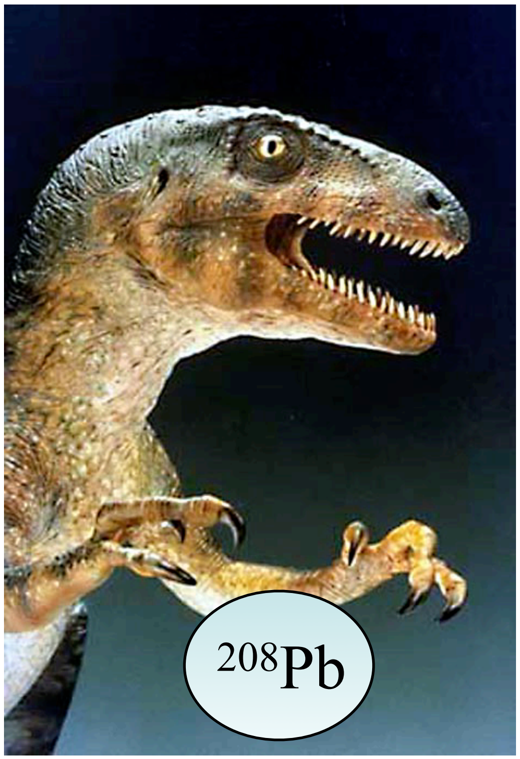
PREX and Bulk Properties of Neutron Rich Matter



- The lead radius experiment uses parity v. to measure the neutron radius of ^{208}Pb.
- Implications for
  - nuclear structure.
  - neutron stars.
  - atomic parity experiments.

FRIB Workshop, MSU, Nov. 2008

C. J. Horowitz, Indiana University

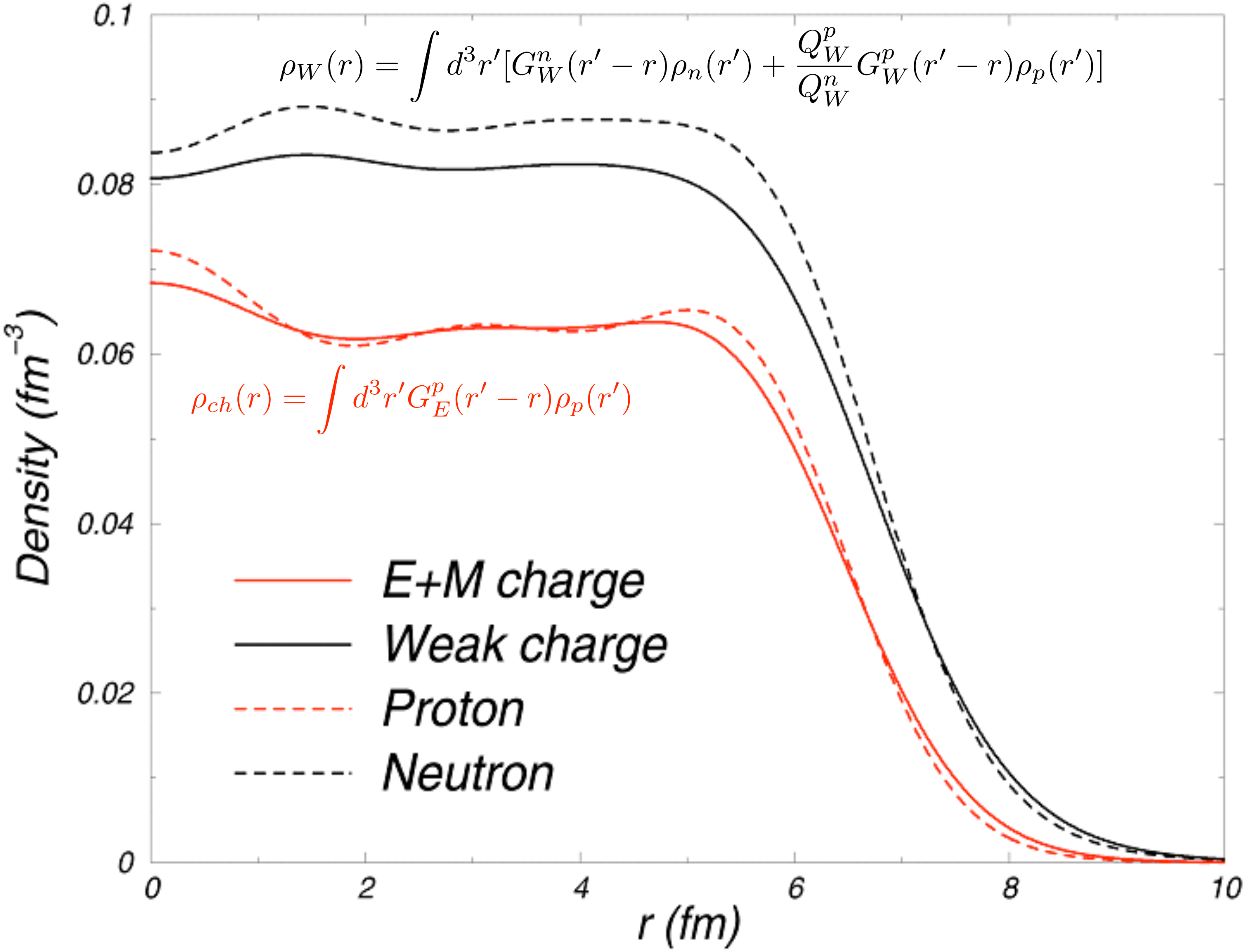
Neutron Weak Charge

- In Standard Model Z^0 boson couples to mixture of weak and E+M currents.
- Weak charge: $Q_W = 2[\text{Weak isospin} - 2\sin^2\Theta_W Q_{E+M}]$
- Important accident? $\sin^2\Theta_W \approx 0.25$

  $Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$
- Weak interactions (at low Q^2) probe neutrons.

	Weak isospin	Q_{E+M}	Q_W
p	1/2	1	$1 - 4\sin^2\Theta_W$
n	-1/2	0	-1

^{208}Pb Weak + E+M Charge Densities



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

Parity Violation Isolates Weak Form Factor

D,D,S

- 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

$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)} \qquad F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- PREX will measure A_{pv} for 1 GeV e scattering from ^{208}Pb at 5 degrees to 3% (A $\approx$ 0.6 ppm). This gives neutron radius to 1% ($\pm$ 0.05 fm).
- Purely electroweak reaction is model independent

Coulomb distortions

- Interested in neutron densities of heavy nuclei. These have large Z and important coulomb distortions.
- Solve Dirac equ for electron in both coulomb V(r) and weak axial A(r) potentials.

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

- In helicity basis, right handed e feels pot V+A and left handed feels V-A

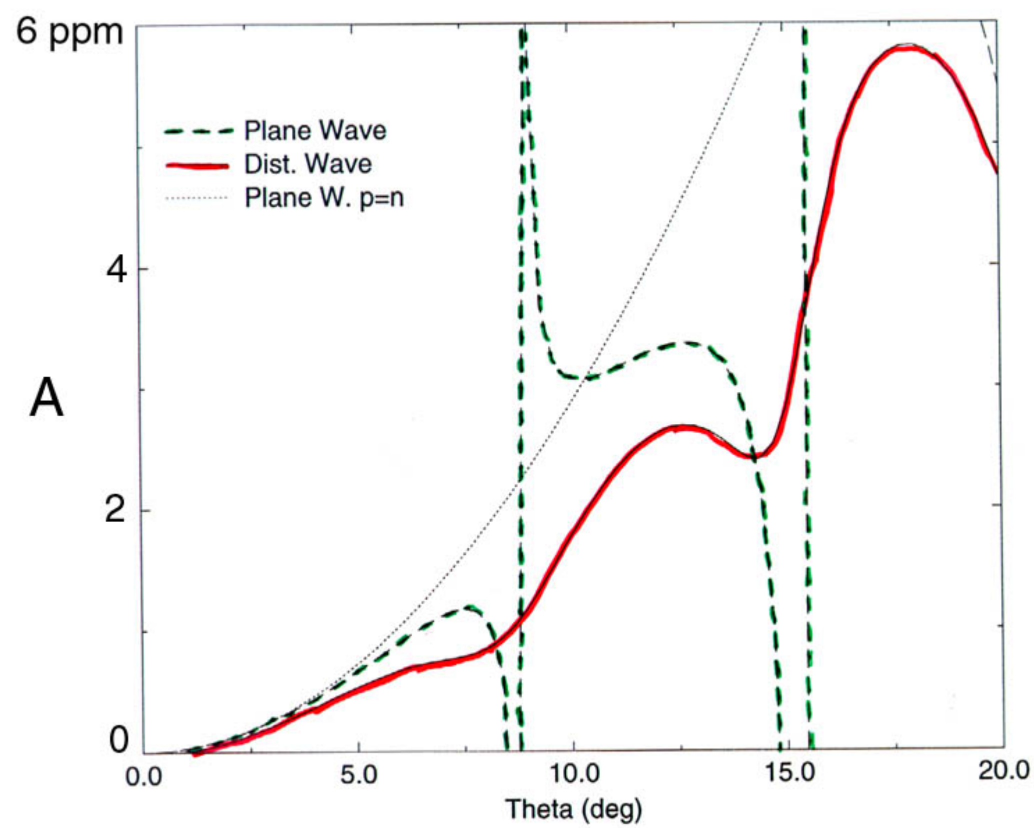
$$A_{sym} = \Big(d\sigma/d\Omega|_{V+A} - d\sigma/d\Omega|_{V-A} \Big) / (2 d\sigma/d\Omega)$$

- Subtract cross sec for V-A from cross sec V+A

Coulomb distortion results

- Distortions reduce asym. by ~30% and somewhat reduce sensitivity to neutron density.
- Largest correction to asymmetry.
- Can be accurately calculated and charge density is known.

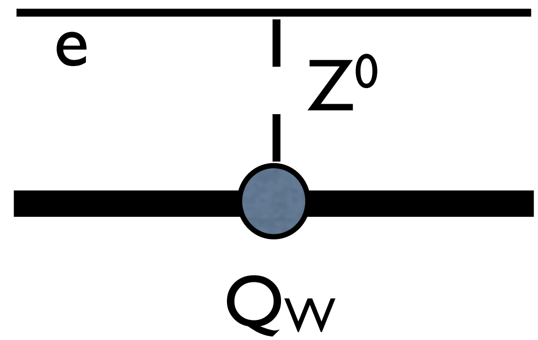
^{208}Pb at 850 MeV

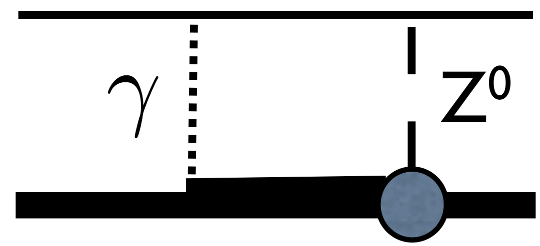


CJH + ED Cooper

Radiative Corrections

- Tree level diagram is order Q_W.
- Radiative correction is order $\alpha/\pi = 0.2\%$
- Probably not big issue for PREX but very important for QWeak experiment on proton because Q_W is so small.
- Radiative correction for QWeak $\frac{\alpha}{\pi Q_W} = 6\%$

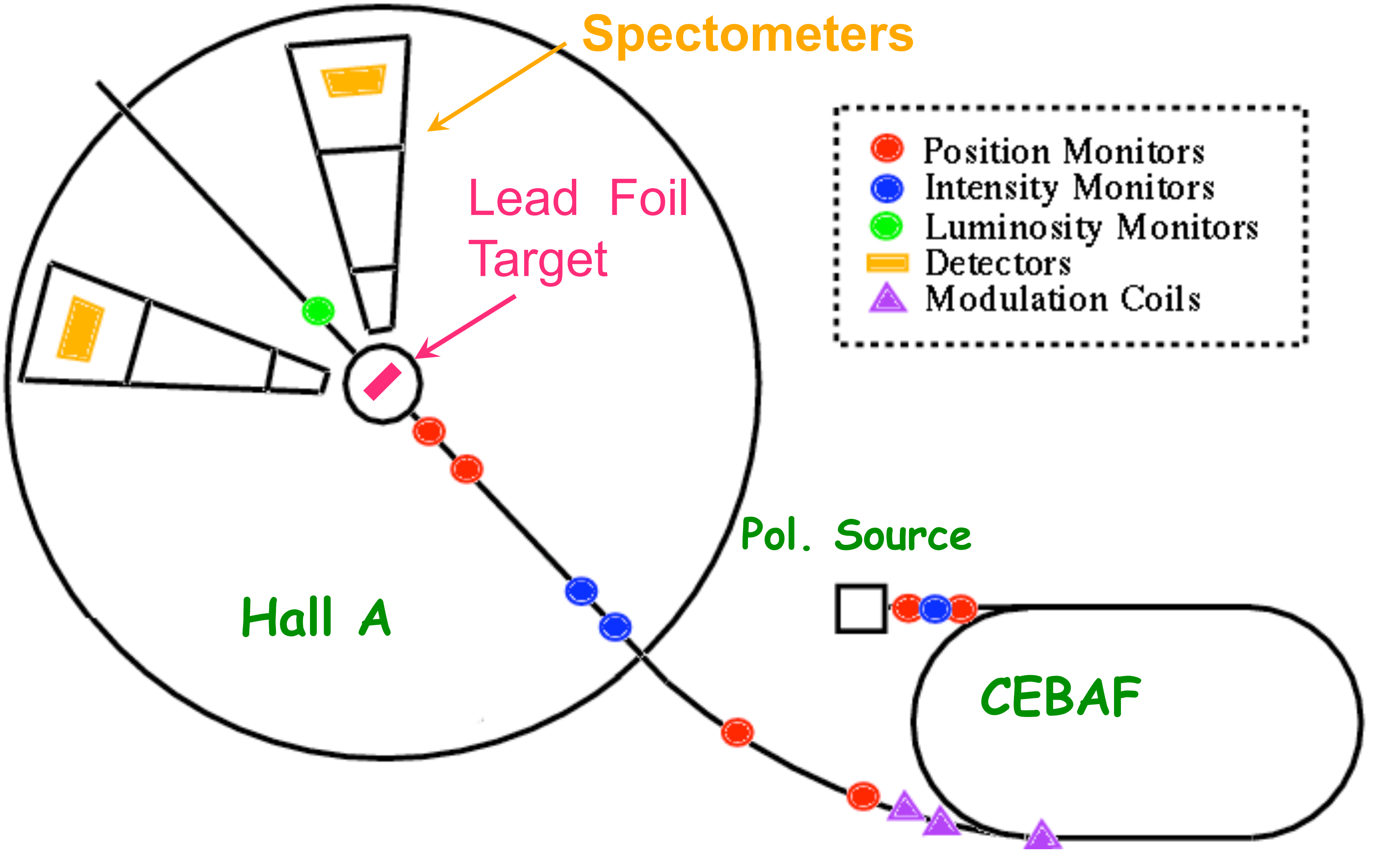




Z coupling to inelastic proton state can be large

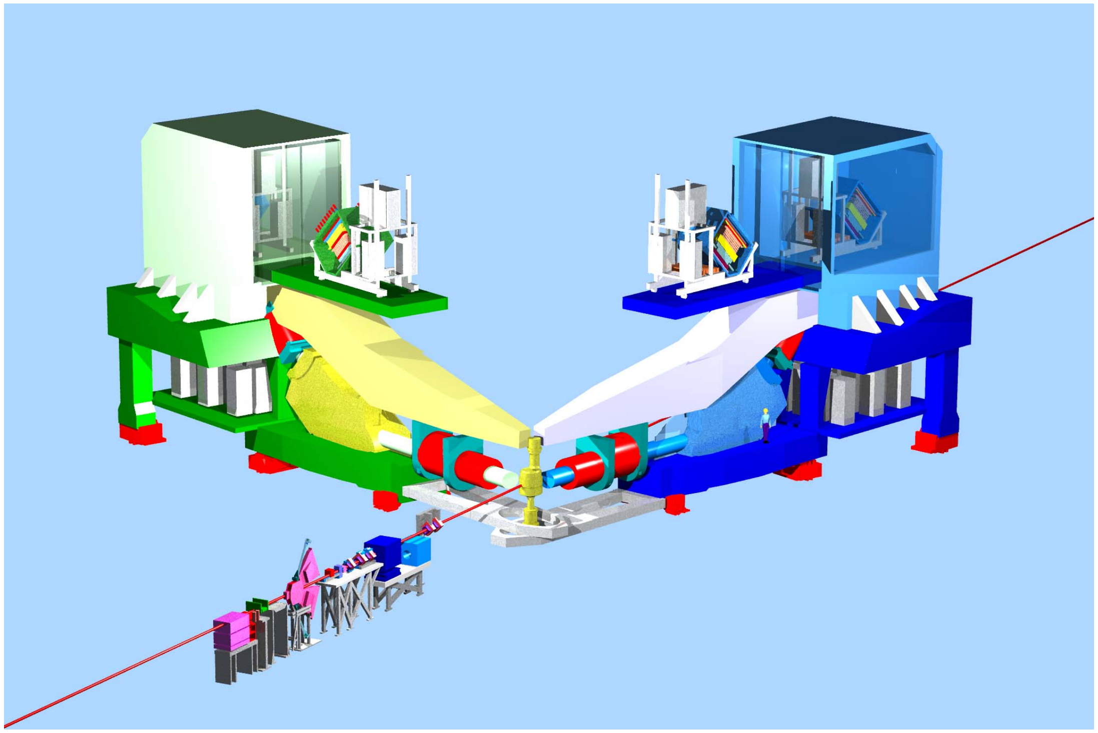
CJH+ M. Gorshteyn

PREX in Hall A at JLab



R. Michaels

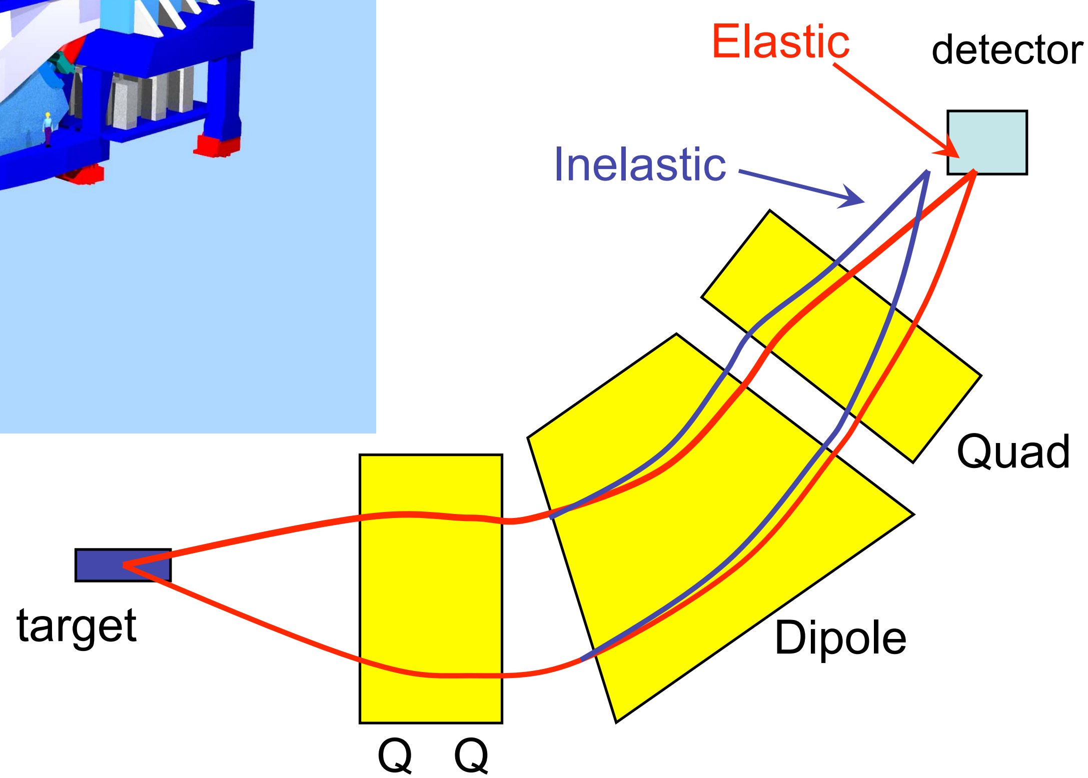
High Resolution Spectrometers



Left-Right symmetry to control transverse polarization systematic

Spectrometer Concept:
Resolve Elastic

1st excited state Pb 2.6 MeV

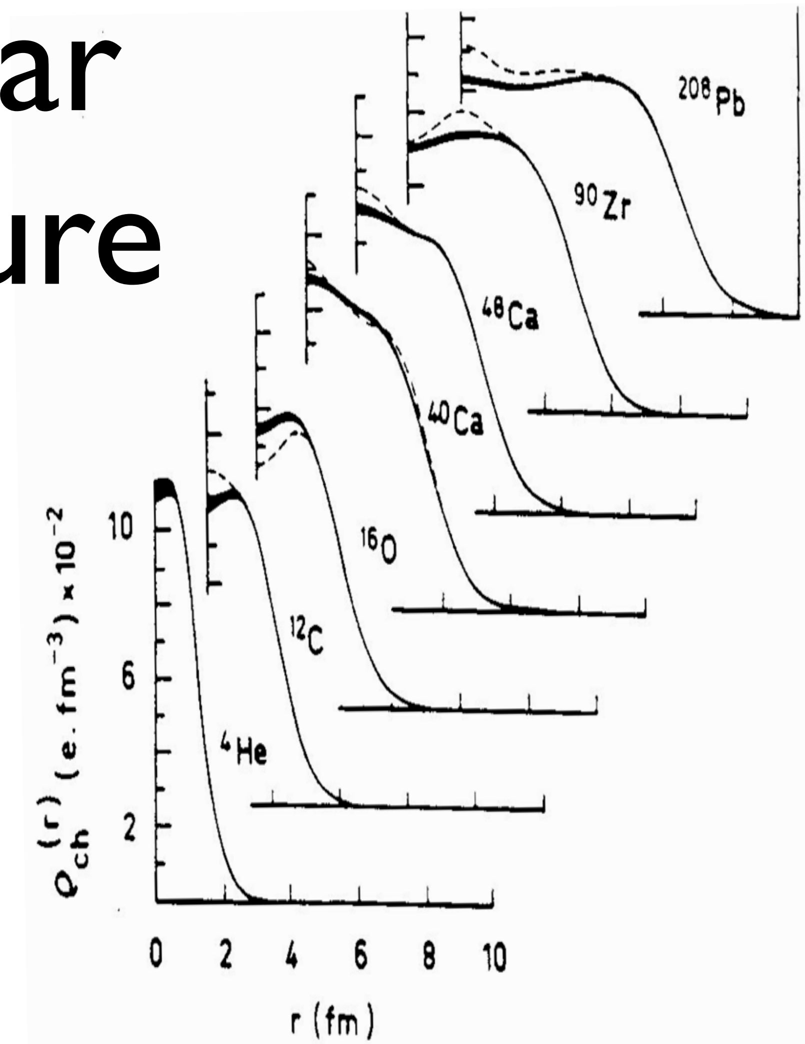


R. Michaels

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. Measured in previous exp.
- Hall A parity group have completed several successful parity experiments.

PREX and Nuclear Structure



Experimental charge densities from electron scattering

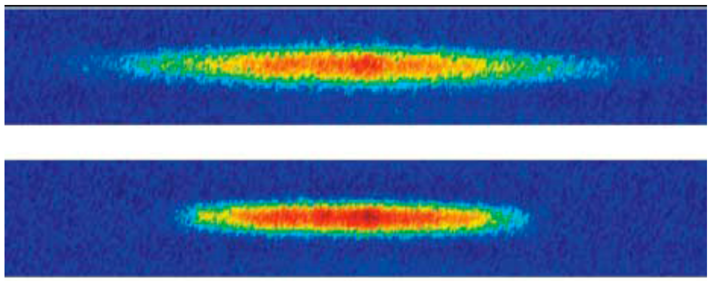
Neutron Skins for Dummies

- ^{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? Or both places?
- Relevant microphysics: A pn pair in bound $^3S_1$ state has more attractive interaction than pp or nn pair in unbound $^1S_0$ state.

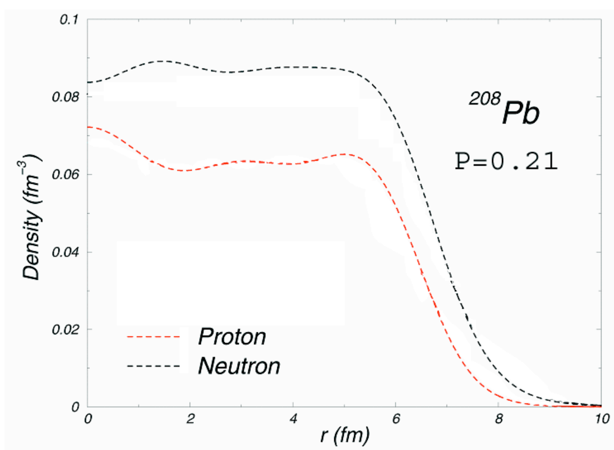
Monty ('That One')

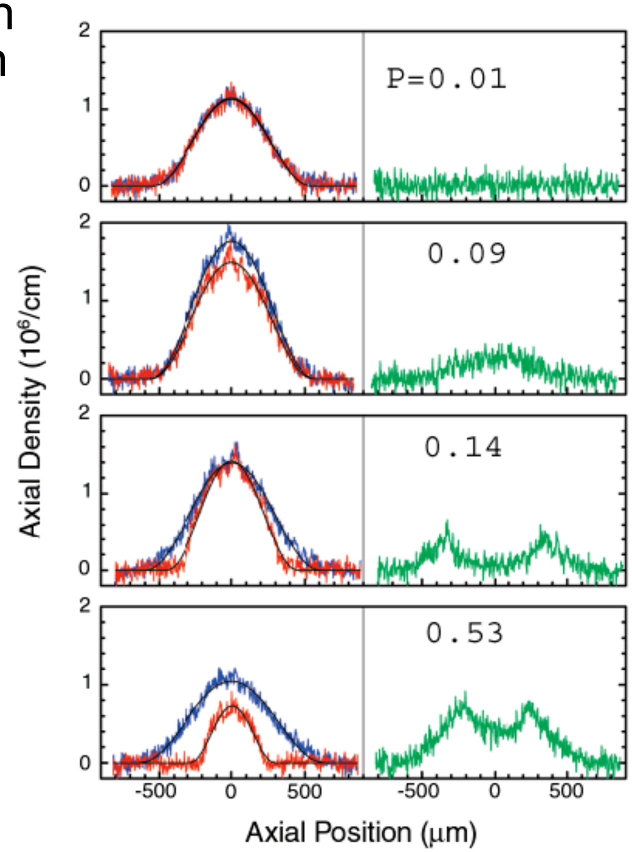
Spin Skins in Cold Atom Systems

- Fermions in asymmetric trap. Call spin up ^{6}Li atoms "neutrons" and spin down "protons". P=(N-Z)/(N+Z)



Neutrons (top) and protons for P=0.14





G. Partridge et al, Science **311**('06) 503

Attractive interaction (zero E bound state) for unlike spins, no interaction for like spins.

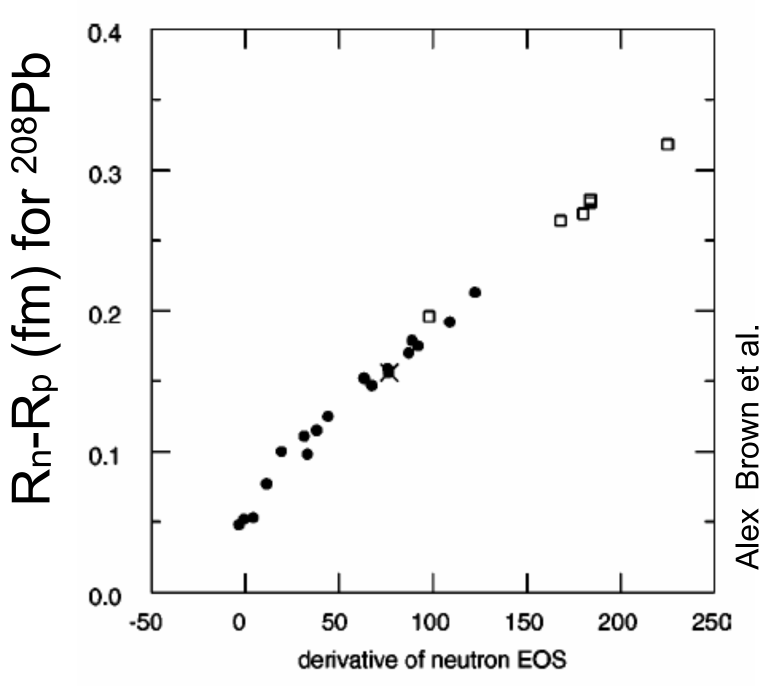
Pb Radius Measurement

- 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.

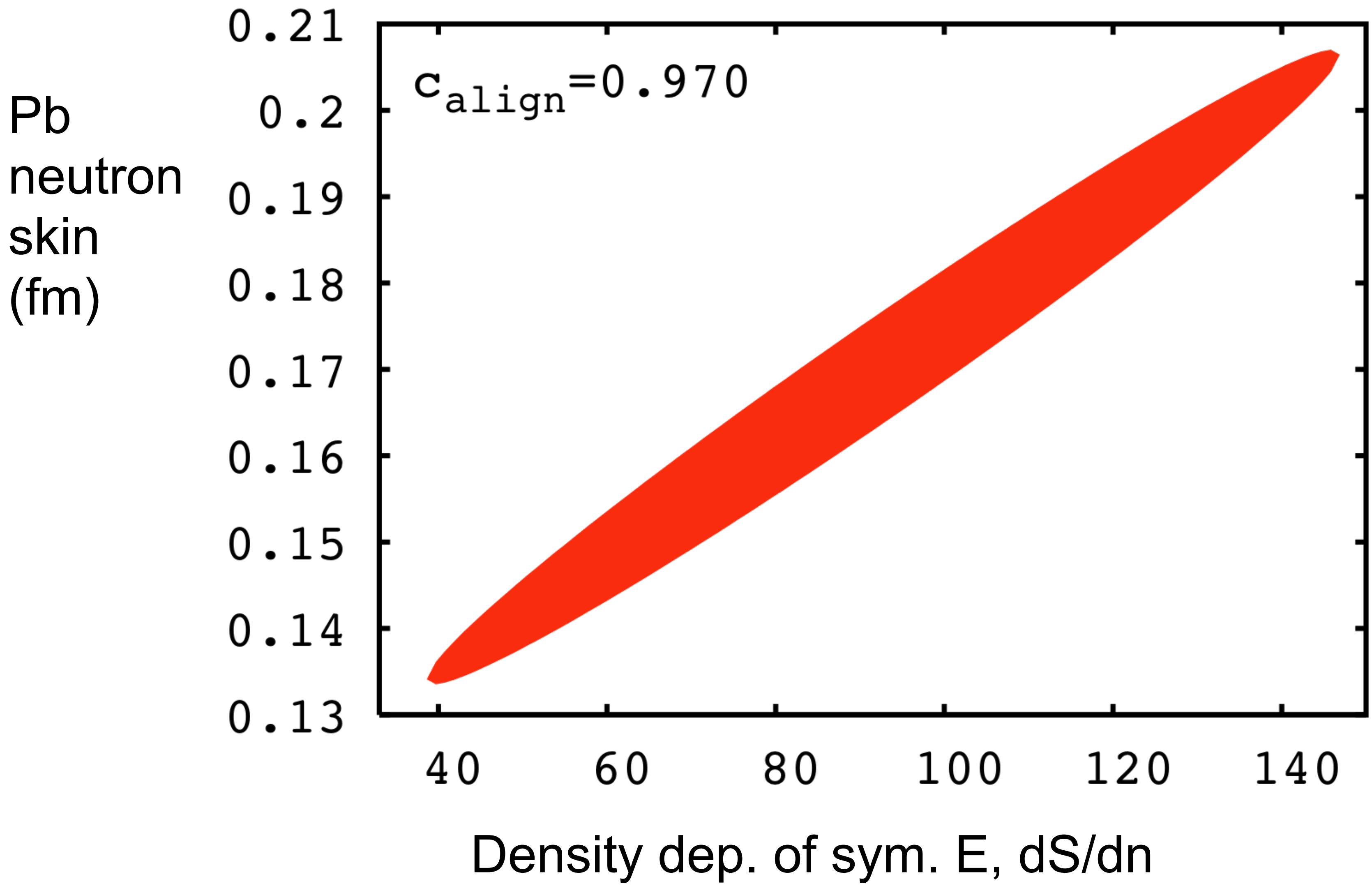
$$E_{neutron} = E_{nuclear} + S(\rho)$$

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

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

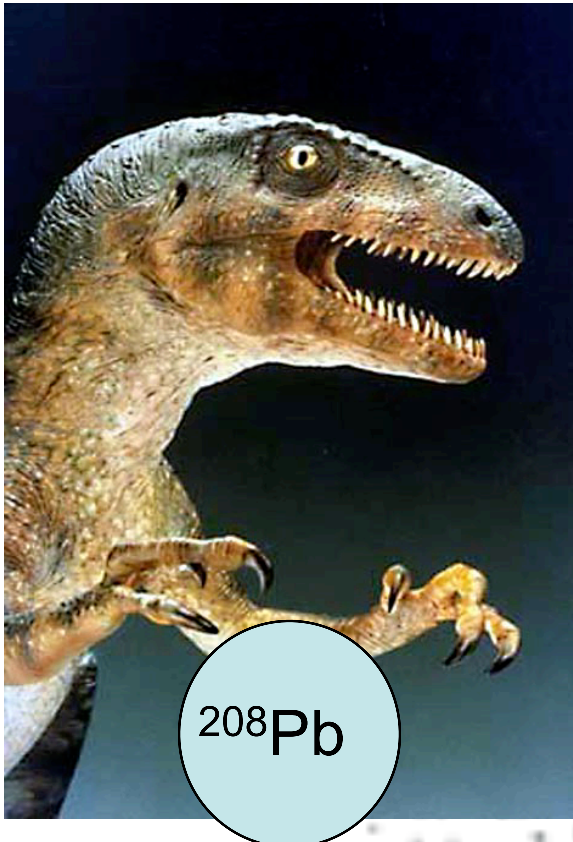


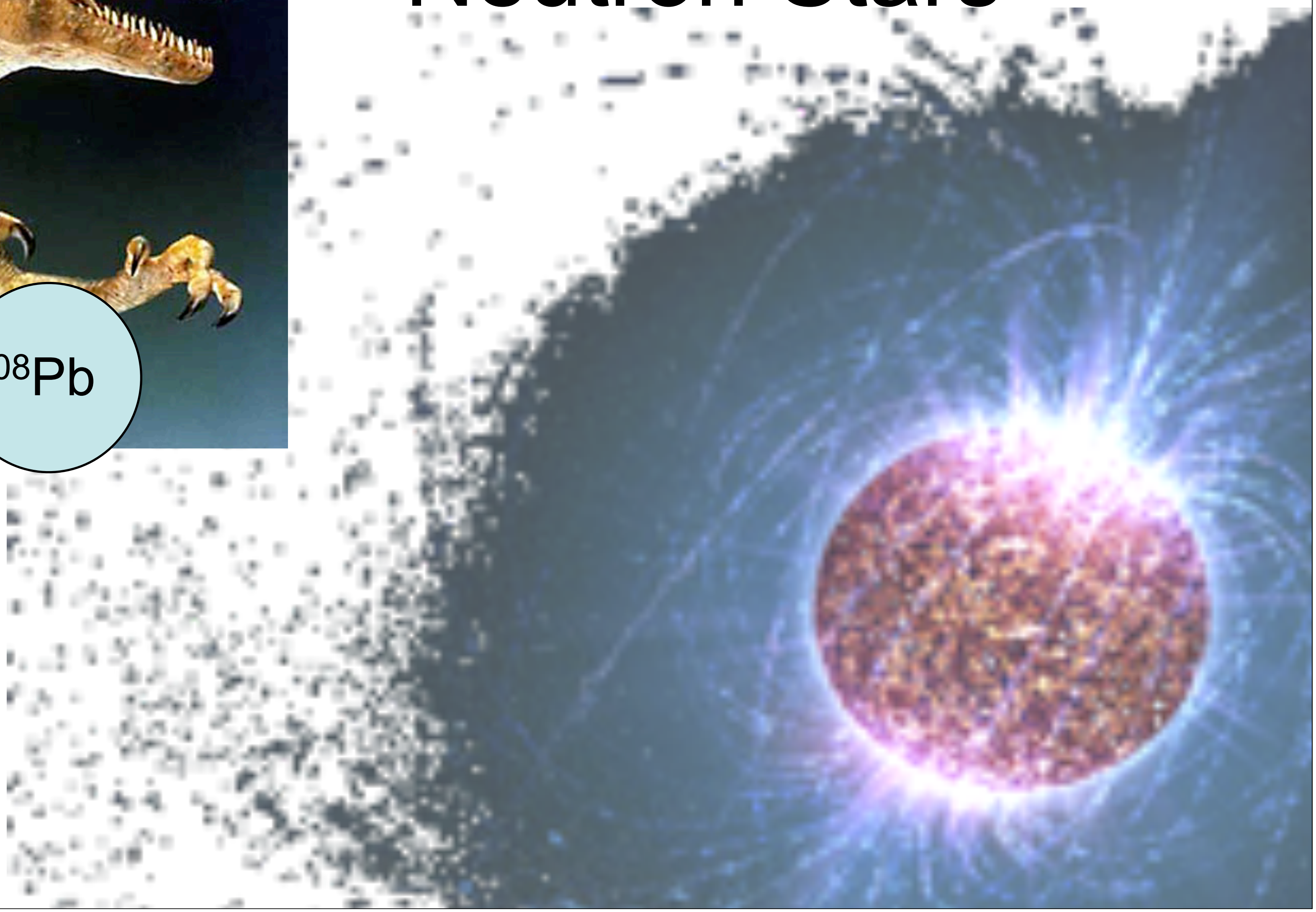
Neutron minus proton rms radius of Pb versus pressure of pure neutron matter at ρ=0.1 fm^{-3}.



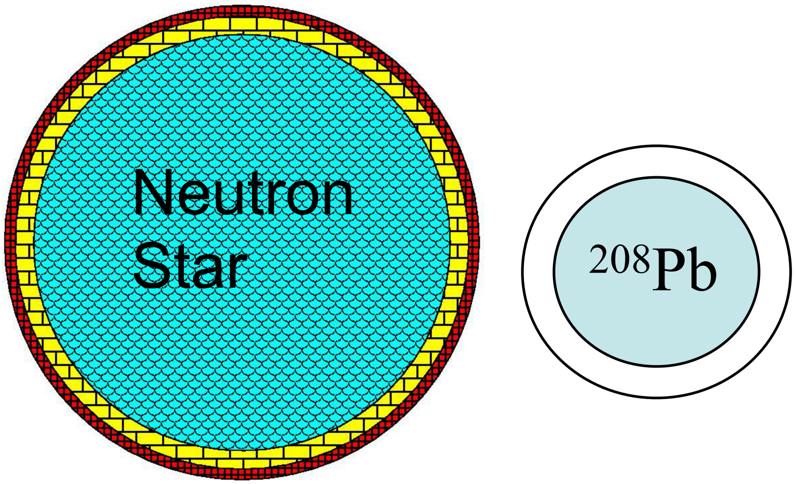
Correlation between Pb skin and dS/dn from full error matrix of Skyrme Fit --Witold Nazarewicz

PREX and Neutron Stars



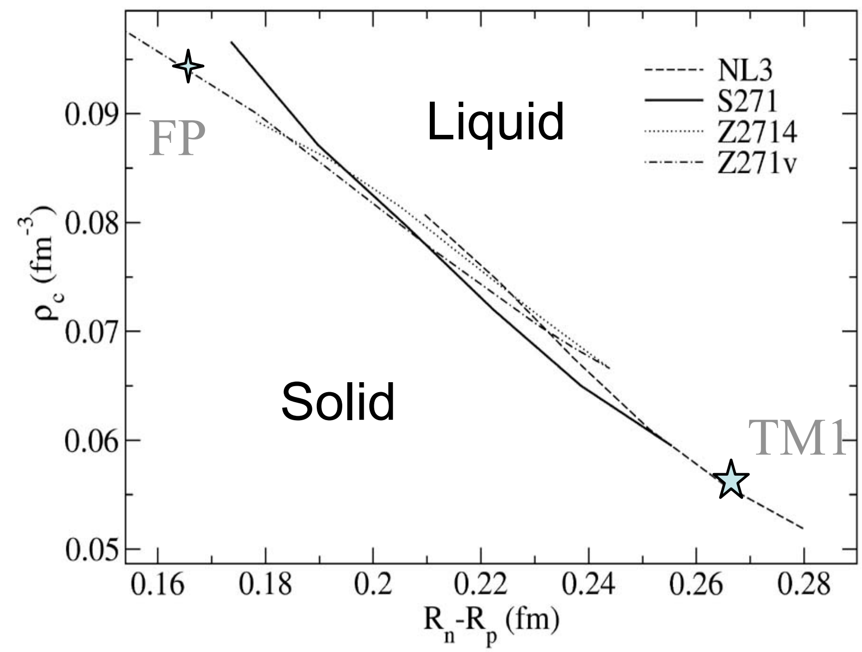


Neutron Star Crust vs Pb Neutron Skin



• 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

Pb Radius vs Neutron Star Radius

- The ^{208}Pb radius constrains the pressure of neutron matter at sub-nuclear densities.
- The NS radius depends on the pressure at nuclear density and above. Central density of NS few to 10 x nuclear density.
- Most interested in density dependence of equation of state (EOS) from a possible phase transition.
- Important to have both low density and high density measurements to constrain density dependence of EOS.
  - 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…

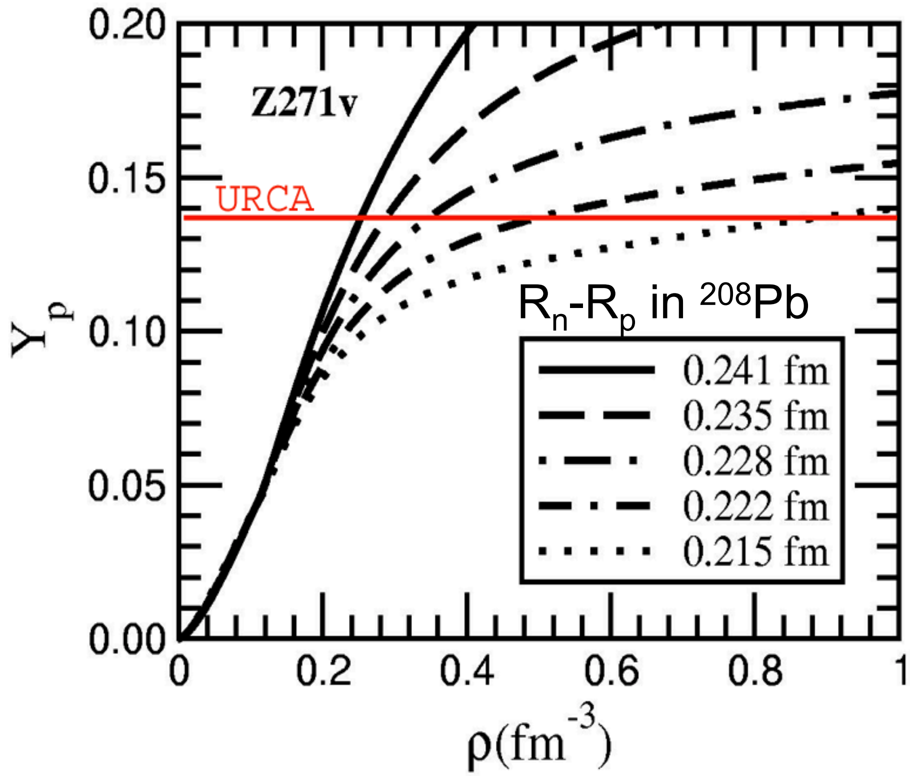
J Piekarewicz, CJH

PREX Constrains Rapid Direct URCA Cooling of Neutron Stars

- Proton fraction Y_p for matter in beta equilibrium depends on symmetry energy S(n).

$$S \approx \mu_n - \mu_p = \mu_e$$

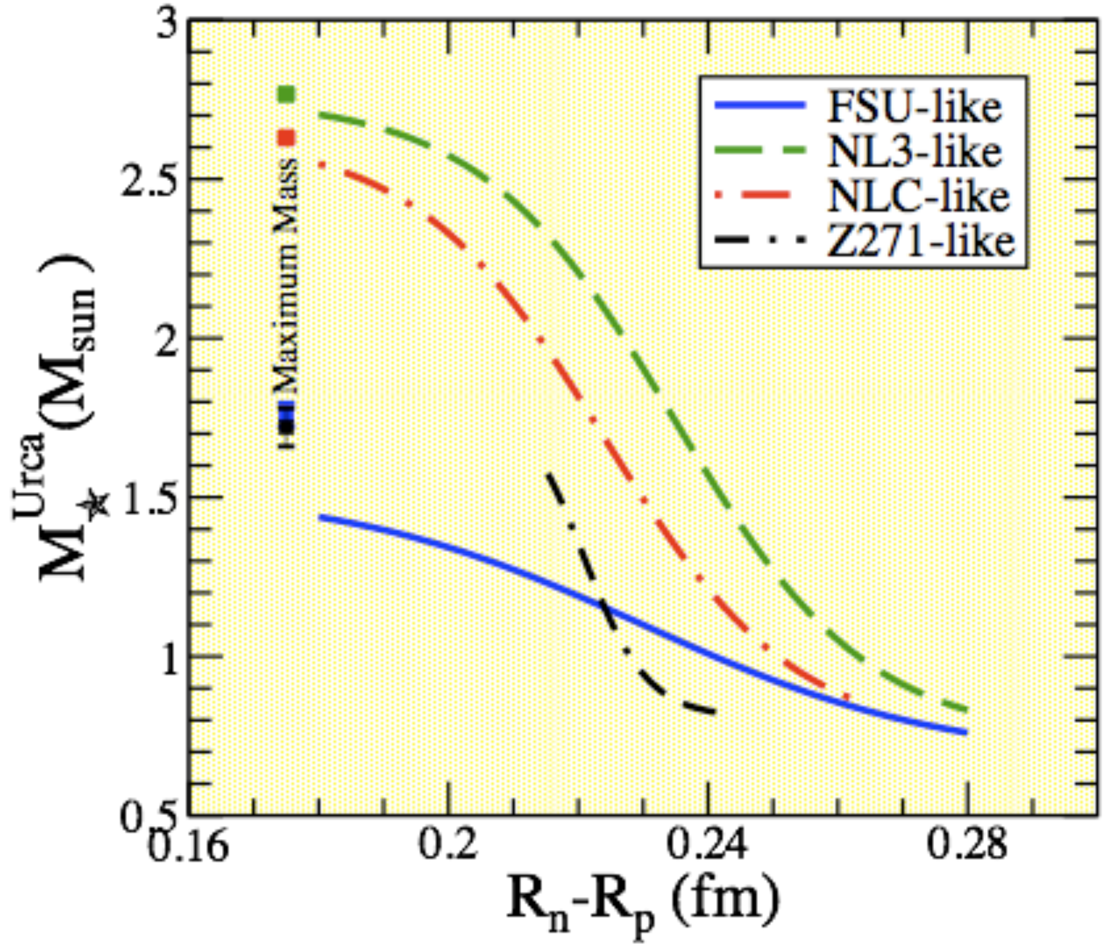
- R_n in Pb determines density dependence of S(n).
- The larger R_n in Pb the lower the threshold mass for direct URCA cooling.
- If R_n-R_p<0.2 fm all EOS models do not have direct URCA in 1.4 $M_\odot$ stars.
- If R_n-R_p>0.25 fm all models do have URCA in 1.4 $M_\odot$ stars.



If Y_p > red line NS cools quickly via direct URCA $n \rightarrow p+e+\nu$

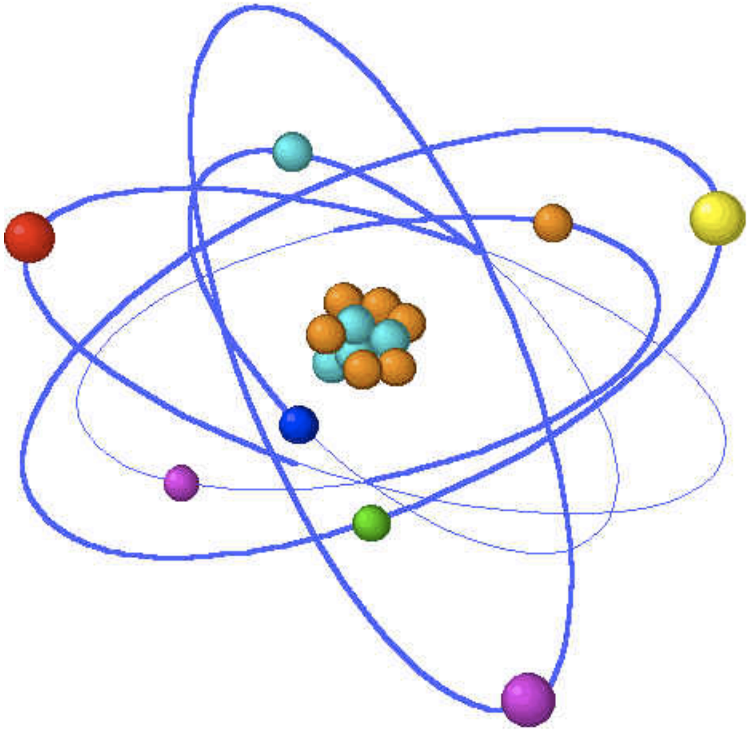
J Piekarewicz, CJH

Minimum Mass for Direct URCA



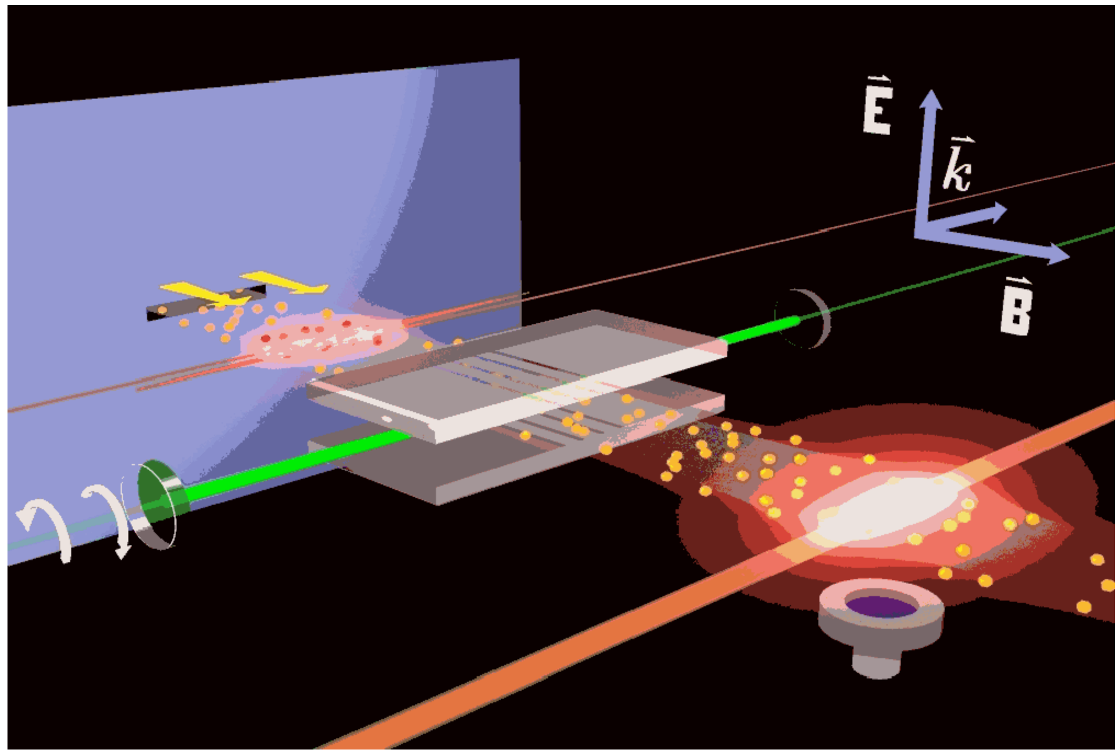
Jorge Piekarewicz

Atomic Physics and PREX



Atomic Parity Nonconservation

- Depends on overlap of electrons with neutron density.
- Cs exp. good to 0.3%.
- Not limited by R_n but future 0.1% exp would need R_n to 1%
- Combine neutron radii from PV e scattering with an atomic PNC exp for best low energy test of standard model.



Colorado Cs Experiment

Atomic parity violation in ytterbium

Dmitry Budker

University of California, Berkeley

Nuclear Science Division, LBNL

Large PNC effect in Yb (~100 Cs) but atomic structure complicated.

- Atomic PV calculation errors cancel in isotopic ratios
- But enhanced sensitivity to the neutron distribution $\rho_n(r)$
- Atomic PV ↔ Neutron distributions

- For ^{170}Yb-^{176}Yb, $Q_W \approx -100$; ΔQ_W(Standard Model) ≈ 6,

  ΔQ_W(Neutron Skin) ≈ 3

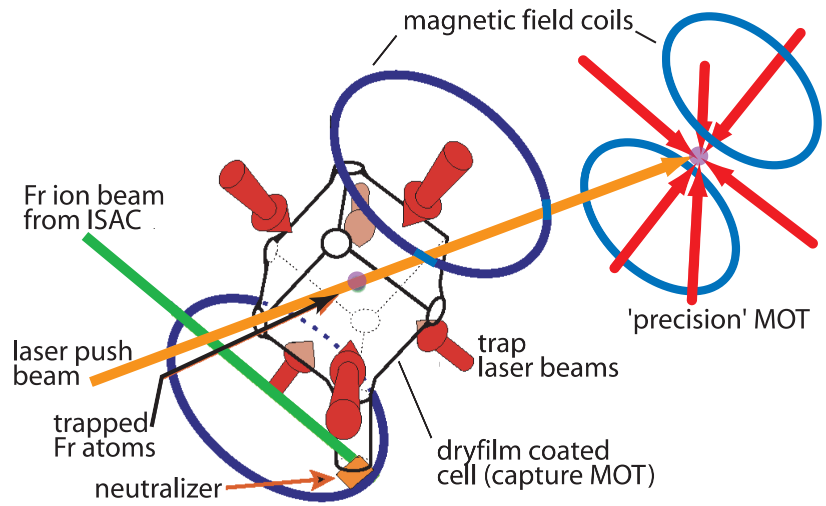
http://socrates.berkeley.edu/~budker/

Francium PNC at TRIUMF

- Atomic PNC in Fr 18x Cs and atomic structure understood at same level.
- But no stable isotopes and more sensitive to neutron radius.
- TRIUMF will produce Fr with actinide target.
- PREX will improve knowledge of n skins.

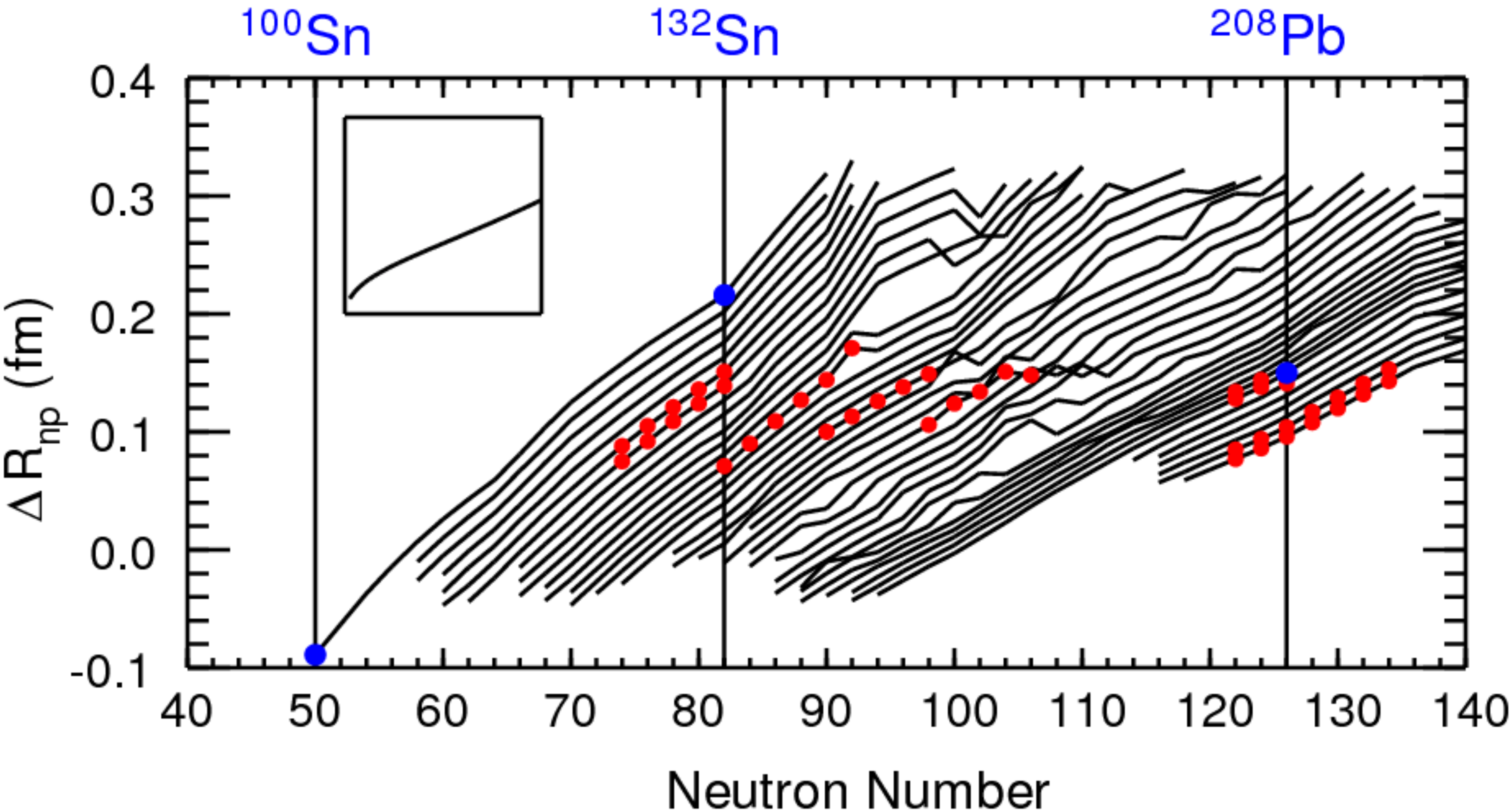
Boulder Cs: massive atomic beam
(10^{13} s^{-1} cm^{-2})
key figure: 10^{10} 6s-7s excitations /sec

Fr trap:
excitation rate per atom: 30 s^{-1}
but asymmetry 18x larger
APNC possible with 10^6 - 10^7 atoms!



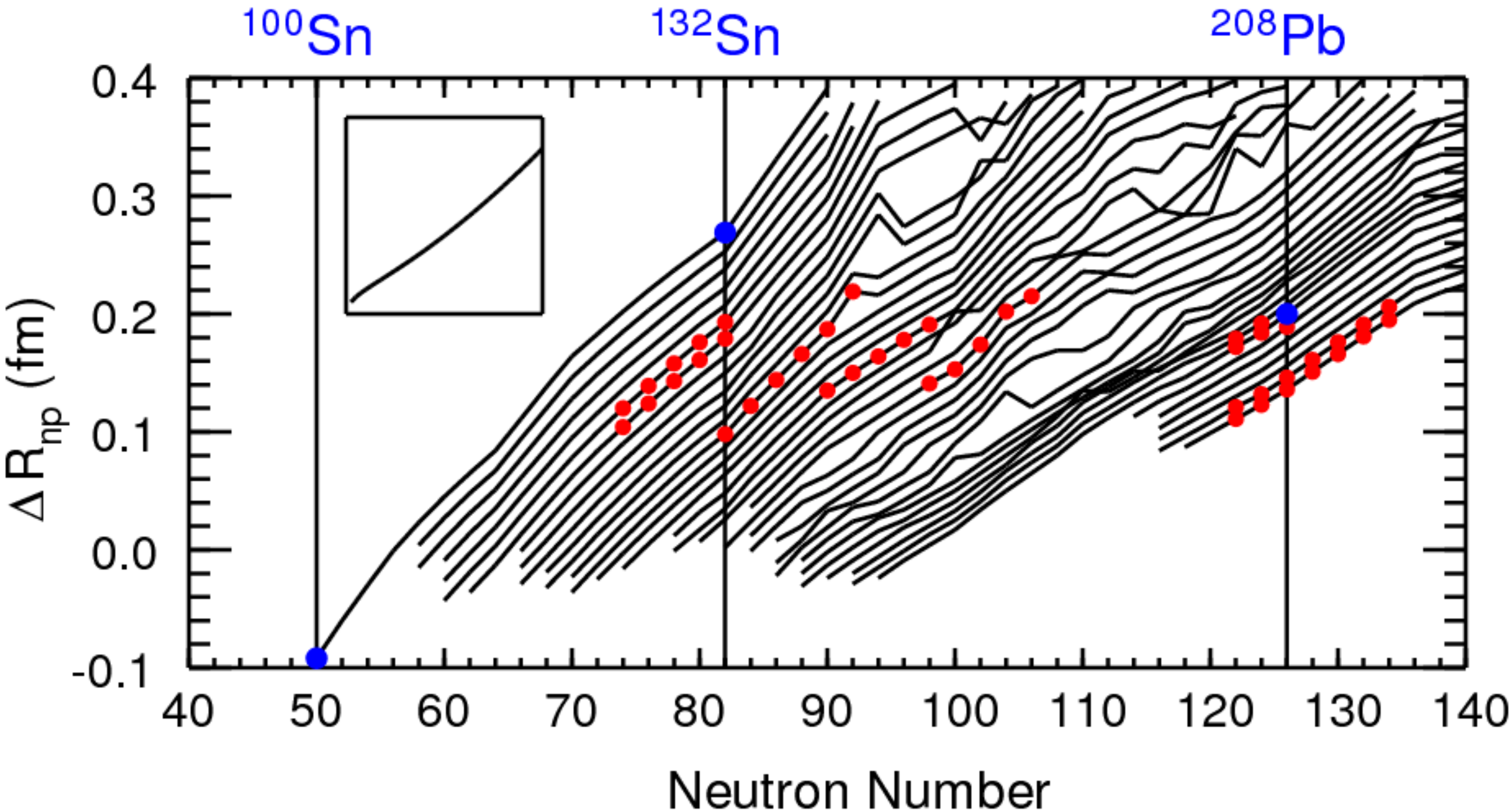
G. Gwinner

Neutron Skins for Atomic PNC



- A. Brown claims n skins of APNC isotopes track ^{208}Pb. PREX constrains them.

Neutron Skins for Atomic PNC



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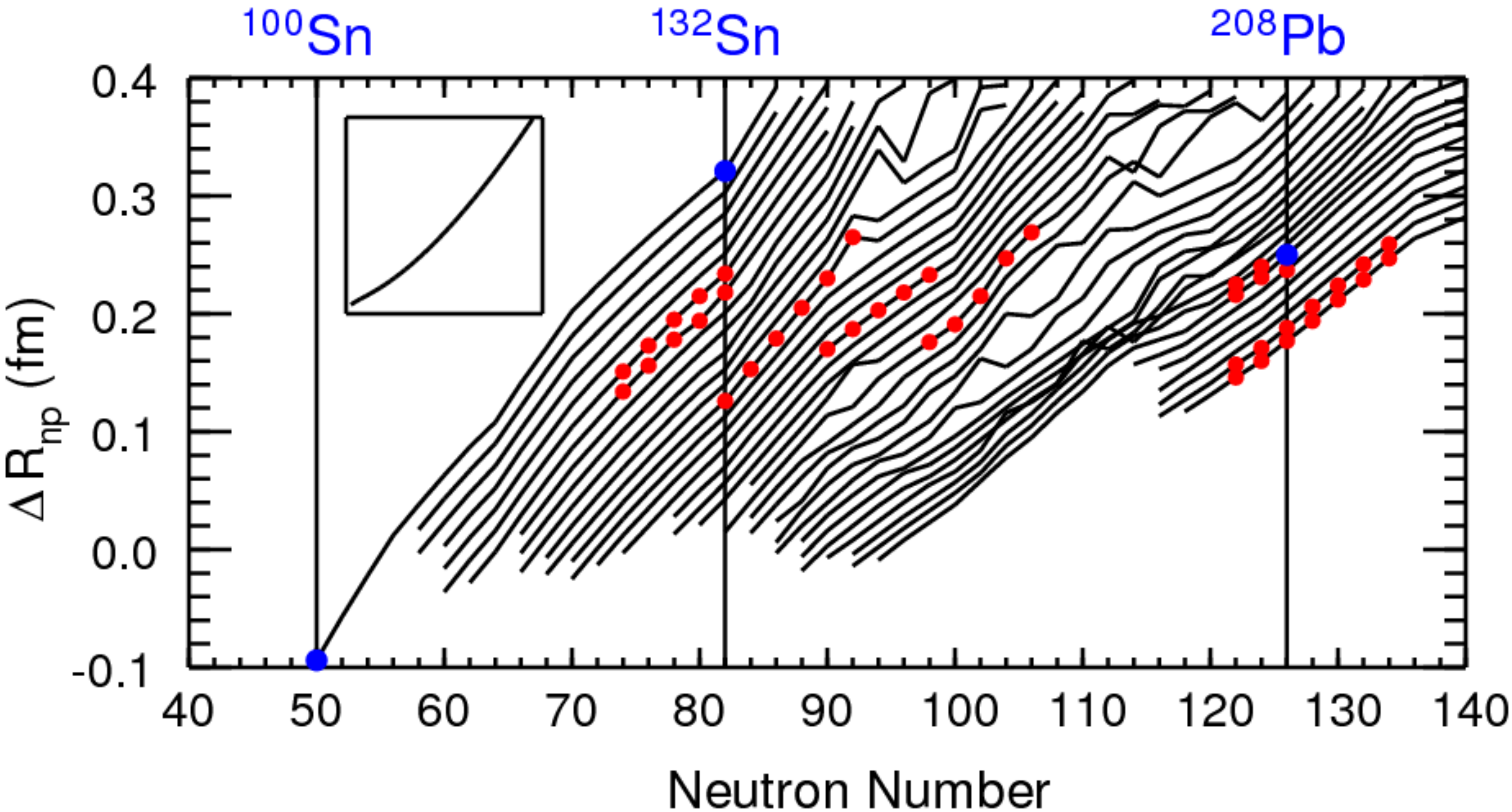
Neutron Skins for Atomic PNC



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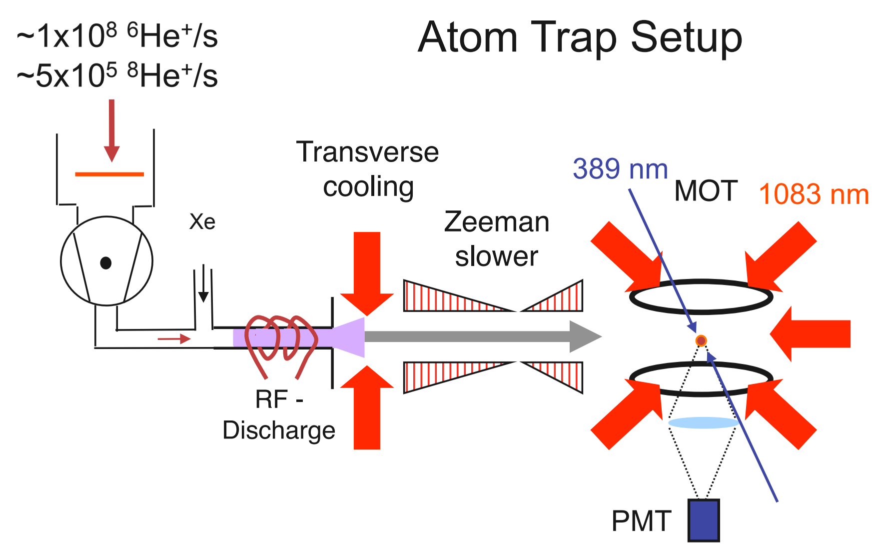
Brown Skin Scaling

- The pressure of neutron matter controls the neutron skins (R_n-R_p) of nuclei of interest for atomic parity experiments.
- Therefore all the skins approx. scale with the neutron skin of ^{208}Pb.
- “Neutron skins have no finger prints”: nothing identifies skin of given nucleus.
- Example: deformation changes proton radius but not skin thickness.
- This is a testable hypothesis.

Charge Radii of ^{6}He, ^{8}He

- Isotope shift of precision He spectroscopy sensitive to nuclear charge radius.
- Protons recoil against neutrons so some sensitivity to neutron distribution.
- Radioactive atoms trapped for measurement.

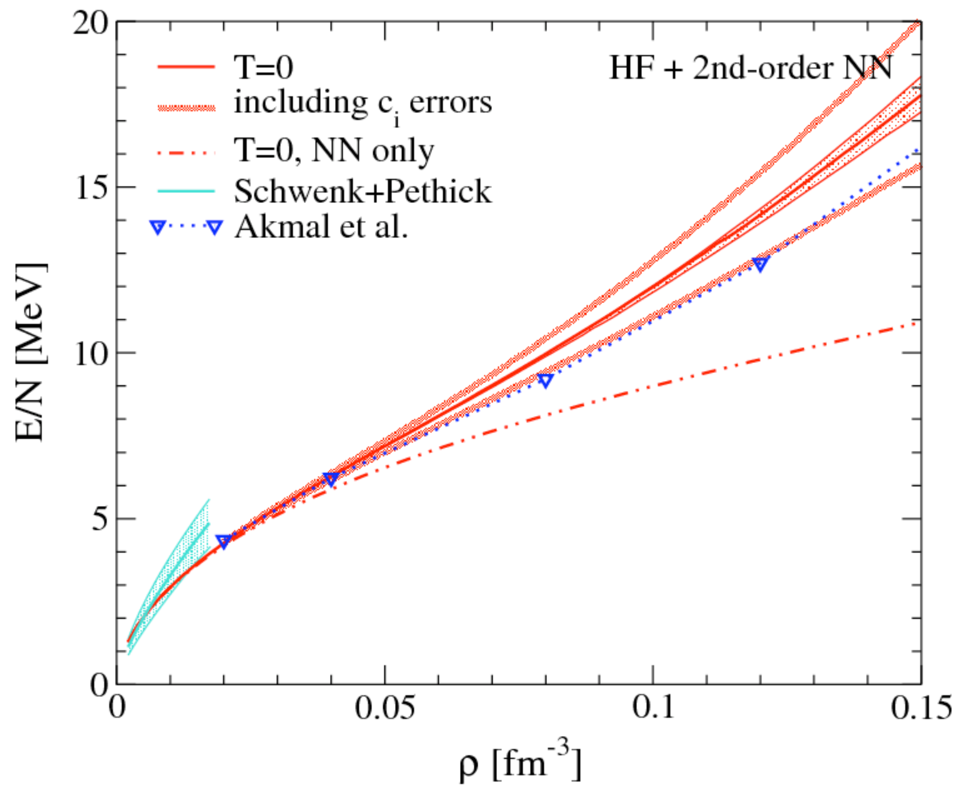


Argonne group P. Mueller et al. measure ^{6}He at Argonne and ^{8}He at GANIL.

Three Neutron Forces

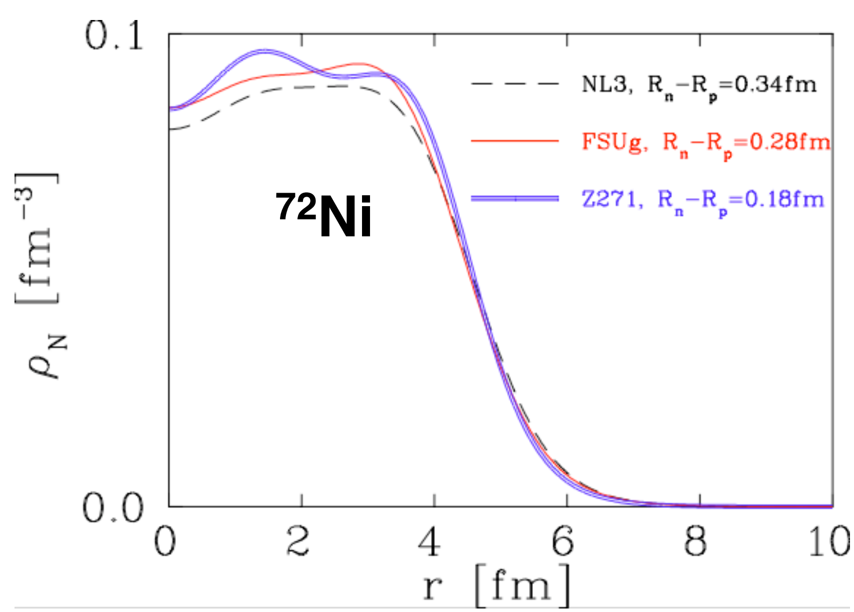
- Detailed observations in light neutron rich nuclei coupled with theoretical and phenomenalogical (phase shift ...) analysis can provide more direct information on three neutron forces.
- A. Schwenk et al. calc. neutron matter including uncertainty in chiral 3 neutron force.
- PREX and Pb radius sensitive to pressure.

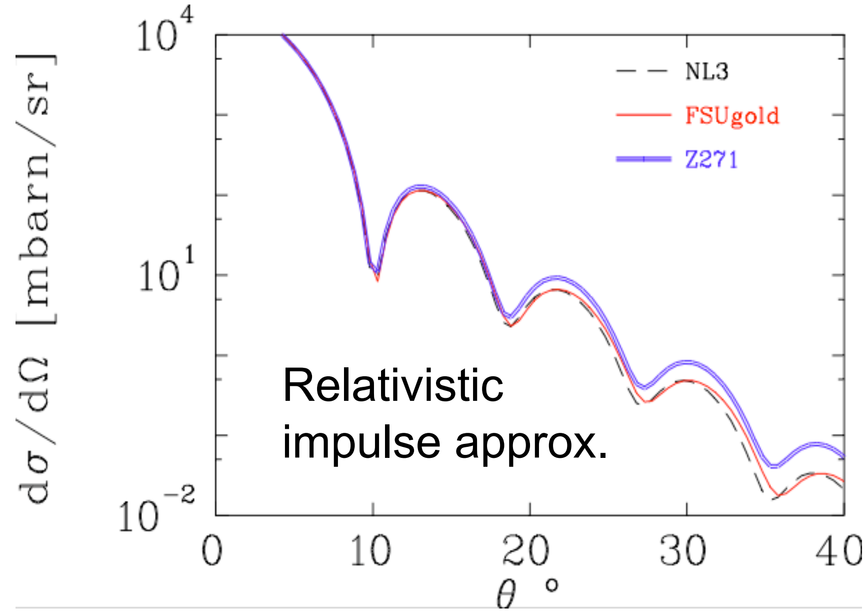
Neutron matter with NN and NNN forces.



Joint exp., phenom., theory, program on 3N forces important.

^{72}Ni+p elastic scattering at 400MeV/A





- Calibrate proton-nucleus elastic scattering reaction model by reproducing PREX neutron radius with p-^{208}Pb scattering.
- Measure neutron radii of exotic nuclei with p elastic scattering using radioactive beams in inverse kinematics.
- Example GSI experiment with ^{72}Ni beam on solid H target.

Helber Dussan

PREX and n Rich Matter

- PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb. This has broad implications for nuclear structure, astrophysics, and atomic parity nonconservation.
- People:
  - Coulomb distortions with E.D. Cooper.
  - Neutron Star correlations with J. Piekarewicz.
  - PREX Radiative corrections with M. Gorshteyn.
  - Students: L. Caballero (now at NC State), H. Dussan, G. Shen, J. Hughto.
- PREX spokespersons: Paul Souder, Krishna Kumar, Robert Michaels, and Guido Urciuoli
- Supported in part by DOE and State of Indiana.