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MOdeling
Nuclear
STructure and
REactions

How does subatomic matter organize itself?

A low-energy nuclear physics perspective

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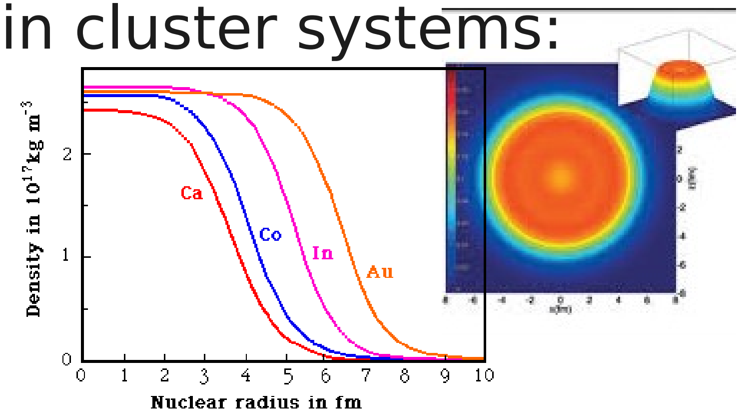
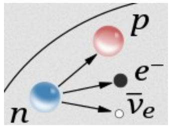
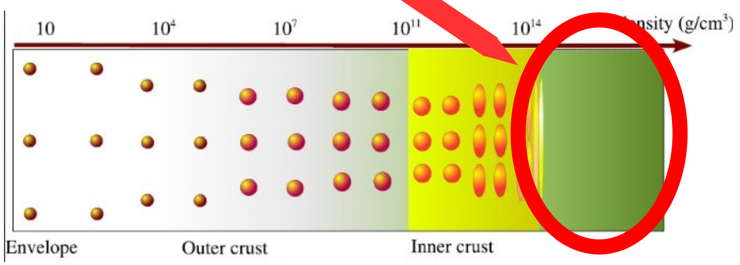
Where can we find neutrons and protons? And in which form? Free? In clusters?

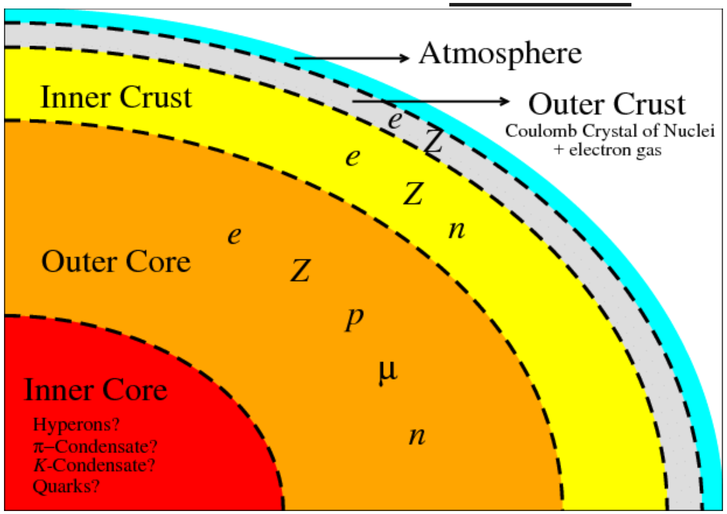
- Neutrons and protons in **Earth** are found in cluster systems: **<u>nuclei</u>**
  - → The **interior** of all nuclei has **constant density** (10^{14} times denser than water) named **saturation density**
  - → Saturation is originated from the **short range** nature of the **nuclear effective interaction**
  - → Neutron in 15 minutes must find a proton or …



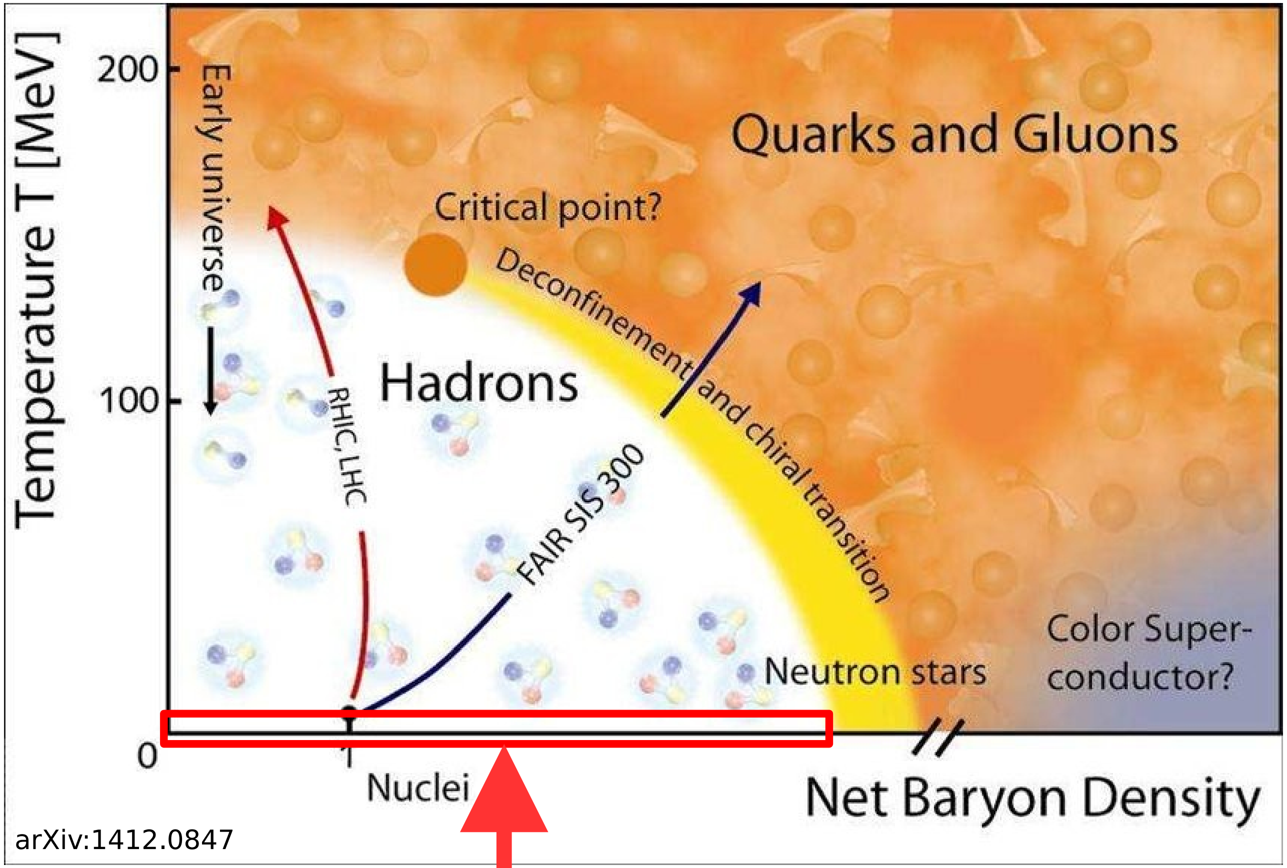


- In **heavens**, neutrons and protons can be also found as an interacting and unbound Fermi liquid: **matter in the <u>outer core</u> of a neutron star**
  - → Densities can reach several times nuclear saturation





QCD phase diagram



This talk: nuclear equation of state at T=0

→ **Neutron stars** (NS): denisties up to several ρ_0 and T ~ 0 MeV.

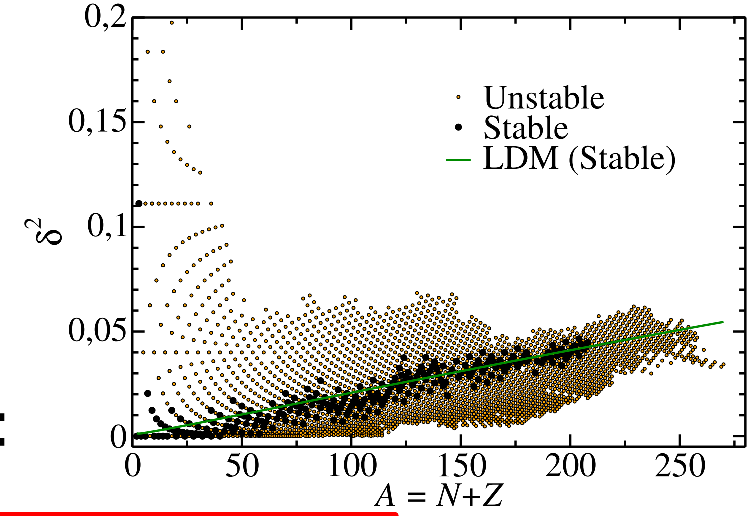
→ **NS-merger**: densities up to $6\rho_0$ and $T<10^2$ MeV.

→ Possible **mixed hadron-quark phase ?** (yellow band).

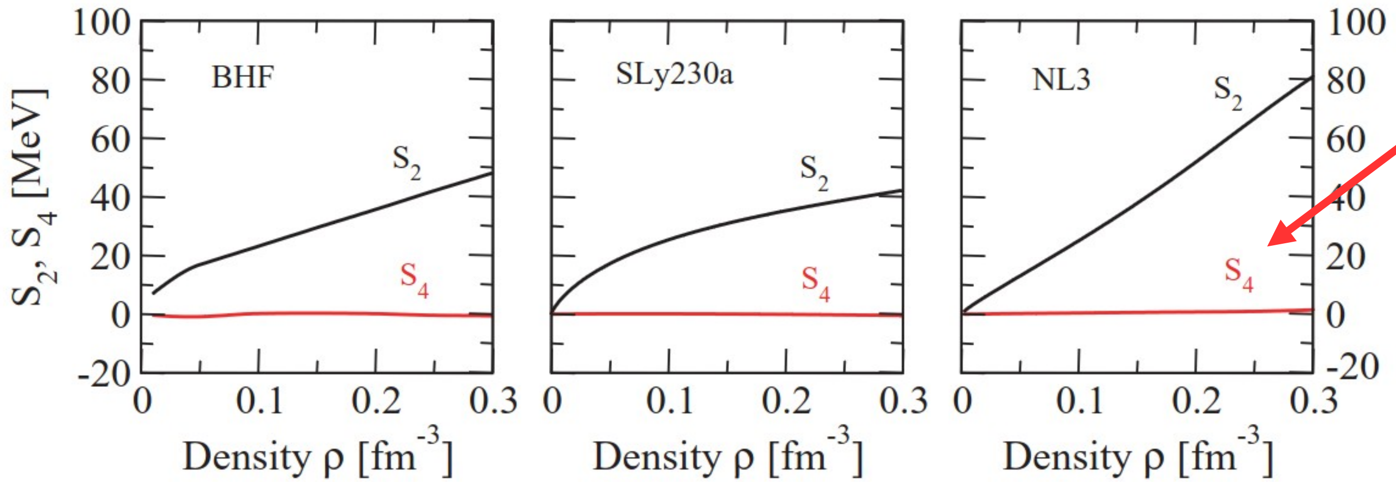
→ Several **facilities** are currently operating, in construction or in discussion, to provide insights into the phase diagram.

Nuclear Equation of State (EoS): E(ρ)

Energy per nucleon (***e***) as a **function** of the **total density** **$\rho=\rho_n+\rho_p$** and the **relative difference** **$\delta=(\rho_n-\rho_p)/\rho$** for **unpolarized uniform matter at T=0** (10^{10}K→1MeV) **assuming isospin symmetry** (even powers of δ). For **δ → 0**:



$$\boxed{e(\rho,\delta) = e(\rho,0) + S_2(\rho)\delta^2 + S_4(\rho)\delta^4 + \mathcal{O}[\delta^6]}$$



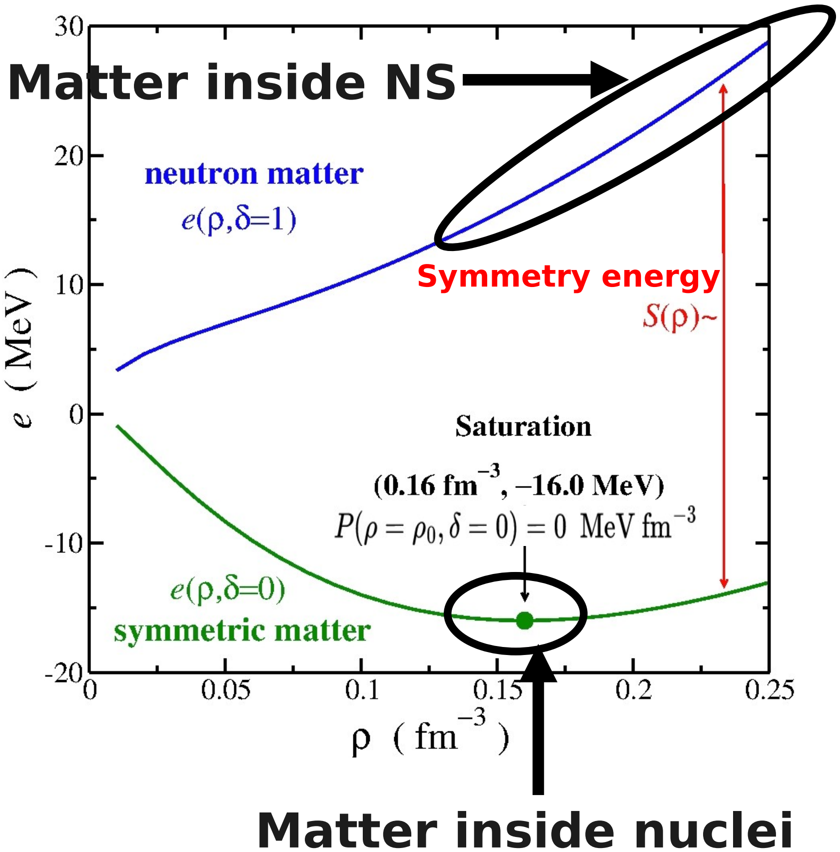
S_4 ~ 0 implies that even for large δ, $S_2(\rho)$ GOOD APPROX

Isaac Vidaña, Constança Providência, Artur Polls, and Arnau Rios
Phys. Rev. C **80**, 045806 – Published 23 October 2009

Nuclear Equation of State (EoS)

Unpolarized, uniform nuclear matter at T=0 assuming isospin symmetry

$$\boxed{e(\rho,\delta) = e(\rho,0) + S_2(\rho)\delta^2}$$



It is customary to also **expand** $e(\rho,0)$ and $S(\rho)$ around nuclear **saturation density** $\rho_0 \sim 0.16\ \text{fm}^{-3}$

$$e(\rho,0) = e(\rho_0,0) + \frac{1}{2}K_0x^2 + \mathcal{O}[\rho^3] \text{ where } x = \frac{\rho-\rho_0}{3\rho_0}$$

$$S(\rho) = J + Lx + \frac{1}{2}K_{\text{sym}}x^2 + \mathcal{O}[\rho^3,\delta^4]$$

K_0 → how **compressible** is symmetric matter at ρ_0

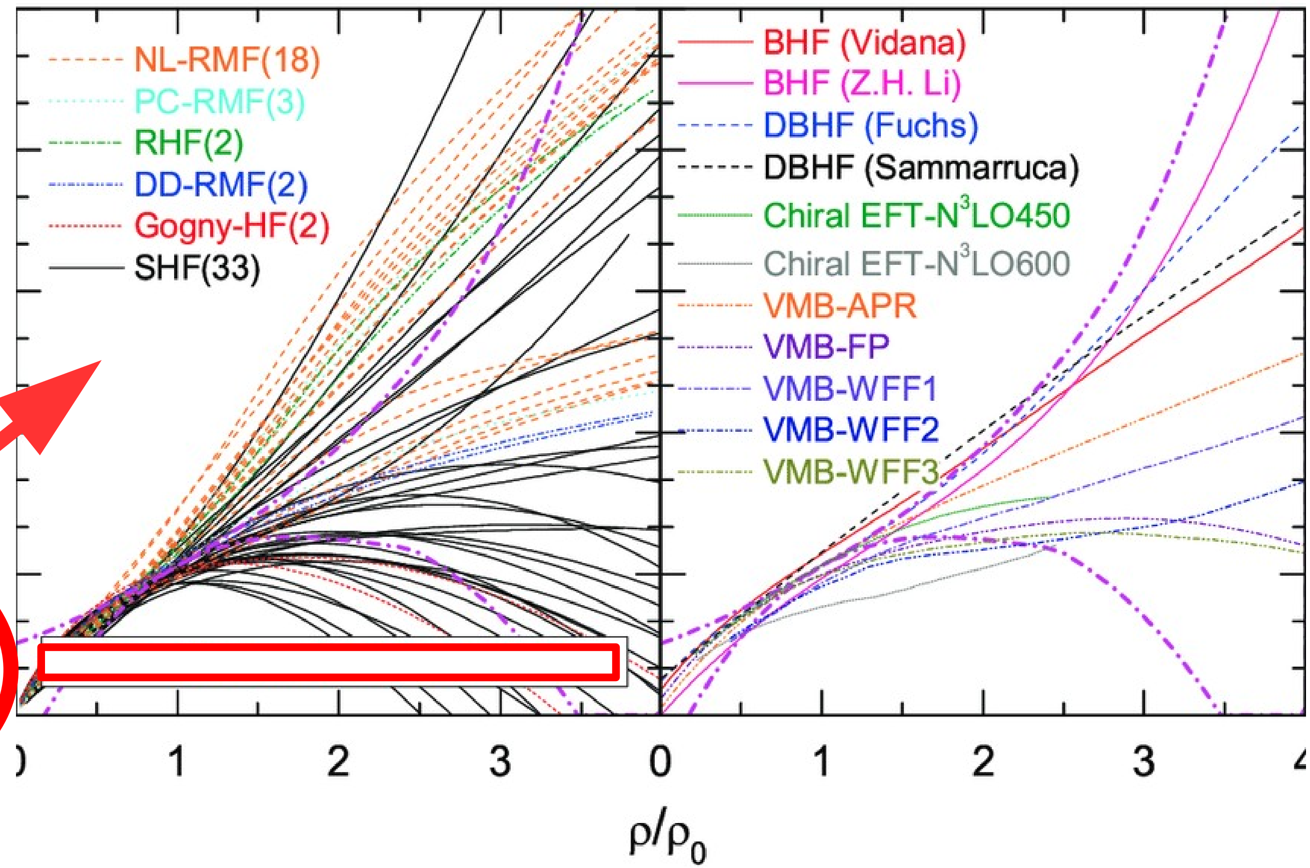
J → **penalty energy** for converting all **protons into neutrons** in symmetric matter at ρ_0

L → **neutron pressure** in neutron matter at ρ_0

State-of-the-art:
symmetry energy $S(\rho) \sim e(\rho,\delta=1)-e(\rho,\delta=0)$

Symmetry energy not well constrained

Phenomeno-logic models



Microscopic models

Towards understanding astrophysical effects of nuclear symmetry energy
Bao-An Li, Plamen G. Krastev, De-Hua Wen & Nai-Bo Zhang EPJ A 55, 117 (2019)

What can we learn from the Earth and the Heavens about the Nuclear Equation of State?

(some examples)

From Heaven: Neutron Star Mass

Nuclear models that account for different nuclear properties on **Earth** predict a large **variety** of **Neutron Star Mass-Radius** relations → **<u>Observation of a 2M_{sun} has constrained nuclear models.</u>**

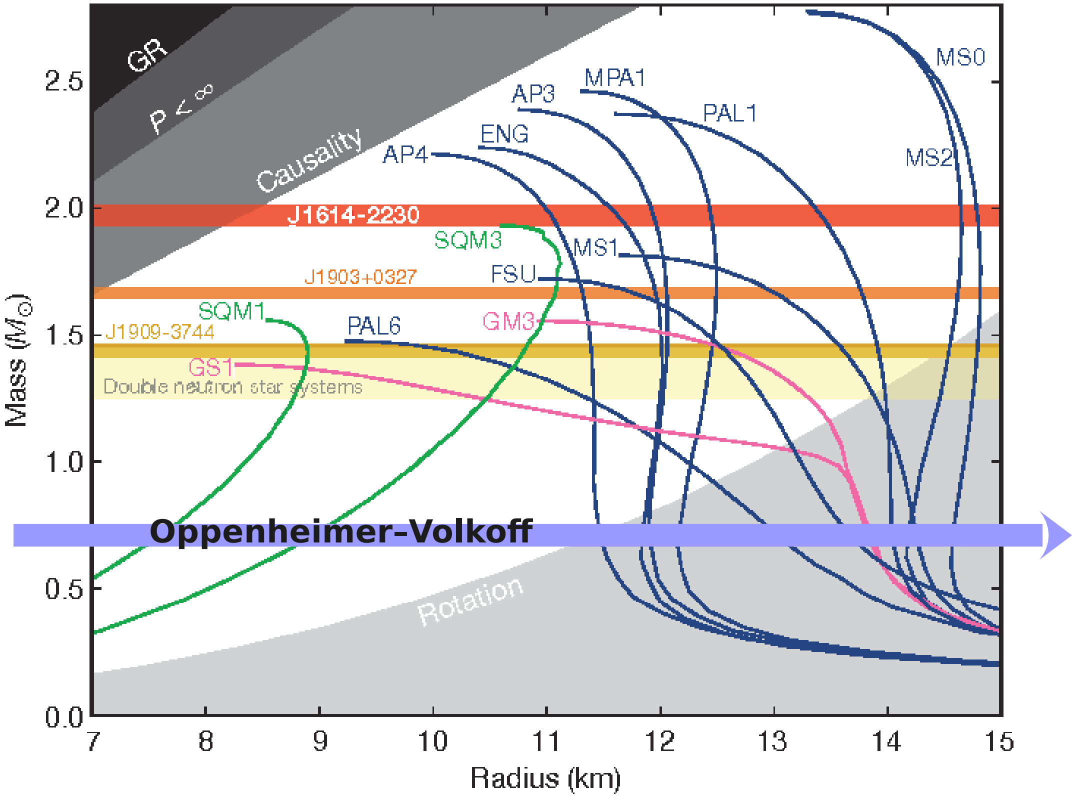
Tolman–Oppenheimer–Volkoff equation (sph. sym.):

$$\frac{dM(r)}{dr} = 4\pi r^2 \mathcal{E}(r);$$

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$\mathcal{E}(r) \rightarrow$ degeneracy pressure from neutrons $\rightarrow M_{\max} = 0.7 M_{\text{sun}}$

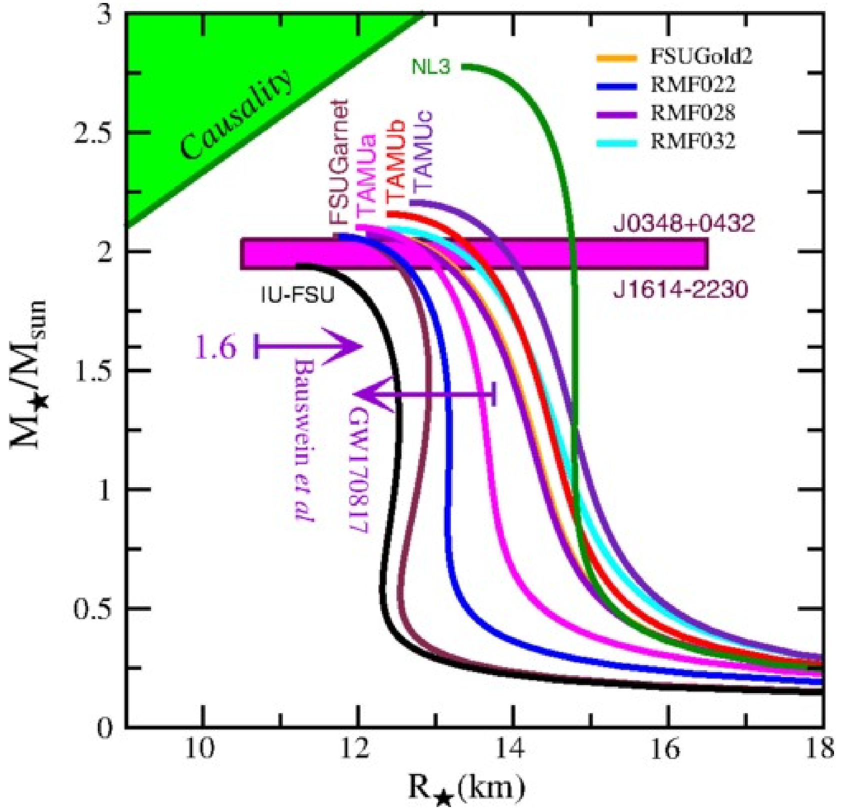
Nuclear Physics input is fundamental

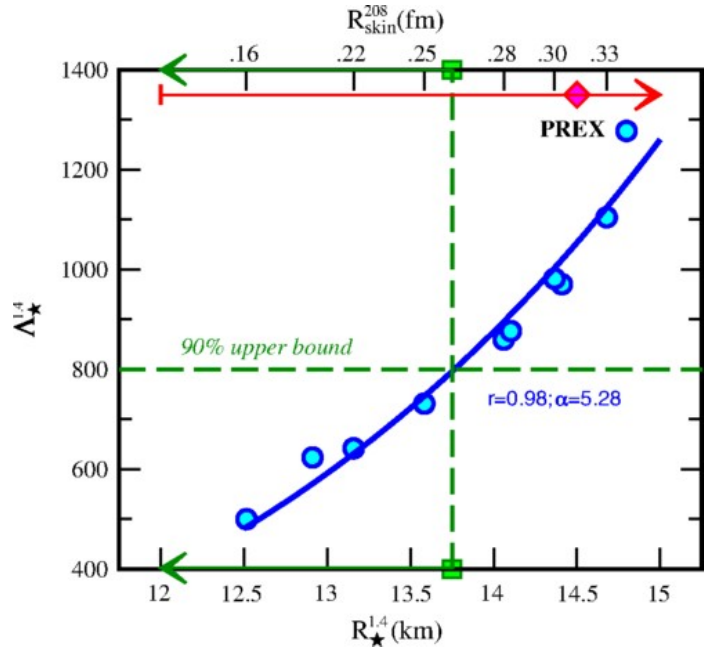


A two-solar-mass neutron star measured using Shapiro delay - P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts & J. W. T. Hessels - Nature volume 467, 1081–1083(2010)

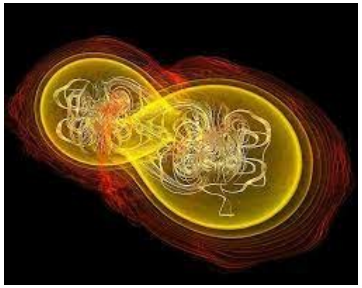
From Heaven: Gravitational wave signal from a binary neutron star merger

GW170817 from the binary neutron star merger → **constraint** neutron star **radius** and, thus, the **nuclear EoS**





Tidal deformability (Λ) is a quadrupole deformation inferred from **GW signal →** proportional to **restoring force.** Hence, sensitive to the **nuclear EoS**



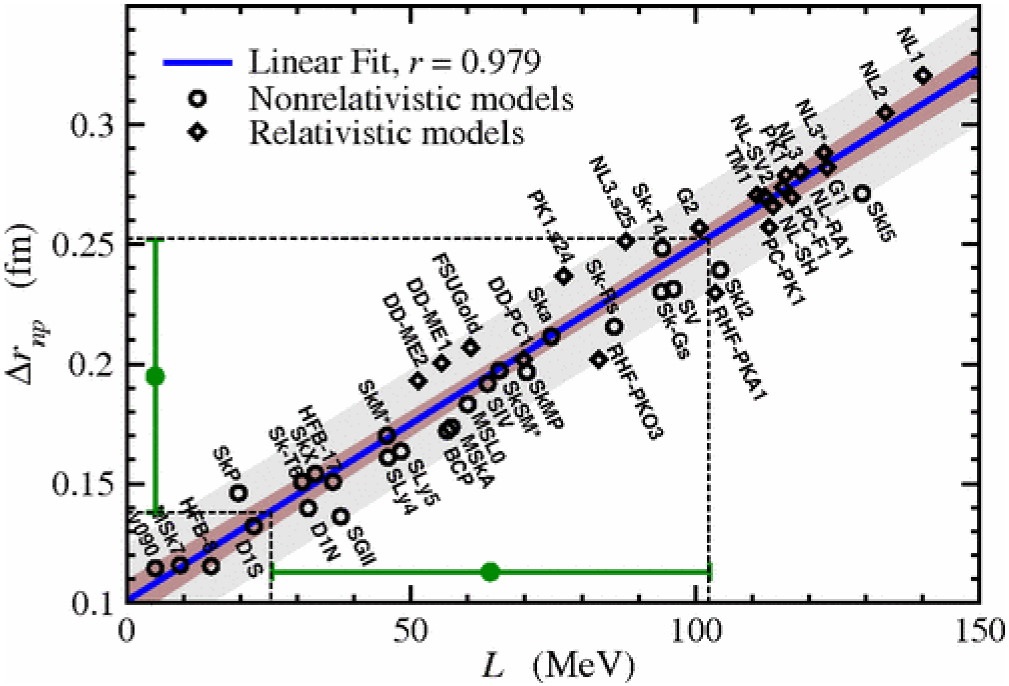
Neutron Skins and Neutron Stars in the Multimessenger Era
F. J. Fattoyev, J. Piekarewicz, and C. J. Horowitz Phys. Rev. Lett. 120, 172702 (2018)

From Heaven & Earth: neutron skin and the Radius of a Neutron Star

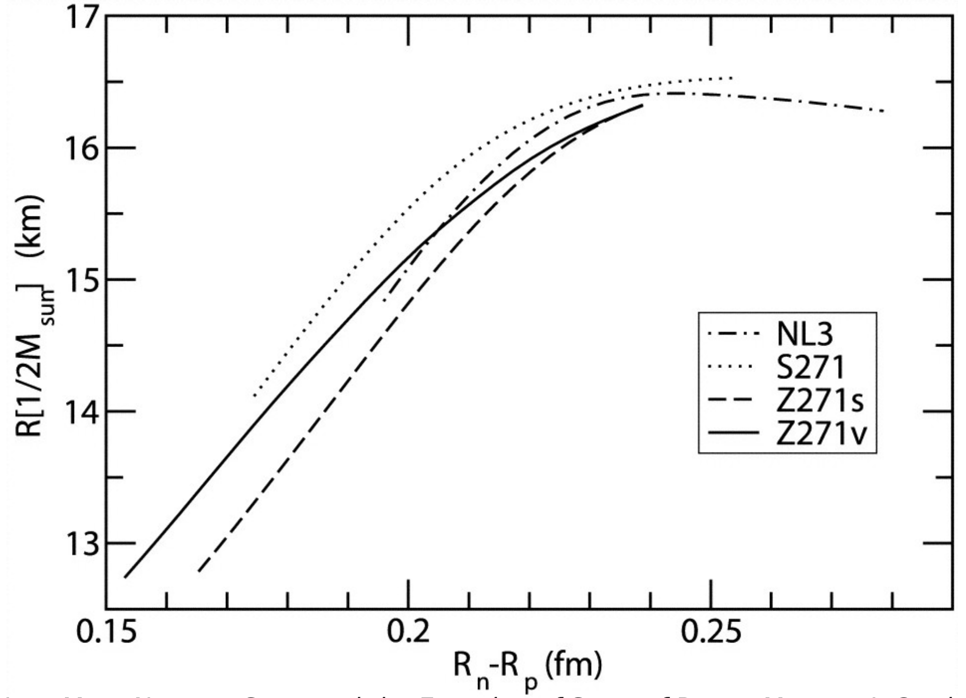
Both, the **neutron skin thickness** ($\Delta r_{np}=r_n-r_p$) in neutron rich nuclei and the **radius** of a **neutron star** are related to the **neutron pressure** in infinite matter. The former around ρ_0 (L) while the latter at larger densities.

$$\Delta r_{np} \approx \frac{1}{12}\frac{N-Z}{A}\frac{R}{J}L$$

→ For **small neutron stars**, that is, for small central densities: nuclear models predict a **linear** relation between **R** and **Δr_{np}**



Neutron Skin of 208Pb, Nuclear Symmetry Energy, and the Parity Radius Experiment
X. Roca-Maza, M. Centelles, X. Viñas, and M. Warda Phys. Rev. Lett. 106, 252501 (2011)



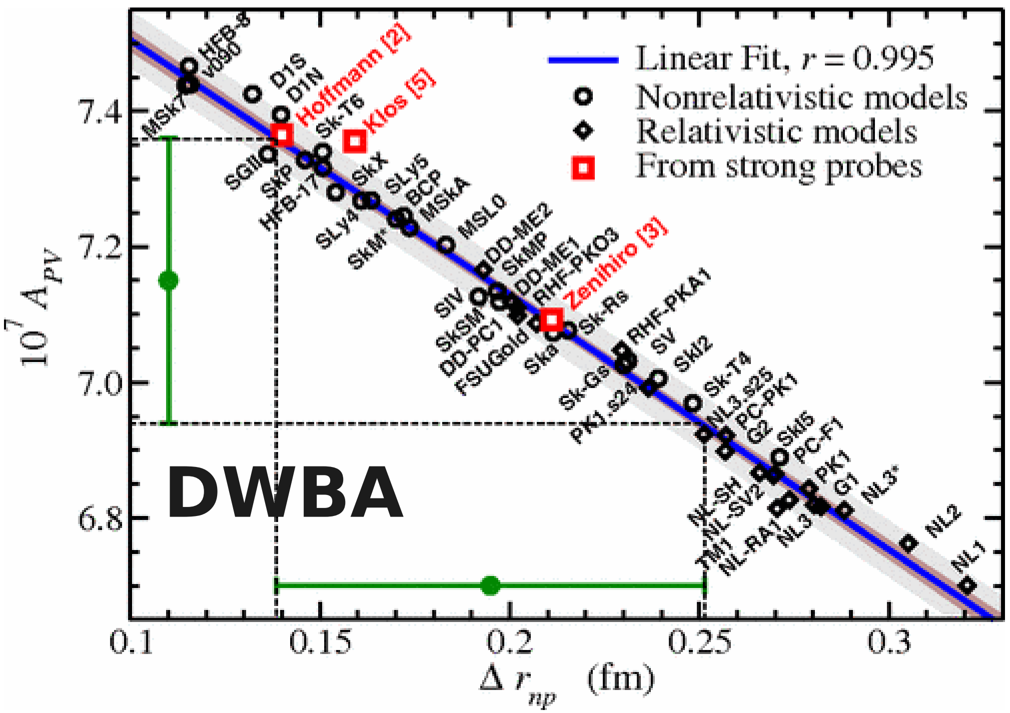
Low-Mass Neutron Stars and the Equation of State of Dense Matter - J. Carriere, C. J. Horowitz, and J. Piekarewicz - The Astrophysical Journal, 593 (2003) 463

From Earth: Parity violating electron scattering and the neutron skin

Polarized electron-Nucleus scattering:

→ In good approximation, **the weak interaction** probes the **neutron distribution** in nuclei while **Coulomb interaction** probes the **proton distribution**

→ **Different experimental efforts @ Jlab (USA) & MAMI (Germany)**



Neutron Skin of 208Pb, Nuclear Symmetry Energy, and the Parity Radius Experiment
X. Roca-Maza, M. Centelles, X. Viñas, and M. Warda Phys. Rev. Lett. 106, 252501 (2011)

→ **Electrons** interact by **exchanging** a **γ** (couples to **p**) or a **Z_0** boson (couples to **n**)

→ **Ultra-relativistic electrons**,depending on their helicity (±), will interact with the nucleus seeing a slightly different potential: **Coulomb** ± **Weak**

$$A_{pv} = \frac{d\sigma_+/d\Omega - d\sigma_-/d\Omega}{d\sigma_+/d\Omega + d\sigma_-/d\Omega} \sim \frac{\text{Weak}}{\text{Coulomb}}$$

→ Main **unknown** is **ρ_n**

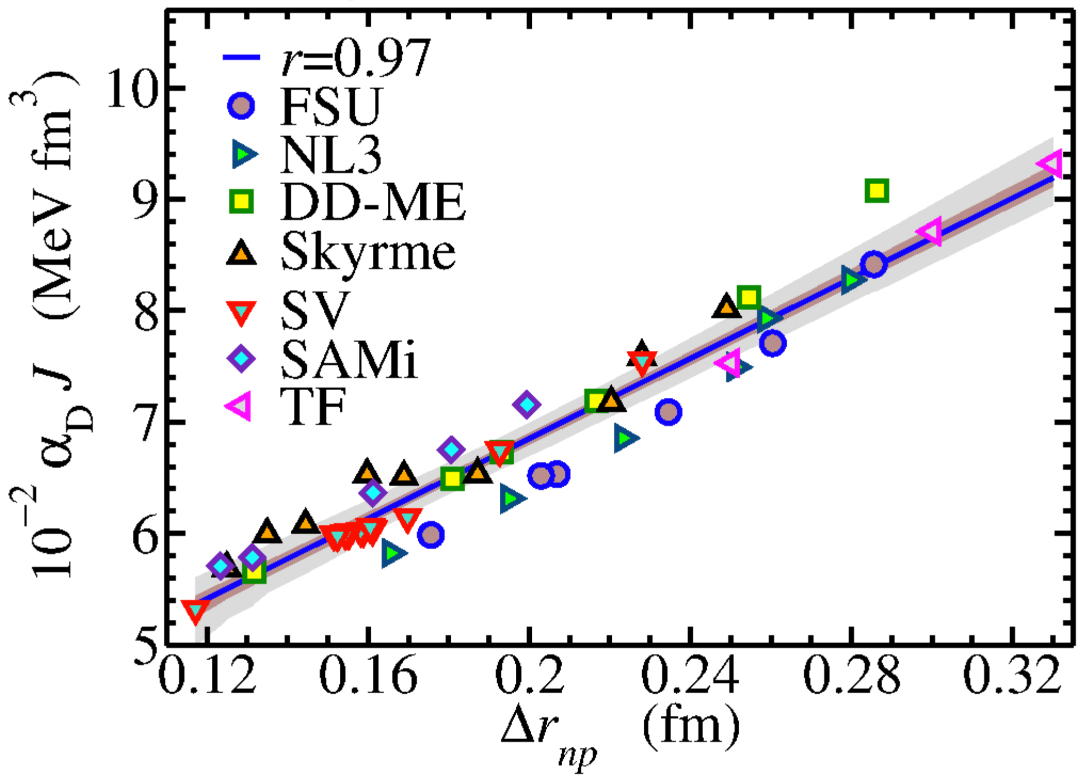
→ In **PWBA** for small momentum transfer **q**:

$$A_{pv} = \frac{G_F q^2}{4\sqrt{2}\pi\alpha}\left(1 - \frac{q^2 r_p^2}{3F_p(q)}\right)\Delta r_{np}$$

From Earth: dipole polarizability and neutron skin

The dipole **polarizability** measures the **tendency** of the nuclear **charge** distribution to be **distorted.**

From a macroscopic point of view **α ~ (electric dipole moment)/(external electric field)**



→ Using the **dielectric theorem**: the polarizability can be computed from the expectation value of the Hamiltonian in the constrained ground state H′=H+λD

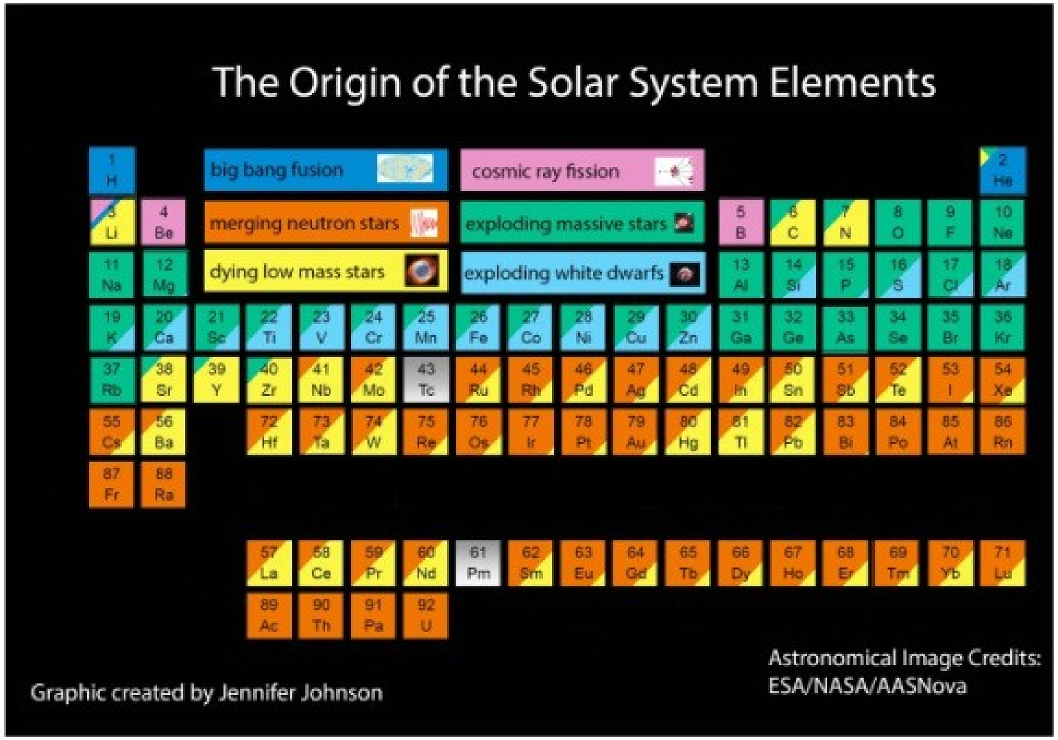
→ For guidance assuming the **Droplet model** for H, one would find:

$$\alpha_D \approx \frac{\pi e^2}{54}\frac{\langle r^2\rangle}{J}A\left(1+\frac{5}{2}\frac{\Delta r_{np}-\Delta r_{np}^{\rm surf}-\Delta r_{np}^{\rm Coul}}{\langle r^2\rangle^{1/2}(I-I_{\rm Coul})}\right)$$

Electric dipole polarizability in 208Pb: Insights from the droplet model - X. Roca-Maza, M. Brenna, G. Colò, M. Centelles, X. Viñas, B. K. Agrawal, N. Paar, D. Vretenar, and J. Piekarewicz

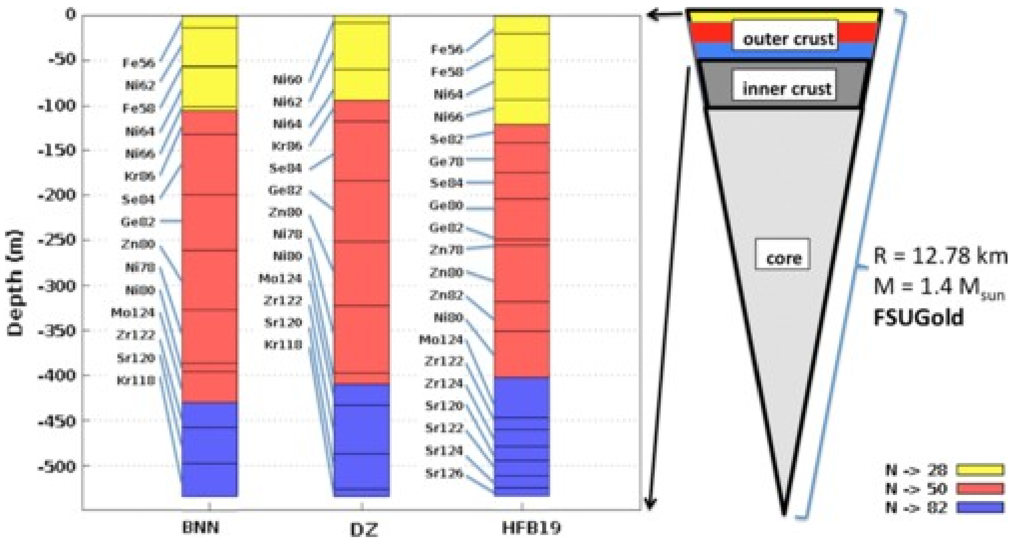
Phys. Rev. C 88, 024316 (2013)

From Heaven: Origin of elements



Binary neutron star merger produced about **10^{29}kg** of **heavy elements**!

The **crust** of a **NS** is made of very **exotic neutron rich nuclei,** stable only due to the extreme conditions (large densities). **Different nuclear models predict different compositions**



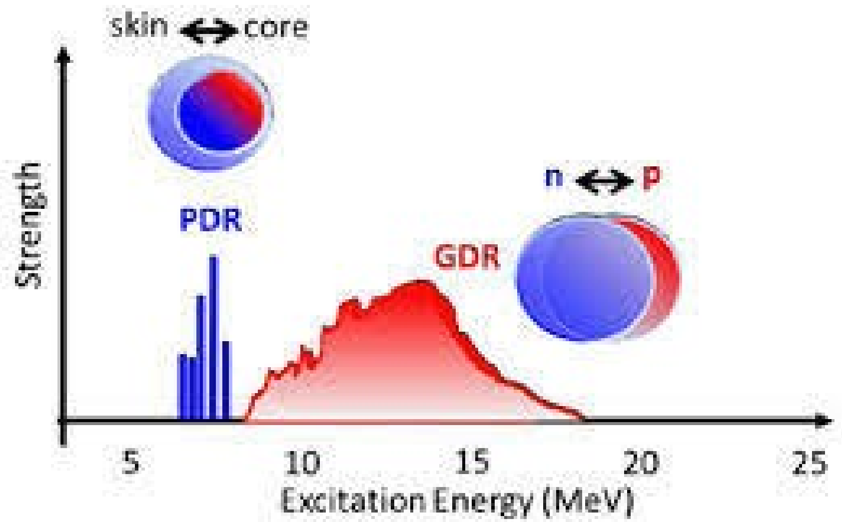
Nuclear mass predictions for the crustal composition of neutron stars: A Bayesian neural network approach R. Utama, J. Piekarewicz, and H. B. Prosper, Phys. Rev. C 93, 014311 (2016)

From Heaven & Earth: low energy dipole response and nucleosynthesis

The **largest** the **neutron pressure** among neutrons (~L), the more the **excess neutrons** (~skin) are ***"pushed out"*** in the **outermost** part of the **nucleus →** spatial ***decorrelation*** of some of those neutrons with the nucleons in the core produces **larger low lying** responses**.**

GDR=Giant Dipole Resonance

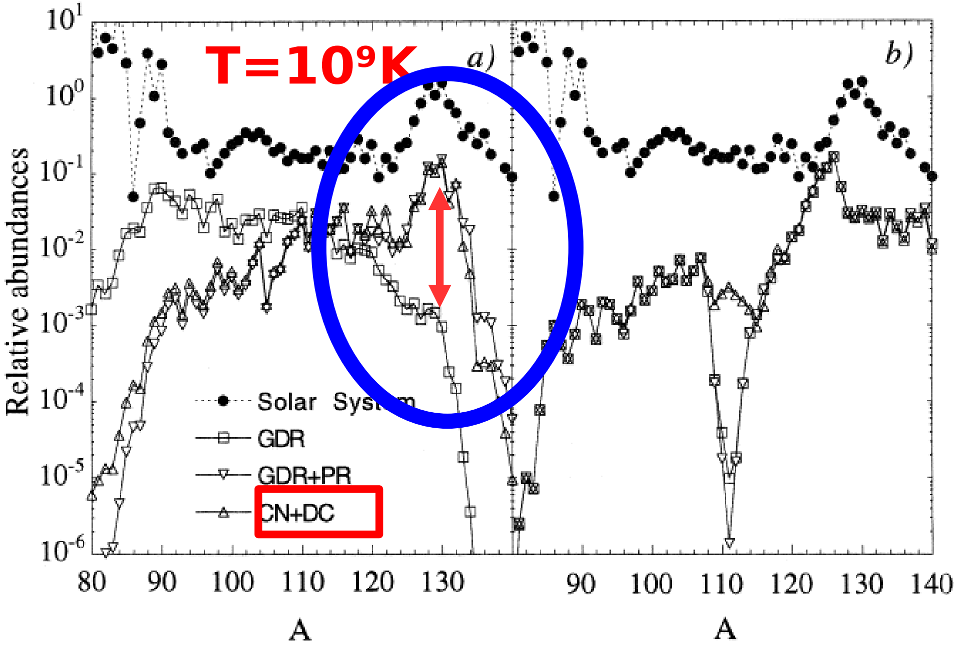
PDR= Pygmy Dipole Resonance



(nature of PDR still under debate)

Radiative neutron captures by neutron-rich nuclei and the r-process nucleosynthesis

S. Goriely, Phys.Lett.B 436 (1998) 10-18

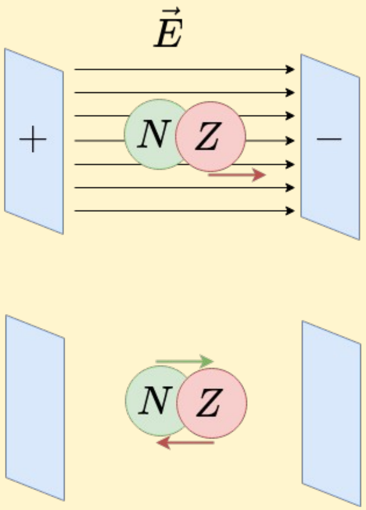


Low energy dipole strength in neutron-rich nuclei influences the neutron capture cross section and, thus, the r-process nucleosynthesis

Conlcusions

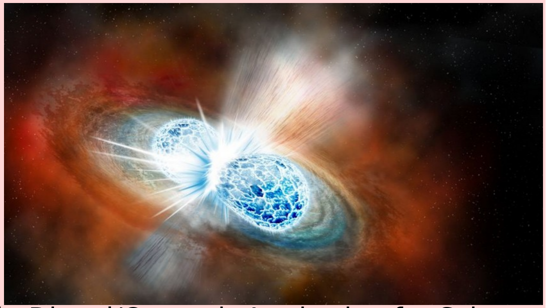
In order to improve our knowledge on the nuclear EoS (T=0):

→ **Measurements** on the **mass, radius** and **polarizabilities** in **exotic nuclei** with large N to Z asymmetries as well as **accurate** measurements of the **neutron radius** and **polarizabilities** in **stable nuclei** would be **instrumental**



$0 < \rho < \rho_0$

→ **Observations** on the **mass, radius and deformability** in **neutron stars**


Robin Dienel/Carnegie Institution for Science

$0 < \rho <$ few/several times ρ_0

Collaborators:

→ **Students:**

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→ Gianluca **Colò** & Enrico **Vigezzi** (University of Milan)

→ Hiroyuki **Sagawa** (University of Aizu & RIKEN)

→ Shihang **Shen** (Forschungszentrum Jülich)

→ Xavier **Vinyes** & Mario **Centelles** (University of Barcelona)

→ Jorge **Piekarewicz** (Florida State University)

→ Nils **Paar** (University of Zagreb)

→ P.-G. **Reinhard** (University of Erlangen-Nürnberg)

→ Misha **Gorchtein** & Oleksandr **Koshchii** (Johannes Gutenberg-Universität)

→ Chuck **Horowitz** (Indiana University)

→ Haozhao **Liang** (University of Tokyo)

→ Witold **Nazarewicz** (FRIB and Michigan State University)