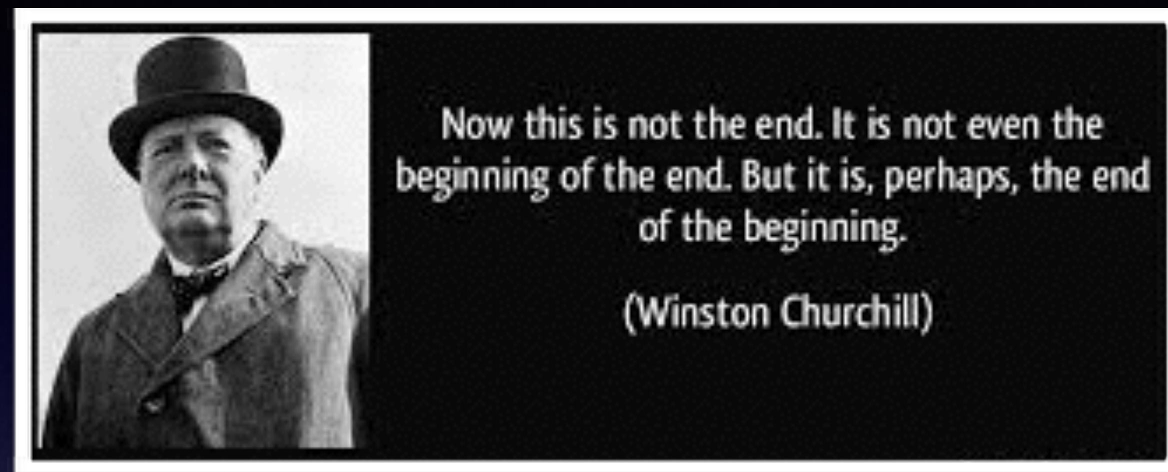
The End of the Beginning

Jorge Piekarewicz - Florida State University



Neutron Skins of Nuclei: From Laboratory to Stars

May 4-7, 2015

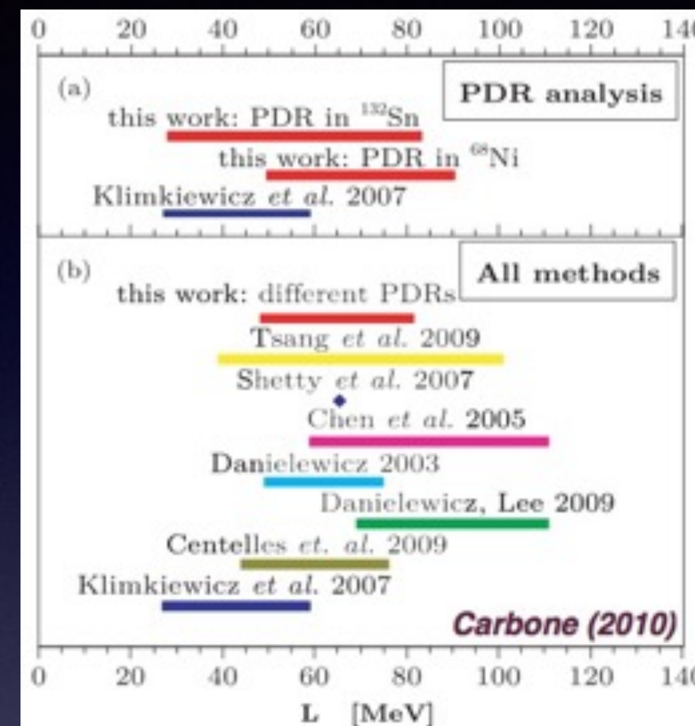
Mainz Institute for Theoretical Physics

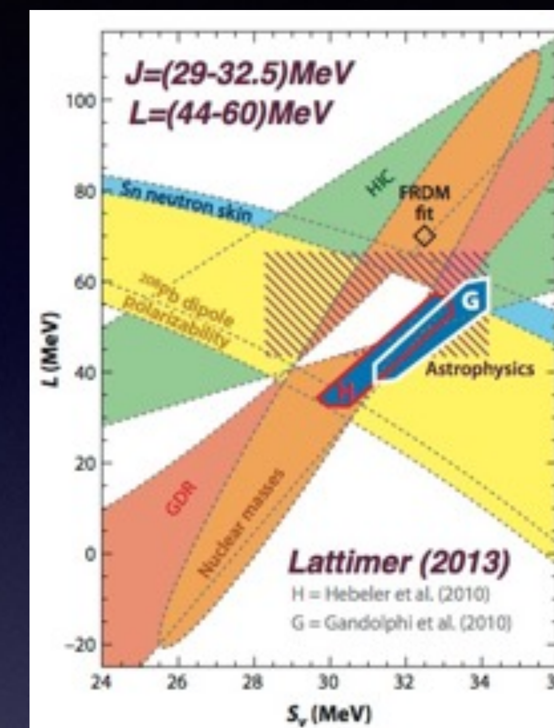
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

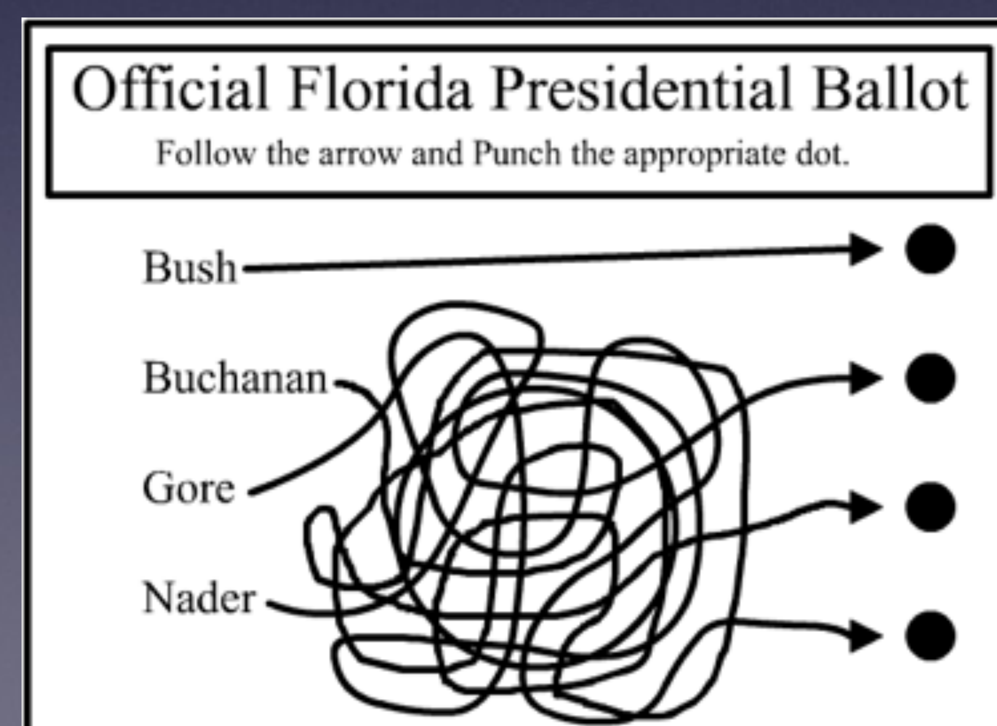
The Beginning of the End
May 17-27, 2016

From Measurable Observables to the Neutron Skin

- What is actually measured?
  Cross section, asymmetry, spin observables, …
- How is the measured observable connected to the neutron skin?
- What are the assumptions implicit in making this connection?
  Impulse approximation, off-shell ambiguities, distortion effects, …
- How sensitive is the extraction of the neutron radius/skin to these assumptions?
- Quantitative assessment of both statistical and systematic errors







All observables are equal, but some observables are more equal than others … Pedigree!

Theory Informing Experiment

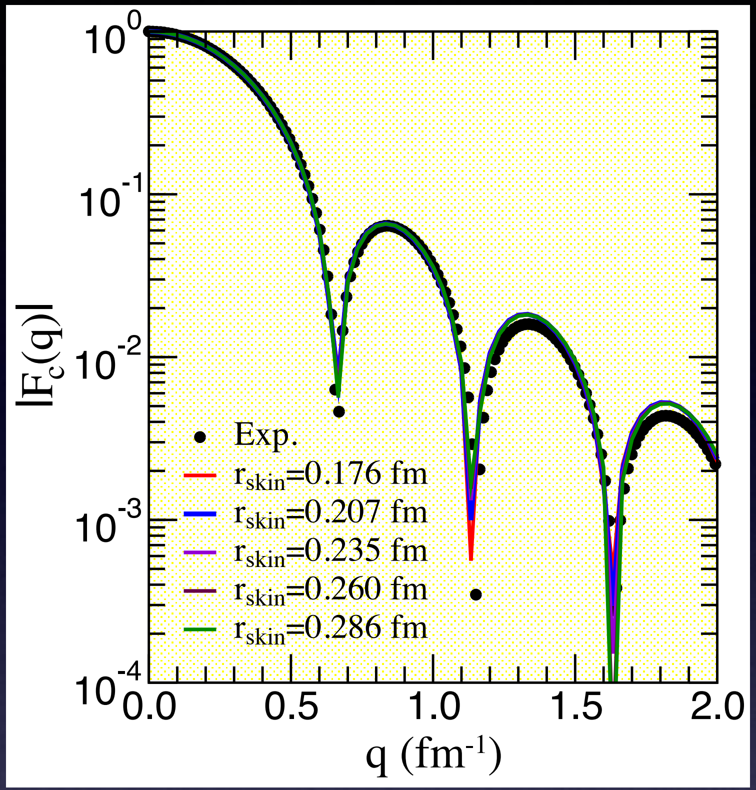
- Quantitative assessment of both statistical and systematic errors; theory must provide error bars!
  Uncertainty quantification and covariance analysis (theoretical errors & correlations)

- Precision required in the determination of the neutron radius/skin?
  - As precisely as "humanly possible" - fundamental nuclear structure property
  - To strongly impact Astrophysics?
  - What astrophysical observables to benchmark?

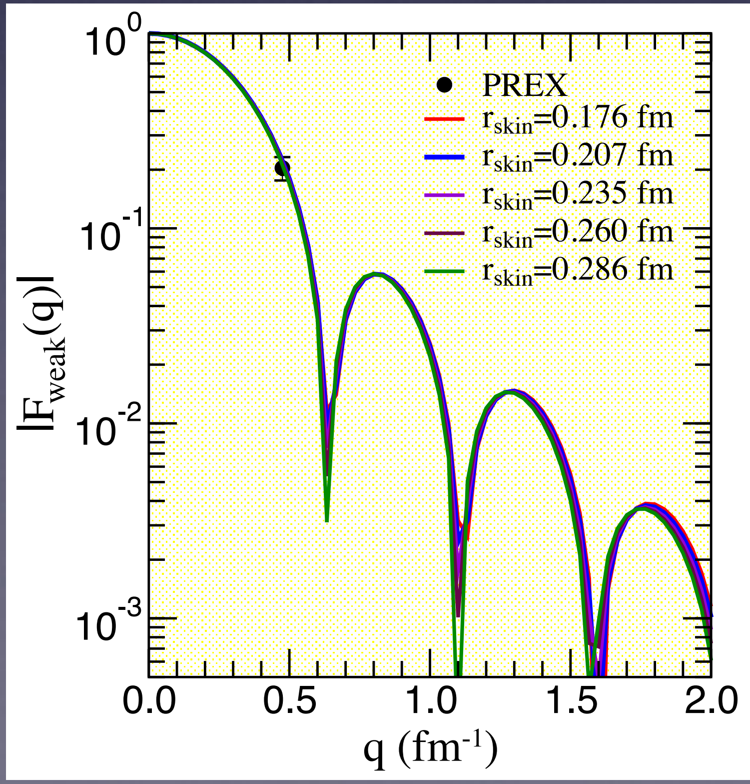
- Is there a need for a systematic study over "many" nuclei?
  PREX, CREX, SREX, ZREX, …

- Is there a need for more than one Q-square point?
  Radius and diffuseness … the whole form factor?

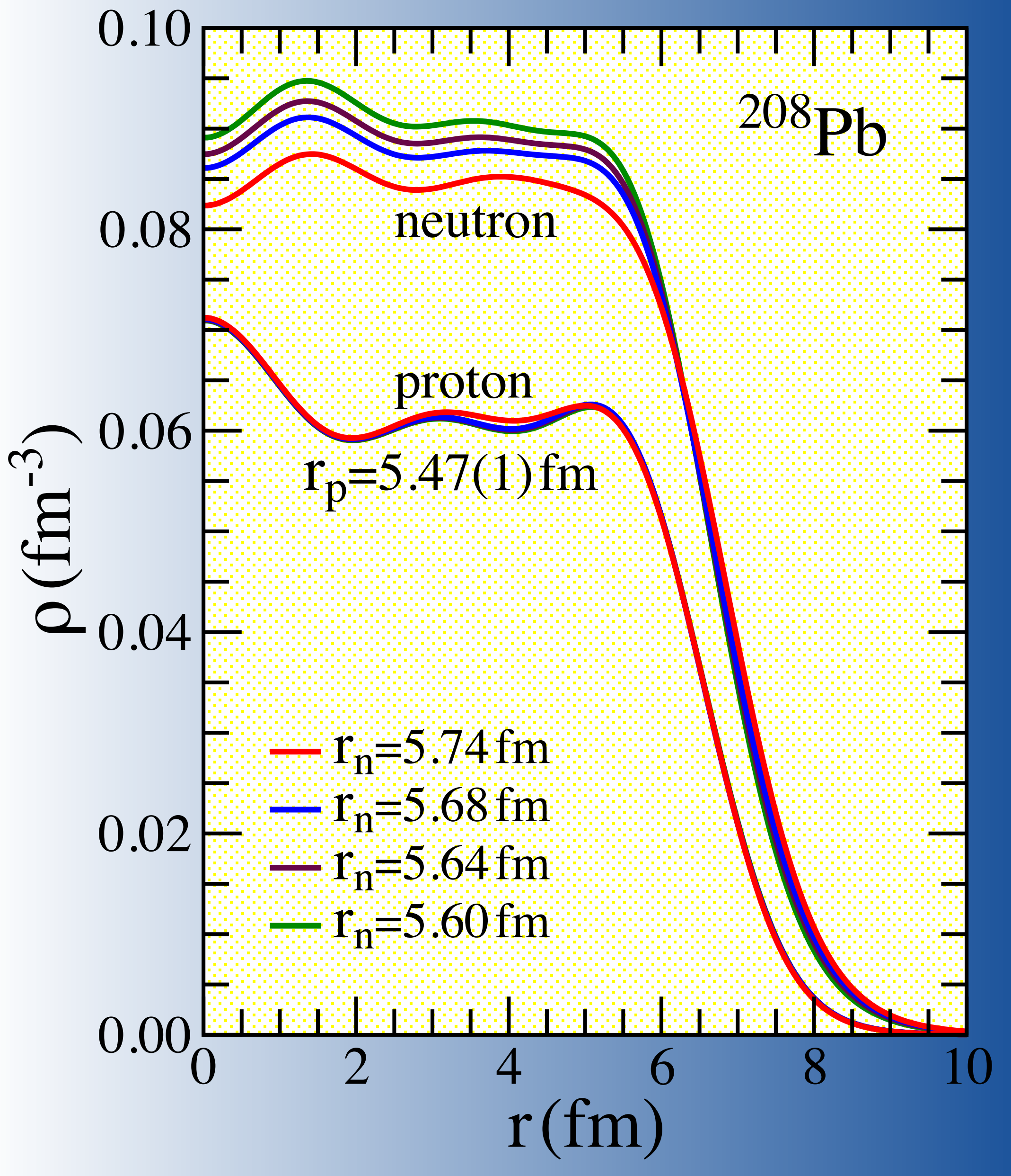
$R_{ch} = 5.5012(13)$ fm

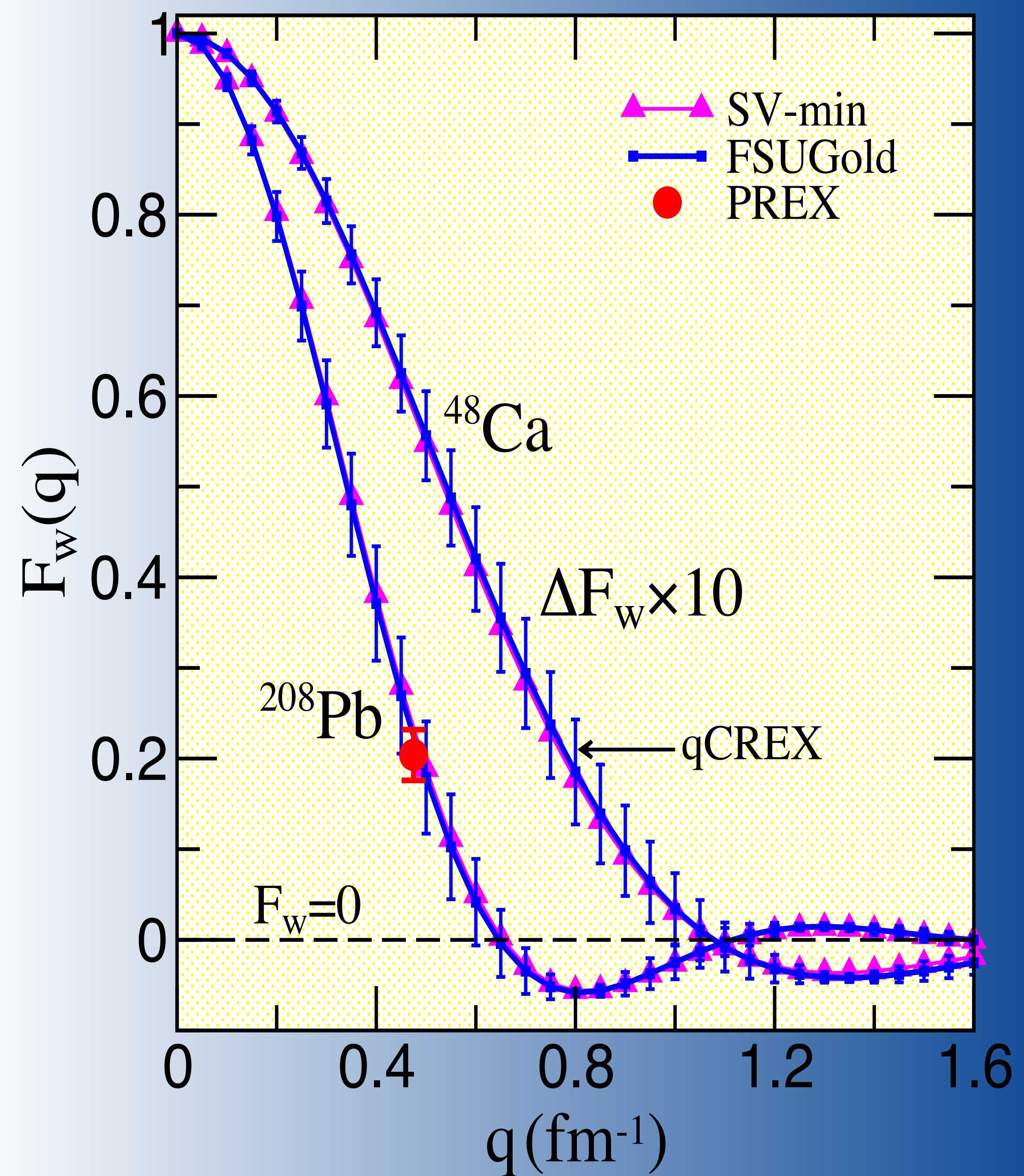


$R_{wk} = 5.826(181)$ fm



Uncertainty Quantification





Need both; Systematic and Statistical Theoretical Errors

Nuclear Structure, Error Bars, and Correlations: Statistical

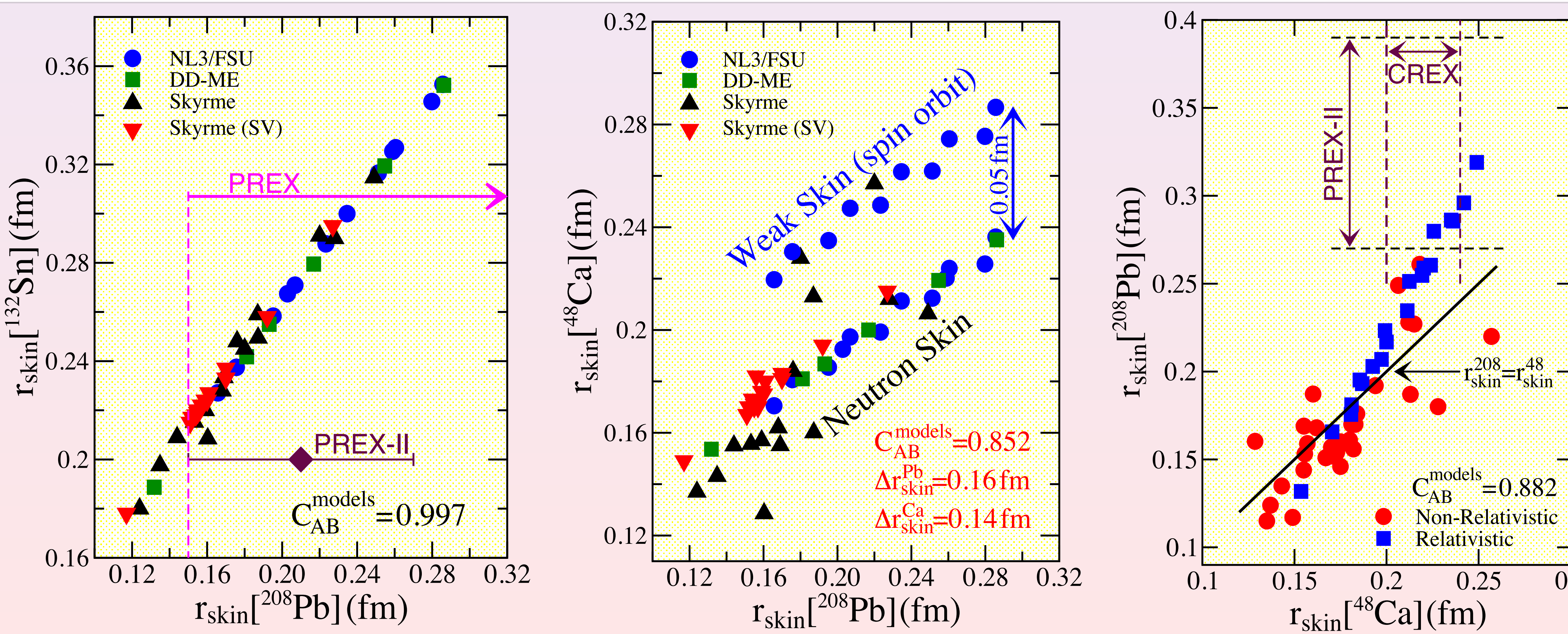
Reinhard-Nazarewicz, PRC81 (2010) 051303(R)   Fattoyev-Piekarewicz, PRC86 (2012) 015802; PRC84 (2011) 064302

- Empirical constants determined from optimization of a quality measure

$$\chi^2(\mathbf{p}) = \sum_{n=1}^{N} \left(\frac{\mathcal{O}_n^{(\mathrm{th})}(\mathbf{p}) - \mathcal{O}_n^{(\mathrm{exp})}}{\Delta \mathcal{O}_n} \right)^2 = \chi^2(\mathbf{p}_0) + \mathbf{x}^T \hat{\Sigma}^{-1} \mathbf{x} + \ldots$$

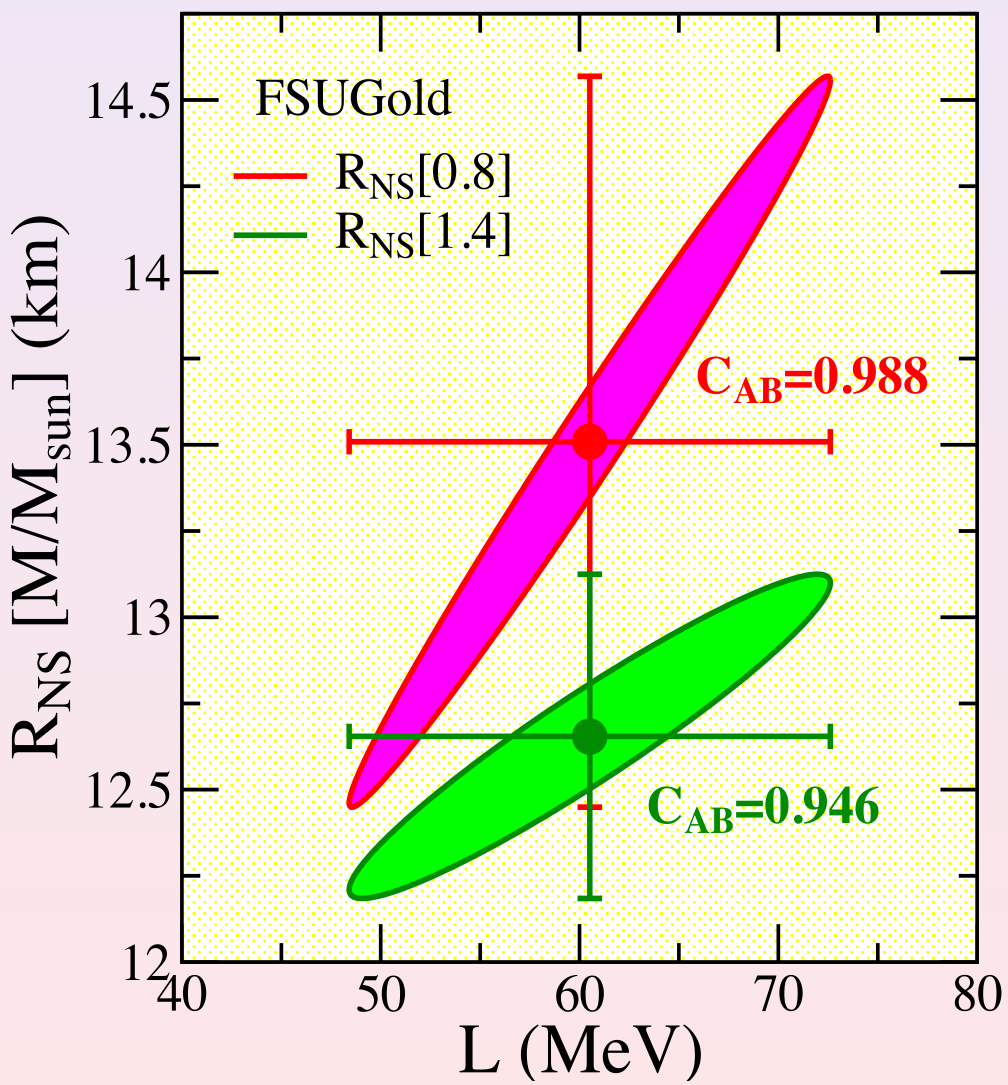
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations

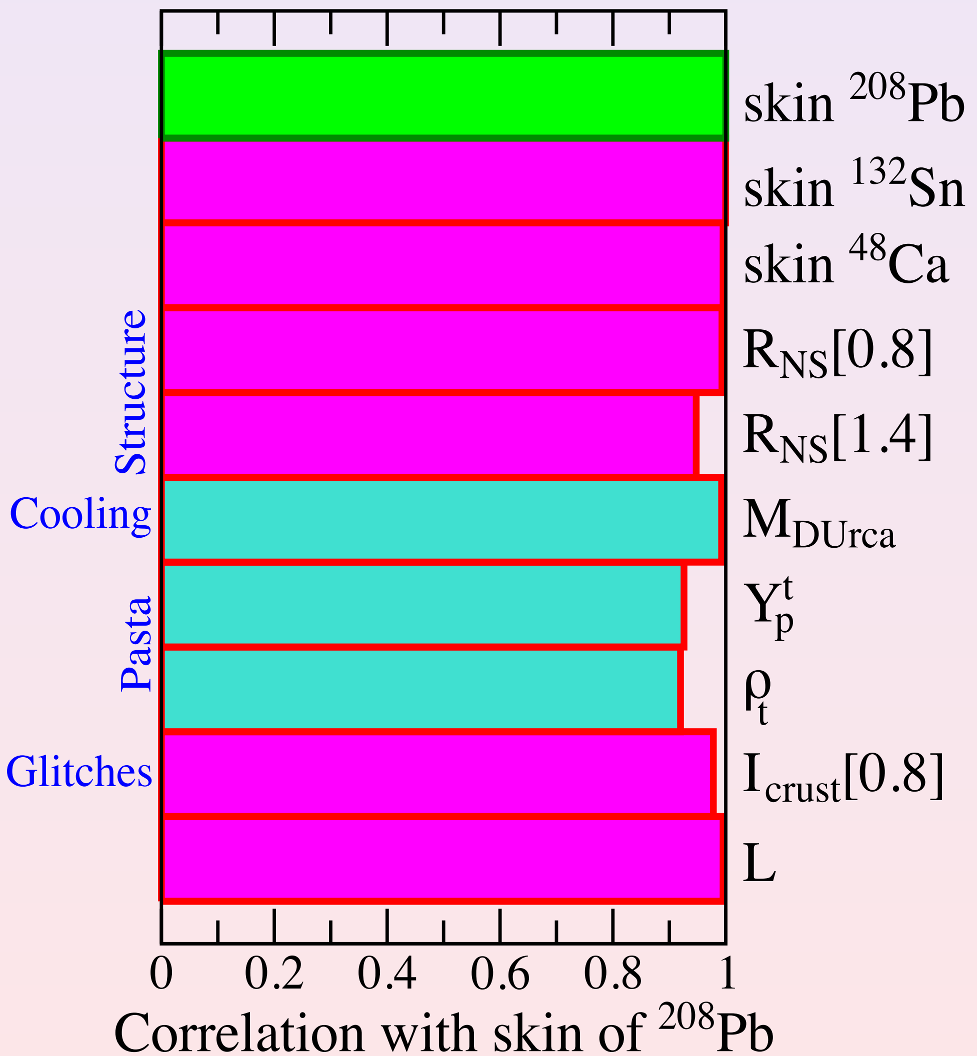
$$\mathrm{Cov}(A,B) = \partial_i A \, \hat{\Sigma}_{ij} \, \partial_j B \, ; \qquad \mathrm{Corr}(A,B) = \frac{\mathrm{Cov}(A,B)}{\sqrt{\mathrm{Var}(A)\mathrm{Var}(B)}}$$



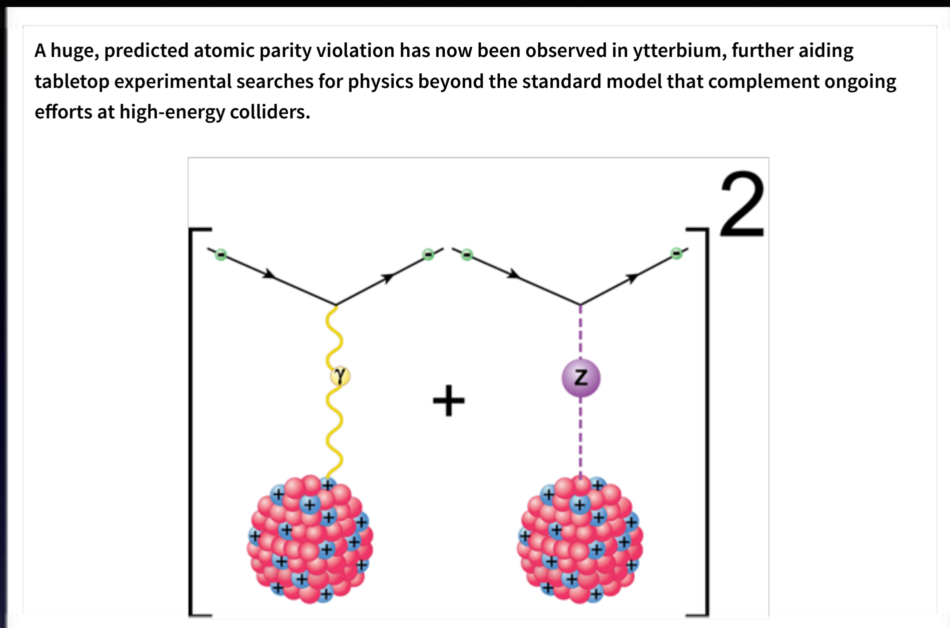
The Enormous Reach of the Neutron Skin: Covariance Analysis

- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- New era: predictability typical – uncertainty quantification demanded
- Neutron skin strongly correlated to a myriad of neutron star properties:
  Radii, Enhanced Cooling, Moment of Inertia, . . .





Electroweak Measurements


A huge, predicted atomic parity violation has now been observed in ytterbium, further aiding tabletop experimental searches for physics beyond the standard model that complement ongoing efforts at high-energy colliders.

PV elastic e-scattering

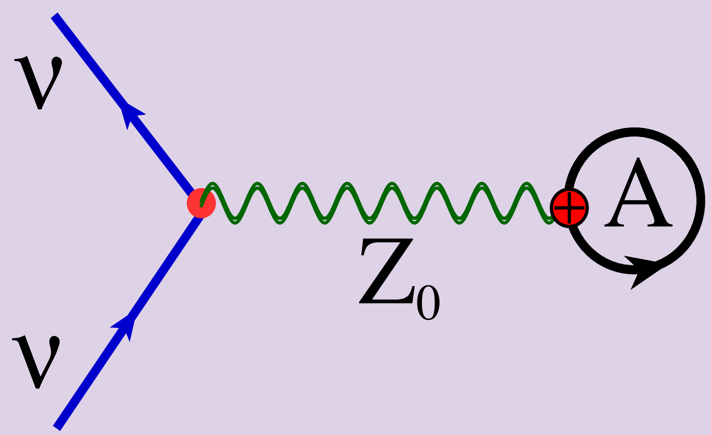
Atomic PV
measured in long-chains (e.g., Yb) to eliminate uncertainties in atomic theory (Dima Budker)

Enormously Clean …
Extraordinarily Expensive!

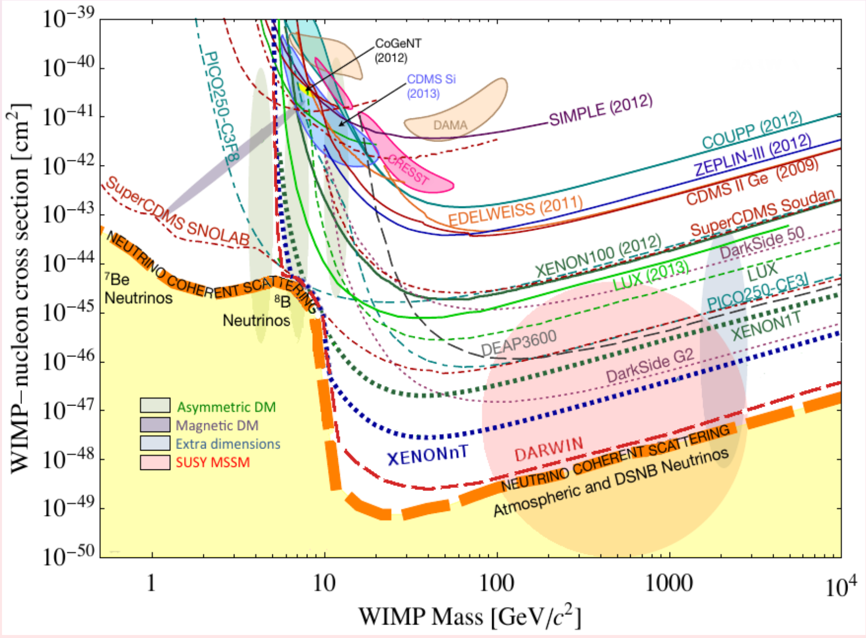
- Weak FF determined in a model independent way (exactly as the Charge FF)
- Very strongly coupled to nSkin …
- "Mild" model dependence going from FF to nSkin (Theory Homework)
- Measuring the FF at two (or more) points (Experiment/Theory Homework)
- Measuring the FF in several nuclei? (Experiment/Theory Homework)
- Understanding dispersive corrections (Theory Homework)

From Dark Matter to Neutron Stars

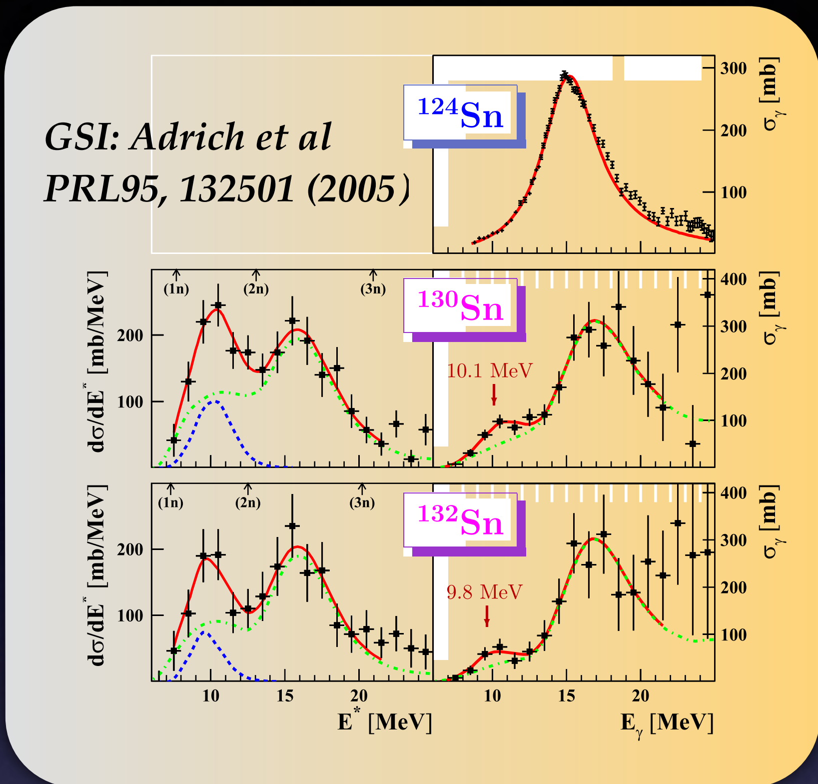
- Coherent elastic ν-Nucleus scattering has never been observed!
- Predicted shortly after the discovery of weak neutral currents
- Enormously challenging; must detect exceedingly slow recoils
- CEvNS (*pronounced "7s"*) are backgrounds for DM searches
- CEvNS is coherent ("large") as it scales $\sim N^2$
- "Piggybacking" on the enormous progress in dark-matter searches

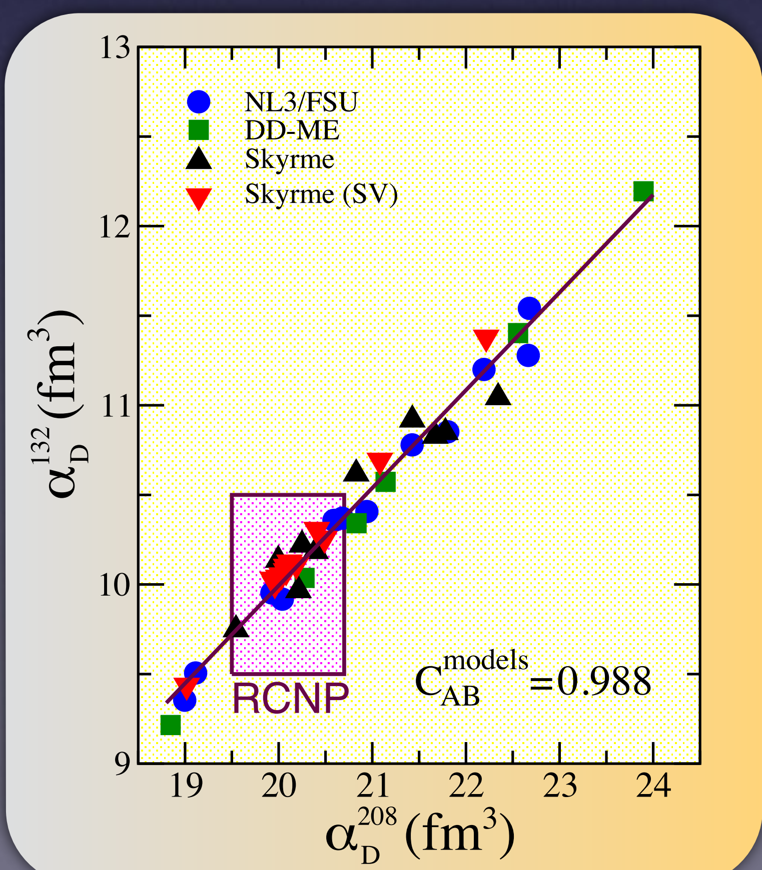


Coherent Elastic ν-Nucleus Scattering at the Spallation Neutron Source (ORNL) may become possible in the "not-so-distant" future



Electric Dipole Polarizability





Enormous progress in sight …

- High quality data on a variety of nuclei at RCNP & GSI, such as Pb, Sn-isotopes, Ni, Ca… (Experiment Homework)

- K,J, L, … are not experimental observables!
- Extract K by reproducing data on GMR
- Extract L by reproducing data on GDR
- (Theory Homework)

One single compelling theoretical picture!

- Impedance matching between theory and experiment; e.g., quasi-D contribution (Experiment/Theory Homework)

- Measure the full dynamic response to learn about FF (Experiment Homework)

$$S(q,\omega)$$

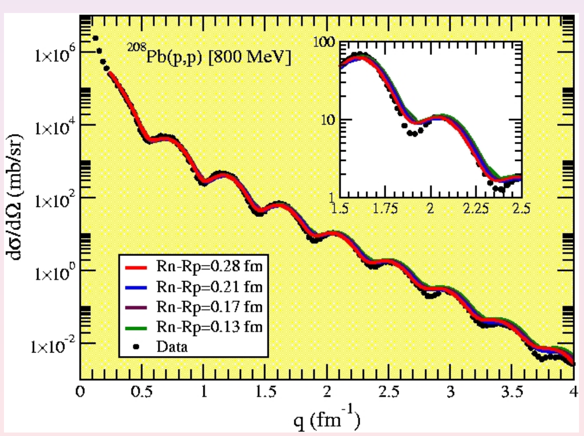
Coherent Elastic Pion and Proton Scattering

PREX-II and CREX as Anchors for FRIB Physics

"One of the main science drivers of FRIB is the study of nuclei with neutron skins 3-4 times thicker than is currently possible. FRIB will provide rare isotopes to explore the properties of halos and skins. JLab uses parity violation to measure the neutron radius of stable lead and calcium nuclei. Studies of neutron skins at JLab and FRIB will help pin down the behavior of nuclear matter at densities below twice typical nuclear density" 2013 Subcommittee Report to NSAC

The Traditional Approach: Proton-Nucleus Scattering

- FRIB will scatter protons from radioactive nuclei in inverse kinematics
- Large and uncontrolled uncertainties in the reaction mechanism
- Enormous ambiguities yield an energy dependent neutron skin
- FRIB must use PREX-II and CREX as calibrating anchors!



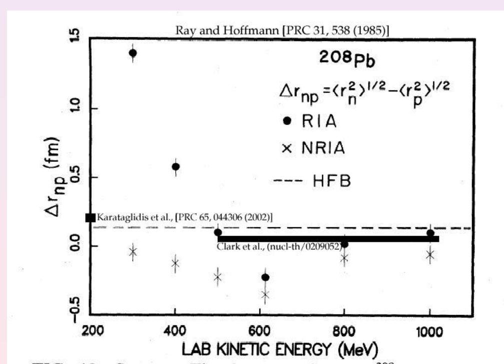
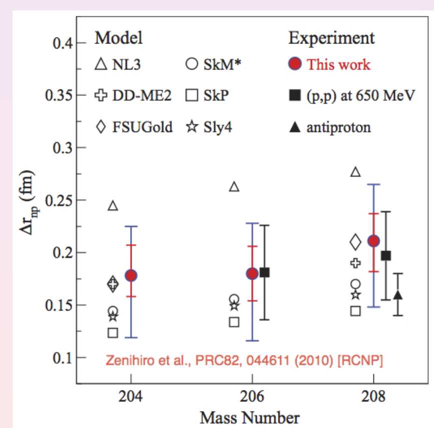


FIG. 10. Same as Fig. 8 except that the ^{208}Pb results are shown. The theoretical value of 0.13 fm (Ref. 39) is indicated by the dashed line.



$$\mathcal{M}_{PWIA} \sim A_1(s,t)\rho_T(Q)/Q \approx A_1(s,t)\rho_V(Q)$$

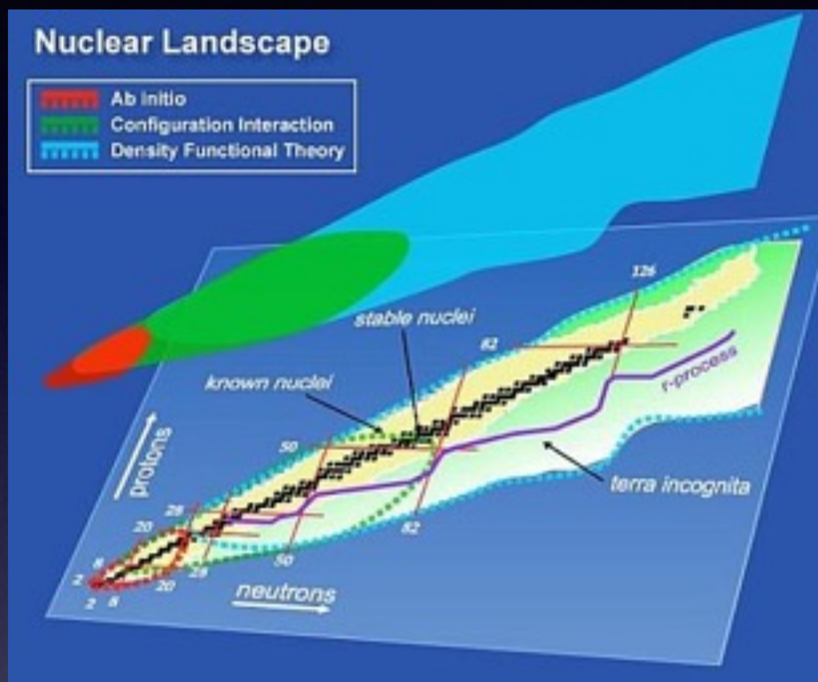
Uncontrolled Uncertainties

- Impulse Approximation
- Off-shell Ambiguities
- Distortion Effects
- ...

$$\frac{Q_2}{Q_1} \approx \left(1 + \frac{\alpha}{2}\frac{\Delta R_{\rm skin}}{R}\right) \simeq (1 + 2\times 10^{-4})$$

Potentially very useful observables
Difficult Experiment/Theory
Homework

What else ?



A CREX deliverable:
Theory informing Theory

Coupled Cluster Meets DFT

Extra Credit Homework
and Planning

- What worked in 2015; what did not?
- Deliverables for May 2016?
- Breadth vs Depth for May 2016?
- Goals for two weeks in May 2016?
- …

Thank you all for Coming!

See You in One Year
May 17-27, 2016