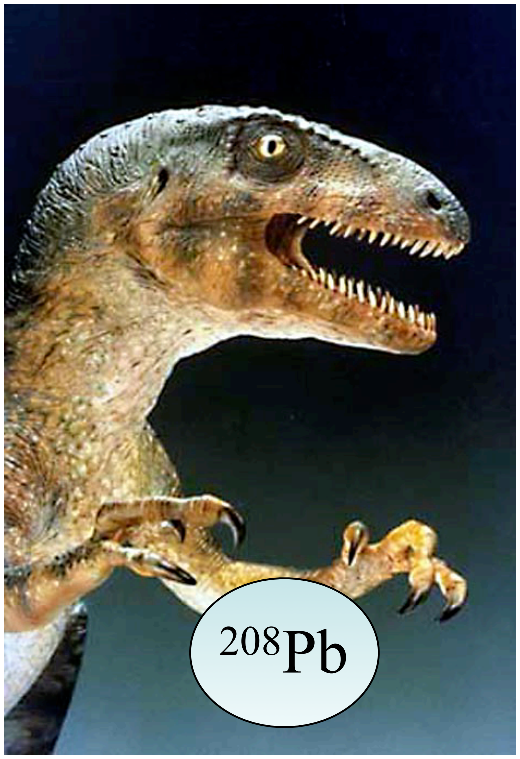
Neutron stars at JLAB and the Pb Radius Experiment

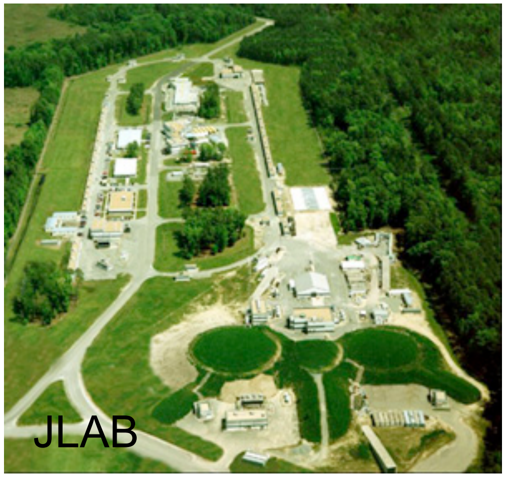


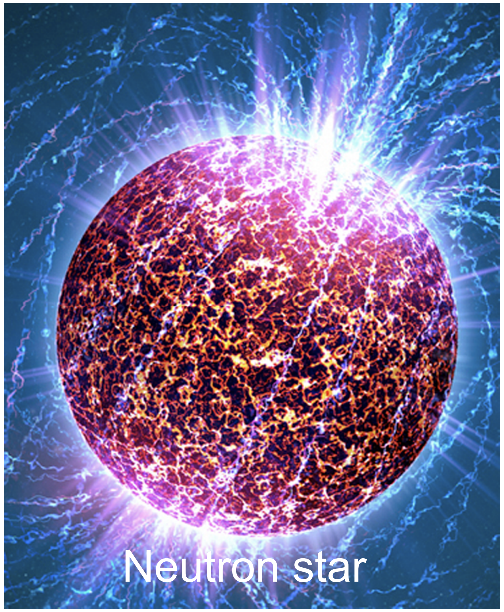
PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.

This has many implications for nuclear structure, astrophysics, atomic parity non-conservation, and low energy tests of the Standard Model.

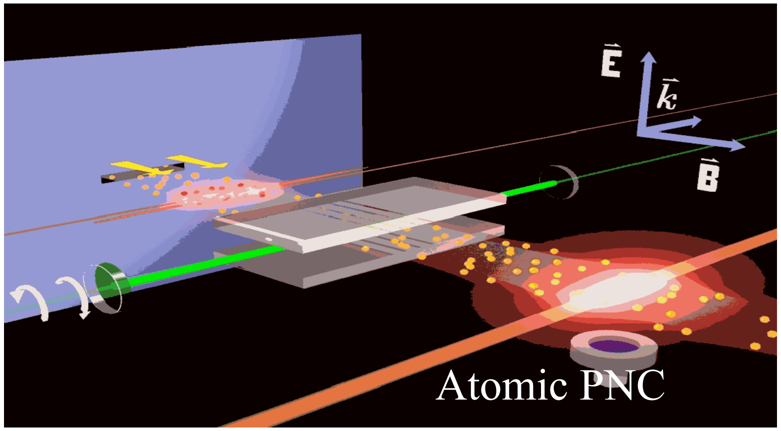
JLAB Users Group Meeting, June 2009
C. J. Horowitz, Indiana University

PREX and Related Physics





- Introduction: PREX exp.
- PREX and:
  - Atomic PNC.
  - Nuclear structure.
  - Neutron stars.
- Radiative corrections to PREX and Qweak.



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

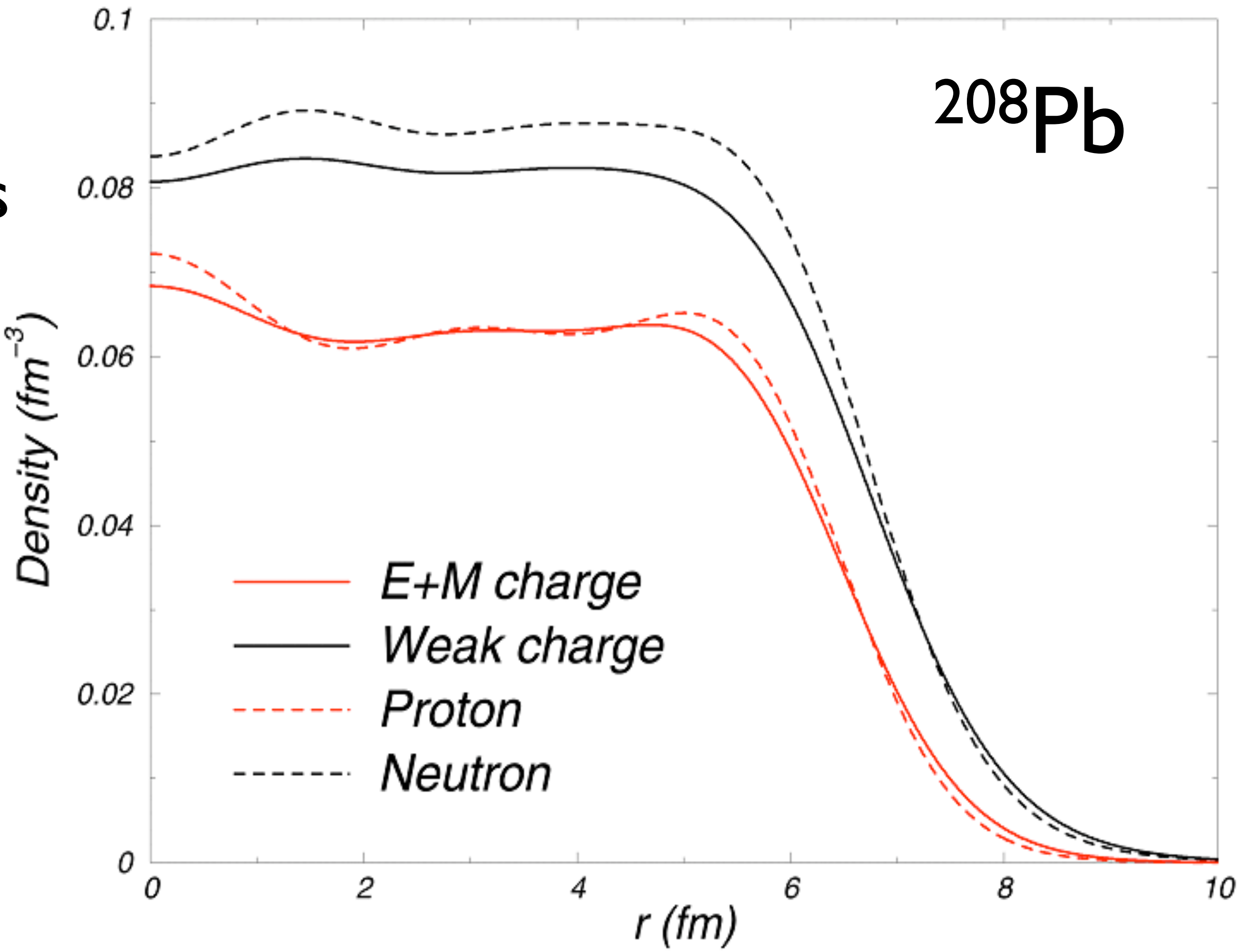
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

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

- PREX will measure A_{pv} for 1.05 GeV electrons scattering from ^{208}Pb at 5 degrees to 3%. This gives neutron radius to 1% ($\pm$0.05 fm).

  – Donnelly, Dubach, Sick first suggested using PV to measure neutrons.

Weak and E+M charge densities



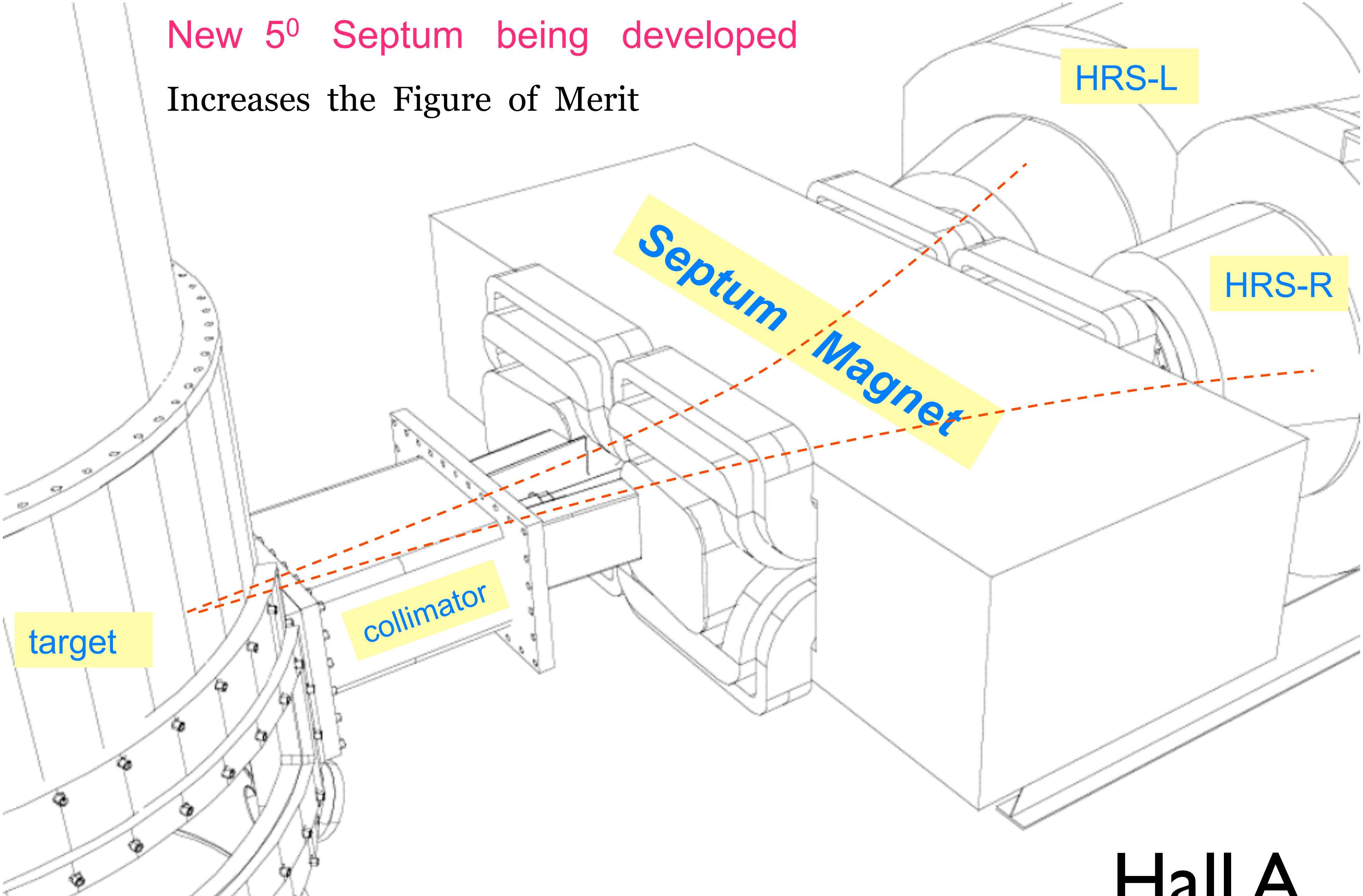
Relativistic mean field calculation showing point proton and neutron densities (dashed) and weak and electromagnetic charge densities (solid).

$$\rho_W(r) = \int d^3r' [G_W^n(r'-r)\rho_n(r') + \frac{Q_W^p}{Q_W^n} G_W^p(r'-r)\rho_p(r')]$$

Total weak charge of nucleus $\quad Q_W = \int d^3 r \rho_W(r) = N - (1 - 4\sin^2\Theta_W)Z$

New 5^0 Septum being developed

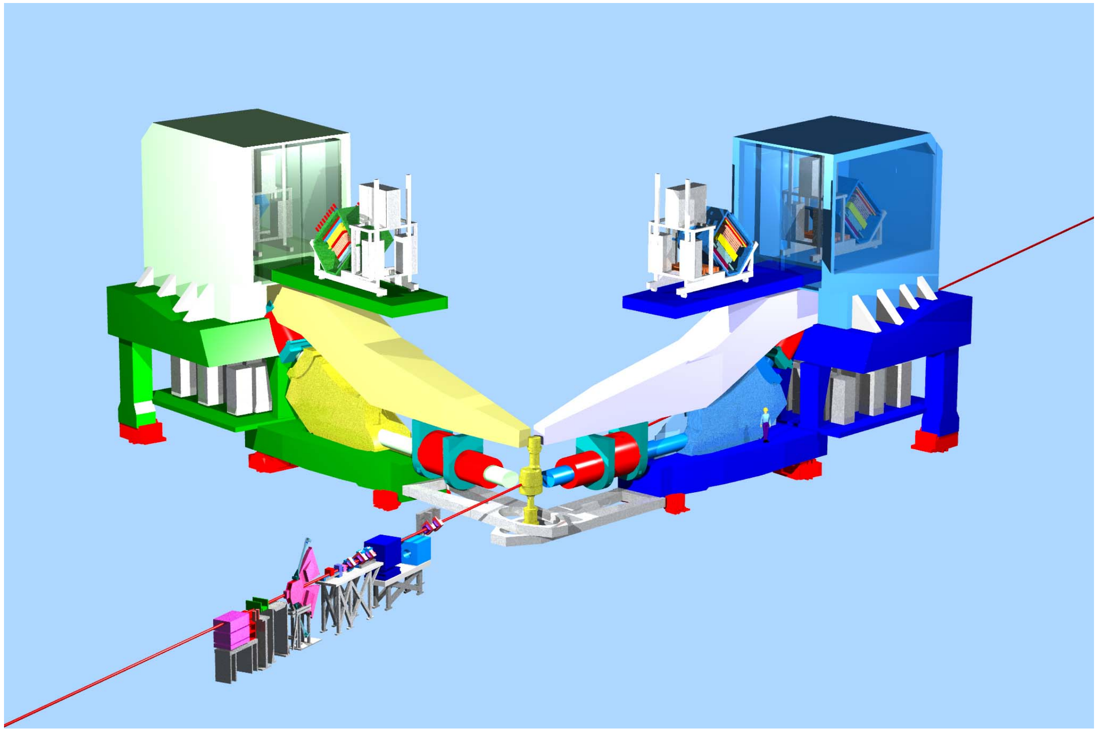
Increases the Figure of Merit



Hall A

R. Michaels

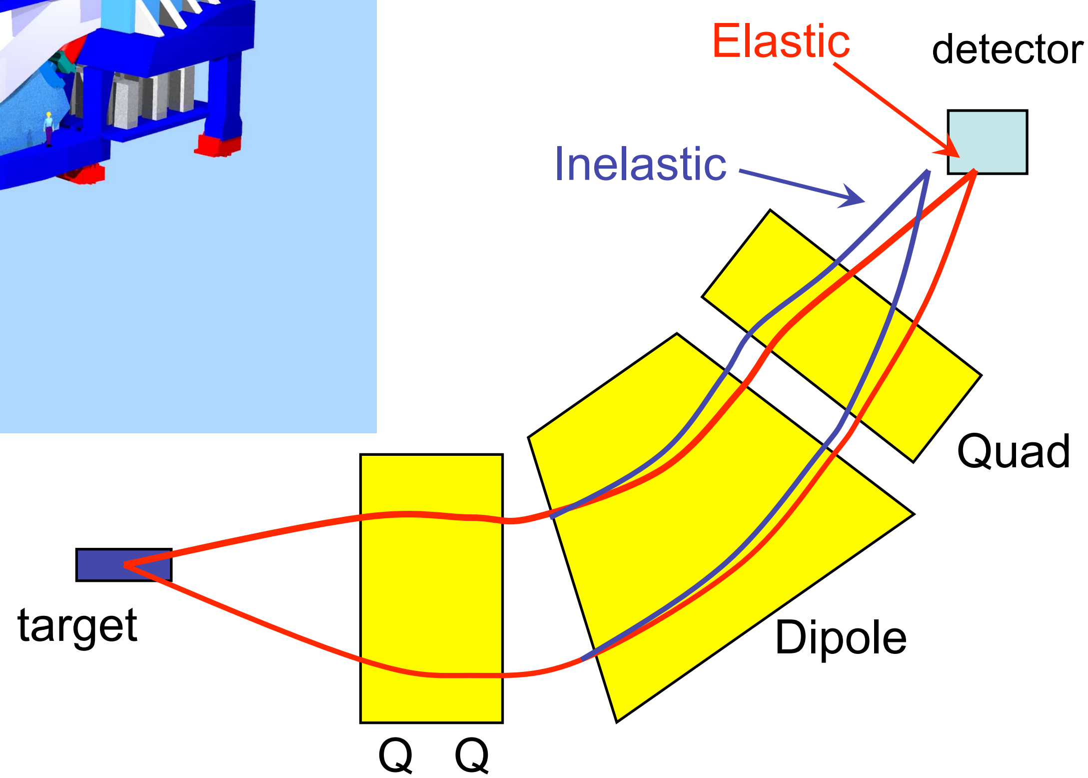
High Resolution Spectrometers



Left-Right symmetry to
control transverse
polarization systematic

Spectrometer Concept:
Resolve Elastic

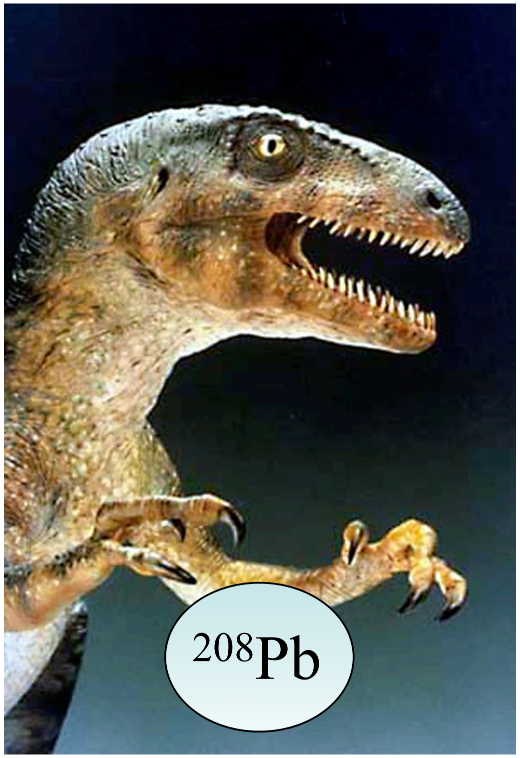
1^{st} excited state Pb 2.6 MeV



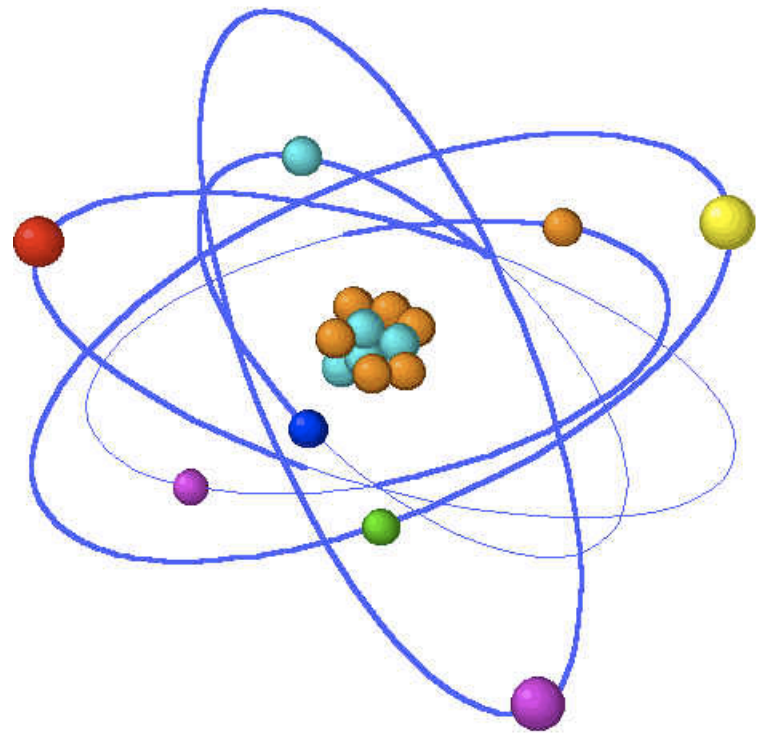
R. Michaels

Systematic Error Challenges

- Small asymmetry: $500 \pm 15 \text{ ppb}$
- High precision: $\delta A_{pv}/A_{pv} \pm 3\%$
- No backgrounds (not what you might think ---> spectrometers)
- 1% normalization (polarimetry).
- Analyzing power ~ 10 A_{pv}. Need to measure and control transverse components of polarization.
- Need excellent control of helicity correlated beam properties.
- Hall A parity collaboration has completed a number of successful parity experiments.



PREX and Atomic Parity Nonconservation



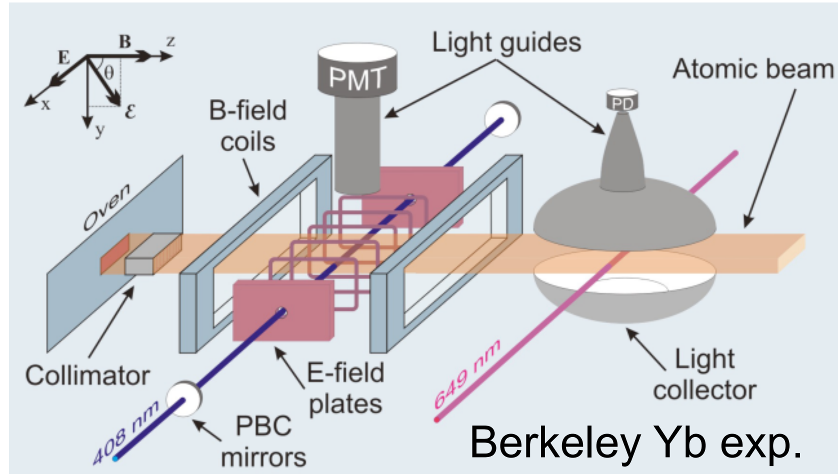
Atomic Parity Nonconservation

• Atomic PNC depends on overlap of electrons with neutrons in nucleus.

• Cs experiment good to 0.3%. Not limited by R_n but future 0.1% exp would need R_n to 1%

• Measurement of R_n in ^{208}Pb constrains nuclear theory for R_n in other atomic PNC nuclei.

• Combine neutron radius from PV e scattering with an atomic PNC exp for best low energy test of standard model.



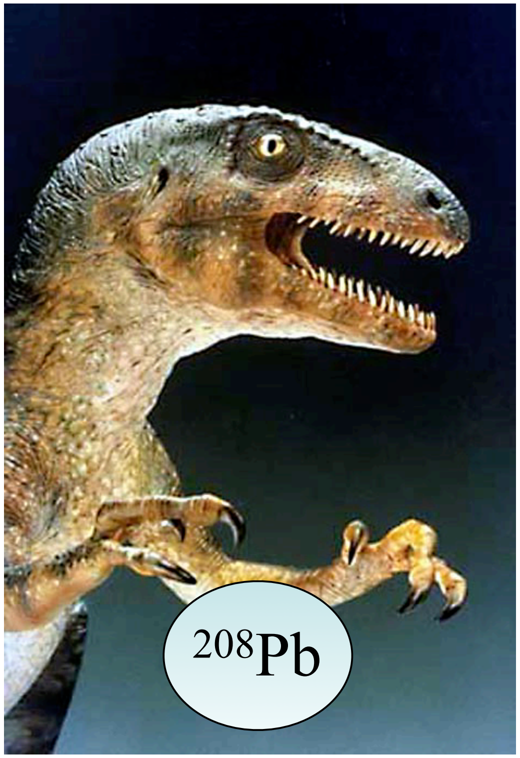
• Recent Atomic PNC Progress:

• Improved atomic theory for Cs.

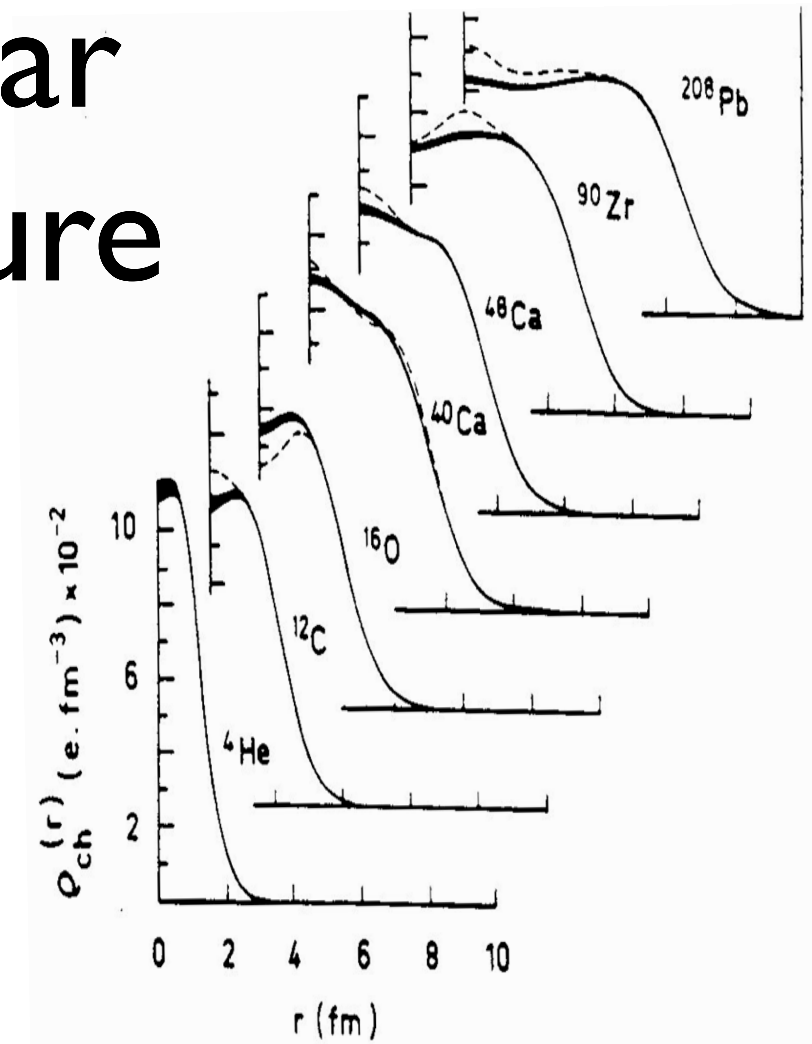
• First PNC results from Berkeley Yb experiment.

• Start of TRIUMF program for laser trapped radioactive Fr.

• KVI program on PNC in Ra+.



PREX and Nuclear Structure



Experimental charge densities from electron scattering

Neutron Skin and Symmetry E

- ^{208}Pb has Z=82 protons and N=126 neutrons.
- ***Where do the N-Z=44 extra neutrons go?*** In the center of the nucleus? At the surface?
- Relevant microphysics: A pn pair in bound $^3S_1$ state has more attractive interaction than pp or nn pair in unbound $^1S_0$ state.

The symmetry energy S(n) describes how E of nuclear matter rises when one goes away from N=Z.

$$E(n,\delta) \approx E(n,\delta=0) + \delta^2 S(n)$$
$$\delta = (N-Z)/A$$

PREX will constrain density dependance of sym. E, dS/dn.

Symmetry E very important to extrapolate to neutron rich systems in astrophysics.

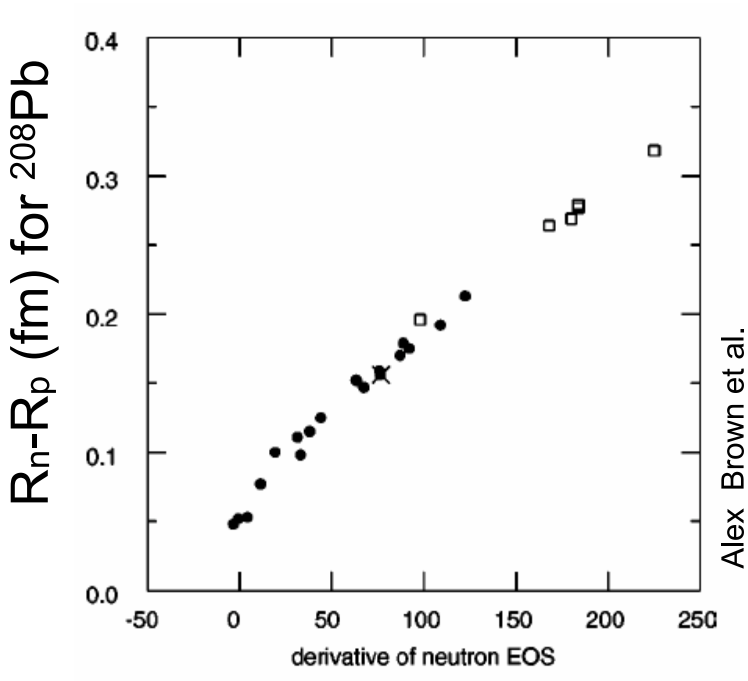
Pb Radius Measurement

- Pressure forces neutrons out against surface tension. Large pressure gives large neutron radius.
- Pressure depends on derivative of energy with respect to density.
- Energy of neutron matter is E of nuc. matter plus symmetry energy.

$$E_{neutron} = E_{nuclear} + S(\rho)$$

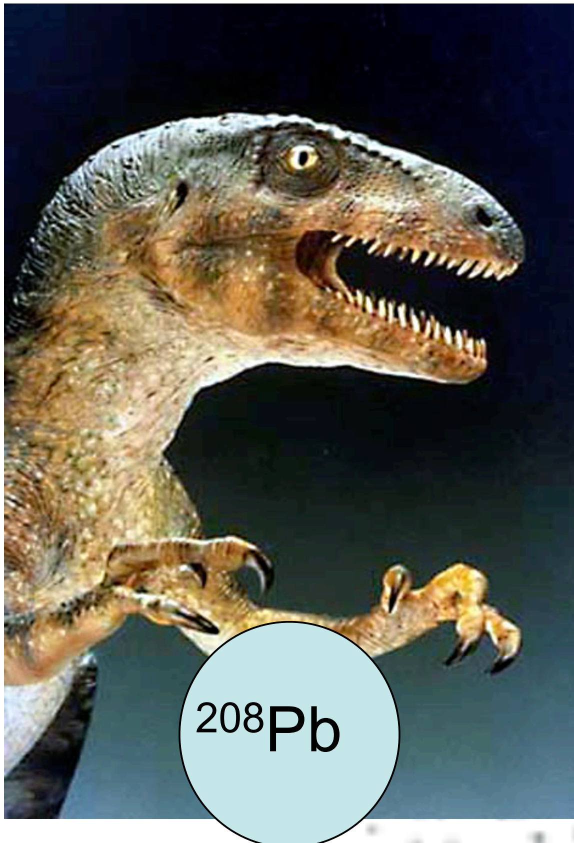
$$P \rightarrow dE/d\rho \rightarrow dS/d\rho$$

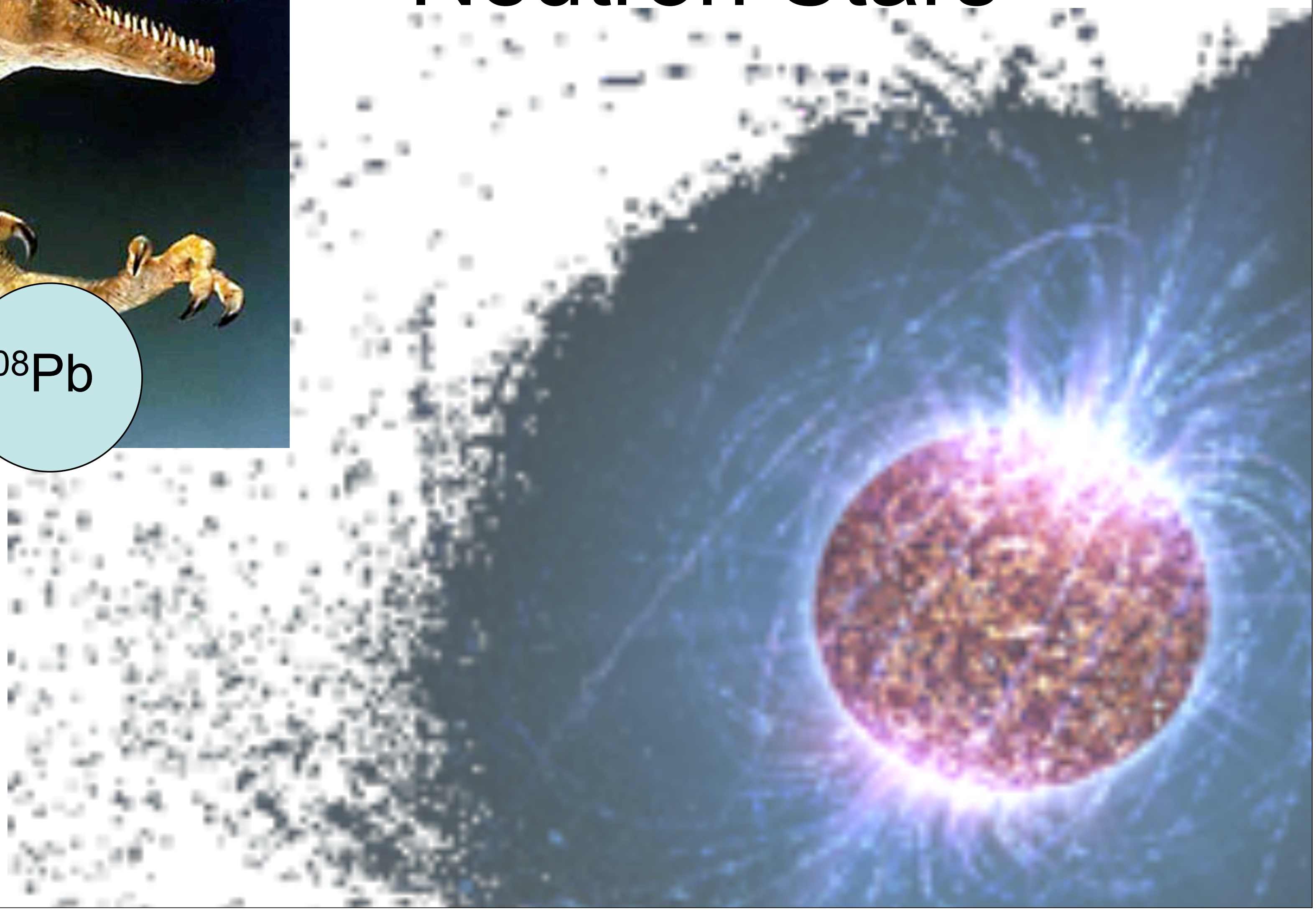
- **Neutron radius determines P of neutron matter at ≈ 0.1 fm^{-3} and the density dependence of the symmetry energy dS/dρ.**



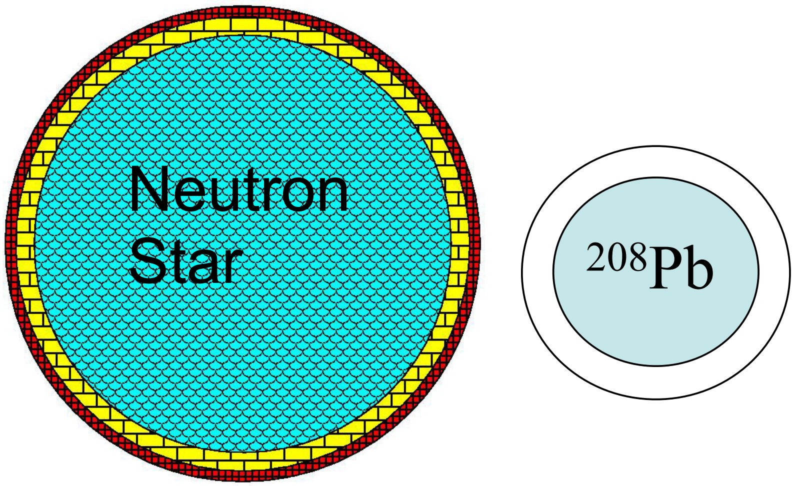
Neutron minus proton rms radius of Pb versus pressure of pure neutron matter at ρ=0.1 fm^{-3}.

PREX and Neutron Stars



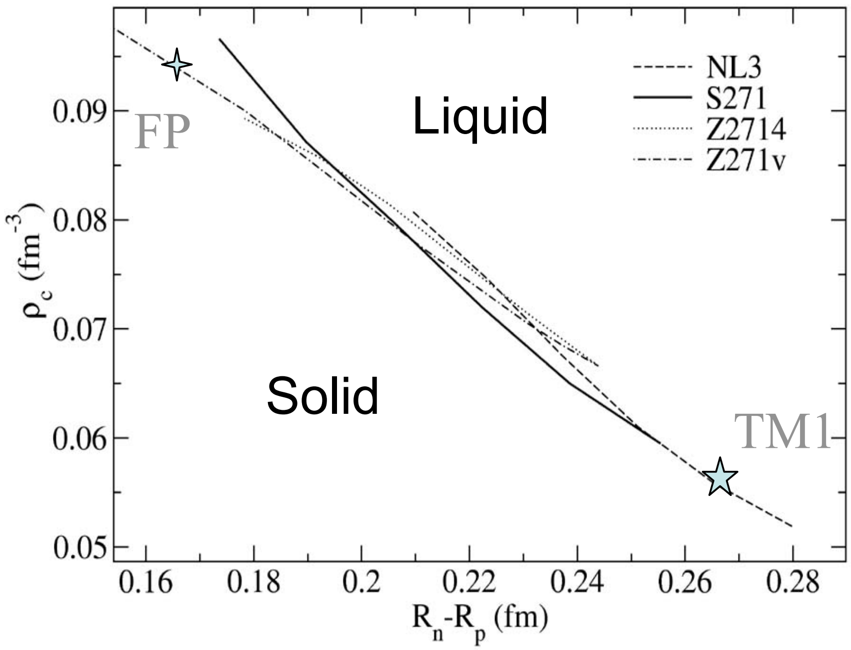


Neutron Star Crust vs ^{208}Pb Neutron Skin



- Neutron star has solid crust (yellow) over liquid core (blue).
- Nucleus has neutron skin.
- Both neutron skin and NS crust are made out of neutron rich matter at similar densities.
- Common unknown is EOS at subnuclear densities.

Liquid/Solid Transition Density



- Thicker neutron skin in Pb means energy rises rapidly with density-> Quickly favors uniform phase.
- Thick skin in Pb->low transition density in star.

J Piekarewicz, CJH

Neutron Star Quadrupole Moment and Gravitational Waves

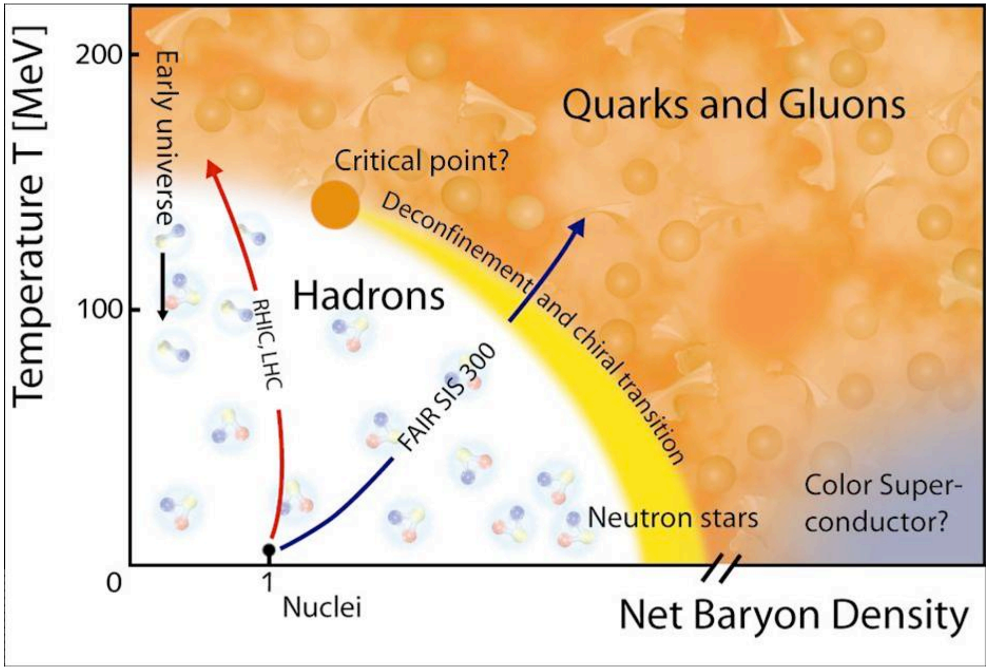
- A solid crust can support an off axis mass quadrupole moment.
- Rapidly rotating NS quad. moment efficiently radiates gravitational waves.
- Very active ongoing/ future searches for continuous GW at LIGO, Virgo, Advanced LIGO...
- How big can the quad. moment be? This depends on the thickness and strength of the crust (before any mountain collapses under the extreme gravity of a NS).
- We have performed large scale molecular dynamics simulations of the crust breaking stress, including effects of defects, impurities, and grain boundaries...
- We find: neutron star crust is the strongest material known. *It is 10 billion times stronger than steel.* Very promising for GW searches.

LIGO
Hanford

--- with Kai Kadau (LANL), PRL102, 191102 (2009)

Pb Radius vs Neutron Star Radius

- The ^{208}Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above. Central density of NS few to 10 x nuclear density.
- Important to have both low density and high density measurements to constrain density dependence of EOS from a possible phase transition.
  - If Pb radius is relatively large: EOS at low density is stiff with high P. If NS radius is small than high density EOS soft.



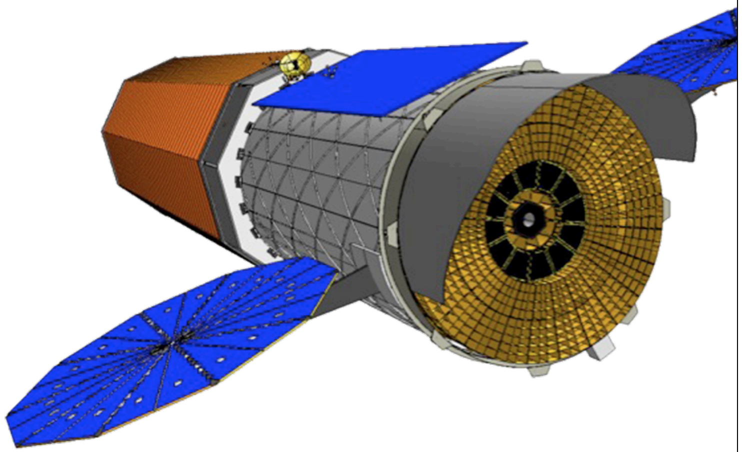
  - This softening of EOS with density could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, color superconductor…

J Piekarewicz, CJH

Measuring Neutron Star Radii

- Deduce surface area from luminosity, temperature from X-ray spectrum.
- Complications:
  - Need distance (from parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
- Proposed International X-ray Observatory (larger collecting area) can measure both R and mass.

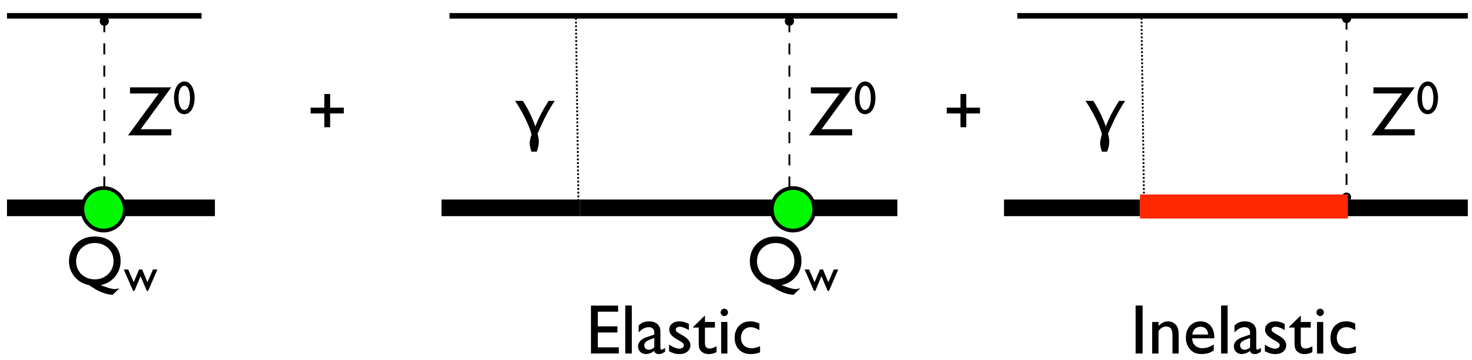
$$L_\gamma = 4\pi R^2 \sigma_{\mathrm{SB}}\, T^4$$



IXO could be an important machine to study dense QCD.

Radiative Corrections

γ-Z Box Diagrams



- Elastic intermediate states are coherent, order $Z\alpha$. Important for PREX (Pb has Z=82).
- Inelastic is order α/Q_w compared to tree level. Possibly important for Qweak exp on proton. Note inelastic involves weak transition form factor and not weak charge Q_w!

Coulomb Distortions for PREX

- We sum elastic intermediate states to all orders in $Z\alpha$ by solving Dirac equ for e moving in coulomb V and weak axial A potentials.

$$A \propto G_F \rho_W(r) \approx 10 \text{ eV} \qquad V(r) \approx 25\text{MeV}$$

- Right handed e sees V+A, left handed V-A

$$A_{pv} = [d\sigma/d\Omega|_{V+A} - d\sigma/d\Omega|_{V-A}]/2d\sigma/d\Omega$$

- Coulomb distortions reduce A_{pv} by ~30%, but they are accurately calculated.

--- With E.D. Cooper!

Inelastic γZ box correc. for Qweak

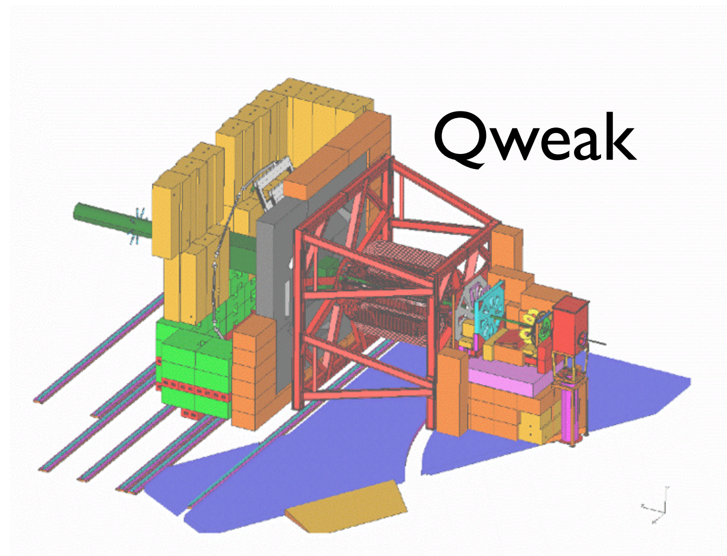
- Not obviously big for PREX, but important for the Qweak experiment because of the small weak charge of the proton.
- We sum over excited nucleon states with a dispersion integral using a model that fits photo-absorption data.
- Two main contributions: Resonances ~2%, dominated by Delta.
- High E non resonant contribution that we evaluate using a generalized vector meson dominance model ~4%.
- For 1.16 GeV kinematics of Qweak we find a total correction of 5.7% to the parity violating asym. compared to the exp error goal of 2% (statistical).

with M. Gorchtein, Phys. Rev. Let. **102**, 091806

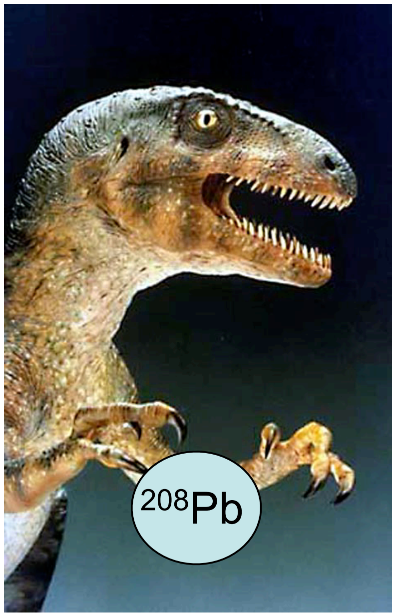
We don’t want Qweak to be another NuTeV

- NuTeV is a beautiful Fermi Lab neutrino experiment that has proved difficult to interpret as a Standard Model test.

- Important to have more work on radiative corrections to Qweak involving excited nucleon intermediate states. This should be done soon.



Pb Radius Experiment



- PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb. This has implications for nuclear structure, astrophysics, and atomic parity nonconservation.
- People:
  - Coulomb distortions with E.D. Cooper.
  - Correlations with J. Piekarewicz.
  - Radiative corrections with M. Gorshtein.
- PREX spokespersons: Paul Souder, Krishna Kumar, Robert Michaels, and Guido Urciuoli. Exp. to run Spring 2010.
- Supported in part by DOE and State of Indiana.