PAC39 Report on CREX

- **Issue:** The main question is: why repeat the PREX-II measurement with another nucleus? While the PAC believes that a strong case can be made based on the fact that a measurement on 48Ca can be used to test microscopic models and confirm the PREX-II result, the current proposal did not convincingly make this case. **No microscopic calculations for 48Ca were provided in the proposal** and the arguments for how the experiment would test three nucleon effects were only indirect. The case for the measurement based on figure 2 of the proposal was not convincing since the experimental error bars will be large compared to the spread of the theoretical predictions. The arguments to test anomalies in transverse parity violation and the connection to atomic parity violating experiments were not viewed as convincing.
- **Recommendation:** The experiment is conditionally approved, with a C2 status. The proponents should return to a future PAC with a proposal that makes a stronger case demonstrating how the 48Ca result will test microscopic models.

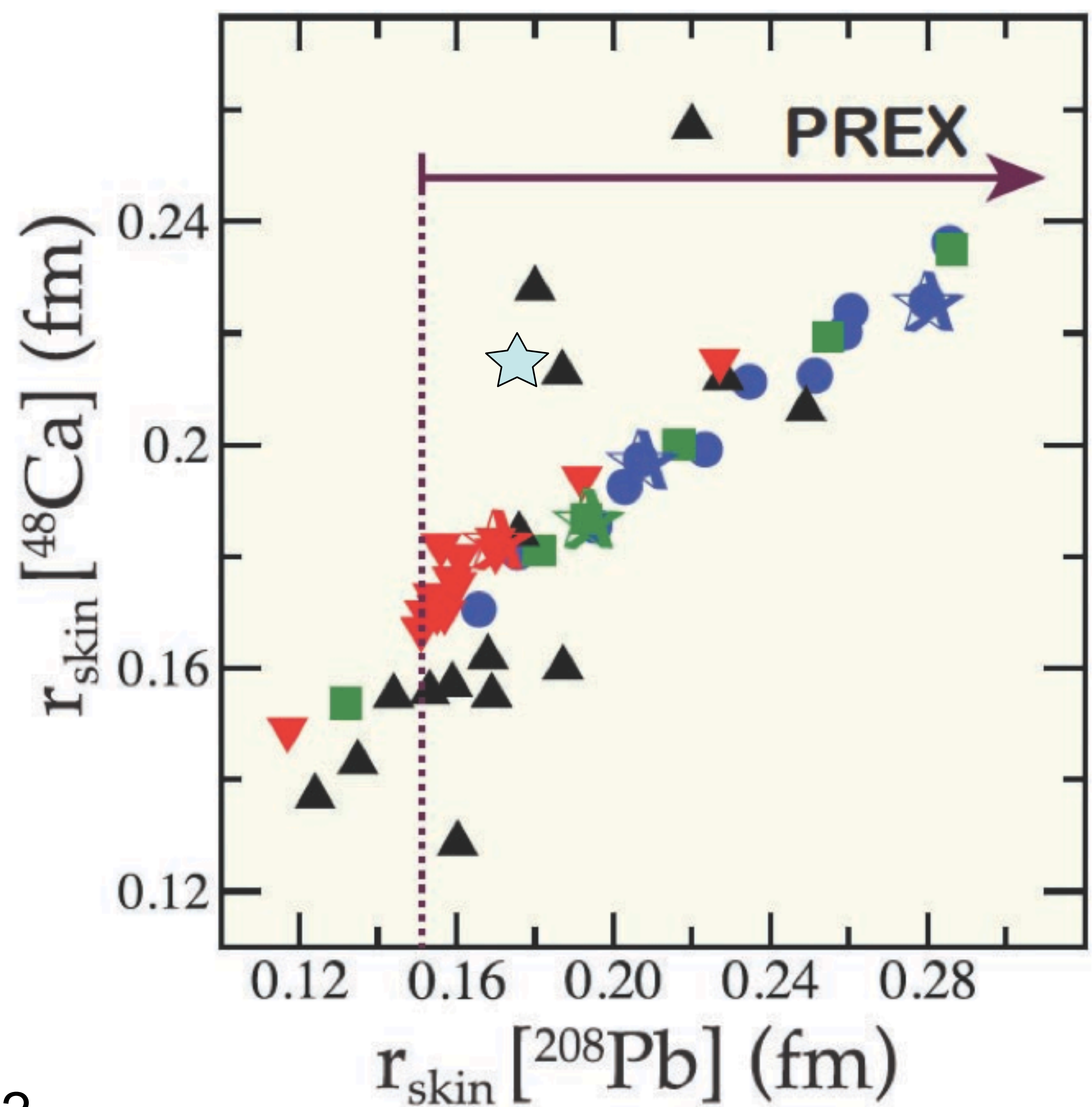

PREX
0.24
0.2
0.16
0.12
0.12
0.16
0.20
0.24
0.28
r_{skin} [^{48}Ca] (fm)
r_{skin} [^{208}Pb] (fm)

Fig 2

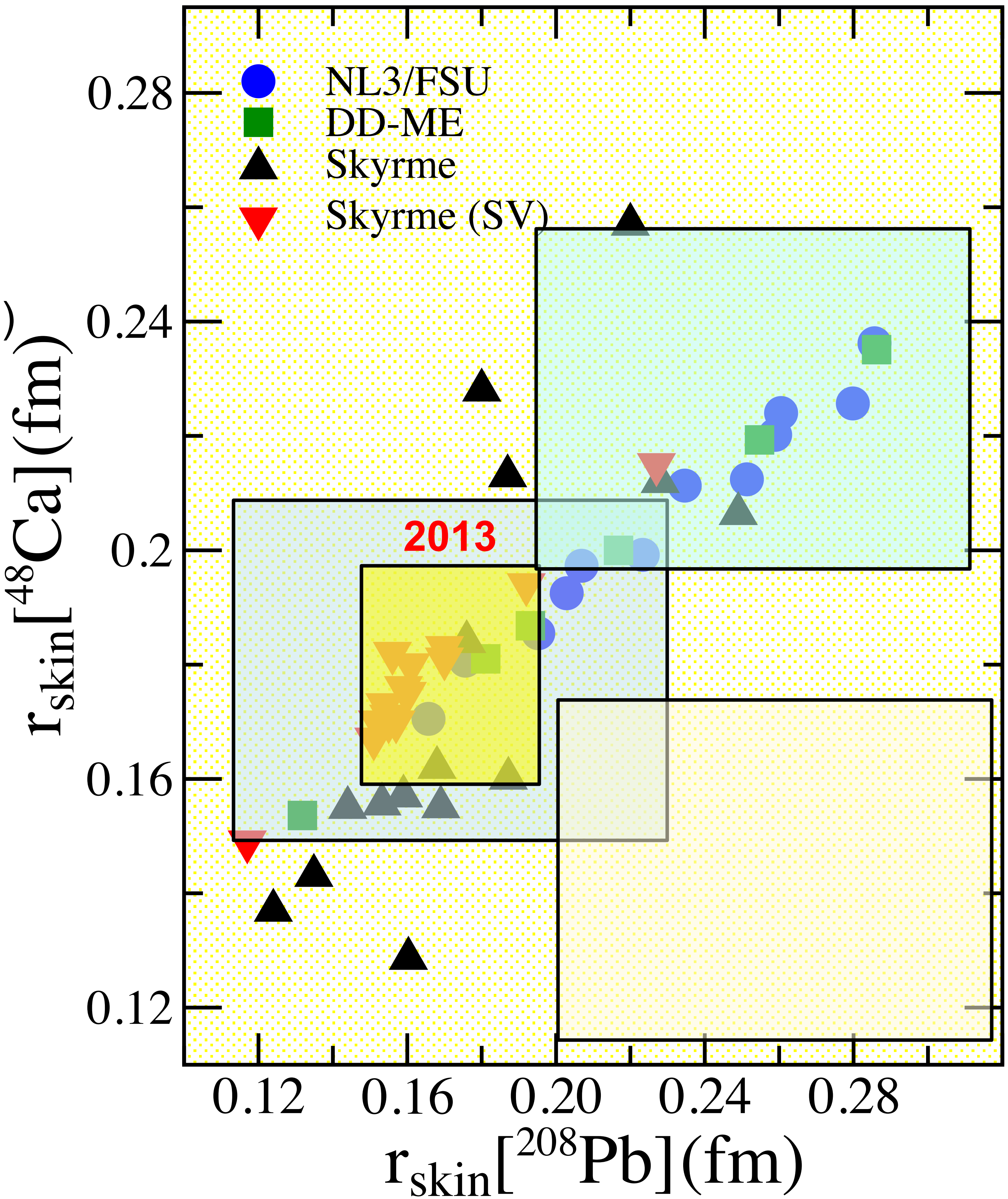
Projected uncertainties

J. Piekarewicz et al.,
Phys. Rev. C 85, 041302(R) (2012)

r_{skin}=(0.168 ± 0.022) fm in ^{208}Pb
r_{skin}=(0.176 ± 0.018) fm in ^{48}Ca

Mammei (Sunday):

Δr_{skin}= ± 0.06 fm in ^{208}Pb
Δr_{skin}= ± 0.03 fm in ^{48}Ca



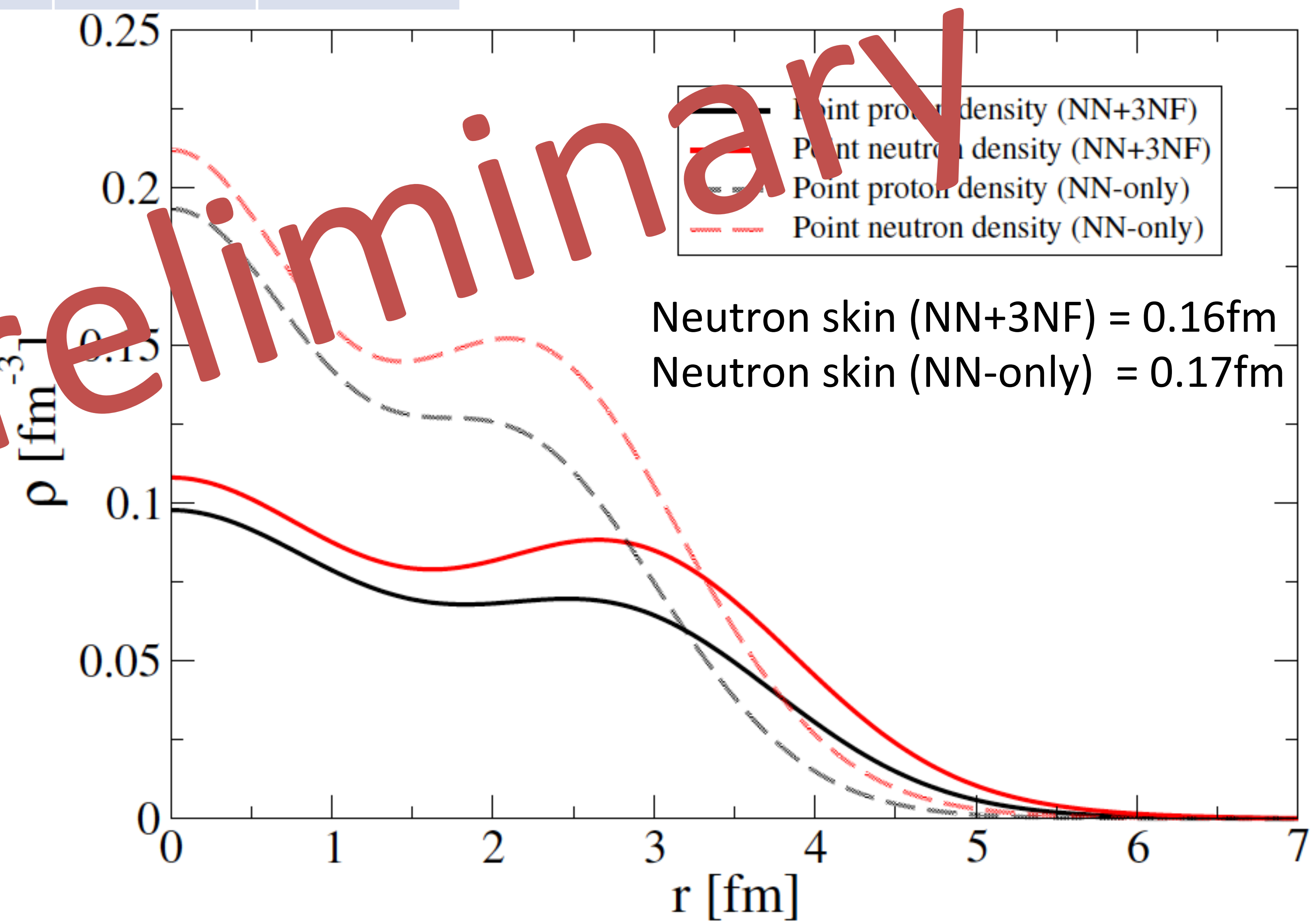
Microscopic model

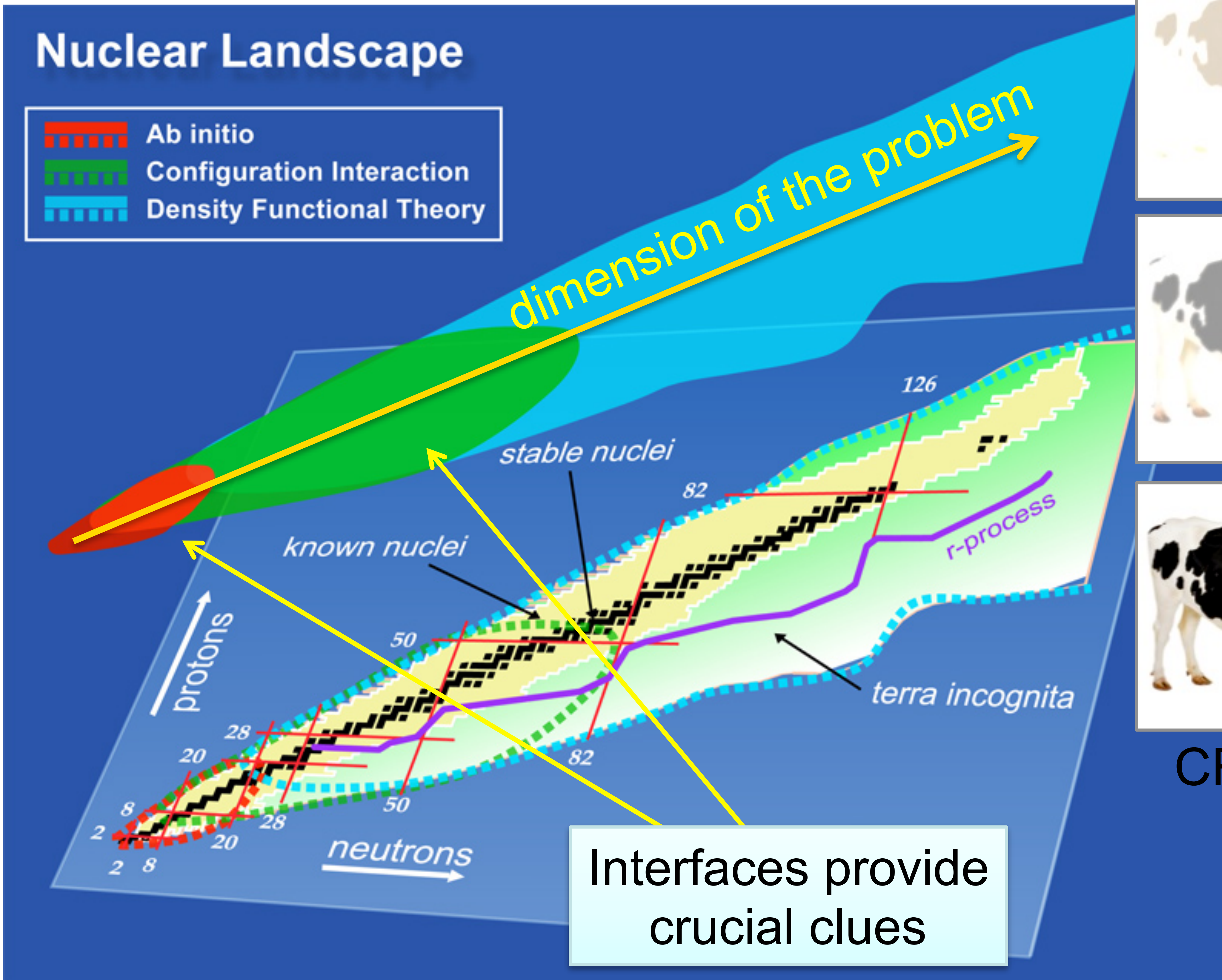
Point radii from NNLO-POUNDerS

	^{16}O	^{22}O	^{24}O	^{48}Ca
NN-only	2.29	2.55	2.69	2.97
NN+3NF	2.57	2.85	3.01	3.49
Exp	2.54(2)	2.75(15)	3.19(13)	

G. Hagen

- Modelspace: N =14 major harmonic oscillator for the NN interaction while E_{3max}= 12 for three-nucleon force.
- Binding energies of Calcium isotopes are not converged => need E_{3max}~ 20.

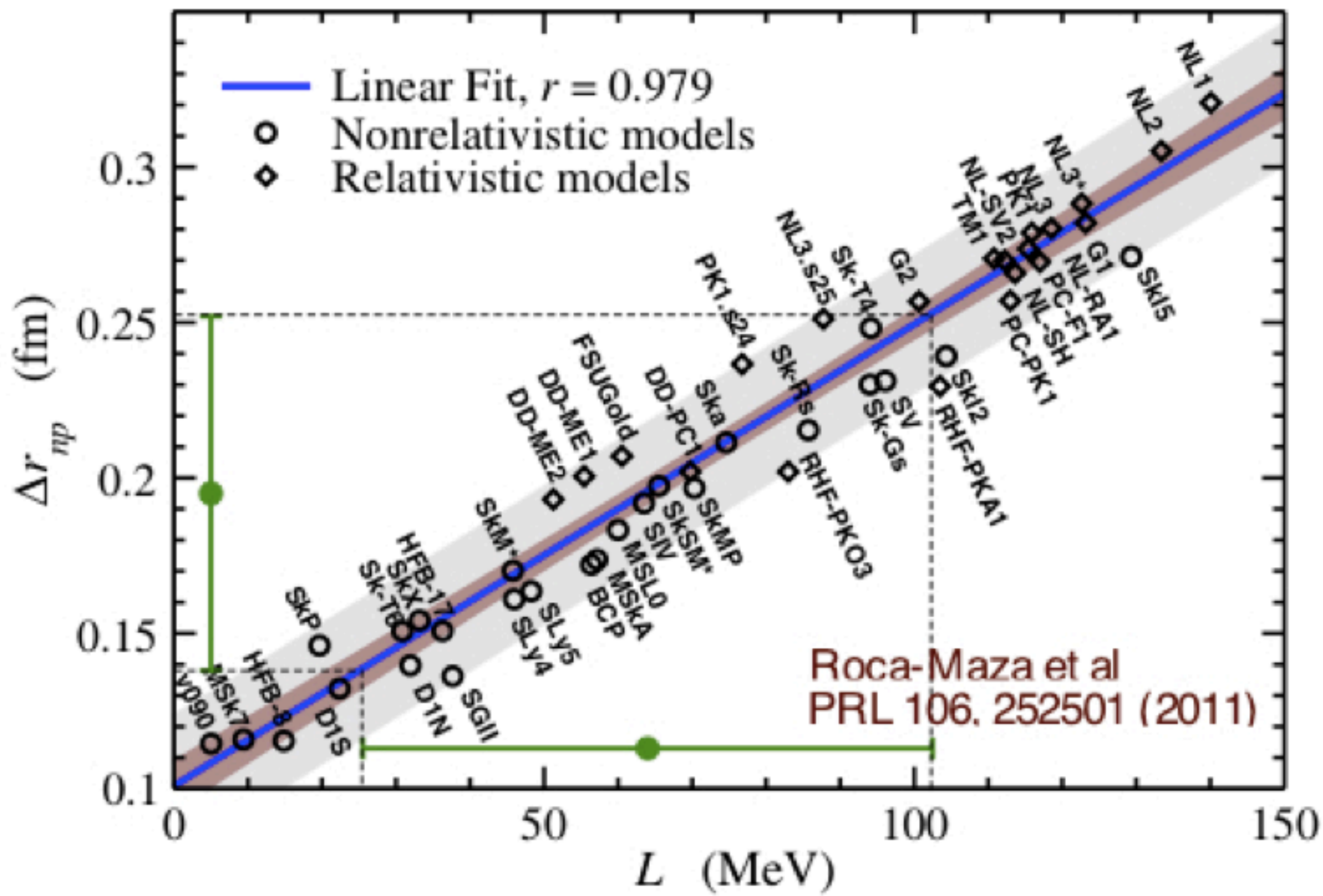




Nuclear Landscape
Ab initio
Configuration Interaction
Density Functional Theory
dimension of the problem
stable nuclei
known nuclei
r-process
terra incognita
protons
neutrons
126
82
50
28
20
8
2
Interfaces provide crucial clues

CREX?

What is best way to constrain L? What is needed accuracy?



What is A_{PV} for low lying excited states?

It is useful to estimate the inelastic asymmetry. The first excited state in ^{208}Pb is at 2.6 MeV and has spin and parity 3^-. This is a collective density oscillation [32]. We expect the longitudinal to dominate over the transverse or axial responses (at forward angles). In plane wave Born approximation the asymmetry for a natural parity spin J excitation is then [2],

$$A = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\Big\{4\sin^2\theta_W - 1 + \frac{F_n^J(Q^2)}{F_p^J(Q^2)}\Big\}, \tag{5.22}$$

with G_F the Fermi constant. Here the neutron transition form factor is,

$$F_n^J(Q^2) = N\int r^2 dr j_J(qr)\rho_n^{tr}(r), \tag{5.23}$$

in terms of the neutron transition density $\rho_n^{tr}(r)$ and a similar expression for the proton transition form factor $F_p^J(Q^2)$ in terms of the proton transition density $\rho_p^{tr}(r)$.

The collective density oscillation can be modeled as a deformation of the ground state density [32]. If the elastic neutron density is characterized by a radius R_n^0 then the excited state has a density parameter $R_n^0(\theta)$,

$$R_n^0(\theta) \approx R_n^0[1 + \alpha_J^n Y_{J0}(\theta)], \tag{5.24}$$

where the small amplitude α_J^n can be adjusted to reproduce the magnitude of the cross section. Likewise the proton density is characterized by $R_p^0(\theta)$,

$$R_p^0(\theta) \approx R_p^0[1 + \alpha_J^p Y_{J0}(\theta)], \tag{5.25}$$

with amplitude α_J^p. We assume the radius parameter R_n^0 is proportional to the root mean square radius R_n and R_p^0 is proportional to R_p, see Eqs. 5.9- 5.10.

The transition density is then,

$$\rho_n^{tr}(r) \approx -\alpha_J^n R_n^0 \frac{d}{dr}\rho_n(r). \tag{5.26}$$

The experiment is at a low Q^2 well below the maximum in the inelastic form factor so one can expand the spherical Bessel function and integrate by parts to obtain,

$$\frac{F_n^J(Q^2)}{F_p^J(Q^2)} \approx \frac{\alpha_J^n N}{\alpha_J^p Z}\Big(\frac{R_n}{R_p}\Big)^J. \tag{5.27}$$

The 3^- state has the neutrons and protons oscillating primarily in phase ("isoscalar"),

$$\alpha_J^n \approx \alpha_J^p. \tag{5.28}$$

We will discuss this in more detail below. With Eq. 5.28 the asymmetry is,

$$A \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\Big\{4\sin^2\theta_W - 1 + \frac{N}{Z}\Big(\frac{R_n}{R_p}\Big)^J\Big\}. \tag{5.29}$$

In the limit $R_n \approx R_p$ this reduces to,

$$A \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\Big\{4\sin^2\theta_W - 1 + \frac{N}{Z}\Big\}. \tag{5.30}$$

In the same limits, plane wave and $R_n \approx R_p$, the elastic asymmetry also reduces to Eq. 5.30. Therefore, *the asymmetry for collective natural parity "isoscalar" excited states is similar to the elastic asymmetry.* This reduces the effect of the inelastic contamination.

Collective "isovector" excitations where the neutrons oscillate out of phase from the protons,

$$\alpha_J^p \approx -\alpha_J^n, \tag{5.31}$$

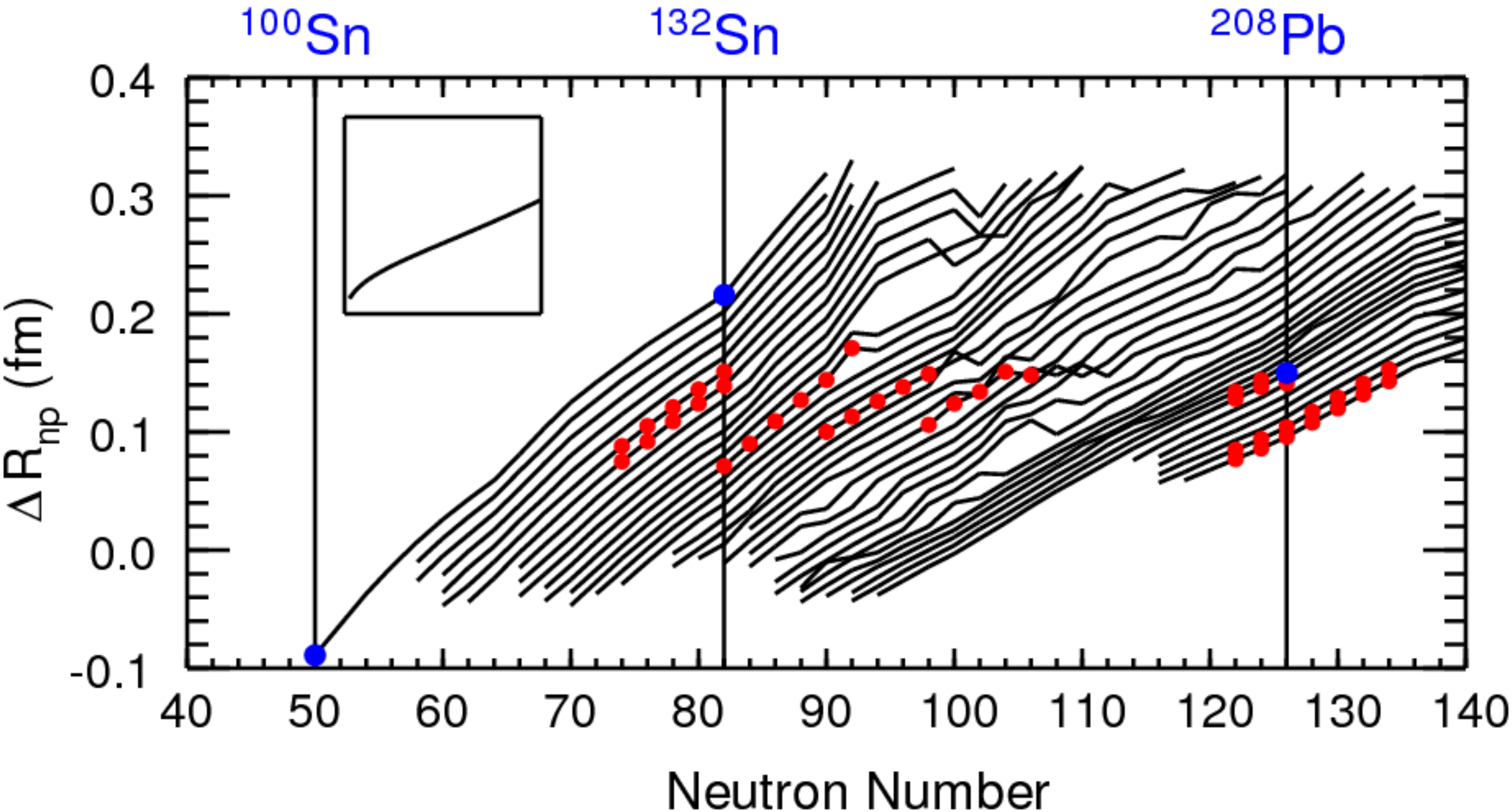
have a different asymmetry. In principle, these could be a concern. However, we believe it is possible to use existing (e, e') and (p, p'), (p, n), etc. cross section data to rule out large "isovector" strength.

C. J. Horowitz, S. J. Pollock, P. A. Souder, R. Michaels

How well does CREX, in addition to PREX, allow us to predict R_n all across periodic table?

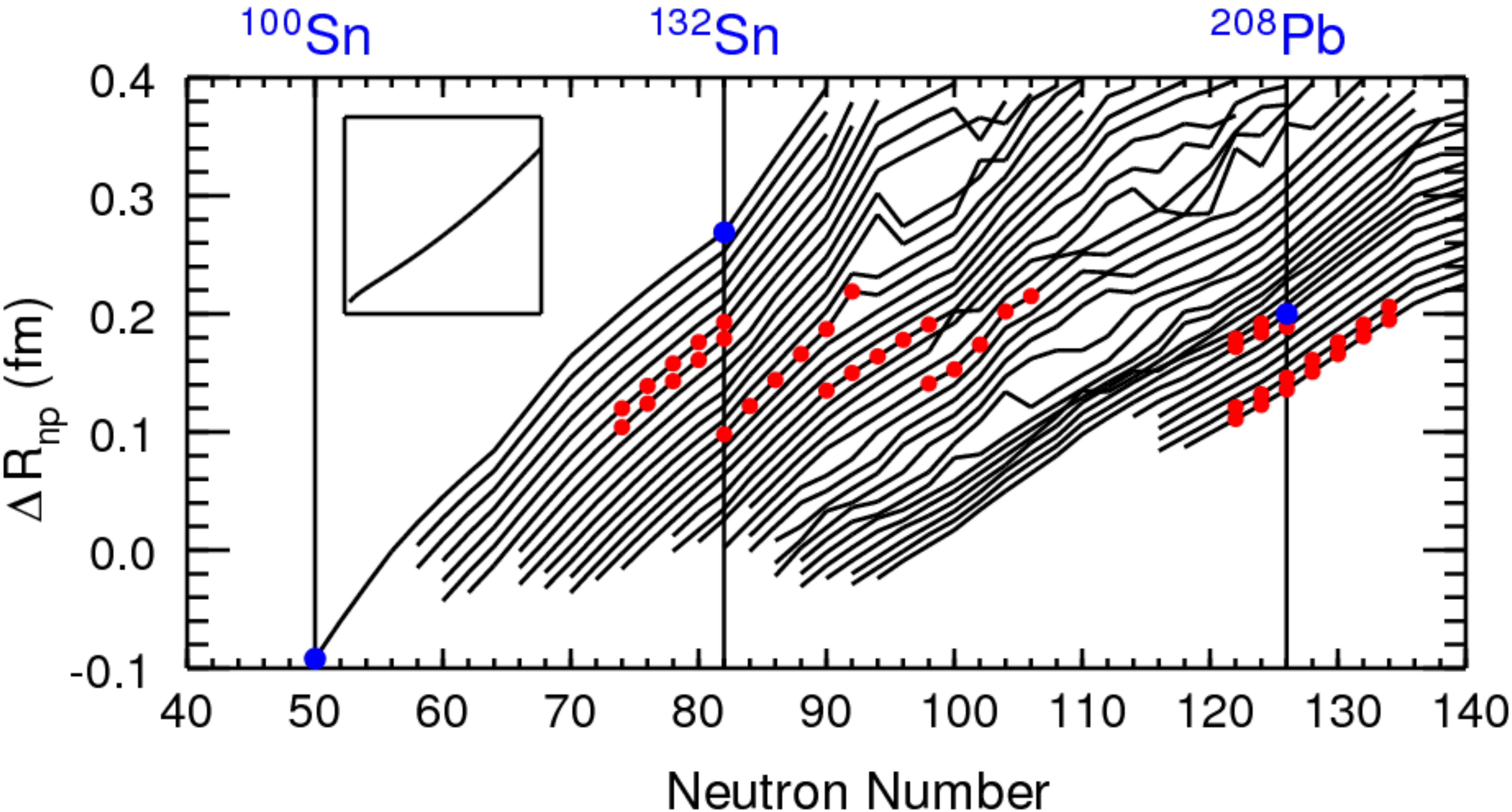
- in particular for atomic parity nuclei?
  - How does deformation change neutron skin thickness?
  - What about Rn for individual Fr or other isotopes? Crossing closed shells, individual orbitals, pairing ...?

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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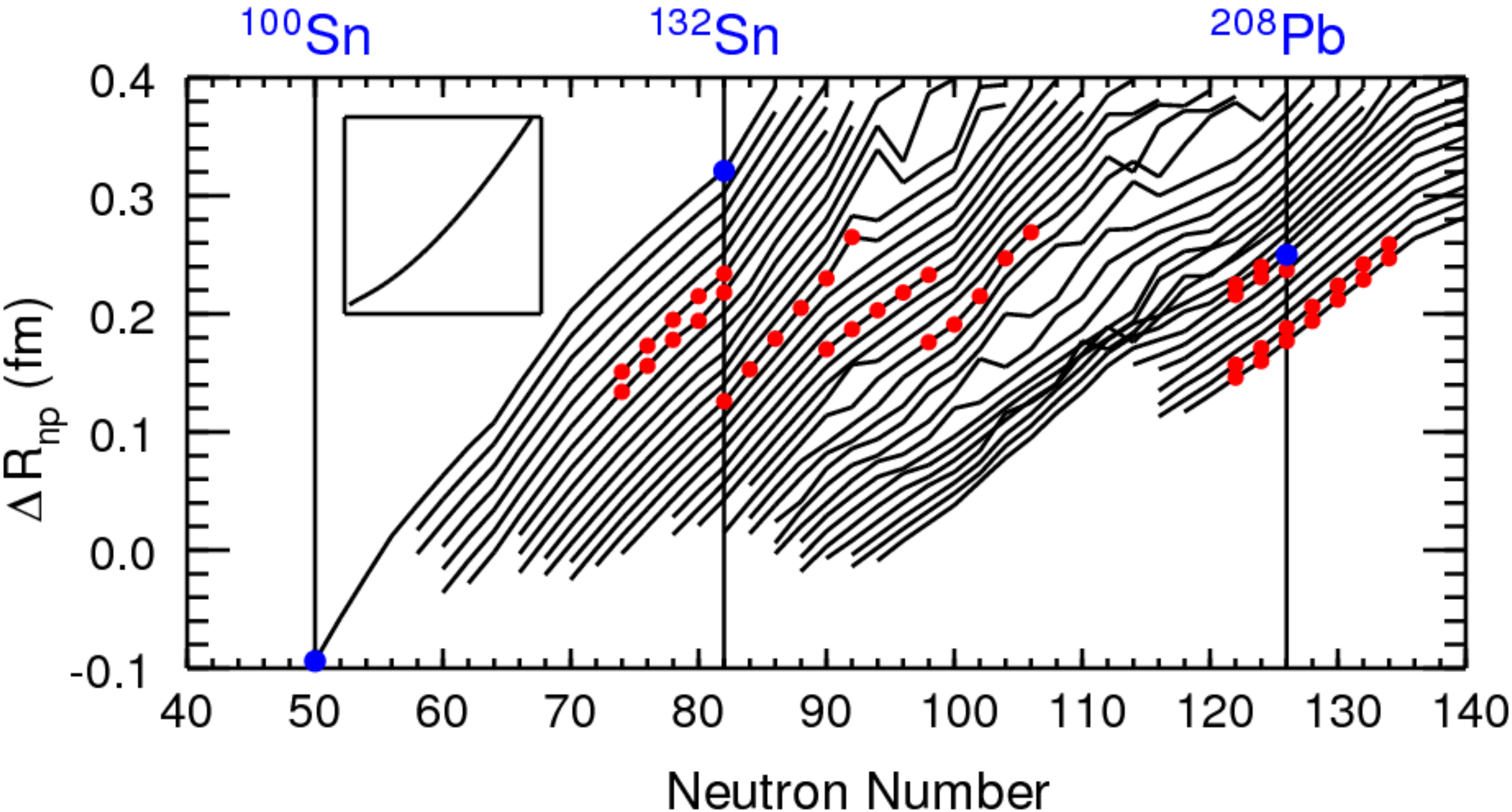

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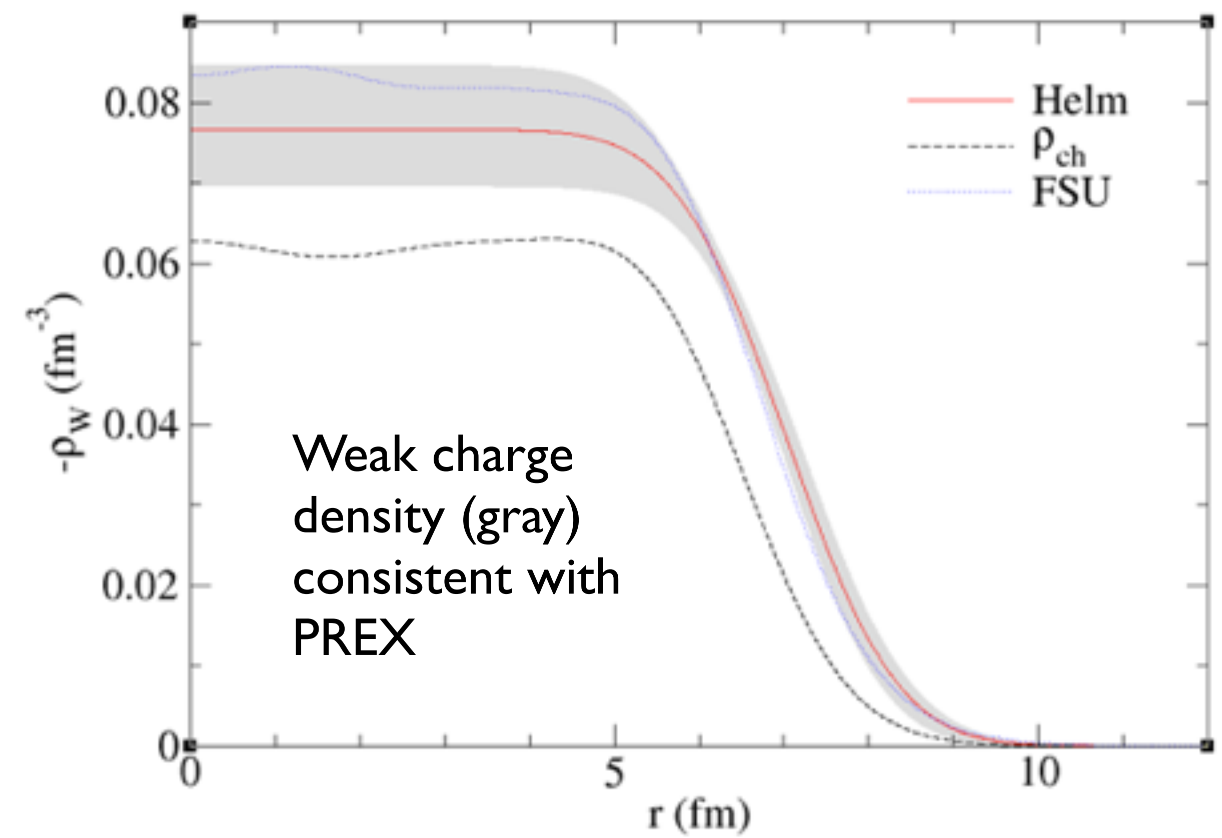
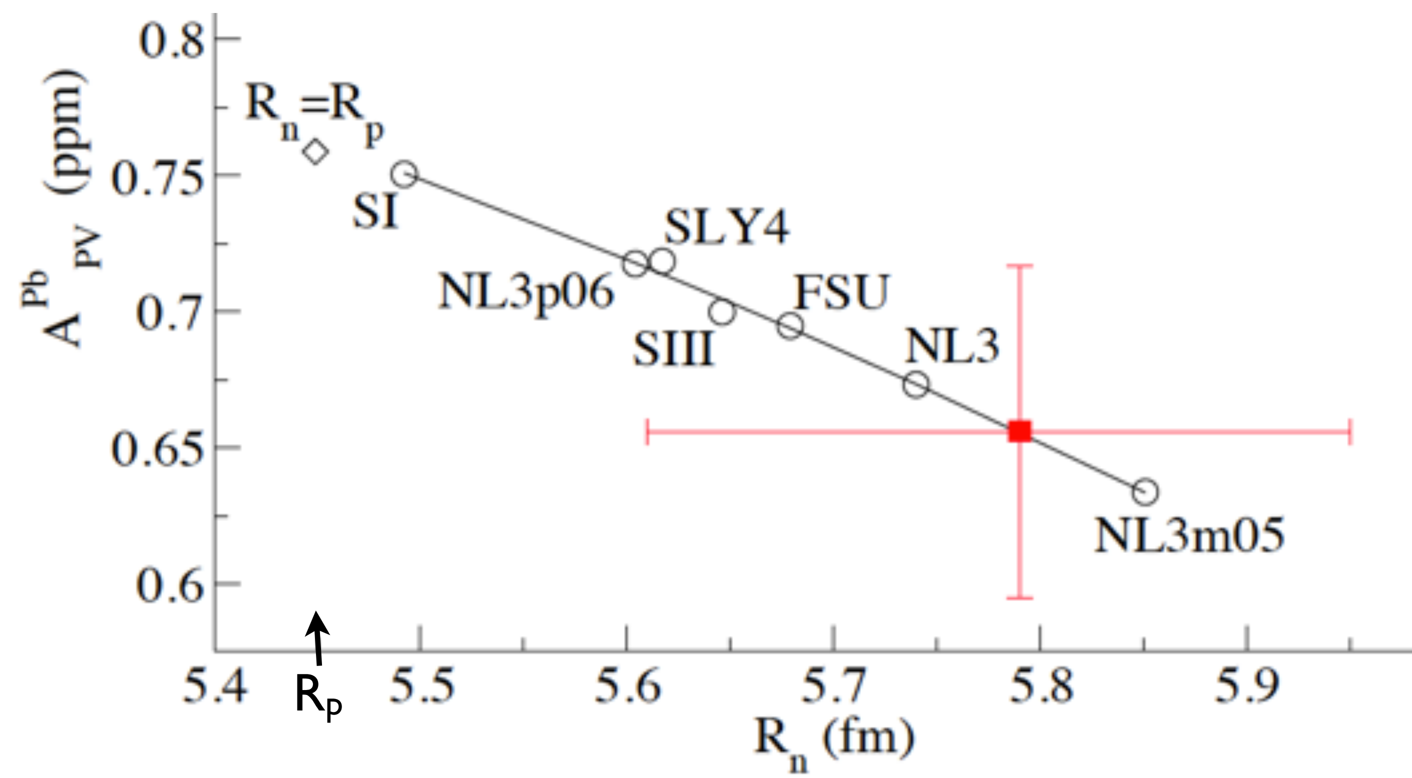
PREX results from 2010 run

- 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 ± 0.028
- Radius of weak charge distr.
  R_W = 5.83 ± 0.18 ± 0.03(model) fm
- Compare to charge radius R_{ch}=5.503 fm --> weak skin:
  $R_W - R_{ch}$ = 0.32 ± 0.18 ± 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)





Experiment Questions

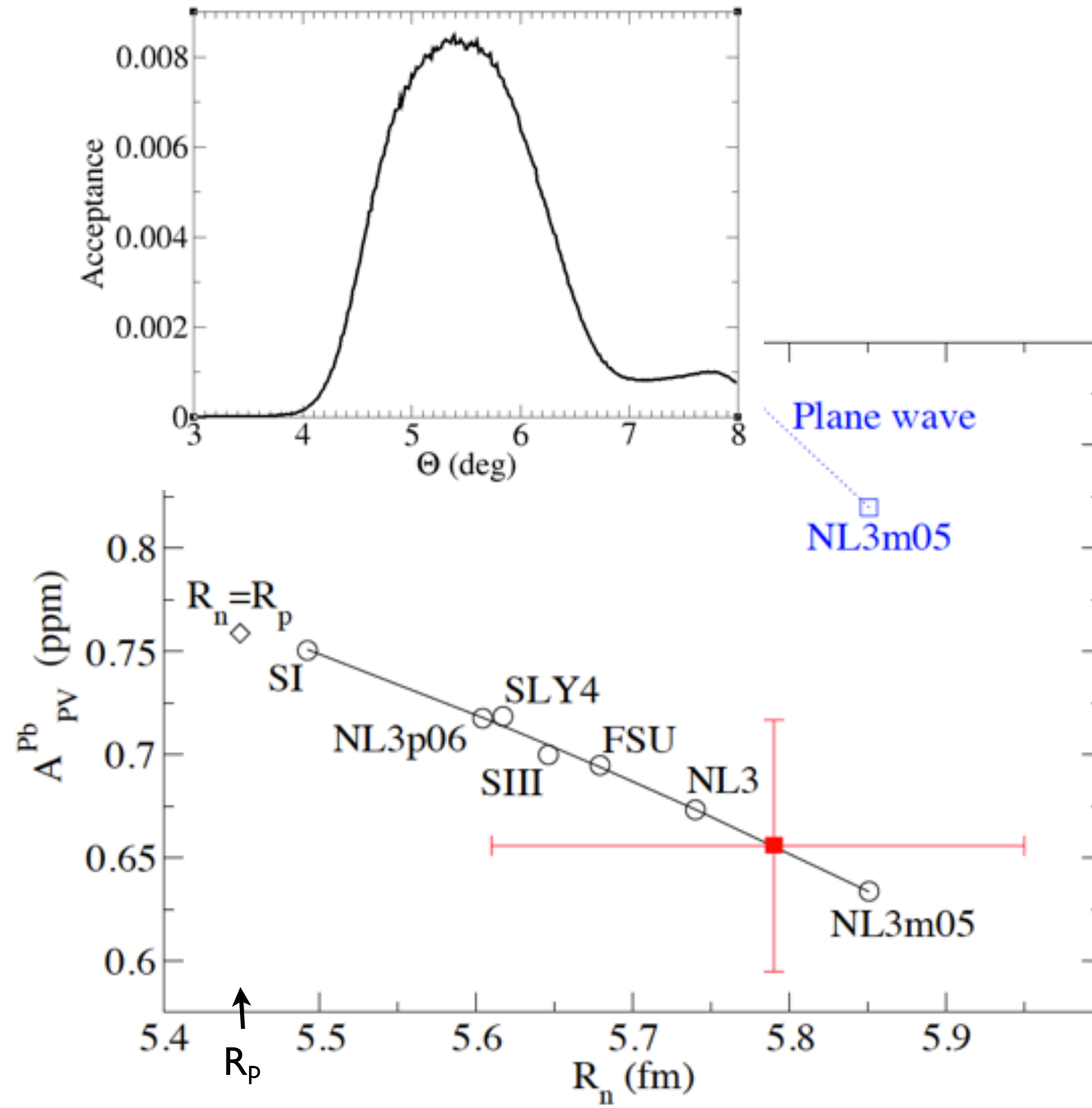
1. Is the current design of CREX and the projected total error on A_PV in the JLab proposal well matched to make an important and unique contribution to nuclear structure and nuclear astrophysics?
2. At the Q of the experimental design, what are the relative rates and the relative sizes of PV asymmetries (with appropriate theoretical errors) on the first few excited states of Ca-48? Our acceptance falls off to zero above about 5 MeV, but we may accept a small fraction of events up to 5 MeV of inelasticity.
3. At the level of accuracy proposed, are there any other outstanding theoretical issues that might cloud the interpretation of results such as radiative corrections, specific box graph uncertainties and vector analyzing power?
4. Is it worth thinking about improved accuracy beyond CREX for Ca-48? This might be feasible at Mainz if the motivation is compelling enough.
5. How big is the vector analyzing power for Ca-48 at 2 GeV as well as lower beam energy (e.g. 150 MeV) at the proposed Q?
6. What is the importance and significance of improving the Pb-208 A_PV beyond PREX-II at the same Q? It seems feasible to do a factor of 2 better than PREX-II at Mainz
7. How different is vector analyzing power expected to be for Pb-208 at the same Q but a beam energy of 150 or 200 MeV, in light of the PREX-I measurement of an unusually small vector analyzing power?
8. Does the surprising measurement of small A_T in PREX-I motivate dedicated new measurements of A_T on Pb-208 or other nuclei?
9. Under what circumstances of potential PREX and CREX results would it be motivated to contemplate new A_PV measurements at other Q points in Ca-48 or Pb-208 or in new nuclei? By the same token, is there a scenario where the results of PREX-II and CREX, assuming they achieve their proposed errors, form a pair of definitive measurements that provide the necessary information for nuclear structure and nuclear astrophysics being sought?

Theory / Nuclear Structure Questions

1. How does the ratio of 3N/NN contributions to bulk properties vary with mass?
2. What is the role played by 3N T=3/2 forces in finite nuclei?
3. How does structure of 48Ca depend on 3N forces?
4. What do we know about the spin-isospin dependence of 3N forces and what can 48Ca teach us about them?
5. How does structure of 48Ca depend on isovector fields?
6. Can the precise data on the neutron radius of 48Ca reduce the theoretical uncertainties of low-energy coupling constants of nuclear models and discriminate between various models?
7. How stringent do precise data on (i) the neutron radius of 48Ca, (ii) the neutron radius of 208Pb, and (iii) the electric dipole polarizability of 208Pb constrain the density dependence of the symmetry energy (or the isovector sector of EDFs)?
8. Do "ab-initio" calculations of 48Ca place stringent constrain on EDFs?
9. Do "exact" calculations of dilute pure neutron matter place stringent constraints on the neutron radius of 48Ca?
10. Is it realistic to measure the weak-charge form factor of 48Ca [or 208Pb] at an additional momentum transfer to extract both the radius and the diffuseness?
11. Are radiative corrections / coulomb distortions really under control? How can this be verified?
12. How well does CREX, in addition to PREX, allow us to predict Rn all across periodic table? in particular for atomic parity?
13. What is best way to constrain L (density dep of symmetry E) from Rn measurements? What is needed accuracy?

PREX Analysis 1: Fit to Mean Field Models

- Consider set of seven mean field models that give good charge densities and binding energies, and span a large range of neutron radius R_n.
- Calculate weak charge density from model ρ_n and ρ_p , $\rho_W(r)=q_p\rho_{ch}(r)+q_n\int d^3r'[G_E^p\rho_n +G_E^n\rho_p]$
- Solve Dirac Eq. to calculate $A_{PV}(\theta)$ given ρ_W and experimental ρ_{ch}.
- Integrate $A_{PV}(\theta)$ over angular acceptance --> $<A_{PV}>$
- Compare least squares fit of model R_n vs predicted $<A_{PV}>$ to measured $A_{PV} = 0.657 \pm 0.060(\text{stat}) \pm 0.014(\text{sym})$ ppm
- Phys Rev Let. **108**, 112502 (2012)



Analysis 1 Result: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm

also Roca-Maza

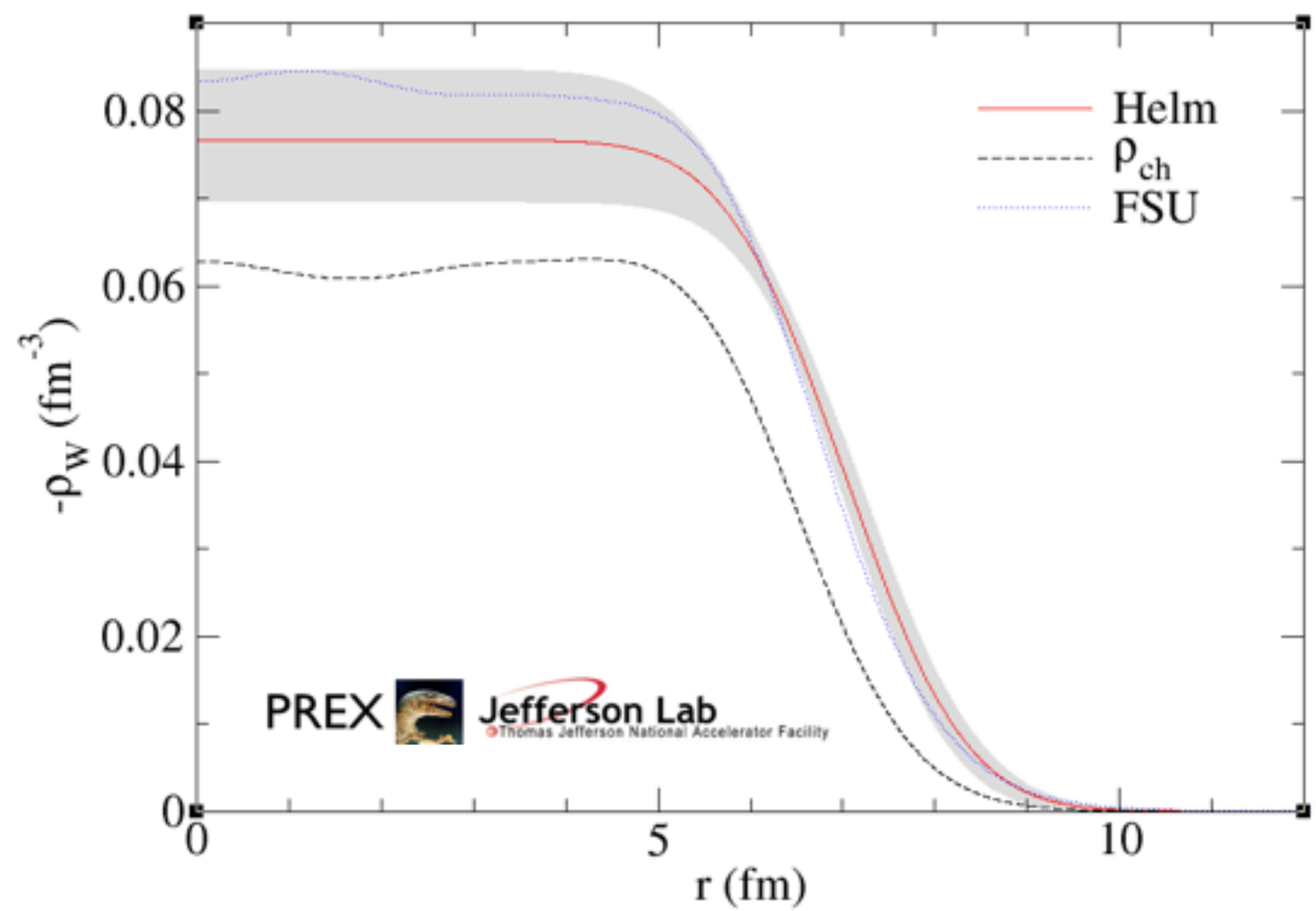
Analysis II: Helm model weak form factor

- Solve Dirac eq. for wood saxon ρ_W and experimental ρ_{ch}. Integrate over acceptance.
- Adjust ρ_W until $\langle A_{PV} \rangle$ agrees with PREX measurement.
- Calculate weak form factor $F_W(q) = \int d^3r \, \sin qr/qr \, \rho_W(r) / Q_W$.

  $F_W(q) = 0.204 \pm 0.028$ at $q = 0.475 \text{ fm}^{-1}$

- Helm model for $F_W(q) = 3/qR_0 \, j_1(qR_0) \exp[-q^2\sigma^2/2]$ with diffraction radius R_0.
- Use surface thickness $\sigma = 1.02 \pm 0.09$ fm from least sqs. fit to mean field models.
- Weak radius: $R_W = [3/5(R_0^2 + 5\sigma^2)]^{1/2}$

  $R_W = 5.83 \pm 0.18(\text{exp}) \pm 0.03(\text{model})$ fm



Helm model weak charge density for ^{208}Pb (red) Gray band includes exp. and model errors. Blue dots is a typical mean field model (FSU). Black dashes is (E+M) charge density.

Analysis II: Weak form factor

- Compare R_w to well measured R_{ch}=5.503 fm implies ***weak charge skin*** R_w-R_{ch}=0.32±0.18(exp)±0.03(model) fm. Experimental milestone: direct evidence that weak charge density is more extended than E+M charge density.
- R_{ch} slightly larger than point proton radius, $R_{ch}^2=R_p^2+\langle r_p^2\rangle+N/Z\langle r_n^2\rangle$ (neglecting small spin-orbit and meson exchange currents).
- Proton size $\langle r_p^2\rangle$=0.769 fm^2, neutron $\langle r_n^2\rangle$=-0.116 fm^2 --> R_p=5.45 fm.
- $(Q_w/q_nN)R_w^2=R_n^2+(q_pZ/q_nN)R_{ch}^2+\langle r_p^2\rangle+Z/N\langle r_n^2\rangle-(A/q_nN)\langle r_s^2\rangle$
- Total weak charge $Q_w=Nq_n+Zq_p$=-118.55. Radiative corrected neutron weak charge is q_n=-0.9878, proton q_p=0.0721.
- Nucleon strangeness radius $\langle r_s^2\rangle\leq\pm$0.04 fm^2 from HAPPEX, G0, A4...
- From R_w deduce R_n=5.751 ±0.175(exp) ±0.026(model) ±0.005(strange) fm.
- Neutron skin: R_n-R_p=0.302 ±0.175 ±0.026 fm, consistent with Analysis I, R_n-R_p=$0.33^{+0.16}_{-0.18}$ fm, within limitations of Helm model (≈ ± model error).

-- Phys. Rev. C 85, 032501(R) (2012)

Possible parity violating neutron density measurements

- R_n exp. are feasible for nuclei with low density of states.
  - ^{208}Pb (relation to sym E / neutron matter P)
  - ^{48}Ca (smaller nucleus with large N excess)
  - Tin isotopes,... Your favorite nucleus here!
- Measure 2nd Q^2 point --> surface thickness of n density.
  - What nuclear structure does one learn?
  - How accurately does one need to measure?
  - Which nuclei are most interesting?
- "Ultimate exp." over longer time scale: measure 5 or 6 Fourier Bessel coefficients of neutron density of ^{48}Ca. Hard but not as hard as it sounds. Minimize run time for high Q^2 points: asym grows with Q^2, need less accuracy, measure at high energies and small angles where cross section is larger. This directly tells us ***where the neutrons and protons are in a nucleus.***

1) Is there a way to more carefully vary the T=1/2 and T=3/2 three-nucleon forces within the QMC, Skyrme and RMF formalisms?

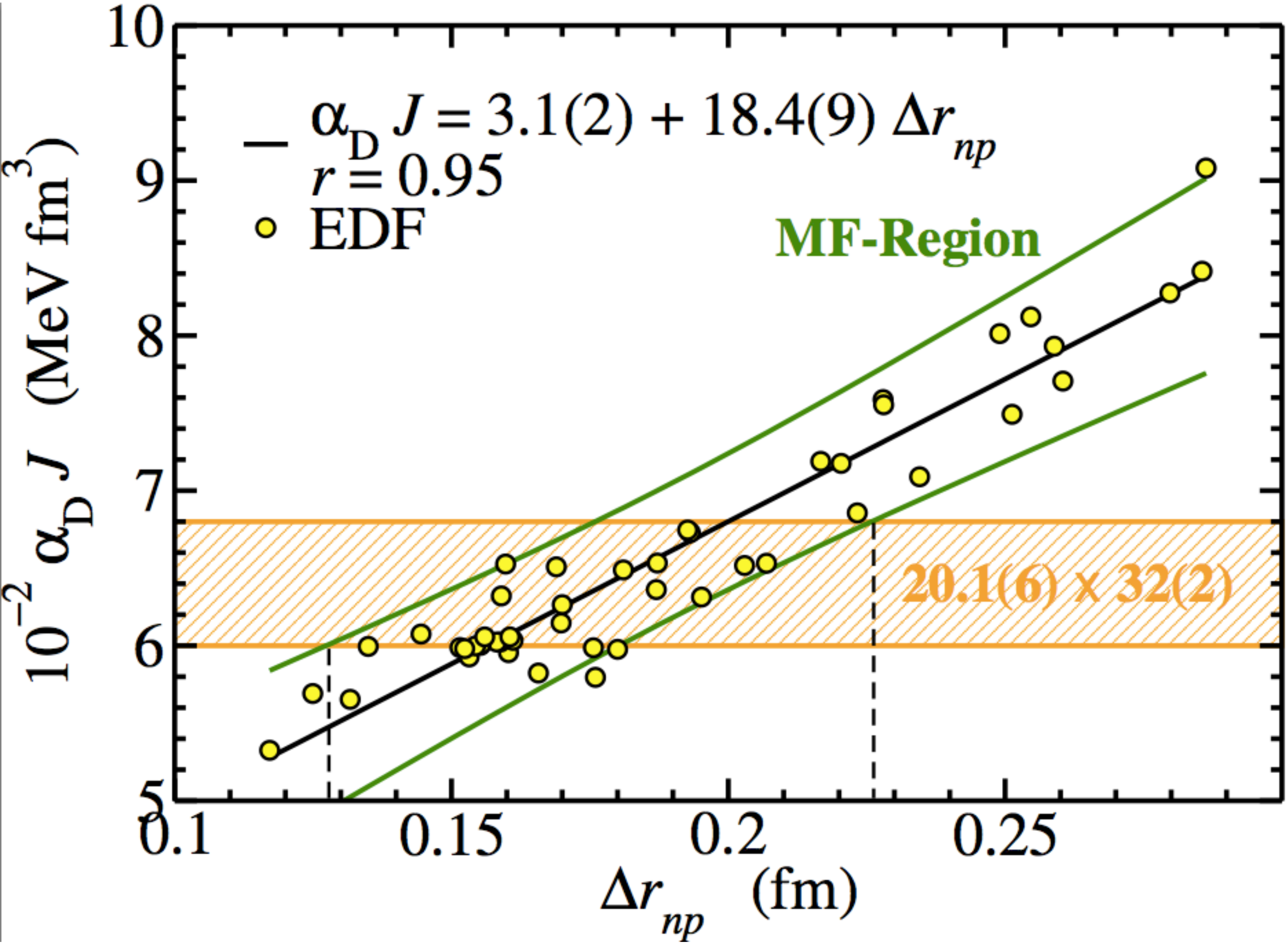
2) Can we clearly demarcate how the models react to a variation in R_n for Ca for fixed R_n in Pb and what basic physics underlies that variation?

3) How do the uncertainties in the three-nucleon force affect the opacities near the neutrinosphere in mergers and core-collapse supernovae?

4) How does the physics of the neutron star crust depend on three-nucleon forces?

5) Does CREX teach us something new about the nature of the nuclear surface, e.g. diffuseness?

Take care,
Andrew



$\alpha_D J = 3.1(2) + 18.4(9)\,\Delta r_{np}$
$r = 0.95$
EDF
MF-Region
20.1(6) x 32(2)
$10^{-2}\,\alpha_D J$ (MeV fm^3)
Δr_{np} (fm)
10
9
8
7
6
5
0.1
0.15
0.2
0.25