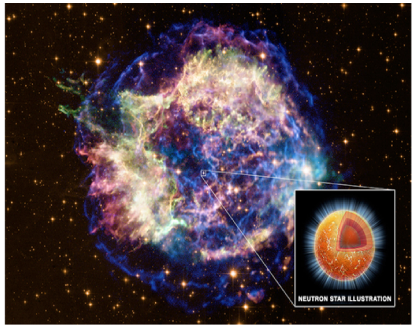
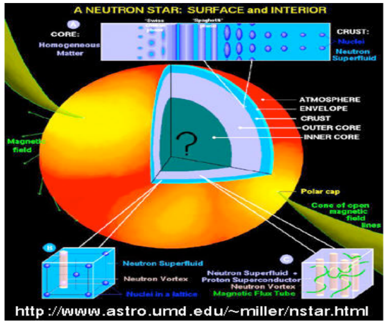
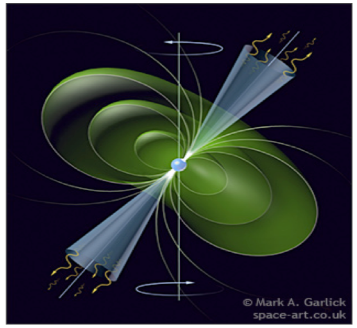






Hyperons in Neutron Stars

FIAS Frankfurt Institute for Advanced Studies

Laura Tolós

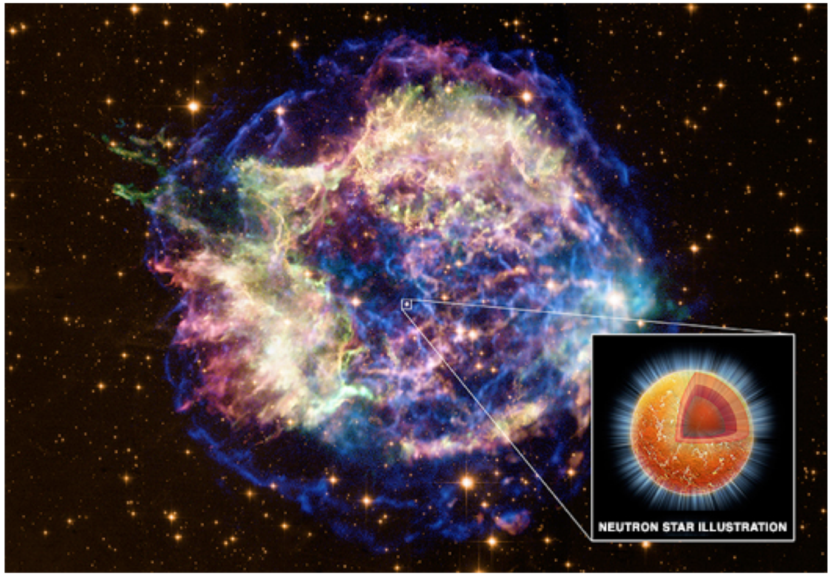
Institute of Space Sciences
CSIC IEEC
Consejo Superior de Investigaciones Científicas

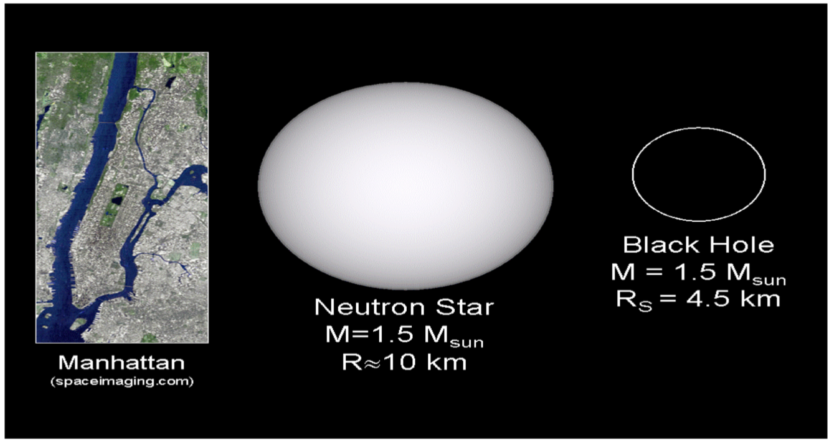
FNHP2022
FRONTIERS IN NUCLEAR AND HADRONIC PHYSICS
School at the Galileo Galilei Institute for Theoretical Physics
Florence, February 21 - March 04, 2022

Outline

- What is a Neutron Star?
- Observations:
  Masses, Radius & GW170817
- Internal structure and composition:
  the Core
- Baryonic (nucleonic) matter in the core
- Baryonic (hyperonic) matter
- Structure Equations for neutron stars
- Mass-Radius relation
- Bibliography

What is a Neutron Star?





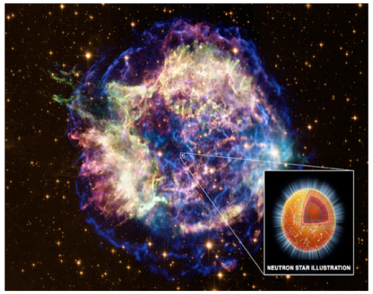
A neutron star is a stellar compact object with

$M \approx 1\text{-}2\ M_{\odot}$

$R \approx 10\text{-}12$ Km

densities up to $5\text{-}10\ n_0$
($n_0 \sim 3 \times 10^{14}$ g/cm^3)

Neutron stars are some of the densest manifestations of massive objects in the universe.



Neutron stars offer the possibility to study fascinating phenomena of *matter under extreme density conditions*.
It is a very active field of research inmany physics disciplines:

- For **astronomers** neutron stars are very small stars visible as radio-pulsars, or also as a source of X and γ rays

- For **particle physicists** a neutron star is a source of neutrinos (in some early stage of its evolution) and also one of the few places were quark matter can exist

- For **nuclear physicists**, they are considered as the largest nucleus in the universe and can be used to determine the EoS of neutron matter in a wide range of densities

- For **cosmologists**, they are considered as almost black holes

- For **computational physicists**, the simulation of their birth and evolution is a real headache

When was discovered?

Baade and Zwicky predicted in the 1930s that neutron stars are born in supernova explosions. Neutron stars were thus expected to be seen in X-rays. But observations remained unconclusive until pulsars were discovered in 1967.

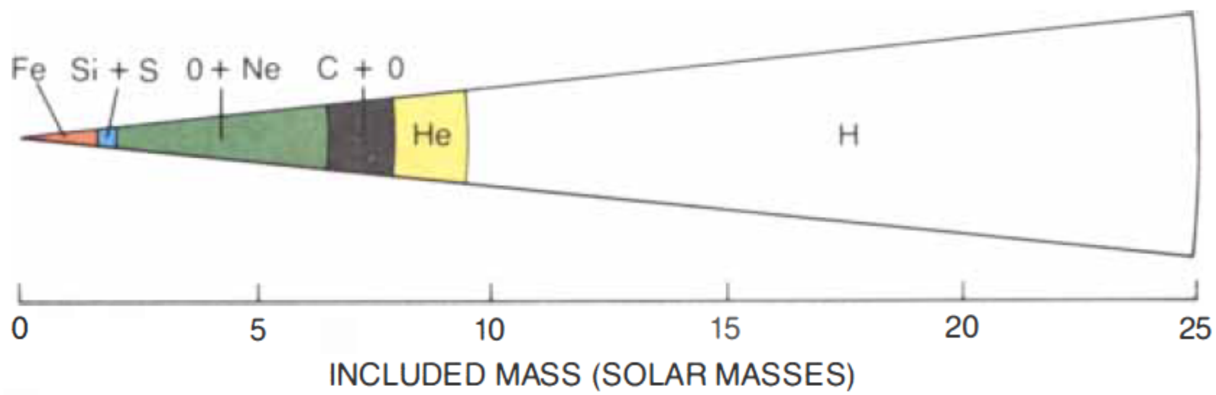
Wilhelm Walter Baade
1893-1960

Fritz Zwicky
1898-1974

In 1967 Jocelyn Bell, a graduate student in astronomy, discovered very regularly spaced bursts of radio noise in data from the radio telescope at Cambridge University. After eliminating any possible man-made sources she realized this emission must be coming from space. The regularity of these pulses at first made her and her co-workers think they had discovered alien life (they named the signal LGM-1: “little green men”). Later they realized these must be due to rapidly spinning neutron stars.

How is a neutron star formed?

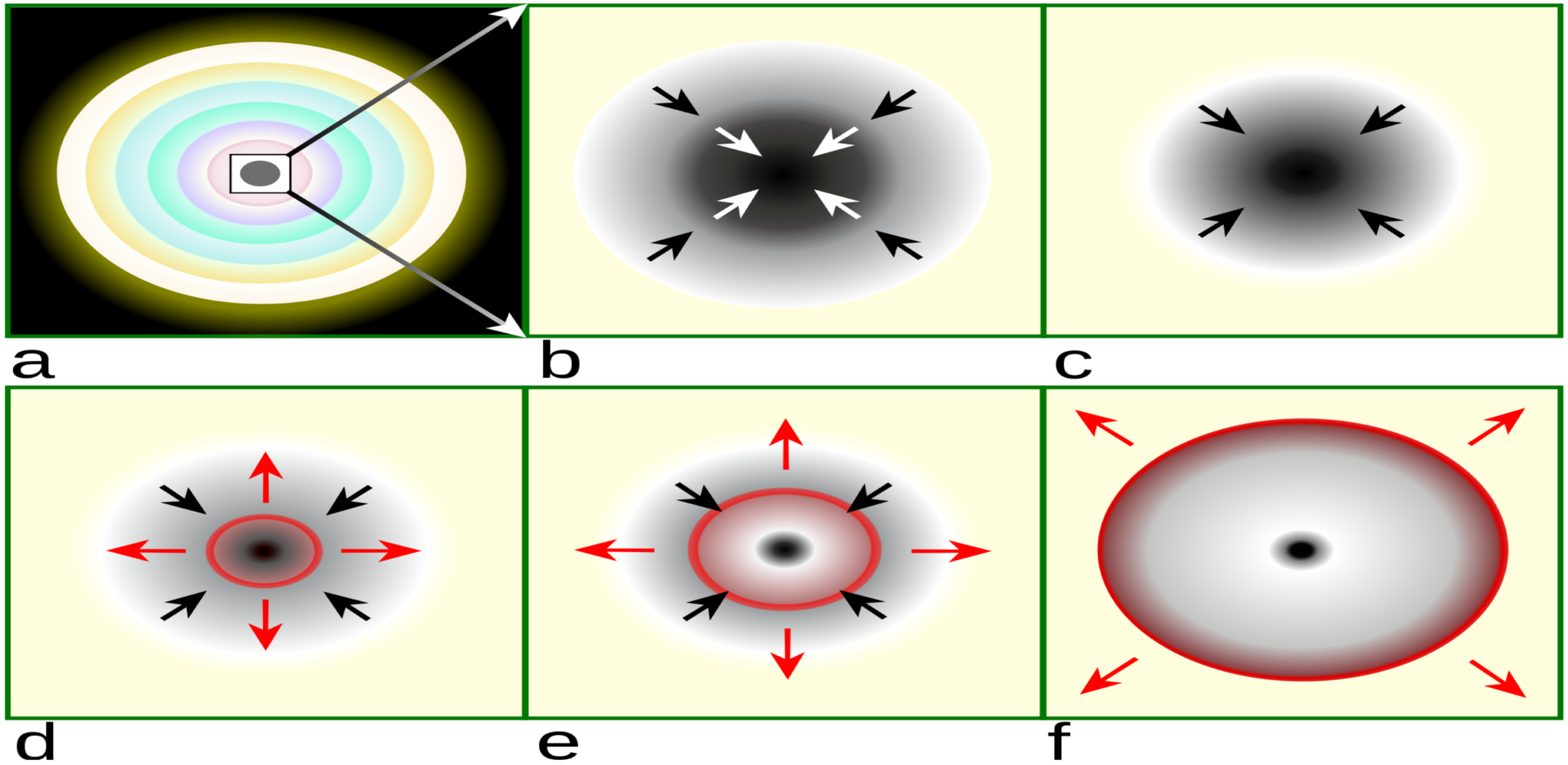
When a large star runs out of nuclear fuel, the core collapses in milliseconds. The subsequent "bounce" of the core generates a shock wave so intense that it blows off most of the stars mass.



As a result of Silicon fusion, an inert core of Iron (Fe) plasma is steadily building up at the center. Once this core reaches the Chandrasekhar mass, the iron can no longer sustain its own mass and it undergoes a collapse.

This can result in a supernova explosion.

How a supernova explodes
Brown, G.; Bethe, H. A.
Scientific American 252, May 1985, p. 60-68.



Within a massive, evolved star (a) the onion-layered shells of elements undergo fusion, forming an iron core (b) that reaches Chandrasekhar-mass and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.

What do we know about neutron stars?

Observations include binary pulsars, thermal emission from isolated neutron stars, glitches from pulsars and quasi-periodic oscillations from accreting neutron stars. They provide information about neutron star masses, radii, temperatures, magnetic fields, ages and internal compositions.

Mass: $M \sim 1\text{-}2\ M_\odot$, Hulse-Taylor pulsar: $M_{PSR1913+16} = 1.4411 \pm 0.0035\ M_\odot$

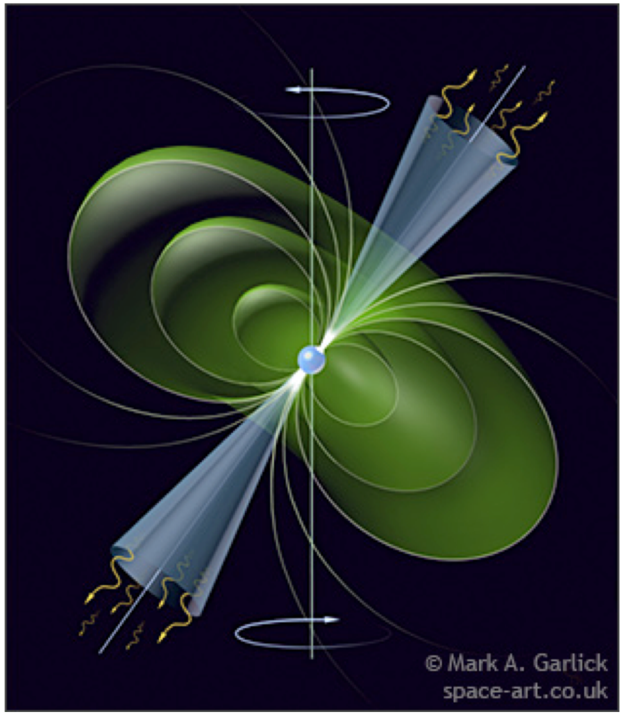
Radius: $R \sim 10\text{-}12$ km

Density:

$n \sim 10^{14}\text{-}10^{15}$ g/cm^3 $\quad$ $n_{universe} \sim 10^{-30}$ g/cm^3

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

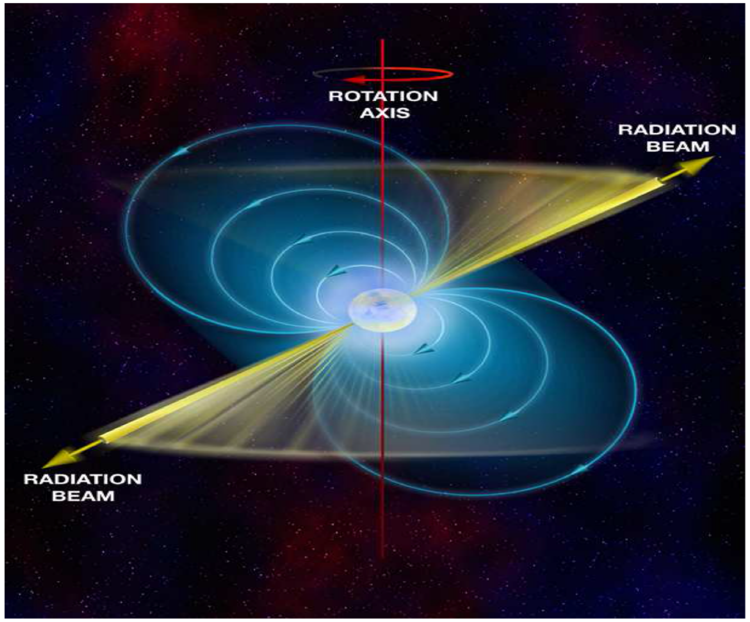
$n_{earth} \sim 5.5$ g/cm^3



Magnetic field: $B \sim 10^{8 \ldots 16}$ G ($10^{4 \ldots 12}$ T)

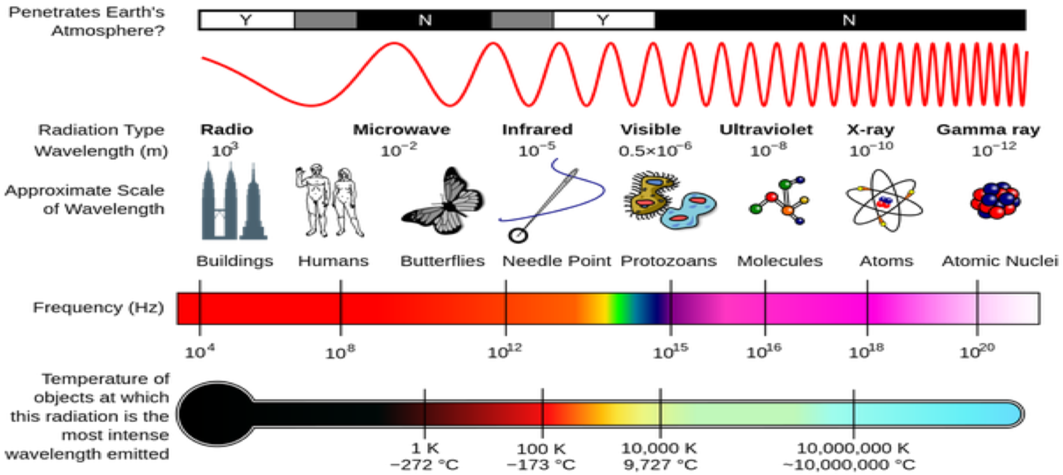
Temperature: $T \sim 10^{6 \ldots 11}$ K

Rotational periods: P ~ ms … s

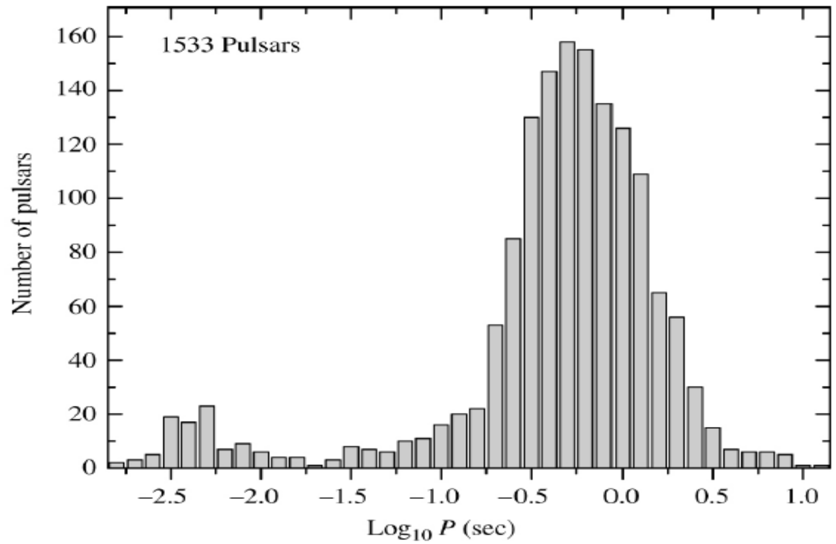


Pulsars are magnetized rotating neutron stars emitting a highly focused beam of electromagnetic radiation oriented long the magnetic axis.
The misalignment between the magnetic axis and the spin axis leads to a lighthouse effect: from Earth we see pulses

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



Most of them have been detected as radio pulsars, but also some 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

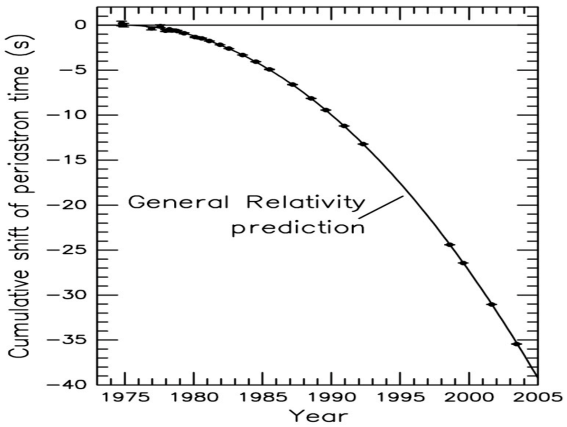
- > 2500 pulsars known

- best determined masses:

Hulse-Taylor pulsar

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

Hulse-Taylor Nobel Prize 94



- PSR J1614-2230[1]

$M = (1.97 \pm 0.04)\ M_\odot$;

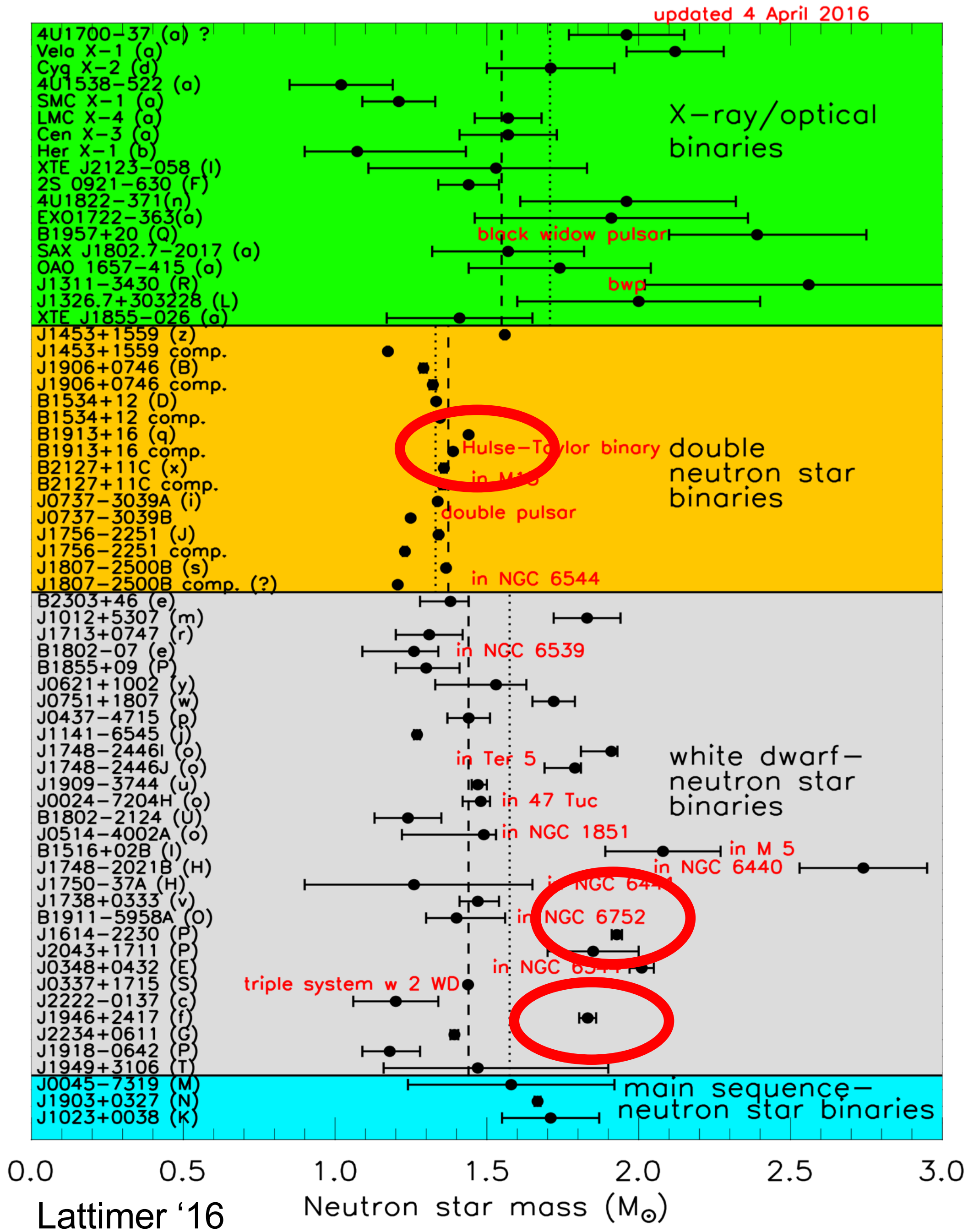
PSR J0348+0432[2]

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

MSP J0740+6620[3]

$M = (2.14 + 0.1 - 0.09)\ M_\odot$

[1]Demorest et al '10; [2]Antoniadis et al '13; [3]Cromartie et al '19



Lattimer '16

Observations: Radius

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

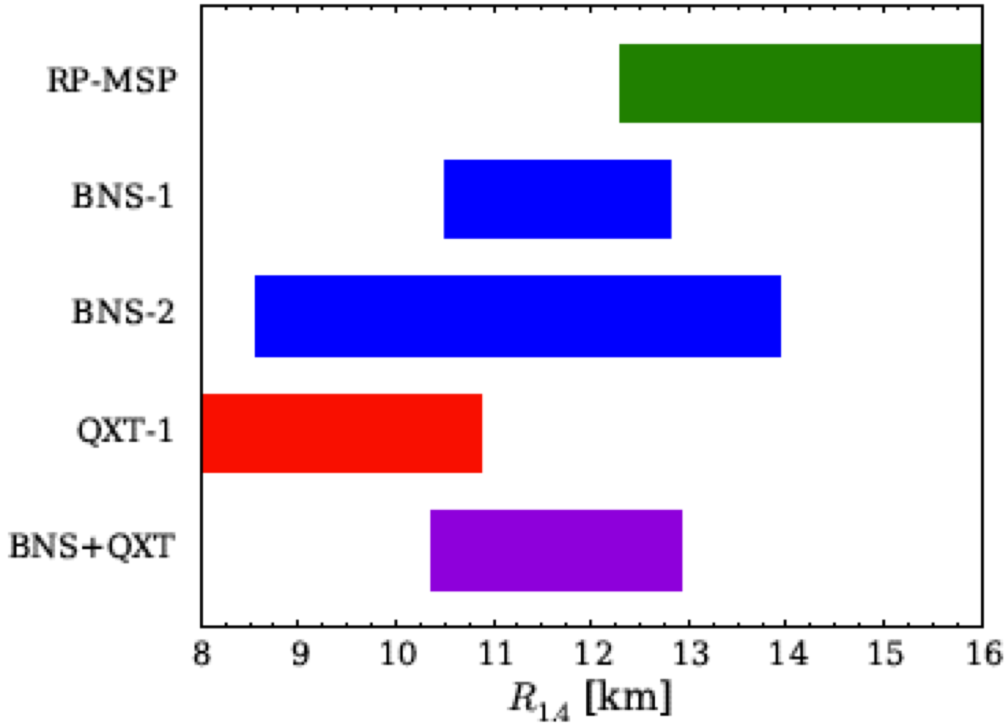
analysis of X-ray spectra from neutron star (NS) atmosphere:

- 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



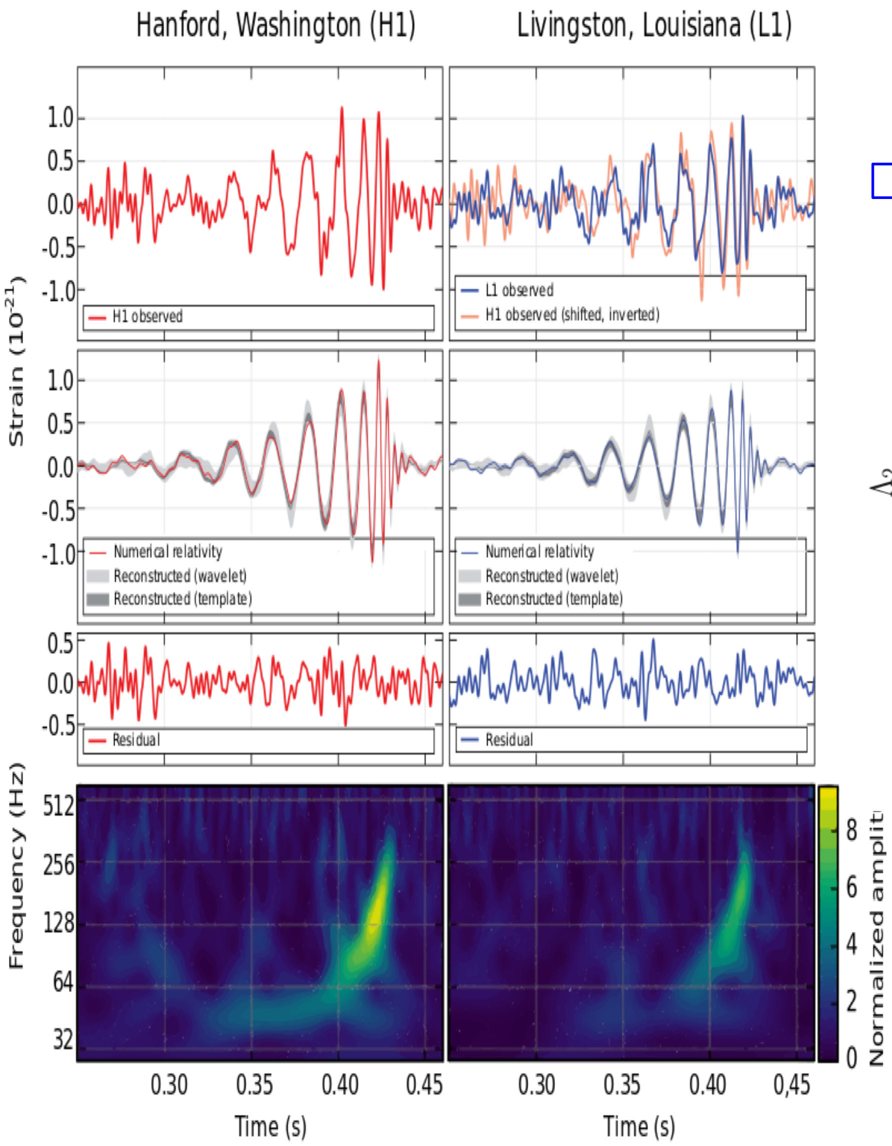
Some conclusions:

✓ marginally consistent analyses, favored R < 13 Km (?)
✓ X-ray telescopes (NICER, eXTP) with precision for M-R of ~ 5%
(NICER: PSR J0030+0451 with R~13 km and M~1.3-1.4 $M_{\odot}$;
PSR J0740+6620 with R~12-14 km and M~2.1 $M_{\odot}$)
✓ what about GW events: GW170817, GW190814, GW250419?

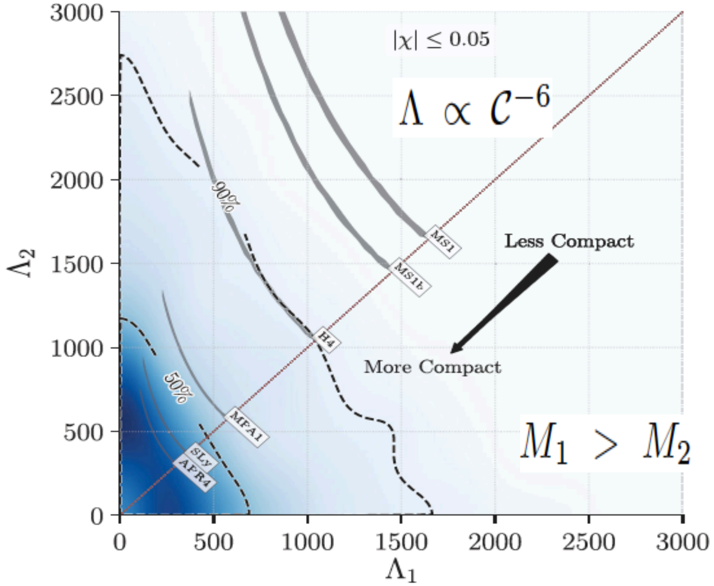
Observations: GW170817

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)	$(0, 630)$



Abbot et al. (LIGO-VIRGO) ‘17



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

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

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

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, ..

Internal structure and composition: the Core

A. Watts et al. ‘15

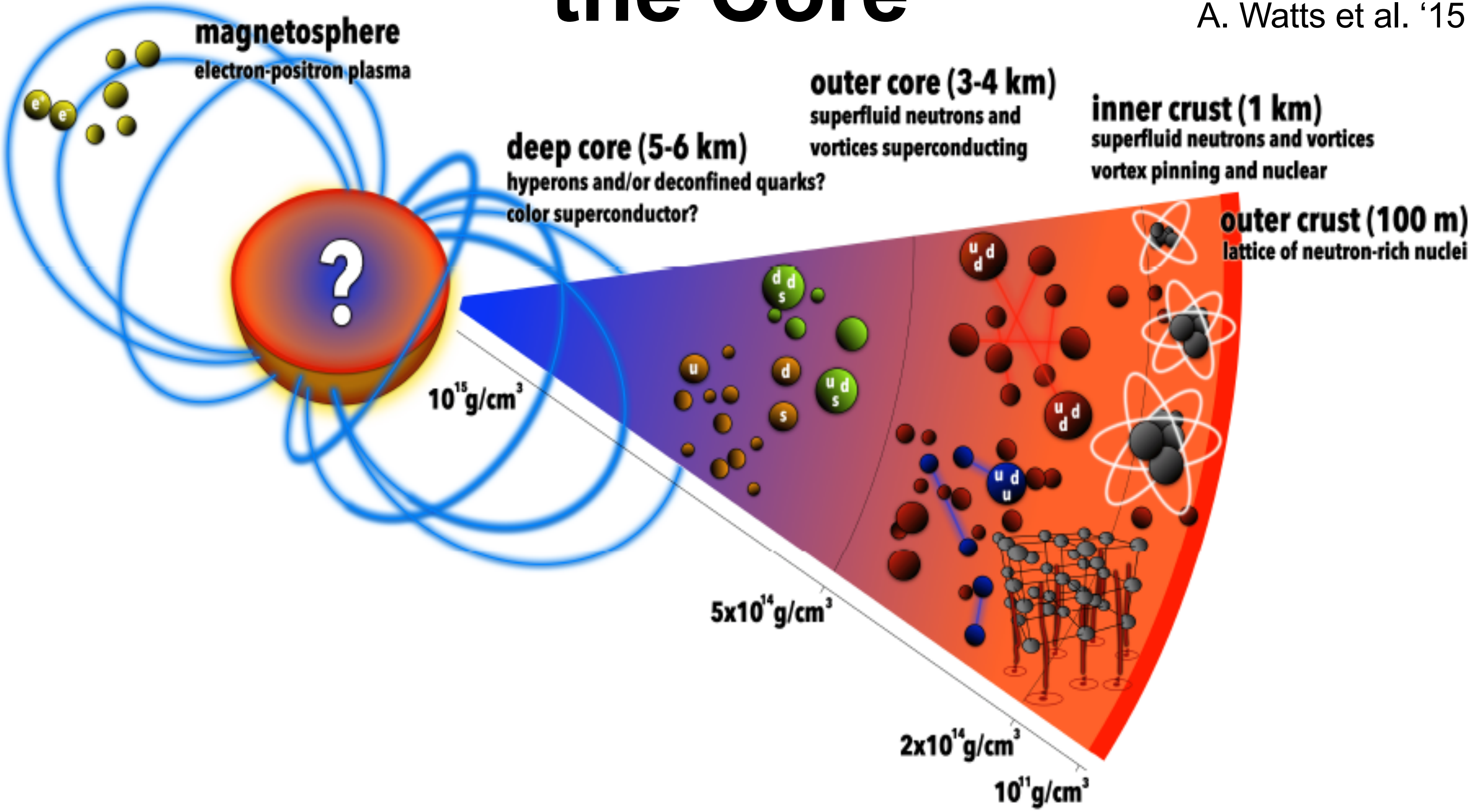


Figure 1: Schematic structure of a NS. The outer layer is a solid ionic crust supported by electron degeneracy pressure. Neutrons begin to leak out of nuclei at densities $\sim 4\times10^{11}$ g/cm^3 (the neutron drip line, which separates inner and outer crust), where neutron degeneracy also starts 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).

- Atmosphere

few tens of cm, $\rho \leq 10^4$ g/cm^3 made of atoms

- Outer crust and Envelope

few hundred m's, $\rho=10^4$-$4 \cdot 10^{11}$ g/cm^3 made of free e^- and lattice/liquid of nuclei

- Inner crust

1-2 km, $\rho=4 \cdot 10^{11}$-10^{14} g/cm^3 made of free e^-, neutrons and neutron-rich atomic nuclei

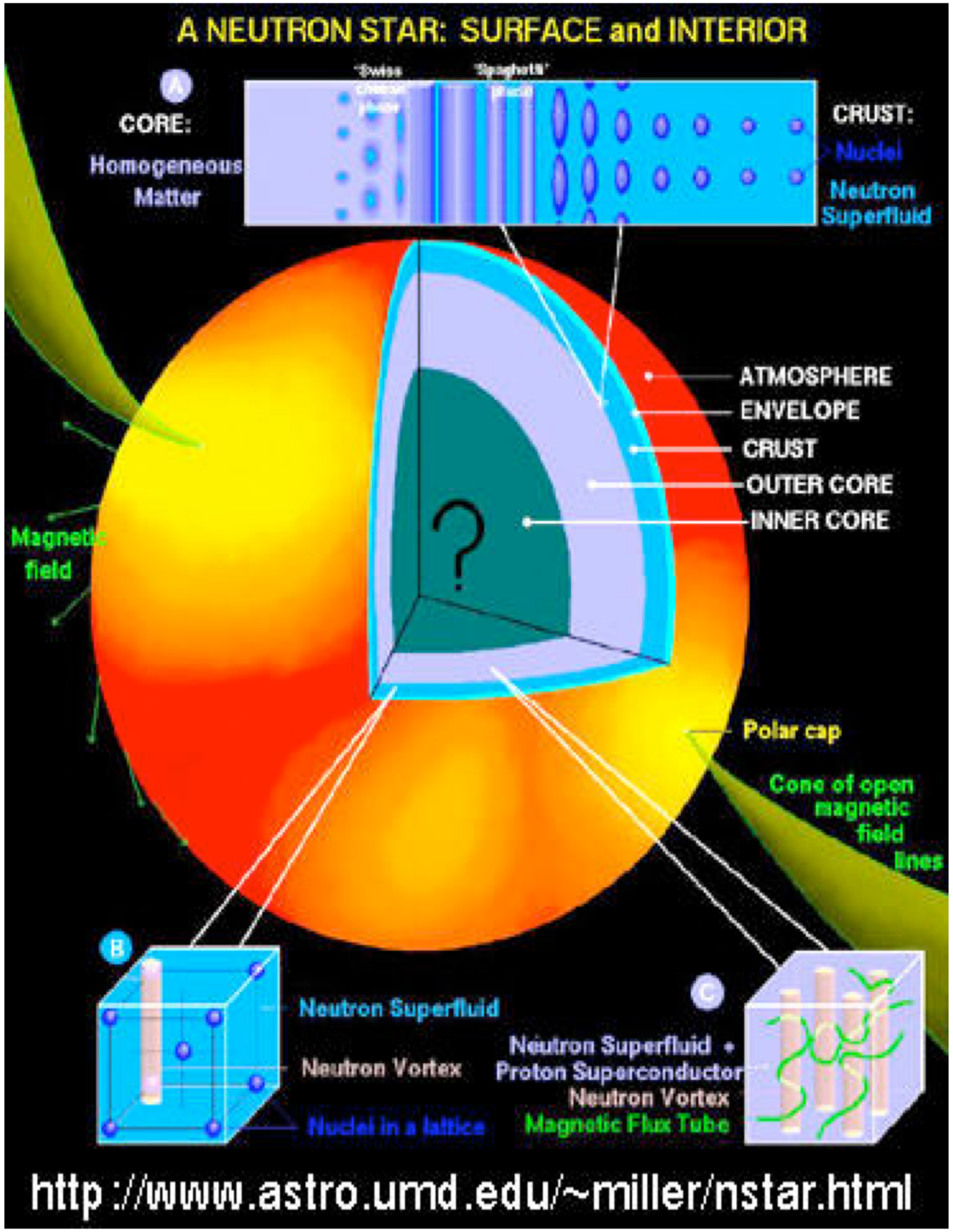
$\sim\rho_0/2$: uniform fluid of n,p,e^-

- Outer core

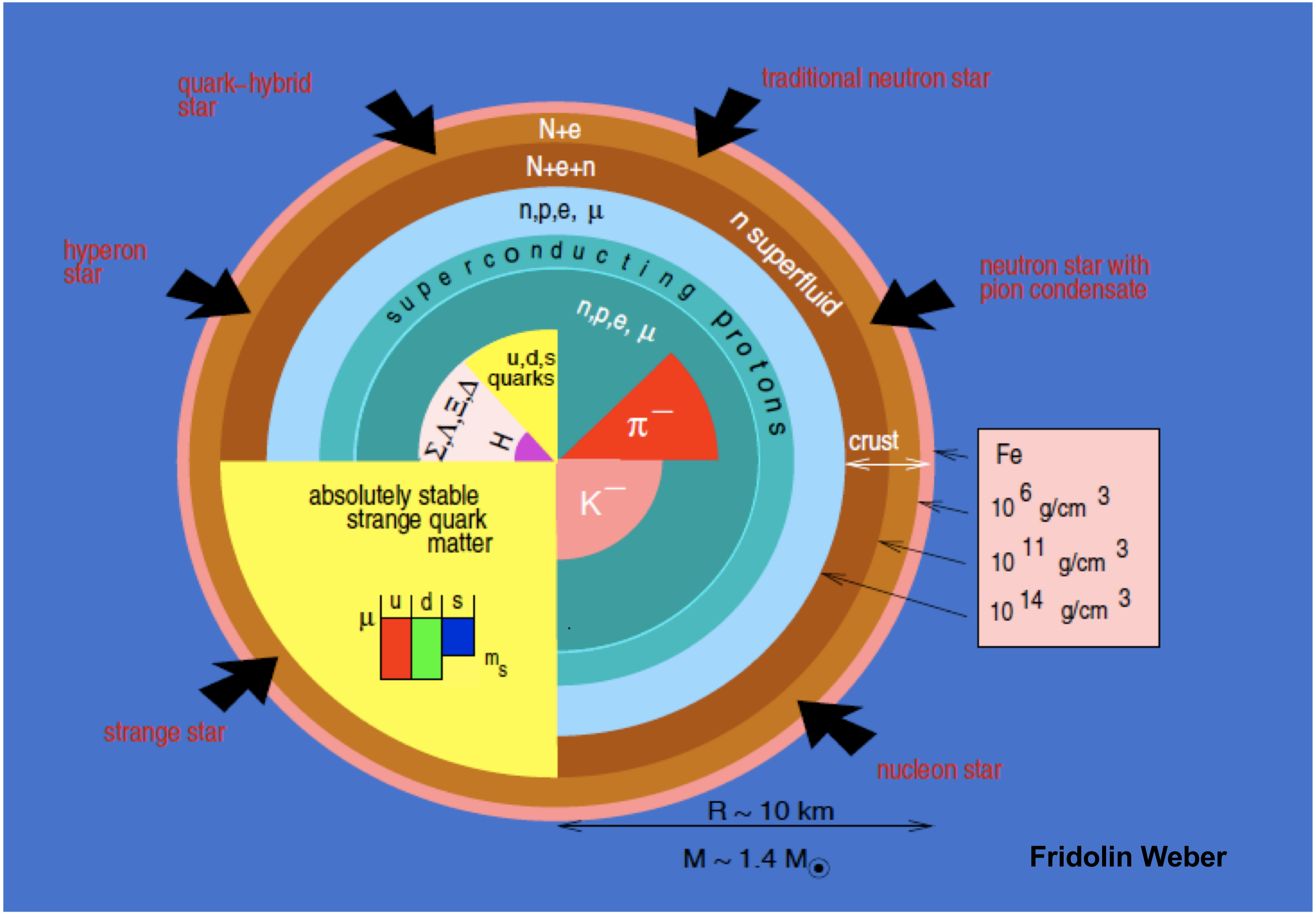
$\rho_0/2$-$2\rho_0$ is a soup of n,e^-,μ and possible neutron $^3P_2$ superfluid or proton $^1S_0$ superconductor

- Inner core (?)

2-10 ρ_0 with unknown interior made of hadronic, exotic or deconfined matter



The Core of a Neutron Star



Baryonic (nucleonic) matter in the core

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

1. 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!

2. the Fermi gas model ignores nuclear interactions, which give important contributions to the energy density

3. 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

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

Baryonic (nucleonic) matter in the core

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

1. **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!**

2. the Fermi gas model ignores nuclear interactions, which give important contributions to the energy density

3. 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

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

1. npe in β-equilibrium

The composition of neutron star matter is found by demanding equilibrium against weak interaction processes (β-stability). Therefore, the reaction for the decay of a free neutron:

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

(responsible for the free neutron lifetime of 15 minutes) is halted in neutron star matter by the presence of protons and electrons. Protons and neutrons in their lowest levels of their corresponding Fermi seas are occupied and the reaction is Pauli blocked.

In this regime the decay reaction is equilibrated with the electron capture one:

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

This equilibrium can be expressed in terms of the chemical potentials.

Since the mean free path of the ν_e is >> 10 km, they freely escape

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

Charge neutrality is also ensured by demanding ρ_p=ρ_e, i.e. k_{Fp}=k_{Fe}

$$\rho_p = \rho_e$$

Note that baryon number is conserved too: $\rho = \rho_n + \rho_p$

2. Nuclear interactions

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

At T=0, $\boxed{E(\rho,\delta) = E(\rho,0) + S(\rho)\delta^2}$ with $\delta = (N-Z)/A$, $A = N+Z$

baryon density

neutron number

proton number

mass number

energy of symmetric nuclear matter $$E(\rho,0) = E(\rho_0) + \frac{1}{18}K_0\ \varepsilon^2$$

$$\varepsilon = \frac{\rho-\rho_0}{\rho_0}$$

symmetry energy $$S(\rho) = S_0 + \frac{1}{3}L\varepsilon + \frac{1}{18}K_{\mathrm{sym}}\ \varepsilon^2$$

$$E(\rho_0)/A \equiv E_0/A$$

$$\rho_0 = 0.16 \pm 0.01\ \mathrm{fm}^{-3}$$

$$E_0/A = -16 \pm 1.0\ \mathrm{MeV}$$

binding energy per nucleon at saturation density n_0

$$K_0 \equiv 9\rho_0^2\left(\frac{\partial^2 E}{\partial\rho^2}\right)_{\rho=\rho_0,\delta=0}$$

incompressibility at n_0

$$S_0 \equiv \frac{1}{2}\left(\frac{\partial^2 E}{\partial\delta^2}\right)_{\rho=\rho_0,\delta=0}$$

symmetry energy at n_0

$$L \equiv 3\rho_0\left(\frac{\partial S(\rho)}{\partial\rho}\right)_{\rho=\rho_0}$$

$$K_{\mathrm{sym}} \equiv 9\rho_0^2\left(\frac{\partial^2 S(\rho)}{\partial\rho^2}\right)_{\rho=\rho_0}$$

Constraints on Nuclear Equation of State from Nuclear Physics Experiments

- E/A from experimentally measured nuclear masses

$$\rho_0 = 0.16 \pm 0.01 \ \mathrm{fm}^{-3}$$
$$E_0/A = -16.0 \pm 1.0 \ \mathrm{MeV}$$

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

? 180 MeV < K_0 < 270 MeV ?

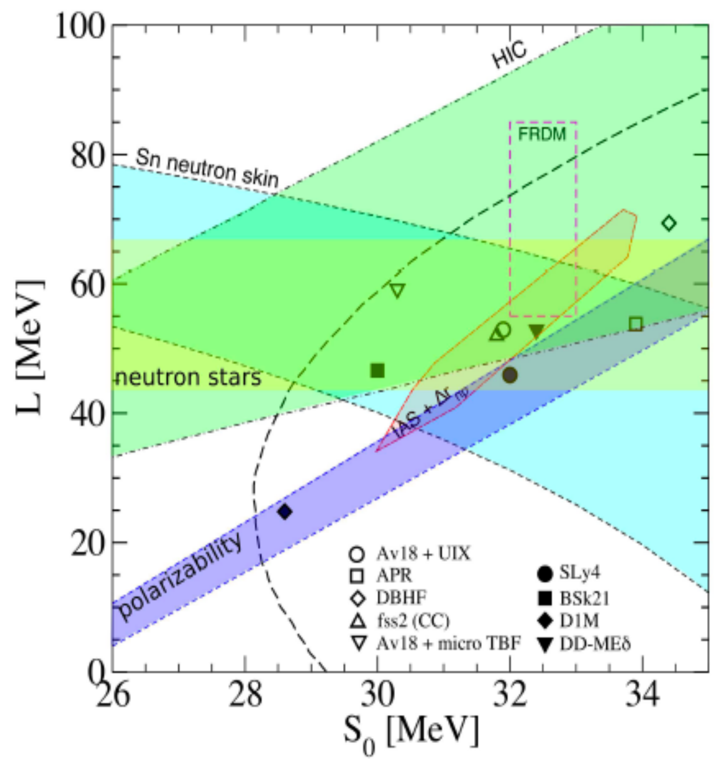
- S_0 from nuclear masses, isobaric analog state phenomenology, neutron skin thickness and HiCs; aditionally from NS data (fairly well constrained)

$S_0 \sim$ 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 (review) ‘18



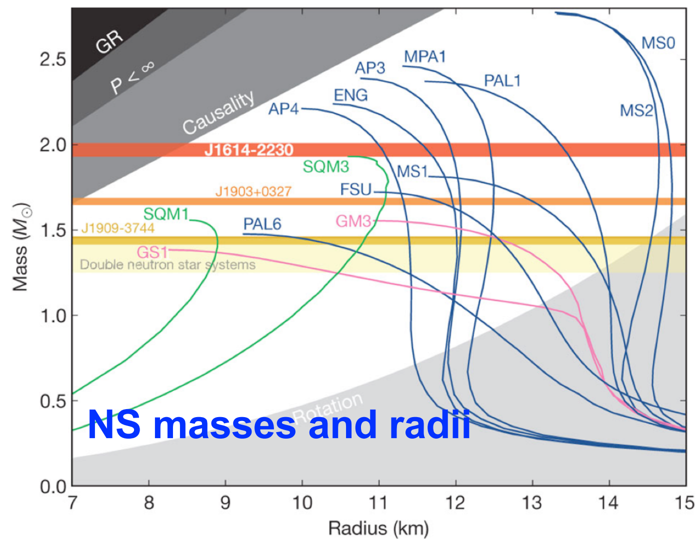
Constraints on Nuclear Equation of State from Astrophysical Observations

- NS masses

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

$$1.5M_\odot \lesssim M_{\rm max} \lesssim 2.5M_\odot$$

Ozel et al '16



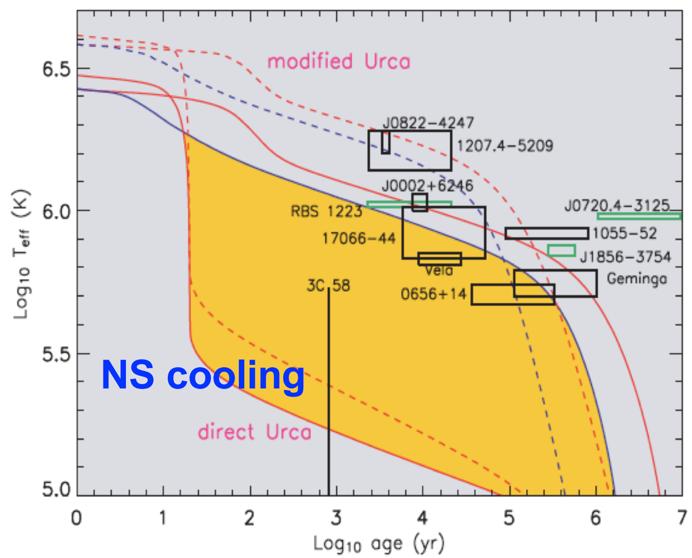
- NS radii

  - precise estimations of NS radii are very difficult because observations are indirect
  - need of simultaneous mass-radius measurement
  - future: NICER, ATHENA+, eXTP

- NS cooling

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

Lattimer and Prakash' 04



- NS moment of inertia

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

- Gravitational waves and quasi-periodic oscillations

Ab-initio versus Phenomenological Models

Microscopic Ab-initio Approaches

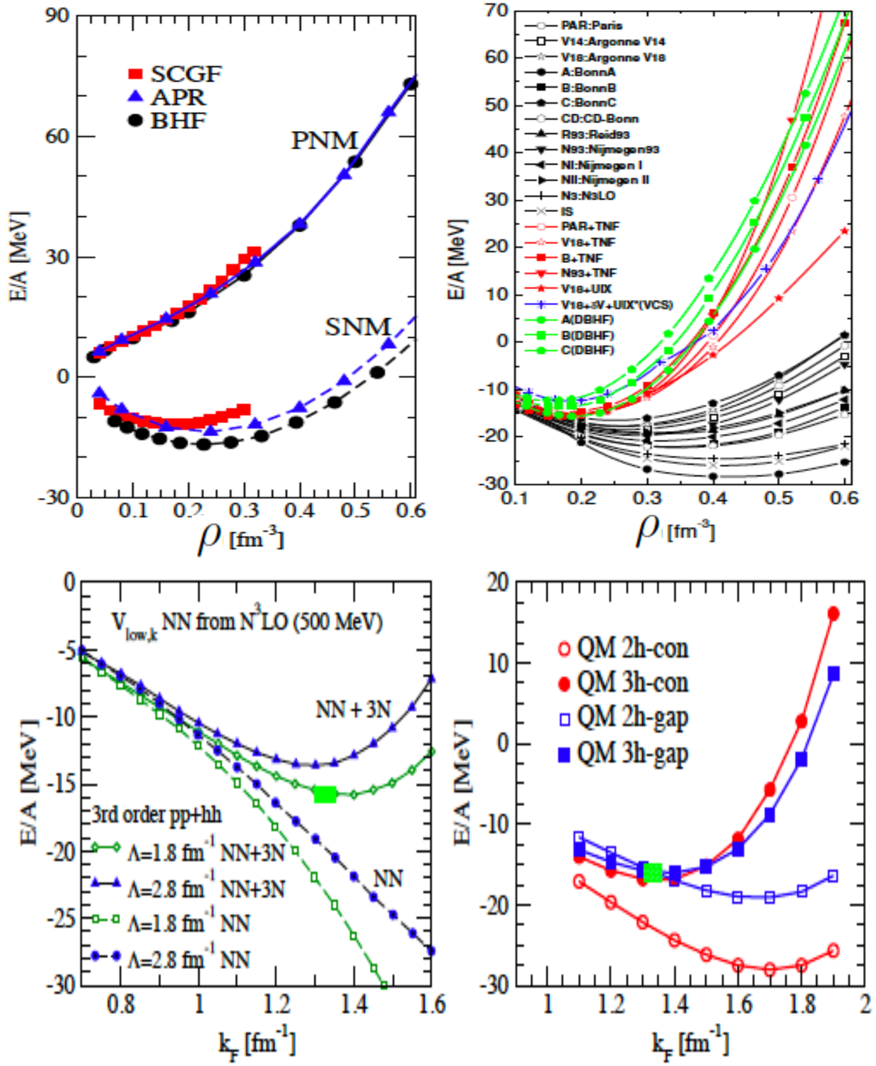
Based on solving the many-body problem starting from two- and three-body interactions

- *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 ~ 1-2ρ_0)

Burgio and Fantina (review) '18



Ab-initio versus Phenomenological Models

<u>Phenomenological Models</u>

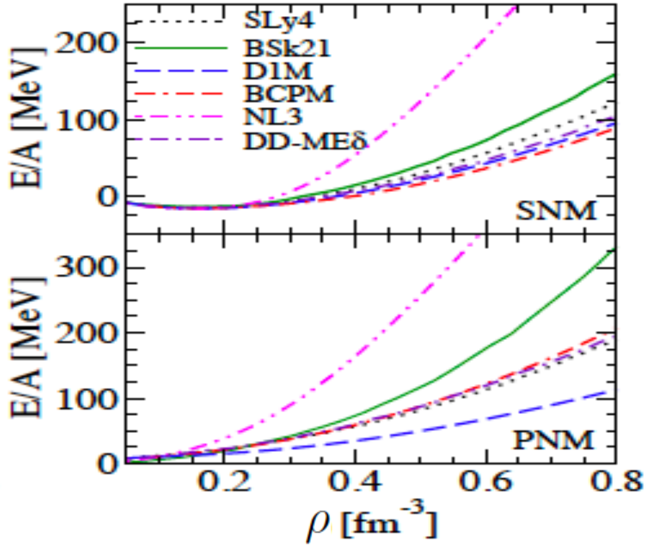
Based on density-dependent interactions adjusted to nuclear observables and neutron star observations

- *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..*

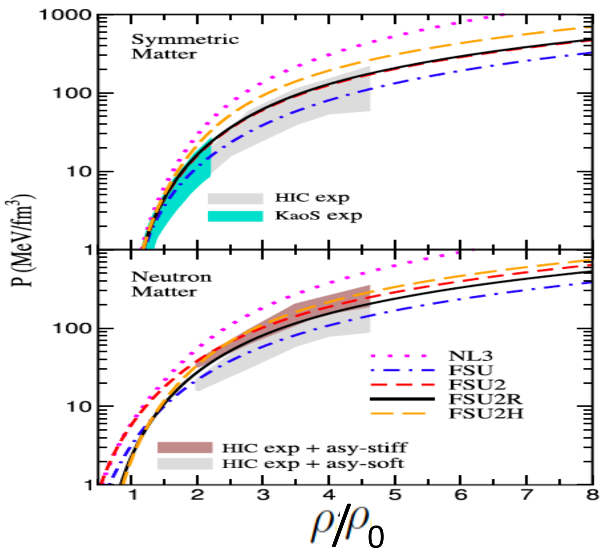
Advantage: applicable to high densities beyond ρ_0

Disadvantage: not systematic

Burgio and Fantina (review) ‘18



LT, Centelles and Ramos ‘17



Baryonic (hyperonic) matter in the core

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

1. 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!

2. the Fermi gas model ignores nuclear interactions, which give important contributions to the energy density

3. 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

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

3. Hyperons might be present

Hyperon	Quarks	I(J^P)	Mass (MeV)
Λ	uds	0(1/2$^+$)	1115
Σ^+	uus	1(1/2$^+$)	1189
Σ^0	uds	1(1/2$^+$)	1193
Σ^-	dds	1(1/2$^+$)	1197
Ξ^0	uss	1/2(1/2$^+$)	1315
Ξ^-	dss	1/2(1/2$^+$)	1321
Ω^-	sss	0(3/2$^+$)	1672

First proposed in 1960 by Ambartsumyan & Saakyan

Traditionally neutron stars were modeled by a uniform fluid of neutron rich nuclear matter in equilibrium with respect to weak interactions (β-stable matter)

$$\left.\begin{array}{l} n \rightarrow p + e^- + \bar{\nu}_{e^-} \\ p + e^- \rightarrow n + \nu_{e^-} \end{array}\right\} \longrightarrow \mu_p = \mu_n - \mu_{e^-}$$

but more exotic degrees of freedom are expected, in particular hyperons, due to:

- high value of density at the center and

- the rapid increase of the nucleon chemical potential with density

Hyperons are expected at $\rho \sim (2\text{-}3)\rho_0$

β-stable hyperonic matter

- Equilibrium with respect to weak interactions

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

$$(\mu_n = \mu_p + \mu_{e^-})$$

$$n\, n \leftrightarrow p\, \Sigma^- \quad (\text{or} \;\; e^- \, n \leftrightarrow \Sigma^- \, \nu_e)$$

$$(\mu_{e^-} + \mu_n = \mu_{\Sigma^-})$$

$$n\, n \leftrightarrow n\, \Lambda \quad (\text{or} \;\; e^- \, p \leftrightarrow \Lambda \, \nu_e)$$

$$(\mu_n = \mu_\Lambda)$$

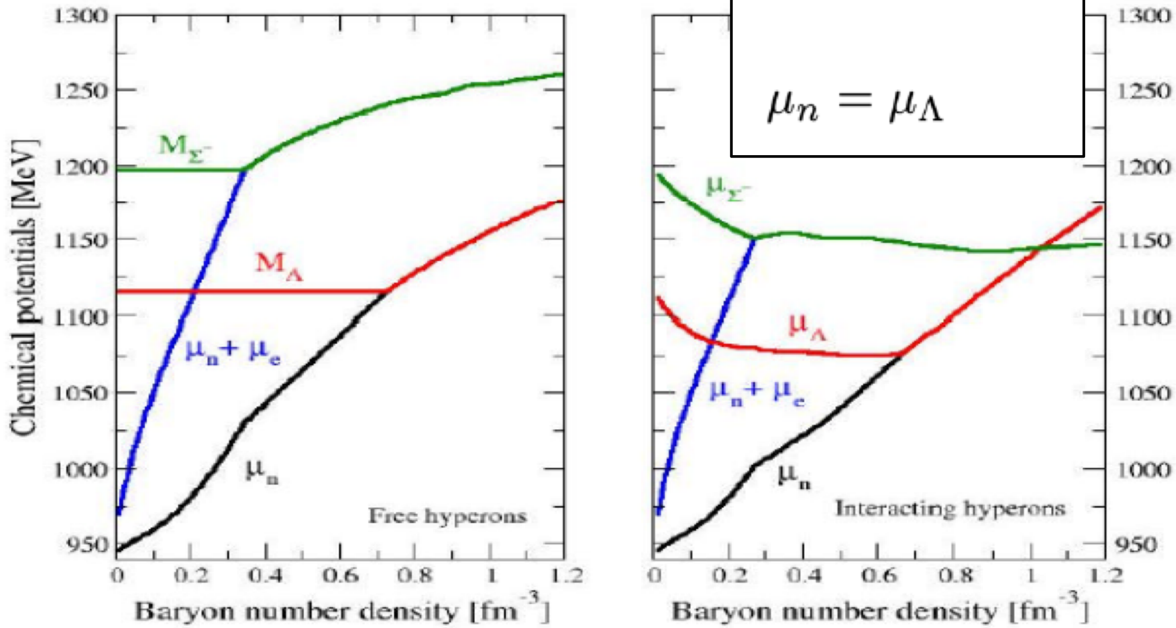
- Charge neutrality

$$n_p + n_{\Sigma^+} = n_{e^-} + n_{\mu^-} + n_{\Sigma^-} + n_{\Xi^-}$$

Baryochemical potentials in hyperonic matter: the composition of neutron stars depends on hyperons properties in matter

$$\mu_{e^-} + \mu_n = \mu_{\Sigma^-}$$

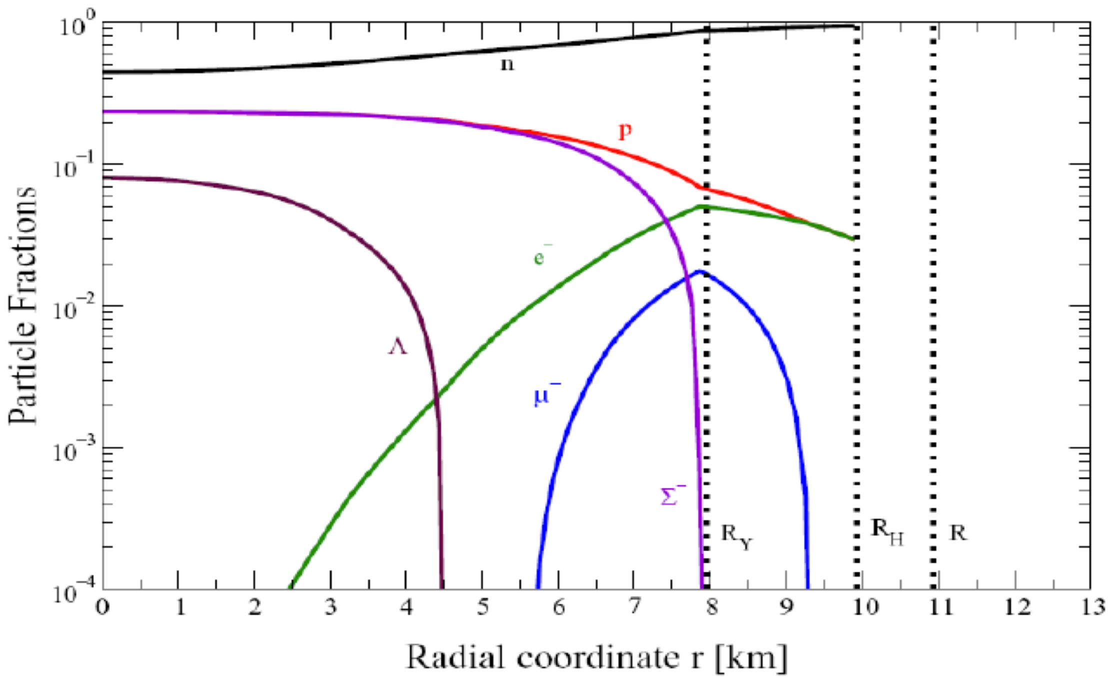
$$\mu_n = \mu_\Lambda$$



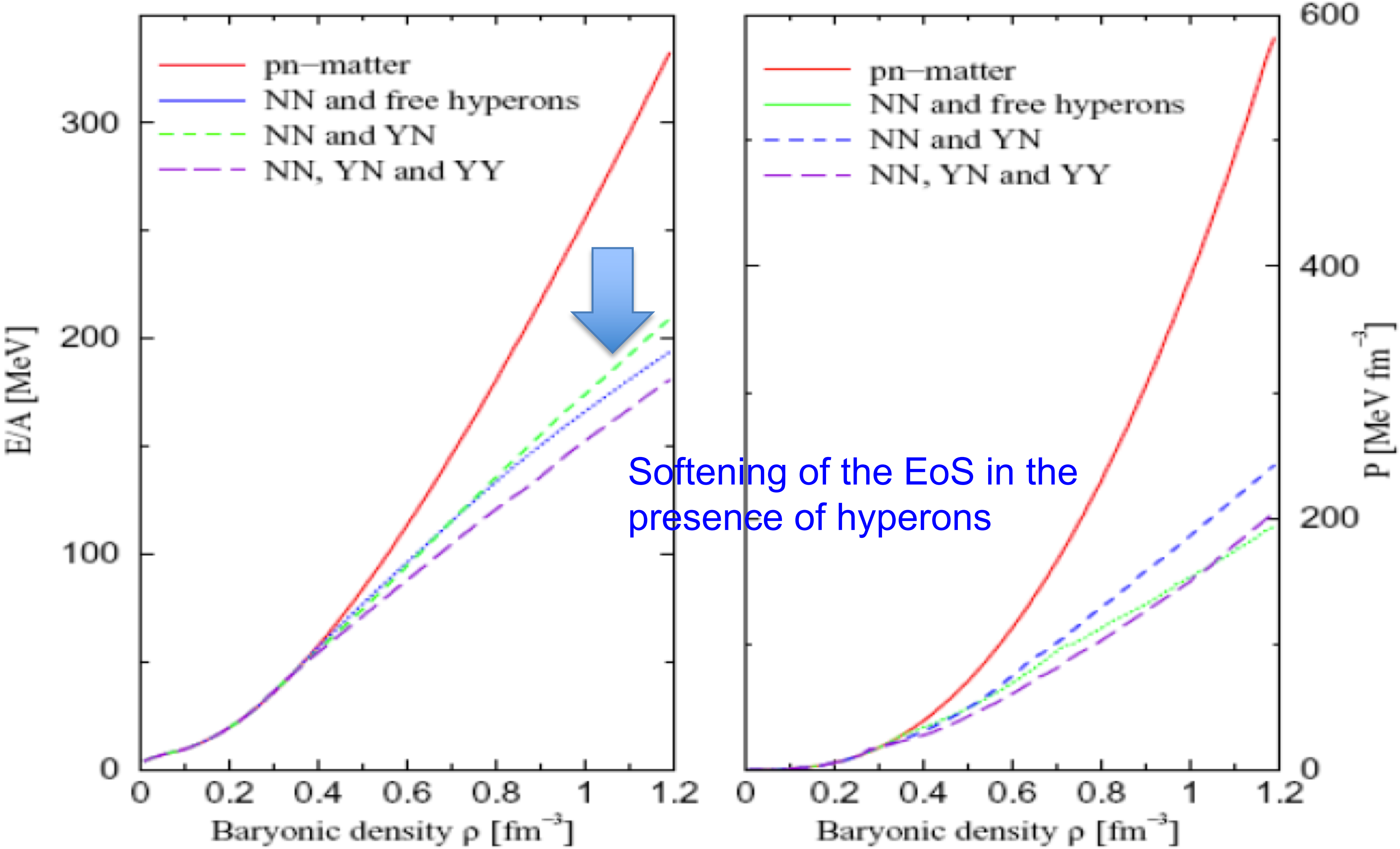
Vidana PhD thesis ‘01

Profile of a neutron star with hyperons

Vidana, Polls, Ramos, Engvik & Hjorth-Jensen, PRC 62 (2000) 035801



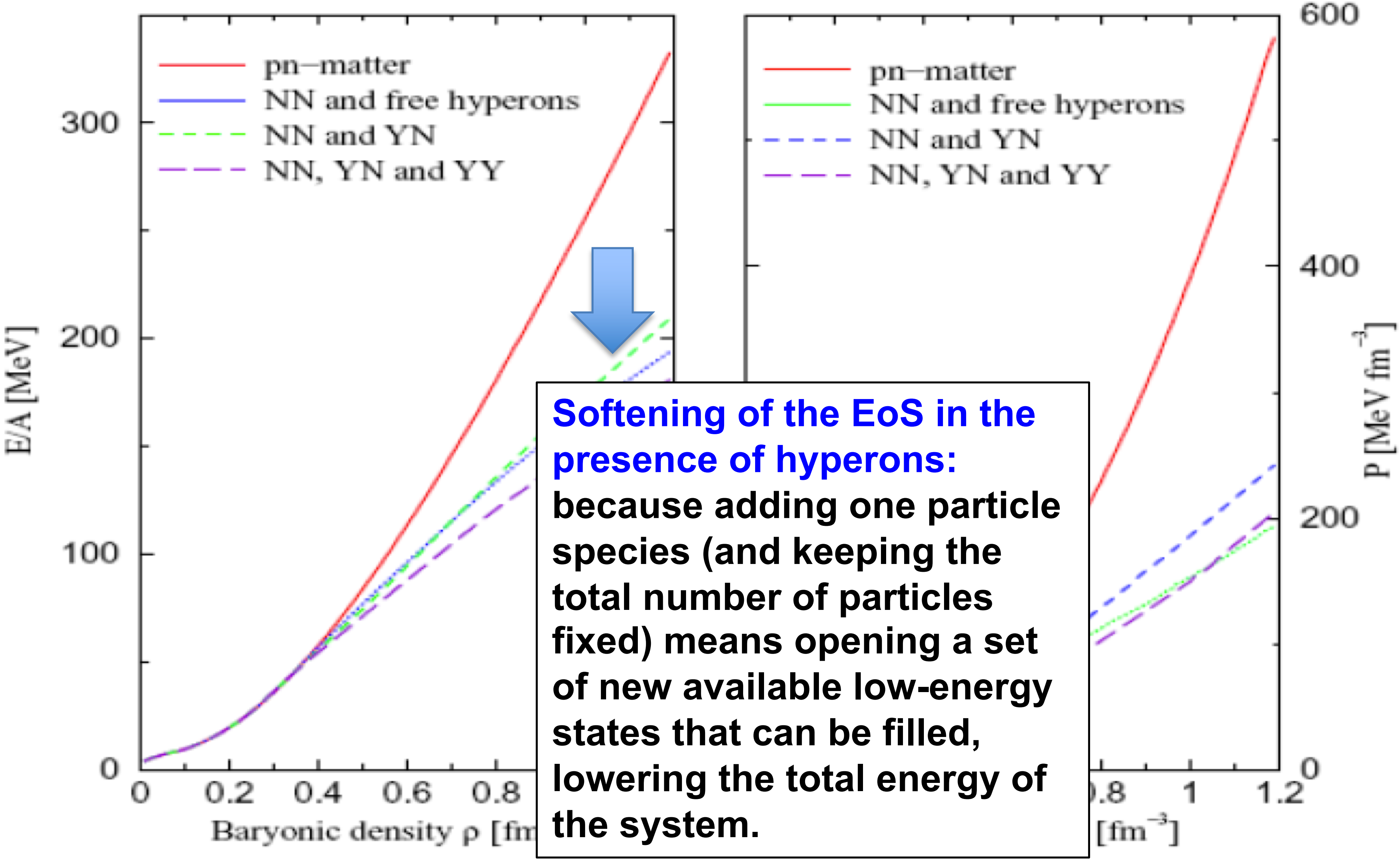
Equation of State of Hyperonic Matter



Softening of the EoS in the presence of hyperons

Vidana, Polls, Ramos, Engvik & Hjorth-Jensen, PRC 62 (2000) 035801

Equation of State of Hyperonic Matter



Softening of the EoS in the presence of hyperons:
because adding one particle species (and keeping the total number of particles fixed) means opening a set of new available low-energy states that can be filled, lowering the total energy of the system.

Vidana, Polls, Ramos, Engvik & Hjorth-Jensen, PRC 62 (2000) 035801

Structure Equations for neutron stars

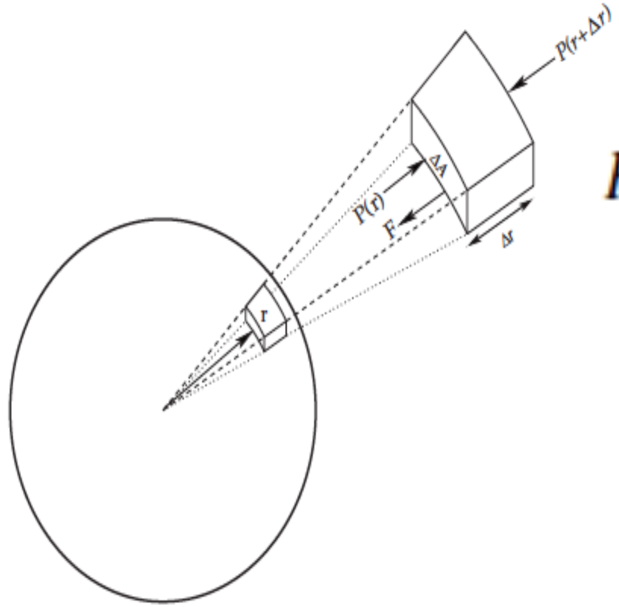


Figure 1. The radial force acting on a small mass element a distance r from the centre of the star.

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

dividing by
$\Delta V = \Delta A\, \Delta r$ → $$-\frac{GM(r)\rho(r)}{r^2} - \frac{dP}{dr} = \rho(r)\frac{d^2 r}{dt^2} = 0$$

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

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

$$\frac{dP}{dr} = -\frac{GM(r)\bar{\rho}(r)}{r^2}, \qquad P(r=0) \equiv P_c;$$

$$\frac{dM}{dr} = +4\pi r^2 \bar{\rho}(r), \qquad M(r=0) \equiv 0,$$

Newtonian formulation

General Relativity Corrections

Since neutron stars have masses M ~1-2 $M_\odot$ and radii R ~ 10-20 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 of a star with 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: $dP/d\rho > 0$ (from TOV equations)

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

3) Causality constraint (sound speed must be smaller than the speed of light)

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

4) Rotation must not pull the star apart (the centrifugal force for a particle on the surface cannot exceed the gravitational force)

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

"Recipe" for neutron star structure calculation

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

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

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

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

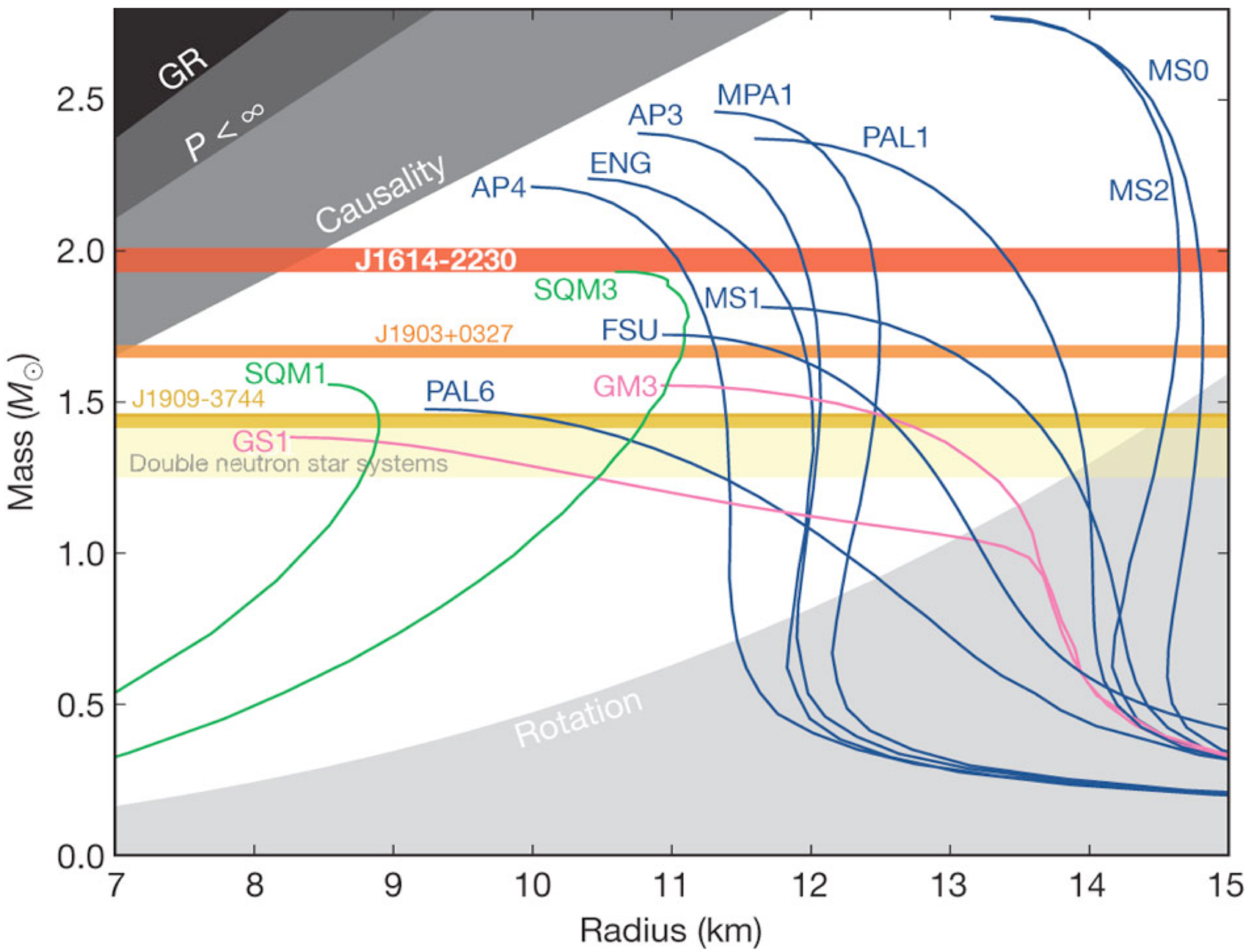
$$m(r=R)=M \quad P(r=R)=0$$

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

Shulze@Compstar07

Mass-Radius relation

M-R diagram for various EoS, showing also constrained areas



Ozel et al '16

LETTER

Demorest et al. , Nature 467 (2010) 1081

PSR J1614−2230

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Neutron stars are composed of the densest form of matter known to exist in our Universe, the composition and properties of which are still theoretically uncertain. Measurements of the masses or radii of these objects can strongly constrain the neutron star matter equation of state and rule out theoretical models of their composition[1,2]. The observed range of neutron star masses, however, has hitherto been too narrow to rule out many predictions of 'exotic' non-nucleonic components[3–6]. The Shapiro delay is a general-relativistic increase in light travel time through the curved space-time near a massive body[7]. For highly inclined (nearly edge-on) binary millisecond radio pulsar systems, this effect allows us to infer the masses of both the neutron star and its binary companion to high precision[8,9]. Here we present radio timing observations of the binary millisecond pulsar J1614-2230[10,11] that show a strong Shapiro delay signature. We calculate the pulsar mass to be $\boxed{(1.97 \pm 0.04) M_\odot}$, which rules out almost all currently proposed[2–5] hyperon or boson condensate equations of state ($M_\odot$, solar mass). Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not 'free' quarks[12].

long-term data set, parameter covariance and dispersion measure variation can be found in Supplementary Information.

As shown in Fig. 1, the Shapiro delay was detected in our data with extremely high significance, and must be included to model the arrival times of the radio pulses correctly. However, estimating parameter values and uncertainties can be difficult owing to the high covariance between many orbital timing model terms[14]. Furthermore, the χ^2 surfaces for the Shapiro-derived companion mass (M_2) and inclination angle (i) are often significantly curved or otherwise non-Gaussian[15]. To obtain robust error estimates, we used a Markov chain Monte Carlo (MCMC) approach to explore the post-fit χ^2 space and derive posterior probability distributions for all timing model parameters (Fig. 2). Our final results for the model

Table 1 | Physical parameters for PSR J1614-2230

Parameter	Value
Ecliptic longitude (λ)	245.78827556(5)°
Ecliptic latitude (β)	−1.256744(2)°
Proper motion in λ	9.79(7) mas yr^{-1}
Proper motion in β	−30(3) mas yr^{-1}
Parallax	0.5(6) mas

Anaylsis improved recently: M = 1.928(7) $M_\odot$ (Arzoumanian et al. 2015)

Antoniadis et al., Science 340, 6131 (2013)

J0348+0432

Science 26 April 2013:
Vol. 340 no. 6131
DOI: 10.1126/science.1233232

RESEARCH ARTICLE

A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis[1,*], Paulo C. C. Freire[1], Norbert Wex[1], Thomas M. Tauris[2,1], Ryan S. Lynch[3], Marten H. van Kerkwijk[4], Michael Kramer[1,5], Cees Bassa[5], Vik S. Dhillon[6], Thomas Driebe[7], Jason W. T. Hessels[8,9], Victoria M. Kaspi[3], Vladislav I. Kondratiev[8,10], Norbert Langer[2], Thomas R. Marsh[11], Maura A. McLaughlin[12], Timothy T. Pennucci[13], Scott M. Ransom[14], Ingrid H. Stairs[15], Joeri van Leeuwen[8,9], Joris P. W. Verbiest[1], David G. Whelan[13]

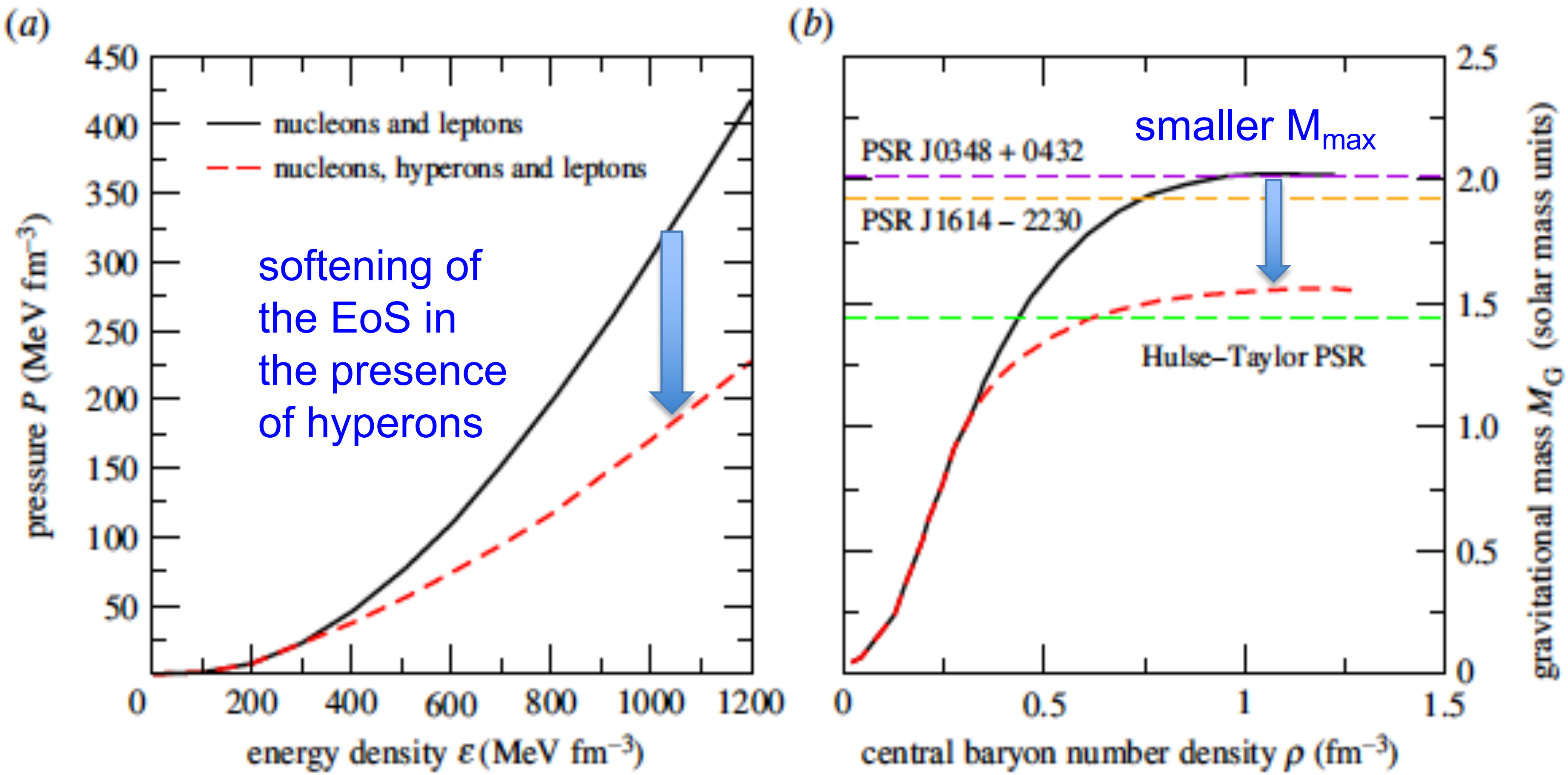
+ Author Affiliations

*Corresponding author. E-mail: jantoniadis@mpifr-bonn.mpg.de

ABSTRACT | STRUCTURED ABSTRACT | EDITOR'S SUMMARY

Many physically motivated extensions to general relativity (GR) predict substantial deviations in the properties of spacetime surrounding massive neutron stars. We report the measurement of a $\boxed{2.01 \pm}$ 0.04 solar mass ($M_\odot$) pulsar in a 2.46-hour orbit with a 0.172 ± 0.003 $M_\odot$ white dwarf. The high pulsar mass and the compact orbit make this system a sensitive laboratory of a previously untested strong-field gravity regime. Thus far, the observed orbital decay agrees with GR, supporting its validity even for the extreme conditions present in the system. The resulting constraints on deviations support the use of GR-based templates for ground-based gravitational wave detectors. Additionally, the system strengthens recent constraints on the properties of dense matter and provides insight to binary stellar astrophysics and pulsar recycling.

Inclusion of hyperons….

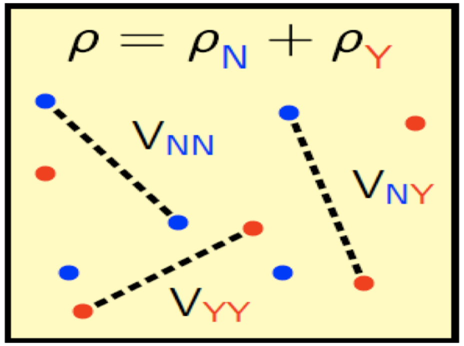


….. induces a strong softening of the EoS that leads to $M_{max} < 2M_\odot$

Chatterjee and Vidana, Eur.Phys.J. A52 (2016) 29
Vidana, Proc. Roy. Soc. Lond. A474 (2018) 0145

The Hyperon Puzzle

Experimental data scattering and hypernuclei



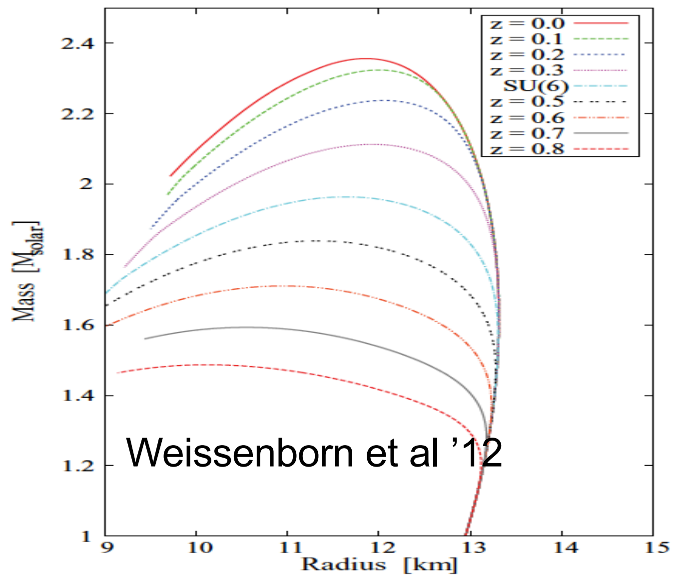
- YN: < 50 scattering data points
- NΛ: Λ-hypernuclei for A=3-209, $U_\Lambda(\rho_0)$= -30 MeV
- NΣ: Σ^- atoms but one Σ-hypernuclei, $U_\Sigma(\rho_0)$= 30 MeV ?
- NΞ: few Ξ hypernucleus $U_\Xi(\rho_0)$= -24 MeV ?
- ΛΛ: few ΛΛ hypernuclear events, slighttly attractive ?
- YY: Y=Λ, Σ, Ξ unknown!

Theoretical models for hyperons in neutron stars

- Relativistic mean field models
Glendenning ’85; Knorren, Prakash & Ellis ’95; Schaffner & Mishustin ’96..
- Non-relativistic potential model
Balberg & Gal ’97…
- Quark-meson coupling model
Pal et al ’99..
- Chiral effective lagrangians
Hanauske et al. ’00…
- Density dependent hadron field model Hofmann, Keil & Lenske ’01..
- DBHF/BHF approaches
Brockmann & Machleidt ’90; Baldo, Burgio,Schulze ’00; Vidana et al. ’00; Jong and Lenske ’98..
- Low-momentum interactions
Schwenk, Pethick, Hebeler, Friman, LT, Djapo..
- Quantum Monte Carlo
Leonardi et al ’14..

Solutions to the Hyperon Puzzle?

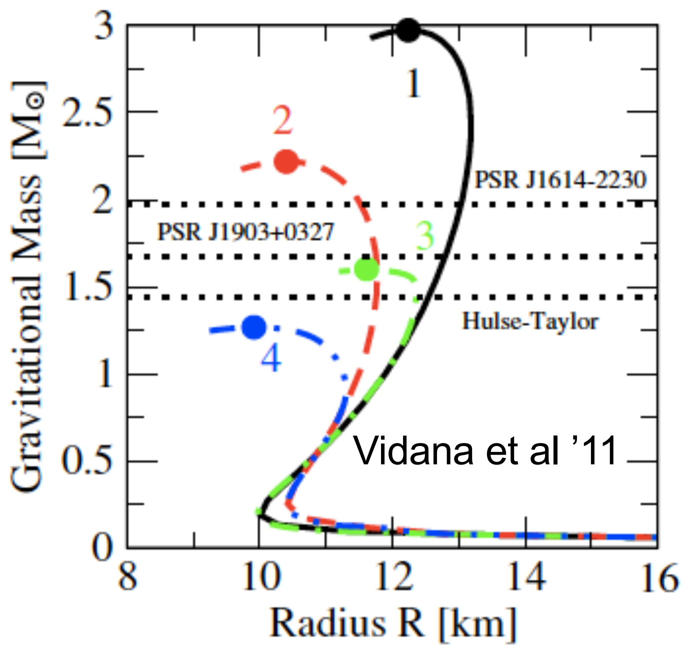
I. Stiffer YN and YY interactions



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;
Oertel 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

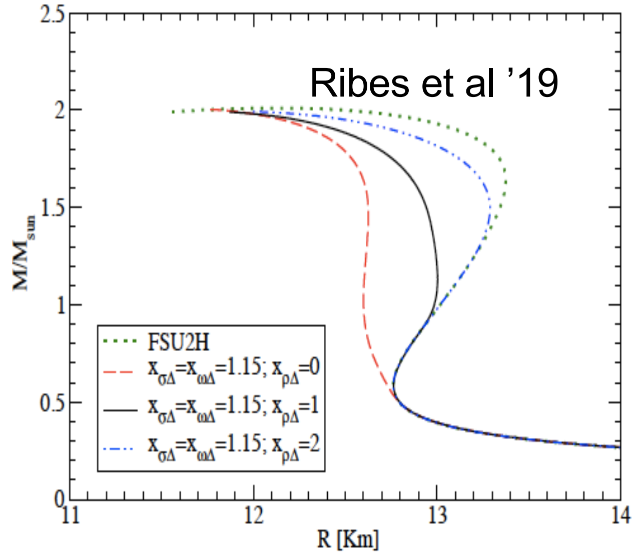


not yet a general consensus:
while for some models $2M_\odot$ are reached,
Taktasuka et al ‘02 ’08; Yamamoto et al ‘13 ’14..
for others $M_{max} < 2M_\odot$ Vidana et al ’11
while results from Lonardoni ‘15 are not conclusive as they strongly depend on ΛNN force.
Hyperonic 3-body forces in EFT might solve the hyperon puzzle??

Solutions to the Hyperon Puzzle?

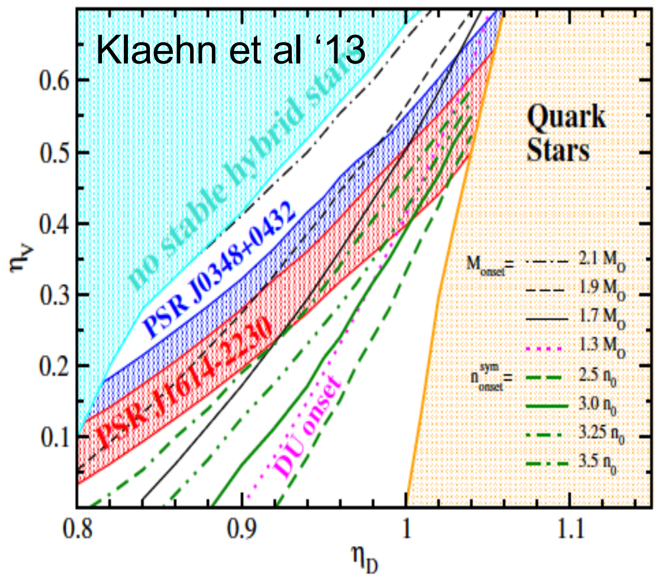
III. Push of Y onset by Δ-isobars or meson condensates

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



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

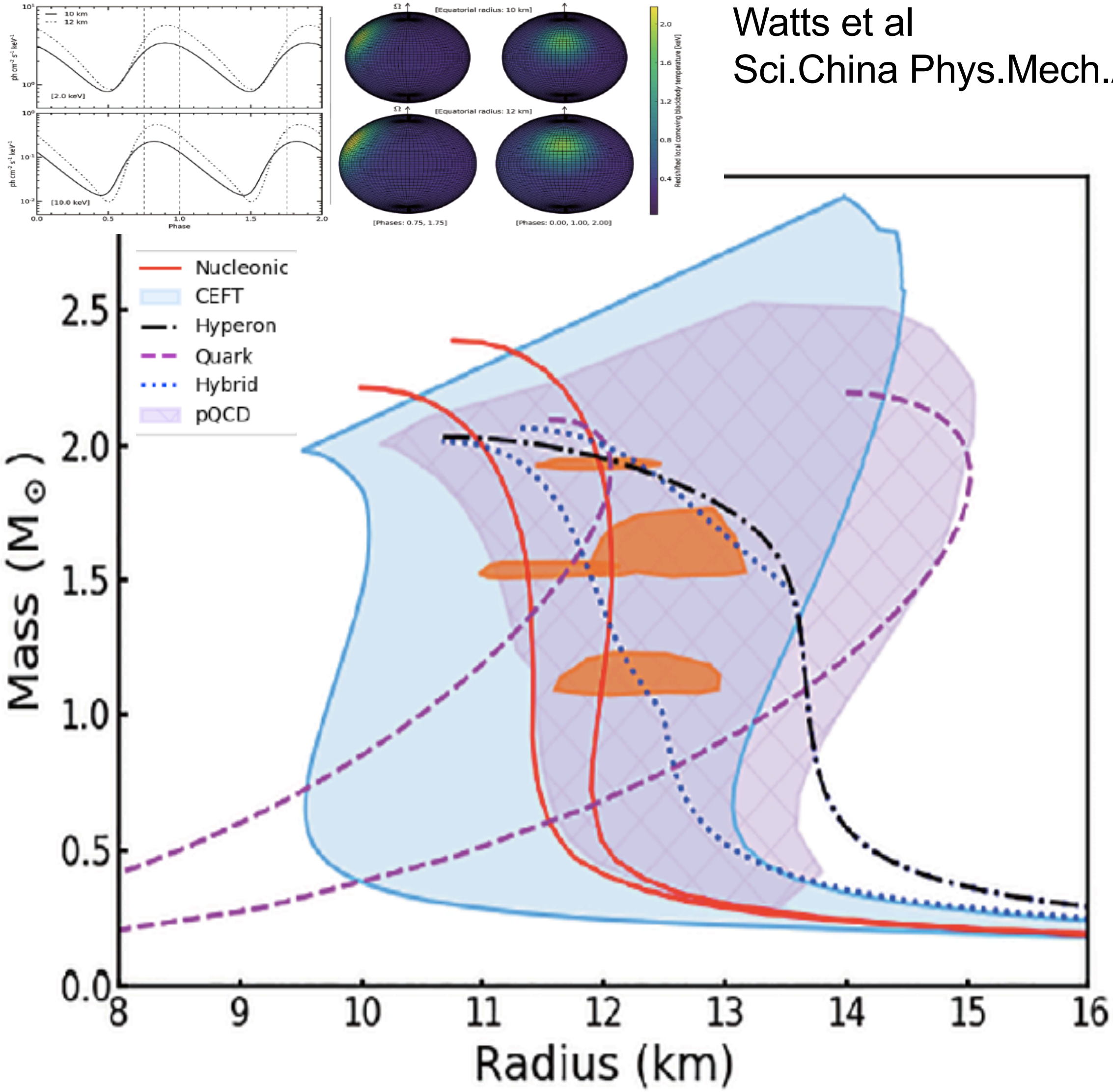


early transition to quark matter below Y onset, with quarks providing enough repulsion to reach $2M_{sun}$
Weissenborn et al '11; Klaehn et al '13; Bonanno et al '12; Lastowiecki et al '12…

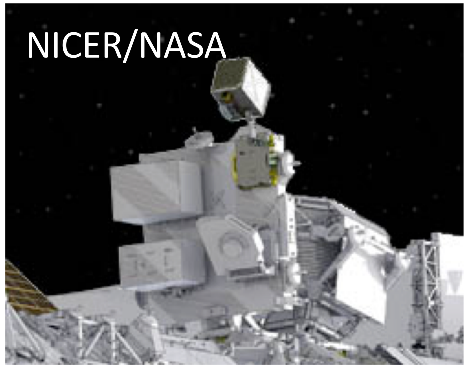
V. Others: modified gravity, dark matter..

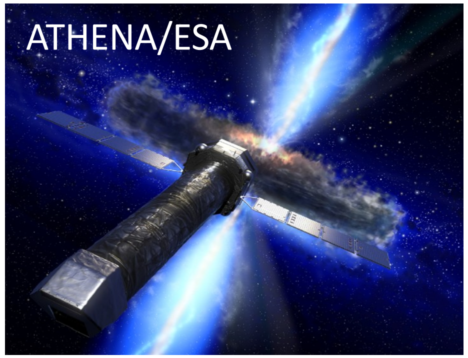
Space missions to study the interior of NS

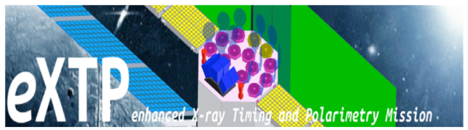
Watts et al
Sci.China Phys.Mech.Astron. 62 (2019) 2, 29503



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







Bibliography

C.B. Jackson, J. Taruna, S.L. Pouliot, B.W. Ellison, D.D. Lee and J. Piekarewicz, Eur. J. Phys. 26 (2005) 695

S.L. Shapiro and S.A. Teukolsky, “Black Holes, White Dwarfs, and Neutron Stars”, (Wiley, 1983)

A.C. Phillips, “The Physics of Stars”, (John Wiley & Sons, 1994)

R.R. Silbar and S. Reddy, “Neutron stars for undergraduates”, Am. J. Phys. 72 (2004) 892. Erratum: Am. J. Phys. 73 (2005) 286.

Lectures notes of Angels Ramos, Assum Parreno and Laura Tolos in “Master in Nuclear Physics” , https://master.us.es/fisicanuclear/

Other references mentioned in the lecture!