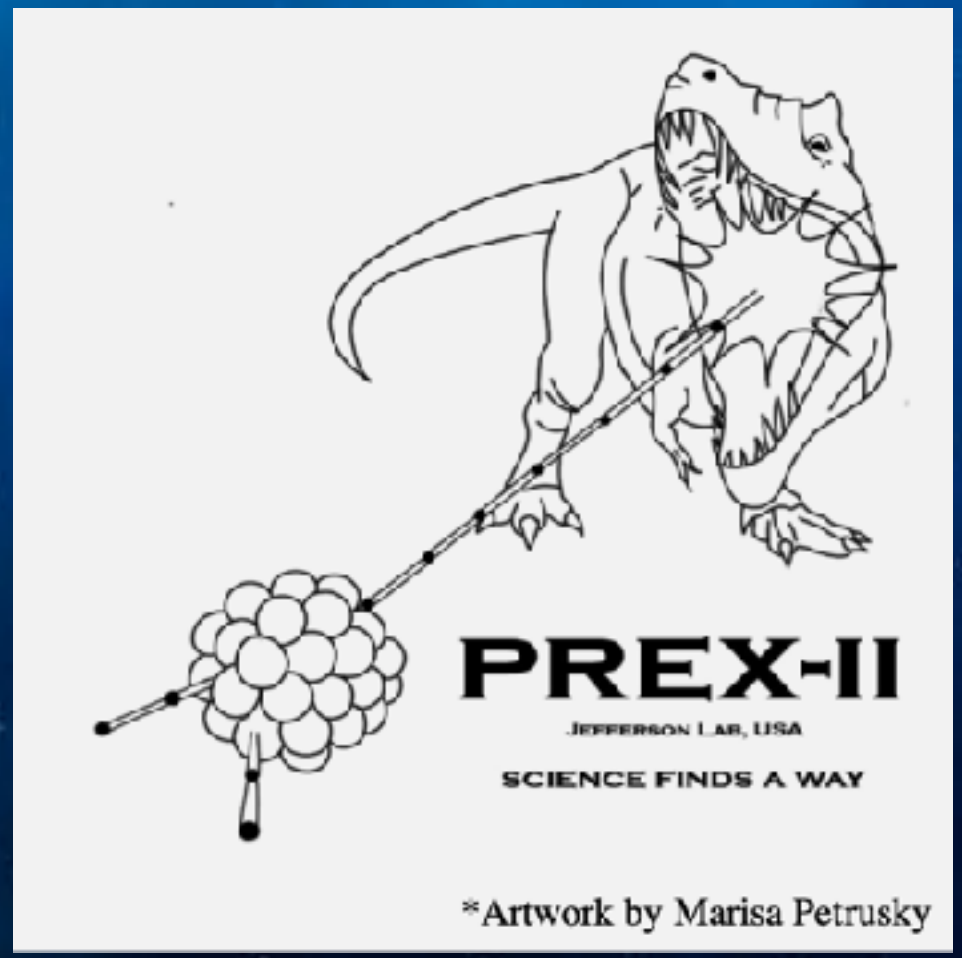
Neutron Densities, PREX / CREX, and Neutron Stars

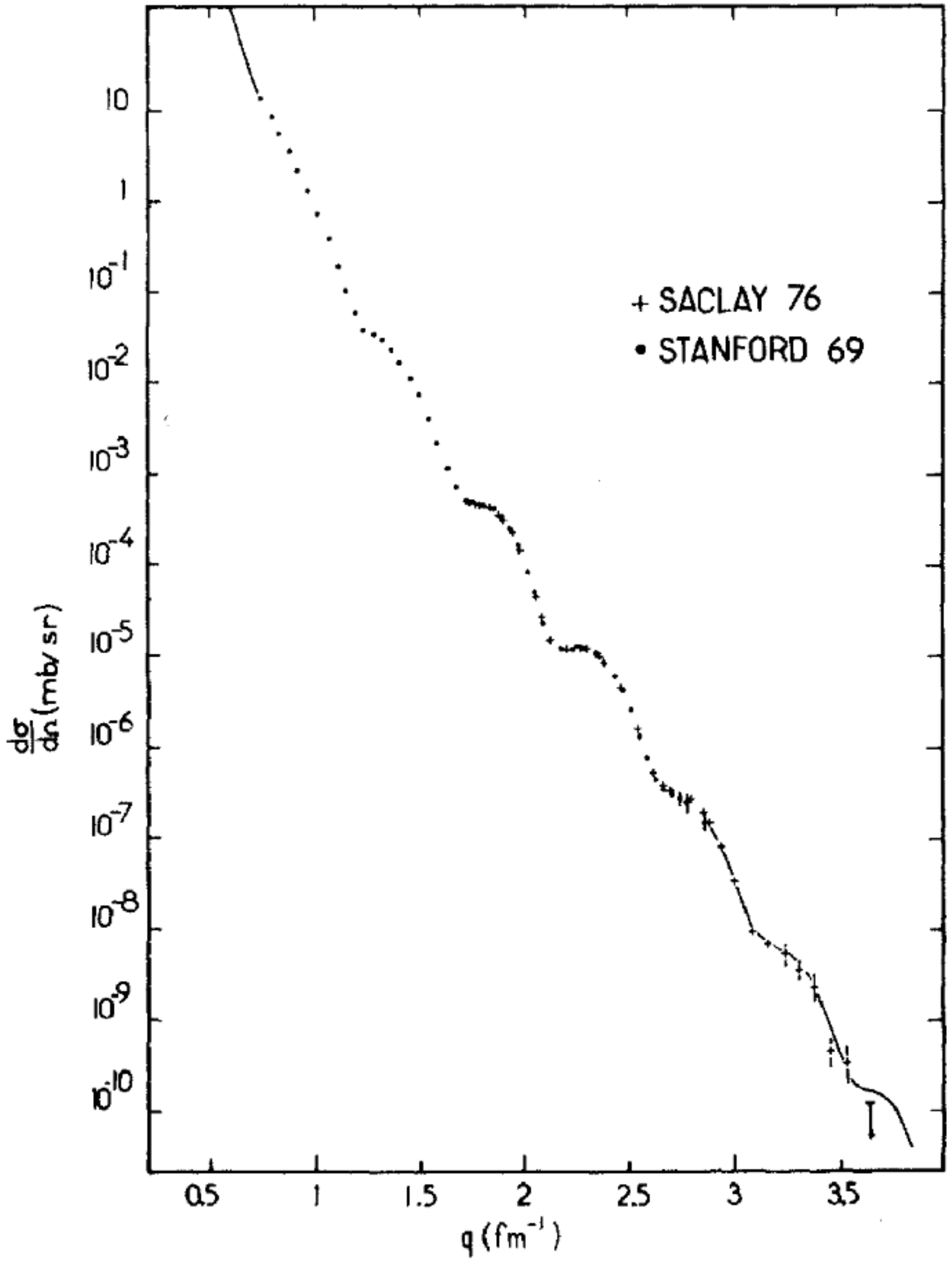


Chuck Horowitz, Indiana U.   Heaven and Earth, INT 2022

Neutron densities, PV electron scattering, and neutron stars

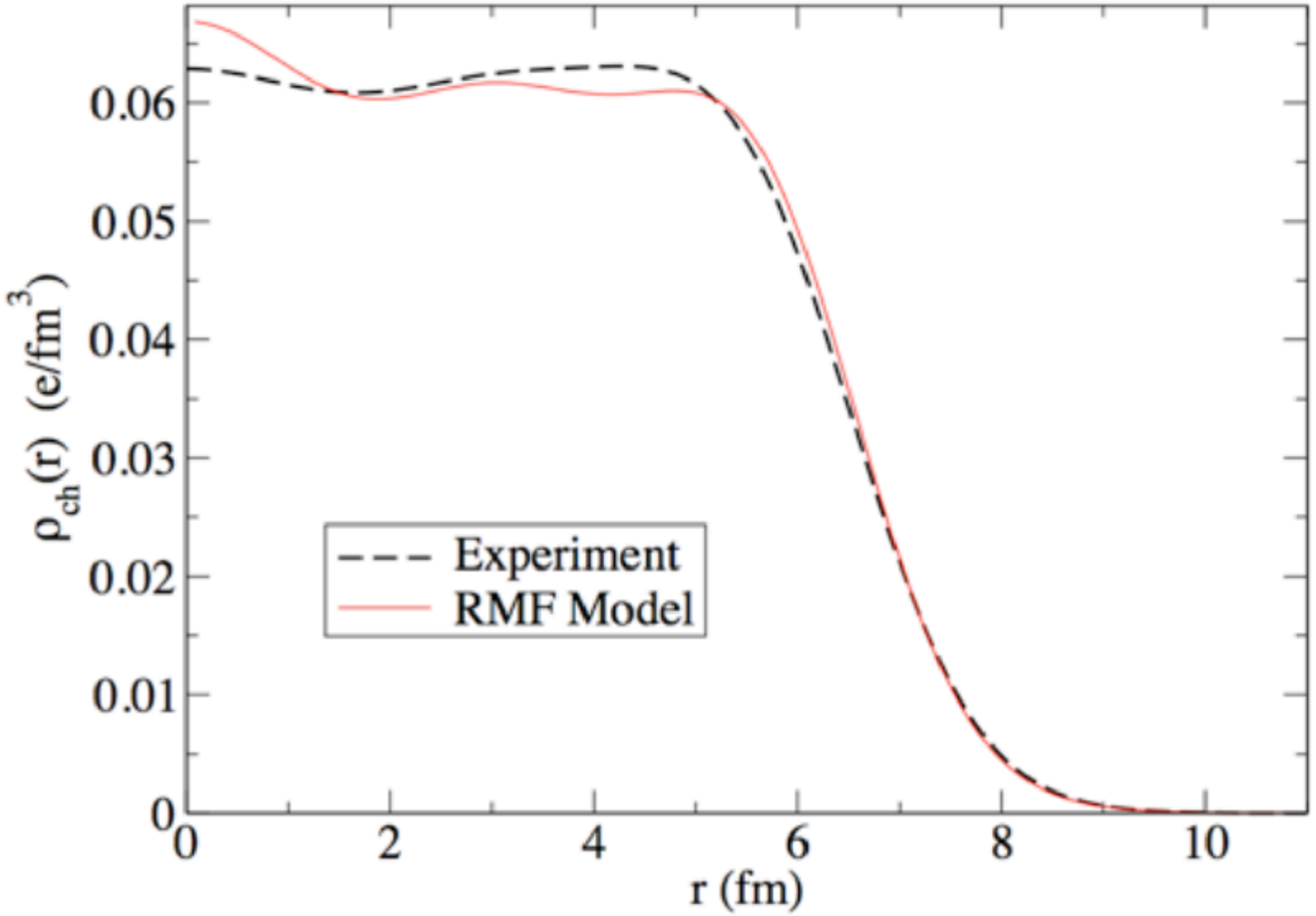
- Neutron densities and PREX
- Neutron stars and gravitational waves
- CREX PV electron scattering experiment on ^{48}Ca
- Work done with student Brendan Reed!

Neutron Densities in Nuclei

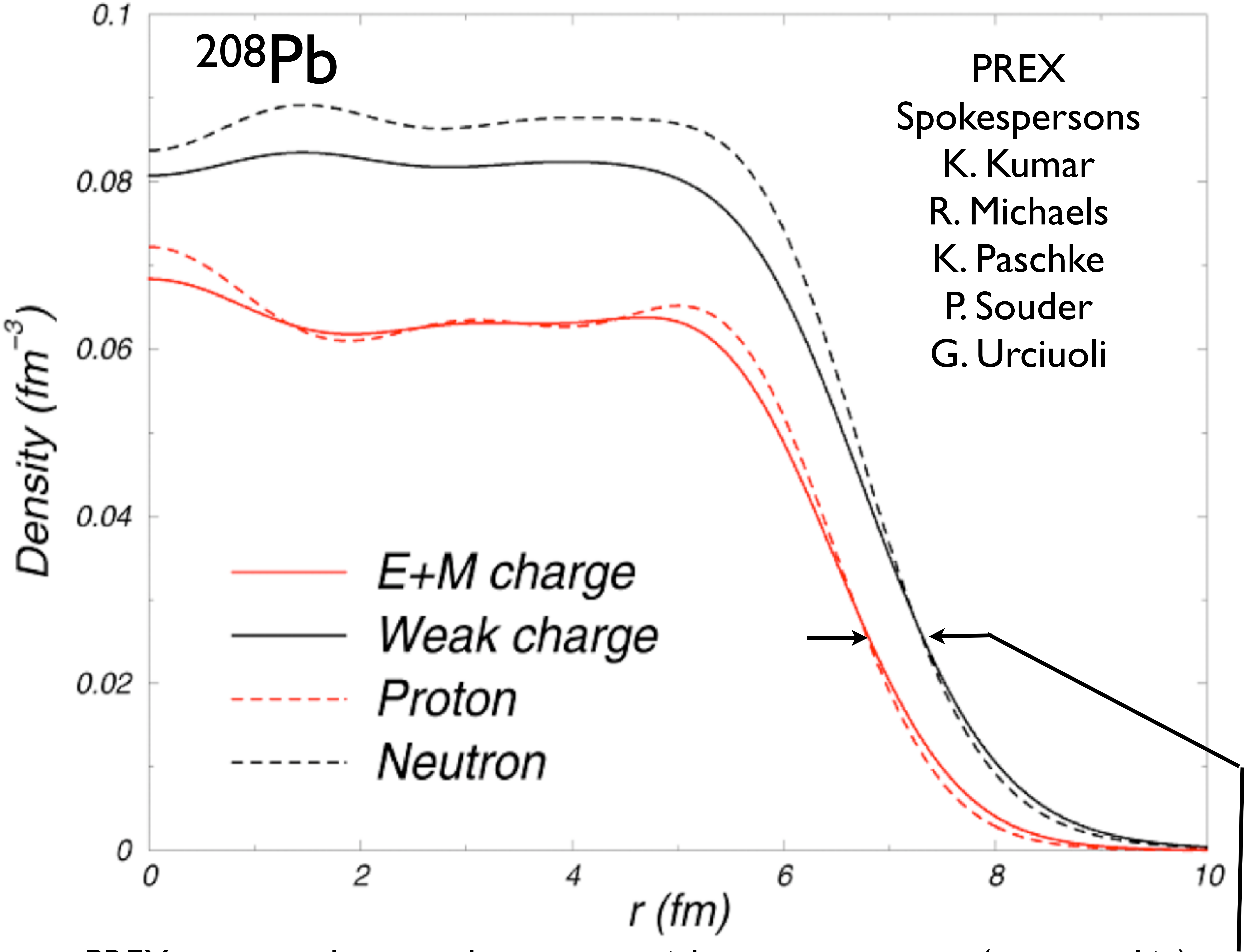


Cross section measured over 12 orders of magnitude.

Charge Density of ^{208}Pb, accurately measured in elastic electron scattering.



These elastic charge densities ***are*** our picture of the atomic nucleus!



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

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.**

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

Weak Density and Form Factor

- The weak charge density $\rho_w(r)$ is neutron density folded with weak charge distribution of single neutron…

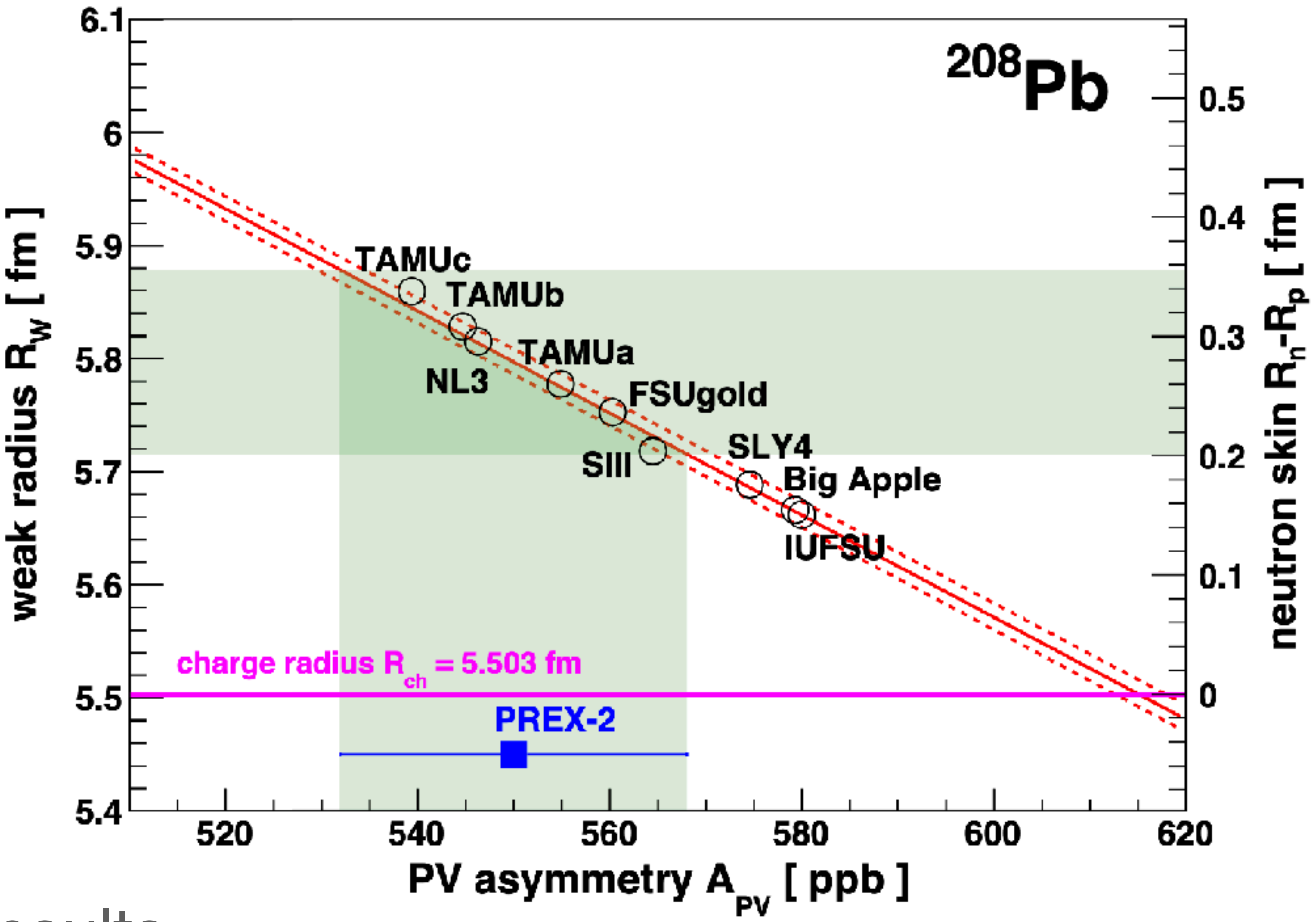
$$\rho_W(r) = \int d^3r' \left[G_{En}^Z(r')\rho_n(|\vec{r}-\vec{r}'|) + G_{Ep}^Z(r')\rho_p(|\vec{r}-\vec{r}'|)\right]$$

- The weak form factor $F_W(q)$ is F.T. of ρ_w.

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

- Neutron skin is R_n-R_p and weak skin is R_w-R_{ch}

PREX-II



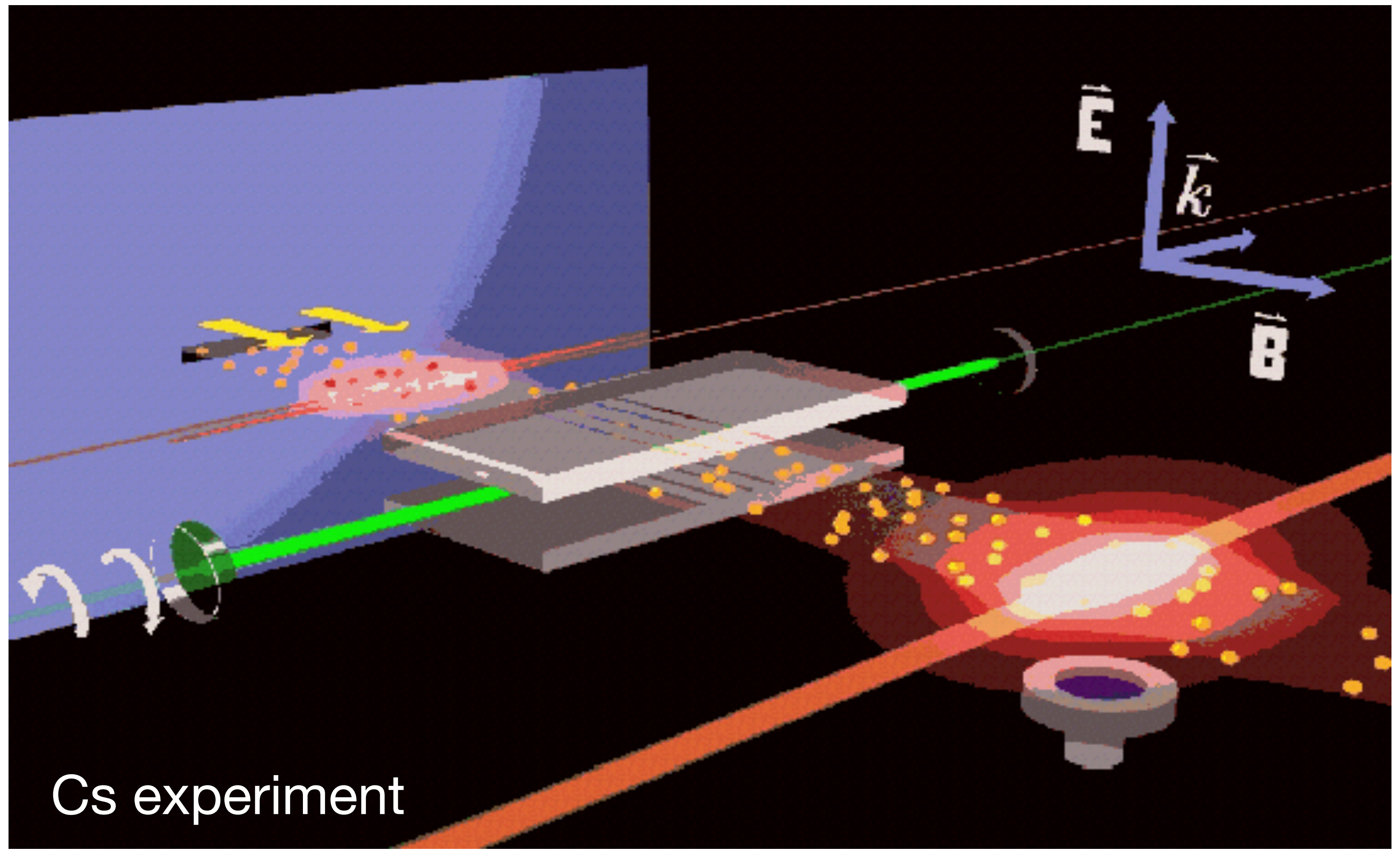
PREX-I+II Results

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

PREX-2 weak form factor:
$F_W(q=0.398\text{fm}^{-1})=0.3676\pm.0125$

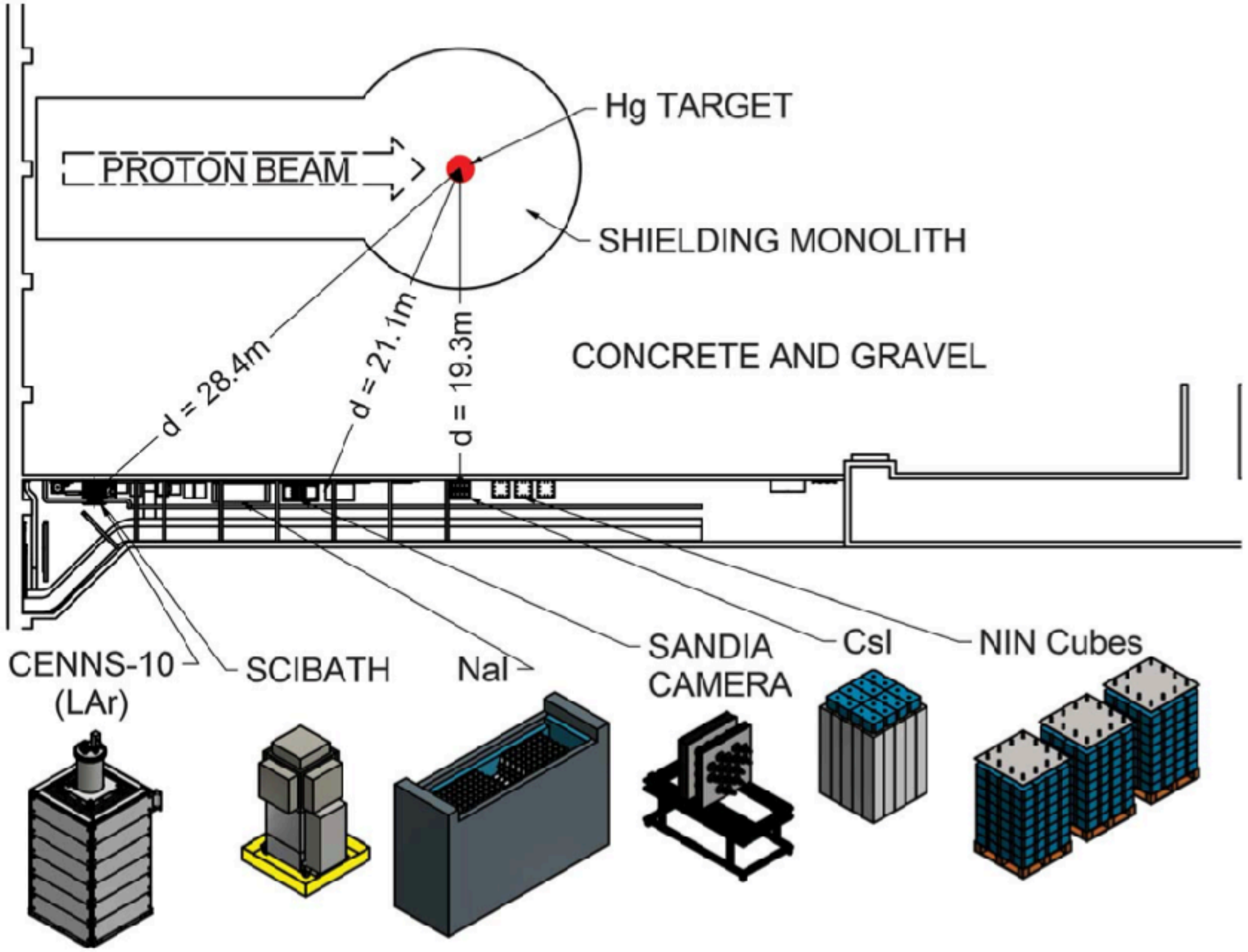
Atomic Parity Nonconservation

- Atomic PNC depends on overlap of electrons with neutrons in nucleus.
- Cs experiment good to 0.3%. Not limited by R_n but future 0.1% exp would need R_n to 1%
- Measurement of R_n in ^{208}Pb and ^{48}Ca constrains nuclear theory for R_n in other atomic PNC nuclei.
- Combine neutron radius from PV e scattering with an atomic PNC exp for strong low energy test of standard model.



- Atomic PNC Experiments:
  - Berkeley/ Mainz Yb experiment can look at PNC for isotope ratios.
  - PNC in radioactive Fr is x18 larger than for Cs because of higher electron density at nucleus of high Z nucleus.

Neutrino nucleus elastic scattering



COHERENT experiment at SNS in Oak Ridge, TN
Rex Tayloe and others at IU

Neutrino nucleus scattering involves same weak form factor as PV electron scattering

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \frac{Q_W^2}{4} F^2(Q^2) \times \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right]$$

Coherent probed CsI average R_n to ~15%

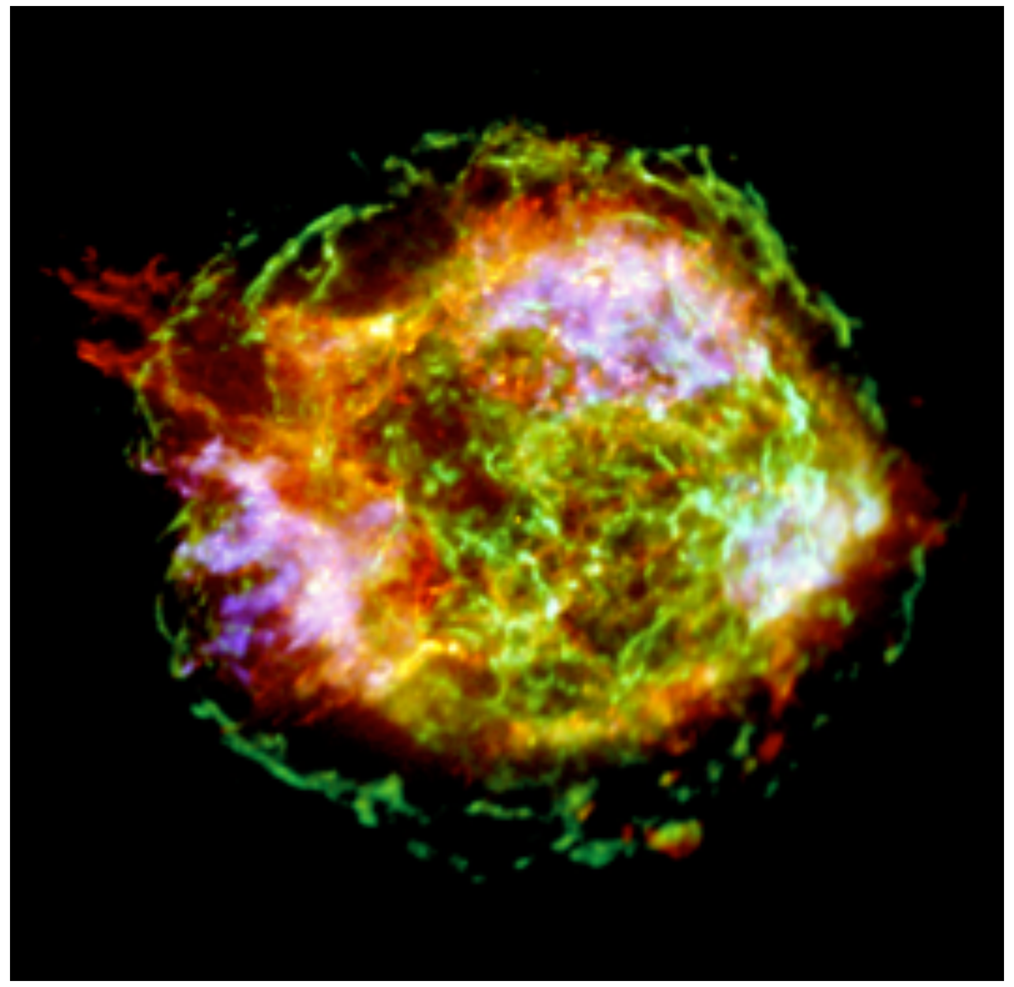
PREX measured $R_W(^{208}Pb)$ to 1.3%
CREX probed $R_W(^{48}Ca)$ to 0.7%
Qweak measured $R_n(^{27}Al)$ to 3.8%

Use PV to constrain nuclear structure. This allows coherent neutrino scattering to probe non-standard neutrino interactions.

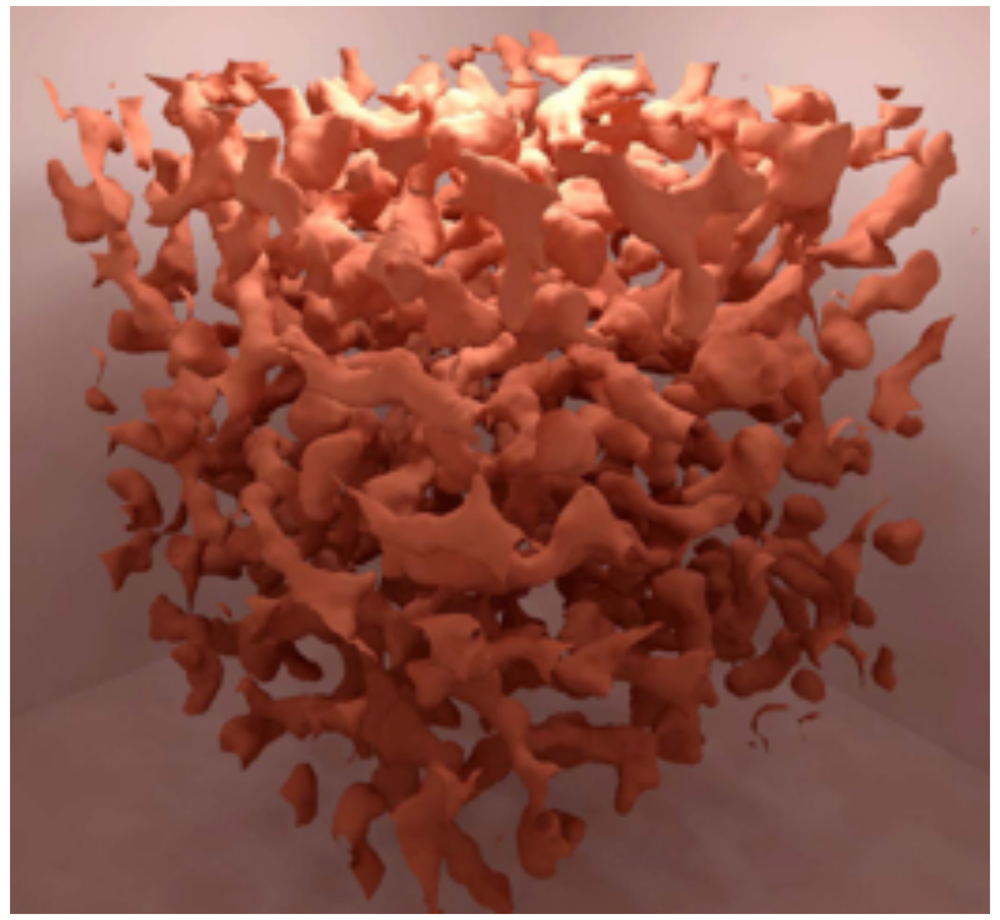
Neutron Stars

Neutron Rich Matter in Astrophysics

- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?
- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor (T_c=10^{10} K!), superfluid, color superconductor...*
- For example a heavy nucleus such as ^{208}Pb expected to have neutron rich skin.



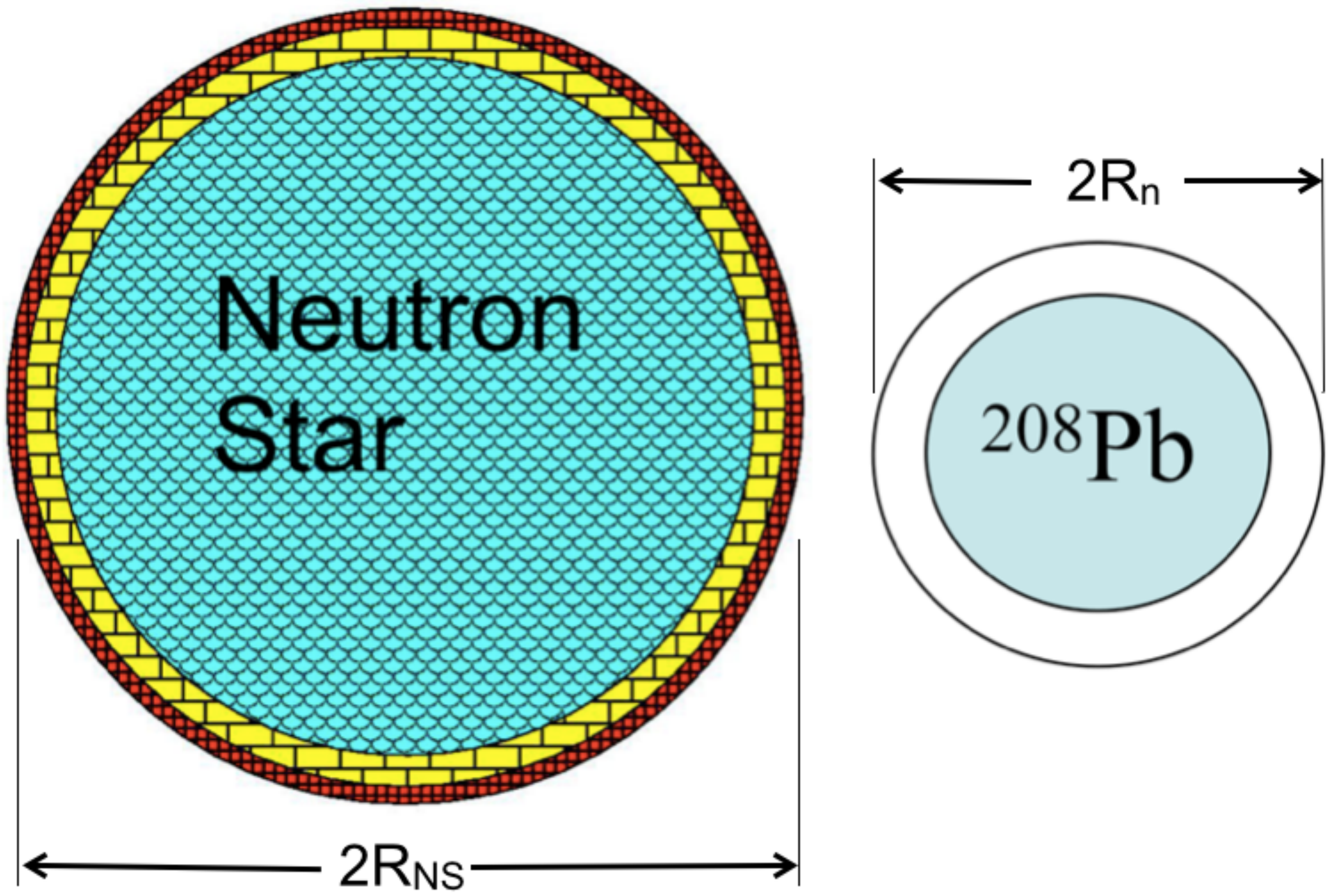
Supernova remanent Cassiopea A in X-rays



MD simulation of Nuclear Pasta with 100,000 nucleons

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.

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

LIGO and deformability of NS

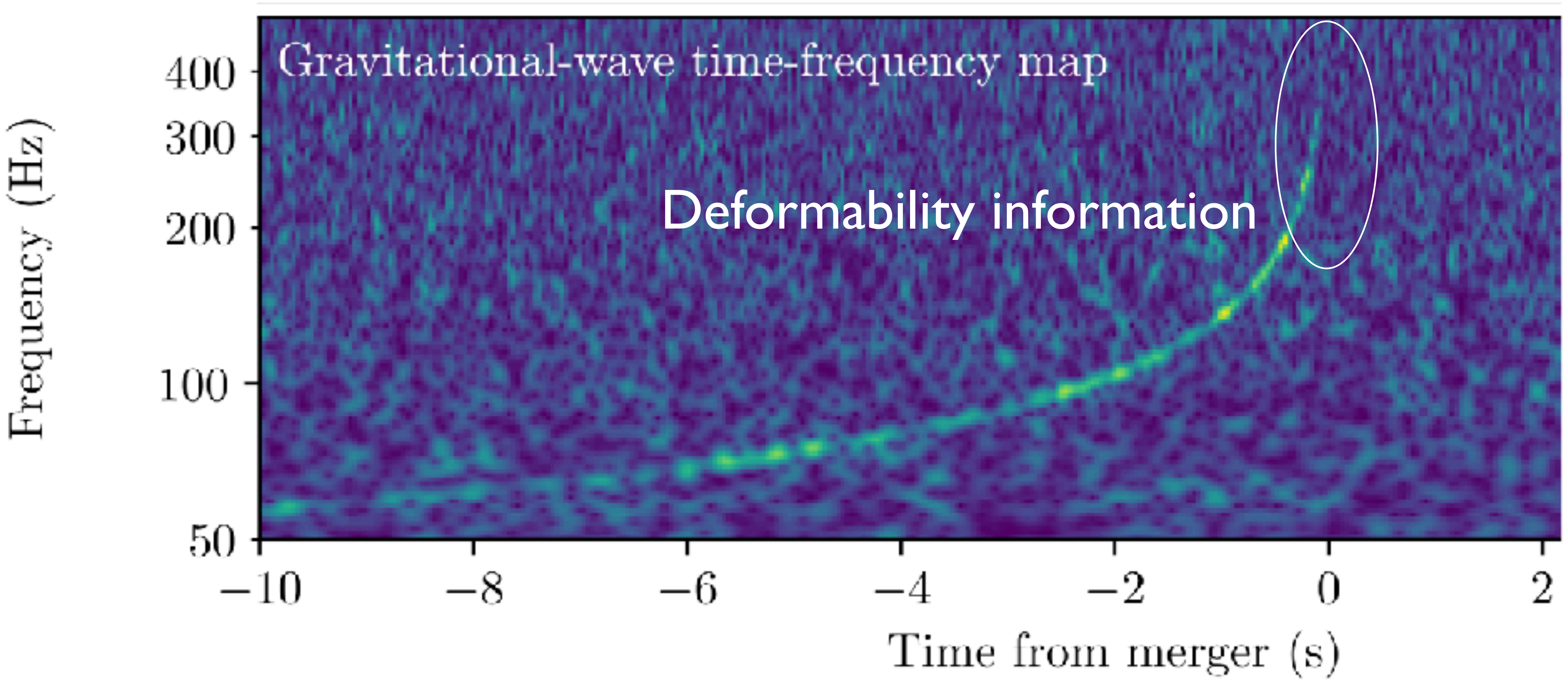
- Gravitational tidal field distorts shapes of neutron stars just before they merge.
- Dipole polarizability of an atom ~ R^3.

$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

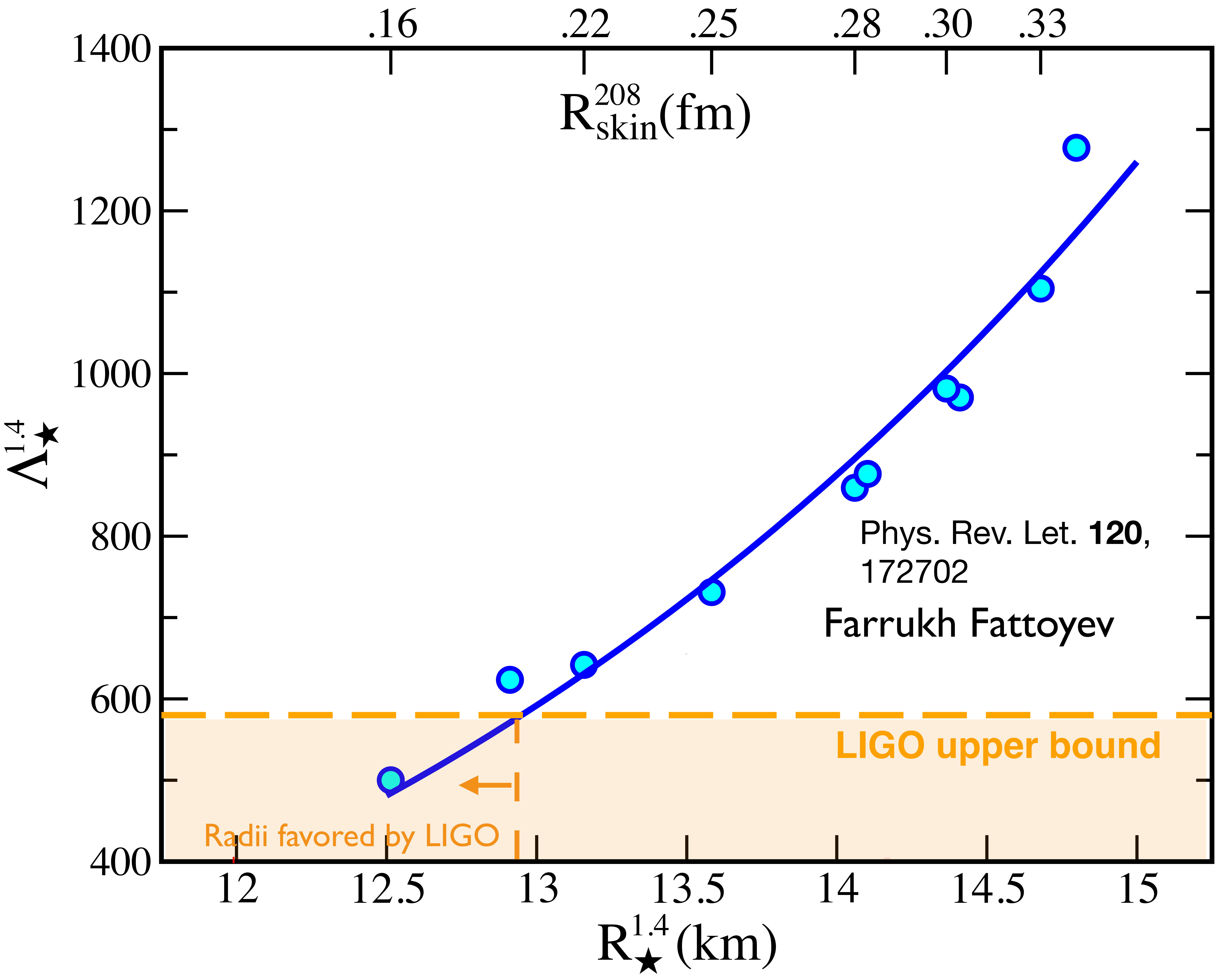
- Tidal deformability (or quadrupole polarizability) of a neutron star scales as R^5.

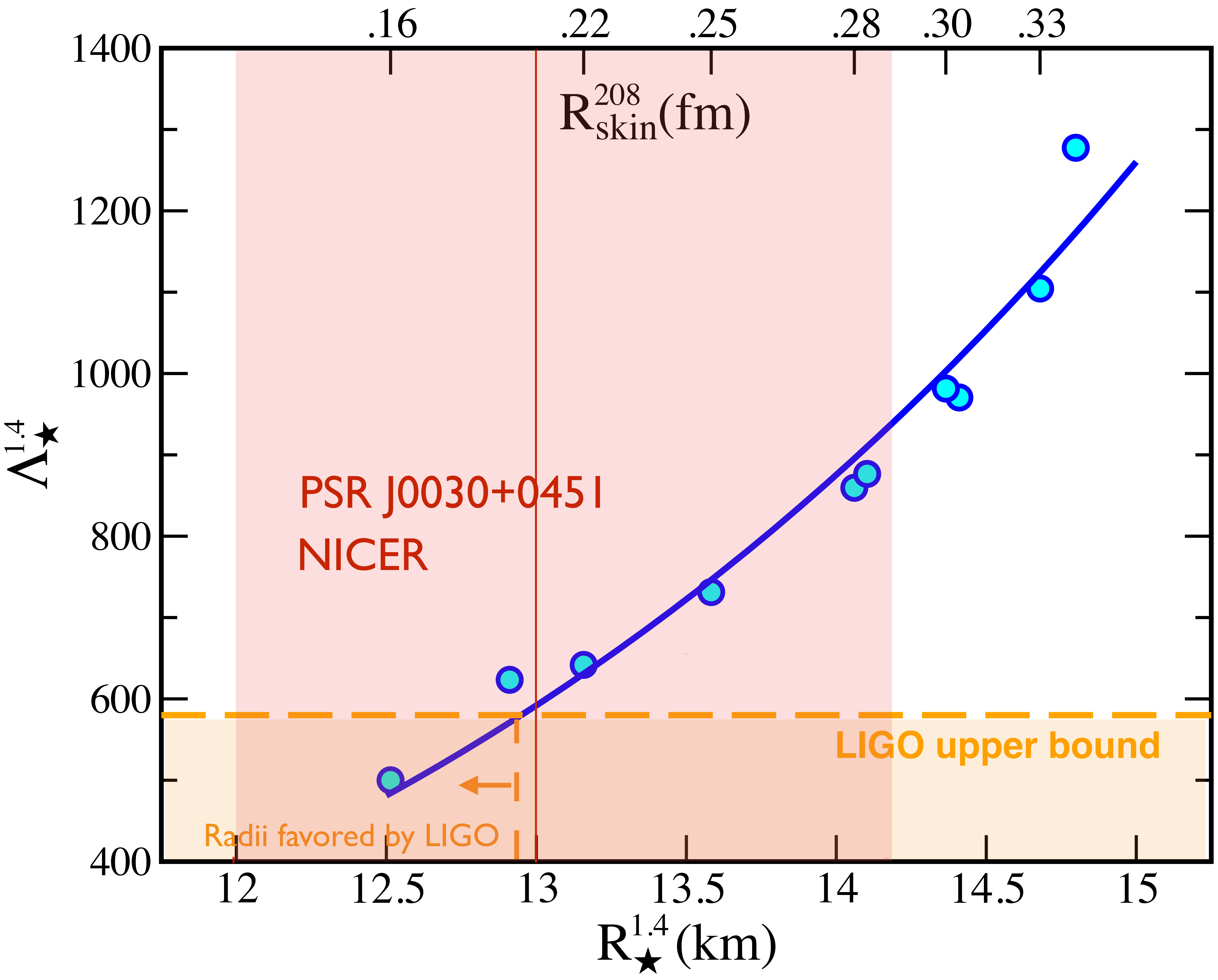
$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

- GW170817 observations set upper limit on Λ.



- For NS sum over excited states = sum over osc. modes. Most important is f_2 mode.
- Response to static tidal or electric field -> static polarizability or deformability.
- Response to time dependent fields -> dynamical polarizability or dynamical tides.


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



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R^{208}_{skin}(fm)
1400
1200
1000
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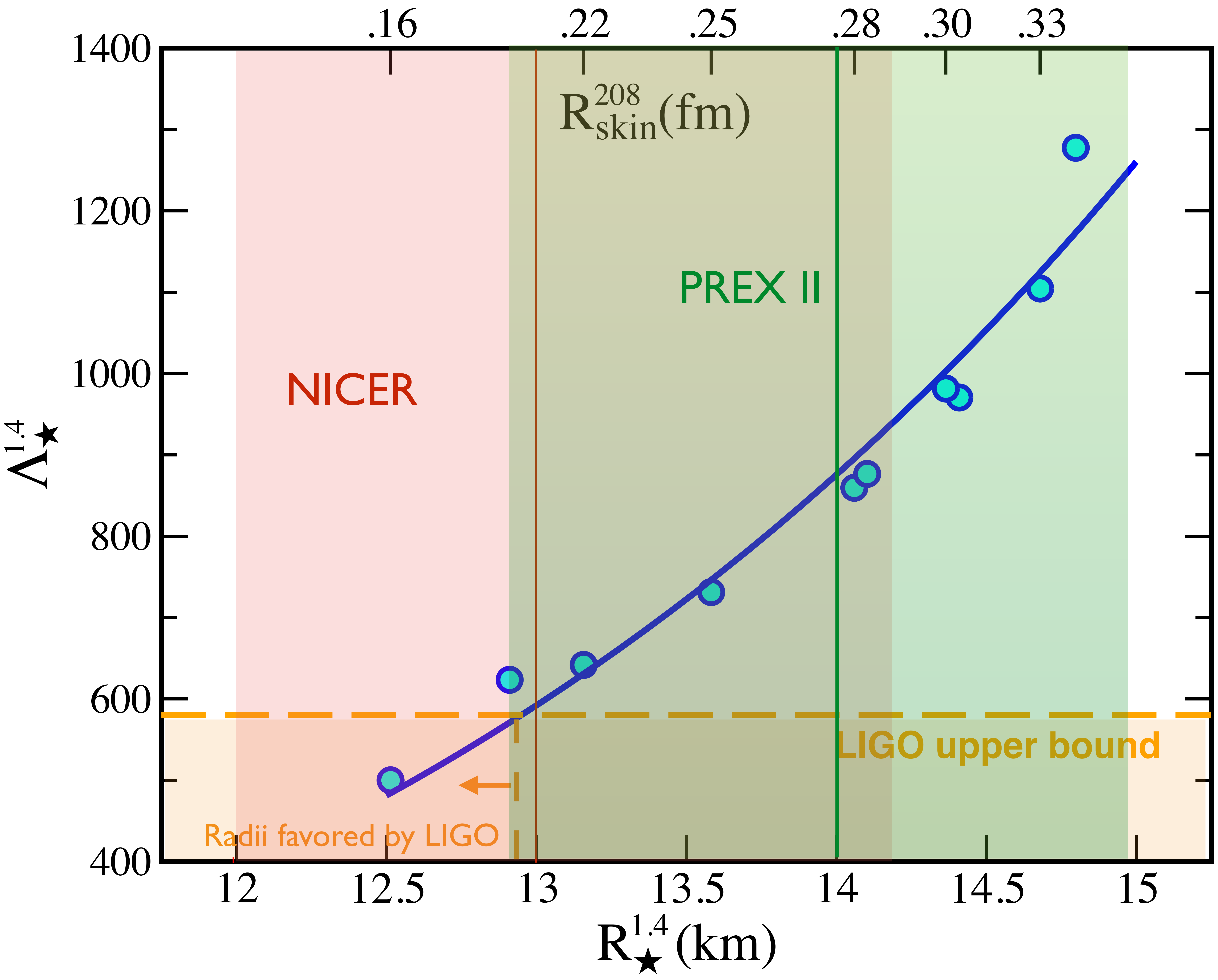
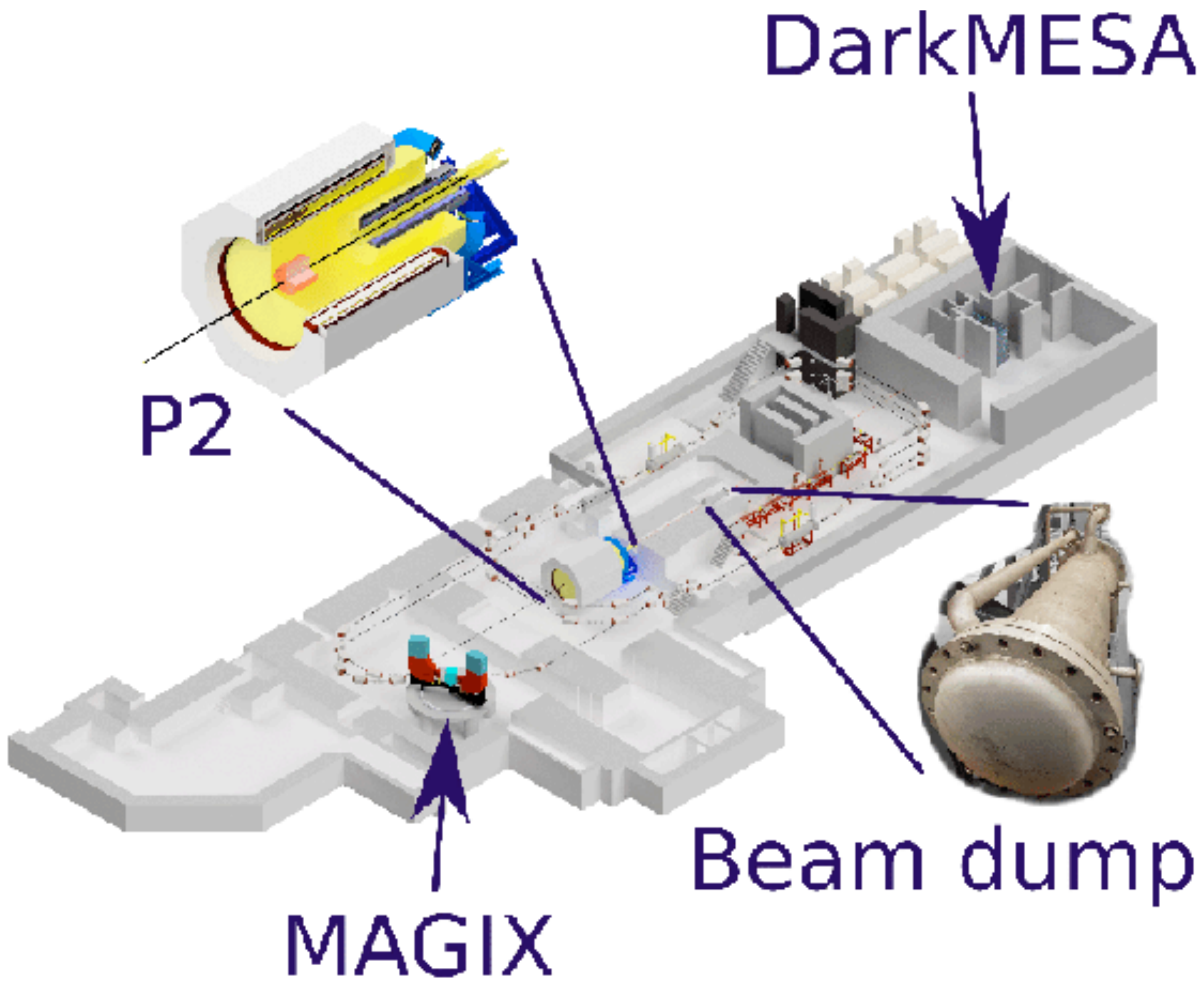
400
$\Lambda^{1.4}_{\star}$
PSR J0030+0451
NICER
LIGO upper bound
Radii favored by LIGO
12
12.5
13
13.5
14
14.5
15
$R^{1.4}_{\star}$(km)


.16
.22
.25
.28
.30
.33
R^{208}_{skin}(fm)
PREX II
NICER
LIGO upper bound
Radii favored by LIGO
1400
1200
1000
800
600
400
$\Lambda^{1.4}_{\star}$
12
12.5
13
13.5
14
14.5
15
$R^{1.4}_{\star}$(km)

MREX experiment at Mainz

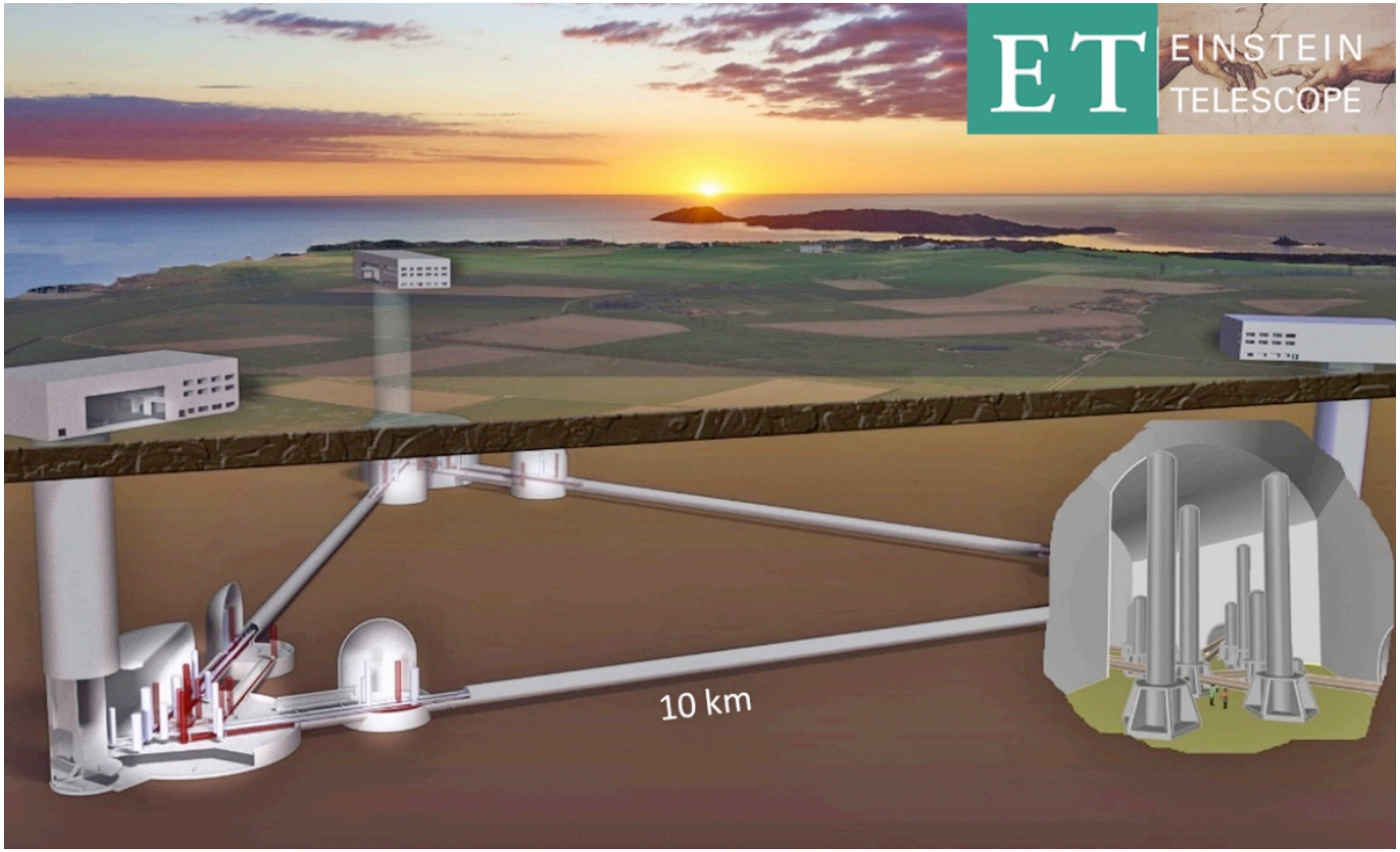


- MESA is high current low energy electron accelerator being built at Mainz.
- Mainz Radius Experiment (MREX) will use MESA and large acceptance P2 detector to measure the neutron skin of ^{208}Pb more accurately than PREX.
- PREX measured R_n to 1.3% (+/- 0.07 fm), MREX goal 0.5% (+/- 0.03 fm)

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 %

Next generation gravitational wave observatories

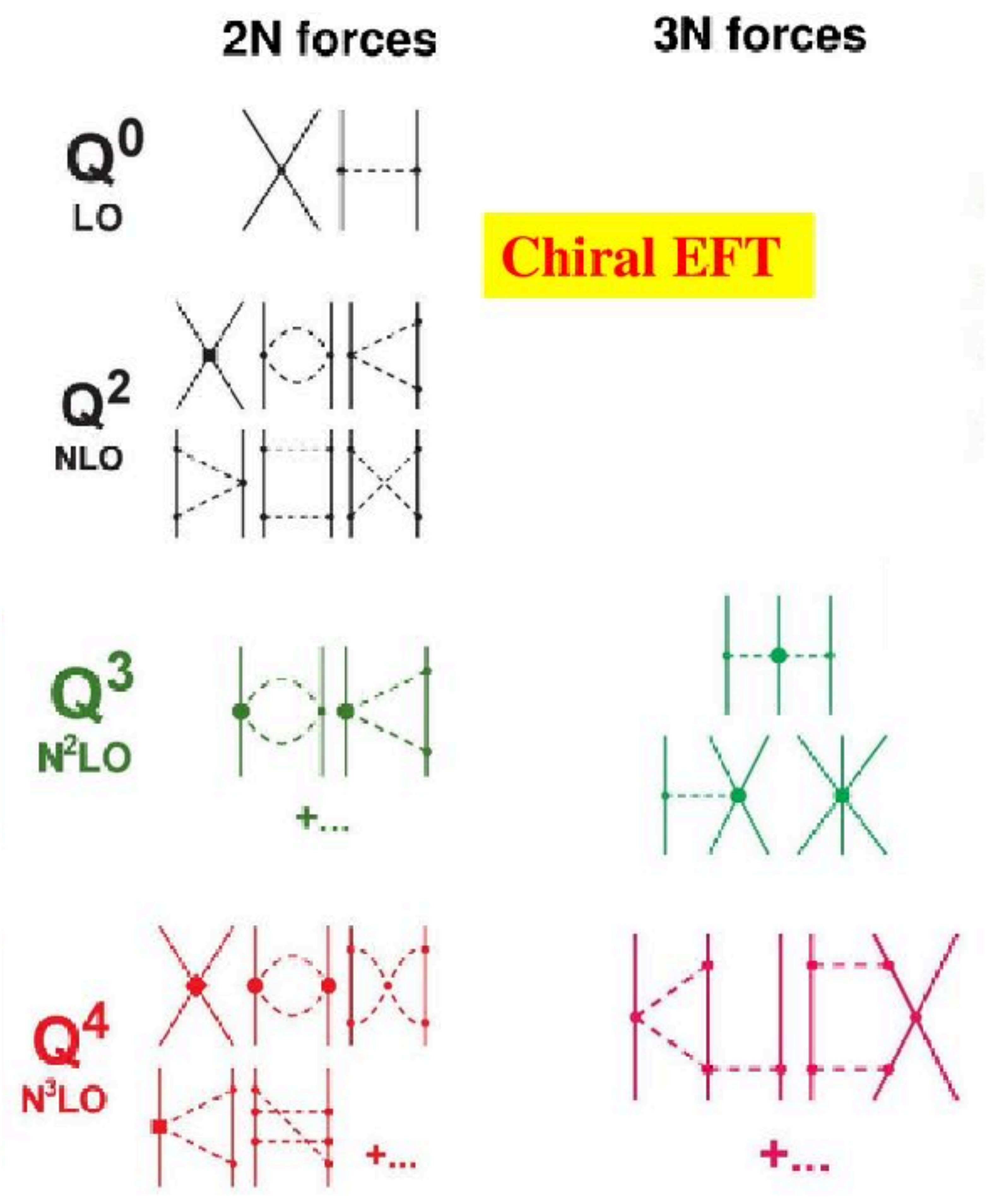
- The Einstein Telescope is proposed GW detector to be built at Dutch-Belgian-German border or in Sardinia.
- Cosmic explorer is proposed US detector with 40 km arms.
- 10 times more sensitive, 1000 x detection rate, of existing LIGO and VIRGO.
- They could accurately measure deformability of neutron stars.



CREX

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.



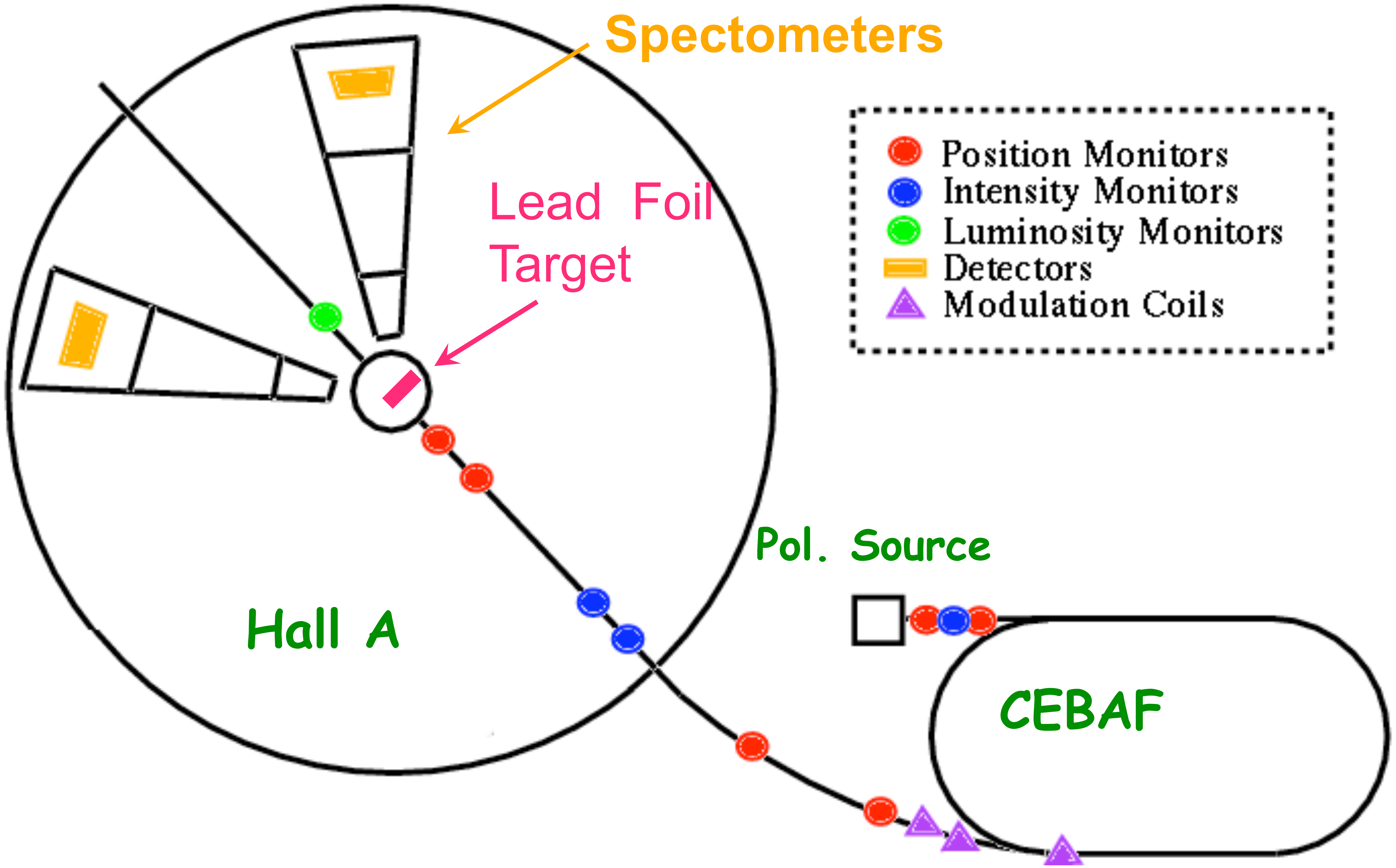
CREX

- 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 γ − Z box radiative corrections.

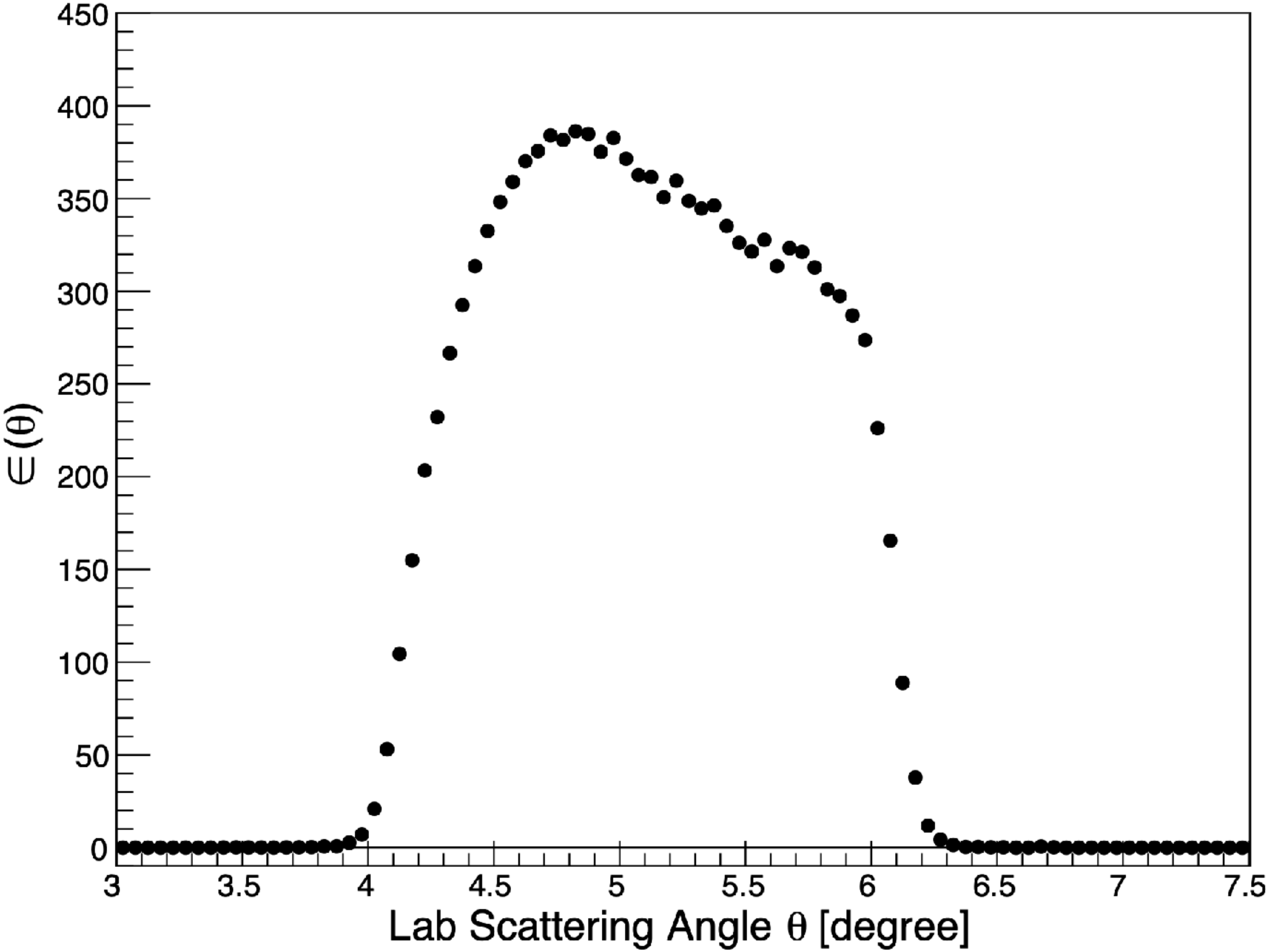
A_{PV} corrections and corresponding systematic errors

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%

PREX in Hall A at JLab



R. Michaels



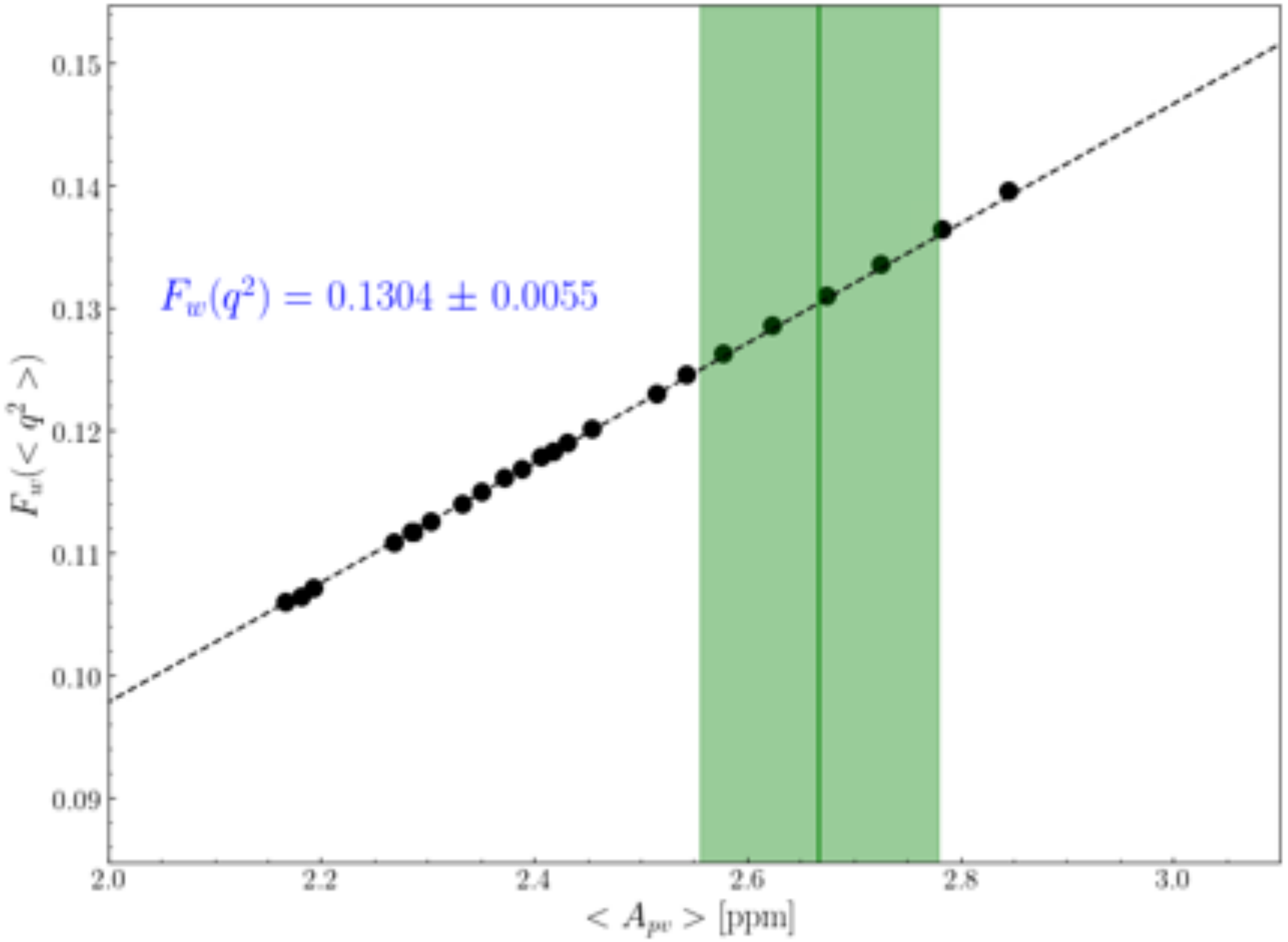
450
400
350
300
250
200
150
100
50
0
∈(θ)
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Lab Scattering Angle θ [degree]

Weak Form Factor

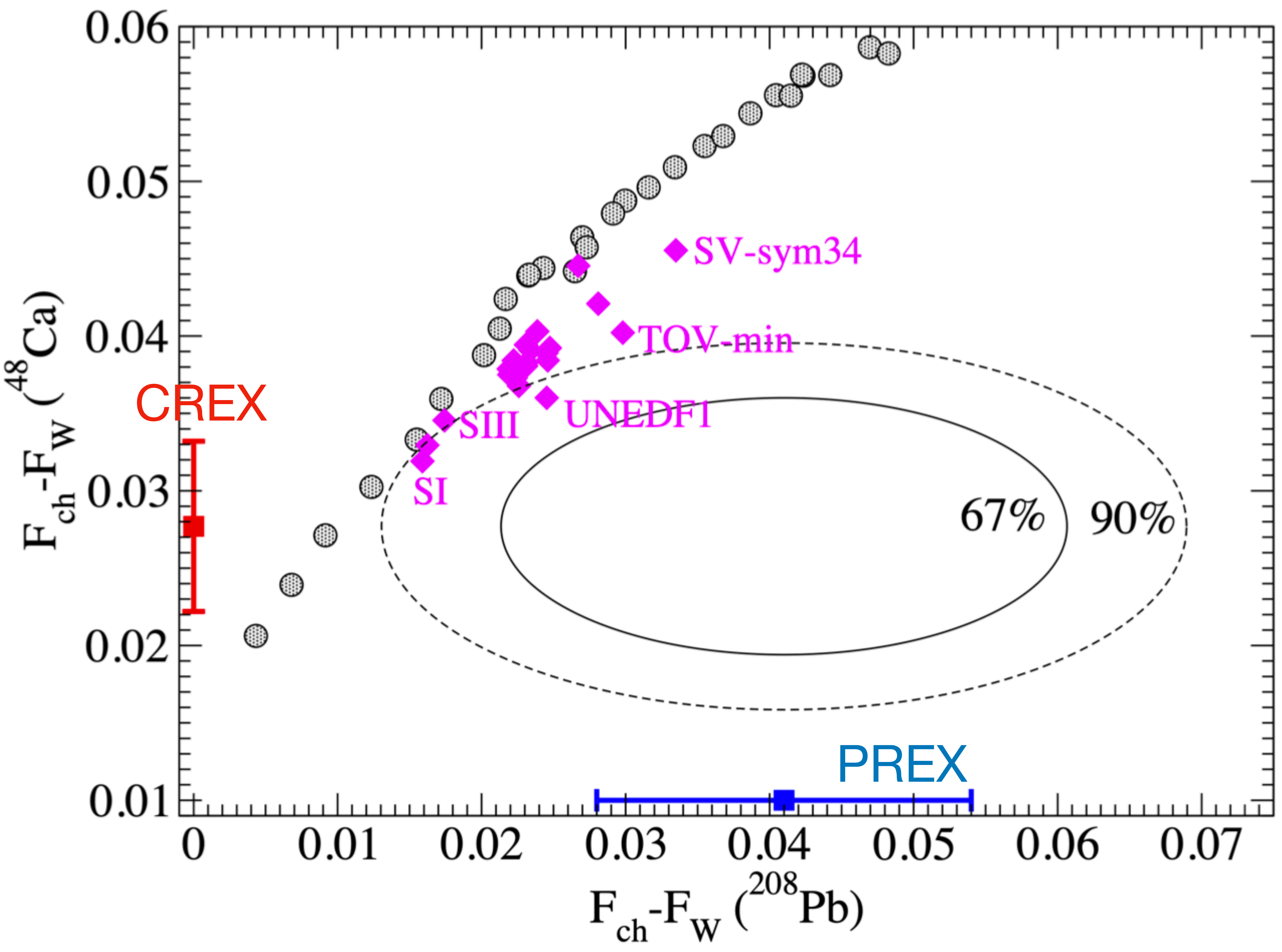
$$A_{PV} = \frac{G_F Q^2 Q_W^2 F_W(q)}{4\pi\alpha\sqrt{2} Z F_{ch}(q)}$$

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

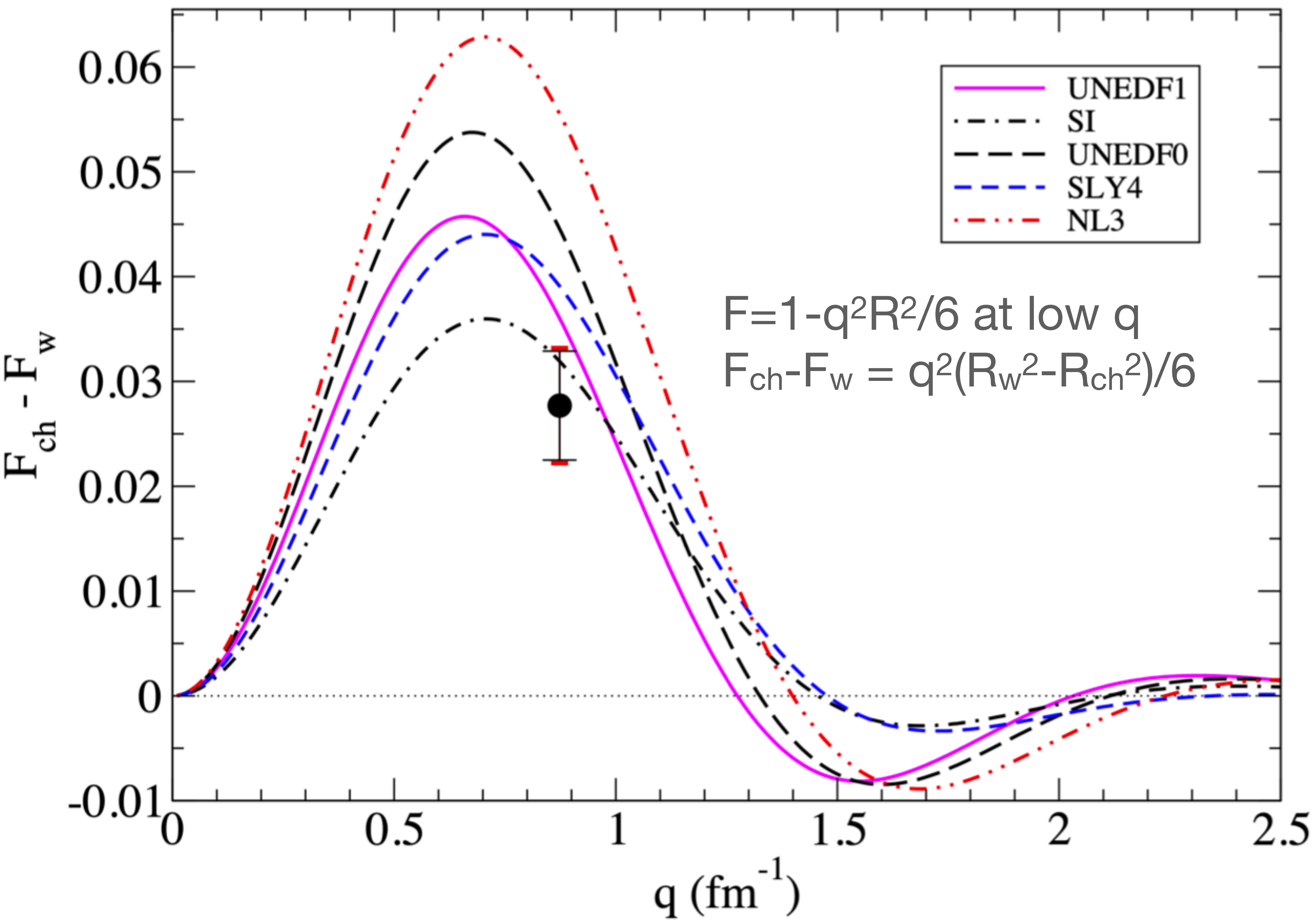
$$F_{\rm ch}(q) - F_{\rm W}(q) = 0.0277 \pm 0.0055 \text{ (exp)}$$



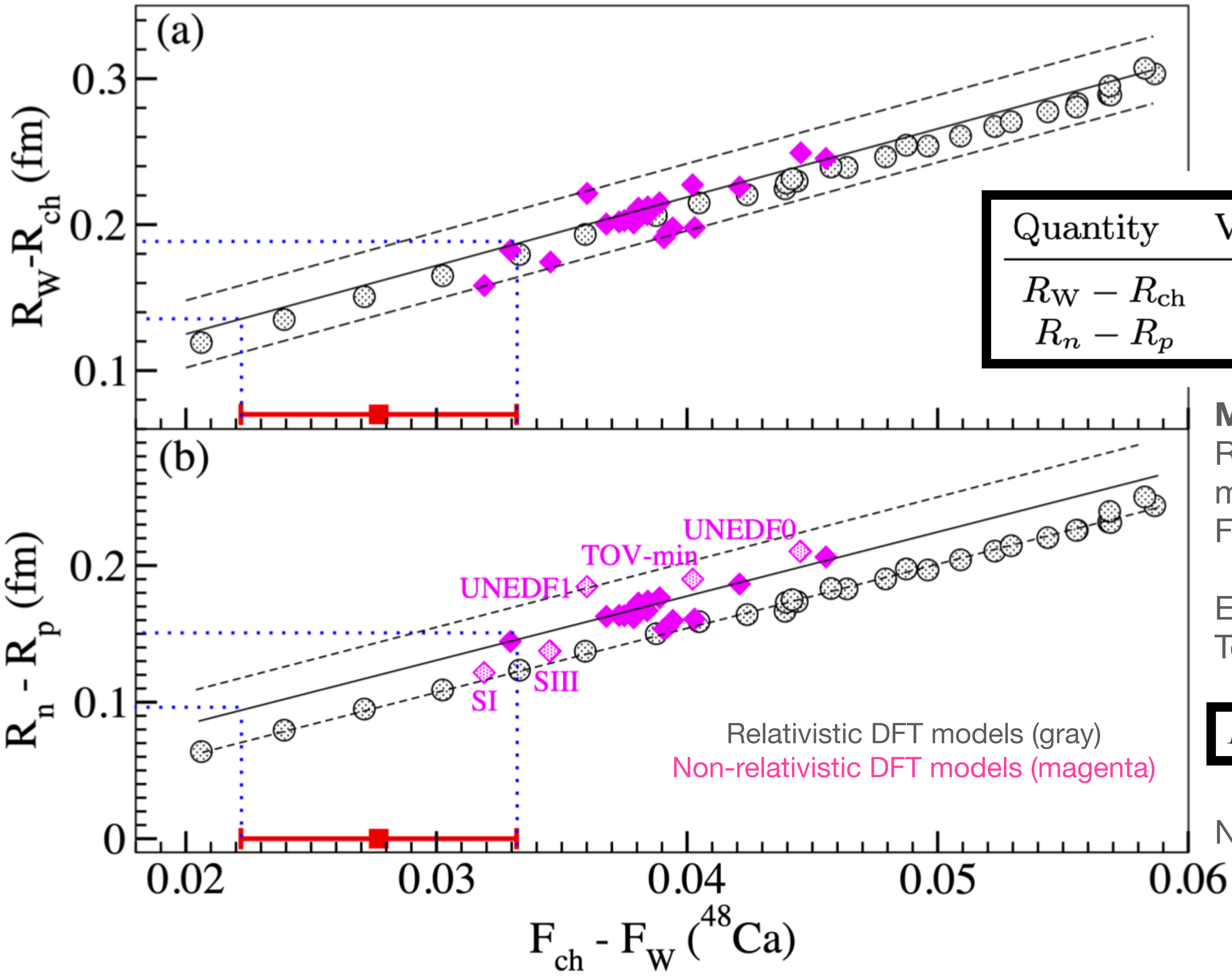
Quantity	Value ± (stat) ± (sys)
q	0.8733 fm^{-1}
$F_{\rm W}(q)/F_{\rm ch}(q)$	$0.8248 \pm 0.0328 \pm 0.0124$
$F_{\rm ch}(q)$	0.1581
$F_{\rm W}(q)$	$0.1304 \pm 0.0052 \pm 0.0020$
$F_{\rm ch}(q) - F_{\rm W}(q)$	$0.0277 \pm 0.0052 \pm 0.0020$



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 (48Ca)
F_ch-F_W (208Pb)



UNEDF1
SI
UNEDF0
SLY4
NL3
F=1-q²R²/6 at low q
$F_{ch}-F_w = q^2(R_w^2-R_{ch}^2)/6$
$F_{ch} - F_w$
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



Quantity	Value ± (exp) ± (model) [fm]
$R_W - R_{ch}$	$0.159 \pm 0.026 \pm 0.023$
$R_n - R_p$	$0.121 \pm 0.026 \pm 0.024$

Model error in extraction of R_W-R_{ch} or R_n-R_p from spread in model predictions for given F_{ch}-F_W.

Exp. error in R_n +/-0.026 fm (.7%)
Total error in R_n +/-0.035 fm (1%)

$$R_n - R_p = 0.121 \pm 0.035(\text{total})\ \text{fm}$$

No model error in F_{ch}-F_W

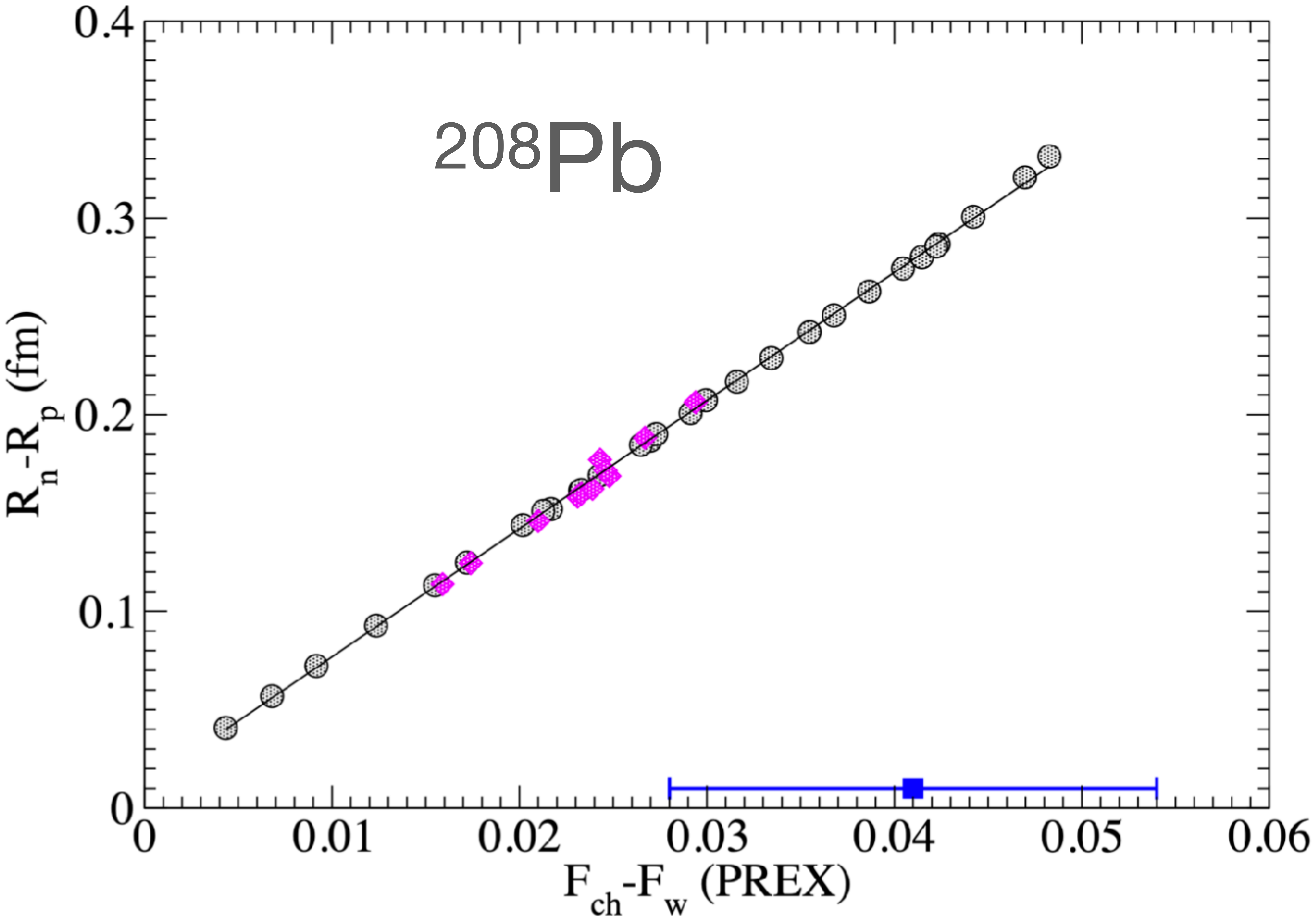
$$F_{\text{ch}}(q) - F_{\text{W}}(q) = 0.0277 \pm 0.0055\ (\text{exp})$$

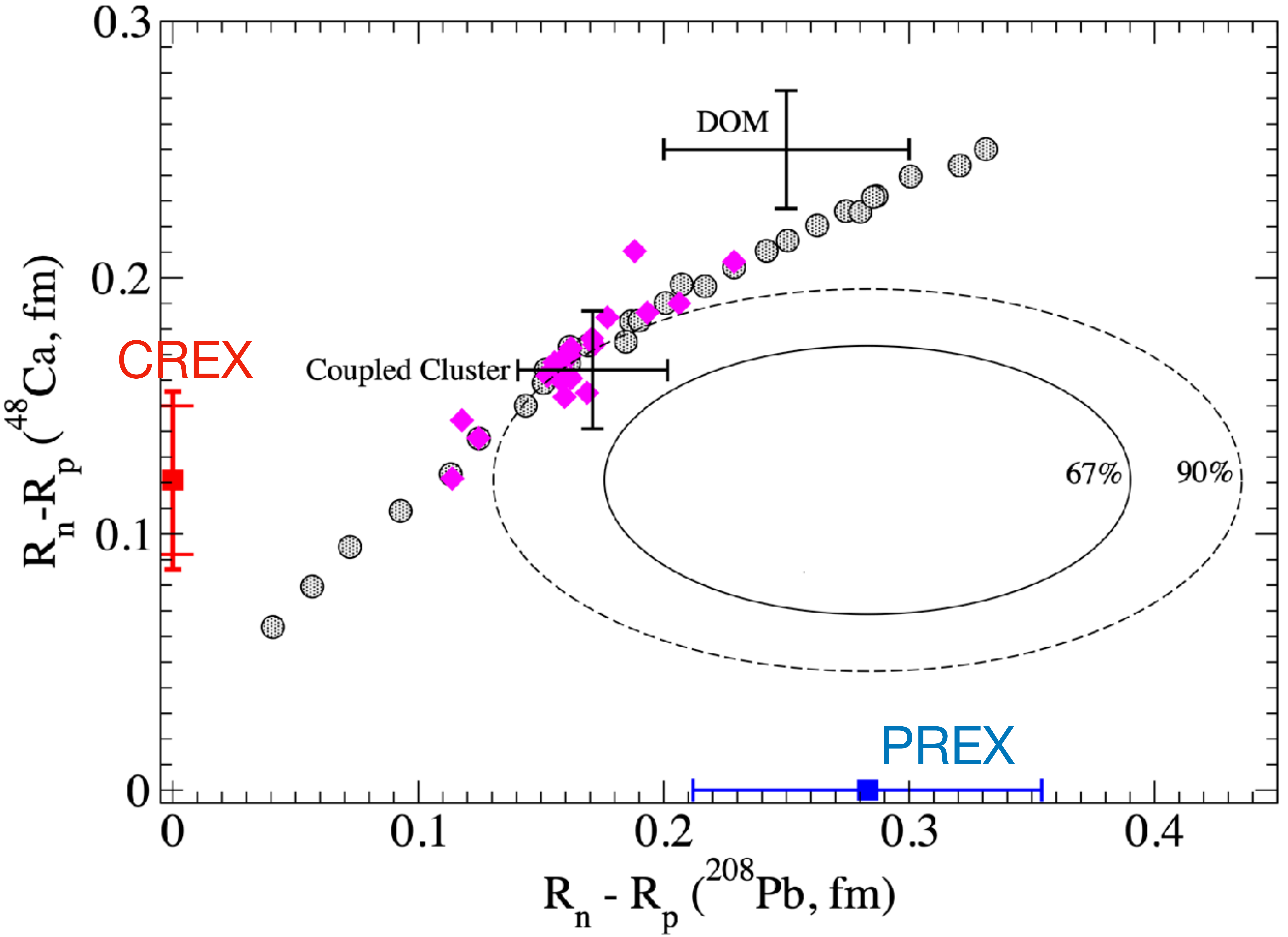
Small Model Error for PREX

PREX was run at lower q then CREX —> Less sensitive to surface thickness of weak density and has a smaller model error.

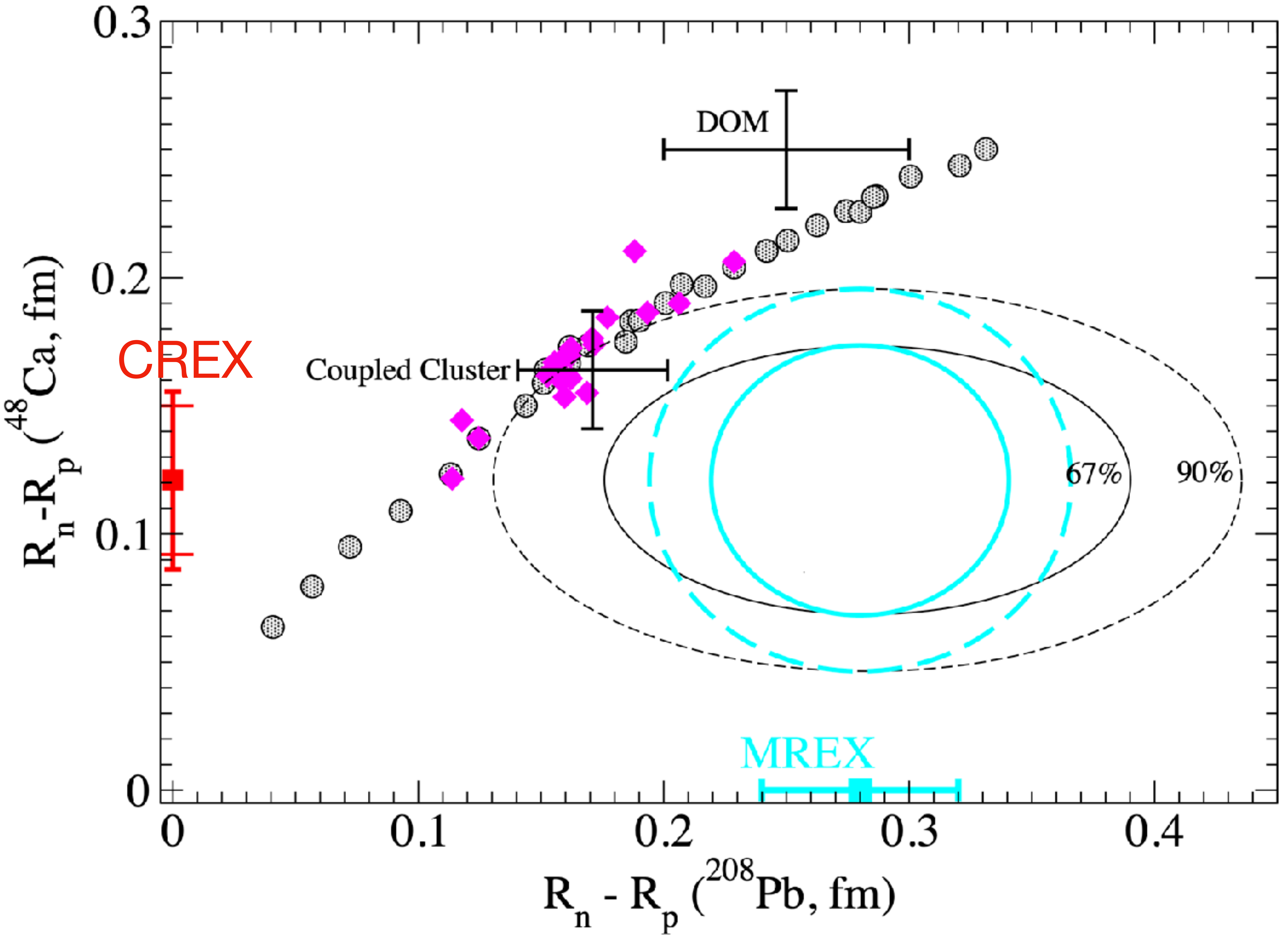
q_{PREX}=0.4 fm^{-1}
q_{CREX}=.8733 fm^{-1}

$q_{PREX}\ R_{ch}(^{208}Pb)$=2.2
$q_{CREX}\ R_{ch}(^{48}Ca)$=3.0

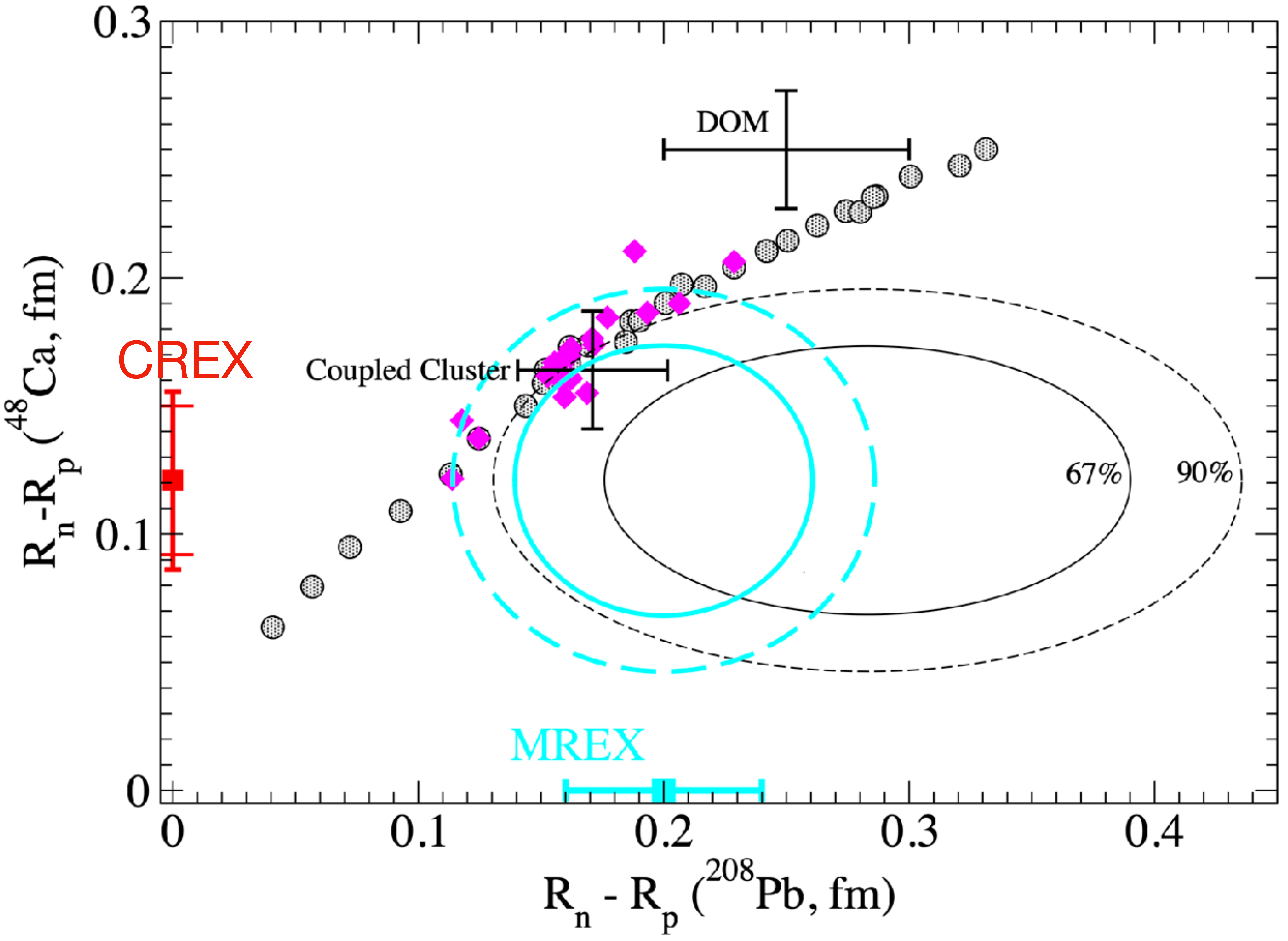




0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
DOM
Coupled Cluster
CREX
PREX
67%
90%
R_n - R_p (^{208}Pb, fm)
R_n-R_p (^{48}Ca, fm)



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



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

CREX Experiment

- New and precise measurement of A_{PV} from ^{48}Ca at q=0.8733 fm^{-1}
- Main result (model independent):

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

- Extract with small model dependence from shape of $\rho_w(r)$

Quantity	Value ± (exp) ± (model) [fm]
$R_{\rm W} - R_{\rm ch}$	$0.159 \pm 0.026 \pm 0.023$
$R_n - R_p$	$0.121 \pm 0.026 \pm 0.024$

- Compared to many density functional models, neutron skin of ^{48}Ca is somewhat thin and ^{208}Pb somewhat thick. However, a number of models are consistent with both PREX and CREX.

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

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

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Student **Brenden Reed** made important contributions!