

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



## Parity Violation and Related Topics (MITP Virtual Workshop) July 2020 J. Piekarewicz (FSU)



### The 208 $P_b$ Radius Experiment

and Neutron Rich Matter in the Heavens and on Earth

August 17-19 2008

Jefferson Lab  
Newport News, Virginia

PREX IS A FASCINATING EXPERIMENT THAT USES PARITY VIOLATION TO ACCURATELY DETERMINE THE NEUTRON RADIUS IN  $^{208}\text{Pb}$ . THIS HAS BROAD APPLICATIONS TO ASTROPHYSICS, NUCLEAR STRUCTURE, ATOMIC PARITY NON-CONSERVATION AND TESTS OF THE STANDARD MODEL. THE CONFERENCE WILL BEGIN WITH INTRODUCTORY LECTURES AND WE ENCOURAGE NEW COMERS TO ATTEND.

FOR MORE INFORMATION CONTACT [horowitz@indiana.edu](mailto:horowitz@indiana.edu)

#### TOPICS

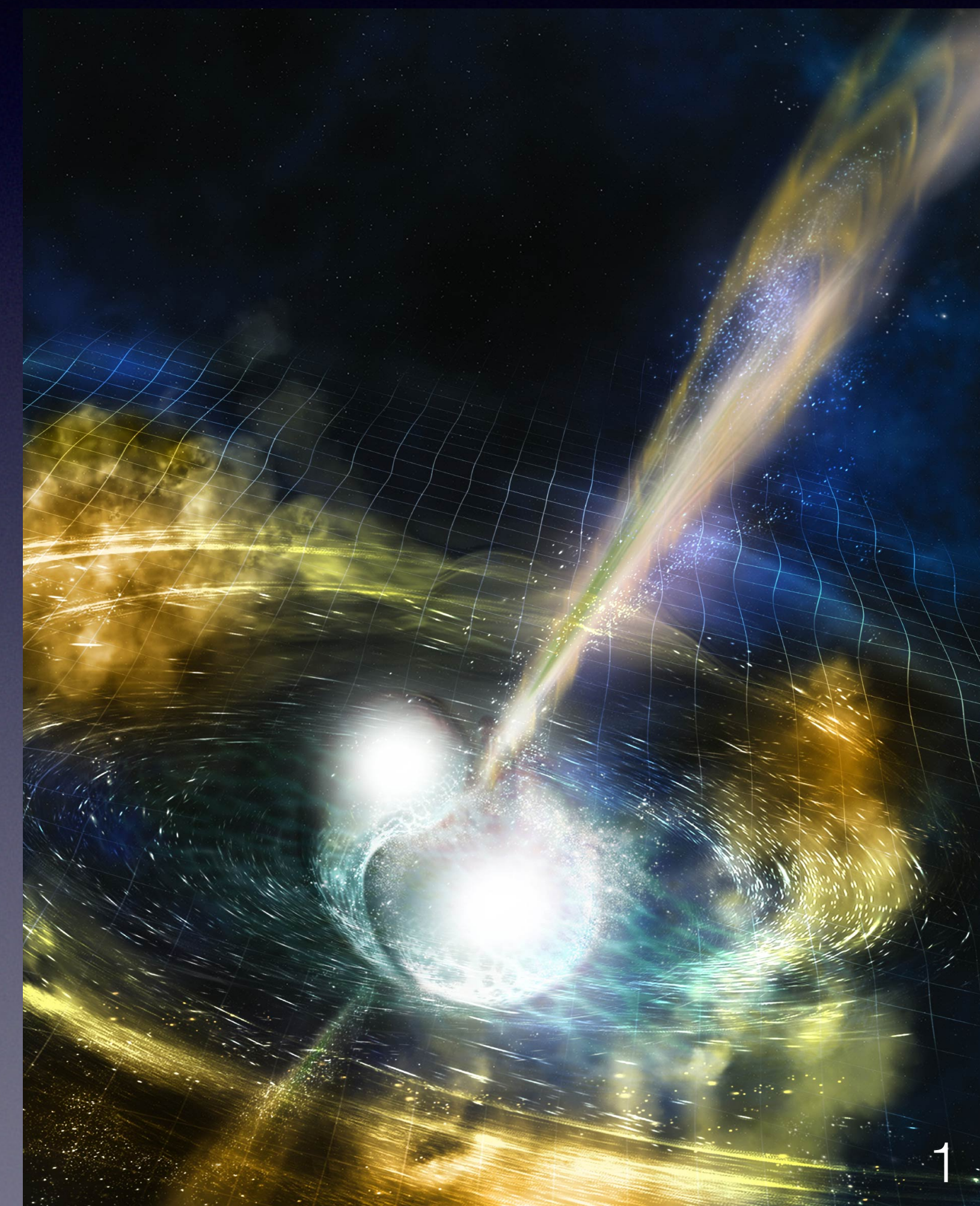
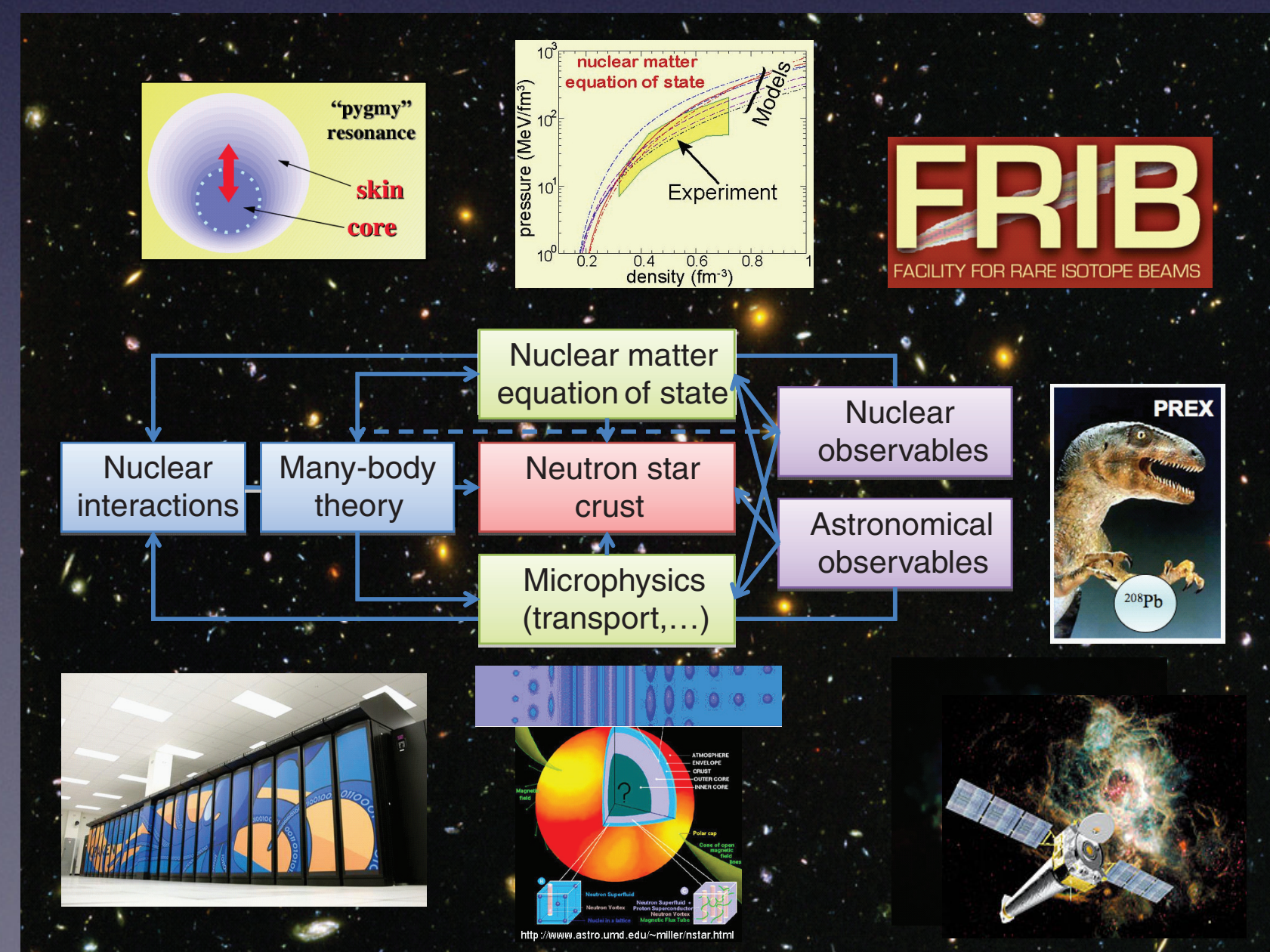
- PARITY VIOLATION
- THEORETICAL DESCRIPTIONS OF NEUTRON-RICH NUCLEI AND BULK MATTER
- LABORATORY MEASUREMENTS OF NEUTRON-RICH NUCLEI AND BULK MATTER
- NEUTRON-RICH MATTER IN COMPACT STARS / ASTROPHYSICS

WEBSITE: <http://conferences.jlab.org/PREX>

#### ORGANIZING COMMITTEE

- CHUCK HOROWITZ (INDIANA)
- KEES DE JAGER (JLAB)
- JIM LATTIMER (STONY BROOK)
- WITOLD NAZAREWICZ (UTK, ORNL)
- JORGE PIEKAREWICZ (FSU)

SPONSORS: JEFFERSON LAB, JSA

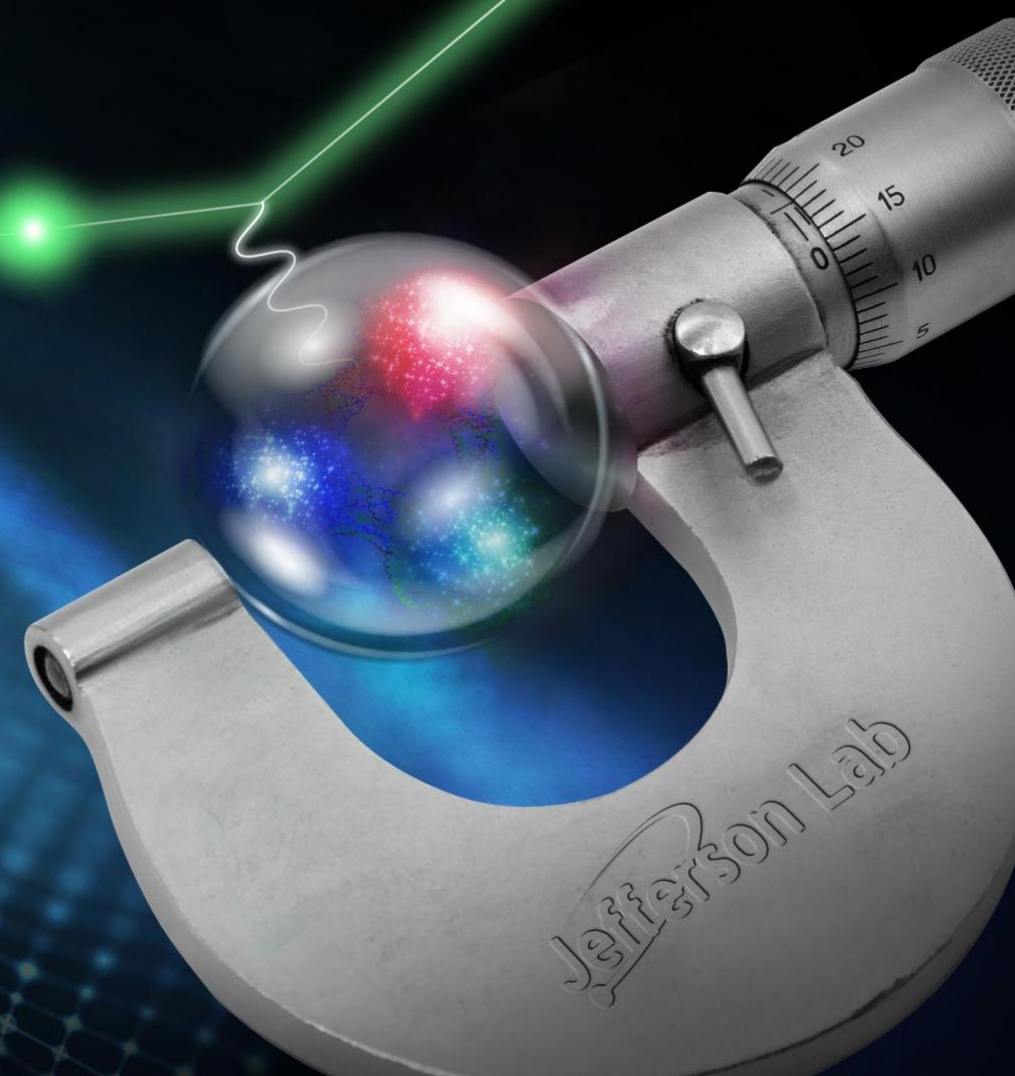




# Mass-Radius Relation: From Mesons, to Baryons, to Nuclei, to Neutron Stars!

- 📌 **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, ...?**

$r=0.84$  fm

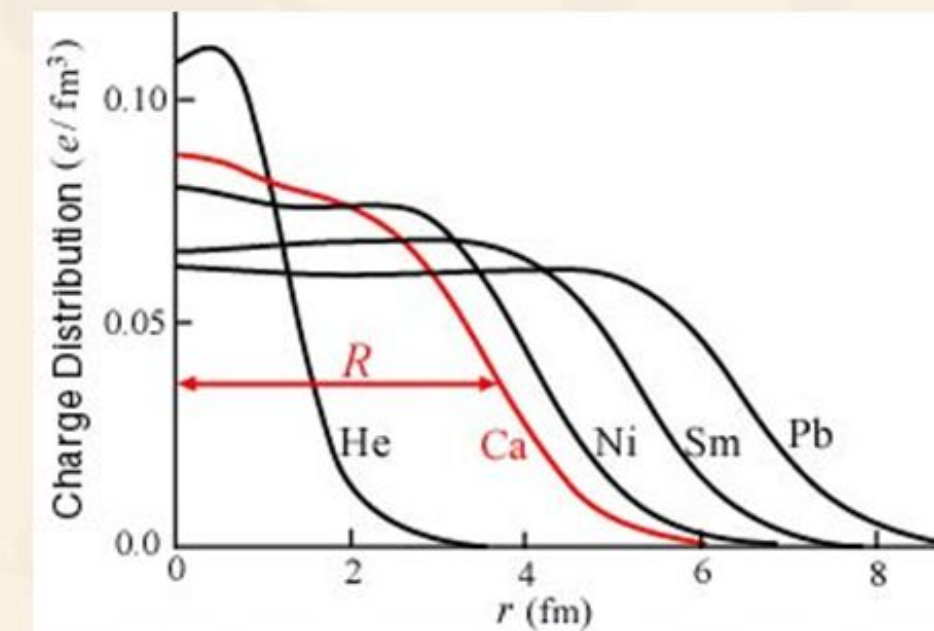


2 Nuclear charge distribution  $\rho_c =$  total charge divided by its volume.

$$\rho_c = \frac{Q}{V} \approx \frac{3Ze}{4\pi r_0^3 A} \quad (4)$$

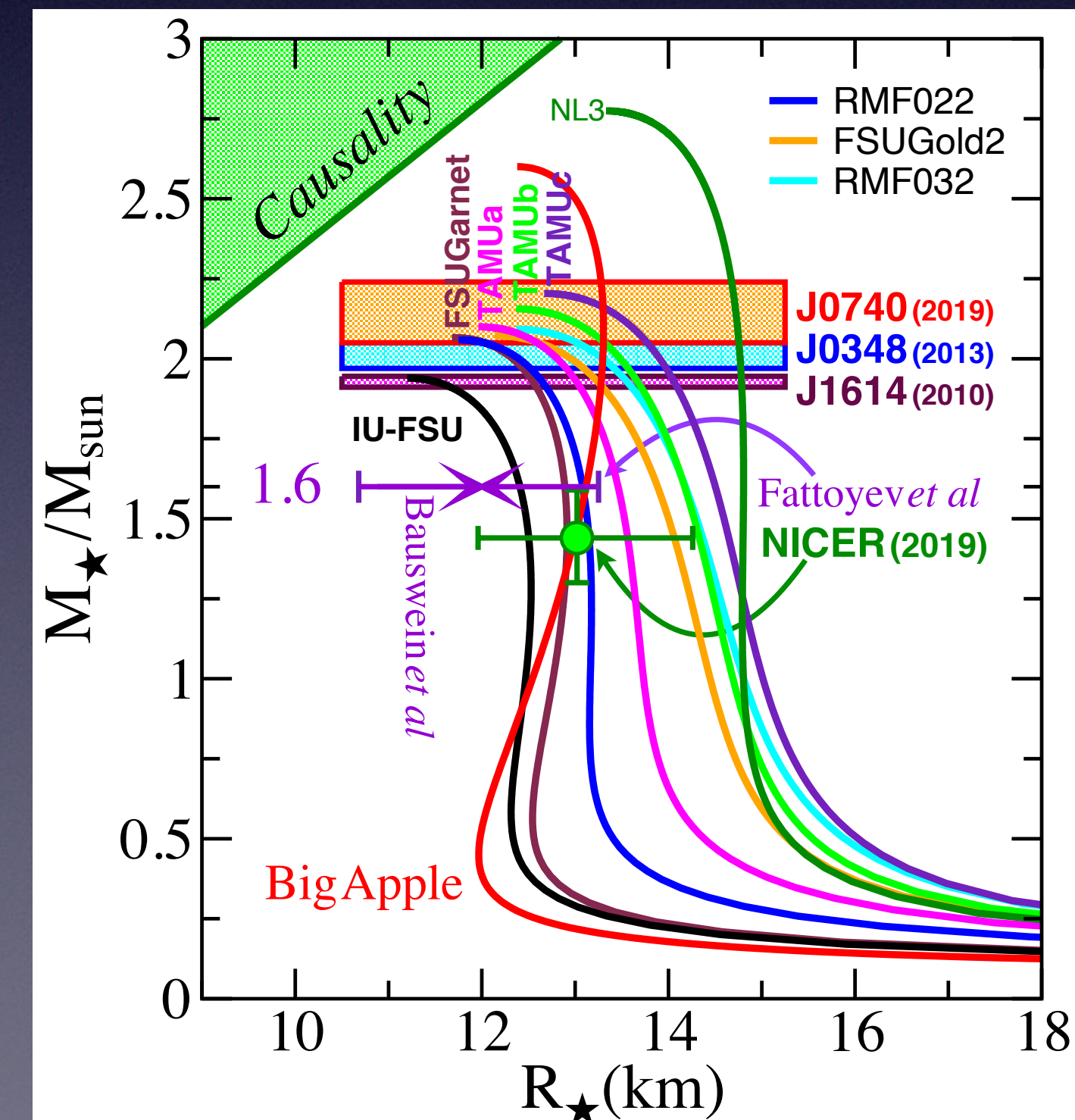
Since  $N \sim Z \sim A/2$

$$\rho_c = \frac{Q}{V} \approx \frac{3Ze}{4\pi r_0^3 A} \approx \frac{3e}{8\pi r_0^3} \text{ C/m}^3 \quad (5)$$



$r = \text{few fm}$

It is roughly a constant.





# The Liquid Drop Model

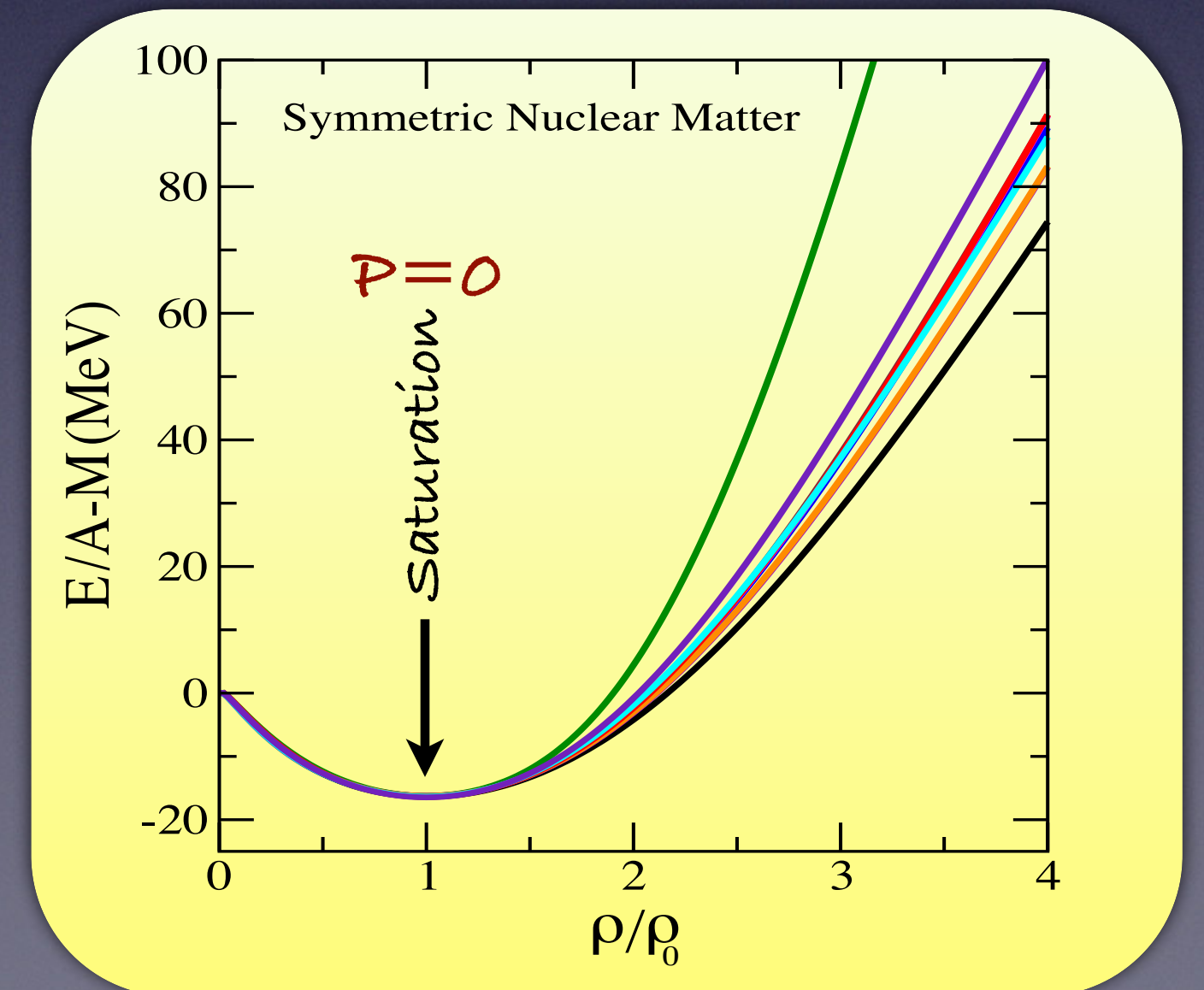
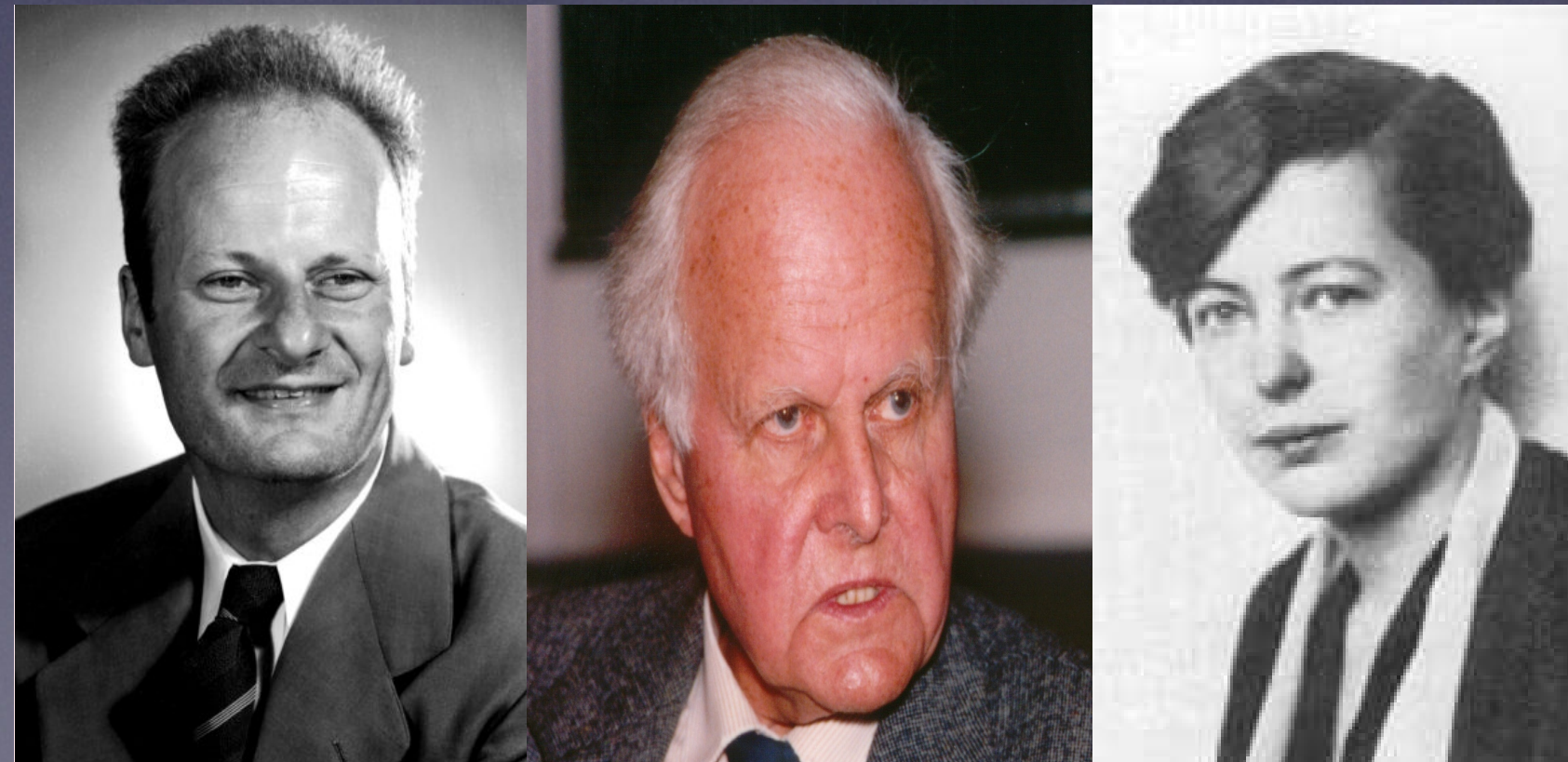
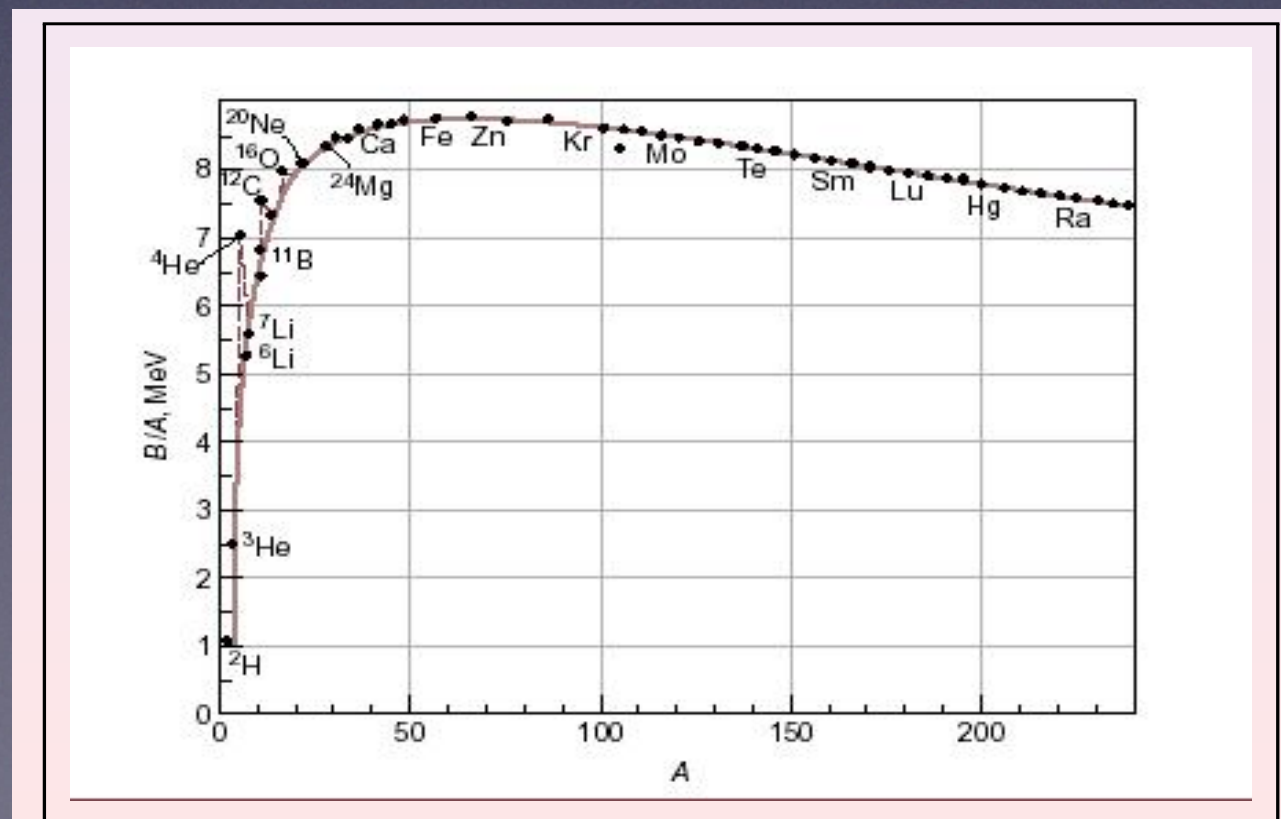
Bethe-Weizsäcker Mass Formula (circa 1935-36)

- Nuclear forces saturate  $\longrightarrow$  equilibrium density  $\rho_0 \approx 0.15 \text{ fm}^{-3}$
  - Nuclei penalized for developing a surface  $R(A) = r_0 A^{1/3} \approx (1.2 \text{ fm}) A^{1/3}$
  - Nuclei penalized by Coulomb repulsion
  - Nuclei penalized for isospin imbalance ( $N \neq Z$ )
- Nucleus as an incompressible liquid drop made of two quantum fluids

$$B(Z, N) = -a_v A + a_s A^{2/3} + a_c Z^2 / A^{1/3} + a_a (N - Z)^2 / A + \dots$$

+ shell corrections (2, 8, 20, 28, 50, 82, 126, ...)

$$a_v \simeq 16.0, a_s \simeq 17.2, a_c \simeq 0.7, a_a \simeq 23.3 \text{ (in MeV)}$$





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

## My FSU Collaborators

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



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





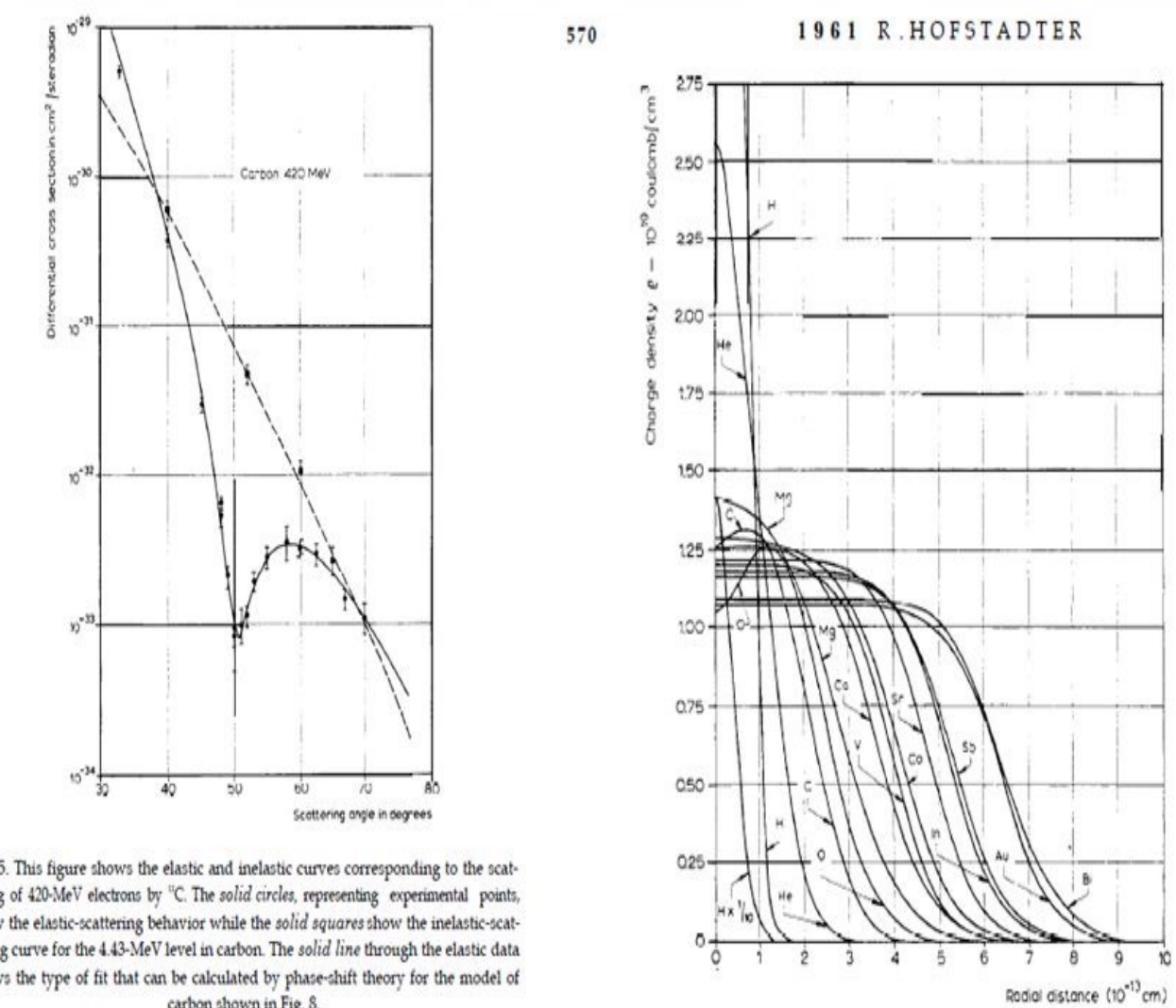


Fig. 5. This figure shows the elastic and inelastic curves corresponding to the scattering of 420-MeV electrons by <sup>12</sup>C. The solid circles, representing experimental points, show the elastic-scattering behavior while the solid squares show the inelastic-scattering curve for the 4.43-MeV level in carbon. The solid line through the elastic data shows the type of fit that can be calculated by phase-shift theory for the model of carbon shown in Fig. 8.

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

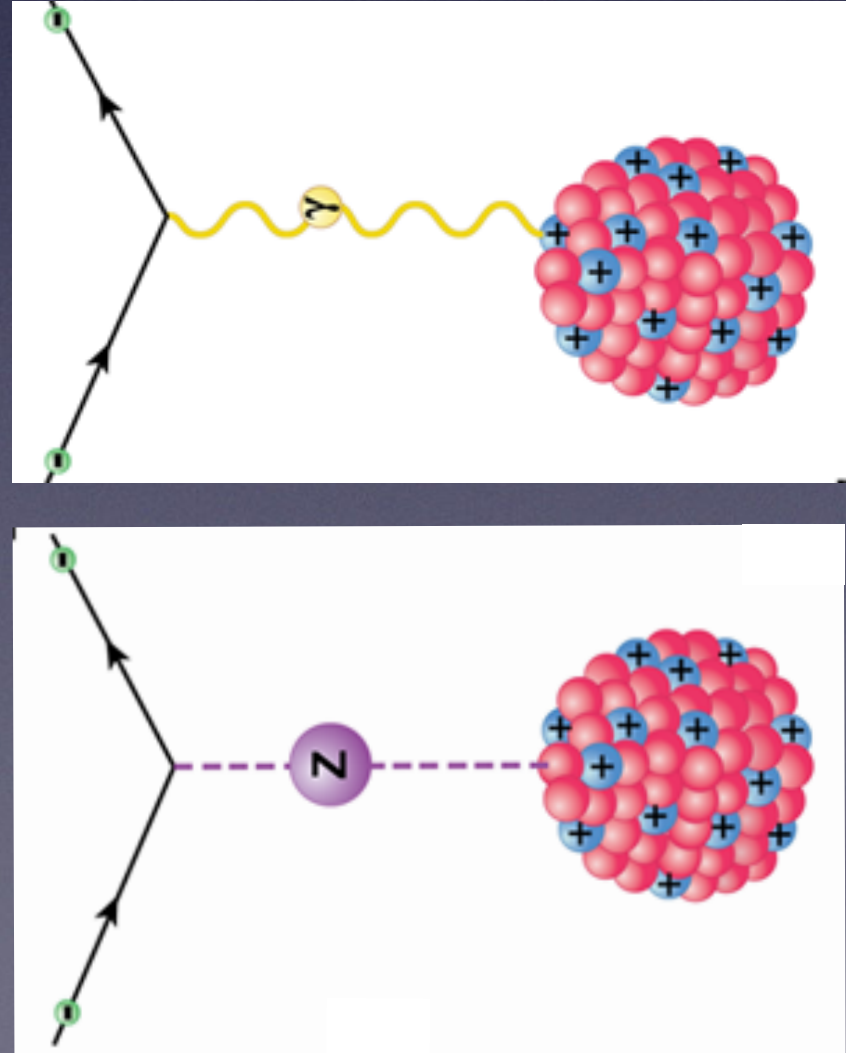
# Electroweak Probes of Ground State Densities

## A fundamental nuclear-structure problem

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

$$g_v = 2t_z - 4Q \sin^2 \theta_W \approx 2t_z - Q$$

- Charge density known with enormous precision
  - Probed via parity-conserving elastic e-scattering
  - $\gamma$  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

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

$$F_{SF}(q) \rightarrow \frac{\cos(qc + \delta)}{qc} e^{-\pi qa}$$

$c$  = half-density radius  
 $a$  = surface diffusion

Diffractive Oscillations (“ $c$ ”) modulated by an exponential falloff (“ $\pi a$ ”)

## Diffraction – Hofstadter, Nobel (1961)

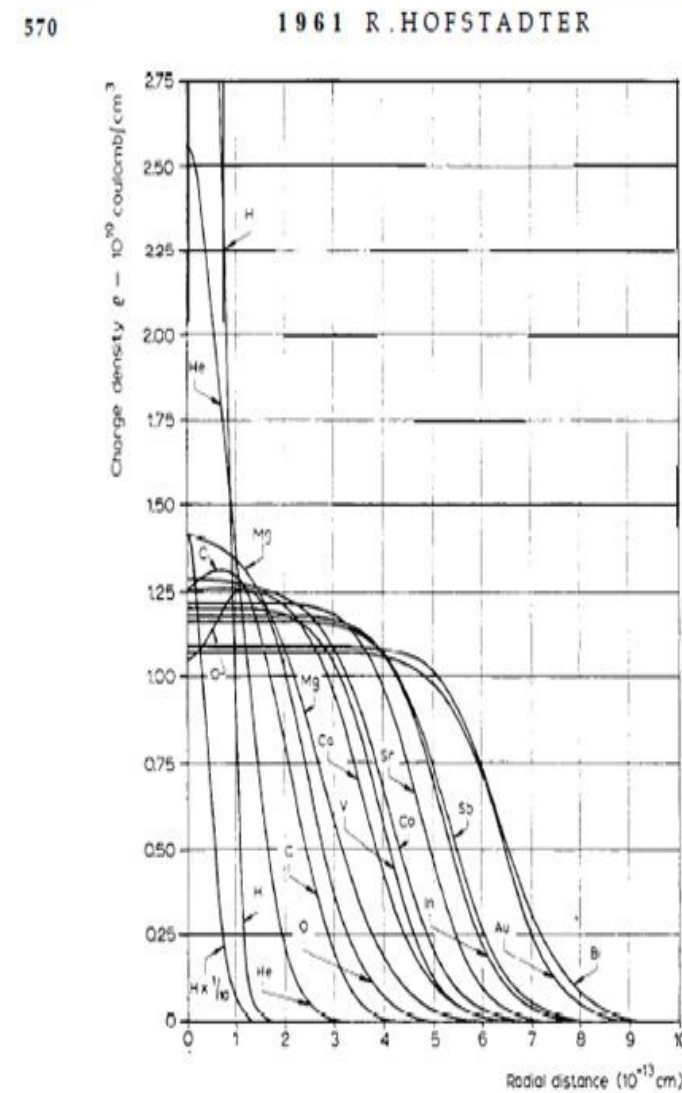
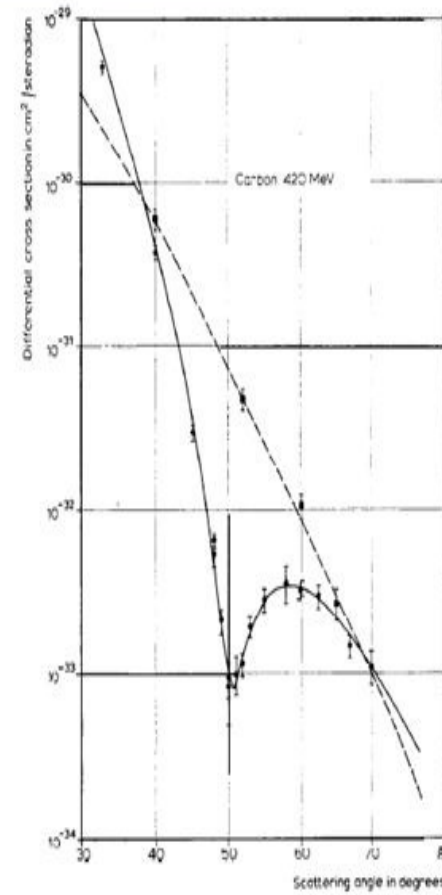
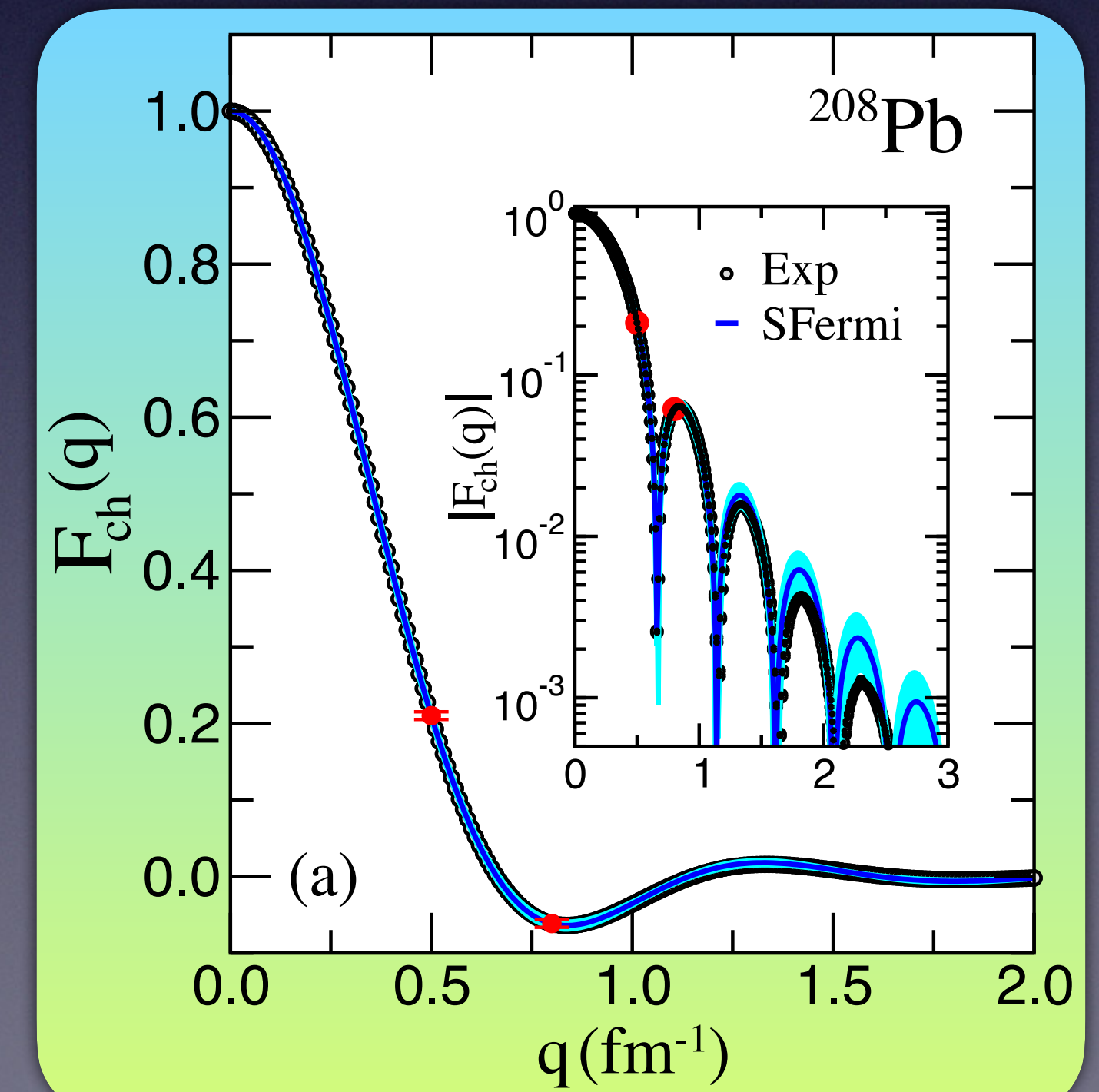
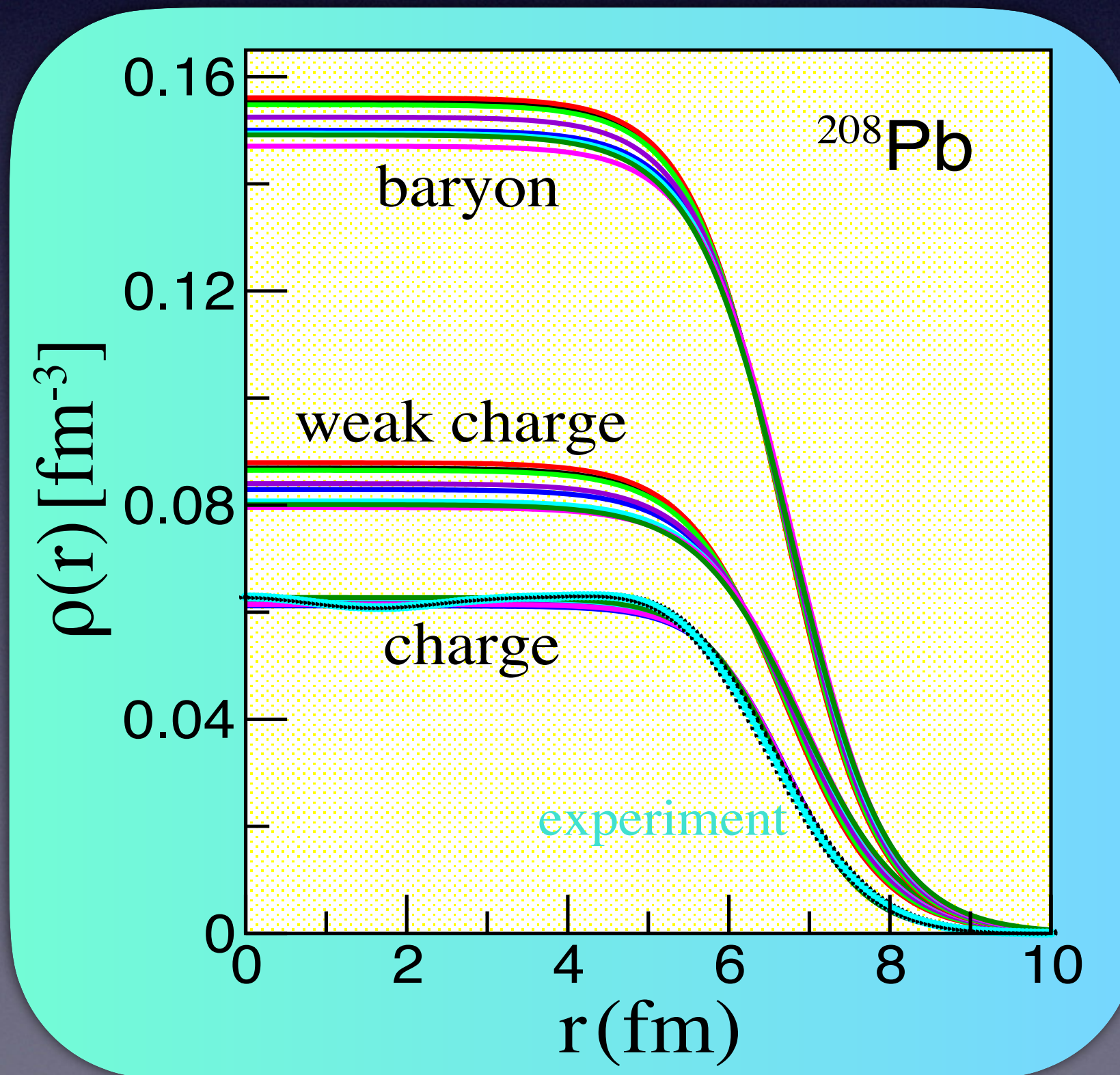


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# Experimental Extraction of Charge and Weak Form Factors

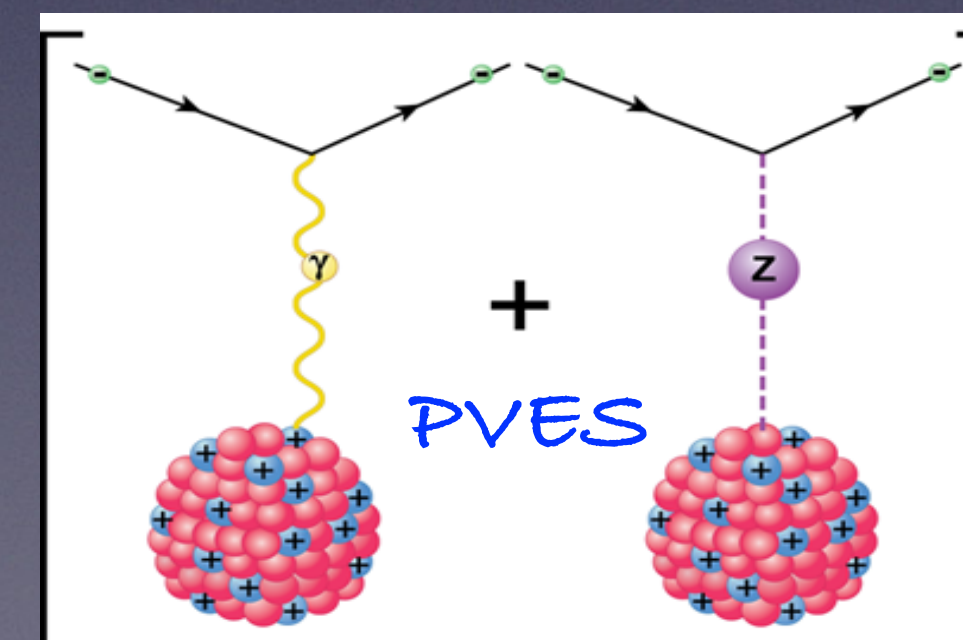
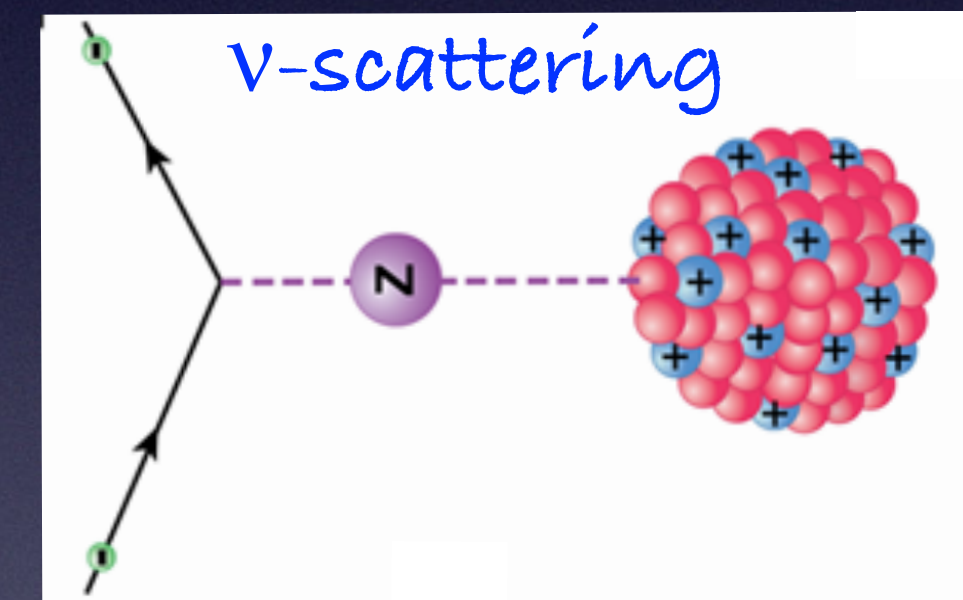
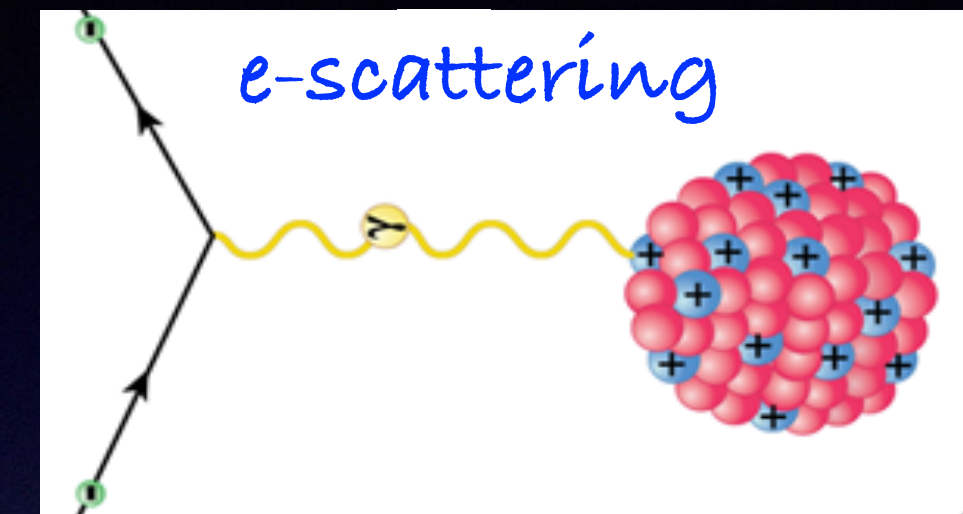
Form Factors are the Fourier transform of the corresponding densities

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

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

$$A_{\text{PV}} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{R}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{L}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{R}} + \left(\frac{d\sigma}{d\Omega}\right)_{\text{L}}}\bigg|_{J=0} = \left(\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right) \frac{Q_{\text{wk}} F_{\text{wk}}(Q^2)}{Z F_{\text{ch}}(Q^2)}$$

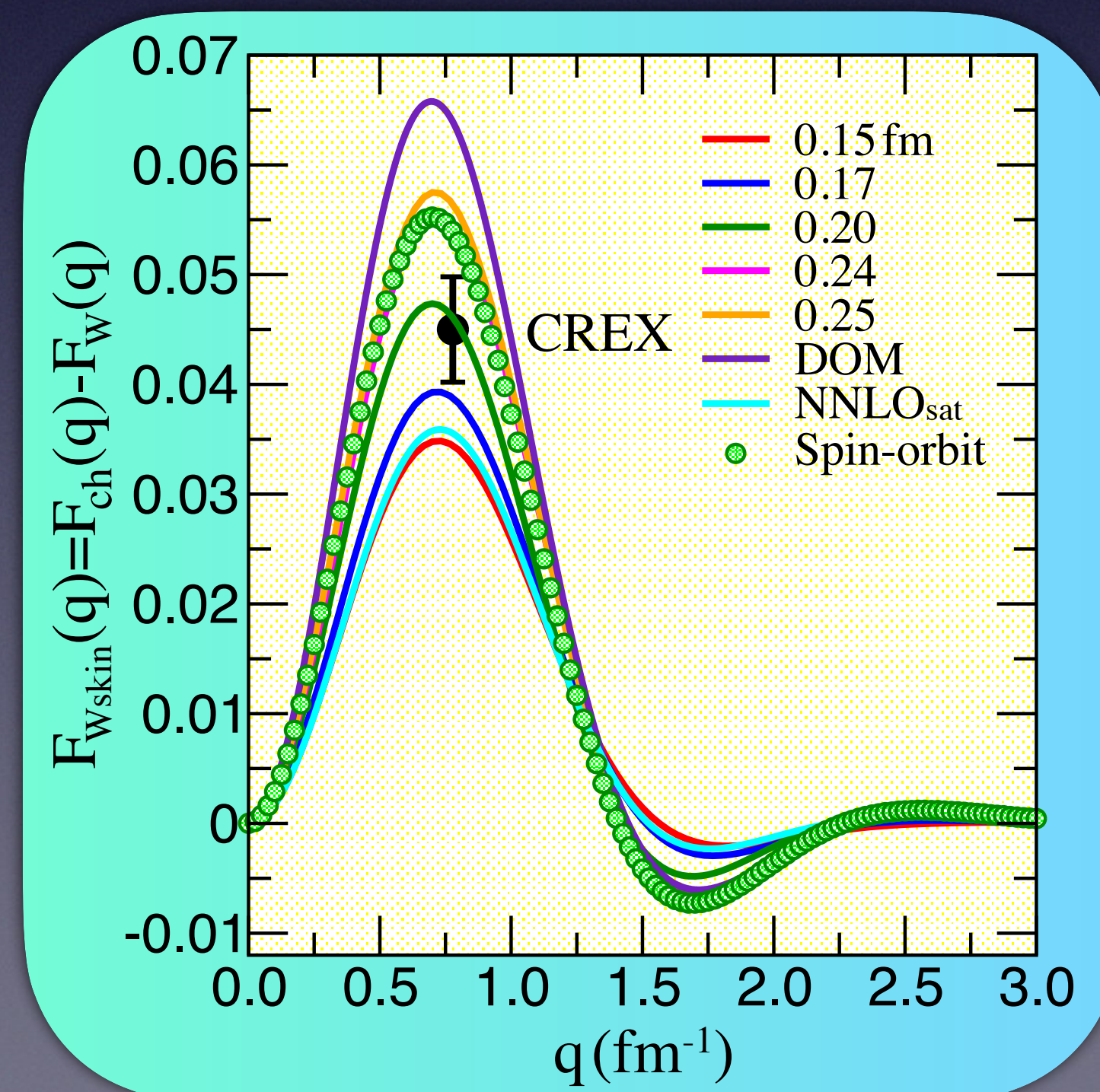
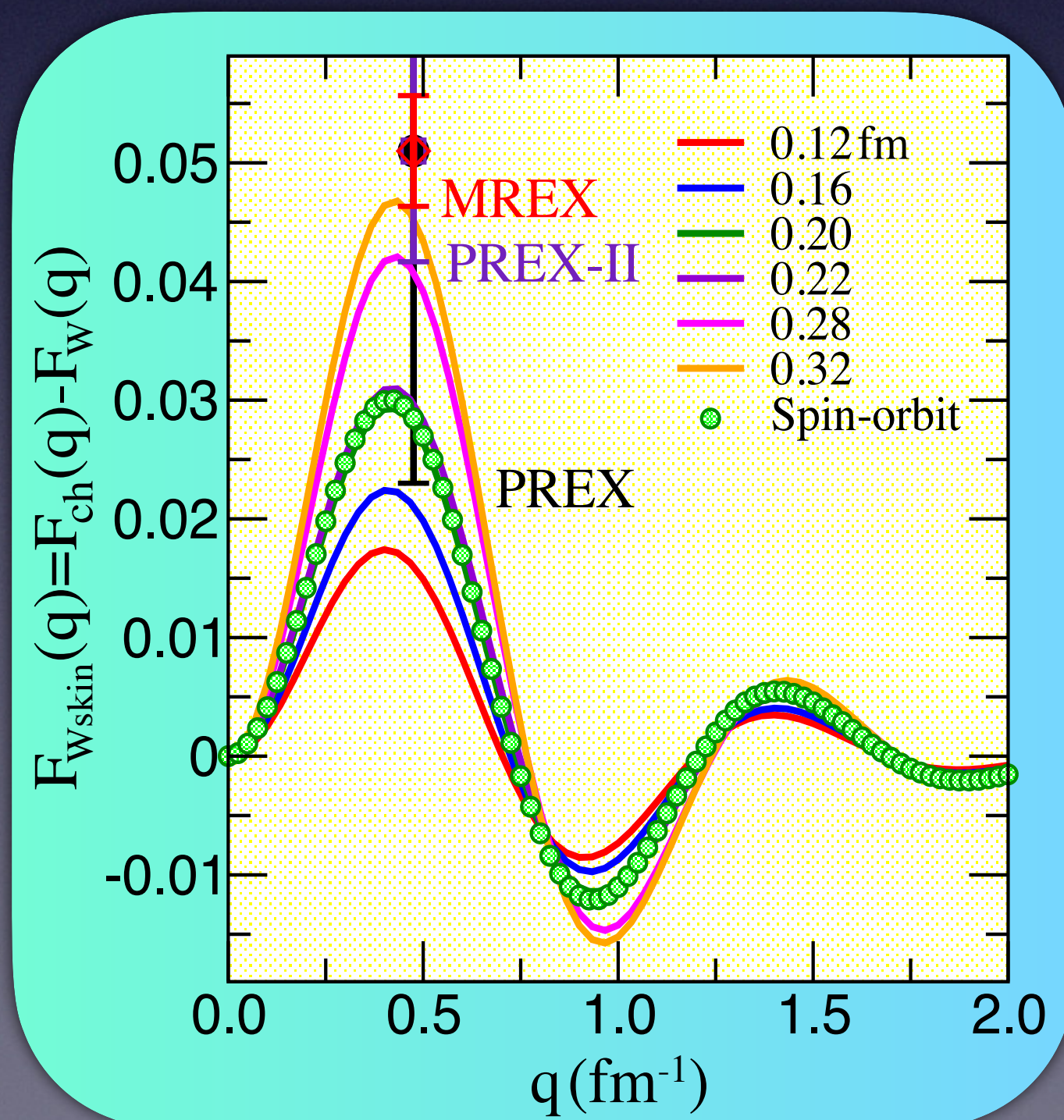
$$Q_{\text{wk}} = -N + (1 - 4\sin^2 \theta_W)Z = \text{weak charge}$$





# The Future: PREX-II, CREX, and MREX

- PREX obtained  $R_n - R_p = 0.33^{+0.16}_{-0.18}$  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

$$F_{Wskin} \equiv F_{ch} - F_w \approx \frac{q^2}{6} (R_{wk}^2 - R_{ch}^2) + \dots$$

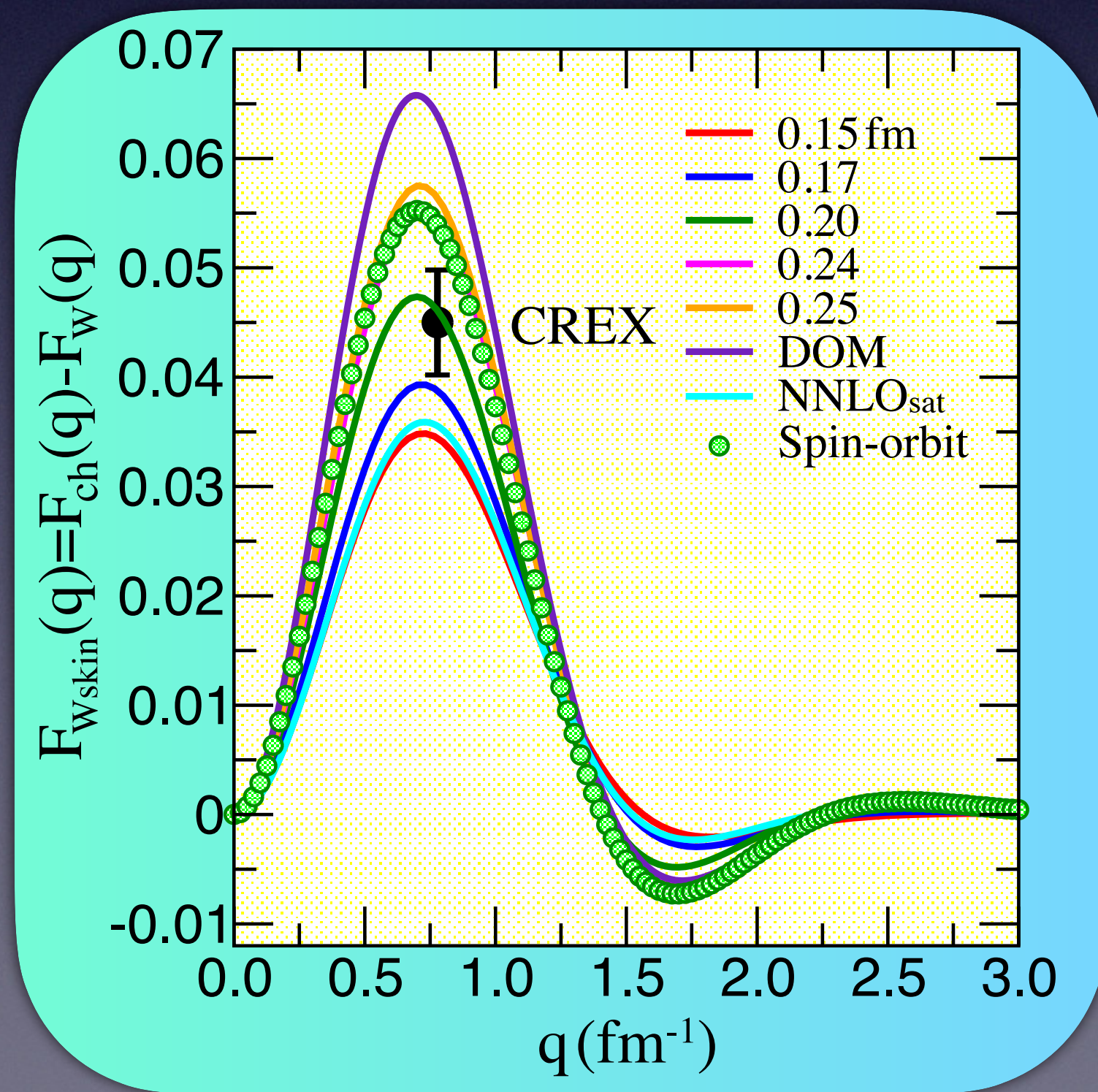
*Spin-orbit currents*  
Vanish for fully occupied  
spin-orbit partners

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



# CREX and CEvNS ( $^{40}\text{Ar}$ )

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



## Standard Model prediction

### for differential cross section

(probability of kicking a nucleus with recoil energy  $T$ )

$E_\nu$ : neutrino energy  
 $T$ : nuclear recoil energy  
 $M$ : nuclear mass  
 $Q = \sqrt{2MT}$ :  
 momentum transfer

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M Q_W^2}{2\pi \cdot 4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

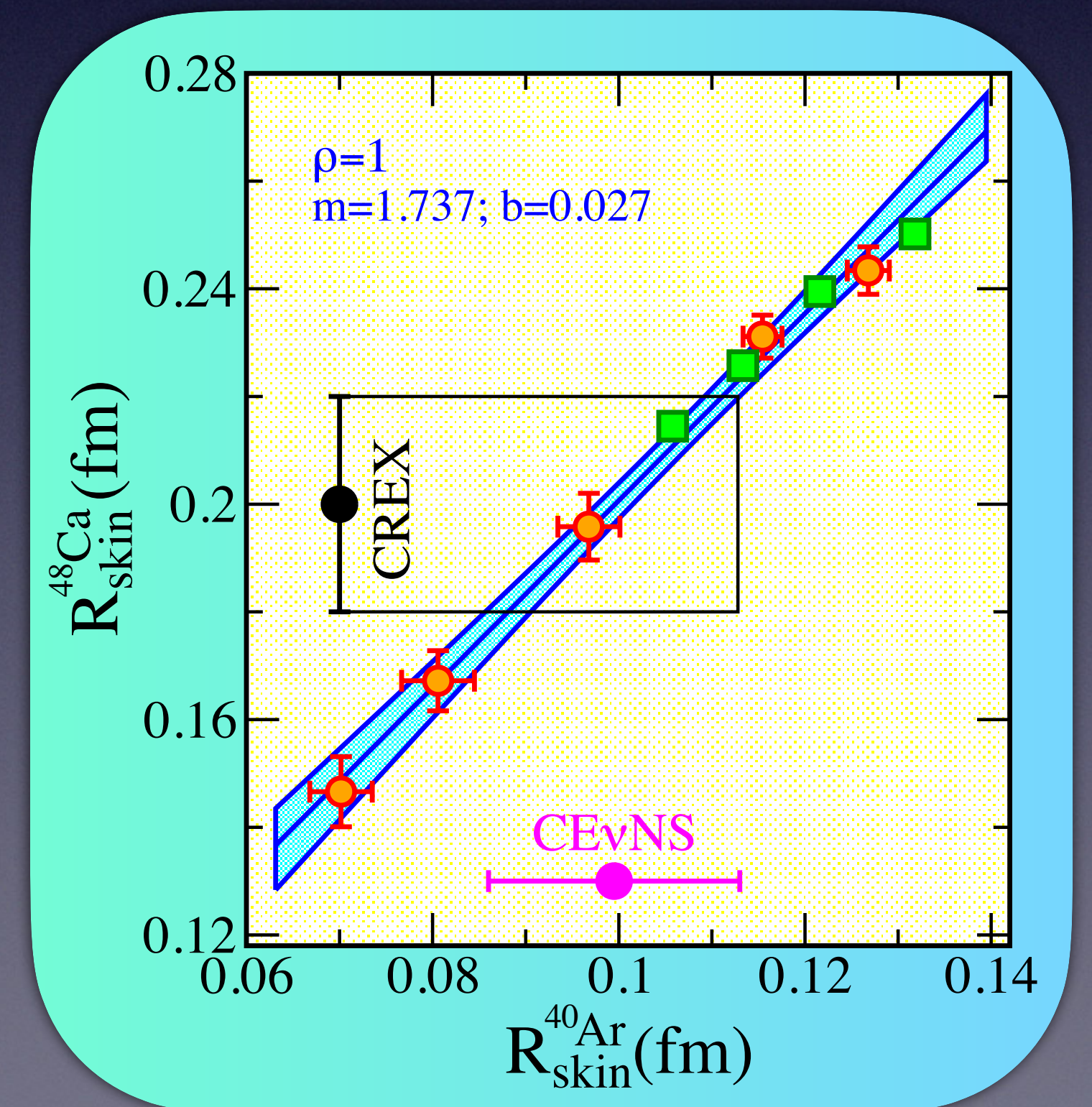
kinematics:  
ping-pong ball hits bowling ball

Form factor:  $F=1 \rightarrow$  full coherence

weak nuclear charge

$$Q_W = N - (1 - 4 \sin^2 \theta_W) Z$$

Fermi constant (SM parameter)





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

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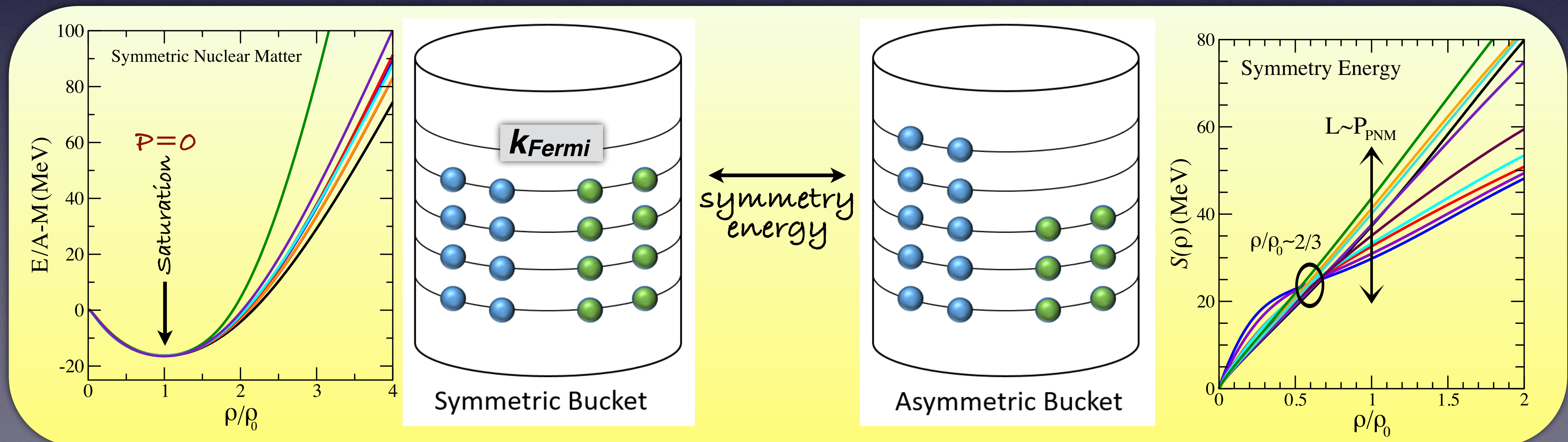


# The Equation of State of Neutron-Rich Matter

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

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

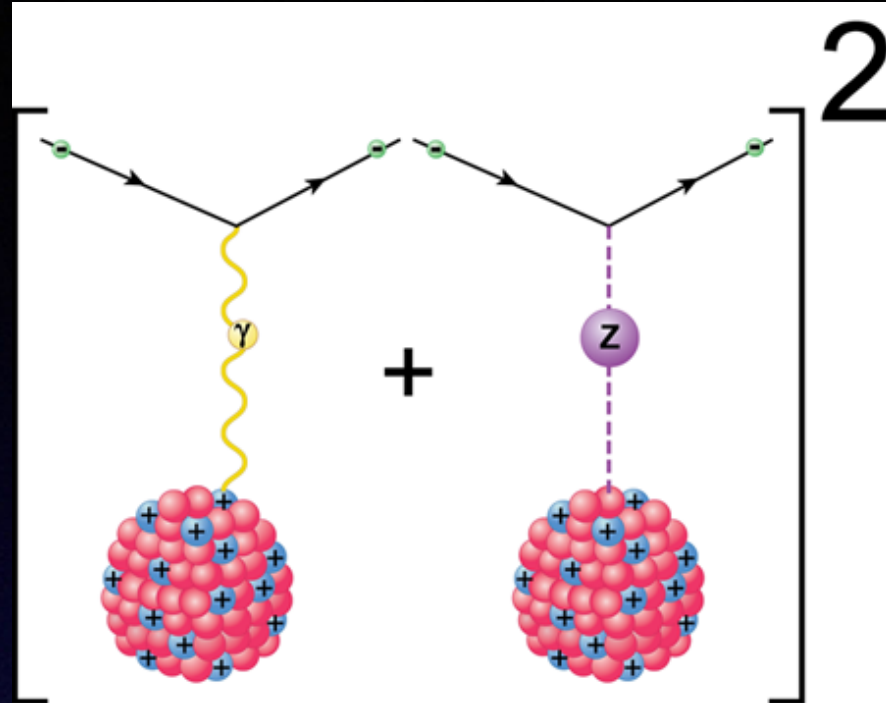
- Density dependence of symmetry energy poorly constrained!!  
 “L” symmetry slope  $\sim$  pressure of pure neutron matter at saturation





# Parity Violating e-Scattering at JLAB

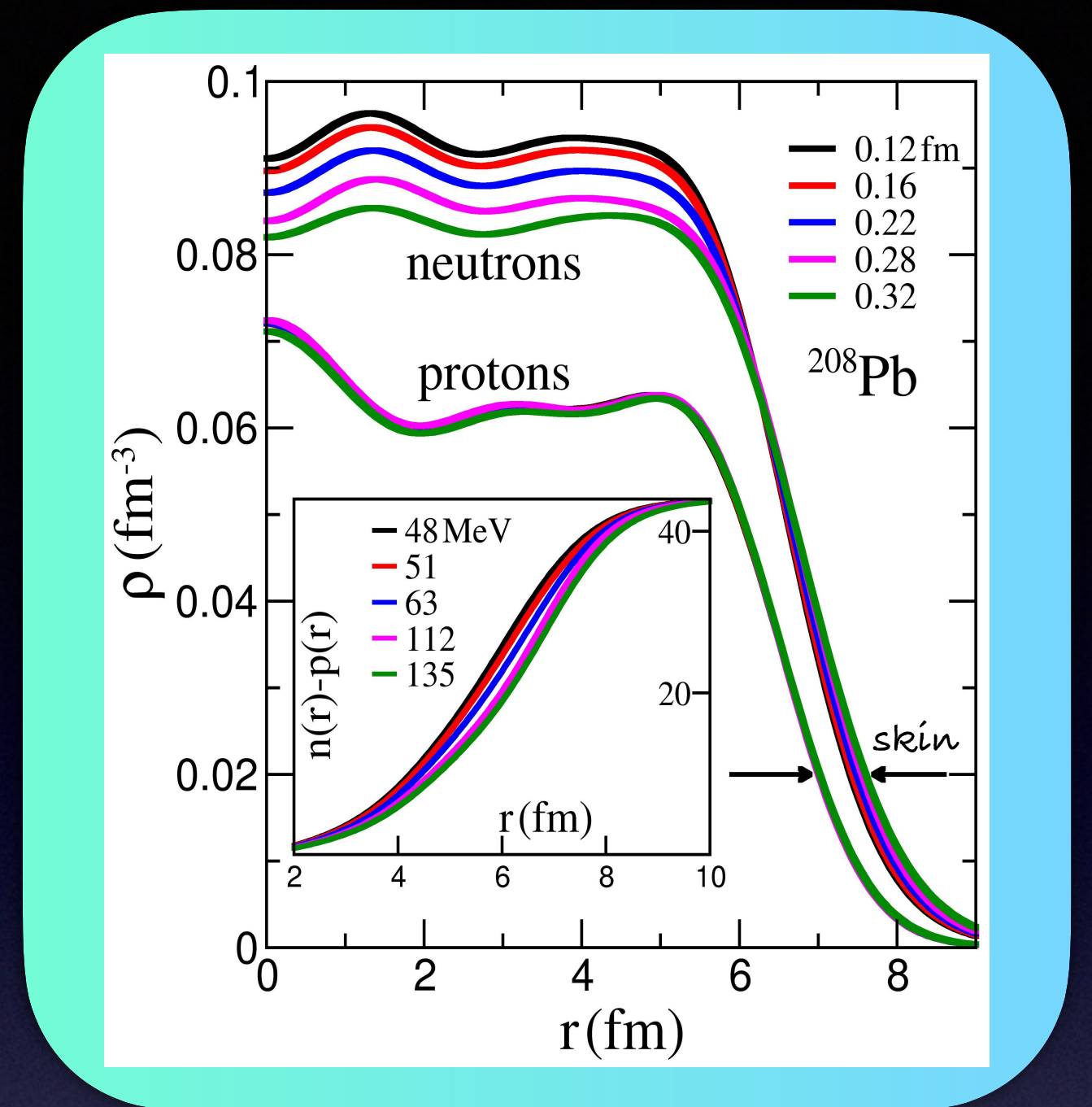
Determining the neutron skin  $R_n - R_p$  of Pb



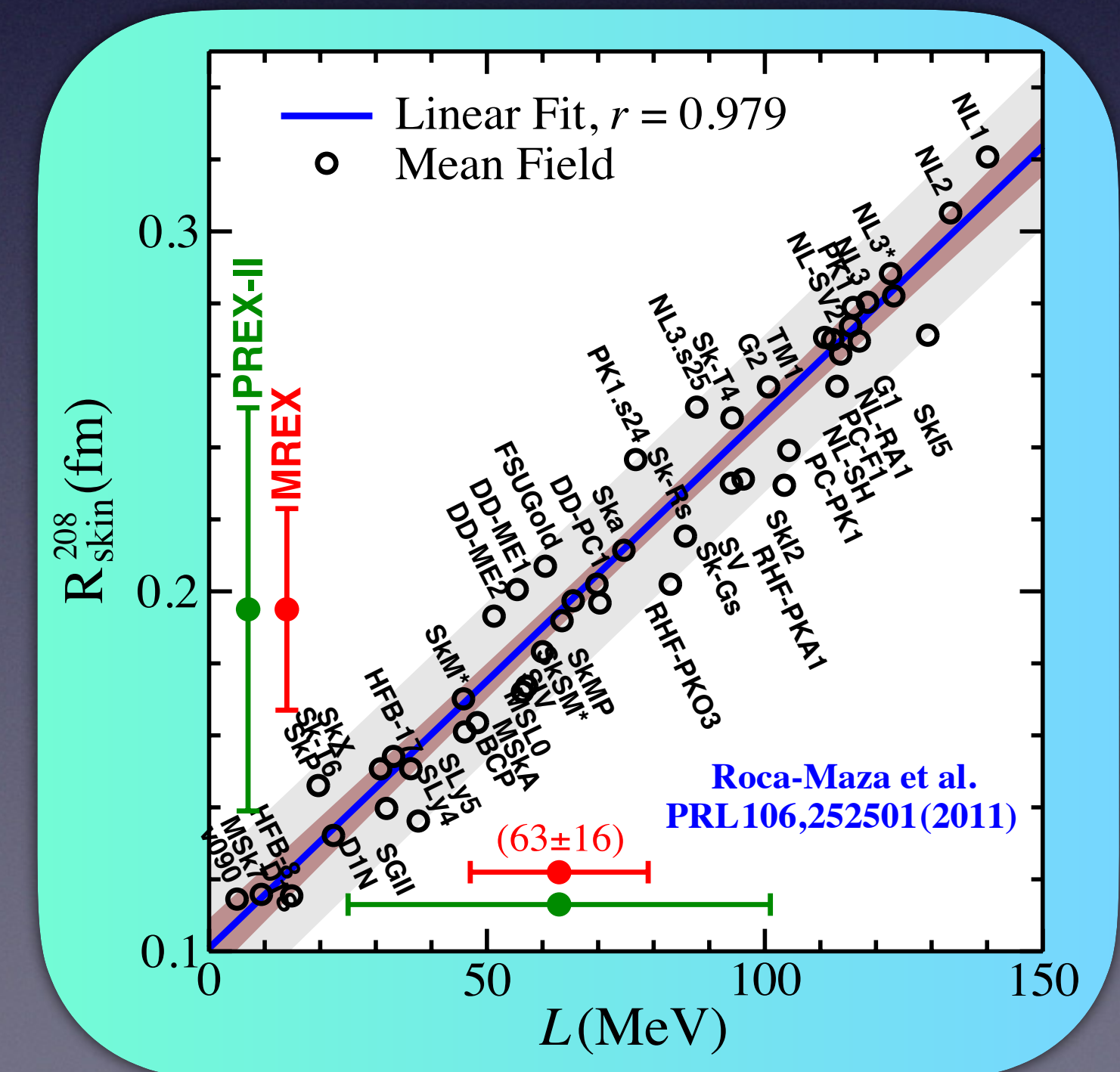
Abrahamyan *et al.*, PRL 108, 112502 (2012)

Horowitz *et al.*, PRC 85, 032501(R) (2012)

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



- PREX@JLAB: First **Electroweak** evidence in favor of a neutron rich skin in Pb:  $R_{skin} = 0.33(16)$  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/<sup>208</sup>Pb seems worthwhile

Analytic insights on the information content of new observables

Wei-Chia Chen\*

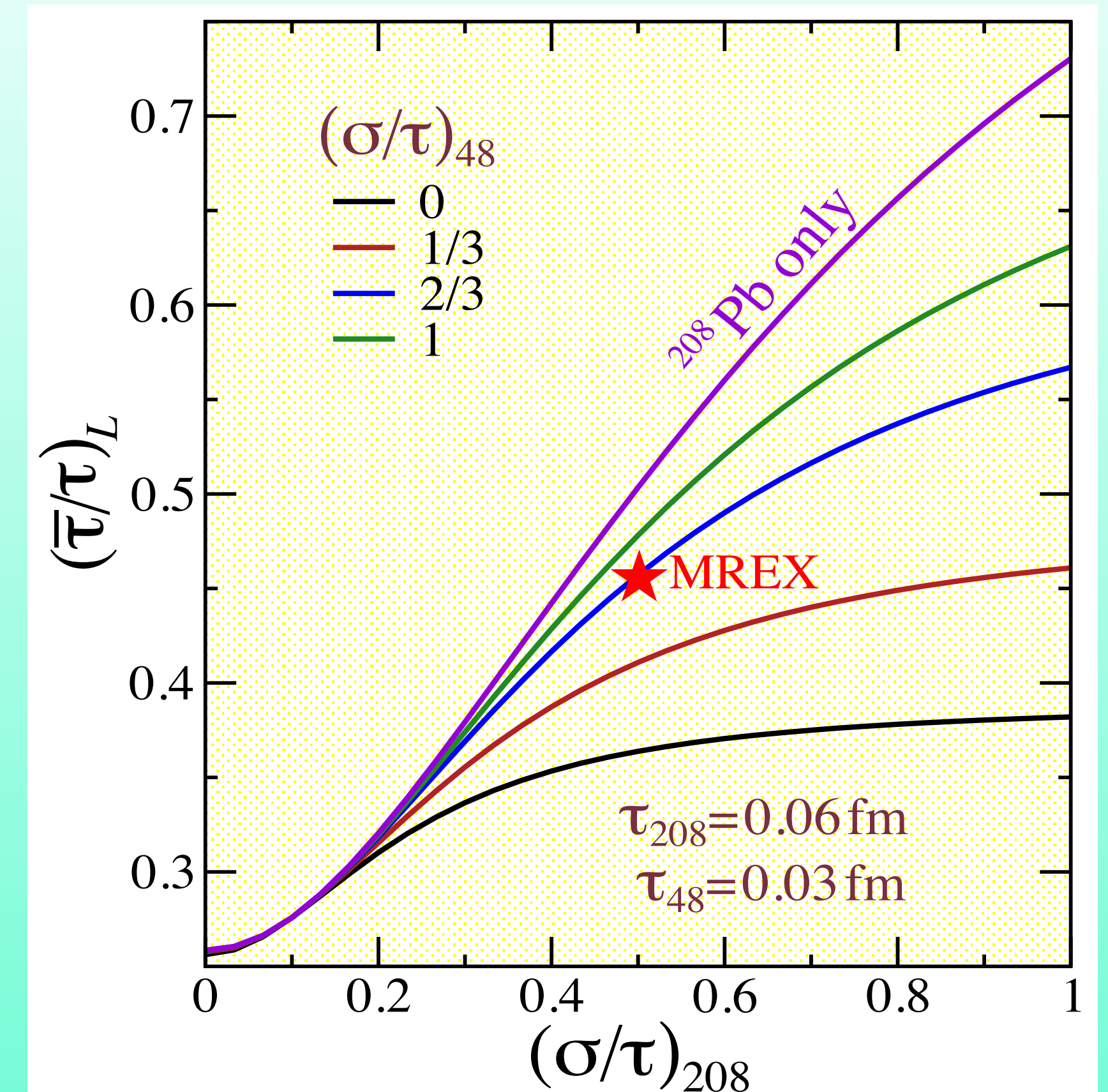
Simons Center for Quantitative Biology, Cold Spring Harbor Laboratory, Cold Spring Harbor, NY 11724, USA

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

(Dated: June 16, 2020)

2006.08405 [nucl-th]



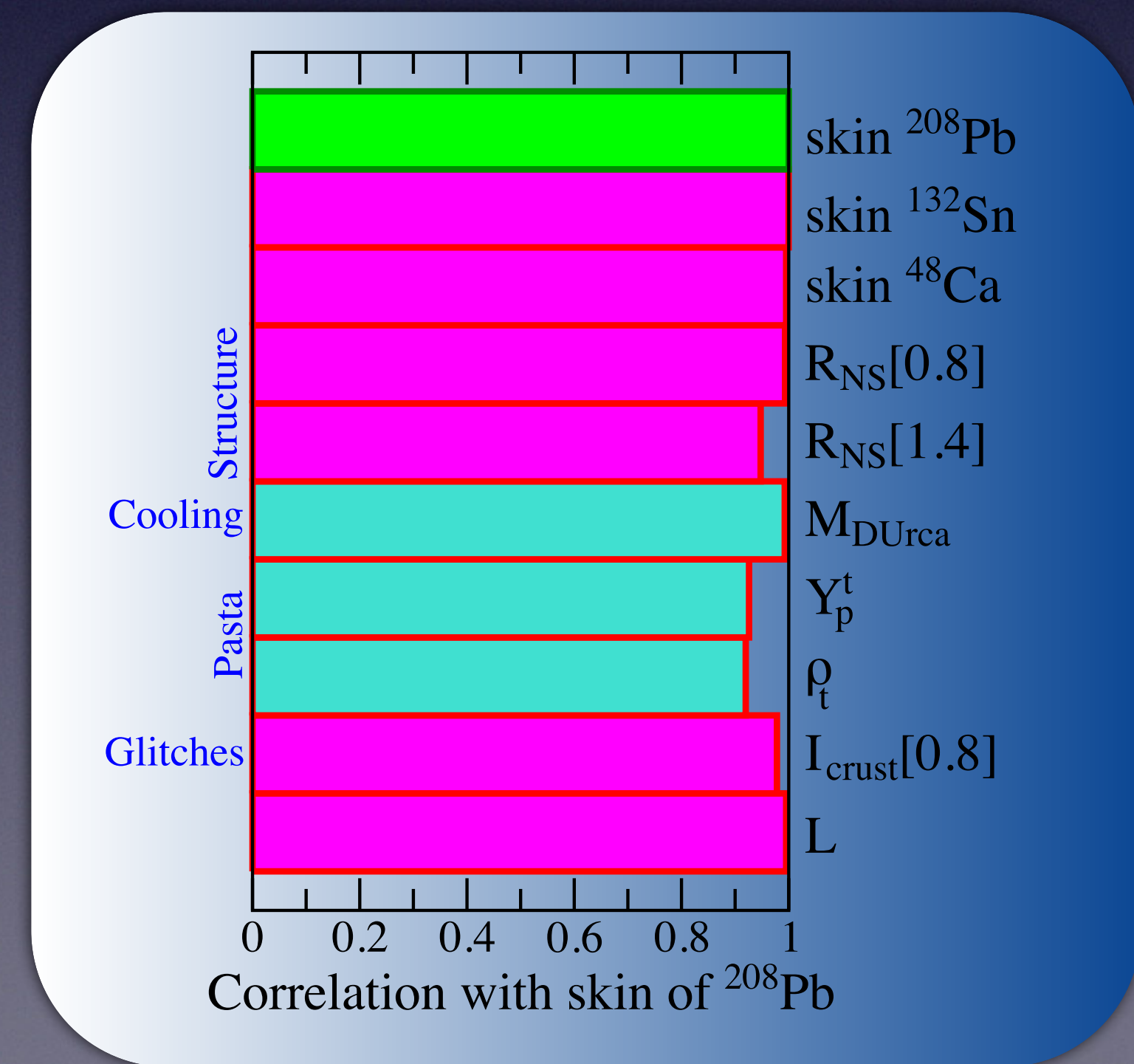
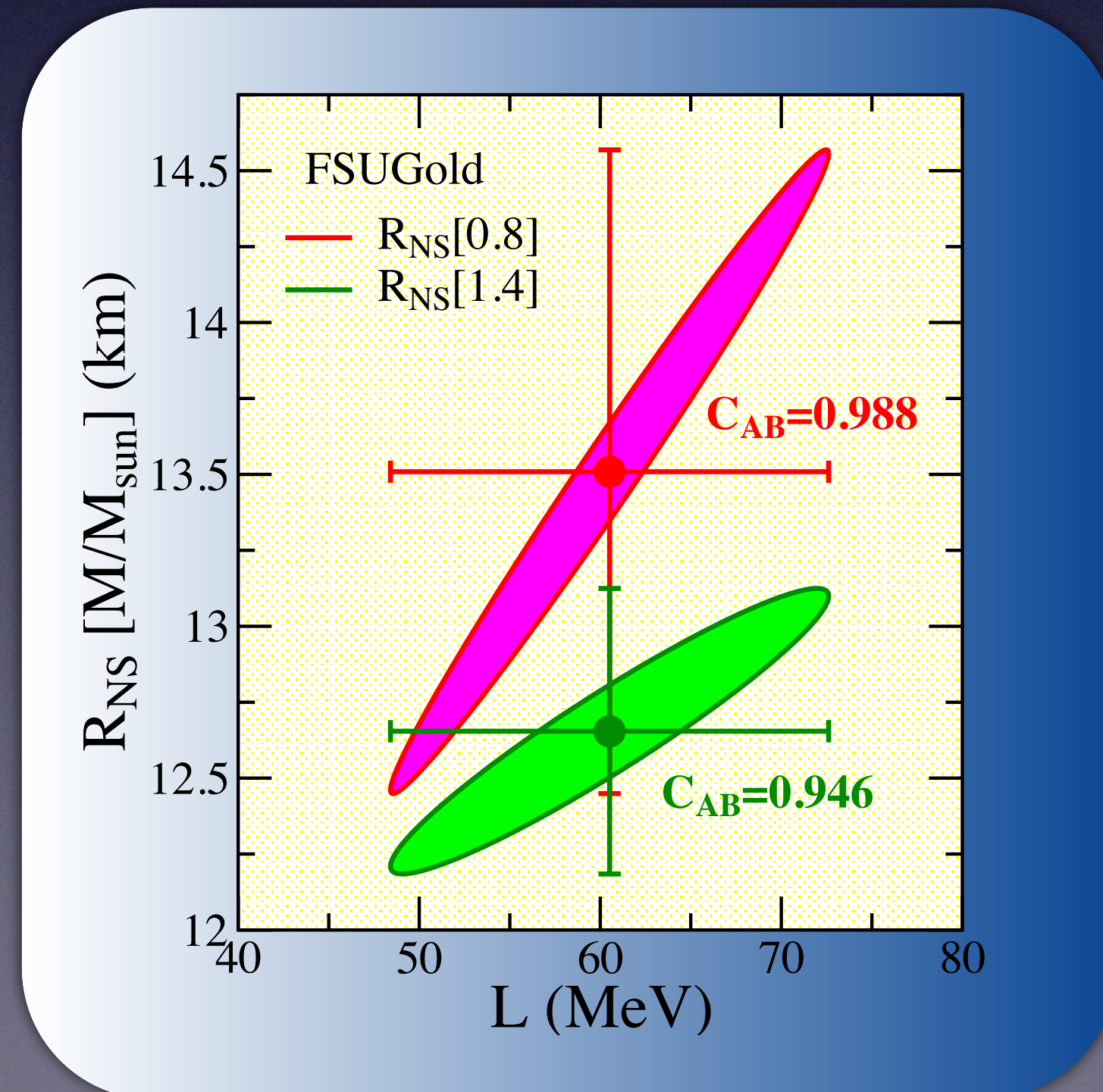
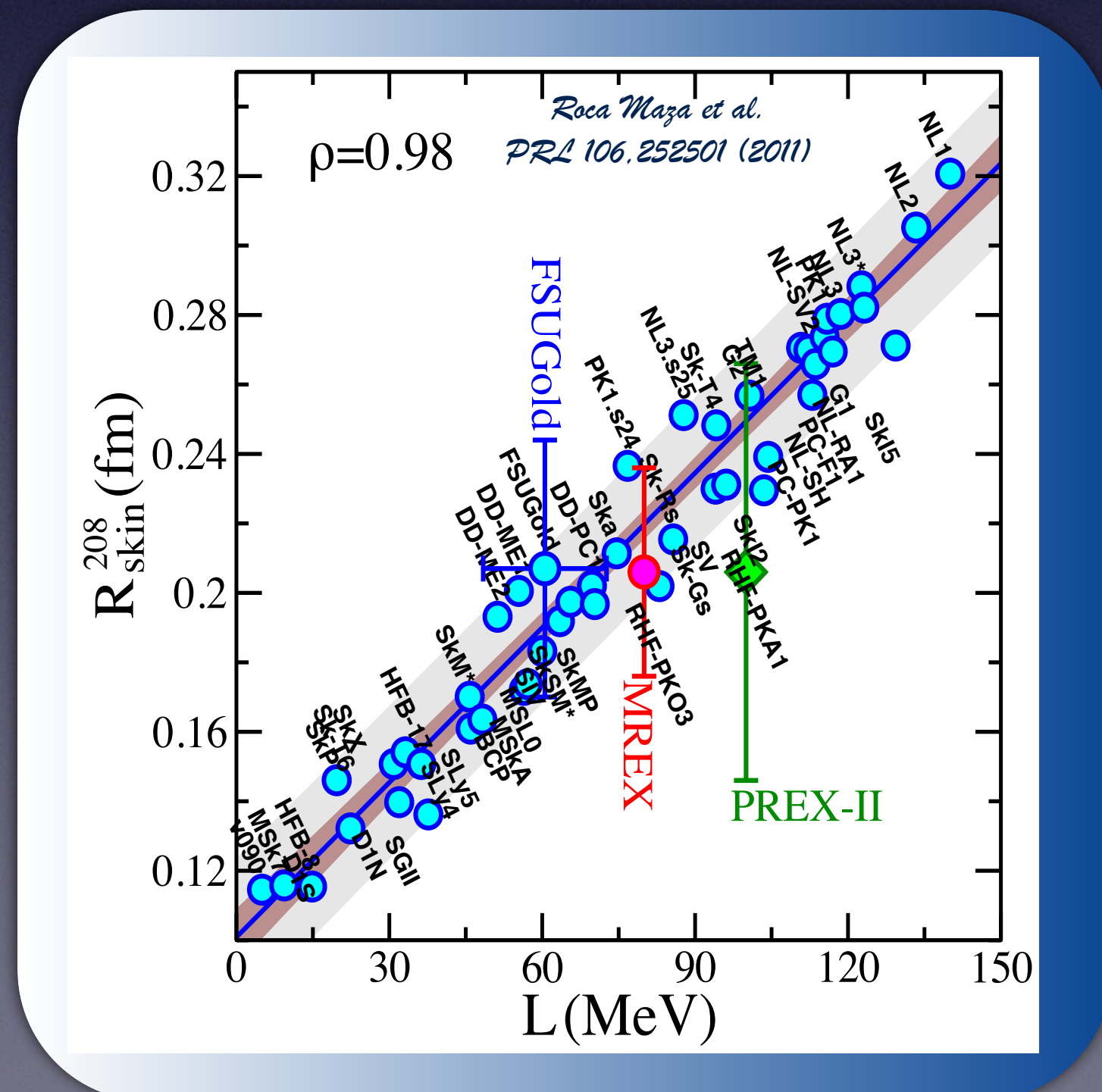


# Neutron Rich Matter on Earth:

## 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  $^{208}\text{Pb}$  and **L**
- L** controls both the neutron skin of  $^{208}\text{Pb}$  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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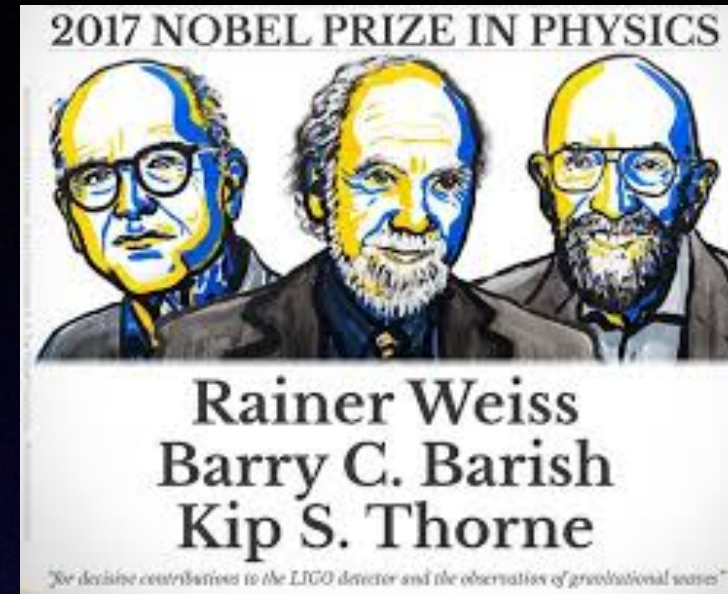
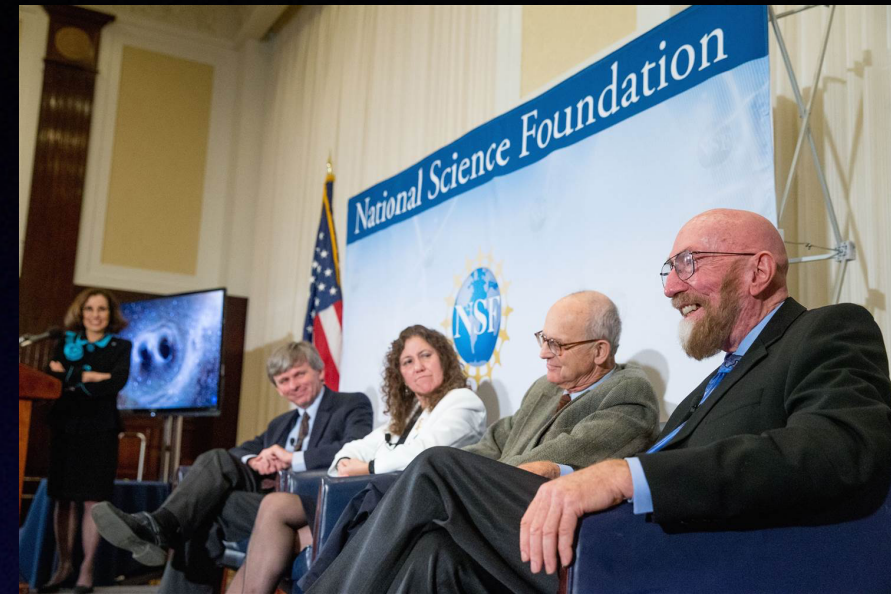
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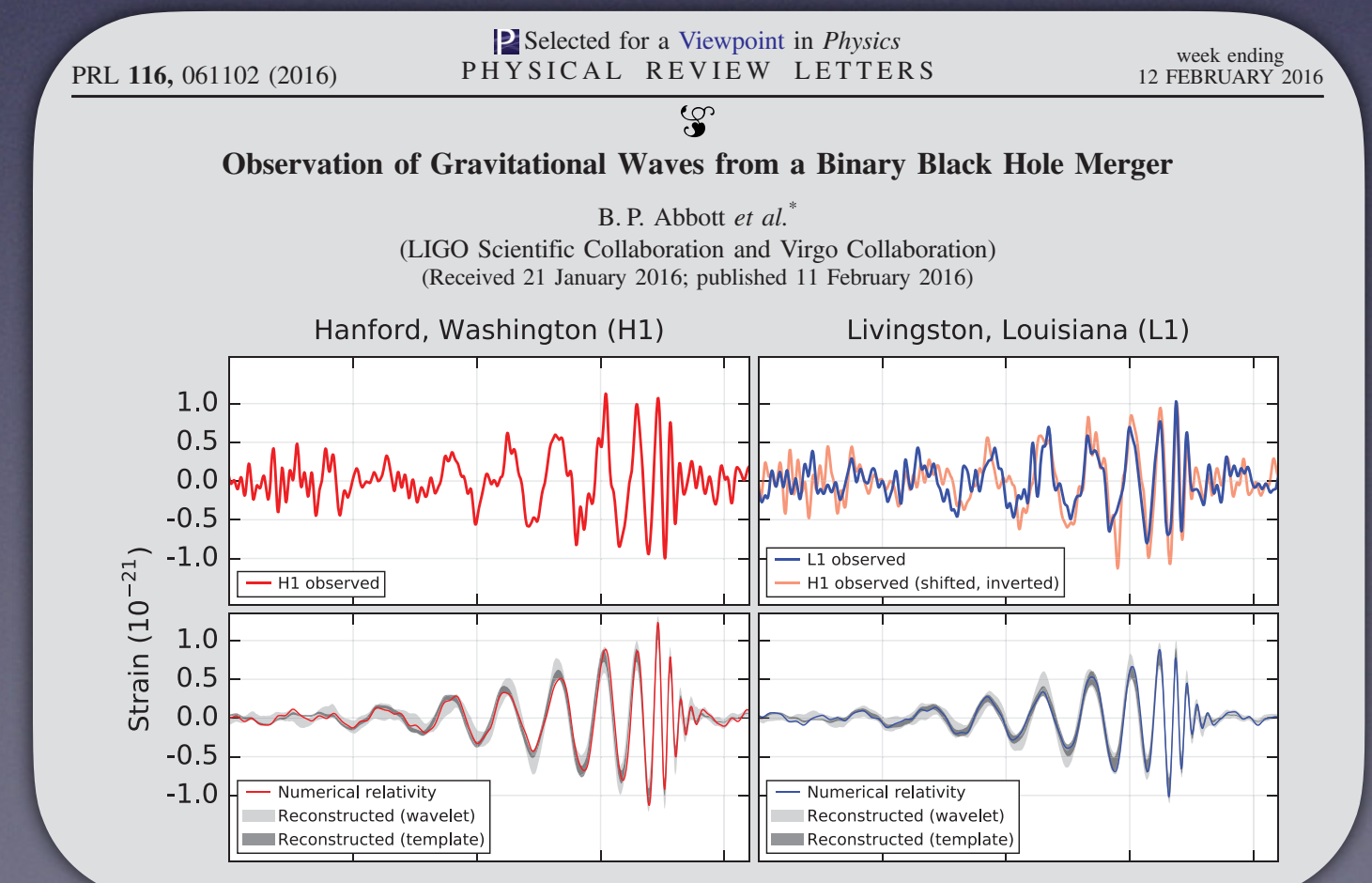


"We have detected gravitational waves; we did it"  
David Reitze, February 11, 2016

**GW170817**



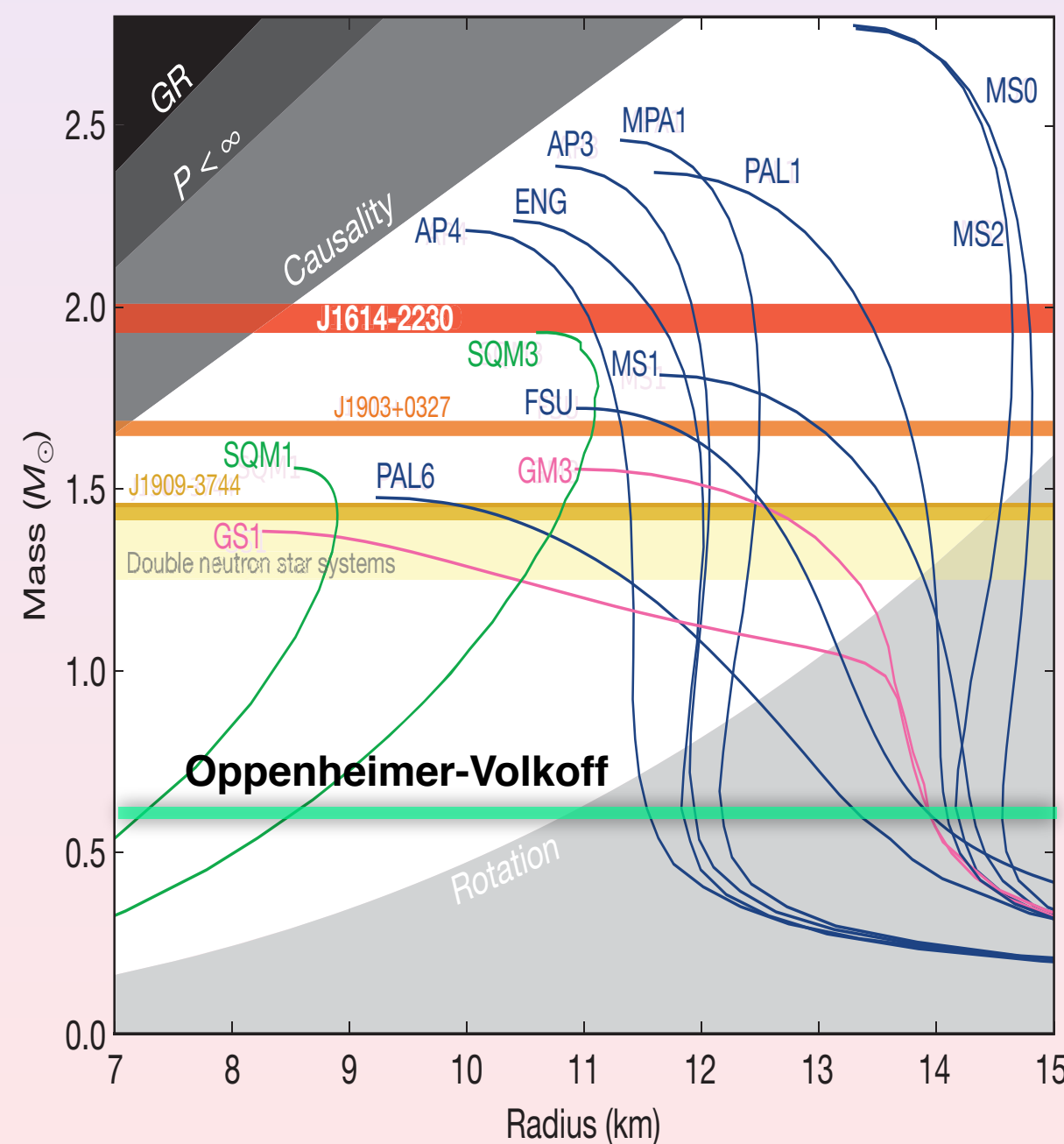
- The dawn of a new era: GW Astronomy
- Initial black hole masses are 36 and 29 solar masses
- Final black hole mass is 62 solar masses;  
*3 solar masses radiated in Gravitational Waves!*





# 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 ( $v_{\text{esc}}/c \sim 1/2$ )
- 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



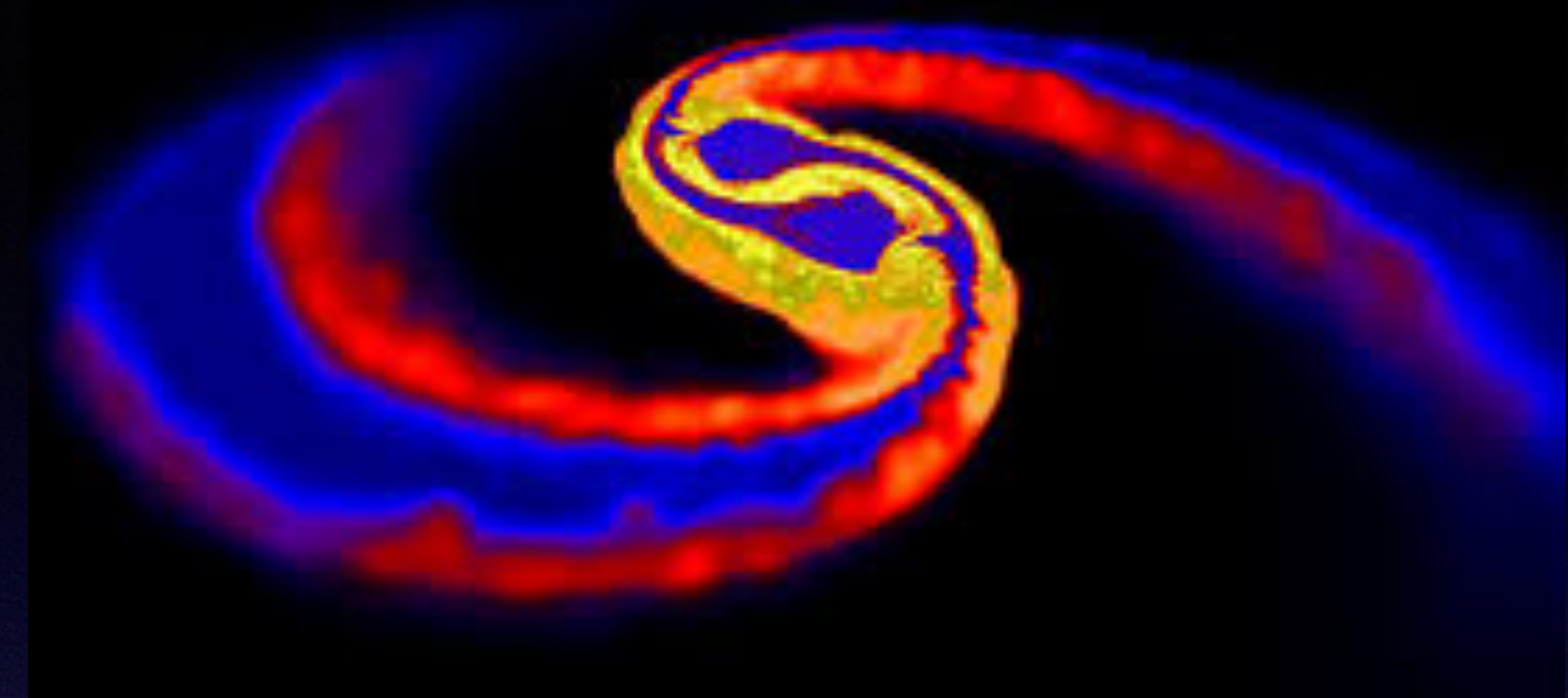
# Tidal Polarizability and Neutron-Star Radii

## Electric Polarizability:

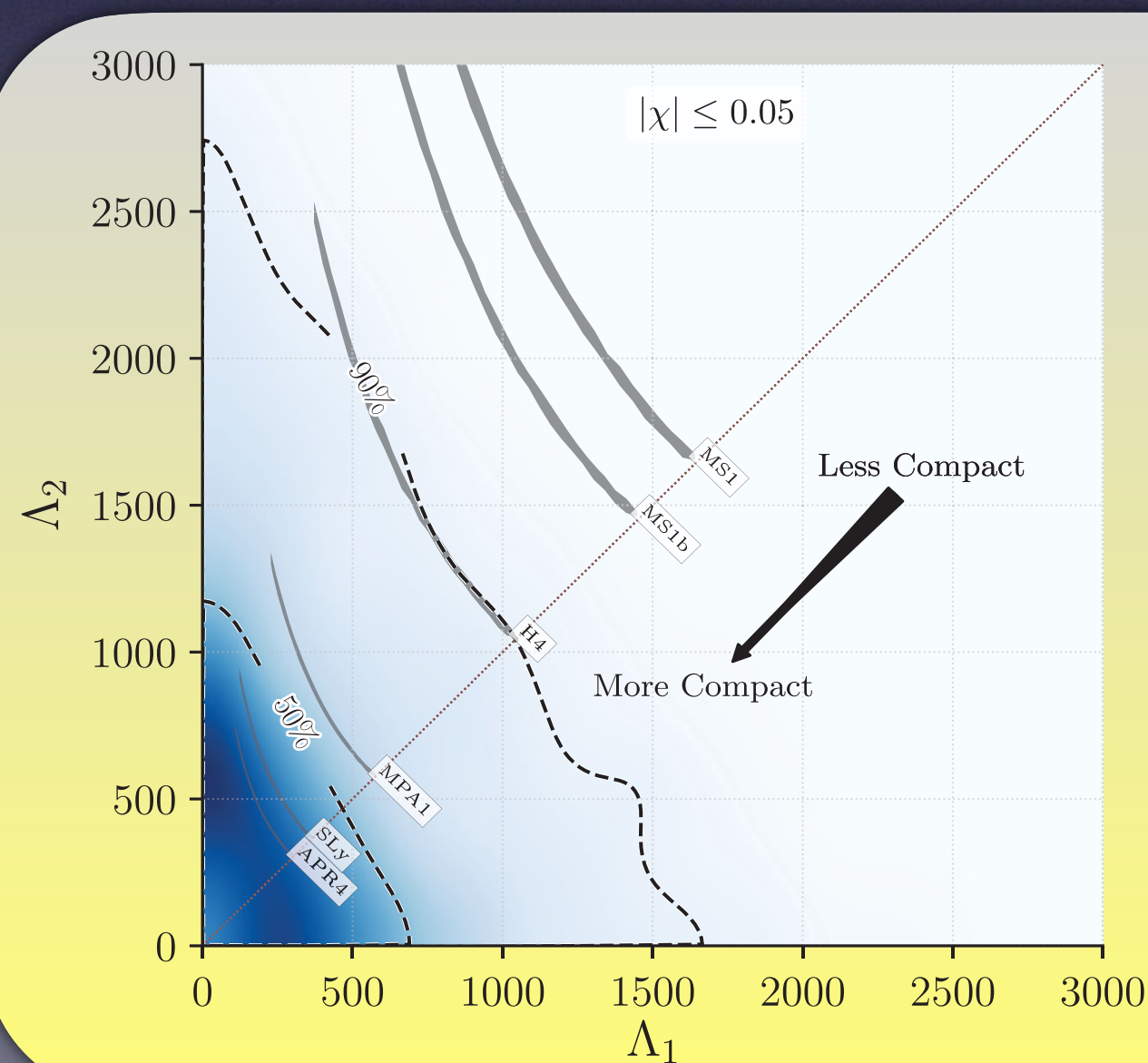
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves:  $P_i = \chi E_i$

## Tidal Polarizability:

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



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

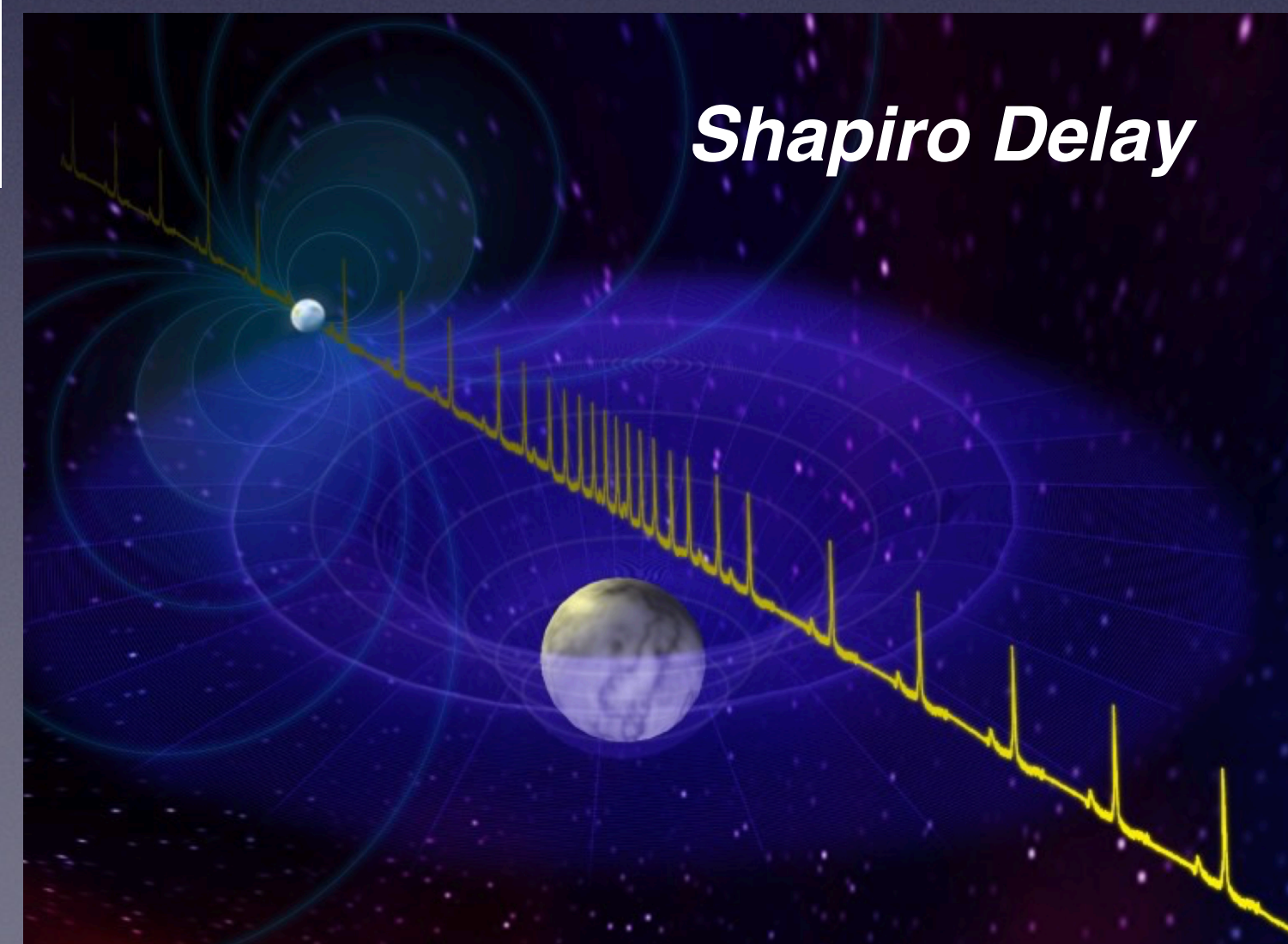
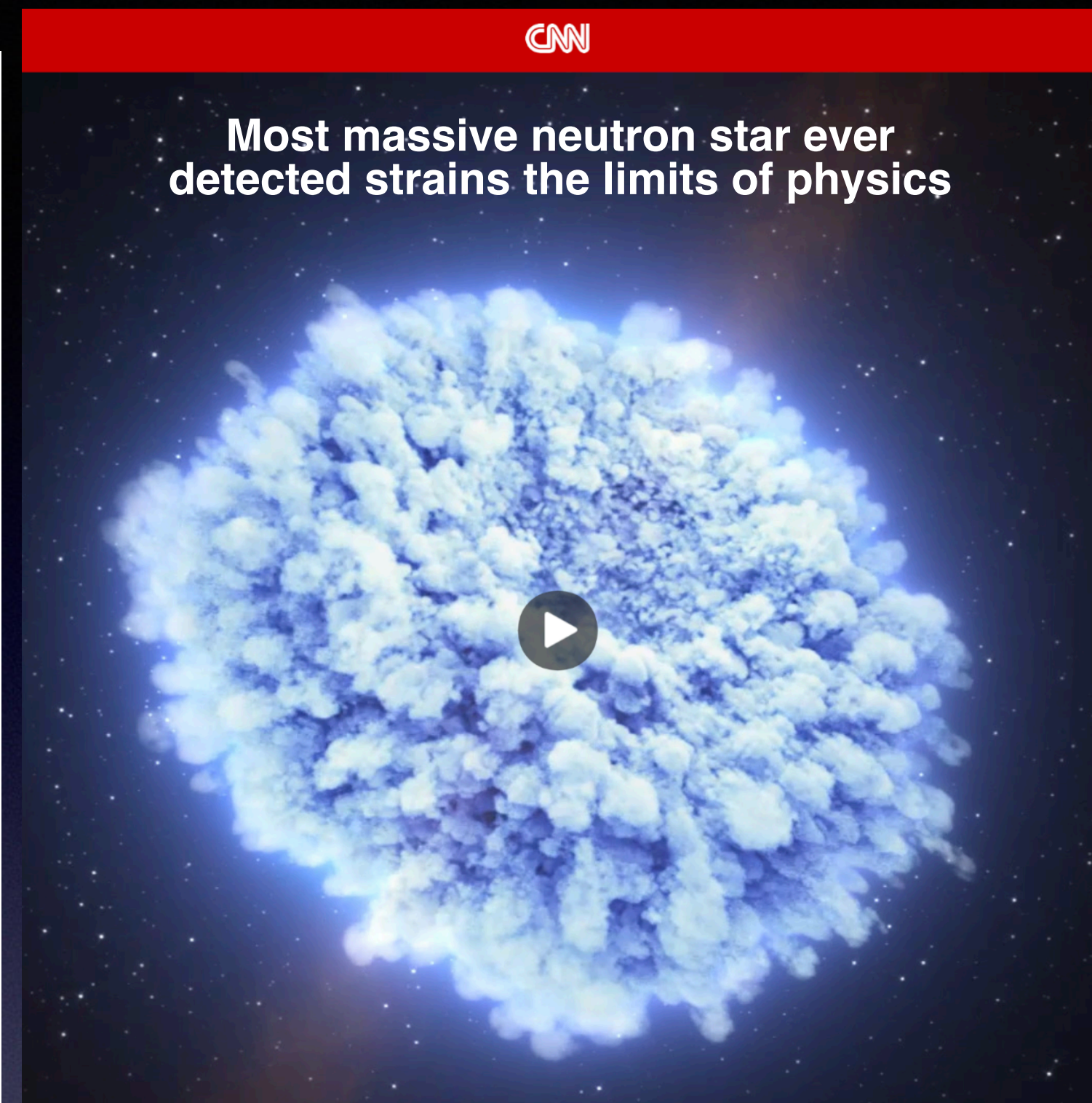
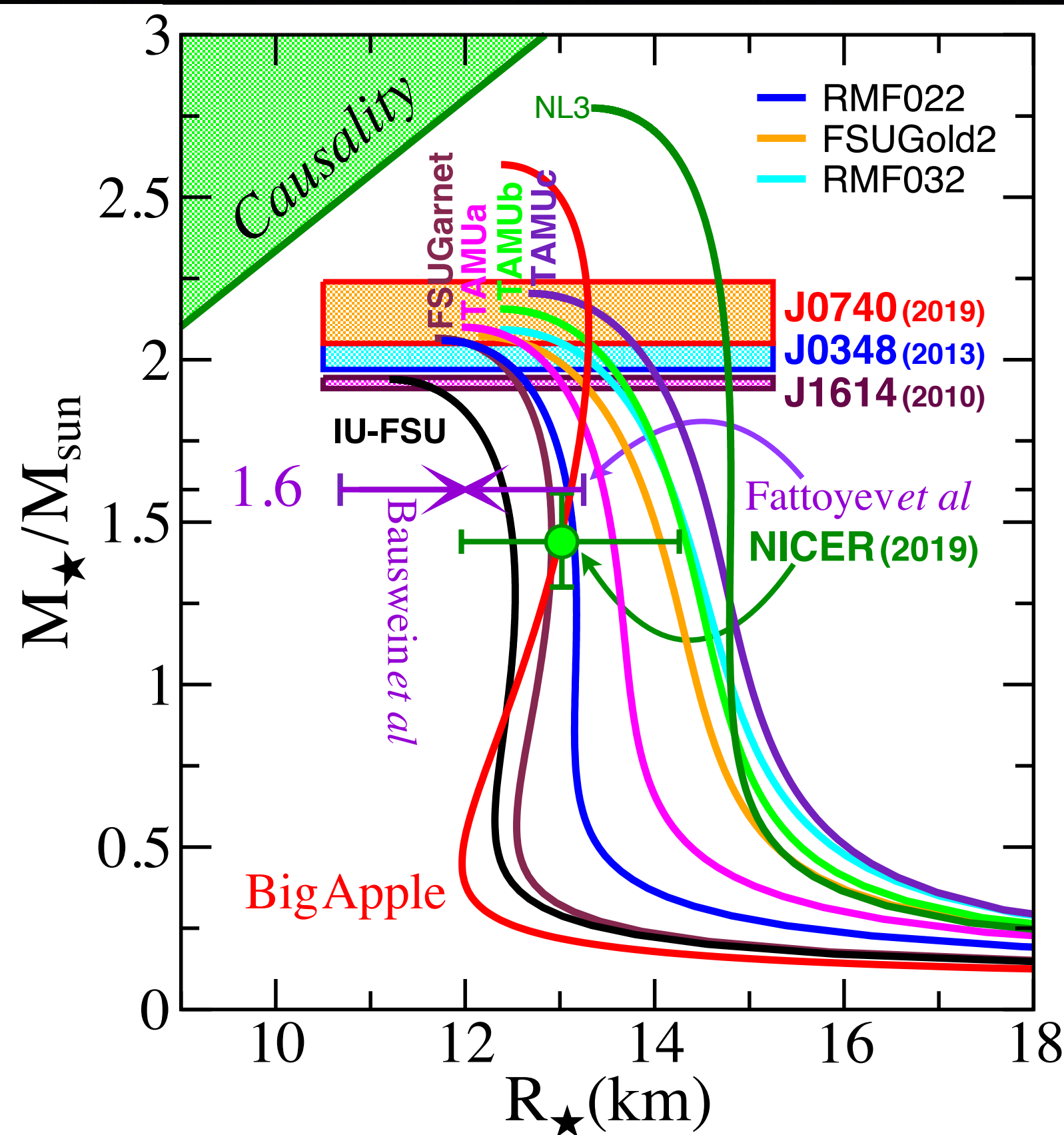
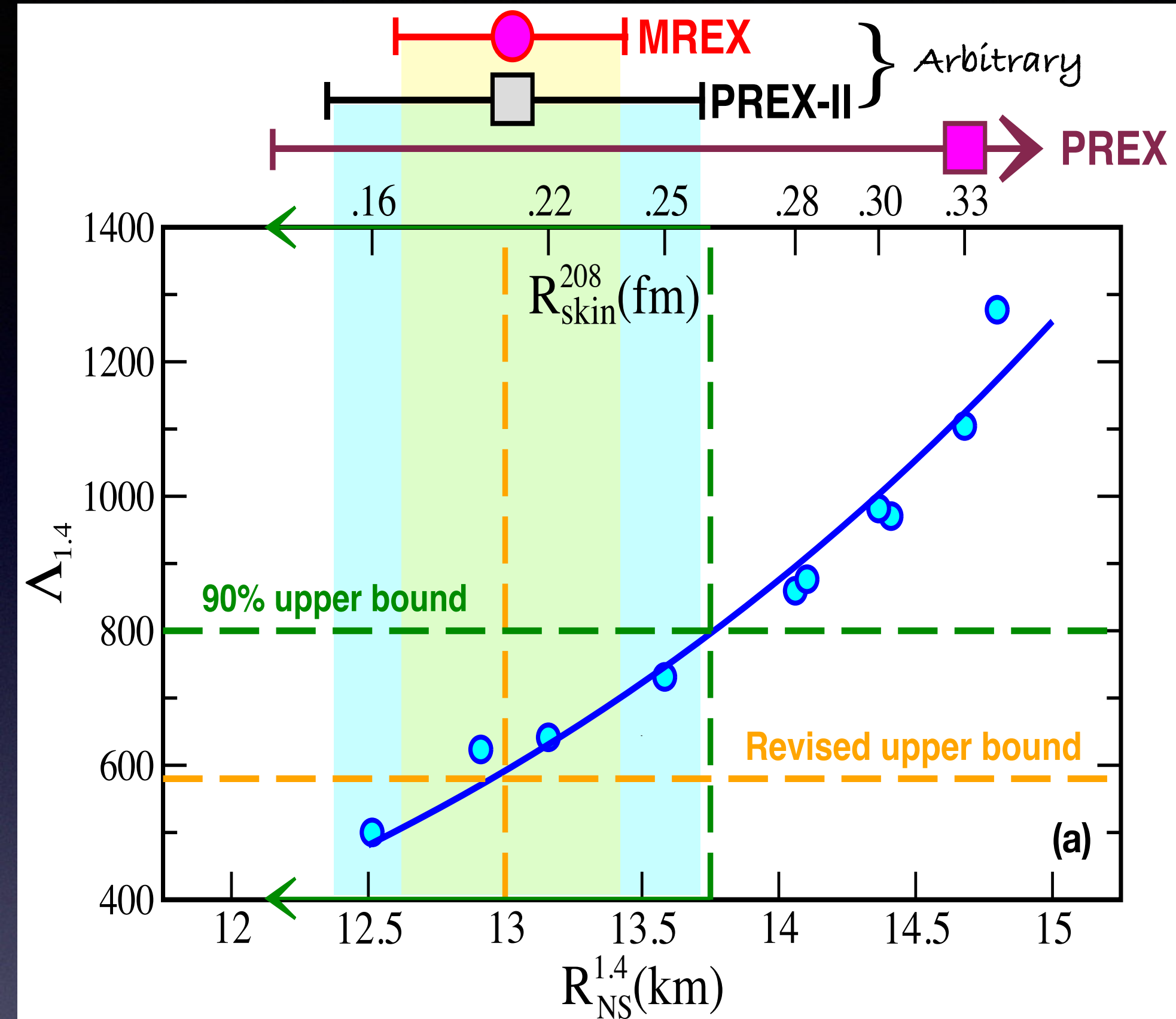


GW170817  
rules out very large  
neutron star radii!  
Neutron Stars  
must be compact

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?)**

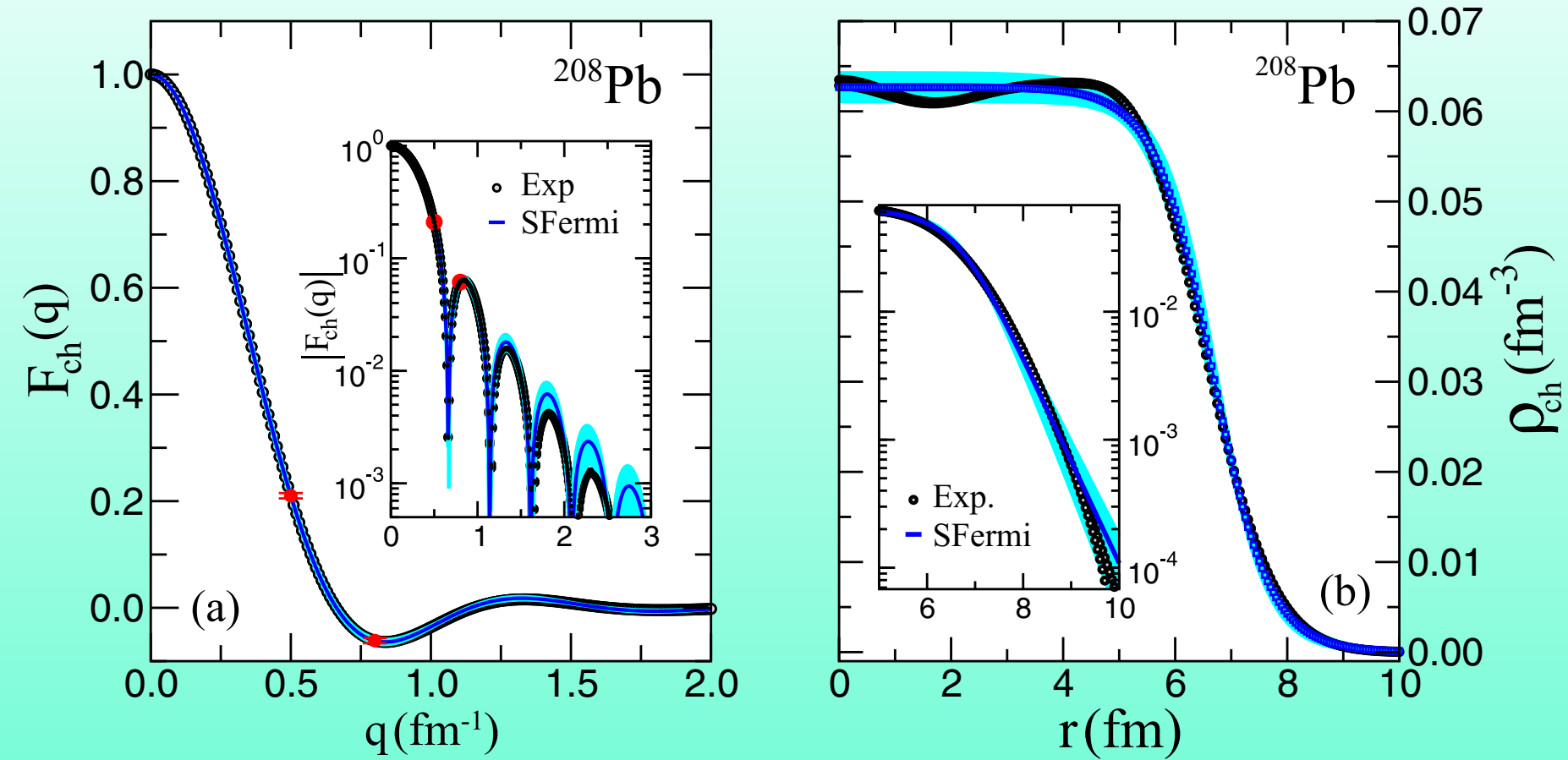


# General Discussion

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

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

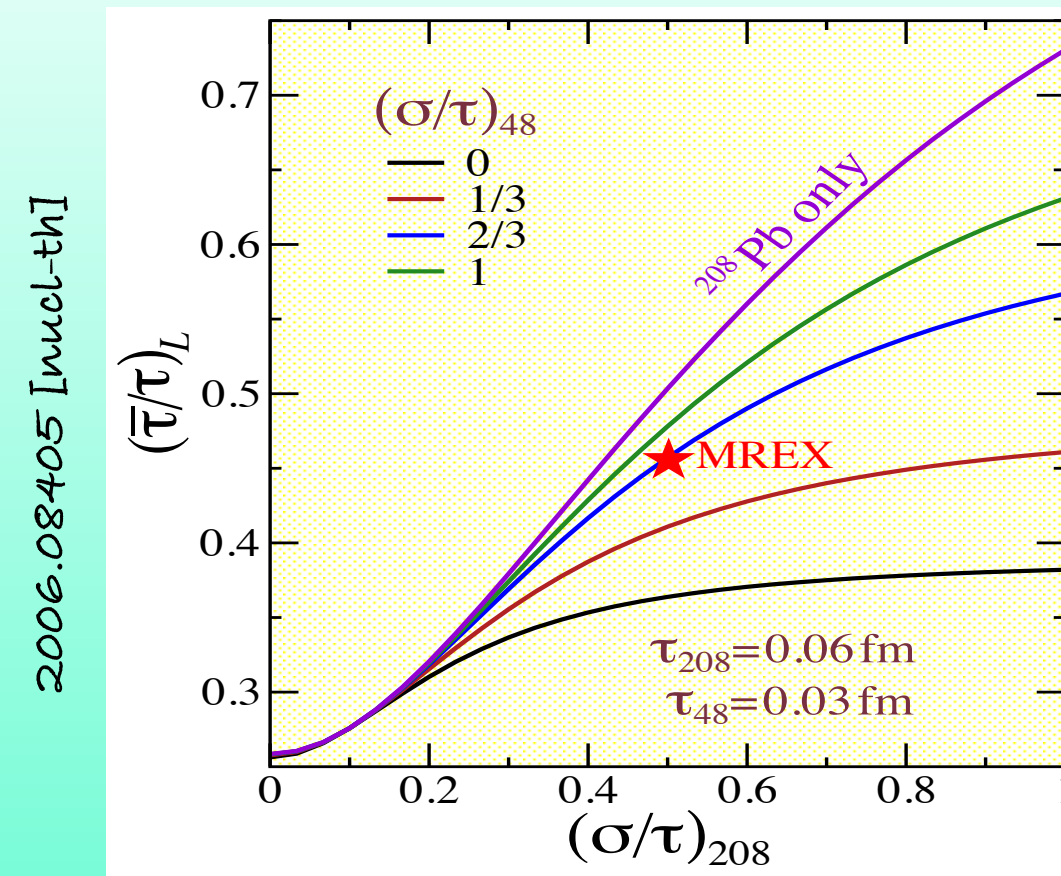
J. Piekarewicz,<sup>1,\*</sup> A. R. Linero,<sup>2,†</sup> P. Giuliani,<sup>1,‡</sup> and E. Chicken<sup>2,§</sup>



Analytic insights on the information content of new observables

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(Dated: June 16, 2020)



### GW190814

The coalescence of a black-hole and a compact, unknown companion object

**Discovery** 14 August 2019

**Distance** 800 million light years away

**3 Detectors** Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

**Binary Black Hole Merger (Probably)** We can't be sure what the lighter object is - it's either the lightest black hole we've ever observed, or possibly the heaviest neutron star.

**Unequal Masses** There is an almost nine-fold difference between the two objects' masses.

**Higher Harmonics** This event allowed the hum of higher harmonics to be measured in the signal. These are even stronger in this signal than for GW190412, thanks to the greater asymmetry between the objects' masses. These allow new tests of General Relativity. Everything continues to be consistent with Einstein's theory following these tests.

Masses: 23.2, 2.6, 25.6, 0.2 (in solar masses)

Phases: BBH?, Premerger, Merger, Remnant

## Measuring nuclear density with parity violating electron scattering

C. J. Horowitz,<sup>1,\*</sup> J. Piekarewicz,<sup>2,†</sup> and Brendan Reed<sup>1,3,‡</sup>

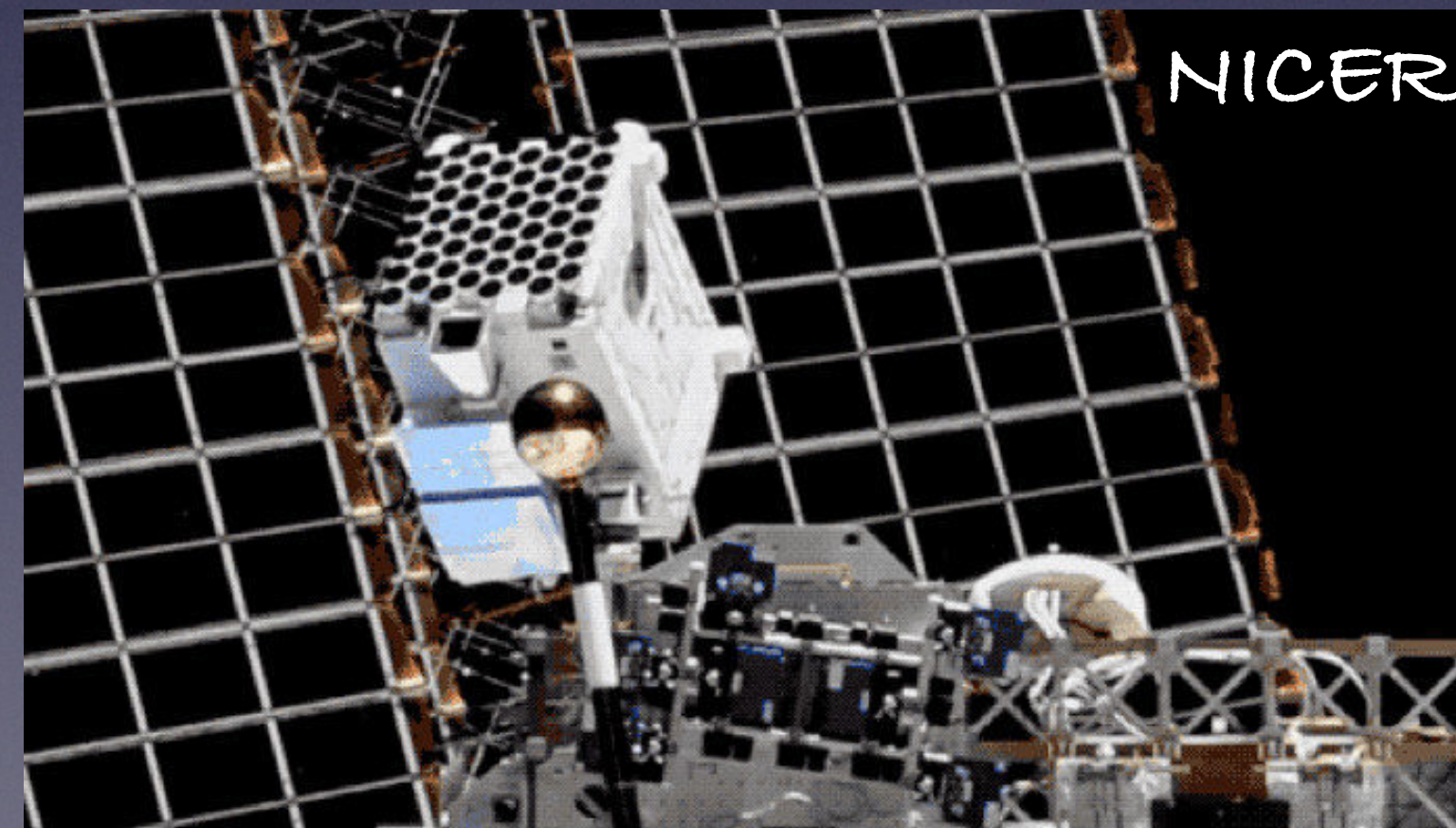
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(Dated: July 15, 2020)

The saturation density of nuclear matter  $\rho_0$  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  $^{208}\text{Pb}$ . We use parity violating electron scattering to determine the average interior weak charge and baryon densities in  $^{208}\text{Pb}$ . This requires not only measuring the weak radius  $R_{\text{wk}}$  but also determining the surface thickness of the weak charge density  $a$ . We obtain  $\rho_0 = 0.150 \pm 0.010 \text{ fm}^{-3}$ , where the 7% error has contributions from 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

