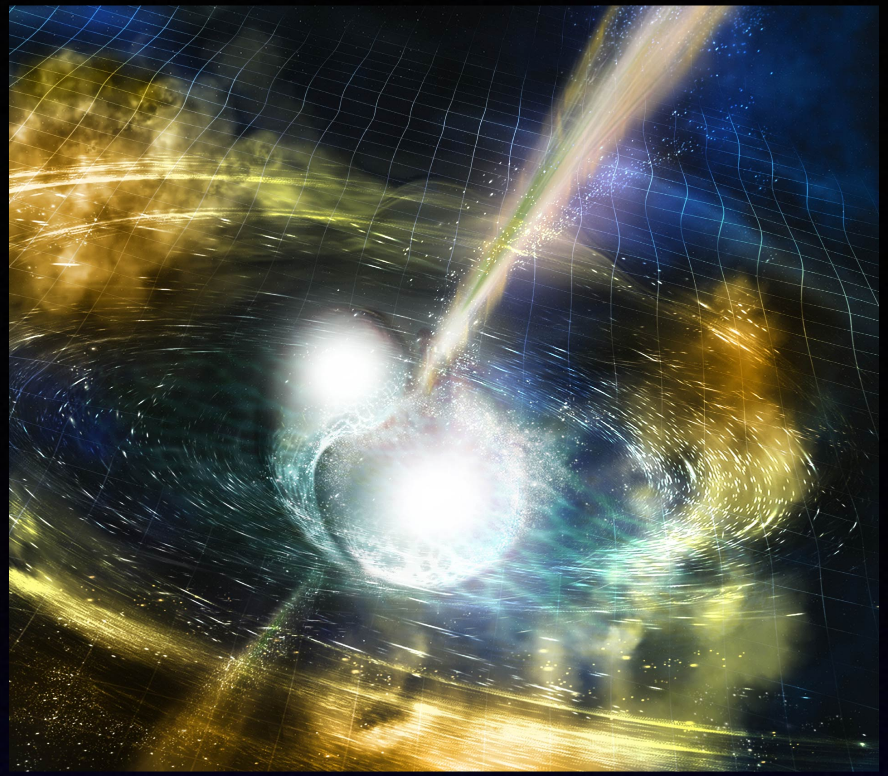
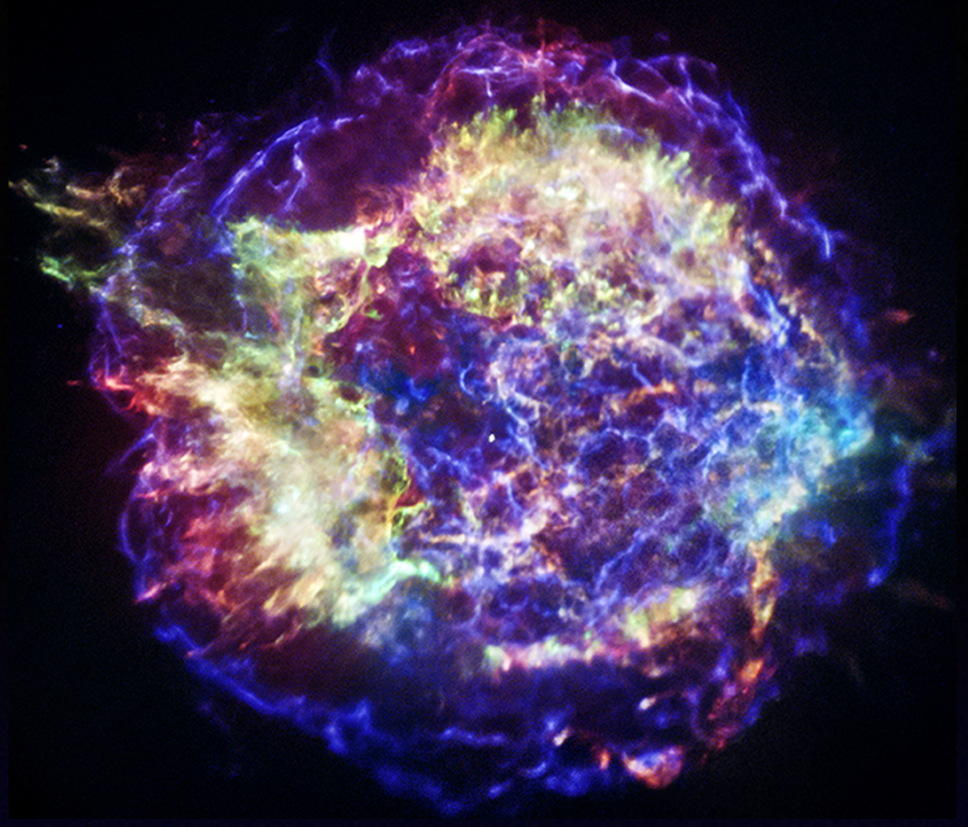
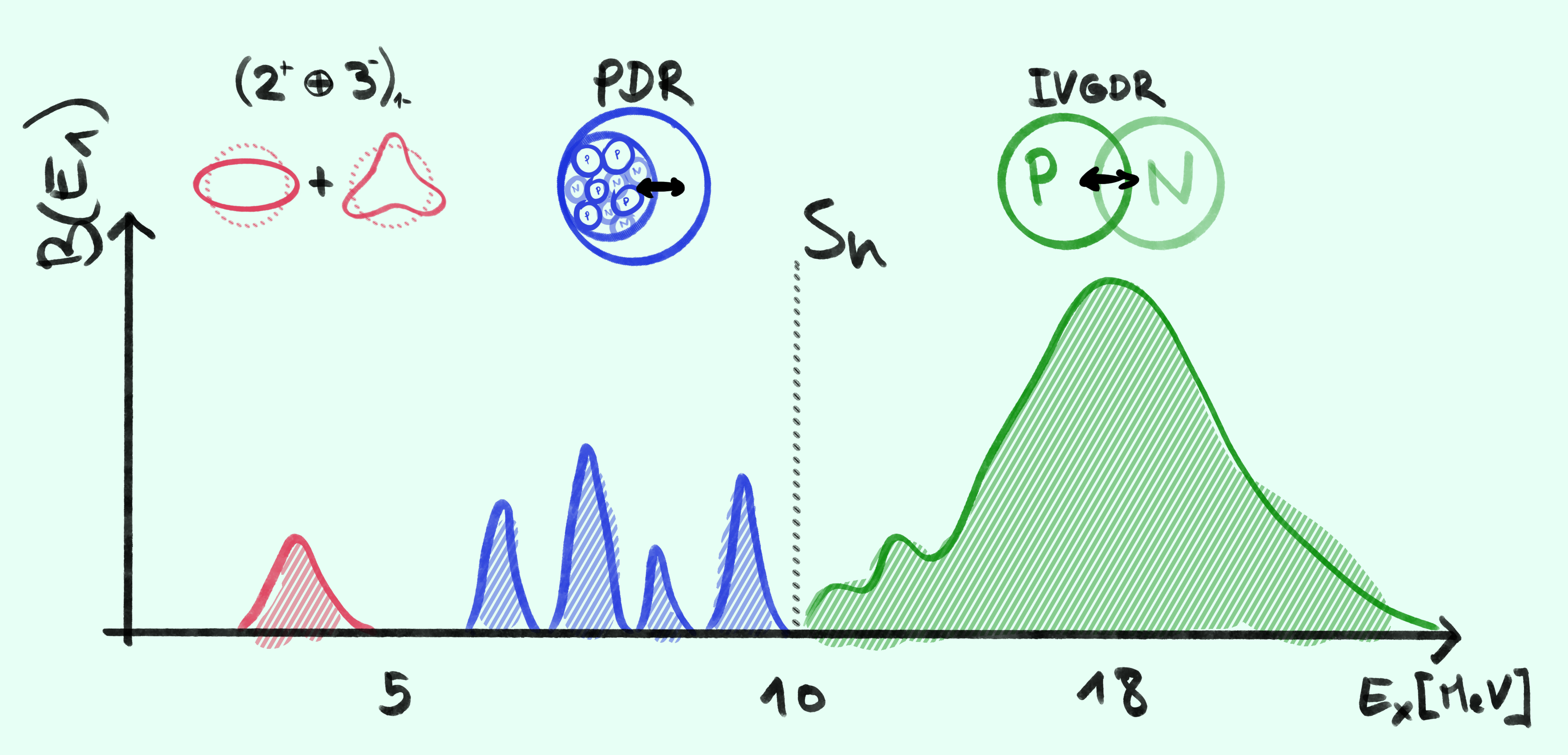


Nuclear Astrophysics in the Multimessenger Era



Gamma Factory Workshop

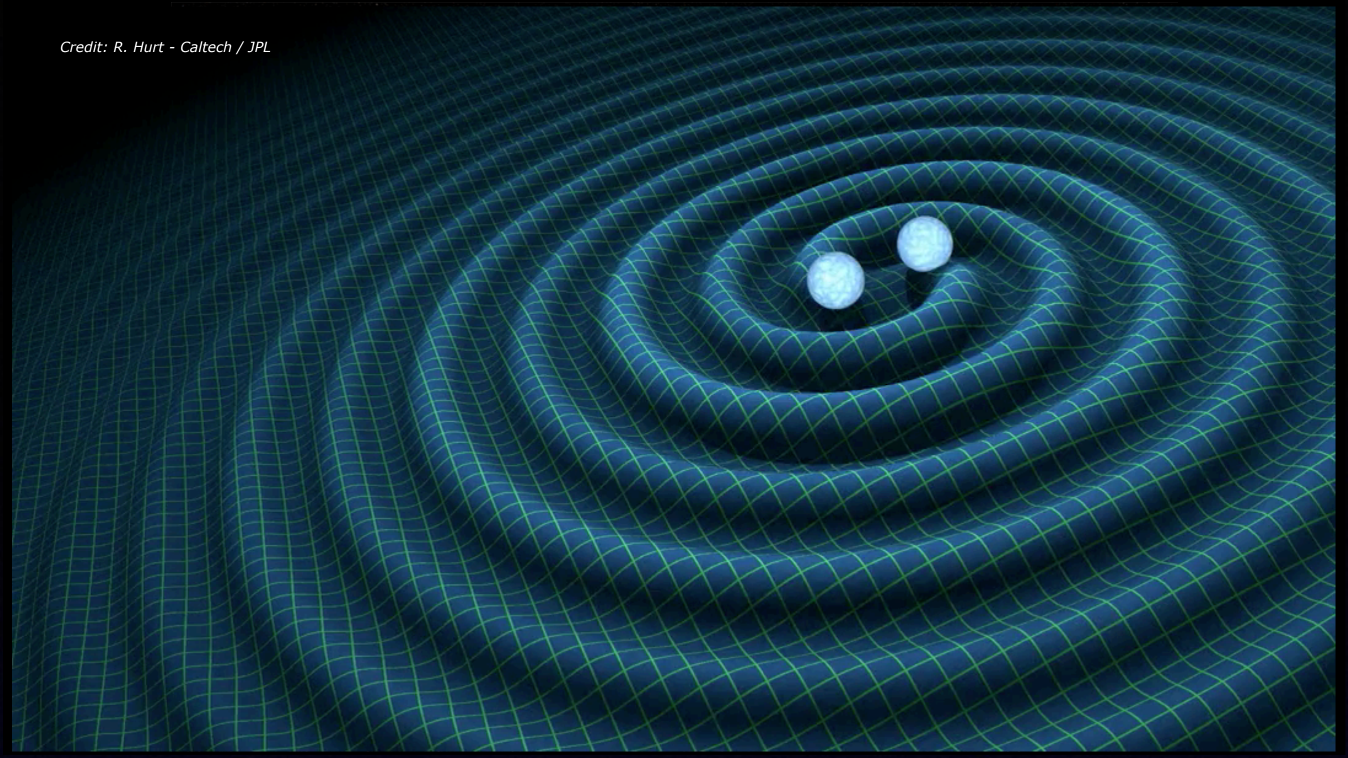
(November 30 — December 4, 2020)

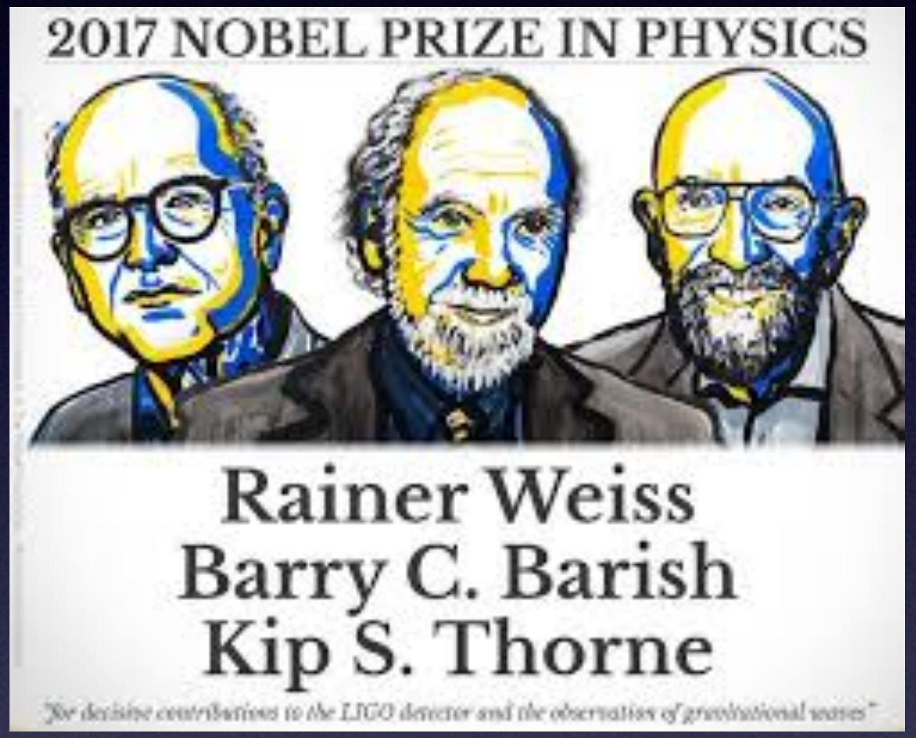


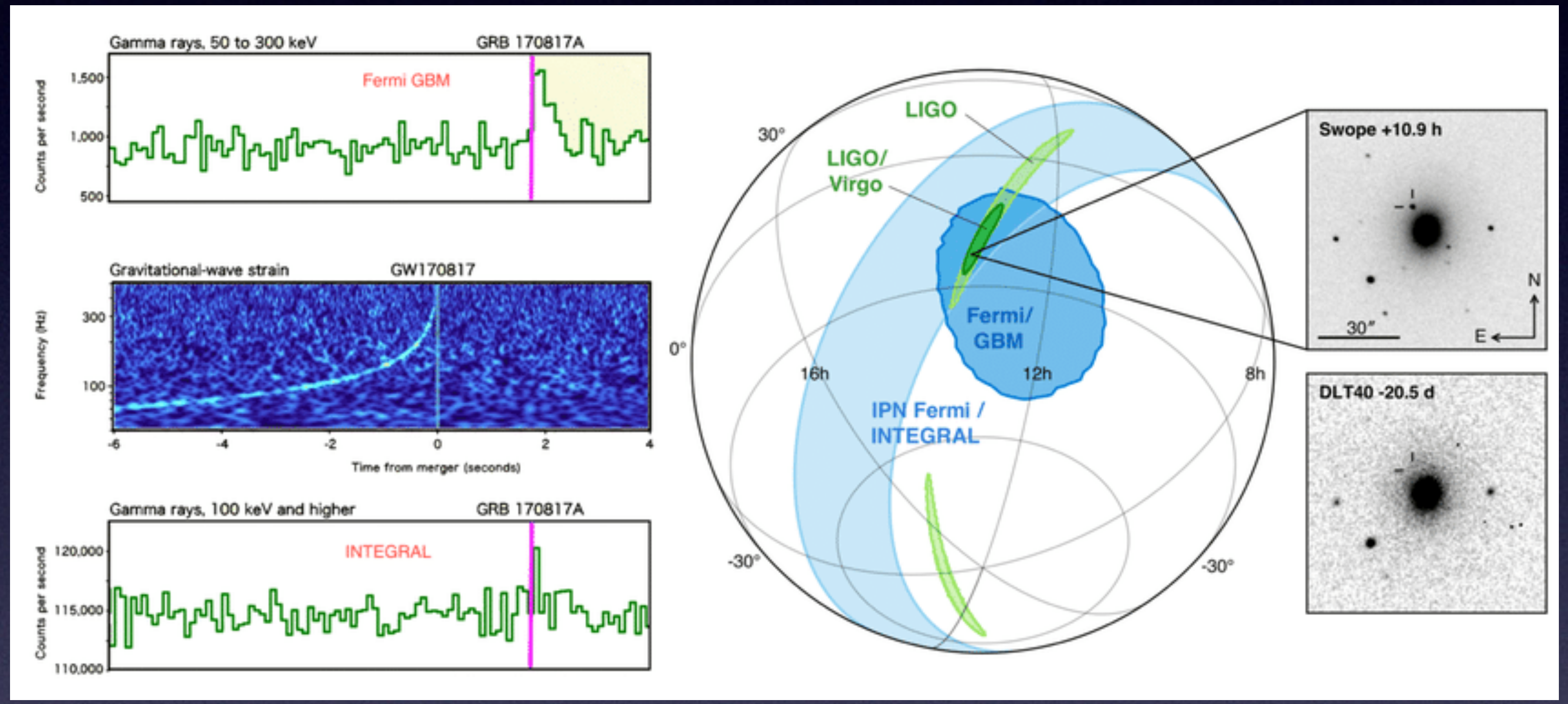
U.S. DEPARTMENT OF ENERGY | Office of Science

FLORIDA STATE UNIVERSITY VIRES ARTES MORES 1851

The Beginning of the Multimessenger Era

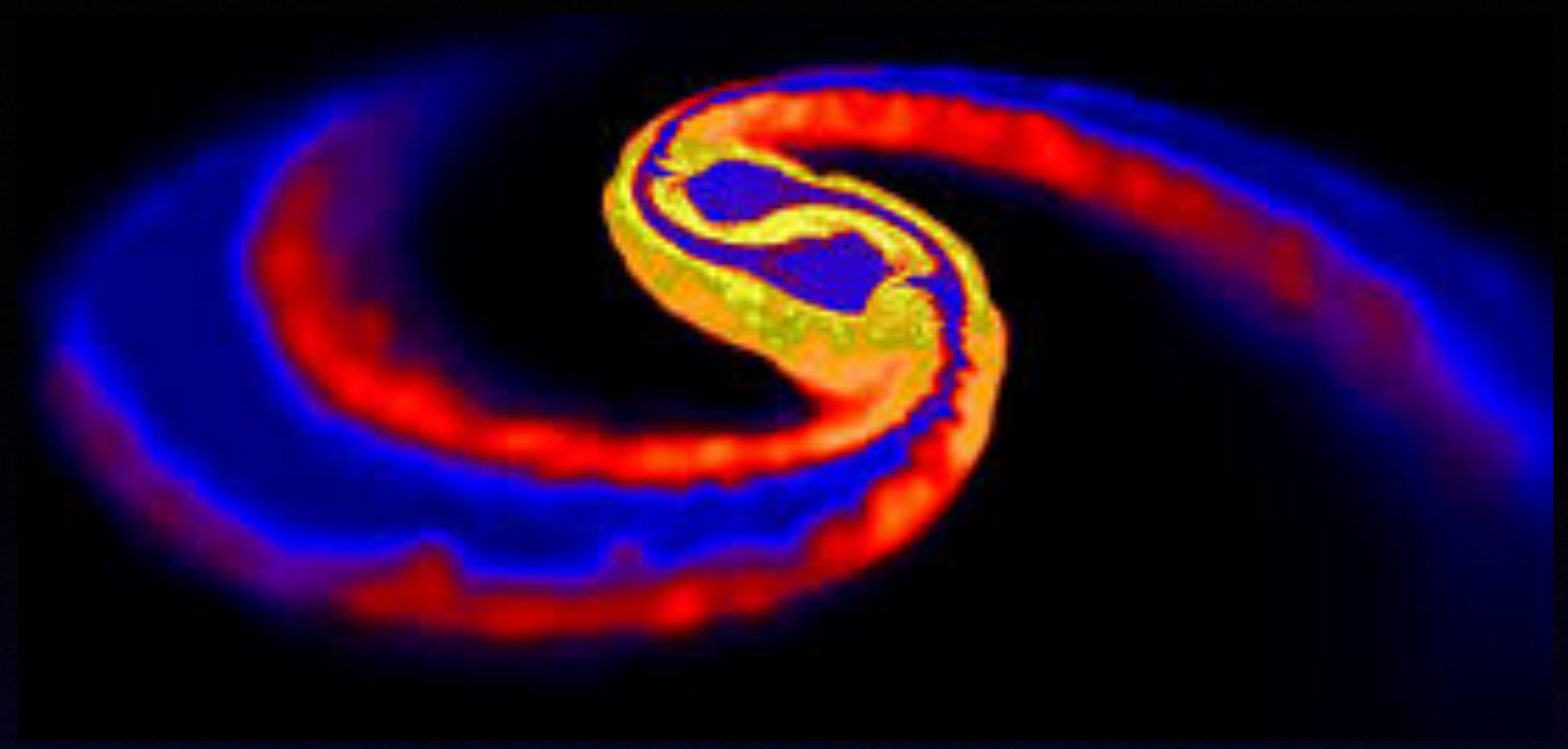




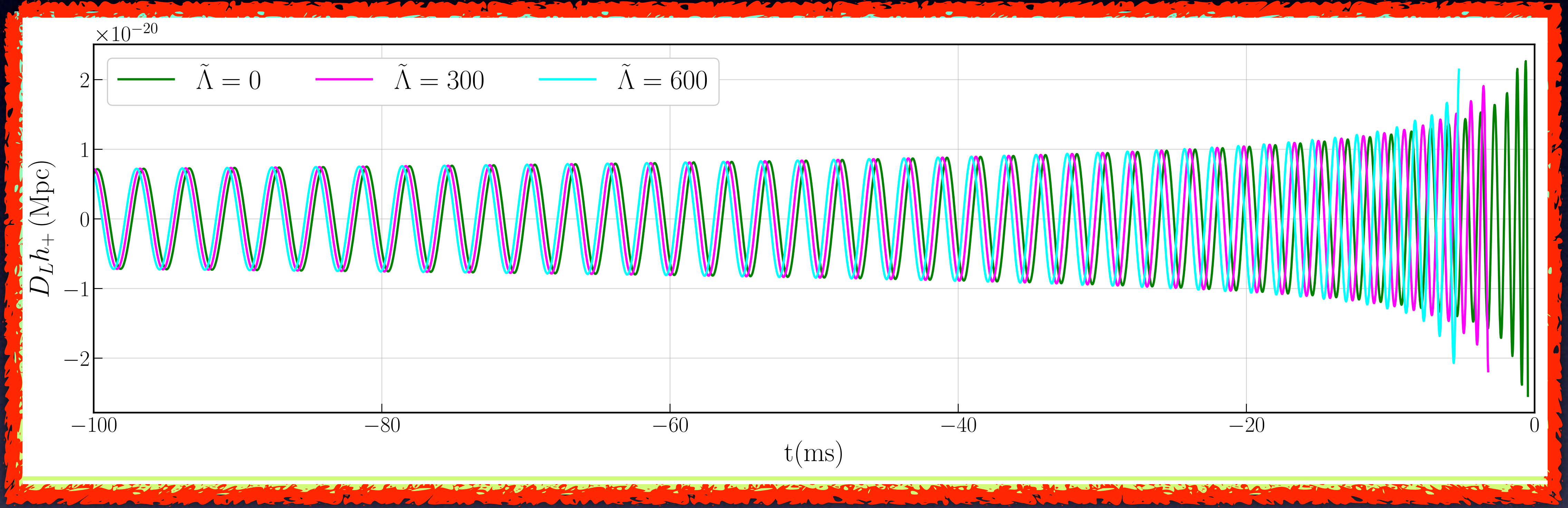


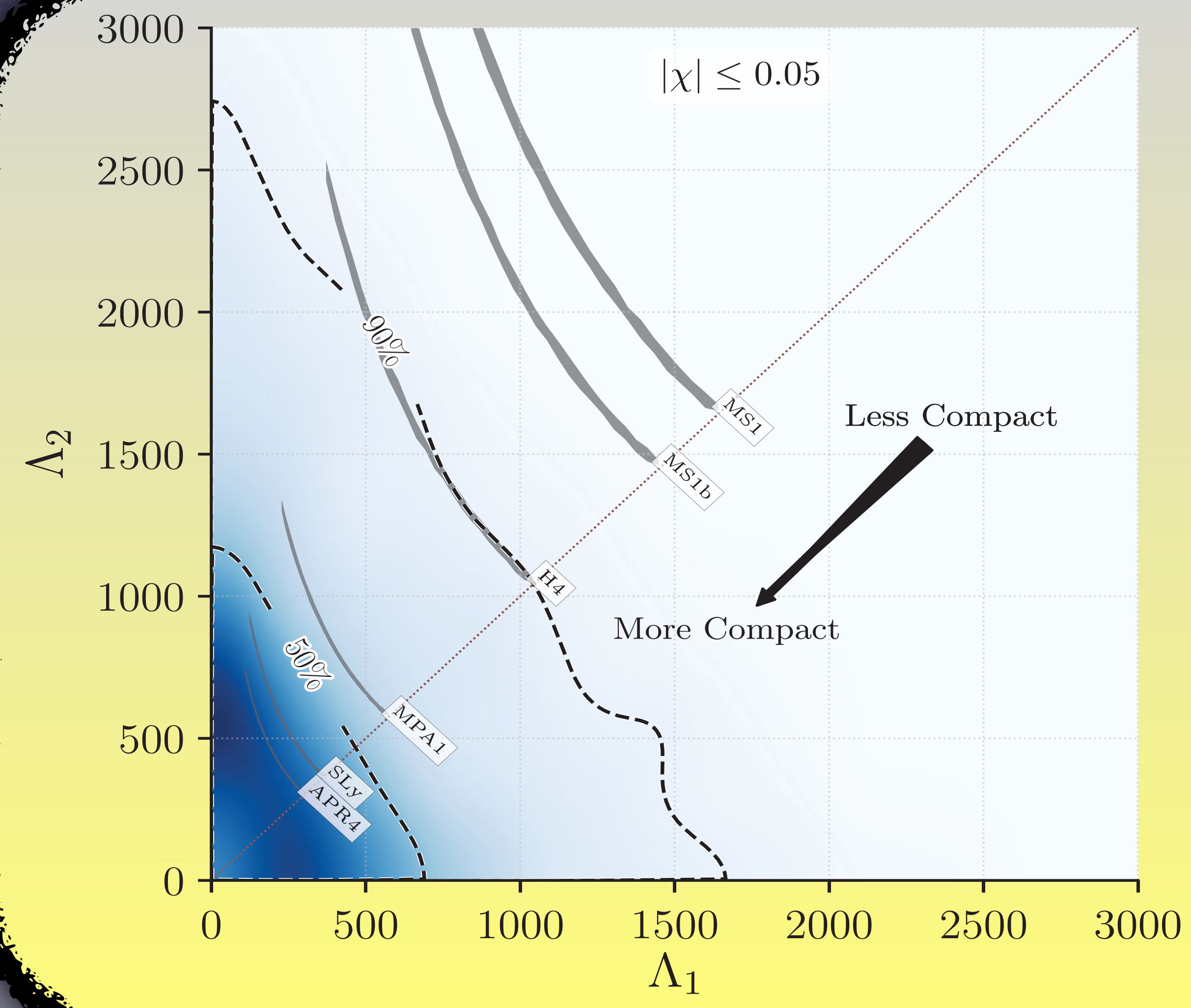
GW170817

Tidal Deformability and NS Radius



- **Electric Polarizability:**
  - Electric field induced a polarization of charge
  - A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$
- **Tidal Polarizability:**
  - Tidal field induces a polarization of mass
  - A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$





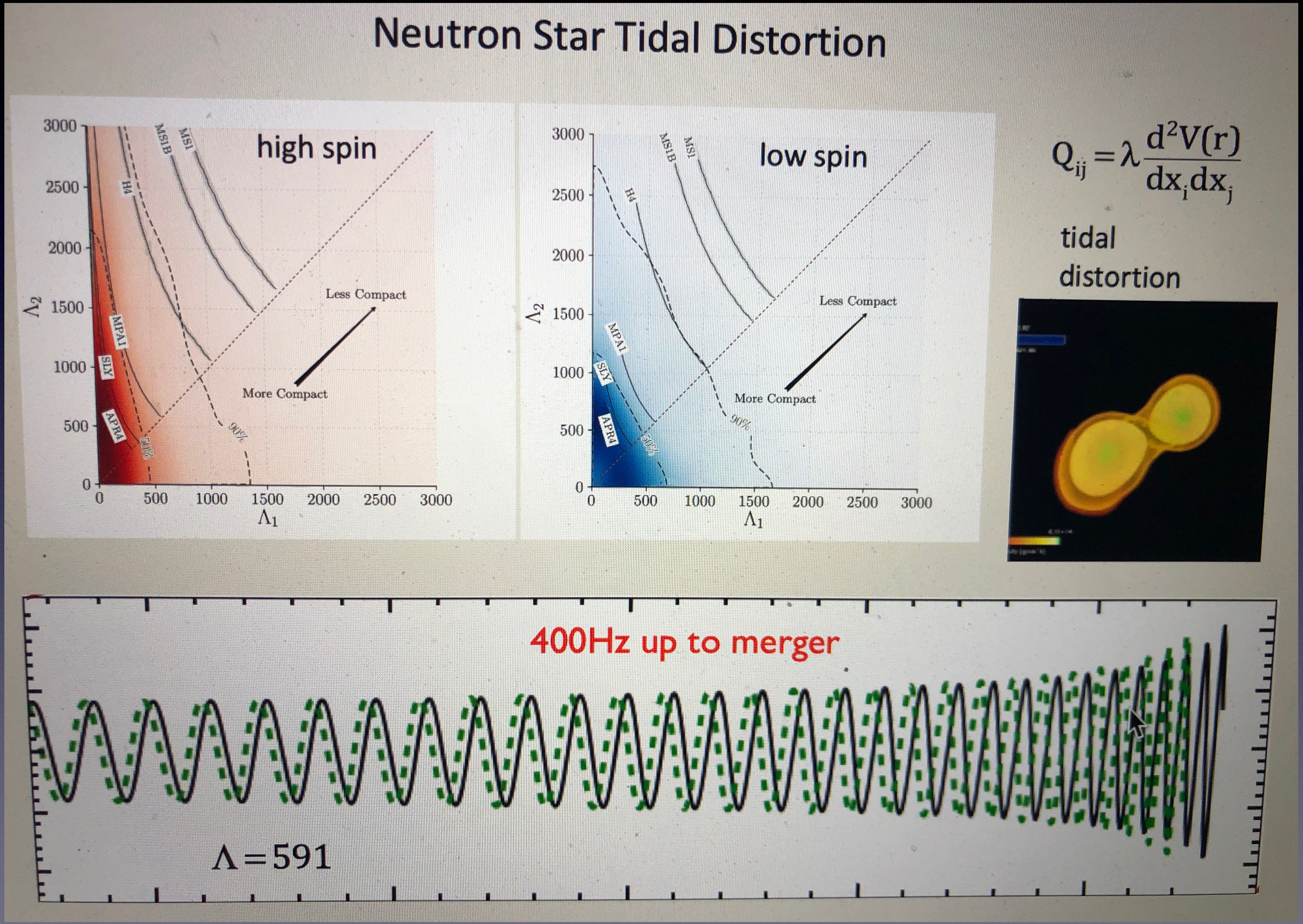
GW170817 rules out very large neutron star radii!

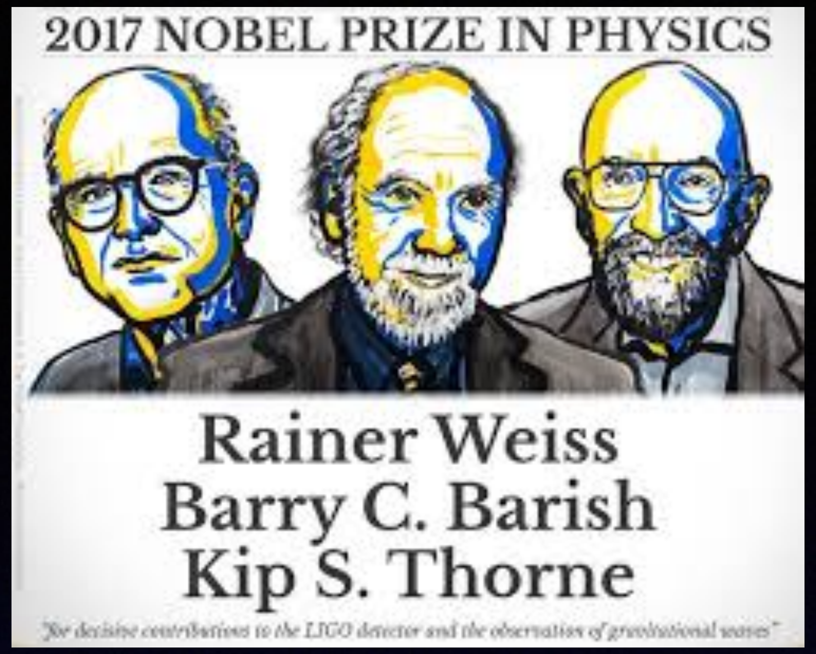
Neutron Stars must be compact

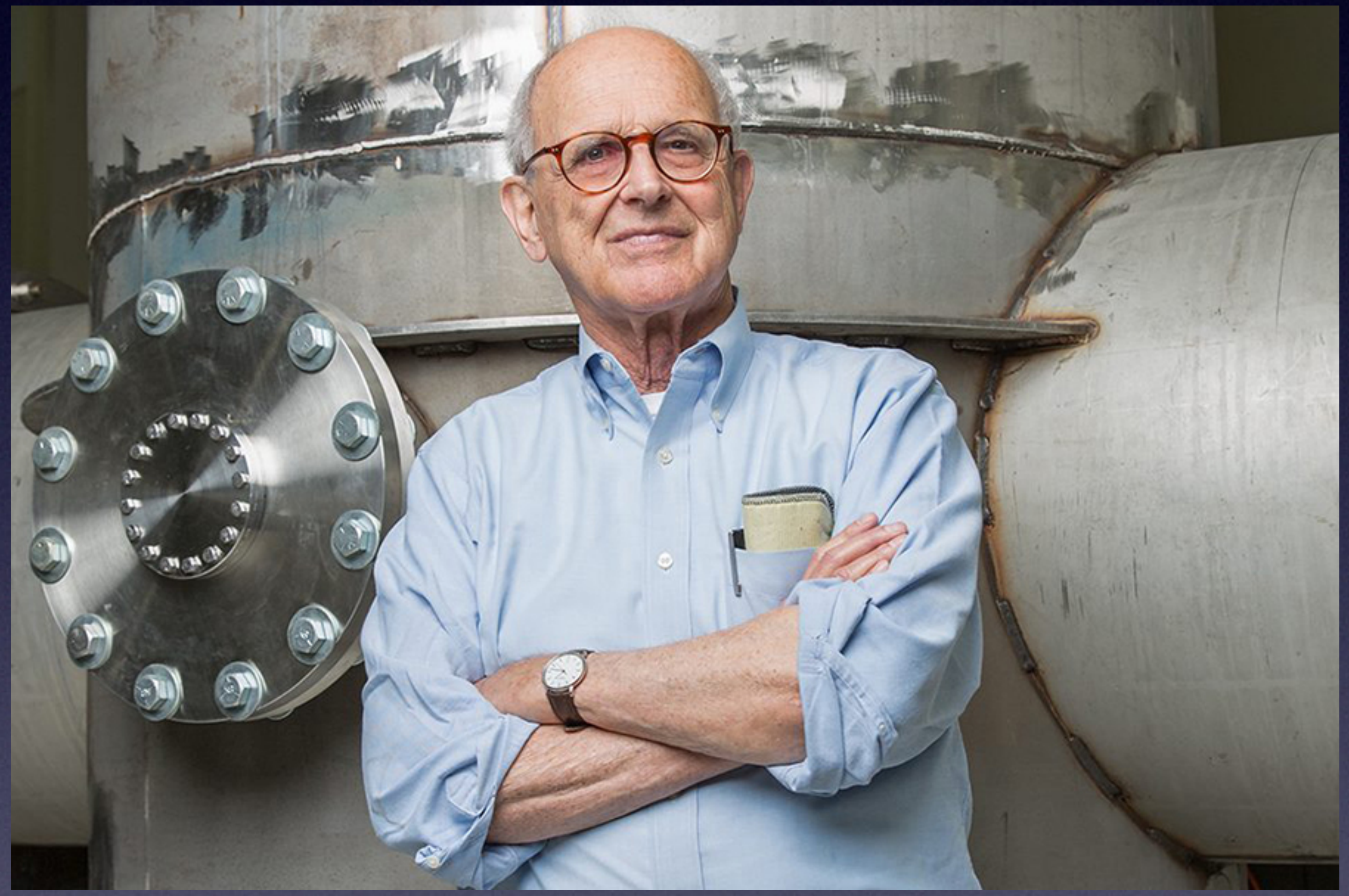
$$\Lambda = k_2 \left(\frac{c^2 R}{2GM}\right)^5 = k_2 \left(\frac{R}{R_s}\right)^5$$

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation

Tidal Deformability and NS Radius







From the 2020 Dirac Lectures

Florida State University

October, 2020

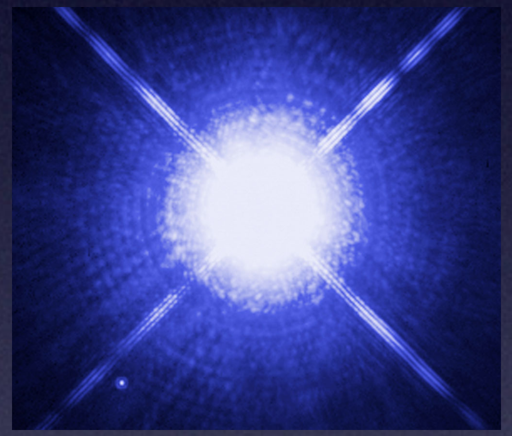
The Equation of State of Neutron-Rich Matter

Equation of state: textbook examples

- Non-interacting classical gas
  high temperature, low density limit

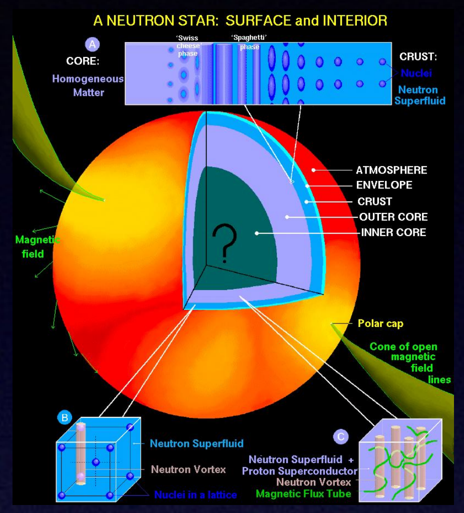
$$P(n,T) = nk_{\mathrm{B}}T \leftrightarrow P(\mathcal{E}) = \frac{2}{3}\mathcal{E}$$

- Non-interacting (UR) quantum gas
  high density, low temperature limit

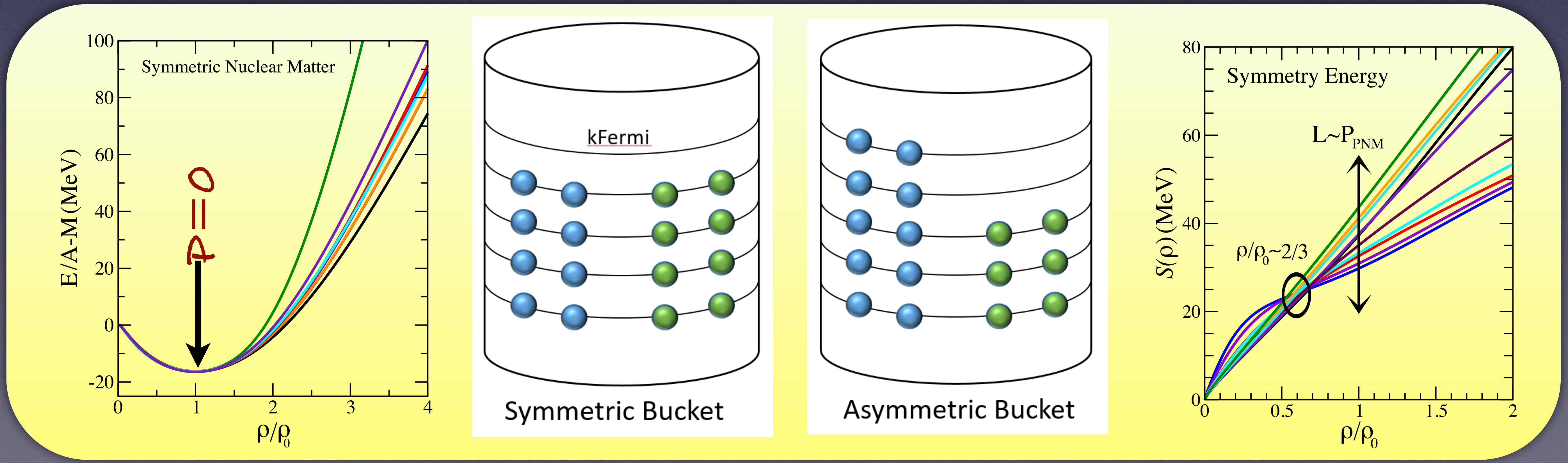


$$P(n,T\!=\!0) \approx n^{4/3} \leftrightarrow P(\mathcal{E}) = \frac{1}{3}\mathcal{E}$$

Equation of state of neutron-rich matter: NON-textbook example



- Strongly-interacting quantum fluid
  high density, low temperature limit
- Two “quantum liquids” in µ-equilibrium
- Charge-neutral system (neutralizing leptons)
- Density dependence and isospin asymmetry of the EOS poorly constrained

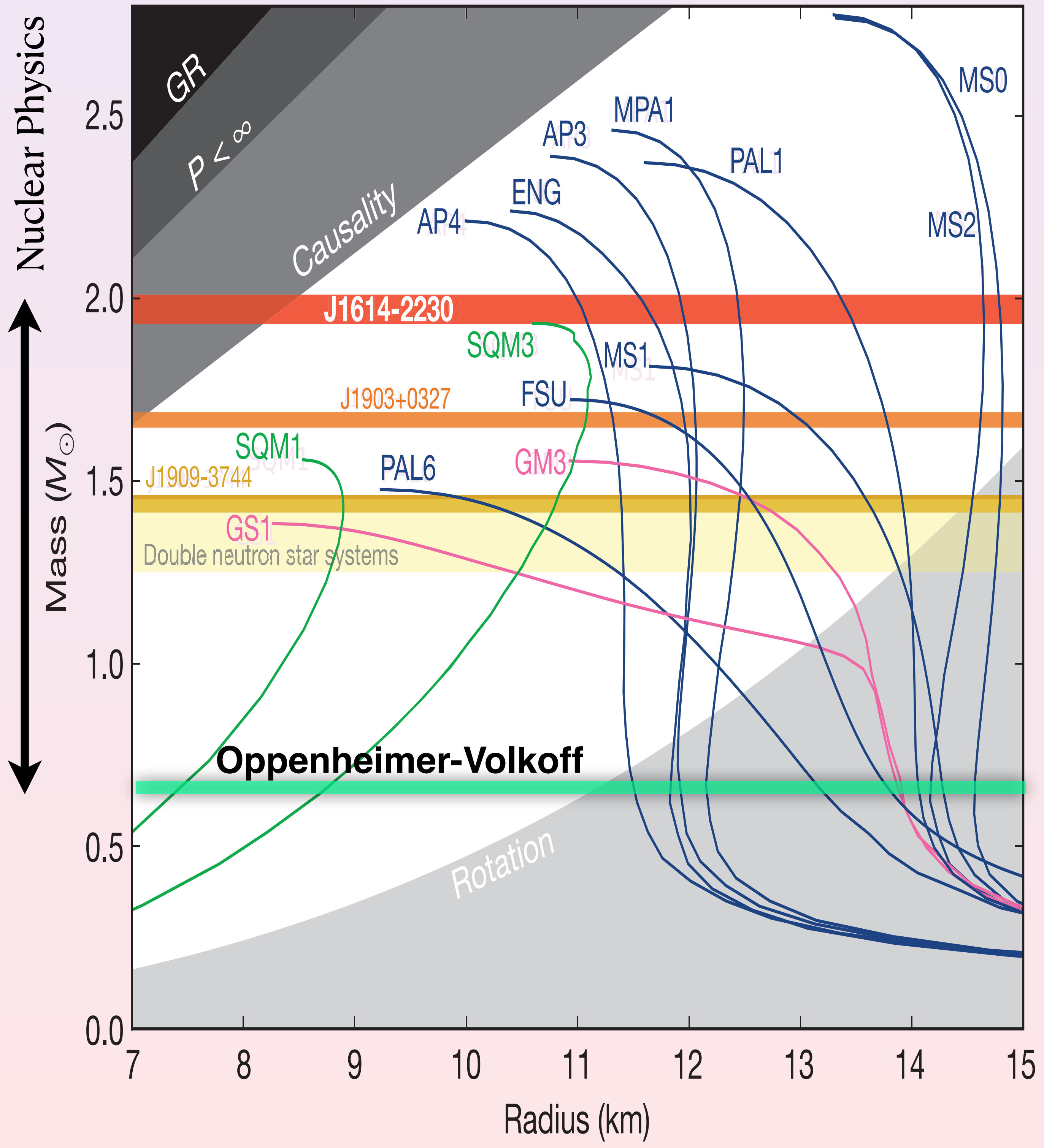


$$S(\rho_0) \approx \Big(E_{\mathrm{PNM}} - E_{\mathrm{SNM}}\Big)(\rho_0) = J$$

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

Neutron Stars: Unique Cosmic Laboratories

- Neutron stars are the remnants of massive stellar explosions
  Satisfy the TOV equations: Newtonian Gravity to Einstein Gravity
- Only Physics that the TOV equation is sensitive to: Equation of State
- Increase from 0.7 → 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

Nuclear Physics Critical

Status before GW170817

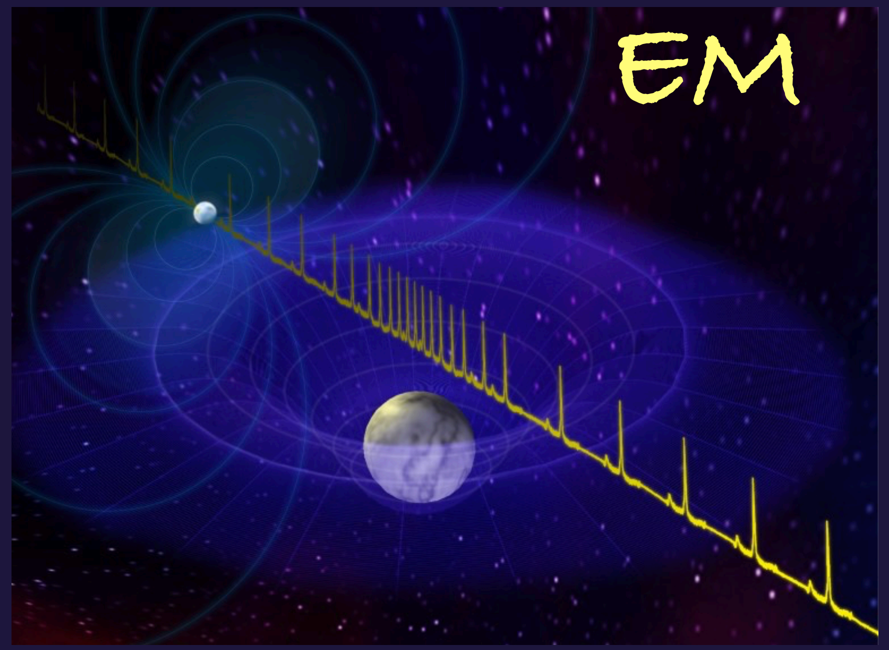
Many nuclear models that account for the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

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

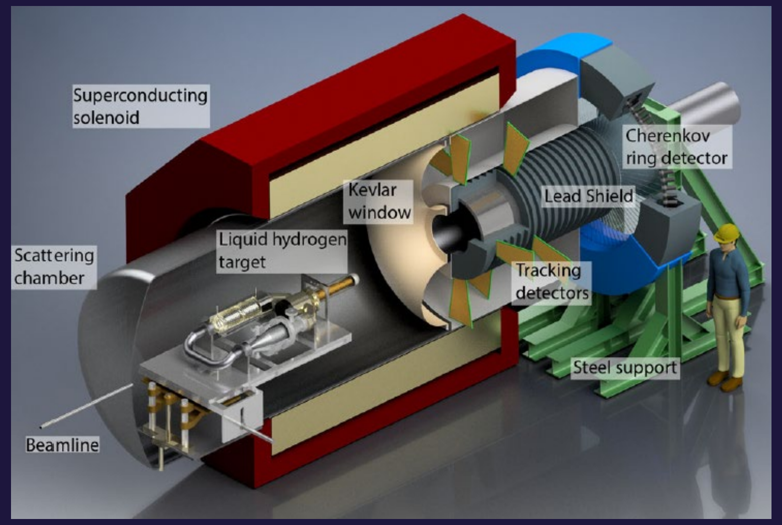
The Quest for the EOS: Status After GW170817

- *GW170817:* first detection of Gravitational Waves from a binary neutron-star merger
  (obtained a wealth of information!)
- *GW190425*: second detection of BNS
  (Hanford offline; no sky localization)
- *GW190814*: BNS or NSBH merger?
  (2.6 M_{sun} heaviest NS or lightest BH?)

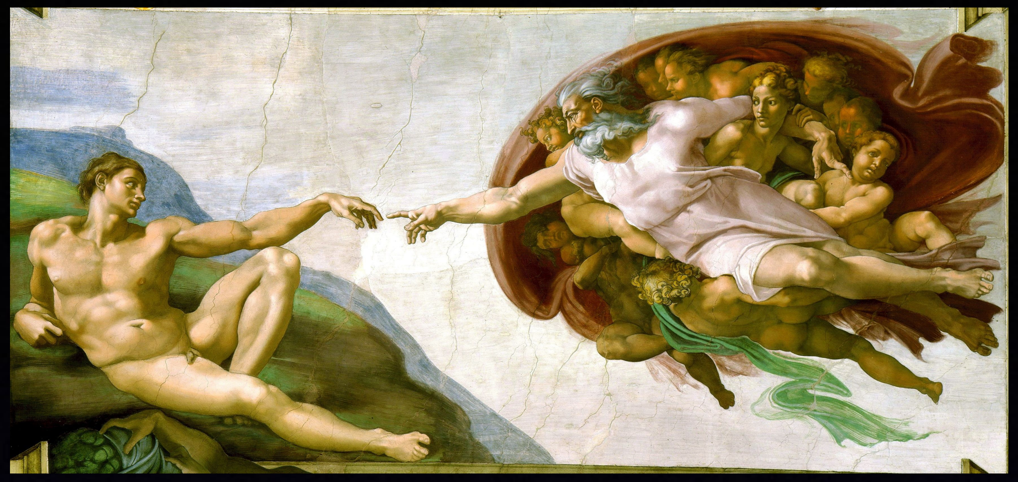
- *J0740+6620*: Most massive star (2019)
  (2.14 M_{sun} — Thankful Cromartie et al)
- *J0030+0451:* NICER aboard the ISS (2019)
  (First ever mass-radius determination)



- *PREX-II:* Neutron-skin thickness of ^{208}Pb
  (Just announced at DNP meeting!)



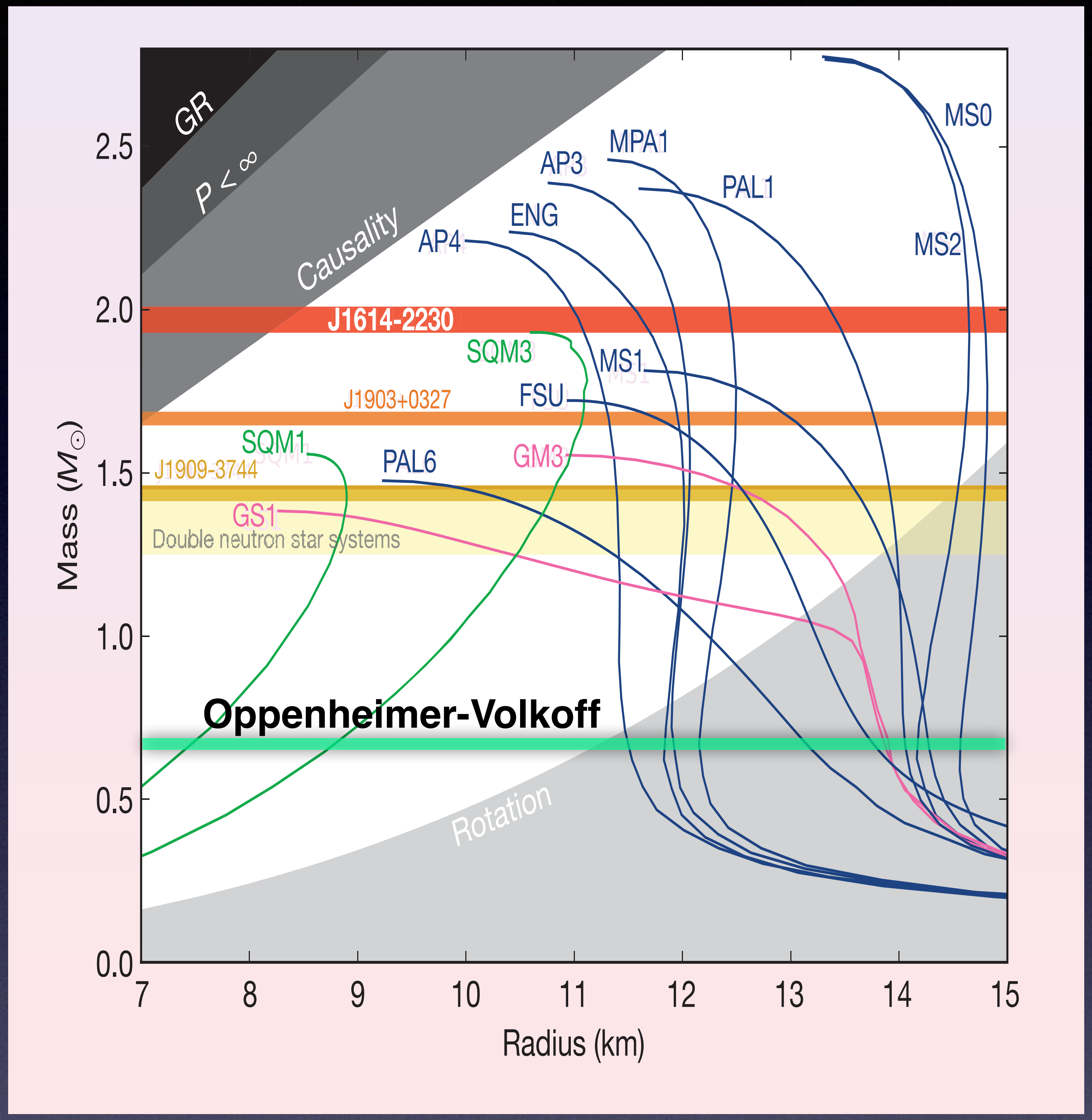
Terrestrial experiments

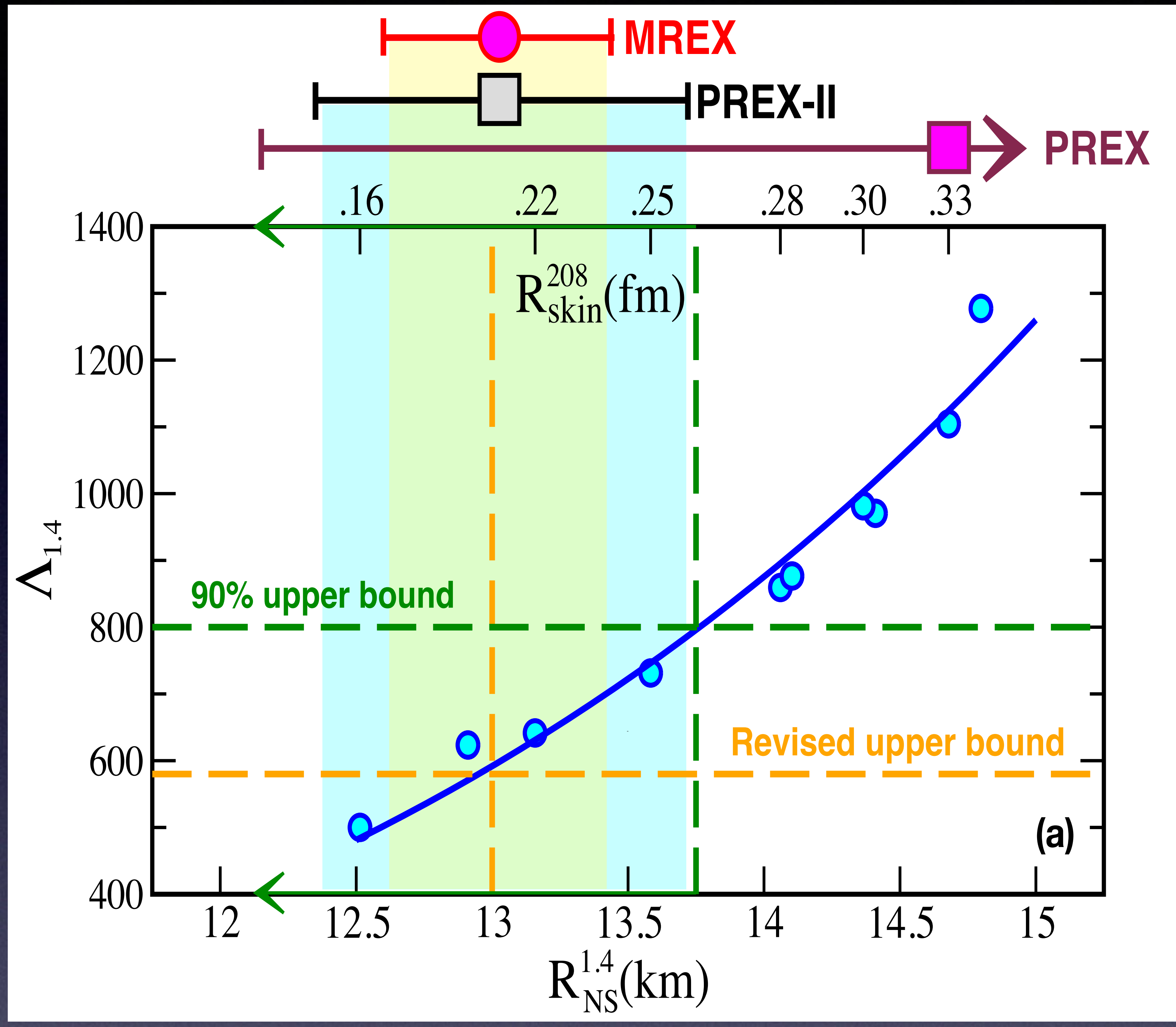


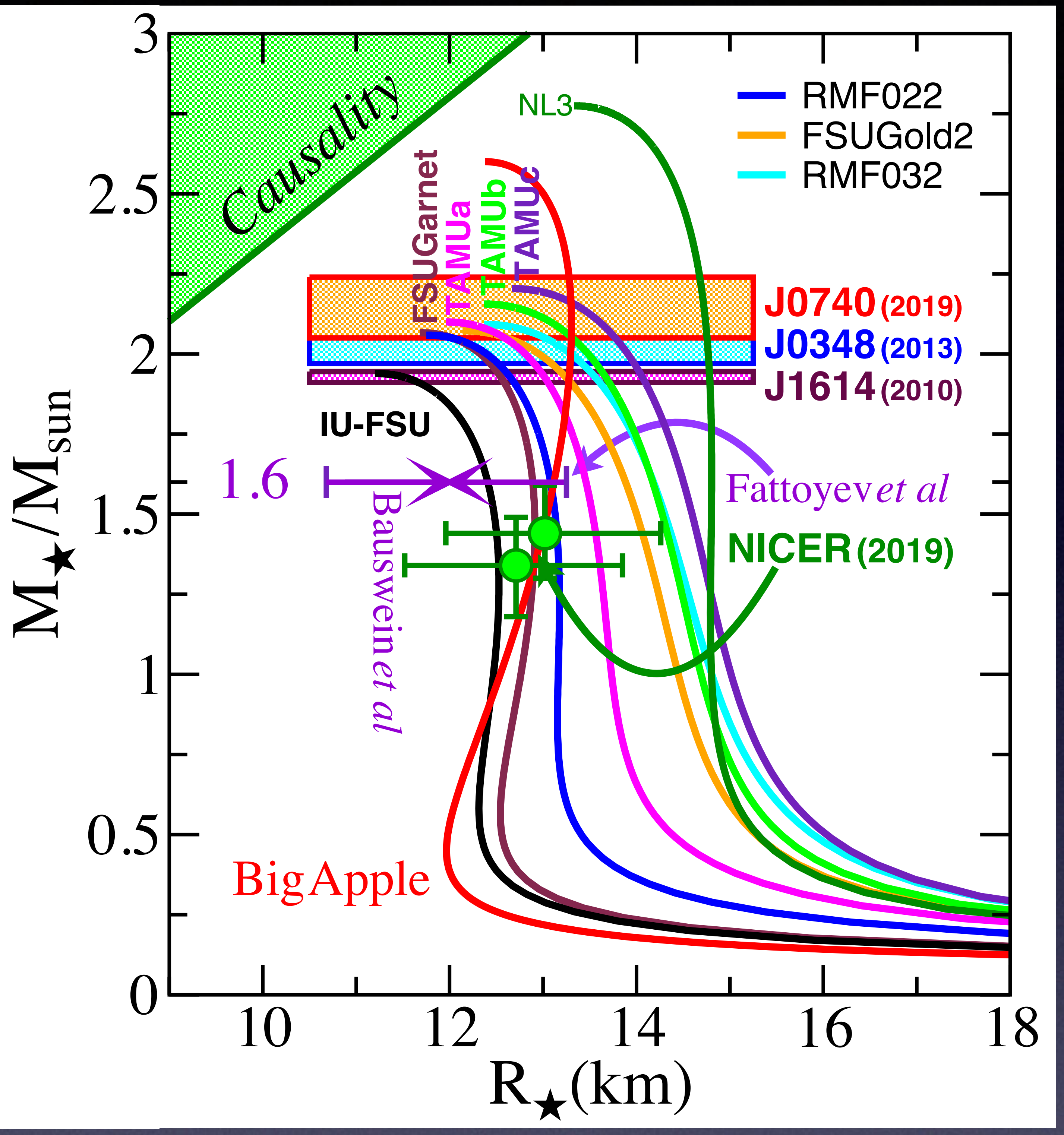
Heaven and Earth

Powerful synergy developing between terrestrial experiments, electromagnetic observations, and gravitational-wave detections:
A brand new era of Multimessenger Astronomy!

Status After GW170817: The start of a golden era





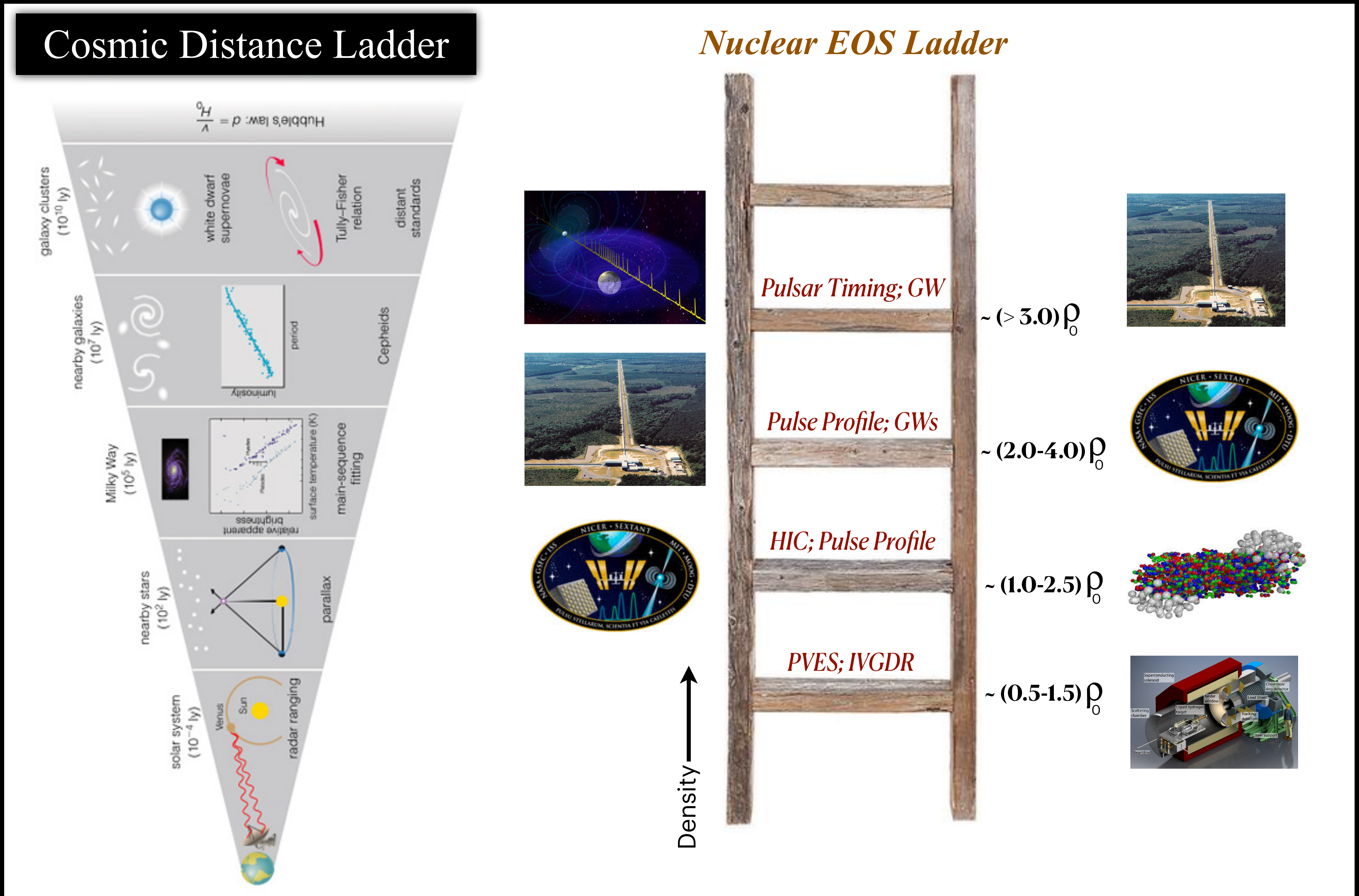


Tantalizing Possibility

- *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?)

The Nuclear Equation of State Density Ladder



Cosmic Distance Ladder

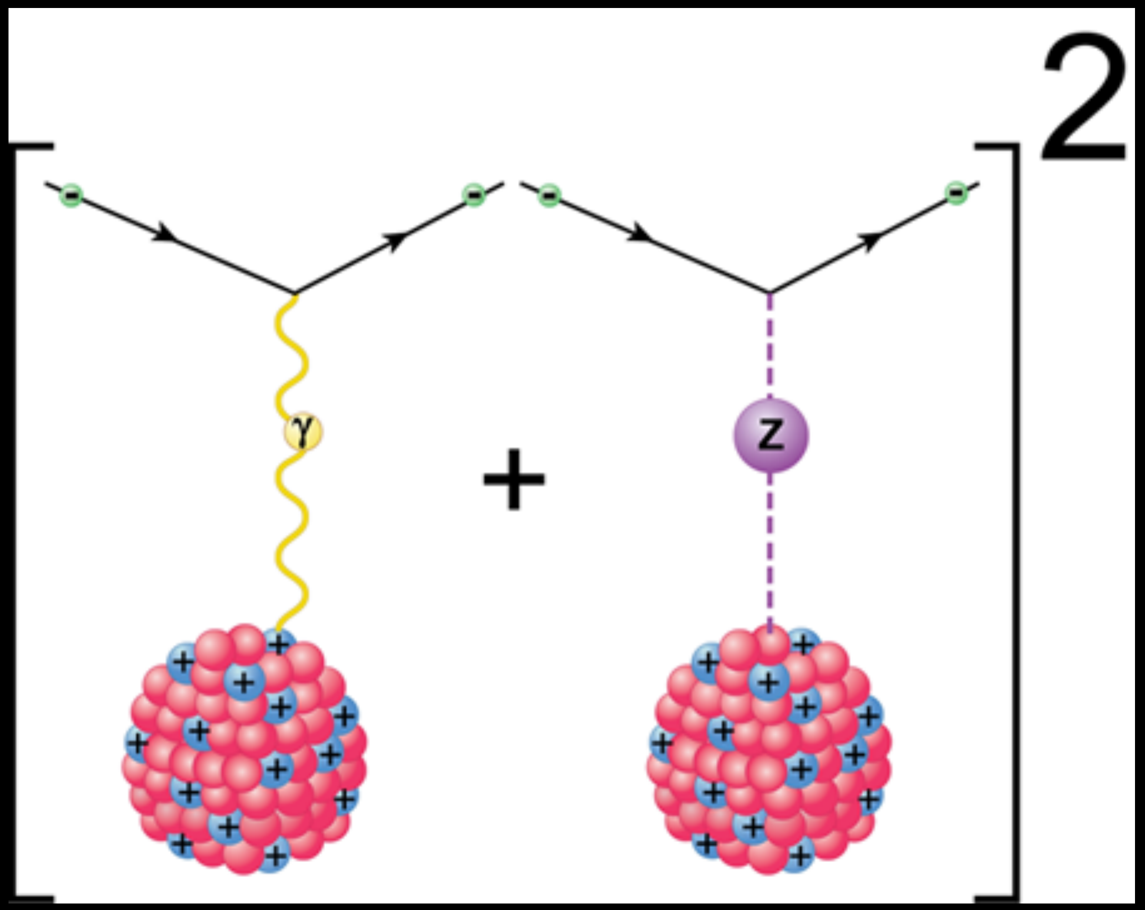
The cosmic ladder has “rungs” of objects with certain properties that let astronomers confidently measure their distance. Jumping to each subsequent rung relies on methods for measuring objects that are ever farther away, the next step often piggybacking on the previous one

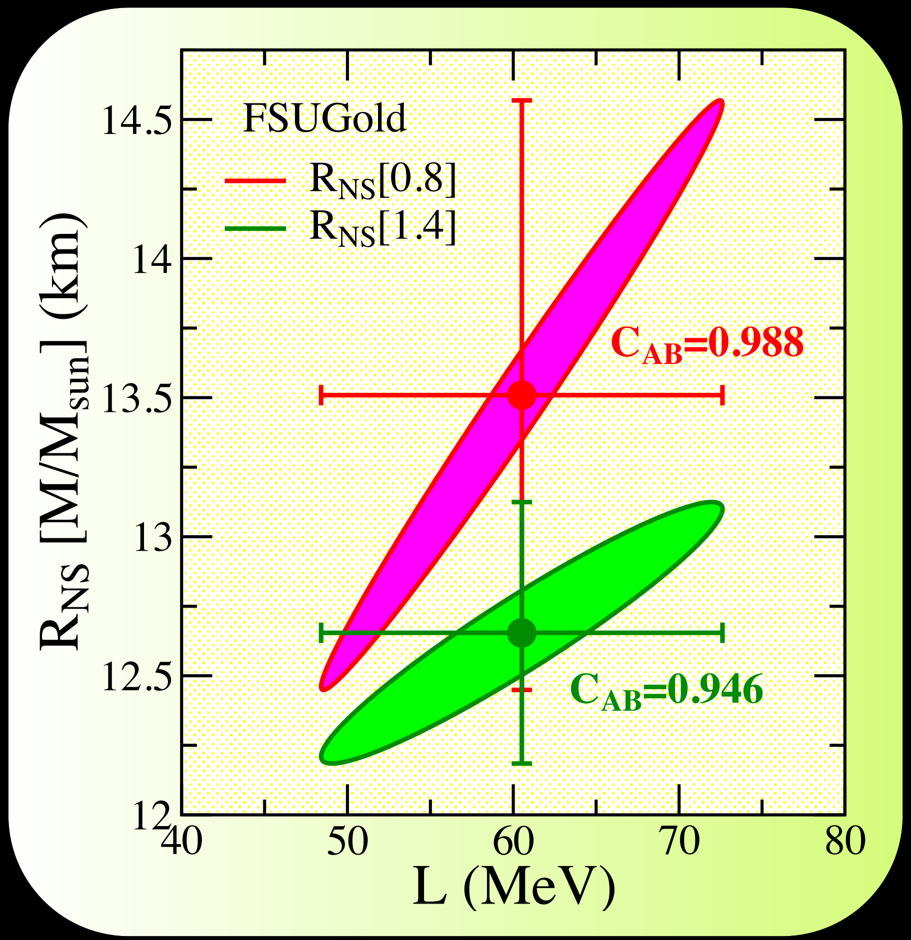
Nuclear EOS Density Ladder

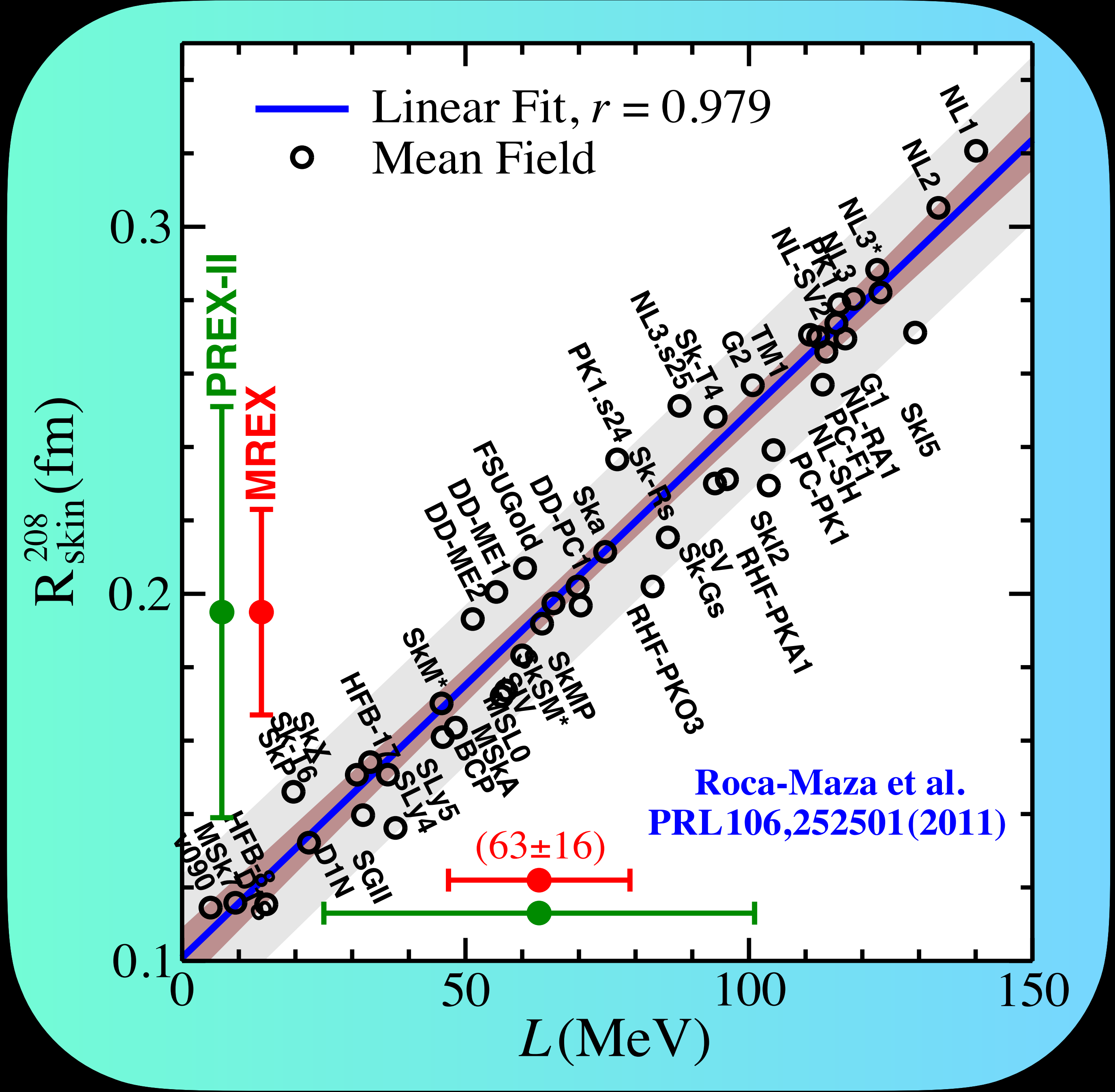
The **EOS** ladder has “rungs” of objects with certain properties that let scientists confidently measure the **EOS**. Jumping to each subsequent rung relies on methods for measuring objects that are ever **denser**, the next step often piggybacking on the previous one

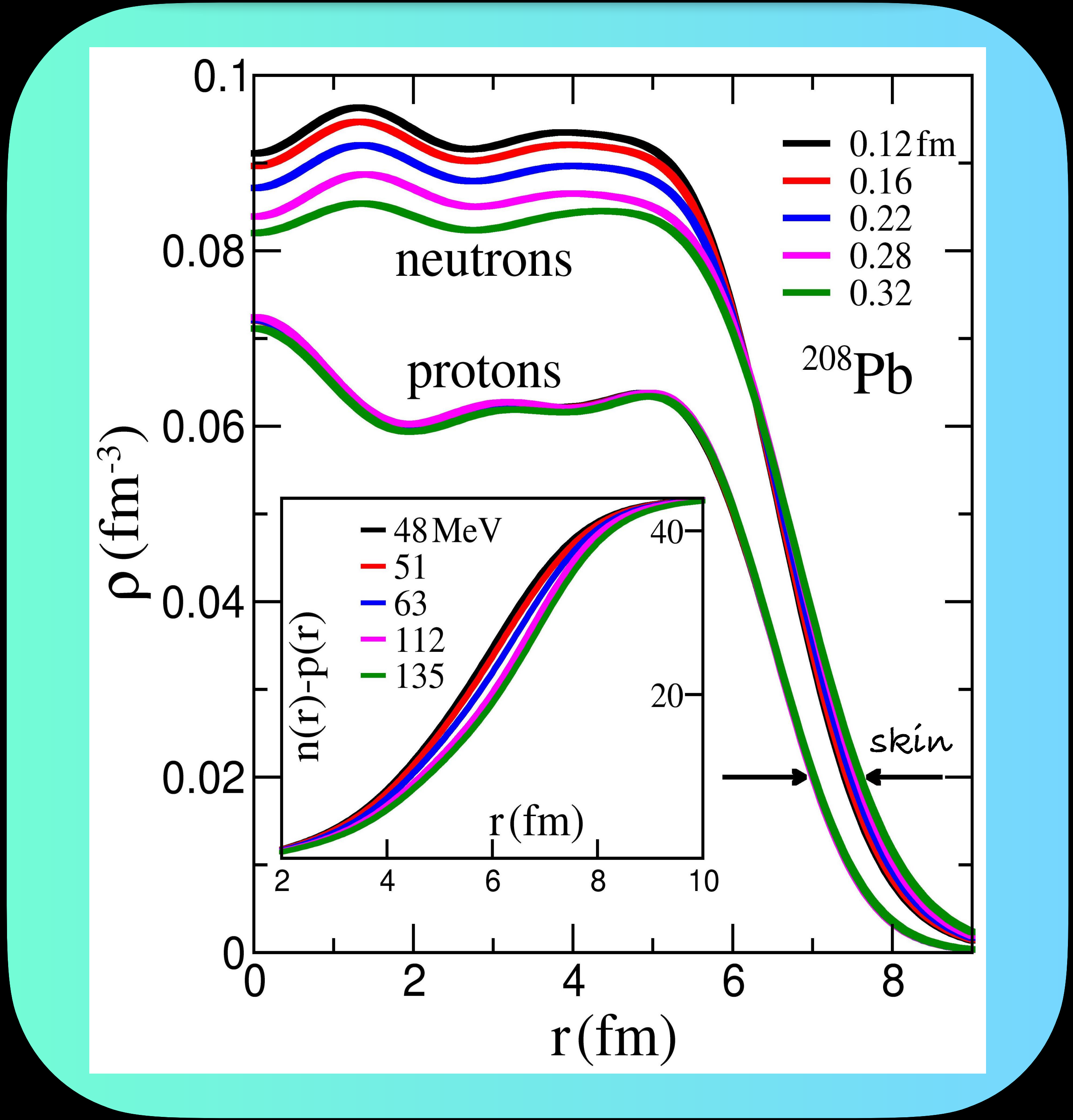
Heaven and Earth

Laboratory Constraints on the EOS



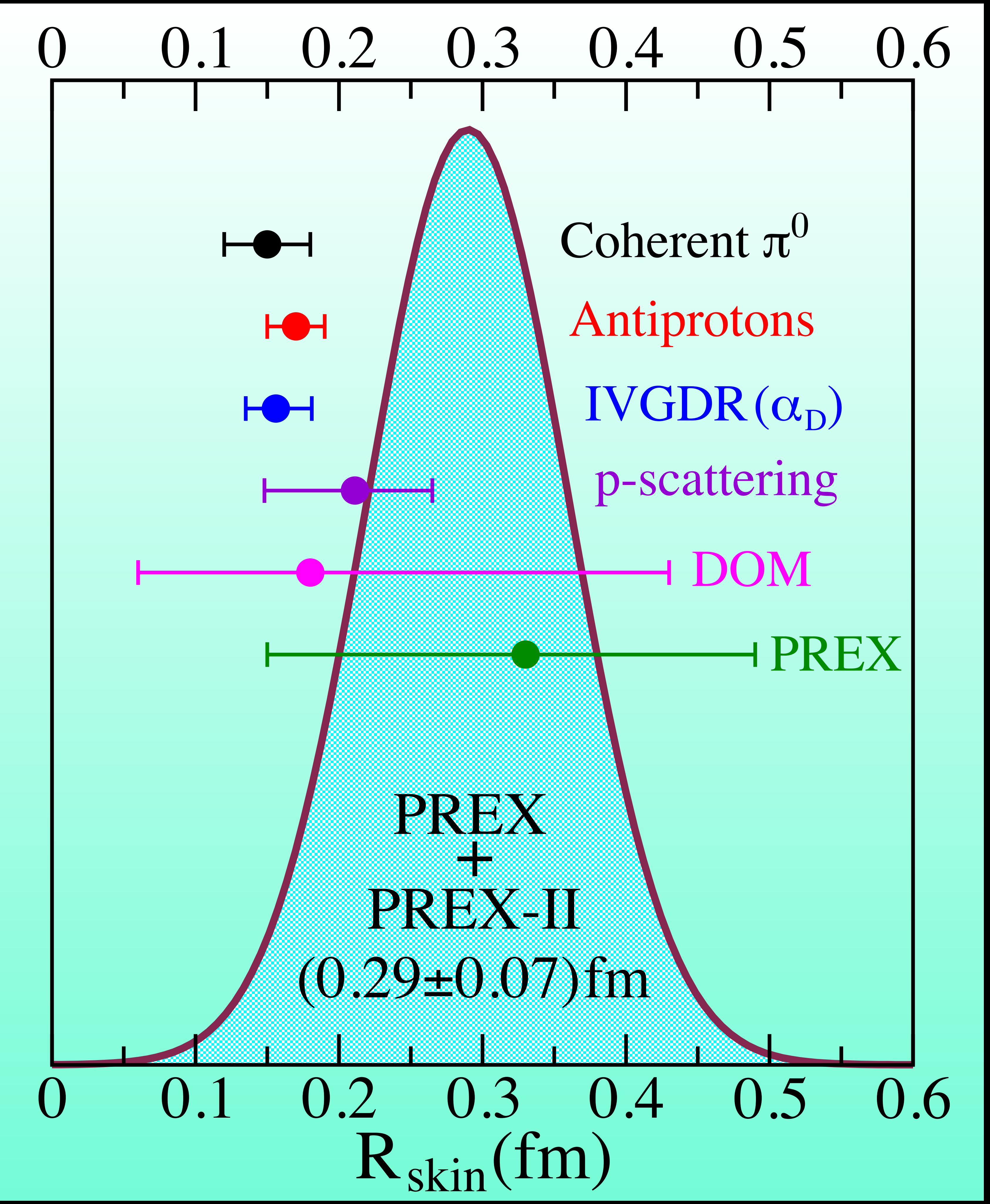




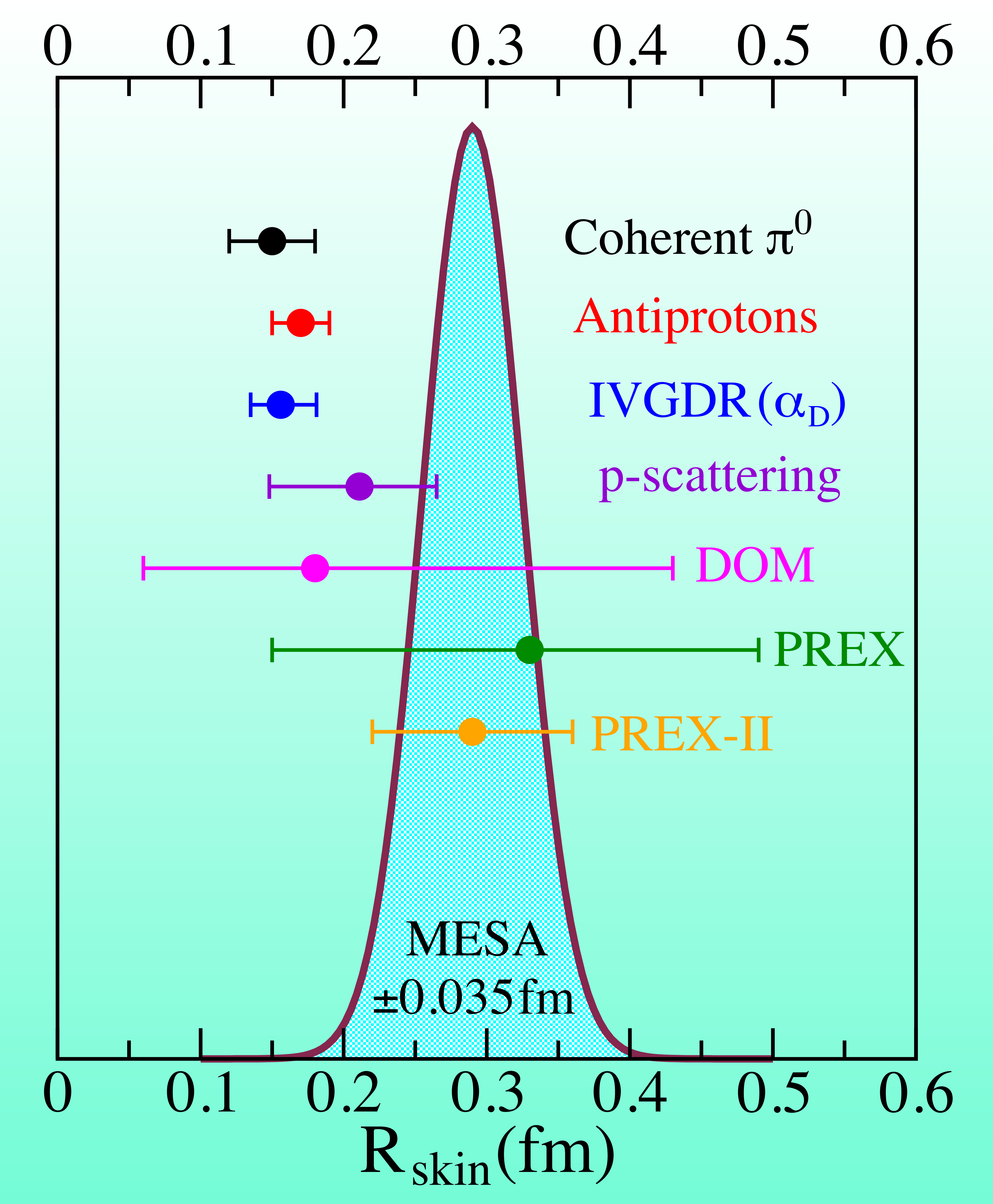


- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: P_{PNM}=L
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as ^{208}Pb
- Parity-violating elastic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

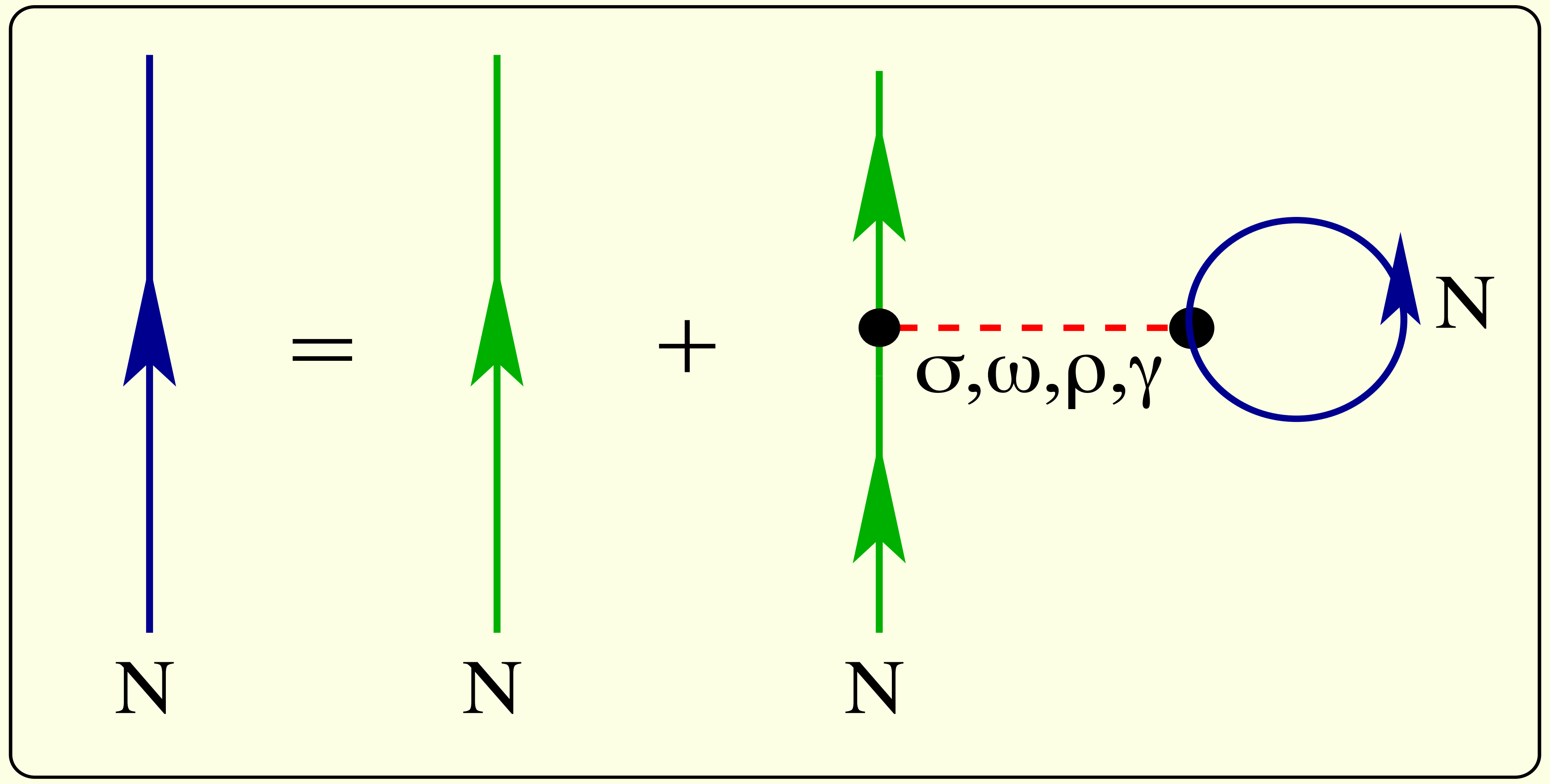
The Future: MREX
A Highly Compelling Science Case



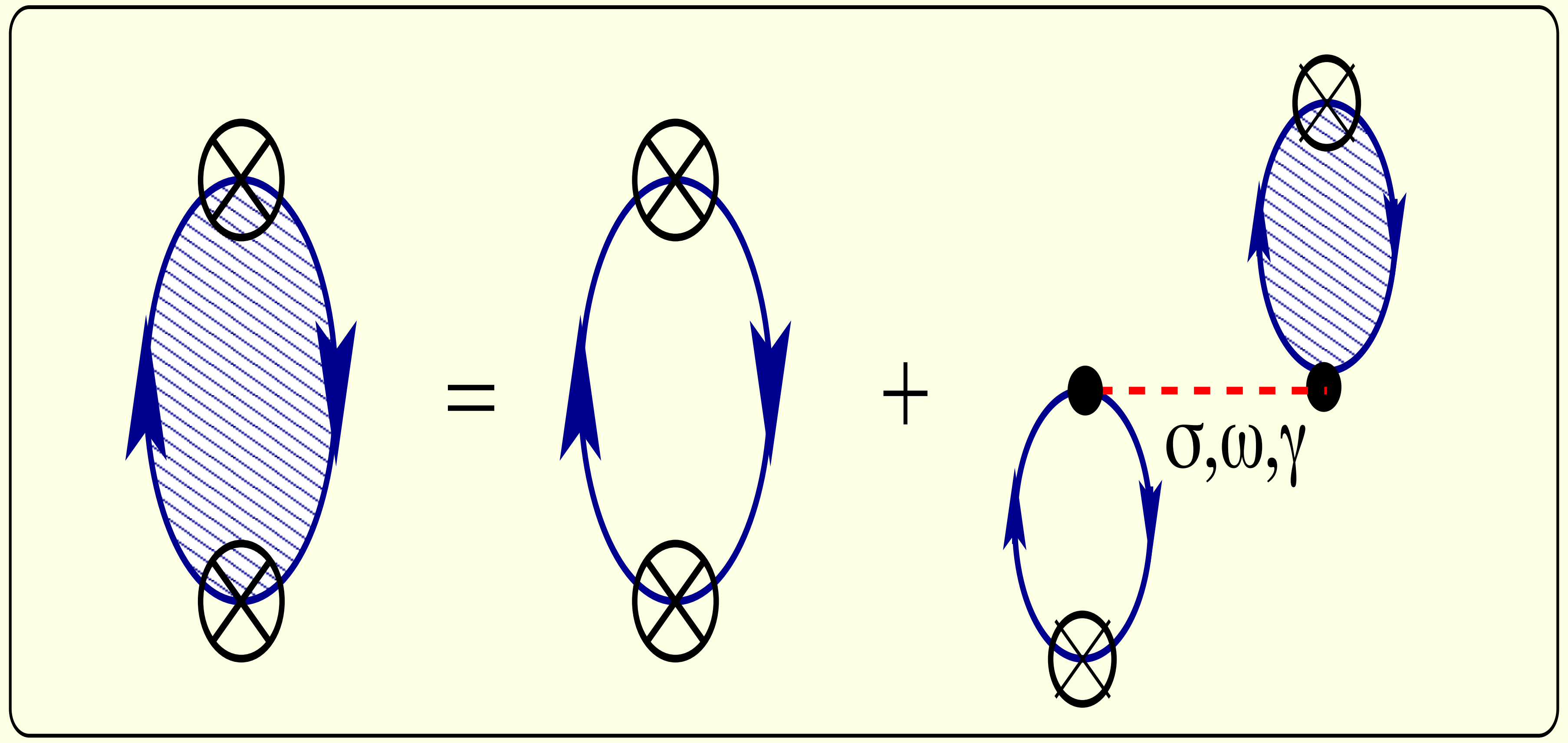
- MREX will provide the most stringent constraint on the EOS of neutron-rich matter at saturation density
- An additional measurement can also constrain the entire baryon density of ^{208}Pb and provide unique insights into the saturation mechanism
- MREX will provide fundamental anchors for future campaigns at FRIB and other future exotic beam facilities



Covariant Density Functional Theory



Self–consistent mean–field ground state



Consistent response of the mean–field ground state

Anatomy of a self-consistent Covariant DFT calculation

The Hohenberg-Kohn Theorem: The ground state energy can be obtained variationally: the density that minimizes the total energy is the exact ground state density

- Ground state properties (charge and weak charge densities) emerge from functional minimization
- Collective excitations (e.g., electric dipole response) is the consistent linear response of the ground state to a small perturbation

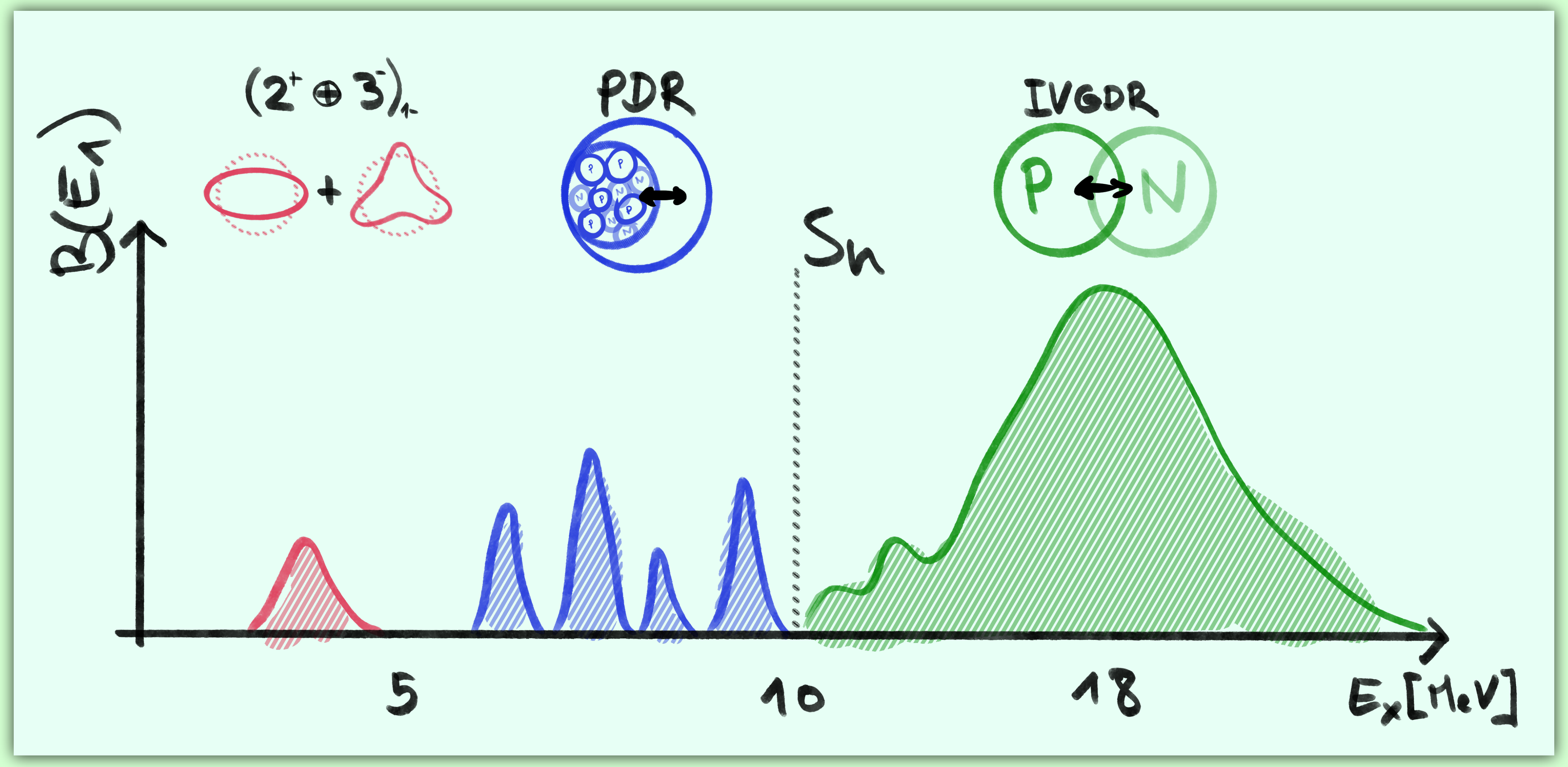
Electric Dipole Response

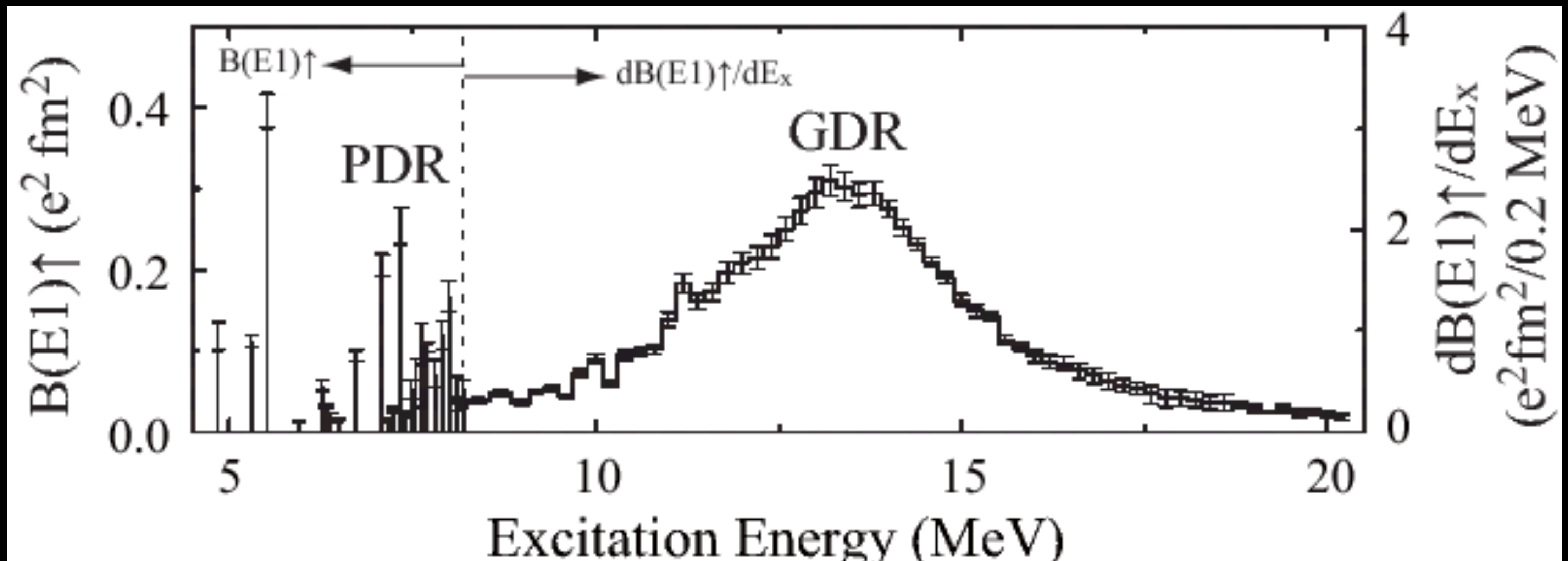
Journal of Physics G: Nuclear and Particle Physics

TOPICAL REVIEW

Neutron skins of atomic nuclei: per aspera ad astra

To cite this article: M Thiel *et al* 2019 *J. Phys. G: Nucl. Part. Phys.* **46** 093003





IVGDR: The quintessential nuclear excitation

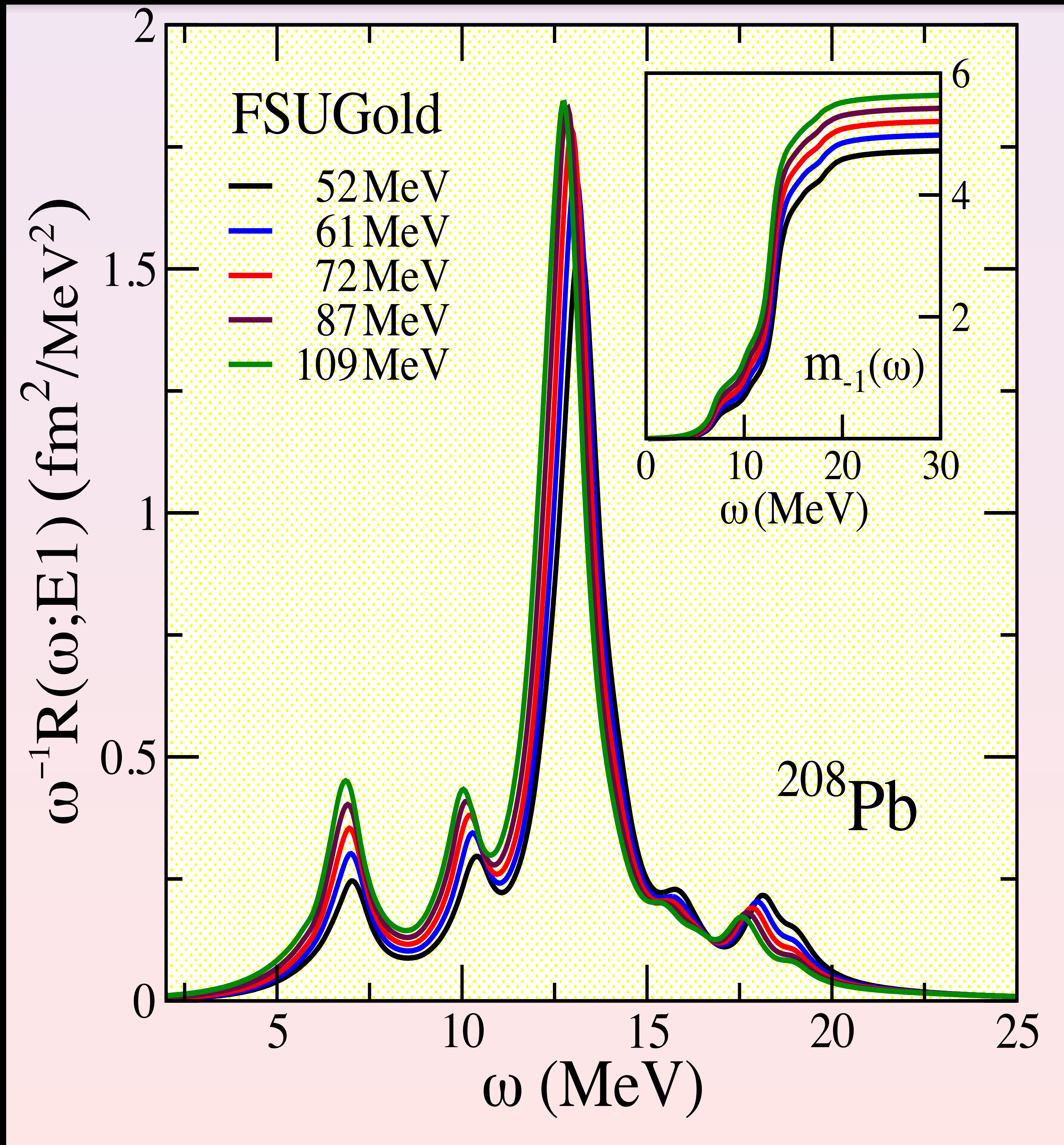
- Out-of-phase oscillation of neutrons vs protons
  - Symmetry energy acts as restoring force
- Energy weighted sum rule largely model independent
- Inverse energy weighted sum strongly correlated to L
  - Important contribution from Pygmy resonance
- High quality data from RCNP, GSI, HIGS, ...
  - On a variety of nuclei such as Pb, Sn, Ni, Ca, ...
  - hopefully in the future along isotopic chains

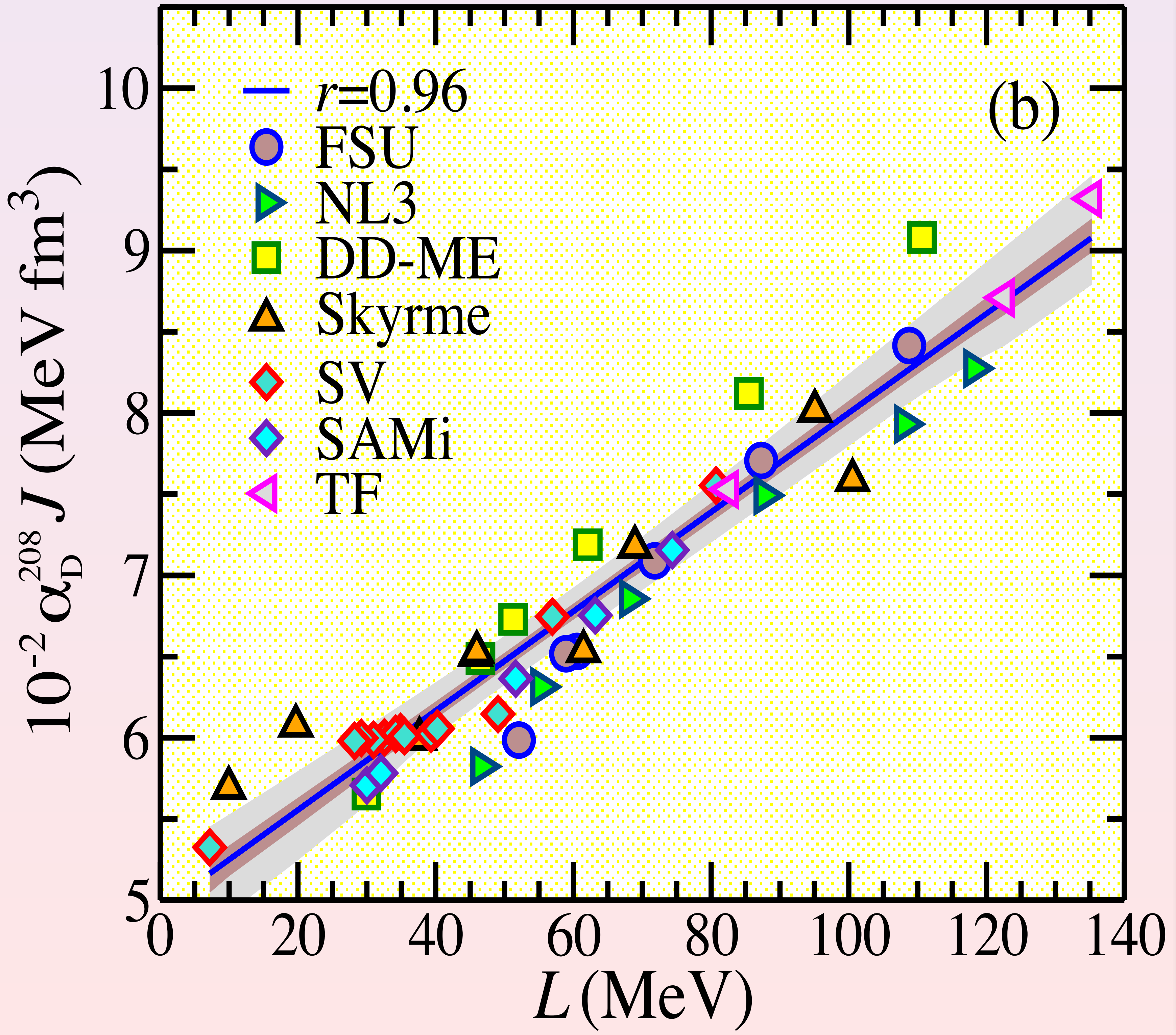
$$\mathrm{EWSR} = \int_0^\infty \sigma(\omega)\,d\omega \approx 60\left(\frac{NZ}{A}\right)\ \mathrm{MeV\ mb}$$

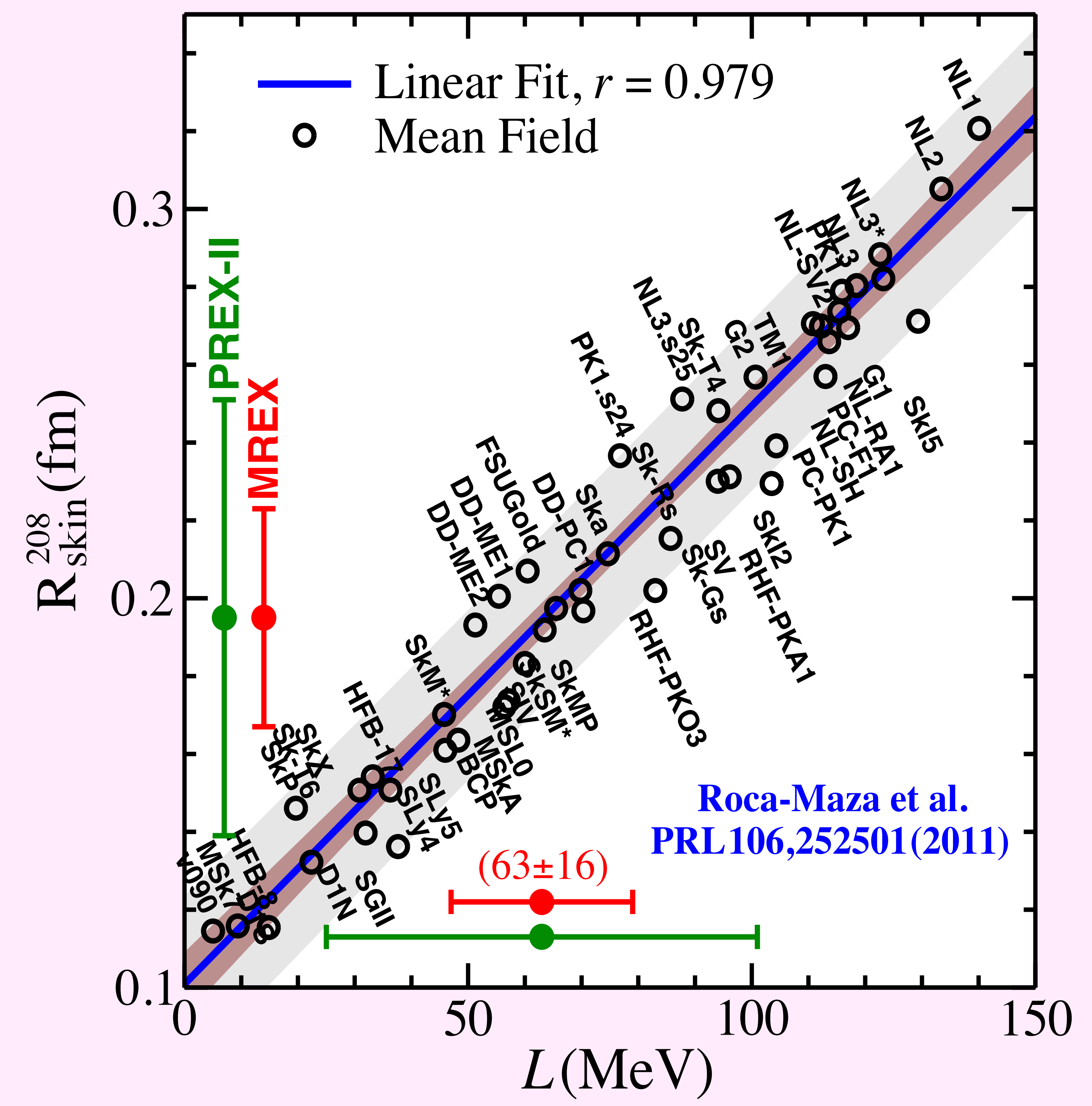
$$\alpha_D = \left(\frac{\hbar c}{2\pi^2}\right)\int_0^\infty \frac{\sigma(\omega)}{\omega^2}\,d\omega = \left(\frac{8\pi e^2}{9}\right) m_{-1}$$

Electric Dipole Polarizability α_D

- Electric dipole polarizability a powerful electroweak complement to Rskin
  Important contribution from Pygmy resonance (inverse energy weighted sum)
- Low-energy strength of relevance to (n,g) reactions in stellar environments

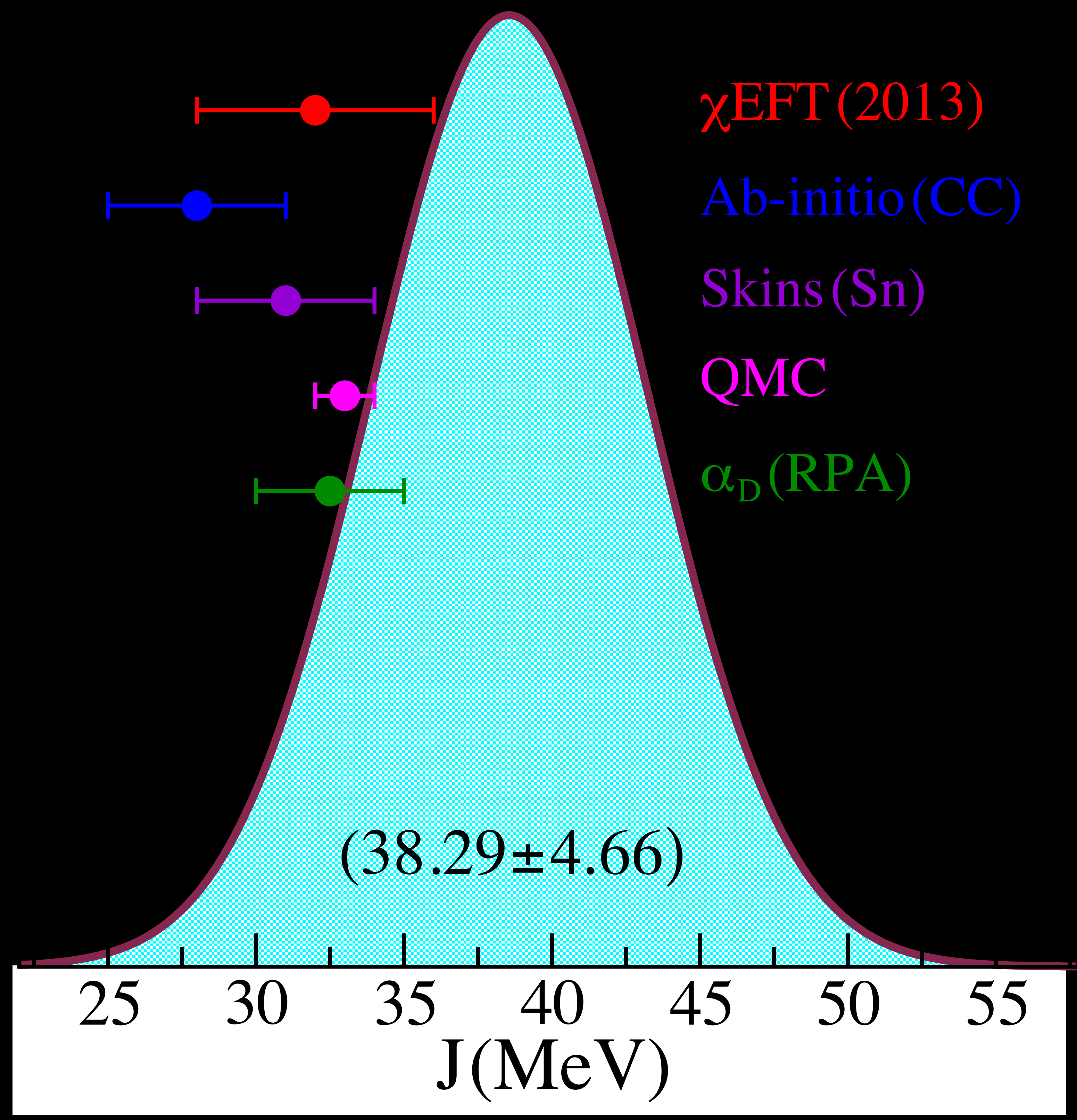


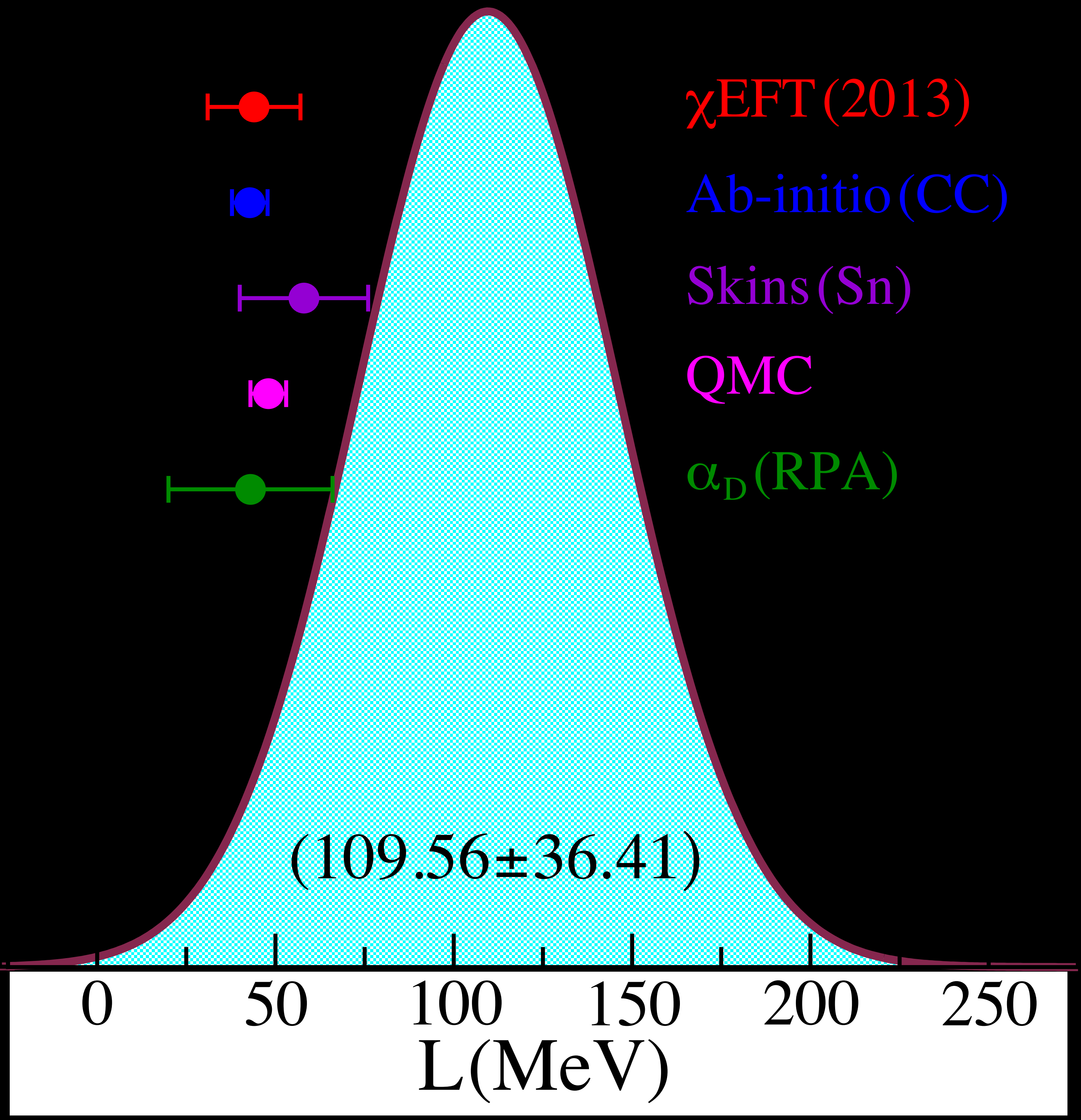


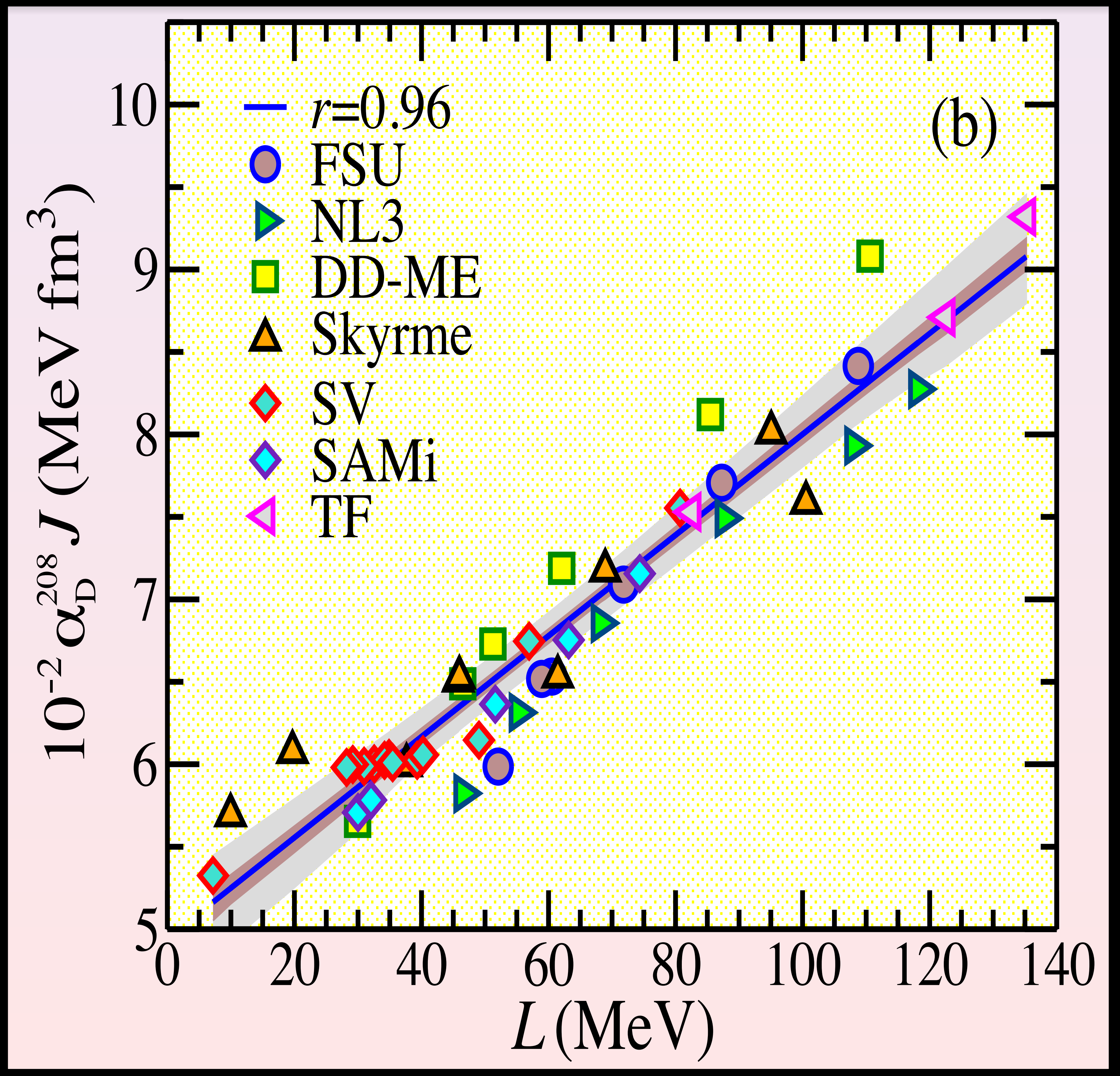


PREX-II Constraints on the EOS of Neutron Rich Matter

RCNP: Electric Dipole Polarizability of ^{208}Pb







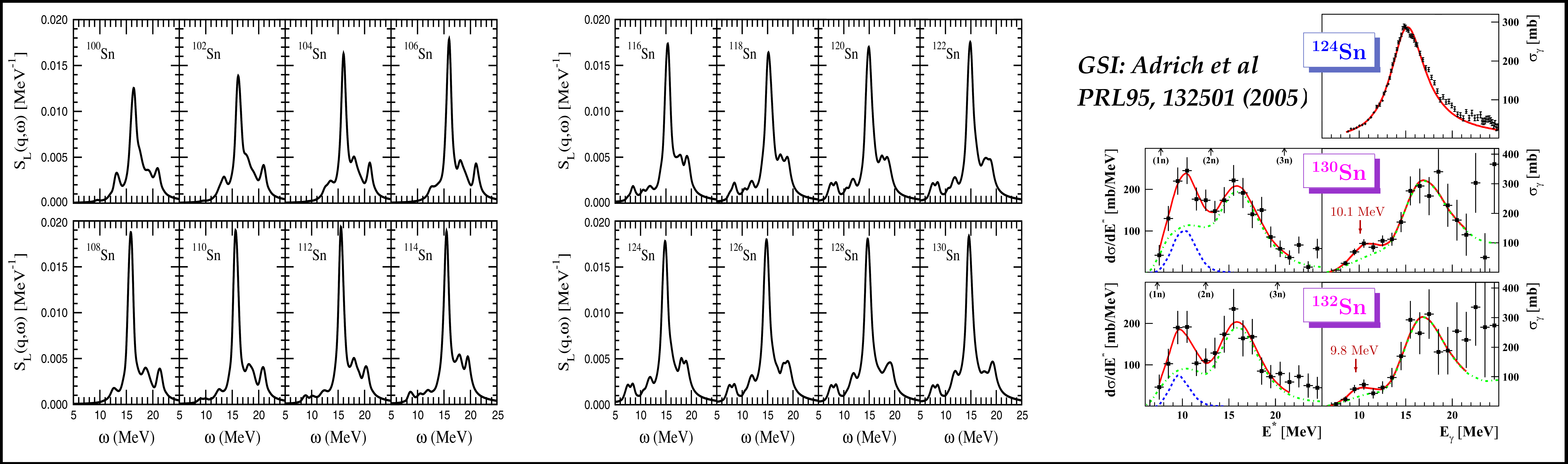
Some slight tension between PREX-II and RCNP — yet PREX-II error still a bit too large!

$$\alpha_D^{208} = \frac{(a+bL)}{J} \approx (22.11 \pm 6.81)\ \mathrm{fm}^3$$

$$\alpha_D^{208}(\mathrm{RCNP}) = (19.6 \pm 0.6)\ \mathrm{fm}^3$$

Electric Dipole Polarizability of Unstable Neutron-Rich Nuclei

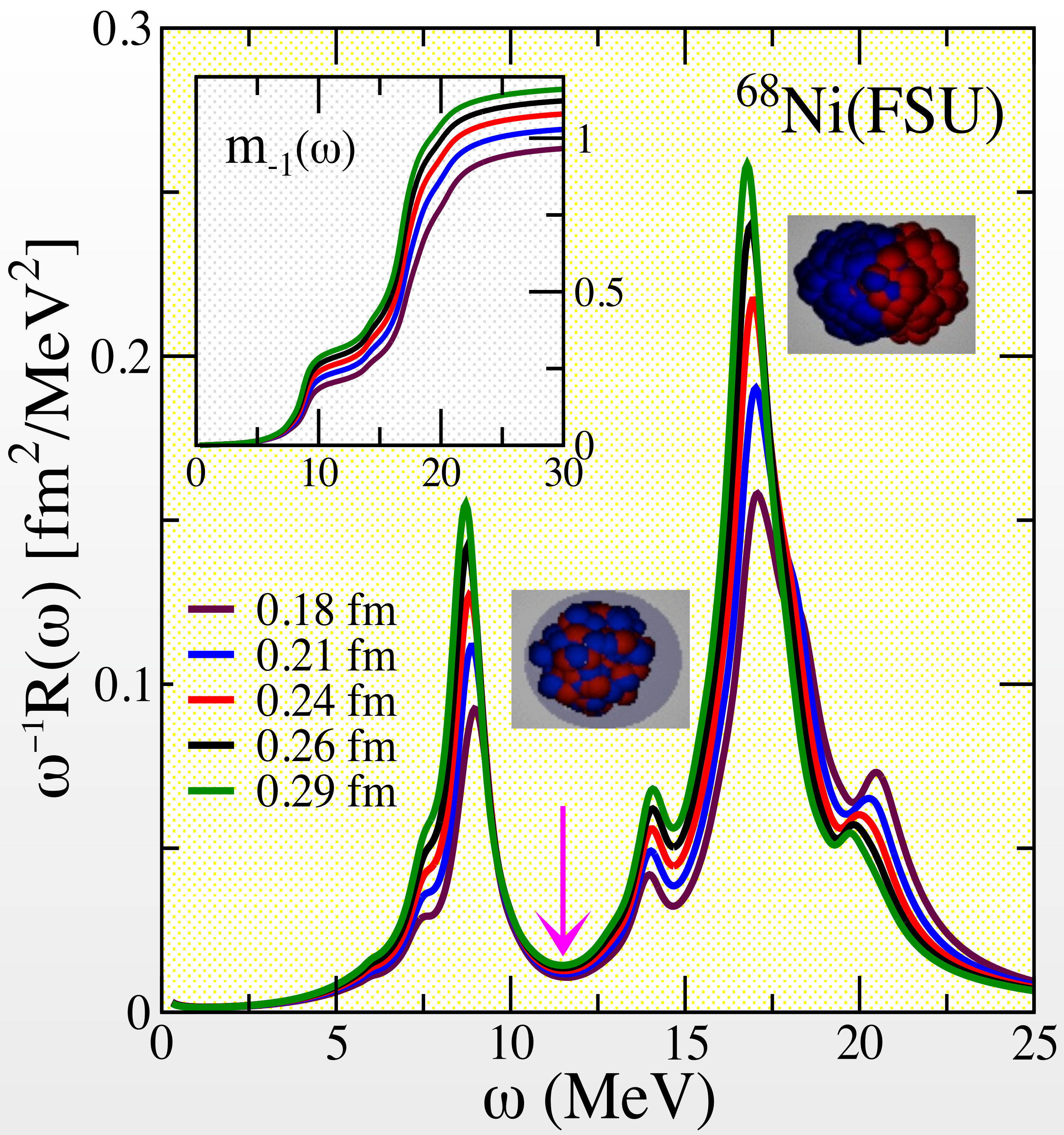
Most stringent constraint on EOS of neutron-rich matter from nuclei with huge skins — preferably along long isotopic chains (e.g., tin)



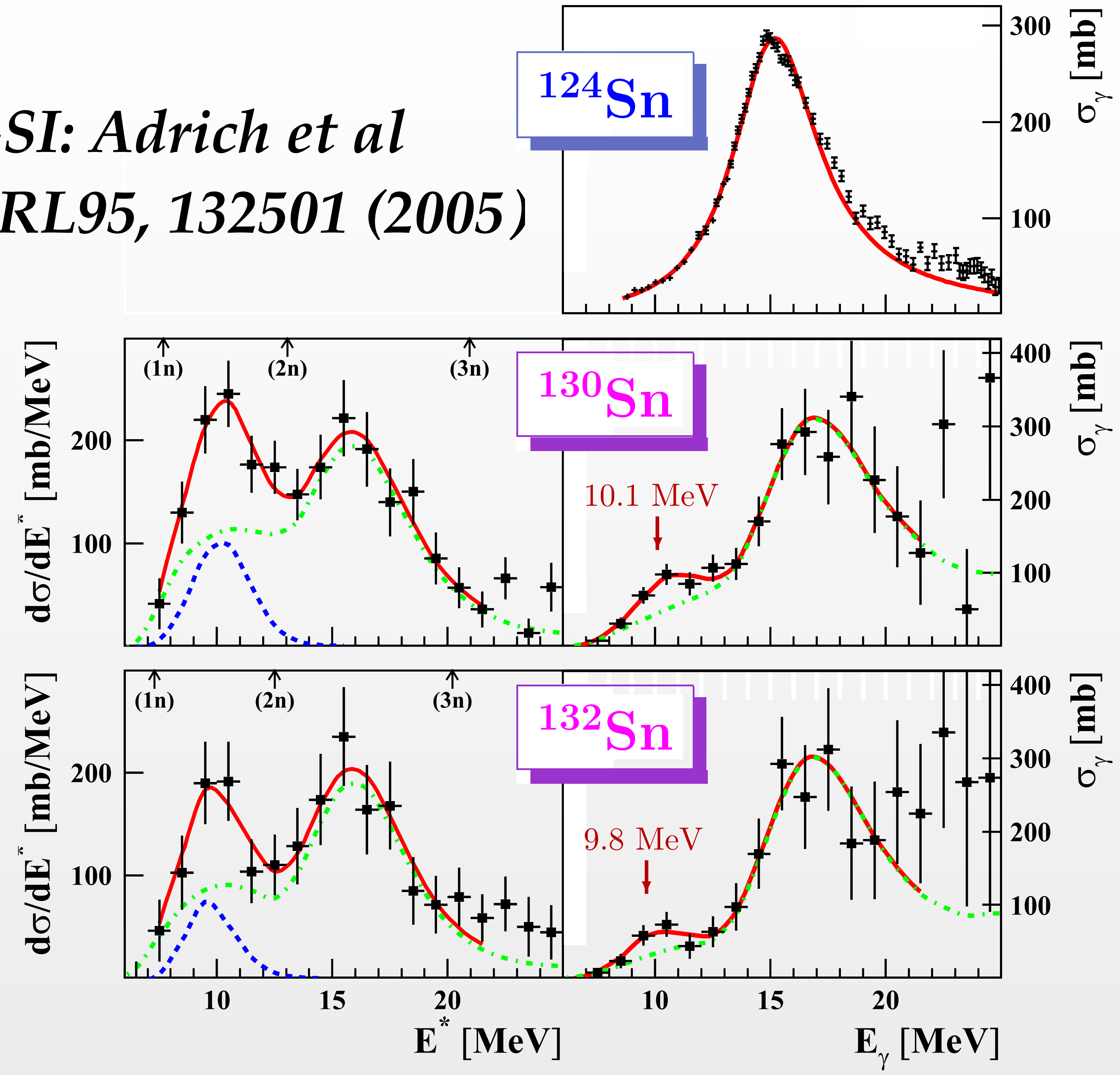
Electric Dipole Polarizability of Unstable Neutron-Rich Nuclei

Most stringent constraint on EOS of neutron-rich matter from nuclei with huge skins — preferably along long isotopic chains (e.g., tin)

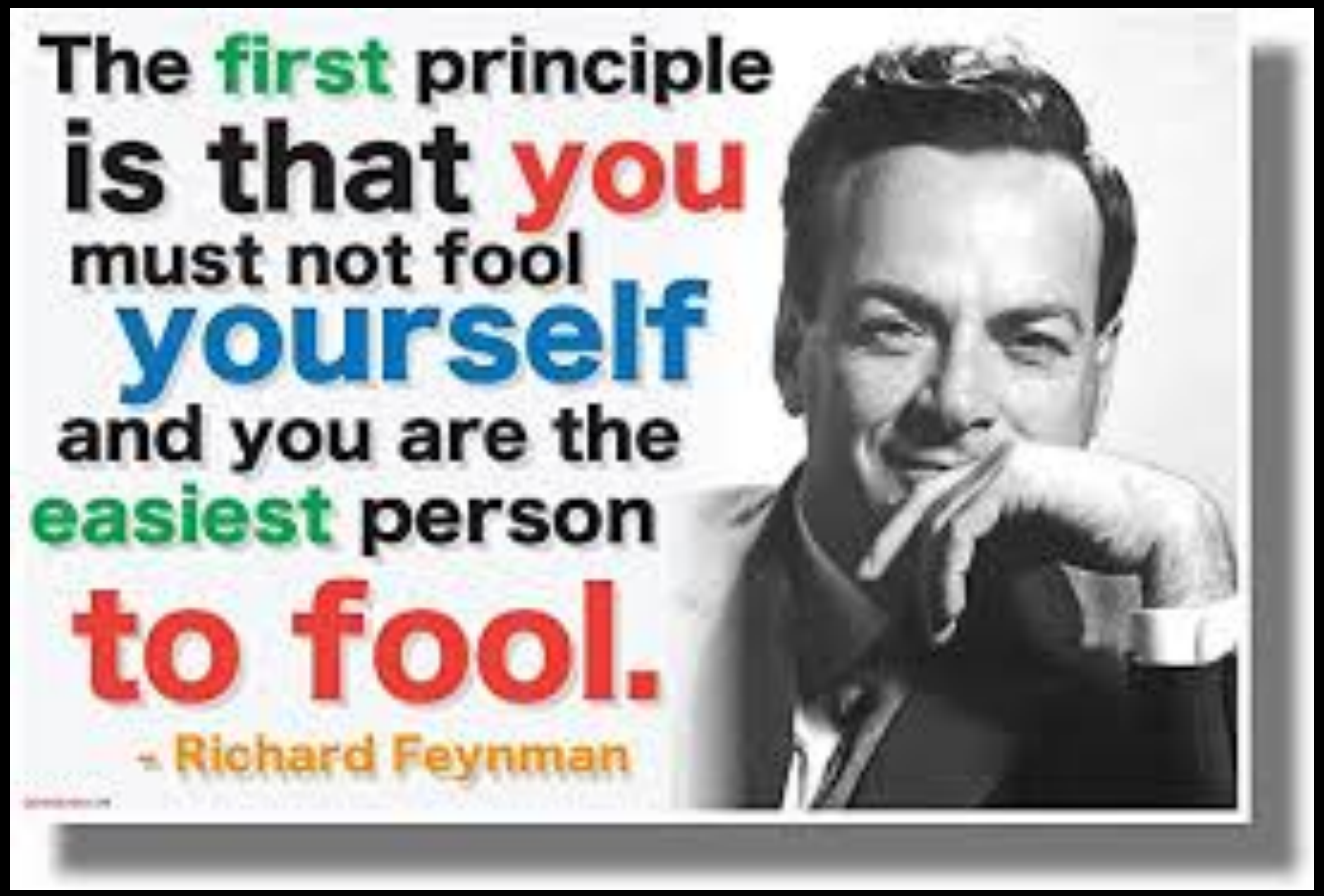
Giant (Hercules) Awakes and Drives off the Pygmies by Lucas Cranach The Younger (1551)

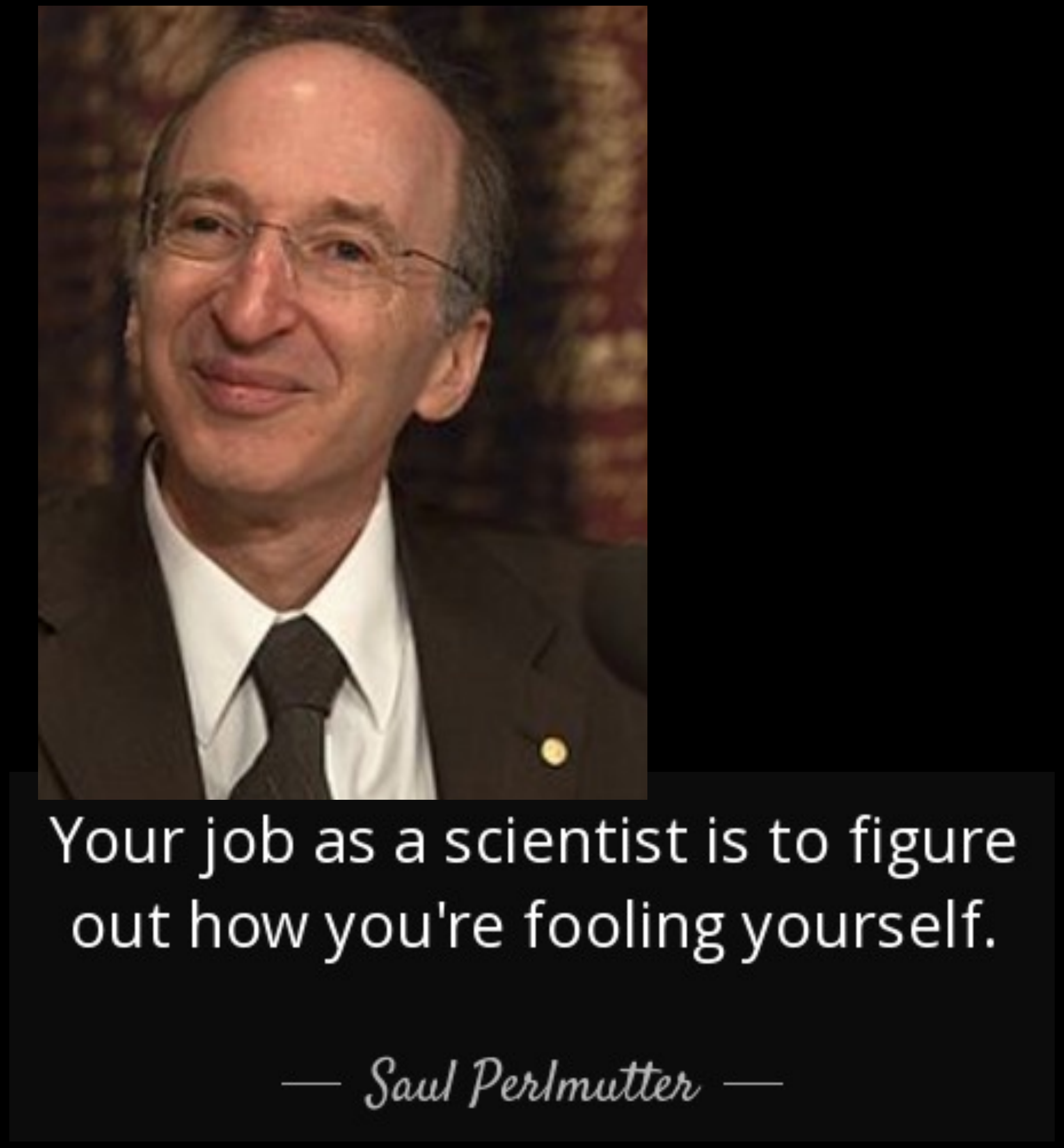


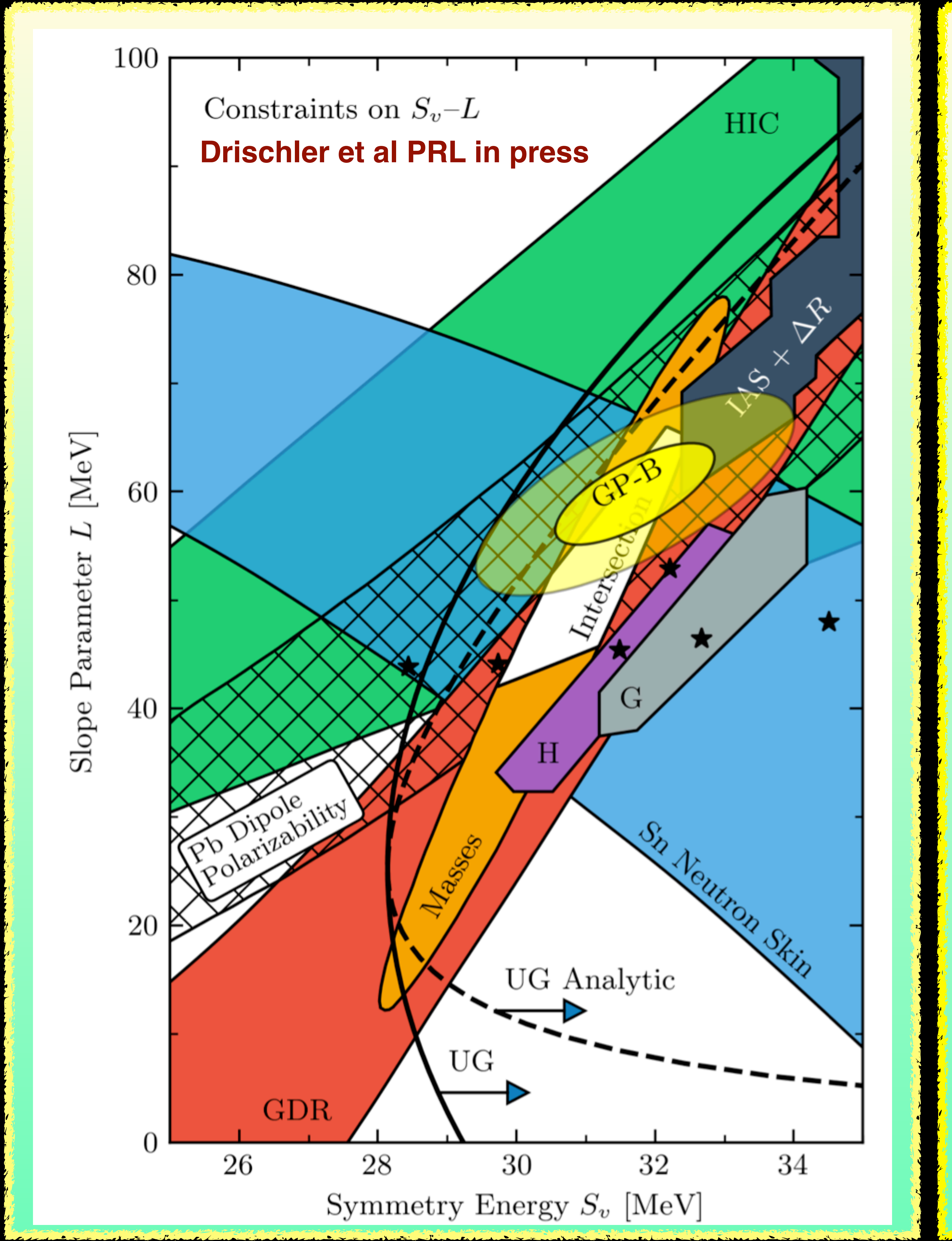
GSI: Adrich et al PRL95, 132501 (2005)

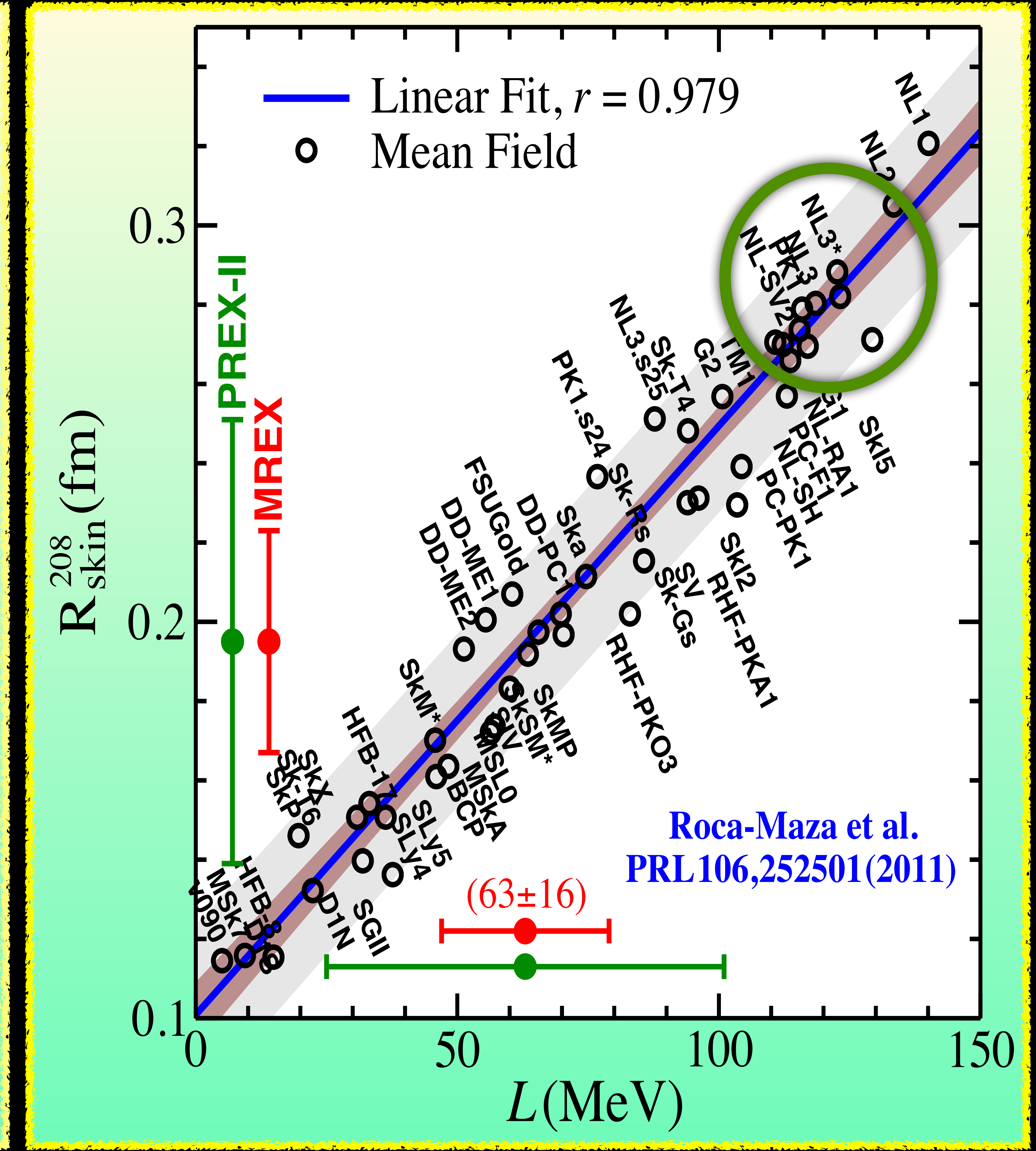


That is why you play the game ...
because often the underdog wins!

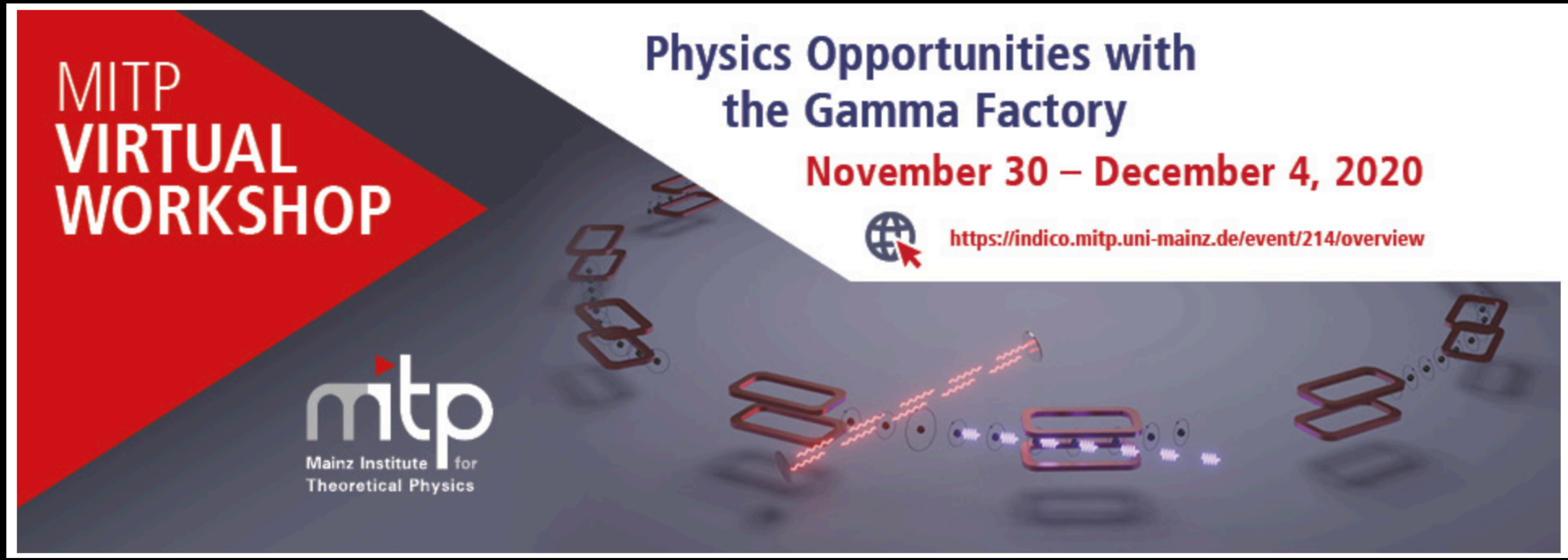








A few concluding remarks …

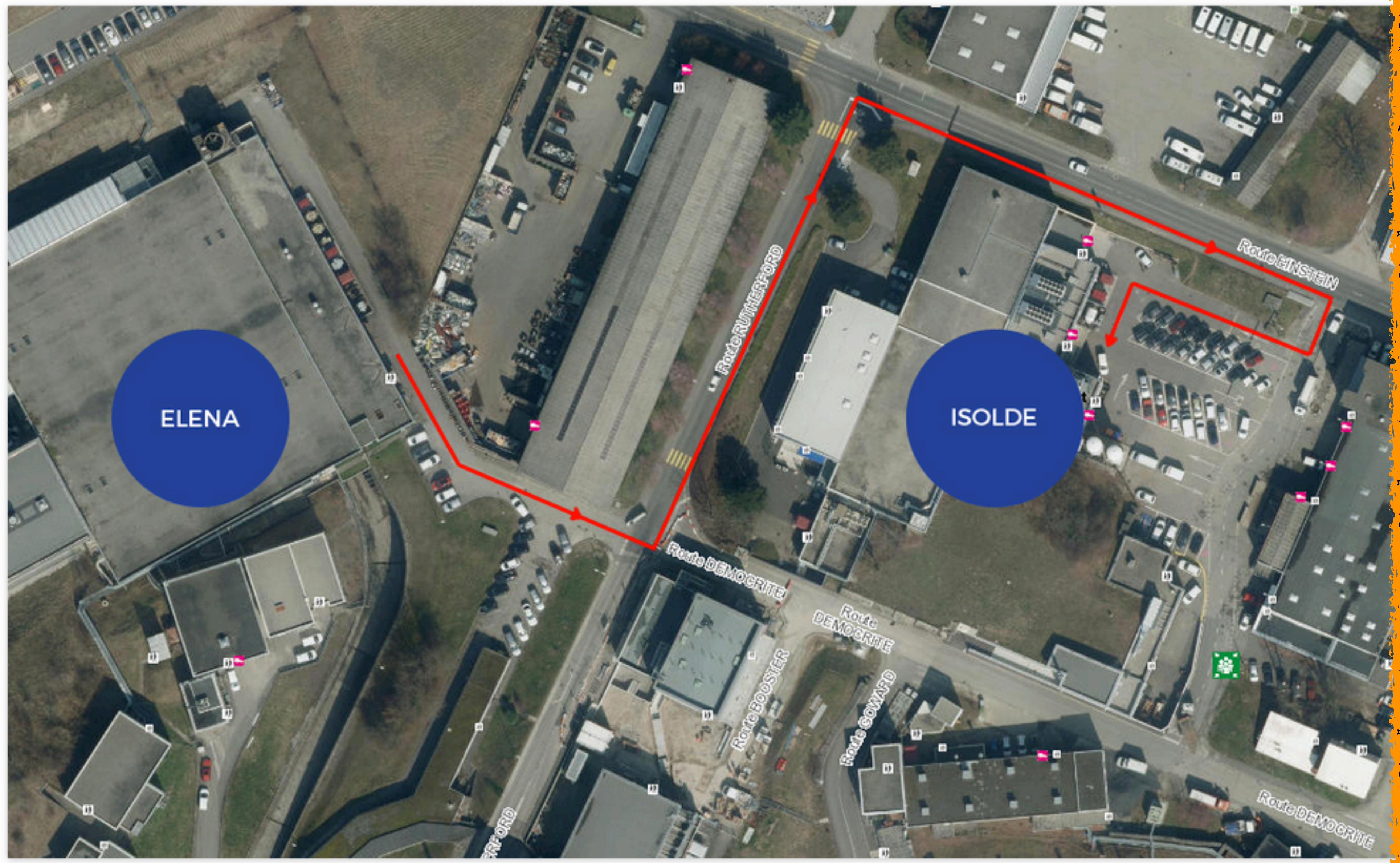


- Nuclear Physics is paramount in the quest for the EOS of neutron-rich matter in the new era of gravitational-wave astronomy (“first rung” in the density ladder)
- Electroweak measurements — PV e-scattering and photoabsorption experiments — the cleanest tools that inform the EOS
- Mainz may play a leadership role in both efforts!

The PUMA project: Antimatter goes nomad

A new European project linking ELENA and ISOLDE plans to trap antimatter in order to explore quantum phenomena in radioactive nuclei

11 MARCH, 2018 | By Cristina Agrigoroae



Antimatter’s journey between the ELENA and ISOLDE facilities (Image: CERN)

Antimatter is extremely vulnerable, as it vanishes instantly on contact with matter. However, it has successfully been stored at CERN in the framework of various experiments. Recently, the BASE experiment succeeded in storing a few antiprotons for an exceptionally long period of over a year, with no loss. Now, a new European project aims to achieve a storage time of several weeks for one billion antiprotons, which would allow them to be transported. This would be the first time that antimatter had embarked on an inter-facility journey, which is possible only between two experiments at CERN. But why transport it if it’s so fragile?

This original idea is the brainchild of Alexandre Obertelli, a physicist from the Darmstadt technical university (*TU Darmstadt*), who started working on it two years ago. His project, called PUMA (antiProton Unstable Matter Annihilation), aims to explore new quantum phenomena that might emerge from low-energy interactions between antiprotons and slow exotic nuclei. For this to be done, scientists need to trap antimatter and transport it to a facility that delivers radioactive ion beams. This project is thus a bridge between the GBAR experiment at ELENA, which produces antiprotons, and ISOLDE, which will supply the trap with the short-lived nuclei.