

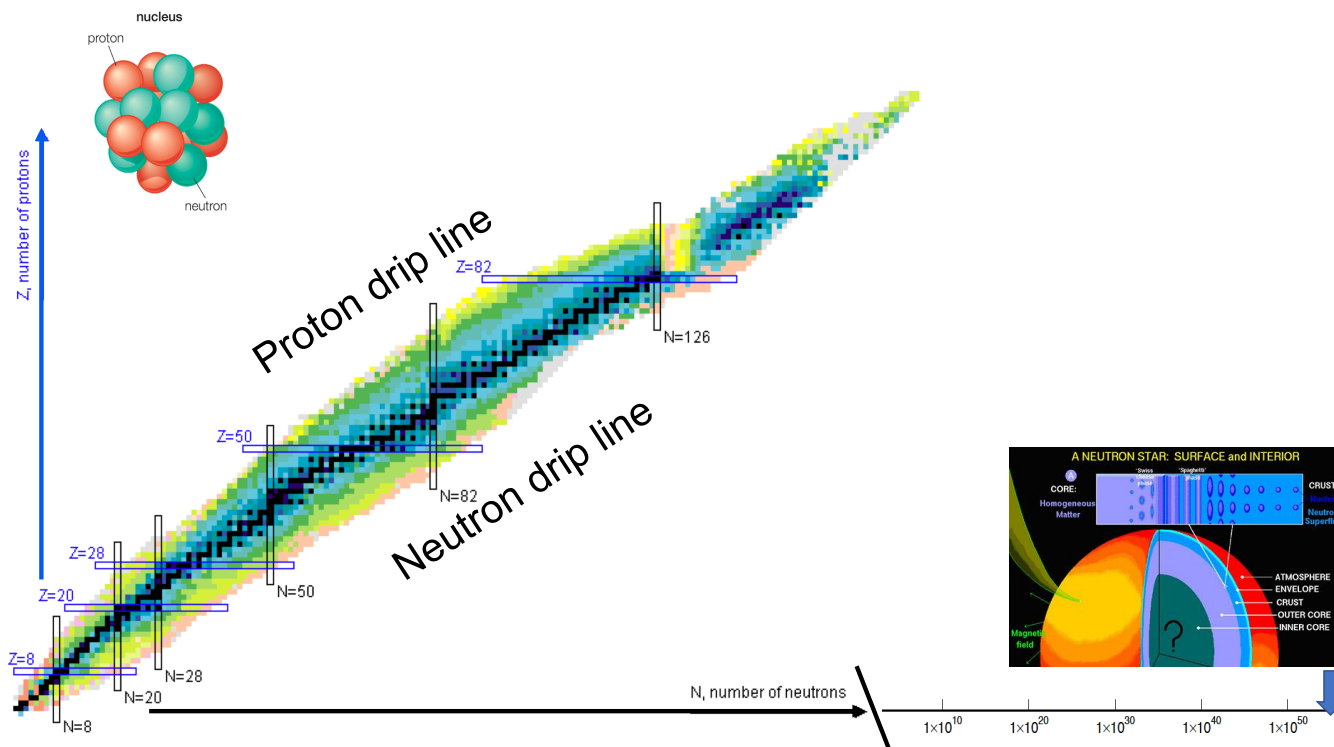
Nuclear structure for neutron stars

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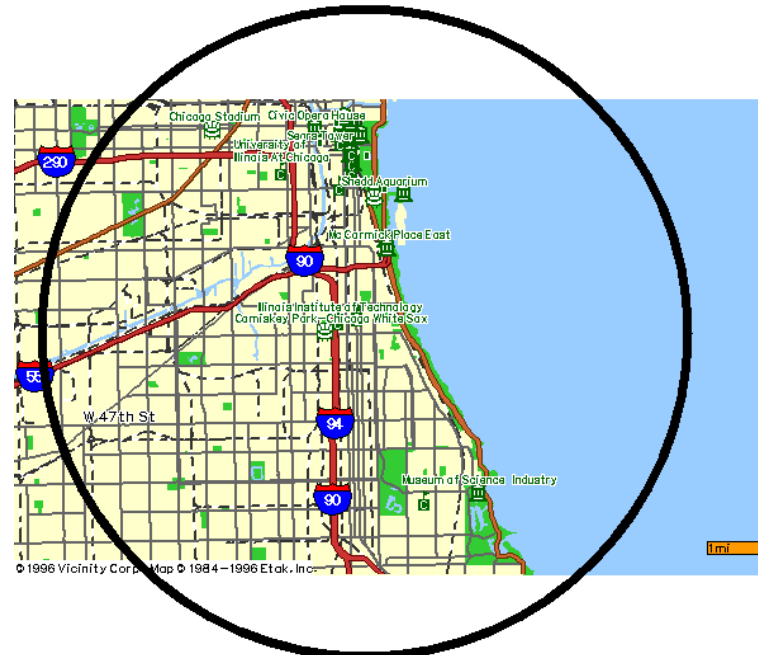


There is a complementarity between observations of NSs and nuclear structure experiments. No nuclear structure experiment can directly probe a NS but **plenty of them are much related to NS physics.**

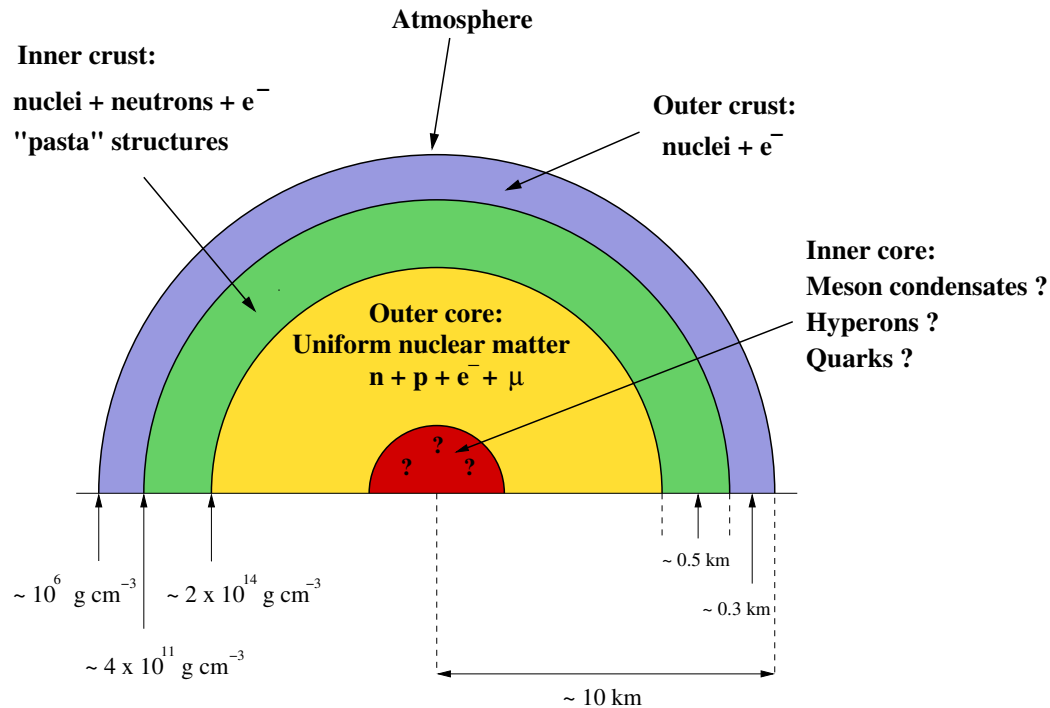
Keywords: masses, isovector states and symmetry energy, low-lying spectra, pairing ...



- 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.



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.

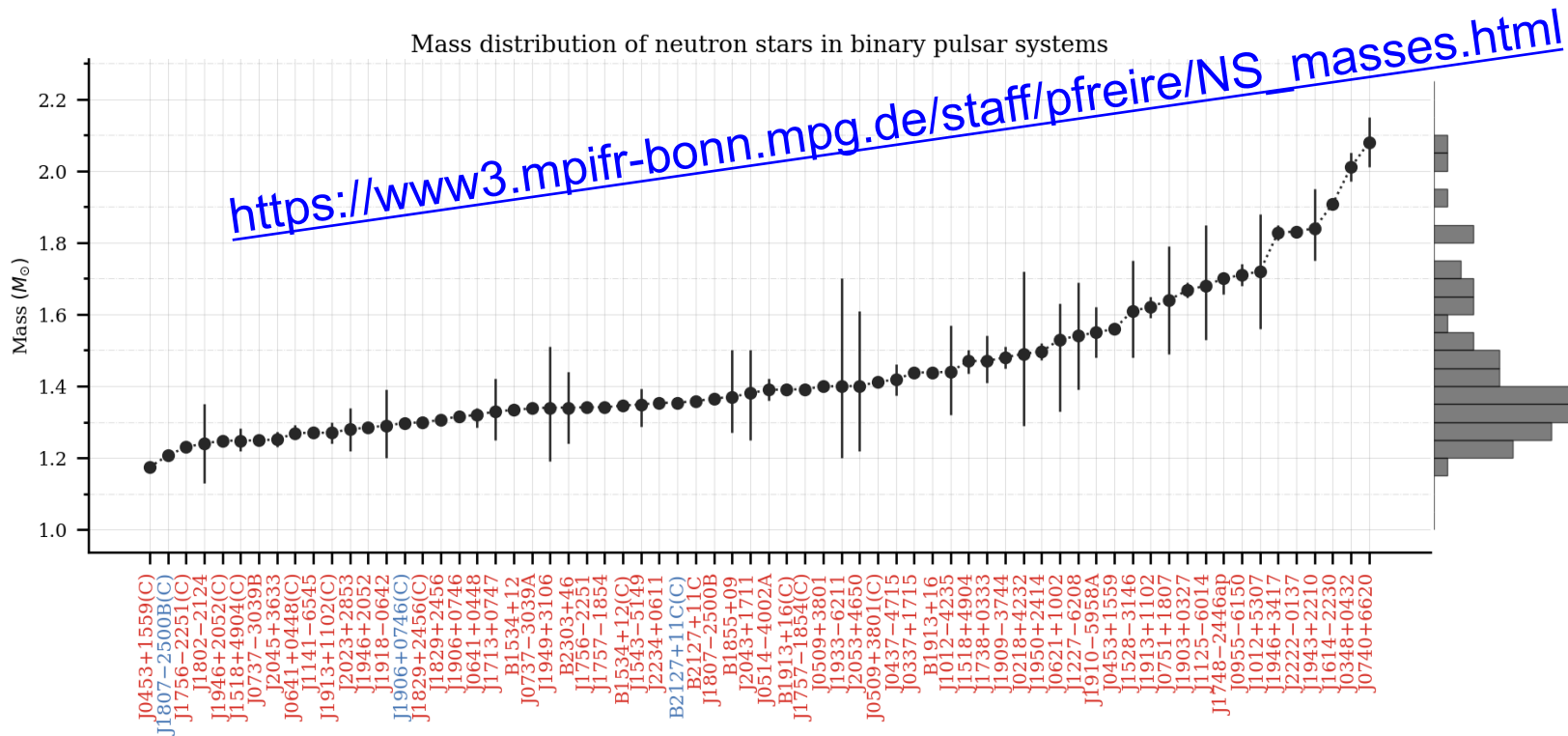
Inner crust: nuclei "drip neutrons out".

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??



Masses and radii

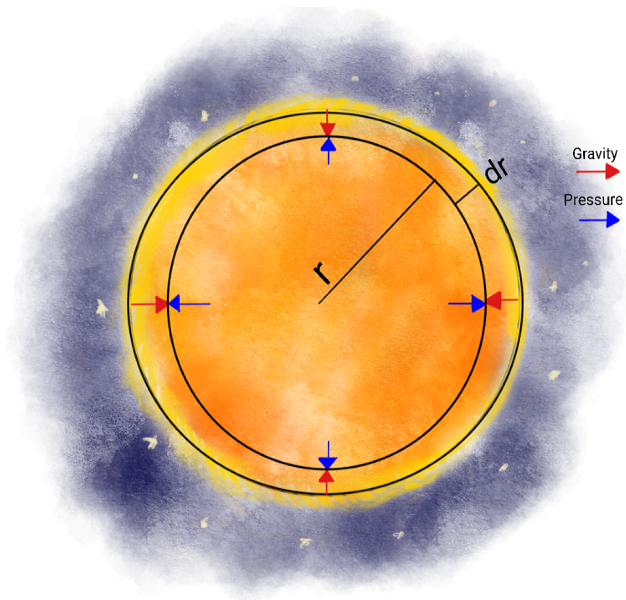


Up to a while ago, measurements of radii have been plagued by large uncertainties. Moreover, radii and masses were determined for different systems.

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

The TOV equation

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



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** (see H. Tamura).

QCD phase diagram at finite density (?).



The nuclear EoS and the symmetry energy

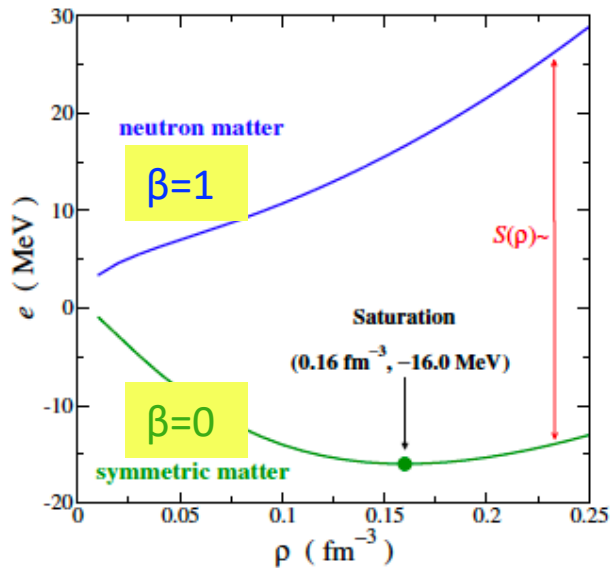
Nuclear matter EOS

$$\frac{E}{A}(\rho, \beta) = \frac{E}{A}(\rho, \beta \downarrow = 0) + S(\rho)\beta^2$$

Symmetric matter EOS

Symmetry energy S

$$\beta \equiv \frac{\rho_n - \rho_p}{\rho}$$



In turn, the symmetry energy can be expanded around saturation density.

$$\begin{aligned} S(\rho_0) &\equiv J \\ S'(\rho_0) &\equiv L/3\rho_0 \\ S''(\rho_0) &\equiv K_{\text{sym}}/9\rho_0^2 \end{aligned}$$

M. Oertel *et al.*, RMP **89**, 015007 (2017); B.A. Li *et al.*, Prog. Part. Nucl. Phys. **99**, 29 (2018)

To sustain NS masses of the order of two solar masses the EoS must be STIFF enough (we actually talk about β -equilibrated matter).



Stiffness of the EoS, non-nuclear degrees of freedom

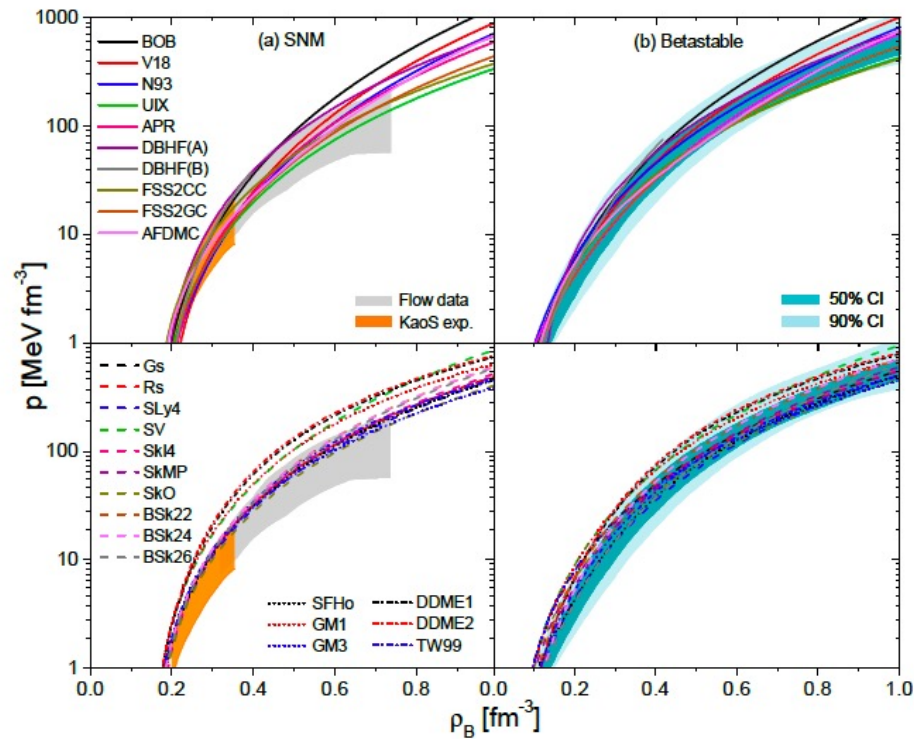


Figure 3. Pressure vs. baryon density for the symmetric case (left panels), and the beta-stable case (right panels). The upper (lower) panels display results for microscopic (phenomenological) EOSs. Constraints derived from HIC data are displayed in the left panels as orange (KaoS experiment) and grey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

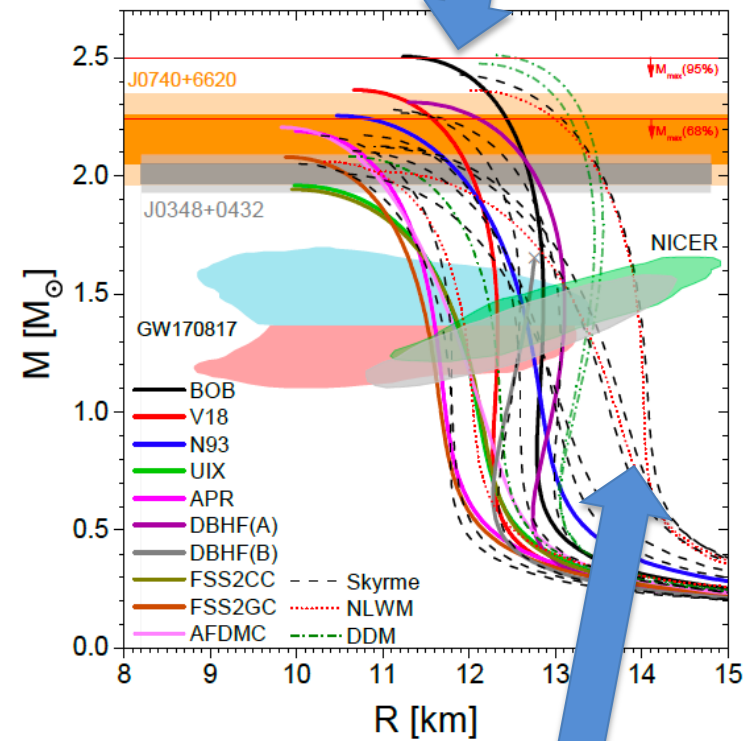


Figure 4. Mass-radius relations predicted by the different EOSs listed in Table 1. The observed masses of the millisecond pulsar PSR J0740 + 6620 [12] and of J0348 + 0432 [11] are also shown, as well as constraints inferred from the analysis of the GW170817 event and observations reported by the NICER mission [18,19]. See text for details.

Treatment of the crust

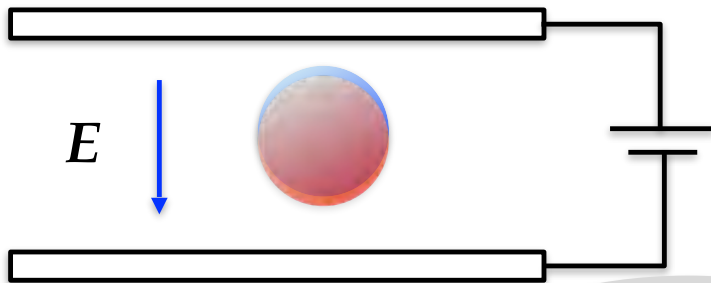


Measurements to constrain the nuclear EoS

1. Masses of drip-line nuclei

P. Möller et al., PRL 108, 052501 (2012).

3. DIPOLE polarizability

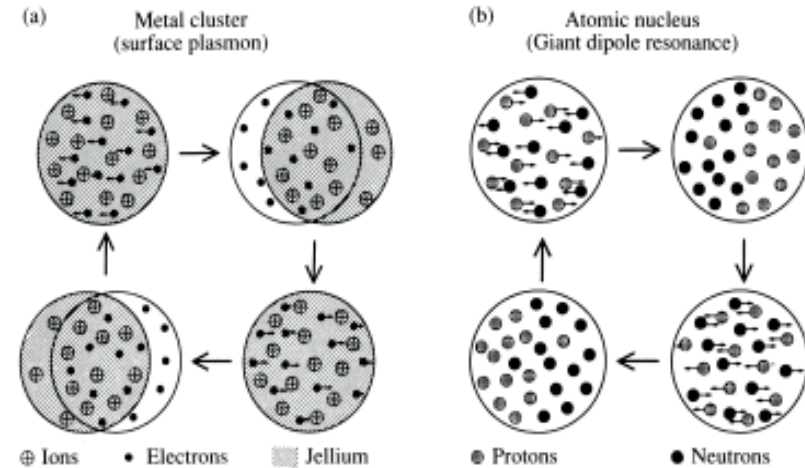


$$p = \alpha_D E$$

A. Migdal, J. Phys. Acad. Sci. USSR 8(1-6), 331-336 (1944)

$$\alpha_D = \frac{\pi e^2}{54} \frac{A \langle r^2 \rangle}{J}$$

2. ISOVECTOR nuclear excited states



4. Heavy Ion Collisions

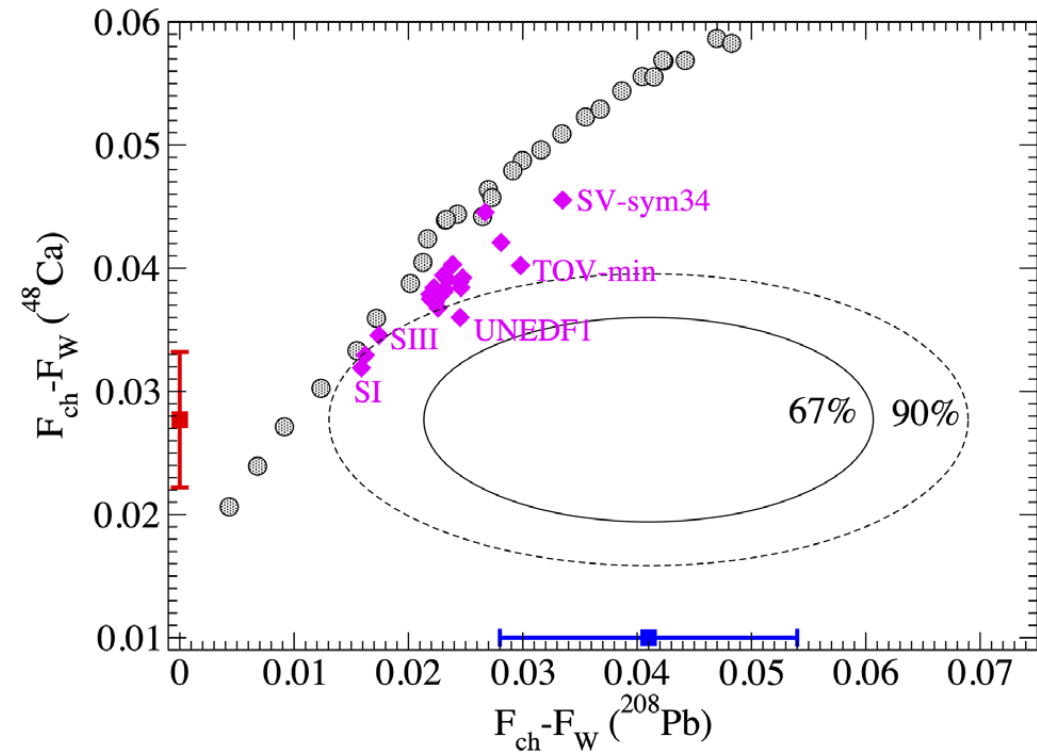
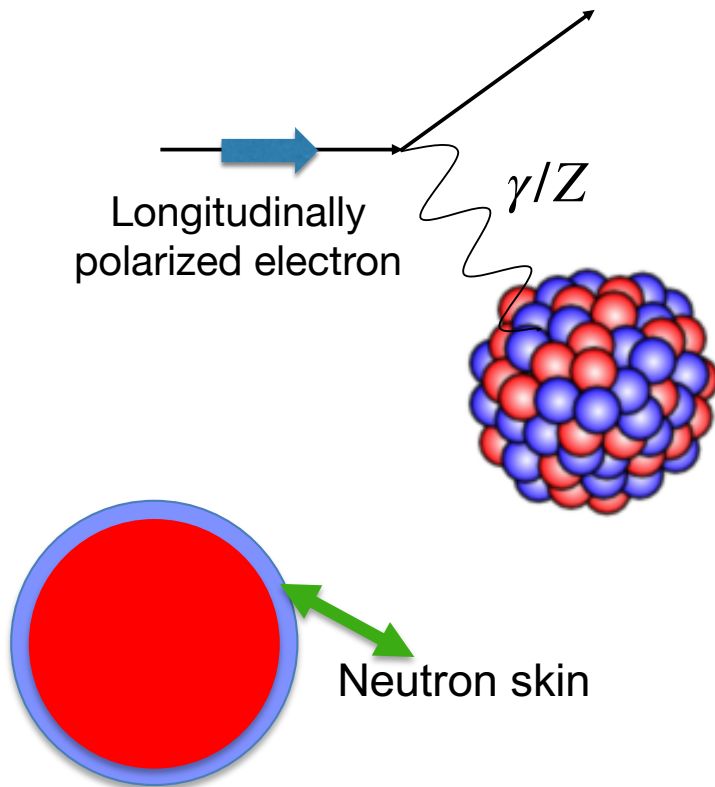
TMEP

Nuclear Science Symposium, 4/26



Parity-violating asymmetry (and weak FF)

Parity-violating asymmetry measured in electron scattering is a probe of the **neutron distribution** (in principle, a model-independent probe).



D. Adhikari *et al.*, Phys. Rev. Lett. 129, 042501 (2022)

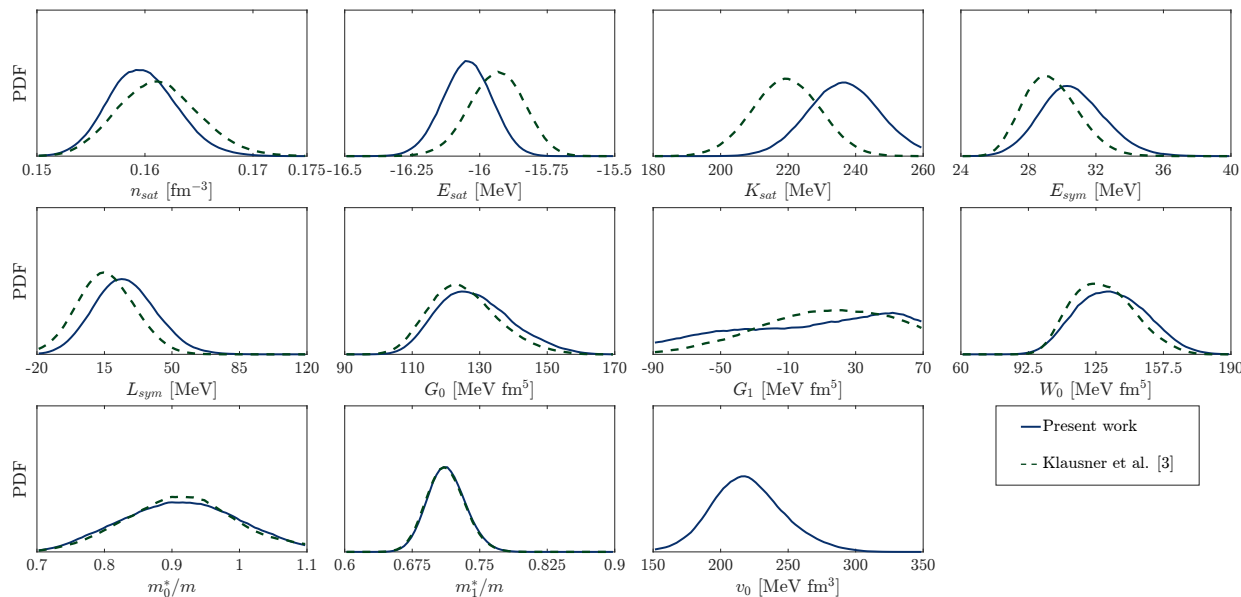


It would be worth to measure again at other facilities and/or with a different kinematics

Bayesian inference of nuclear and NS observables

P. Klausner *et al.*, arXiv:2604.11358v1 [nucl-th]

- It is possible to **reconcile, to some extent**, nuclear data and NS data (at the price of decoupling the low- and high-density behaviour of the EoS).
- It is not possible to accommodate the A_{PV} measurement.
- It is confirmed that **neutron-rich nuclei affect the posterior distribution of J, L.**

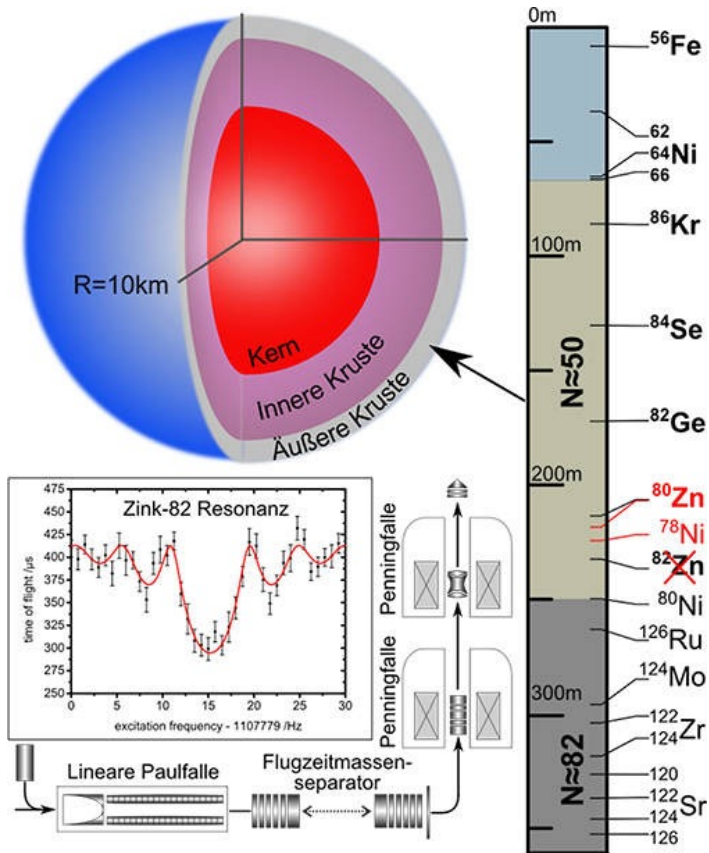


The posterior distributions involve either model-dependent or model-independent parameters.

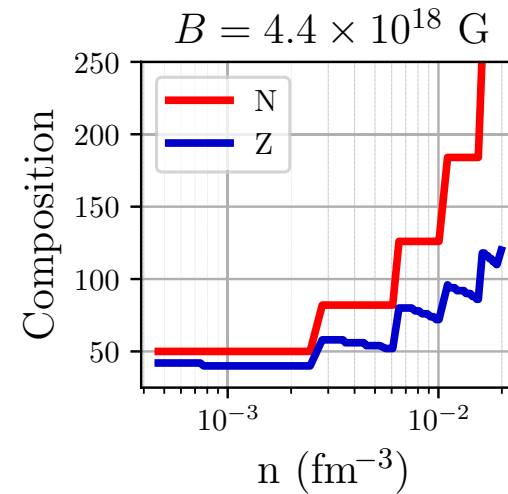
These latter should be confronted with the finding from other models.

Ab initio (chiral H):
Y. Lim and A. Schwenk, PRC
109, 035801 (2024)

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**.



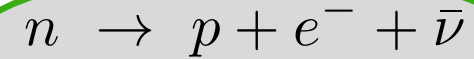
R. N. Wolf et al., PRL
110, 041101 (2013)

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}

Cooling of NS

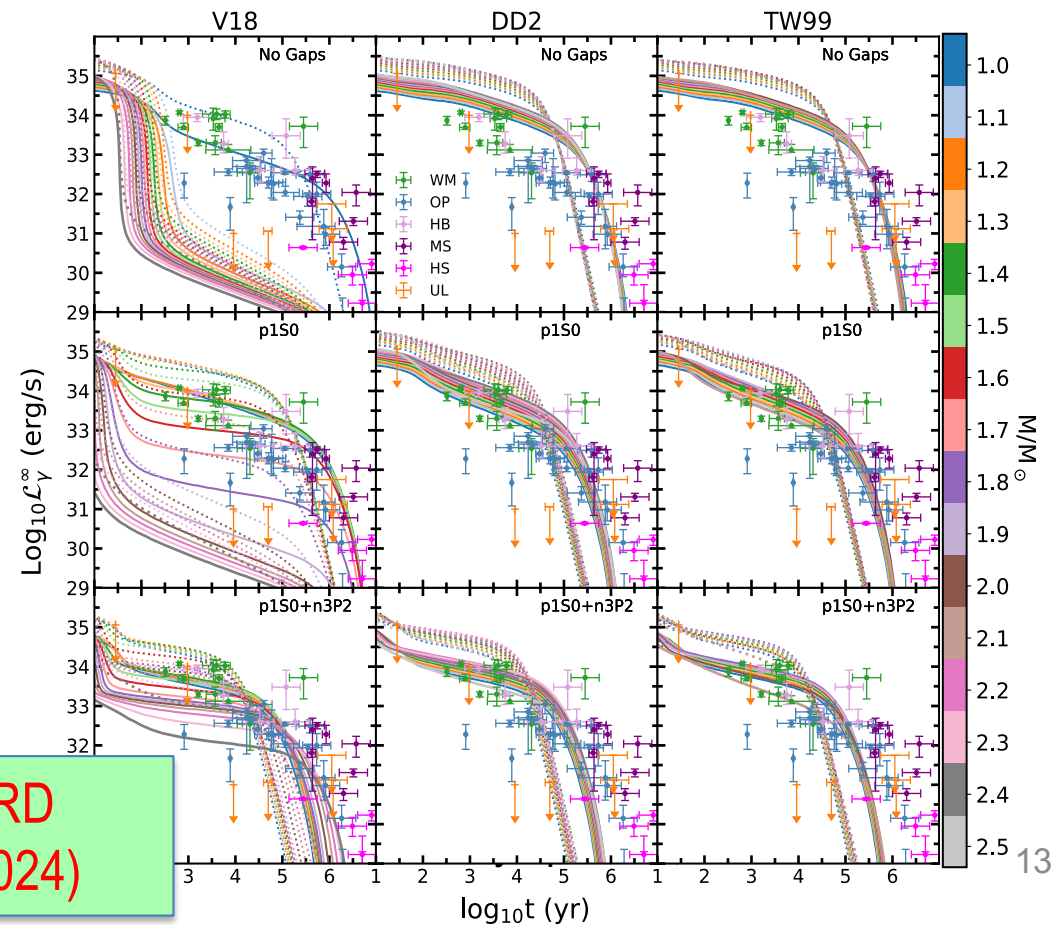
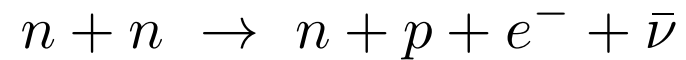
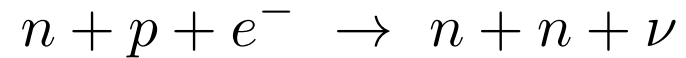


- **Neutrino emission** is the main source of cooling.

- 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.**

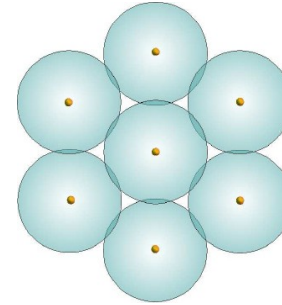


H. Das *et al.*, PRD
109, 123018 (2024)

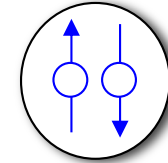


Pairing in the inner crust of NS (I)

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

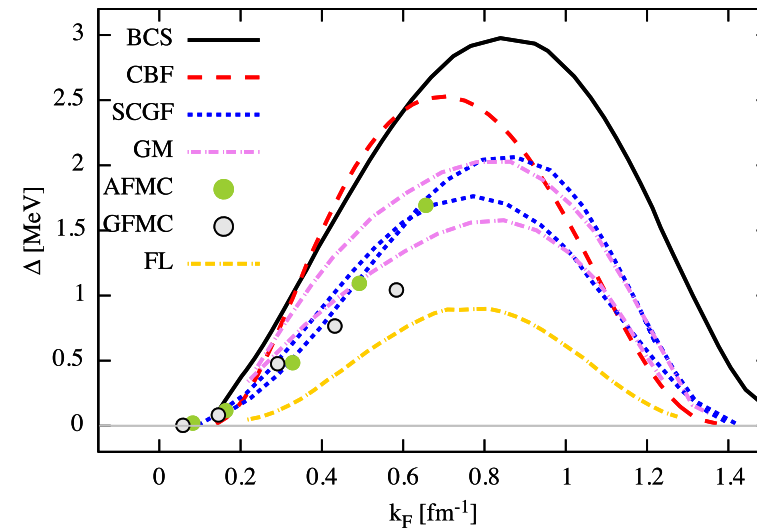
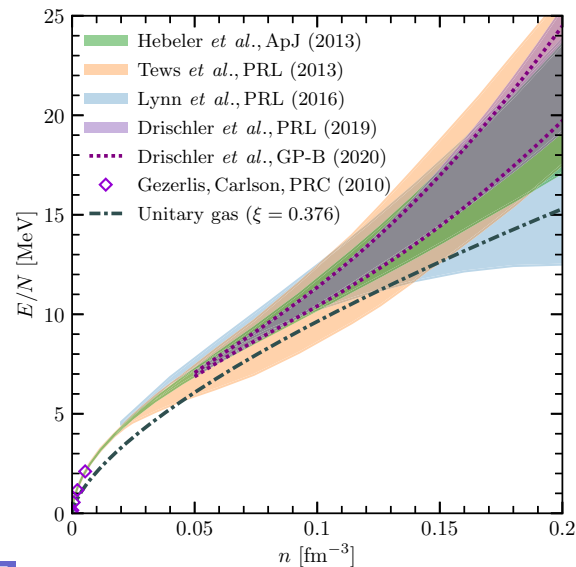


Cooper pairs



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**.

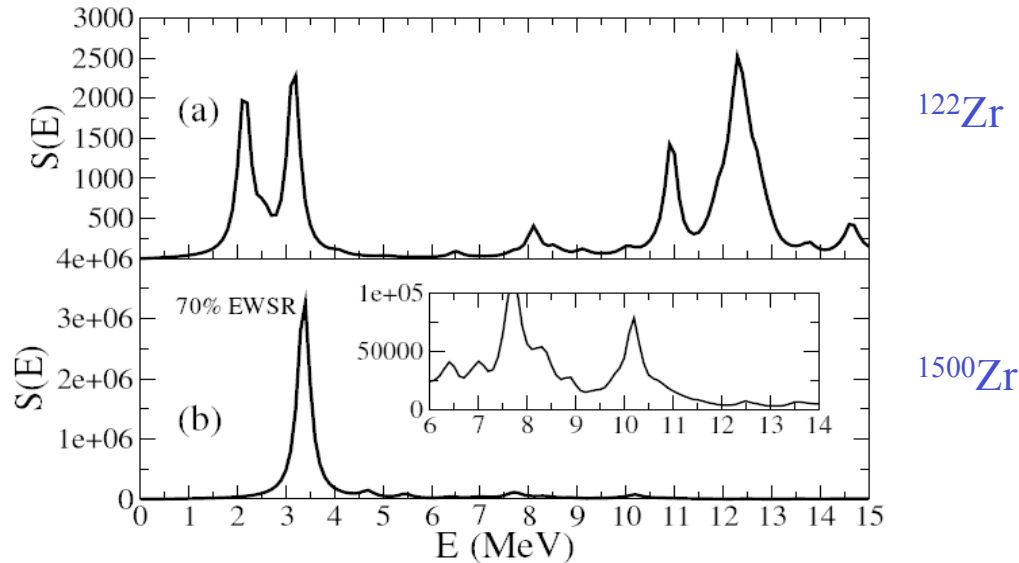
S. Huth *et al.*,
PRC 103,
025803 (2021)



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



Pairing in the inner crust of NS (II)



M. Grasso *et al.*, NPA 807, 1 (2008)

Extracting pairing in neutron matter from *ab initio* is desirable.

At the same time, **experimental data concerning low-lying spectroscopy in neutron-rich nuclei may inform us about pairing.**

Ultimately, one may find the best constraint is the elusive **Giant Pairing Vibration.**

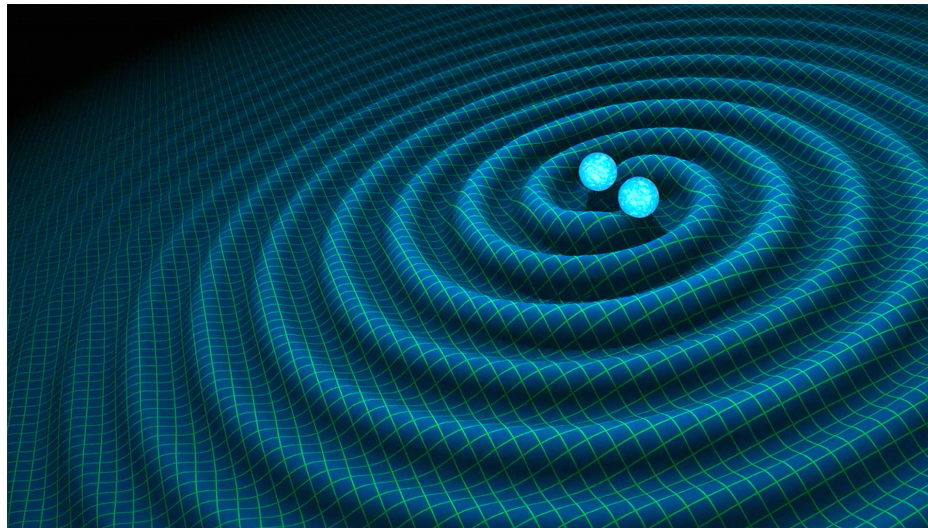


Merging of neutron stars AND the nuclear EoS

- 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)

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

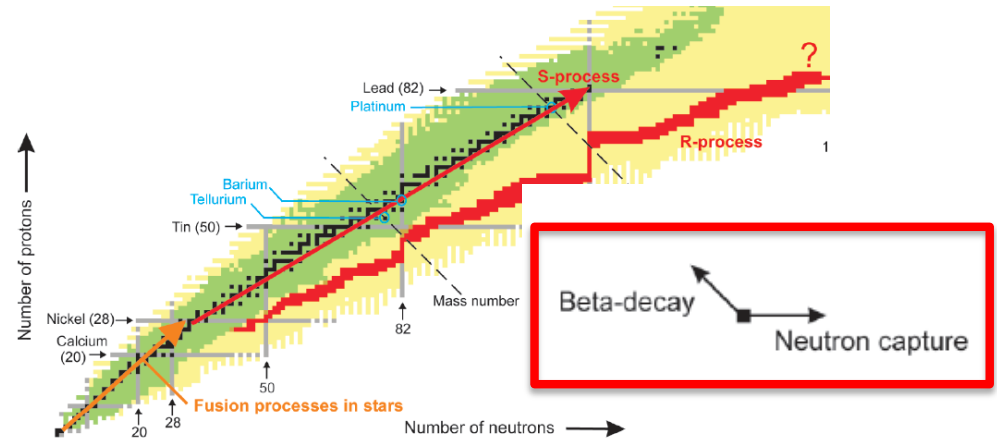
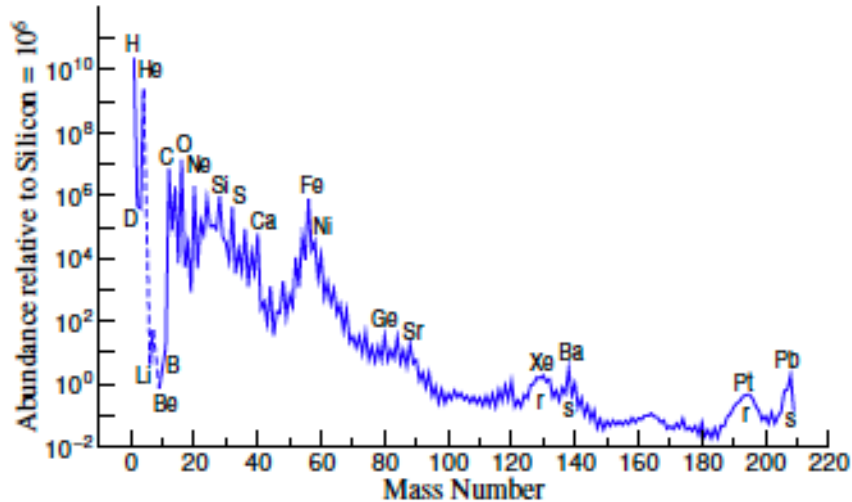
Probing the Incompressibility of Nuclear Matter at Ultrahigh Density through the Prompt Collapse of Asymmetric Neutron Star Binaries

Albino Perego^{1,2,*}, Domenico Logoteta^{3,4}, David Radice^{5,6,7}, Sebastiano Bernuzzi⁸, Rahul Kashyap^{5,6},
Abhishek Das^{5,6}, Surendra Padamata^{5,6} and Aviral Prakash^{5,6}



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

The nucleosynthesis problem



The r-process is related to NS.

Sites:

- 1) core-collapse supernovae
- 2) ejection from NS crust, merging

For (n, γ) rates:

Level density

E1 transition rates (overlap with the previous physics)



Conclusions

- In addition to measurements of “direct” interest to nuclear astrophysics (like e.g. cross sections for reactions in astrophysical environment), there are **plenty of measurements with indirect and yet high impact.**
- Still model dependence exist for nuclear physics results like the EoS; however, **there are now tools to improve our estimate of the theoretical uncertainty.**
- Easy tools to integrate nuclear data, observational data, theoretical results should be encouraged.
- **One big question is up to which density we can extrapolate “ordinary” nuclear physics (?).**



Backup slides



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

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

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



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

