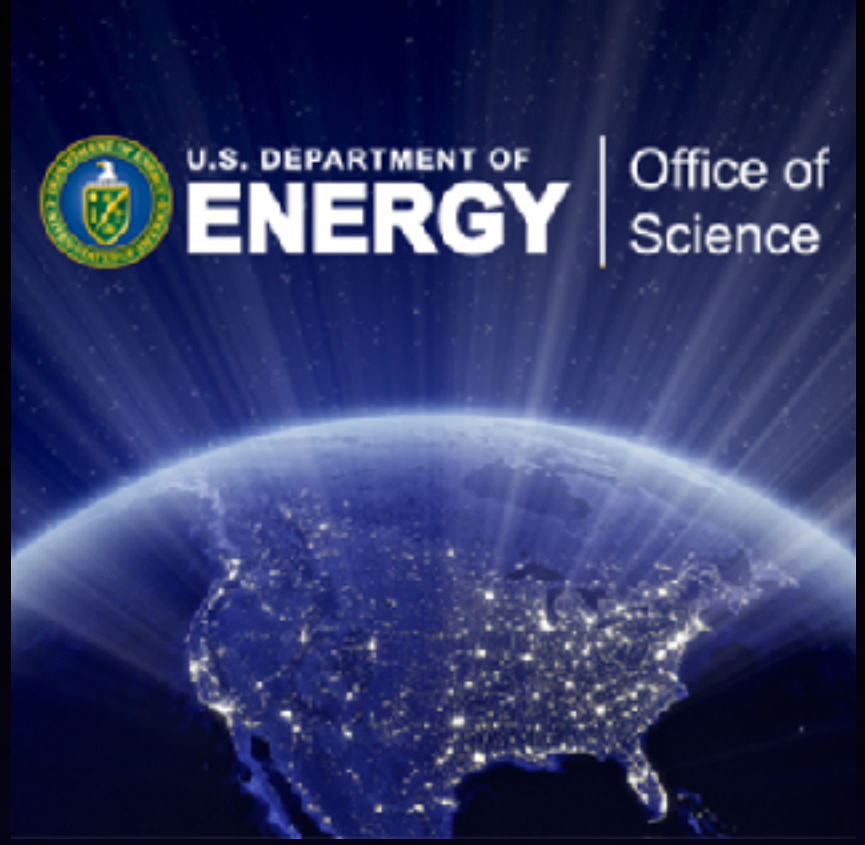
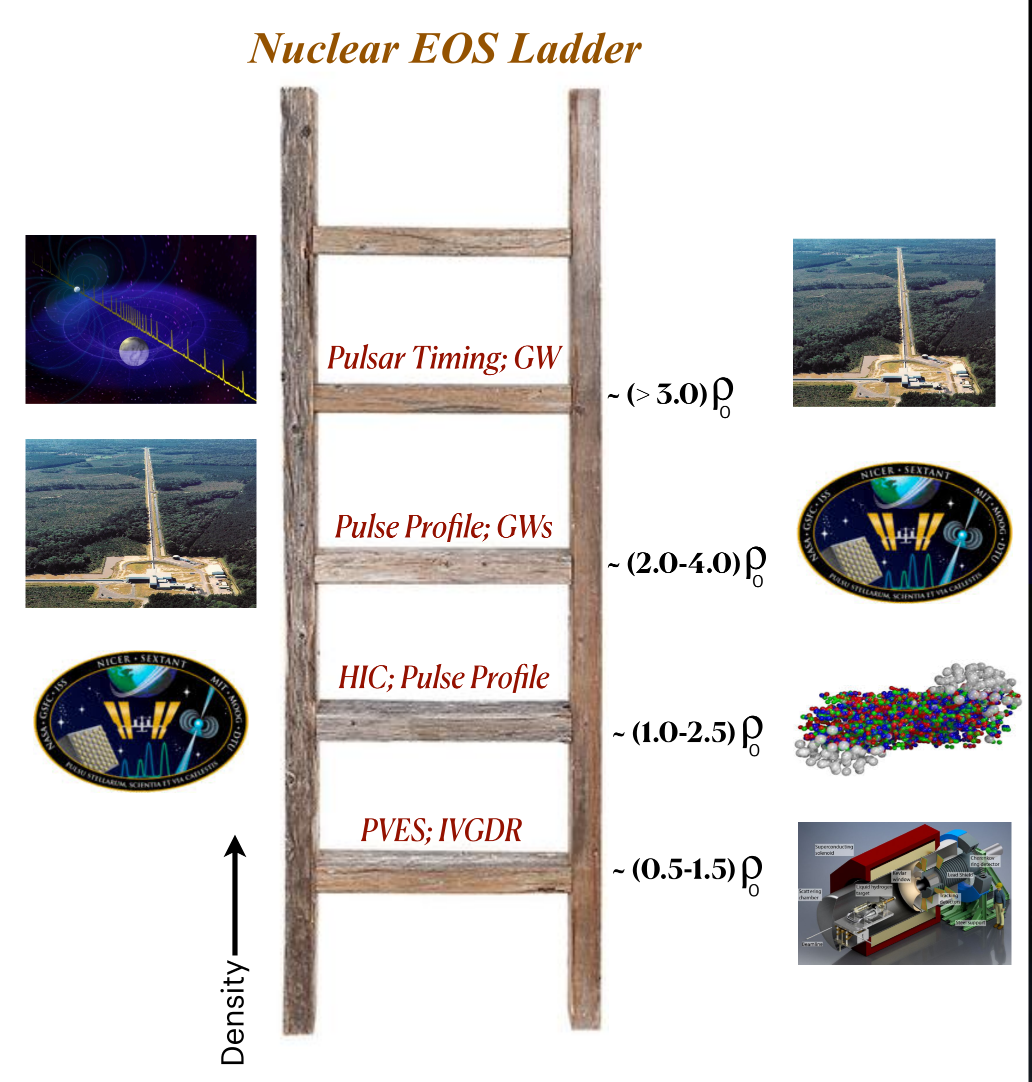
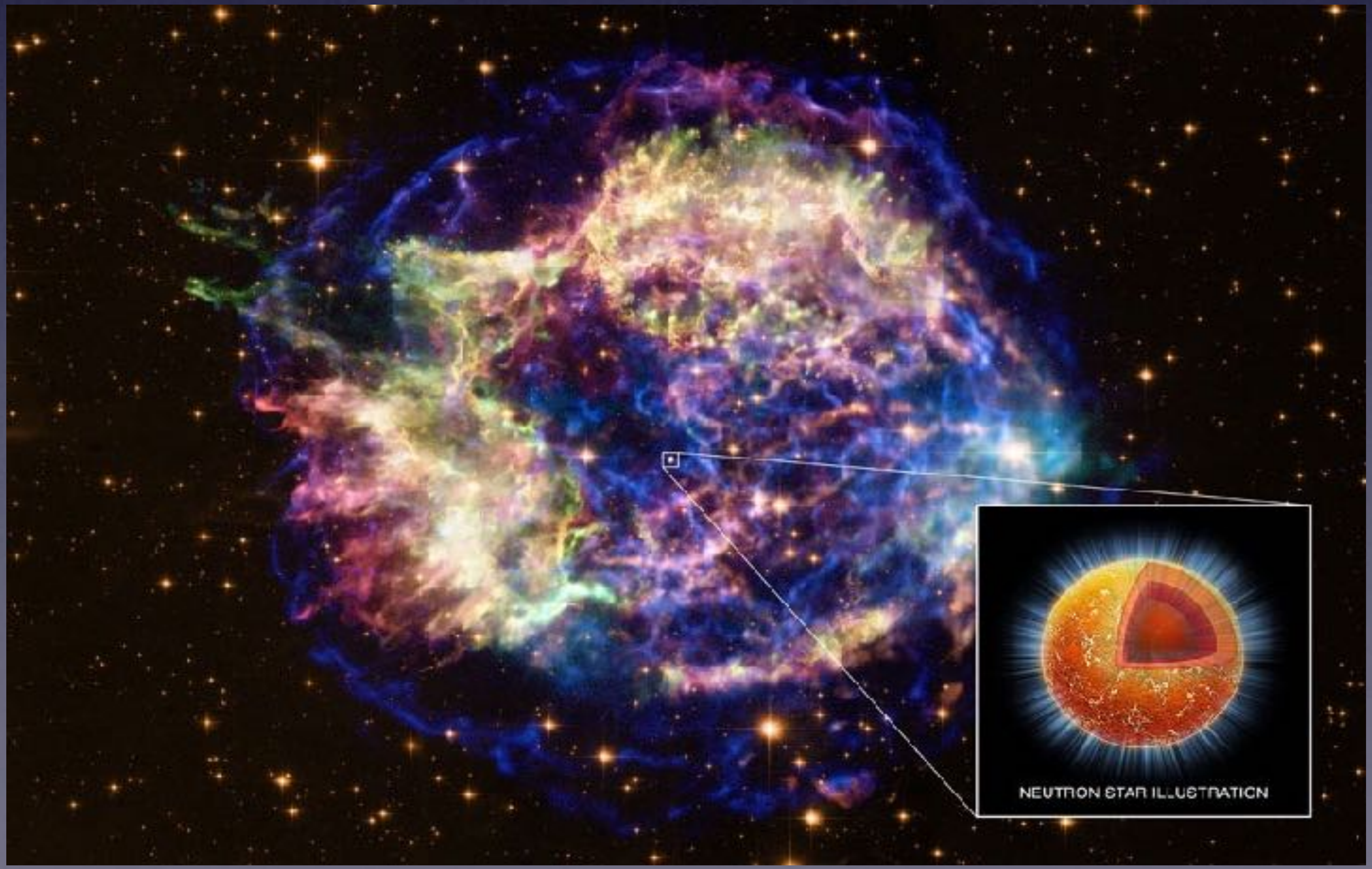
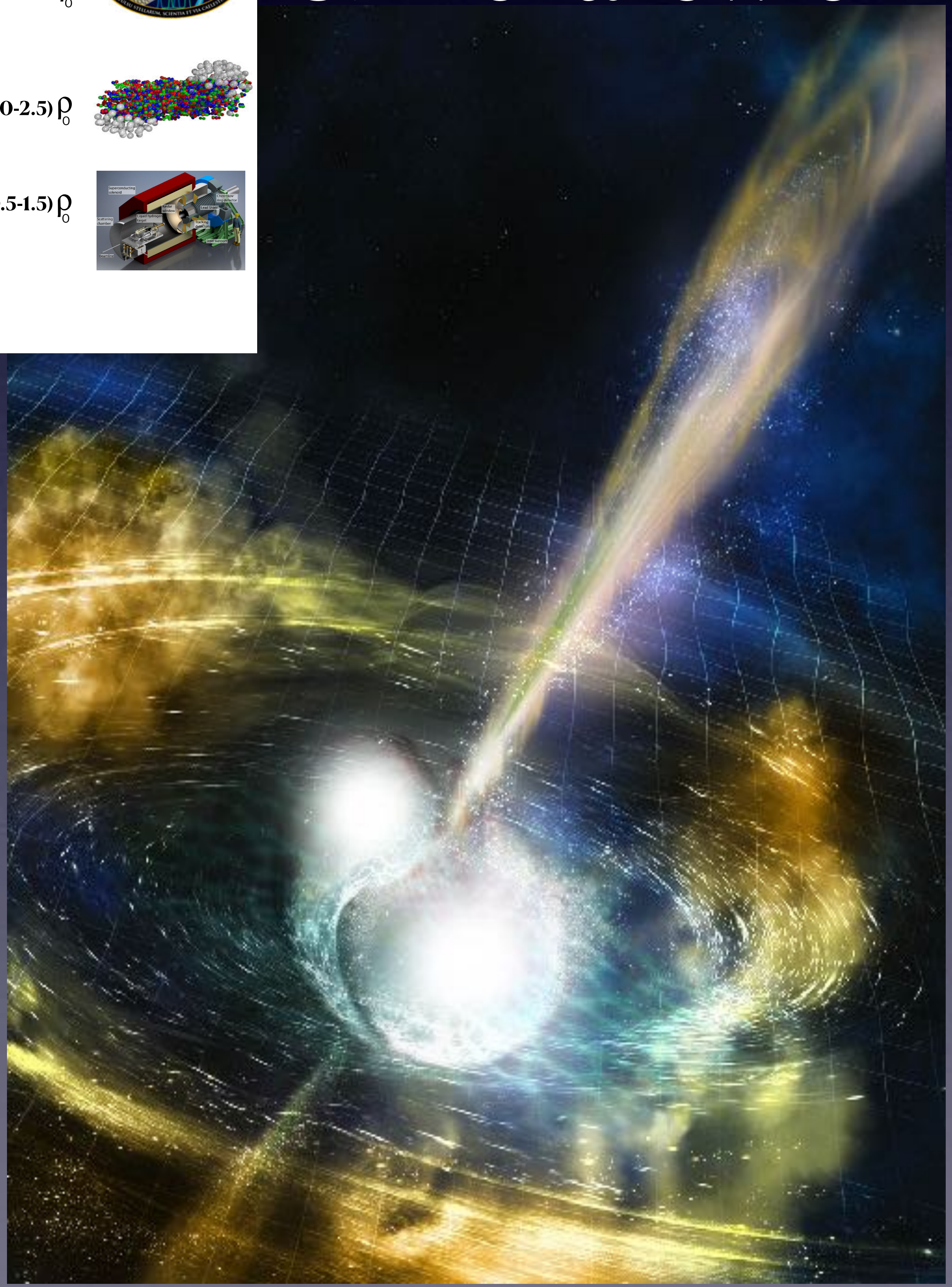
The Equation of State Ladder in the Era of Multimessenger Astronomy



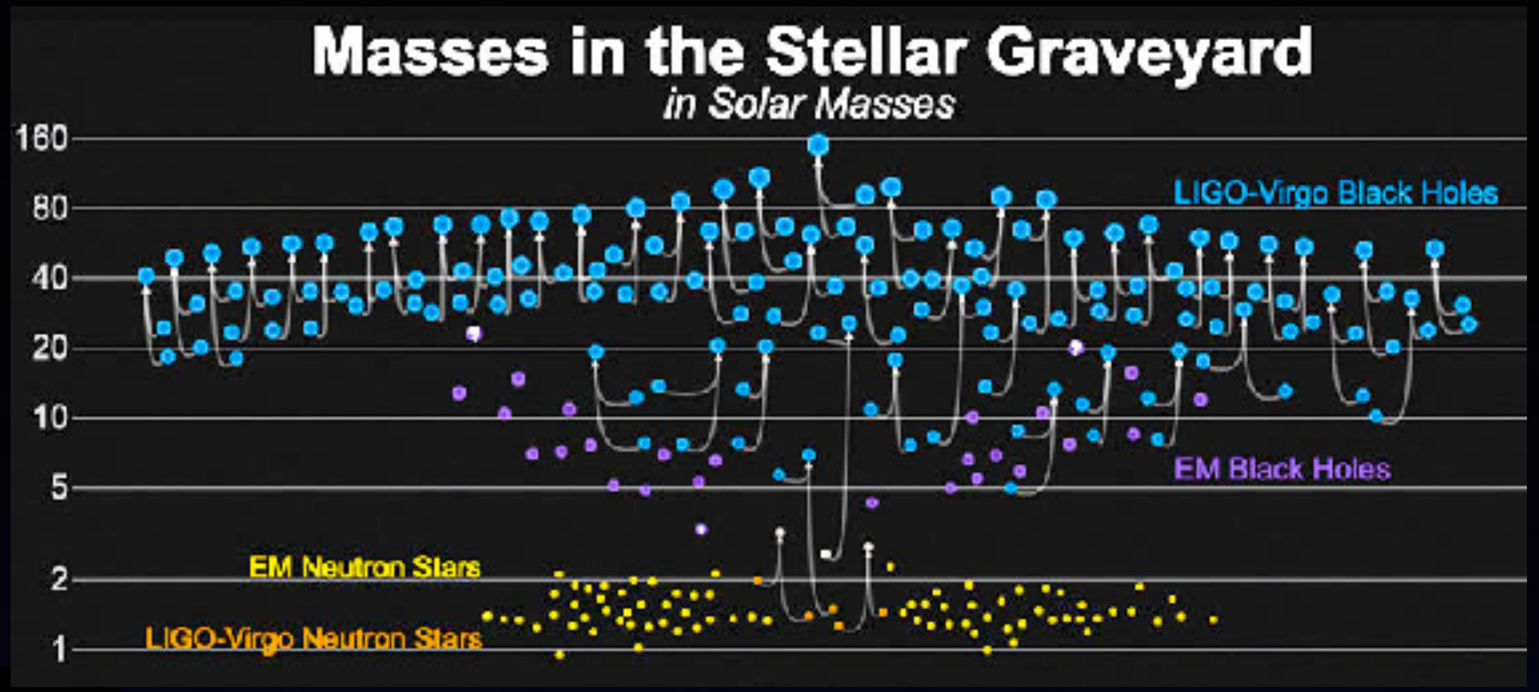


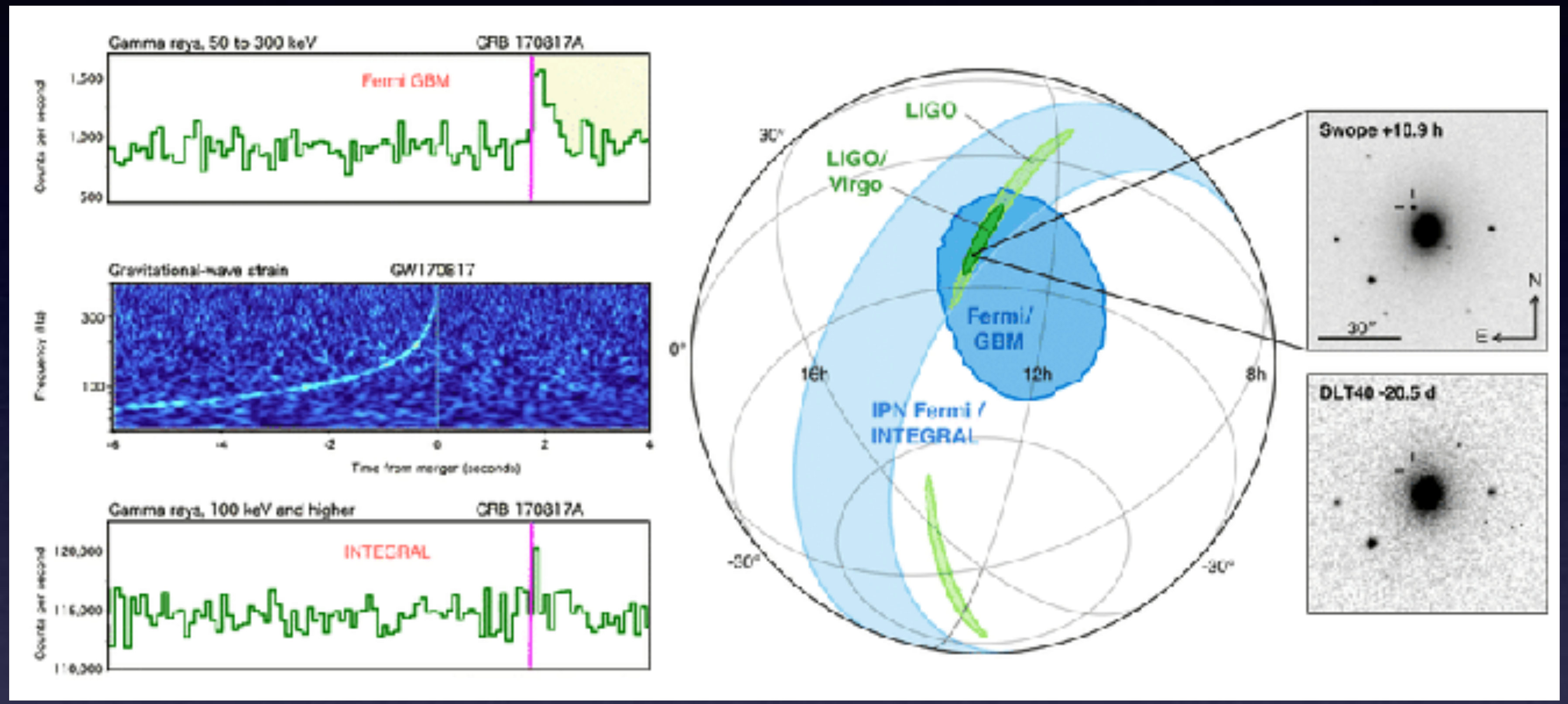
J. Piekarewicz

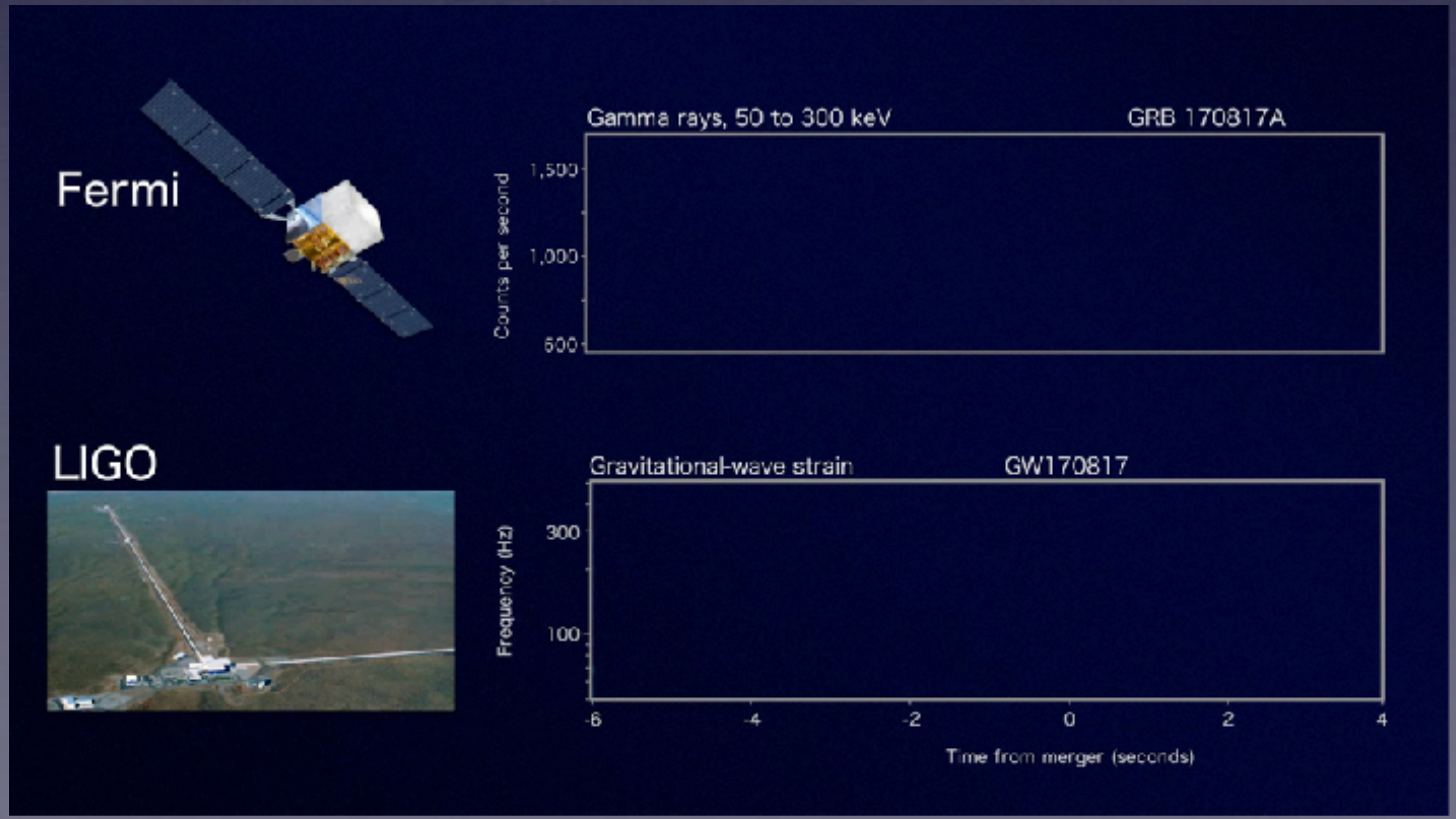




GW170817: The Beginning of the Multimessenger Era







GW170817

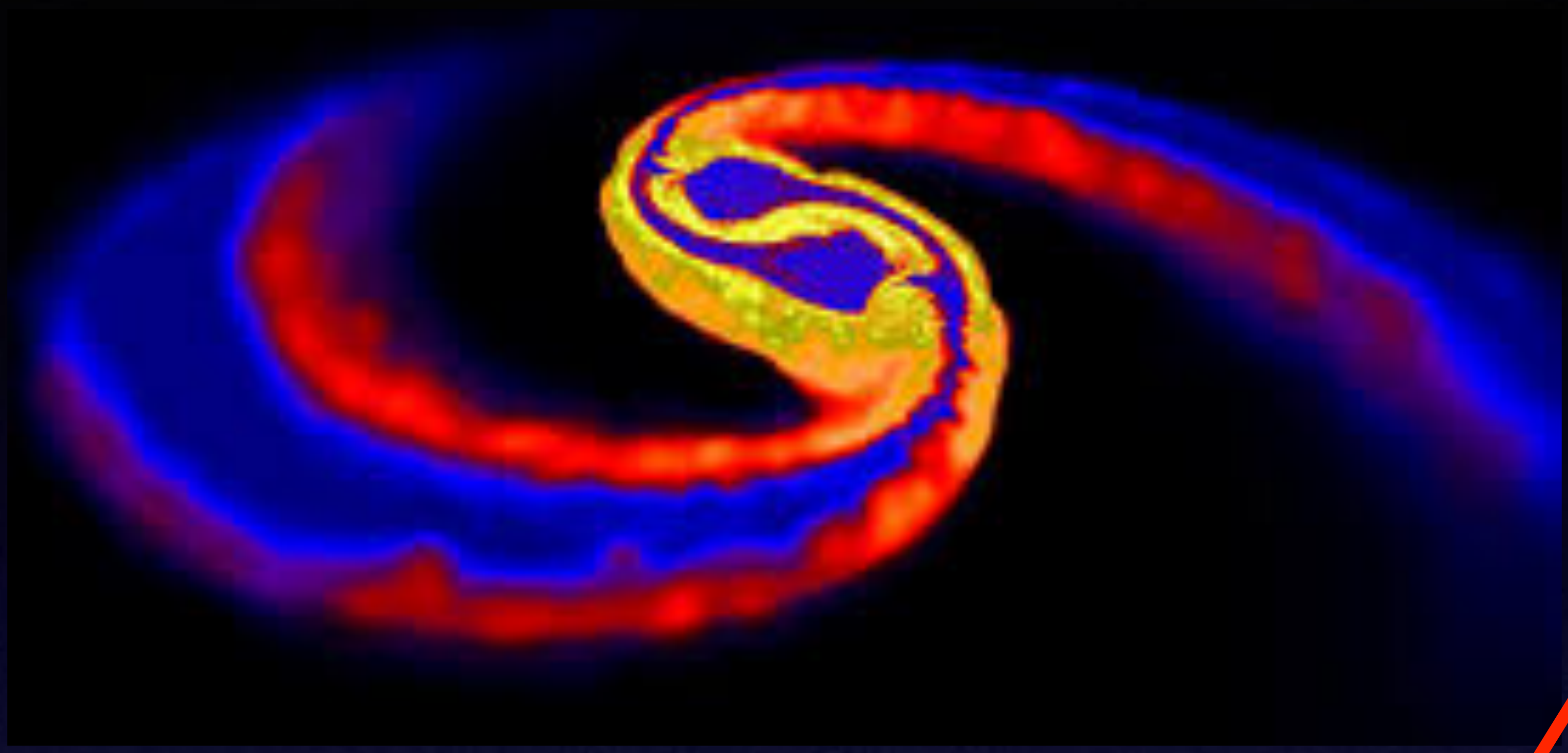
Tidal Polarizability and Neutron-Star Radii (2017)

Electric Polarizability:

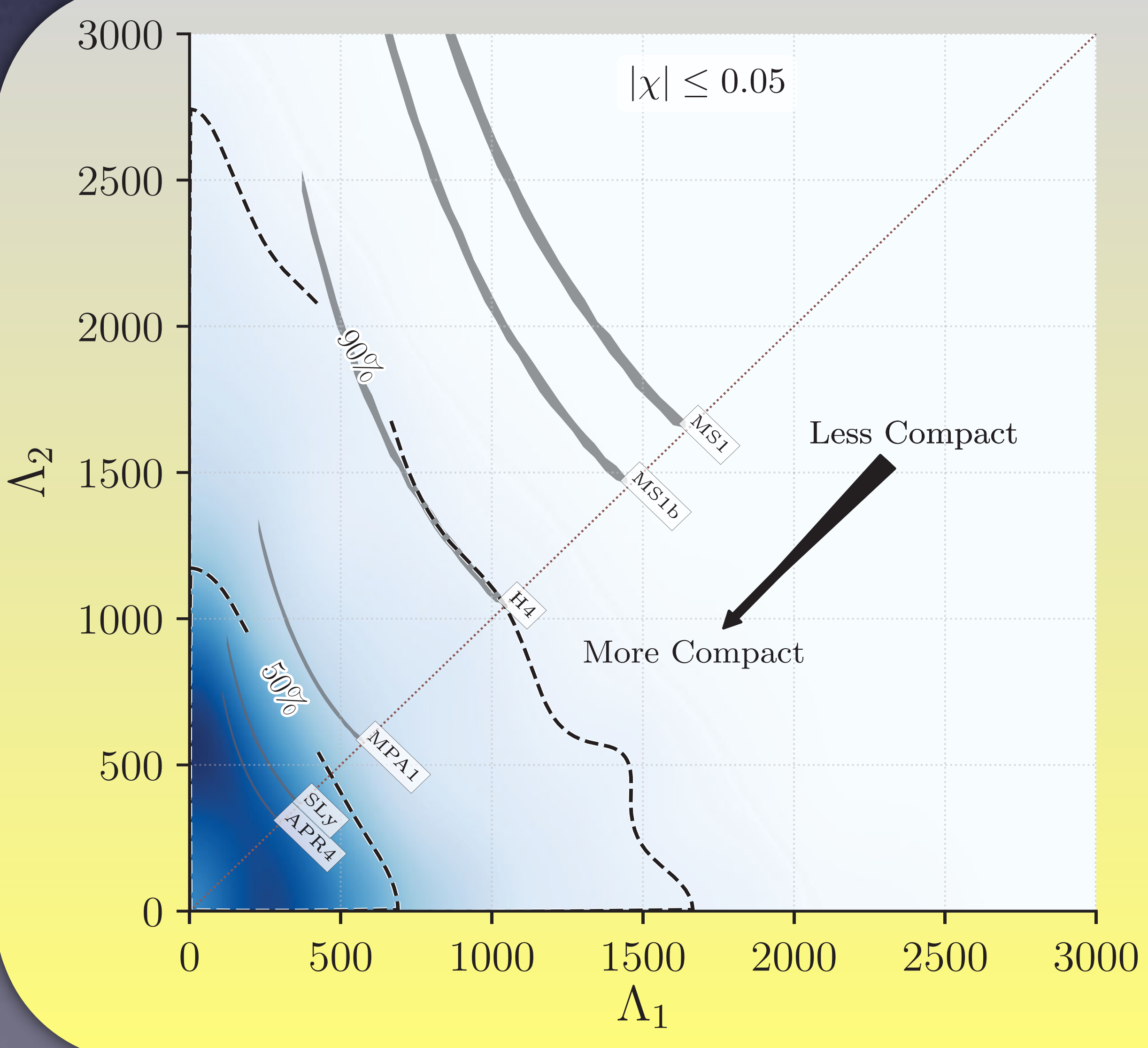
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$

Tidal Polarizability (Deformability):

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



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



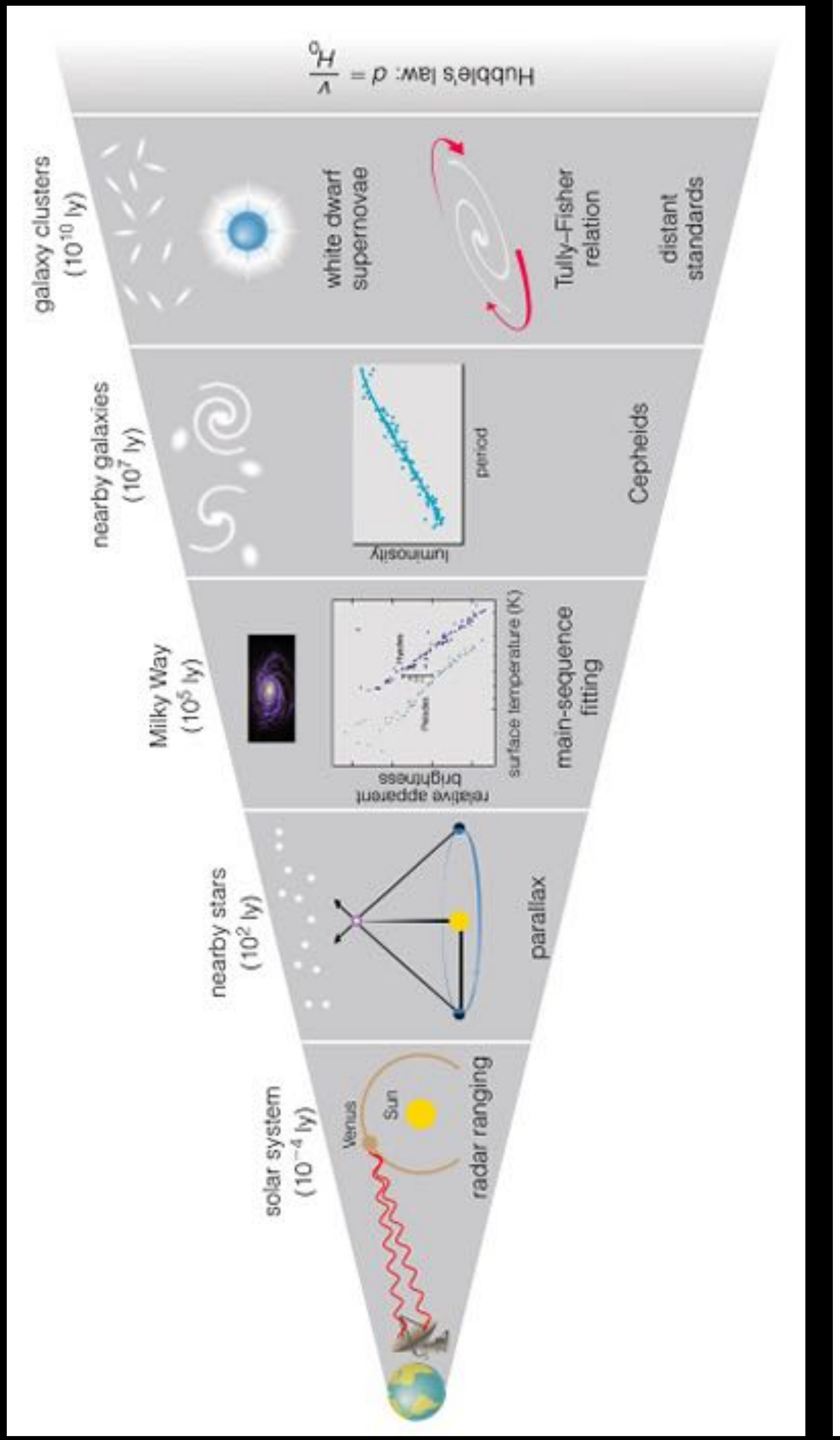
GW170817 rules out very large neutron star radii!

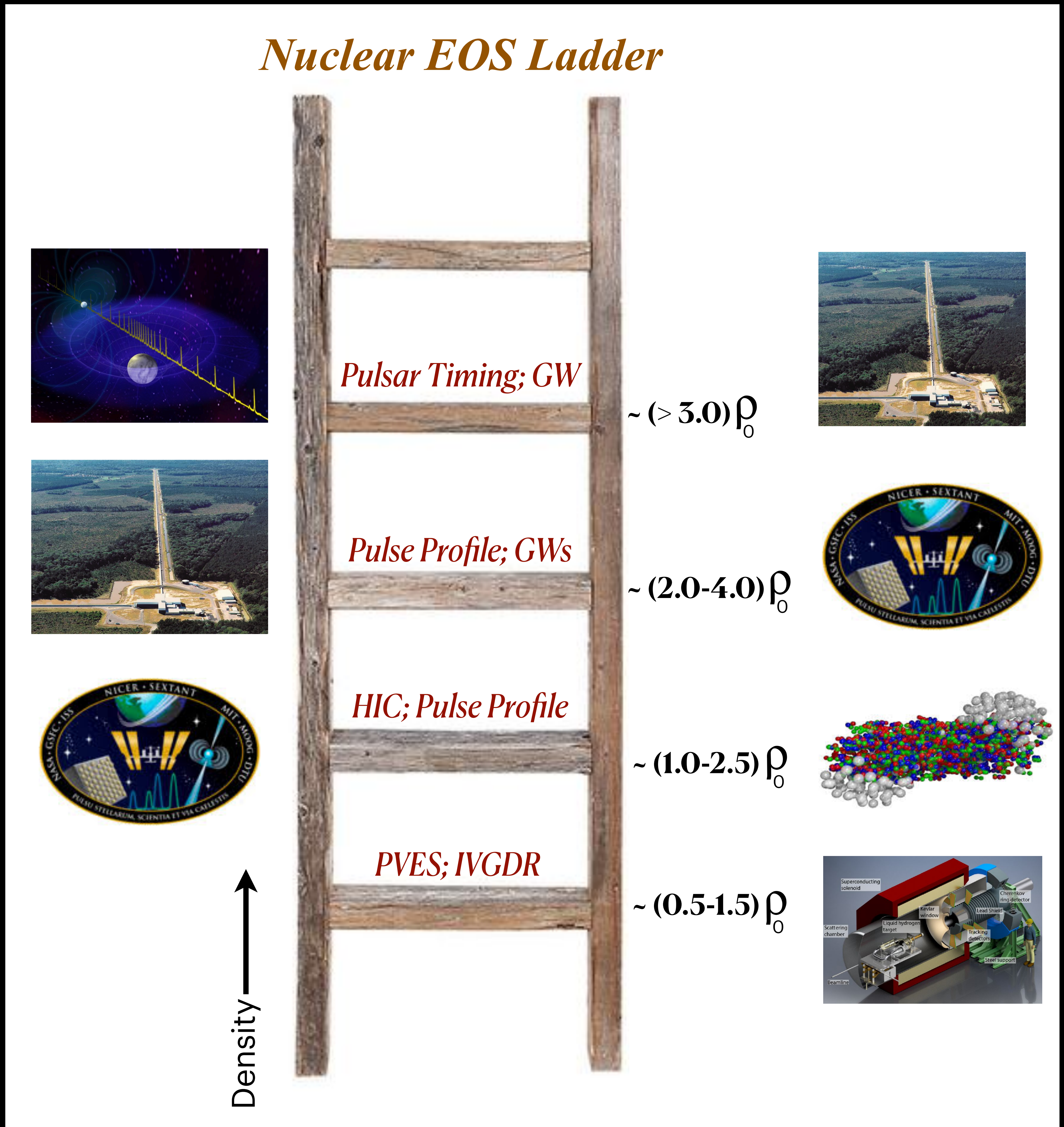
Neutron Stars must be compact

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

The Nuclear Equation of State Density Ladder

Cosmic Distance Ladder





Cosmic Distance Ladder

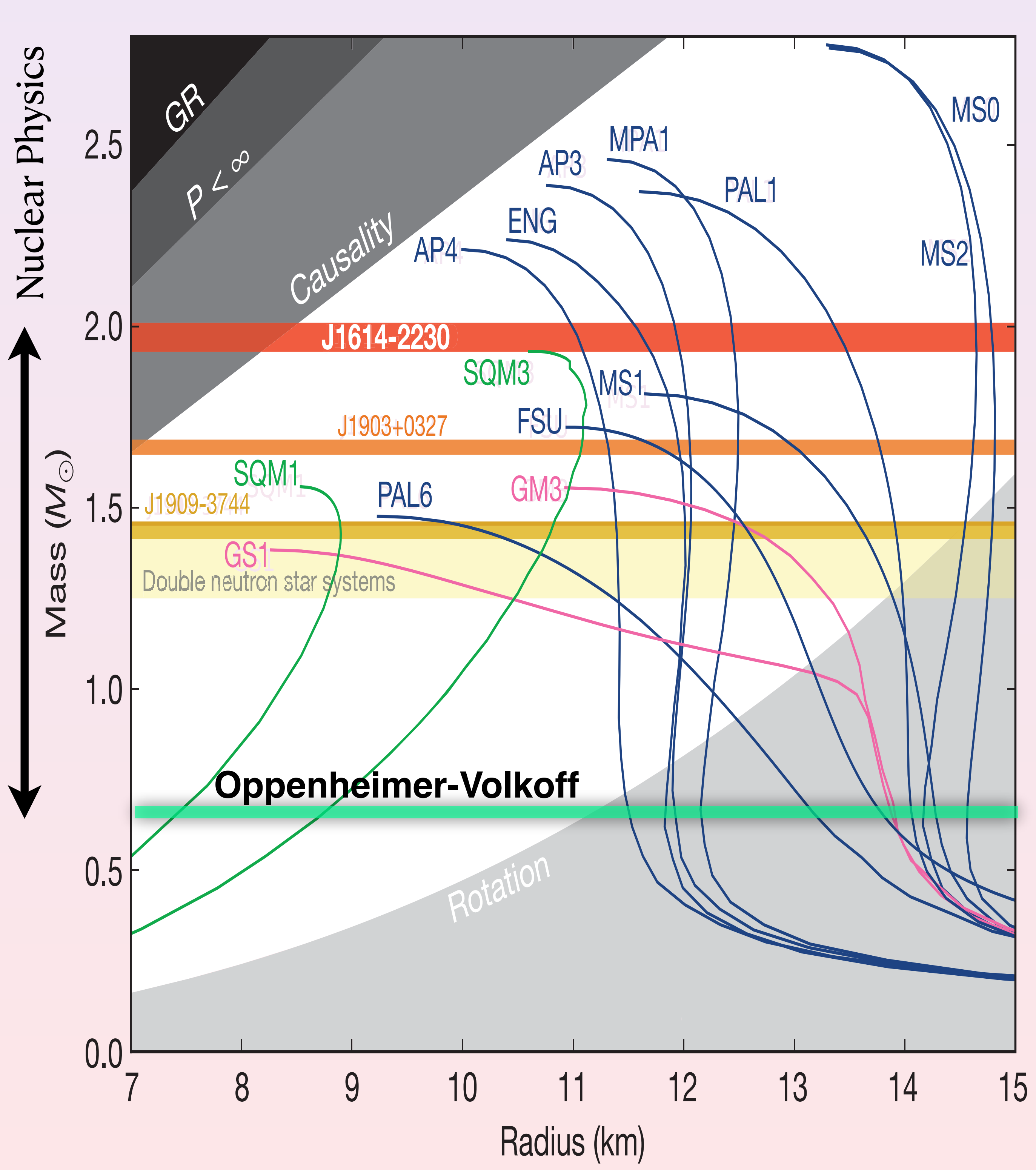
The cosmic ladder has "rungs" of objects with certain properties that let astronomers confidently measure their distance. Jumping to each subsequent rung relies on methods for measuring objects that are ever farther away, the next step often piggybacking on the previous one.

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.

Neutron Stars: Unique Cosmic Laboratories

- 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

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

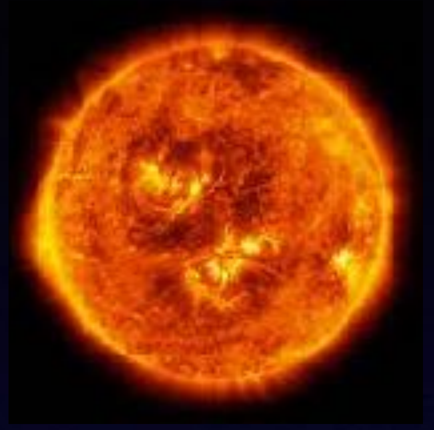
Only observational constraint in the form of two neutron stars with a mass in the vicinity of $2M_{sun}$

The Equation of State of Neutron-Rich Matter

Equation of state: textbook examples

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

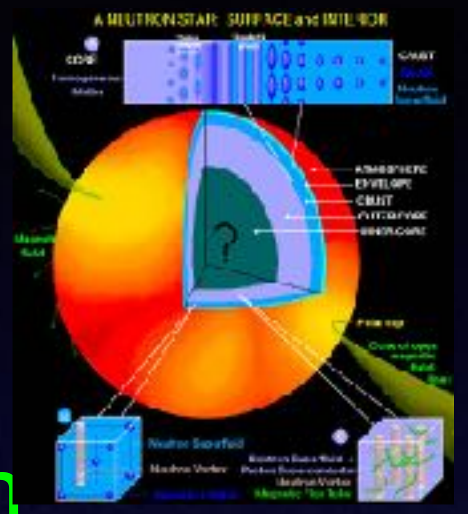
$$P(n,T) = nk_{\rm B}T \leftrightarrow P(\mathcal{E}) = \frac{2}{3}\mathcal{E}$$



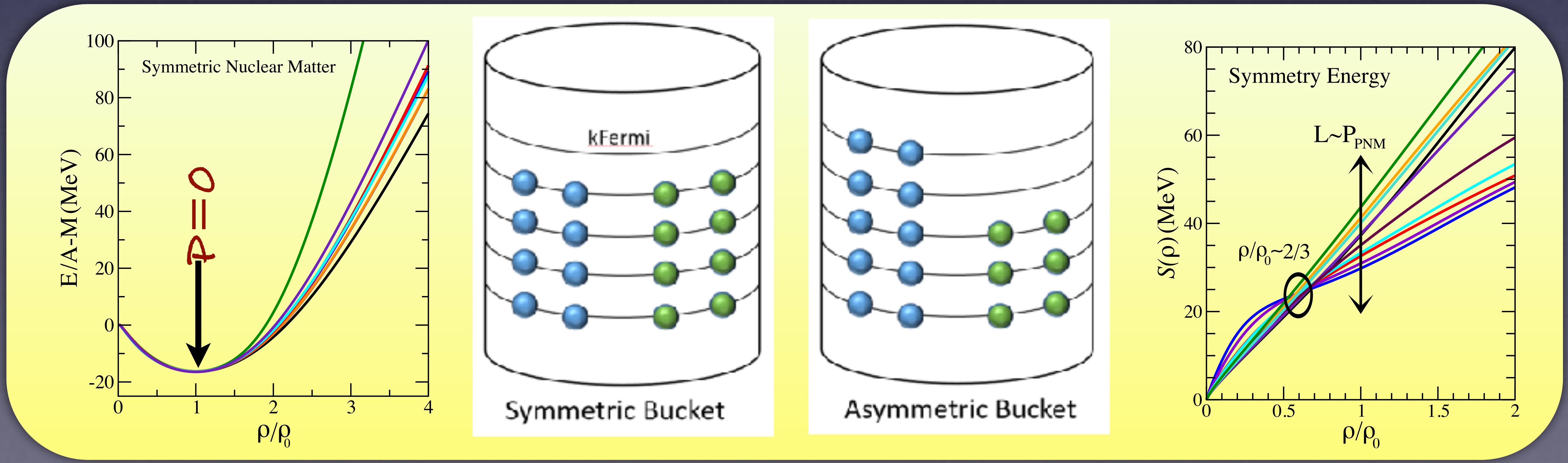
- Non-interacting (UR) quantum gas
  high density, low temperature limit

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

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



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



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

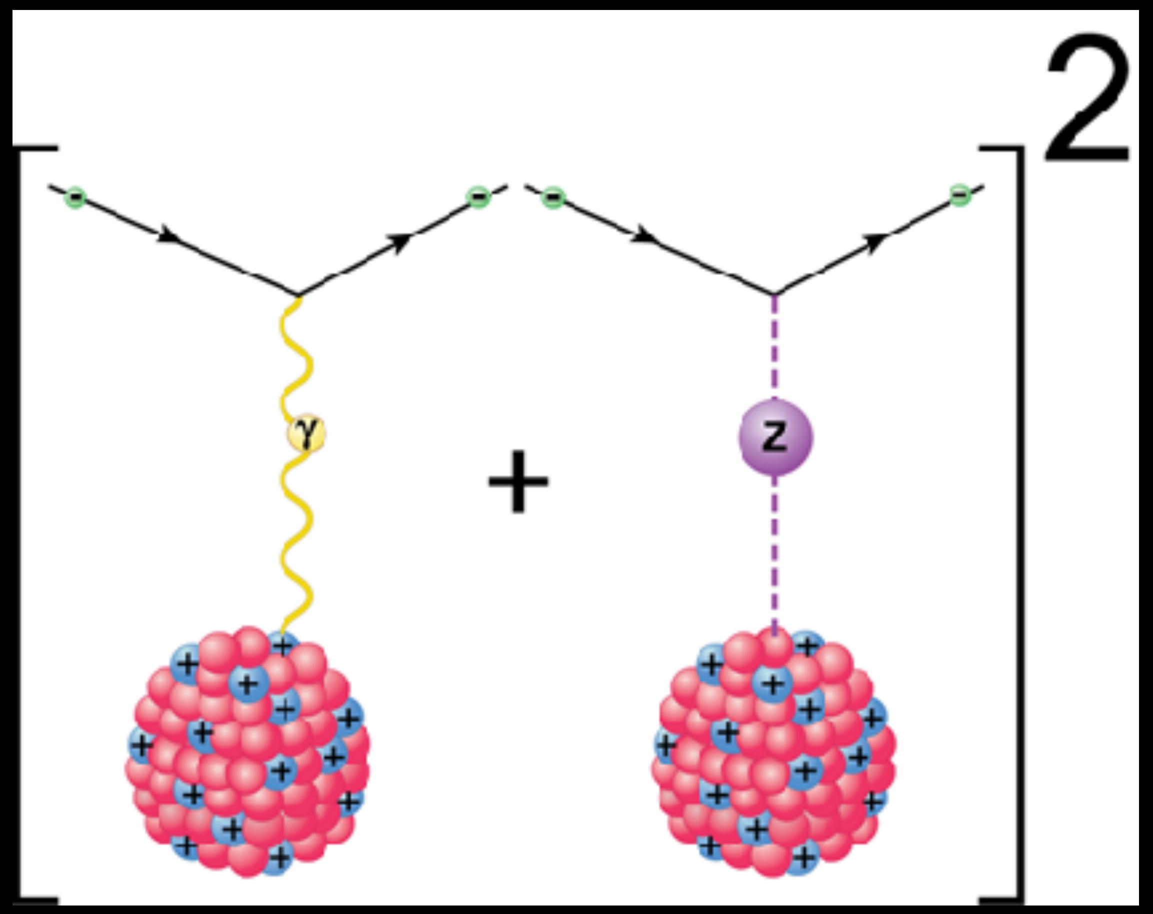
$$P_{\rm PNM} \approx \frac{1}{3}L\rho_0 \ \text{(Pressure of PNM)}$$

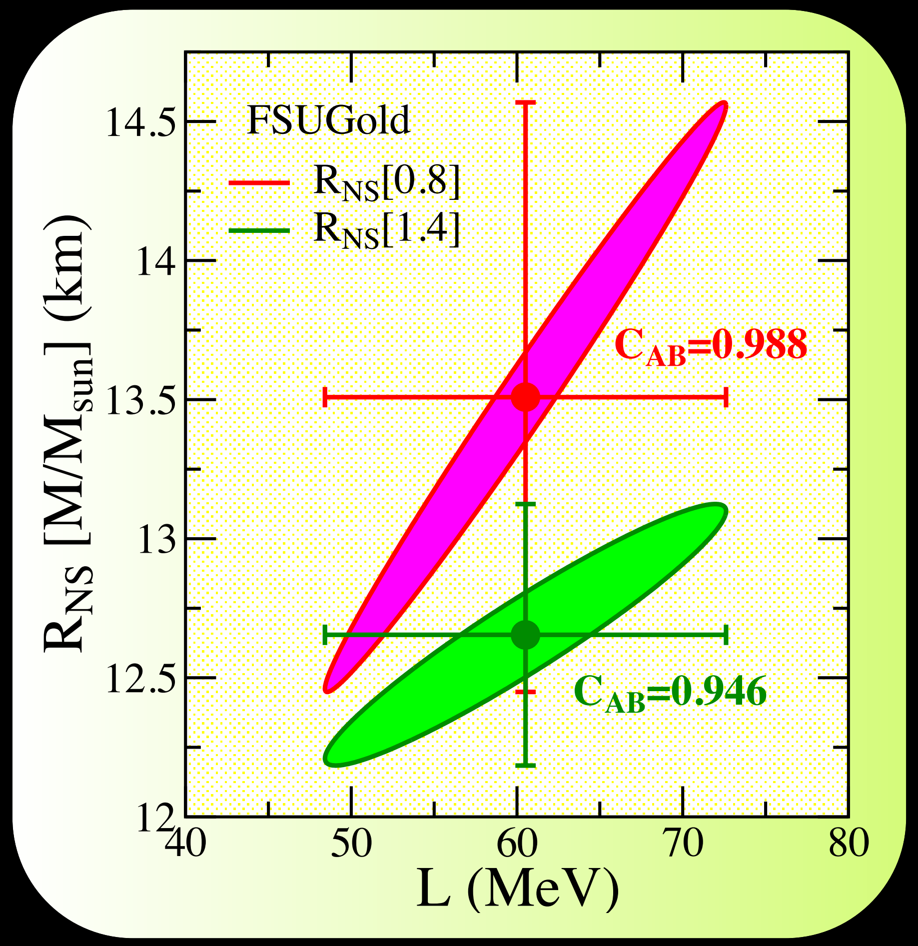
"Stiff" ⟶ L large

"Soft" ⟶ L small

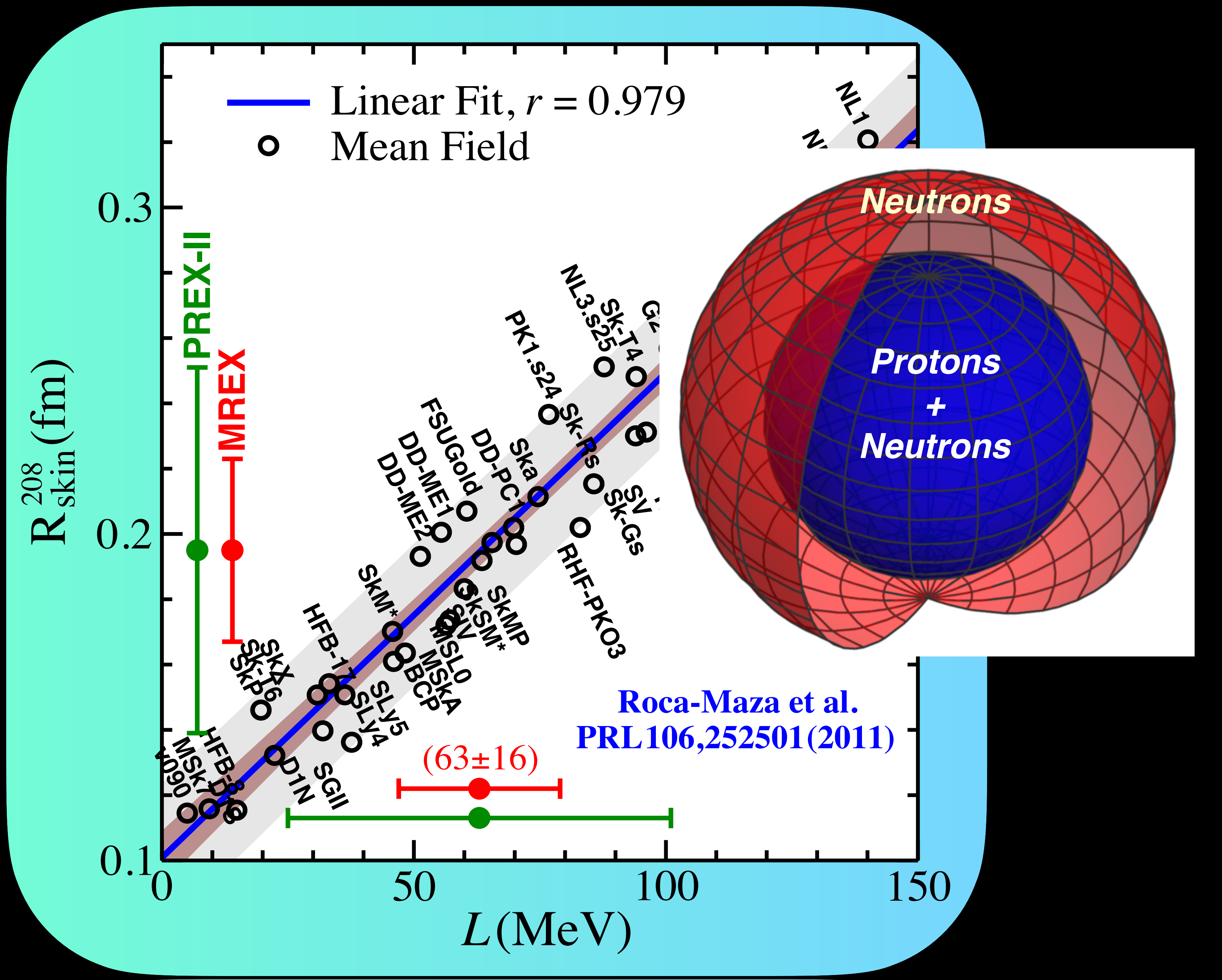
Heaven and Earth

Laboratory Constraints on the EOS

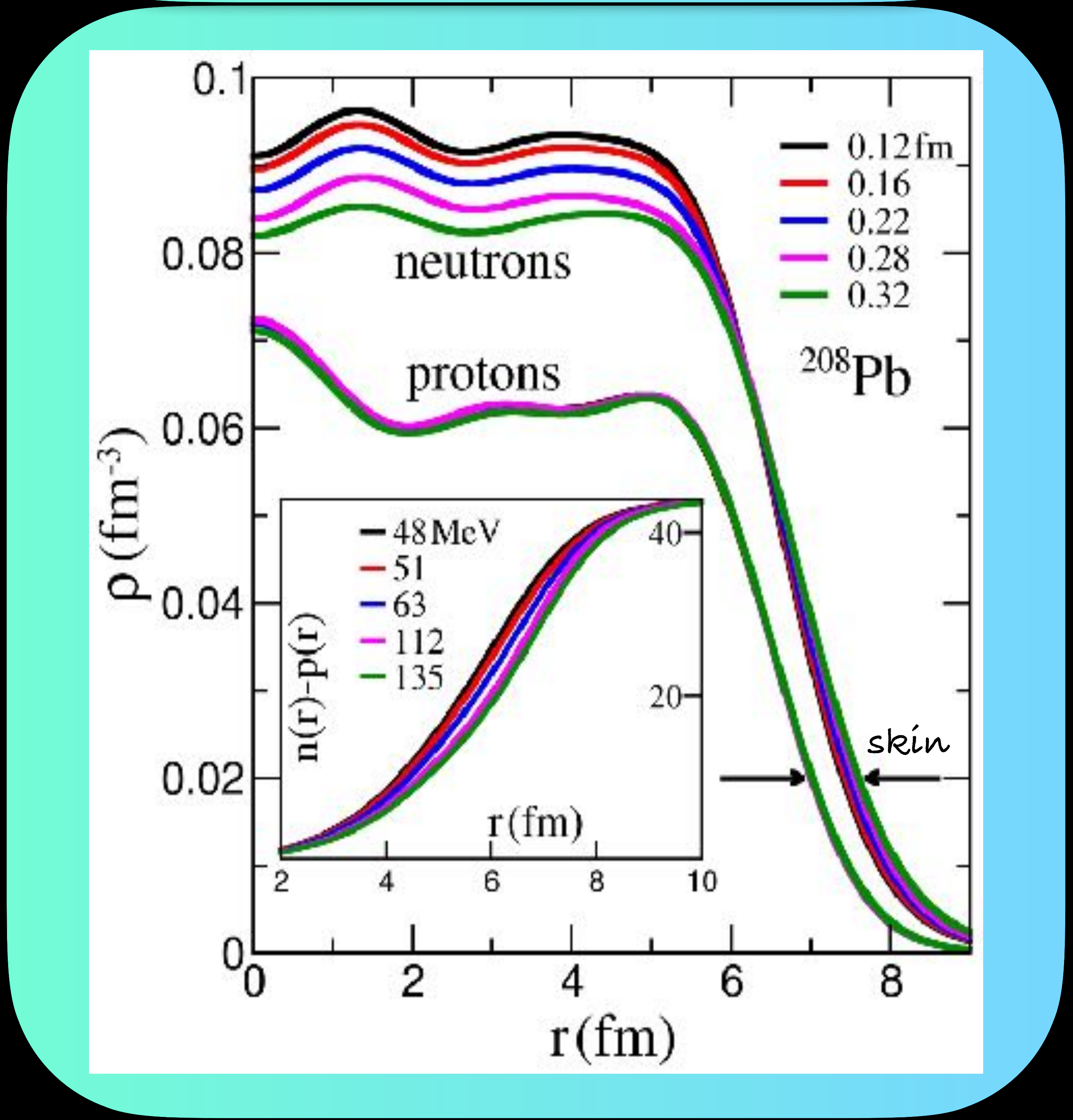




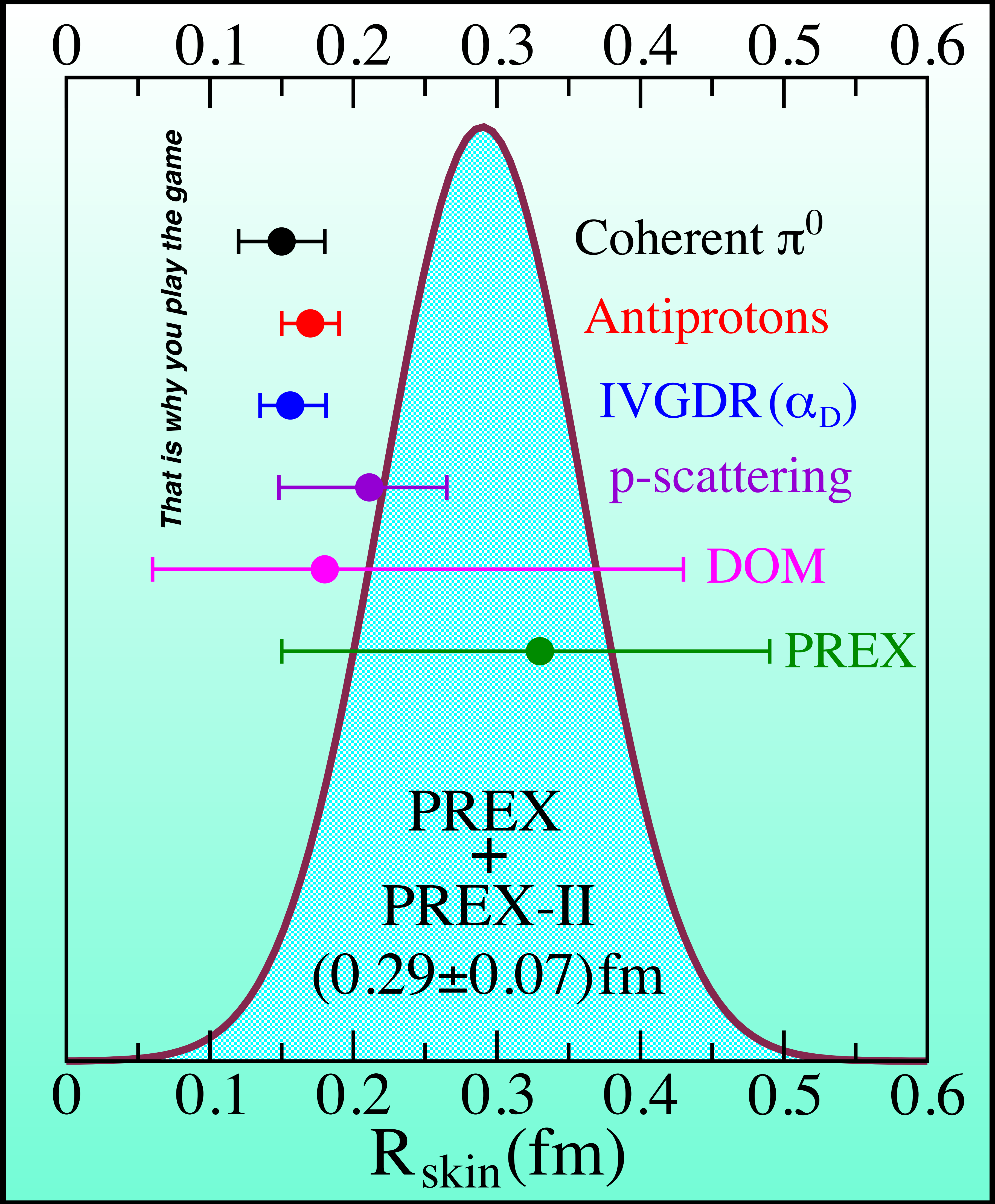
18 orders magnitude



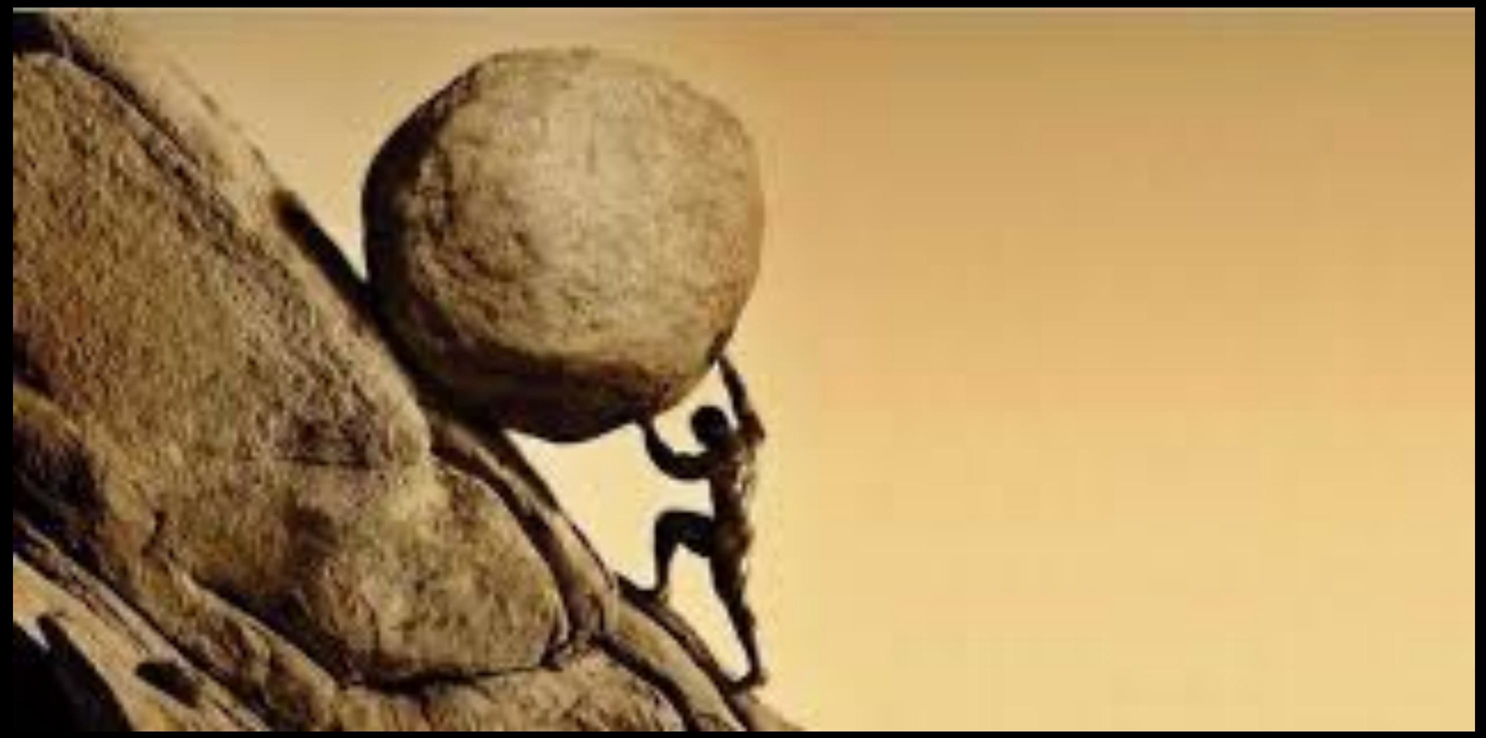
- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: $P_{PNM}=L$
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as ^{208}Pb
- Parity-violating elastic 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 determination of the EOS (P vs E) of neutron-rich matter in the immediate vicinity of saturation density



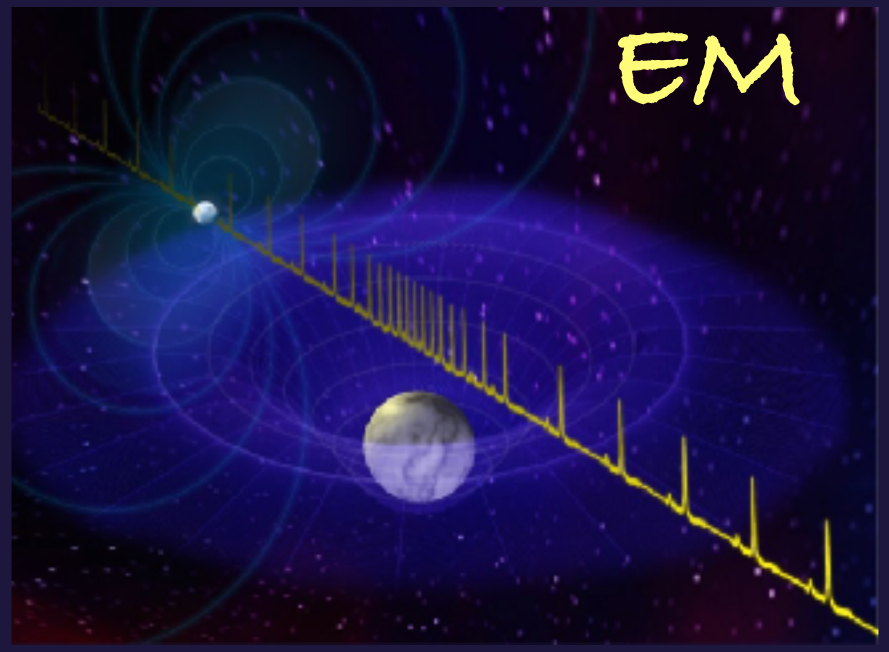
Heroic effort from our experimental colleagues

- Coherent p0 g-production
  PRL 112, 242502 (2014)
- Antiprotons
  PRL 87, 082501 (2001)
  PRC 76, 014311 (2007)
- Electric dipole polarizability
  PRL 107, 062502 (2011)
- Elastic p-nucleus scattering
  PRC 82, 044611 (2010)
- Dispersive optical model
  PRL 125, 102501 (2020)
- PREX
  PRL 108, 112502 (2012)

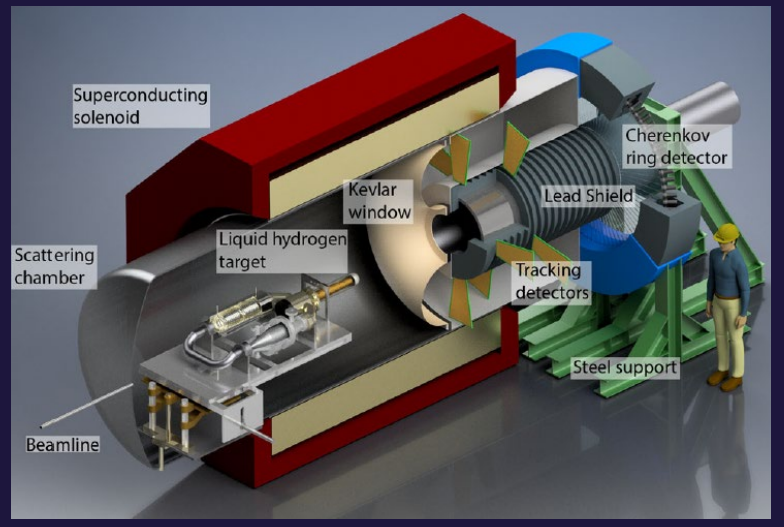
The Quest for the EOS: Status After GW170817

- *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!)

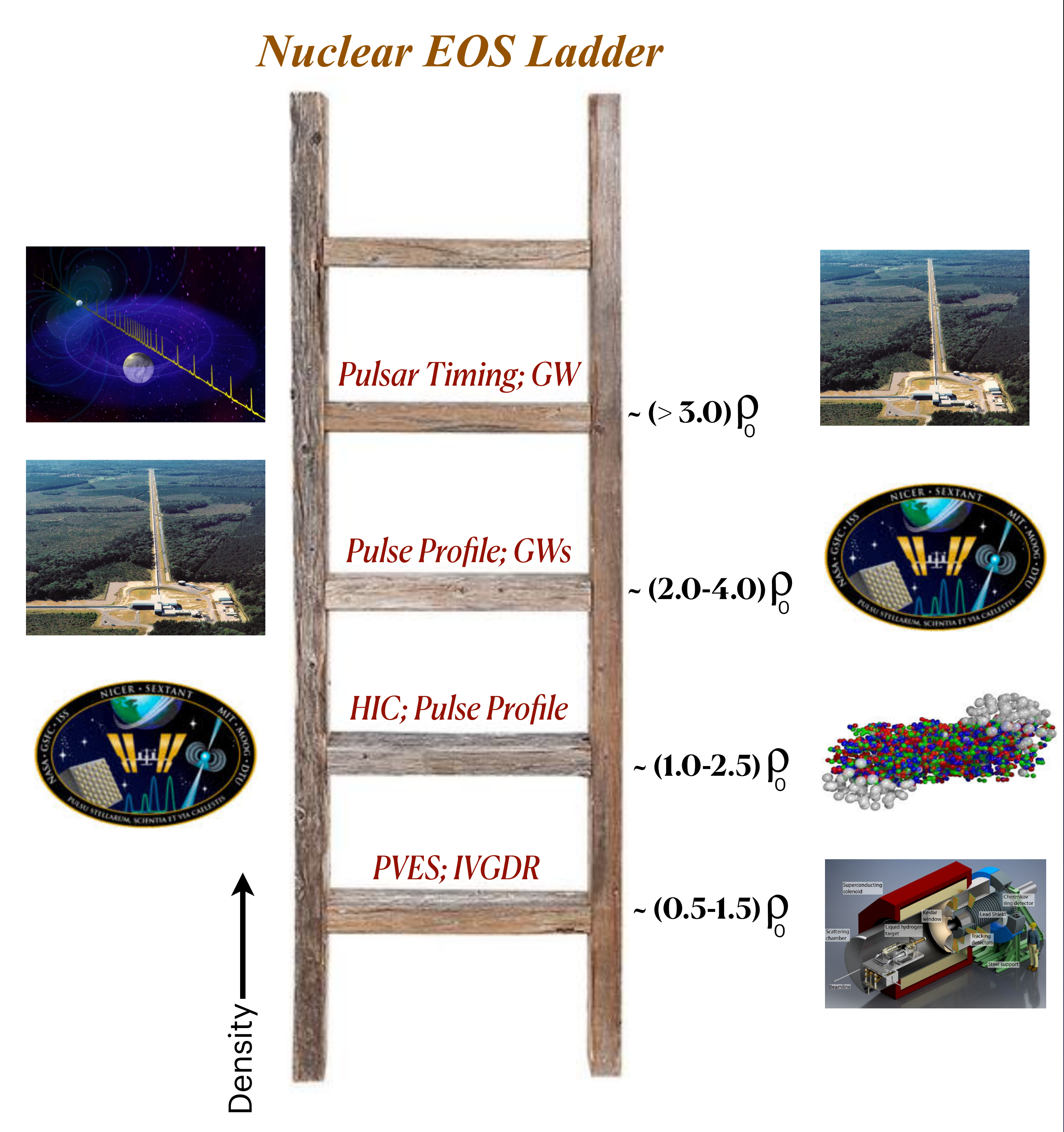


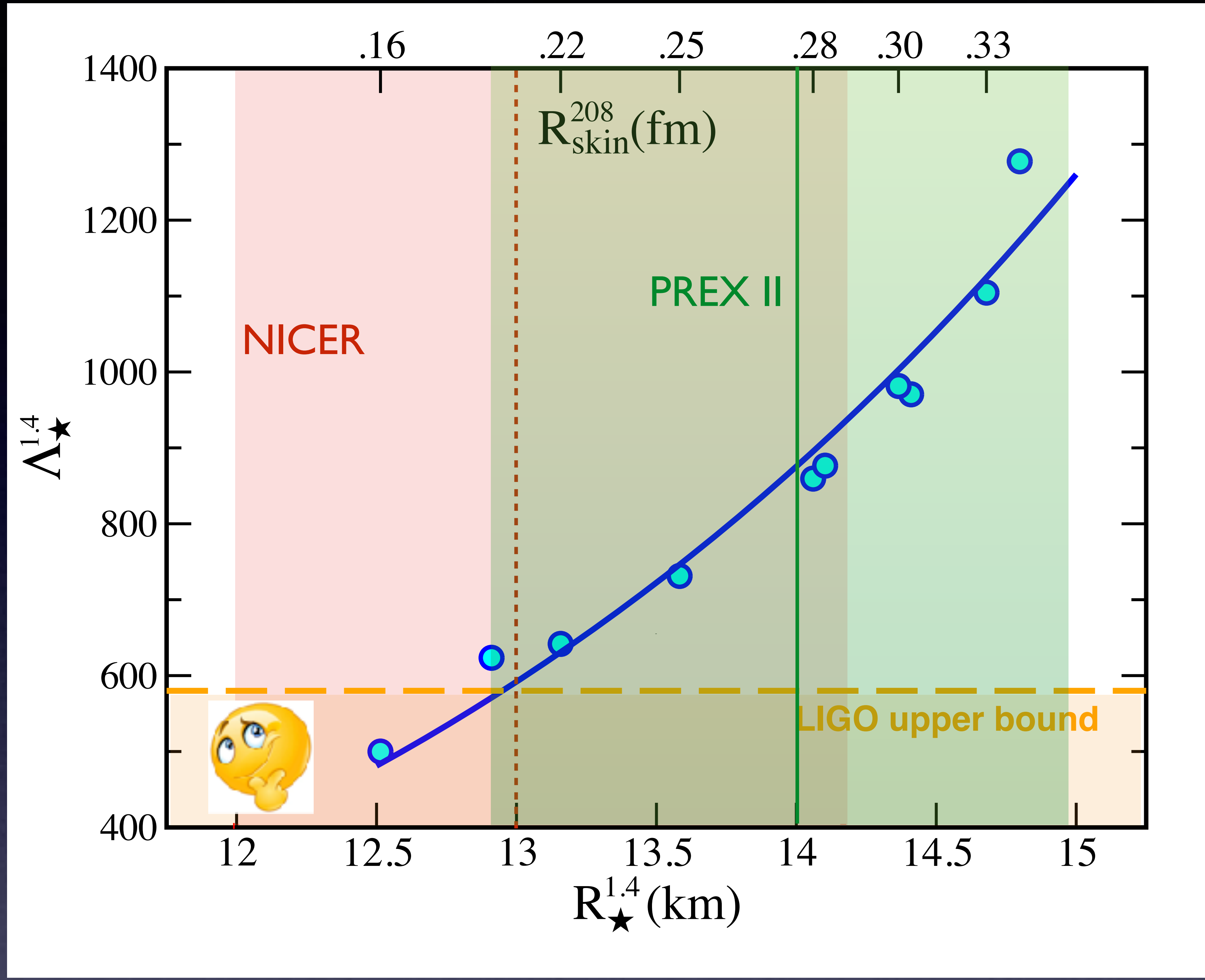
Terrestrial experiments

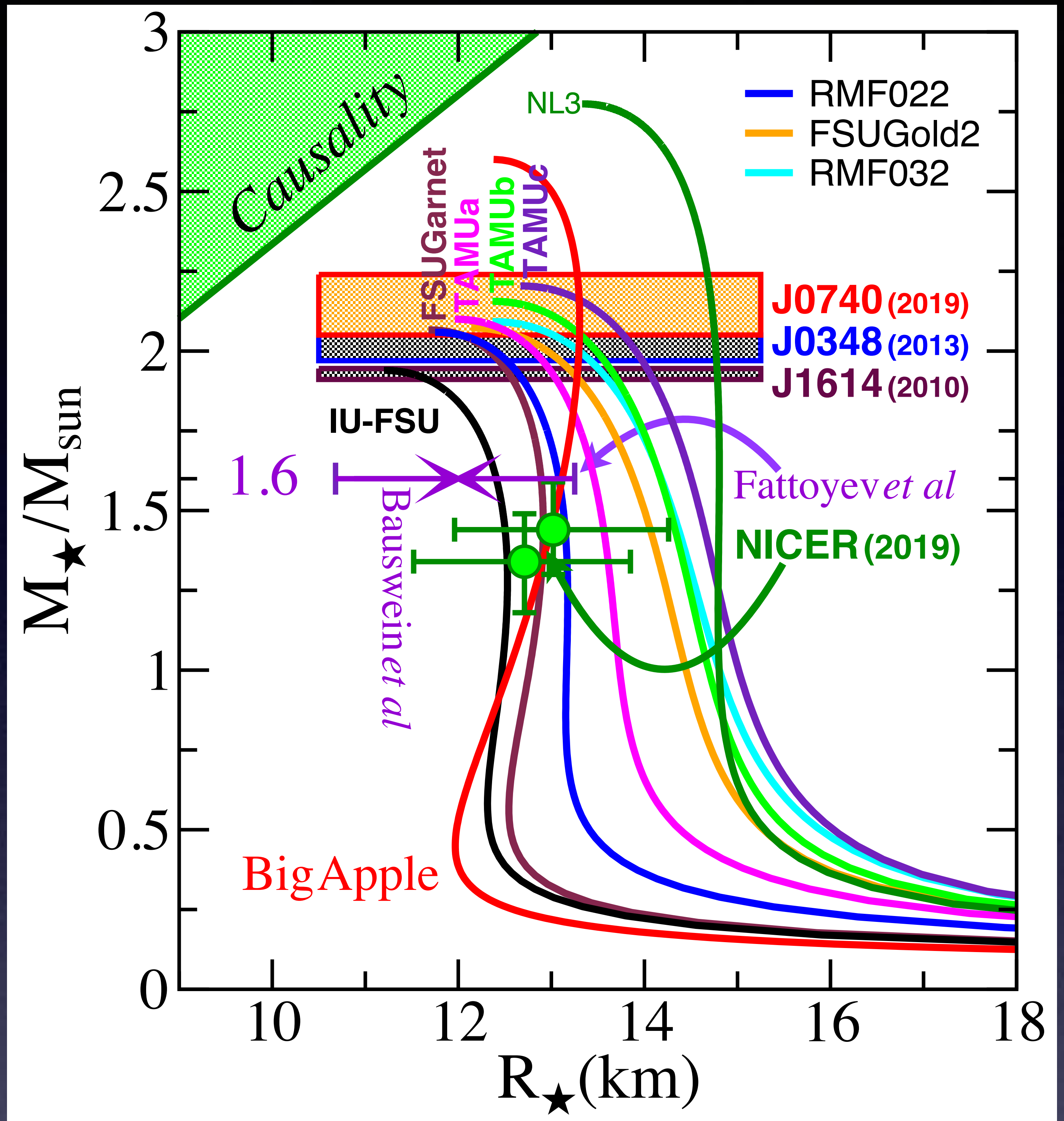
Heaven and Earth

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







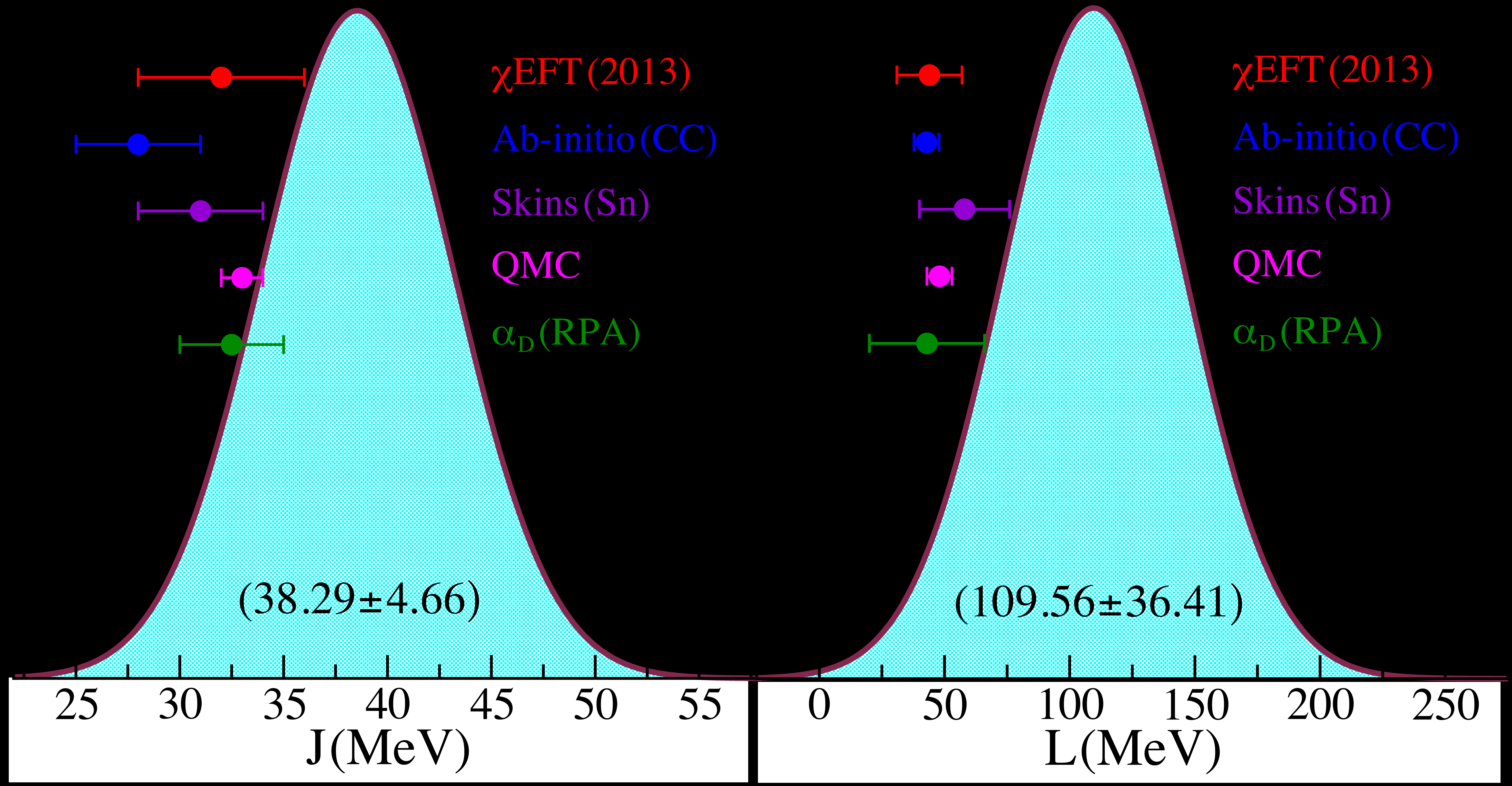
Tantalizing Possibility

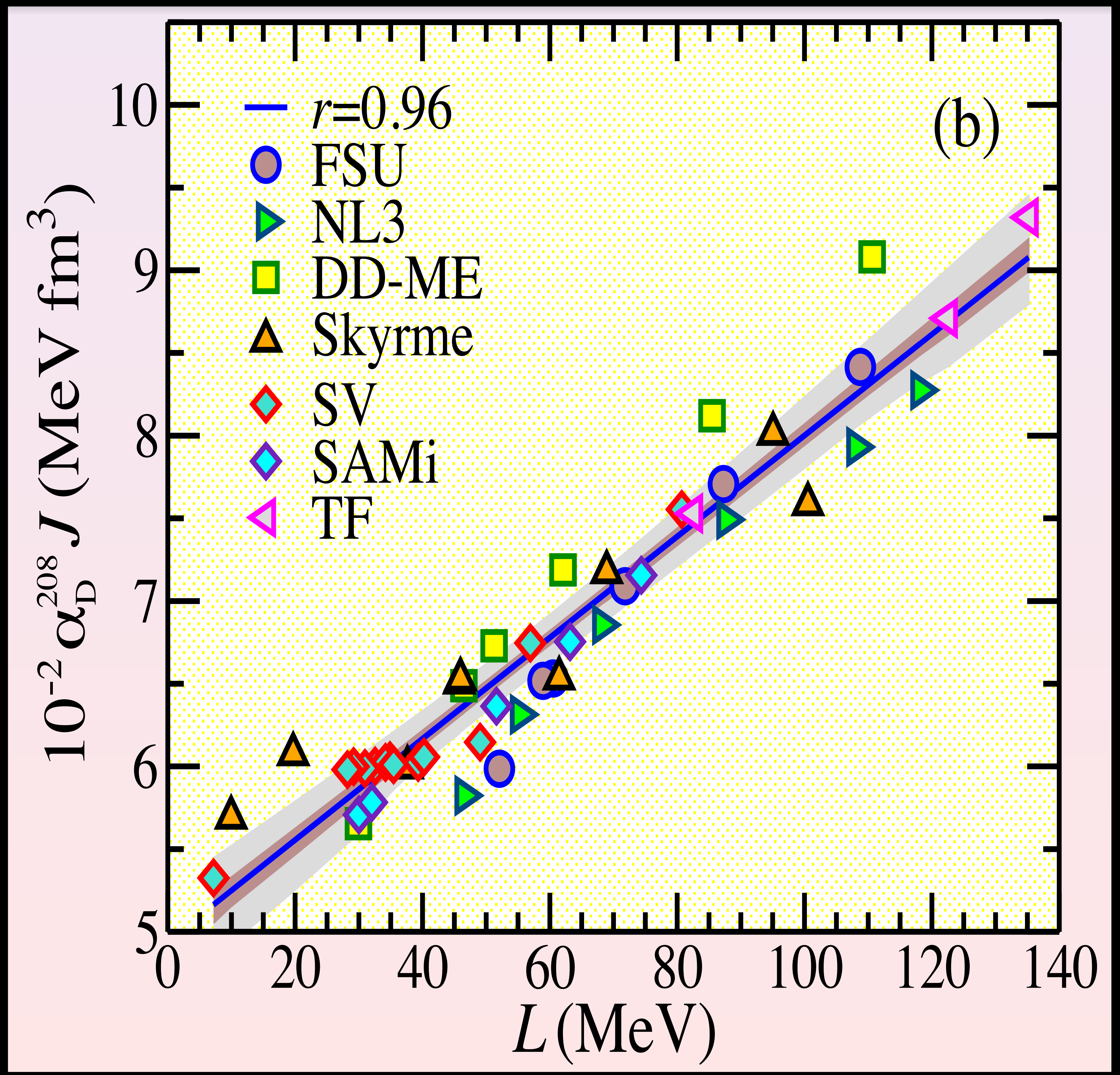
- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

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

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!

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

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

The incompressibility of neutron rich matter: Why is tin so fluffy?

Workshop on Nuclear Incompressibility

University of Notre Dame
July 14-15, 2005

J I N A

The Joint Institute for Nuclear Astrophysics (JINA) will organize a 2-day Workshop focused on **Nuclear Incompressibility and the Nuclear Equation of State**, to be held at the University of Notre Dame during July 14-15, 2005.

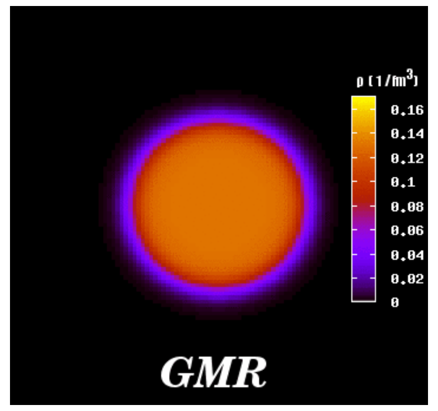
This meeting follows a similar Workshop held at Notre Dame in January 2001, and the **Symposium on Nuclear Equation of State used in Astrophysics Models**, held at the ACS meeting in Philadelphia last Summer.

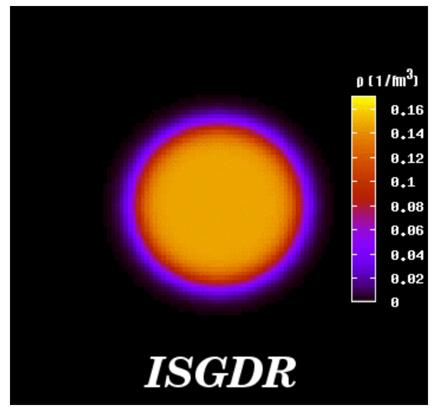
The primary aim of the Workshop is to bring together interested physicists from the areas of Astrophysics, Giant Resonances, and Heavy-Ion Reactions, to discuss current status of experiments and theoretical models related to nuclear incompressibility and the equation of state, and to explore what experiments might be needed to clarify some of the outstanding issues.

Most of the Workshop will be devoted to talks, with a lot of time allowed for discussions and interactions. In that spirit, we will follow a somewhat flexible schedule for the talks.

There is no registration fee but participants are requested to register via the **webpage** (www.jinaweb.org), so that we can make appropriate arrangements.

For further information, please contact:
Kathy Burgess (kburgess@nd.edu)
or
Umesh Garg (garg@nd.edu)





The Joint Institute for Nuclear Astrophysics
May 18, 2005

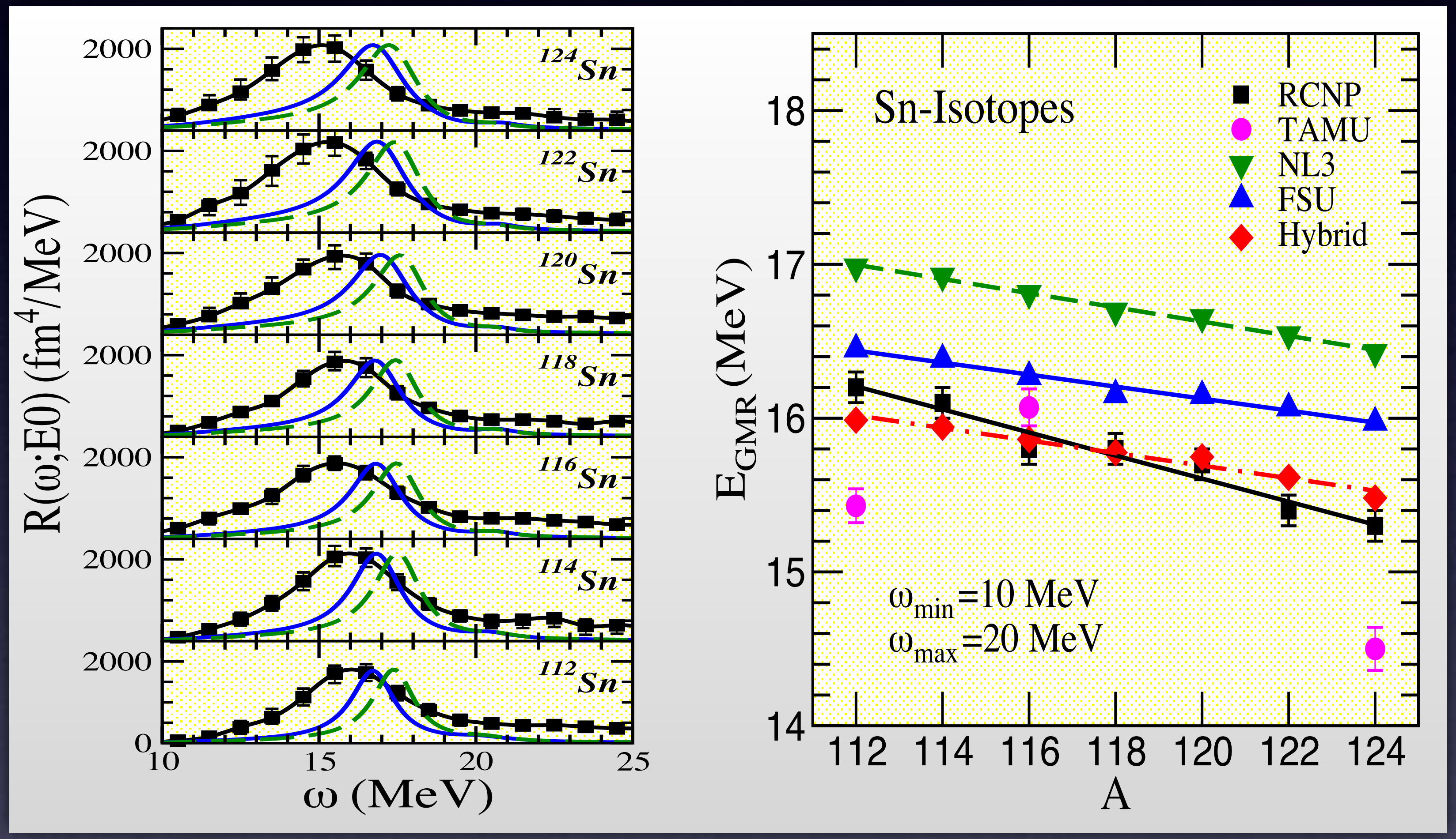
Outcome: A window into L through systematic measurements of the GMR across a long isotopic chain

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
NUCLEAR PHYSICS A
Nuclear Physics A 788 (2007) 36c–43c

The Giant Monopole Resonance in the Sn Isotopes: Why is Tin so "Fluffy"?

U. Garg,[a] T. Li,[a] S. Okumura,[b] H. Akimune[c] M. Fujiwara,[b] M.N. Harakeh,[d] H. Hashimoto,[b] M. Itoh,[e] Y. Iwao,[f] T. Kawabata,[g] K. Kawase,[b] Y. Liu,[a] R. Marks,[a] T. Murakami,[f] K. Nakanishi,[b] B.K. Nayak,[a] P.V. Madhusudhana Rao,[a] H. Sakaguchi,[f] Y. Terashima,[f] M. Uchida,[h] Y. Yasuda,[f] M. Yosoi,[b] and J. Zenihiro[f]

$$K_0(\alpha) = K_0 + K_\tau \alpha^2;$$
$$K_\tau = K_{\rm sym} - 6L + \ldots$$



PHYSICAL REVIEW C 76, 031301(R) (2007)

Why is the equation of state for tin so soft?

J. Piekarewicz
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA
(Received 10 May 2007; published 4 September 2007)

PHYSICAL REVIEW C 78, 064304 (2008)

Microscopic linear response calculations based on the Skyrme functional plus the pairing contribution

Jun Li (李俊),[1,2,*] Gianluca Colò,[1,†] and Jie Meng (孟杰)[2,3,4,5,‡]

PHYSICAL REVIEW C 79, 034309 (2009)

Description of the giant monopole resonance in the even-A $^{112-124}$Sn isotopes within a microscopic model including quasiparticle-phonon coupling

V. Tselyaev,[1,2] J. Speth,[1] S. Krewald,[1] E. Litvinova,[3,4,5] S. Kamerdzhiev,[1,5] N. Lyutorovich,[1,2] A. Avdeenkov,[1,6] and F. Grümmer[1]

PRL 99, 162503 (2007) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2007

Isotopic Dependence of the Giant Monopole Resonance in the Even-A $^{112-124}$Sn Isotopes and the Asymmetry Term in Nuclear Incompressibility

T. Li,[1] U. Garg,[1] Y. Liu,[1] R. Marks,[1] B. K. Nayak,[1] P. V. Madhusudhana Rao,[1] M. Fujiwara,[2] H. Hashimoto,[2] K. Kawase,[2] K. Nakanishi,[2] S. Okumura,[2] M. Yosoi,[2] M. Itoh,[3] M. Ichikawa,[3] R. Matsuo,[3] T. Terazono,[3] M. Uchida,[4] T. Kawabata,[5] H. Akimune,[6] Y. Iwao,[7] T. Murakami,[7] H. Sakaguchi,[7] S. Terashima,[7] Y. Yasuda,[7] J. Zenihiro,[7] and M. N. Harakeh[8]

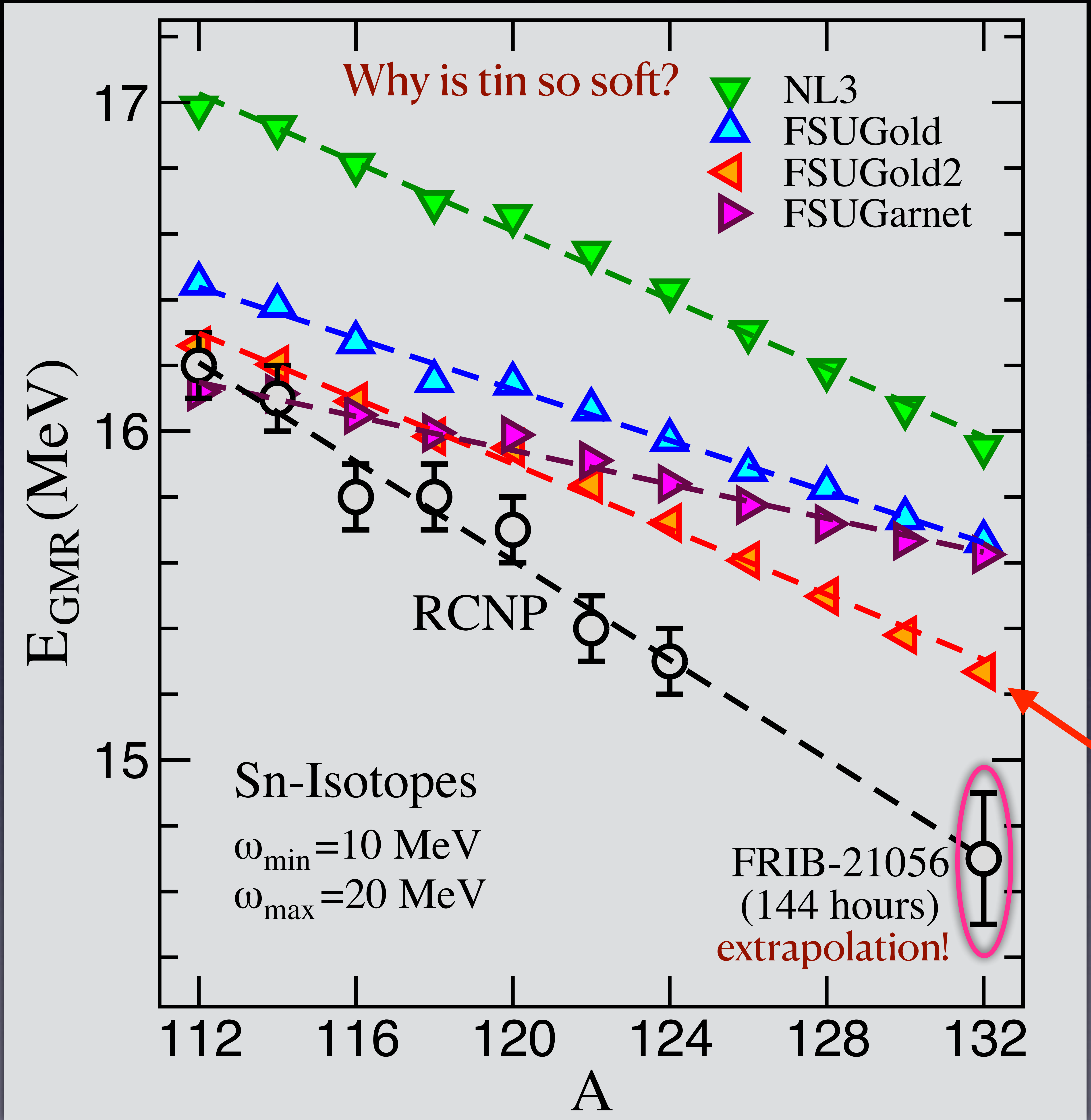
PHYSICAL REVIEW C 86, 024303 (2012)

Giant monopole resonances and nuclear incompressibilities studied for the zero-range and separable pairing interactions

P. Veselý,[1,*] J. Toivanen,[1] B. G. Carlsson,[2] J. Dobaczewski,[1,3] N. Michel,[1] and A. Pastore[4]

Onwards and upwards to GMRs in unstable nuclei!

The Incompressibility of Neutron-Rich Matter



$$K_0(\alpha) = K_0 + K_\tau \alpha^2$$

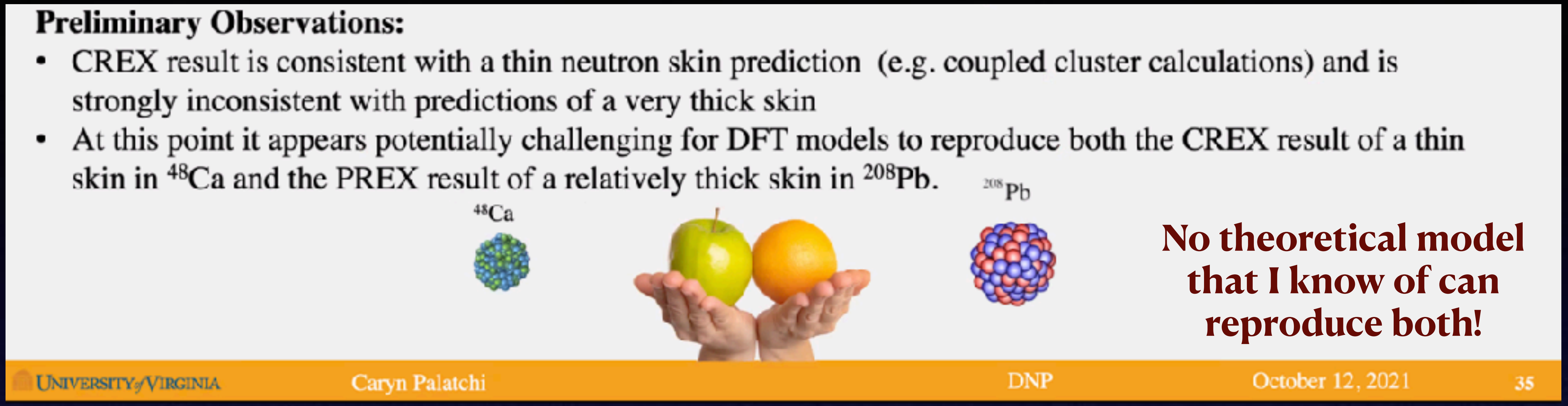
$$K_\tau = K_{\rm sym} - 6L - \frac{Q_0}{K_0} L$$

$$\alpha = \left(\frac{N-Z}{N+Z}\right)_{132} = 0.24 \rightarrow \alpha^2 = 0.06$$

- Even a neutron-rich nucleus as ^{132}Sn provides a short lever arm ($\mathbf{a}^2$=0.06)
- FSUGold2 — consistent with PREX and hence with a very large value of L— is inconsistent with RCNP data! **RCNP seems to like an even larger L!**

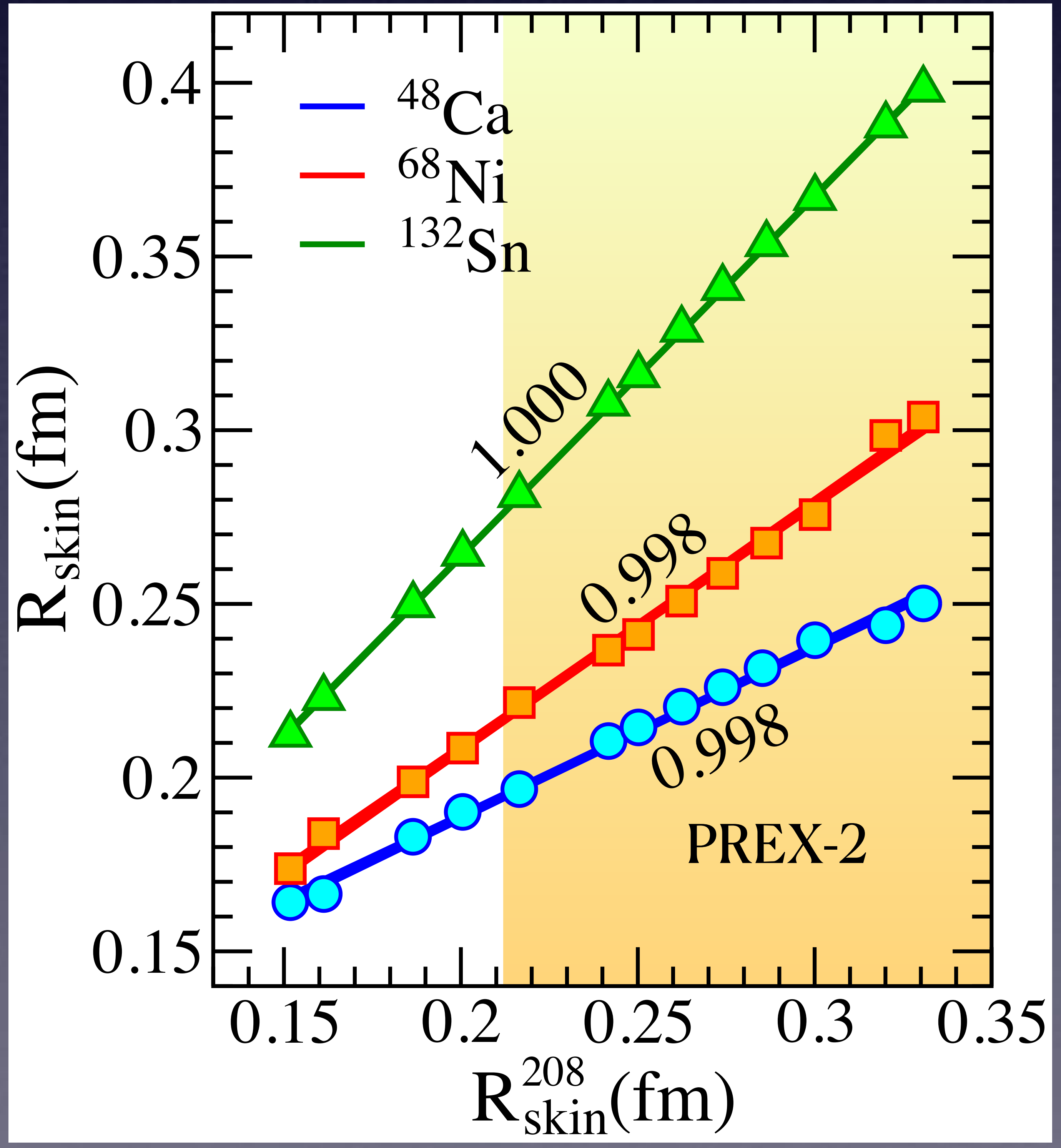
Who Ordered That?

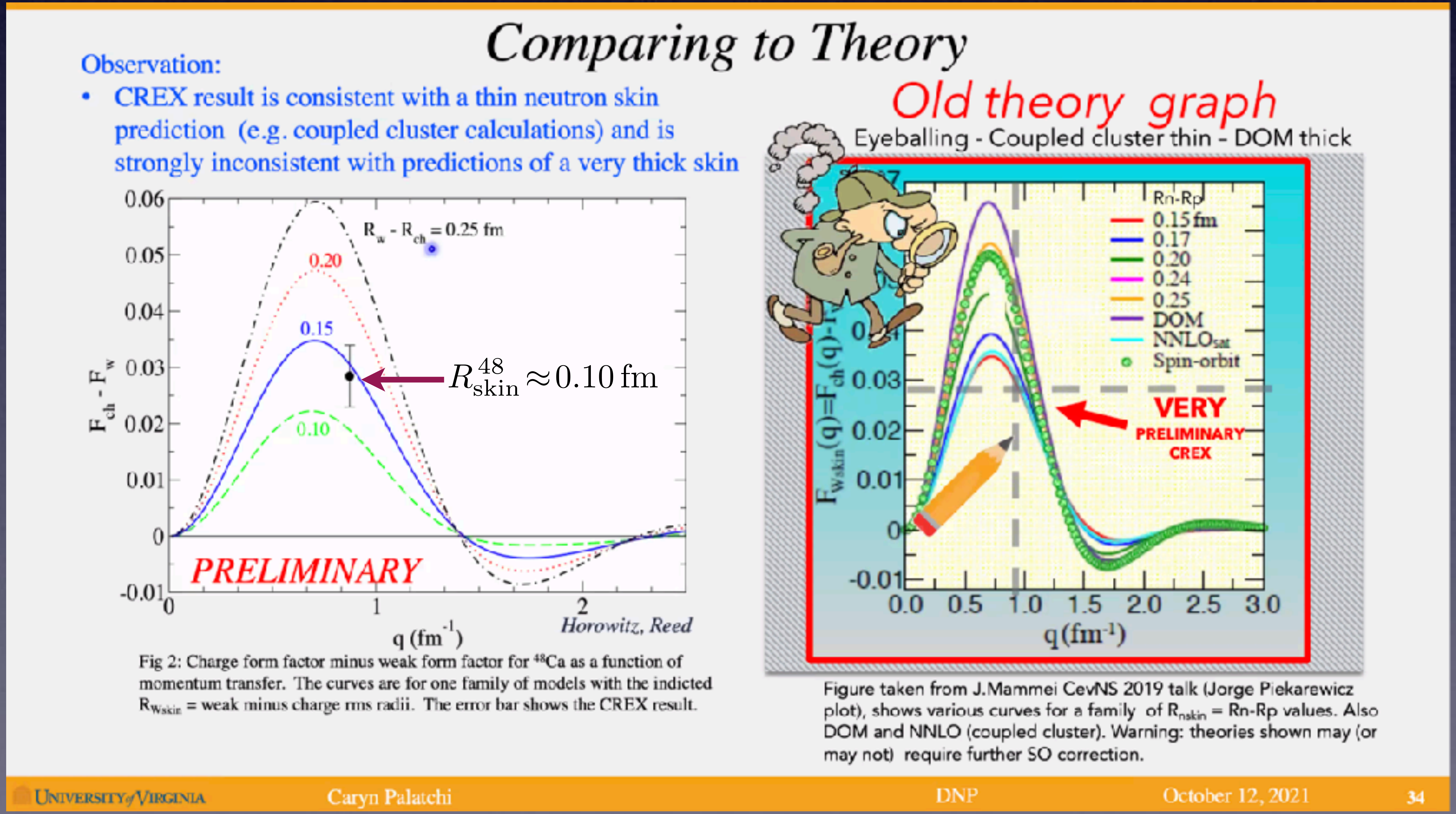
Isidor Isaac Rabi



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.





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

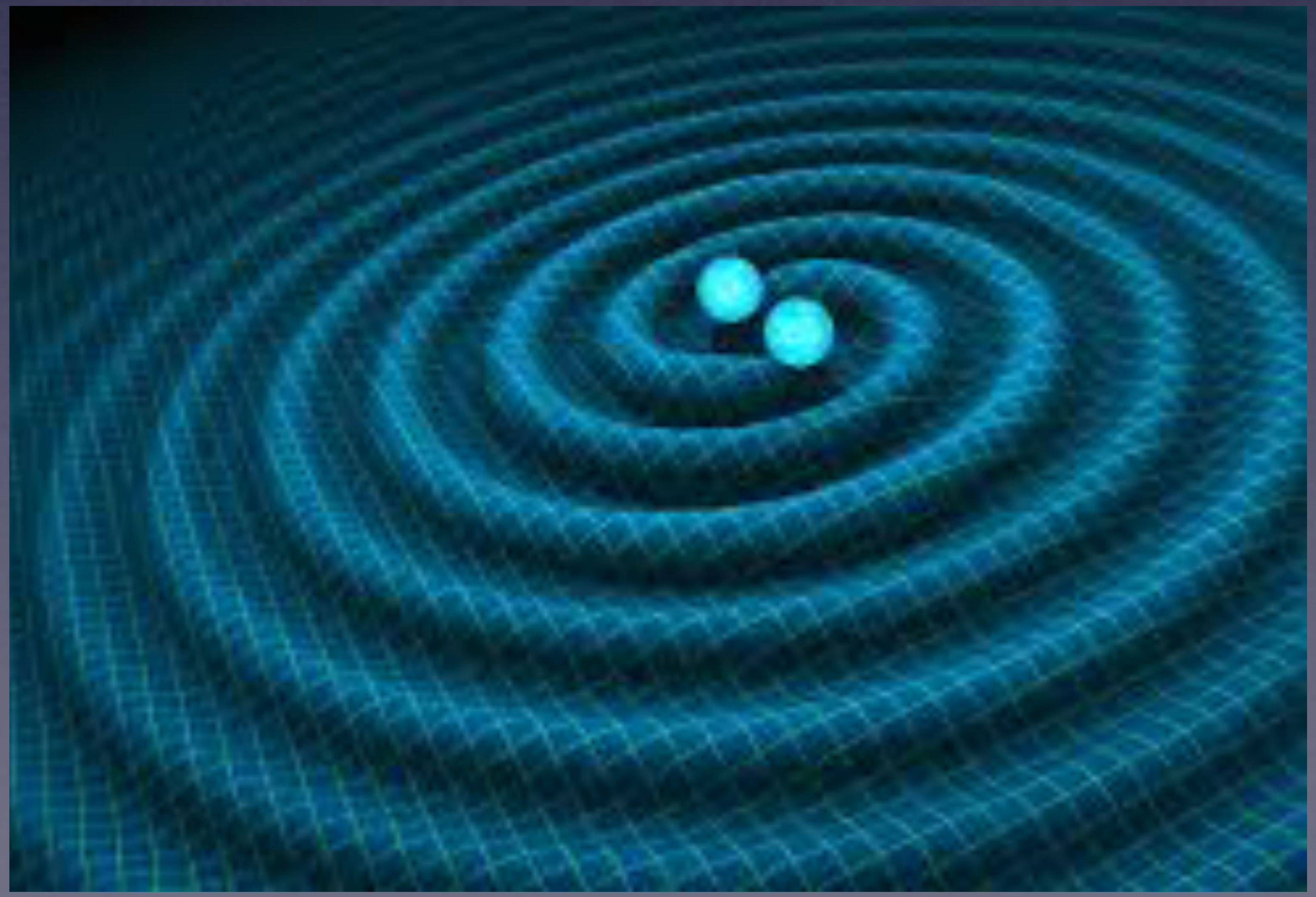
Fig 2: Charge form factor minus weak form factor for ^{48}Ca as a function of momentum transfer. The curves are for one family of models with the indicted R_{Wskin} = weak minus charge rms radii. The error bar shows the CREX result.

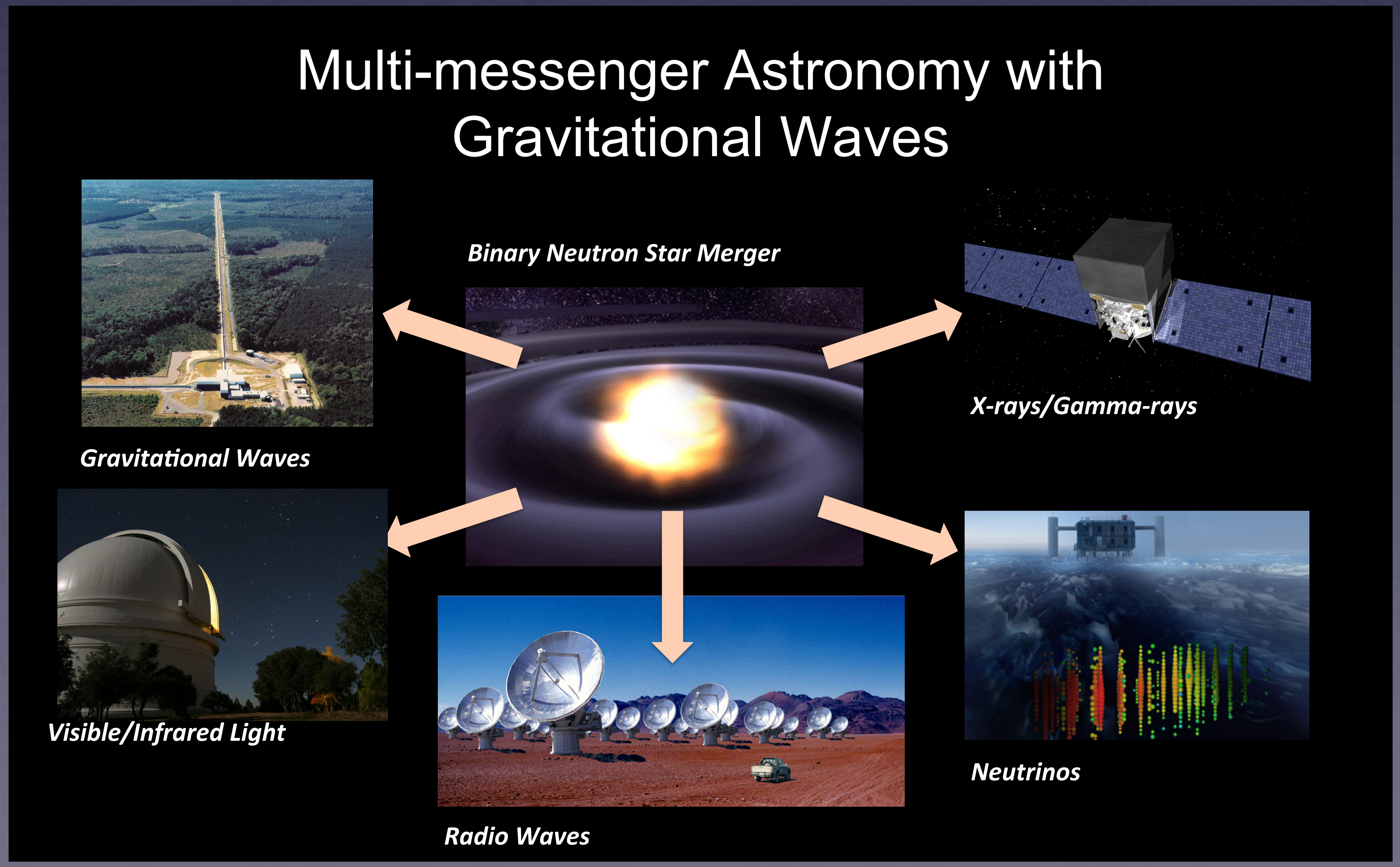
Figure taken from J.Mammei CevNS 2019 talk (Jorge Piekarewicz plot), shows various curves for a family of R_{nskin} = Rn-Rp values. Also DOM and NNLO (coupled cluster). Warning: theories shown may (or may not) require further SO correction.

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!



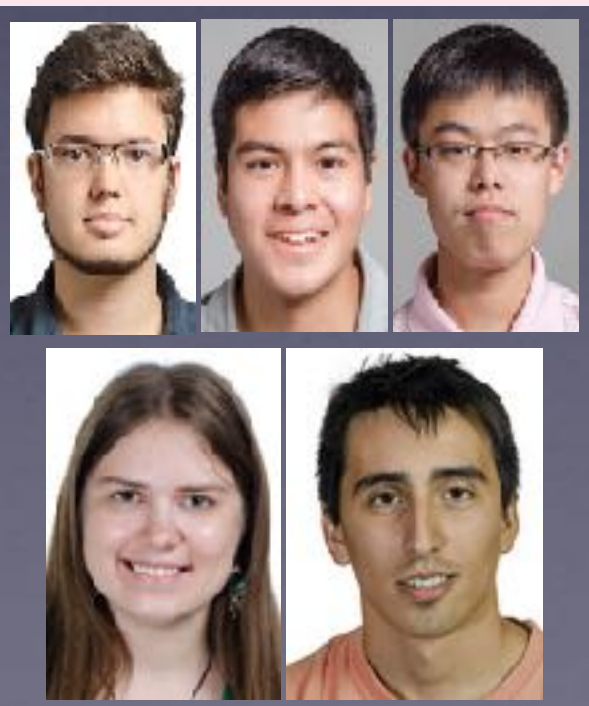


My FSU Collaborators

- 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)



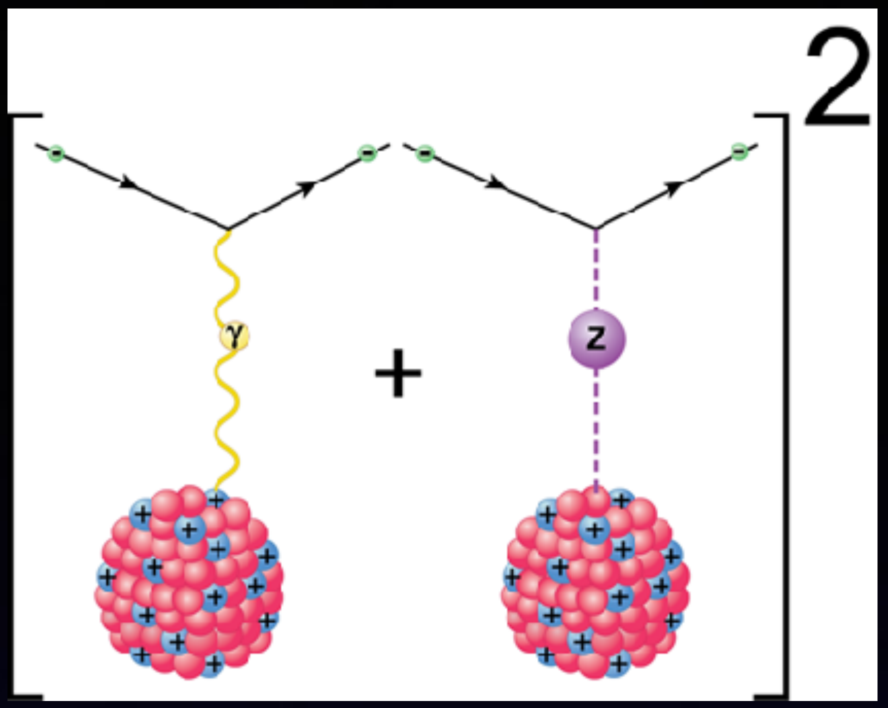
The "Old" Generation

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

The New Generation

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

Backup Slides

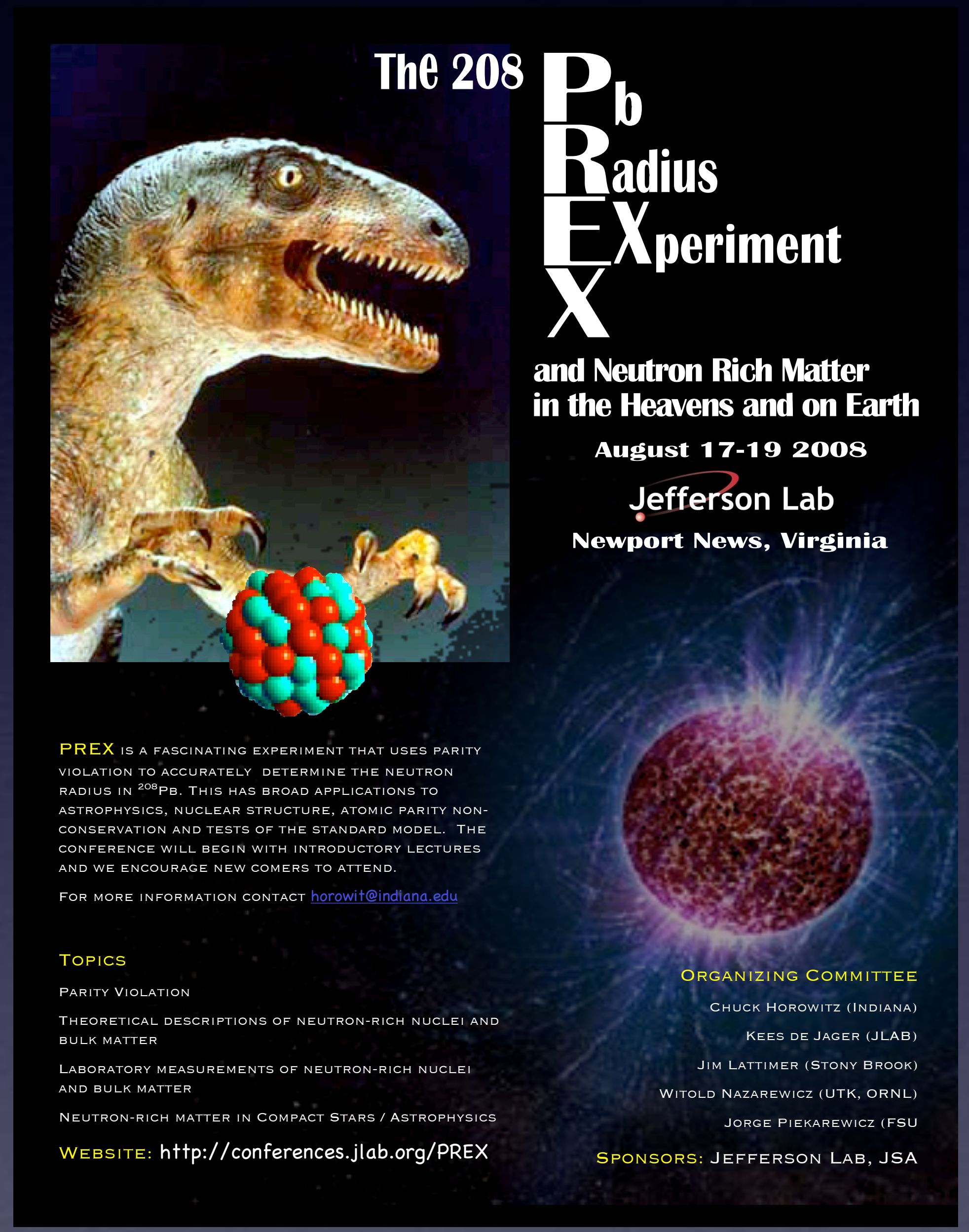


Parity Violating e-Nucleus Scattering

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

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



$$R_{\rm skin}^{208} = (0.283 \pm 0.071)\ {\rm fm}$$

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

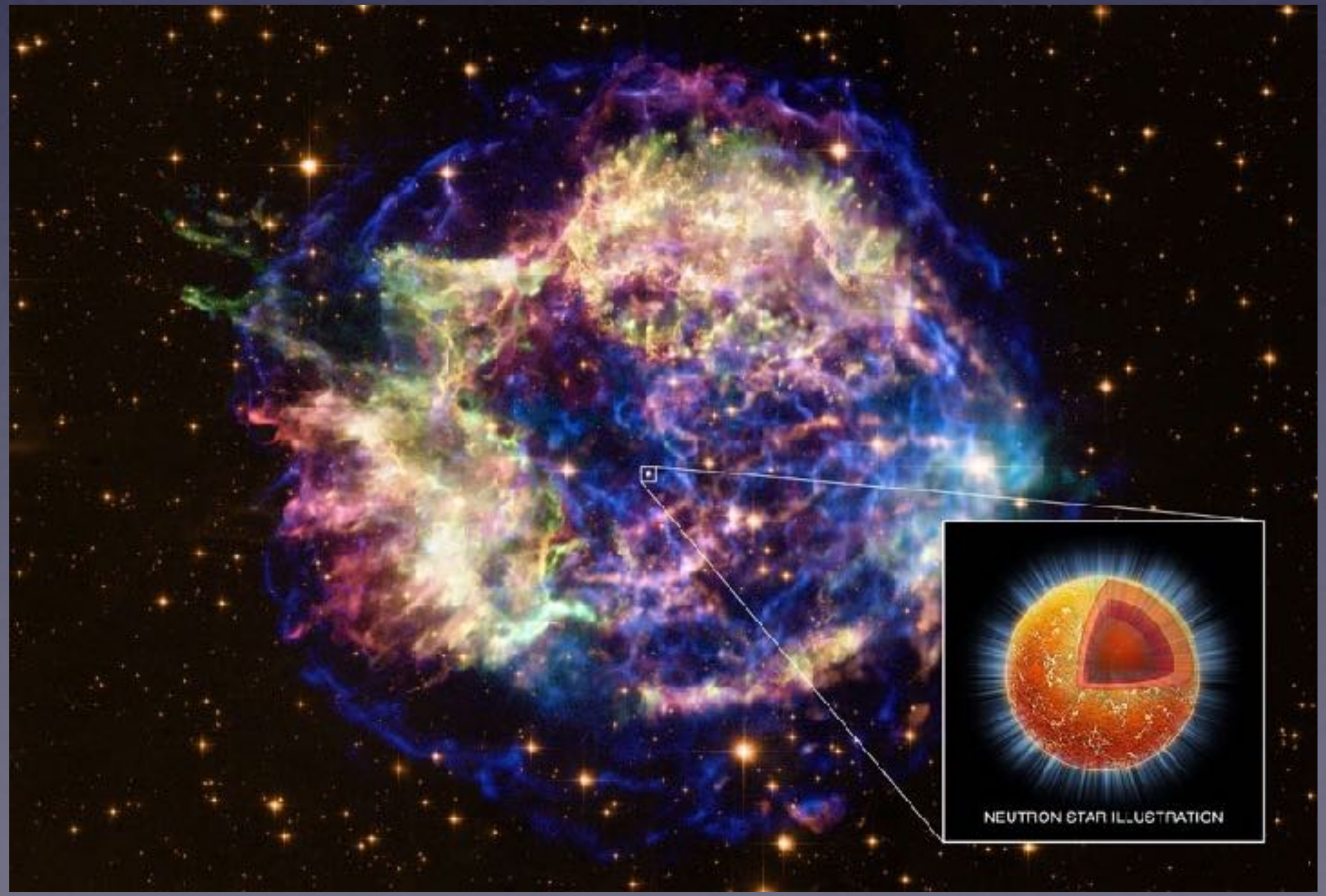
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

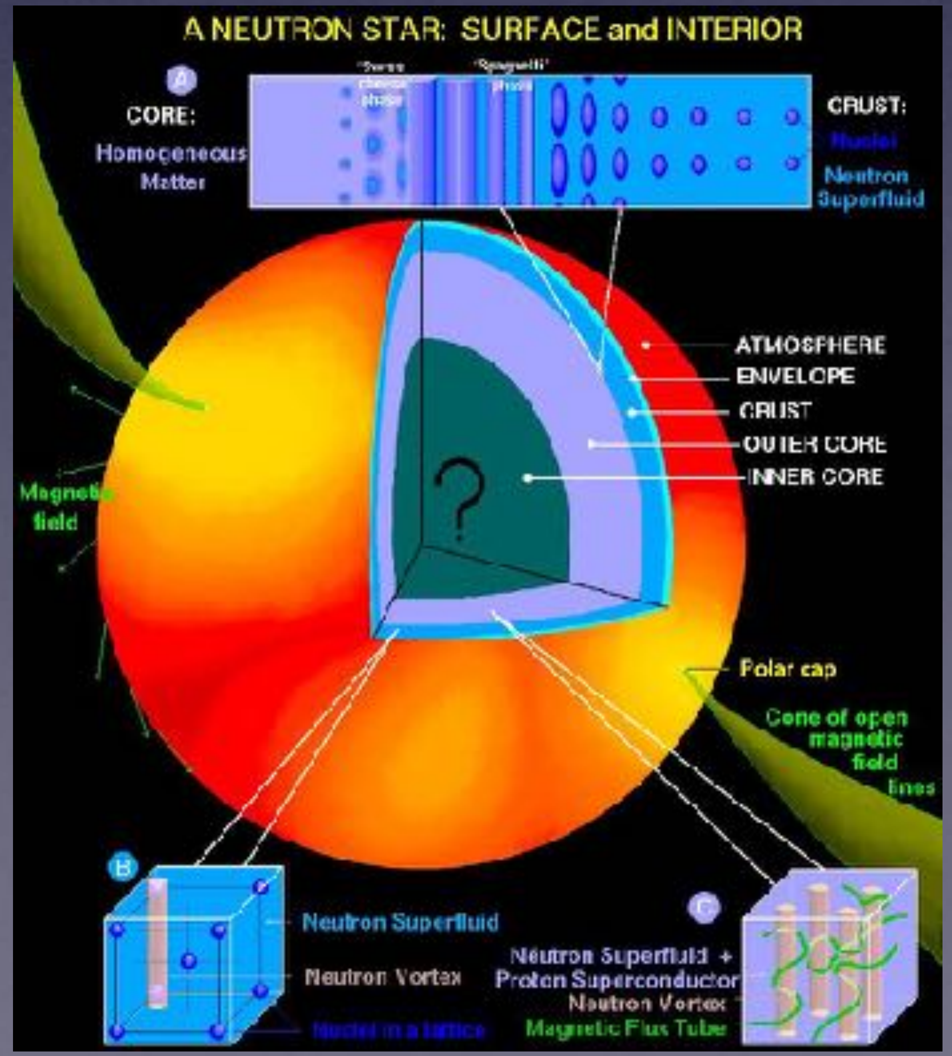
Electroweak experiments will provide fundamental anchors for future campaigns at FRIB and other exotic beam facilities

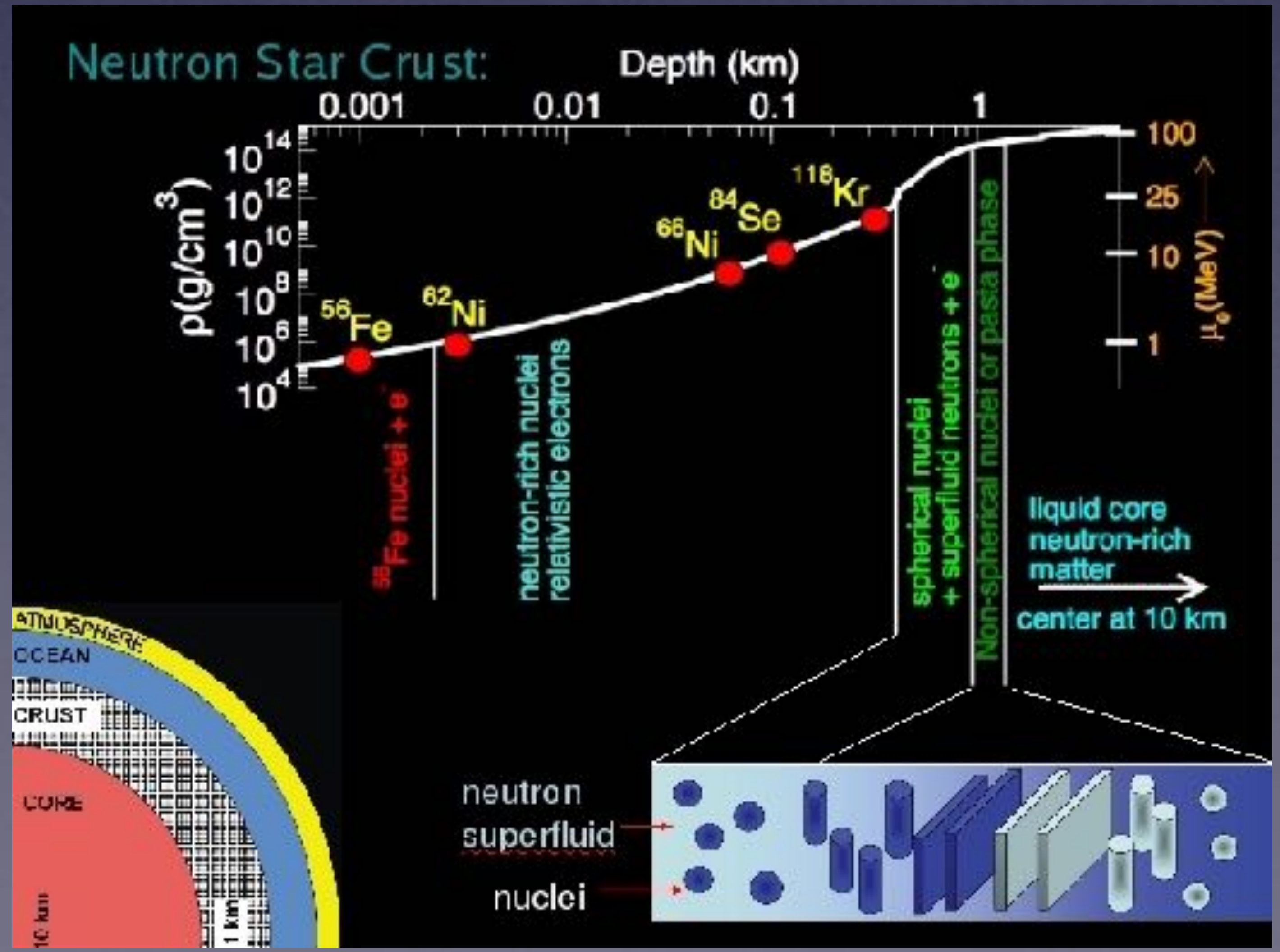
How Does Matter Organize Itself?
What is the ground state of matter at a given density?

The Anatomy of a Neutron Star

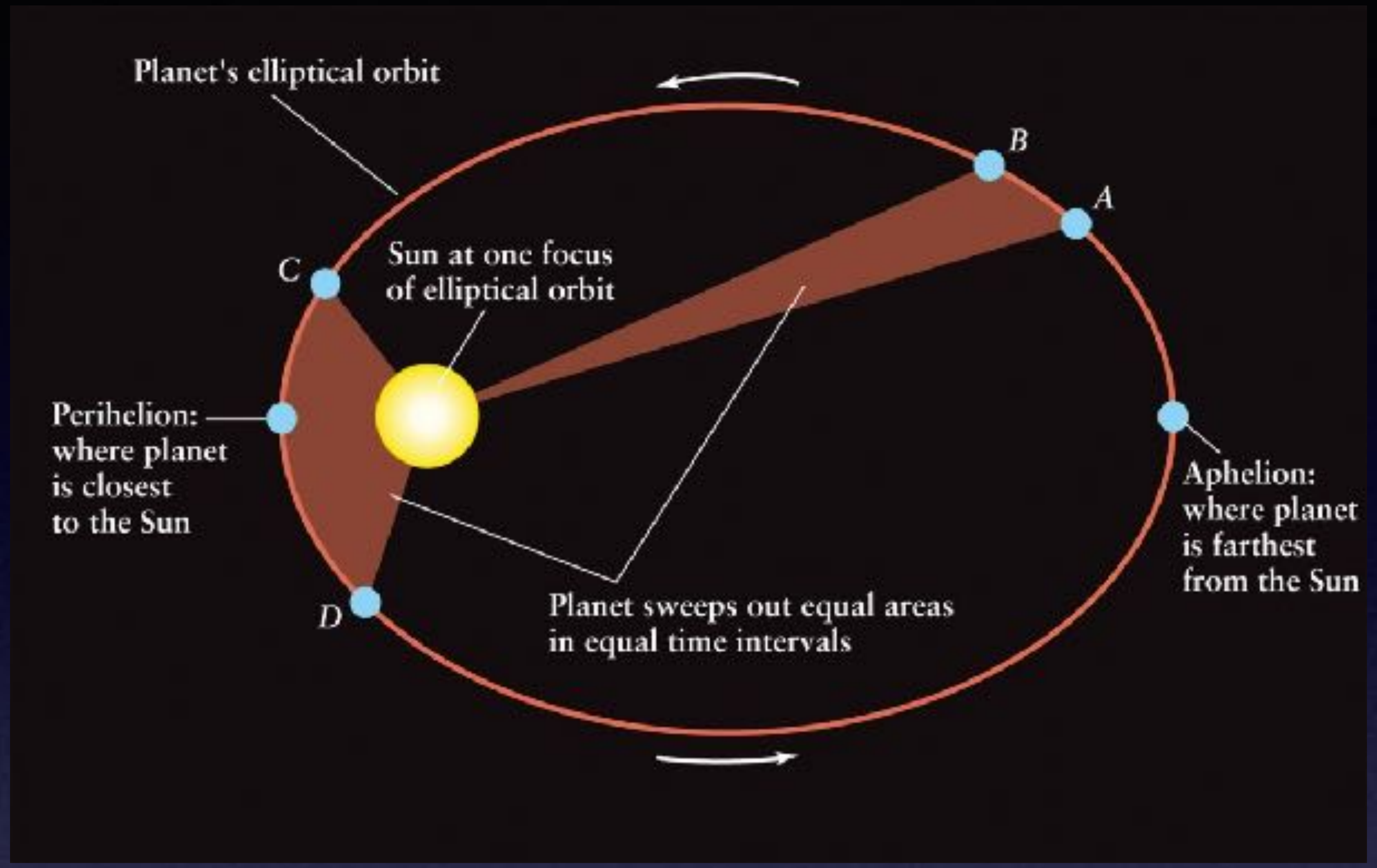
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4psR^2T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K 4 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")
- Outer Core (10 km): Uniform Neutron-Rich Matter (n,p,e,m)
- Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)





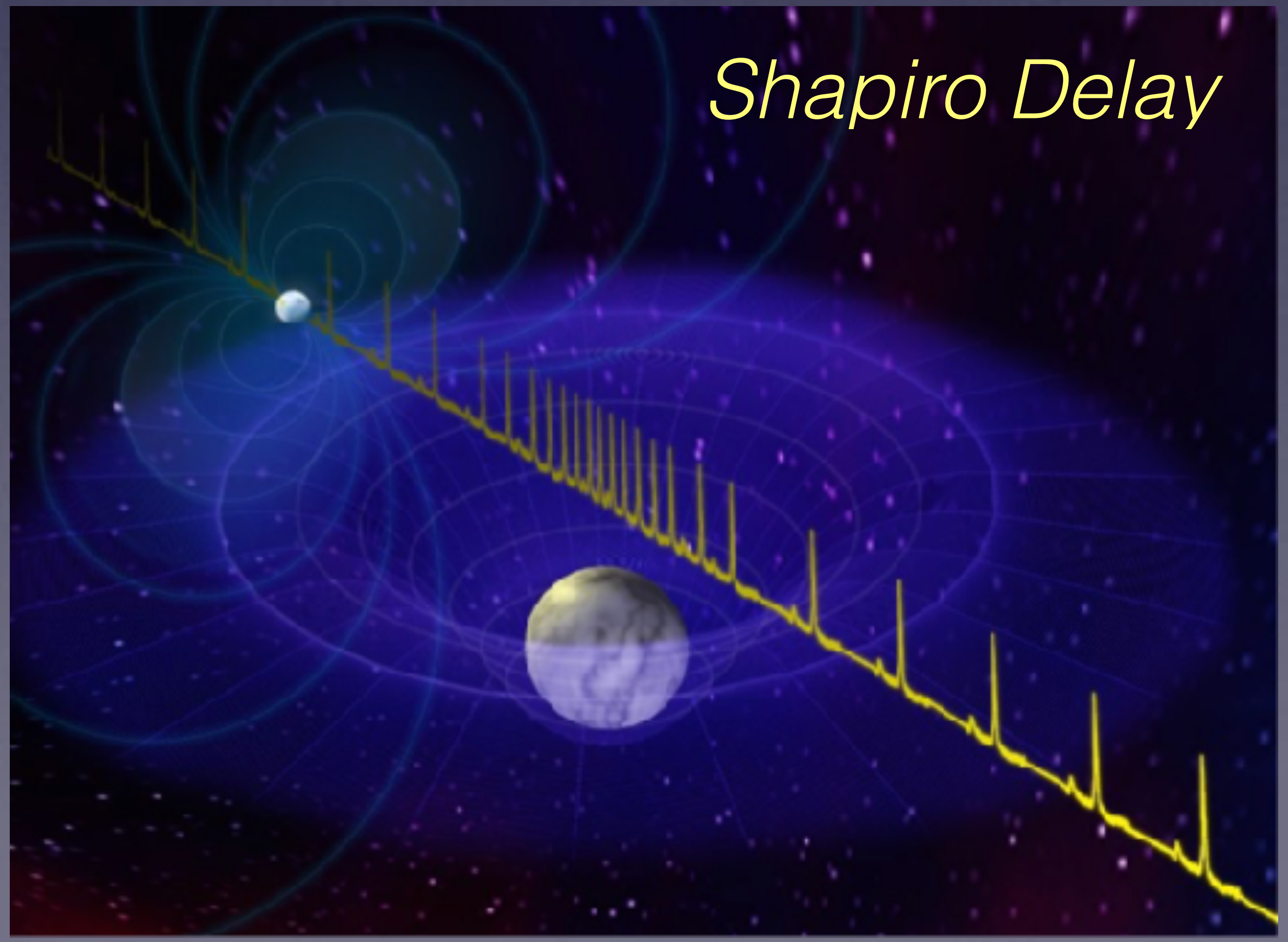


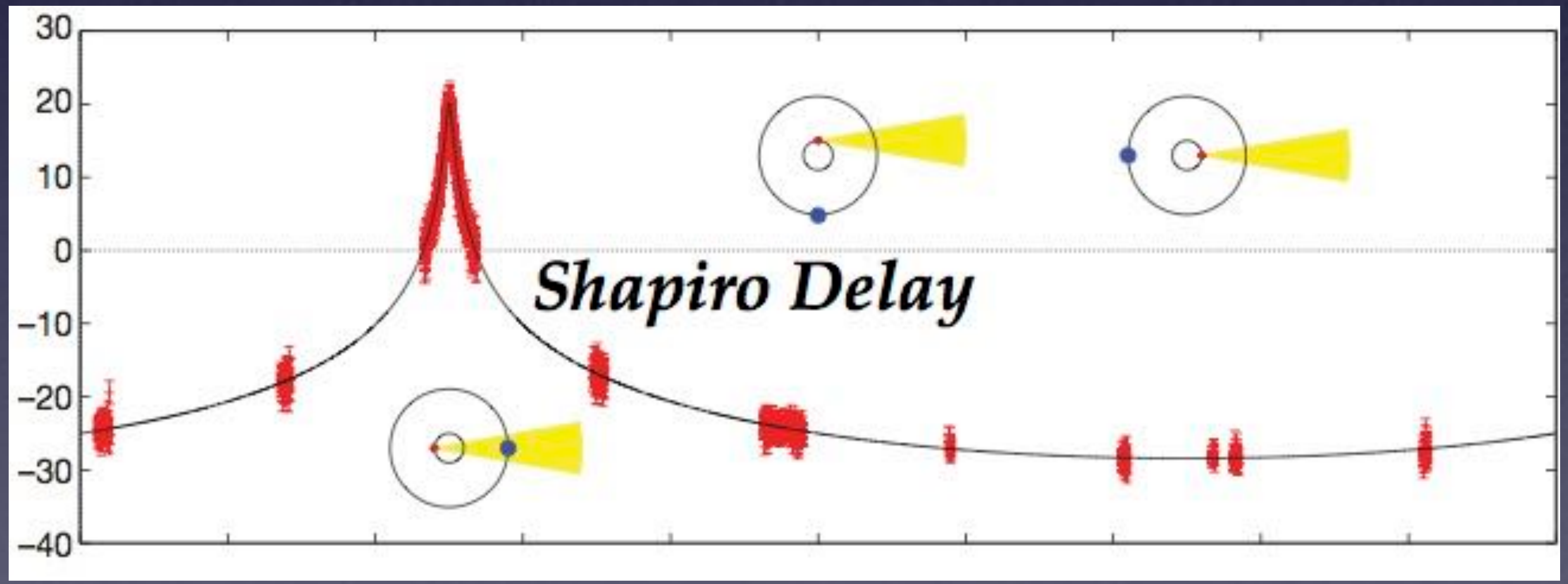
Measuring Heavy Neutron Stars (2019)
Shapiro Delay: General Relativity to the Rescue



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

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

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!

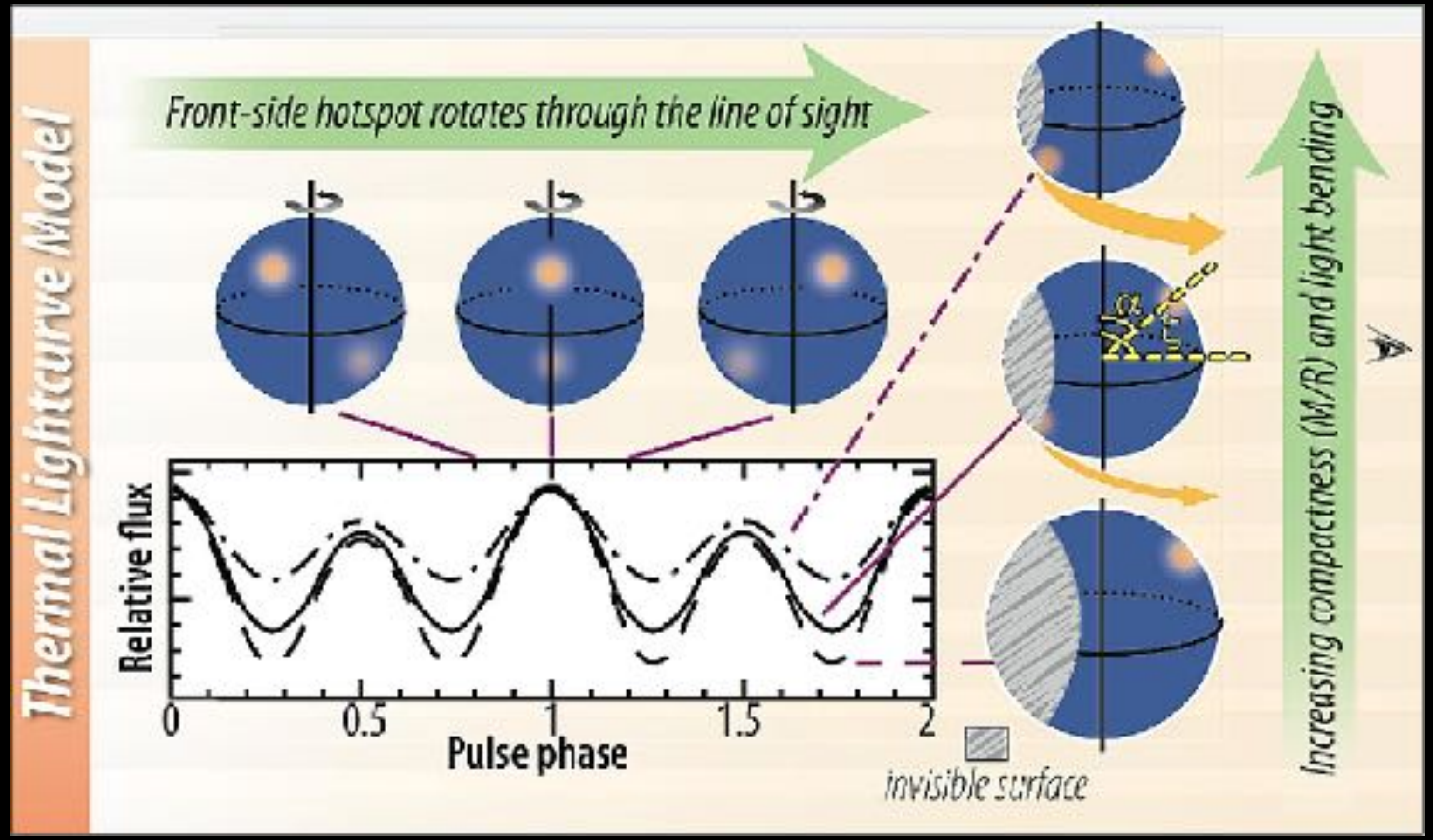
Pulse Profile: The stellar compactness controls the light profile from the hot spot

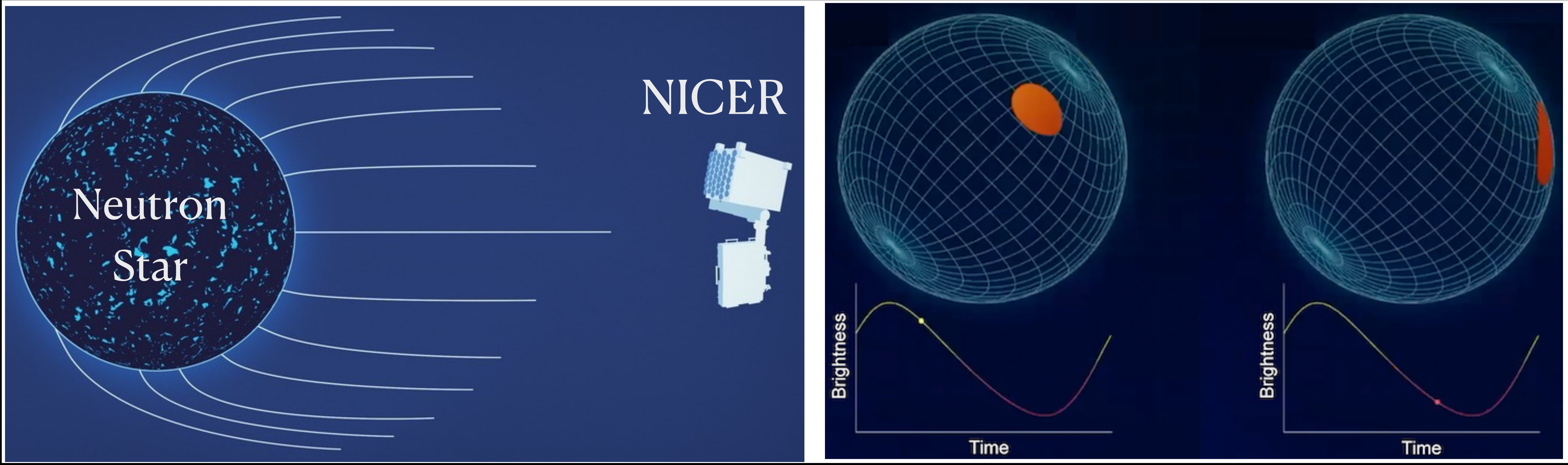
$$\xi = \frac{2GM}{c^2 R} = \frac{R_S}{R}$$

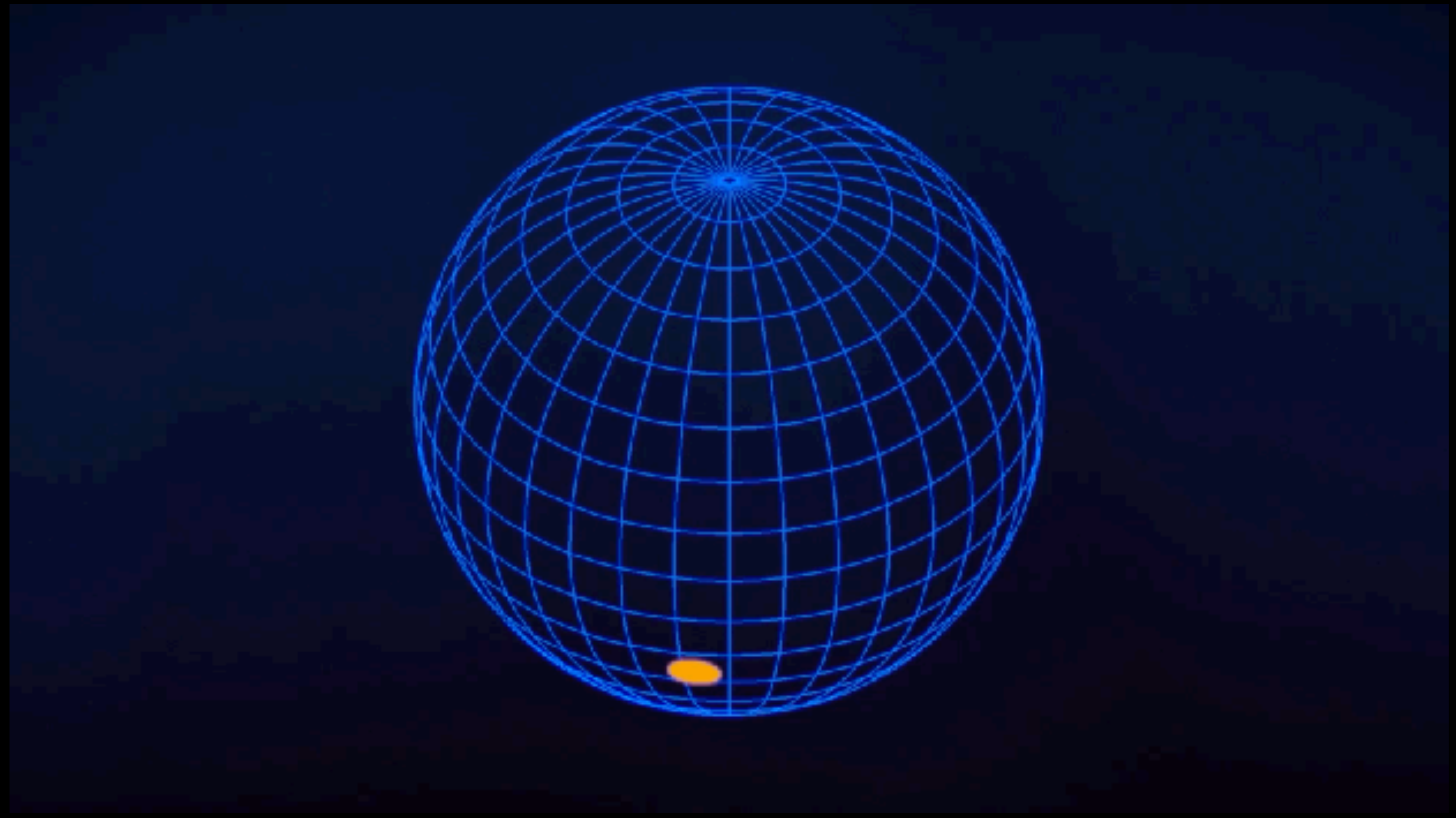
$M = 2.08 \pm 0.07\,\mathrm{M}_\odot$
Shapiro delay: Cromartie *et al.* (2020)

$R_{2.0} = 12.39^{+1.30}_{-0.98}$ km
Riley *et al.* (2021)

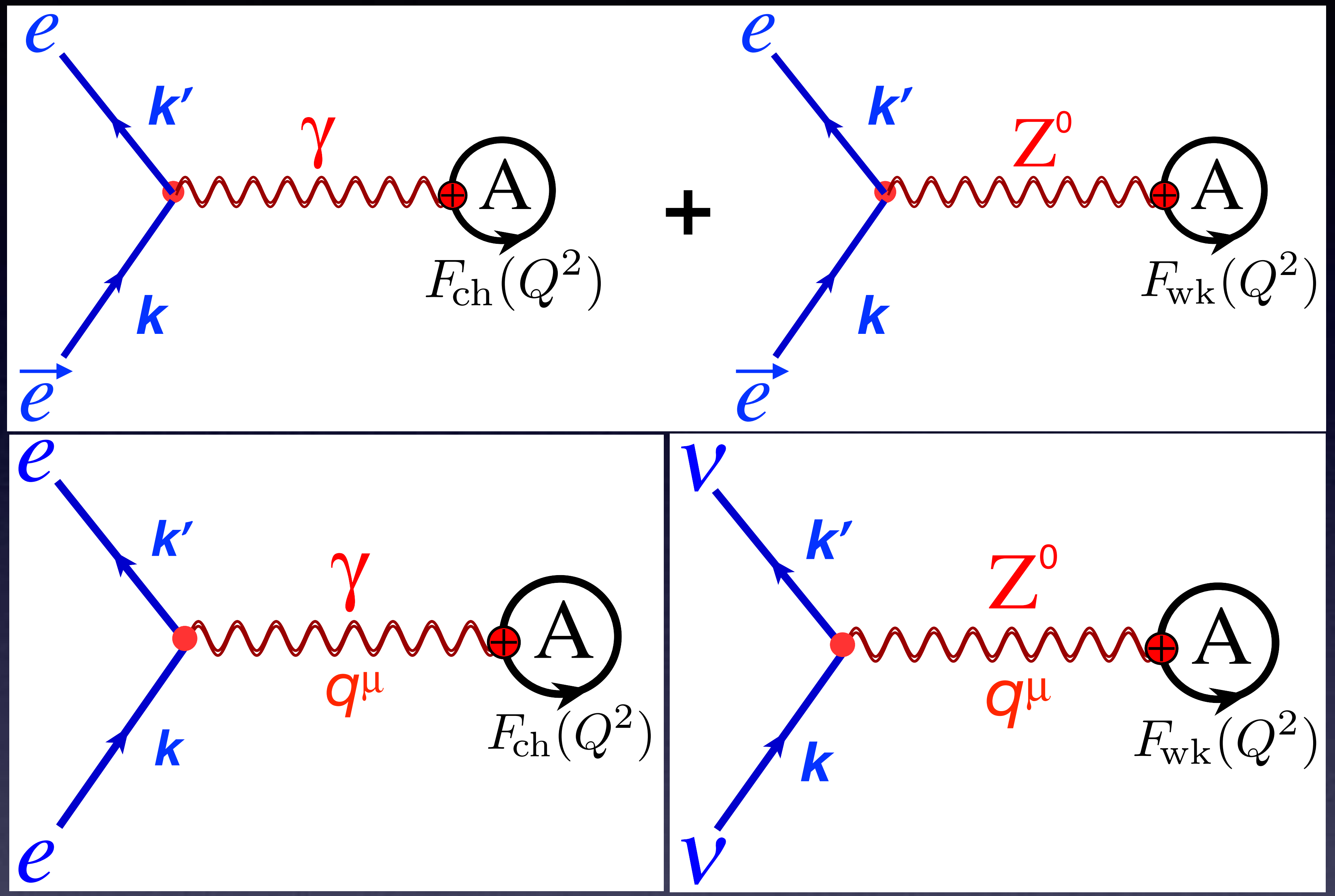
$R_{2.0} = 13.7^{+2.6}_{-1.5}$ km
Miller *et al.* (2021)







Electroweak Probes of Nuclear Densities

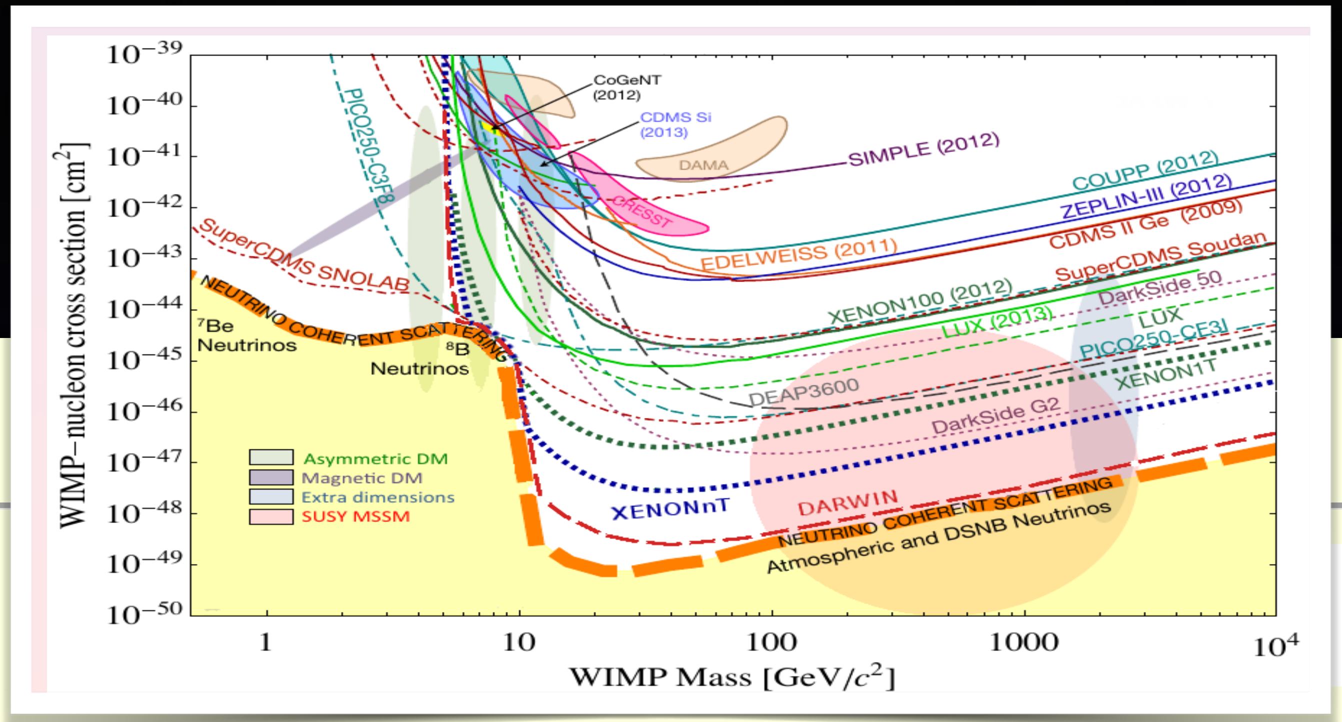


$$A_{PV}(Q^2) = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_{wk} F_{wk}(Q^2)}{Z F_{ch}(Q^2)}$$

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

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

CEvNS



Science

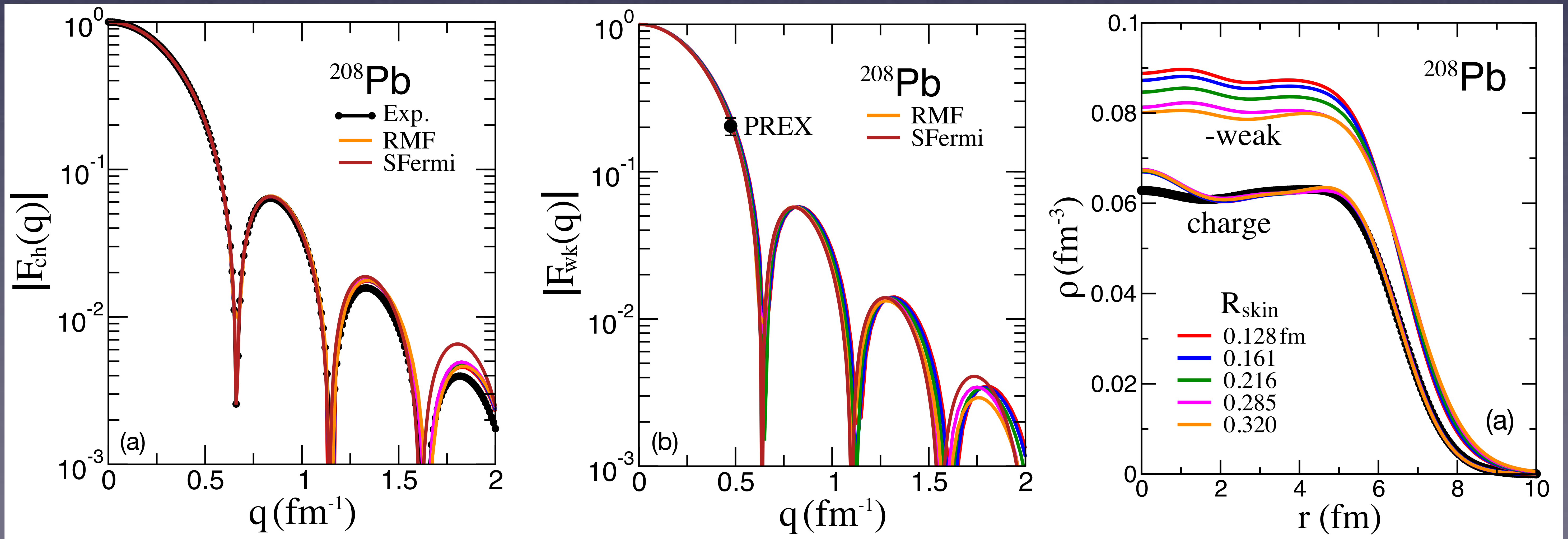
REPORTS

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



"Listening" to the GW Signal
LIGO-Virgo detection band

- Early BNS Inspiral:
  - Indistinguishable from two colliding black holes
  - Analytic "Post-Newtonian-Gravity" expansion

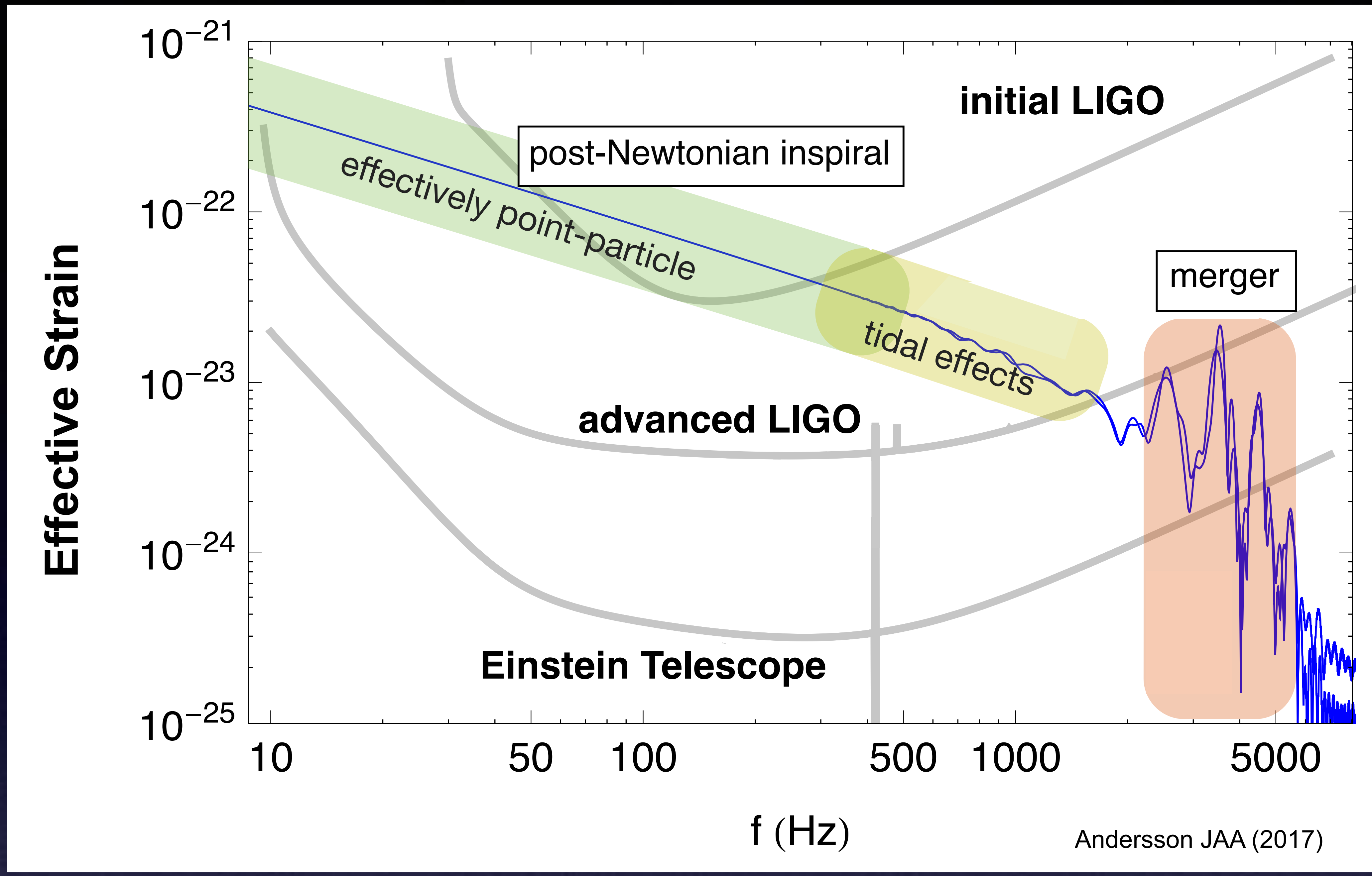
    Orbital separation:1000 km (20 minutes)

- Late BNS Inspiral:
  - Tidal effects become important
  - Sensitive to stellar compactness ⟶ EOS

    Orbital separation: 200 km (2 seconds)

- BNS Merger:
  - GRelativity in the strong-coupling regime
  - Numerical simulations with hot EOS

    Orbital separation: 50 km (0.01 seconds)



Dimensionless strain: $h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$

I = mass quadrupole moment of the source

R = source distance

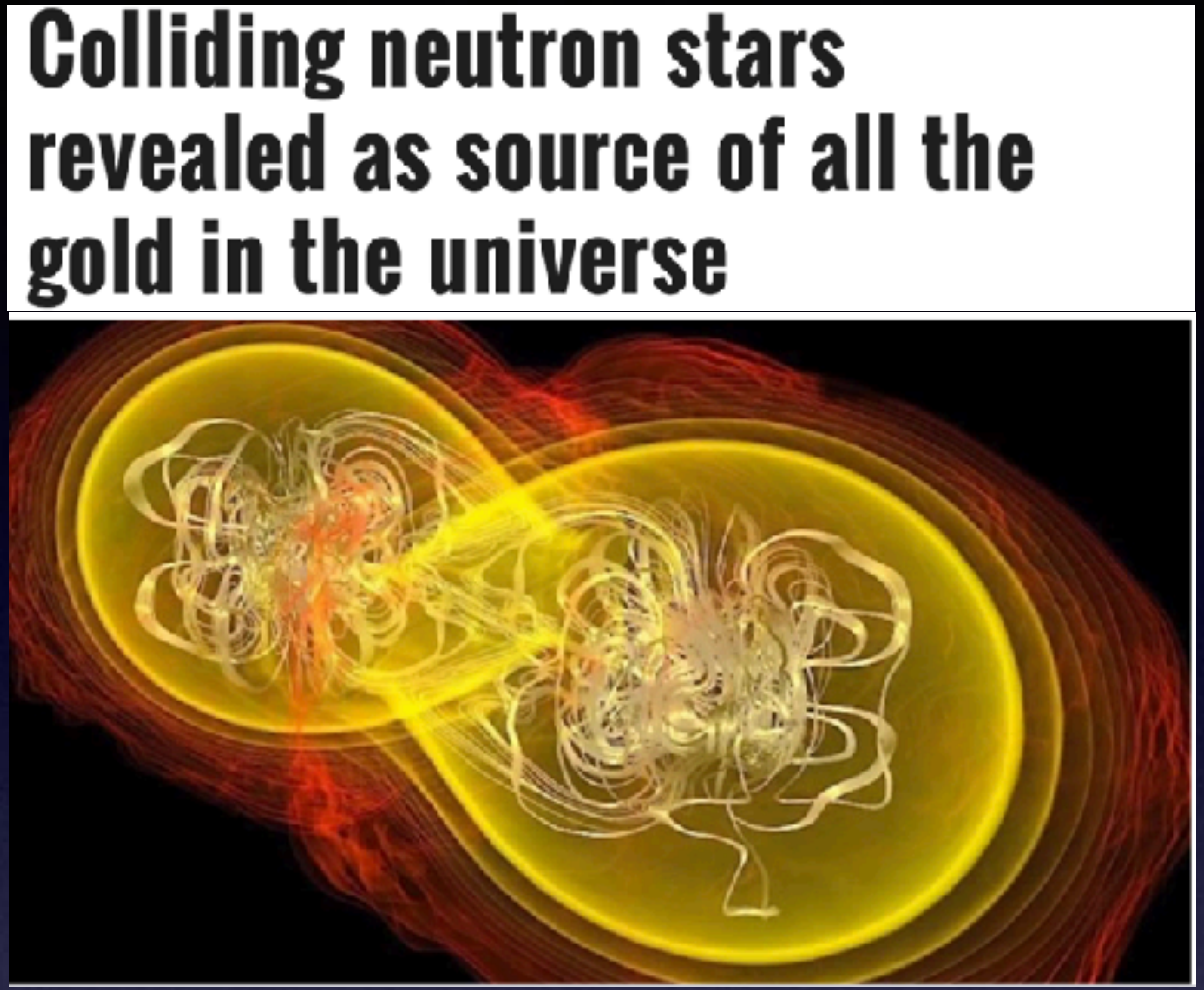
If $\ddot{I}(t) \rightarrow Ma^2\omega^2$

$$h(t) = \left(\frac{2GM}{c^2 R}\right)\left(\frac{a}{\lambda}\right)^2 = \left(\frac{R_s}{R}\right)\left(\frac{a}{\lambda}\right)^2$$

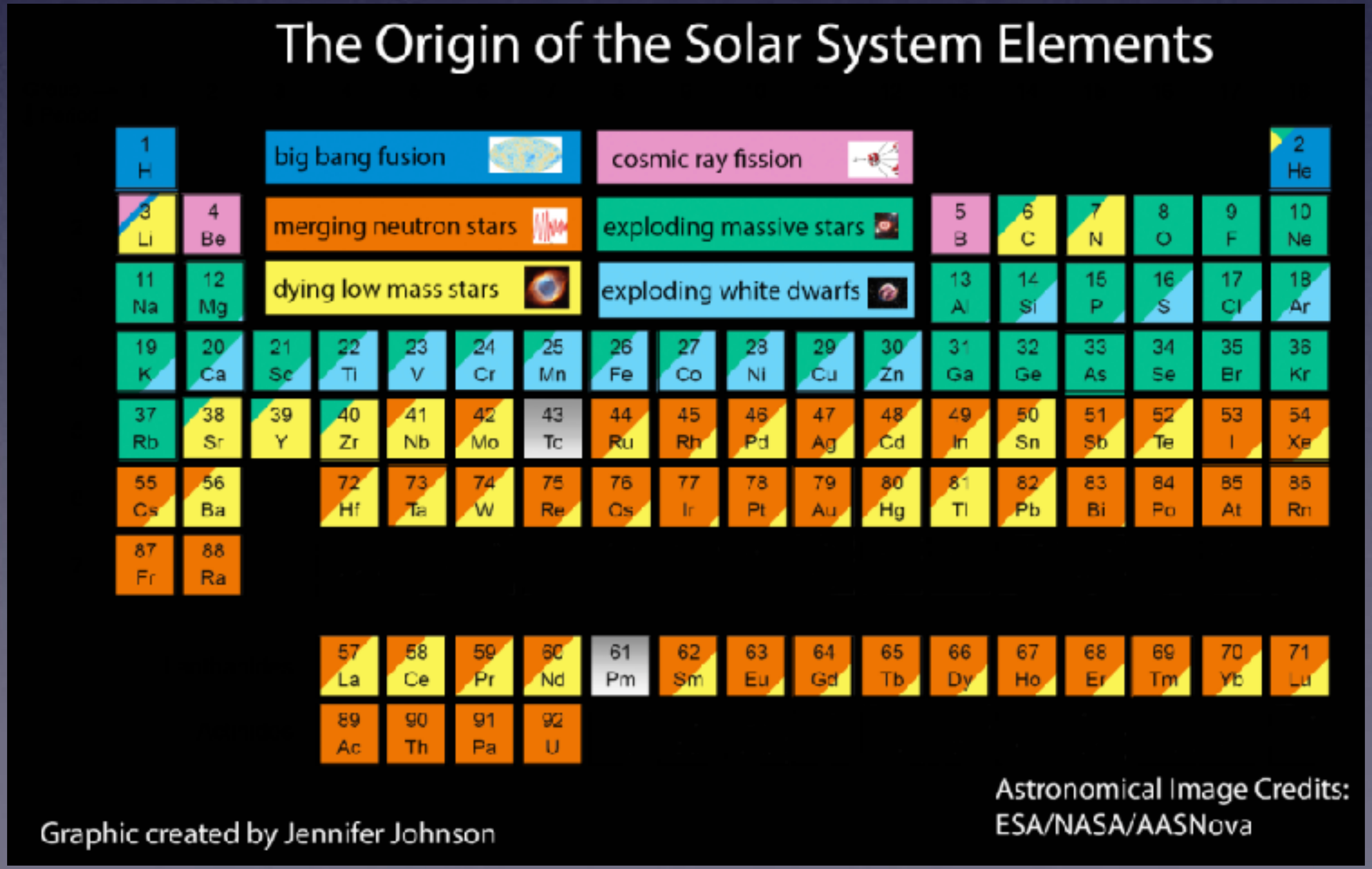
$$\sim 10^{-2}\left(\frac{R_s}{R}\right) \sim 10^{-23} \ @ \ [40\,\mathrm{Mpc}]$$

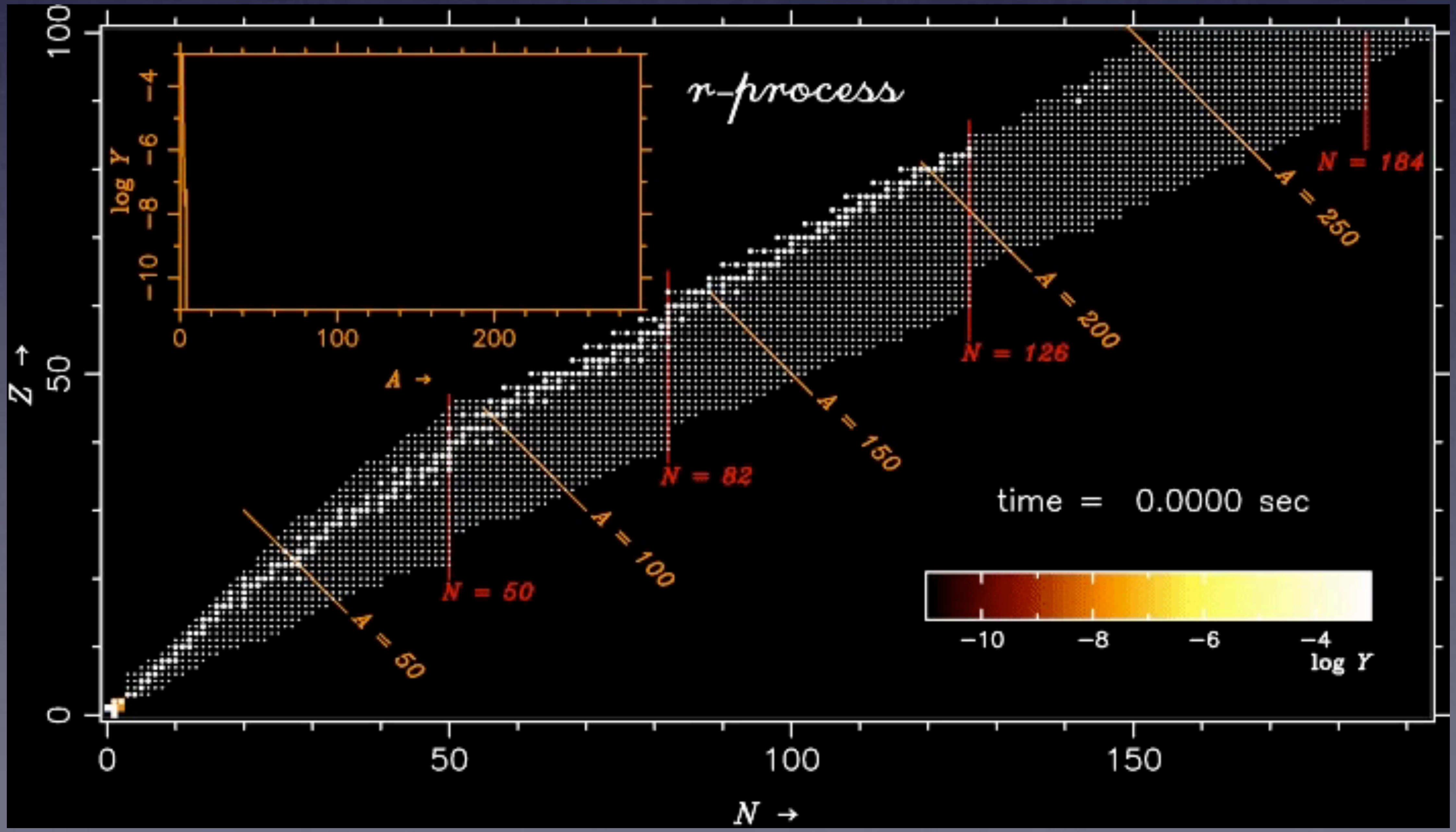
At h=10^{-21} and with an arm length of 4km displacement is 1000 times smaller than proton!

The New Periodic Table of the Elements



The optical counterpart SSS17a produced at least 5% solar masses (10^{29} kg!) of heavy elements - demonstrating that NS-mergers play a role in the r-process





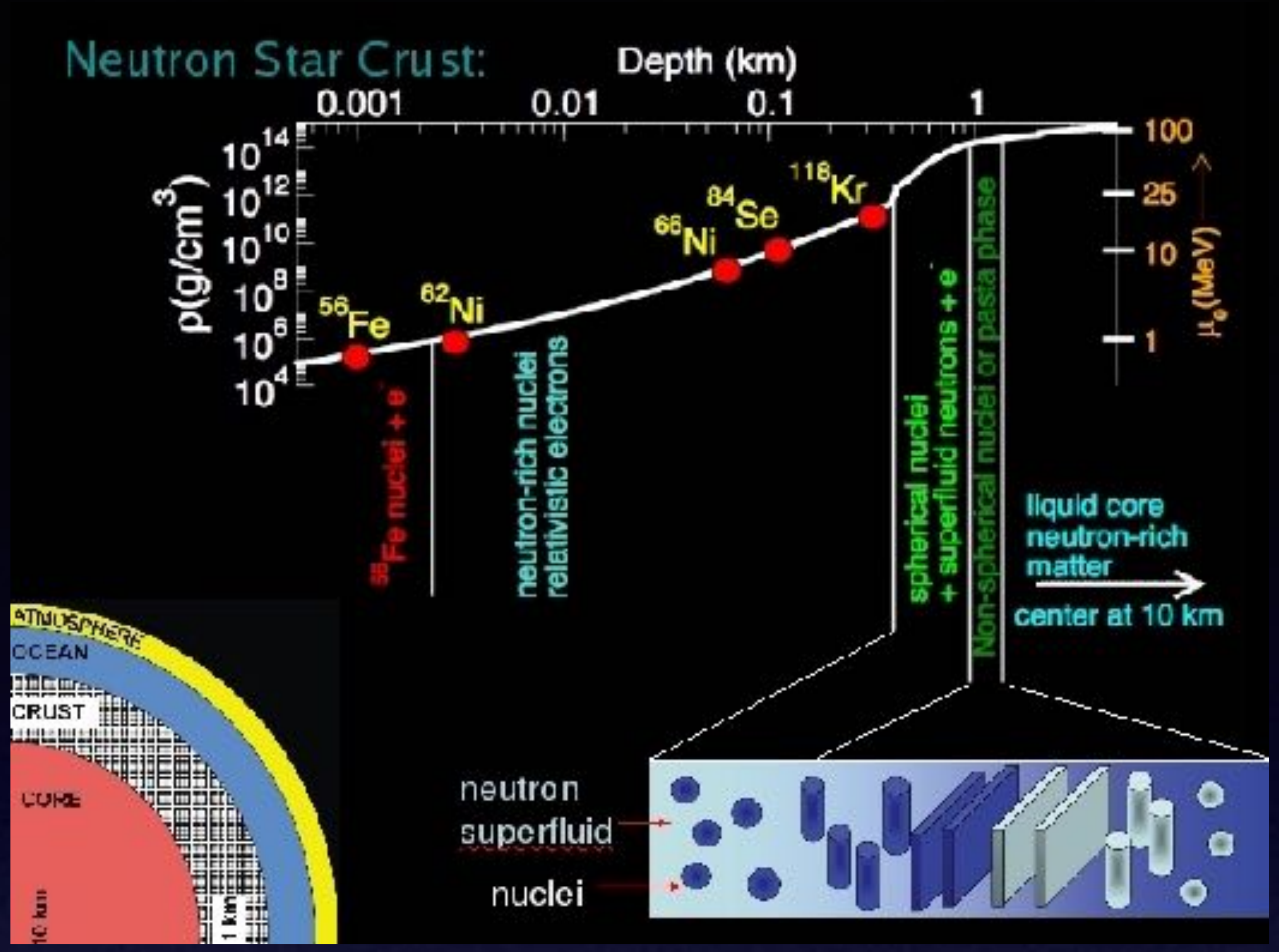
The Composition of the Outer Crust

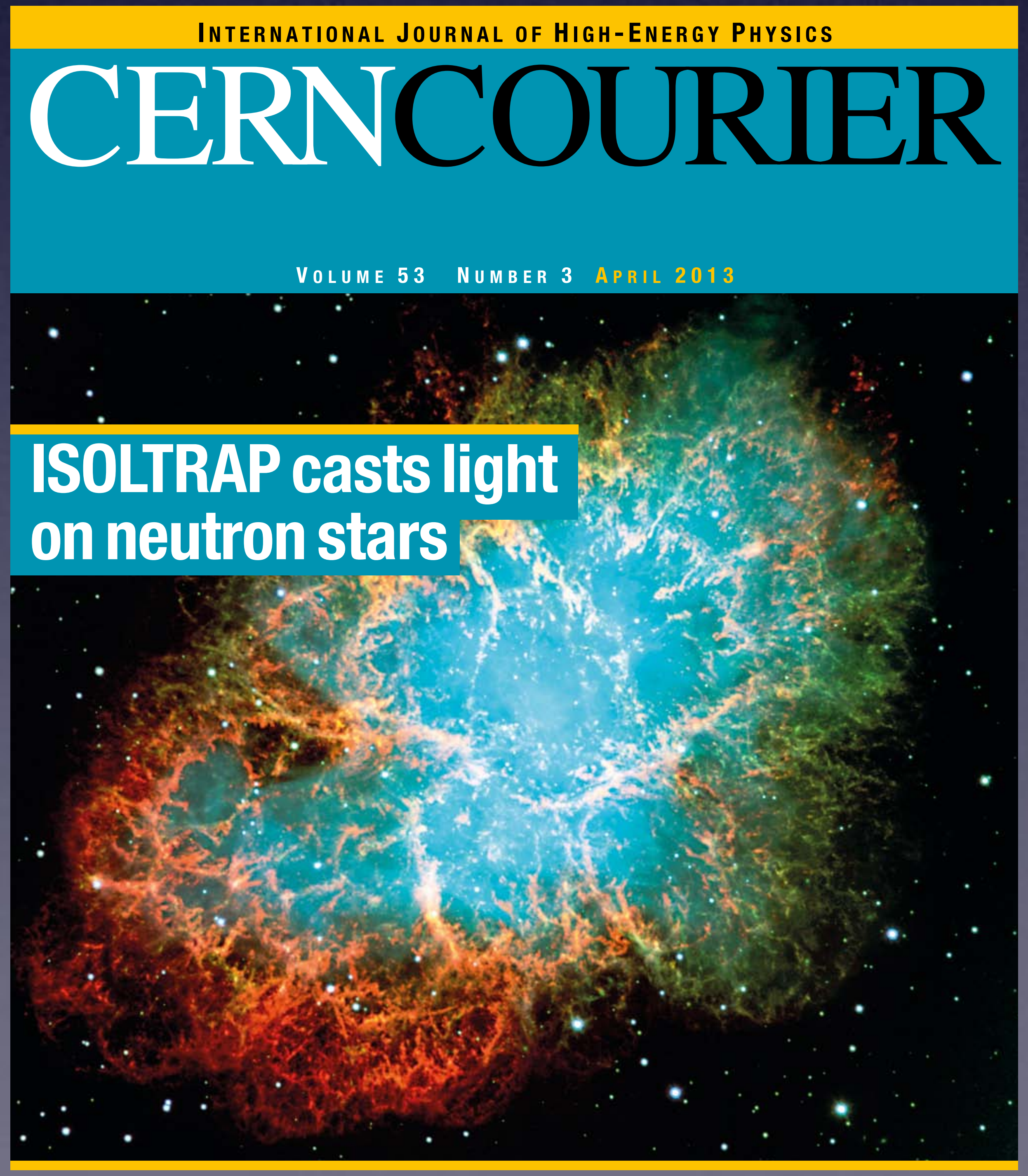
Enormous sensitivity to nuclear masses

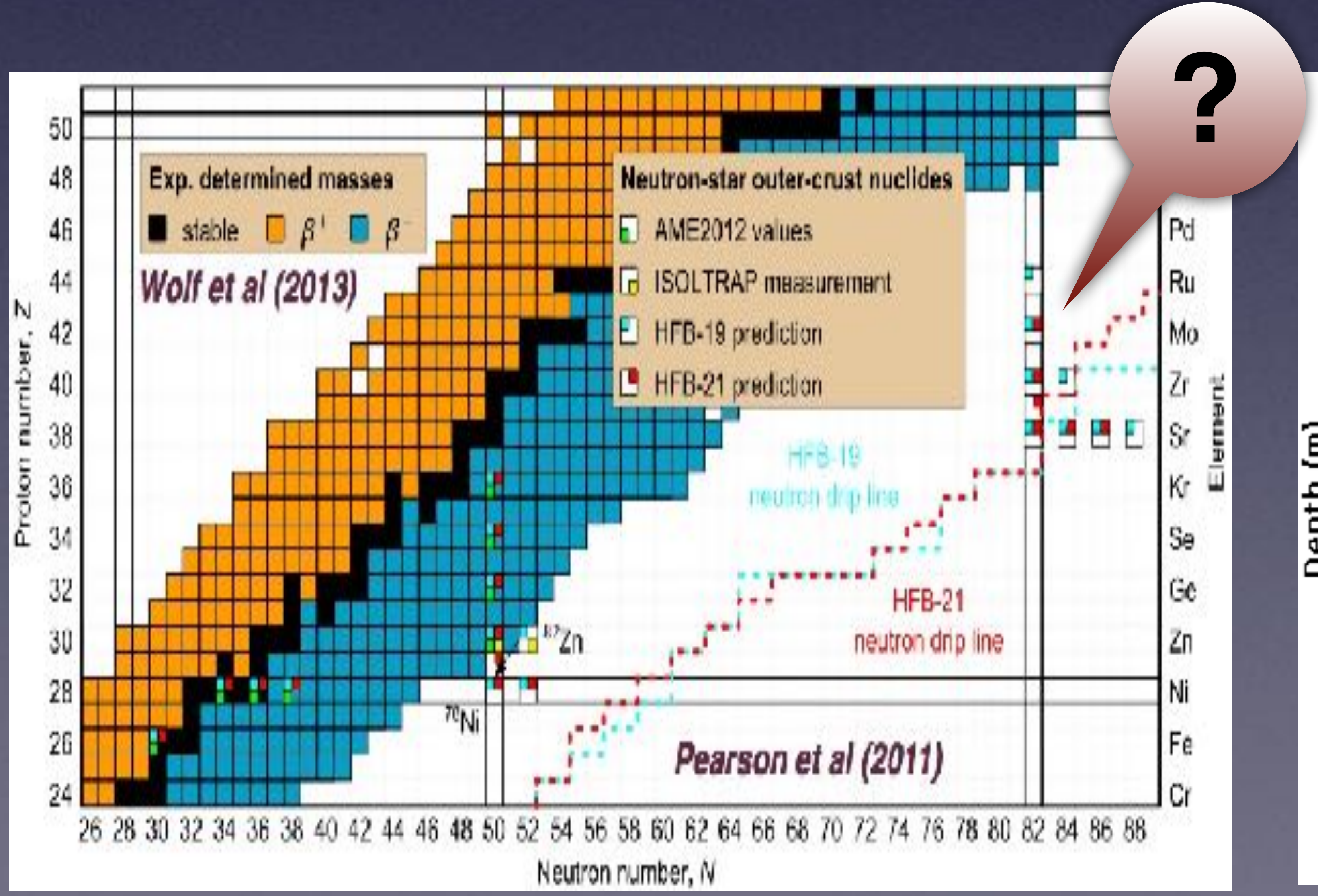
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

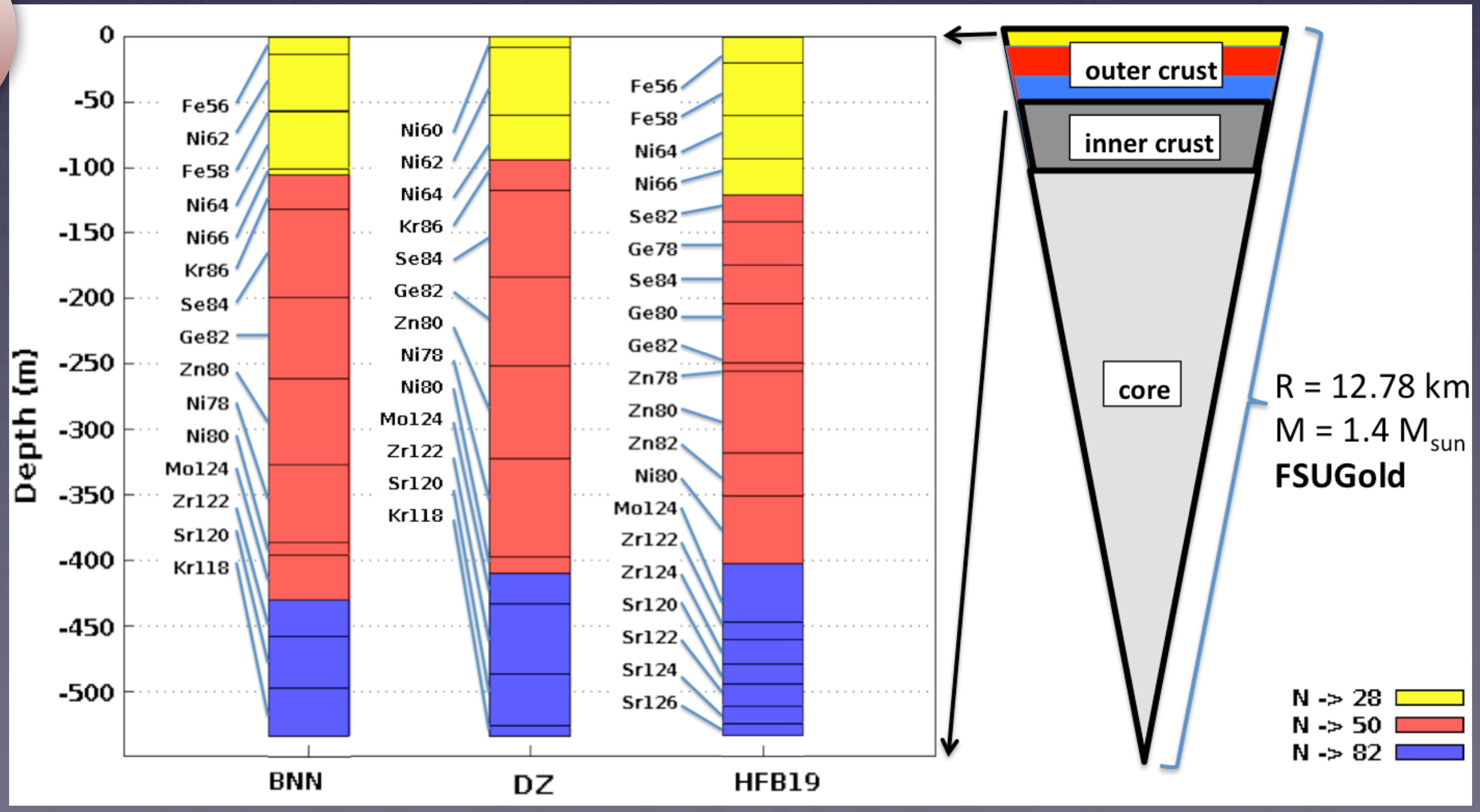
$$E/A_{\rm tot} = M(N,Z)/A + \frac{3}{4} Y_e^{4/3} {\rm k_F} + {\rm lattice}$$

- Mass measurements of exotic nuclei is essential
  - For neutron-star crusts and r-process nucleosynthesis

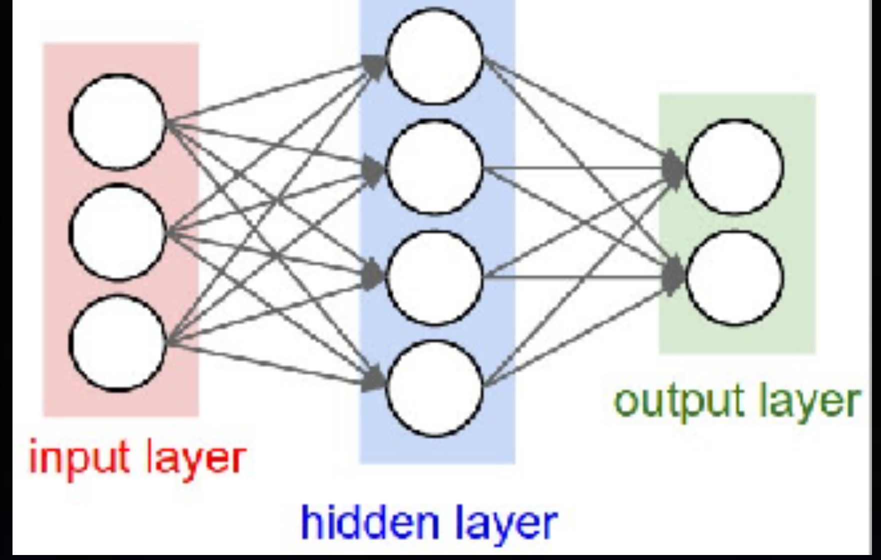








Nuclear Theory meets Machine Learning



- Use DFT to predict nuclear masses
- Train BNN by focusing on residuals

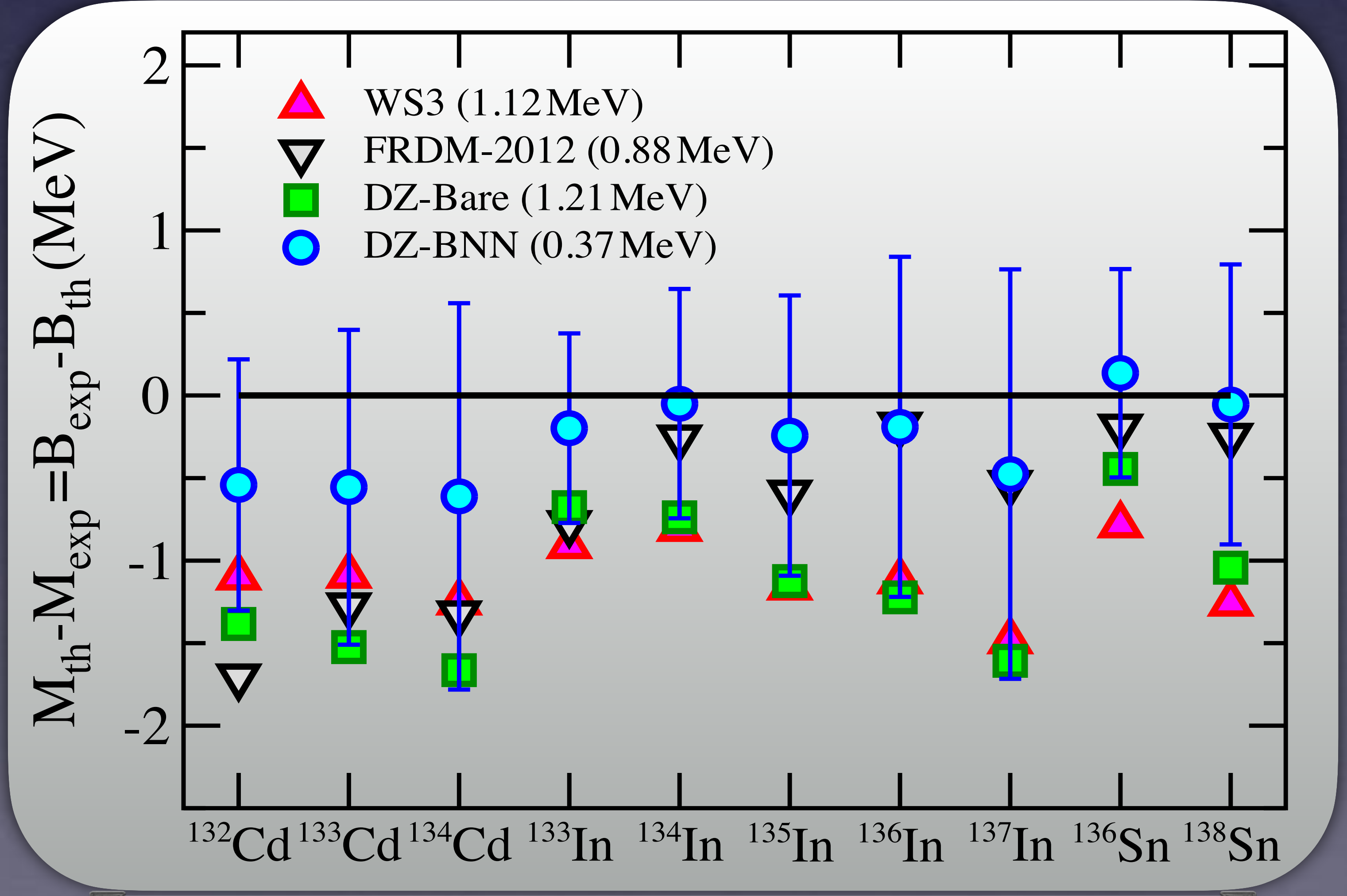
} *The paradigm*

$$M(N,Z) = M_{DFT}(N,Z) + \delta M_{BNN}(N,Z)$$

- Systematic scattering greatly reduced
- Predictions supplemented by theoretical errors

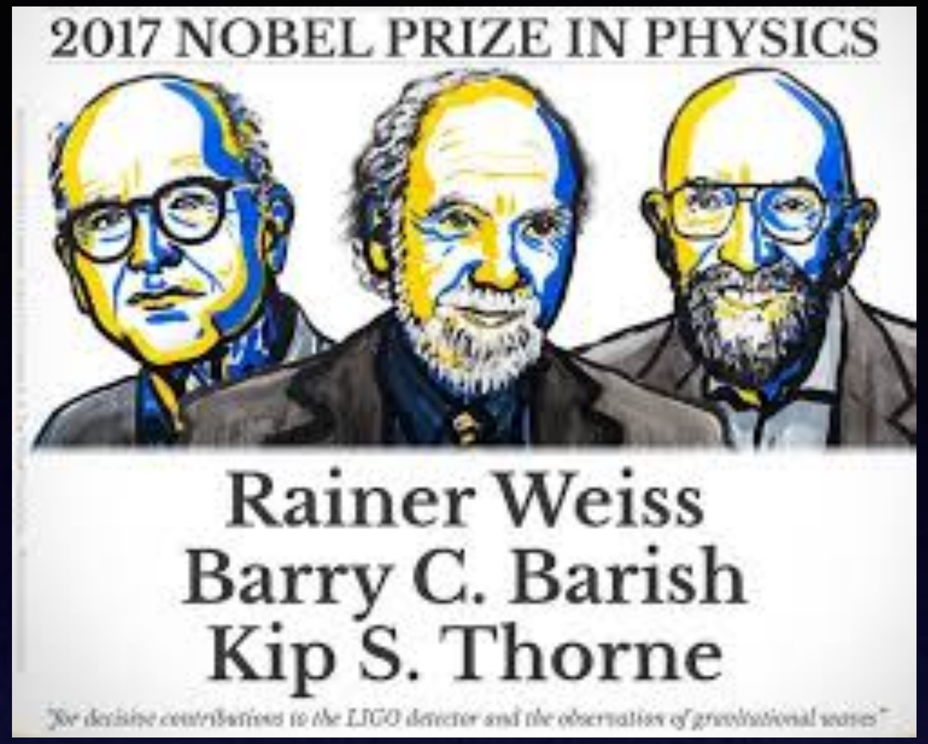
Train with AME2012 then predict AME2016

Re-generating Richard Feynman



Duflo-Zuker + BNN

"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016



- The dawn of a new era: GW Astronomy
  - Initial black hole masses are 36 and 29 solar masses
  - Final black hole mass is 62 solar masses;
    3 solar masses radiated in Gravitational Waves!