Studying the Dark Side of the Nucleus: Nuclear Neutron Skin Measurements at Jefferson Lab

Seamus Riordan
seamus@anl.gov

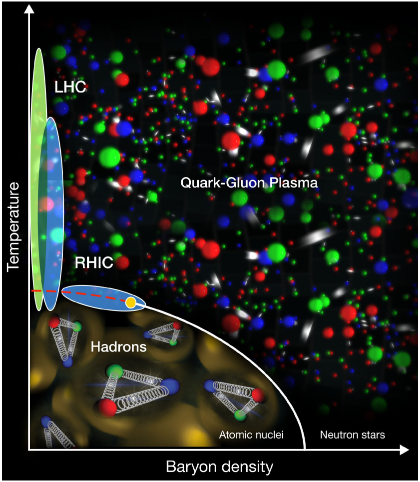
Argonne NATIONAL LABORATORY

October 1, 2017

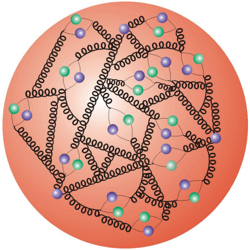
Outline

- Big Picture, Neutron Skins, and Neutron Stars
- Imaging Nuclei through Weak Force Interactions
- PREX and CREX Neutron Radius Program

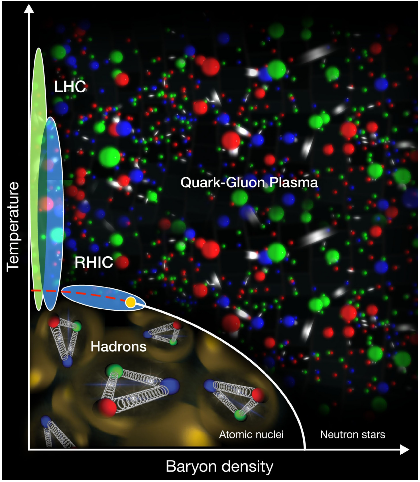
Strong Nuclear Force Physics



- QCD is force we know least about
- Not yet calculable at low energies - can't yet derive "nuclear" physics from first principles
- Broad phase space for observables need many approaches to explore



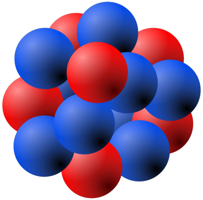
Strong Nuclear Force Physics

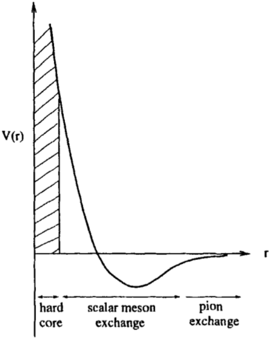


- Much to still be learned looking at low-energy, “practical” degrees of freedom:

  Protons , neutrons, and nuclei

- Next experimental stages probing extreme limits of nuclei





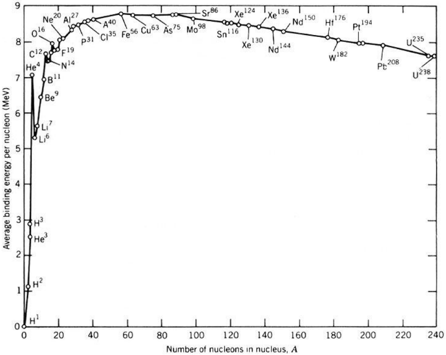
Wong, Intr. Nucl. Phys (1999)

- Emperical models contain a lot of intuitive ideas

Bethe-Weizsäcker Semi-empirical Mass Formula:

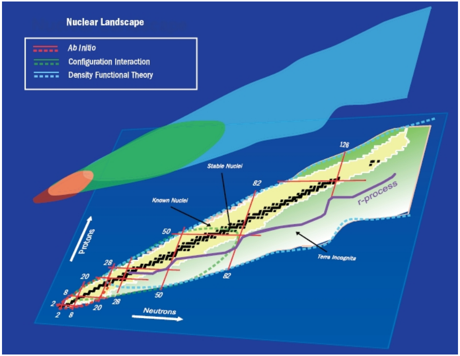
$$E_b = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \delta(A,Z)$$

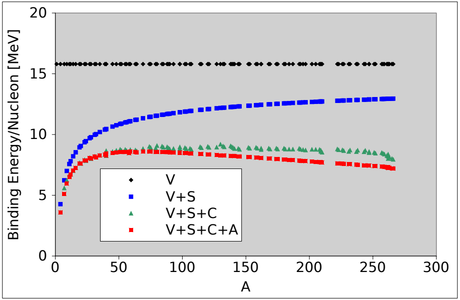
- Volume Term - nucleons bind with nearest neighbors
- Surface Term - nucleons on the outside aren't held as tightly
- Coulomb Term - Charge repulsion
- Symmetry Term - Pauli
- Pairing Term - Pauli



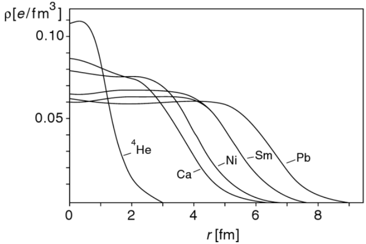
Nuclear Binding Energy - Breakdown

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

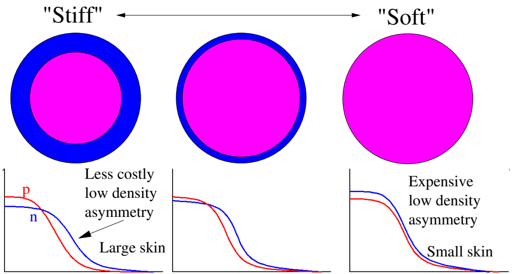




- Matter becomes more neutron-heavy going to higher A
- Symmetry term contributes 10-15% modification at large A

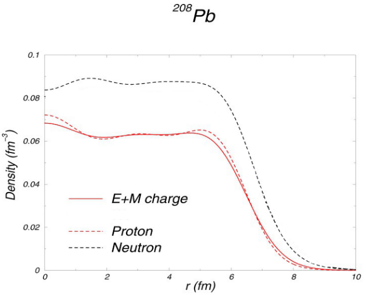


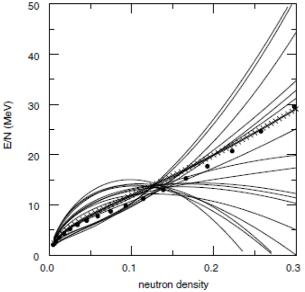
- Surfaces aren't sharp - lower density at larger radii
- Size depends on competing terms: Surface energy, Coulomb repulsion, density dependence of symmetry energy



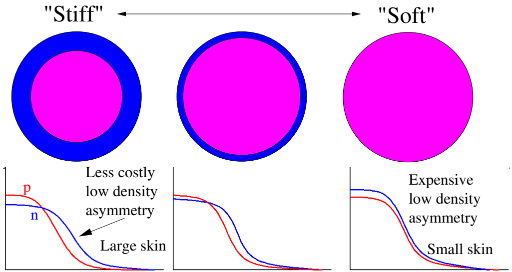
$$R_{\text{skin}} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

What more? Extend Ideas to Nuclear Structure

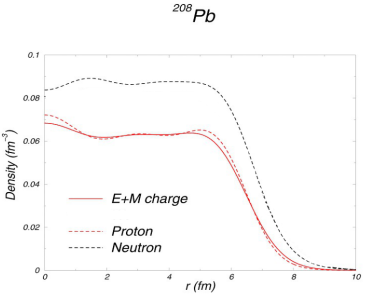


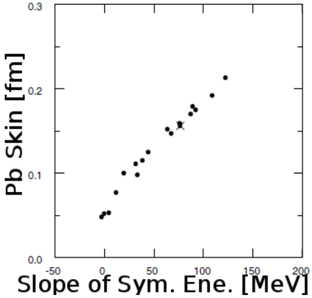


B. Alex Brown, PRL 85, 5296 (2000)

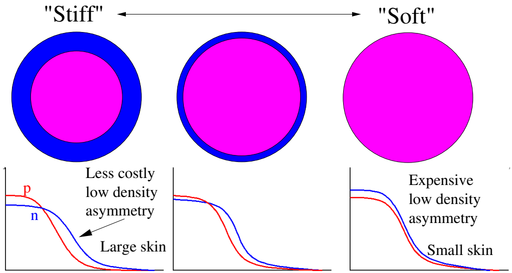


$$R_{\text{skin}} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$



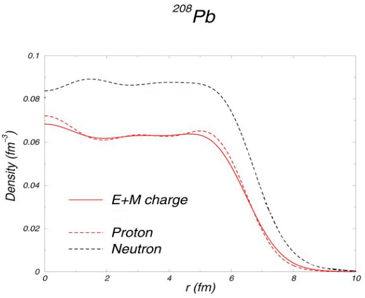


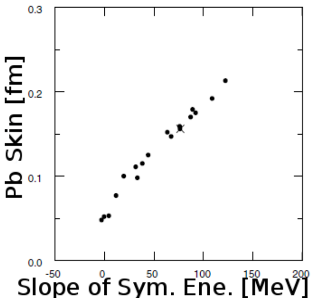
B. Alex Brown, PRL 85, 5296 (2000)



$$R_{\text{skin}} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

What more? Extend Ideas to Nuclear Structure

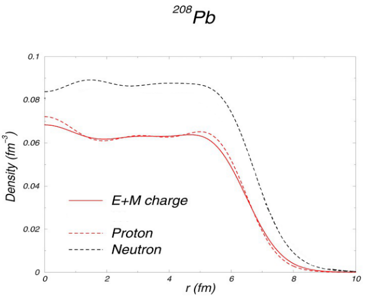


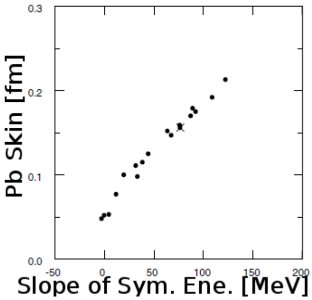


B. Alex Brown, PRL 85, 5296 (2000)

$$
\begin{aligned}
E/N &= -B + \frac{K_0}{18}\left(\frac{n}{n_s}-1\right)^2 + \frac{K_0'}{162}\left(\frac{n}{n_s}-1\right)^3 + \\
&+ \left[S_v + \frac{n_s}{3n}\color{red}{L}\left(\frac{n}{n_s}-1\right) + \ldots\right]\left(\frac{N-Z}{A}\right)^2 + \ldots
\end{aligned}
$$

What more? Extend Ideas to Nuclear Structure

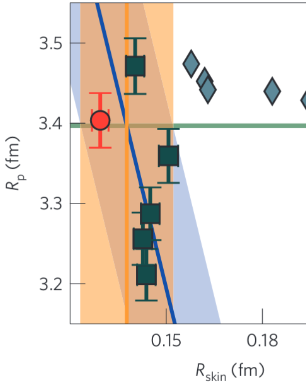




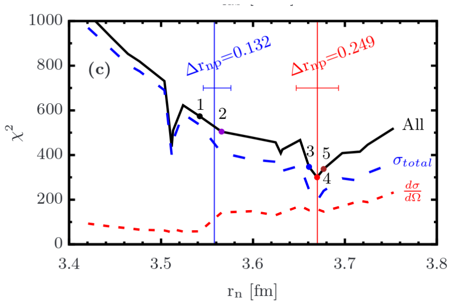
B. Alex Brown, PRL 85, 5296 (2000)

- Smaller symmetry energy at lower density creates *neutron skins* - sensitive to isovector details of nuclear force
- Want to understand the full *equation of state* of nuclear matter
- Lots of models make predictions but require data for inputs - difficult to measure $\rightarrow$ poorly constrained

Coupled Cluster



DOM



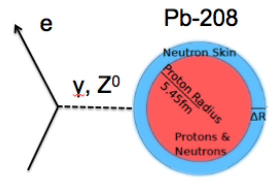
Hagen et al Nature Physics 12 (2016) 186

Mahzoon et al arXiv:1704.06719

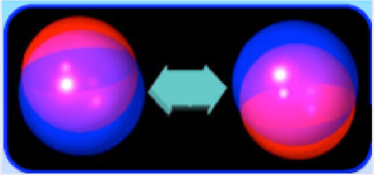
Where else does this come into play?

Lots of nuclear phenomena depend on this information!

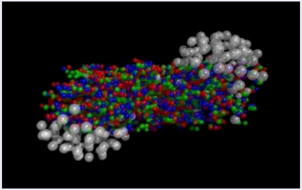
Neutron Skins



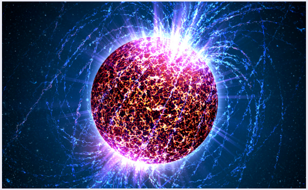
Dipole Polarizability



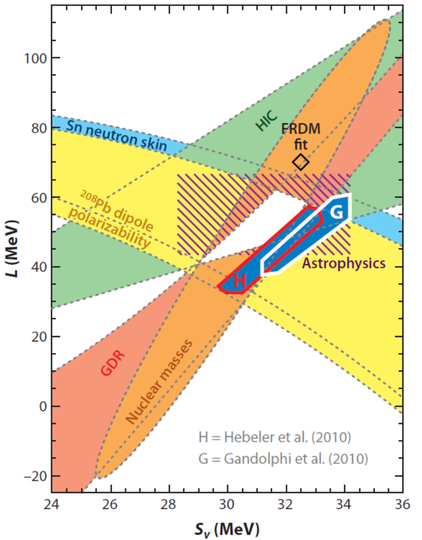
Heavy Ion Collisions



Neutron Stars



L vs. S_v

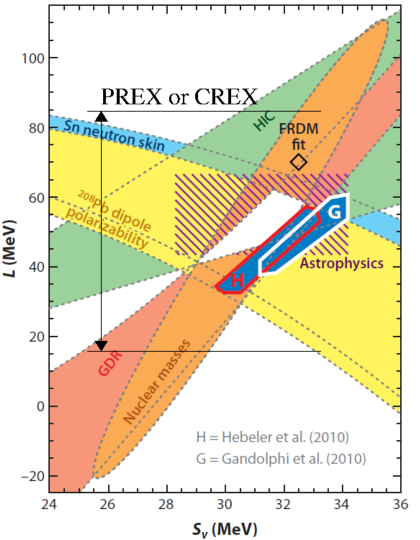


J.M. Lattimer

Annu. Rev. Nucl. Part. Sci. 2012. 62:485

- Different measurement techniques should combine to coherent picture
- Model dependent uncertainties *very hard to constrain* - unknown model dependence problem
- Cleanly interpretable signals critical for any data set

L vs. S_v



J.M. Lattimer

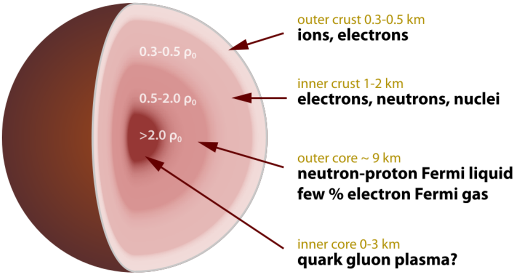
Annu. Rev. Nucl. Part. Sci. 2012. 62:485

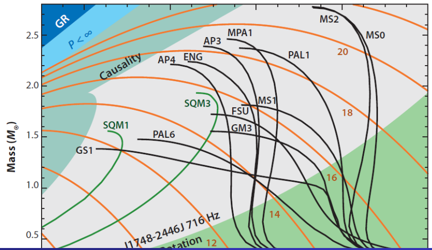
- Different measurement techniques should combine to coherent picture
- Model dependent uncertainties *very hard to constrain* - unknown model dependence problem
- Cleanly interpretable signals critical for any data set

Neutron Stars - Extreme Asymmetric Systems

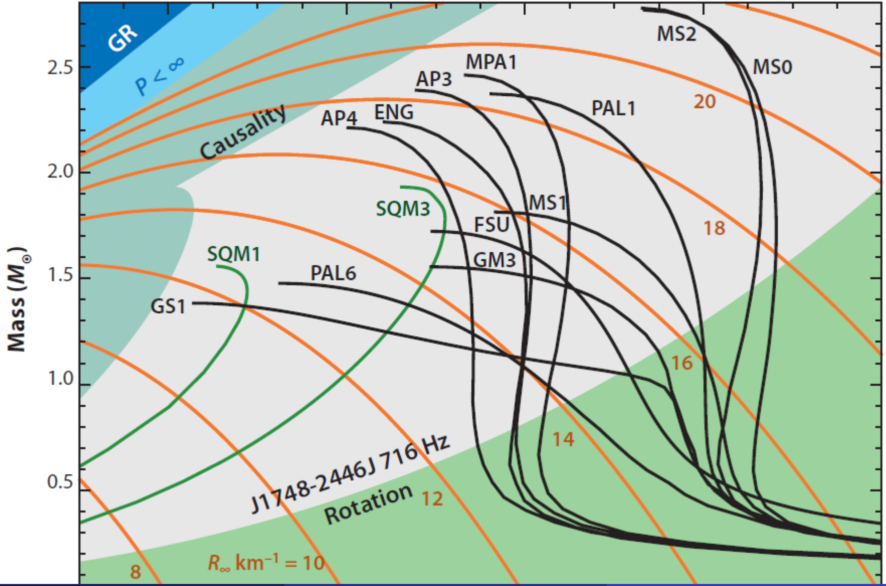
Wikipedia; Robert Schulze

- Neutron stars present interesting challenge to understand - many extremes
- Outward pressure of nuclear force competes against gravity
- Difficult to reproduce environments on earth to test incredibly dense states of matter
- Heavily dependent on EOS symmetry energy - defines parameters for pressure and cooling

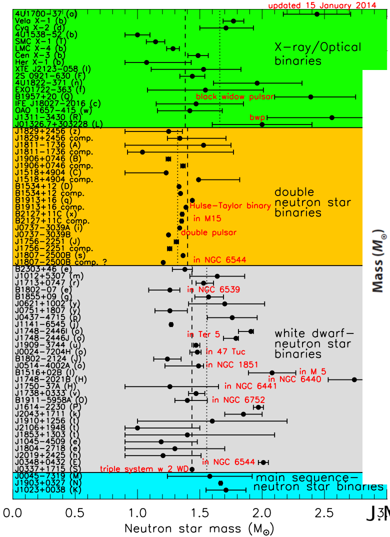


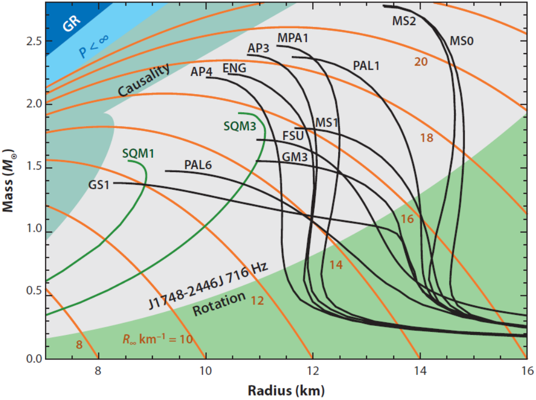


Neutron Stars - EOS

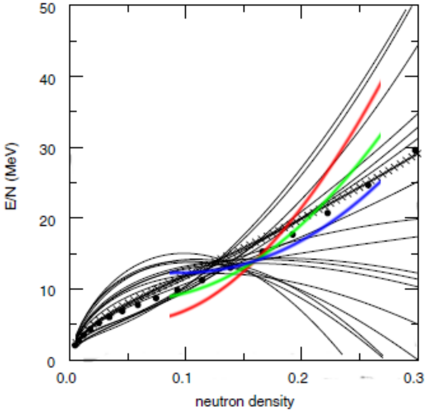


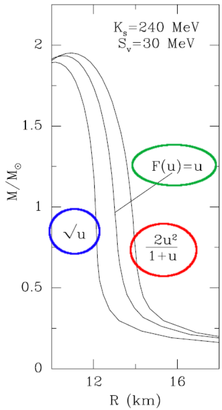
Neutron Stars - EOS





J.M. Lattimer Annu. Rev. Nucl. Part. Sci. 2012. 62:485





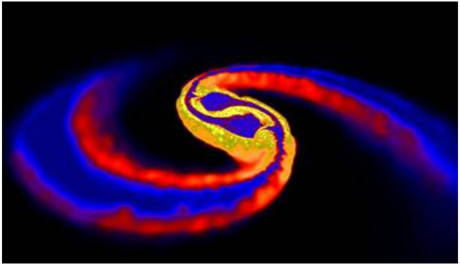
B. Alex Brown, PRL 85, 5296 (2000)

J.M. Lattimer and M. Prakash Astr. Jour., 550:426-442, 2001

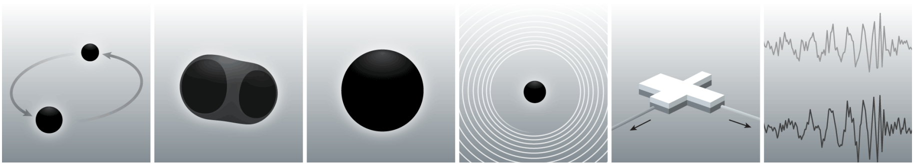
- Slopes of symmetry energy are heavily correlated with radii for given models
- "Stiffer" EOS generates larger internal pressures $\rightarrow$ larger radii

Neutron Stars - Gravity Waves

- Few gravity waves events observed LIGO (so far black hole mergers)
- Rumor of neutron star merger with EM component
- Neutron star struture and EOS have bearing on waveforms that can be observed
- Possibly observe 0.1-100s/yr with full LIGO instrumentation (~2019)?*
- Estimate 0.1 km sensitivity



Kelley et al, AJL 725, L91 (2010)

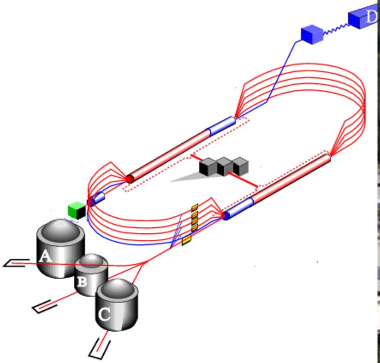


Stolen from NYT

*Abbott et al, LIGO & Virgo Collaborations - http://www.livingreviews.org/lrr-2016-1

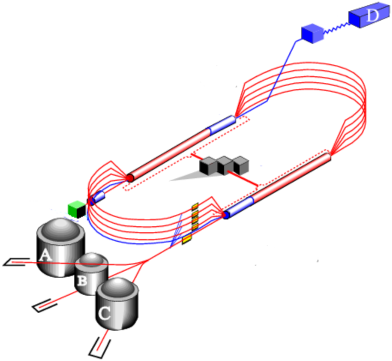
Jefferson Lab

Continuous **E**lectron **B**eam **A**ccelerator **F**acility
at Jefferson Lab, Newport News, VA
"World's most powerful microscope"



Jefferson Lab

Continuous **E**lectron **B**eam **A**ccelerator **F**acility
at Jefferson Lab, Newport News, VA
"World's most powerful microscope"



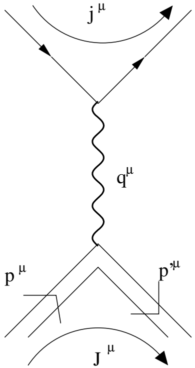
- Electron accelerator by superconducting RF cavities
- 4 experimental halls
- E up to 11 GeV ($\lambda \sim r_p/50$)
- $I_{\mathrm{max}} = 200\ \mu\mathrm{A}$
- $P_e = \sim 90\%$
- Ideal for studying insides of nucleons and nuclei!

What does electron elastic scattering tell us?

For electron scattering from spin-0 particle, "one-photon":

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Mott}} \times |F(Q^2)|^2$$

$$\text{pointlike} \times \text{structure}$$

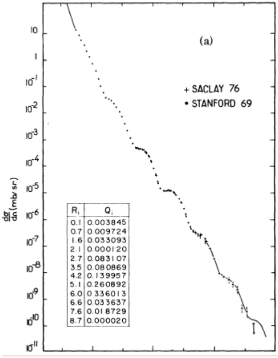


- Differential cross section factorizes into point-like and structure part
- Structure part is just function dependent on 4-momentum transfer, $Q^2 = 2EE'(1 - \cos\theta)$
- $F(Q^2)$ is just the Fourier transform!

Electormagnetic Electron Scattering

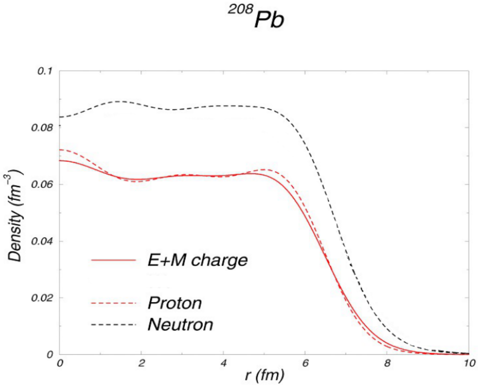
Electron scattering γ exchange provides R_p through nucleus FFs, spin 0:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} F^2(Q^2)$$



q $[fm^{-1}]$

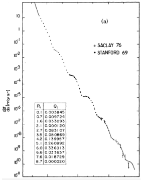
$\rightarrow$



Electormagnetic Electron Scattering

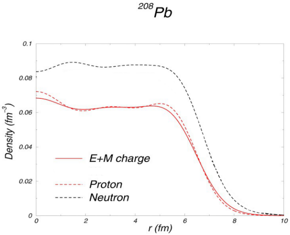
Electron scattering γ exchange provides R_p through nucleus FFs, spin 0:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} F^2(Q^2)$$



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

$\rightarrow$



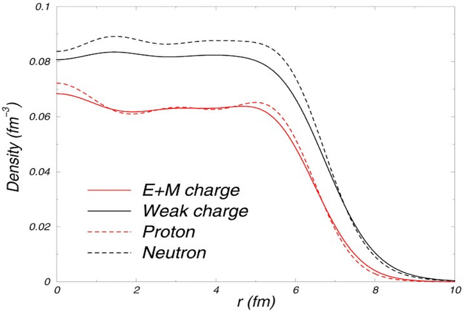
- In limit of small Q^2

$$F(Q^2) \approx F(0) + Q^2 \frac{dF}{dQ^2}\bigg|_{Q^2=0} + \ldots = \int \rho(\vec{x}) d^3x - \frac{1}{6} Q^2 \langle r^2_{\text{charge}} \rangle + \ldots$$

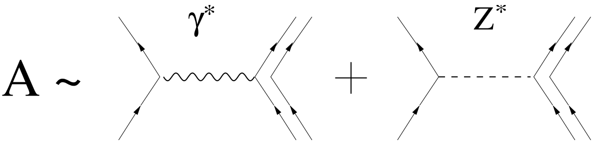
- So small Q^2 measurements give RMS radius ($R_{n/p}$)

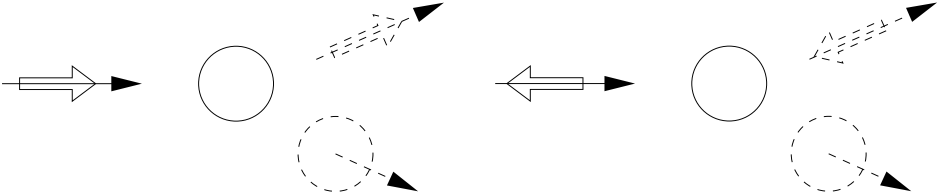
What's new that we can do?
Look at weak-force interactions!
Primarily couples to neutron and (mostly) not proton!

$$Q_{\rm weak}^{\rm proton} \propto 1 - 4\sin^2\theta_{\rm W} \approx 0.076, \quad Q_{\rm weak}^{\rm neutron} \propto -1$$



- We can use parity violation to pick out the weak interaction component over the electromagnetic

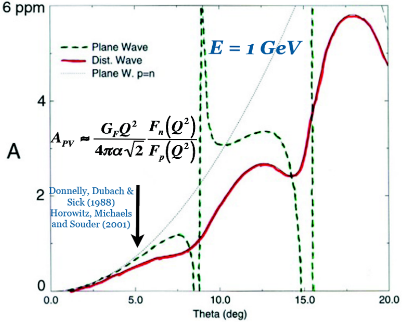


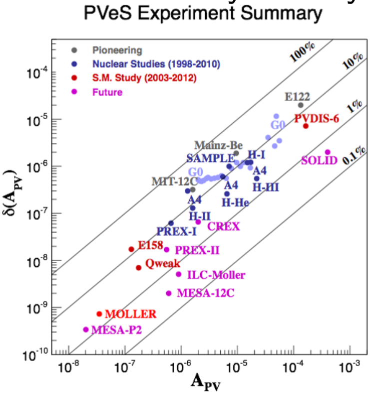


Rates are different if parity is violated

Asymmetry

Measure *relative* rates in form of an asymmetry

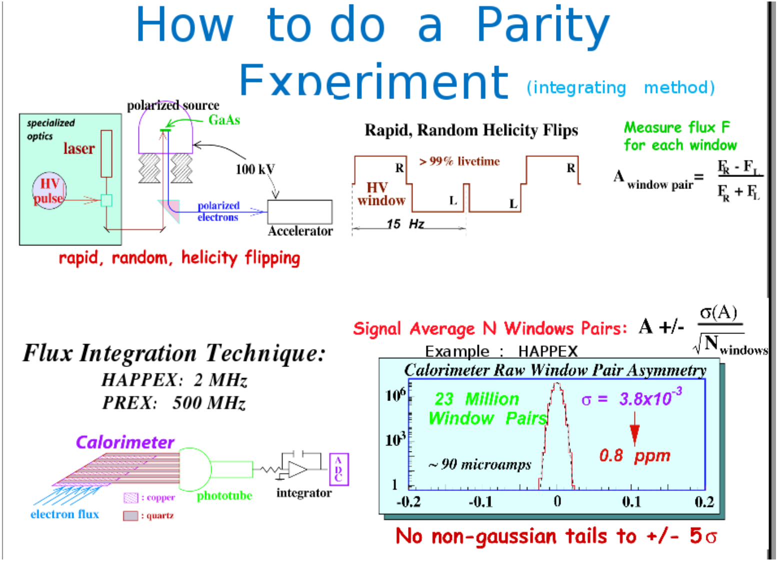




$$A_{\rm PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- Higher order effects (Coulomb distortions) wash things out

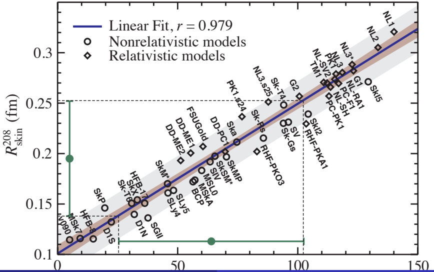
Typical Experiment



Stolen from R. Michaels

PREX - Neutron Radius of ^{208}Pb

- Ultimate goal to measure R_n to 0.06 fm (1%), $R_n - R_p \sim 0.2$ fm
- Ran Spring 2010 in Hall A at JLab
- Approved for $\sim$35 days
- $\sim 50\mu$A, 1.1 GeV at 5°
- ^{208}Pb because
    - Large neutron excess
    - Doubly-magic nucleus
    - Spin 0
    - First inelastic state 2.6 MeV



PREX Experimental Configuration - HRS

Pair of High Resolution Spectrometers (HRS) magnetically separate elastic scattering events

10^{-3} *hardware* momentum resolution, $\Omega \sim 5$ msr

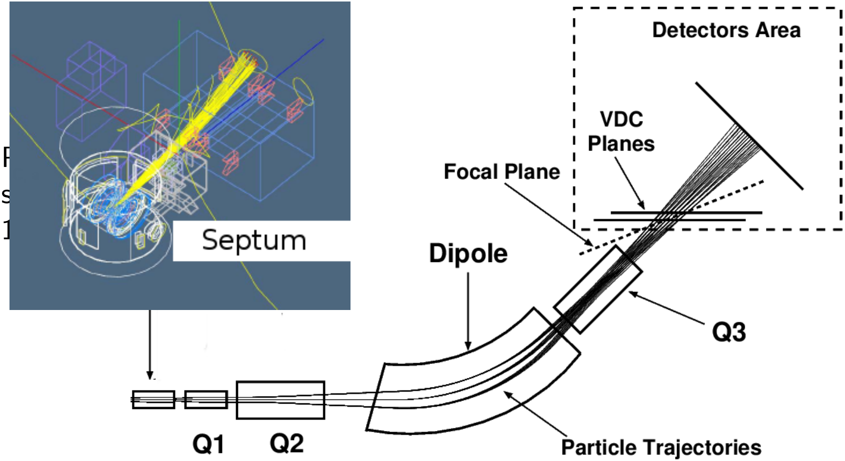
PREX Experimental Configuration - HRS

Pair of High Resolution Spectrometers (HRS) magnetically separate elastic scattering events

10^{-3} *hardware* momentum resolution, $\Omega \sim 5$ msr

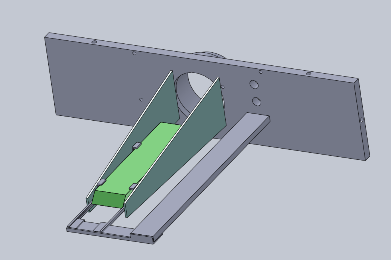
PREX Experimental Configuration - HRS

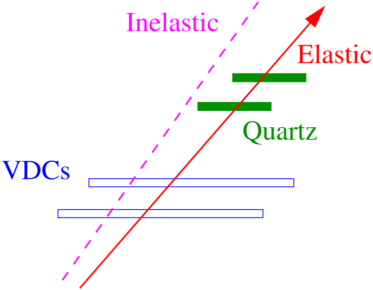
- HRS minimum 12.5°, for 5° insert $\sim$ 0.5 T·m dipole



HRS and Quartz Detectors

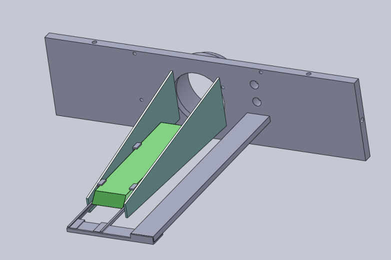
- Quartz detectors used as integrating detectors
- Electrons emit Cherenkov radiation - few hundred photons, $\sim$30 pe's/$e-$
- Integrate signal from PMT over helicity windows
- PMTs should be quiet (low gain) and linear (better than few %)

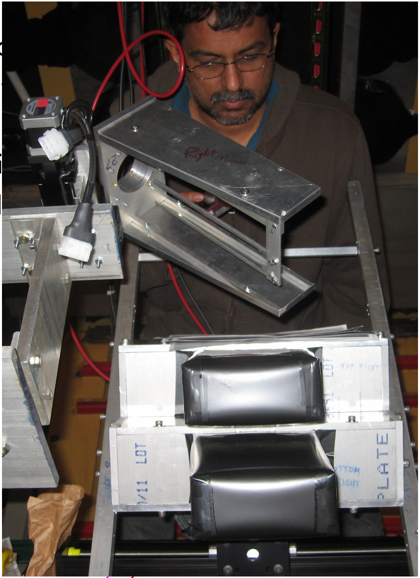




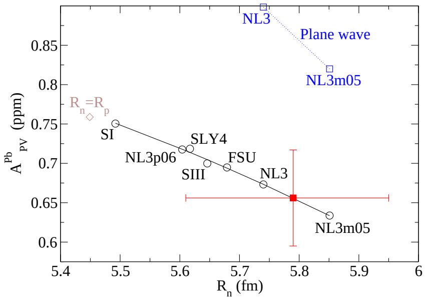
HRS and Quartz Detectors

- Quartz detectors used as integrating c
- Electrons emit Cherenkov radiation - ~$\sim$30 pe's/$e-$
- Integrate signal from PMT over helici
- PMTs should be quiet (low gain) and (better than few %)





Results

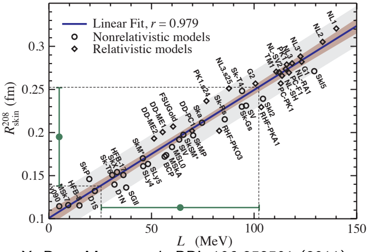


- Set 95% CL on existence of neutron skin
- $R_n - R_p = 0.34 + 0.15 - 0.17 \text{ fm}$
- Goal of 2% systematics (polarimetry, detector linearity, beam asymmetries each $\sim 1\%$) reached!
- Publications
  - S. Abrahamyan *et al.* Phys. Rev. Lett. 108, 112502 (2012)
  - C.J Horowitz *et al.* Phys. Rev. C 85, 032501(R) (2012)

Next round!

PREX-II - ^{208}Pb

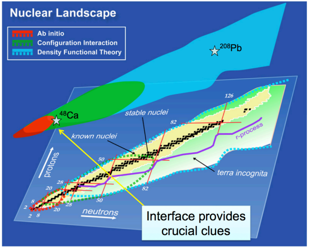
- Aims to each goal of $\delta R_n \sim 0.06$ fm
- Improved shielding and more advanced targets allow for full running
- Will provide reliable constraints on slope of symmetry energy



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

CREX - ^{48}Ca

- Measurements on ^{48}Ca to 0.02 fm
- Gives broader reach over periodic table
- Contributing systematics slightly different
- $A \sim 40$ now within reach of microscopic calculations



Summary

- Neutron skins contain important information on asymmetric nuclear matter
- Density dependence of the symmetry energy is an important aspect to study with applications to detailed nuclear structure to neutron stars
- Electron scattering provides a powerful method to map out both the proton *and* neutron distributions using EM and Weak forces
- The PREX and CREX programs aim to measure δR_n to a precision of 0.06 fm and 0.02 fm respectively in the upcoming years

PREX and CREX Collaborations

Krishna Kumar	Stony Brook
Robert Michaels	Jefferson Lab
Kent Paschke*	University of Virginia
Paul Souder	Syracuse University
Guido Urcioli	INFN Rome

Seamus Riordan*	Stony Brook
Silviu Covrig	Jefferson Lab
Juliette Mammei	Manitoba
Dustin McNulty	Idaho State University
Robert Michaels	Jefferson Lab
Kent Paschke	University of Virginia
Paul Souder	Syracuse University

J. Mammei, J. Birchall, M. Gericke, R. Mahurin, W.T.H. van Oers, S. Page
University of Manitoba

S. Riordan, P. Decowski, K. Kumar, T. Kutz, J. Wexler
University of Massachusetts, Amherst

K. Paschke, G.D. Cates, M. Dalton, D. Keller, X. Zheng
University of Virginia

P.A. Souder, R. Beminiwattha, R. Holmes
Syracuse University

R. Michaels, K. Allada, J. Benesch, A. Camsonne, J.P. Chen, D. Gaskell, J. Gomez, O. Hansen, D.W. Higinbotham, C.E. Keppel, J. LeRose, B. Moffit S. Nanda, P. Solvignon-Slifer, B. Wojtsekhowski, J. Zhang
Thomas Jefferson National Accelerator Facility

Konrad Aniol
California State University, Los Angeles

G.B. Franklin, B. Quinn
Carnegie Mellon Univerisity

D. Watts, L. Zana
The University of Edinburgh

P. Markowitz
Florida International University

P. Gueye
Hampton University

E. Cisbani, A. del Dotto, S. Frullani, F. Garibaldi
INFN Roma gruppo collegato Sanità and Italian National Institute of Health, Rome, Italy

M. Capogni
INFN Roma gruppo collegato Sanità and ENEA Casaccia, Rome, Italy

V. Bellini, A. Giusa, F. Mammoliti, G. Russo, M.L. Sperduto, C.M. Sutera
INFN - Sezione di Catania

D. McNulty, P. Cole, T. Forest, M. Khandaker
Idaho State University

C.J. Horowitz
Indiana University

M. Mihovilovič, S. Širca
Jožef Stefan Institute and University of Ljubljana, Slovenia

A. Glamazdin
Kharkov Institute of Physics and Technology

T. Holmstrom
Longwood University

S. Kowalski, R. Silwal, V. Sulkosky
Massachusetts Institute of Technology

M. Shabestari
Mississippi State University

S.K. Phillips
University of New Hampshire

E. Korkmaz
University of Nortern British Columbia

P. King, J. Roche, B. Waidyawansa
Ohio University

C.E. Hyde
Old Dominion University

F. Meddi, G.M. Urciuoli
Sapienza University of Rome and INFN - Sezione di Roma

A. Blomberg, Z.-E. Meziani, N. Sparveris
Temple University

M. Pitt
Viriginia Polytechnic Institute and State University

D. Armstrong, J.C. Cornejo, W. Deconinck, J.F. Dowd, V. Gray, and J. Magee
College of William and Mary

D. Androic
University of Zagreb

and the Hall A Collaboration