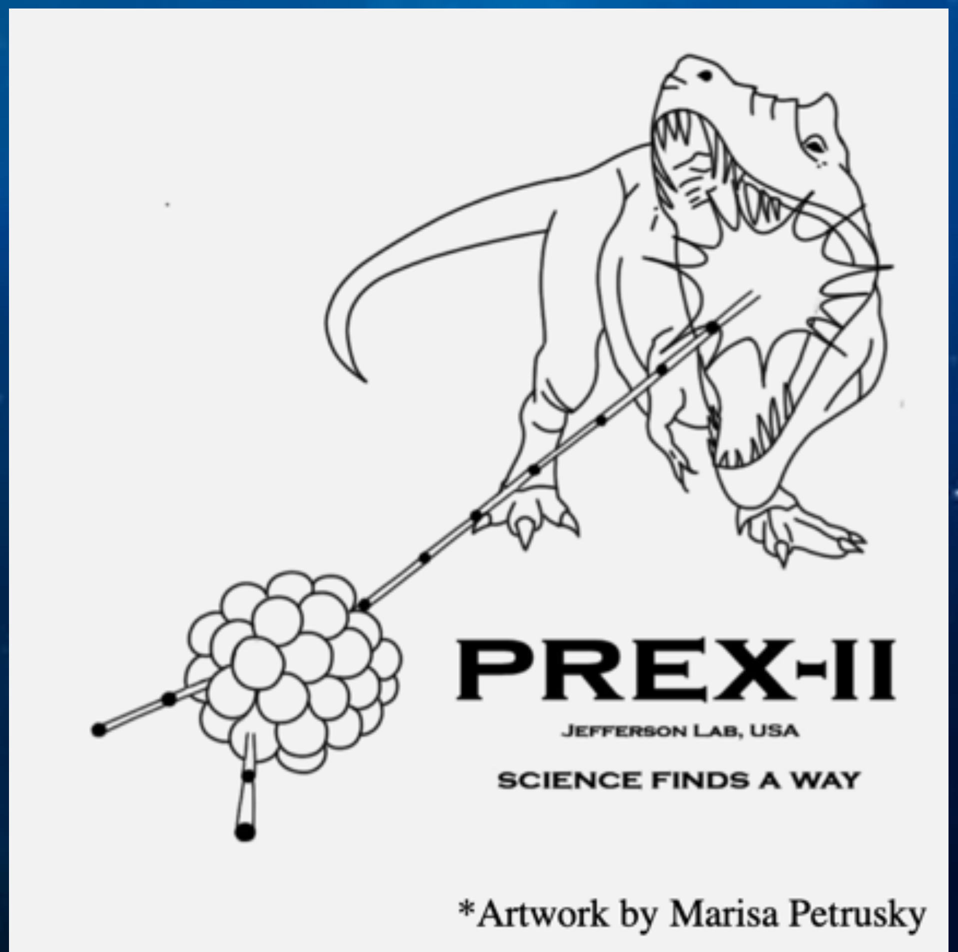
FRIB vs LIGO: neutron skins to neutron stars



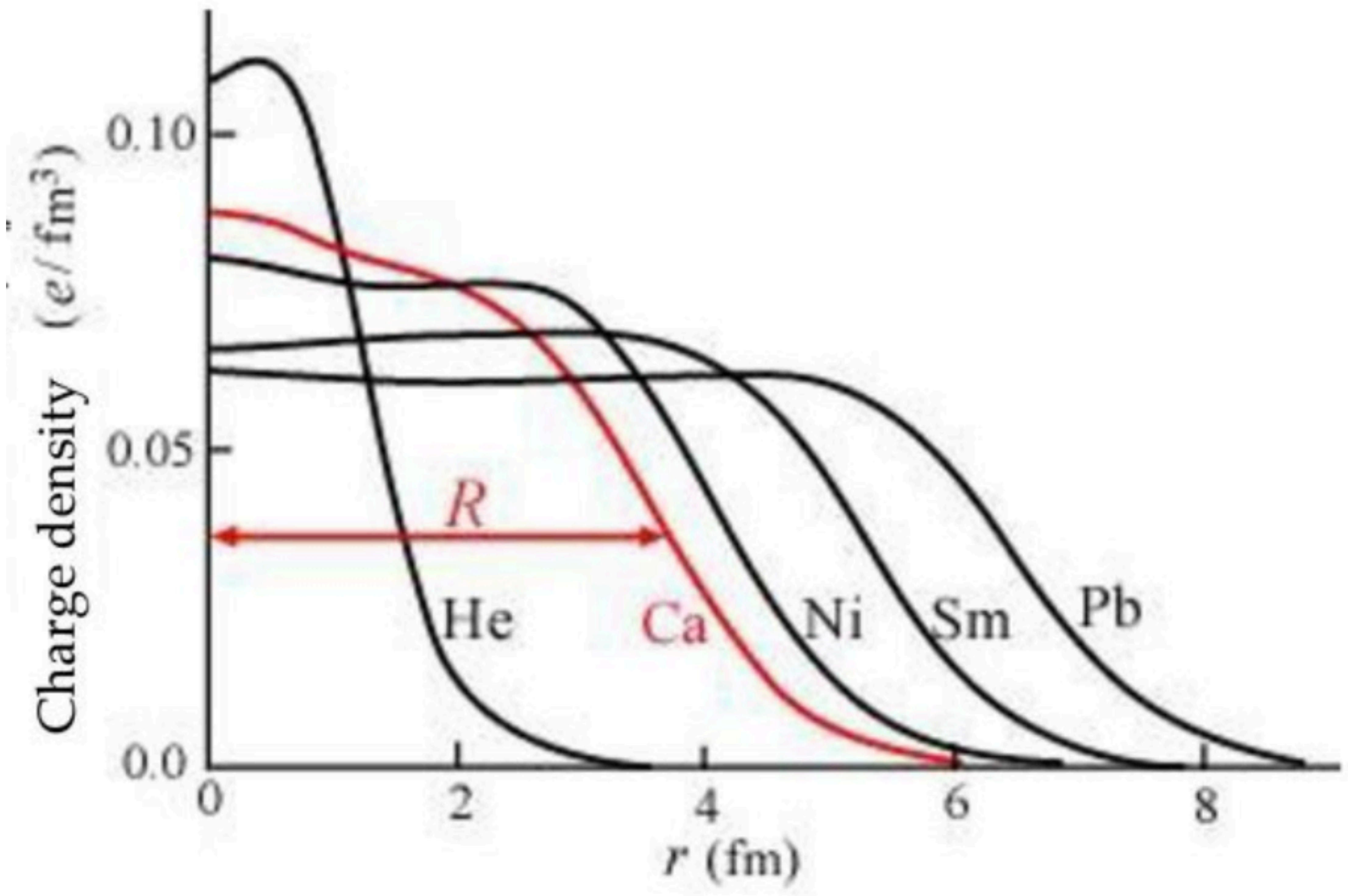
Chuck Horowitz, FRIB+Indiana U. FRIB, May 2023

U.S. DEPARTMENT OF ENERGY Office of Science

Nuclear saturation is fundamental

- In 1930s semi-empirical mass formula: $BE=a_1A+a_2A^{2/3}$… suggested nuclear saturation:
  - –Minimum in E vs density curve for nuclear matter. Consensus $\rho_0 \approx 0.16$ fm^{-3}
  - –Baryon density $\boldsymbol{\rho}_b(r)$ approx constant in interior of heavy nucleus. *Never been directly and cleanly observed.*
  - –Have interior charge densities for heavier N>Z systems but not neutron or baryon densities.

— ρ_0



Parity Violation Isolates Neutrons

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

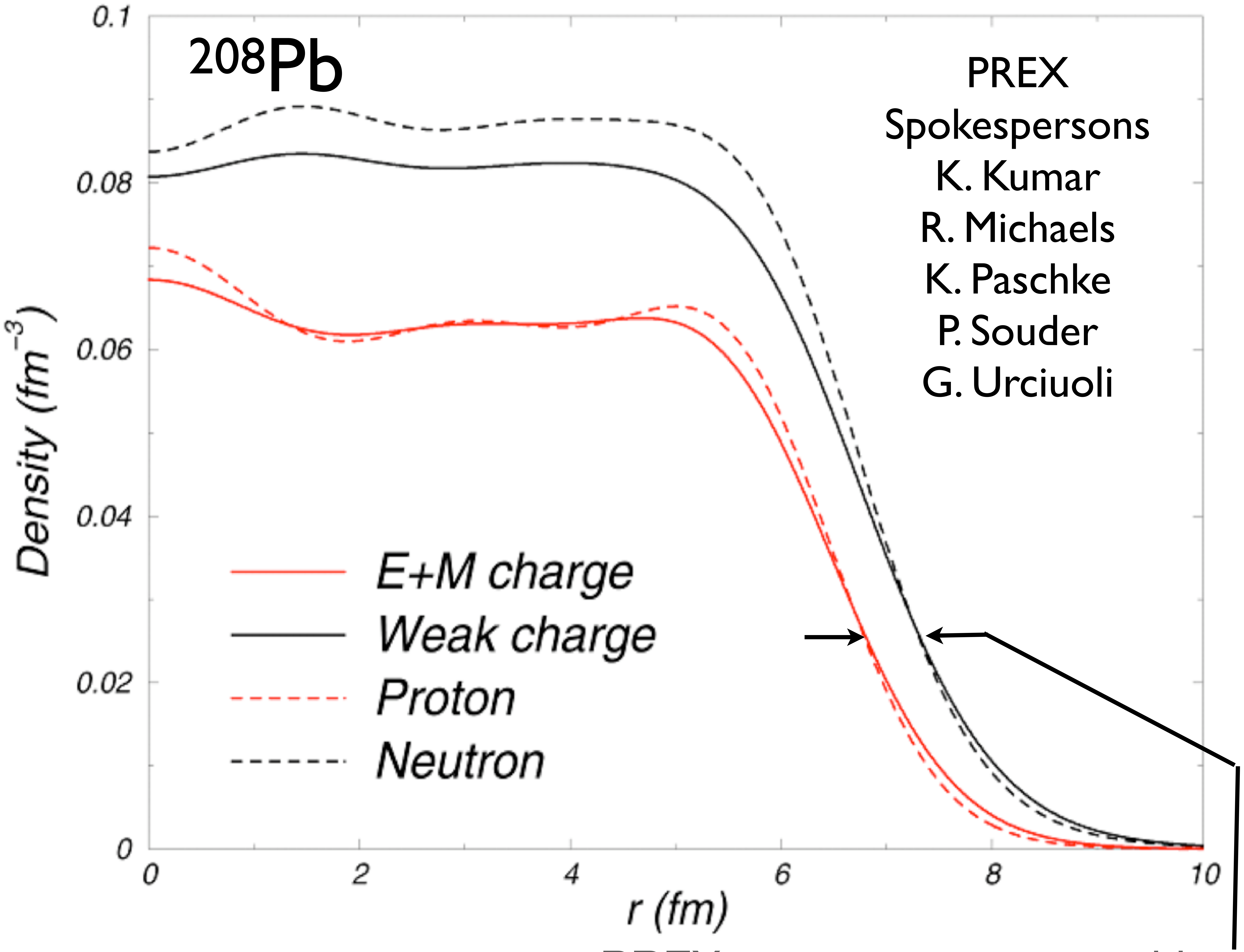
$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- 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

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

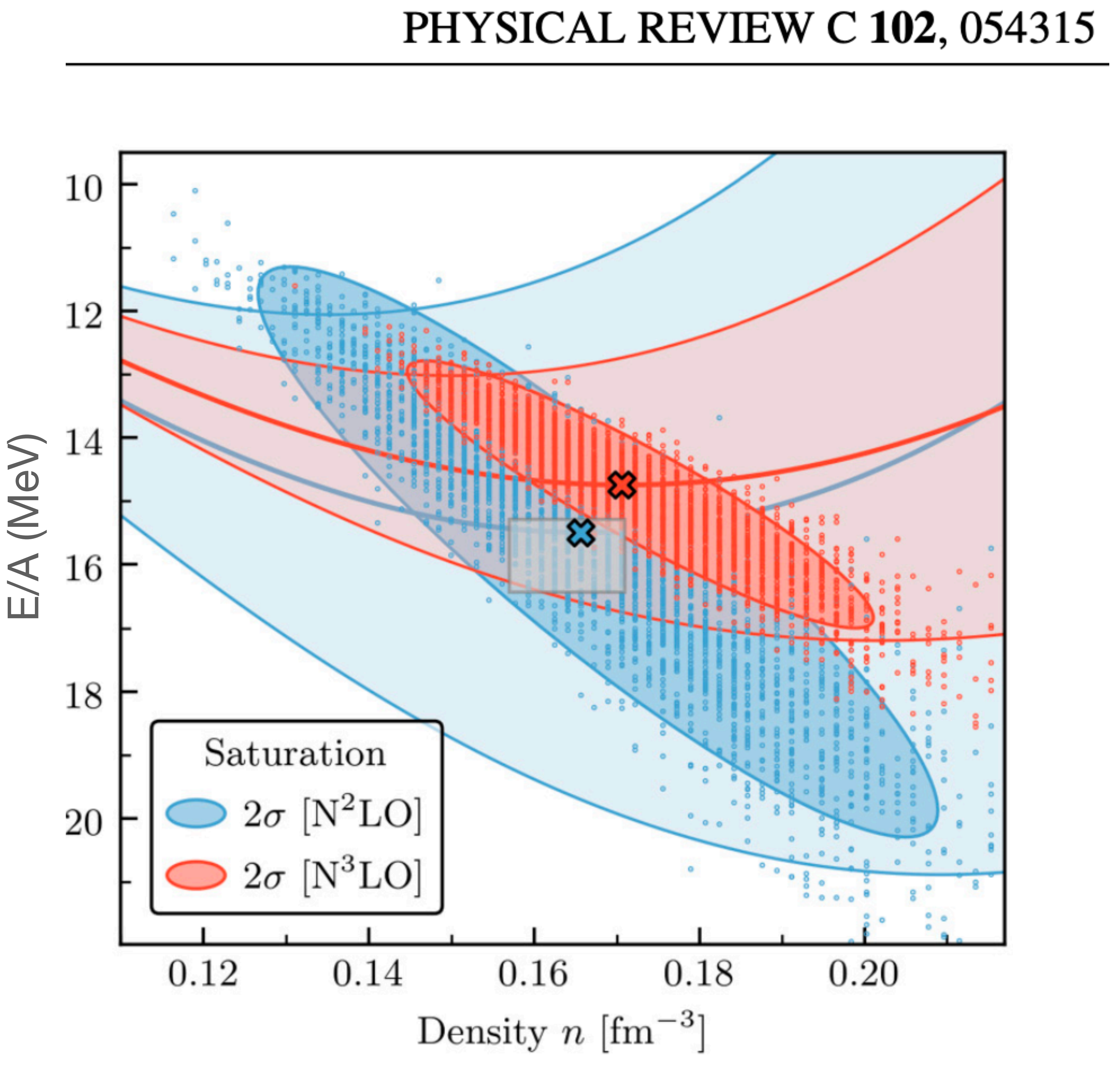


PREX Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

PREX measures neutron skin

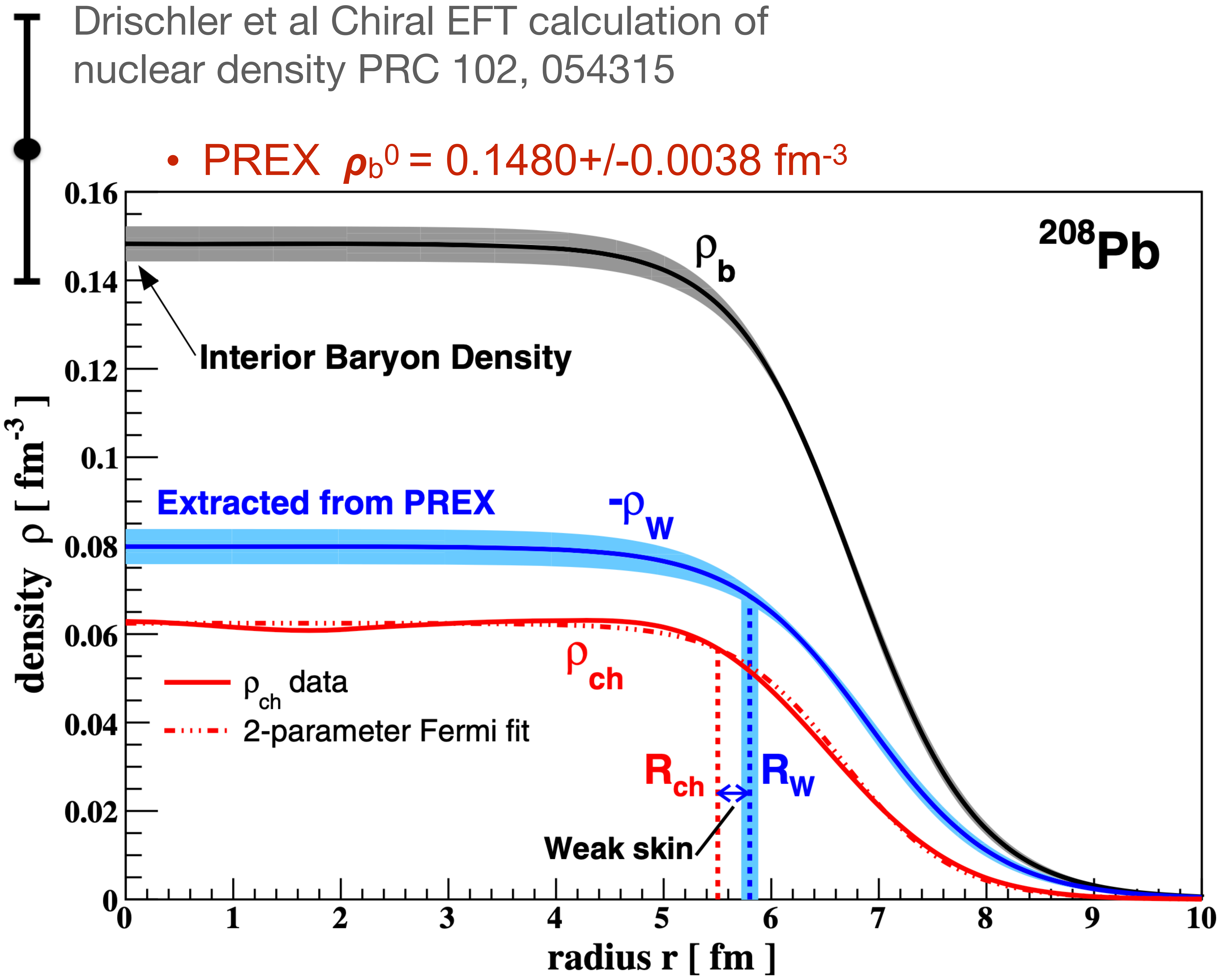
How does nuclear saturation depend on neutron excess?

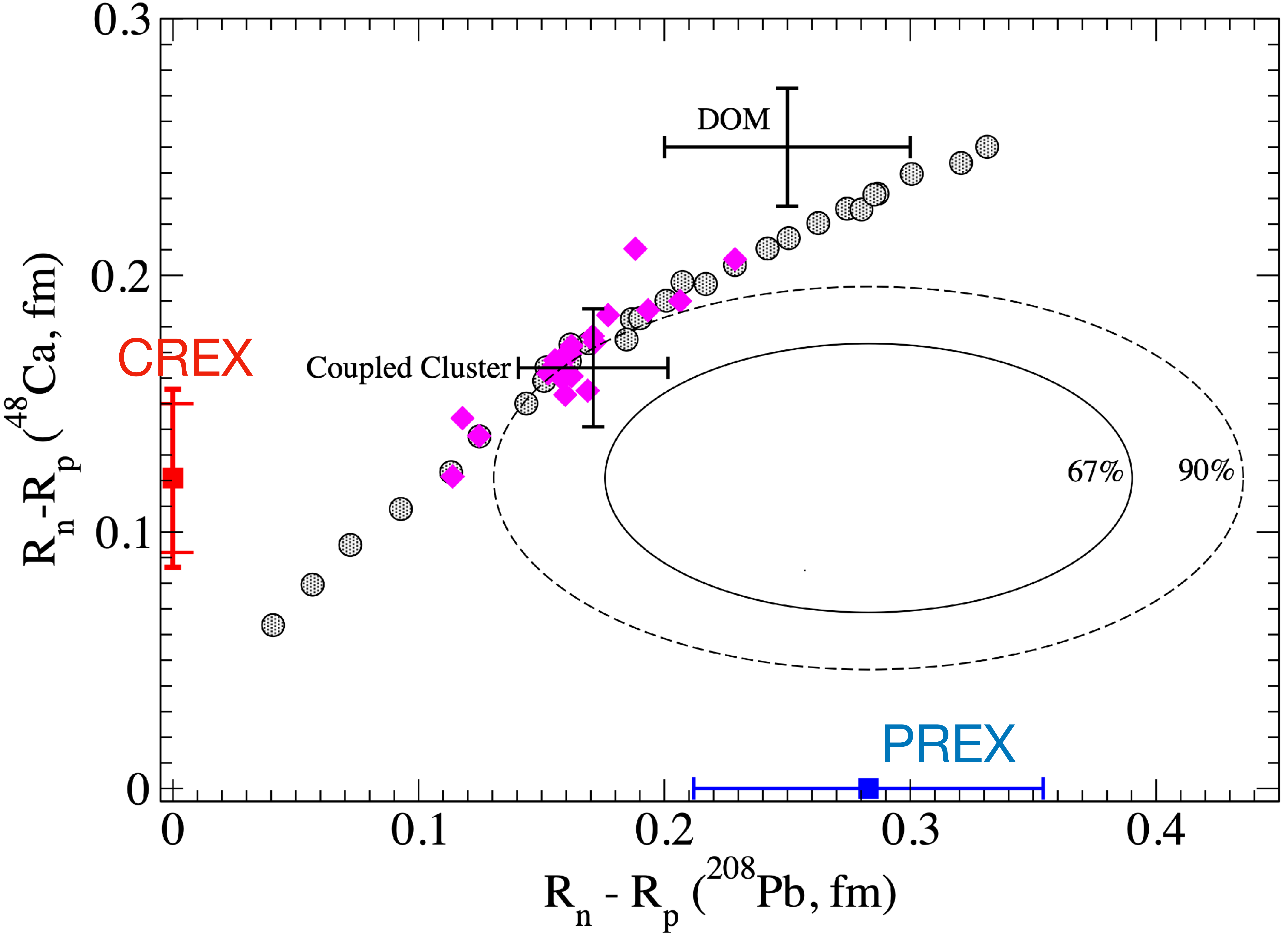
Example: giant monopole in ^{132}Sn at FRIB (PAC I)



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

- PREX $\rho_b^0 = 0.1480 +/- 0.0038\ fm^{-3}$

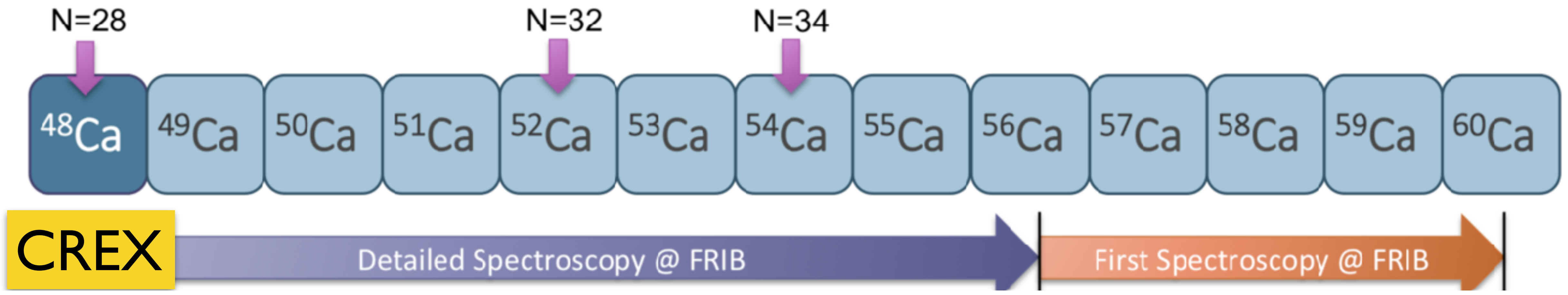


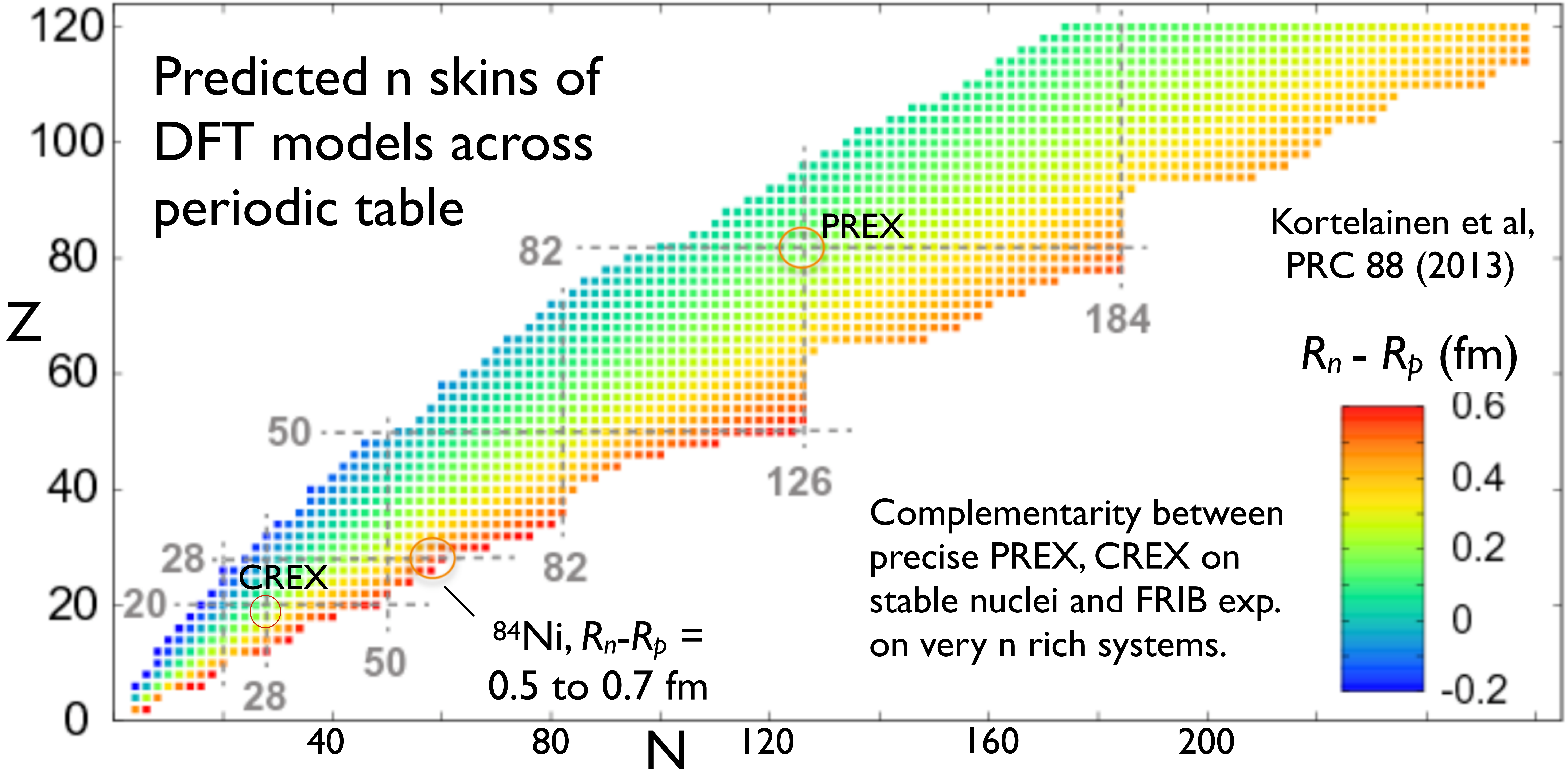


Symmetry energy describes how E rises when one goes away from N=Z. Rapid density dependence of symmetry energy (L) pushes excess n out of center into skin

Study more n rich nuclei at FRIB

- ^{40}Ca (Z=N=20) is stable. FRIB can make ^{60}Ca (N=40)





Resolve n skin with better probes or thicker skins

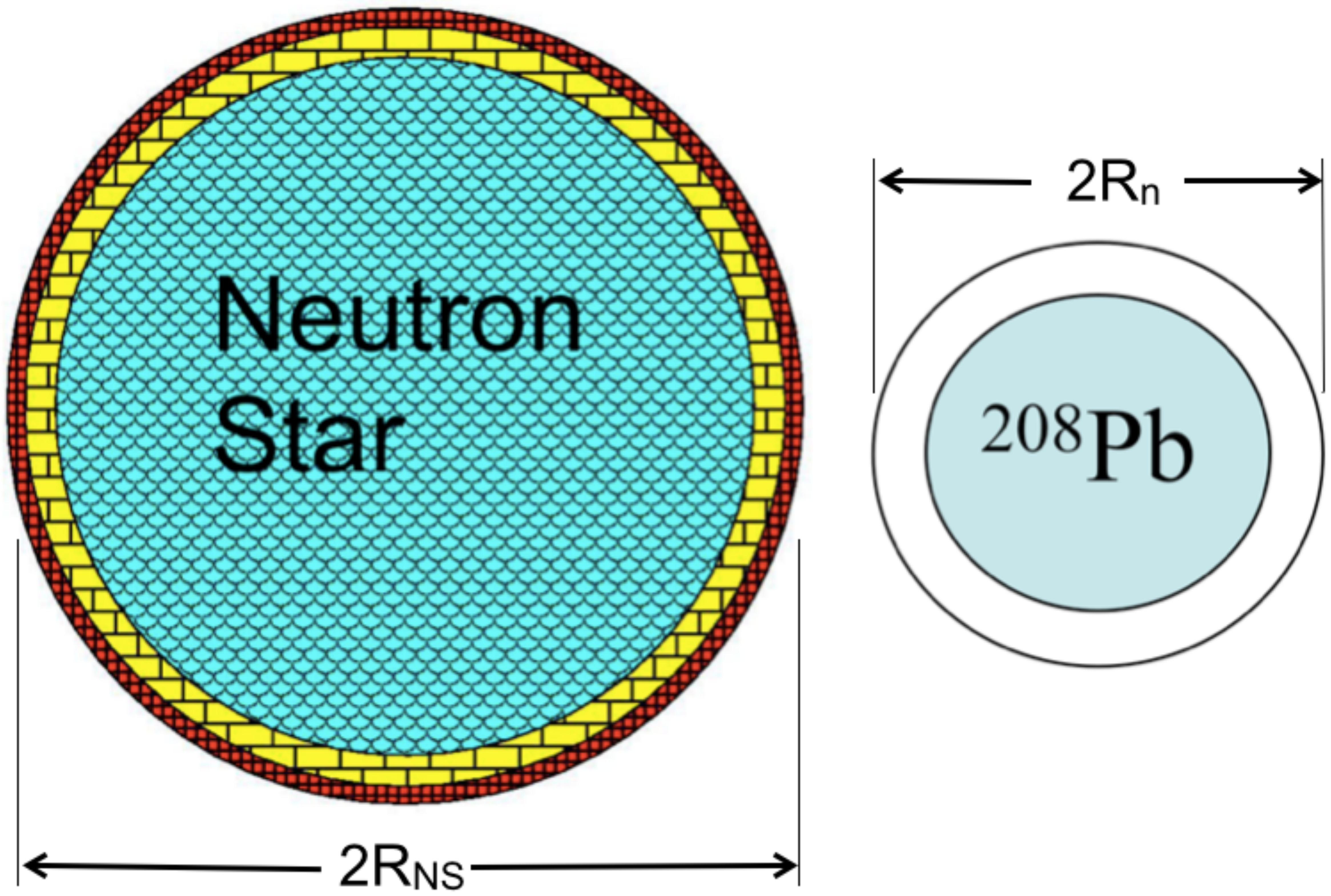
- Rxns to measure neutron or matter radii:
  - Proton elastic scattering in inverse kinematics, Alpha scattering, Charge exchange, Other rxns?
  - What beam E? What energy resolution? *What beam intensity?*
  - Theory questions— Impulse approx with what NN amplitudes? How does Chiral EFT help? Glauber at higher E??
- How n rich can we reach? Which nuclei?
- How are n rich measurements complementary to stable nuclei?

Fusion of n rich nuclei

- Fusion of n rich light to medium mass nuclei below, at, above barrier
- Pycnonuclear (density driven) fusion on neutron stars. Provides heat, changes composition of crust.
- Rate strong function of Z. Carbon burns already. Oxygen isotopes may fuse near drip line at 10^{11} g/cm^3. Thus $^{24}O+^{24}O$ may occur.
- How does large n excess impact fusion? Is there **new dynamics involving large n skins**? Pygmi osc? n-rich neck? n transfer? …?
- Fusion big cross section, can be instrumented efficiently (1000 pps)
- DeSouza et al $^{20,21,22}O$ on ^{12}C.
- How n rich can one measure? $^{22}O+^{48}Ca$? $^{54}Ca+^{48}Ca$?

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.

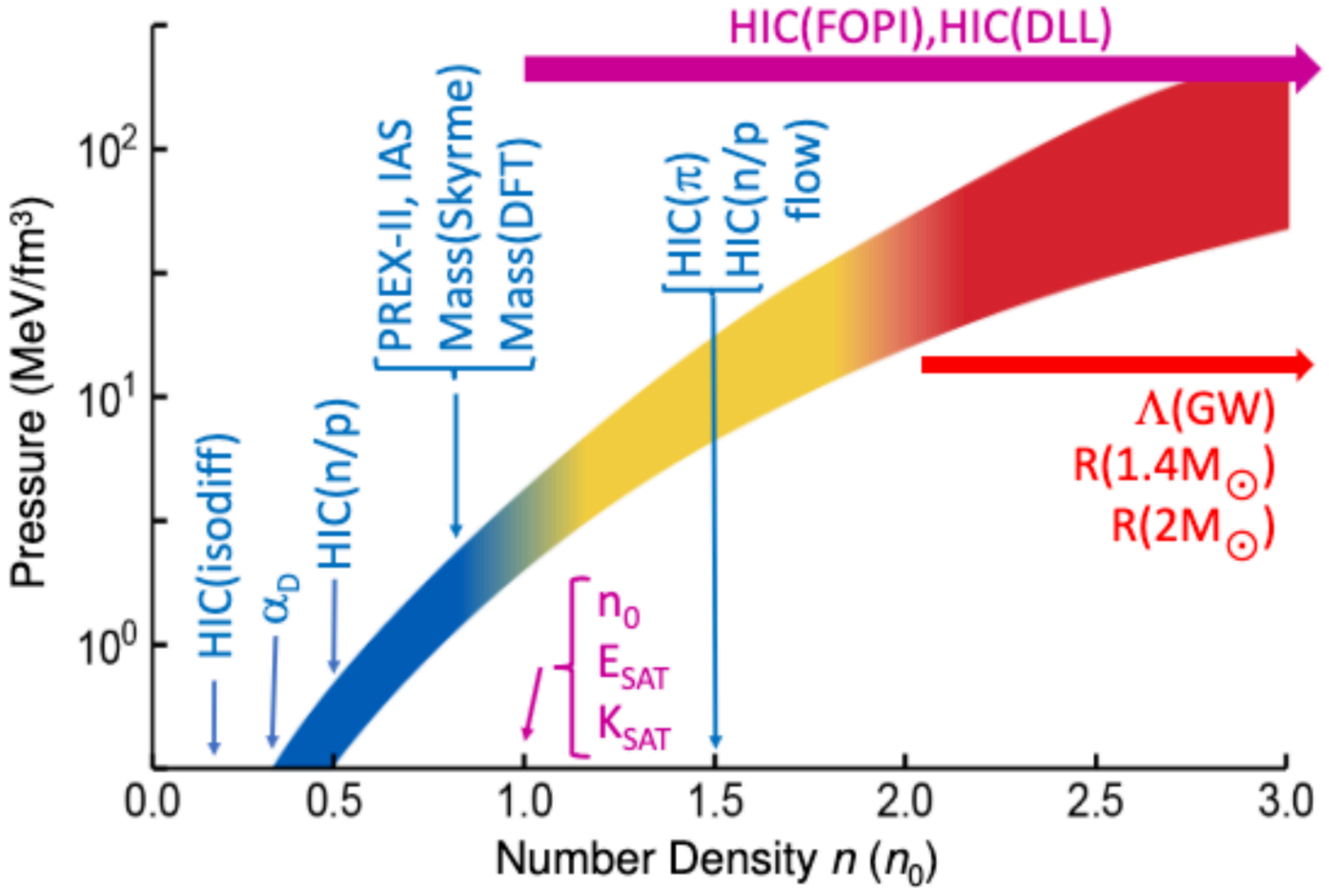
Electric **dipole polarizability** from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

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

EOS from exp. + astro. observ.

- Chun Yuen Tsang,
- ManYee Betty Tsang,
- William Lynch,
- Rohit Kumar,
- CJH



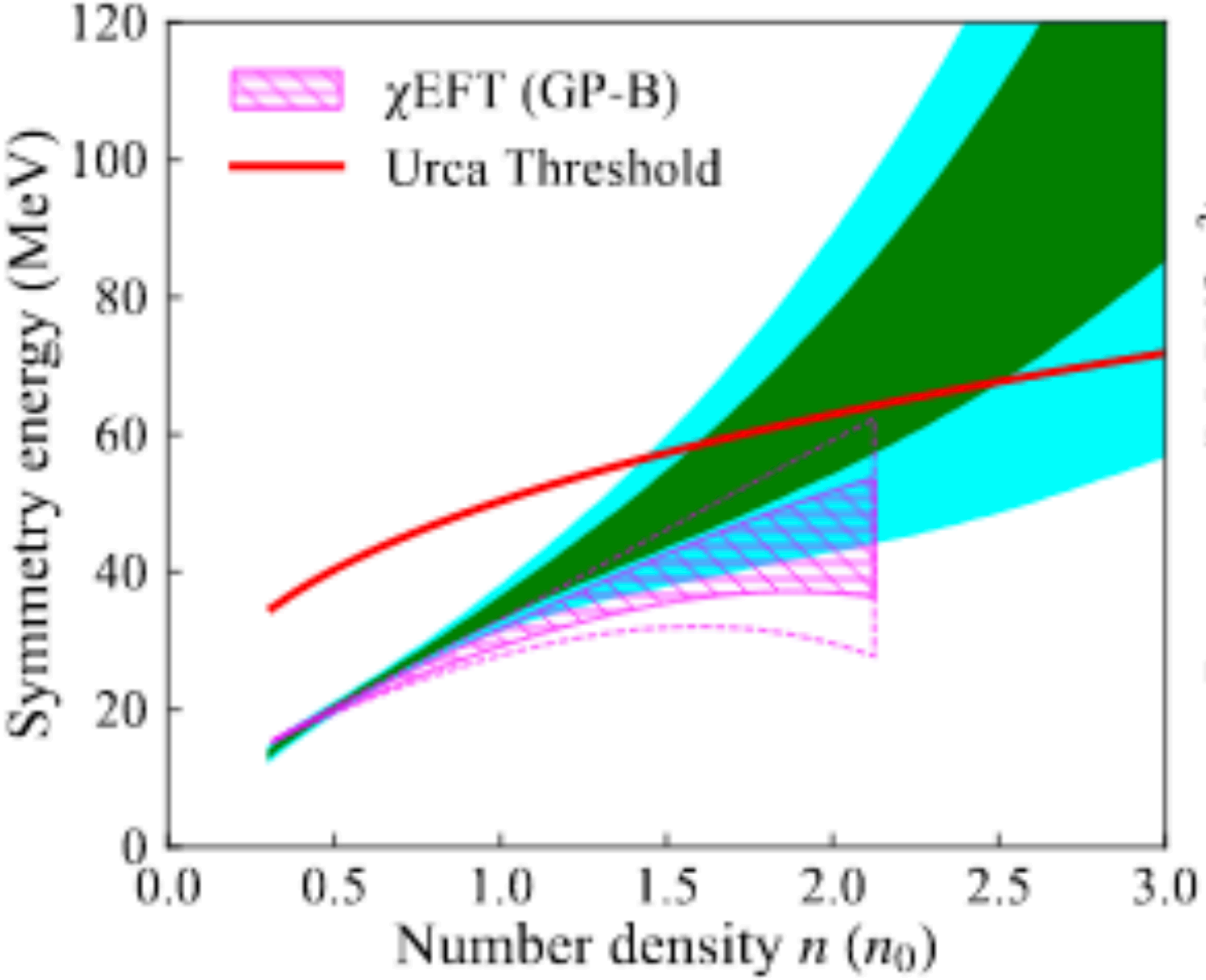
Heavy ion collisions+FRIB

- Symmetry E near $2n_0$ is lab observable most closely related to neutron star structure.
- FRIB gives HI with range of N/Z. Measure sym. E AND p of symmetric matter.
- **What are neutron stars made of?** [EOS is steam table]
- Measure S(n) and infer proton fraction in beta equilibrium.

$$[4S(n)(1-2y_p)]^3 + \left\{[4S(n)(1-2y_p)]^2 - m_\mu^2\right\}^{3/2} = 3\pi^2 n y_p$$

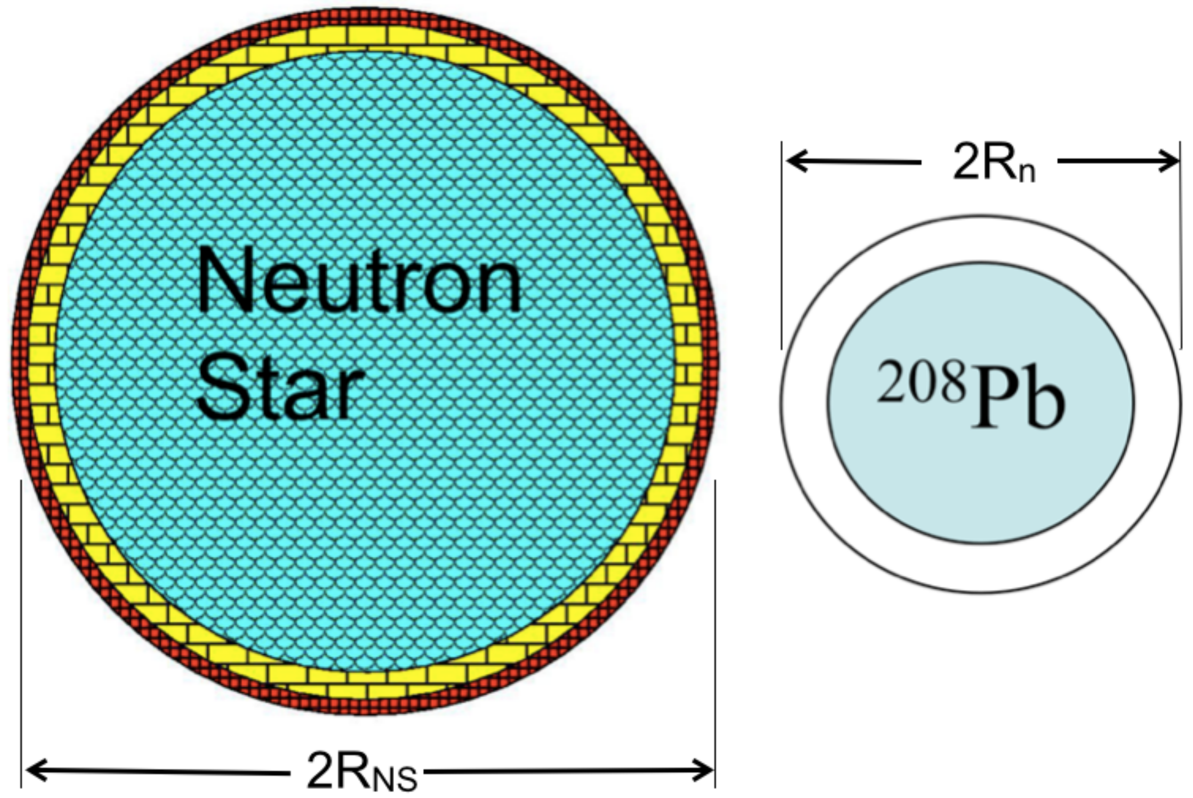
Neutron star cooling
(NS beta decay)

- If proton fraction above ~1/9 (URCA threshold) single n can beta decay and conserve momentum and E.   If so NS may cool much more quickly.
- Otherwise may need pair of nucleons to conserve E and p. Gives much slower beta decay rate.
- **Proton fraction can be inferred** from observations of pressure (or symmetry pressure) of both nuclear matter and neutron matter.



FRIB vs LIGO: neutron skins to neutron stars

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli…
- Graduate student: Brendan Reed



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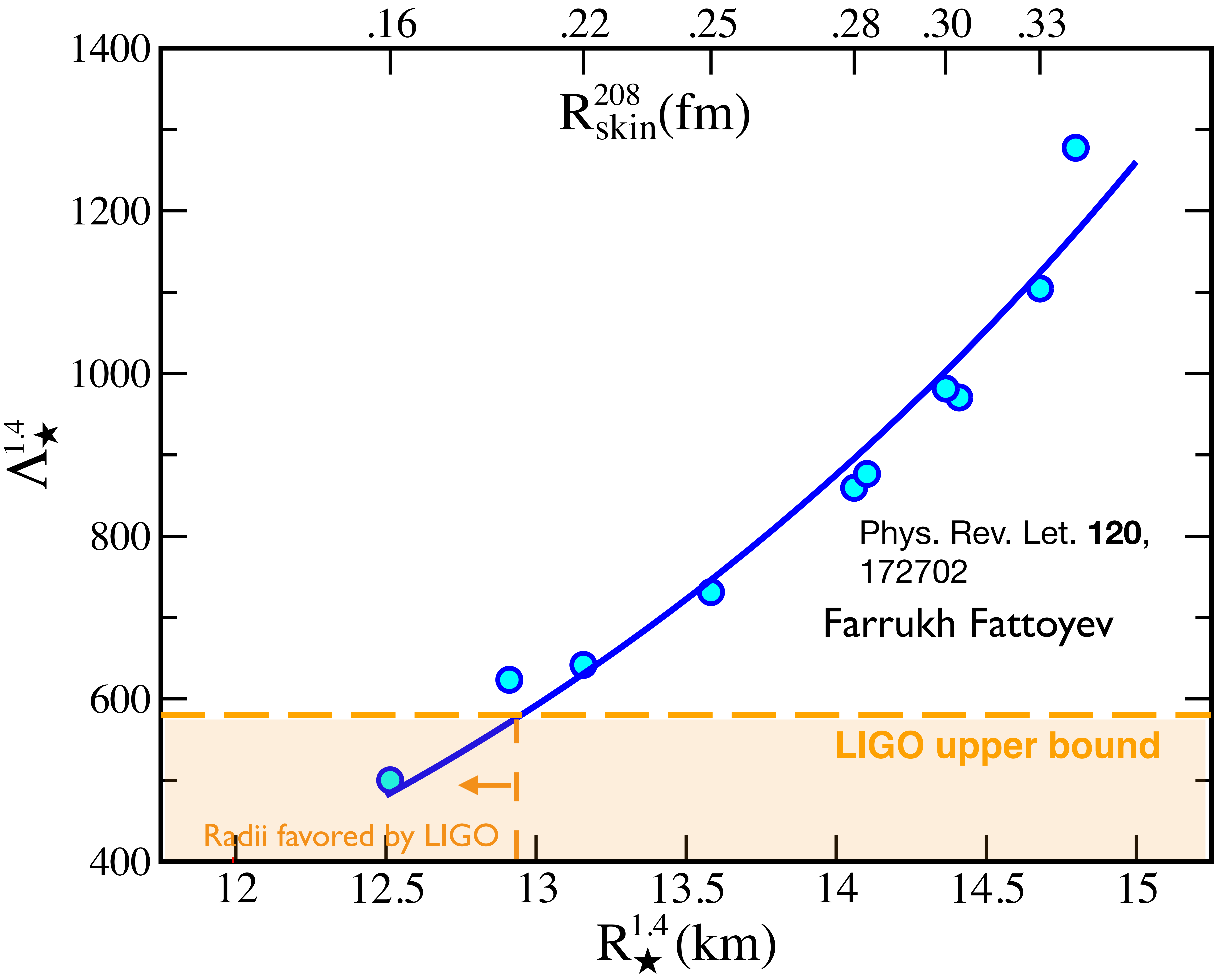
C. J. Horowitz, Indiana U., horowit@indiana.edu FRIB May 2023

Back up slides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R_{skin}^{208}(fm)
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400
$\Lambda_\star^{1.4}$
Phys. Rev. Let. **120**, 172702
Farrukh Fattoyev
LIGO upper bound
Radii favored by LIGO
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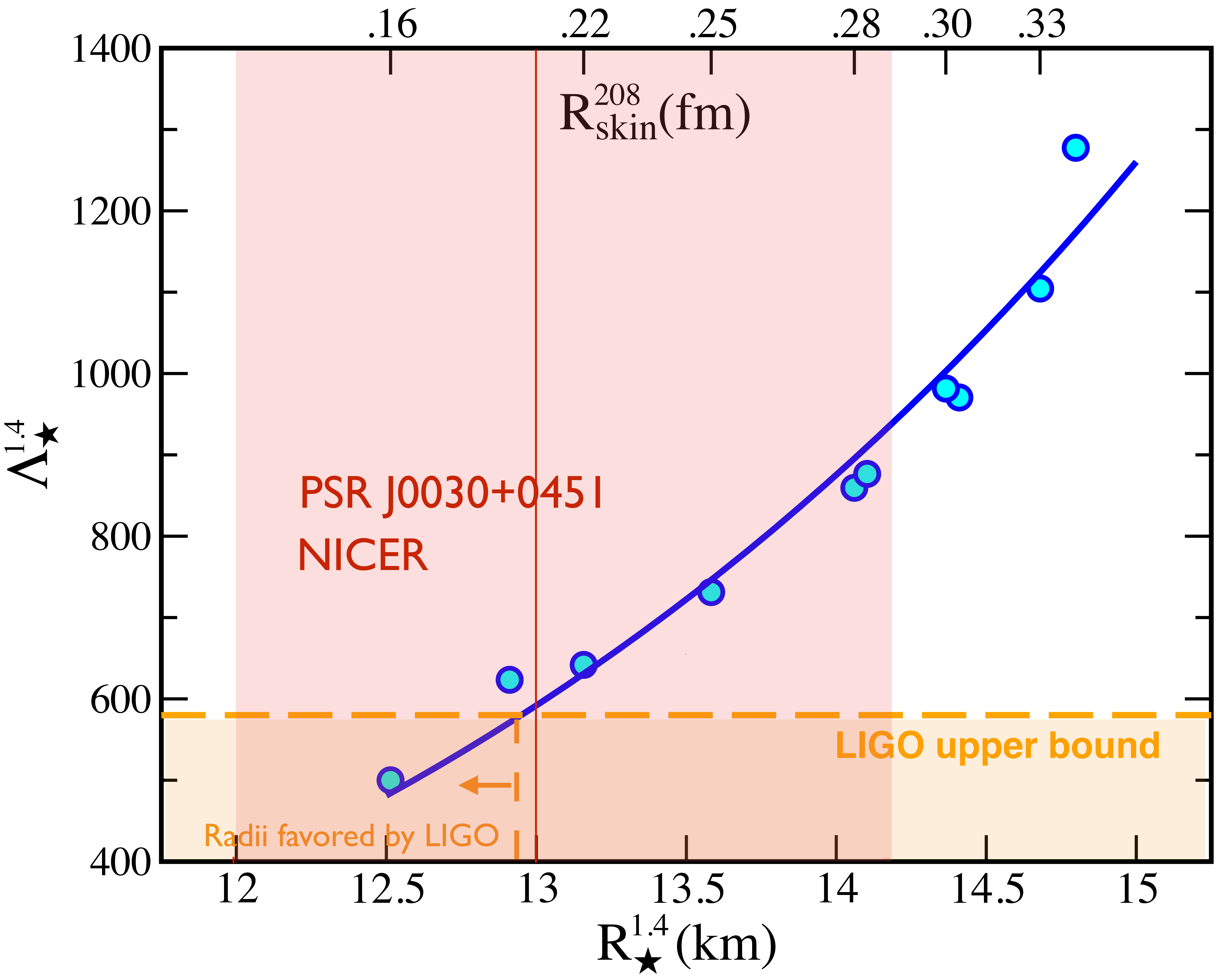
$R_\star^{1.4}$(km)



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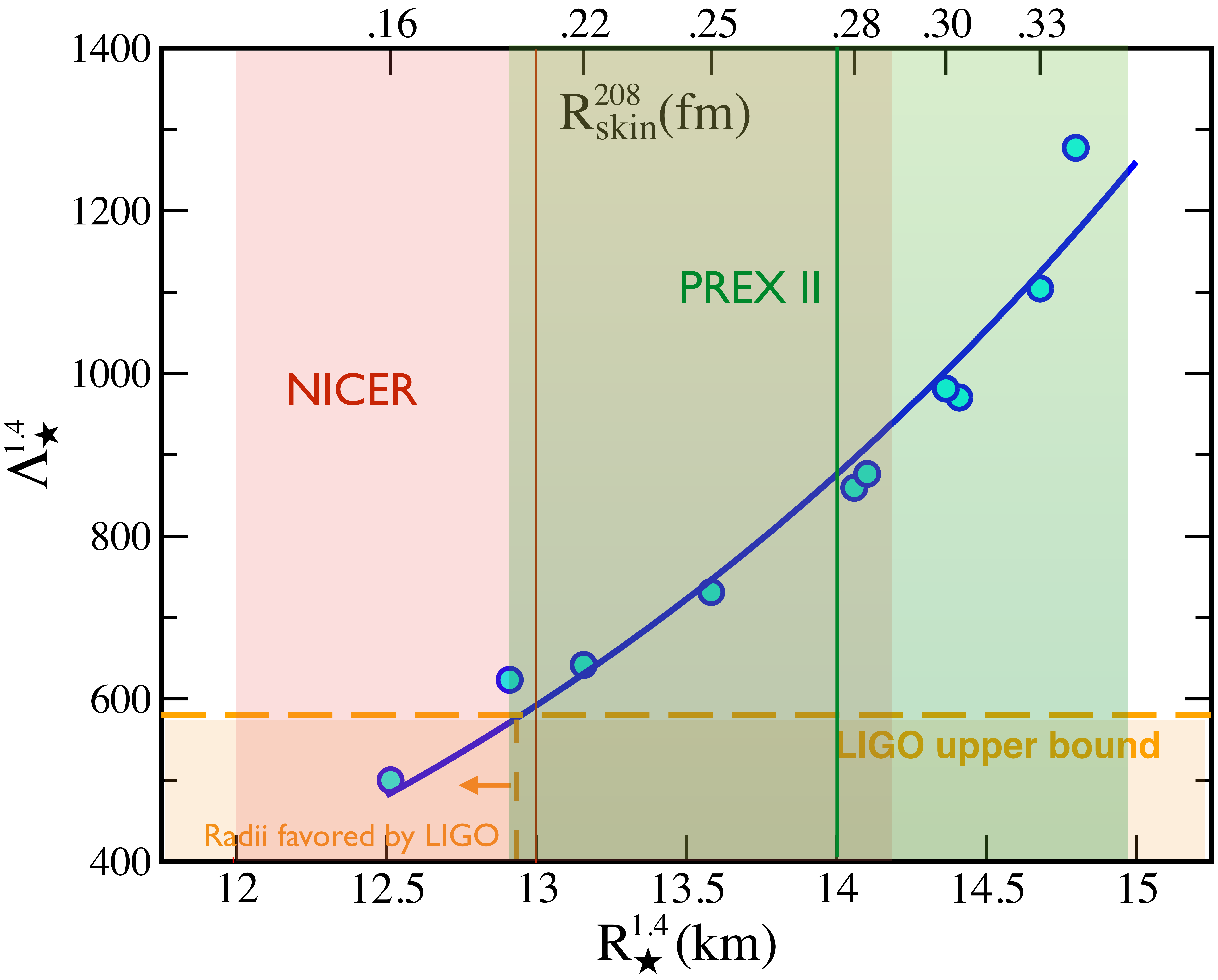
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R^{208}_{skin}(fm)
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NICER
$\Lambda^{1.4}_{\star}$
LIGO upper bound
Radii favored by LIGO
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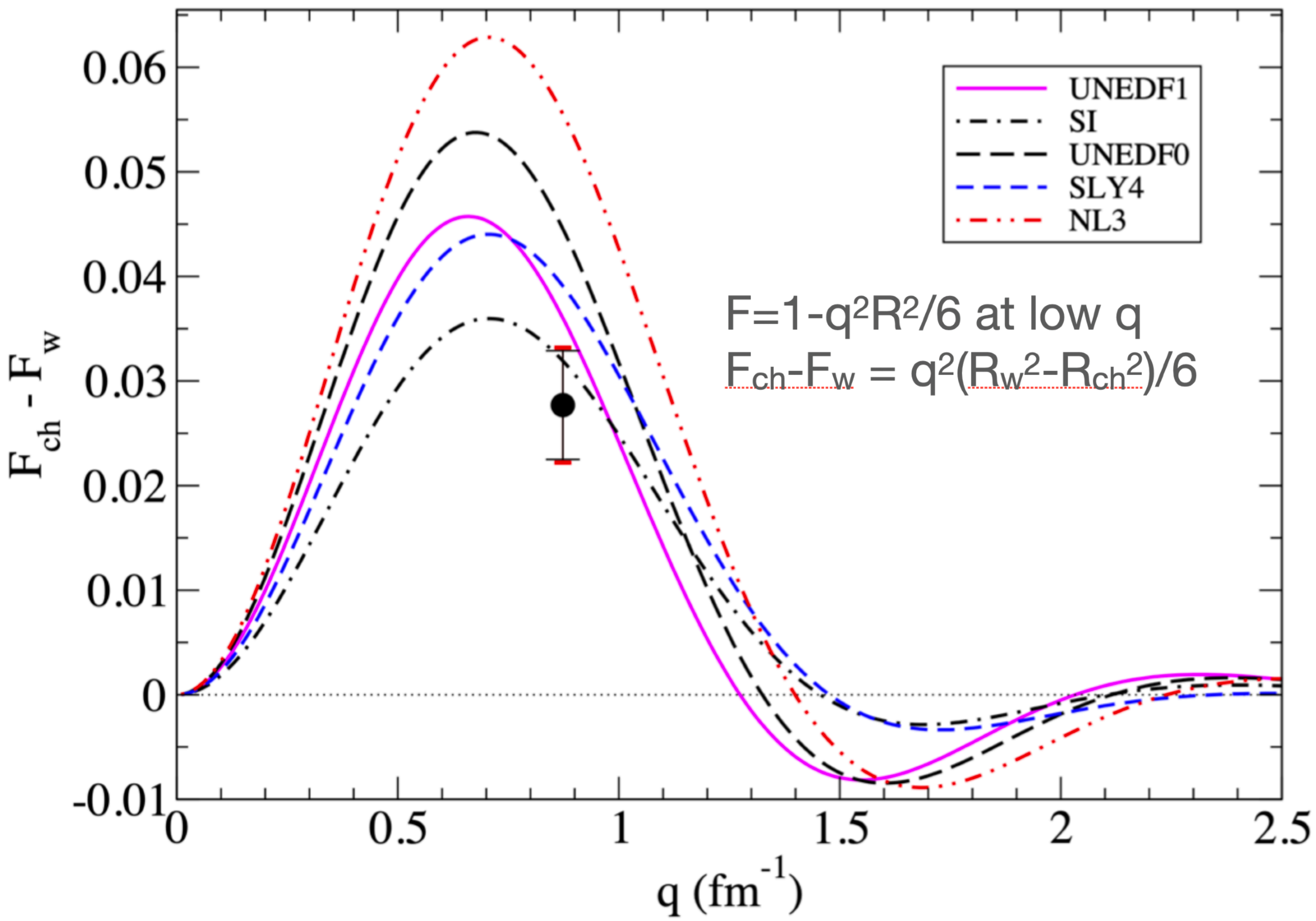
15
$R^{1.4}_{\star}$(km)

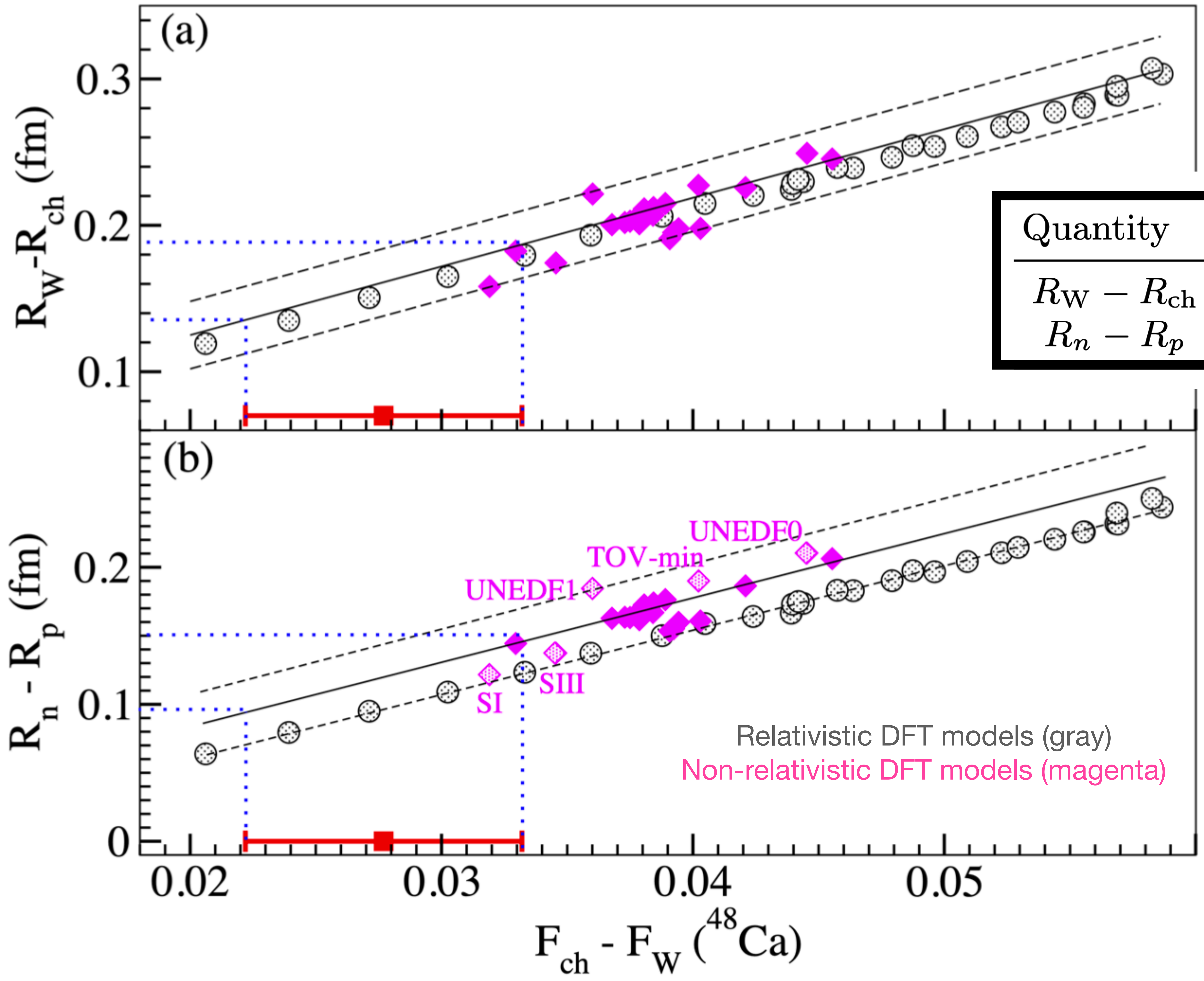
Weak Form Factor

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

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

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





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%)

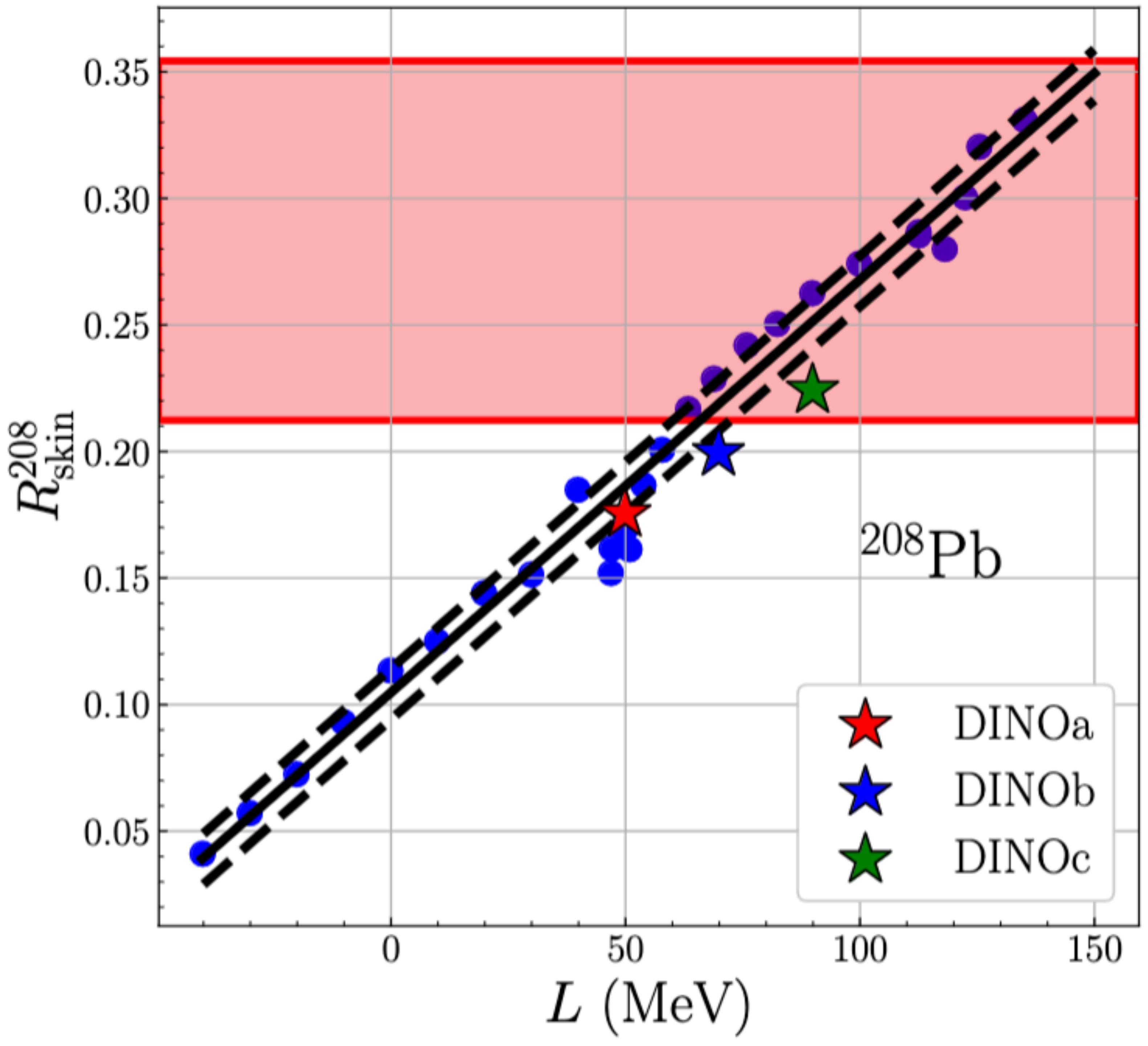
$$R_n - R_p = 0.121 \pm 0.035(\text{total})\ \text{fm}$$

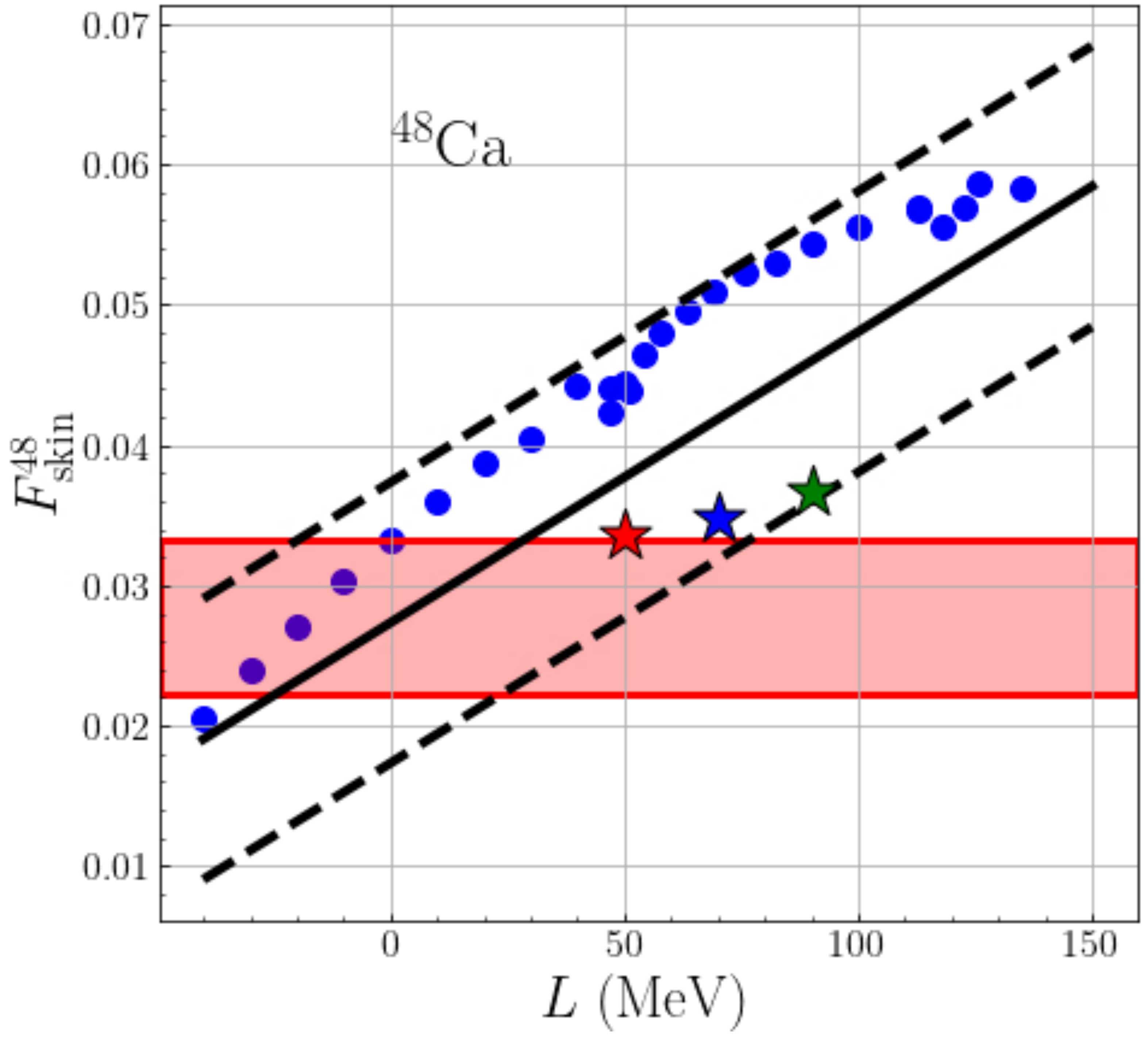
No model error in F_{ch}-F_W

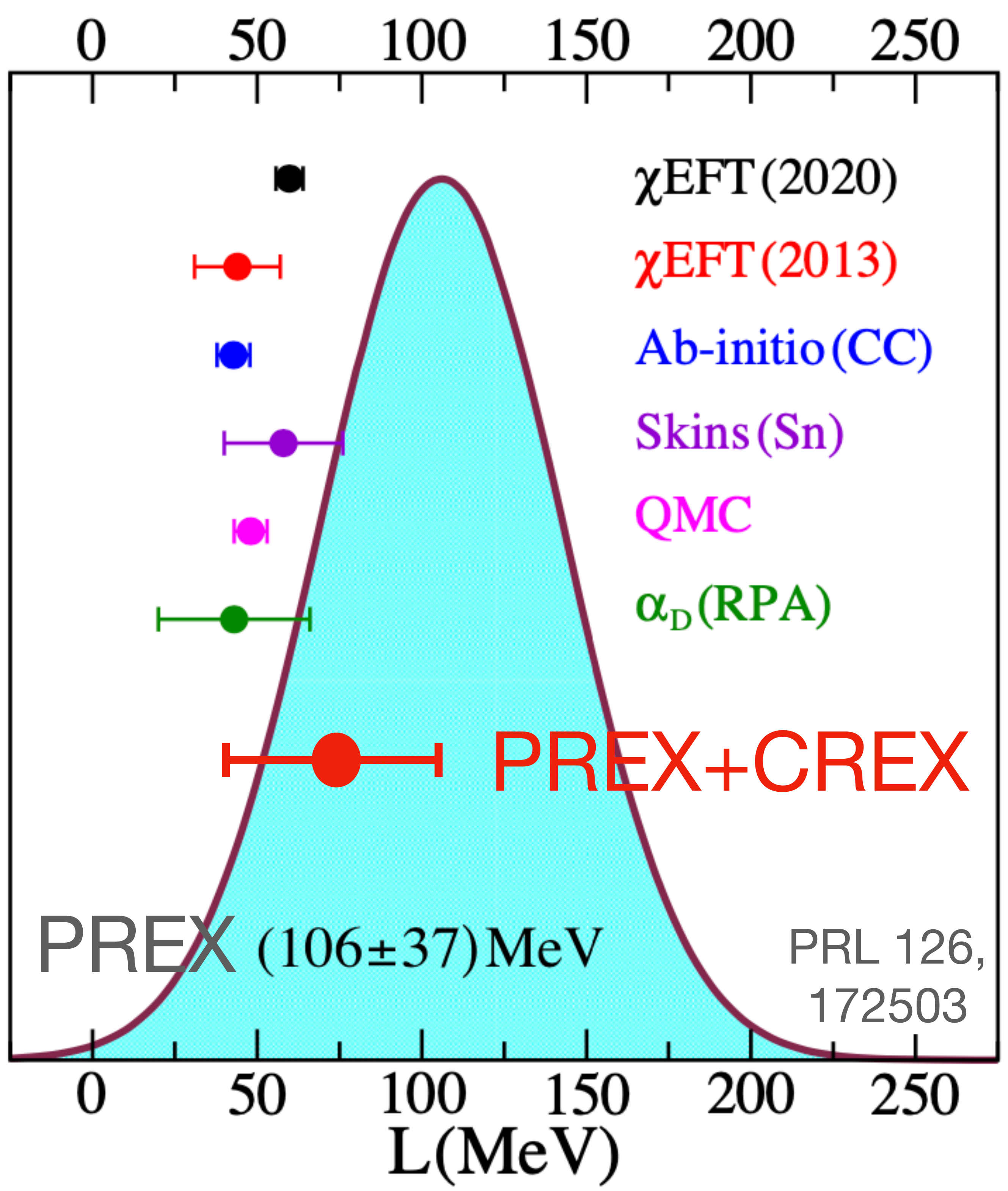
$$F_{ch}(q) - F_W(q) = 0.0277 \pm 0.0055\ (\text{exp})$$

PREX measured R_n to 1.3%

Symmetry Energy from PREX, CREX







- Symmetry energy S(n) describes how E of nuc. matter rises as one moves away from N=Z
- $L=3n_0 dS(n)/dn|_{n0}$ 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**