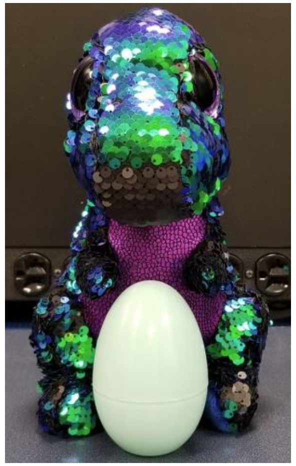
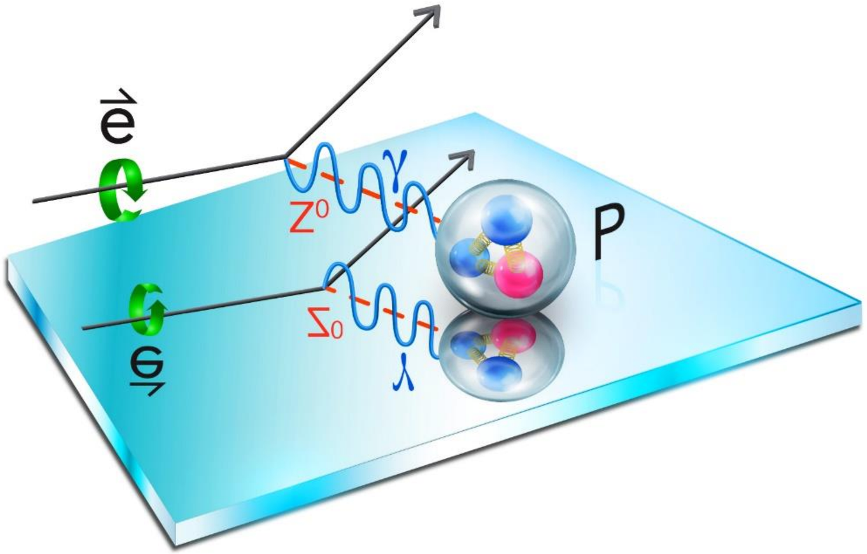
PREX/CREX Overview

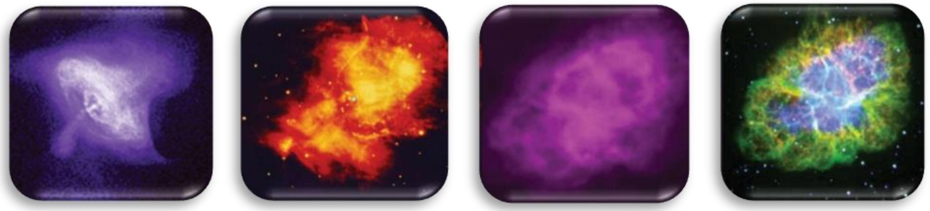


Juliette Mammei

for the PREX and CREX Collaborations



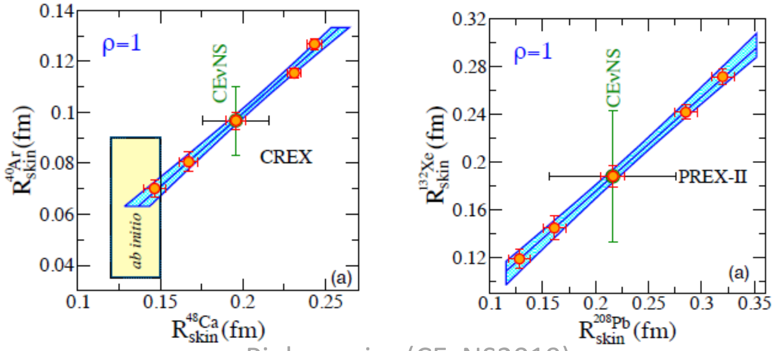
Connecting heaven and earth



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

Gravitational (LIGO/Virgo)

It all has to hang together…



Piekarewicz (CEvNS2019)

coherent neutrino scattering

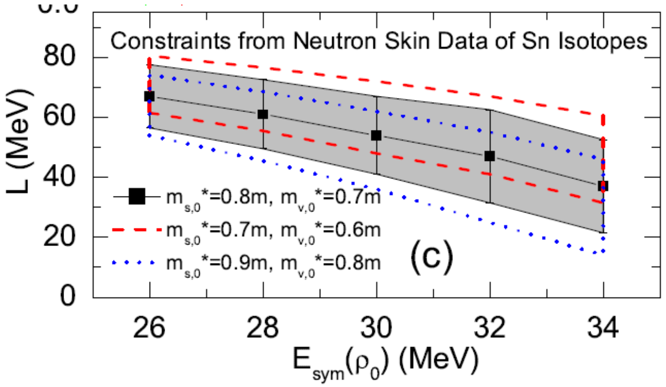
Earth-based (nuclei)

Heavy ion collisions
GDR
neutron skin in Tin isotopes
nuclear masses
Dipole polarizability
Coherent neutrino scattering

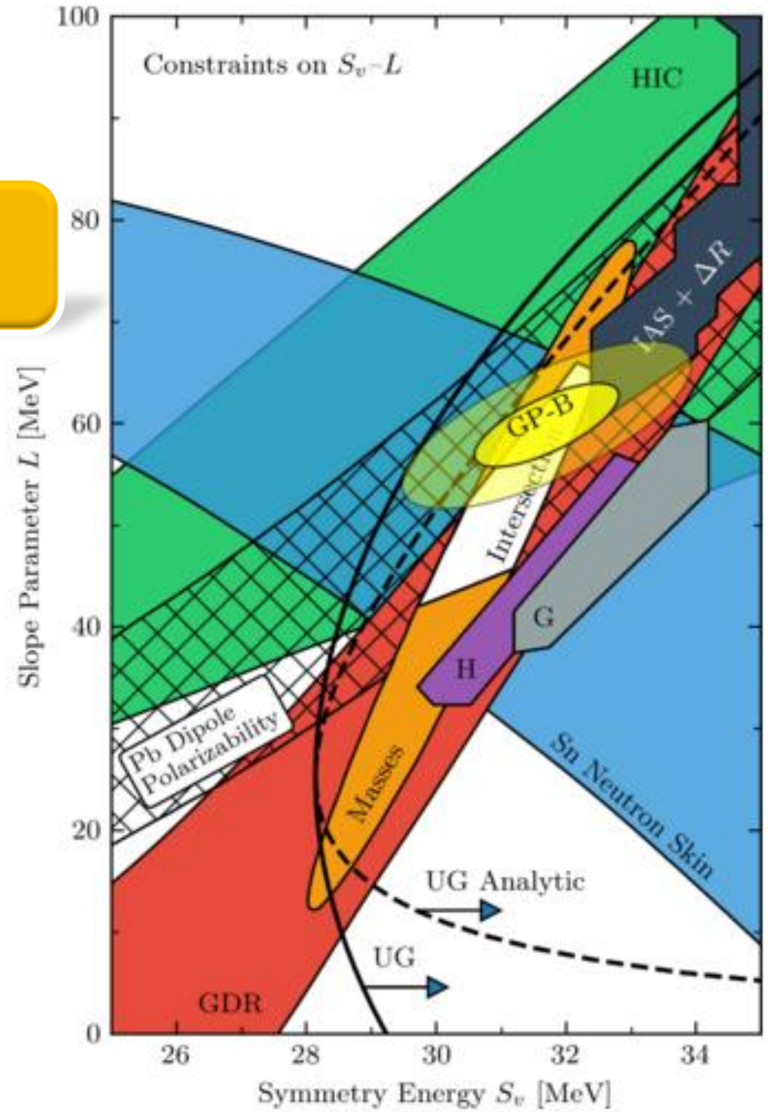
Space-based (neutron stars)

NICER – EM
LIGO/Virgo – tidal deformability

Same particles, same EOS,
18 orders of magnitude different in size!



Chen et al.
http://arxiv.org/abs/1004.4672v2



Drischler et al.
https://arxiv.org/abs/2004.07232

Equation of State of Neutron Matter

E/A for symmetric nuclear matter

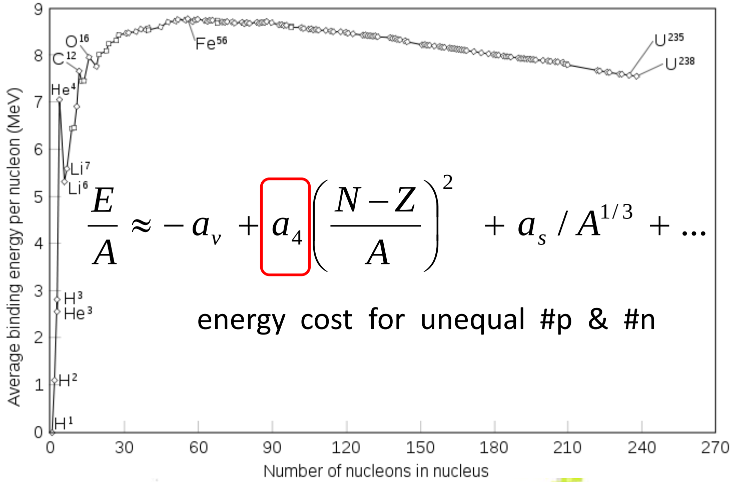
Symmetry energy

$$\varepsilon(\rho, \alpha = 1) \approx \varepsilon_0(\rho) + \alpha^2 S(\rho) \approx \epsilon_0 + Lx$$

EOS of pure neutron matter

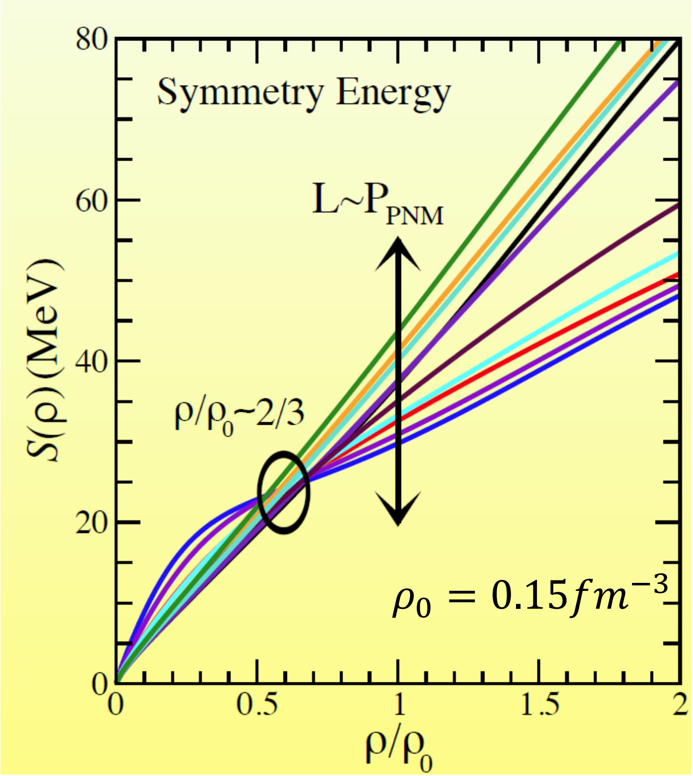
$$\alpha = (N - Z)/A$$

$$x = (\rho - \rho_0)/3\,\rho_0$$



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

energy cost for unequal #p & #n

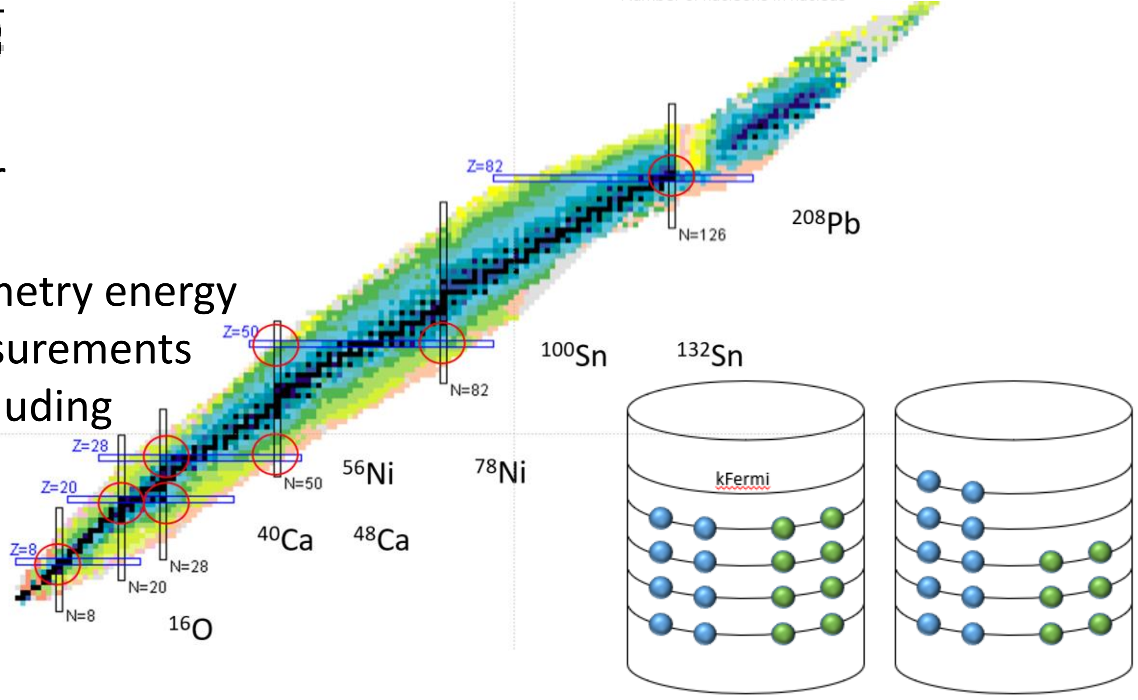


$$P_0 = \left(\rho^2 \frac{\partial \varepsilon_{PNM}}{\partial \rho}\right)\Bigg|_{\rho=\rho_0} \approx \rho_0 \frac{L}{3}$$

Pressure of pure neutron matter

L – density dependence of symmetry energy unconstrained by isoscalar measurements (~symmetric nuclear matter, including nuclear binding energies, etc.)

Doubly-magic and neutron rich nuclei to simplify corrections

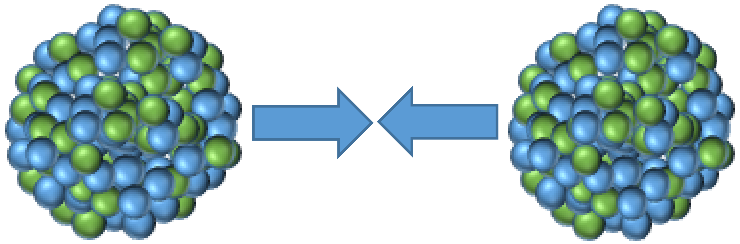


Symmetric Bucket

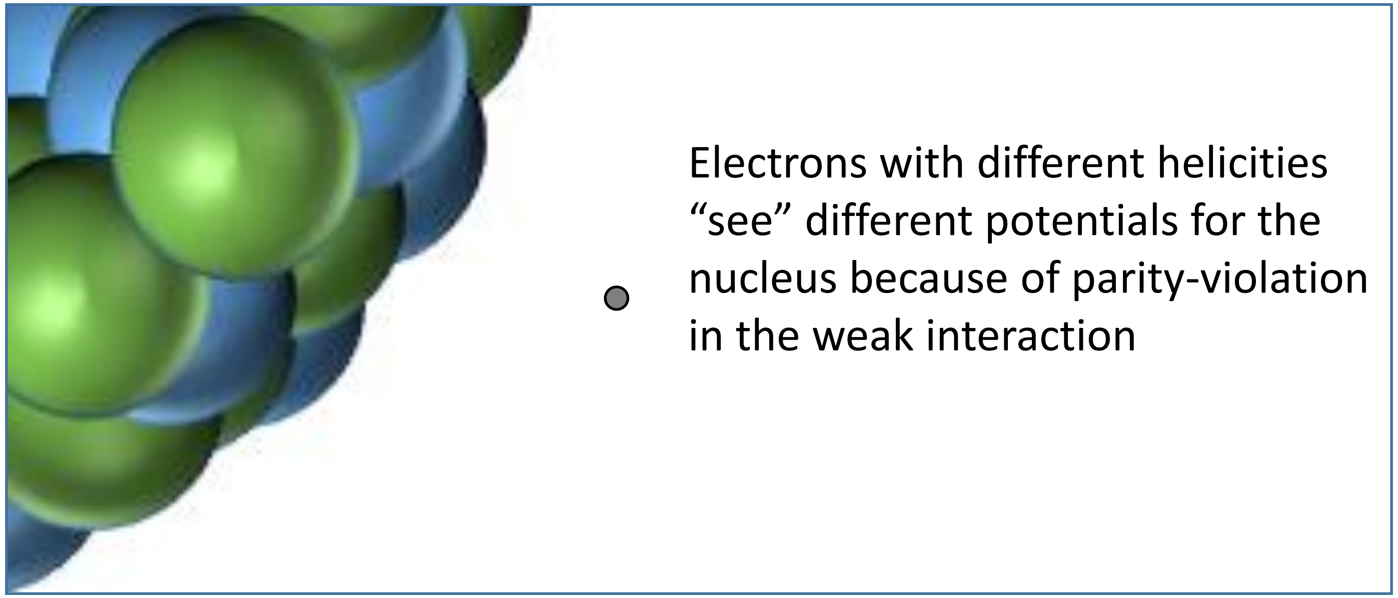
Asymmetric Bucket

Parity-violating electron scattering (PVES)

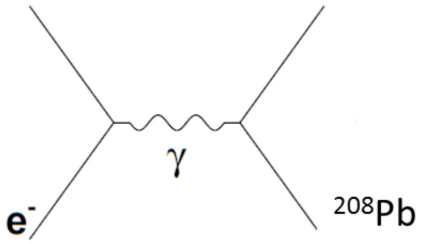
other methods, like HIC, have
strong interaction uncertainties

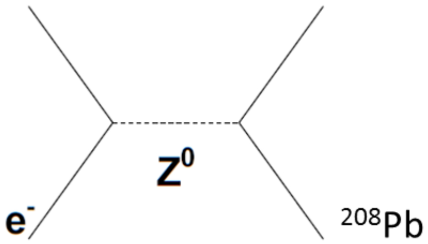


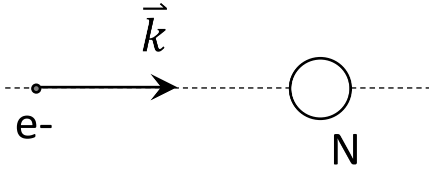
in electron scattering the probe
doesn't interact via the strong force

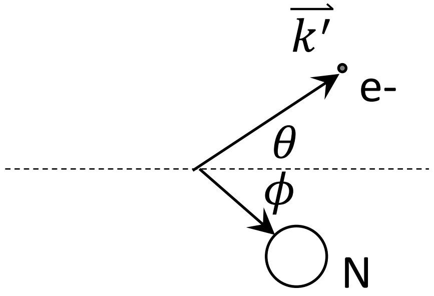


does interact via the E&M and weak forces









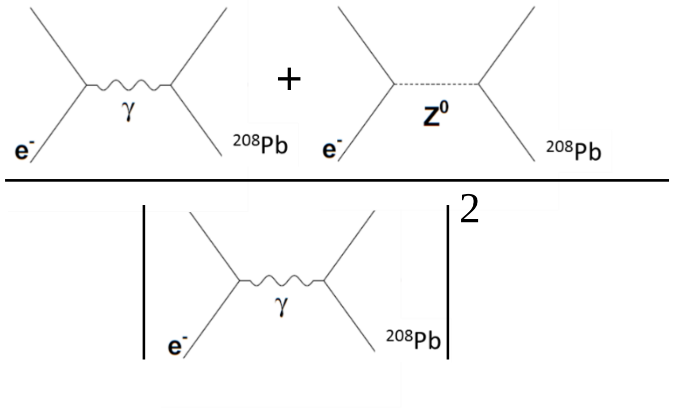
$q^2 = (\vec{k'} - \vec{k})^2$

Elastic scattering

$\Rightarrow -q^2 = Q^2 = 4EE' sin^2\theta$

Neutron skin with PVES

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx$$

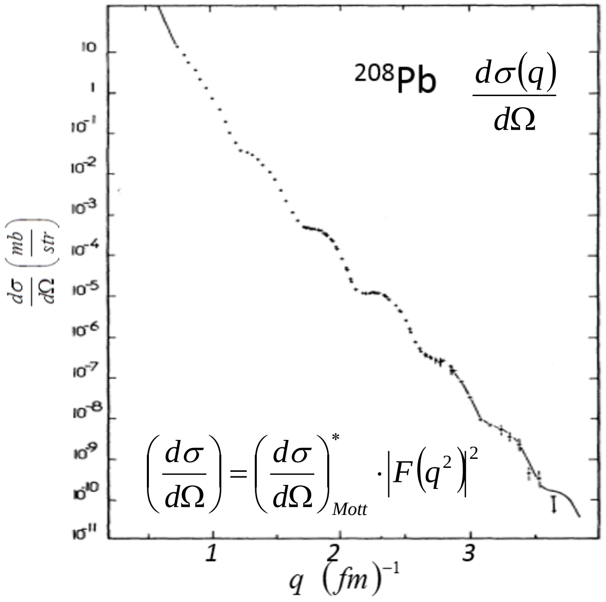


$$\approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

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

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

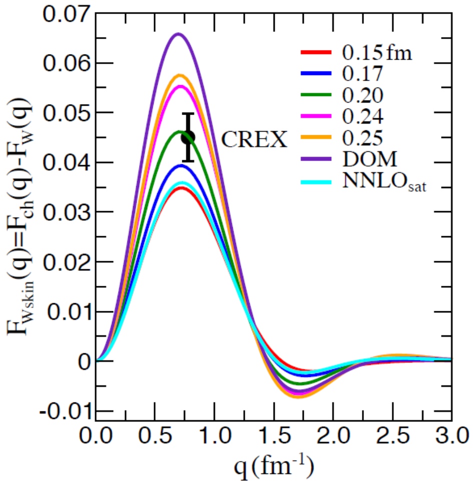
$$Q^n_{weak} = -1$$



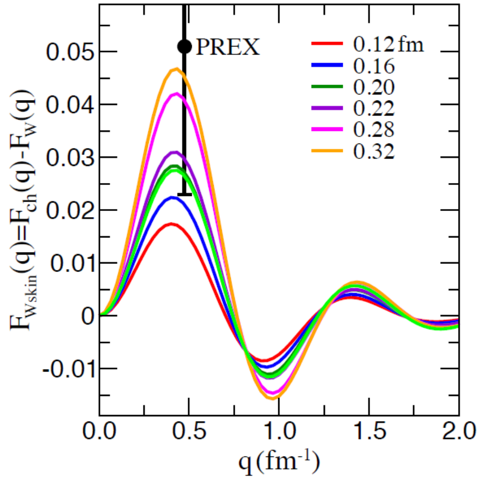
$$F_n(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_n(r)$$

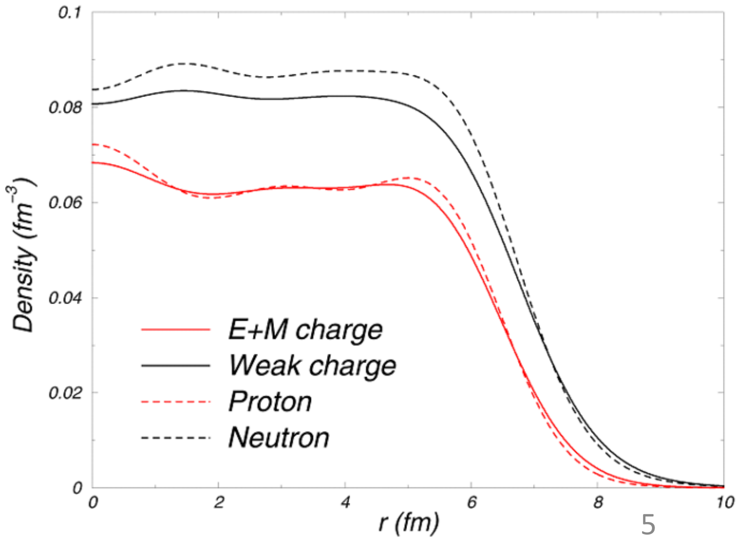
Measurement of $F_n(Q^2)$ at a single Q^2 translates to a measurement of R_n via mean-field nuclear models

At low Q^2 there is a tight correlation between R_n and $F_n(Q^2)$



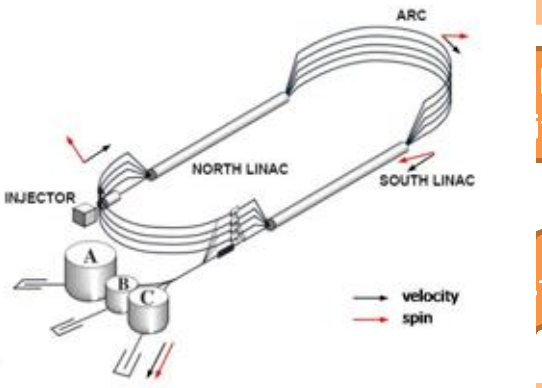
https://arxiv.org/pdf/1904.12269.pdf





Measuring A_{PV} with ES

A_{PV}



lo
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polarized beam

target

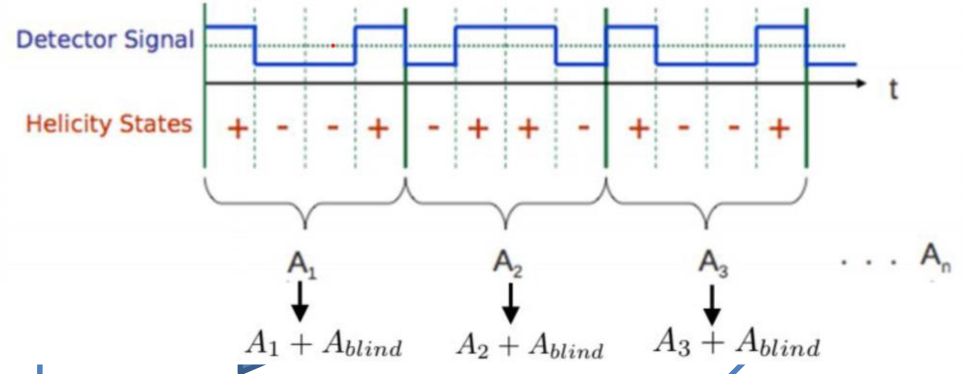
cooling

position

spectrometer

Collimators

Magnets



detectors

main detector

tracking detectors

background determination

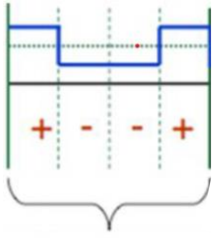
luminosity monitors

electronics

$$A_{sig} = \frac{A_{corr} - A_{back}\, f_{back}}{f_{sig}}$$

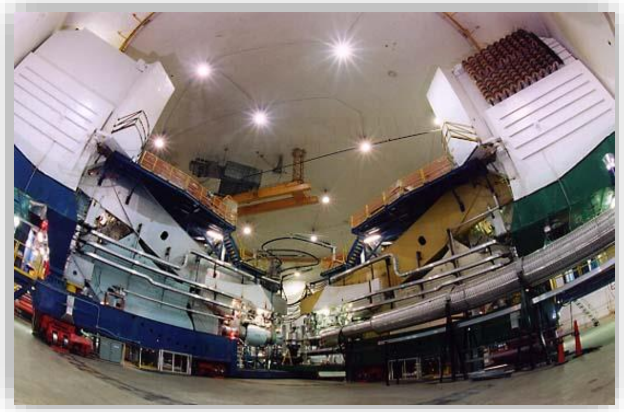
$$A_{corr} = A_{meas} - \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

where $\Delta P_i = P_+ - P_-$



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

Hall A High resolution spectrometers

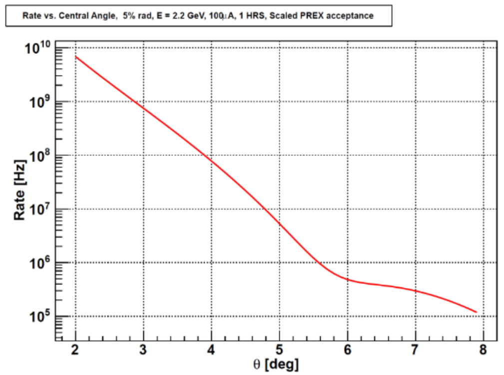


1 (2.2) GeV electron beam, 50-70 (150) μA

high polarization, ~89%

helicity reversal at 120 Hz or 240 Hz

PREX (CREX) Parameters

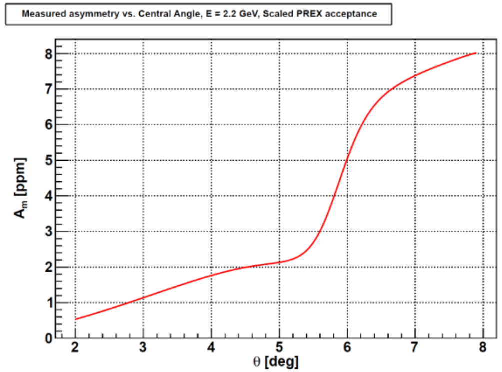


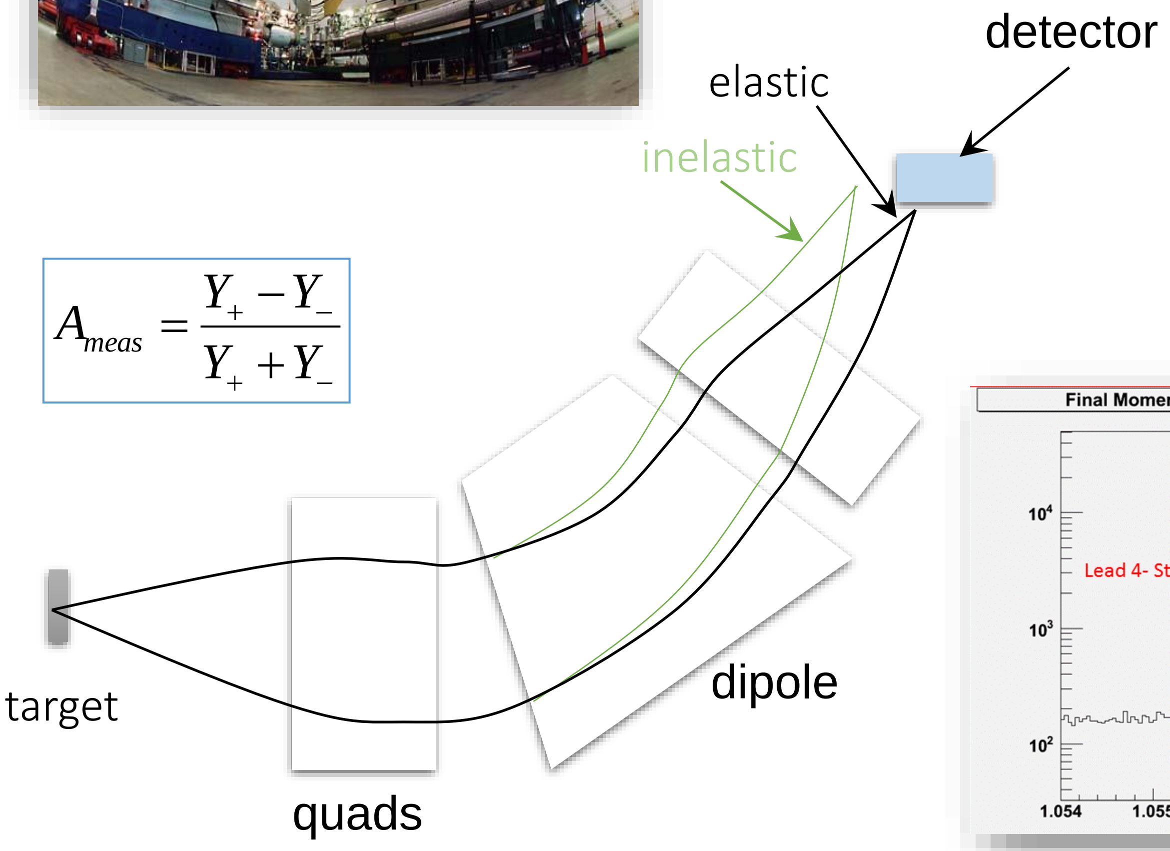
0.5 (5) mm thick Pb (Ca) target

5° (4°) scattered electrons

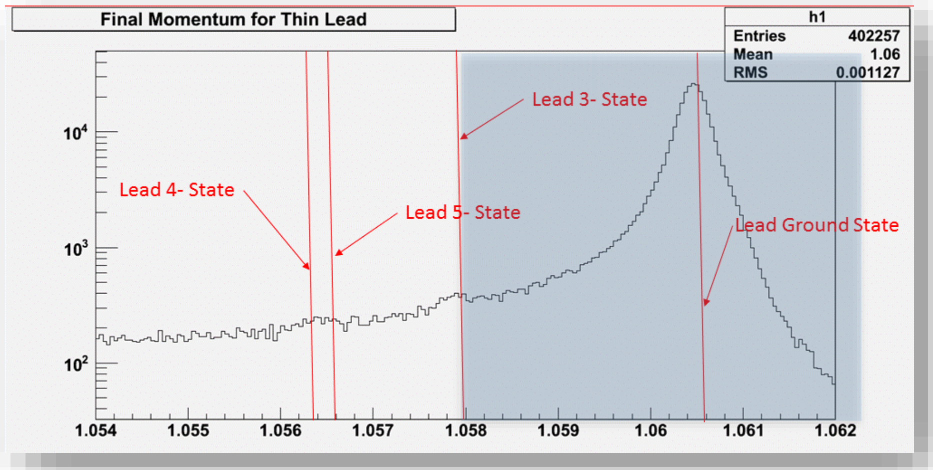
Q^2 =0.0088 (0.022) GeV^2/c^2

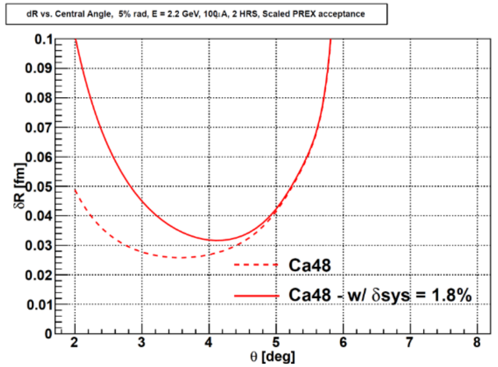
thick and thin quartz detectors



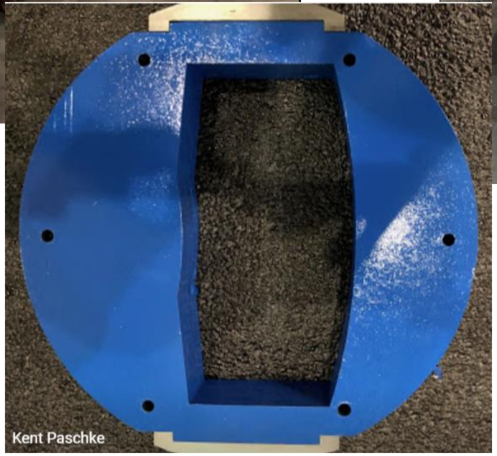


$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$





Special equipment

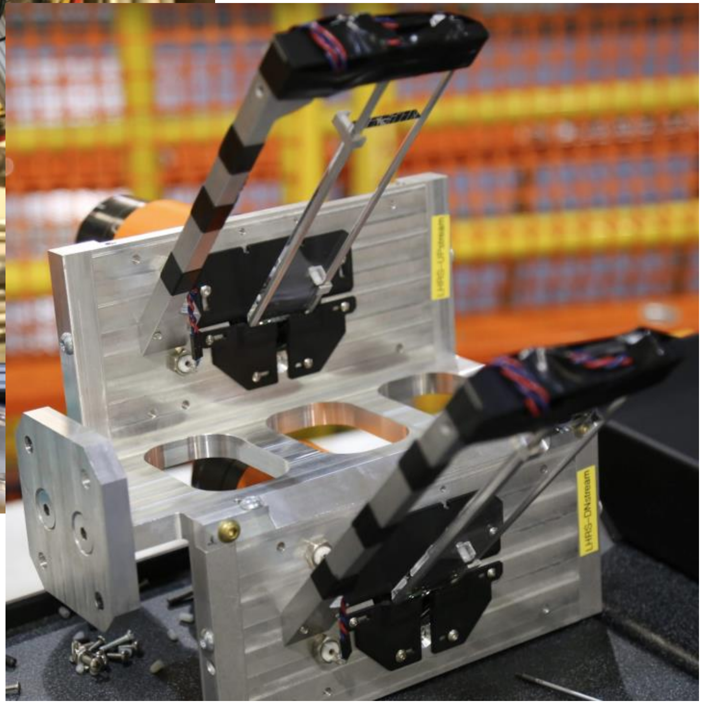


Septum magnet needed because to reach the low angles

Vacuum vessel to transport scattered electrons in vacuum to detector hut

Precision collimators to define the acceptance

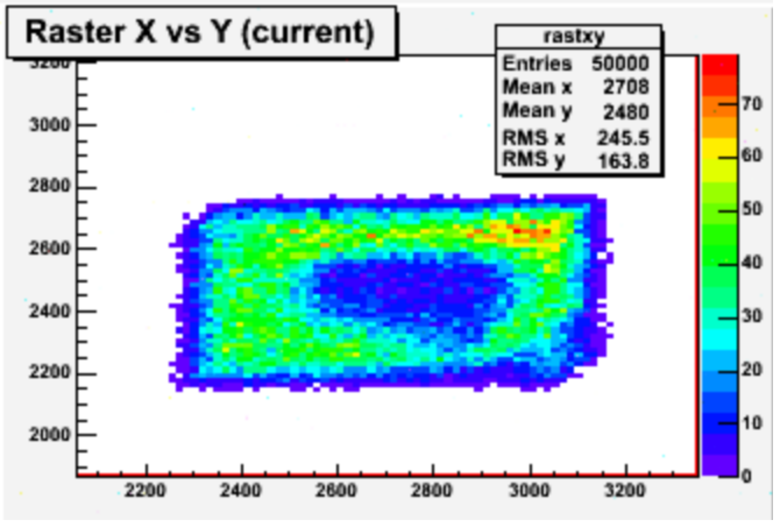
Special equipment, cont.



Integrating detectors (reduce deadtime effects)

Thick and thin quartz bars (different systematics)

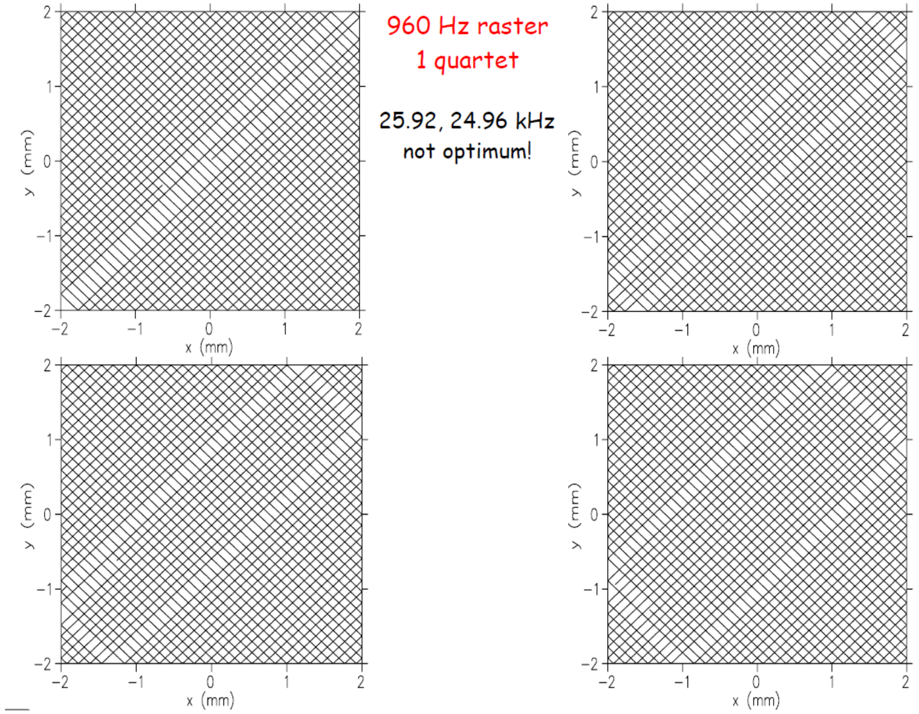
Target performance



Solutions:

Sync the raster

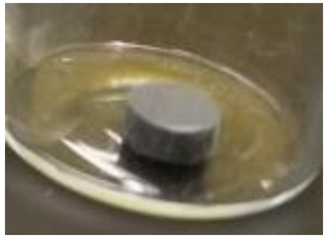
Run with 10 targets



Acquire new ^{48}Ca

Don't expose it to air

sanded

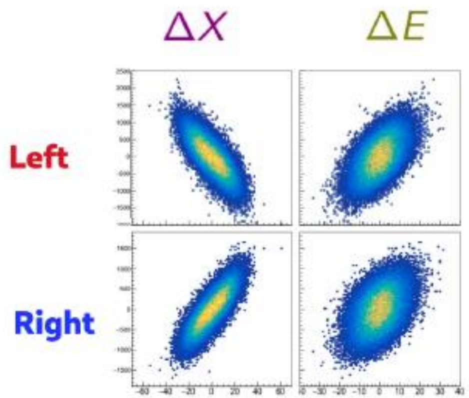


oxidized 24 hours

Calcium target for CREX was in the scattering chamber during PREX-2

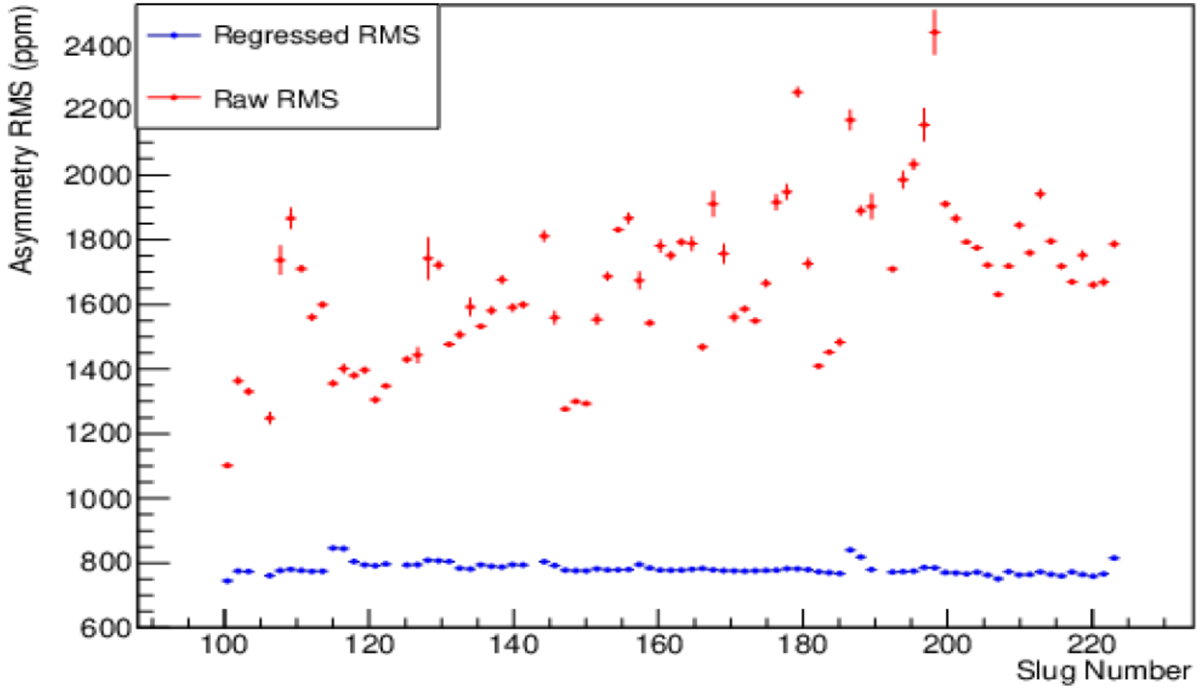
Vacuum level in target chamber monitored VERY closely

Beam Corrections, examples

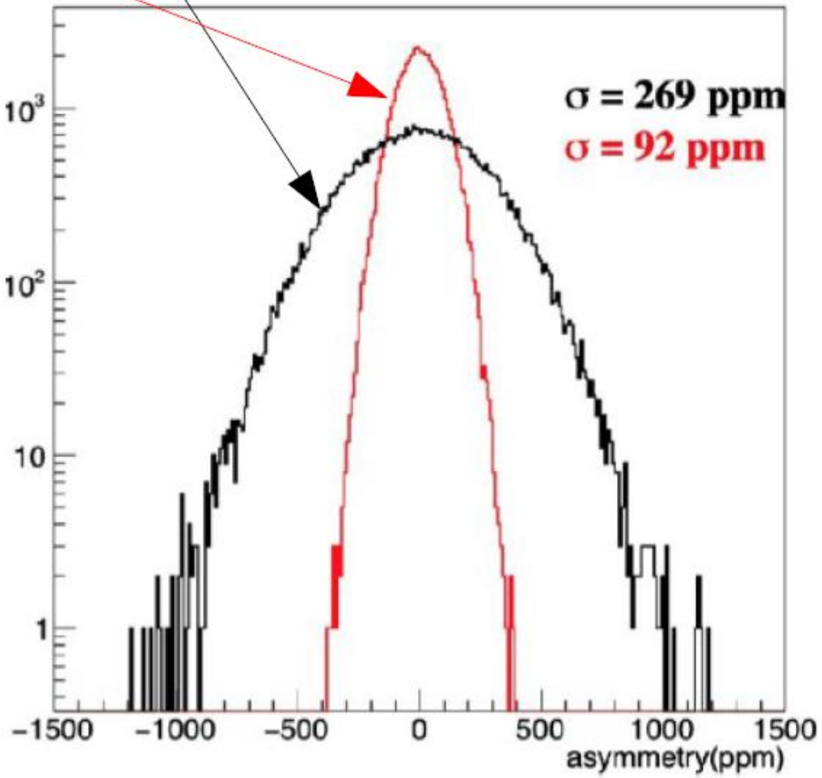


$$\Delta X = \frac{\langle X^+ \rangle - \langle X^- \rangle}{2}$$

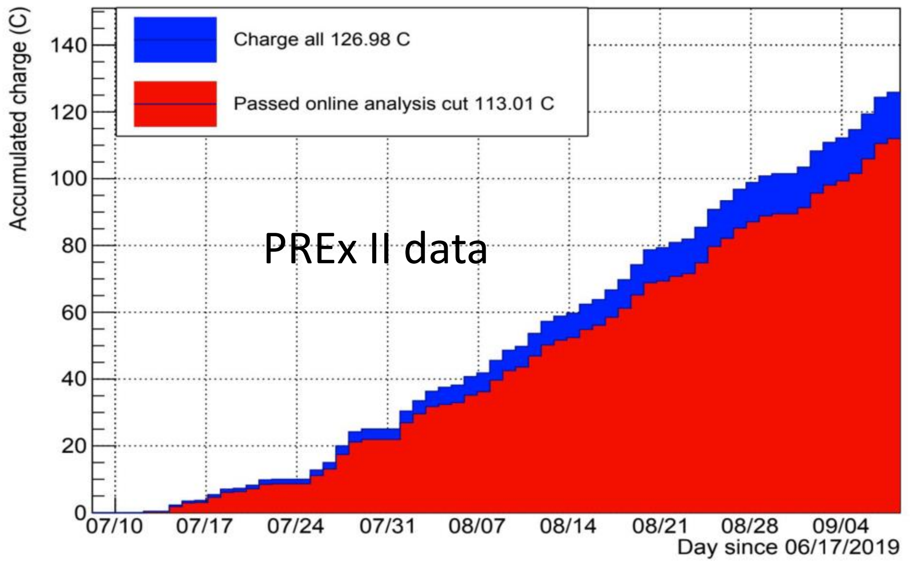
	ΔX	ΔE
Jitter	15 um	6 um
Left Arm Slope	-32 ppm/um	44 ppm/um
Right Arm Slope	28 ppm/um	36 ppm/um
Averaged Slope	-2 ppm/um	40 ppm/um

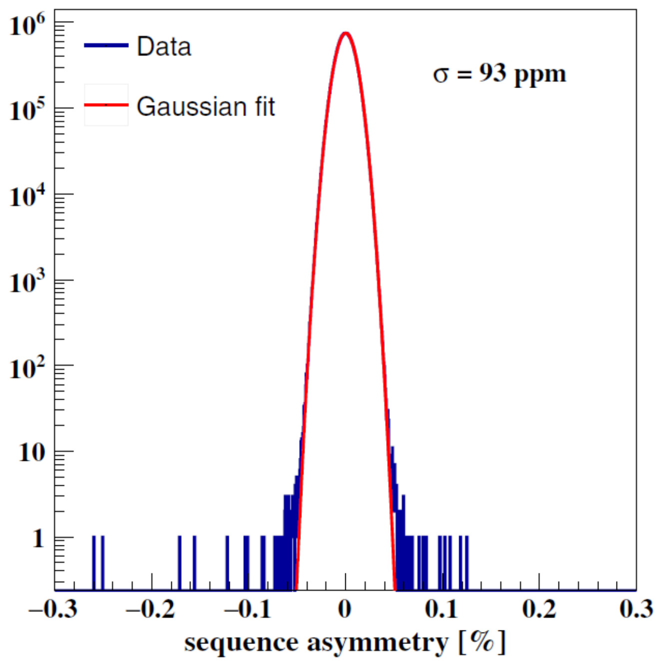


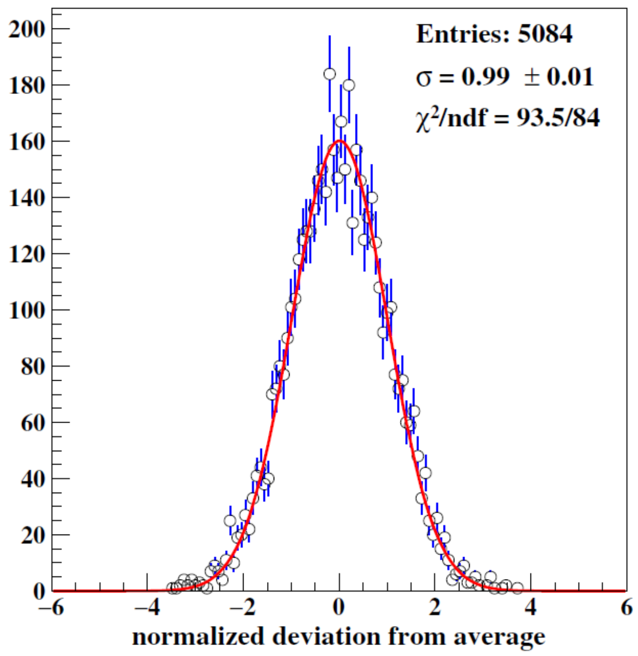
$$A_{corr} = A_{meas} - \sum_{i=1}^{N} B_i \, \Delta x_i$$



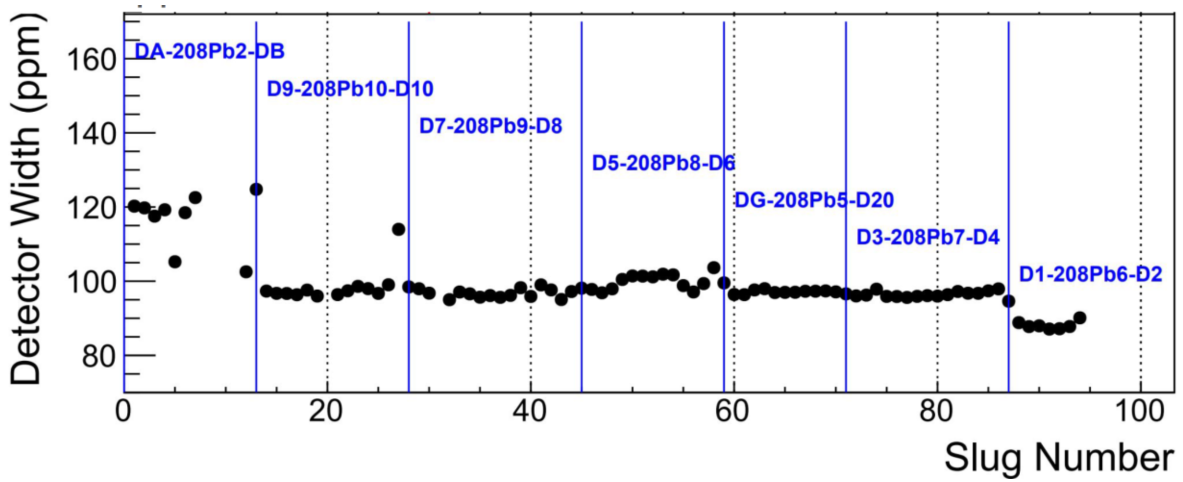
Summary of Data Quality







HWP/Wien	A_{corr} sign	$A_{\mathrm{PV}}^{\mathrm{meas}}$ [ppb]	χ^2	#slugs
IN/Left	$-$	540.7 ± 29.9	46.9	27
OUT/Left	$+$	598.8 ± 29.1	31.6	29
IN/Right	$+$	506.2 ± 34.1	18.3	19
OUT/Right	$-$	536.4 ± 37.7	16.0	21



The detector system performed well; able to take ~2.5GHz on 10 x 3.5 cm^2 quartz in each arm

$$\sigma_A = \left(\frac{1}{flip\ rate} \times I\ (\mu A) \times R\ (Hz/\mu A) \times \#flips\ \times \#\ dets\right)^{-1/2}$$

Accurate Determination of the Neutron Skin Thickness of Pb208 through Parity-Violation in Electron Scattering

The High Resolution Spectrometer in Hall A at Jefferson Lab used by the PREX-2 experiment. Selected for a Viewpoint in *Physics* and an Editors' Suggestion.

From the article:

Accurate Determination of the Neutron Skin Thickness of Pb208 through Parity-Violation in Electron Scattering

D. Adhikari et al. (PREX Collaboration)

Phys. Rev. Lett. **126**, 172502 (2021)

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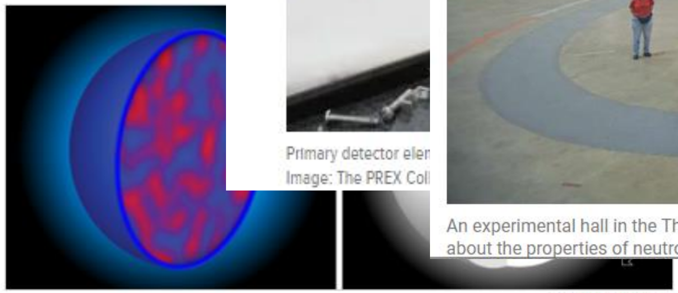
Probing the Skir

Kate Scholberg
Physics Department, Duke University, Durhan

April 27, 2021 • *Physics* 14, 58

Researchers make the most precise measure implications for the structure of neutron sta



APS/Alan Stonebraker

Figure 1: A cartoon image of a lead-208 nucleus, showing the mixed proton-neutron core and the neutron "skin" (left). Measuring the thickness of the neutron skin offers clues about how neutron stars are structured (right).

GIZMODO We come from the future

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Physic 'What

Isaac Schul
4/27/21 3:16

Primary detector eler
Image: The PREX Coll

The Academic Times

First direct 'neutron s

By Zack Fishman
April 27, 2021

An experimental hall in the Thomas Jefferson N about the properties of neutrons. (DOE's Jeffers

SciTechDaily

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Highly Accurate Measurements Show Neutron Star "Skin" Is Less Than a Millionth of a Nanometer Thick

TOPICS: Astrophysics DOE Neutron Star Particle Physics Popular

By THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY APRIL 27, 2021

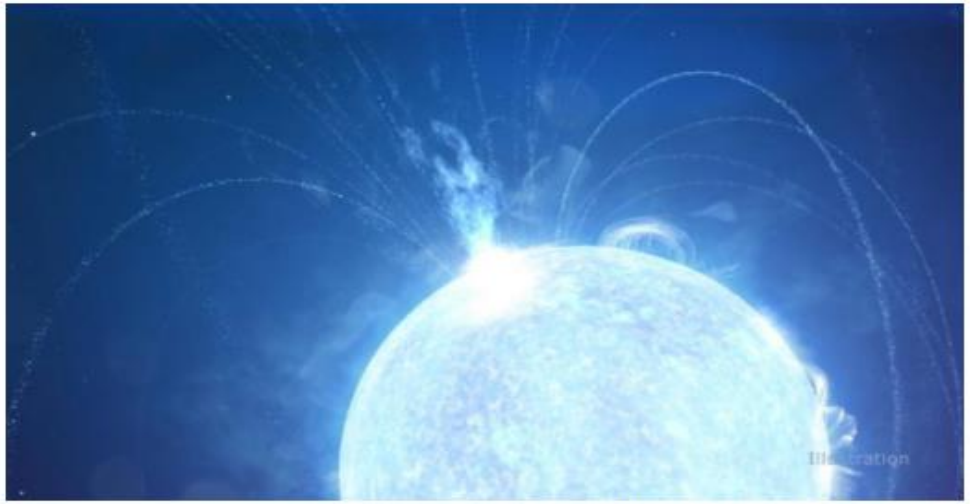

Illustration of a powerful X-ray burst erupts from a magnetar — a supermagnetized version of a stellar remnant known as a neutron star. Credit: NASA's Goddard Space Flight Center/Chris Smith (USRA)

Nuclear physicists make new, high-precision measurement of the layer of neutrons that encompass the lead nucleus, revealing new information about neutron stars.

https
8
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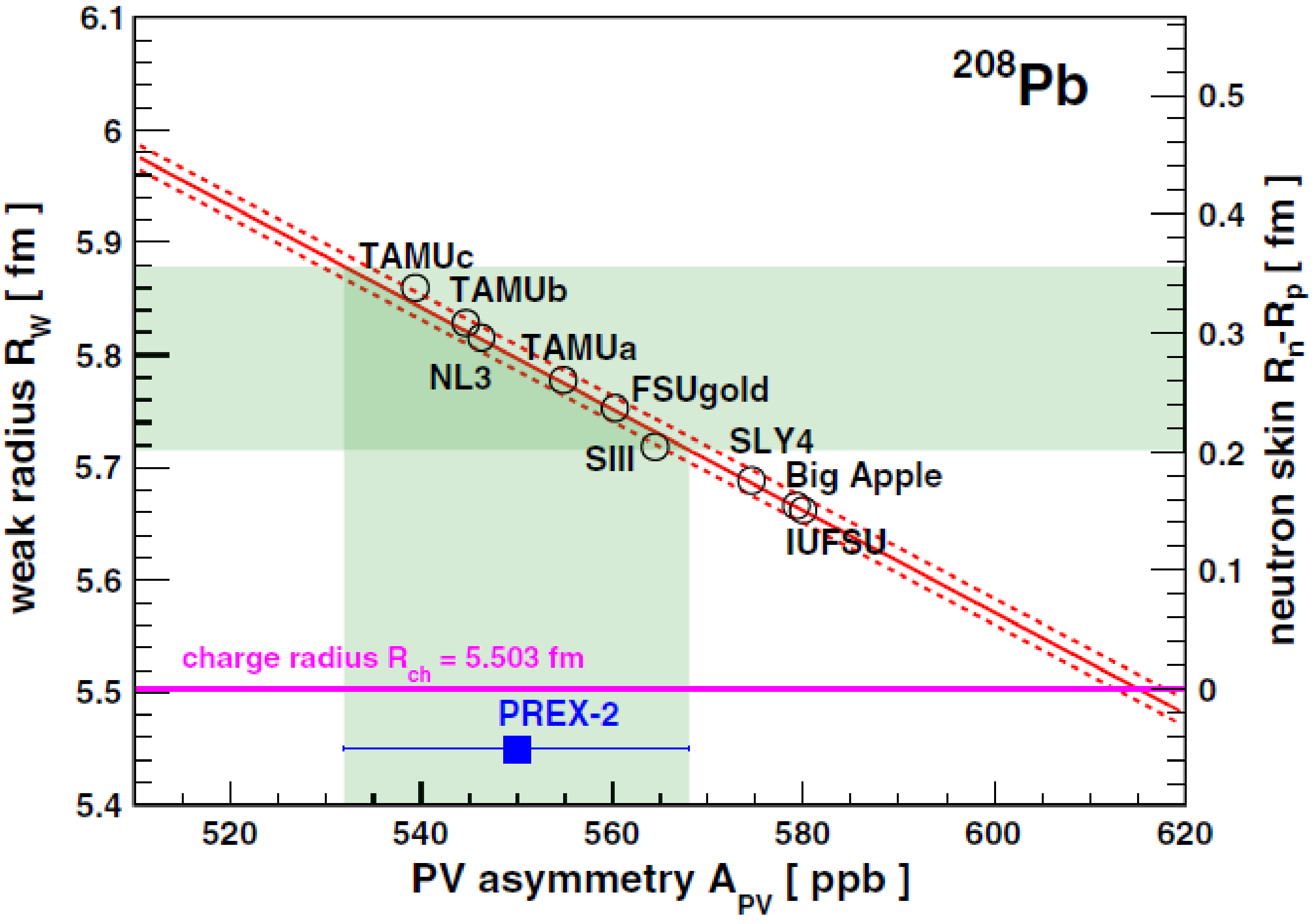
021/04/ne
expected-measurement
suggests
https://www.sciencene
lead-thick-neutron-skin-
new-measure-physics

PREX-2 Result

Correction	Absolute [ppb]	Relative [%]
Beam asymmetry	-60.4 ± 3.0	11.0 ± 0.5
Charge correction	20.7 ± 0.2	3.8 ± 0.0
Beam polarization	56.8 ± 5.2	10.3 ± 1.0
Target diamond foils	0.7 ± 1.4	0.1 ± 0.3
Spectrometer rescattering	0.0 ± 0.1	0.0 ± 0.0
Inelastic contributions	0.0 ± 0.1	0.0 ± 0.0
Transverse asymmetry	0.0 ± 0.3	0.0 ± 0.1
Detector nonlinearity	0.0 ± 2.7	0.0 ± 0.5
Angle determination	0.0 ± 3.5	0.0 ± 0.6
Acceptance function	0.0 ± 2.9	0.0 ± 0.5
Total correction	17.7 ± 8.2	3.2 ± 1.5
A_{PV}^{meas} and statistical error	550 ± 16	100.0 ± 2.9



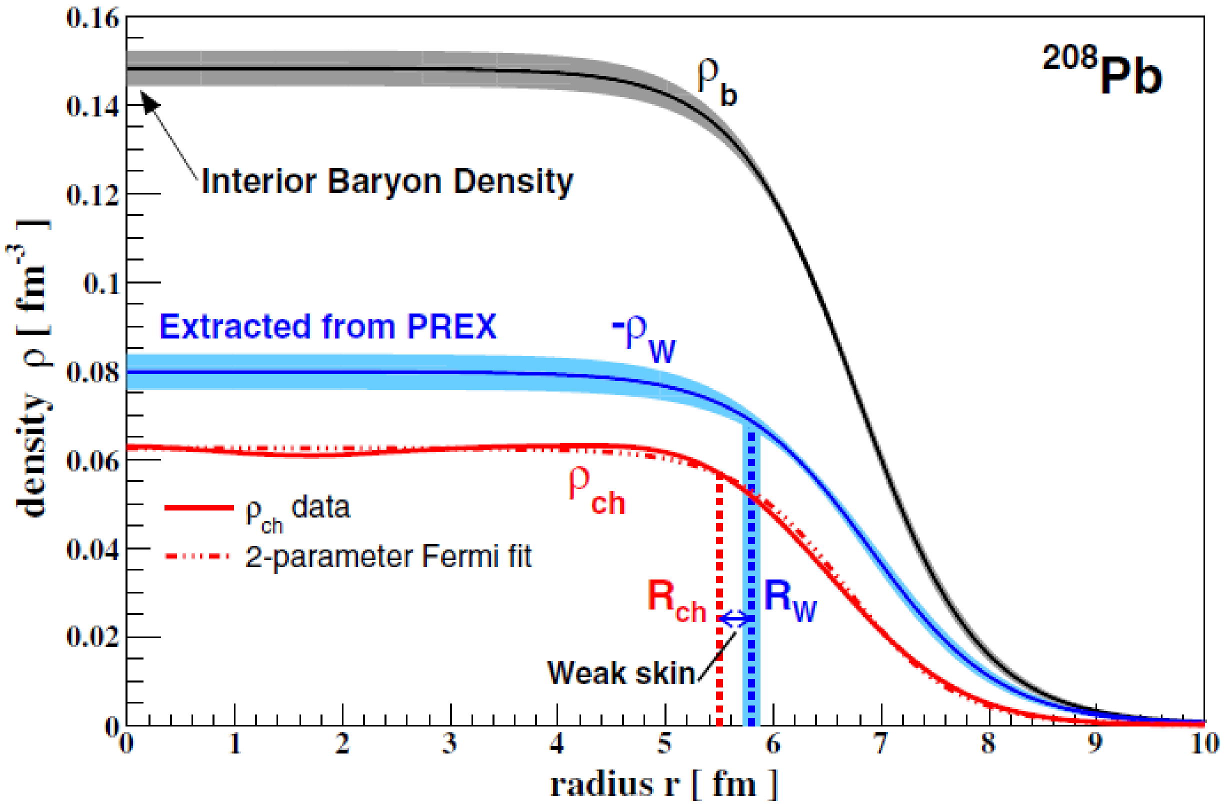
$$A_{PV}^{meas} = 550 \pm 16\,(\mathrm{stat}) \pm 8\,(\mathrm{syst})\ \mathrm{ppb}$$

$$R_W = 5.795 \pm 0.082(\mathrm{exp}) \pm 0.013(\mathrm{theo})\ \mathrm{fm}$$

PREX 1 result: $R_n - R_p = 0.30 \pm 0.18\ \mathrm{fm}$

$$R_n - R_p = 0.278 \pm 0.078(\mathrm{exp}) \pm 0.012(\mathrm{theo})\ \mathrm{fm}.$$

Interior Baryon Density



Interior weak density:

$$\rho_W^0 = -0.0798 \pm 0.0038\,(\text{exp}) \pm 0.0013\,(\text{theo})\ \text{fm}^{-3}.$$

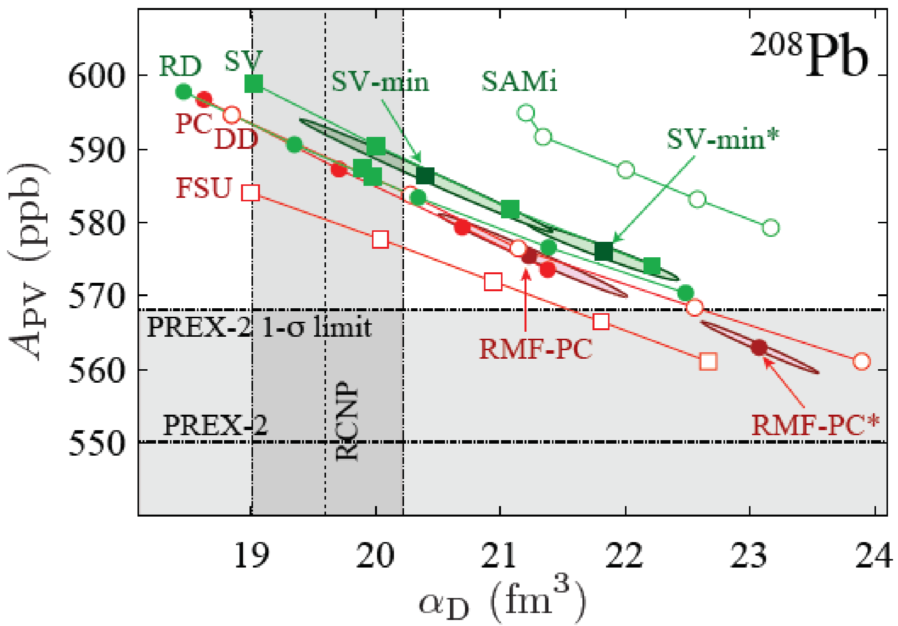
Interior baryon density from PREX combined and charge density data:

$$\rho_b^0 = 0.1482 \pm 0.0040\ \text{fm}^{-3}$$

Note: acceptance function needed to interpret correctly

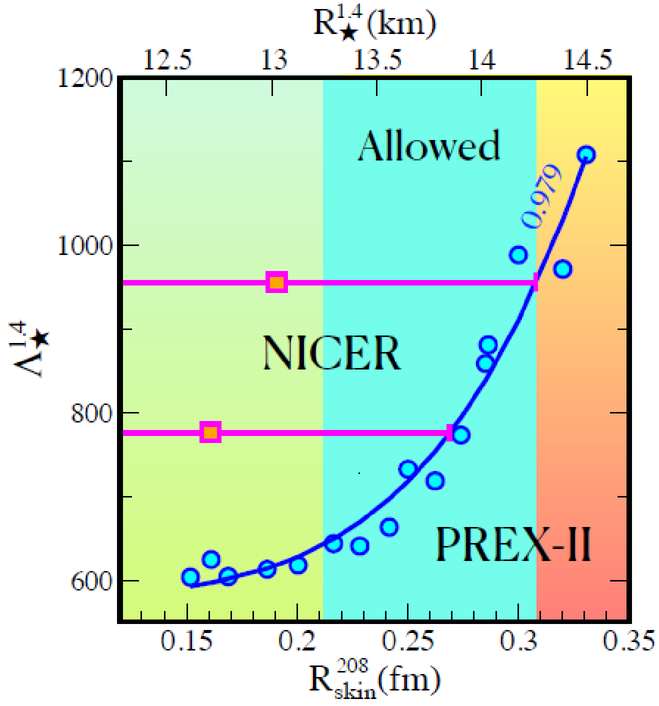
$$\langle A_{\rm PV} \rangle = \frac{\int d\theta \sin\theta\, A(\theta) \frac{d\sigma}{d\Omega} \epsilon(\theta)}{\int d\theta \sin\theta \frac{d\sigma}{d\Omega} \epsilon(\theta)}$$

Context and Implications - Tension



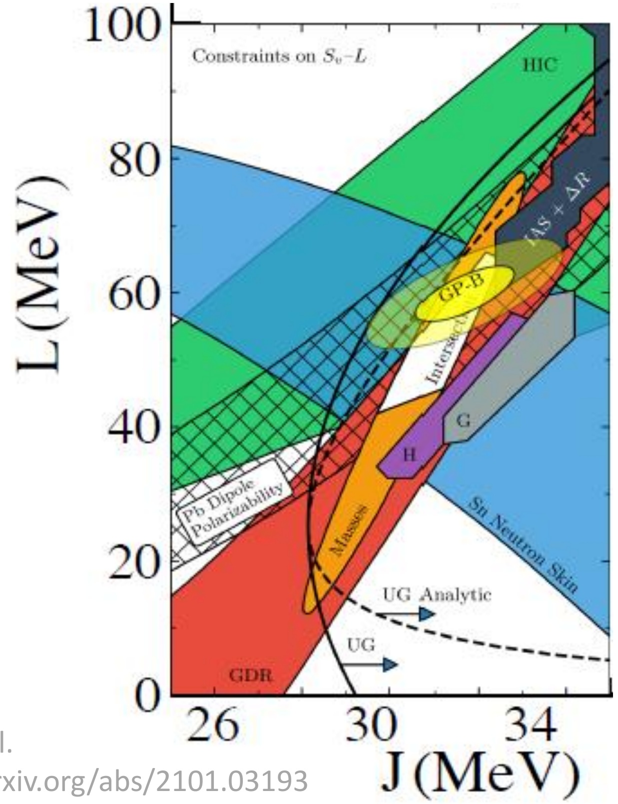
Reinhard et al.
https://arxiv.org/pdf/2105.15050.pdf

There is no model which is able to simultaneously reproduce A_{PV} and α_D within the experimental 1 σ error bands



$R_{skin}^{208} \lesssim 0.31$ fm and a lower limit on the stellar radius of $R_\star^{1.4} \gtrsim 13.25$ km

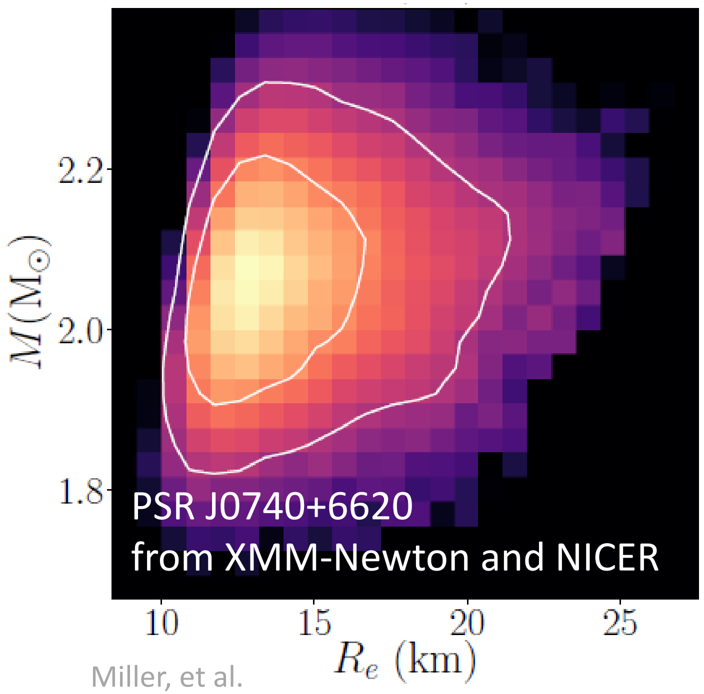
Reed et al.
https://arxiv.org/abs/2101.03193



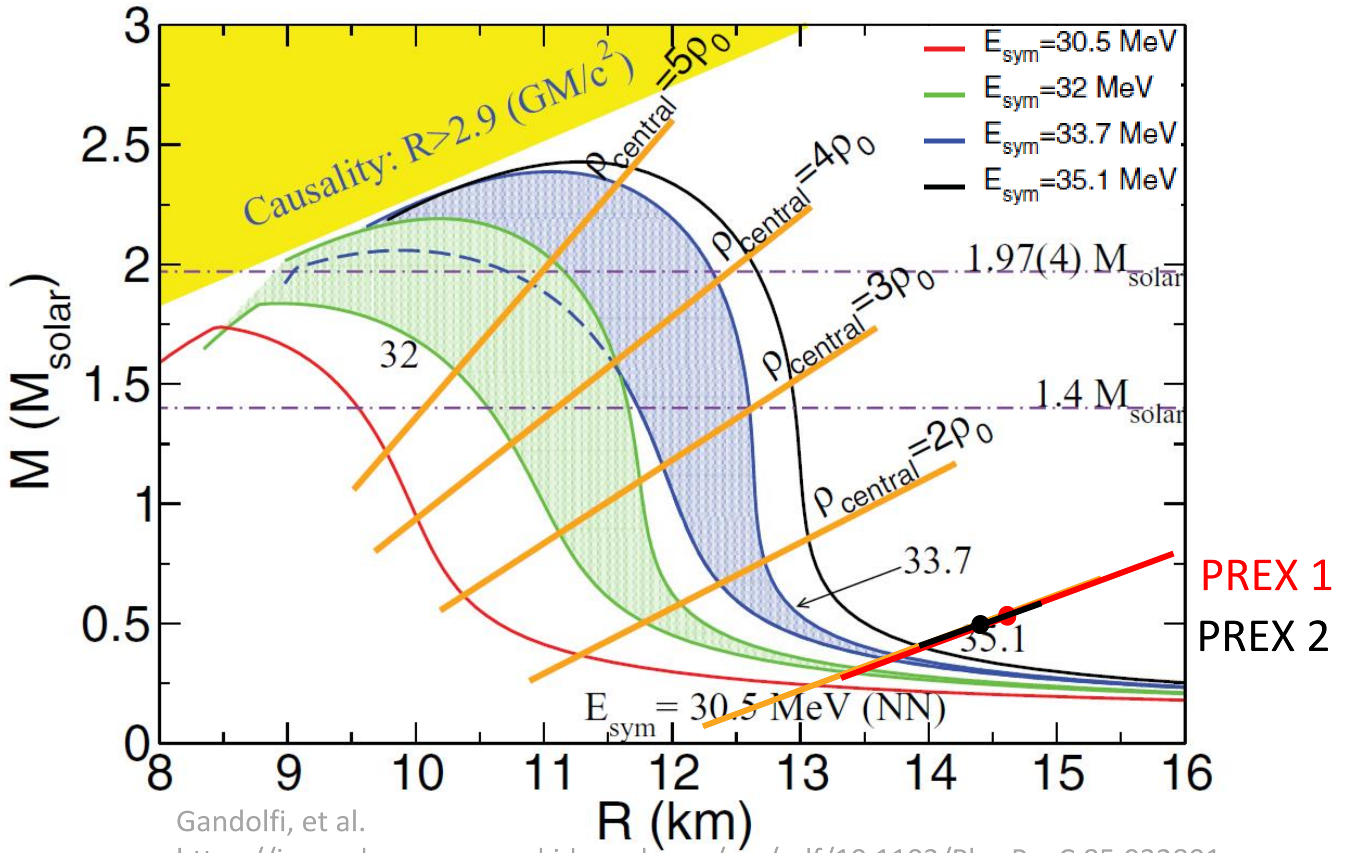
The PREX-II result is relatively model-independent

Relating PREX and CREX to Neutron Stars

- The mass of a neutron star as a function of radius can be determined from neutron star observations
- Nuclear structure models can produces EOS curves relating the mass and radius, using different assumptions (values of E_{sym}, NNN interactions)



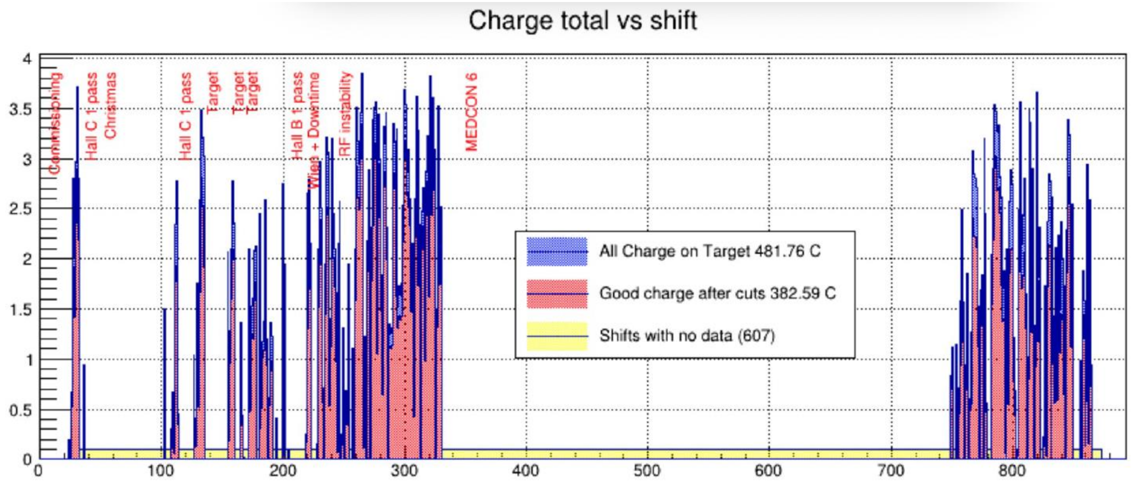
Miller, et al.
https://arxiv.org/abs/2105.06979



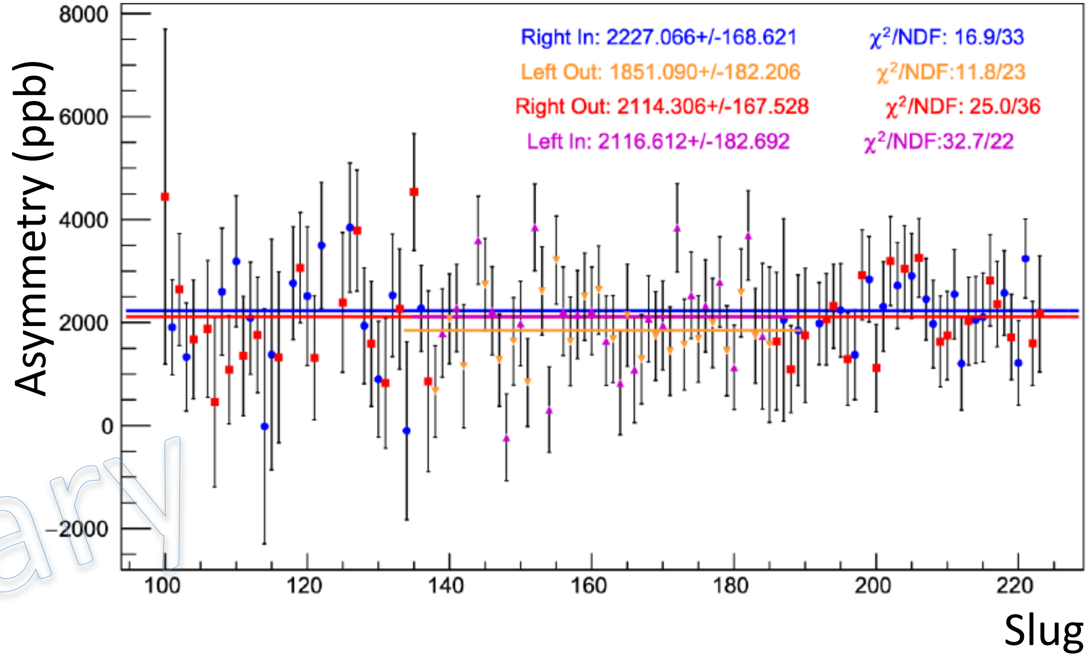
Gandolfi, et al.
https://journals-aps-org.uml.idm.oclc.org/prc/pdf/10.1103/PhysRevC.85.032801

- In this plot, E_{sym} =35.1 MeV corresponds to L = 63.6 MeV (E_{sym} =30.5 MeV ~ L = 31.1 MeV)
- Combined PREX gives 106 ± 37 MeV (in a different model)
- CREX will help narrow the width of the 3N bands

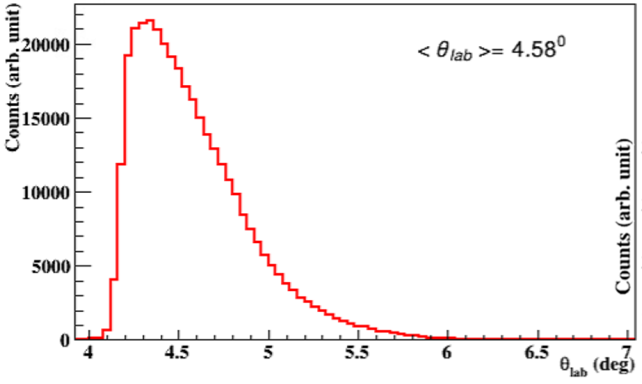
CREX Status

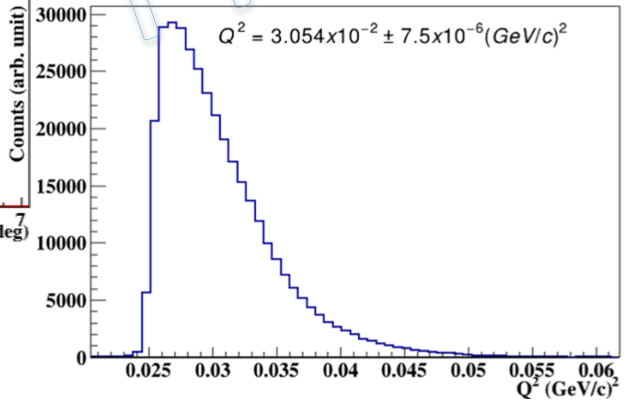


Data collected at beam energy of 2.2 GeV @150 μA collecting a total of 481 C during production running



Preliminary



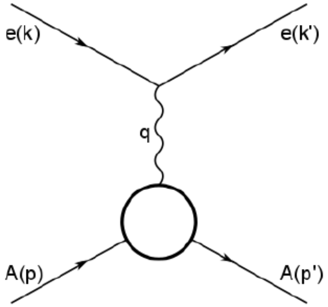


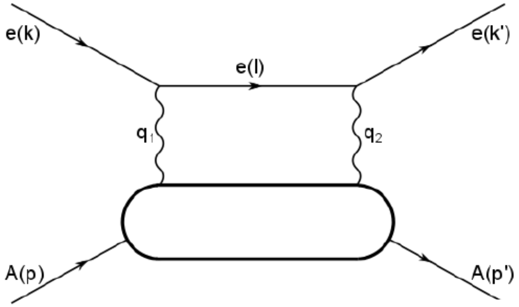
- CREX data is being analyzed
- Expect to unblind by end of summer
- Publish this fall

Expected systematic

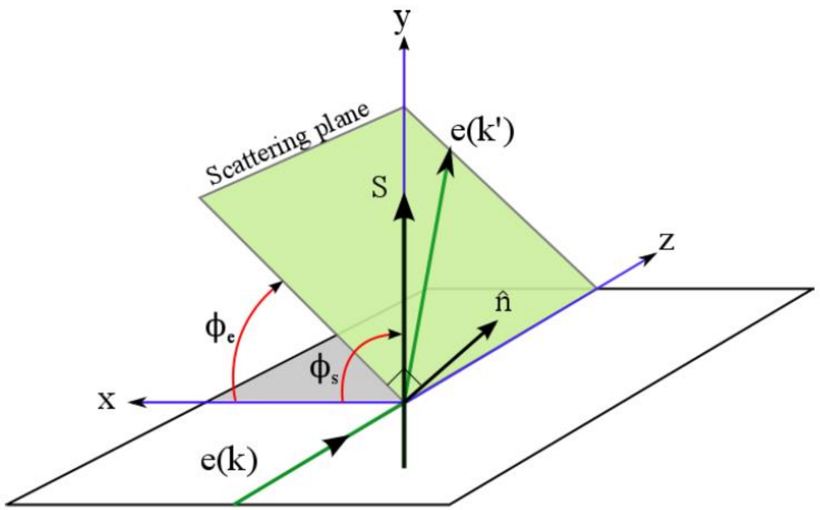
Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse	0.1%
Polarization	0.8%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total	1.2%

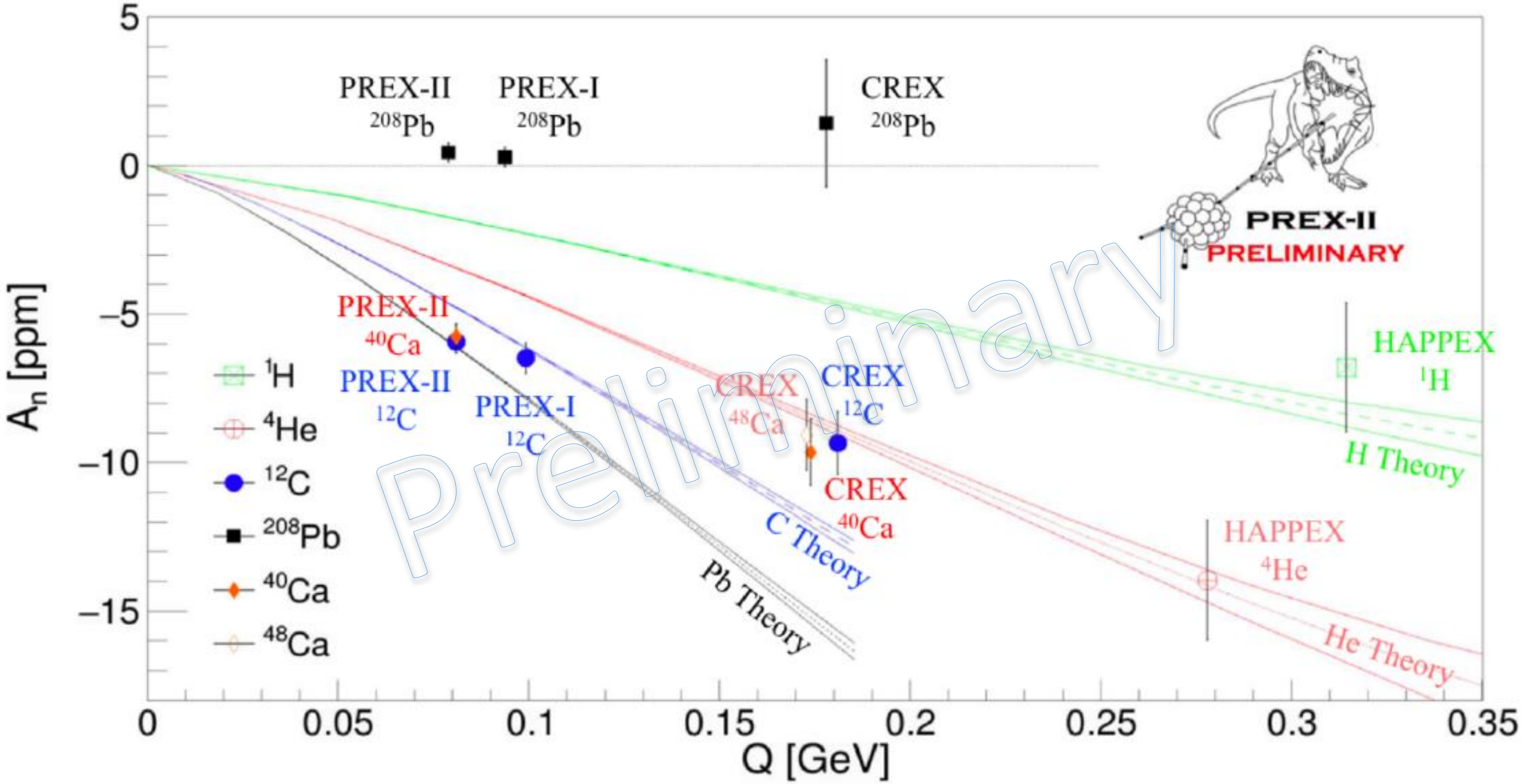
Transverse





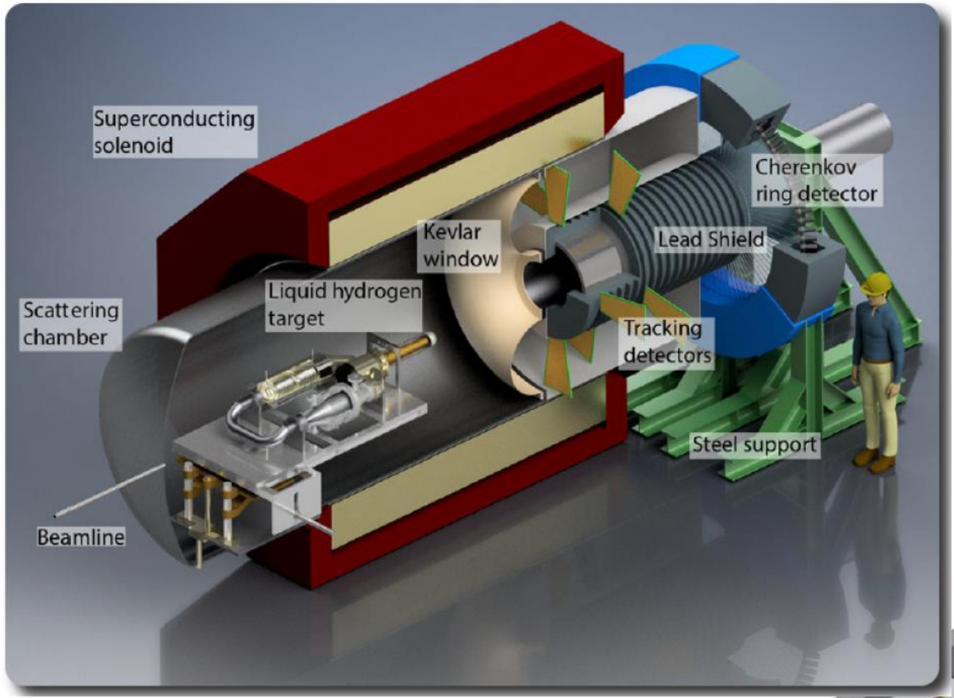
$$A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx 0 + \frac{2\mathrm{Im}(T_{2\gamma} \cdot T_{1\gamma}^*)}{|T_{1\gamma}|^2}$$

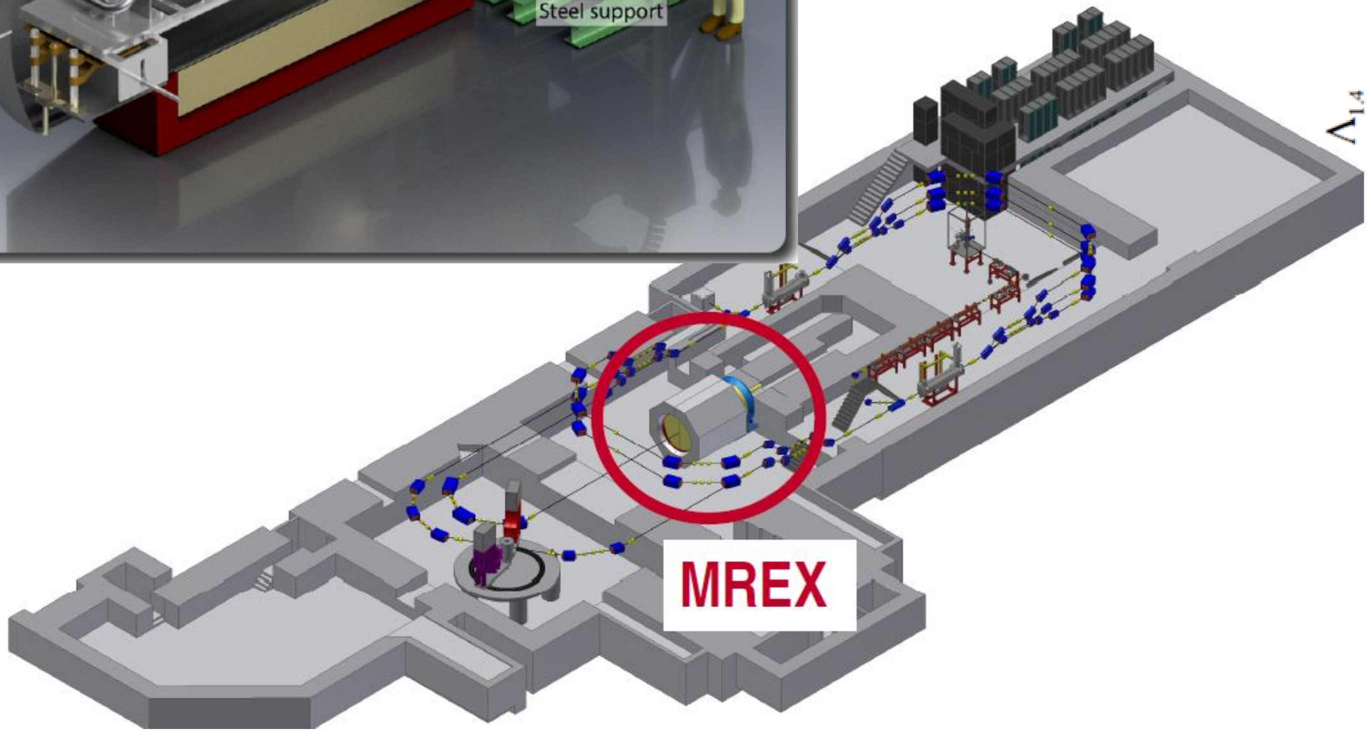


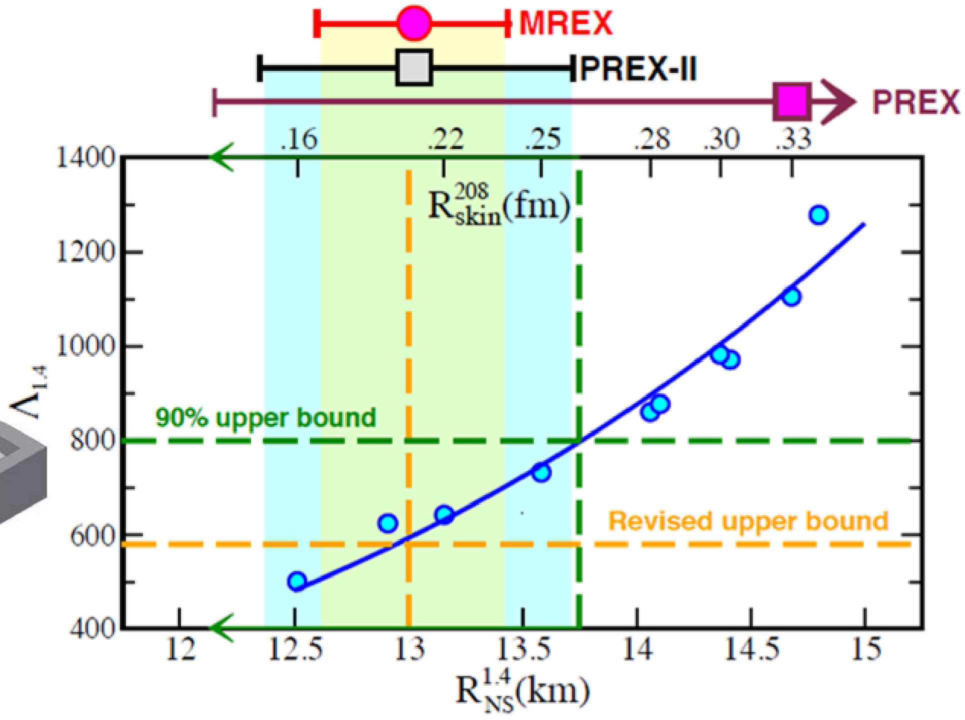


$$\mathcal{A}_{meas}(\phi_e) = \mathcal{A}_n(\vec{S}_e \cdot \hat{n}) = \mathcal{A}_n|\vec{S}_e|\sin(\phi_e - \phi_s)$$

MREX – at the Mainz Microtron - MESA







https://arxiv.org/pdf/1904.12269.pdf

Conclusion

- PREX 2 is complete
  - Weak form factor
  - Weak radius
  - Neutron skin
  - Interior baryon density
- CREX data is being analyzed – expect to publish in Fall 2021
- Future experiment at Mainz to improve the precision

L = 106 ± 37 MeV

In tension with NICER, dipole polarizability, tidal deformability