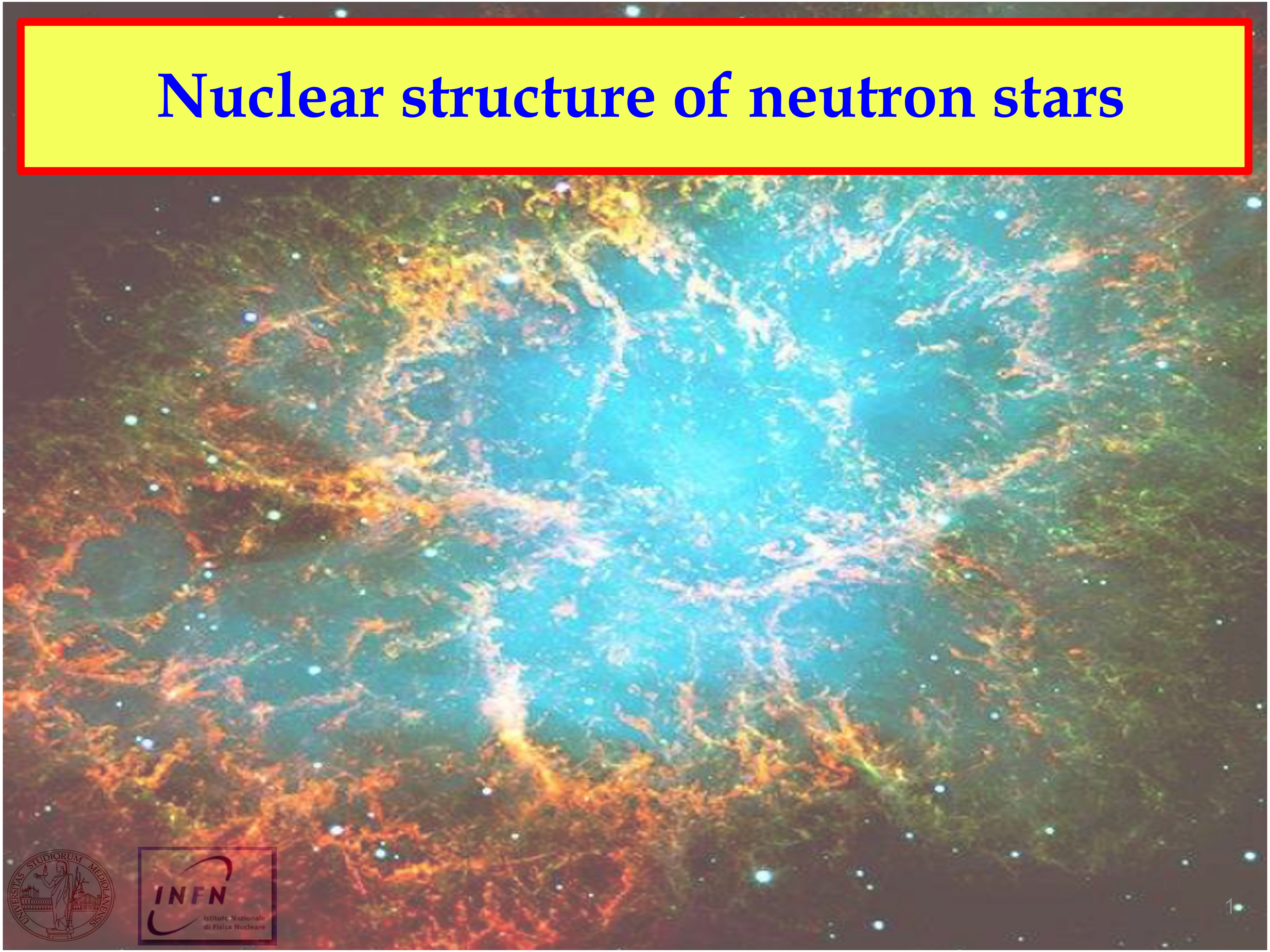
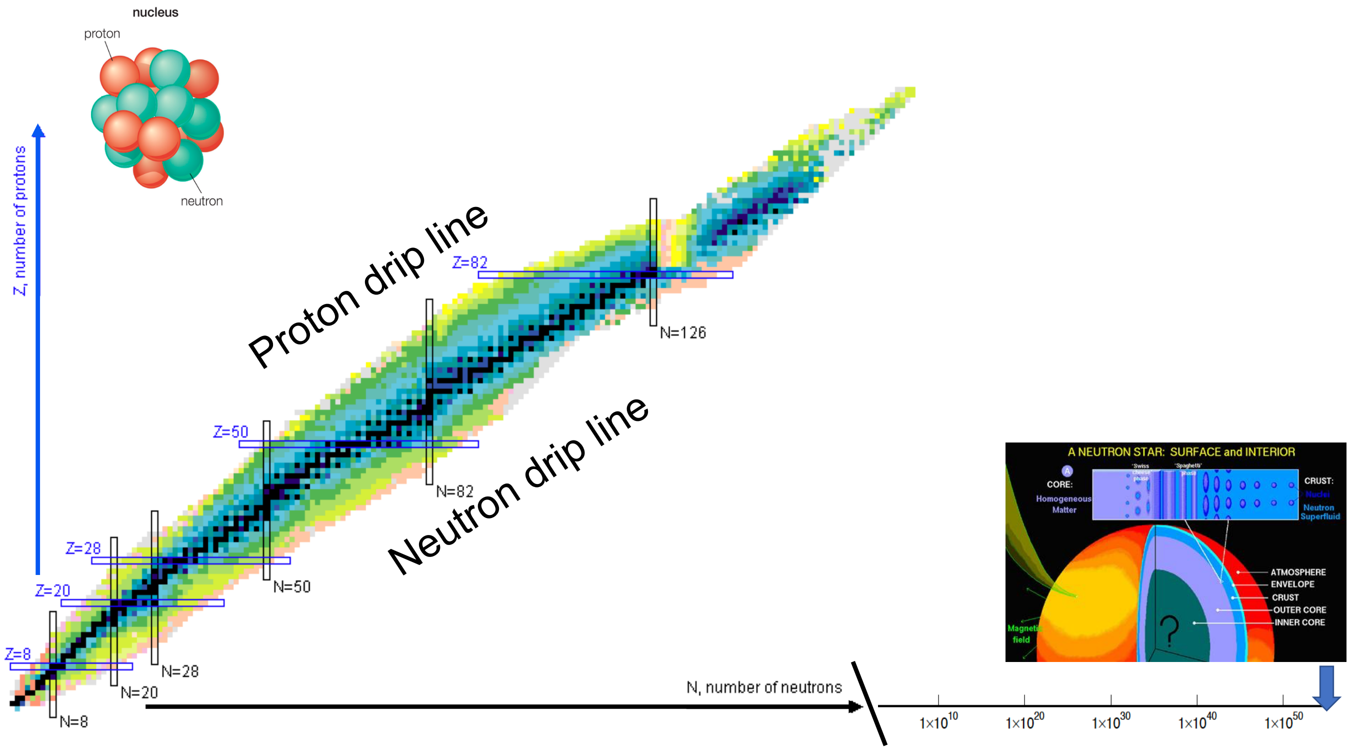
Nuclear structure of neutron stars



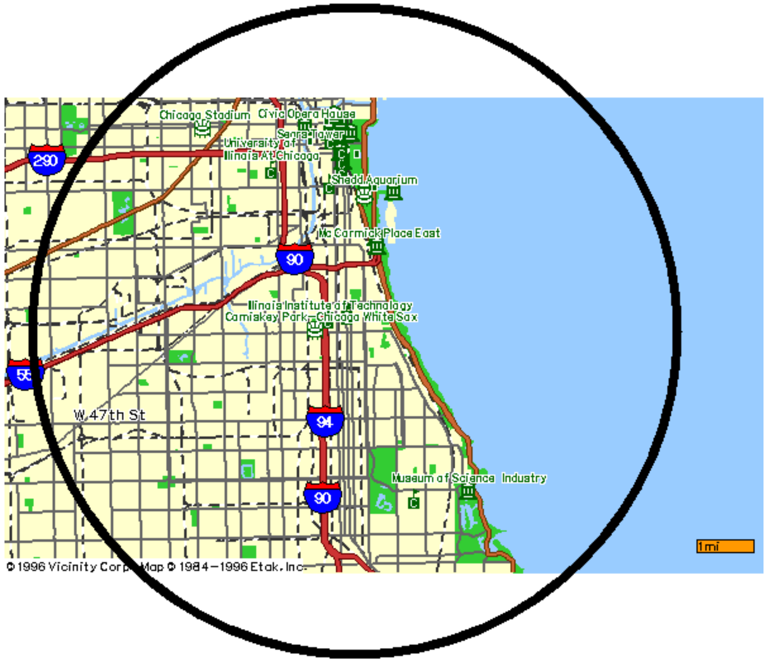
There is a complementarity between observations of NSs and nuclear structure experiments. No nuclear structure experiment can directly probe a NS but **plenty of them are much related to NS physics.**



- It is often said that Landau hinted NSs could exist during a conversation with Bohr and Rosenfeld (cf. https://arxiv.org/abs/1210.0682).

- The discovery came much later, under the form of pulsars (1967). J. Bell and A. Hewish were authors of this discovery, but the Nobel prize was awarded to Hewish only.

- ”Compact” objects. About 1.4-2 solar masses ($\approx 10^{30}$ kg) within a radius of 10 km.



Let us compare the escape velocity v_e from a self-gravitating body to the speed of light c:

$$\frac{1}{2}mv_e^2 = \frac{GMm}{R} \text{ and } \frac{v_e^2}{c^2} = \frac{2GM}{Rc^2} = \Xi$$

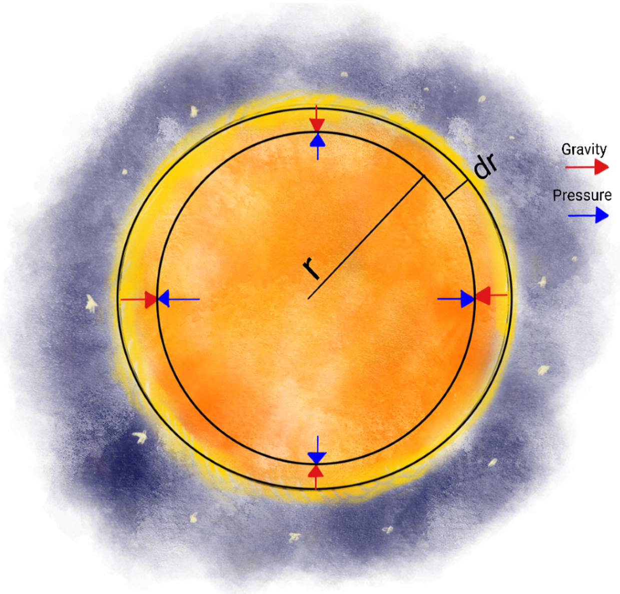
Ξ is called the compactness parameter of the body, and also measures the ratio between the gravitational potential energy and the mass energy. It value is

- 10^{-6} for our Sun,
- 10^{-3} for a white dwarf,
- 0.4 for a neutron star and
- 1 for a black hole

From: Jérôme Novack, houches07.pdf

The TOV equation

$$\frac{dP(r)}{dr} = -\frac{GM(r)\varepsilon(r)}{r^2c^2}\frac{\left(1+\frac{P(r)}{\varepsilon(r)}\right)\left(1+\frac{4\pi r^3P(r)}{M(r)c^2}\right)}{1-\frac{2GM(r)}{rc^2}}$$



Credit: M. Bolis

The EQUATION OF STATE

$P(\rho)$ is needed

Only (n,p) with (e,μ): link with the EoS at nuclear densities (see later).

Hyperons: 2-body and 3-body interactions **NEEDED.**

QCD phase diagram at finite density (?).

Stiffness of the EoS, non-nuclear degrees of freedom

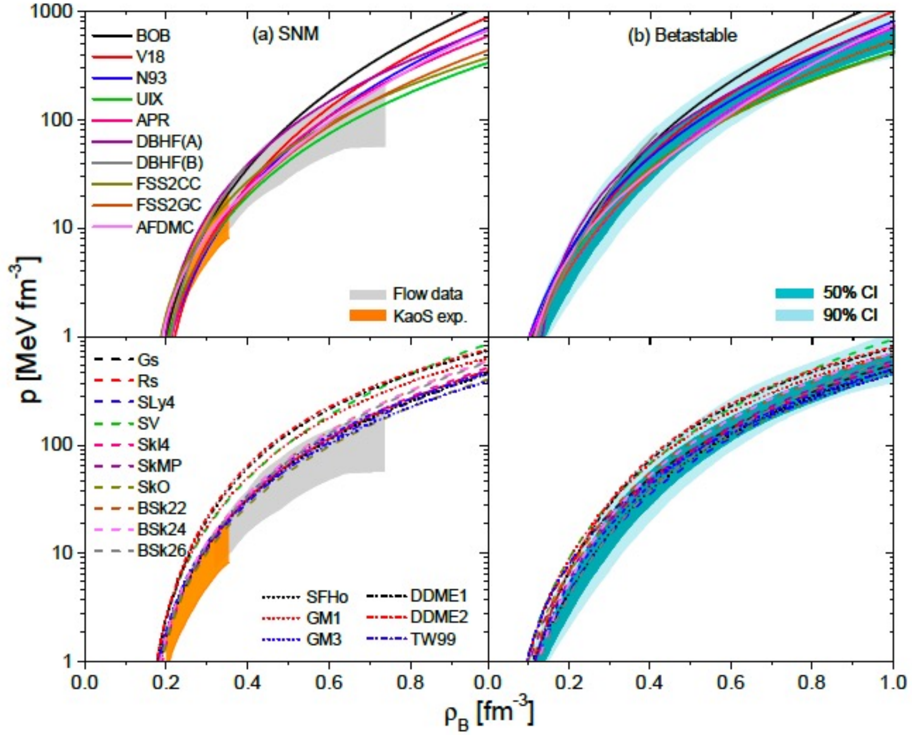


Figure 3. Pressure vs. baryon density for the symmetric case (**left** panels), and the beta-stable case (**right** panels). The upper (lower) panels display results for microscopic (phenomenological) EOSs. Constraints derived from HIC data are displayed in the left panels as orange (KaoS experiment) and grey (flow data) bands. Limits deduced by the GW170817 event are labelled by blue bands in the right panels. See text for details.

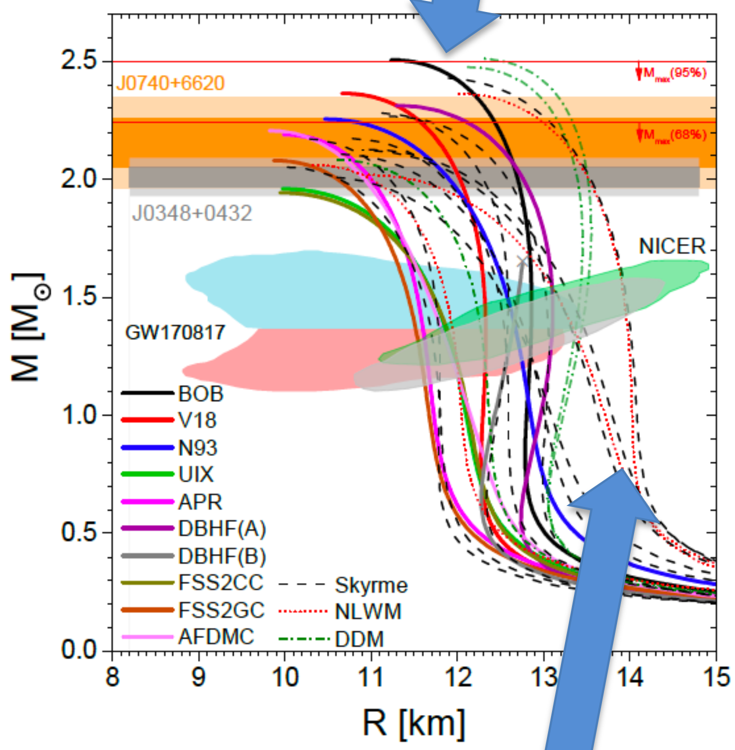
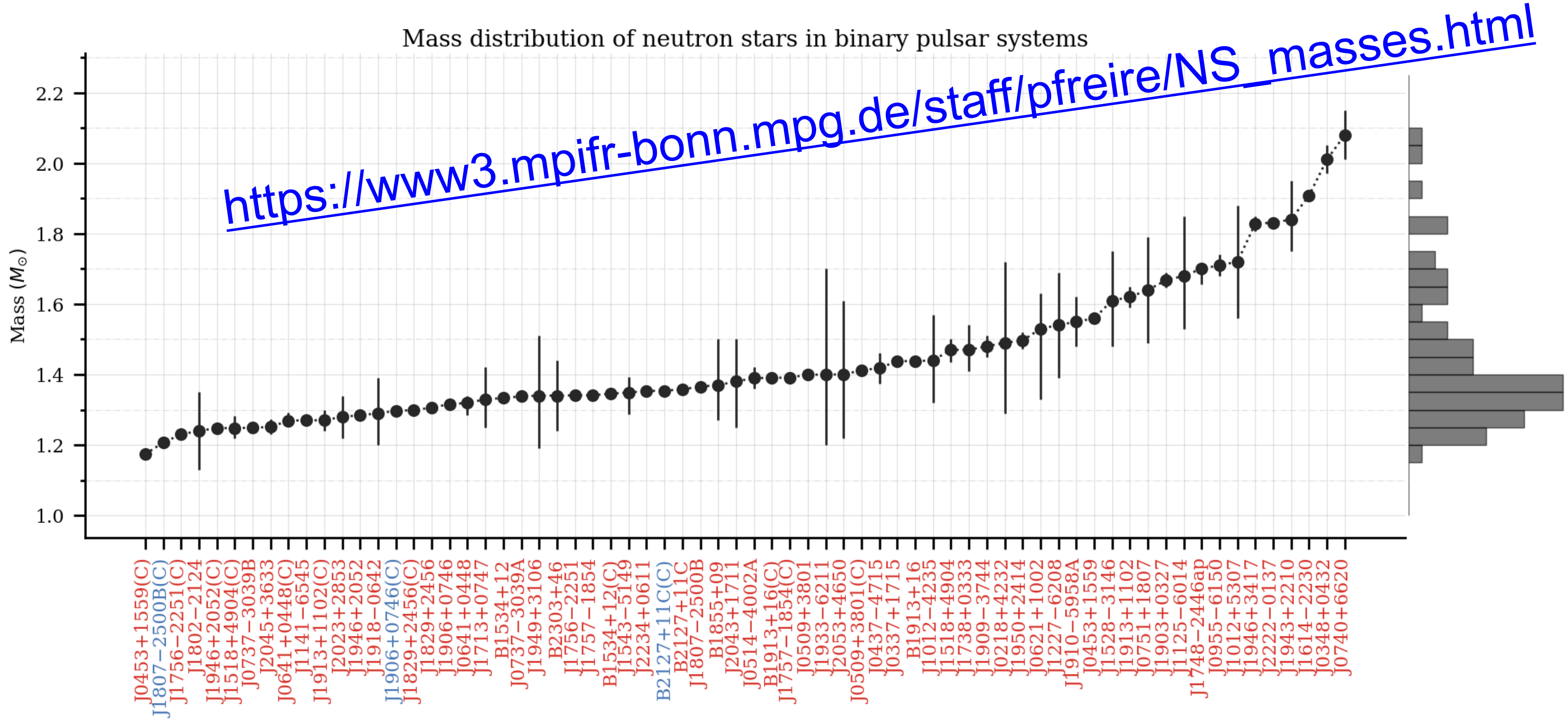


Figure 4. Mass-radius relations predicted by the different EOSs ... in Table 1. The observed masses of the millisecond pulsar PSR J0740 + 6620 [12] and of J038... [11] are also shown, as well as constraints inferred from the analysis of the GW170817 event ... observations reported by the NICER mission [18,19]. See text for details.

Treatment of the crust

F. Burgio *et al.*, Symmetry 13, 400 (2021)

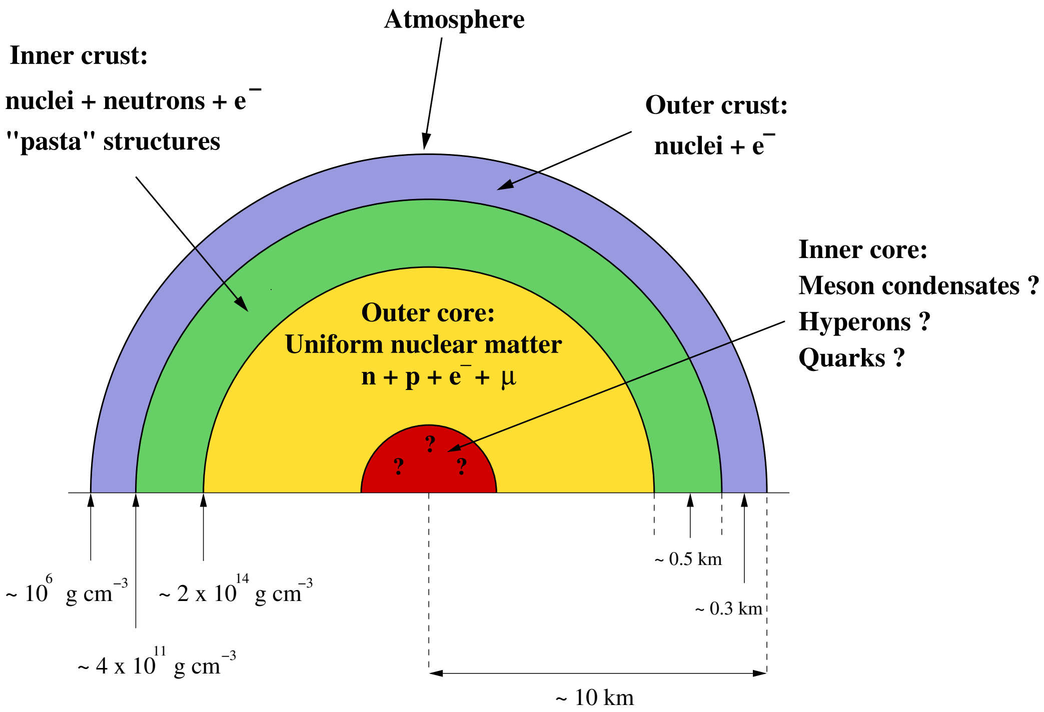
Masses and radii



Up to a while ago, measurements of radii have been plagued by large uncertainties. Moreover, radii and masses were determined for different systems.

NASA's NICER mission has measured, for the first time, mass and radius of the same stars.

Structure of neutron stars



Outer surface of the star: ^{56}Fe atoms.

With increasing density, atoms are ionized and the electrons become relativistic.

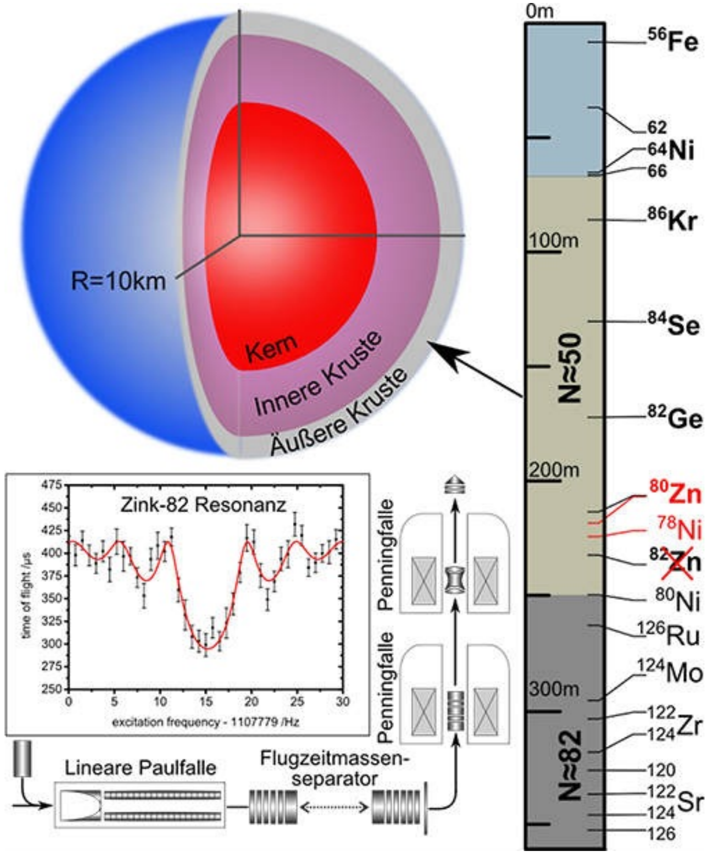
Outer crust: nuclei in a lattice, plus electron gas. Electron capture: nuclei become neutron-rich.

Inner crust: nuclei "drip neutrons out".

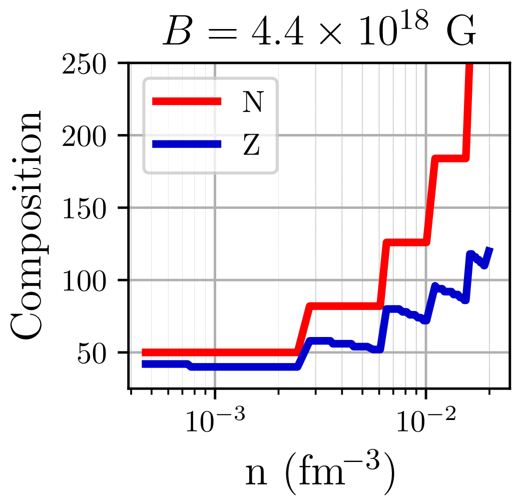
Outer core: nuclei and free neutrons coalesce. This defines the so-called outer core. Elongated shapes vs. uniform matter? Balance between surface energy and Coulomb energy.

Inner core: completely uncertain is the composition of neutron stars at even higher densities. Leptons, Σ, Λ, Ξ hyperons? Quark matter??

Composition of the outer crust



- Observable consequences?
- In the crust, nuclei become neutron-rich.
- With ultra-high magnetic fields, we predict the **synthesis of SUPER-HEAVIES.**



R. N. Wolf et al., PRL 110, 041101 (2013)

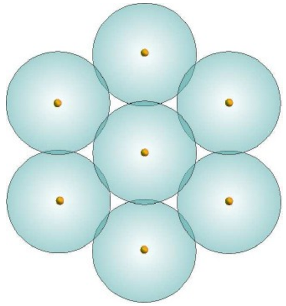
PHYSICAL REVIEW C **112**, 015801 (2025)

Synthesis of superheavy elements in the outer crust of a magnetar

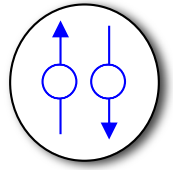
D. Basilico,[1,2] G. Colò,[1,2] and Xavier Roca-Maza[1,2,3,4]

Pairing in the inner crust of NS (I)

In the inner crust, nuclei are in **Wigner-Seitz cells**; they are surrounded by **neutrons, that drip out of nuclei.**

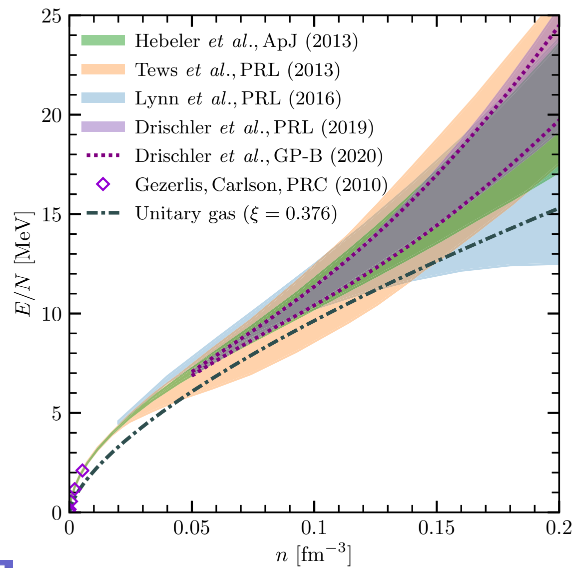


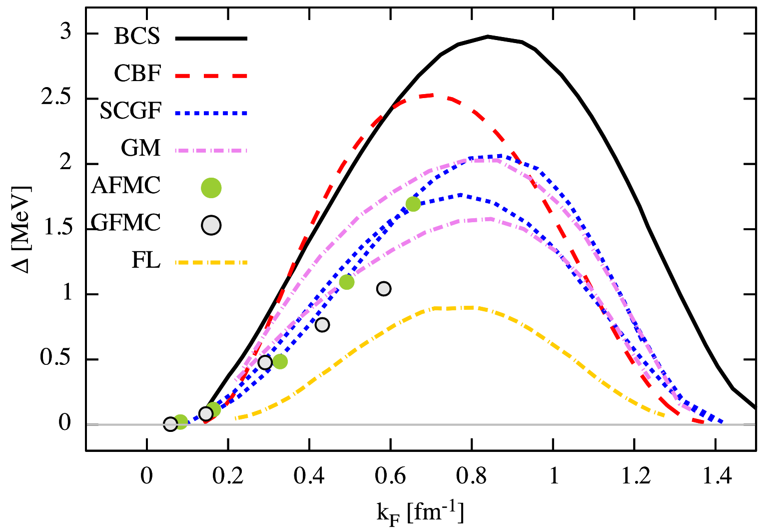
Cooper pairs



What is the behaviour of neutron matter at densities between about 10^{-3} to 1/3 of the saturation densities? *Ab initio* calculations predict some range for the EoS, but they are not yet so reliable about **pairing**.

S. Huth *et al.*, PRC 103, 025803 (2021)





A. Sedrakian and J.W. Clark, EPJA 55, 167 (2019)

Deconfined quark hypothesis

Some authors have suggested an early phase transition to deconfined quark matter as solution to the hyperon puzzle. Massive neutron stars could actually be hybrid stars with a stiff quark matter core.

To yield $M_{max} > 2M_{\odot}$ Quark Matter should have:

- significant overall quark repulsion $\longrightarrow$ stiff EoS
- strong attraction in a channel $\longrightarrow$ strong color superconductivity

Ozel et al., (2010), Weissenborn et al., (2011), Klaehn et al., (2011), Bonano & Sedrakian (2012), Lastowiecki et al., (2012), Zdunik & Haensel (2012)

From: Isaac Vidaña

Cooling of NS

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

- **Neutrino emission** is the main source of cooling.

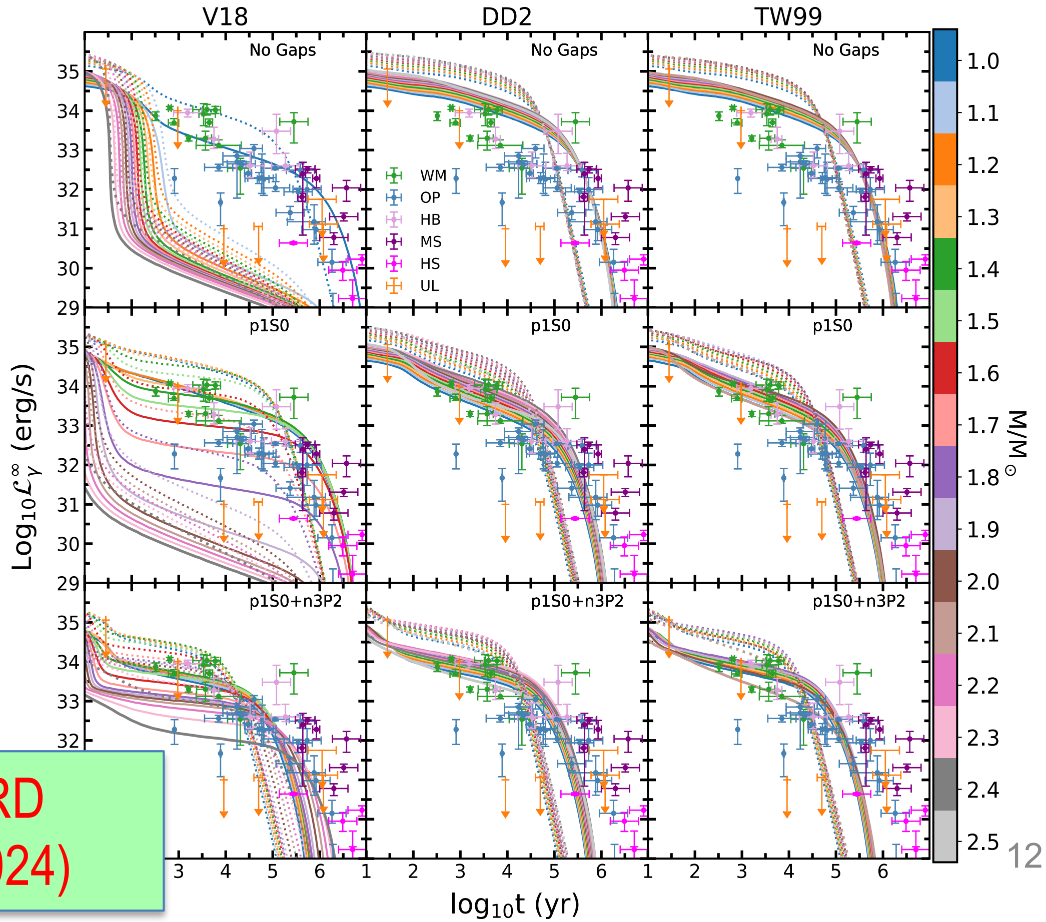
$$n + p + e^- \rightarrow n + n + \nu$$

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

- The direct URCA process is possible if the **proton fraction** is larger than a given threshold.

- **The proton fraction is related to the EoS.**

- **Pairing affects significantly the cooling.**



H. Das *et al.*, PRD 109, 123018 (2024)

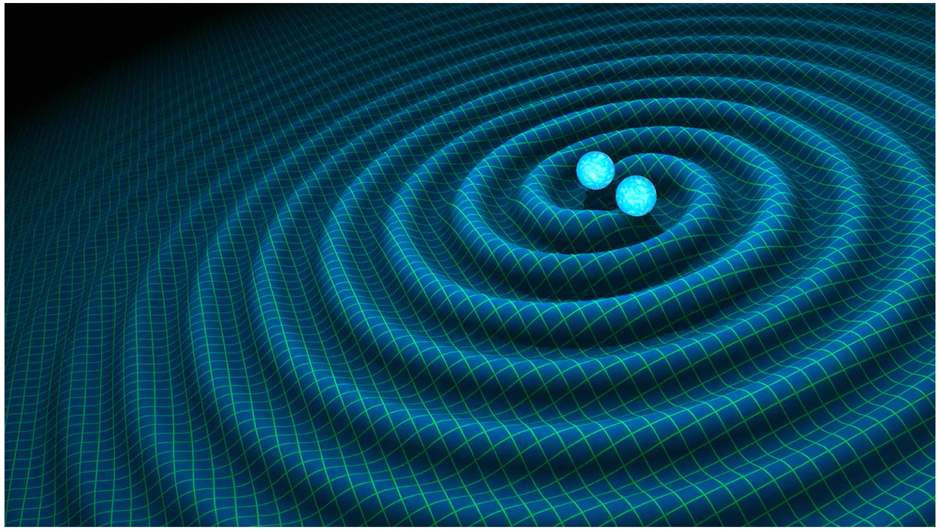
Merging of neutron stars AND the nuclear EoS

- 17/8/2017 ”multi-messenger” observation of NS merging (GW, GRB, X-rays...).

B.P. Abbott et al., Astrophysical J. Lett. 848:L12 (2017)

GW170817 Press Release

LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars



Tidal polarizability: ratio quadrupole moment / gravitational field

$$\Lambda = \frac{2}{3} k_2 \left(\frac{c^2 R}{GM} \right)^2$$

PHYSICAL REVIEW LETTERS **129,** 032701 (2022)

Probing the Incompressibility of Nuclear Matter at Ultrahigh Density through the Prompt Collapse of Asymmetric Neutron Star Binaries

Albino Perego,[1,2,*] Domenico Logoteta,[3,4] David Radice,[5,6,7] Sebastiano Bernuzzi,[8] Rahul Kashyap,[5,6] Abhishek Das,[5,6] Surendra Padamata,[5,6] and Aviral Prakash[5,6]

Numerical general relativity simulations are improving and partly oriented to NS microphysics.

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J. Margueron *et al*., EPJA 62, 22 (2026)