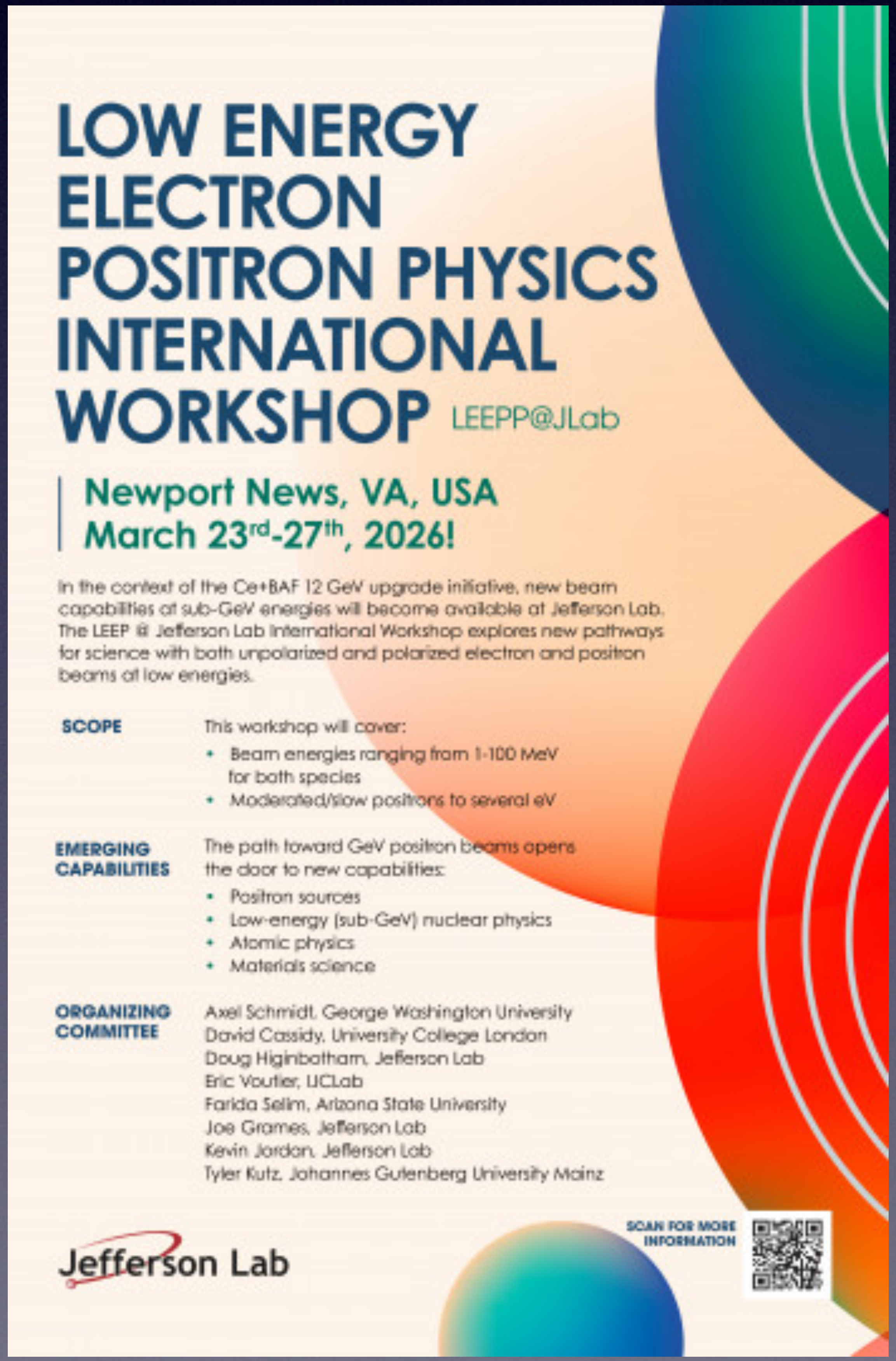
Heaven and Earth:
Connecting JLab to the Cosmos

J. Piekarewicz

LEEPP@JLab
March 23-27, 2026


LOW ENERGY ELECTRON POSITRON PHYSICS INTERNATIONAL WORKSHOP LEEPP@JLab

Newport News, VA, USA
March 23rd-27th, 2026!

In the context of the Ce+BAF 12 GeV upgrade initiative, new beam capabilities at sub-GeV energies will become available at Jefferson Lab. The LEEP @ Jefferson Lab International Workshop explores new pathways for science with both unpolarized and polarized electron and positron beams at low energies.

SCOPE

This workshop will cover:
- Beam energies ranging from 1-100 MeV for both species
- Moderated/slow positrons to several eV

EMERGING CAPABILITIES

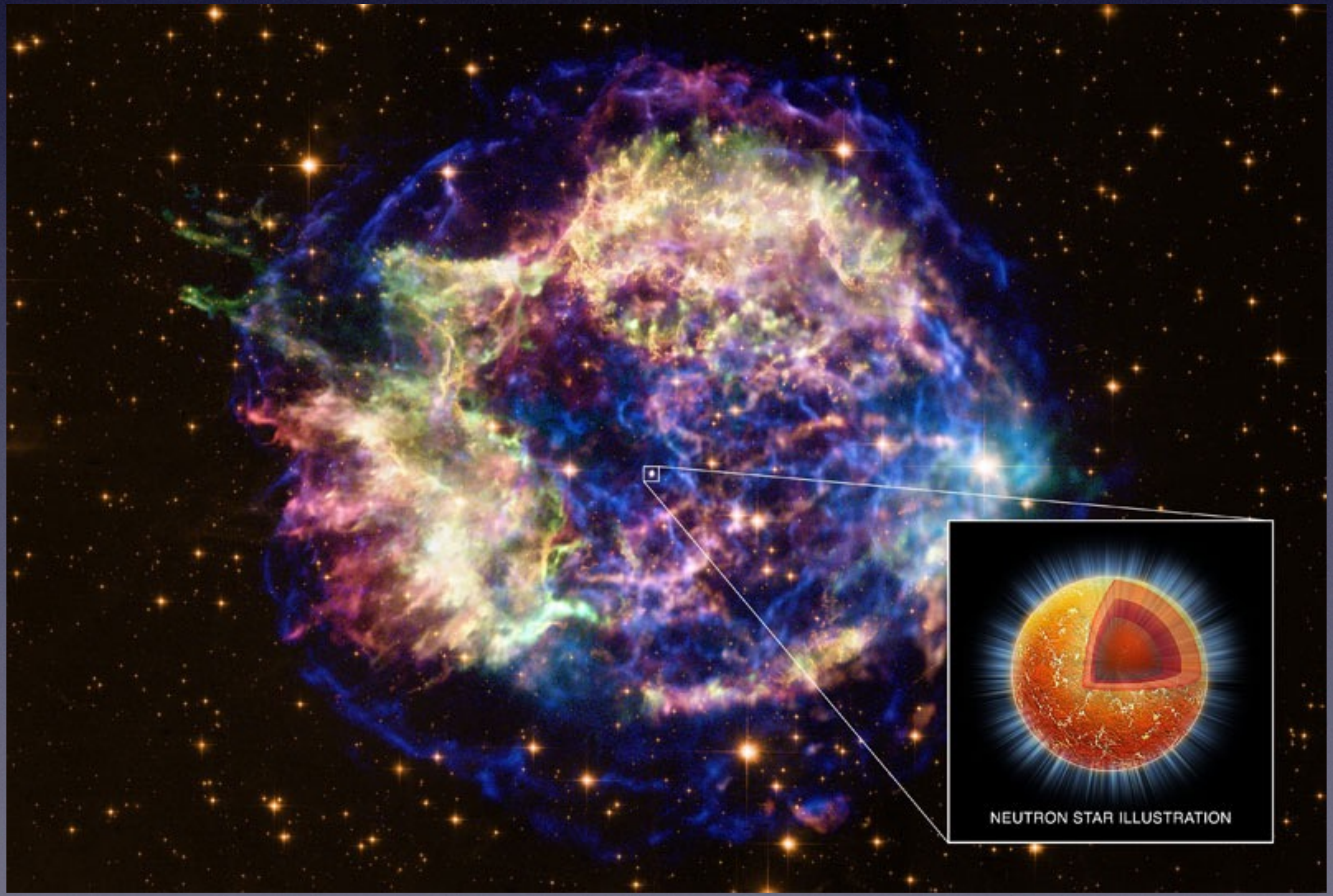
The path toward GeV positron beams opens the door to new capabilities:
- Positron sources
- Low-energy (sub-GeV) nuclear physics
- Atomic physics
- Materials science

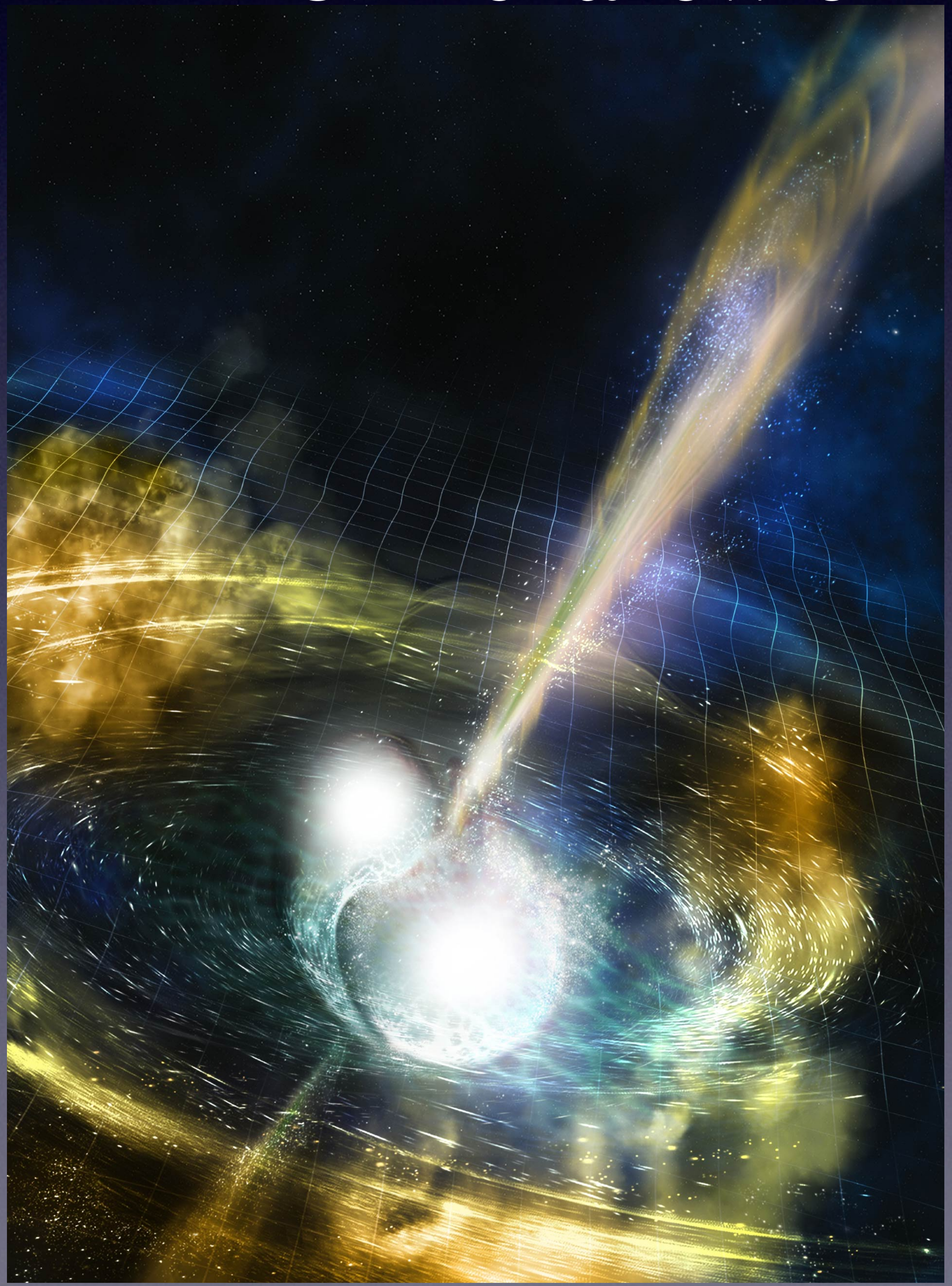
ORGANIZING COMMITTEE

Axel Schmidt, George Washington University
David Cassidy, University College London
Doug Higinbotham, Jefferson Lab
Eric Voutier, IJCLab
Farida Selim, Arizona State University
Joe Grames, Jefferson Lab
Kevin Jordan, Jefferson Lab
Tyler Kutz, Johannes Gutenberg University Mainz

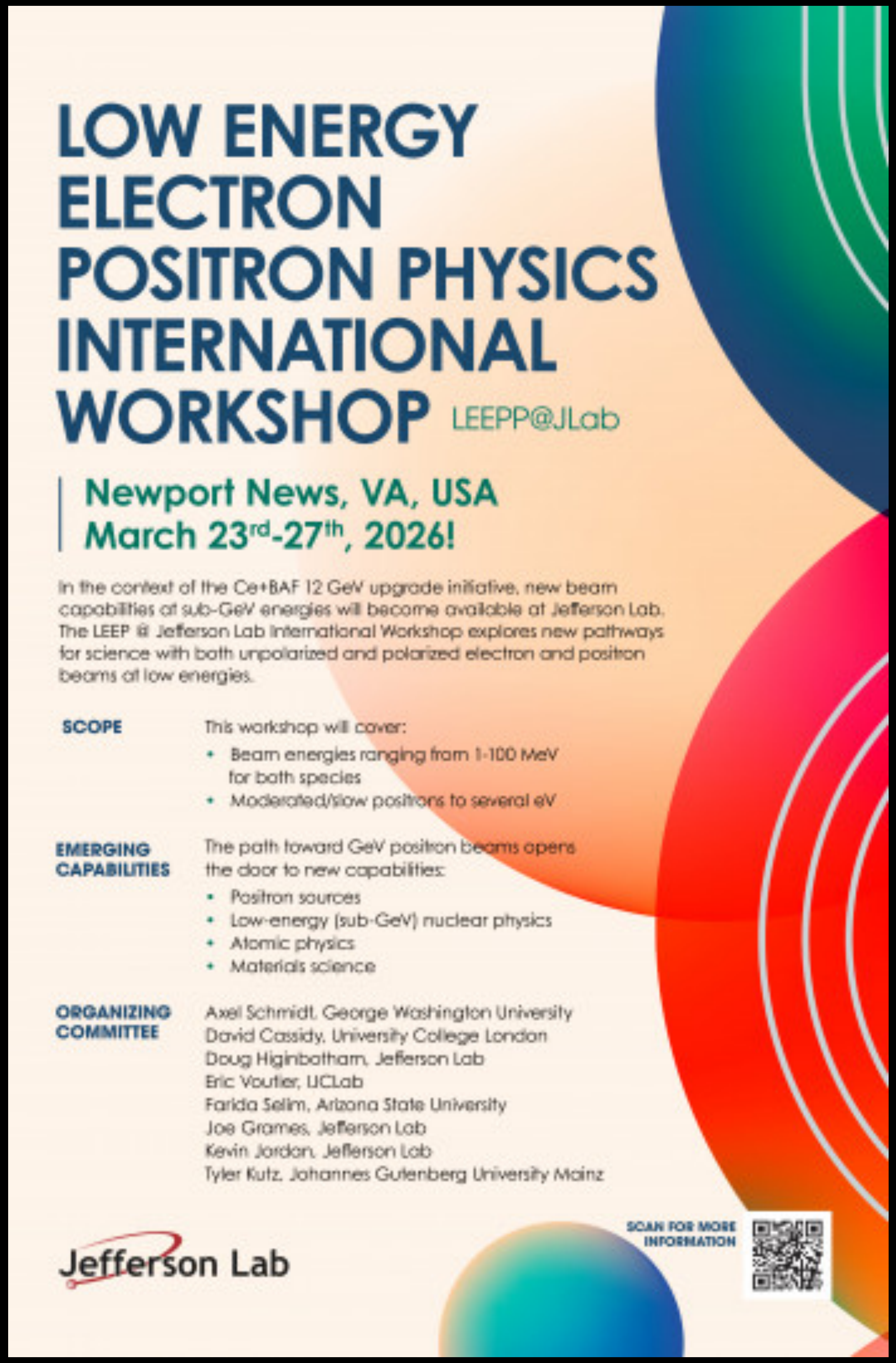
Jefferson Lab

SCAN FOR MORE INFORMATION





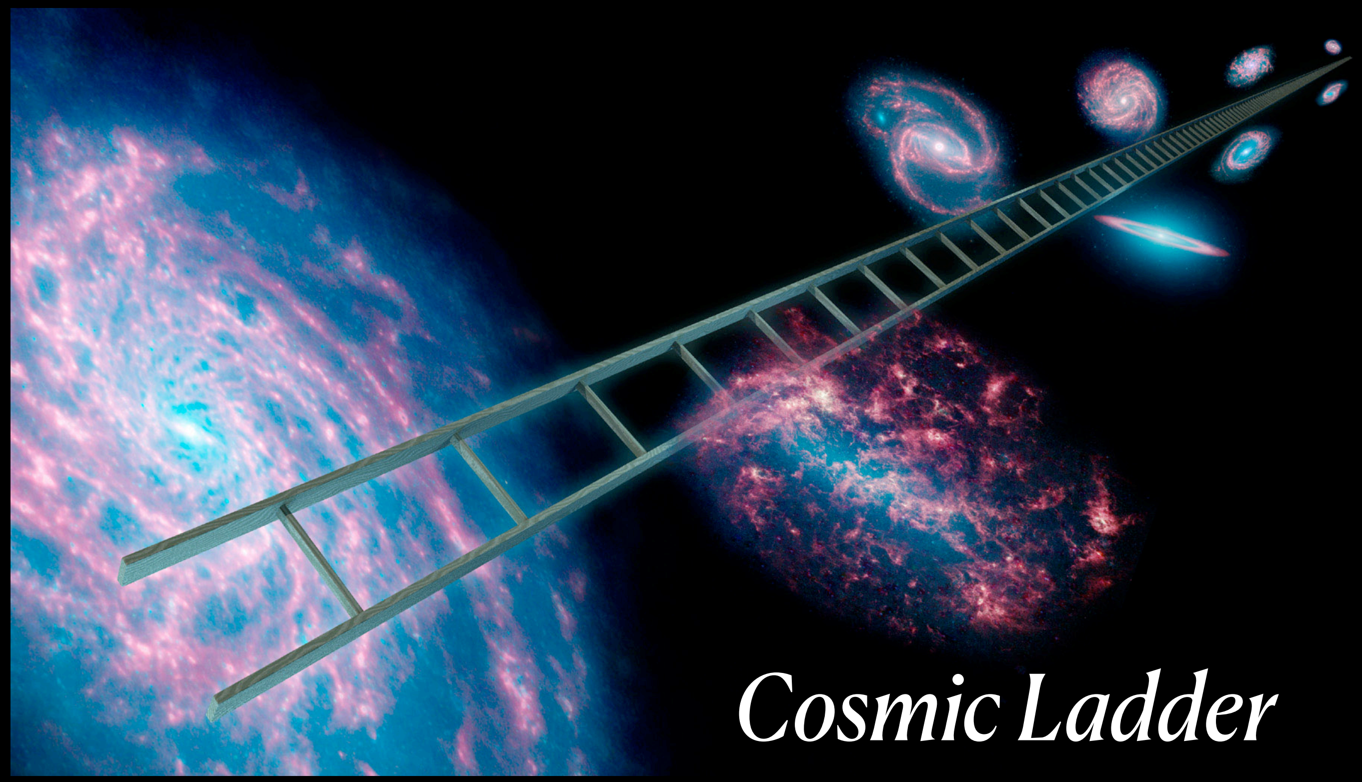
Can you ("ChatGPT") think about some interesting JLab physics that can be done with positrons that cannot be done with electrons?

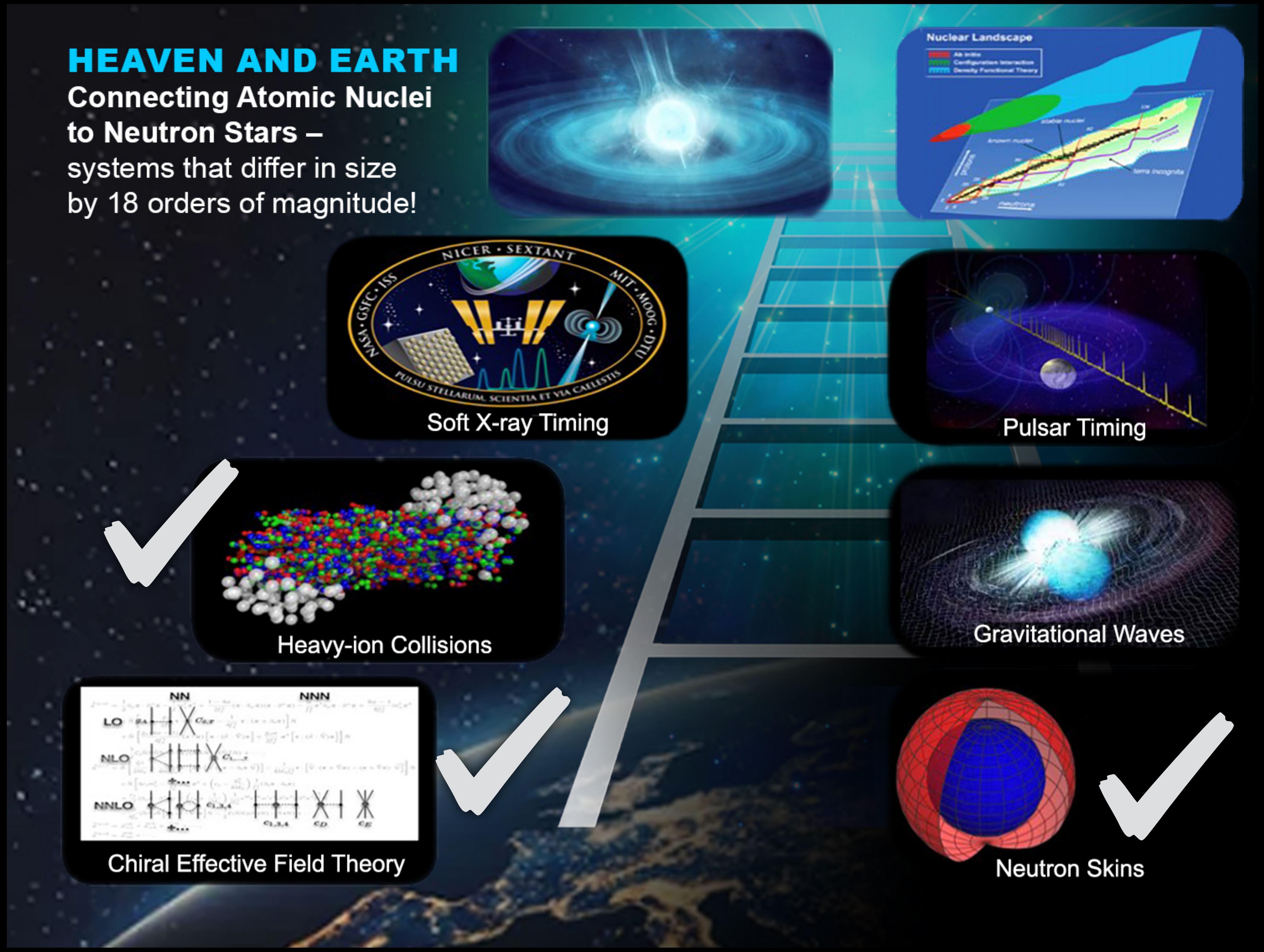


- ★ **Two Photon Exchange:** Direct comparison of e- vs e+ isolates charge puzzles in proton form factors and radiative corrections.
- ★ **GPDs & DVCS:** Beam-charge asymmetry flips sign, giving clean access to the interference term enabling a model-independent extraction of Compton form factors.
- ★ **Electroweak Structure:** e+/e- comparisons disentangle γ-Z interference, reducing theoretical uncertainties in weak charge measurements and standard models tests.
- ★ **Nuclear Effects:** Positrons provide new sensitivity to Coulomb distortions and meson exchange currents, offering a complementary window on nuclear structure observables.
- ★ **BSM Physics:** Combining e+ and e- beams greatly reduces systematic errors in searches for dark bosons, lepton universality violations, and other rare signals.

Heaven and Earth: Nuclear EOS Density Ladder

No single method can constrain the EOS over the entire density domain. Instead, each rung on the ladder provides information that can be used to determine the **EOS** at neighboring rungs



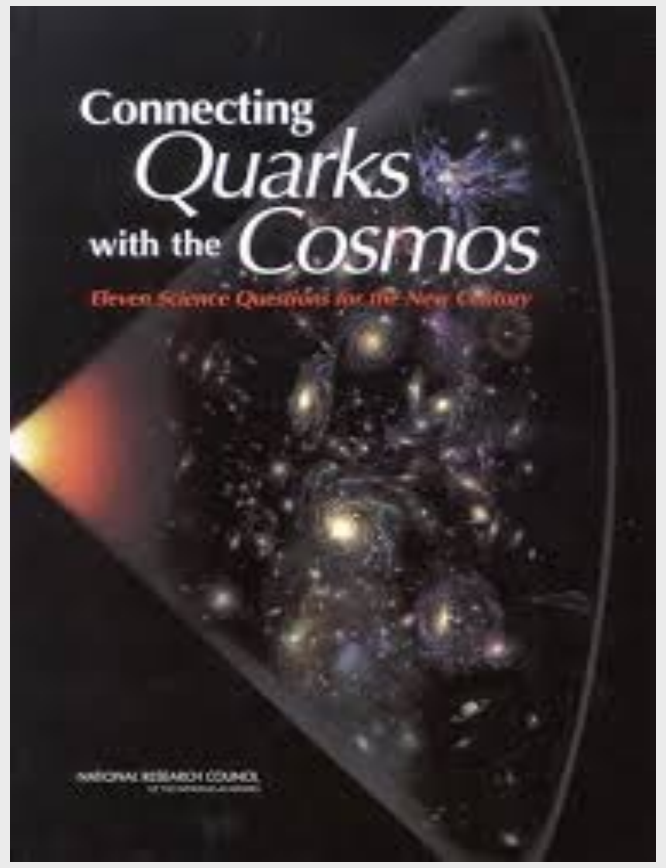


Nuclear Physics and Neutron Stars

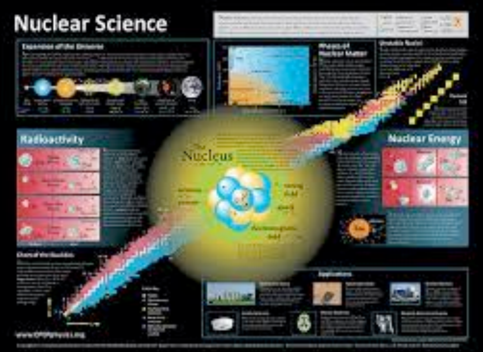
The Nuclear Physics of Neutron Stars

How were the heavy elements from iron to uranium made?

Are there new states of matter at ultrahigh temperatures and densities?

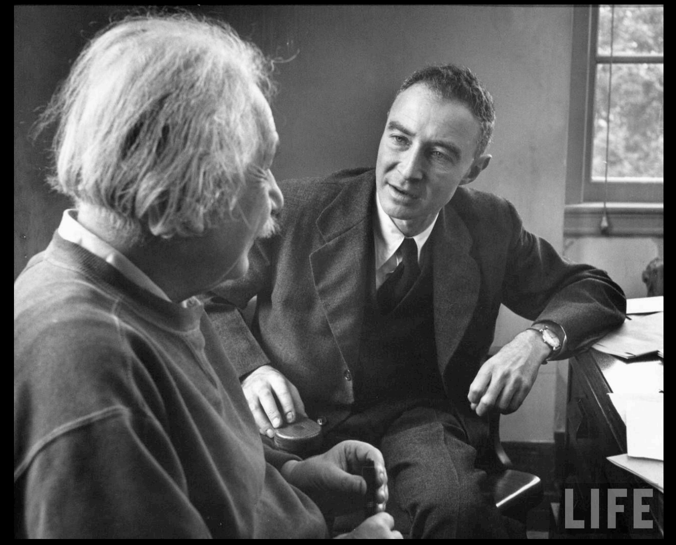


Neutron Stars: The Role of Nuclear Science

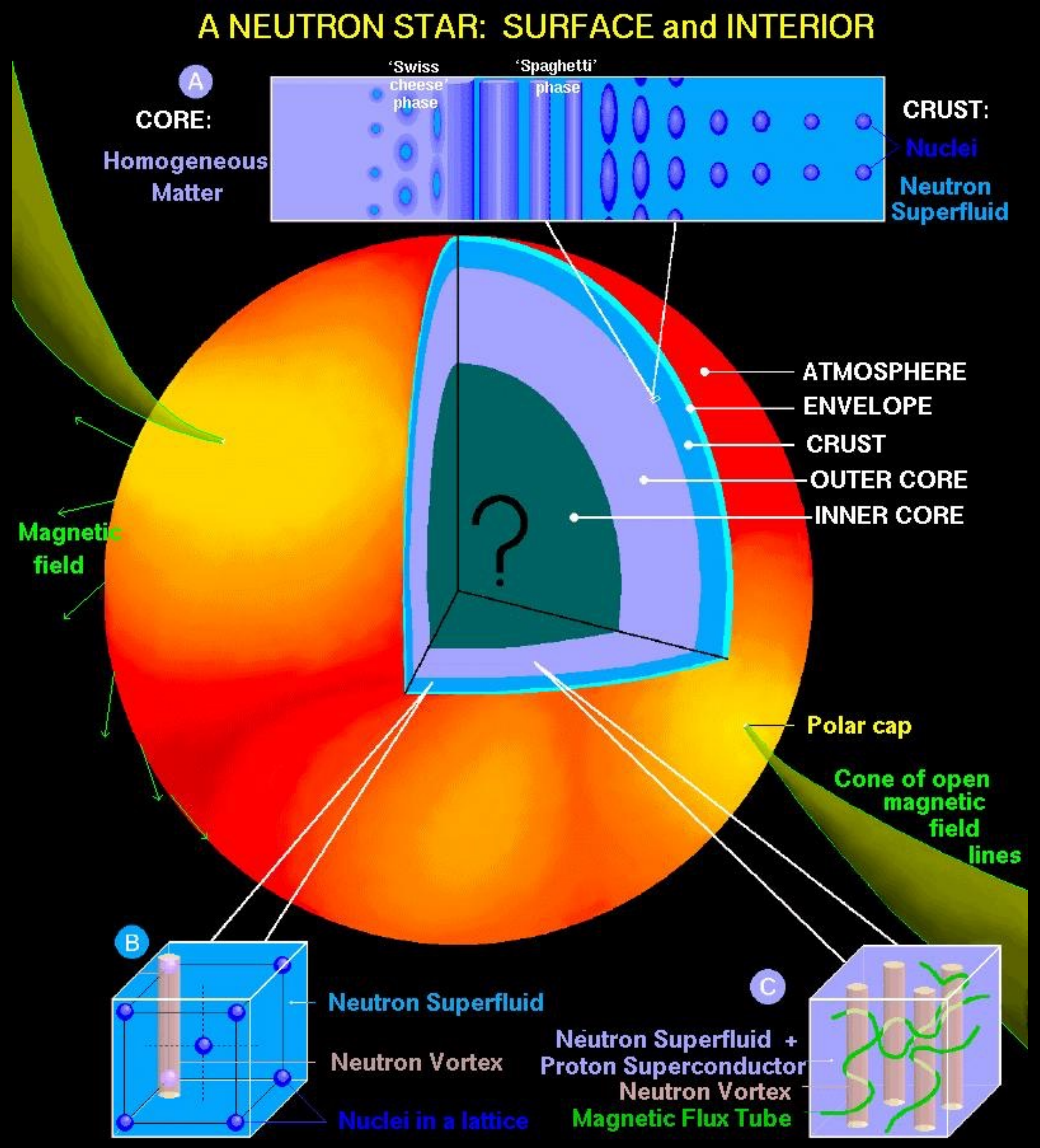


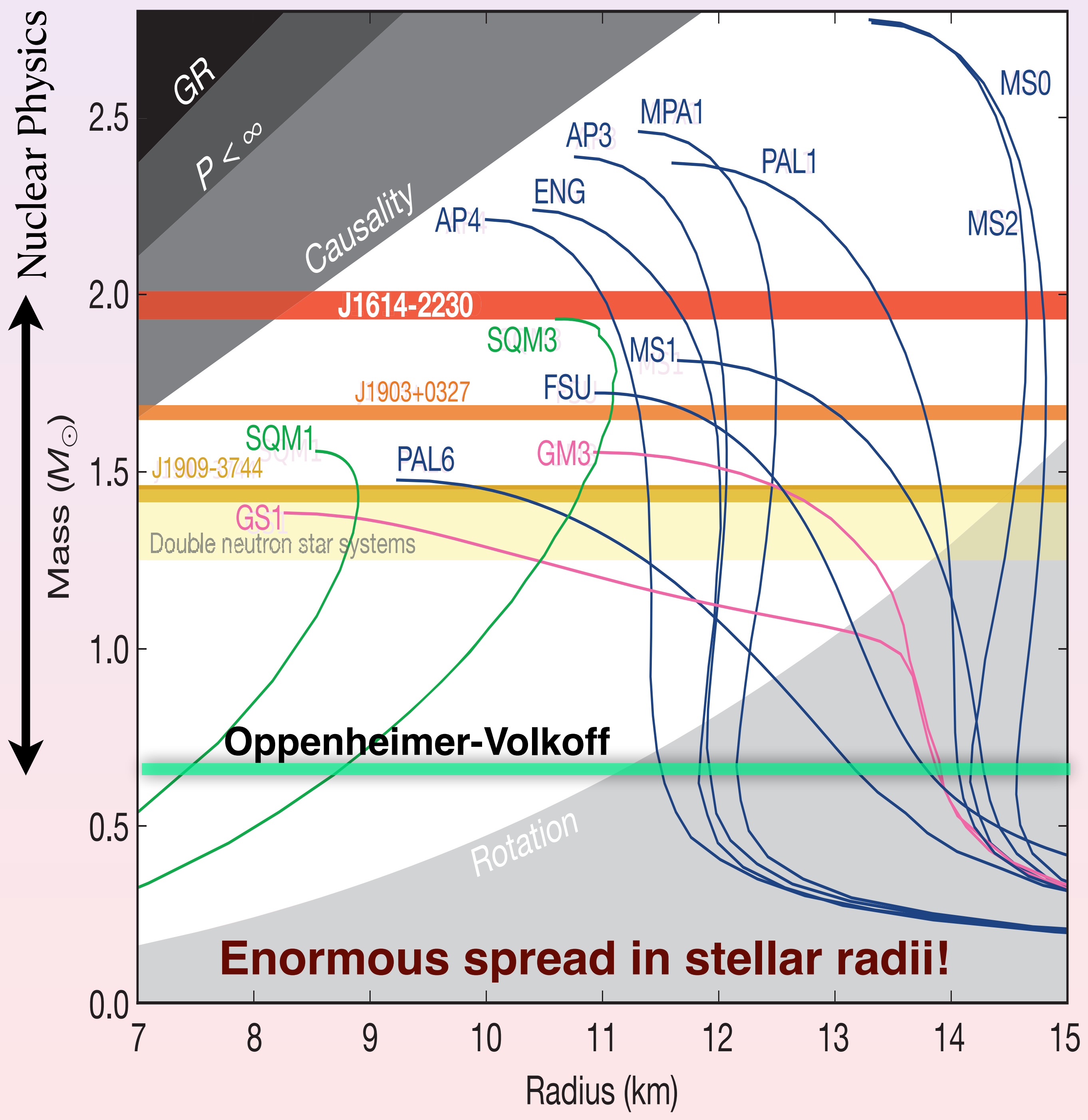
- Neutron stars are the remnants of massive stellar explosions (CCSN)

  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!





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

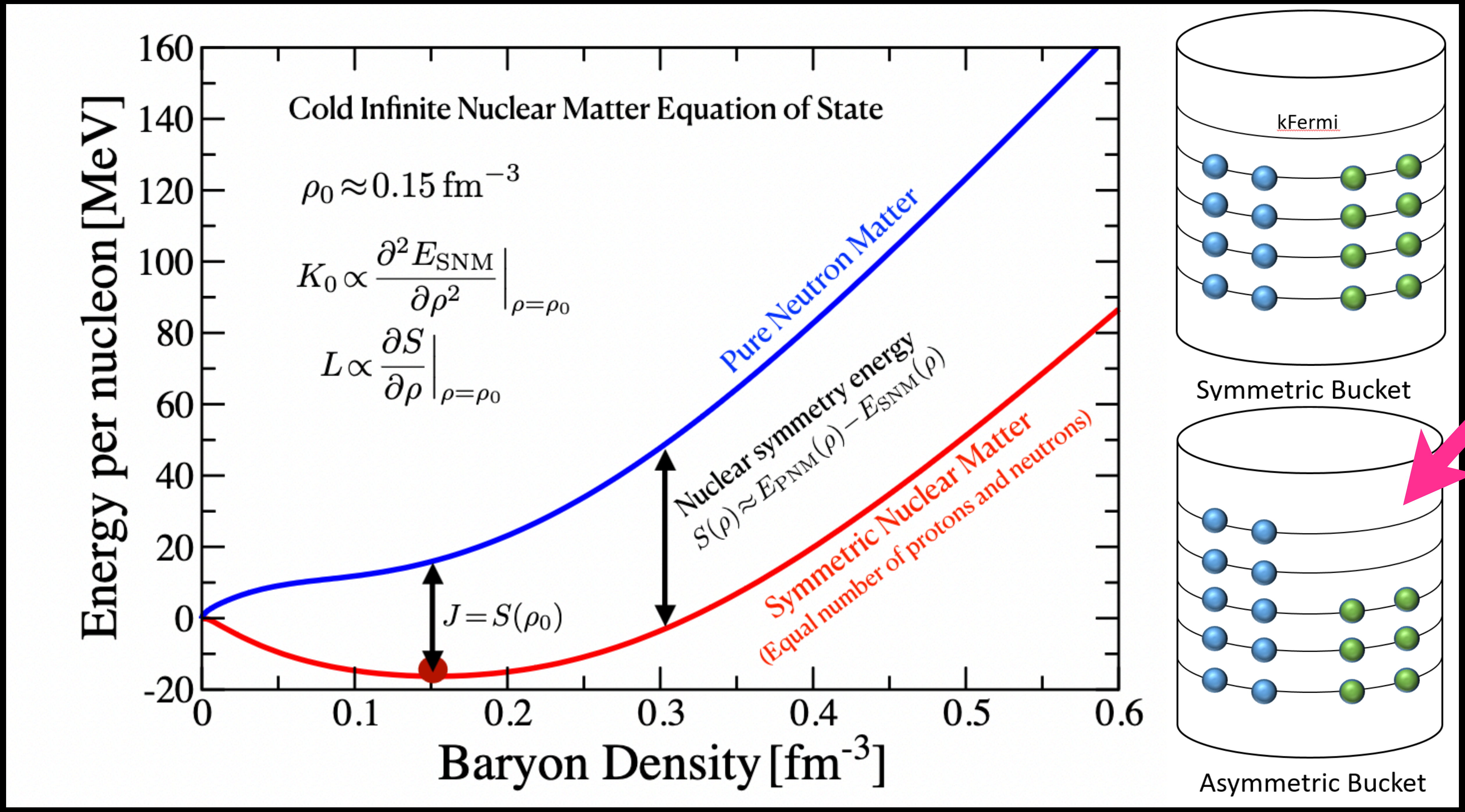
$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

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

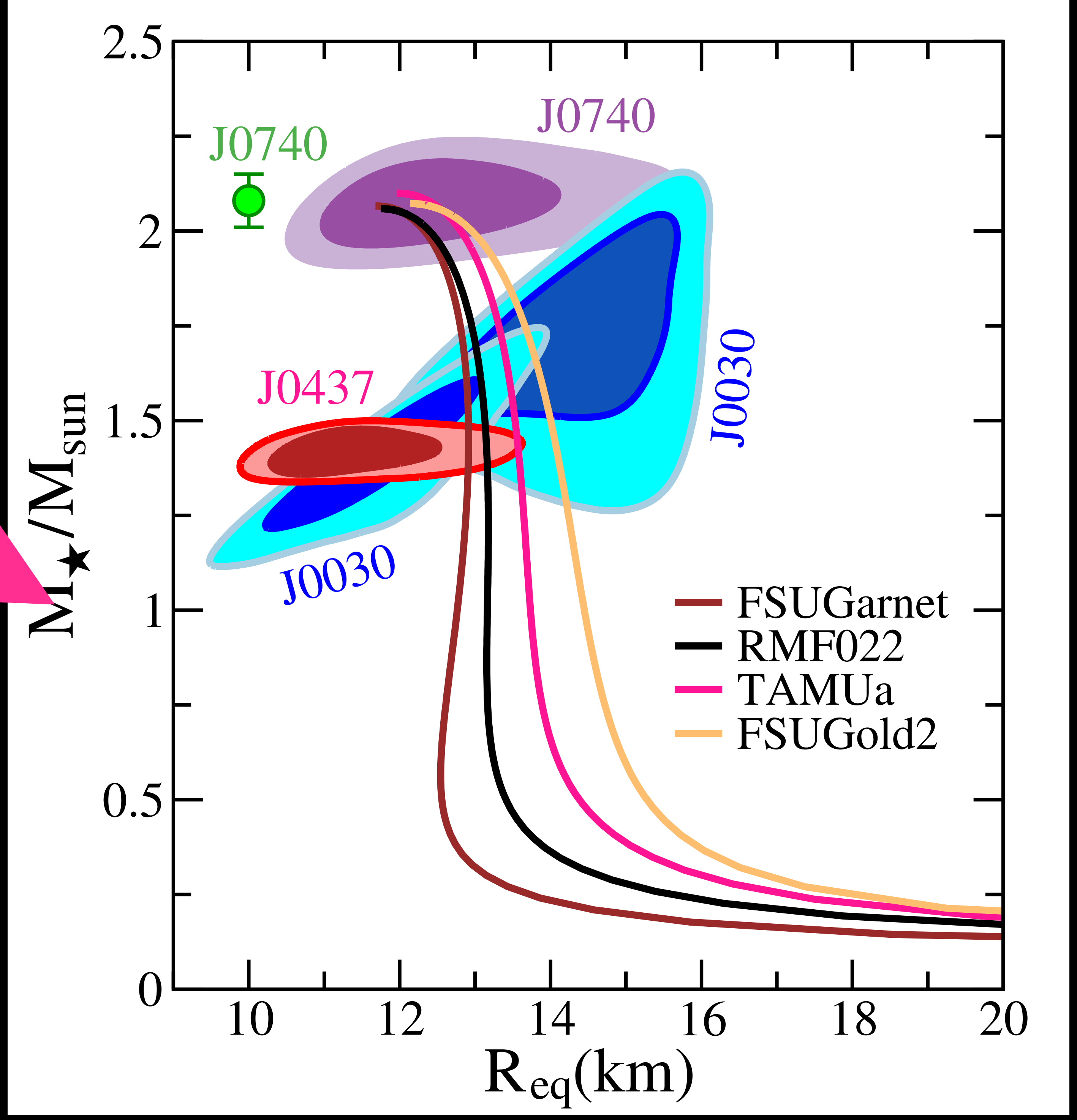
Nuclear Physics Critical

Micro-macro connection

Neutron Stars and The Equation of State of Neutron-Rich Matter



Micro-Macro Connection



Only Physics that the TOV equation is sensitive to is the Equation of State

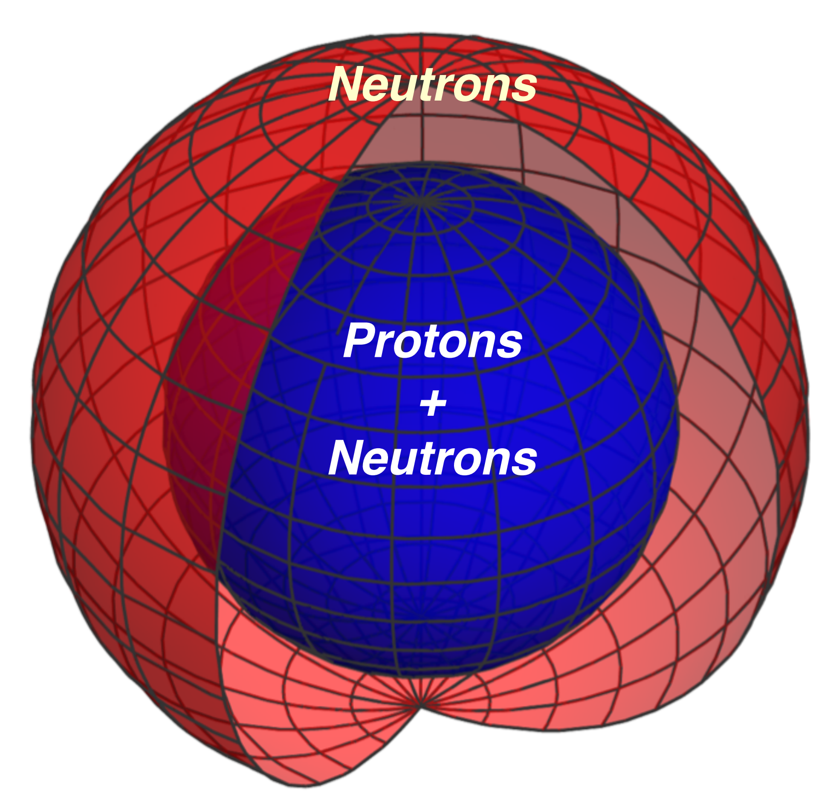
$$S(\rho_0) \approx \left(E_{\mathrm{PNM}} - E_{\mathrm{SNM}}\right)(\rho_0) = J$$

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

"Stiff" ⟶ L large

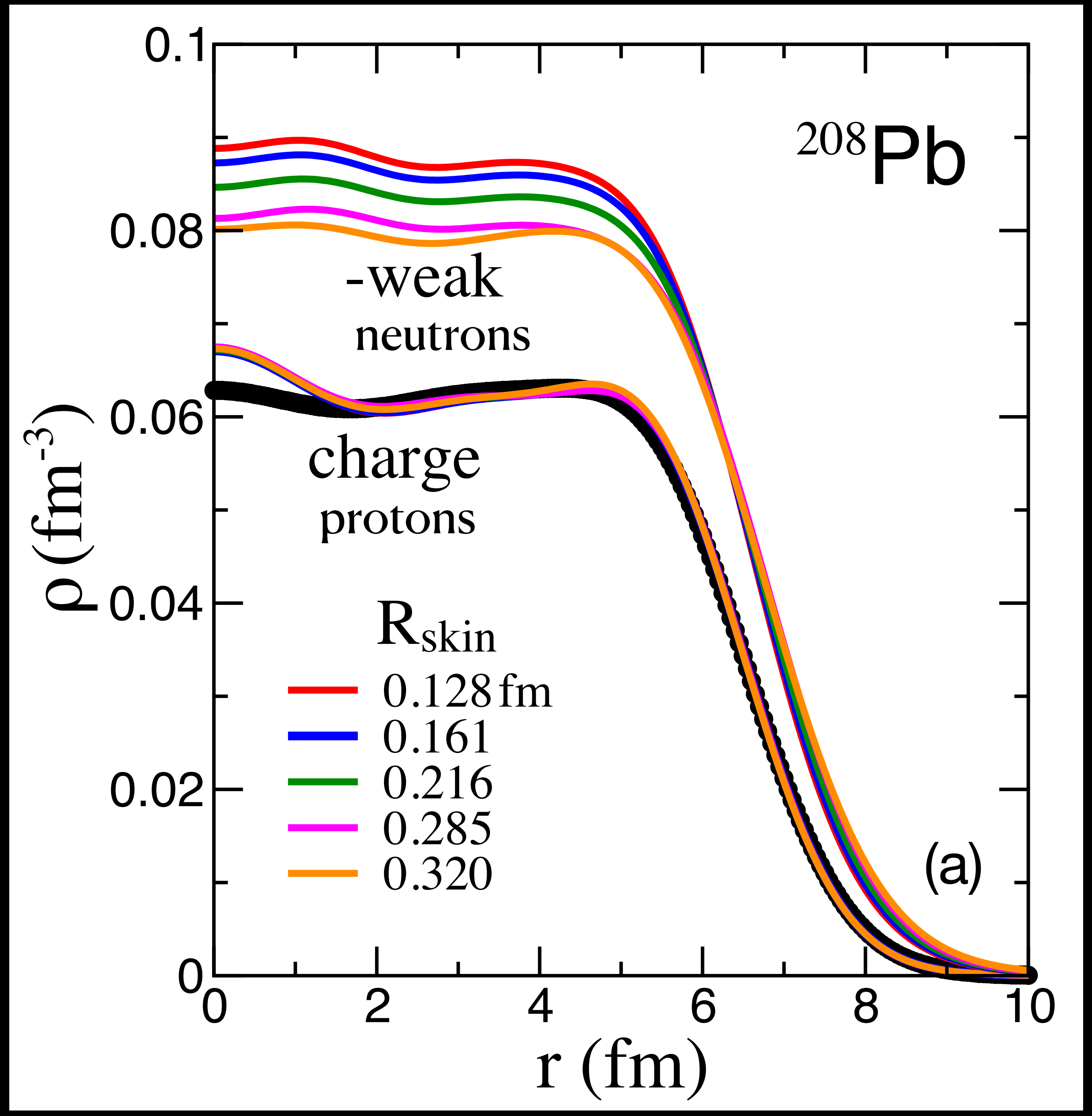
"Soft" ⟶ L small

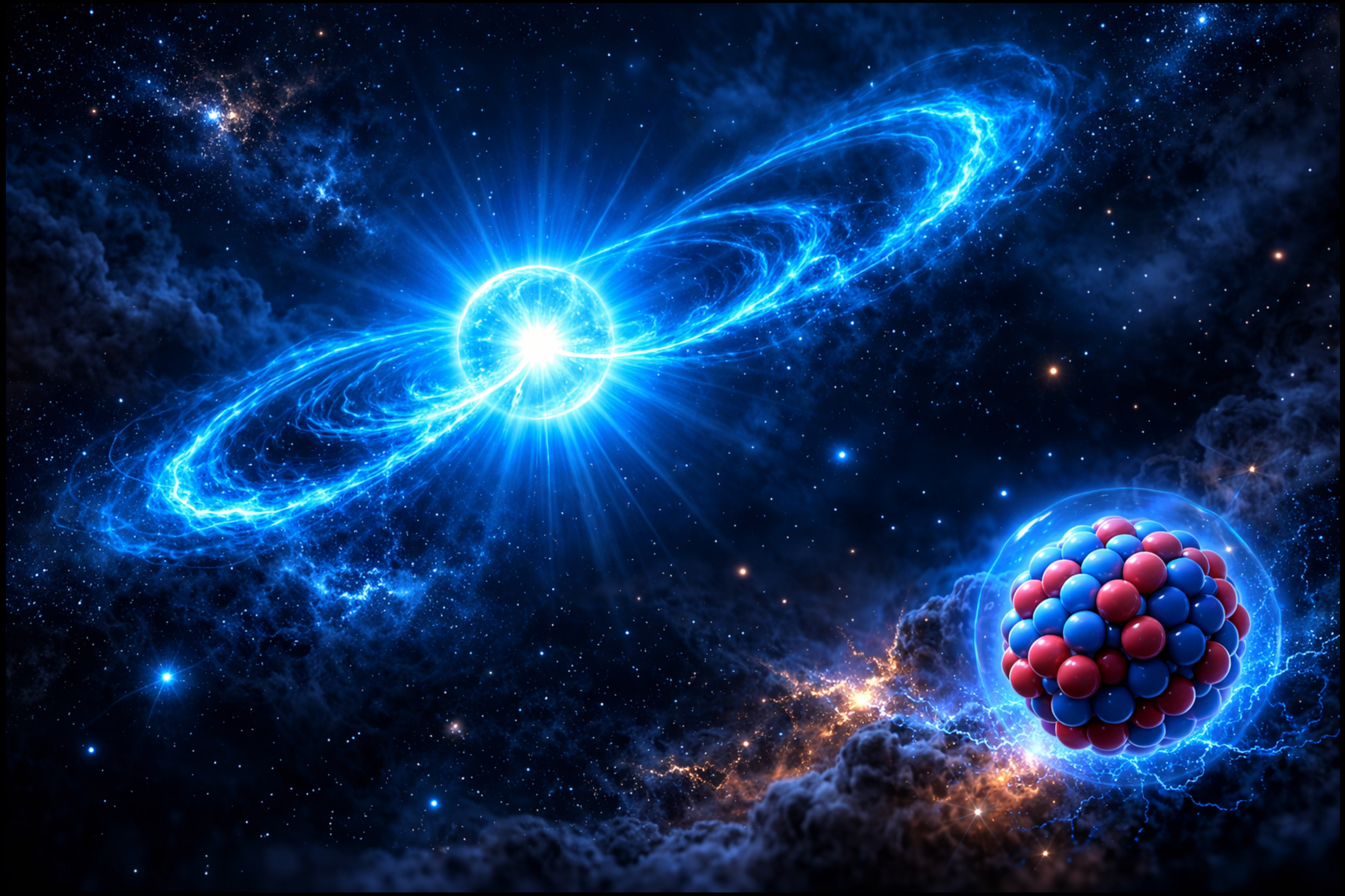
PREX constrains L!

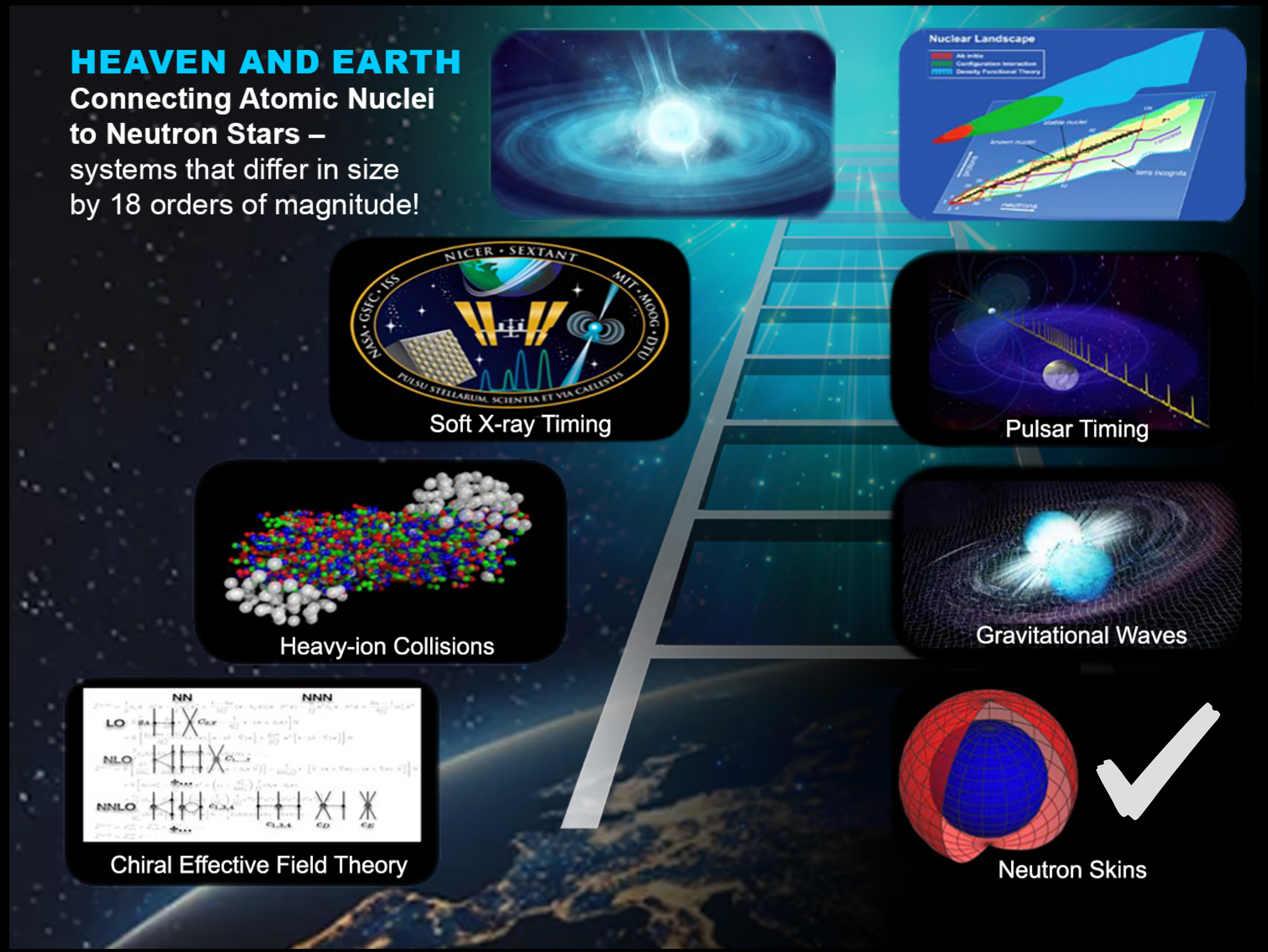


Neutron Skins

$$R_{\text{skin}} \equiv R_n - R_p$$

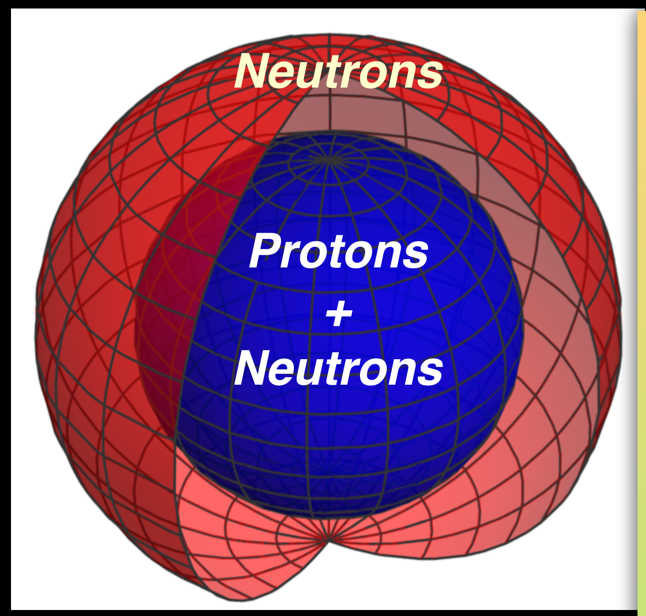


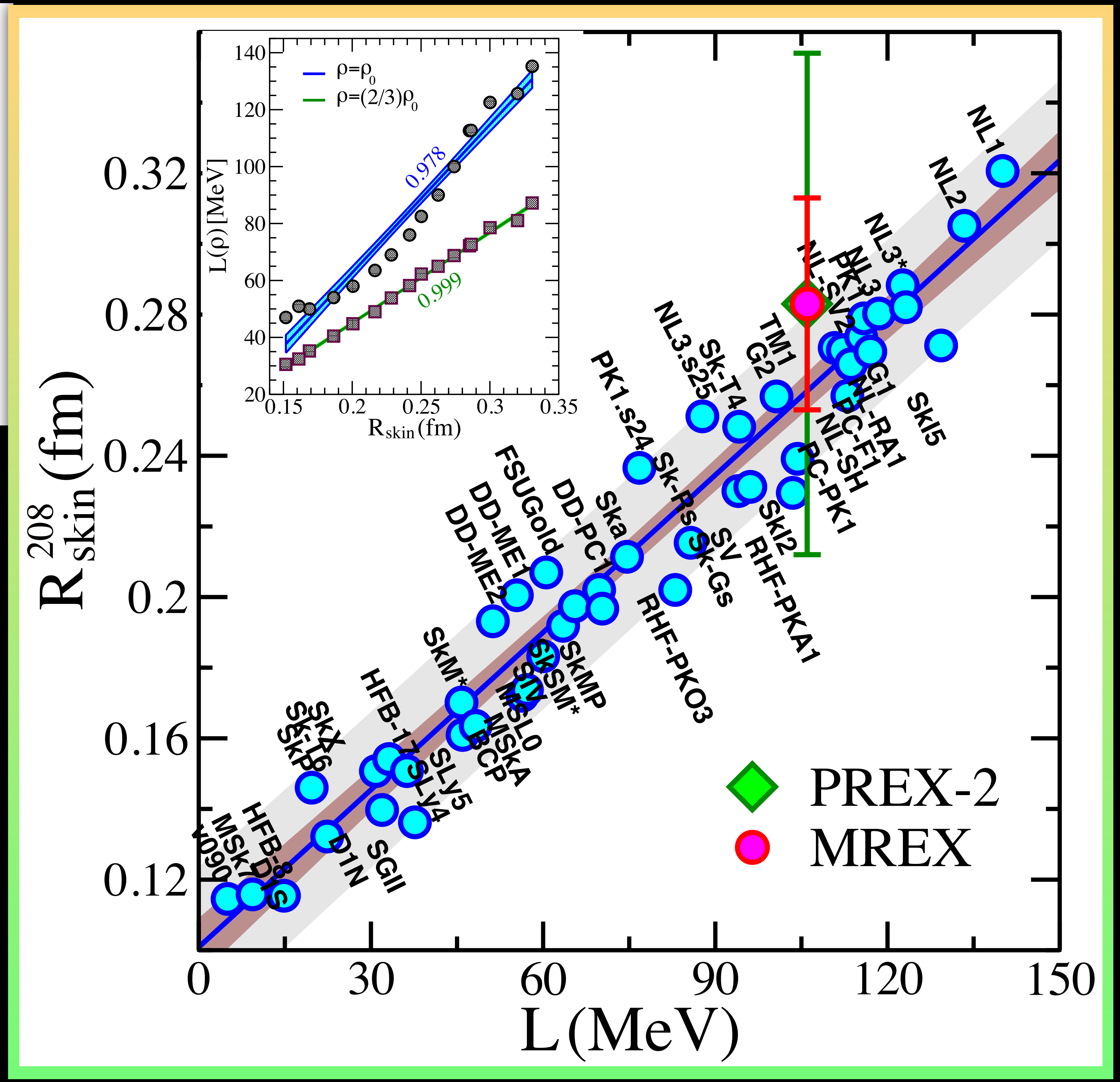




Heaven and Earth

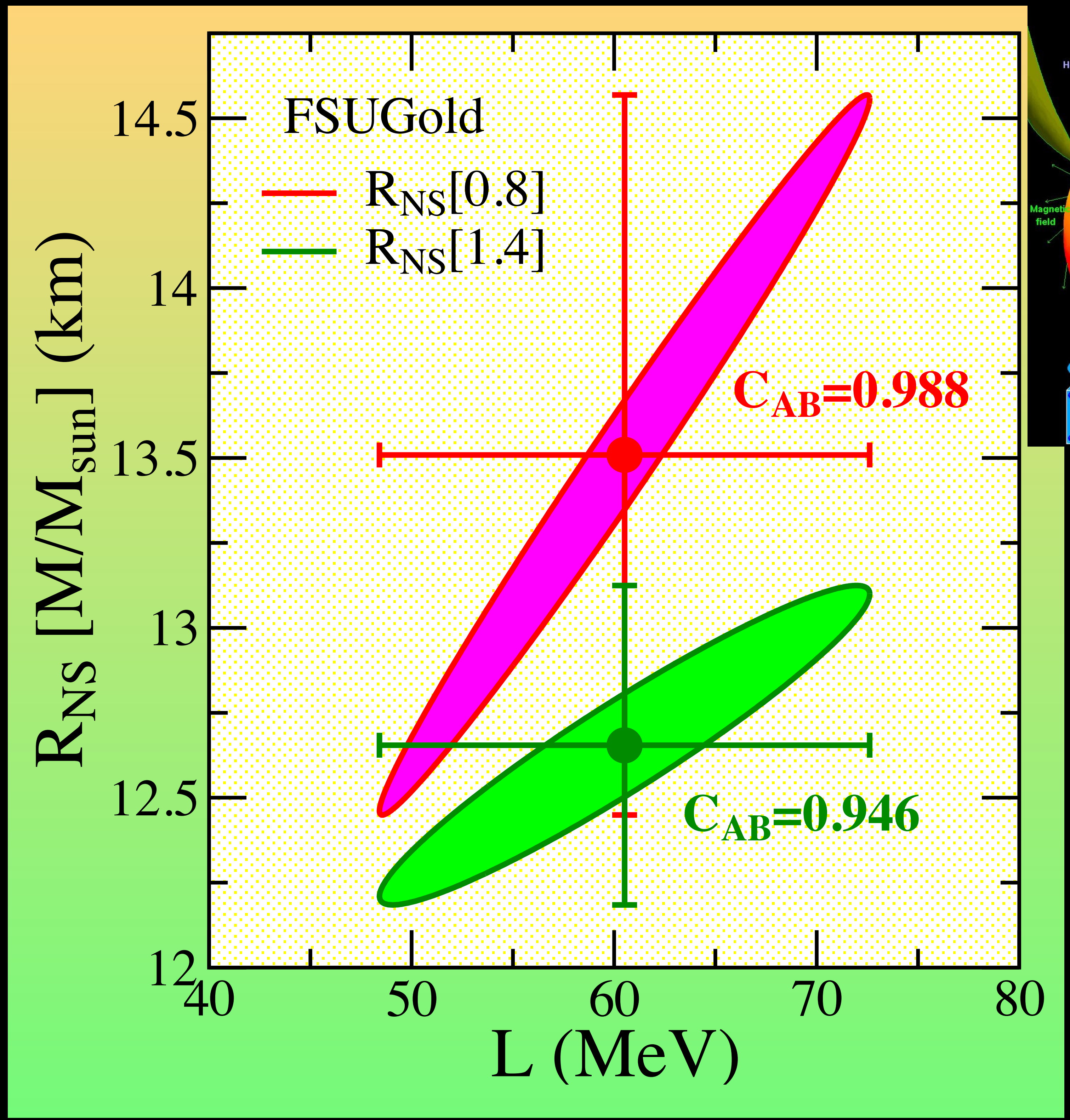
Laboratory Constraints on the EOS

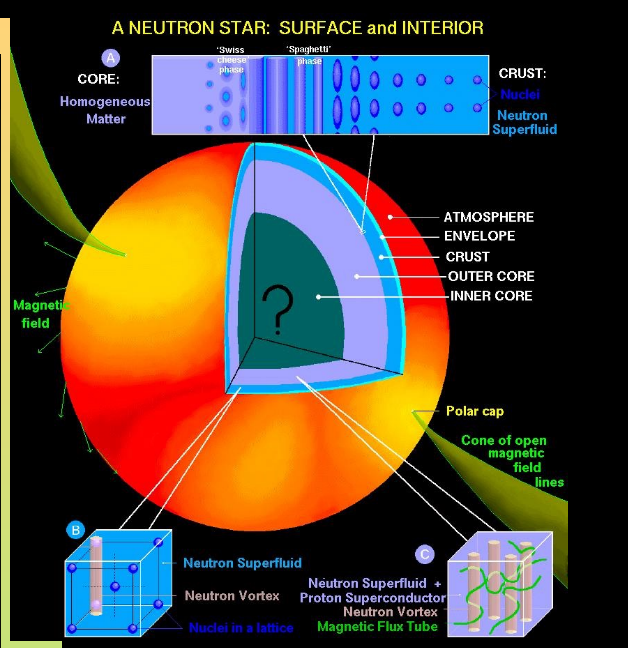




18 orders

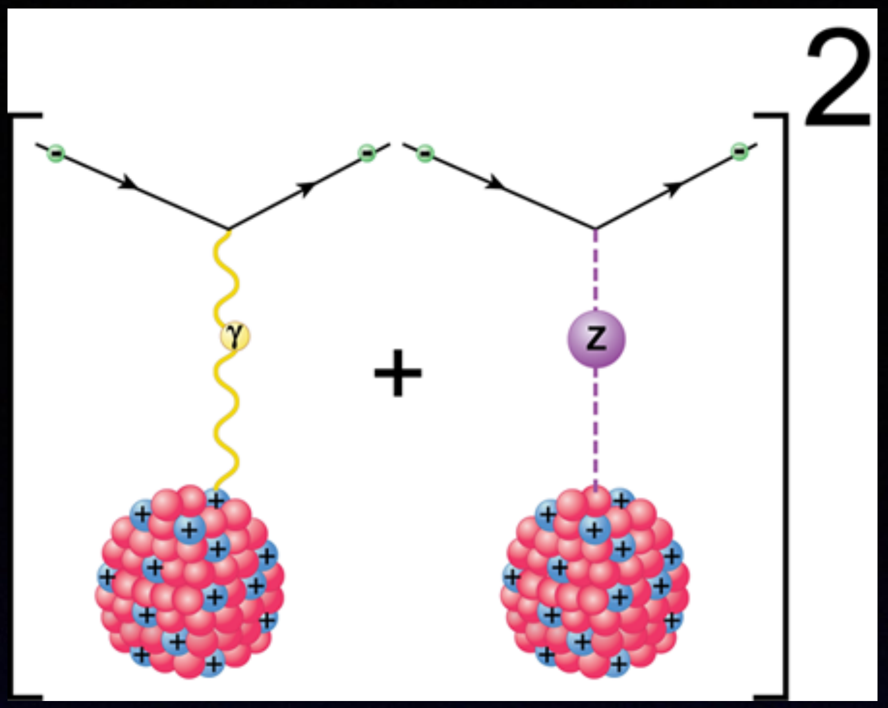
magnitude





The nuclear interaction is responsible for describing finite nuclei and neutron stars!

The pressure of pure neutron matter (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!

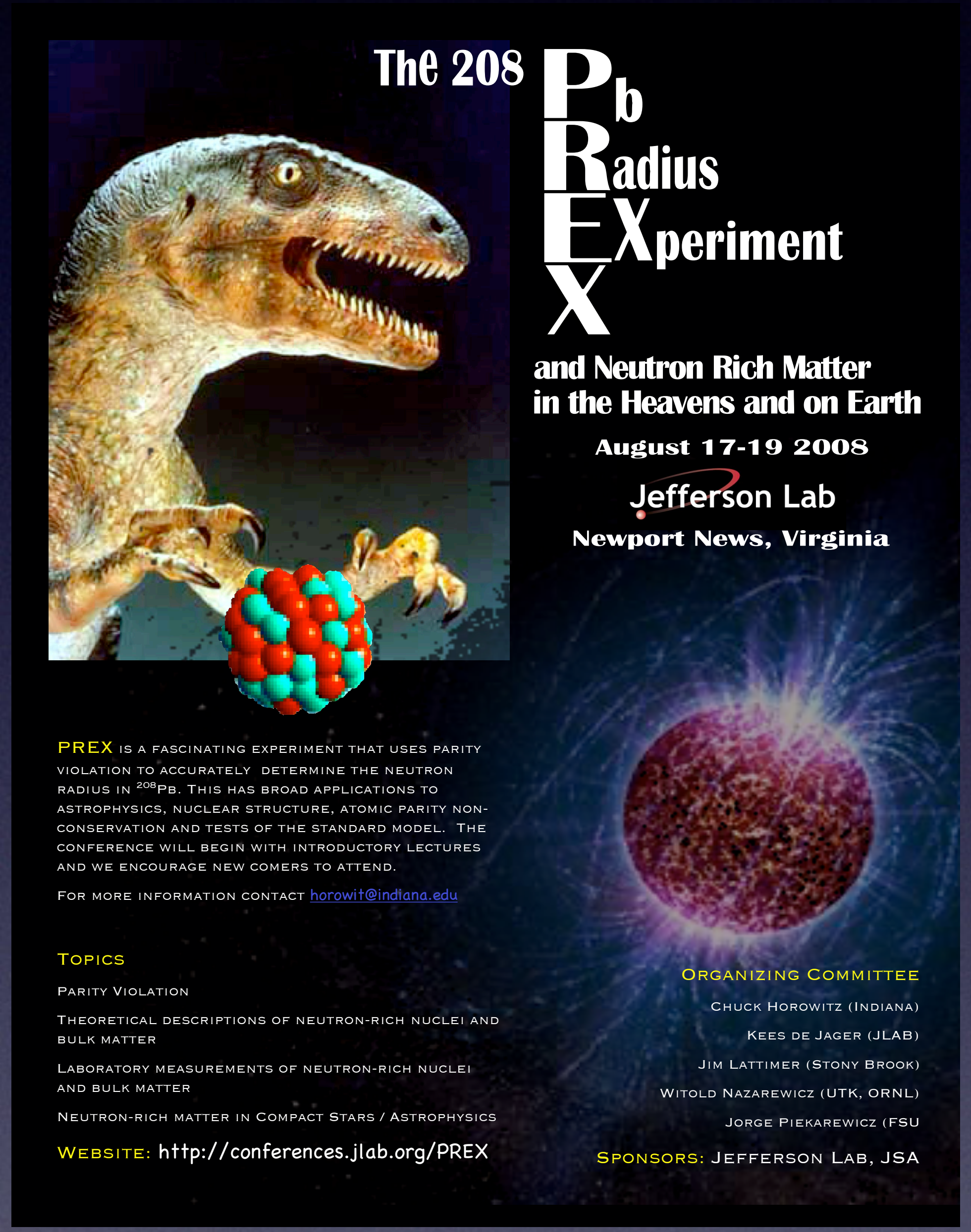


Parity Violating e-Nucleus Scattering

Searching fo our most accurate picture of the nuclear weak-charge distribution!

- Charge (proton) density known with enormous precision
  - Probed via parity-conserving elastic e-scattering
- Weak-charge (neutron) density known very poorly known
  - Probed via parity-violating asymmetry in elastic e-scattering
  - Z_0 couples preferentially to neutrons in the target

$$A_{\rm PV} \equiv \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L}\right] = \left(\frac{G_{\rm F}Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} \simeq 10^{-6}$$



$$R^{208}_{\rm skin} = (0.283 \pm 0.071)\,{\rm fm}$$

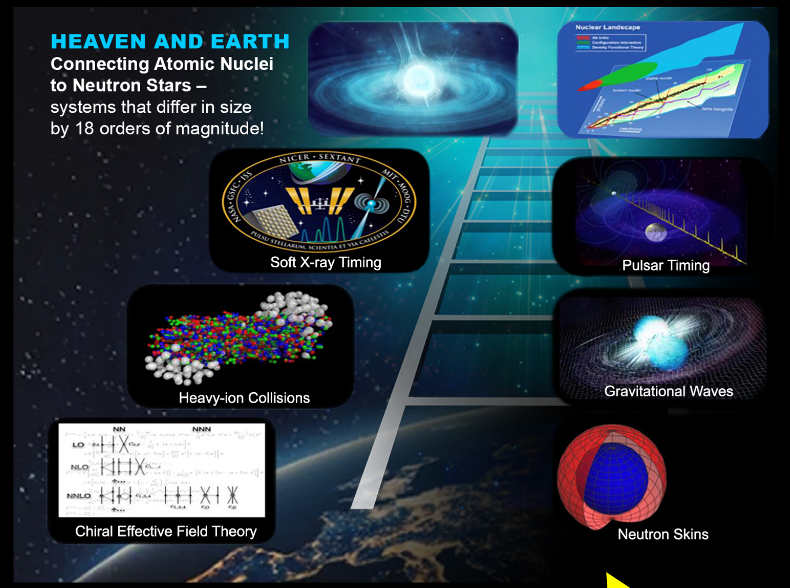
PREX-2021: L is BIG!

	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

Electroweak experiments will provide fundamental anchors for future campaigns at FRIB and other exotic beam facilities

Adhikari et al., PRL 126, 172502 (2021)



Pb **R**adius **EX**periment

Neutron Skins

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

PREX-Informed Value:

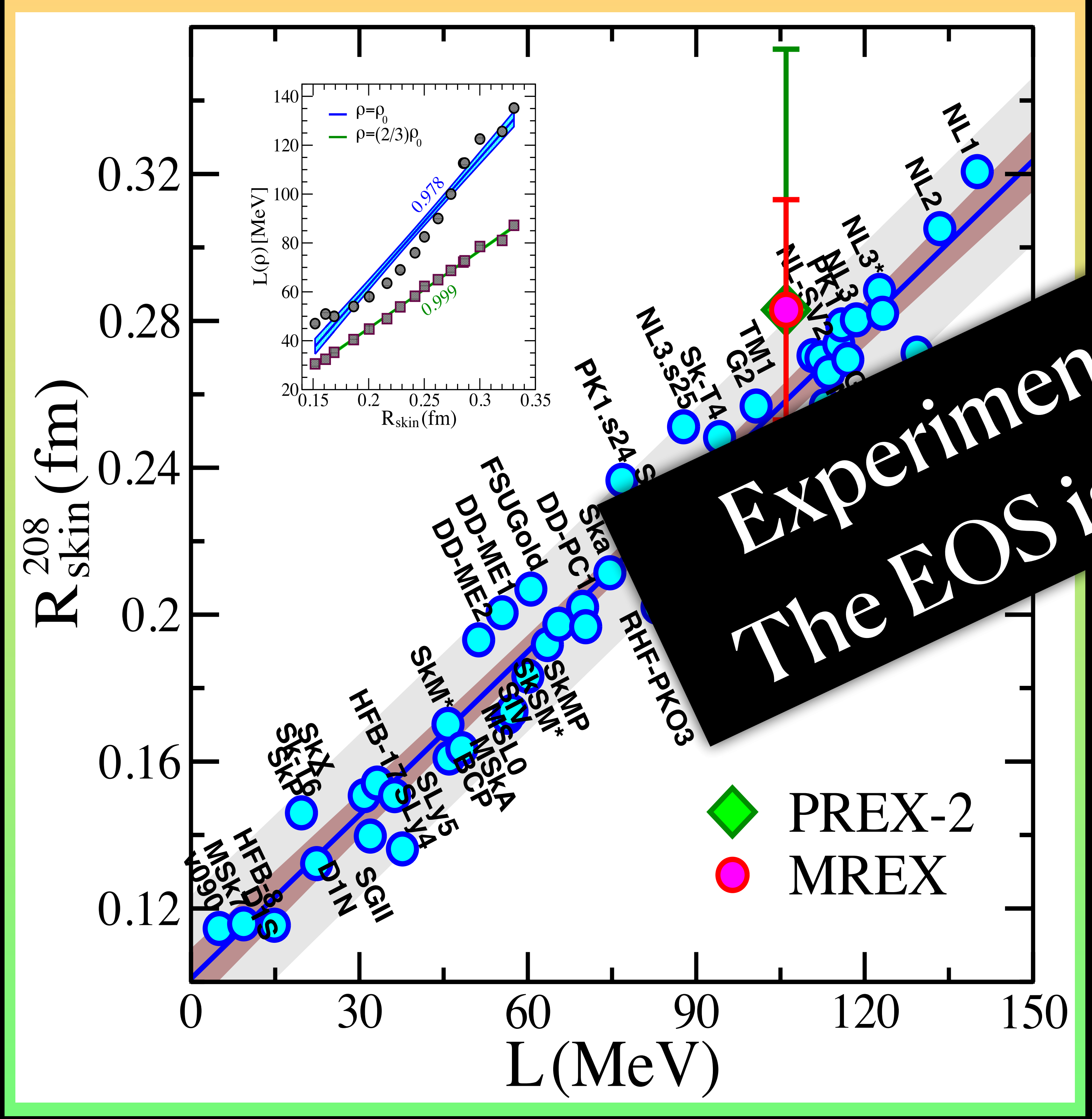
$P(\rho_0) = (5.23 \pm 1.83)$ MeV /...

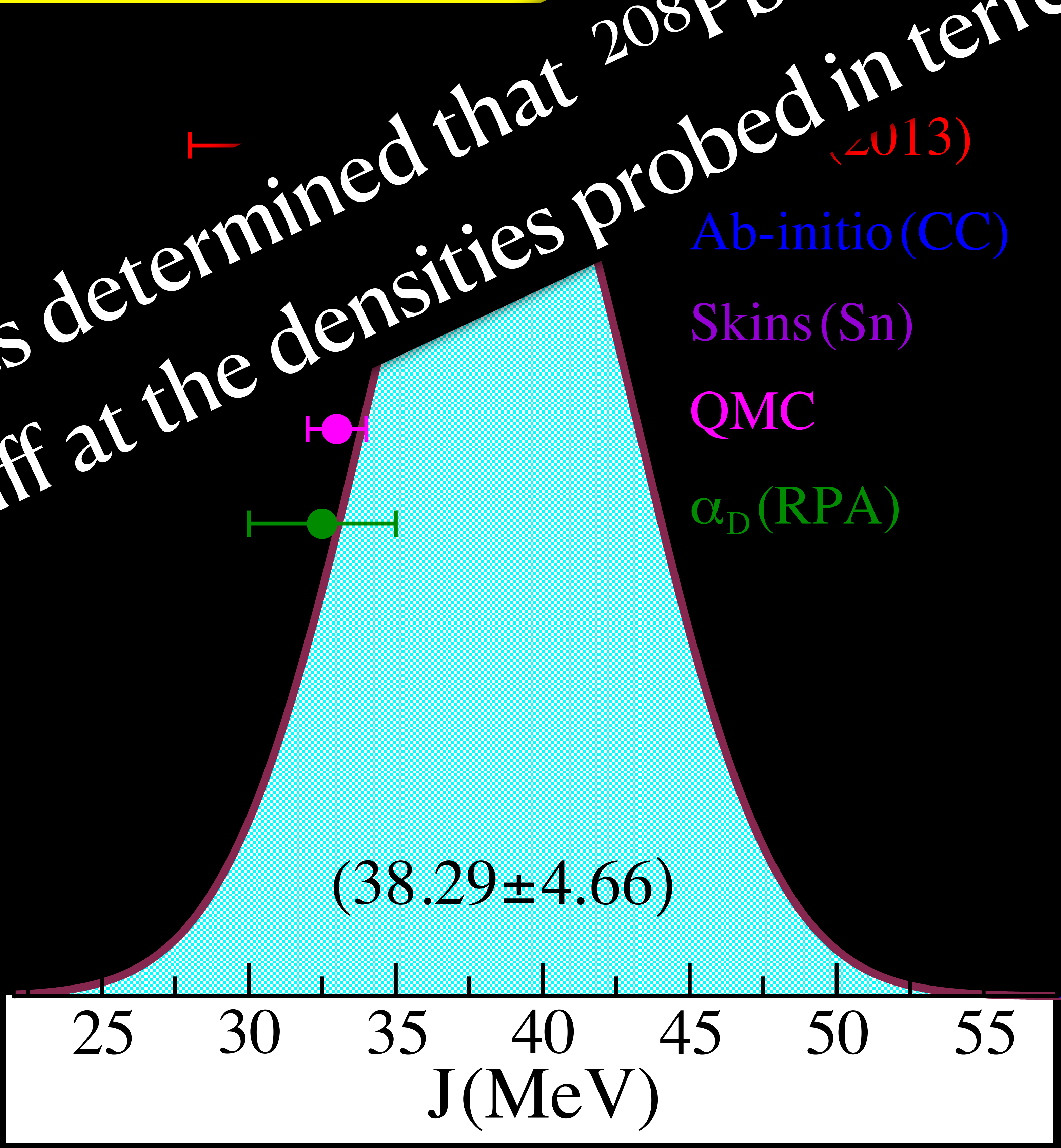
🌐 Relevance for Nuclear Physics, Astrophysics, an... for You

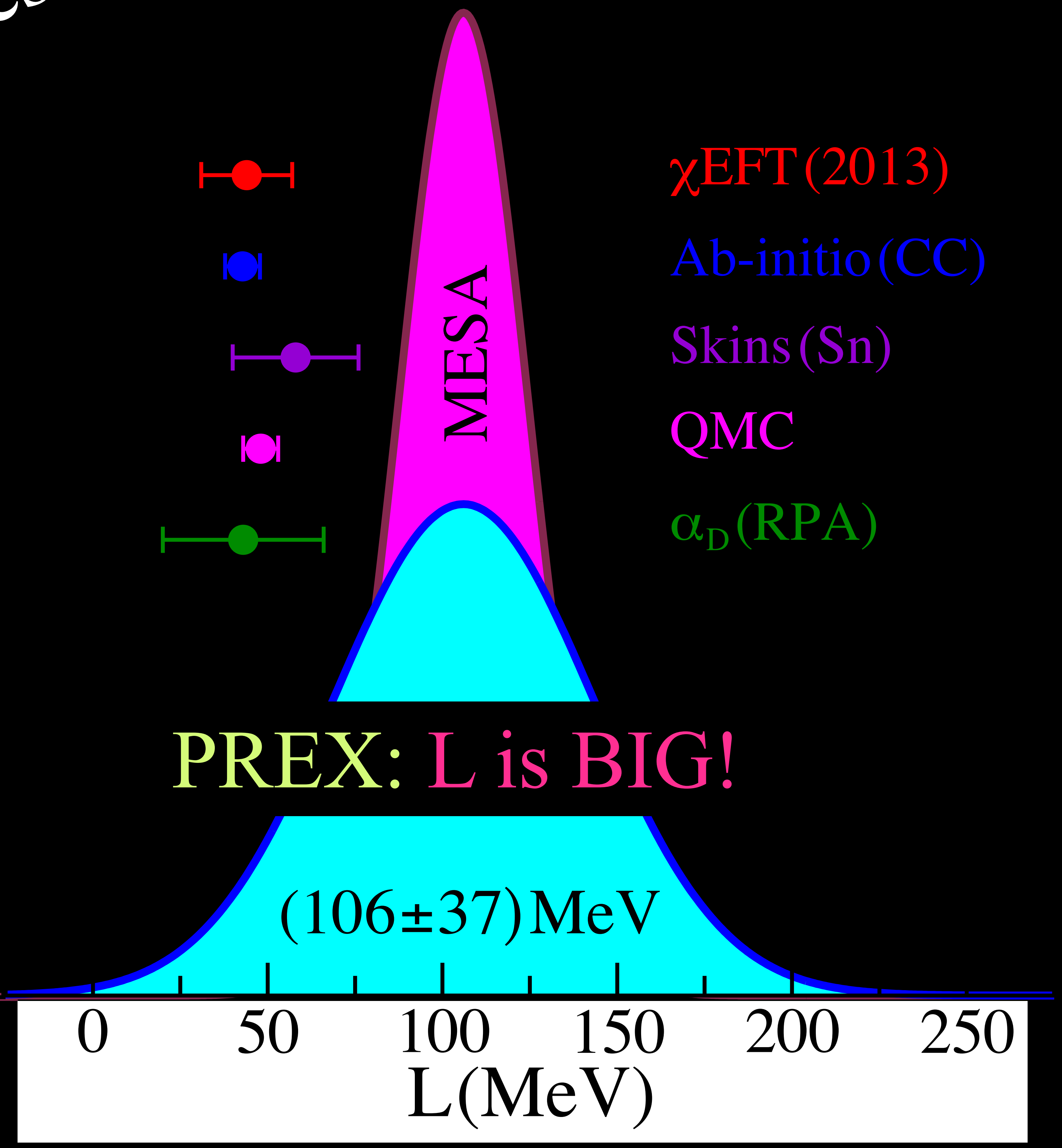
Given your own stron... in neutron skins, equation-of-stat... odels, **MREX is directly** ... th to a *higher-*... ...ence neutron-skin ...ent for Pb-208.

Experiment has determined that 208Pb has a thick neutron skin.

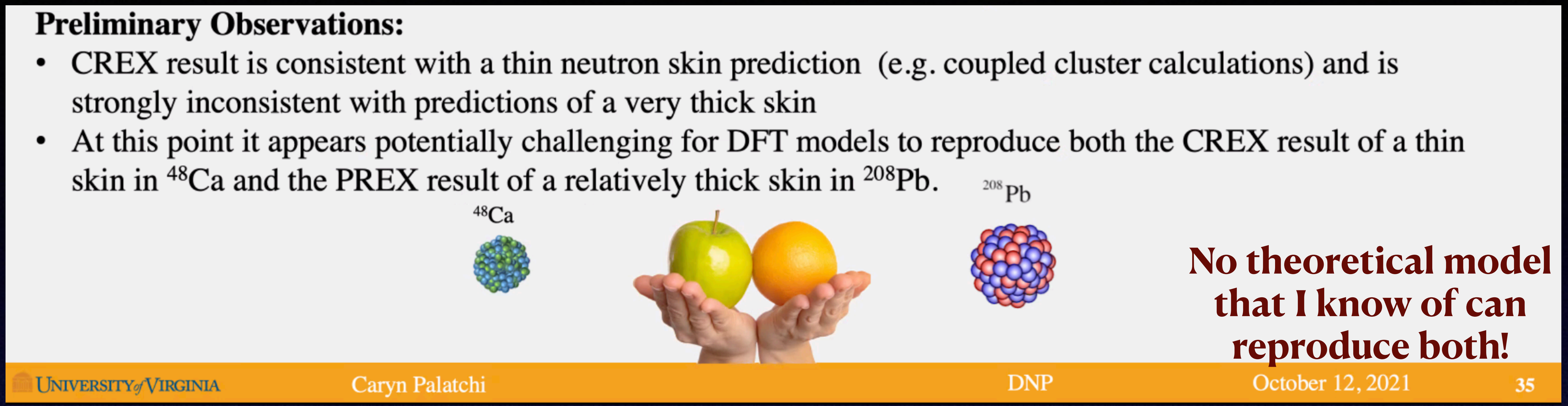
The EOS is stiff at the densities probed in terrestrial experiments!



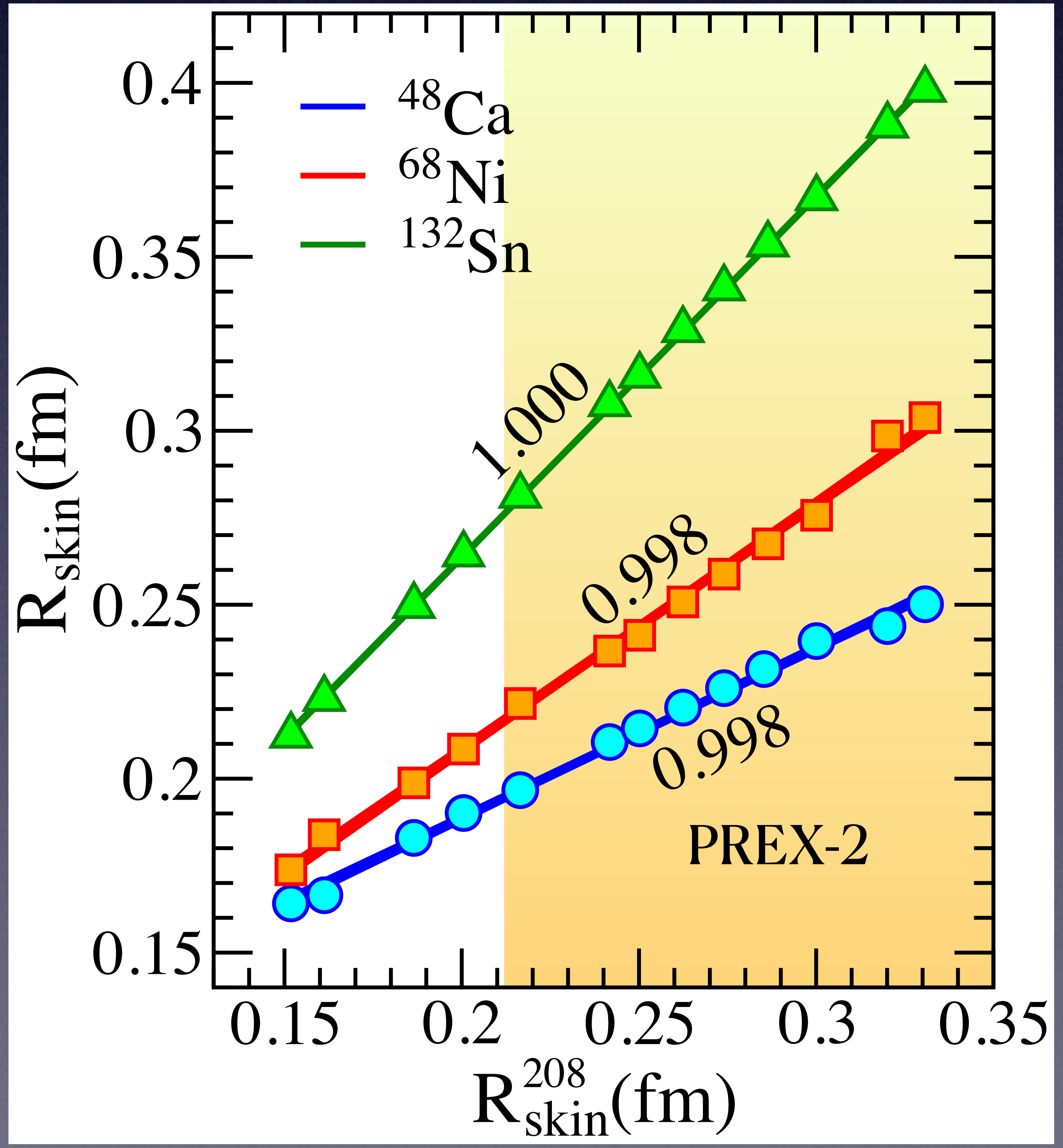


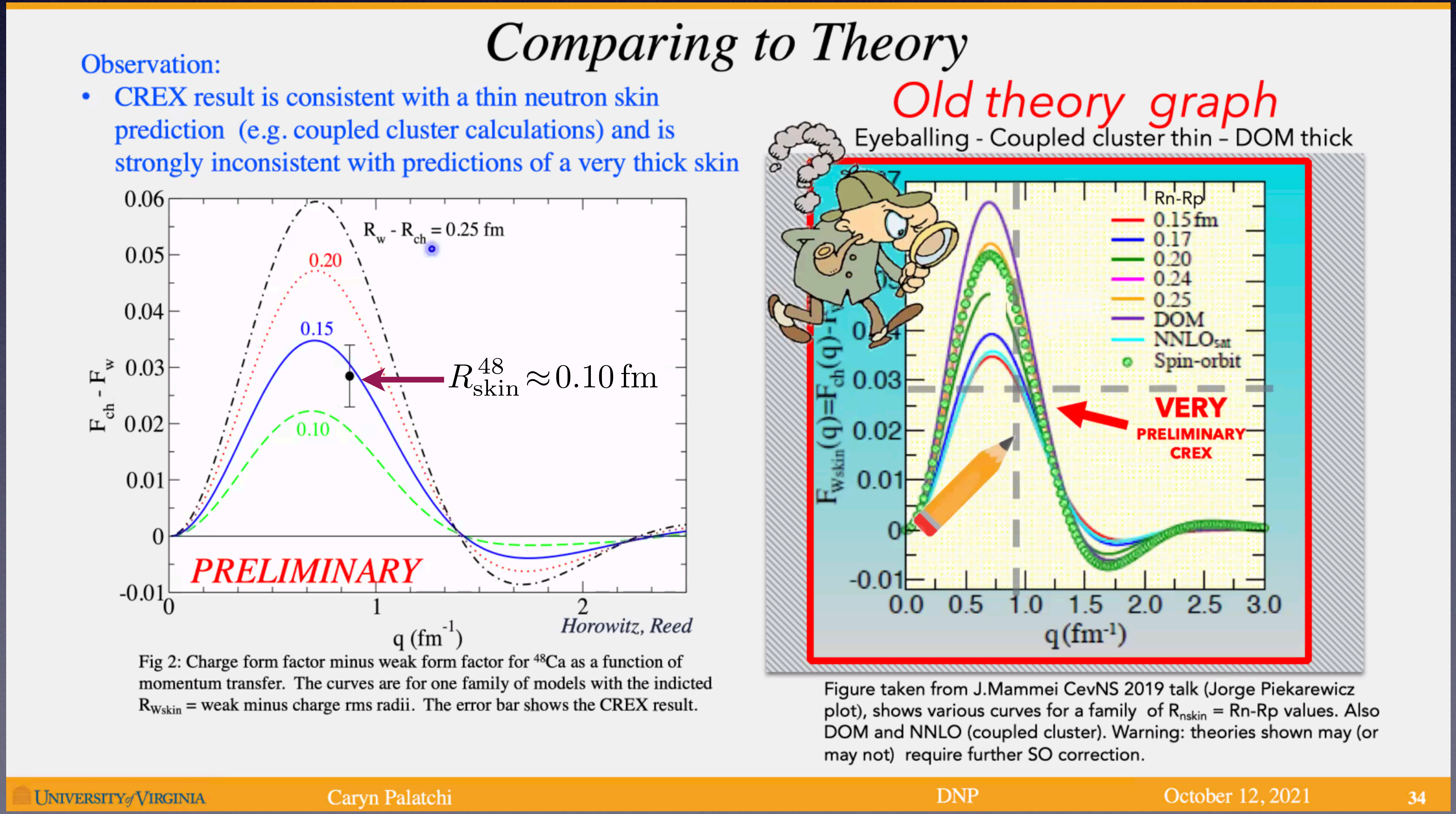


Among the Open Questions: Who Ordered That?



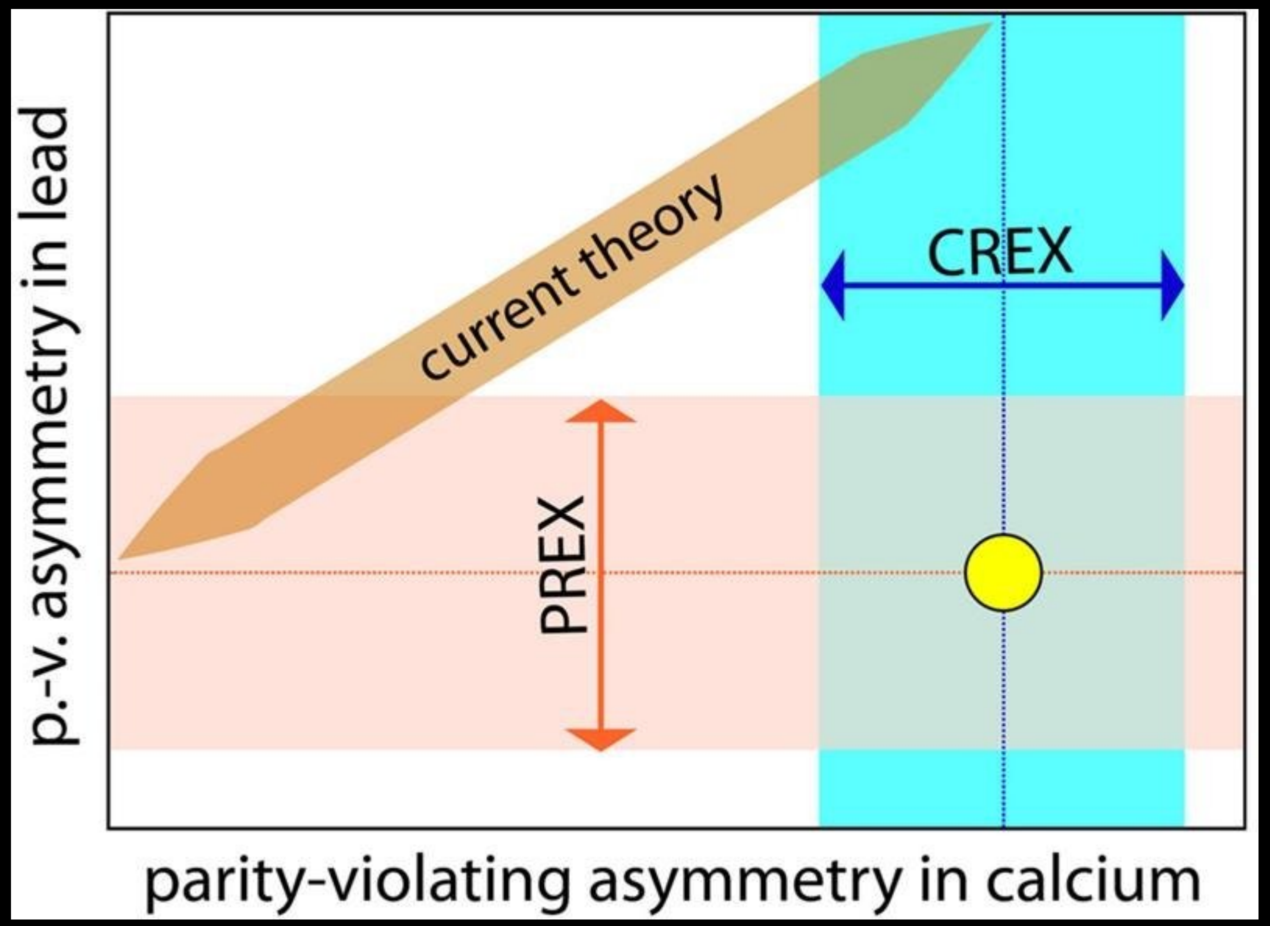
Isidor Isaac Rabi

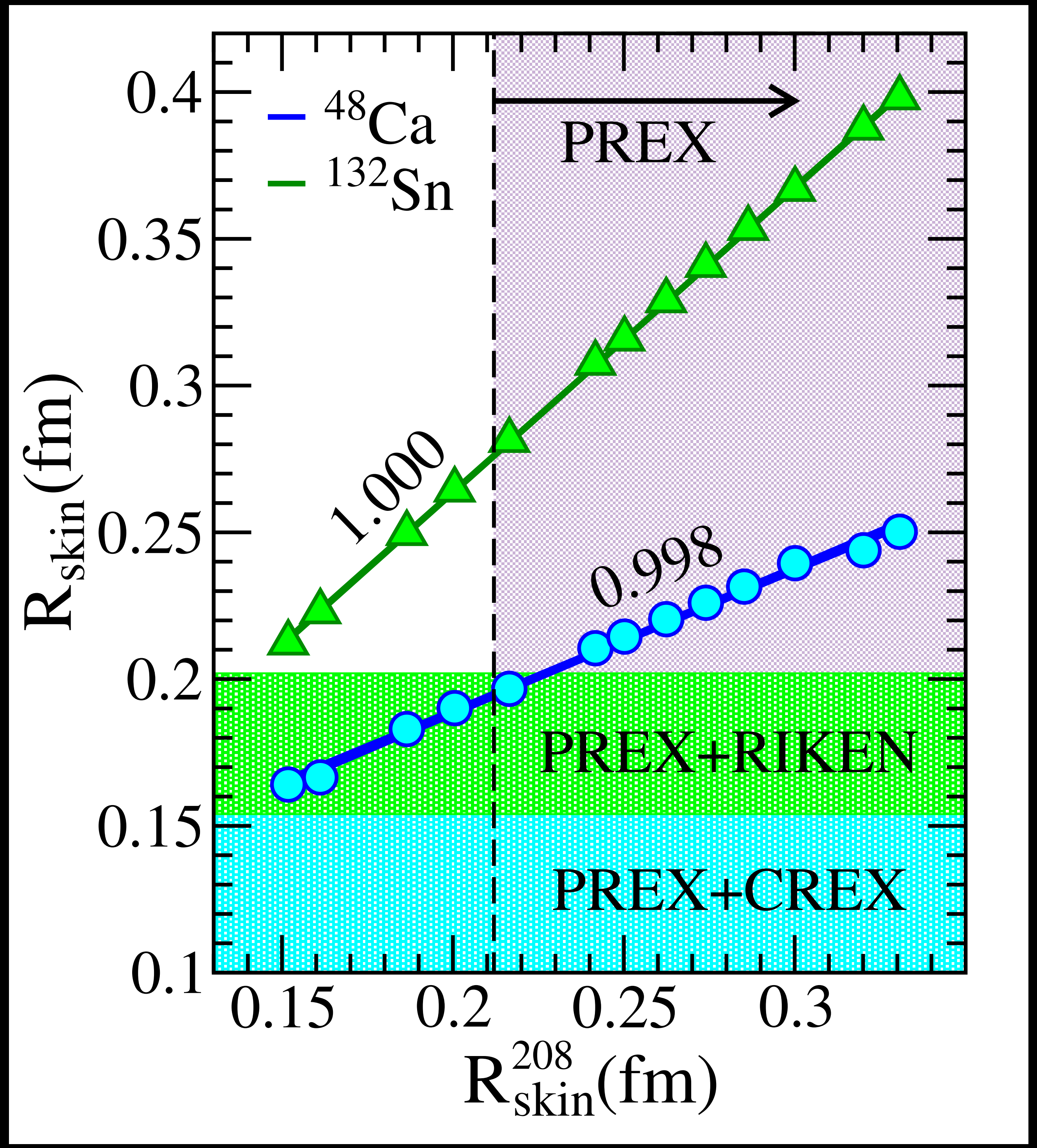


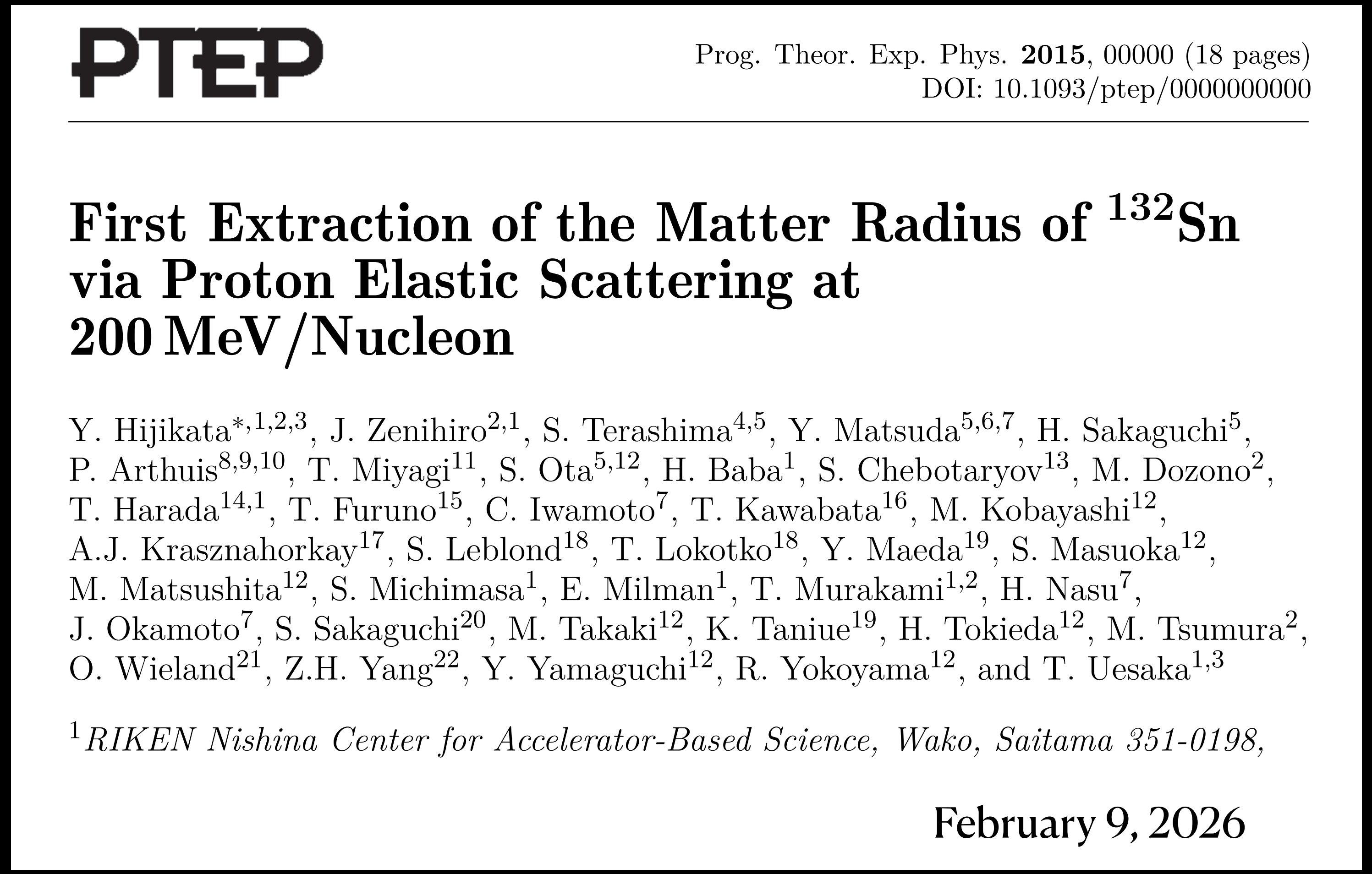


THE PLOT THICKENS

The PREX-CREX-SREX Dilemma







PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (18 pages)
DOI: 10.1093/ptep/0000000000

First Extraction of the Matter Radius of ^{132}Sn via Proton Elastic Scattering at 200 MeV/Nucleon

Y. Hijikata[*,1,2,3], J. Zenihiro[2,1], S. Terashima[4,5], Y. Matsuda[5,6,7], H. Sakaguchi[5], P. Arthuis[8,9,10], T. Miyagi[11], S. Ota[5,12], H. Baba[1], S. Chebotaryov[13], M. Dozono[2], T. Harada[14,1], T. Furuno[15], C. Iwamoto[7], T. Kawabata[16], M. Kobayashi[12], A.J. Krasznahorkay[17], S. Leblond[18], T. Lokotko[18], Y. Maeda[19], S. Masuoka[12], M. Matsushita[12], S. Michimasa[1], E. Milman[1], T. Murakami[1,2], H. Nasu[7], J. Okamoto[7], S. Sakaguchi[20], M. Takaki[12], T. Taniue[19], H. Tokieda[12], M. Tsumura[2], O. Wieland[21], Z.H. Yang[22], Y. Yamaguchi[12], R. Yokoyama[12], and T. Uesaka[1,3]

[1] *RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198,*

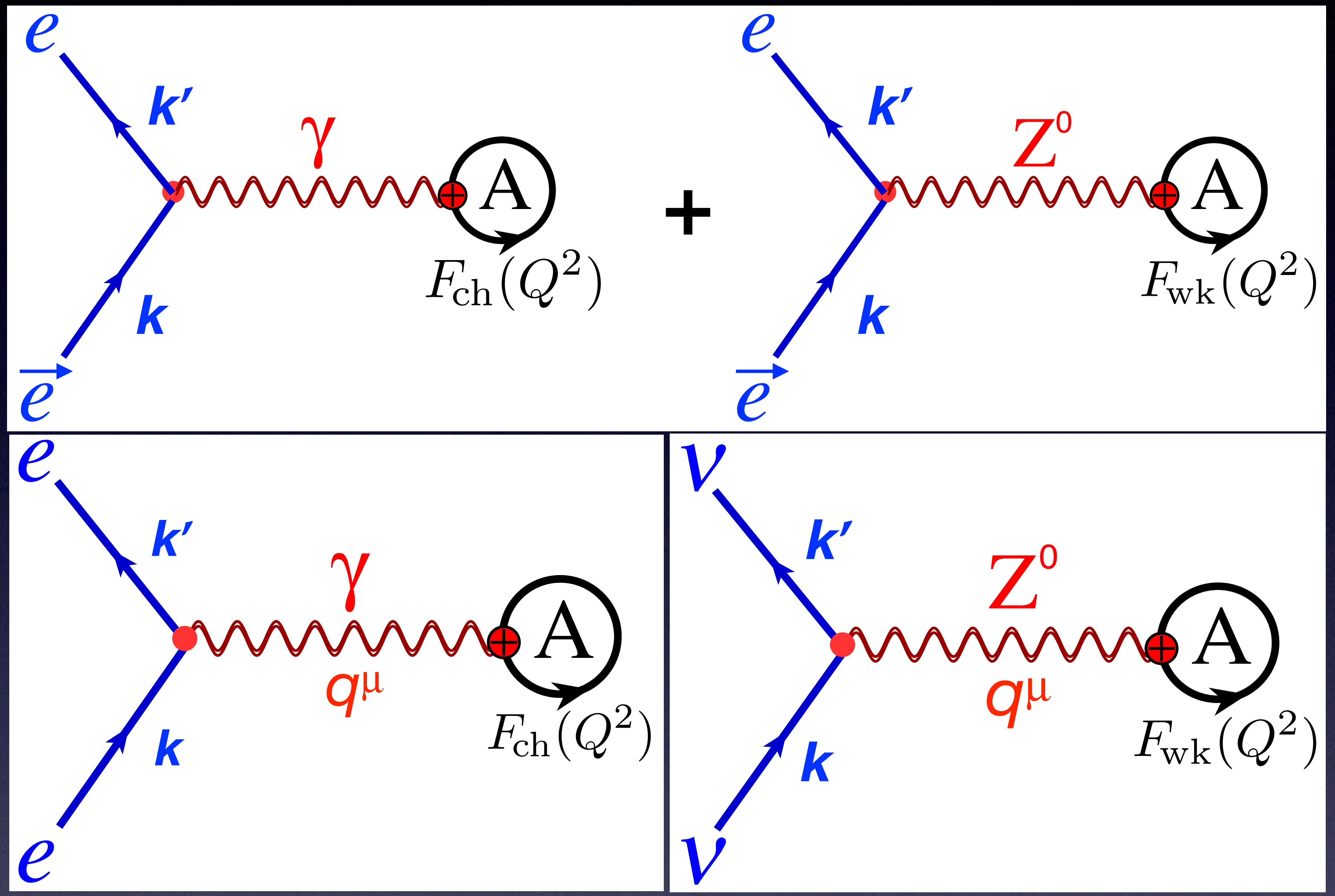
February 9, 2026

$$R_{\rm skin}^{208} = (0.283 \pm 0.071)\ {\rm fm}$$
$$R_{\rm skin}^{48} = (0.121 \pm 0.035)\ {\rm fm}$$
$$R_{\rm skin}^{132} = (0.178 \pm 0.024)\ {\rm fm}$$

JLAB+RIKEN

“FRIB offers an unprecedented opportunity to investigate the structure of neutron-rich nuclei, including the thickness of their neutron skins—key to understanding nuclear forces and the behavior of matter under extreme conditions”

Electroweak Probes of Nuclear Densities

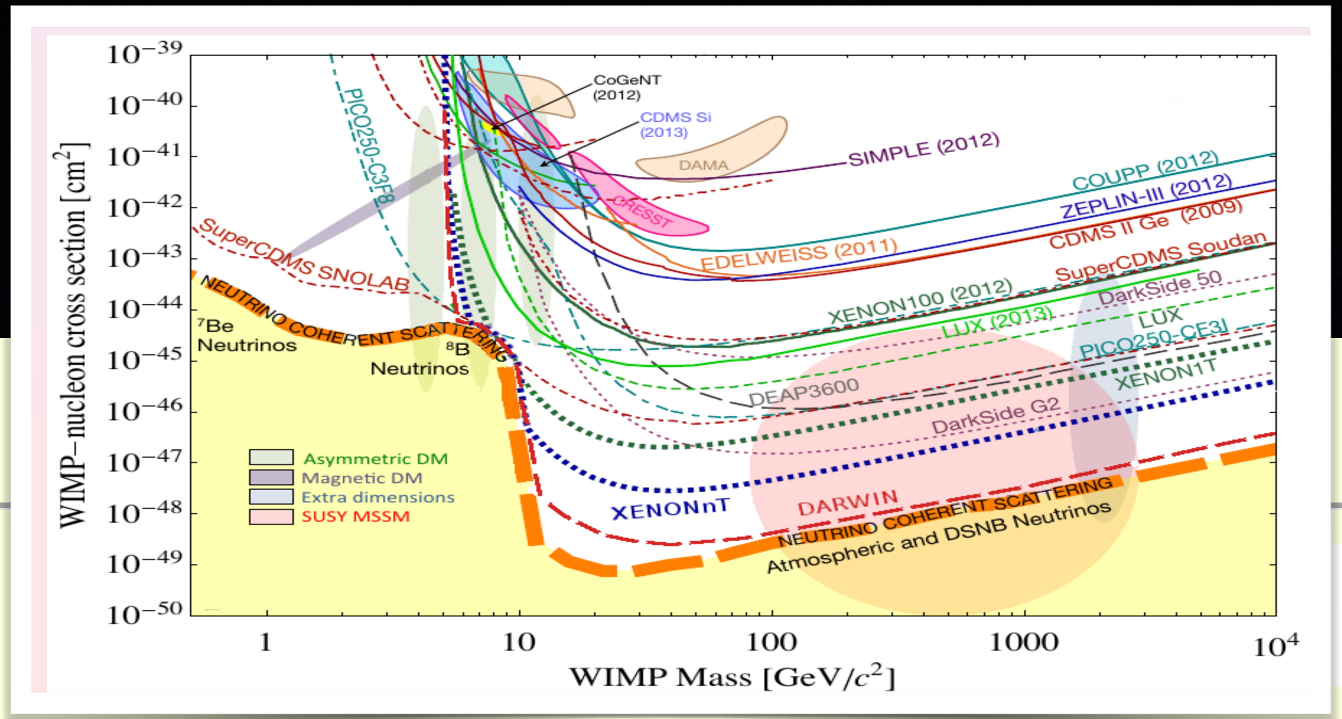


$$A_{PV}(Q^2) = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_{wk} F_{wk}(Q^2)}{Z F_{ch}(Q^2)}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{EM} = \left[\frac{\alpha^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)}\left(\frac{E'}{E}\right)\right] Z^2 F_{ch}^2(Q^2)$$

$$\left(\frac{d\sigma}{dT}\right)_{NC} = \frac{G_F^2}{8\pi} M \left[2 - 2\frac{T}{E} - \frac{MT}{E^2}\right] Q_{wk}^2 F_{wk}^2(Q^2)$$

CEvNS



Science

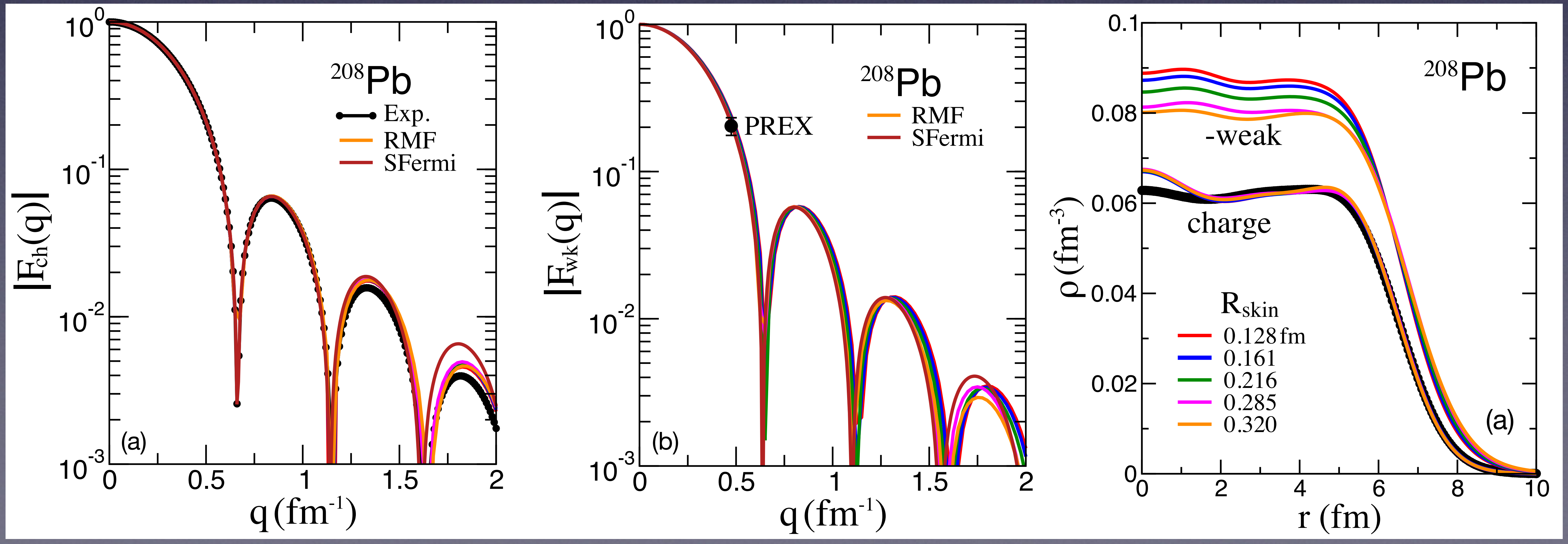
REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

FRIB

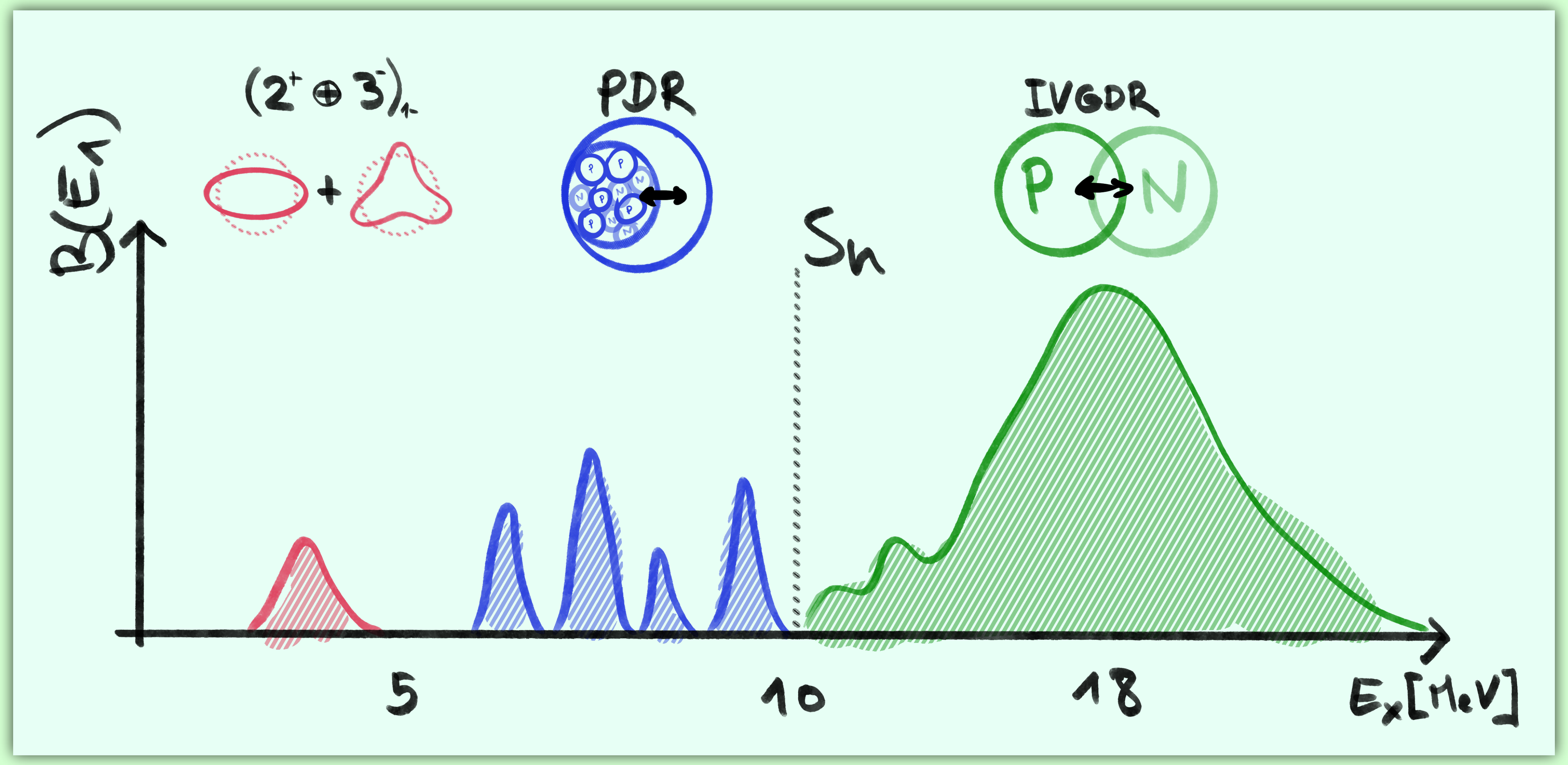


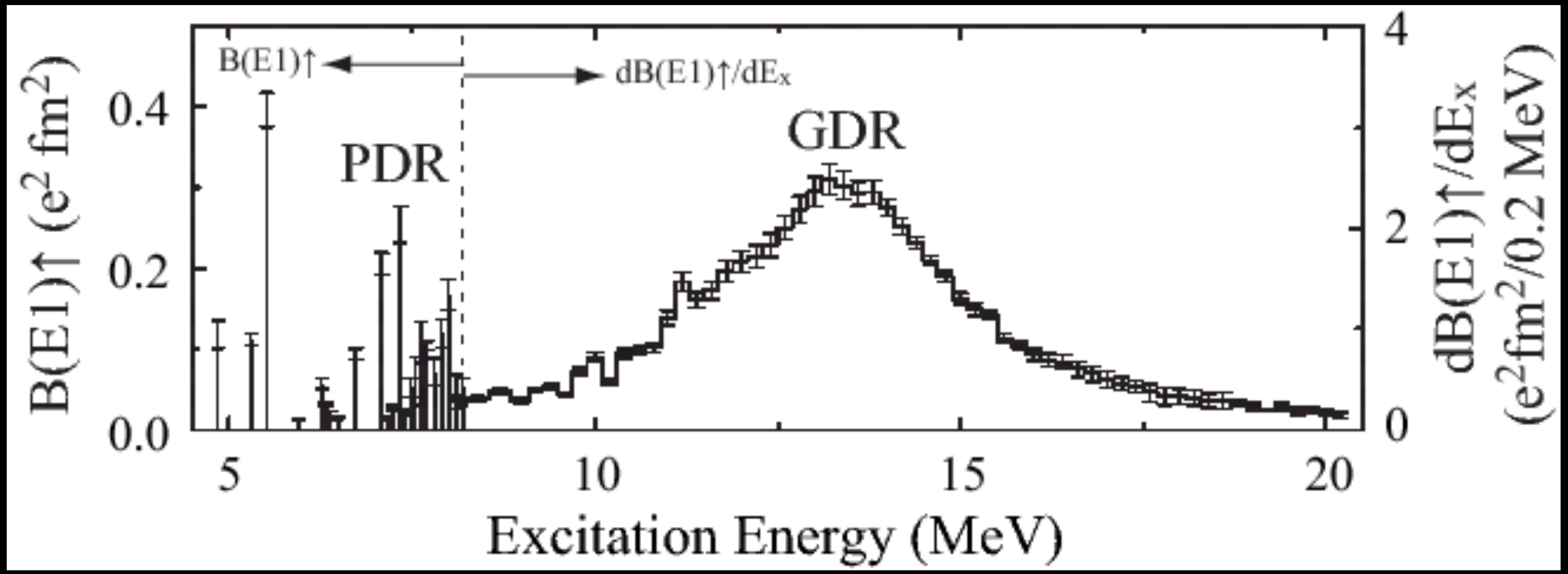
Electric Dipole Response

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
- Pygmy dipole resonance a soft mode with neutron rich skin oscillating against the symmetric core
- 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 at FRIB, RIKEN, FAIR, and MAGIX@MESA

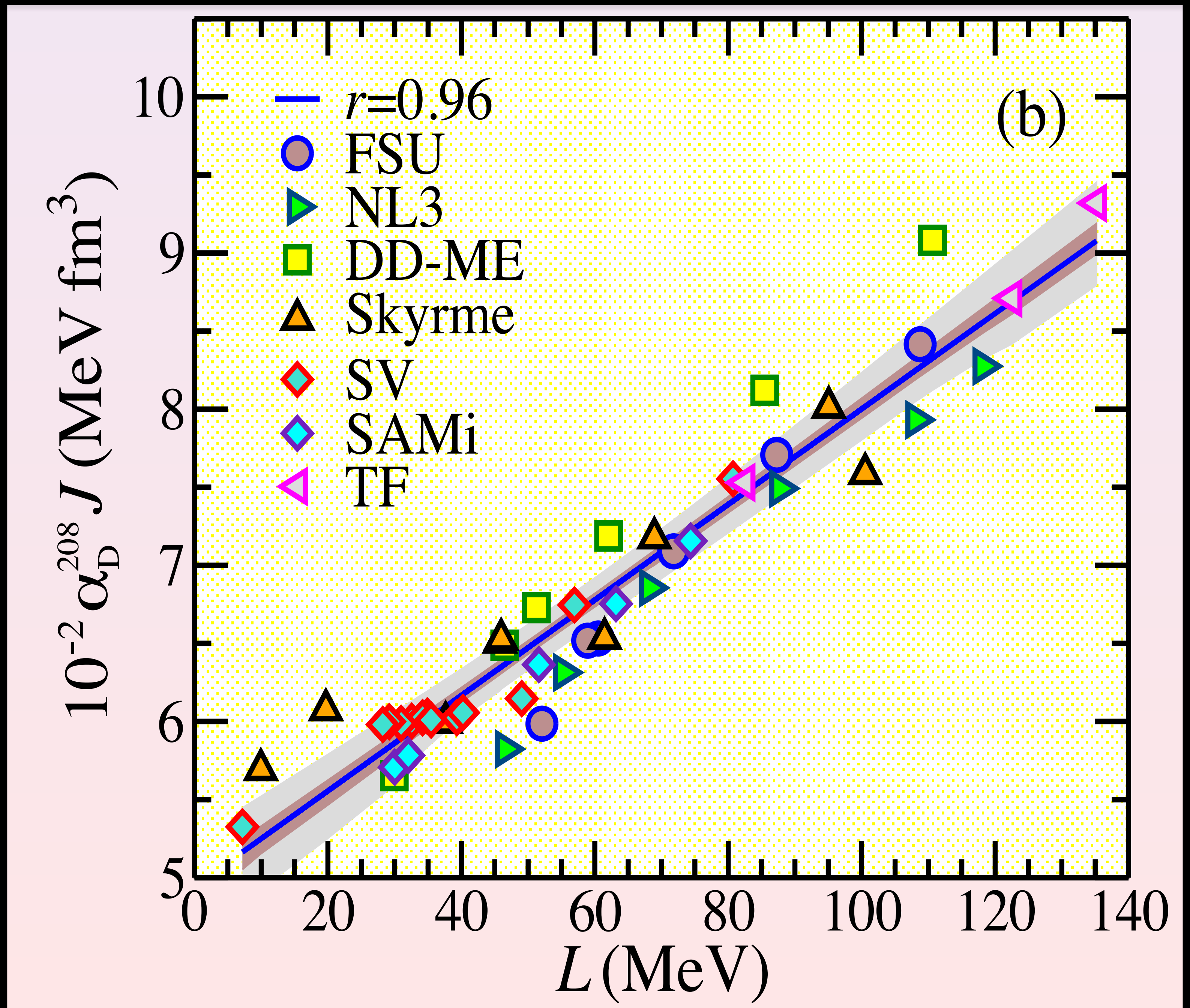
Electric Dipole Polarizability α_D

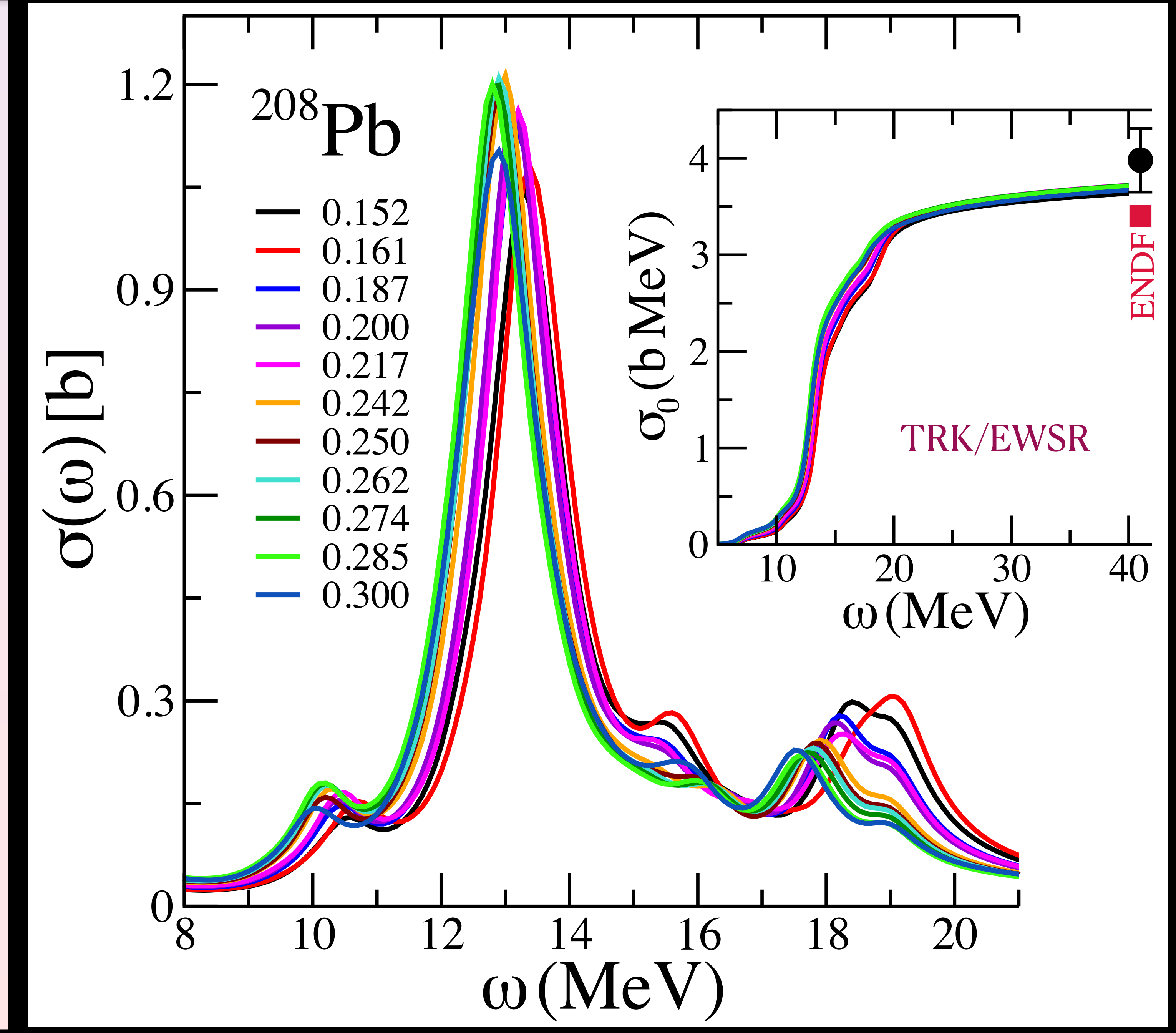
- A powerful electroweak complement to Rskin (γ-absorption experiments)
- Correlation to symmetry energy almost as strong as in the case of Rskin
- Energy weighted sum rule largely model independent
- Inverse energy weighted sum strongly correlated to L

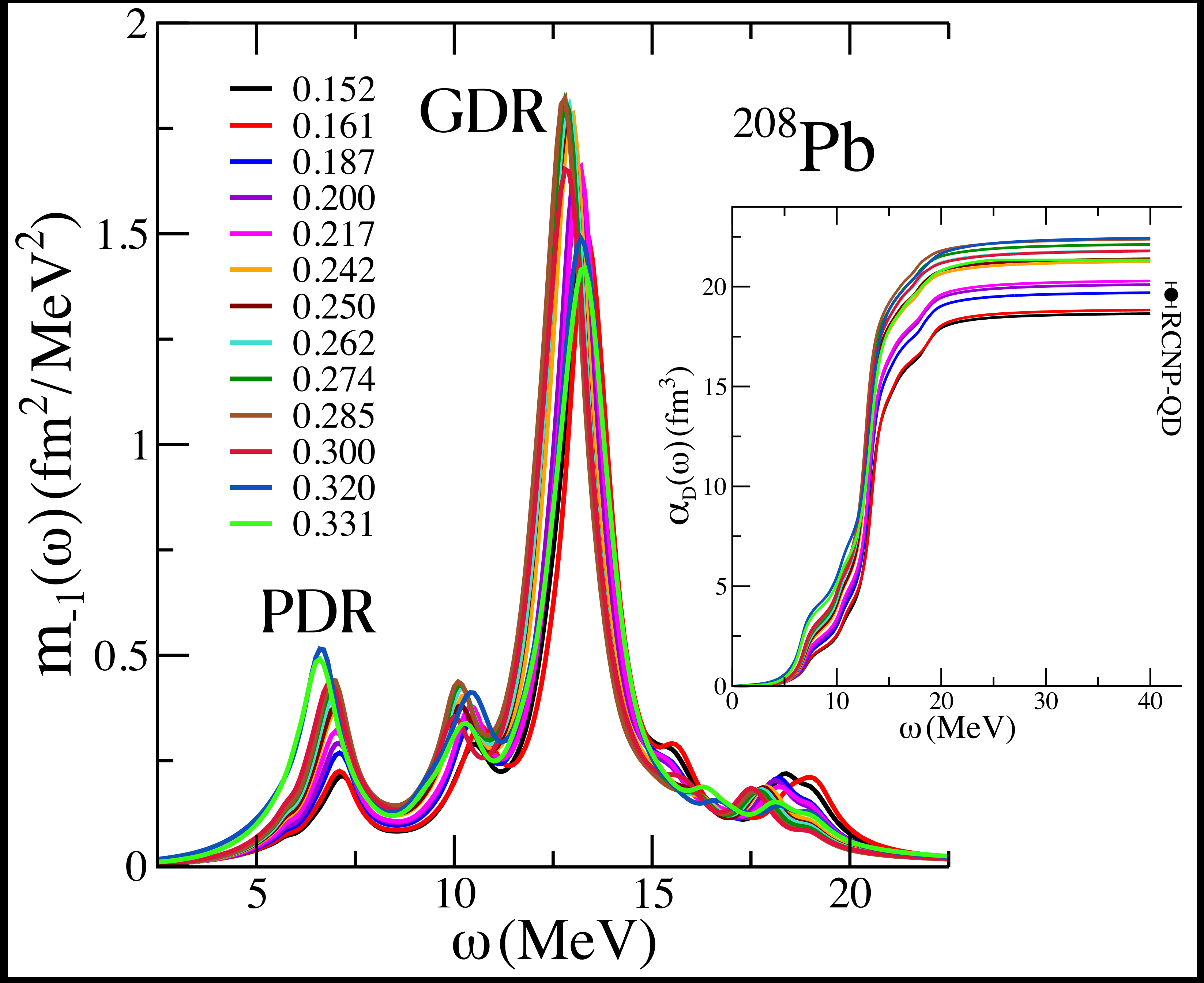
    Important contribution from PDR

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

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

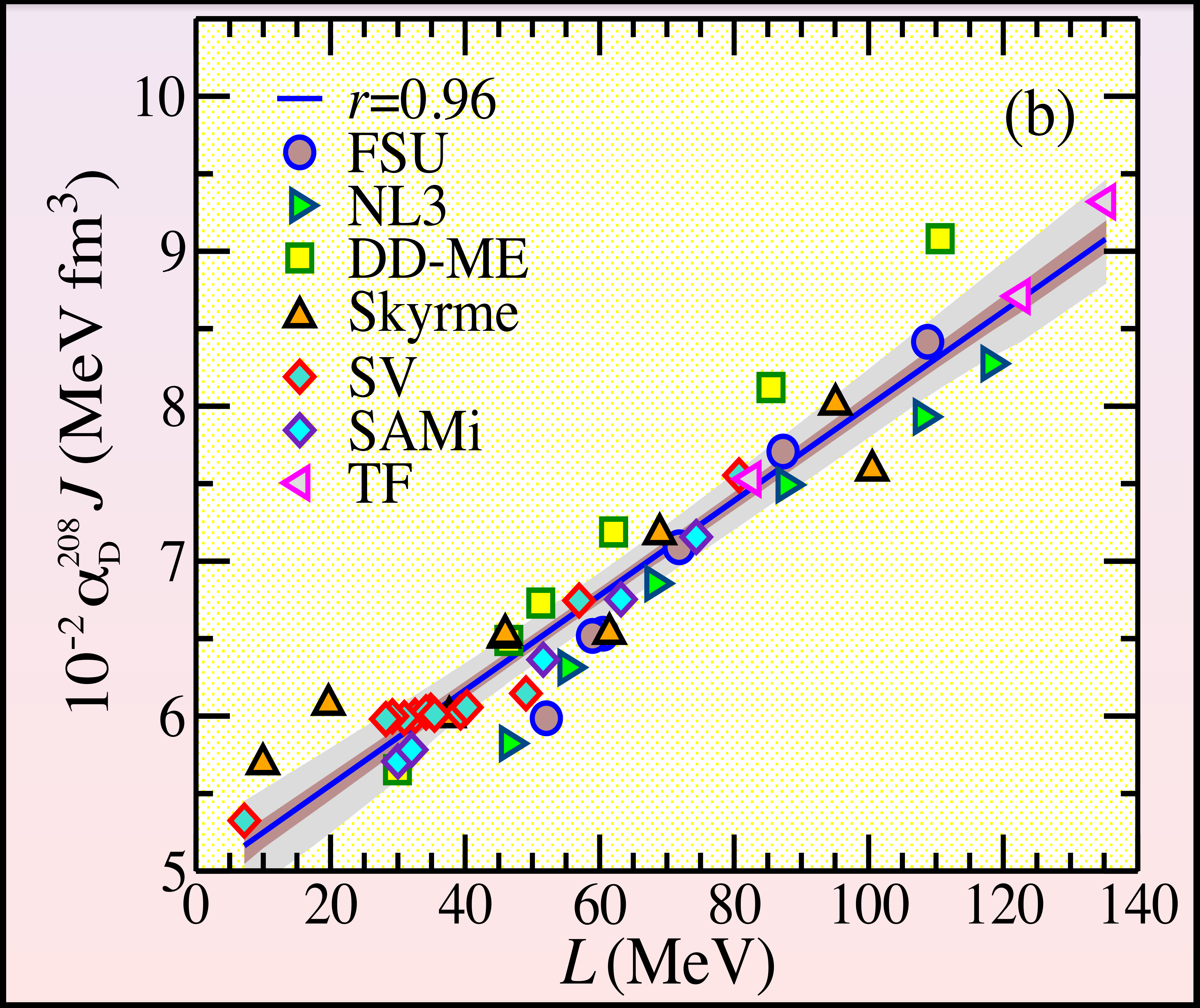


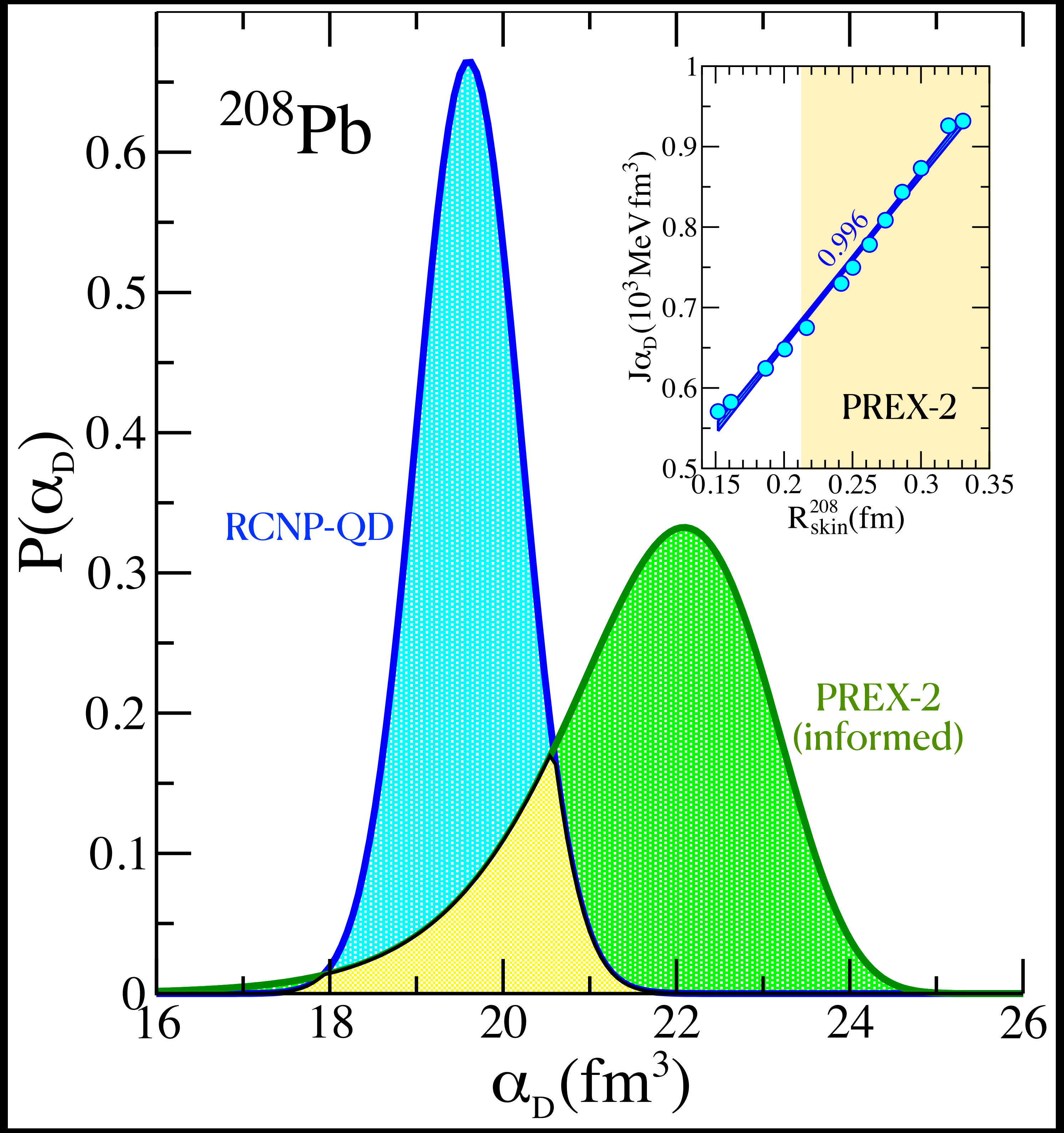


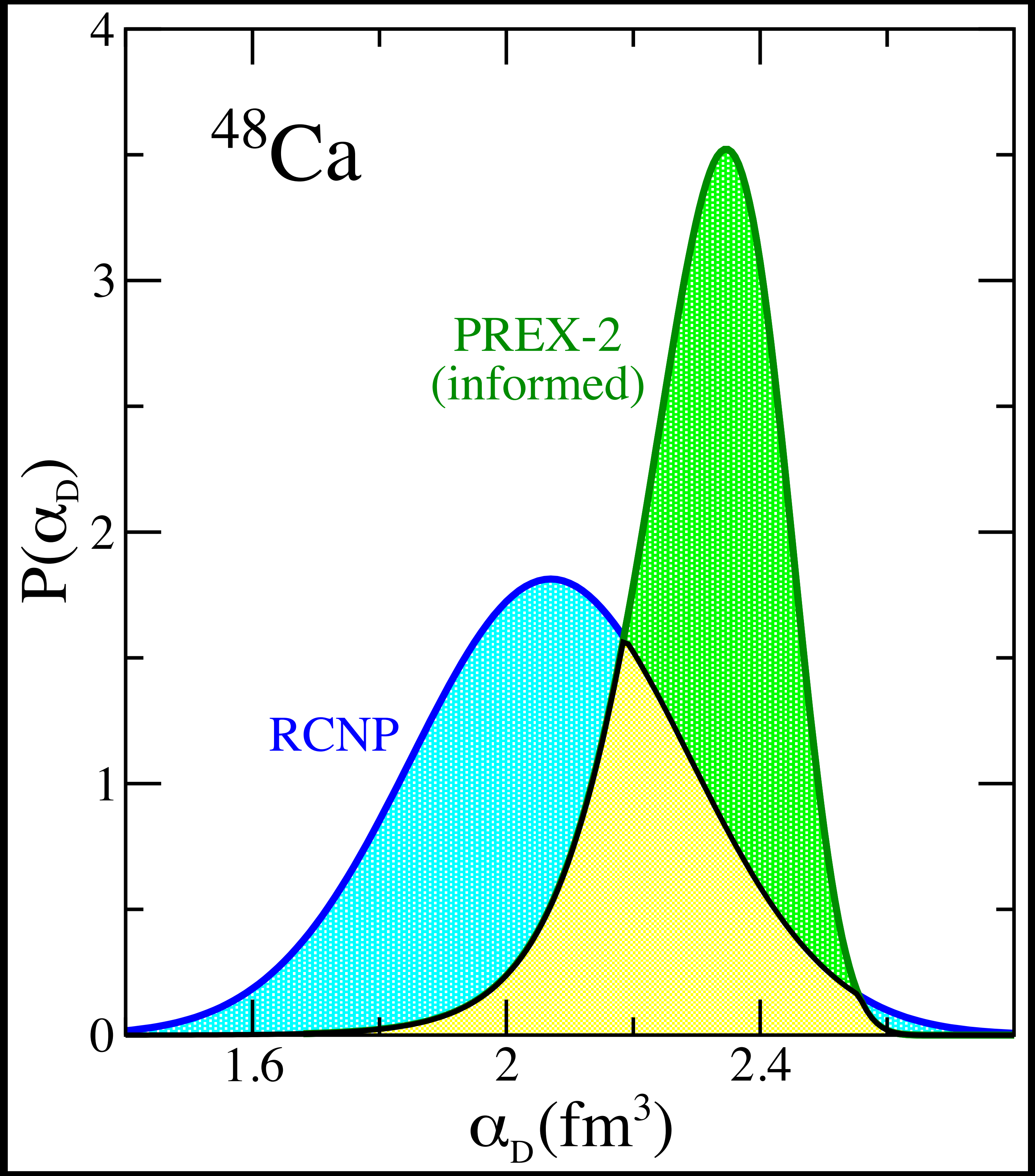


Implication of PREX on α_D

- A large and representative set of EDFs validate the strong correlation between $J\alpha_D$ and L
- For a representative set of covariant EDFs one determine the "PREX-informed" probability distribution of α_D
- The PREX-informed probability distribution is in tension with the experimental determination from RCNP
- The PREX-informed extraction systematically overestimates the experimental results (^{208}Pb, ^{48}Ca, ^{68}Ni)

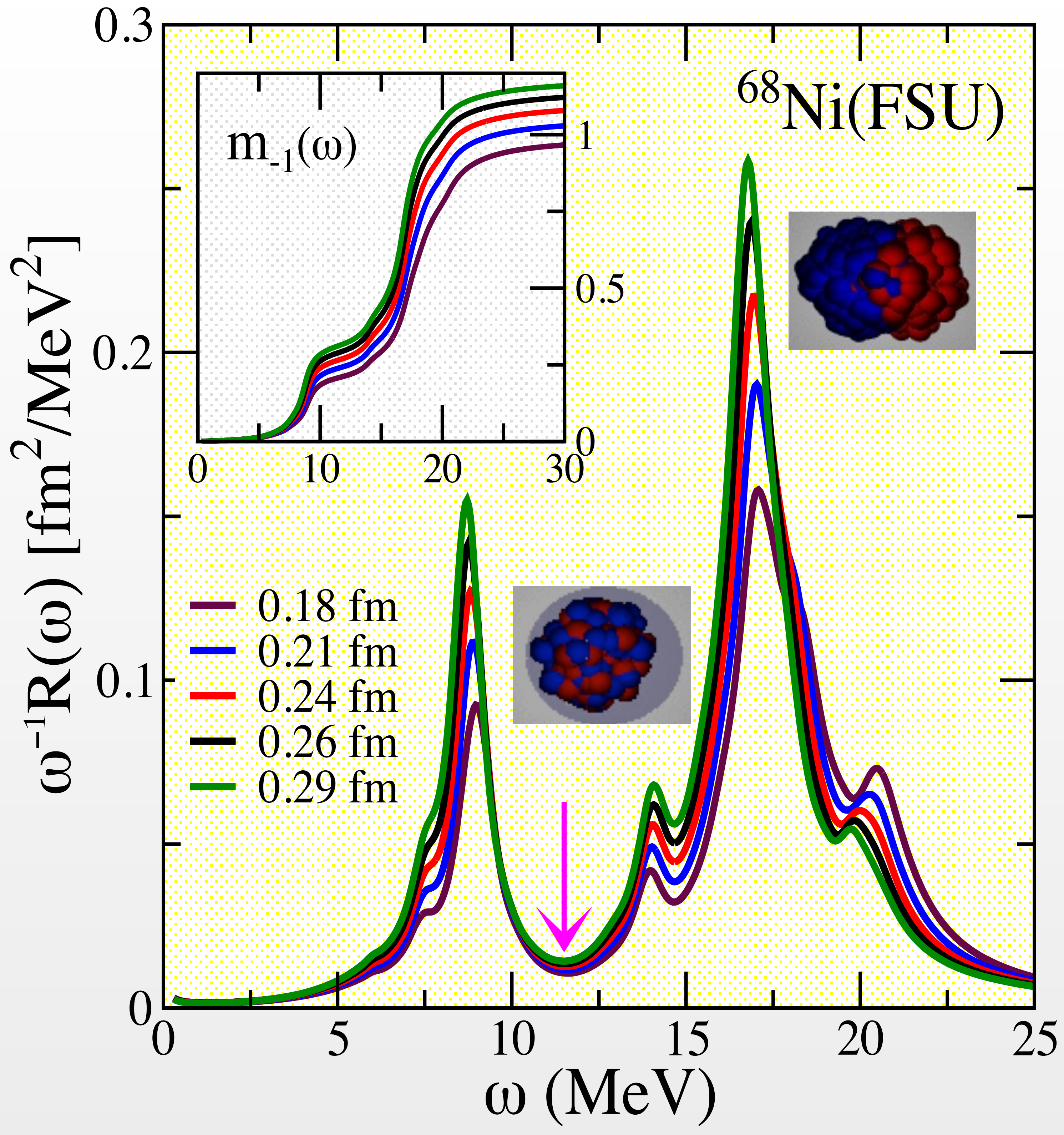




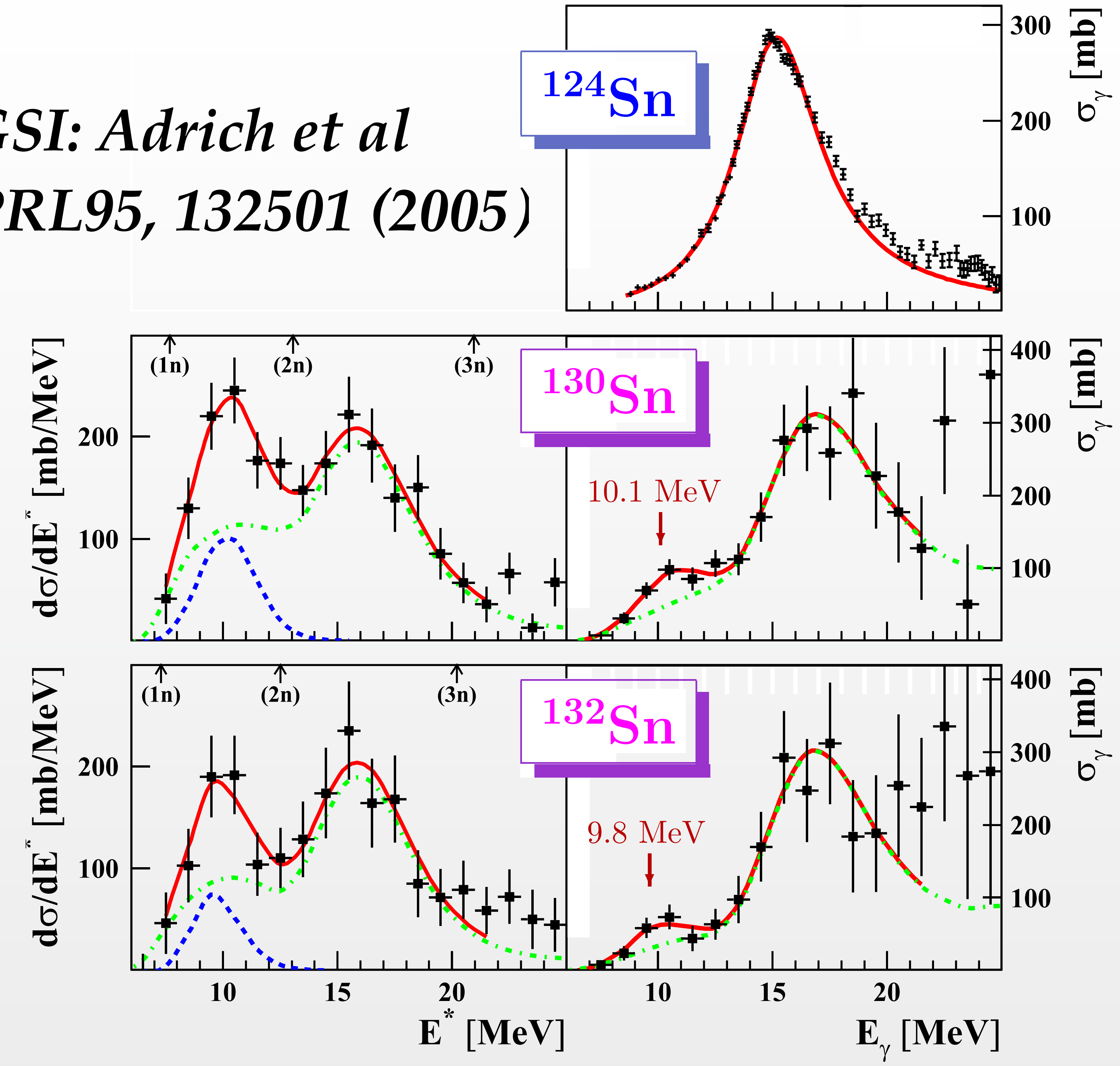


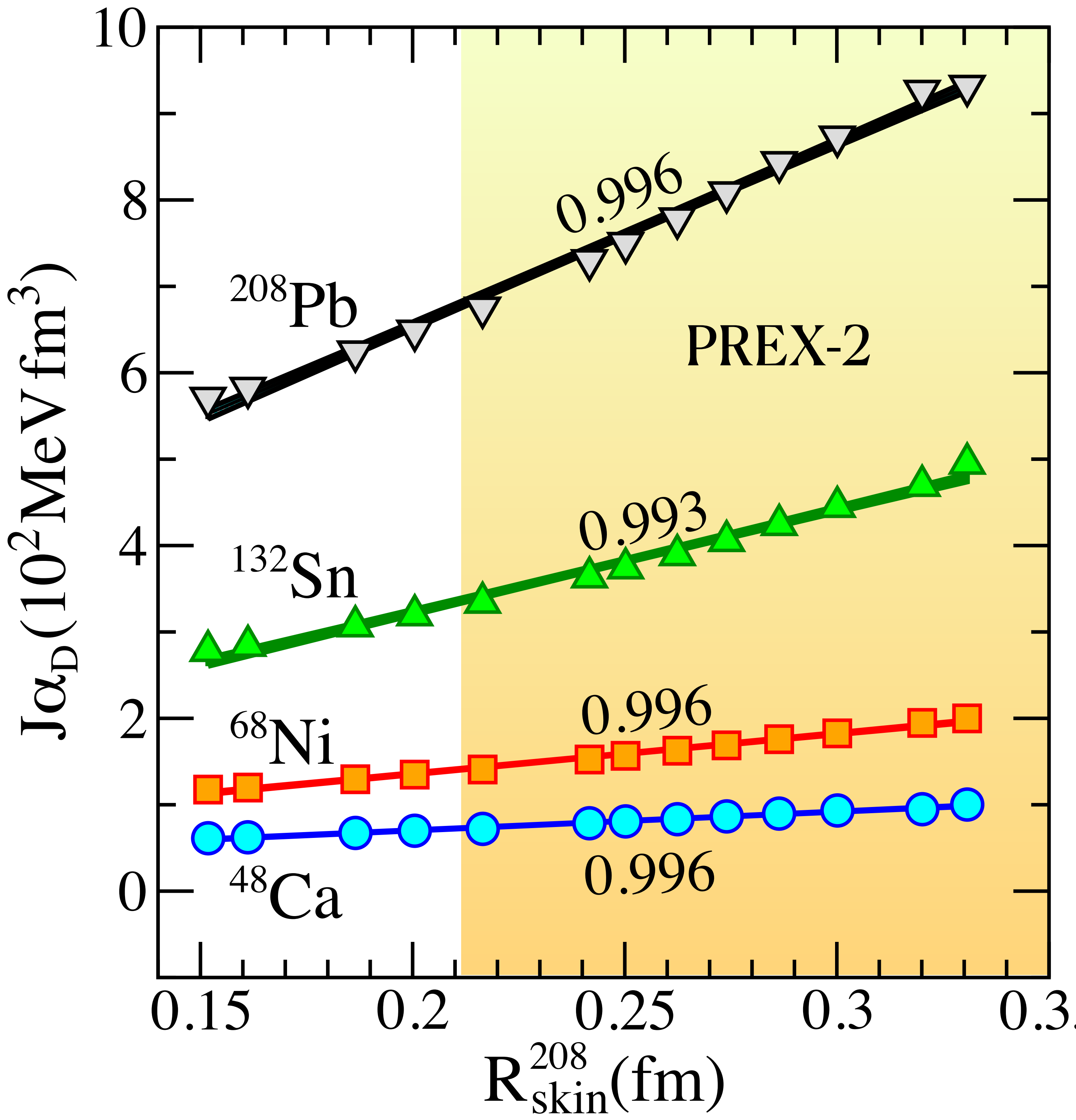
Electric Dipole Polarizability of Unstable Neutron-Rich Nuclei

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

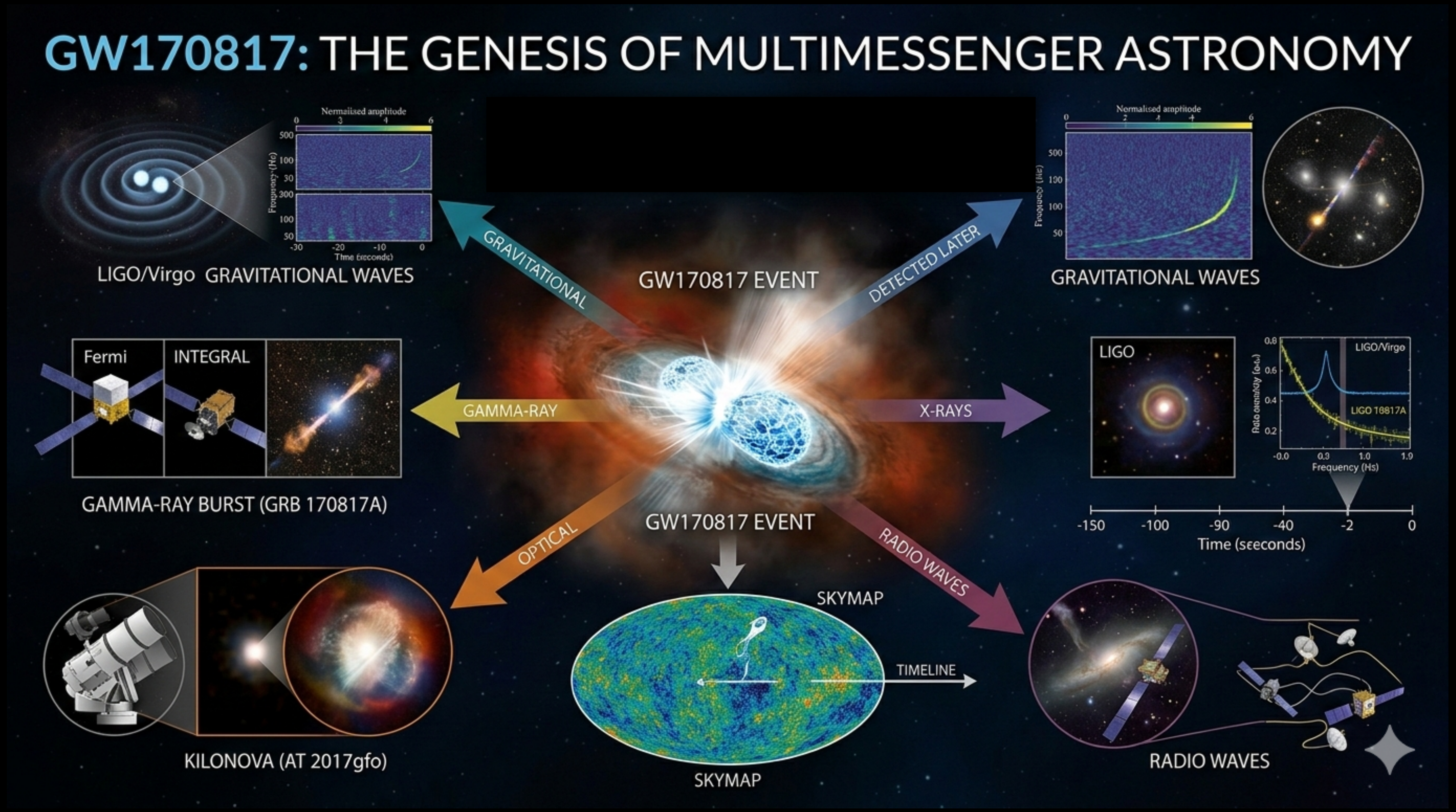


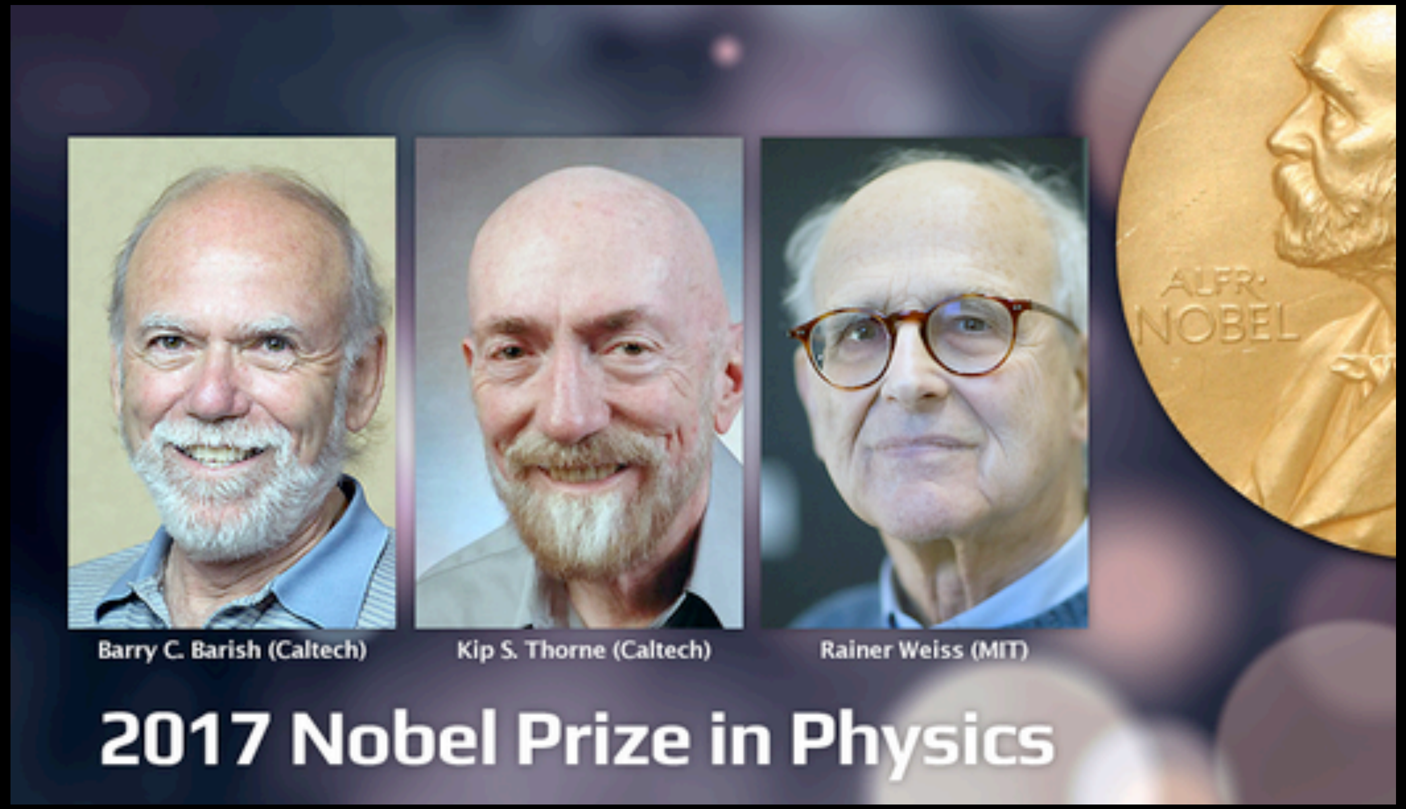
GSI: Adrich et al
PRL95, 132501 (2005)

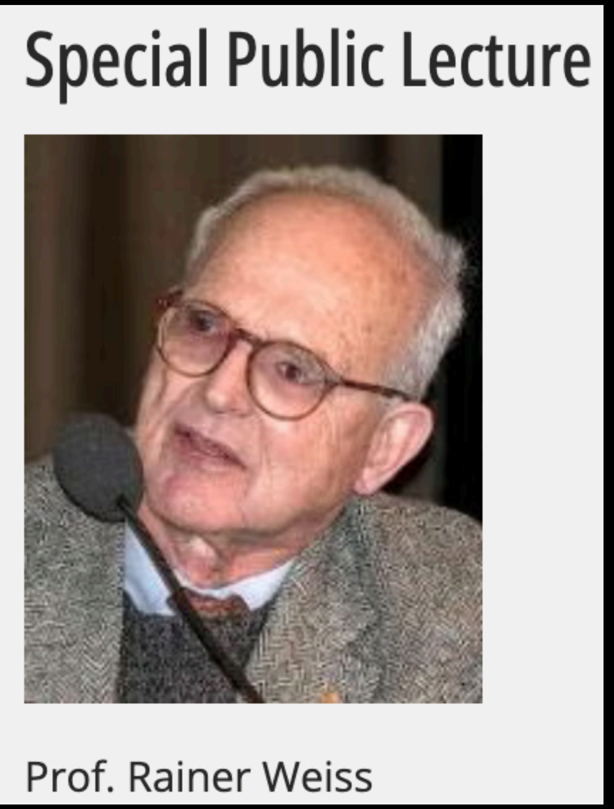


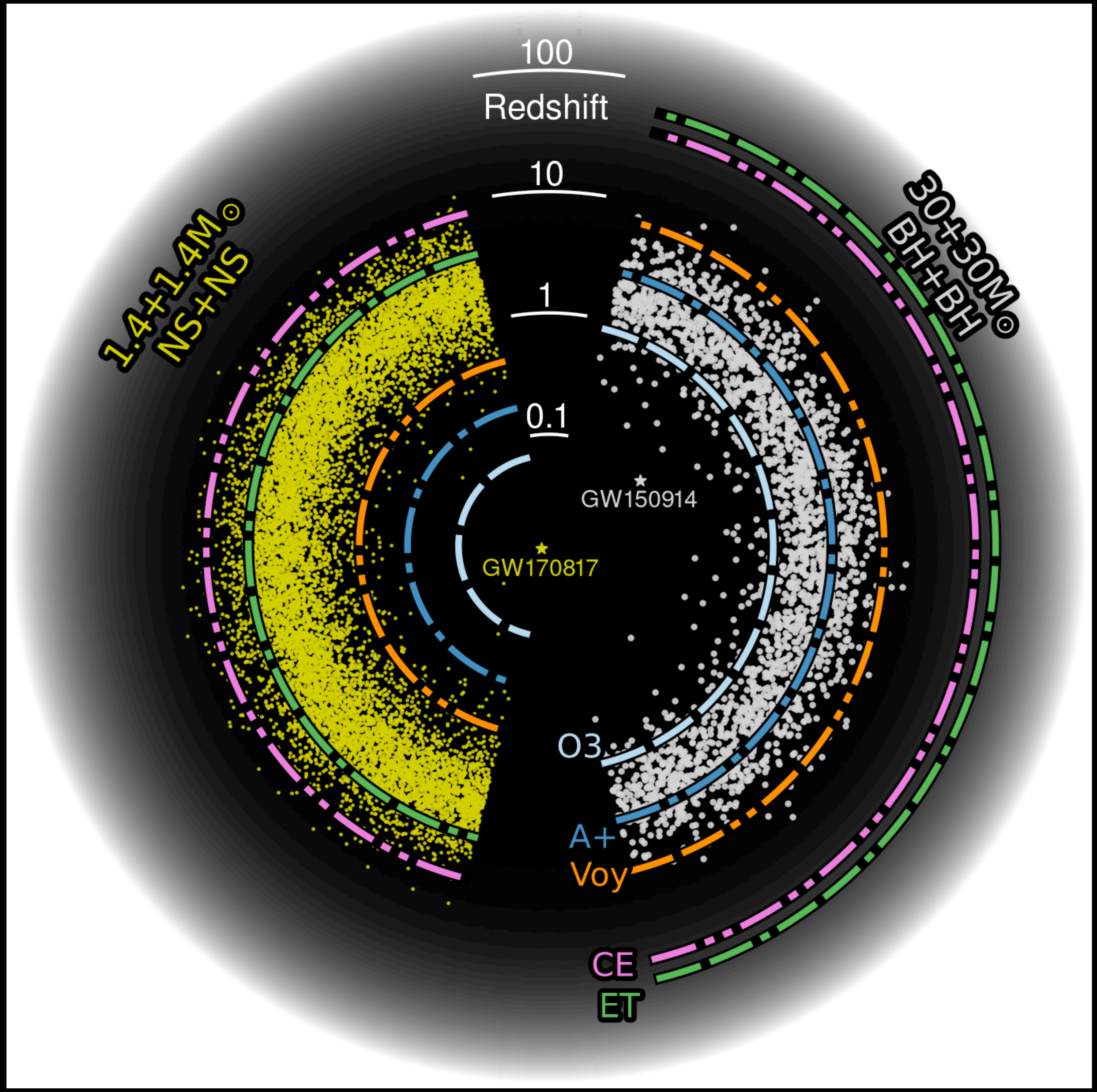


GW170817 Direct Detection of Gravitational Waves









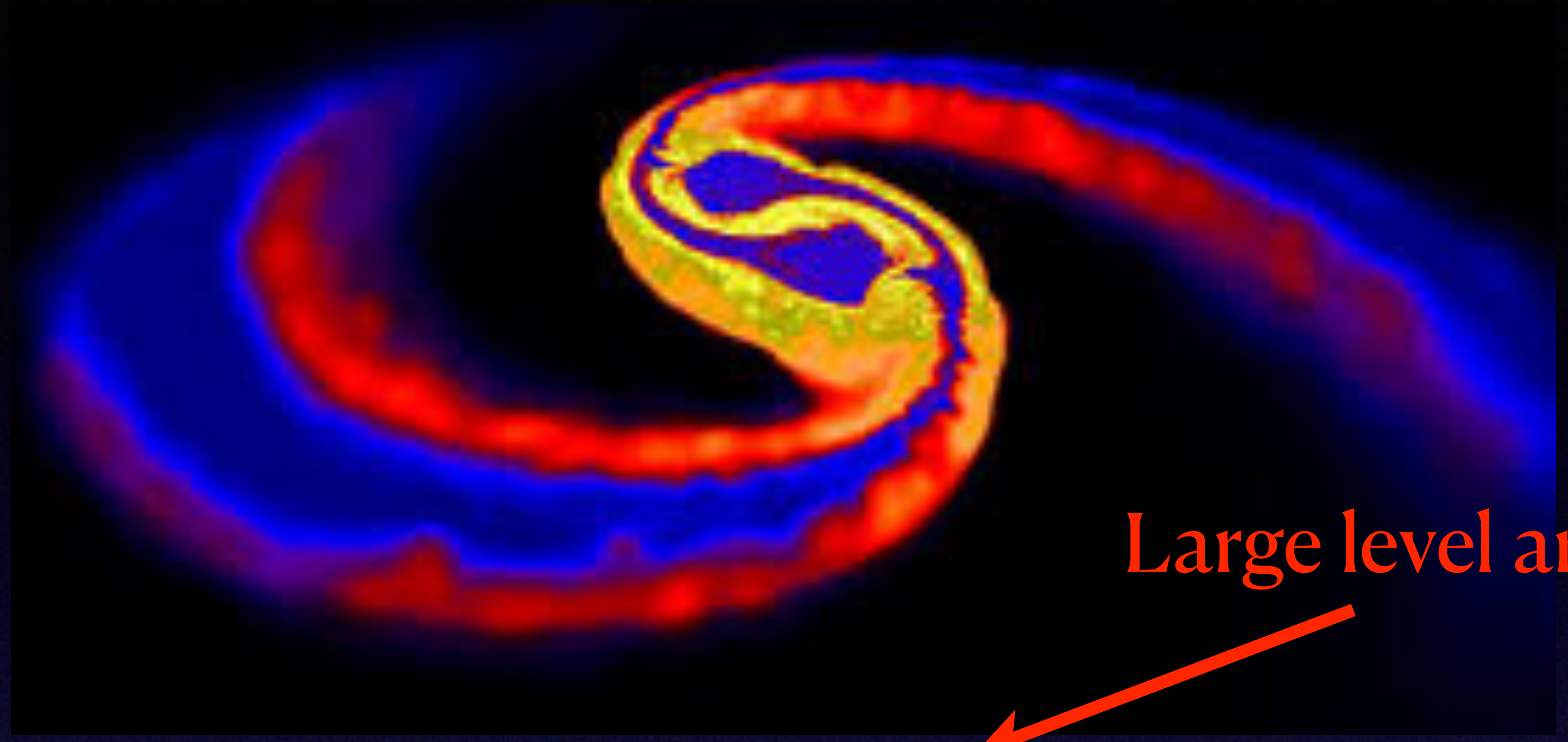
2020 FSU Dirac Lectures

GW170817: Tidal Polarizability (2017)

Electric Polarizability: $P_i = \chi E_i$

Tidal Polarizability(Deformability):

- Tidal field induces a mass polarization
- A time dependent mass quadrupole emits gravitational waves

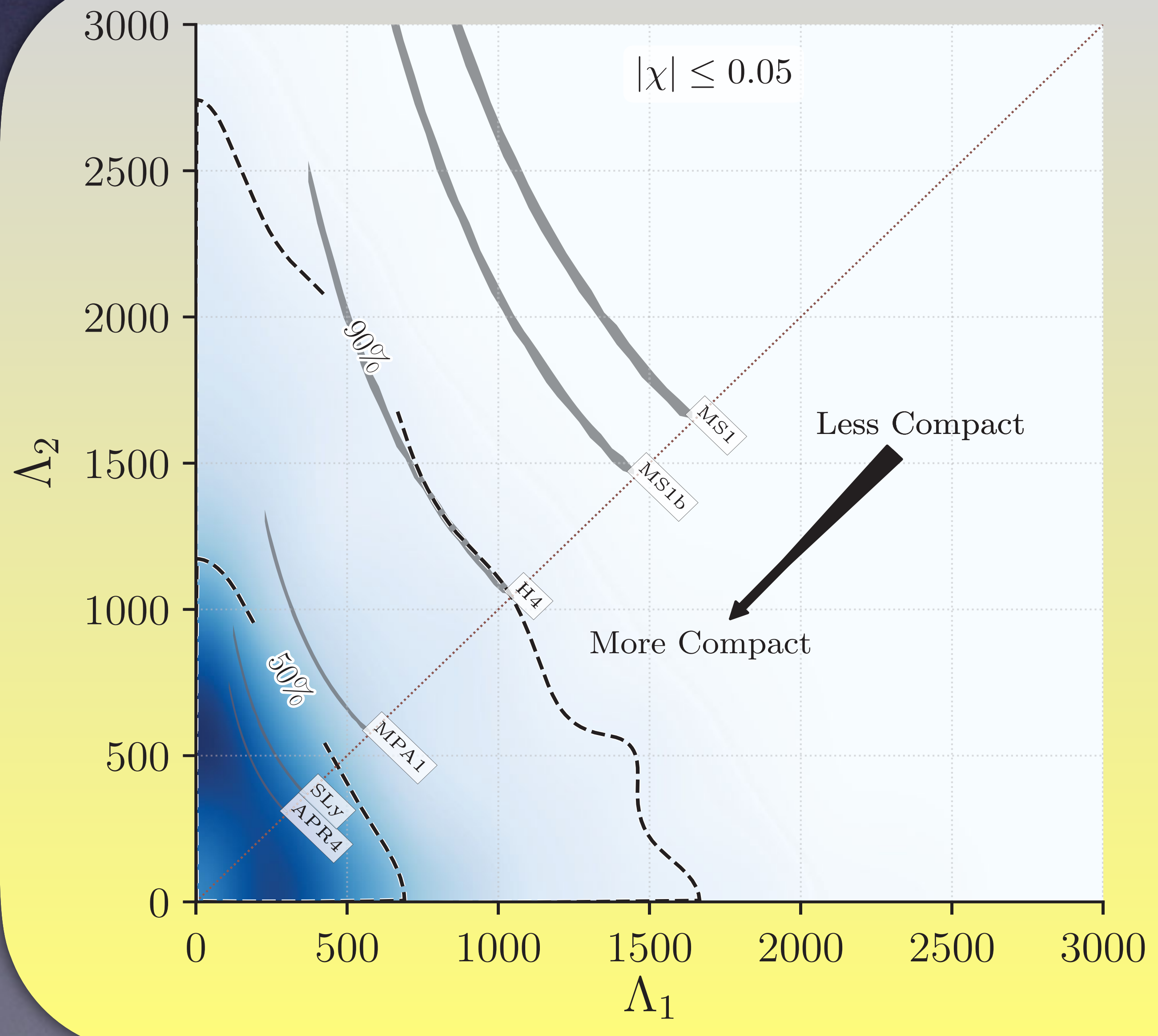


Large level arm!

Micro-Macro

$$Q_{ij} = \Lambda \mathcal{E}_{ij} \qquad \Lambda = k_2 \left(\frac{c^2 R}{2GM}\right)^5 = k_2 \left(\frac{R}{R_s}\right)^5$$

Soft EOS! Small L!



GW170817 rules out very large neutron star radii!

Neutron Stars must be compact

$$\Lambda_{1.4} = 390^{+190}_{-120}\ (90\%)$$

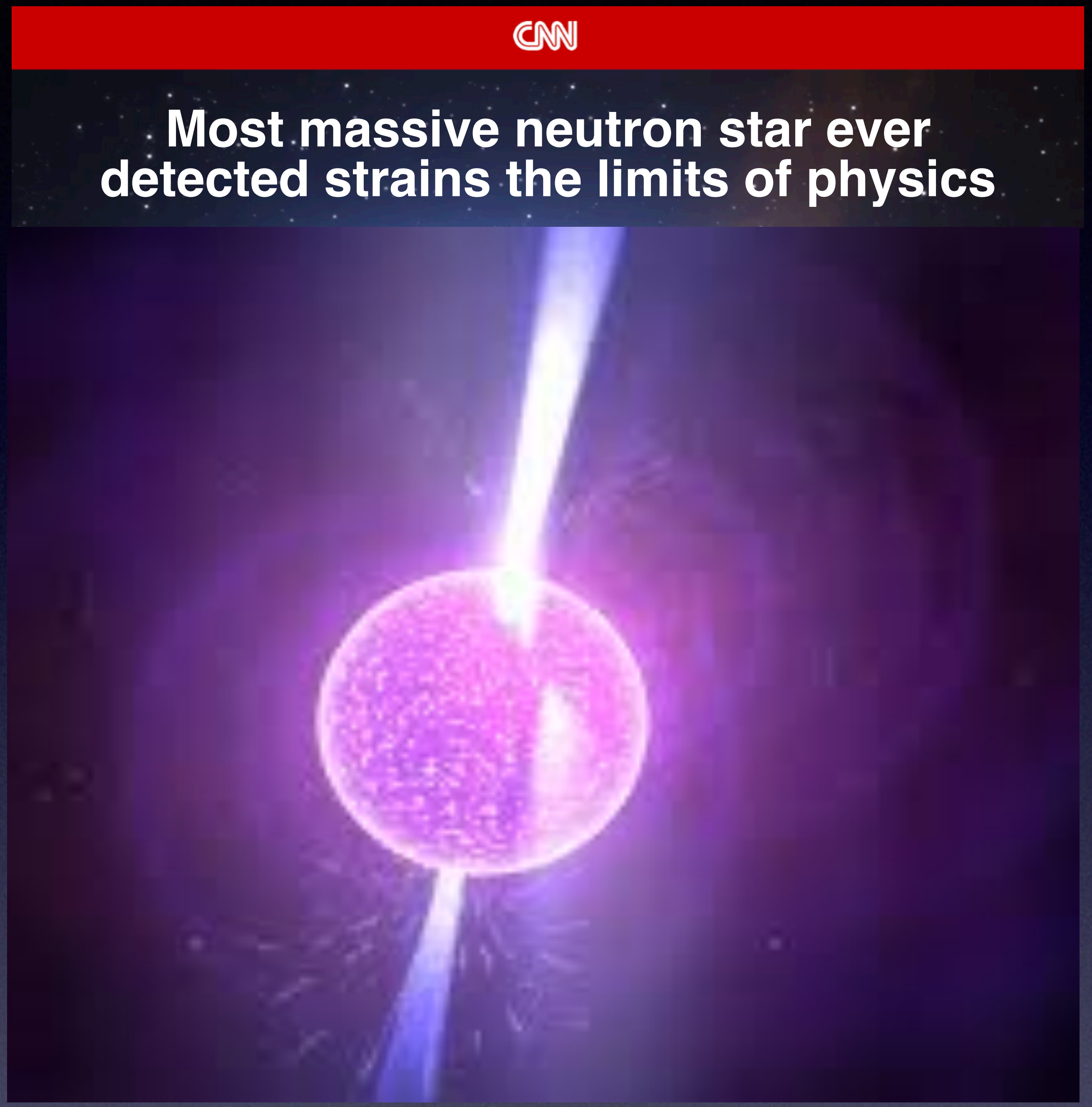
(Latest LIGO/Virgo analysis)

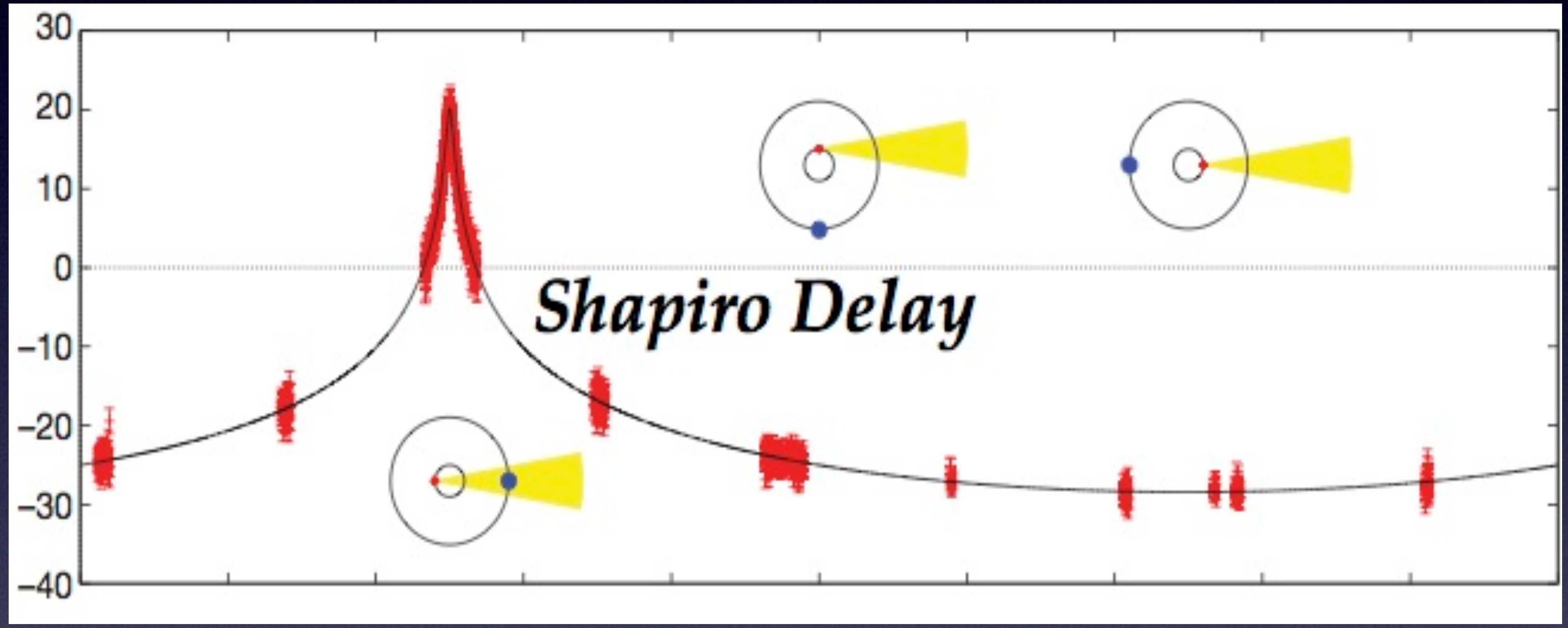
The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation. Very sensitive to stellar radius!

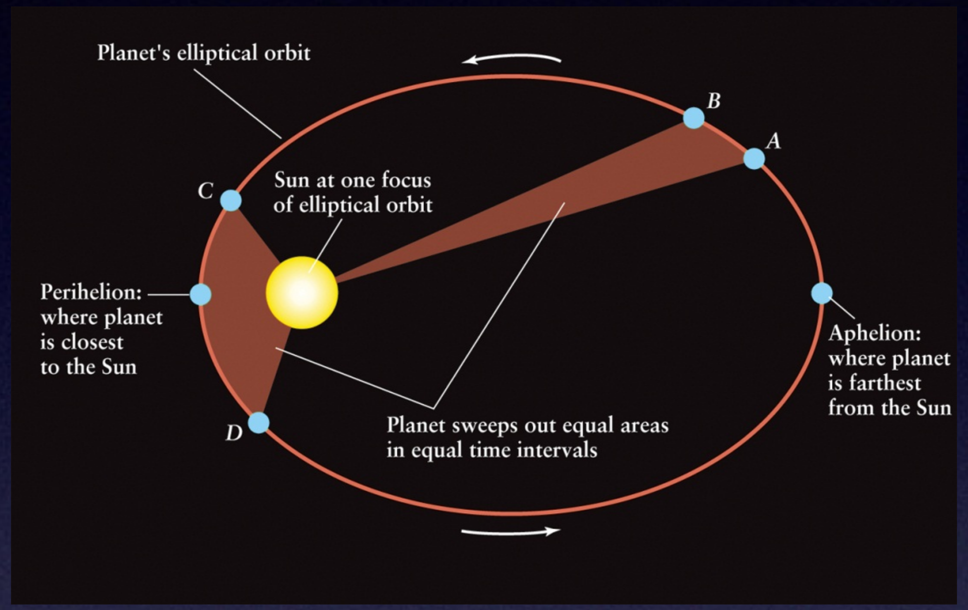
Measuring Heavy Neutron Stars by Shapiro Delay

Possibly the two most important properties of neutron stars—their maximum masses and typical radii—are not yet well known. These properties reflect rather different aspects of the dense matter equation of state (EOS). The neutron star maximum mass, which is a consequence of general relativity and does not exist in Newtonian gravity, has a limit of, at most, 3 $M_\odot$, assuming causality [5]. The maximum mass is controlled by the stiffness of the dense matter EOS at densities in excess of a few fimes times n_s. The introduction of non-nucleonic degrees of freedom at supra-nuclear

J.M. Lattimer & M. Prakash; Physics Reports 442 (2007)



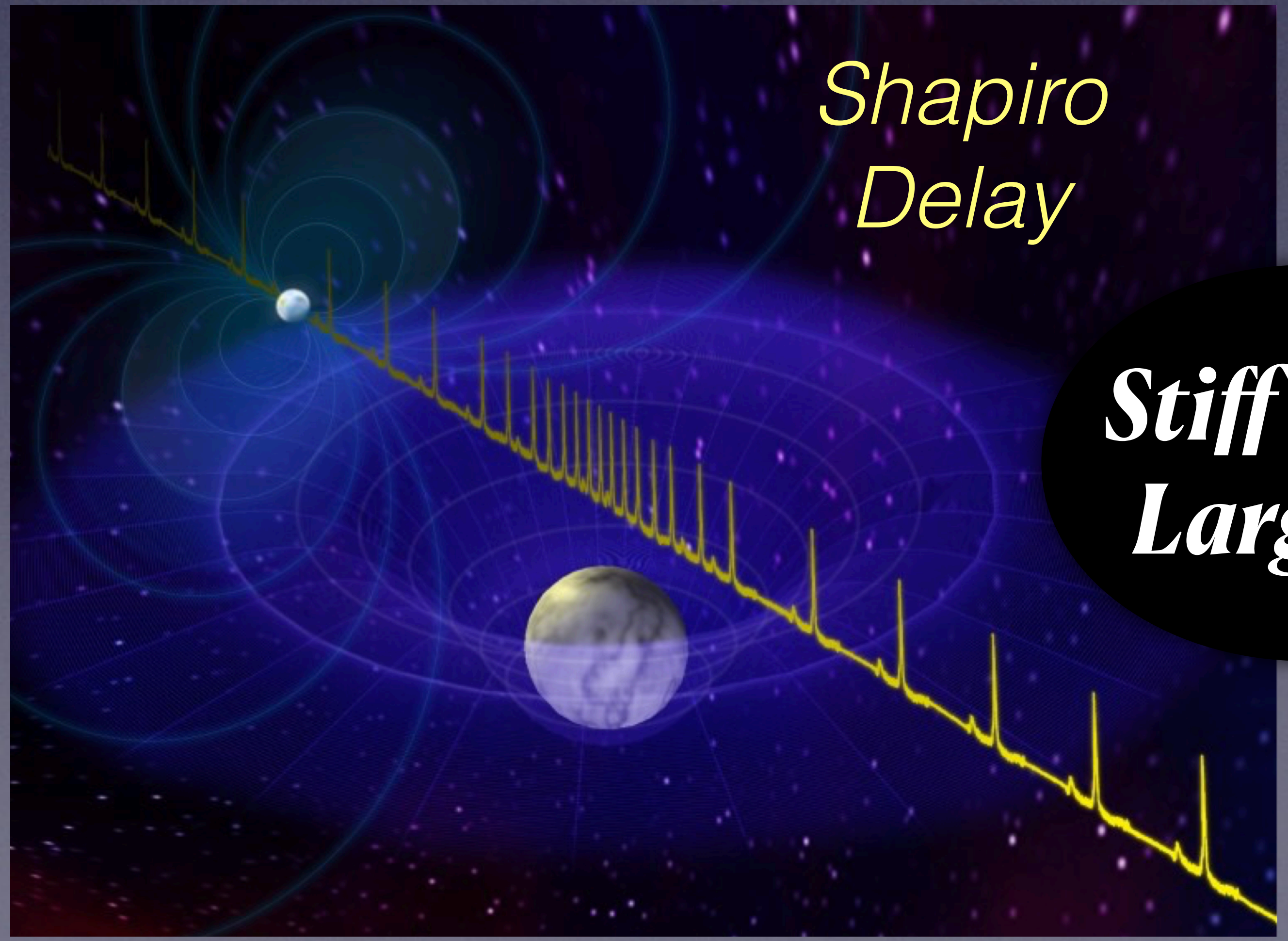




Newtonian Gravity sensitive to the total mass of the binary
Kepler's Third Law

$$\delta t = \frac{GM_{\rm wd}}{c^3}\ln\left(\frac{4r_1r_2}{d^2}\right) \approx 10\mu s$$

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



Stiff EOS! Large L!

Cromartie/Fonseca et al. (2020)

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

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

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

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

$$M = 2.08 \pm 0.07\,M_\odot$$

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

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

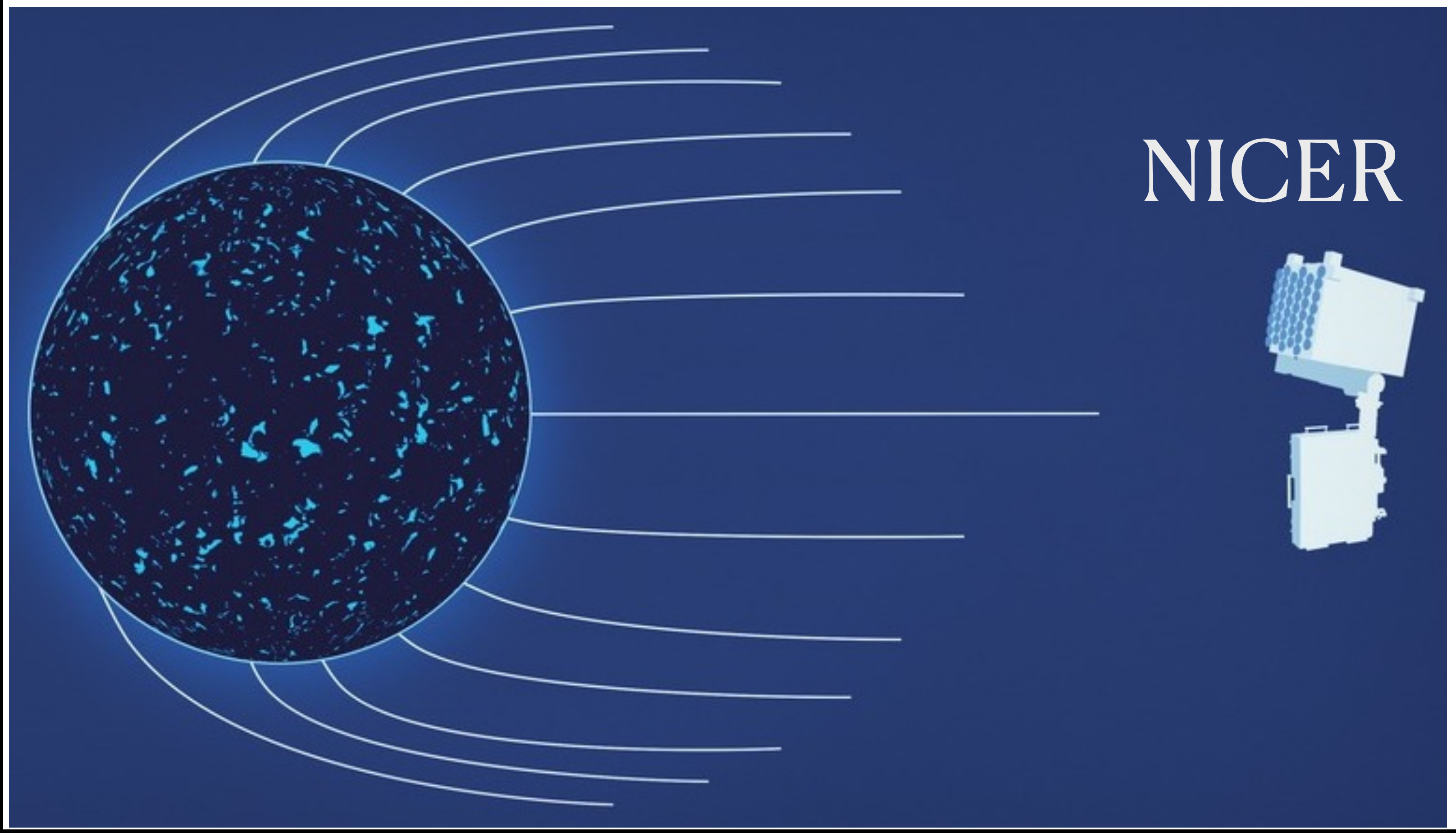
Riley *et al.* (2021)

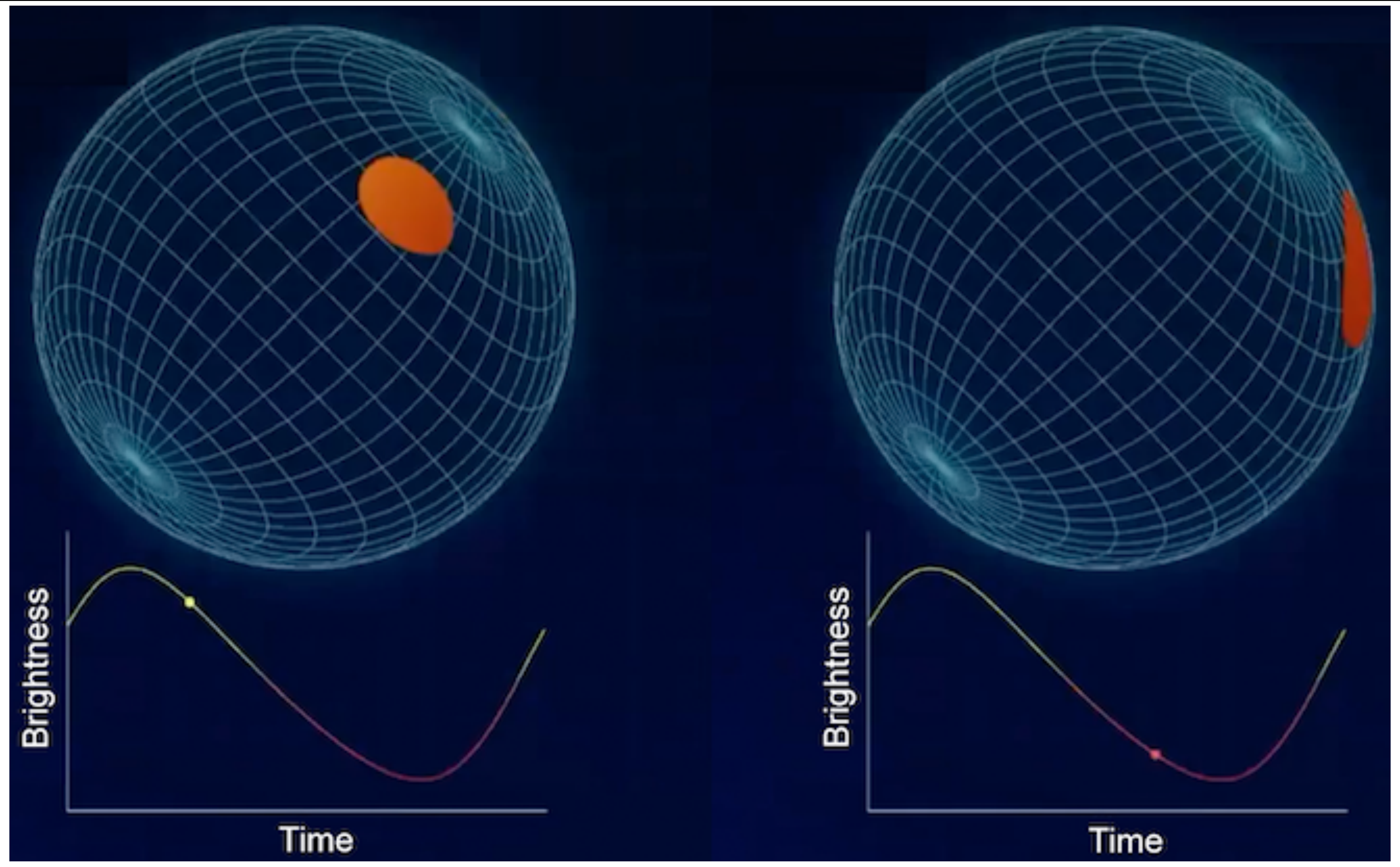
$$R_{2.0} = 13.7^{+2.6}_{-1.5}\ \mathrm{km}$$

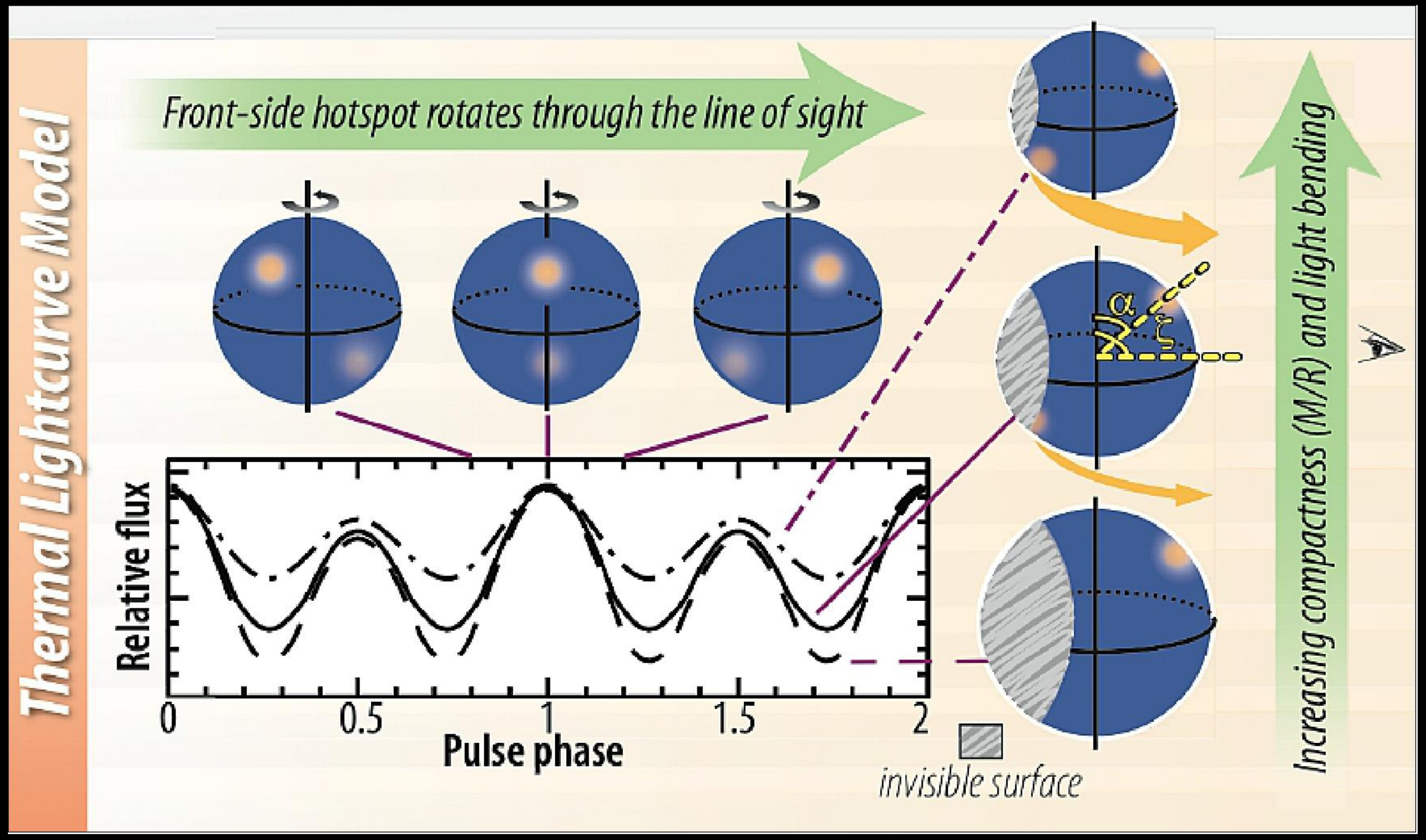
Miller *et al.* (2021)

Micro-Macro

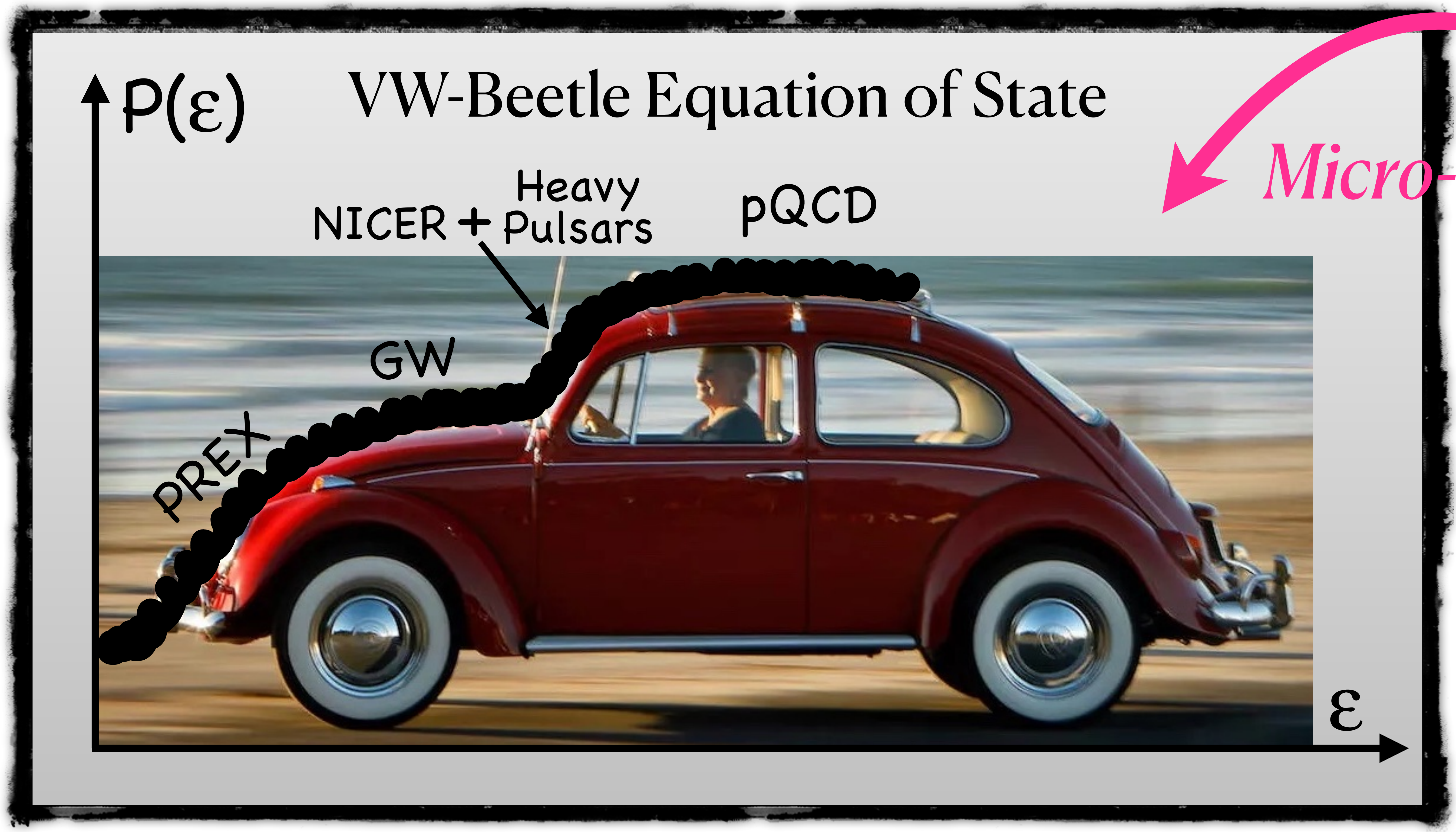
Stiff EOS! Large L!



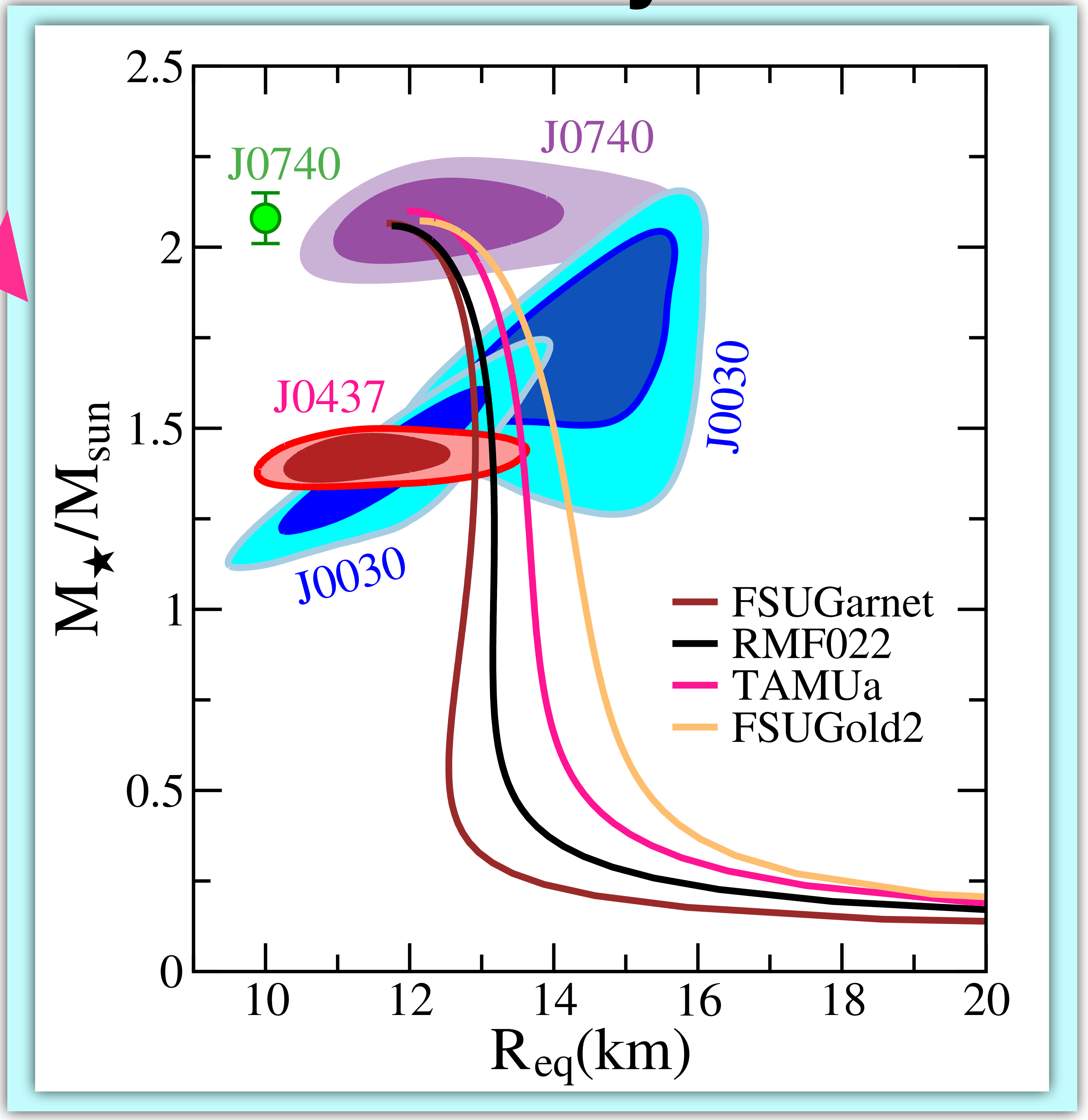




The Dawn of a Golden Era in Neutron-Star Physics



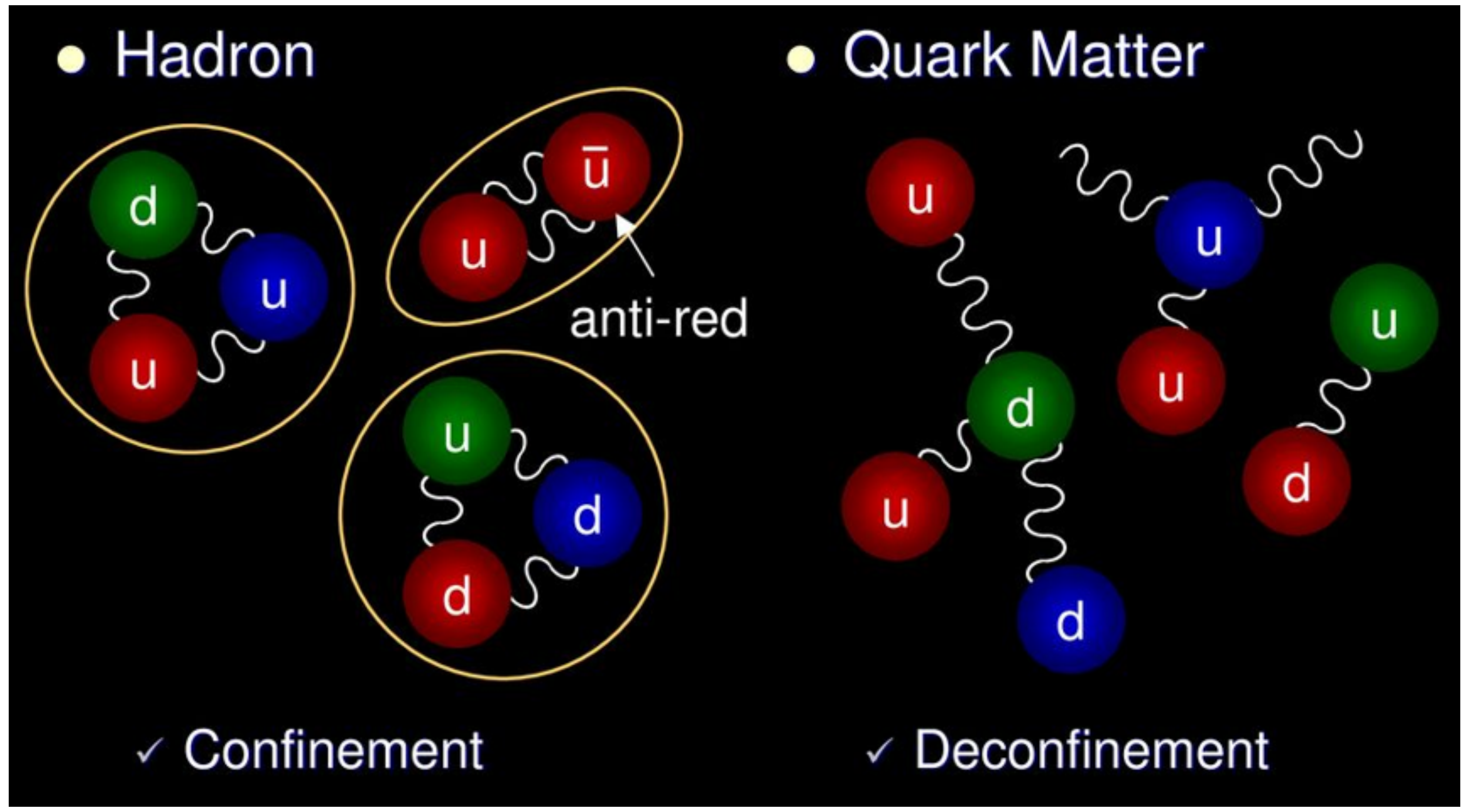
Micro-Macro



What have we learned since GW170817

- PREX suggest a **stiff** EOS around saturation density although CREX has muddled the waters!
- LIGO-Virgo favor a **soft** EOS at around $2n_0$ although see Gamba et al., PRD 103, 124015 (2021)
- NICER/Pulsar Timing suggest a **stiff** EOS at $\sim 4n_0$

Phase Transition?



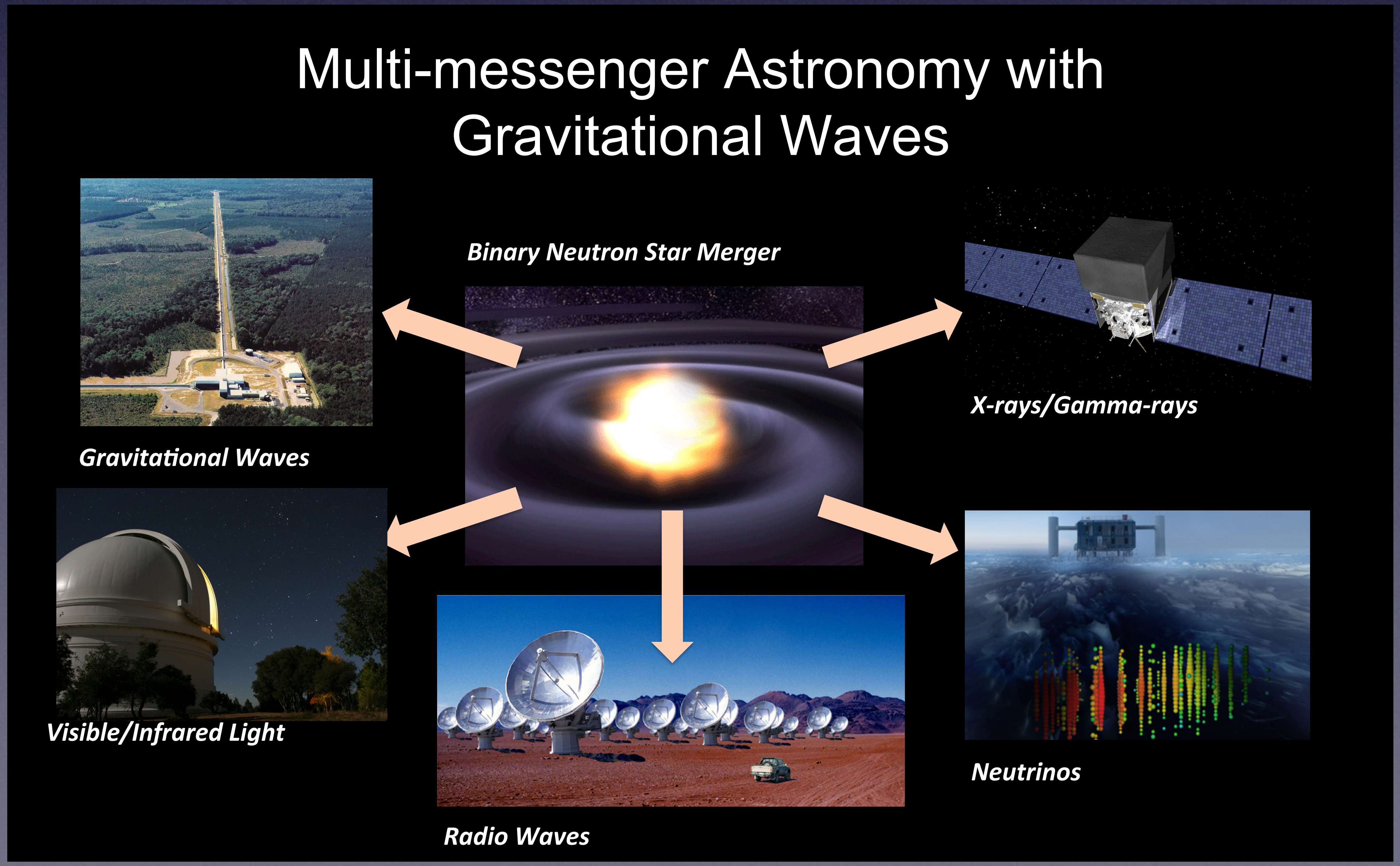
My Students and Collaborators

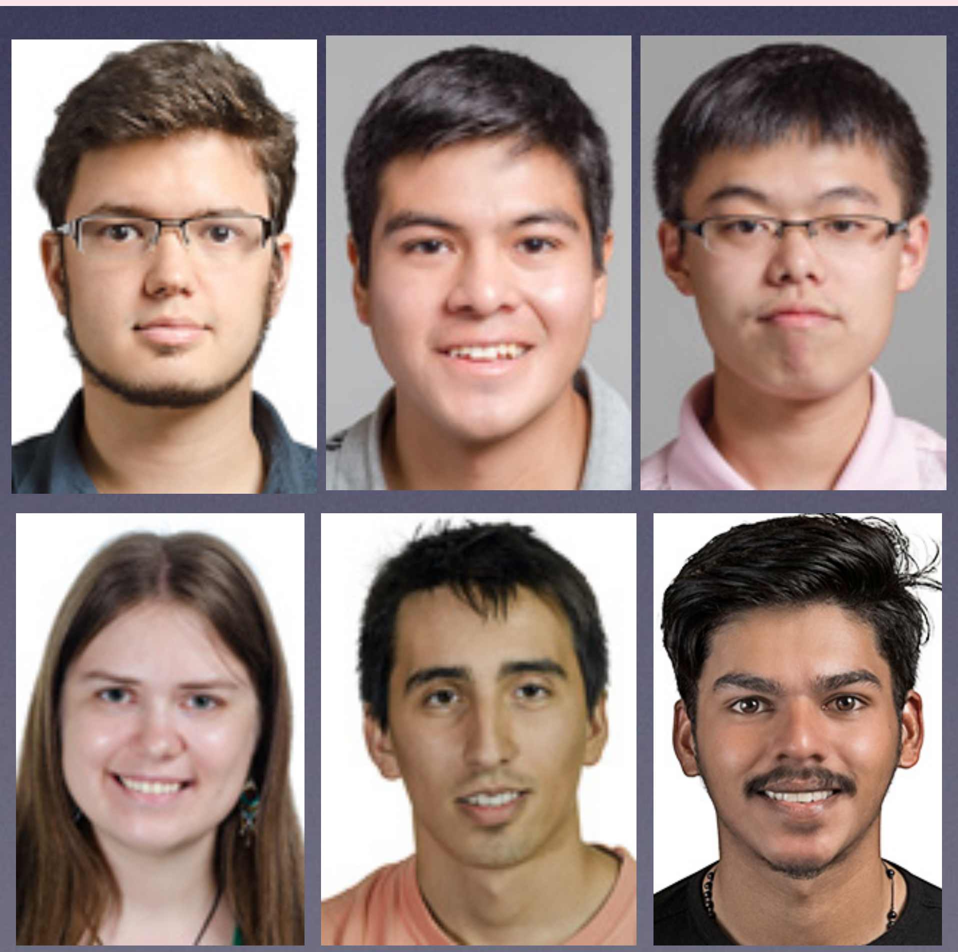
My FSU Collaborators

- 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

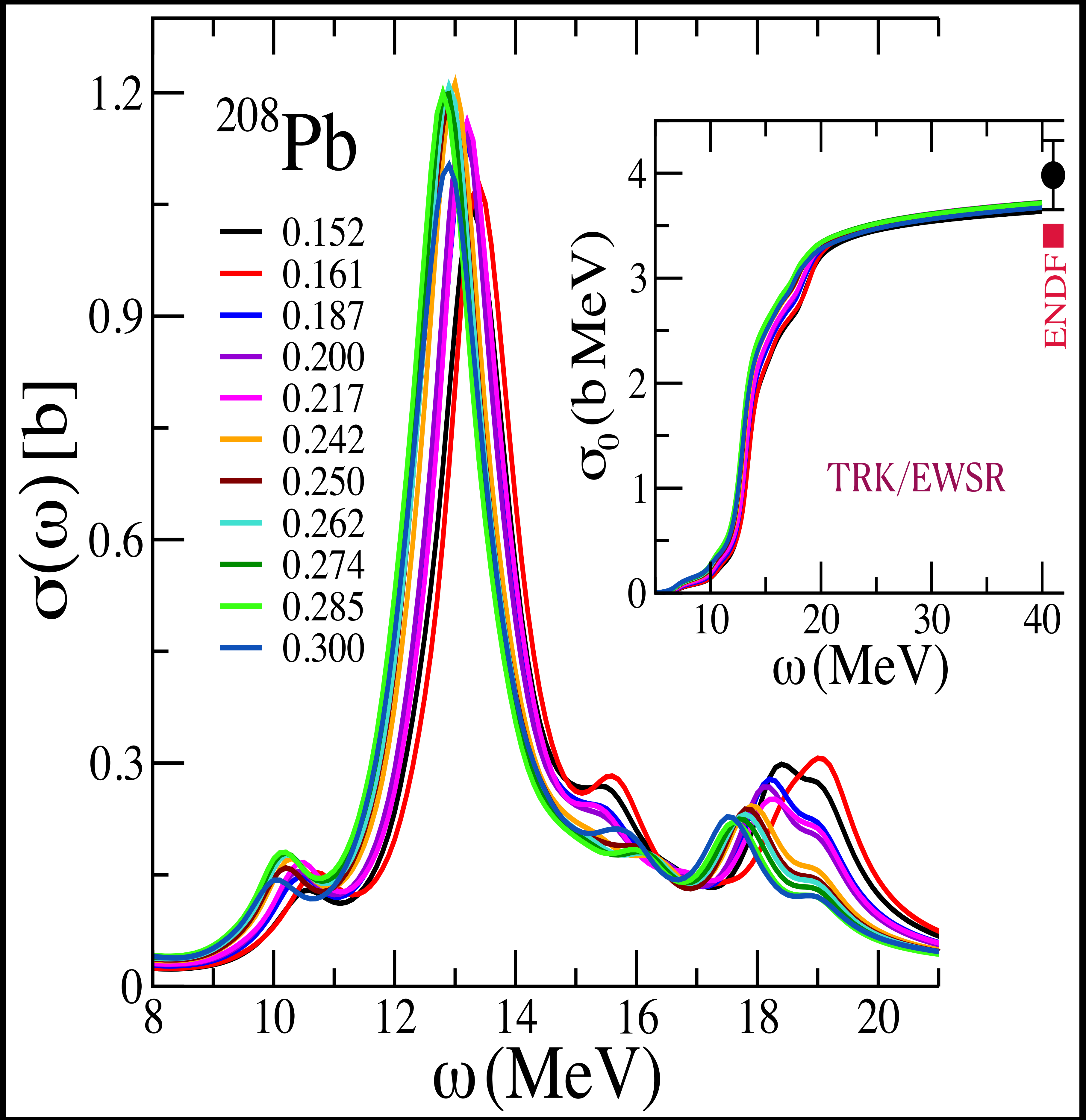
- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**

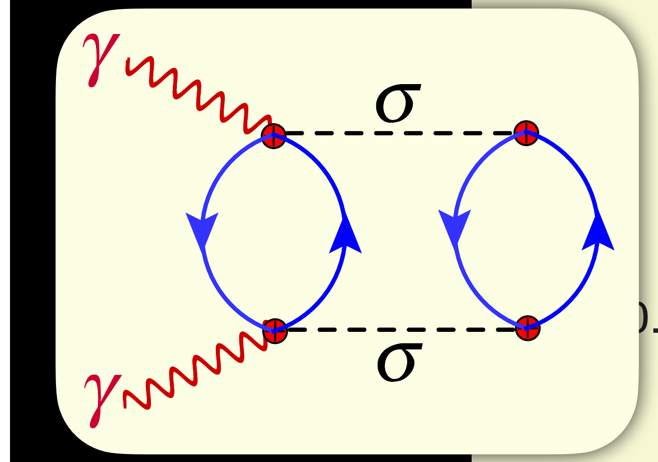
The New Generation

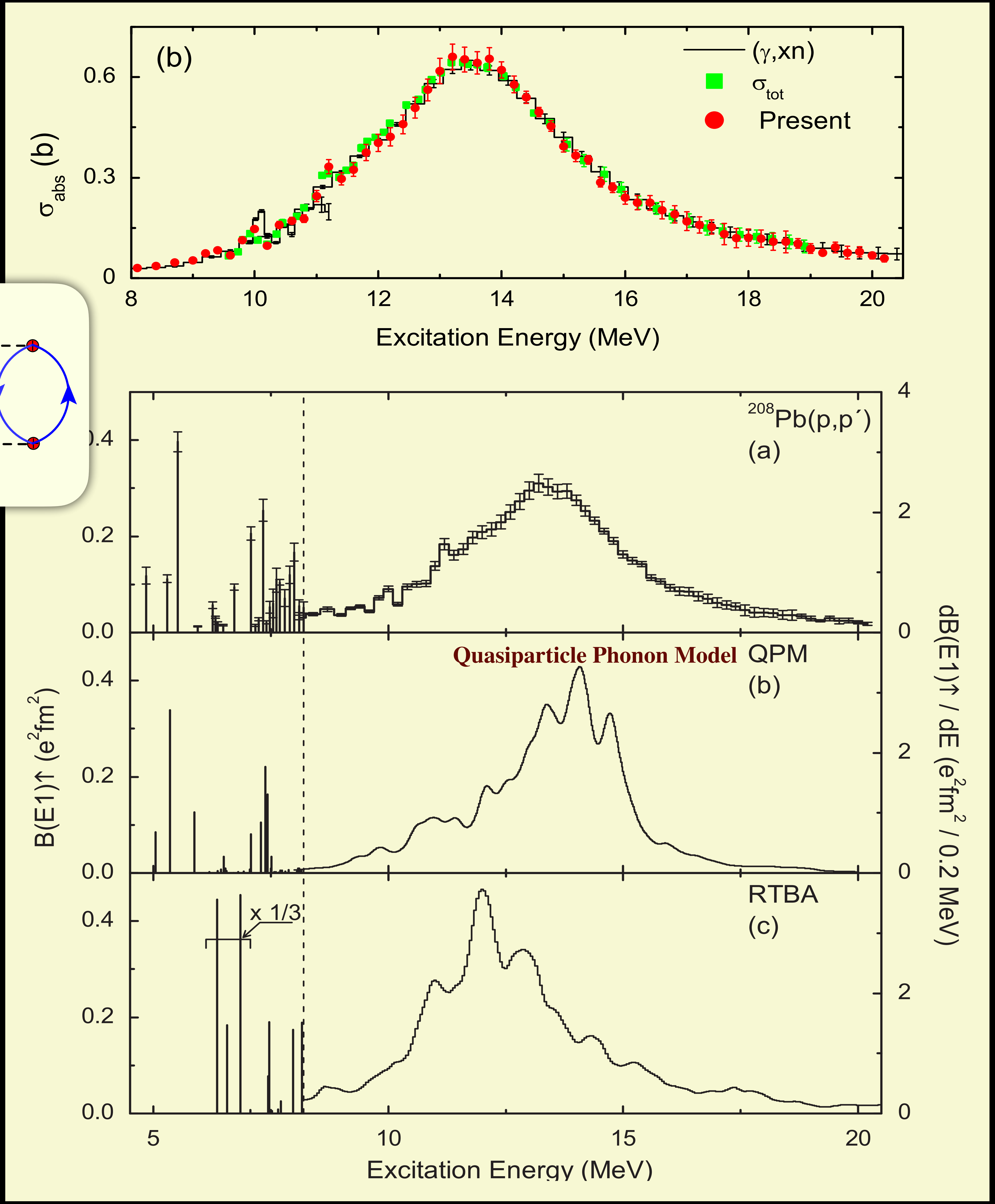
- **Amy Anderson**
- **Marc Salinas**
- **Athul Kunjipurayil**

Backup Slides

Some Limitations of the DFT Approach







- RPA treats the continuum (escape) width correctly
- Not so the spreading width — emerging from coupling to more complicated (2p-2h, …) configurations!

The PREX-CREX Dilemma

(No theoretical model can reproduce both!)

Combined Theoretical Analysis of the Parity-Violating Asymmetry for ^{48}Ca and ^{208}Pb

Paul-Gerhard Reinhard[1,*] Xavier Roca-Maza[2,†] and Witold Nazarewicz[3,‡]

"We conclude that the simultaneous accurate description of the PV asymmetry in calcium and lead cannot be achieved by our models that accommodate a pool of global nuclear properties …"

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- Density Functional Theory in all its flavors predicts a strong correlation
- 34 "non-implausible" chiral interactions also display a similar correlation
- Modifications to existent DFT models can "break" the strong correlation — but at the expense of generating unphysical behavior in other observables

THE PLOT THICKENS