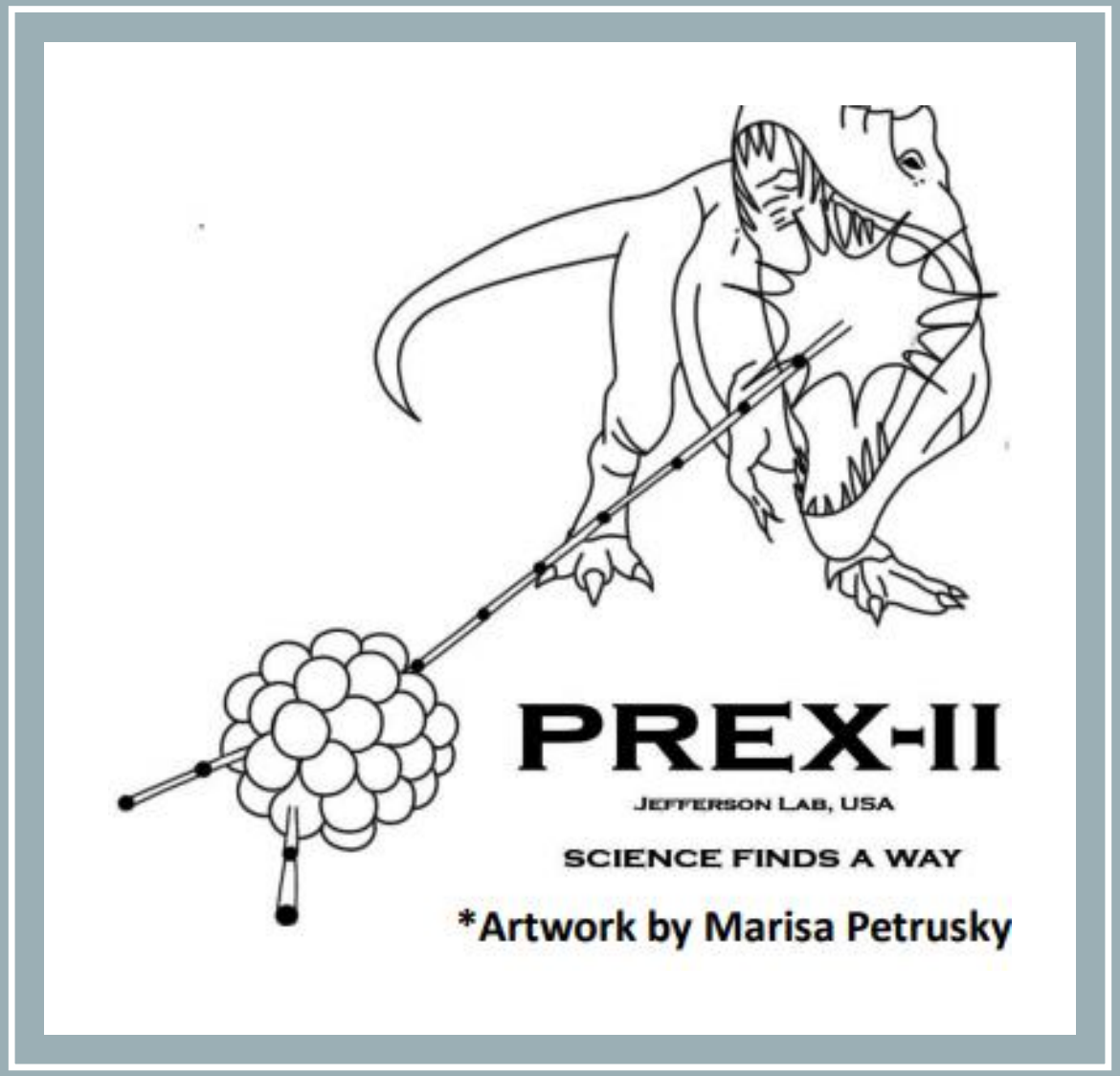


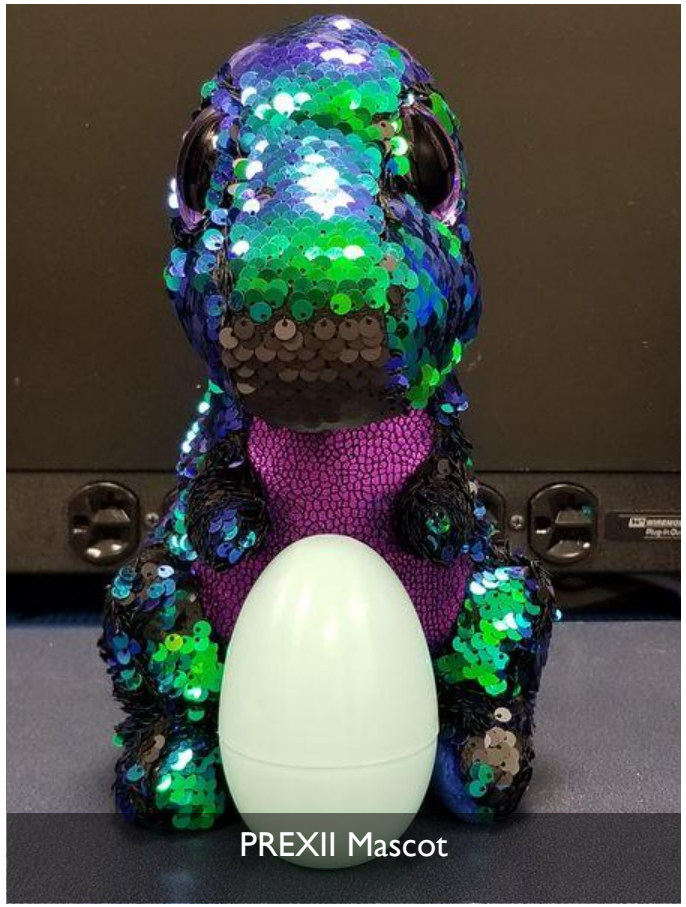
MEASURING THE WEAK CHARGE RADIUS OF PB^{208} WITH PREX-II

Brendan Reed

Indiana University

OVERVIEW

- Physics Background
- PREX-II Experiment
- Implications of results
  - Neutron matter
  - Neutron stars
  - Nuclear density
- Future experiments



PREXII Mascot

WEAK CHARGE DENSITY

EM-Charge

- EM charge densities in nuclei have been very well measured for years
- EM charge is coupled to photon
- Very good probe of the proton density

Weak Charge

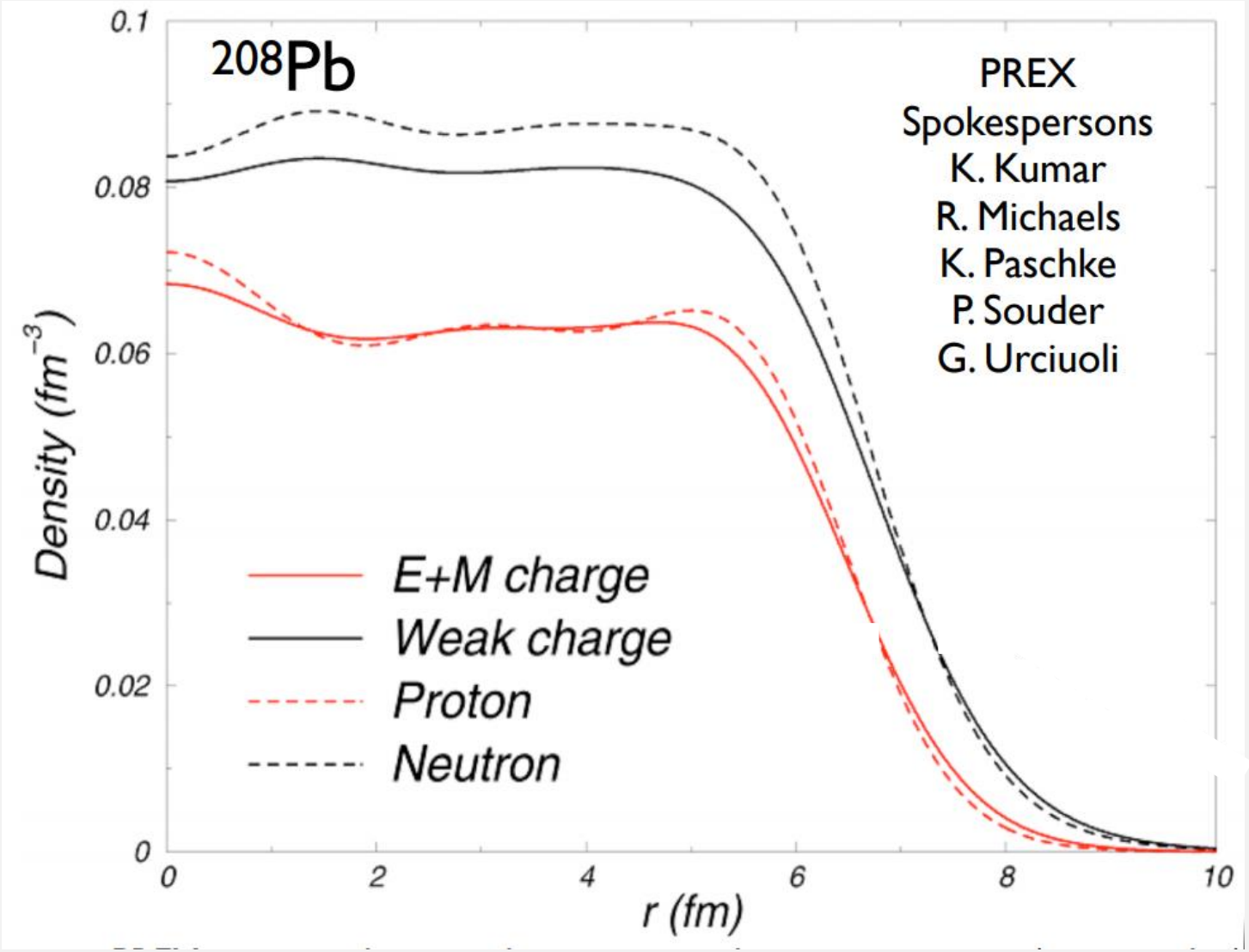
Z-boson couples to the weak charge

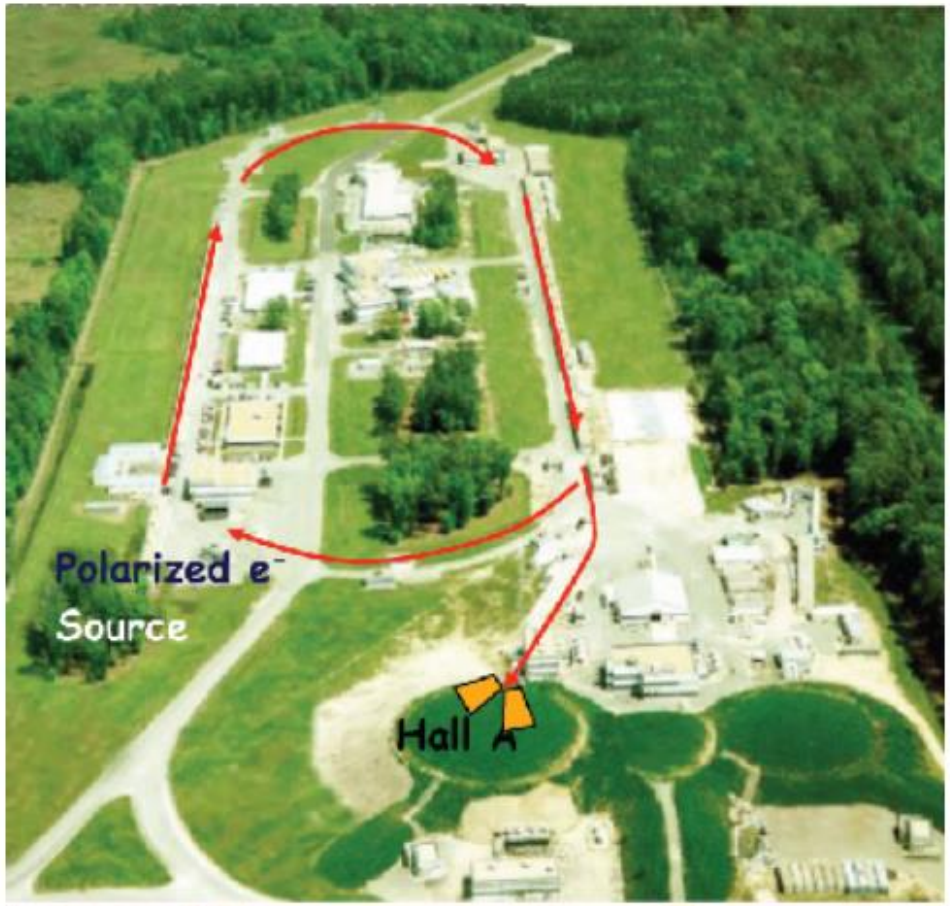
Proton weak charge is small, and the neutron weak charge is big

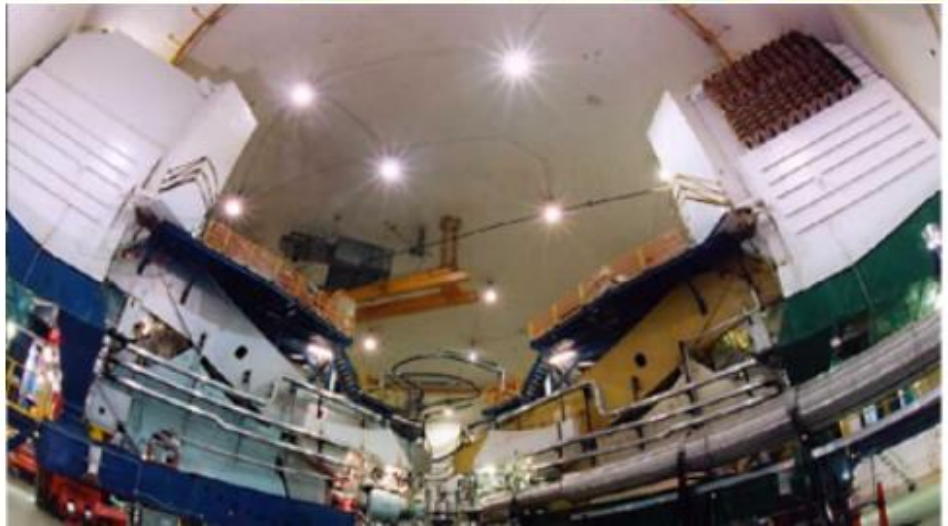
$$Q_w^p \approx -.07$$

$Q_w^n \approx .99$ → Neutrons strongly linked to weak charge of nucleus!

Can probe neutrons at low q^2 using weak interactions


208Pb
PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli
E+M charge
Weak charge
Proton
Neutron
Density (fm−3)
r (fm)
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10





PREX-II EXPERIMENT

- PREX-II ran from May-Sept. 2019 at Jefferson Laboratory
- Uses parity violating electron scattering to measure weak charge radius of Pb208
- 950 MeV electrons scattering with angle $\approx 5°$ off Pb^{208}
- q^2 average of 0.00616 GeV^2
- Elastically scattered electrons detected via two spectrometers

PARITY VIOLATING ELECTRON SCATTERING

- PV-asymmetry A_{pv} is cross section difference between (+) and (-) helicity electrons
- A_{pv} arises from photon and Z-boson exchange interference

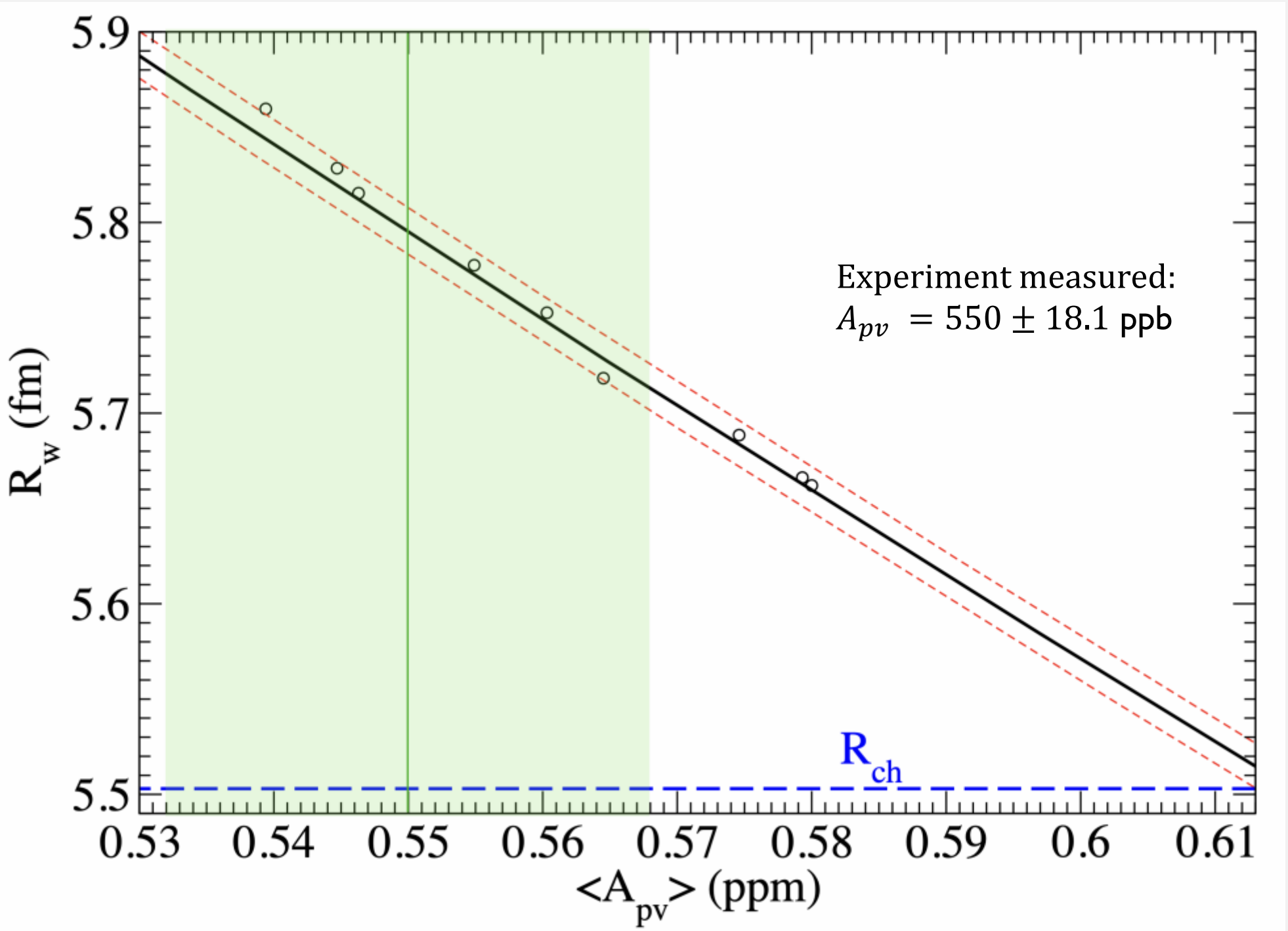
$$A_{pv} = \frac{\frac{d\sigma}{d\Omega_+} - \frac{d\sigma}{d\Omega_-}}{\frac{d\sigma}{d\Omega_+} + \frac{d\sigma}{d\Omega_-}}$$

- In Born approximation:

$$A_{pv} \approx \frac{G_F q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(q^2)}{F_{ch}(q^2)}$$

$$F_W(q^2) = \int d^3r \frac{sin(qr)}{qr} \rho_w(r)$$

- Model independent way to map out distribution of weak charge in a nucleus
- Coulomb distortions are included from numerical solution of Dirac equation


5.9
5.8
5.7
5.6
5.5
R_w (fm)
0.53
0.54
0.55
0.56
0.57
0.58
0.59
0.6
0.61
<A_{pv}> (ppm)
R_{ch}
Experiment measured:
$A_{pv} = 550 \pm 18.1$ ppb

SUMMARY OF DIRECT RESULTS

- $R_w = 5.795 \pm 0.082$ fm, **1.4% uncertainty!**
- $R_w - R_c = 0.292 \pm 0.082$ fm

  $R_c = 5.503$ fm
- Parity violating electron scattering is a very accurate method of measuring R_w

Accurate weak radii of Pb208 from PREX-II and Ca48 soon to come from CREX (in analysis)

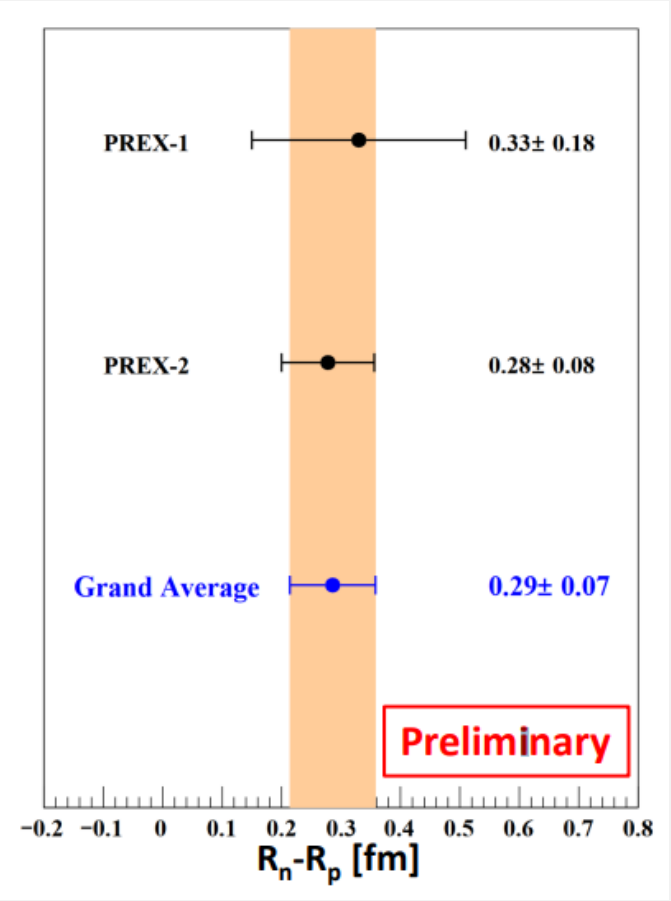
NEUTRON SKIN

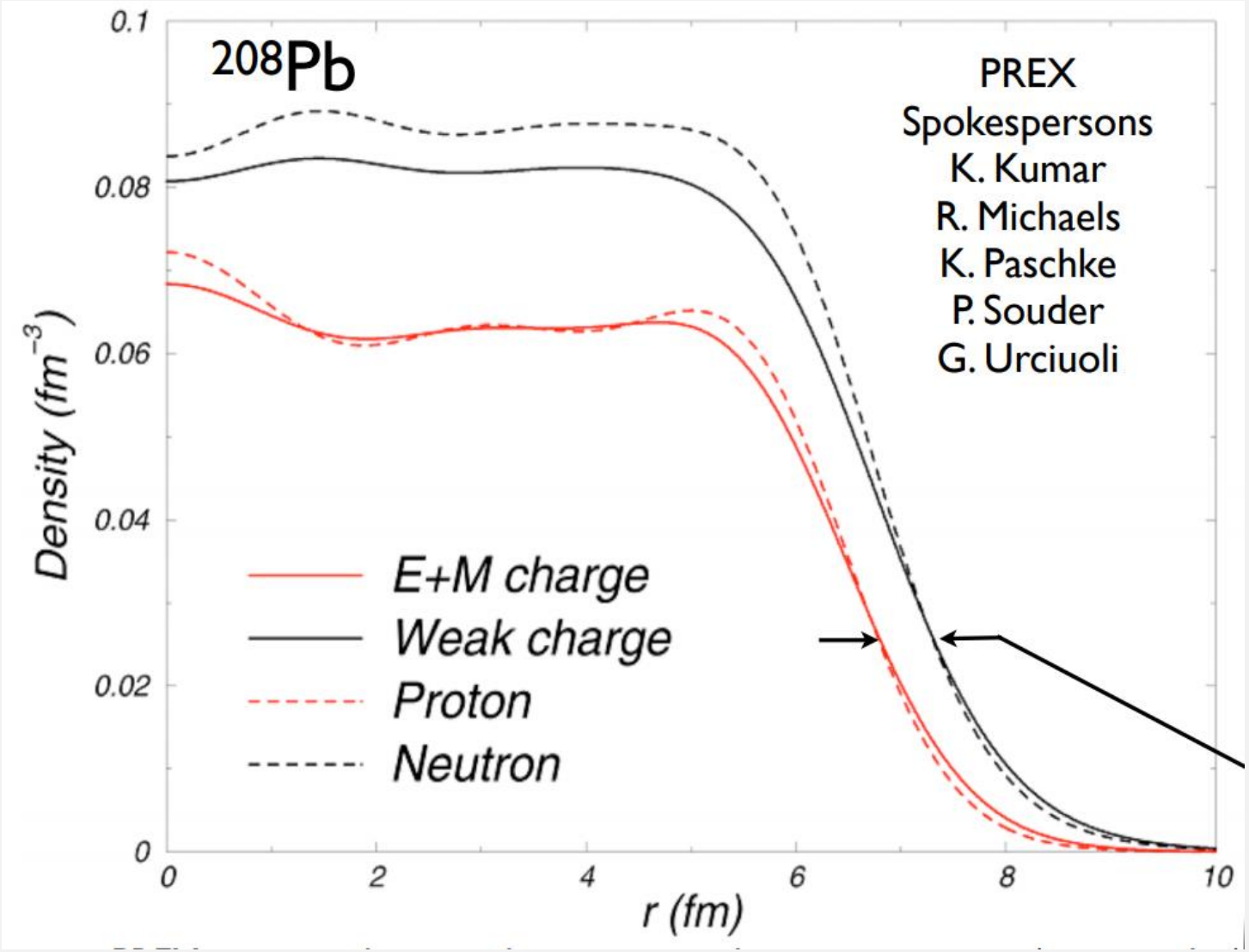
- $R_n - R_p$ is difference in point neutron and proton radius
- $R_n - R_p = \left[1 + \frac{ZQ_p}{NQ_n}\right](R_w - R_c)$
- Most published models provide this quantity
- For Pb^{208}, use experimental result for R_p and R_c

$$R_{ch} = 5.503 \text{ fm}$$

$$R_p = \sqrt{R_{ch}^2 - r_p^2} = 5.432 \text{ fm}$$

$$\boldsymbol{R_n - R_p = 0.278 \pm 0.078 \text{ fm}}$$

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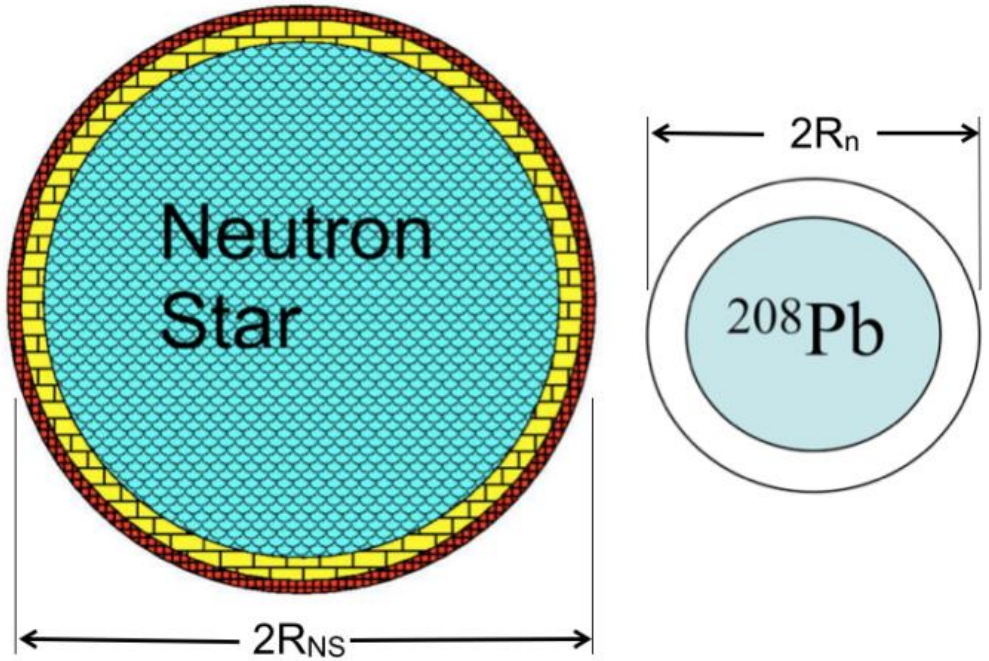
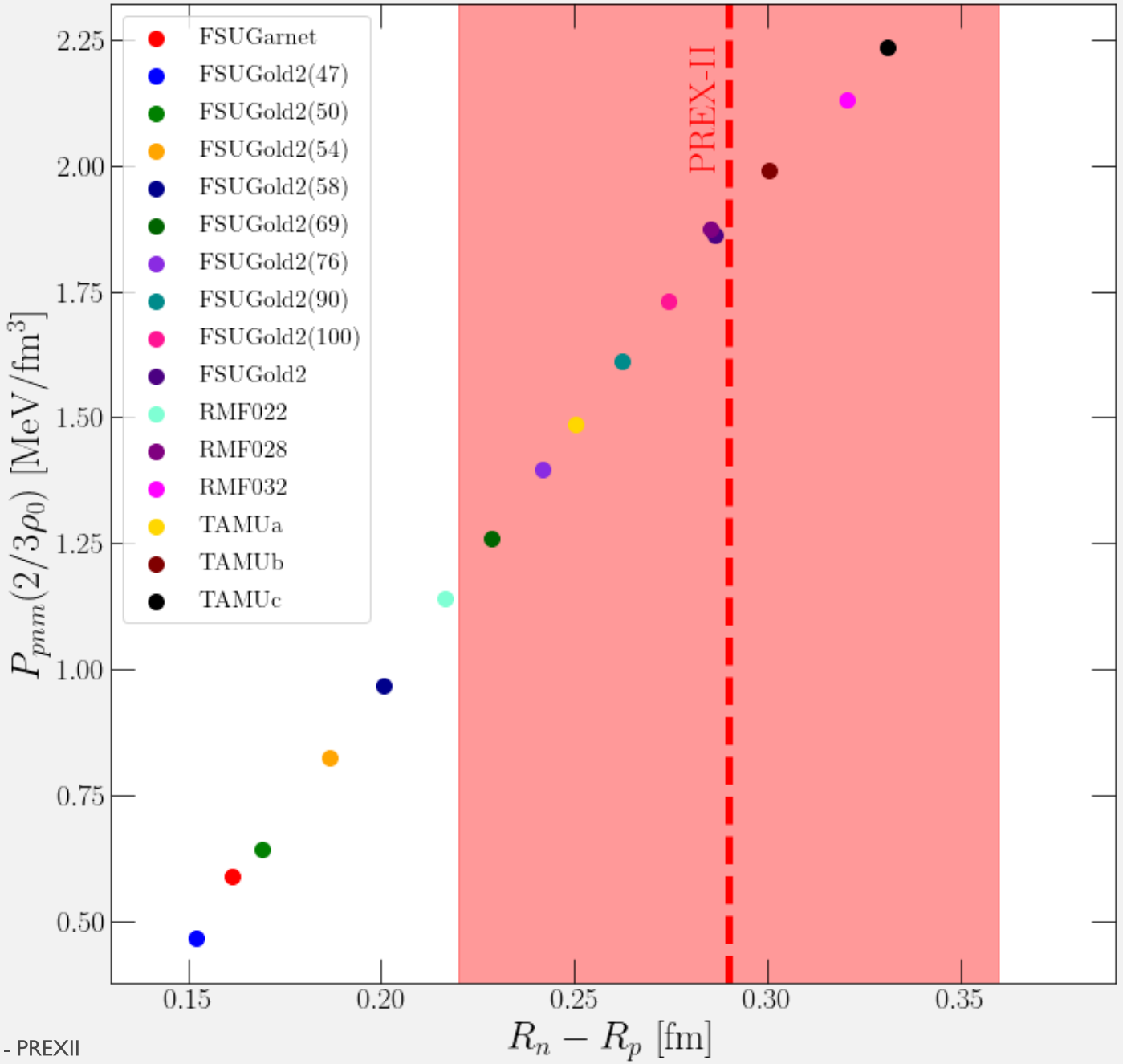
10

NEUTRON STARS AND PB208

- Pressure of neutron matter pushes neutrons out against surface tension
  - Neutron skin correlated with pressure of neutron matter
- Radius of a neutron star also depends on pressure of neutron matter
- Remarkably, PREX-II measurement has important implications on the structure of neutron stars

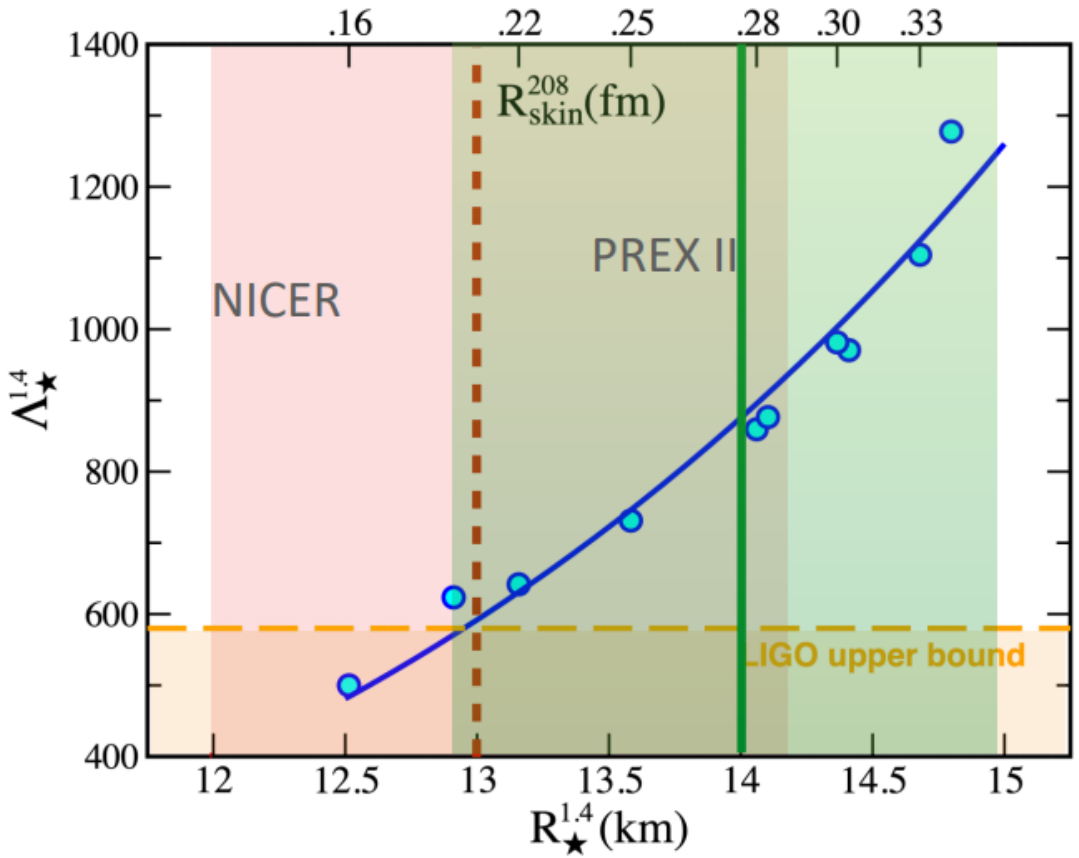




PREX-II favors medium to stiff equations of state

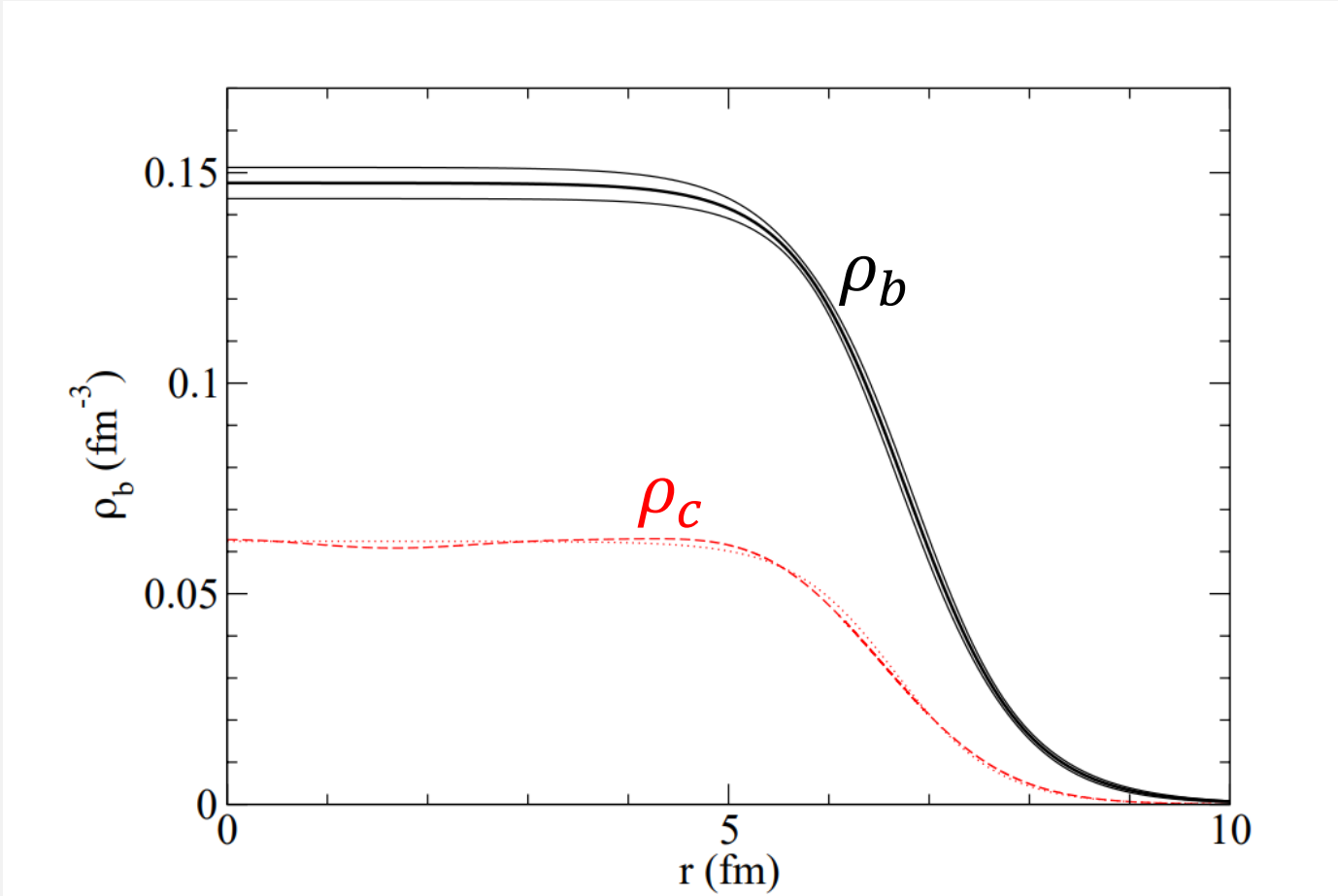
NEUTRON STARS AND PREX-II

- Can use existing models to relate calculations of all three observables
- Combining constraints from GW, NICER, and PREX-II results in this figure
- Slight tension between deformability and PREX-II
- In good agreement with NICER results
- Seem to favor moderately stiff equations of state



NUCLEAR SATURATION DENSITY

- Energy minimum of nuclear matter is at a density, n_0
- This is fundamental to nuclear structure
- Very hard to calculate even with Chiral EFT
  - Many dynamical effects necessary for accuracy
- Interior baryon density of heavy nuclei should be approximately constant and equal to n_0
- Direct measurement never cleanly observed, Ca40 too small



INTERIOR WEAK CHARGE DENSITY

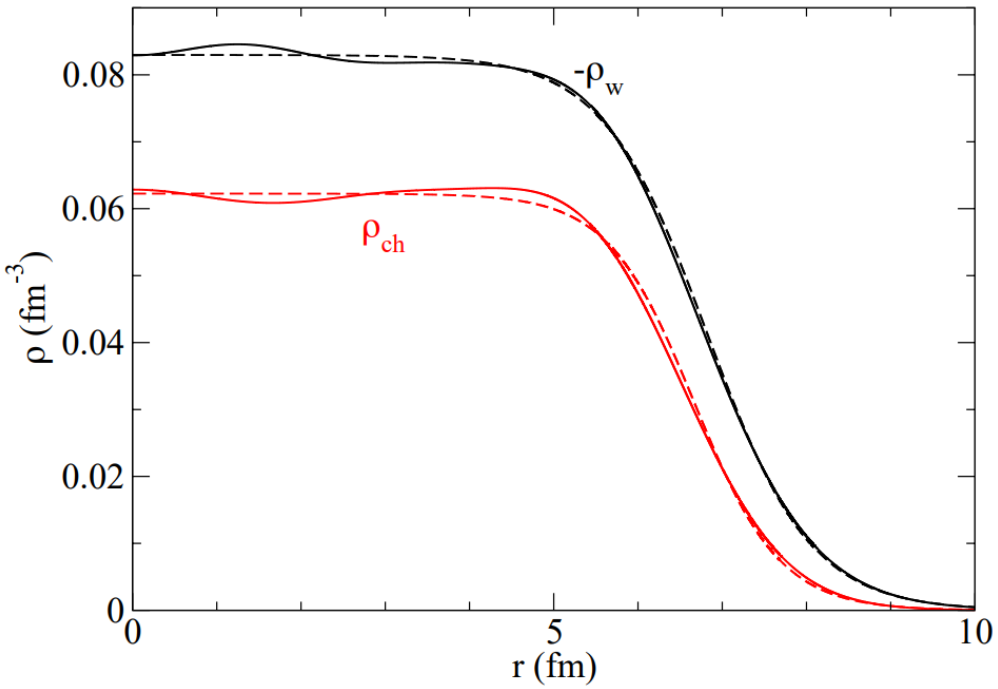
- Can calculate the average interior weak charge density of Pb208 using a 2-parameter Fermi function

$$\rho_w(r,c,a) = \rho_w^0 \frac{\sinh\left(\frac{c}{a}\right)}{\cosh\left(\frac{r}{a}\right) + \cosh\left(\frac{c}{a}\right)}$$

$$\rho_w^0 = \frac{3Q_w}{4\pi c(c^2 + \pi^2 a^2)}$$

$$R_w^2 = \frac{1}{Q_w}\int r^2 \rho_w(r) d^3r = \frac{3}{5}c^2 + \frac{7}{5}(\pi a)^2$$

$$\rightarrow \quad \rho_w^0 = \frac{27Q_w}{4\pi(5R_w^2 - 4\pi^2 a^2)\sqrt{15R_w^2 - 21\pi^2 a^2}}$$



- Have constraints on a from theory
- Can measure with 2nd PVE experiment

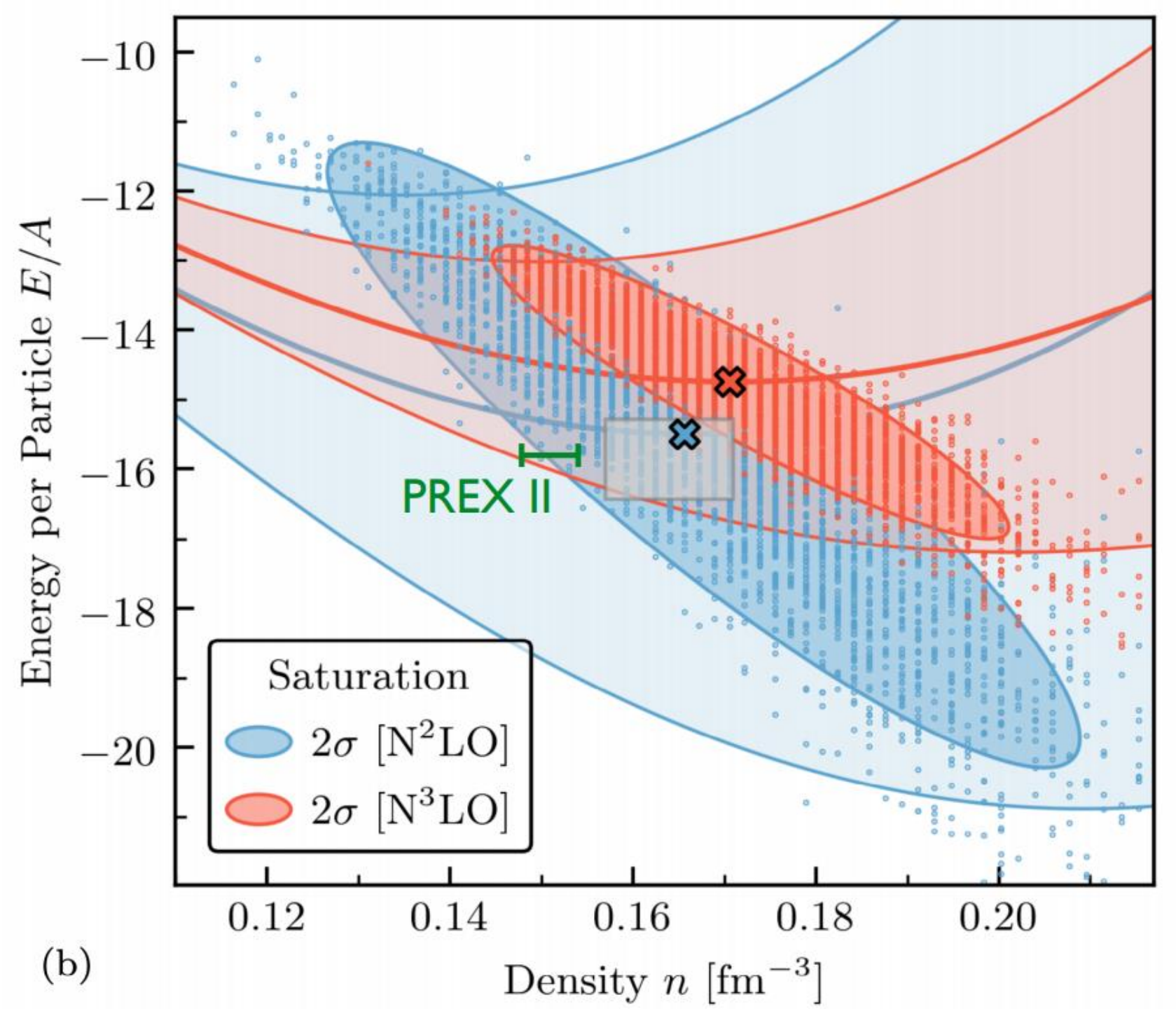
INTERIOR DENSITY EXTRAPOLATION

$$\rho_w^0 = \frac{27Q_w}{4\pi(5R_w^2 - 4\pi^2a^2)\sqrt{15R_w^2 - 21\pi^2a^2}}$$

- $R_w = 5.795 \pm 0.082$ fm
- Assume $a = 0.605 \pm 0.025$ fm from theory
- $Q_w = NQ_w^n + ZQ_w^p = -118.78$
- $\rho_w^0 = 0.080 \pm 0.004\ fm^{-3}$

$$\rho_b^0 = \frac{-\rho_w^0}{q_n} + \left(1 - \frac{q_p}{q_n}\right)\rho_c^0$$

$$\boldsymbol{\rho_b^0 = .148 \pm .004\ fm^{-3}}$$


−10
−12
−14
−16
−18
−20
Energy per Particle E/A
PREX II
Saturation
2σ [N^{2}LO]
2σ [N^{3}LO]
0.12
0.14
0.16
0.18
0.20
(b)
Density n [fm^{-3}]

FUTURE

- NICER has more data, expect modest improvements in near future
- GW170817 was a lucky event, most recent observing run didn't detect anything comparable. LISA space interferometer expected to have 10 times LIGO/VIRGO sensitivity
- CREX will measure R_w in Ca48
- Mainz laboratory "Super PREX" in the works to further improve PREX-II

CONCLUSION

- PREX-II uses parity violating electron scattering to probe the neutron density in Pb^{208}
- PVE scattering measures R_w with incredibly high precision
- This measurement has several implications on a variety of nuclear systems
- Suggests weak tension with GW observations, favors moderately stiff equations of state in neutron stars
- PREX-II has helped constrain the saturation density of nuclear matter

Big thanks to my graduate advisor
Charles Horowitz and all the people
involved in the PREX-II collaboration