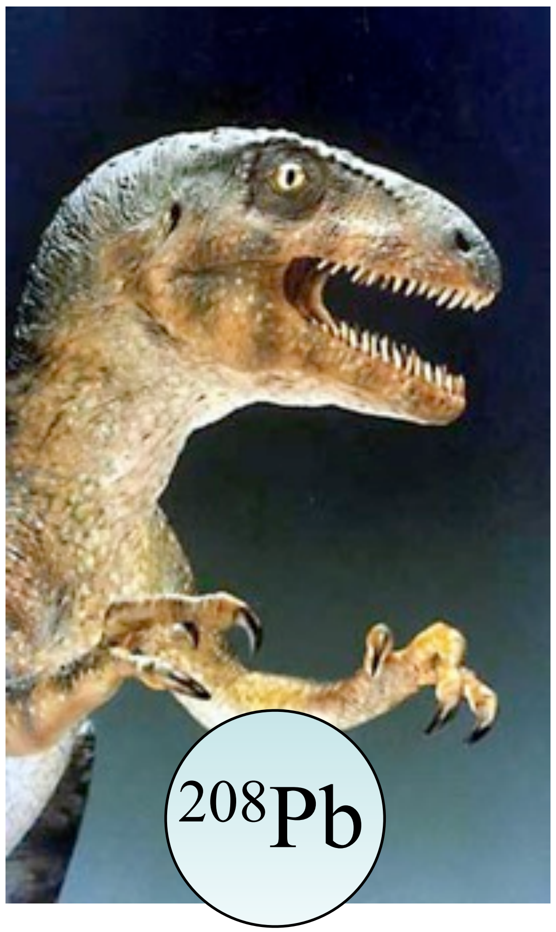
Radiative Corrections to PREX and QWEAK



Implications of PREX for:

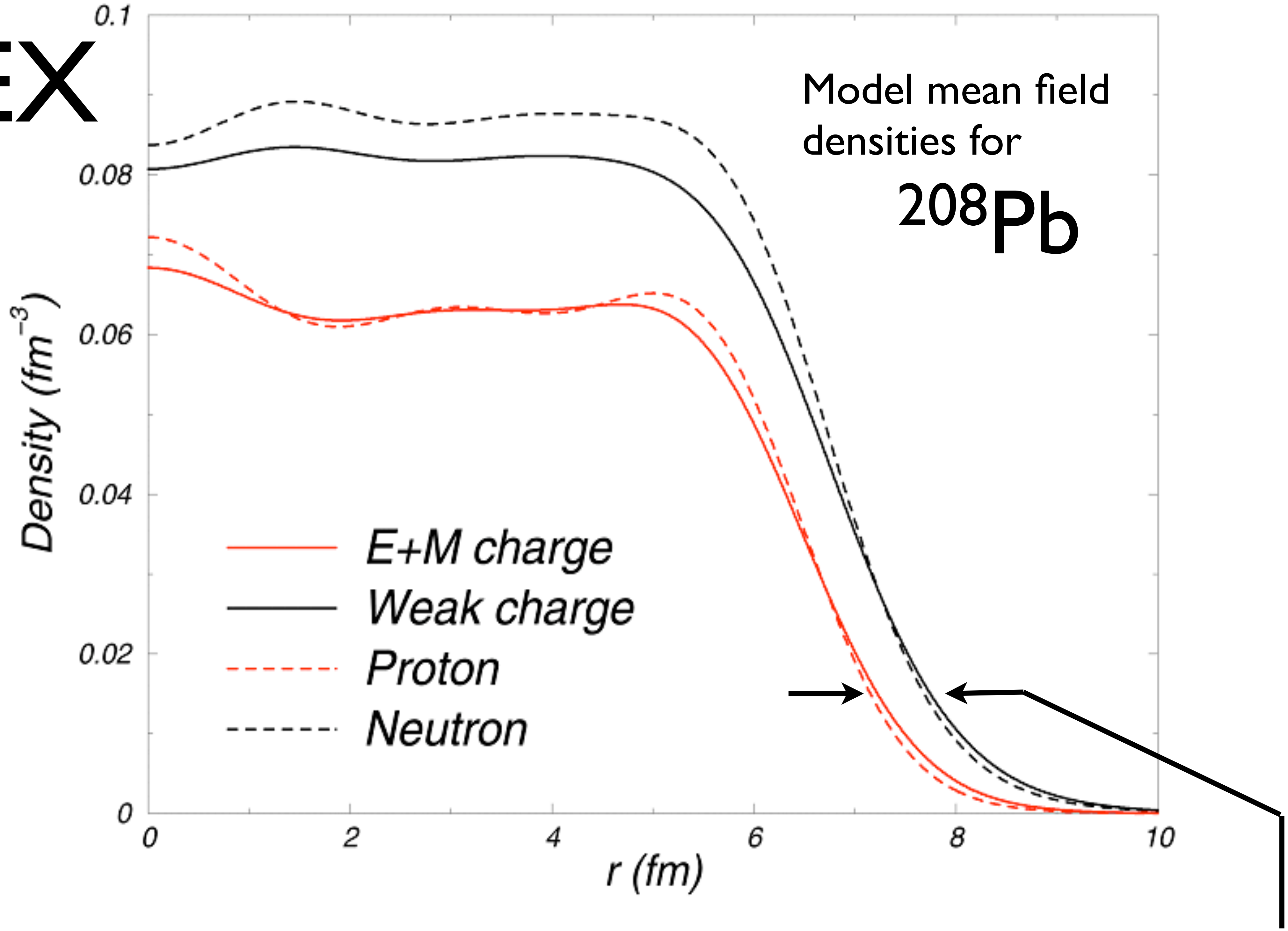
- Theory and chiral EFT three neutron forces.
- Astrophysics X-ray obs of neutron star radii.
- Nuclear structure and dipole polarizability.
- Heavy ion collisions and symmetry energy.

Coulomb distortion, dispersion Corrections for:

- PREX
- Transverse asymmetry
- QWEAK

PAVI11, Rome, Sept. 2011
C. J. Horowitz, Indiana University

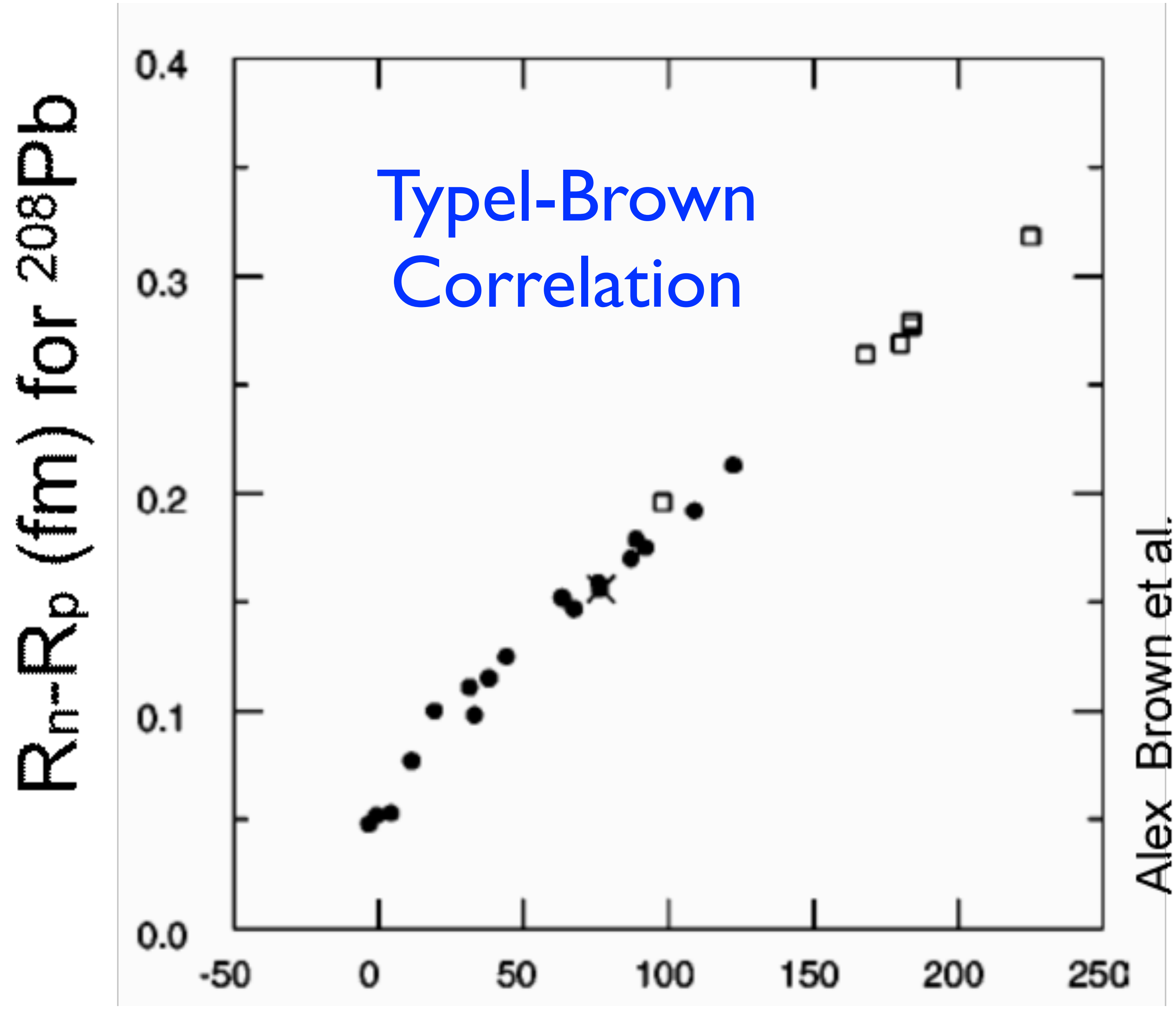
PREX



- PREX measures how much neutrons stick out past protons (neutron skin).
- First measurement of parity violating asymmetry for elastic electron scattering from ^{208}Pb at 1050 MeV and about 5 degrees.
- Interpretation of electroweak reaction is model independent.

^{208}Pb radius and Equation of State

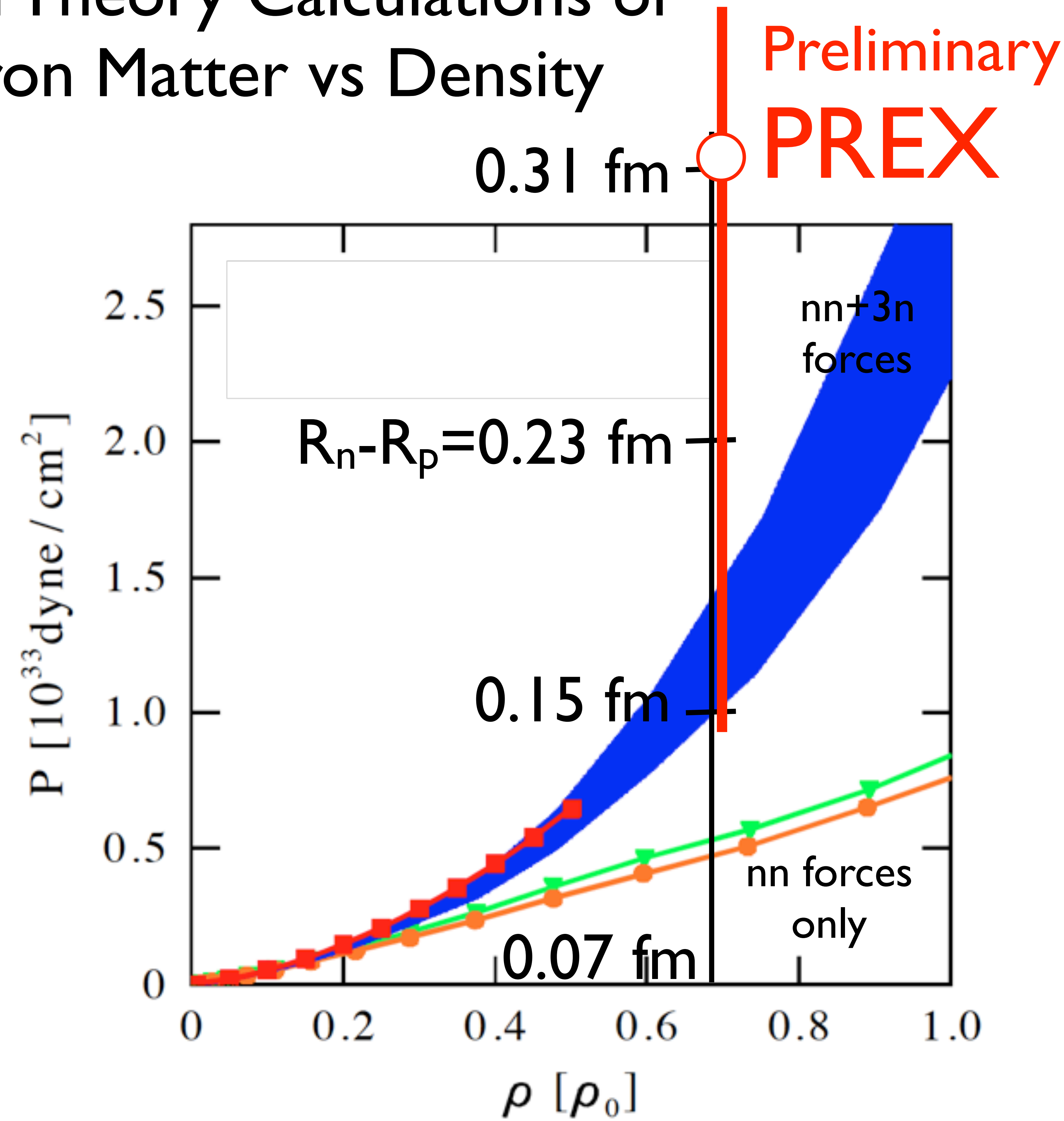
- Pressure of neutron matter forces neutrons out against surface tension. A large pressure gives a large neutron skin.
- Measuring R_n in ^{208}Pb constrains the pressure of neutron matter at $\sim 2/3\rho_0 = 0.1\ fm^{-3}$.



Neutron matter P (MeV/fm^3) x100 at a density of 0.1 fm^{-3}.

Chiral Effective Field Theory Calculations of Pressure of Neutron Matter vs Density

- Chiral EFT calc. of pressure P of neutron matter by Hebeler et al. including three *neutron* forces (blue band) PRL **105**, 161102 (2010)
- Their calculated P and Typel-Brown correlation --> R_n-R_p=0.14 to 0.2 fm
- PREX agrees with results including 3n forces. Three *neutron* forces are very interesting, unconstrained. Some information on 3 *nucleon* forces in ^{3}H, ^{3}He...



A Neutron Star is Newton's 10 km Apple

- In astrophysics and in the laboratory it is the same neutrons, the same strong interactions, the same neutron rich matter, and the same equation of state. A measurement in one domain has important implications in the other domain.

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.
- 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 super-conductor…

J. Piekarewicz, CJH

- Measure area of NS from luminosity, temp. from X-ray spectrum.

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

- Complications:

– Non-blackbody corrections from atmosphere models.

– Curvature of space: measure combination of radius and mass.

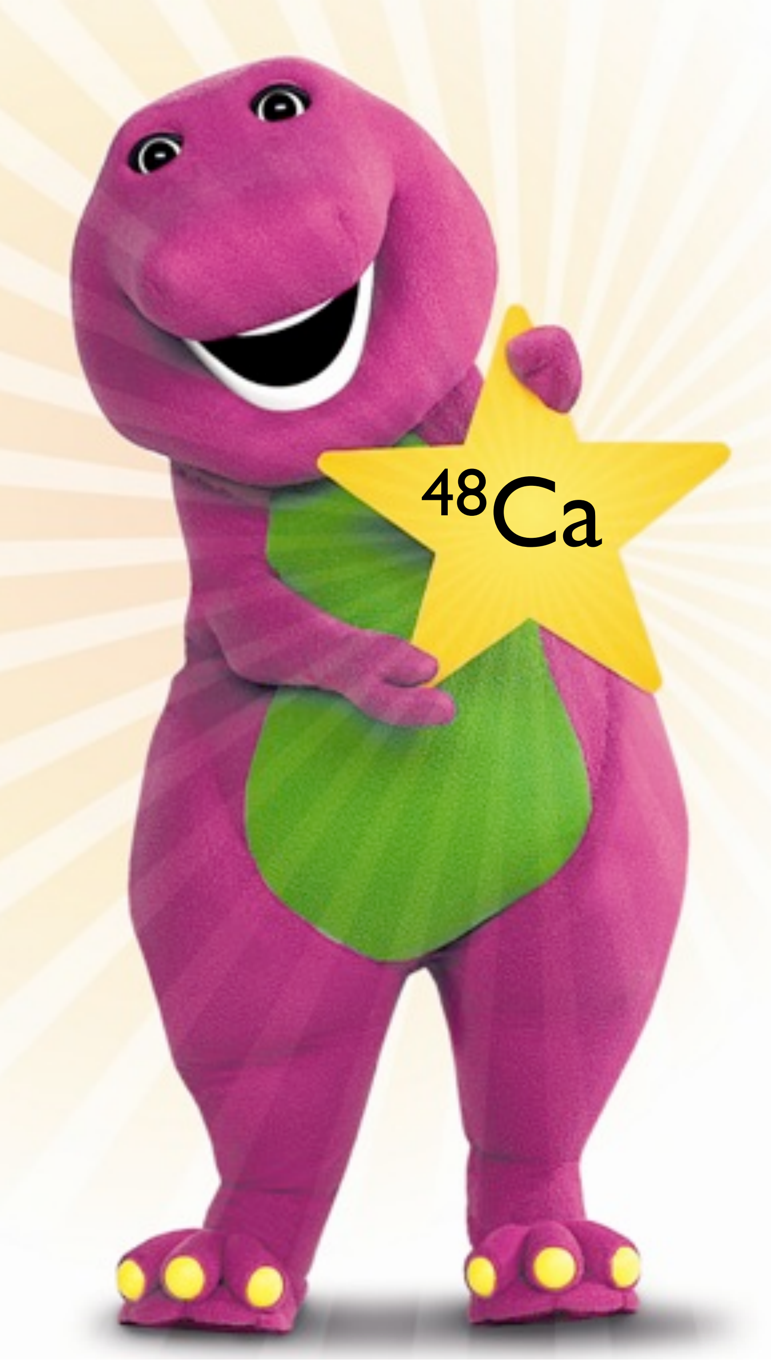
- Steiner, Lattimer, Brown [ArXiv: 1005.0811] combine observations of NS in X-Ray bursts and globular clusters and deduce radii + EOS.

– EOS + Typel-Brown correlation -> Predict ^{208}Pb neutron skin: R_n-R_p=0.15+/- 0.02 fm.

– Model dependent. F. Ozel et al. get smaller radii for NS and softer EOS.

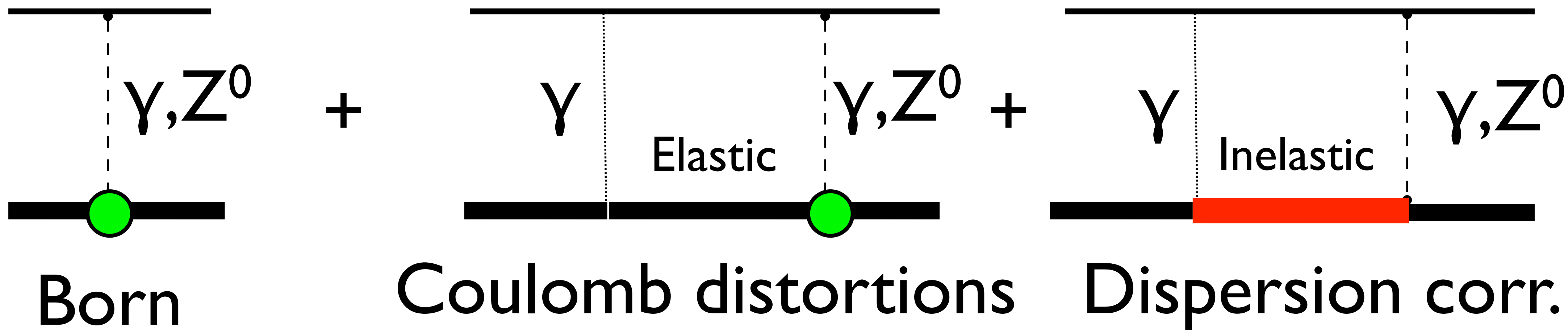
PREX next Steps

- Important to run again with ^{208}Pb to reach 1% goal on R_n (3% for A). Provides sharp test of several theoretical, astrophysical, and nuclear structure predictions. Approved by JLAB PAC.
- Very attractive to also measure R_n in ^{48}Ca. Smaller nucleus can be measured at higher Q^2 (and beam energy) where experimental figure of merit is higher. Microscopic coupled cluster and no-core shell model calculations can directly relate R_n (^{48}Ca) to three neutron forces.



Radiative Corrections

Radiative corrections



- Coulomb distortions are coherent, order $Z\alpha$. Important for PREX (Pb has Z=82).

- Dispersion corrections order α (not $Z\alpha$). Important for QWEAK because correction is order $\alpha/Q_w \sim 10\%$ relative to small Born term (Q_w).

- Both Coulomb distortion and dispersion cor. can be important for Transverse Beam Asymmetry A_n for ^{208}Pb. Note Born term gives zero by time reversal symmetry.

Coulomb Distortions for PREX

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

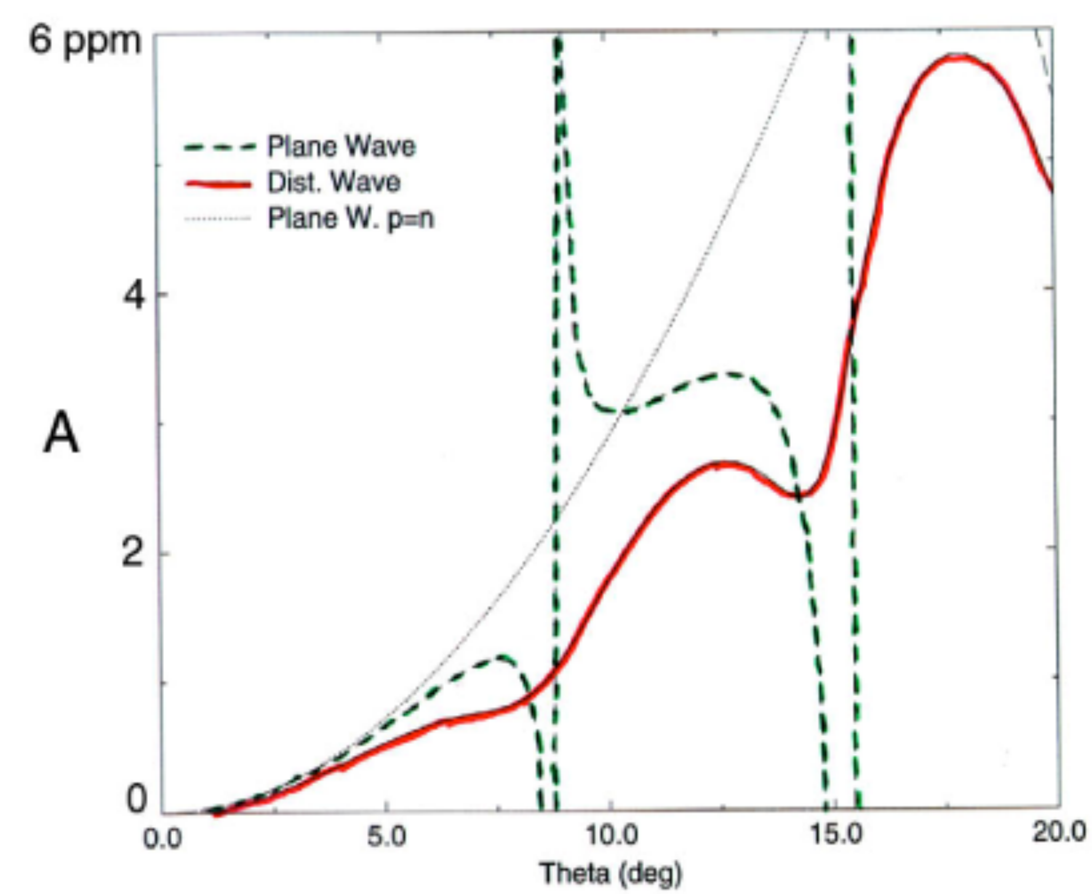
$$A \propto G_F \rho_W(r) \approx 10 \text{ eV} \qquad V(r) \approx 25\text{MeV}$$

- 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. Q^2 shared between "hard" weak, and soft interactions so weak amplitude $G_F Q^2$ reduced.

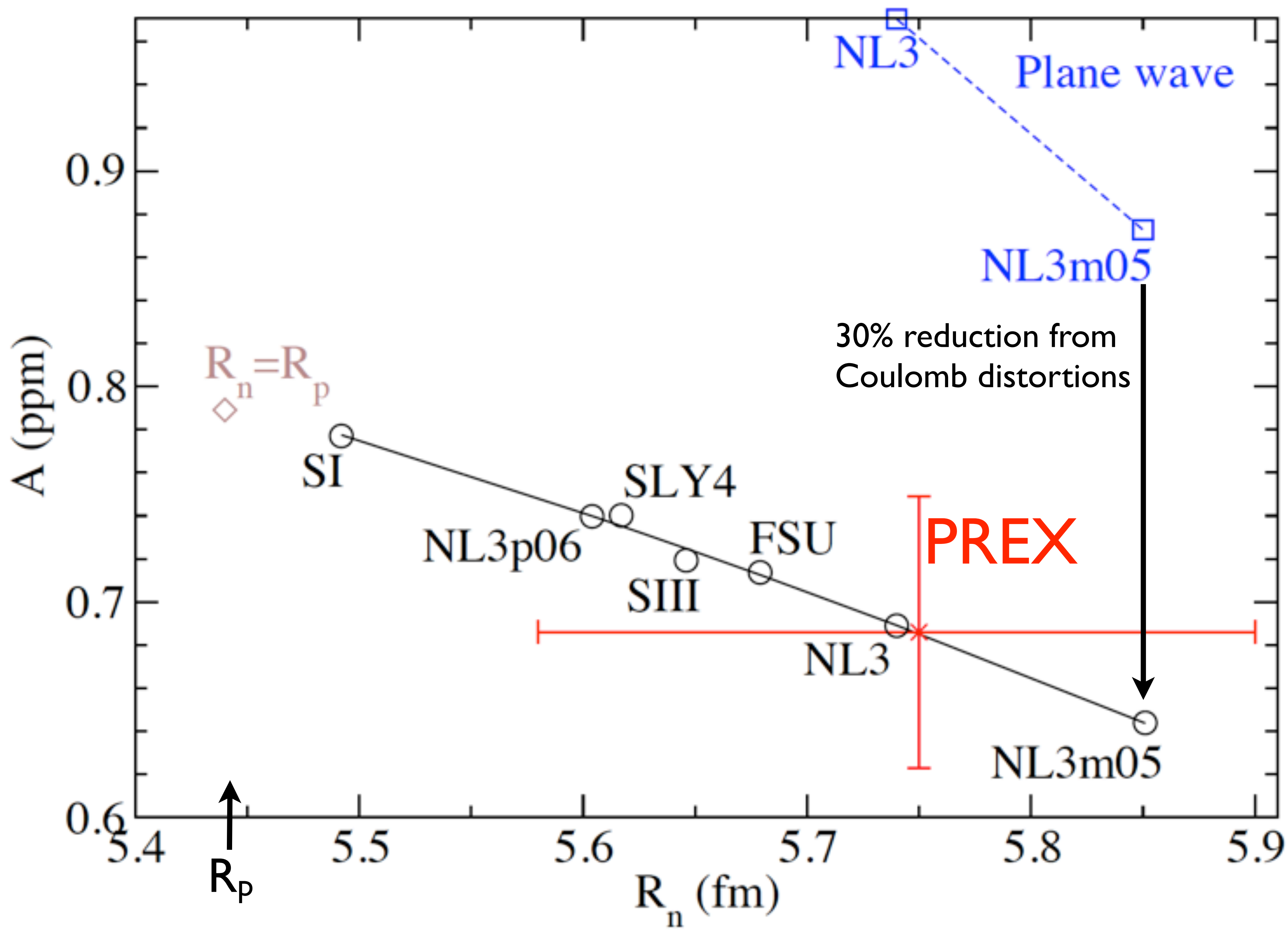
^{208}Pb at 850 MeV



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

--- With E.D. Cooper!

Preliminary PREX result



- Need final acceptance to compare theory/ exper.

Dispersion correction to QWEAK

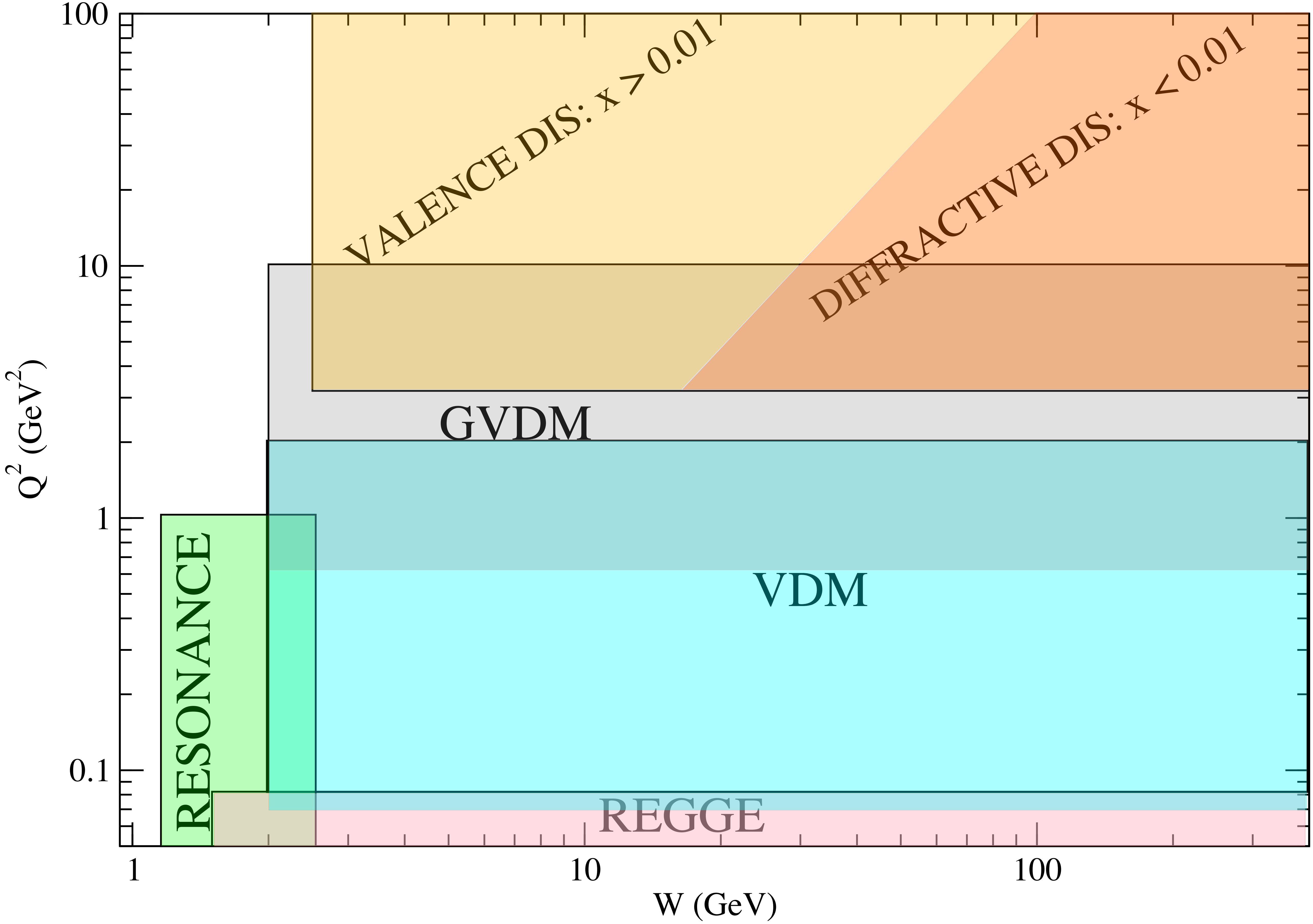
$$A^{PV} = \frac{G_F t}{4\sqrt{2}\pi\alpha_{\rm em}}\left[(1+\Delta\rho+\Delta_e)(1-4\sin^2\hat\theta_W(0)+\Delta_e')+\Box_{WW}+\Box_{ZZ}+\Box_{\gamma Z}\right]+\cdots,$$

$$\mathrm{Im}\Box_{\gamma Z_A}(\nu) = \alpha_{\rm em} g_A^e \int_{W_\pi^2}^{s}\frac{dW^2}{(s-M^2)^2}\int_0^{Q^2_{max}}\frac{dQ^2}{1+\frac{Q^2}{M_Z^2}}\left[F_1^{\gamma Z}+\frac{s(Q^2_{max}-Q^2)}{Q^2(W^2-M^2+Q^2)}F_2^{\gamma Z}\right]$$

$$\mathrm{Re}\Box_{\gamma Z_A}(\nu) = \frac{2\nu}{\pi}\int_{\nu_\pi}^{\infty}\frac{d\nu'}{\nu'^2-\nu^2}\mathrm{Im}\Box_{\gamma Z_A}(\nu')$$

* Short ranged WW, ZZ, and γZ box contributions renormalized. Important energy dependent γ-Z box correction of intermediate range and size α/Q_W=10%!
* Need interference structure functions $F_i^{\gamma Z}(x,Q^2)$. In principle can use PVDIS (and not so DIS) data.
* Instead use real+virtual photo-absorption data and isospin rotation $F_i^{\gamma\gamma}$-->$F_i^{\gamma Z}$.

Kinematics: Resonance and VDM regions important



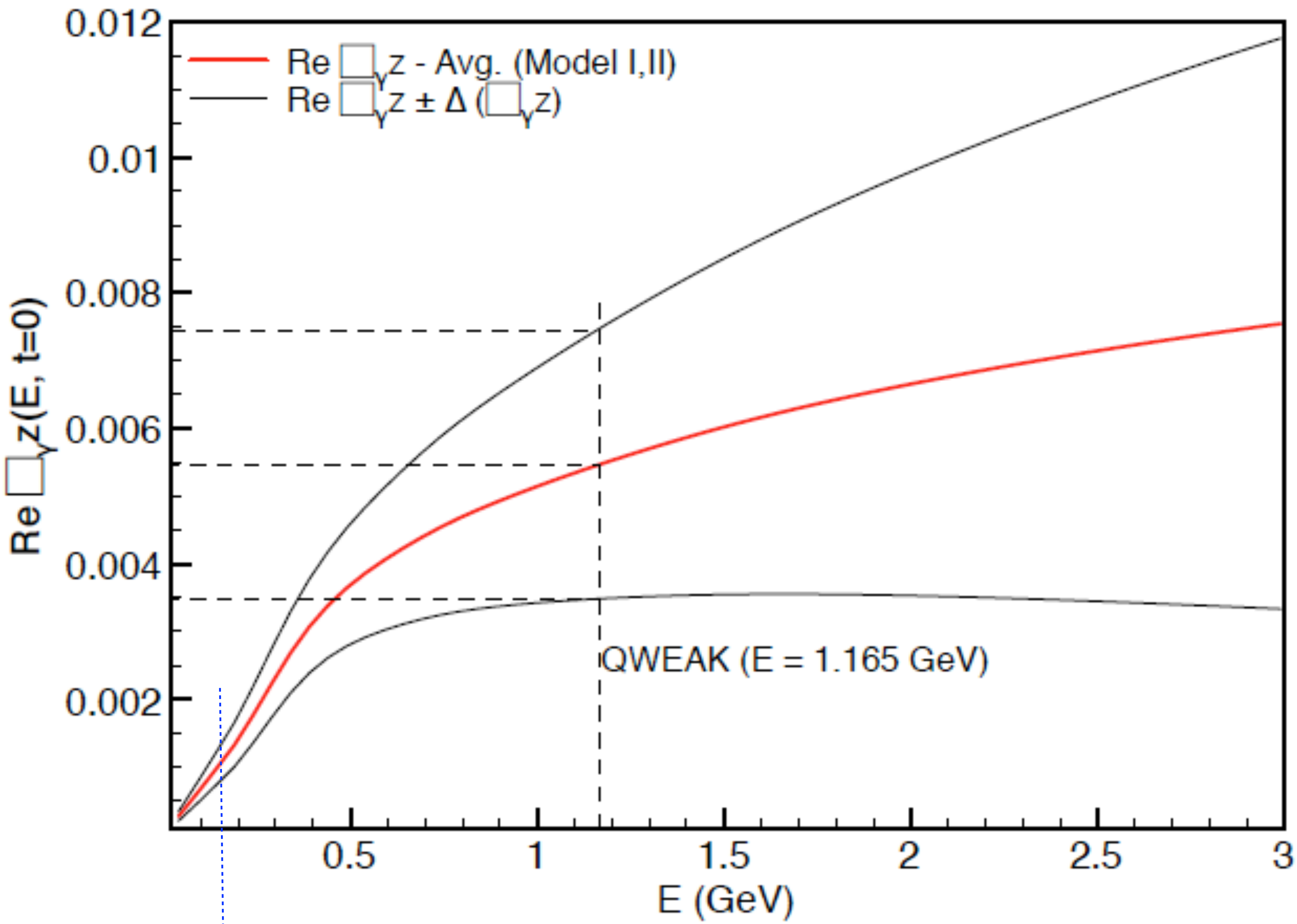
Result at QWEAK kinematics

$$\mathrm{Re}\,\Box_{\gamma Z_A}(E = 1.165\,\mathrm{GeV}, t = -0.03\,\mathrm{GeV}^2) \;=\; \left[5.39 \pm 0.27\,(\mathrm{mod.\,avg.}) \;\pm\; 1.88\,(\mathrm{backgr.})^{+0.58}_{-0.49}\,(\mathrm{res.}) \pm 0.07\,(t-\mathrm{dep.})\right] \times 10^{-3}$$

$$Q_W^p = 0.0713 \pm 0.0008 \qquad \frac{\mathrm{Re}\,\Box_{\gamma Z_A}}{Q_W^p} = (7.6 \pm 2.8)\%$$

- Error is dominated by uncertainty in isospin rotation of background. [Example in simple VD model photon goes to omega, rho, and phi mesons of known isospin.]
- Can measure isospin of background with PV(not so deep) inelastic scattering at low to moderate Q^2.
- Compared to small weak charge we predict a 7.6 +/- 2.8 % correction.

Energy dependence for Mainz



Mainz: at 180 MeV correction is smaller with a six times smaller uncertainty than for QWEAK.

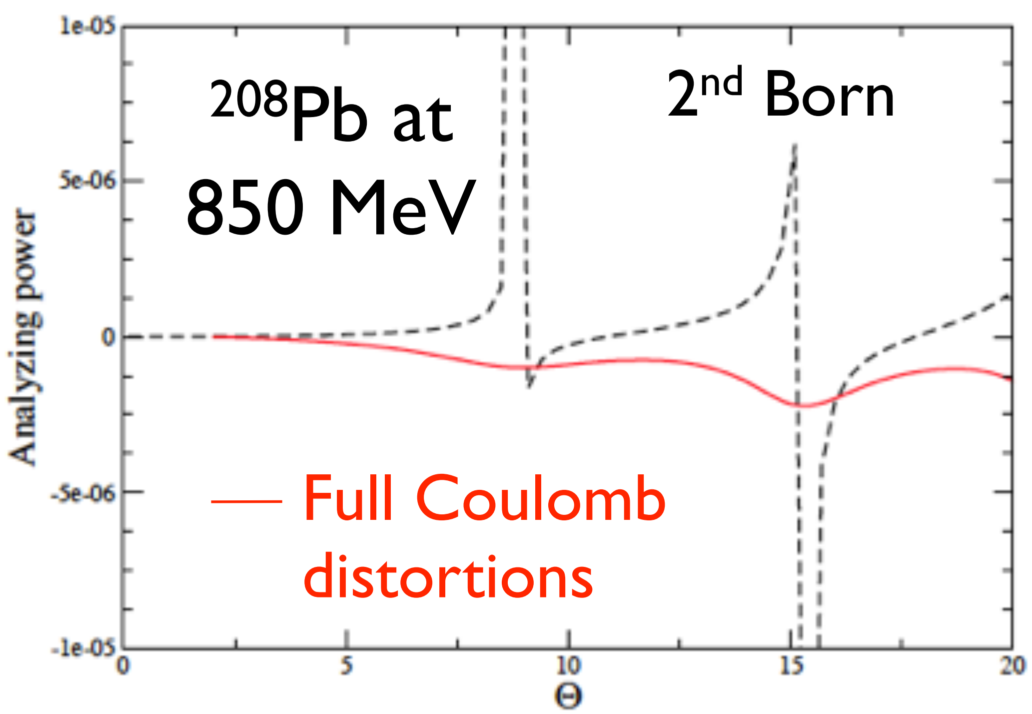
$$\mathrm{Re}\,\Box_{\gamma Z}(E = 0.180\,\mathrm{GeV}, t = 0) \; = \; [1.32 \pm 0.05\,(\mathrm{mod.\,avg.}) \; \pm 0.27\,(\mathrm{backgr.})^{+0.11}_{-0.08}\,(\mathrm{res.})] \times 10^{-3}$$

Transverse Beam Asymmetry A_n for PREX (^{208}Pb)

- Left / Right cross section asymmetry for electrons with transverse polarization.
- Potential systematic error for PV from small trans components of beam polarization.
- Relativistic effects make A_n of order m/E.
- A_n vanishes in Born approx (time reversal) --> Sensitive probe of 2 or more photon effects.

Coulomb Distortions

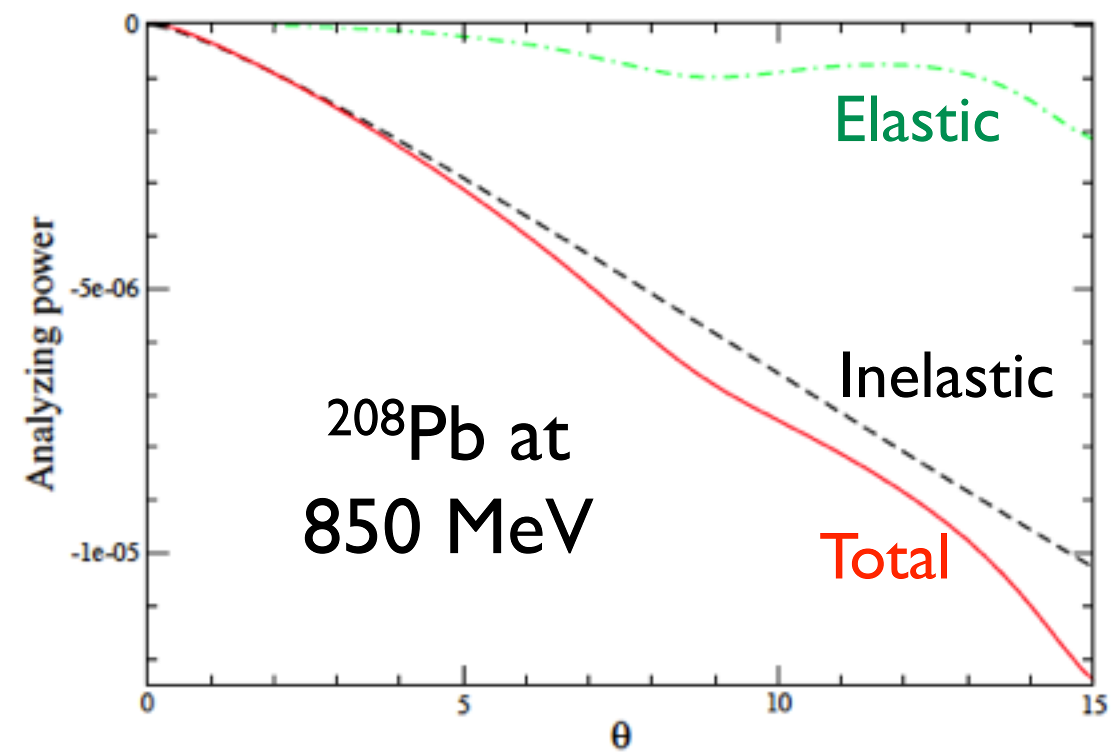
- Only keep elastic intermediate states.
- Just solve Dirac Eq. for electron of mass m in Coulomb potential (very hard numerically at high energies).
- Coulomb distortion contribution to A_n very sensitive to Z of target and small for small Z.
- 2nd Born bad for large Z.



Dispersion contributions

- Sum over excited states in 2nd Born approximation with dispersion relation.

$$A_n^{inelast} \approx -\frac{1}{4\pi^2}\frac{m_e}{E_{lab}}\frac{M}{\sqrt{s}}\frac{A}{Z}\frac{g_N(Q^2)}{F_N(Q^2)}\tan\frac{\theta_{c.m.}}{2}$$
$$\times \int_0^{E_{lab}} d\omega\omega\sigma_{\gamma p}(\omega)\ln\left[\frac{Q^2}{m^2}\left(\frac{E_{lab}}{\omega}-1\right)^2\right]$$



Note: 2nd Born is probably not good for inelastic but that is all that has been calculated.

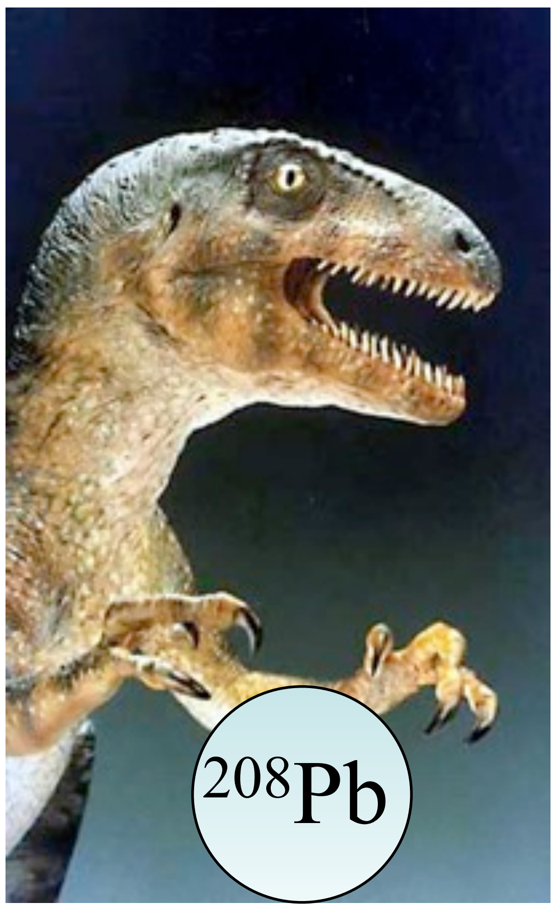
A_n for different nuclei

- Dispersion correction calculations (to order α^2) suggest that A_n should scale roughly as A/Z and should only weakly depend on energy.
- This qualitatively agrees for H, ^{4}He, and ^{12}C but not ^{208}Pb.
- Preliminary PREX results (see R. Michaels talk)
  - $A_n(^{12}C)$ = -6.52 +/- 0.36 +/- 0.35 ppm
  - $A_n(^{208}Pb)$ = 0.13 +/- 0.19 +/- 0.36 ppm
- The large difference for ^{208}Pb is likely from Coulomb distortions. Measure A_n for different nuclei between C and Pb. Measure A_n vs Q^2 near diffraction minimum. Calculate dispersion corrections with Coulomb distortions.

Three Photon Observables

- The large difference between A_n for ^{208}Pb and ^{12}C is an observable that likely requires the exchange of three (or more) photons.
- Full 2 photon exchange calculations predict similar A_n for C and Pb. Difference is likely due to Coulomb distortions in Pb that involve the exchange of additional photons.

Radiative Corrections to PREX and QWEAK

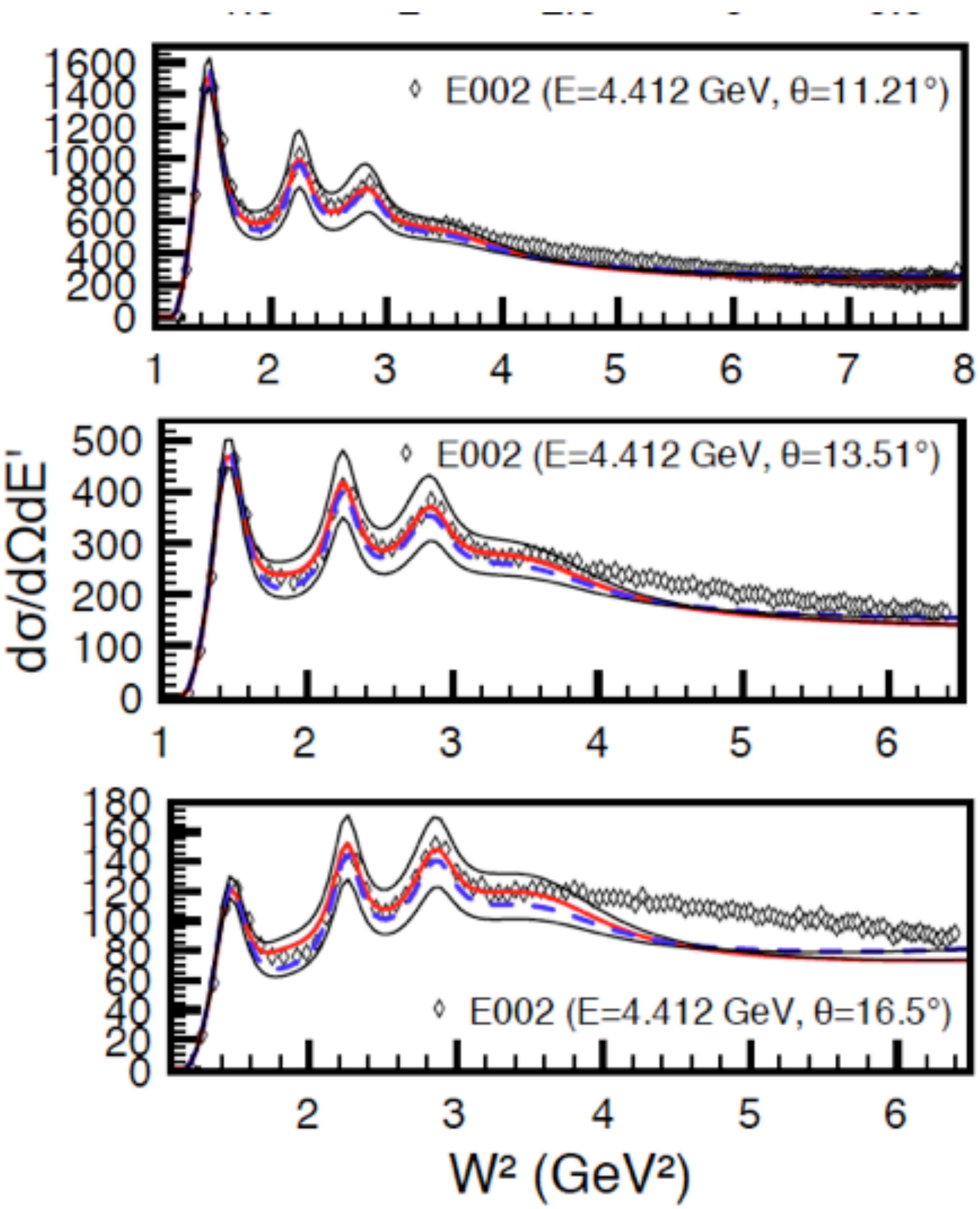


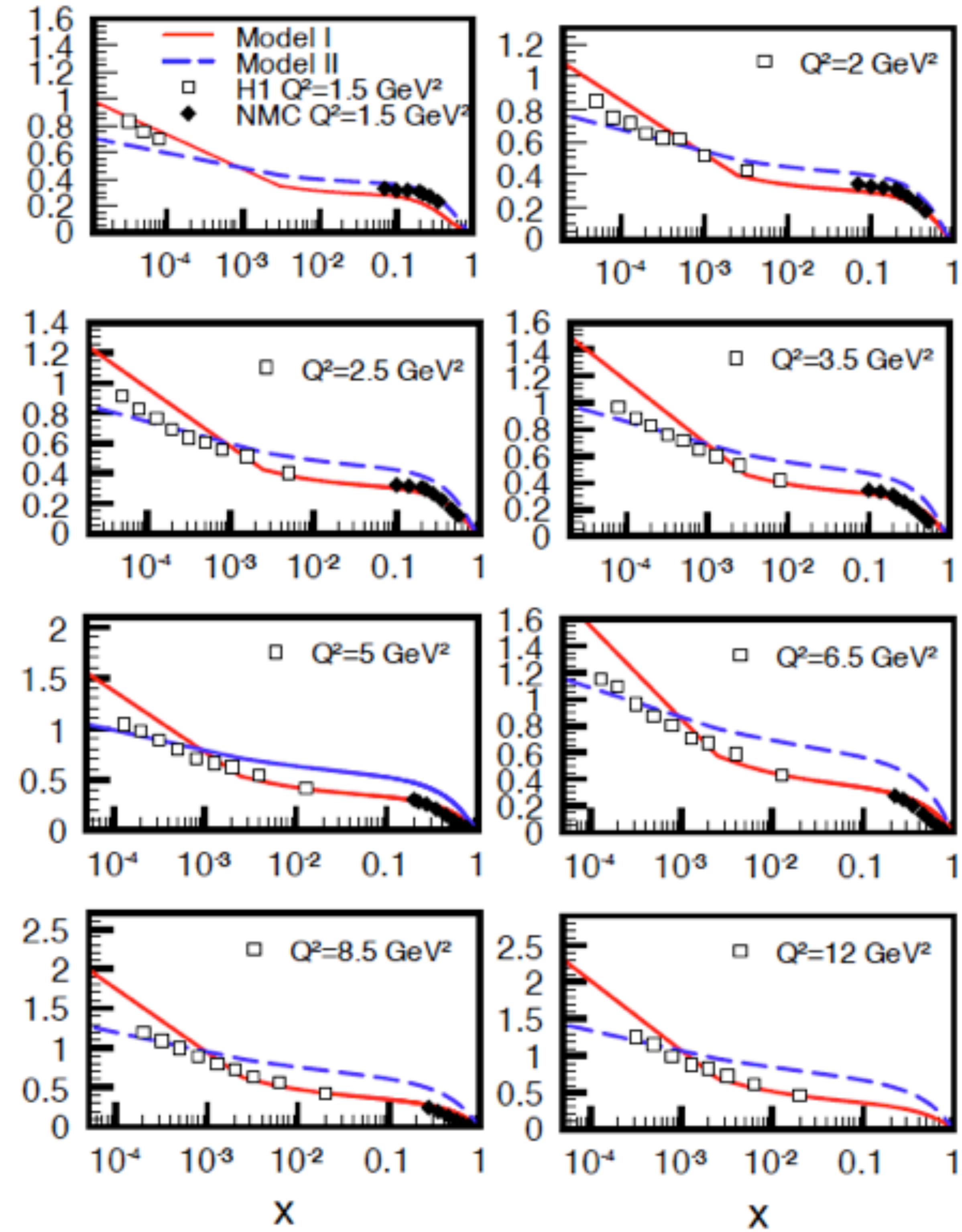
- Collaborators: *Mikhail Gorchtein*, M. Ramsey-Musolf, Shufang Ban
- PREX spokespersons: Krishna Kumar, Robert Michaels, Kent Paschke, Paul Souder, Guido Urciuoli
- Supported in part by DOE

C. J. Horowitz, Indiana University, PAVI11, Rome, Sept. 2011.

Models

- Model I:
  - Resonances fit to electro-production data [Cristy+Bosted, PRC81 (2010) 055213, (background adjusted for our high W form)]
  - High W part from hybrid GVD/color dipole approach [Cvetic et al, Eur. Phys. J C13(2000) 301.]
- Model II:
  - High W part from “naive” GVD model [Alwall et al, Phys Lett B596 (2004) 77.]

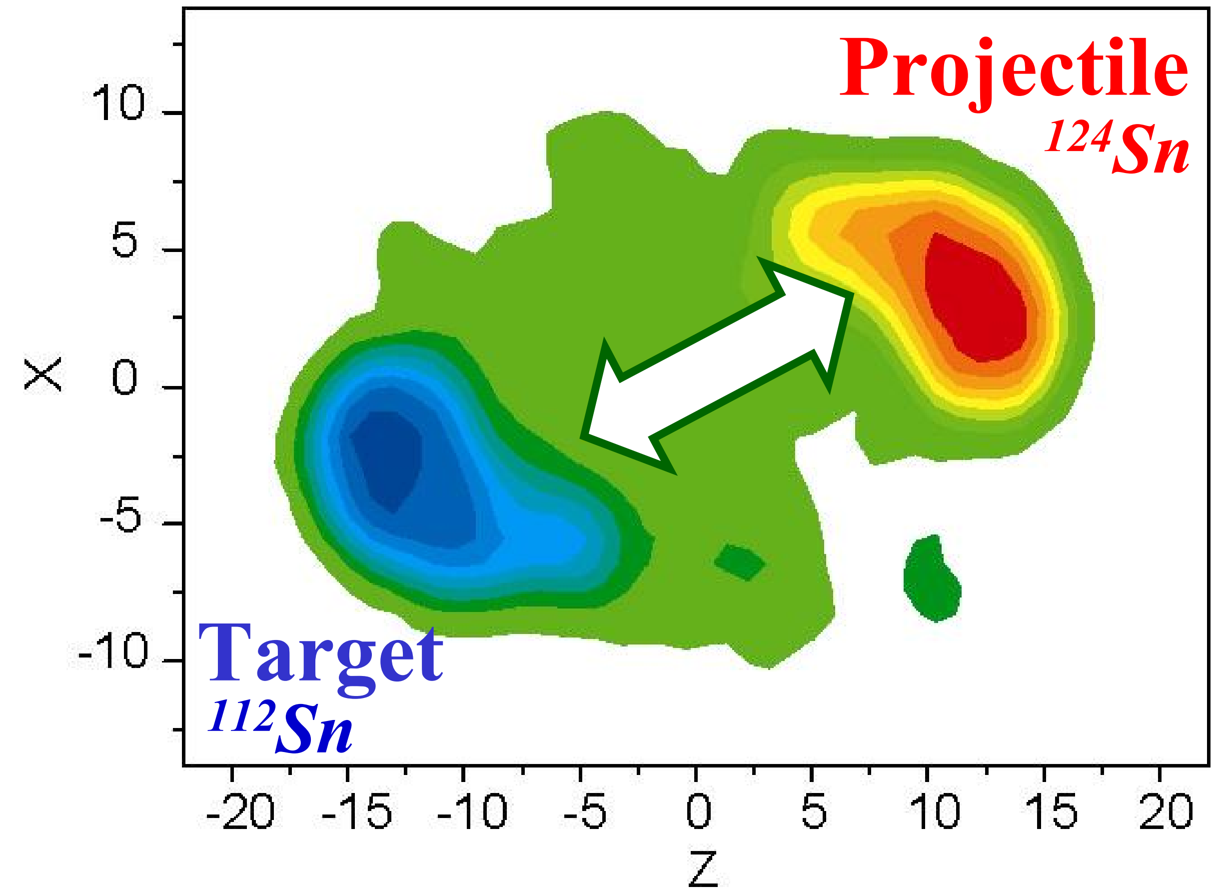




- Resonances left, and DIS F_2 structure function right. Model I is red, model II is blue dashed.

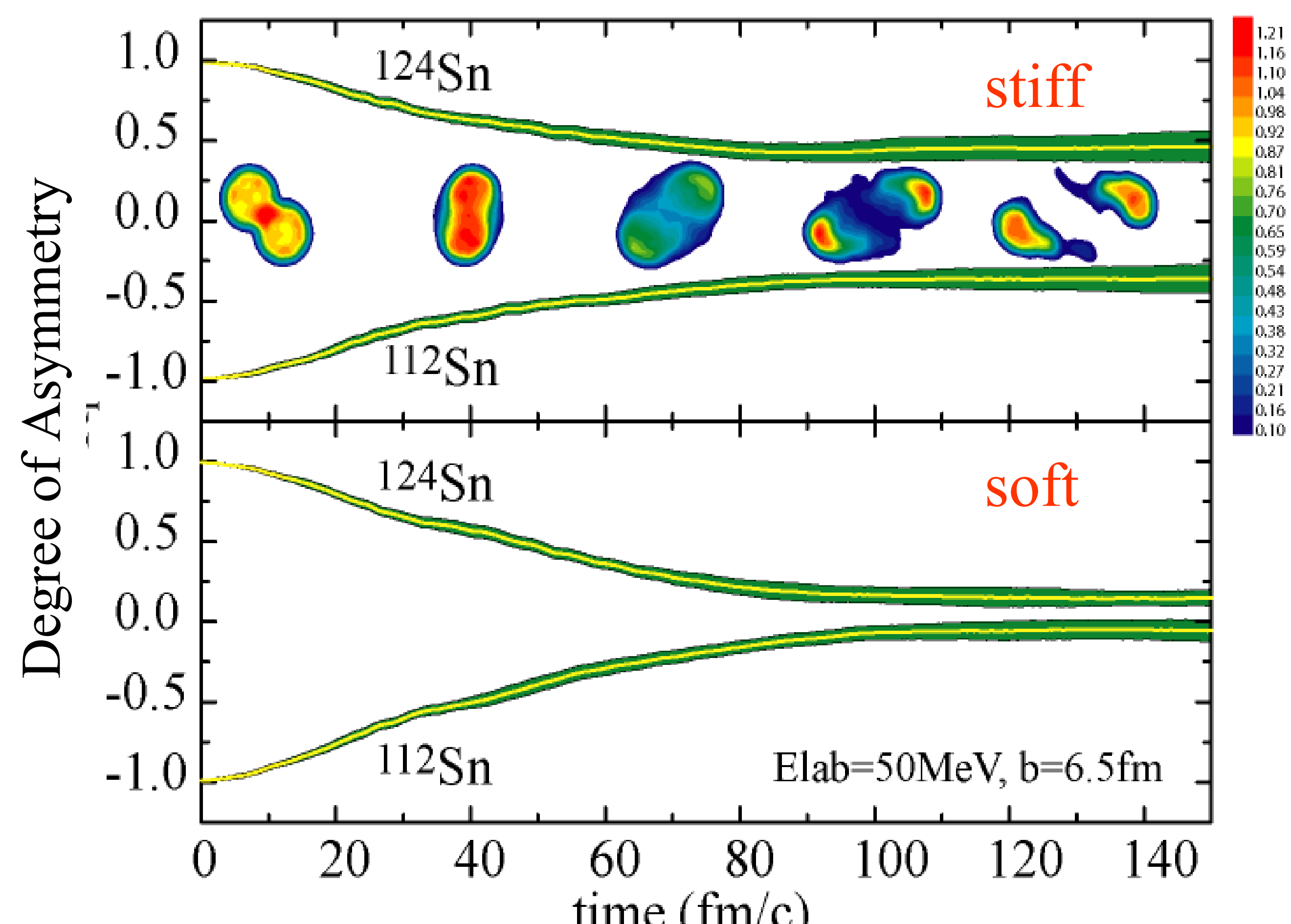
Isospin Diffusion
in Heavy Ion Collisions

- *Probe the symmetry energy at subsaturation densities in peripheral collisions, e.g. $^{124}Sn + ^{112}Sn$*
- ***Isospin "diffuse" through low-density neck region***
- *Symmetry energy drives system towards equilibrium.*
  - *stiff EOS → small diffusion*
  - *soft EOS → fast equilibrium*



Require measurements of collisions of nuclei with no isospin asymmetries for scaling due to existence of non-isospin diffusion effects:

- ***Pre-equilibrium emissions***
- ***Sequential decays***
- ***Coulomb effects***



From sym. E -> ^{208}Pb skin
Can measure sym. E at high densities!

B. Tsang

Observing Neutron Star Radii, Masses

- Deduce surface area from luminosity, temperature from X-ray spectrum.

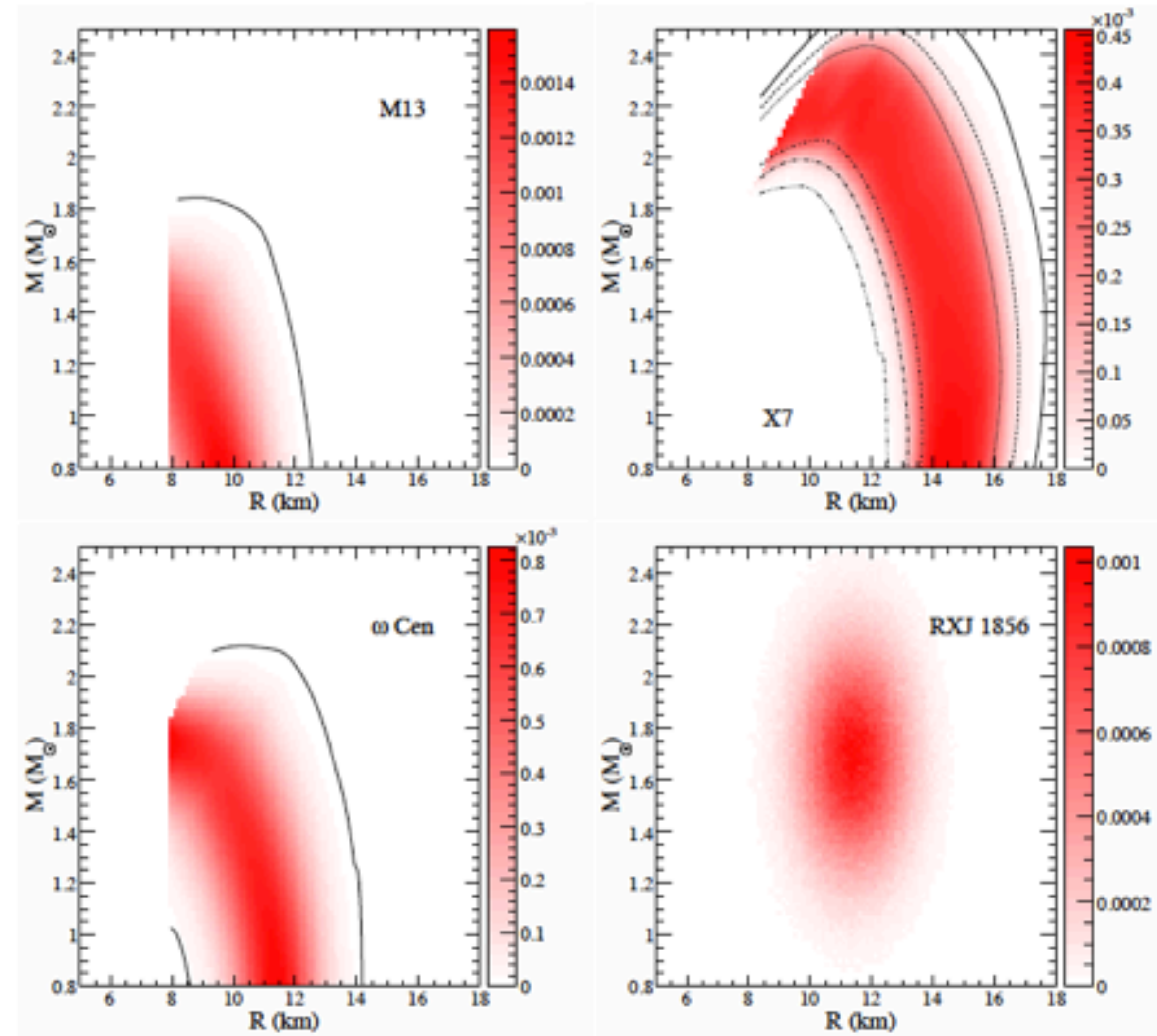
$$L_\gamma = 4\pi R^2 \sigma_{SB} T^4$$

- Complications:
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
- Steiner, Lattimer, Brown [ArXiv: 1005.0811] combine observations of NS in X-Ray bursts and globular clusters and deduce
  - EOS is soft at low density so 1.4 M_{sun} star has 12 km radius.
  - EOS + Typel-Brown correlation -> Predict ^{208}Pb neutron skin: R_n-R_p=0.15+/- 0.02 fm.

- Important to test this model dependent extraction of EOS with accurate PREX measurement.
  - Depends on assumptions about X-ray bursts.
  - F. Ozel et al. get smaller radii.
- Radio observations of PSR J1614 find M=1.97+/-0.04 M_{sun}! From binary with 0.5 M_{sun} WD, see relativistic Shapiro delay.
  -- P. Demorest et al., Nature **467** (2010) 1081.
- All soft high density EOS including many with exotic high density phases are ruled out.
- Real progress on EOS of cold dense matter is being made with astro-physical observations.

Observations of NS Radii and Masses

- A. Steiner, E. Brown, J. Lattimer, ArXiv:1005.0811, combine observations of 7 NS in 3 classes: X-Ray bursts (important modeling uncertainties), NS in globular clusters, and an isolated nearby NS.
  - Observations favor stiff high density EOS with ~2 M_{sun} maximum NS mass.
  - EOS is soft at low densities so 1.4 M_{sun} star has ~12 km radius.
- Predict neutron skin in ^{208}Pb: R_n-R_p=0.15+/- 0.02 fm.
- If true, important implications for cold dense QCD.



Error bands for masses and radii of 4 neutron stars.

Statistical error at JLAB Hall A:

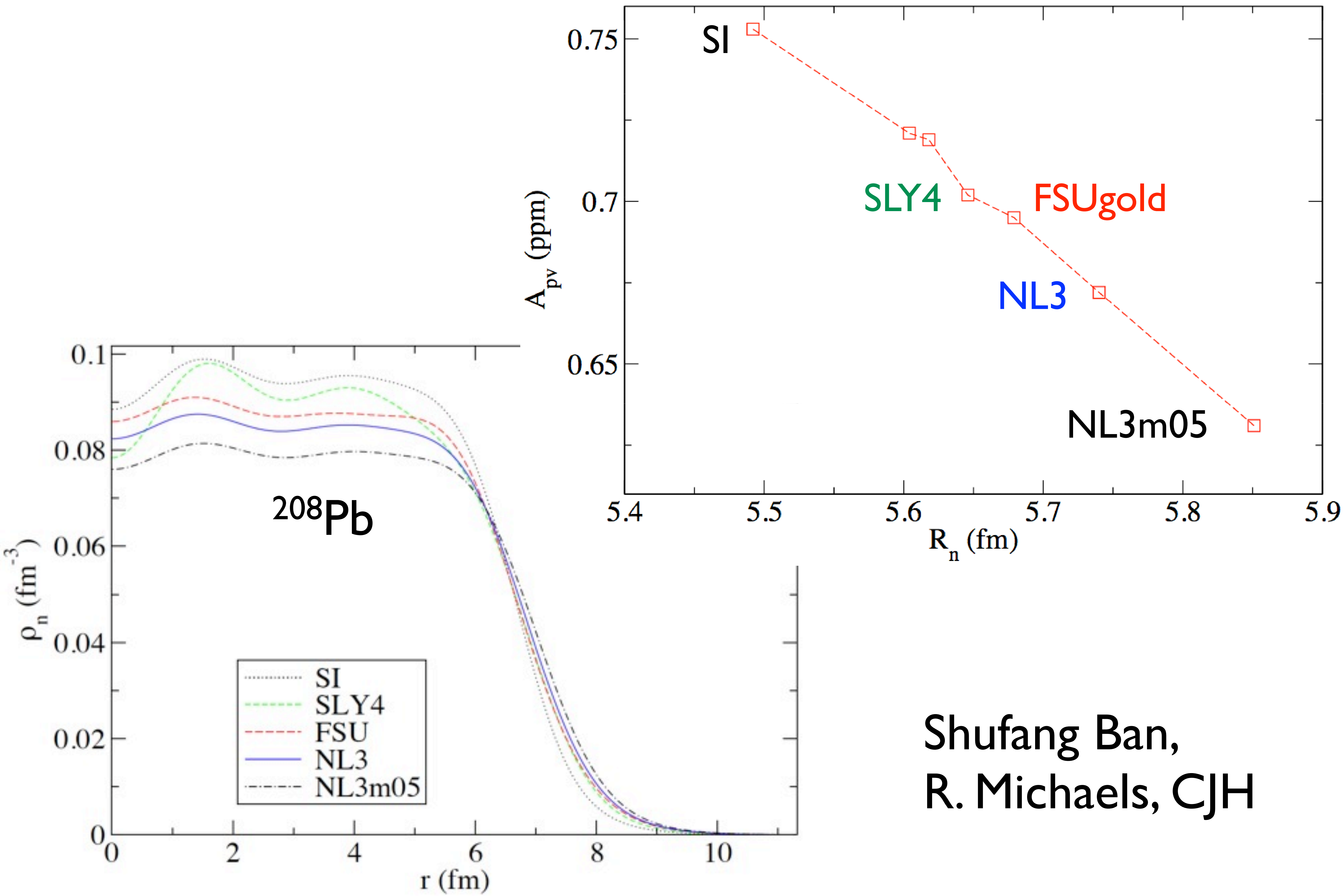
assuming 100μA, 5° for 30 days

	E	Rate	A_{pv}	R_n	$t(1\%)$	a
	(GeV)	MHZ	ppm	%	days	%
^{208}Pb	1.05	1700	0.72	0.66	**13**	
	1.8	53	2.1			8.0
^{120}Sn	1.2	1080	1.06	0.56	**9.4**	
^{48}Ca	1.7	270	2.2	0.43	**5.5**	
	2.1	21	2.8			**3.0**

Surface thickness *a* for $\rho(r) = \rho_0/[1 + \mathrm{e}^{(r-R_0)/a}]$

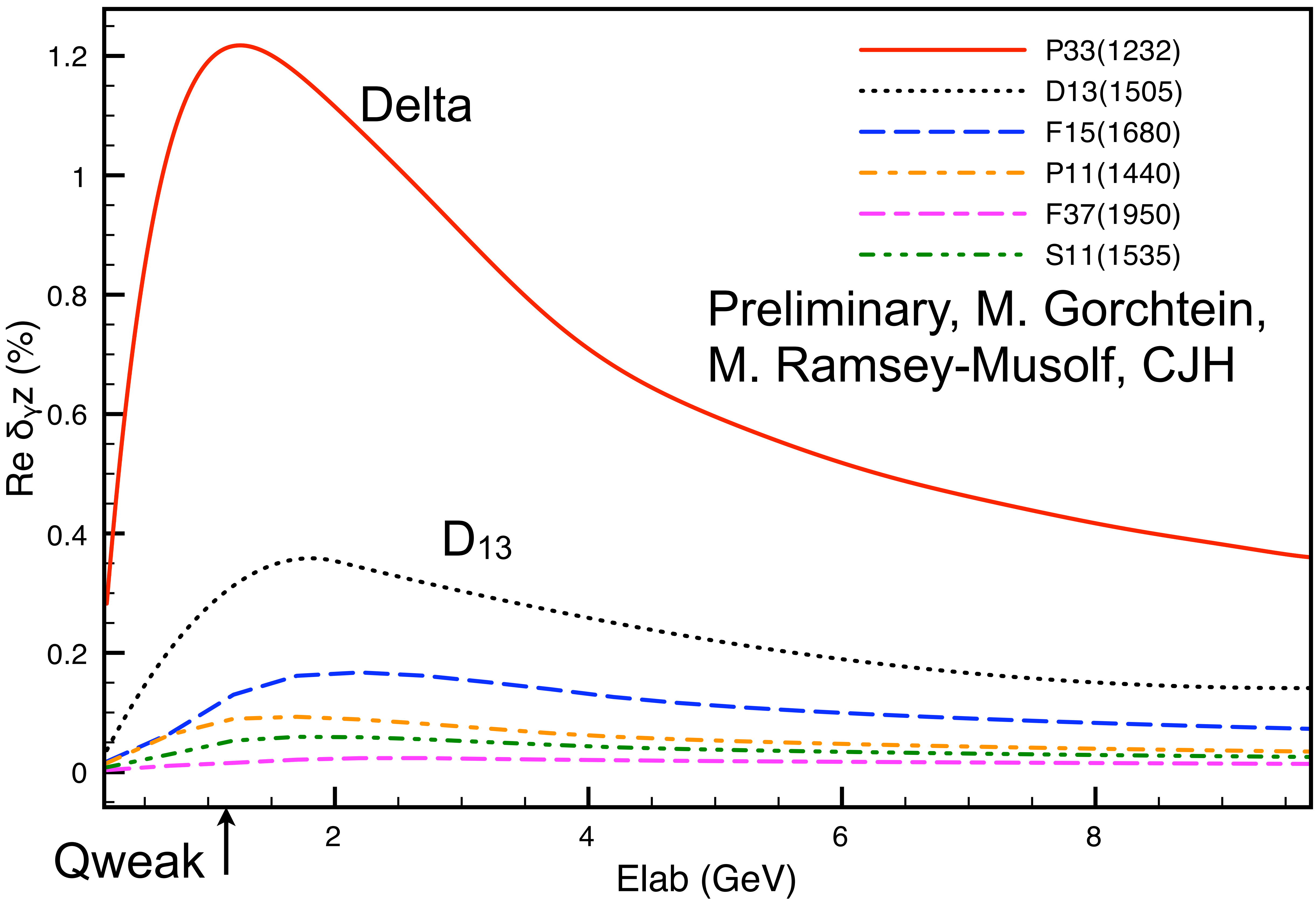
--- Shufang Ban, Bob Michaels, CJH

Parity violating asym. vs neutron radius



Shufang Ban,
R. Michaels, CJH

Resonance contributions, ~1.8%

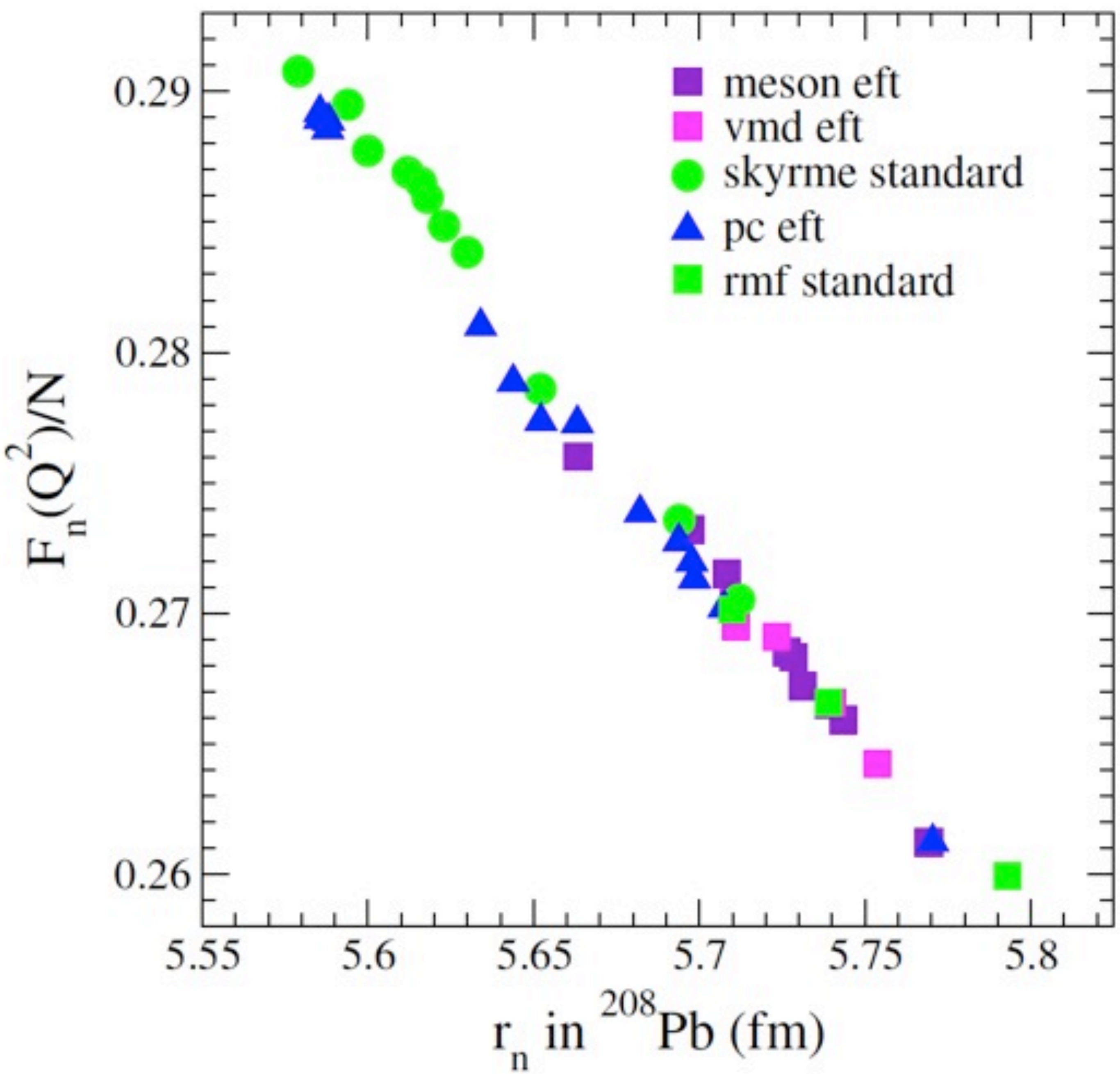


Total 1.8% dominated by Delta but D_{13} also

Calcium 48

- Calcium 48 with 20 protons and 28 neutrons is a closed shell neutron rich nucleus "far" from ^{208}Pb.
- New microscopic coupled cluster and no core shell model calculations are now feasible for ^{48}Ca but not ^{208}Pb. Relate measured neutron density to two nucleon and three nucleon forces (including 3 neutron forces).
- Calcium 48 is an important double beta decay nucleus that allows a test if neutrinos are their own antiparticles. Understanding structure of ^{48}Ca important for calculations of decay matrix element.
- PV exp needs a target involving about a gram of ^{48}Ca.

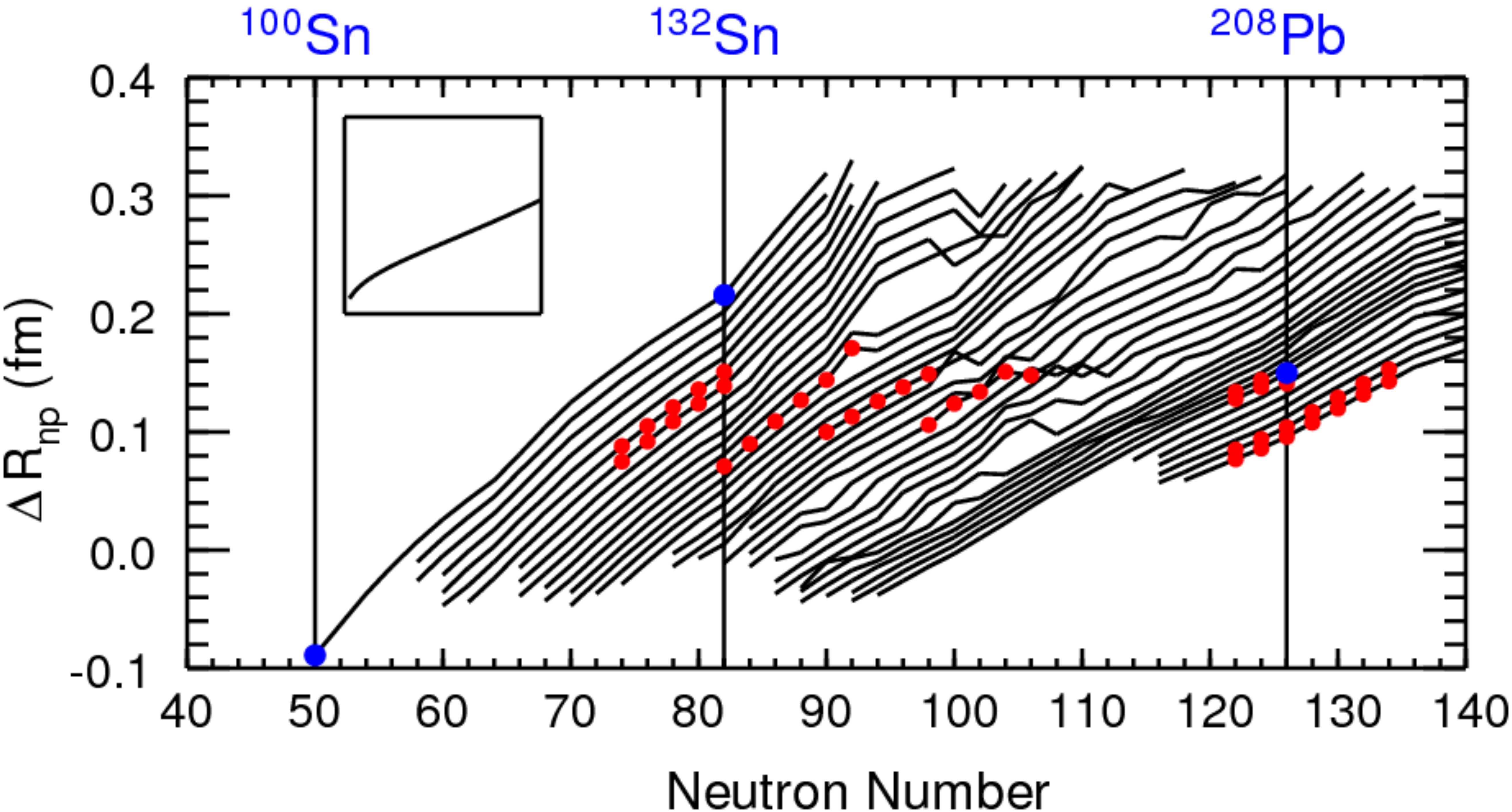
Form Factor at Low Q^2 vs. Neutron Radius in Pb



- How are the low momentum form factor and r_n correlated?
  - Form factor: $F_n(Q^2) = \int d^3r\, \rho_n(r)\, j_0(qr)$
  - PREX: $q \equiv (Q^2)^{1/2} = 0.45\,\text{fm}^{-1}$

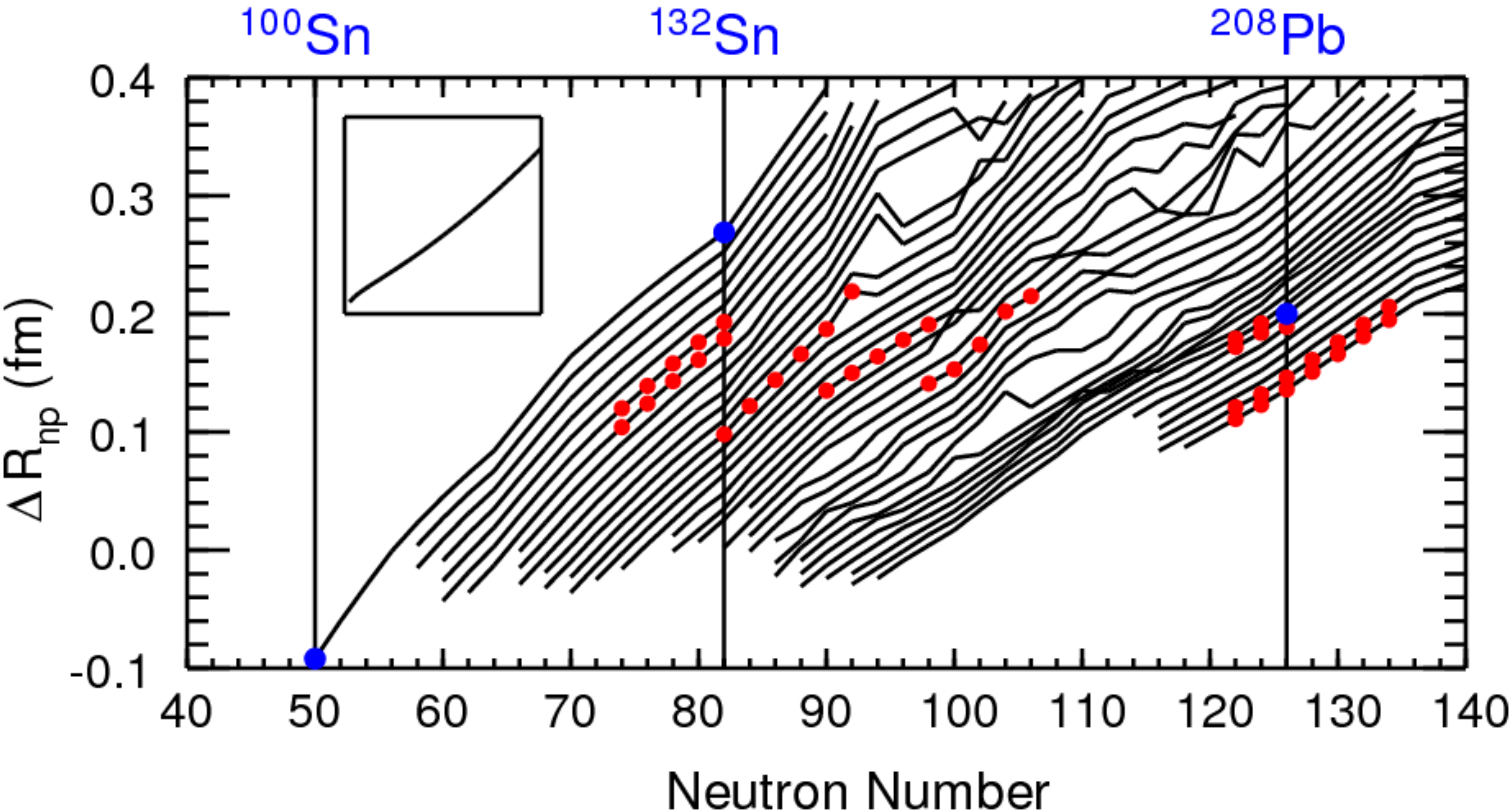
R. Furnstahl

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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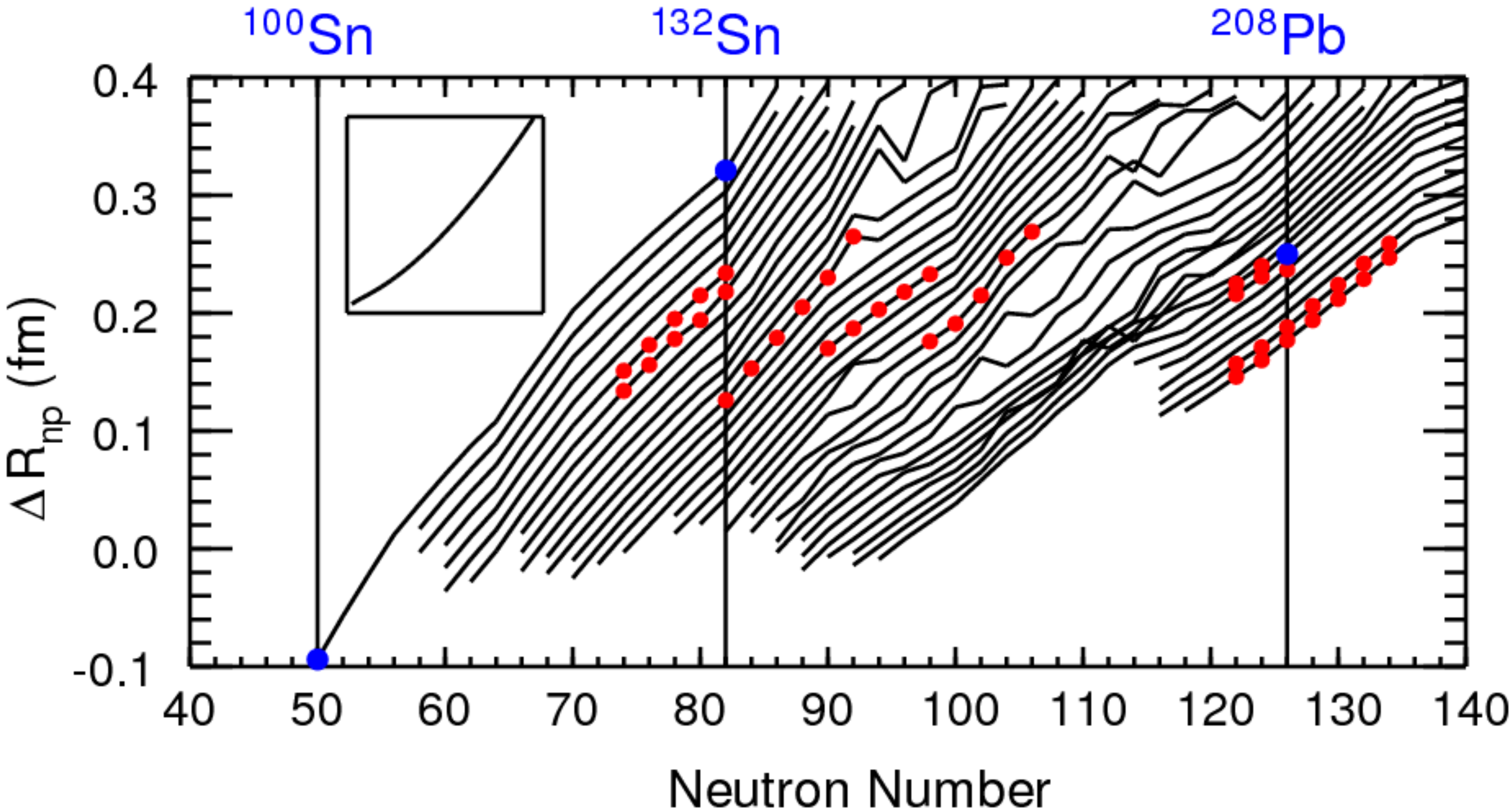
Neutron Skins for Atomic PNC



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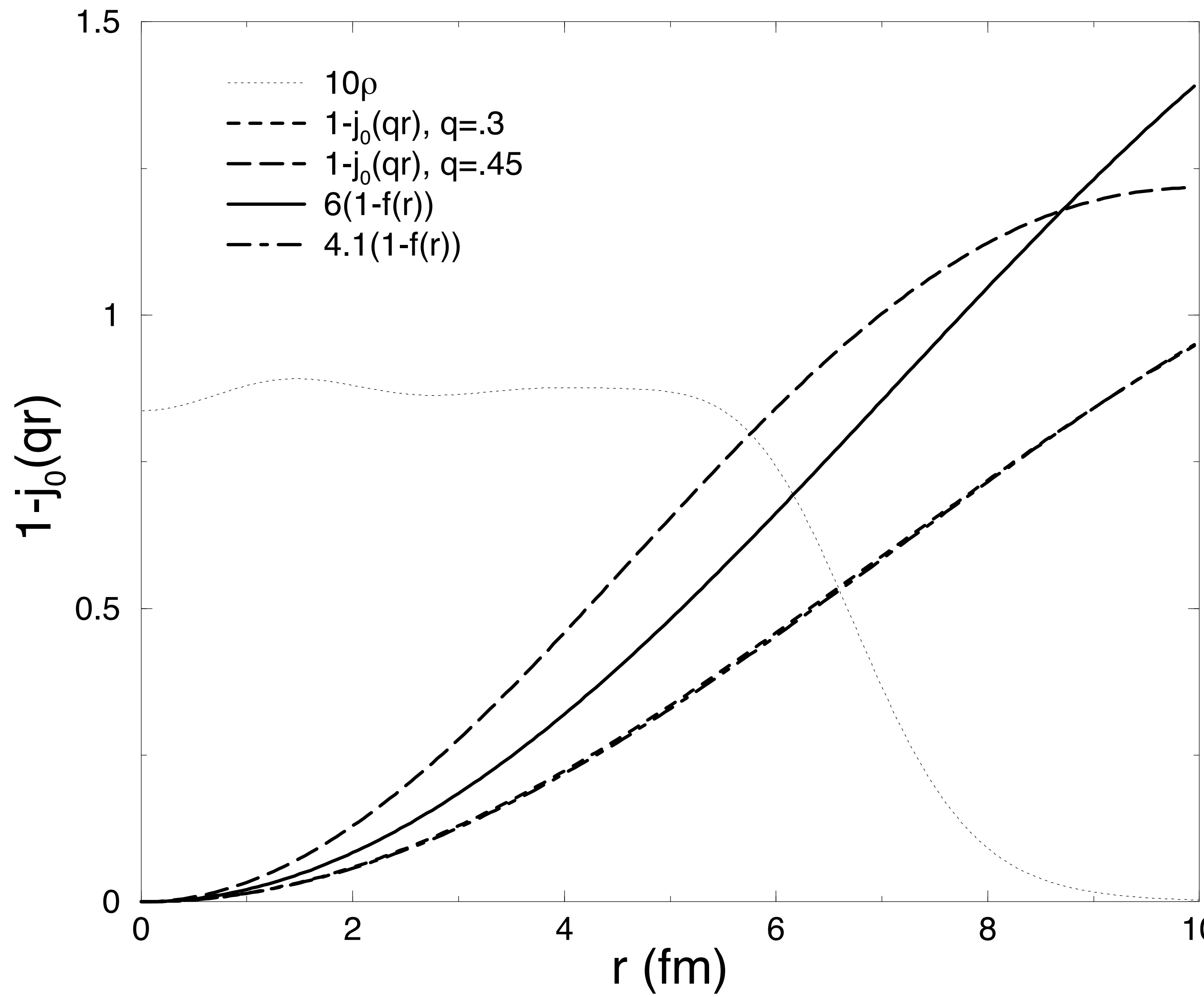
Atomic Parity Overlap

Atomic PV depends on overlap of elec. axial transition matrix element with nuclear weak density.

$$f(r) \approx \psi_p^\dagger(r)\gamma_5\psi_s(r)$$

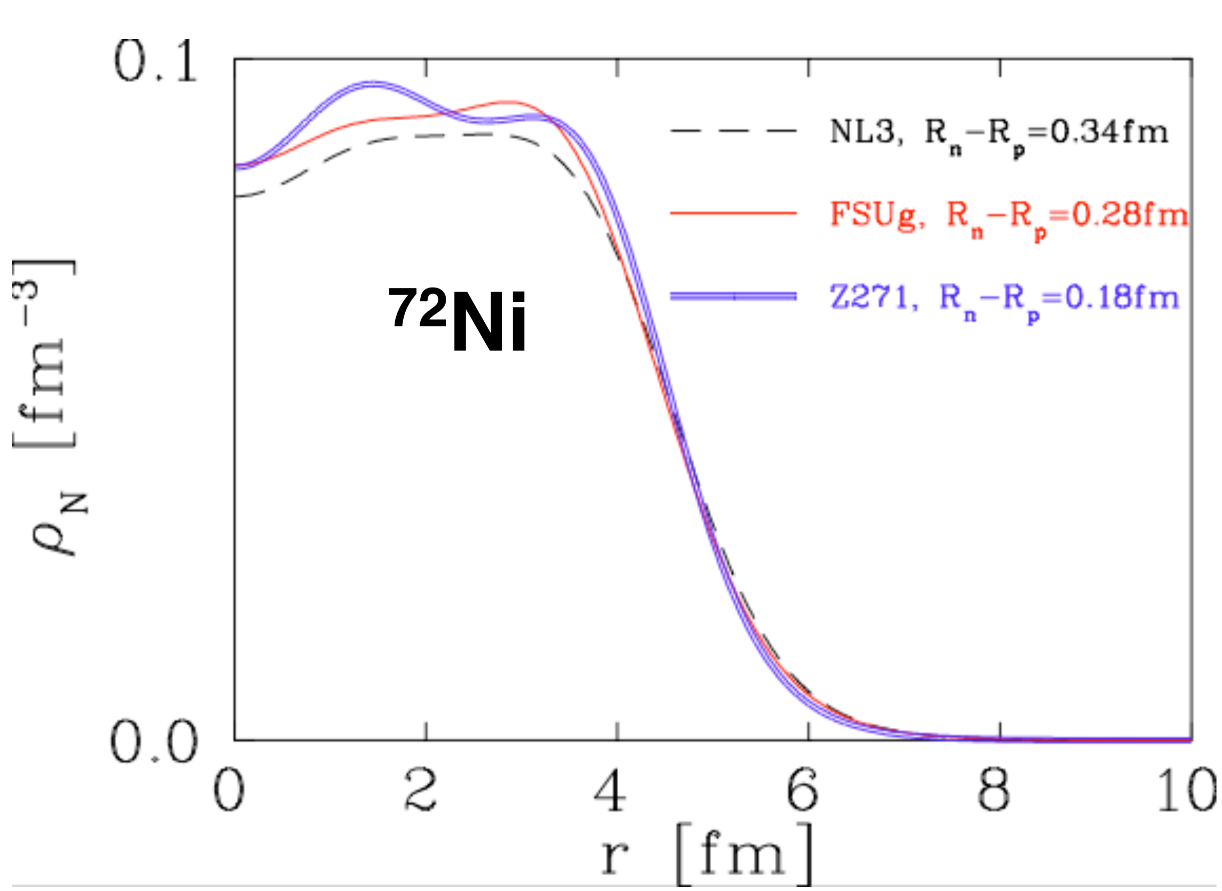
For Pb, f(r) looks like $j_0(qr)$ for q~0.3 fm^{-1}

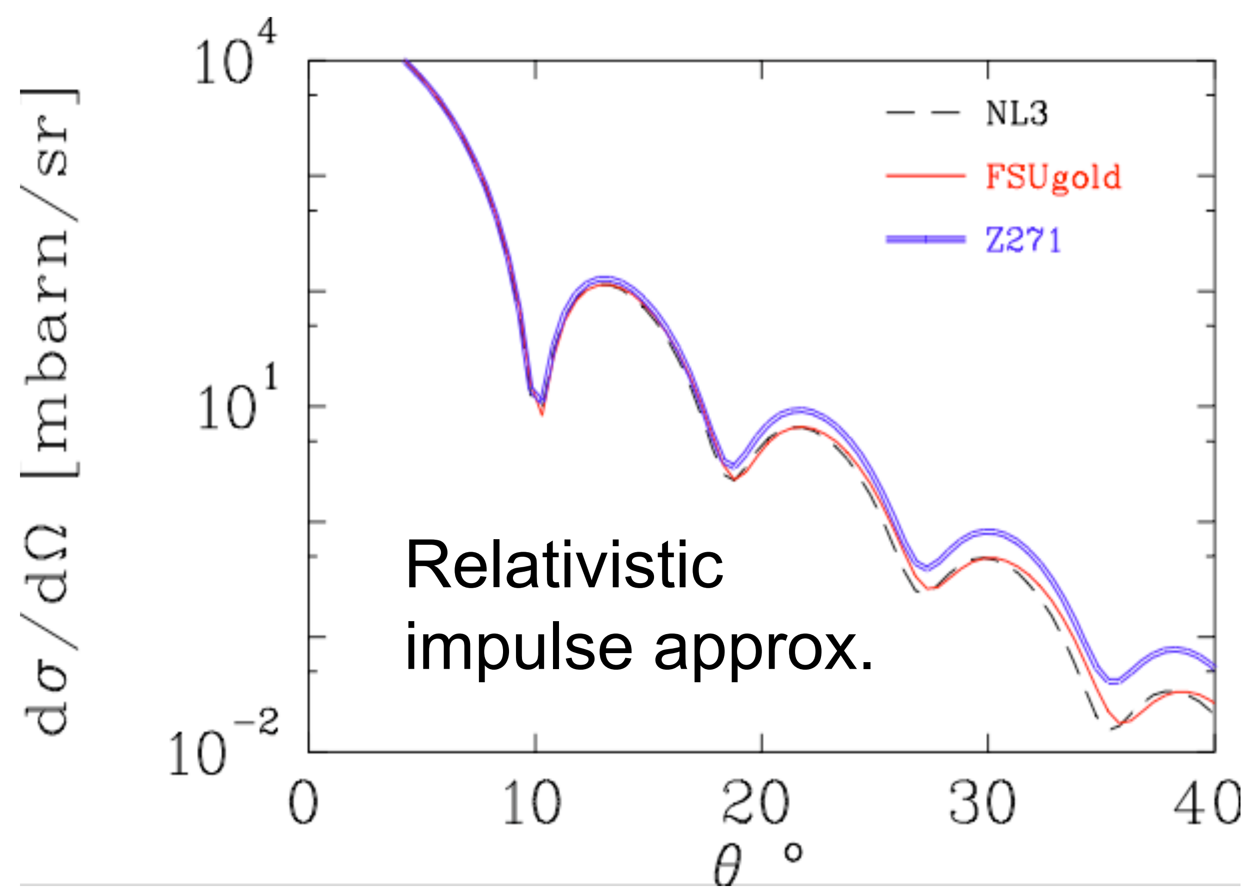


Hadronic Probes of Neutron Density

- Anti-protons are sensitive to low density tail, not rms radius. [Model dependent to fit wood-saxon ... to tail and use it to calculate rms radius.]
- Proton and or alpha elastic scattering can measure neutron density.
  - What are systematic errors of rxn mechanism?
  - Calibrate with PREX ^{208}Pb result.
  - Measure n densities of rare isotopes in inverse kinematics.

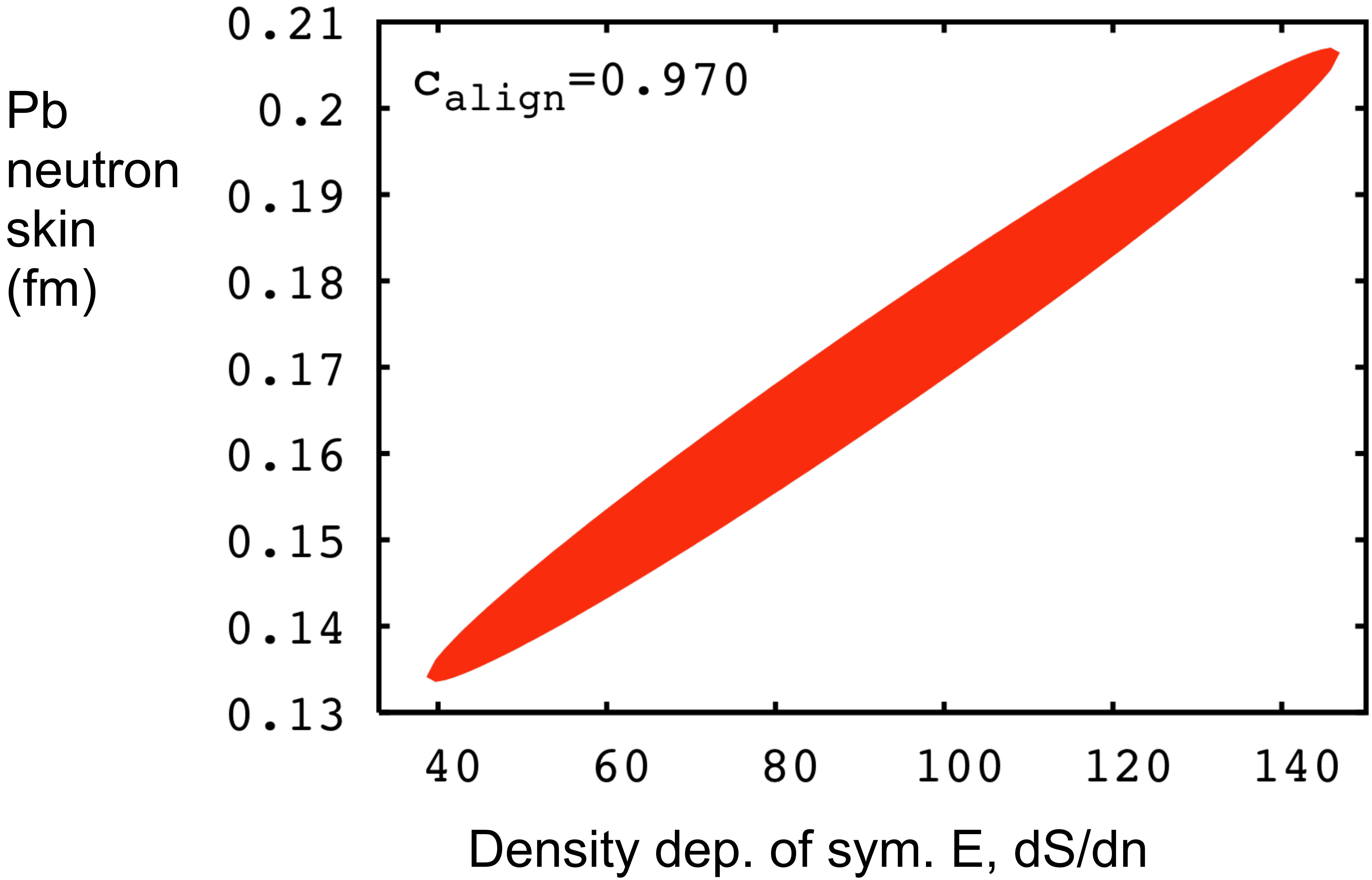
^{72}Ni+p elastic scattering at 400MeV/A





- 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



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