Acknowlegements:
PREX/CREX and MOLLER Collaborations, C. Horowitz, C. Palatchi, B. Reed
www.particleadventure.org

How Thick is the Neutron-Rich Skin of a Heavy Nucleus?

New Results from PREX and CREX at Jefferson Lab

Krishna Kumar
University of Massachusetts, Amherst

Physics & Astronomy Department Colloquium
Michigan State University, March 24, 2022

Outline

- **Electron Scattering & Subatomic Structure**
- **Electron Scattering and the Weak Force**
  - The weak force component in electroweak scattering is parity-violating
- **Parity-Violating Electron Scattering and the Neutron Skin**
- **The Jefferson Laboratory Experiments**
  - *PREX2: Precision Measurement on ^{208}Pb* (Phys.Rev.Lett. 126 (2021) 17, 172502)
  - *CREX: Followup precision measurement on ^{48}Ca*
- **Implications and Outlook**

Modern Electroweak Nuclear Physics

Outline

- ✦ **Electron Scattering & Subatomic Structure**
- ✦ **Electron Scattering and the Weak Force**
  - ★ The weak force component in electroweak scattering is parity-violating

Historical Perspective
~ 20 minutes

- ✦ **Parity-Violating Electron Scattering and the Neutron Skin**
- ✦ **The Jefferson Laboratory Experiments**
  - ★ *PREX2: Precision Measurement on ^{208}Pb* (Phys.Rev.Lett. 126 (2021) 17, 172502)
  - ★ *CREX: Followup precision measurement on ^{48}Ca* Paper submission imminent!

Experimental Measurements
~ 25 minutes

- ✦ **Implications and Outlook** For the experts!

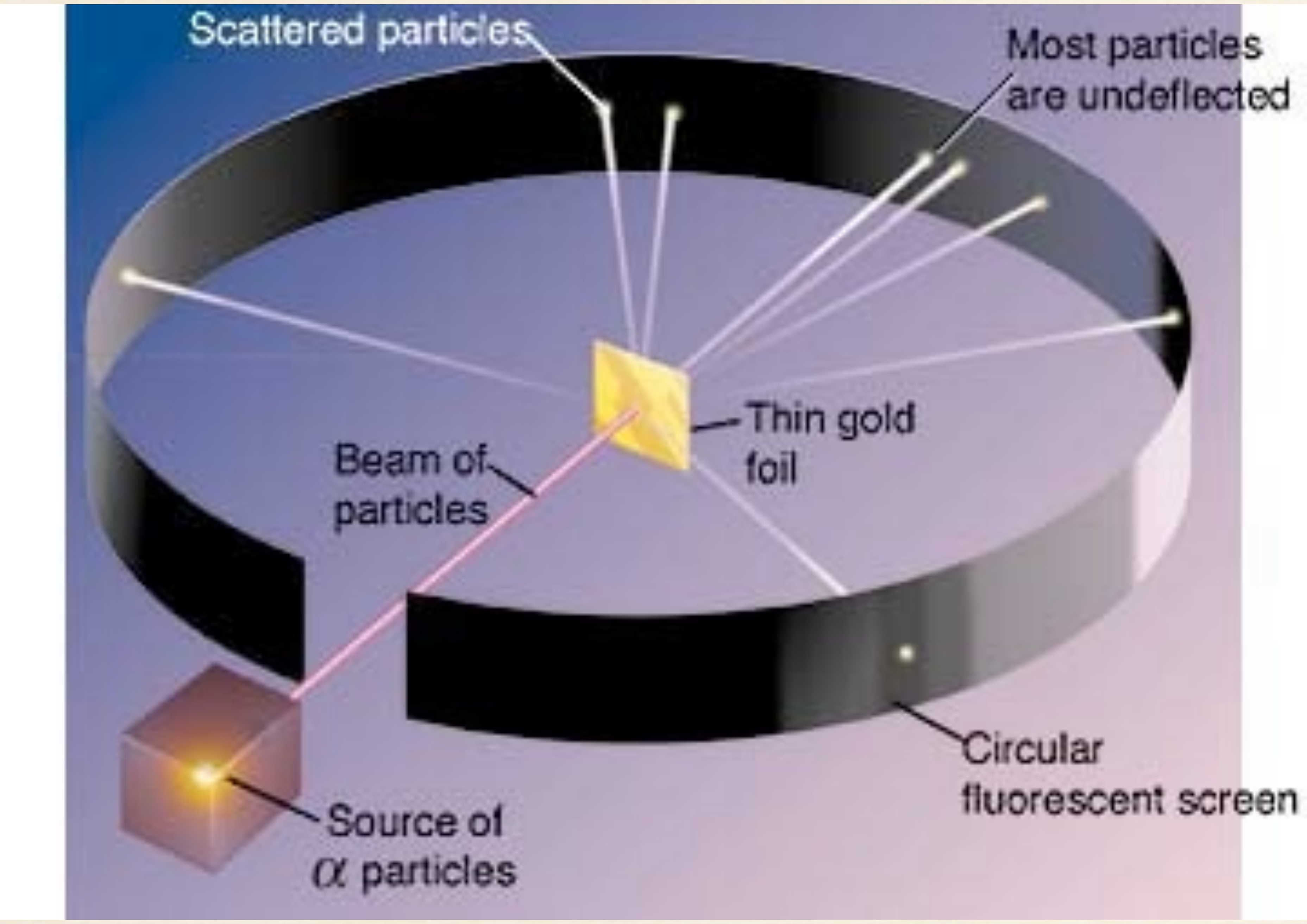
Electron Scattering and the Subatomic Structure

~ 1910

Rutherford Scattering

The first fixed target scattering experiment

Rutherford devised a scattering experiment involving a beam of alpha particles scattering off a gold foil



differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right) \times \Delta\Omega \quad \frac{\text{\# alphas scattered into solid angle per unit time}}{\text{Incident beam intensity}}$$

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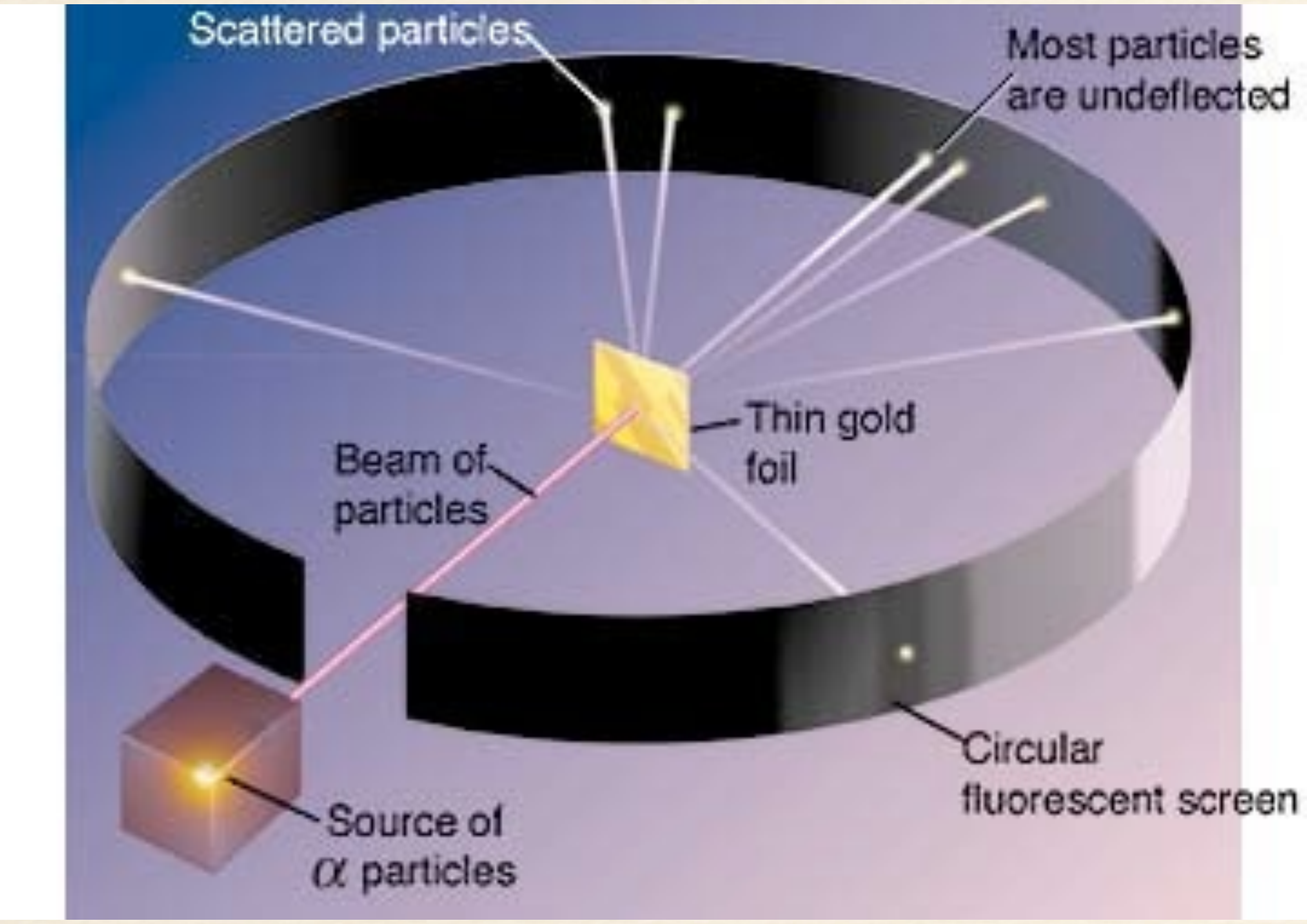
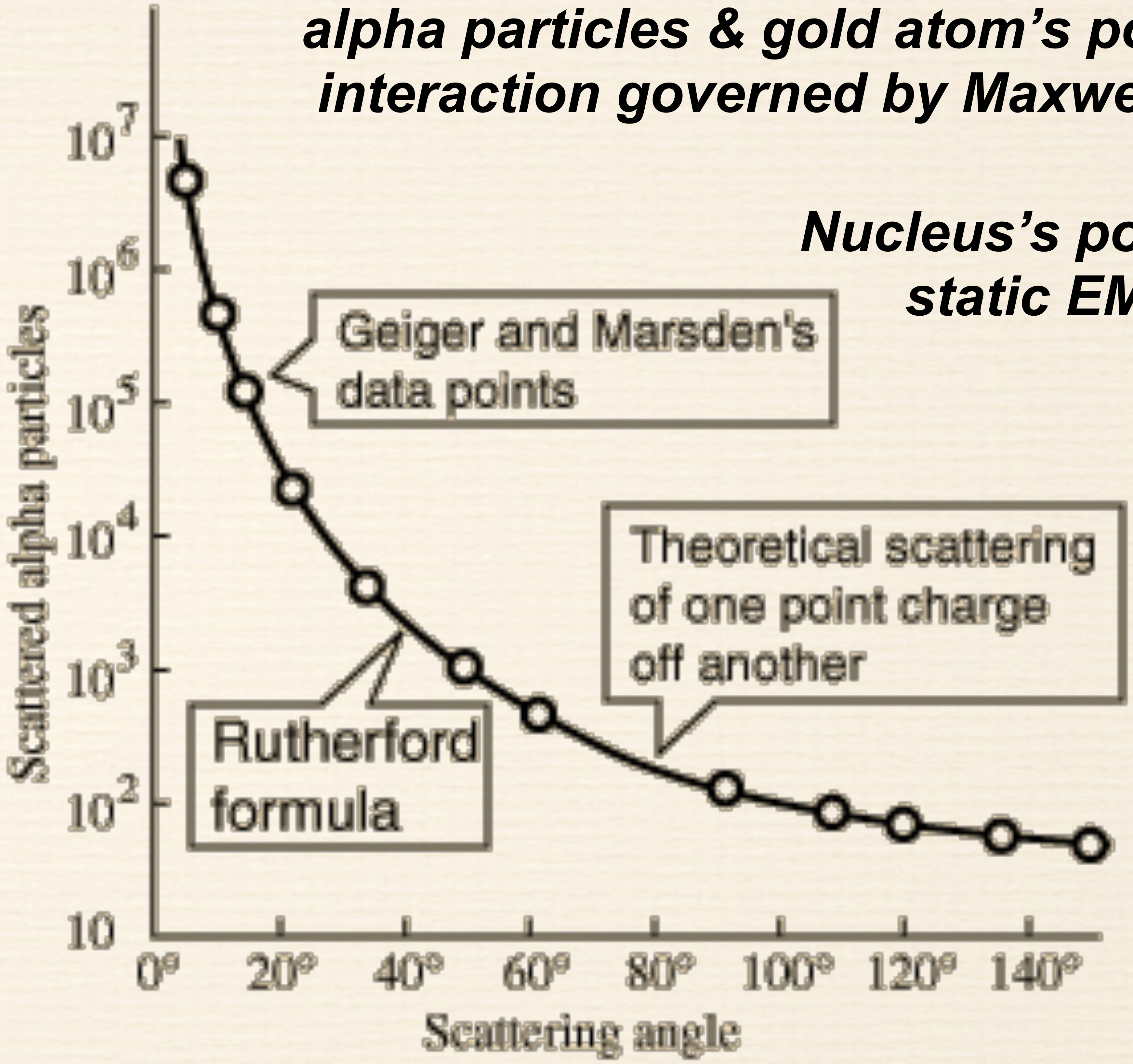


alpha particles & gold atom's positive charge: interaction governed by Maxwell's equations

Nucleus's positive charge: static EM potential



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$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{Z_1 Z_2 \alpha}{2mv^2 \sin^2(\theta/2)}\right)^2$$

A femtoscope

Electron Scattering

- ***Established that atoms have a tiny nuclear core ~ 10^{-14} m***
- ***Nuclear size << atomic size of 10^{-10} m***
- ***Revolutionized experimentation: particle scattering as a microscope***

San Francisco

Interstate
280

San Jose

A femtoscope

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Going beyond Rutherford Scattering with Quantum Mechanics

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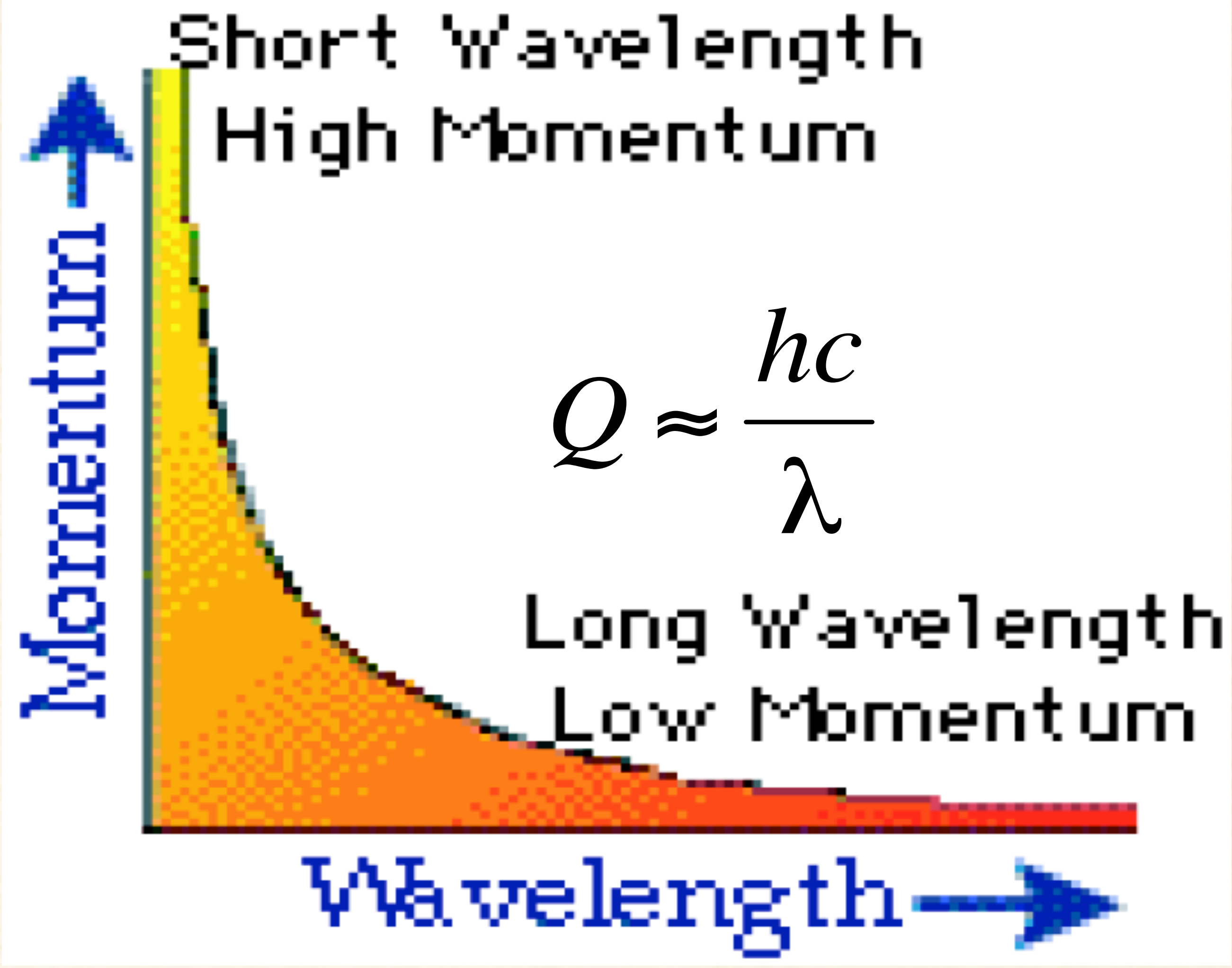

At nuclear scales, particles behave mostly like waves

How to produce femtometer wavelengths in the laboratory?

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A femtoscope

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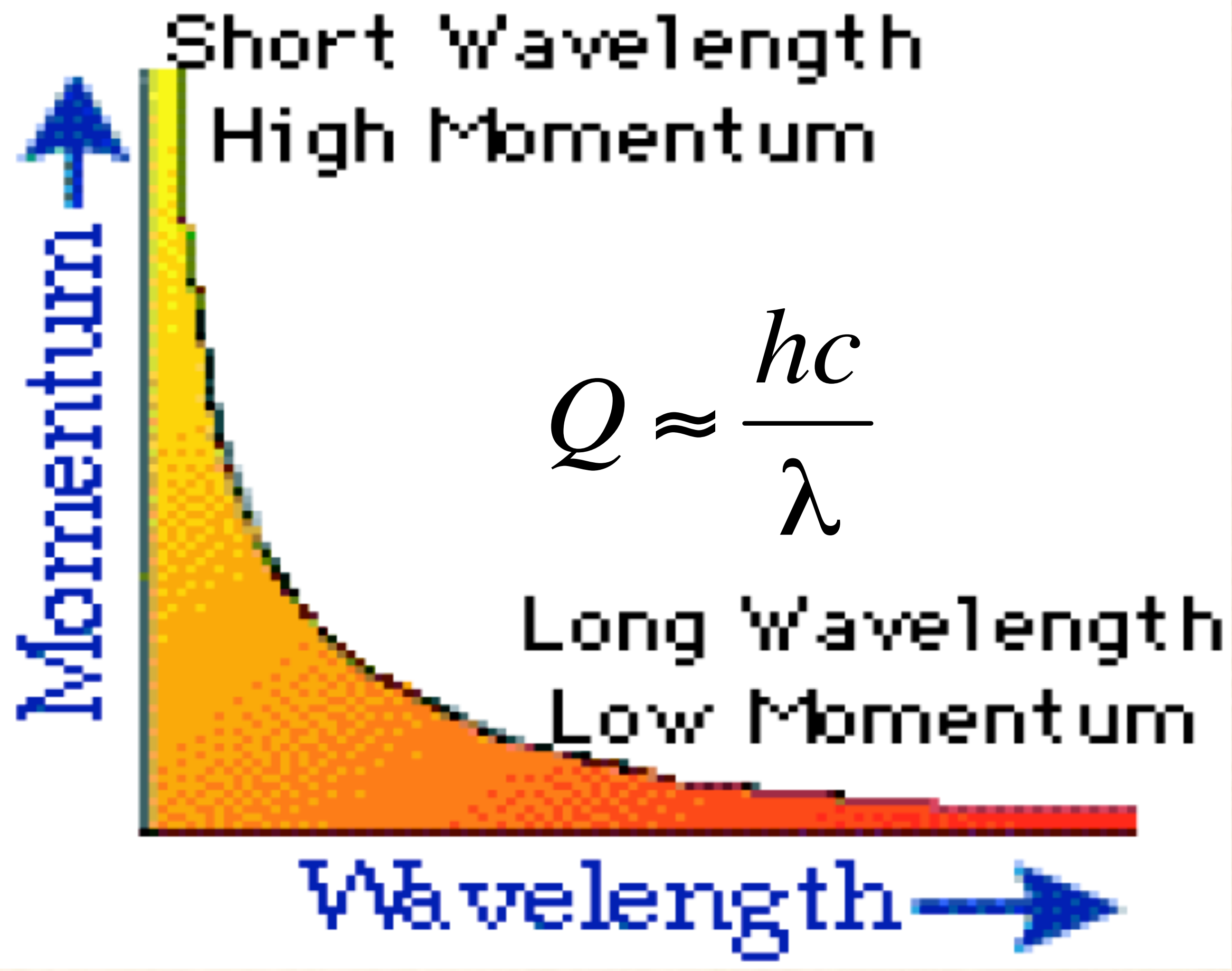

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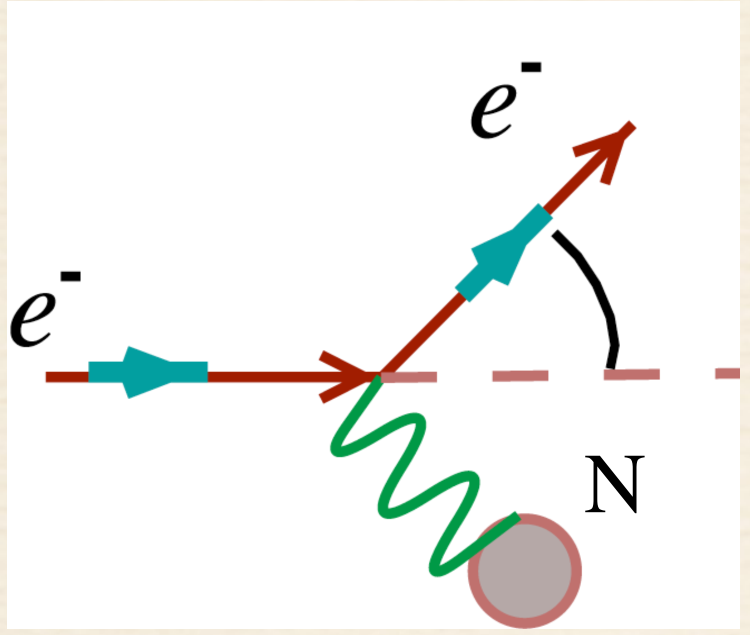
Electron Scattering and the Size of a Nucleus

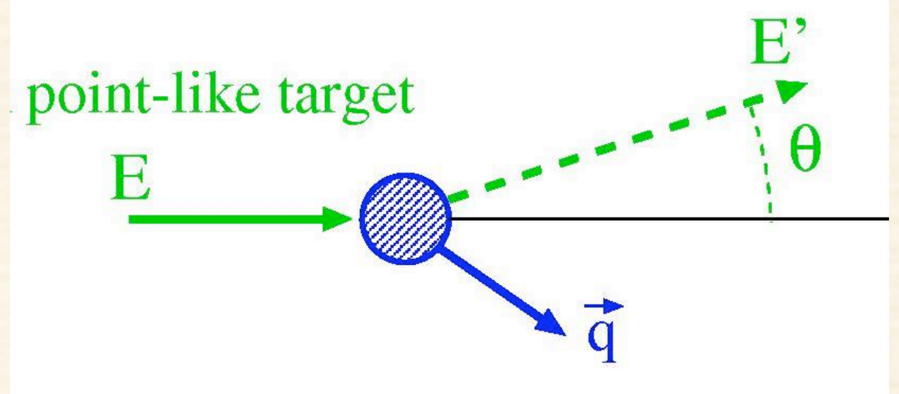
Special Relativity, Dirac Equation and Quantum Mechanics

Quantum Electrodynamics



electromagnetic interaction described as an exchange of a virtual photon

q^2: (4-momentum)^2 of virtual photon



$$q^2 = -4EE'\sin^2\frac{\theta}{2}$$

Mott: spin 1/2 electrons scattering off infinitely heavy point spinless nucleus

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

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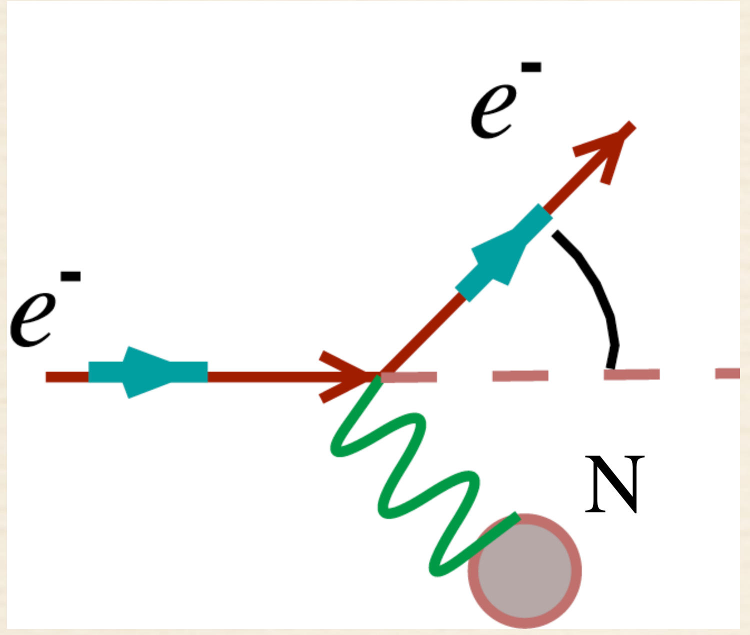

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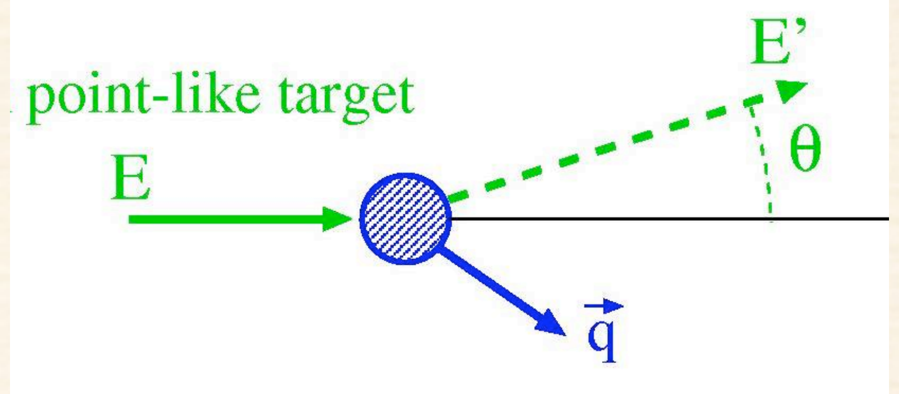

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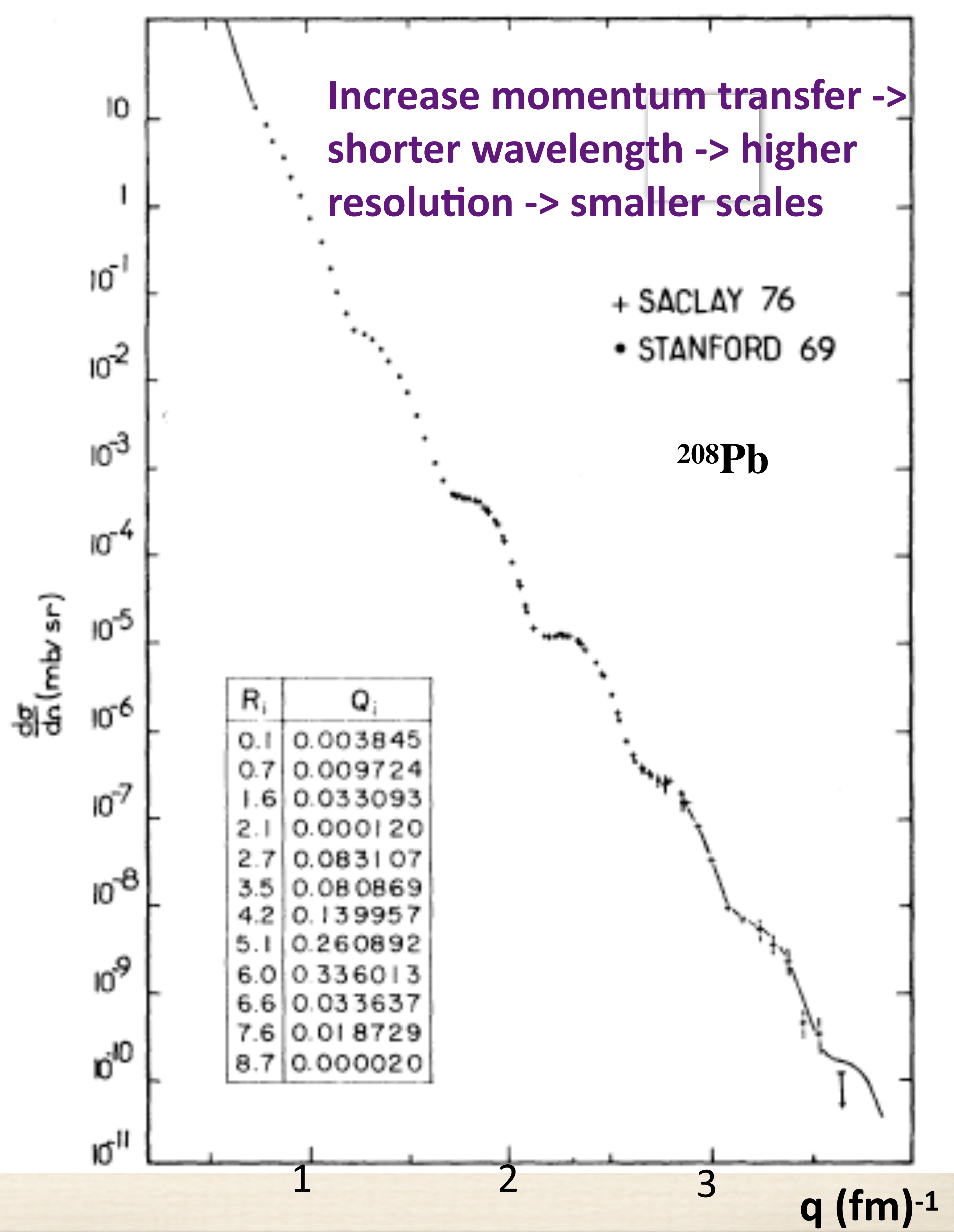

R_i	Q_i
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1.6	0.033093
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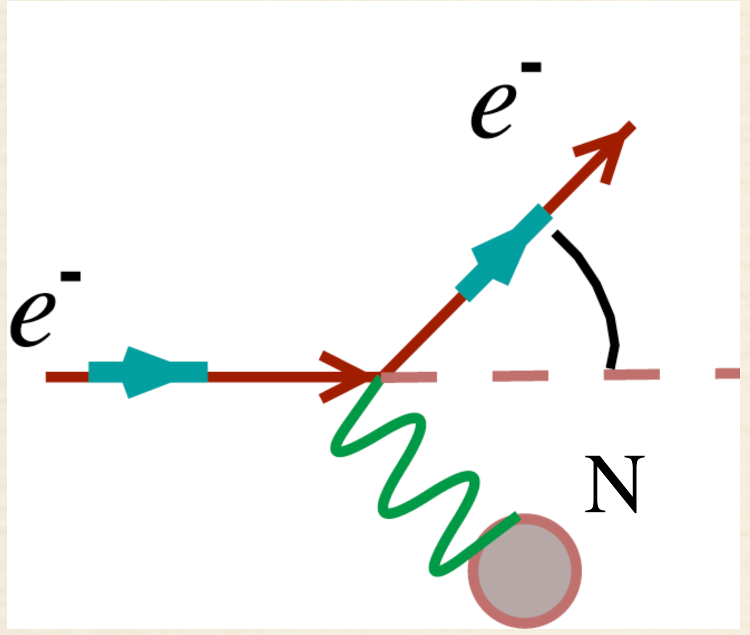

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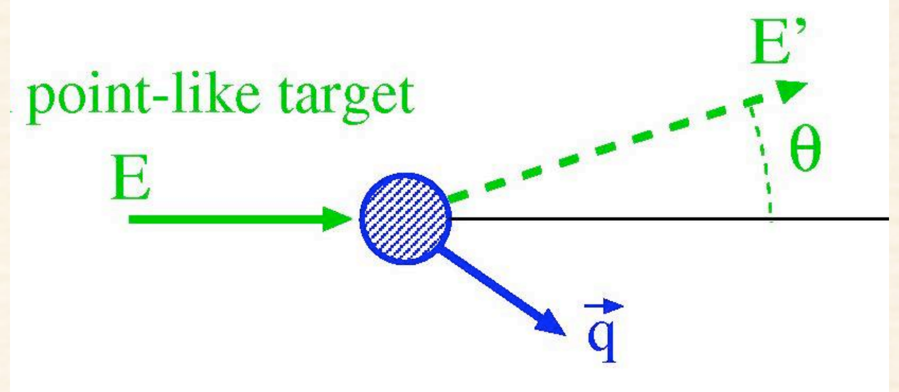

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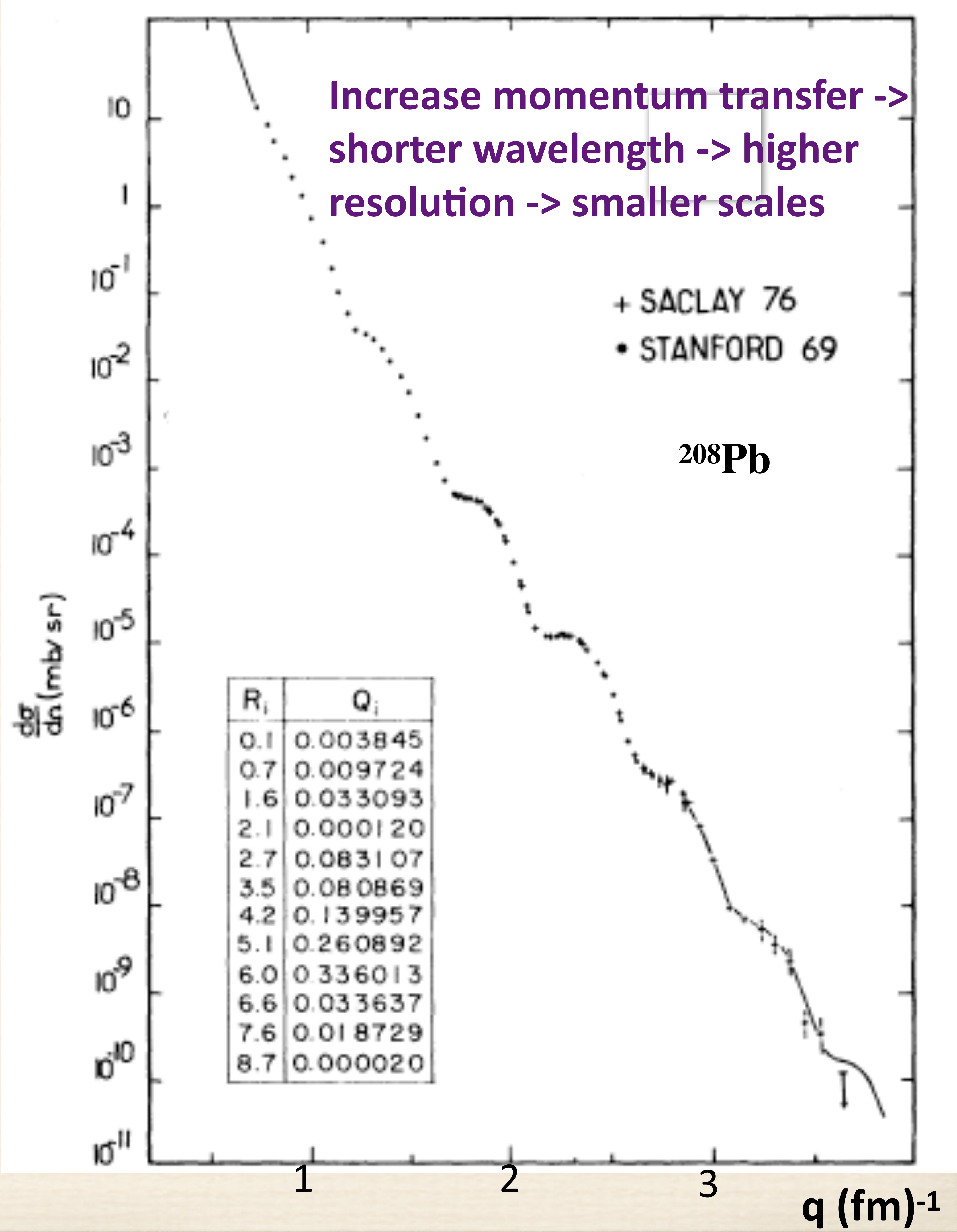

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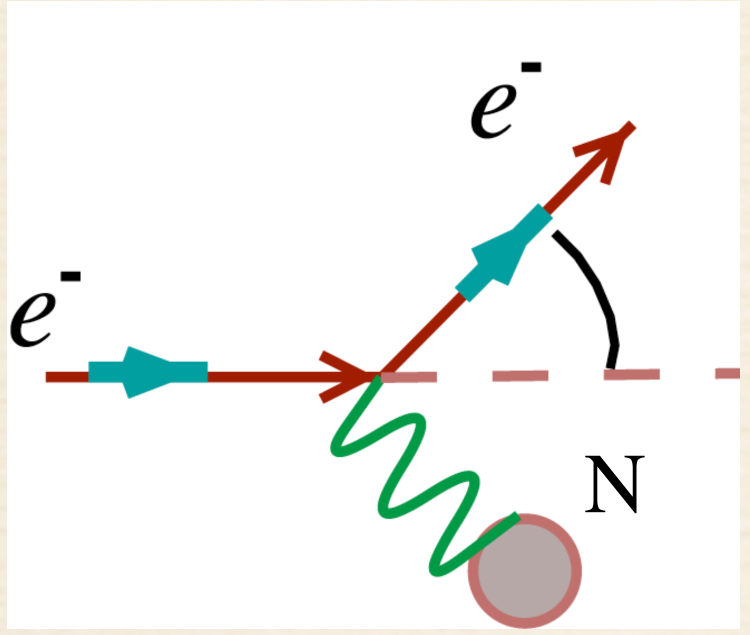

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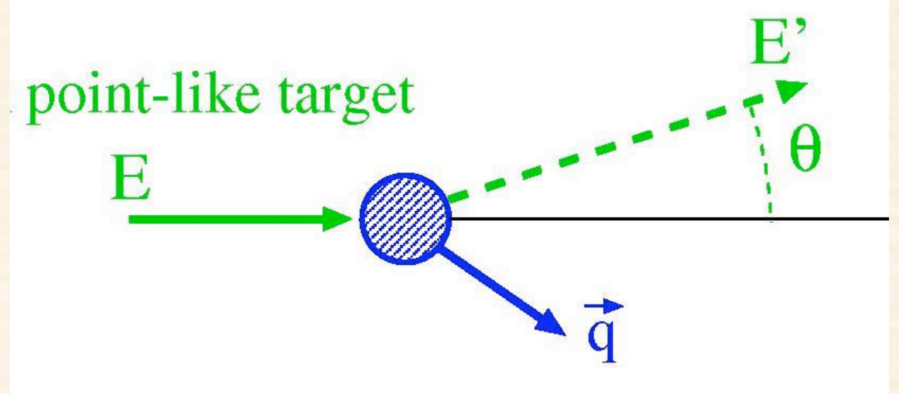

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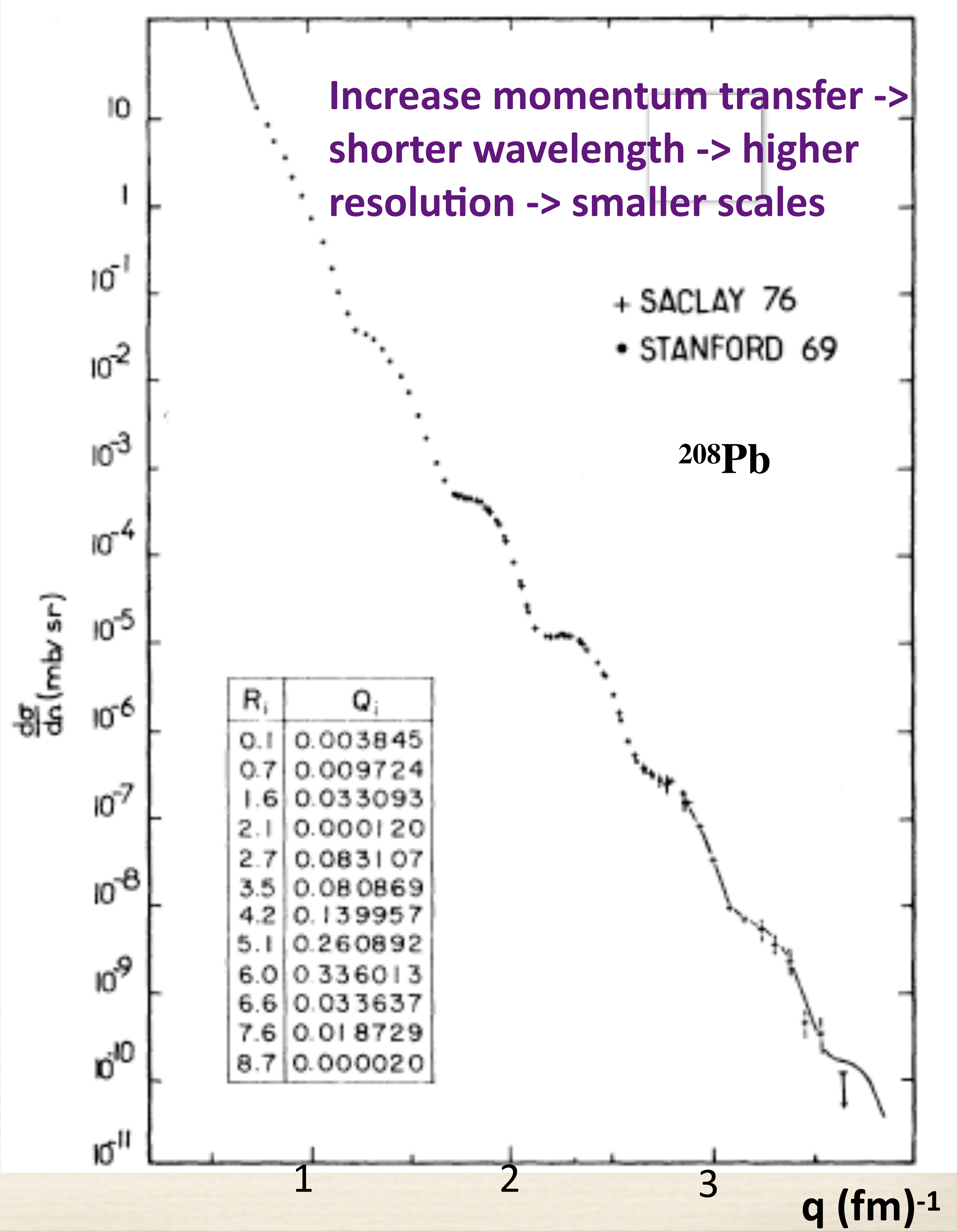
The point-like scattering probability modified: Introduce a "form factor"

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

$$F(q) = \int e^{iqr}\rho(r)d^3r$$

Form factor is the Fourier transform of charge distribution



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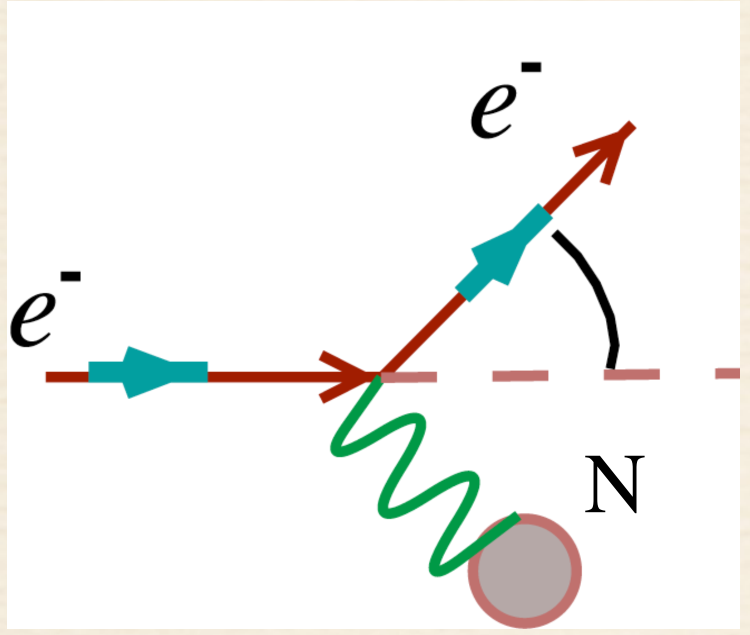

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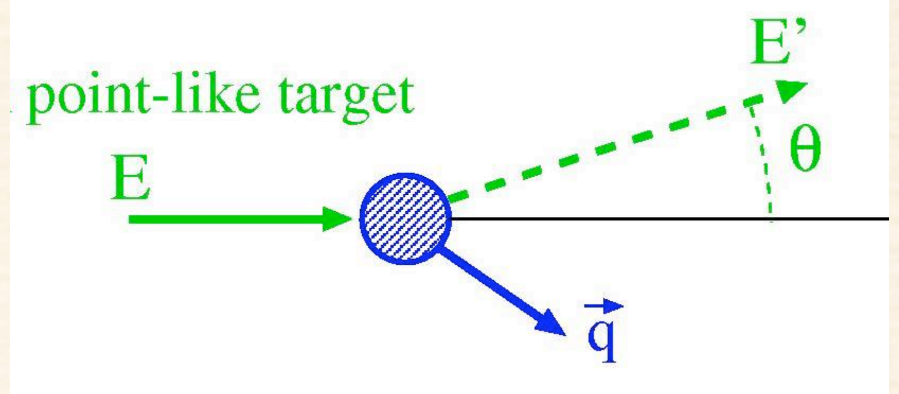

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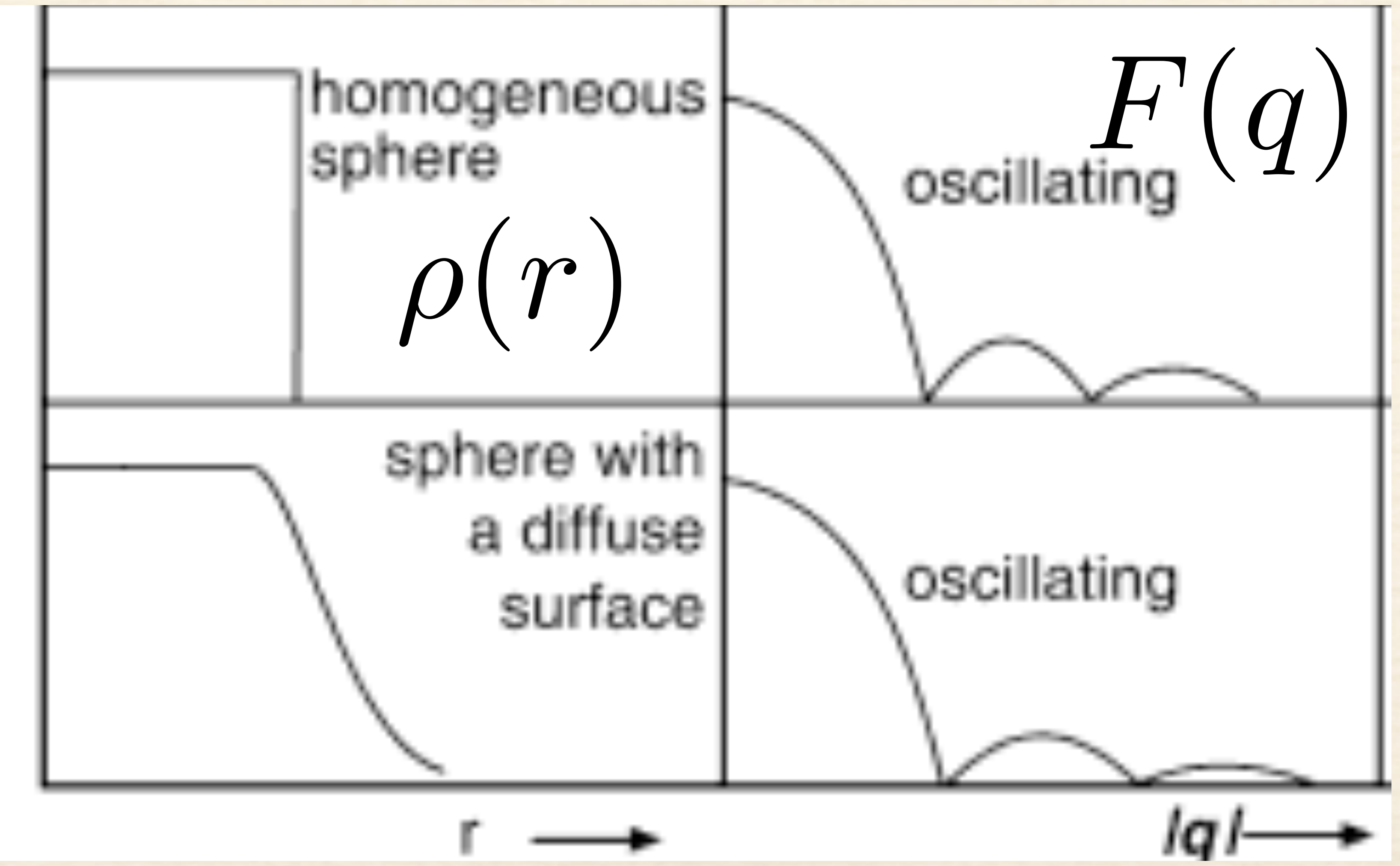

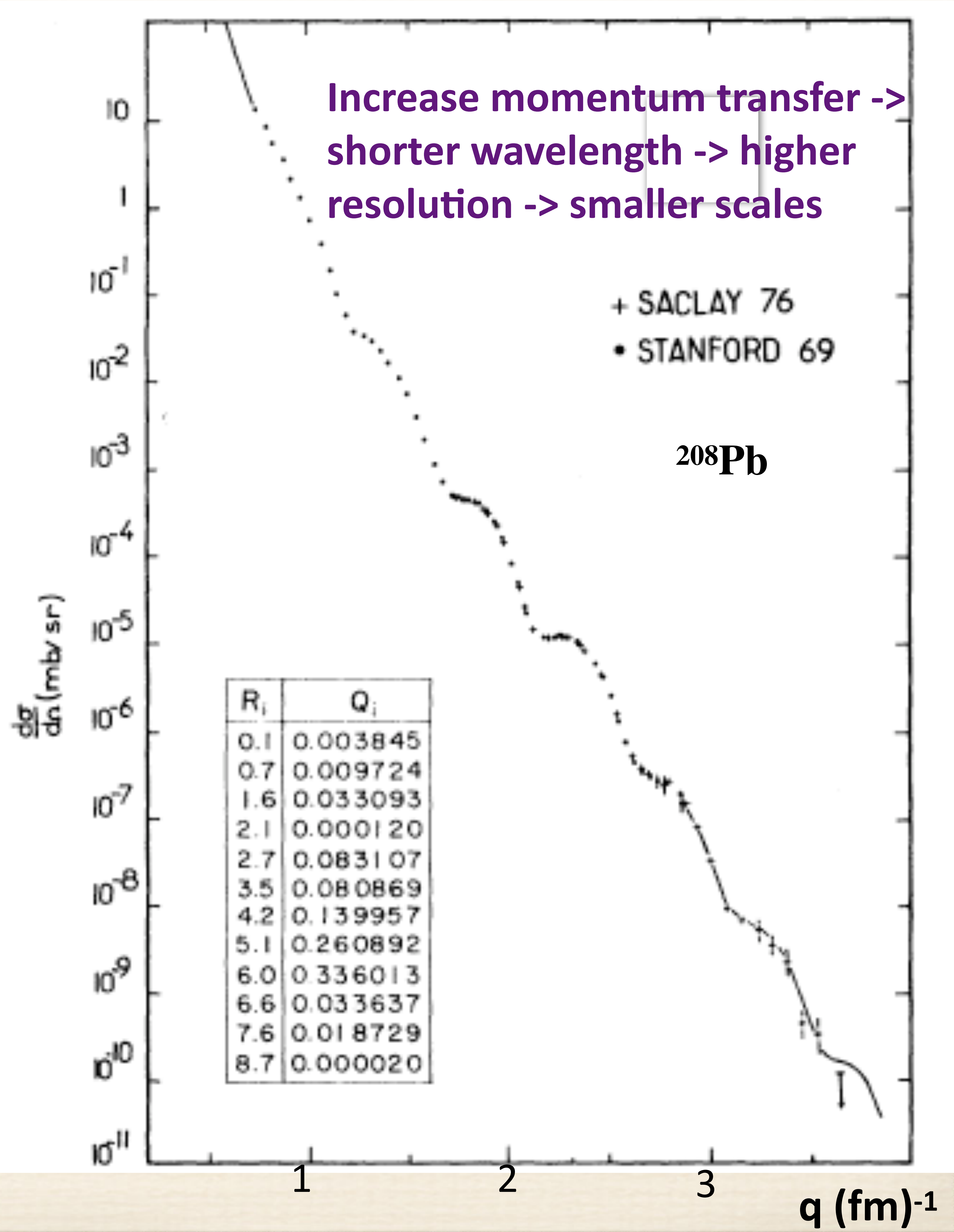

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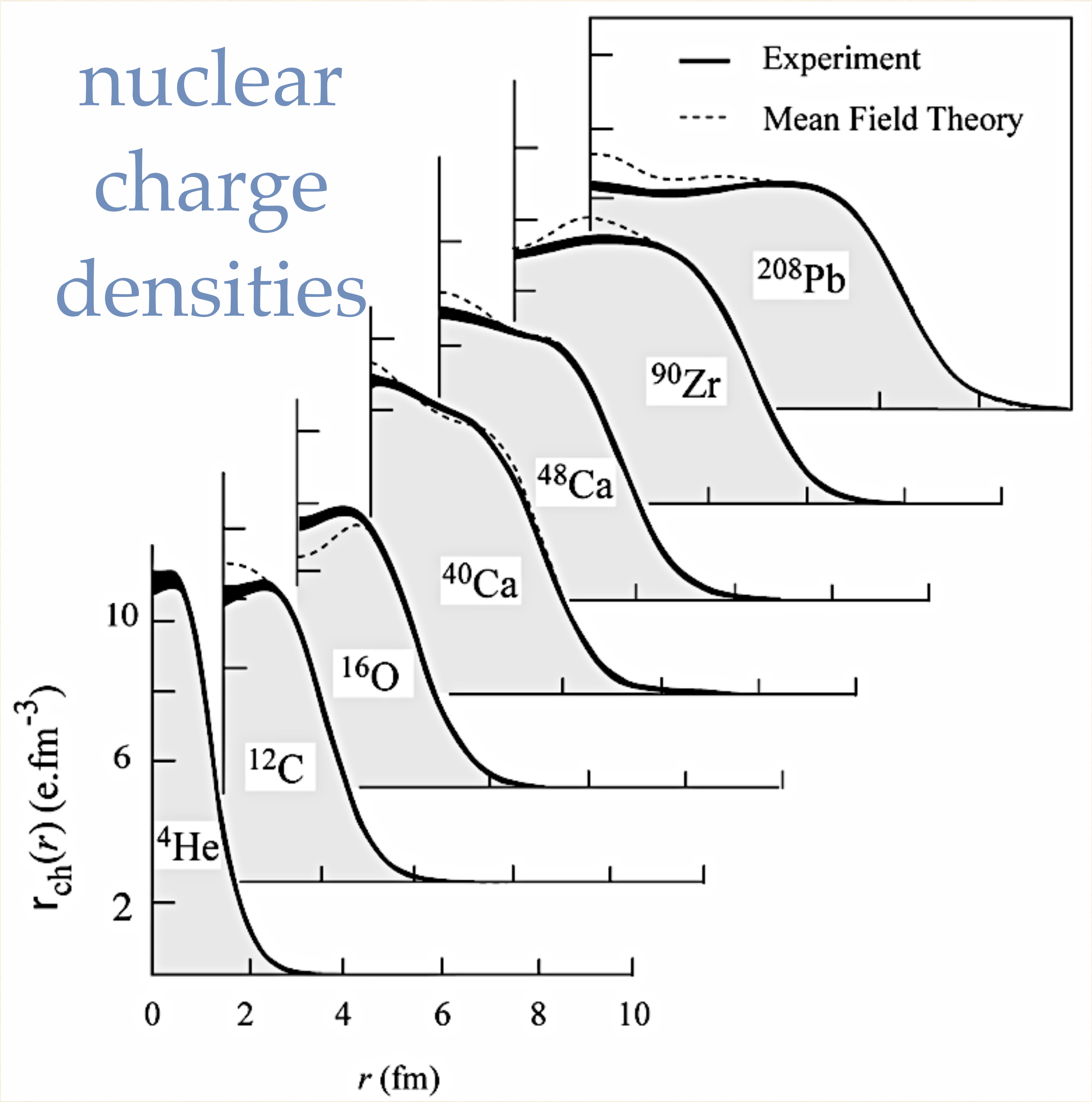
From the 1960's to the 2020's

Subatomic Structure



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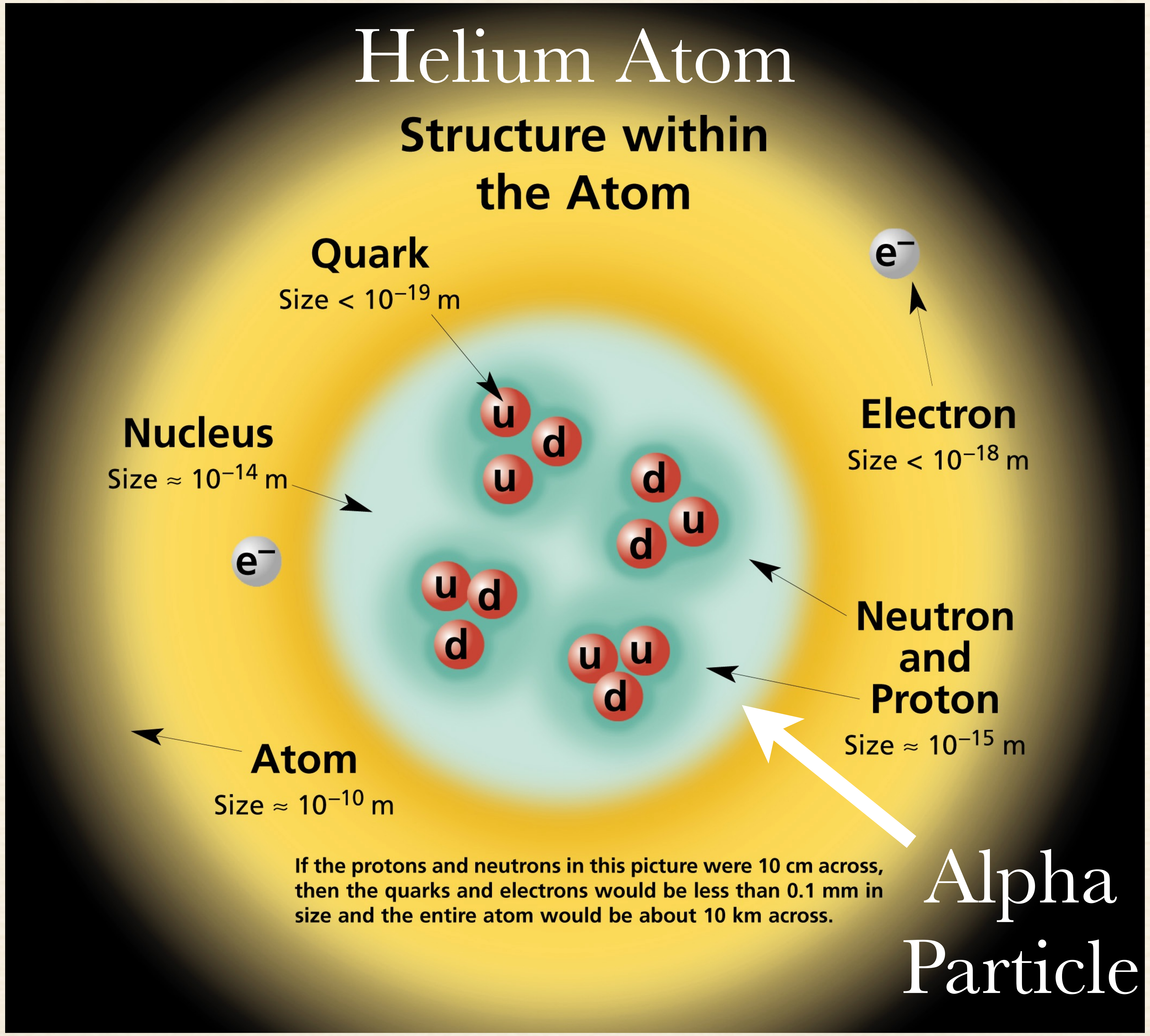

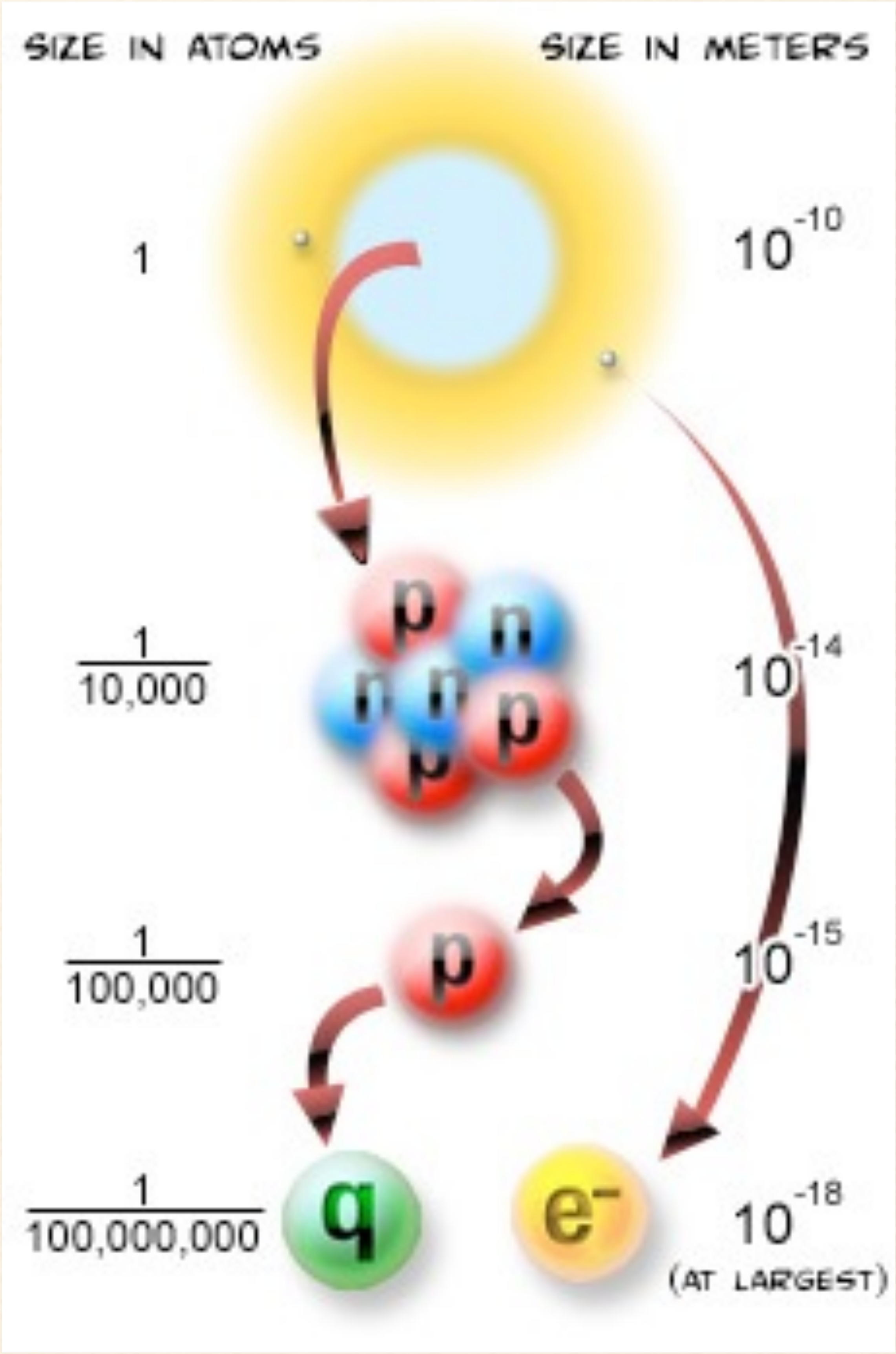

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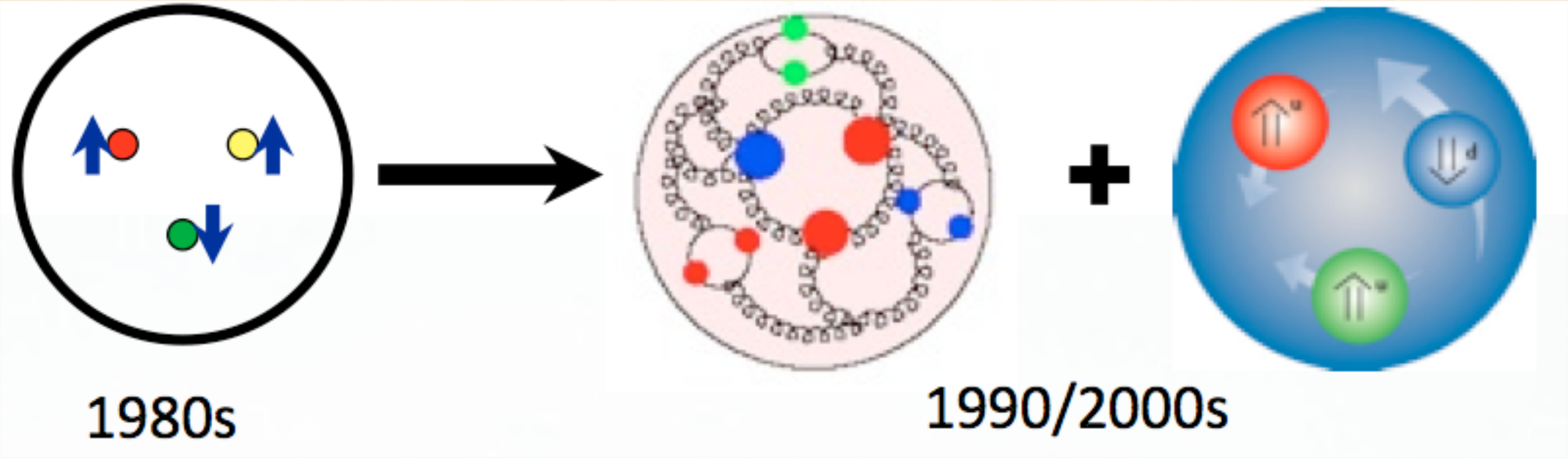

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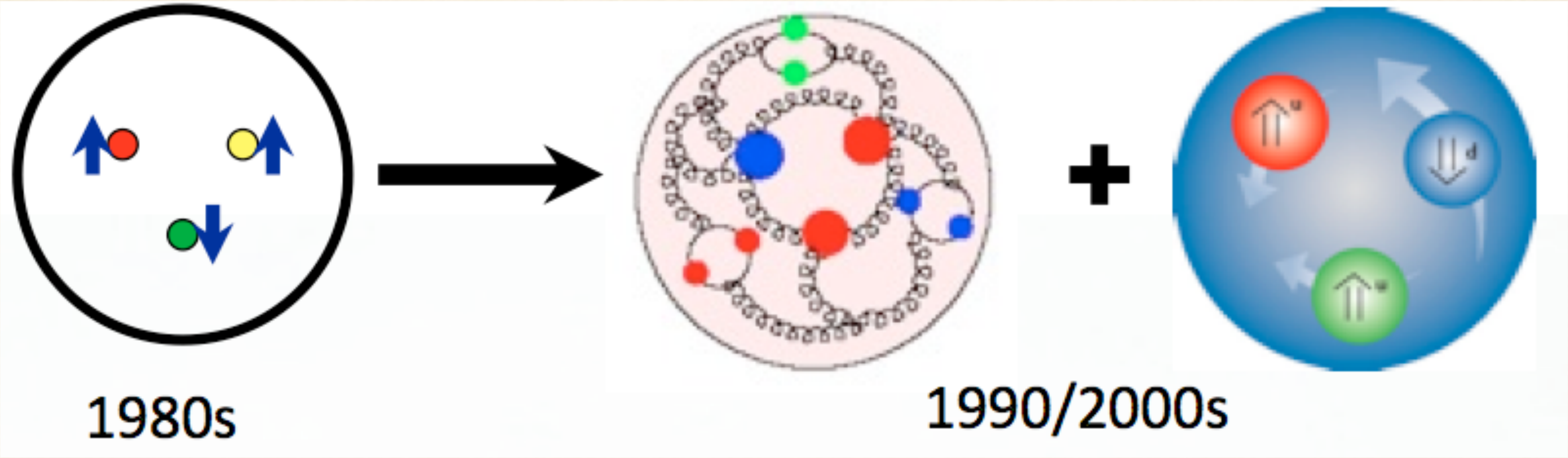

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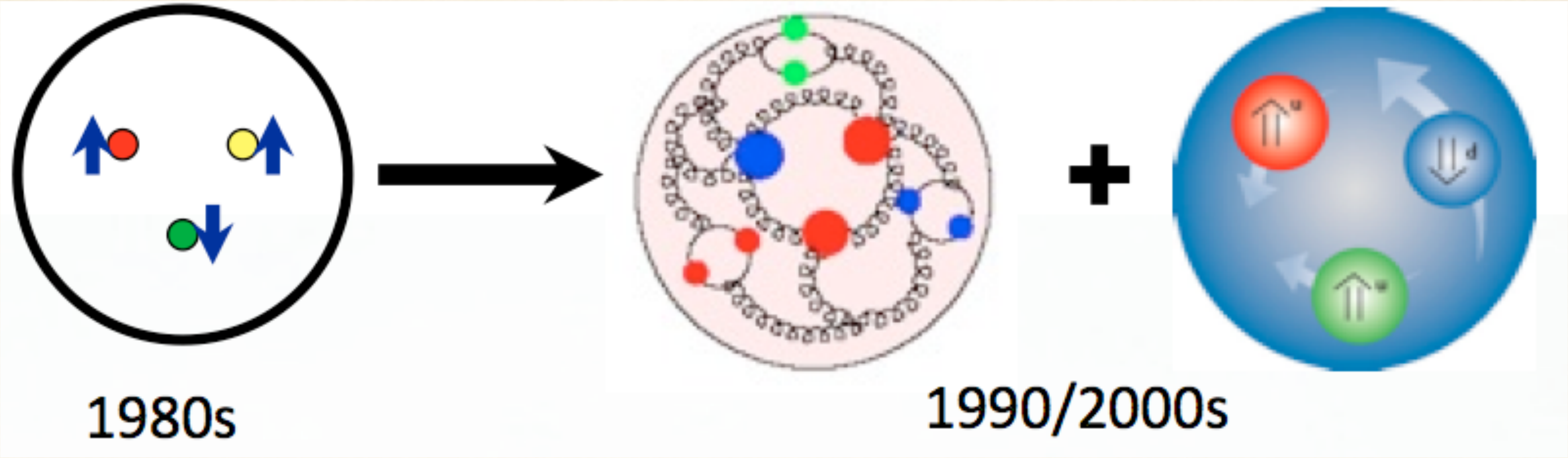

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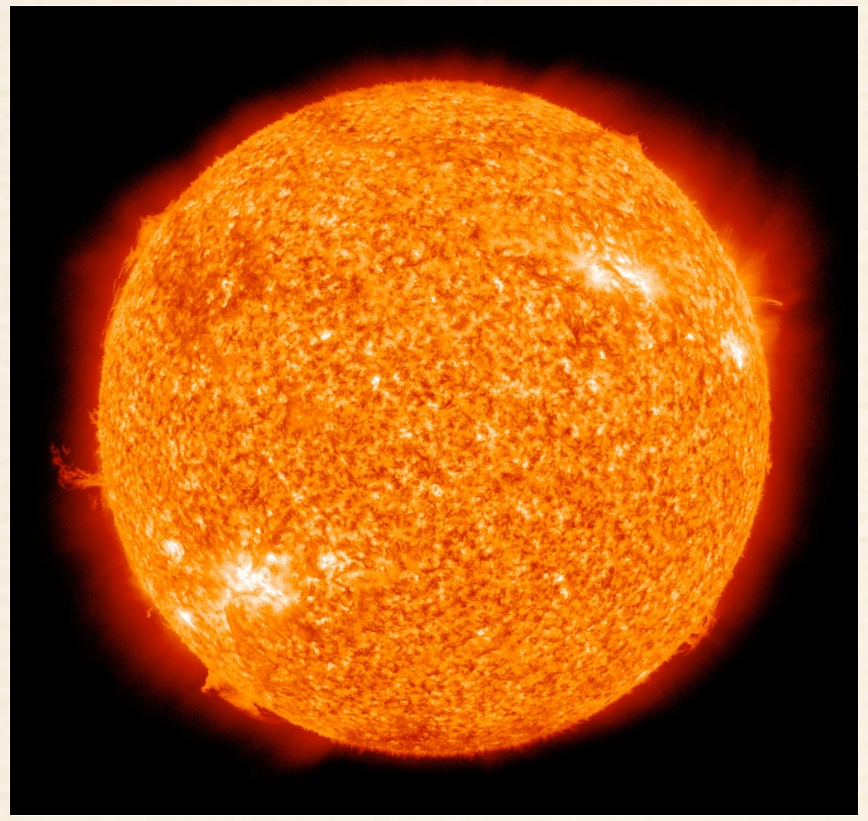
Early 2030s: Role of gluons and orbital angular momentum to understand the dynamical origins of proton, mass, spin and other static properties from first principles:

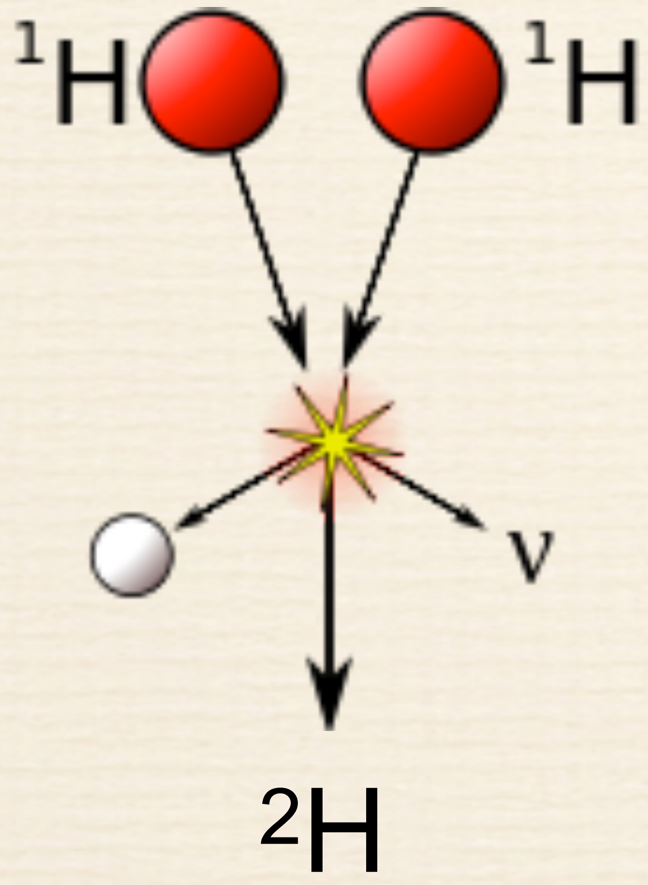
The Electron Ion Collider (EIC)

The Weak Force and Particle Handedness

The Weak Force

Solar p-p chain





Radioactivity

The Weak Force

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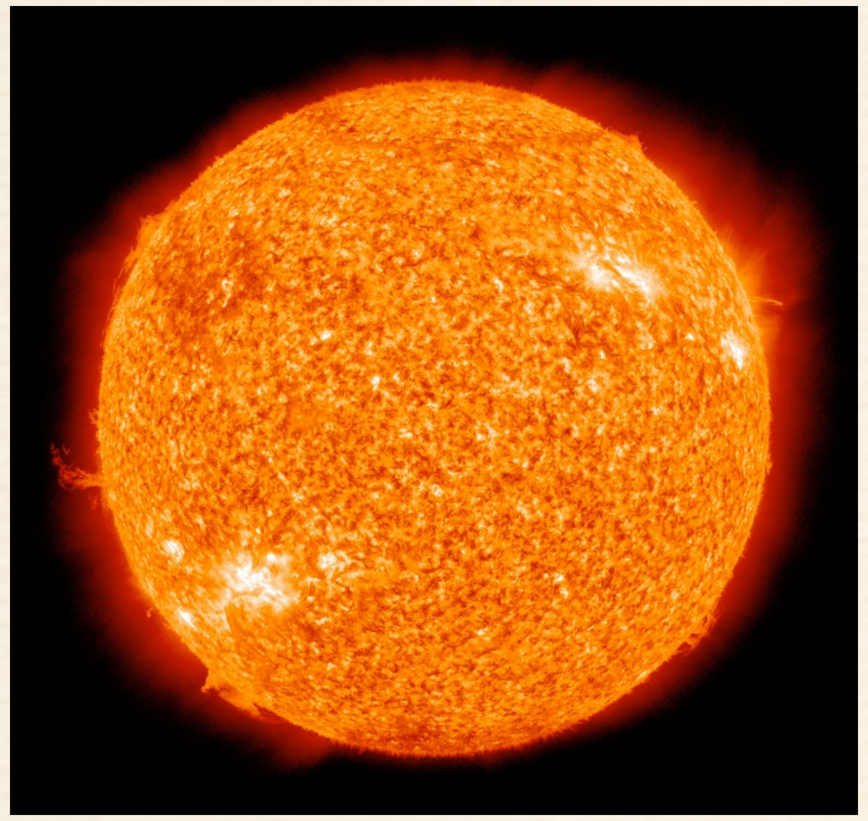
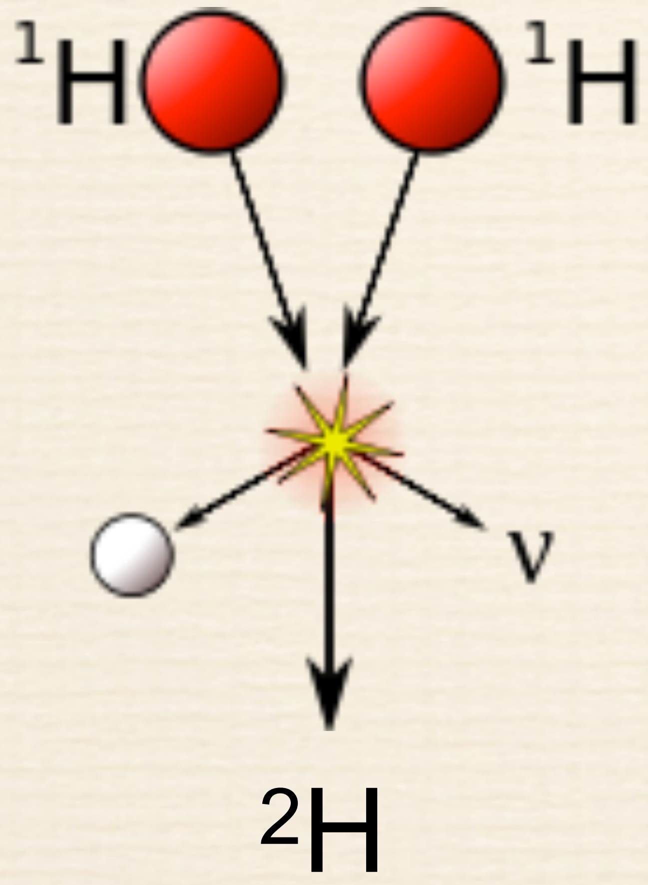
Radioactivity

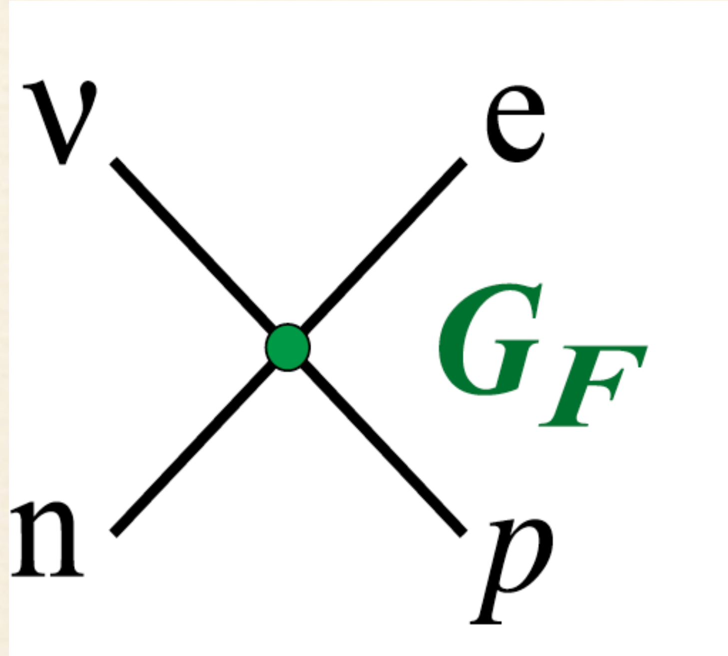




Fermi Theory for weak interactions (1940s)

Universal strength: coupling constant G_F

"Effective" low energy theory that explains many observed properties of radioactive nuclear decays



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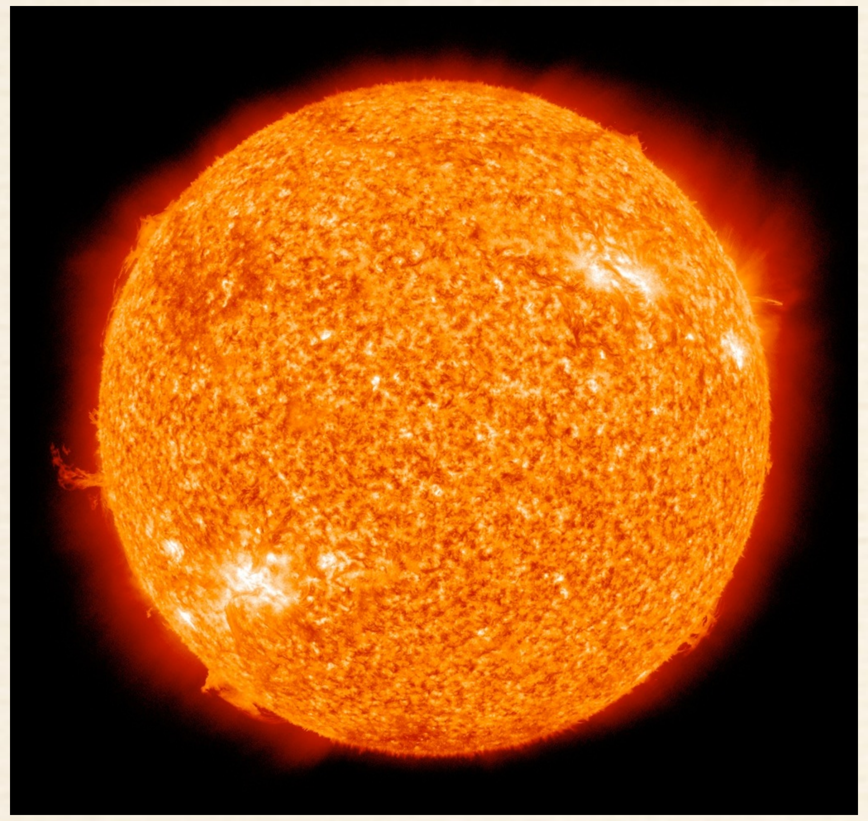

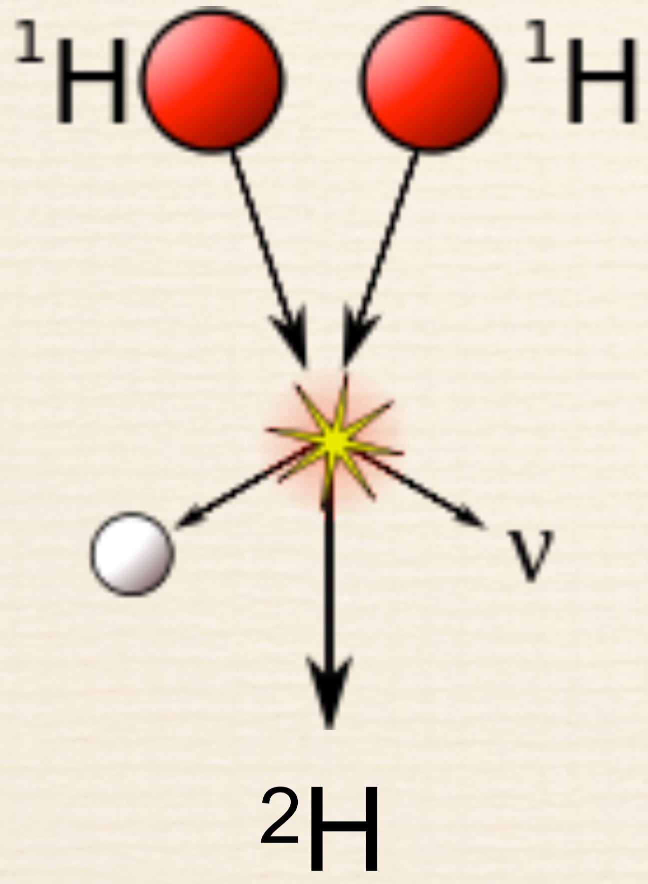

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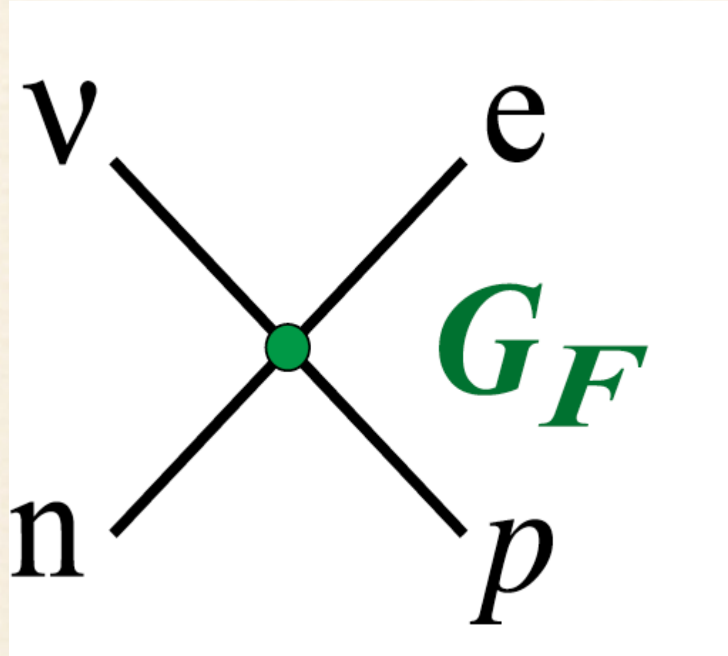
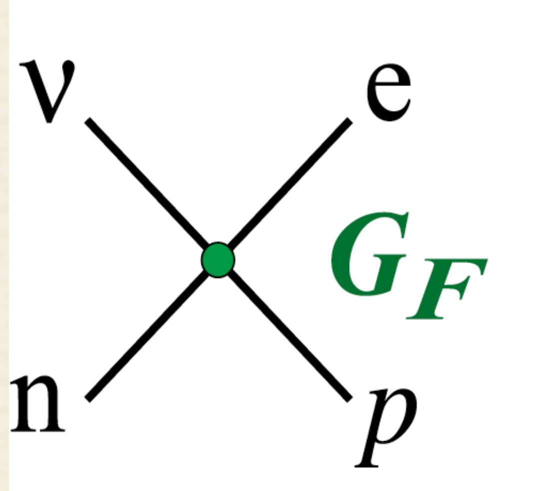
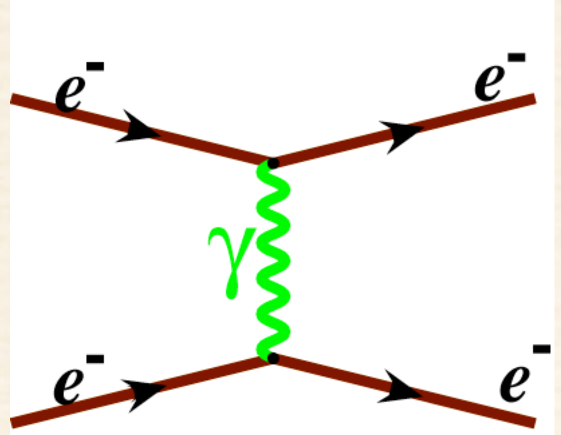


Theory known to breakdown at energy > 100 GeV

Electroweak Unification

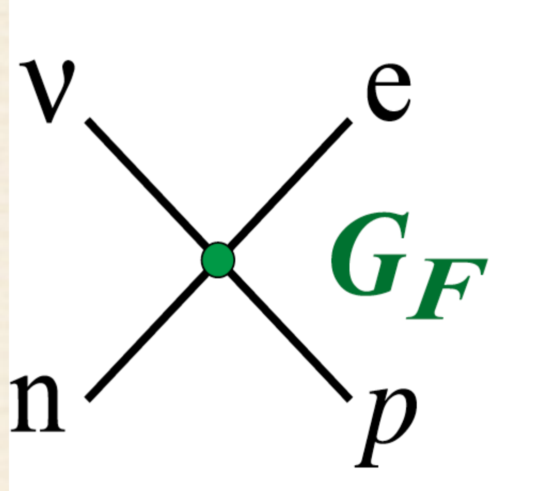


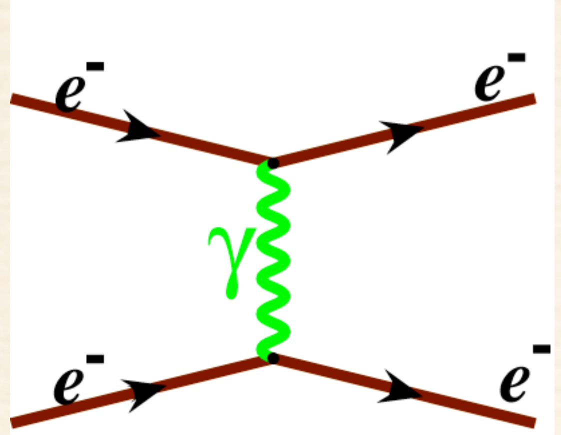


Early 1950s: first attempts to describe weak and electromagnetic interactions under one unified framework

Weak interactions are short range (much shorter than 1 fm)

Electroweak Unification





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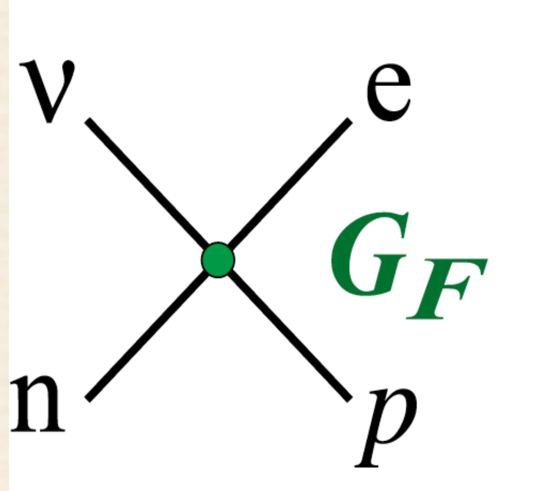

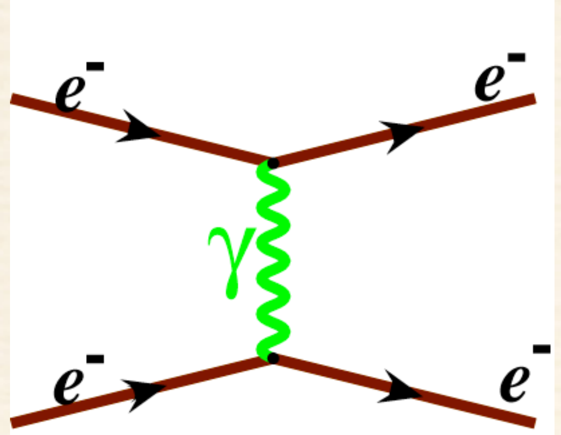

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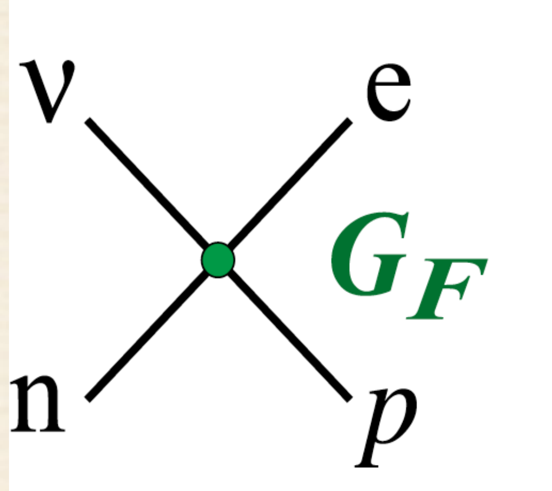

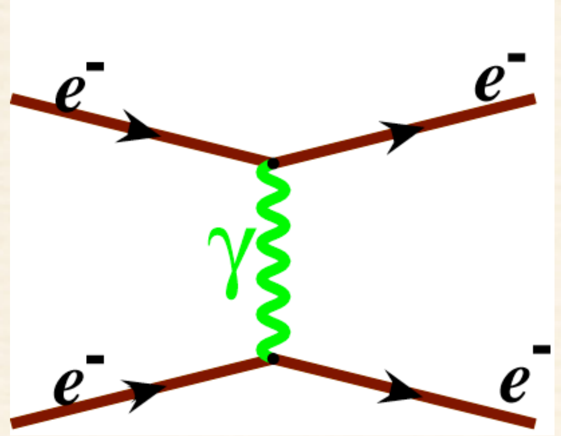

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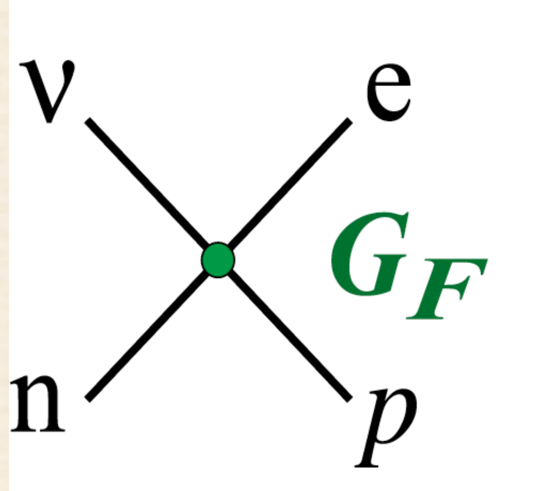

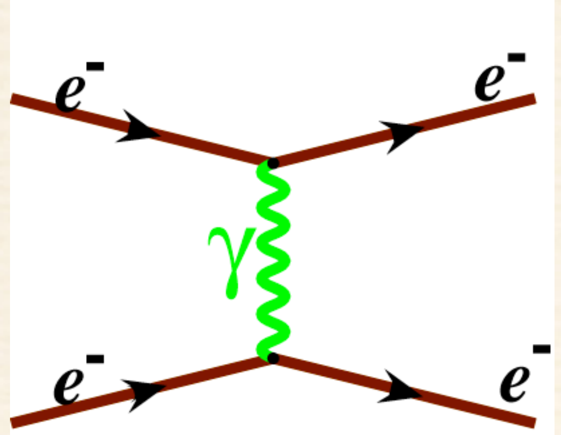

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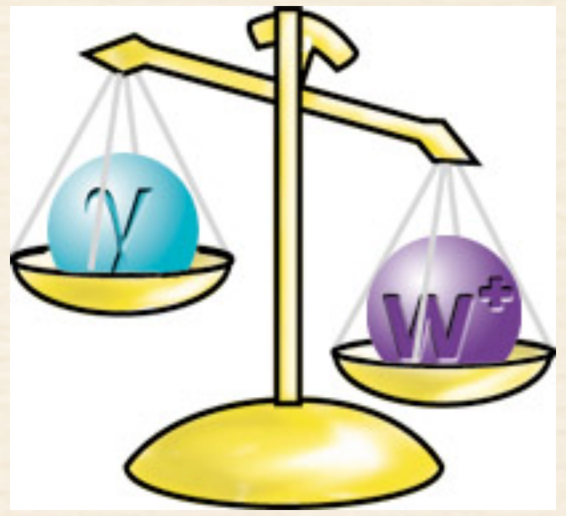
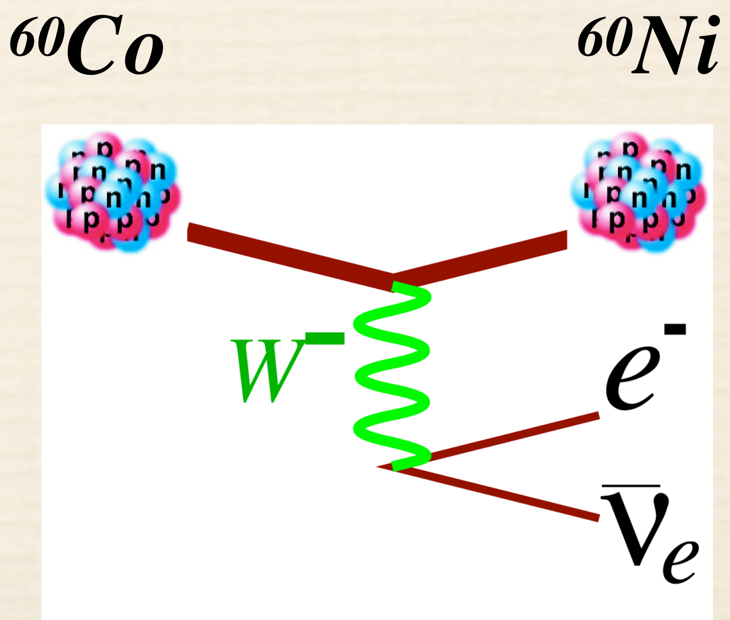


$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}e^{-\left[\frac{mc}{\hbar}\right]r}$$

$e^{[-0.45\,(\text{attometer})^{-1}\times r]}$

massive force carriers are W bosons ~ 80 GeV



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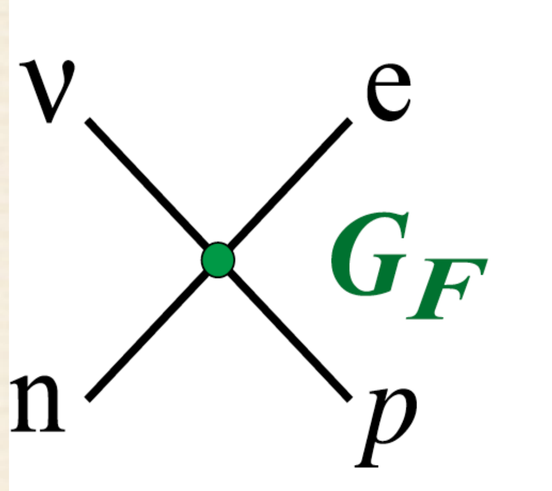

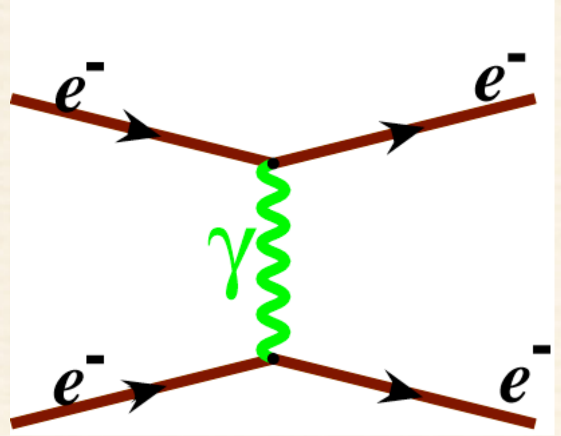

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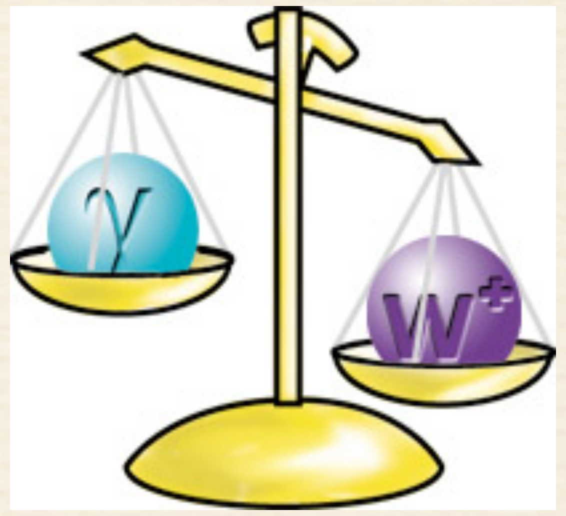
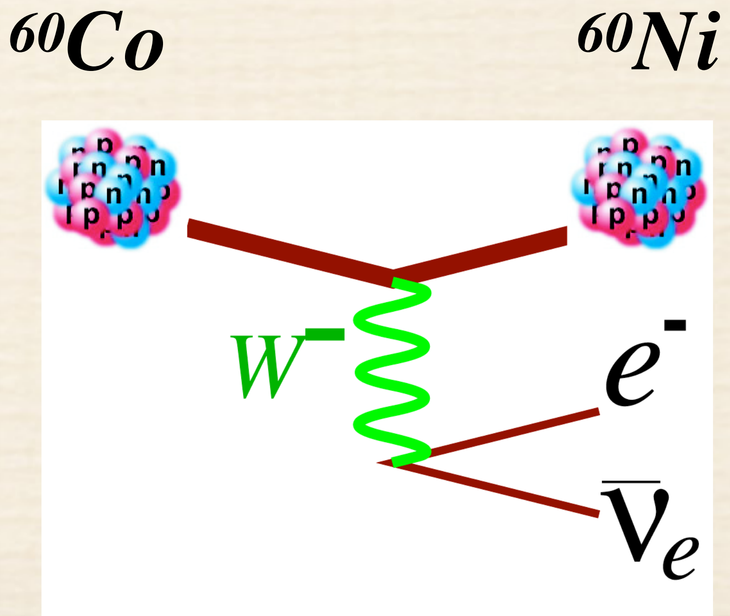


$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}e^{-\left[\frac{mc}{\hbar}\right]r}$$

$$e^{[-0.45\ (\text{attometer})^{-1} \times r]}$$

massive force carriers are W bosons ~ 80 GeV

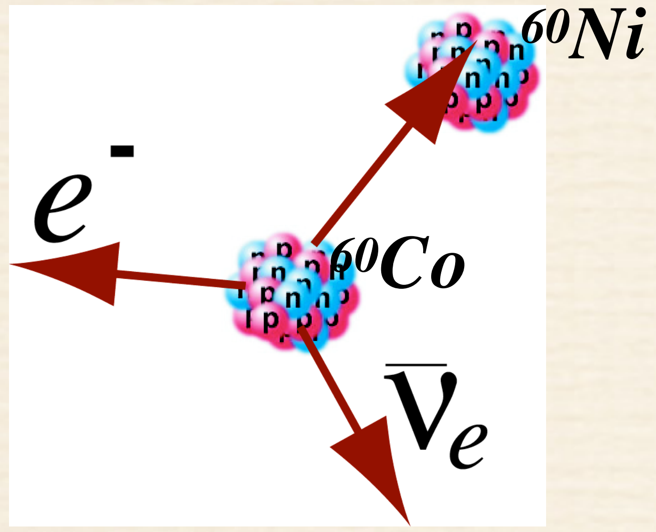


*Weak interactions do **not** obey mirror symmetry*

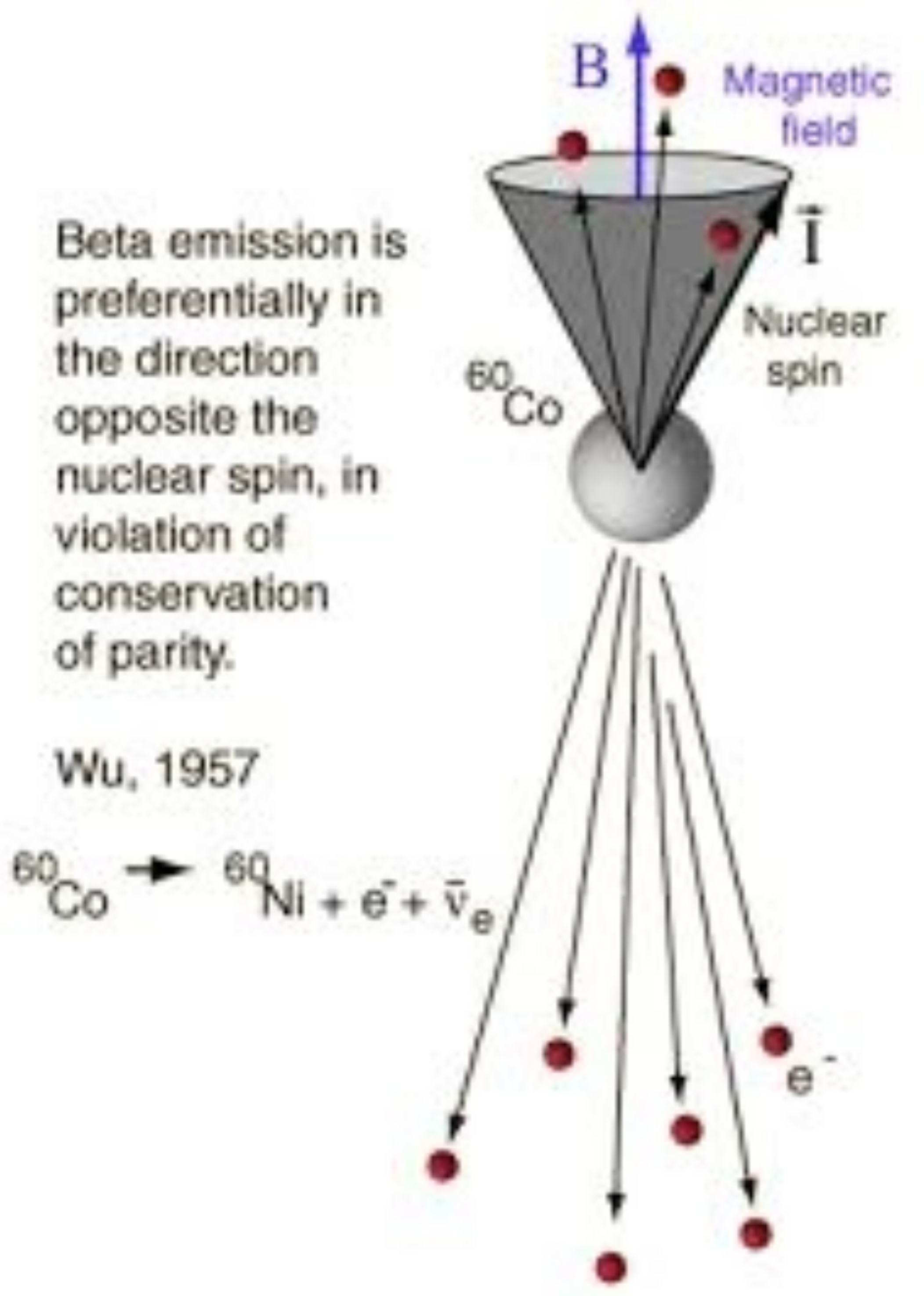
particles involved not ambidextrous

Discovery of Parity Violation in Weak Force Phenomena

Failure of Ambidexterity



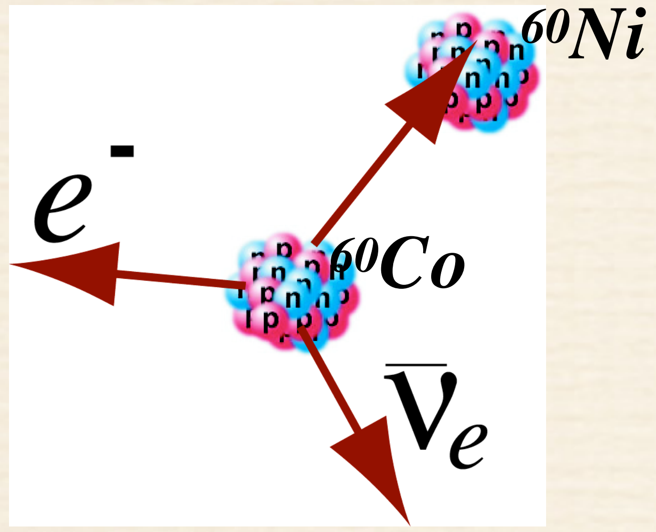
Weak decay of ^{60}Co Nucleus



Failure of Ambidexterity

parity transformation (reflection)

$$x,y,z \rightarrow -x,-y,-z$$



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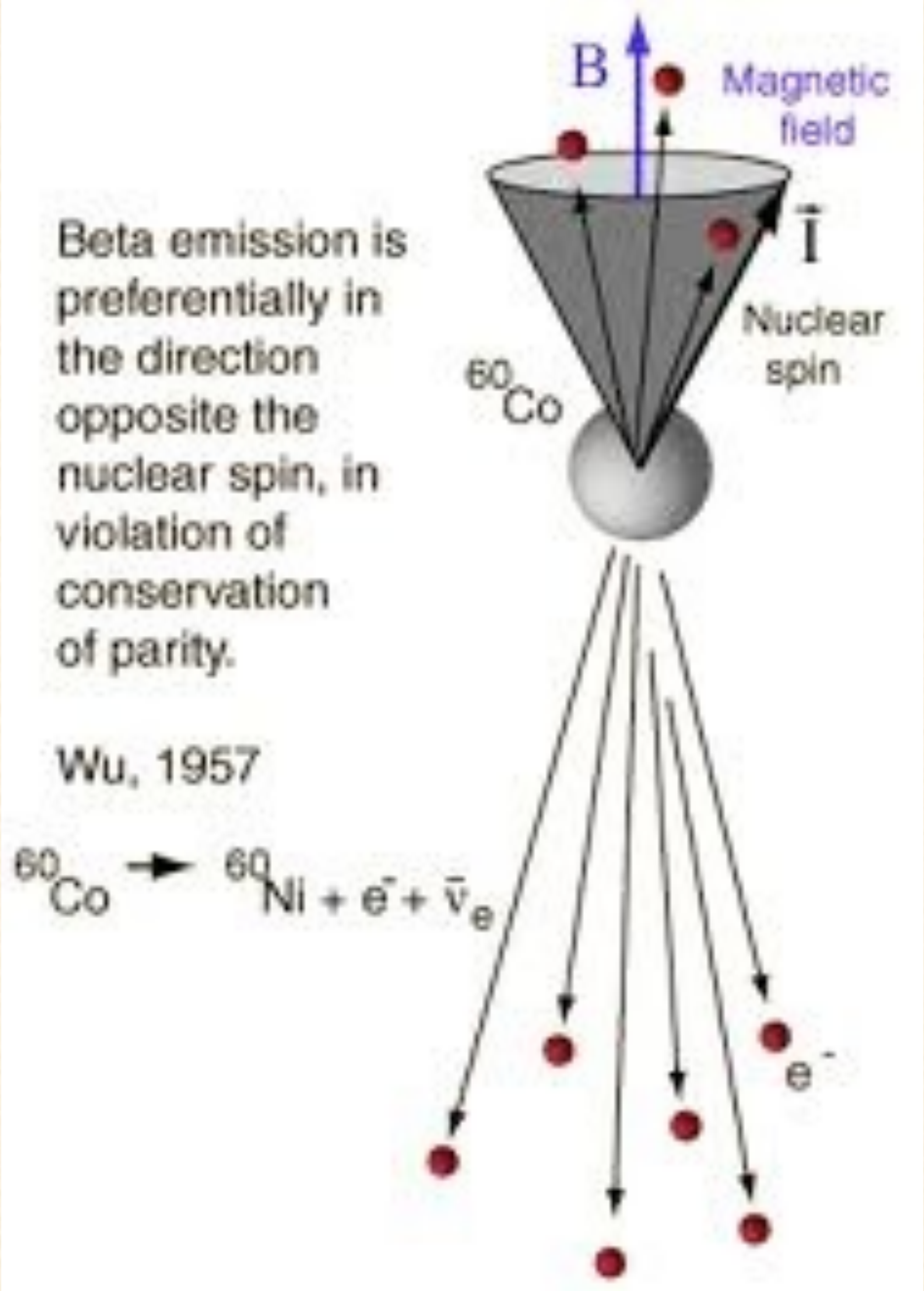

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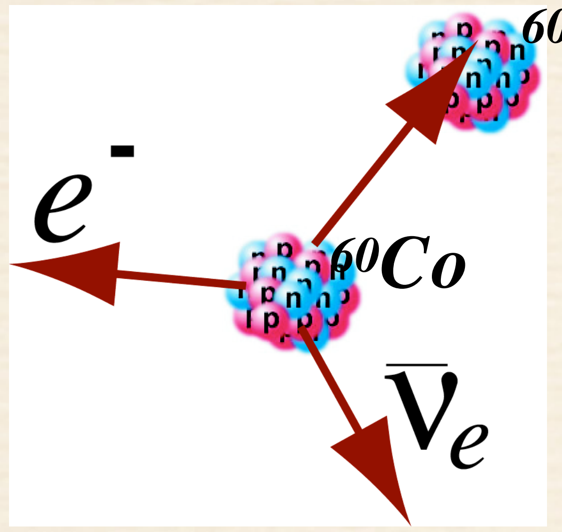

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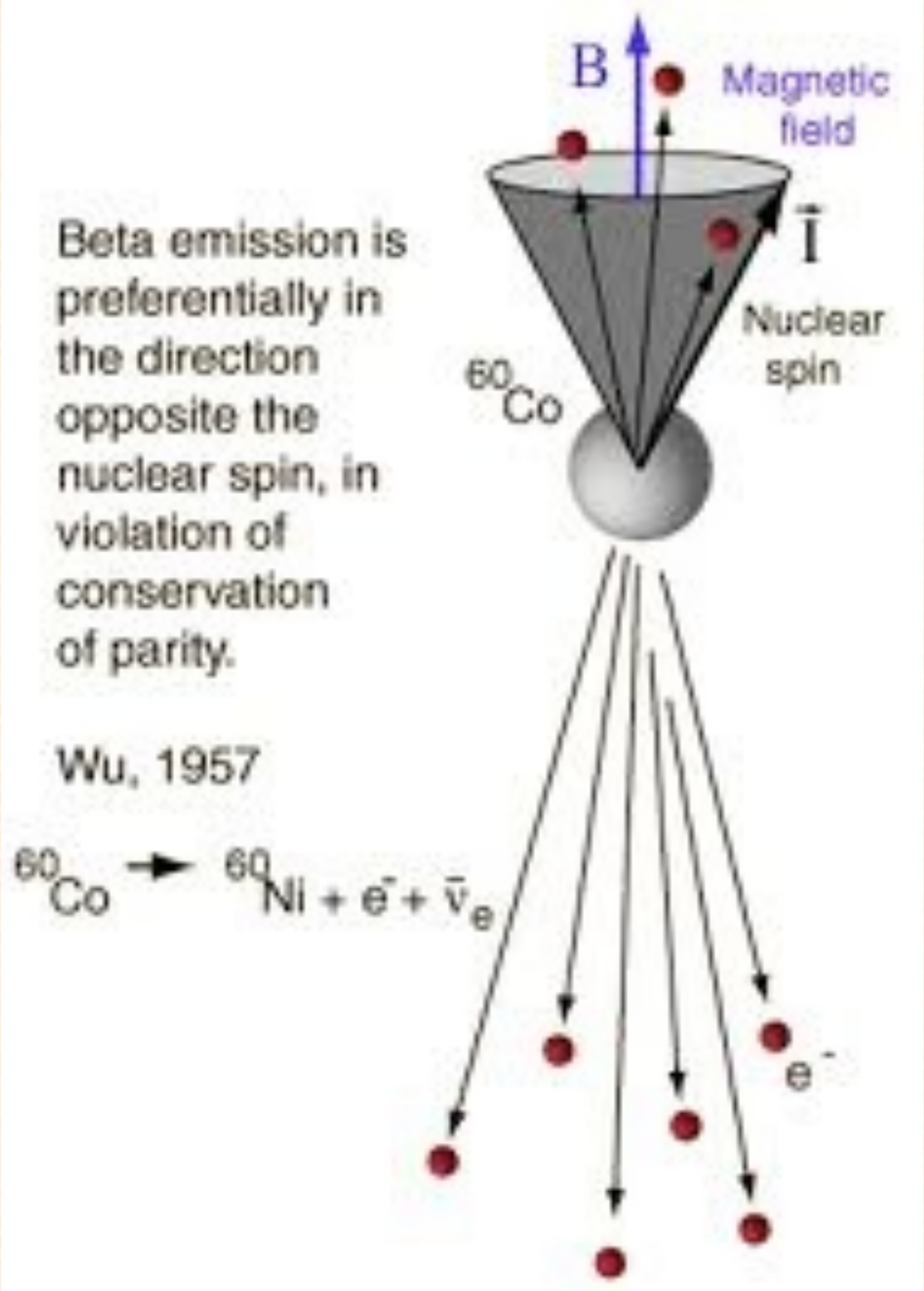

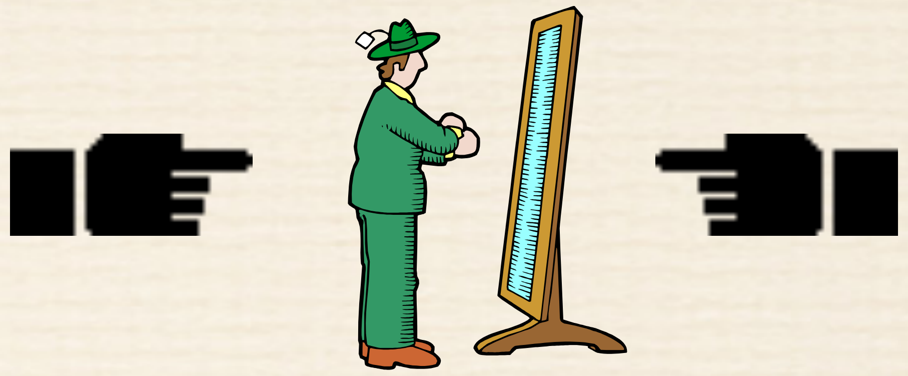

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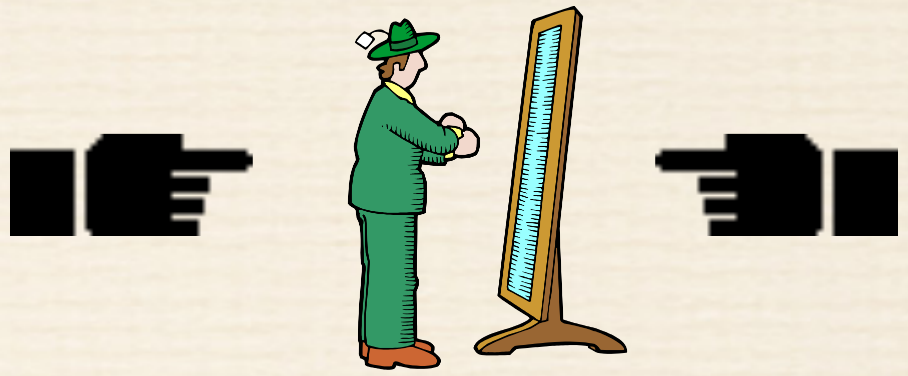

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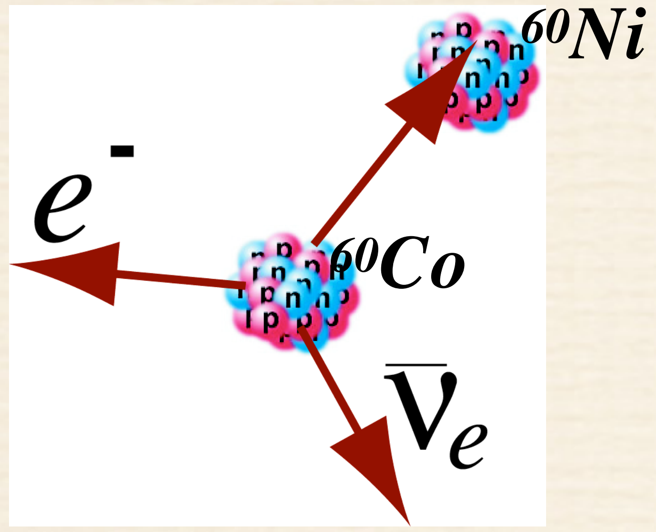

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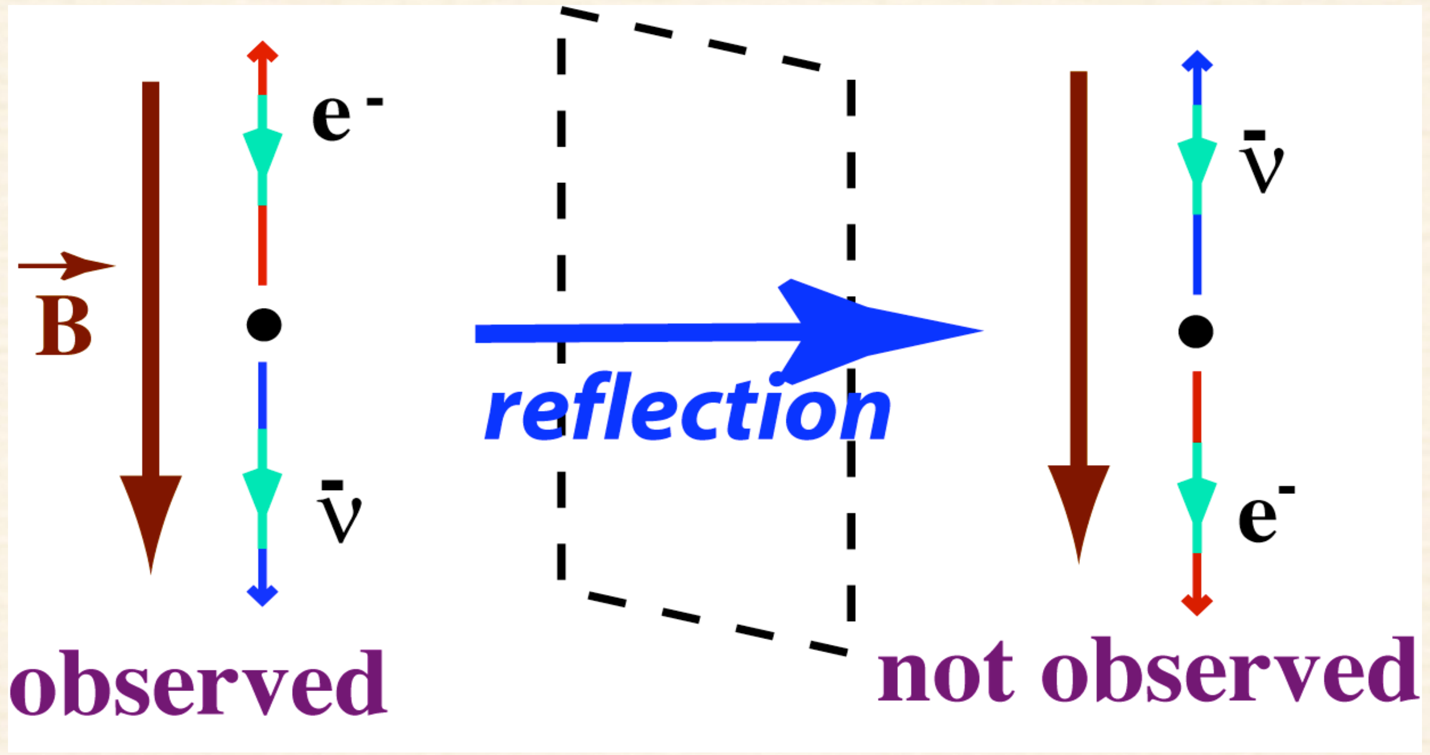

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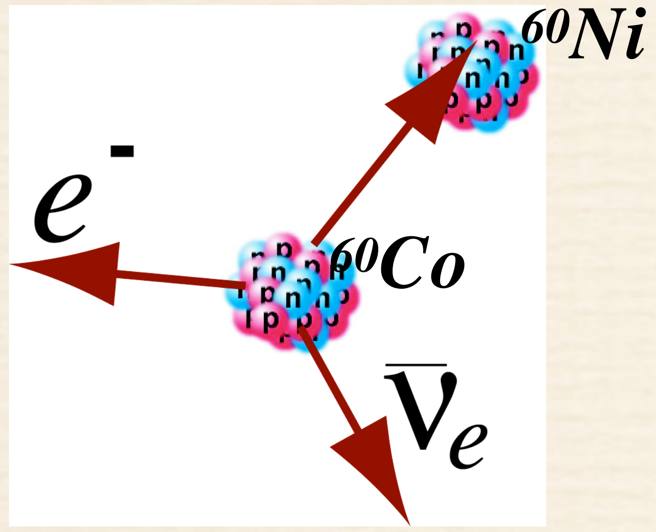

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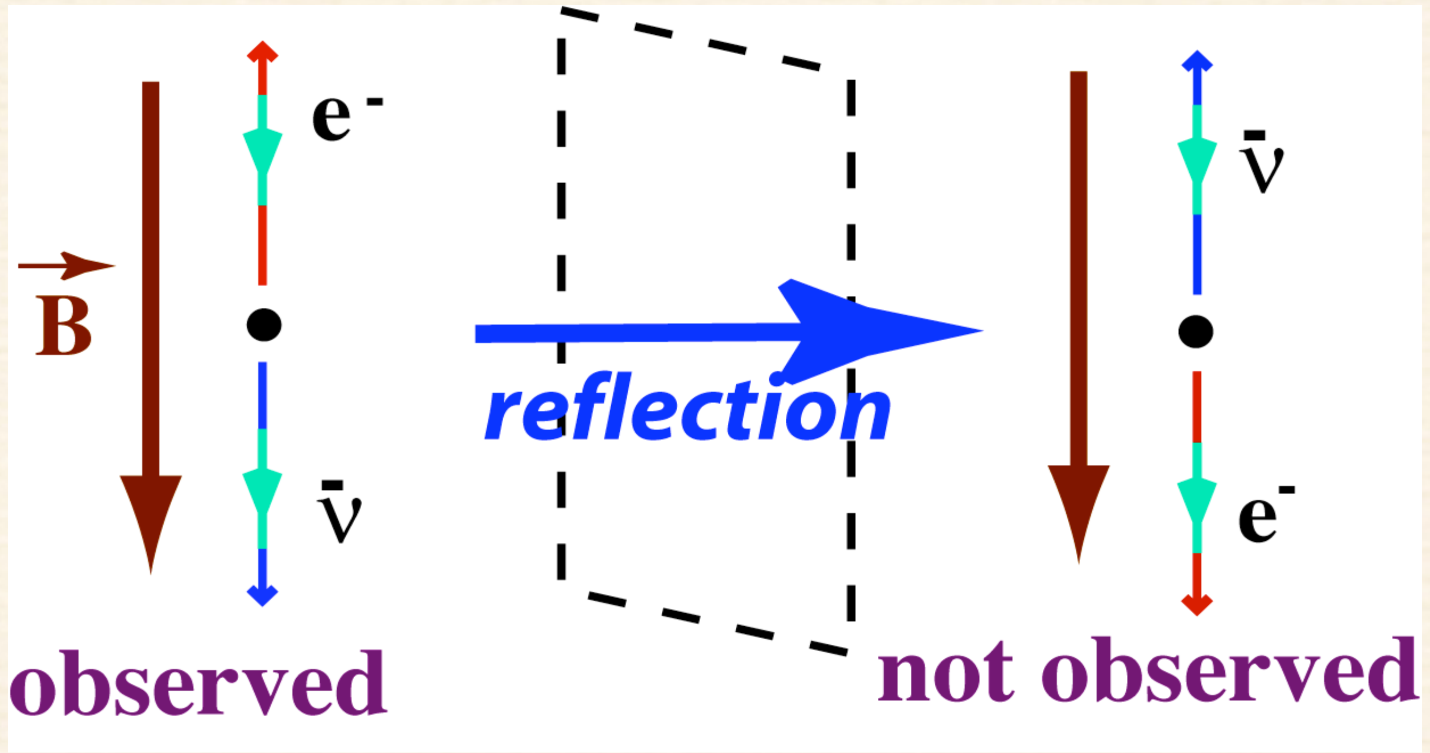

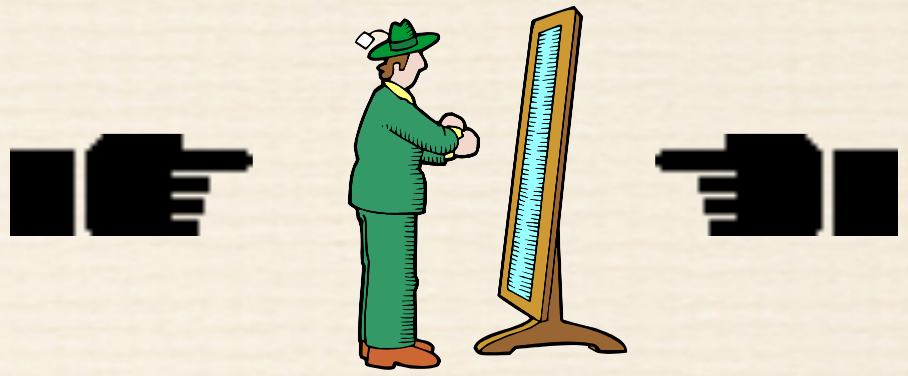

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matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

handedness or ***helicity/chirality***

Discovery of Parity Violation in Weak Force Phenomena

Failure of Ambidexterity

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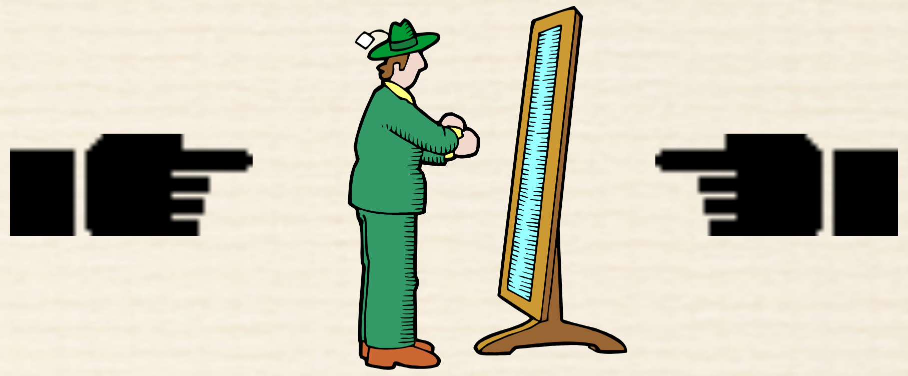

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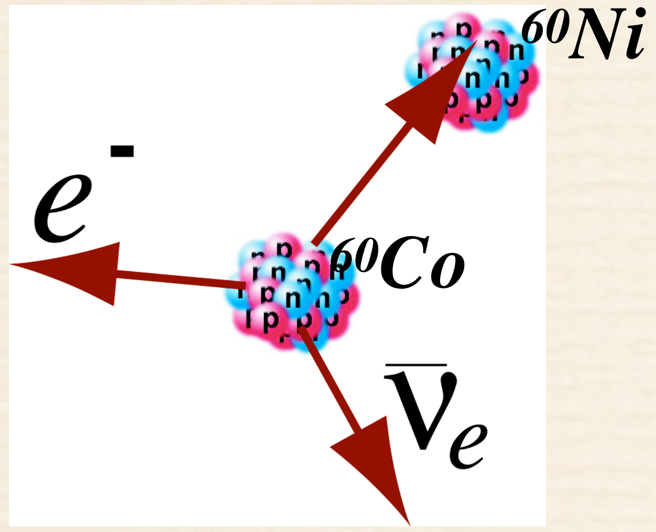

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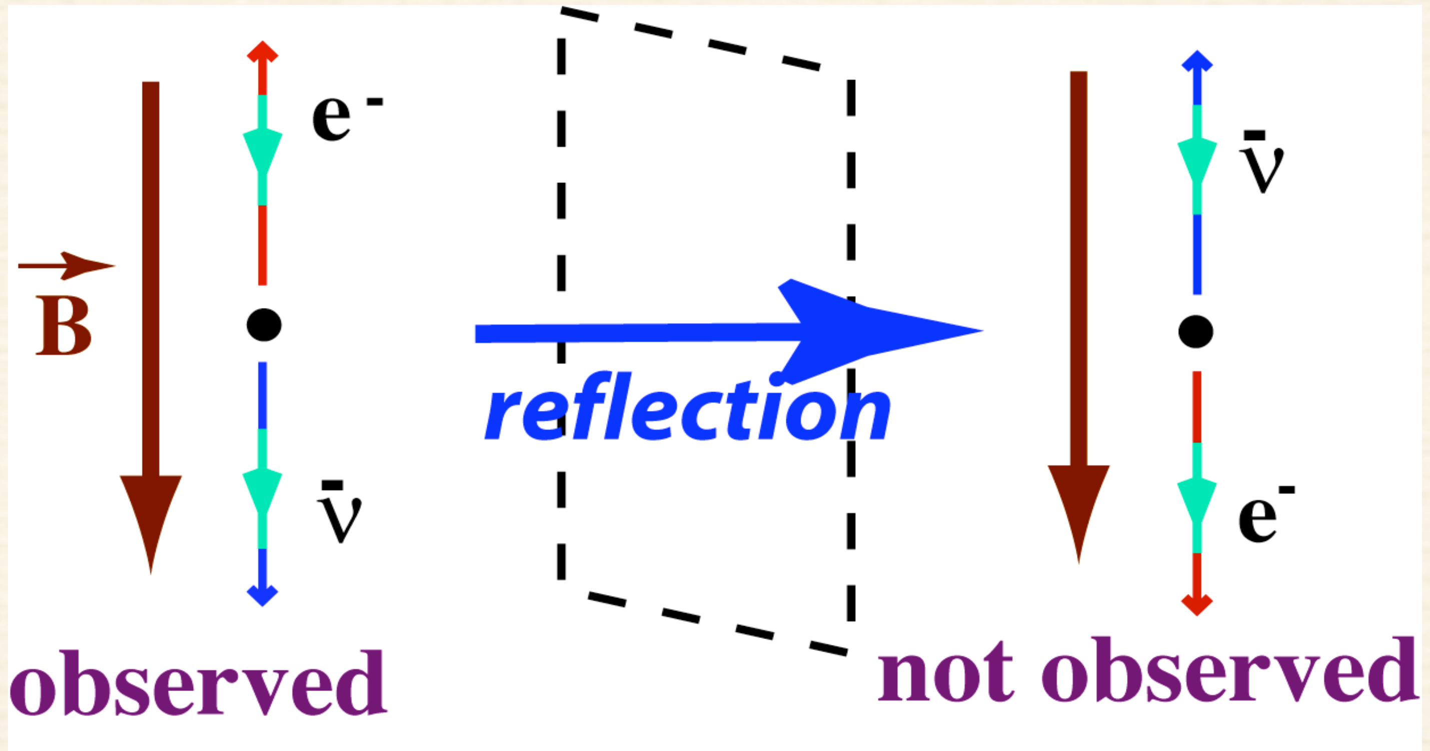

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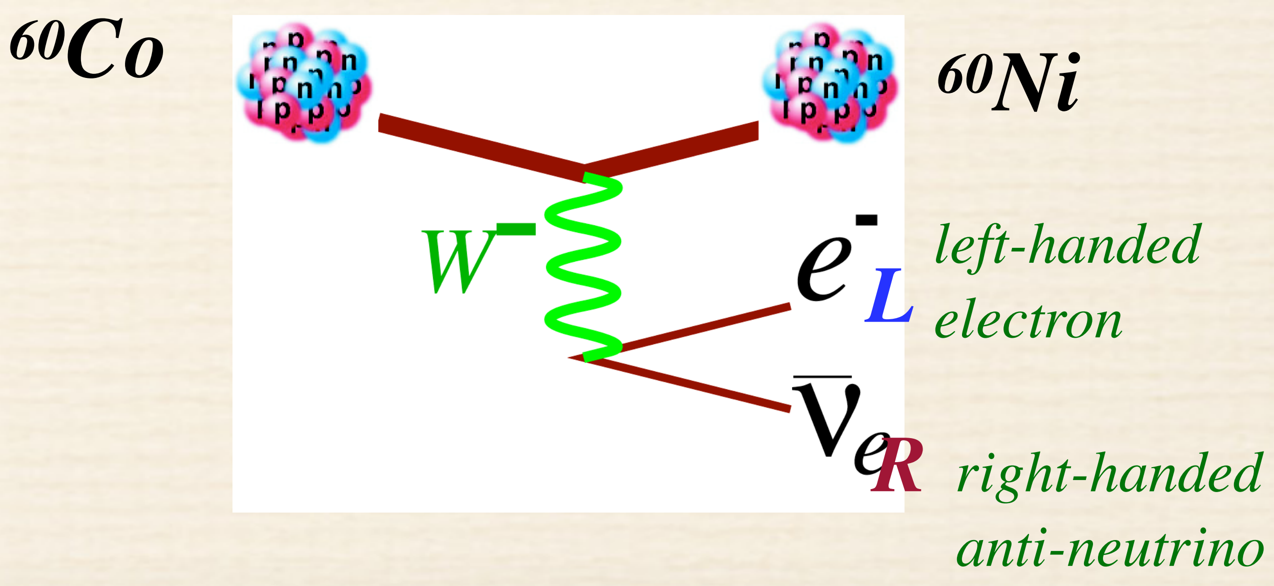
Mirror reflection flips sign of helicity

Left-handed ⟺ *right-handed*

Only left-handed particles can exchange W bosons

(right-handed anti-particles)



Discovery of Parity Violation in Weak Force Phenomena

Failure of Ambidexterity

Nature is not "mirror-symmetric"

parity transformation
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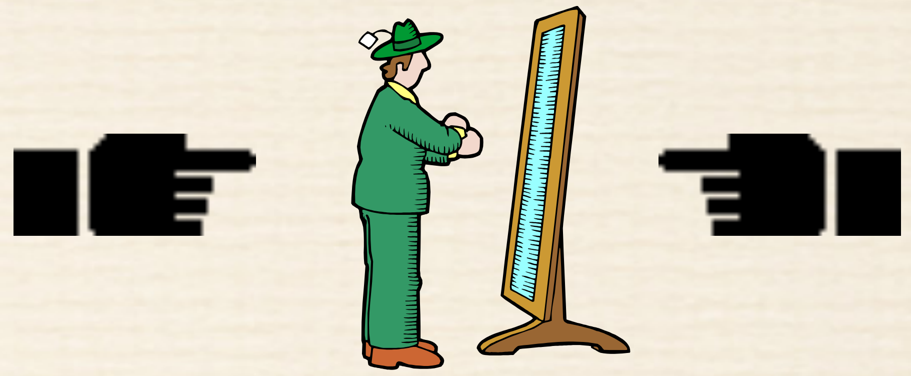

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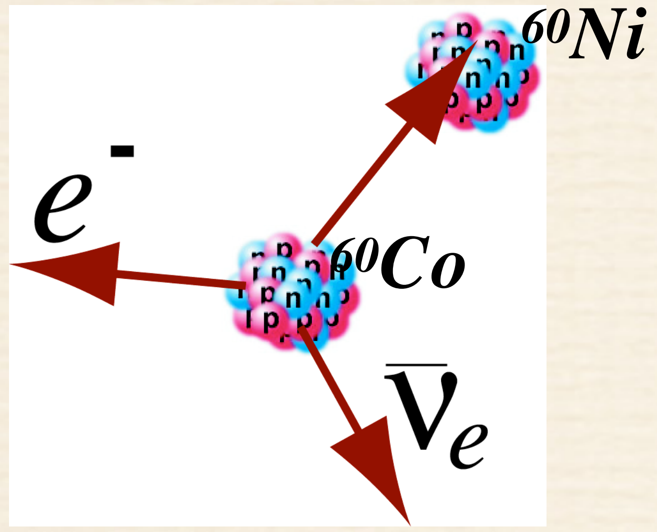

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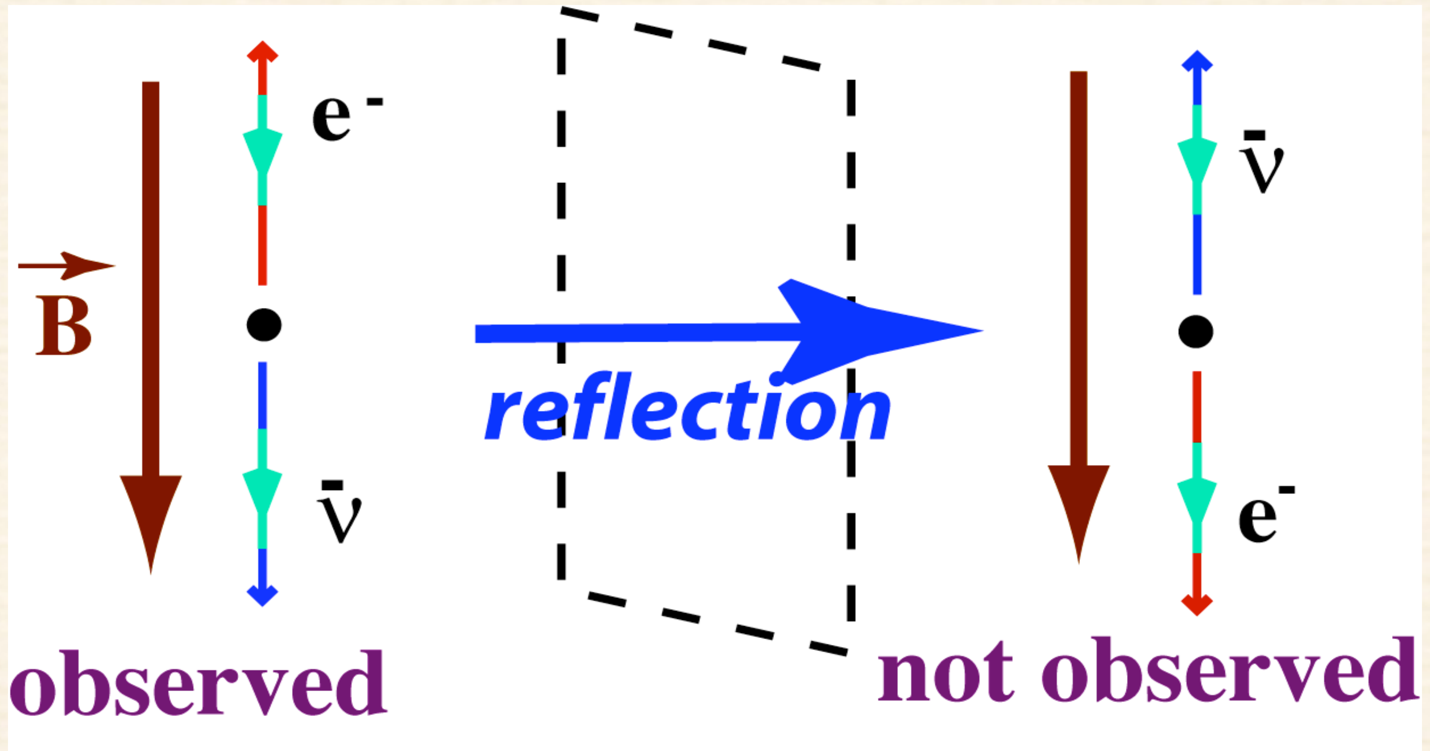

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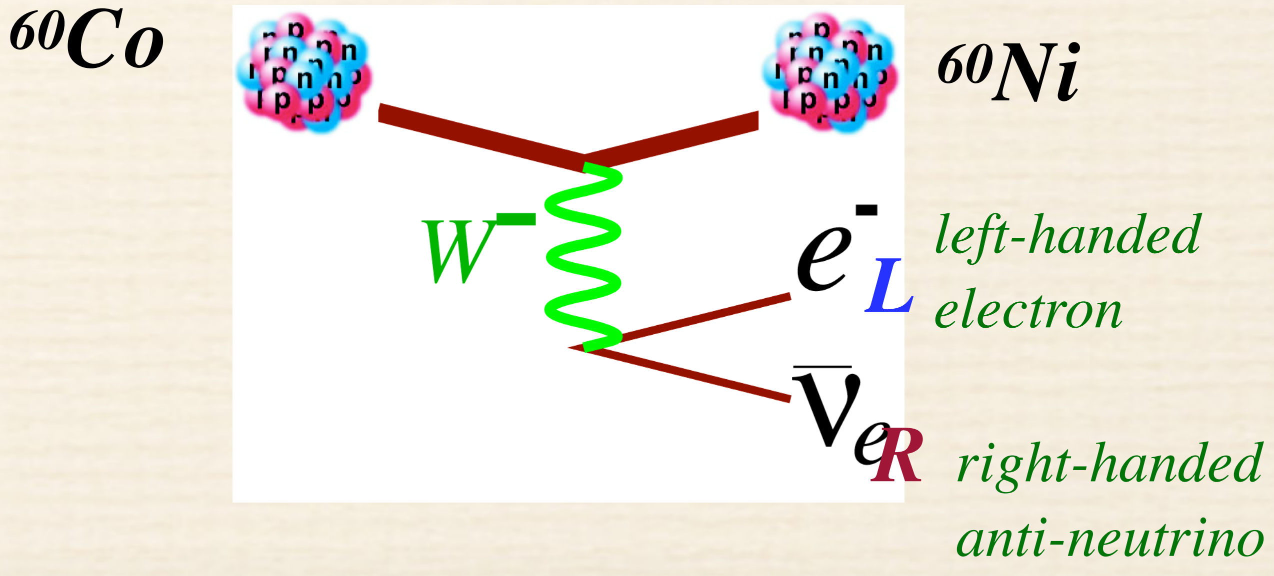

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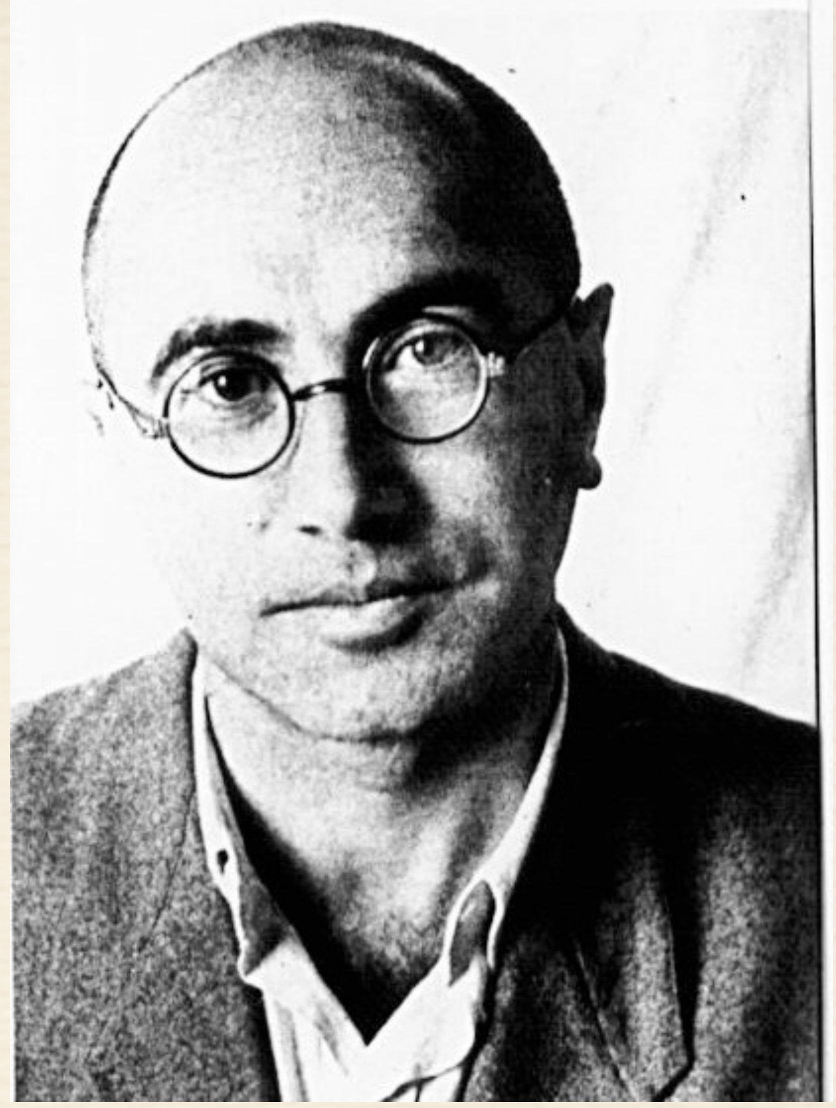
Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964-966 (March, 1959)

Is Electron Scattering Mirror-Symmetric?

A Classic Paper



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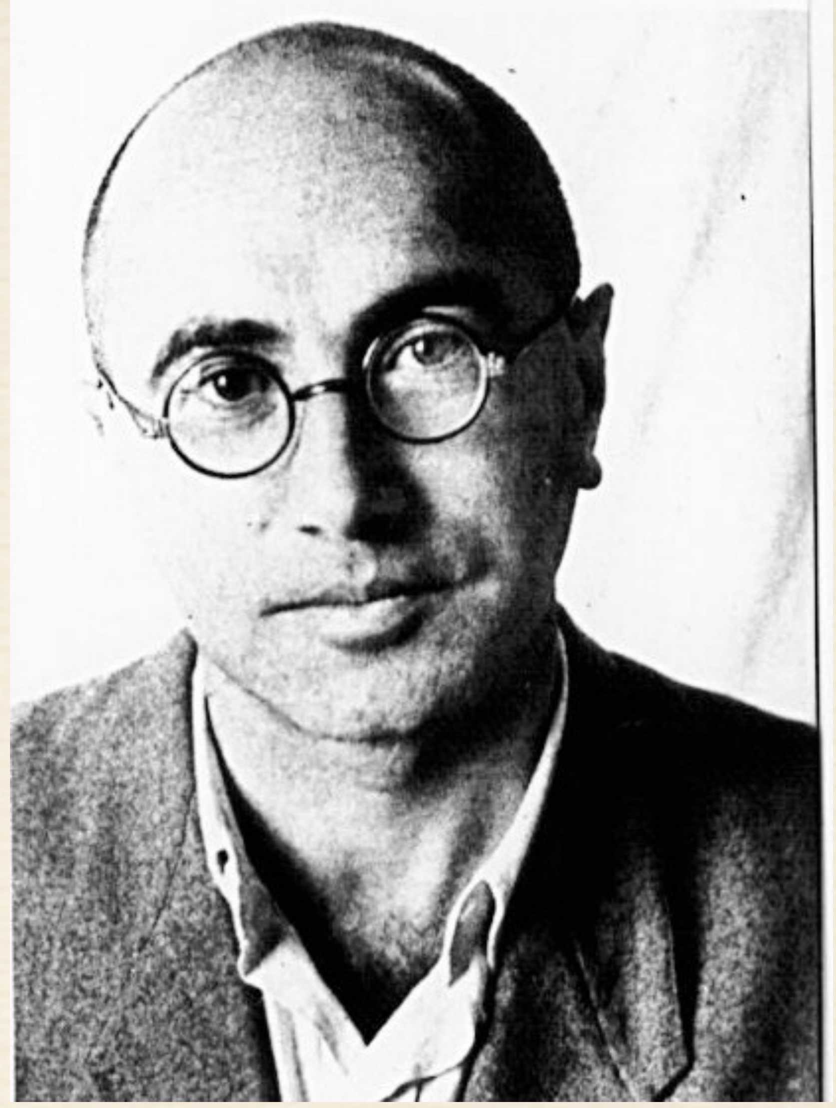
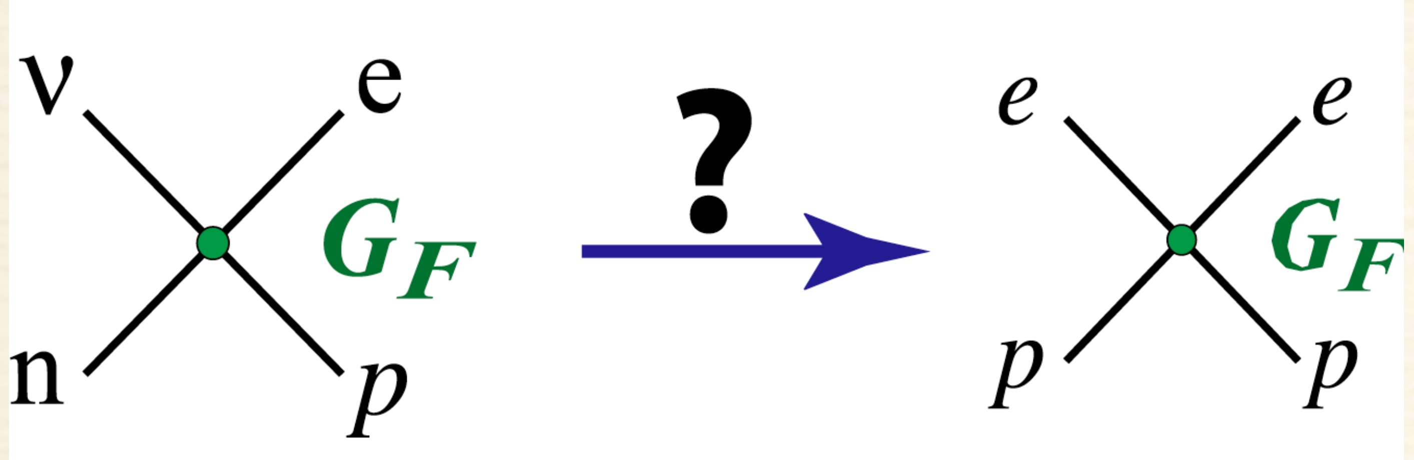


Is there a neutral analog of the “charged” weak force?

Neutron β Decay

Electron-proton Weak Scattering



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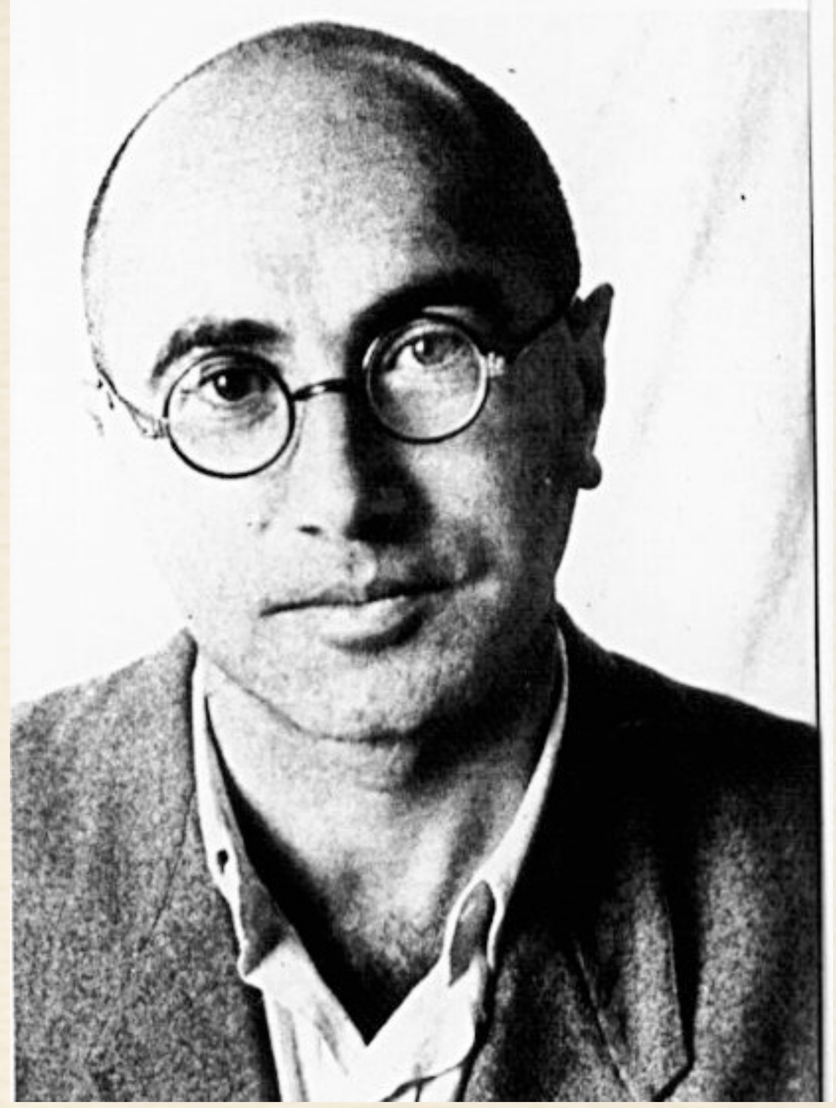

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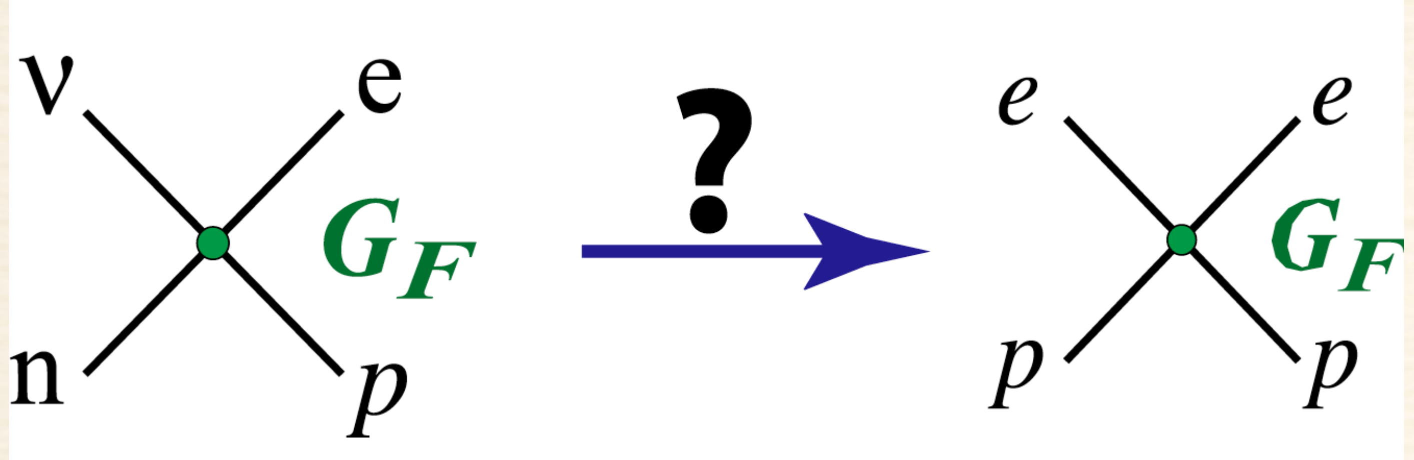

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$$\sim \left|A_{EM}\right|^2 + 2A_{EM}A^*_{weak} + \ldots$$

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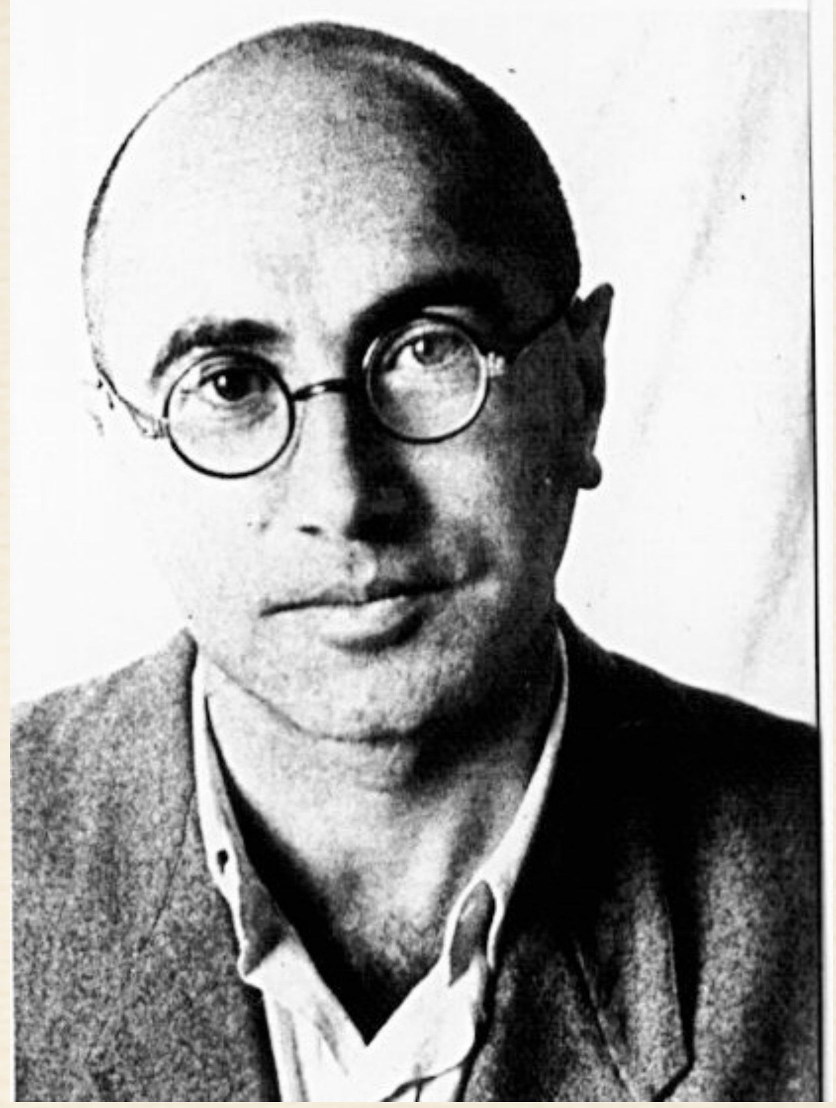

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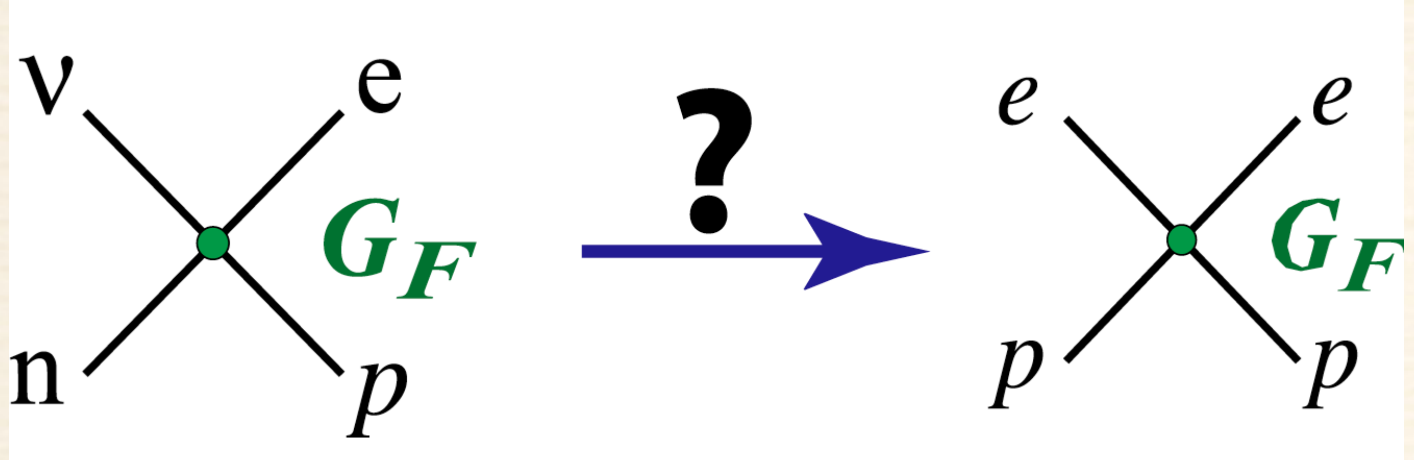

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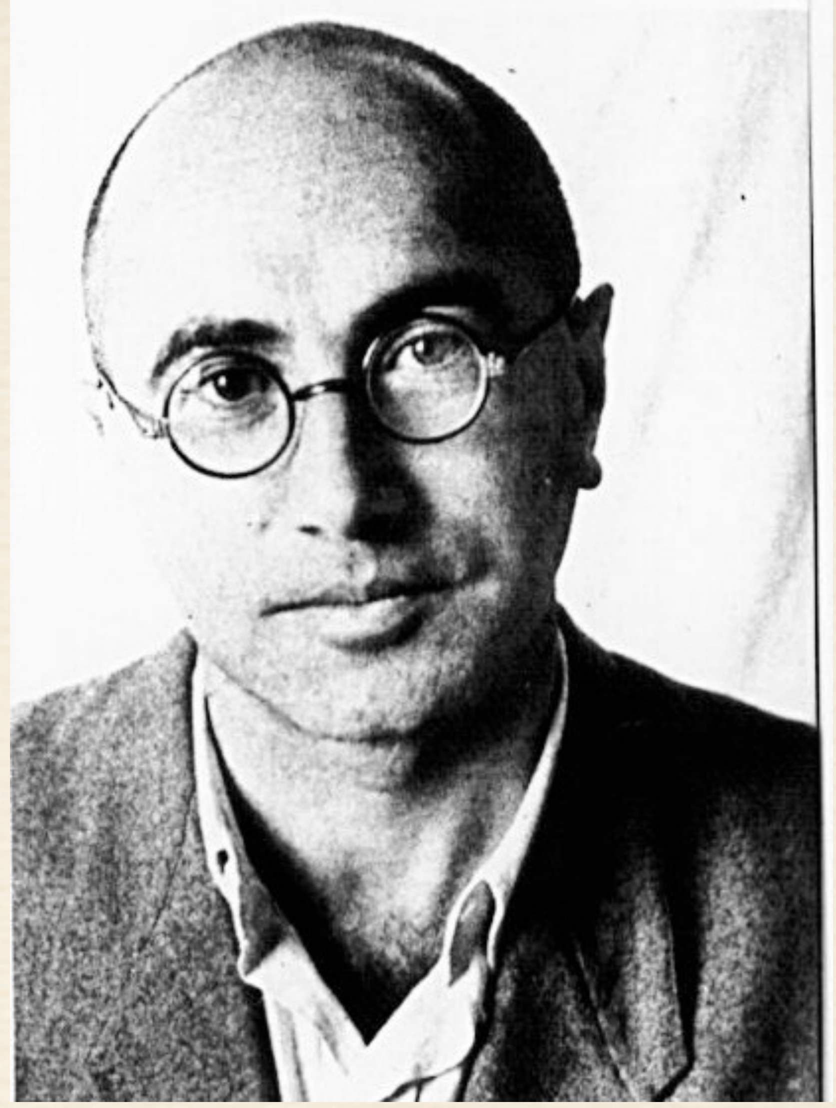

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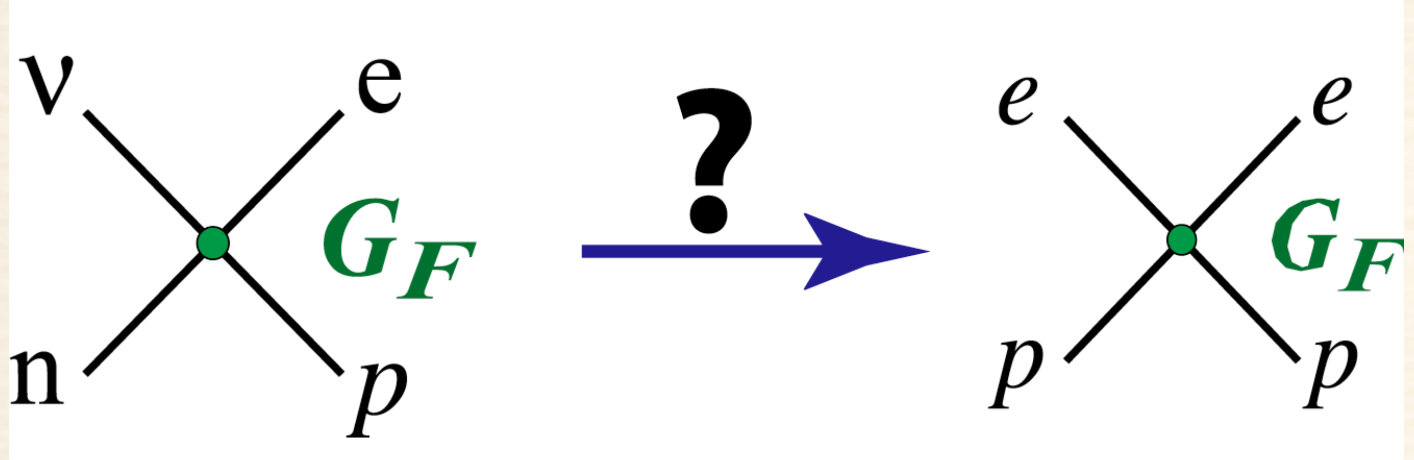

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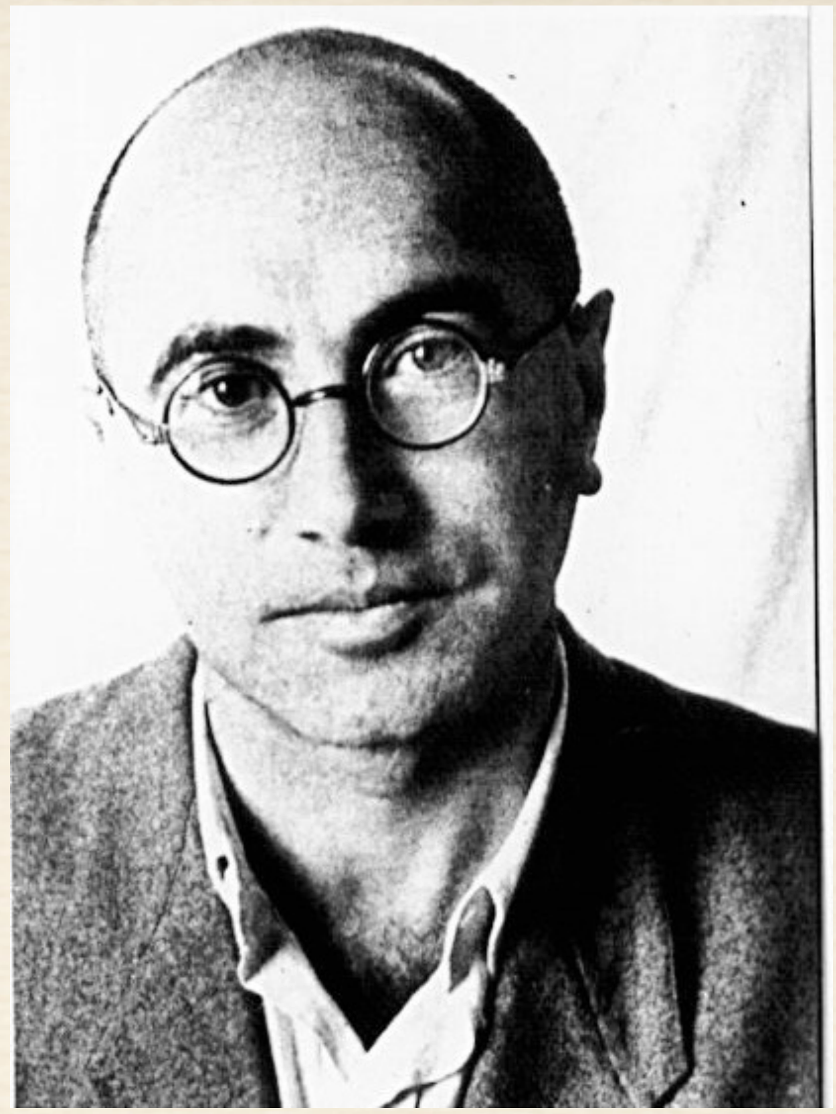

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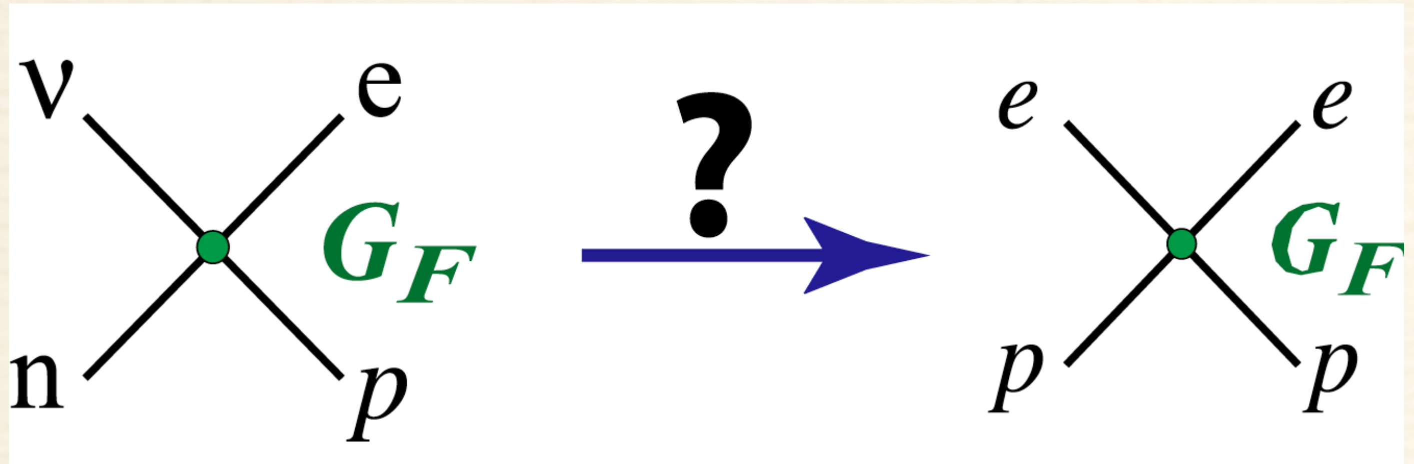

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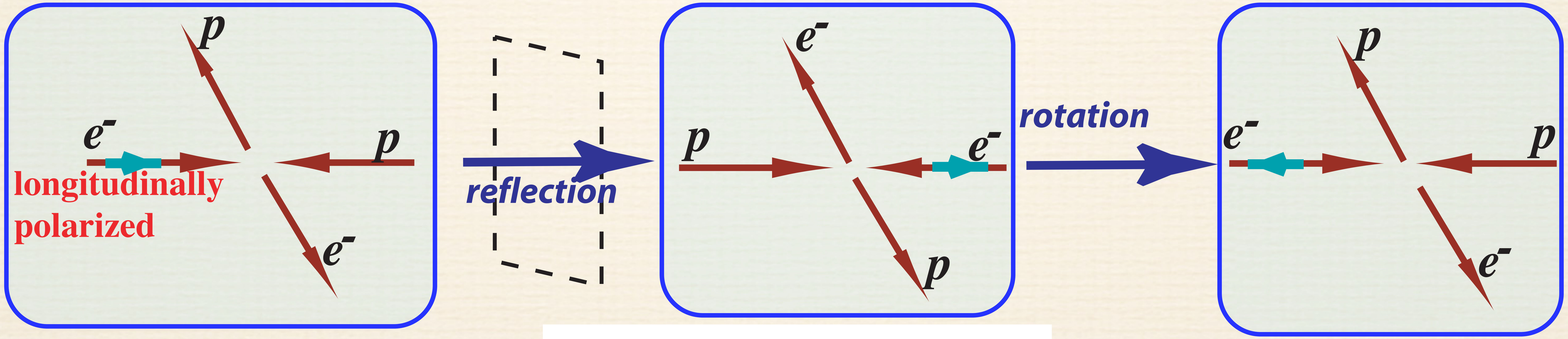

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Parity-Violating Electron Scattering

Small Asymmetry: Worth the Effort?

- *Incident beam longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

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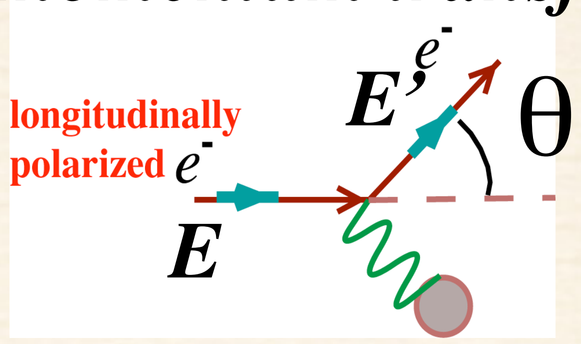

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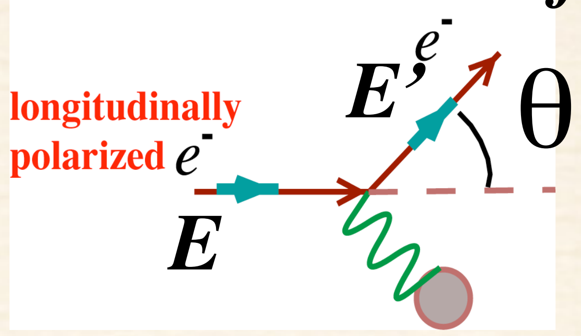

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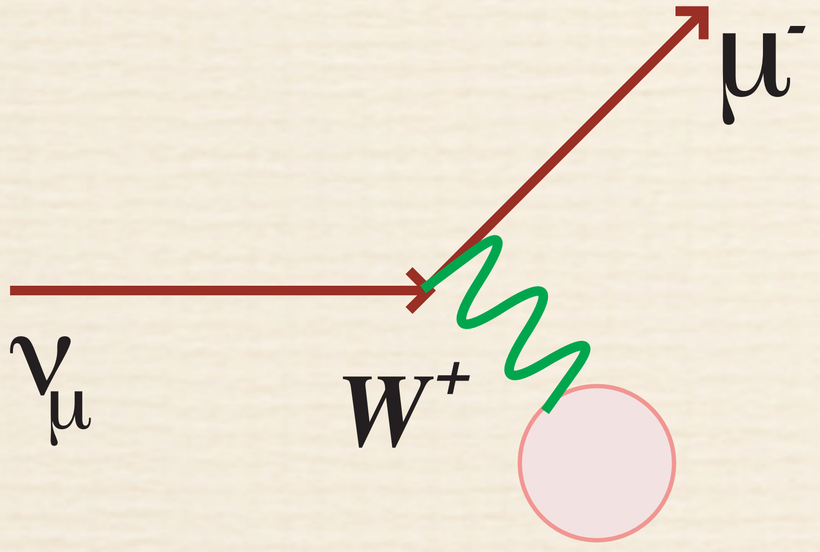
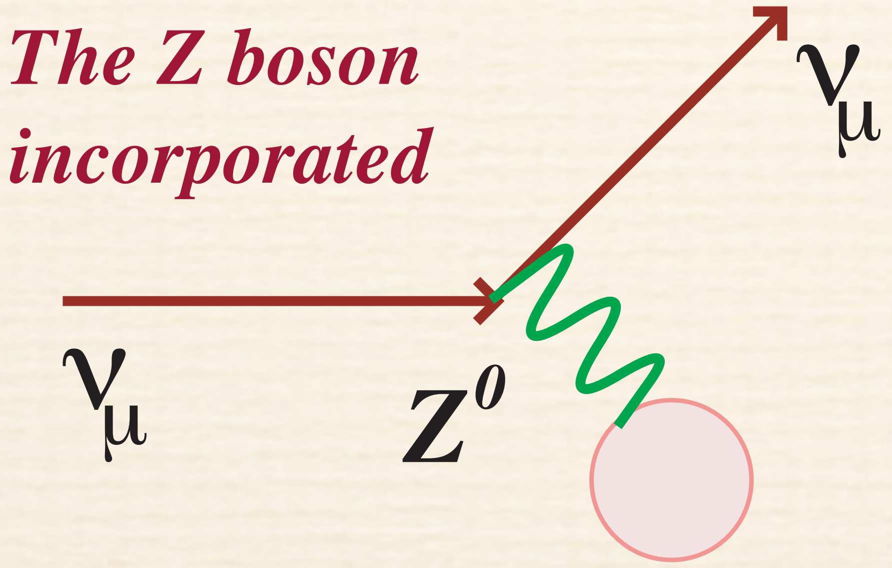
A Model of Leptons:
Steven Weinberg (1967)

The correct description of the neutral weak force



Charged Current

The Z boson incorporated



Neutral Current

First observed in the early 1970s

One free parameter: weak mixing angle θ_W

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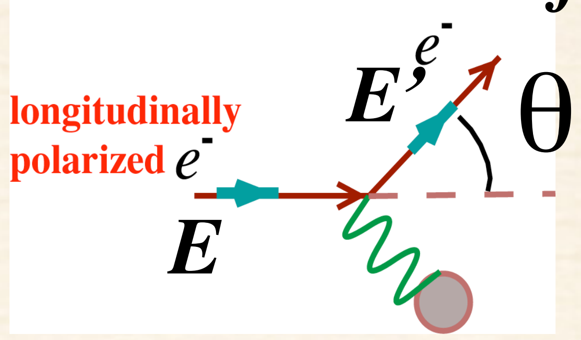

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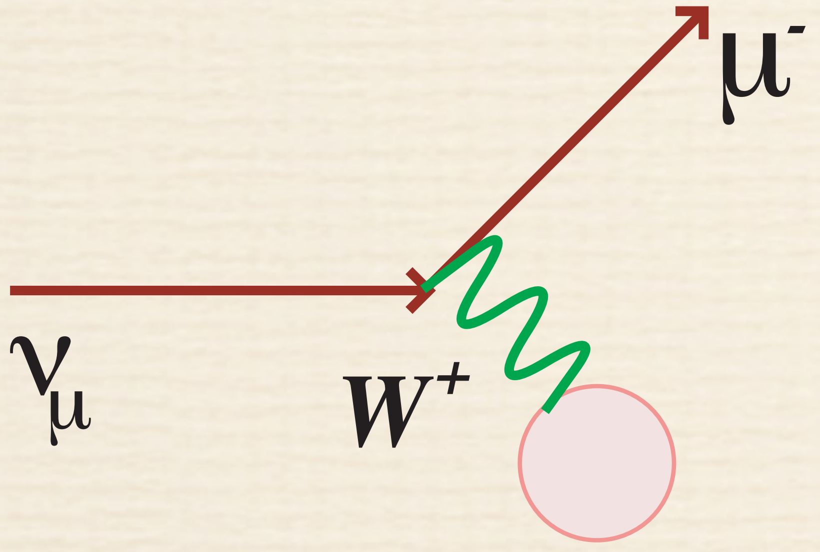

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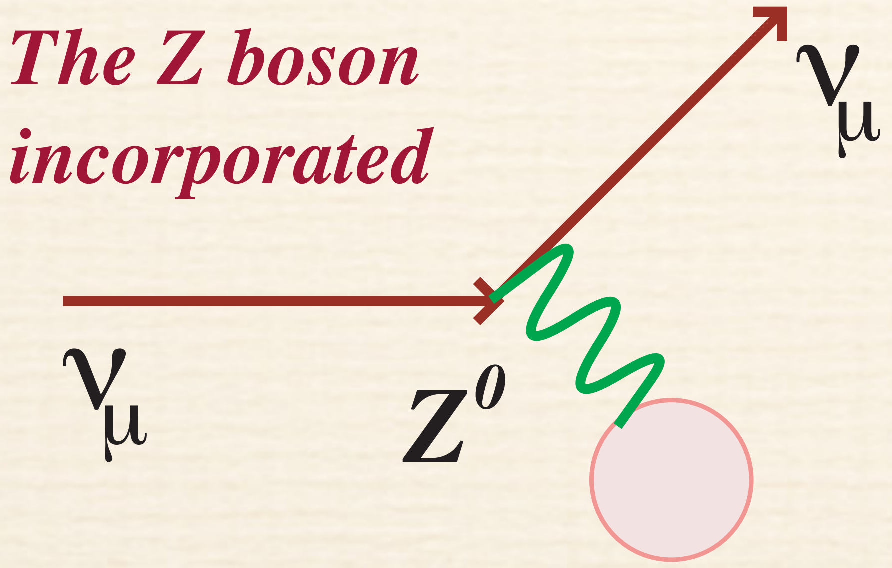

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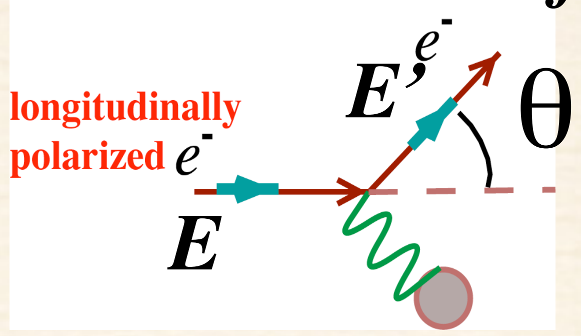

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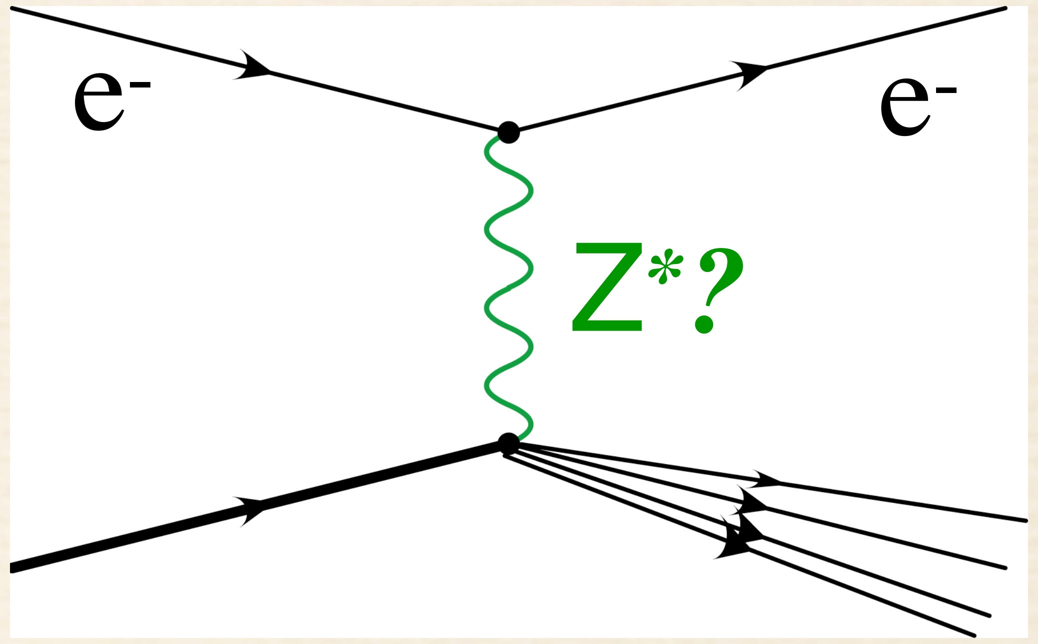

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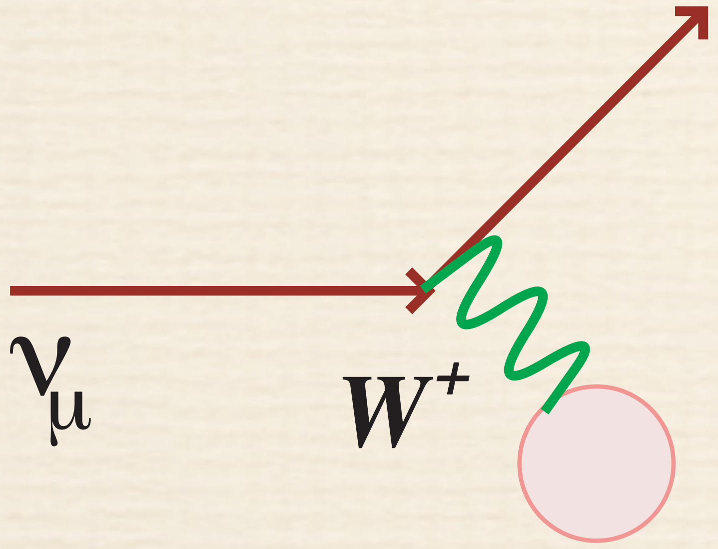

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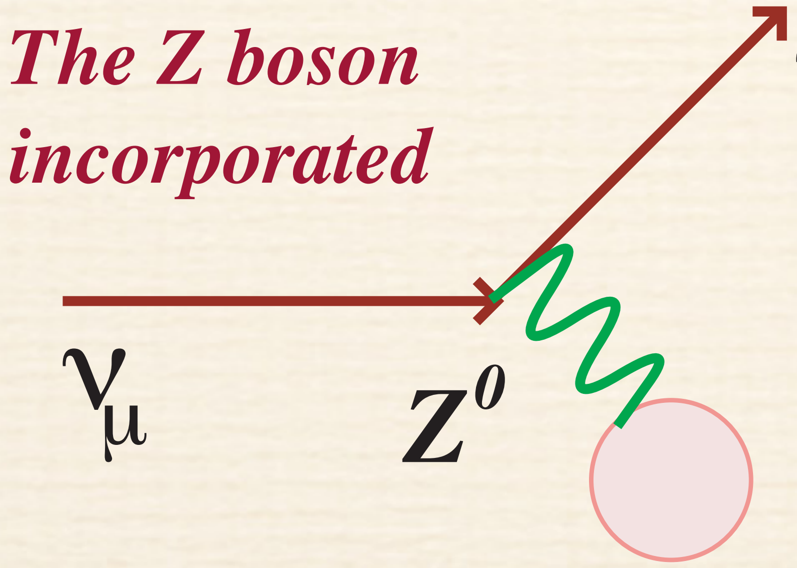

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Is parity violated in electron-nucleon scattering?

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

Weinberg model

Parity is violated

$$A_{PV} \sim 10^{-4}$$

or

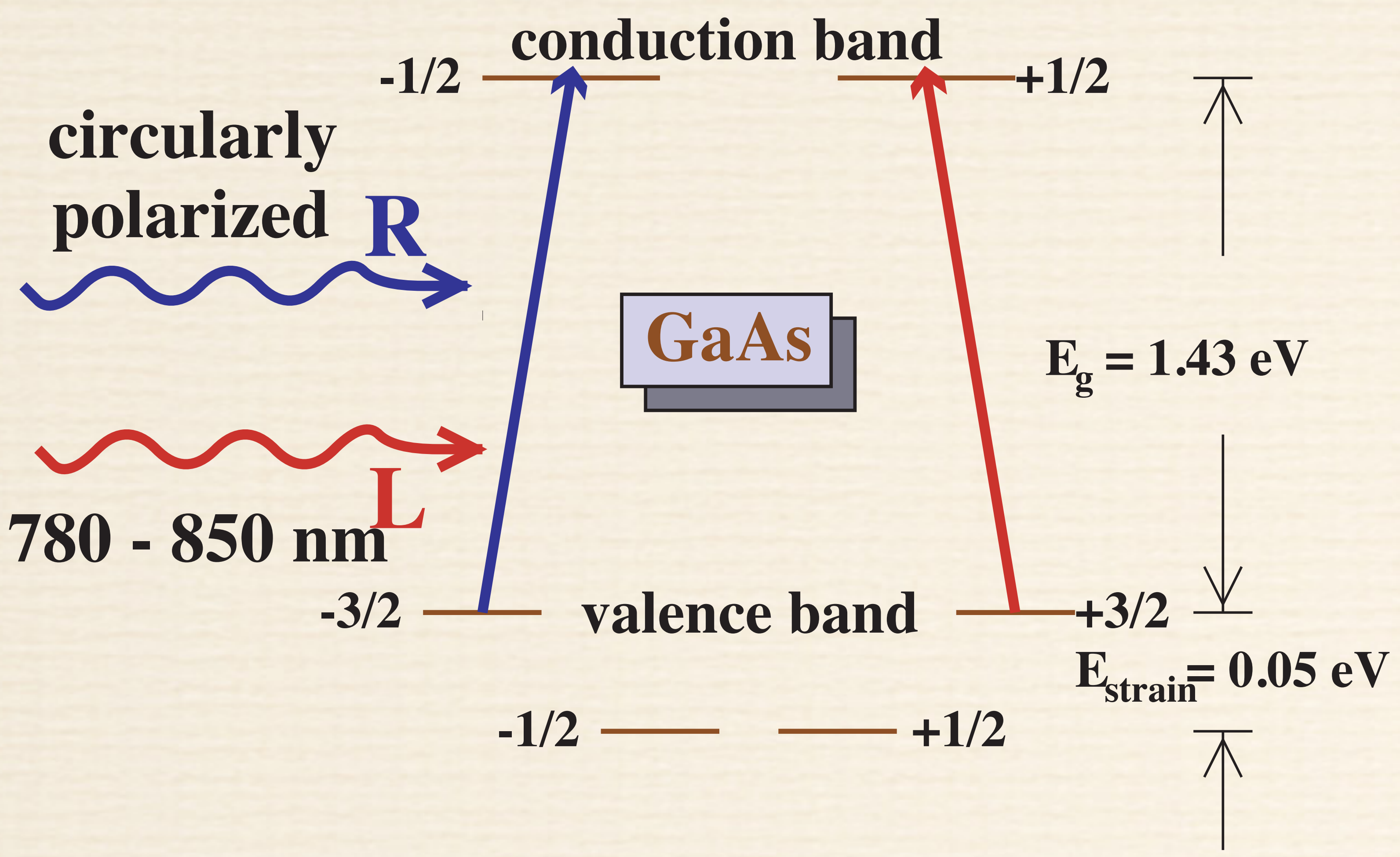
$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^0\\ e\end{pmatrix}_r$$

Parity is conserved

polarized electron-unpolarized deuteron deep inelastic scattering

SLAC E122

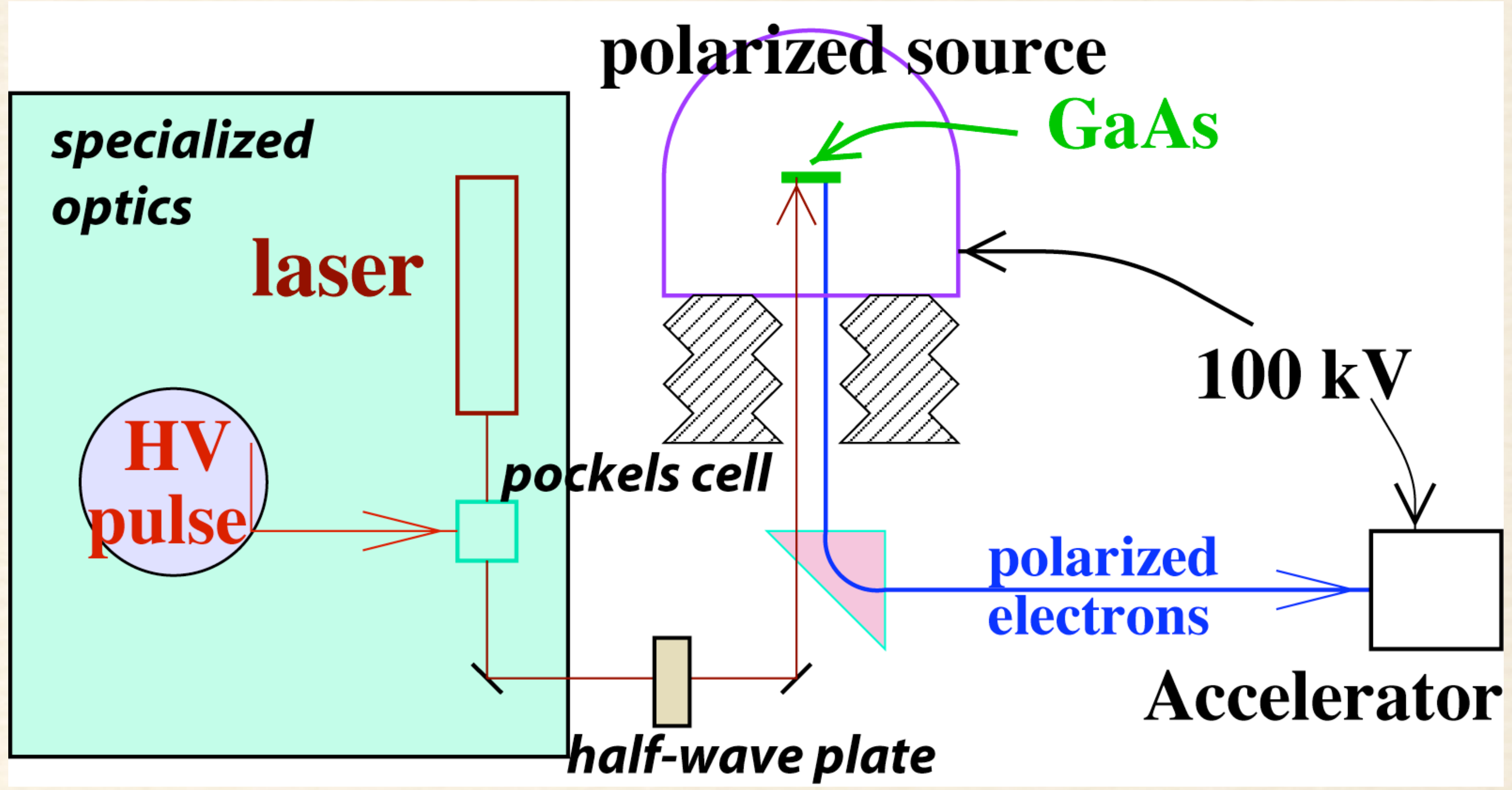
C.Y. Prescott et al, 1978



need more than 10^{10} events

$$A_{PV} \sim 10^{-4}$$

$$\delta(A_{PV}) \sim 10^{-5}$$



polarized electron-unpolarized deuteron deep inelastic scattering

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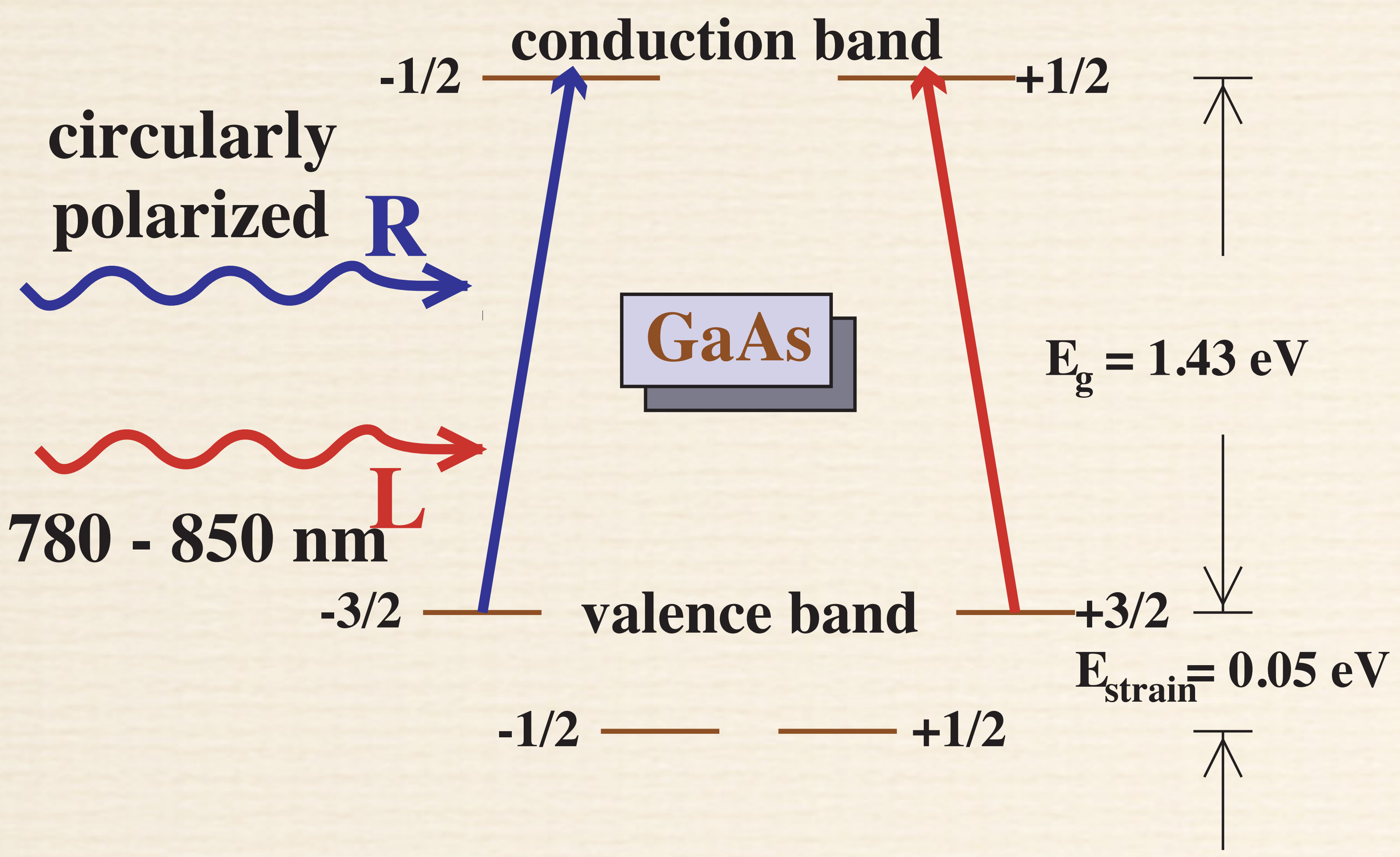

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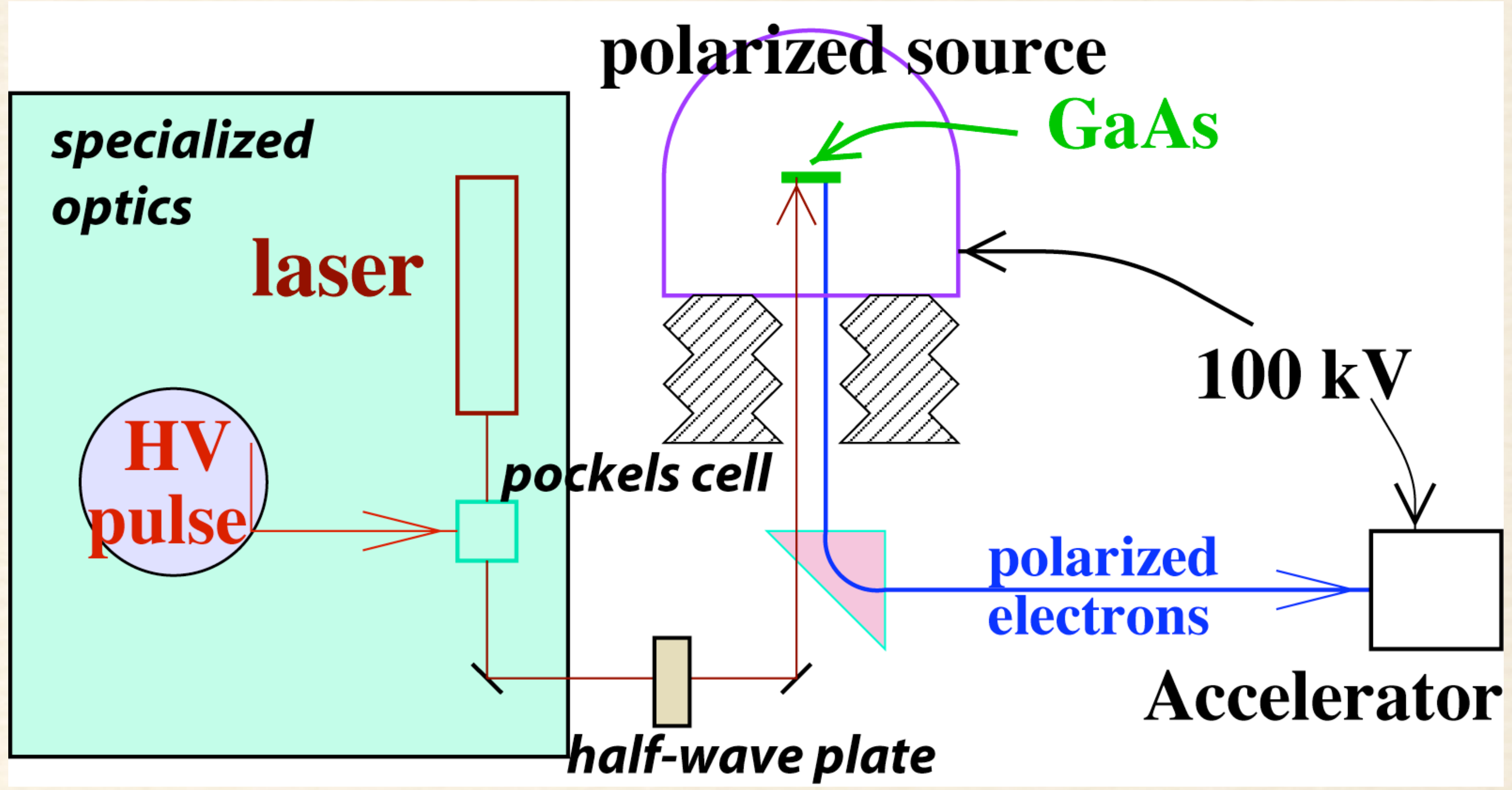

- Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency
- Rapid helicity reversal: polarization sign flips ~ 100 Hz to minimize the impact of drifts
- Helicity-correlated beam motion: under sign flip, beam stability at the micron level

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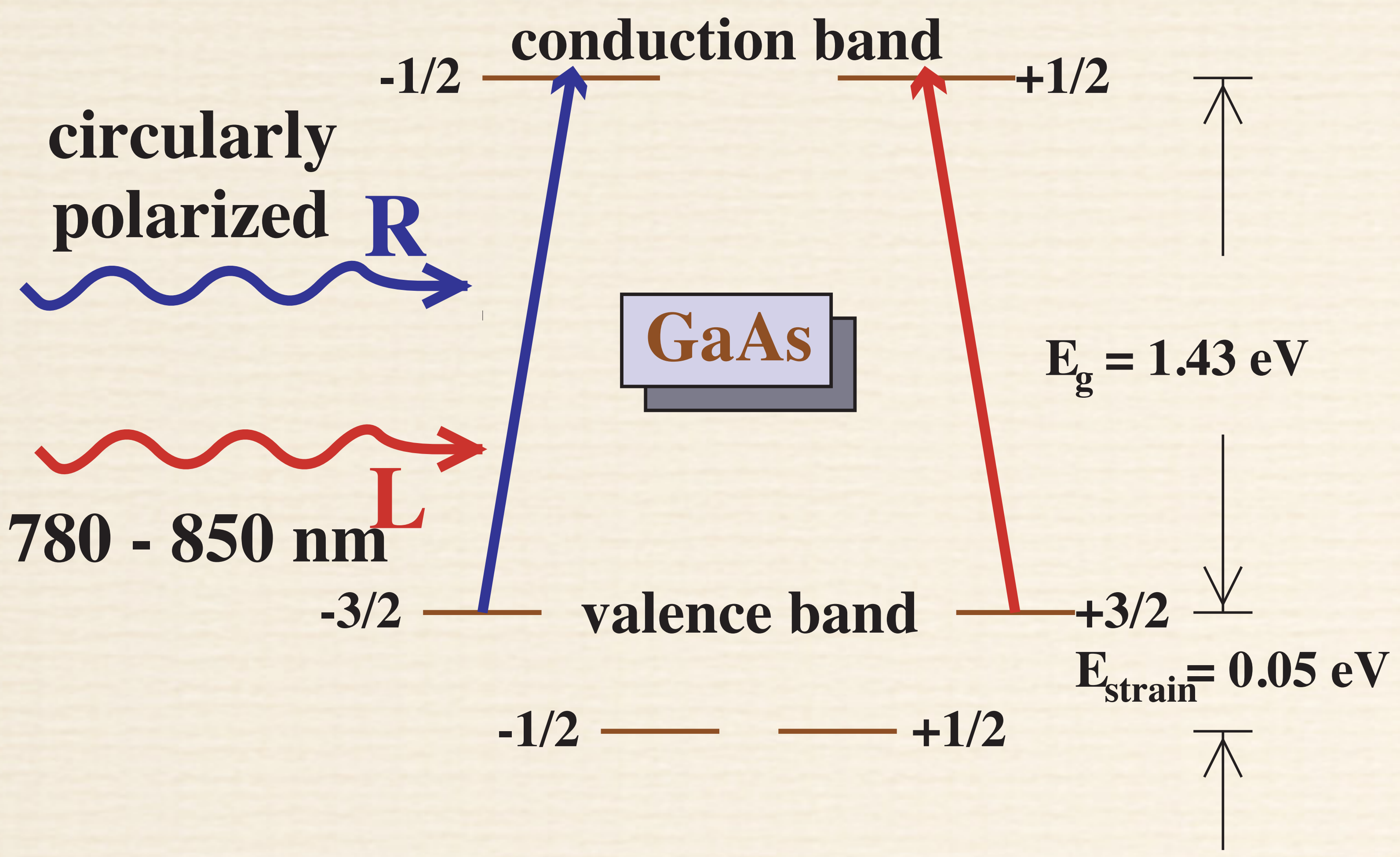

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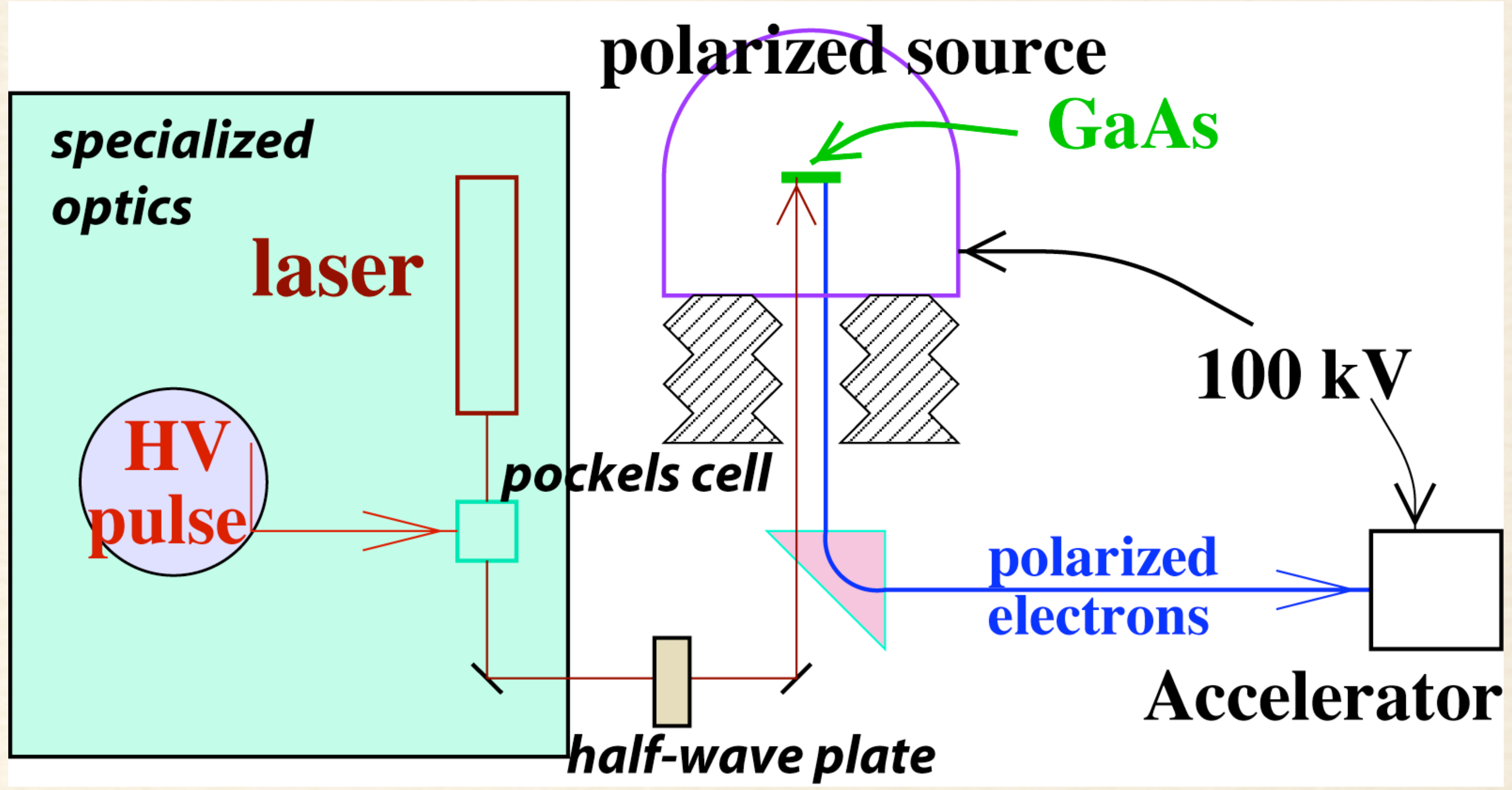

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- *helped established the Standard Model (SM) of electroweak & strong interactions*

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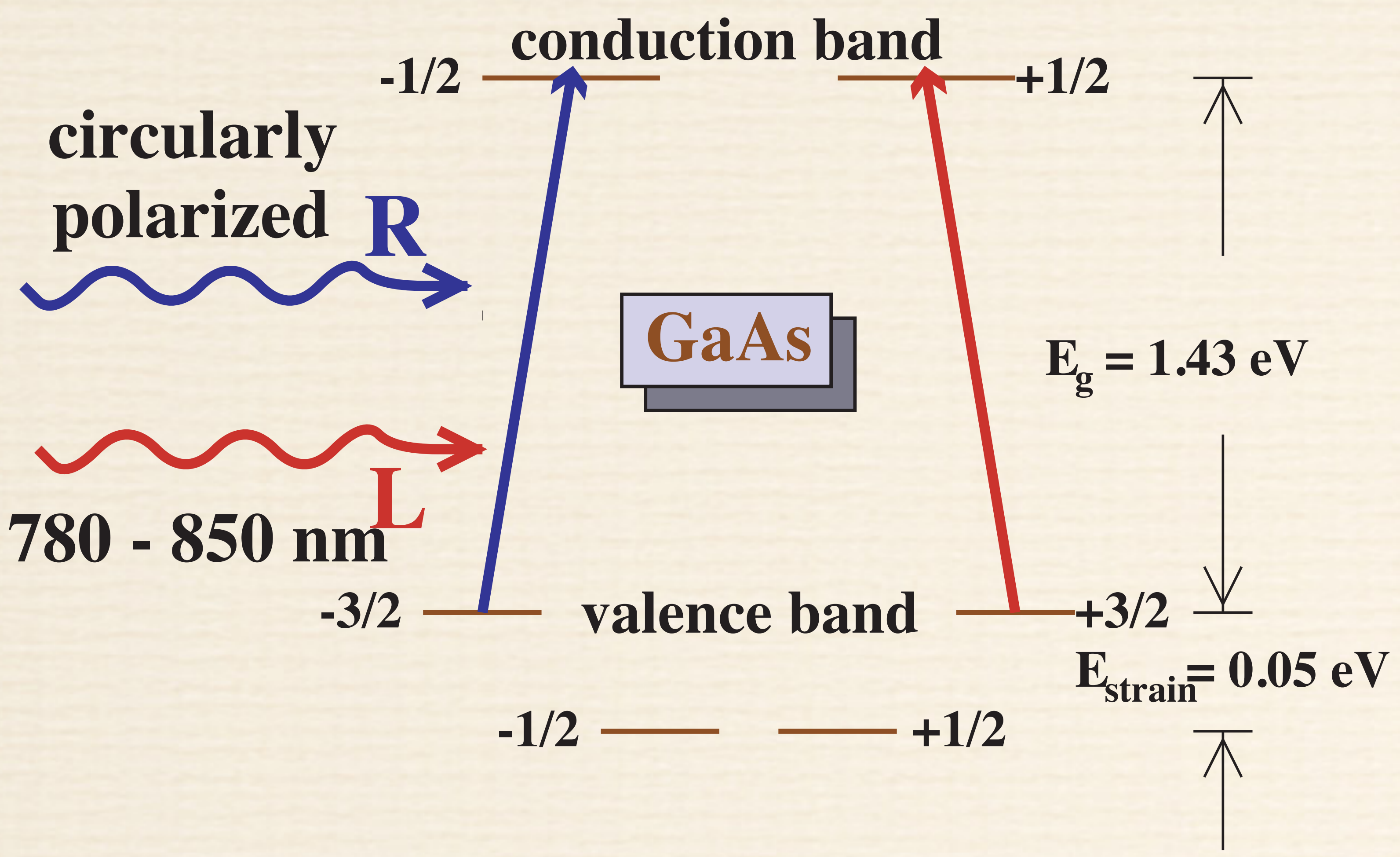
Glashow, Weinberg, Salam Nobel Prize awarded in 1979



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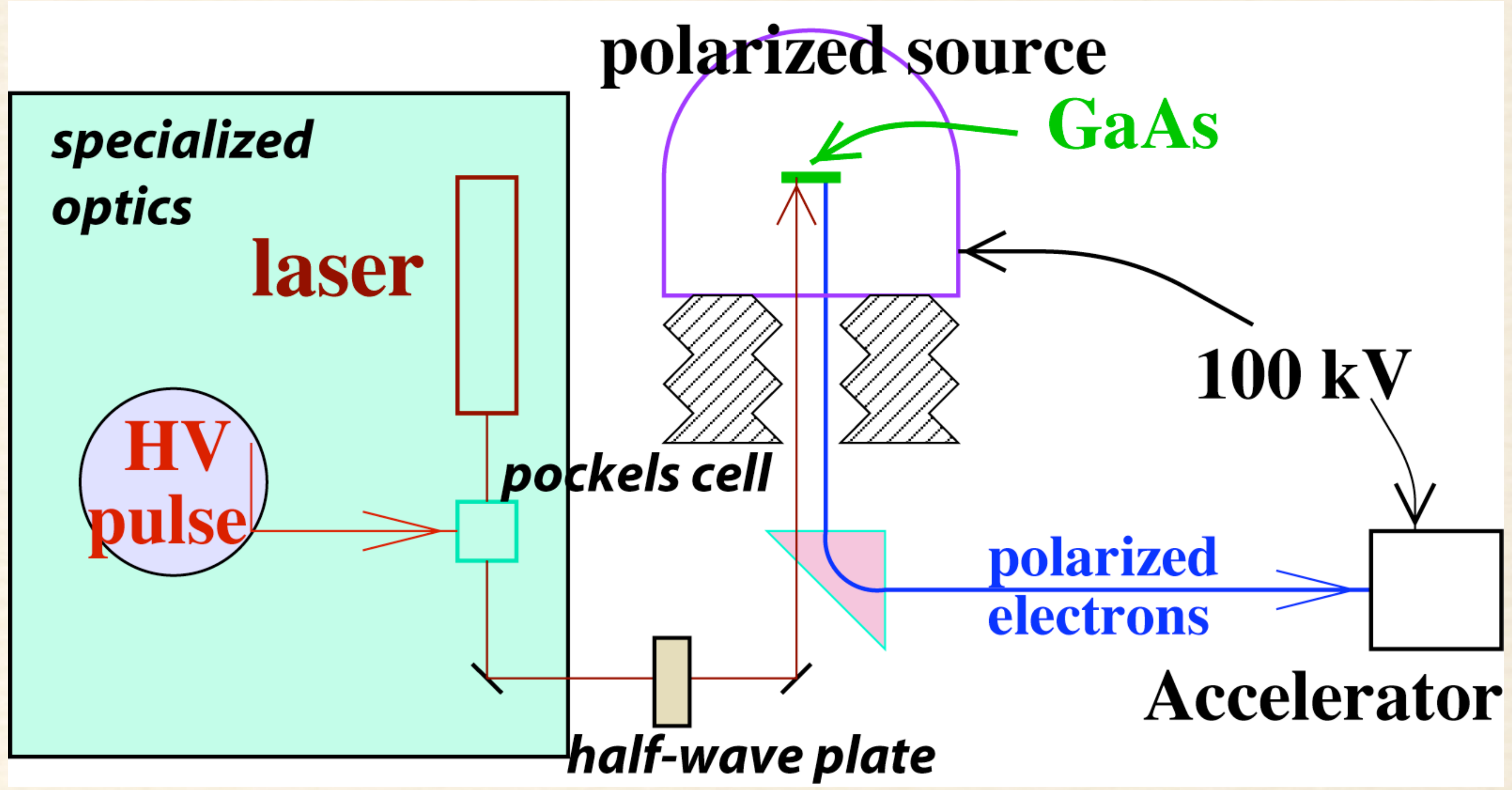

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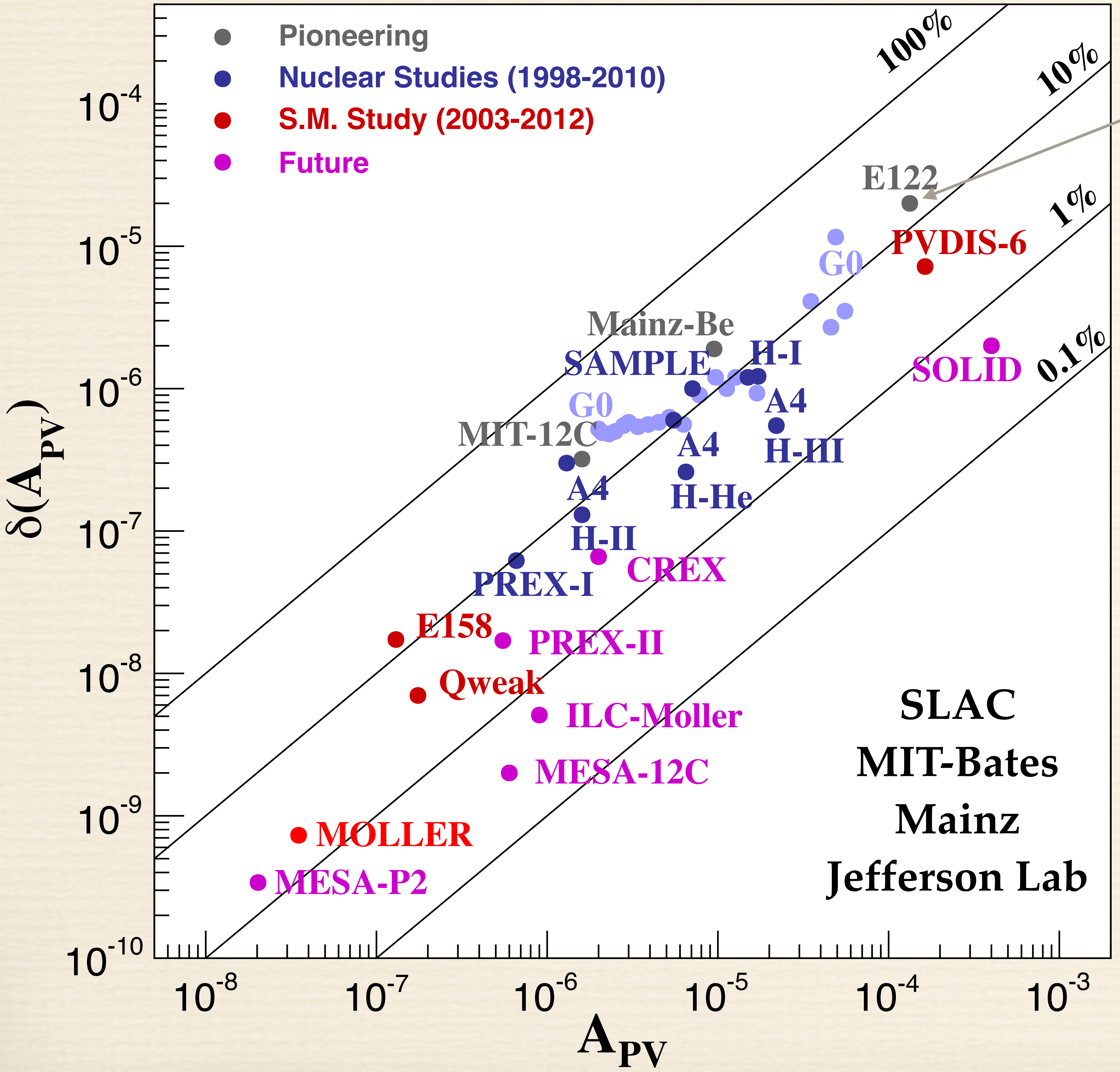
4 Decades of Progress

Parity-violating electron scattering has become a precision tool

PVeS Experiment Summary



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

Continuous interplay between probing hadron structure and electroweak physics

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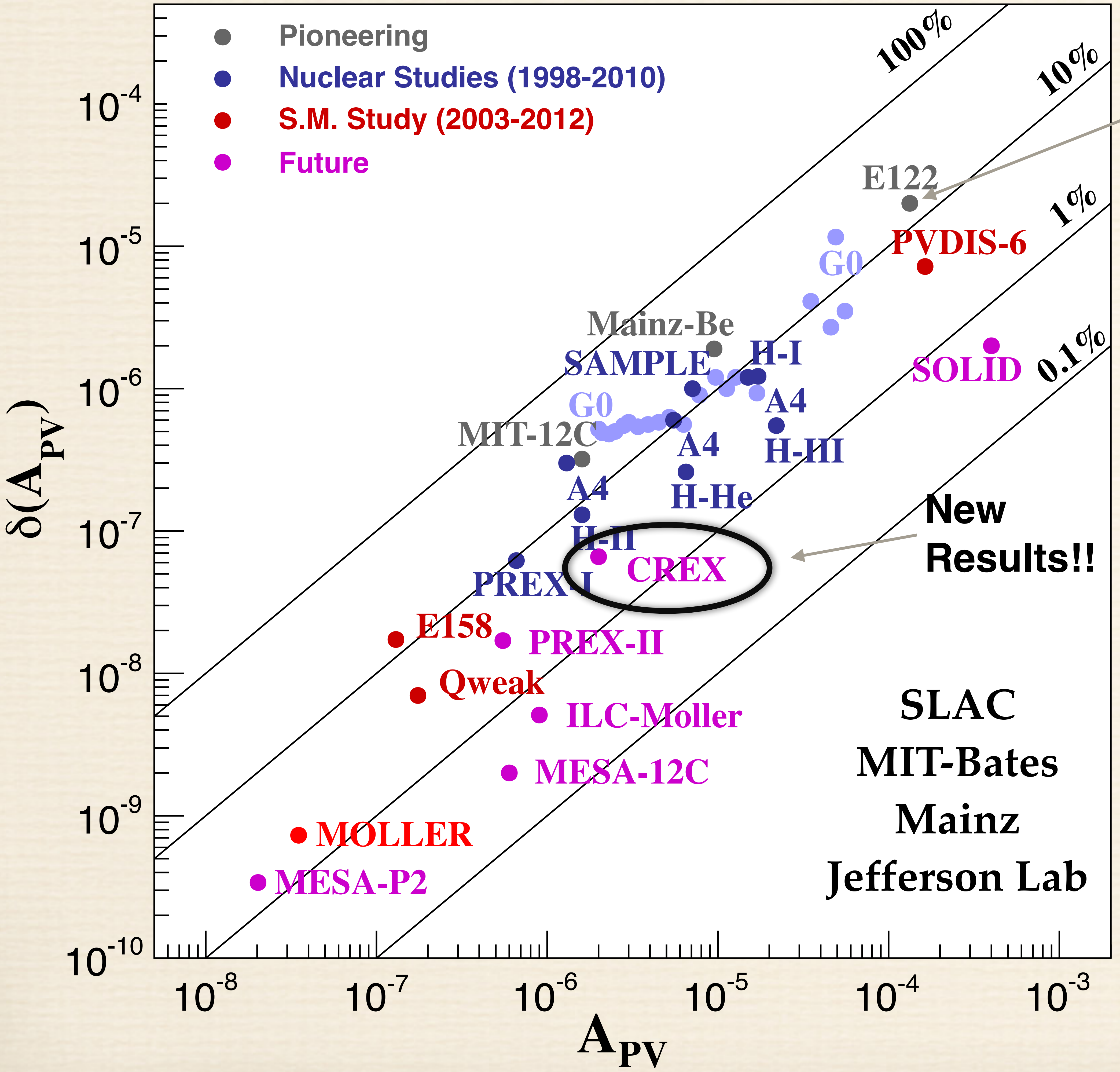

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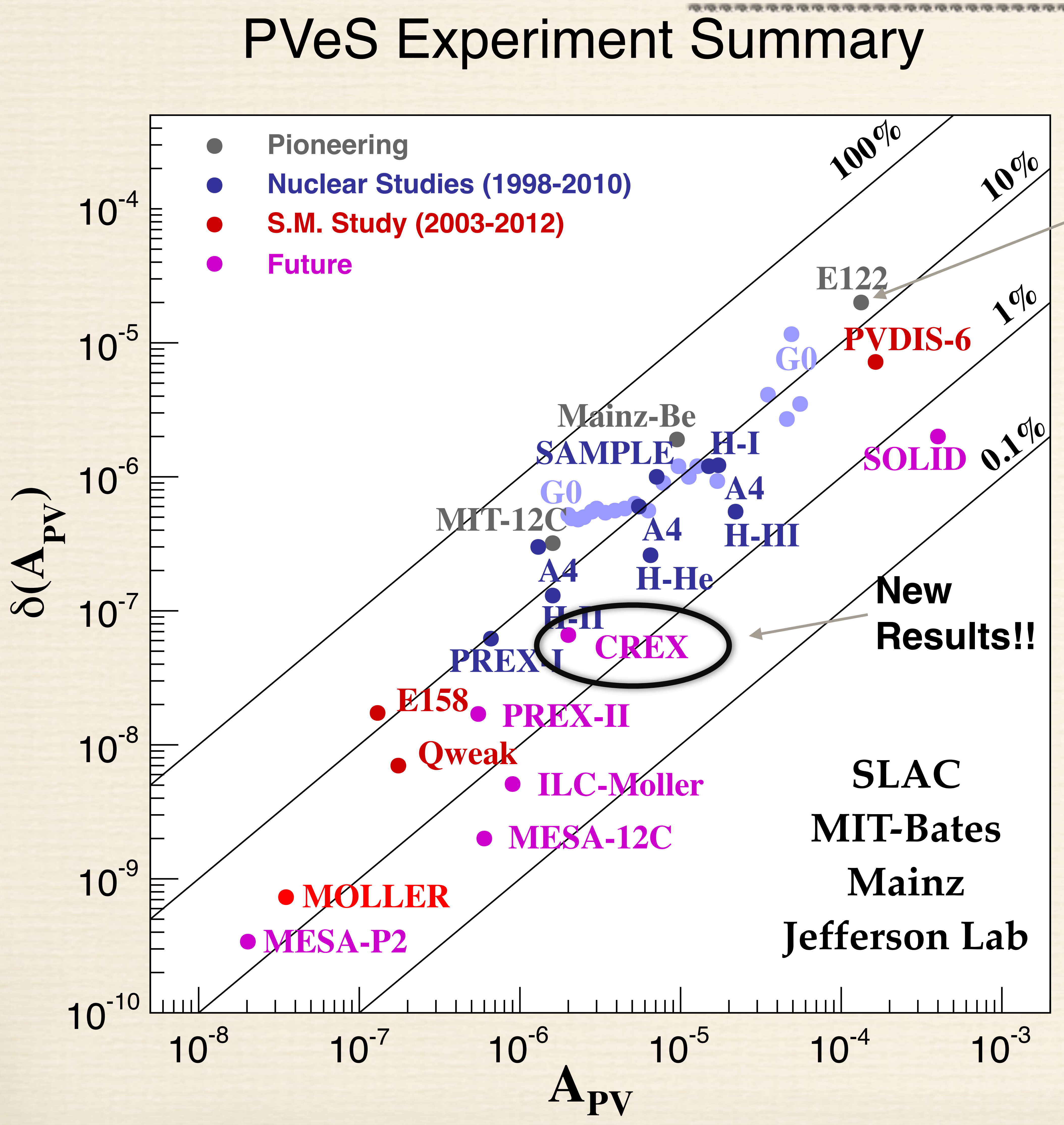

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New Results!!

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Physics Topics

- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*
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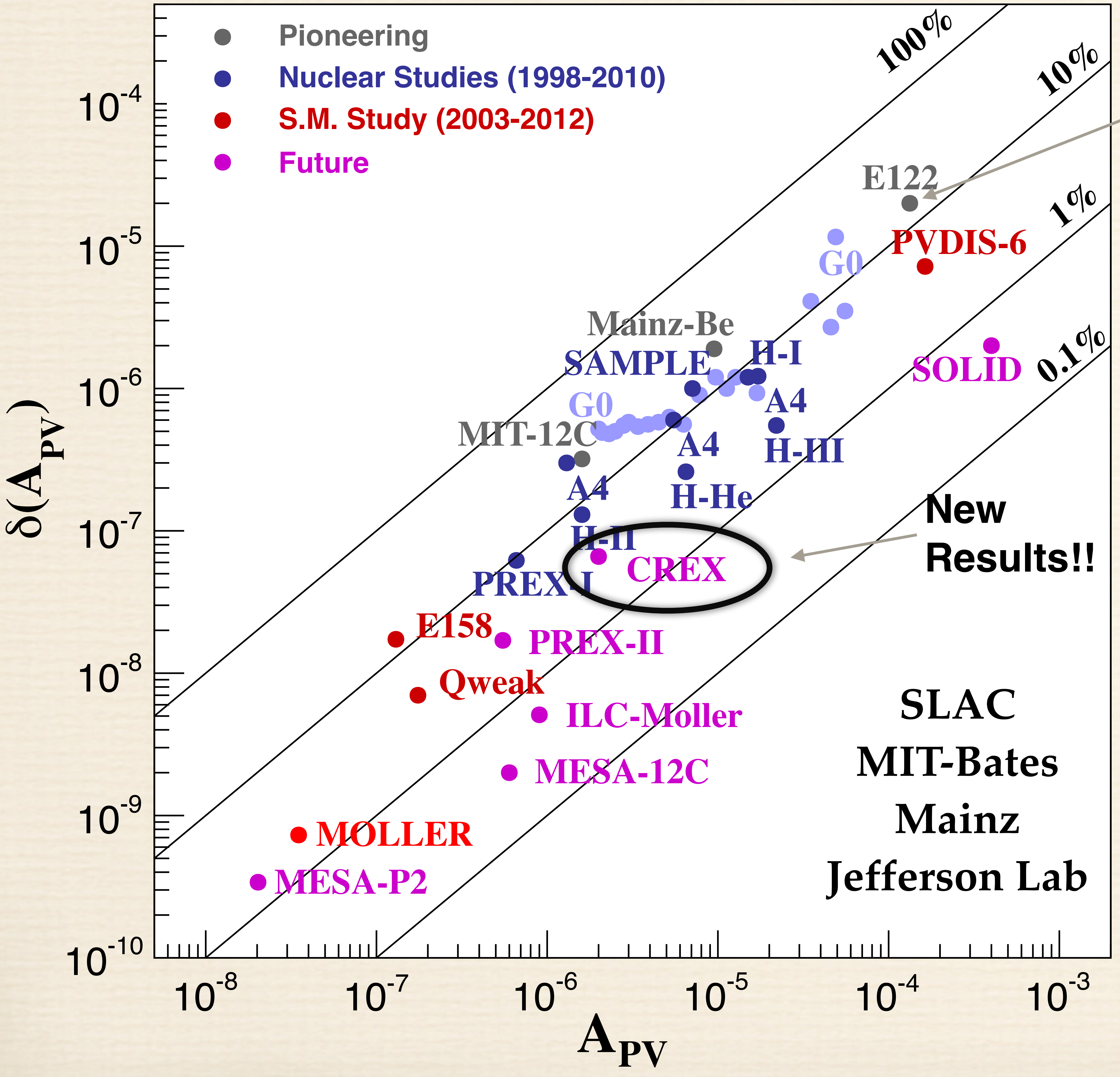

Pioneering electron-quark PV DIS experiment SLAC E122

photocathodes, polarimetry, high power cryotargets, novel spectrometer concepts, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

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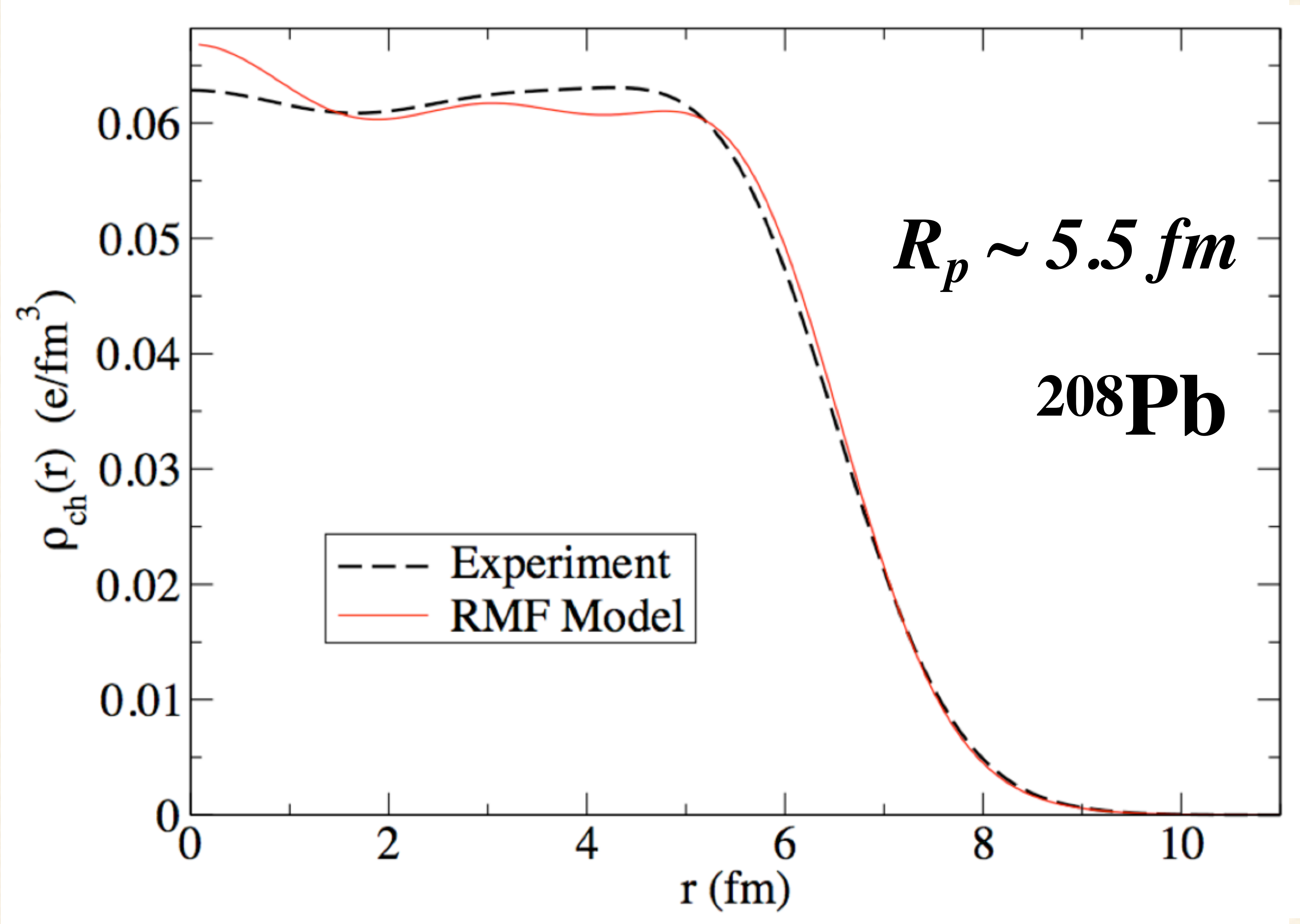
Neutron Skin of a Heavy Nucleus

EM Charge vs Weak Charge Density



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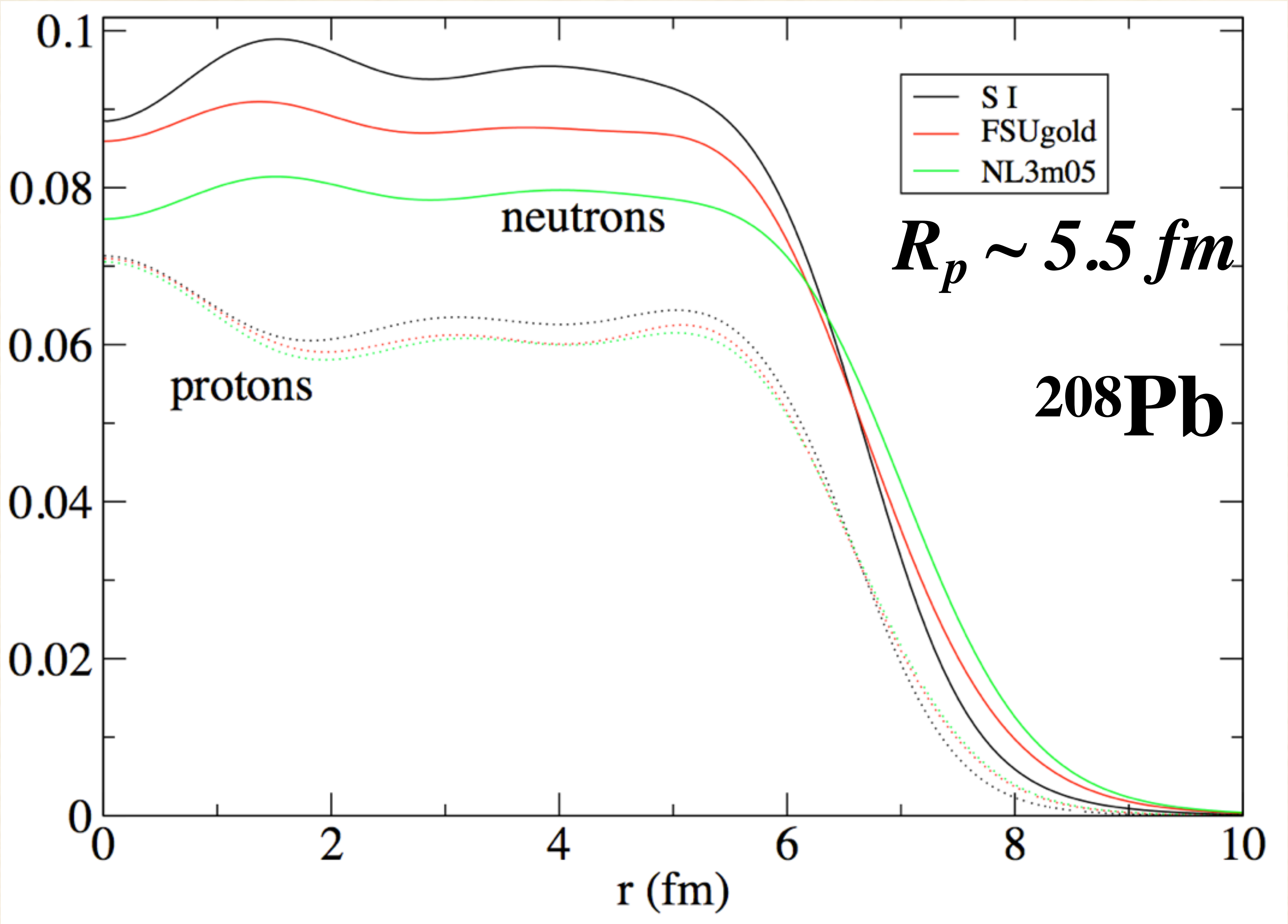

neutrons expected to occupy a larger volume

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim 1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

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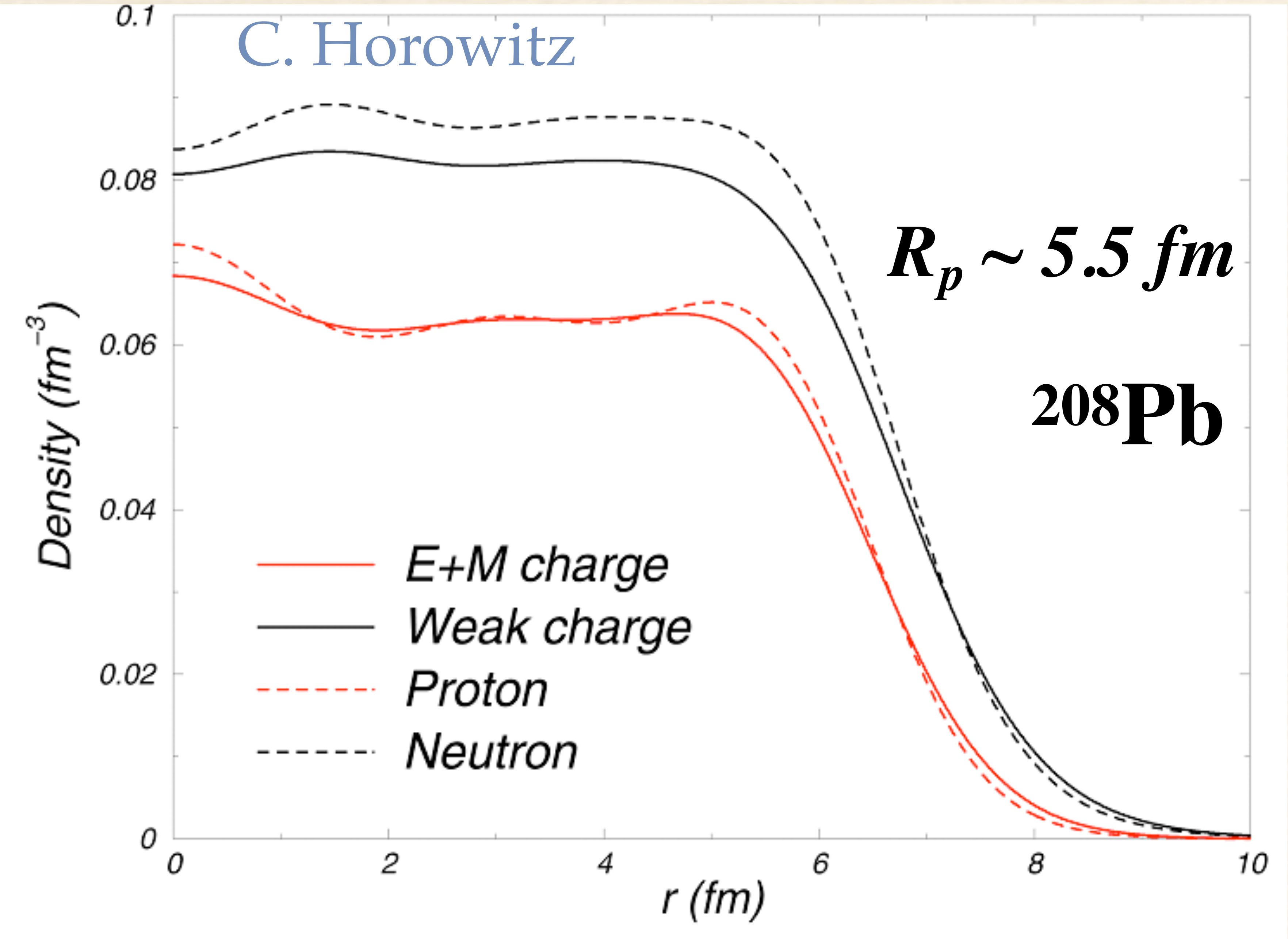

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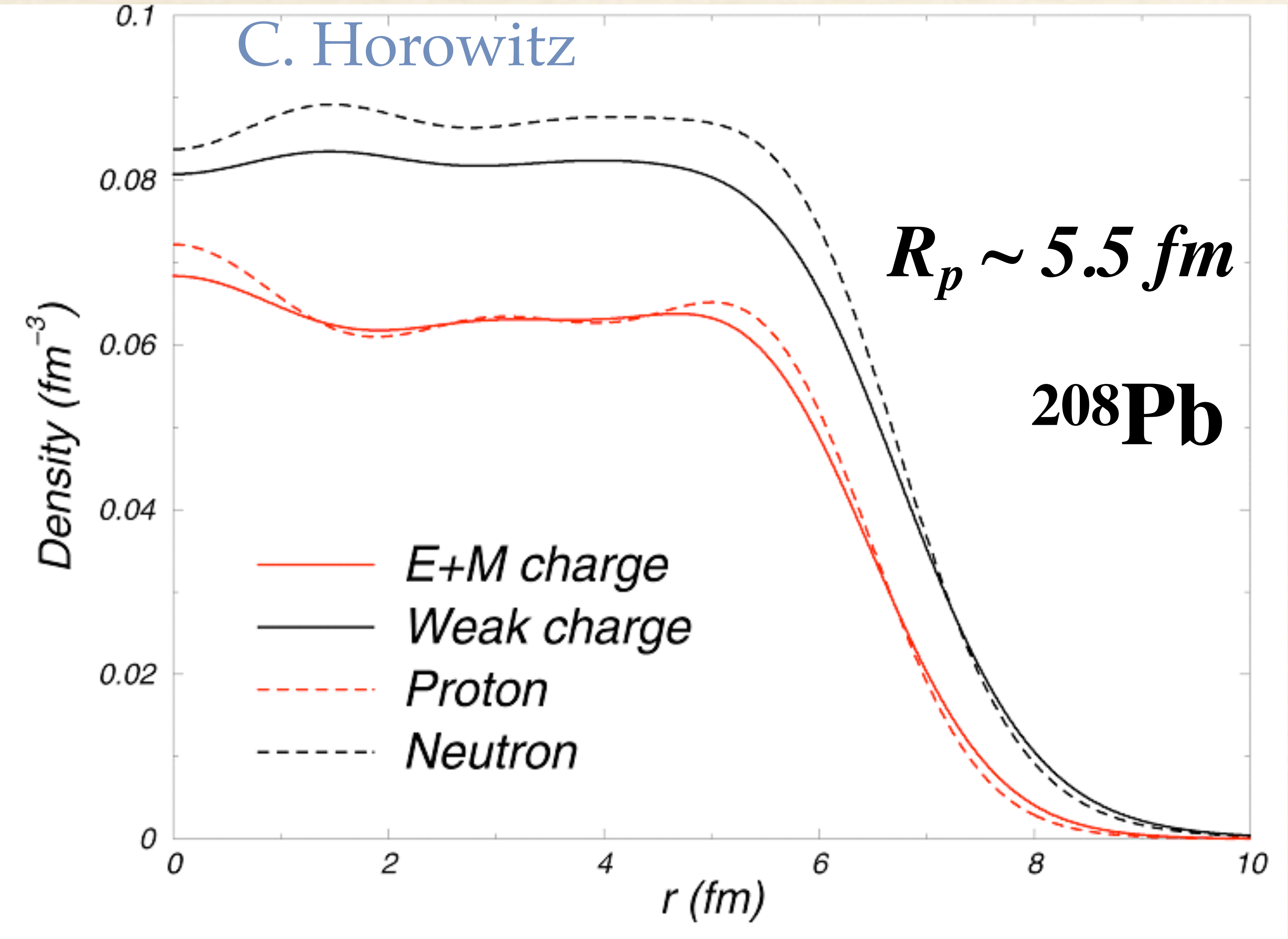

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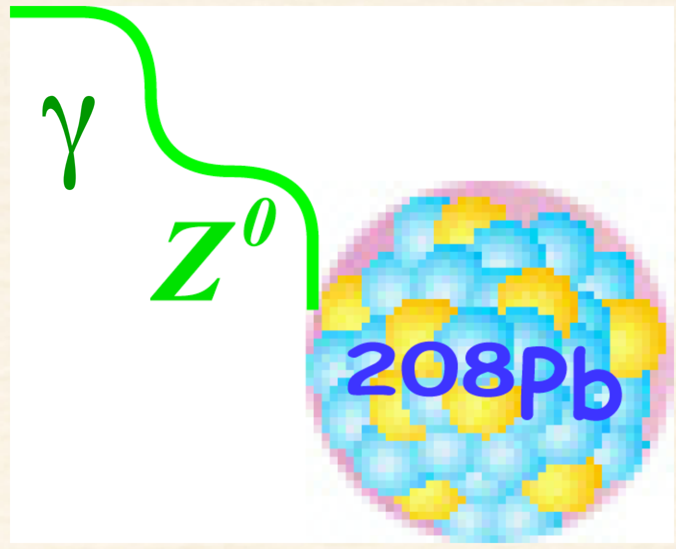

	proton	neutron
Electric (γ) charge	1	0
Weak (Z^0) charge	-0.08	1

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

parity-violating electron scattering can directly constrain the RMS radius r_n of a heavy spinless nucleus

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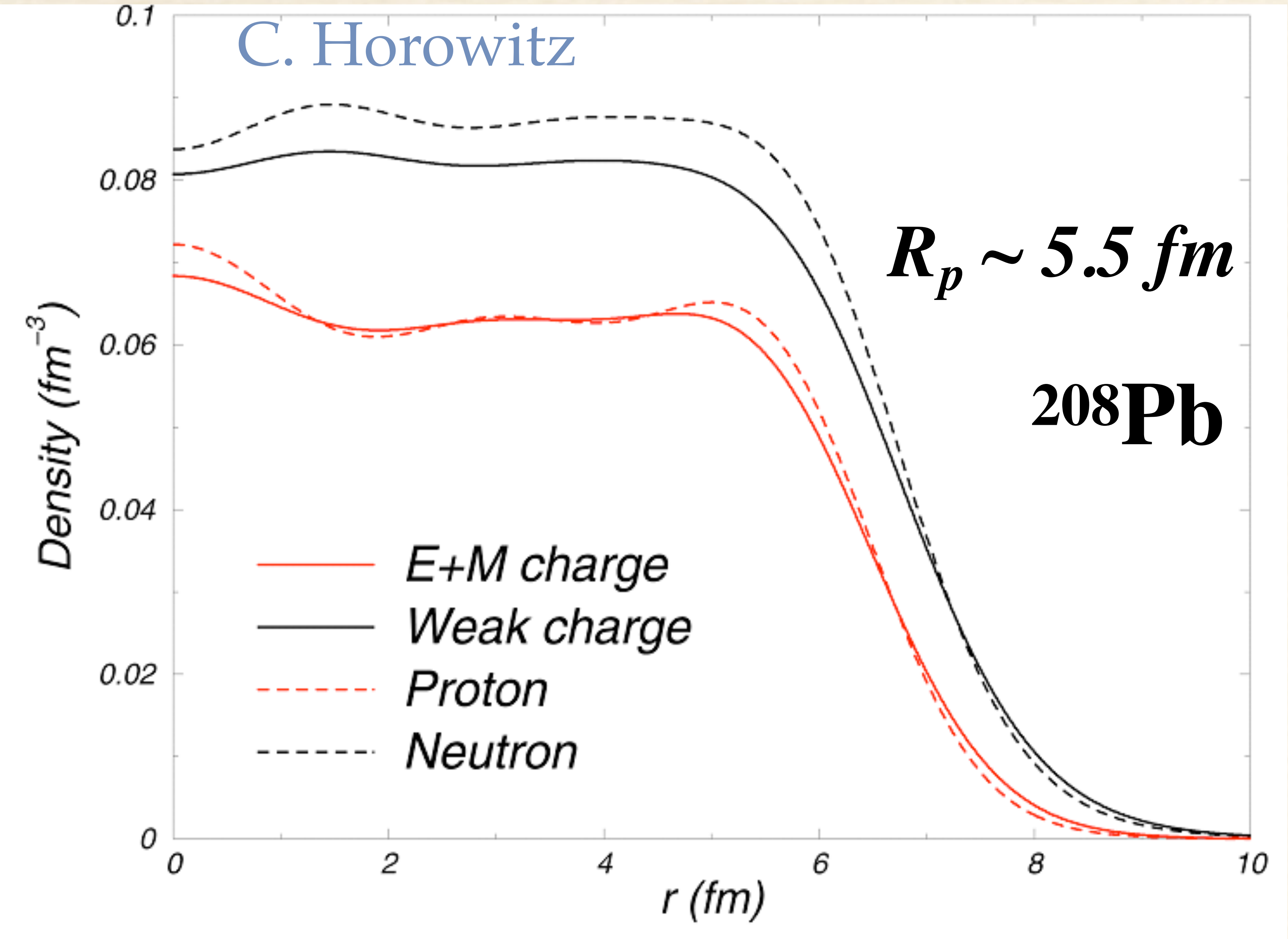

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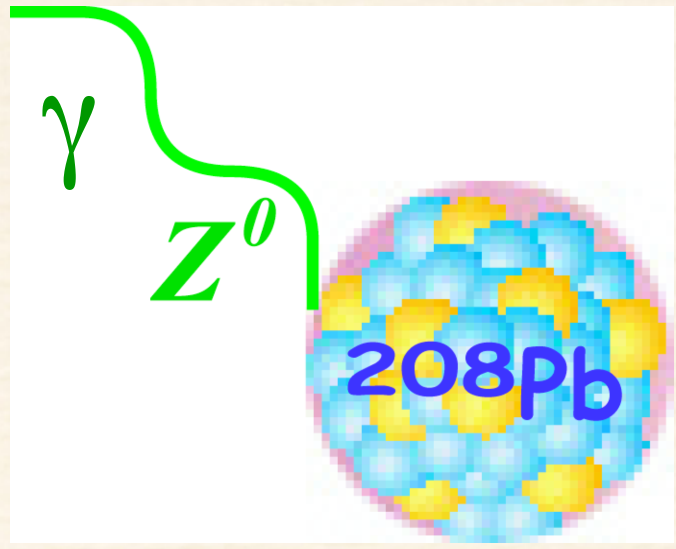

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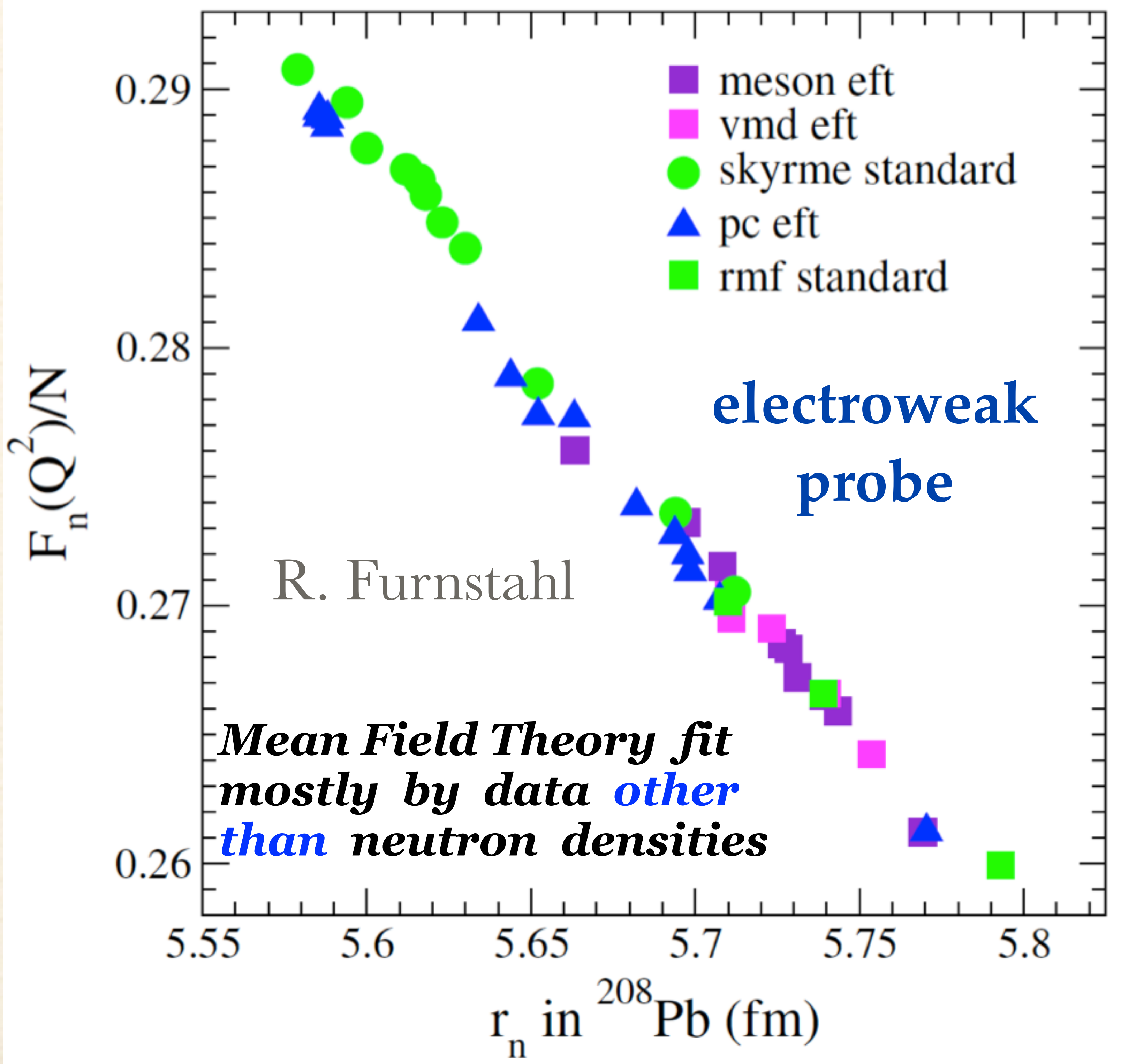

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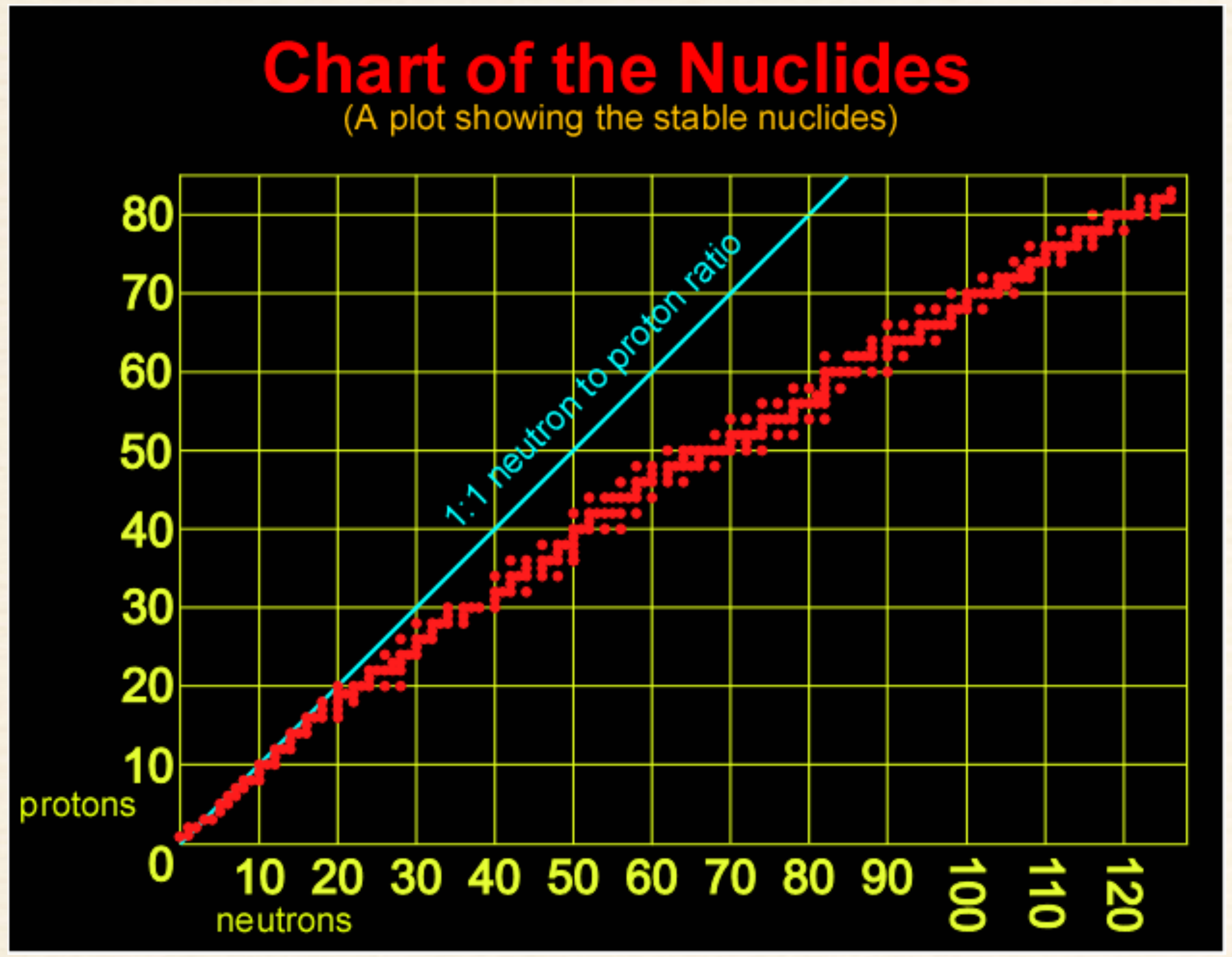
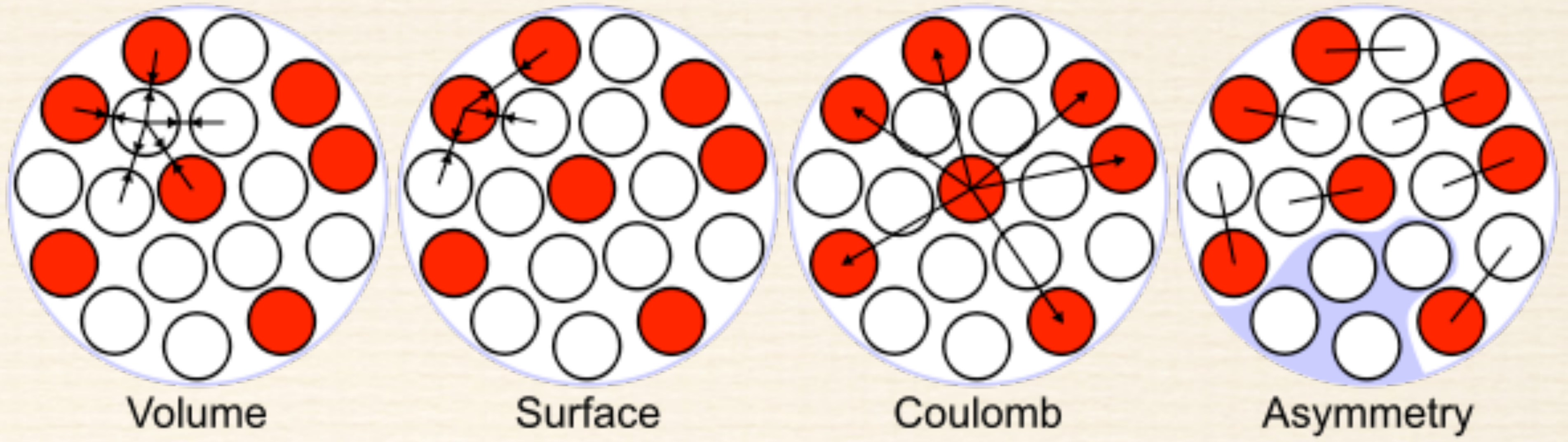
Neutron Distribution in a Nucleus

What is the physics? .....And why is it interesting?





pressure pushes against surface tension

Symmetry Energy

Equation of state (EOS) of dense nuclear matter

$$E(\rho, \delta) = E_0(\rho, \delta = 0) + S(\rho)\delta^2$$

$$\delta = \frac{(\rho_n - \rho_p)}{\rho}$$

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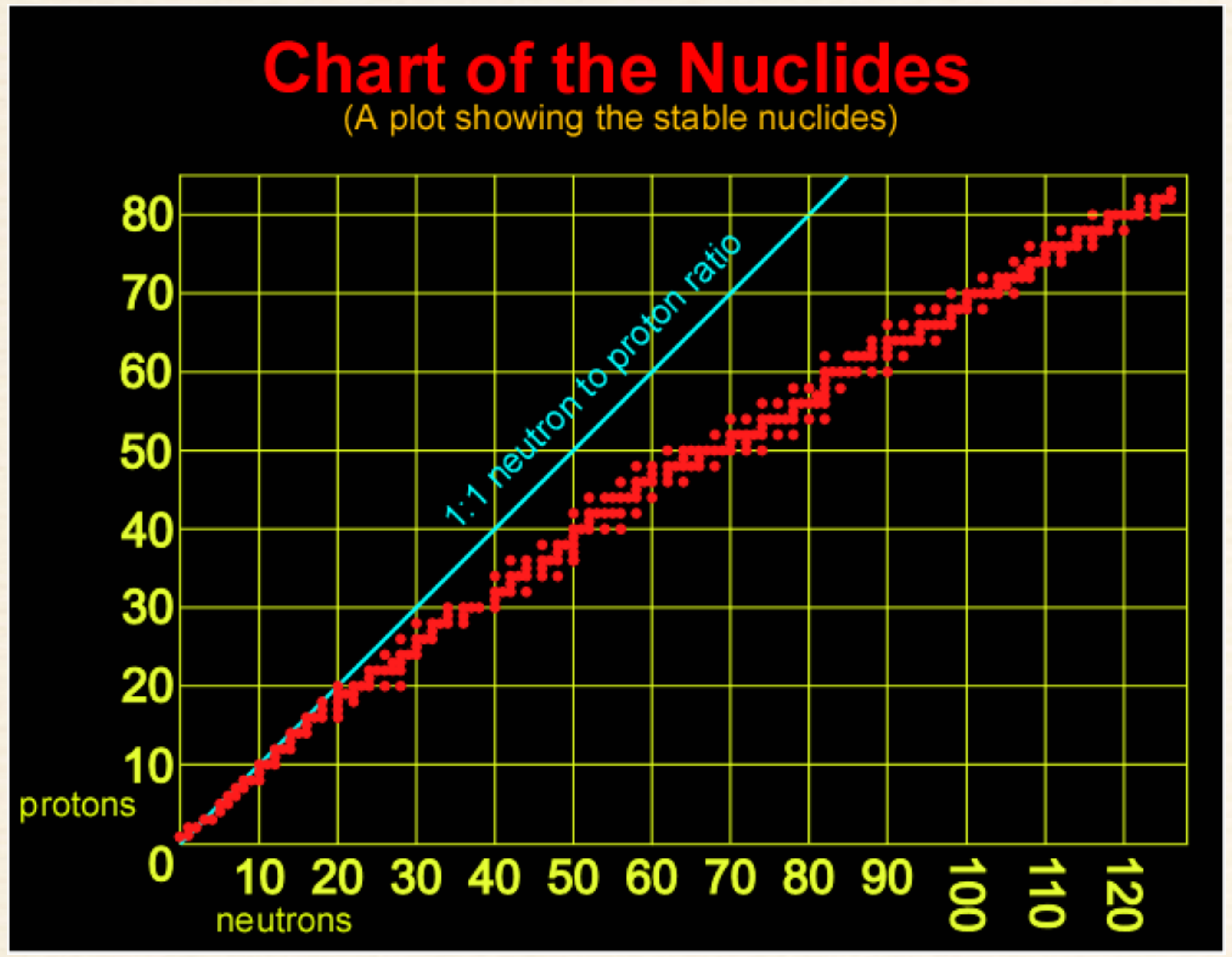

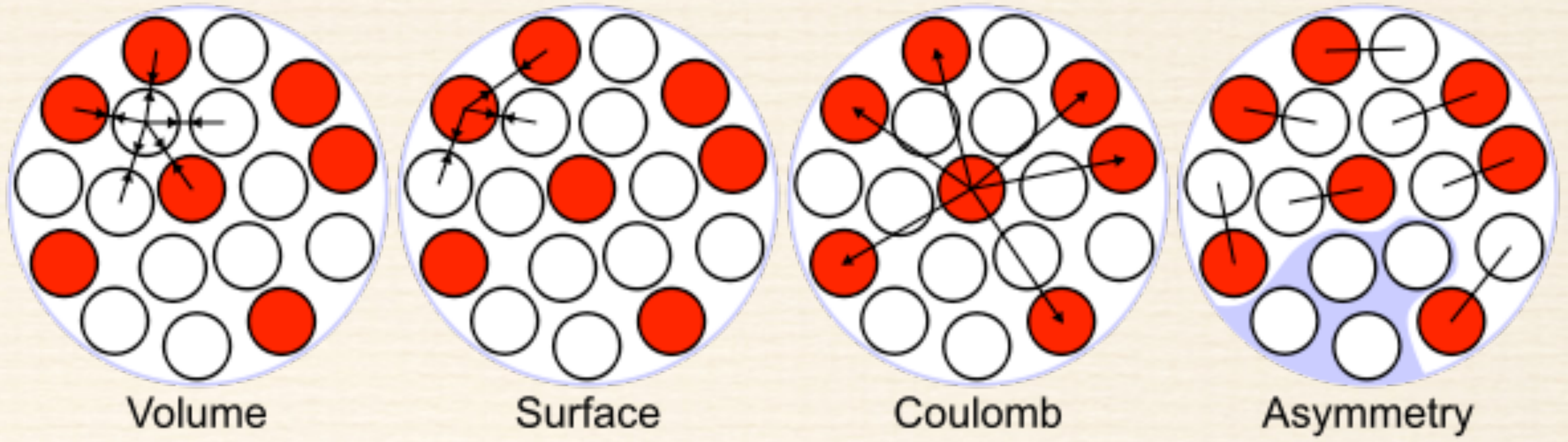

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  - Antiprotonic Atoms

Involve model dependence and strong force uncertainties

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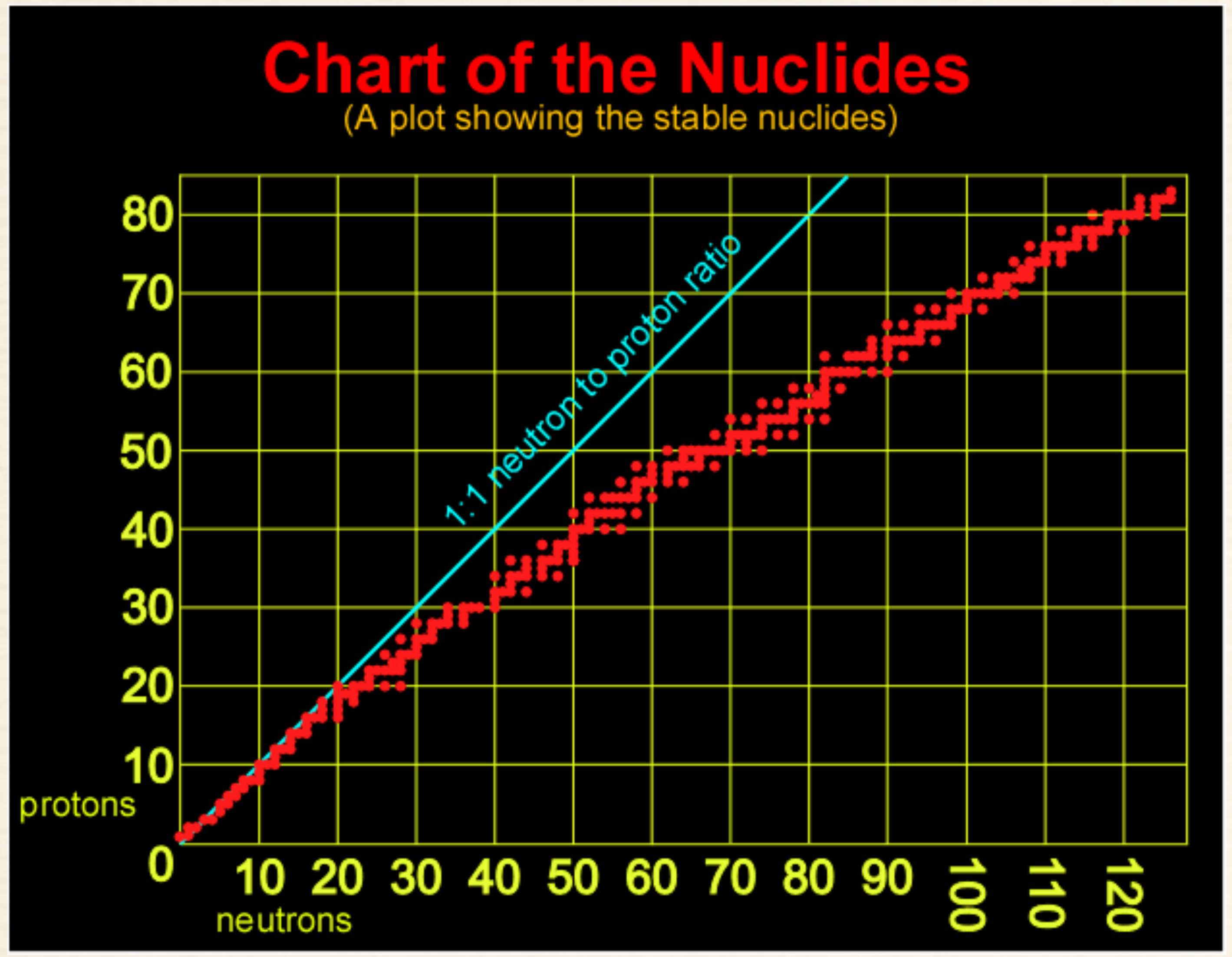

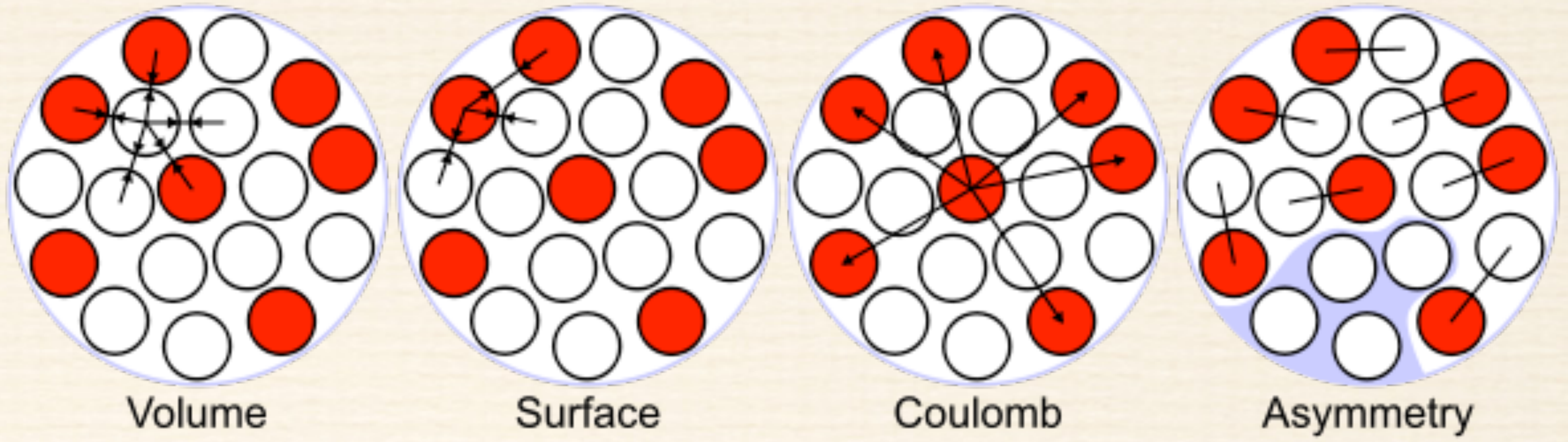

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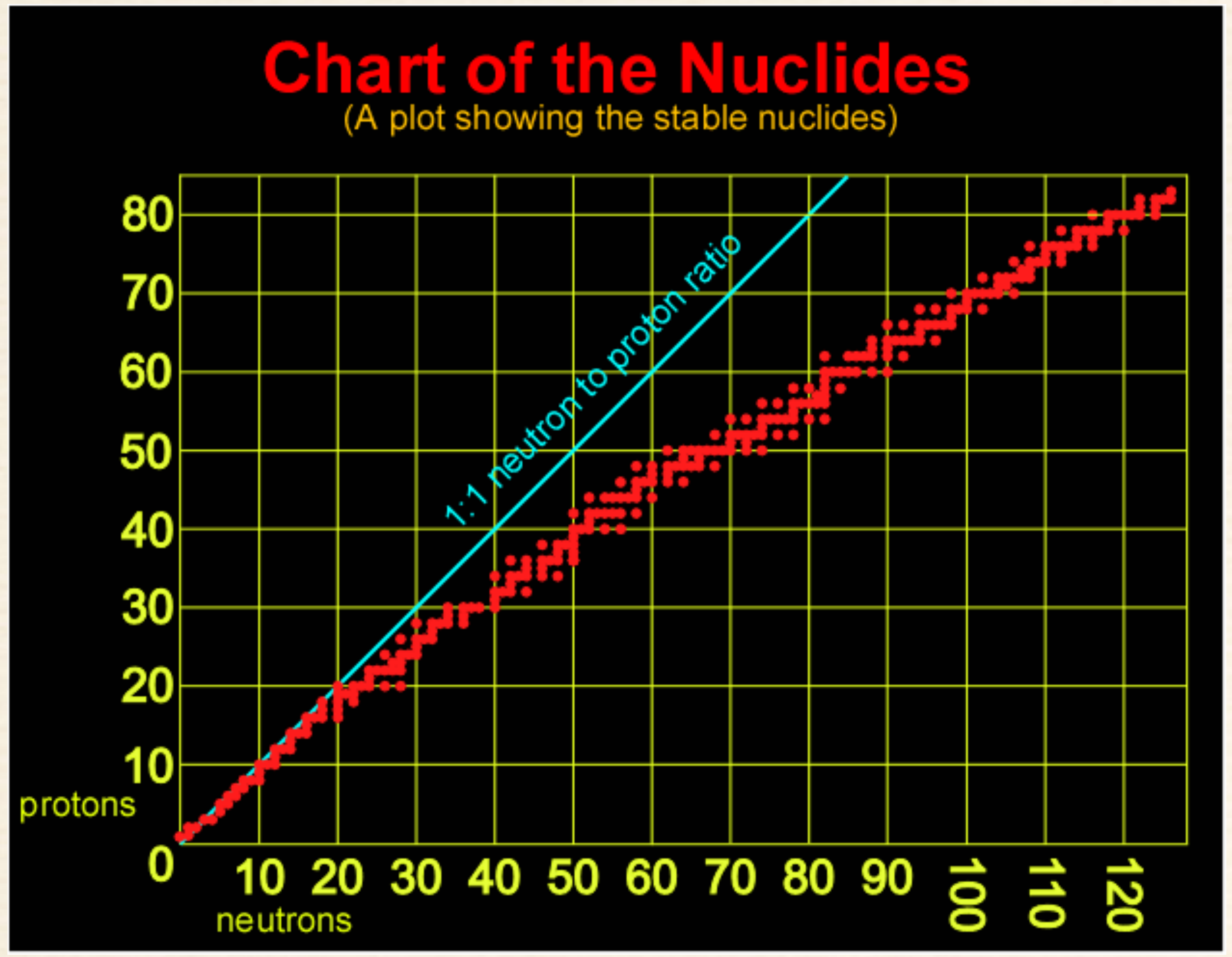

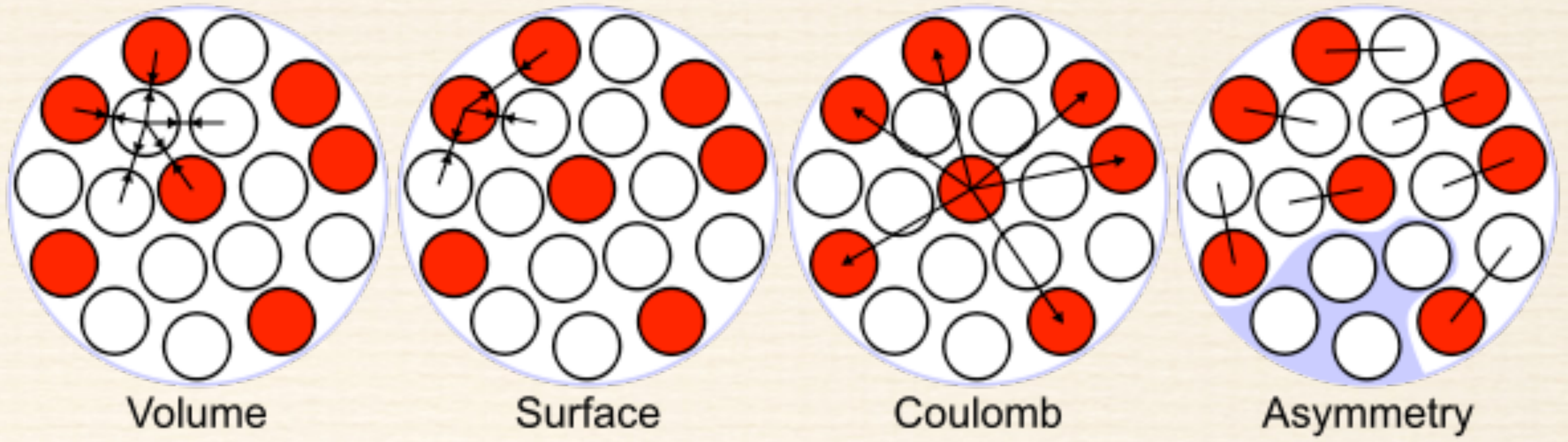

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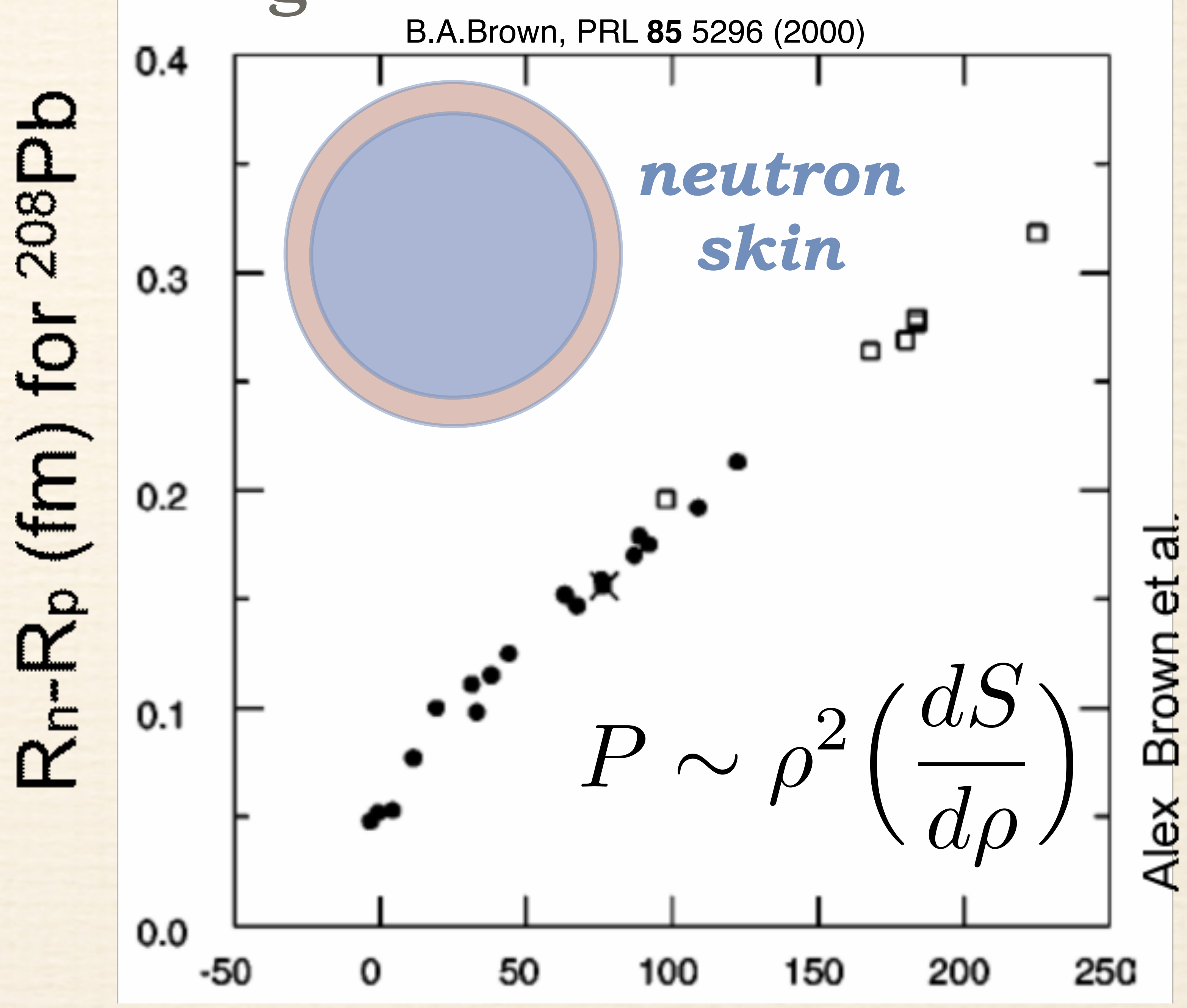

Neutron matter P (MeV/fm^3)
x100 at a density of 0.1 fm^{-3}.

size of neutron "skin" measures density dependence of symmetry energy

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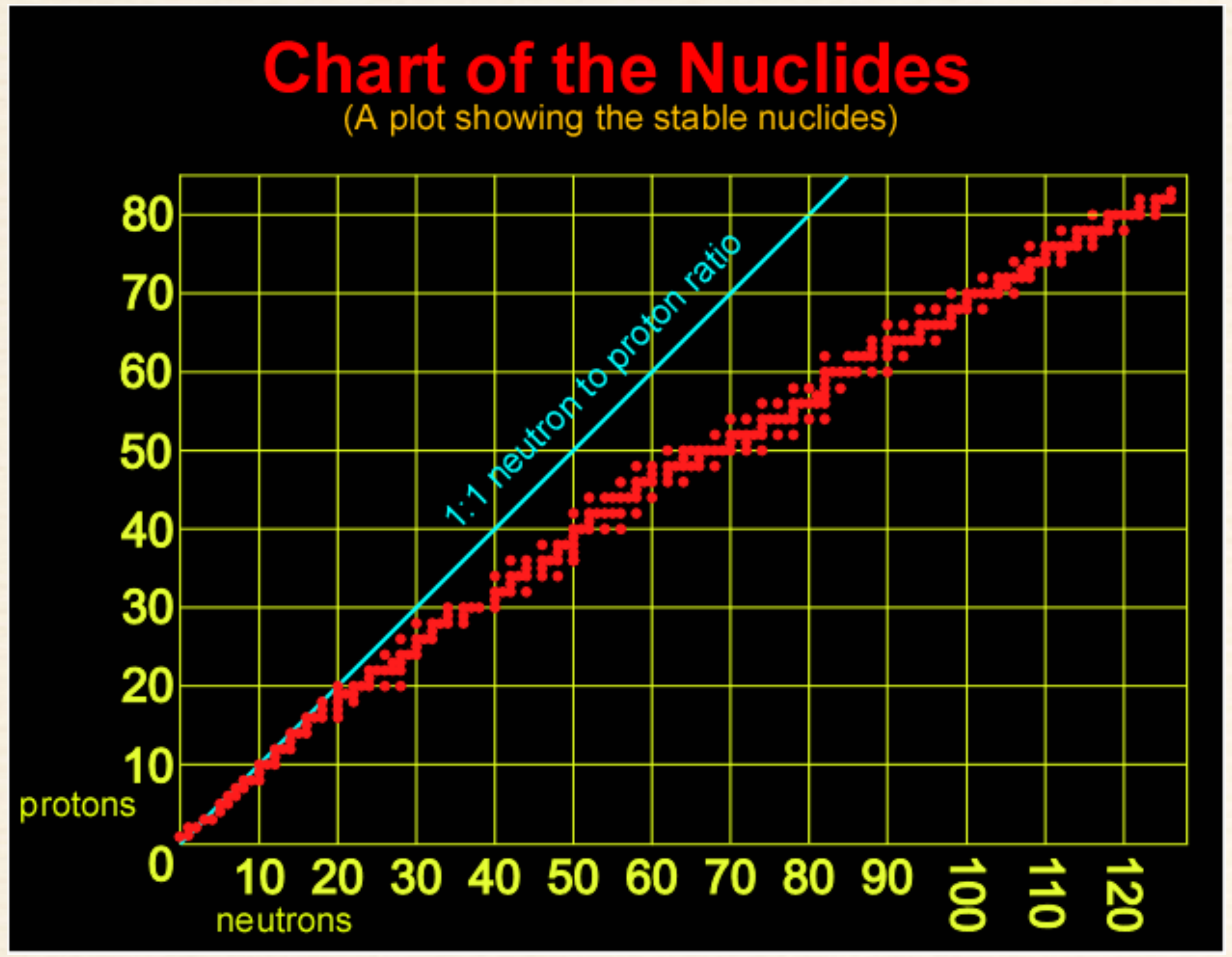

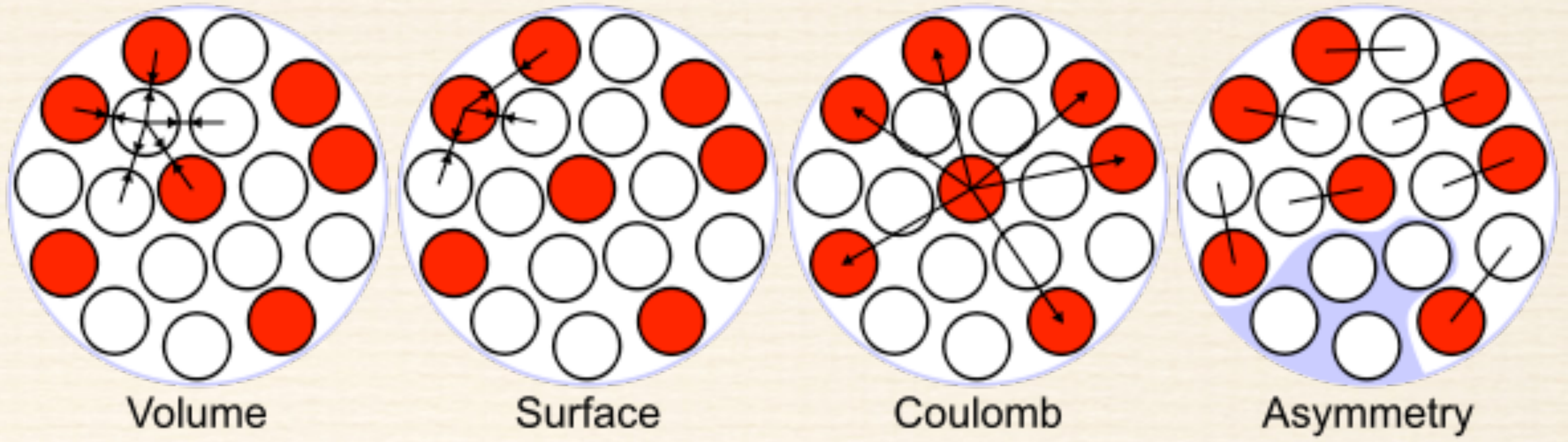

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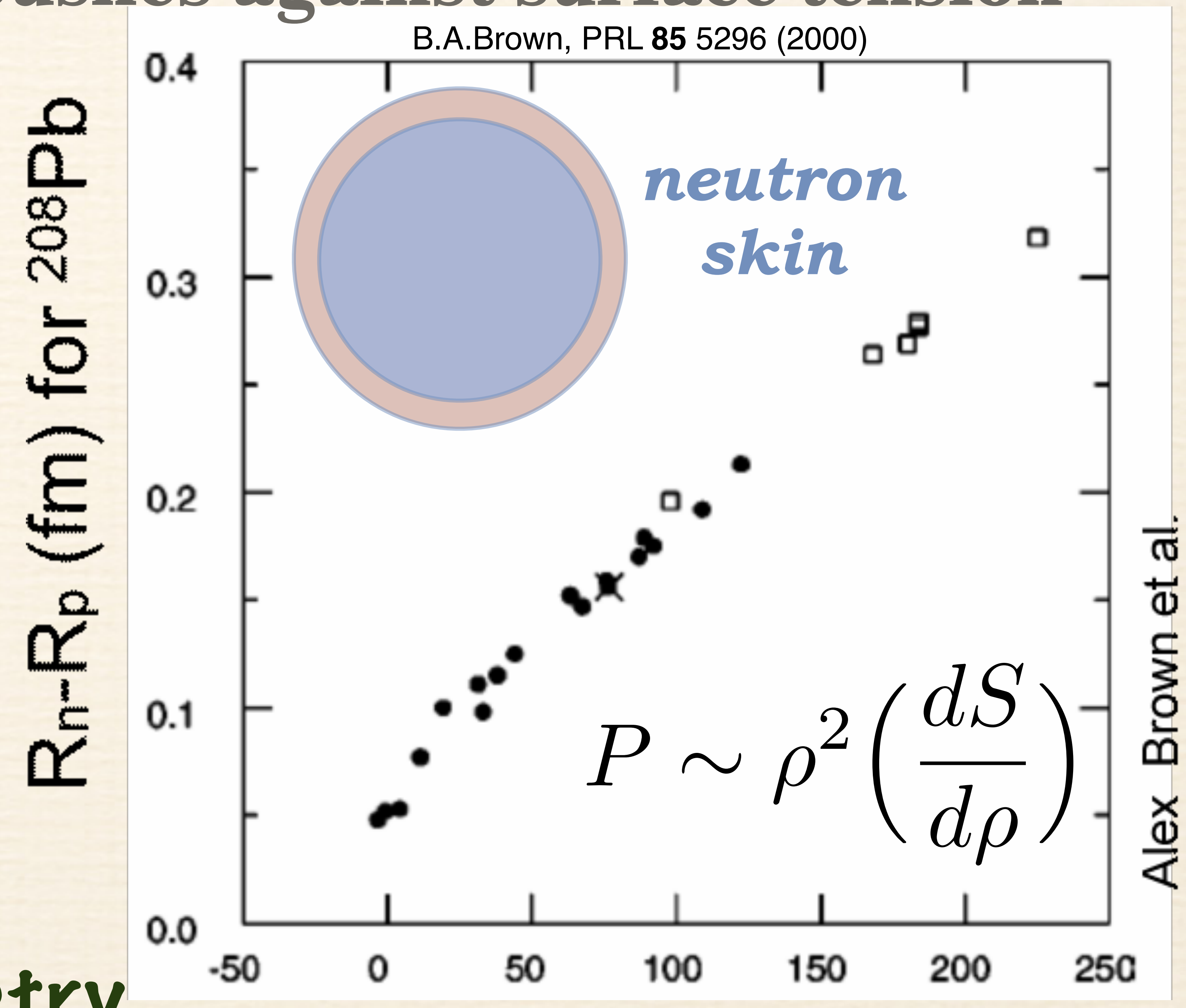
size of neutron skin

pressure → density dependence of symmetry energy at subnuclear densities



$$P \sim \rho^2\left(\frac{dS}{d\rho}\right)$$

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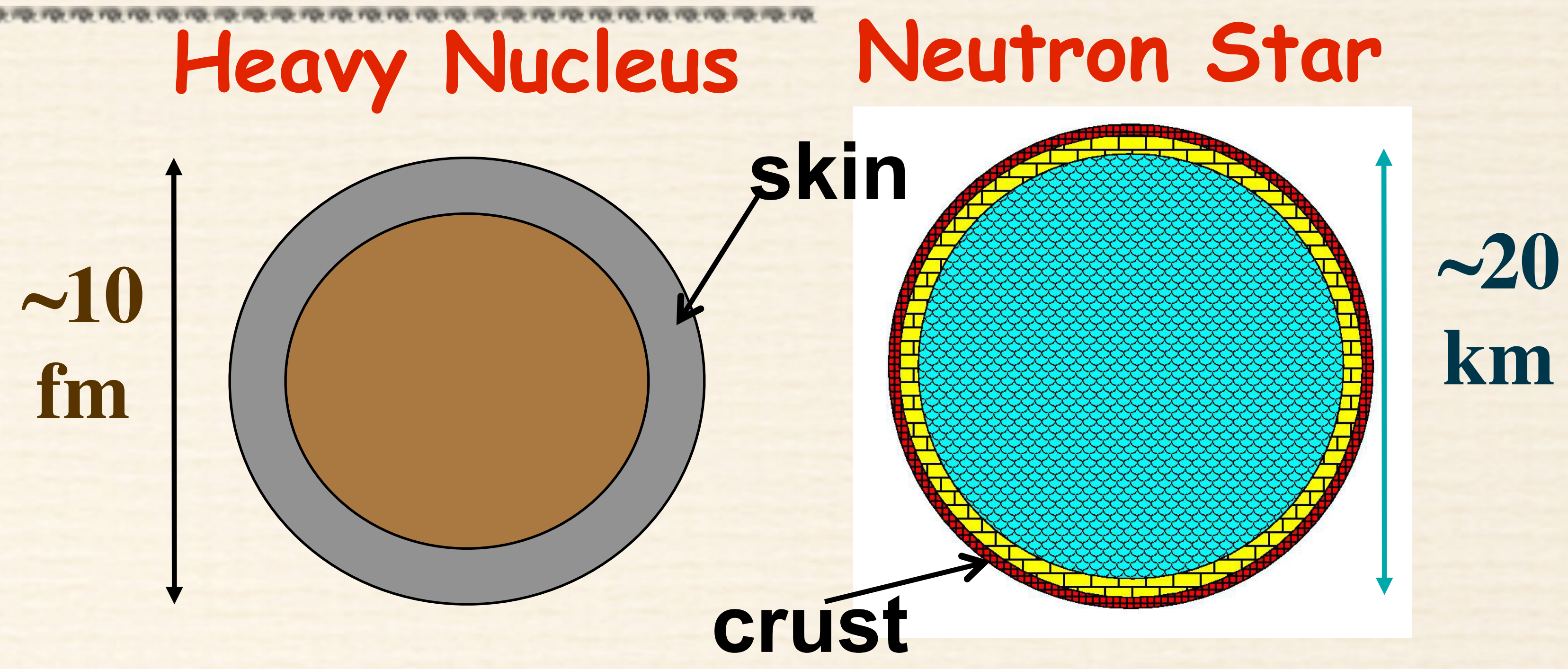
Neutron Skins and Neutron Stars

Horowitz and Piekarewicz, PRL 86 (2001)

Lattimer and Prakash, Science 304 (2004)

- Heavy nucleus has neutron skin
- Neutron star has solid crust over liquid core

Both neutron skin and neutron star crust are made out of neutron rich matter at similar densities.



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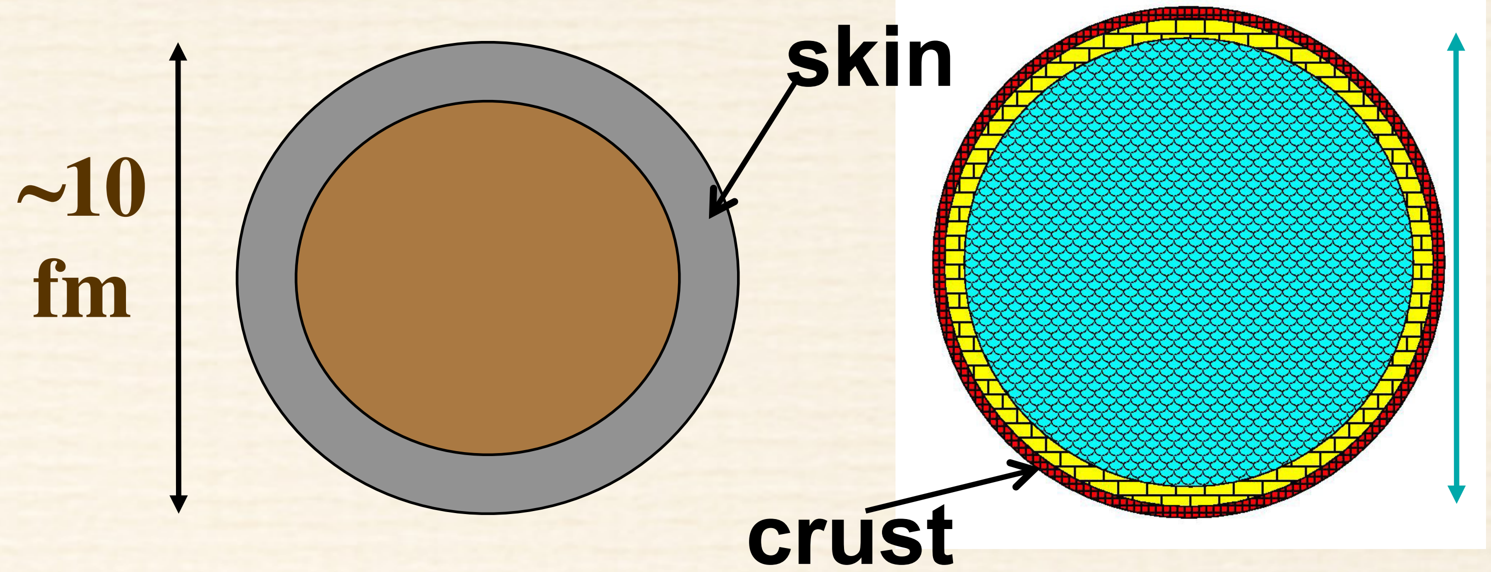

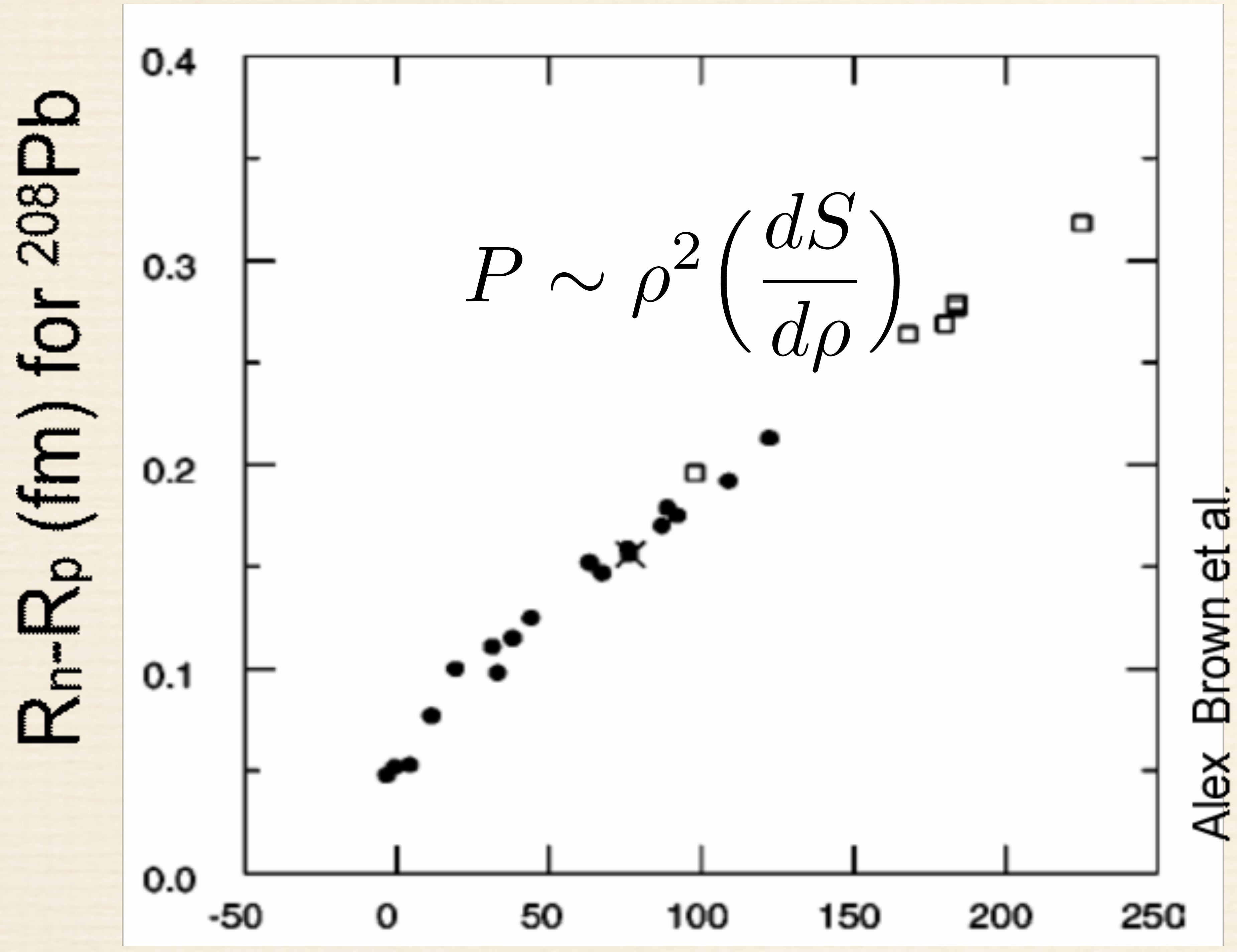

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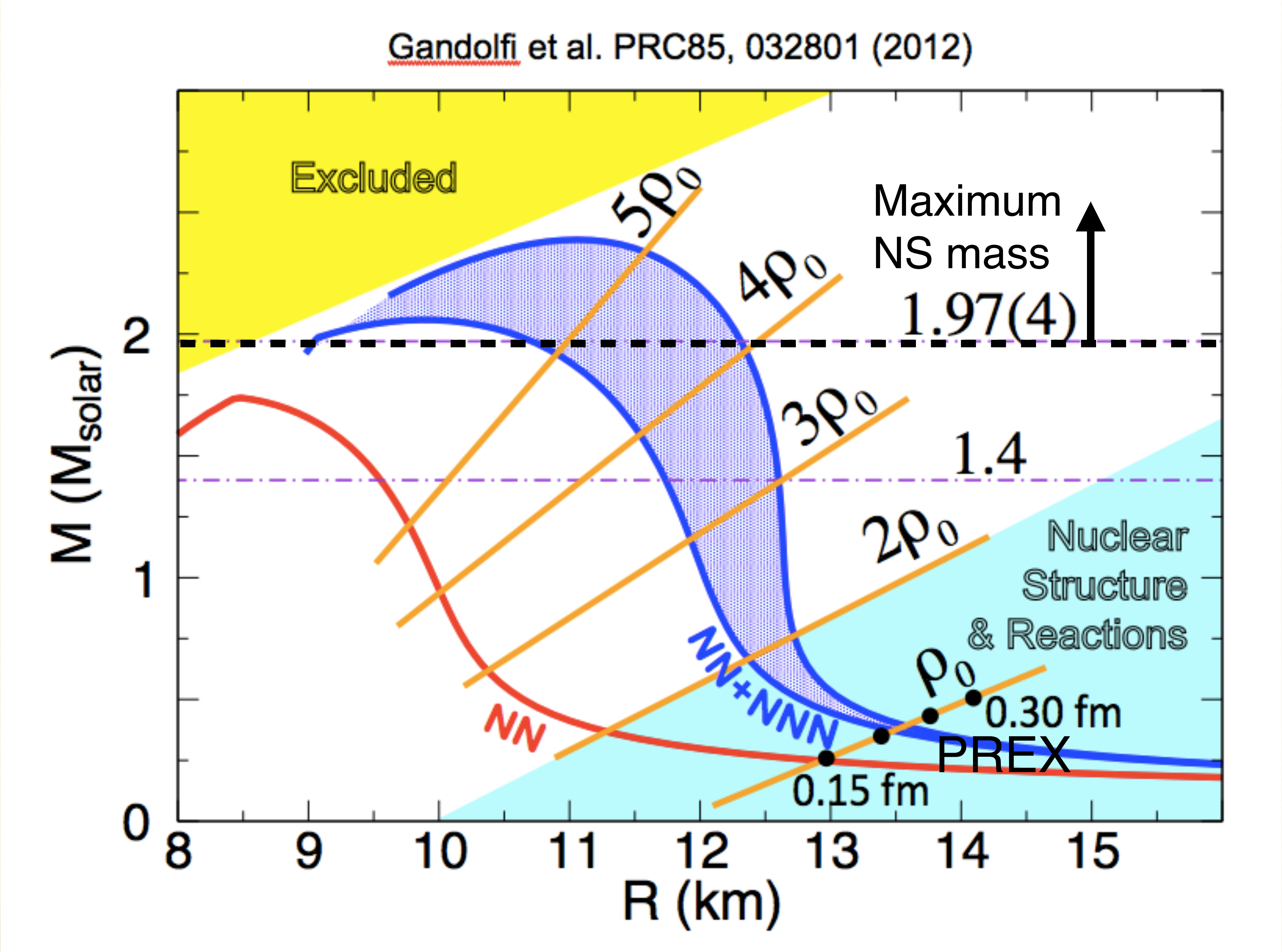
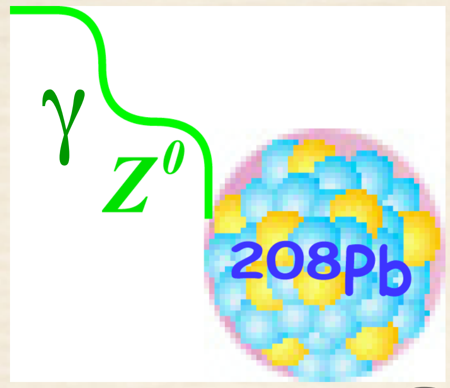


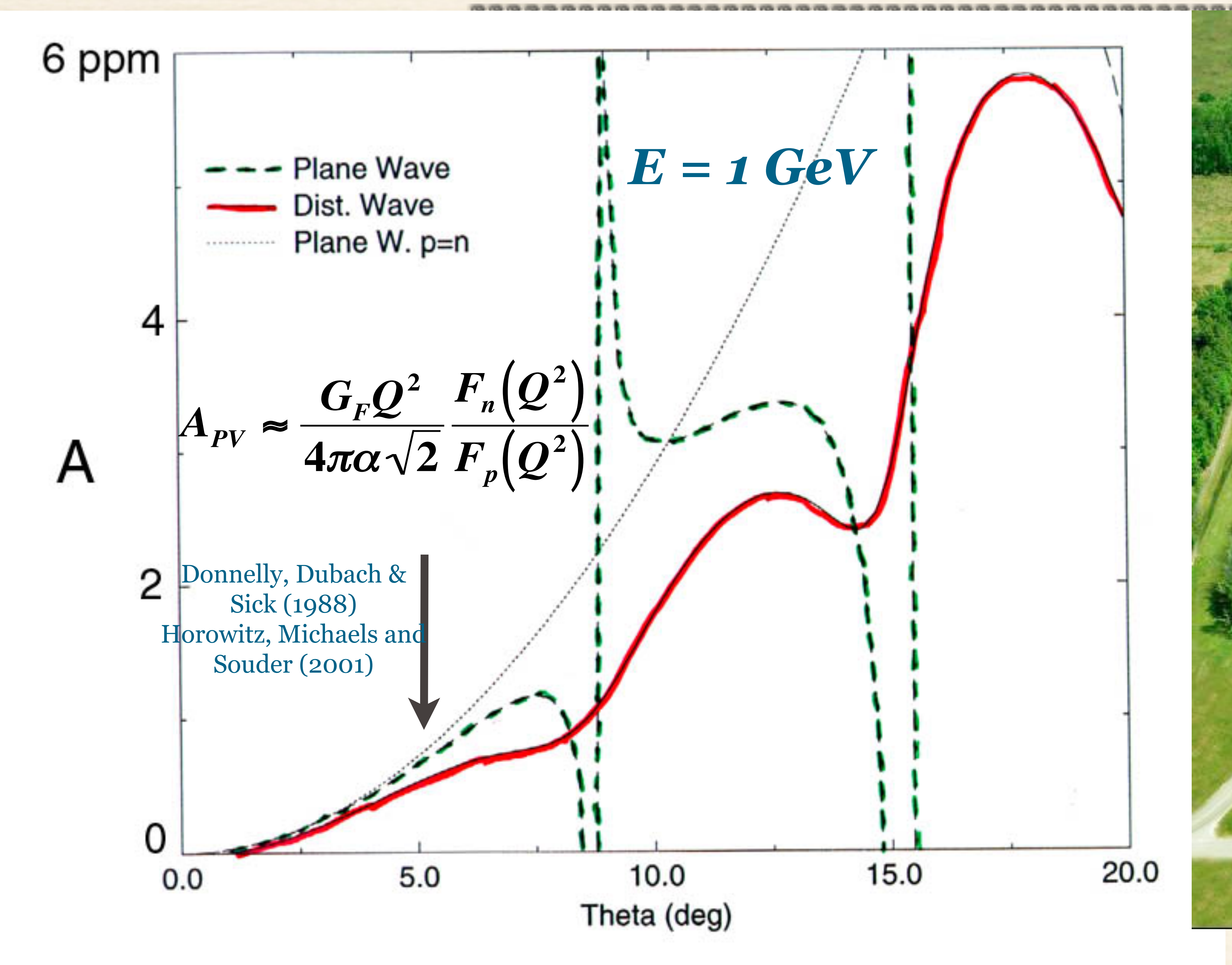
The Lead (Pb) Radius EXperiment PREX

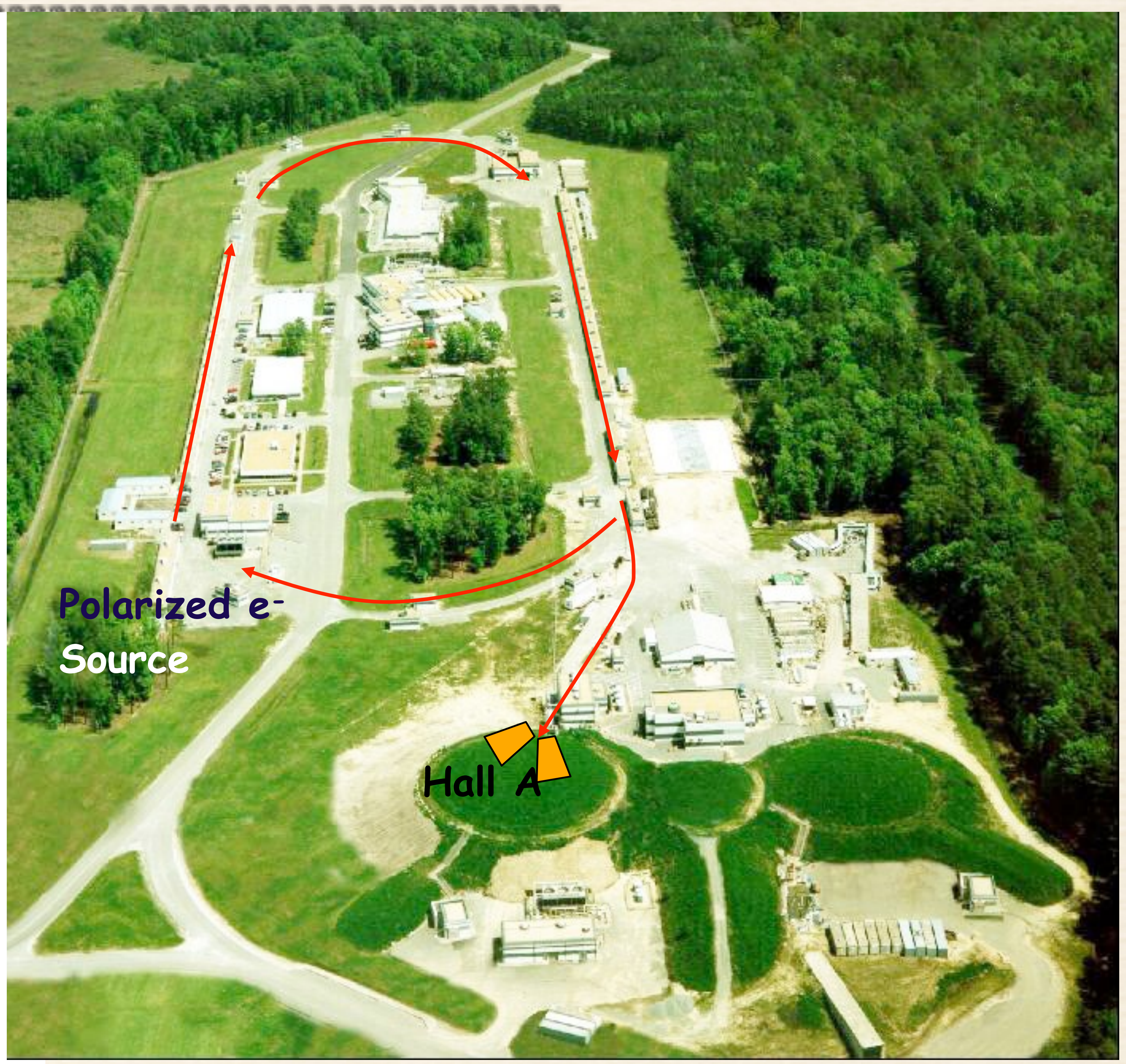
The Pb Radius EXperiment

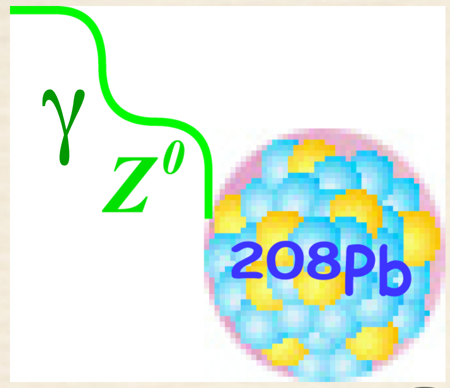
Concept: PREX

at the Thomas Jefferson National Accelerator Facility









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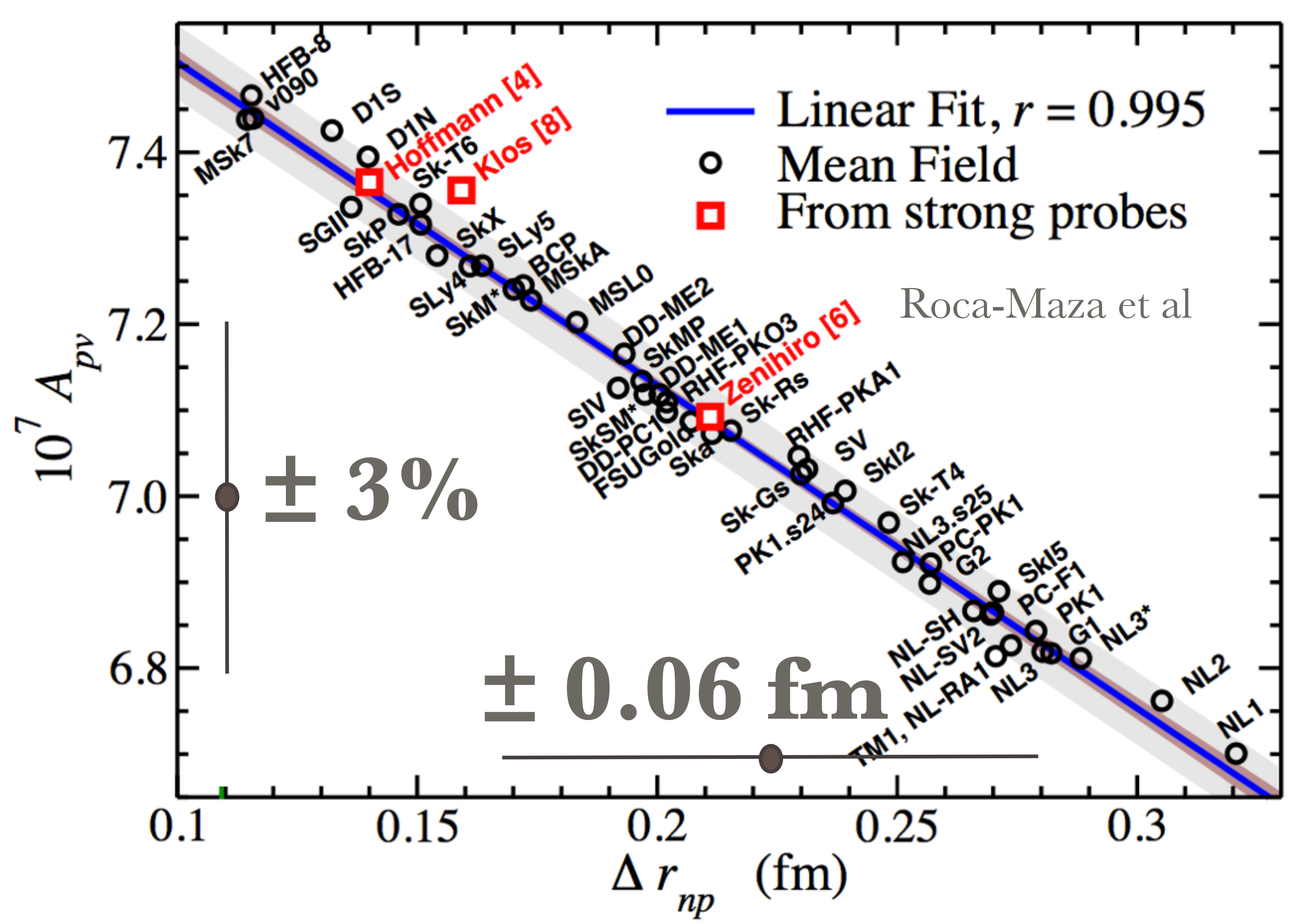

$Q^2 \sim 0.01$ GeV^2

$A_{PV} \sim 0.7$ ppm

Rate ~ 1 GHz

$\Delta(A_{PV}) \sim 20$ ppb

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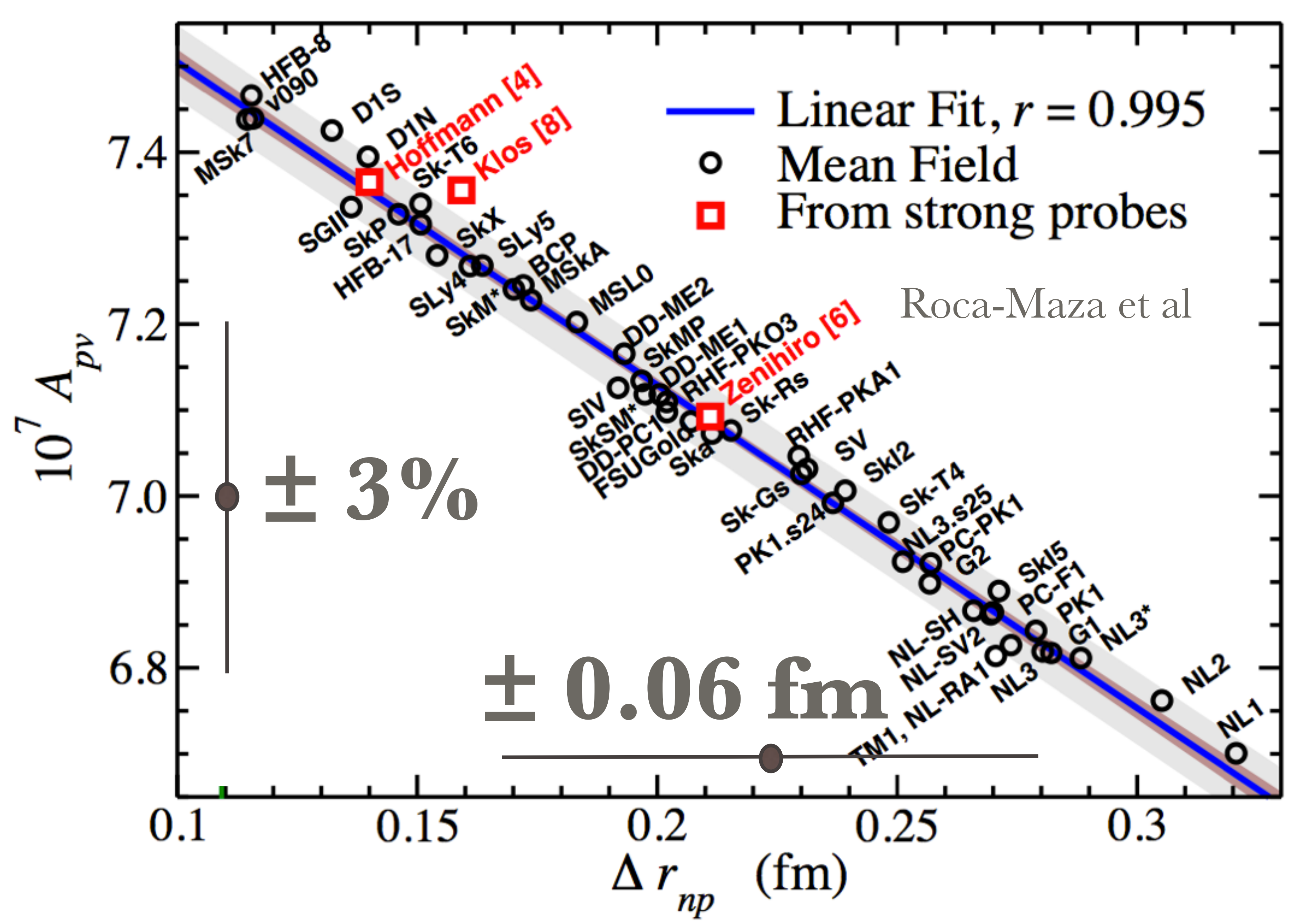

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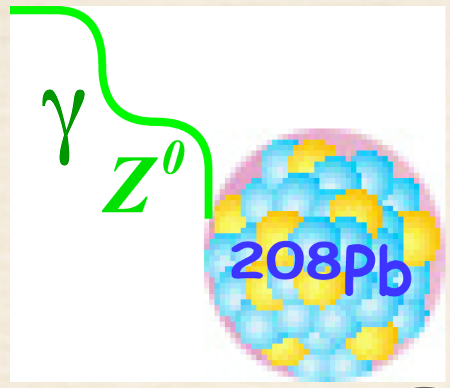

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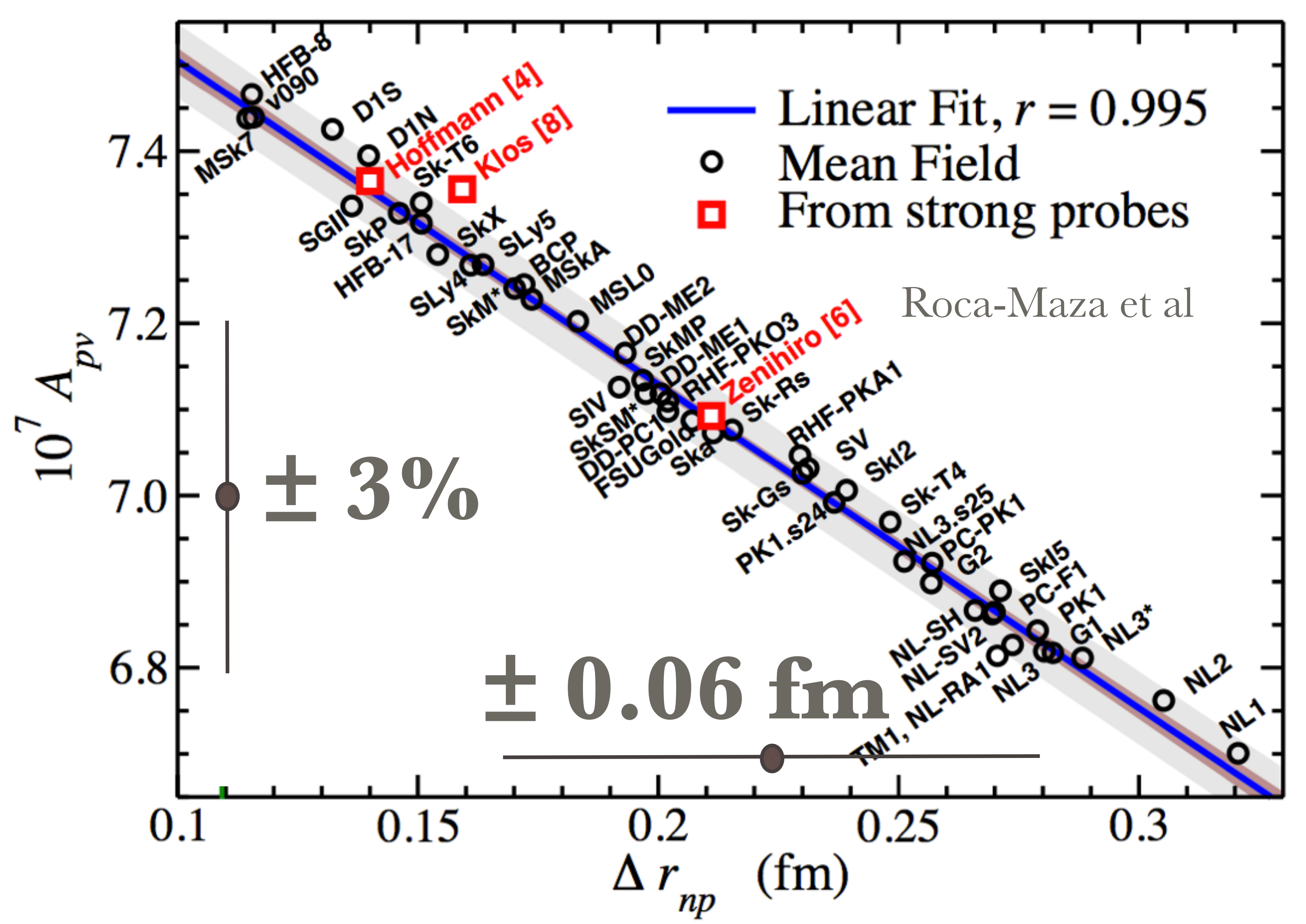

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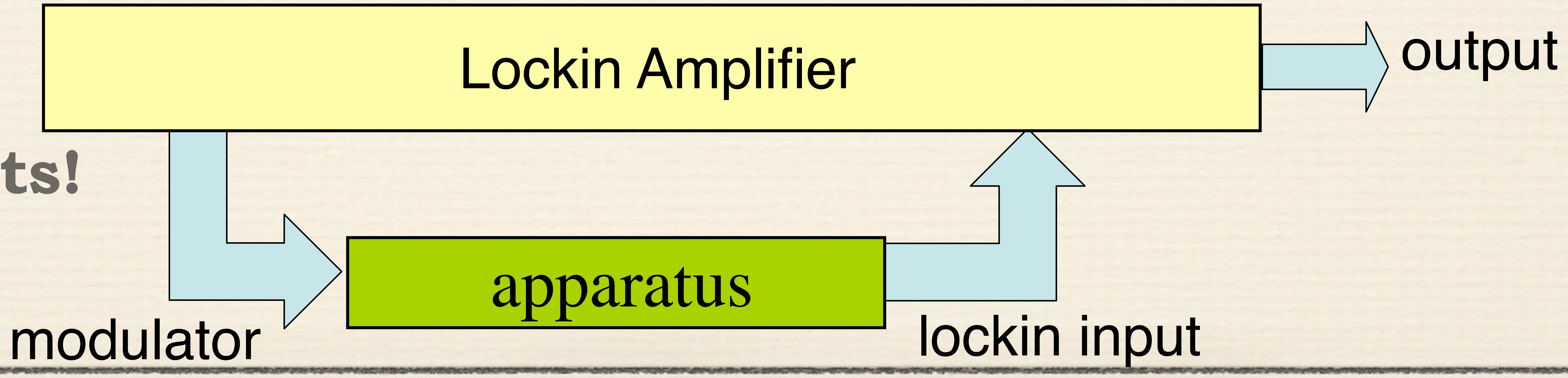

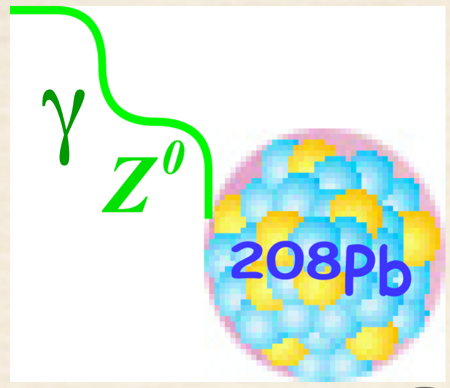

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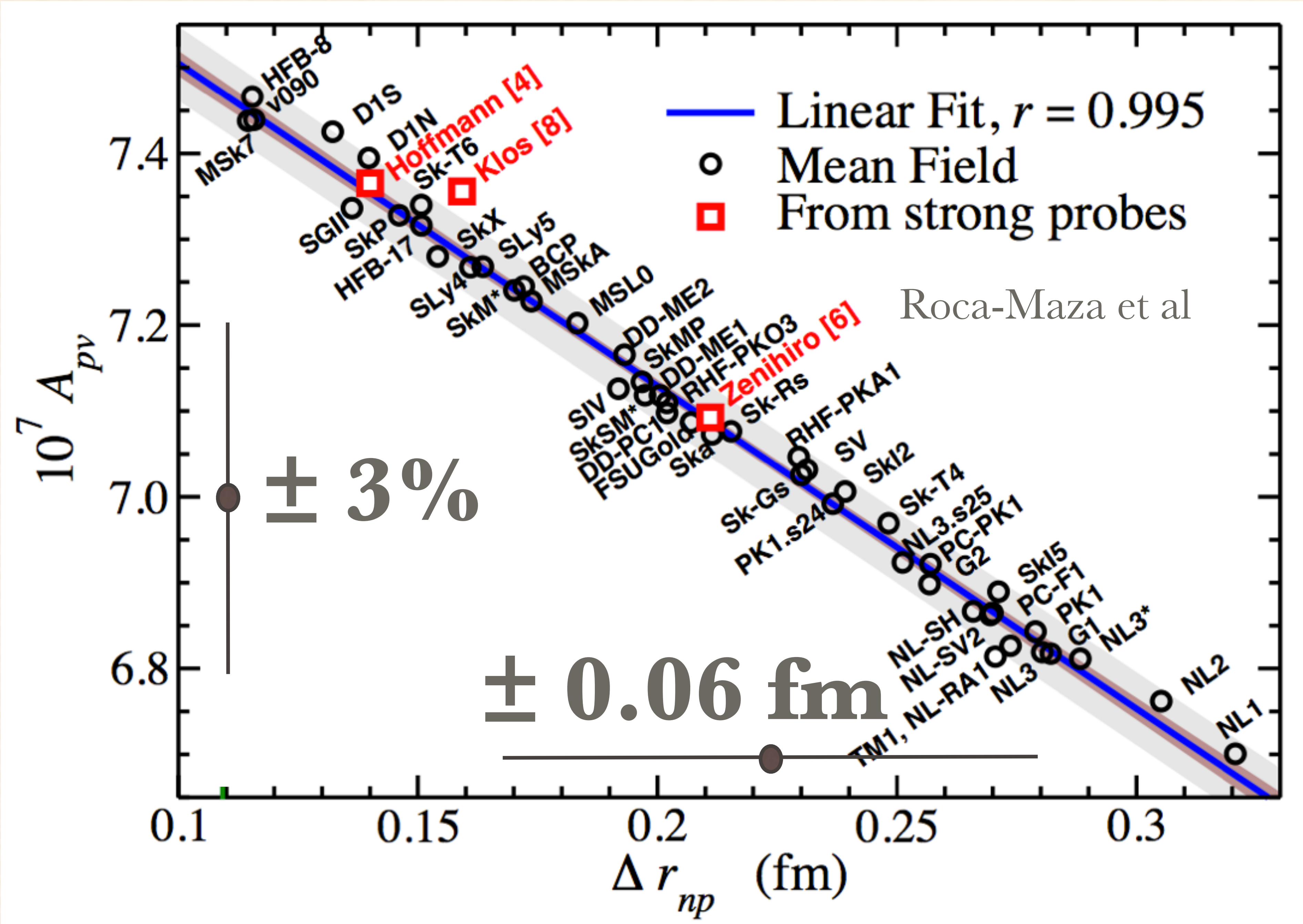

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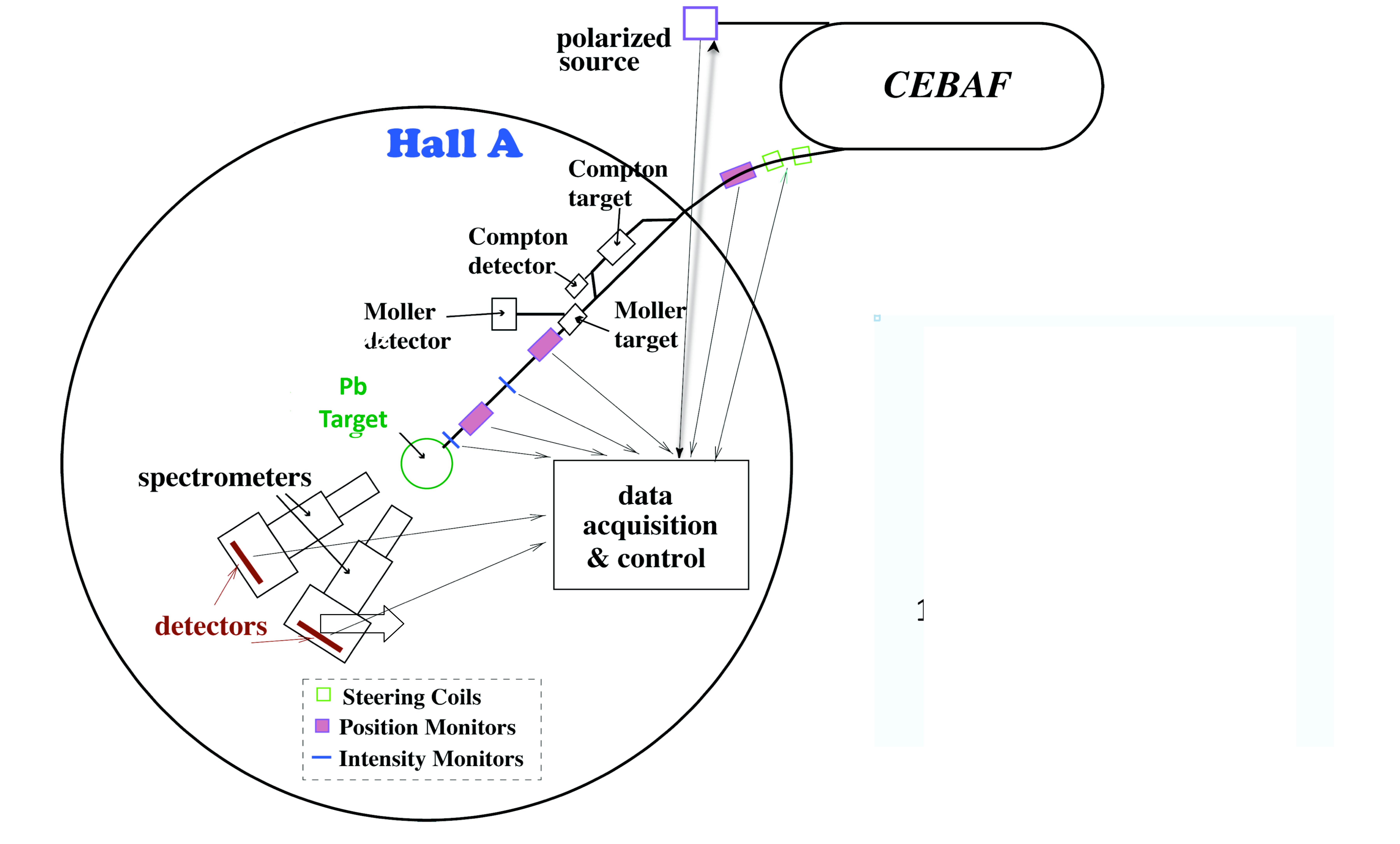
Lockin Amplifier → output

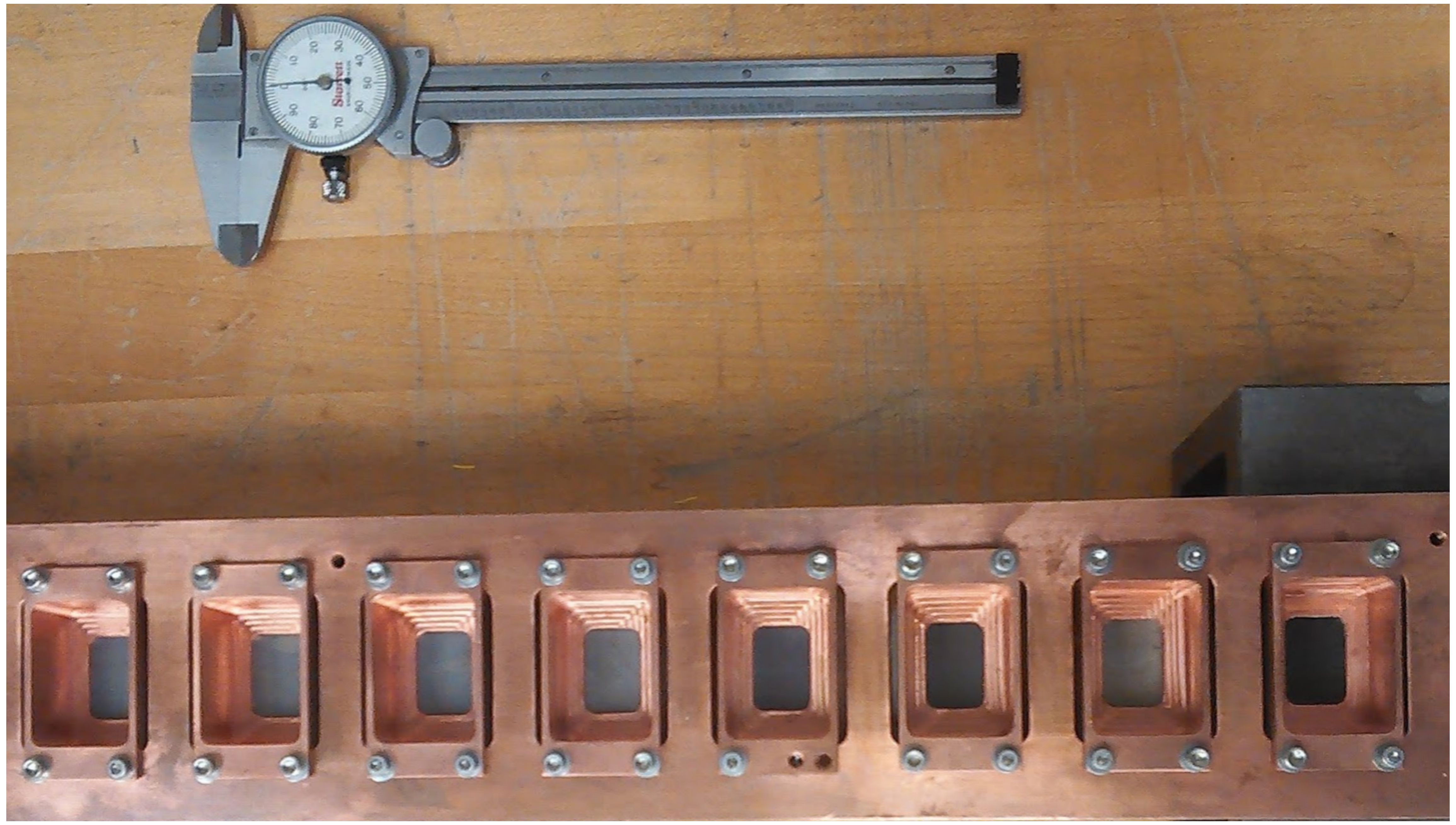
> 10^{15} events!

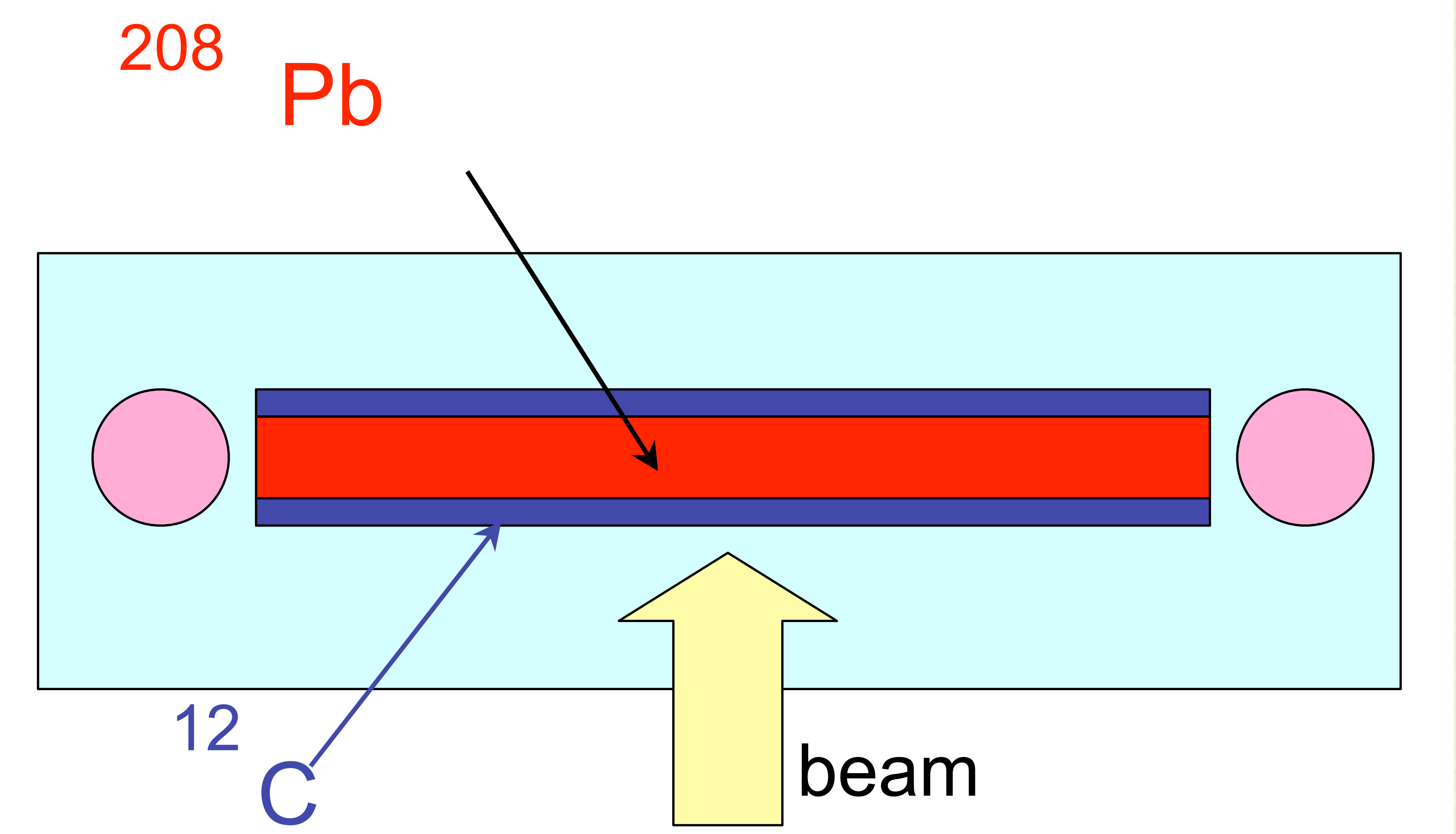
injector → *accelerator* → *target* → *spectrometer* → *detector*

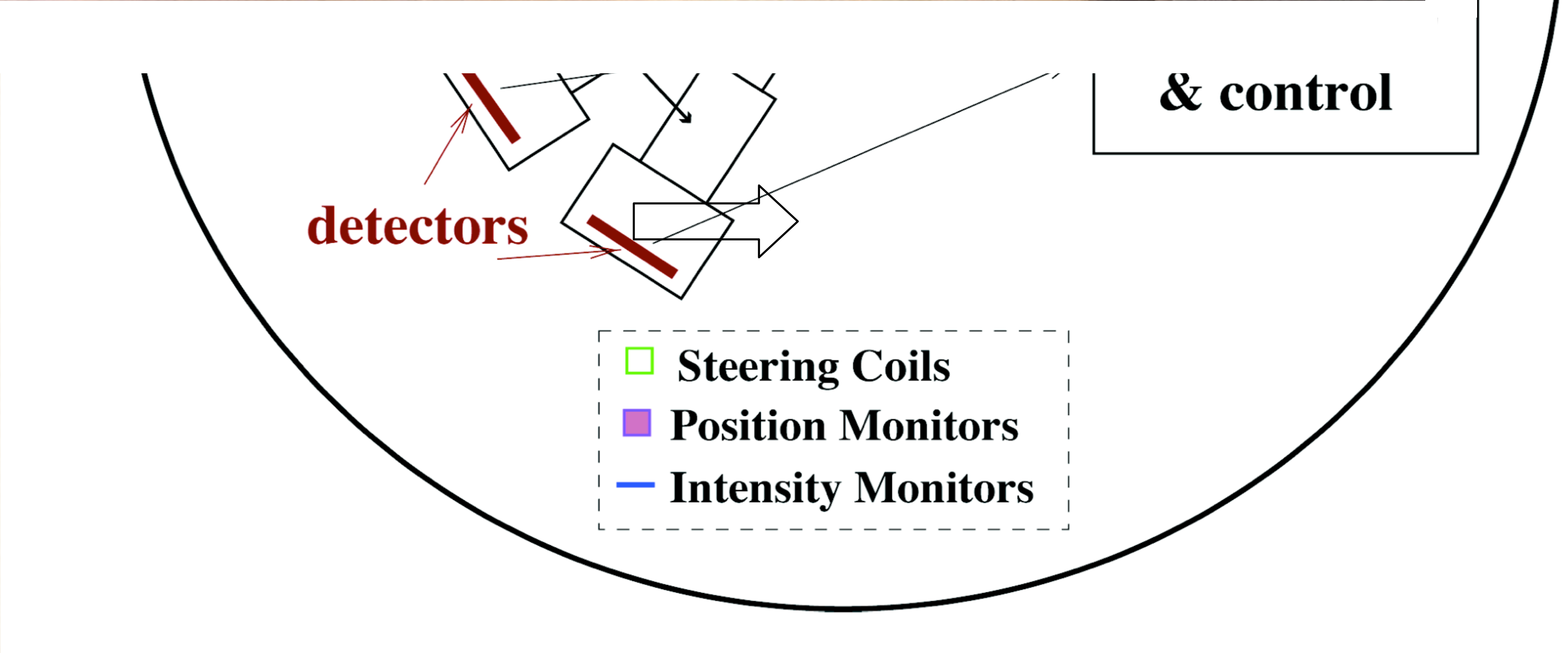
PREX @JLab Hall A: Overview

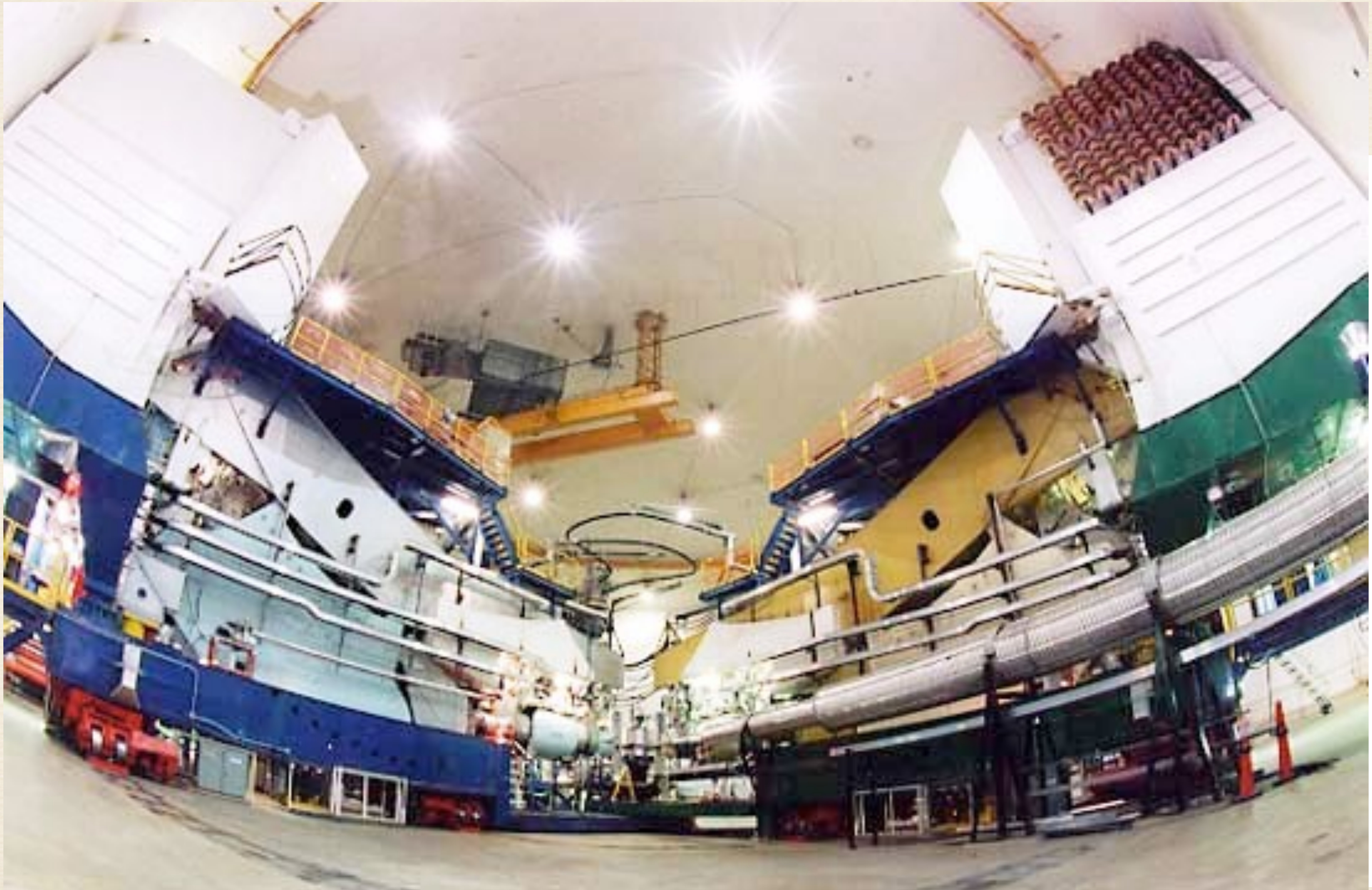


PREX @JLab Hall A: Overview





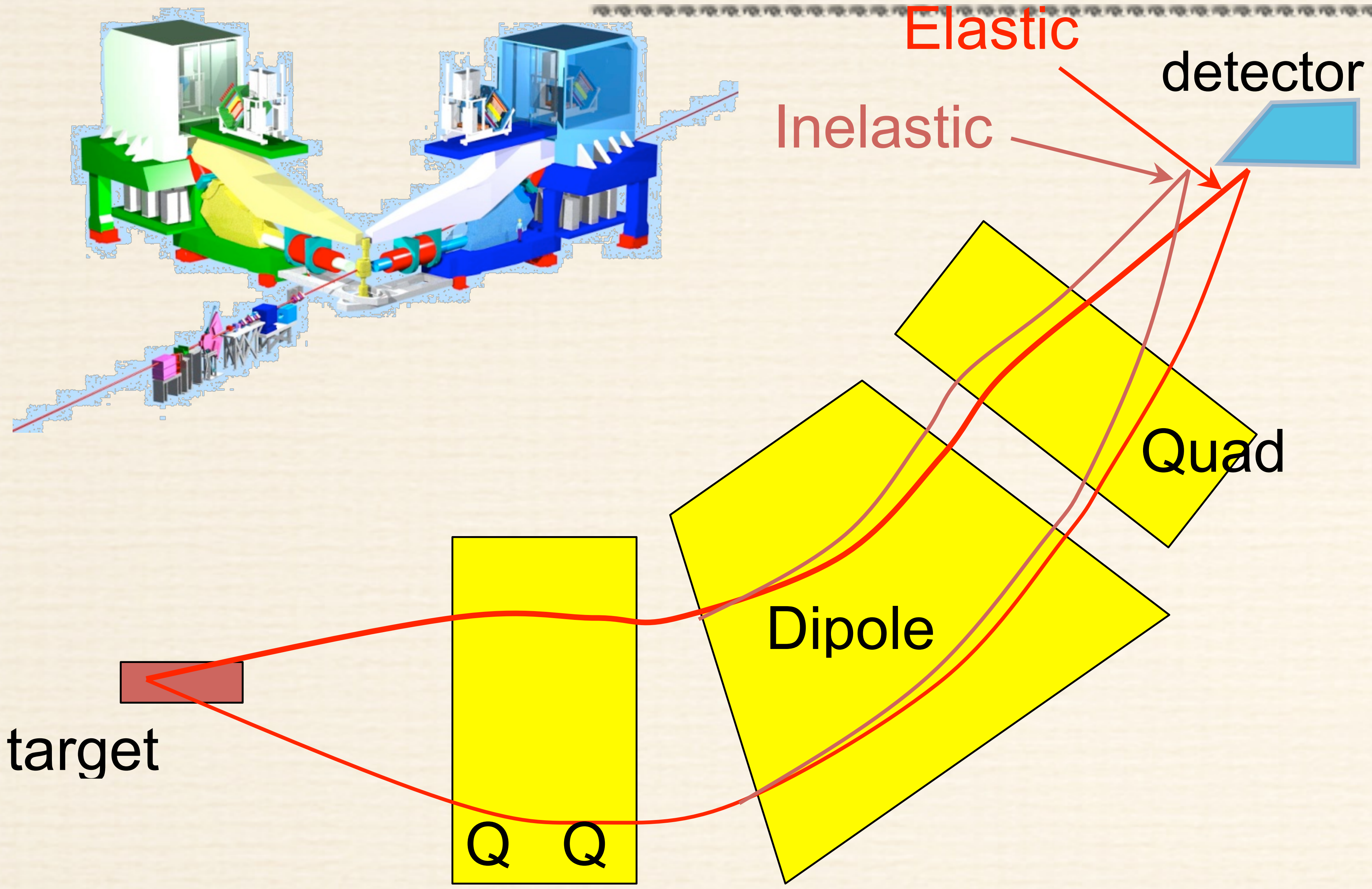


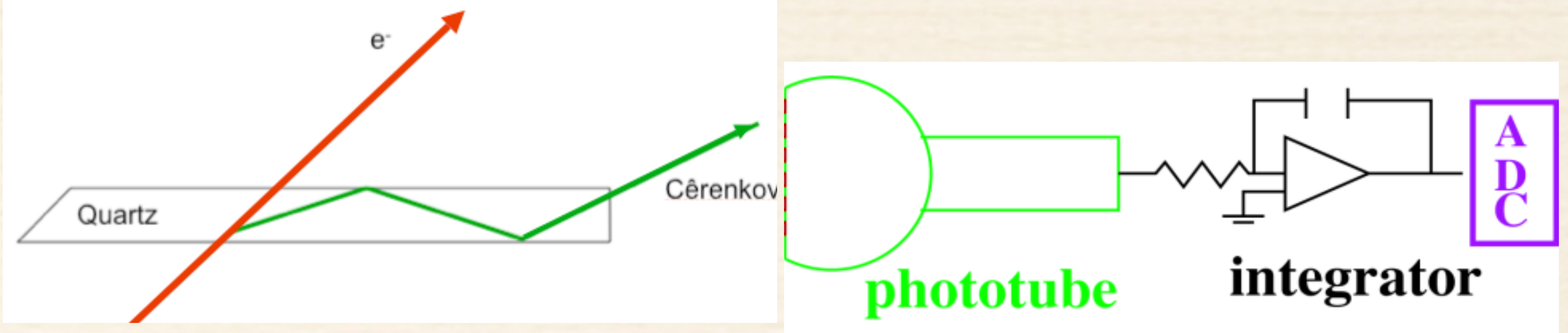


second major SLAC E122 innovation: “flux integration”

High Flux, Low Background

Hall A High Resolution Spectrometers





1 GHz scattered flux

1 x 10^{-4} statistical uncertainty
30 times per second

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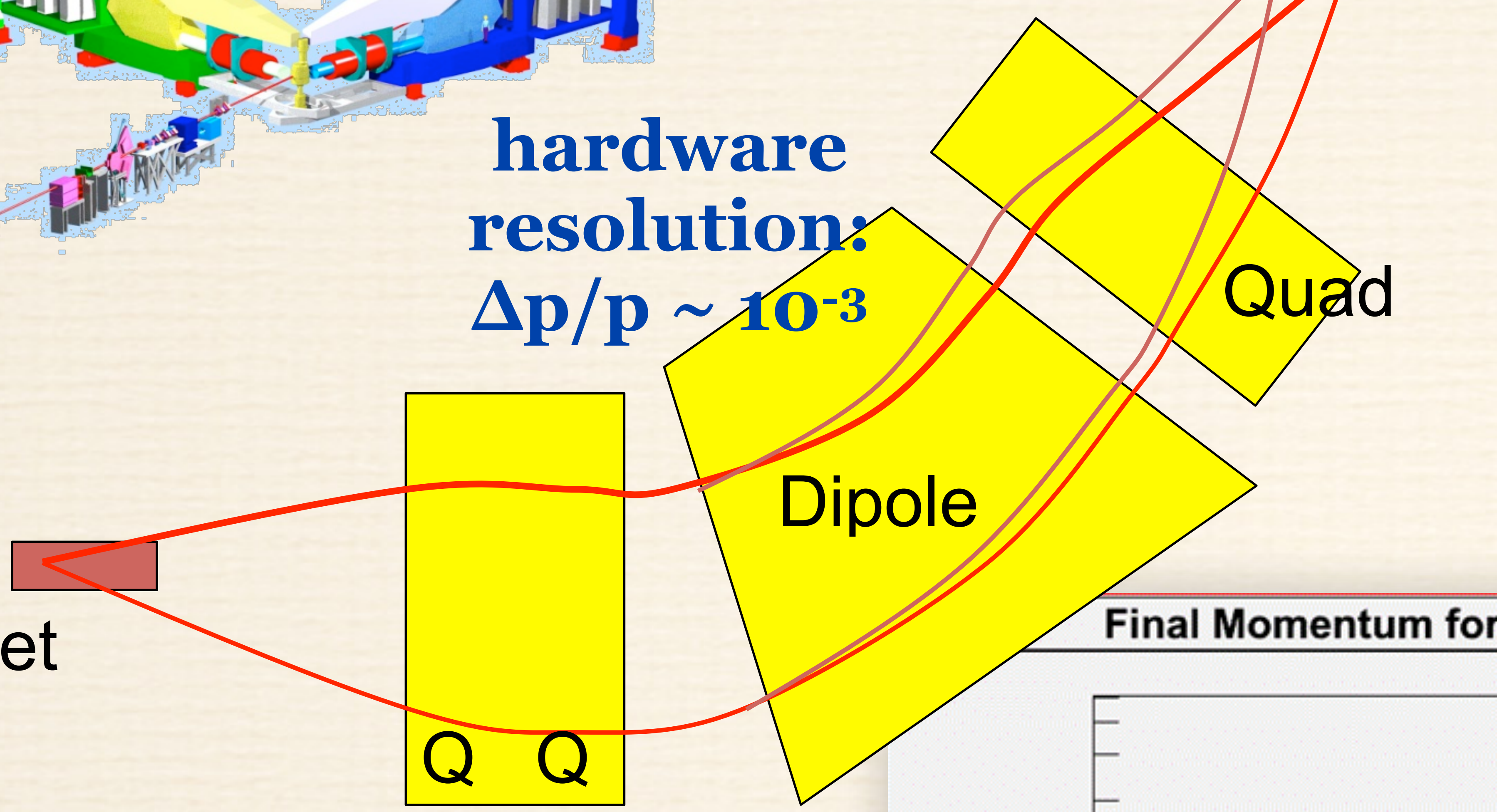
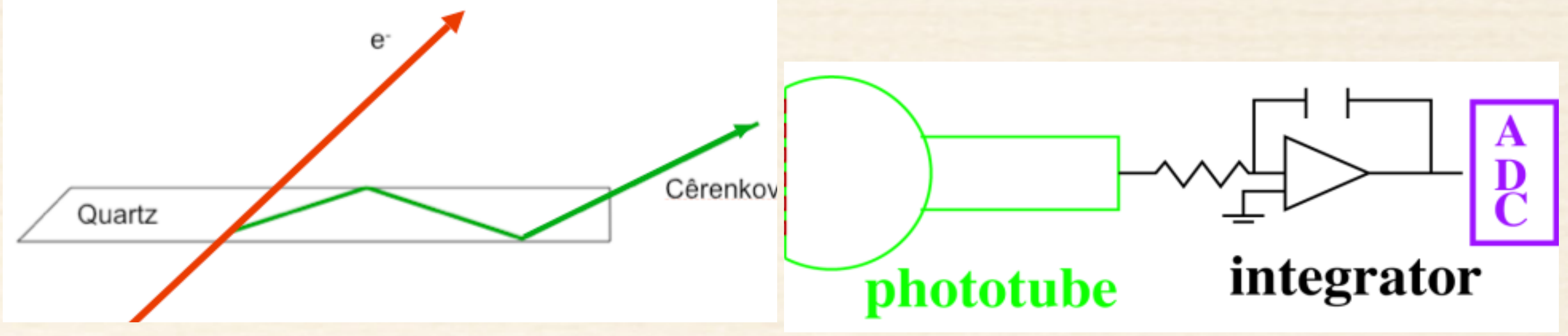


hardware resolution: $\Delta p/p \sim 10^{-3}$



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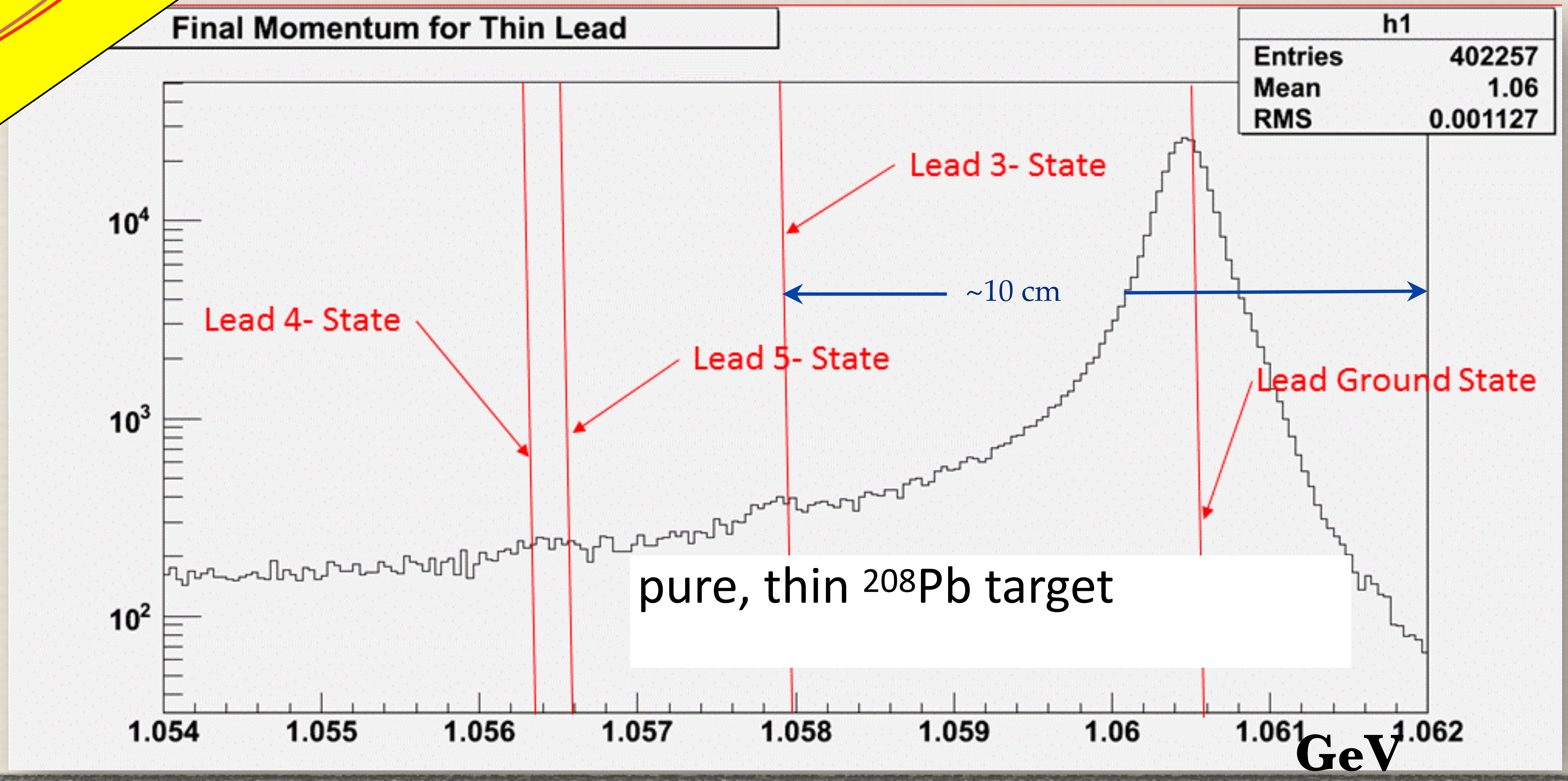
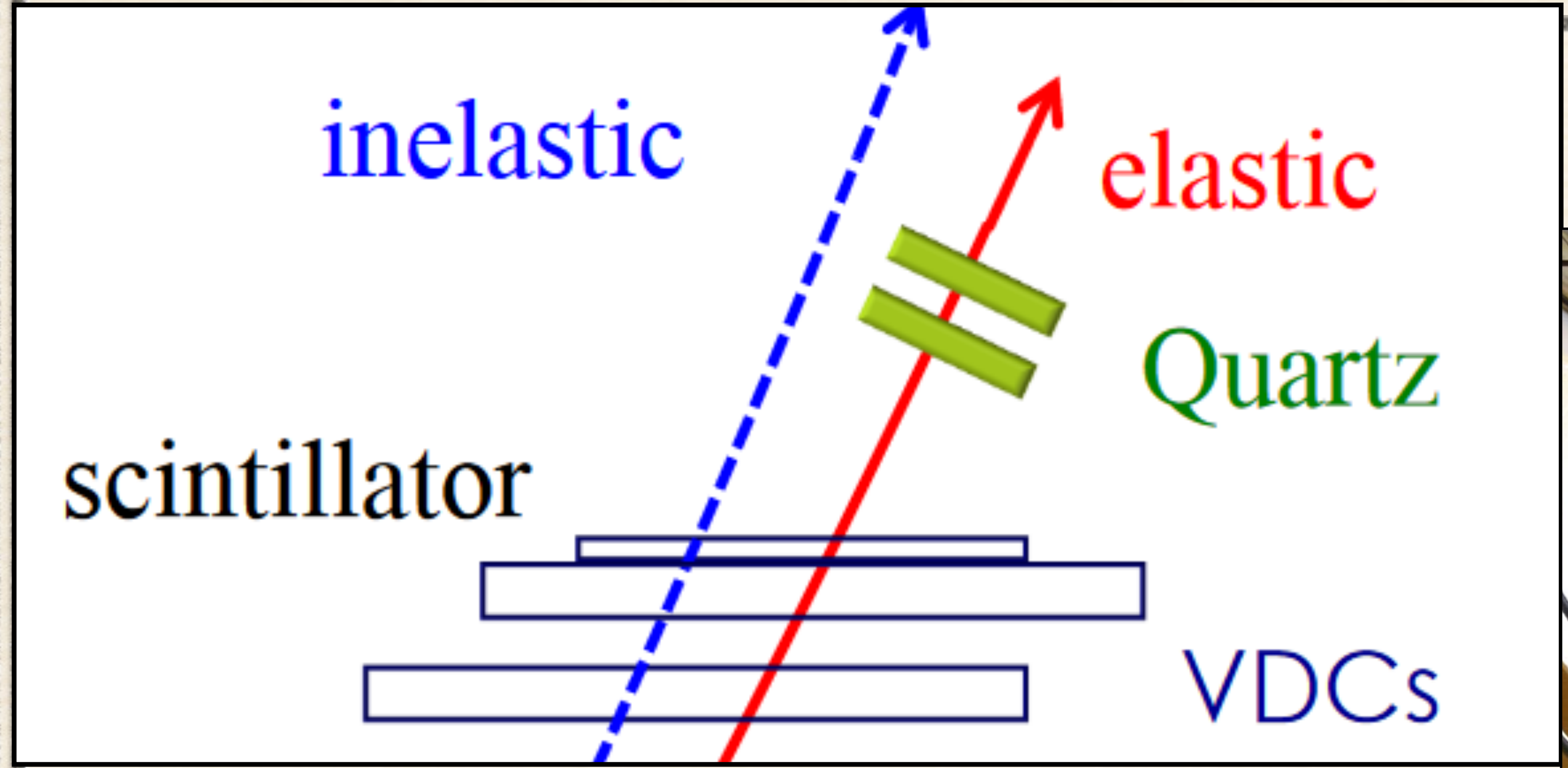
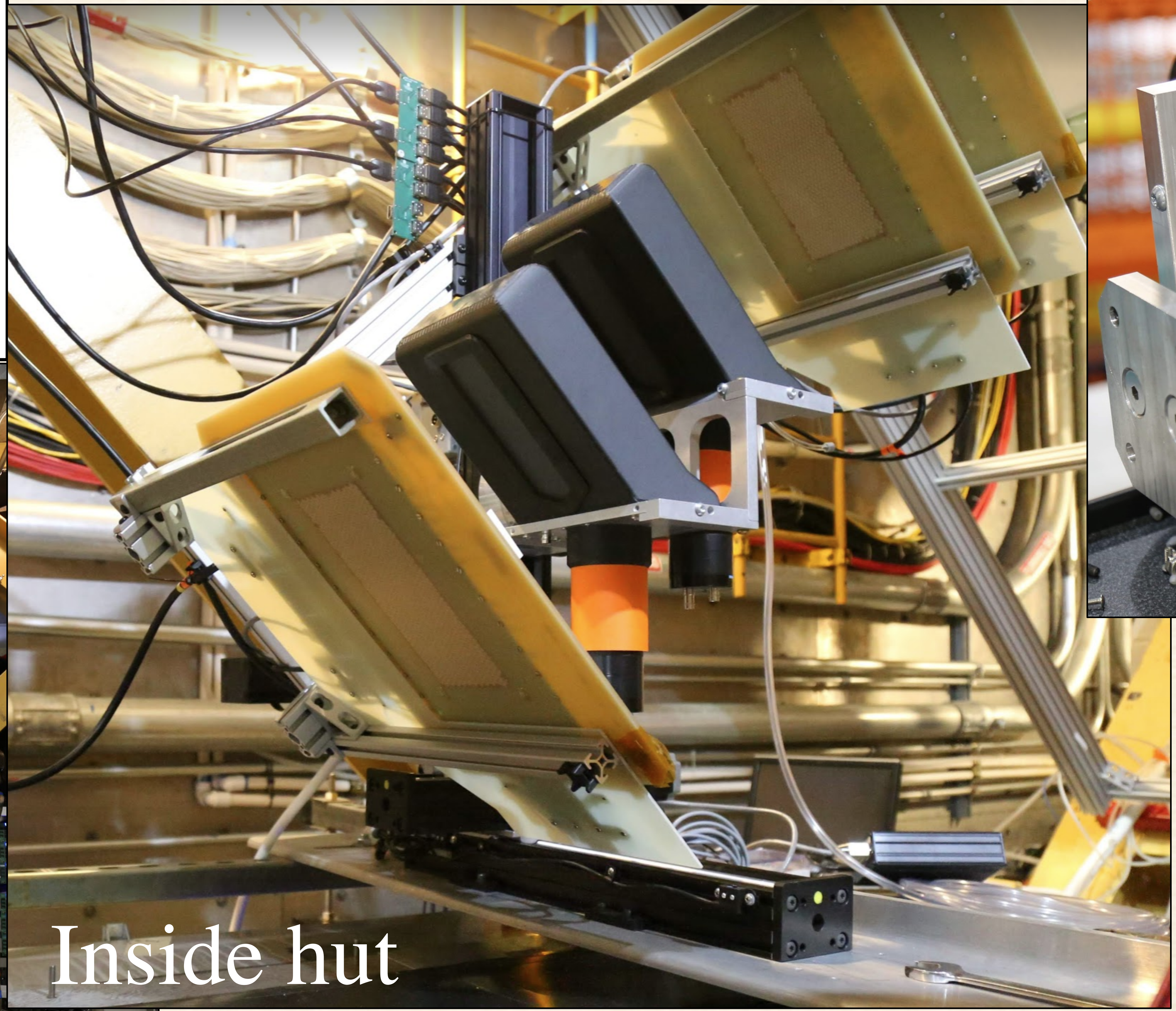
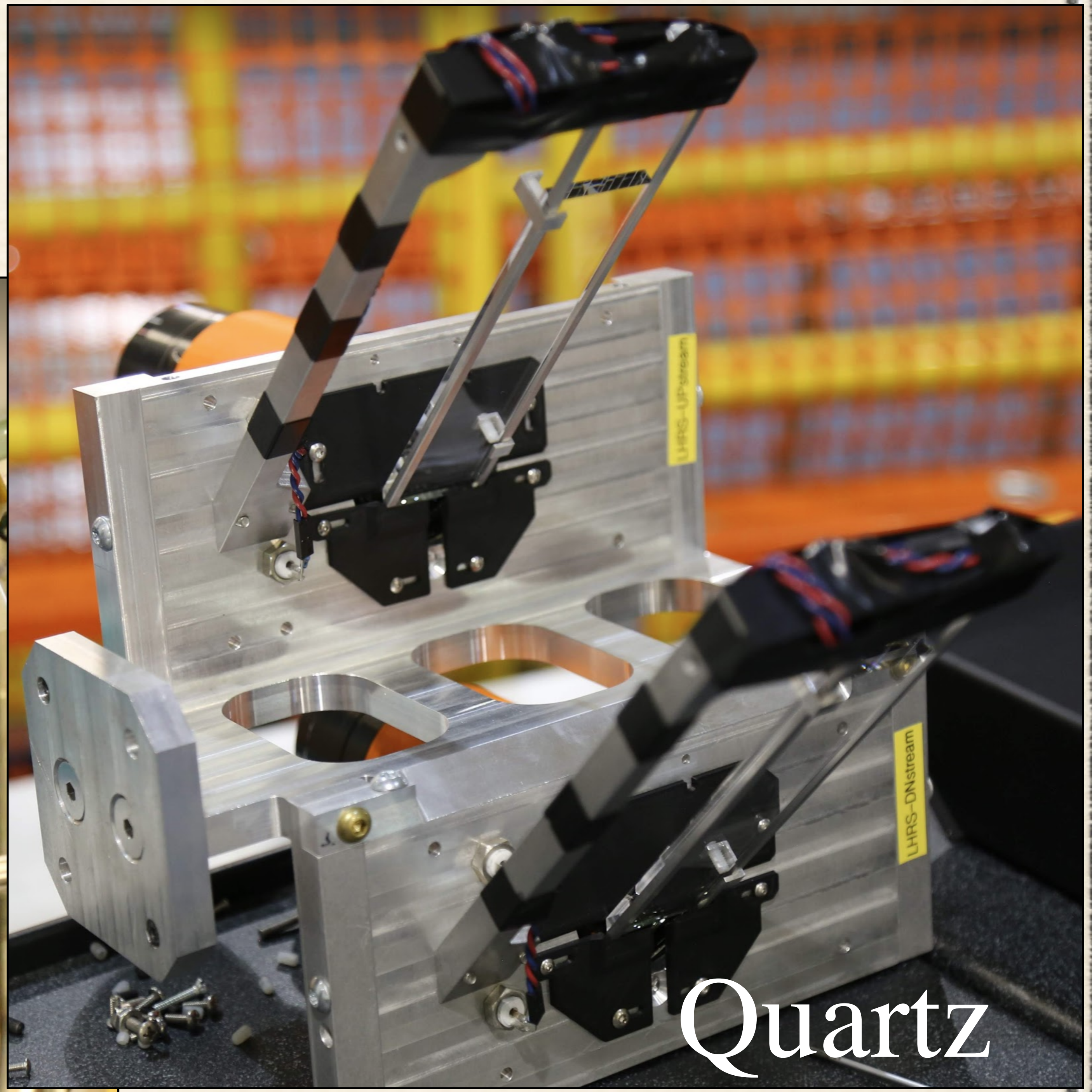


Inelastic backgrounds negligible

Inside the HRS “Counting Hut”







- Integrating detectors (reduce deadtime effects)
- Thick and thin quartz bars (different systematics)

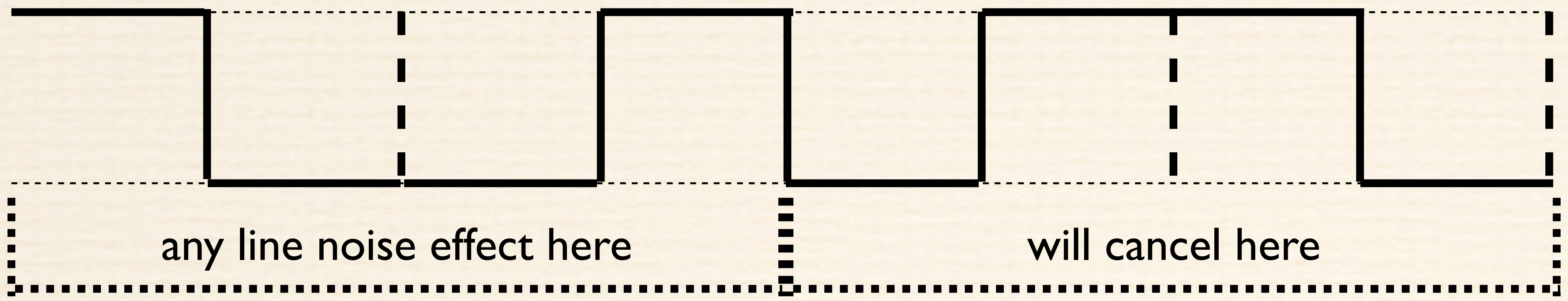
CW electron beam: scattered signal rate ~ 3 GHz

Flux Integration

10 ppb (average 3.3×10^6 s)

sequence of "window multiplets"

Example: at 240 Hz reversal



$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

Detector D, Current I: F = D/I $A_{pair} = \frac{\Delta F}{2F} + \Delta A$

CW electron beam: scattered signal rate ~ 3 GHz

Flux Integration

30 Hz Stat. Width: 100 ppm → N = 100 M: 10 ppb (average 3.3×10^6 s)

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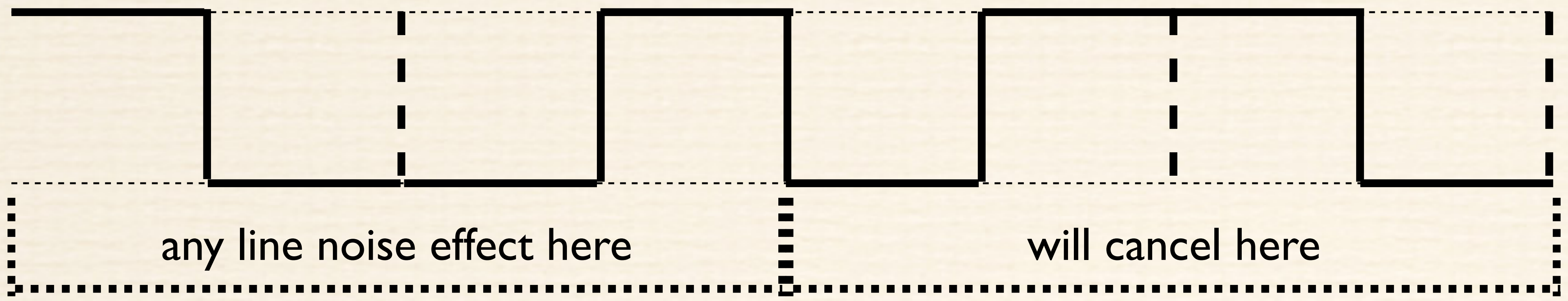

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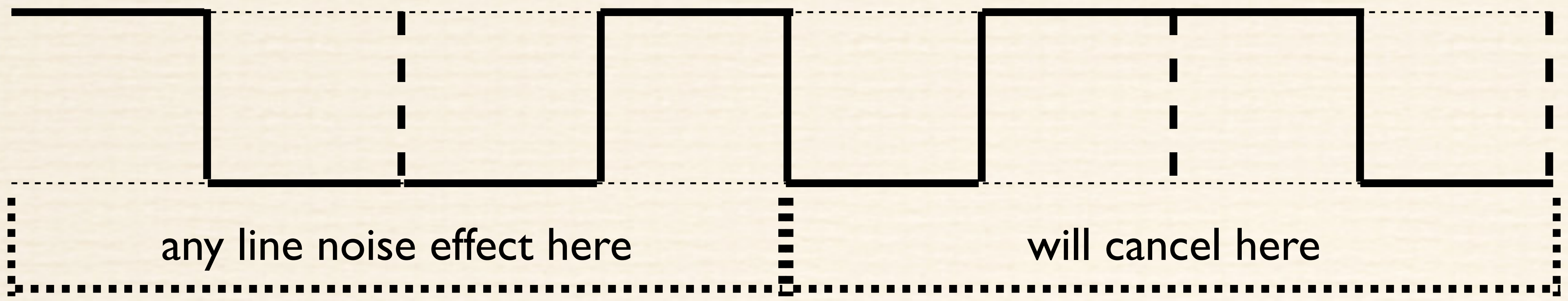

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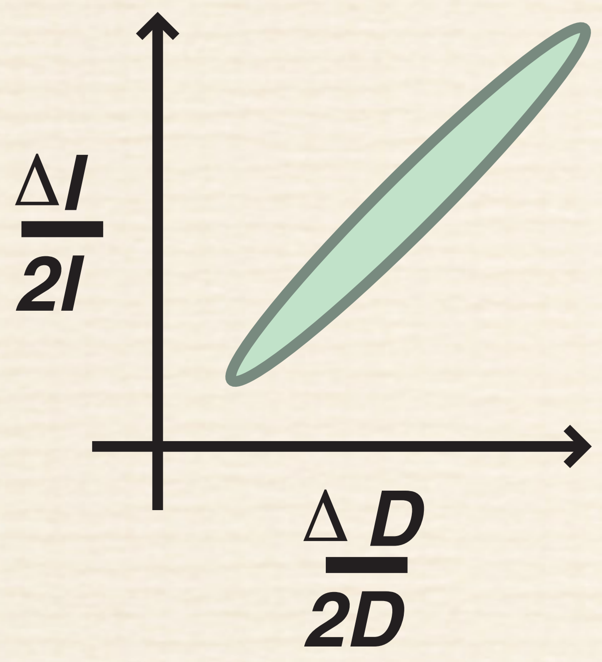

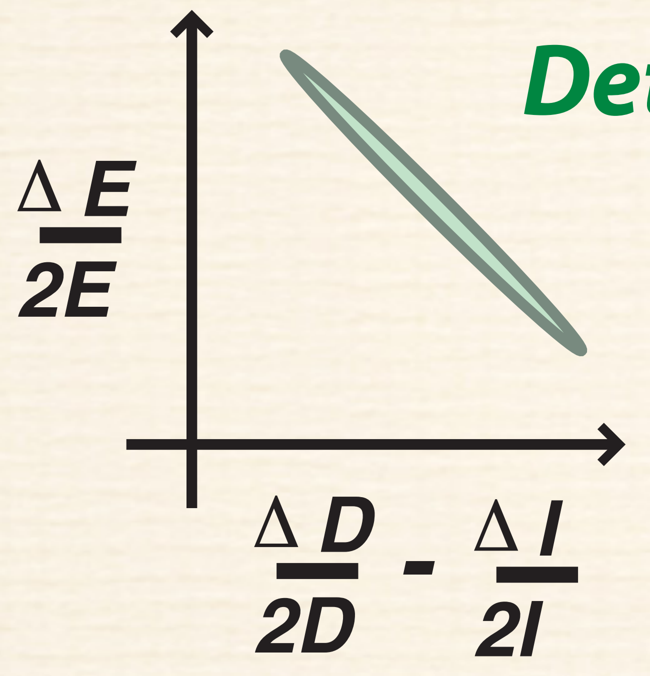

I order: $x, y, \theta_x, \theta_y, E$
II order: e.g. spot-size

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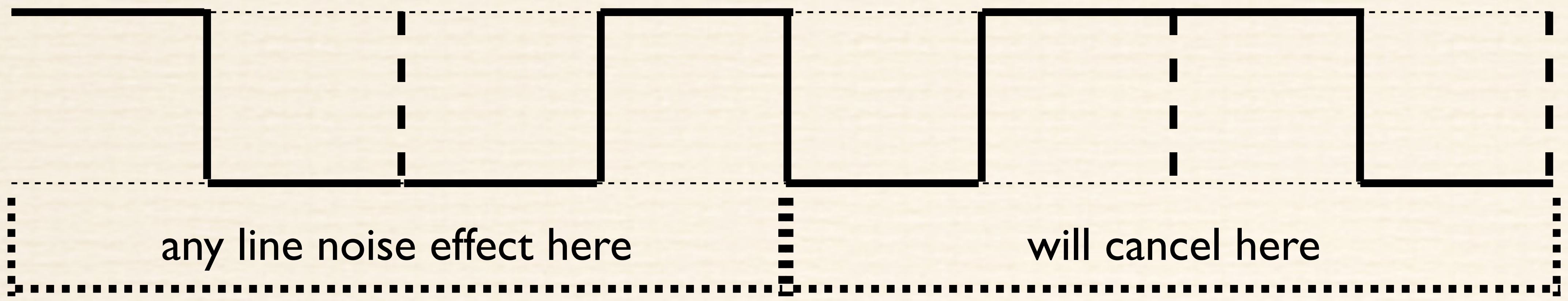

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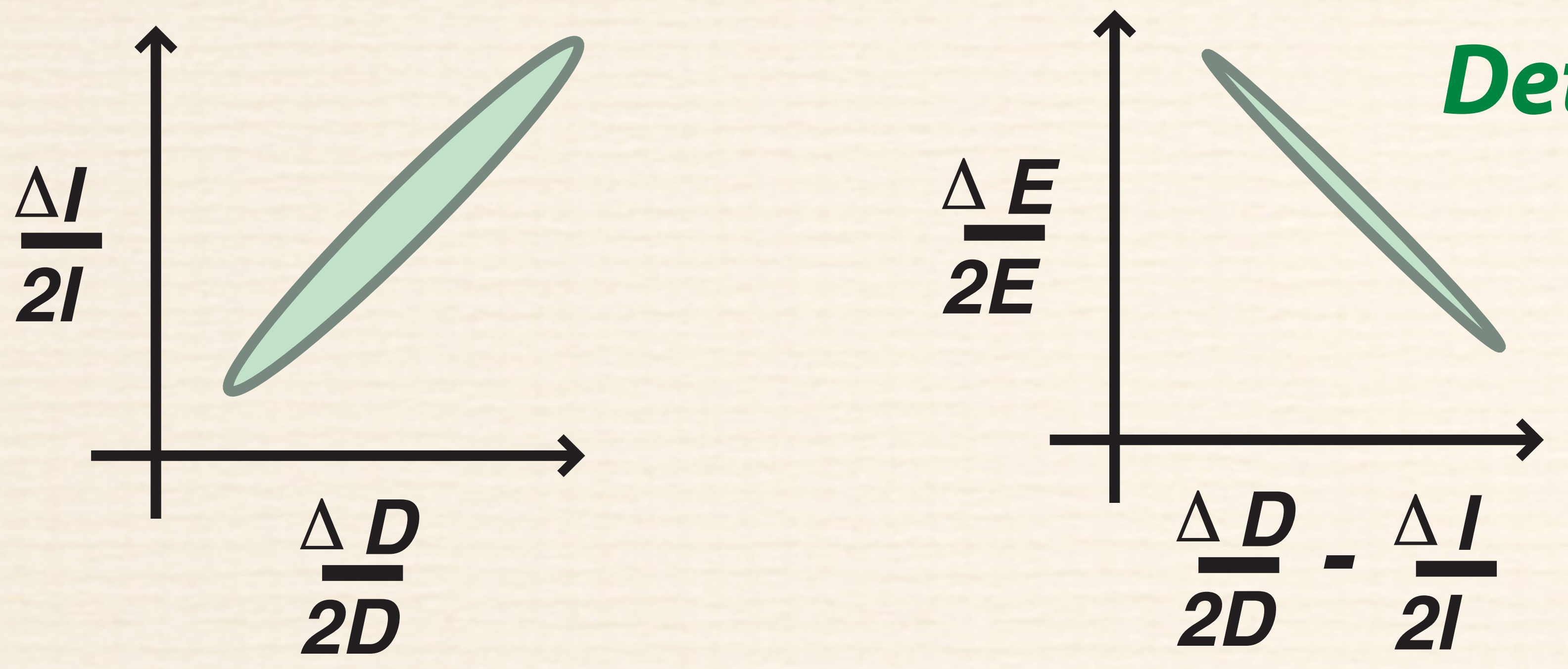

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Must minimize (both) random and helicity-correlated fluctuations in average window-pair response of electron beam trajectory, energy and spot-size.

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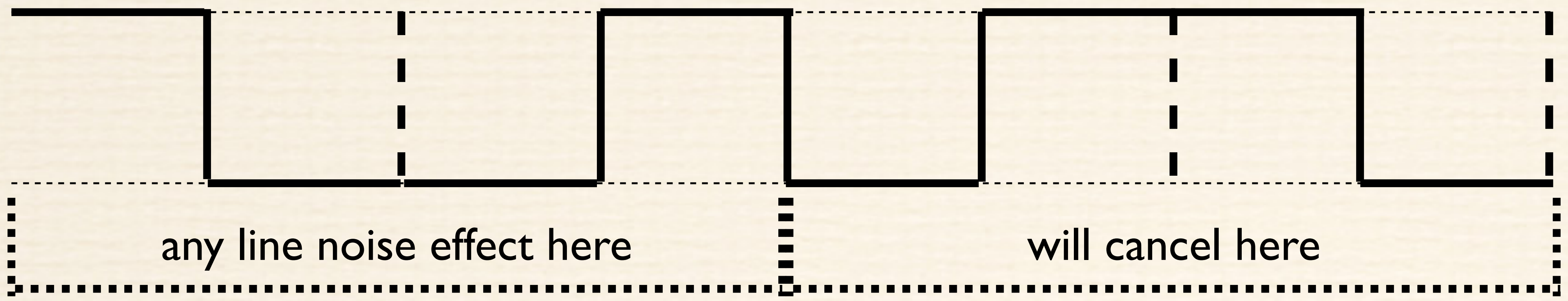

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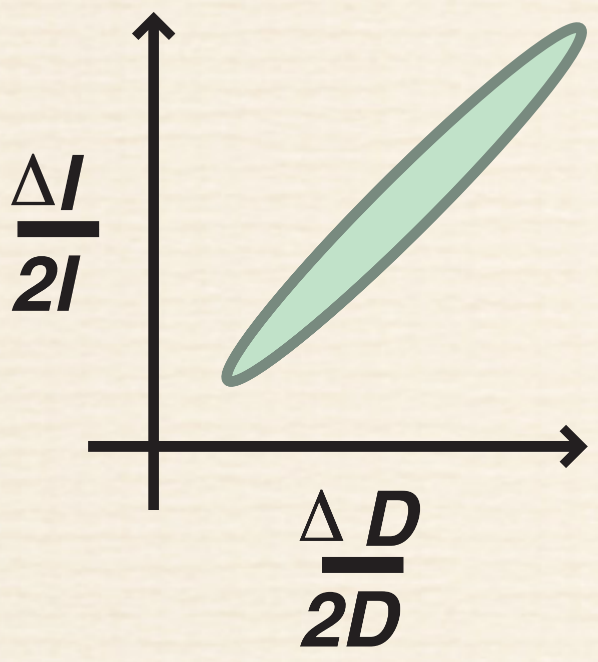

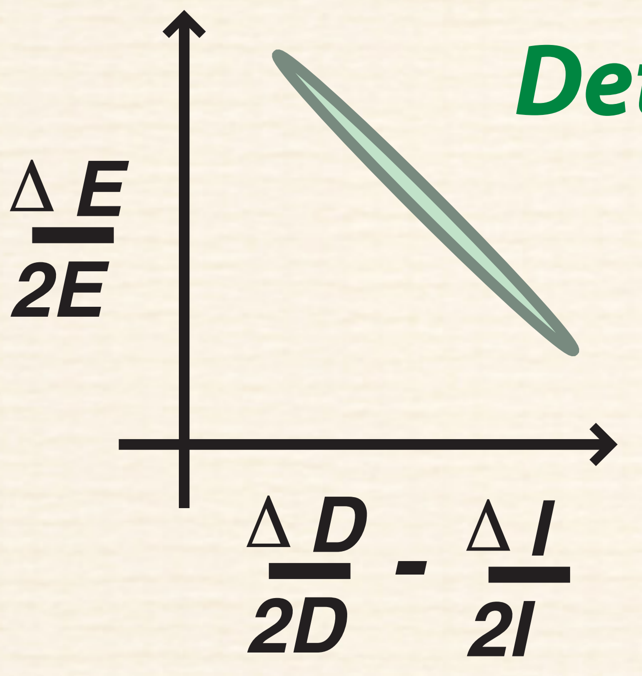

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After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm at 30 Hz; central value then reflects A_{phys}

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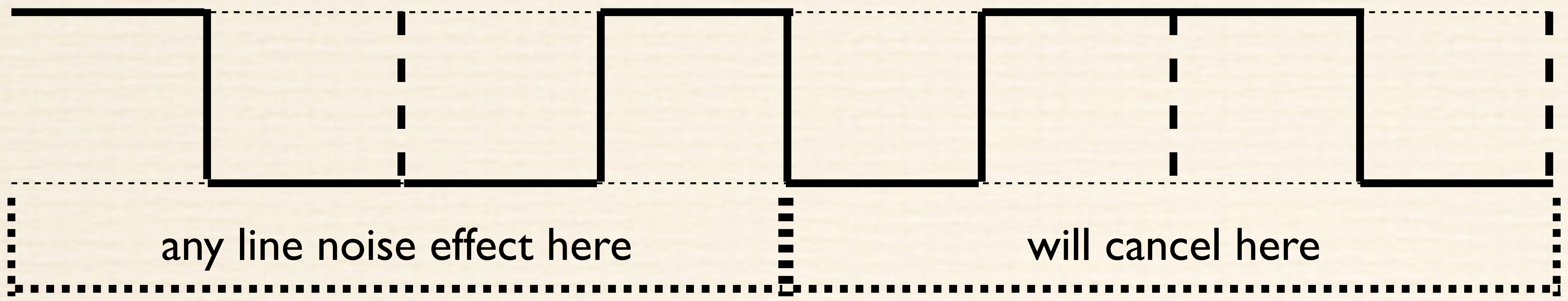

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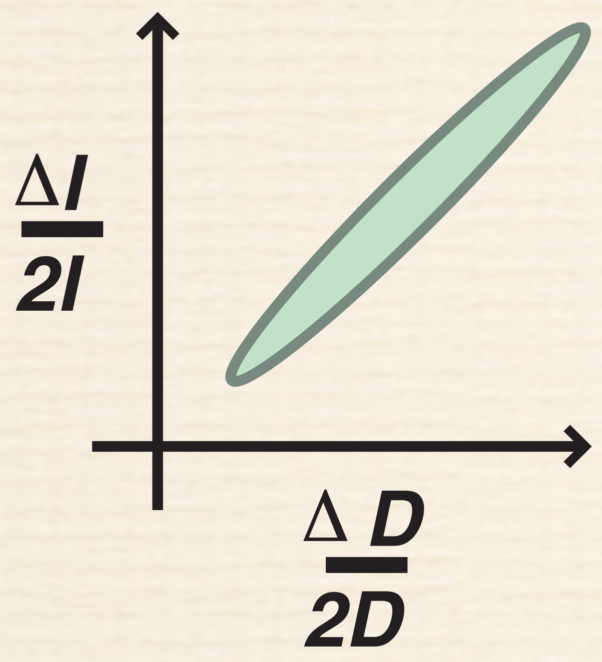

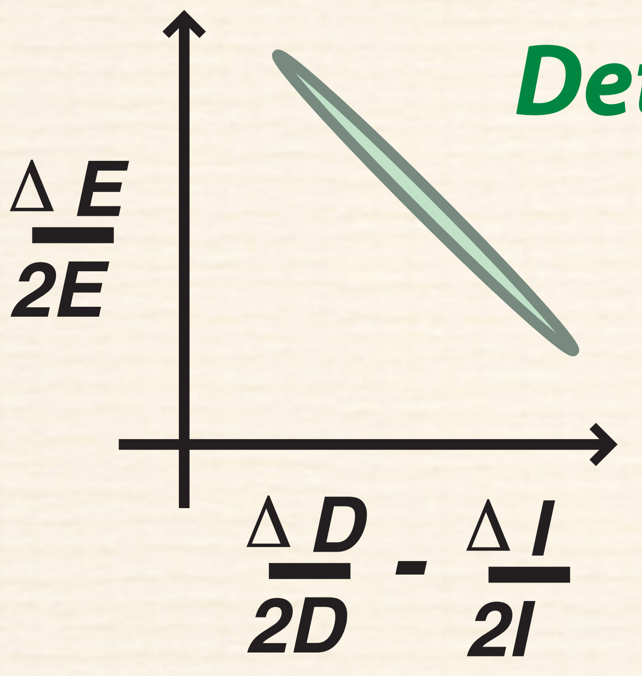

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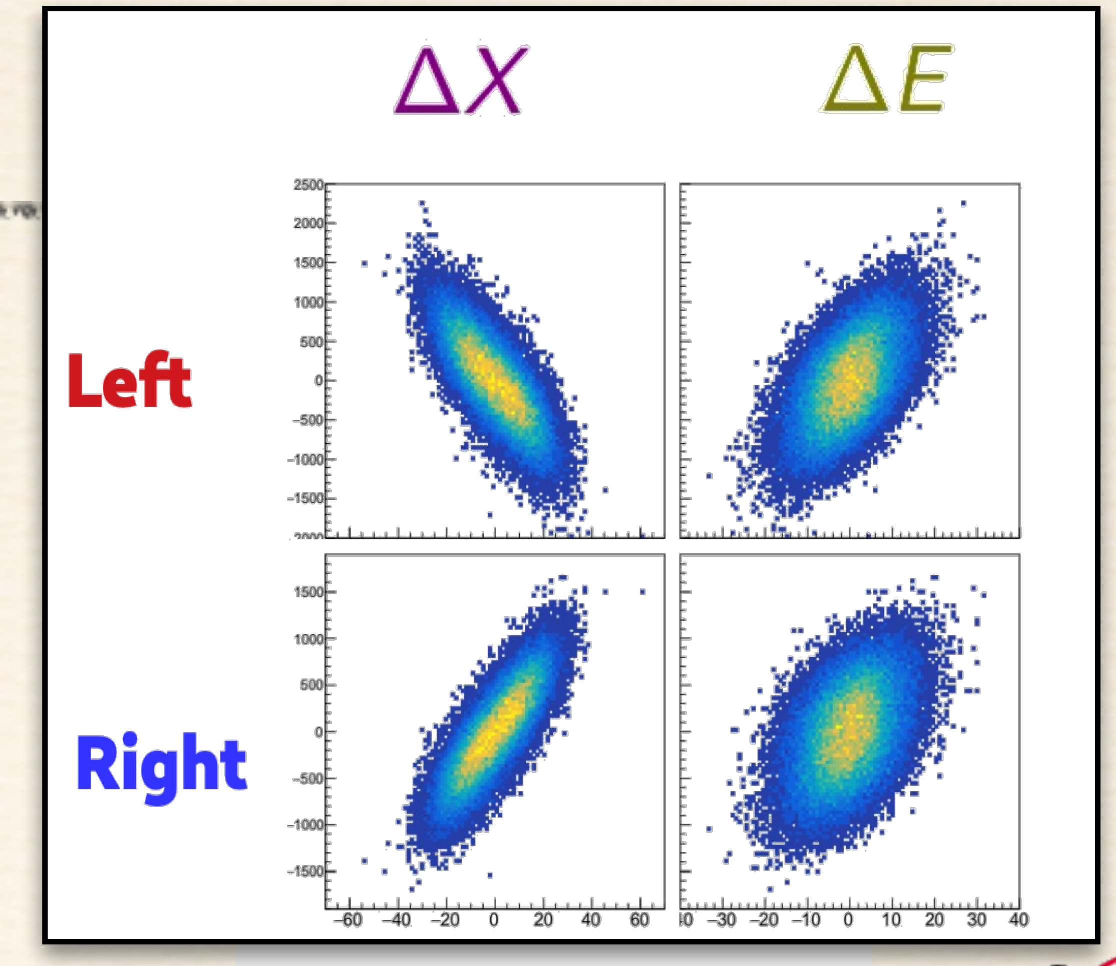
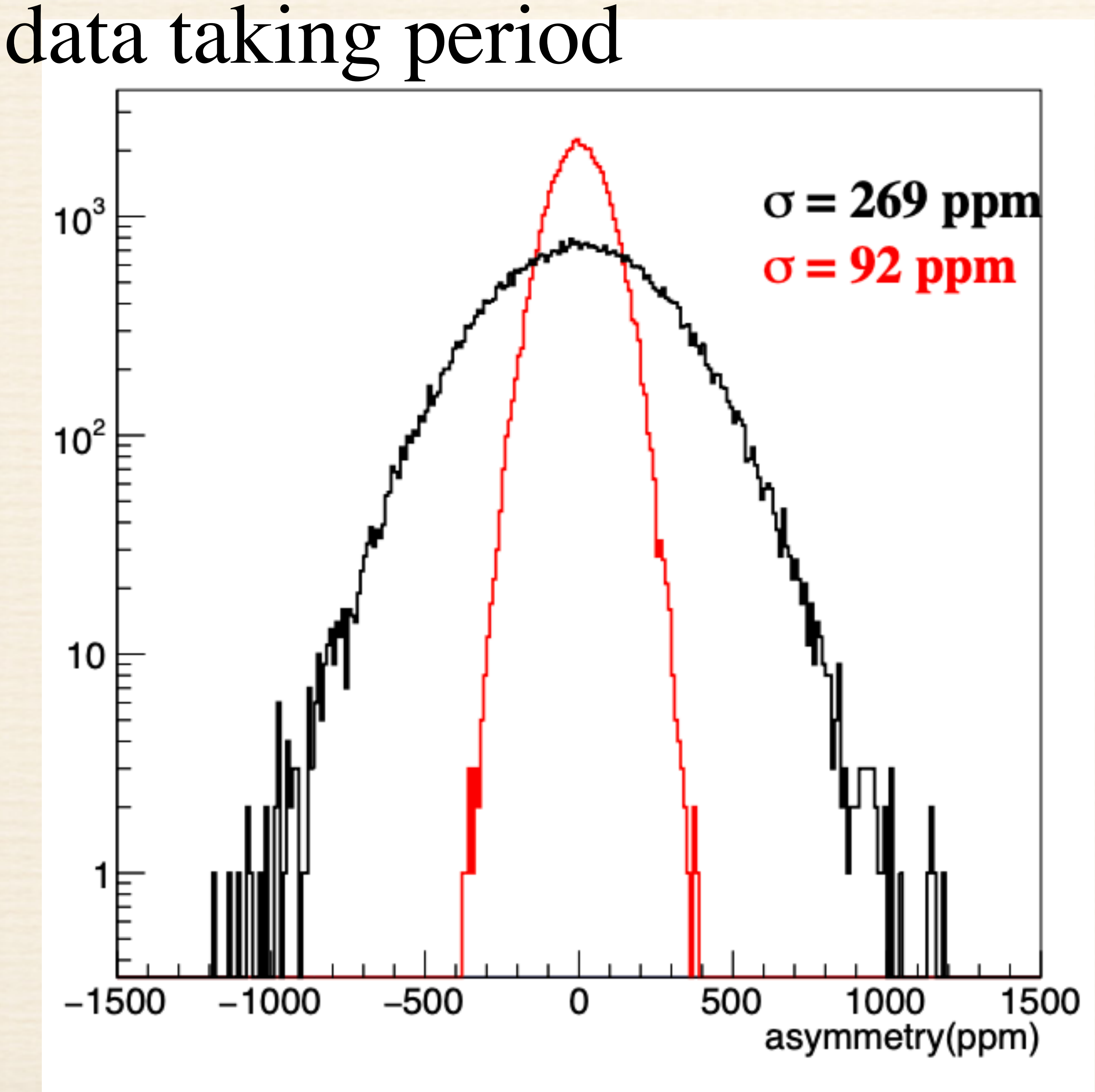
After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm at 30 Hz; central value then reflects A_{phys}

Goal: corrections no bigger than statistical uncertainty: ~ppm, microns over minutes, ~ppb, nm over days,

Corrections for Beam Fluctuations

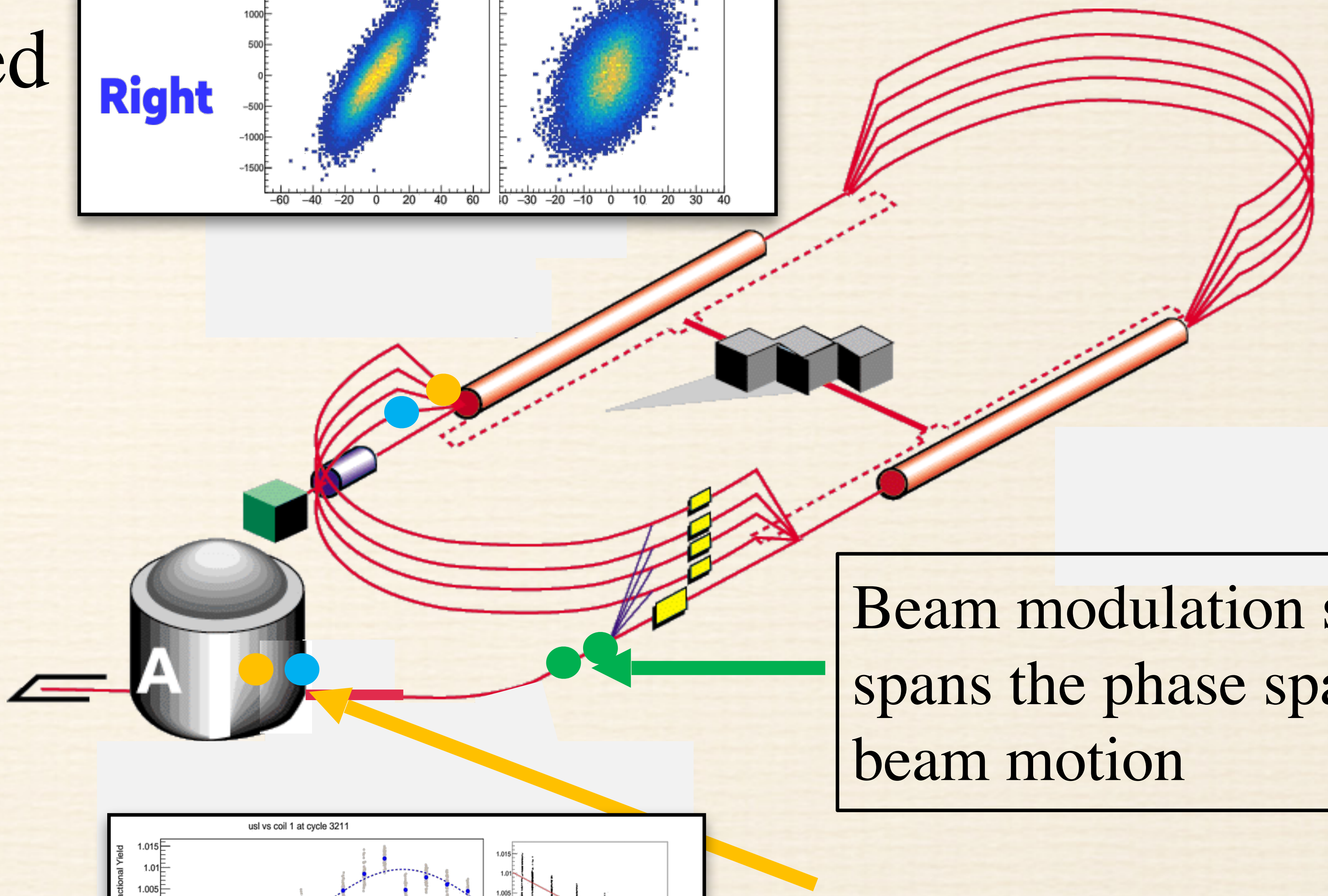
- To span the 5 dimension phase space of beam motion at the target (position, angle, energy) we made use of a set of 6 coils and an energy vernier
  - This modulation is automated and was performed throughout the data taking period



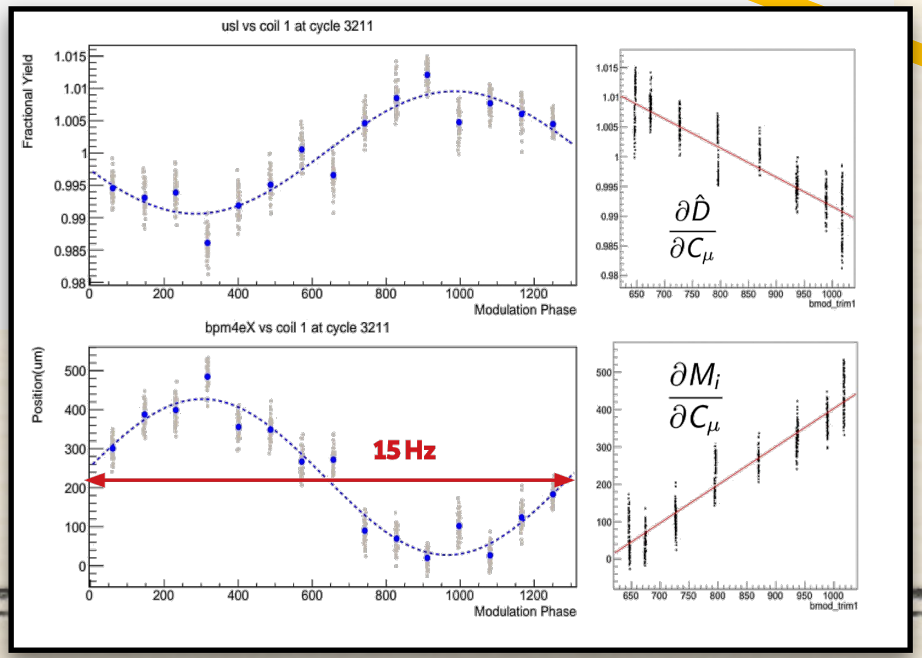


$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$

$A_{corr} \sim 500$ ppb



Beam modulation system spans the phase space of beam motion



Beam monitors determine trajectory and parameters onto target

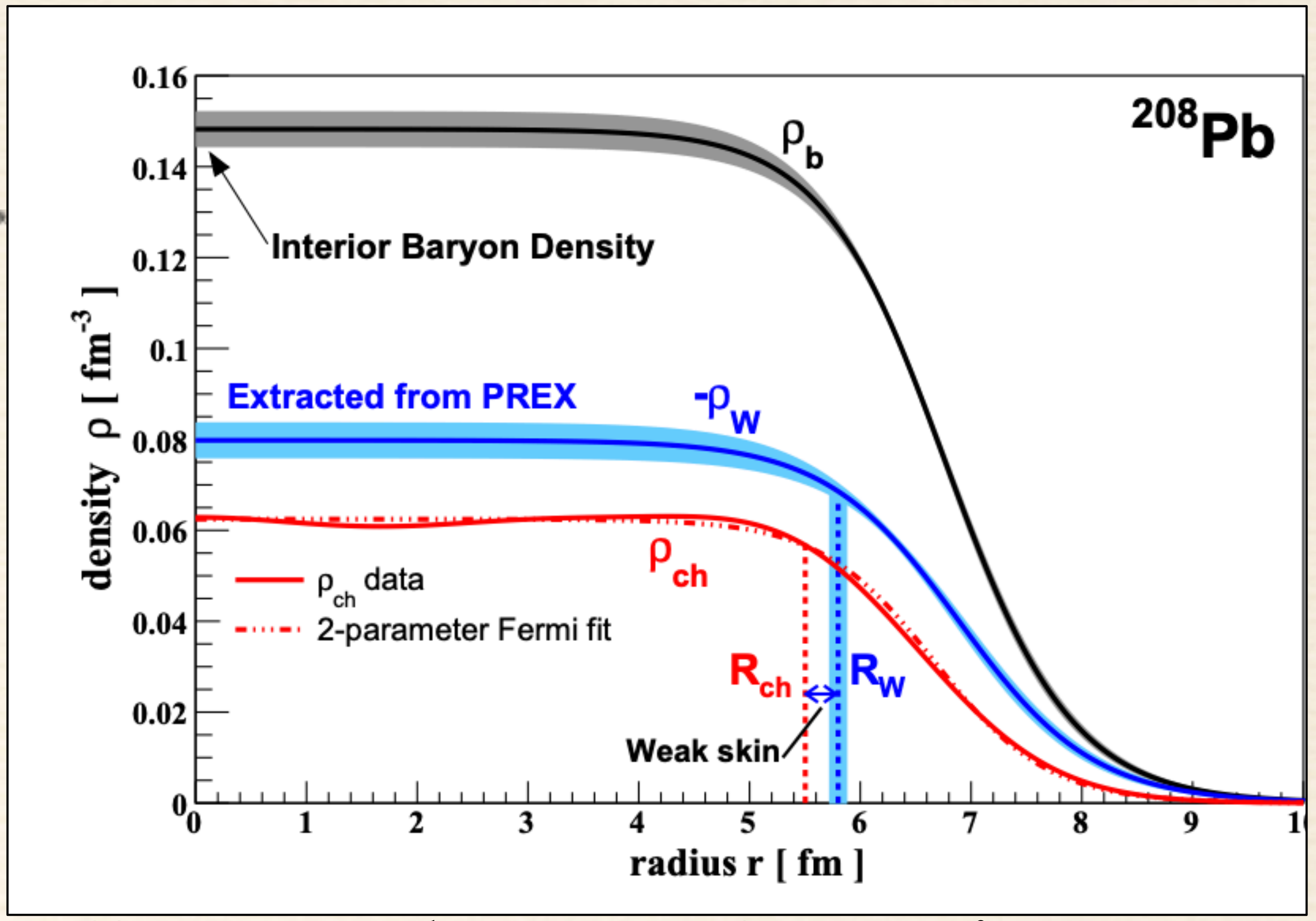
The PREX-2 Result

Measured the parity violating elastic scattering asymmetry of electrons from Pb-208 nucleus

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

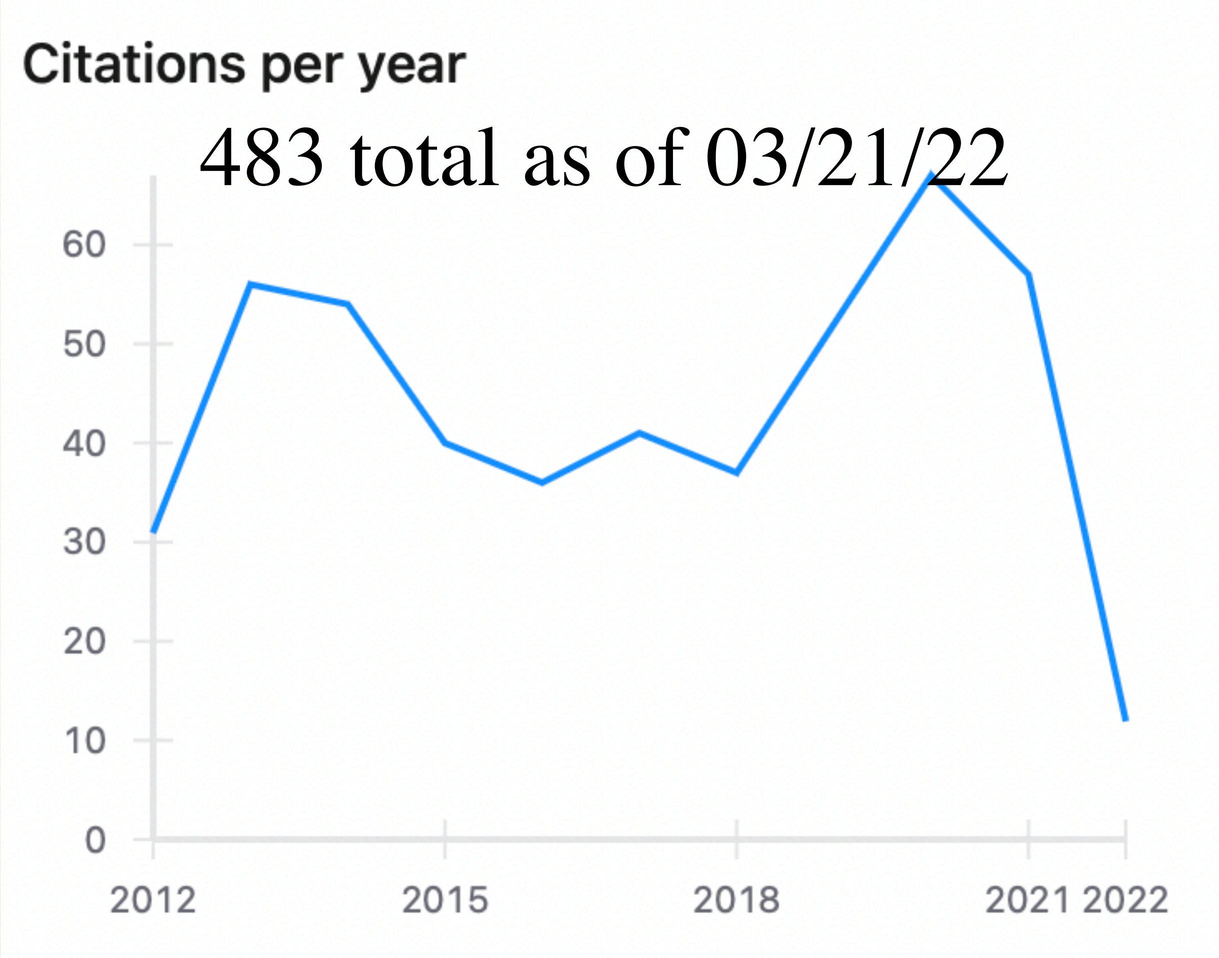
Implied neutron skin thickness

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

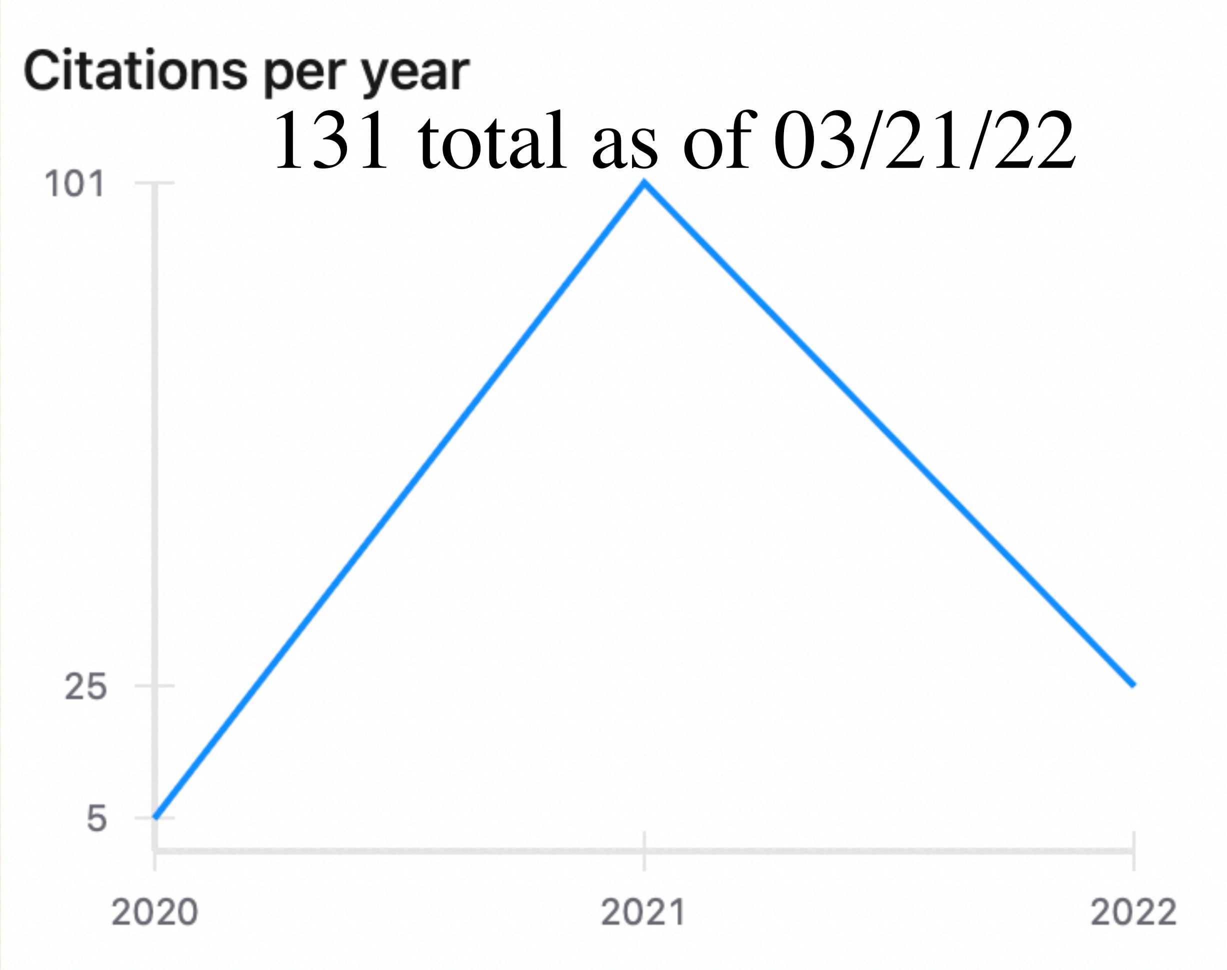


Citations indicate community interest

PREX-1 Published Jan 2012

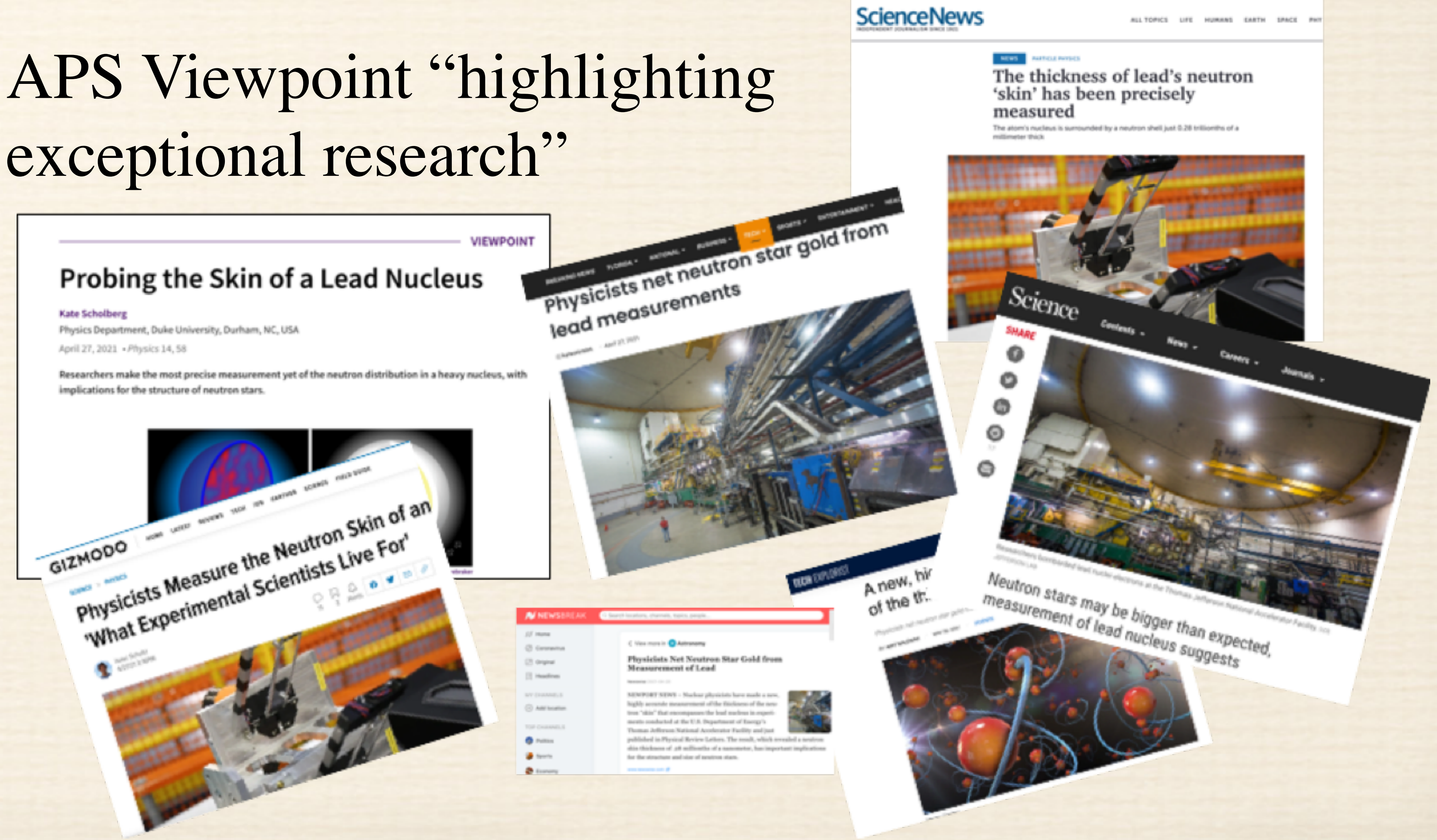


PREX-2 Published Feb 2021



Garnered Press Attention

APS Viewpoint "highlighting exceptional research"



Interest extends well beyond the electron scattering community into nuclear structure and astrophysics

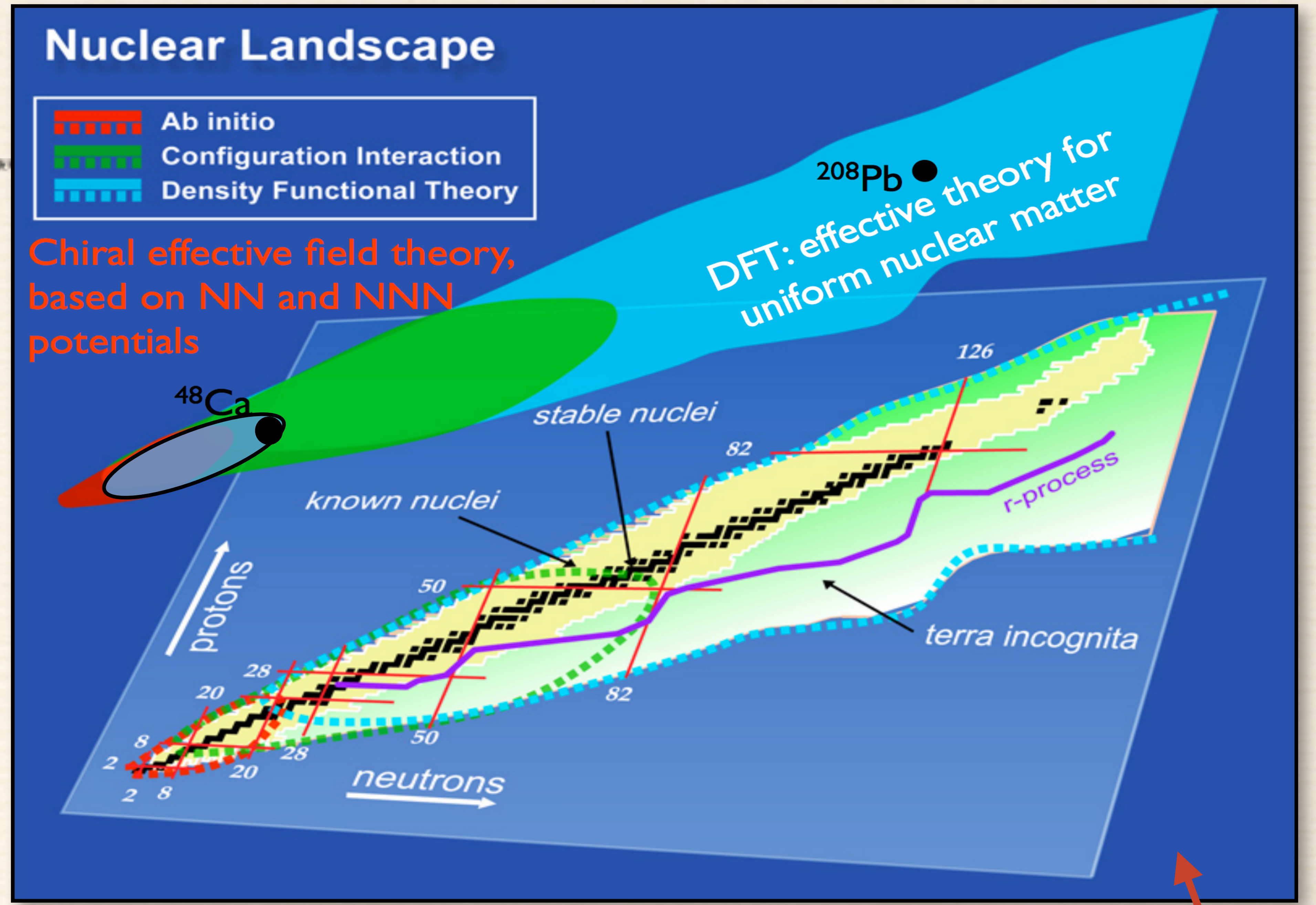
New Experimental Result: CREX

Motivation for Measuring a Second Nucleus

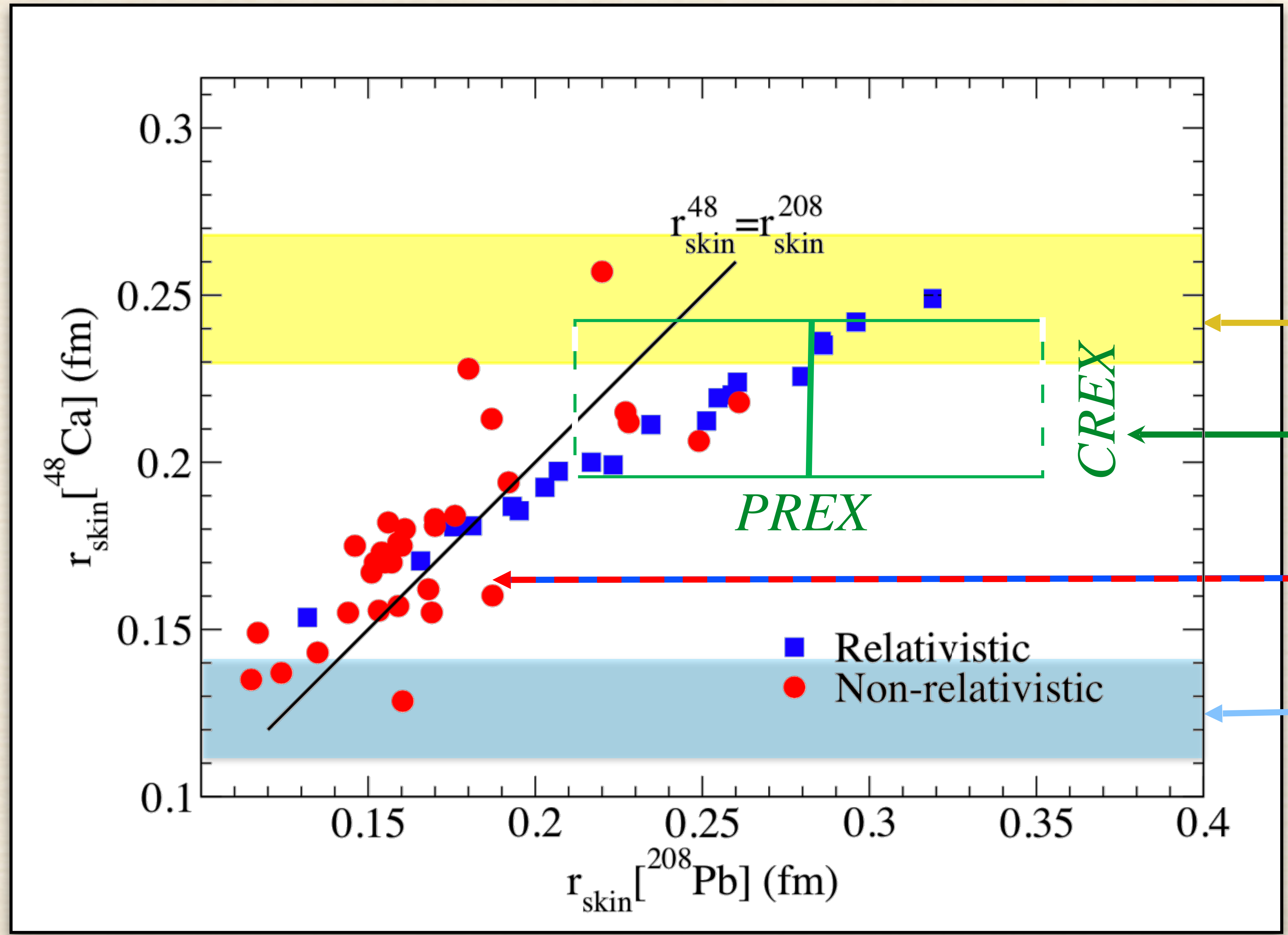
PREX: ^{208}Pb large, uniform nucleus, DFT

CREX: neutron FF ^{48}Ca

- moderate size system
- finite size effects
- Within reach of microscopic calculations (which suggest the importance of 3-nucleon forces)

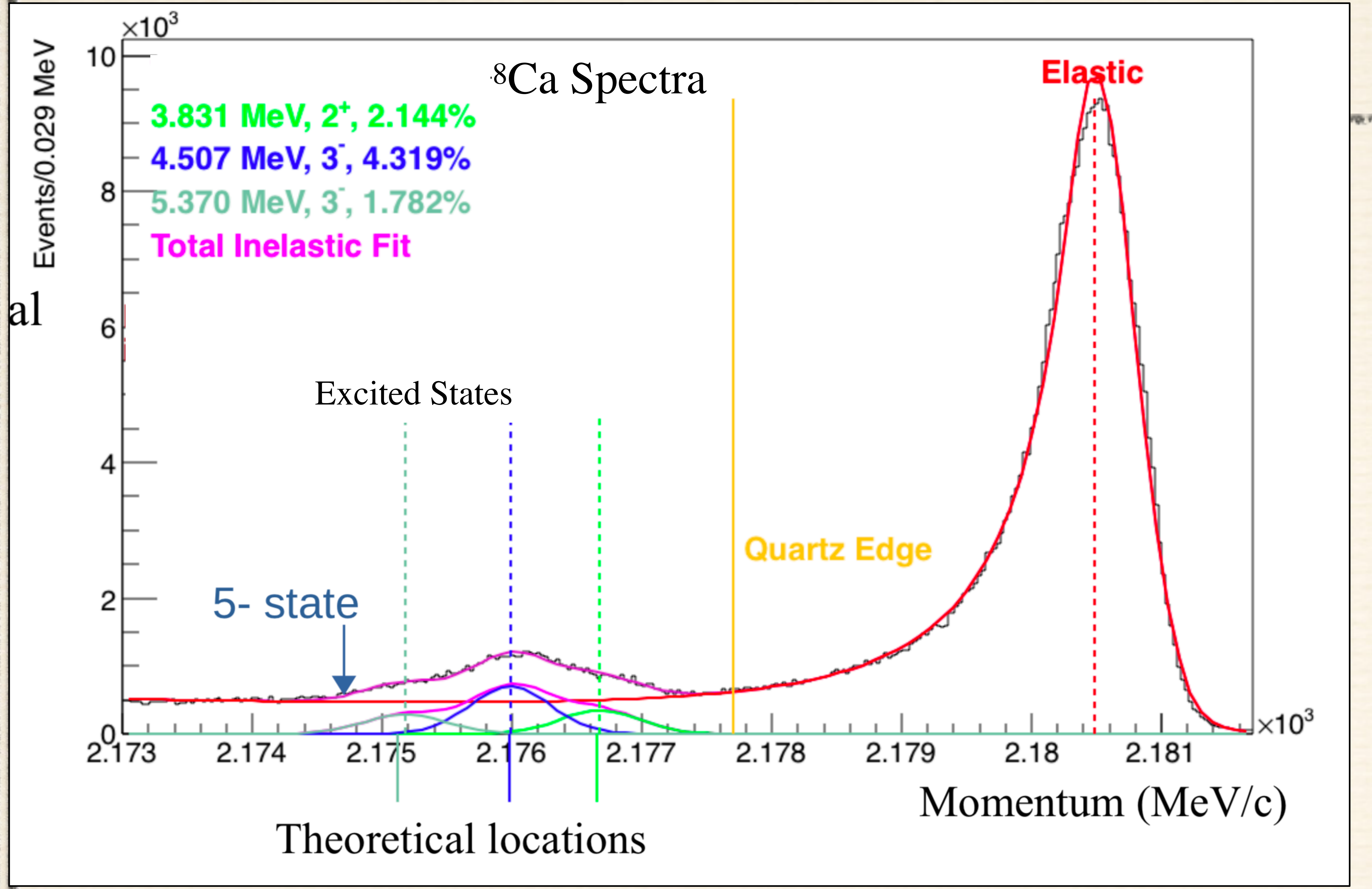


Picture likely "stolen" from this someone in this audience!!

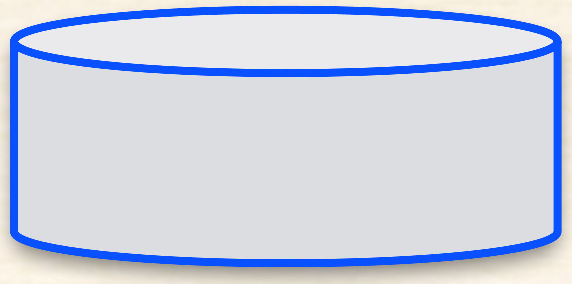


- DOM (Dispersive Optical Model)
  W. Dickoff *et al*, PRL 119, 222503(2017)
- *Arbitrary CREX central value*
- DFT (Relativistic, Non-relativistic)
  Fattoyev, Piekarewicz, PRC 85, 015802 (2012)
- Coupled cluster calculations predict a neutron skin of: $0.12 \leqq R_{skin} \leqq 0.15$ fm
  G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)

^{48}Ca Target



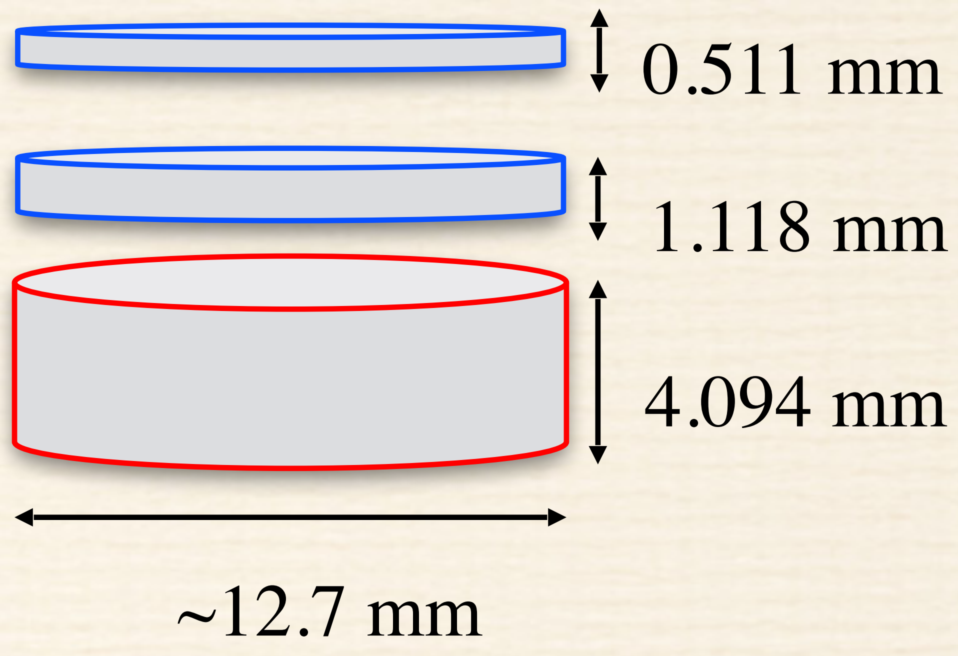
Target 1



Element:	Calcium
Symbol:	Ca
Isotope:	48
Series:	LO
Batch:	140042

- Single puck
- 5mm thick
- 96% ^{48}Ca
- 3.84% ^{40}Ca

Target 2



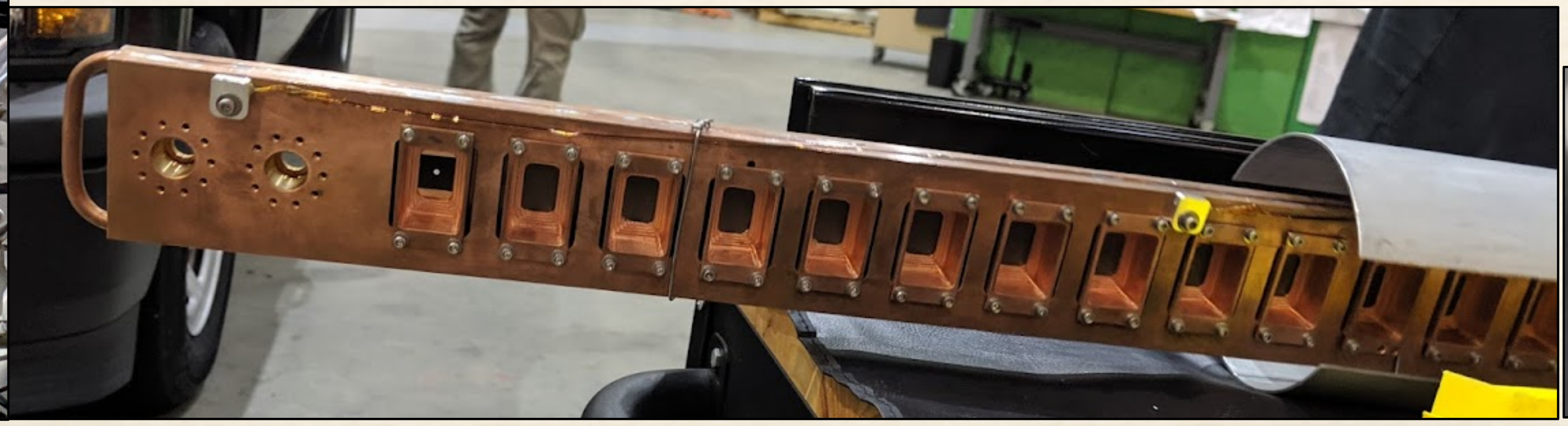
Element:	Calcium
Symbol:	Ca
Isotope:	48
Series:	
Batch:	900242

*Oak Ridge

- 1puck+2 foils sandwiched
- ~5.7mm thick total
- ~91.7% ^{48}Ca
- ~7.96% ^{40}Ca

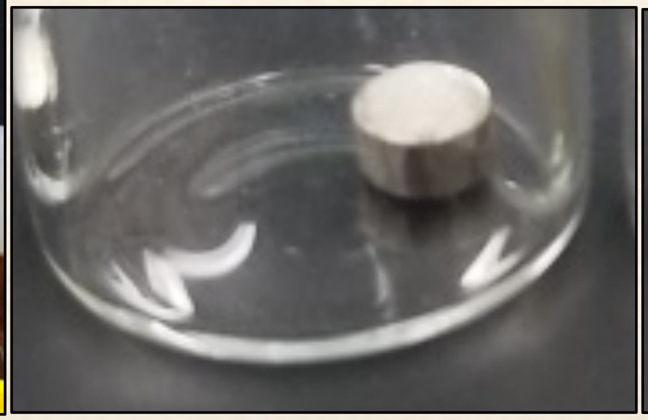
Delicate Installation

Cooled Copper Target Ladder

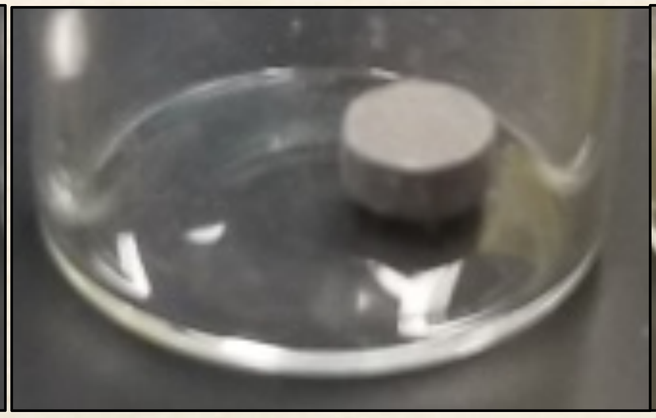


Stored in mineral oil until installed
Protected against oxidation

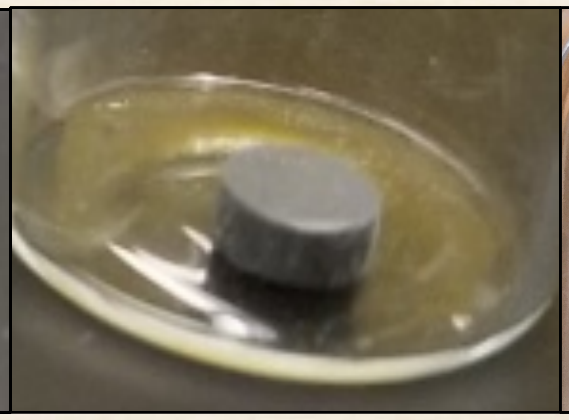
sanded



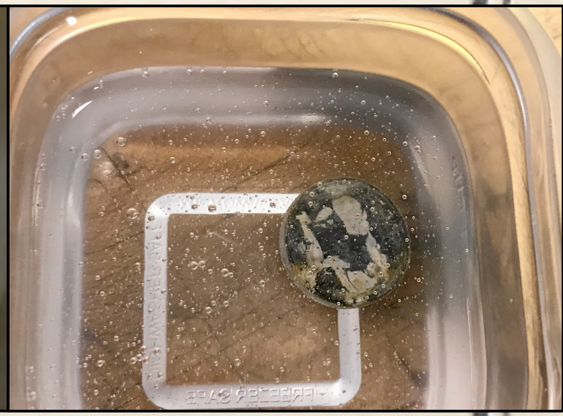
Oxidized 1hr



Oxidized 24hr



mineral oil



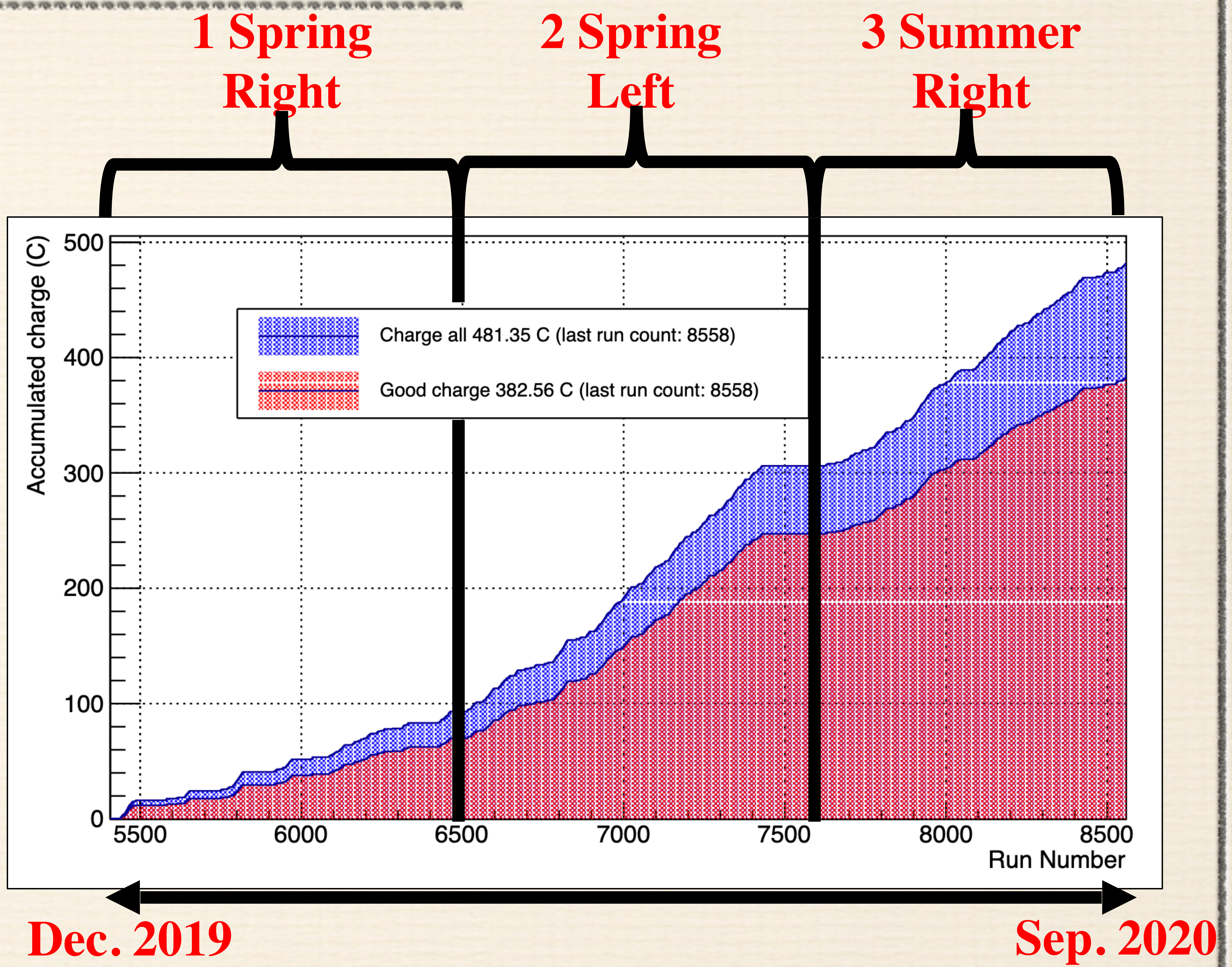
The CREX Physics Runs

13 Ph.D. students, 7 postdocs, a total of about 80 scientists

Data Divided Into 3 Run Periods

- Part 1) Wien* Right Spring
- Part 2) Wien* Left Spring
  …Covid hit….
- Part 3) Wien* Right Summer
- * "Wien" = Spin Manipulator

- Very close watch on-line data stream - beam conditions, detector response, etc.
- Frequent contact with MCC operators to maintain running conditions
- "prompt" analysis process flagged more subtle problems
- Daily grooming and review in "WAC" process
- (analysis development leader Paul King)



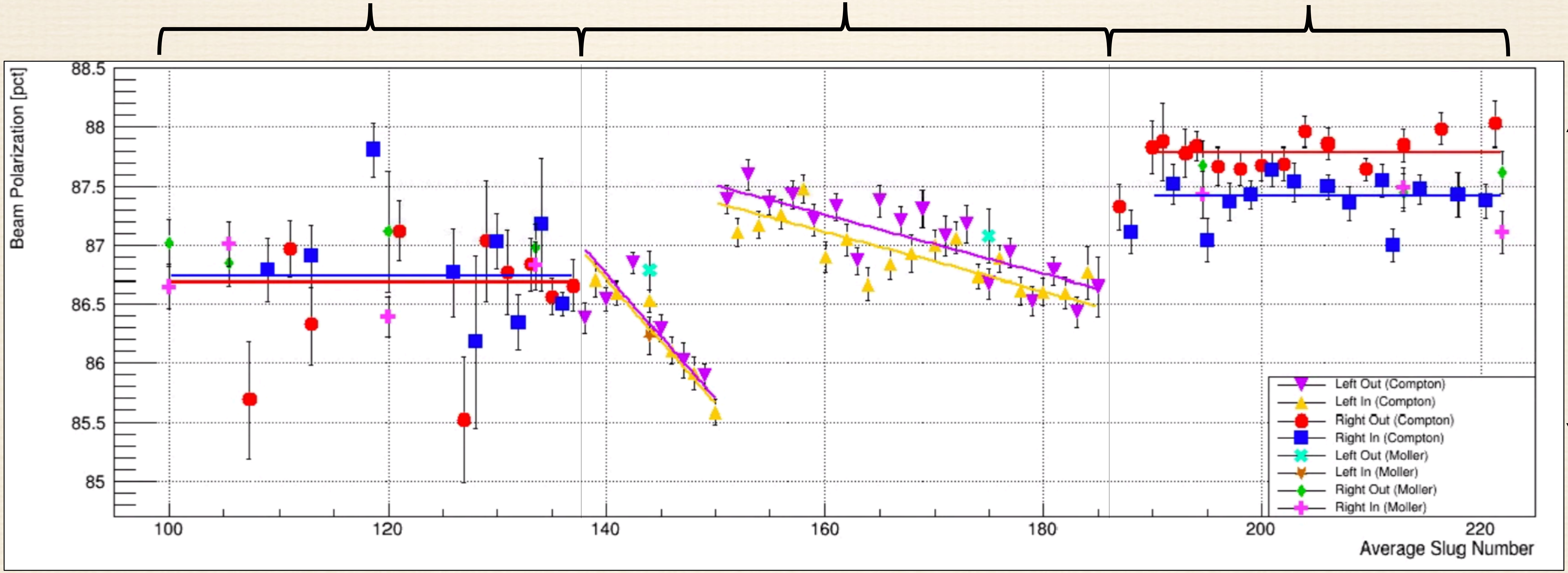
- **At the end of the experiment after our realtime analysis we collected about 383 C of charge on target which passed online analysis cuts(i.e. not excluded in calibrations or due to poor beam conditions, trip recovery, beam excursions, or beam monitor issues)**

Beam Polarimetry

1 Spring
Right (In/Out)

2 Spring
Left (In/Out)

3 Summer
Right (In/Out)



Spans ~ +-1.3% relative error

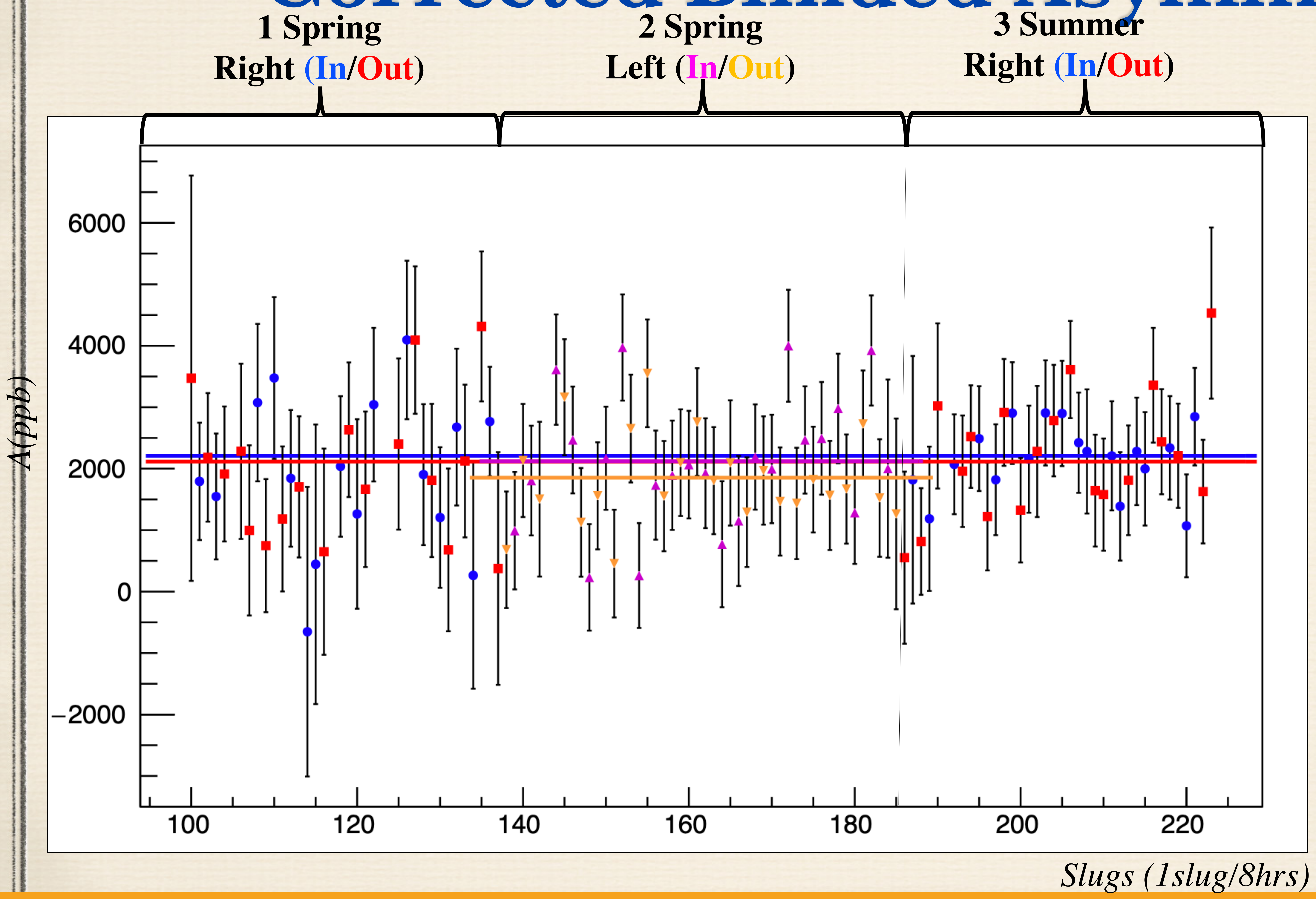
Acknowledgments: A.J. Zec, J. C. Cornejo, M. Dalton, C. Gal, D. Gaskell, C. Palatchi, K. Paschke, A. Premithilake, B. Quinn

Average Compton polarization:
87.10 ± (0.52% dP/P)

CREX Polarimetry Result:
P_e=87.09 +/- (0.44% dP/P)

Average Moller polarization:
87.06 ± (0.85% dP/P)

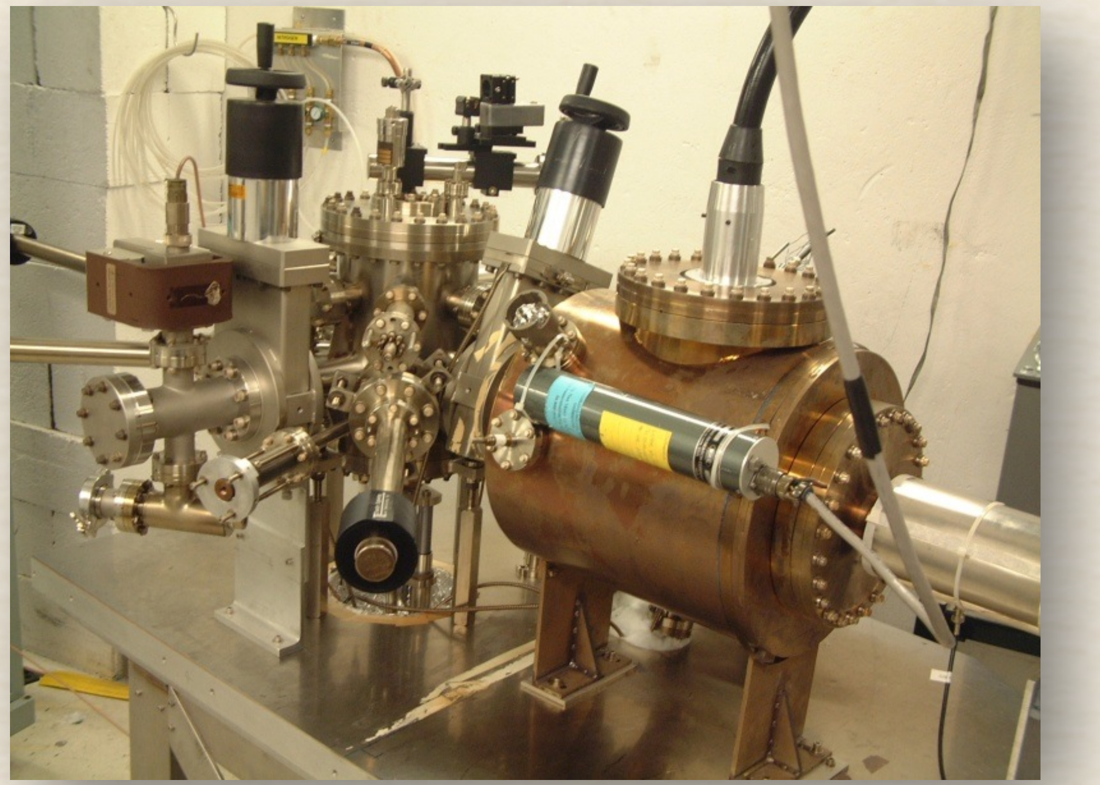
Corrected Blinded Asymmetries



We were looking at the final data set after carefully removing unstable run periods with multiple checks on log books by about the middle of Summer 2021

Statistical Uncertainty: 80 to 90 parts per billion

Stability of Polarized Beam at JLab



Beam helicity is chosen pseudo-randomly at 30 Hz

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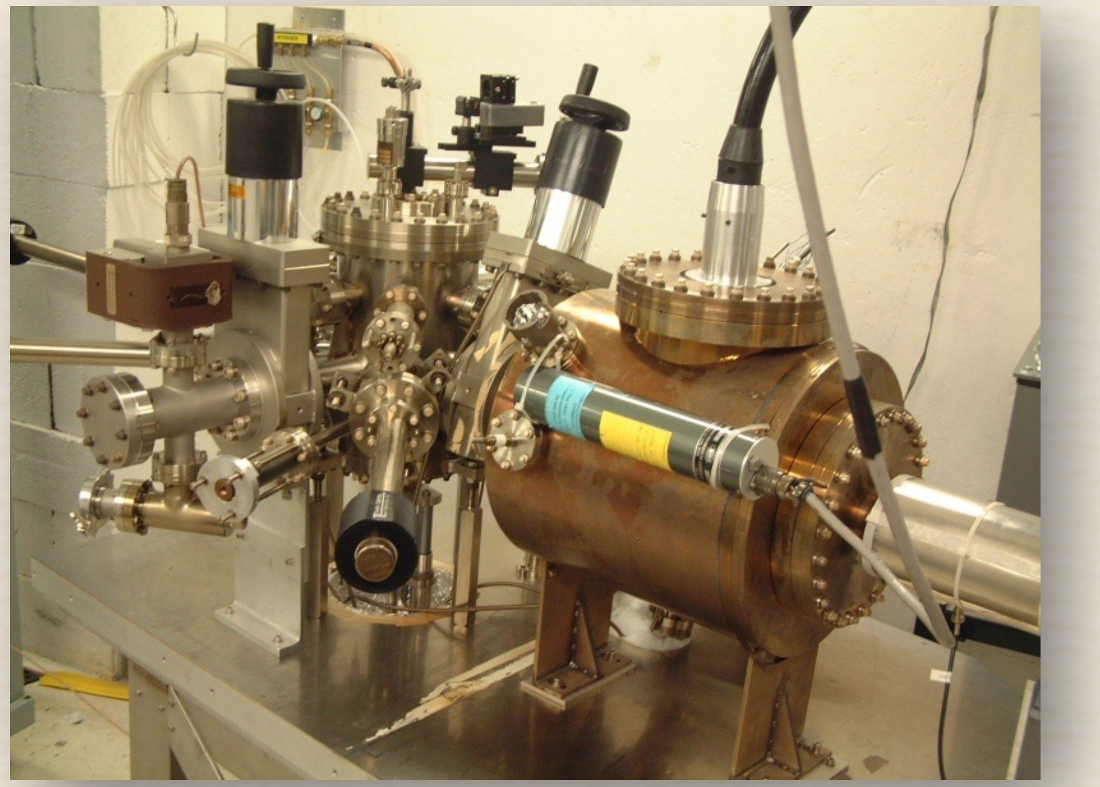

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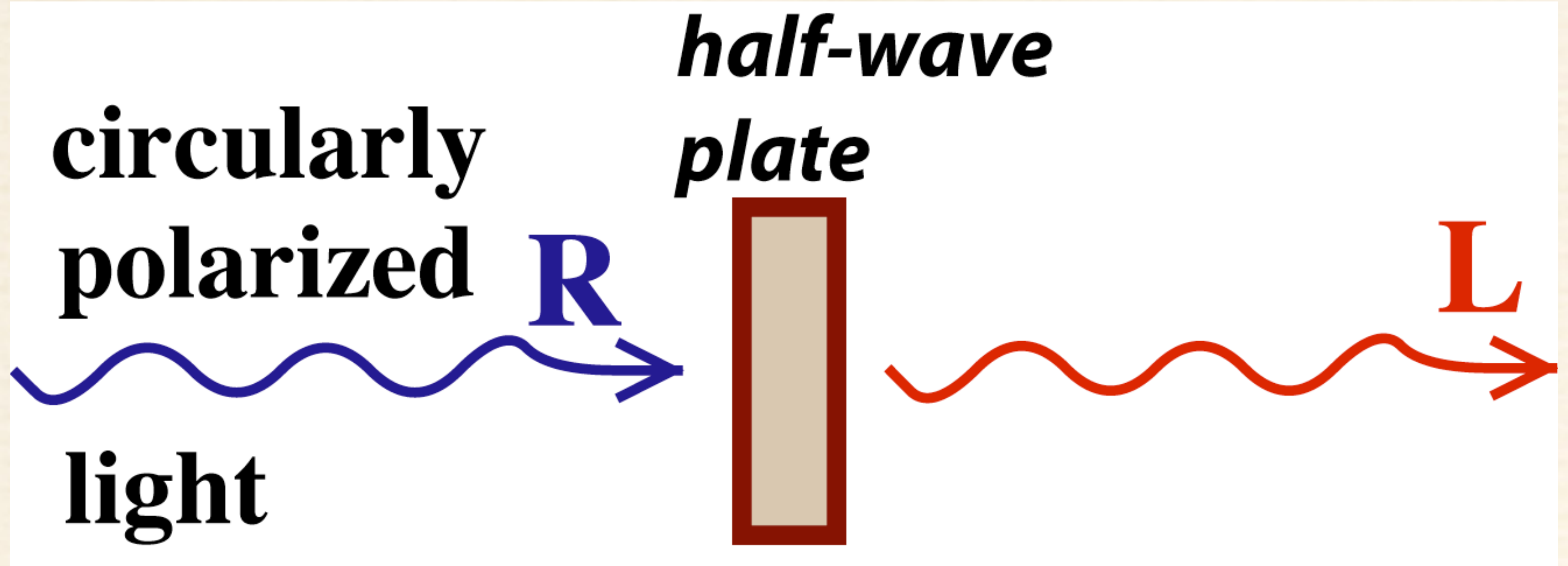

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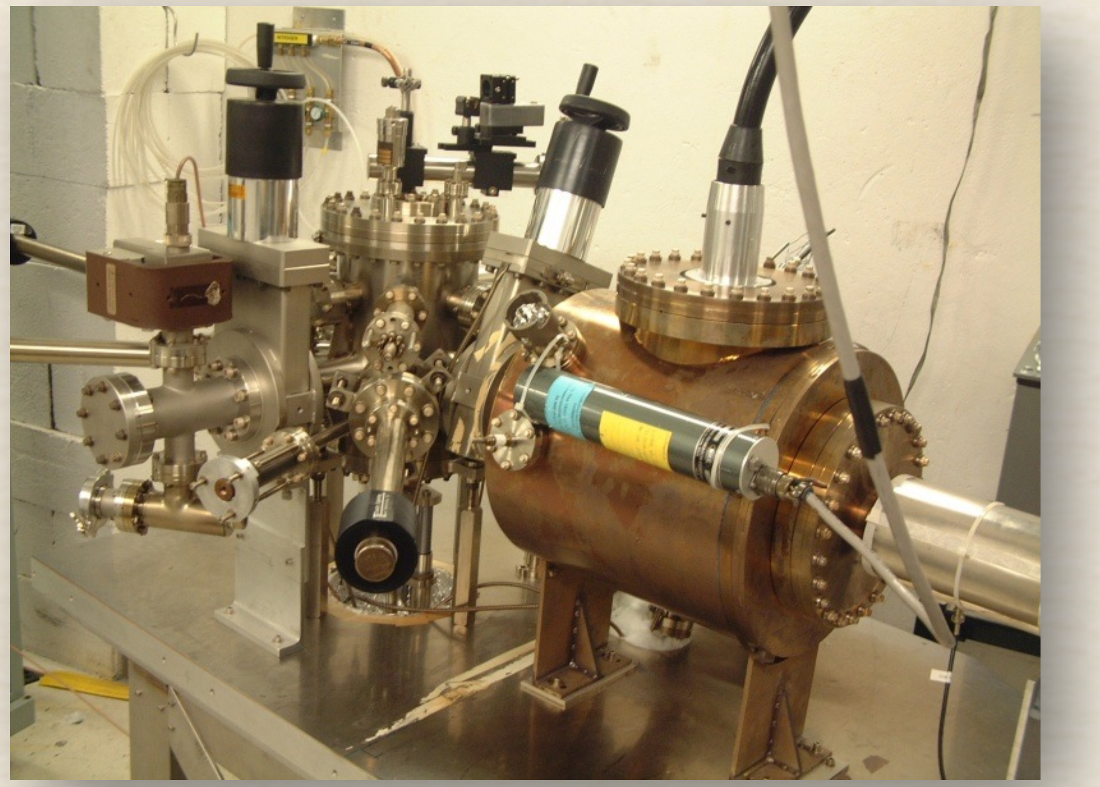

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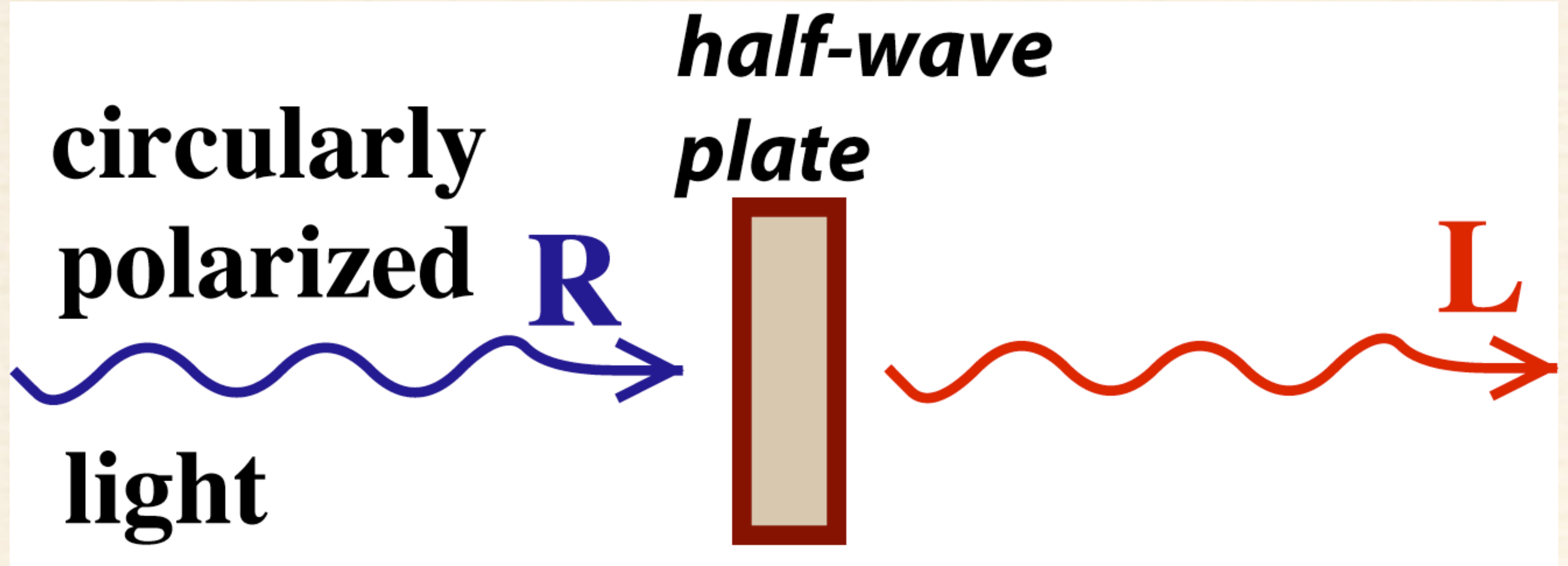

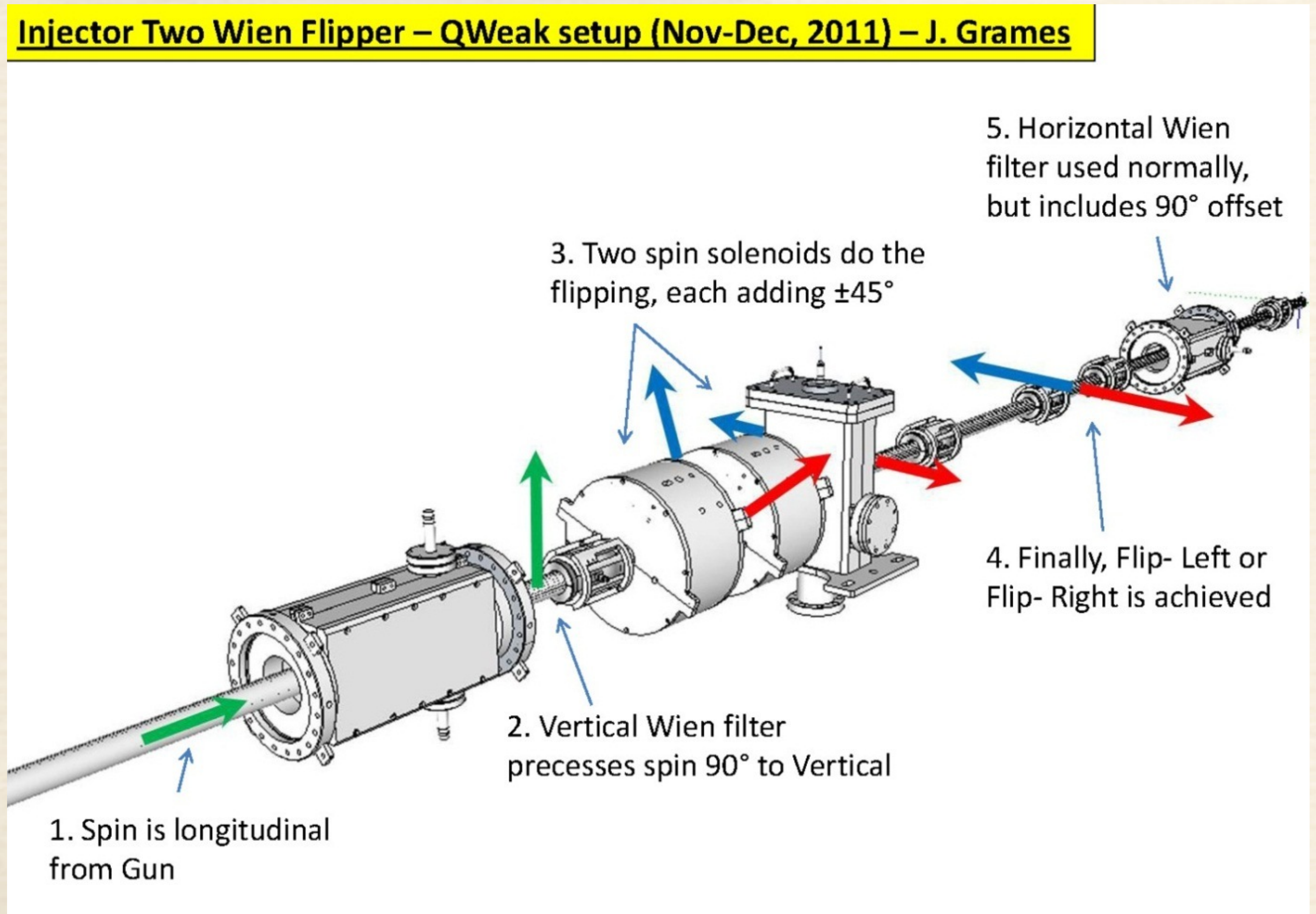

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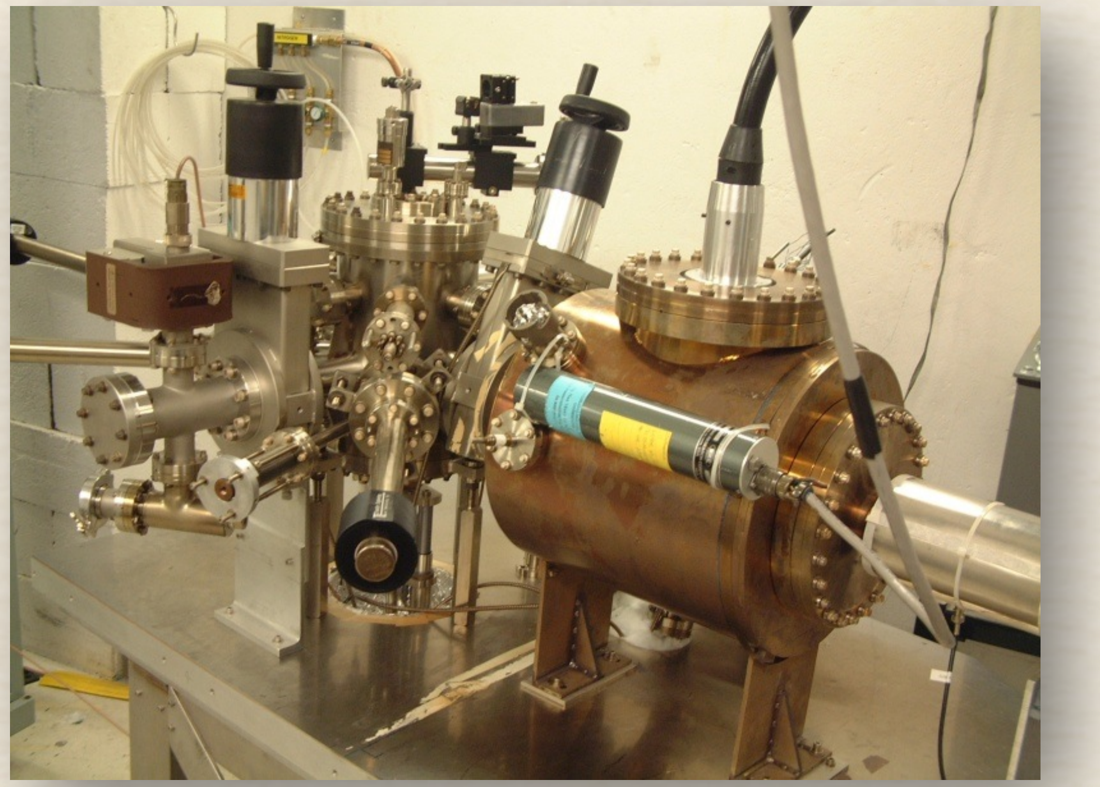
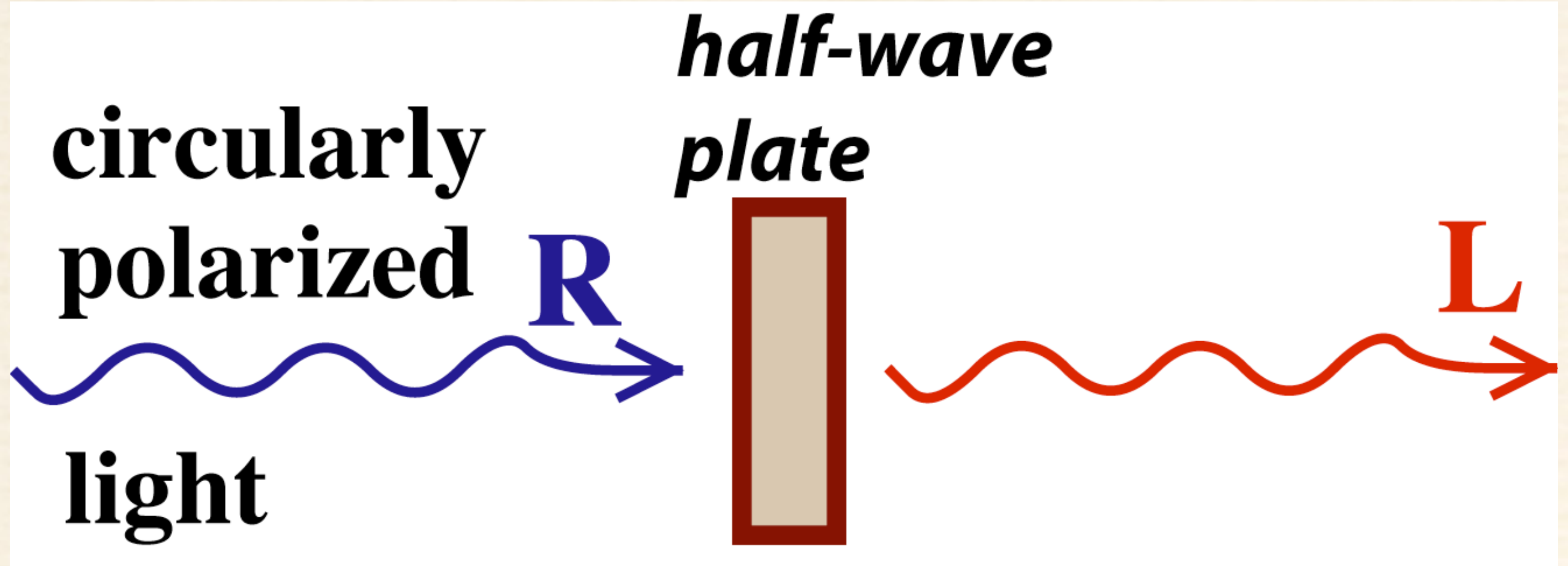
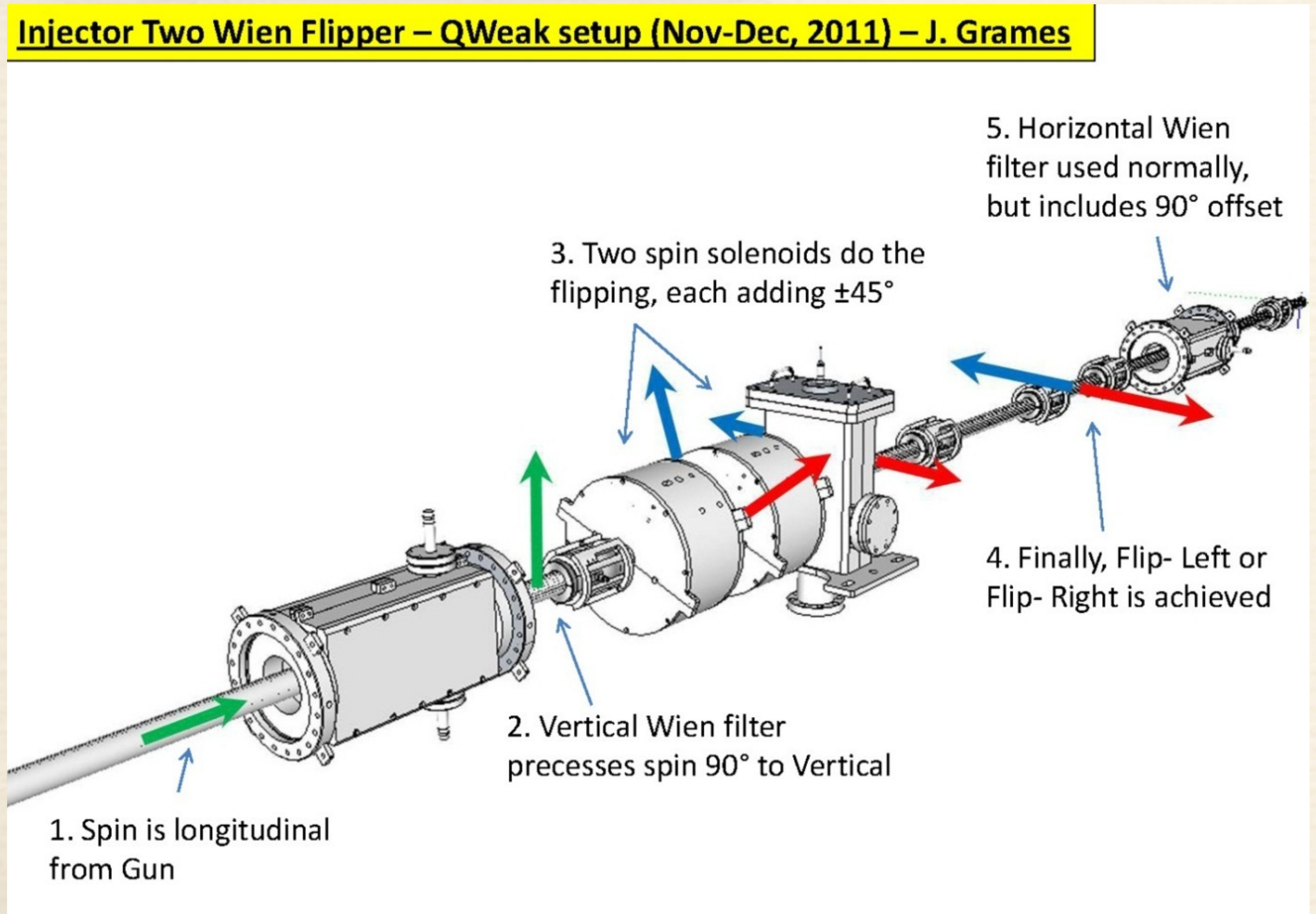


Beam helicity is chosen pseudo-randomly at 30 Hz

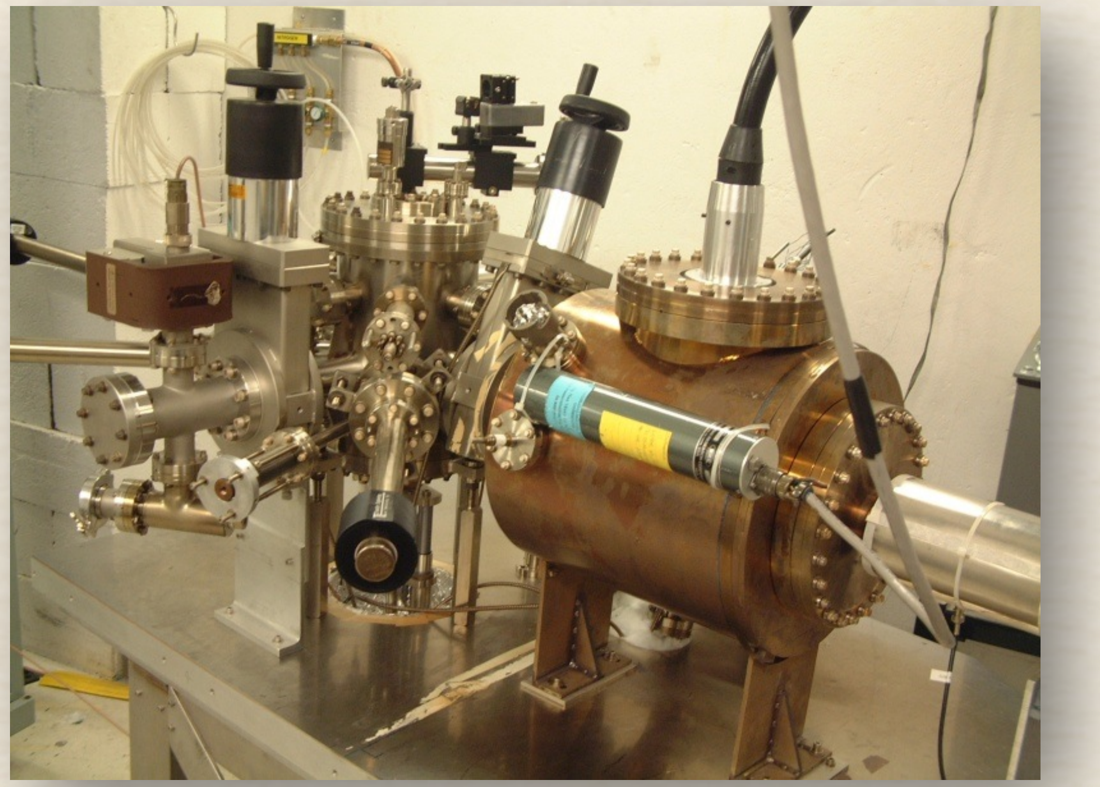


$A_{corr} \sim 2000$ ppb

$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$



Stability of Polarized Beam at JLab



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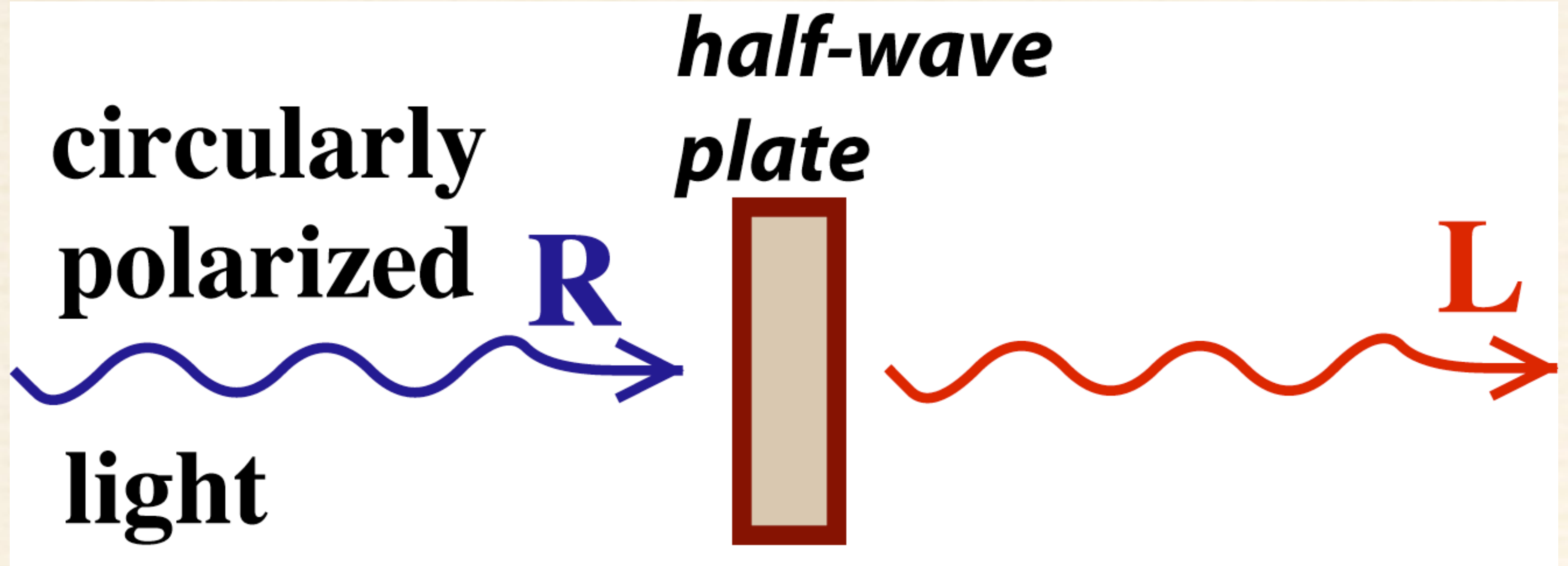

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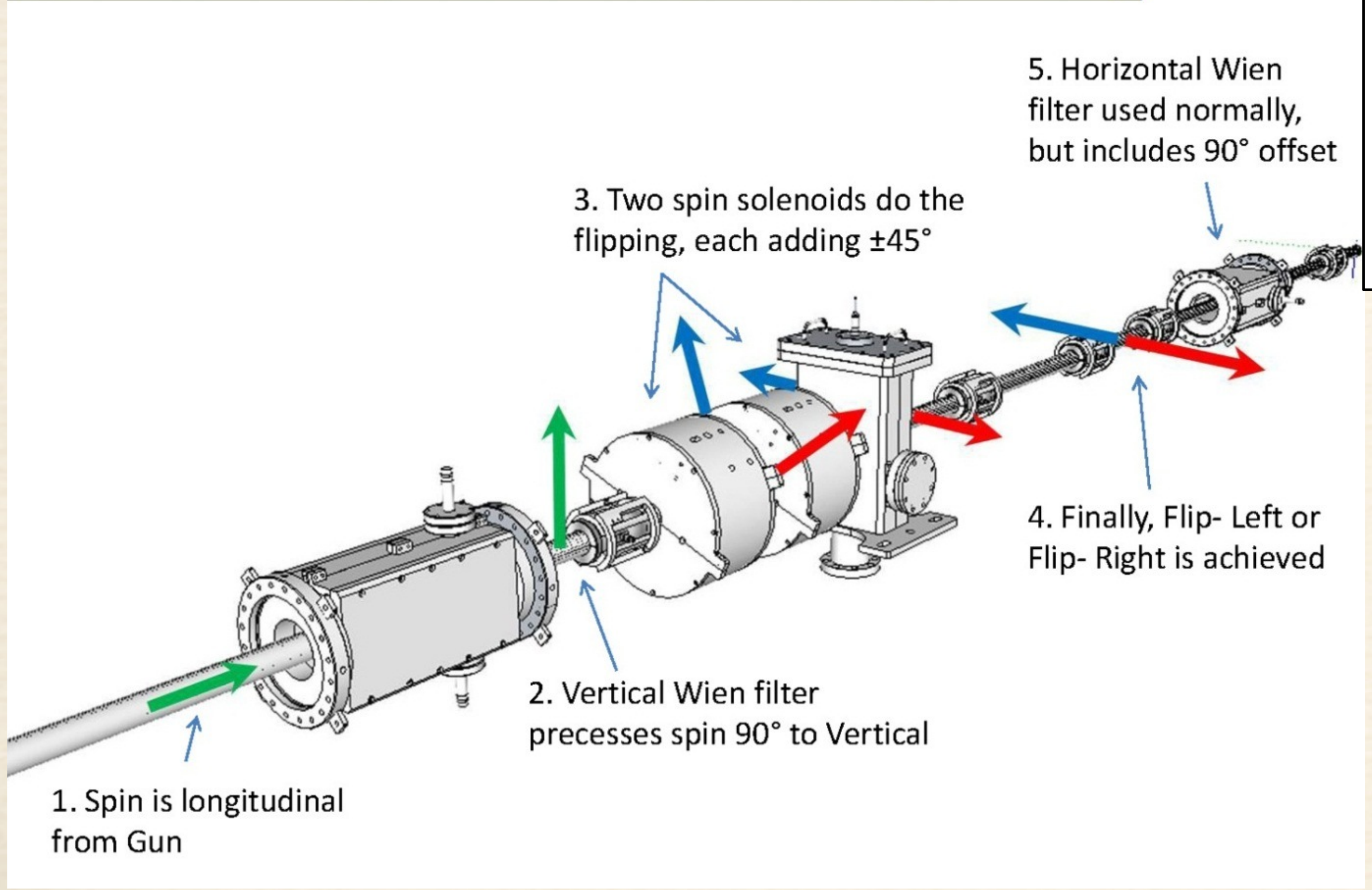
Injector Two Wien Flipper – QWeak setup (Nov-Dec, 2011) – J. Grames



Wien	Weight	X (nm)	Y (nm)	θ X (nrad)	θ Y (nrad)	E dpp
R 1	18.0%	1.6 ± 3.7	-2.4 ± 2.0	-0.26 ± 0.17	-0.11 ± 0.12	$-2.0 \pm 2.0e^{-9}$
Left	45.2%	-4.1 ± 1.6	0.3 ± 1.1	0.08 ± 0.04	-0.024 ± 0.10	$0.32 \pm 1.5e^{-9}$
R 2	36.9%	-2.8 ± 4.1	-0.2 ± 1.7	-0.06 ± 0.09	-0.28 ± 0.17	$0.84 \pm 1.9e^{-9}$
	Avg	-2.6 ± 1.8	-0.4 ± 0.9	-0.03 ± 0.05	-0.13 ± 0.08	$0.09 \pm 1.0e^{-9}$

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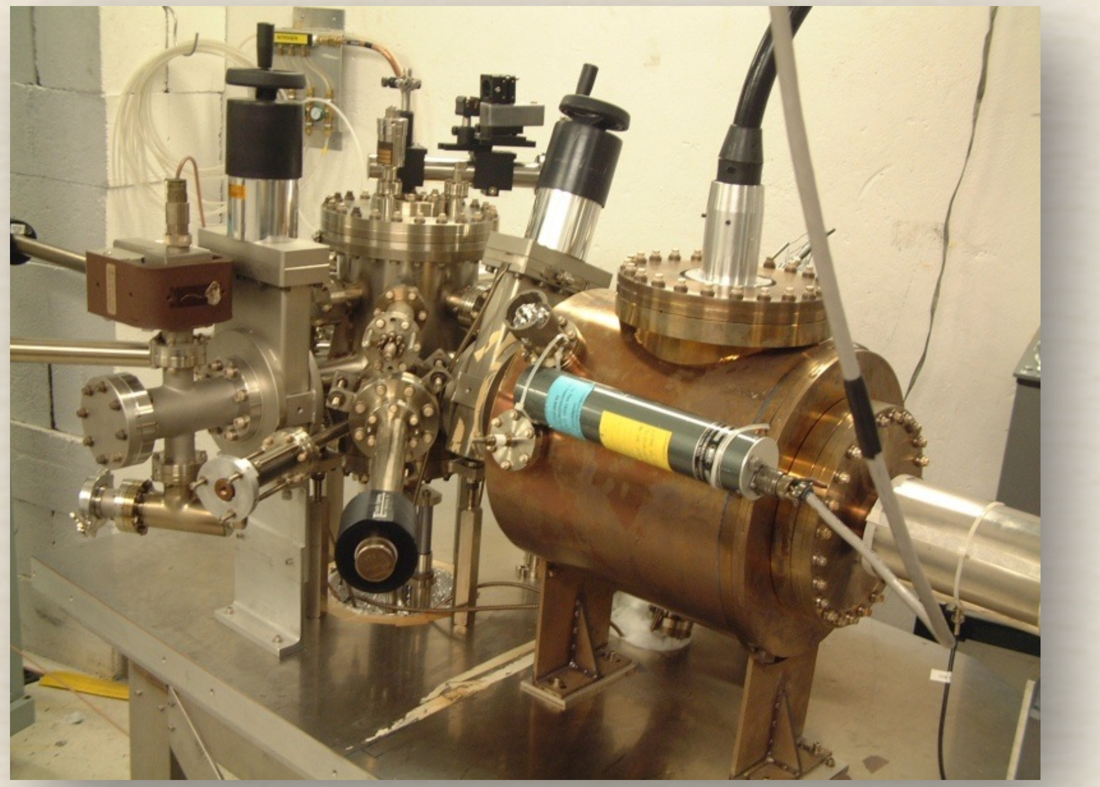

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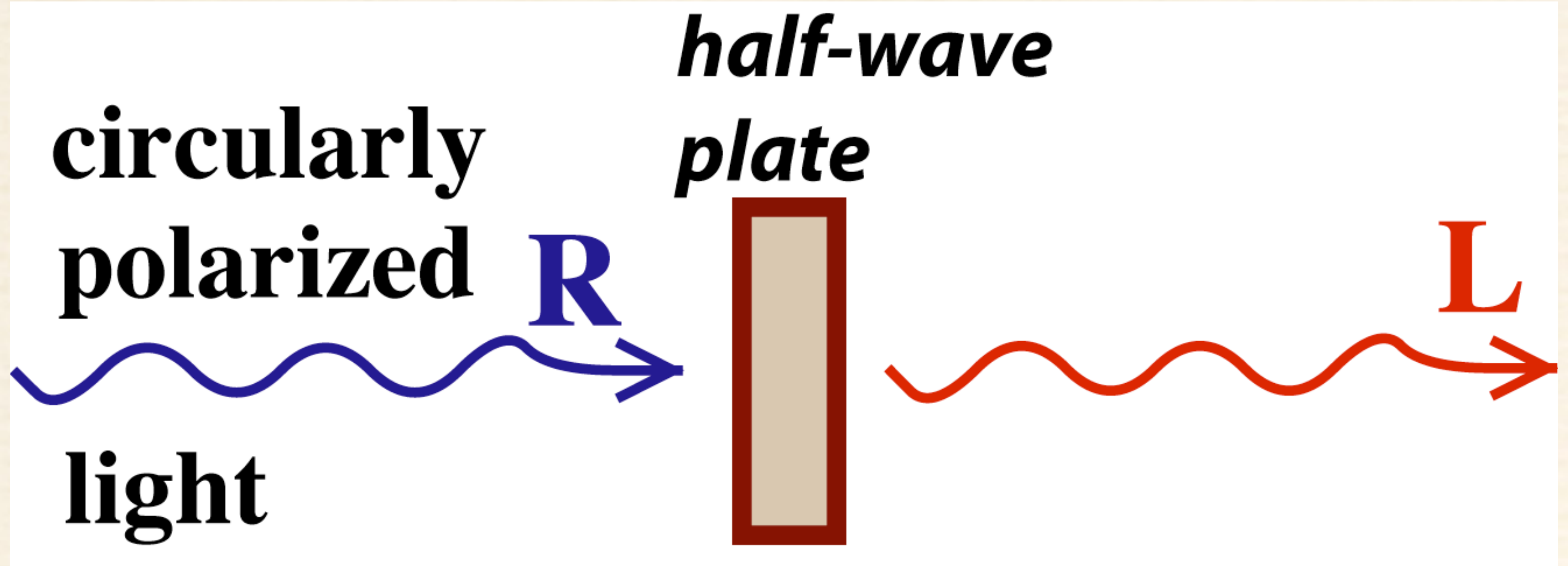

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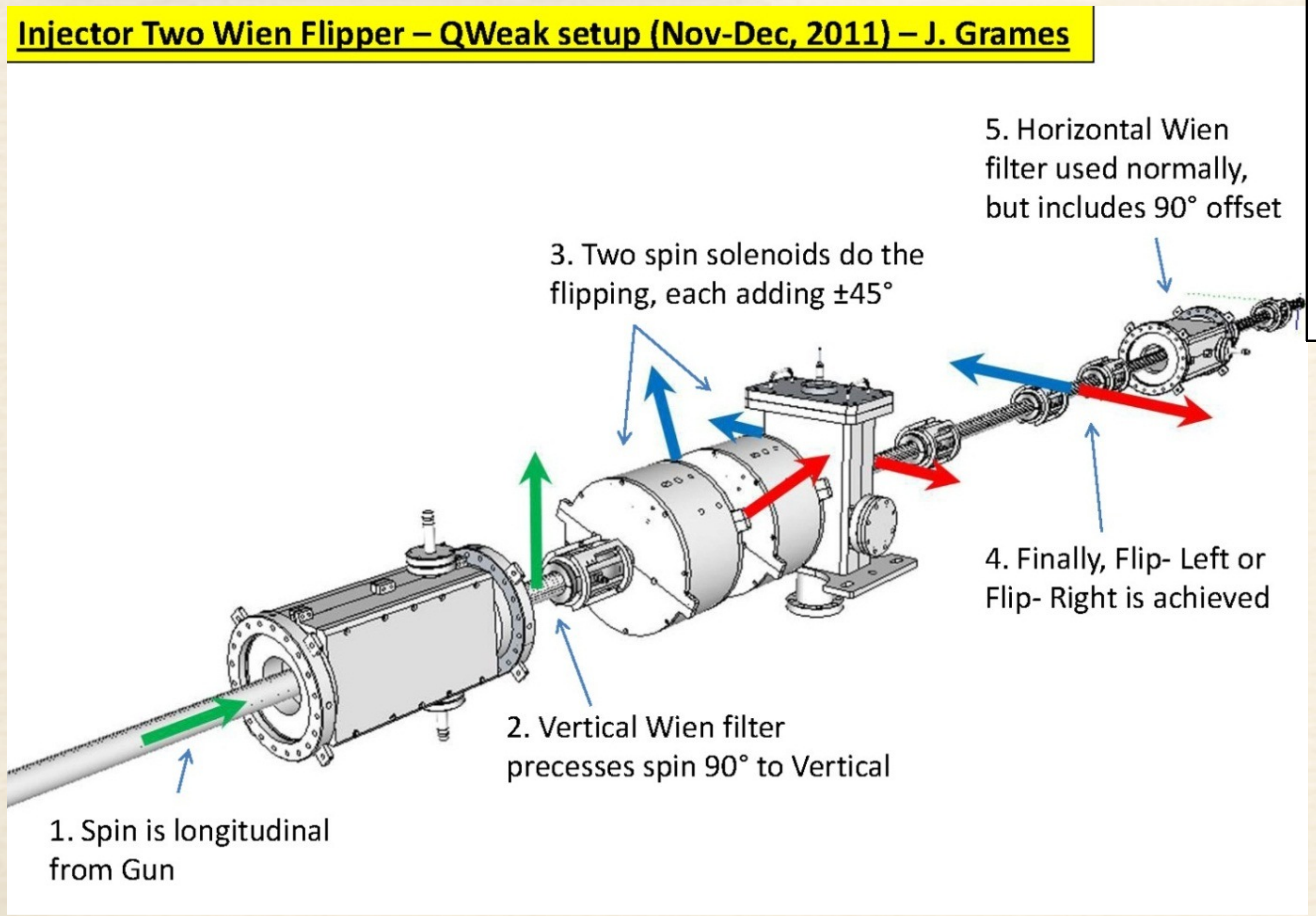

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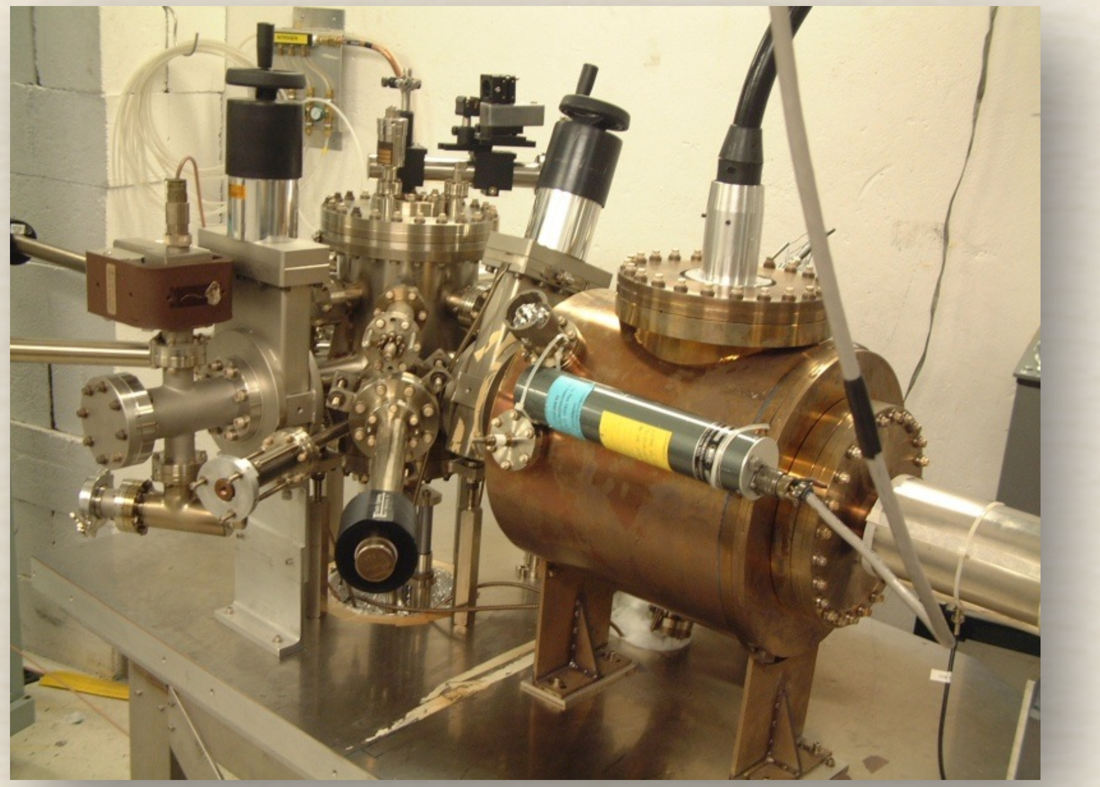
- Three independent techniques agree across 3-parts of data set
- For beam correction, decided to use 12 BPM Lagrange Multiplier 3-part eigenvector correction, 5% slope uncertainty
- Left/right symmetric detectors, so correction dominated by E

Stability of Polarized Beam at JLab



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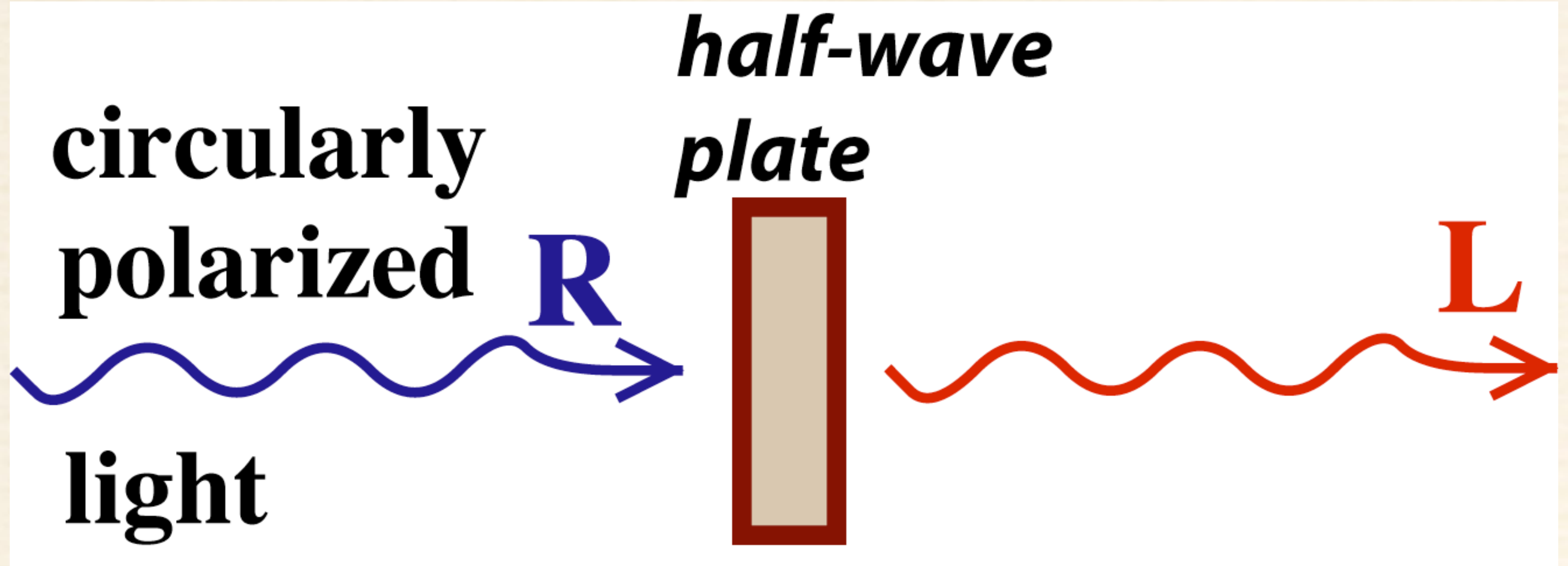

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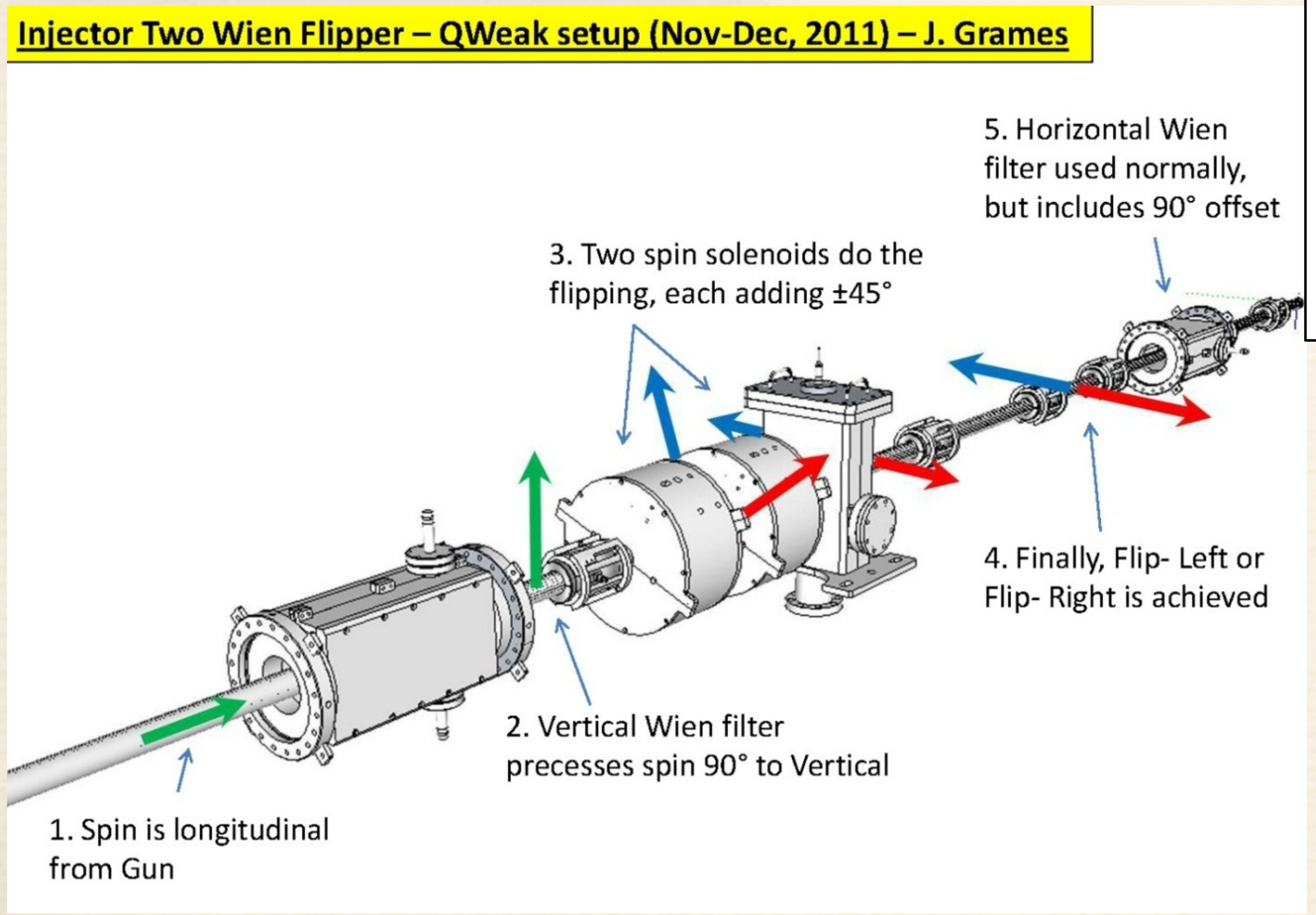

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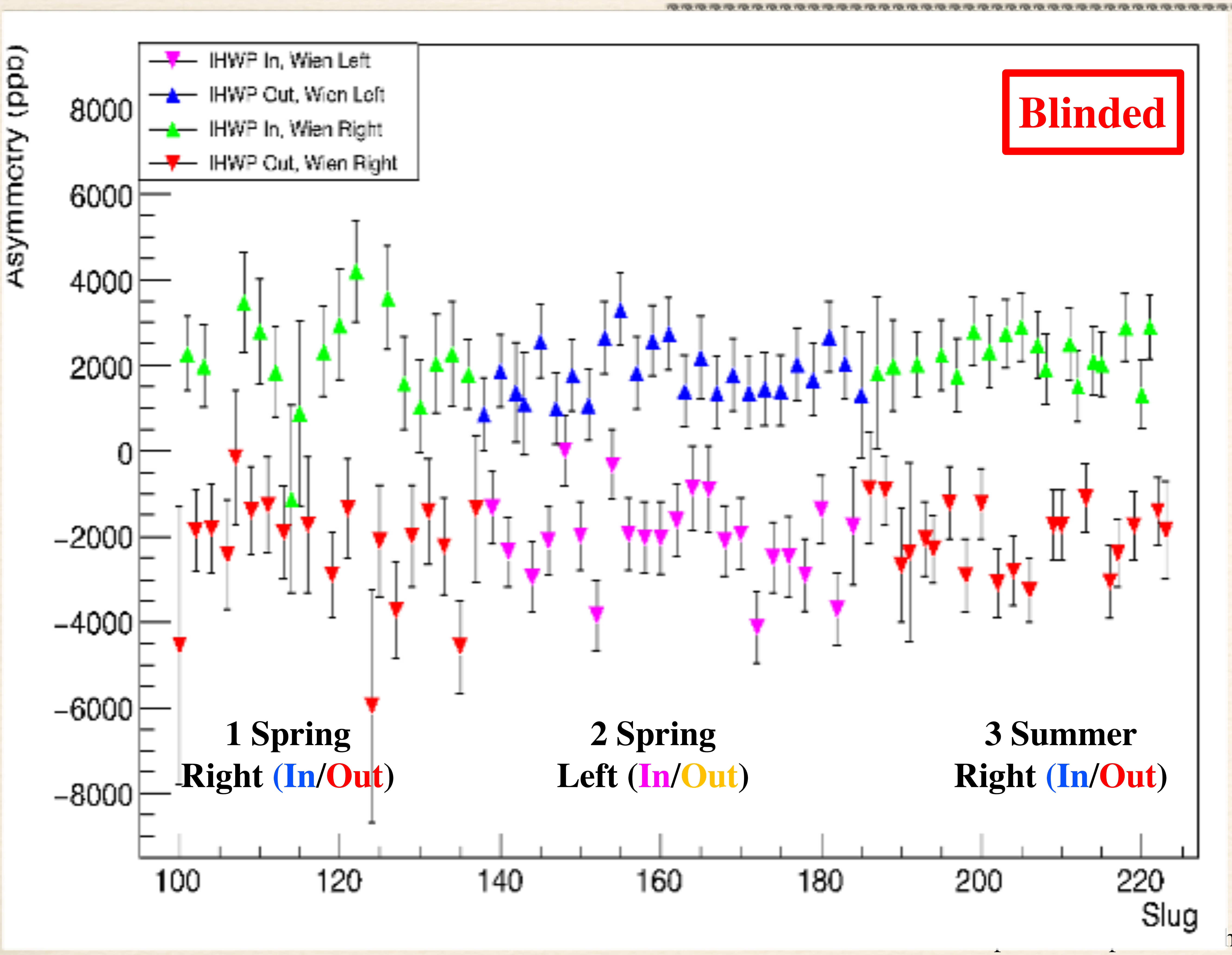
Total beam corrections:
A_{beam}=(53.5 ± 5.4) ppb

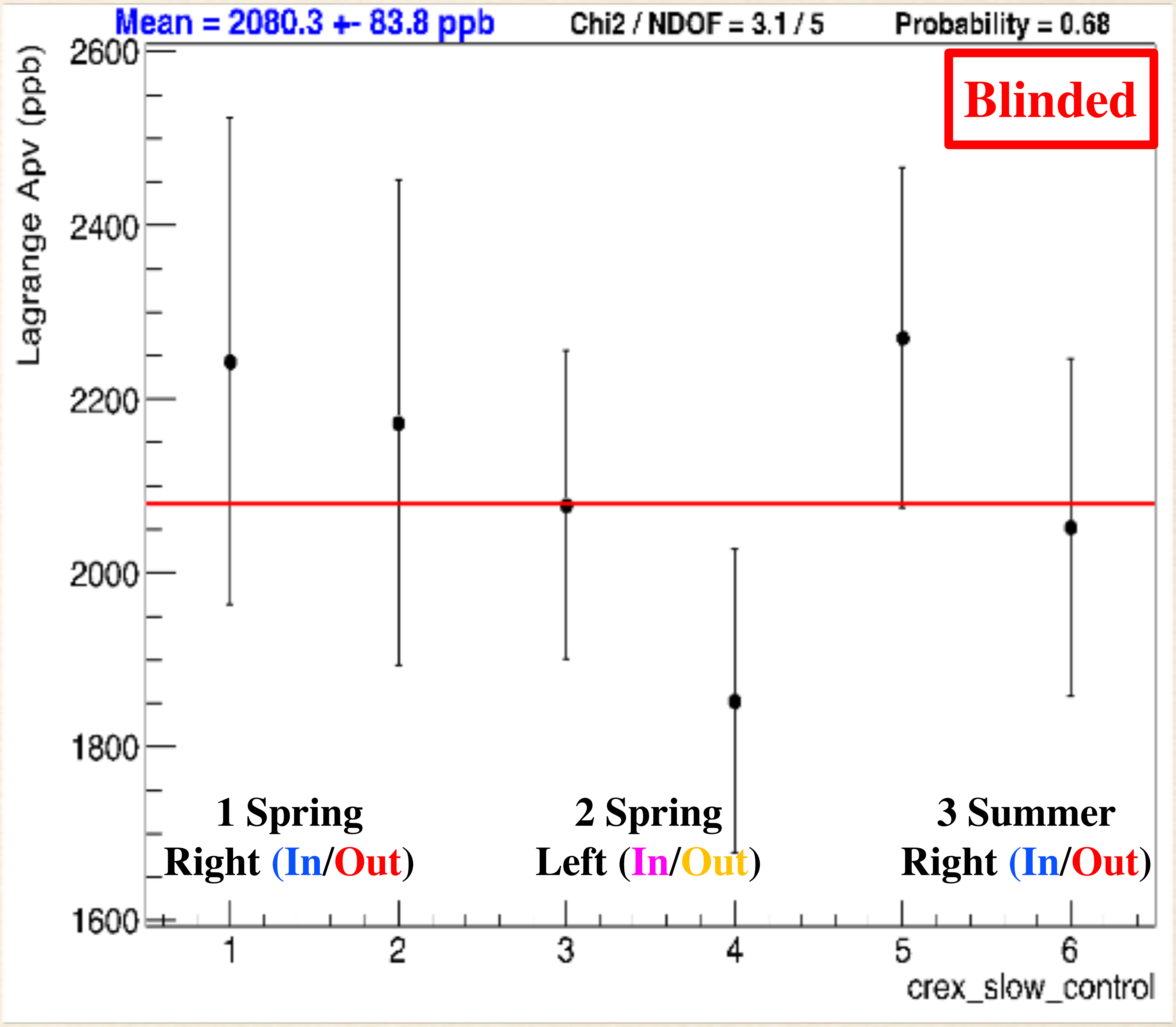
Half Wave Plate: IN/OUT Wien(Spin Manipulator): Left/Right

Demonstration of Systematic Control

Sign-uncorrected, Each point: 8h time-scale



Sign-corrected, Each point: ~1week time-scale



he right (zoomed in y-scale)

- Measuring continuously flipping sign by 2 methods (IHWP, Wien)
- The corrected asymmetry removed effects from beam asymmetries and noise

Grand Corrected Asymmetry

Final result averaging over all IHWP
and 3 Part Wien flip configurations

C. Clarke

	Wien	Weight	A_{raw} (ppb)	A_{det} (ppb)	A_Q (ppb)
1 Right (In/Out)	Right 1	17.9%	2460.15 ± 391.95	2207.90 ± 197.69	-94.1 ± 69.6
2 Left (In/Out)	Left	45.2%	1871.06 ± 278.39	1963.65 ± 124.64	148.1 ± 40.1
3 Right (In/Out)	Right 2	36.9%	2006.57 ± 335.29	2160.94 ± 137.95	-376.3 ± 38.7
	Weighted Average		2026.81 ± 189.88	2080.26 ± 83.77	-88.8 ± 26.2

Blinded Corrected Asymmetry A_{corr}:
2080.3 ± 83.8ppb

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Careful and painstaking analyses by multiple students on each of the small corrections to extract the physics asymmetry

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

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

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Unblinding!! Week before Fall DNP Meeting

Blinded A_{PV}:
2334.8 ± 112.4ppb (4.8%)

"Blinding box": an additive term on every quartet asymmetry, randomly selected (flat) at the start of the run, from ± 900 ppb

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

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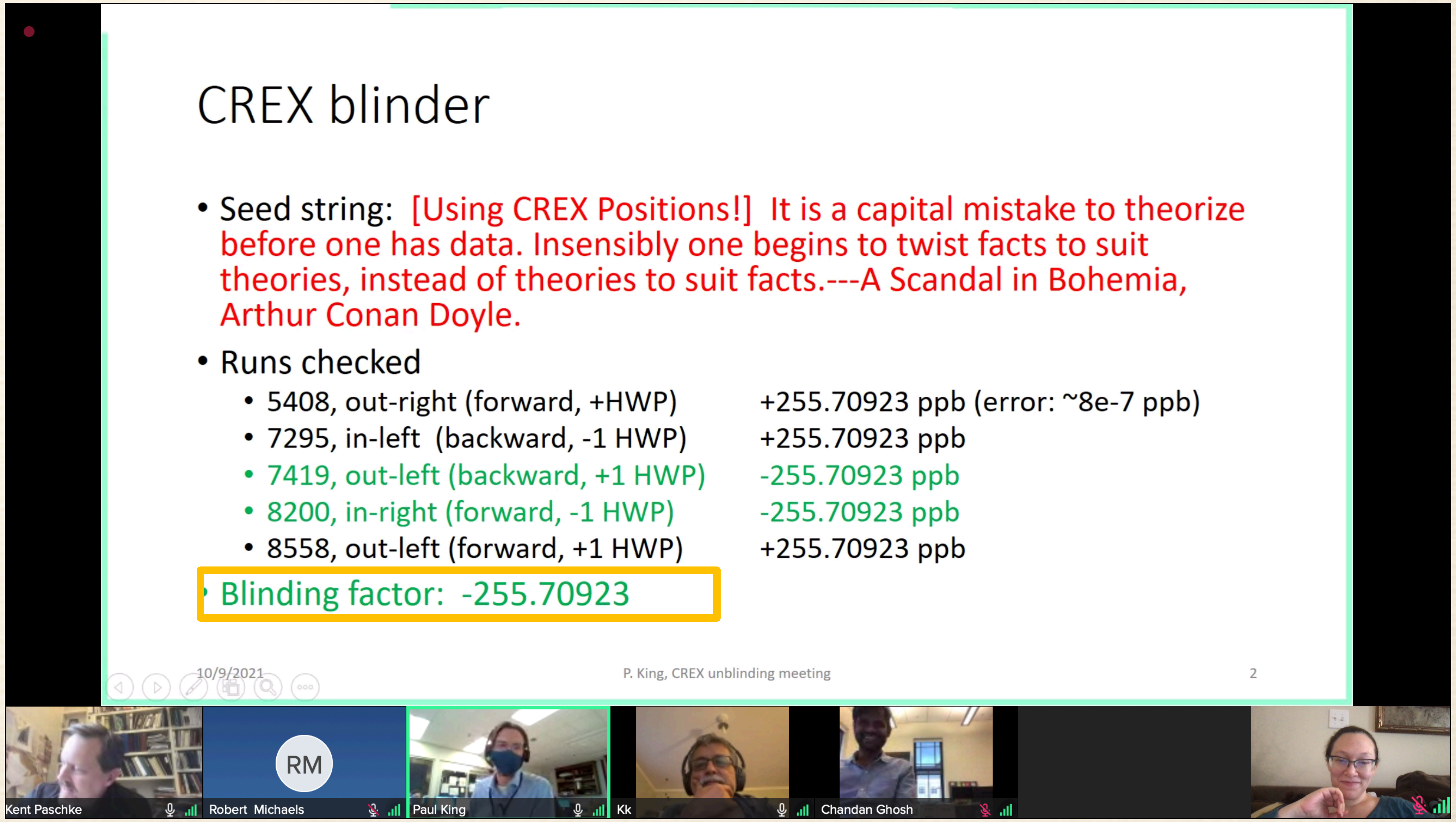
Unblinded A_{PV}:
2658.6 ± 113.2ppb (4.3%)



CREX Result Summary

	A_{PV} uncertainty contribution [ppb]	A_{PV} uncertainty contribution [%]
Polarization	13.1	0.49%
Horizontal Polarization	12.7	0.48%
Vertical Polarization	0.9	0.03%
Acceptance normalization	23.9	0.90%
Beam correction	6.9	0.26%
Non-linear detector response	6.7	0.25%
Ca40 background	8.8	0.33%
Charge correction	1.1	0.04%
Inelastic contamination 2+	18.9	0.71%
Inelastic contamination 3-(1)	10.2	0.38%
Inelastic contamination 3-(2)	3.6	0.13%
Rescattering	0.5	0.02%
Total	**39.4**	**1.5%**

Unblinded Corrected Asymmetry A_{corr}:
2336.0 ± 84.8ppb

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

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

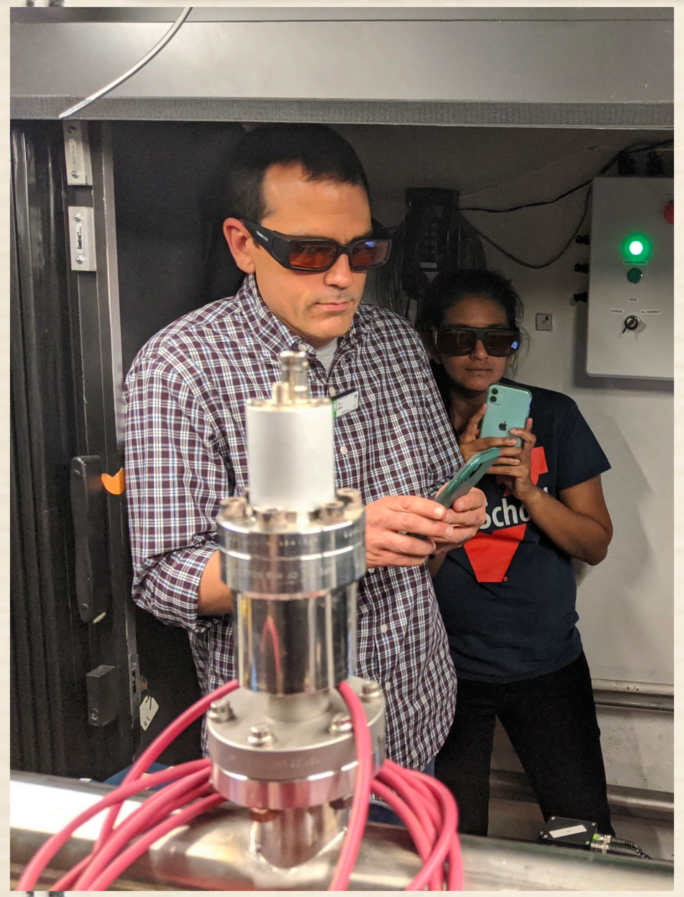
Unblinded A_{PV}:
2658.6 ± 106.1(stat) ± 39.4(sys)ppb
[± 113.2ppb(tot) (4.3%)]

- When taken all into account the experimental systematic uncertainty comes to 1.5%, less than half the 4.0% statistical uncertainty
- Total uncertainty of is 113.2ppb (4.3%)

Our Crew

PhD Student

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

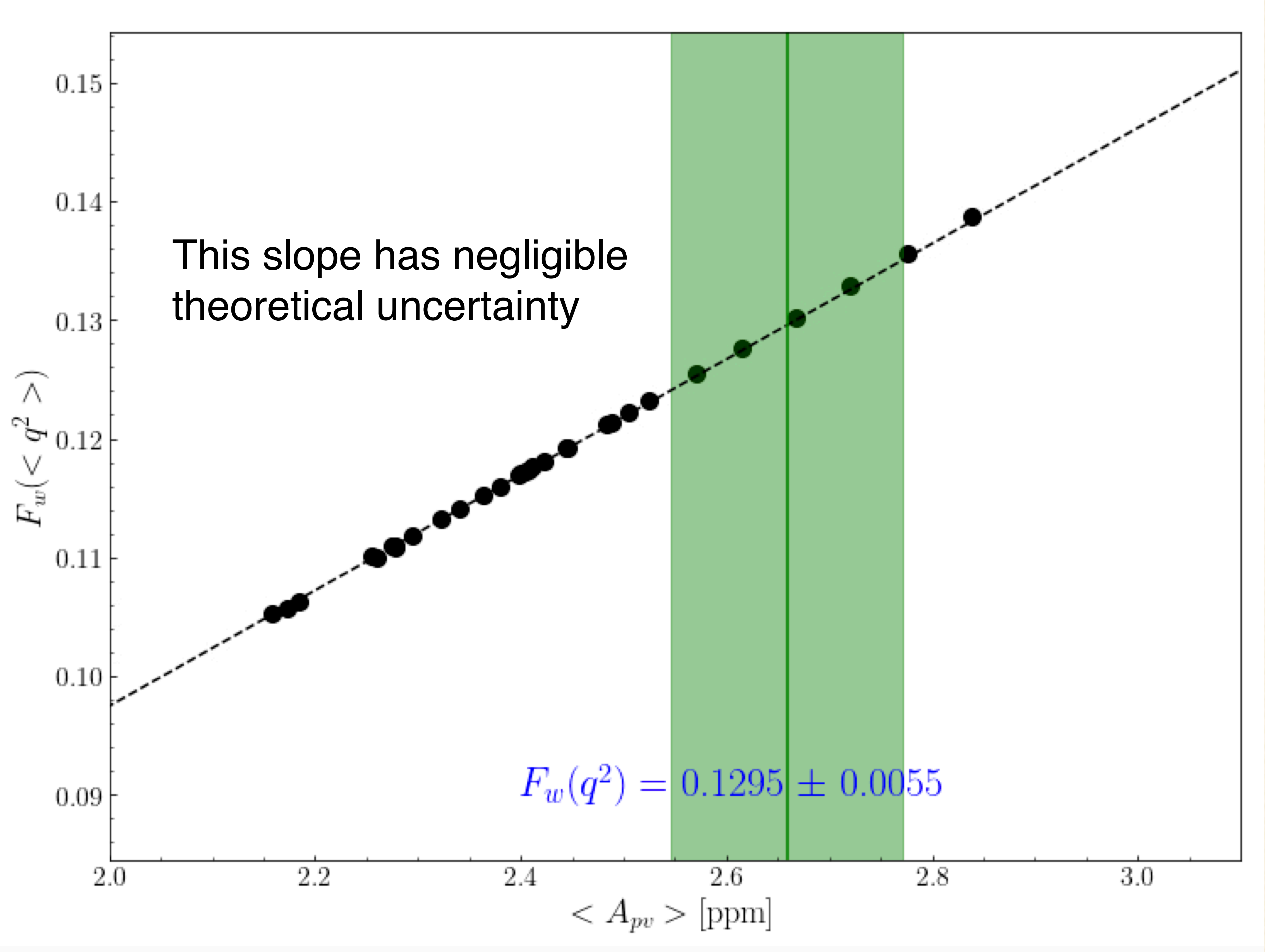
Spokespeople: D. McNulty, J. Mammei, P. Souder, S. Covrig Dusa, R. Michaels, K. Paschke, S. Riordan

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

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

PREX/CREX
Implications and Outlook

Main Derived Parameter:
The Weak Form Factor at $Q^2 = 0.0297$ GeV^2



F_W: 0.1295 ± 0.0055

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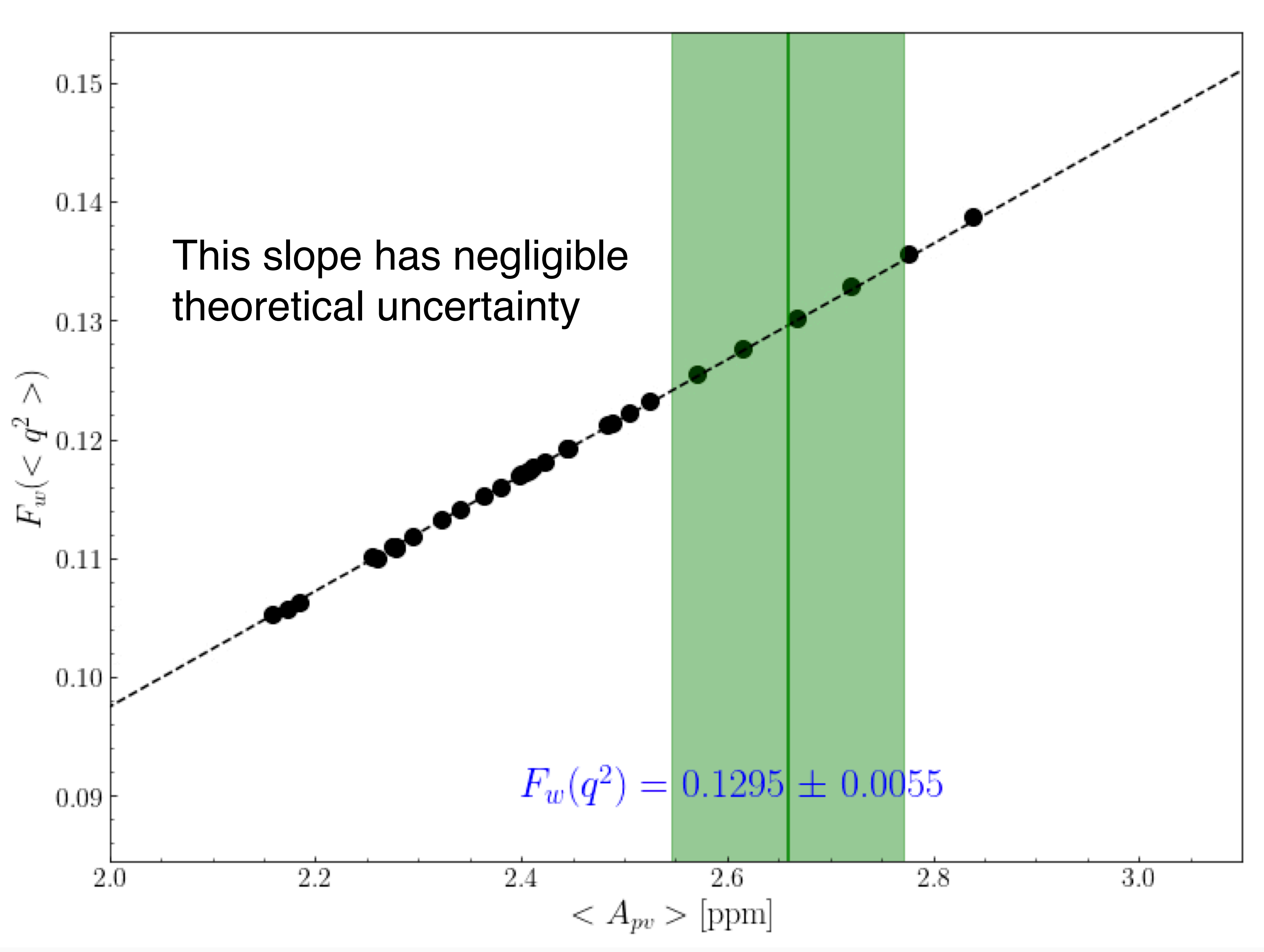

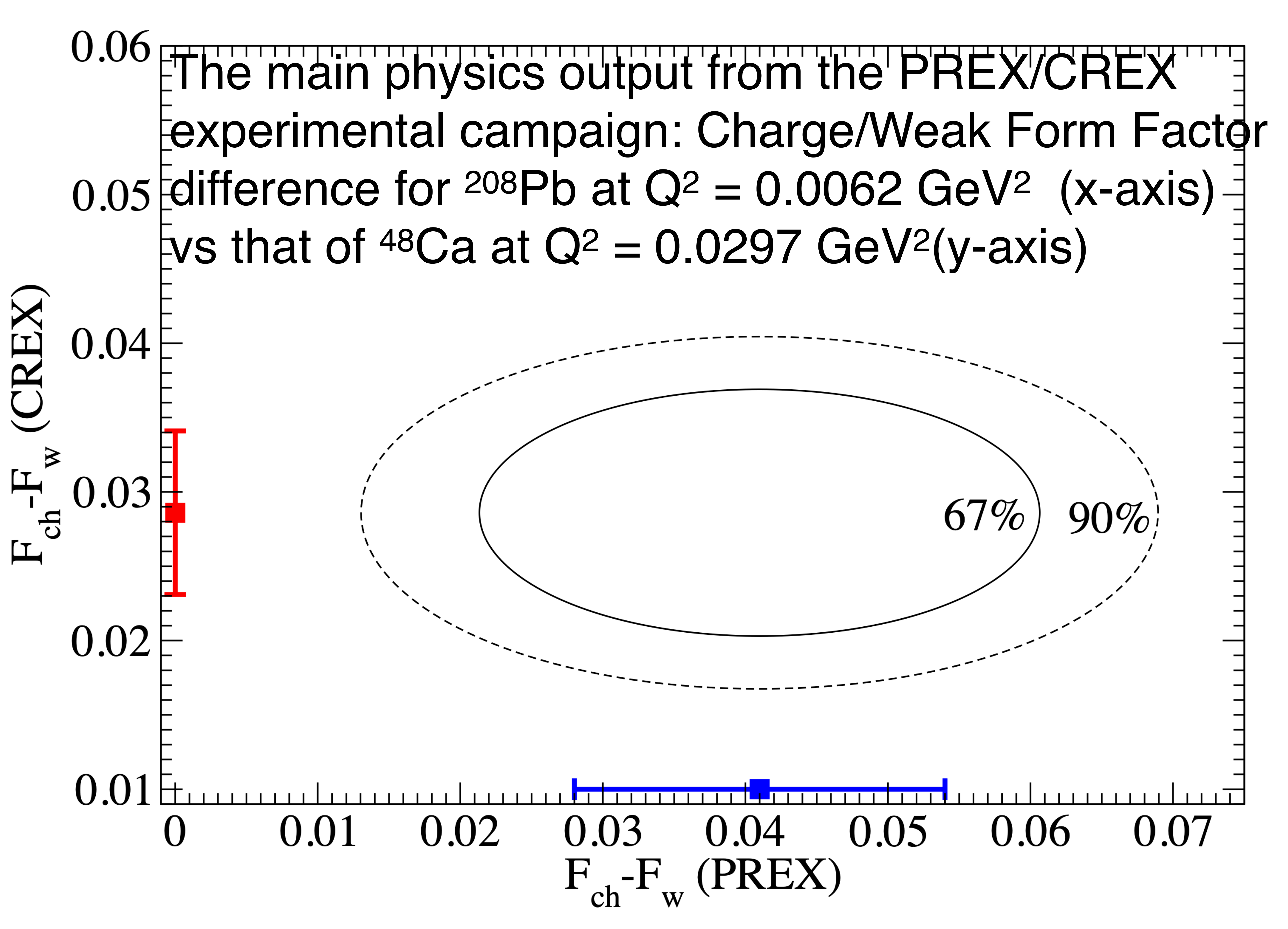

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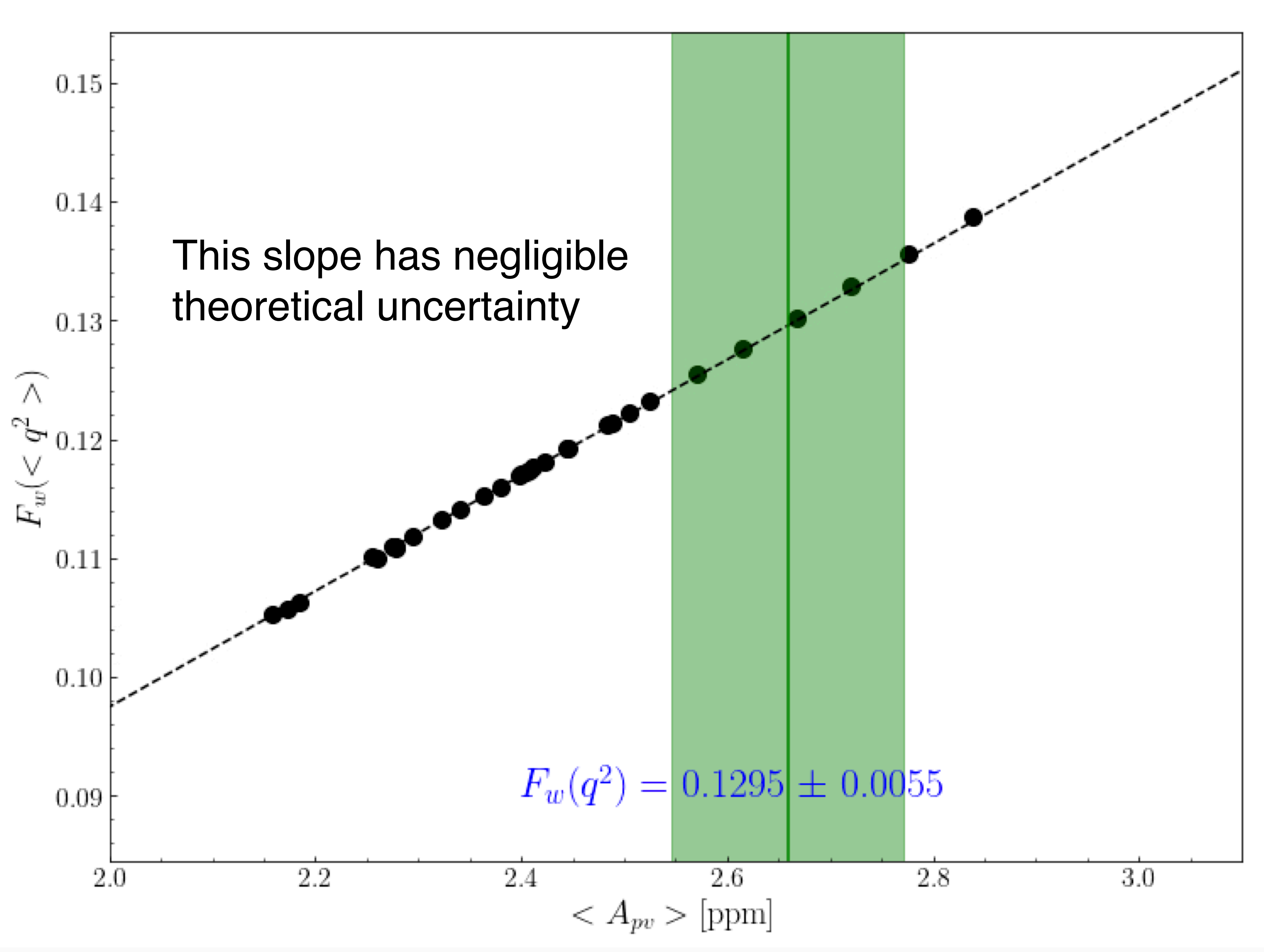

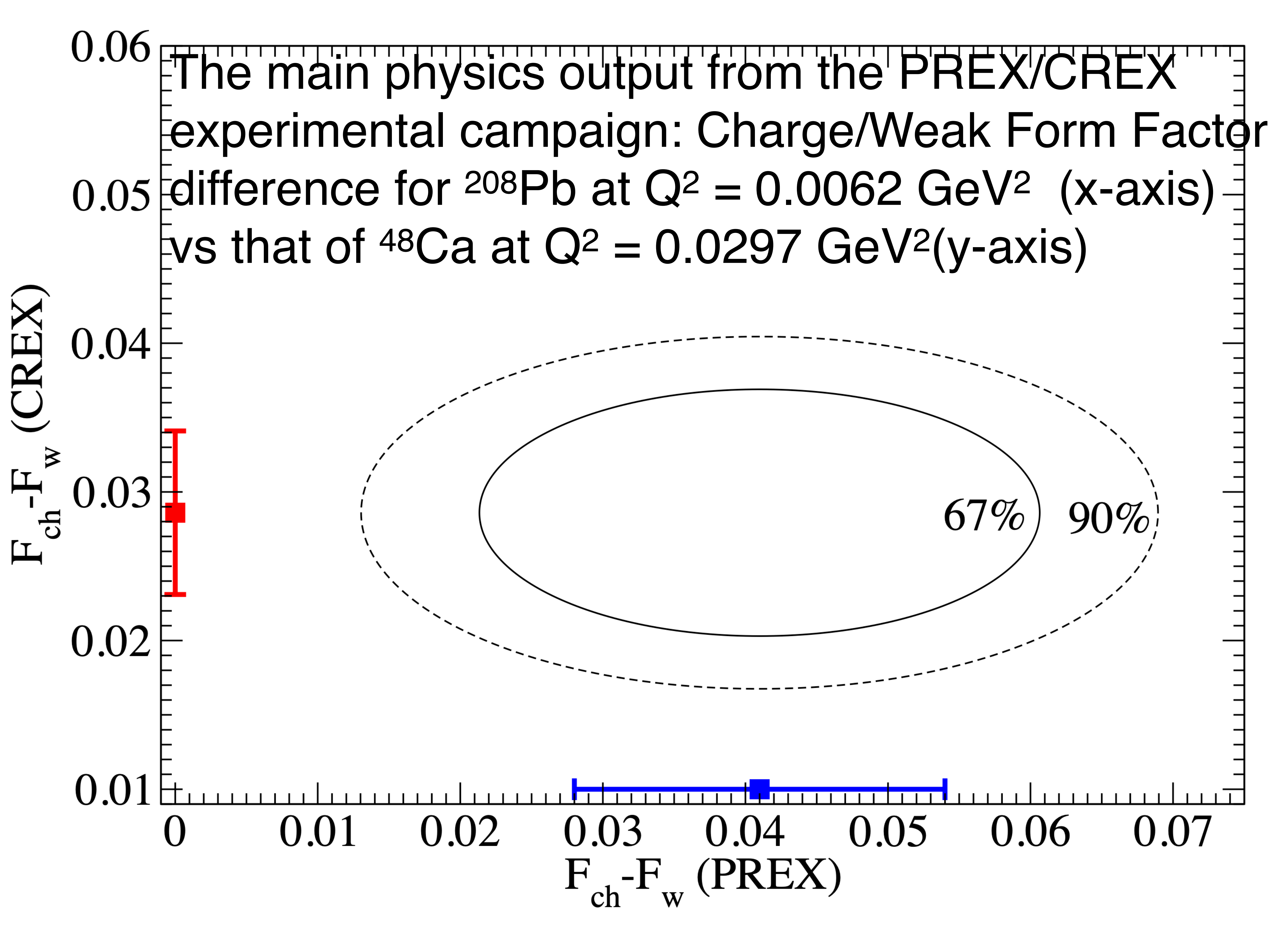

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Observation:
CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin

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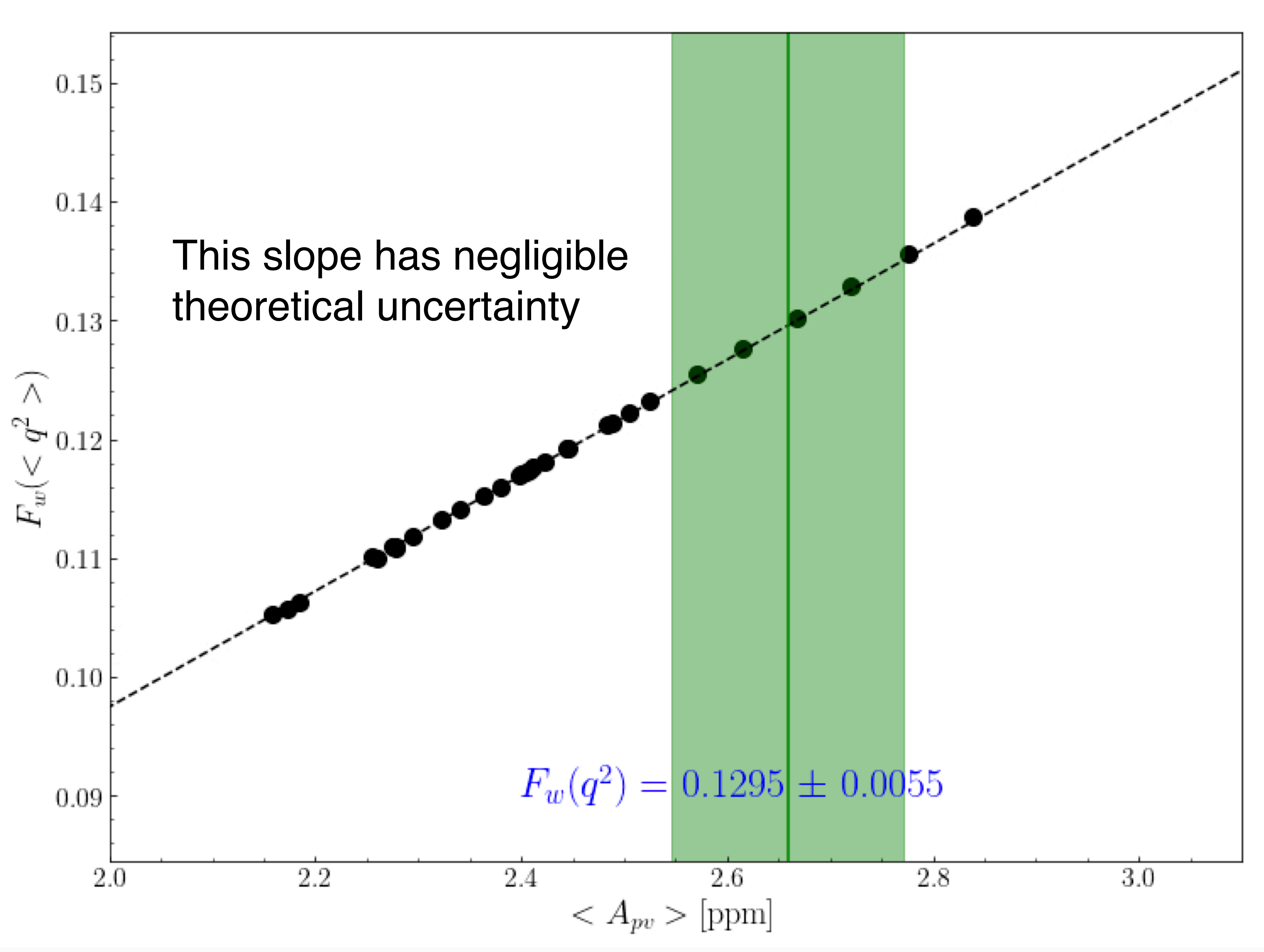

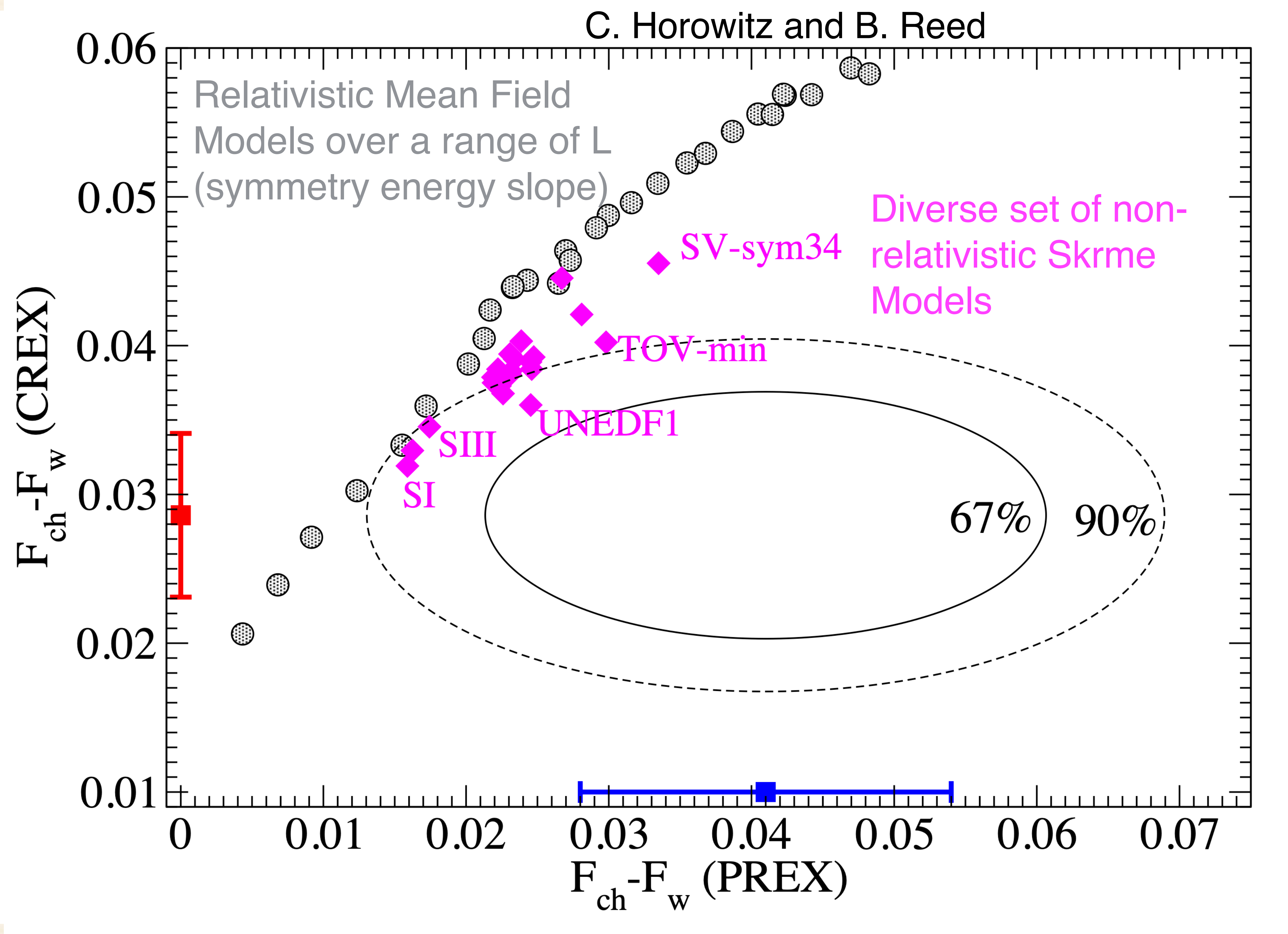

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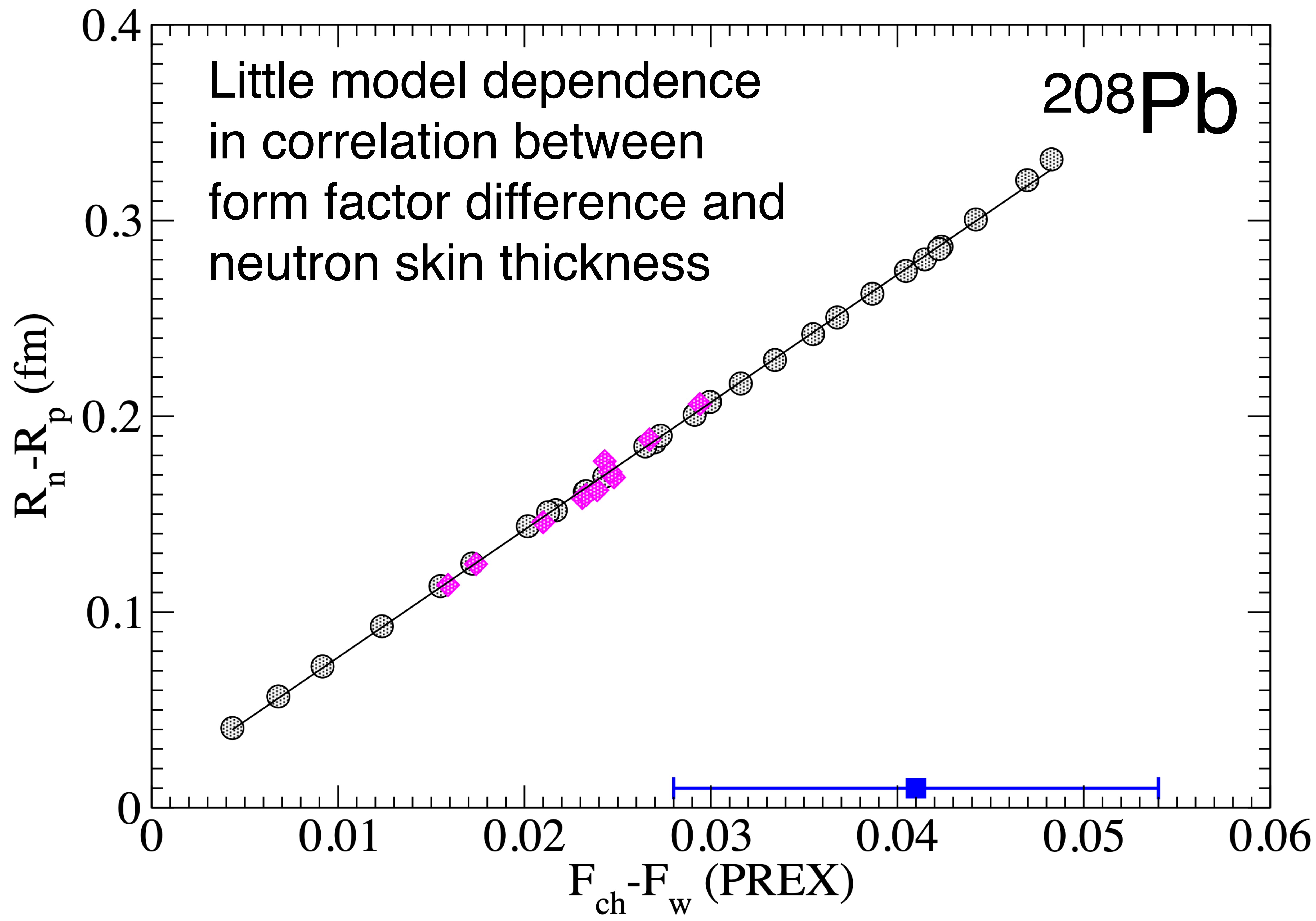
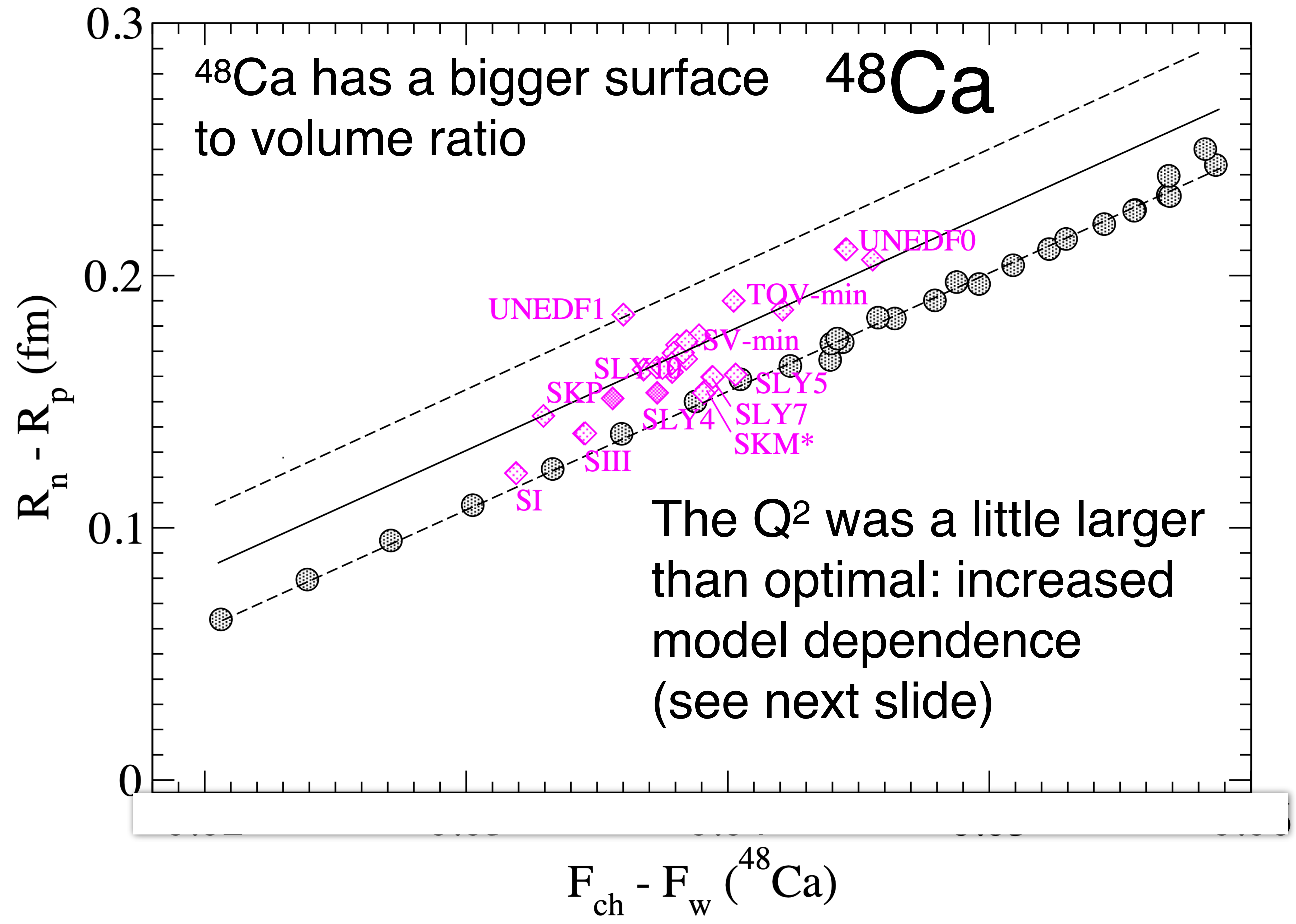
Neutron Skin Extraction: Model Dependence

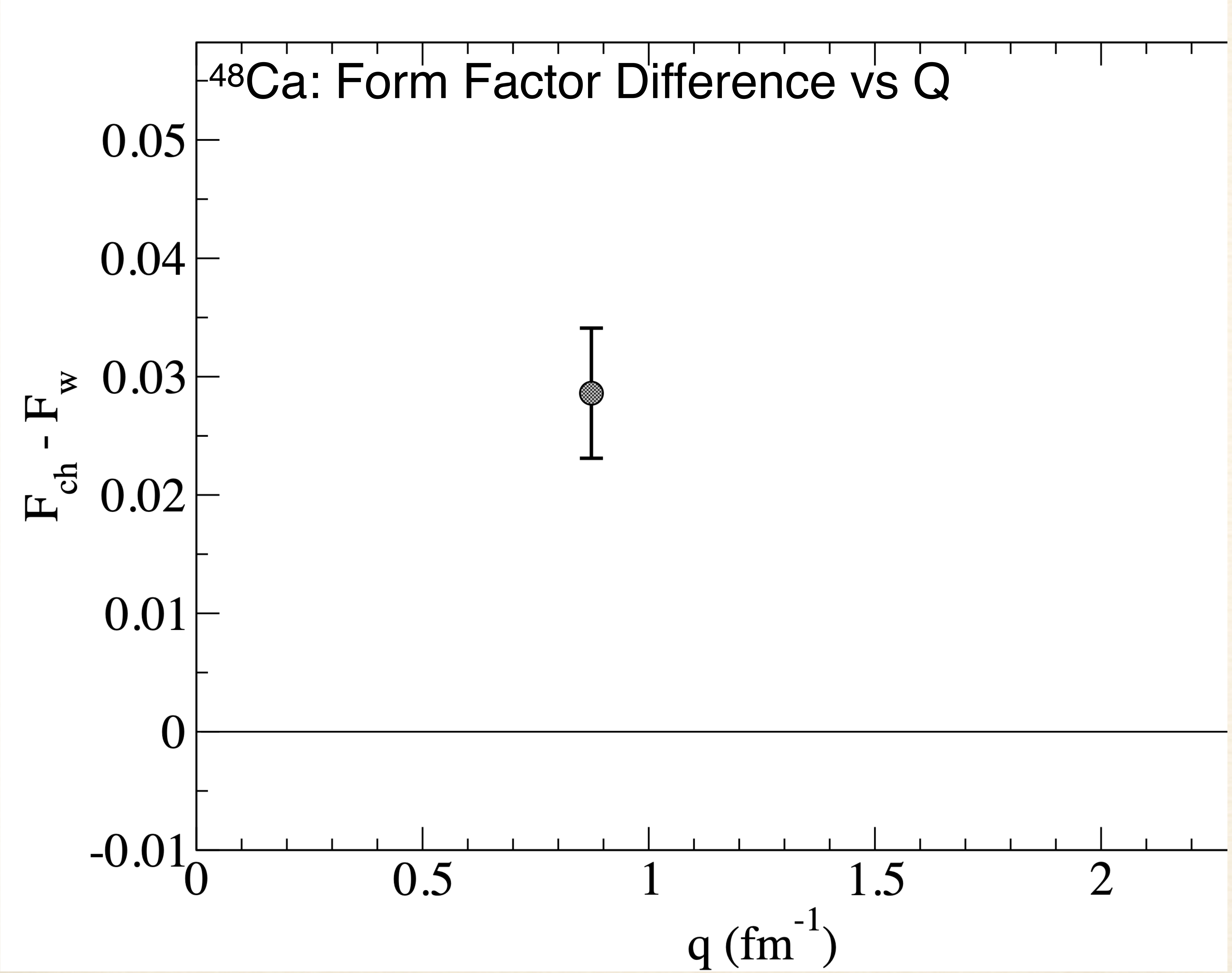




^{48}Ca: Projected experimental skin thickness uncertainty ~ 0.026 fm

Projected skin thickness model uncertainty ~ 0.023 fm

CREX Result Discussion and Plans



- **Publication on final CREX results under preparation**
  - A_{PV} and Weak Form Factor
  - Neutron Skin Thickness with an uncertainty of ~ +/- 0.035 fm
- **Community Discussion of Implications Beginning**
  - Interplay between ^{208}Pb and ^{48}Ca underscores rich dynamics
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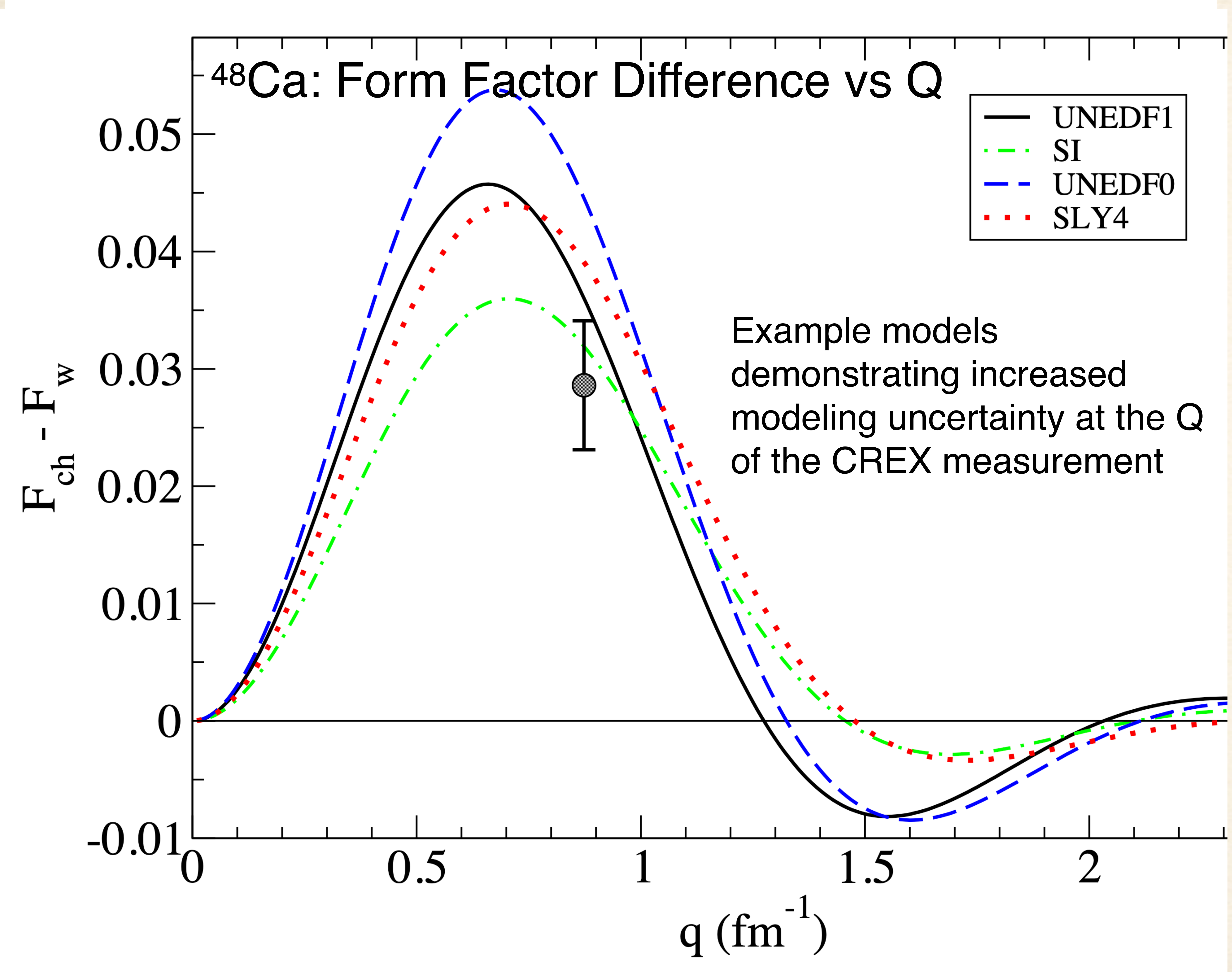
CREX Result Discussion and Plans



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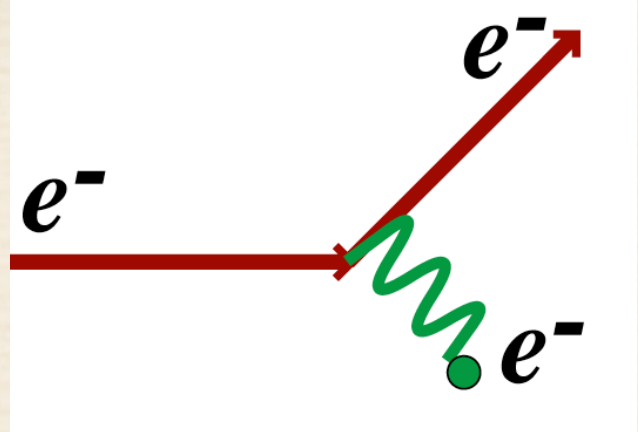
Outlook from PREX & CREX Campaigns

- ✦ **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 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

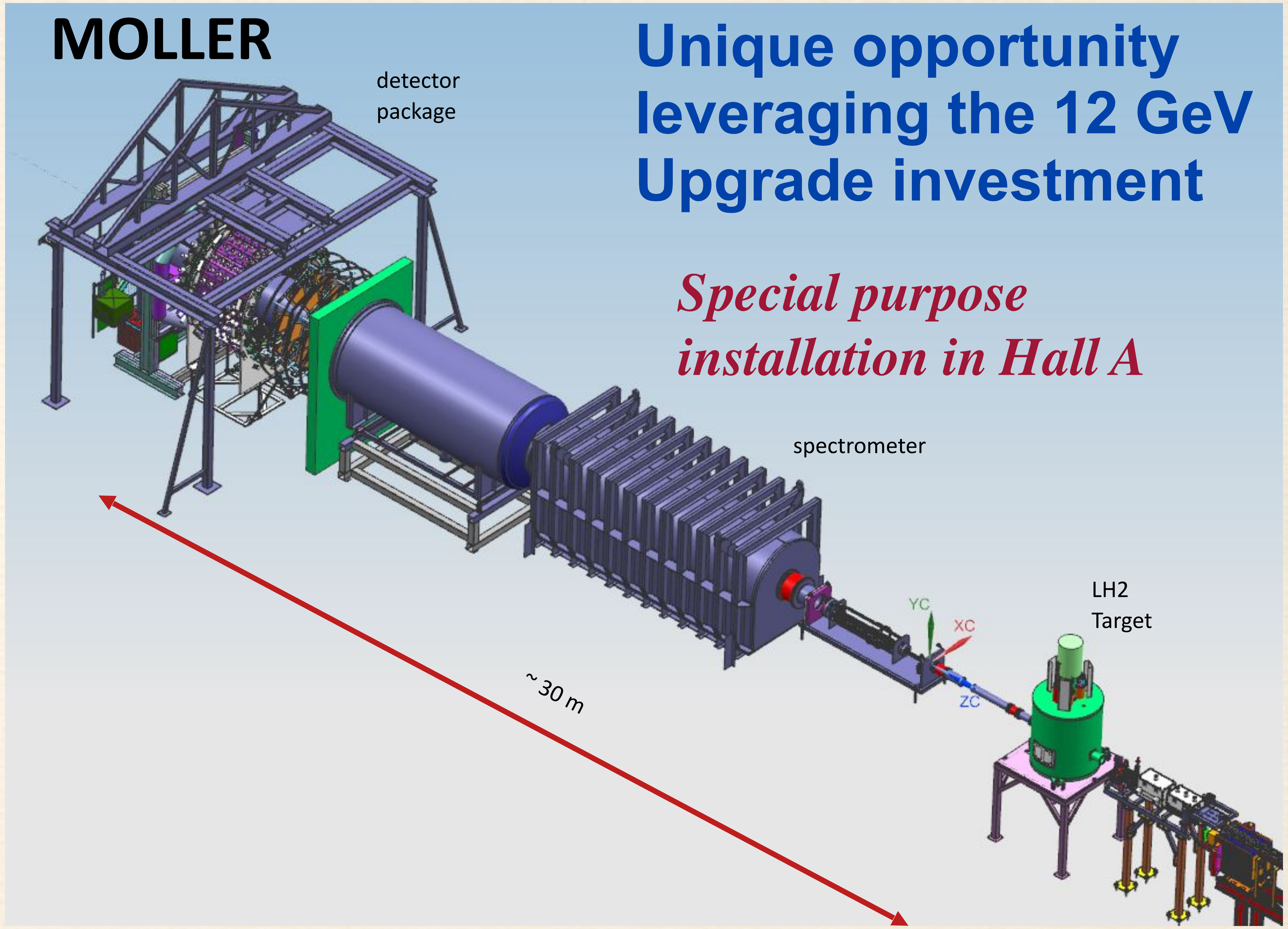
11 GeV Møller scattering



MOLLER at JLab

A_{PV} ~ 32 ppb

$\delta(A_{PV})$ ~ 0.8 ppb



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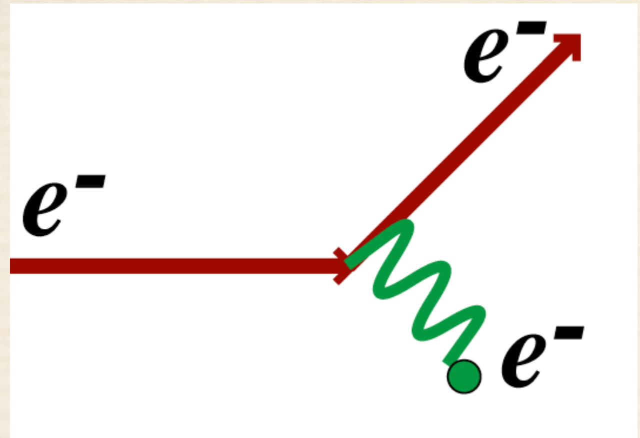

MOLLER at JLab

50 M$ DOE NP MIE

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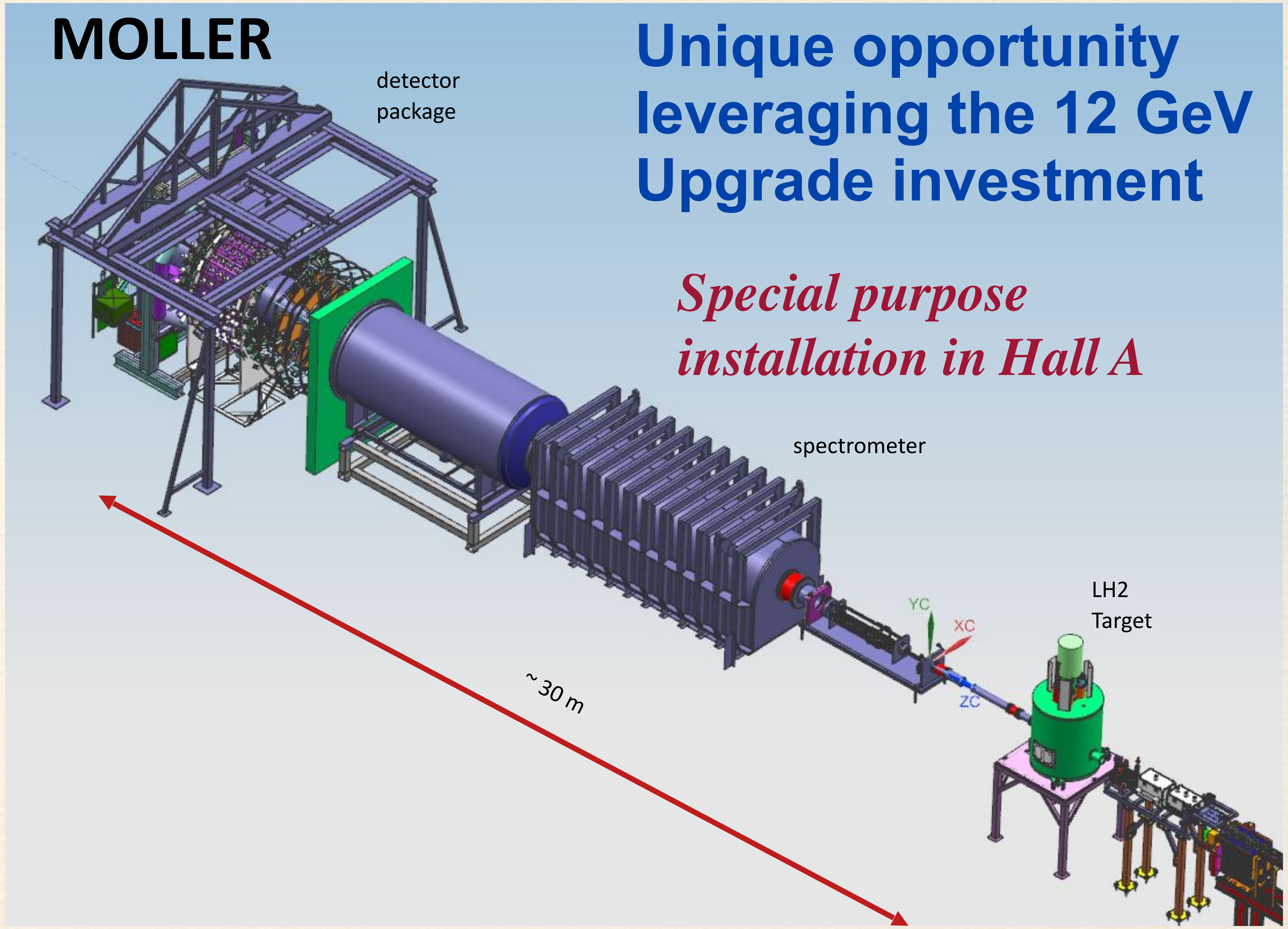

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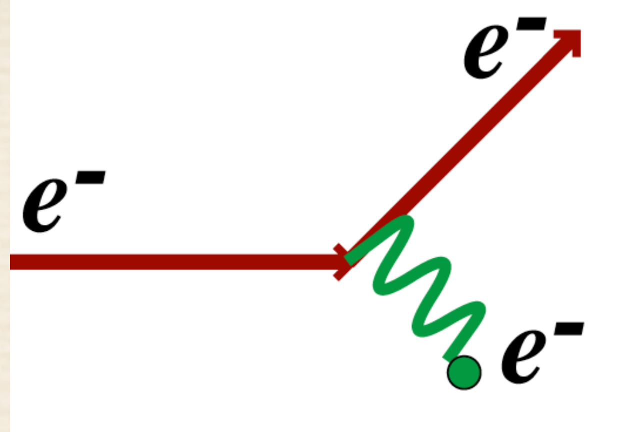

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$\delta(A_{PV})$ ~ 0.8 ppb

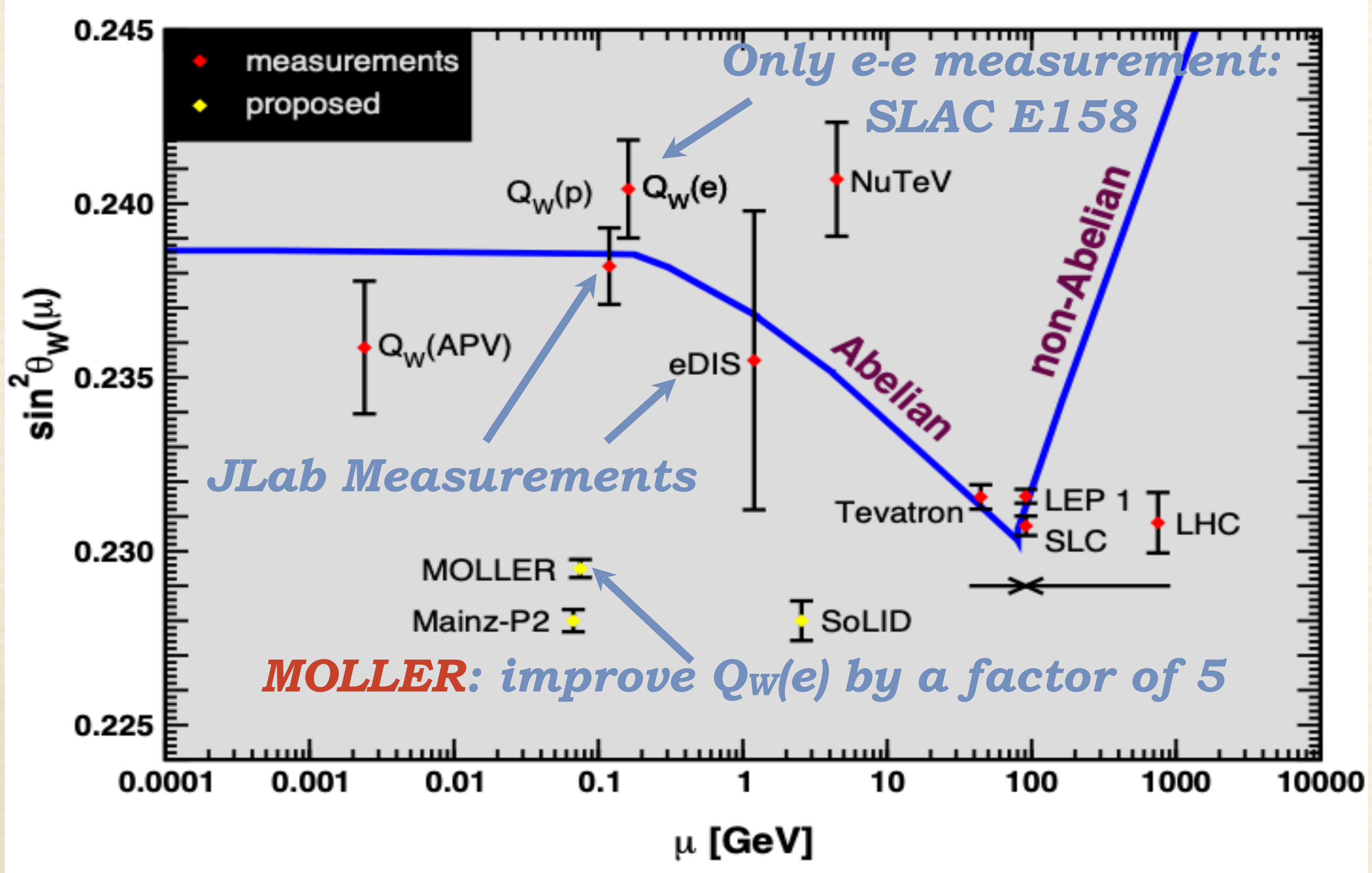
$\delta(\sin^2\theta_W) = \pm\, 0.00023\ (stat.) \pm 0.00012\ (syst.)$

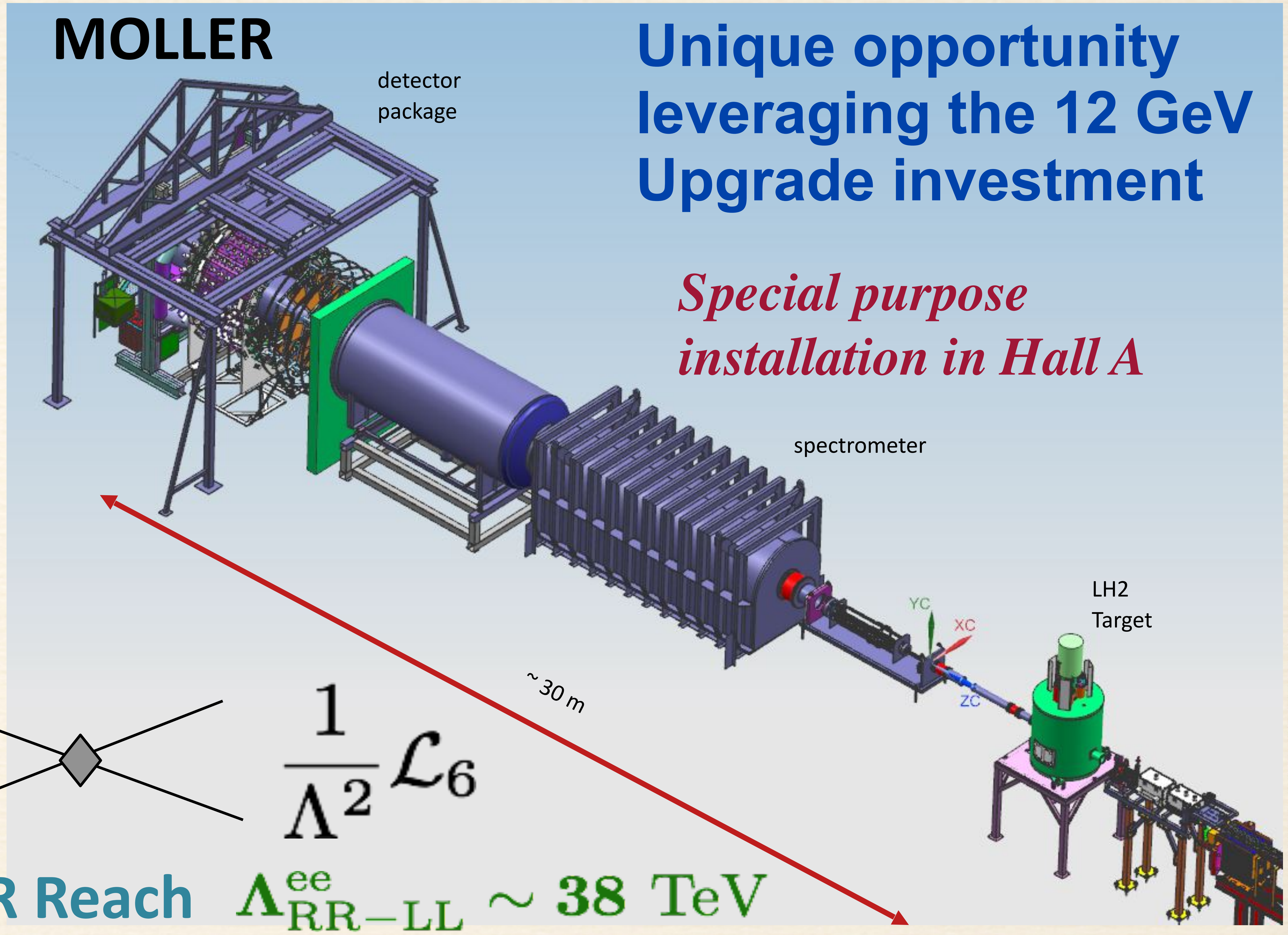
⇨ ~ 0.1%

- Unique (purely leptonic) new physics reach

Search for new flavor diagonal neutral currents

Look for tiny but measurable deviations from precisely calculable predictions for SM processes





Unique opportunity leveraging the 12 GeV Upgrade investment

Special purpose installation in Hall A

A_{new}

$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

MOLLER Reach $\Lambda^{ee}_{RR-LL} \sim 38\ \text{TeV}$

Unique discovery space: beyond that of a 500 GeV lepton collider

Take Away Message

New CREX Result

Unblinded A_{PV}:
2658.6 ± 106.1(stat) ± 39.4(sys)ppb
[± 113.2ppb(tot) (4.3%)]

F_W: 0.1295 ± 0.0055

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Publication in preparation

- ✦ **Parity-Violating Electron Scattering**
  - ★ Enabled unique studies of the weak force
  - ★ Technical progress has enabled unprecedented precision
  - ★ flagship experiments at electron accelerators
- ✦ **Fundamental Nuclear/Nucleon Physics**
  - ★ Neutron RMS radii of heavy nuclei (PREX, CREX)
  - ★ valence quark structure of protons and neutrons (SOLID)
- ✦ **Fundamental Electroweak Physics**
  - ★ Search for new TeV scale dynamics (MOLLER, SOLID, P2)
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*

Productive research program that will continue to flourish over the next decade