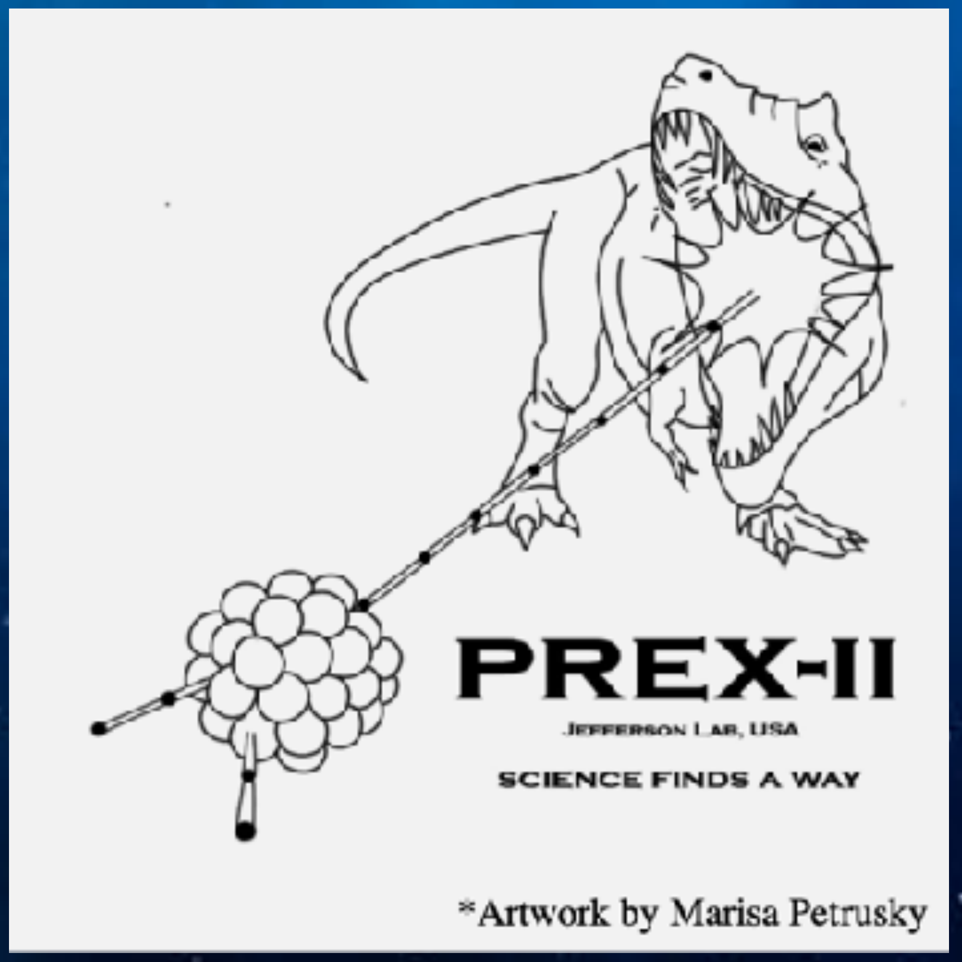
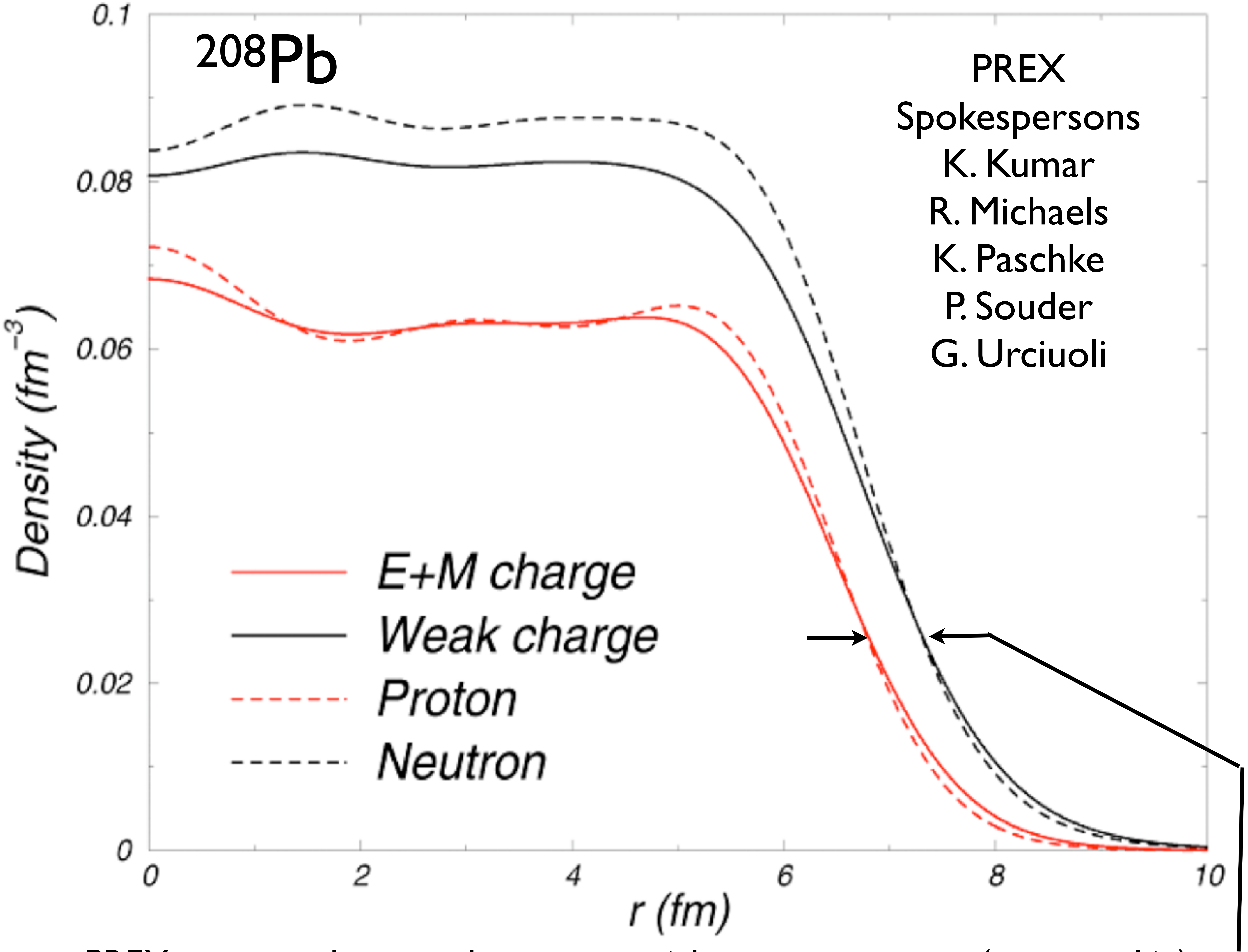
The PREX and CREX neutron density experiments and neutron stars

Chuck Horowitz, Indiana U., Quarks and Nuclear Physics, Sep. 2022





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

PREX uses Parity V. to Isolate Neutrons

- Standard Model Z^0 couples to 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 Z^0 exchange.
- Determines weak form factor

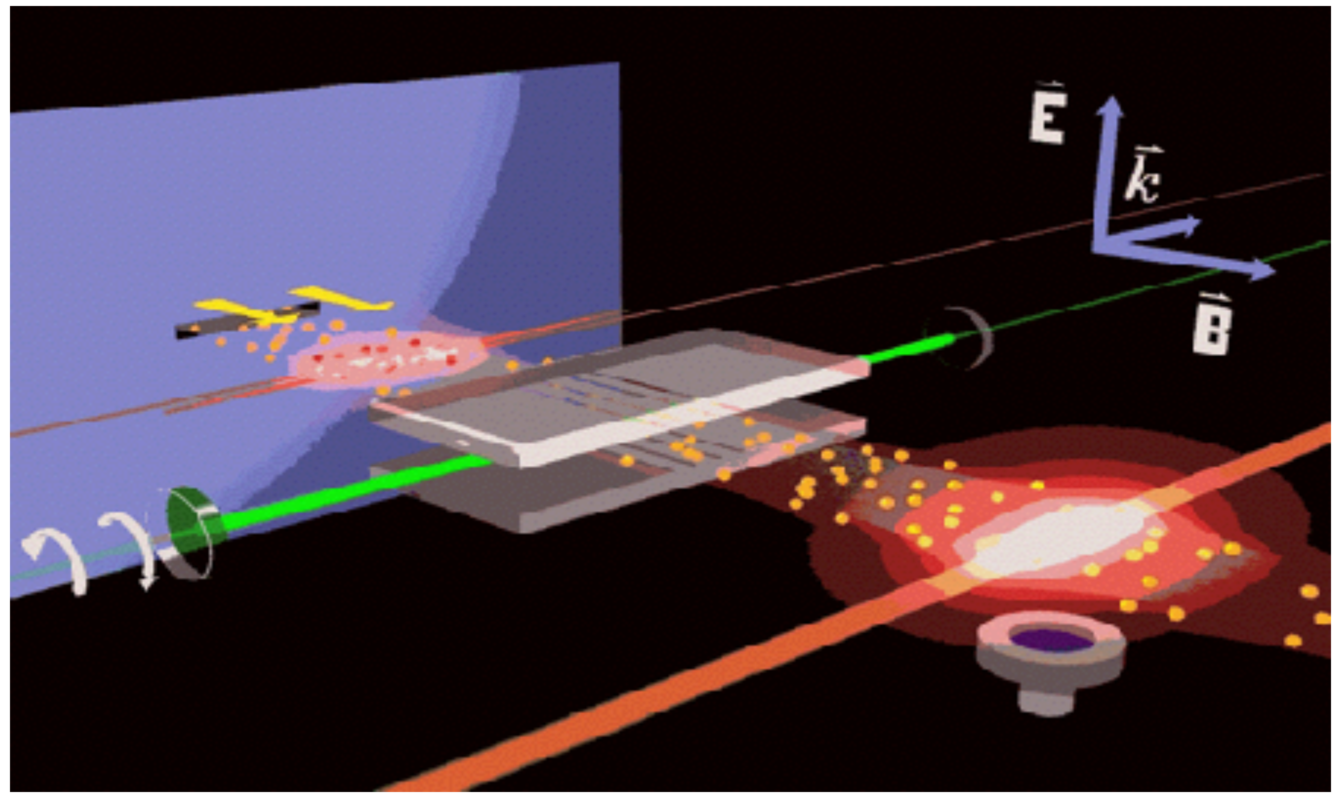
$$F_W(q) = \frac{1}{Q_W}\int d^3r j_0(qr)\rho_W(r)$$

- 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-2 ^{208}Pb results R_W=5.800+/- 0.075 fm (R_{ch}=5.503) and R_n-R_p=0.283+/-0.071 fm

Atomic Parity Nonconservation and Coherent Neutrino Scattering



- 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 a strong low energy test of standard model.

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

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

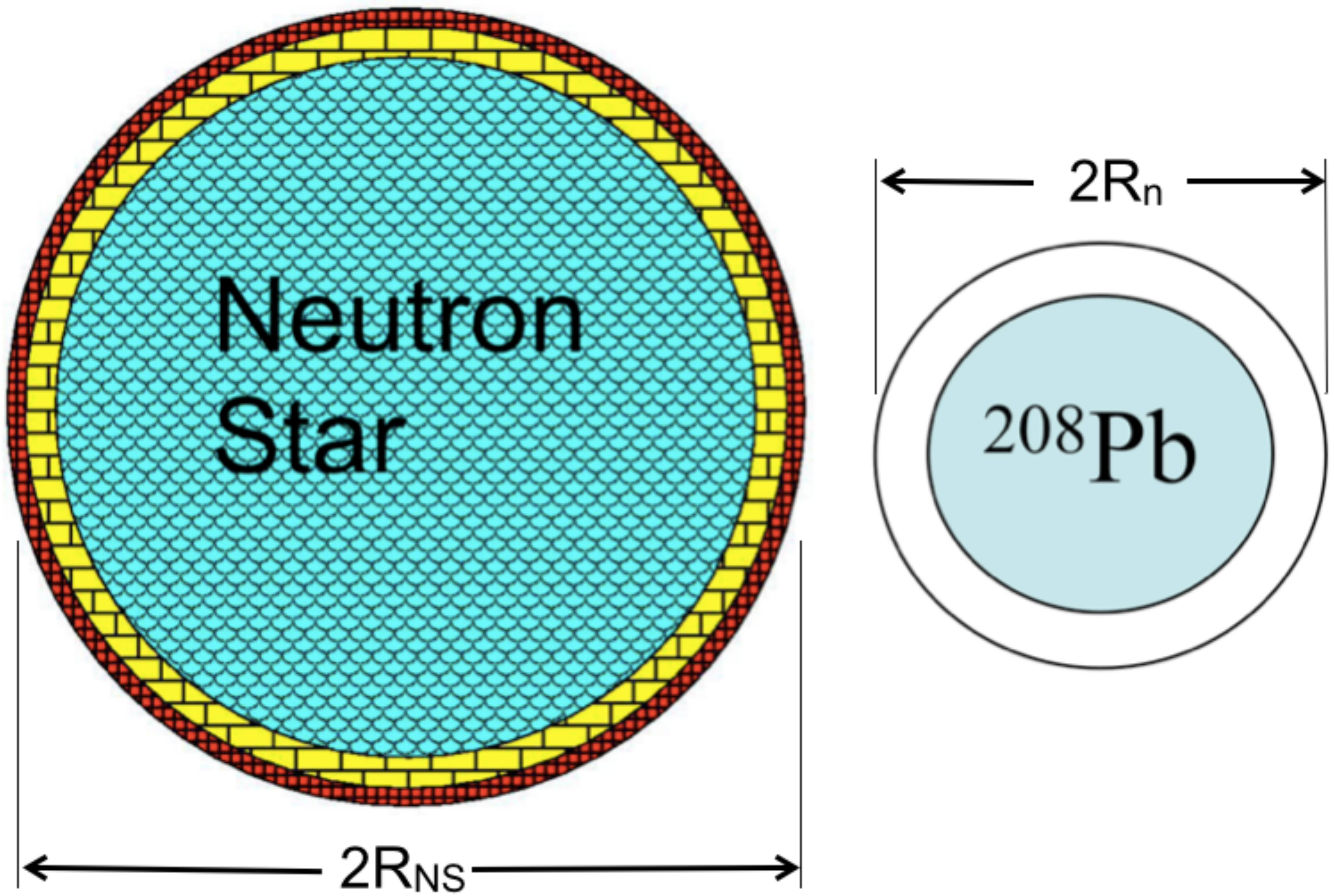
Coherent at SNS probed CsI average R_n to ~15%

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

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

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.

LIGO and deformability of NS

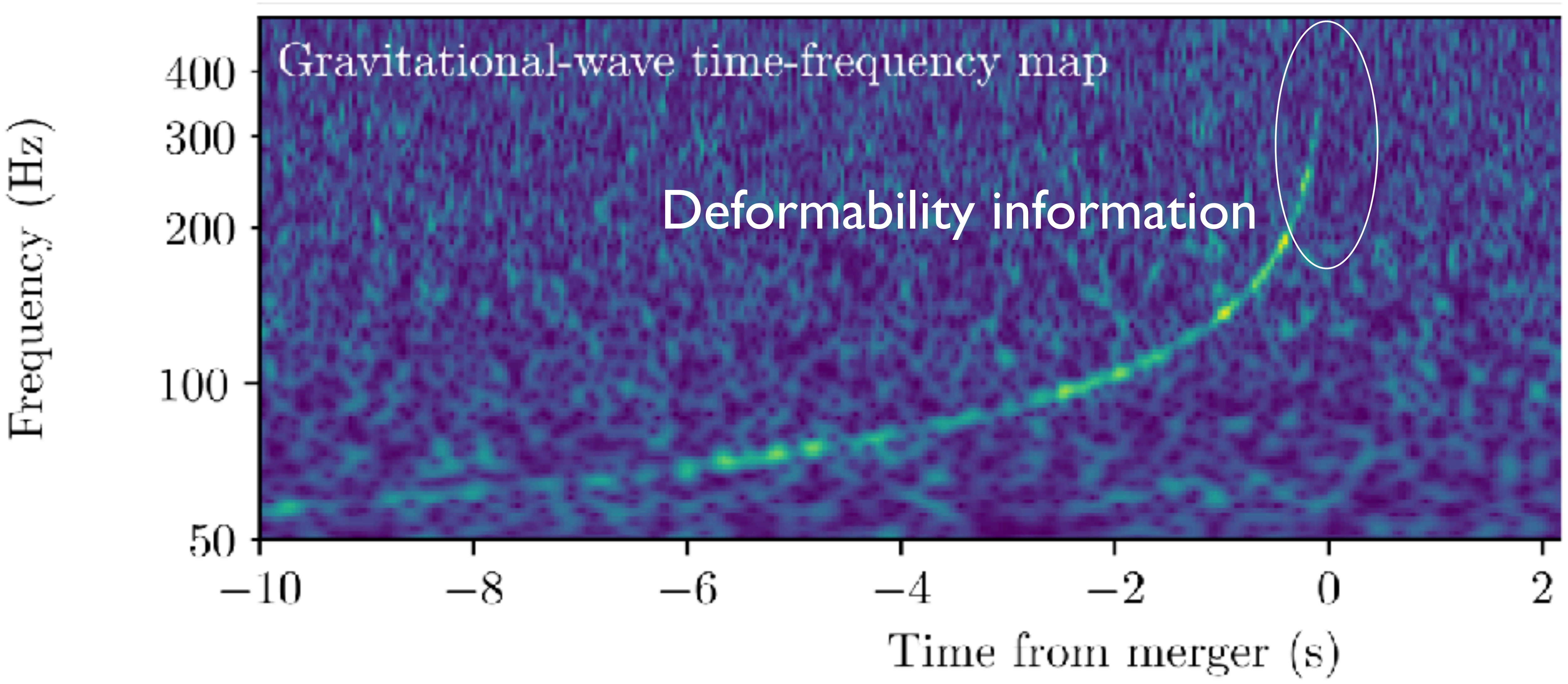
- Gravitational tidal field distorts shapes of neutron stars just before they merge.
- Dipole polarizability of an atom ~ R^3.

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

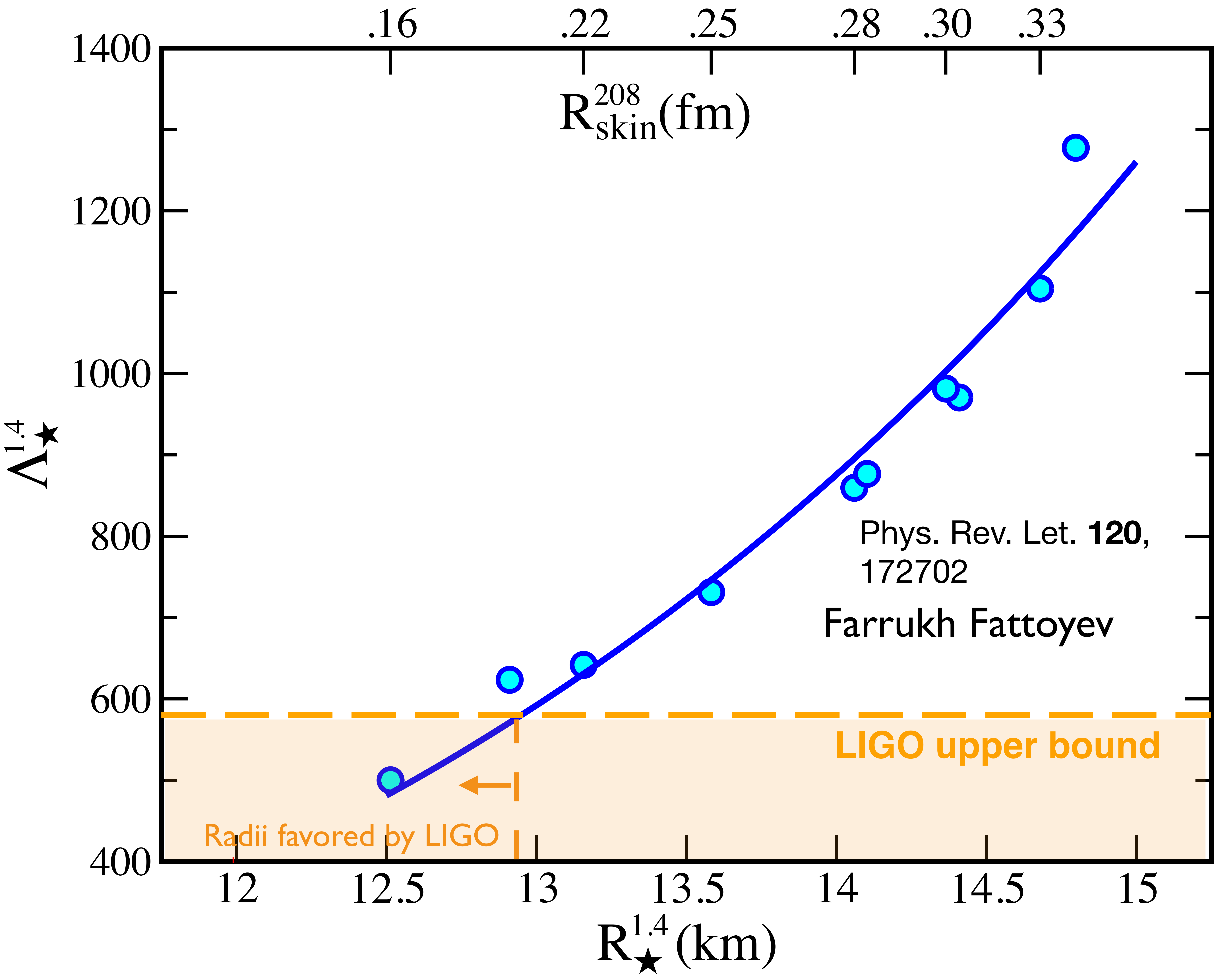
- Tidal deformability (or quadrupole polarizability) of a neutron star scales as R^5.

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

- 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.



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.33
1400
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1000
800
600
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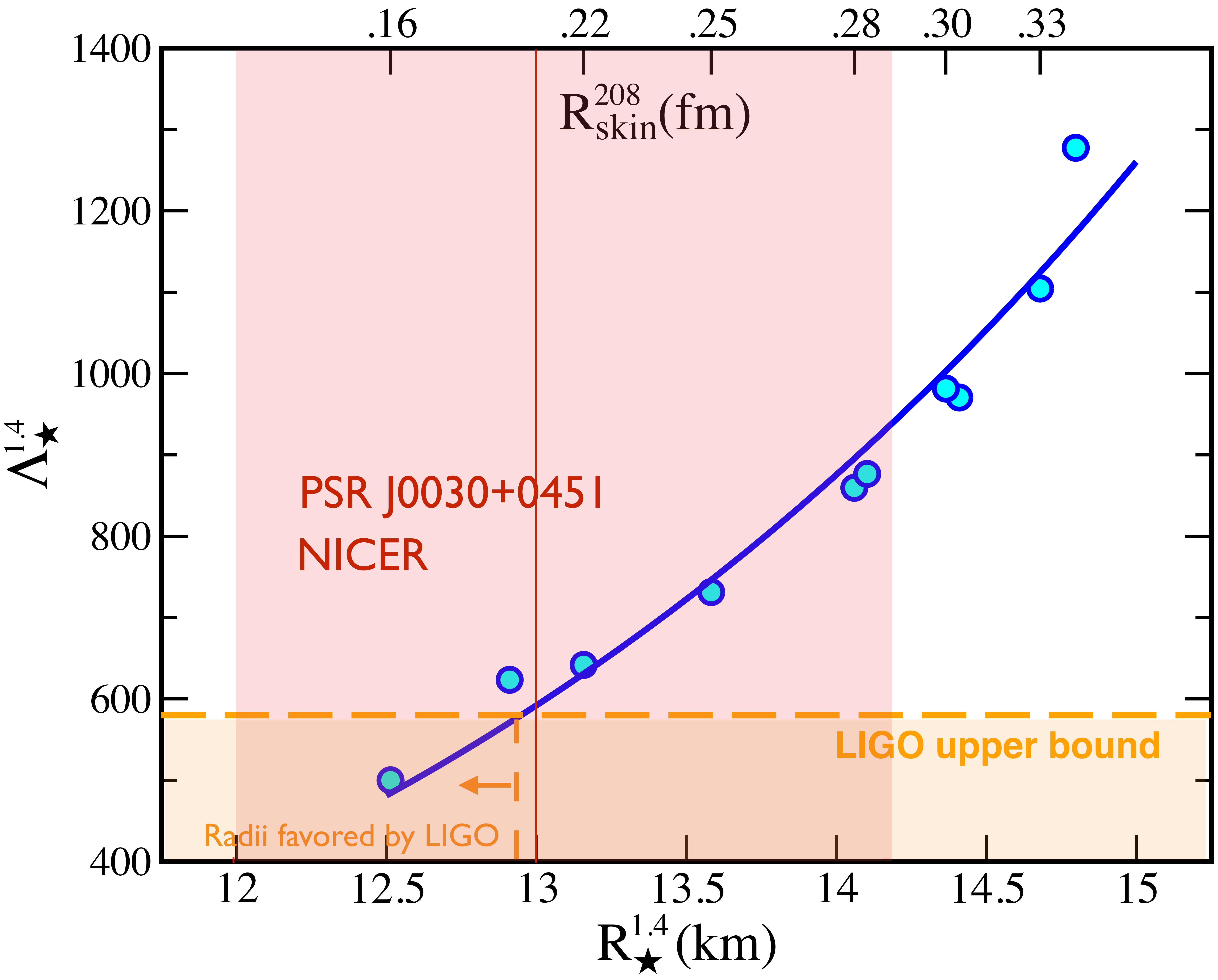
R$^{208}_{skin}$(fm)
$\Lambda^{1.4}_{\star}$
Phys. Rev. Let. **120**, 172702
Farrukh Fattoyev
LIGO upper bound
Radii favored by LIGO
12
12.5
13
13.5
14
14.5
15
R$^{1.4}_{\star}$(km)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R_{skin}^{208}(fm)
1400
1200
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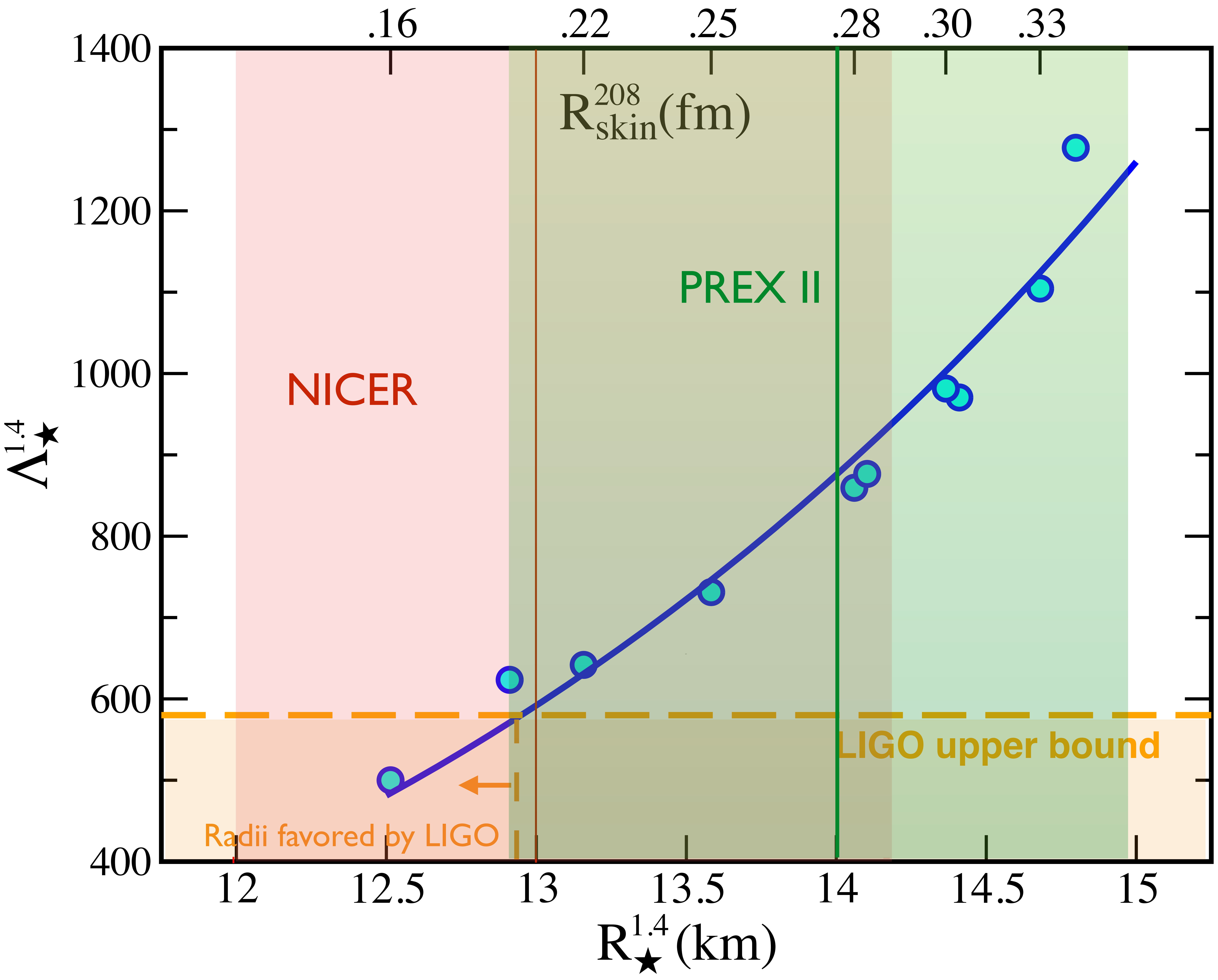
$\Lambda_\star^{1.4}$
PSR J0030+0451
NICER
LIGO upper bound
Radii favored by LIGO
12
12.5
13
13.5
14
14.5
15
$R_\star^{1.4}$(km)



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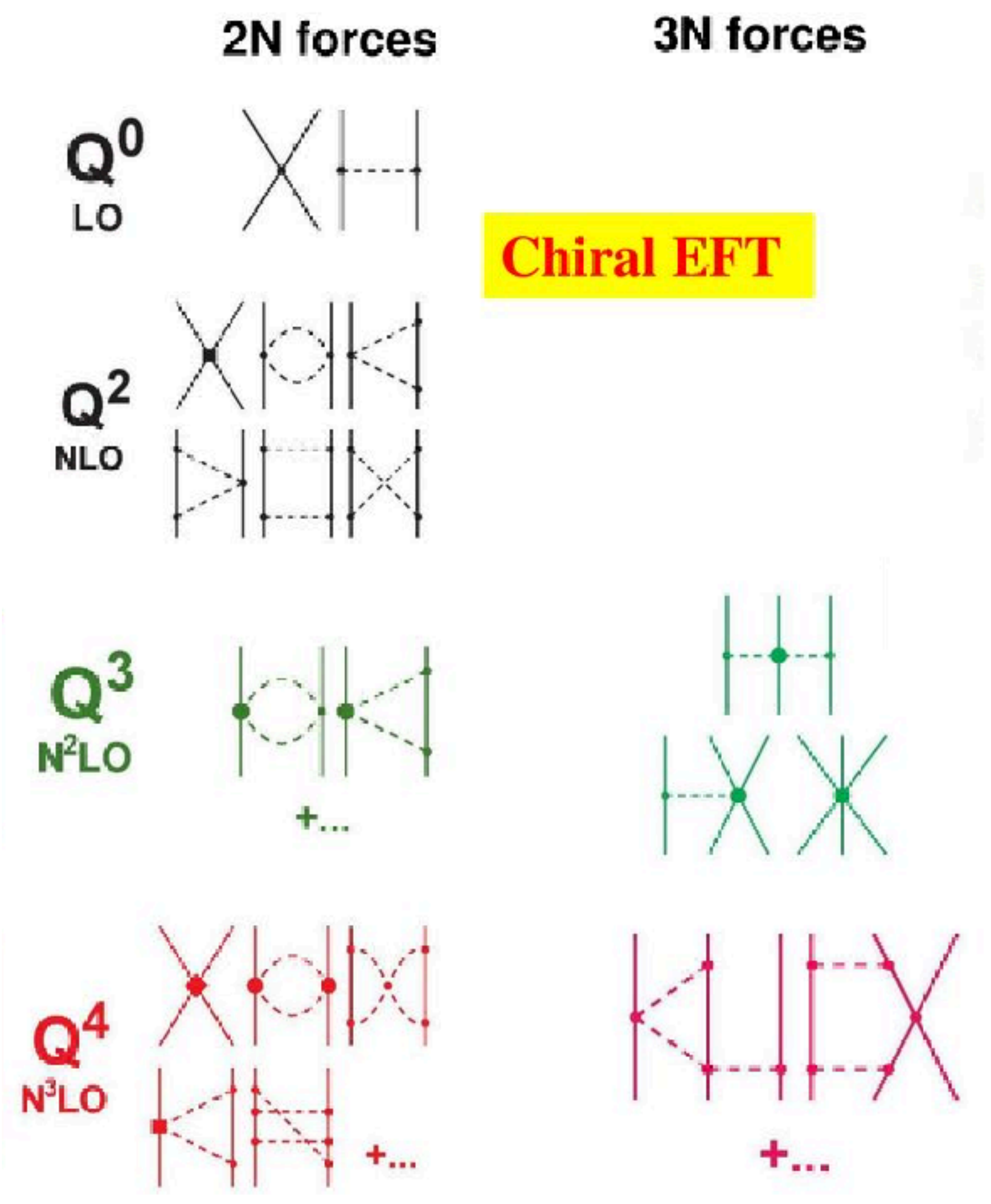
R_{skin}^{208}(fm)
PREX II
NICER
LIGO upper bound
Radii favored by LIGO
1400
1200
1000
800
600
400
$\Lambda_\star^{1.4}$
12
12.5
13
13.5
14
14.5
15
$R_\star^{1.4}$(km)

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.

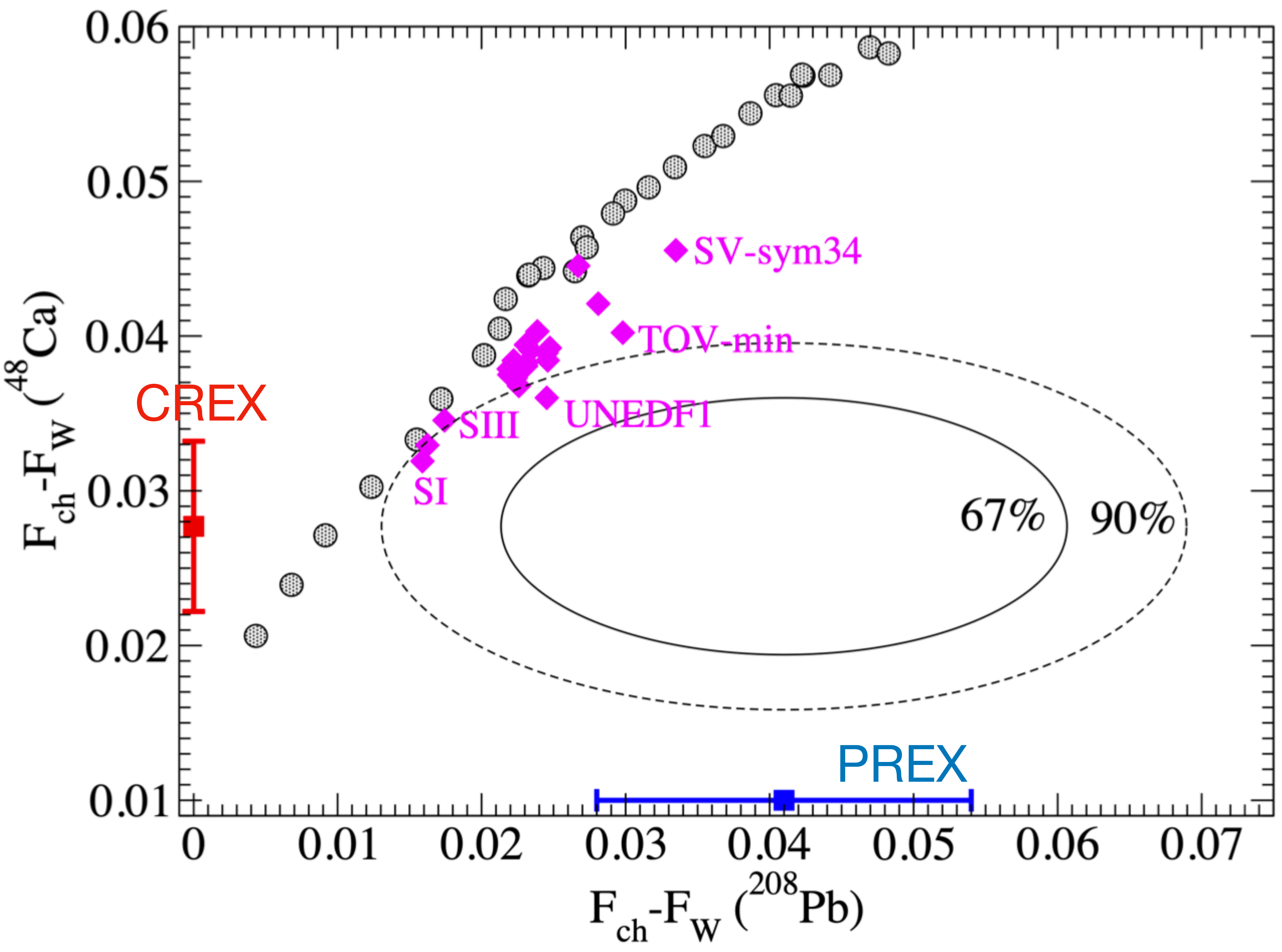


CREX

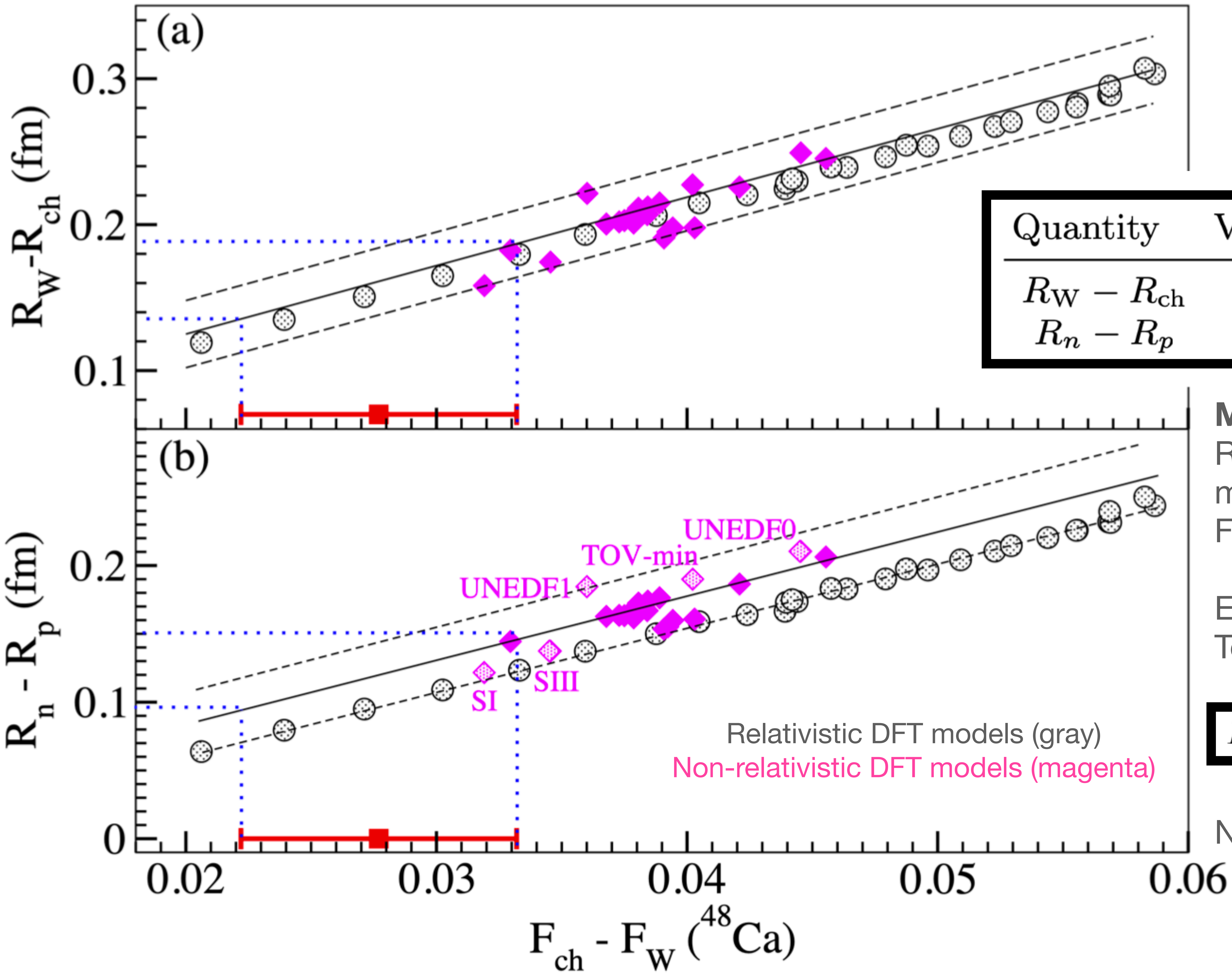
- 2.182 GeV electrons scattering with q=0.8733 fm^{-1} from ^{48}Ca.
- Target 8% ^{40}Ca, 0.6%, 0.6%, 0.2% of rate from first three excited states (2^+,3^-,3^-).
- A_{PV}=2668+/-106+/-40 ppb
- We thank J. Piekarewicz, P. G. Reinhard and X. Rocca-Maza for RPA calculations of ^{48}Ca excited states and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



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)
CREX
PREX
SV-sym34
TOV-min
UNEDF1
SIII
SI
67%
90%



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

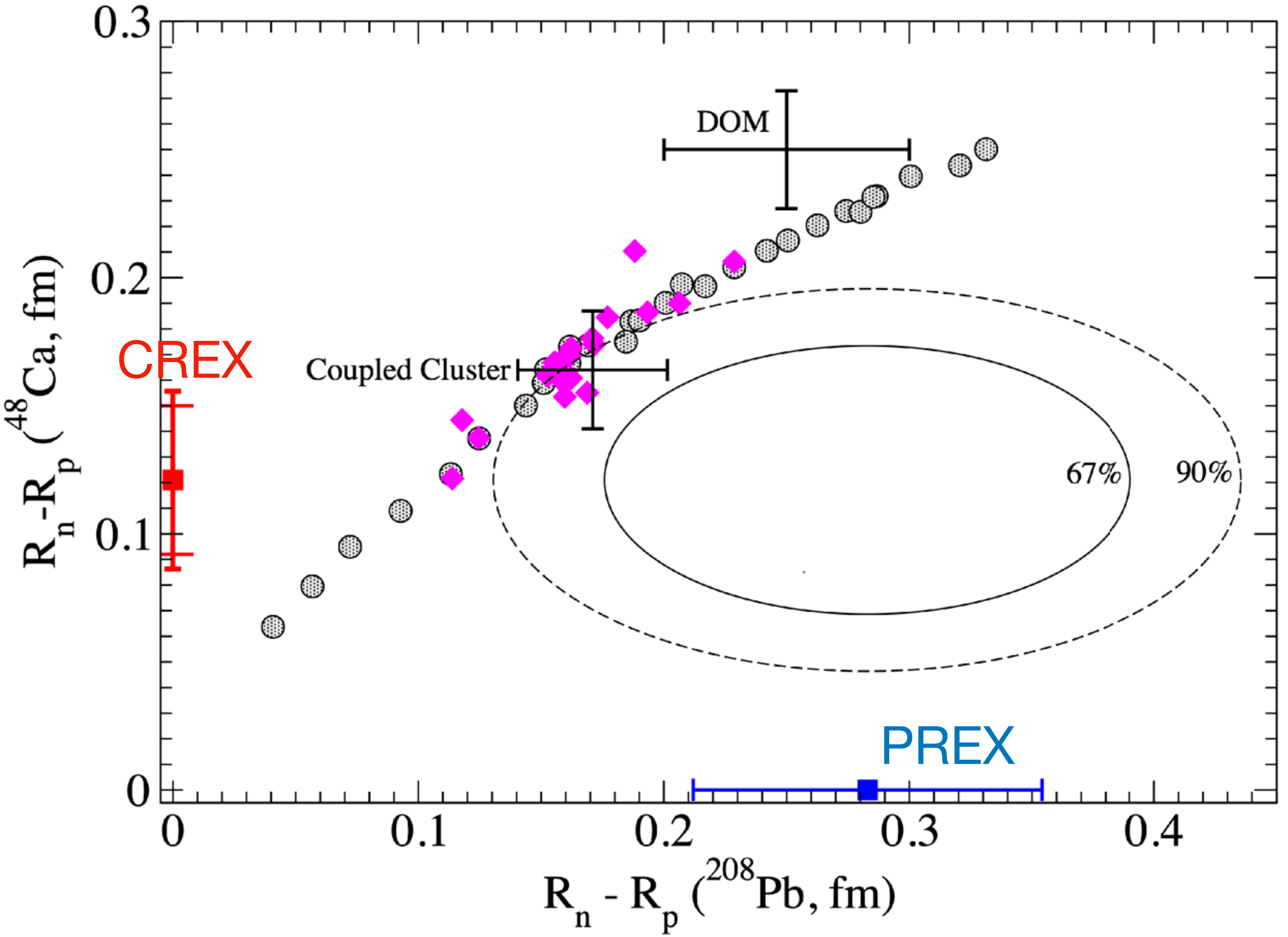
Model error in extraction of R_W-R_{ch} or R_n-R_p from spread in model predictions for given F_{ch}-F_W.

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

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



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)

CREX Experiment

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

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

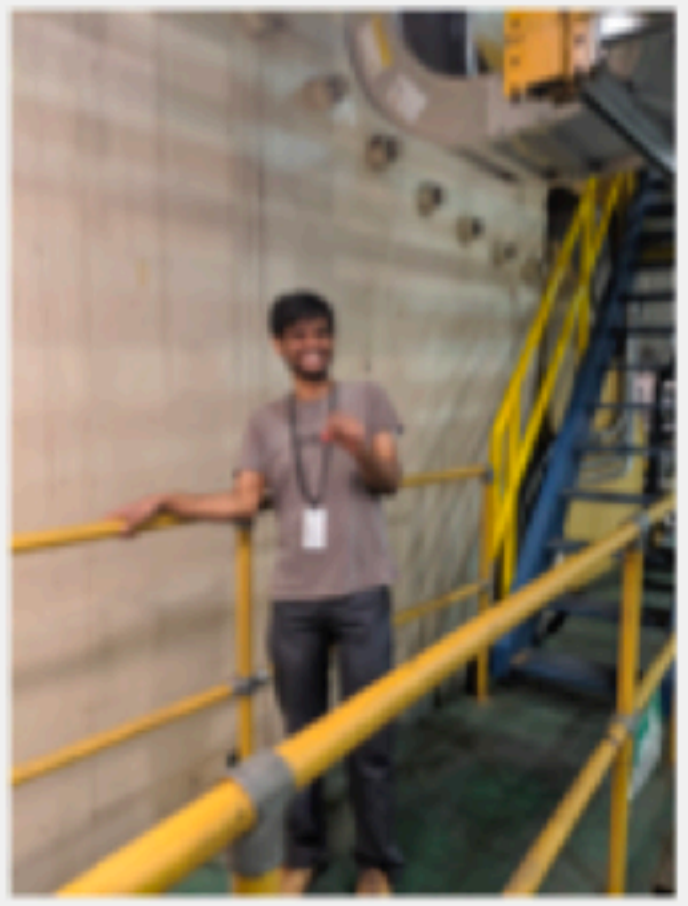
- Extract with small model dependence from shape of $\rho_w(r)$

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

- 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 (at 90%) 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



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

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Student **Brenden Reed** made important contributions!

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