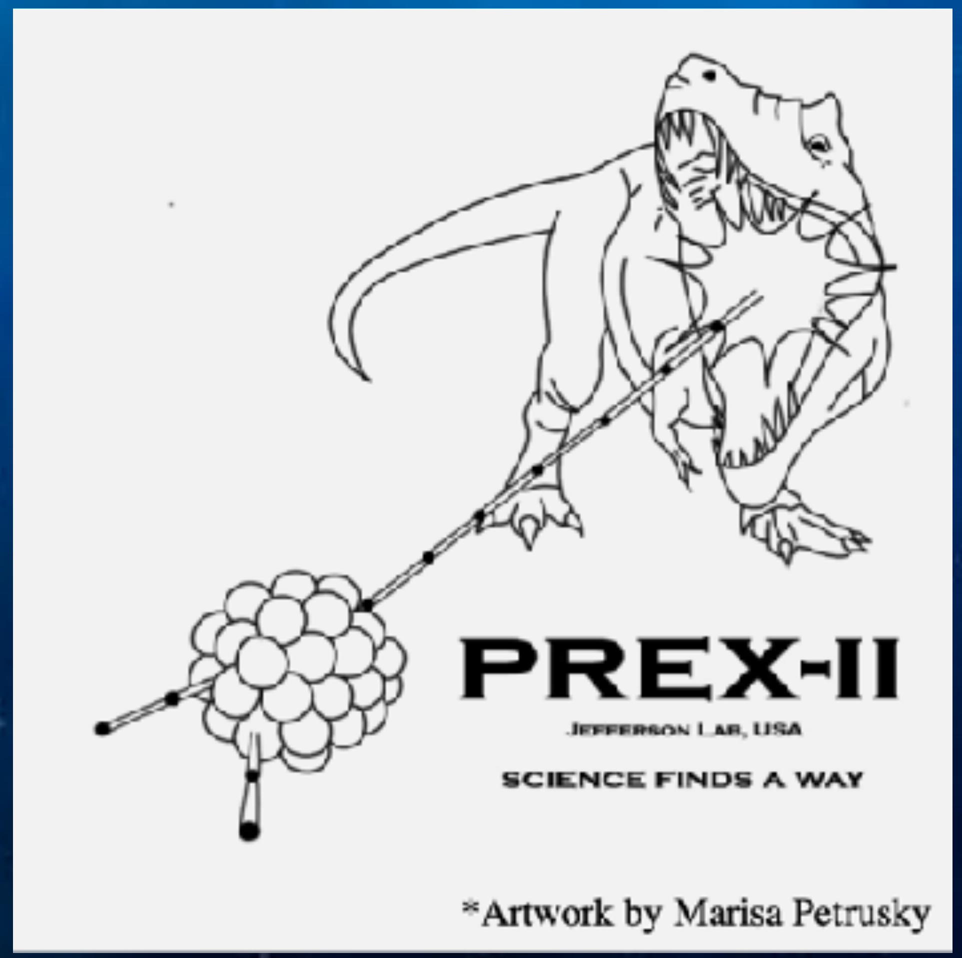
PREX and CREX experiments and equation of state



U.S. DEPARTMENT OF ENERGY Office of Science

Chuck Horowitz, Indiana U. INT, June 2023


School of Athens, Rafael

PREX uses Parity V. to Isolate Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

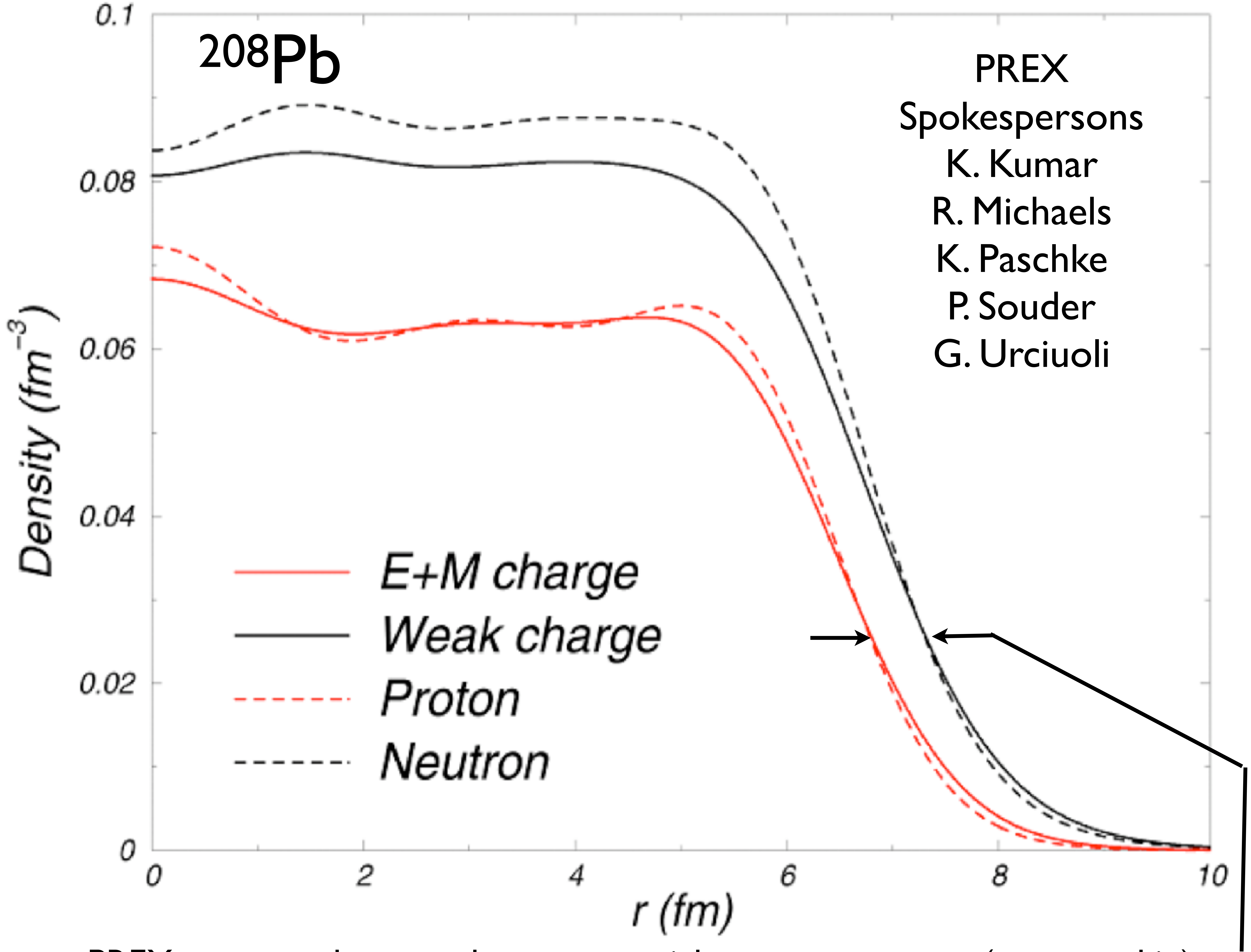
- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

- A_{pv} from interference of photon and Z^0 exchange.
- Determines weak form factor

$$F_W(q) = \frac{1}{Q_W} \int d^3r j_0(qr) \rho_W(r)$$

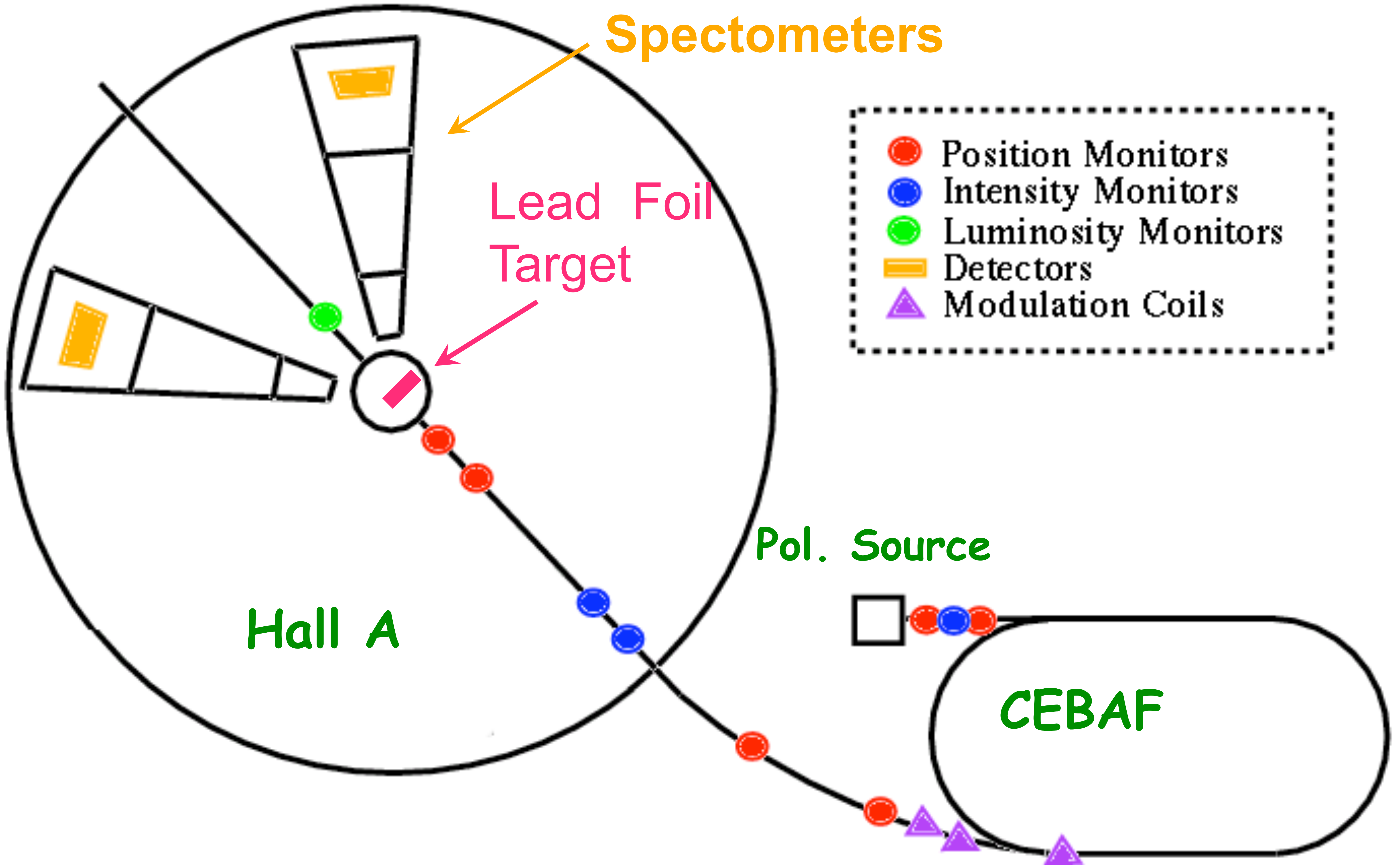
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} \approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$



- PREX measures how much neutrons stick out past protons (neutron skin).

PREX in Hall A at JLab



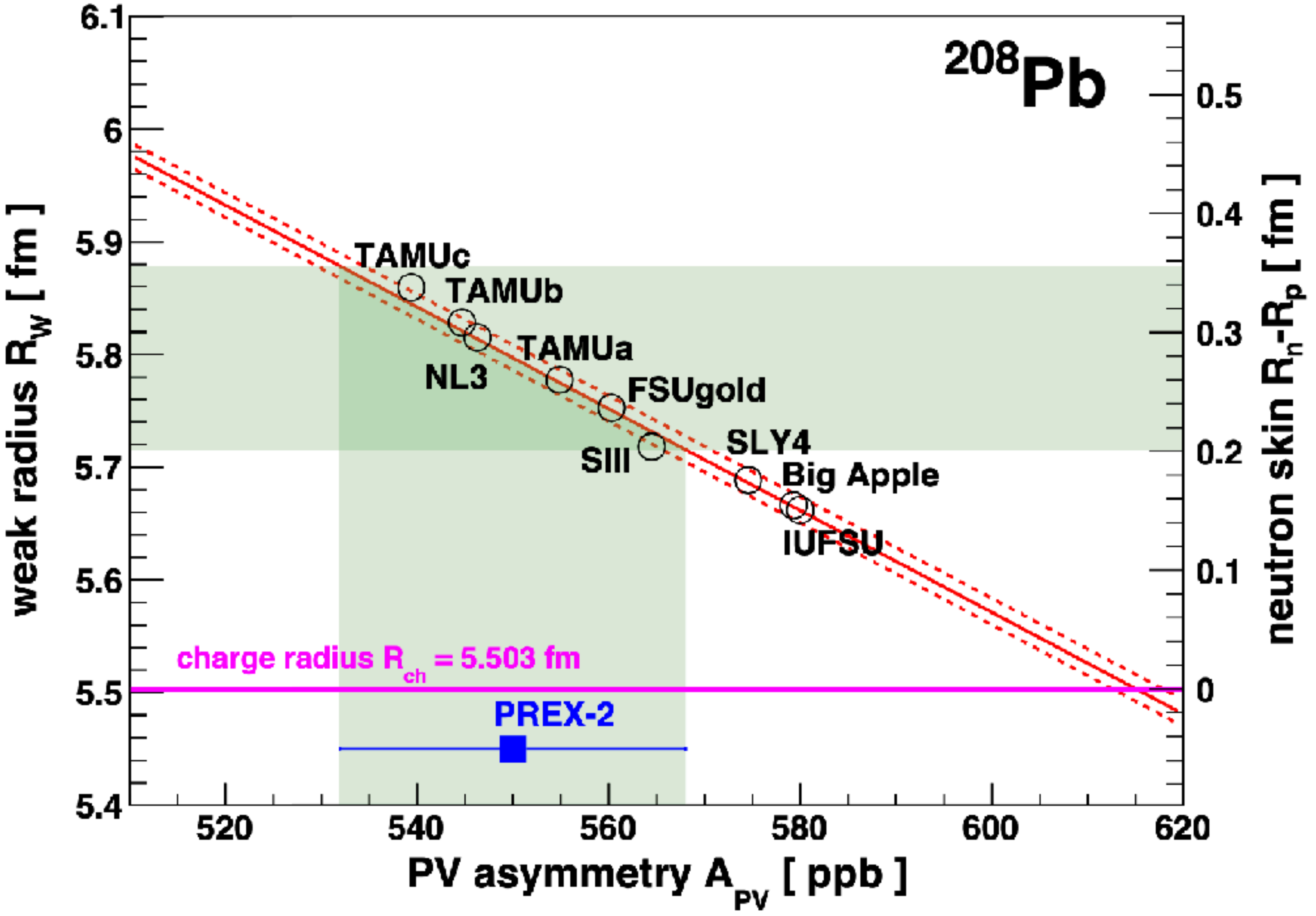
R. Michaels


Accelerator
Hall A

PREX-II

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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



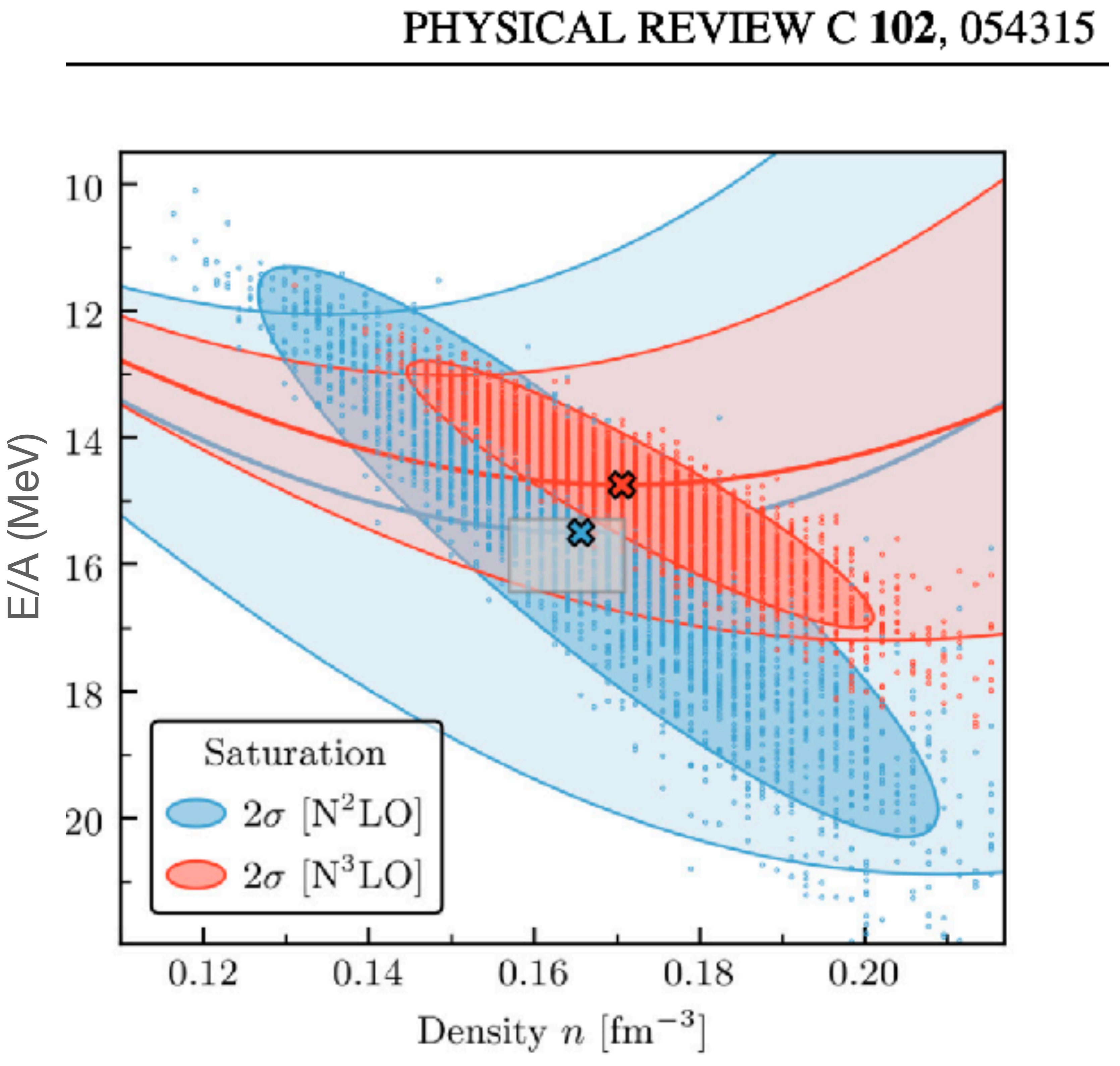
PREX-I+II Results

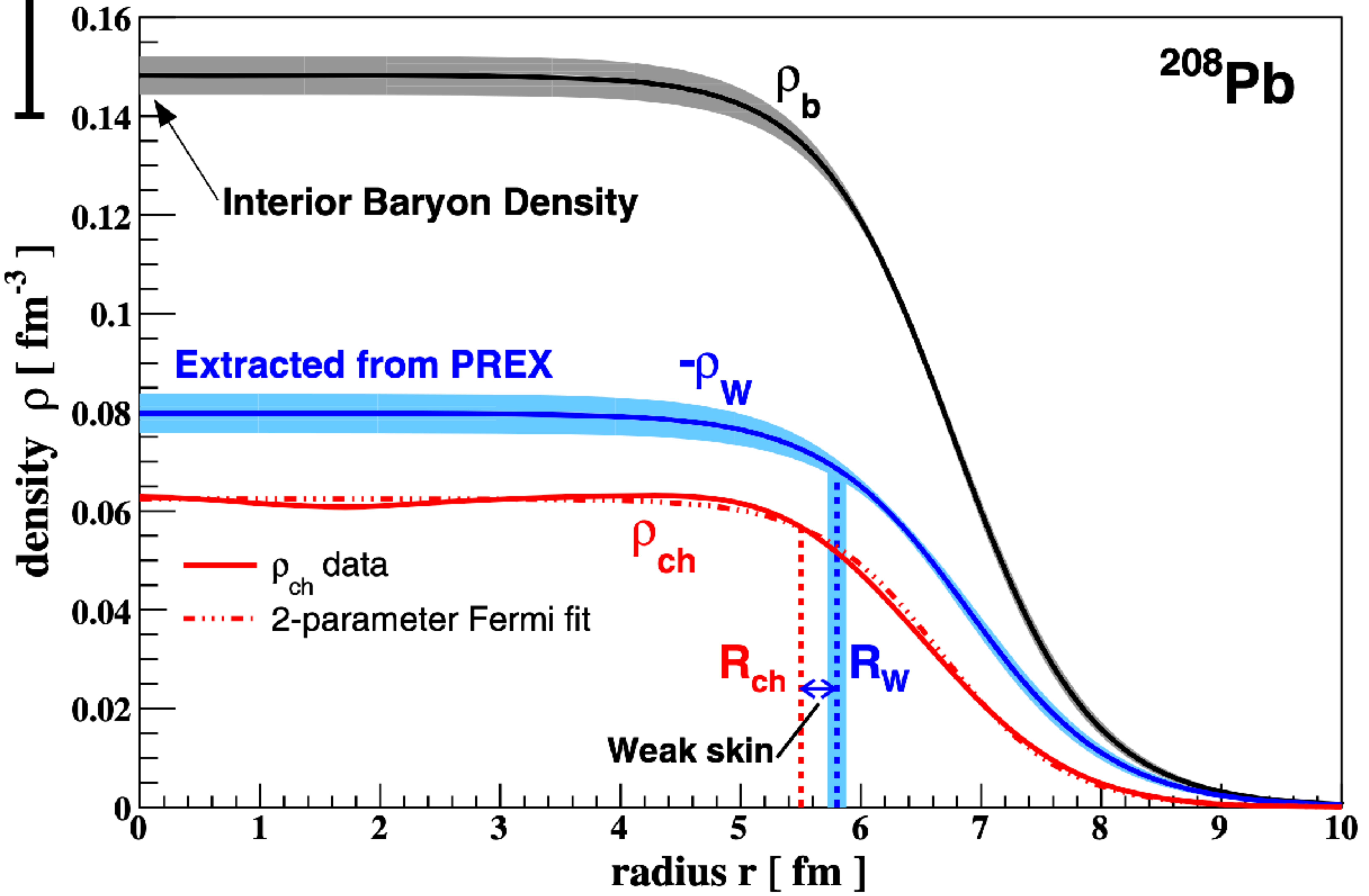
^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ^0_W)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ^0_b)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

$$F_W(q) = \frac{1}{Q_W} \int d^3r j_0(qr) \rho_W(r)$$

$F_W(q=0.398\text{fm}^{-1})=0.3676$+/-.0125

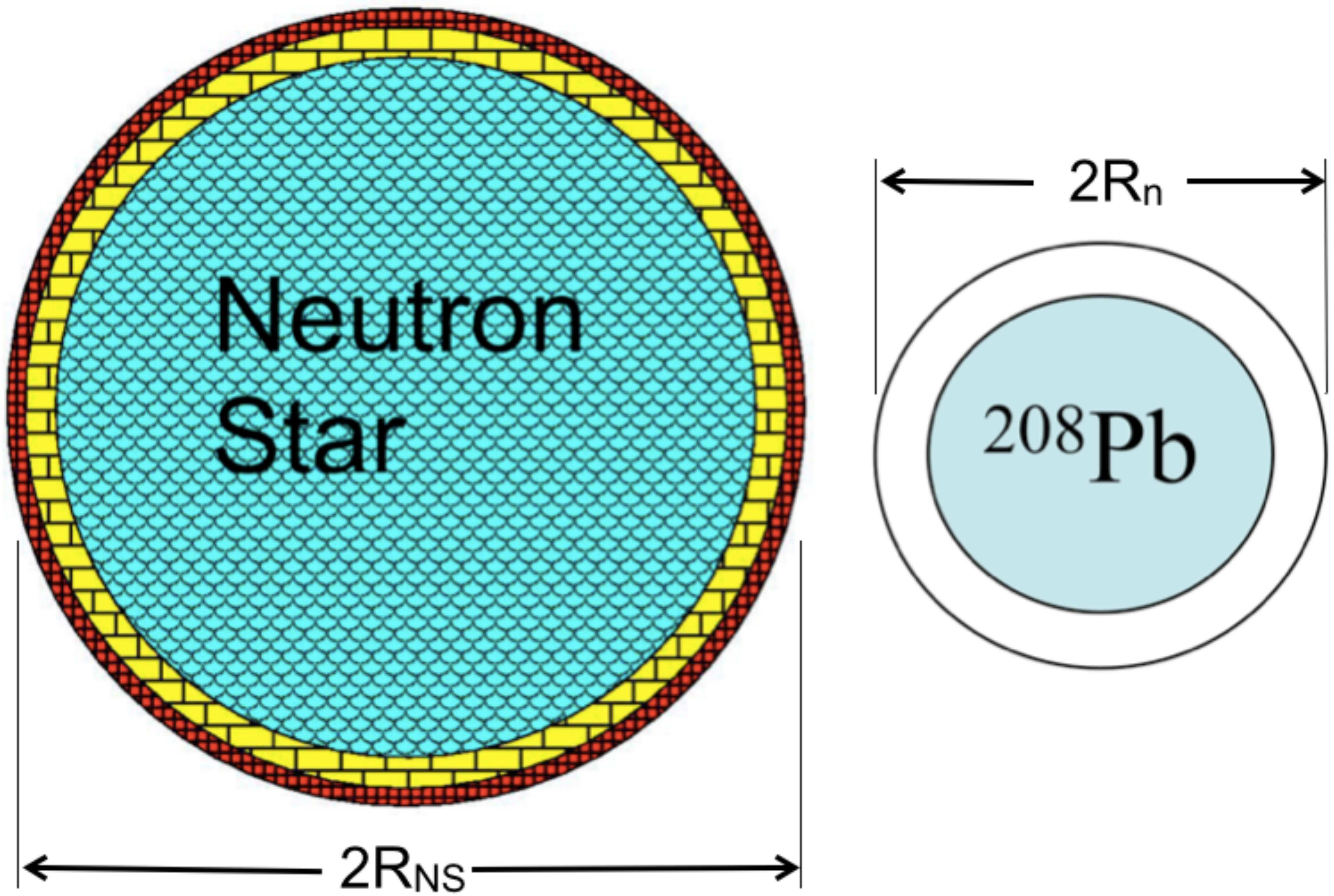
Drischler et al Chiral EFT calculation of nuclear density PRC 102, 054315





Radii of ^{208}Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



Neutron star is 18 orders of magnitude larger than Pb nucleus but both involve neutron rich matter at similar densities with the same strong interactions and equation of state.

Nuclear measurement vs Astronomical Observation

To probe equation of state

PREX, CREX measure neutron radius of ^{208}Pb and ^{48}Ca. Clean electroweak rxn.

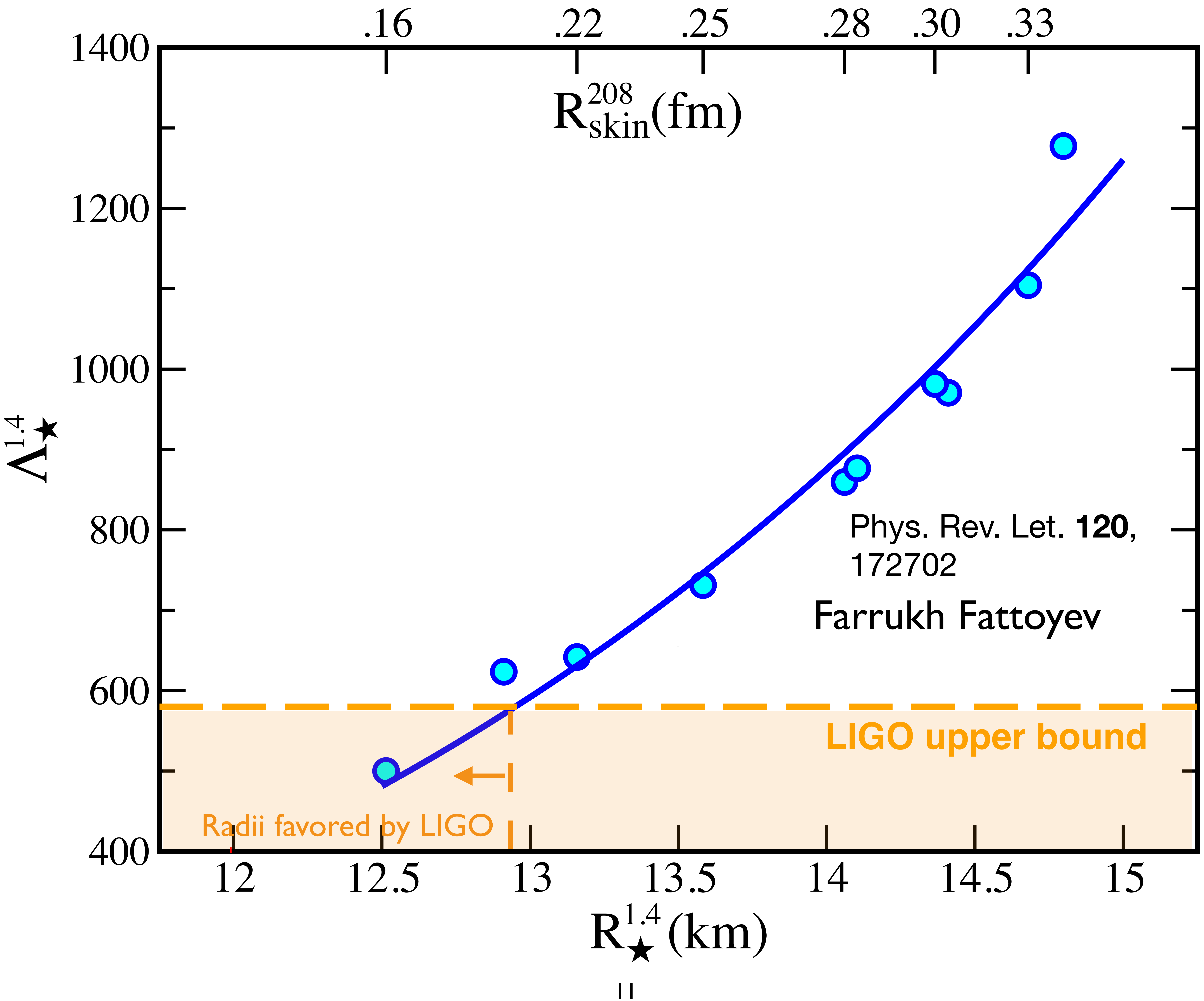
NICER measures NS radius from X-ray light curve. Some systematic errors.

Electric **dipole polarizability** from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

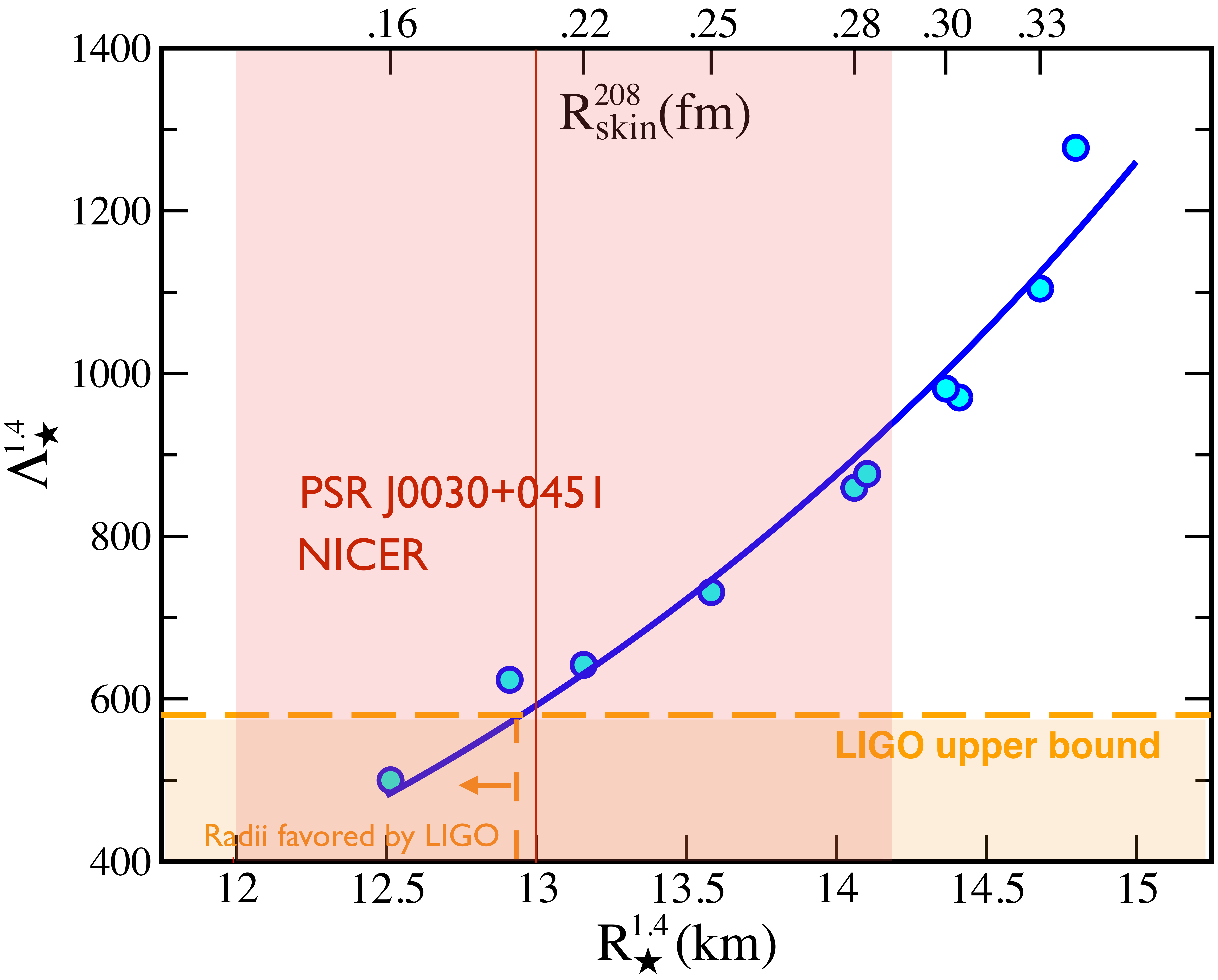
LIGO measured **gravitational deformability** (quadrupole polarizability) of NS from tidal excitation. Statistics limited but systematic errors controllable.

$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2 Y_{20}|i\rangle|^2}{E_f - E_i} \propto R^5$$

	Laboratory measurements on nuclei	Astronomical observations of neutron stars
Radius	PREX, CREX	NICER
Polarizability	Electric dipole	Gravitational deformability



.16
.22
.25
.28
.30
.33
R_{skin}^{208}(fm)
1400
1200
1000
800
600
400
$\Lambda_{\star}^{1.4}$
Phys. Rev. Let. **120**, 172702
Farrukh Fattoyev
LIGO upper bound
Radii favored by LIGO
12
12.5
13
13.5
14
14.5
15
$R_{\star}^{1.4}$(km)



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R^{208}_{skin}(fm)
$\Lambda^{1.4}_{\star}$
PSR J0030+0451
NICER
LIGO upper bound
Radii favored by LIGO
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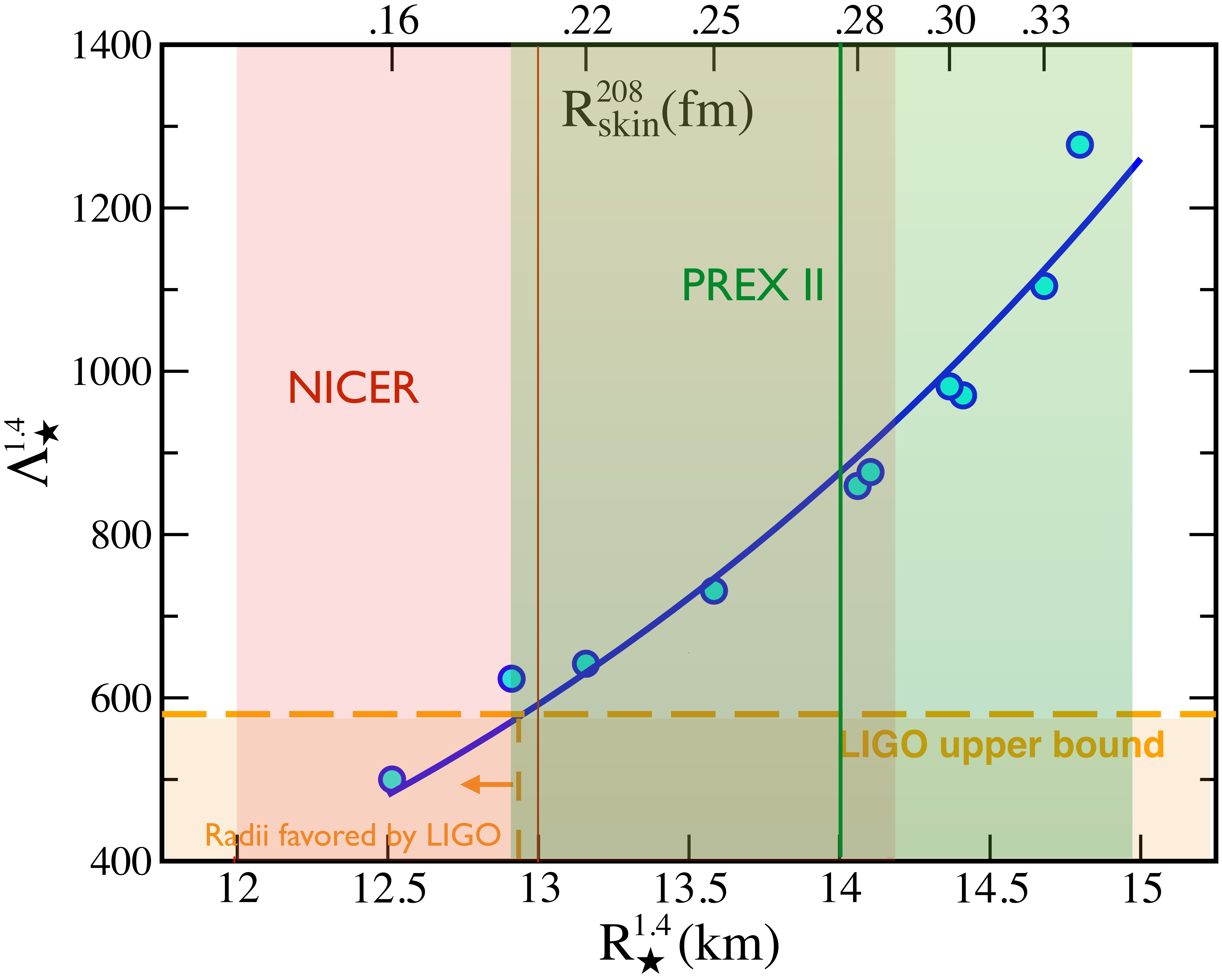
15
$R^{1.4}_{\star}$(km)



.16
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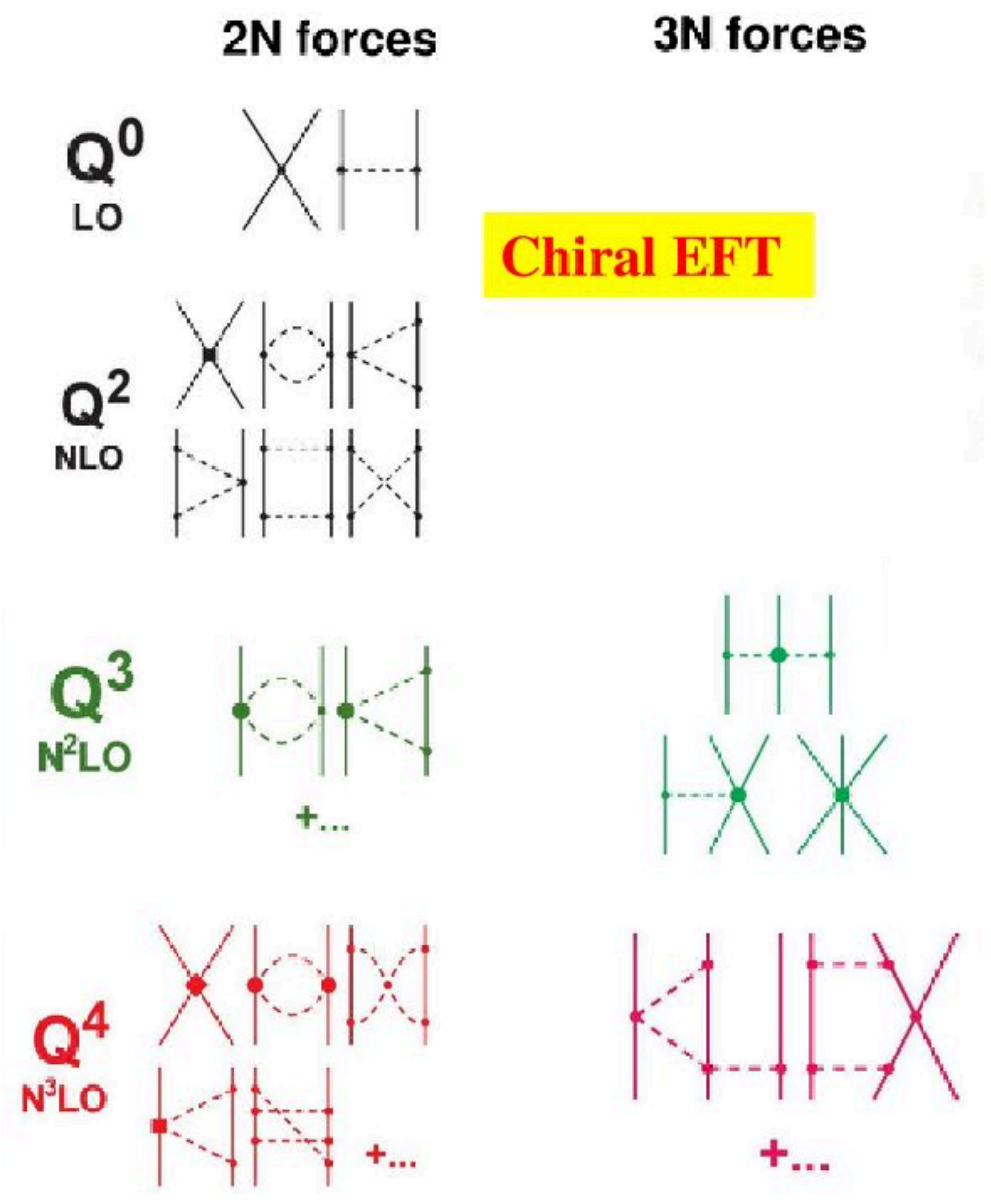
R^{208}_{skin}(fm)
PREX II
NICER
LIGO upper bound
Radii favored by LIGO
$\Lambda^{1.4}_{\star}$
1400
1200
1000
800
600
400
12
12.5
13
13.5
14
14.5
15
$R^{1.4}_{\star}$(km)

CREX on ^{48}Ca and Chiral EFT

- Chiral EFT expands 2, 3, … nucleon interactions in powers of momentum transfer over chiral scale.
- **Three neutron forces** are hard to directly observe. They increase the pressure of neutron matter and the neutron skin thickness of both ^{208}Pb and ^{48}Ca.
- Only stable, neutron rich, closed shell nuclei are ^{48}Ca and ^{208}Pb.
- PREX for ^{208}Pb better for inferring pressure of neutron matter and structure of neutron stars.
- CREX measures neutron skin in ^{48}Ca. Smaller system allows direct comparison to Chiral EFT calculations and very sensitive to 3 *neutron* forces.



CREX

- 2.182 GeV electrons scattering with q=0.8733 fm^{-1} from ^{48}Ca.
- Target 8% ^{40}Ca, 0.6%, 0.6%, 0.2% of rate from first three excited states (2^+,3^-,3^-).
- A_{PV}=2668+/-106+/-40 ppb
- We thank J. Piekarewicz, P. G. Reinhard and X. Rocca-Maza for RPA calculations of ^{48}Ca excited states and J. Erler and M. Gorshteyn for calculations of $\gamma - Z$ box radiative corrections.

A_{PV} corrections and corresponding systematic errors

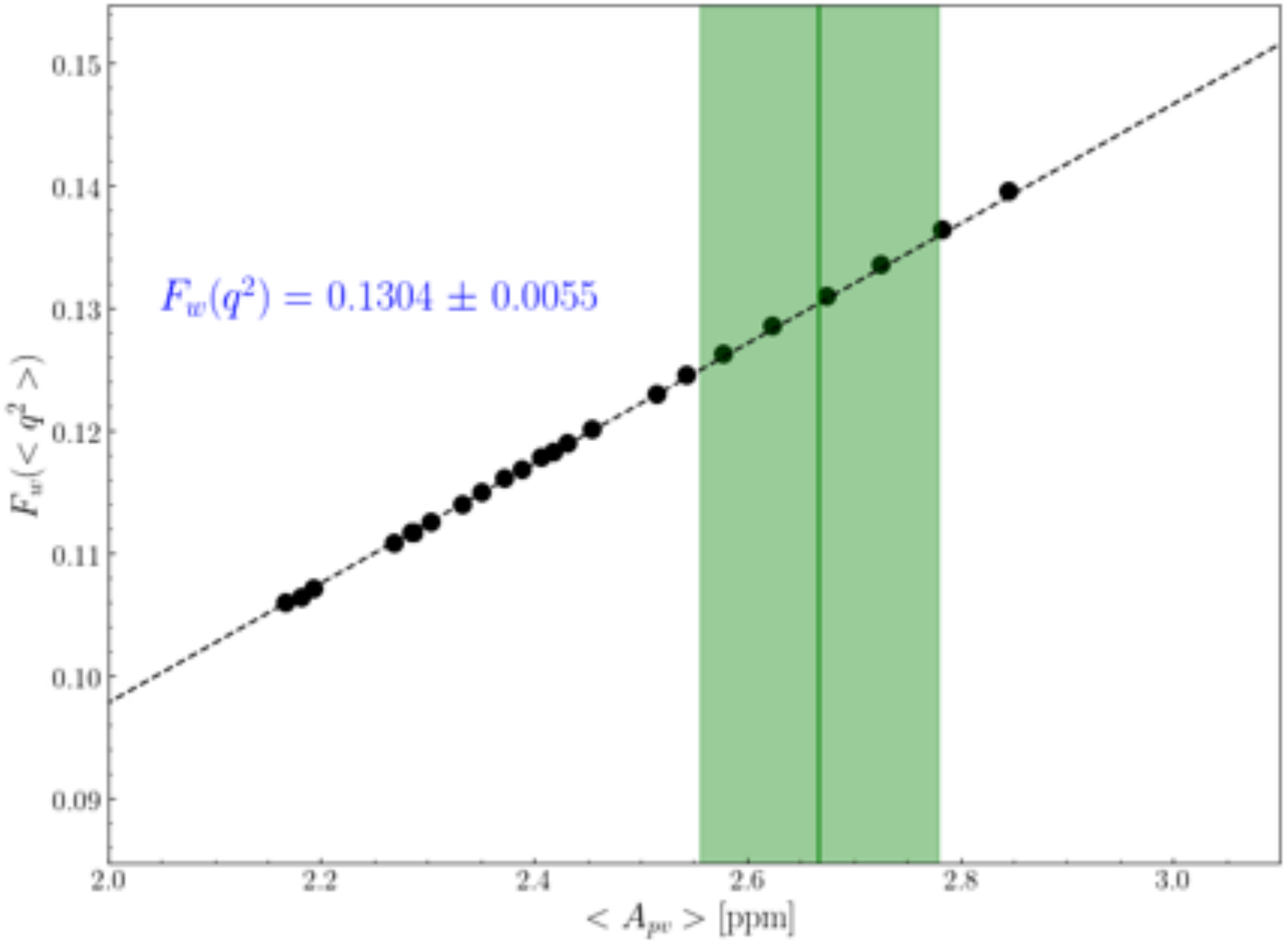
Correction	Absolute [ppb]	Relative [%]
Beam polarization	382 ± 13	14.3 ± 0.5
Beam trajectory & energy	68 ± 7	2.5 ± 0.3
Beam charge asymmetry	112 ± 1	4.2 ± 0.0
Isotopic purity	19 ± 3	0.7 ± 0.1
3.831 MeV (2^+) inelastic	-35 ± 19	-1.3 ± 0.7
4.507 MeV (3^-) inelastic	0 ± 10	0 ± 0.4
5.370 MeV (3^-) inelastic	-2 ± 4	-0.1 ± 0.1
Transverse asymmetry	0 ± 13	0 ± 0.5
Detector non-linearity	0 ± 7	0 ± 0.3
Acceptance	0 ± 24	0 ± 0.9
Radiative corrections (Q_W)	0 ± 10	0 ± 0.4
Total systematic uncertainty	40 ppb	1.5%
Statistical Uncertainty	106 ppb	4.0%

Weak Form Factor

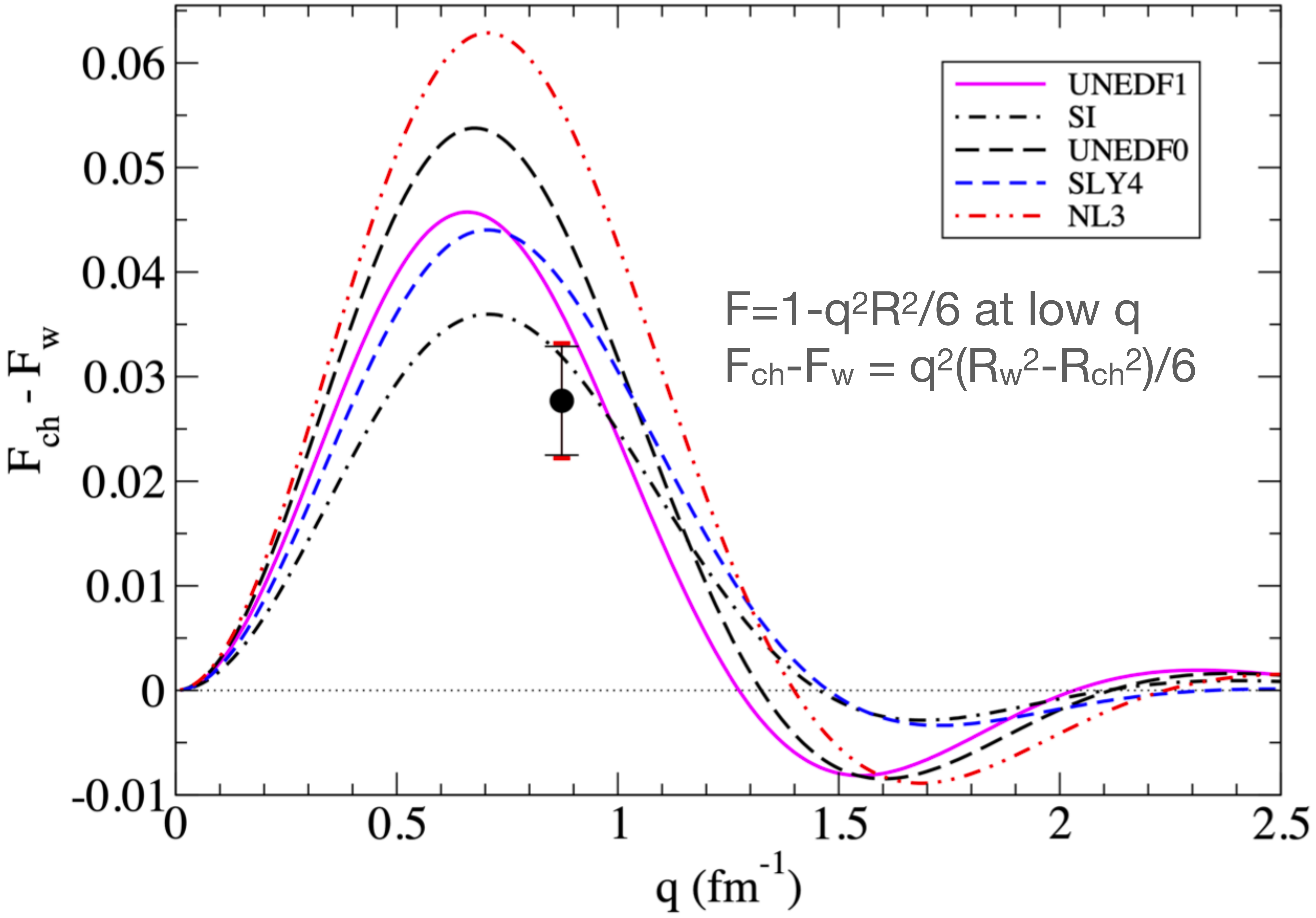
$$A_{PV} = \frac{G_F Q^2 Q_W^2 F_W(q)}{4\pi\alpha\sqrt{2} Z F_{ch}(q)}$$

- Determine ratio F_W/F_{ch} from A_{PV} (Include Coulomb distortions and averaging over acceptance)
- Main result:

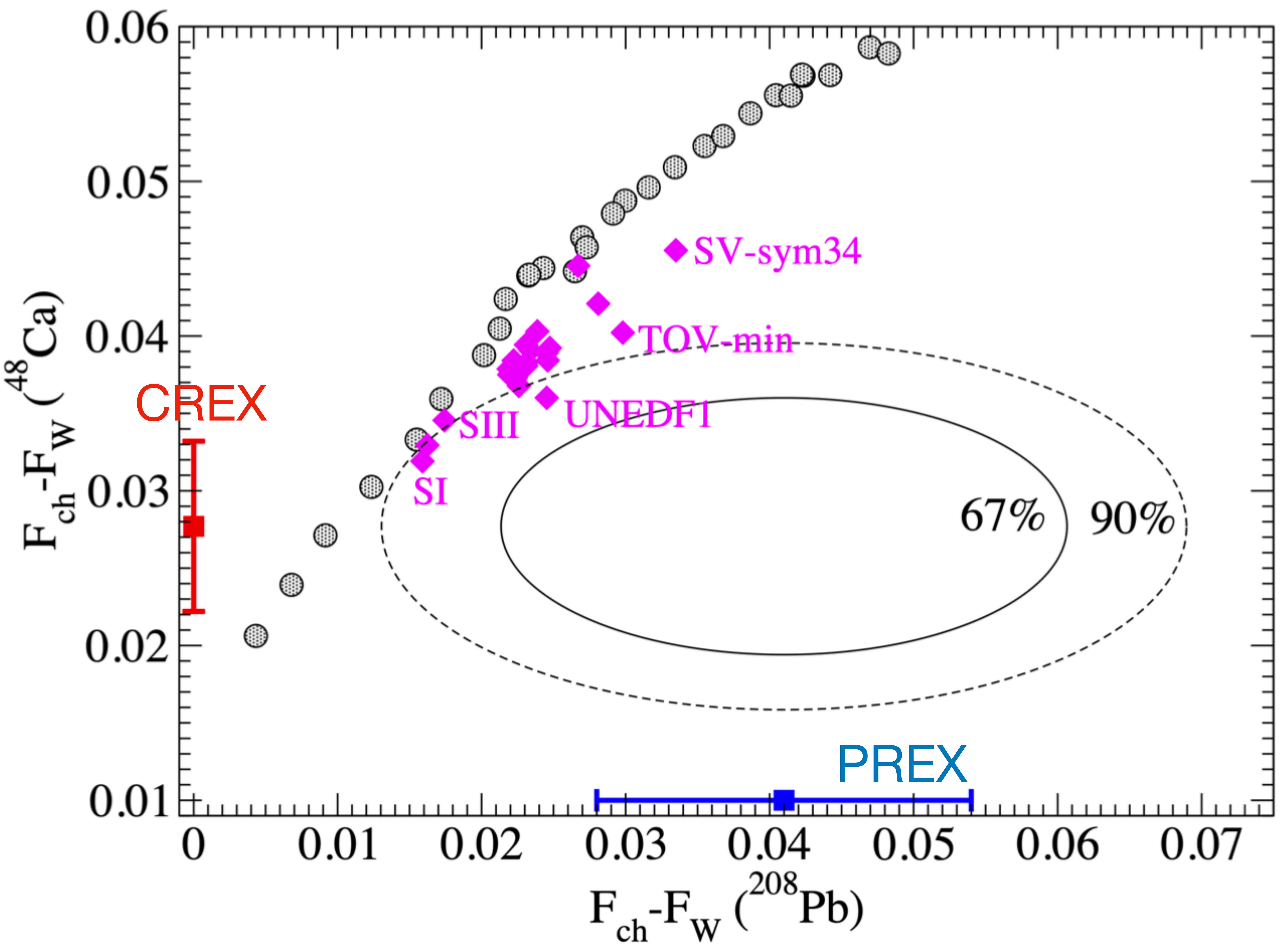
$$F_{\rm ch}(q) - F_{\rm W}(q) = 0.0277 \pm 0.0055 \text{ (exp)}$$



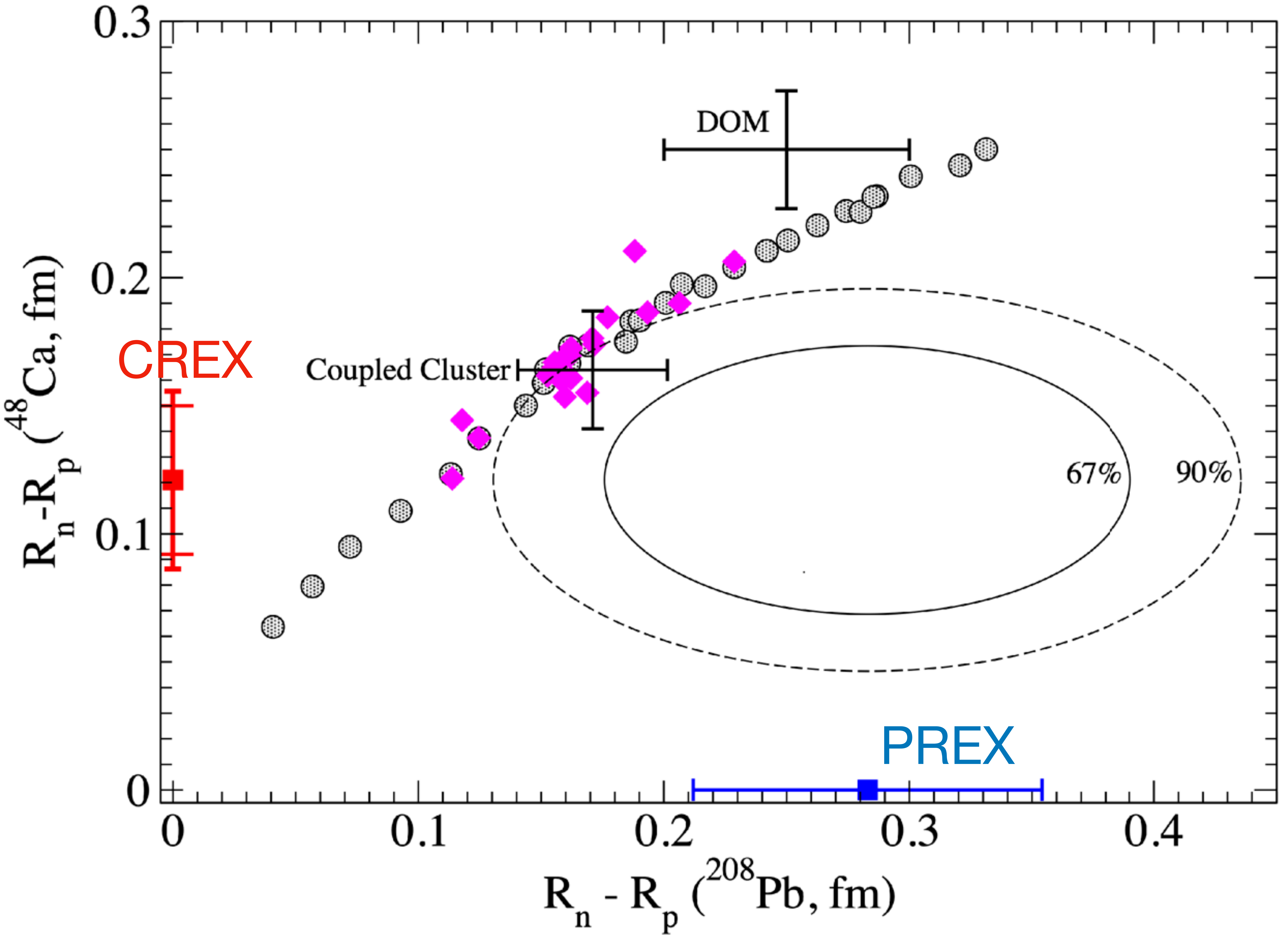
Quantity	Value ± (stat) ± (sys)
q	$0.8733\ \text{fm}^{-1}$
$F_{\rm W}(q)/F_{\rm ch}(q)$	$0.8248 \pm 0.0328 \pm 0.0124$
$F_{\rm ch}(q)$	0.1581
$F_{\rm W}(q)$	$0.1304 \pm 0.0052 \pm 0.0020$
$F_{\rm ch}(q) - F_{\rm W}(q)$	$0.0277 \pm 0.0052 \pm 0.0020$



UNEDF1
SI
UNEDF0
SLY4
NL3
F=1-q²R²/6 at low q
Fch-Fw = q²(Rw²-Rch²)/6
Fch - Fw
q (fm-1)
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
0.5
1
1.5
2
2.5

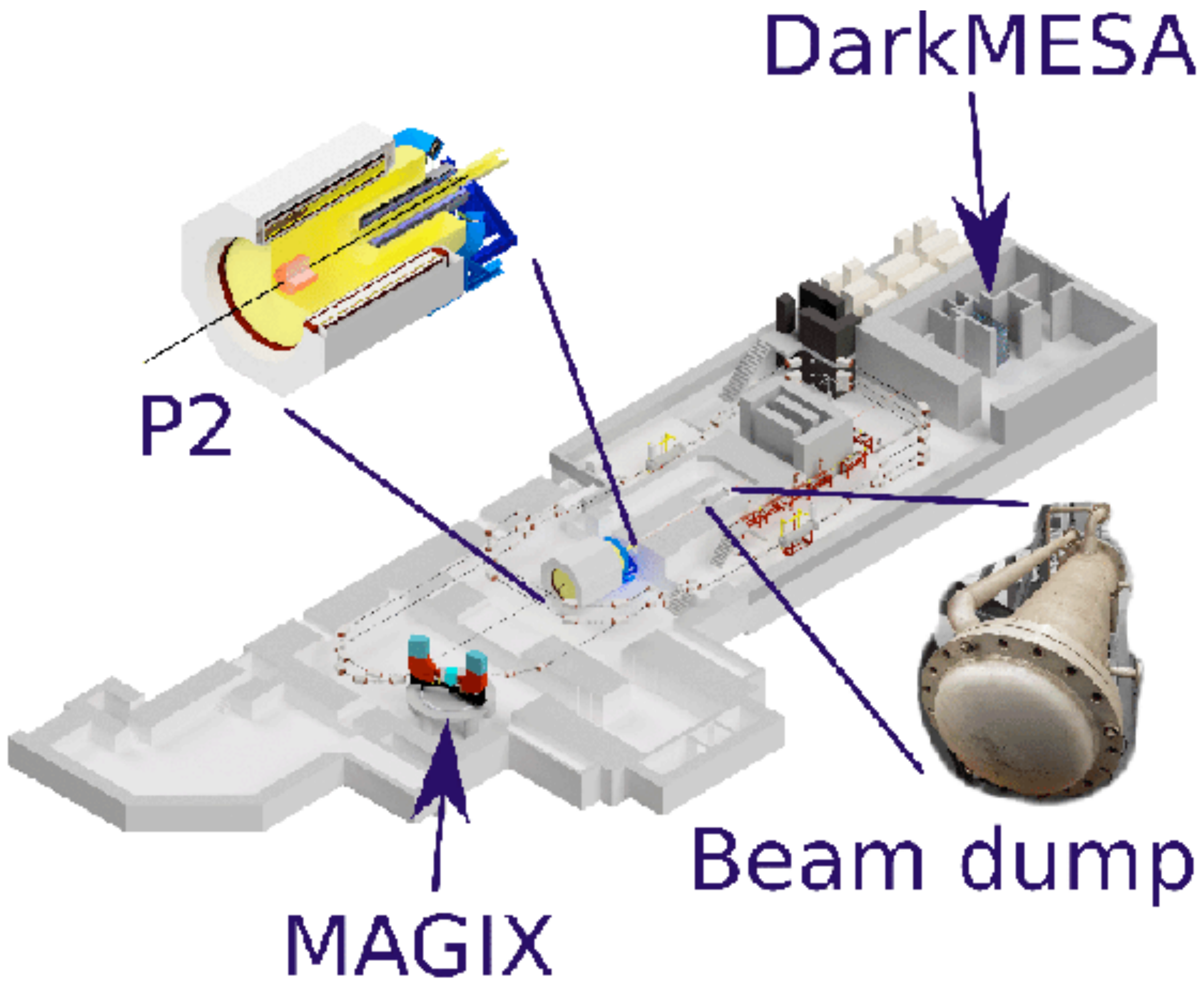


CREX
PREX
SV-sym34
TOV-min
UNEDF1
SIII
SI
67%
90%
0.06
0.05
0.04
0.03
0.02
0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
$F_{ch}-F_W$ (^{48}Ca)
$F_{ch}-F_W$ (^{208}Pb)



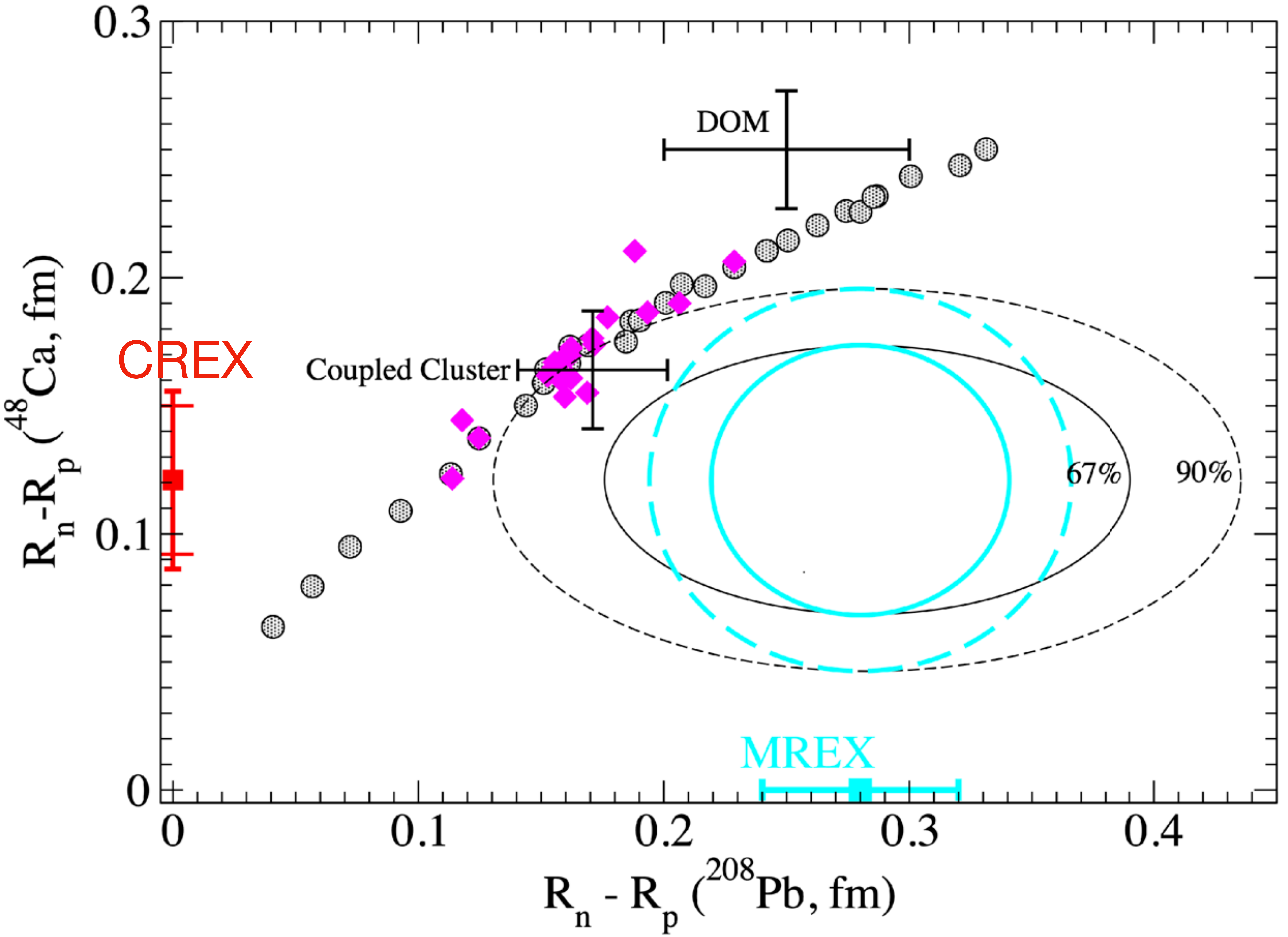
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
DOM
Coupled Cluster
CREX
PREX
67%
90%
$R_n - R_p$ (^{48}Ca, fm)
$R_n - R_p$ (^{208}Pb, fm)

MREX experiment at Mainz

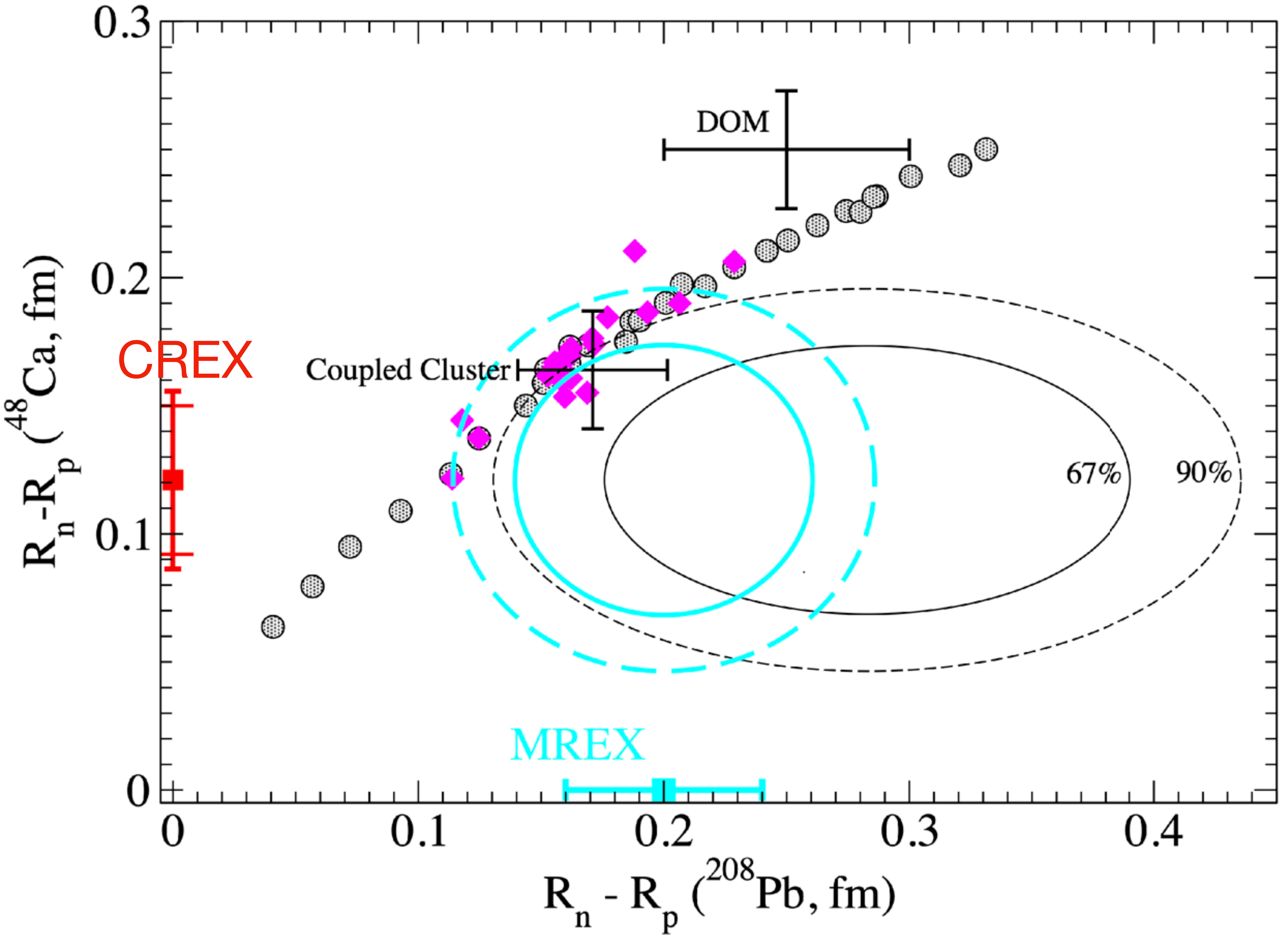


- MESA is high current low energy electron accelerator being built at Mainz.
- Mainz Radius Experiment (MREX) will use MESA and large acceptance P2 detector to measure the neutron skin of ^{208}Pb more accurately than PREX.
- PREX measured R_n to 1.3% (+/- 0.07 fm), MREX goal 0.5% (+/- 0.03 fm)

beam energy	155 MeV
beam current	150 μA
target density	0.28 g/cm^2
polar angle step size	$\Delta\theta = 4°$
polar angular range	30° to 34°
degree of polarization	85 %
parity violating asymmetry	0.66 ppm
running time	1440 hours
systematic uncertainty	1 %
$\delta A^{PV}/A^{PV}$	1.39 %
$\delta R_n/R_n$	0.52 %



CREX
DOM
Coupled Cluster
67%
90%
MREX
0.3
0.2
0.1
0
0.4
R_n-R_p (^{48}Ca, fm)
R_n - R_p (^{208}Pb, fm)

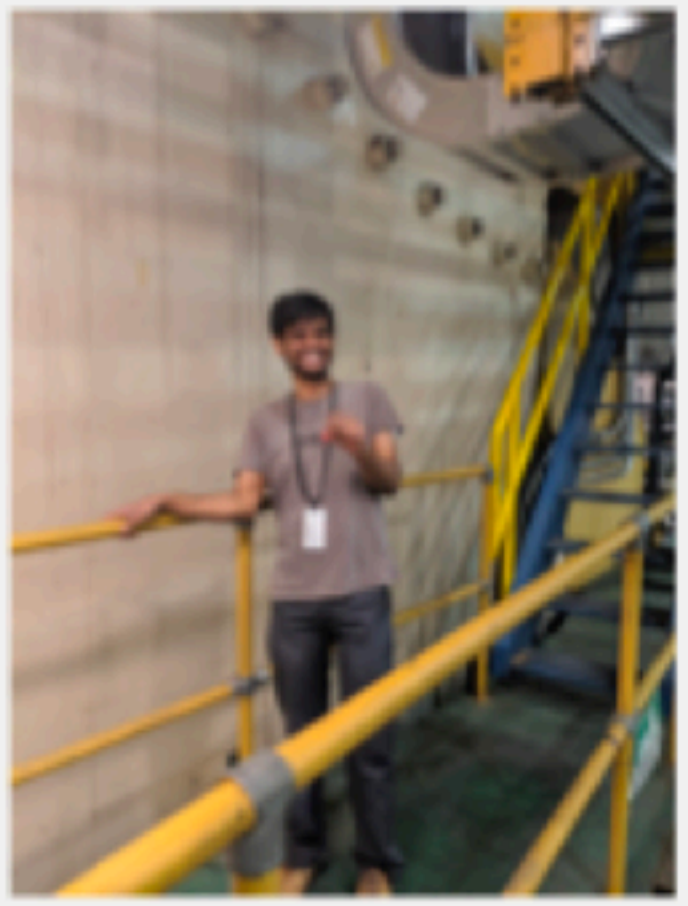


0.3
0.2
0.1
0
CREX
$R_n - R_p$ (^{48}Ca, fm)
DOM
Coupled Cluster
67%
90%
MREX
0
0.1
0.2
0.3
0.4
R_n - R_p (^{208}Pb, fm)

PREX and CREX Collaborations

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, Adam Zec, Weibin Zhang

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Spokespeople: Kent Paschke (contact), Krishna Kumar, Robert Michaels, Paul A. Souder, Guido M. Urciuoli

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