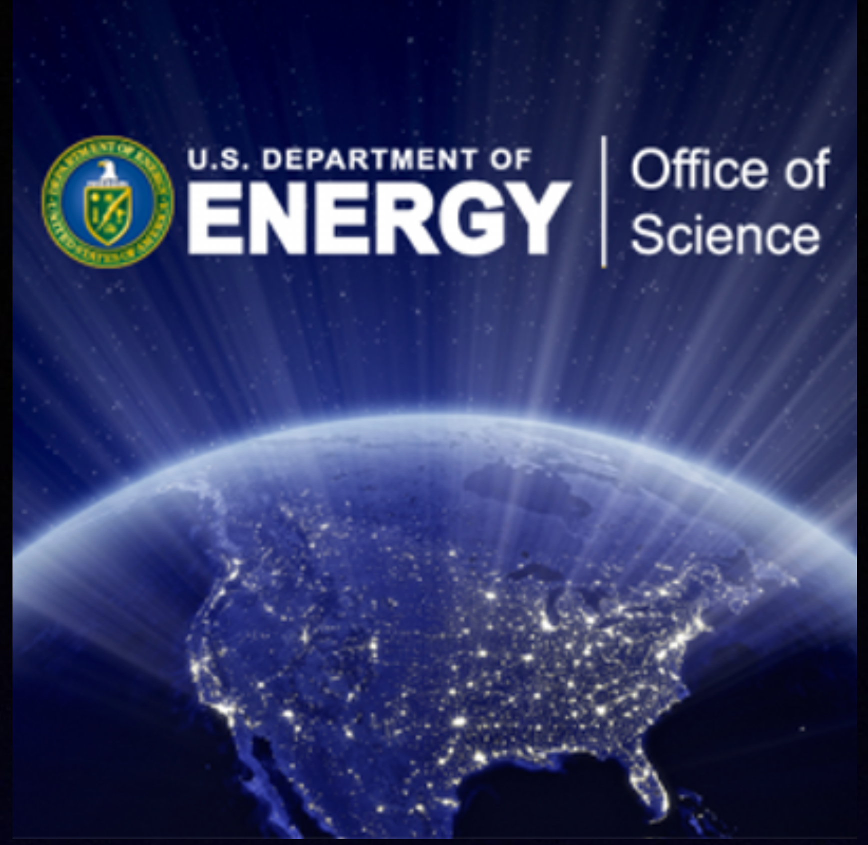
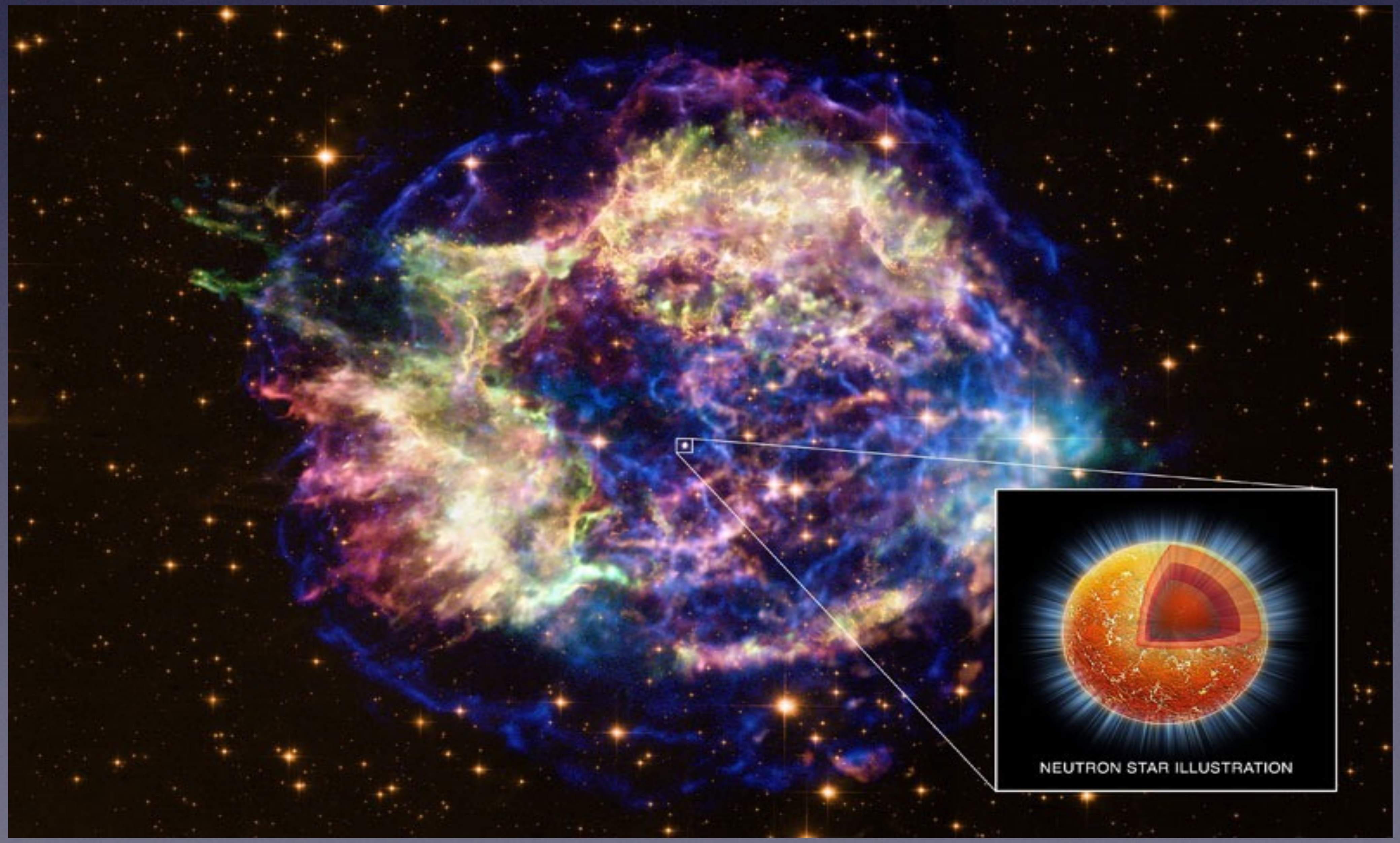
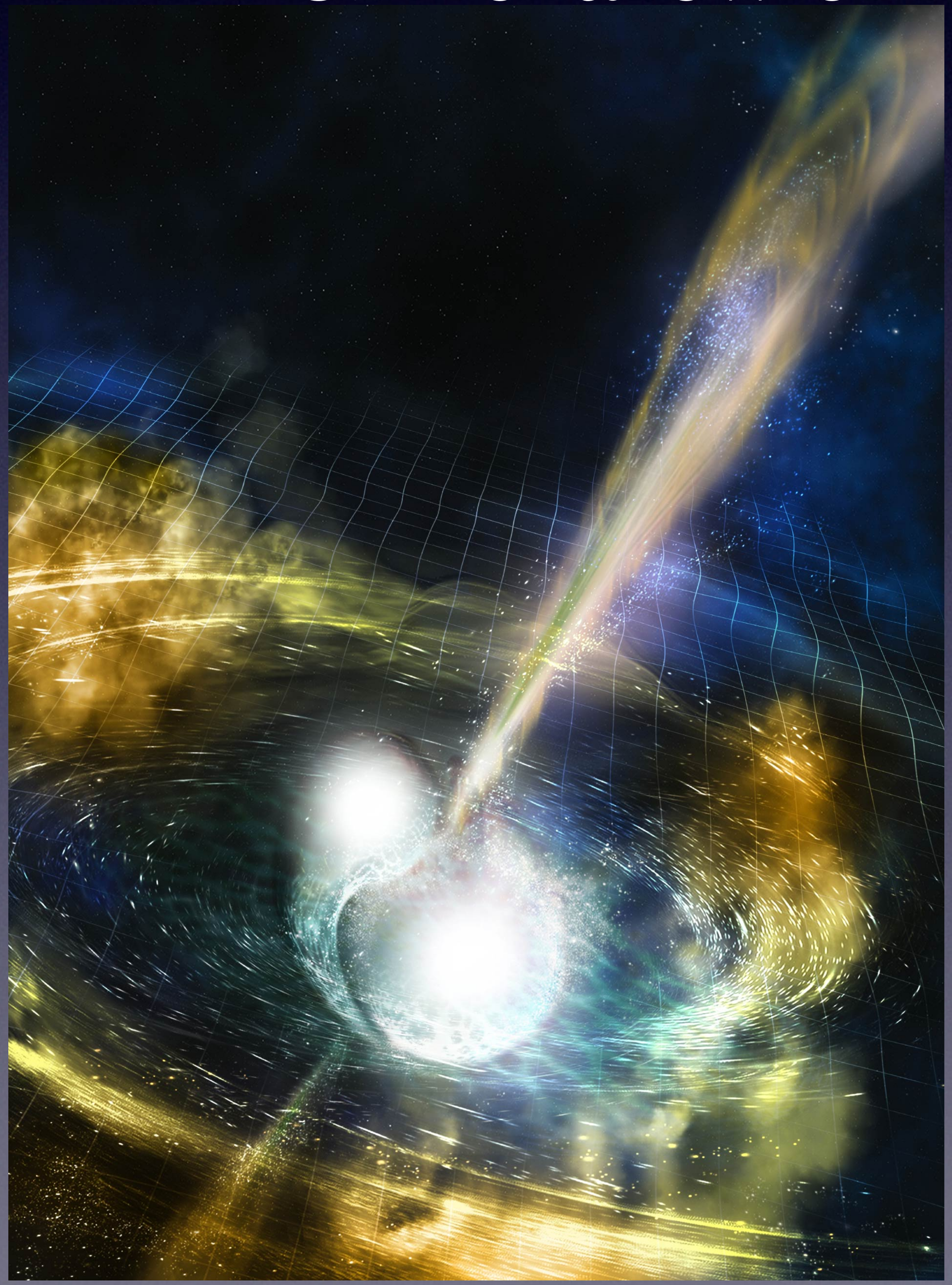


Implications of PREX on the determination of the Nuclear Equation of State

J. Piekarewicz



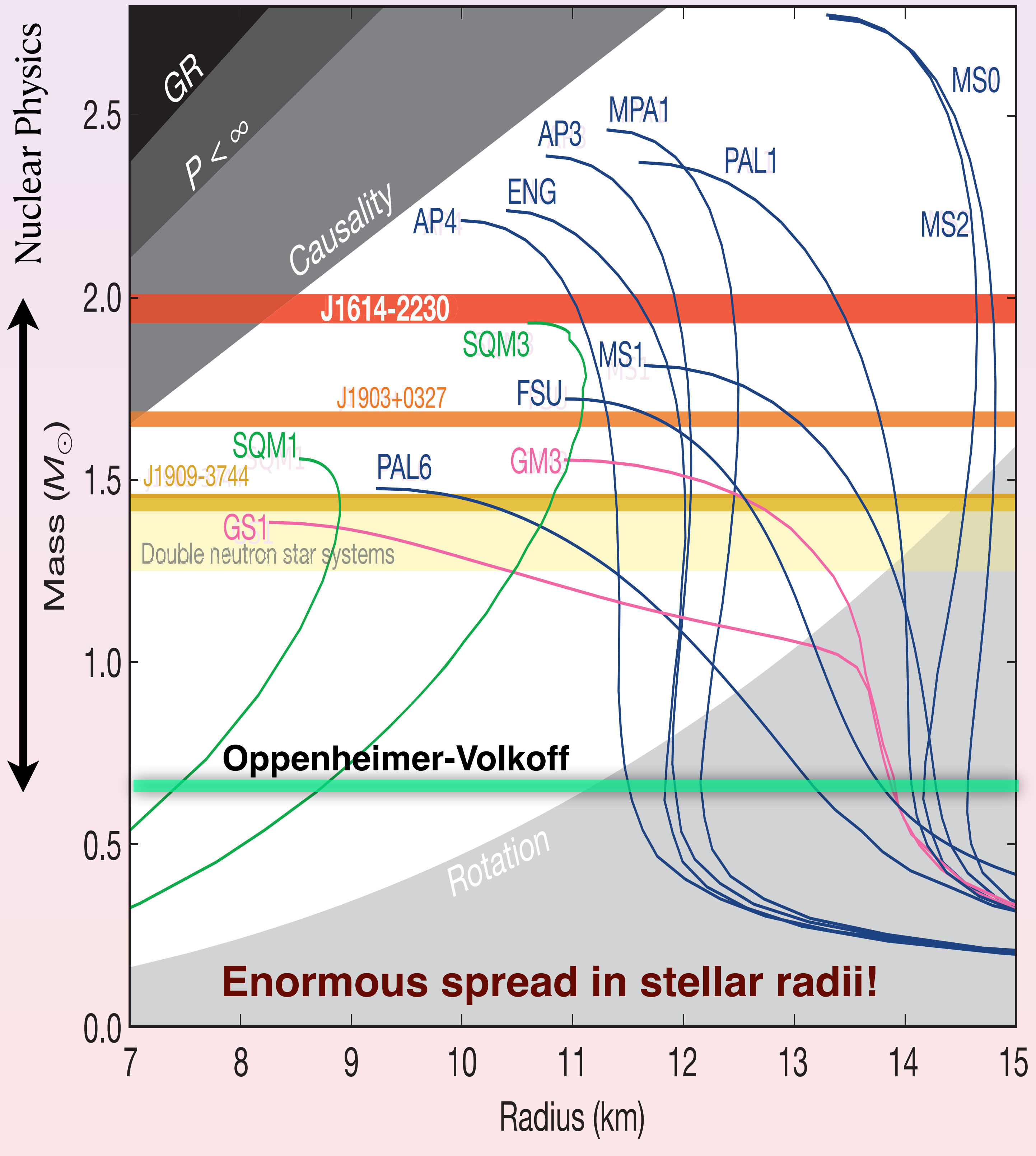


Neutron Stars: Unique Cosmic Laboratories

- Neutron stars are the remnants of massive stellar explosions (CCSN)
  Satisfy the TOV equations: From Newtonian 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!

Nuclear EOS Density Ladder

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

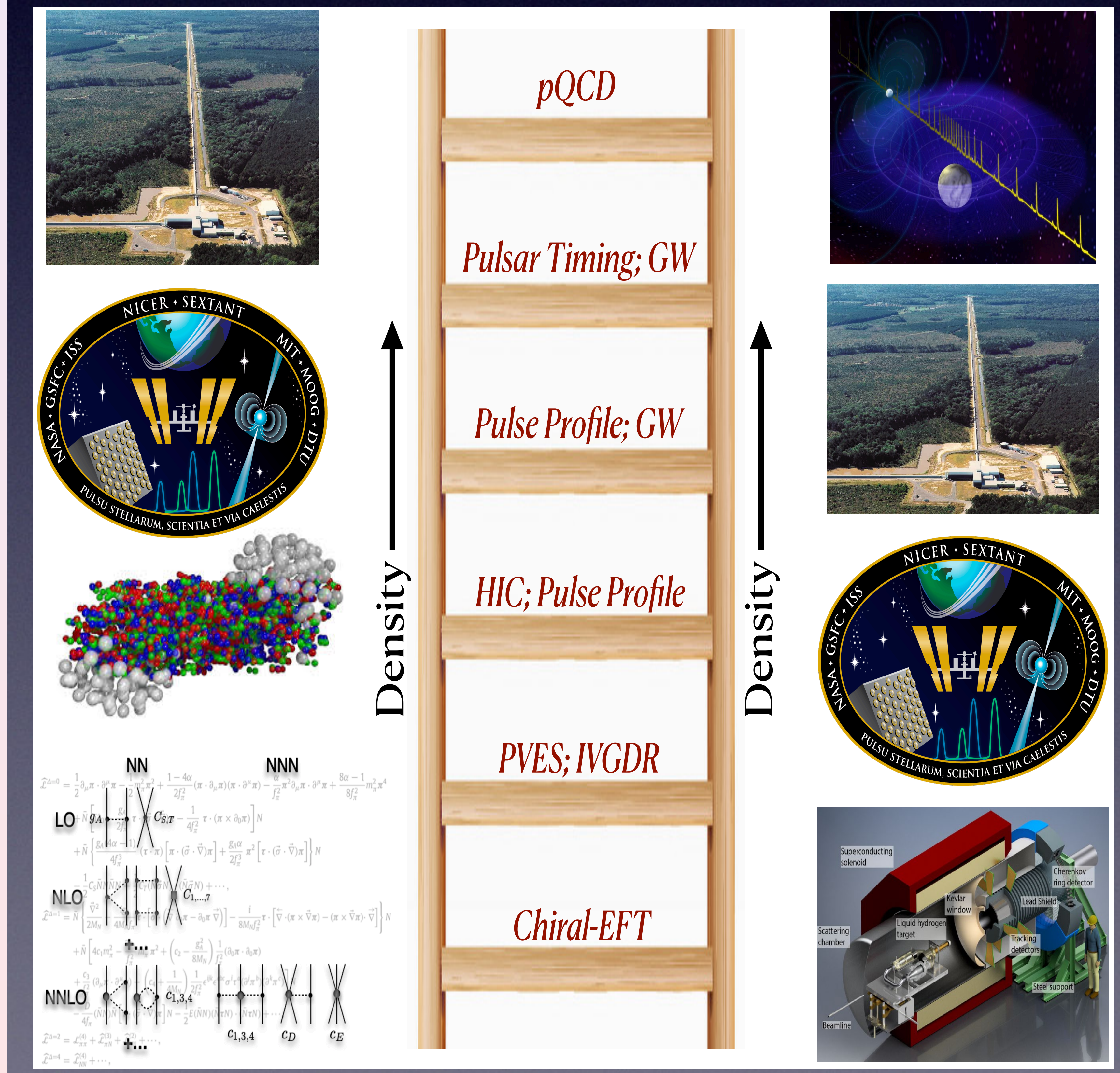


$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

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

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

Nuclear Physics Critical



Tidal Polarizability and Neutron-Star Radii (GW170817)

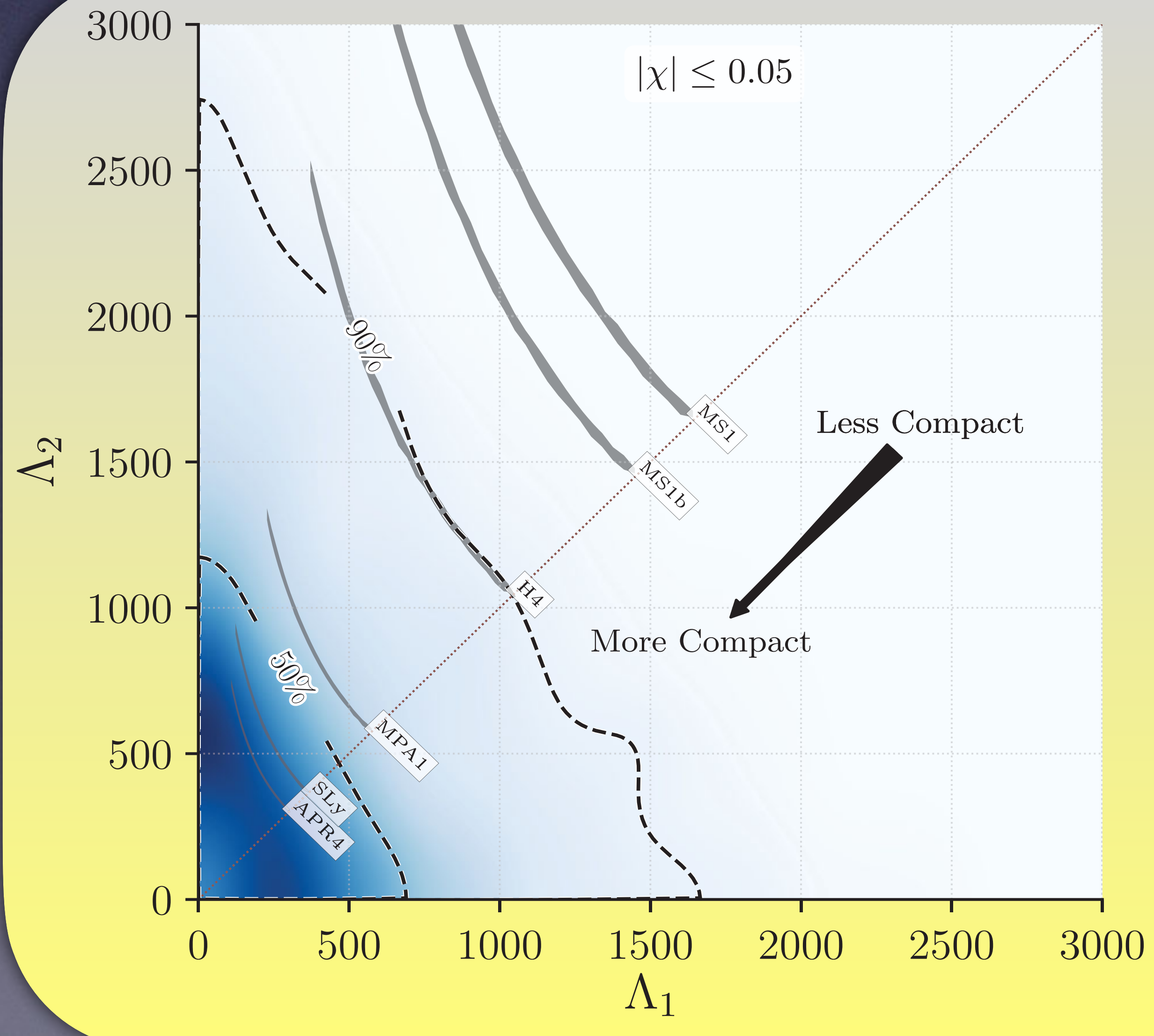
Electric Polarizability:

- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$

Tidal Polarizability (Deformability):

- Tidal field induces a polarization of mass
- A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$

$$\Lambda = k_2 \left(\frac{c^2 R}{2GM} \right)^5 = k_2 \left(\frac{R}{R_s} \right)^5$$

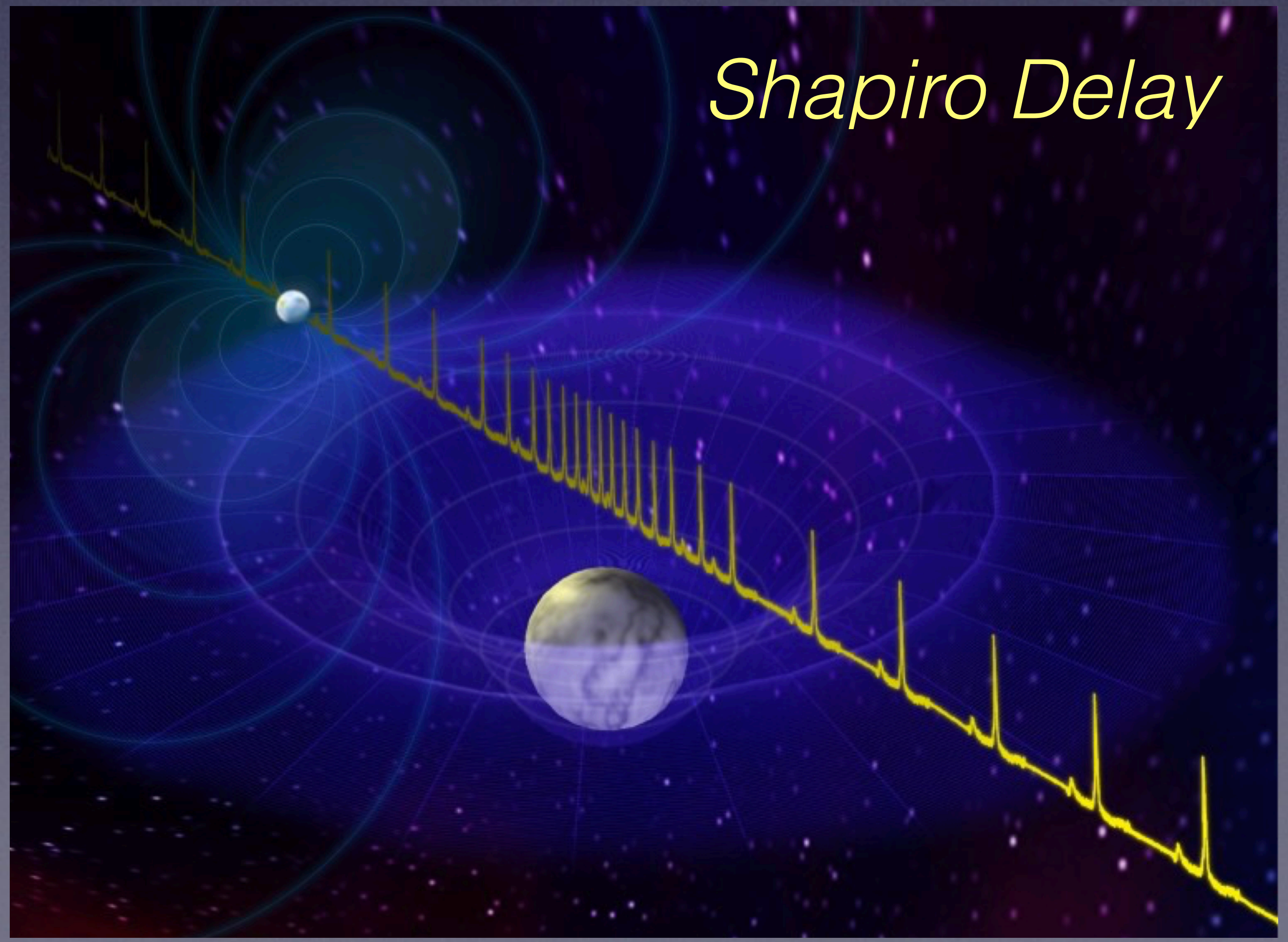


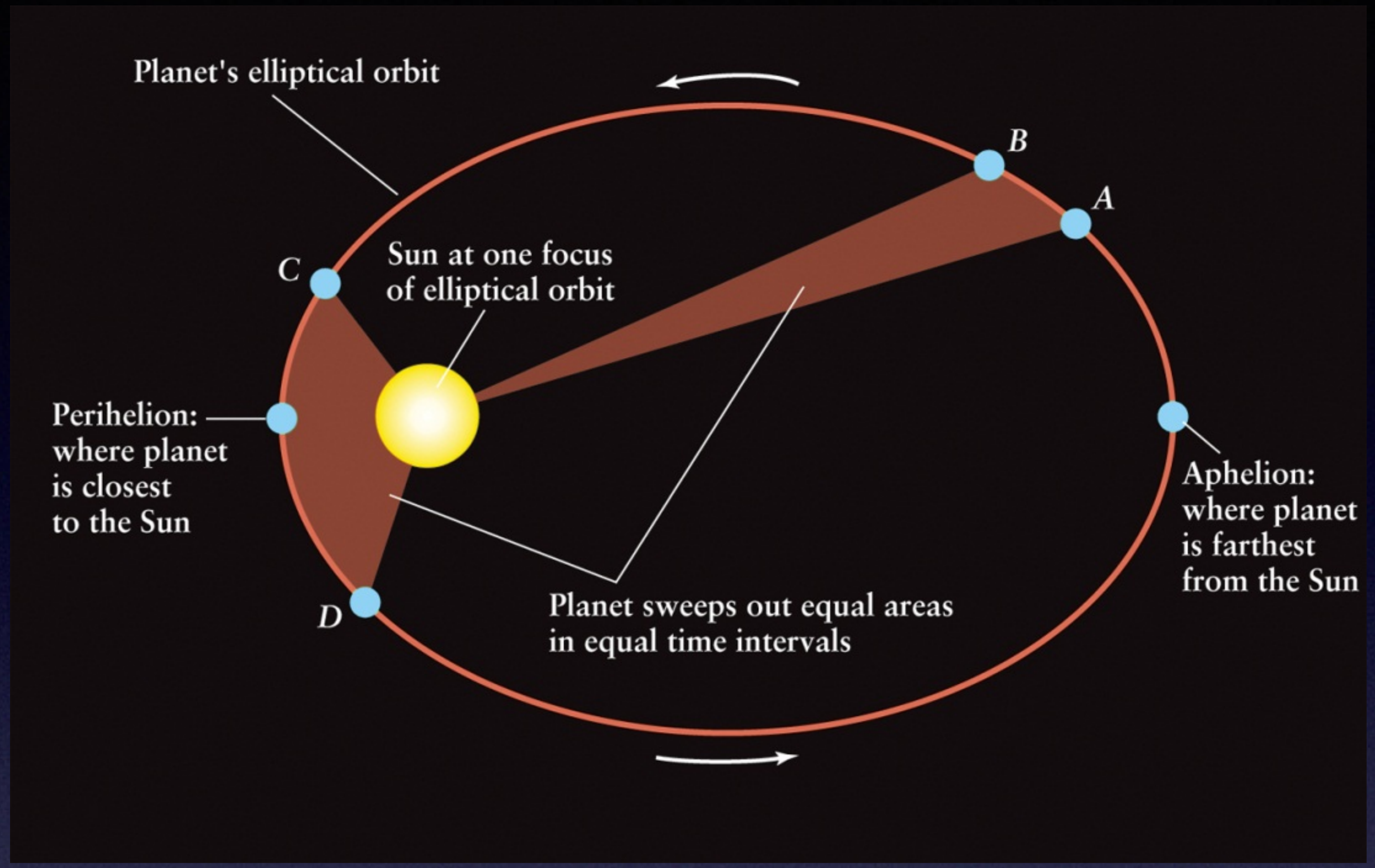
GW170817 rules out very large neutron star radii!

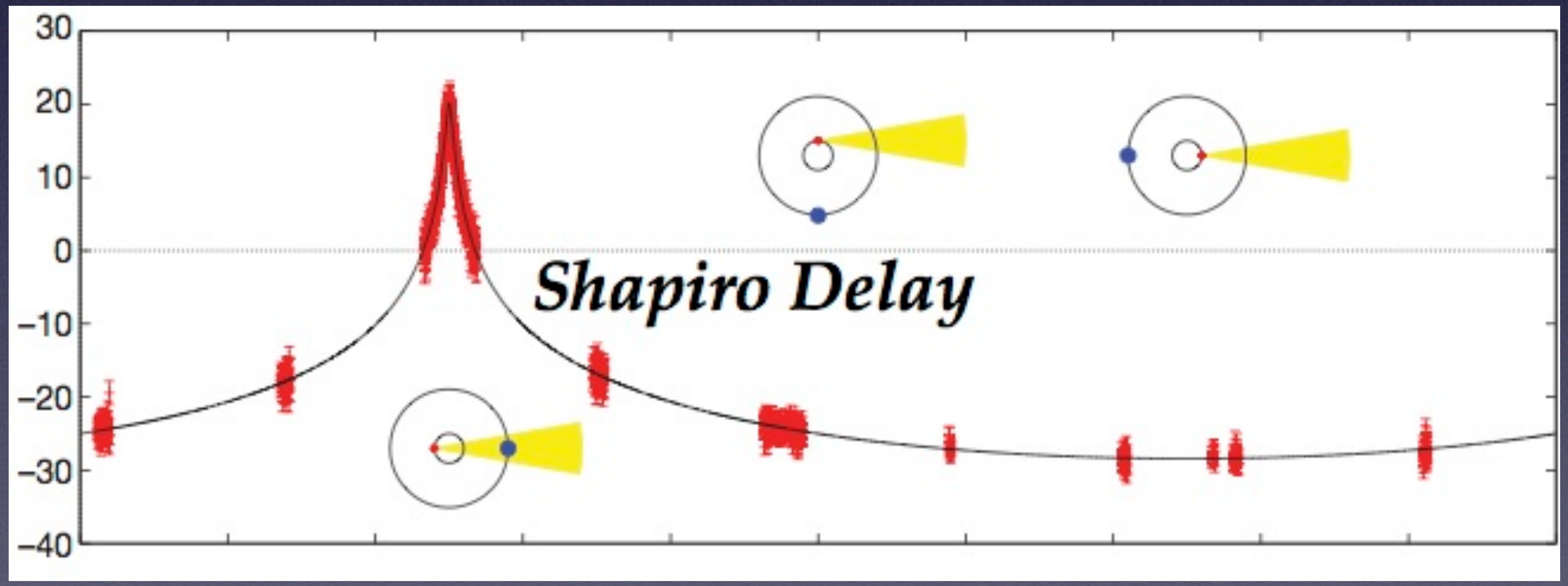
Neutron Stars must be compact

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation. Very sensitive to stellar radius!

Measuring Heavy Neutron Stars (2019)
Shapiro Delay: General Relativity to the Rescue







Newtonian Gravity sensitive to the total mass of the binary
Kepler's Third Law

$$G(M_{\rm ns} + M_{\rm wd}) = 4\pi^2 \frac{a^3}{P^2}$$

Shapiro delay — a purely General Relativistic effect can break the degeneracy

$$\delta t = \frac{GM_{\rm wd}}{c^3} \ln\left(\frac{4r_1 r_2}{d^2}\right) \approx 10\mu s$$

Cromartie et al. (2020)

$$M = 2.08 \pm 0.07 M_{\odot}$$

Neutron-star Interior Composition Explorer (NICER)
Simultaneous Mass and Radius Measurements (2019-2021)

NICER was launched from Kennedy's Space Center on June 3, 2017 aboard SpaceX Falcon 9 Rocket and docked at the International Space Station two days later.

NICER measures the compactness of the Neutron Star by looking at back of the star!

Pulse Profile: The stellar compactness controls the light profile from the hot spot

$$\xi = \frac{2GM}{c^2 R} = \frac{R_S}{R}$$

$$M = 2.08 \pm 0.07\,\mathrm{M}_\odot$$

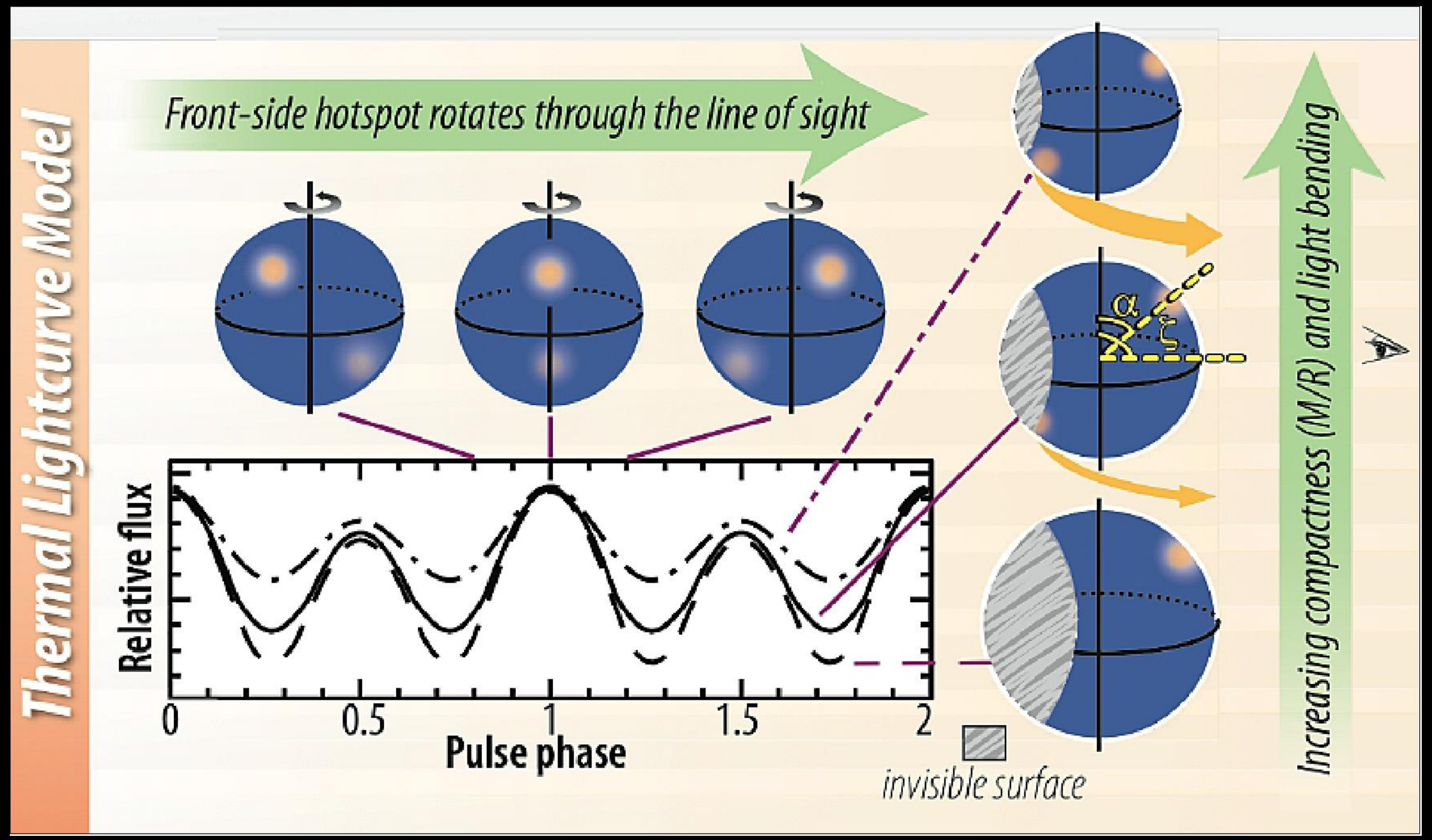
Shapiro delay: Cromartie *et al.* (2020)

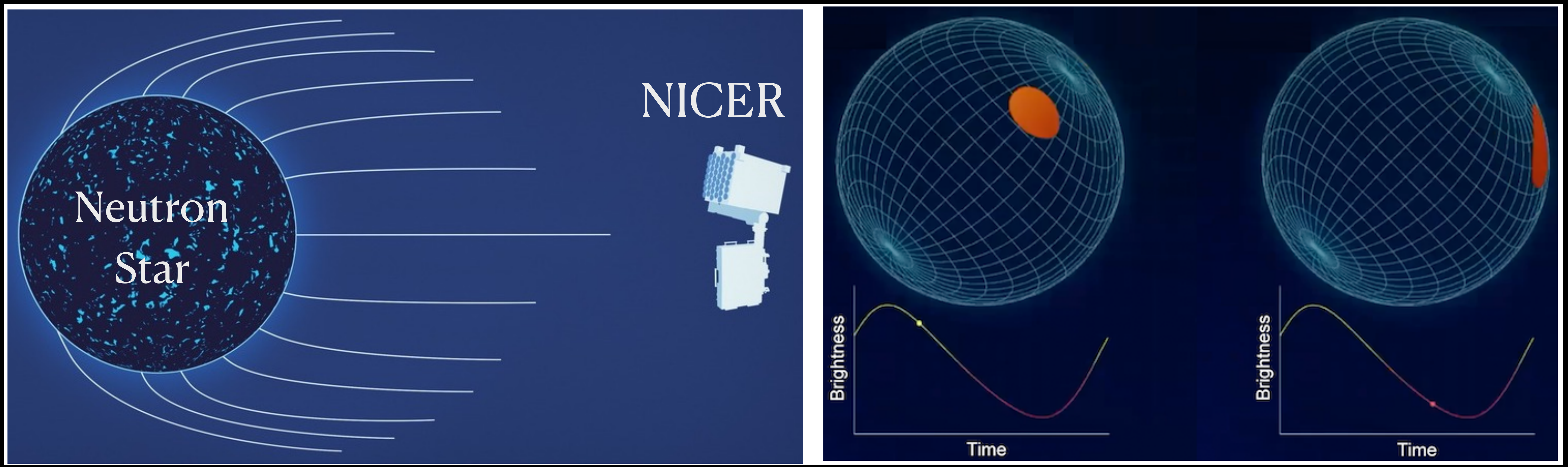
$$R_{2.0} = 12.39^{+1.30}_{-0.98}\ \mathrm{km}$$

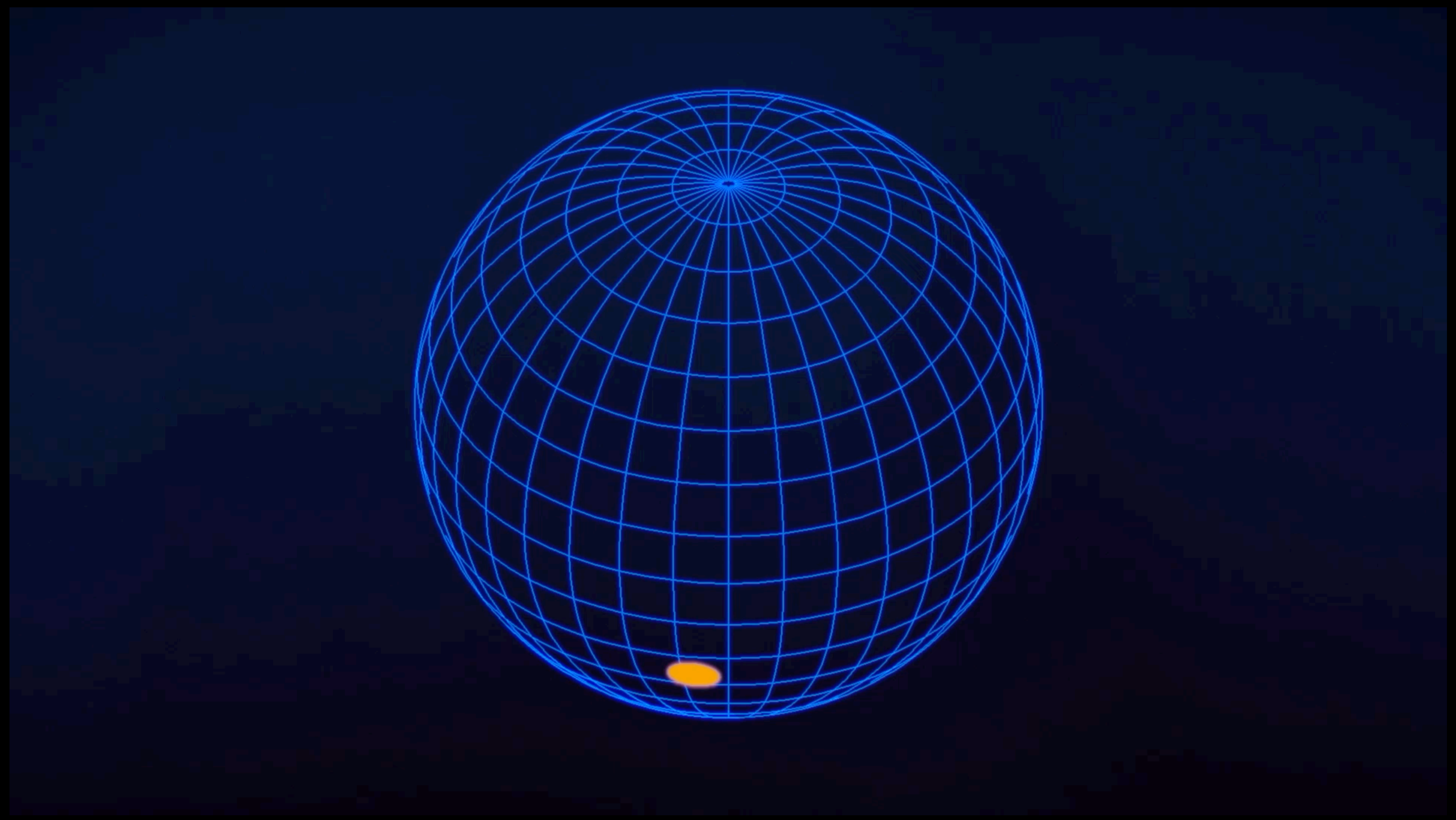
Riley *et al.* (2021)

$$R_{2.0} = 13.7^{+2.6}_{-1.5}\ \mathrm{km}$$

Miller *et al.* (2021)

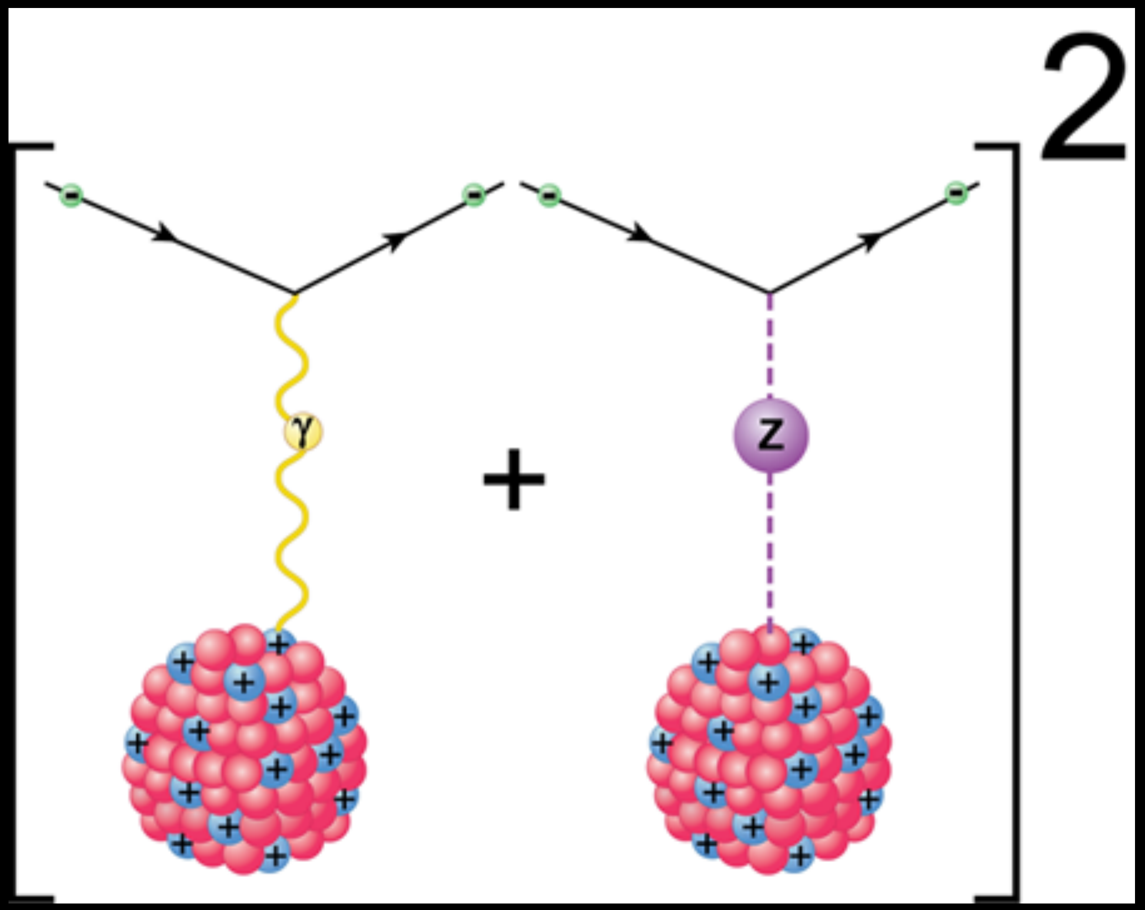


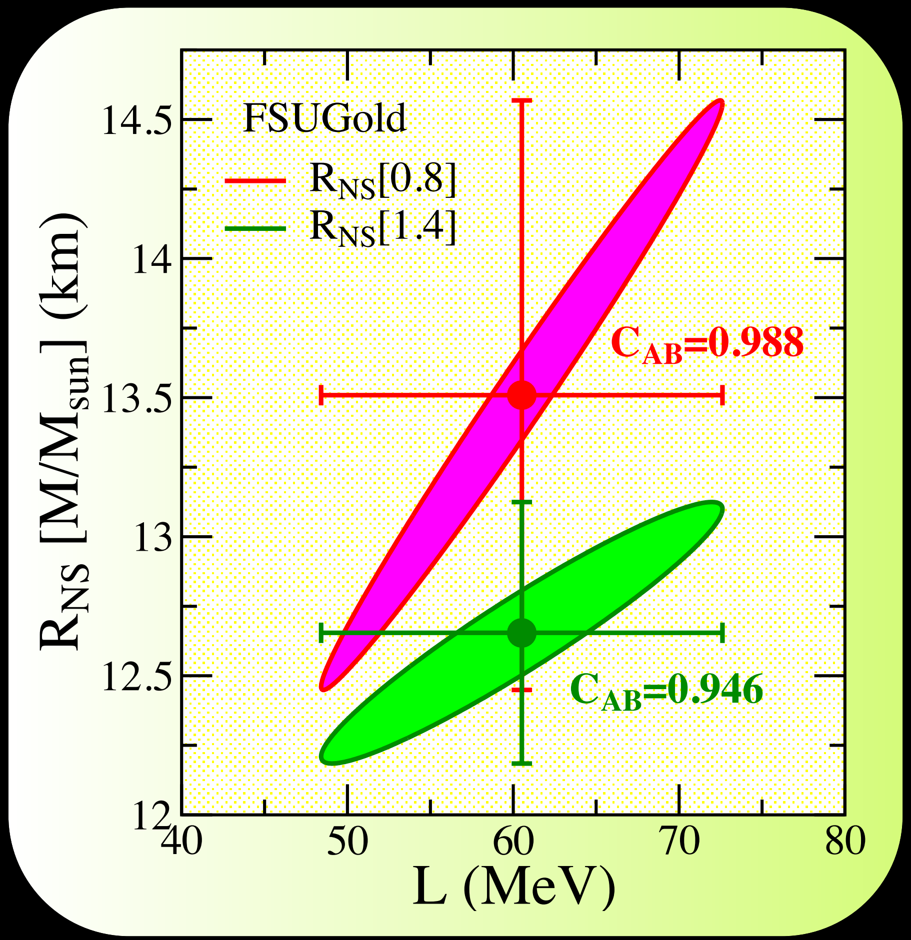




Heaven and Earth

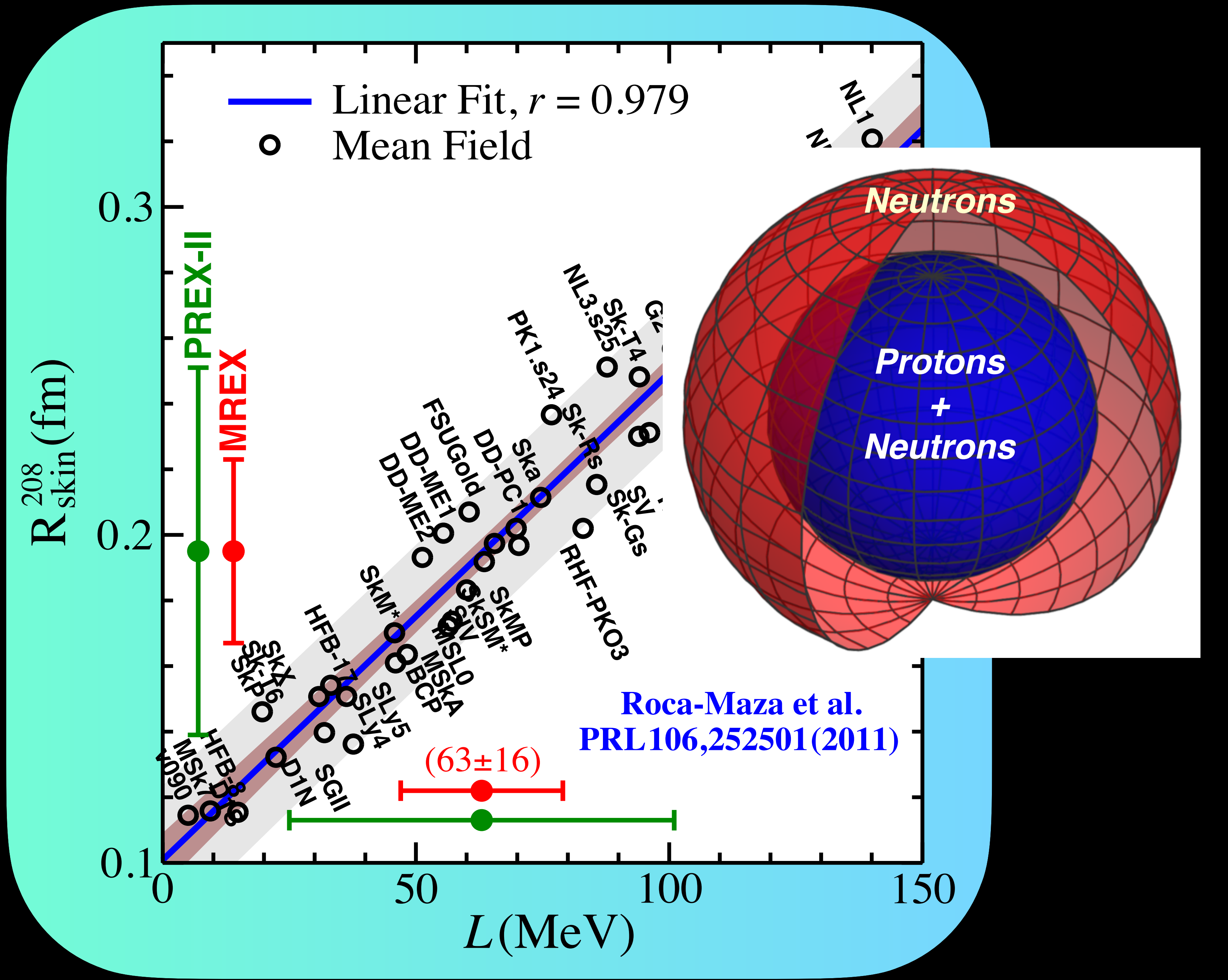
Laboratory Constraints on the EOS

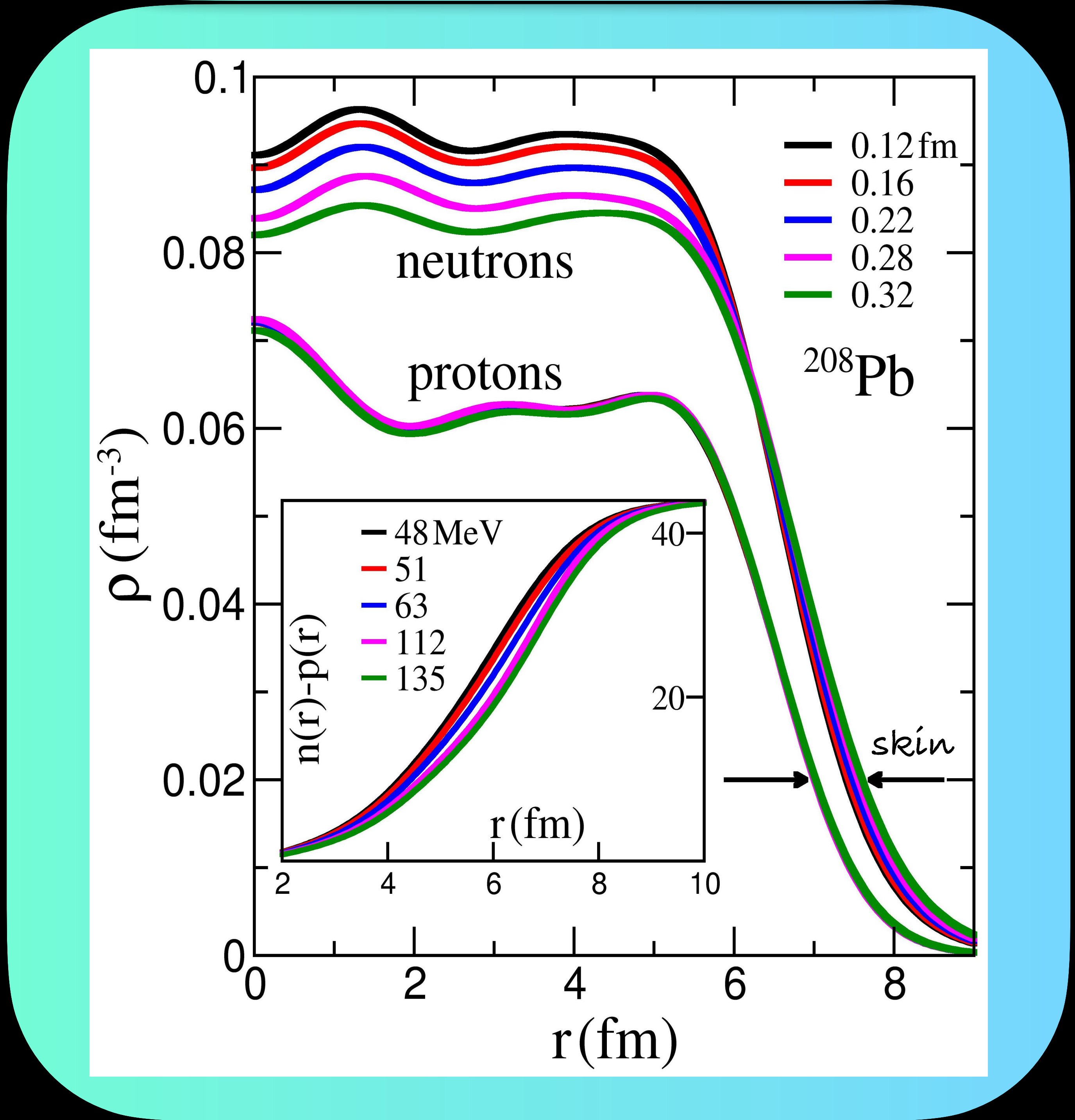




18 orders

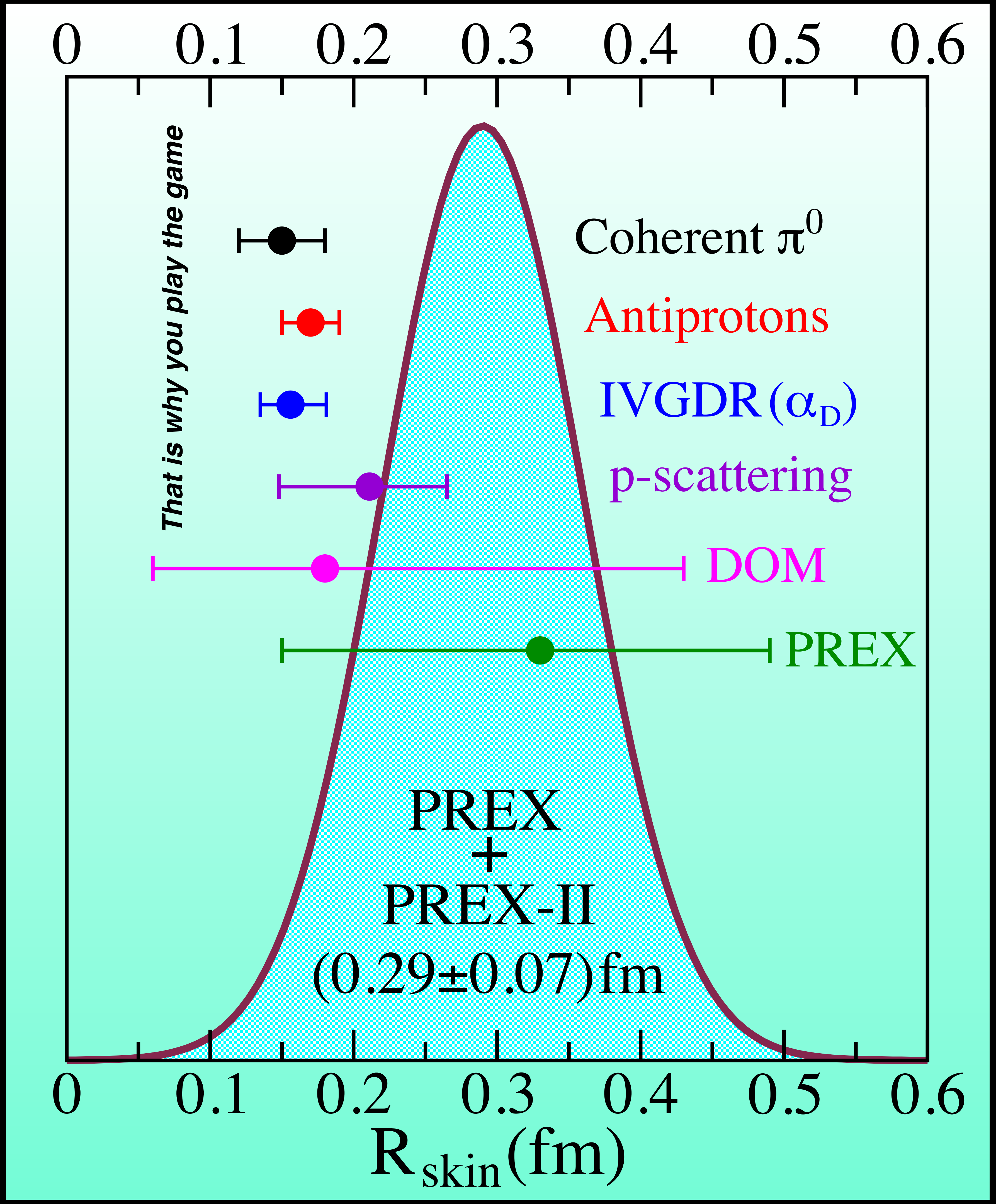
magnitude



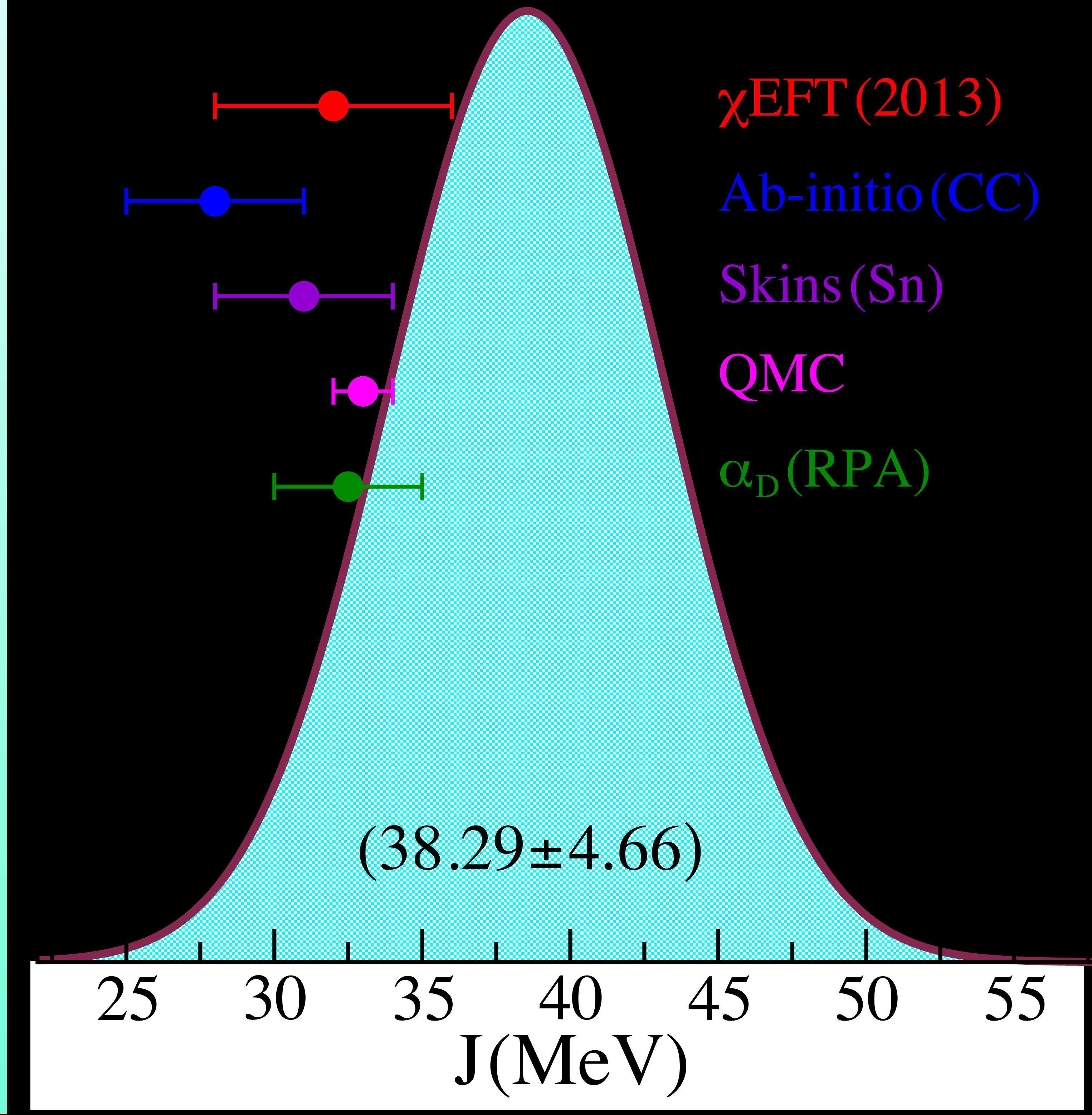


- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: P_{PNM}=L
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as ^{208}Pb
- Parity-violating elastic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

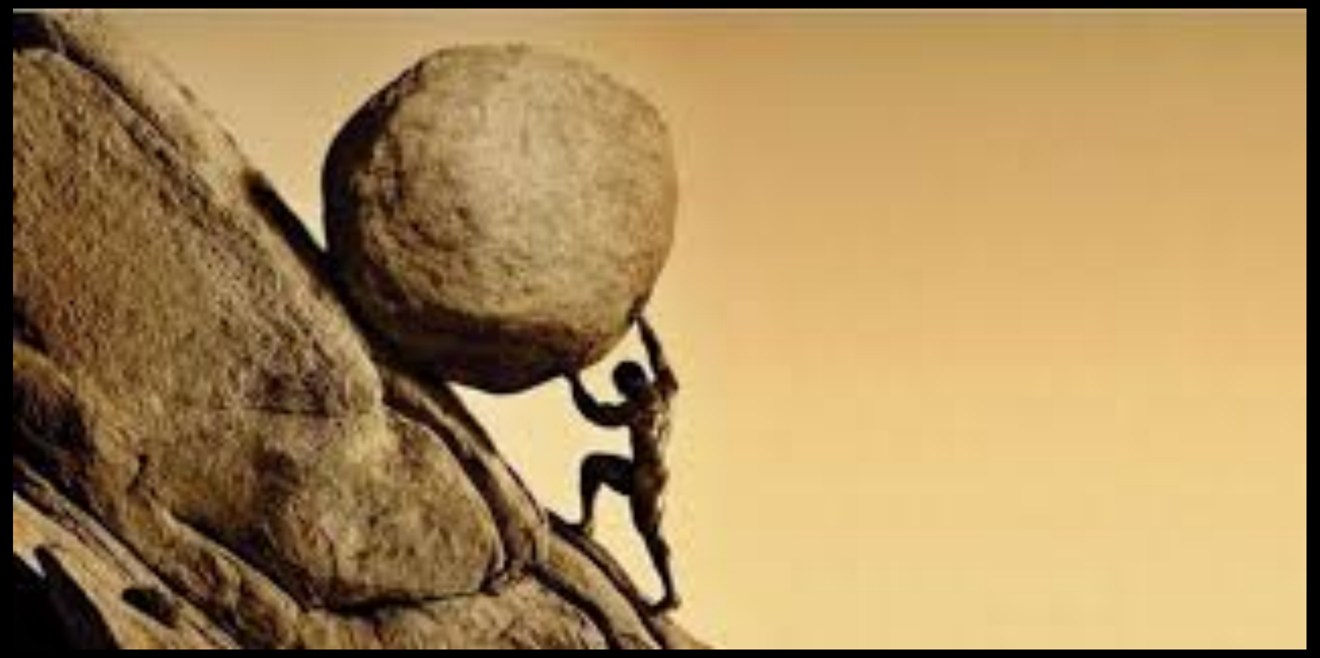
PREX-II (Oct 29, 2020)
Ciprian Gal - DNP Meeting

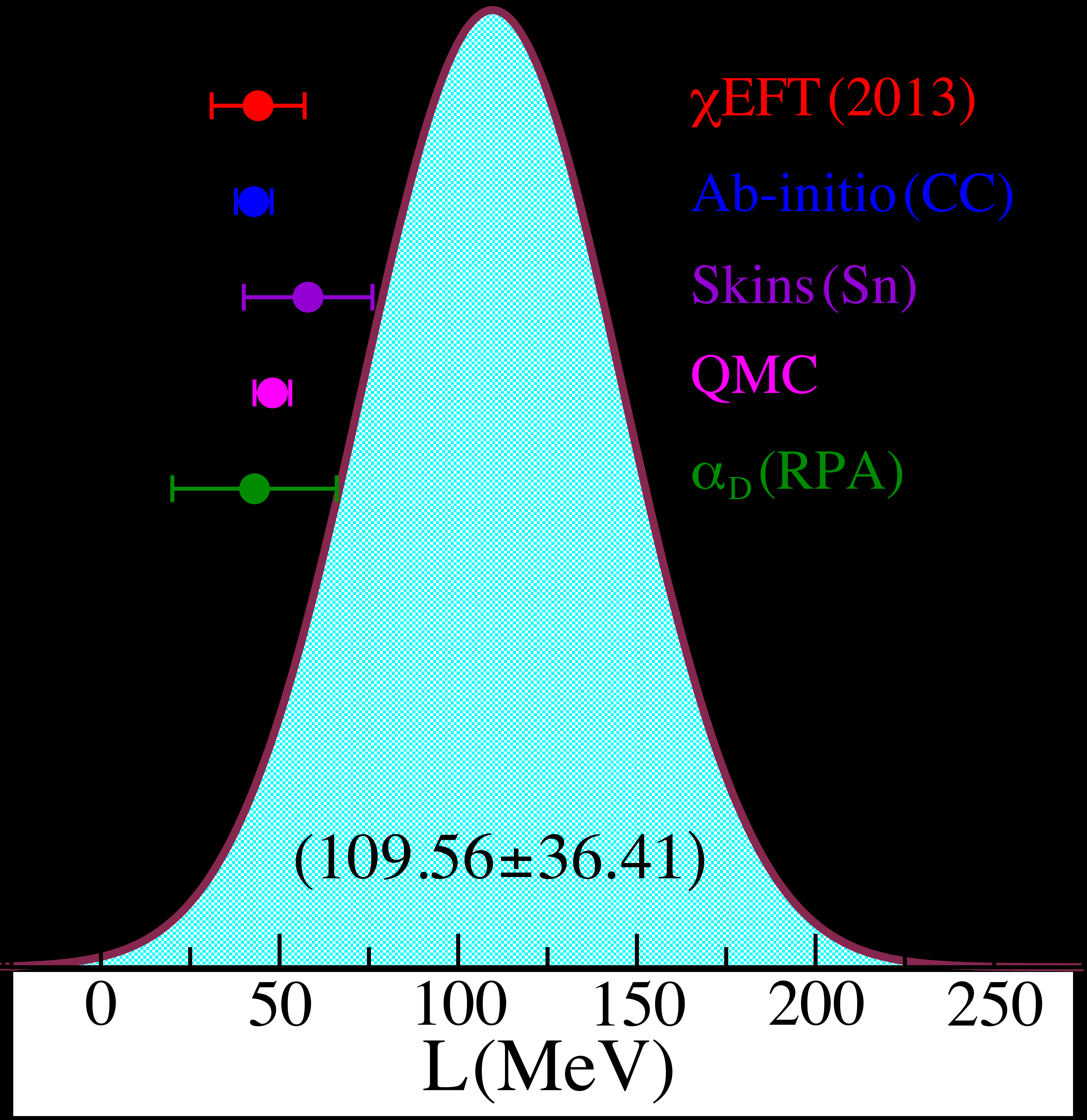


Conservation of difficulty:
PVES provides the cleanest constraint on the EOS of neutron-rich matter in the vicinity of saturation density

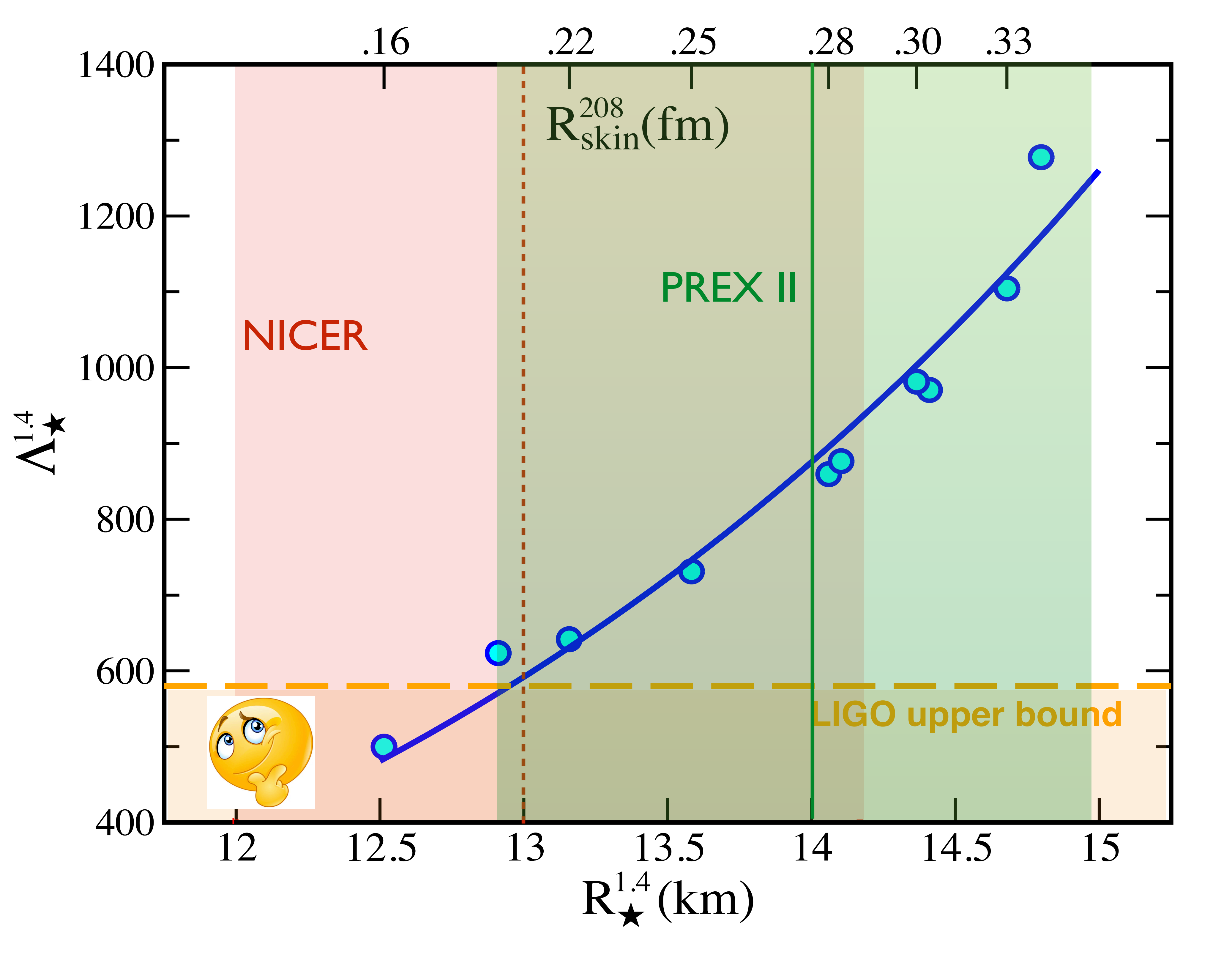


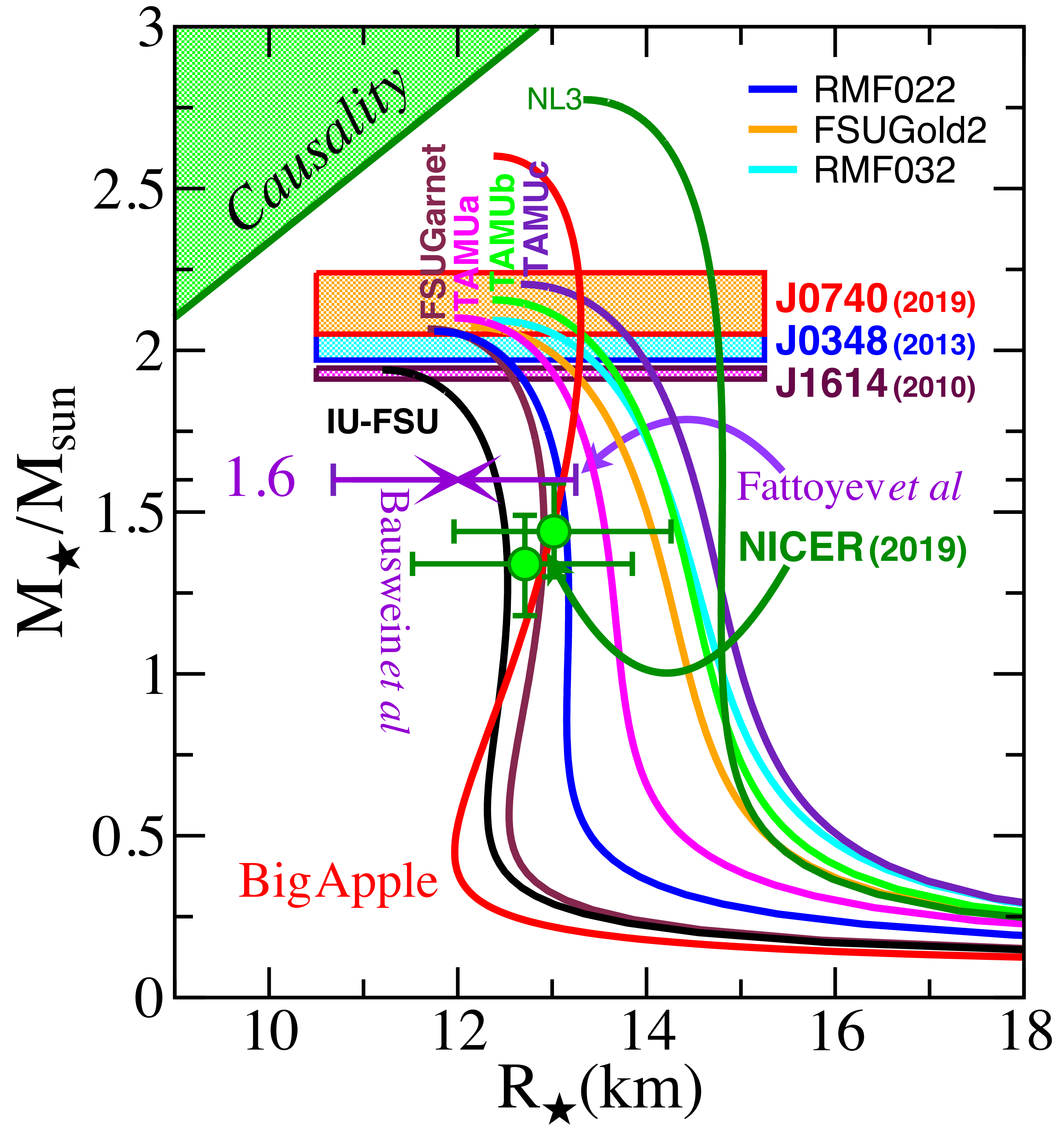
Heroic effort from our experimental colleagues





The golden era of neutron stars … G. Baym

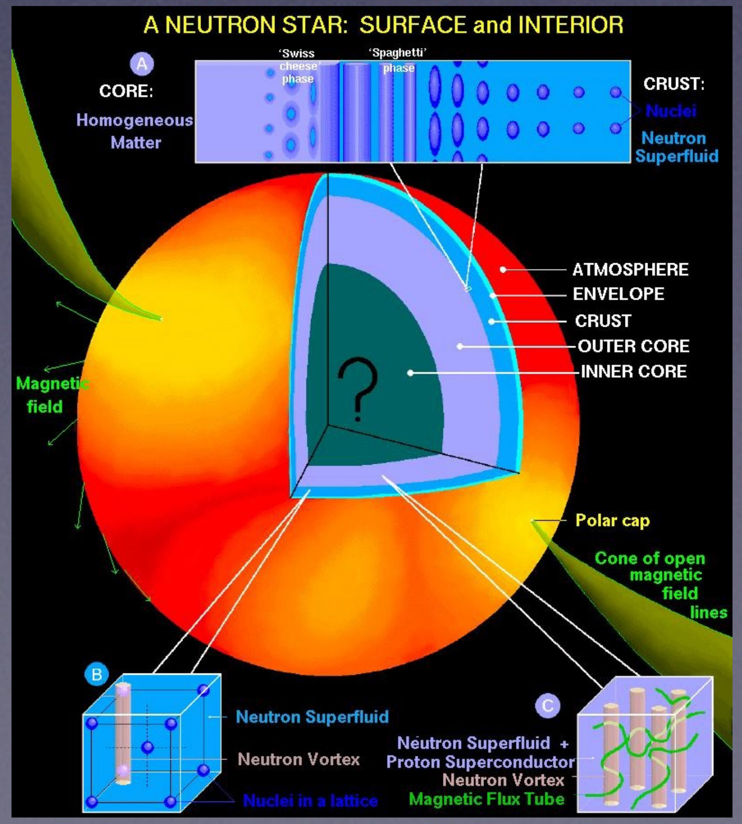




Tantalizing Possibility

- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)



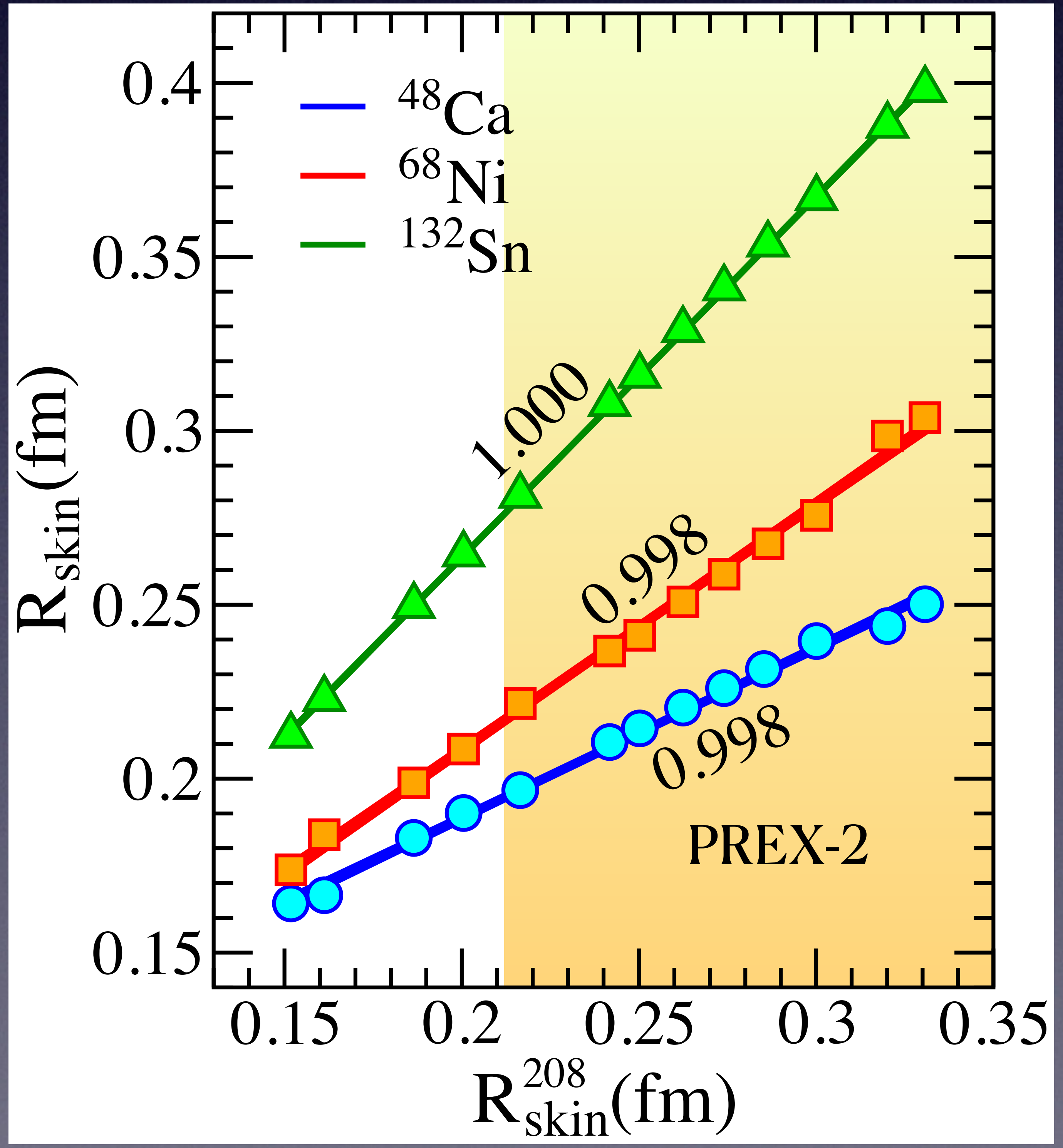
Who Ordered That?

Preliminary Observations:

- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin
- At this point it appears potentially challenging for DFT models to reproduce both the CREX result of a thin skin in ^{48}Ca and the PREX result of a relatively thick skin in ^{208}Pb.

No theoretical model that I know of can reproduce both!

Isidor Isaac Rabi



Comparing to Theory

Observation:

- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin

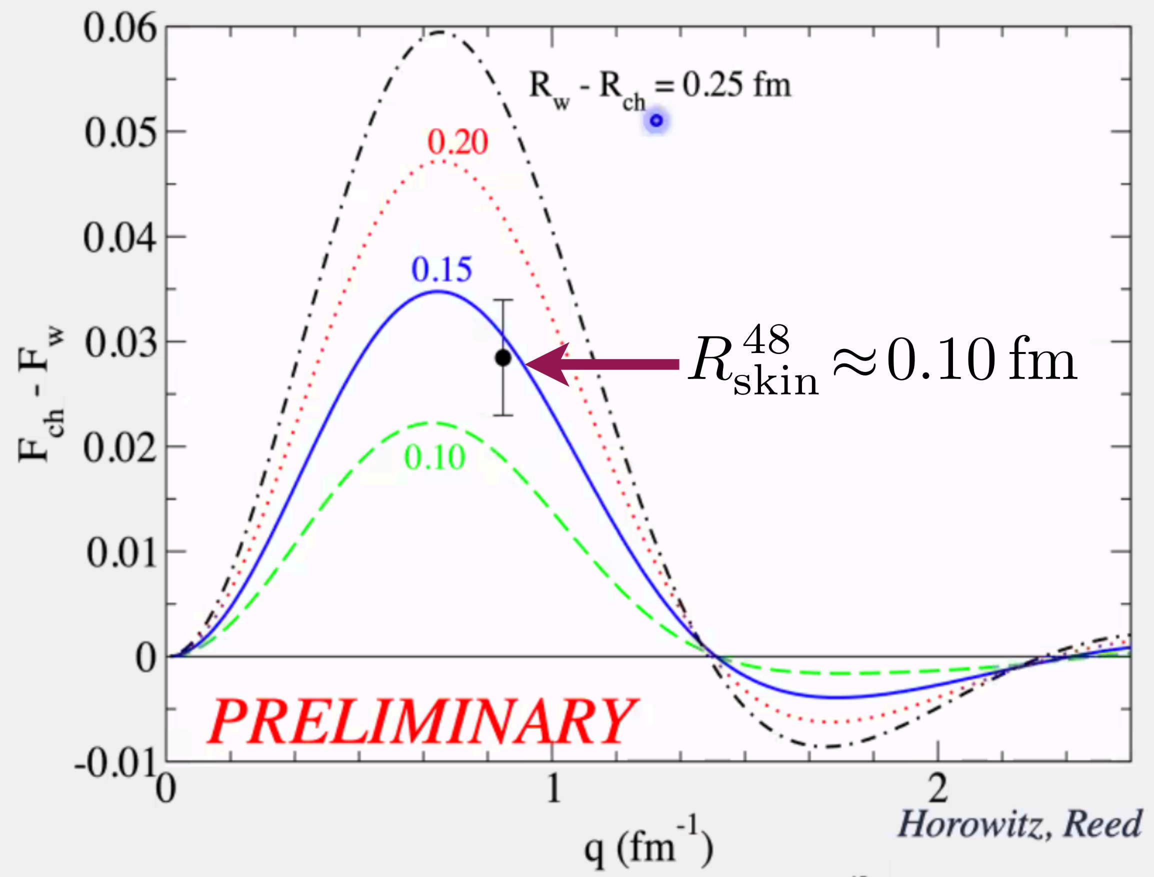


Fig 2: Charge form factor minus weak form factor for ^{48}Ca as a function of momentum transfer. The curves are for one family of models with the indicted R_{Wskin} = weak minus charge rms radii. The error bar shows the CREX result.

Old theory graph

Eyeballing - Coupled cluster thin - DOM thick

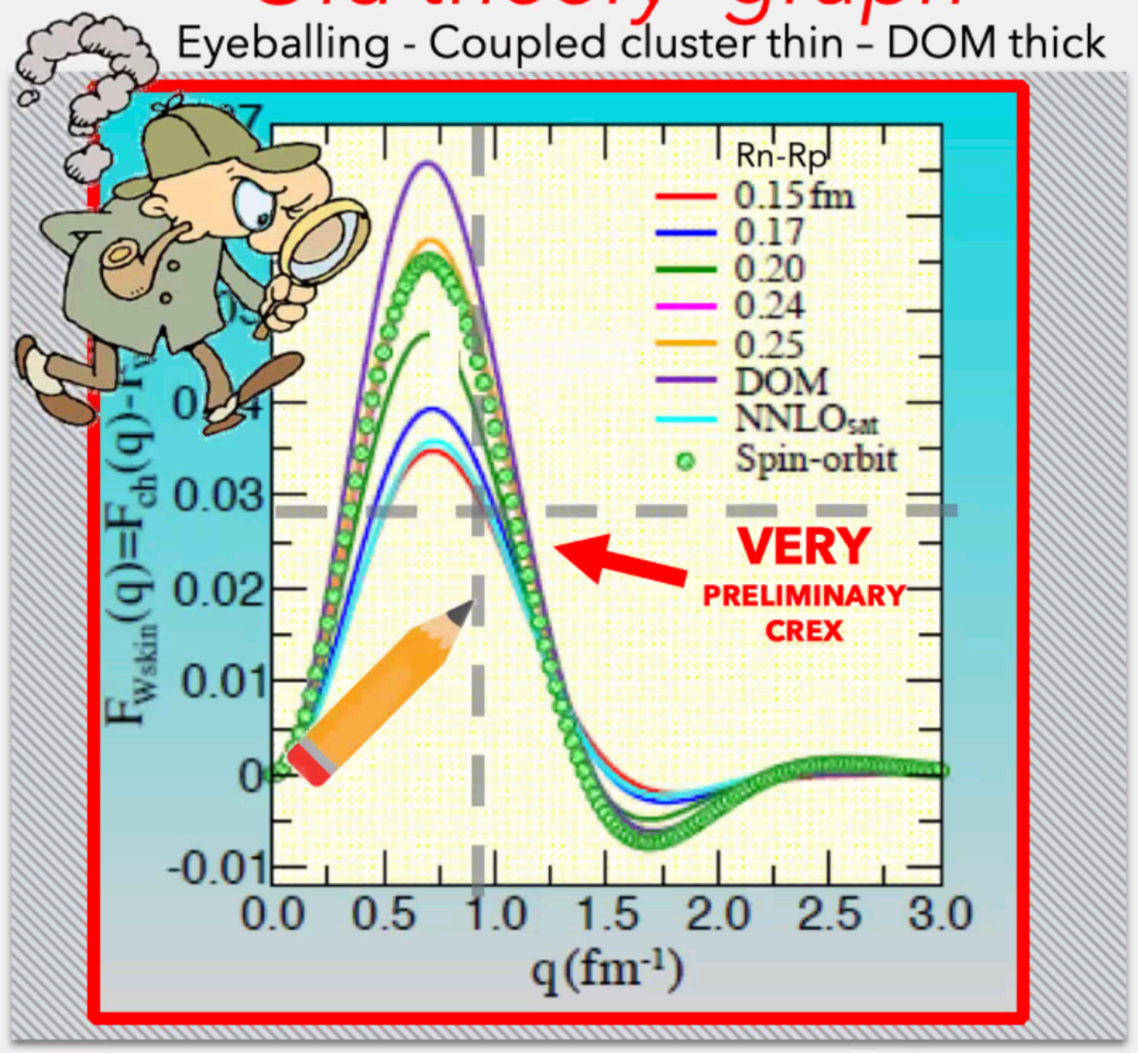
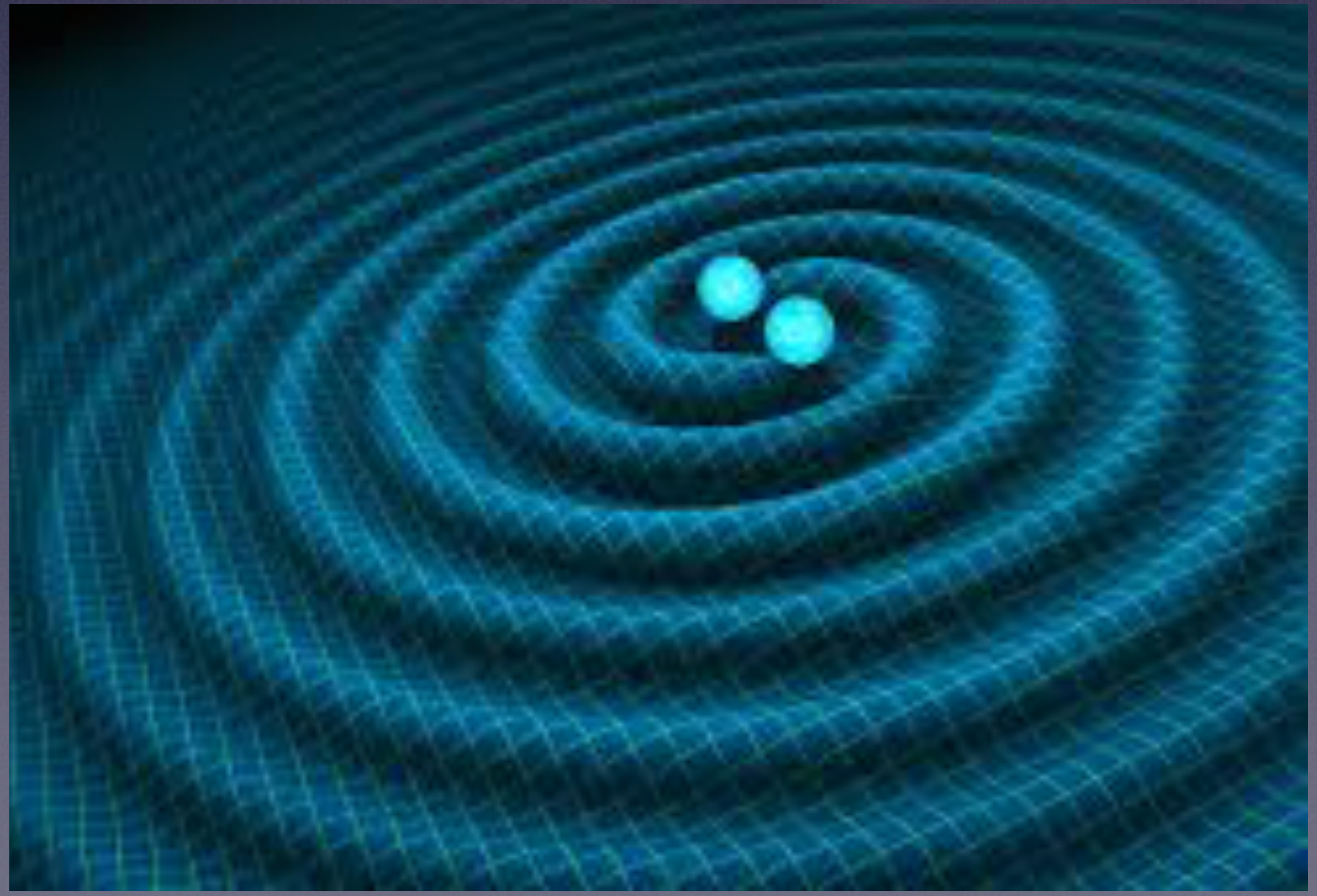


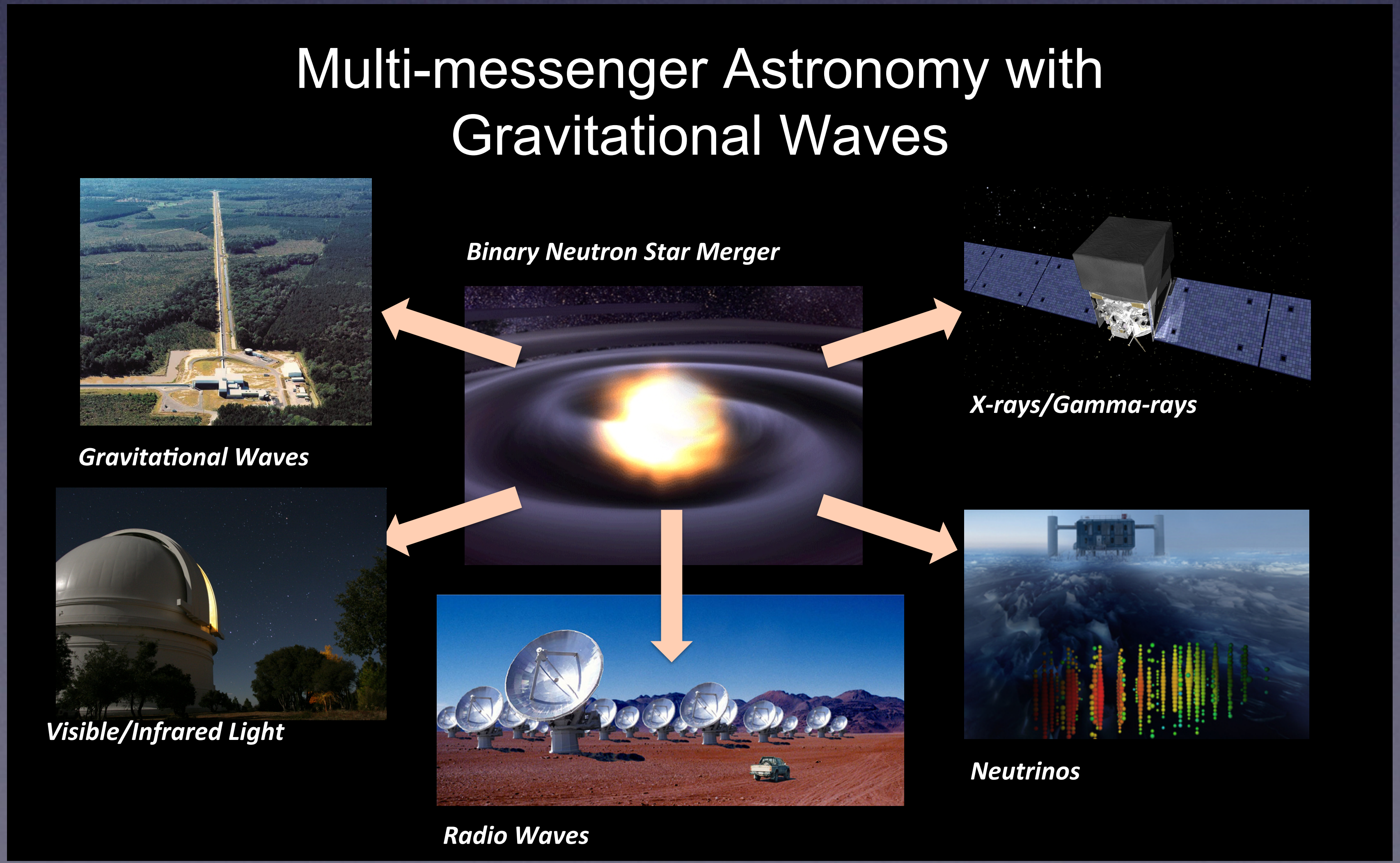
Figure taken from J.Mammei CevNS 2019 talk (Jorge Piekarewicz plot), shows various curves for a family of R_{nskin} = Rn-Rp values. Also DOM and NNLO (coupled cluster). Warning: theories shown may (or may not) require further SO correction.

Conclusions: We have entered the golden era of neutron-star physics

- Astrophysics: What is the minimum mass of a black hole?
- C.Matter Physics: Existence of Coulomb-Frustrated Nuclear Pasta?
- General Relativity: Can BNS mergers constrain stellar radii?
- Nuclear Physics: What is the EOS of neutron-rich matter?
- Particle Physics: What exotic phases inhabit the dense core?
- Machine Learning: Extrapolation to where no man has gone before?

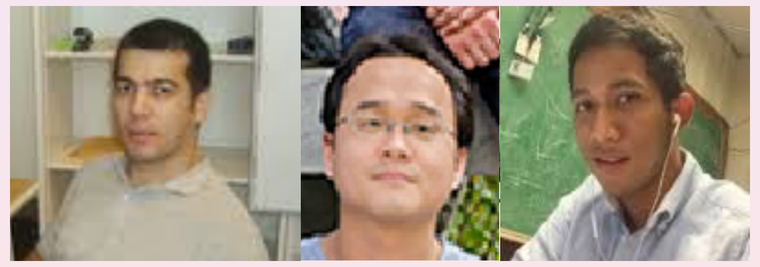
Neutron Stars are the natural meeting place for interdisciplinary, fundamental, and fascinating physics!





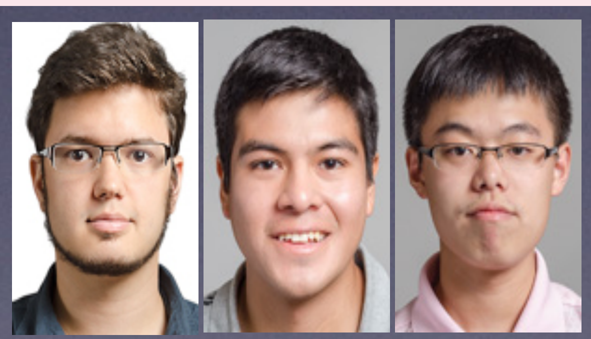
My FSU Collaborators

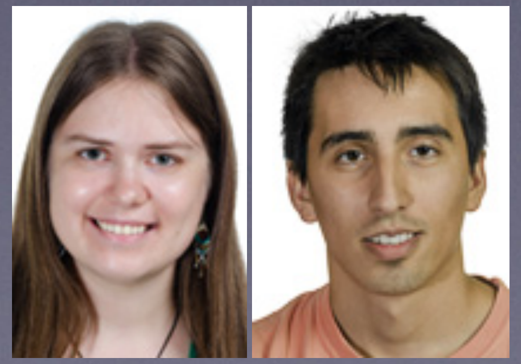
- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- **Raditya Utama**



My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)





The "Old" Generation

- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**

The New Generation

- **Amy Anderson**
- **Marc Salinas**