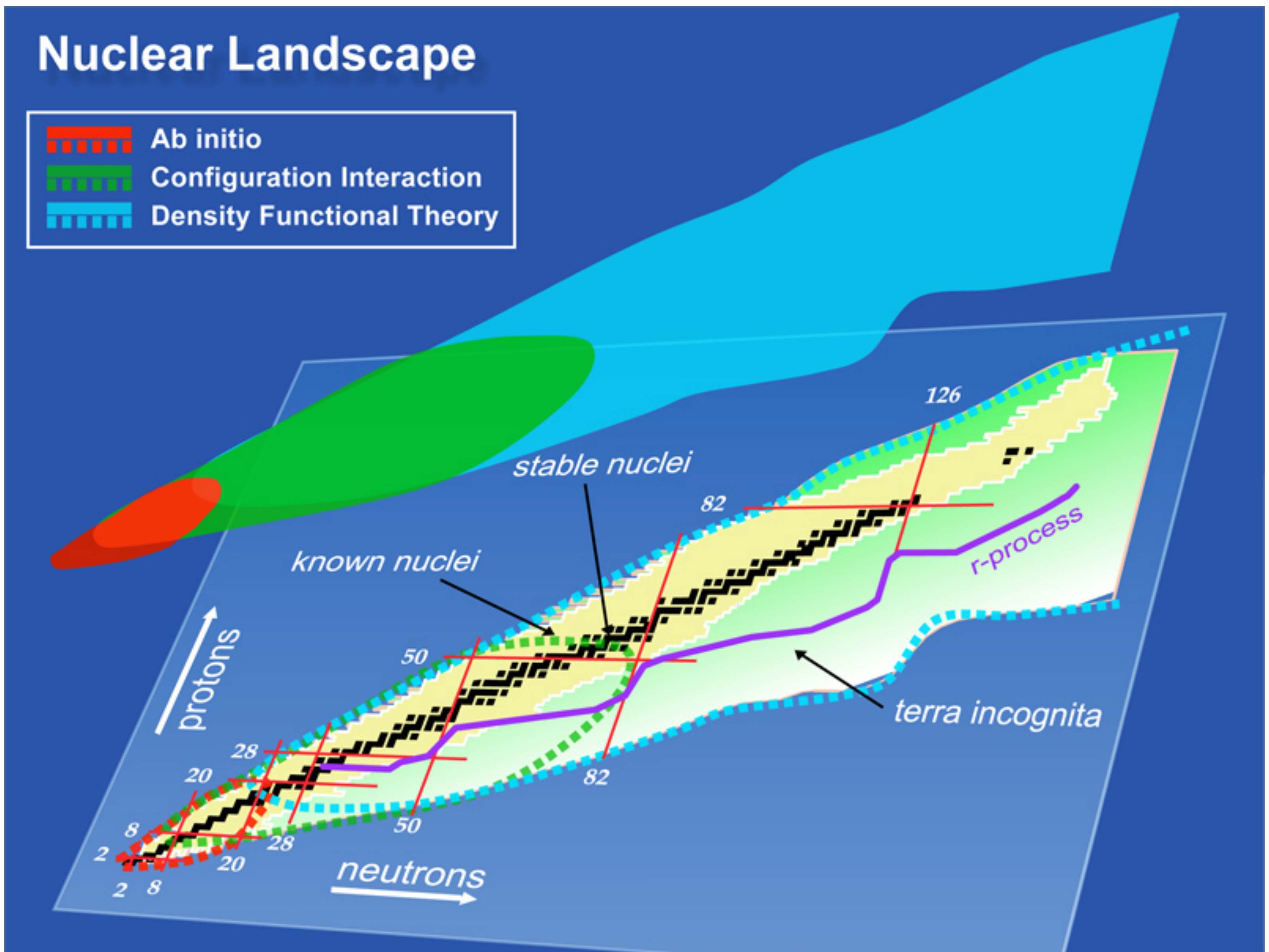
Measurement of the Neutron Skin in Heavy Nuclei



Nuclear Physics: Exploring the Heart of Matter

Mark Dalton

University of Virginia
Arts & Sciences

Outline

Introduction

Physics

- symmetry energy and neutron skin

Calculation methods

- Density Functional Theory and ab initio calculations

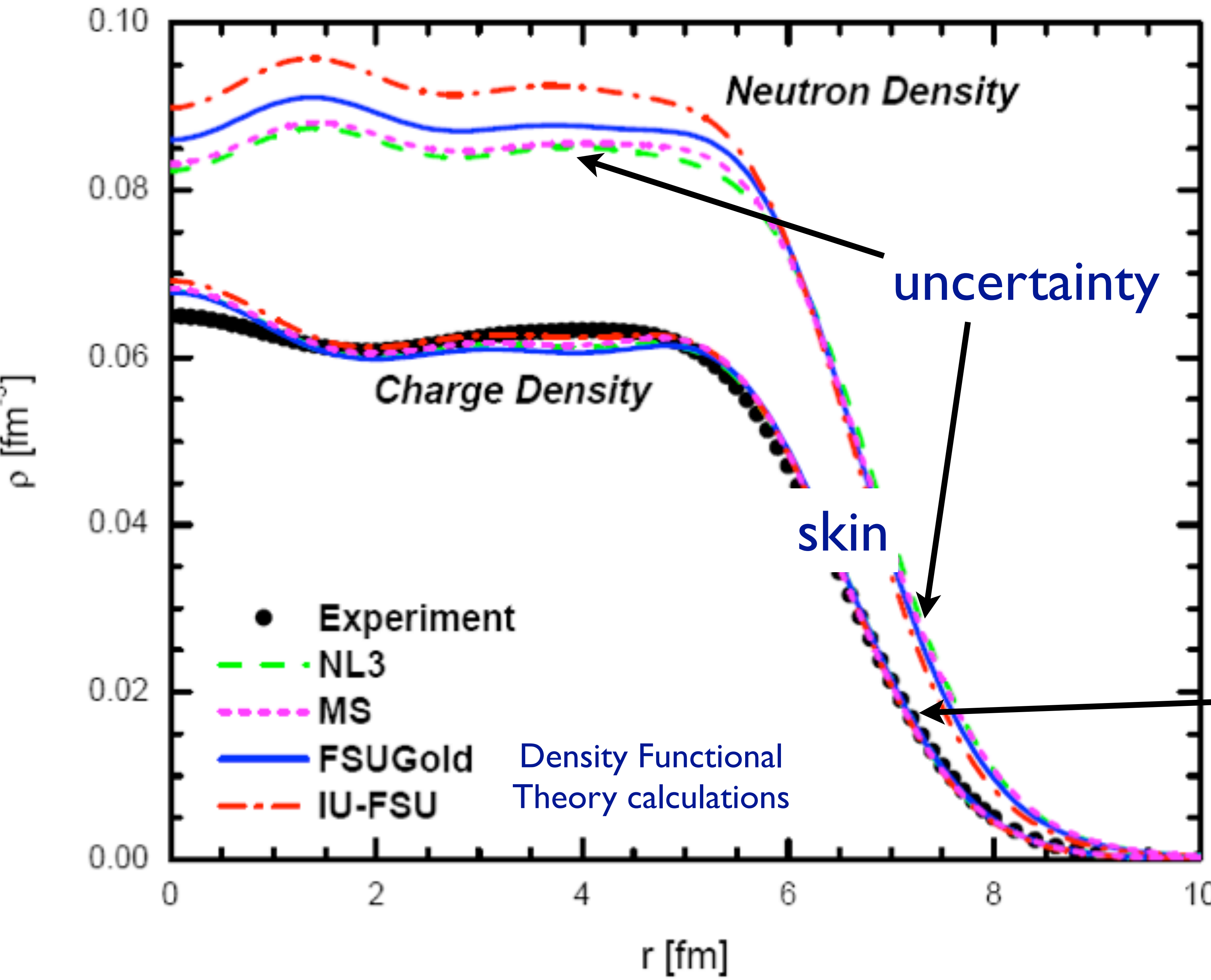
Experimental observables

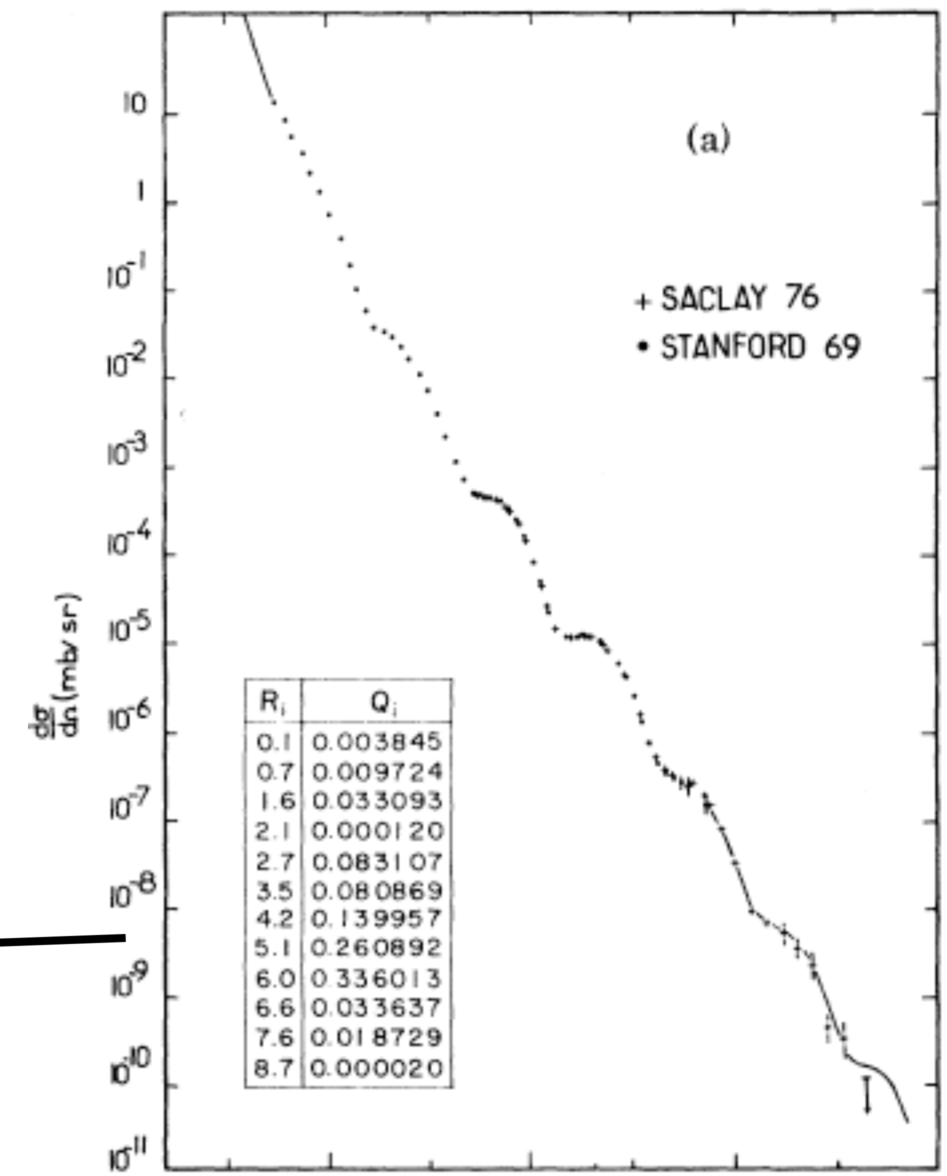
- PREX and CREX experiments

Many slides and figures from CREX Workshop, March 17-19, 2013
Thomas Jefferson National Accelerator Facility
http://www.jlab.org/conferences/crex/program.html

Introduction

neutron skin thickness is highly sensitive to the pressure of pure neutron matter (PNM): the greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.





R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

extensive measurements give size and shape

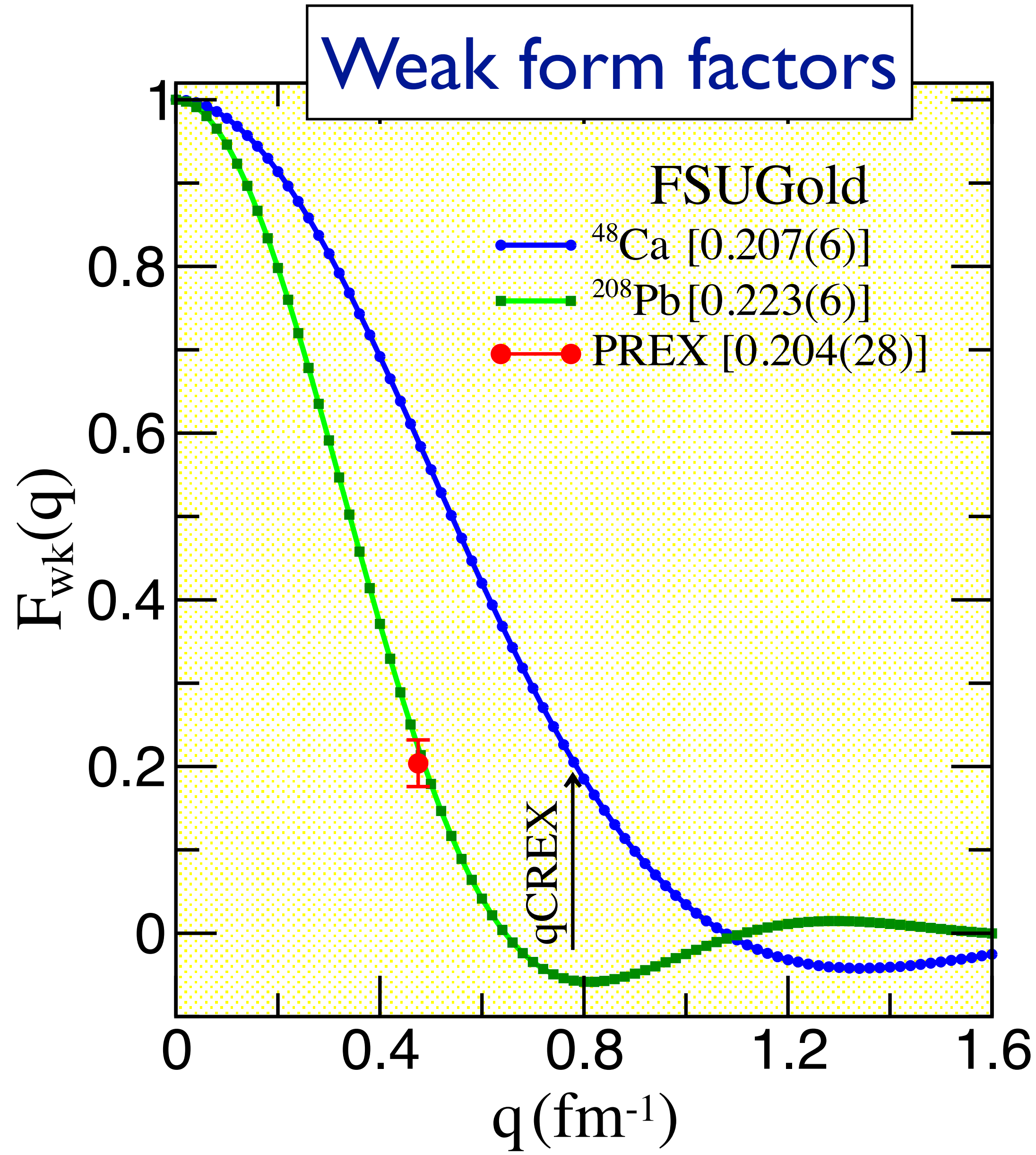
Probe Neutrons Directly

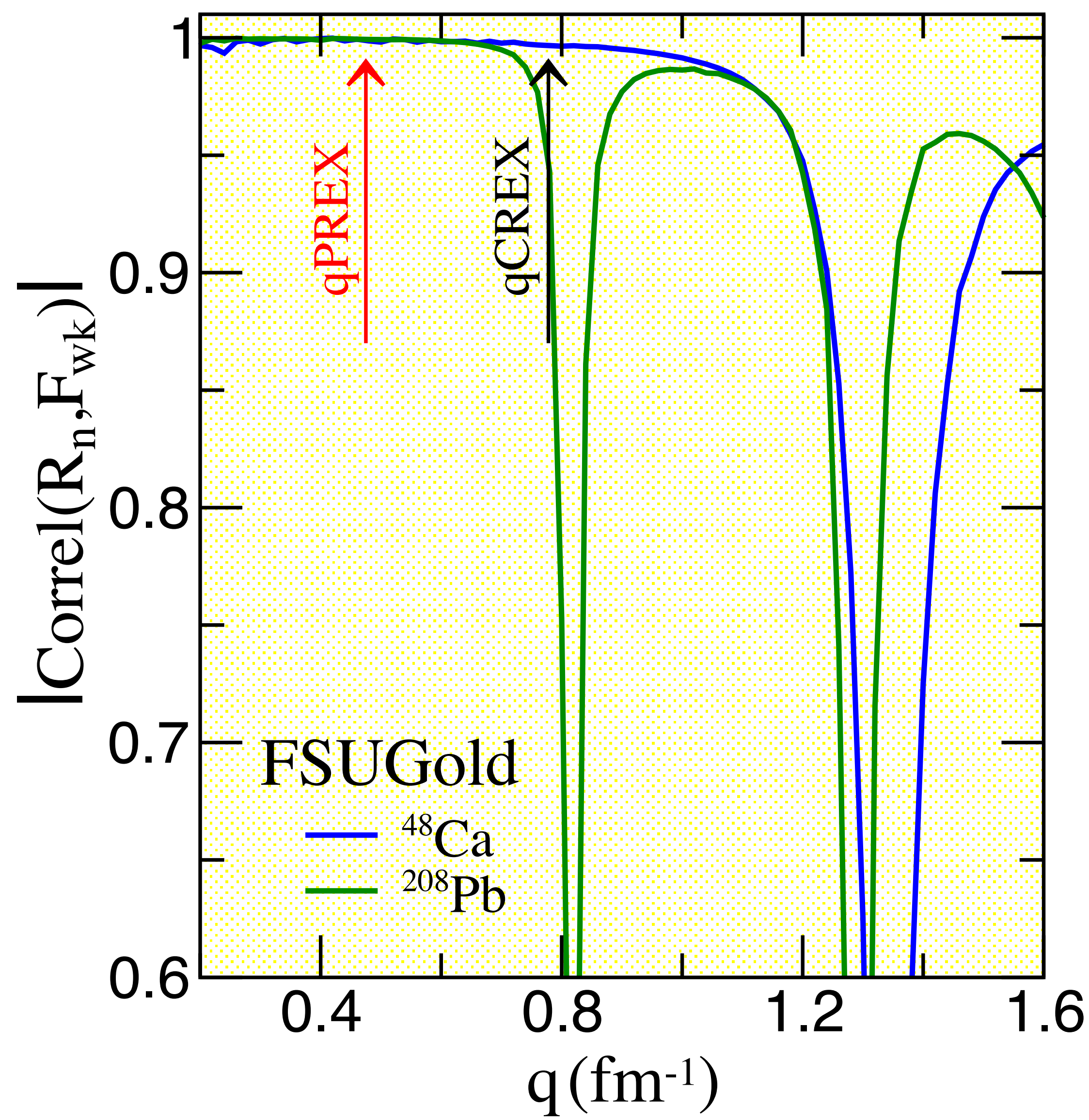
$$A_{\rm PV} \approx \frac{G_{\rm F} Q^2}{4\pi\alpha\sqrt{2}} \frac{F_{\rm W}}{F_{\rm ch}}$$

Parity violating electron scattering proceeds by weak neutral current

Weak form factors dominated by neutron distribution form factors

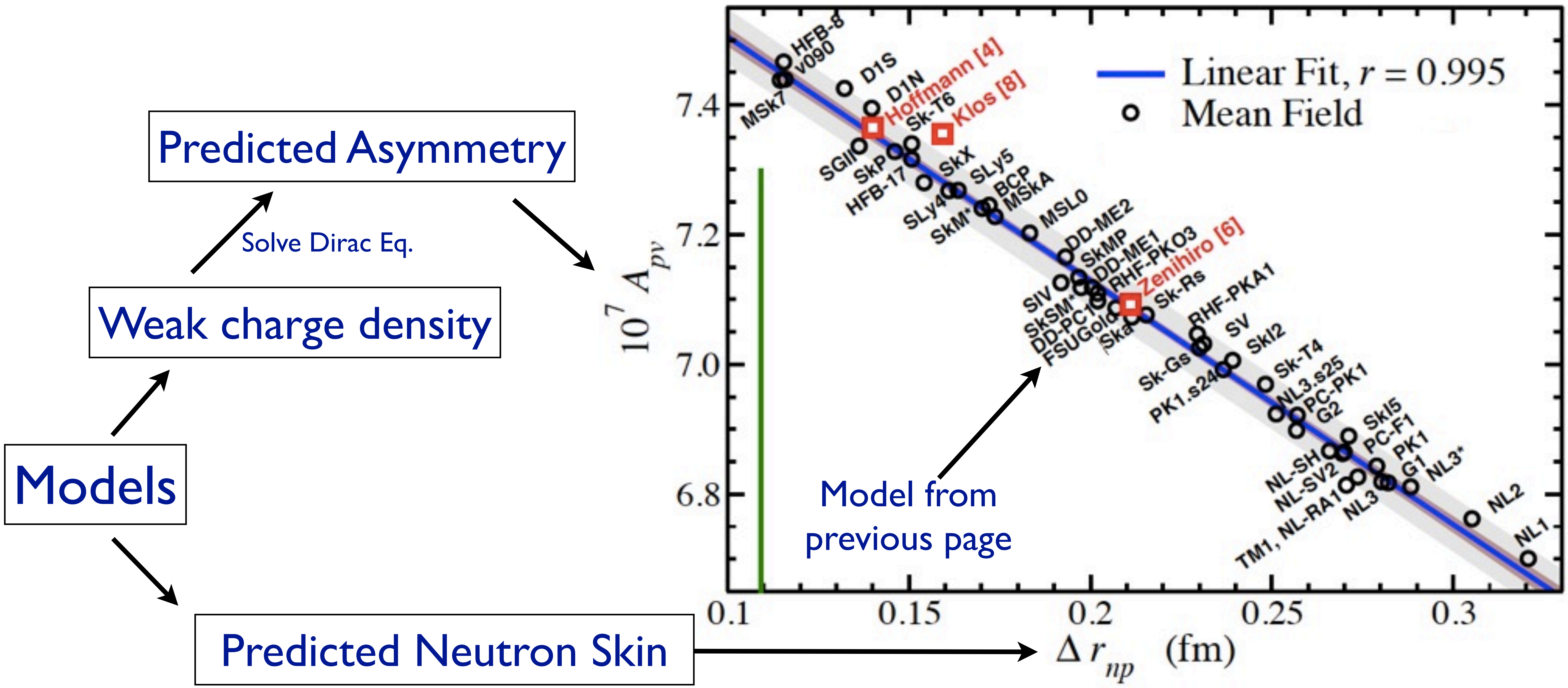
	proton	neutron
Electric charge	1	0
Weak charge	~0.07	1





See talks by Paul Souder, Katherine Myers, Joshua Magee at this meeting.

Asymmetry and Neutron Skin



X. Roca-Maza, M. Centelles, X. Vi˜nas, and M. Warda, Phys. Rev. Lett. 106 252501 (2011)

Linear fit gives neutron skin from measured asymmetry

Asymmetry prediction done specifically for particular experiment acceptance

Asymmetry could be also used directly as data in producing models

Symmetry Energy

Energy penalty for breaking N=Z symmetry $$S = \frac{E}{N}$$

$$L \propto \frac{\partial S(\rho)}{\partial \rho}\Big|_{\rho_0}$$

Slope of symmetry energy at saturation density

Neutron properties in stable medium and heavy nuclei have been mainly measured by using strongly interacting probes. This gives only limited knowledge of isovector properties.

model-dependent description of the non-perturbative strong interaction

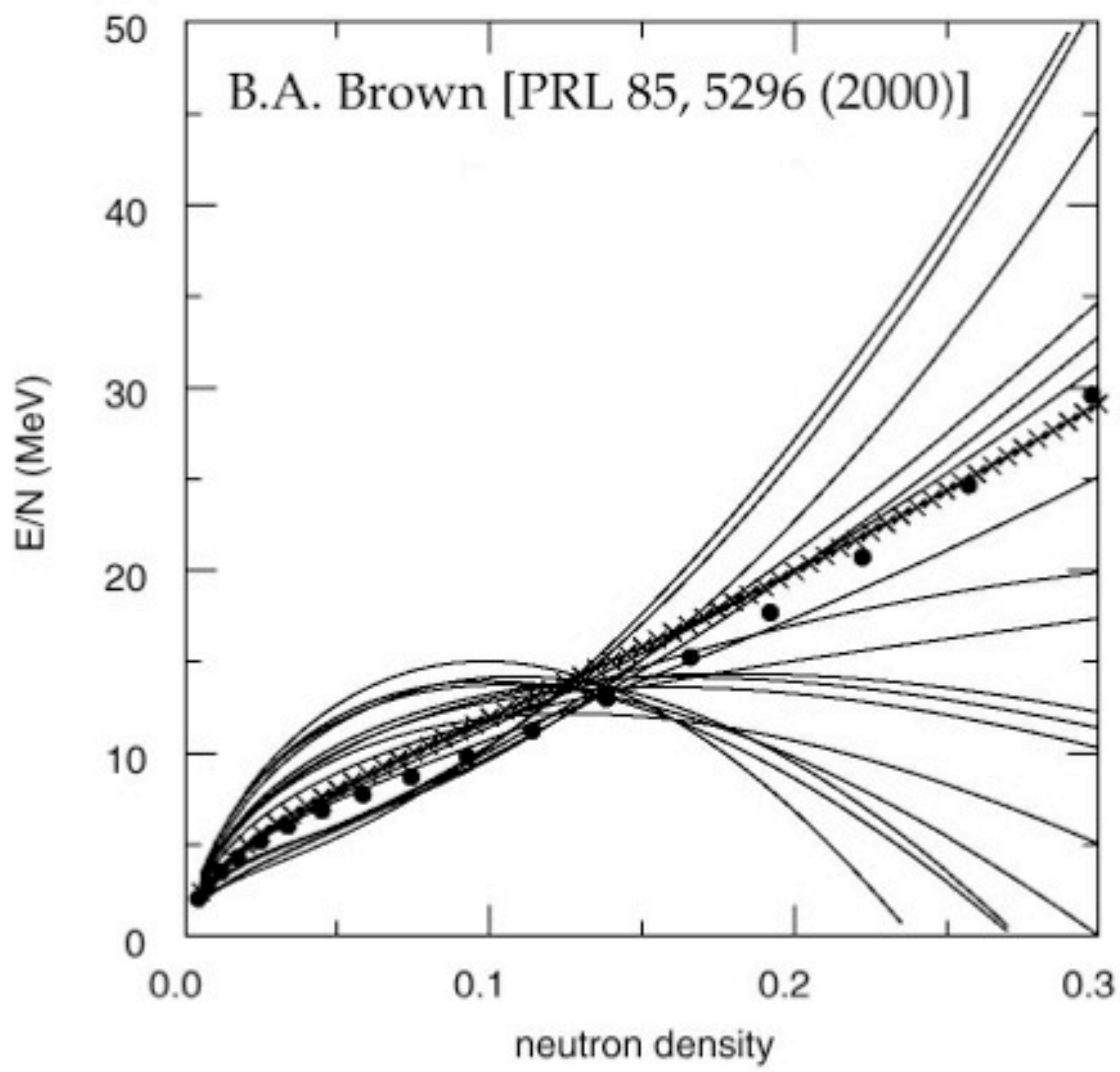
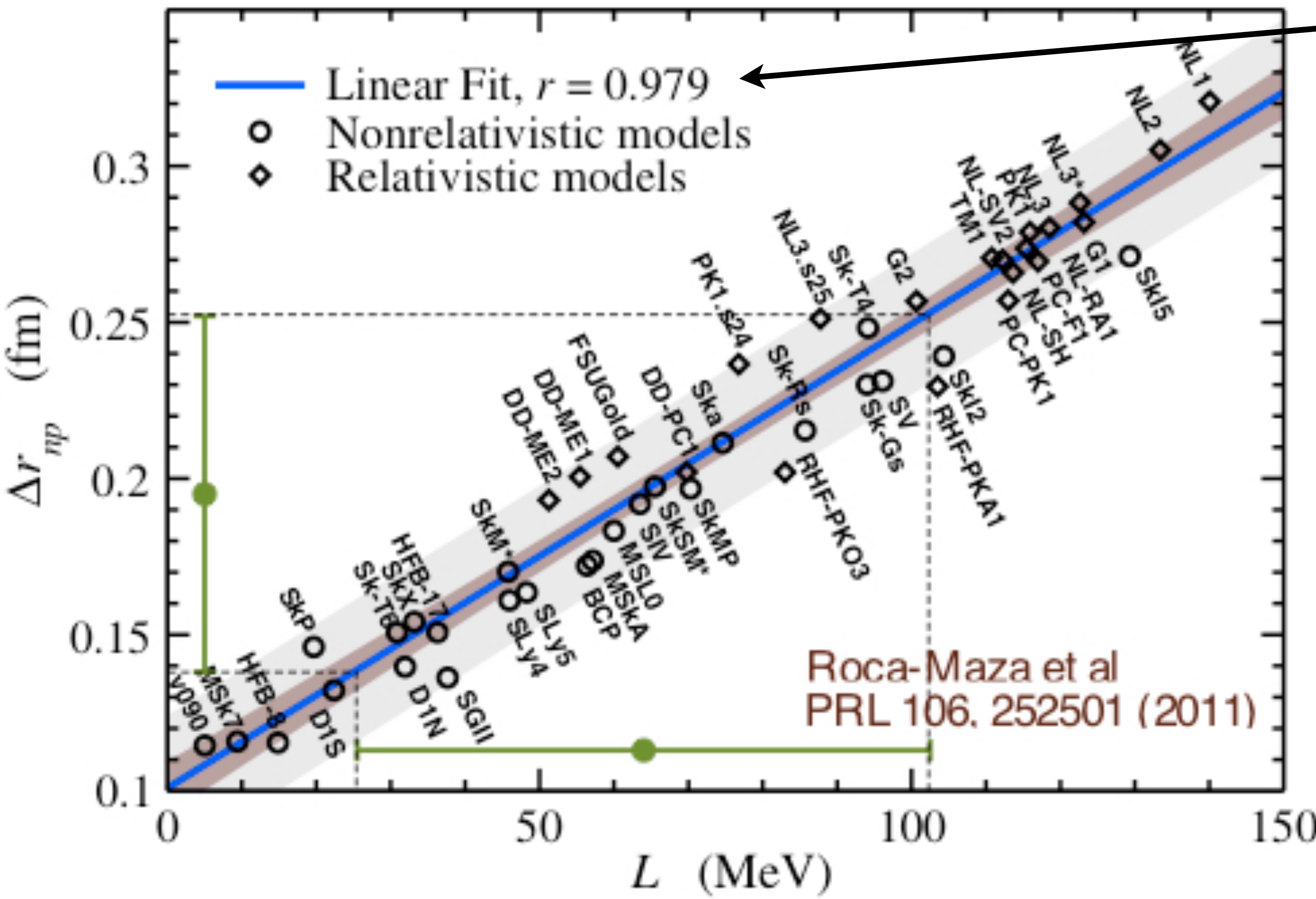


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

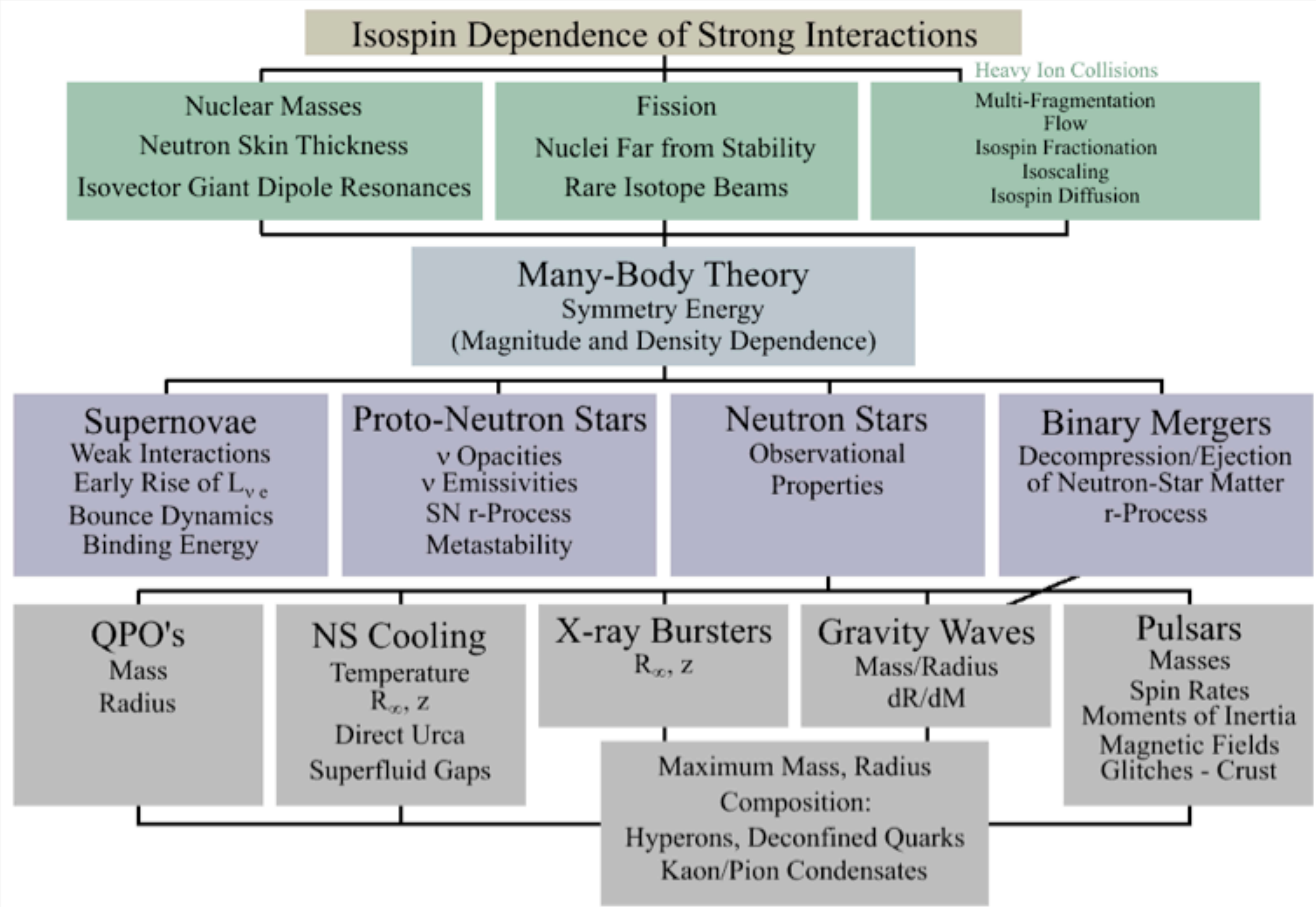
Symmetry Energy

Mean-Field predictions show a clear correlation between neutron skin of a medium and heavy nucleus and the density slope of the symmetry energy.

Measure of correlation strength



There are many correlations...



Steiner, Prakash, Lattimer, and Ellis (2005)

Steiner CREX Workshop

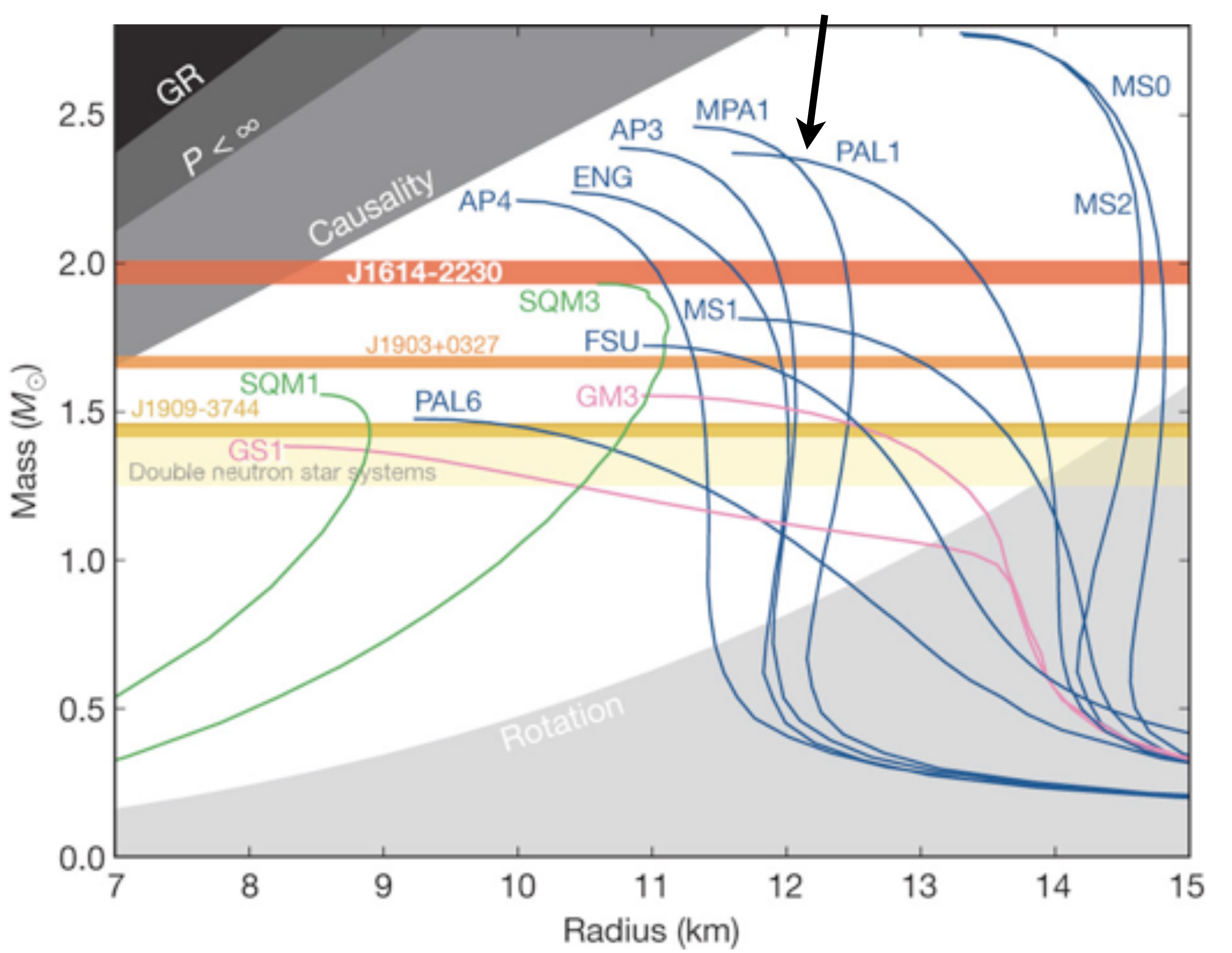
Neutron Stars

Strong analogy to nuclei: Symmetry pressure pushes against **gravity**

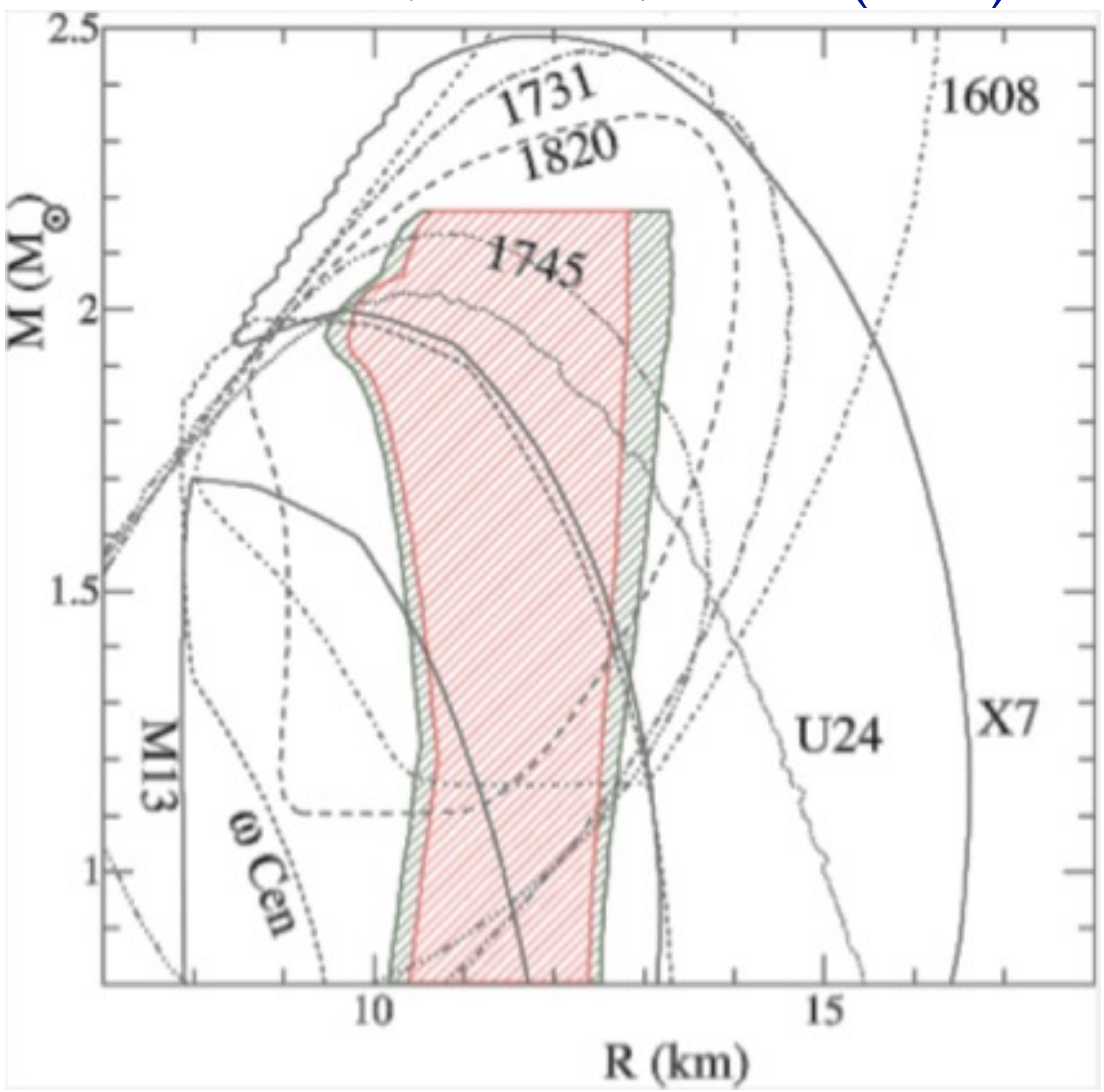
8 accreting neutron stars
in globular clusters

- All neutron star radii between 10.4 and 12.9 km
- Suggests $R_n(^{208}Pb) < 0.2$ fm

curves parametrized by density



Steiner, Lattimer, Brown (2013)



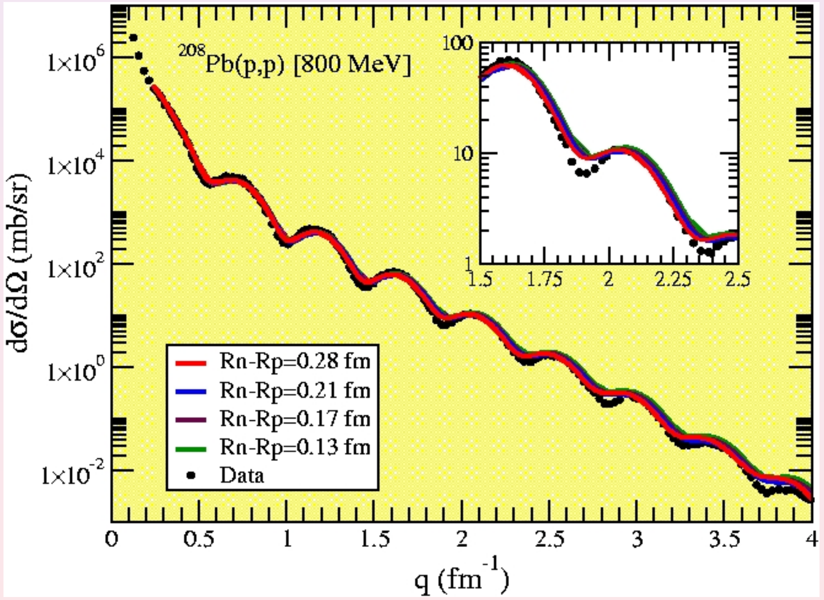
Short Lived Isotopes

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!



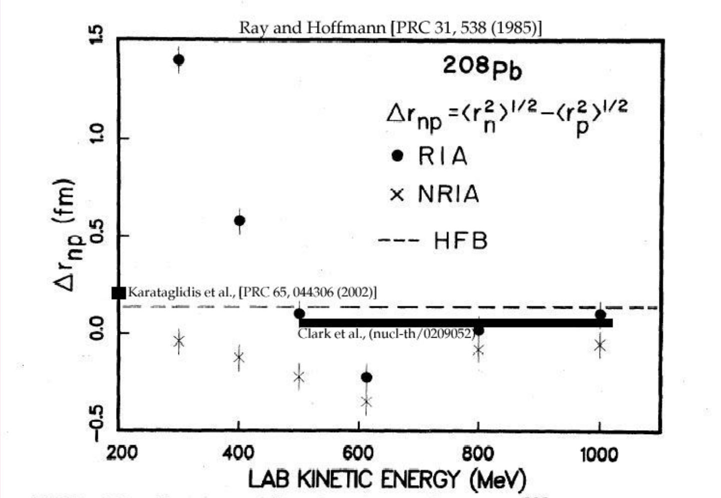
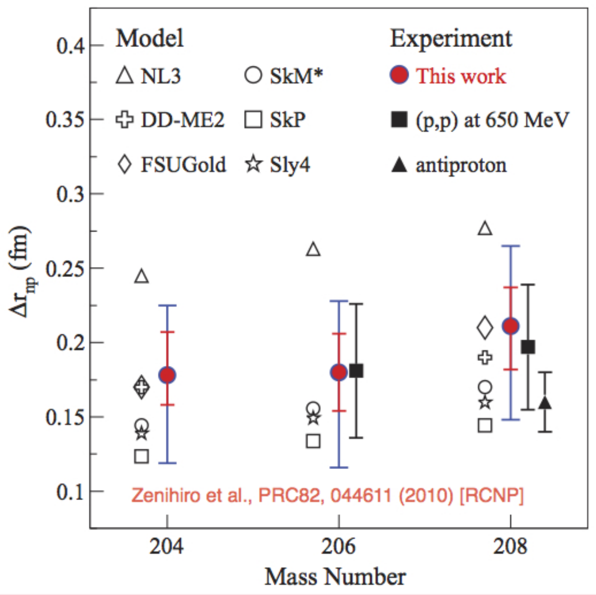
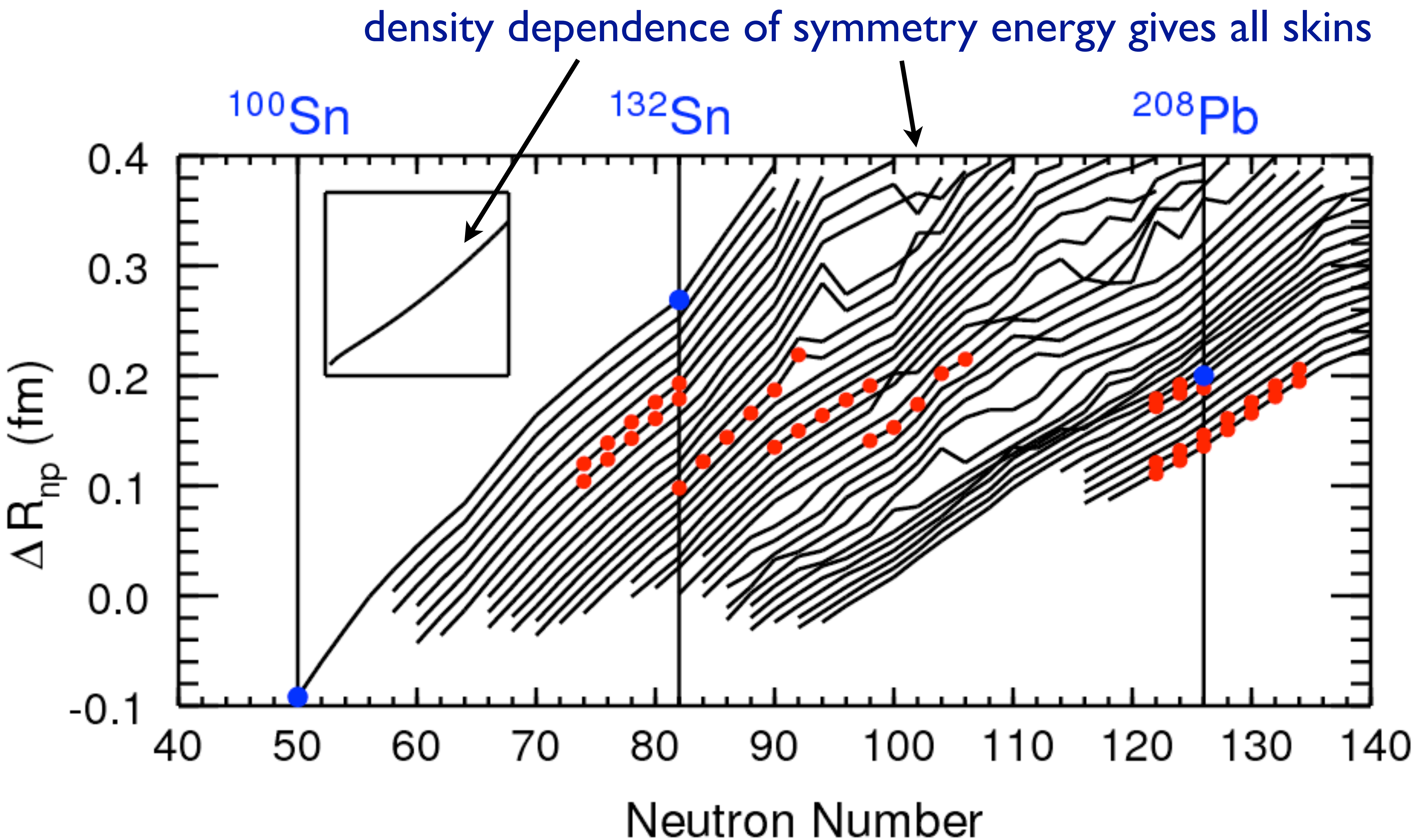


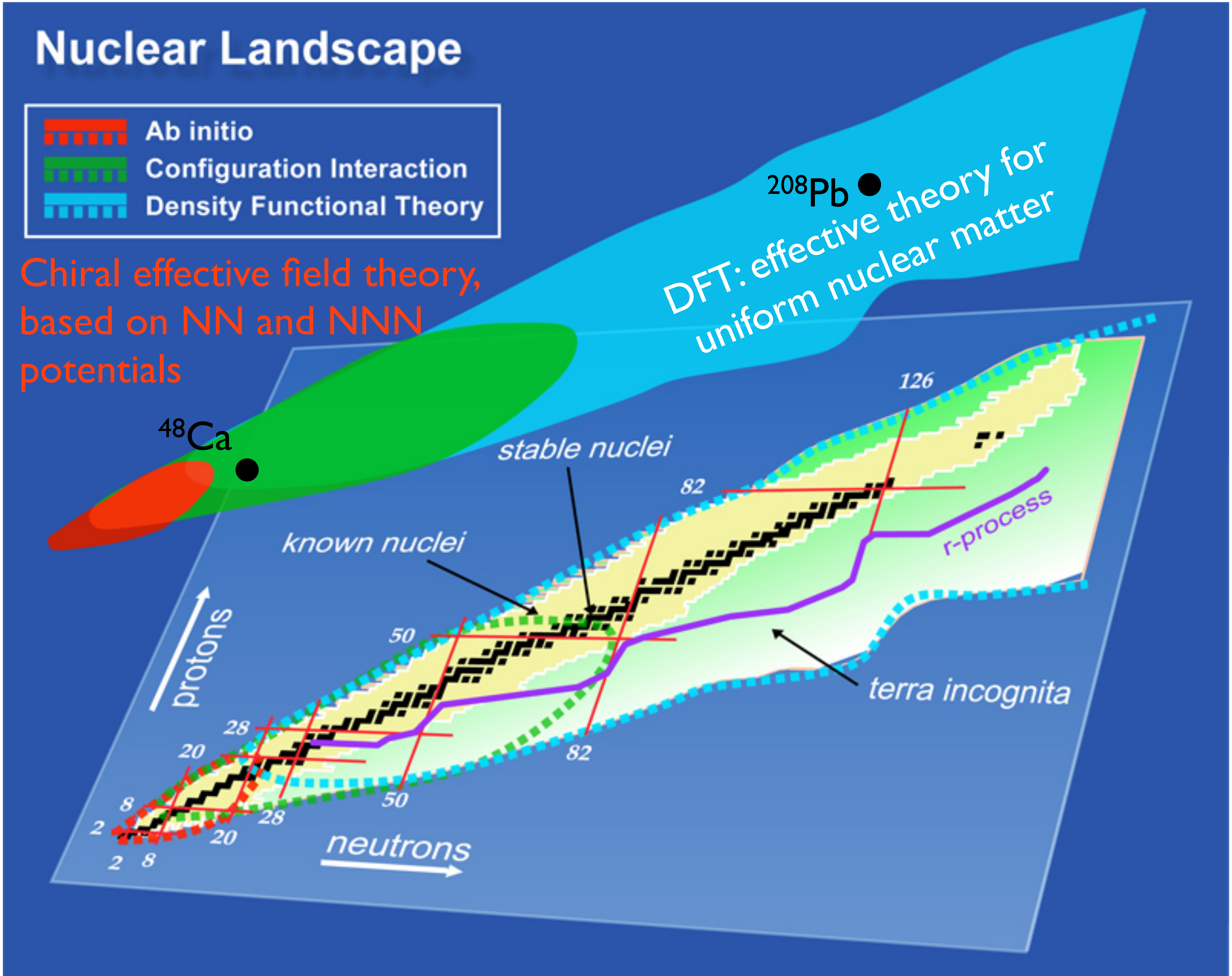
FIG. 10. Same as Fig. 8 except that the ^{208}Pb results are shown. The theoretical value of 0.13 fm (Ref. 39) is indicated by the dashed line.



Atomic Parity Violation

Radius of nuclei interesting for Atomic Parity Violation track the Pb-208 radius. ~A. Brown





Nuclear Landscape
Ab initio
Configuration Interaction
Density Functional Theory
Chiral effective field theory, based on NN and NNN potentials
DFT: effective theory for uniform nuclear matter
208Pb
48Ca
stable nuclei
known nuclei
terra incognita
r-process
protons
neutrons
126
82
50
28
20
8
2

Covariance analysis and correlations

Within any particular DFT model

Empirical constants determined from optimization of a quality measure

$$\chi^2(\mathbf{p}) = \sum_{n-1}^{N} \left(\frac{\mathcal{O}_n^{(\mathrm{th})}(\mathbf{p}) - \mathcal{O}_n^{(\mathrm{exp})}}{\Delta \mathcal{O}_n} \right)^2$$

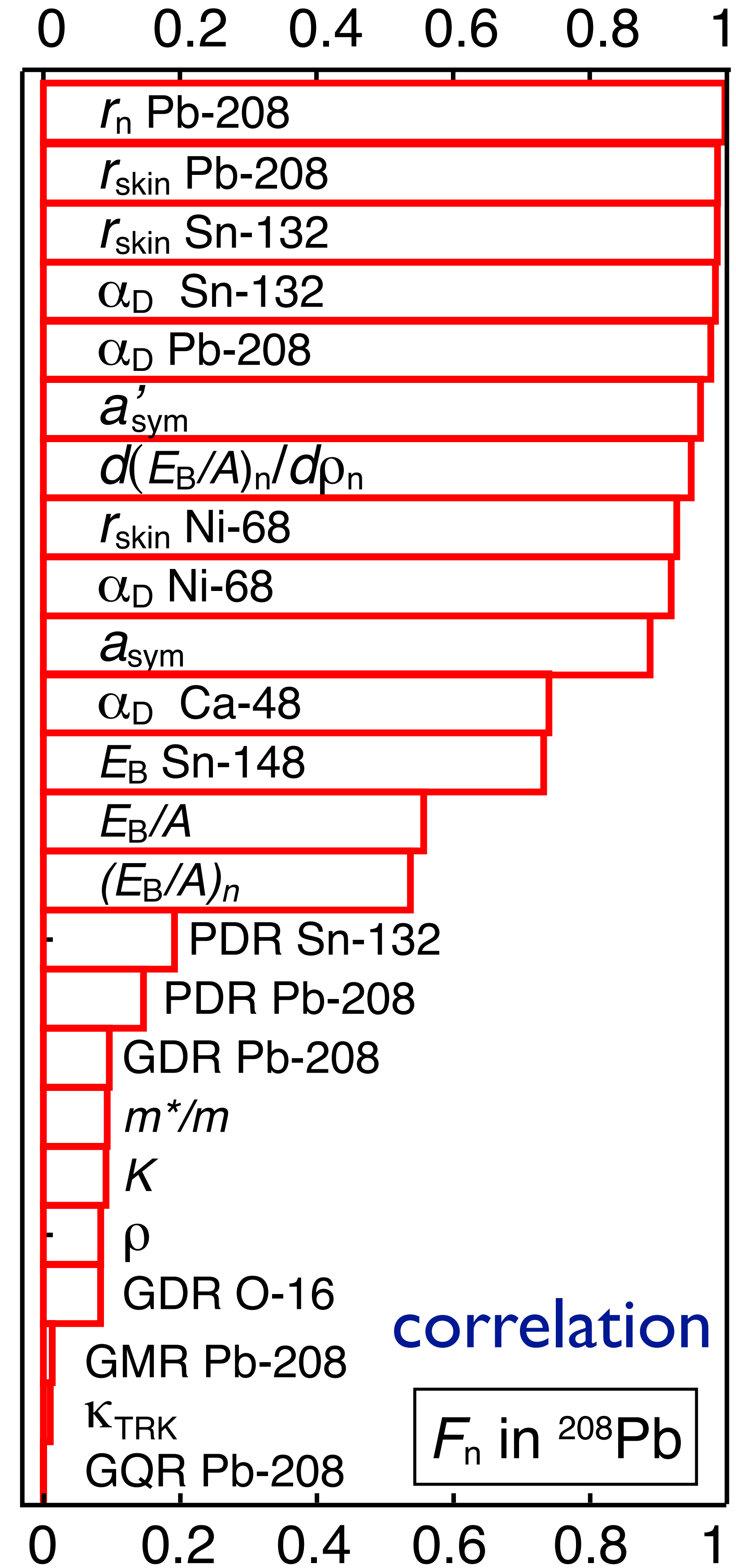
correlation coefficient between two observables

$$\rho(A, B) = \frac{\mathrm{cov}(A, B)}{\sqrt{\mathrm{var}(A)\mathrm{var}(B)}},$$

where $$\mathrm{cov}(A, B) = \sum_{i,j=1}^{F} \frac{\partial A}{\partial x_i} (\hat{\mathcal{M}}^{-1})_{ij} \frac{\partial B}{\partial x_j}$$

and $$\mathcal{M}_{ij} = \frac{1}{2} \left(\frac{\partial \chi^2}{\partial x_i \partial x_j} \right)_{x=0}$$

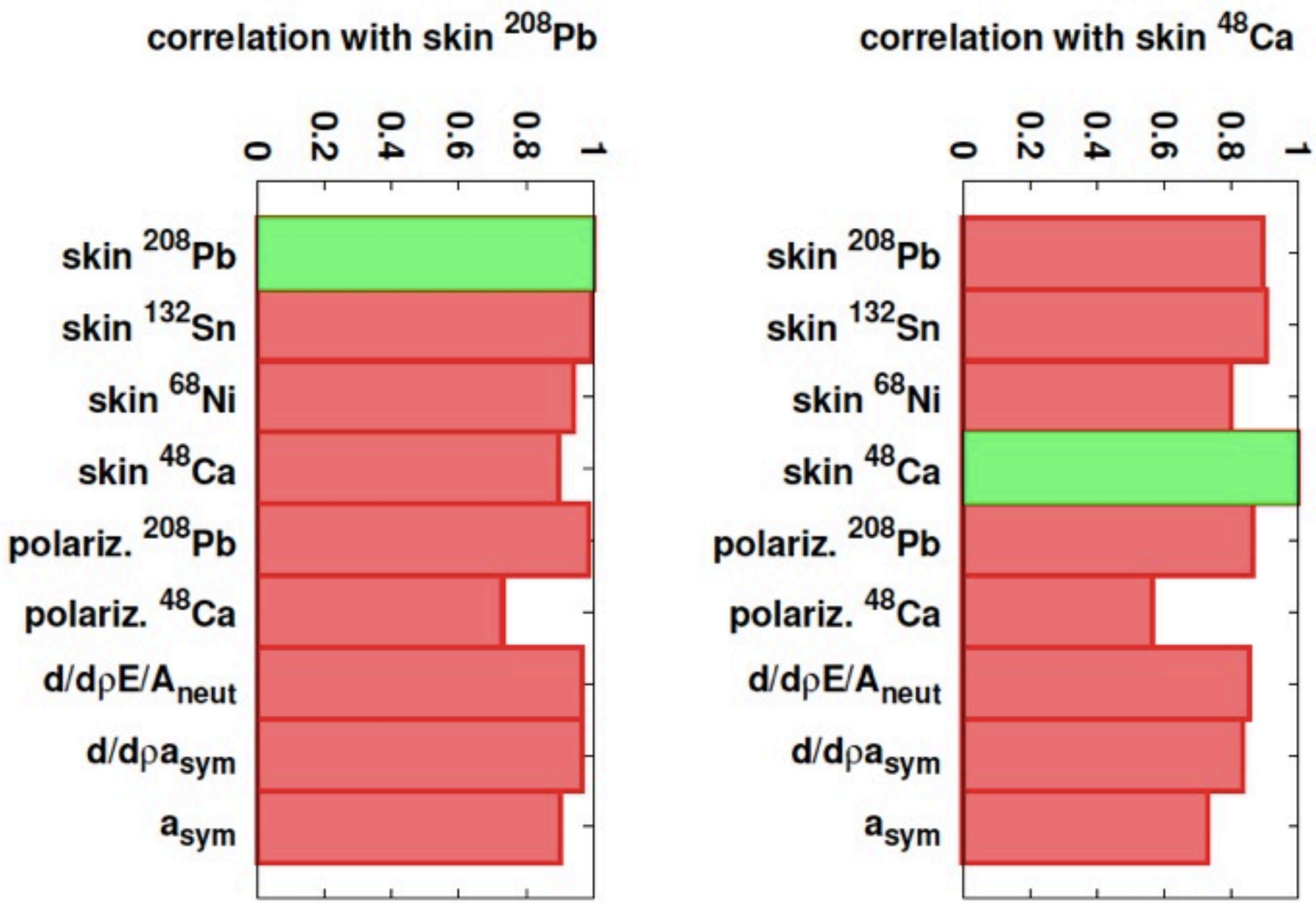
"least biased approach to uncover correlations"
"determine the required accuracy of laboratory experiments"
~Jorge Piekarewicz



Experimental Observables

There are relatively few "isovector" observables (distinguish between neutrons and protons)

Dominated by dipole polarizability and direct measurements of the weak form factor using parity violation

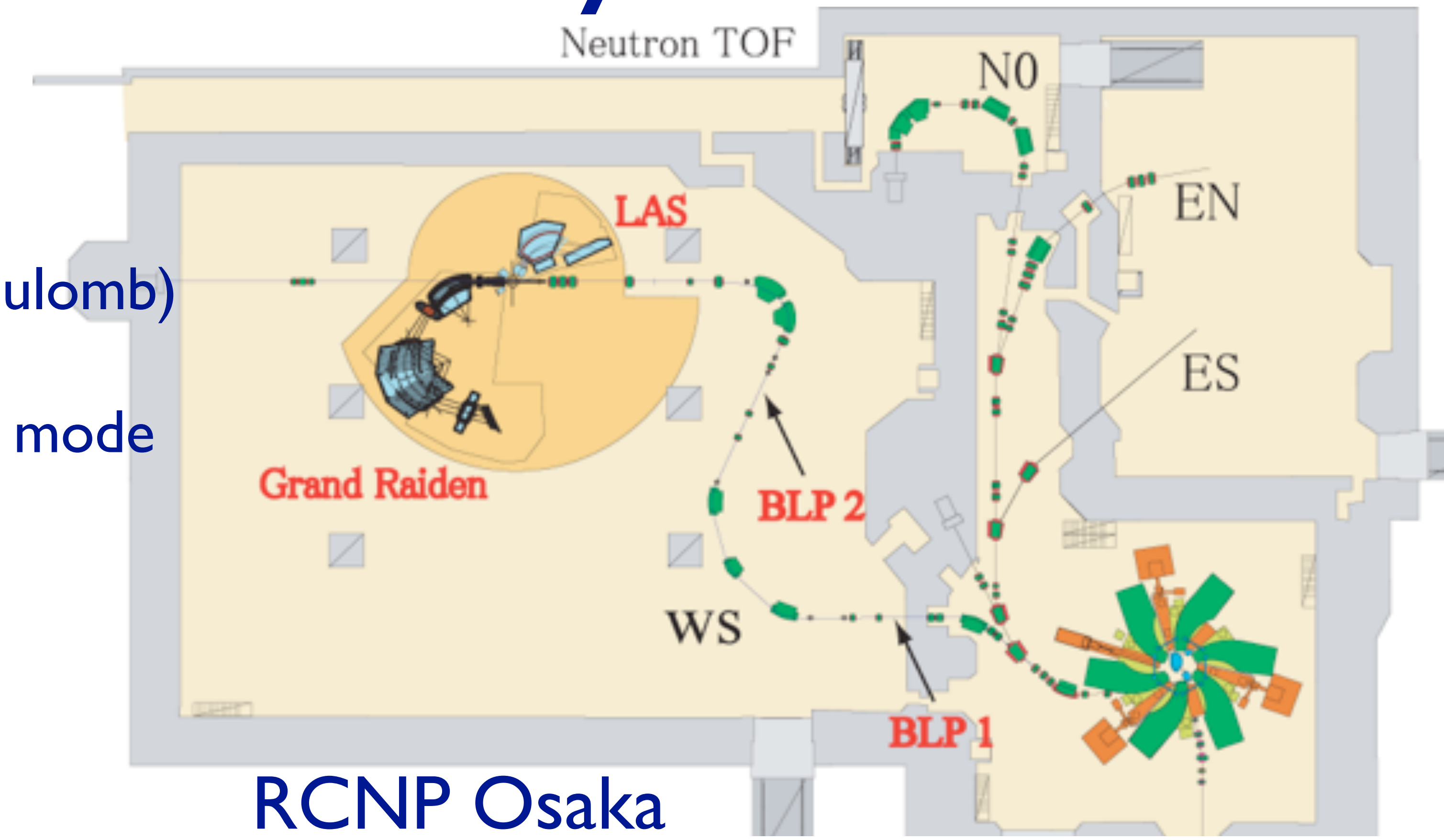


Dipole Polarizability α_D

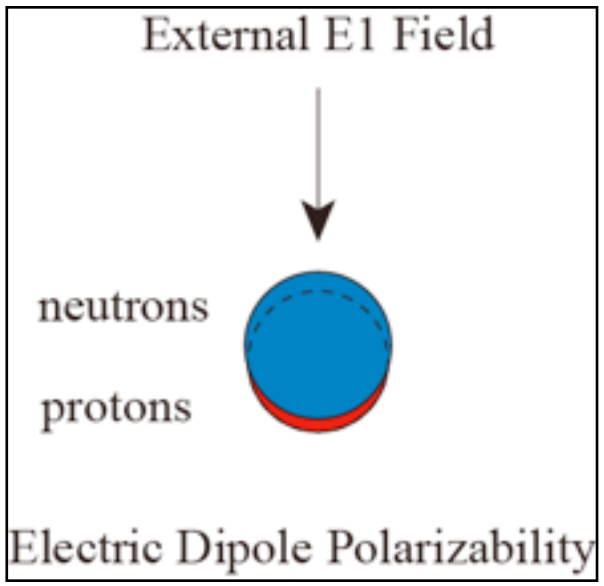
Polarized proton inelastic scattering

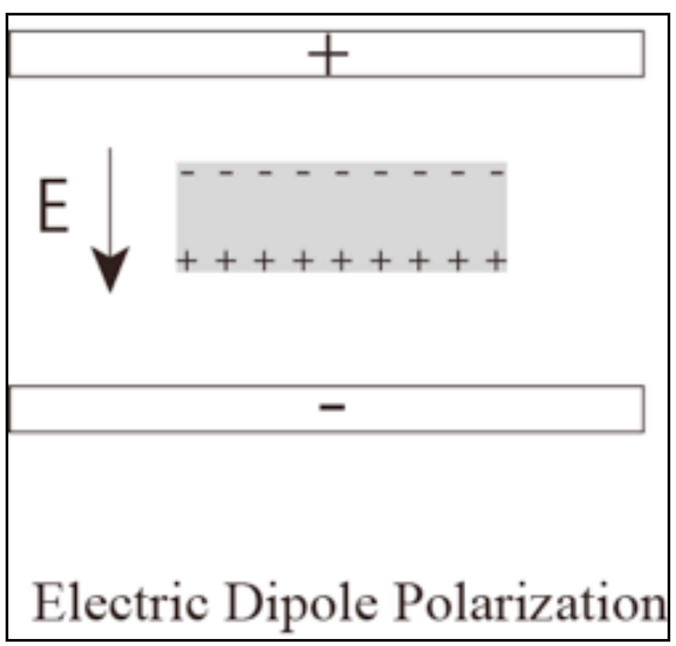
Integrate the electric dipole (E1) response of Pb-208 at very small angles < 2.5° (purely Coulomb)

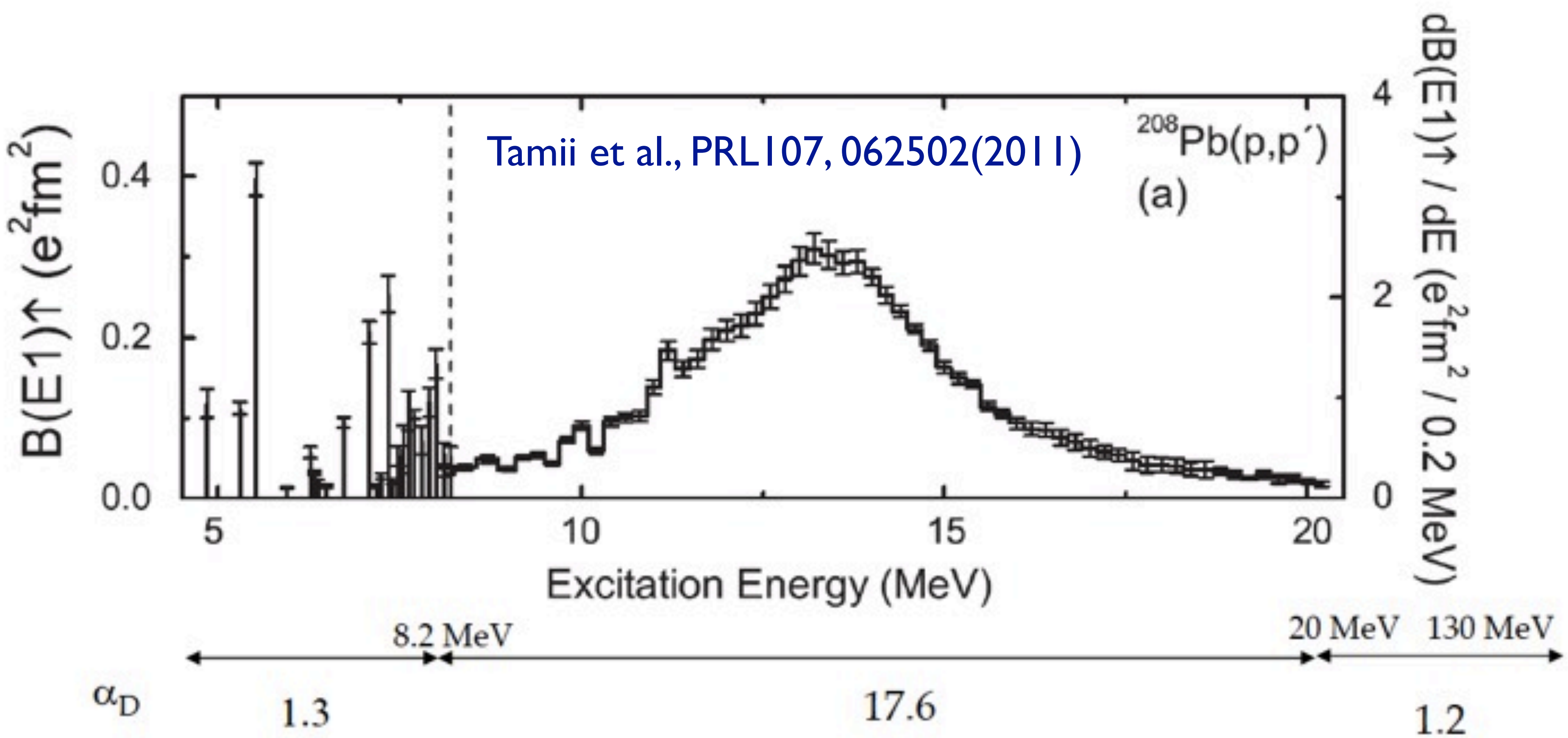
Electromagnetic probe, independent of decay mode



RCNP Osaka







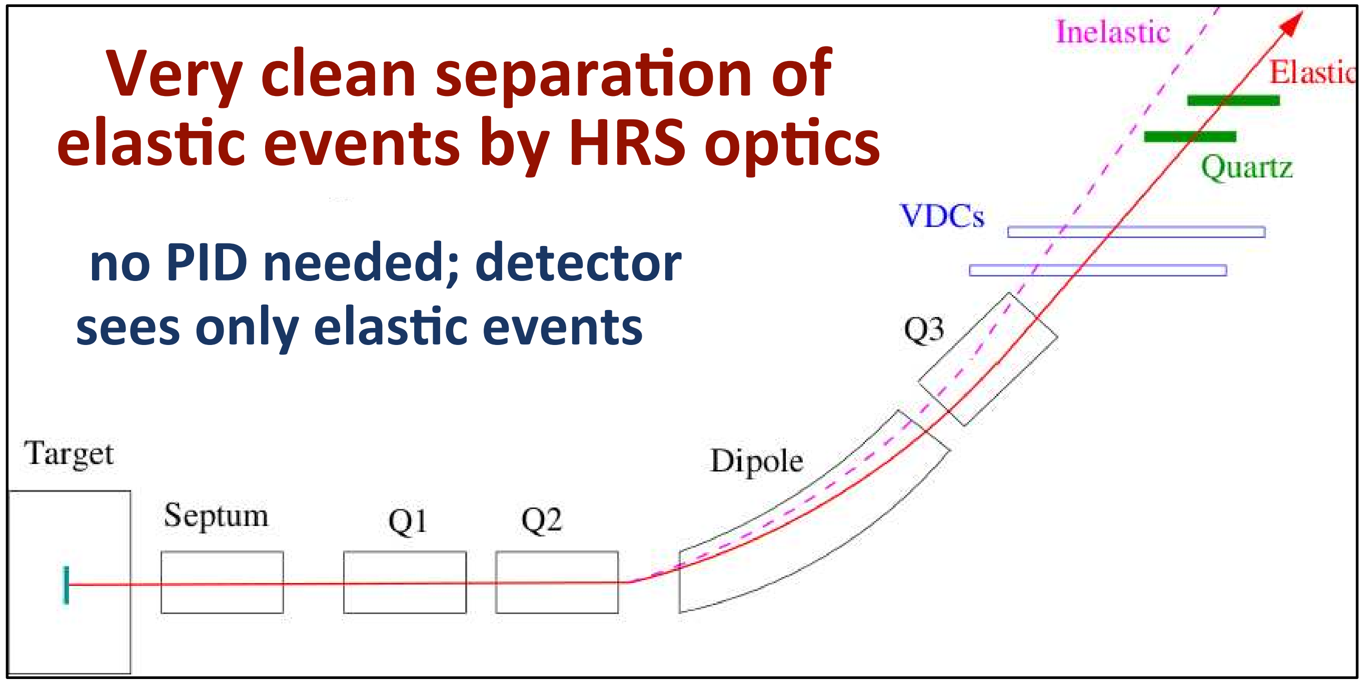
PREX Experiment

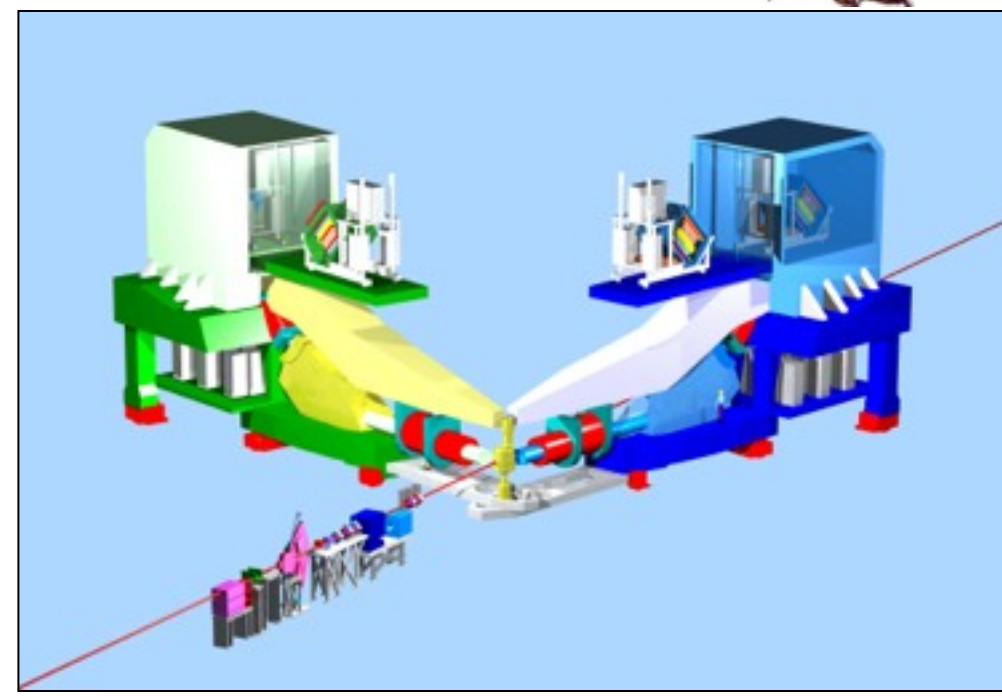
$Q^2 \sim 0.01\ GeV^2$ ⇨ **$A_{PV} \sim 0.6$ ppm**

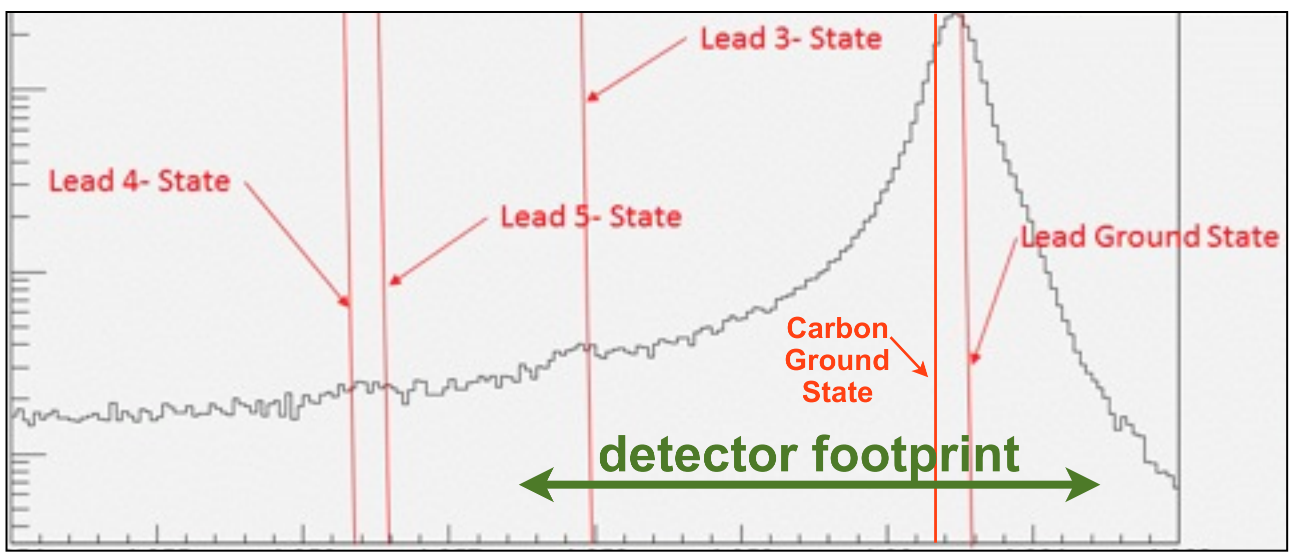
5^o scattering angle **Rate ~1.5 GHz**

Very clean separation of elastic events by HRS optics

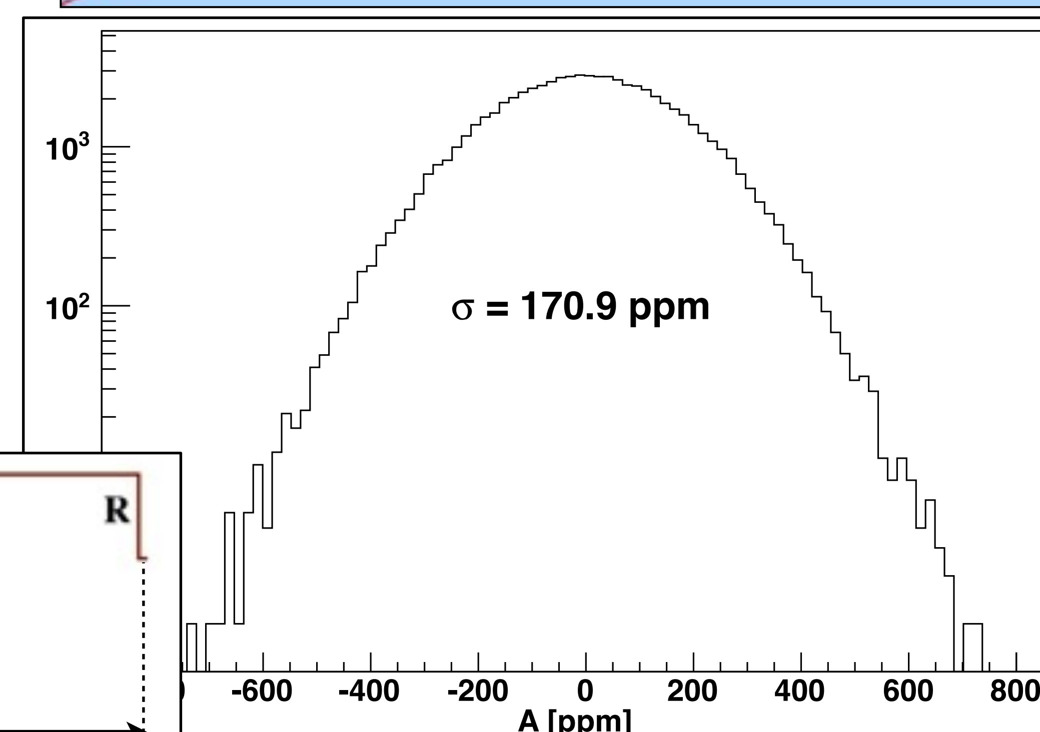
no PID needed; detector sees only elastic events



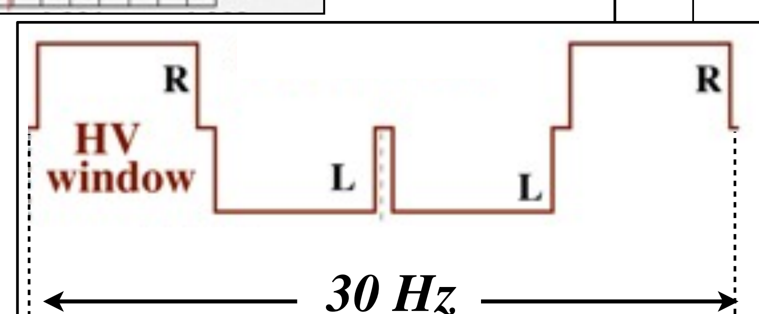




p (GeV/c)

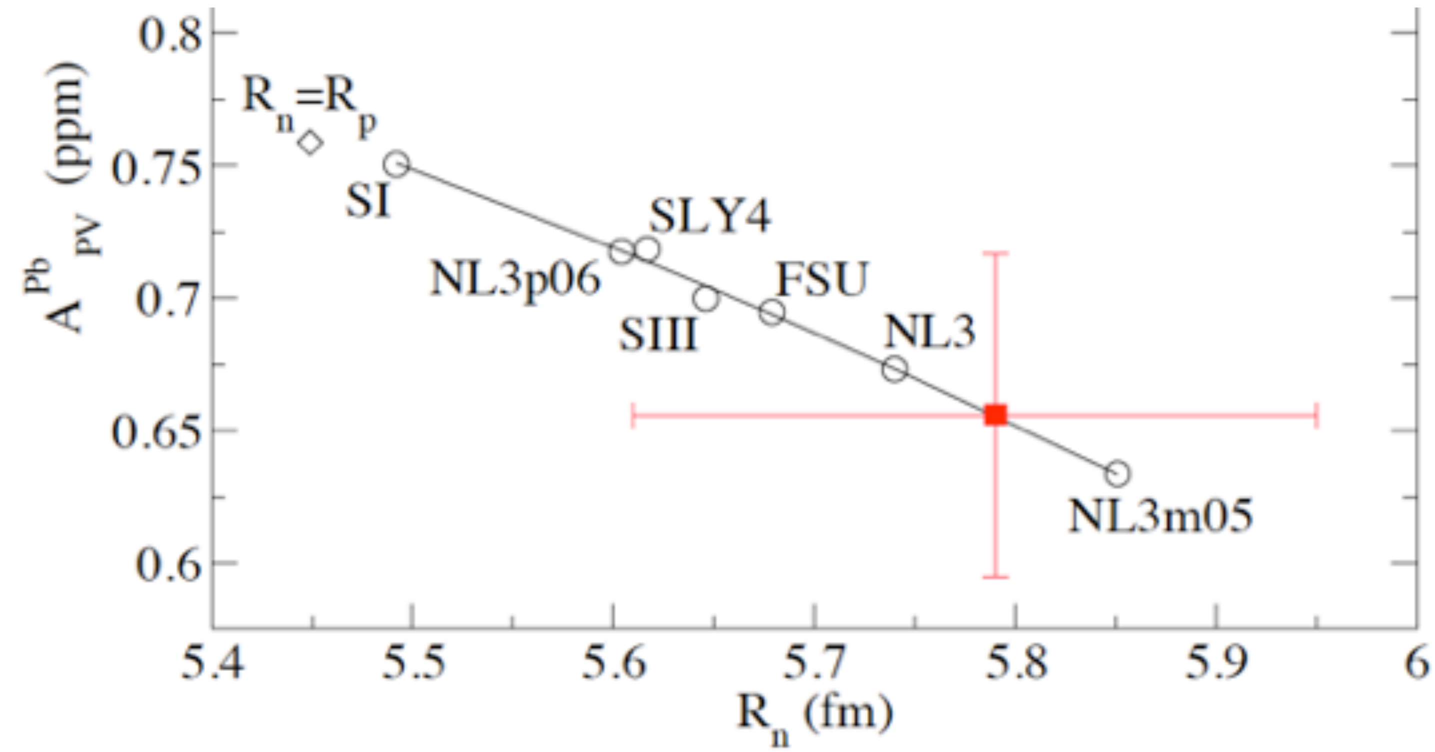


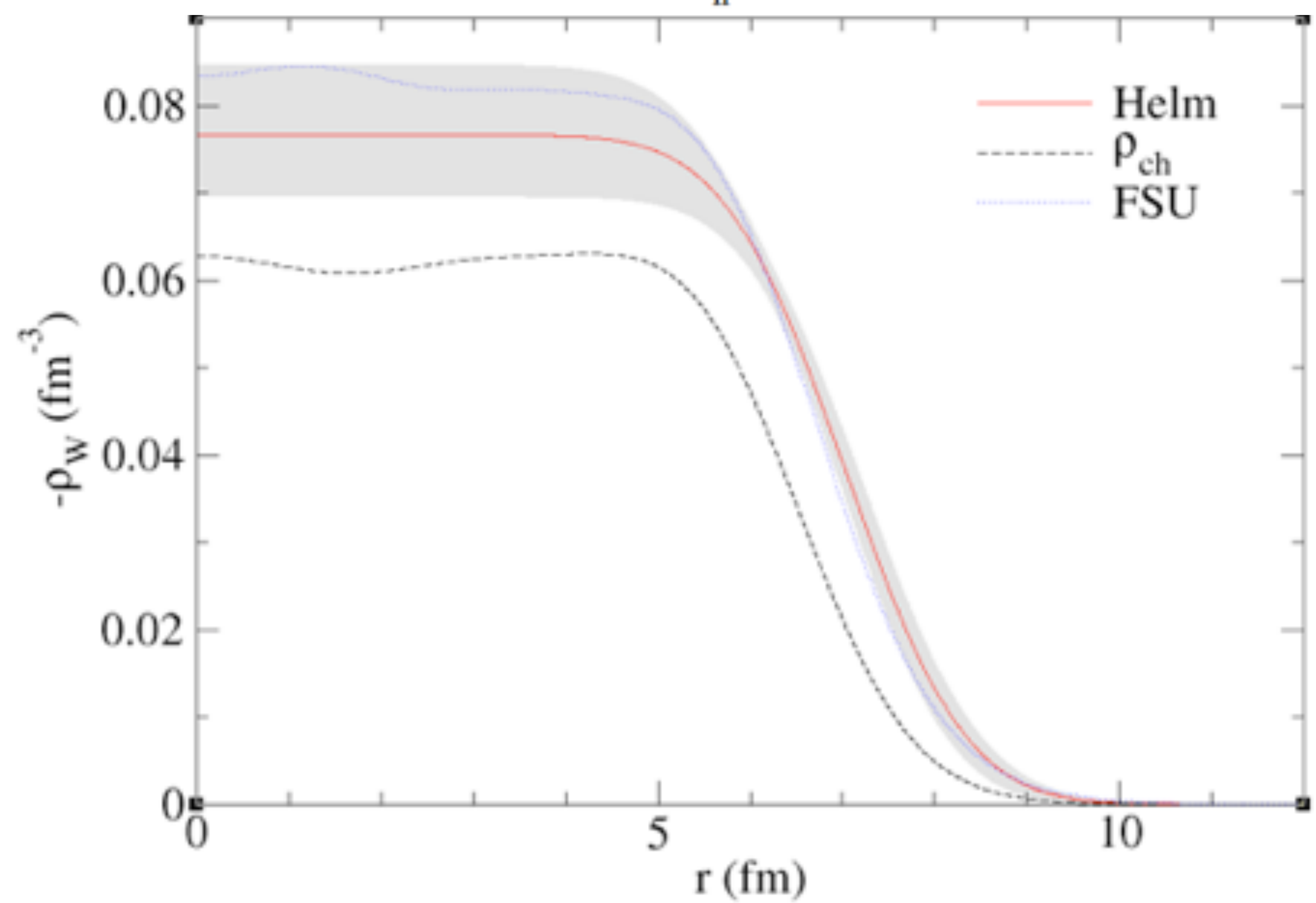
Analog integration of everything that hits the detector



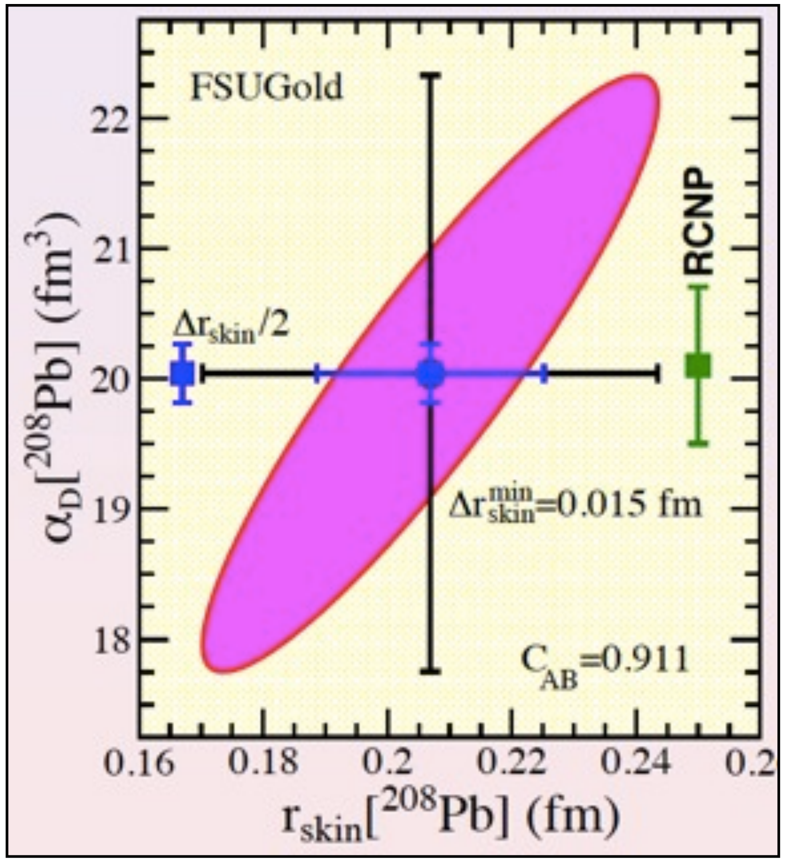
PREX I Result

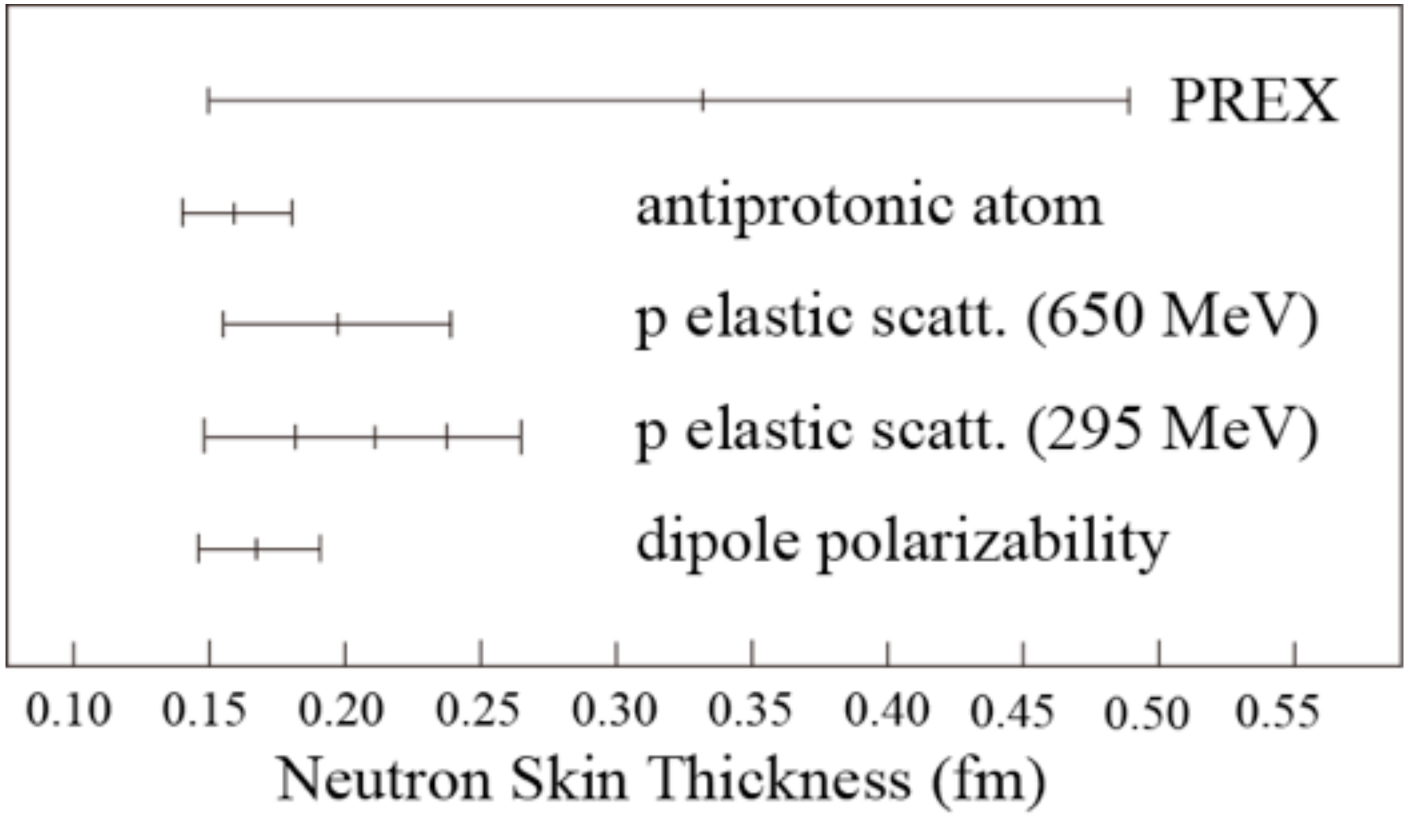
- $A_{PV} = 0.657 \pm 0.060(\text{stat}) \pm 0.014(\text{sym})$ ppm
- Weak form factor at q=0.475 fm^{-1}: $F_W(q) = 0.204 \pm 0.028$
- First observation that weak charge density more extended than (E+M) charge density --> weak skin.
- Unfold nucleon ff--> neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- Phys Rev Let. 108, 112502 (2012), Phys. Rev. C 85, 032501(R) (2012)

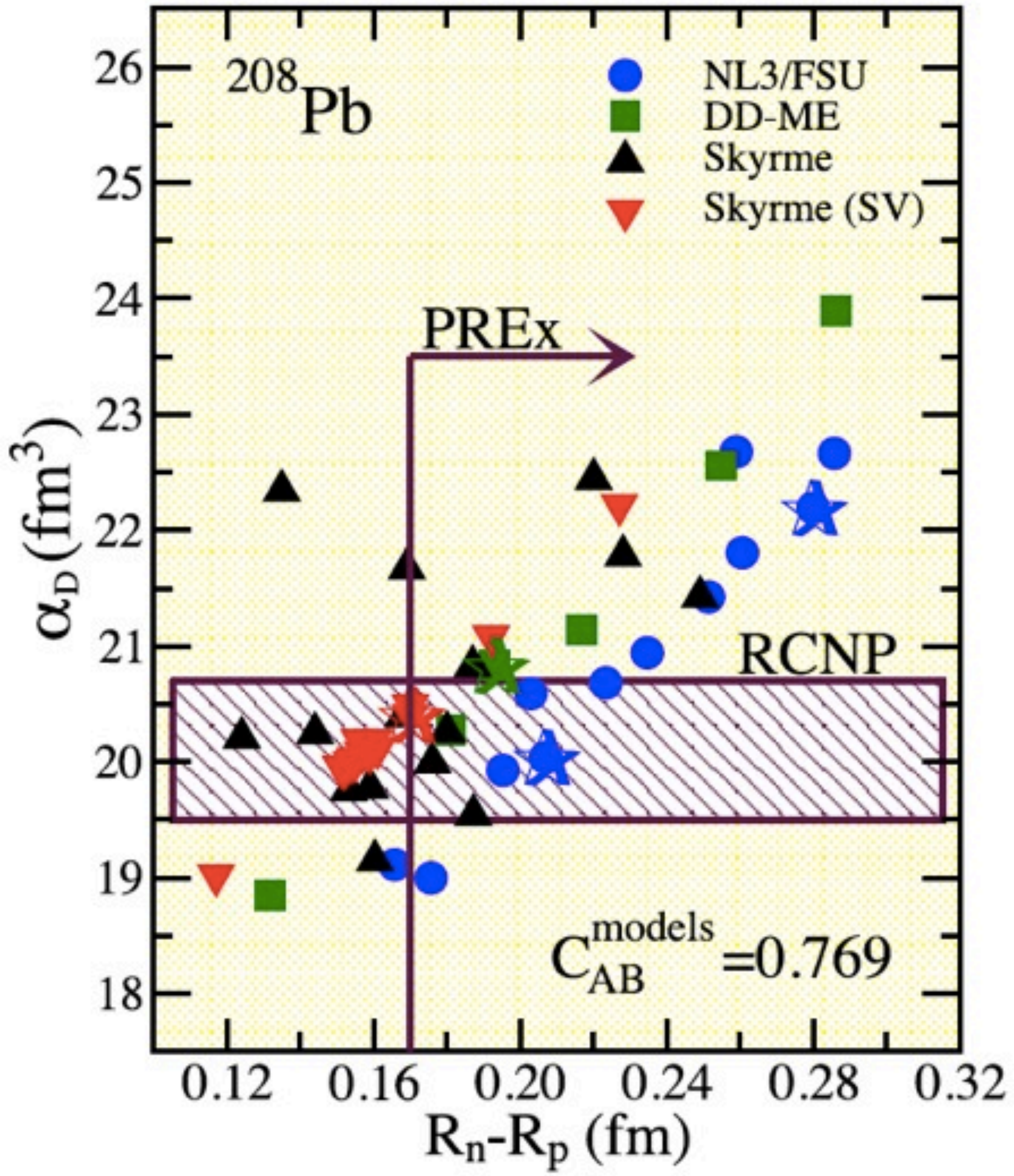




α_D complimentary to neutron skin





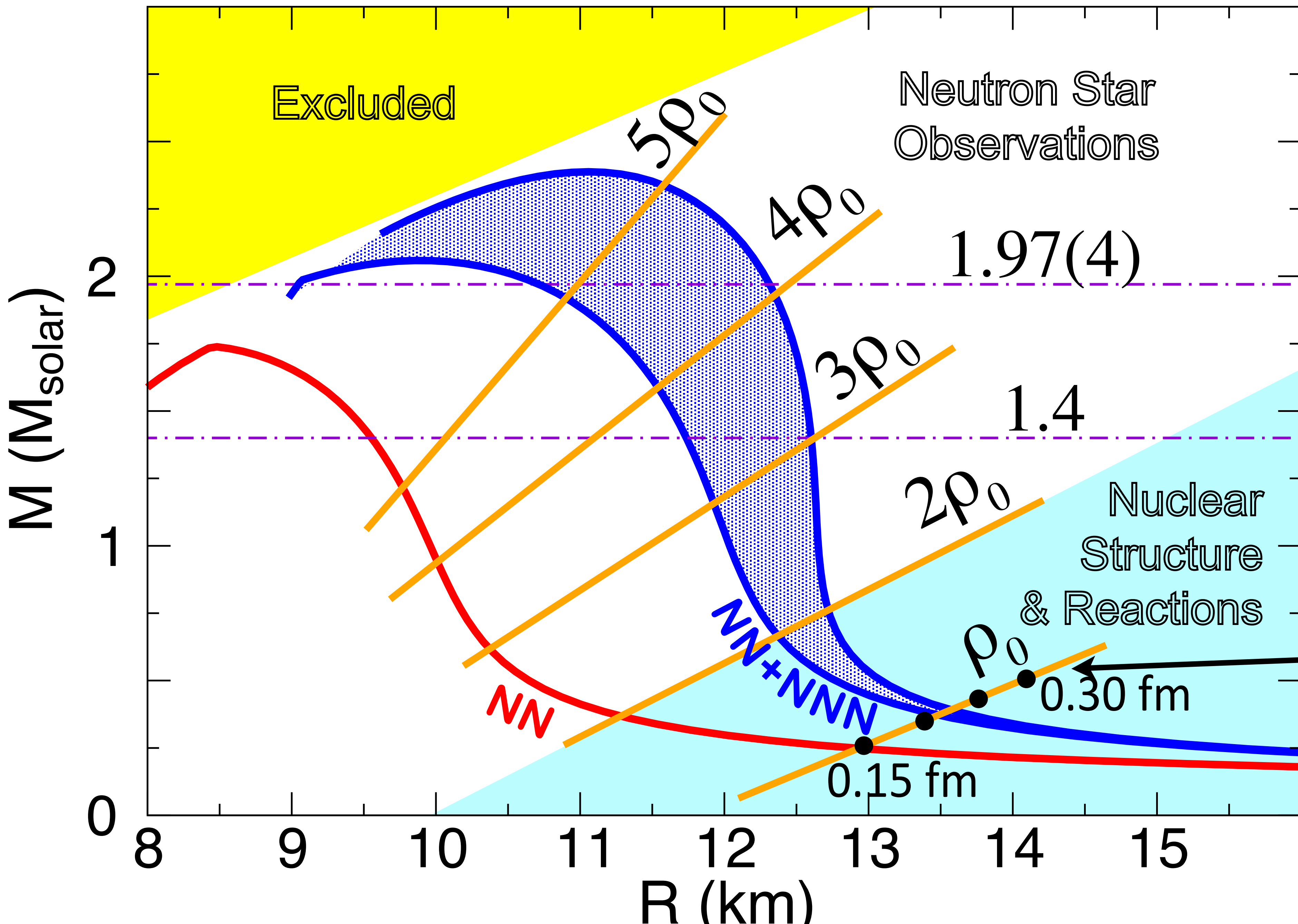


Correlations used to extract neutron skin from polarizability

Neutron Stars

Illustration of PREX impact on neutron star observables.

Potential phase changes disrupt this argument



Current PREX central value inconsistent with measured neutron star properties.

PREX: Successes and Trials

What Worked:

New Septum
We now know how to tune it to optimize FOM

A_T false asymmetry
A_T is small (<1 ppm Pb, <10 ppm C)
and A_{false} will be small if P_T is minimized

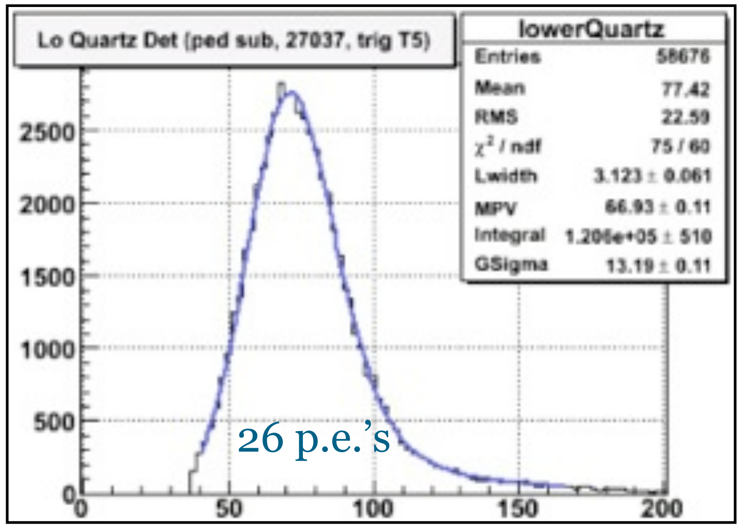
HRS Tune
We have a tune and good first-guess optics matrix for a tune optimized for the small detectors

Fast Helicity Flipping
We know how to control false asymmetries and monitor performance

Lead Target
Survival > 1 wk, 15 C

Injector Spin Manipulation
Second Wein and solenoid are calibrated and used for helicity reversal. Important cancellation for systematic beam asymmetries from the polarized source.

New Detectors
Suitable energy resolution achieved for 1 GeV electrons. <5% precision loss.



Polarimetry at low energy
Moller at 1.3%, Integrating Compton at 1.2%

Beam Modulation System
Fast beam kicks cancel low frequency noise and improve precision of beam position corrections

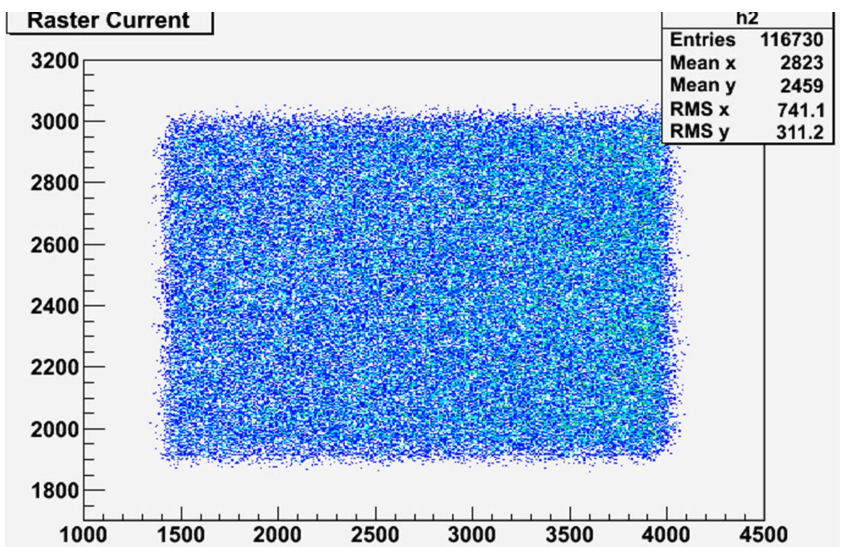
Problems to resolve:
- Lead Target
- Septum Vacuum system
- Radiation damage in Hall

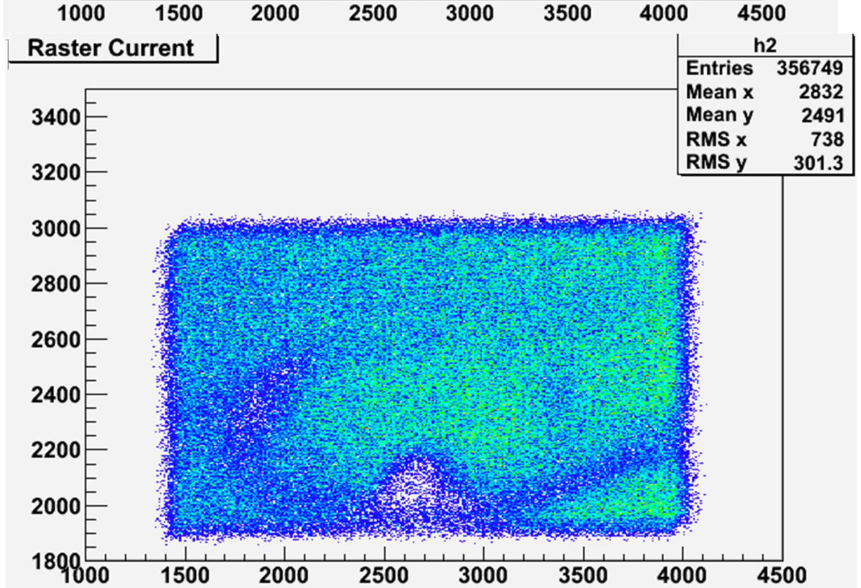
Lead / Diamond Target

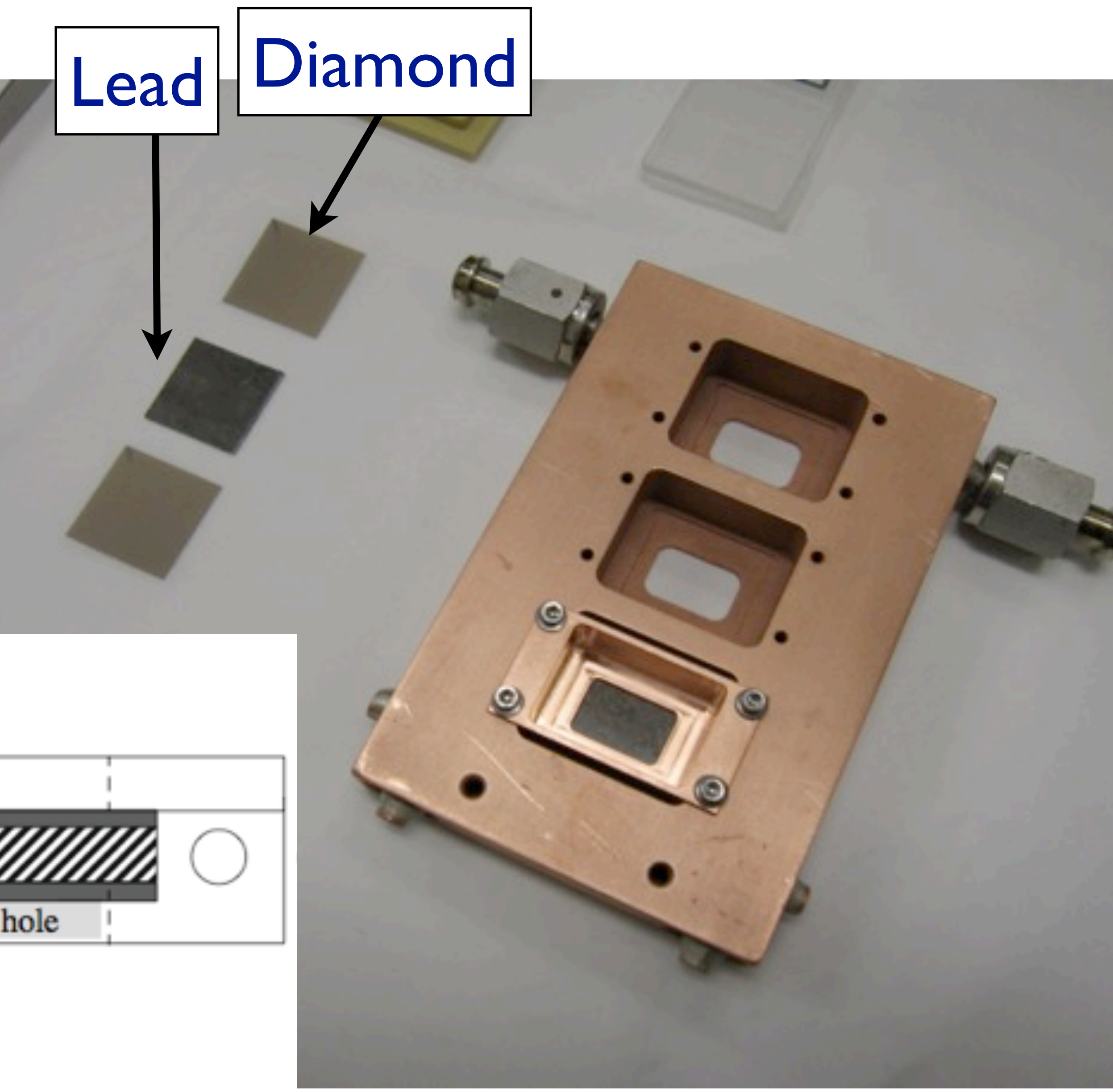
Three bays of:
Lead (0.5 mm) sandwiched by diamond (0.15 mm); Liquid He cooling (30 Watts)

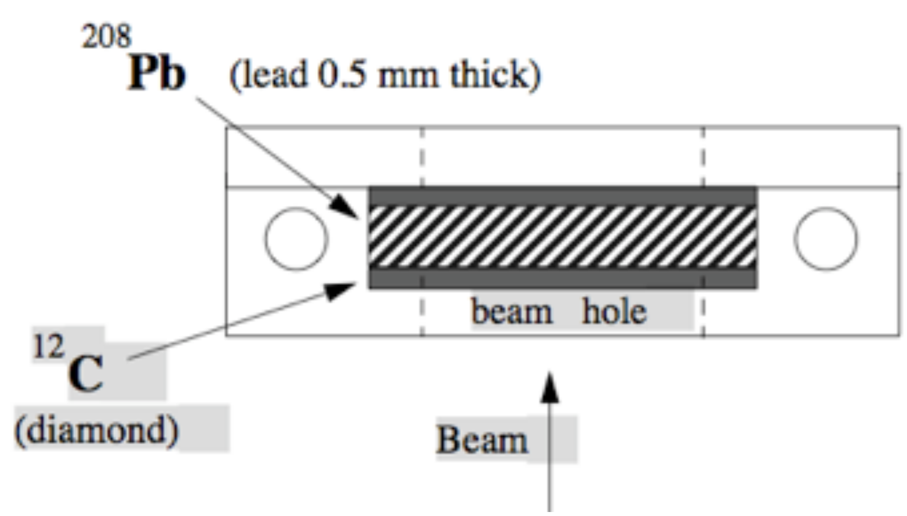
Targets damage gradually then fail dramatically after ~1-2 weeks

Solution: run with more targets



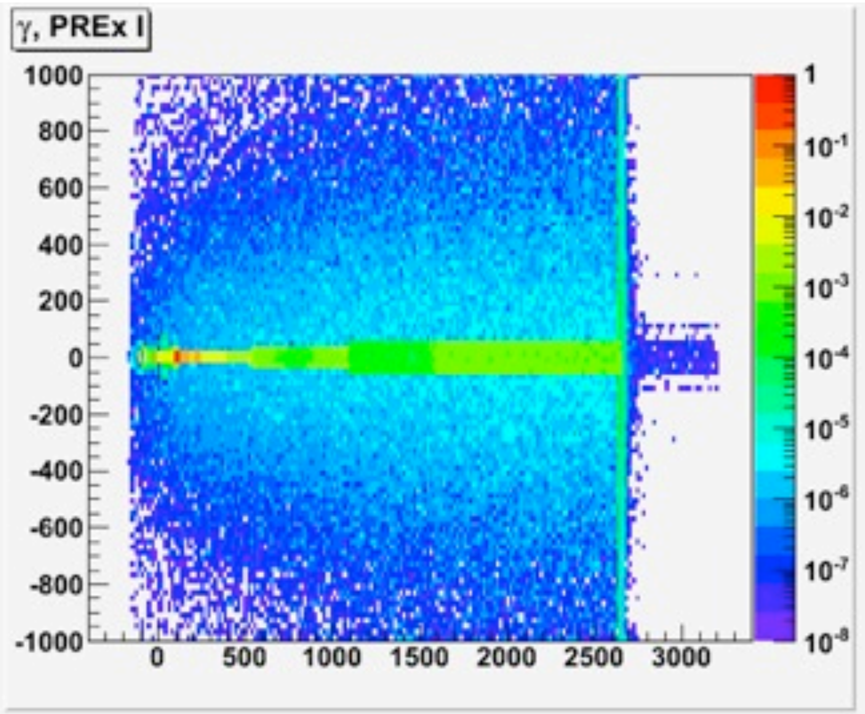


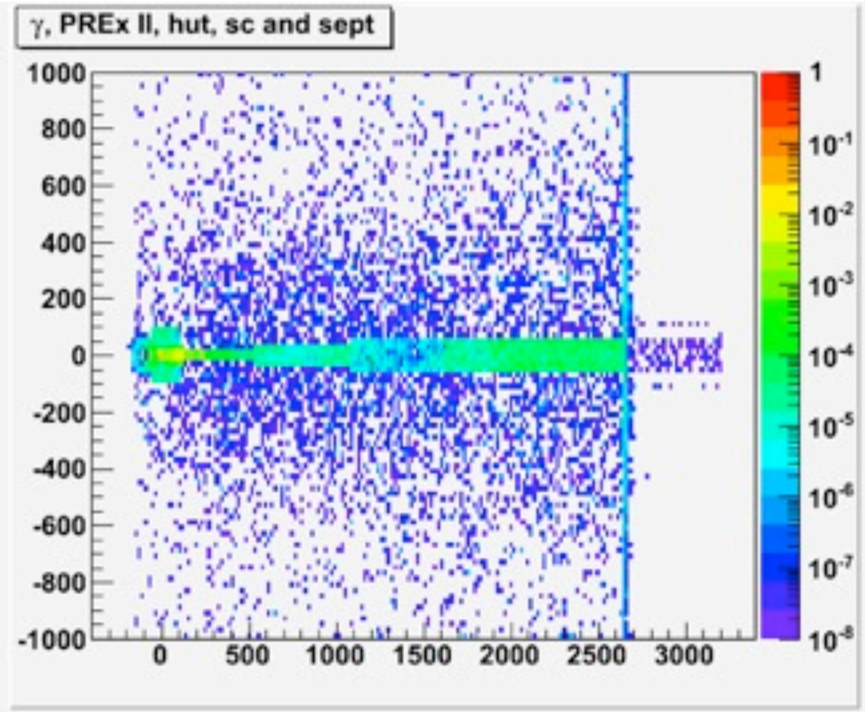




PREX II: Radiation Damage

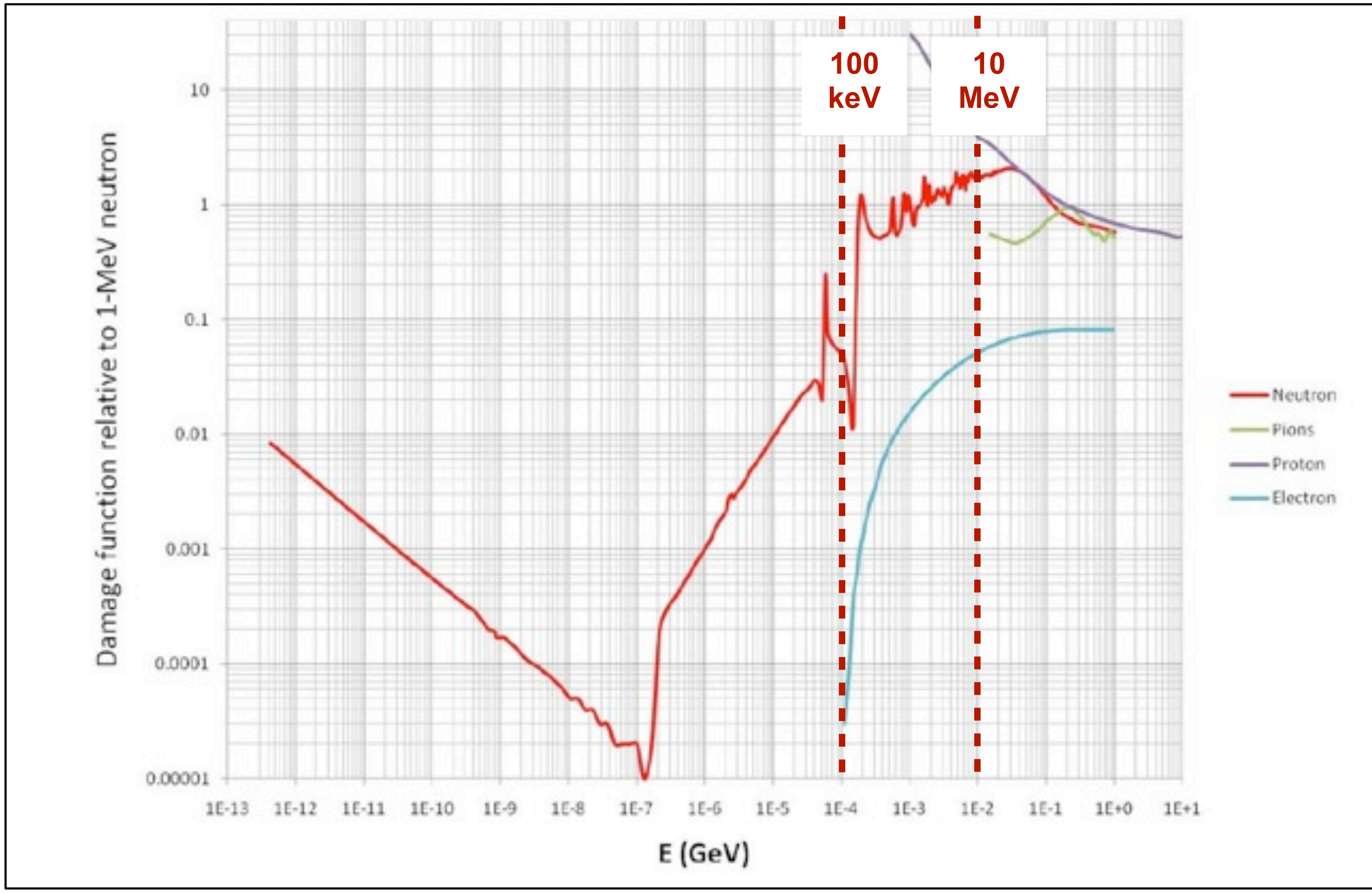
Order of magnitude decrease in neutron damage





PREX-I:
- Problem: >0.1 MeV neutrons damage electronics
- >10MeV (spallation) neutrons not significant source
-Pb elastic rate deposited EM power (and made damaging neutrons) everywhere

PREX-II:
-tighter collimation. whatever gets past the plug gets to the dump
- Polyethelene around collimator region to moderate neutrons below silicon damage range



C-REX

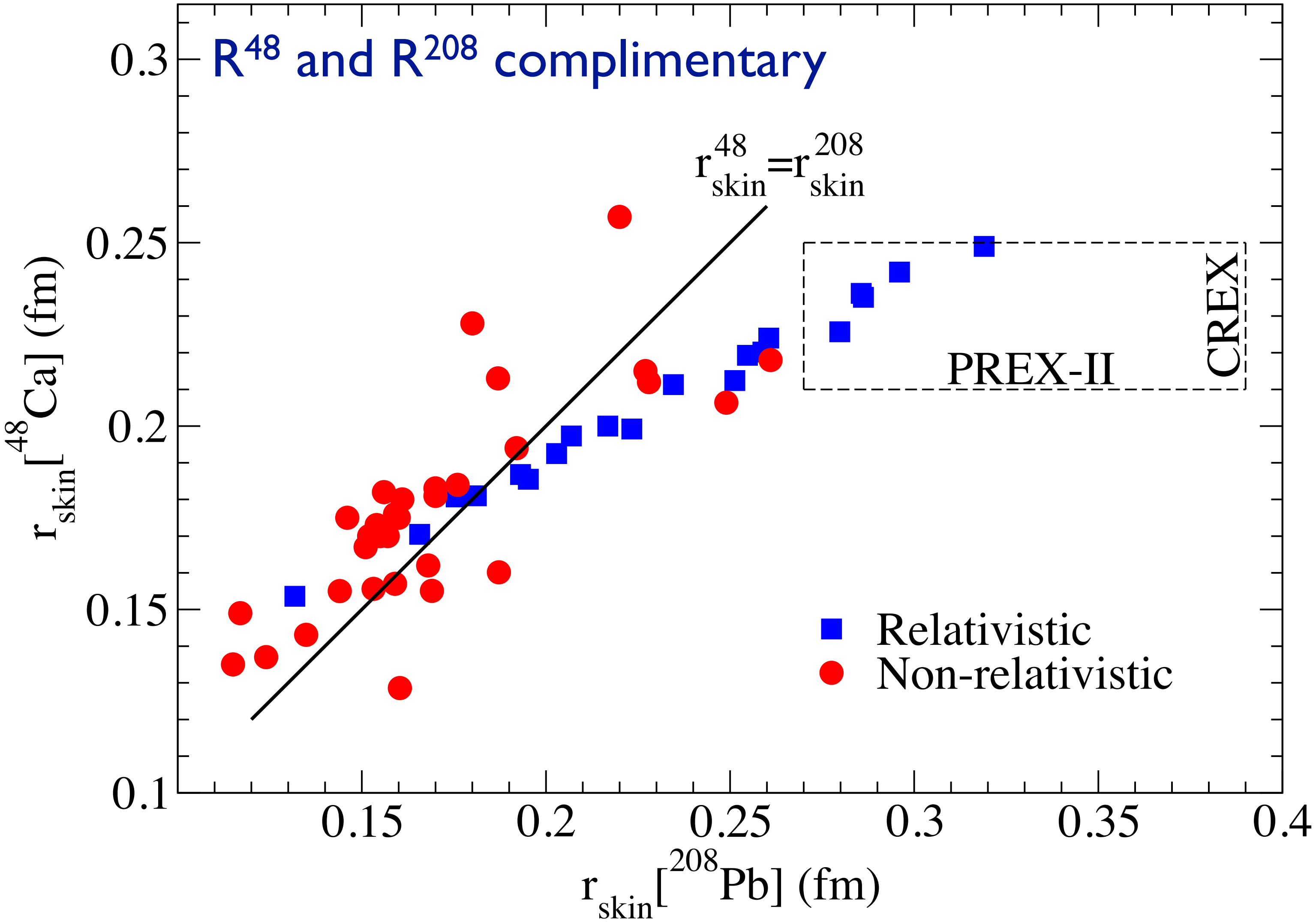
Similar in design to PREX
Different kinematics and different target design

E = 2.2 GeV and θ = 4° at 150 uA

asymmetry error of 2.4% at $q = 0.8\ fm^{-1}$
gives RMS radius Rn = 0.02 fm

^{48}Ca can be computed with ab-initio approaches and with DFT.

^{48}Ca data can provide a test of 3N forces (T=3/2 and T=1/2), which are important for the neutron matter EOS; hence, neutron star physics.



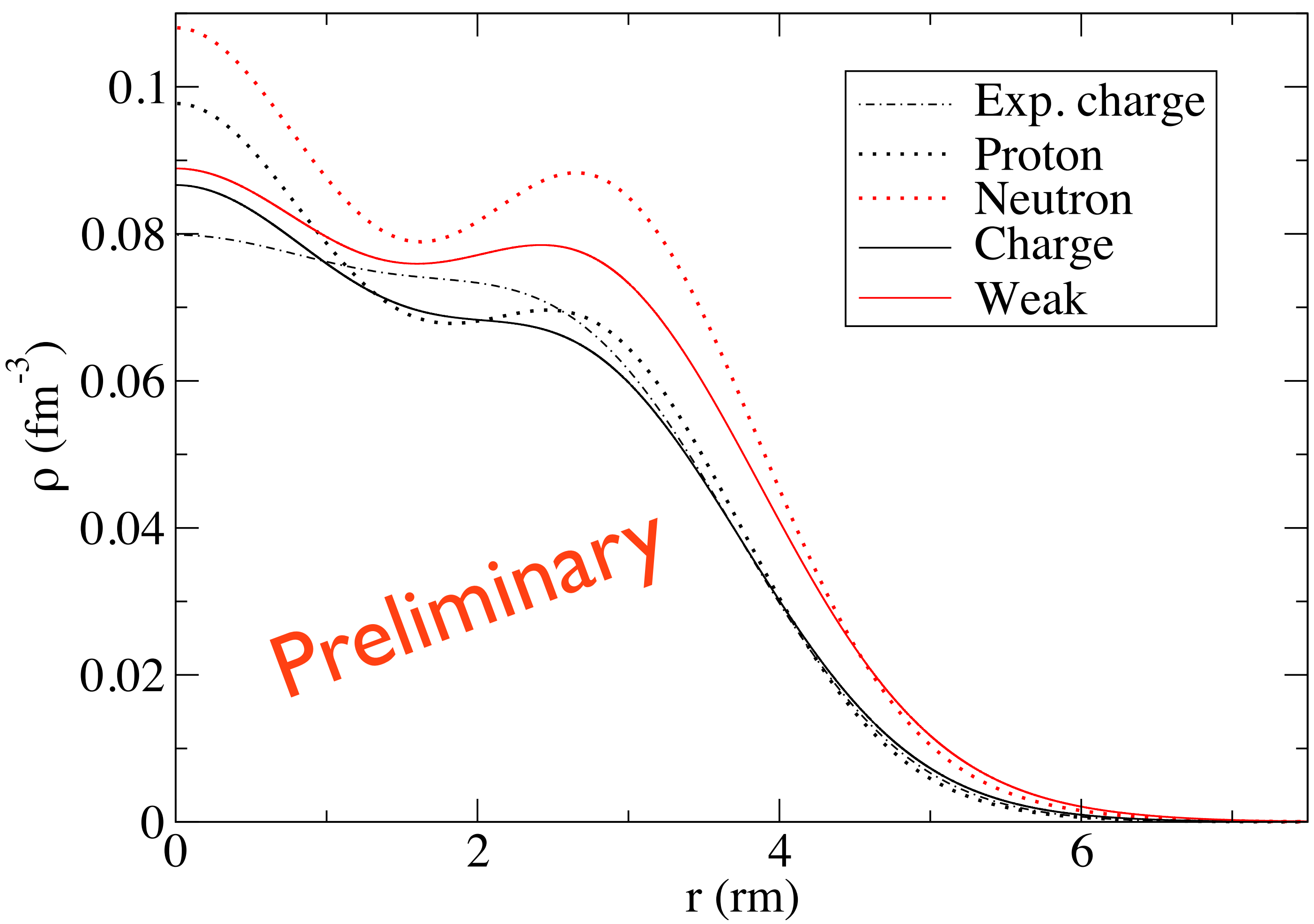
Microscopic Calculations

Ab initio coupled cluster calculations for ^{48}Ca

based on NN and NNN potentials, computationally intensive

Can help provide deeper understanding of DFT by relating to nucleon interactions

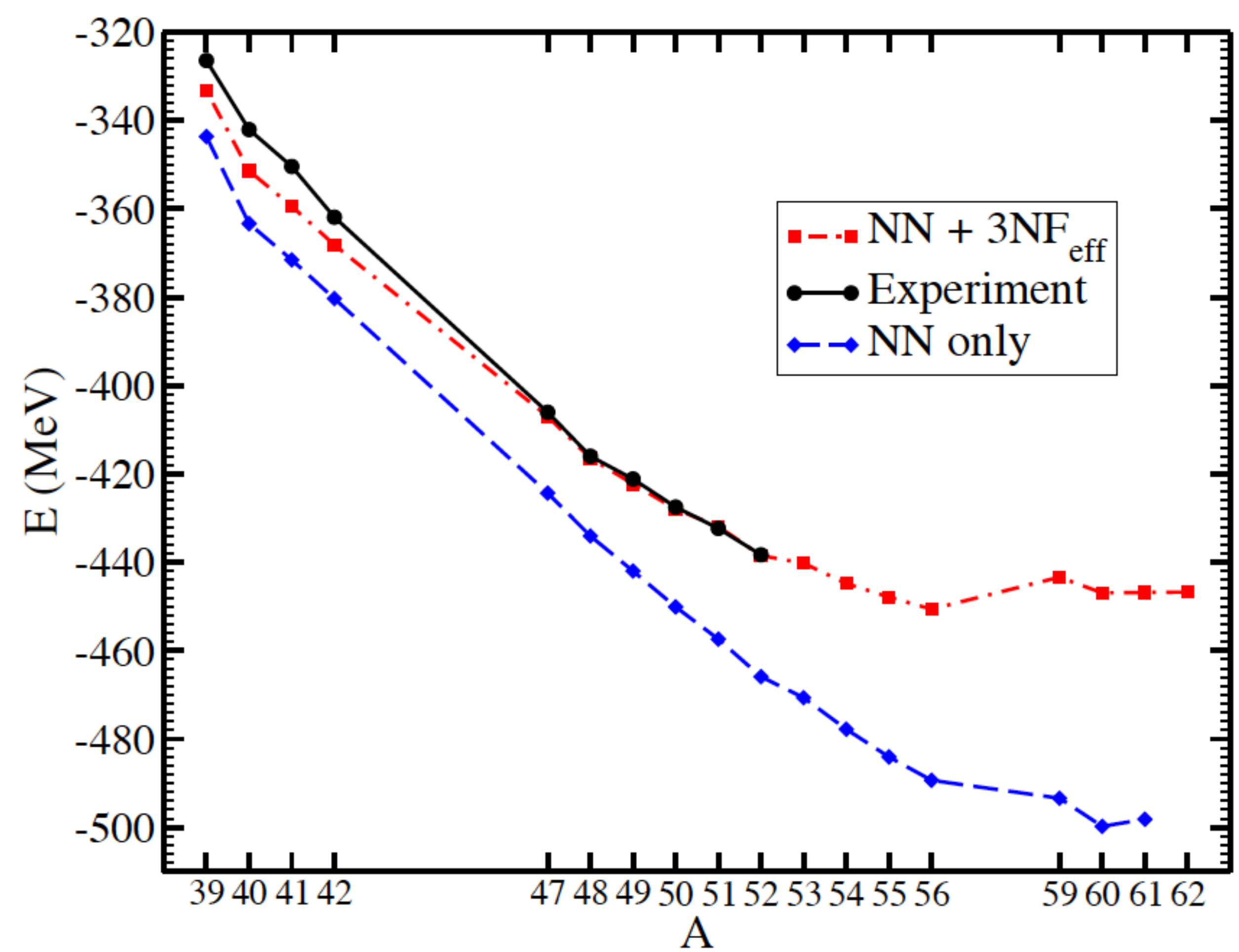
Good agreement with existing data



Hagen et al. Phys. Rev. Lett 109 032502 (2012)

3N forces significant

R^{48} provides important test



Conclusion

"Isovector" properties of nuclei are relatively unconstrained by data and otherwise successful models vary widely.

Such properties are fundamental to a full understanding of nuclei and are important now for calculations of neutron stars, rare nuclei and atomic parity violation.

JLab is poised to make measurements which will significantly reduce the uncertainties on isovector properties.

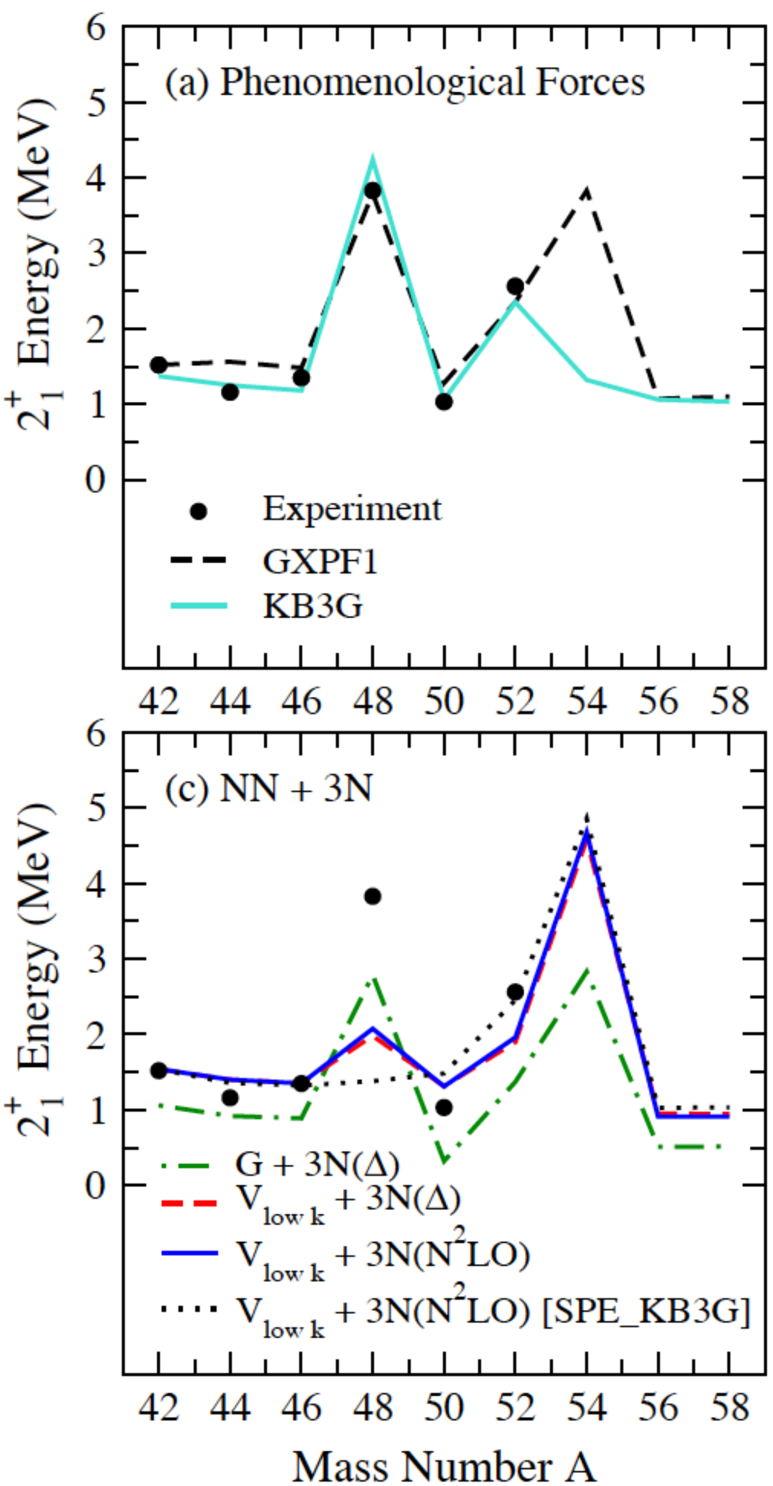
Systematics show a "mild" correlation between R^{48} and R^{208} suggesting they provide complementary information.

There is very strong interest in the PREX and CREX results from nuclear structure community.

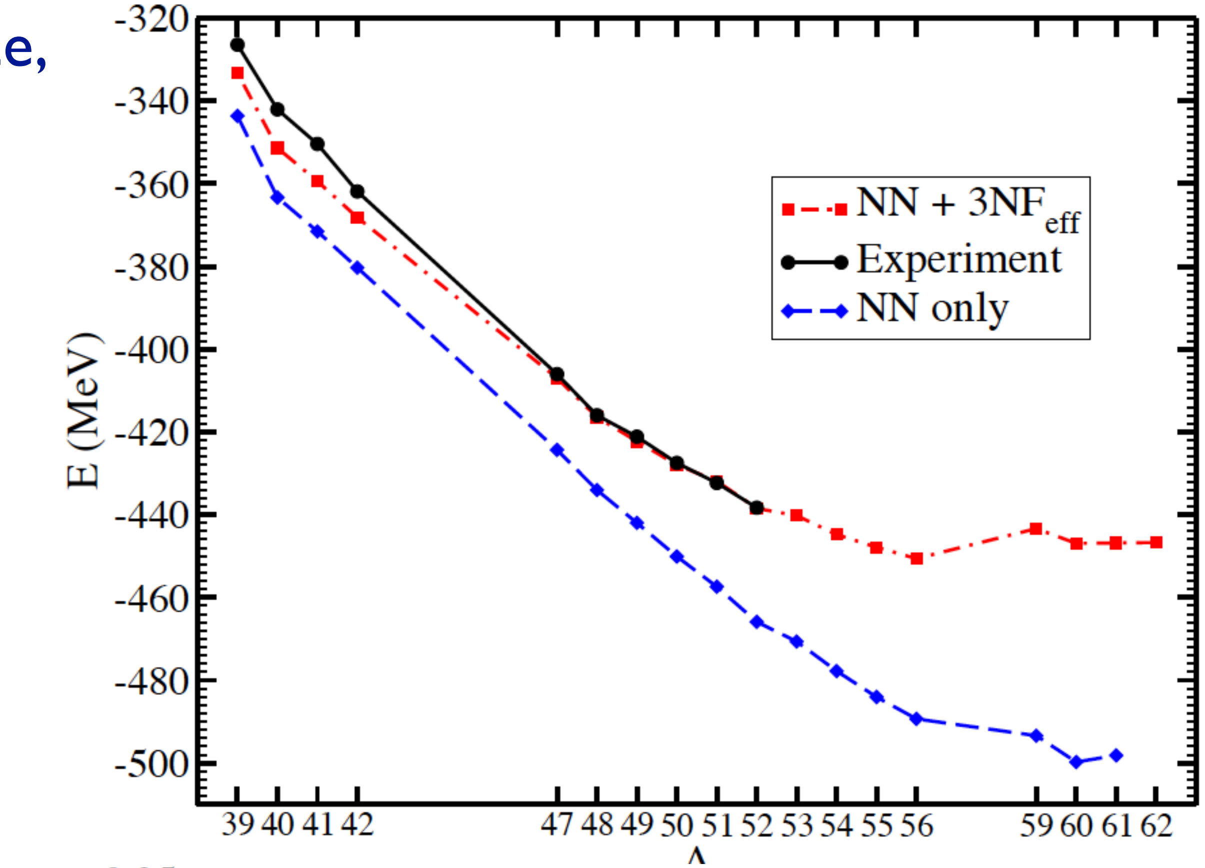
Backup Slides

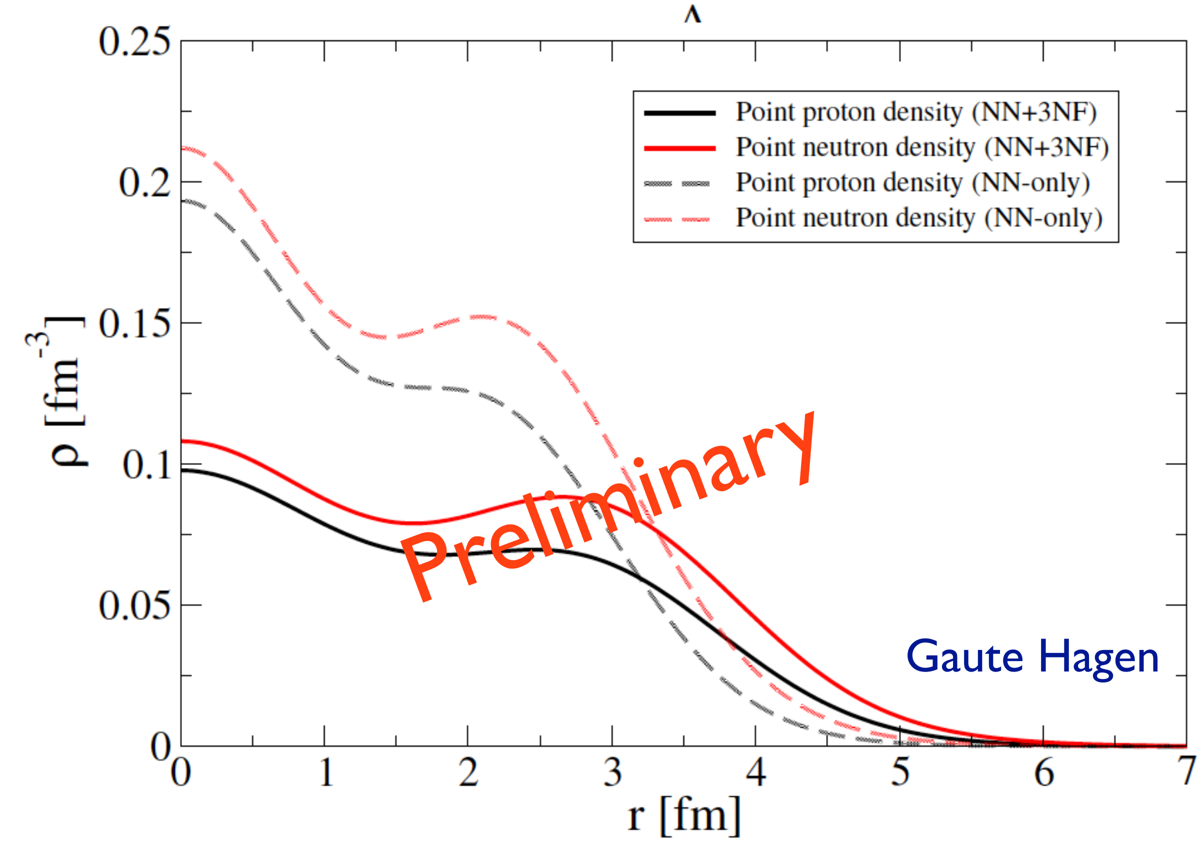
^{48}Ca Calculations

theoretical uncertainties are large and not well quantified: truncating the chiral expansion, parameters of 3N force, model space truncations and omitted terms.

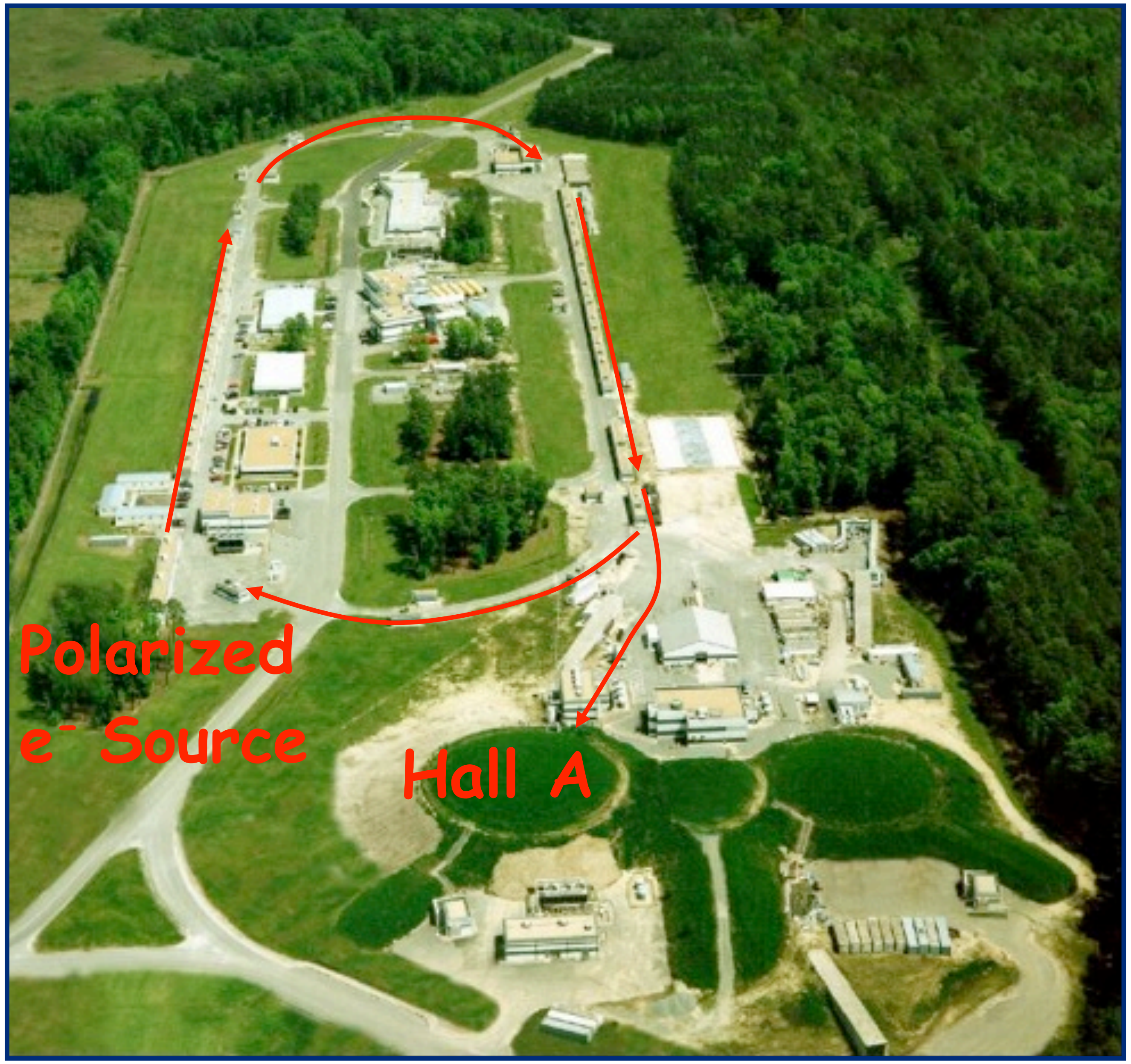


Microscopic



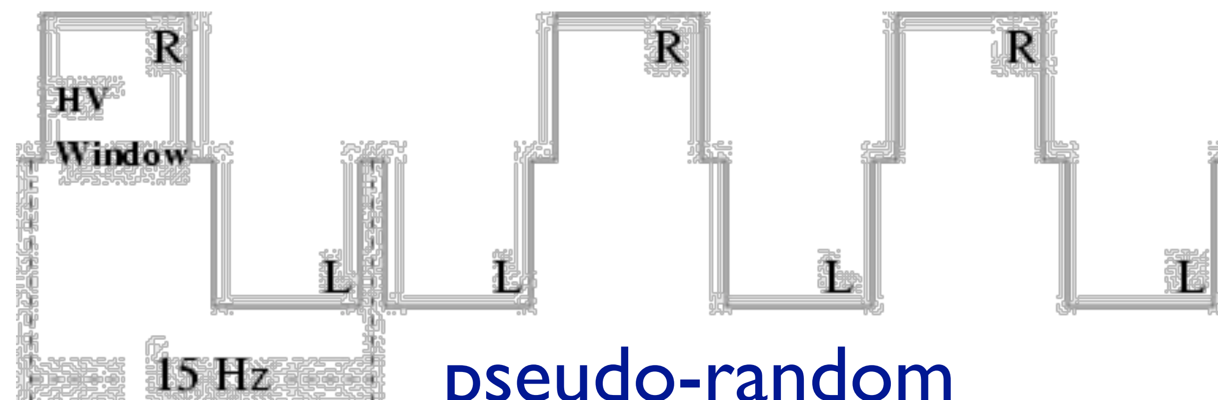


Parity Violating Electron Scattering



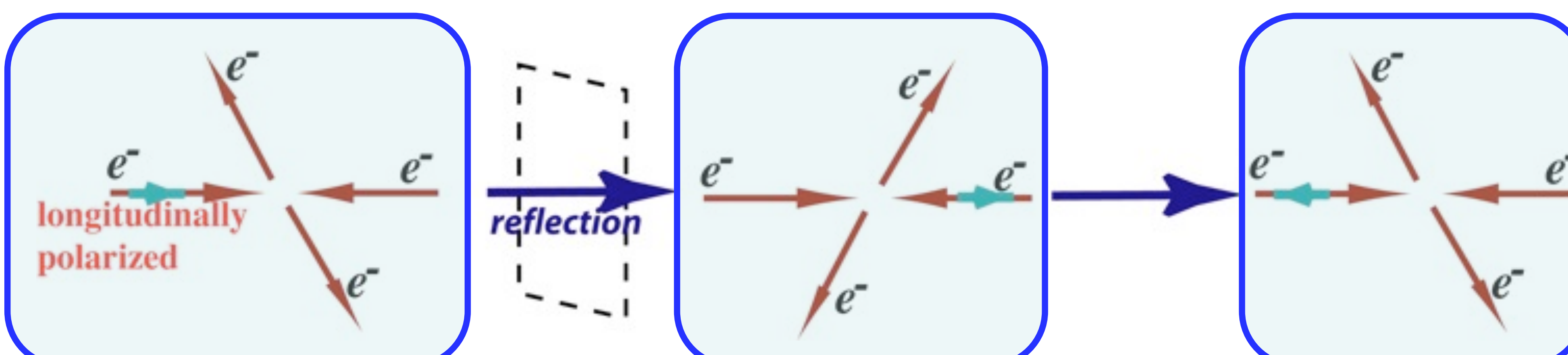
$$\sigma \propto |A_\gamma + A_{\rm weak}|^2$$
$$\sim |A_\gamma|^2 + 2A_\gamma A^*_{\rm weak}$$

interference between neutral weak and electromagnetic amplitudes

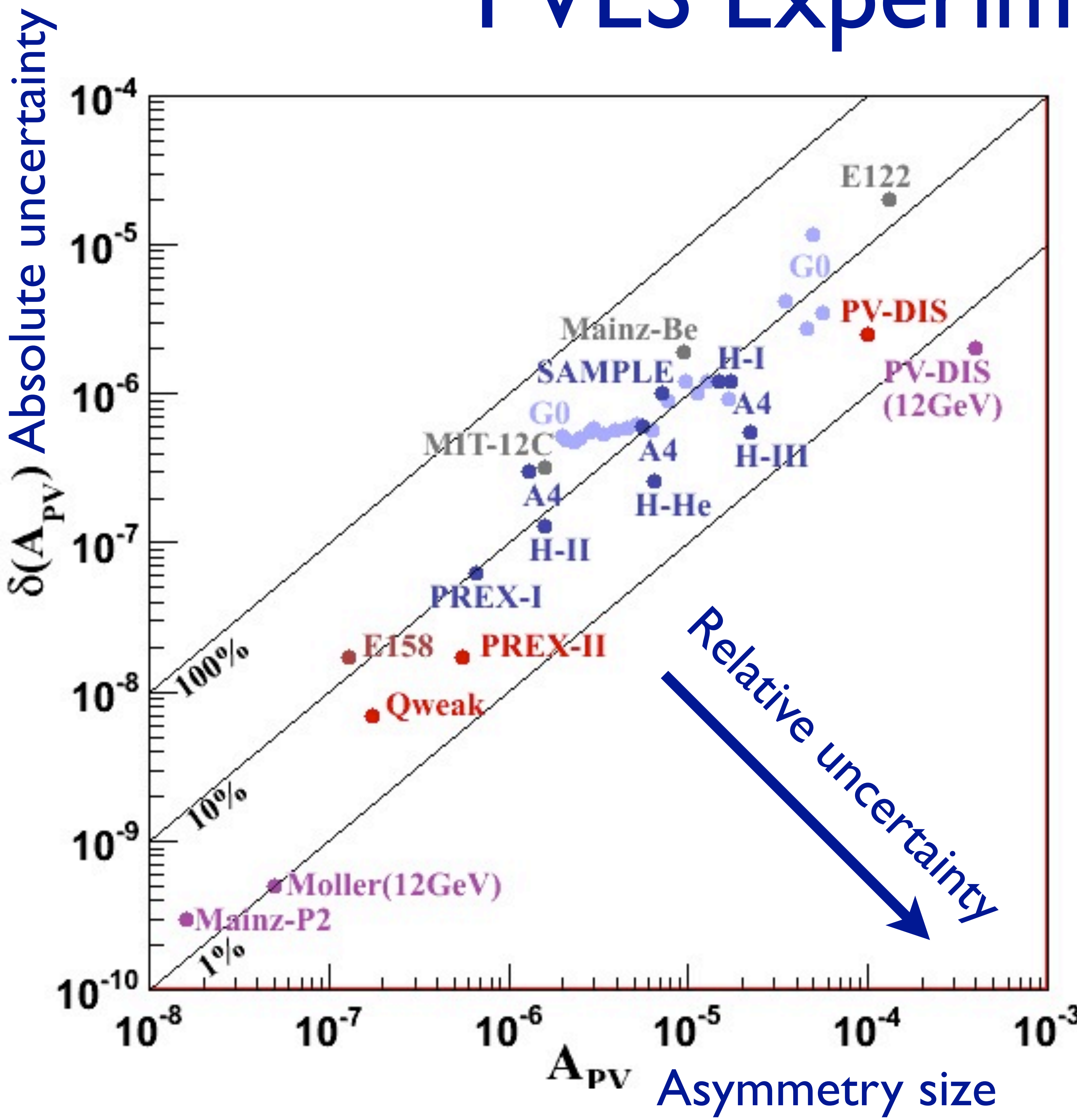


pseudo-random

Change helicity of beam - equivalent to changing parity



PVES Experiments



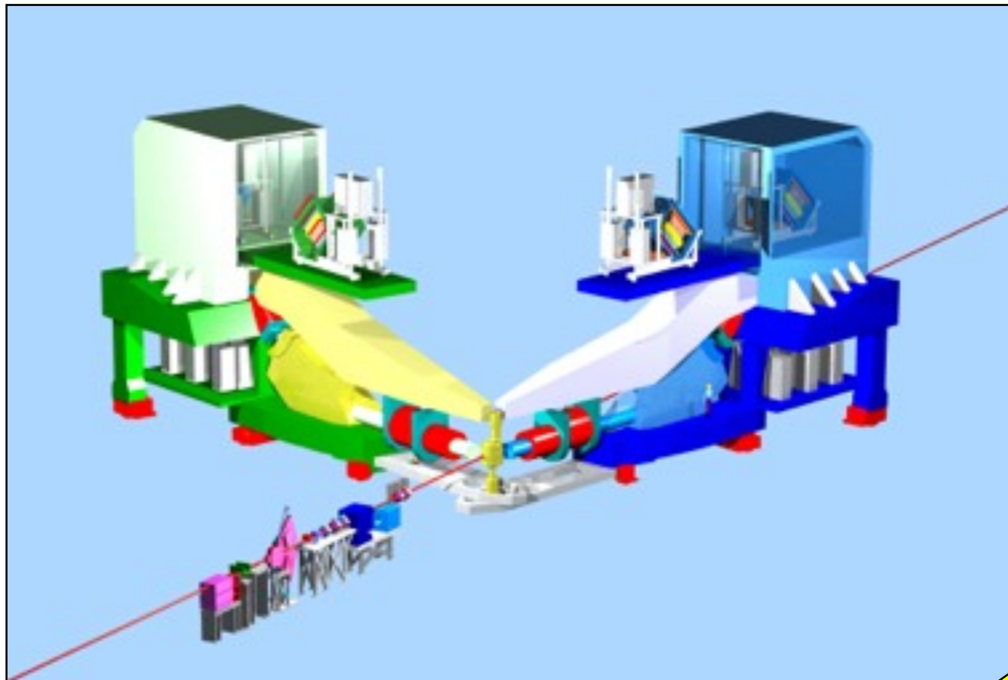
1st generation

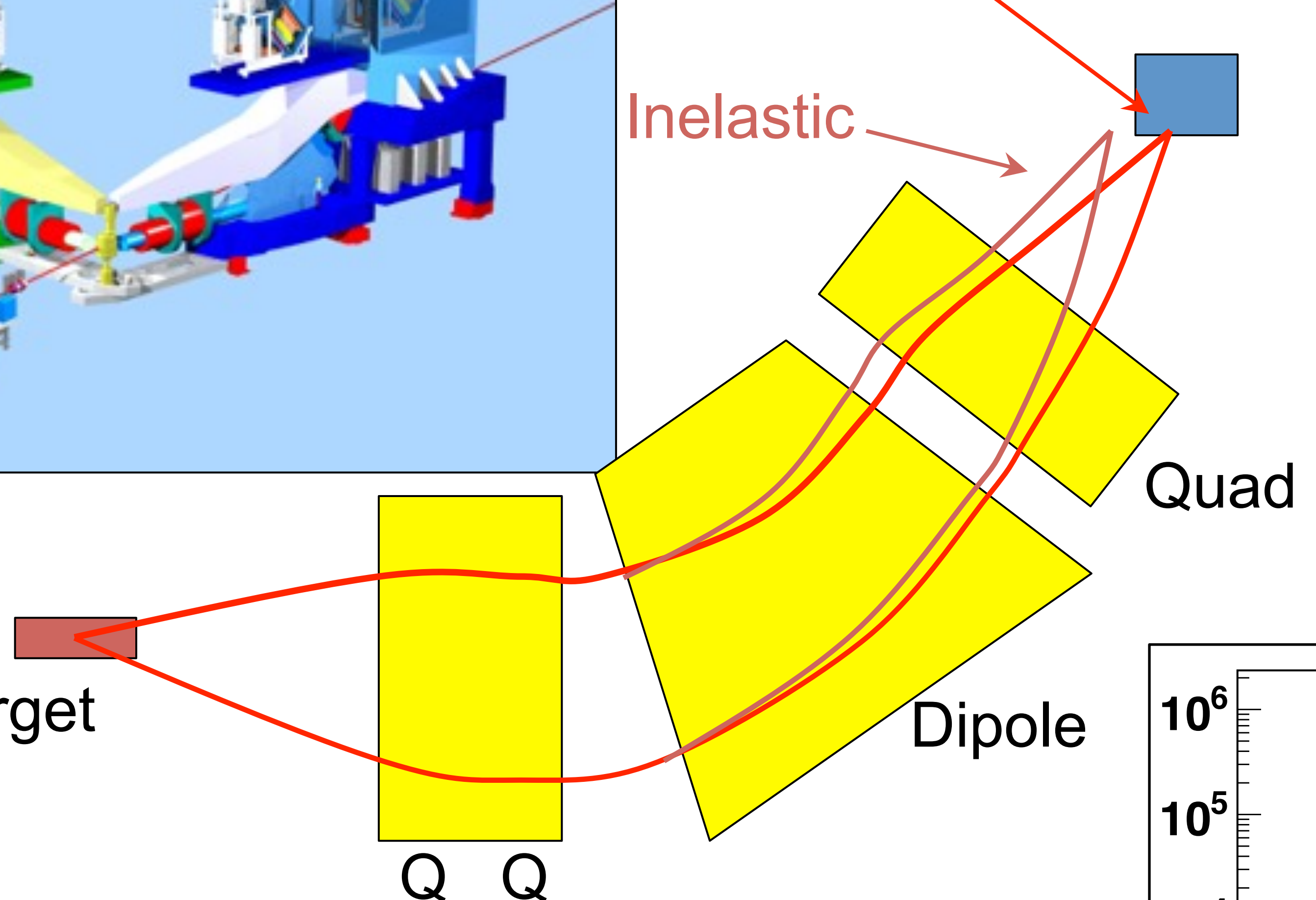
2nd generation

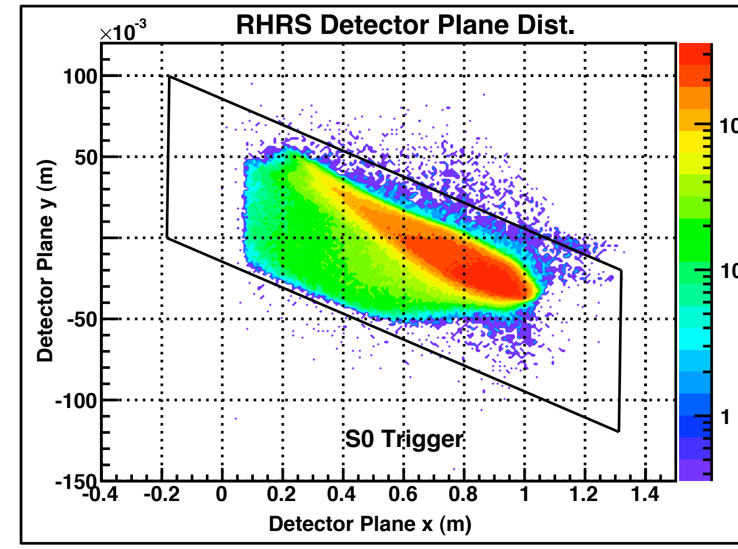
3rd generation

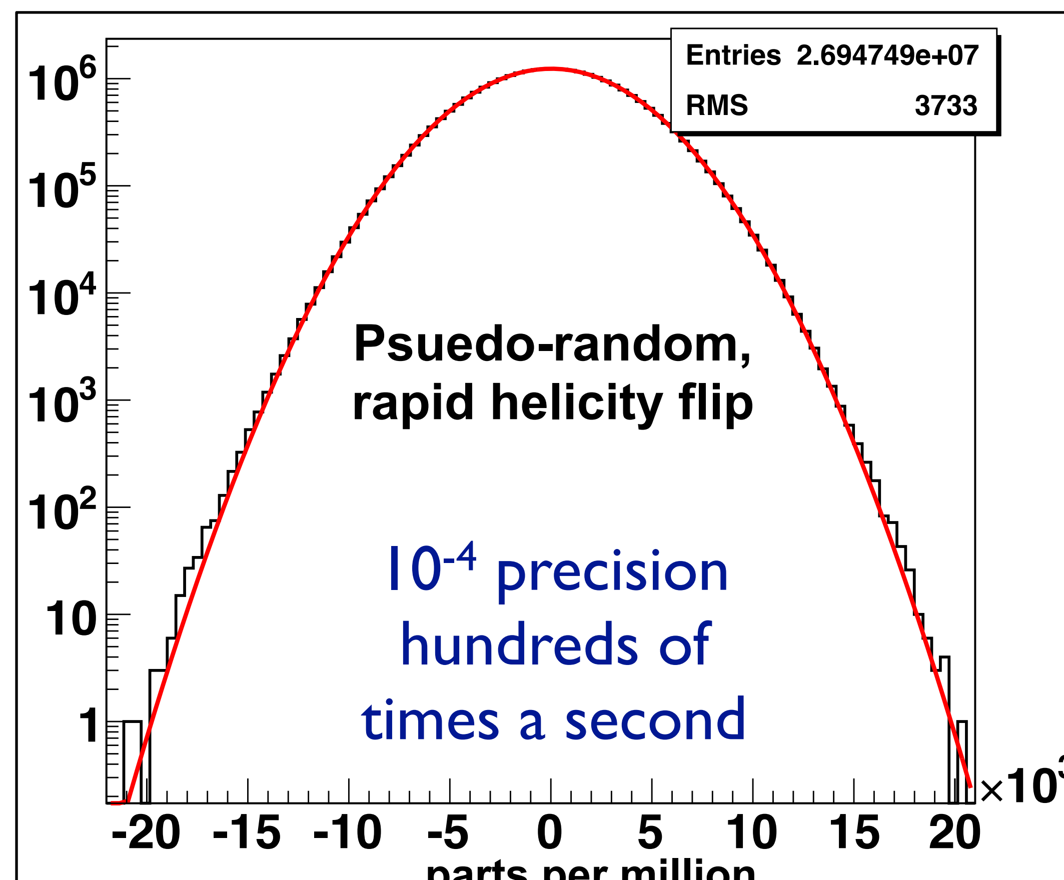
4th generation

Hall A Parity - Standard Setup

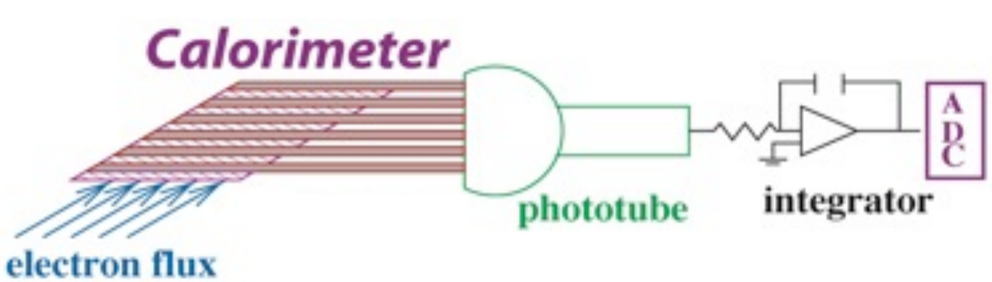








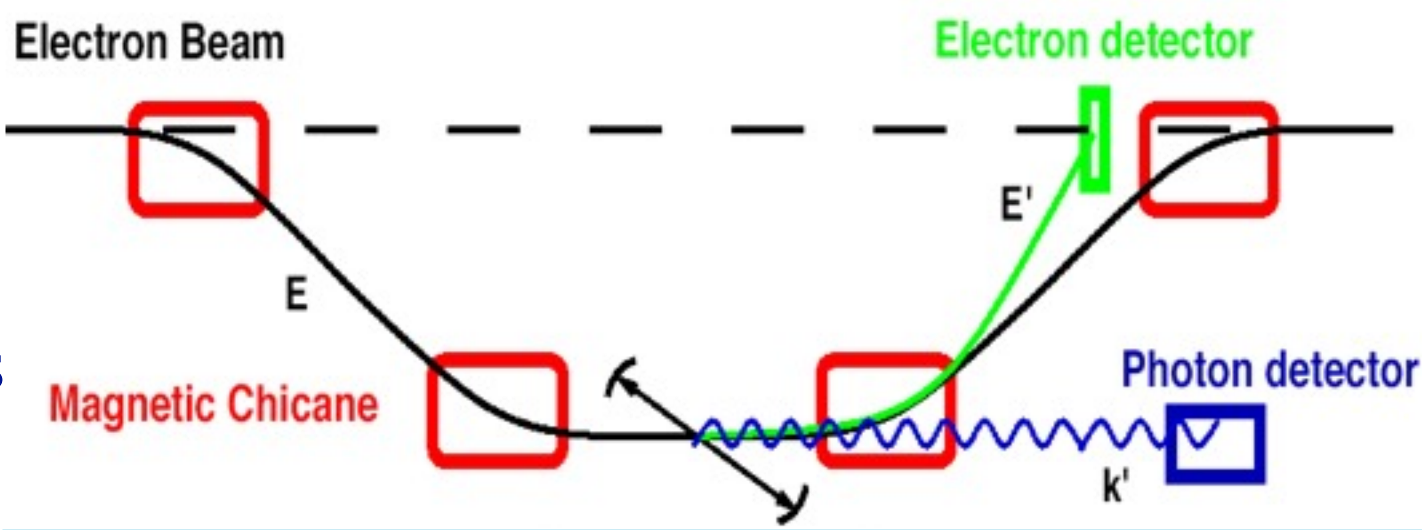
Lead - Lucite Cerenkov Shower Calorimeter
phototube current integrated over fixed time periods



Technical Challenges

Polarization enters result directly

$$A_{PV} = \frac{A_{\rm raw}}{P_e}$$



Resonant cavity "photon target", up to 2kW intensity

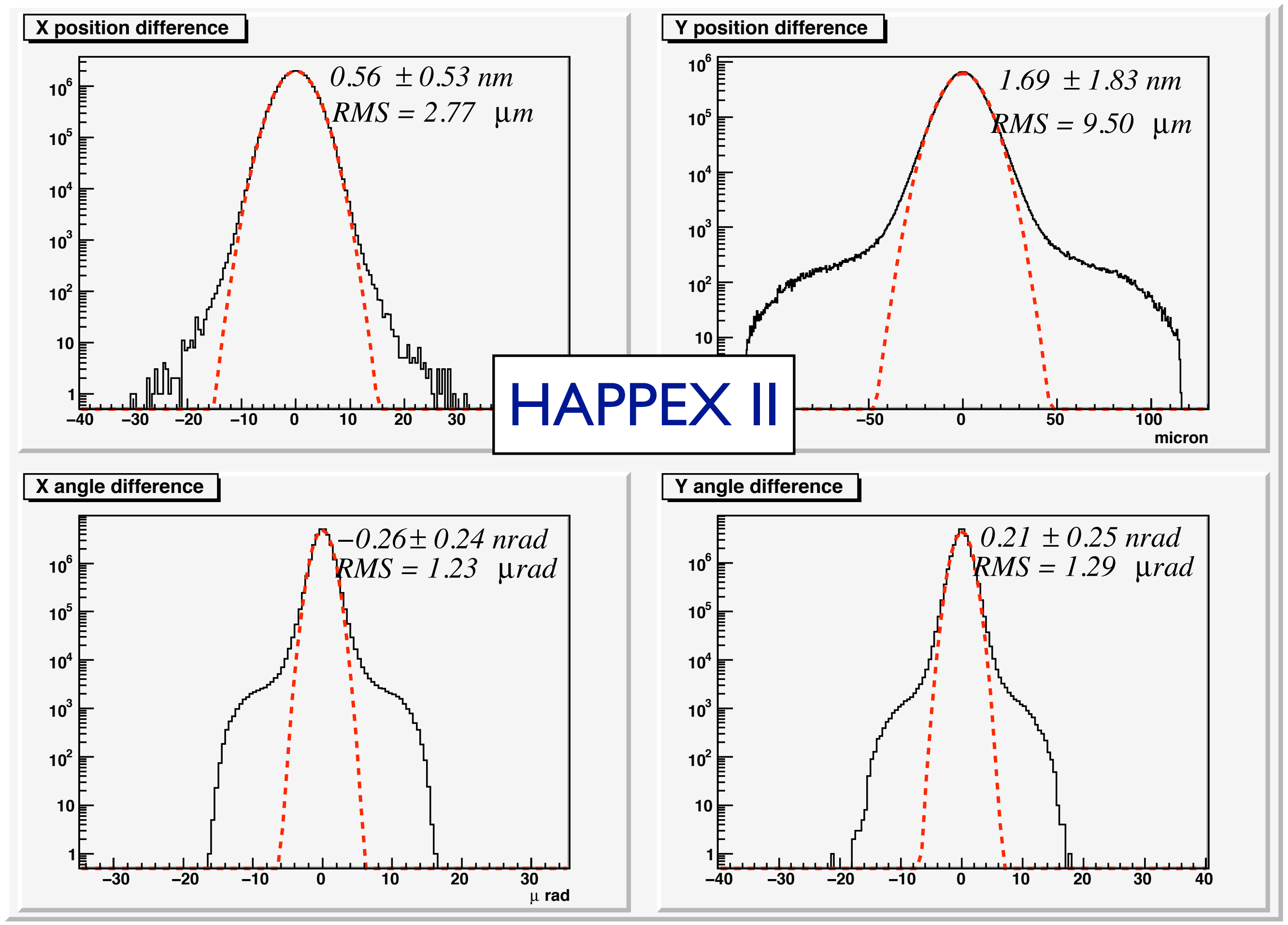
Precision must be better than statistics

V. Tvaskis DLNP building, Thursday 16:50

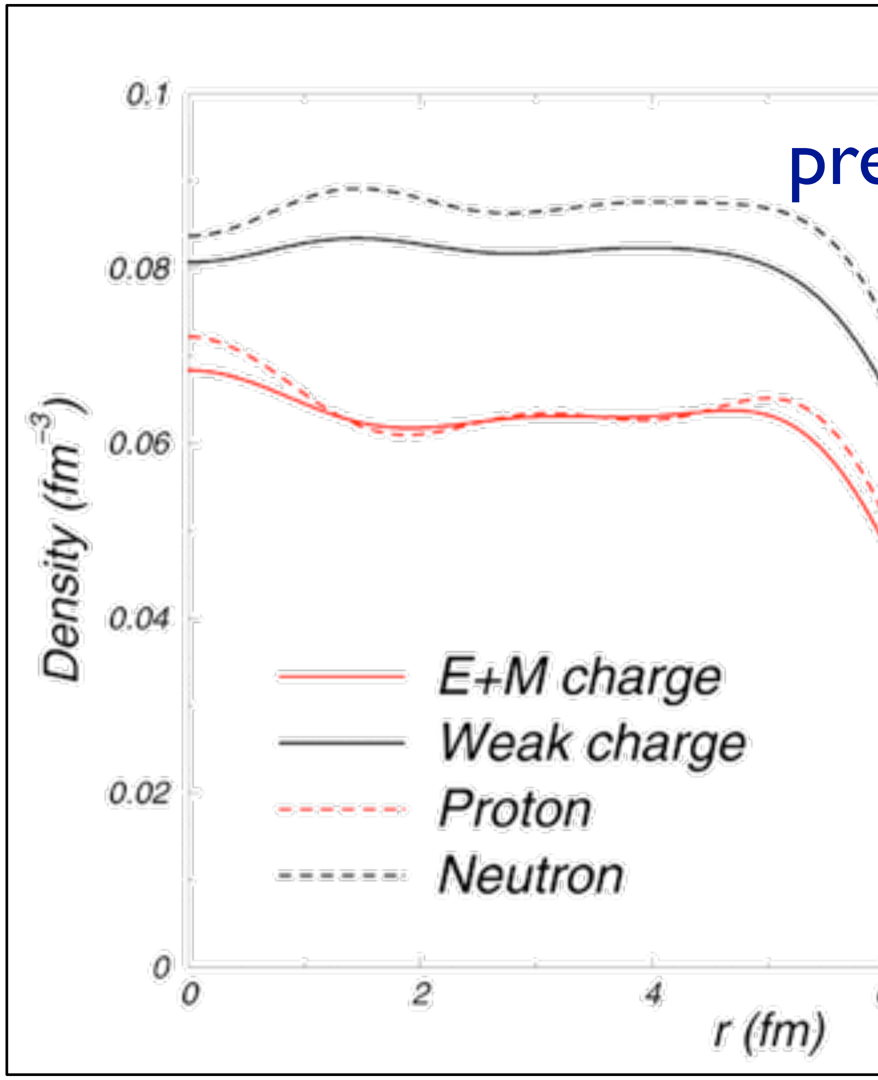
Beam false asymmetries
must be kept small

Currently we achieve ~1nm position differences and <1nrad angle differences

These need to be improved for future experiments!



Weak Charge Distribution of Heavy Nuclei



Nuclear theory predicts a neutron "skin" on heavy nuclei

Neutron distribution is not accessible to the charge-sensitive photon.

knowledge of neutron densities comes primarily from hadron scattering => model-dependent interpretation

Parity Violation can measure weak form factor model independently

	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**

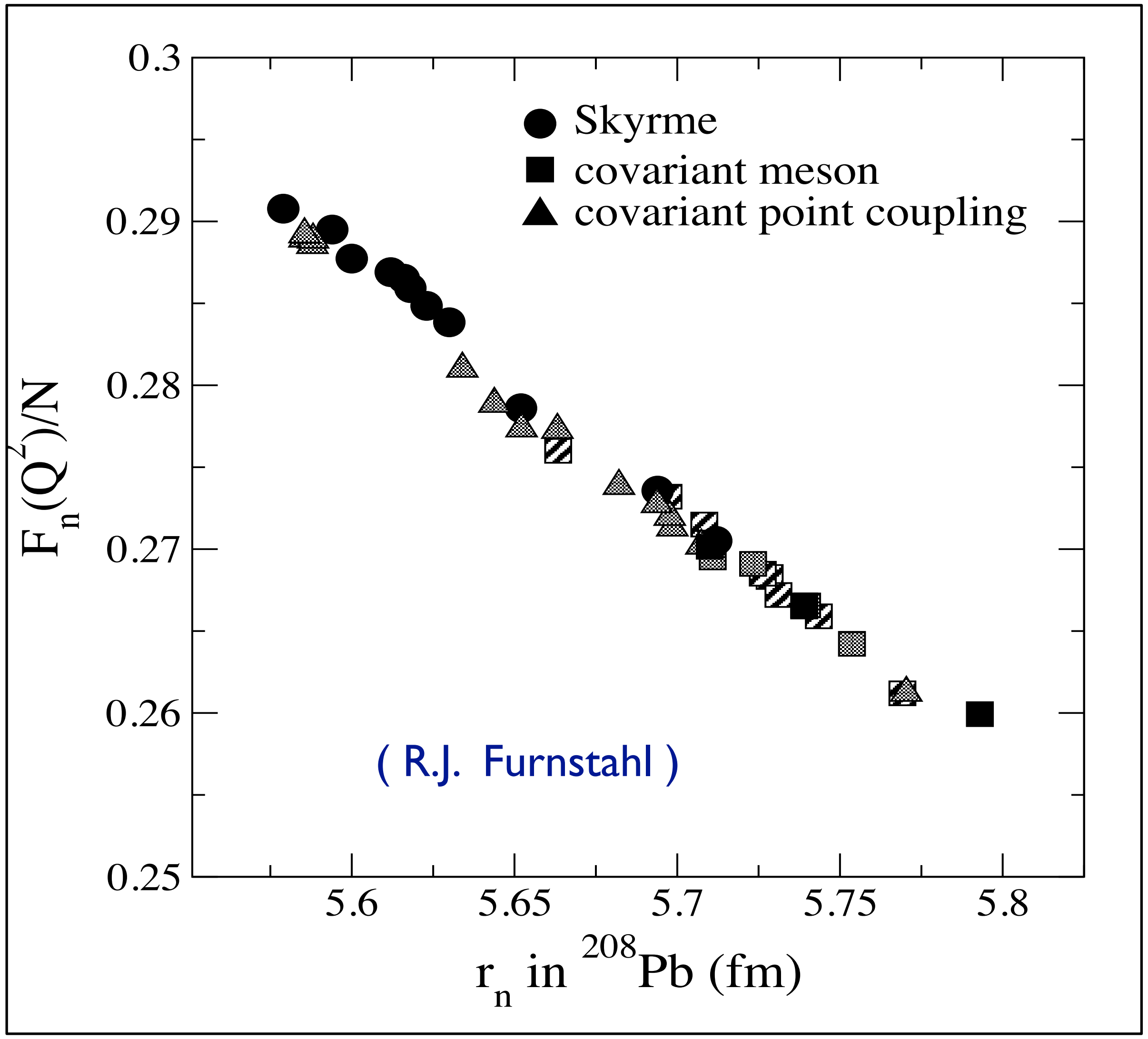
$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

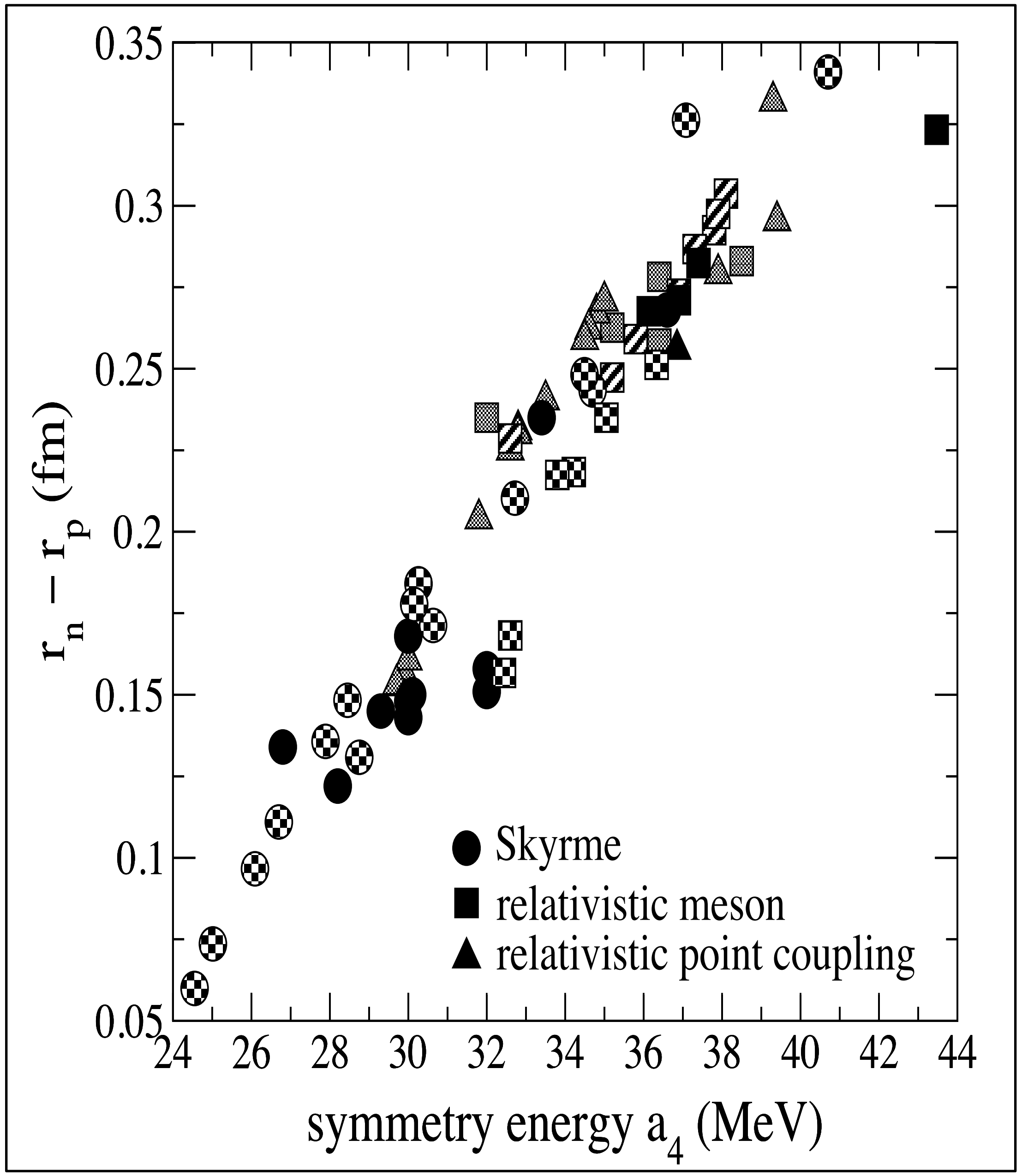
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

A crucial calibration point for nuclear theory

The single measurement of F_n translates to a measurement of R_n via mean-field nuclear models



…and measuring R_N pins down the symmetry energy



R_n calibrates the EOS of neutron rich matter - provides an important calibration point for nuclear theory and description of neutron stars

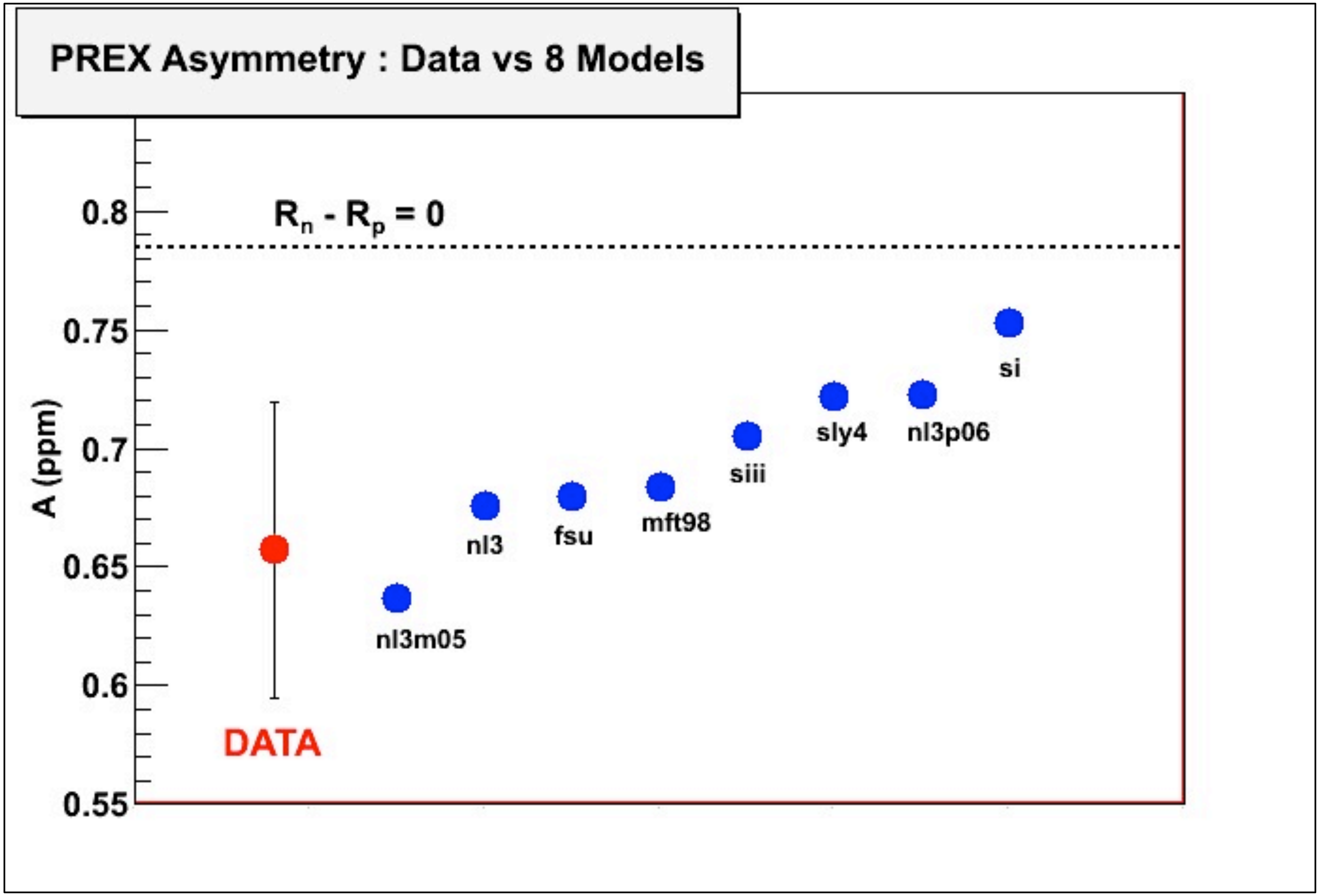
PREX

Lead Radius Experiment

First electroweak observation of the neutron skin of a heavy nucleus (CL=95%)

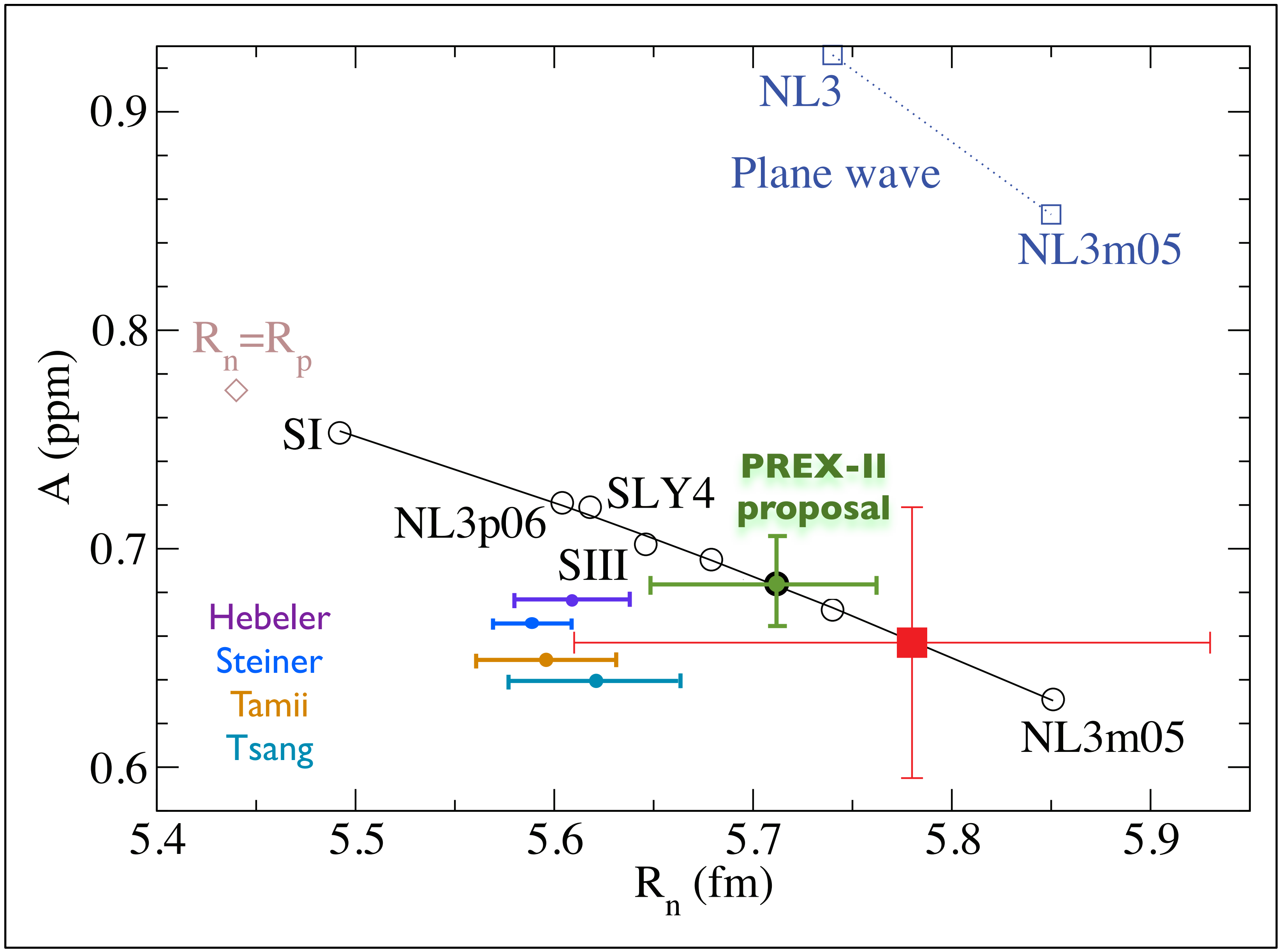
Q^2 ~ 0.01 GeV^2
5° scattering angle

A_{PV} ~ 0.6 ppm
Rate ~1.5 GHz



Recent R_n Predictions Can Be Tested By PREX at Full Precision

PREX could provide an electroweak complement to R_n predictions from a wide range of physical situations and model dependencies



Recent R_n predictions:

Hebeler *et al.* Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

Steiner *et al.* X-Ray n-star mass and radii observation + Brown correlation. (Ozel *et al* finds softer EOS, would suggest smaller R_n).

Tamii *et al.* Measurement of electric dipole polarizability of ^{208}Pb + model correlation with neutron skin.

Tsang *et al.* Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.

These can be tested with

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

Future Studies

Complimentary measurements

PREX II	CREX
^{48}Ca at E = 1.0 GeV and θ = 5°	^{48}Ca at E = 2.2 GeV and θ = 4°
Q2 = 0.009 GeV^2	Q2 = 0.022 GeV^2
Rn measured to 0.06 fm (1.0%)	Rn measured to 0.03 fm (0.9%)
APV ~ 0.6 ppm	APV ~ 2 ppm
better approximation of infinite nuclear matter	larger asymmetry can use higher Q2 and energy microscopic models available

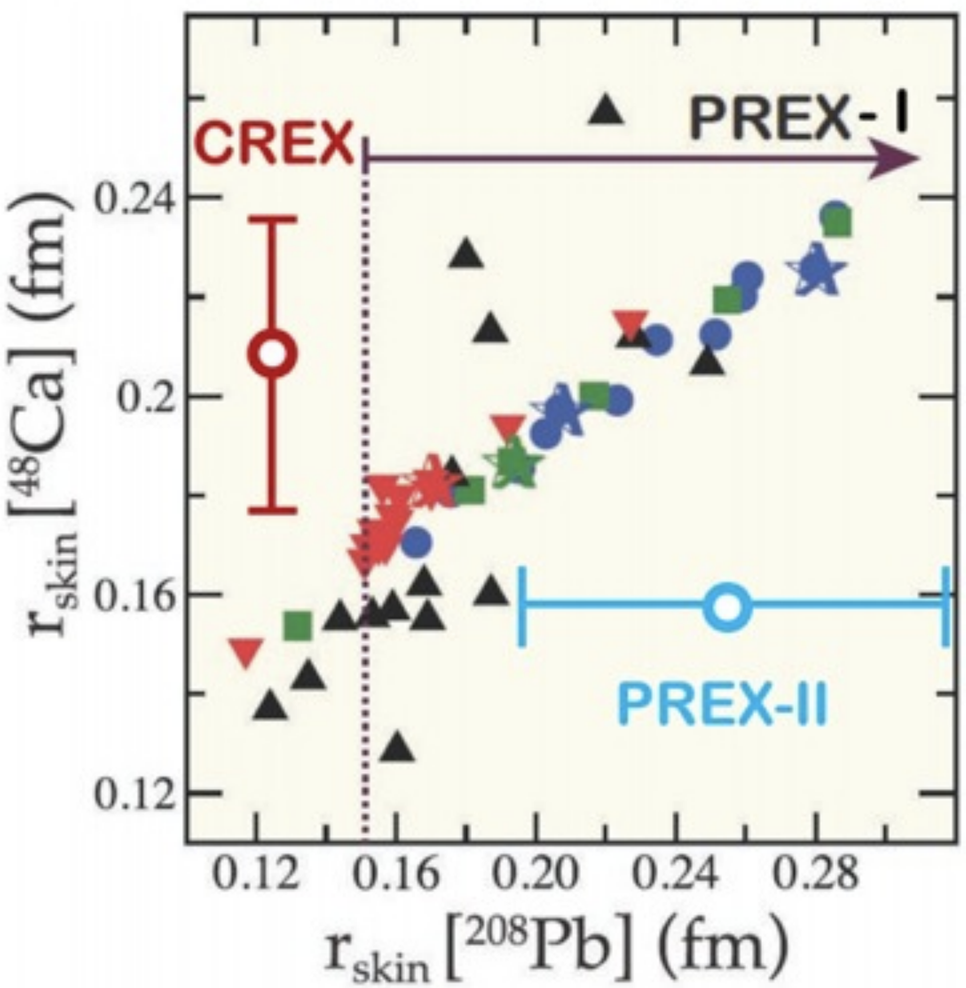
constrain 3-neutron forces
(^{3}He, ^{3}H and p-d scattering for 3-nucleon forces)

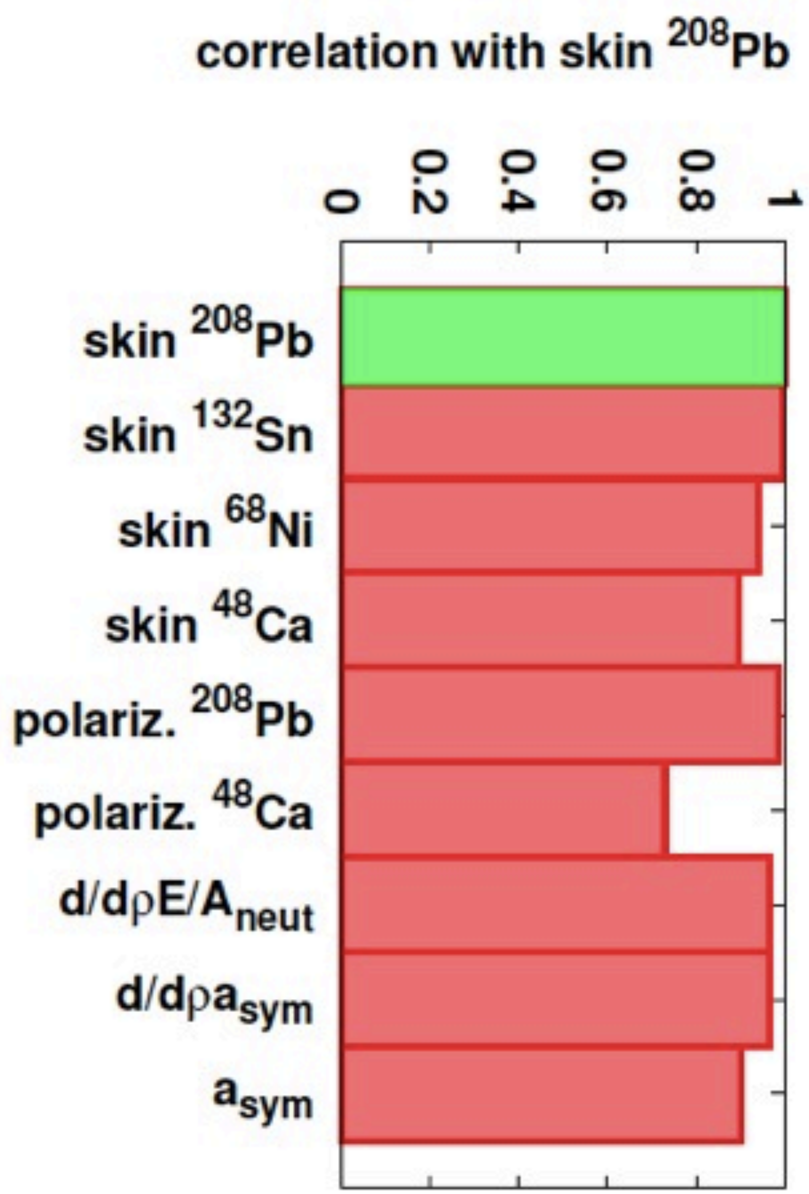
density dependence of the symmetry energy of neutron rich nuclear matter data as input for: neutron star structure, heavy ion collisions and atomic parity violation

Nuclear Parameter Correlations

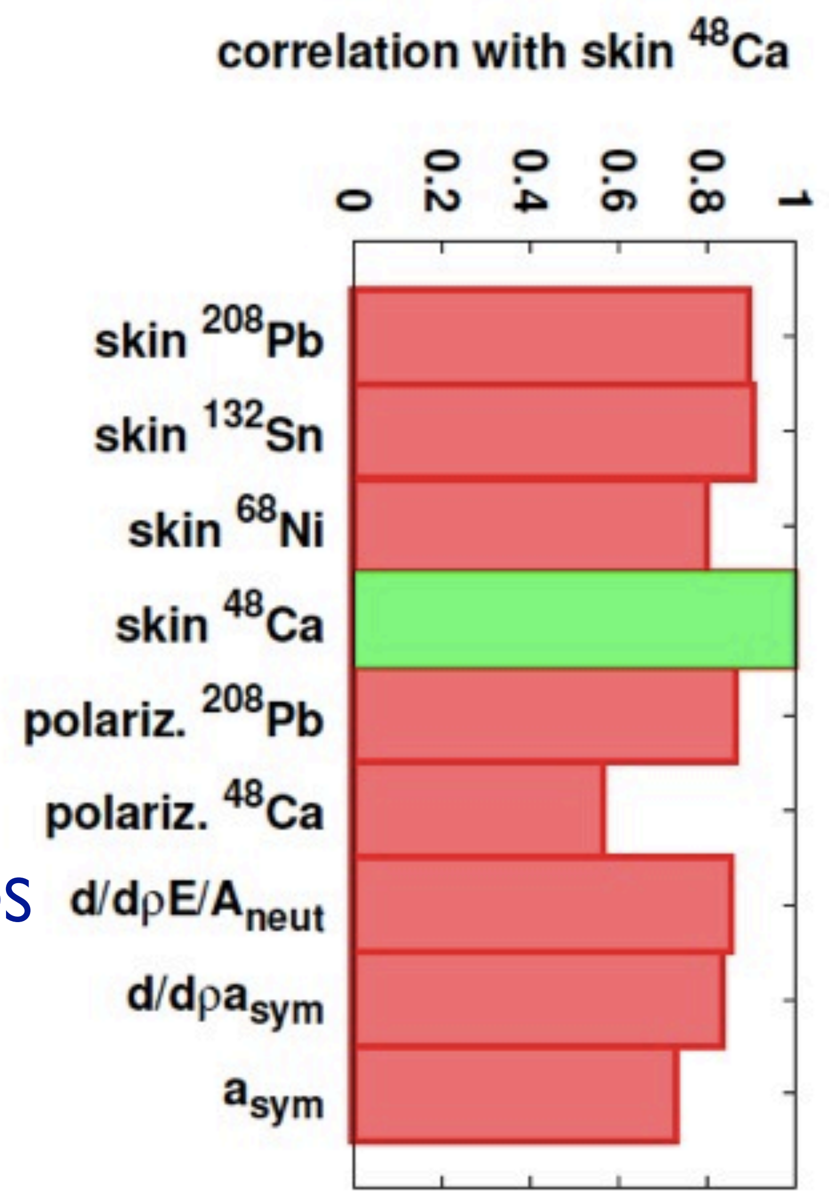
strong correlation between R_N and the pressure of neutron matter
densities near 0.1 fm^{-3}
constrains the equation of state of neutron matter

Combined experiments
reduce uncertainty





EOS



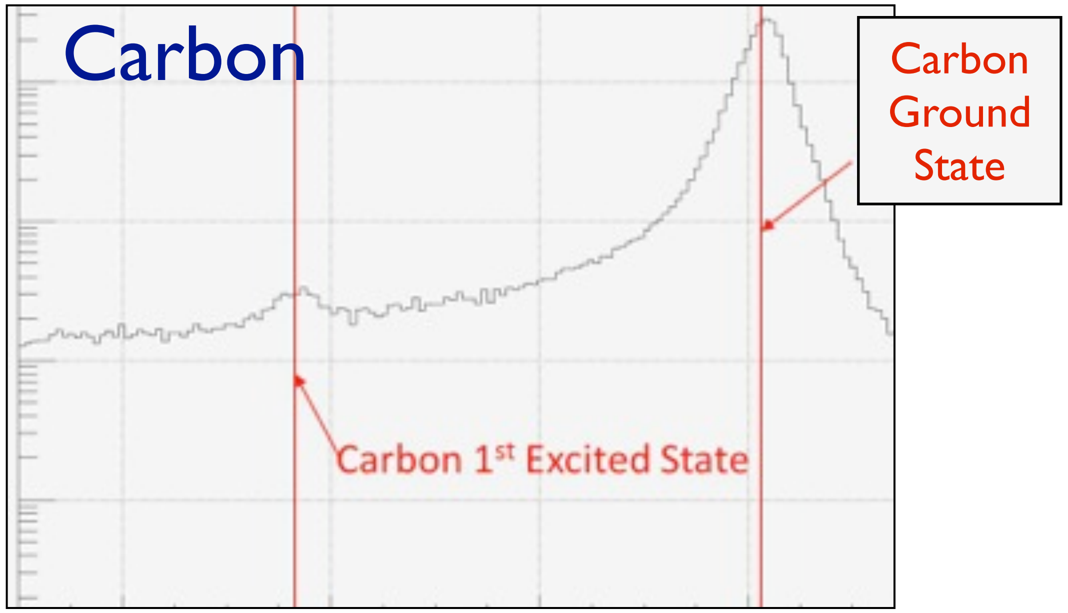
Systematic Errors

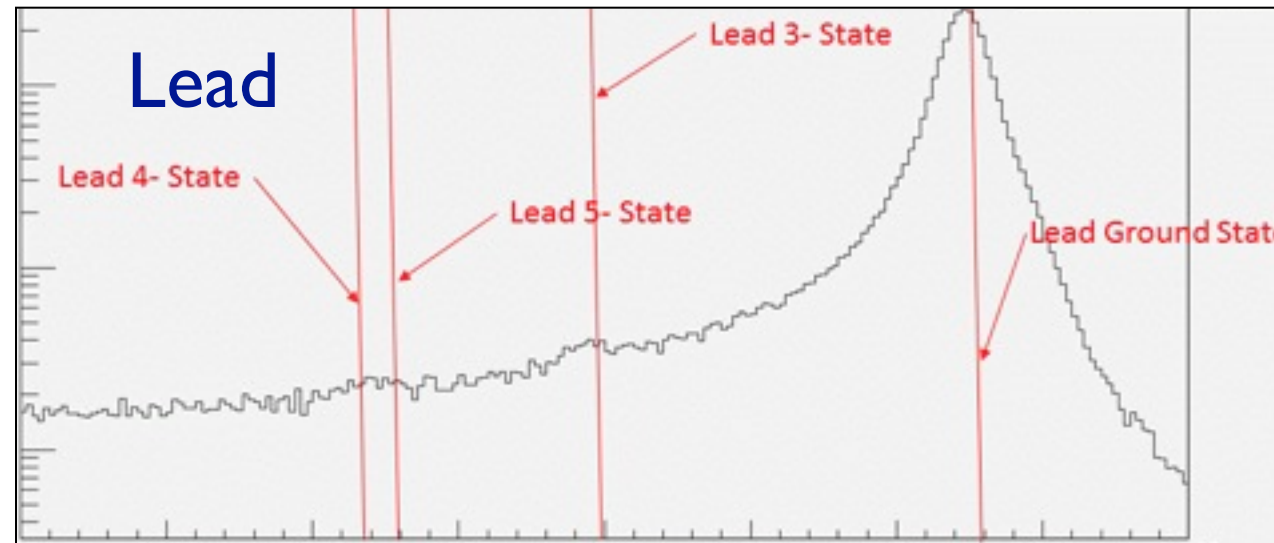
Error Source	Absolute (ppm)	Relative (%)
Polarization (1)	0.0071	1.1
Beam Asymmetries (2)	0.0072	1.1
Detector Linearity	0.0071	1.1
BCM Linearity	0.0010	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2 (1)	0.0028	0.4
Target Thickness	0.0005	0.1
^{12}C Asymmetry (2)	0.0025	0.4
Inelastic States	0	0
TOTAL	**0.0130**	**2.0**

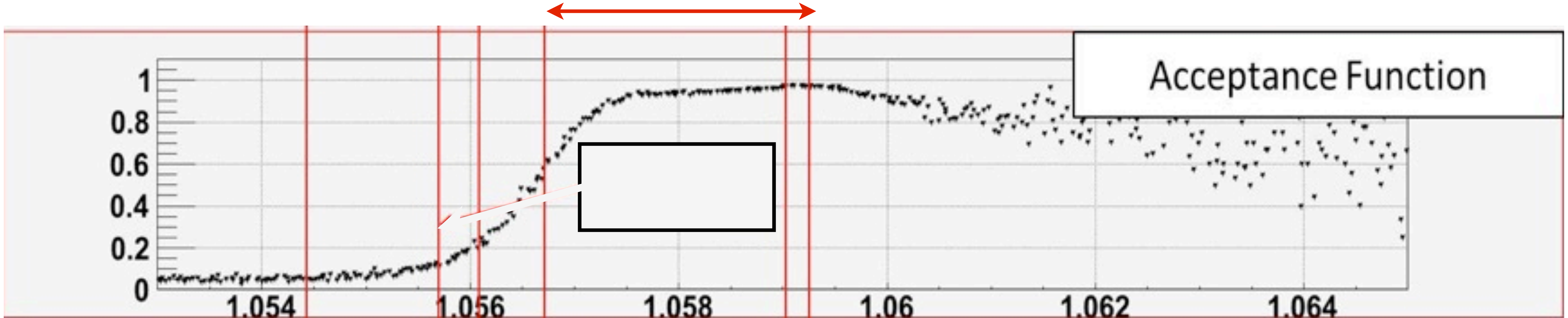
(1) **Normalization Correction** applied

(2) **Nonzero correction** (the rest assumed zero)

High Resolution Spectrometer







Detector integrates the elastic peak.
Backgrounds from inelastics are suppressed.

Negligible contributions from inelastic events rescattering in spectrometer

Beam modulation "Dithering" system

Avoids slow drifts with differential measurement

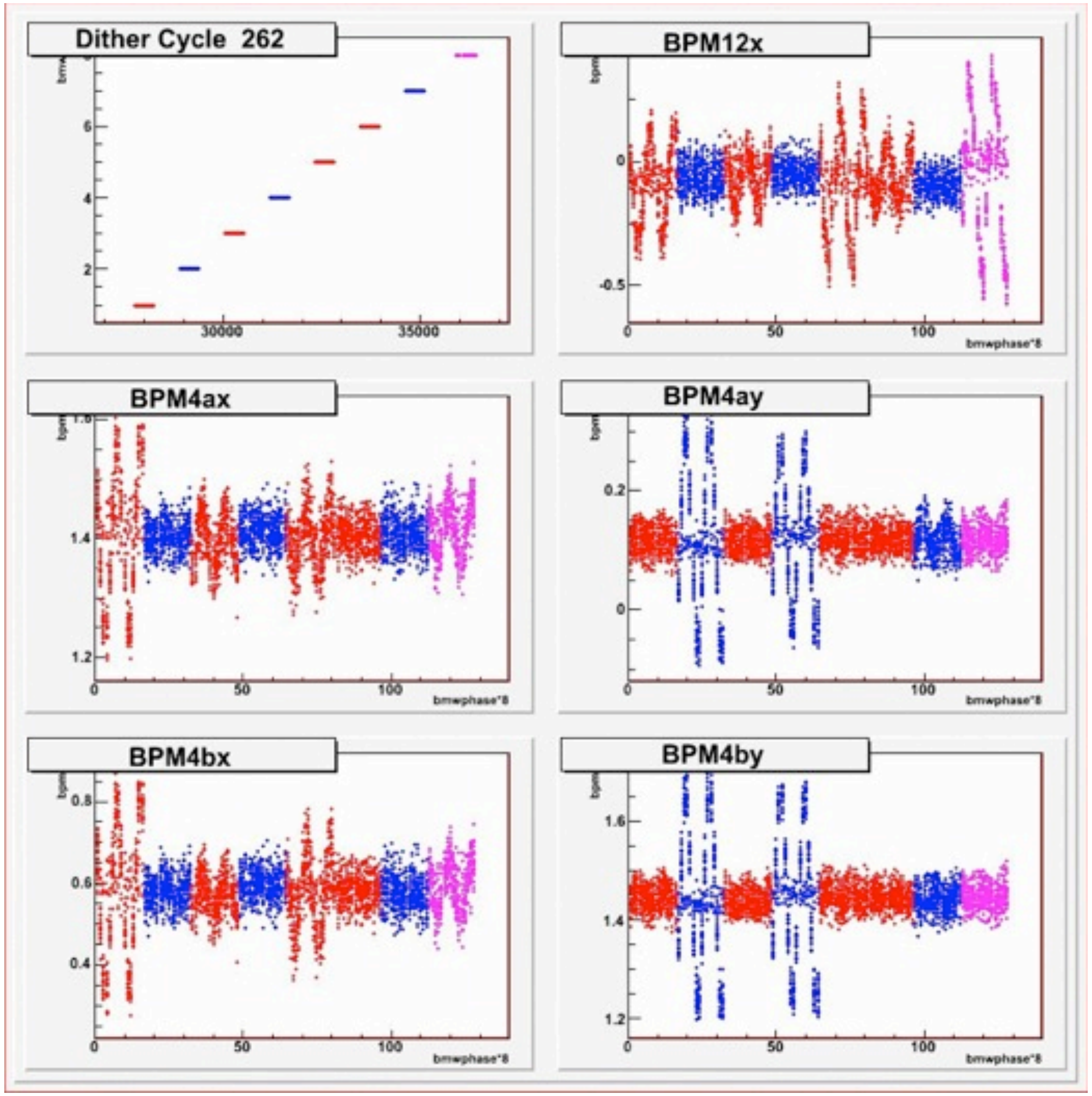
VME function generators drives sine waves

Slower than DAQ readout frequency (i.e. 15 Hz)

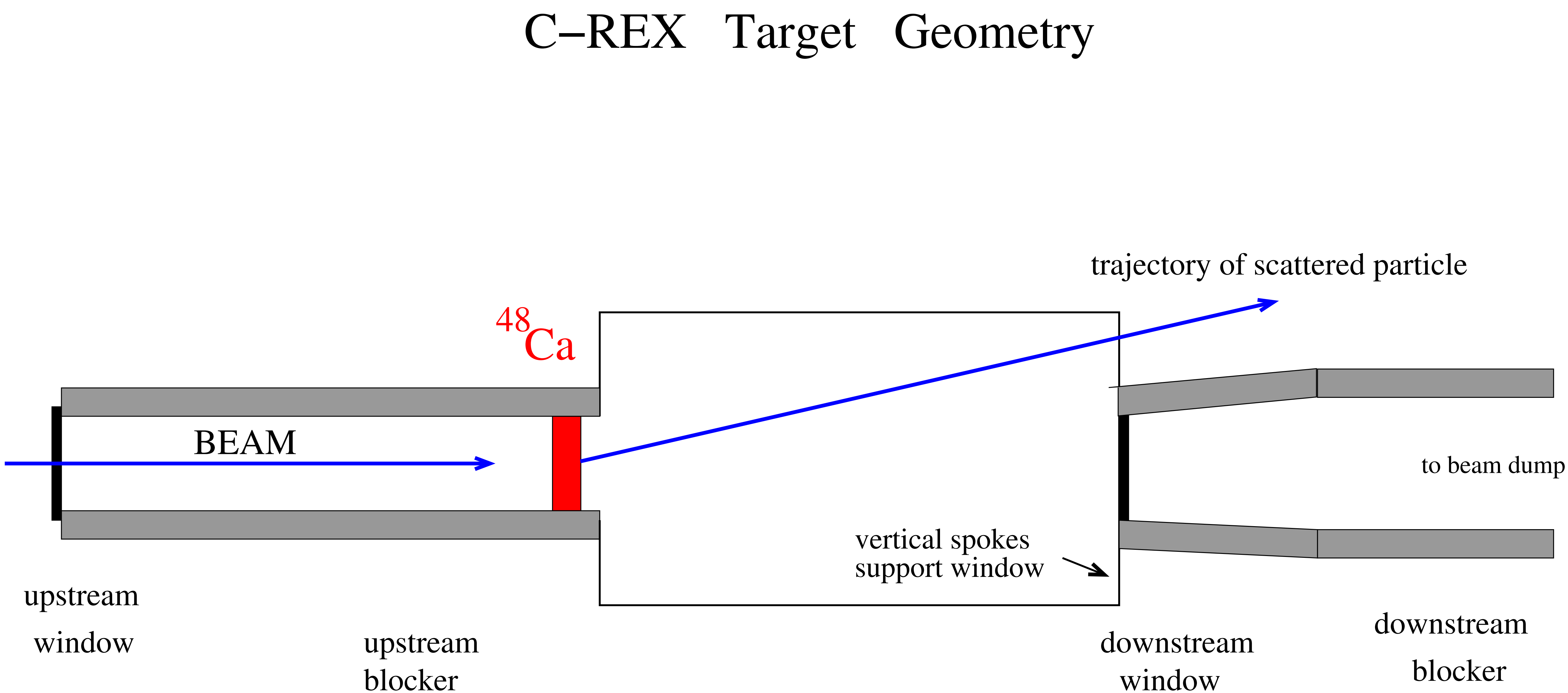
FFB must still be disabled

Uses standard Trim magnet P.S. cards drive readout in DAQ

- Reasonable orthogonality
- Reasonable stability
- Hardware working well
- Slopes change with optics
- energy independent fit more constant



CREX target



C−REX Target Geometry
trajectory of scattered particle
48Ca
BEAM
to beam dump
vertical spokes
support window
upstream
window
upstream
blocker
downstream
window
downstream
blocker