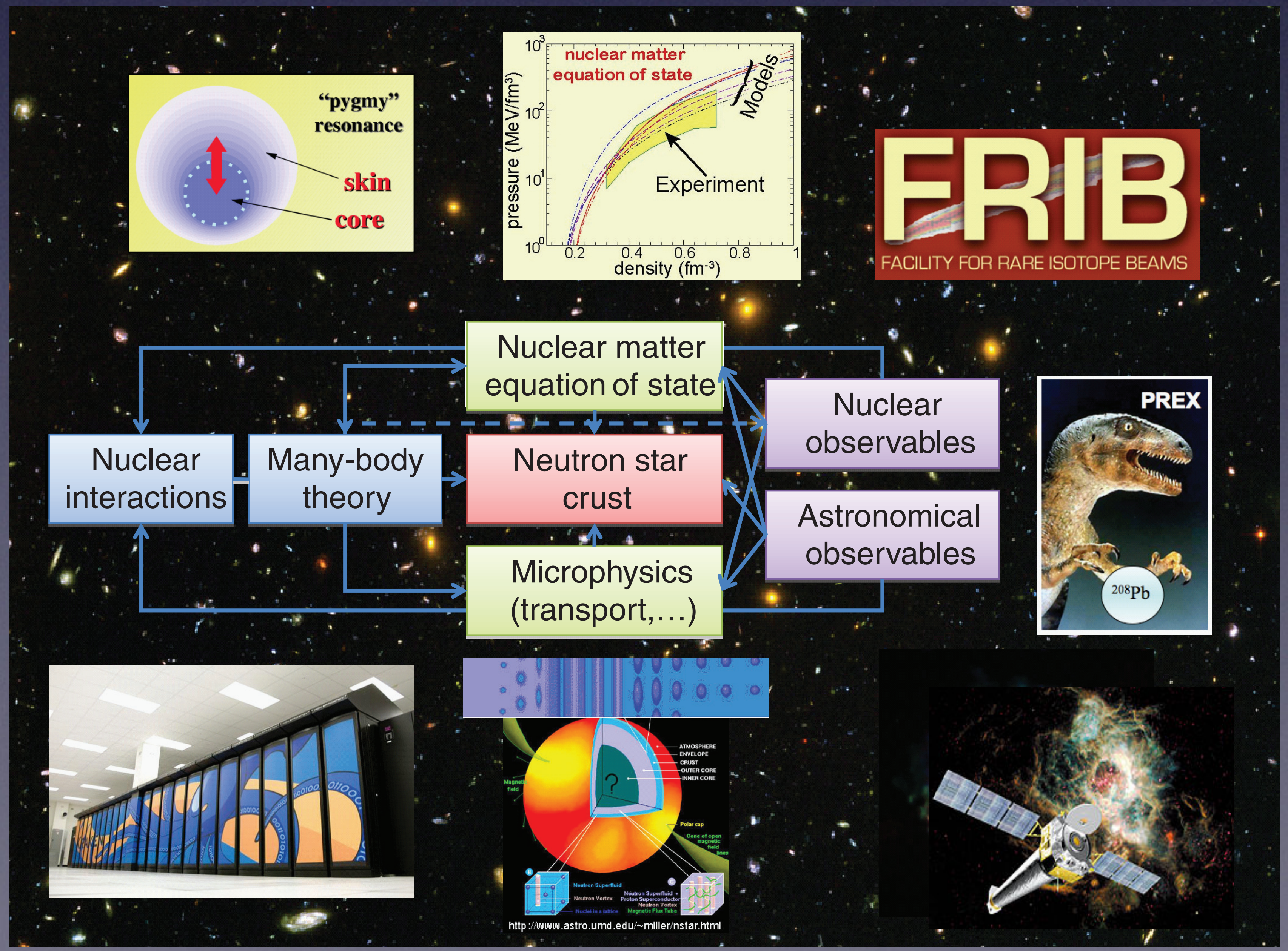
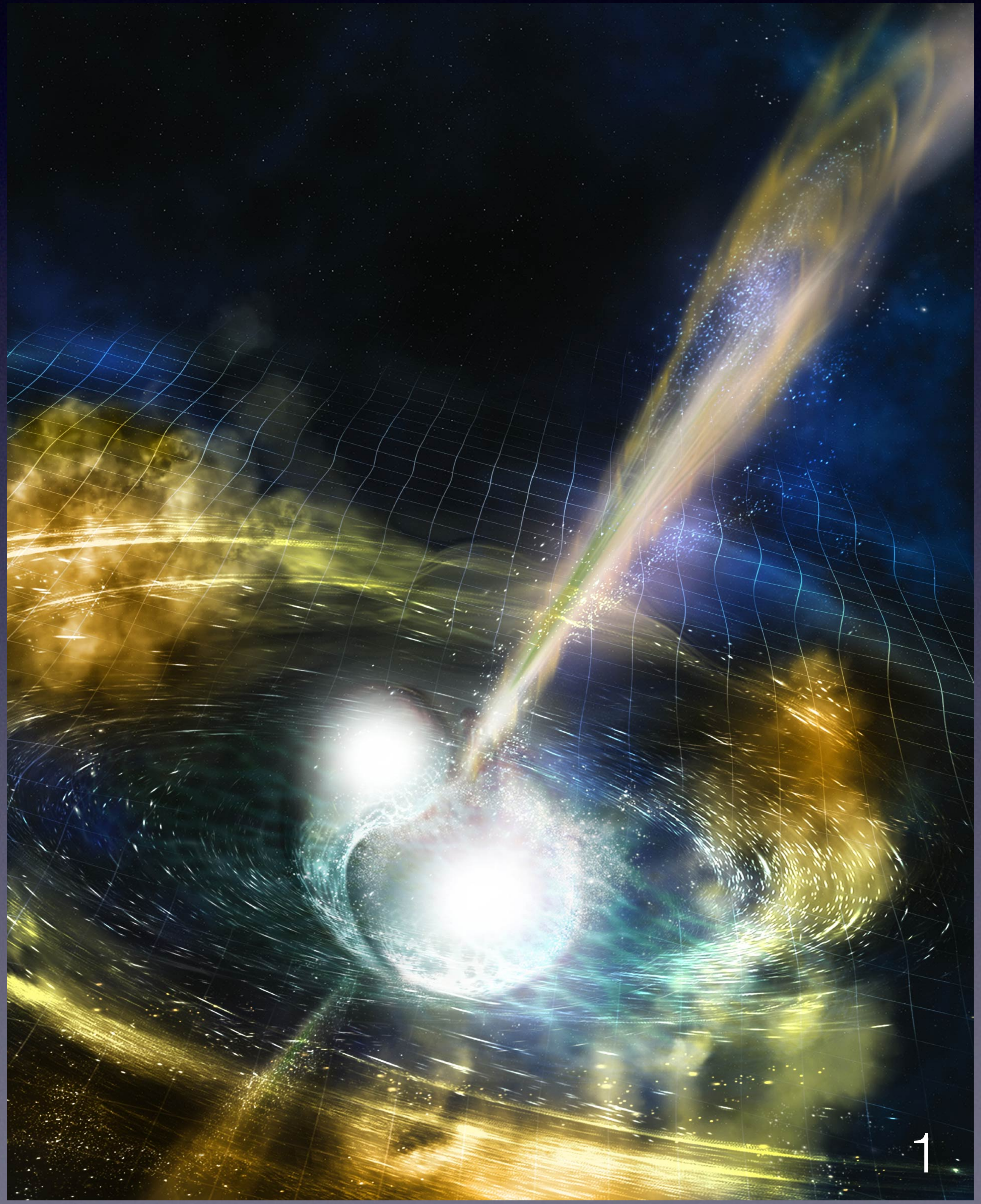
PREX-II and MREX in the New Era of Multimessenger Astronomy

Parity Violation and Related Topics (MITP Virtual Workshop)

July 2020

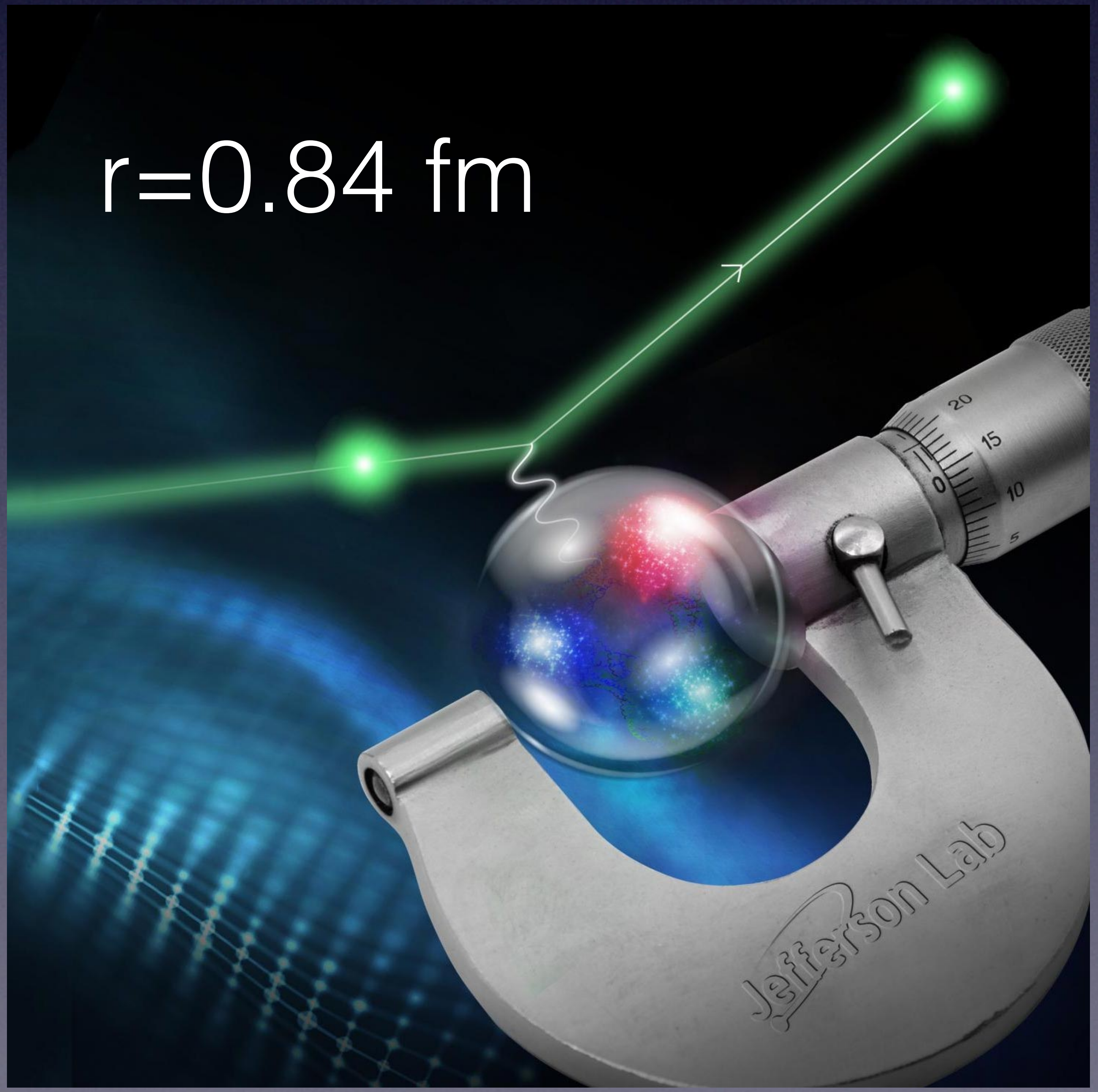
J. Piekarewicz (FSU)

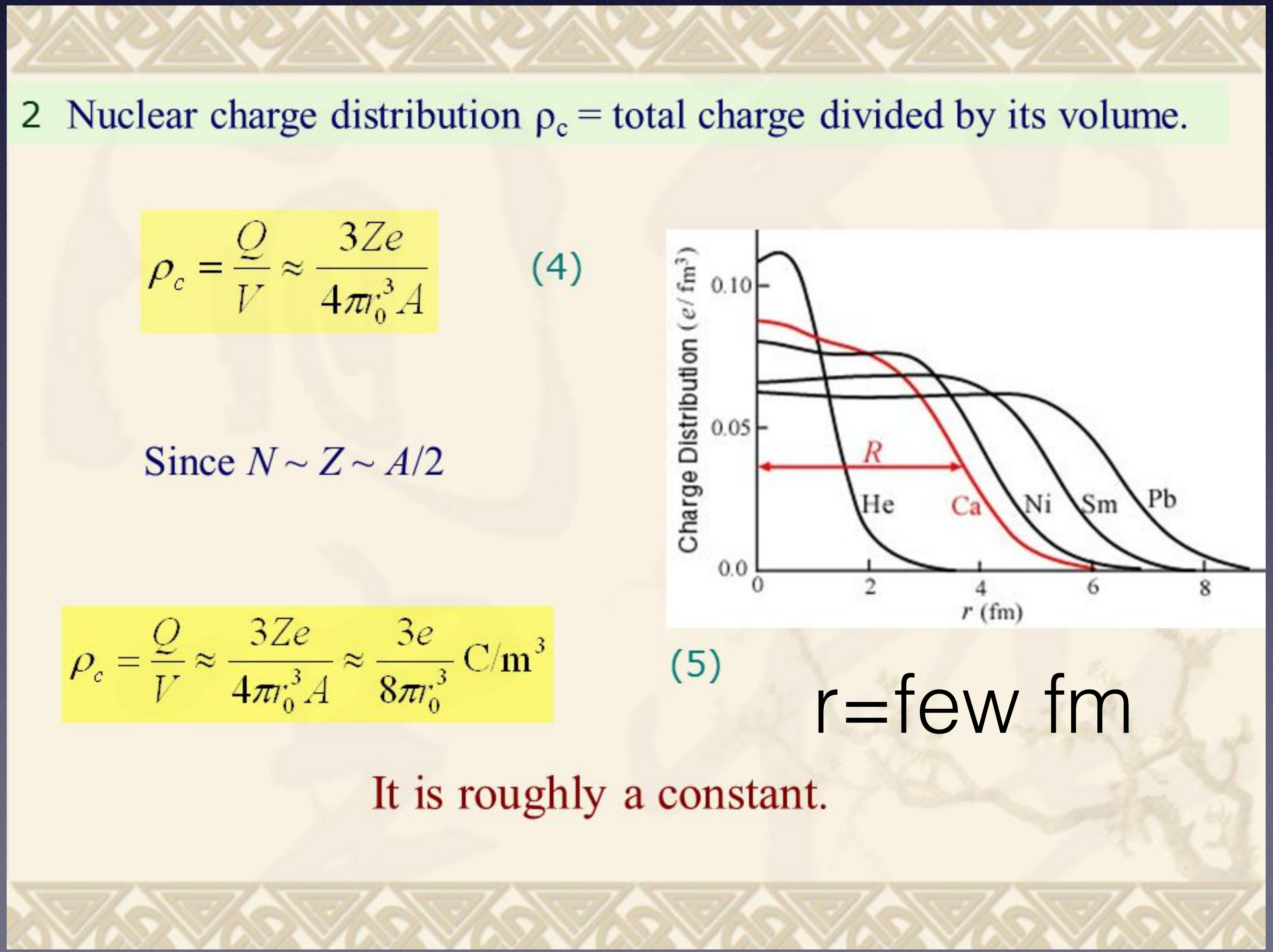


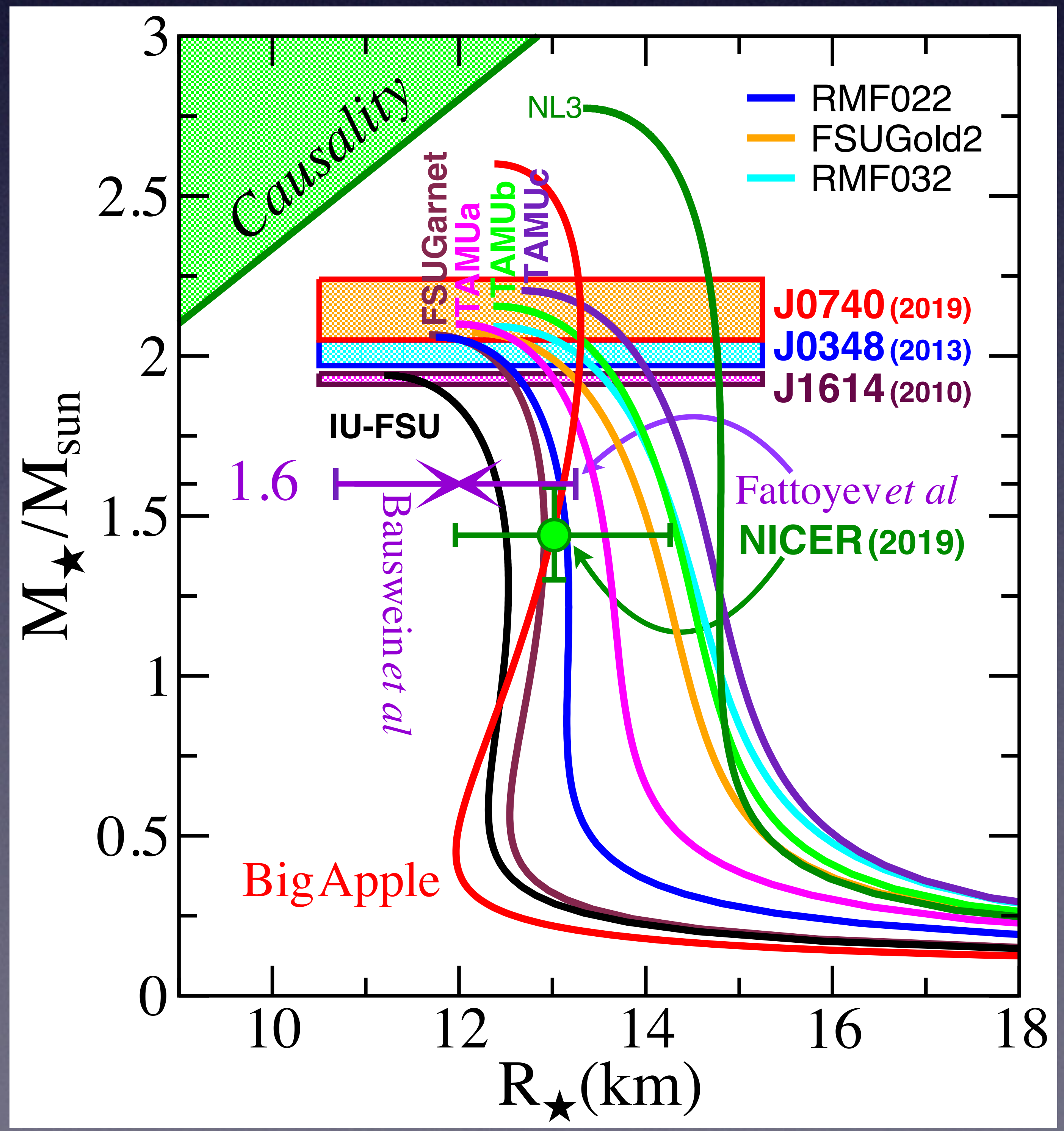


Mass-Radius Relation: From Mesons, to Baryons, to Nuclei, to Neutron Stars!

- A fundamental question in all of nuclear science:
  - What is the size of a system of mass M?
  - What is the distribution of mass, charge, weak-charge, …?







The Liquid Drop Model

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

- Nuclear forces saturate → equilibrium density
- Nuclei penalized for developing a surface
- Nuclei penalized by Coulomb repulsion
- Nuclei penalized for isospin imbalance (N≠Z)

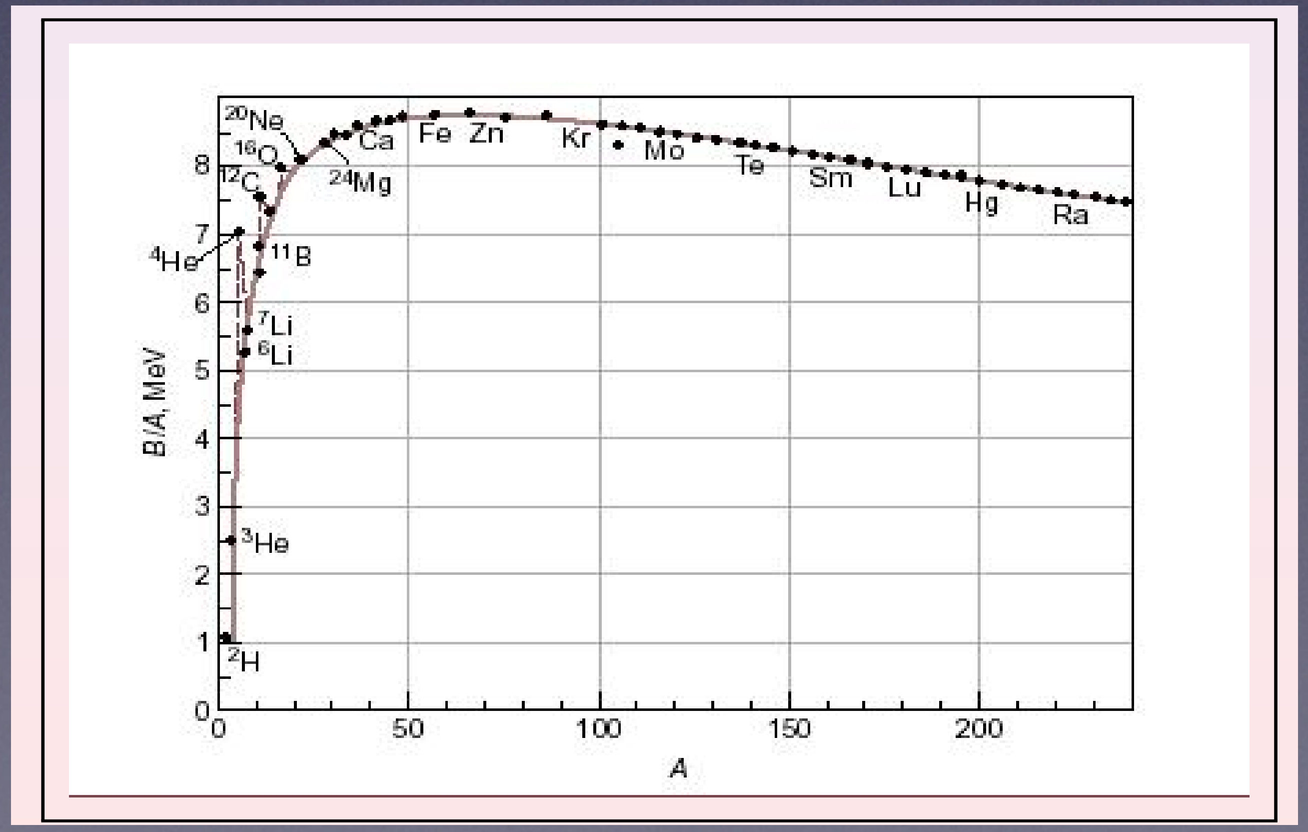
$\varrho_0 \approx 0.15\,\mathrm{fm}^{-3}$

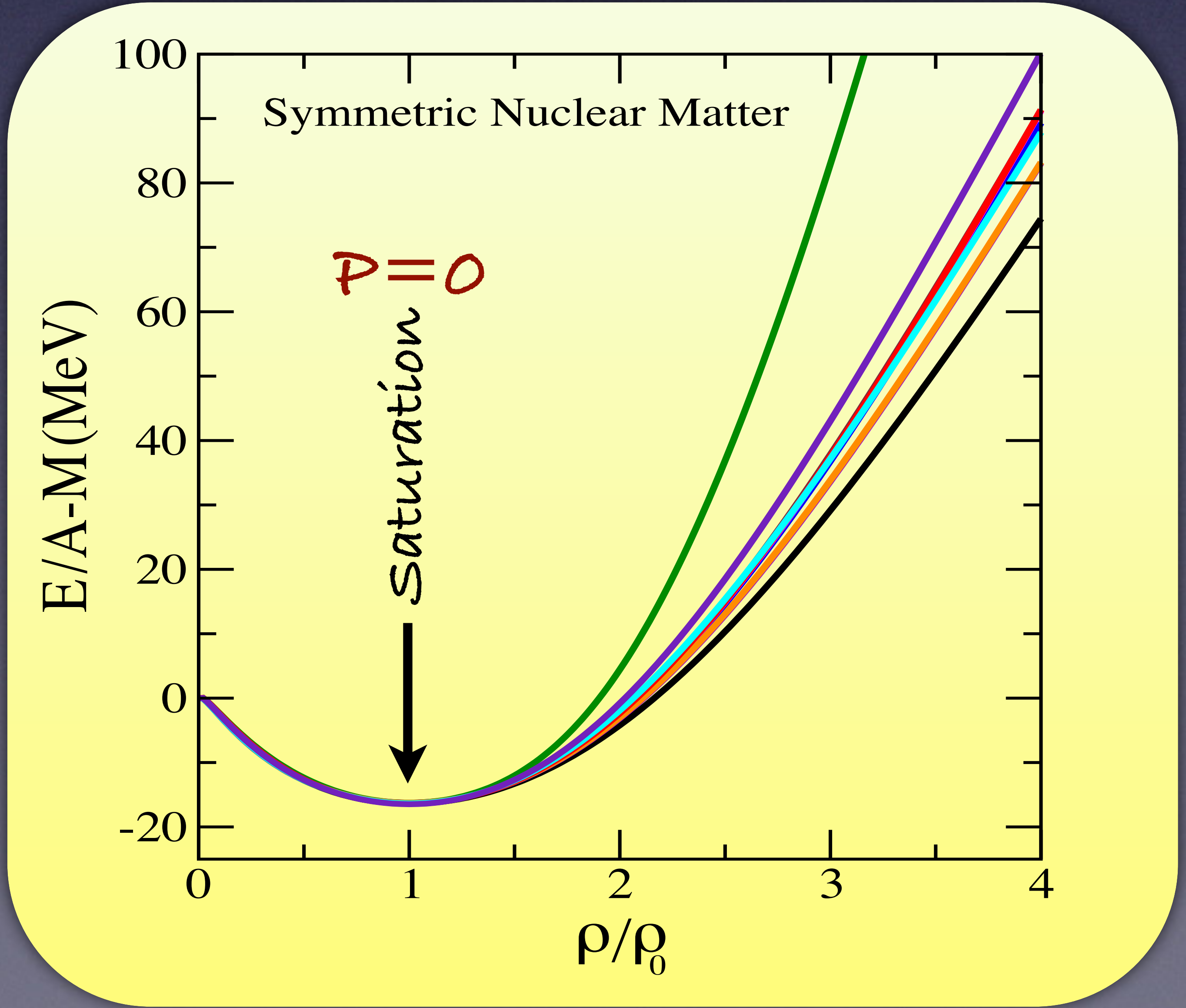
$R(A) = r_0 A^{1/3} \approx (1.2\,\mathrm{fm}) A^{1/3}$

Nucleus as an incompressible liquid drop made of two quantum fluids

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

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





Electroweak Probes of Ground State Densities: A fundamental nuclear-structure problem

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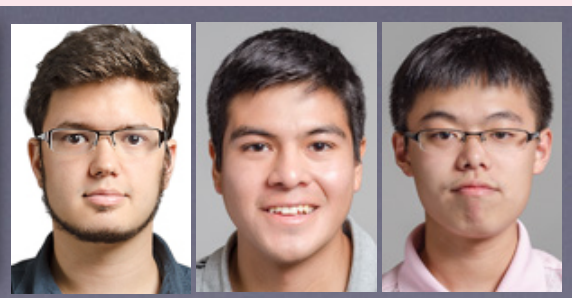
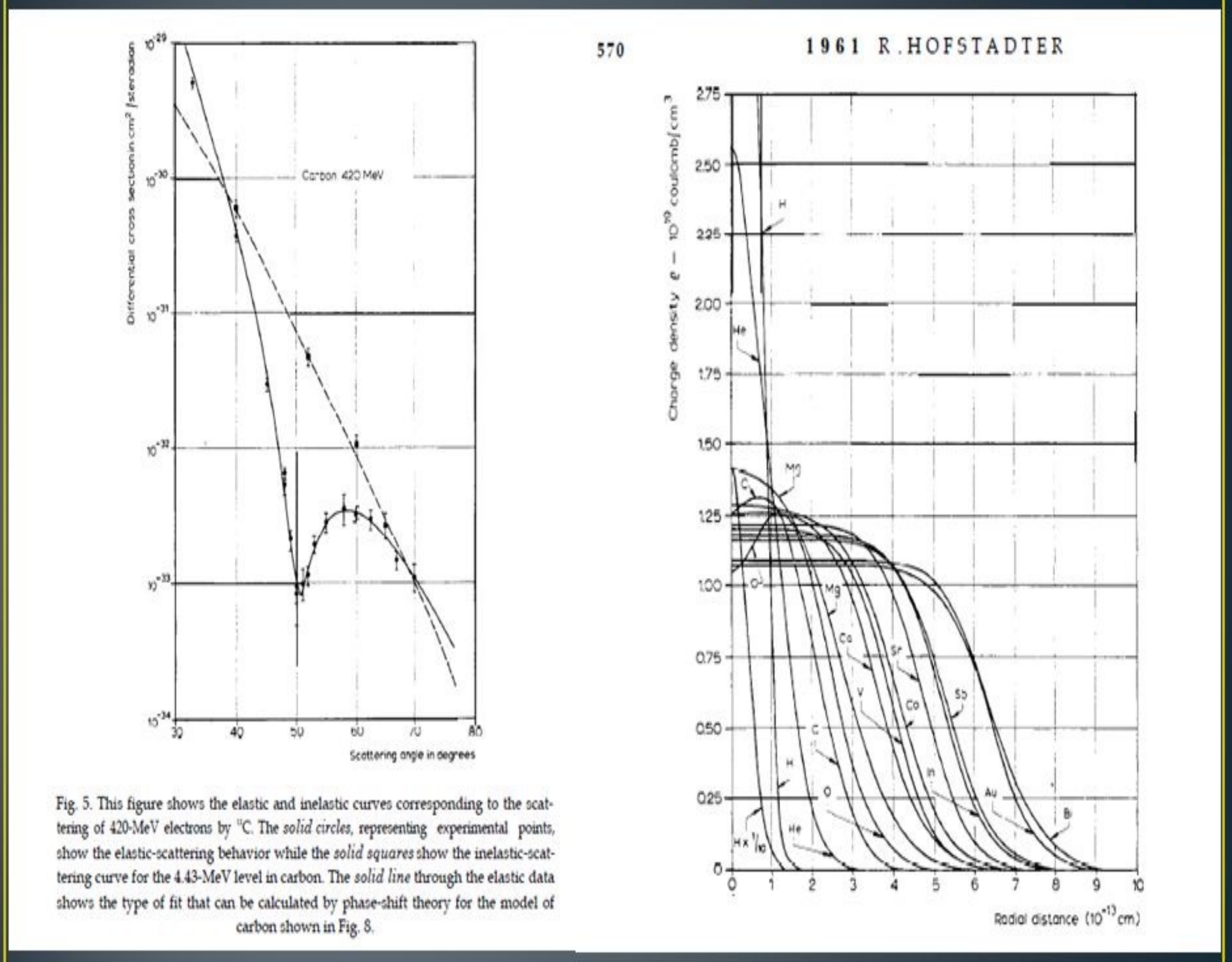


Electroweak Probes of Ground State Densities
A fundamental nuclear-structure problem

	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

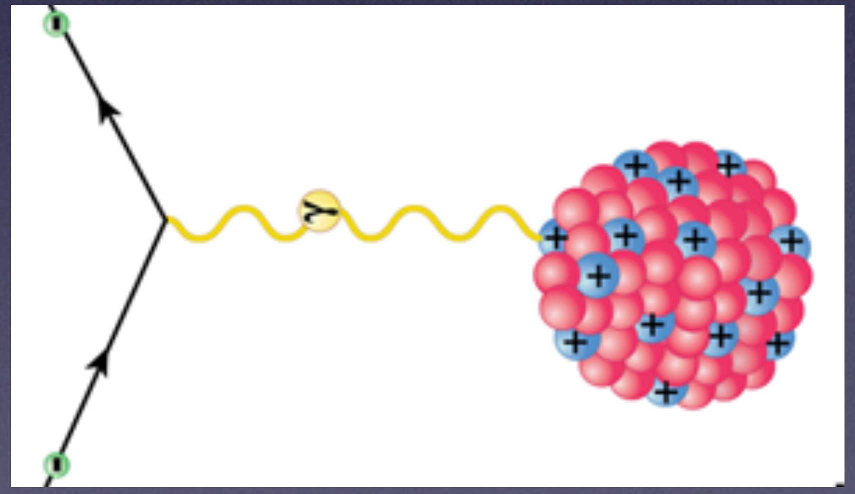
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

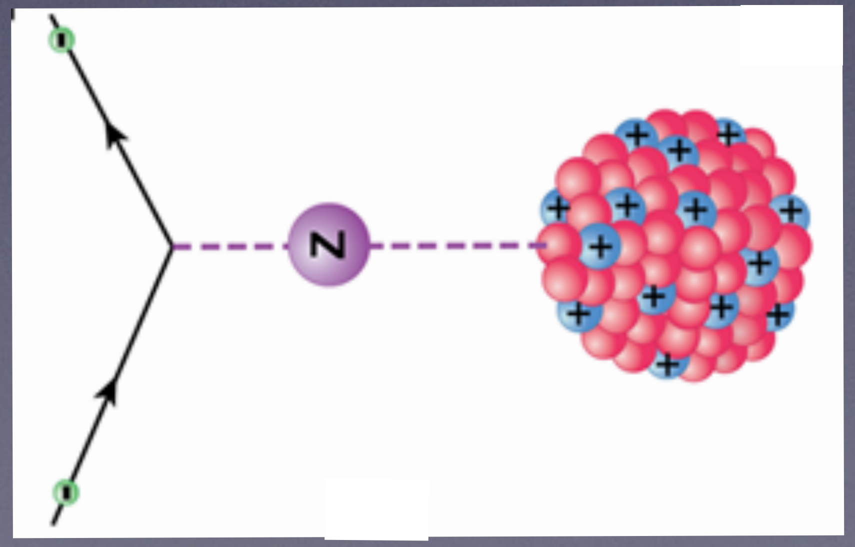
Diffraction – Hofstadter, Nobel (1961)



Diffractive electron scattering on nuclei and the resulting charge density distributions, images of spherical nuclei

- Charge density known with enormous precision
  - Probed via parity-conserving elastic e-scattering
  - γ couples to electric charge, thus preferentially to protons
- Weak-charge density poorly known
  - Probed via parity-violating e-scattering or CEvNS
  - Z_0 couples to weak charge, thus preferentially to neutrons





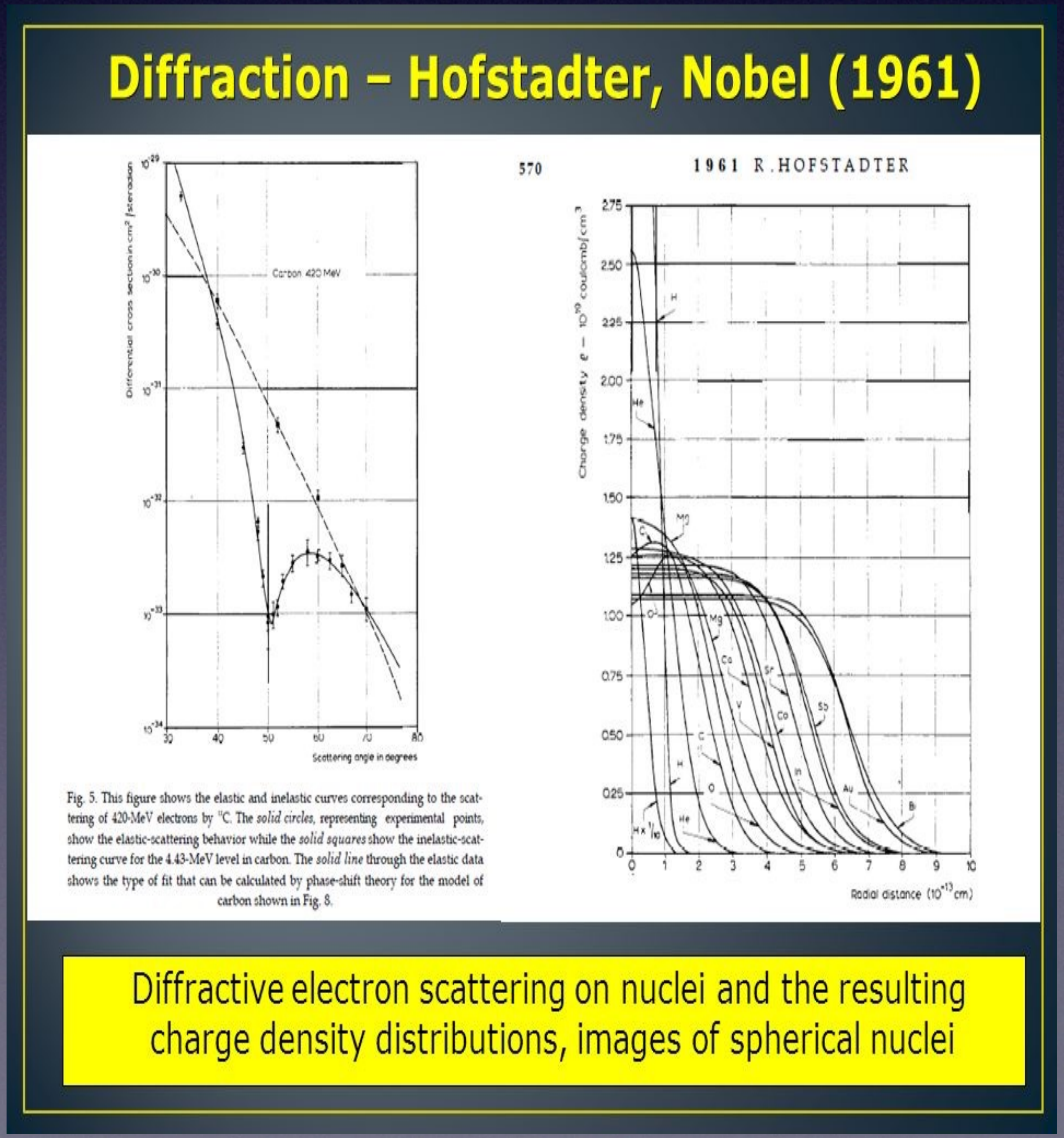
Symmetrized Fermi Function

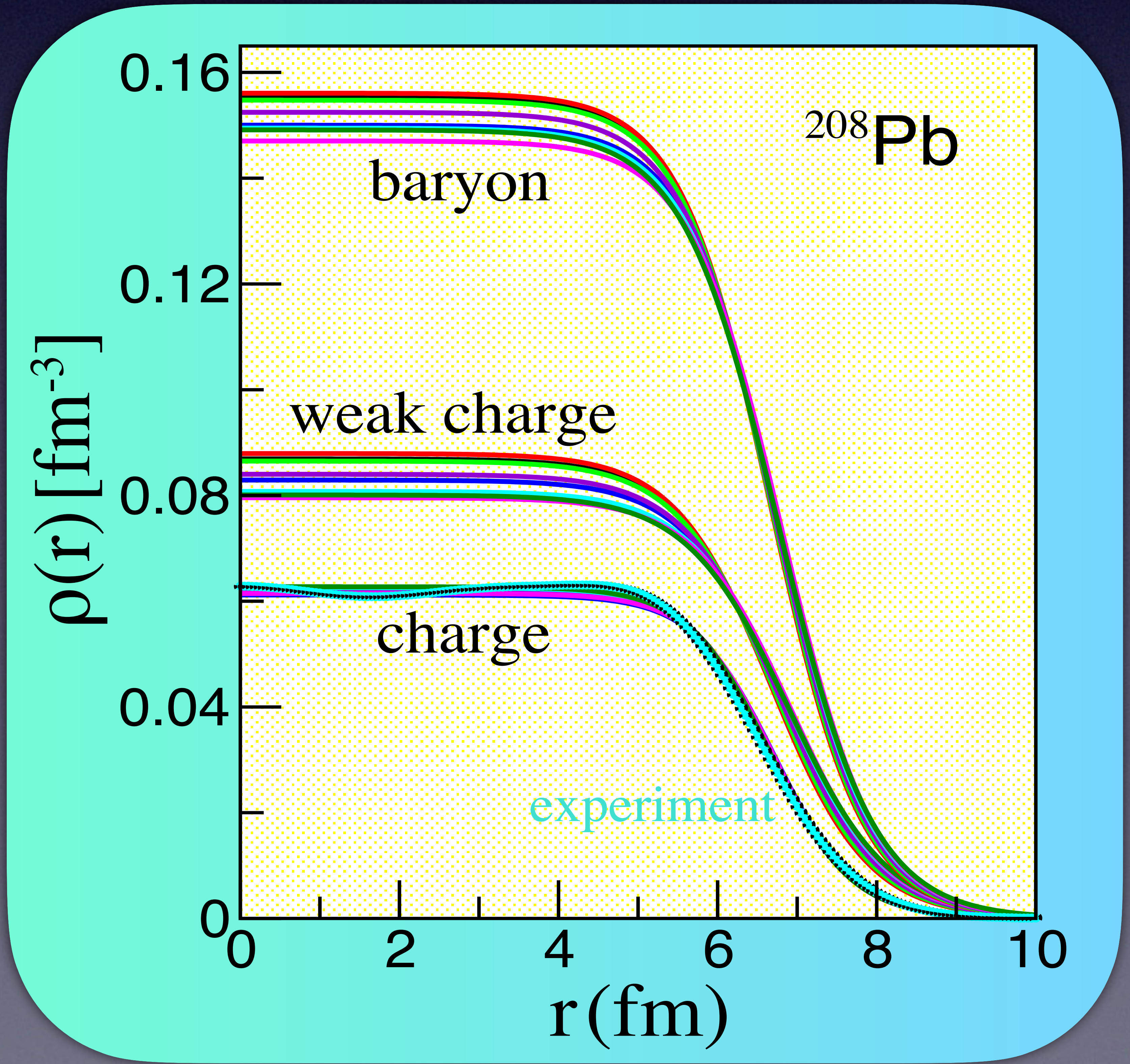
$$\rho_{\rm SF}(r) \equiv \rho_0 \frac{\sinh(c/a)}{\cosh(r/a) + \cosh(c/a)}$$

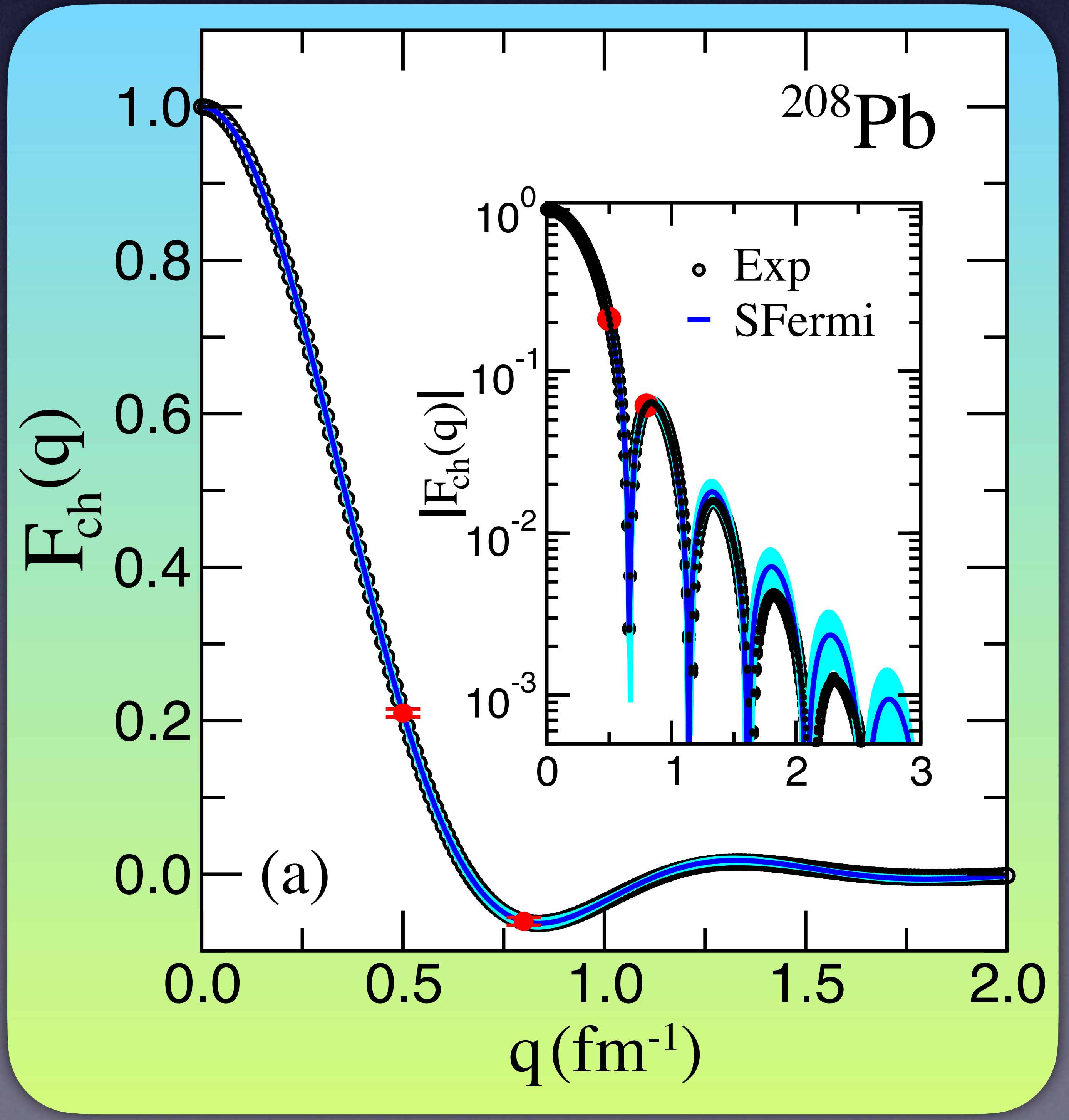
$$F_{\rm SF}(q) \to \frac{\cos(qc+\delta)}{qc} e^{-\pi q a}$$

c=half-density radius
a=surface diffusion

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



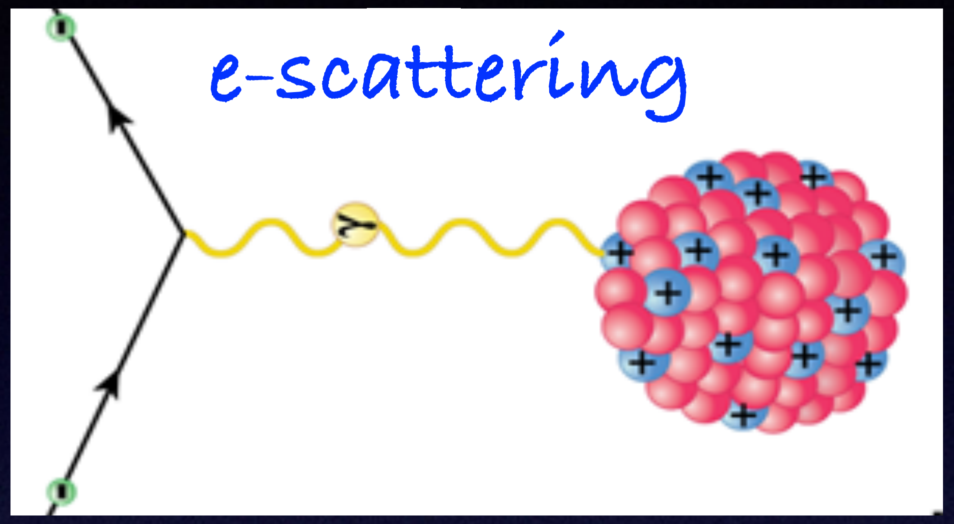




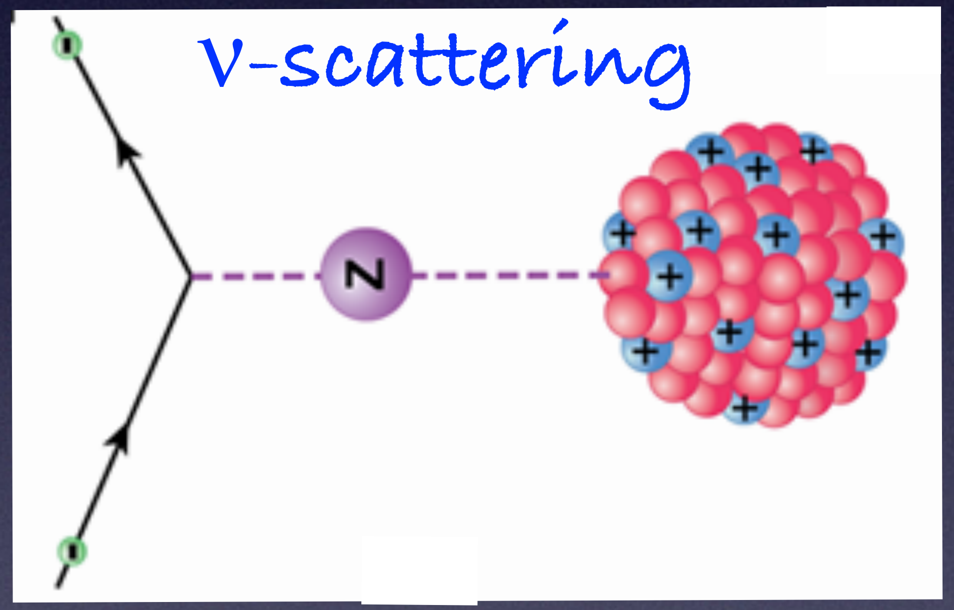
Experimental Extraction of Charge and Weak Form Factors

Form Factors are the Fourier transform of the corresponding densities

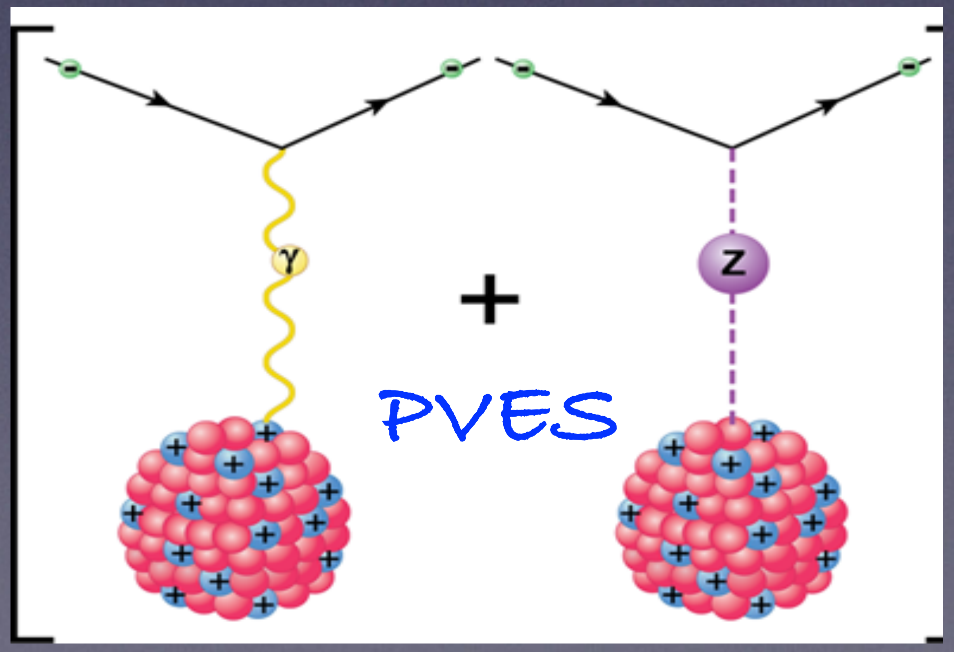
$$\left(\frac{d\sigma}{d\Omega}\right)_{J=0} = \left[\frac{\alpha^2\cos^2(\theta/2)}{4E^2\sin^4(\theta/2)}\left(\frac{E'}{E}\right)\right] Z^2 F_{\rm ch}^2(Q^2)$$



$$\left(\frac{d\sigma}{dT}\right)_{J=0} = \left[\frac{G_{\rm F}^2 M}{4\pi}\left(2-\frac{MT}{E^2}-2\frac{T}{E}\right)\right] Q_{\rm wk}^2 F_{\rm wk}^2(Q^2)$$



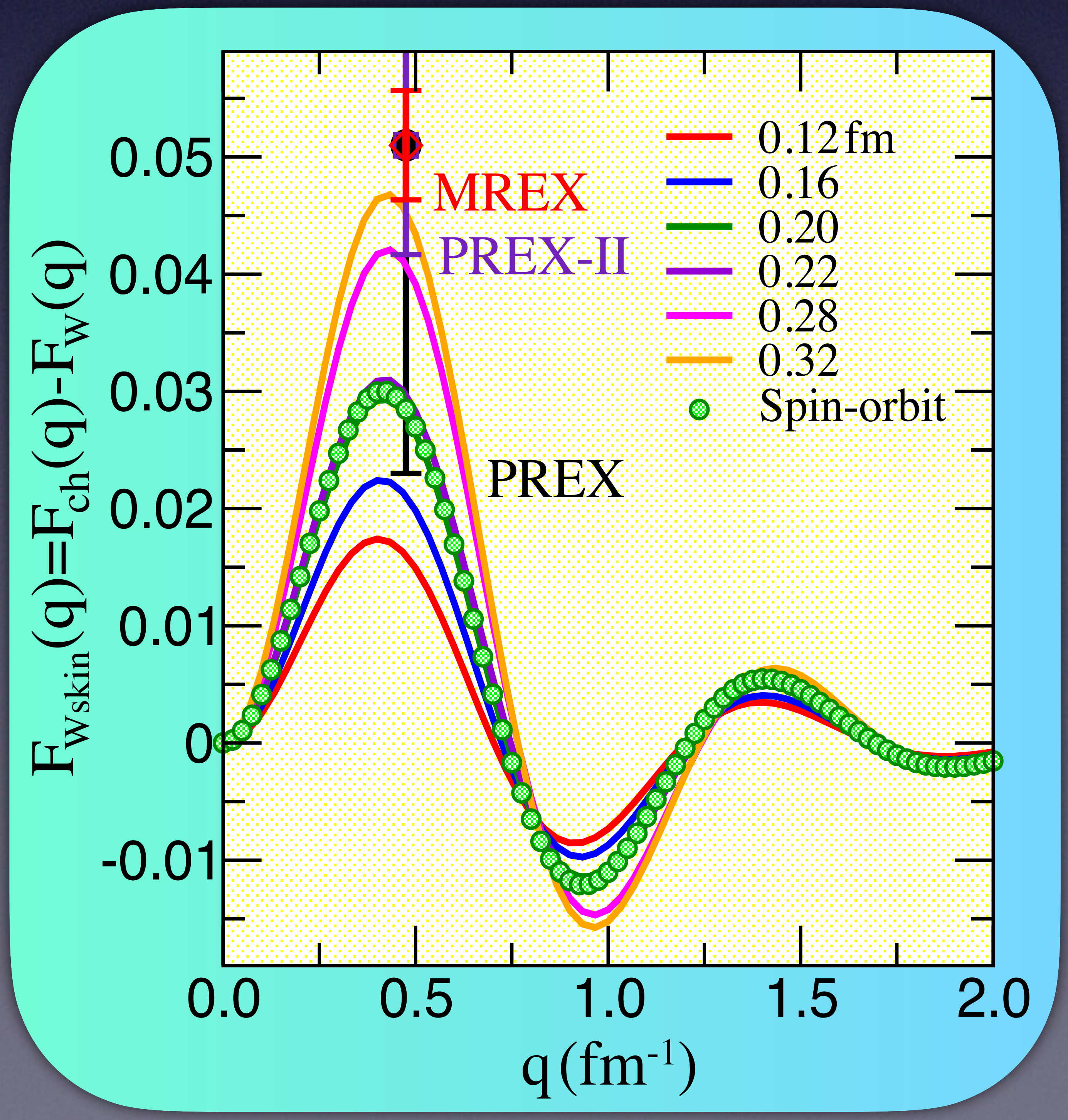
$$A_{\rm PV} = \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_{\rm R} - \left(\frac{d\sigma}{d\Omega}\right)_{\rm L}}{\left(\frac{d\sigma}{d\Omega}\right)_{\rm R} + \left(\frac{d\sigma}{d\Omega}\right)_{\rm L}}\right]_{J=0} = \left(\frac{G_{\rm F}Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{Q_{\rm wk}F_{\rm wk}(Q^2)}{ZF_{\rm ch}(Q^2)}$$

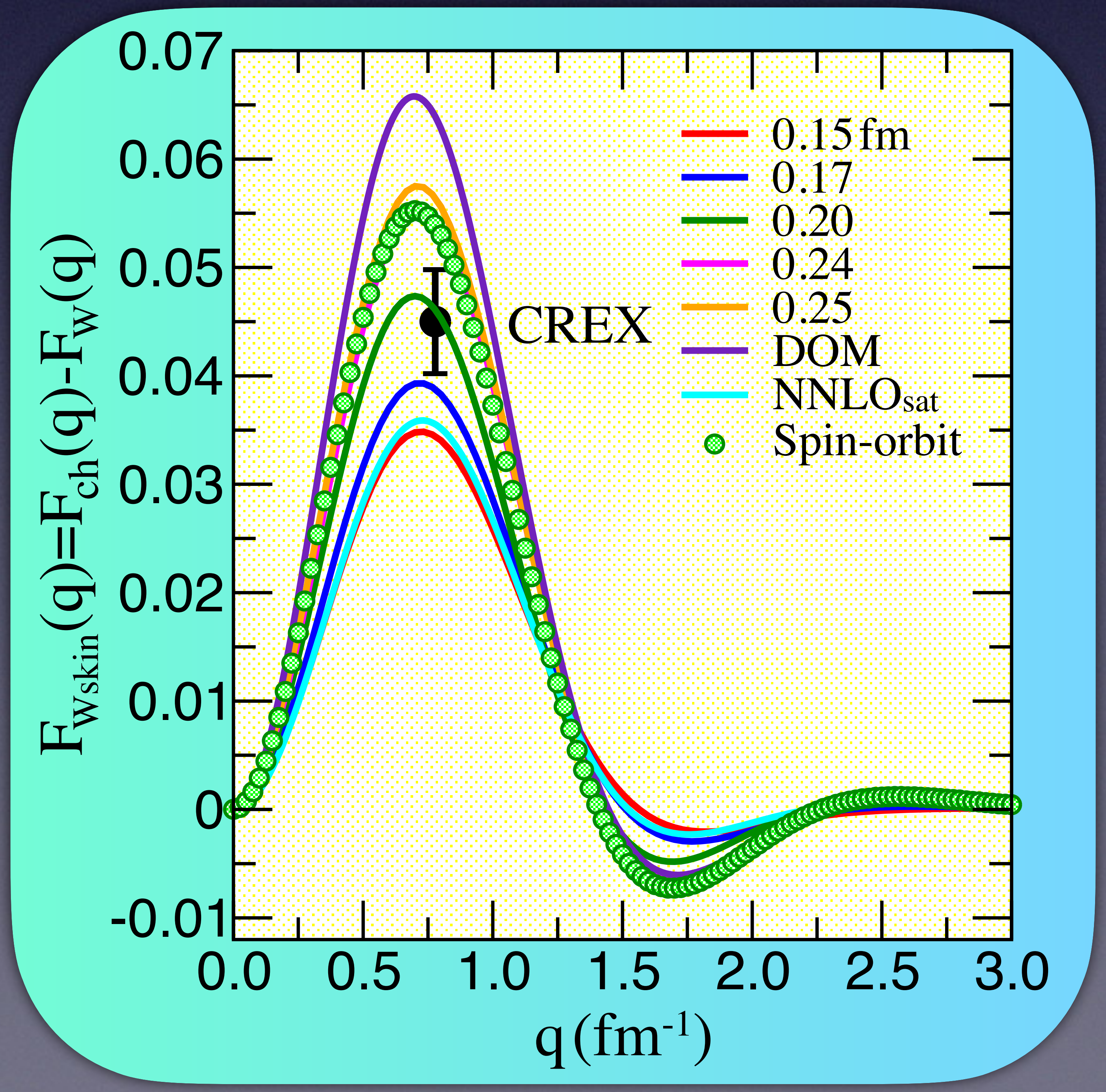


$$Q_{\rm wk} = -N + (1-4\sin^2\theta_{\rm W})Z = \text{weak charge}$$

The Future: PREX-II, CREX, and MREX

- PREX obtained $R_n - R_p = 0.33^{+0.16}_{-0.18}\,\mathrm{fm}$
- PREX-II will improve error by a factor of 3 and determine L (pressure of PNM)
- MREX@Mainz will improve error by an additional factor of 2!
- CREX will provide bridge between ab-initio approaches and nuclear DFTs
- PREX-II and CREX to run in 2019-20 will provide fundamental anchors for future measurements of exotic nuclei at FRIB





The weak-skin form factor

A model-independent observable

$$F_{\rm Wskin} \equiv F_{\rm ch} - F_{\rm wk} \approx \frac{q^2}{6}\left(R_{\rm wk}^2 - R_{ch}^2\right) + \ldots$$

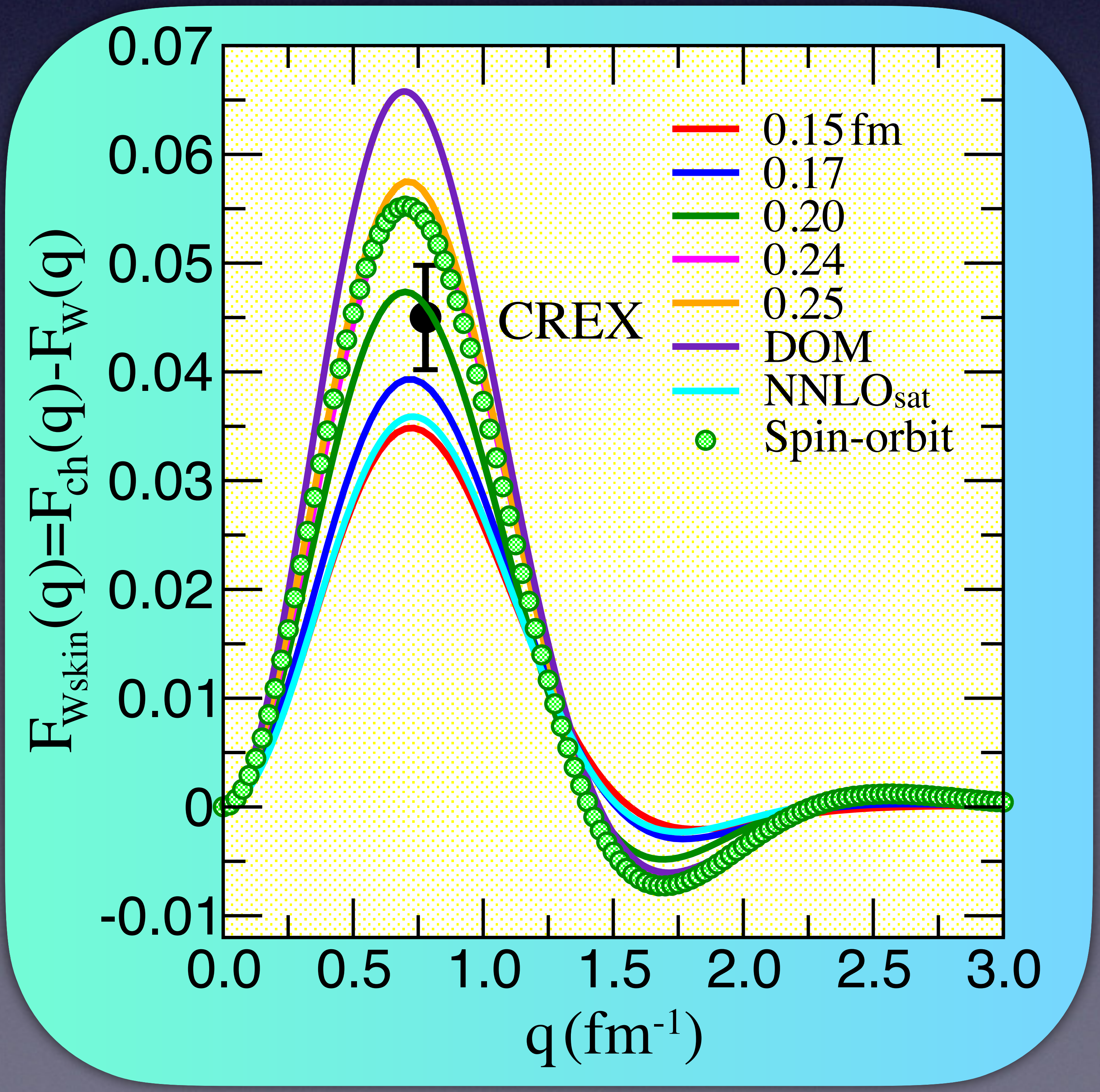
Spin-orbit currents

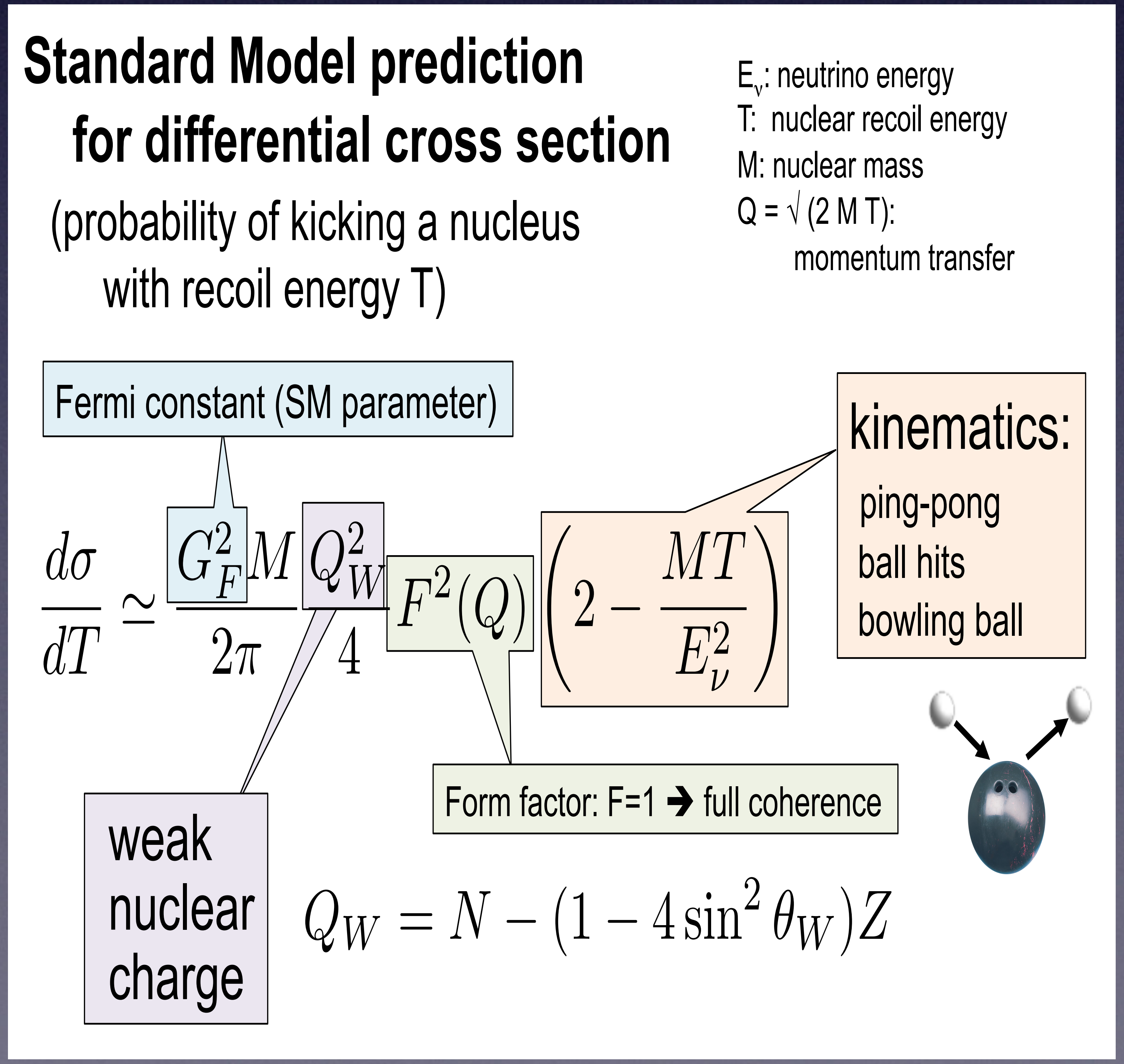
Vanish for fully occupied spin-orbit partners

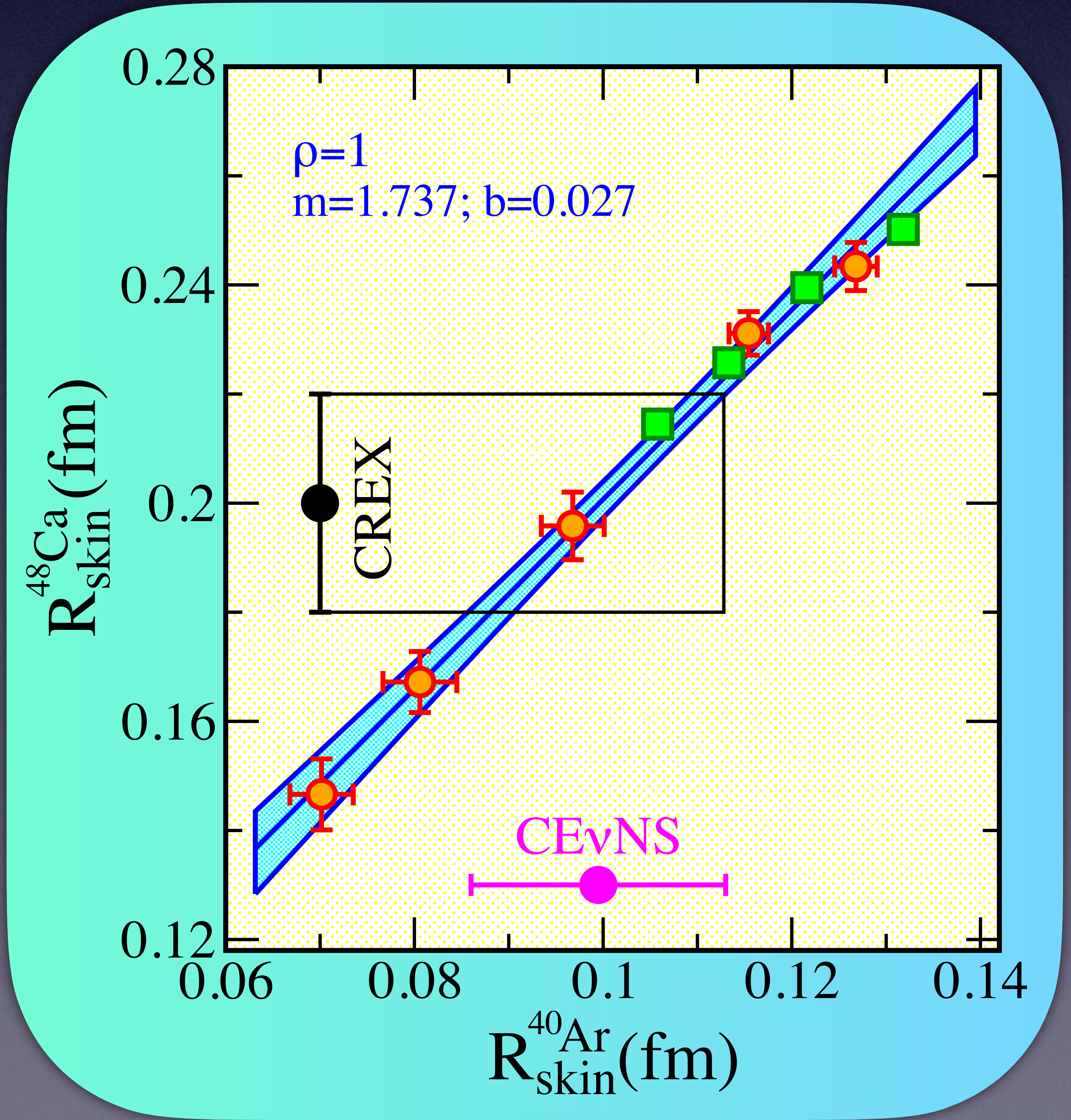
$$J^{\mu} = G_{\rm E}\gamma^{\mu} + \left(\frac{G_{\rm M} - G_{\rm E}}{1+\tau}\right)\left[\tau\gamma^{\mu} + i\sigma_{\mu\nu}\frac{q_{\nu}}{2M}\right]$$

CREX and CEνNS (^{40}Ar)

- What constraints (if any!) does CREX impose on CEνNS (^{40}Ar)?
- ^{48}Ca is a doubly-magic nucleus — ^{40}Ar is not (2p-2h relative to ^{40}Ca)
- Yet, weak skin form factors of both nuclei display same systematics
  Very strong correlation among covariant energy density functionals







Electroweak Probes of Ground State Densities
A fundamental connection to the Equation of State (EOS)

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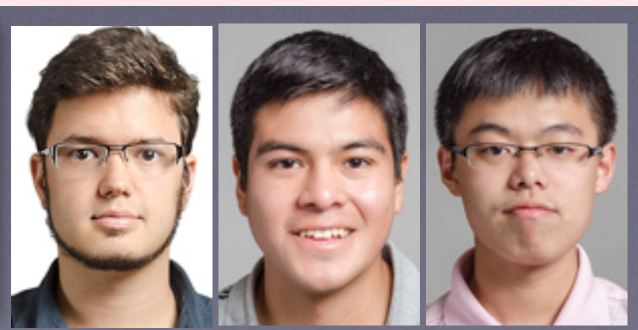
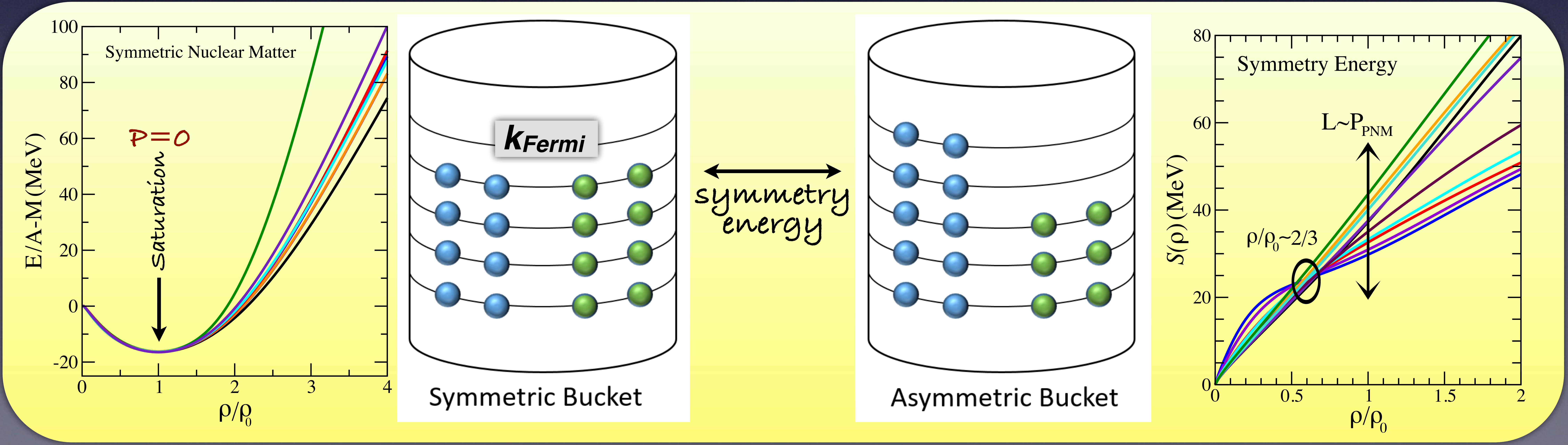


The Equation of State of Neutron-Rich Matter

- Two conserved charges: proton and neutron densities (no weak interactions)
- Equivalently; total nucleon density and asymmetry: ρ and $\alpha=(N-Z)/A$
- Expand around nuclear equilibrium density: $x=(\rho-\rho_0)/3\rho_0$; $\rho_0 \simeq 0.15$ fm-3

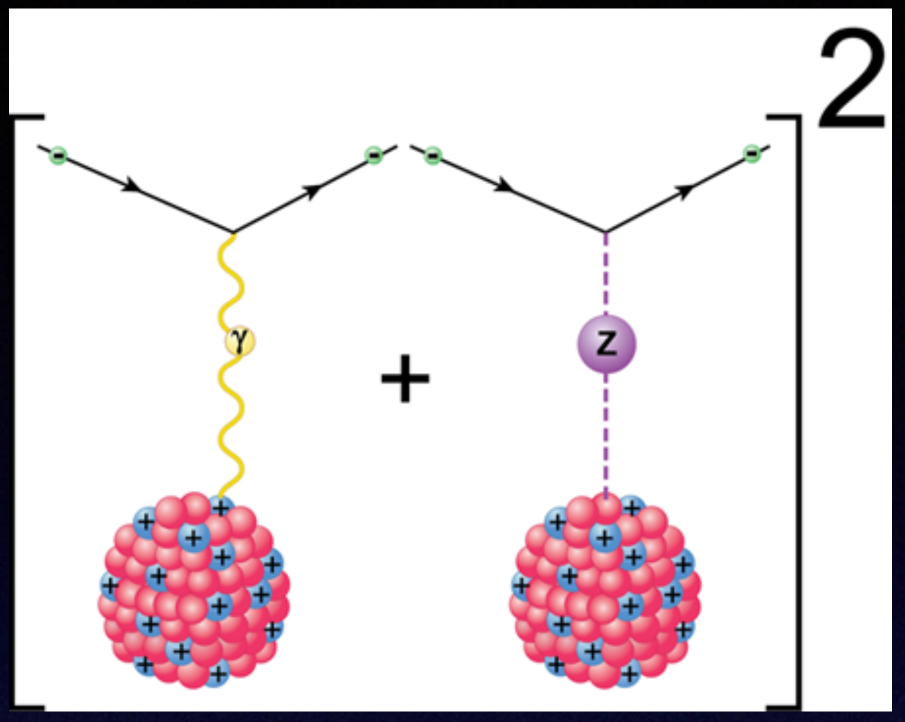
$$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym}x^2\right)\alpha^2$$

- Density dependence of symmetry energy poorly constrained!!
  "L" symmetry slope ~ pressure of pure neutron matter at saturation



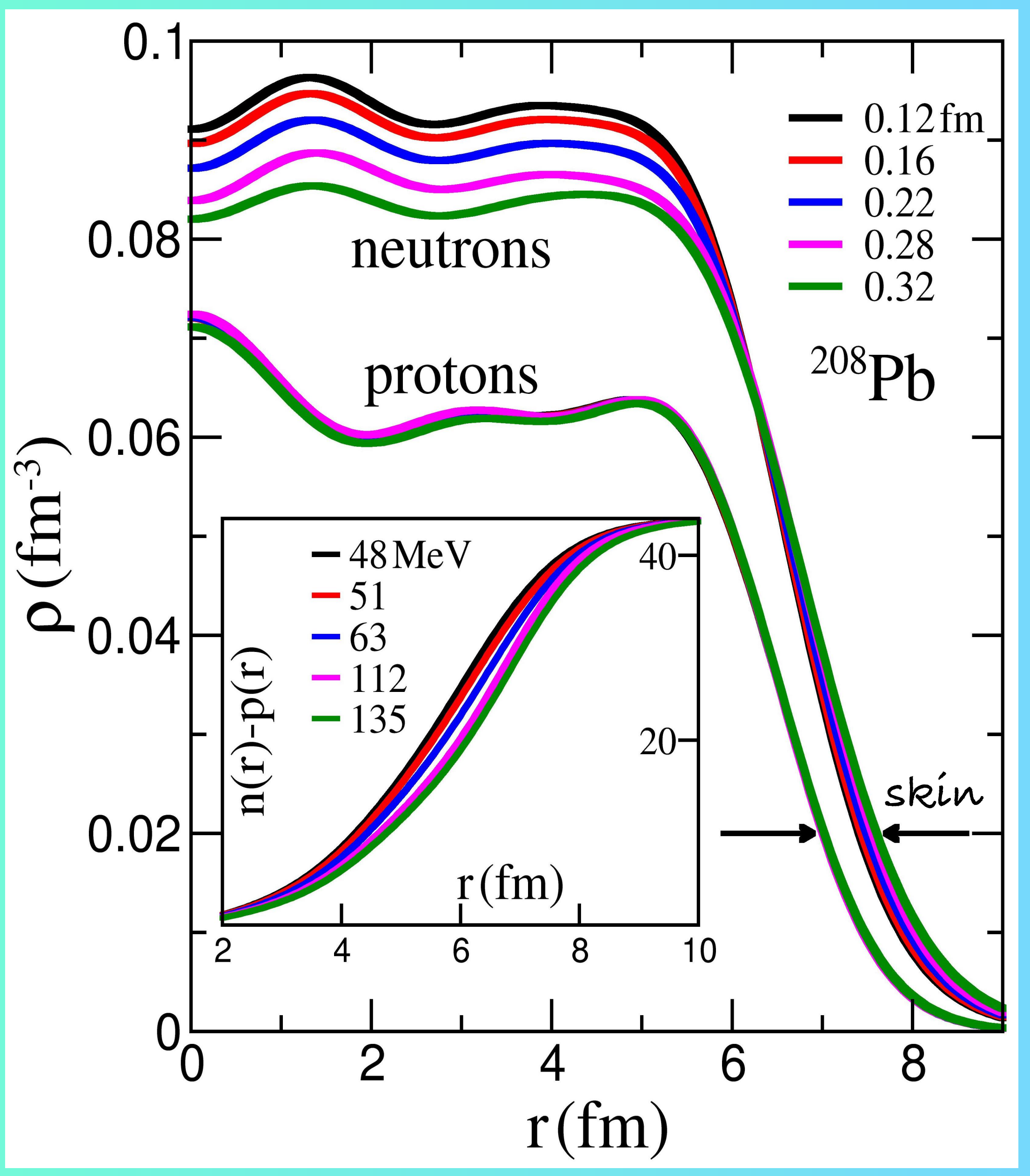
Parity Violating e-Scattering at JLAB

Determining the neutron skin R_n-R_p of Pb

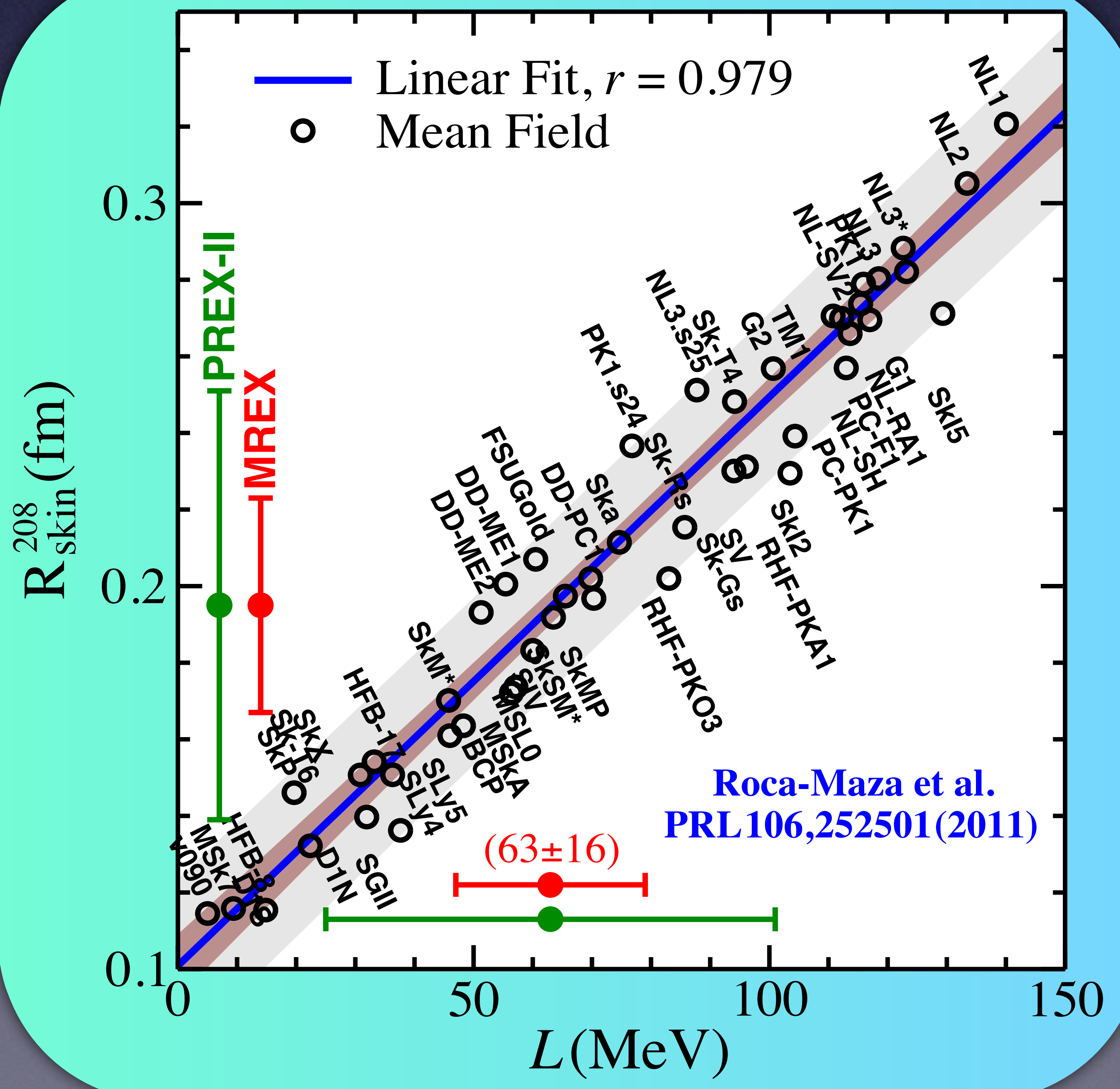


Abrahamyan *et al.*, PRL 108, 112502 (2012)
Horowitz *et al.*, PRC **85**, 032501(R) (2012)

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



- PREX@JLAB: First **Electroweak** evidence in favor of a neutron rich skin in Pb: Rskin=0.33(16) fm
- Neutron skin constraints the poorly known **isovector sector** of the nuclear density functional
- Neutron skin strongly correlated to L: **a fundamental parameter of the EOS of neutron-rich matter**
- PREX-II and CREX to deliver on the original goal of 1% in neutron radius



Analytic Insights on the Information Content of New Observables

Considering the current theoretical knowledge:

- What novel information does new measurement bring in?
- How can new data reduce uncertainties of current theoretical models?

$$\frac{\overline{\tau}_L^2}{\tau_L^2} = 1 - \frac{\varrho^2(L,\mathcal{O}_I)}{1+\sigma_I^2/\tau_I^2} \equiv 1 - \alpha_I^2 \varrho^2(L,\mathcal{O}_I).$$

$$\frac{\overline{\tau}_L^2}{\tau_L^2} = 1 - \left[\frac{\alpha_I^2\varrho^2(L,\mathcal{O}_I) + \alpha_{II}^2\varrho^2(L,\mathcal{O}_{II}) - 2\alpha_I^2\alpha_{II}^2\varrho(L,\mathcal{O}_I)\varrho(\mathcal{O}_I,\mathcal{O}_{II})\varrho(\mathcal{O}_{II},L)}{1-\alpha_I^2\alpha_{II}^2\varrho^2(\mathcal{O}_I,\mathcal{O}_{II})}\right]$$

A slightly more precise MREX/^{208}Pb seems worthwhile

Analytic insights on the information content of new observables

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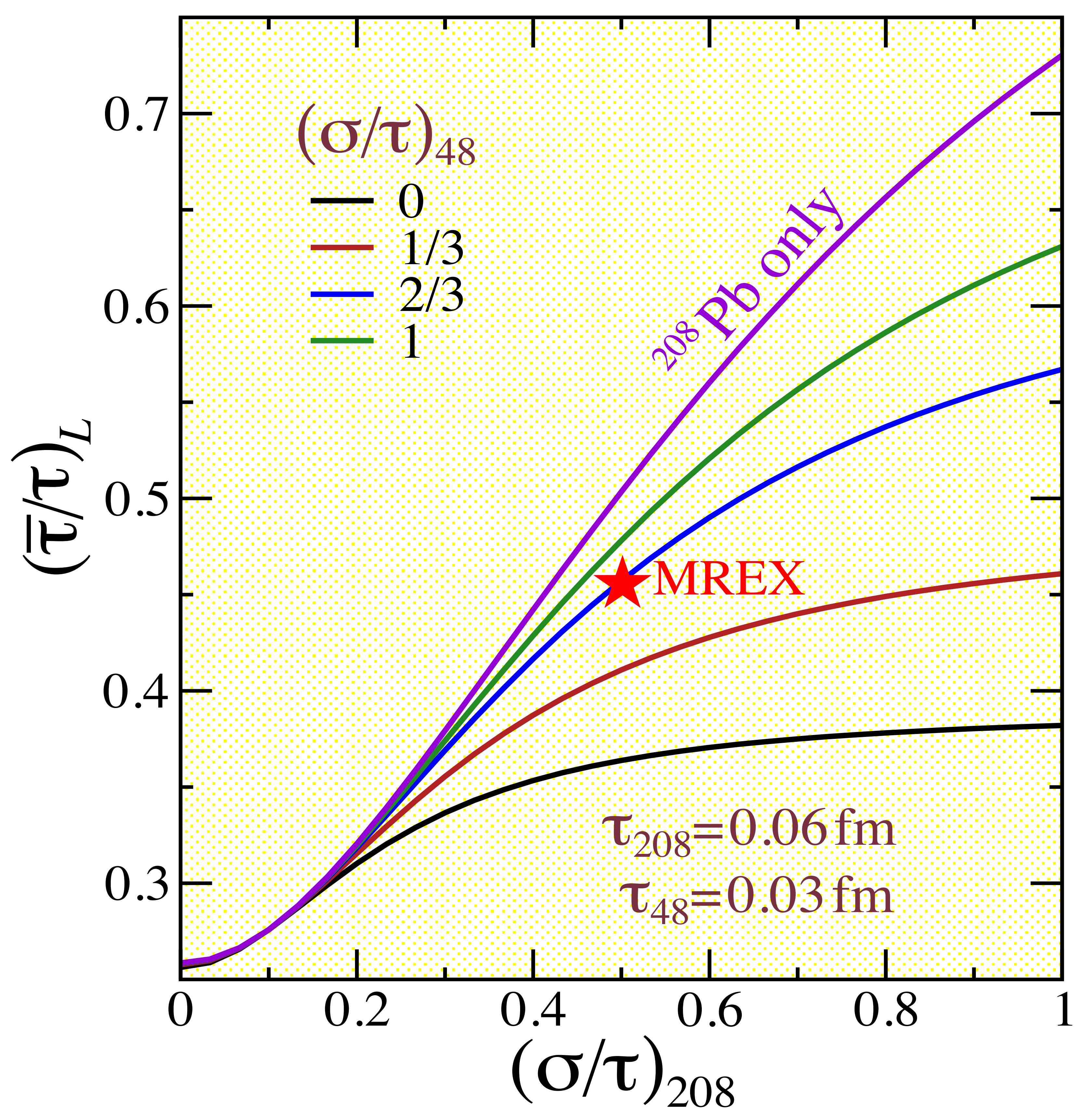
Department of Physics, Florida State University, Tallahassee, FL 32306, USA

(Dated: June 16, 2020)

2006.08405 [nucl-th]

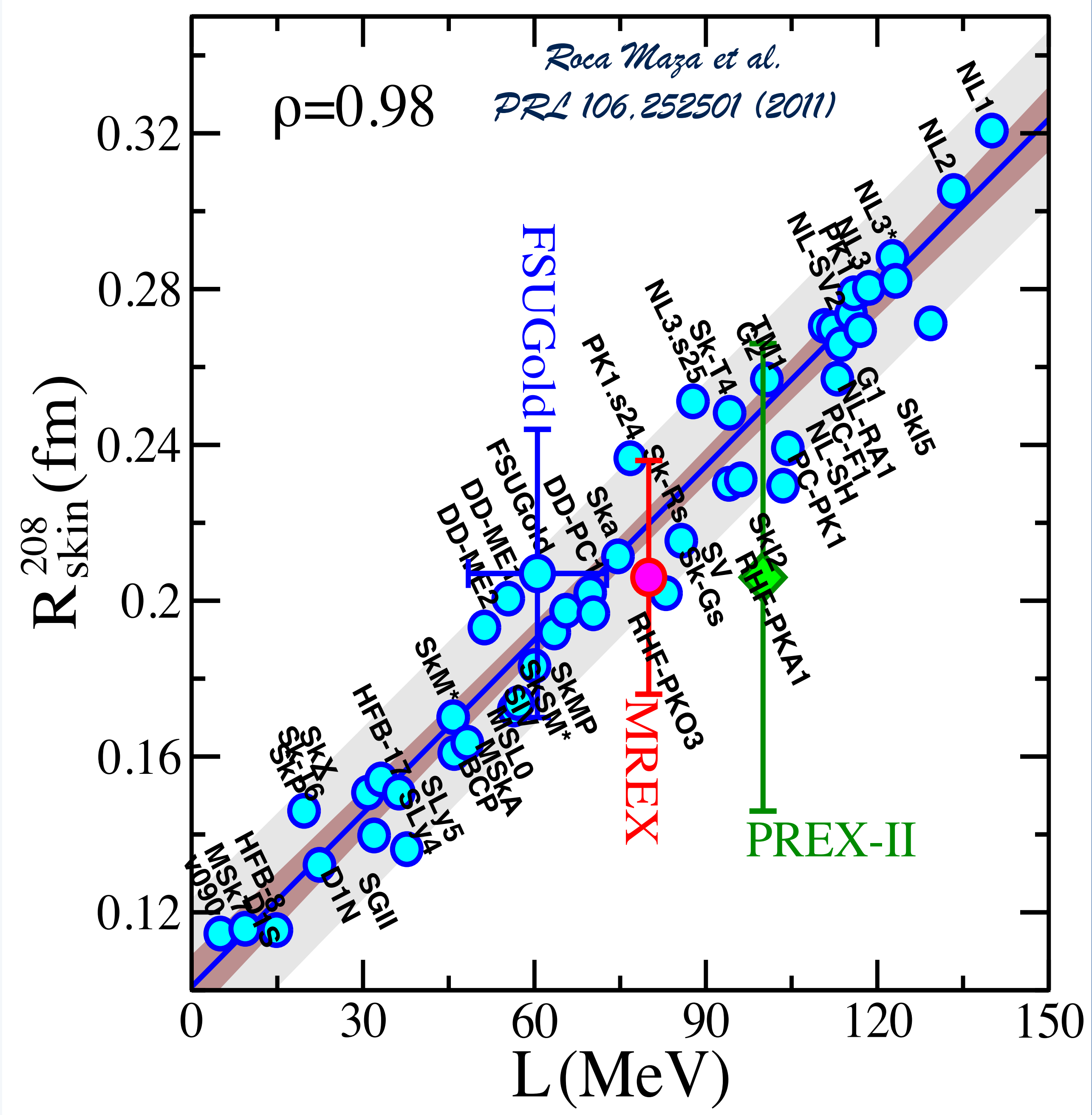


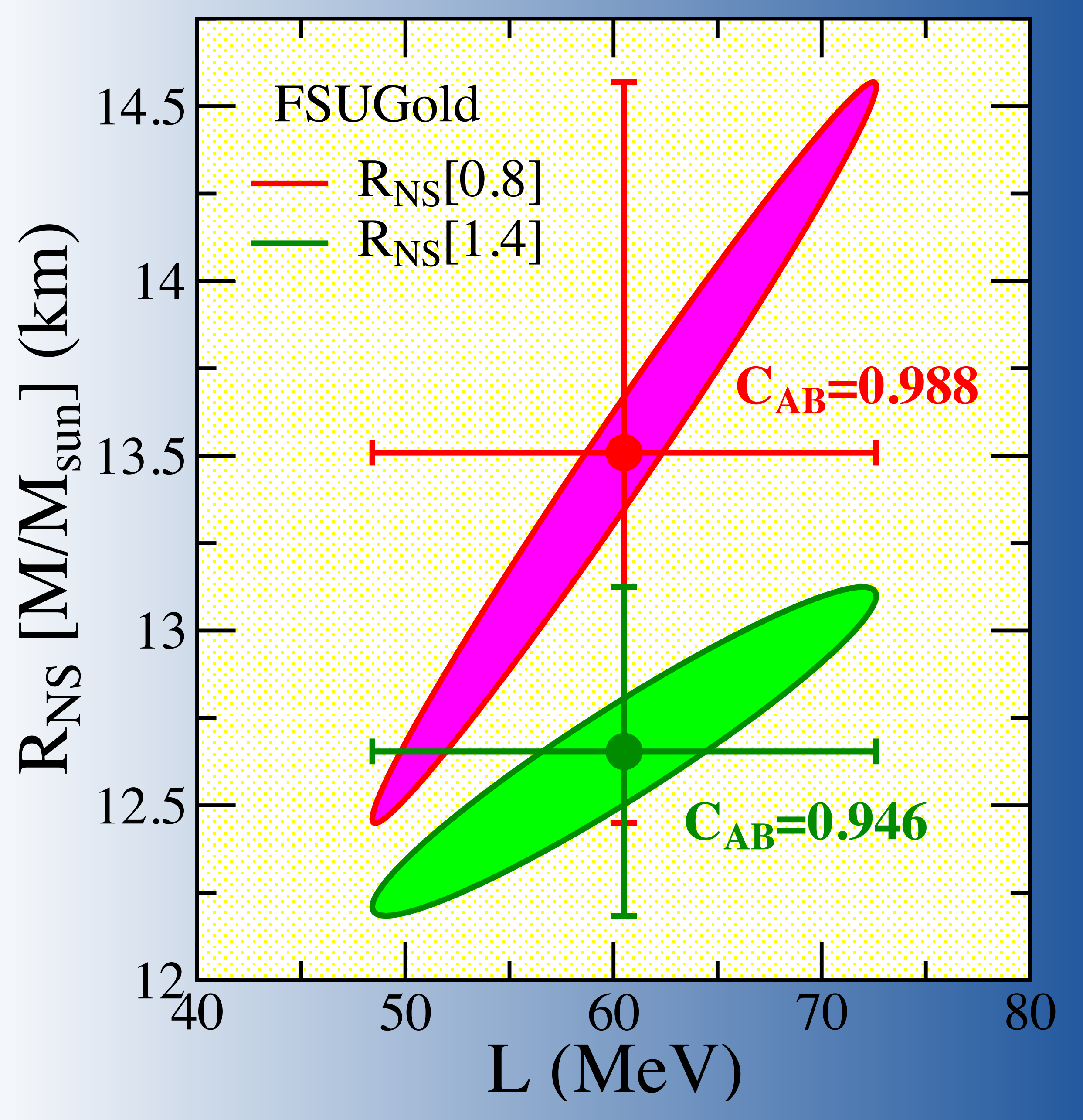
Neutron Rich Matter on Earth:

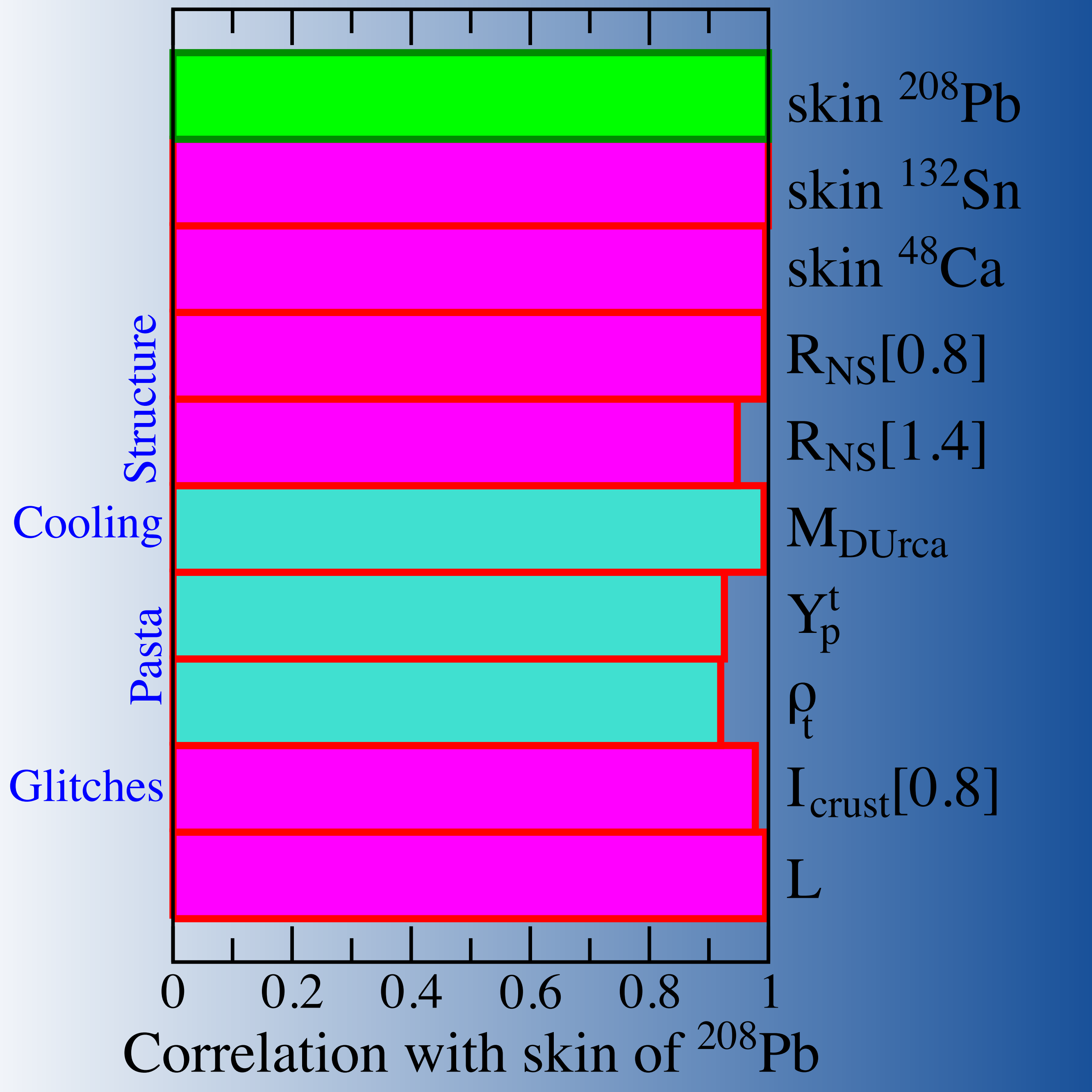
The Quest for “L” at Terrestrial Laboratories

- Although a fundamental parameter of the EOS, L is ***NOT*** a physical observable
- Strong correlation emerges between the neutron skin thickness of ^{208}Pb and L
- L controls both the neutron skin of ^{208}Pb and the radius of a neutron star
- … As well as many other stellar properties sensitive to the symmetry energy

18 orders of magnitude!!







Electroweak Probes of Ground State Densities
A fundamental connection (albeit a bit weaker) to the Structure of Neutron Stars

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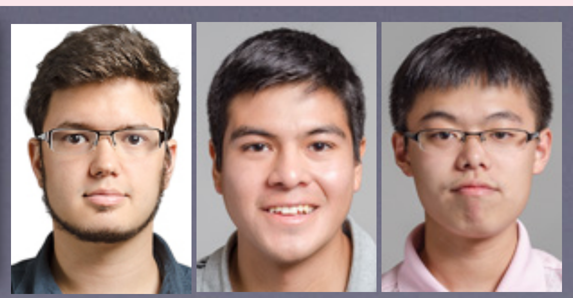
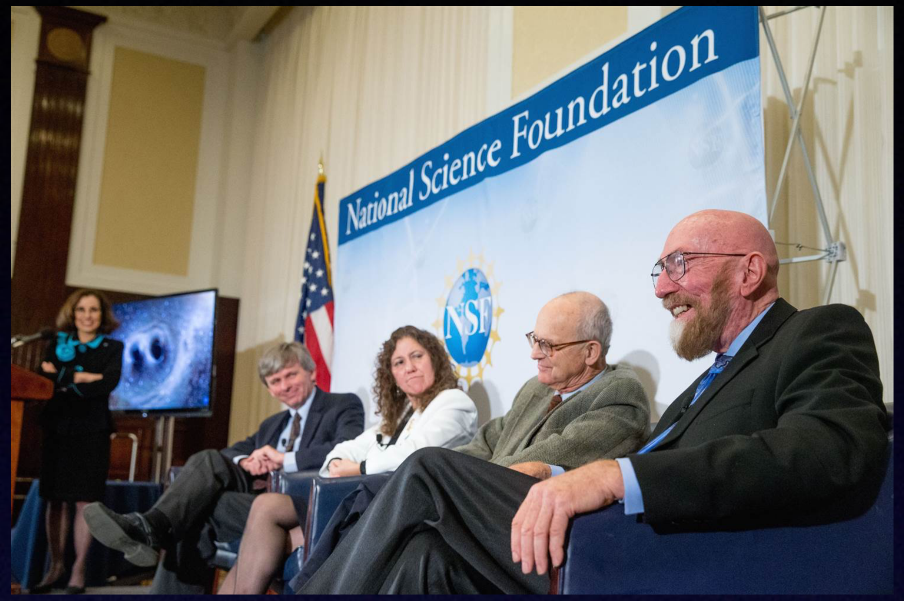
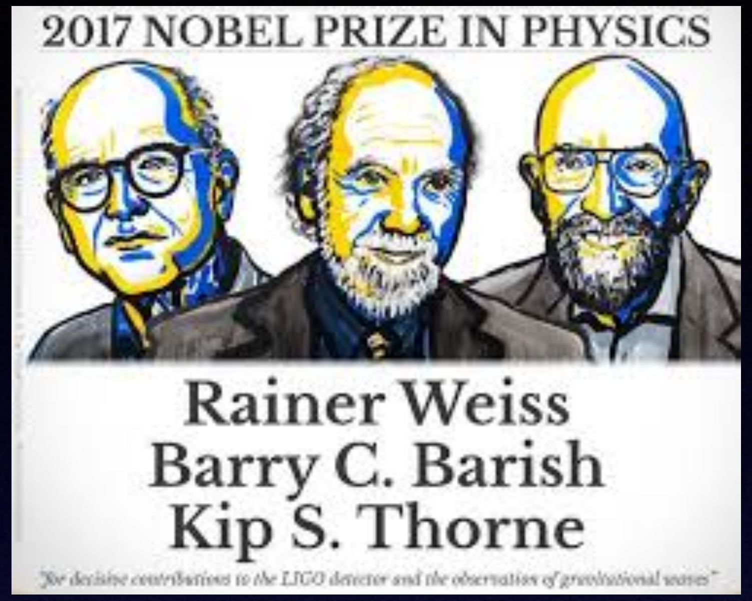


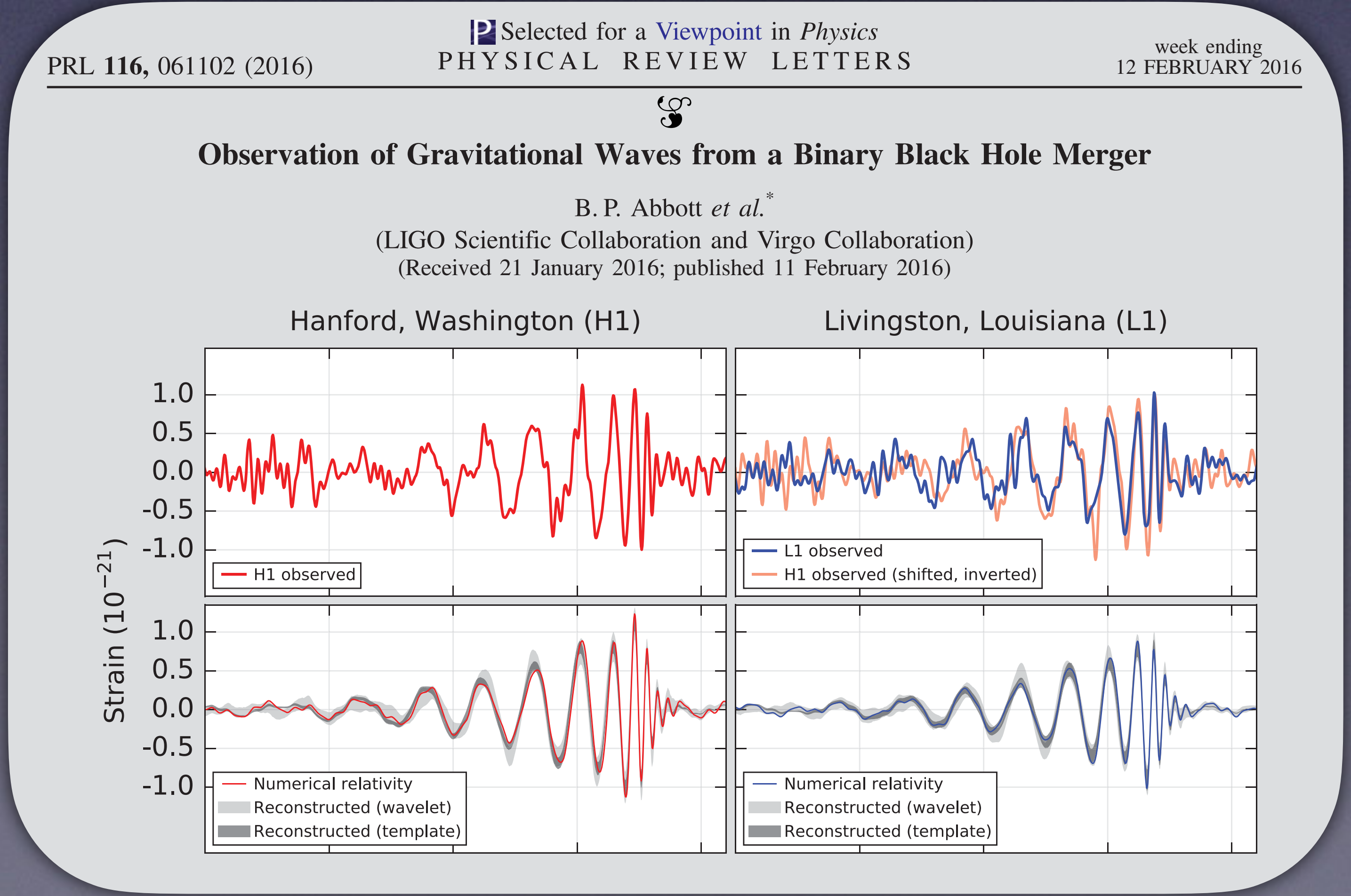
"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016

GW170817





- 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!


Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

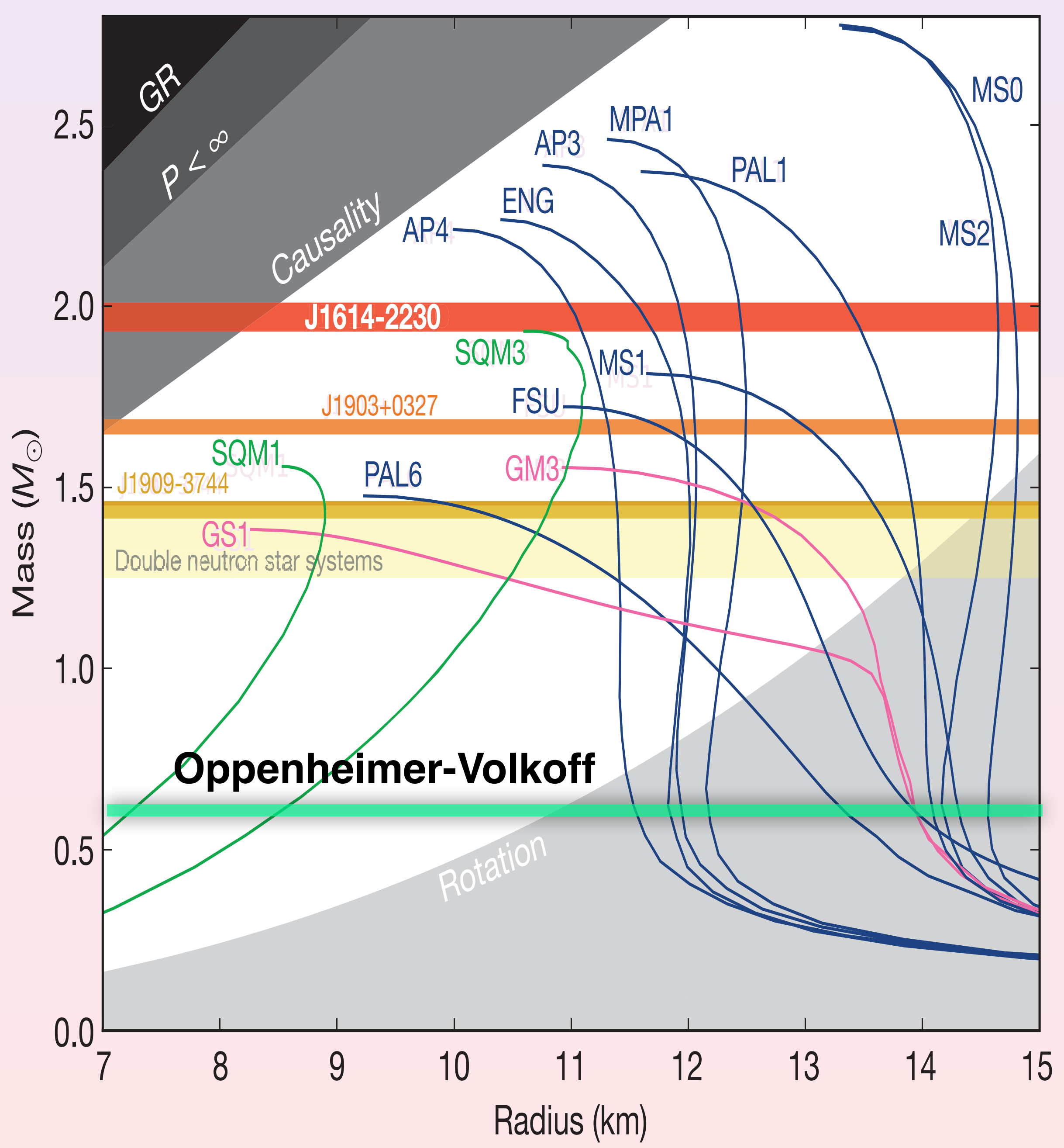
B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

Neutron Stars: Unique Cosmic Laboratories

- Neutron stars are the remnants of massive stellar explosions
  - Bound by gravity — NOT by the strong force
  - Satisfy the TOV equations ($v_{esc}/c \sim 1/2$)
- 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

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

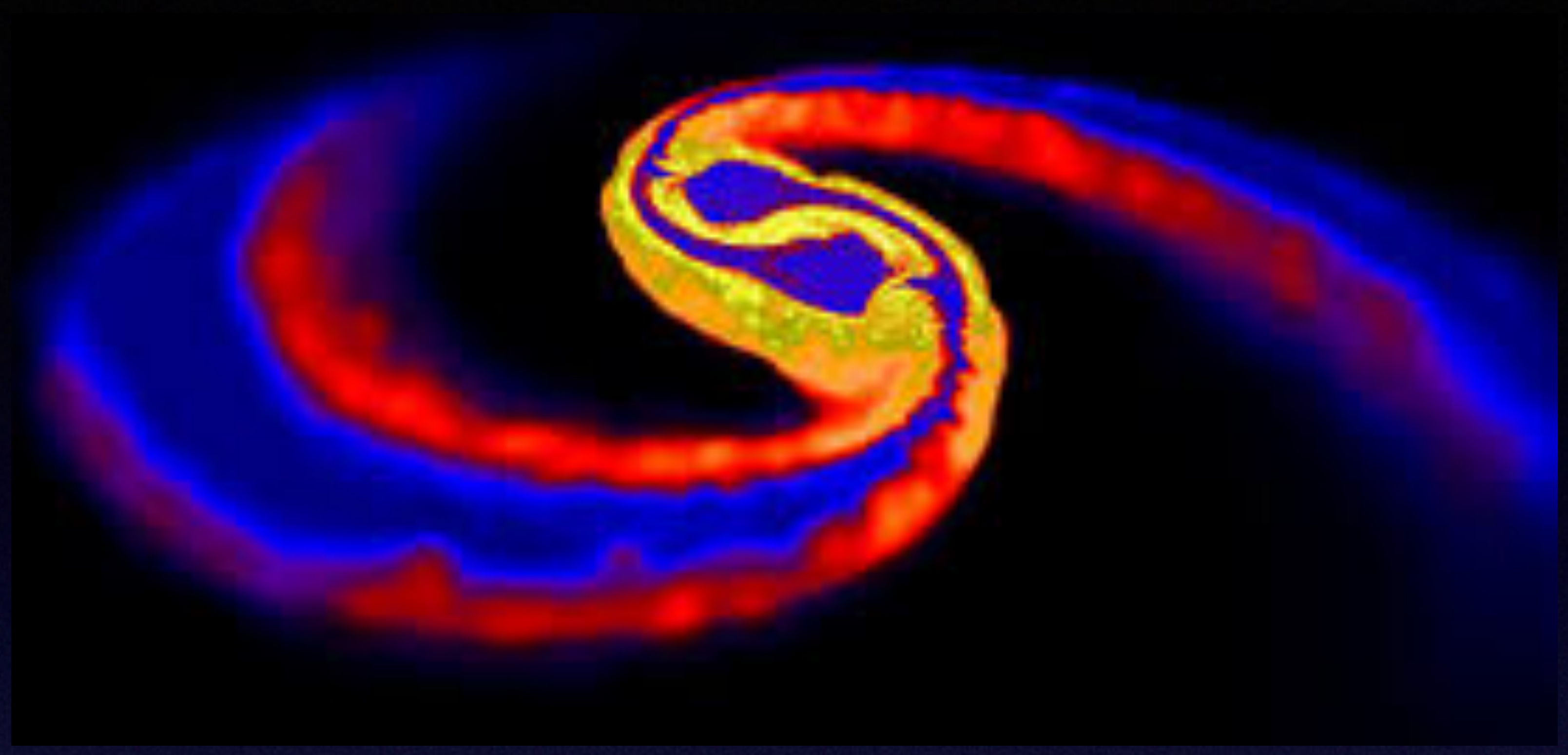
Tidal Polarizability and Neutron-Star Radii

Electric Polarizability:

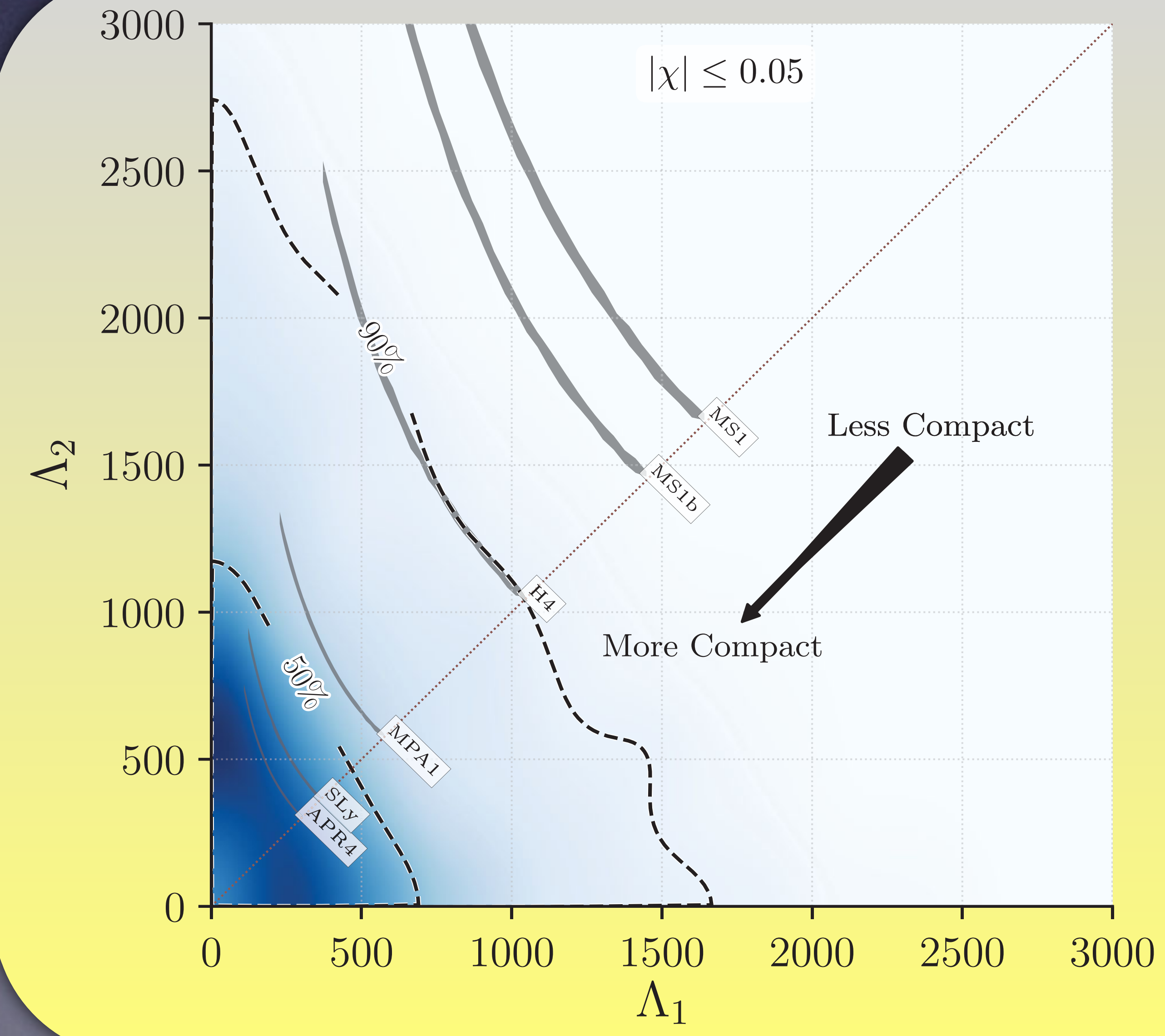
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$

Tidal Polarizability:

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



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

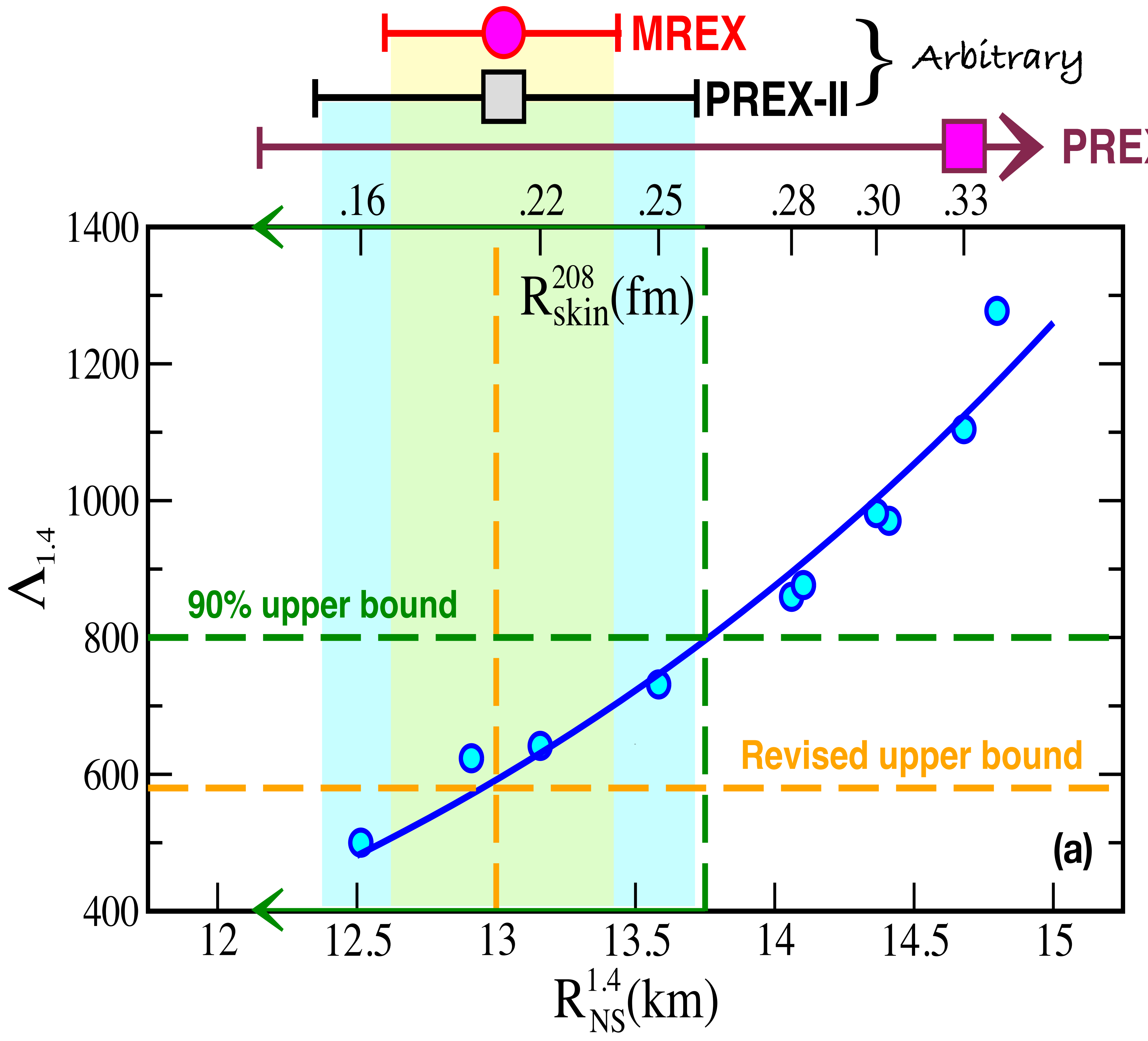


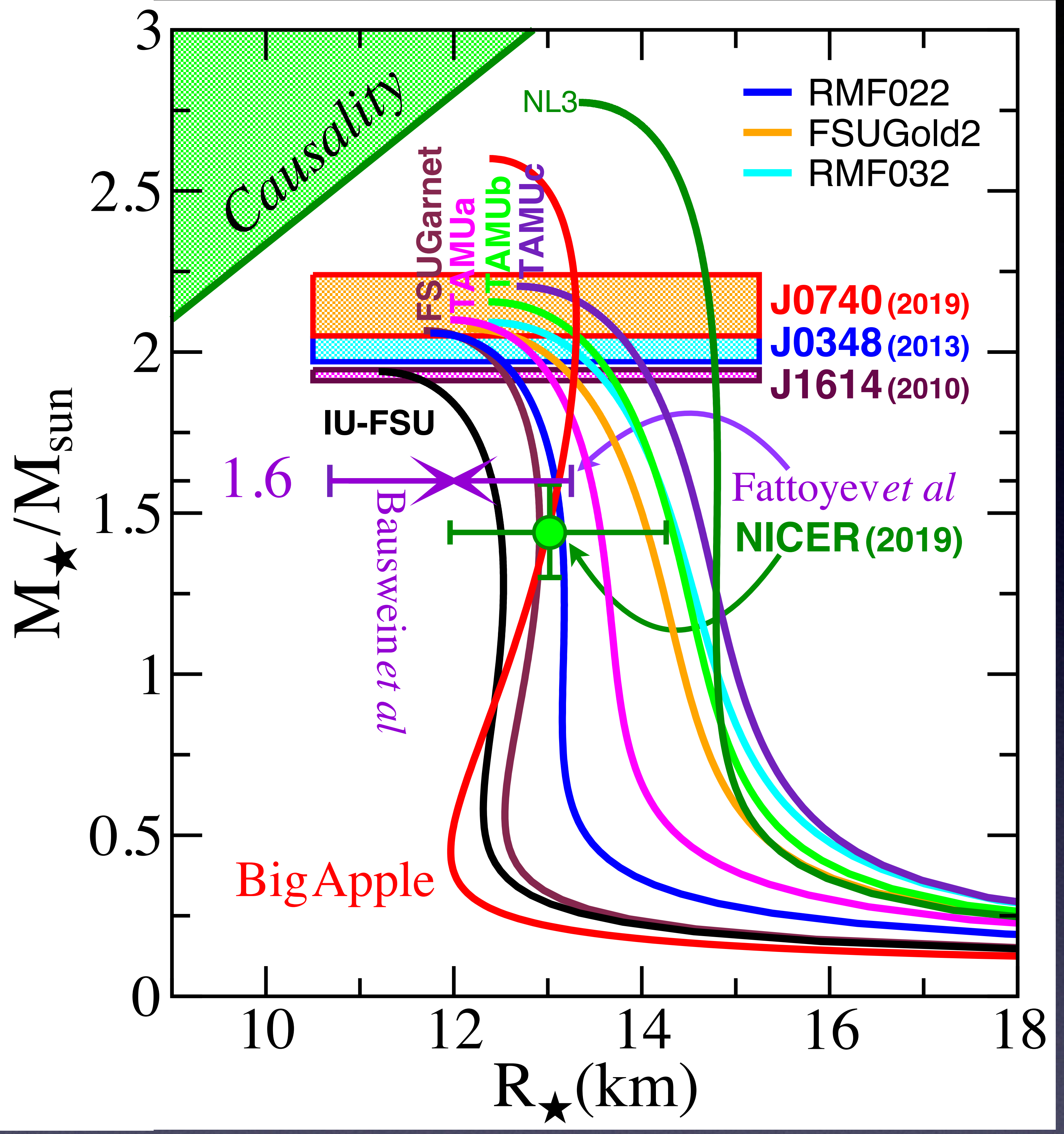
GW170817 rules out very large neutron star radii!

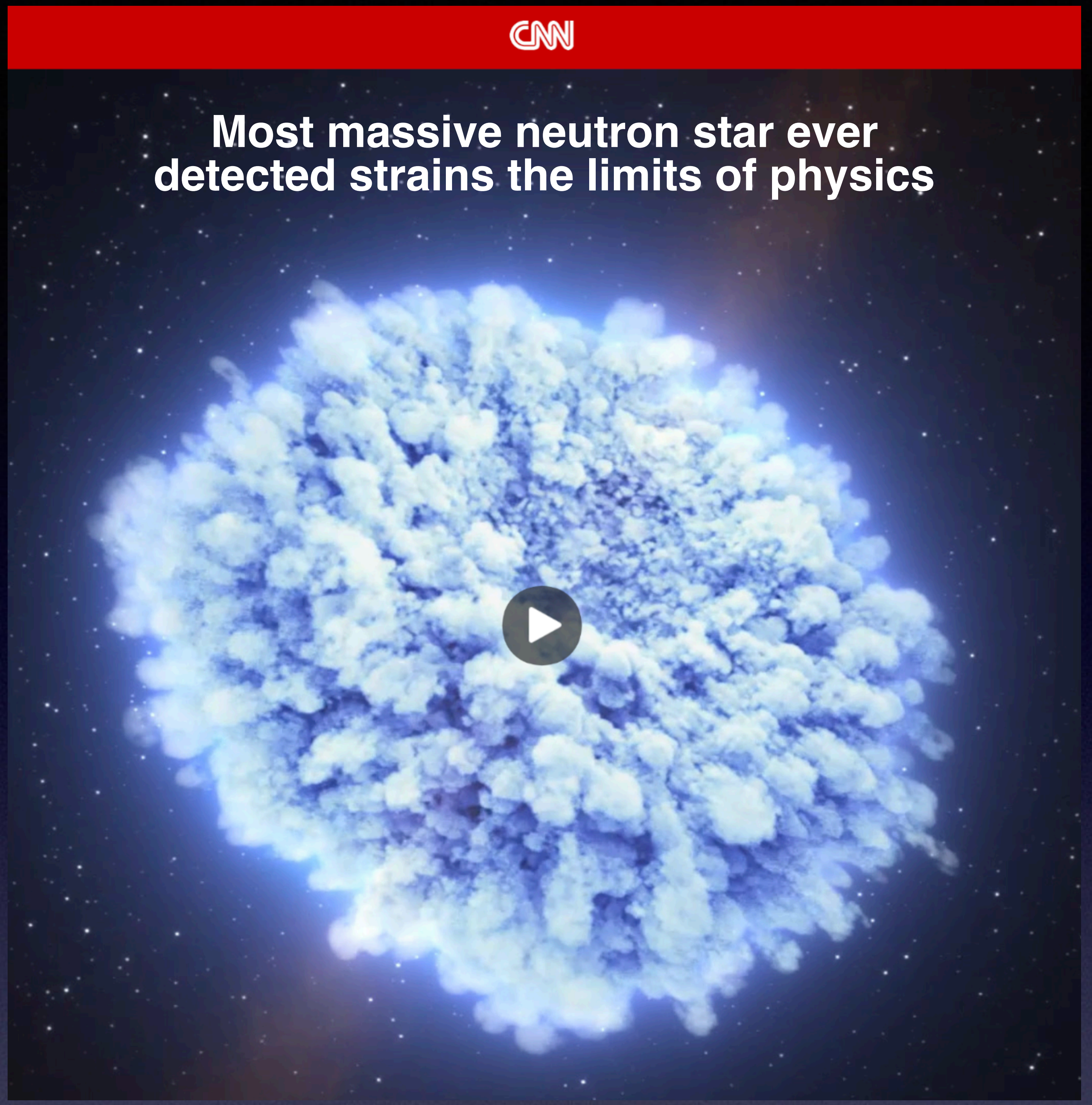
Neutron Stars must be compact

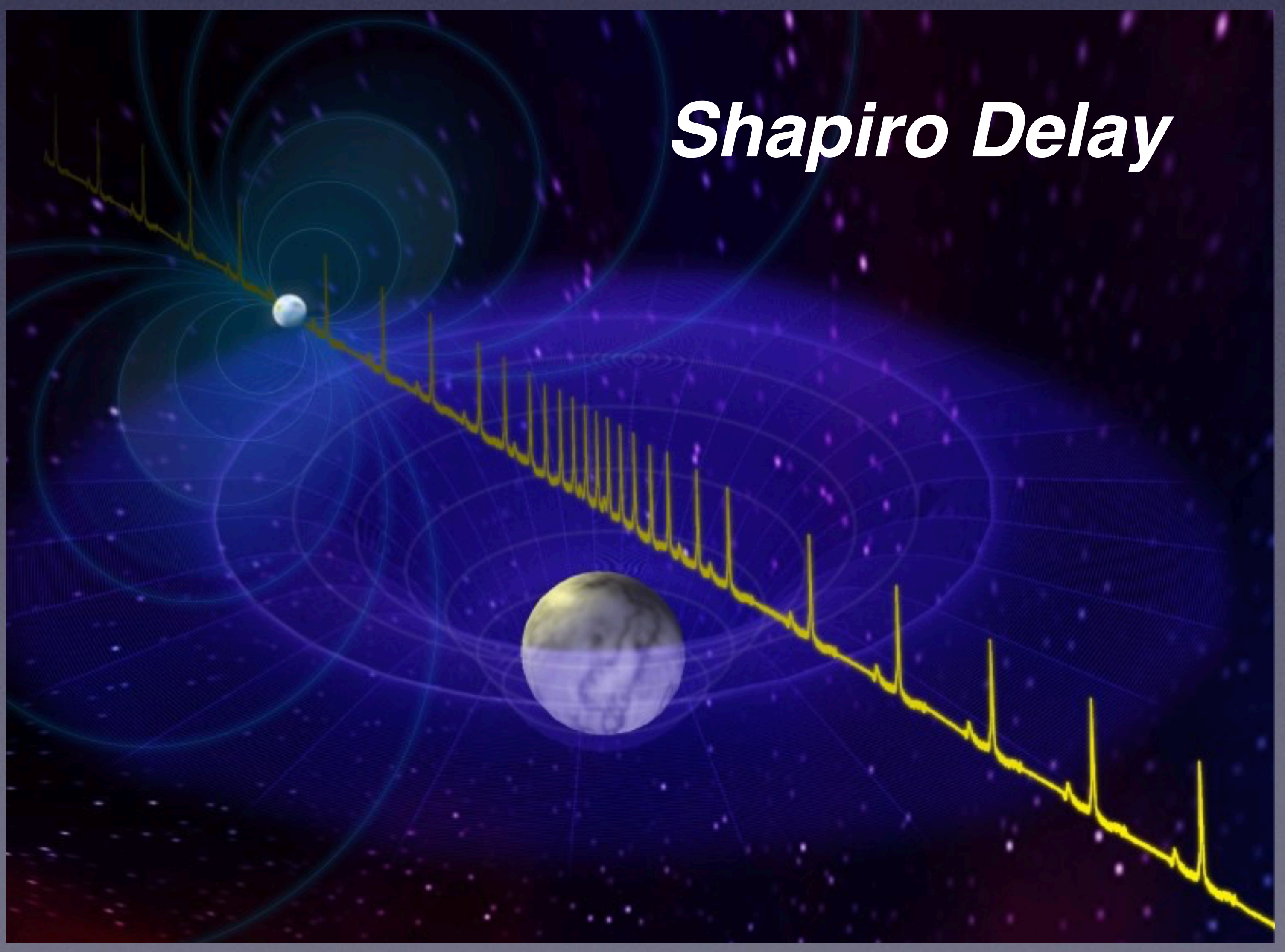
The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation

How can we make massive stars with small radii?







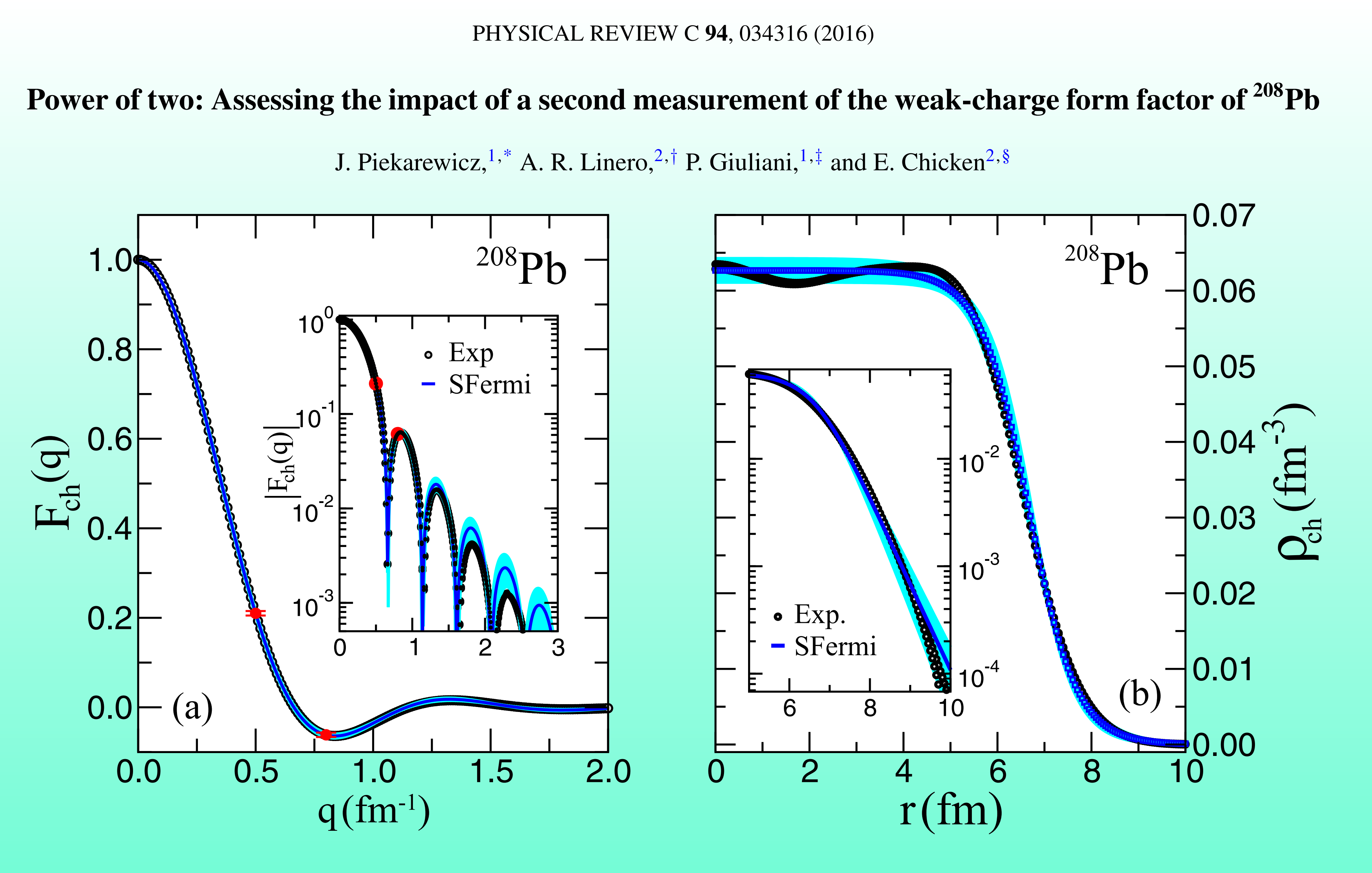


Tantalizing Possibility

- *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* $\gtrsim 4\rho_0$

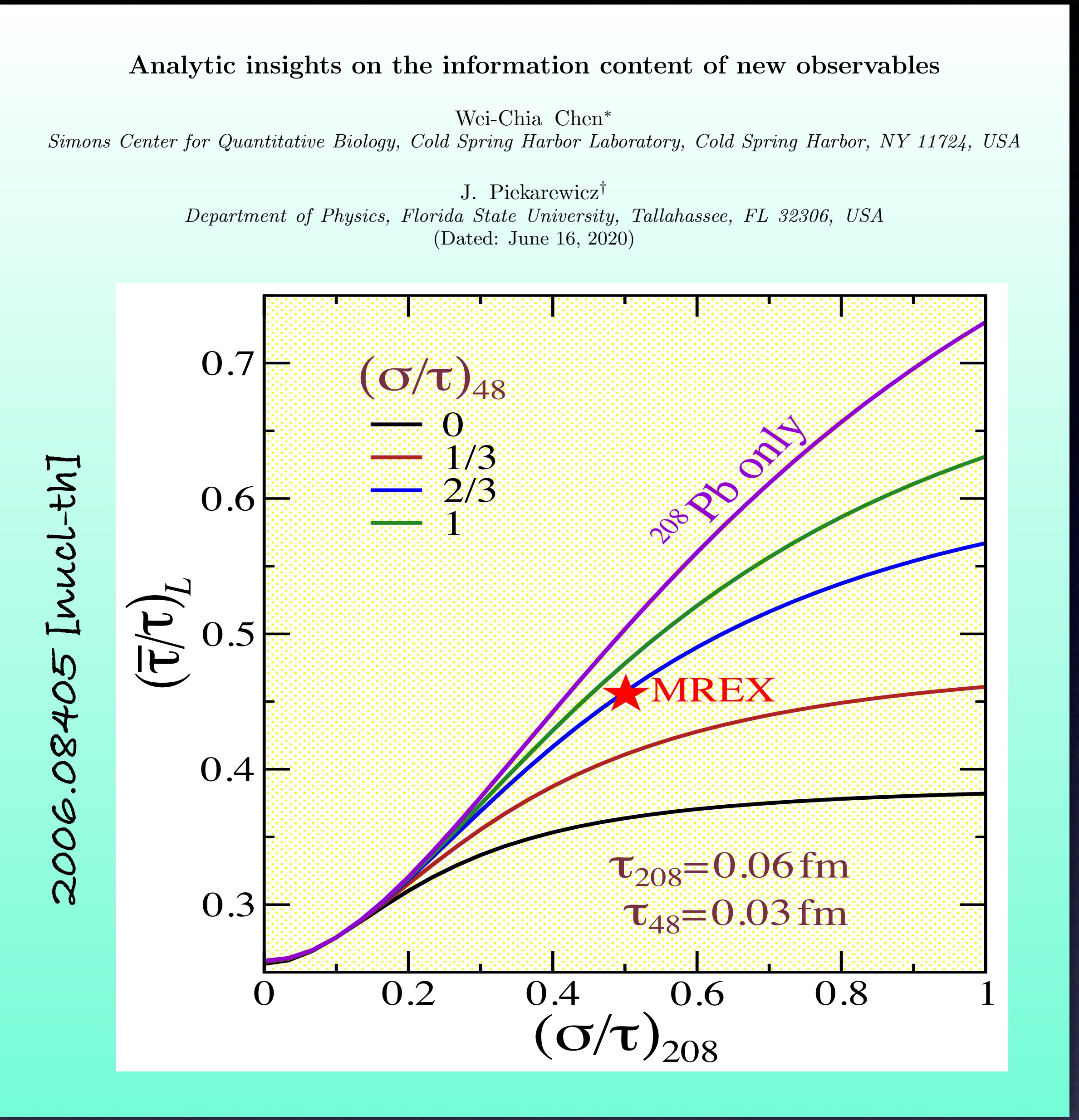
Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)

General Discussion


PHYSICAL REVIEW C **94**, 034316 (2016)

Power of two: Assessing the impact of a second measurement of the weak-charge form factor of ^{208}Pb

J. Piekarewicz,[1,*] A. R. Linero,[2,†] P. Giuliani,[1,‡] and E. Chicken[2,§]


Analytic insights on the information content of new observables

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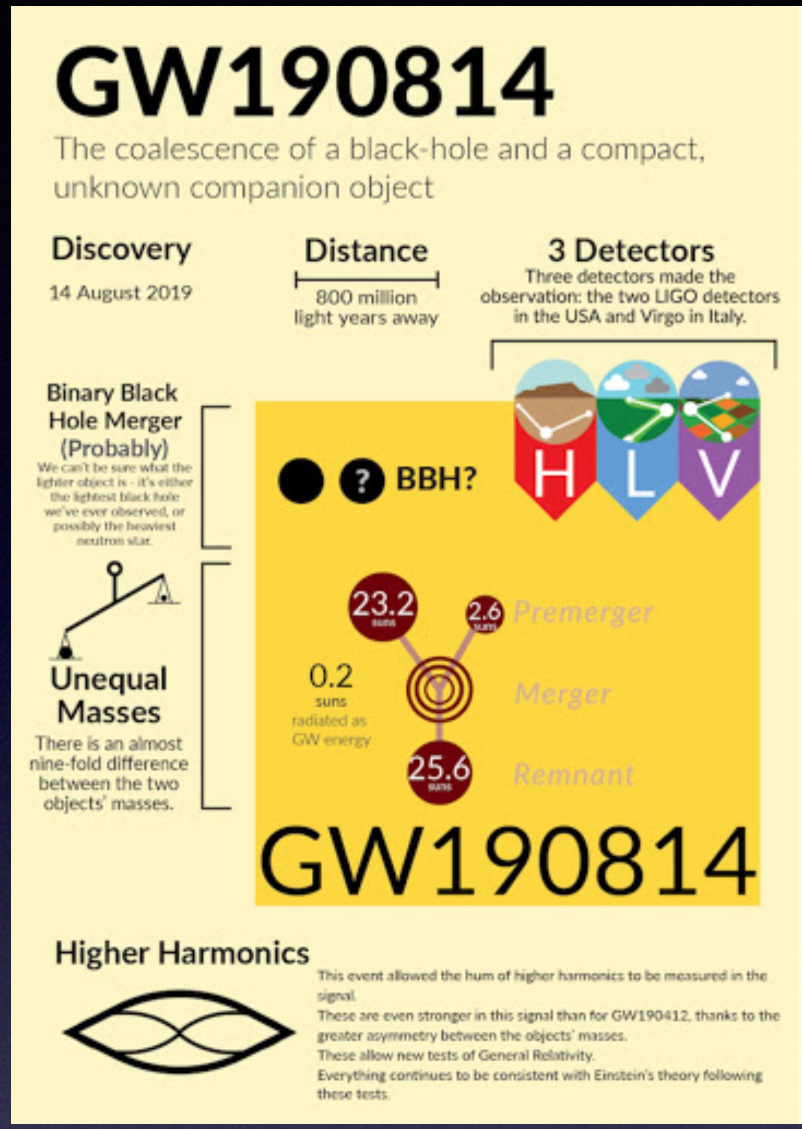
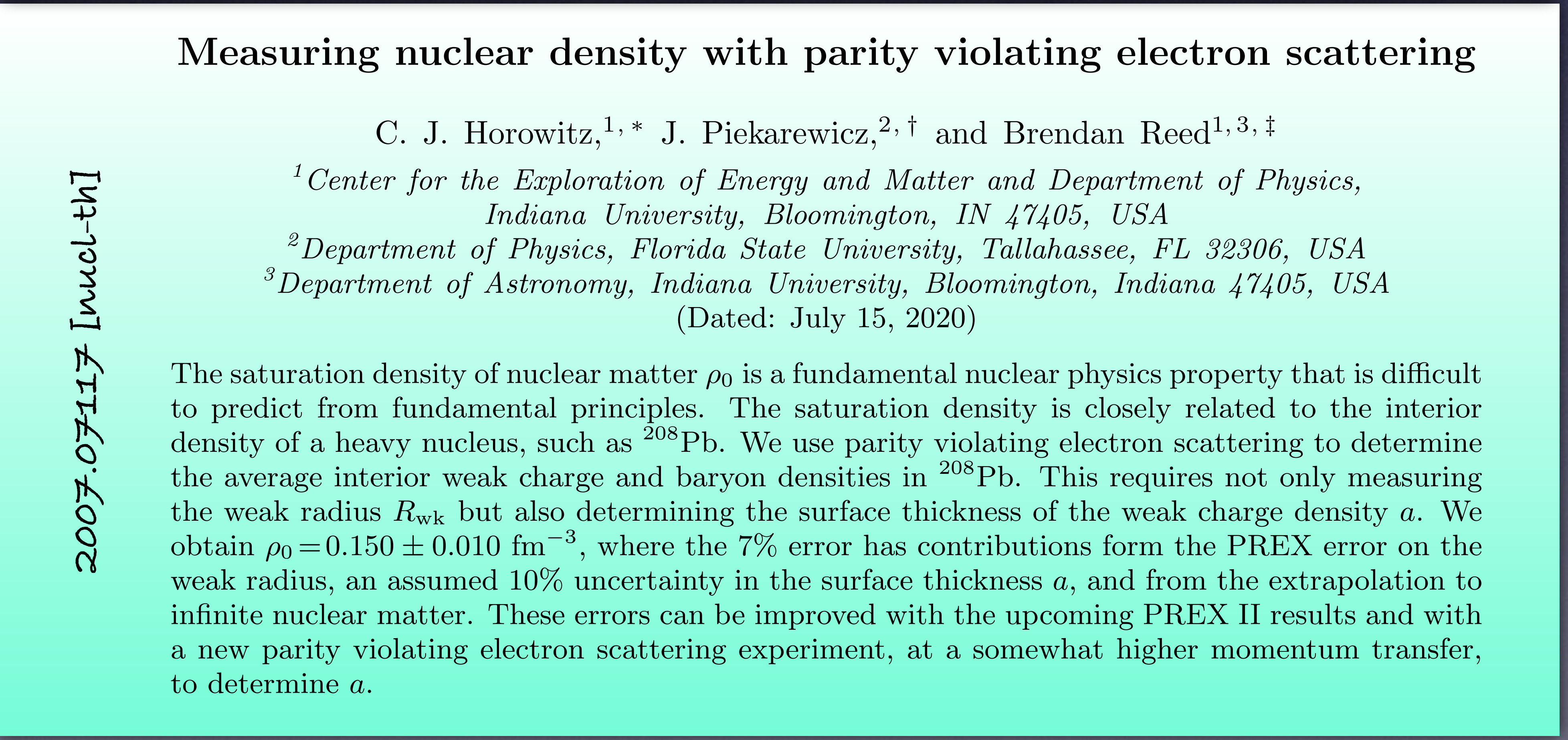
(Dated: June 16, 2020)




Measuring nuclear density with parity violating electron scattering

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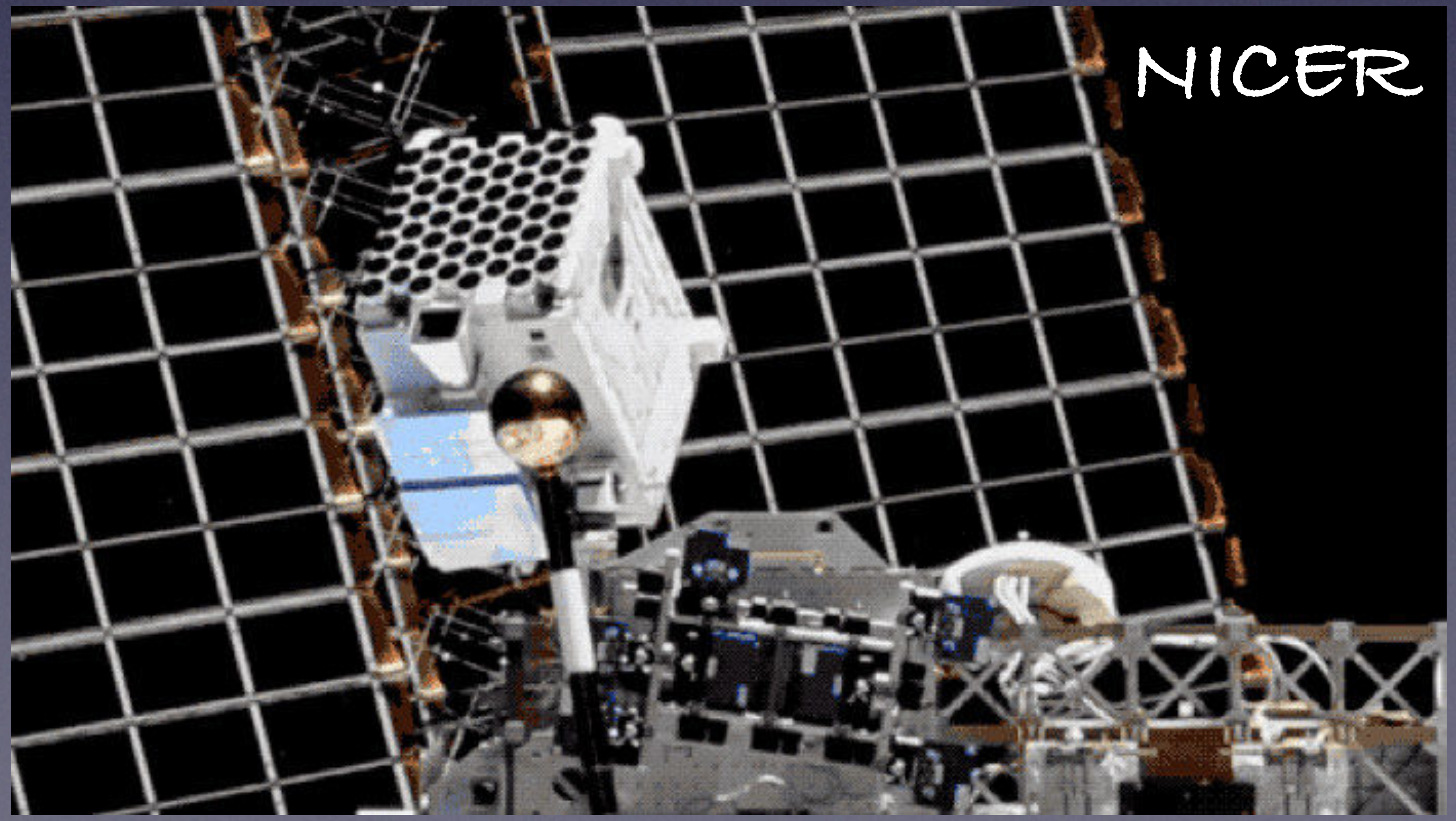
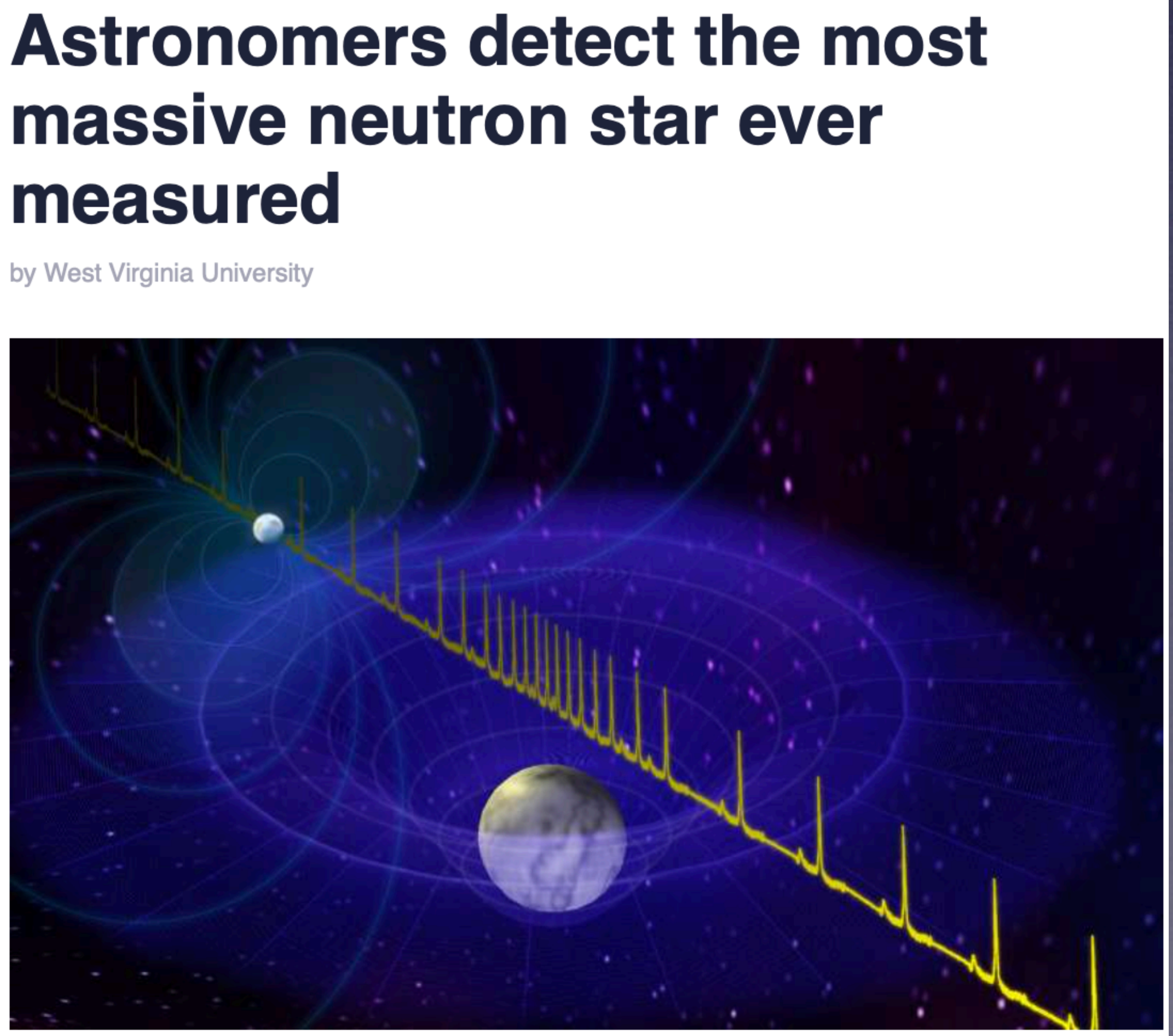
(Dated: July 15, 2020)

2007.07117 [nucl-th]

The saturation density of nuclear matter ρ_0 is a fundamental nuclear physics property that is difficult to predict from fundamental principles. The saturation density is closely related to the interior density of a heavy nucleus, such as ^{208}Pb. We use parity violating electron scattering to determine the average interior weak charge and baryon densities in ^{208}Pb. This requires not only measuring the weak radius $R_{\rm wk}$ but also determining the surface thickness of the weak charge density a. We obtain $\rho_0 = 0.150 \pm 0.010$ fm^{-3}, where the 7% error has contributions form the PREX error on the weak radius, an assumed 10% uncertainty in the surface thickness a, and from the extrapolation to infinite nuclear matter. These errors can be improved with the upcoming PREX II results and with a new parity violating electron scattering experiment, at a somewhat higher momentum transfer, to determine a.




Astronomers detect the most massive neutron star ever measured

by West Virginia University