Electroweak Measurements of Neutron Densities in PREX (and CREX)

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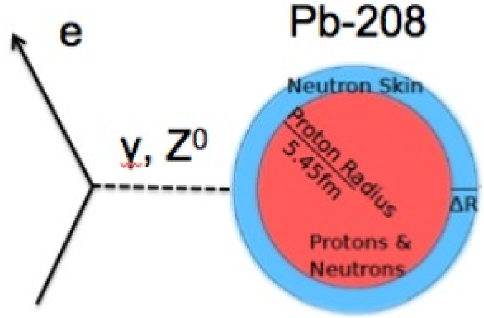
Outline

- Overview
- Progress
- Future plans

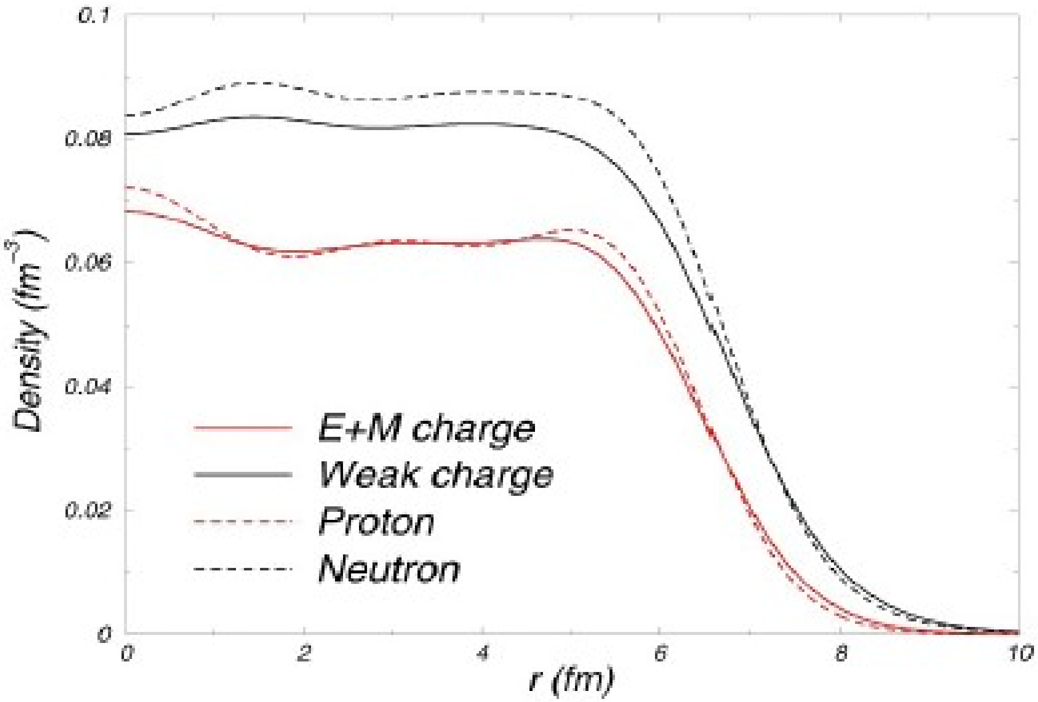
Installation video:
https://hallaweb.jlab.org/tech/pictures/RightSideCamera.AVI

PREX/CREX : Neutral Current as a Probe of the Neutron

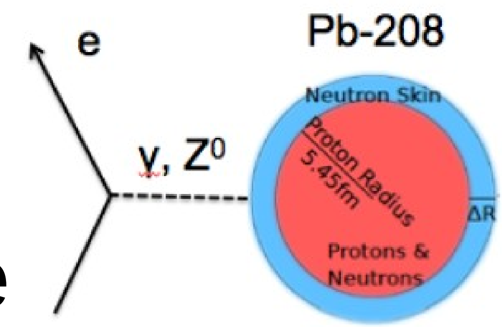


Weak neutral current : A clean probe couples mainly to neutrons

$$Q^{p}_{weak} = 1 - 4\sin^2\theta_W \sim 0.076 \qquad Q^{n}_{weak} \sim -1$$



PREX/CREX : Neutral Current as a Probe of the Neutron



- Weak neutral current : A clean probe couples mainly to neutrons

$$A_{PV} = \frac{\frac{d\sigma^R}{d\Omega} - \frac{d\sigma^L}{d\Omega}}{\frac{d\sigma^R}{d\Omega} + \frac{d\sigma^L}{d\Omega}} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[1 - 4 \cdot \sin^2\theta_W + \frac{F_w(Q^2)}{F_p(Q^2)}\right] \qquad A_{PV} \rightarrow 10^{-6}$$

- It provides theoretically clean method to measure neutron radius and skin thickness

$$A_{PV} \rightarrow F_W(Q^2) \rightarrow R_n \rightarrow (R_n - R_p)$$

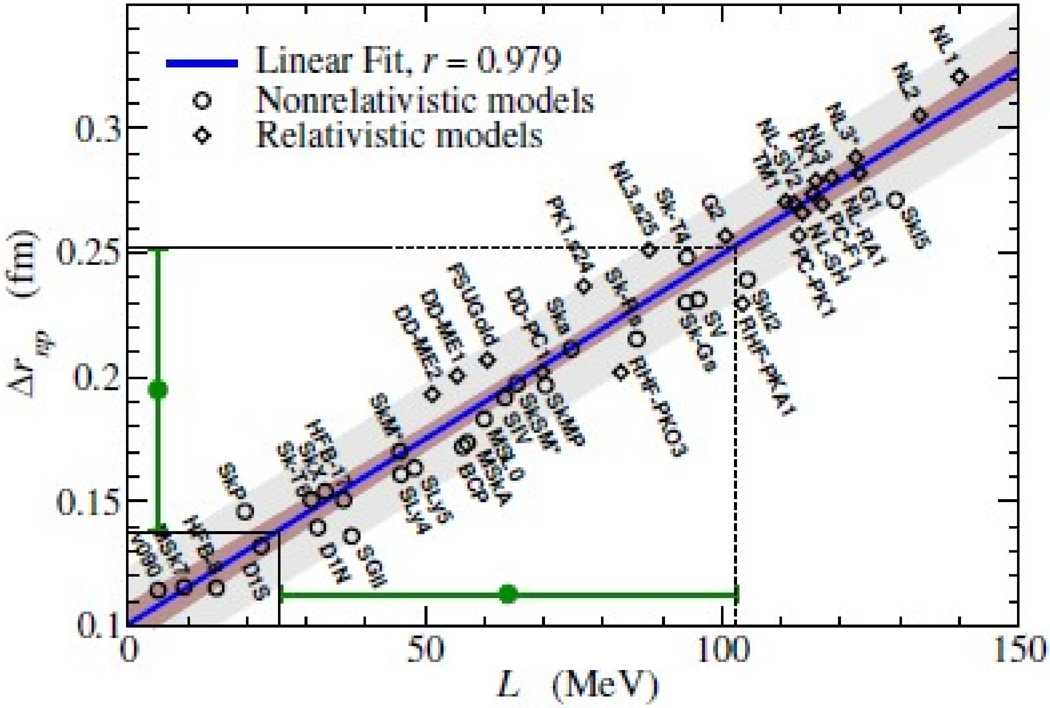
Symmetry energy and Neutron Skin

- PREX can constrain the density dependence of the nuclear symmetry energy $E_{sym}(\rho)$ around normal density ρ_0 denotes as L in the plot below
  - For example, A larger L value implies a higher pressure in neutron matter and a thicker neutron skin in ^{208}Pb

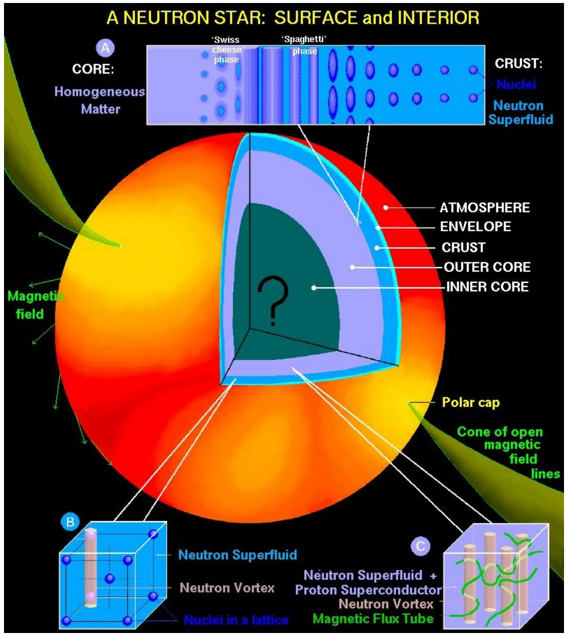
$$E_b = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \delta(A,Z)$$

- Many areas of active research interested in L
  - Structure and the reactions of neutron-rich nuclei,
  - The physics of neutron stars and gravitational radiation from neutron stars

X. Roca-Maza et al.,
PRL 106 252501 (2011)



PREX Implications : Neutron Stars



Courtesy of C.J. Horowitz and J. Piekarewicz

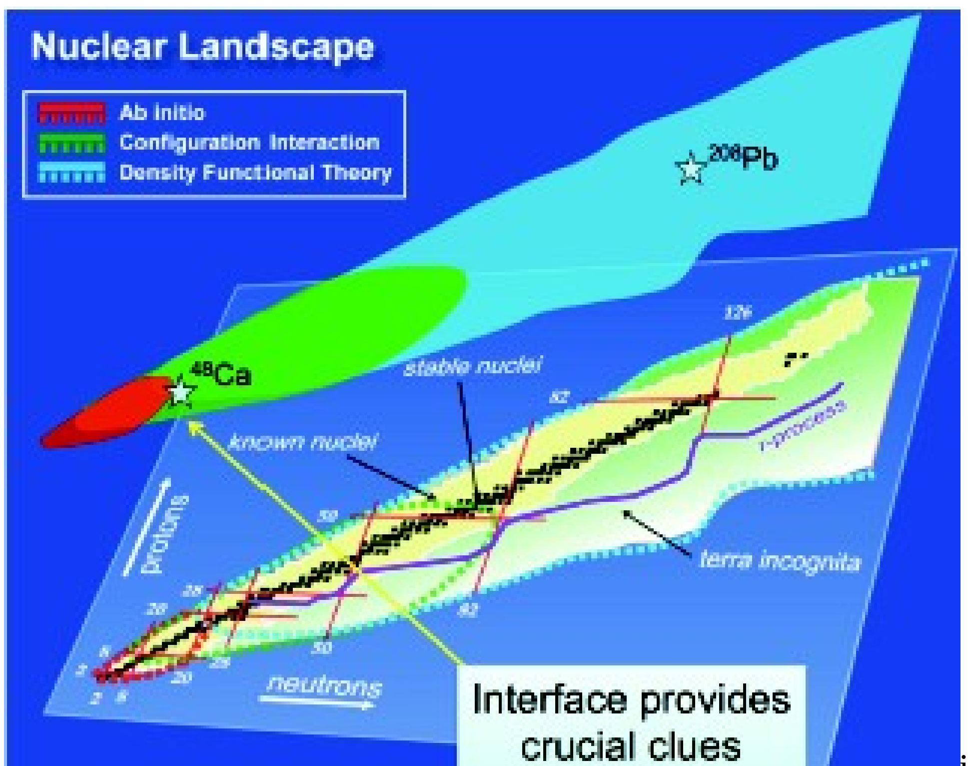
- R_N calibrates equation of state (pressure vs density) of Neutron rich matter
- Combine PREX R_N with observed neutron star radii
  - Prediction for phase transition to “Exotic” Inner Core
- Some neutron stars seem too cold
  - Explained by cooling by neutrino emission (known as URCA process)?
  - Only if $(R_N - R_p) \rightarrow 0.2$ fm : URCA is probable
- LIGO and PREX
  - Gravitational wave observations of massive neutron stars during merger provides information on the equation of state (EOS) of nuclear matter (A. Bauswein and H.-T. Janka. Phys. Rev. Lett., 108:011101, Jan 2012)

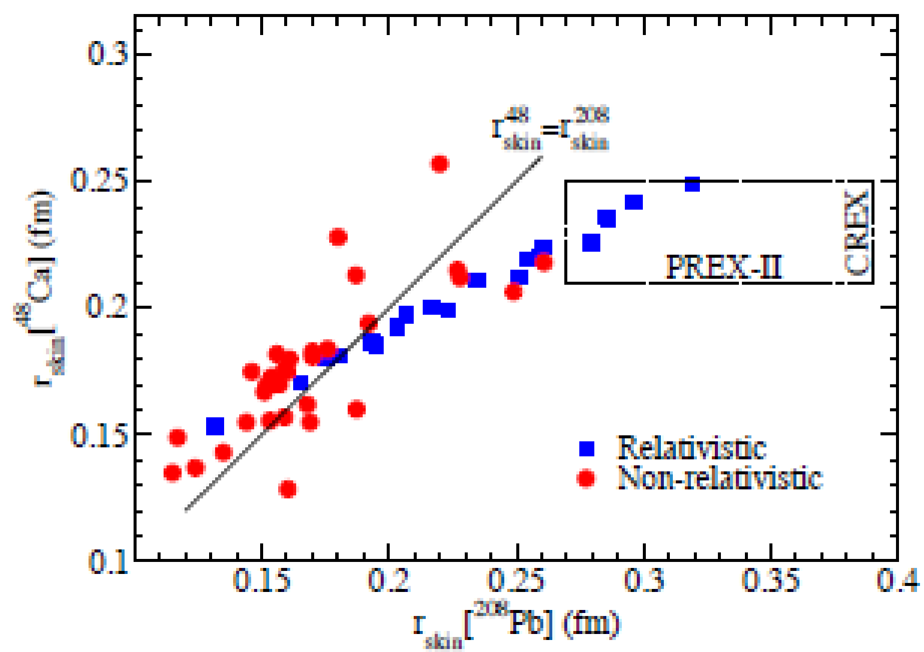
Crab Pulsar

TITLE	CITED BY	YEAR
Measurement of the Neutron Radius of ^{208}Pb through Parity Violation in Electron Scattering S Abrahamyan, Z Ahmed, H Albataineh, K Aniol, DS Armstrong, ... Physical review letters 108 (11), 112502	422	2012

Why Two different Nuclei?

- Ab initio calculations only reach as far as medium nuclei such as ^{48}Ca
  - Experimental data from ^{208}Pb and ^{48}Ca will provide a bridge between medium nuclei ab initio calculations and heavy nuclei Density Functional Theory (DFT) calculations.
- Correlations predicted between neutron skin of ^{208}Pb and ^{48}Ca need experimental validations



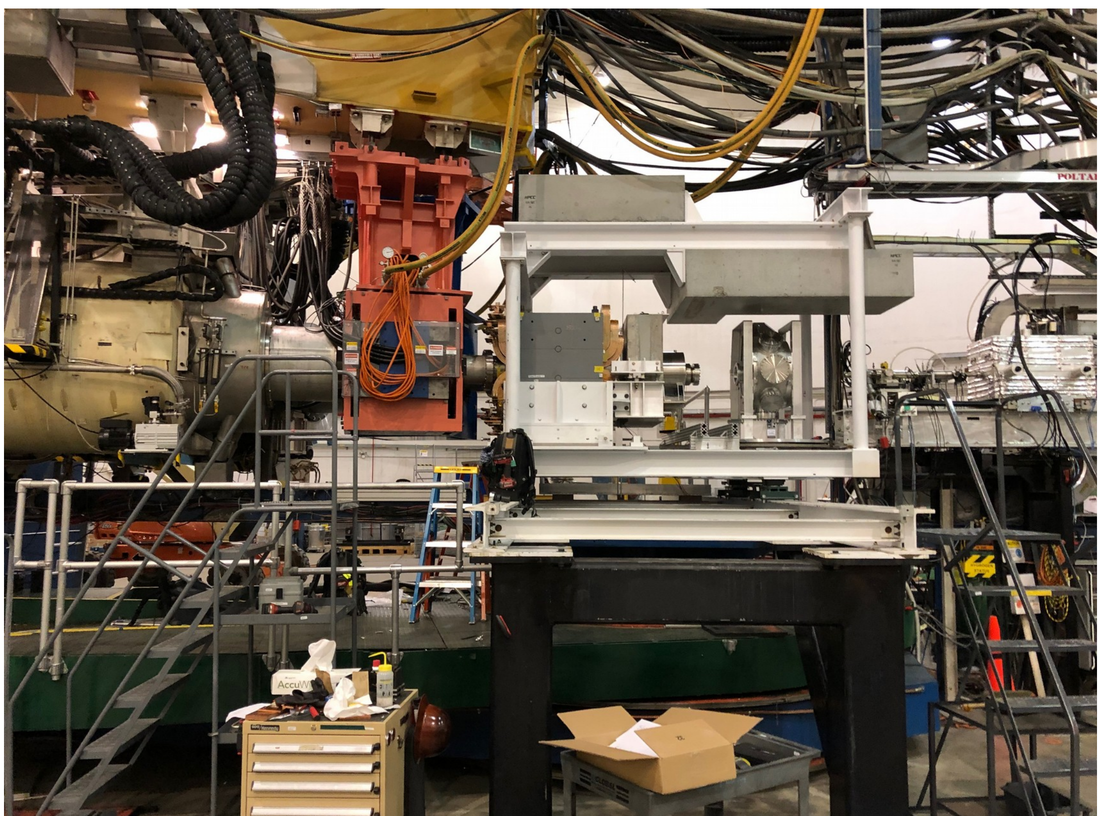
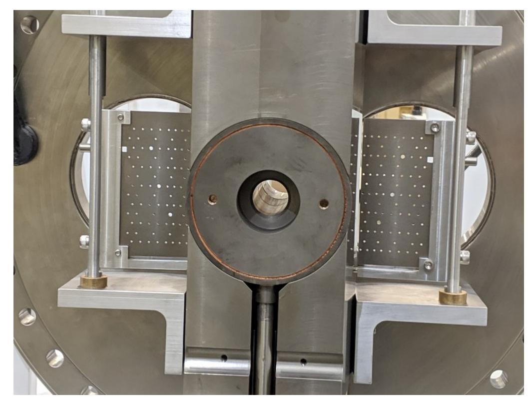


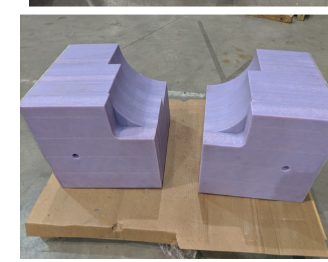
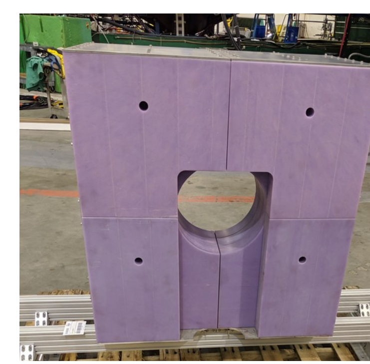
Experimental Setup

- Two High Resolution Spectrometers (HRS) run simultaneously
  - Using a Septum magnet to reach our acceptance at small scattering angles
- Both ^{208}Pb and ^{48}Ca provide large inelastic separation with HRS and have very long life time for a neutron excess nuclei
- Improved shielding and improved lead target design (and more targets!) allow for more statistics
- Improved constrains on systematics
- **PREX E_{beam} = 0.95 GeV up to 70 uA**
  - Aims to reach goal of $\Delta R_n \sim 0.06$ fm (a 1% measurement)
- **CREX E_{beam} = 2.2 GeV up to 150 uA**
  - Aims to reach goal of $\Delta R_n \sim 0.02$ fm (a 0.6% measurement)

Radiation Safety Measures

- New collimator to absorb most of the energy
- New shielding measures around target to septum area
- Lead diffusion barrier to minimize the sky radiation
- Magnetic shielding around septum beamline

Subsystems Updates

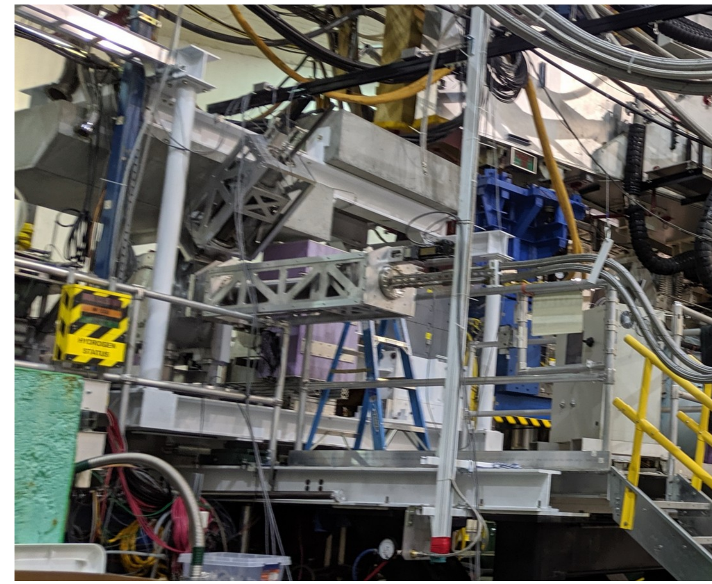
- Injector/beam delivery
  - Basic beam setup, Source and Parity Quality Beam setup are done
- Targets are ready
- Parity and Counting mode DAQ are ready
- Parity and Counting mode Data analysis tools are ready
  - Streamlining software workflows and minor software updates are still ongoing
- Spectrometer checkout ongoing: Dipole and quad tune study
- Integrating and Tracking Detector calibration with beam ongoing
- Polarimetry: Compton and Moller polarimeters are ready
  - Commissioning plans are coming up soon then followup with a spin dance

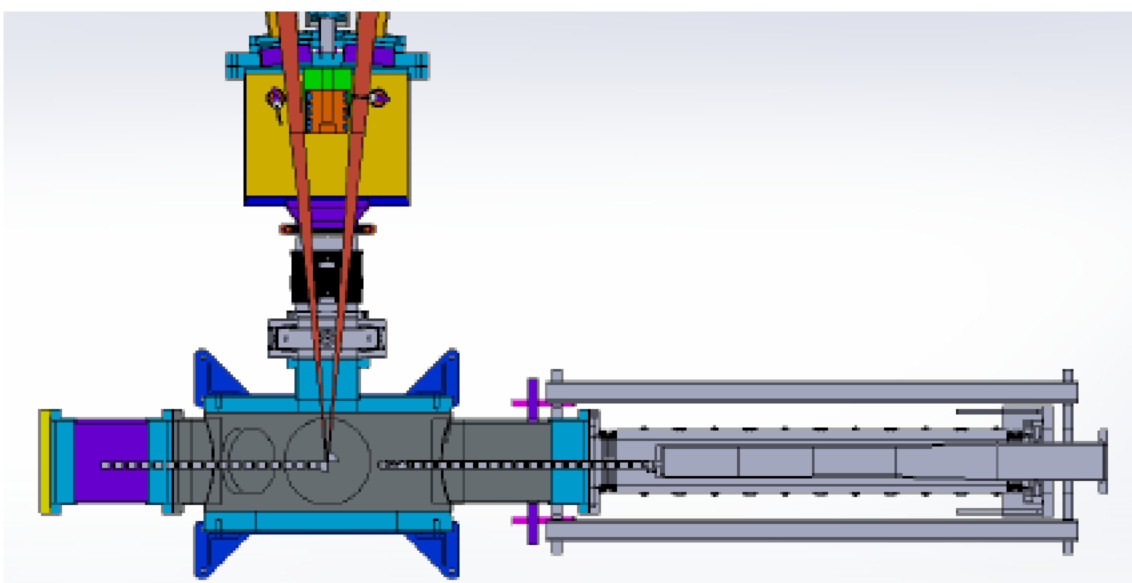
Laser/Injector/Beamline

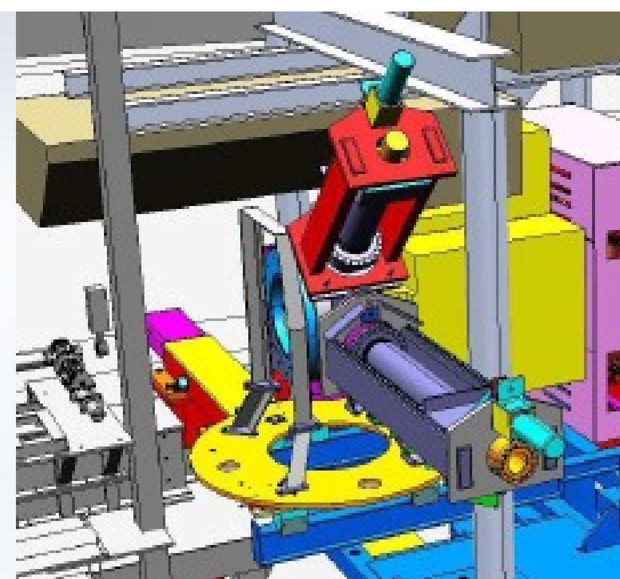
- Basic beam setup, Source and Parity Quality Beam setup are done
  - The RTP Pockels Cell successfully produced e^- beam
  - Both real-time charge and position feedback will be done
- Initial calibrations for BCM, BPM stripline, and BPM Cavities are done
- Small Angle Monitors (SAM) calibrations are ongoing
- Beam modulation
  - Hardware (accelerator) is ready
  - Software (accelerator) seems to be in place and tested
  - Software (control and DAQ) are demonstrated
  - Full BMod is currently tested with beam ON

Target Subsystem

- Production targets: 10 Pb and 2 Ca
- Two target ladders:
  - Warm: water cell and optics targets
  - Cryogenic: for Pb and Ca targets

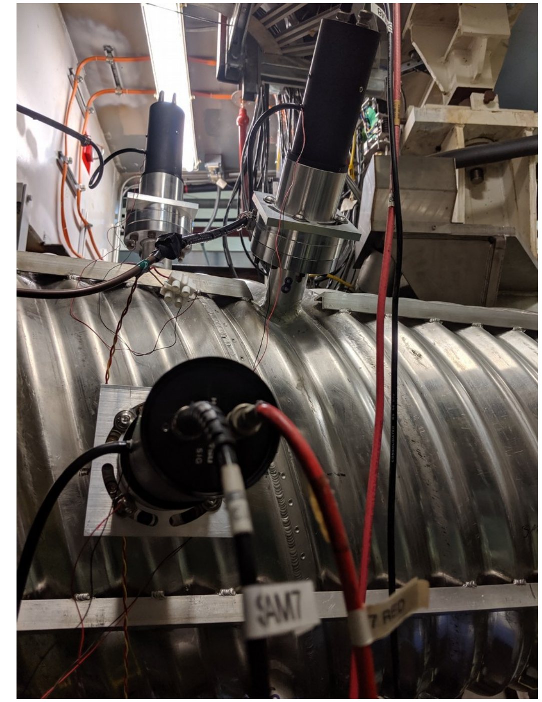


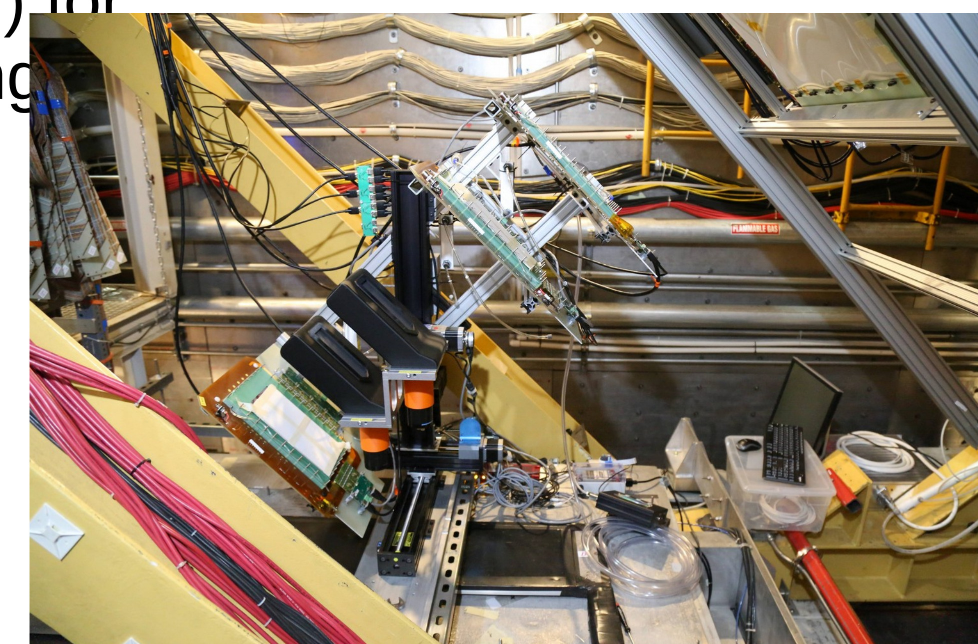


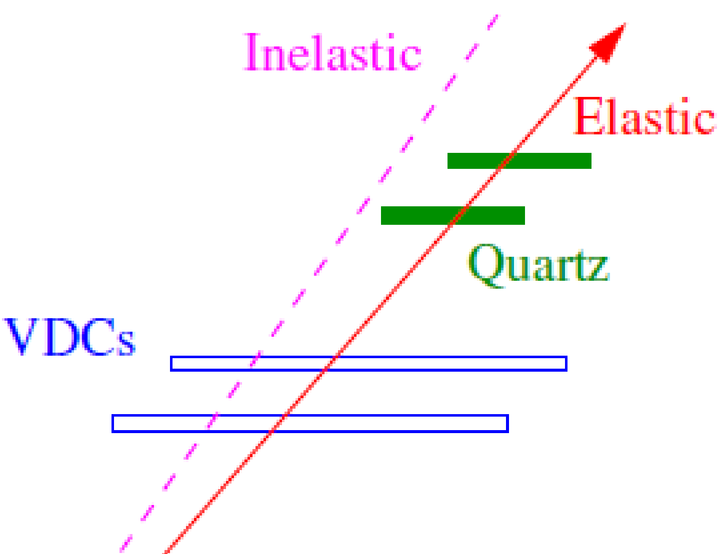


Detectors

- Quartz detectors used for main measurement
- Six GEMs in each arm for high-rate acceptance measurements
- Additional detectors to better constrain transverse asymmetry (A_T) systematic
- New small angle monitors (SAM) for beam-line background monitoring







Progress and Future

- Beam restoration and low current commissioning were completed
- Spectrometer Commissioning on going
  - Tracking checkout: sieve reconstruction, tune septum, inner edge search, Q1 acceptance scan etc.
- High current checkout on going
  - 40 uA beam current, bypassing the Compton chicane was done with acceptable Compton backgrounds
- Establish Production Conditions will follow after above steps
  - Includes BMod, polarimetry commission, spin dance, detector check outs, etc.
- Once all above are done **Start Production**

See https://prex.jlab.org/wiki/index.php/PREX2RunPlan2019

Summary

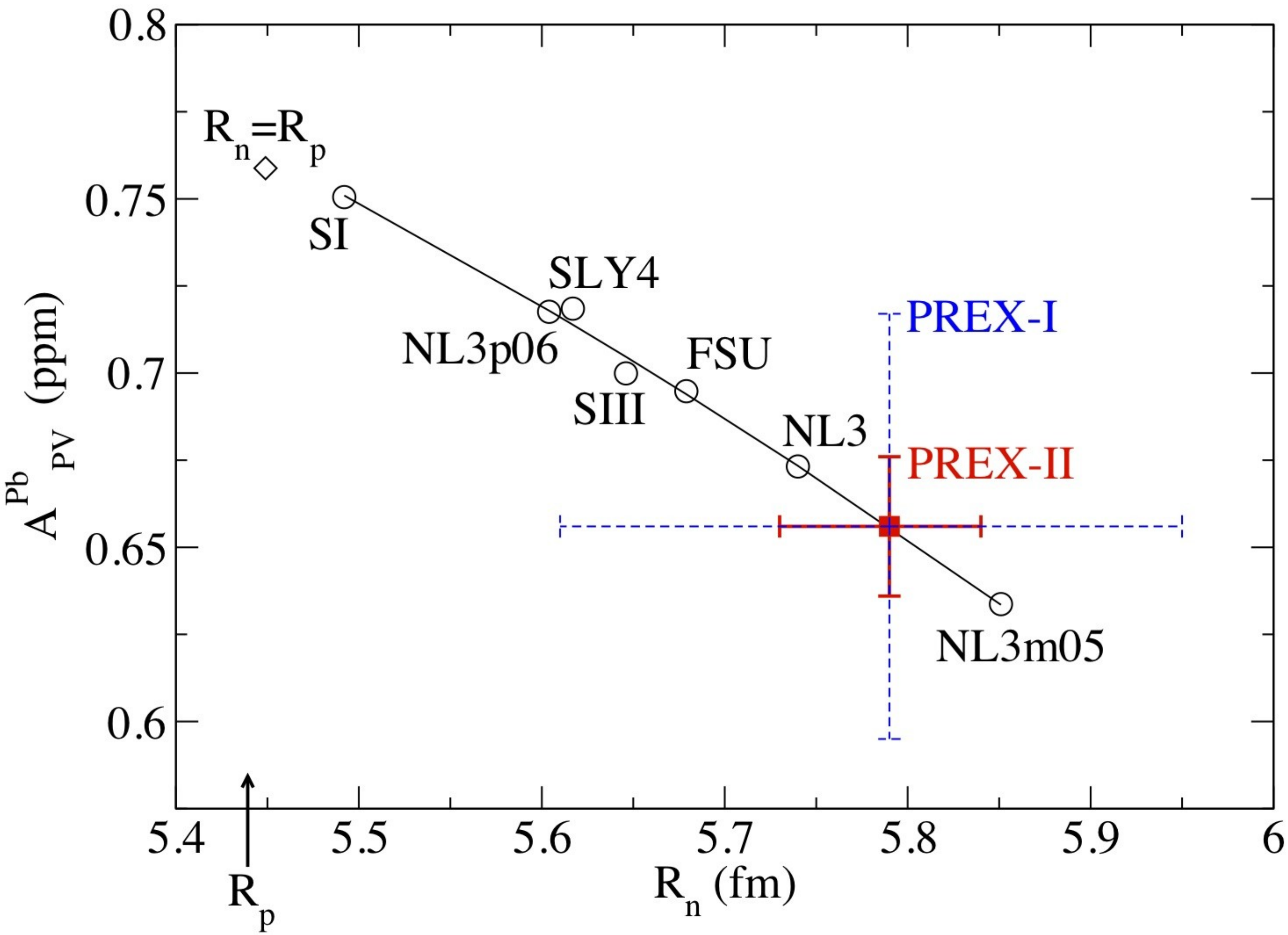
- **Big thank you for Jessie Butler, Jack Segal and company for installation and tech support**
- **On track on all fronts to being ready for high current production running for PREX**
- The PREX and CREX programs will measure ΔR_n to a precision of ±0.06 fm and ±0.02 fm, respectively
- Parity violating electron scattering gives a clean probe to access neutron distributions using weak force
- Neutron densities and skins contain information on heavy and neutron rich nuclear matter including neutron star structure

supplementary

- Plans for 240 Hz or 120 Hz flipping.
- 30Hz flip during CREX.
- Wien flips (suggested 1-2 week time scale, will depends on what on beam conditions)
- Spin flipper study possible early January
- 499 MHz for PREX/CREX?

PREX : Earlier Results

Neutron Skin = R_N - R_P = 0.33 + 0.16 - 0.18 fm



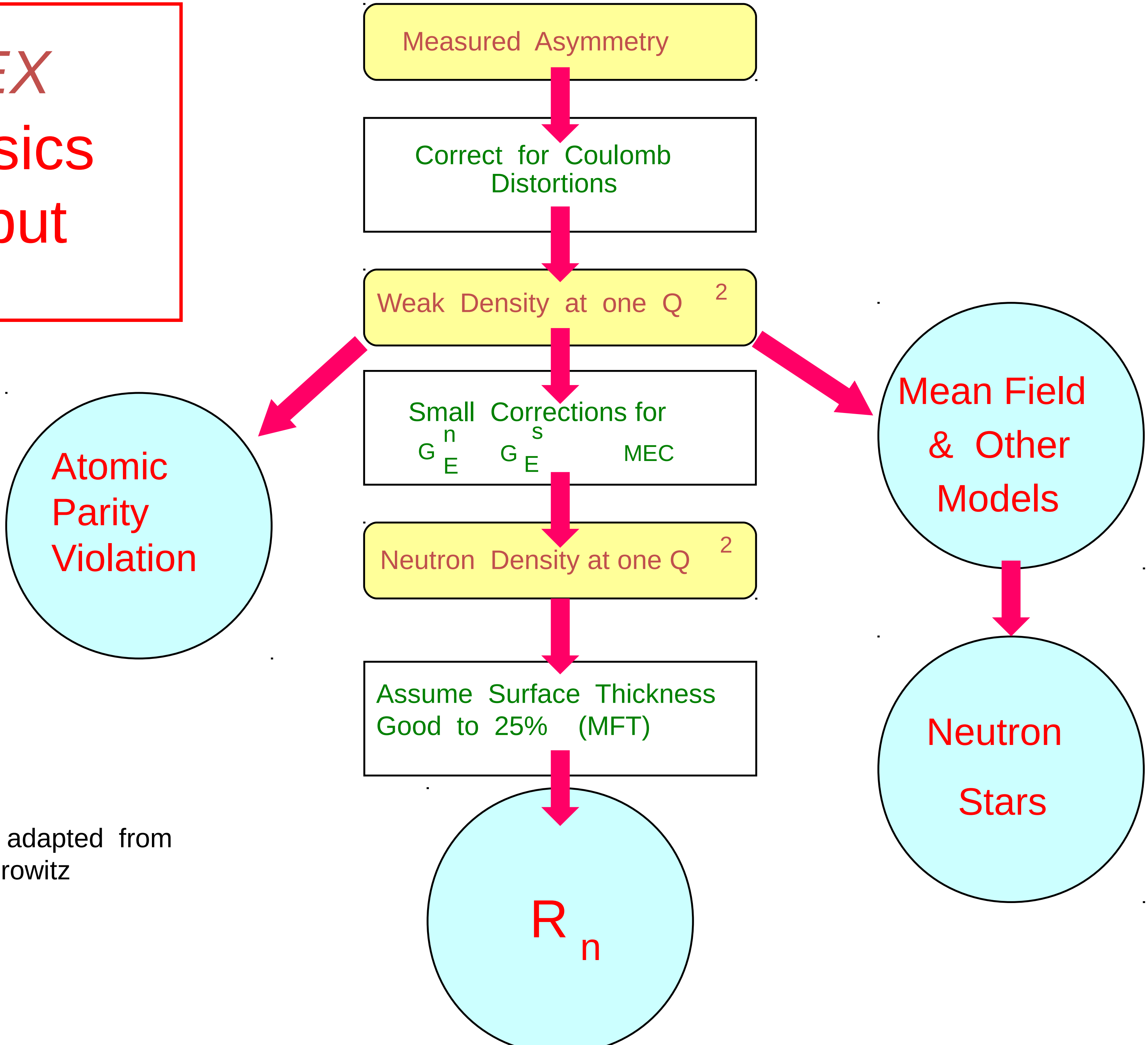
Spokespersons

K. Kumar
R. Michaels
K. Paschke
P. A. Souder
G. Urciuoli

PREX/CREX : Radiation Shielding

- PREX-II made many improvements over several PREX-I radiation damage issues
  - Damaging neutron ($0.1 < E < 10$ MeV) dose is reduced by 78% compared to PREX-I
  - High energy ($E>10$ MeV) photon dose is reduced by 80%
  - Collimator design is almost ready
  - Neutron radiation shielding optimization is underway
  - <u>Final design will further improve dose reduction</u>

PREX Physics Output



Slide adapted from C. Horowitz

Anticipated Errors

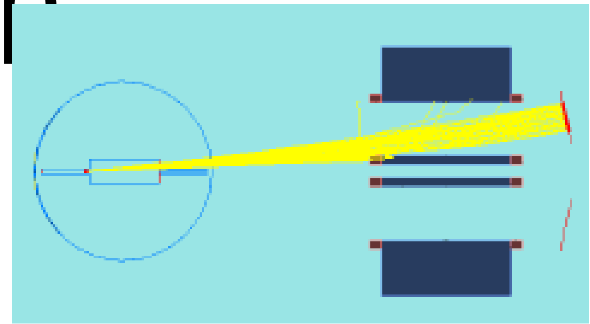
PREX-II at E = 0.95 GeV ; A_{PV} = 0.6 ppm

Systematic Error	Contribution
Charge normalization	0.1%
Beam asymmetries	1.1%
Detector non-linearity	1.0%
Transverse	0.2%
Polarization	1.1%
Inelastic contribution	< 0.1%
Effective Q2	0.4%
Total	**2%**

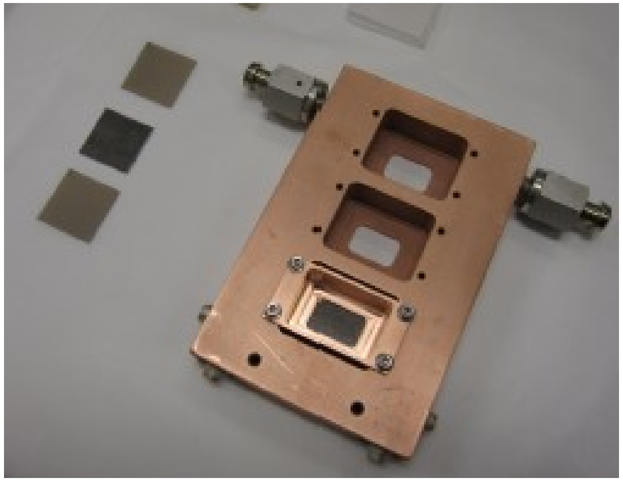
CREX at E = 2.2 GeV; A_{PV} = 2 ppm

Systematic Error	Contribution
Charge normalization	0.1%
Beam asymmetries	0.3%
Detector non-linearity	0.3%
Transverse	0.1%
Polarization	0.8%
Inelastic contribution	0.2%
Effective Q2	0.8%
Total	**1.2%**

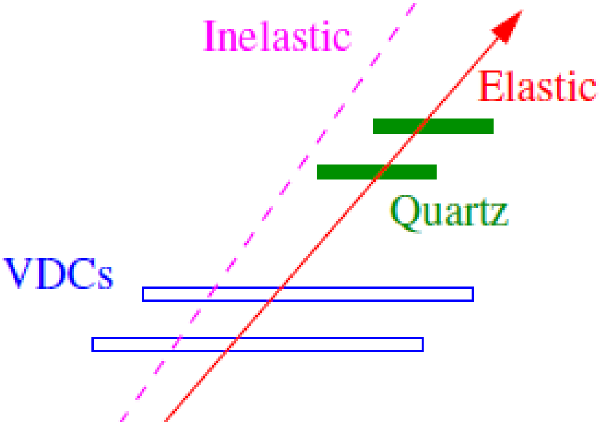
Experimental Setup



- The septum magnet needs to reach 1350 A/cm^3 using a dipole setup
  - Will require new power supply and LCW pumps
- Lead target assembly
  - 0.25 mm diamond layer + 0.5 mm Pb (9% radiator)
  - Cryogenically cooled frame
  - Will use thicker diamond layer to avoid PREX-I high current damage and there will be about 10 targets available

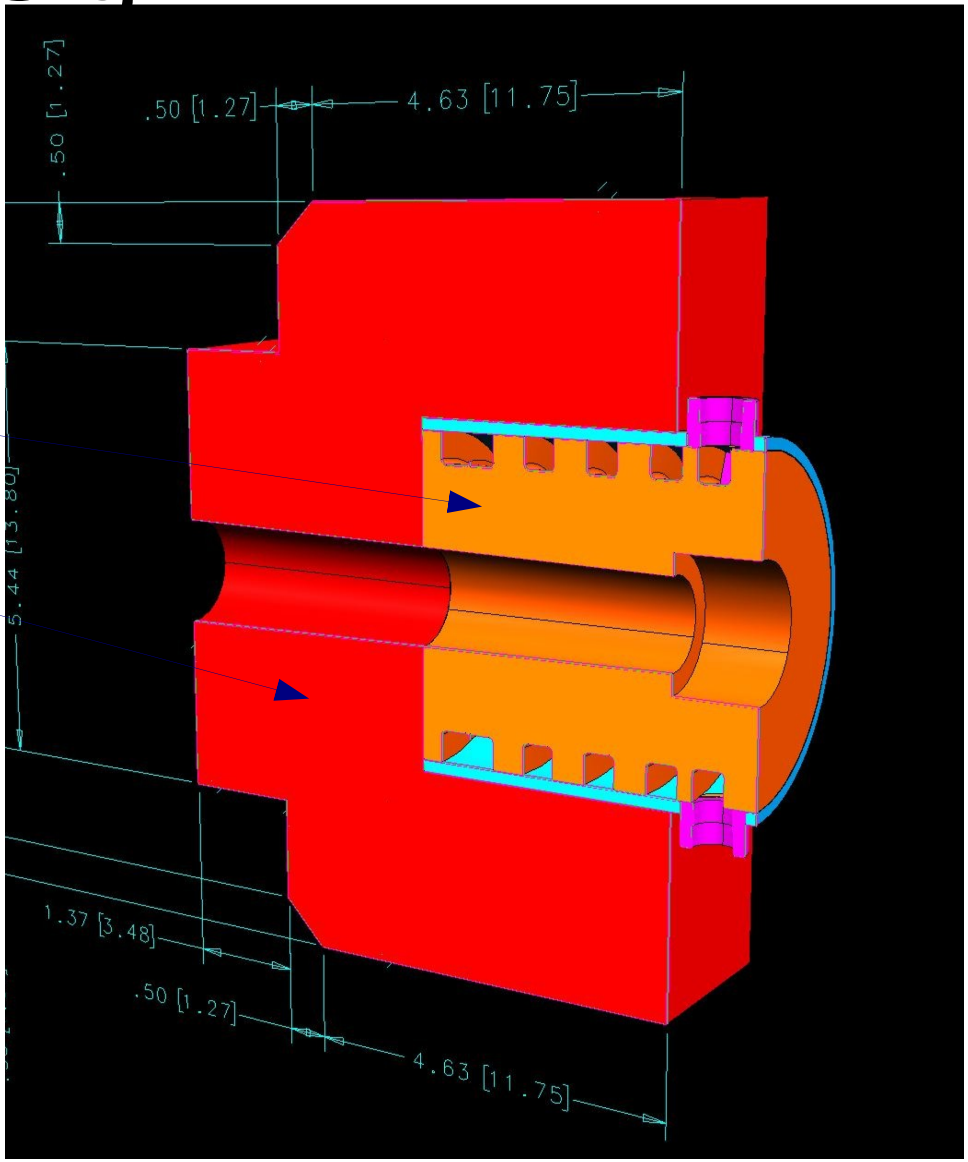


- Calcium target assembly
  - A 5% radiator
  - Must be isolated from air to prevent oxidization
  - Plans for ^{48}Ca target testing during PREX-II
- Quartz detectors will be used to integrate scattered electron signal over helicity windows
  - Place main detectors to minimize the inelastic dilution



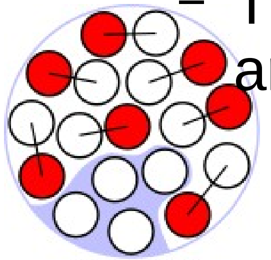
PREX-II Collimator Prototype Design

- The collimator is placed about 85 cm from the target and intercepts scattered electrons from 0.78^o to 3.8^o
  - A hybrid design where water cooled <u>Copper-Tungsten inner cylinder</u> contained in a <u>Tungsten rectangular box</u>
  - Estimated to deposit about 2.1 kW of energy by the electrons
  - Collimator will be water cooled



Physics Motivation for Neutron Densities

- Proton density and radius are precisely known in contrast to neutron counterparts
- A precision measurement of neutron density is a powerful probe of symmetry energy
  - The asymmetry term in Semi-Empirical Mass Formula (SEMF) arises due to the symmetry energy



$$E_b = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \delta(A,Z)$$

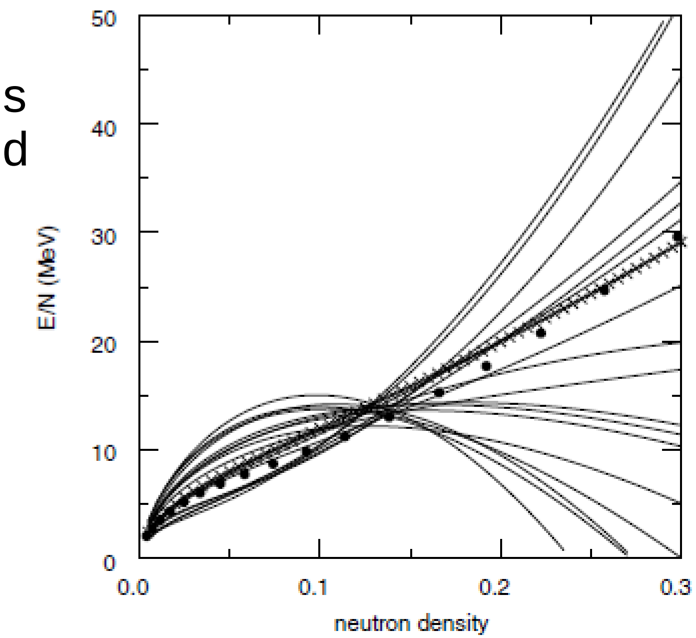
  - Difficult non-pQCD regime theoretical computations
  - Highly model dependence extrapolation to extreme neutron densities in cases like neutron stars
- Therefore experimental guidance is very important

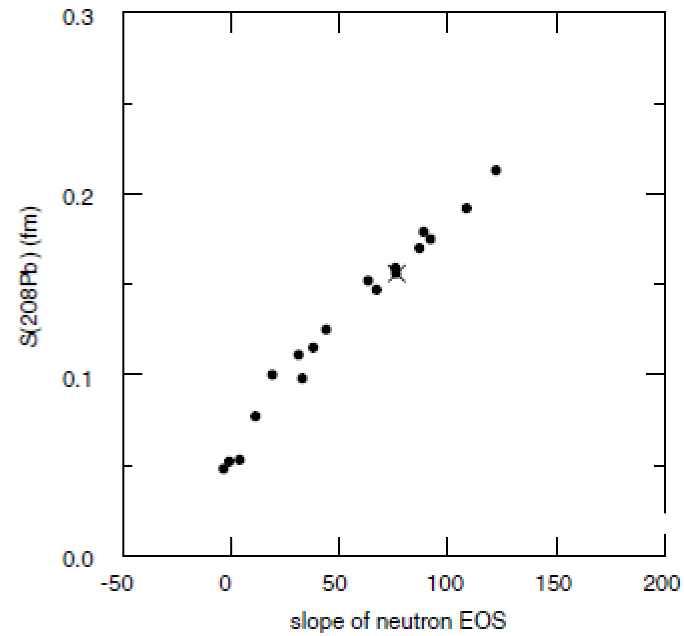
Neutron Density, Radius and Skin Thickness

- Provide constraints on neutron matter Equation Of State (neutron stars for instance) and symmetry energy
  - Can be used to constraint models

B. Alex Brown, PRL 85, 5296 (2000)

Various model predictions of neutron EOS (E/N) and r.m.s neutron skin thickness (S) for 208Pb





- Neutron thickness ΔR_{np} is the difference in r.m.s. neutron and proton radii $\Delta \mathrm{R_{np}} = \mathrm{R_n} - \mathrm{R_p}$
- A measurement of ΔR_{np} can be used to infer density dependence of the symmetry energy