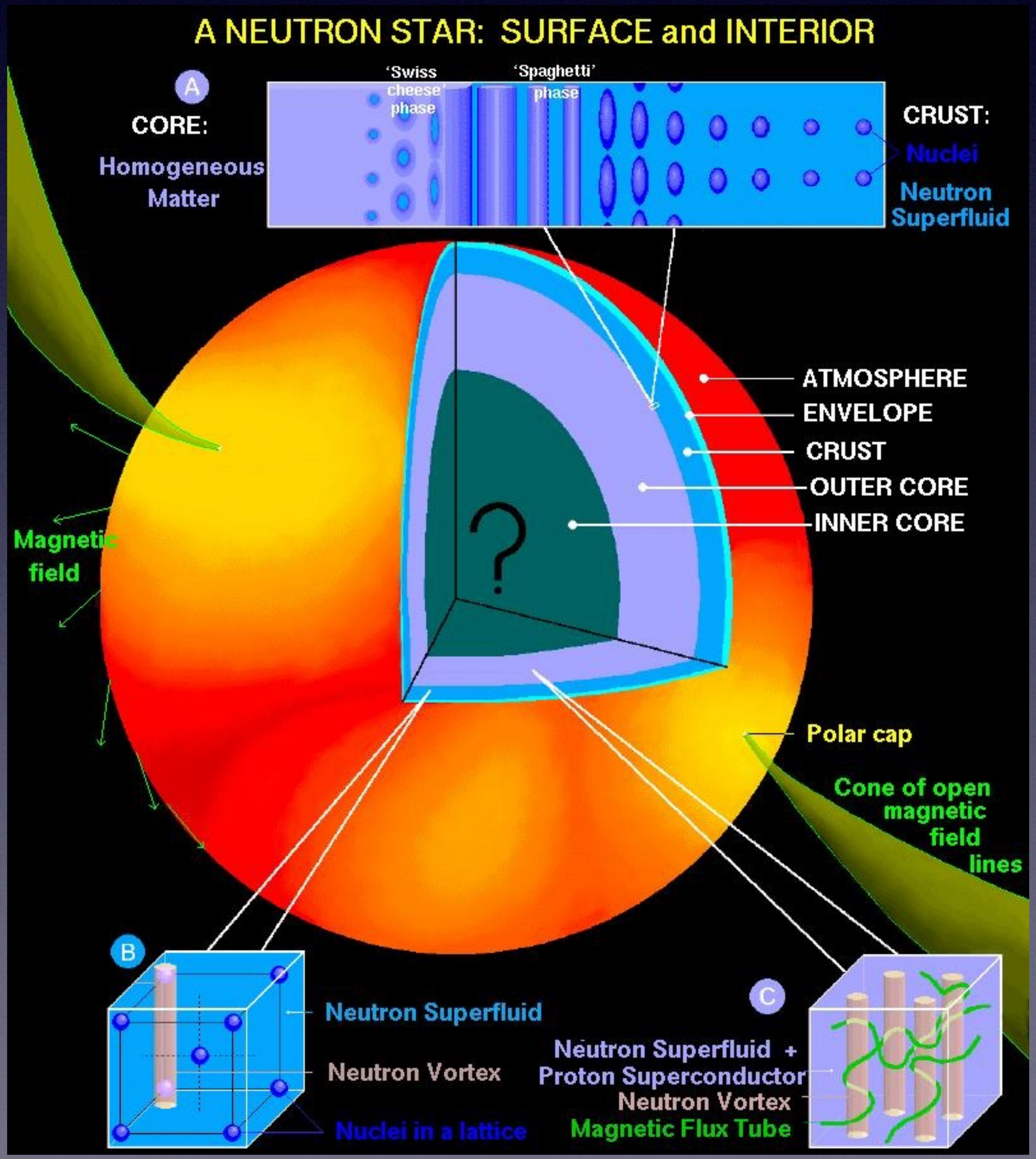
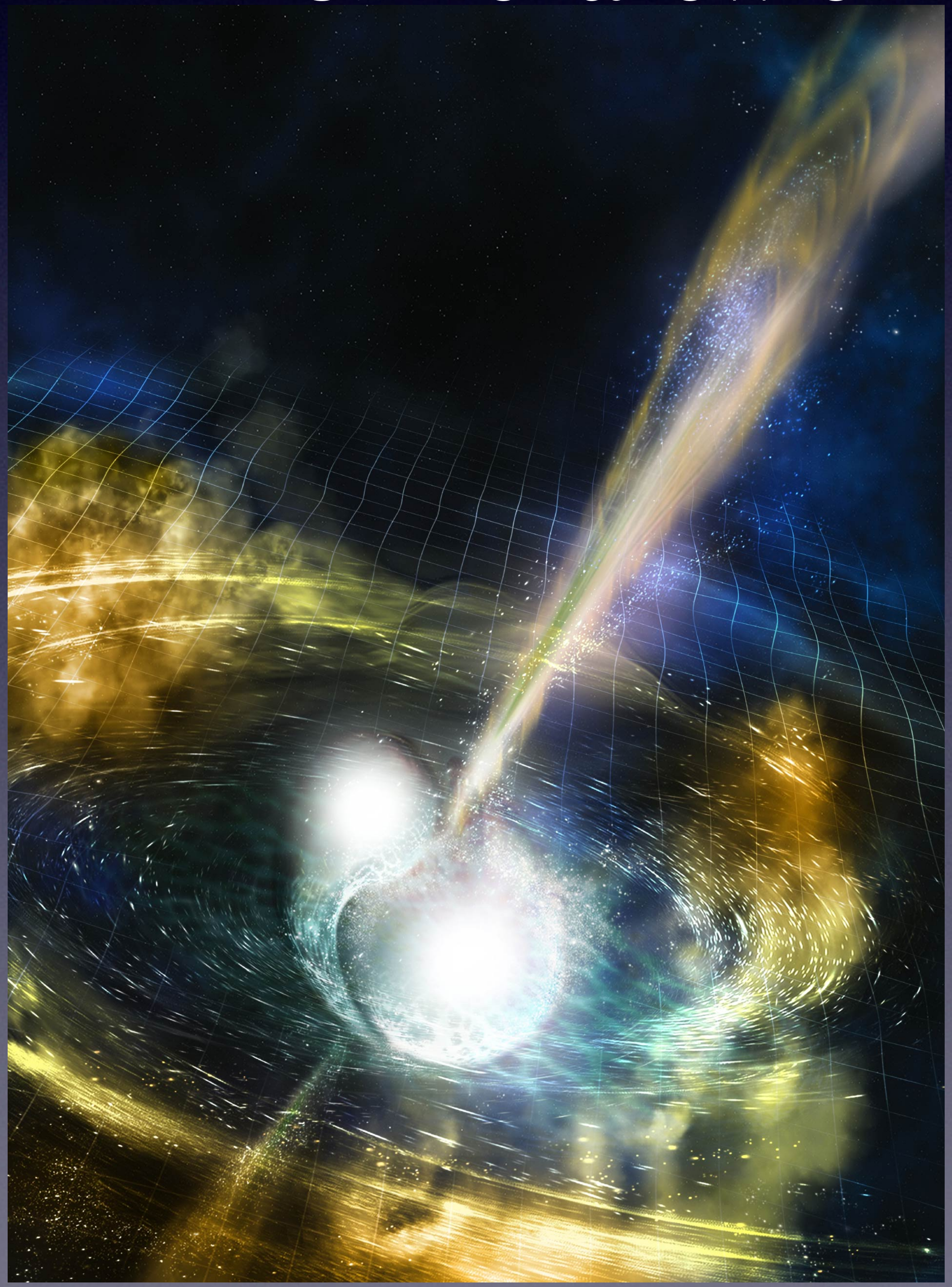
Heaven and Earth: Nuclear Astrophysics in the Multimessenger Era

2023 National Nuclear Physics Summer School

J. Piekarewicz

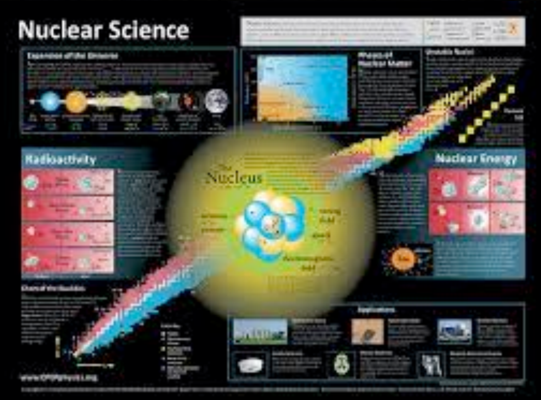




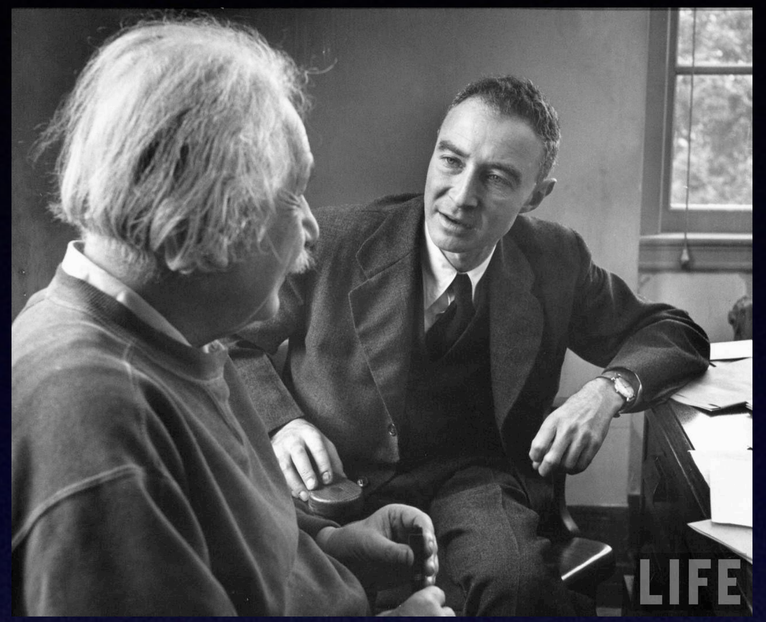
Lectures will attempt to provide an overall <u>personal</u> picture of the emergent field of multi-messenger astronomy from a nuclear physics perspective

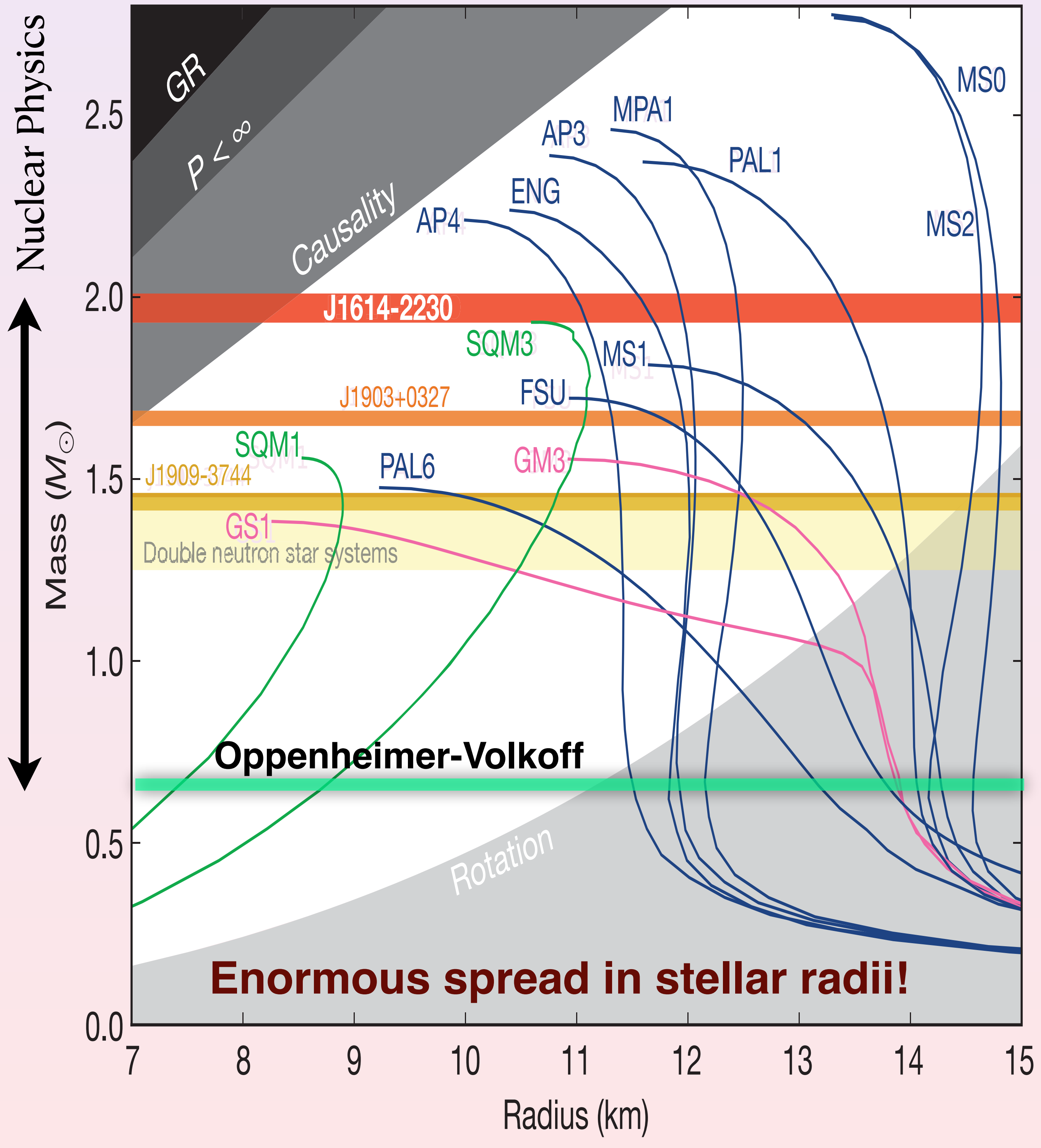
Please ask questions!

Neutron Stars: The Role of Nuclear Science



- Neutron stars are the remnants of massive stellar explosions (CCSN)
  Bound by gravity — NOT by the strong force!
  Satisfy the TOV equations: Transition from Newtonian Gravity to Einstein Gravity
- Only Physics that the TOV equation is sensitive to: Equation of State
- Increase from 0.7 to 2 Msun transfers ownership to Nuclear Physics!





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

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

Need an EOS: $P = P(\mathcal{E})$ relation

$\boxed{\text{Nuclear Physics Critical}}$

Micro-macro connection

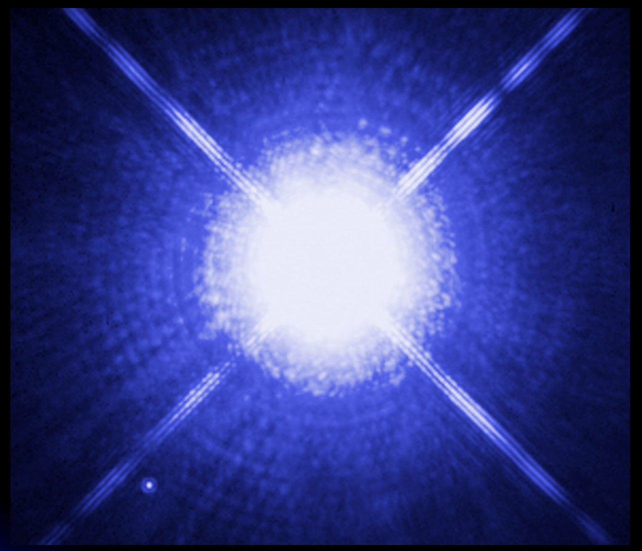
Status before GW170817

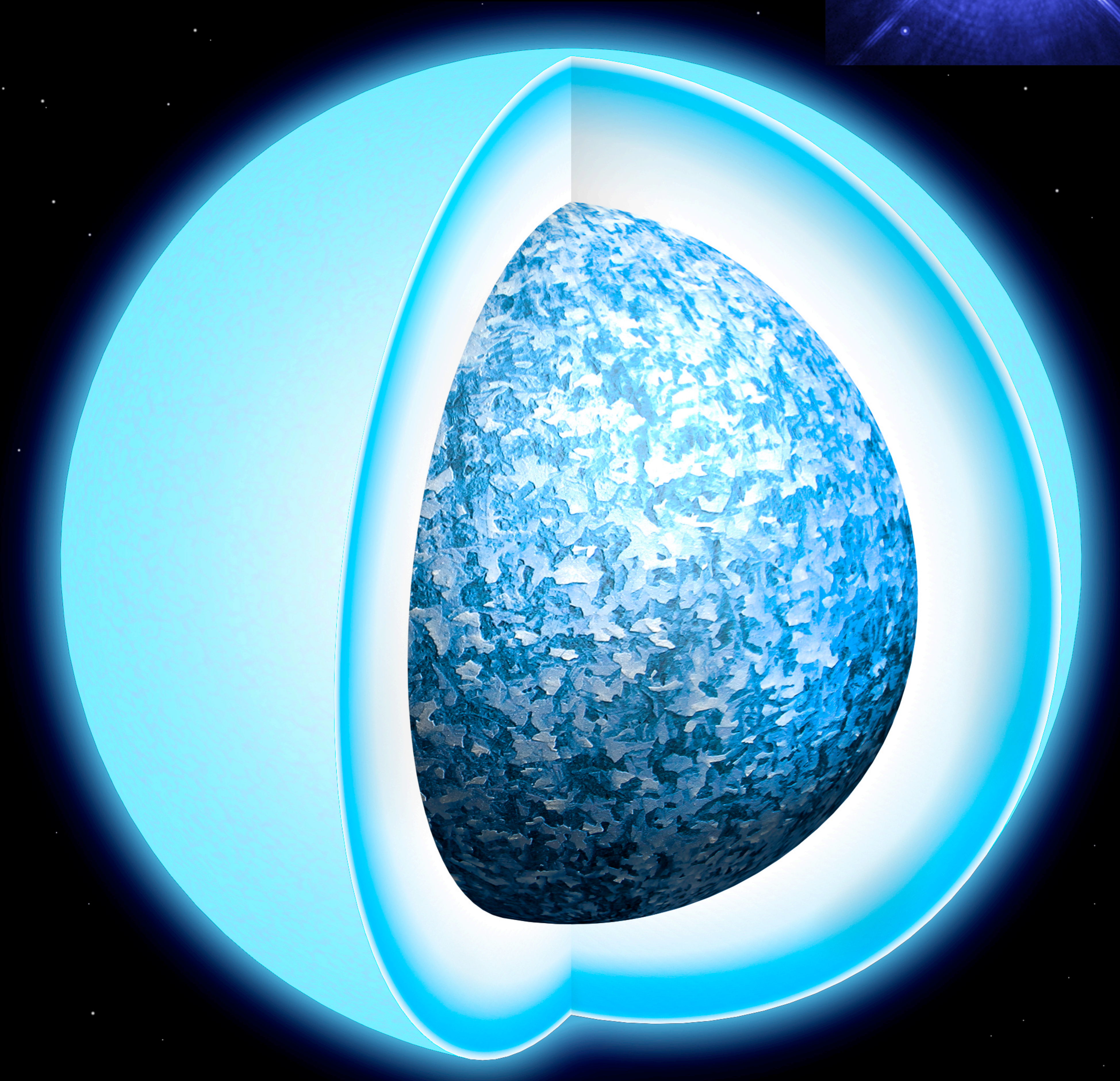
Many nuclear models that account for the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

Only observational constraint in the form of two neutron stars with a mass in the vicinity of $2M_{sun}$

Gravity vs Degeneracy Pressure

Sirius A and B





Why are not all death stars black holes?
What supports death stars
against gravitational collapse?

Scaling the equations: dealing with astronomical numbers

$$M_\odot / m_n \approx 10^{57}$$

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} = -\frac{GM(r)\mathcal{E}(r)}{c^2 r^2}$$

$$\frac{dp}{dx} = -\cancelto{1}{\left(\frac{2GM_0}{c^2 R_0}\right)} \left[\frac{m(x)\varepsilon(x)}{2x^2}\right]$$

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

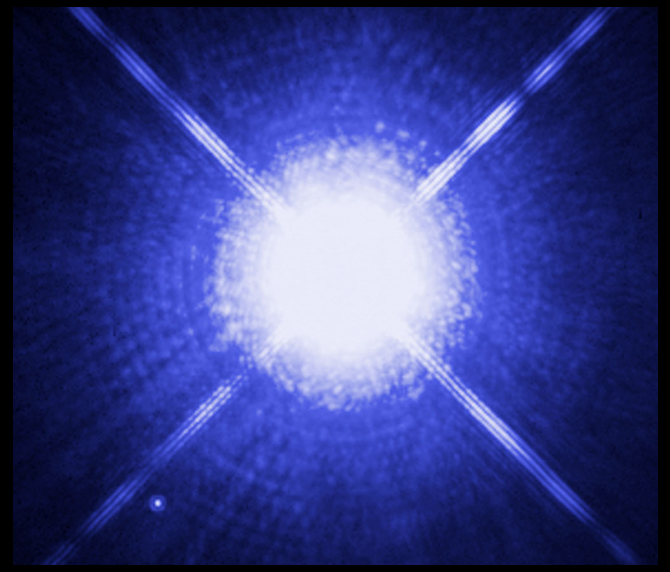
$$\frac{dm}{dx} = \cancelto{1}{\left(\left[\frac{4\pi R_0^3}{3M_0}\right]\left[\frac{\mathcal{E}_0}{c^2}\right]\right)} 3x^2 \varepsilon(x)$$

Relativistic free Fermi Gas

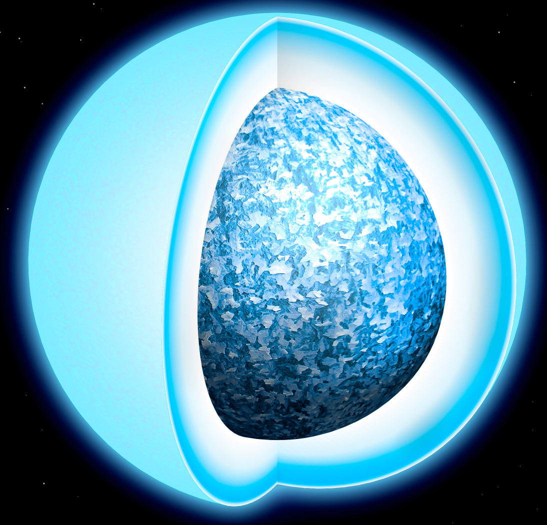
$$\mathcal{E} = \mathcal{E}_0 \left[x_{\mathrm{F}}\, y_{\mathrm{F}} \left(x_{\mathrm{F}}^2 + y_{\mathrm{F}}^2\right) - \ln(x_{\mathrm{F}} + y_{\mathrm{F}})\right]$$

$$\boxed{\begin{aligned} r = R_0\, x;\ \ M &= M_0\, m \\ P = \mathcal{E}_0\, p;\ \ \mathcal{E} &= \mathcal{E}_0\, \varepsilon \end{aligned}}$$

$$\boxed{\begin{aligned} \mathcal{E}_0 &= \frac{1}{8\pi^2}\frac{(mc^2)^4}{(\hbar c)^3} = 1.285\,\mathrm{GeV/fm^3} \\ M_0 &= 2.837\, M_\odot\ ;\ R_0 = 8.378\,\mathrm{km} \end{aligned}}$$



A Toy Model for Newtonian Stars
(A star of uniform density)



Gravitational Energy: $$\frac{E_G(M,R)}{Mc^2} = -\frac{3}{10}\left(\frac{M}{R}\right)$$

NR free Fermi Gas: $$\frac{E_{FG}^{(NR)}(M,R)}{Mc^2} = 1 + K_{NR}\left(\frac{M^{2/3}}{R^2}\right)$$

Equilibrium configuration: $$\frac{R(M)}{R_0} = 1.04\left(\frac{M}{M_0}\right)^{-1/3}$$

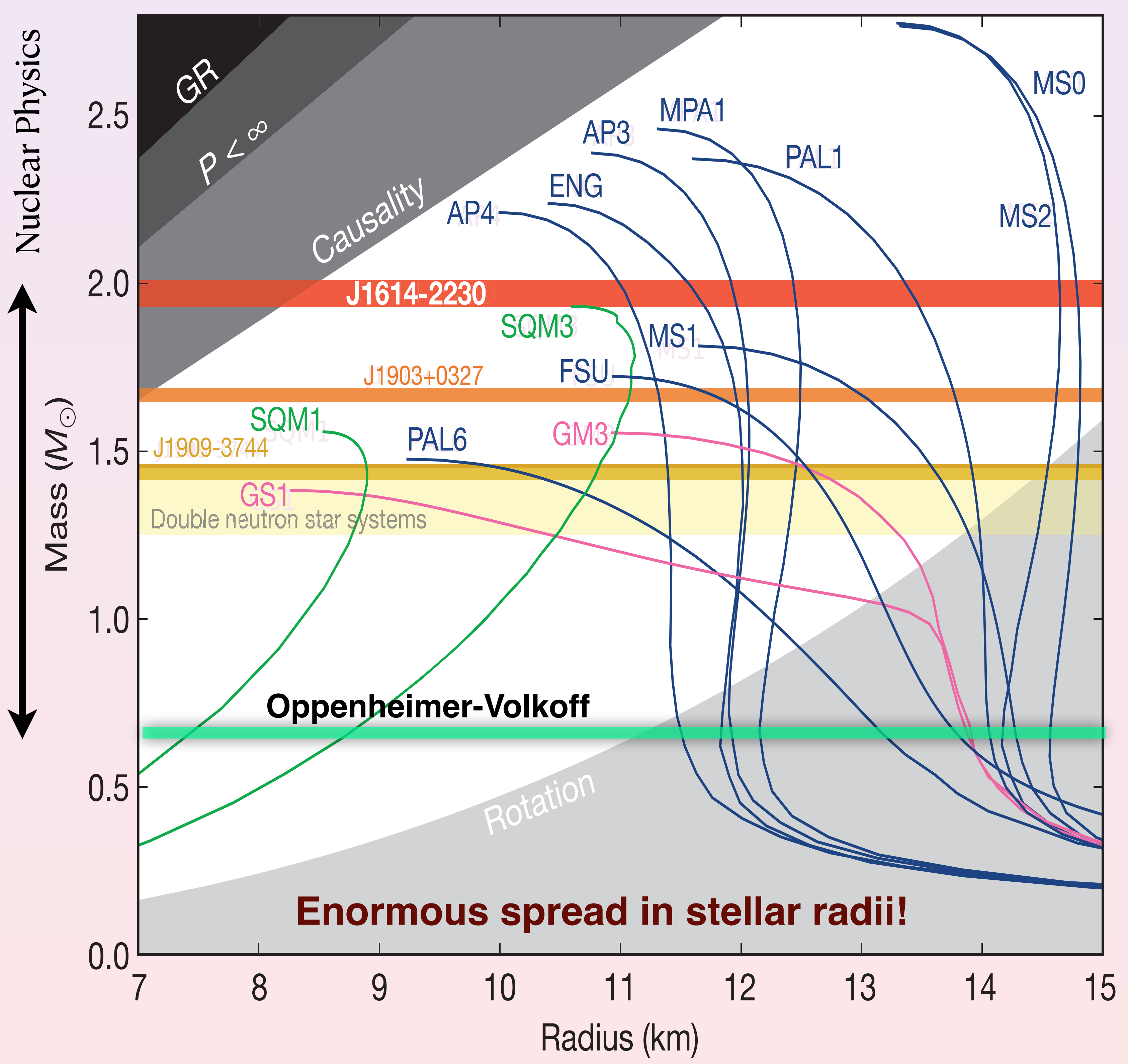
UR free Fermi Gas: $$\frac{E_{FG}^{(UR)}(M,R)}{Mc^2} = K_{UR}\left(\frac{M^{1/3}}{R}\right)$$

Chandrasekhar Mass: $$M_{\rm ch} = 6.88\, M_\odot = 4(1.72\, M_\odot)$$

Neutron Stars are **NOT** Newtonian Stars!

$$\frac{v^2}{c^2} = \frac{2GM}{c^2 R} = \frac{R_s(M)}{R} \approx 1/2$$

- Transition from Newtonian Gravity to Einstein Gravity is essential!
- Neutron stars also collapse (black holes) but by a very different mechanism than WDs
  The hydrostatic configuration becomes unstable against small oscillations ...



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

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

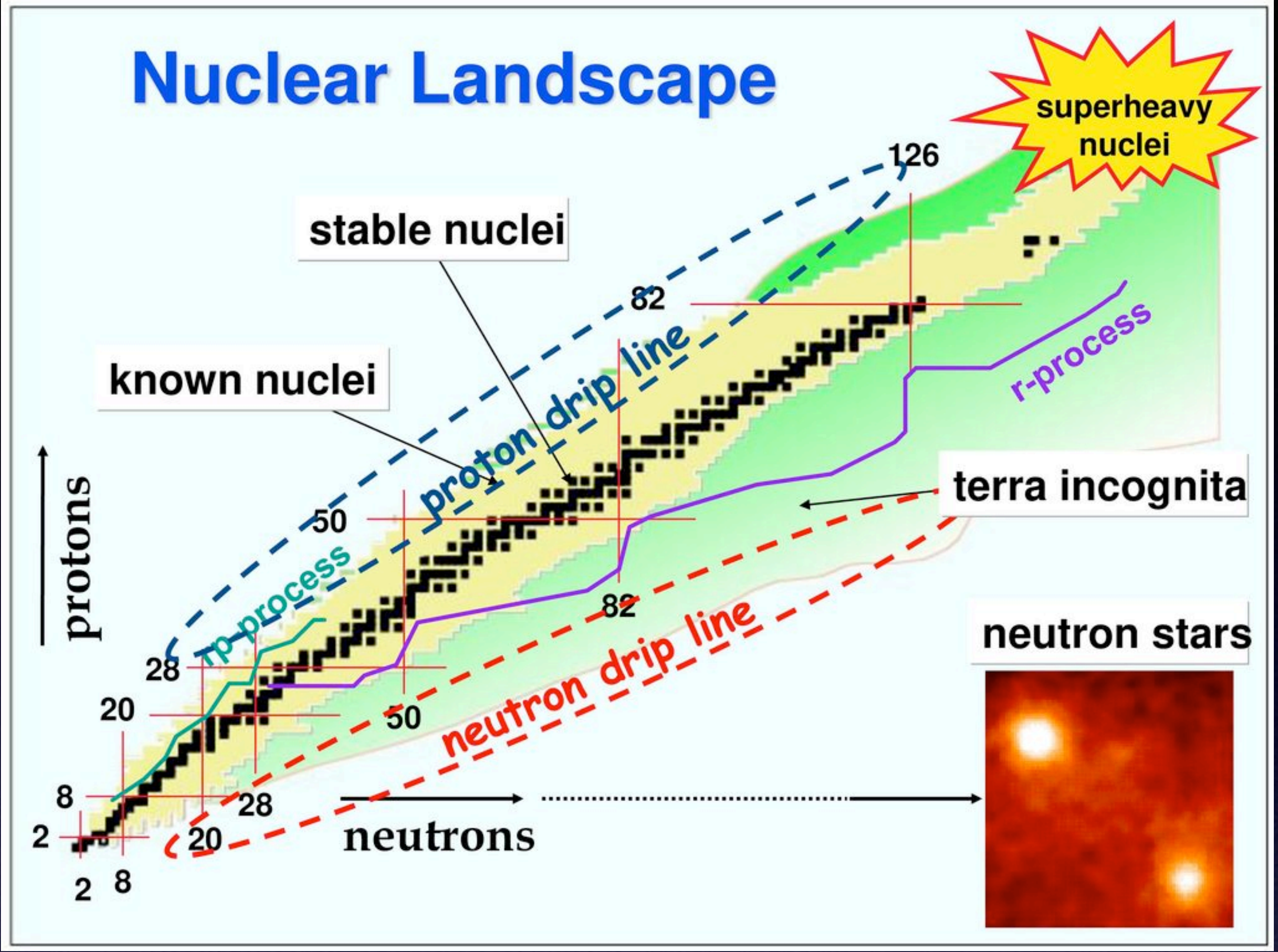
Need an EOS: $P = P(\mathcal{E})$ relation

Nuclear Physics Critical

Micro-macro connection

The Liquid Drop Model

Why is there a neutron drip line?



Bethe-Weizsäcker Mass Formula *(circa 1935-36)*

- Nuclear forces saturate $\xrightarrow{R = r_0 A^{1/3}}$ equilibrium density
- Nuclei penalized for developing a surface
- Nuclei penalized by Coulomb repulsion
- Nuclei penalized for isospin imbalance (N≠Z)

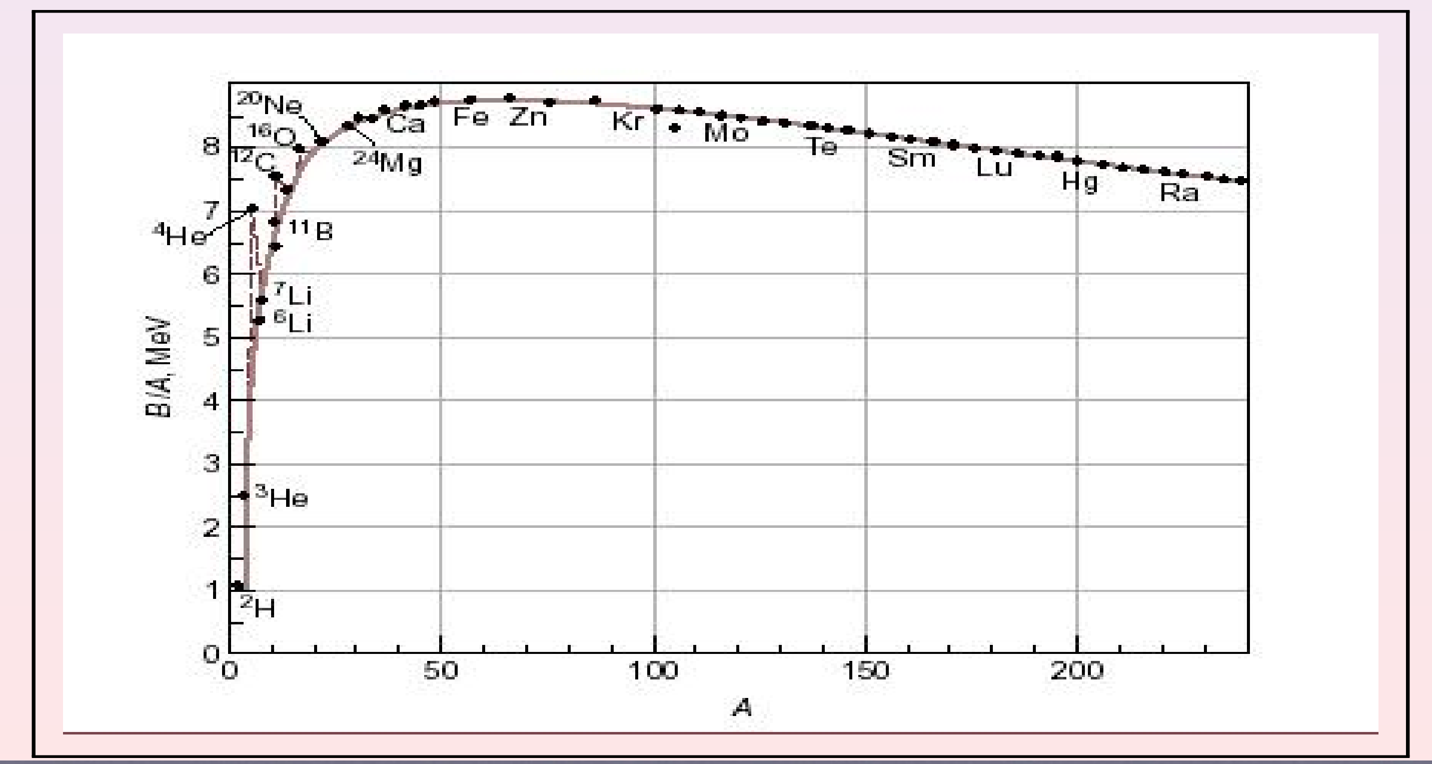
- $B(Z,N) = -a_{\rm v}A + a_{\rm s}A^{2/3} + a_{\rm c}Z^2/A^{1/3} + a_{\rm a}(N-Z)^2/A + \ldots$
  $+$ **shell corrections** $(2, 8, 20, 28, 50, 82, 126, \ldots)$

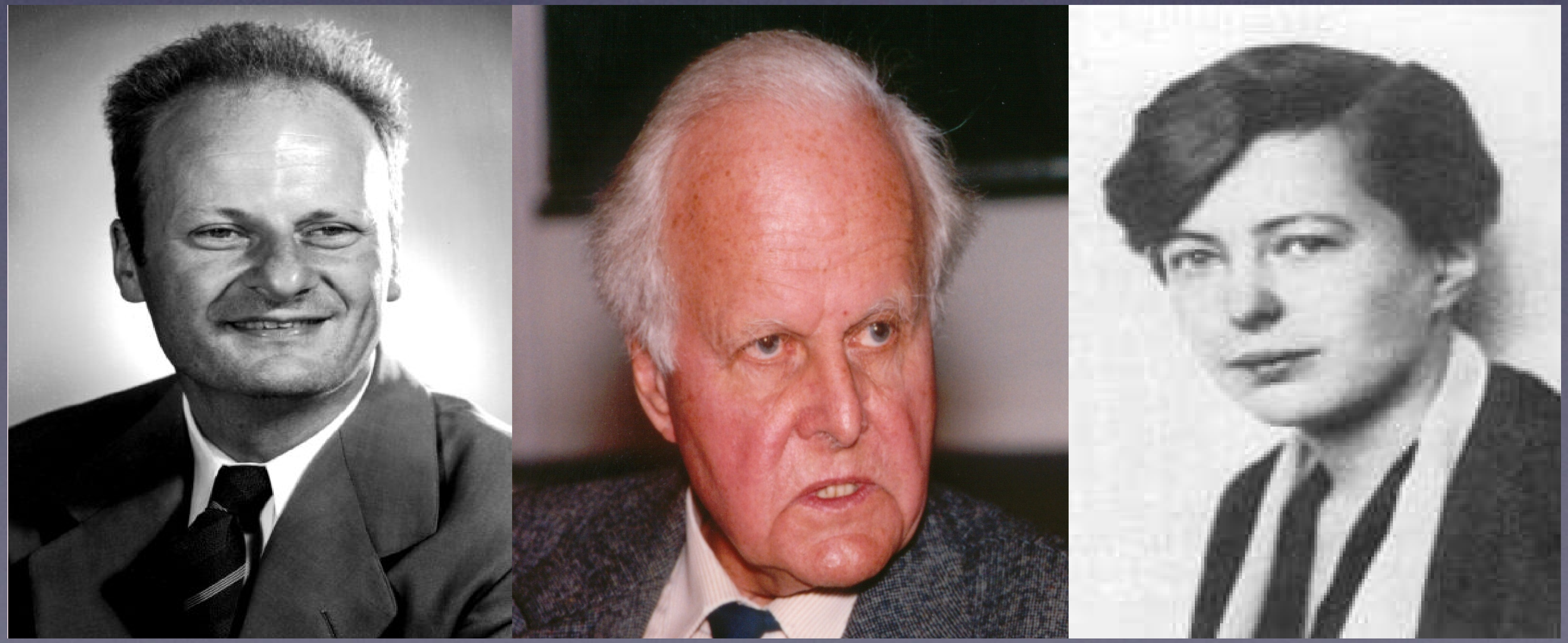
$$\boxed{a_{\rm v} \simeq 16.0,\ a_{\rm s} \simeq 17.2,\ a_{\rm c} \simeq 0.7,\ a_{\rm a} \simeq 23.3 \text{ (in MeV)}}$$

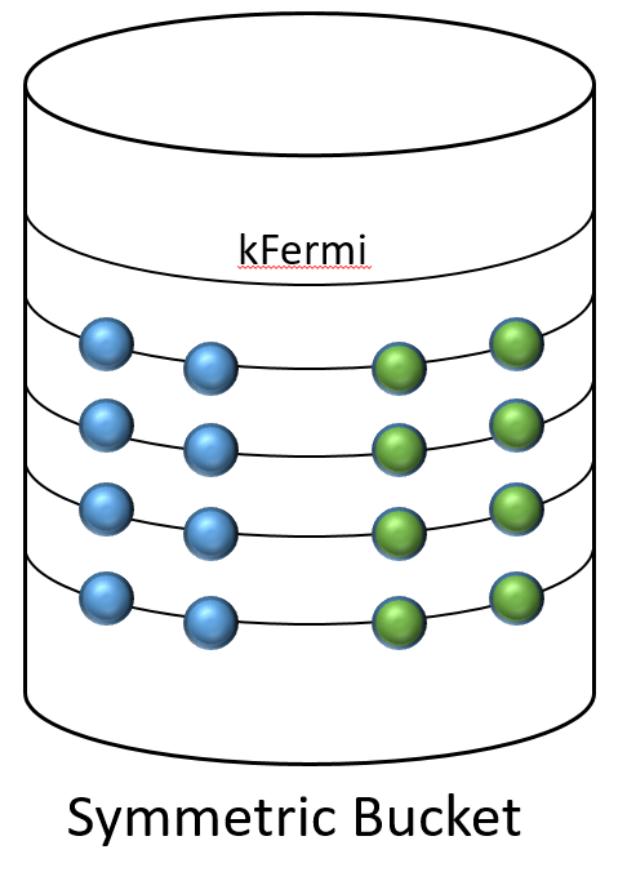
Neutron stars are gravitationally bound!

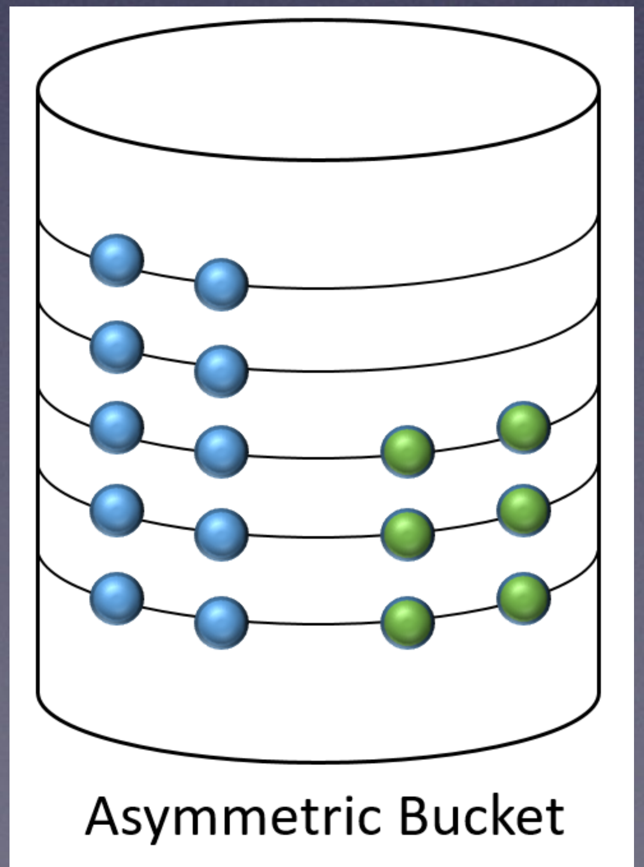
$$S(\rho_0) \approx \Big(E_{\rm PNM} - E_{\rm SNM}\Big)(\rho_0) = J$$

$$P_{\rm PNM} \approx \frac{1}{3} L\rho_0 \ \text{(Pressure of PNM)}$$





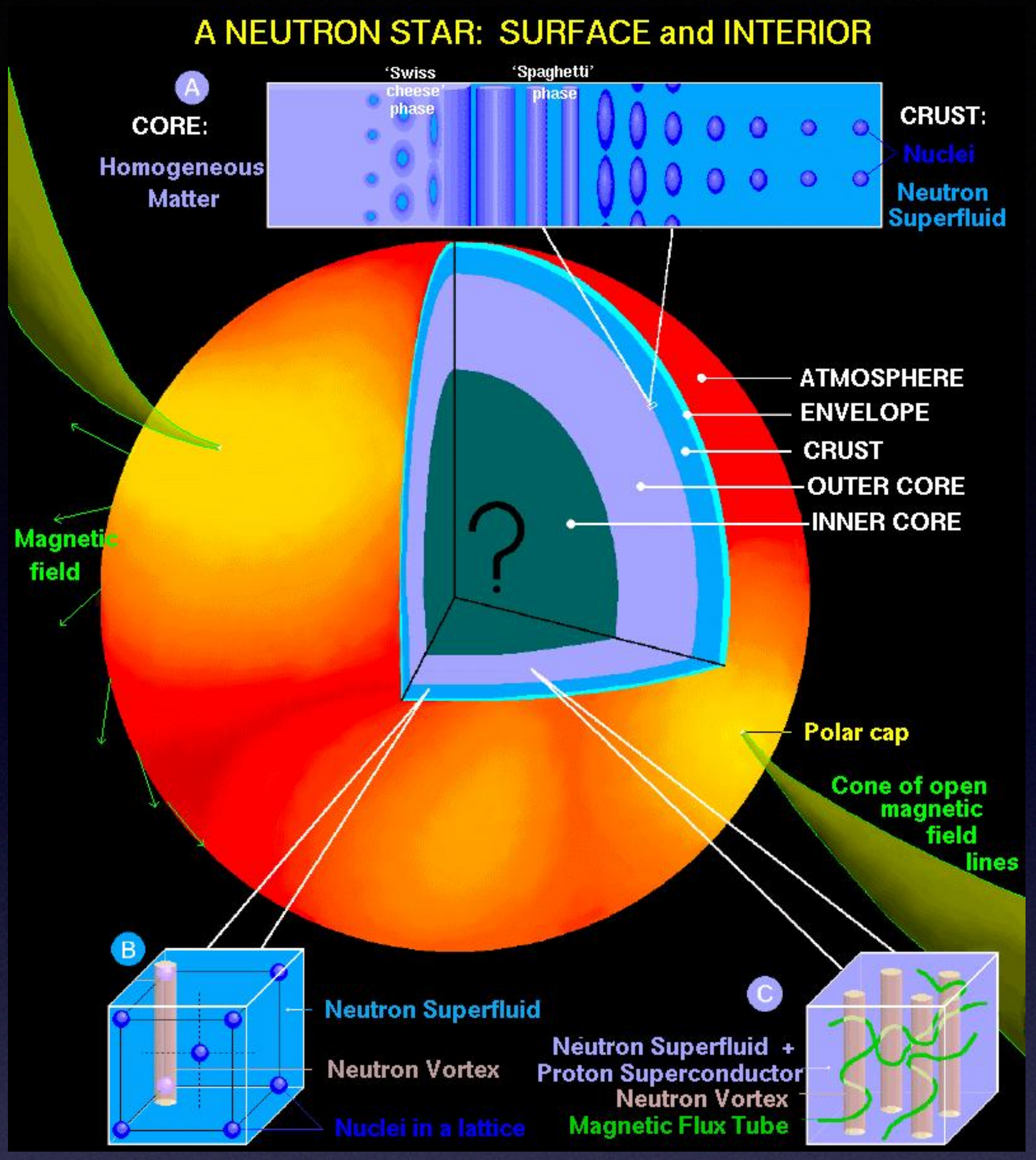




The Equation of State of Neutron-Rich Matter

- The EOS of asymmetric matter: α=(N-Z)/A; $x=(\rho-\rho_0)/3\rho_0$; $T=0$
  - $\rho_0 \simeq 0.15\ \mathrm{fm}^{-3}$ — saturation density ↔ nuclear density

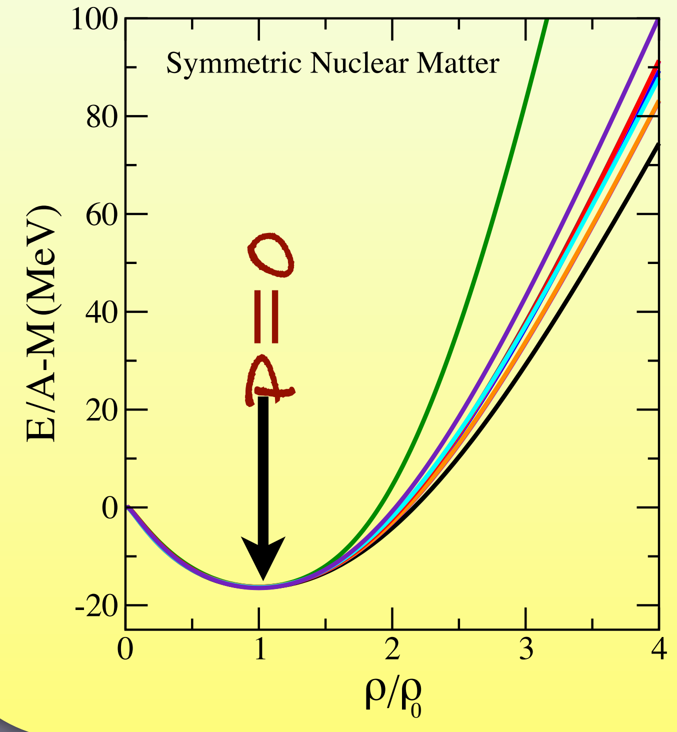
$$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym}x^2\right)\alpha^2$$

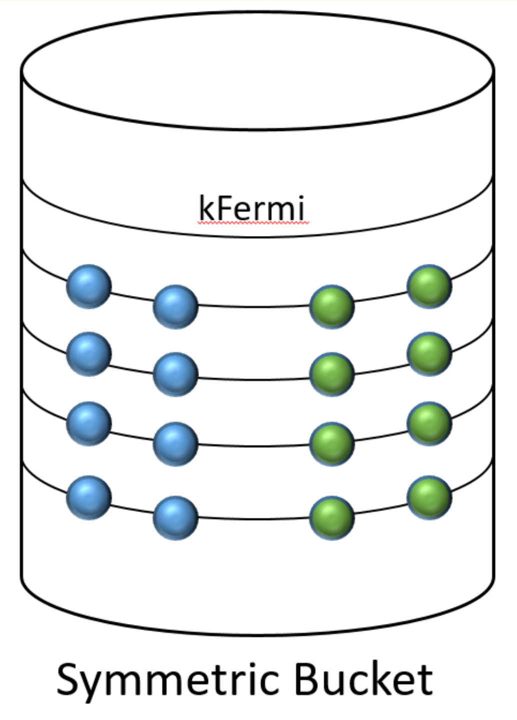


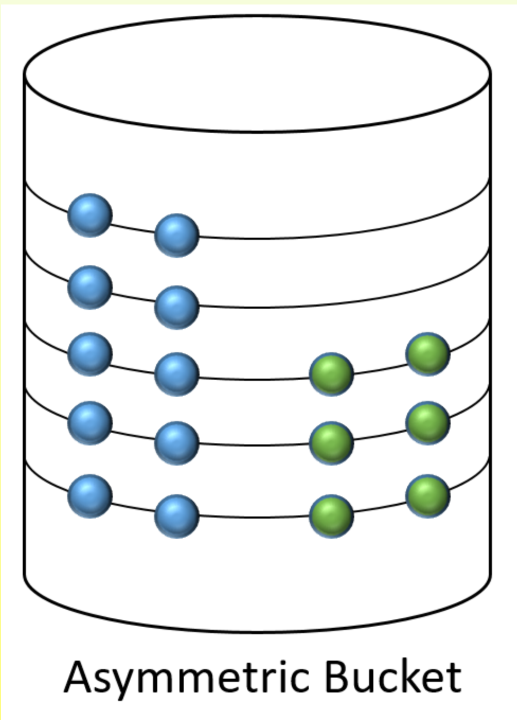
- Symmetric nuclear matter saturates:
  - $\varepsilon_0 \simeq$ -16 MeV — binding energy per nucleon ↔ nuclear masses
  - $K_0 \simeq$ 230 MeV — nuclear incompressibility ↔ nuclear "breathing" mode

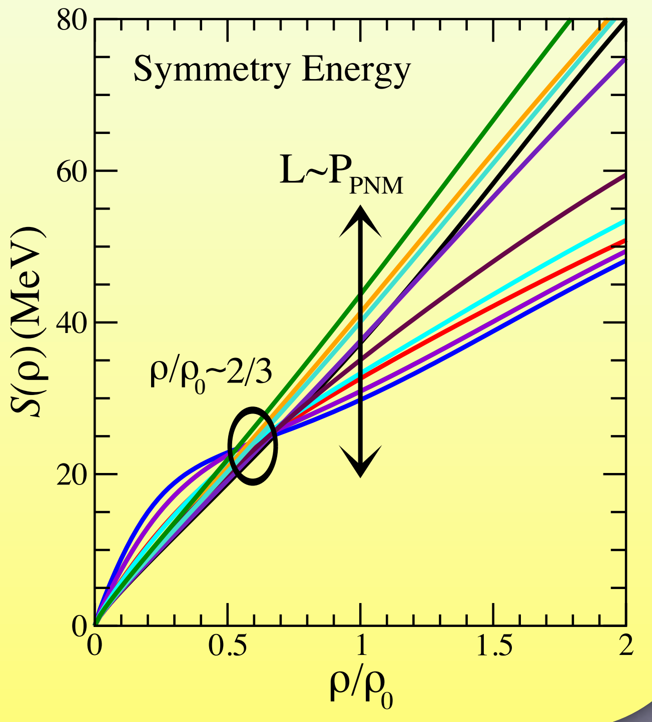
- Density dependence of symmetry poorly constrained:
  - J $\simeq$ 30 MeV — symmetry energy ↔ masses of neutron-rich nuclei
  - L $\simeq$? — symmetry slope ↔ neutron skin (R_n-R_p) of heavy nuclei ?

"Stiff" ⟶ L large
"Soft" ⟶ L small







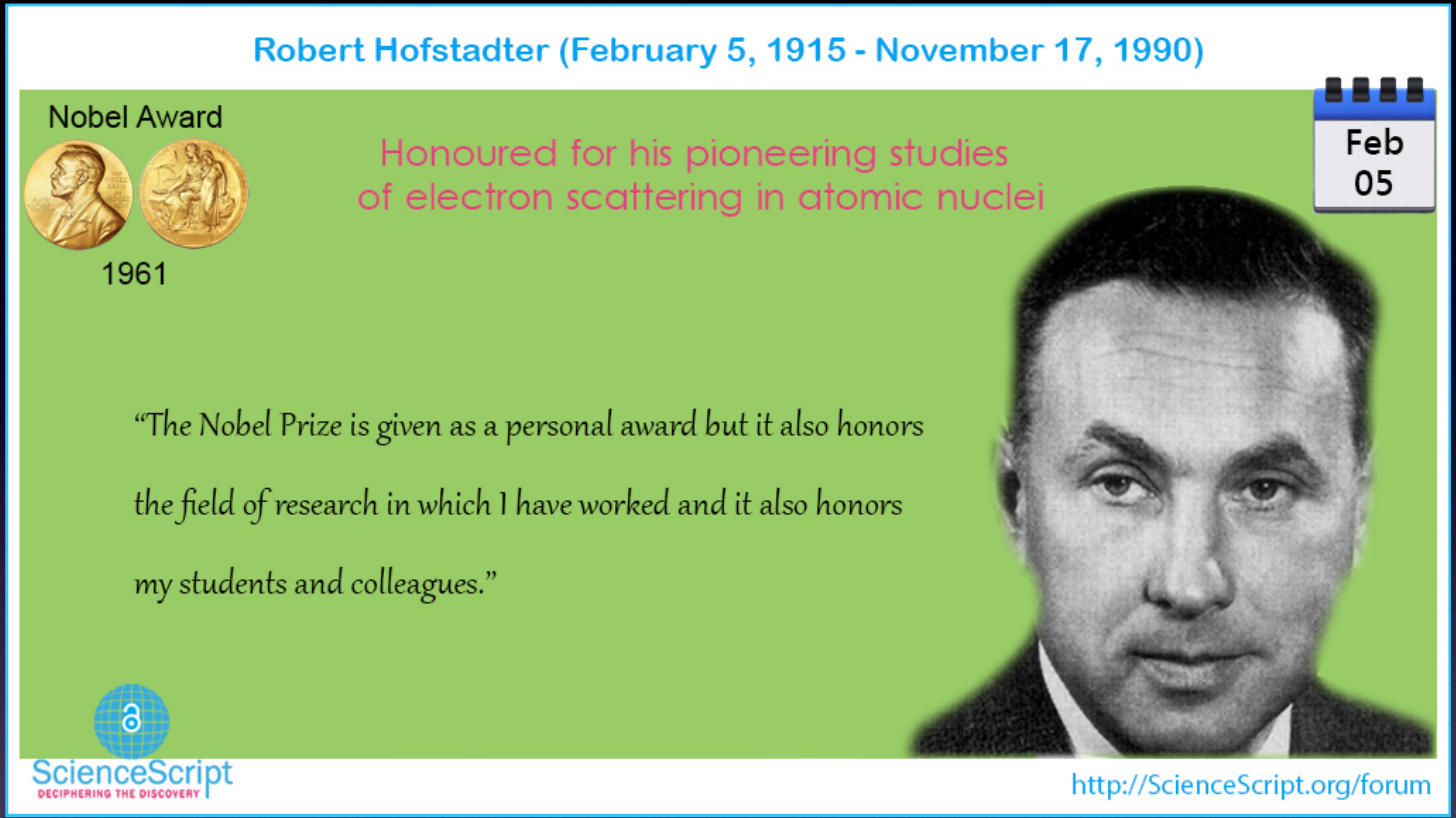


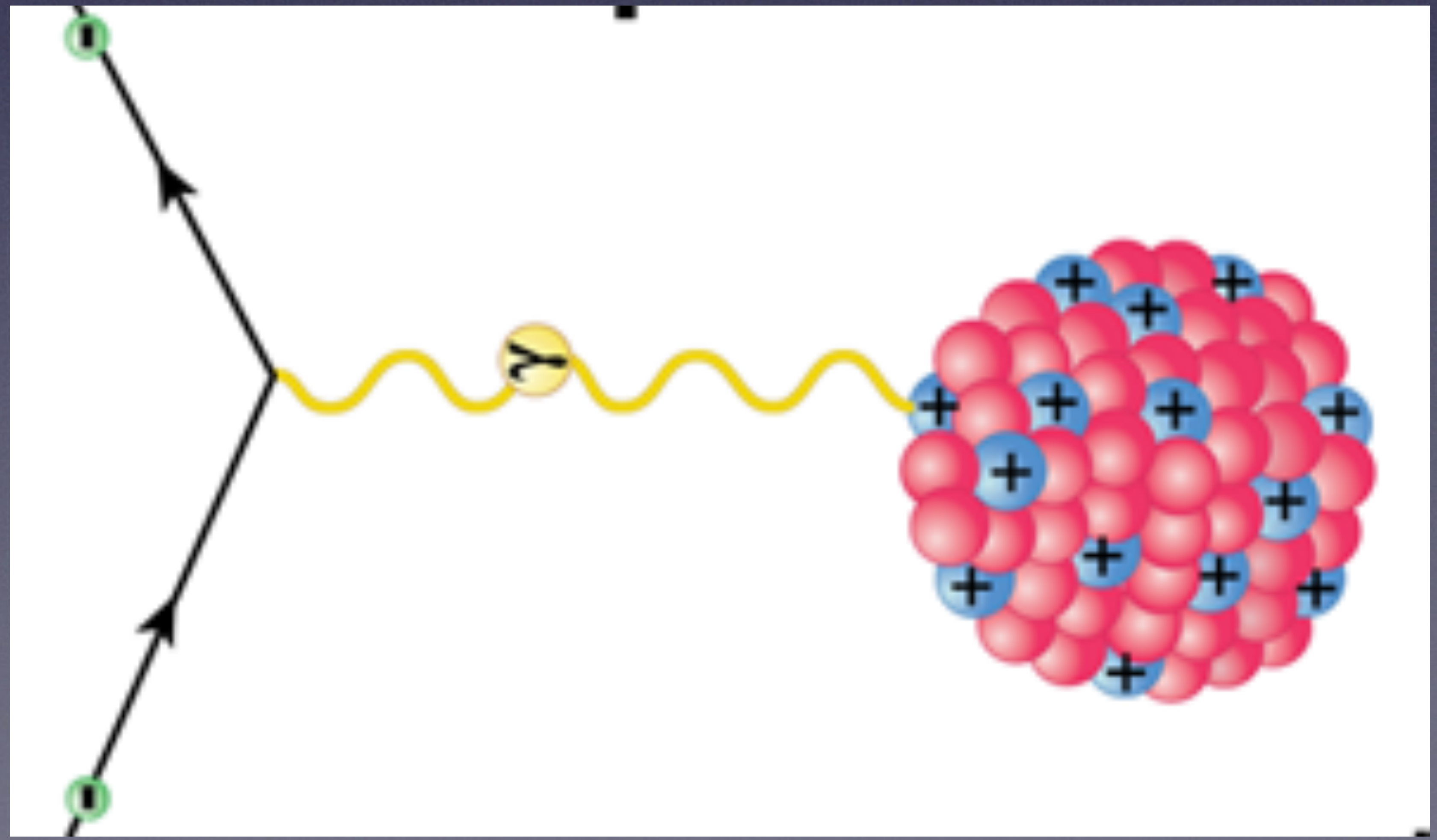
$$S(\rho_0) \approx \Big(E_{\rm PNM} - E_{\rm SNM}\Big)(\rho_0) = J$$

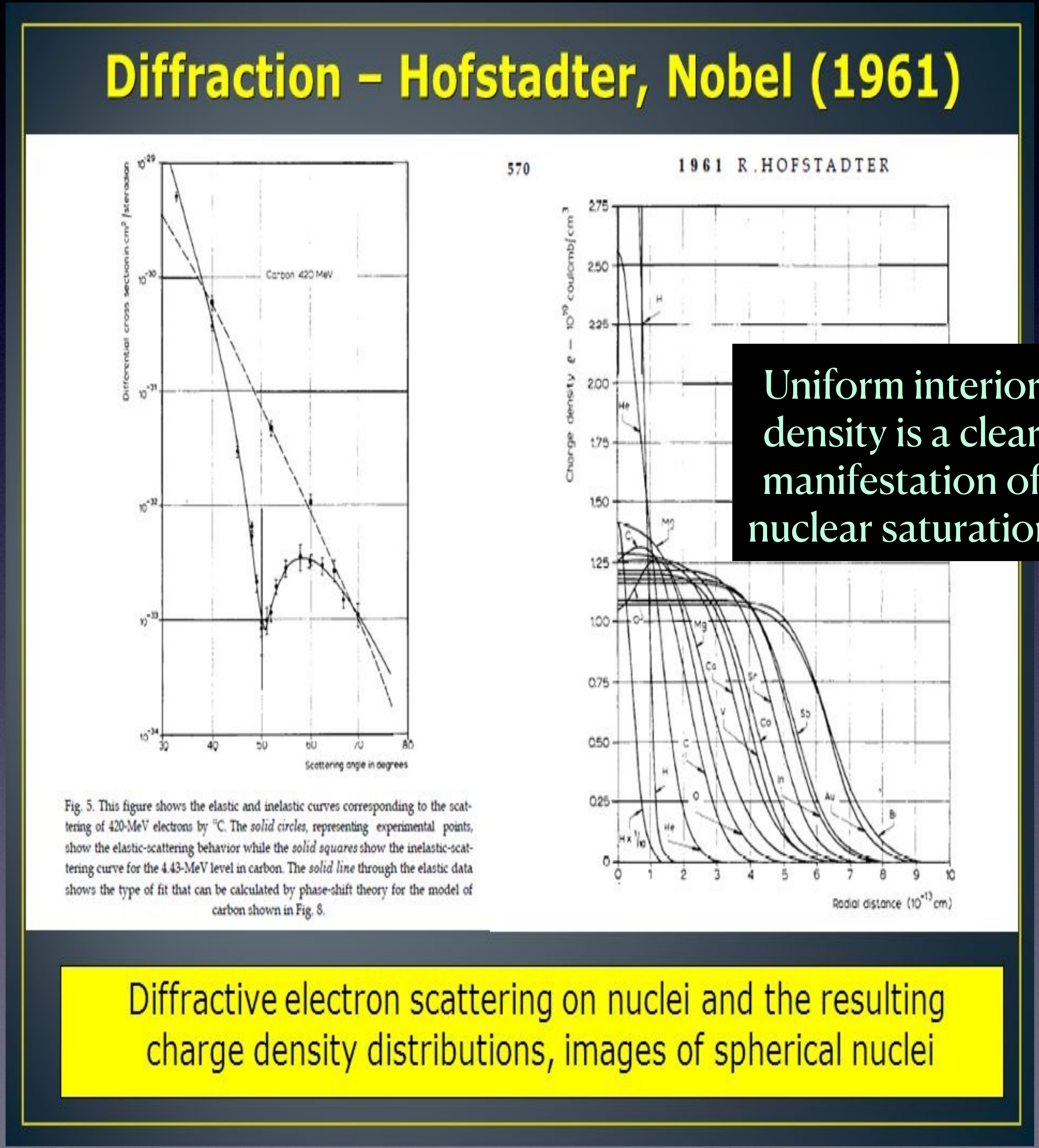
$$P_{\rm PNM} \approx \frac{1}{3} L\rho_0 \ \text{(Pressure of PNM)}$$

e-Scattering at Stanford

Our most accurate picture of the nuclear charge distribution







Uniform interior density is a clear manifestation of nuclear saturation

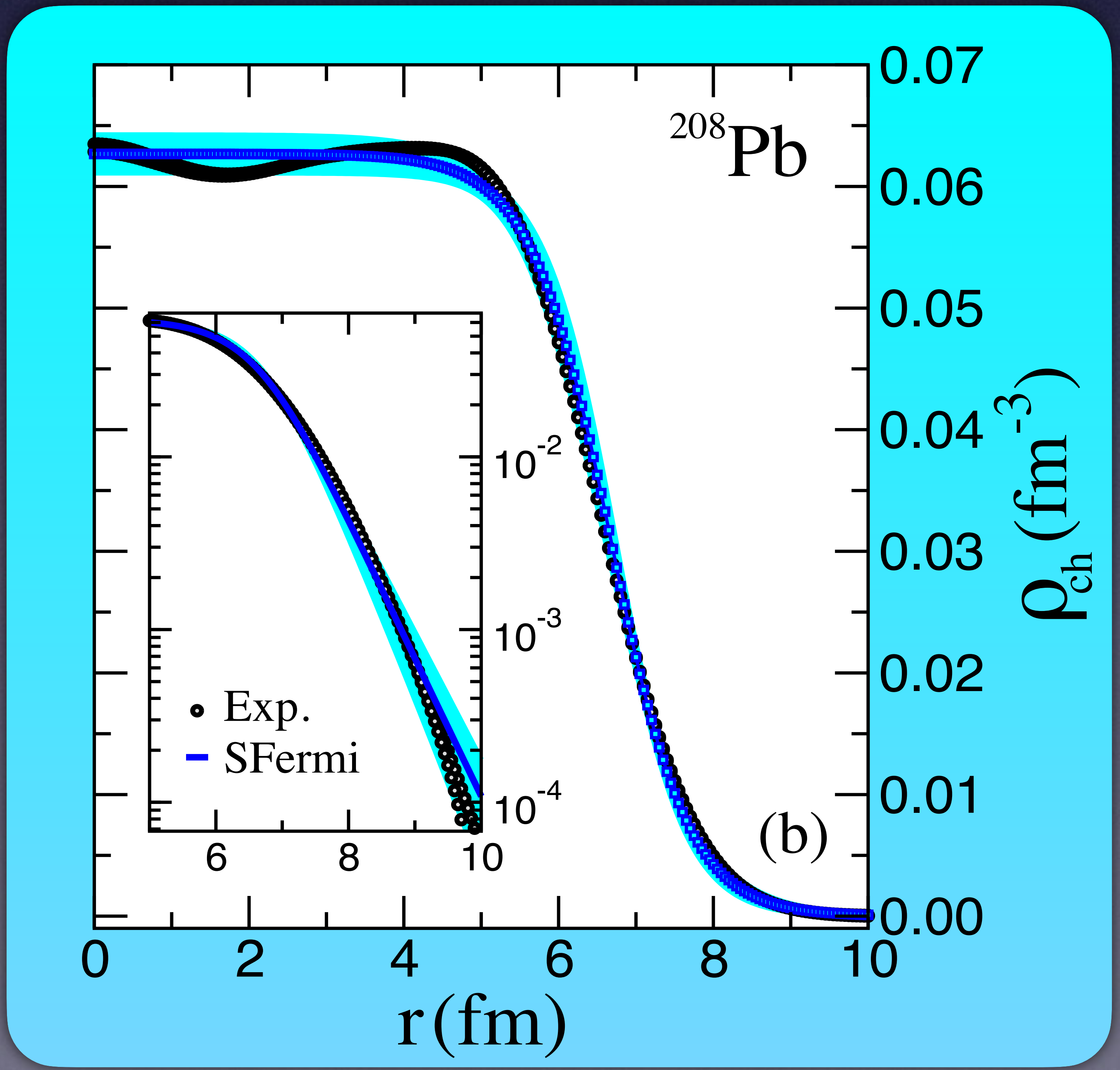
"Symmetrized Fermi" Form Factor

Conventional Fermi function

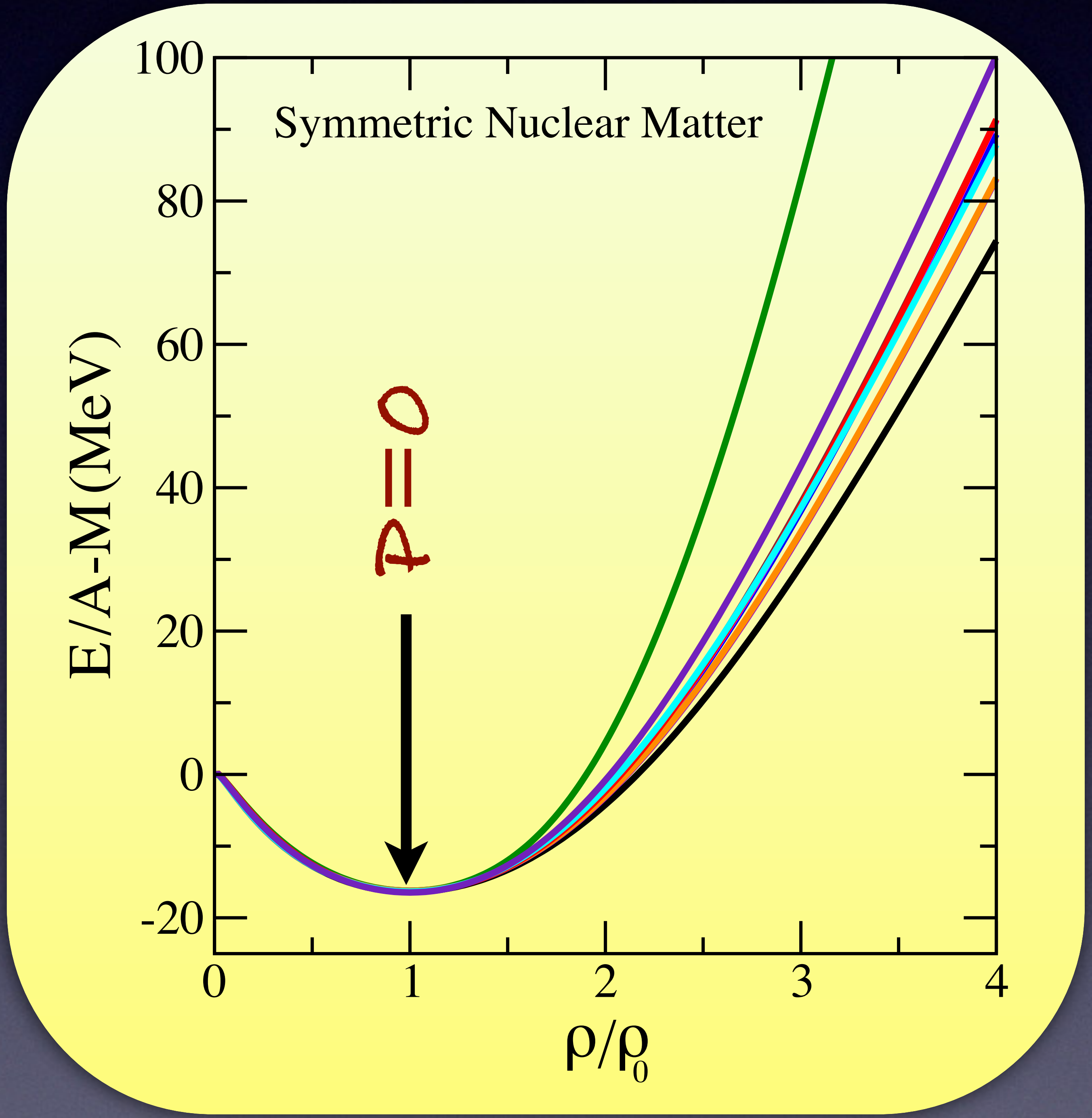
$$\rho_{\mathrm{F}}(r) = \frac{\rho_0}{1 + e^{(r-c)/a}}$$

"Symmetrized Fermi" function

$$\rho_{\mathrm{SF}}(r) = \rho_{\mathrm{F}}(r) + \left[\rho_{\mathrm{F}}(-r) - \rho_0\right]$$



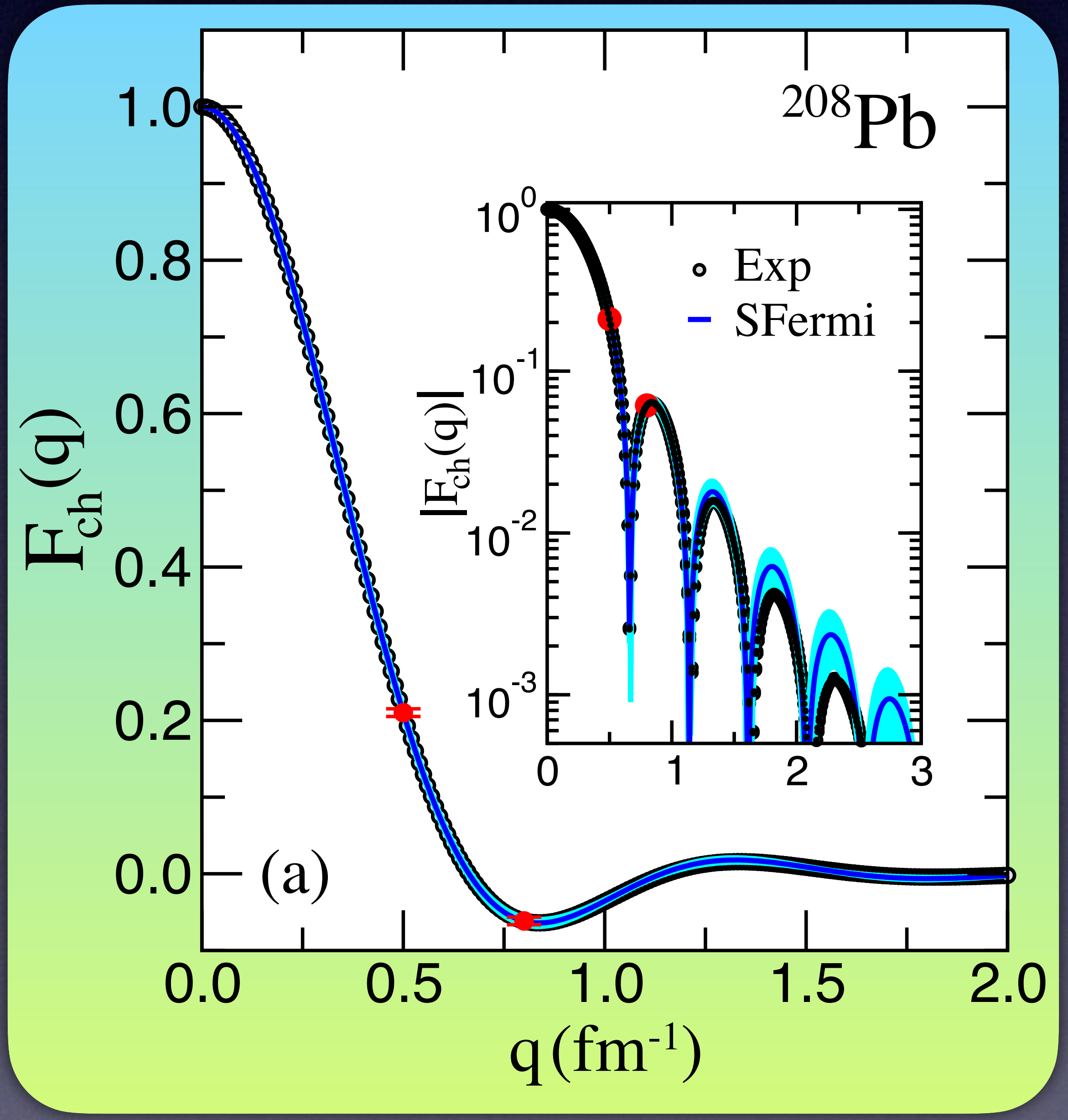
Nuclear saturation — the existence of an equilibrium density — is a hallmark of the nuclear dynamics!



Uniform interior is a clear manifestation of nuclear saturation, namely, the existence of an equilibrium density

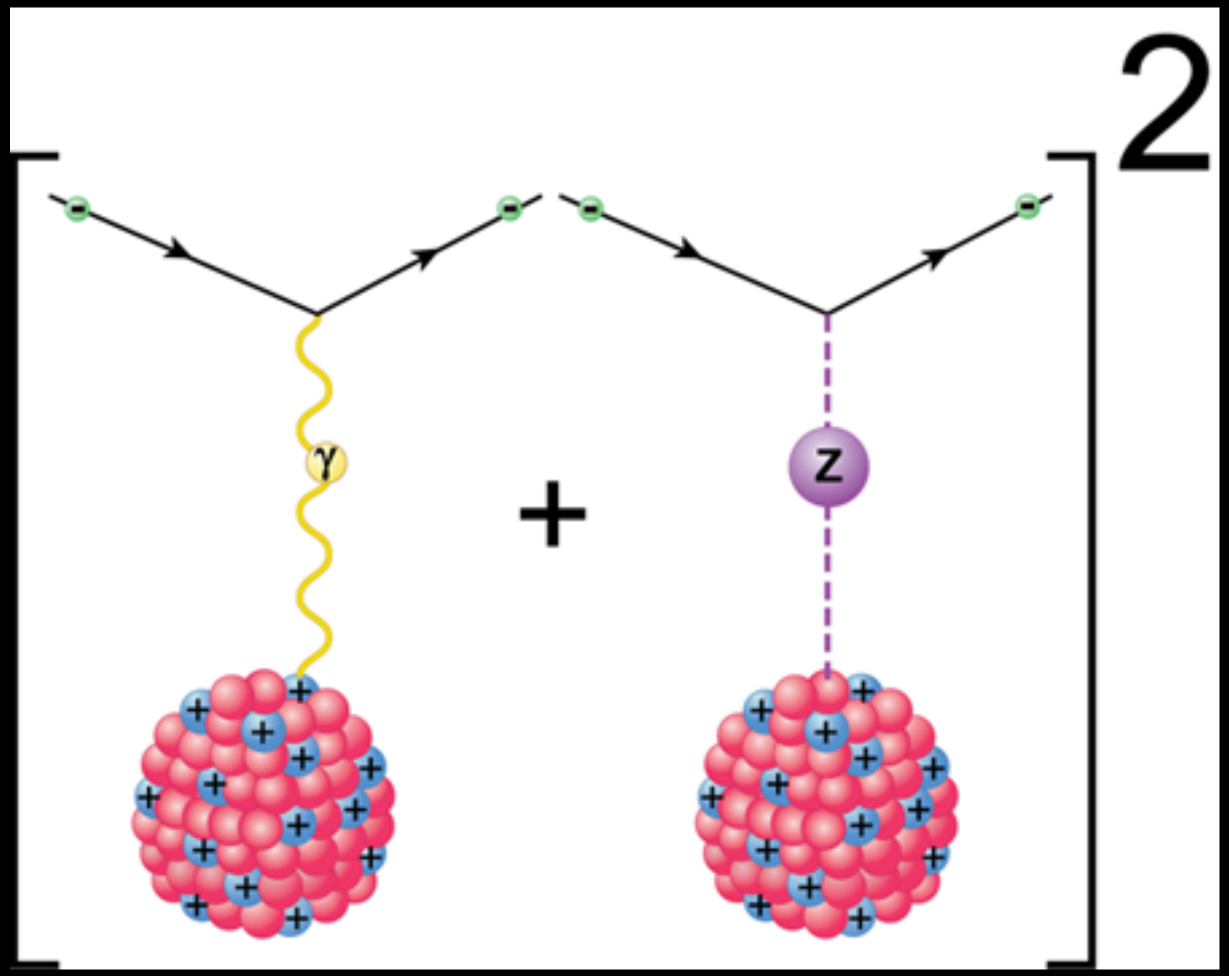
Experimental Form Factor is the Fourier transform of the Density

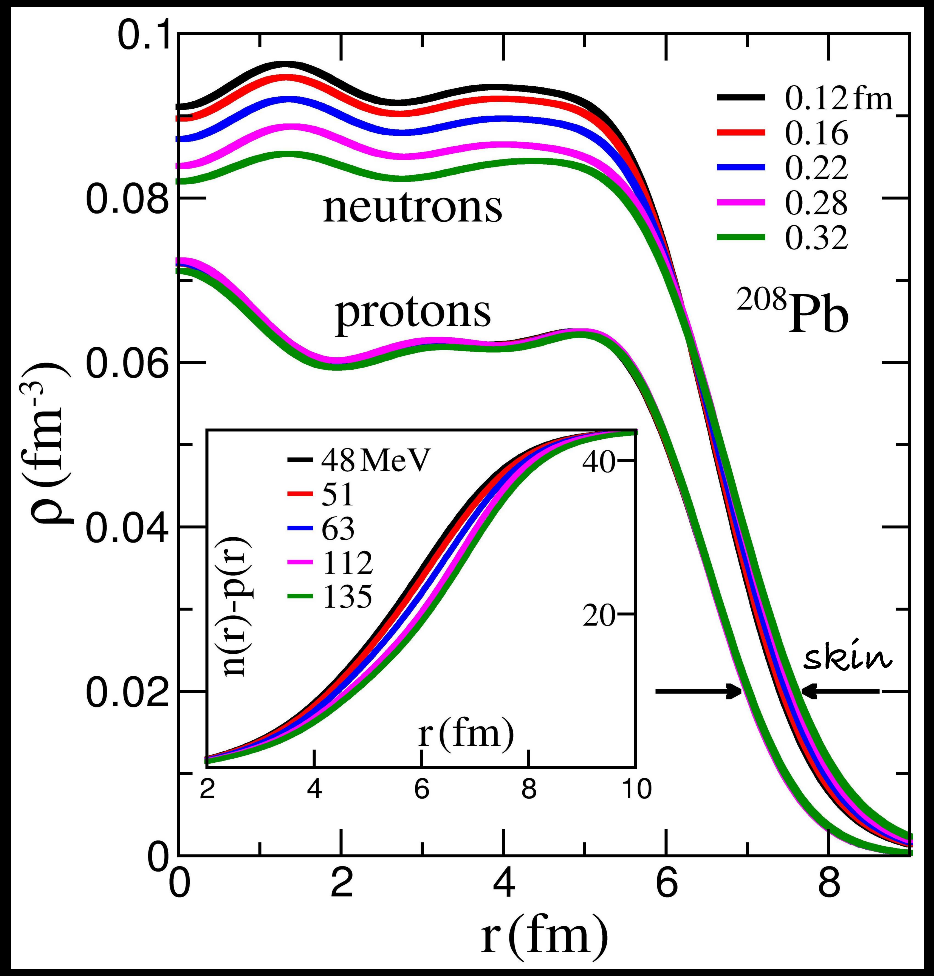
$$F_{\mathrm{SF}}(q) \rightarrow \frac{\cos(qc+\delta)}{qc} e^{-\pi q a}$$



Diffractive Oscillations ("c") modulated by an exponential falloff ("πa")

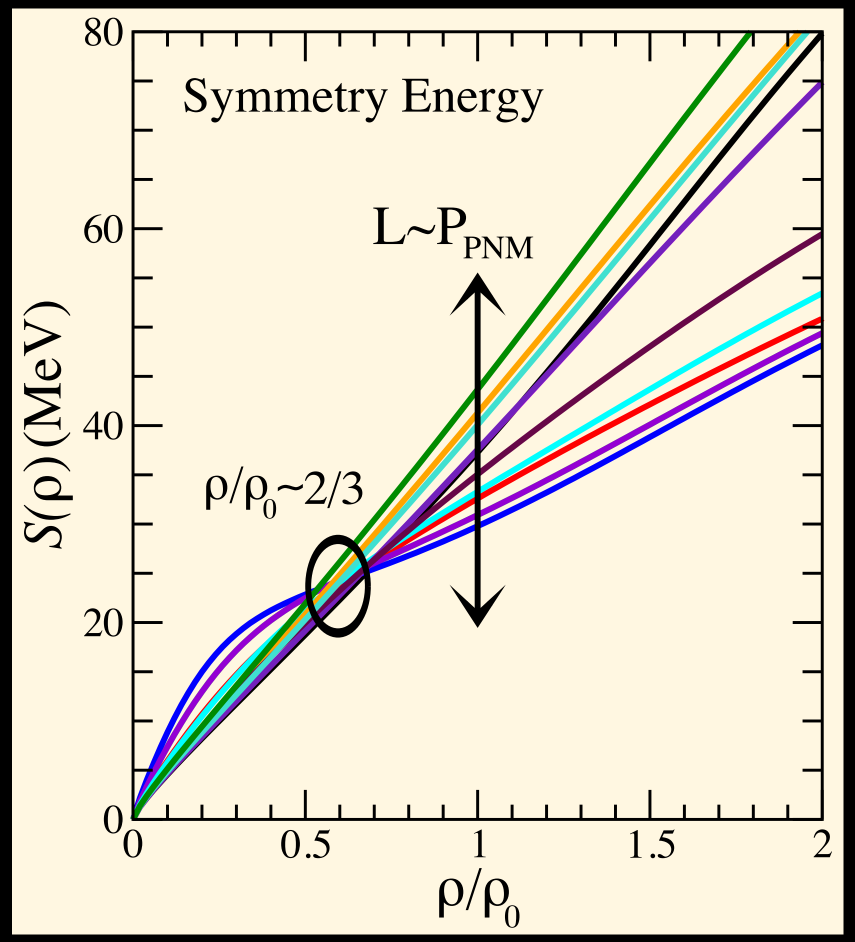
Parity Violating Electron Scattering
Laboratory Constraints on the EOS

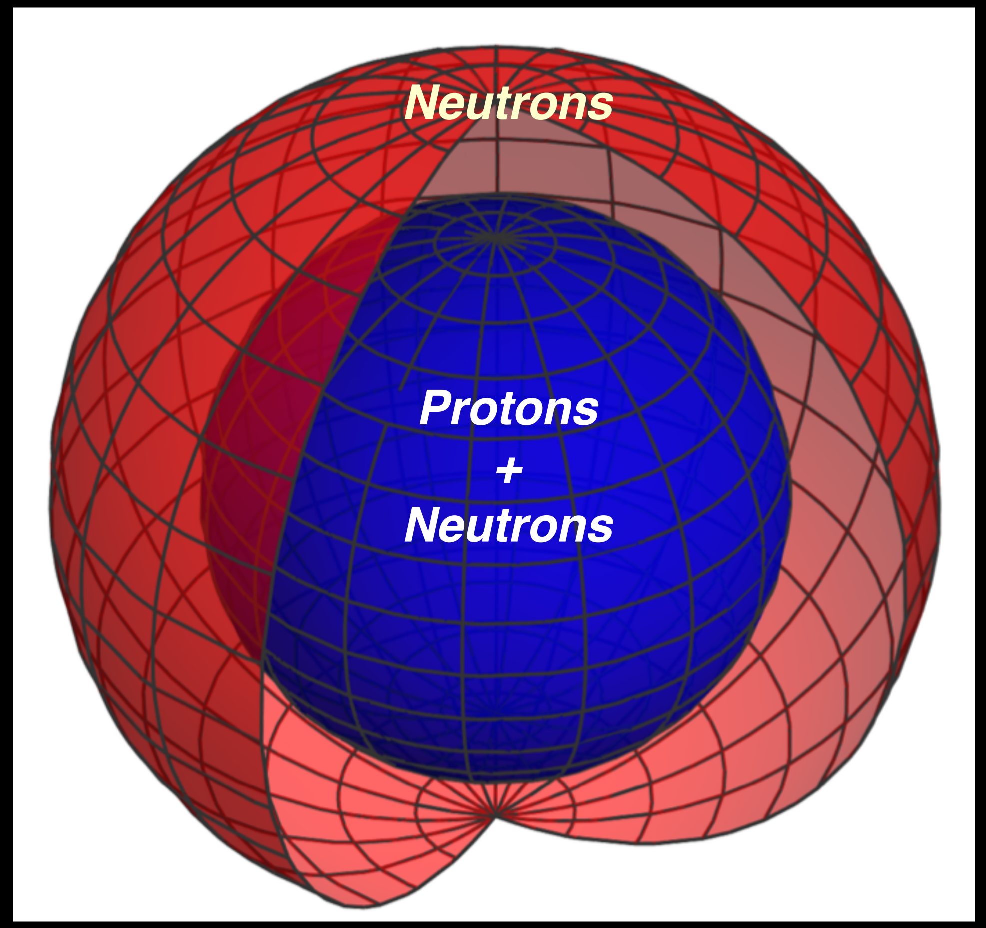


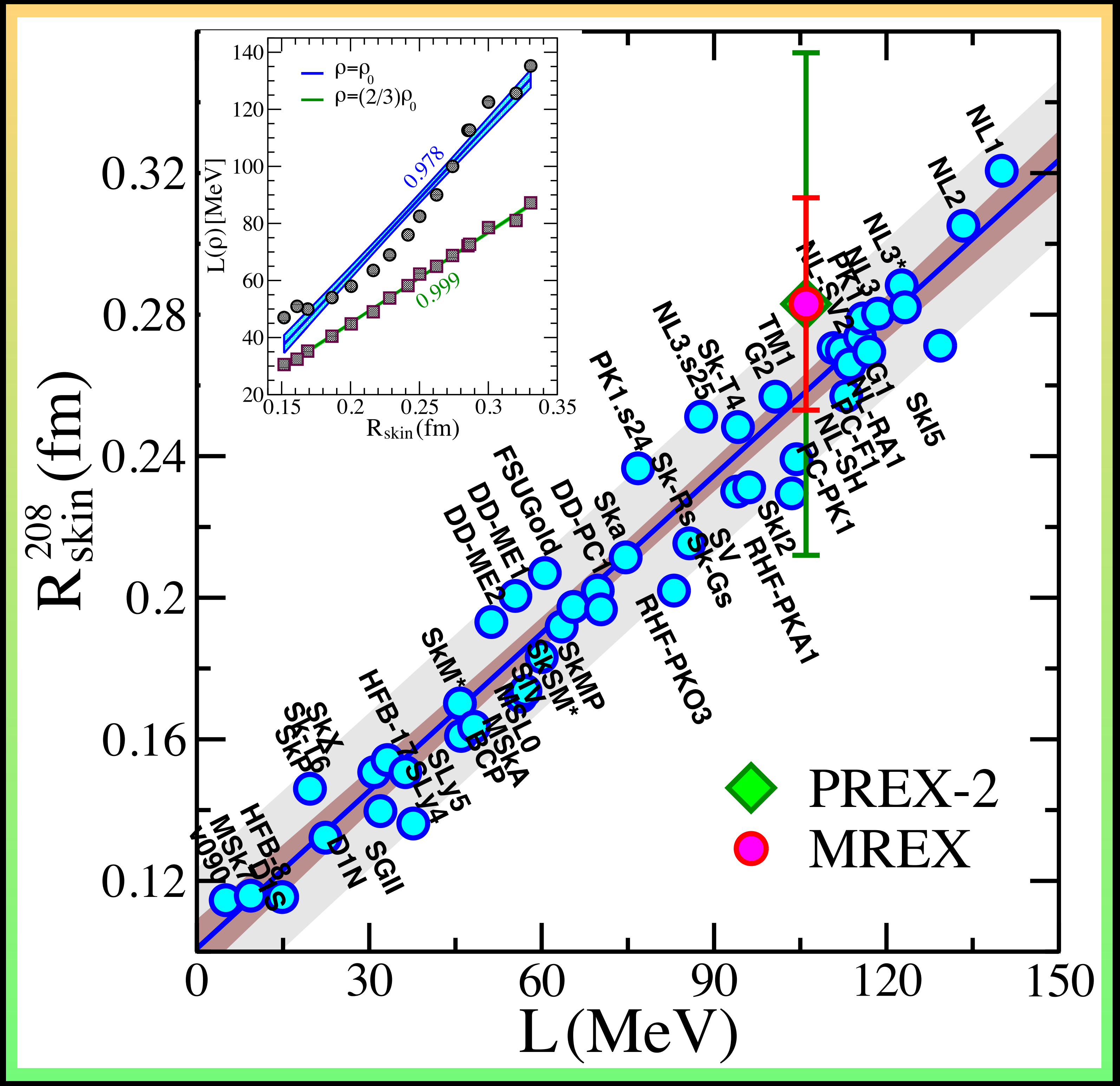


- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: P_{PNM}=L
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as ^{208}Pb
- Parity-violating elastic electron scattering is the cleanest experimental tool to measure the neutron radius of lead (PREX, PREX-II, and MREX)

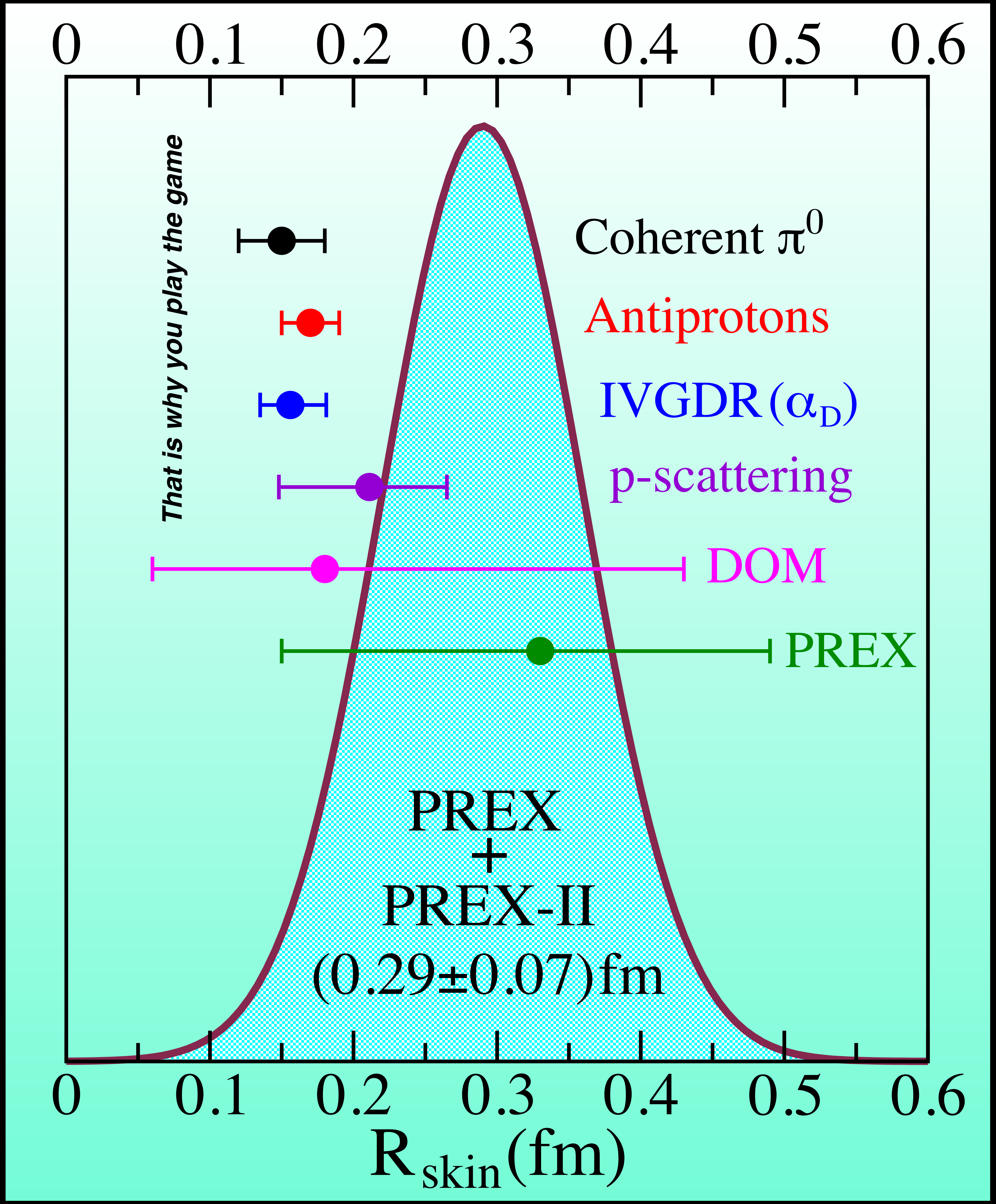
The Quest for L=P_{PNM}

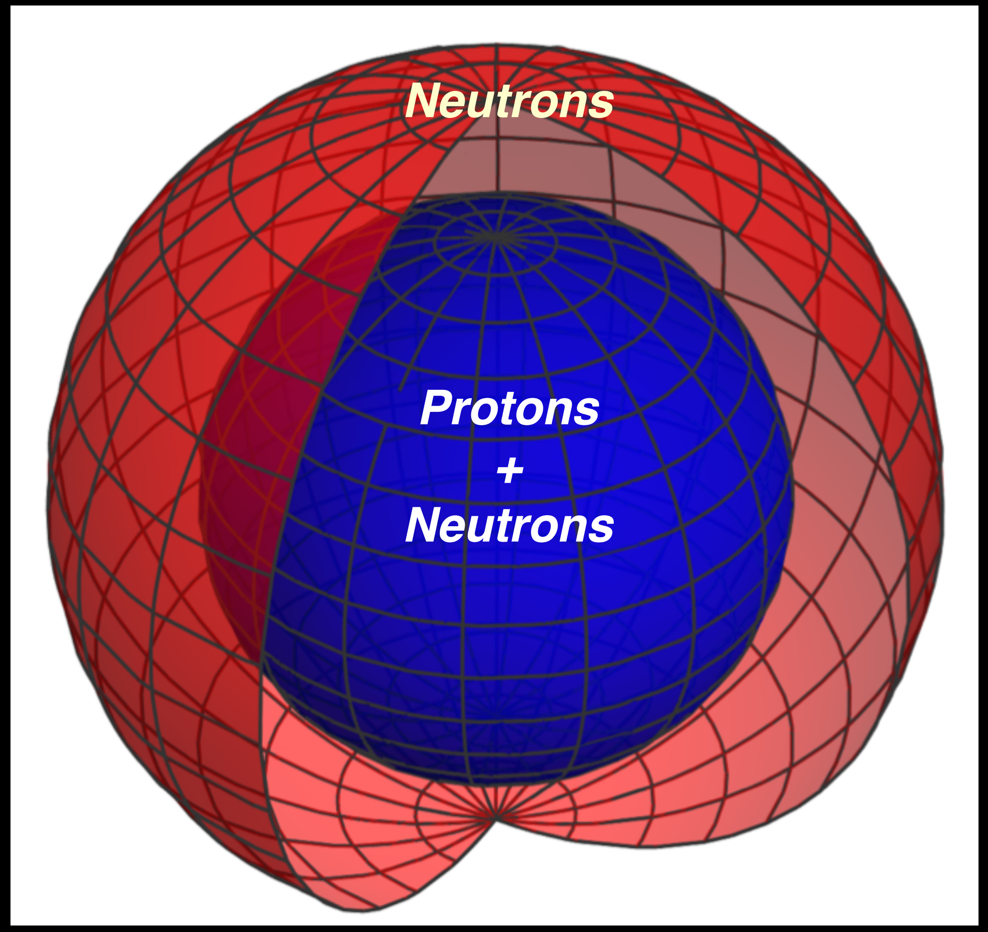


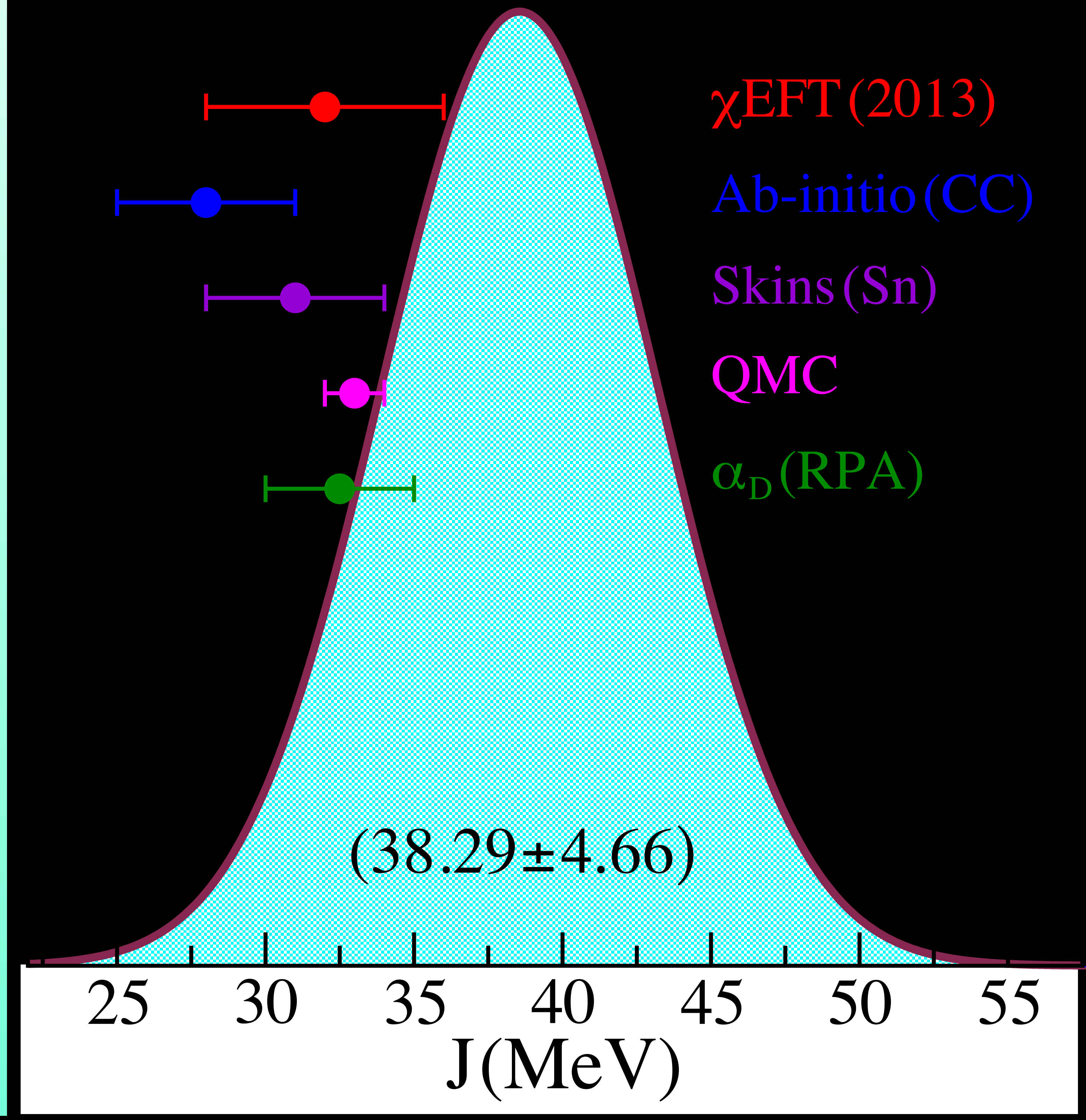




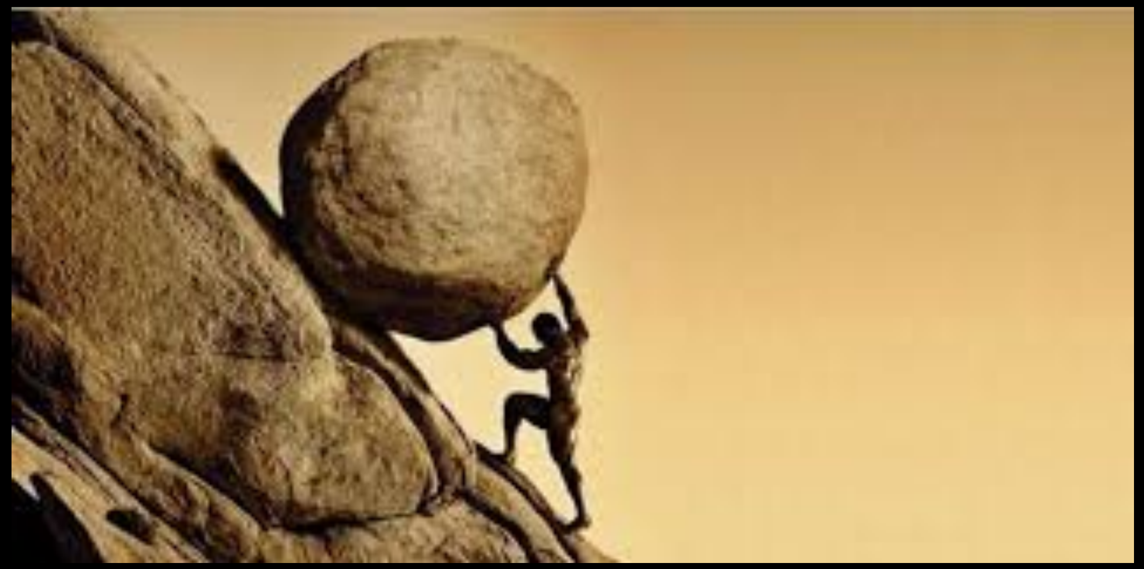
The neutron skin thickness of ^{208}Pb (Z=82, N=126)

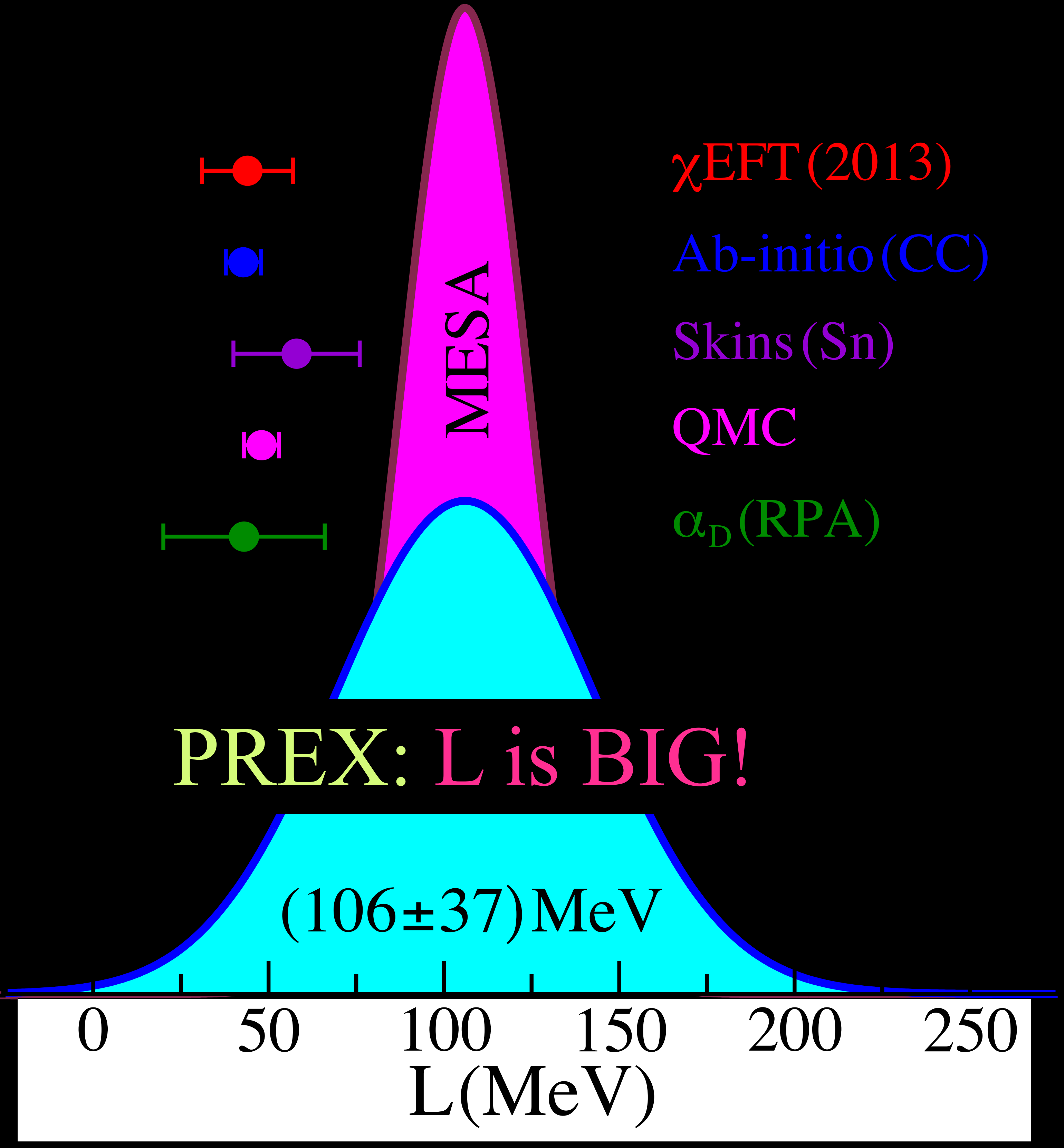






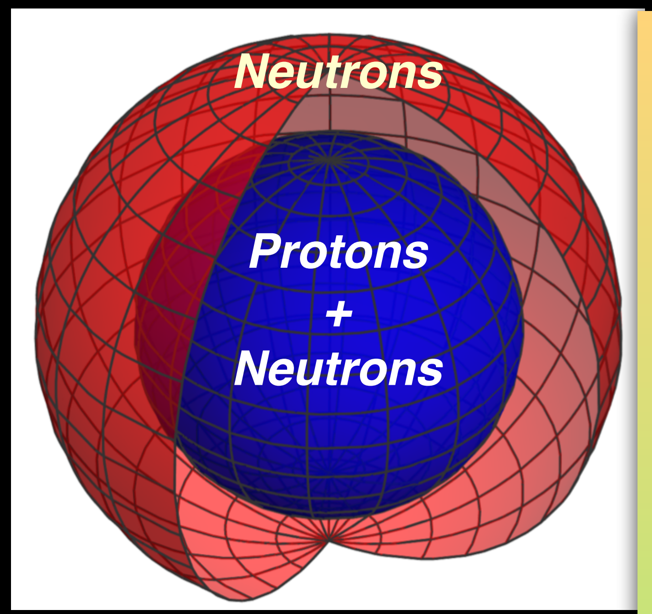
Heroic effort from our experimental colleagues

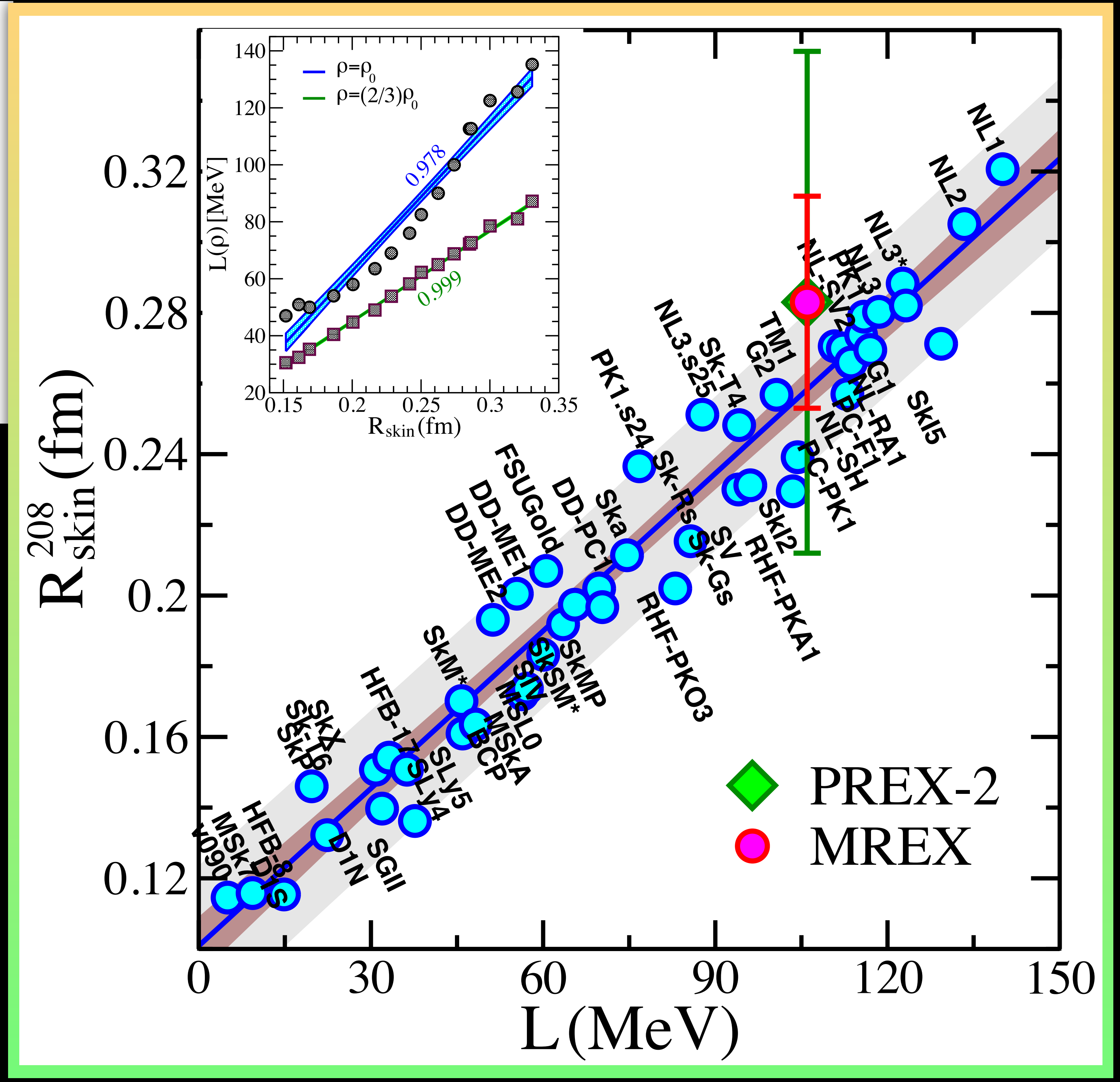




Heaven and Earth

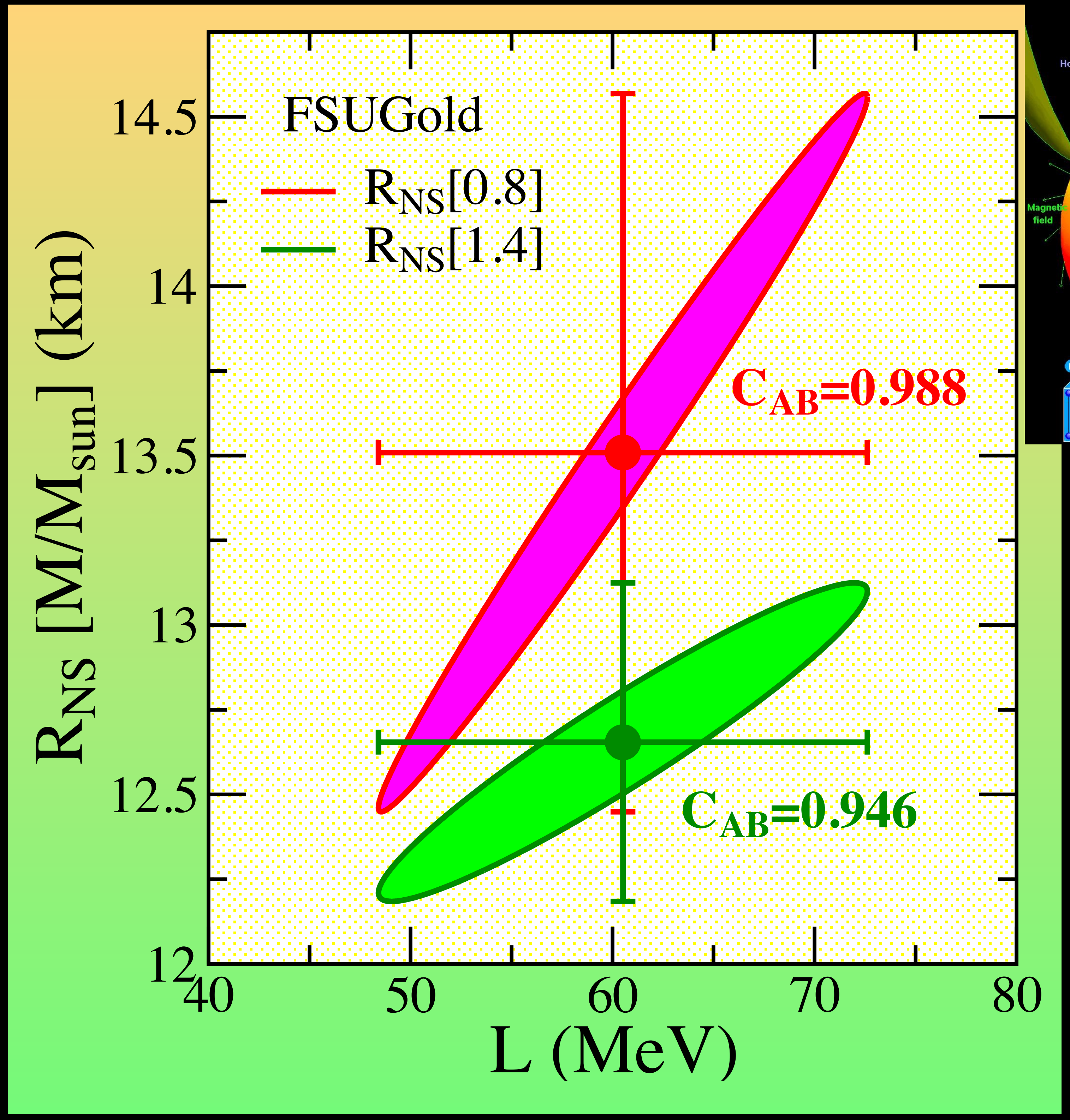
Laboratory Constraints on the EOS

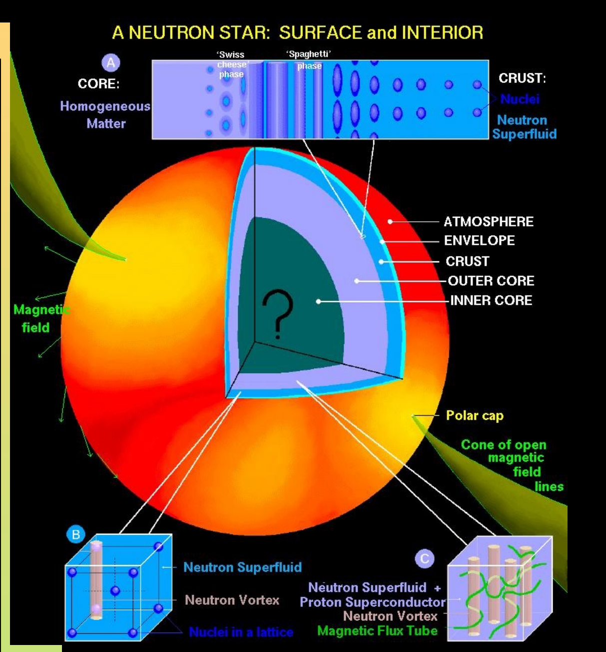




18 orders

magnitude

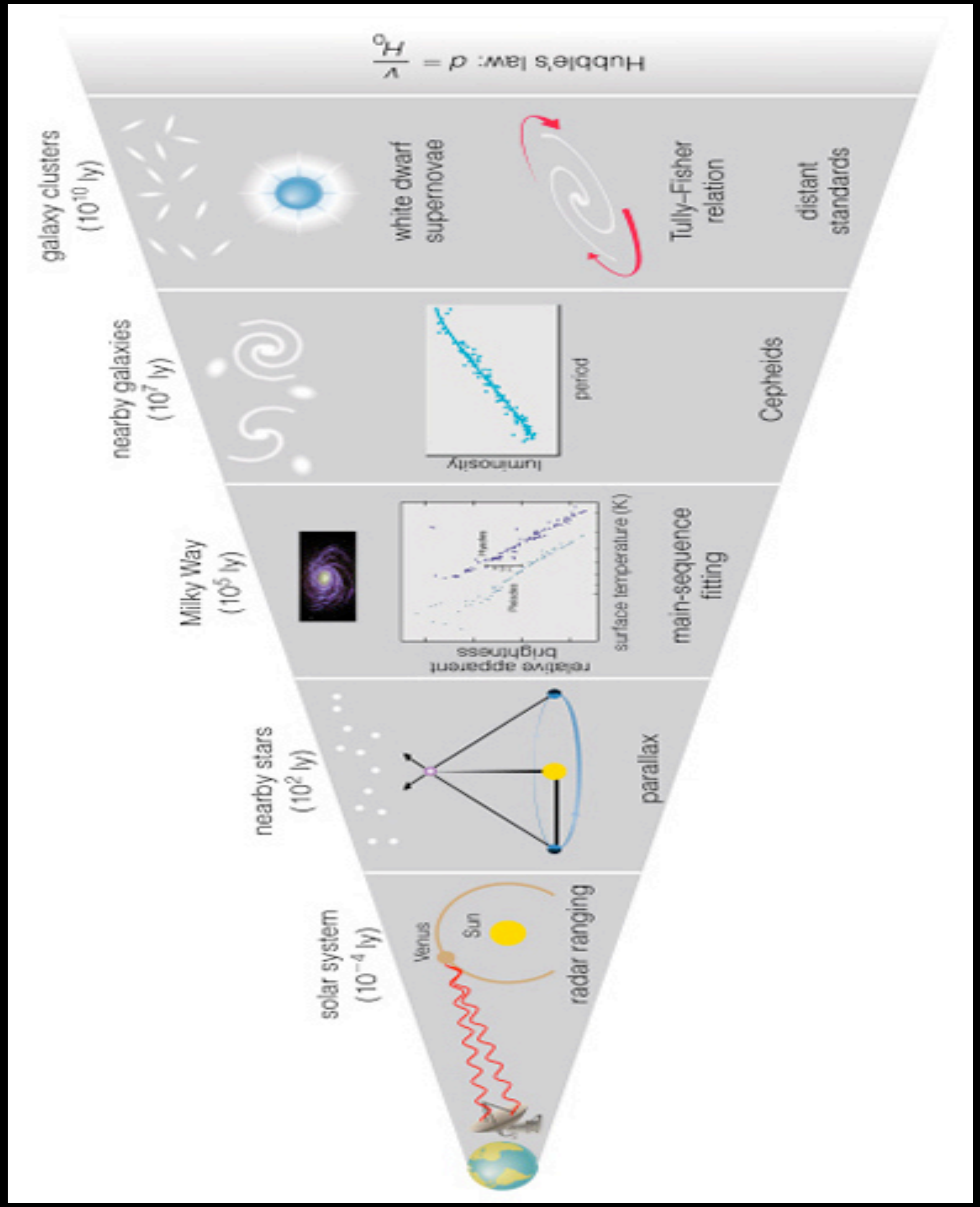




The slope of the symmetry energy L controls both the neutron skin of heavy nuclei as well as the radius of (low mass) neutron stars — objects that differ in size by 18 orders of magnitude!

The Cosmic Distance Ladder

Succession of methods to determine the distances to celestial objects. Each rung of the ladder provides information that can be used to determine the distances at the next higher rung.



The EOS Density Ladder

Each rung on the ladder relies on other methods for measuring the **EOS** that are often piggybacking on a neighboring one.