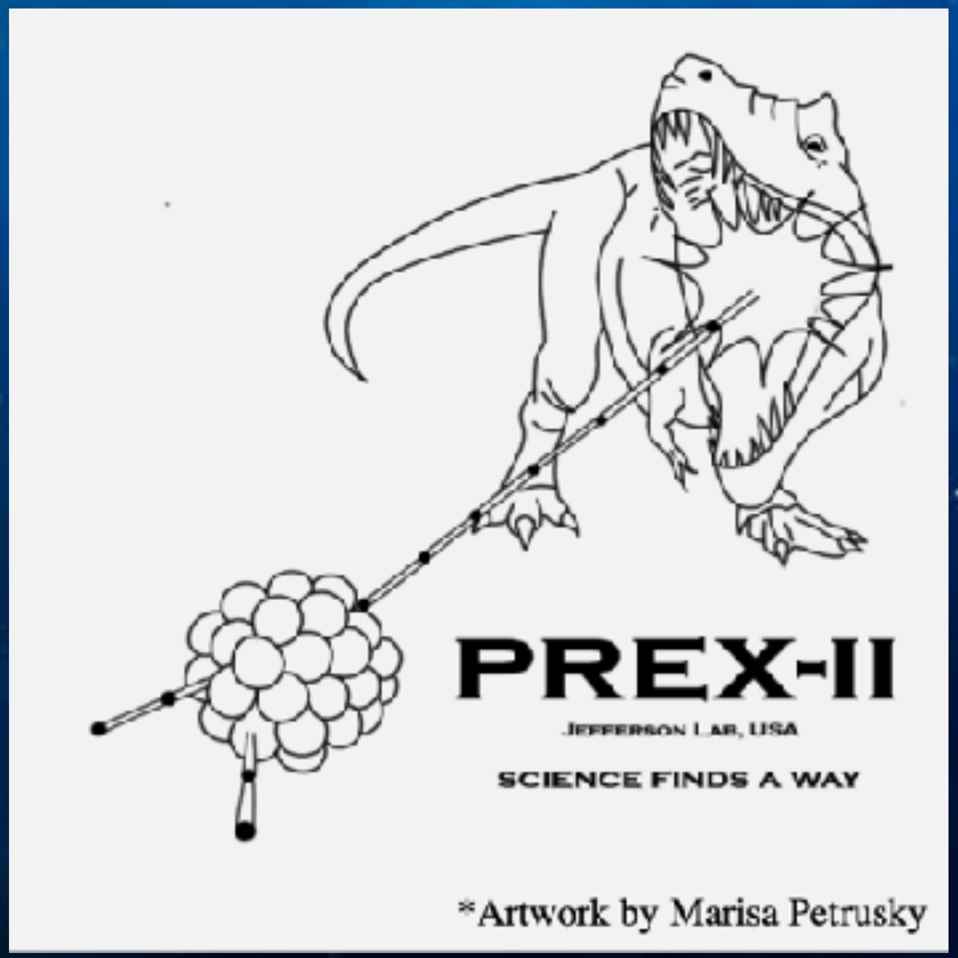
Parity violating electron and coherent neutrino scattering



Chuck Horowitz, FRIB+Indiana U.   INT, Apr. 2023

U.S. DEPARTMENT OF ENERGY Office of Science

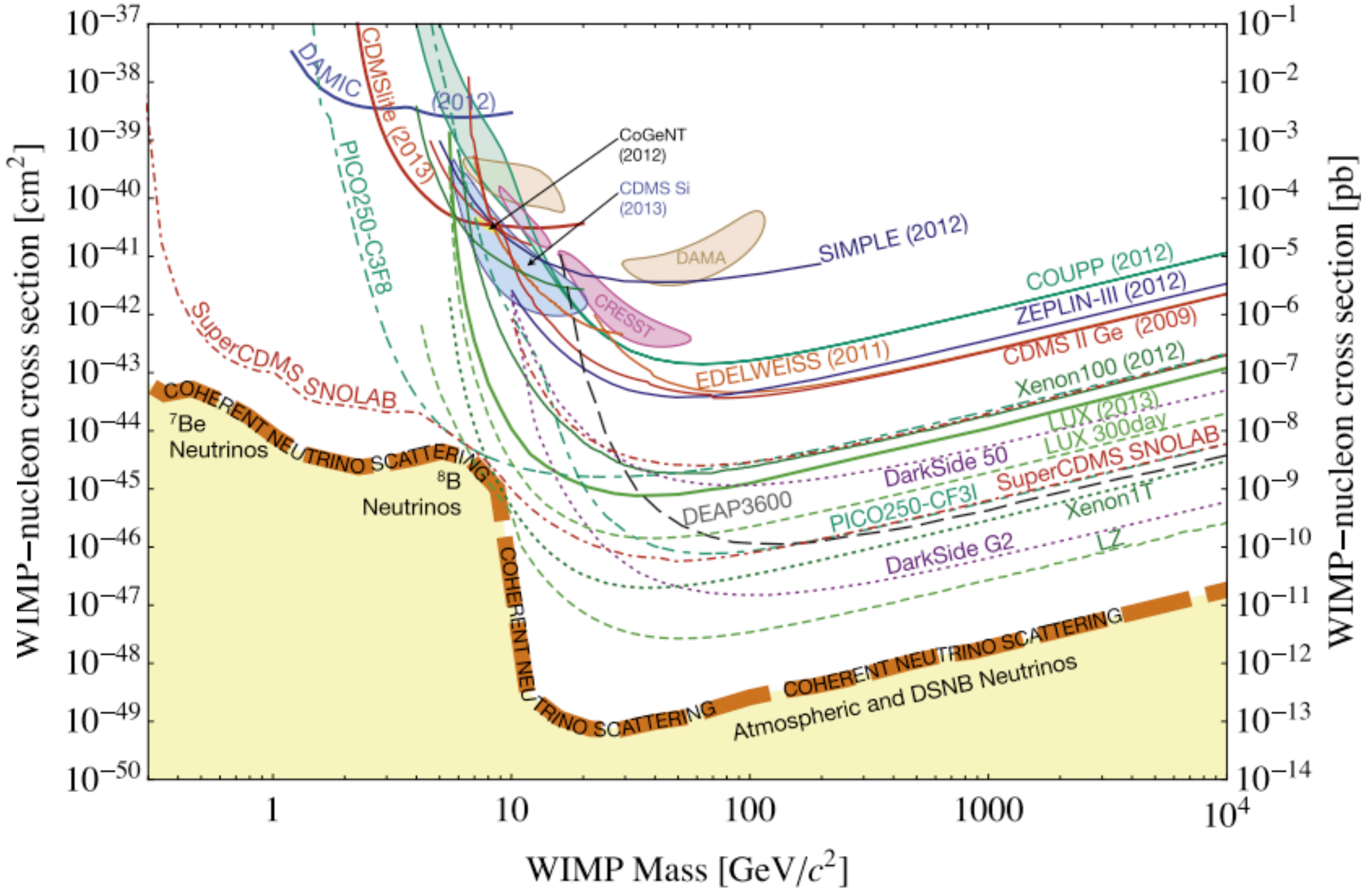
Parity violating electron scattering measures same coherent weak form factor $F_W(Q)$

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F_W^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

weak nuclear charge

Form factor: F=1 ➔ full coherence



Coherent scattering provides neutrino floor for many dark matter searches

PV e scattering and nuclear theory (to extrapolate to neighboring nuclei) may be able to constrain weak from factors better than near future neutrino scattering exps.

This allows coherent neutrino scattering to probe non-standard neutrino interactions.

Present R_W measurements:
PREX-2(^{208}Pb) 1.3%(+/-0.075 fm)
CREX(^{48}Ca) 1(0.7)%(+/-0.03 fm)
Qweak(^{27}Al) 3.8%(+/-0.12 fm)
Future:
MREX(^{208}Pb) goal 0.5%(+/-0.03fm)

Parity Violation Isolates 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:

$$Q_W^n = -1$$

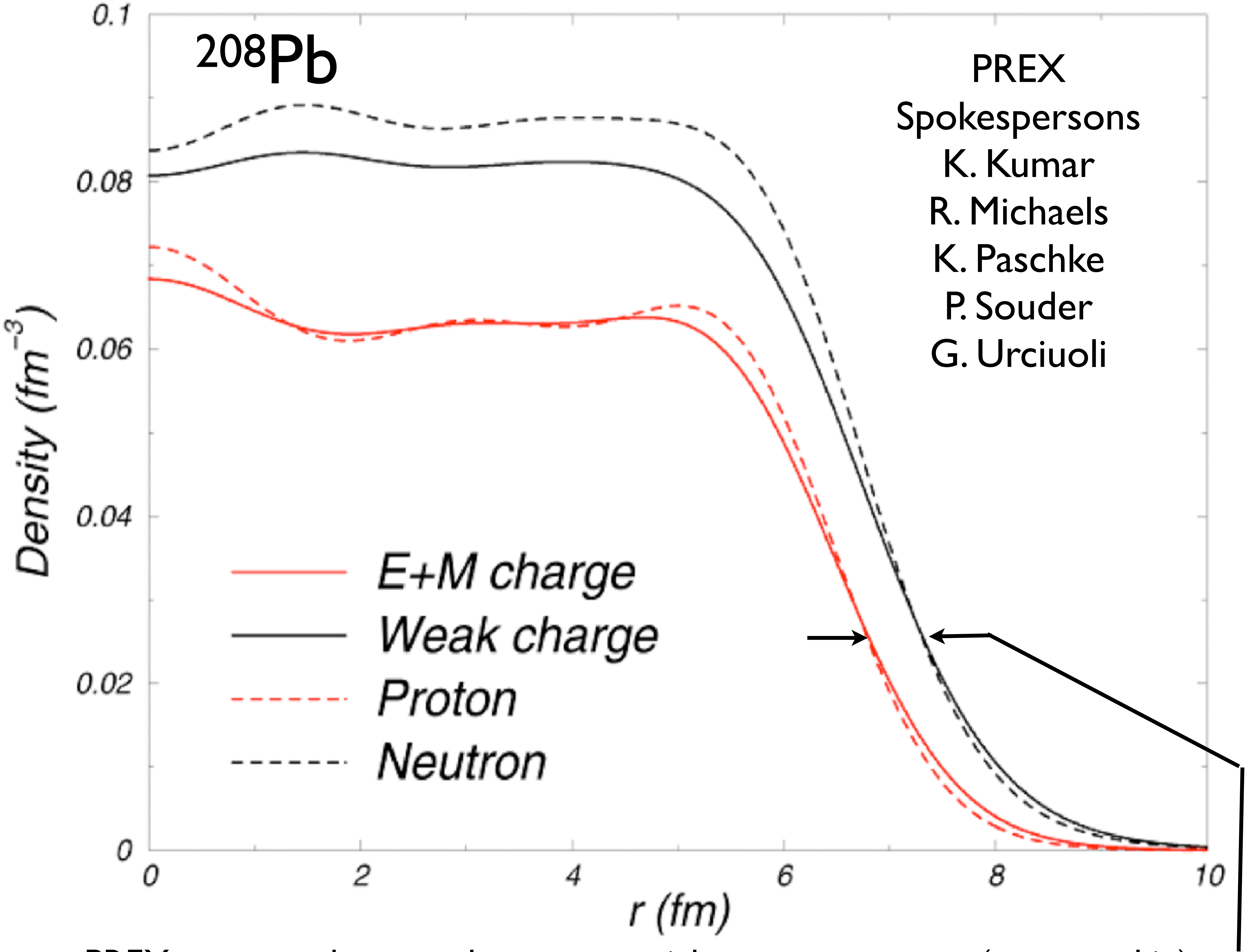
- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

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

$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- Model independently map out distribution of weak charge in a nucleus.
- Coulomb distortions: $A = G_F \rho_W$ Potential $= V + \gamma_5 A$
- **Electroweak reaction free from most strong interaction uncertainties.**



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

Weak Density and Form Factor

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

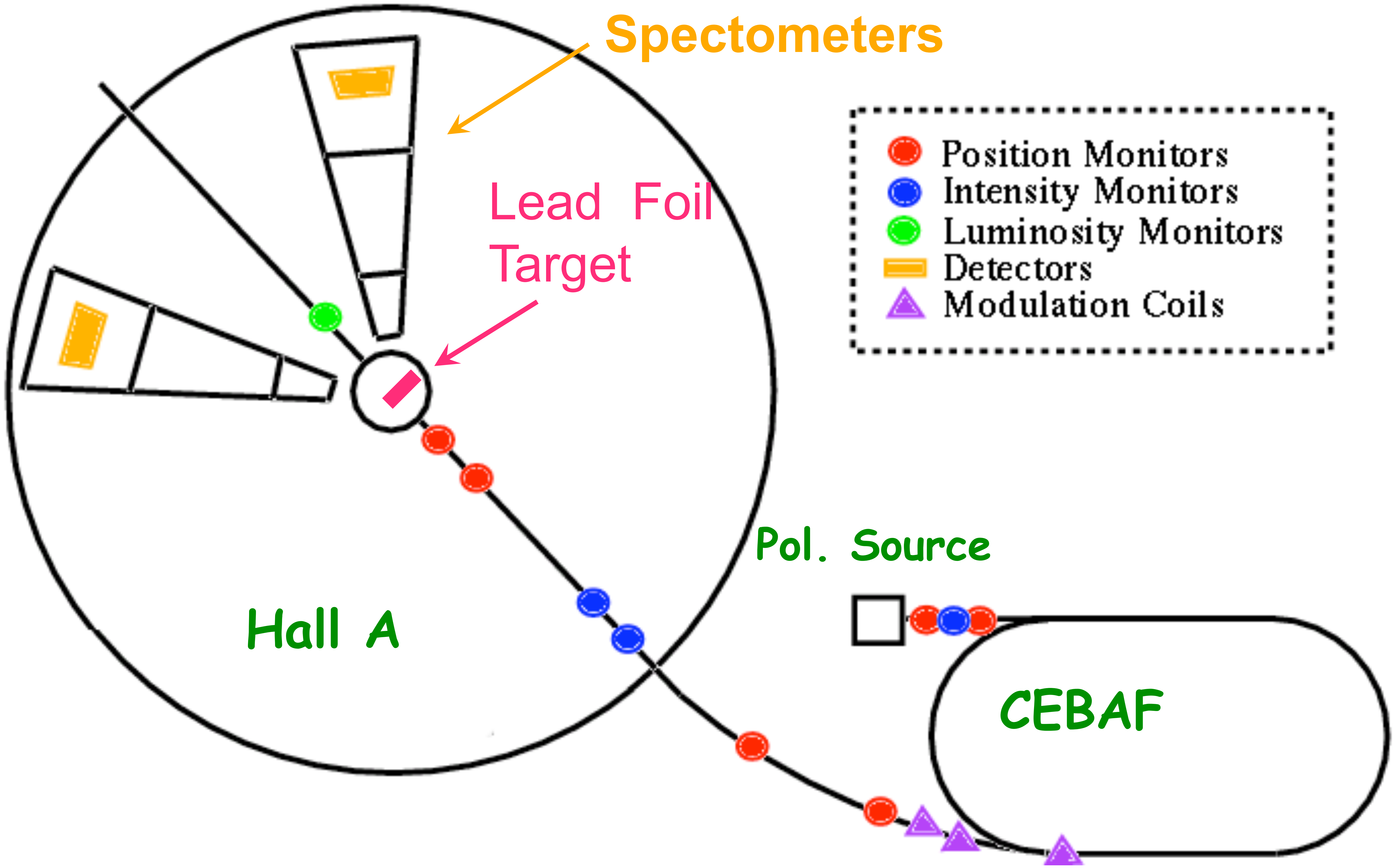
$$\rho_W(r) = \int d^3r' \left[\underbrace{G^Z_{En}}_{q_n=-0.9890}(r')\rho_n(|\vec{r}-\vec{r}'|) + \underbrace{G^Z_{Ep}}_{q_p=0.0711}(r')\rho_p(|\vec{r}-\vec{r}'|) \right]$$

- 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}

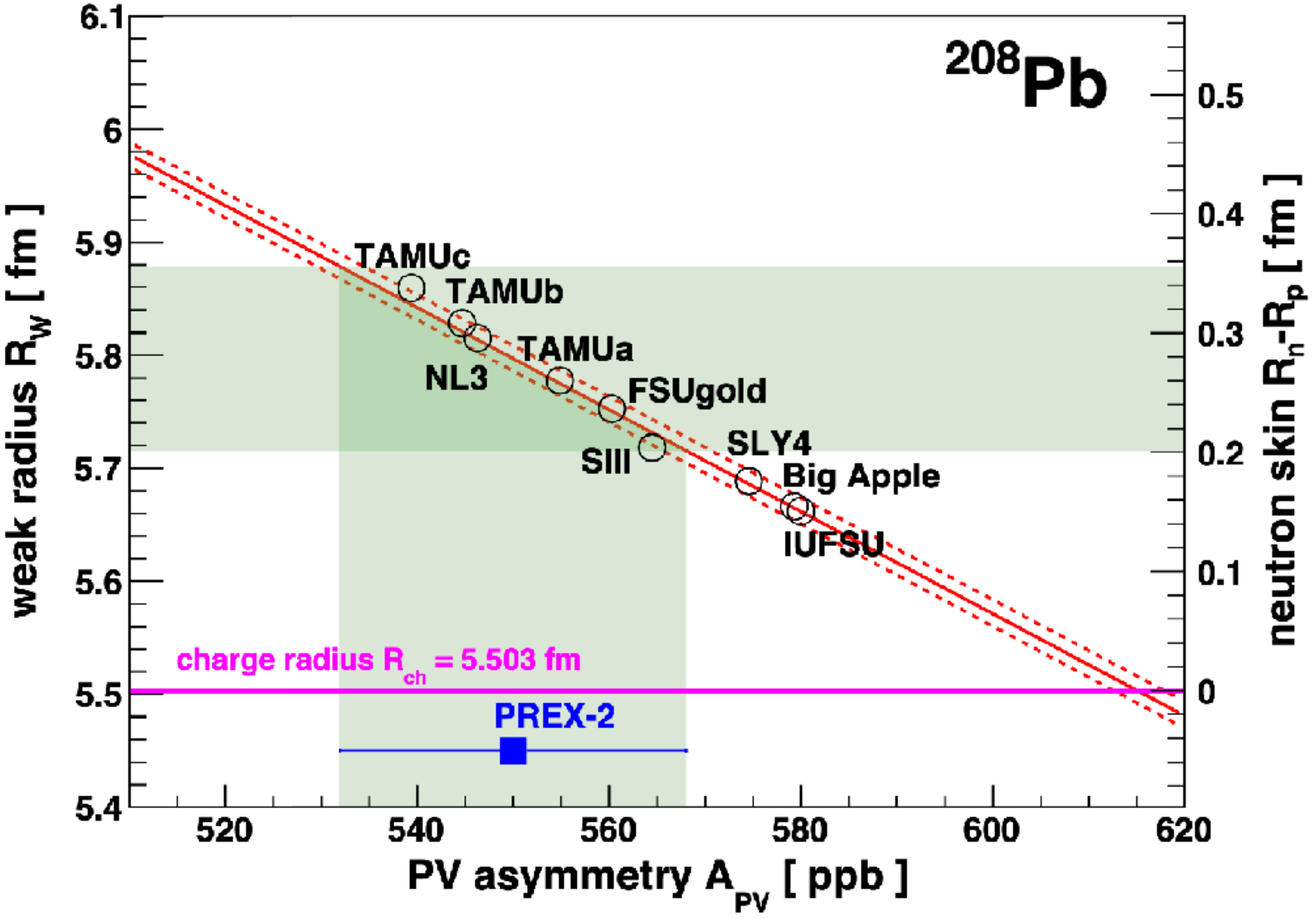
PREX in Hall A at JLab



R. Michaels

PREX-II

Parity violating asymmetry calculated including Coulomb distortions and integration over experimental acceptance



PREX-I+II Results

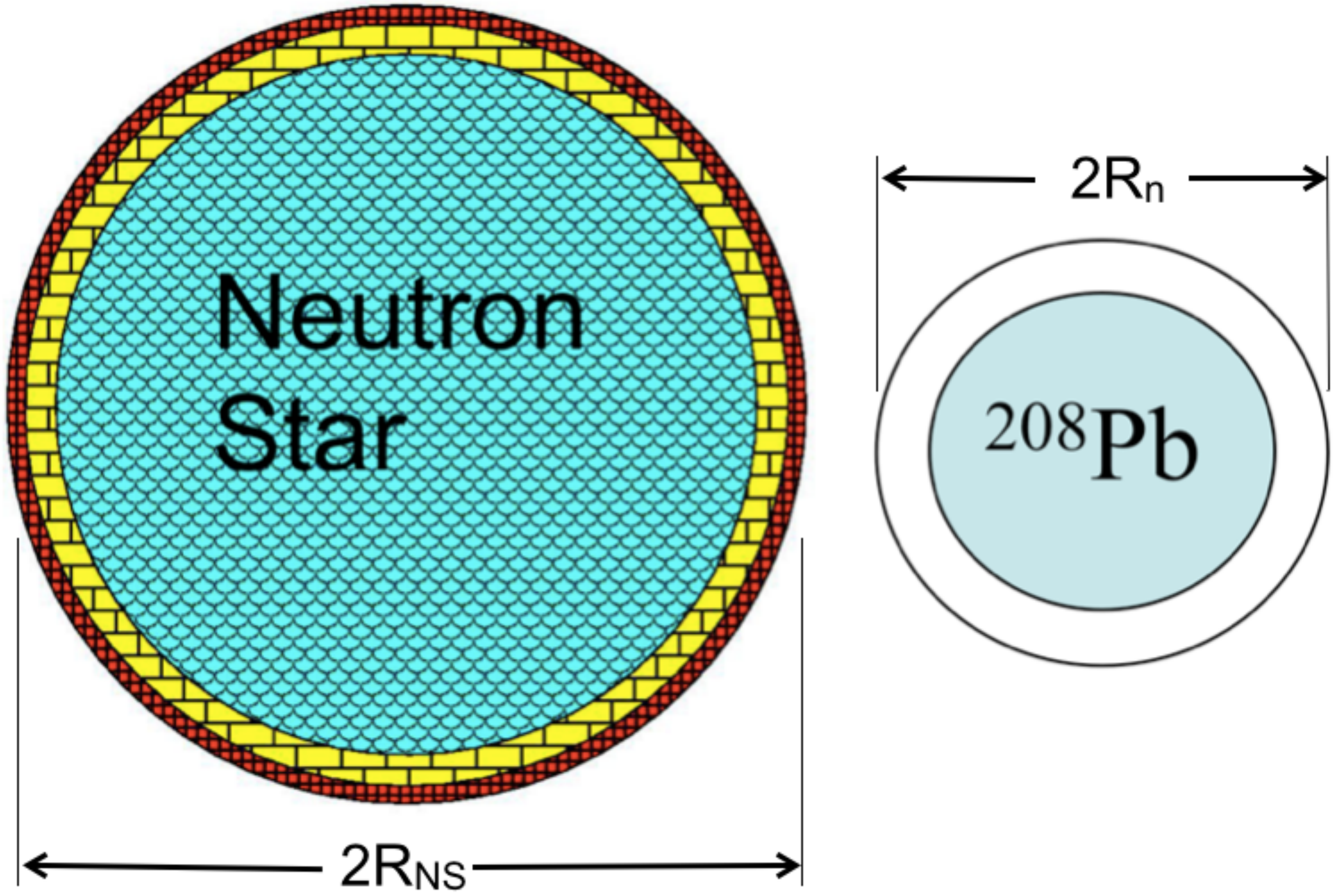
^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ_W^0)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ_b^0)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

PREX-2 ^{208}Pb:
$F_W(q=0.398 fm^{-1})=0.3676+/-.0125$

CREX ^{48}Ca:
$F_W(q=0.8733 fm^{-1})=0.1304+/-.0056$

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 has same neutrons, strong interactions, and equation of state.

Nuclear measurement vs Astronomical Observation

To probe equation of state

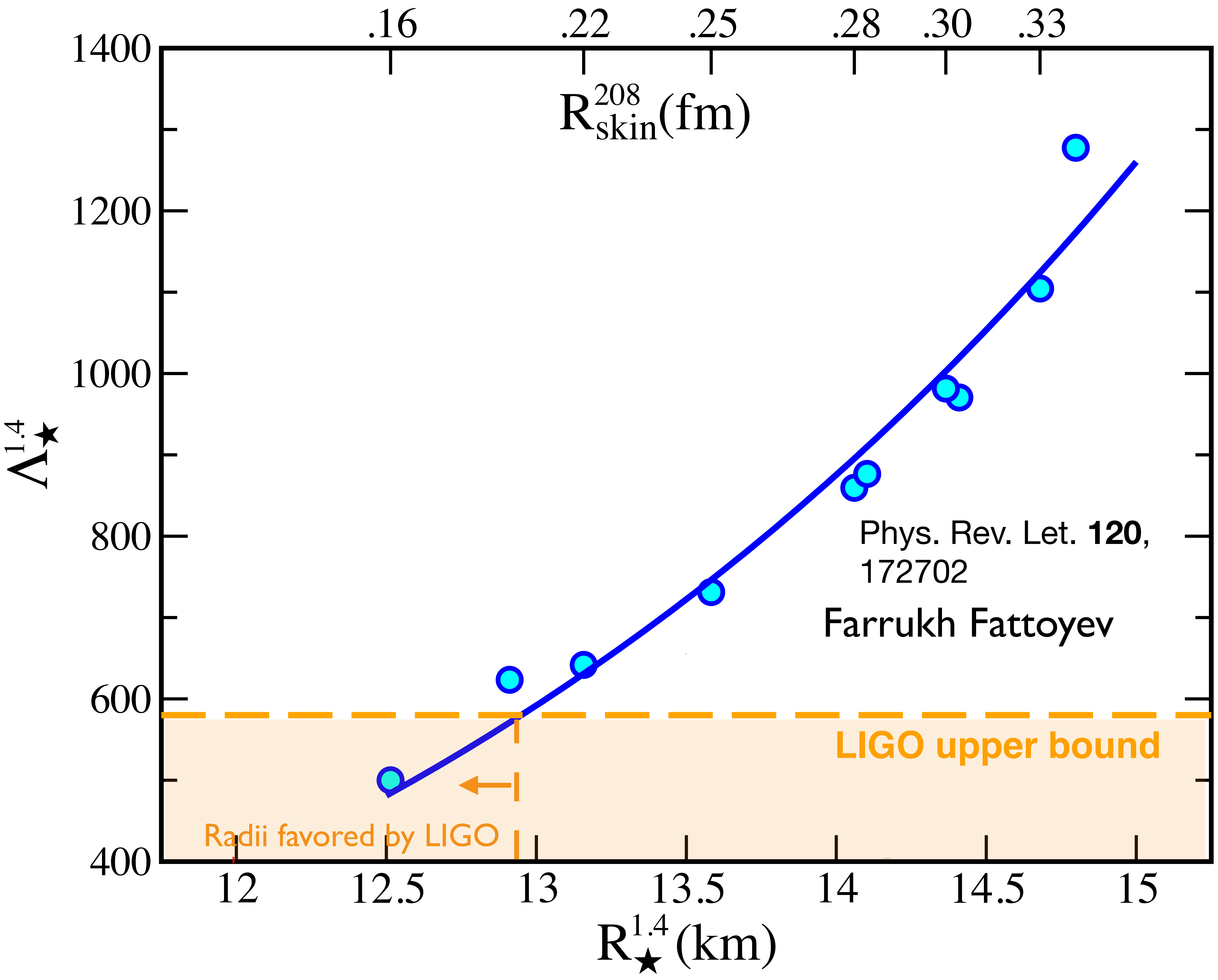
PREX, CREX measure neutron radius of ^{208}Pb and ^{48}Ca. Discuss systematic errors. Future MREX at Mainz

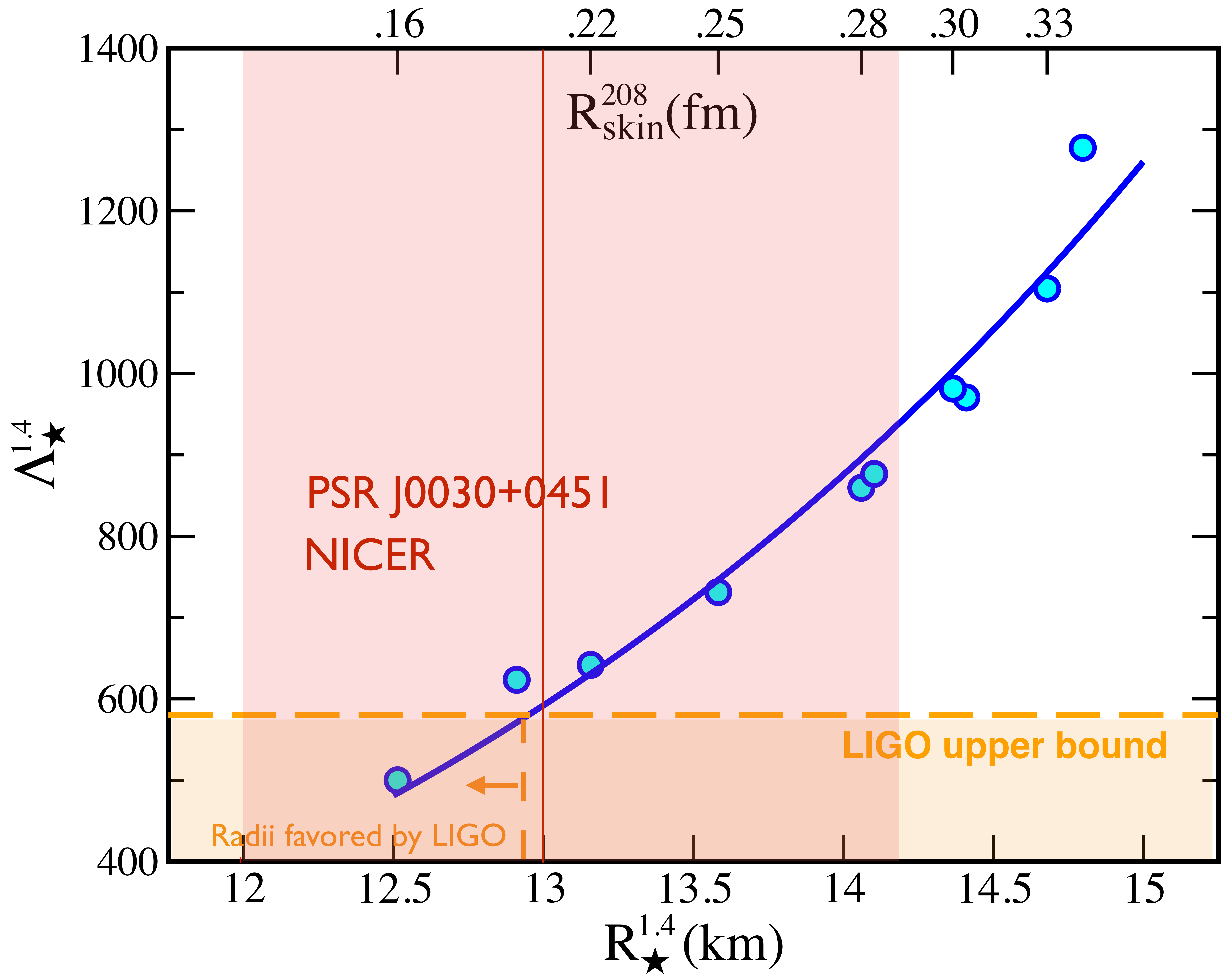
NICER measures NS radius from X-ray light curve. Some systematic errors modeling X-ray emission.

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. Motivates third generation observatory such as Cosmic Explorer (40 km) or Einstein Telescope.

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


.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)



.16
.22
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1400
1200
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R_{skin}^{208}(fm)
$\Lambda_{\star}^{1.4}$
PSR J0030+0451
NICER
LIGO upper bound
Radii favored by LIGO
12
12.5
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14
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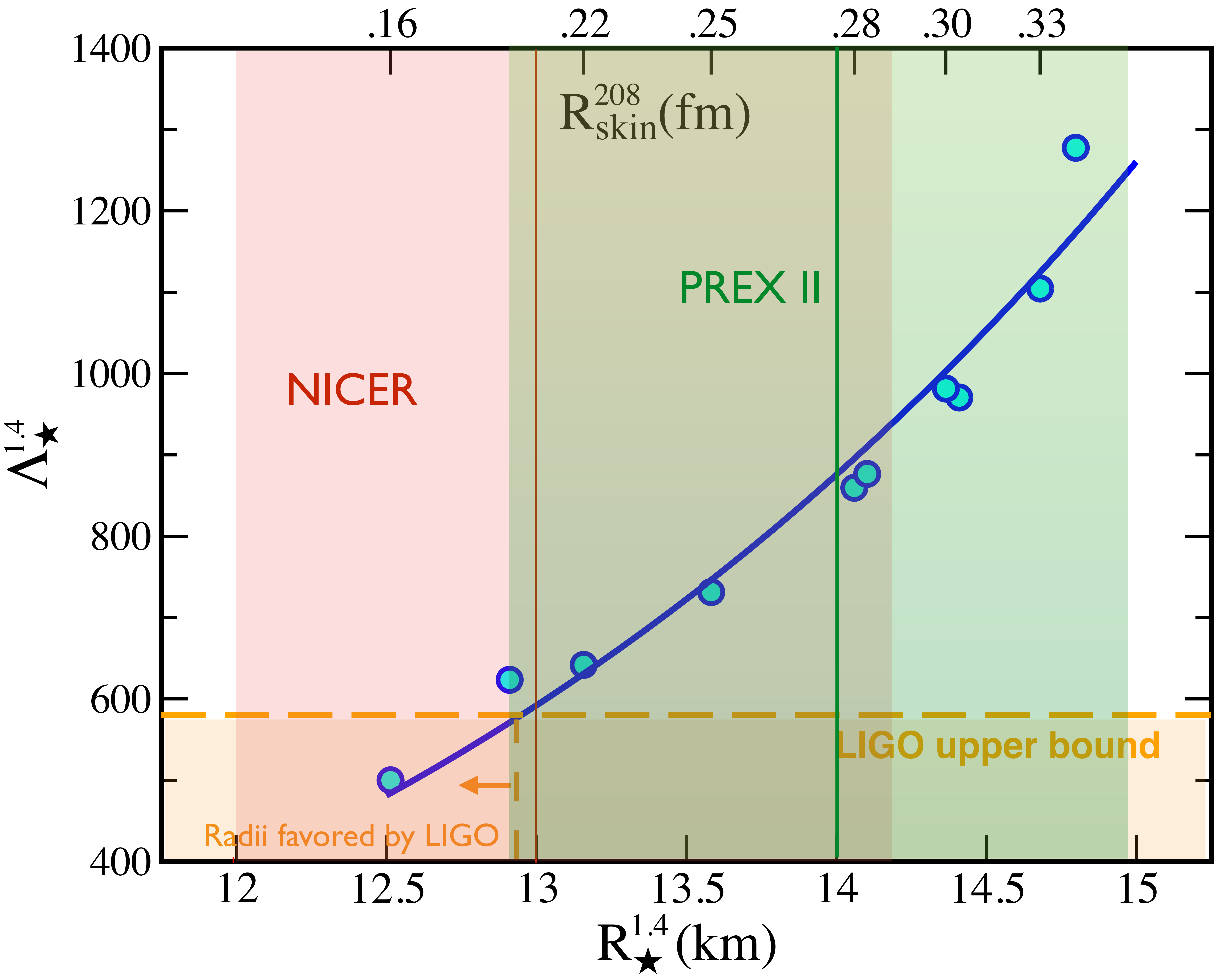
15
$R_{\star}^{1.4}$(km)



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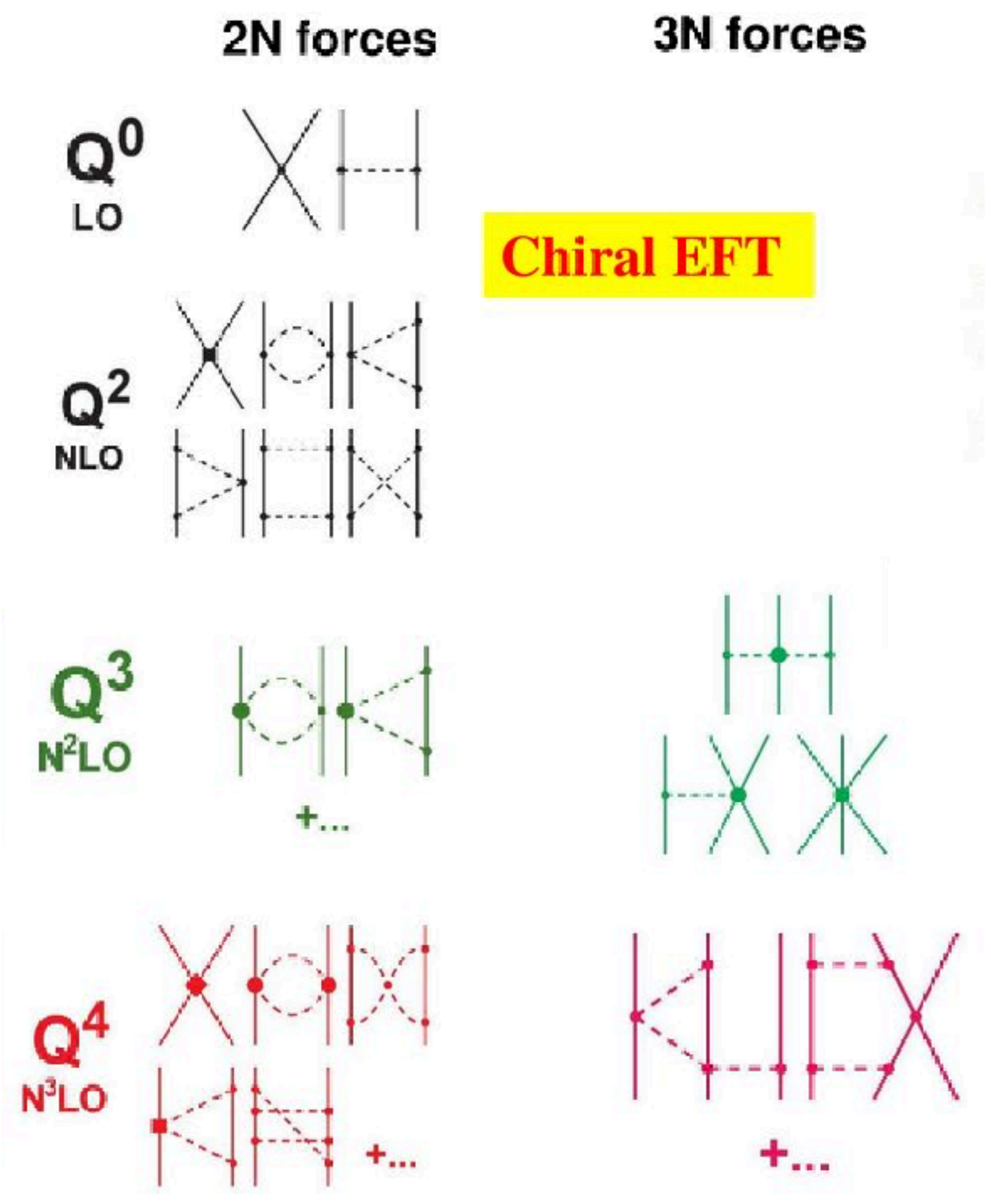
1200
1000
800
600
400
$\Lambda_{\star}^{1.4}$
12
12.5
13
13.5
14
14.5
15
$R_{\star}^{1.4}$(km)

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 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%

First 2+ state in ^{48}Ca

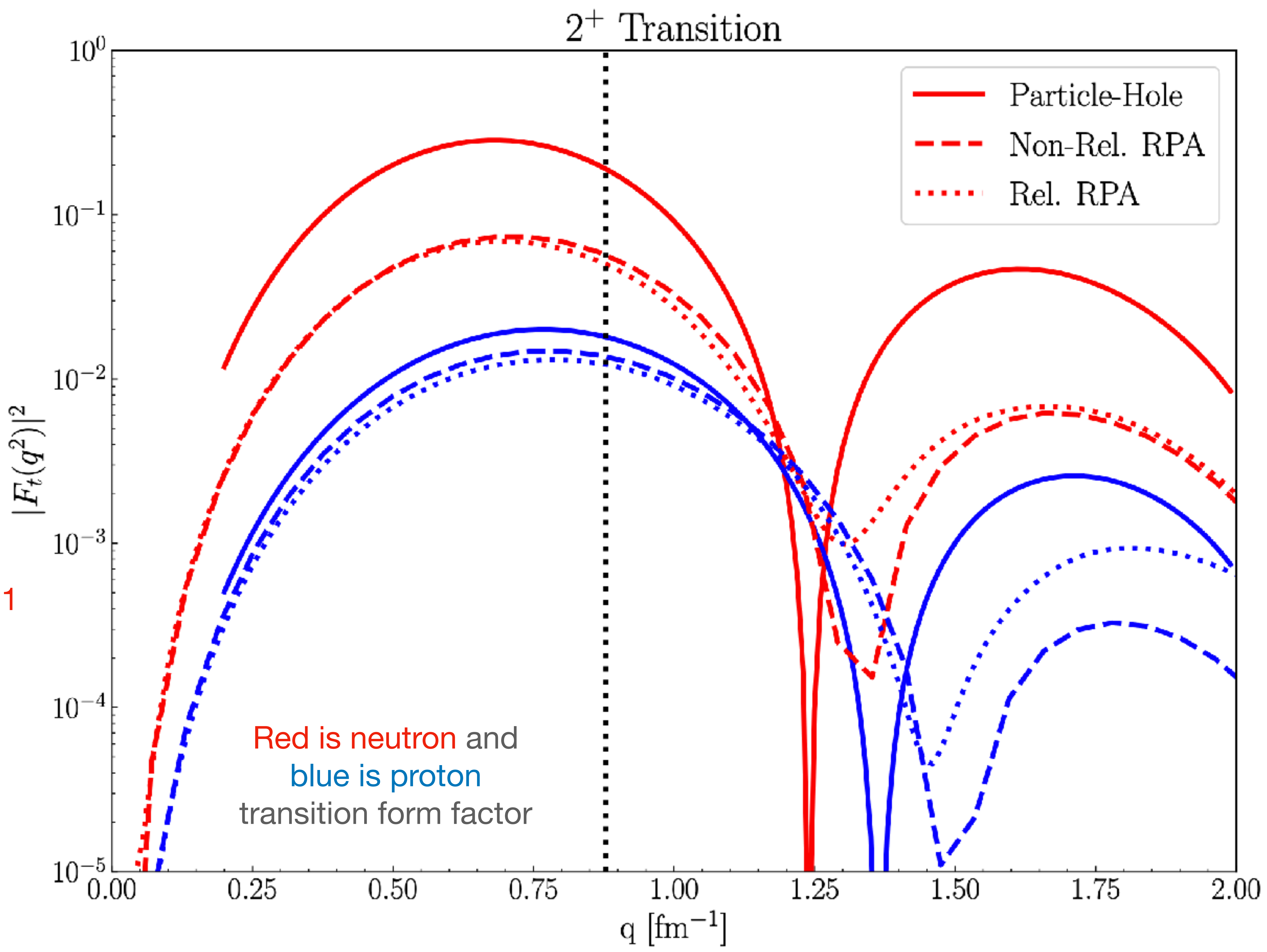
About 0.5% of the rate comes from this excited state.

$$A_{\rm pv} = \frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{F_t^n(q)}{F_t^p(q)}$$

Model	A_{pv}^{inel} [ppm]	Matrix Element
Particle-Hole Core	8.787	3.525
Non-relativistic RPA	5.220	2.036
Relativistic RPA	5.173	2.018
α-Scattering	8.315	3.2
n/p-Scattering	9.910	3.8

3+/-1

Elastic 2.7



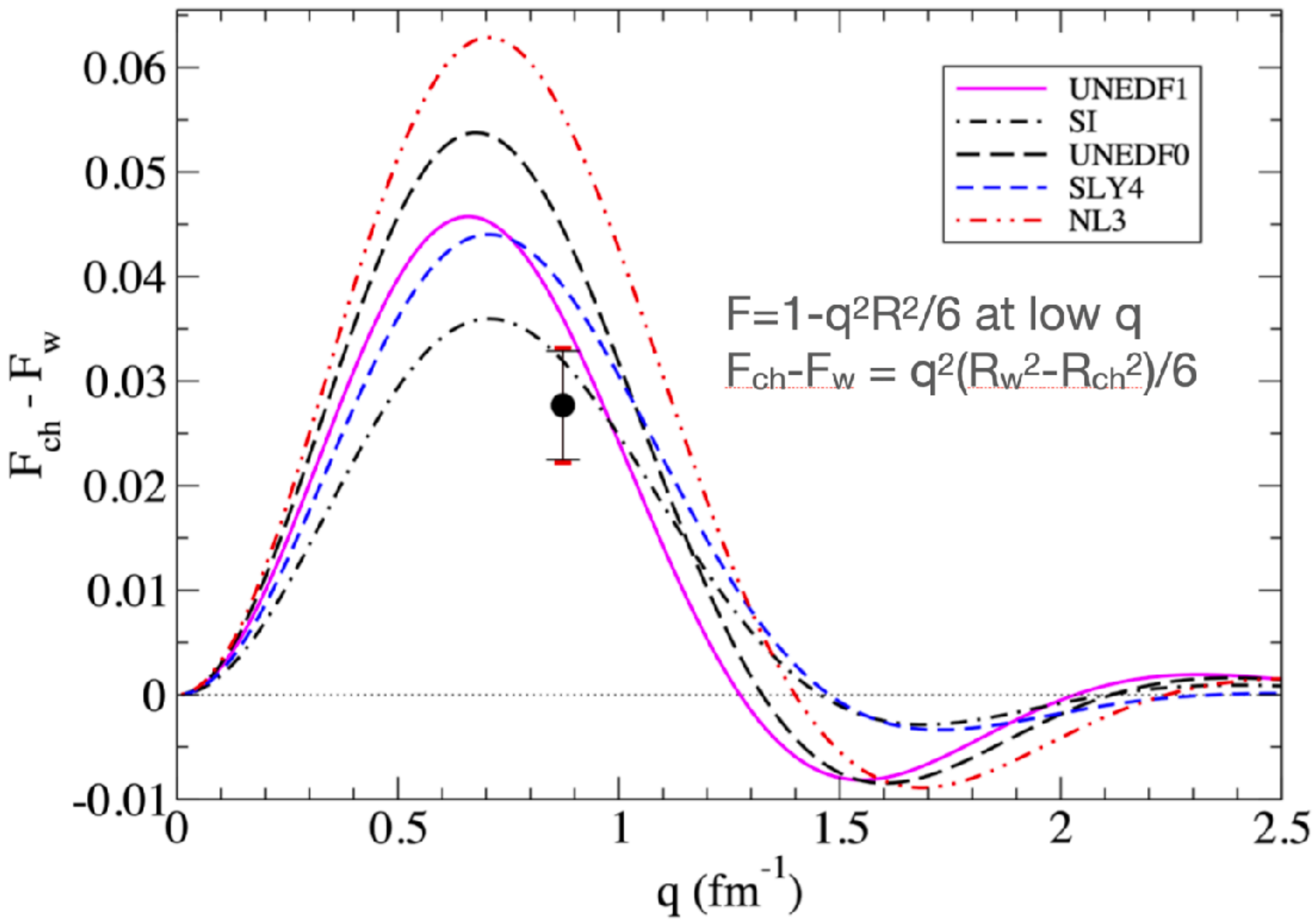
Many thanks to P.-G. Reinhard, X. Roca-Maza, and J. Piekarewicz for RPA calculations!

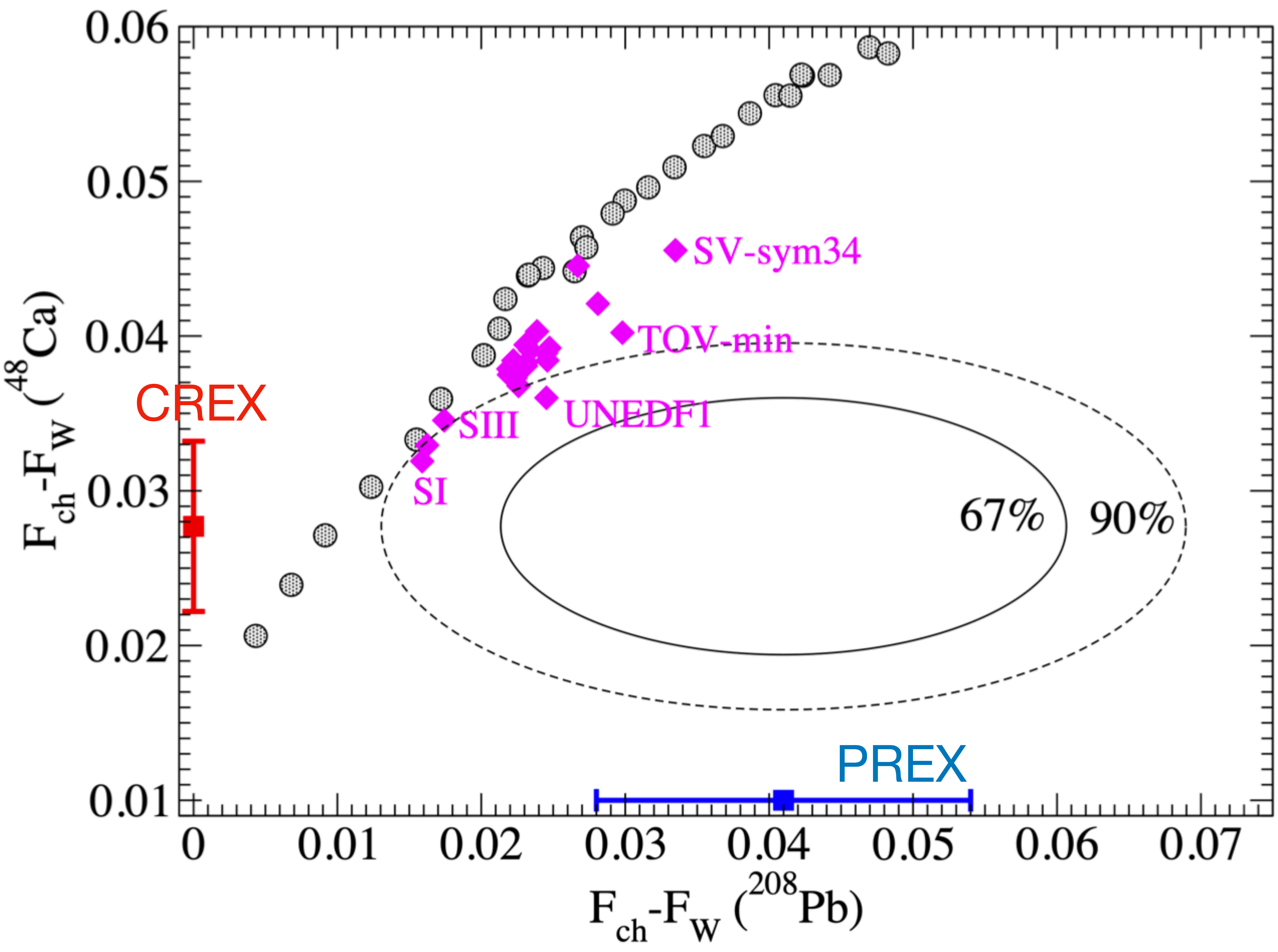
Weak Form Factor

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

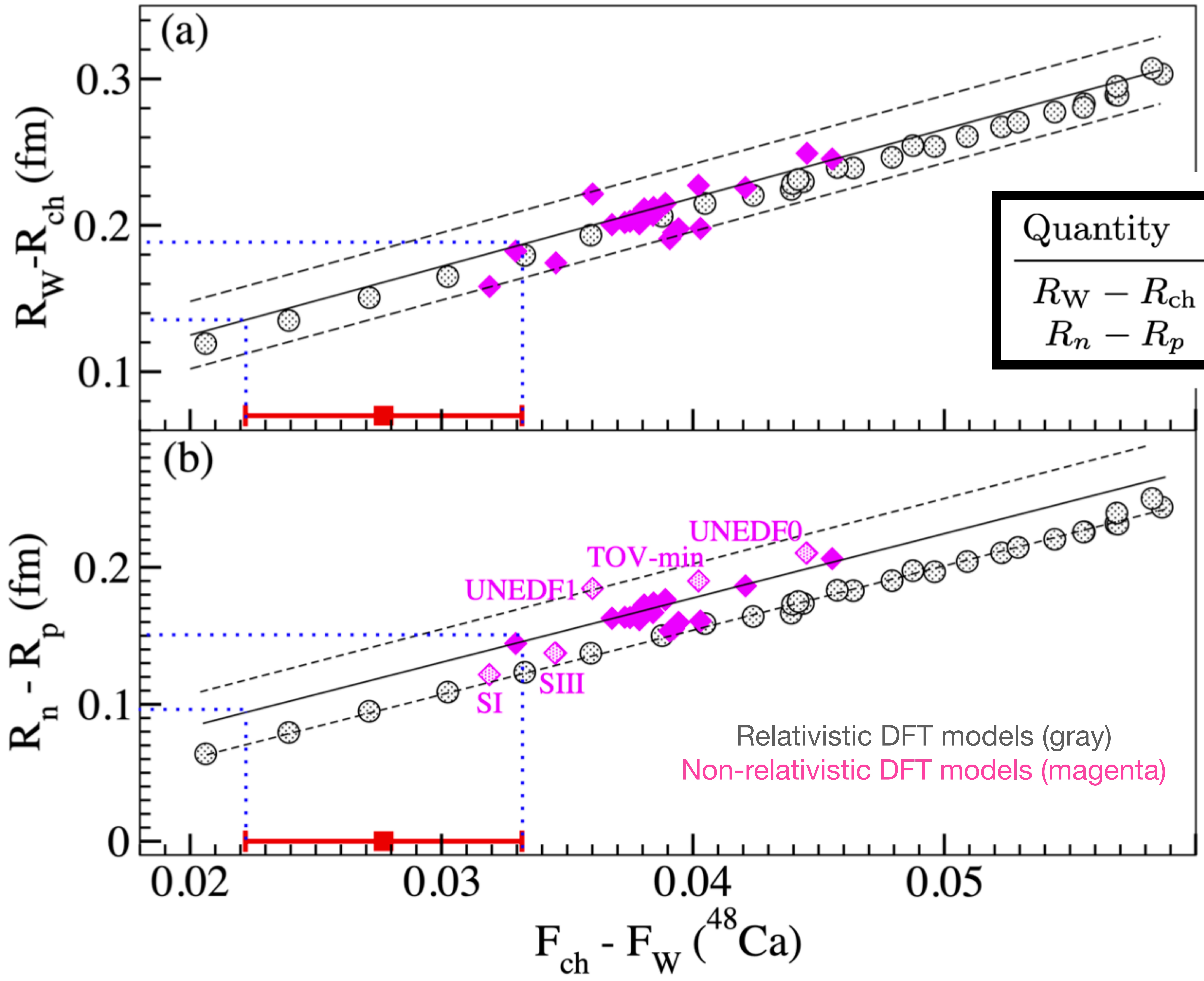
- Determine ratio F_W/F_{ch} from A_{PV} (Include Coulomb distortions and averaging over acceptance)
- Main result ($q=0.8733$ fm^{-1}):

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





CREX
PREX
SV-sym34
TOV-min
UNEDF1
SIII
SI
67%
90%
$F_{ch}-F_W$ (^{48}Ca)
$F_{ch}-F_W$ (^{208}Pb)
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



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.

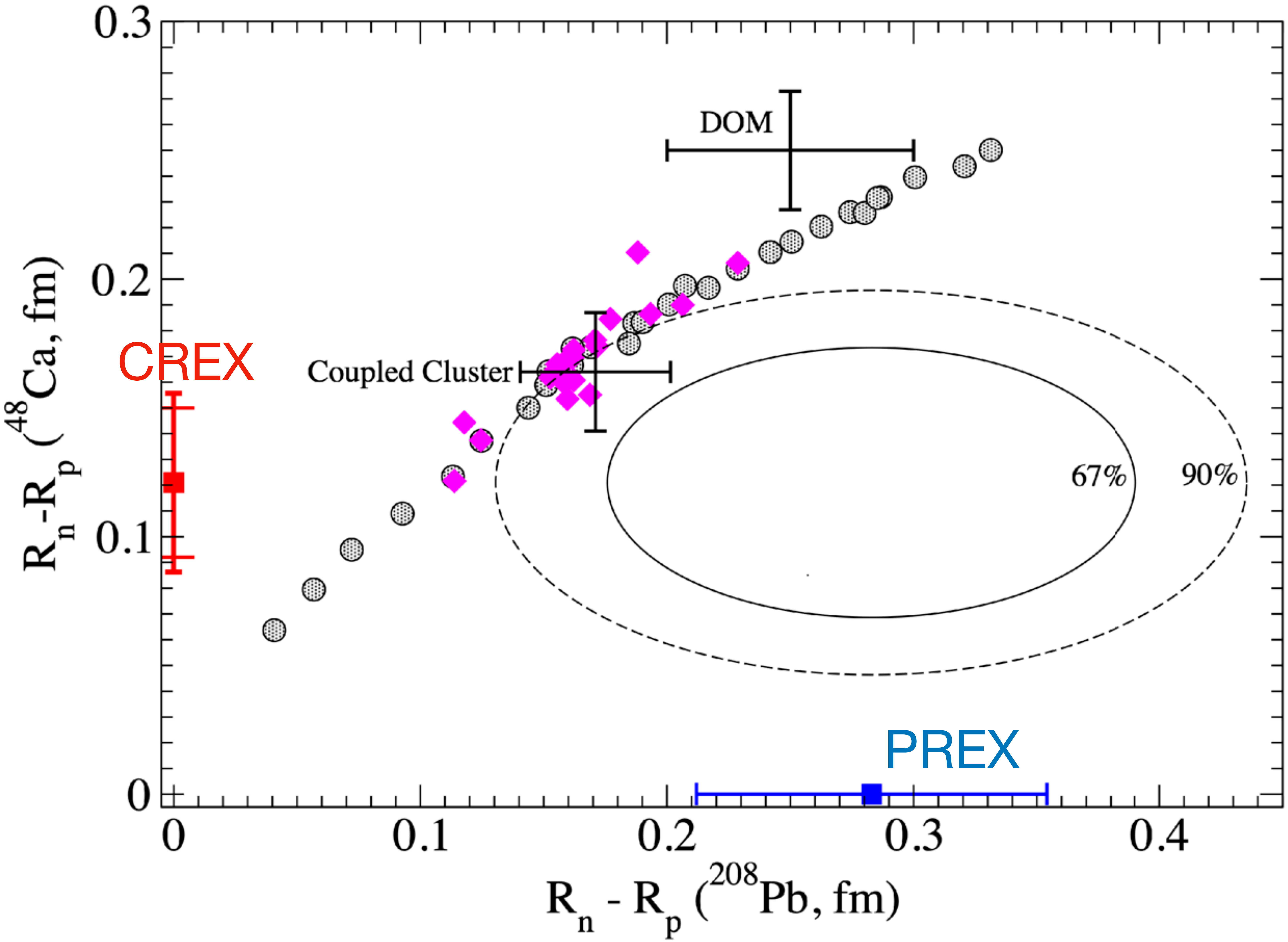
Exp. error in R_n +/-0.026 fm (.7%)
Total error in R_n +/-0.035 fm (1%)

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

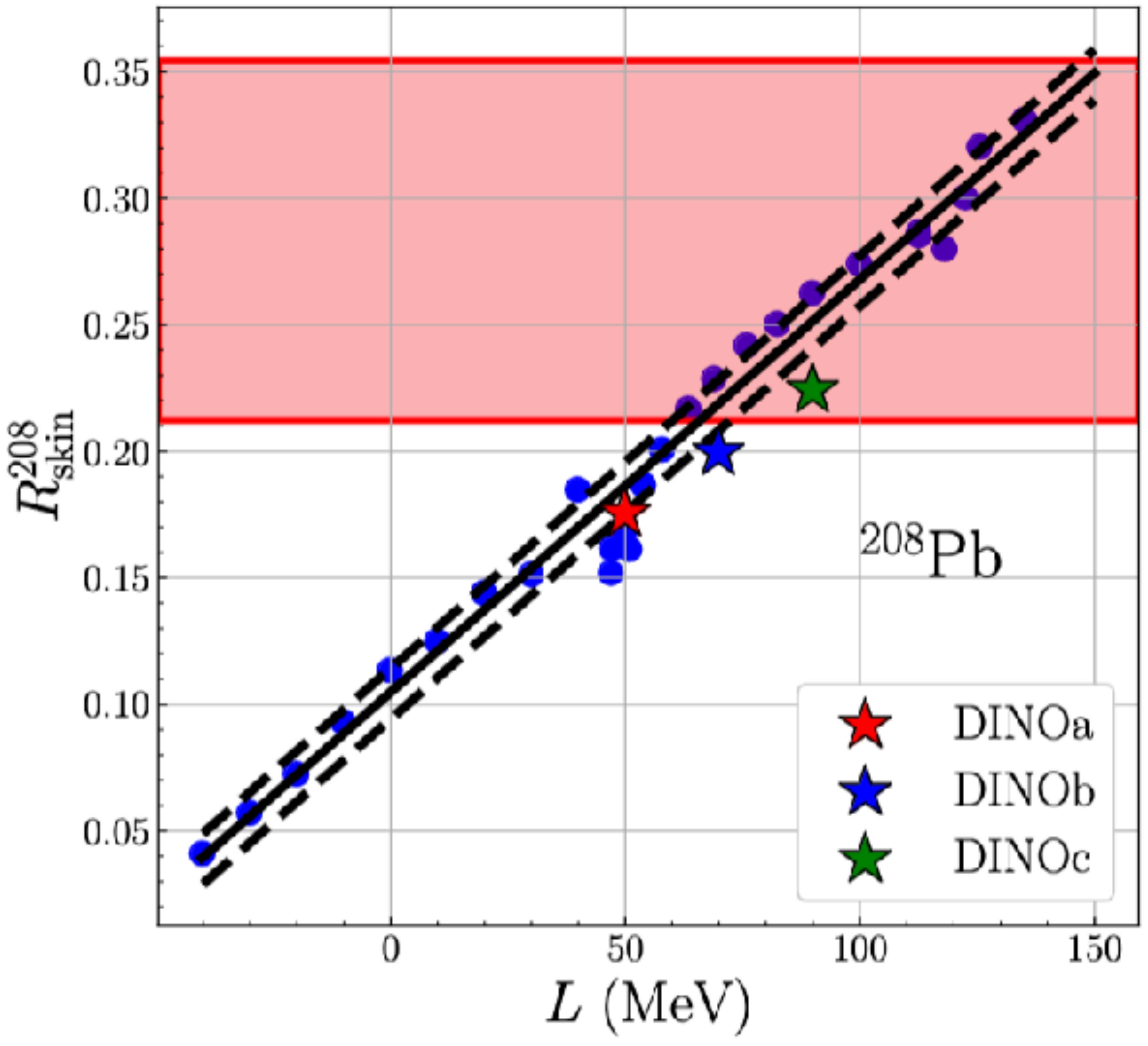
No model error in F_{ch}-F_W

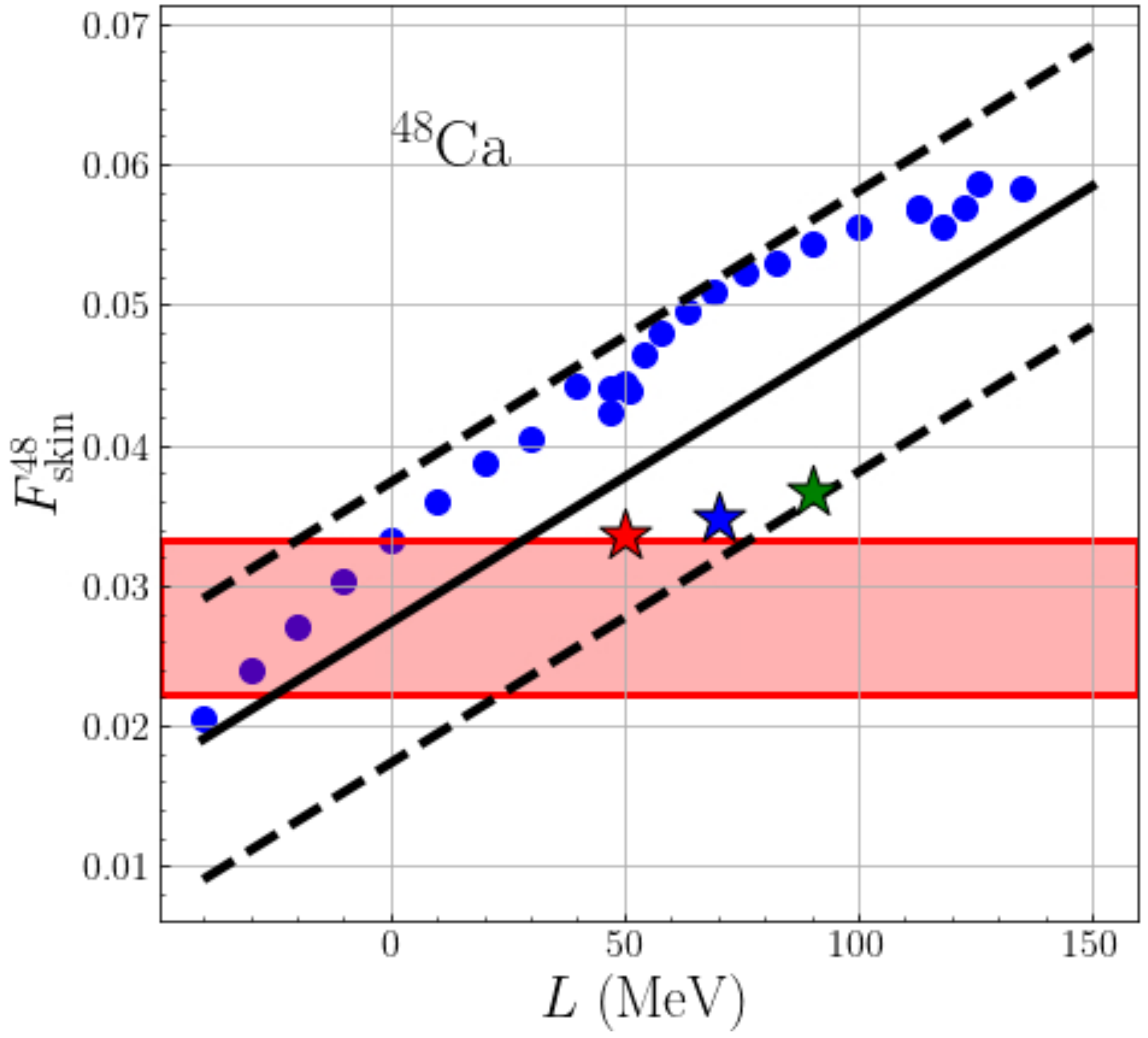
$$F_{ch}(q) - F_W(q) = 0.0277 \pm 0.0055\ (\text{exp})$$

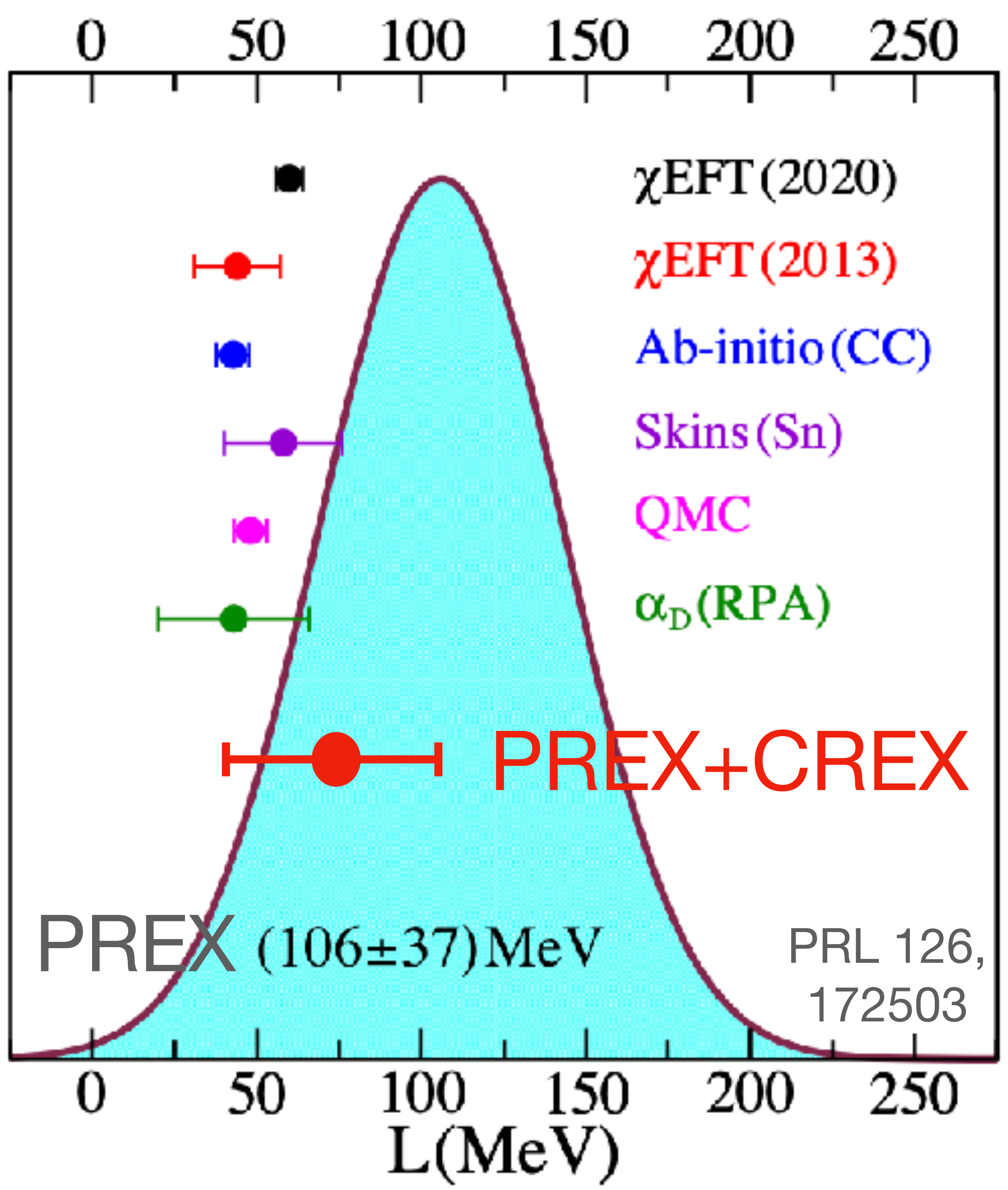
PREX measured R_n to 1.3%


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 (48Ca, fm)
R_n - R_p (208Pb, fm)

Symmetry Energy from PREX, CREX







- Symmetry energy S(n) describes how E of nuc. matter rises as one moves away from N=Z
- $L=3n_0 dS(n)/dn|_{n_0}$ Extracting L from CREX is more model dependent than from PREX.
- L=106 +/- 37 MeV (PREX), 69 +/- 34 MeV (PREX+CREX)
- The DINO RMF interactions have unusual density dependence, fit to both PREX and CREX

Parity violation at Mainz

- At MESA (new high current low energy machine) measure:
  - –Weak charge of proton (improve on Qweak)
  - –Weak charge of ^{12}C ("Atomic PNC without the atomic structure")
  - –MREX: Neutron skin thickness of ^{208}Pb (improve on PREX II by more than factor of two) measure R_w to 0.5%.
- R_w ^{48}Ca to 1% (CREX), ^{208}Pb (PREX 1.3%), (MREX 0.5%)
  - –Nuclear theory can extrapolate R_w-R_{ch} to R_w-R_{ch} in a neighboring nucleus, for example from ^{48}Ca (CREX) to ^{40}Ar.
- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli… **Graduate student: Brendan Reed**