The PREX and CREX Experiments

University of Manitoba

Jefferson Lab

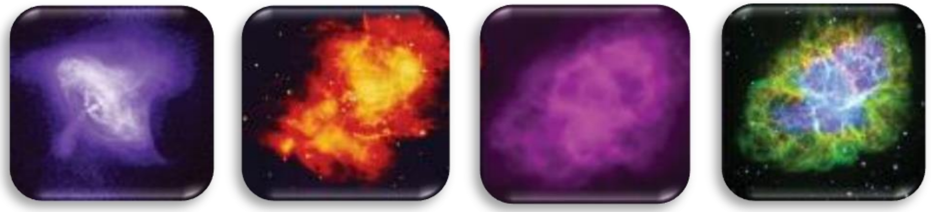
NSERC CRSNG

JSA

Juliette Mammei

*Located on the original lands of the Annishinaageg, Cree, Oji-Cree, Dakota and Dene people, and the Metis nation

Connecting heaven and earth



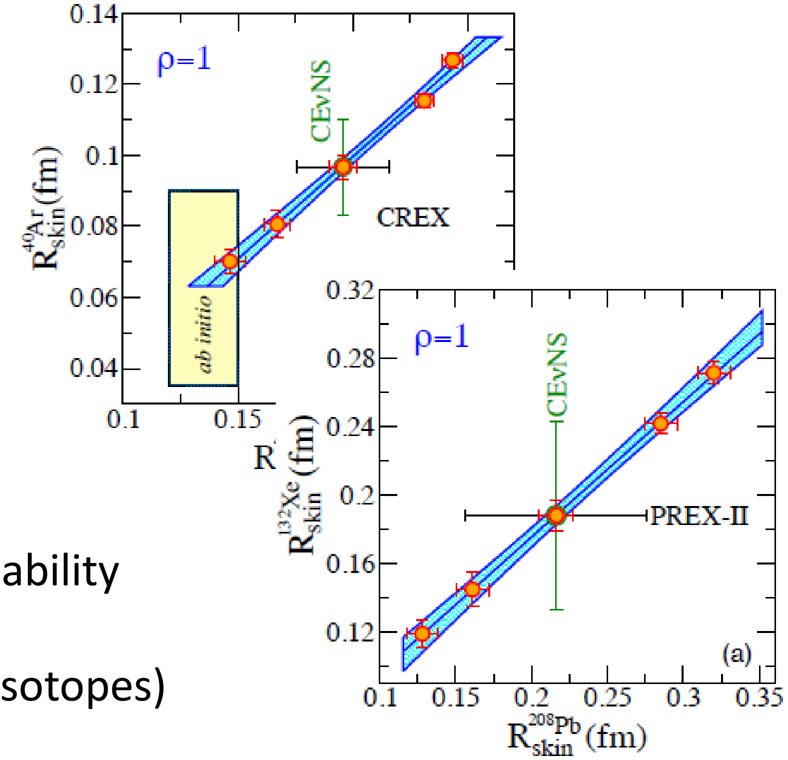
Crab Nebula (X-ray, infrared, radio, visible)

If PREX II (and other earth-based experiments) confirm that R_{skin} is large, and astrophysical observations, including new LIGO-Virgo evidence, continue to suggest that NS-radius is small, this may be evidence of a softening of the EOS at high densities

⇒ phase transition

Gravitational

electric dipole polarizability
heavy ion collisions
spectroscopy (diff in isotopes)



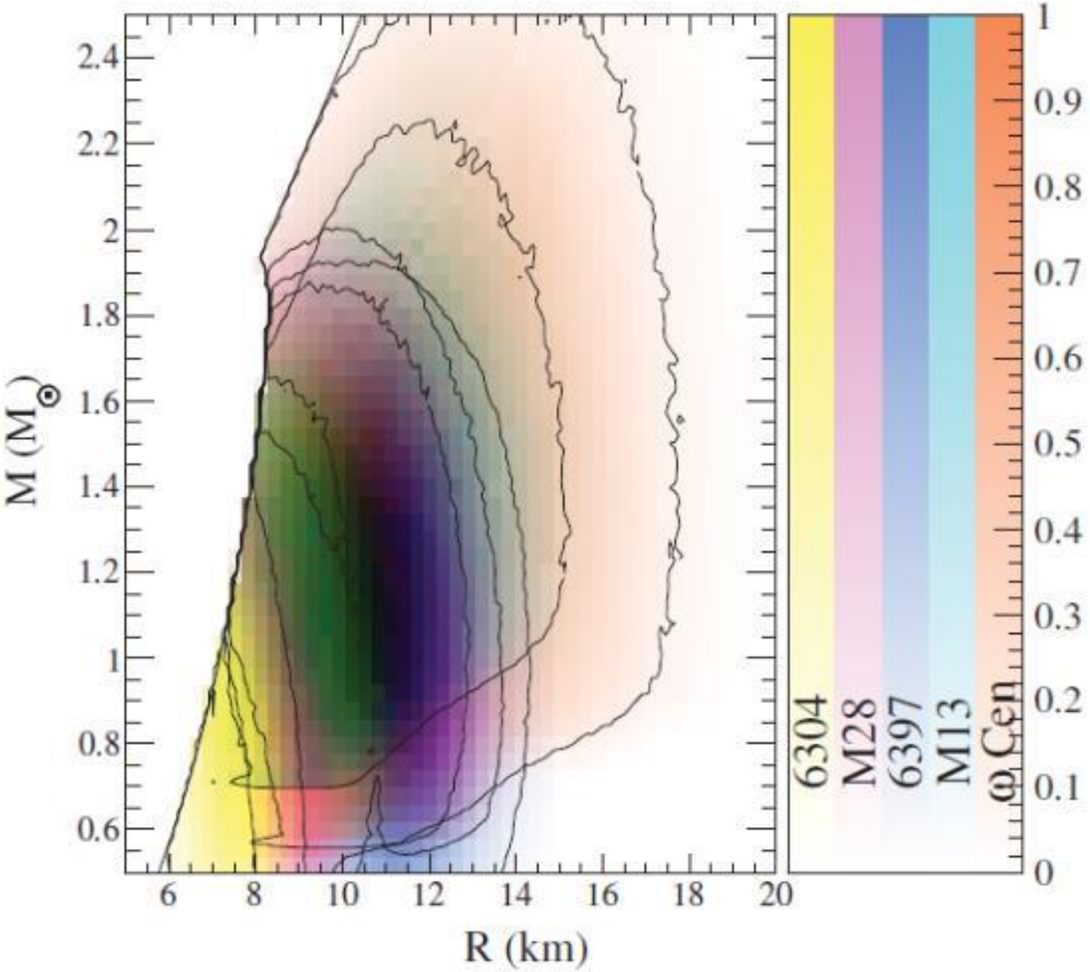
Many of these methods have complications from strong interaction dependencies

A clean measurement of the mean radius of the neutron density distribution in a heavy nucleus, R_n, provides key insight

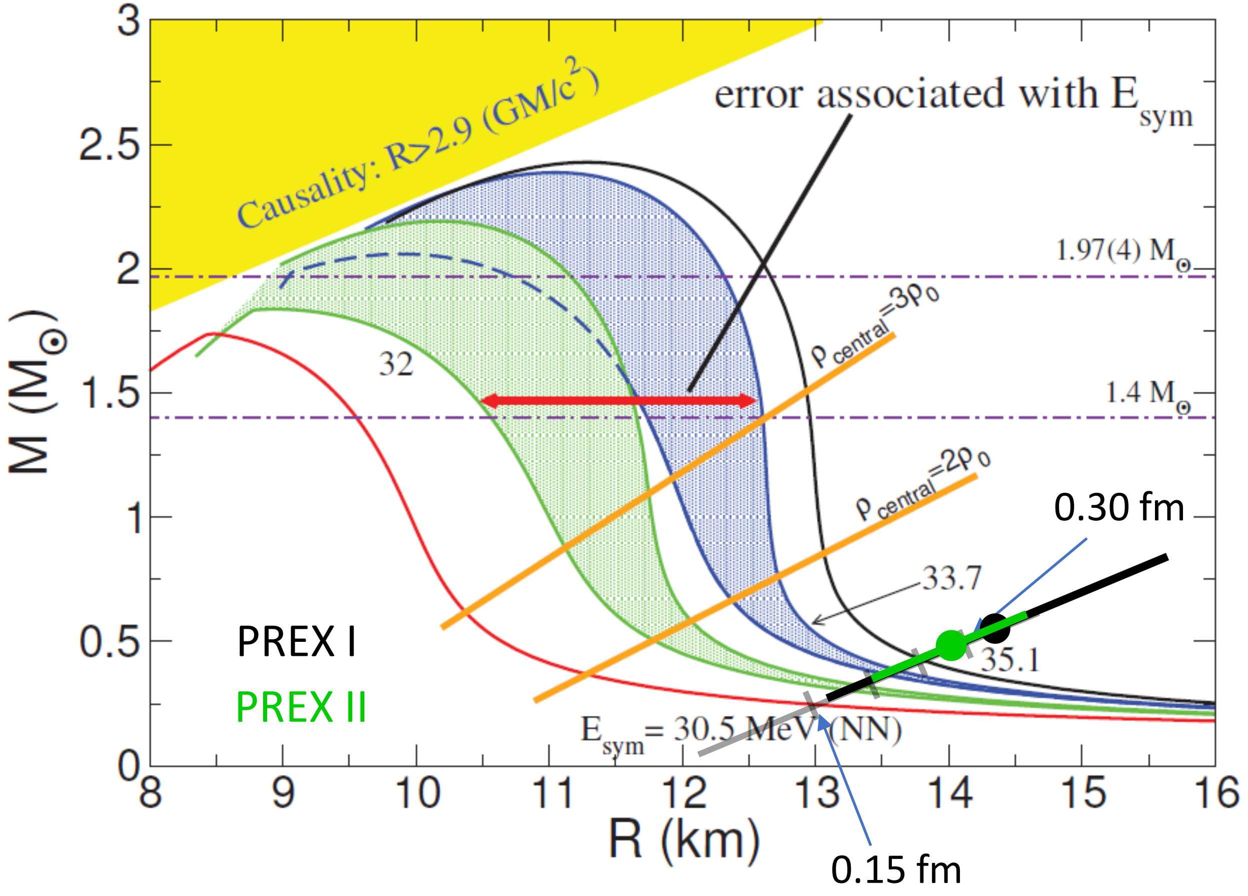
Neutron Star Radii

Using models, one can relate the neutron star radius to the neutron skin of heavy nuclei

J. Lattimer and A. W. Steiner Astrophys. J 784 (2014)



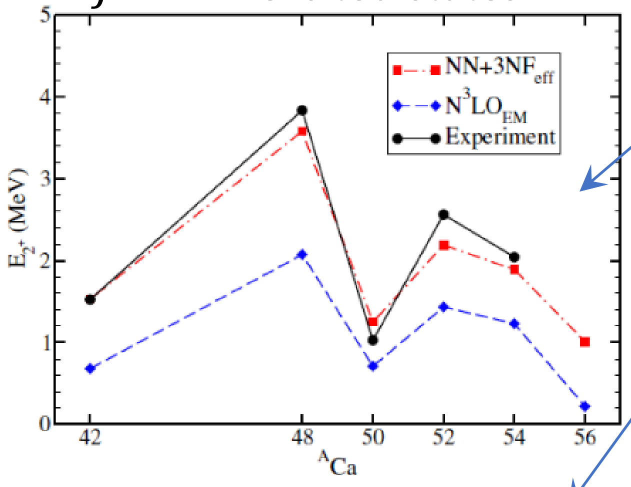
S. Gandolfi and A. W. Steiner J. Phys.: Conf. Ser. 665 (2016)

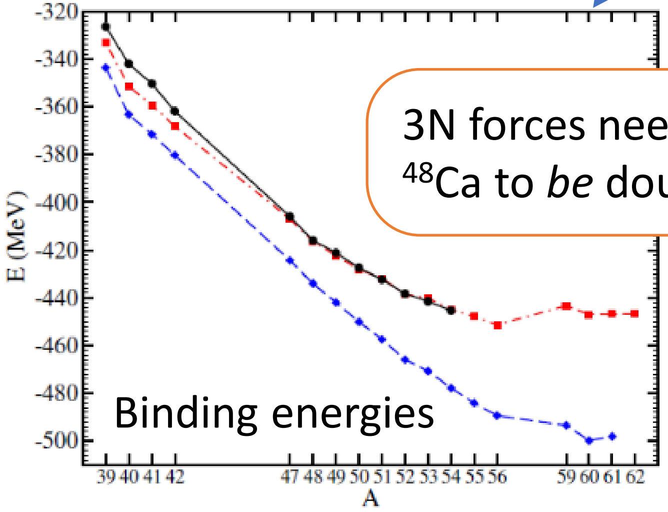


Including 3N forces changes the model predictions; CREX and PREX will help constrain the models

CREX Workshop (2013)

$J^{\pi} = 2^{+}$excited states



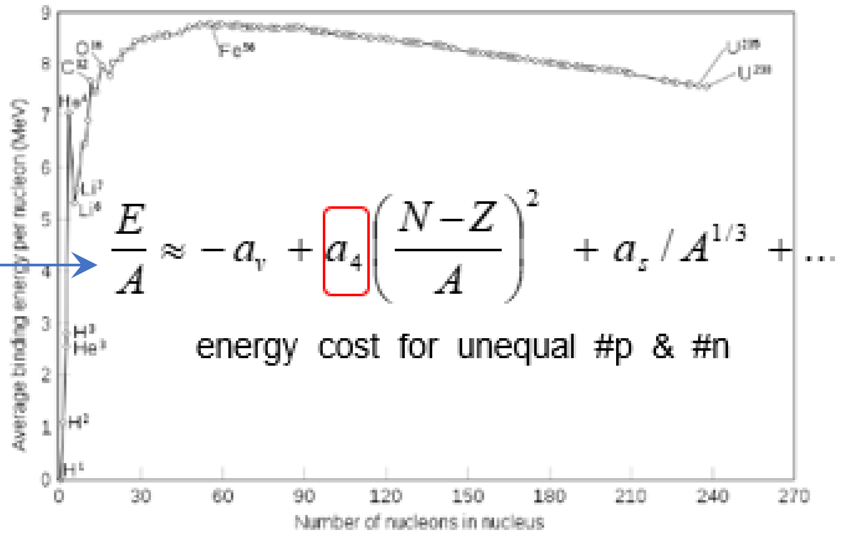


Binding energies

G. Hagen, et. al, 2013

3N forces needed for ^{48}Ca to *be* doubly-magic

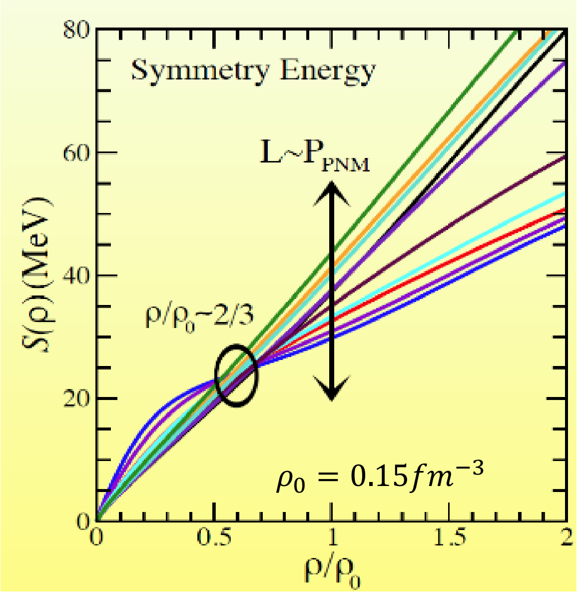
BE and charge radii are well described – but *isoscalar*

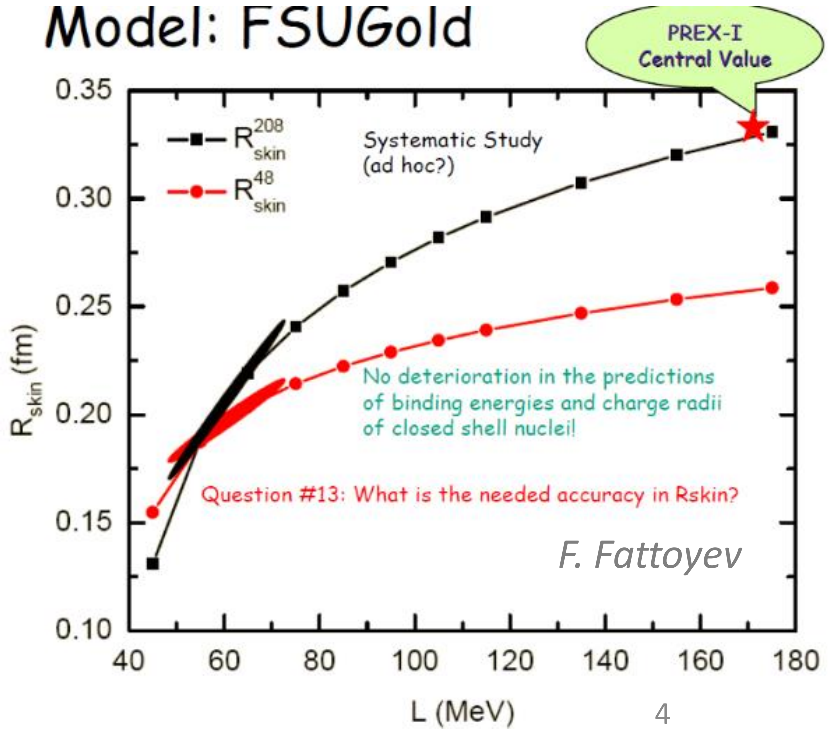


$$\frac{E}{A} \approx -a_v + \boxed{a_4}\left(\frac{N-Z}{A}\right)^2 + a_s / A^{1/3} + \ldots$$

energy cost for unequal #p & #n

The things we know the best are unaffected by *wildly different* values of L



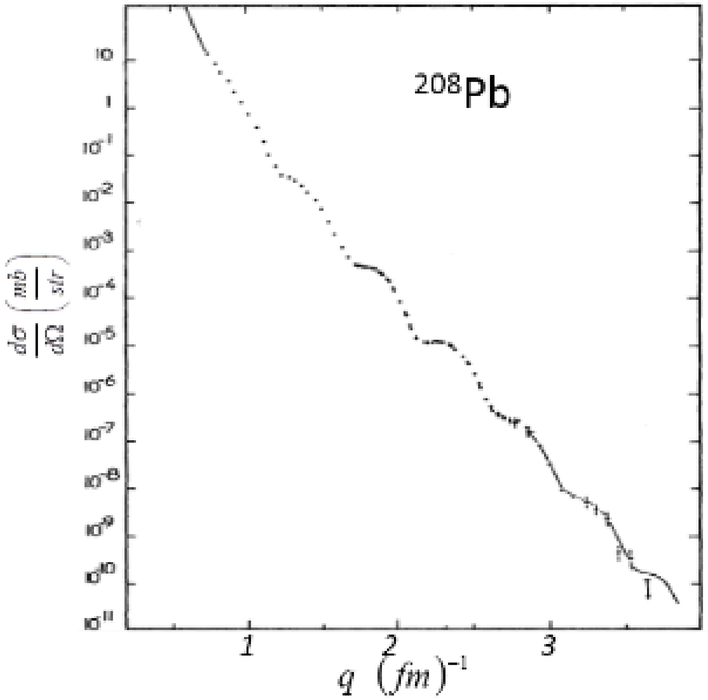


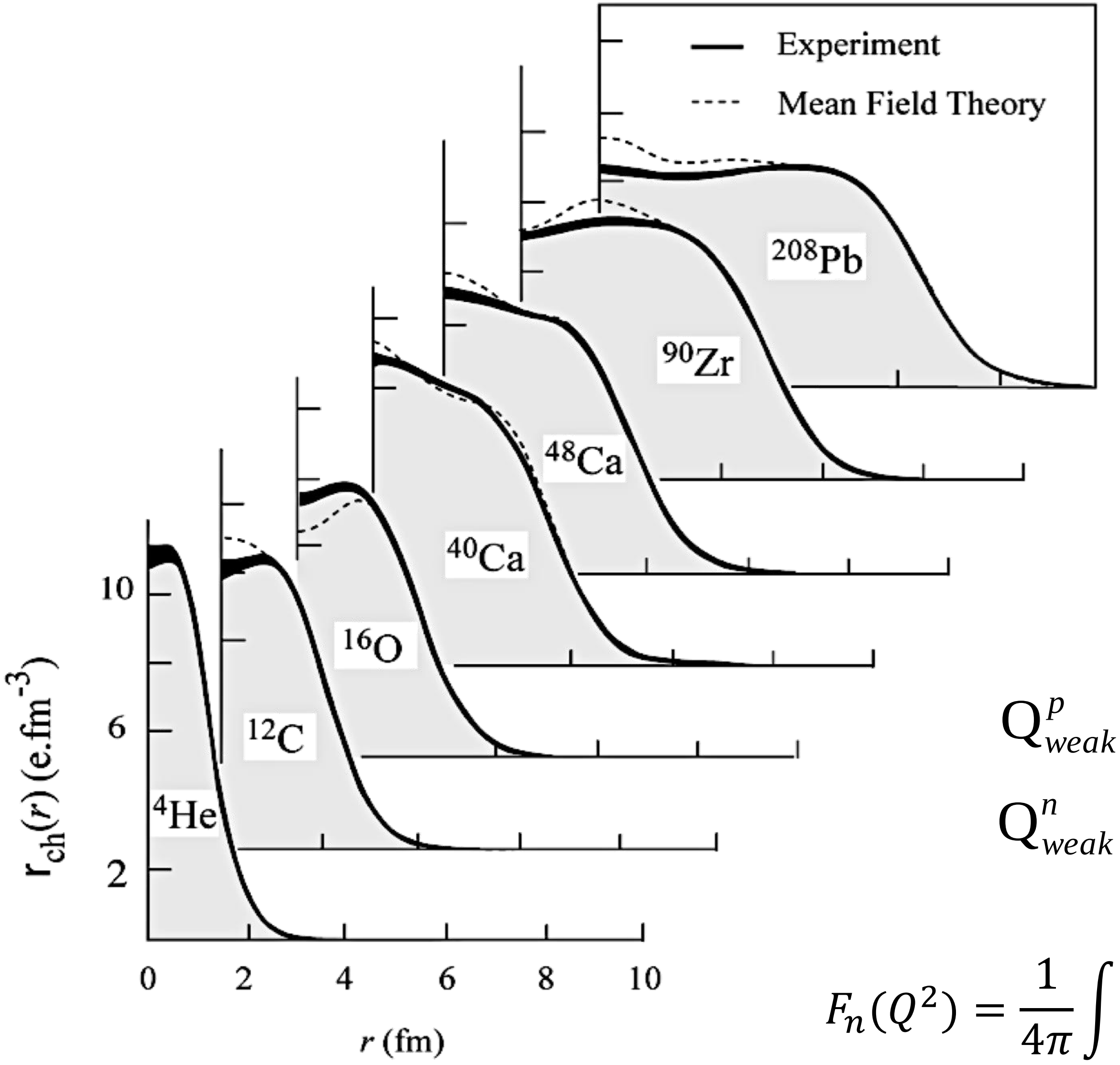
F. Fattoyev

Nuclear sizes from e- scattering – not a new idea!

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} \cdot |F(q^2)|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{4Z^2\alpha^2E^2}{Q^4}$$





$R_p \sim 5.5\ fm$

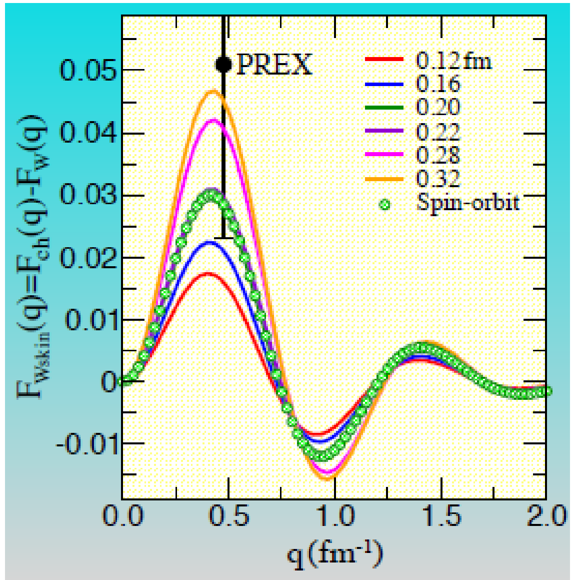
$$Q^{p}_{weak} = 1 - 4\sin^2\theta_W \approx 0$$

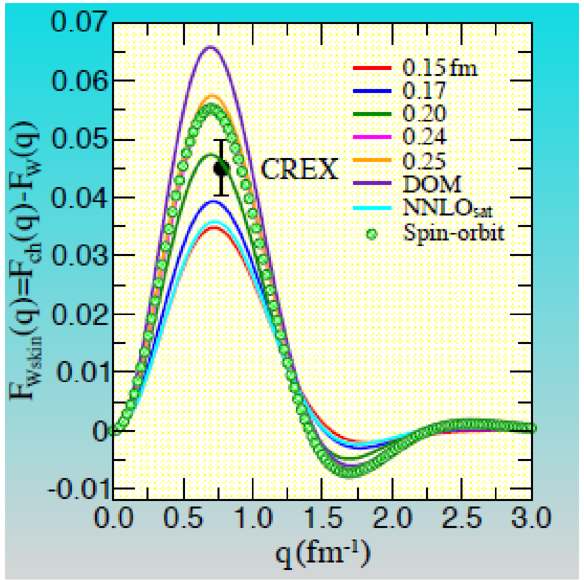
$$Q^{n}_{weak} = -1$$

$$F_n(Q^2) = \frac{1}{4\pi}\int d^3r j_0(qr)\rho_n(r)$$

New information in a poorly measured sector

Many measurements of isovector properties use strongly interacting probes and are sensitive to *p* AND *n*





Relate the parity-violating asymmetry to the "symmetry energy" as a function of density, $S(\rho)$

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

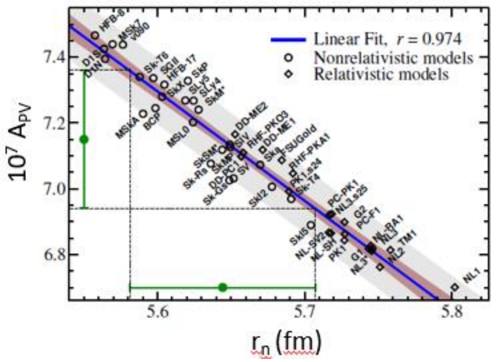
… more specifically, the slope of the symmetry energy at nuclear density, L (a'$_{asym}$)

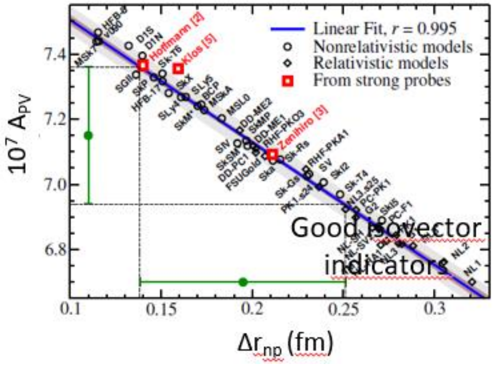
The Fourier transform of the weak "form factor" $F_W(Q^2)$ gives the weak charge density as a function of radius, just as it does for the charge form factor

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\overbrace{1-4\sin^2\theta_W}^{\approx 0} - \frac{\boxed{F_n(Q^2)}}{F_p(Q^2)}\right]$$

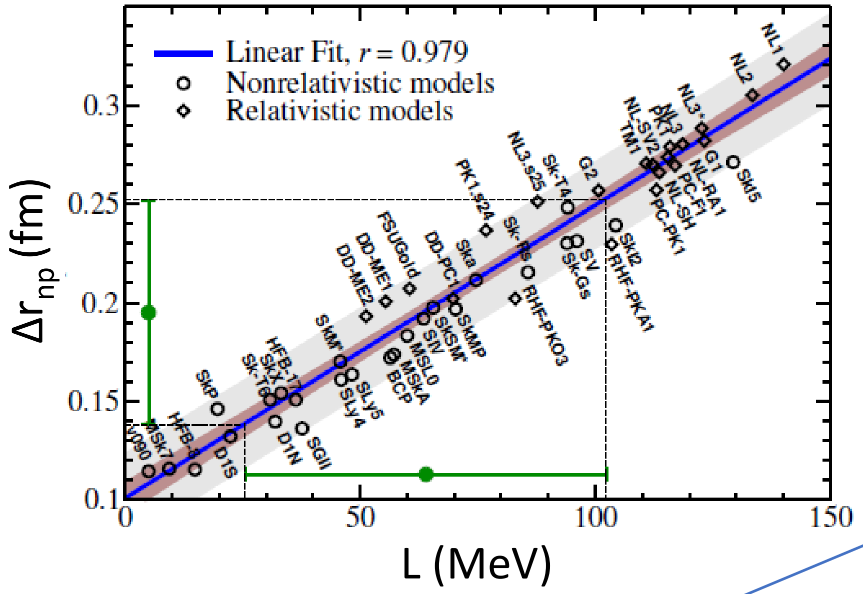
Measurement of $F_n(Q^2)$ at a single Q^2 translates to a measurement of R_n via mean-field nuclear models

New information in a poorly measured sector

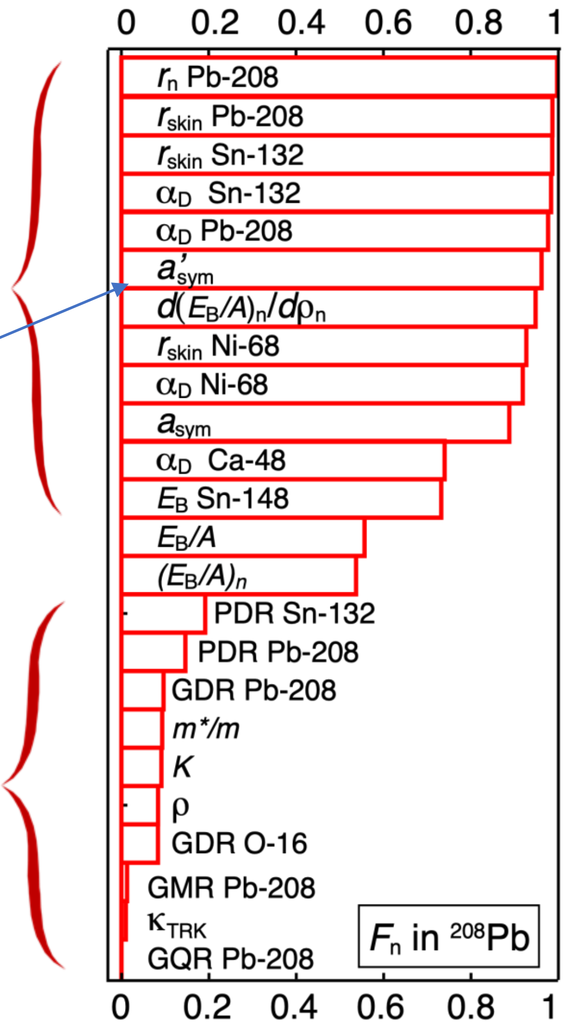




Roca-Maza et al, PRL 106, 25501 (2011)



Correlation of various observables with F_n in ^{208}Pb

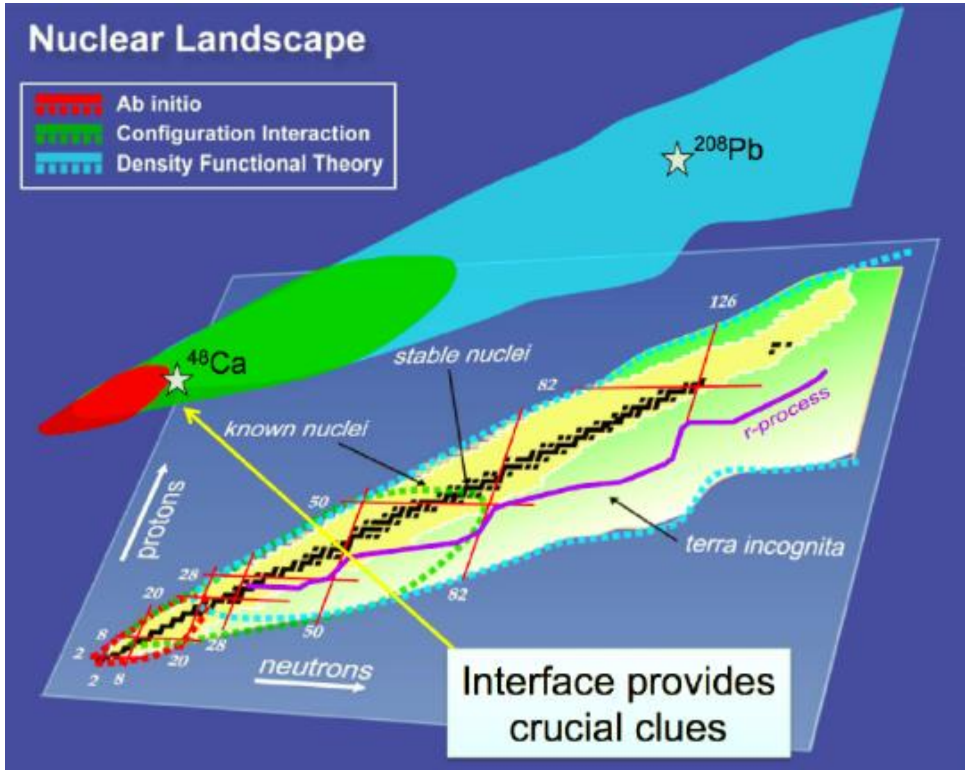


Good isovector indicators

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

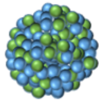
Poor isovector indicators (collective excitations, binding energies, etc.)

Why lead and calcium?

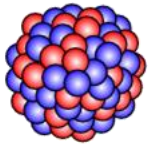


Theory from P. Ring et al. Nucl. Phys. A 624 (1997) 349

^{48}Ca

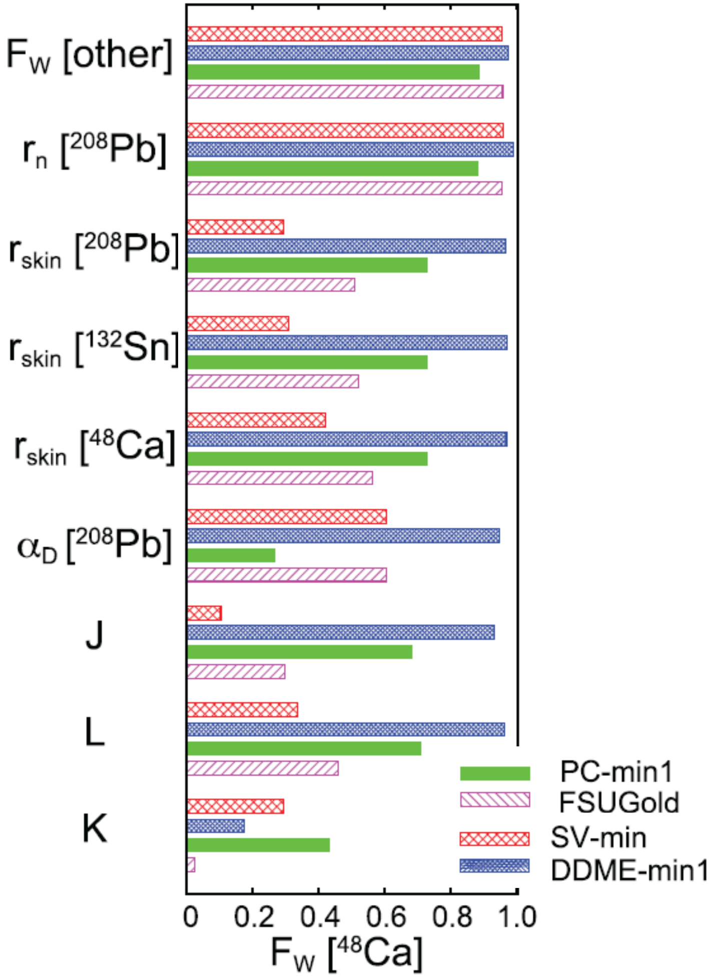


^{208}Pb



- R_n^{208} and R_n^{48} together will test nuclear structure models over a large range of A
- ^{208}Pb more like infinite nuclear matter
- ^{48}Ca nucleus is smaller; measure at Q^2 where the figure of merit is higher
- structure of ^{48}Ca can be addressed in detailed microscopic models; not possible for heavier nuclei
- R_n^{208} and R_n^{48} are correlated, but the correlation *depends on the correctness of the models*

Correlation of various observables with F_W in ^{48}Ca



P.-G. Reinhard, PRC 88, 034325 (2013)

PREX-2 Results – lots of interest

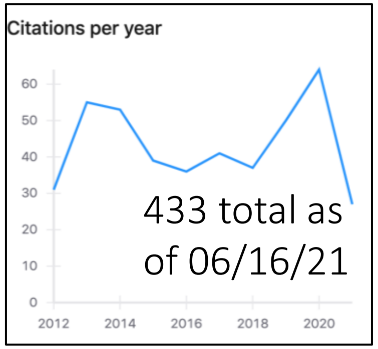
$$A_{\rm PV} = 550 \pm 16({\rm stat}) \pm 8\ ({\rm syst})$$

Implied neutron skin thickness

$$R_n - R_p = 0.283 \pm 0.071\ {\rm fm}$$

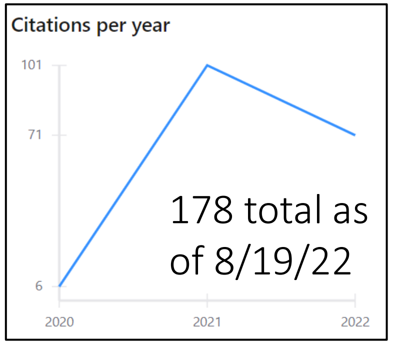
APS Viewpoint
“highlighting exceptional research”

PREX-1 (Jan 2012)



433 total as of 06/16/21

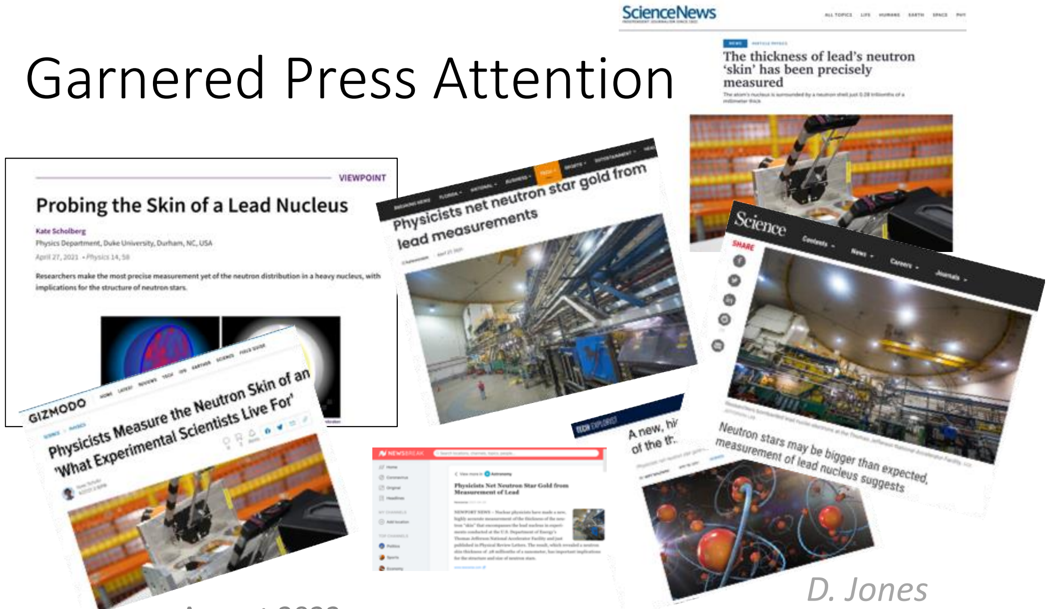
PREX-2 (Feb 2021)



178 total as of 8/19/22

Citations indicate community interest

Garnered Press Attention



ScienceNews

The thickness of lead’s neutron ‘skin’ has been precisely measured

VIEWPOINT

Probing the Skin of a Lead Nucleus

Kate Scholberg

Physics Department, Duke University, Durham, NC, USA

April 27, 2021 • Physics 14, 58

Researchers make the most precise measurement yet of the neutron distribution in a heavy nucleus, with implications for the structure of neutron stars.

Physicists net neutron star gold from lead measurements

GIZMODO

Physicists Measure the Neutron Skin of an 'What Experimental Scientists Live For'

Science

Neutron stars may be bigger than expected, measurement of lead nucleus suggests

NEWSBREAK

Physicists Net Neutron Star Gold from Measurement of Lead

TECH EXPLORIST

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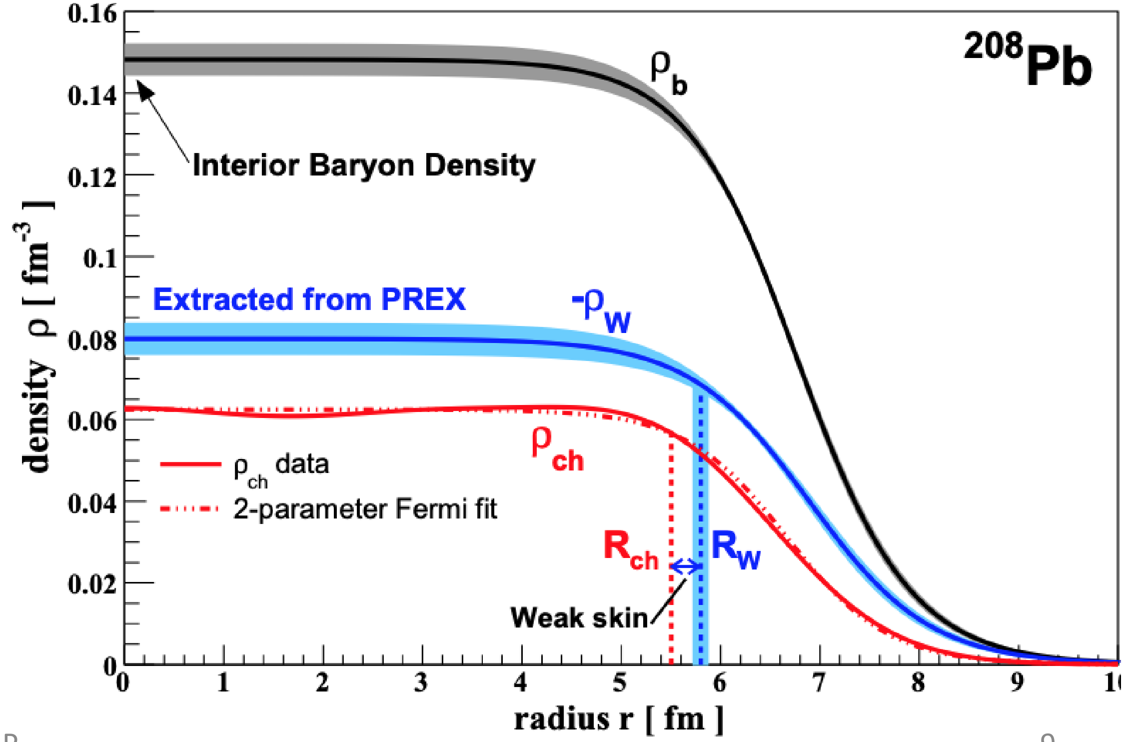
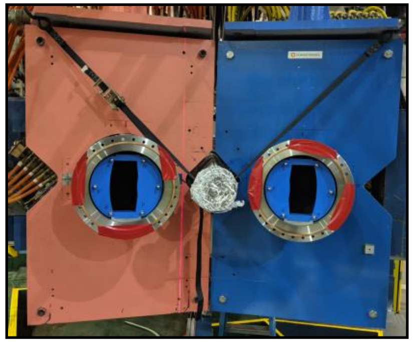
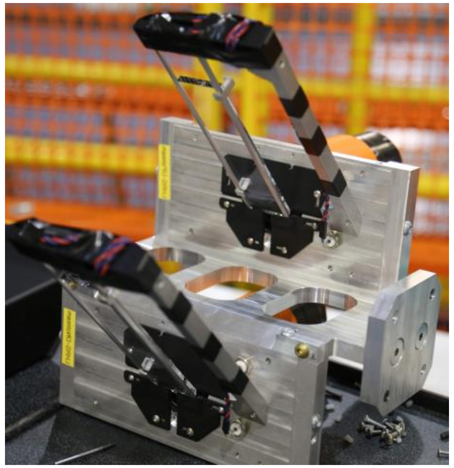


CREX experiment

$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$

2.2 GeV electron beam, 150 μA
helicity reversal at 30 Hz
5 mm thick Ca target
4° scattered electrons
$Q^2 = 0.03\ \mathrm{GeV}^2/c^2$

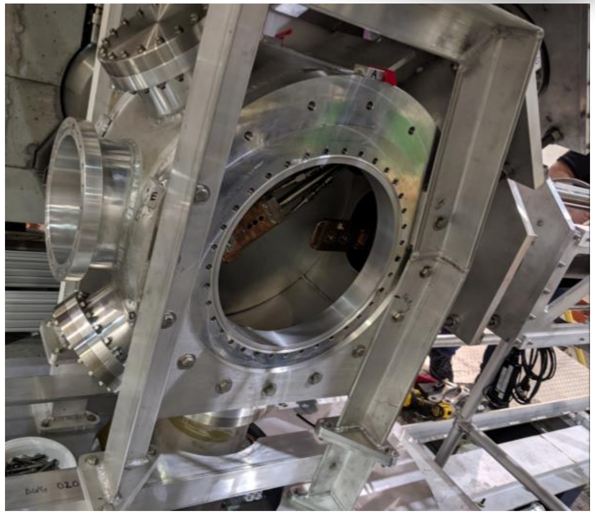




PREX
1 GeV electron beam, 50-70 μA
helicity reversal at 120 Hz
0.5 mm thick Pb target
5° scattered electrons
$Q^2 = 0.006\ \mathrm{GeV}^2/c^2$

Same:

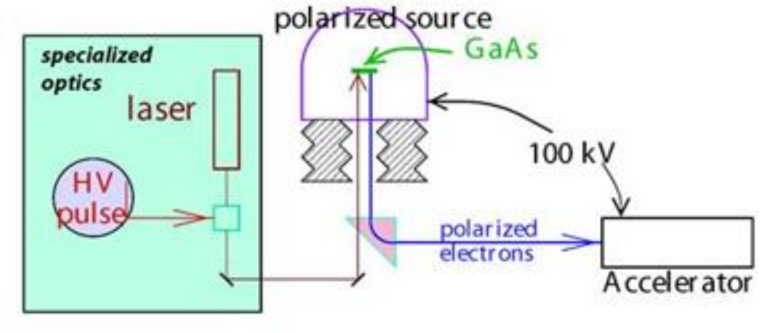
- accelerator
- beam monitors
- septum magnet
- precision collimators
- thick and thin quartz detectors
- tracking detectors
- scattering chamber
- target ladders

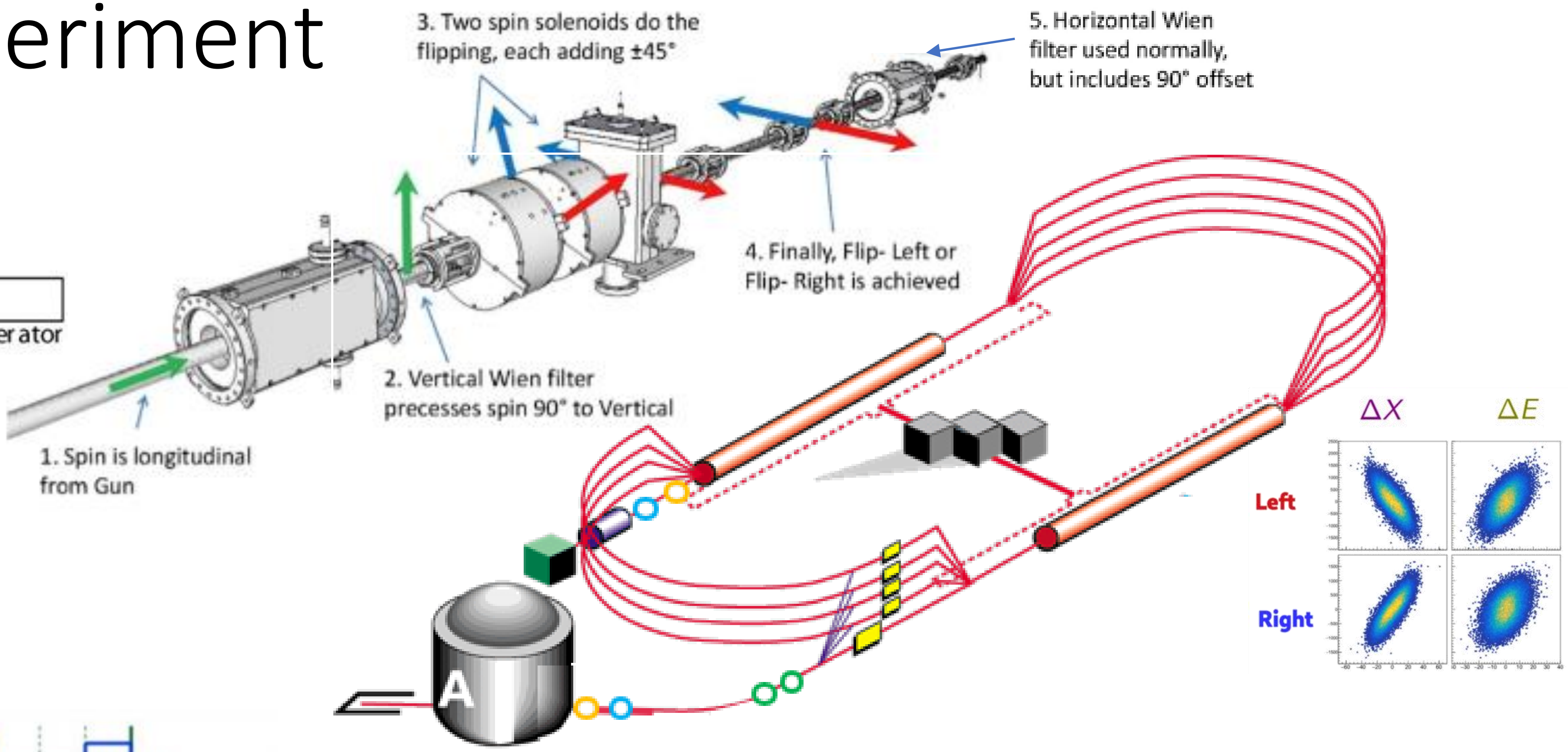


Both had highly polarized (>89%) beam

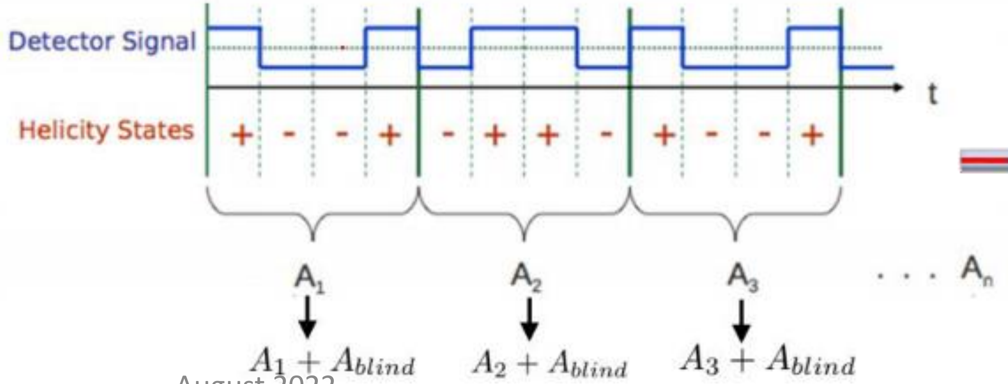
The whole accelerator is part of the experiment

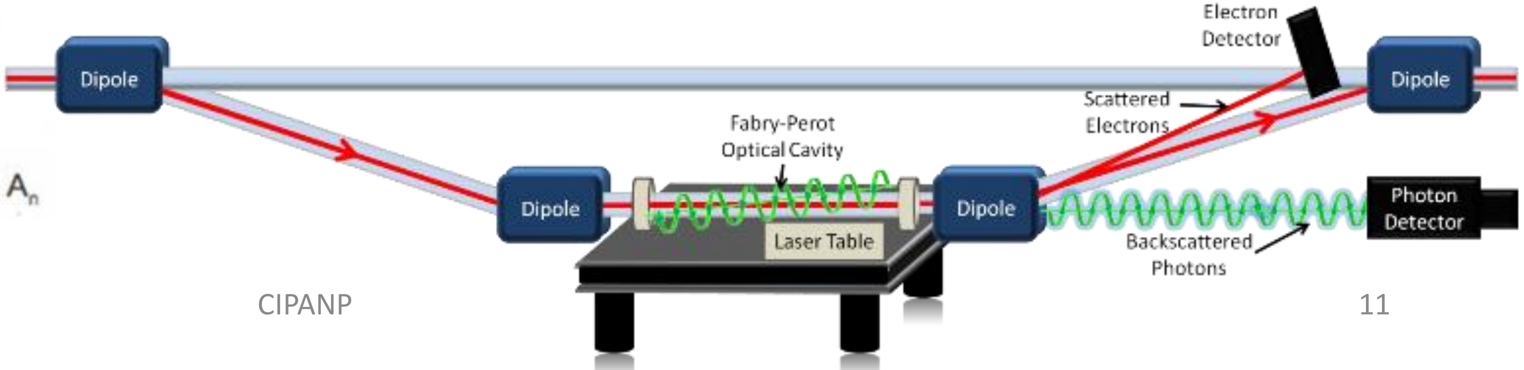
$$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$$





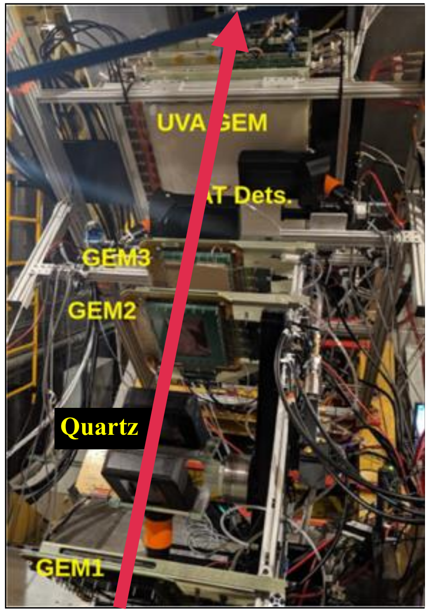
$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

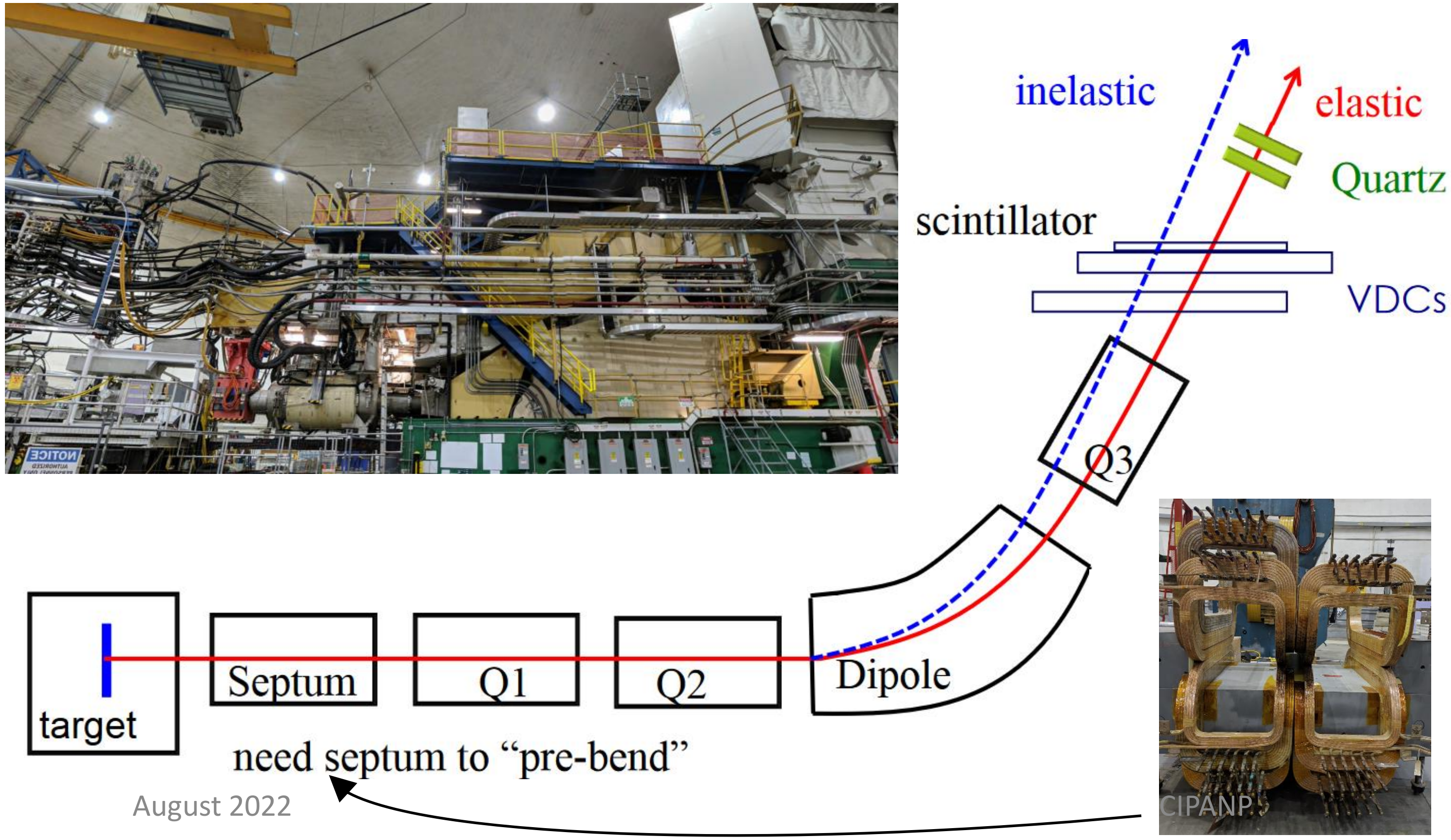


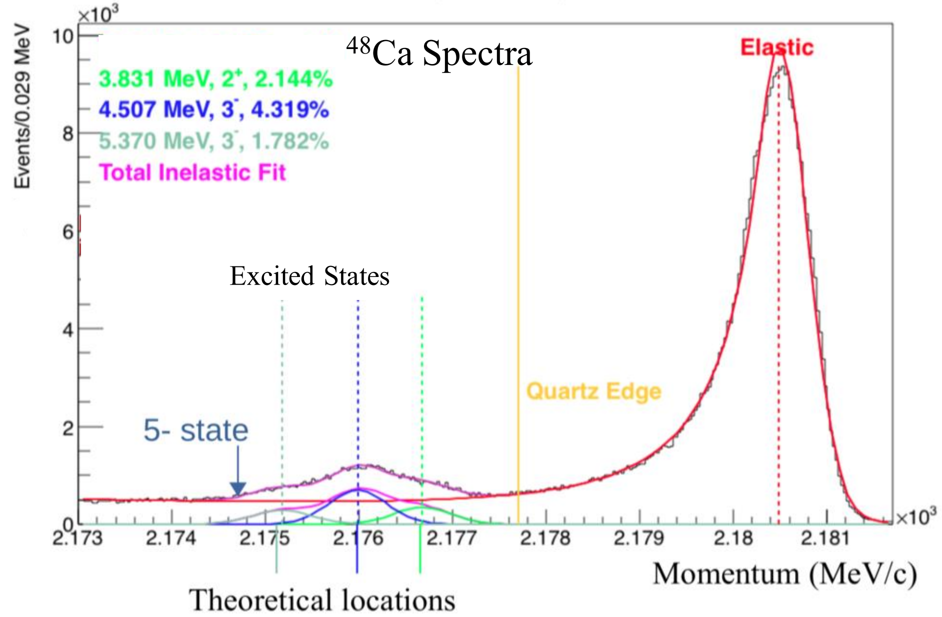


High-Res Spectrometers

- Spectrometer separates elastic peak, directs it onto integrating detector
- Integrate detectors in each of the spectrometer pairs independently
- Counting detectors used in special low current runs

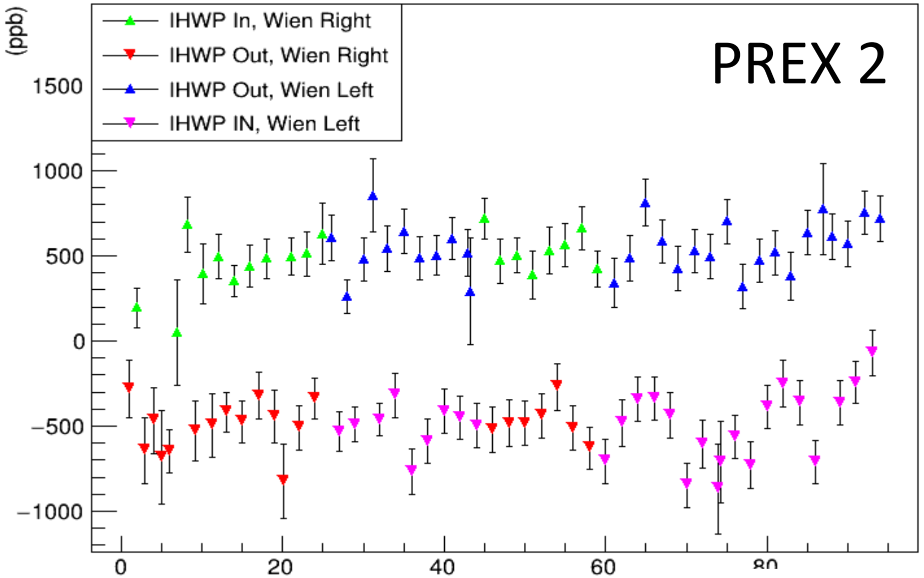




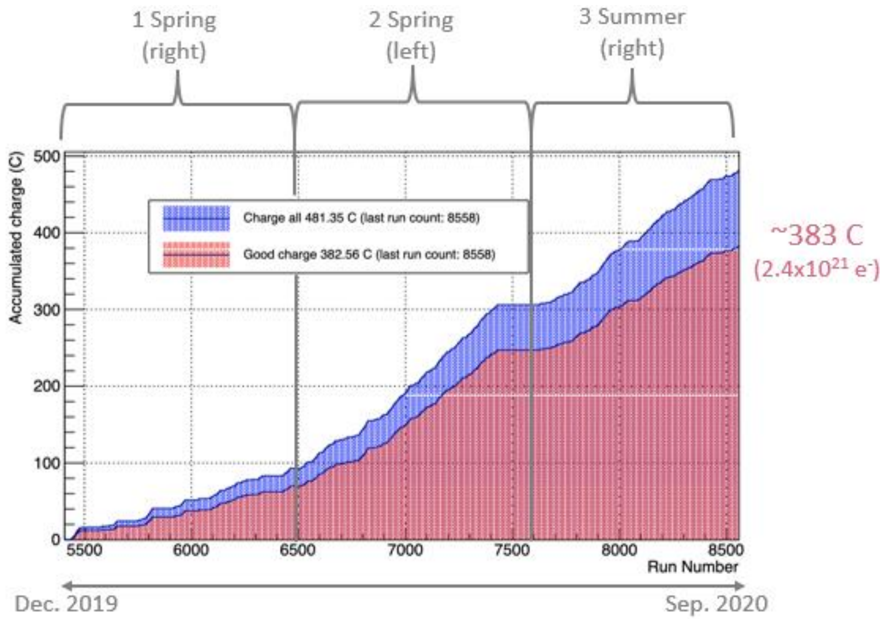


Data quality

$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$

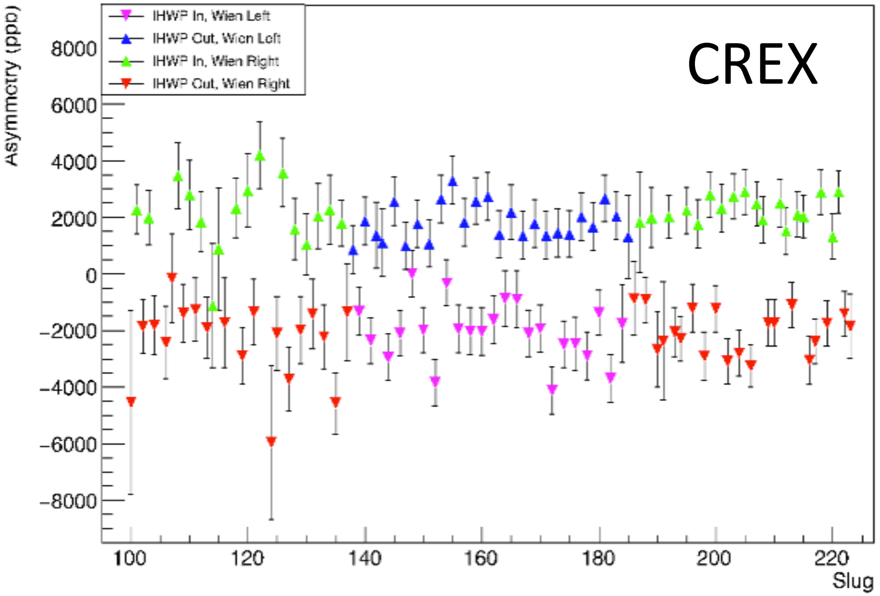


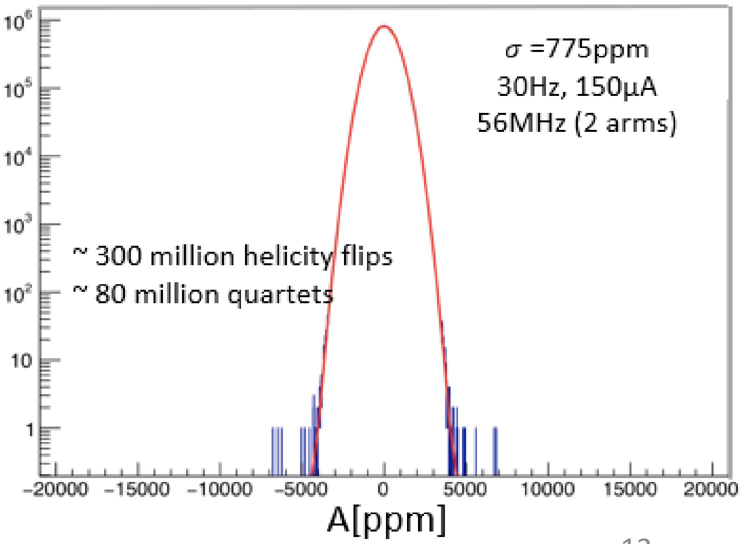
- dominated by counting statistics
- PREX 4GHz, 0.55ppm



~383 C (2.4×10^{21} e$^-$)

- CREX less challenging
  - 50 MHz (1% PREX)
  - larger asymmetry ~ 2 ppm





σ =775ppm
30Hz, 150μA
56MHz (2 arms)

~ 300 million helicity flips
~ 80 million quartets

$$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$$

Extracting A_{PV}

$$= R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

- The total experimental systematic uncertainty is 1.6%
    - Biggest is acceptance normalization at 0.9%
    - Next biggest – inelastic contamination at ~0.8%
    - less than half the 4.5% statistical uncertainty

Blinded A_{PV} → 2334.8 ± 112.4 ppb

Unblinded A_{PV}:

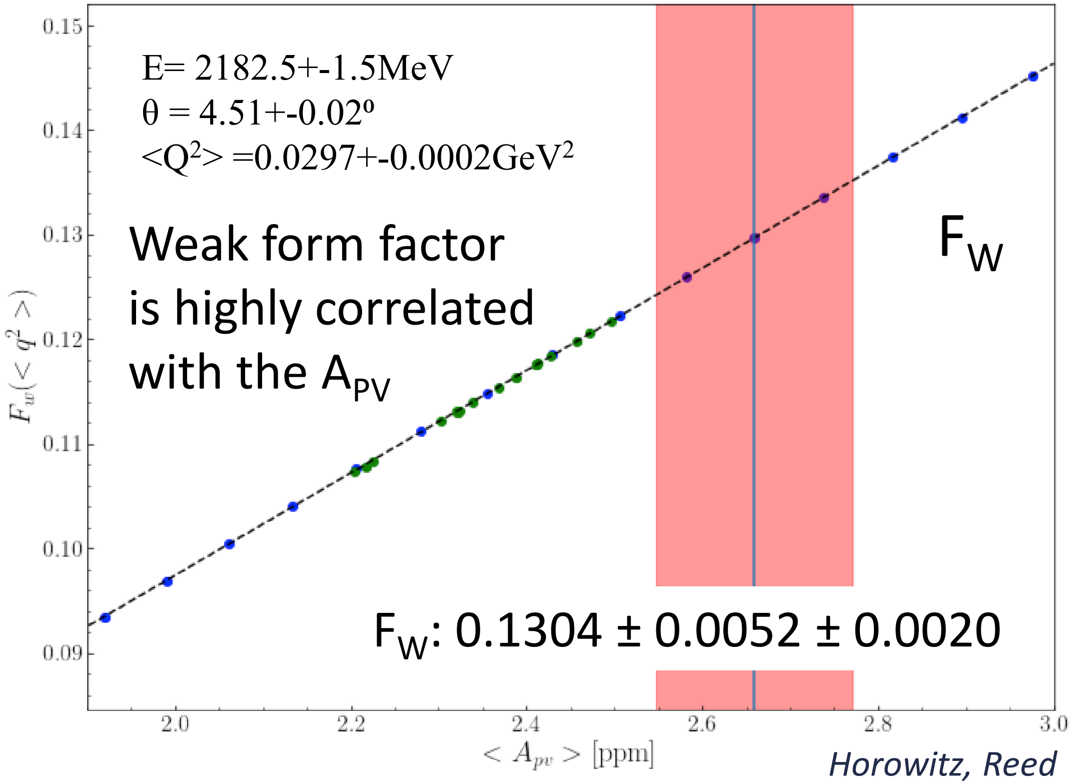
2658.6 ± 113.2ppb (4.3%)

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

	A_{PV} uncertainty contribution [ppb]	**A_{PV} uncertainty contribution [%]**
Polarization	11.7	0.50%
Horizontal Polarization	12.7	0.54%
Vertical Polarization	0.9	0.04%
Acceptance normalization	21.0	0.90%
Beam correction	6.9	0.30%
Non-linear detector response	6.7	0.29%
Ca40 background	8.8	0.38%
Charge correction	1.1	0.05%
Inelastic contamination 2+	19.1	0.82%
Inelastic contamination 3-(1)	10.2	0.44%
Inelastic contamination 3-(2)	3.6	0.15%
Rescattering	0.4	0.02%
Total	**37.3**	**1.6%**

Extracting F_w

$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$

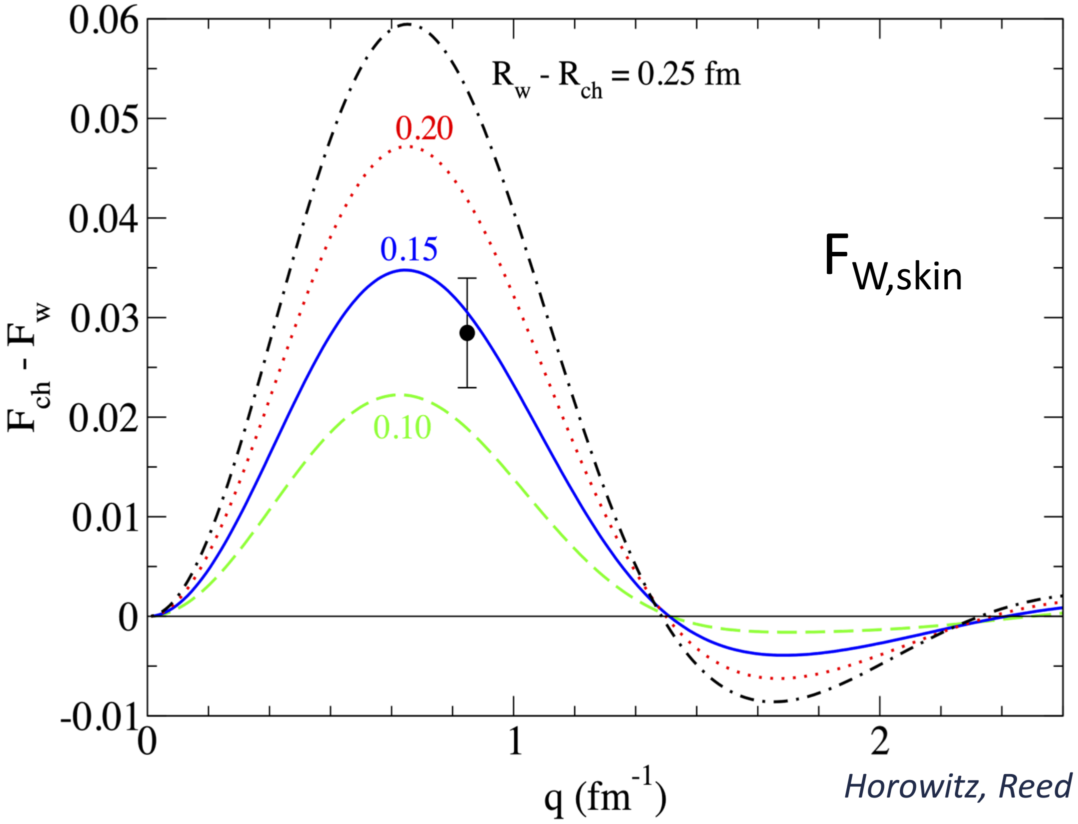


Weak form factor is highly correlated with the A_{PV}

F_W

F_W: 0.1304 ± 0.0052 ± 0.0020

Horowitz, Reed



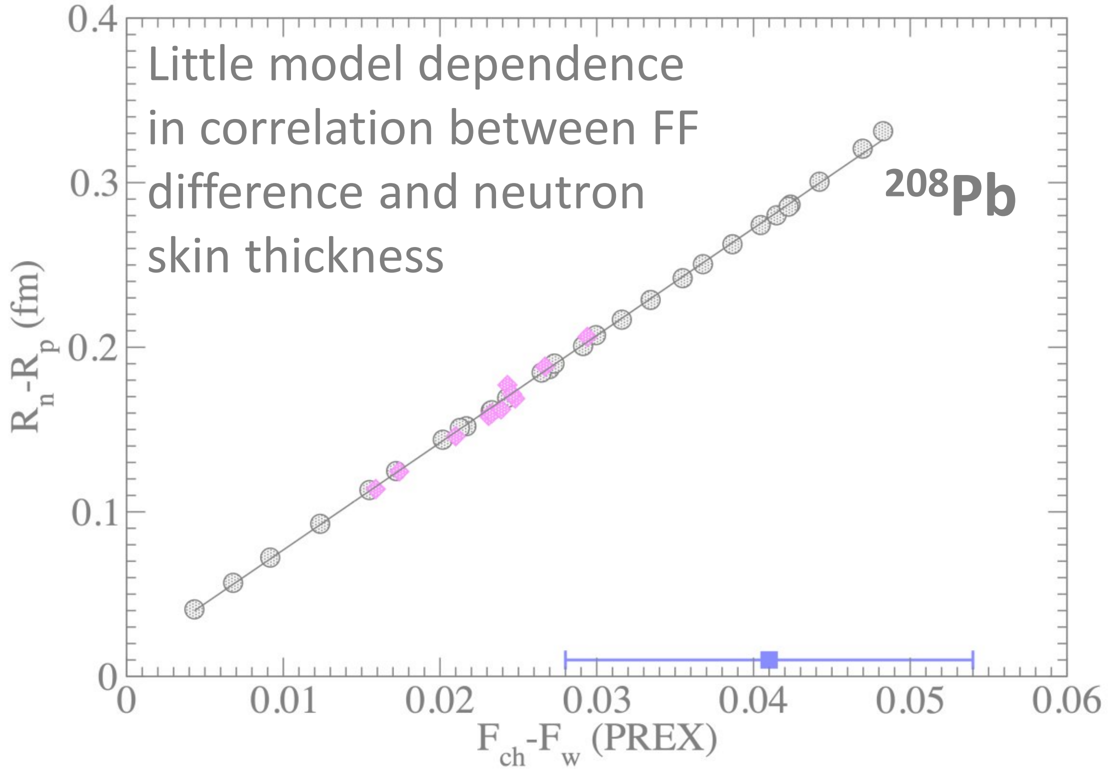
$F_{W,skin}$

Horowitz, Reed

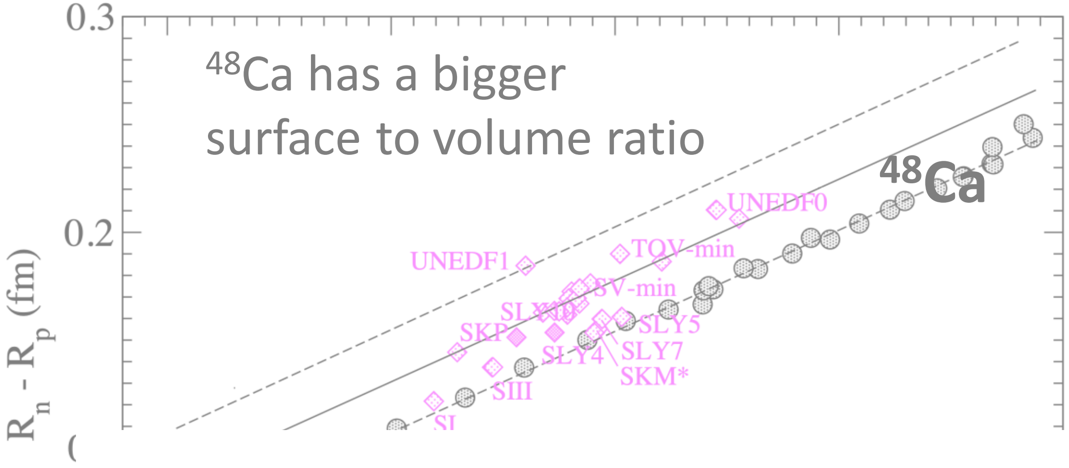
Example models for ΔFF with the CREX measurement at sub-optimal Q

Neutron radius and skin

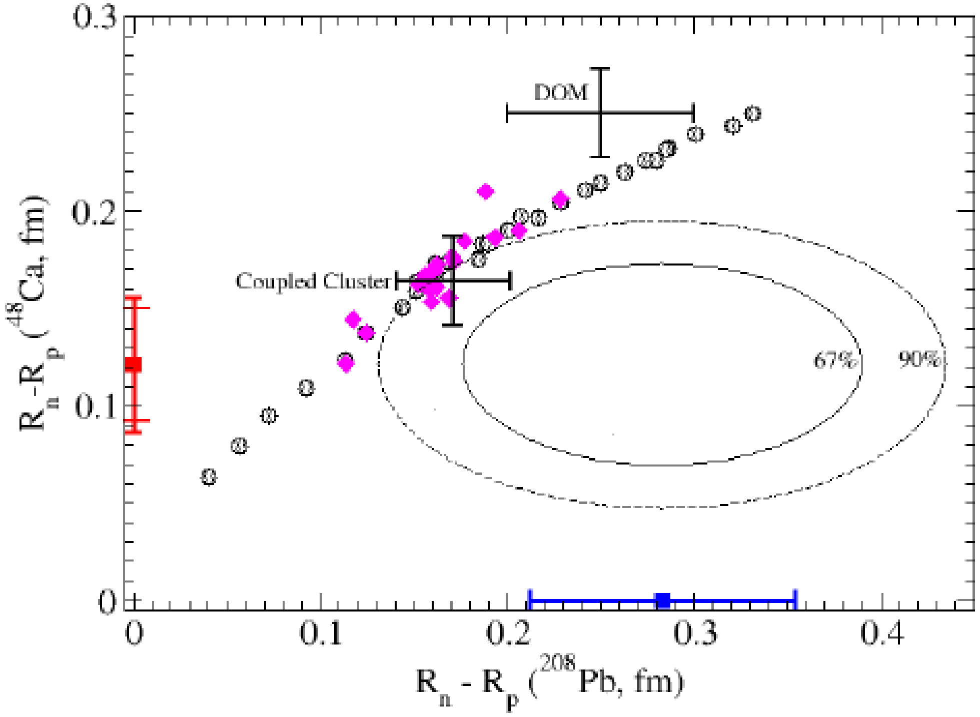
$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$



Little model dependence in correlation between FF difference and neutron skin thickness



^{48}Ca has a bigger surface to volume ratio

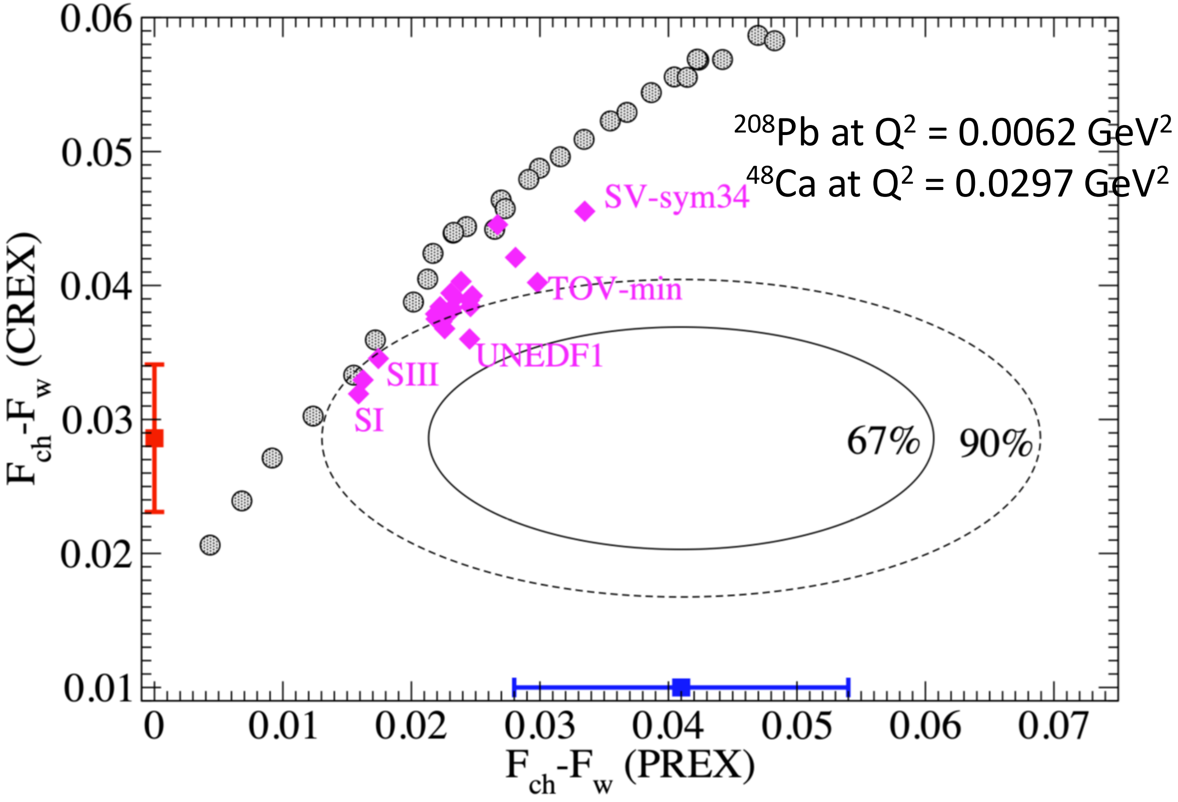


^{48}Ca neutron skin, R_n - R_p

0.121 ± 0.026 (exp) ± 0.024 (model) fm

CREX Implications

$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$



CREX result is **strongly inconsistent** with predictions of a very thick skin; more consistent with a thin neutron skin prediction (e.g. coupled cluster calculations)

The main physics output from the PREX/CREX experimental campaign is the **difference in the charge and weak form factors (FF)** for each

Community is discussing implications…

- Interplay between ^{208}Pb and ^{48}Ca underscores rich dynamics
- CREX is accurate enough to be sensitive to spin-orbit and meson exchange currents in ^{48}Ca
- Full implications for symmetry energy slope L will require continued collaboration between various theoretical and experimental groups
- challenging for DFT models to reproduce both the CREX result of a thin skin in ^{48}Ca and the PREX result of a relatively thick skin in ^{208}Pb

Summary and Outlook

- The PREX measurement of the neutron skin thickness of ^{208}Pb has very little model uncertainty
  - There is a clear and transparent line from the statistical uncertainty in the experimental observable (A_{PV}) to the uncertainty in the neutron skin thickness and then on to slope of the symmetry energy: unique among all measurement techniques!
  - Given the above, improved A_{PV} uncertainty is desirable; a group of us have investigated a possible improved measurement at Mainz, targeting an uncertainty of +/- 0.04 fm

- The CREX measurement is likely the final statement at low Q for ^{48}Ca
  - Before extracting information on slope of the symmetry energy, the community must collaborate to carefully evaluate modeling uncertainties
  - Given the focus of NSCL and FRIB measurements on a range of nuclei of similar A, reconciling all the experimental data is going to lead to important new insights ⇒ Exciting!
  - If found compelling, it might be feasible to devise a new A_{PV} measurement on ^{48}Ca at a different Q value at Mainz

Congratulations to our crew

Students: Devi Adhikari, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, Cameron Clarke, Catherine Feldman, Iris Halilovic, Siyu Jian, Eric King, Carrington Metts, Marisa Petrusky, Amali Premathilake, Victoria Owen, Robert Radloff, Sakib Rahman, Ryan Richards, Ezekiel Wertz, Tao Ye, Allison Zec, Weibin Zhang

Post-docs and Run Coordinators: Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

Spokespeople: D. McNulty, J. Mammei, P. Souder, S. Covrig Dusa, R. Michaels, K. Paschke, S. Riordan

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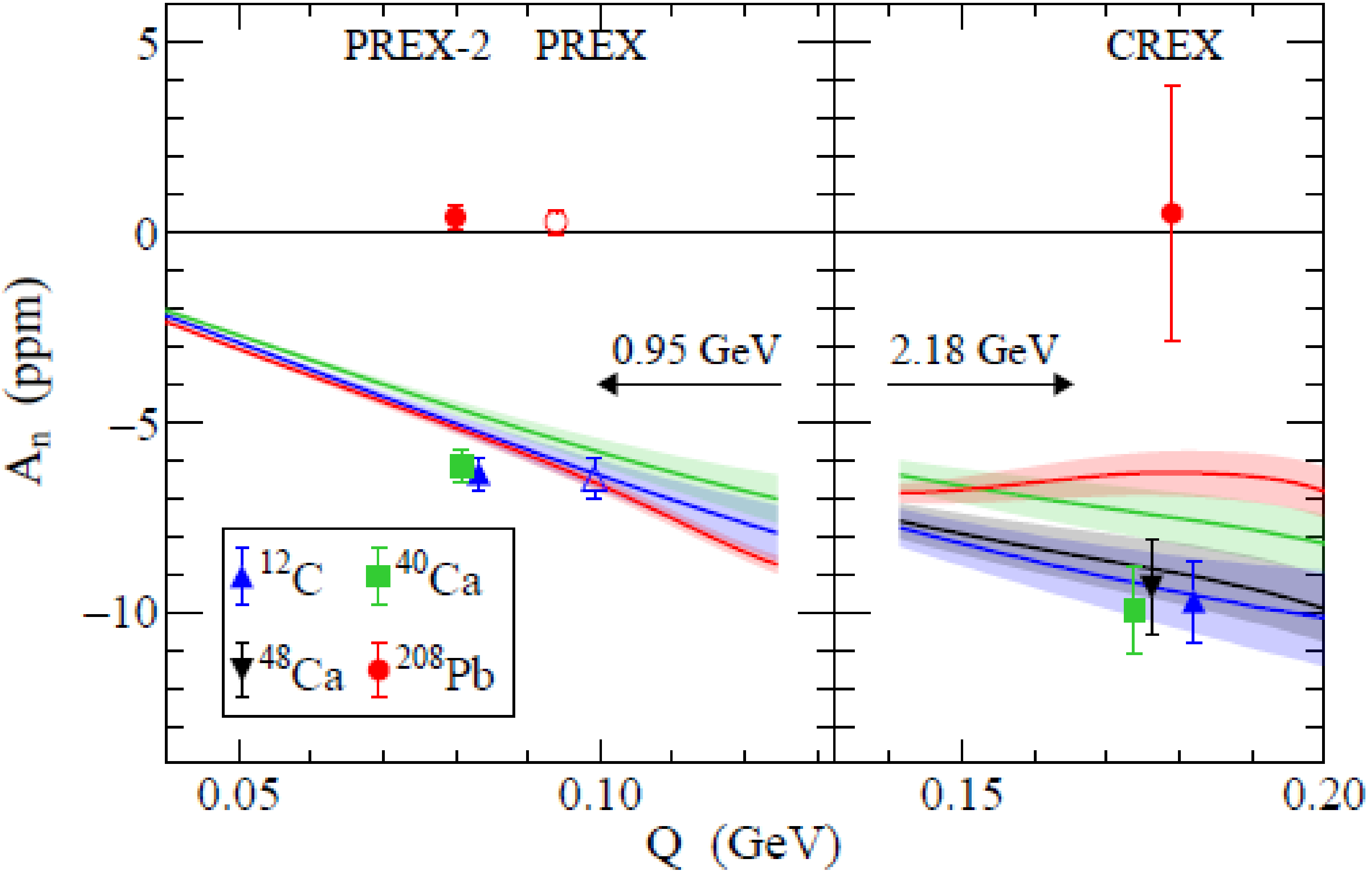
Special thanks to: Charles Horowitz and Jorge Piekarewicz for support and insightful conversations

Especially Chuck and grad student Brendan Reed who have worked to help us interpret our results

Backups

Transverse asymmetry for various nuclei



Special equipment

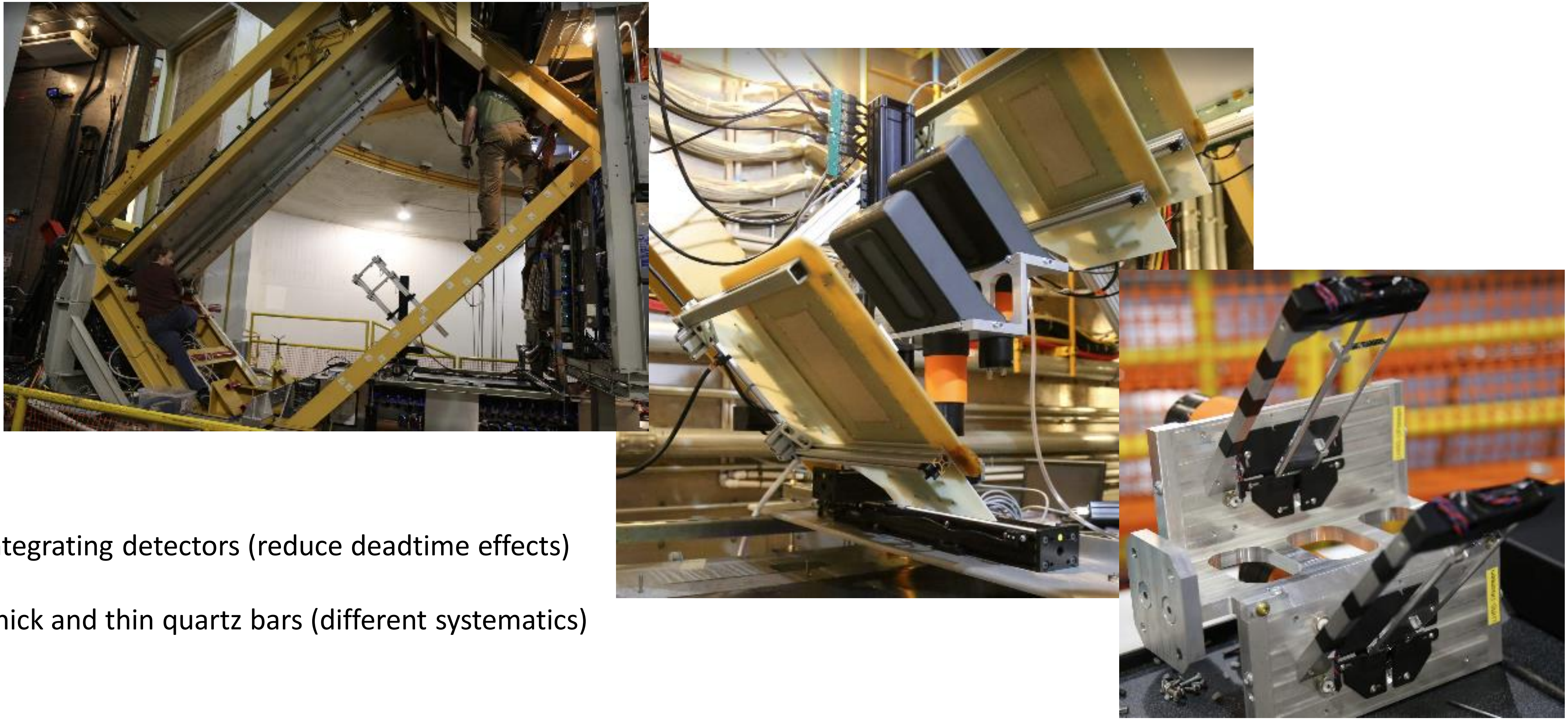
Kent Paschke

Septum magnet needed because to reach the low angles

Vacuum vessel to transport scattered electrons in vacuum to detector hut

Precision collimators to define the acceptance

Special equipment, cont.



Integrating detectors (reduce deadtime effects)

Thick and thin quartz bars (different systematics)

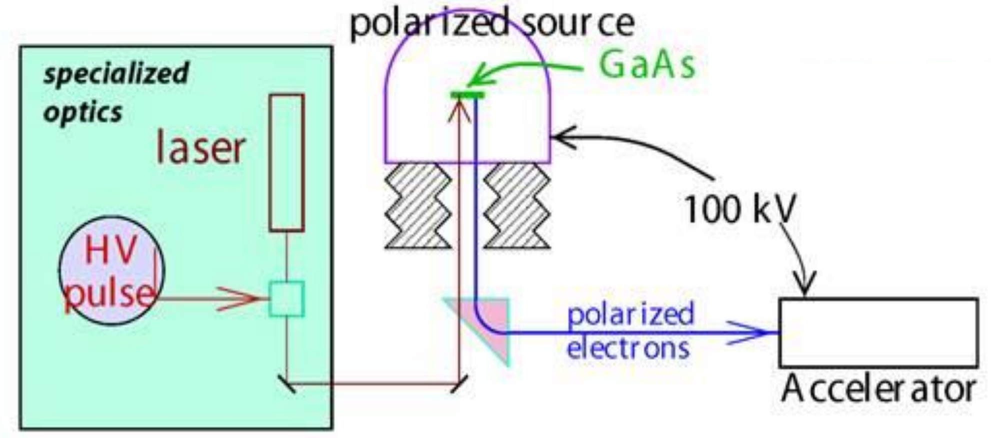
Polarized Electron Source

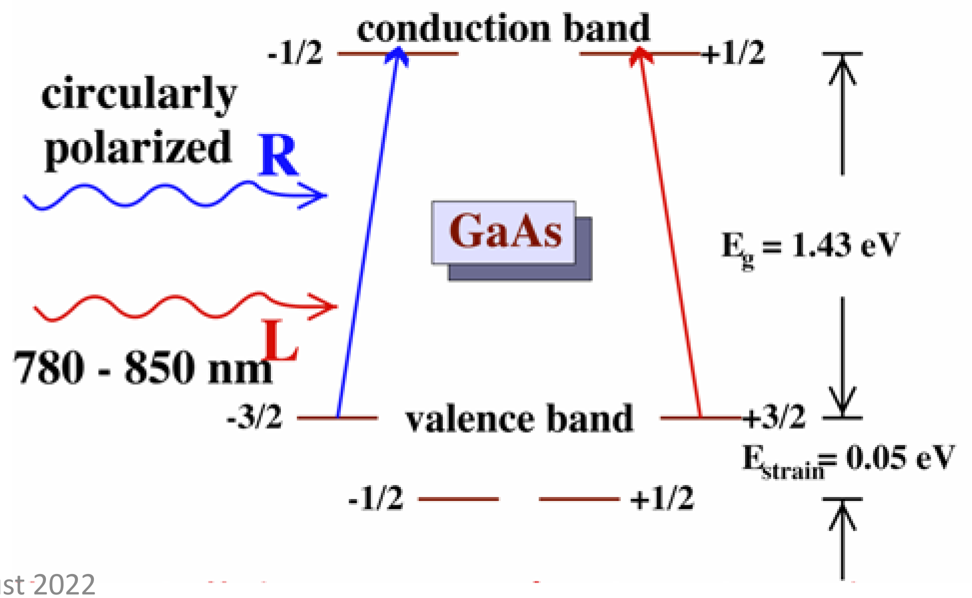
photoemission of electrons from GaAs

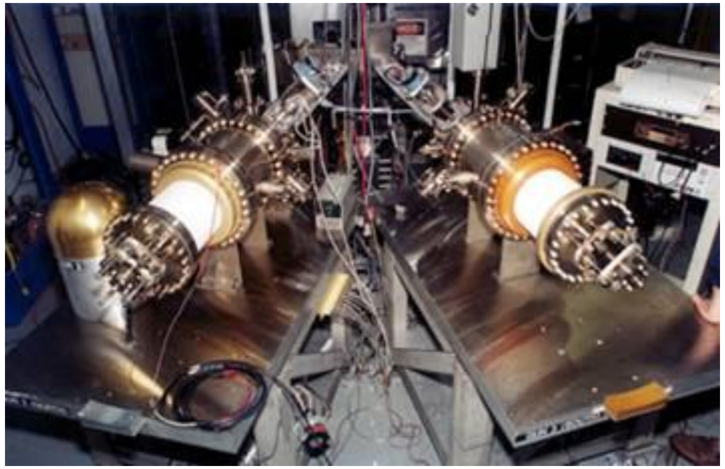
→"Bulk" GaAs typical P_e ~ 37%
theoretical maximum - 50%

→ "Strained" GaAs = typical P_e ~ 80%
theoretical maximum - 100%

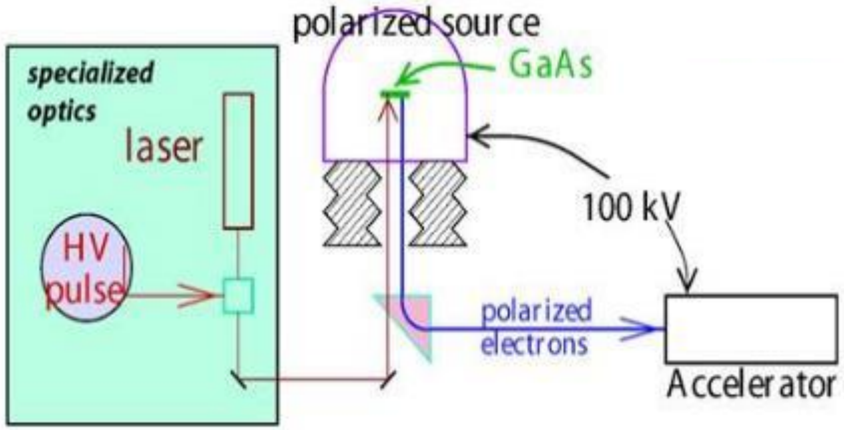
"Figure of Merit" $\propto I P_e^2$

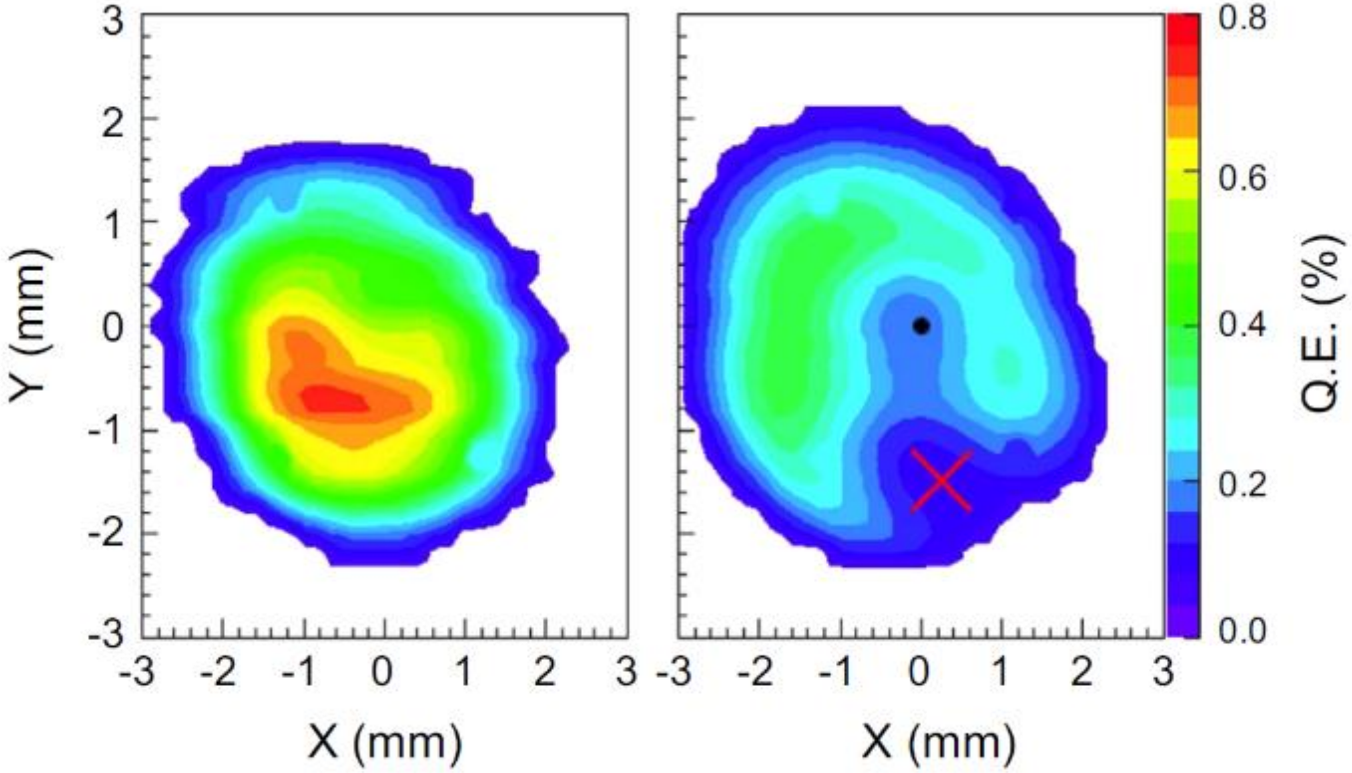






False asymmetries from helicity correlated beam properties



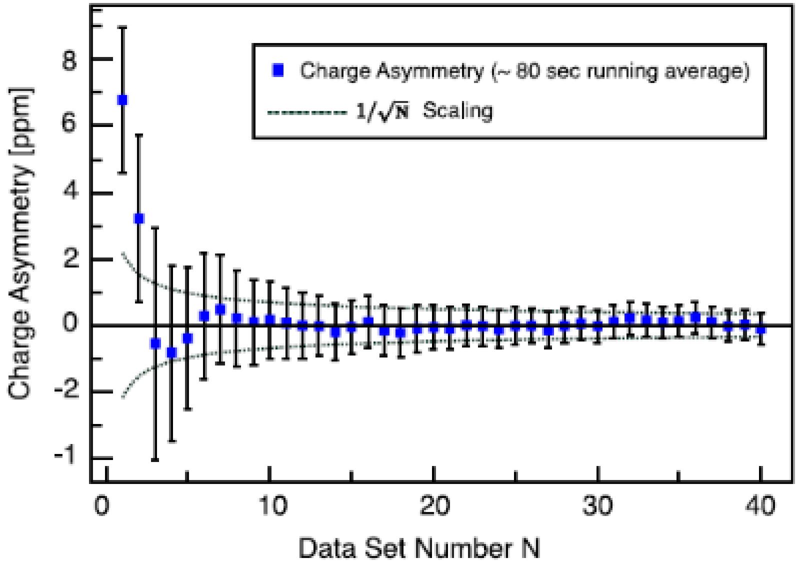


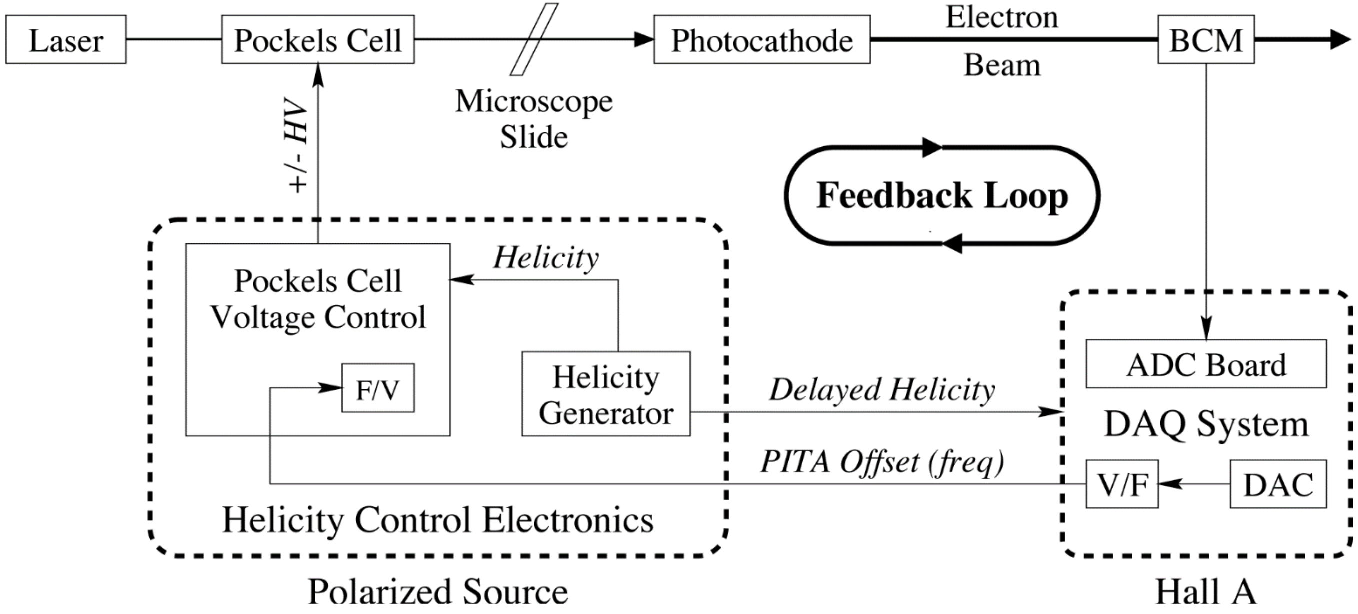
Average position differences at the target controlled to order ~10 nm

The width of human hair is 50,000 nanometers!!!

Intensity Feedback

Adjustments for small phase shifts
to make close to circular polarization

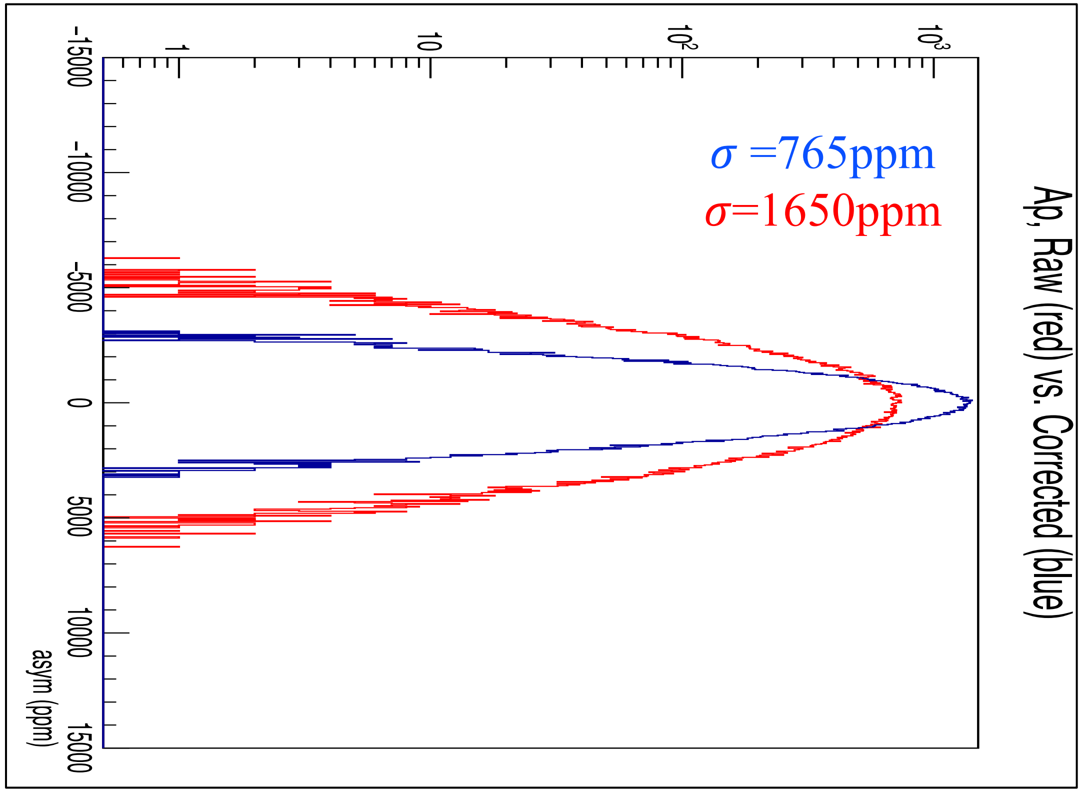




Low jitter and high accuracy allows sub-ppm
cumulative charge asymmetry in ~ 1 hour

Beam Corrections

- Steep form-factor and very forward angle: very sensitive to beam corrections.
- Beam jitter noise several times greater than counting statistics



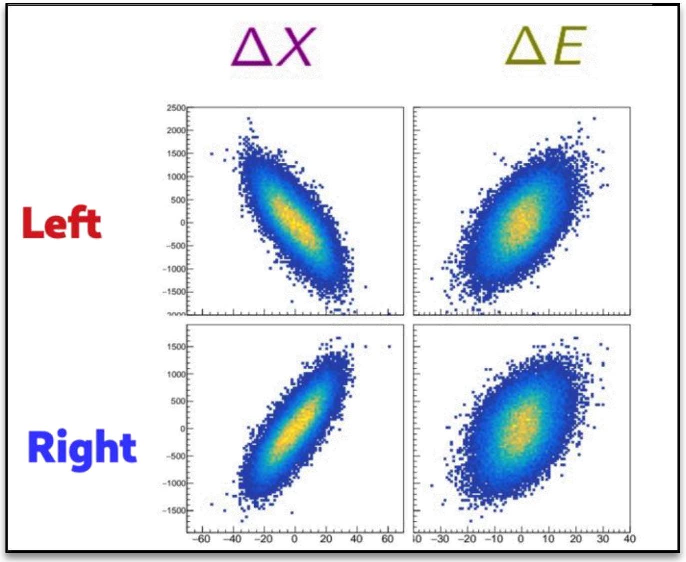
$$A = A_{raw} - A_Q - \sum_i \beta_i \Delta x_i - \beta_E A_E$$

- Potential for systematic error if average beam asymmetries are not well corrected
- Multiple techniques used to calibrate correction factors (β_i)

Beam Correction Techniques

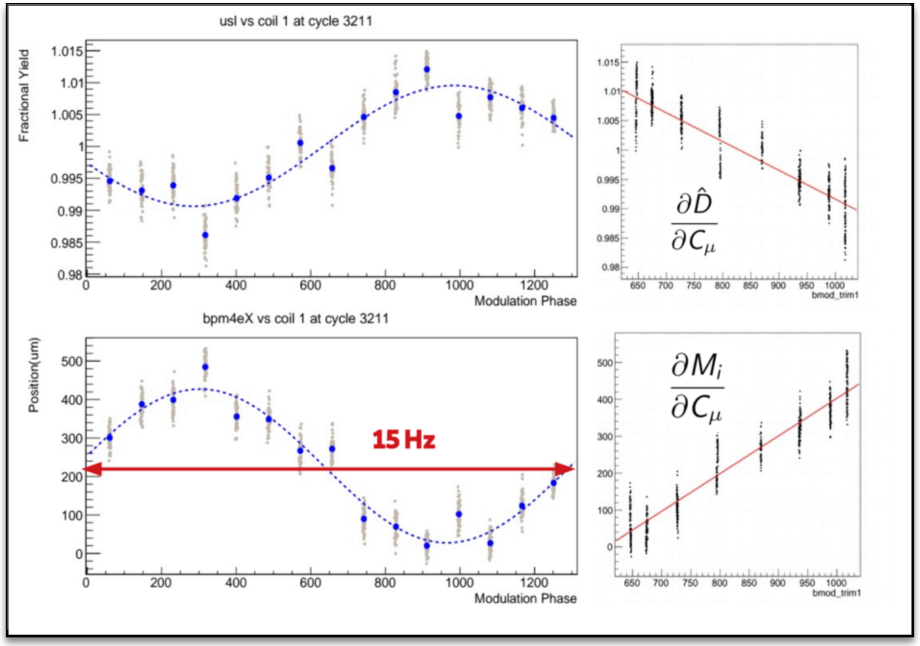
DNP'21
Evaluating the Certainty of Beam Motion Corrections in High-rate Asymmetry Measurements
Cameron S Clarke
(Stony Brook University (SUNY))

Multivariate Regression (A)



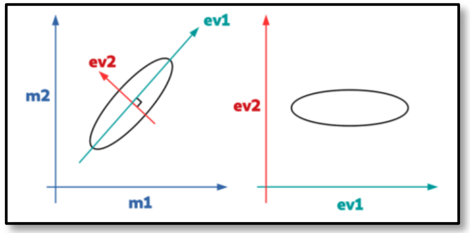
- χ^2 minimization
- Narrowest width
- Best **statistical** precision
- *Slope diluted by monitor resolution*

Beam Modulation (B)

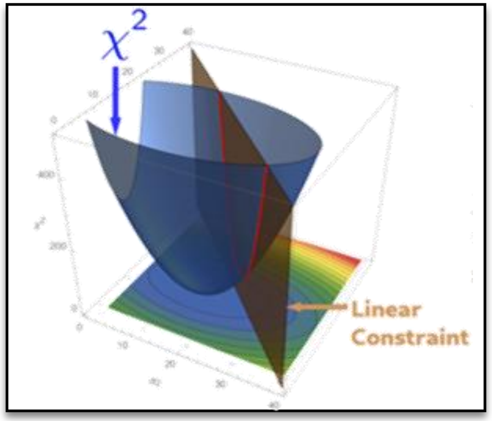


- Spans phase space well
- Constrains sensitivities
- Best **systematic** accuracy
- *Larger widths*

Method of Lagrange Multipliers (C)

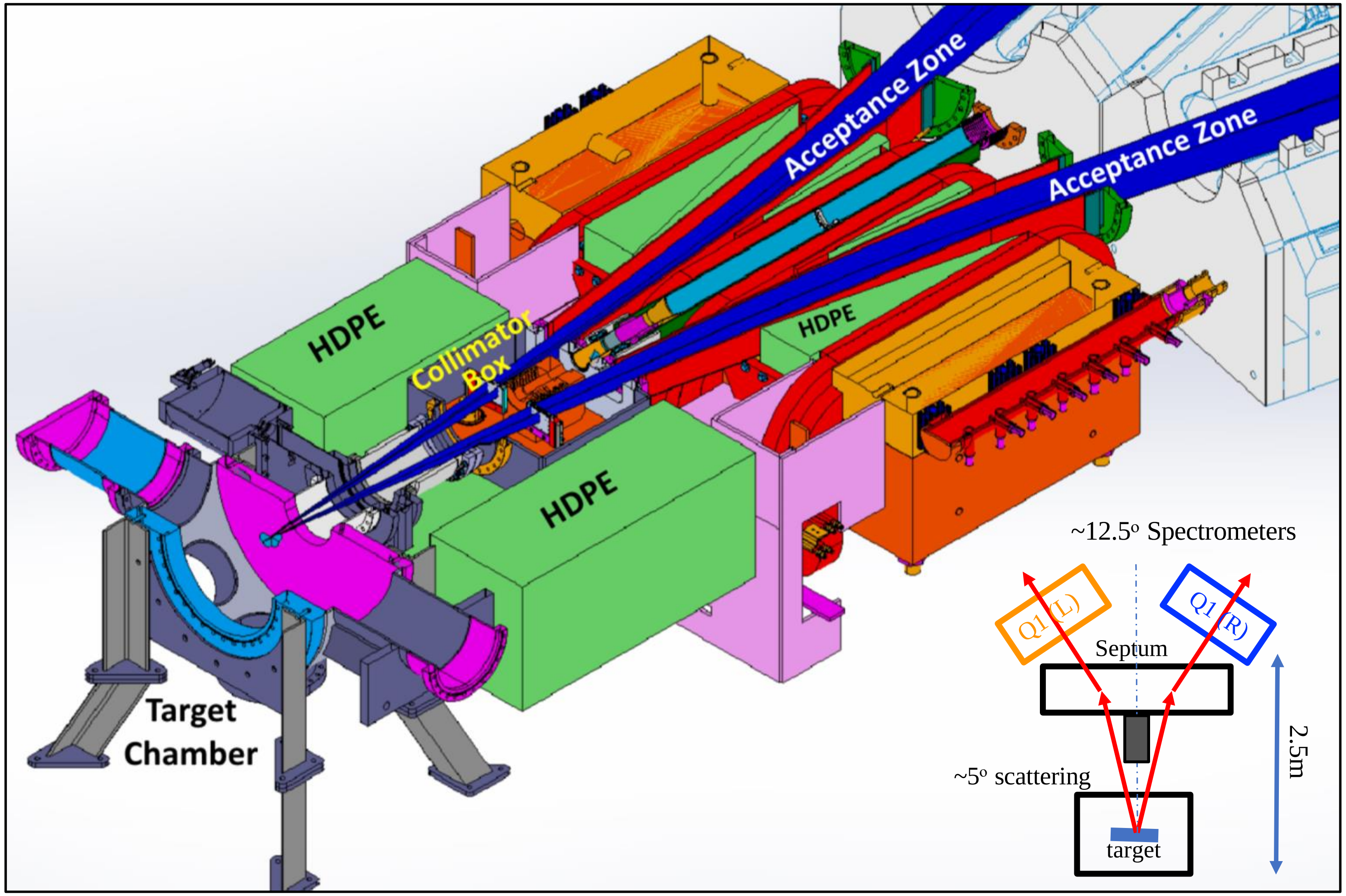


Eigenvector analysis and ranking of beam fluctuations



- “Hybrid" of regression and beam modulation techniques
- Best of both worlds
- Best precision given constraints on sensitivities

Tight fit in the target area

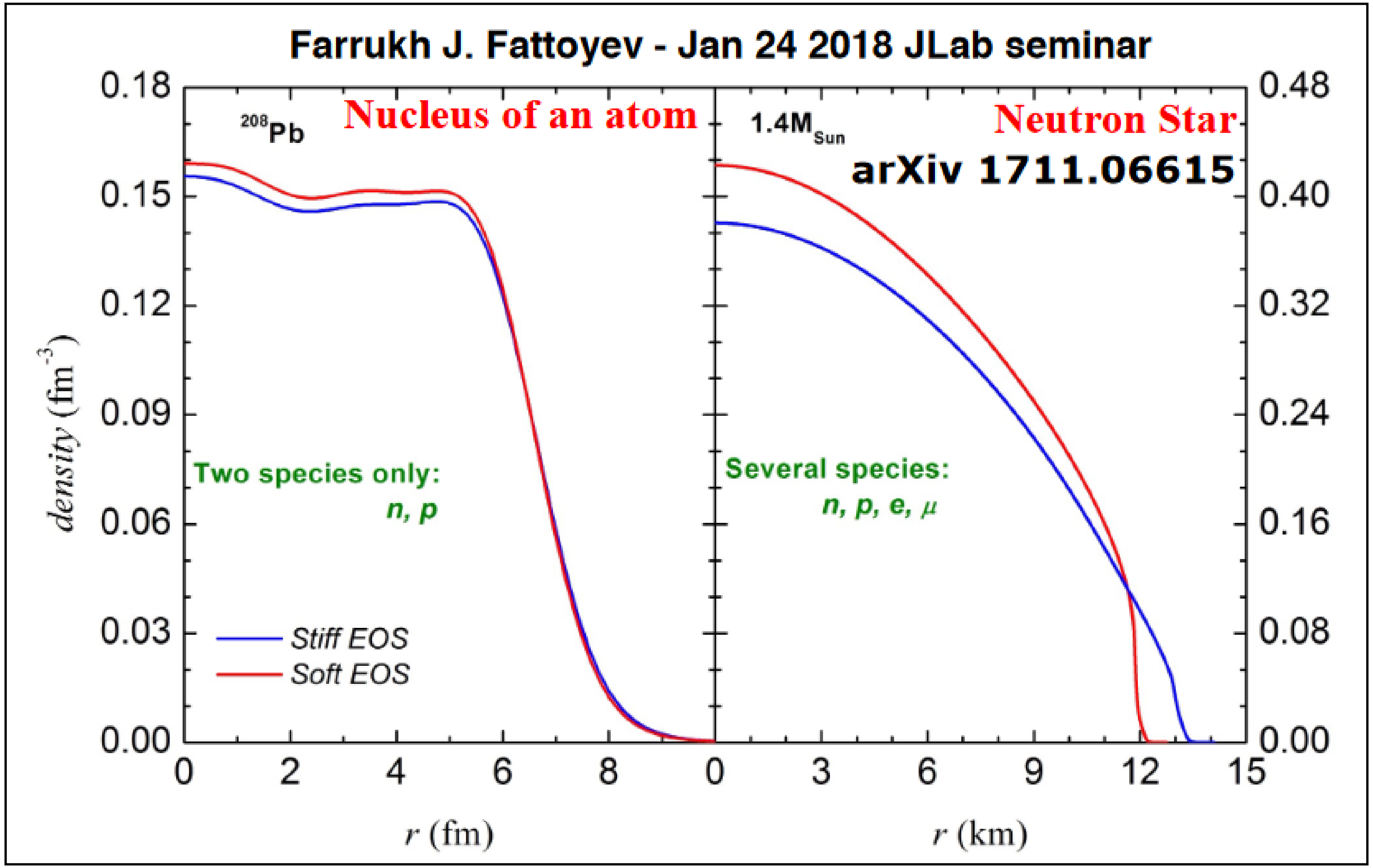


- The experimental hall provides unique challenges for a high luminosity, high Z, low energy experiment
- Large angle scattered electrons need to be stopped close to the target and that region needs to be heavily shielded
- Electronics inside the hall need to be protected from both the electromagnetic and neutron radiation damage that will stop it from functioning properly

- Tight acceptance, space requirements, collimator power, shielding made for tricky installation

(acknowledgements to Hall A designers, Jesse Beams and the Hall A technical staff)

Different Systems, same EOS



While the ^{208}Pb nucleus and a neutron star are separated by 18 orders of magnitude in size they are thought to be made out of the same stuff and obey one equation of state (EOS)

Alternate interpretation of PREX asymmetry measurement

- much lower central value for density dependence of symmetry energy L = 54+/-8 (PREX 2 value: 106+/-37)
- Look directly at asymmetry predictions to constrain models
- tension between the CREX asymmetry measurement with their predicted value based on PREX constraints
  - Their prediction 2400+/-60 ppb
  - Our measurement 2668+/-113 ppb

Reinhard, Roca-Maza, Nazarewicz (2021)

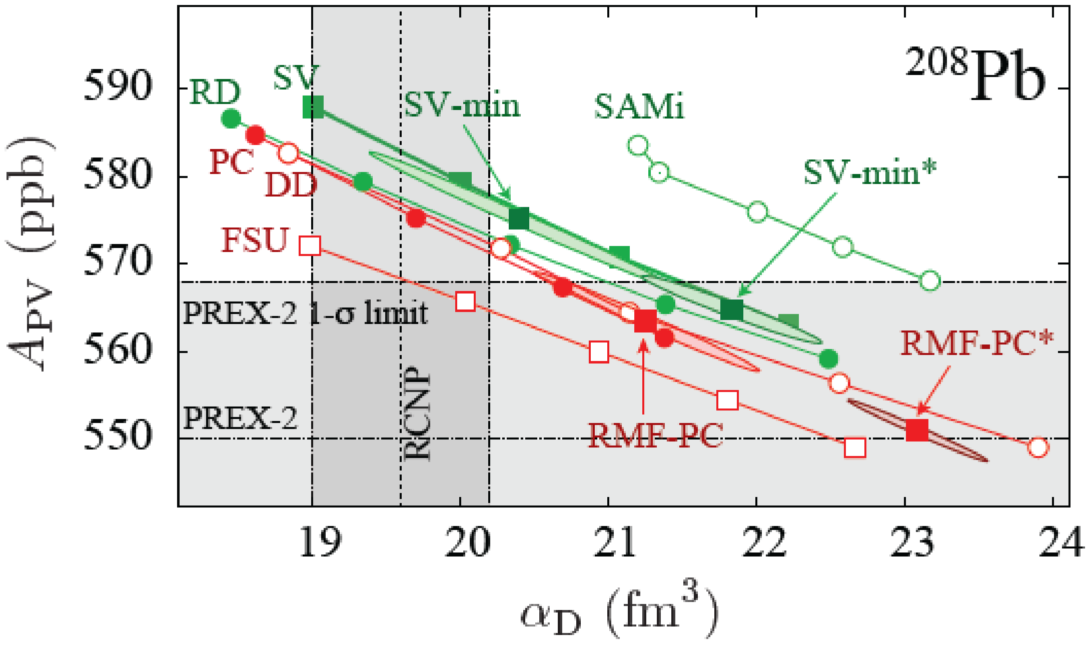
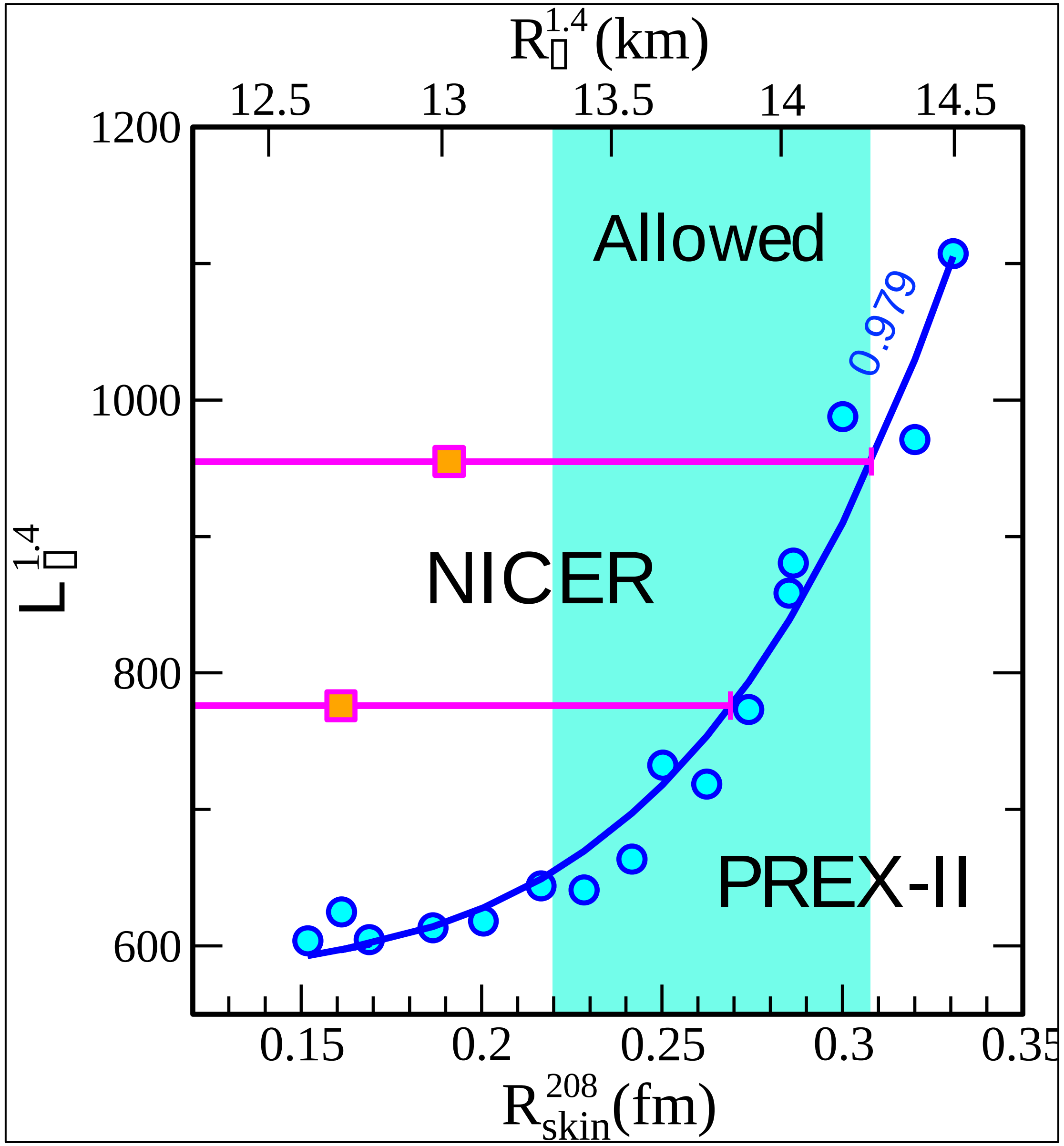
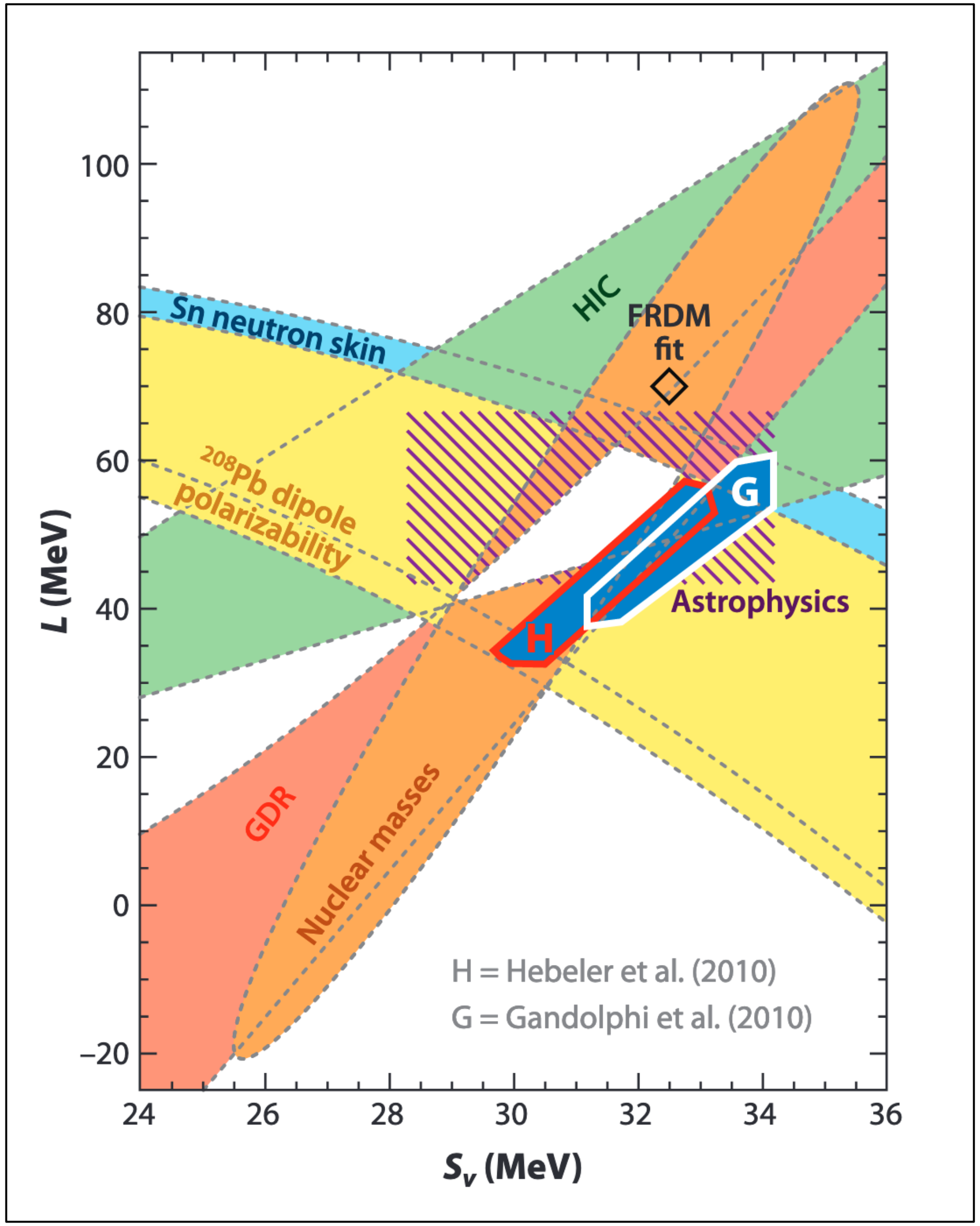


FIG. 2. A_{PV} versus α_D in ^{208}Pb for a set of covariant (red) and non-relativistic (green) EDFs. Sets with systematically varied symmetry energy J are connected by lines. (Note that α_D increases as a function of J.) The SV-min, SV-min*, RMF-PC, and RMF-PC* results are shown together with their 1-sigma error ellipses. The experimental values of α_D [10, 11] and A_{PV} [1] are indicated together with their 1-sigma error bars.


R□1.4(km)
12.5
13
13.5
14
14.5
1200
1000
800
600
L□1.4
Allowed
0.979
NICER
PREX-II
0.15
0.2
0.25
0.3
0.35
R208skin(fm)


100
80
60
40
20
0
−20
L (MeV)
24
26
28
30
32
34
36
Sv (MeV)
Sn neutron skin
HIC
FRDM
fit
208Pb dipole
polarizability
G
H
Astrophysics
GDR
Nuclear masses
H = Hebeler et al. (2010)
G = Gandolphi et al. (2010)

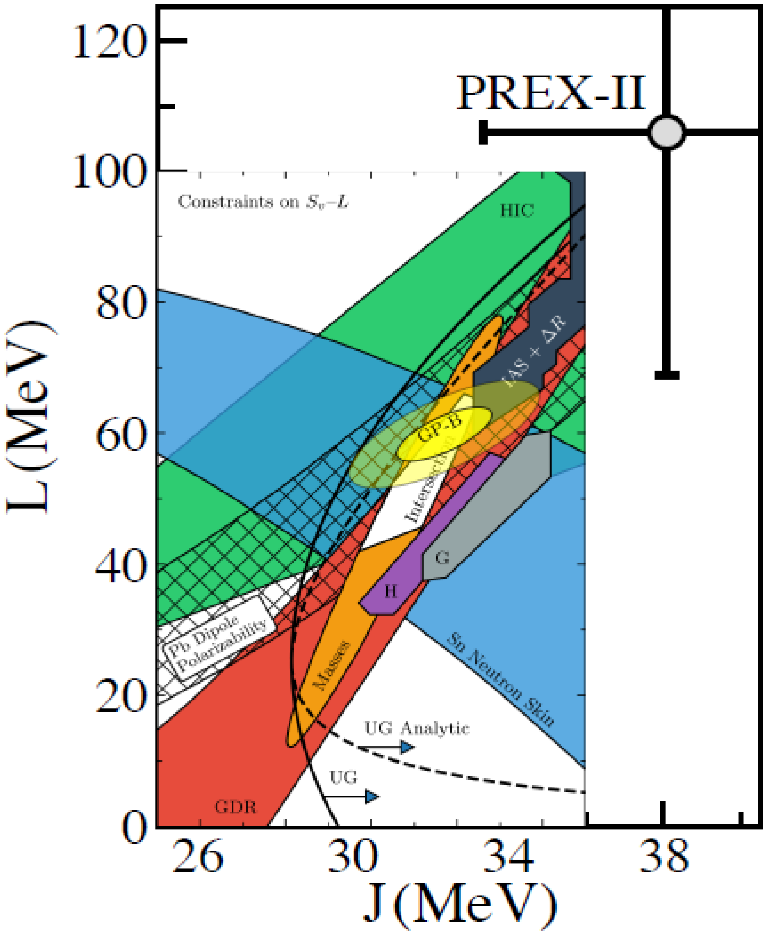
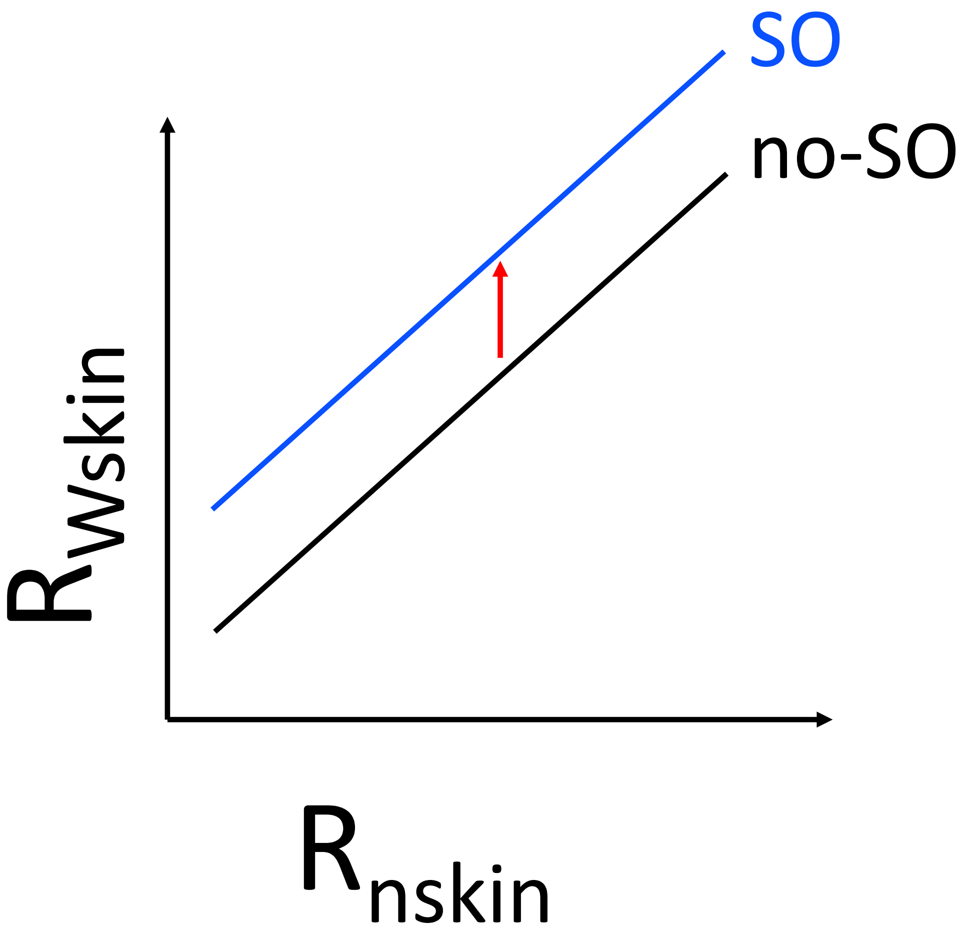
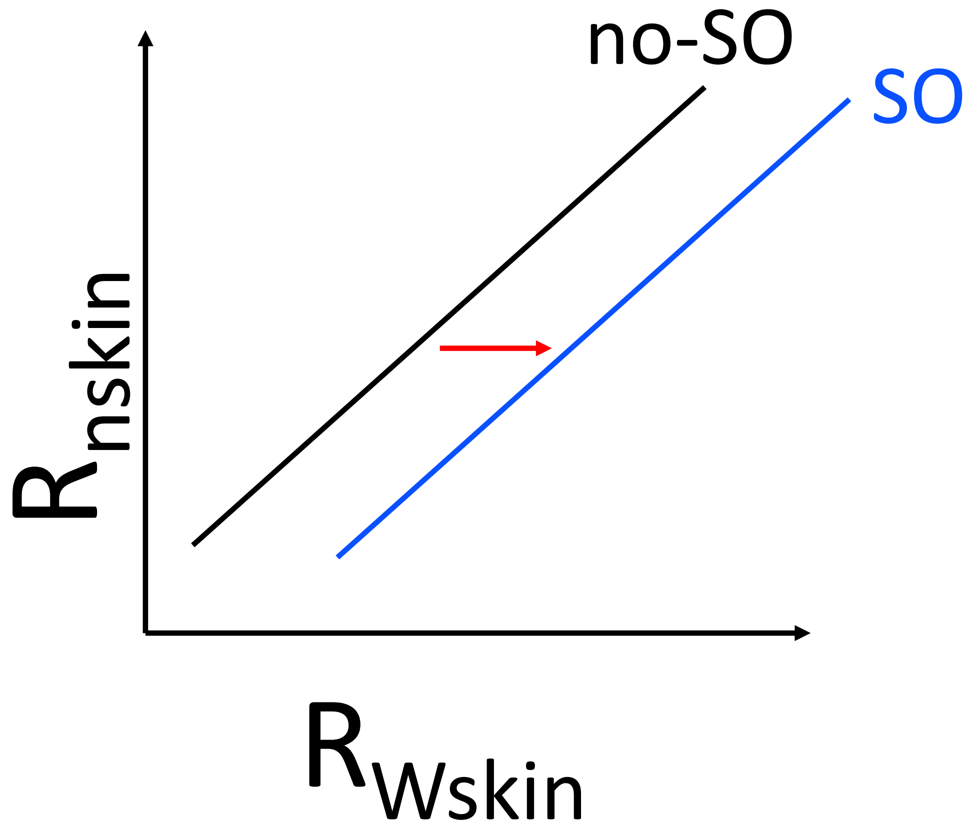


FIG. 2: (Color online). Constraints on the J–L correlation obtained from a variety of experimental and theoretical approaches. The figure was adapted from Refs. [11, 33] and noticeably displays the tension with the recent PREX-II result.





SO (no-SO)

Nucleus	Model	R_p	R_n	R_{ch}	R_{wk}	R_{nskin}	R_{wskin}
^{22}O	NL3	2.593	3.026	2.671(2.700)	3.172(3.158)	0.433	0.502(0.458)
	FSU	2.580	2.997	2.658(2.688)	3.144(3.129)	0.417	0.487(0.442)
^{48}Ca	NL3	3.379	3.605	3.449(3.467)	3.724(3.711)	0.226	0.275(0.243)
	FSU	3.366	3.563	3.435(3.455)	3.683(3.669)	0.197	0.247(0.214)

Horowitz, Piekarewicz arXiv:1208.2249v1 [nucl-th] 10 Aug 2012

Doesn’t arise for 208Pb, (weak SO for lead happens to be smaller, due to which shells are close), F7/2 in ca48 you have all the 8 neutrons where S-O are aligned, and F5/2 unoccupied, so that’s why there’s a net big SO contribution. So Ca48 funny for SO.