Nuclear weak form factors

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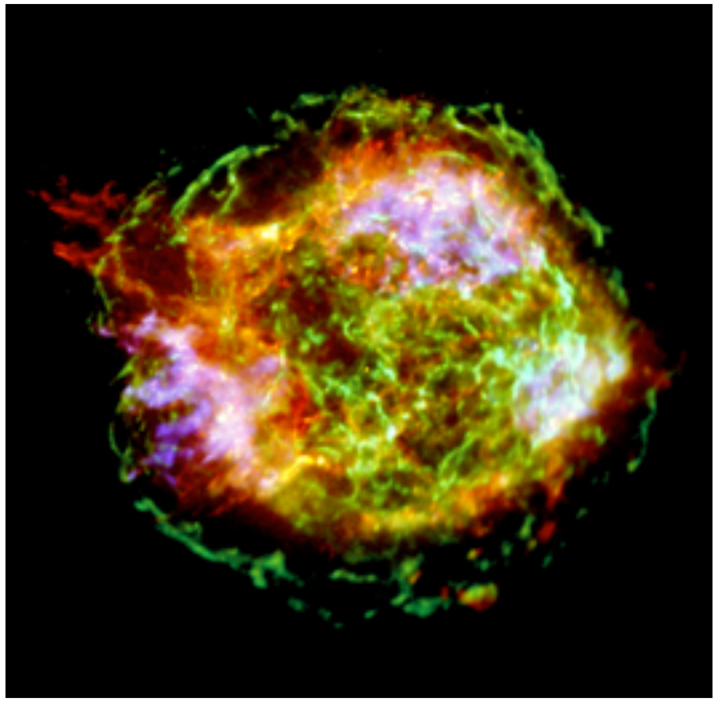
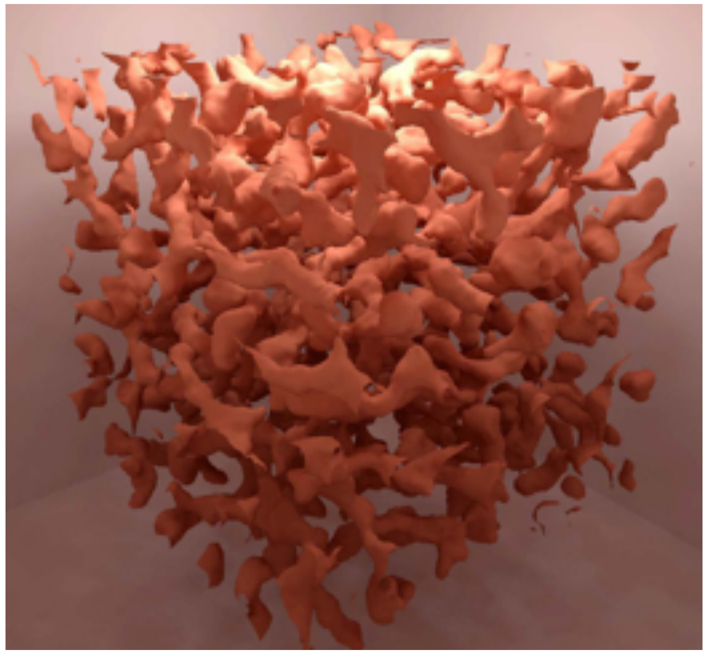
Neutron Rich Matter

- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?
- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor (T_c=10^{10} K!), superfluid, color superconductor...*



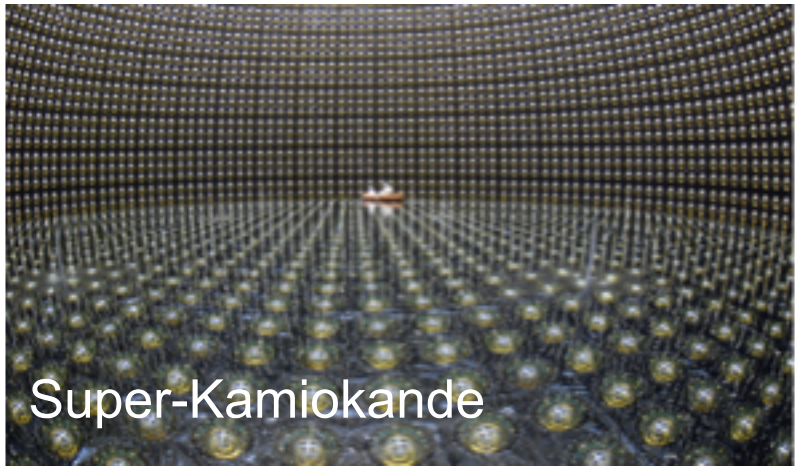
Supernova remanent Cassiopea A in X-rays



MD simulation of Nuclear Pasta with 100,000 nucleons

Neutron rich matter can be studied in the lab. and in the heavens

- **Supernova neutrinos** carry unique flavor information related to nucleosynthesis.
- **Gravitational waves:** Expect historic first detection very soon.
- **Laboratory Experiments:** neutron skin thickness of ^{208}Pb, ^{124}Sn or ^{48}Ca via parity violating electron scattering. Preliminary measurement at JLAB in US, good possibilities at Mainz.

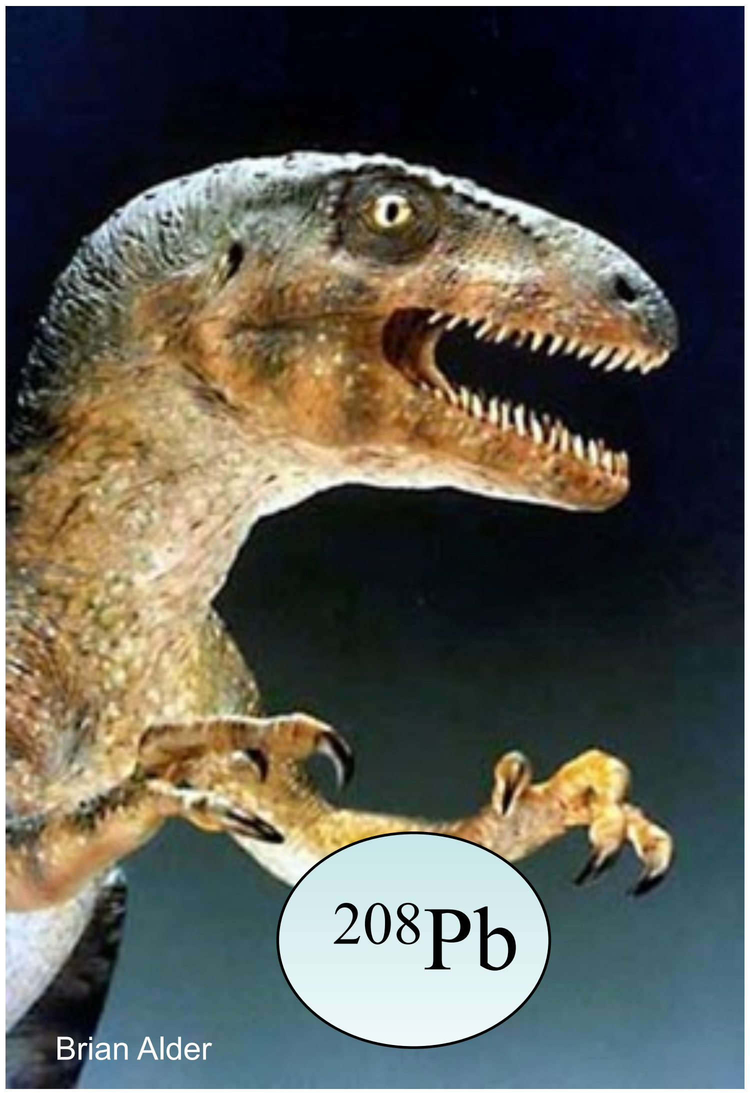


Galileo's Crime

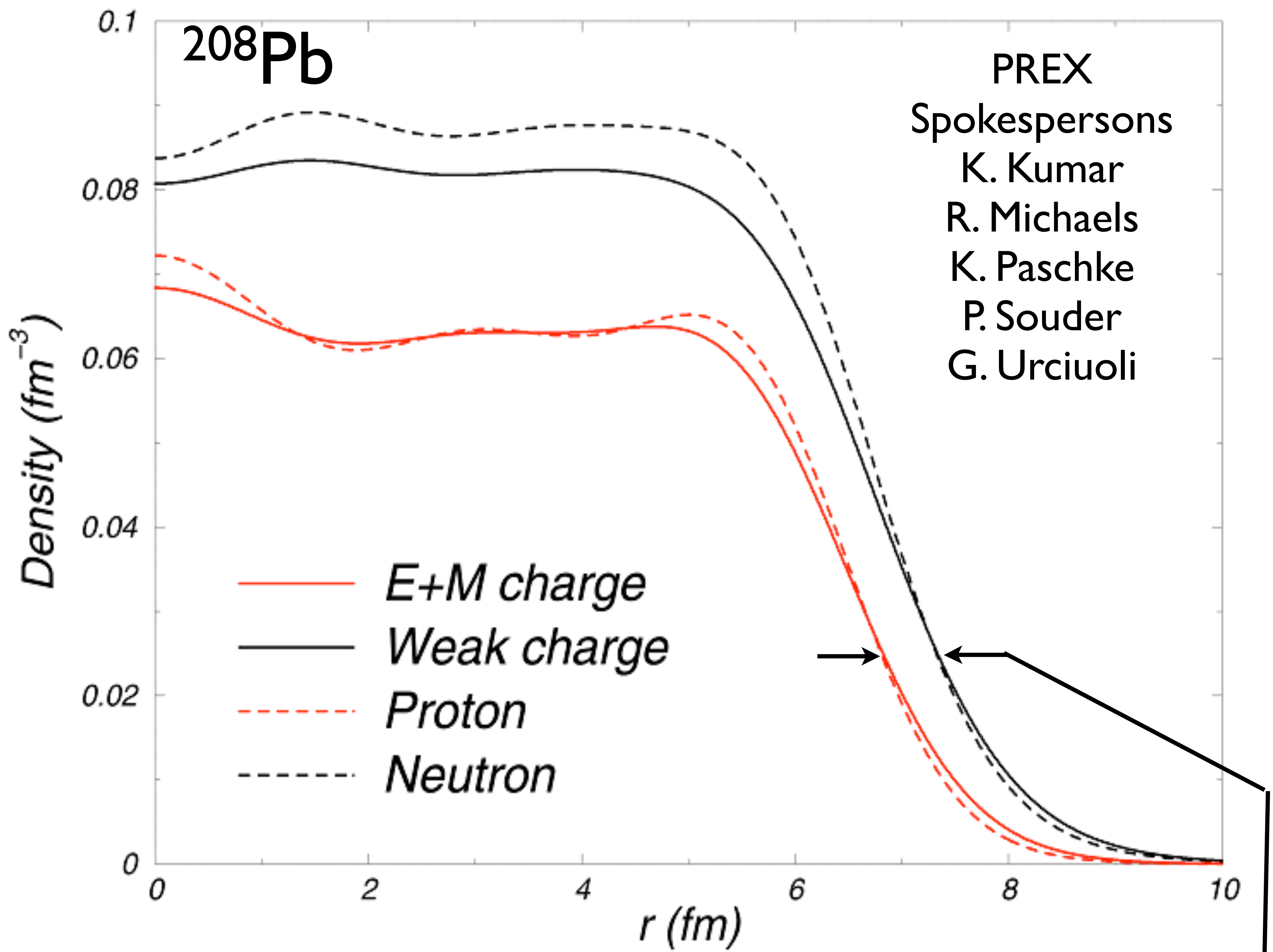
- In they eyes of the church was to assume both the laboratory and the heavens are made of the same material.
- For Newton the material was mass.
- In 19th century it was chemical elements. Observation that spectral lines are the same in lab and in stars created astrophysics.
- 21st century is beginning to address if life is the same in the heavens as on earth.
- Consider neutron rich matter. In astrophysics and in the laboratory it has the same neutrons, the same strong interactions, and the same equation of state.

- A measurement in one domain (astronomy or the lab) has important implications in the other domain.

Probing neutron rich matter in Lab.

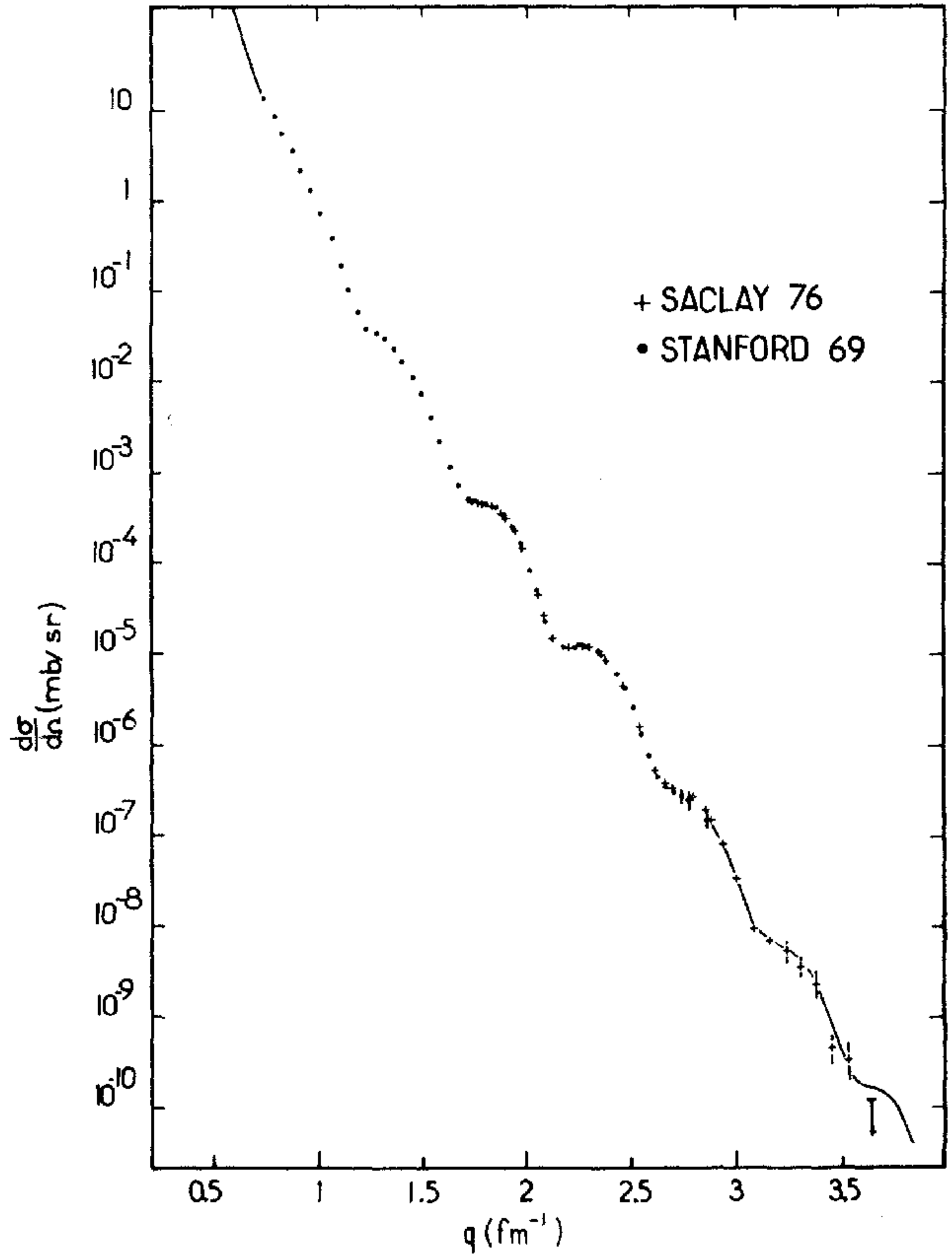


- Heavy nuclei are expected to have neutron rich surface region and this can be probed with sensitive experiments.
- **PREX** uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb. This has important implications for neutron rich matter and astrophysics.
- Can also study more neutron rich radioactive nuclei at GSI/FAIR or FRIB.

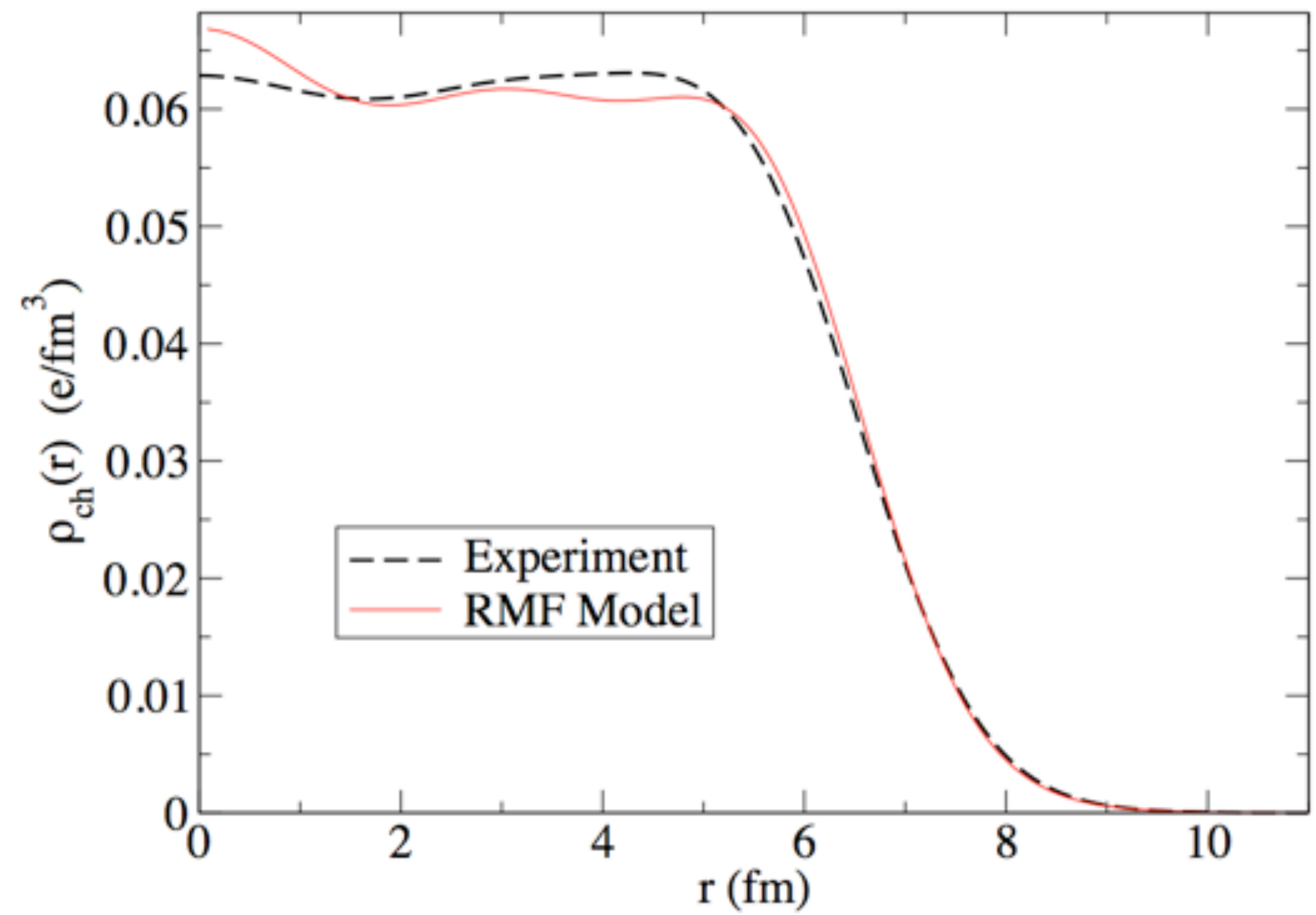


- PREX measures how much neutrons stick out past protons (neutron skin).

Charge Density of ^{208}Pb, accurately measured in elastic electron scattering.



Cross section measured over 12 orders of magnitude.



These elastic charge densities ***are*** our picture of the atomic nucleus!

Parity Violation Isolates Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

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

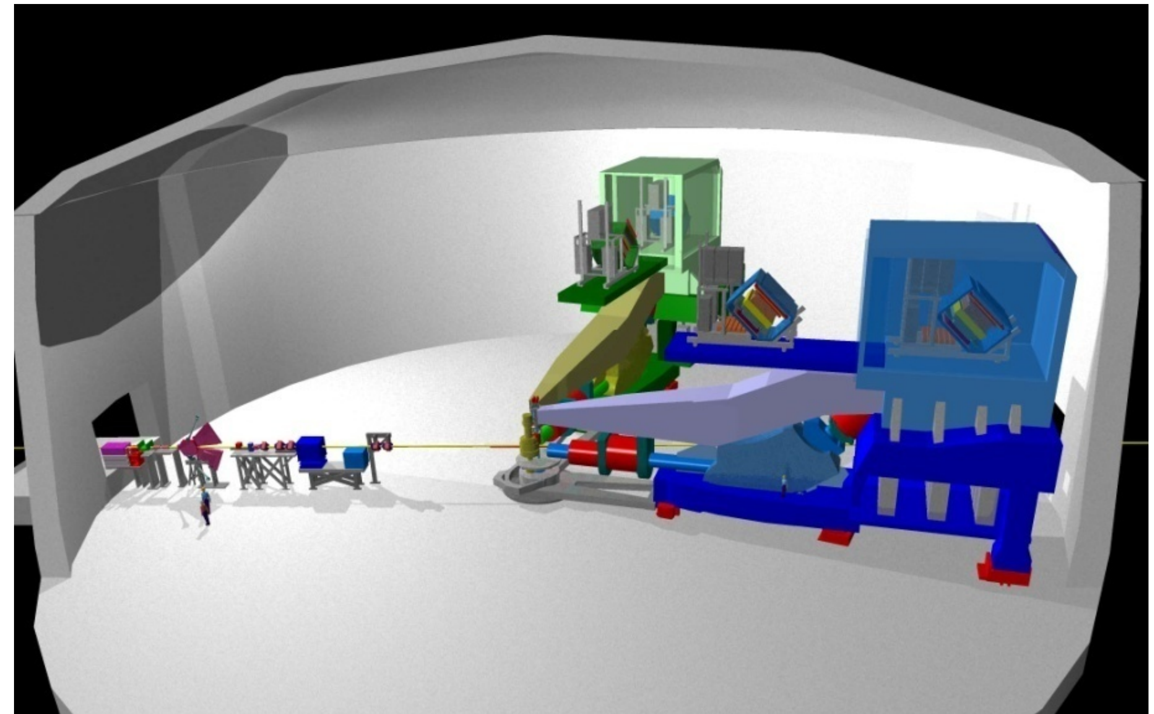
- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

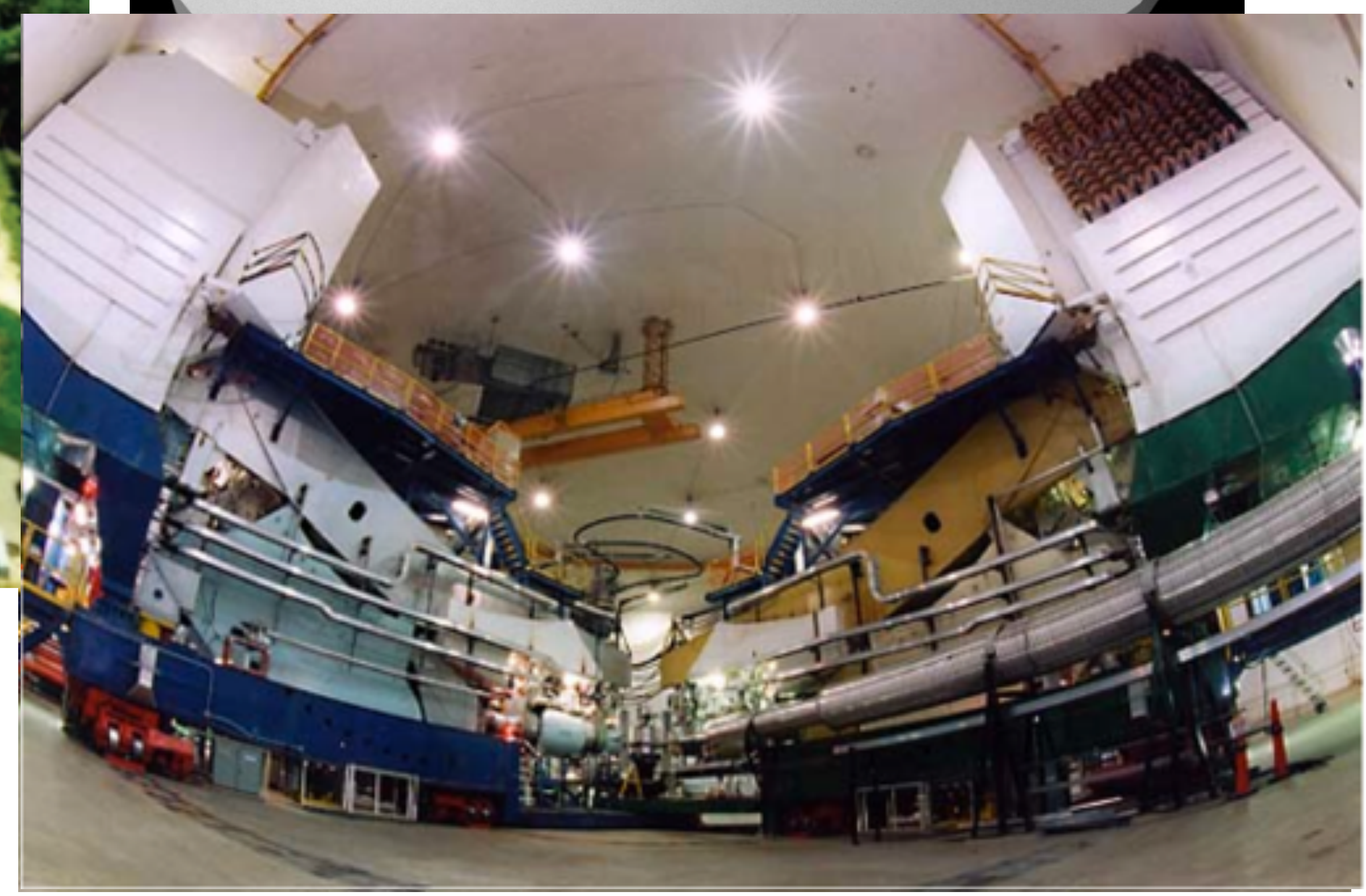
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\text{ch}}(Q^2)}$$

$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**
  - Donnelly, Dubach, Sick first suggested PV to measure neutrons.

Hall A at Jefferson Lab

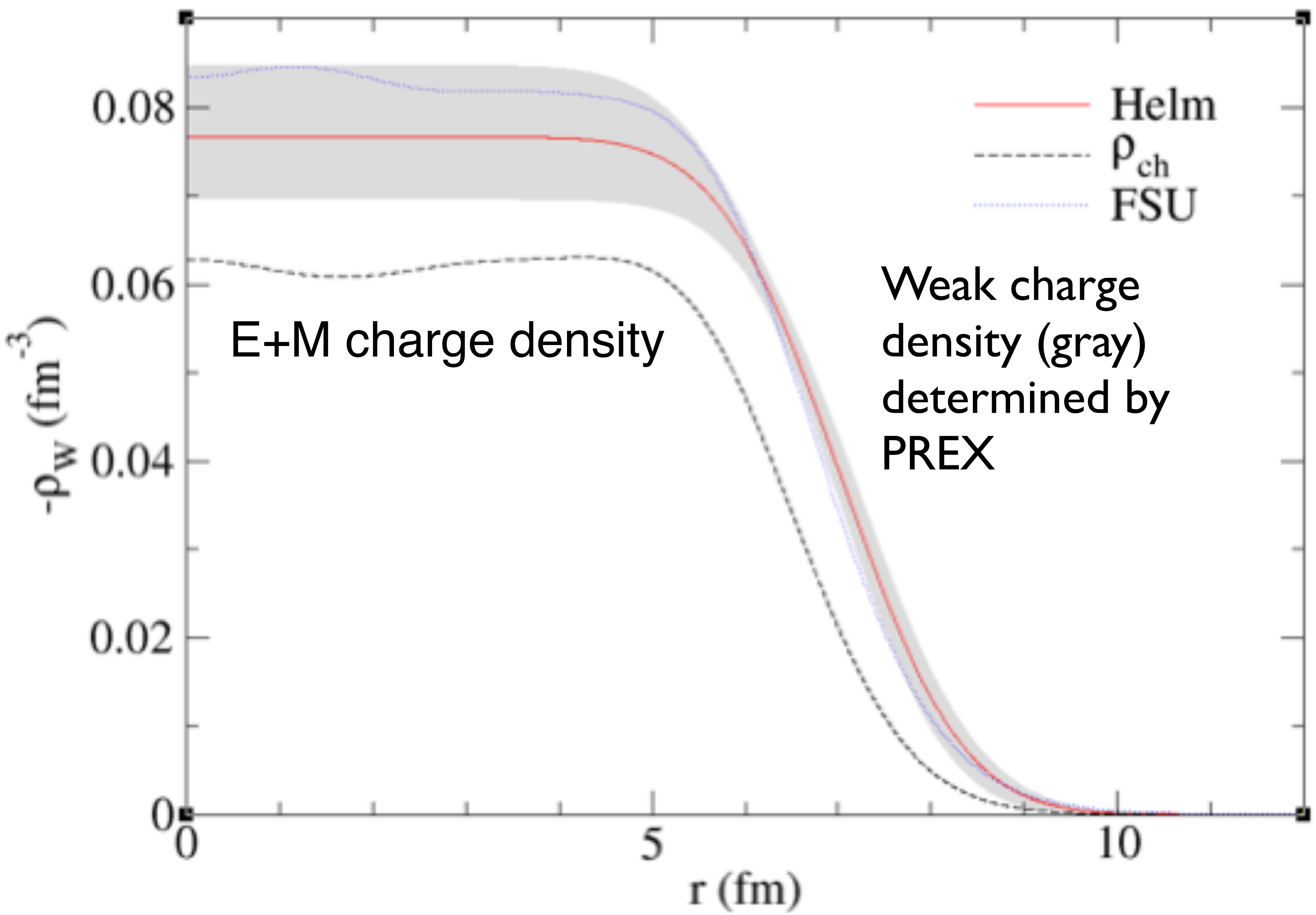




R. Michaels, JLAB

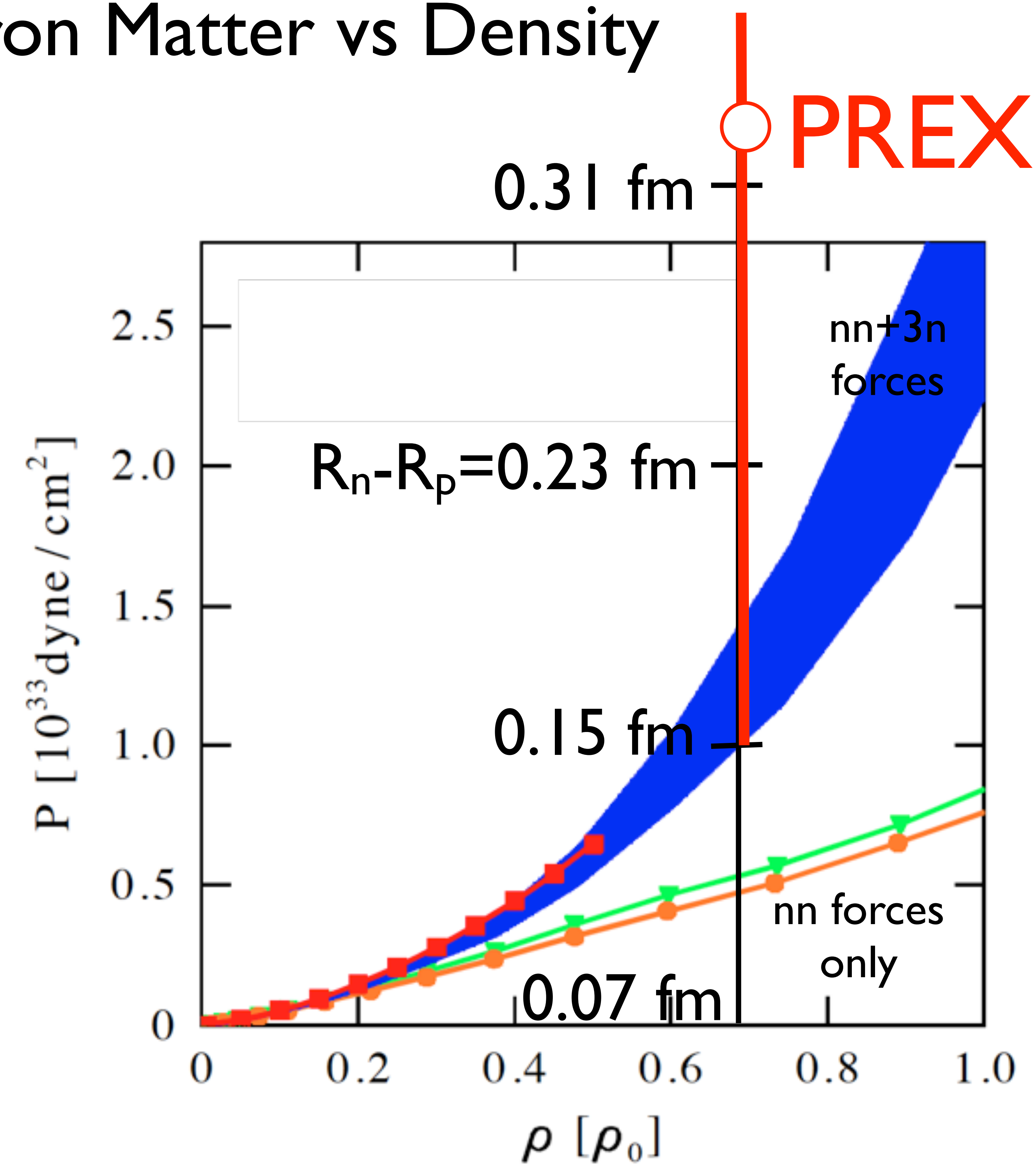
PREX results from 2010 run

- 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb
- **A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm**
- Weak form factor at $q=0.475\ fm^{-1}$: $F_W(q) = 0.204 \pm 0.028$
- Radius of weak charge distr. $R_W = 5.83 \pm 0.18$ fm
- Compare to charge radius R_{ch}=5.503 fm --> weak skin: $R_W - R_{ch} = 0.32 \pm 0.18 \pm 0.03$ fm
- First observation that weak charge density more extended than (E+M) charge density --> weak skin.
- Unfold nucleon ff--> neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- Phys Rev Let. **108**, 112502 (2012), Phys. Rev. C **85**, 032501(R) (2012)



Pressure of Neutron Matter vs Density

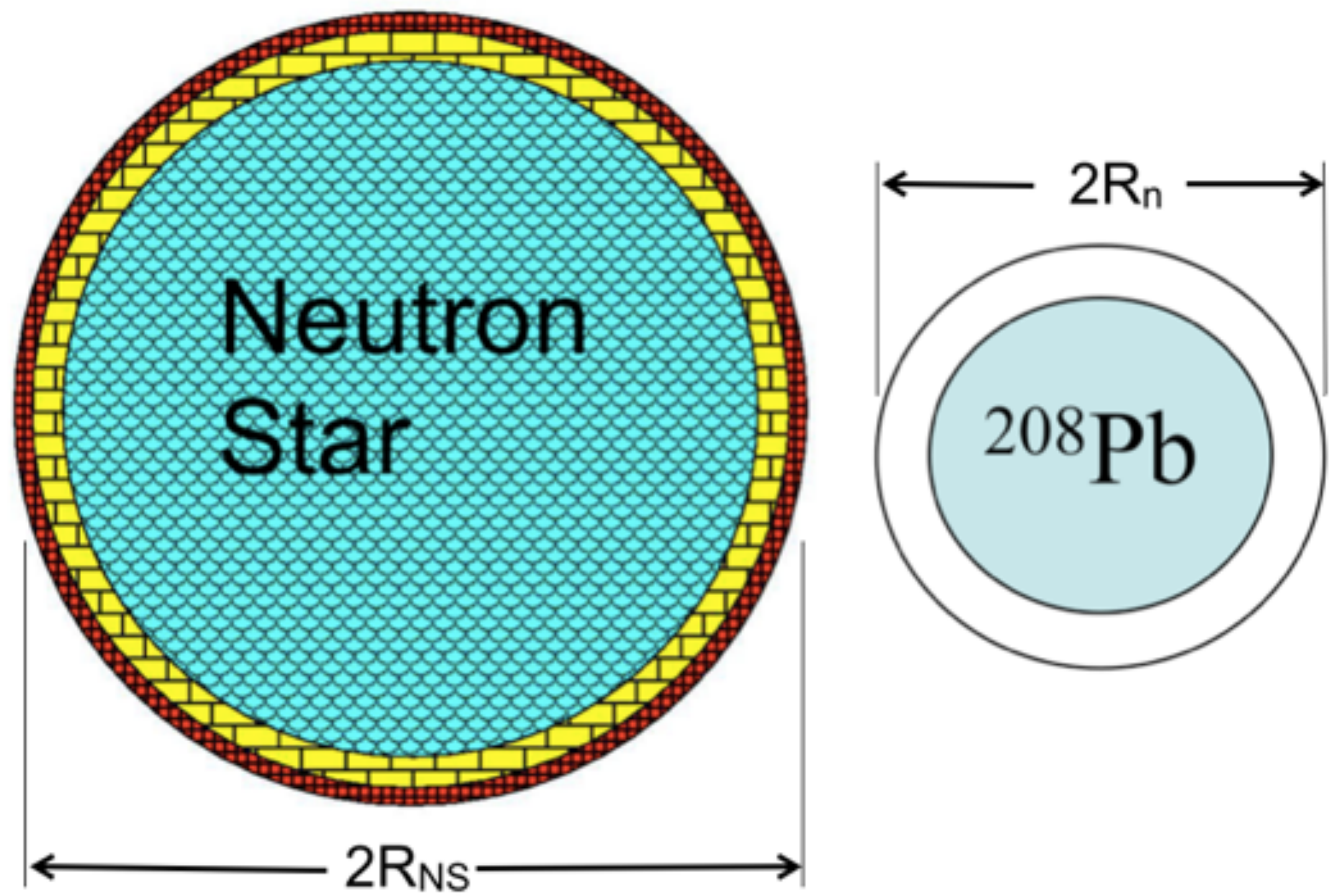
- Alex Brown found strong correlation between $R_n(^{208}Pb)$ and pressure of neutron matter at $2/3\rho_0$.
- Chiral EFT calc. of pressure of neutron matter by Hebeler et al. including three *neutron* forces (blue band) PRL**105**, 161102 (2010)
- PREX agrees with results including 3n forces. Three *neutron* forces are very interesting, unconstrained.



The Laboratory and the Heavens

- Pressure of neutron matter pushes neutrons out against surface tension in ^{208}Pb or out against gravity in a NS.
- PREX result R_n-R_p =0.33 fm suggests a large radius of about 14 km for a 1.4M_{sun} NS, however the error bar is large.
- Follow up laboratory measurements should reduce error in neutron skin thickness.
- X-ray observations yield somewhat controversial NS radii. New missions NICER, Athena will help

Neutron Star radius versus ^{208}Pb Radius



Neutron star is 18 orders of magnitude larger and 55 orders of magnitude more massive but both contain the same neutrons with the same strong interactions and equation of state.

PV Neutron Density Experiments

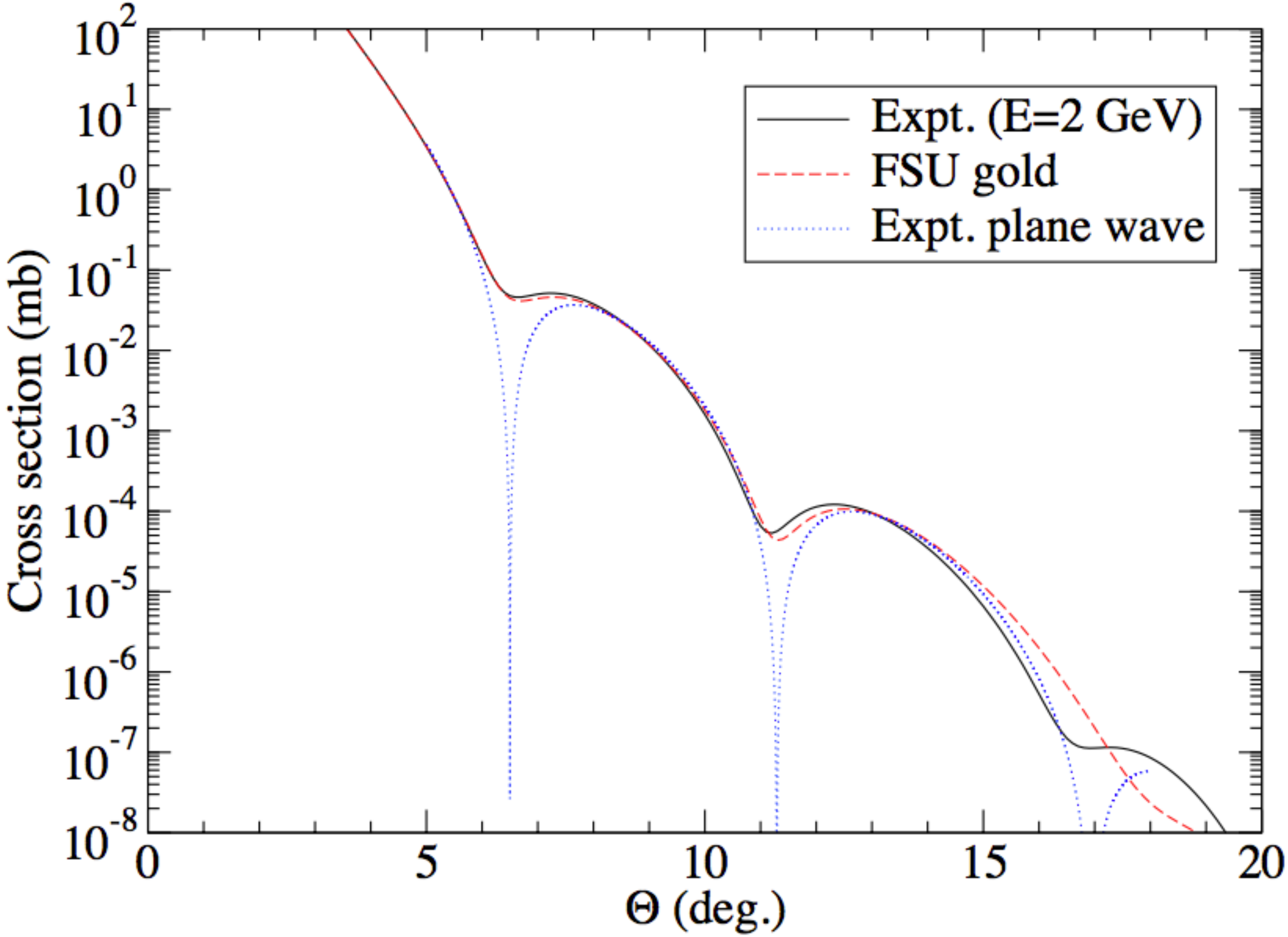
- JLAB completed exp.: PREX R_n-R_p(^{208}Pb)=0.33+/-0.17 fm
- JLAB approved experiments:
  - PREX II improve statistics of PREX with goal of R_n-R_p for ^{208}Pb to +/- 0.06 fm
  - CREX measure R_n-R_p for ^{48}Ca to +/- 0.02 fm
- Possibility at Mainz or at Cornel:
  - A # of parity violating measurements of neutron densities are possible both with the existing machine and with Mesa.
  - "Super PREX" could take advantage of a large acceptance detector and the new intense MESA electron accelerator to measure R_n-R_p for ^{208}Pb to +/- 0.03 fm (half the error of PREXII). Very well motivated to maximize information on density dependence of symmetry energy and the pressure of neutron matter from laboratory exp.

Full ^{48}Ca weak charge density

- Measure A_{pv} at multiple q^2 points to determine the full radial form of the weak density. This is feasible for ^{48}Ca, really hard for ^{208}Pb.
- Expand in Fourier Bessel series:

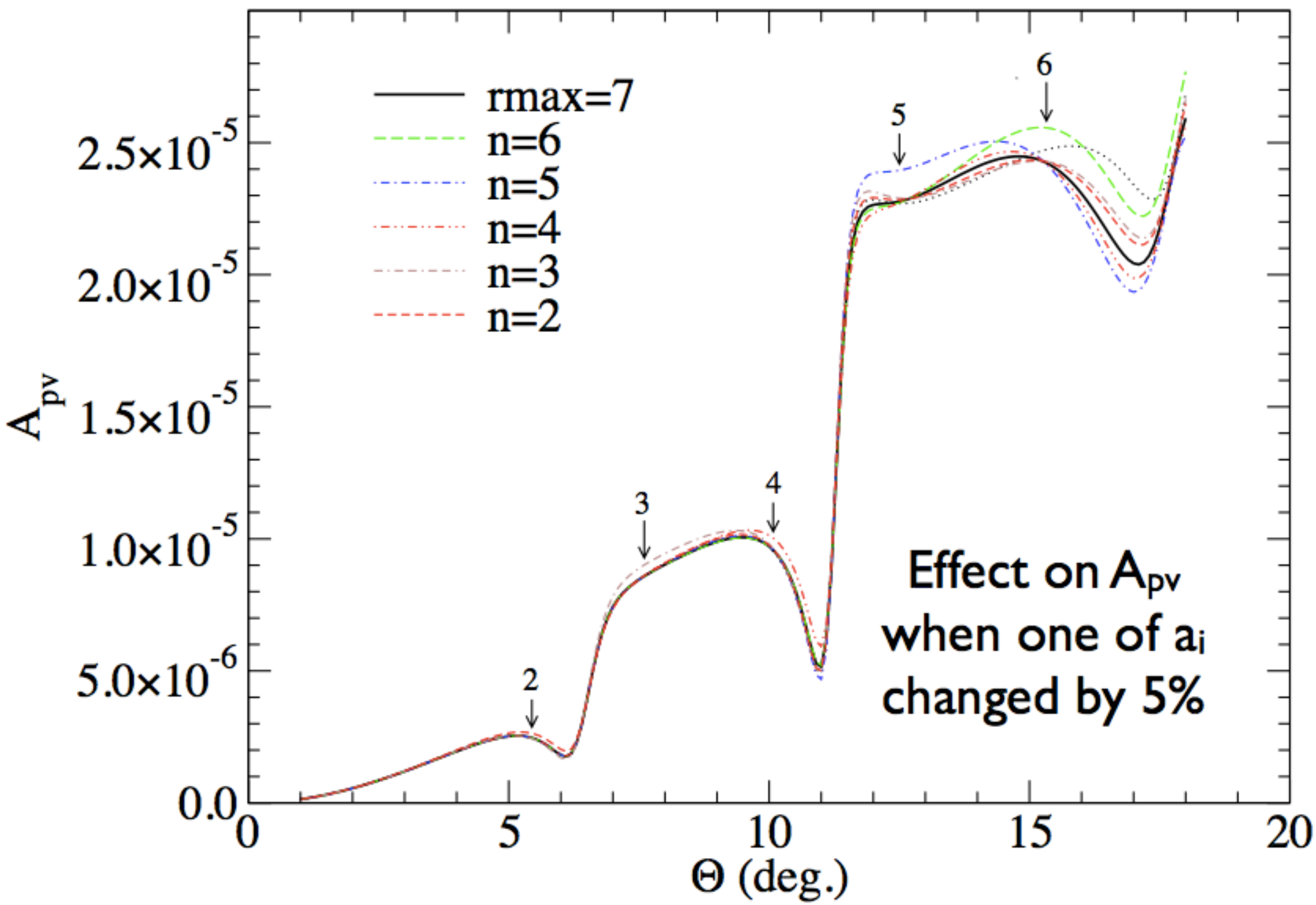
$$\rho_W(r) = \sum_{i=1}^{n_{max}} a_i j_0(q_i r)$$

- $q_i = \pi i / R_{max}$, $j_0(x) = \sin(x)/x$, $n_{max} = 6$, $R_{max} = 7$ fm.



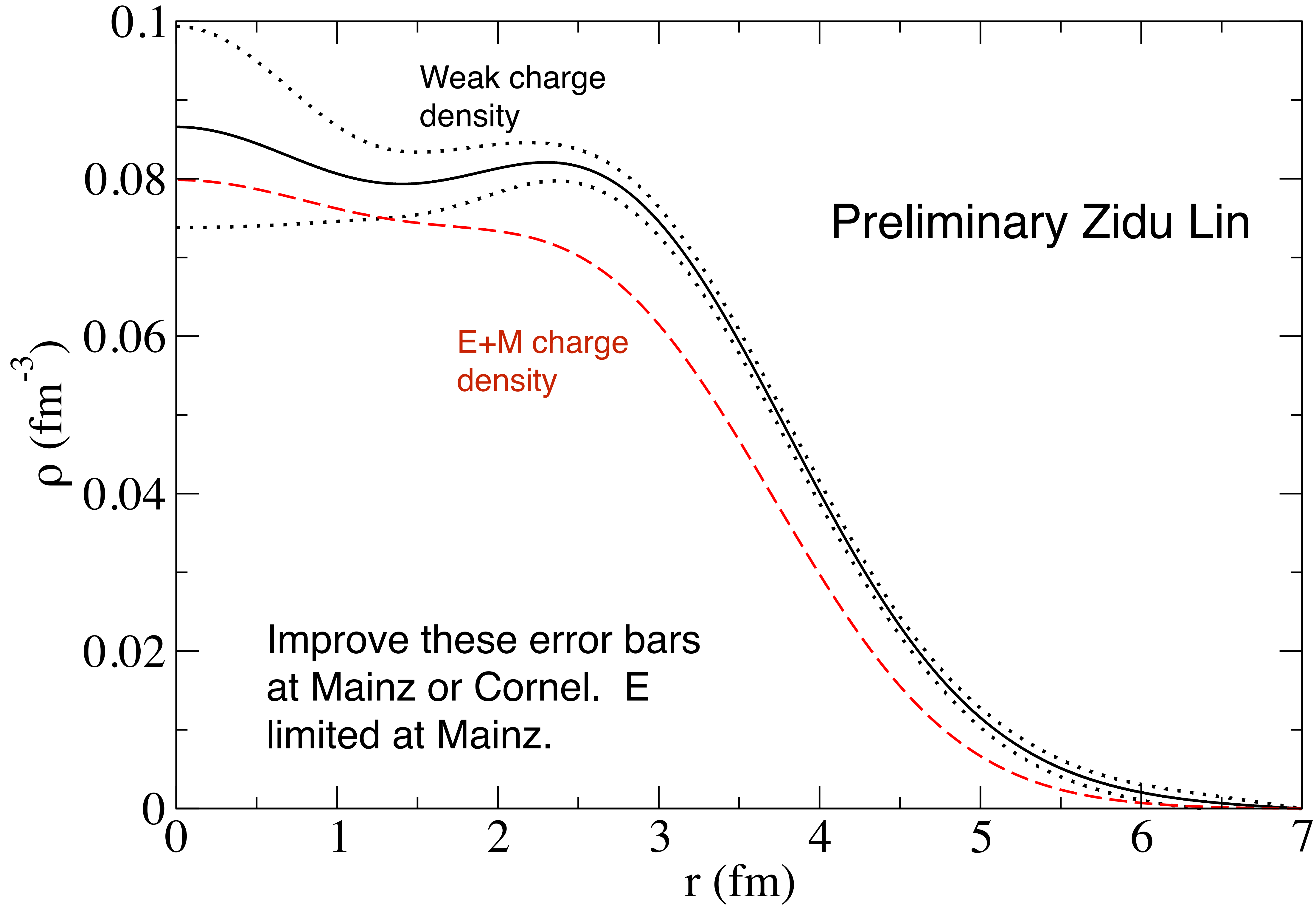
Expt. (E=2 GeV)
FSU gold
Expt. plane wave
Cross section (mb)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
5
10
15
20
Θ (deg.)

^{48}Ca at 2 GeV



rmax=7
n=6
n=5
n=4
n=3
n=2
2
3
4
5
6
2.5×10-5
2.0×10-5
1.5×10-5
1.0×10-5
5.0×10-6
0.0
Apv
0
5
10
15
20
Θ (deg.)
Effect on Apv
when one of ai
changed by 5%

Example statistical error at JLAB: 60 days for all five q^2



Beam Energy

- Want q_{max} ~ 2.7 fm^{-1} to resolve internal weak charge density in ^{48}Ca.
- Need beam energy of order **E_{lab} ~ q_{max} ~ 500 MeV.**
- Measure q_{max} at about 60 degrees in Lab.
- MESA at Mainz is too low energy 150-200 MeV.

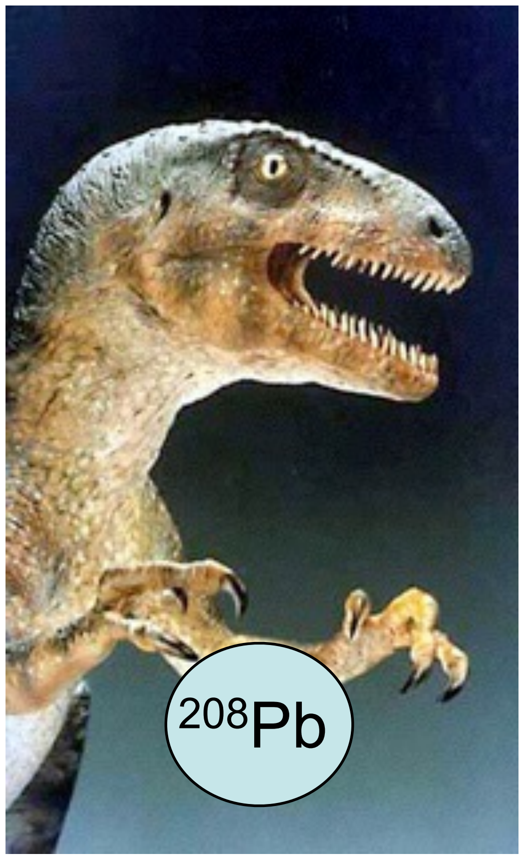
Examples of ^{48}Ca Models

- Many non relativistic and relativistic density functional predictions.
- First microscopic ("ab initio") coupled channel calculation that predicts a good charge density (except for too large shell osc. at small r) and small neutron skin.
- Dispersive optical model fit to large amount of proton-nucleus scattering data gives great charge density and predicts thick neutron skin.

Full ^{48}Ca weak charge density

- Would provide **text book picture of where neutrons and protons are in a nucleus**.
- Learn about shell oscillations of neutrons, saturation density of nuclear matter, neutron skin thickness, surface thickness of the neutrons…
- We expect central baryon density in ^{208}Pb to be approximately constant but we only know what the proton density is.
- Compare to new microscopic calculations of the neutron density in ^{48}Ca based on chiral effective field theory two and three nucleon interactions.

Weak form factors and neutron rich matter



- PREX uses parity violating electron scattering to measure the neutron radius of ^{208}Pb —> determines pressure of n rich matter.
- Complimentary to astronomical observations of neutron matter with photons, neutrinos and gravitational waves.
- Can measure not just radius but full model independent weak form factor with new accelerator

- Collaborators: D. Berry, S. Ban, J. Piekarewicz, R. Michaels, K. Kumar, P. Souder, Students: Z. Lin, M. Caplan…
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