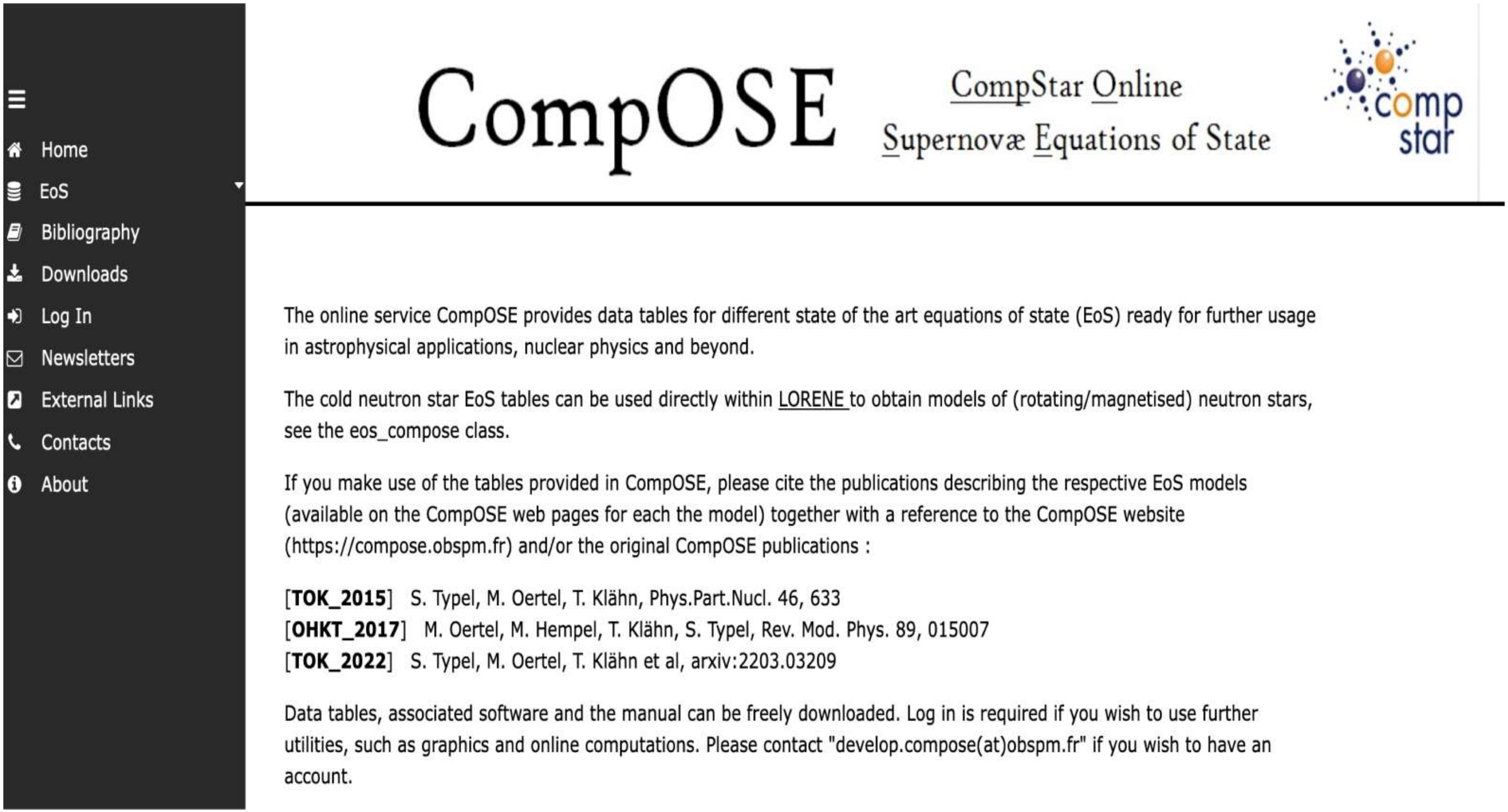
Burgio, Schulze, Vidana and Wei '21

Mass-Radius



credit:
D. Page

https://compose.obspm.fr/



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 :

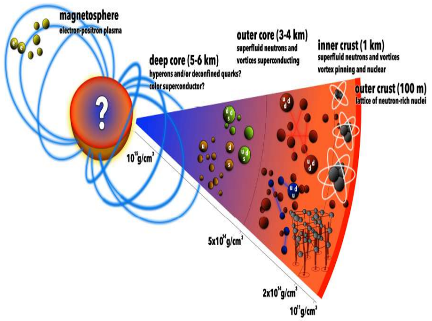
[**TOK_2015**] S. Typel, M. Oertel, T. Klähn, Phys.Part.Nucl. 46, 633
[**OHKT_2017**] M. Oertel, M. Hempel, T. Klähn, S. Typel, Rev. Mod. Phys. 89, 015007
[**TOK_2022**] S. Typel, M. Oertel, T. Klähn et al, arxiv:2203.03209

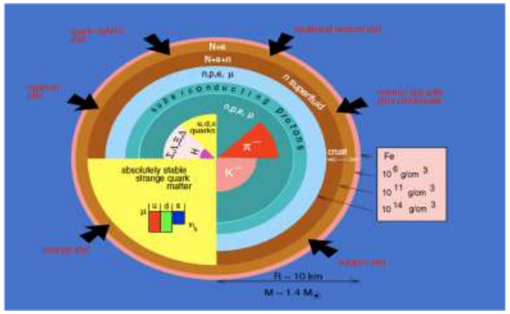
Data tables, associated software and the manual can be freely downloaded. Log in is required if you wish to use further utilities, such as graphics and online computations. Please contact "develop.compose(at)obspm.fr" if you wish to have an account.

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

Next lecture:

Strangeness
in Neutron Stars





Dense Hadronic Matter (Strangeness) in Neutron Stars

Institute of Space Sciences

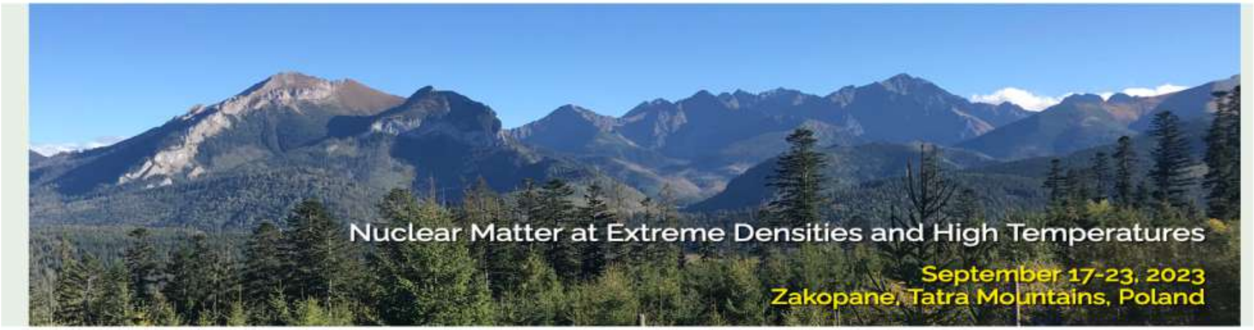
CSIC
Consejo Superior de Investigaciones Científicas

IEEC

Laura Tolós

FIAS Frankfurt Institute for Advanced Studies

63. Cracow School of Theoretical Physics



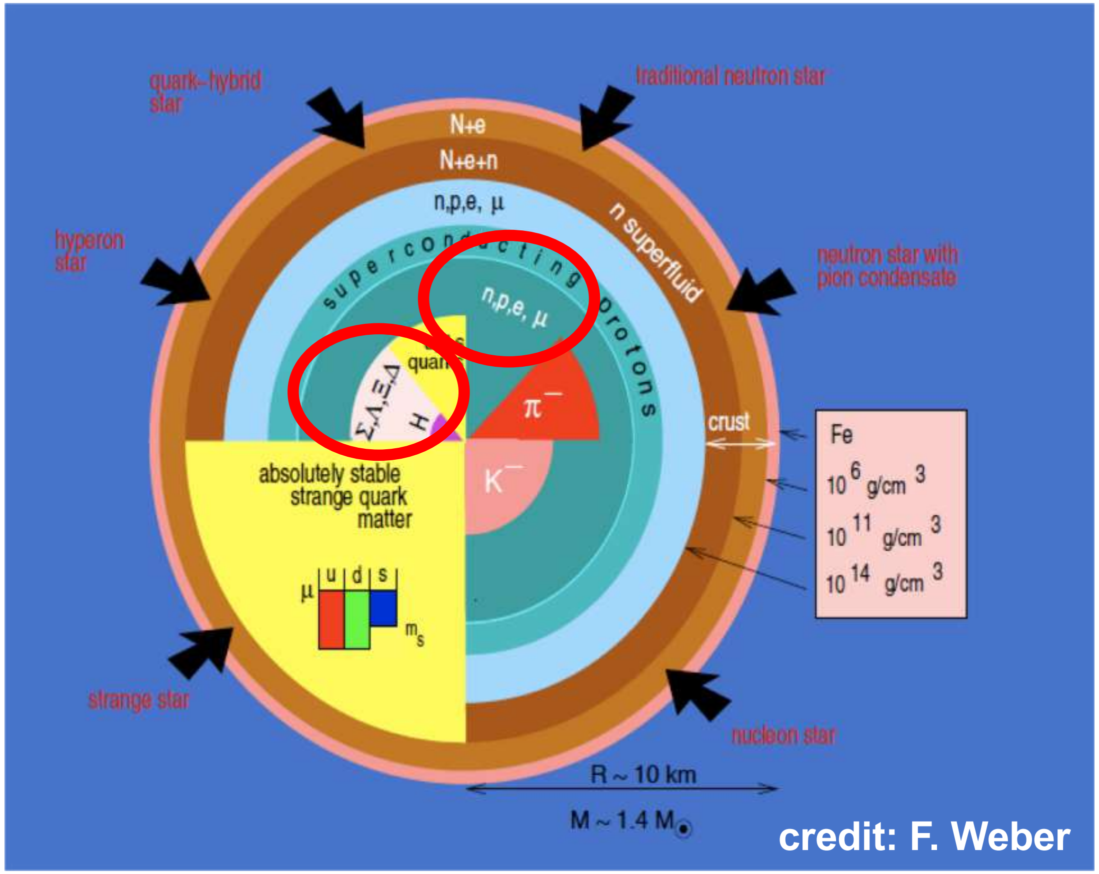
Nuclear Matter at Extreme Densities and High Temperatures

September 17-23, 2023
Zakopane, Tatra Mountains, Poland

Outline

- What is a Neutron Star?
- The Structure of Neutron Stars..
  ..The Inner Core
- Nucleons
- **Strange Baryons - Hyperons**
- **Strange Mesons - Antikaons**
- **Present and Future**

Strange Baryons (Hyperons) in the Inner Core

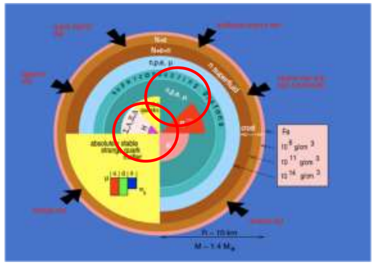


credit: F. Weber

Hyperon (Y)	**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

- Why n,p,e,μ,Y?
- YY and YN Interactions
- Hyperons in Matter
- Hyperons in Neutron Stars
- The Hyperon Puzzle

Why n,p,e,μ,Y?



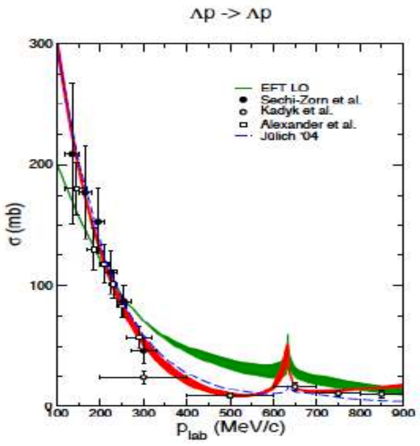
A Fermi gas model for only neutrons inside neutron stars is unrealistic

- real neutron star consists **not just of neutrons**, but contains **a small fraction of protons and electrons** - to inhibit the neutrons from decaying into protons and electrons by their weak interactions!

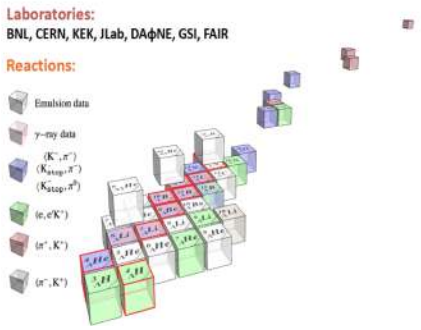
- the Fermi gas model ignores **nuclear interactions**, which give important contributions to the energy density

- more exotic degrees of freedom are expected, in particular **hyperons**, due to the high value of density at the center and the rapid increase of the nucleon chemical potential with density so the small energy difference between nucleons and hyperons is overcome

YN and YY Interactions



- Study strangeness in nuclear physics
- Provide input for hypernuclear physics and astrophysics



Scarce YN scattering data due to the short life of hyperons and the low-density beam fluxes

ΛN and ΣN: < 50 data points
ΞN very few events

NN: > 5000 data
for E_{lab}<350 MeV

Data from hypernuclei:

- more than 40 Λ-hypernuclei
(ΛN attractive)
- few Λ Λ- hypernuclei
(ΛΛ weak attraction)
- few Ξ-hypernuclei
(ΞN attractive)
- evidence of one Σ-hypernuclei
(ΣN repulsive) ?

Data on femtoscopy!

Theoretical approaches to YN and YY

- **Meson exchange models (Juelich/Nijmegen models)**

To build YN and YY from a NN meson-exchange model imposing SU(3)$_{\text{flavor}}$ symmetry

Juelich: Holzenkamp, Holinde, Speth '89; Haidenbauer and Meißner '05
Nijmegen: Maesen, Rijken, de Swart '89; Rijken, Nagels and Yamamoto '10

- **Chiral effective field theory approach (Juelich-Bonn-Munich group)**

To build YN and YY from a chiral effective Lagrangian similarly to NN interaction

Juelich-Bonn-Munich: Polinder, Haidenbauer and Meißner '06; Haidenbauer, Petschauer, Kaiser, Meißner, Nogga and Weise '13
Kohno '10; Kohno '18

- Quark model potentials

To build YN and YY within constituent quark models

Fujiwara, Suzuki, Nakamoto '07
Garcilazo, Fernandez-Carames and Valcarce '07 '10

- $V_{\text{low k}}$ approach

To calculate a "universal" effective low-momentum potential for YN and YY using RG techniques

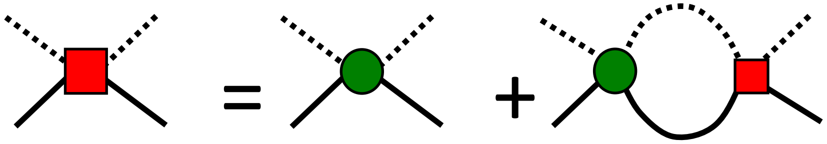
Schaefer, Wagner, Wambach, Kuo and Brown '06

- Lattice calculations (HALQCD/NPLQCD)

To solve YN and YY interactions on the lattice

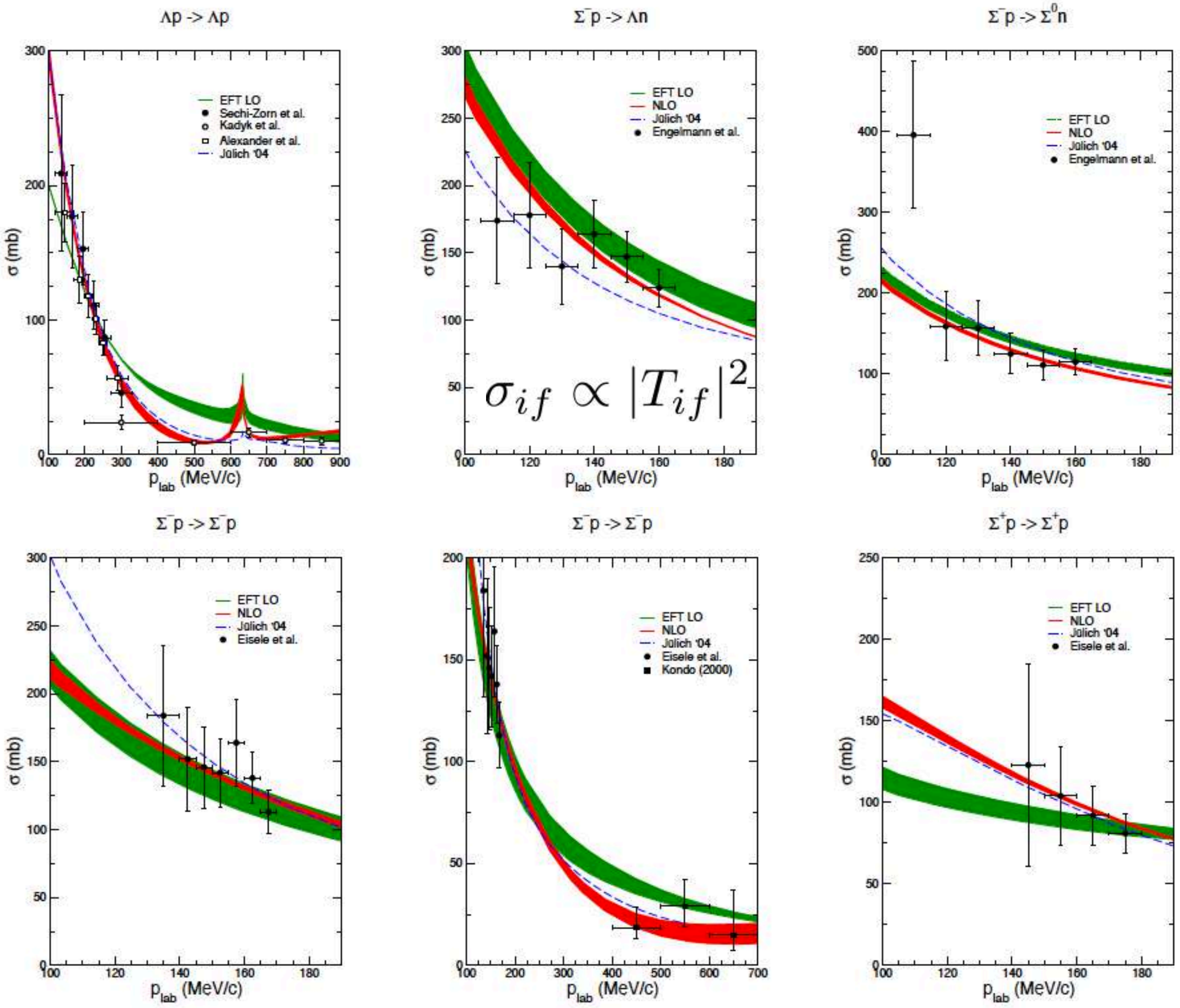
HALQCD: Ishii, Aoki, Hatsuda '07; Aoki, Hatsuda and Ishii '10; Aoki et al '12
NPLQCD: Beane, Orginos and Savage '11; Beane et al '12

ΛN and ΣN scattering



$$T = V + V \frac{1}{E_0 - H_0 + i\eta} T$$

LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.H., N. Kaiser, et al., NPA 915 (2013) 24
Jülich '04: J.H., U.-G. Meißner, PRC 72 (2005) 044005

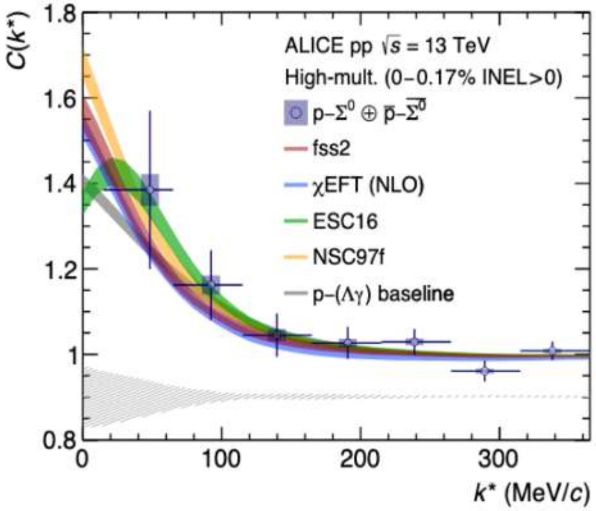


$$\sigma_{if} \propto |T_{if}|^2$$

New results from femtoscopy for **Σ^0p**

$$C(k^*) = \mathcal{N} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

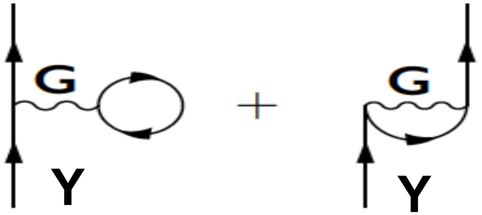
$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$



S. Acharya et al. '19

Hyperons in Matter

Λ and Σ in dense matter



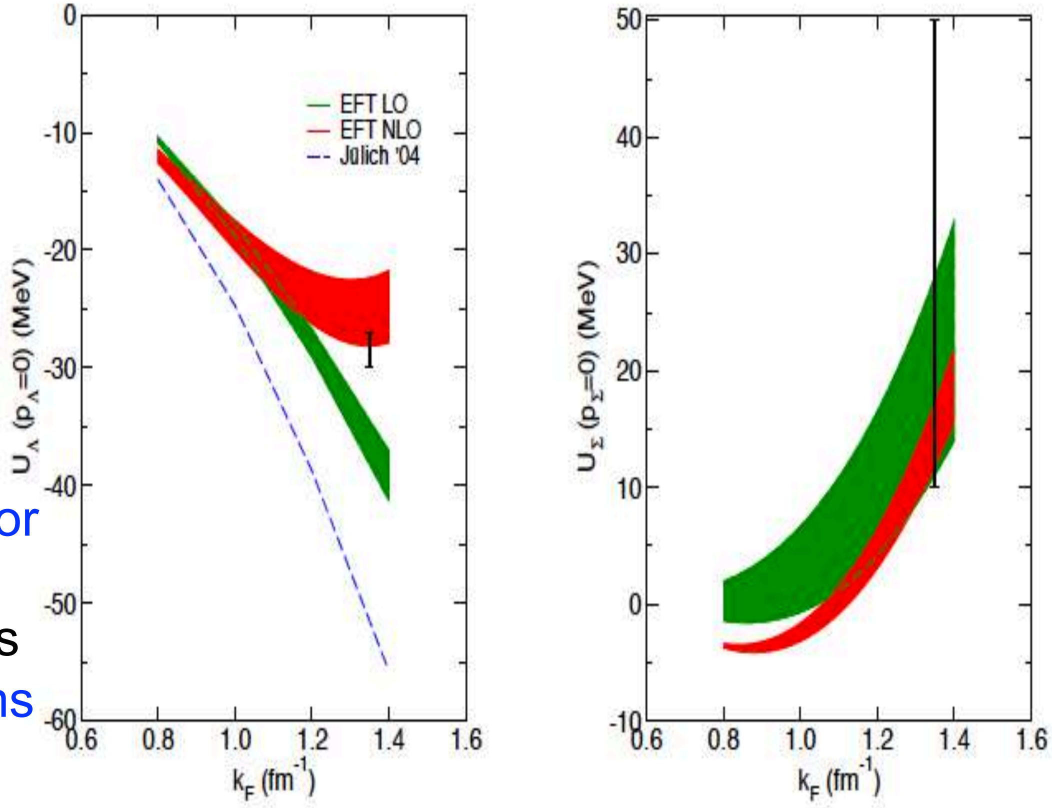
$$G = V + V\frac{Q_{\mathrm{pauli}}}{E_0 - H_0}G$$

$k_F = 1.35\ \mathrm{fm}^{-1}$ $(\rho_0 = 0.166\ \mathrm{fm}^{-3})$

	EFT LO	EFT NLO
Λ [MeV]	550 ··· 700	500 ··· 650
$U_\Lambda(0)$	−38.0 ··· −34.4	−28.2 ··· −22.4
$U_\Sigma(0)$	28.0 ··· 11.1	17.3 ··· 11.9

- Empirical value of Λ binding in nuclear matter ~27-30 MeV

- ΣN (I=3/2): discussion about repulsion or attraction, where $^3S_1$-$^3D_1$ component is decisive. A repulsive $^3S_1$-$^3D_1$ interaction is chosen in accordance to data on Σ^- atoms and (π^-,K^+) inclusive spectra for Σ^- formation in heavy nuclei as well as lattice* indications



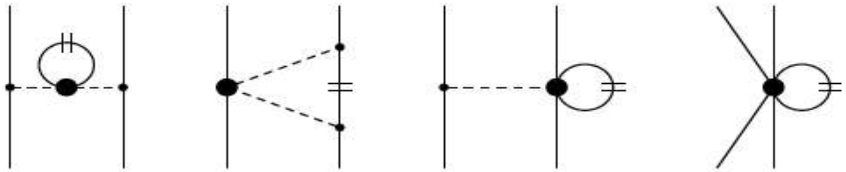
Haidenbauer and Meißner'15

* Nemura et al'18

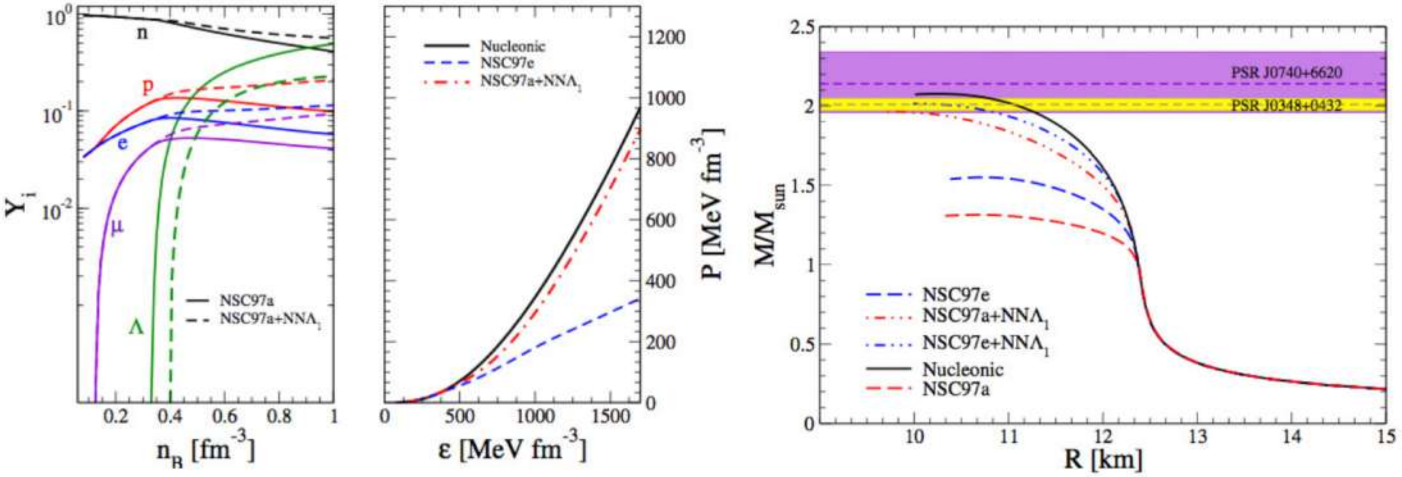
Λ in dense matter: including three-body forces

Three-body forces are required to reproduce few-nucleon binding energies, scattering observables and nuclear saturation in non-relativistic many-body approaches

credit: J. Haidenbauer



Λ in dense matter in χEFT: Hyperon puzzle?

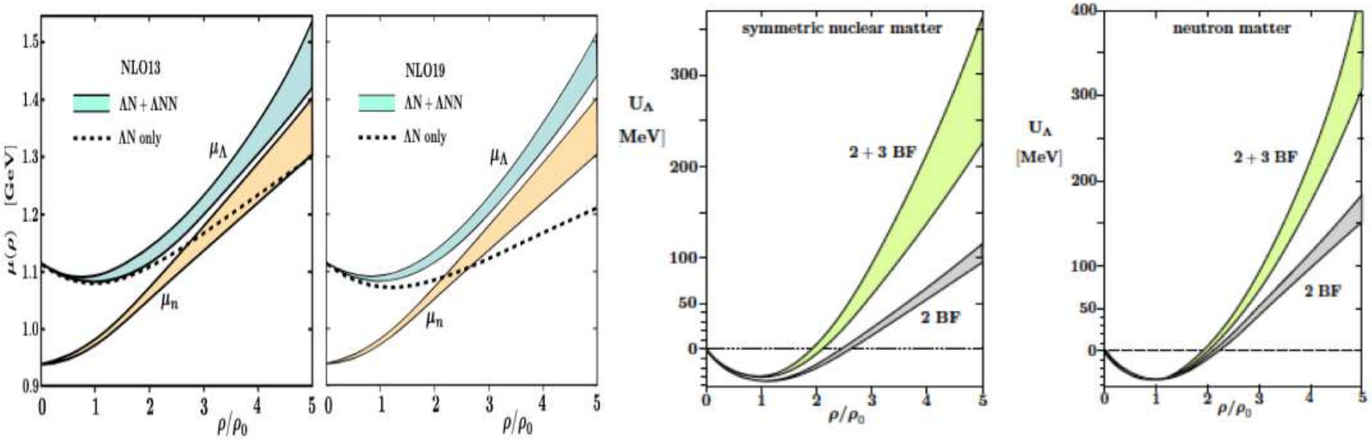


NS matter as mixture of n,p,e$^-$,μ^- ,Λ in β-equilibrium

χEFT (NN, NNN,NNΛ)
+ meson-exchange (NY)

Λ concentration is small but still present in 2M$_\odot$ NS

Logoteta, Vidana and Bombaci ‘19



Gerstung, Kaiser and Weise ‘20

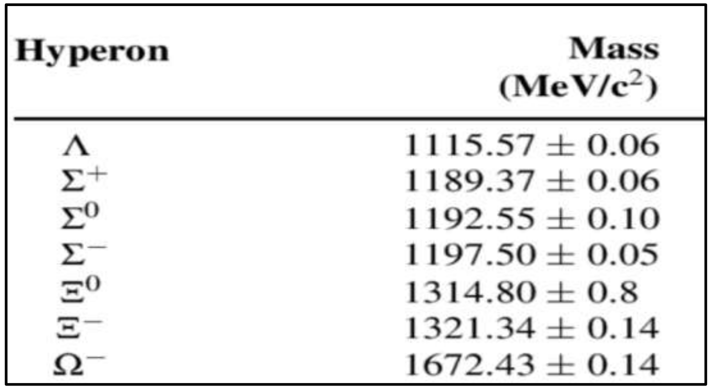
Only symmetric and neutron matter

χEFT NN, NNN,NY, NNΛ

Λ in NS energetically unfavorable, but only neutrons and Λ are considered

Hyperons in Neutron Stars

First proposed in 1960 by
Ambartsumyan & Saakyan



Hyperon	Mass (MeV/c^2)
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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 are 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

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

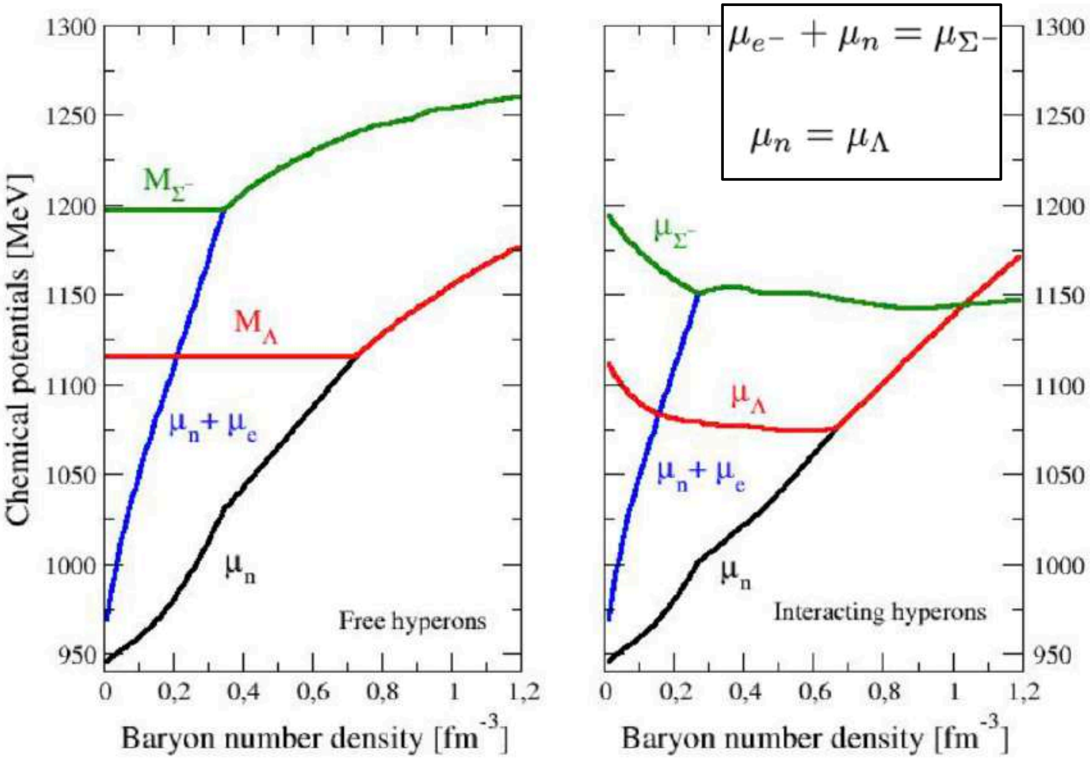
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

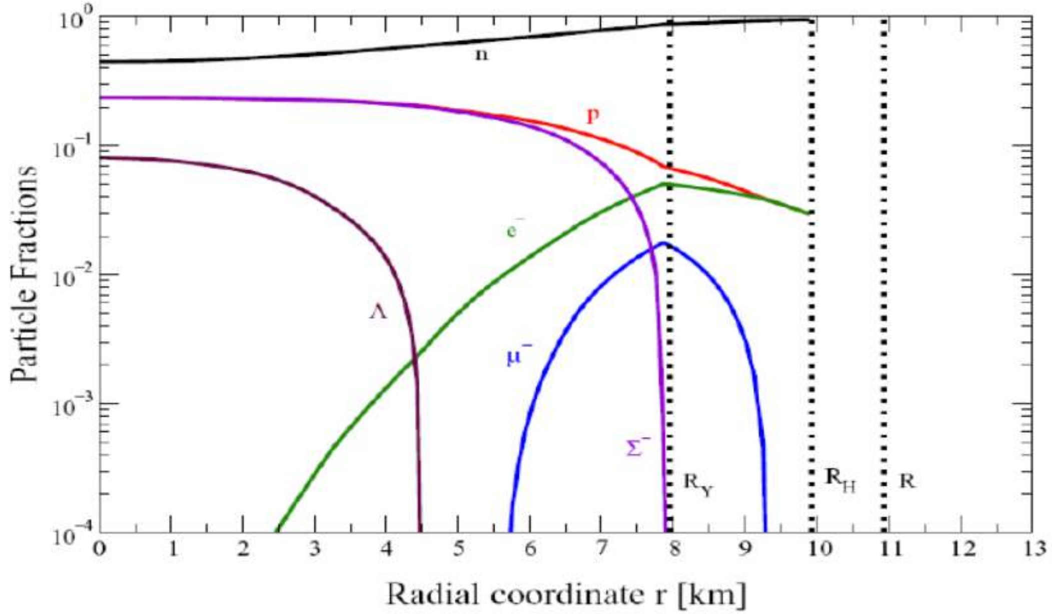
$$n + n \rightarrow p + \Sigma^-$$

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

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

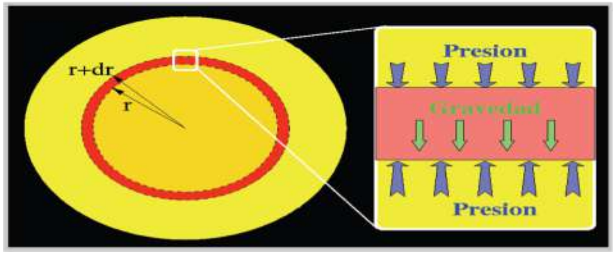
$$\sum_i x_i q_i = 0$$



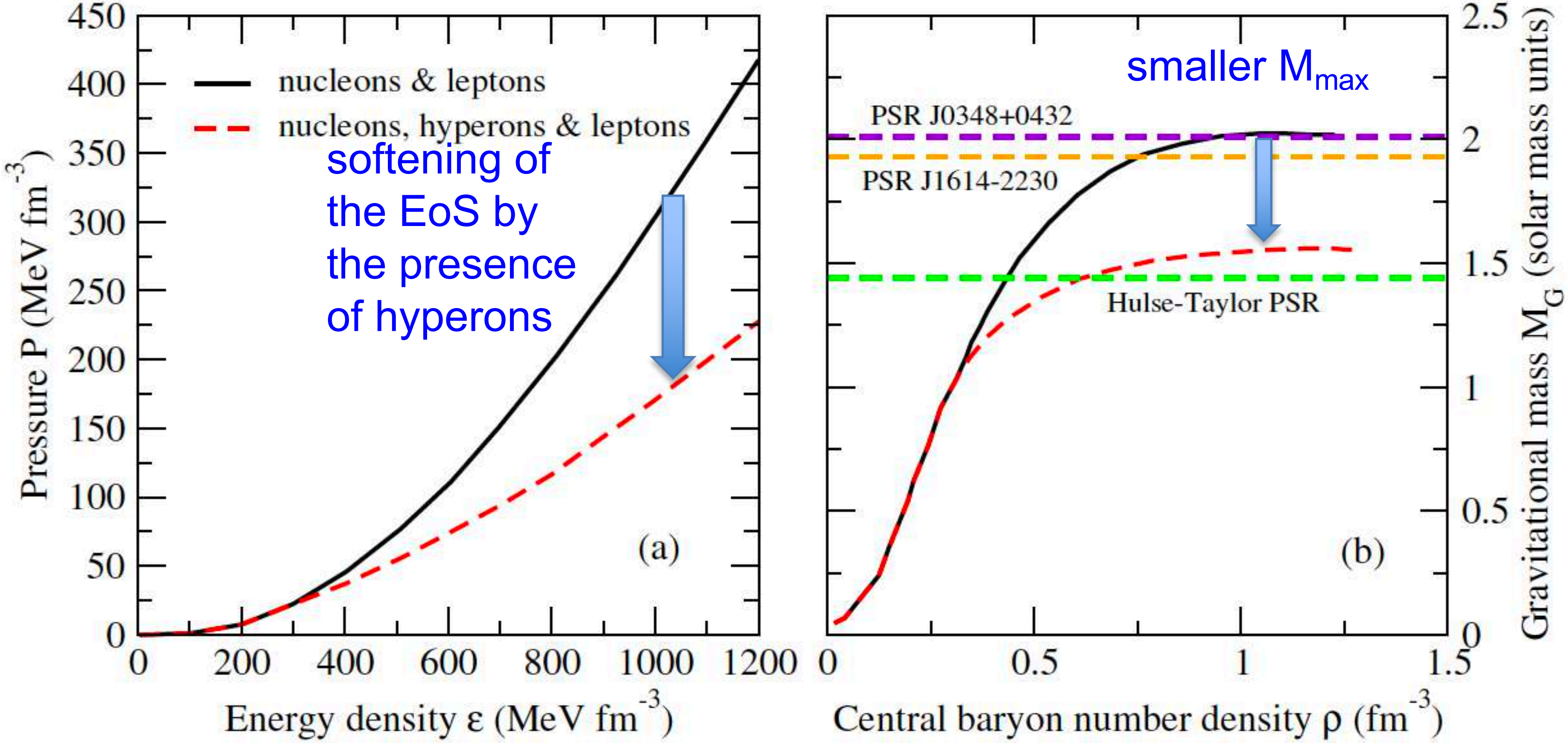


credit: I. Vidana

Inclusion of hyperons….



credit:
D.Page



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

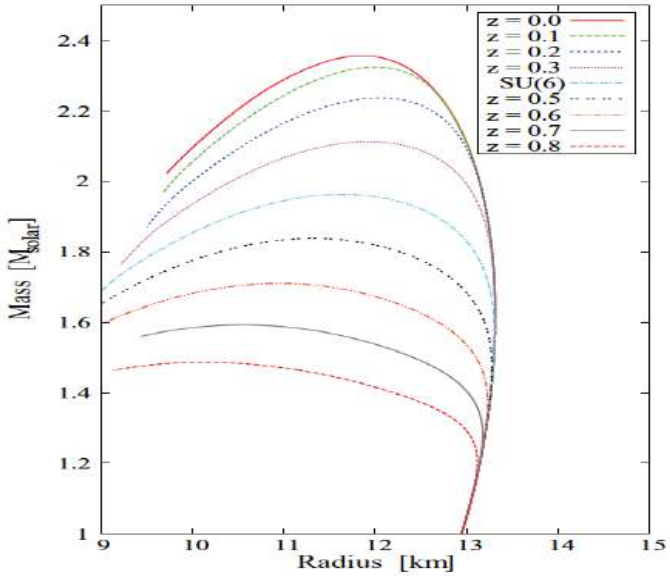
mainly explored in RMF models:
coupling of ϕ to hyperons to shift the onset of hyperons to higher densities

Bednarek et al ‘12; Weissenborn et al ’12;
Oerte et al ‘15; Maslov et al ’15..

results still compatible with $\Delta B_{\Lambda\Lambda}(^{6}\mathrm{He}_{\Lambda\Lambda})$

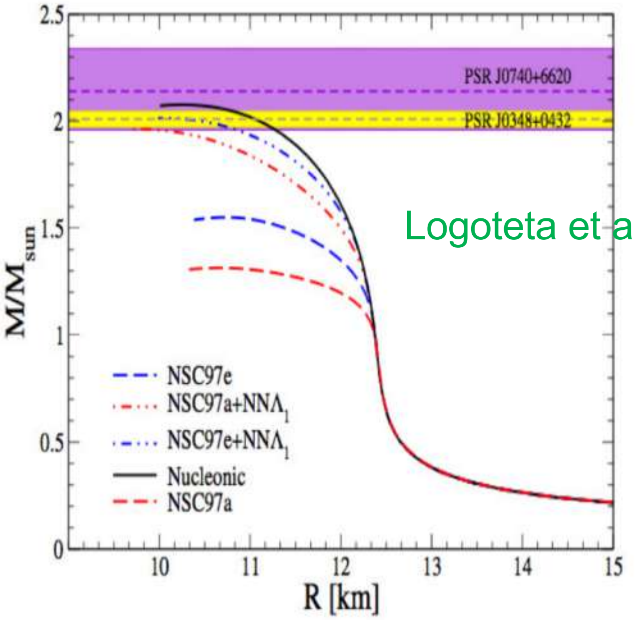
Fortin et al ‘17

Weissenborn et al ’12



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 χEFT gives enough repulsion to have Λ in $2M_\odot$ Logoteta et al ’19
whereas Λ are unfavoured in NS Gerstung et al ’20



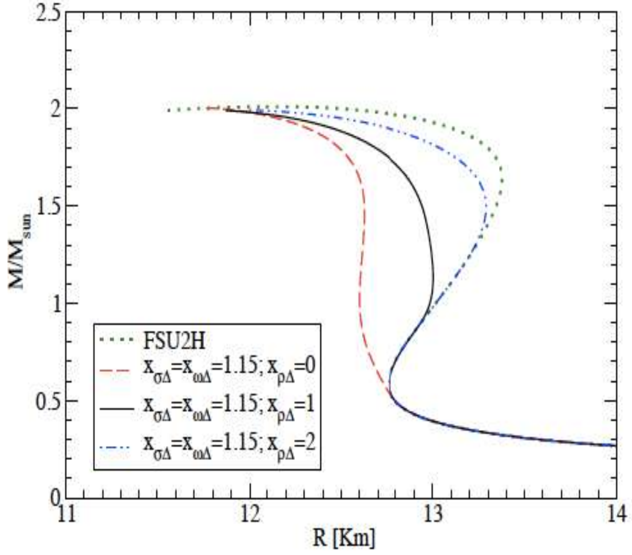
Logoteta et al ’19

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$_\odot$

Ribes et al ’19



Δ

Drago et al ’14 ‘15, Jie Li et al ‘19 ; Ribes et al ’19…

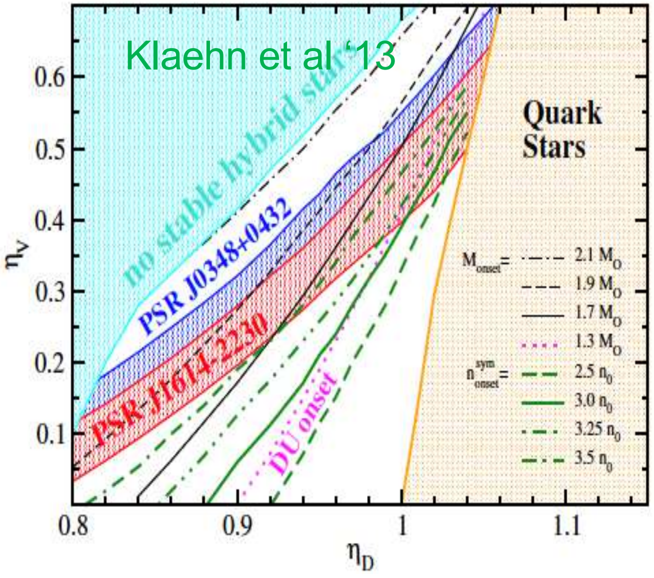
K condensate

Kaplan et al’ 86, Brown et al ‘94; Thorsson et al ’94; Lee ‘96; Glendenning et al ’98..

IV. Quark matter below Y onset

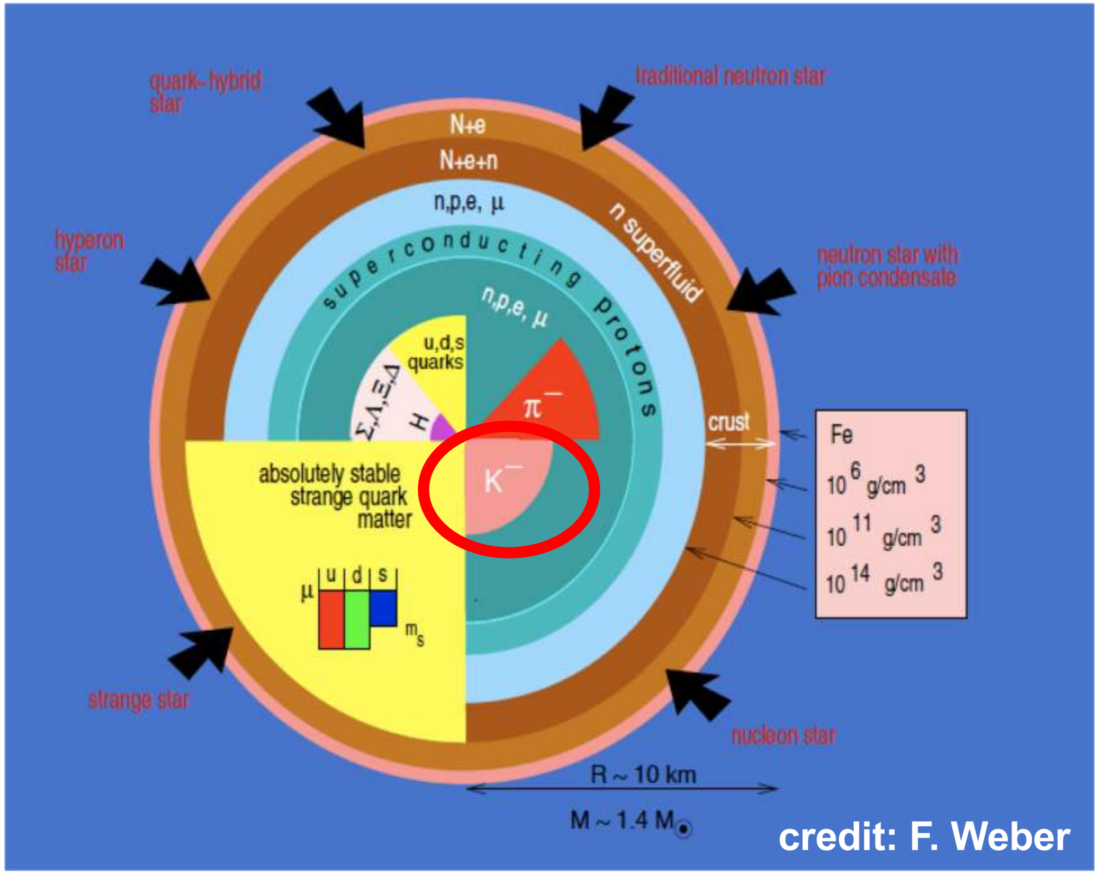
early transition to quark matter below Y onset, with quarks providing enough repulsion to reach 2M$_\odot$

Weissenborn et al ‘11; Klaehn et al ‘13; Bonanno et al ‘12; Lastowiecki et al ’12, Zdunik and Haensel ’12..


Klaehn et al ‘13

V. Others: modified gravity, dark matter..

Strange Mesons (Antikaons) in the Inner Core



credit: F. Weber

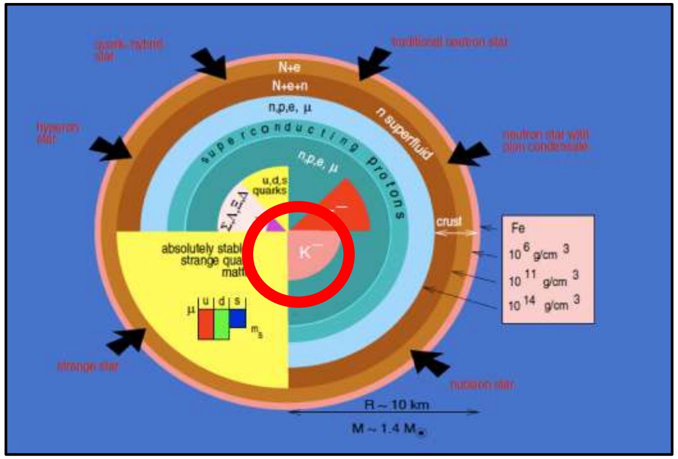
$$\bar{K} = \begin{pmatrix} \bar{K}^0 \\ \\ -K^- \end{pmatrix} \quad \begin{array}{c} \bar{d}\,s \\ \\ \bar{u}\,s \end{array} \quad s=-1$$

- _Why antikaons?
- $\bar{K}N$ interaction: Λ(1405) resonance
- Antikaons in matter
- Experiments and observations: from HiCs to stars

Why antikaons?

Kaon condensation in neutron stars

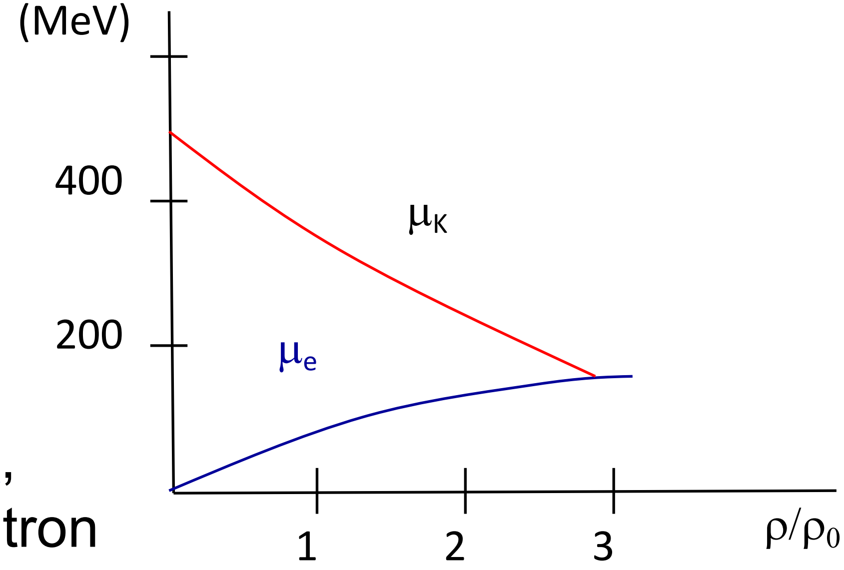
Kaplan and Nelson ‘86
Brown and Bethe ‘94



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

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

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

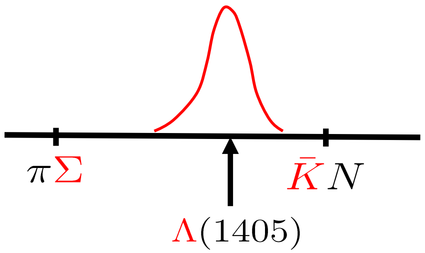


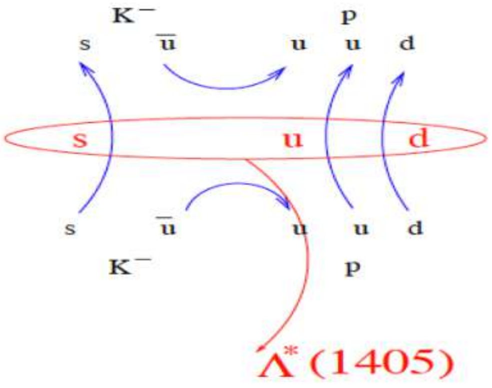
Antikaons are bosons. If $\mu_{K^-} \leq \mu_{e^-}$ for $\rho \geq \rho_c$, with ρ_c being a feasible density within neutron stars, antikaons will condense

$\bar{K}$N interaction: the Λ(1405)

$$\bar{K}=\begin{pmatrix}\bar{K}^0\\ -K^-\end{pmatrix}\begin{array}{l}\bar{d}\,s\\ \bar{u}\,s\end{array}\quad s=-1$$

- $\bar{K}$N scattering in the I=0 channel is governed by the presence of the Λ(1405) resonance, located only 27 MeV below the $\bar{K}$N threshold





- 50’s: idea originally proposed by Dalitz and Tuan
- since 90’s: the study of $\bar{K}$N scattering has been revisited by means of unitarized theories using meson-exchange models or chiral Lagrangians

meson-exchange models

Mueller-Groeling, Holinde and Speth ’90;
Buettgen, Holinde, Mueller-Groeling, Speth and Wyborny ’90;
Hoffmann, Durso, Holinde, Pearce and Speth ’95;
Haidenbauer, Krein, Meissner and Tolos ’11..

chiral Lagrangian

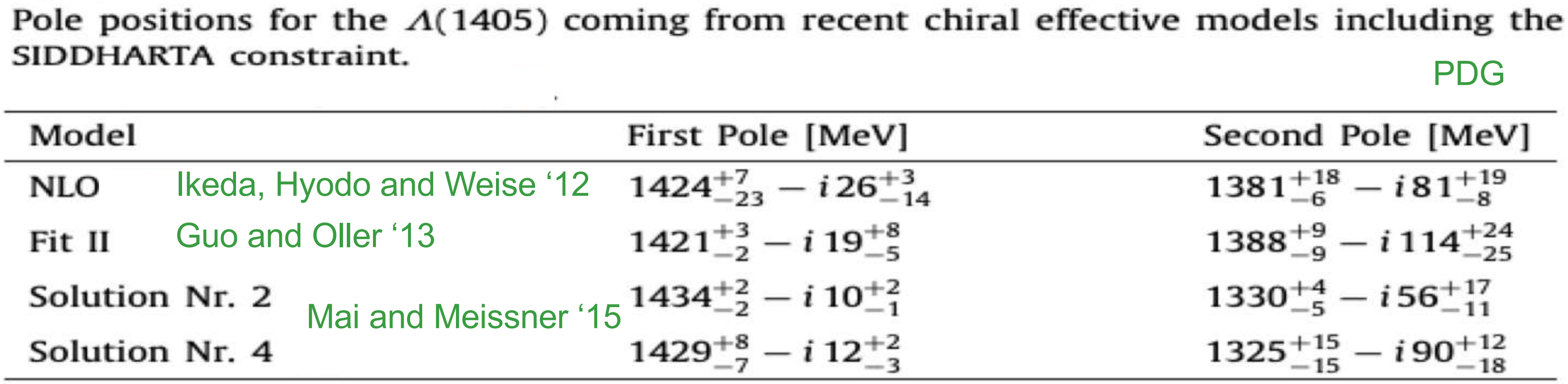
Kaiser, Siegl and Weise, ‘95; Oset and Ramos ‘98;
Oller and Meissner ’01; Lutz, and Kolomeitsev ’02;
Garcia-Recio et al. ’03; Jido et al. ‘03; Borasoy, Nissler, and Weise ’05;
Oller, Prades, and Verbeni ’05; Oller ’06;
Borasoy, Nissler and Weise ’05;
Khemchandani, Martinez-Torres, Nagahiro and Hosaka ’12
Feijoo, Magas and Ramos ’19; Feijoo, Gazda, Magas and Ramos ’21;
Ren, Epelbaum, Gegelia and Meissner ’20 ‘21; Bruns and Cieply ’22..

more channels,
next-to-leading order,
Born terms beyond WT
(s-channel, u-channel),
fits including new data,
higher partial waves...

Double-pole structure of Λ(1405)

Λ(1405) results from the superposition of two poles in the complex plane,
with different coupling to πΣ and K̄N states

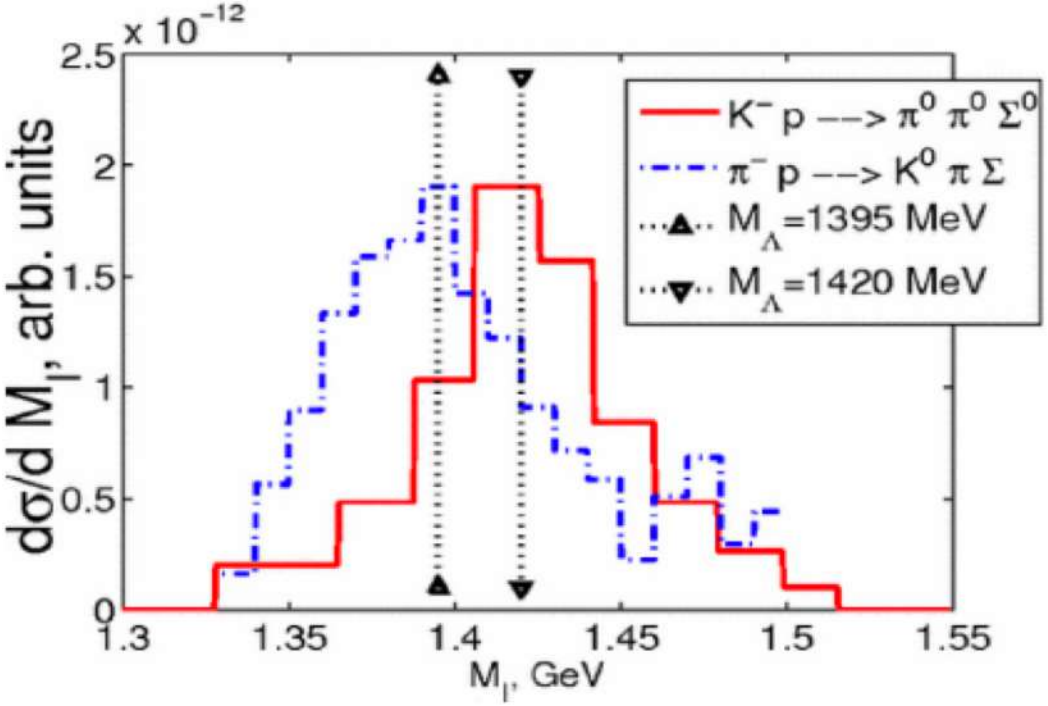
$$T_{ij} \approx \frac{g_i g_j}{z - z_R}$$



Pole positions for the $\Lambda(1405)$ coming from recent chiral effective models including the SIDDHARTA constraint.

PDG

Model		First Pole [MeV]	Second Pole [MeV]
NLO	Ikeda, Hyodo and Weise ‘12	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Fit II	Guo and Oller ‘13	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Solution Nr. 2	Mai and Meissner ‘15	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Solution Nr. 4		$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$



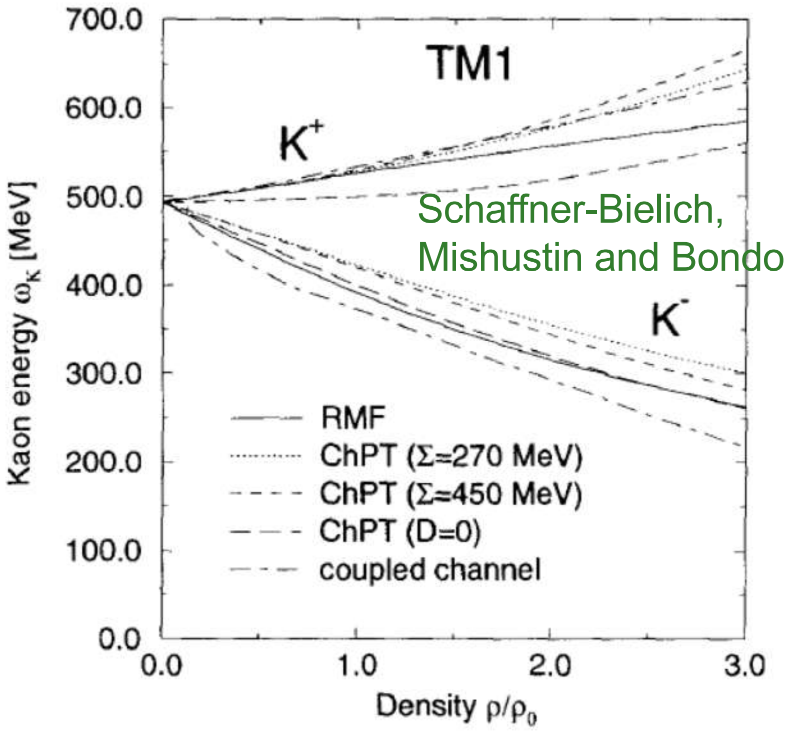
the measured spectra of the Σπ final states associated to the Λ(1405) for kaon- and pion-induced reactions supports the double-pole structure of the Λ(1405)

Magas, Oset and Ramos ’05

Antikaons in matter

RMF schemes,
QMC models…

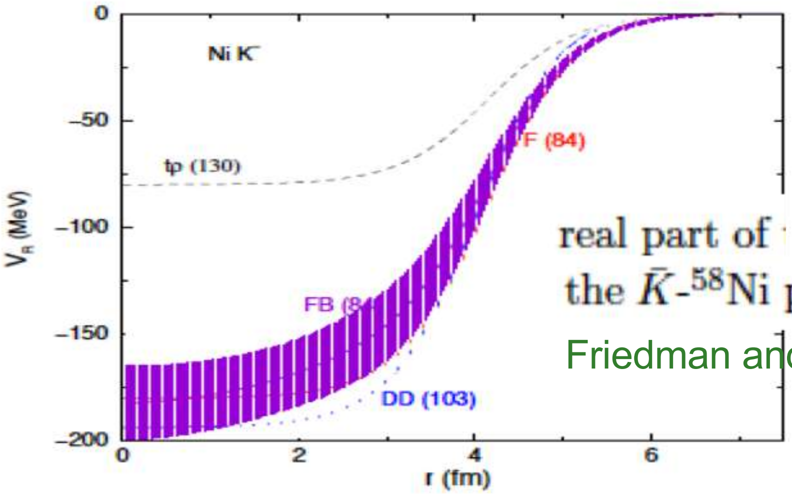
RMF: early works based on meson-exchange picture or the chiral approach for the $\bar{K}N$ interaction on the mean-field level and fit the parameters to the $\bar{K}N$ scattering length



Schaffner-Bielich, Mishustin and Bondorf '97

Phenomenological models

density dependent potentials fitted to kaonic atoms



real part of the $\bar{K}$-^{58}Ni potential

Friedman and Gal '07

$U_{K-}(\rho_0)$ ~ -100 to -200 MeV

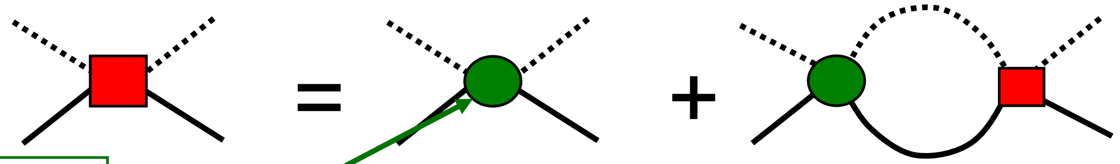
recent K^-N scattering amplitudes from χSU(3) EFT supplemented with phenomenological terms for K^- multinucleon interactions:
kaonic atoms test densities $\rho < \rho_0$

Friedman and Gal '17

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

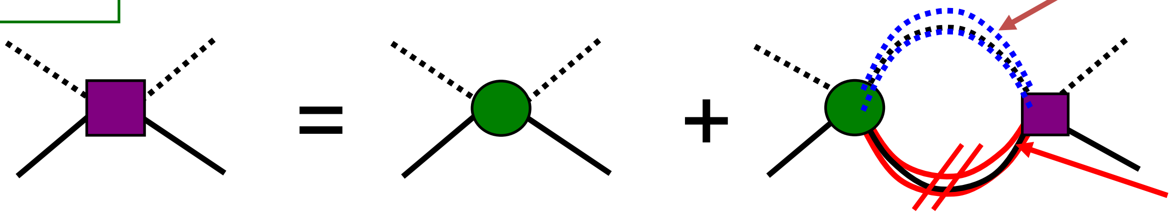


potential from chiral dynamics or meson-exchange models

$T_{ij} = V_{ij} + V_{il}\ G_l\ T_{lj}$

meson dressing

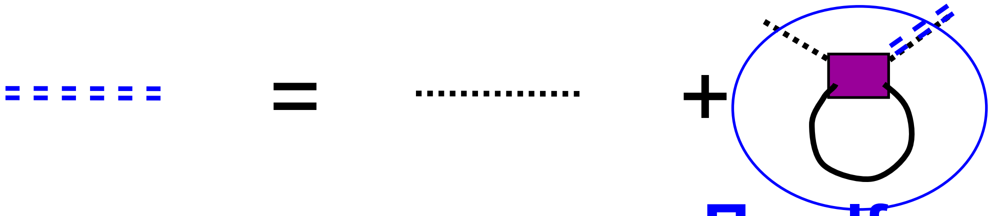
Medium



Pauli blocking and baryon dressing

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

Dressed meson:

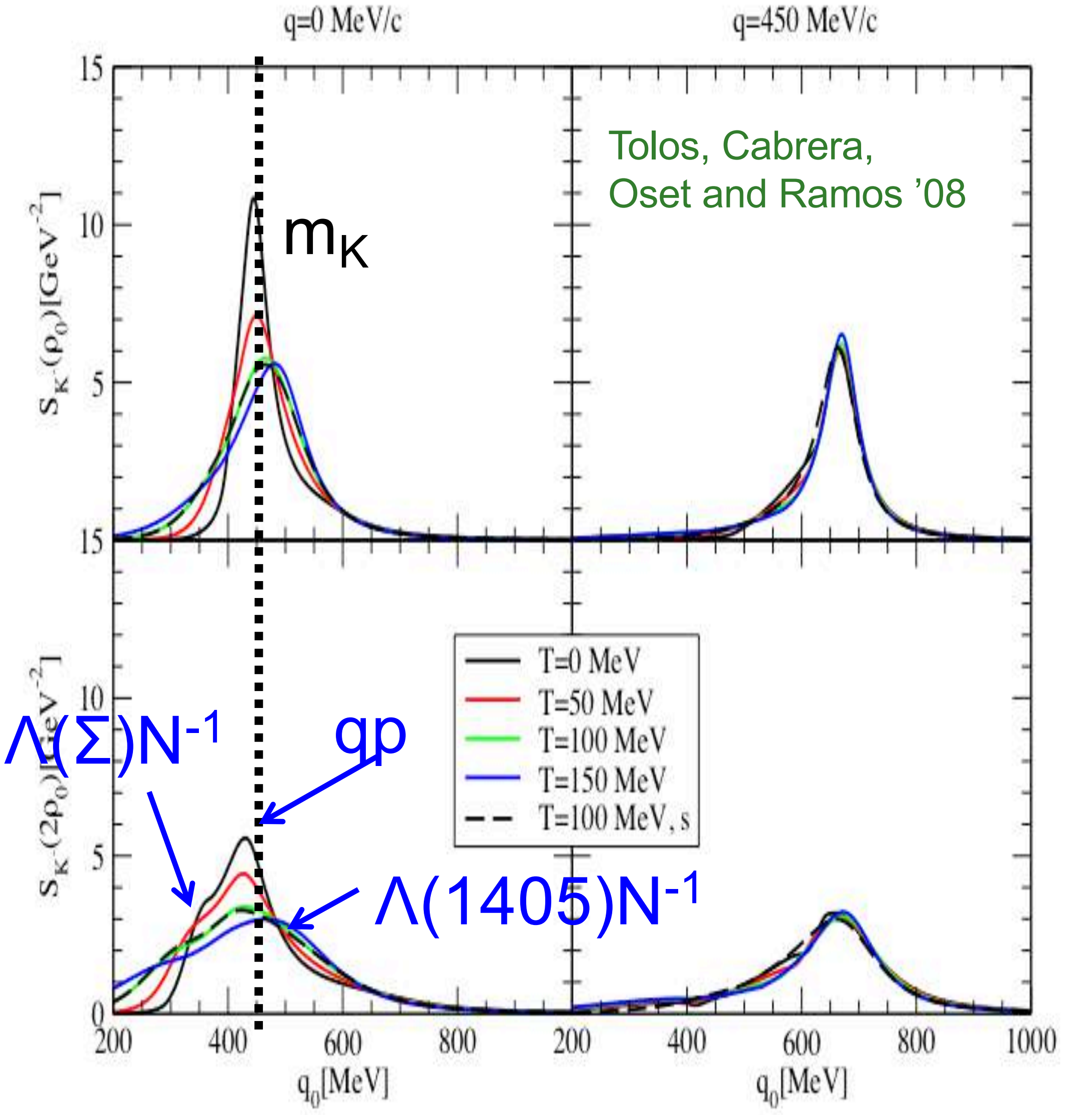


Π self-energy

$\bar{K}$ spectral function in matter

$$S = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi}{[q_0^2-\vec{q}^{\,2}-m^2-\mathrm{Re}\Pi]^2+\mathrm{Im}\Pi^2}$$

Koch ’94; Waas and Weise ’97;
Kaiser et al ’97; Oset and Ramos’98;
Lutz ’98; Schaffner-Bielich et al ’00;
Ramos and Oset ’00; Lutz et al ’02 ;
Tolos et al ’01 ’02; Jido et al ‘02 ’03;
Magas et al ’05; Tolos et al ’06 ’08;
Lutz et al ’08; Cabrera et al ’14…



Tolos, Cabrera, Oset and Ramos ’08

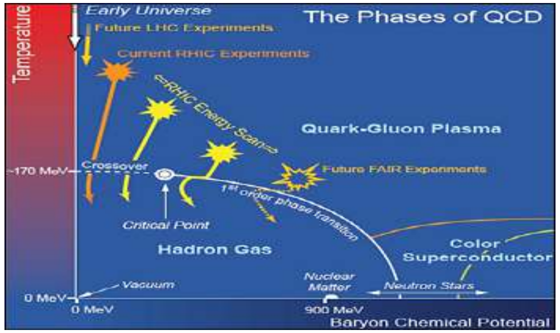
Re $U_{K^-}(\rho_0)$ ~ -50 to -80 MeV
Im $U_{K^-}(\rho_0) \gtrsim$ Re $U_{K^-}(\rho_0)$

- **s-wave** $\bar{K}$N interaction governed by Λ(1405): attraction due to modified Λ(1405) in the medium using a self-consistent coupled-channel approach

- **p-wave (and beyond)** contributions to $\bar{K}$N interaction: not important for atoms but important for heavy-ion collisions due to large momentum

Experiments and observations: from HICs….

credit: DOE



strangeness production in matter
is one of the major research domains in heavy-ion collisions from SIS/GSI to LHC and RHIC up to the future FAIR/NICA/BESII/J-PARC-HI

low-energy HICs:
KaoS/SIS18: K^+,K^- ,..
FOPI/SIS18: K^+,K^-, $\phi(1020)$..
HADES/SIS18: K^+, $K^*(892)^0$, K_s^0, $\phi(1020)$, Λ, $\Xi(1321)$,Ω..

(FOPI) Ritman et al ’95; Crochet et al ’00; Bastid et al, ‘07; Zinyuk ’14..
(KaoS) Menzel et al ‘00; Ploskon ‘05; Uhlig et al ‘05;Foerster et al ’07..
(HADES) Agakishiev et al ’09 ‘10 ‘11 ’13 ’14;
Galatyuk ’17; Adamczewski-Musch ‘18 ‘19...

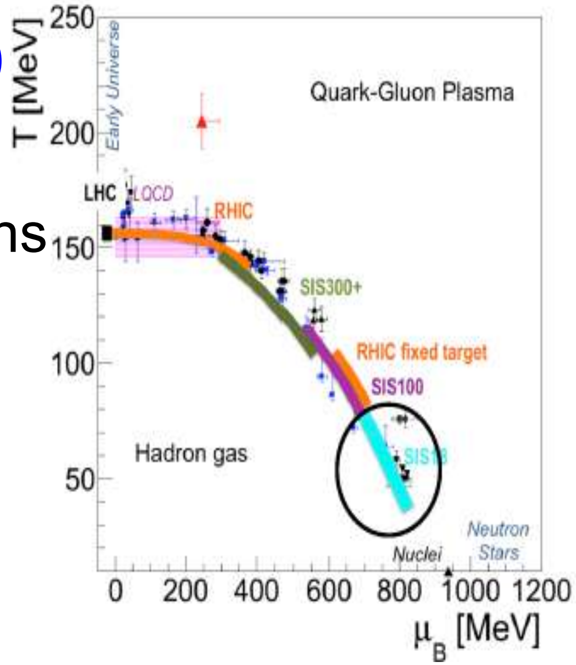
high-energy HICs:
STAR/RHIC: $K^*(892)^0$, $\phi(1020)$, Ω..
ALICE/LHC: $K^*(892)^0$, $\phi(1020)$, $\Sigma^{+-}(1385)$, $\Xi(1530)^0$..

Adams et al. (STAR) ’05
Aggarwal et al (STAR) ’11
Kumar et al (STAR) ‘15
Abelev (ALICE) ’15
Adam (ALICE) ‘16
Badala (ALICE) ’17..

future:
CBM/FAIR
BM@N/NICA
BESII/RHIC
J-PARC-HI

CBM (FAIR) Physics Book ’11
NICA: http://theor0.jinr.ru/twiki-cgi/view/NICA
Aggarwal et al (BES STAR White Paper) ‘10
JPARC: http://silver.j-parc.jp/sako/white-paper-v1.21.pdf-HI

K^- and K+ at high μ_B (**FOPI/HADES @ SIS18**)



KaoS: from systematics of the experimental results and detailed comparison to transport model calculations

Foerster et al (KaoS) '07

- K^+ probe a soft EoS
- K^+ and K^- yields are coupled by strangeness exchange:

$$NN \rightarrow K^+YN$$
$$K^-N \Leftrightarrow \pi Y$$

- K^+ and K^- exhibit different freeze-out conditions
- repulsion for K+ and attraction for K- seemed to be confirmed

but, for example, what is the role of $\phi \rightarrow K^+ K^-$?

Results from **HADES** and **FOPI** indicate

Zinyuk et al (FOPI)'14; Gasik et al (FOPI) '16; Piasecki et al (FOPI) '16; Adamczewski-Musch et al (HADES) '17..

- K^+ in-medium potential is repulsive: $U_{KN}(\rho_0) \approx 20...40$ MeV
- K^- from Φ decay wash out the effects of the potential (spectra and flow!!)

- separate direct kaons (→ COSY)/elementary reactions
- more systematic, high statistic data on K^- production necessary

conclusions from Leifels-SQM2017

Recent results on kaon and antikaon production in HiCs using a PHSD model with in-medium strange mesons compared to KaoS, FOPI and HADES experimental data

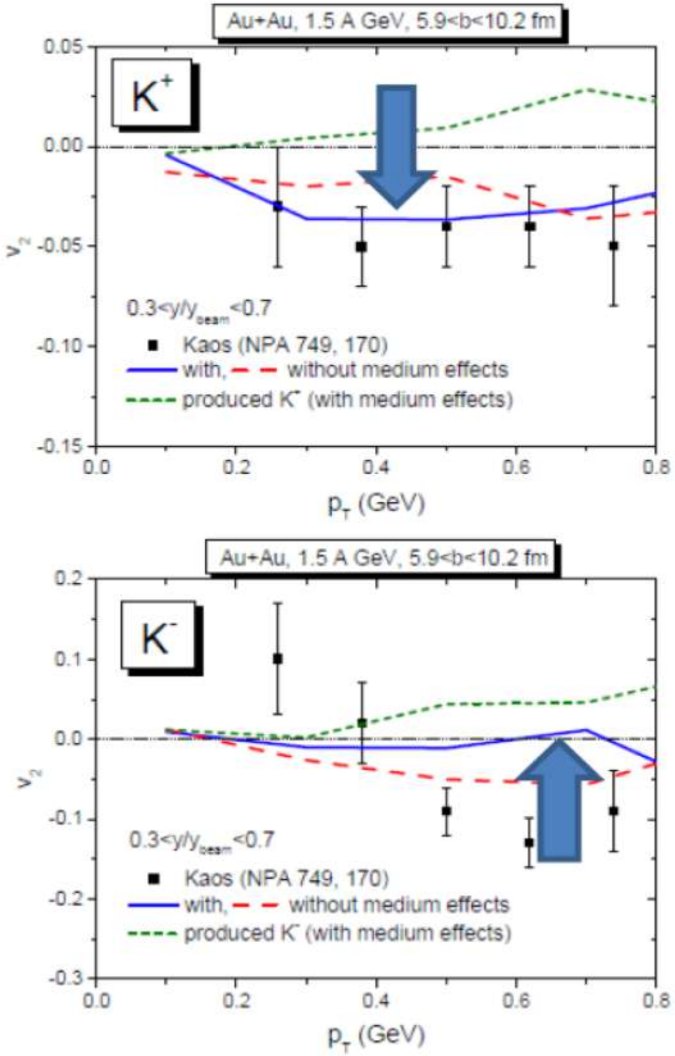
- The nuclear effects on (anti)kaon are more prominent in the collision of large nuclei

- (Anti)kaon production is (enhanced)suppressed due to (broadening of spectral function)repulsive kaon potential

- (Anti)kaon spectrum becomes (softer)harder in nuclear matter, whereas y-distribution (shrinks)broadens

- Different behaviour of v1/v2 for antikaons and kaons due to the attractive vs repulsive character of the interaction with nucleons

- A moderate EoS (K~300 MeV) reproduces the experimental HiC data better

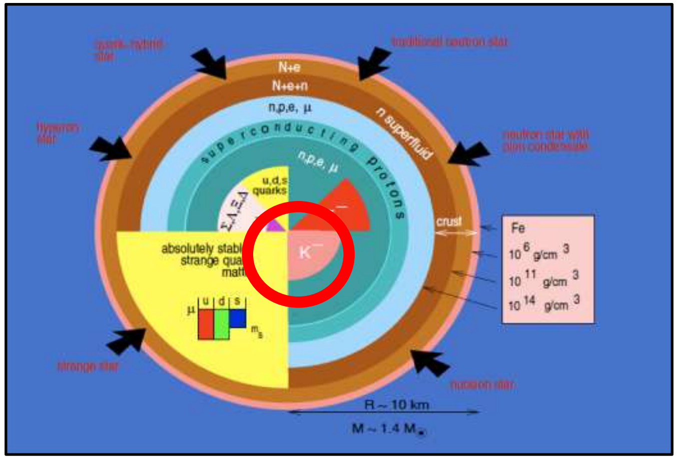


Song, LT, Wirth, Aichelin and Bratkovskaya ‘21

Experiments and observations:
…. to stars

Kaon condensation in neutron stars

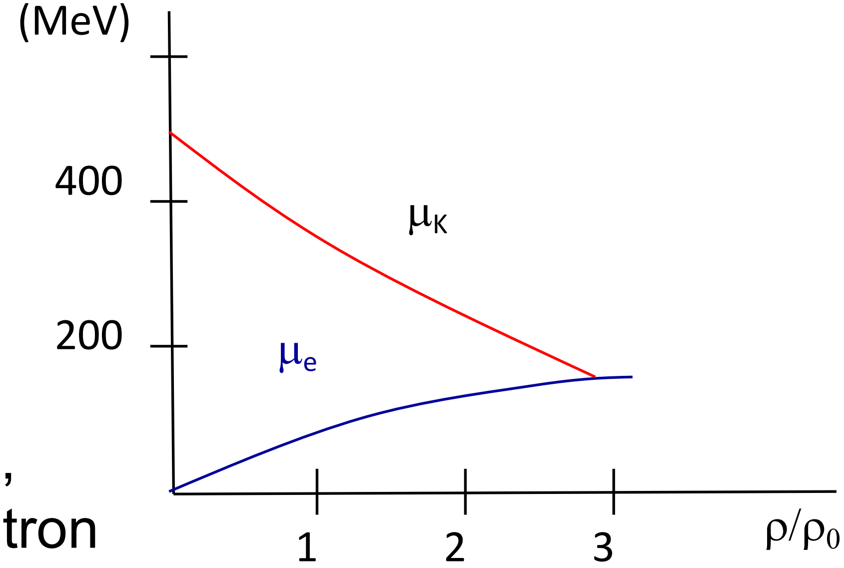
Kaplan and Nelson '86
Brown and Bethe '94



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 antikaons have to lower mass drastically

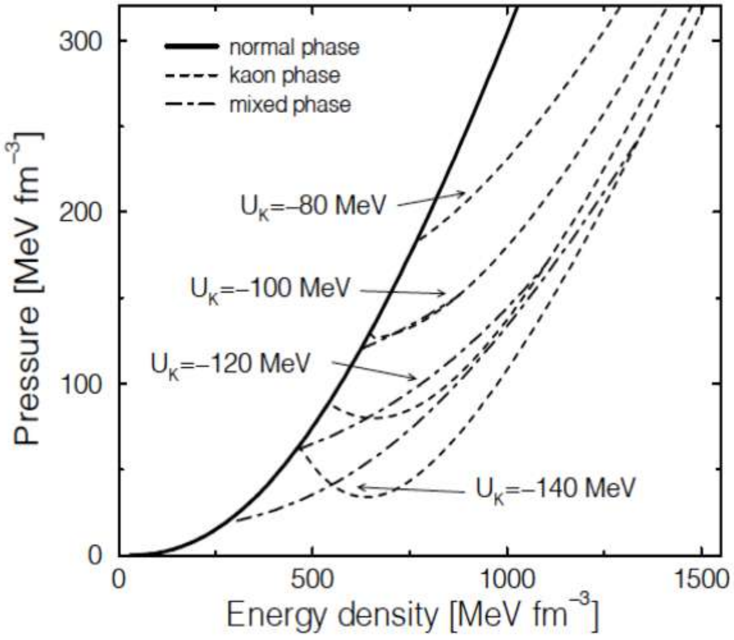
Kaplan and Nelson ’86

Medium effects on antikaons important: kaon condensation is possible!

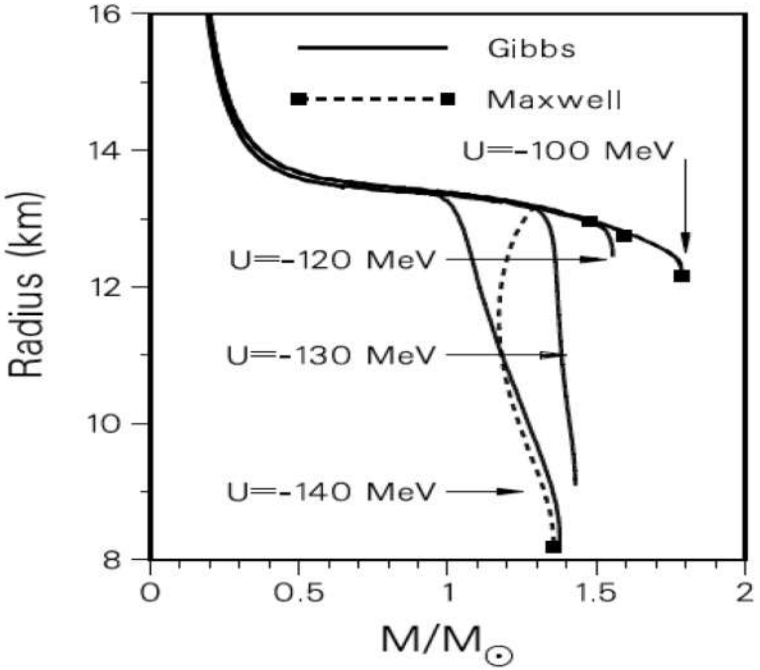
Brown, Kubodera, Rho and Thorsson’92; Thorsson, Prakash and Lattimer ’94;
Fujii, Maruyama, Muto and Tatsumi ’96; Li, Lee and Brown ’97; Knorren, Prakash and Ellis ’95; Schaffner and Mishustin ’96; Glendenning and Schaffner-Bielich ’98 ’99

Renewed interest on antikaon-nucleon interaction

Glendenning and Schaffner-Bielich ’99



EoS is softened
due to kaon condensation



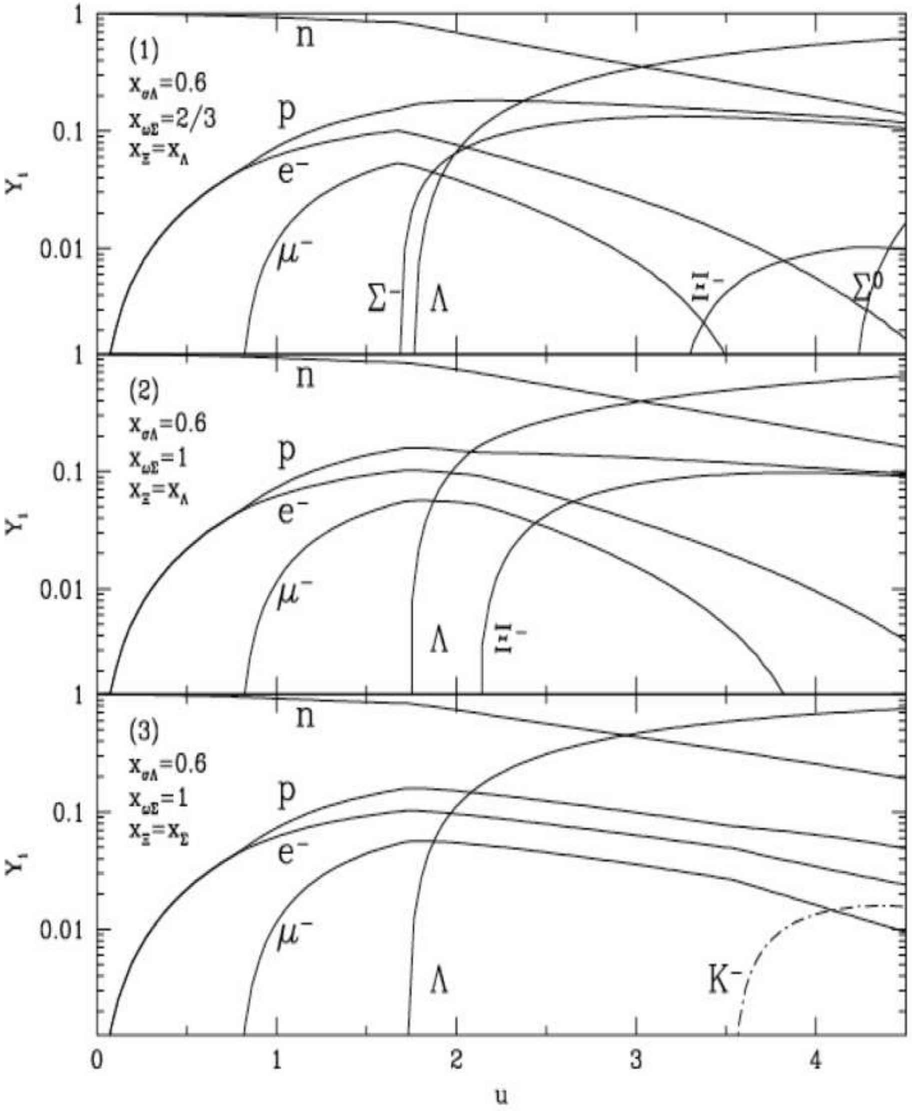
The maximum mass is lowered with
increasing attractive K^-N potential

Hyperonization on kaon condensation

Knorren, Prakash and Ellis ’95

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

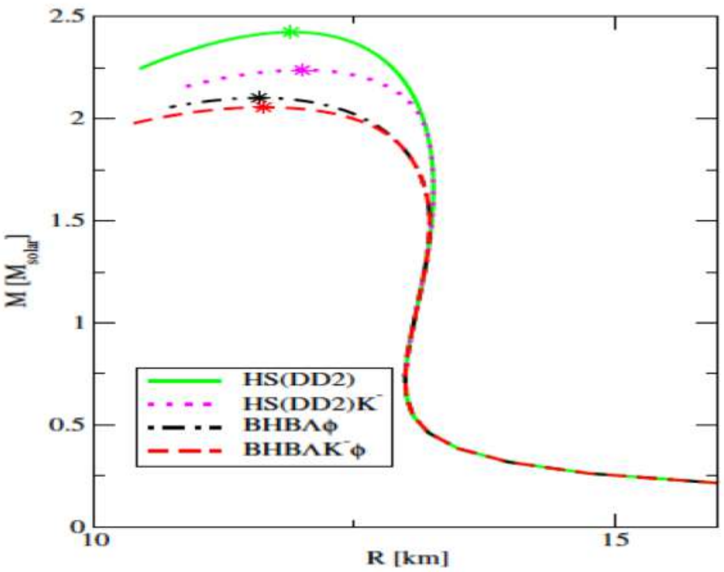
Knorren, Prakash and Ellis ’95



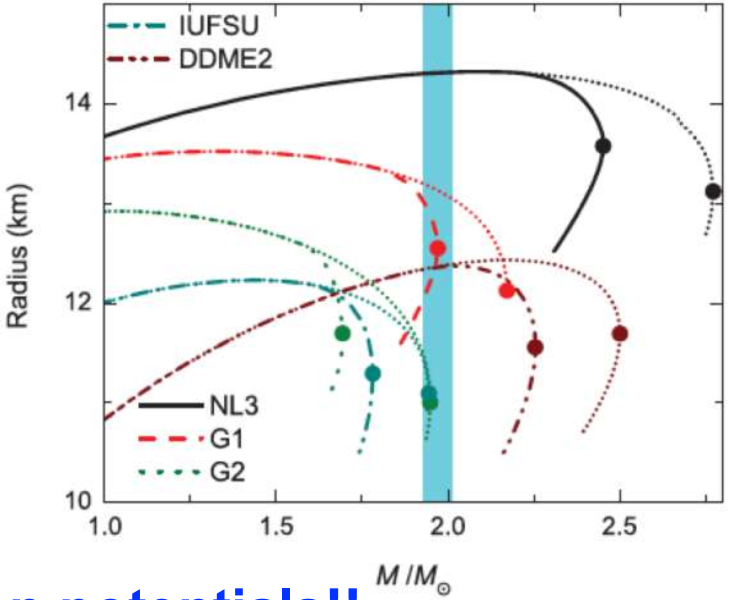
Later on different groups have worked on **improved relativistic-mean field models** to include kaon condensation and to fulfill neutron star properties and to study proto-neutron stars, supernova or neutron star mergers

RMF models

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

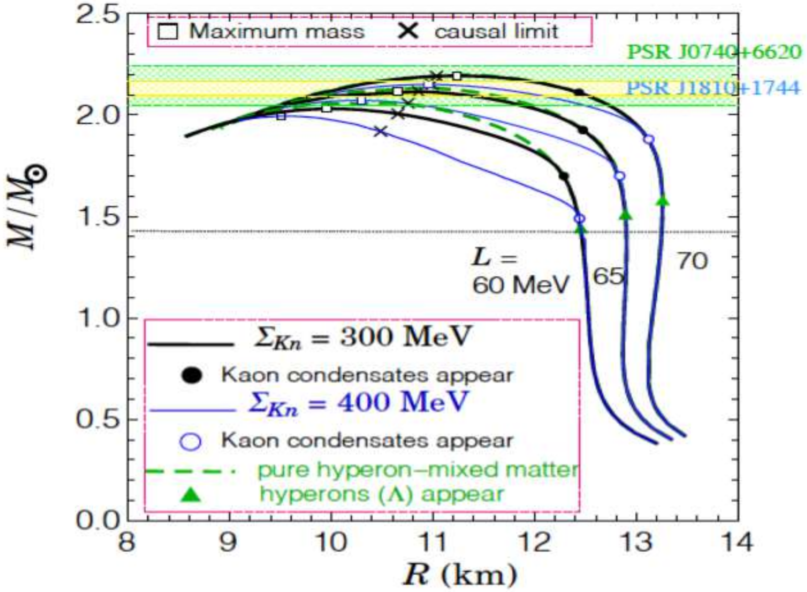


Gupta and Arumugam ‘12 ‘13

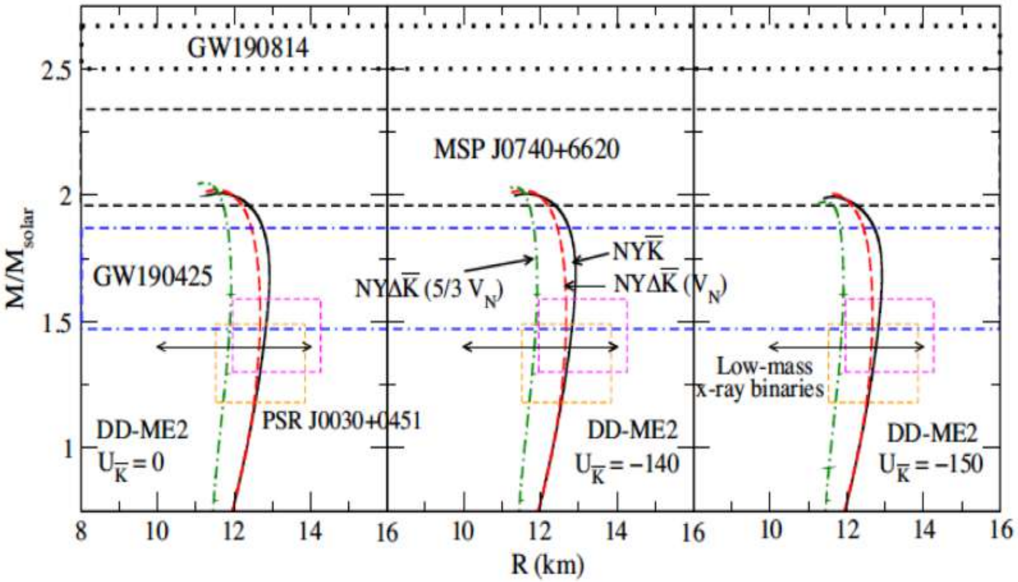


Need of large antikaon potentials!!

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

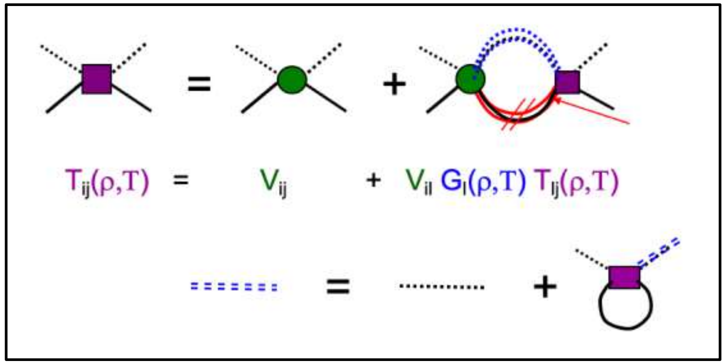


Thapa and Sinha ‘20
Thapa, Sinha, Li and Sedrakian ‘21



Using microscopic unitarized schemes…

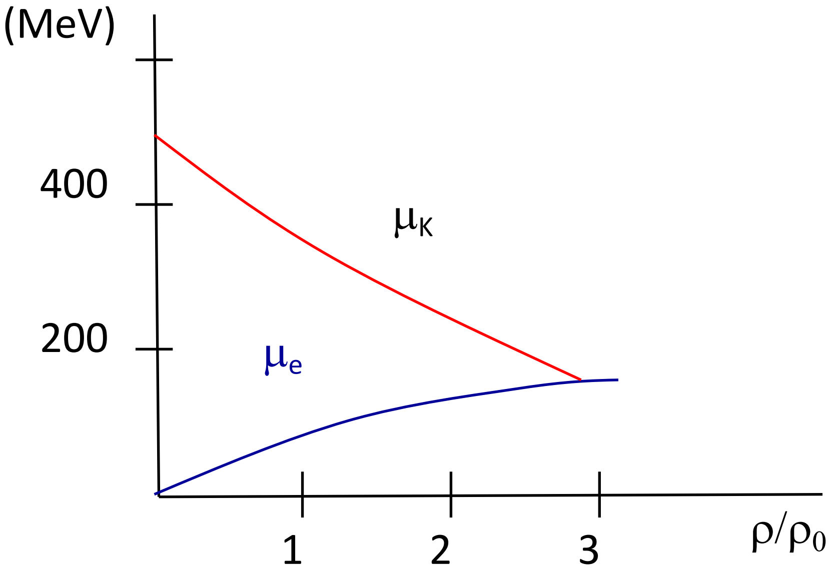
The condition $\mu_{e^-} \geq m^*_{K^-}$ for a given ρ_c implies that $m_{K^-} - m^*_{K^-}(\rho_c) \approx 200, 300$ MeV.



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

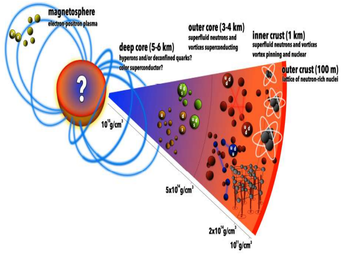
Tolos and Fabbietti ’20

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

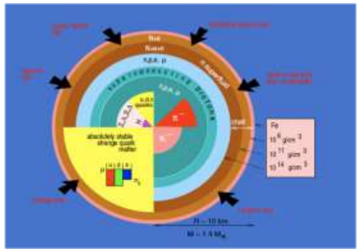


Lutz ‘98
Ramos and Oset ‘00
Tolos, Polls, Ramos ’01
Tolos, Ramos and Oset ‘06
Tolos, Cabrera and Ramos ‘08
Cabrera, Tolos, Aichelin and Bratkovskaya’14…

Kaon condensation seems very unlikely!



Present and Future



A lot of observational and theoretical effort has been invested in studying hadronic matter in neutron stars, in particular strangeness inside the core

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

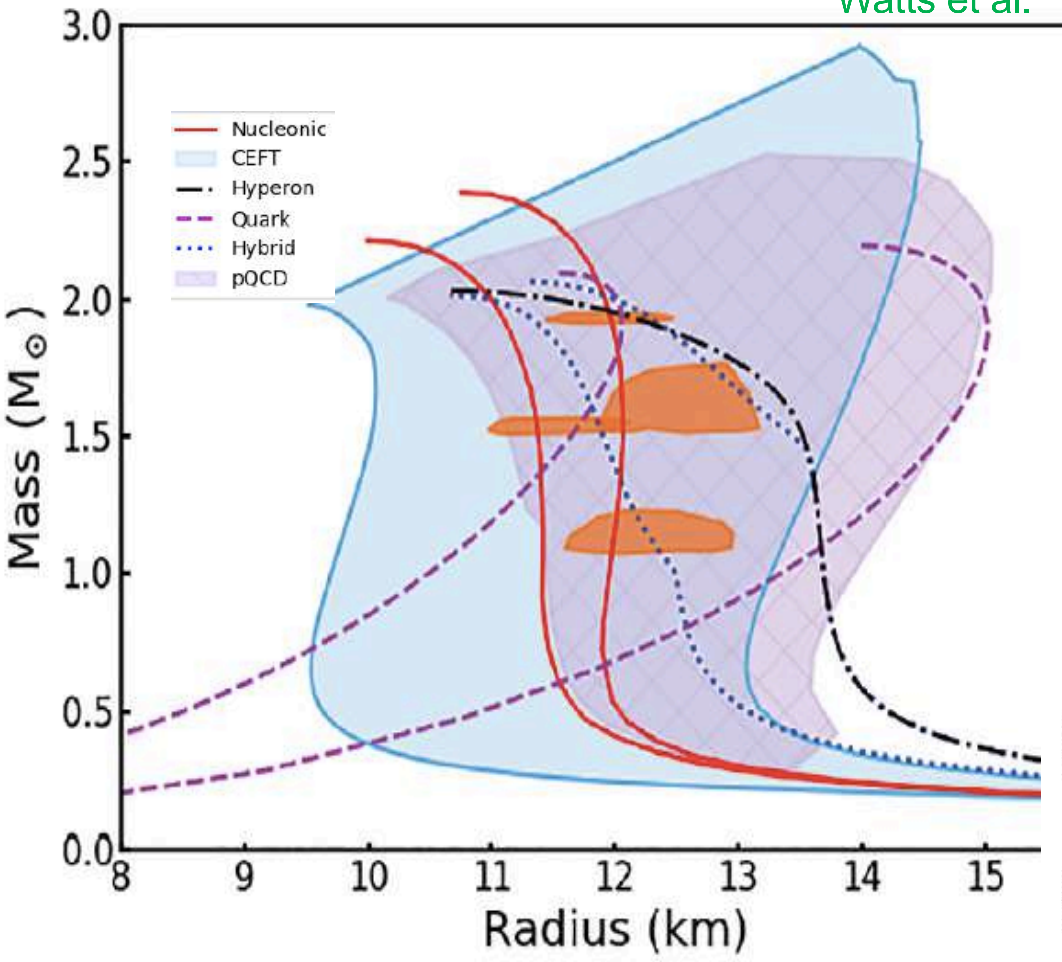
The presence of antikaons in neutron stars is controversial

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

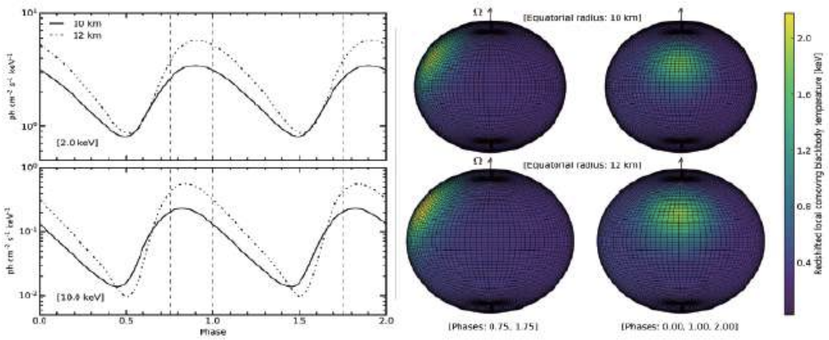
STRONG 2020
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

Space missions to study NS

Watts et al. ‘19



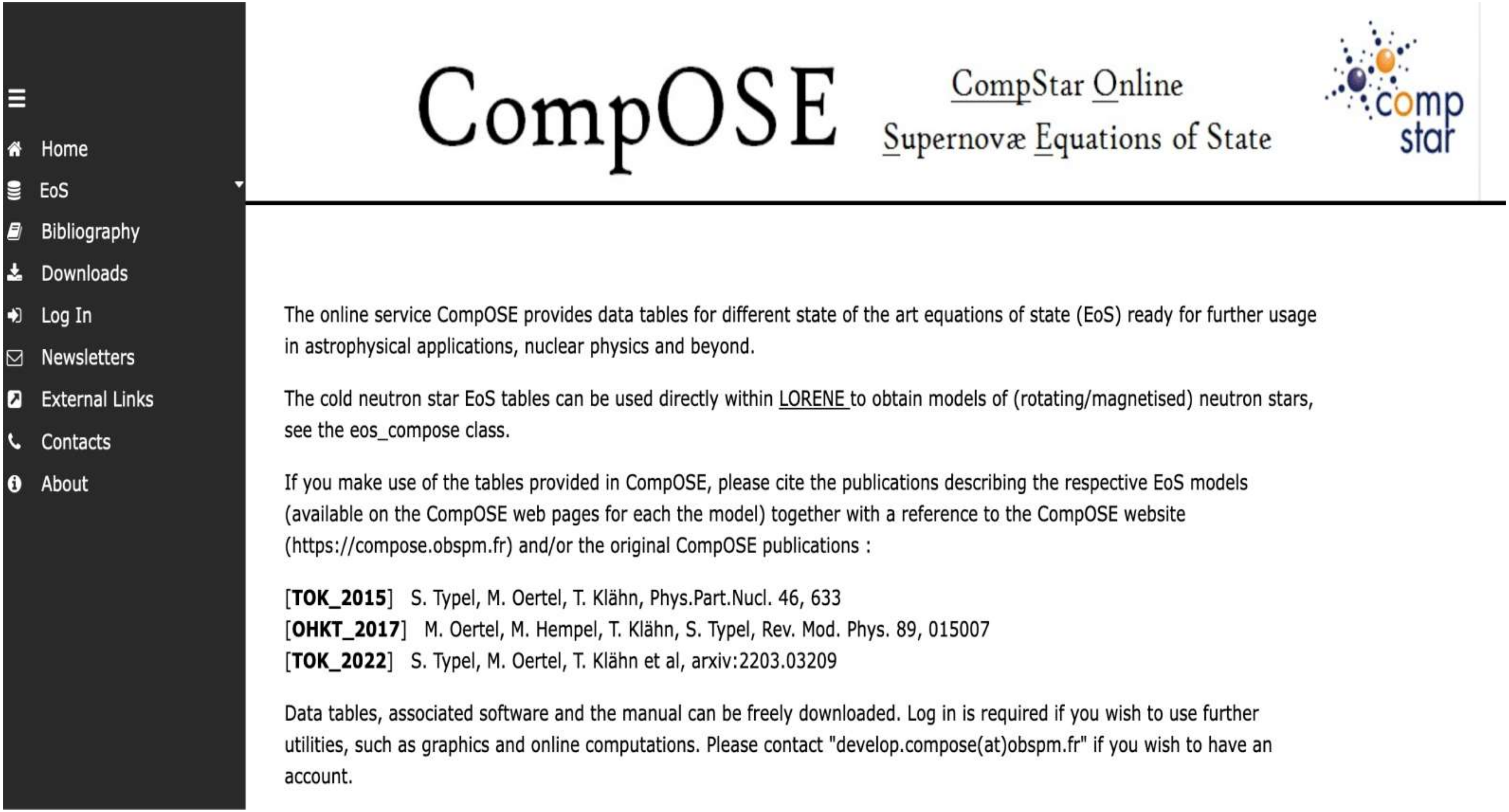
STROBE-X



Constraints from pulse profile modelling of rotation-powered pulsars with eXTP

and multimessenger astronomy!

https://compose.obspm.fr/



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