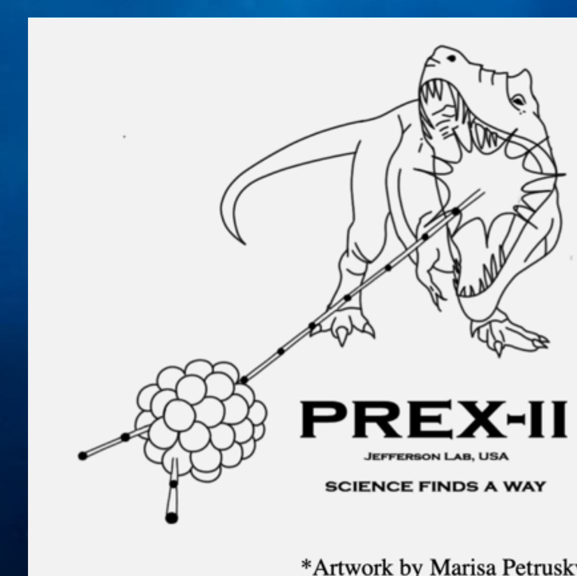
PREX/CREX experiments and neutron rich matter in the Lab



Chuck Horowitz, Indiana U.

APS GHP workshop, Apr. 2021

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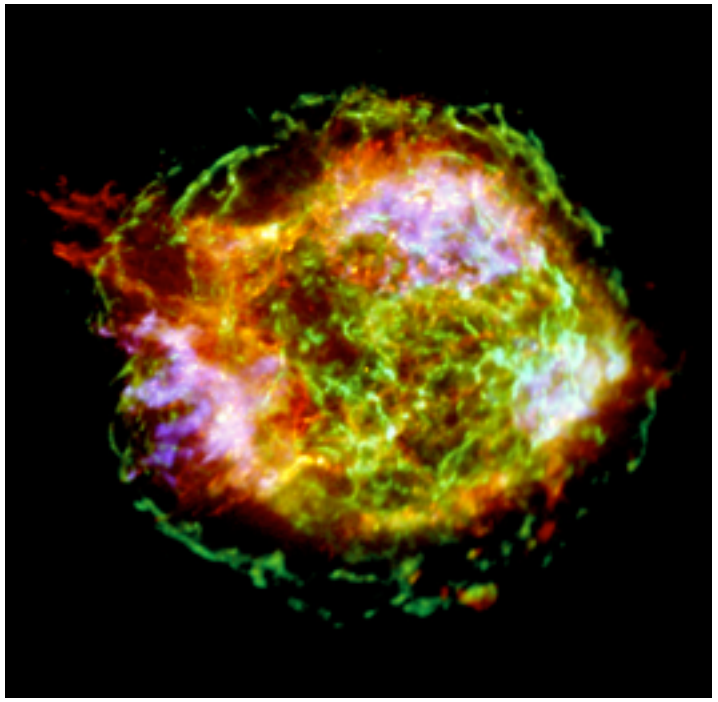
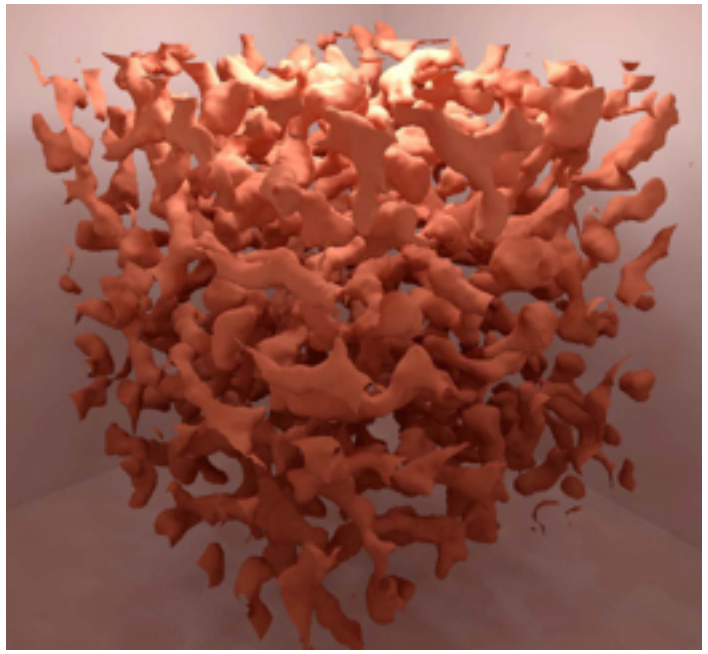
Neutron Rich Matter

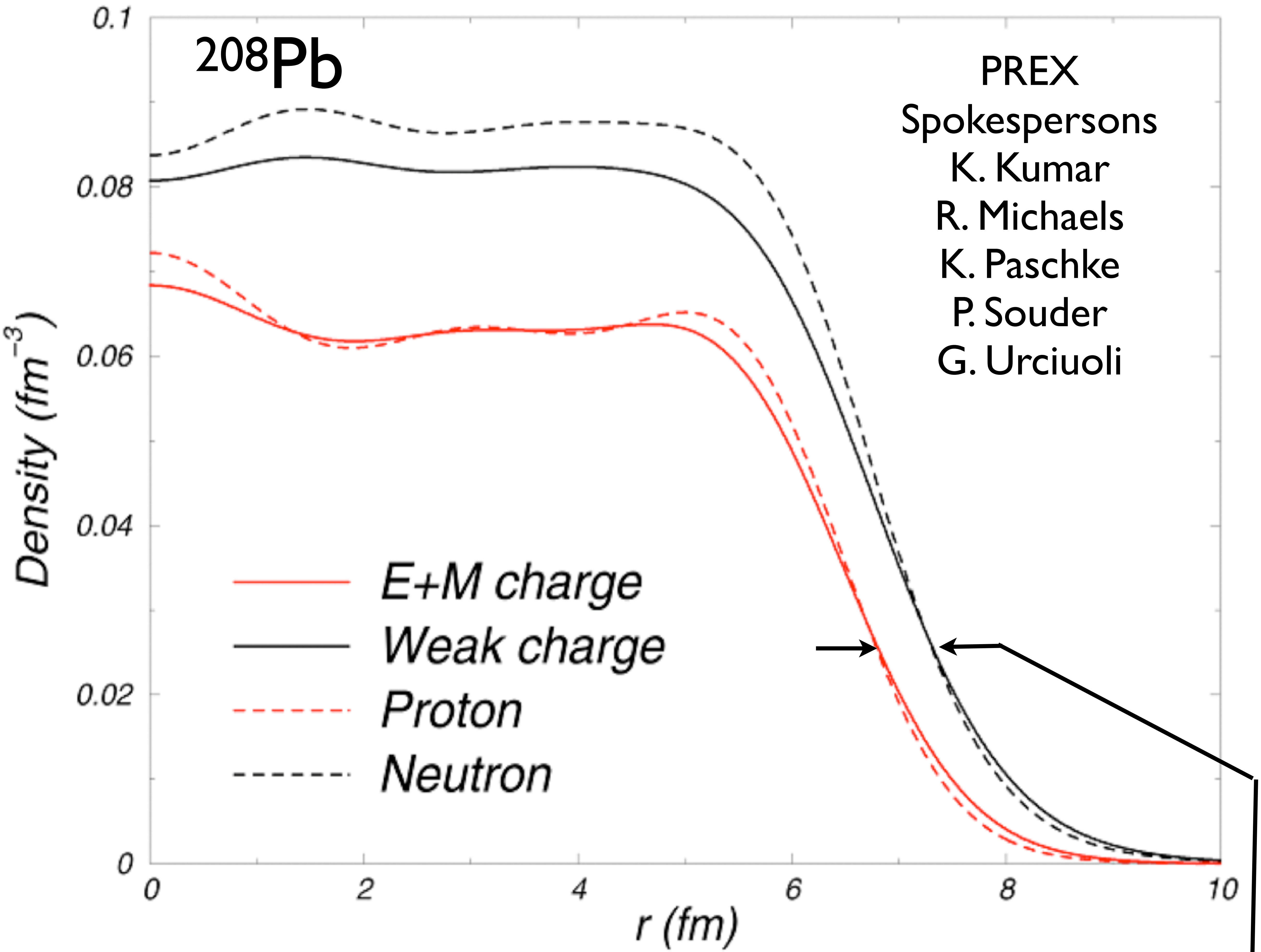
- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What 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



- 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

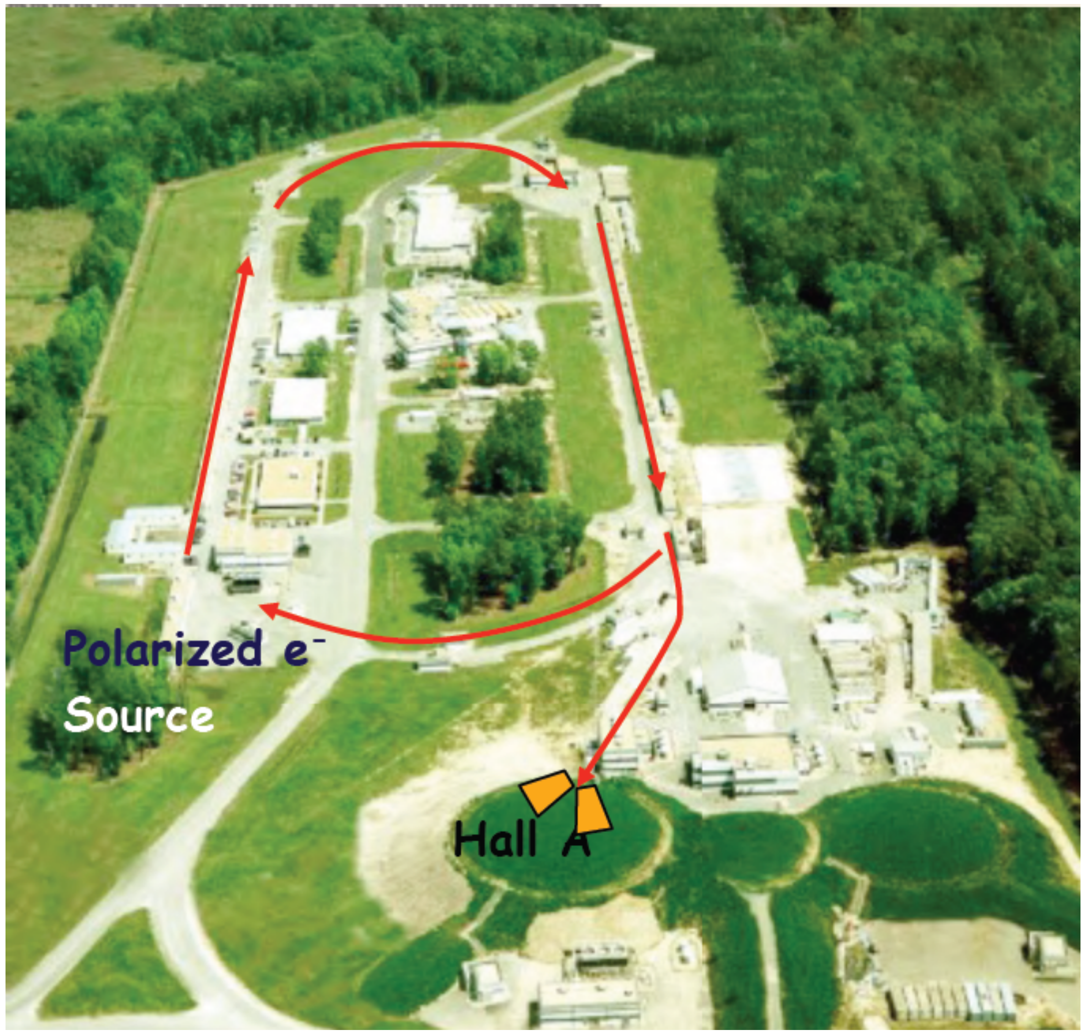
$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L - \sigma_R} \approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

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

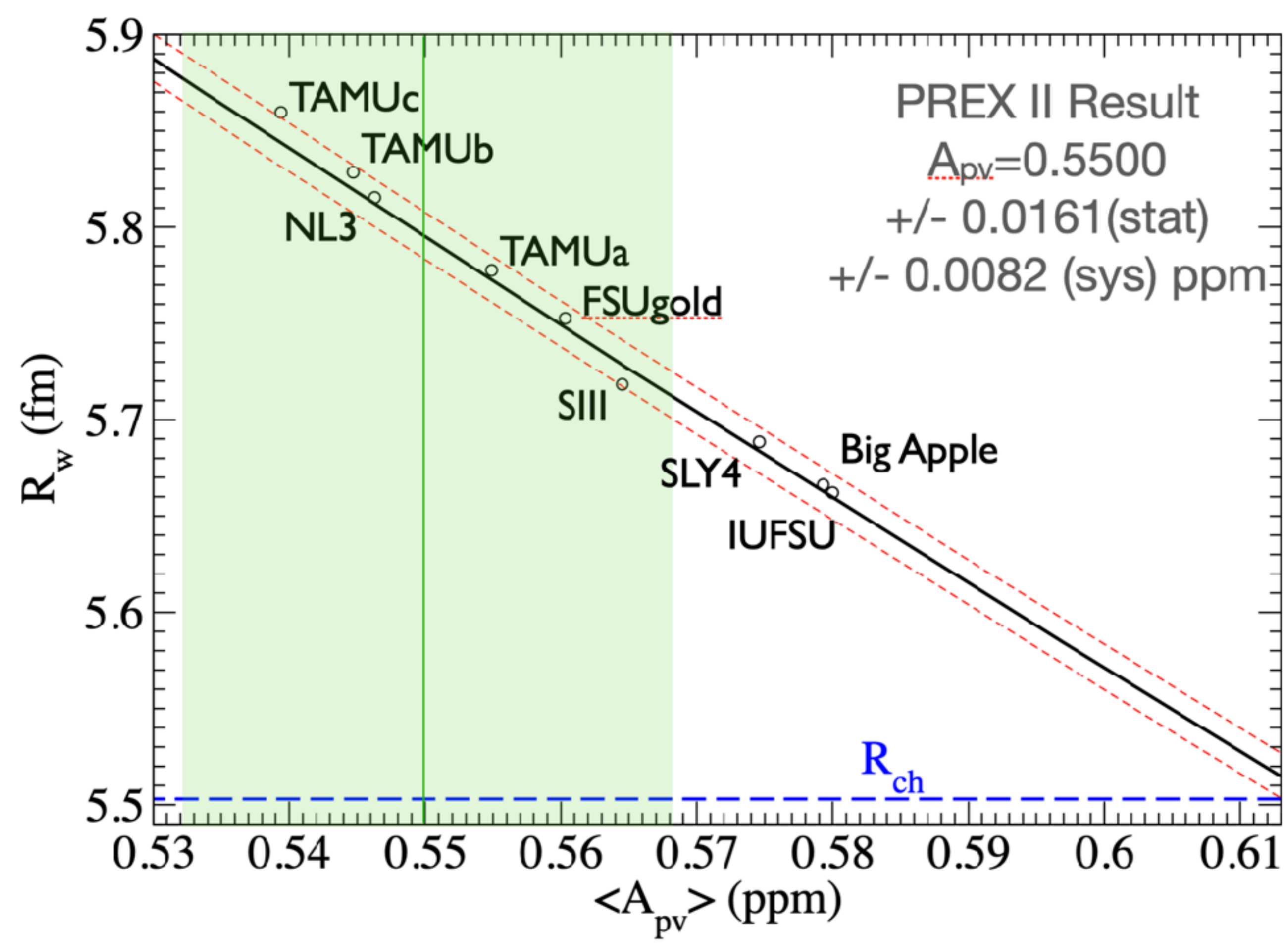
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

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

PREX in Hall A at Jefferson Lab

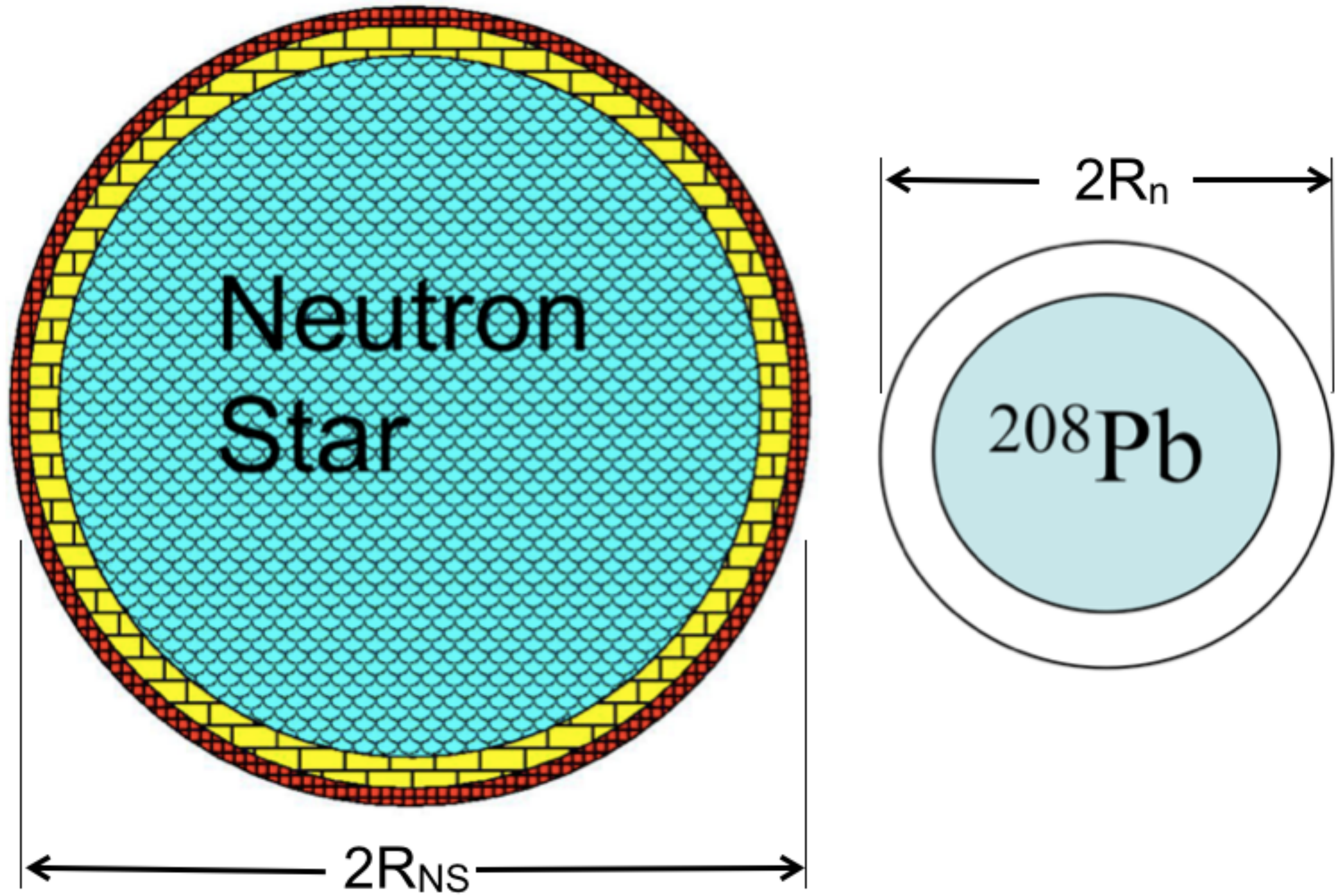


- One GeV e scattered at ~ 5 deg.
- R_W=5.795 +/- 0.082 fm
  [R_{ch}=5.503 fm]
- R_W-R_{ch}=0.292 +/- 0.082 fm
- R_n-R_p=0.278 +/- 0.078 fm



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.

LIGO and deformability of NS

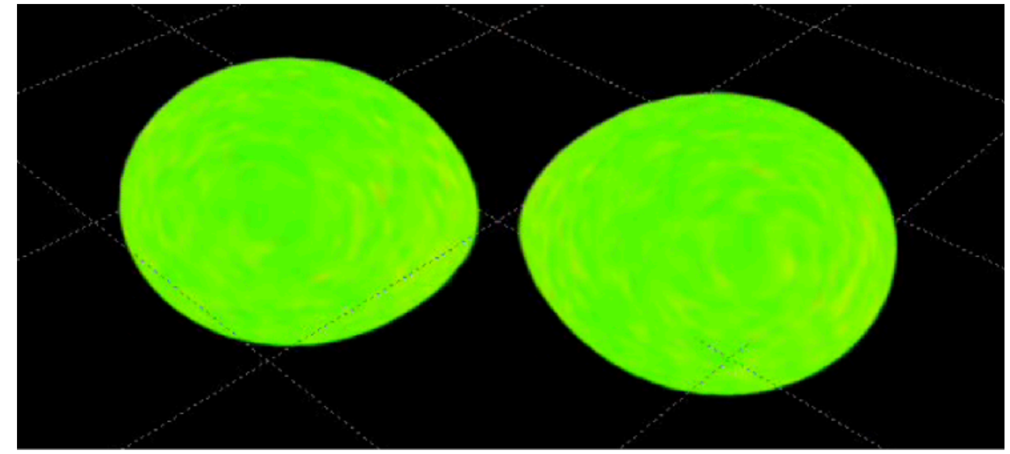
- Gravitational tidal field distorts shapes of neutron stars just before they merge.
- Dipole polarizability of an atom ~ R^3.

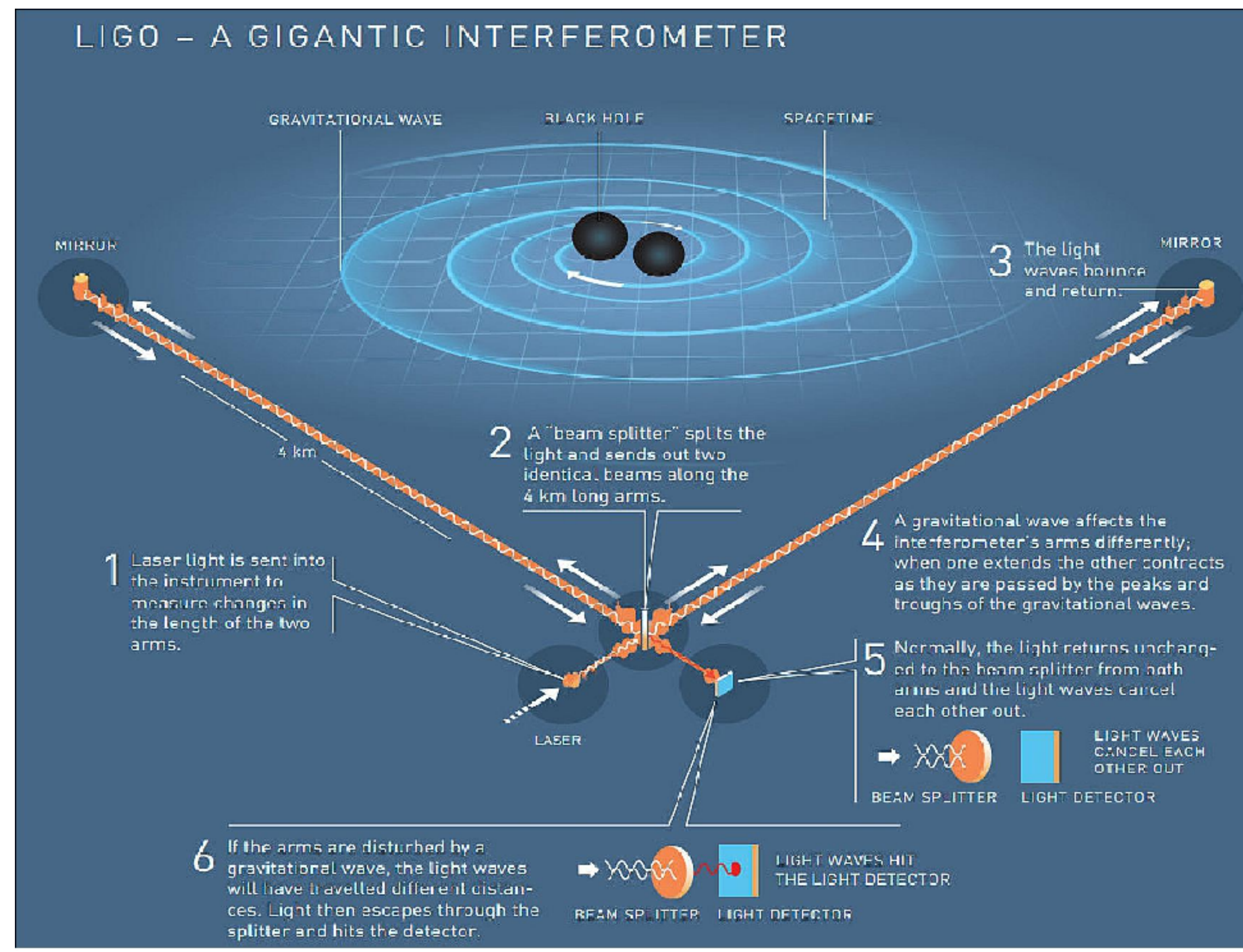
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

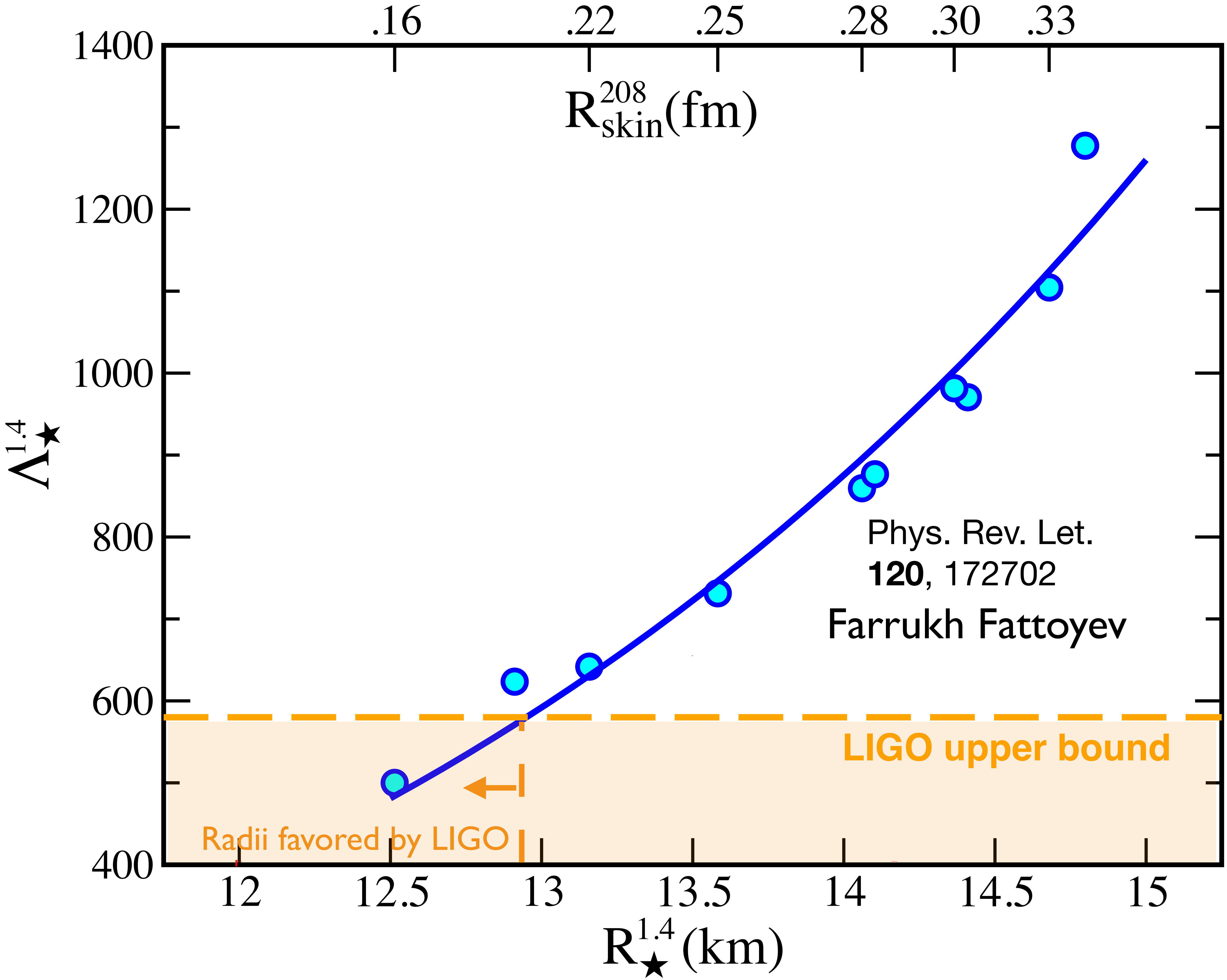
- Tidal deformability (or quadrupole polarizability) of a neutron star scales as R^5.

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

- GW170817 observations set upper limit on Λ.







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R_{skin}^{208}(fm)
1400
1200
1000
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600
400
$\Lambda_\star^{1.4}$
Phys. Rev. Let.
120, 172702
Farrukh Fattoyev
LIGO upper bound
Radii favored by LIGO
12
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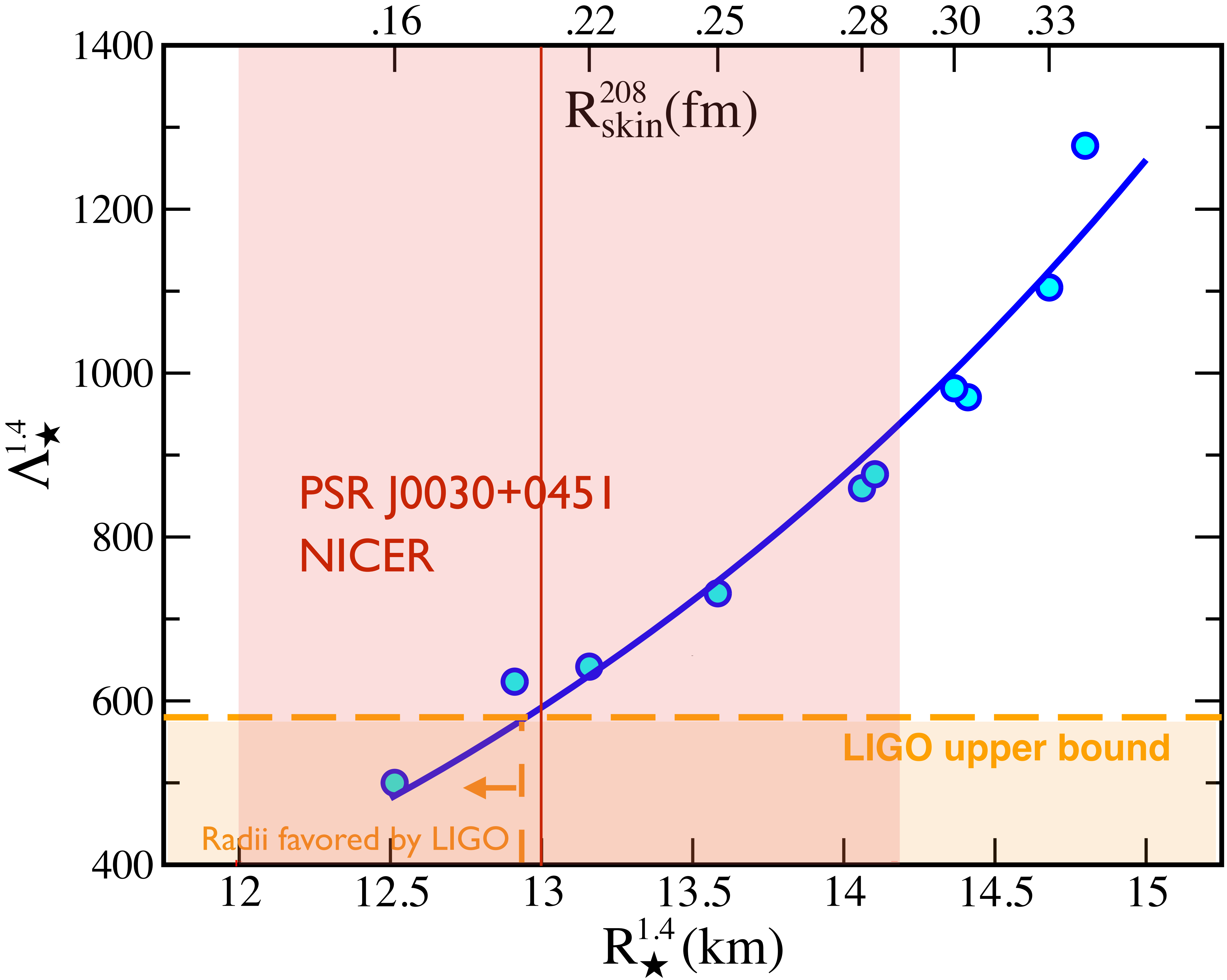
$R_\star^{1.4}$(km)



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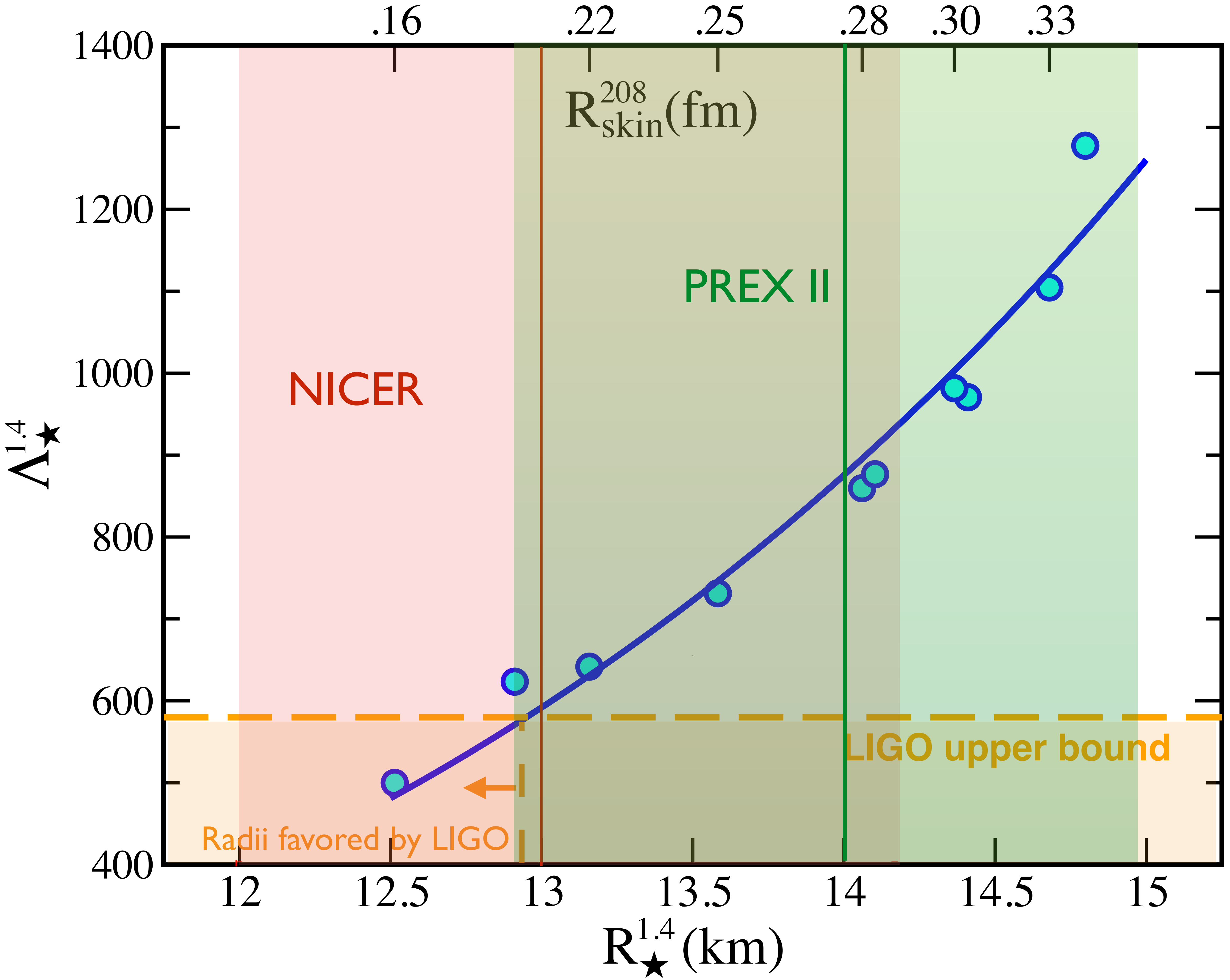
$R_\star^{1.4}$(km)



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$R_{\rm skin}^{208}$(fm)
PREX II
NICER
LIGO upper bound
Radii favored by LIGO
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$\Lambda_\star^{1.4}$
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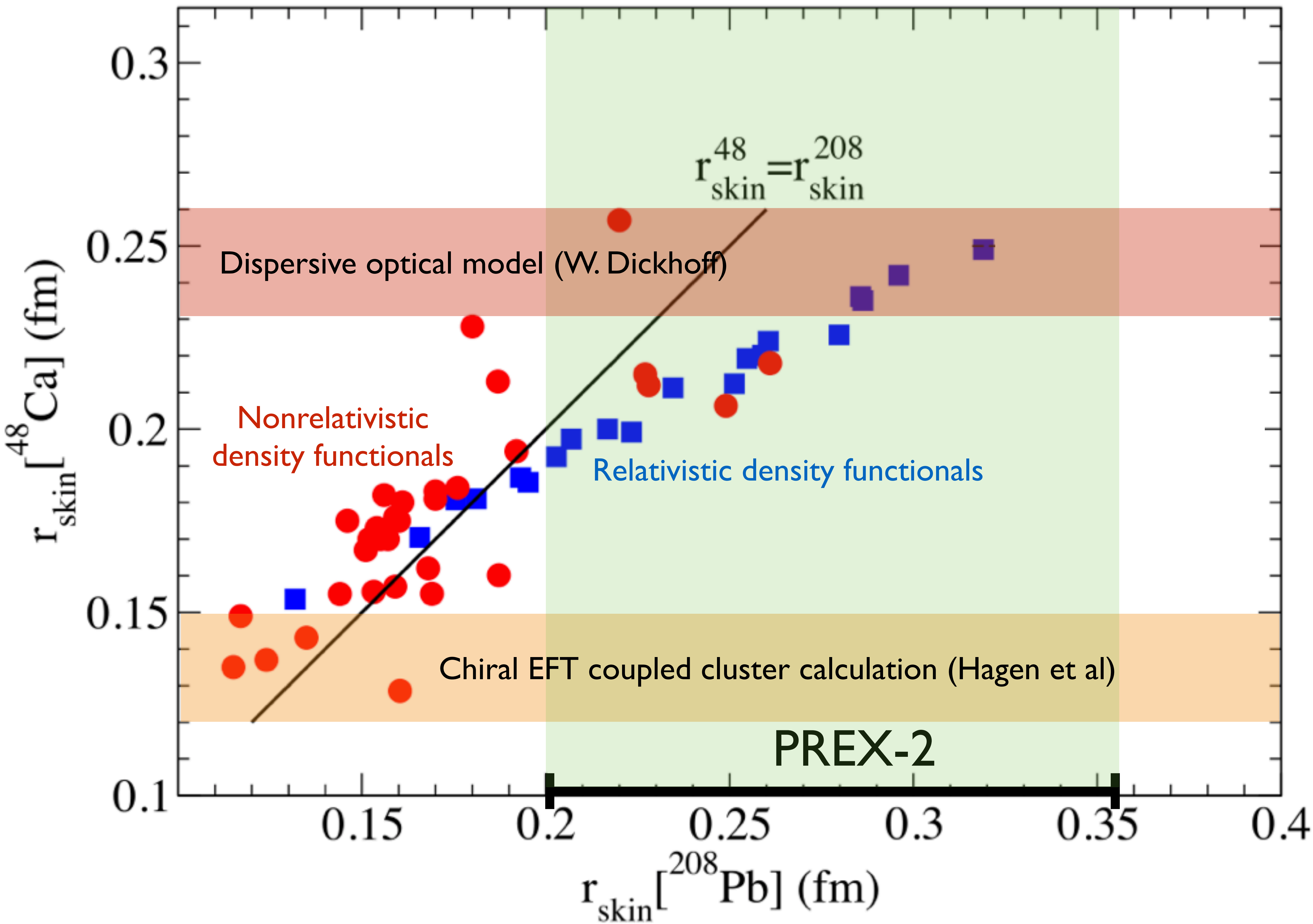
$R_\star^{1.4}$(km)

CREX and Chiral EFT

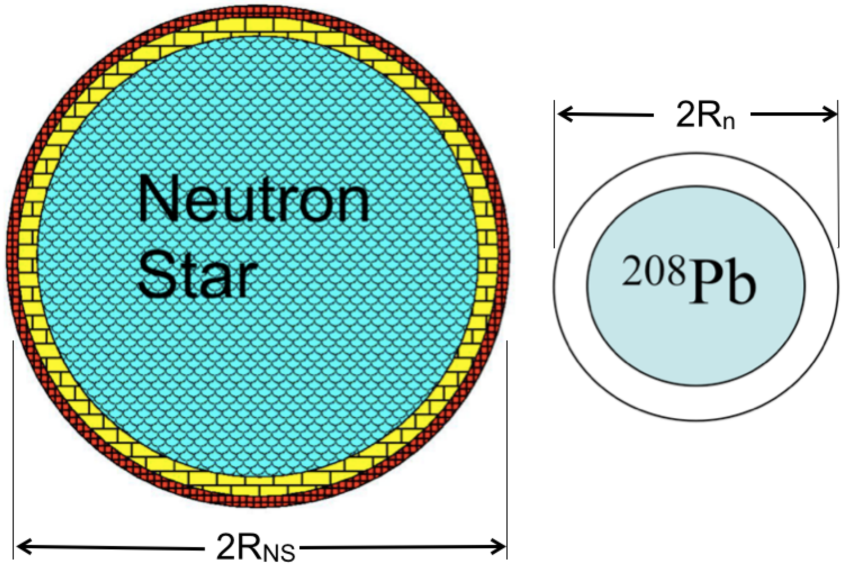
- Chiral EFT expands 2, 3, … nucleon interactions in powers of momentum transfer over chiral scale.
- **Three neutron forces** are hard to directly observe. They increase the pressure of neutron matter and the neutron skin thickness of both ^{208}Pb and ^{48}Ca.
- Only stable, neutron rich, closed shell 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. Data taking complete. Analysis underway.



$r^{48}_{skin}=r^{208}_{skin}$
Dispersive optical model (W. Dickhoff)
Nonrelativistic density functionals
Relativistic density functionals
Chiral EFT coupled cluster calculation (Hagen et al)
PREX-2
$r_{skin}[^{48}Ca]$ (fm)
$r_{skin}[^{208}Pb]$ (fm)
0.1
0.15
0.2
0.25
0.3
0.35
0.4

PREX/CREX experiments and neutron rich matter in the Lab

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli…
- NS deformability vs ^{208}Pb skin: **Farrukh Fattoyev**, Jorge Piekarewicz
- Graduate students: **Brendan Reed**, Zidu Lin (2018), Jianchun Yin, Matt Caplan (2017)…



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