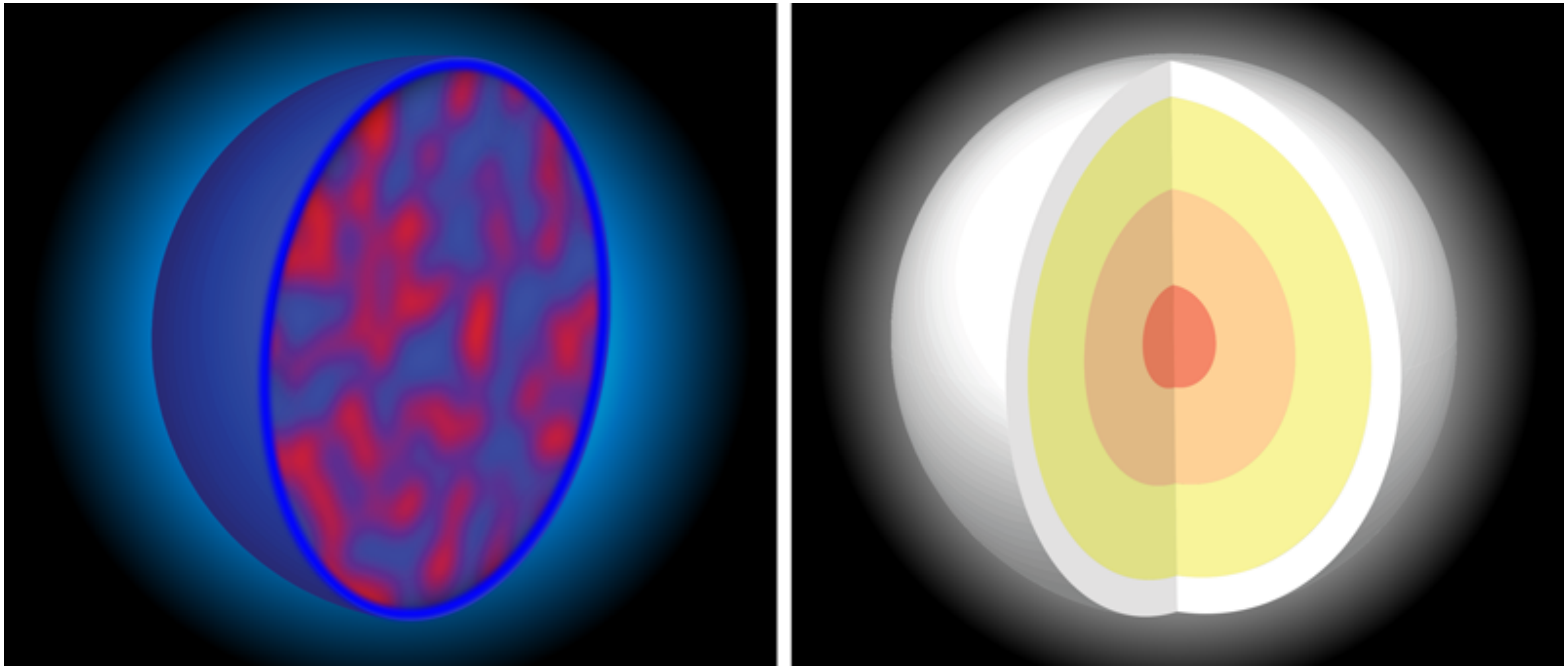
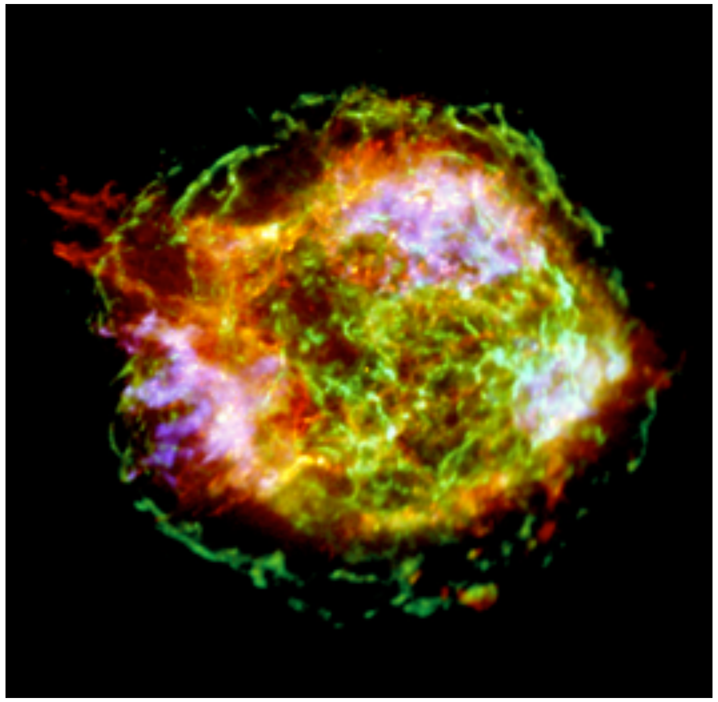


PREX-2 experiment and neutron rich matter in the laboratory

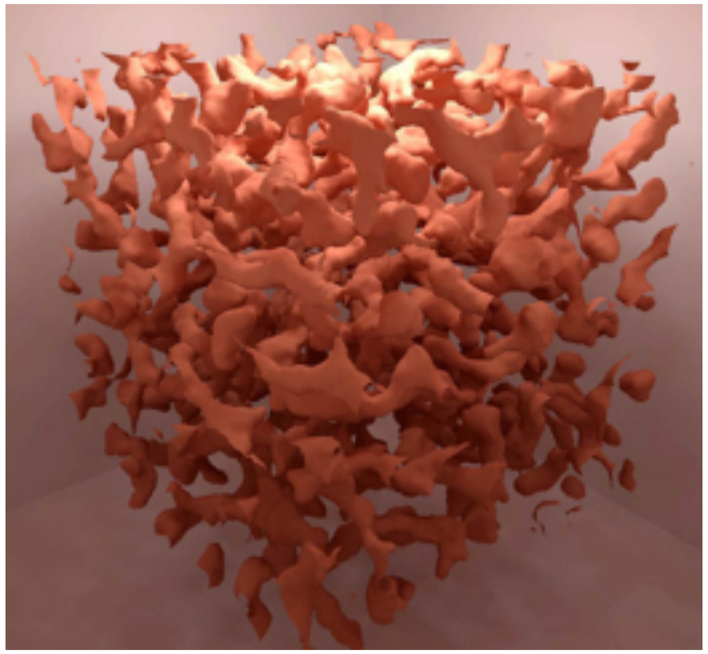
Chuck Horowitz, Indiana University, NS as multi-messenger labs for dense matter, ECT*, June 2021

Neutron Rich Matter

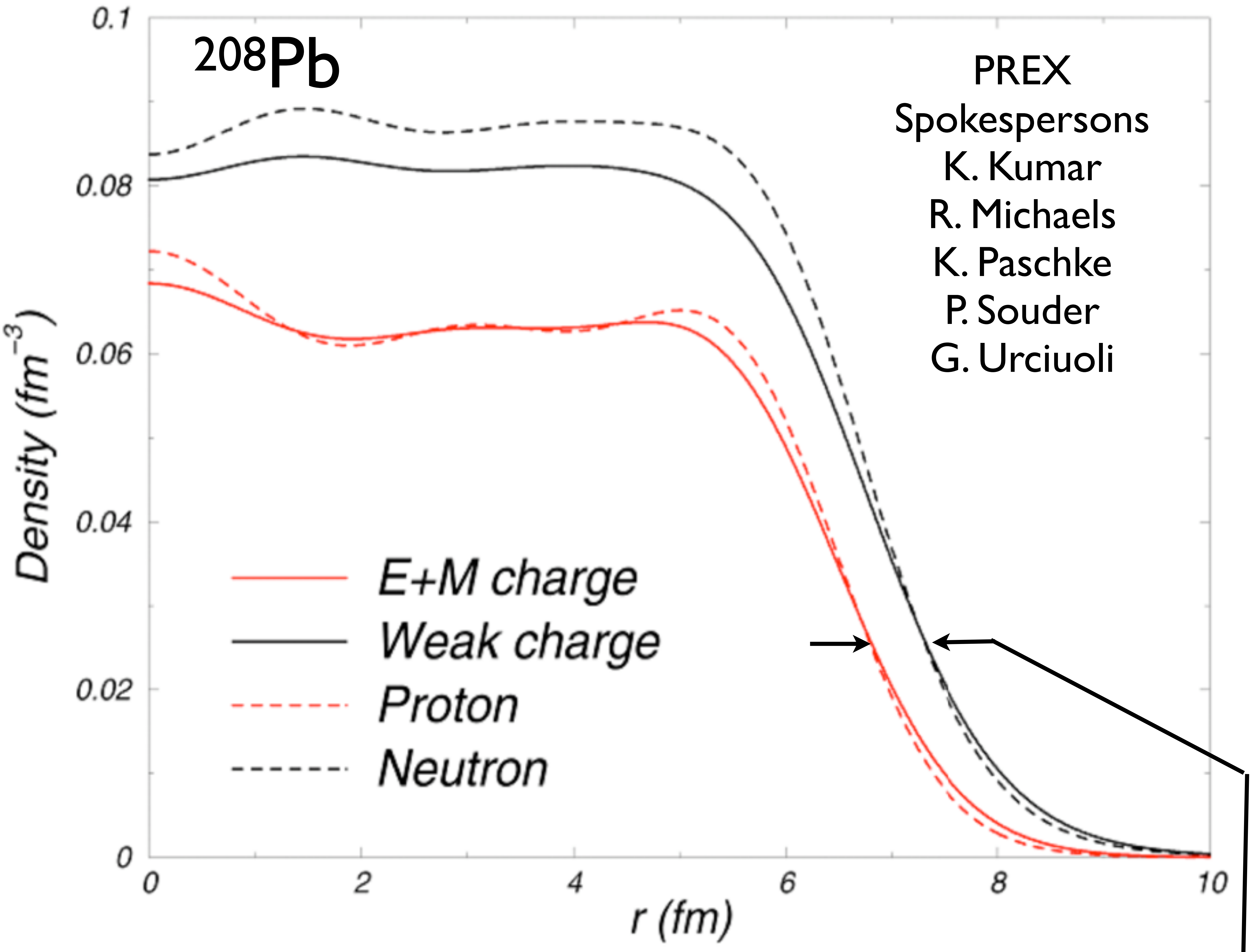
- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What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

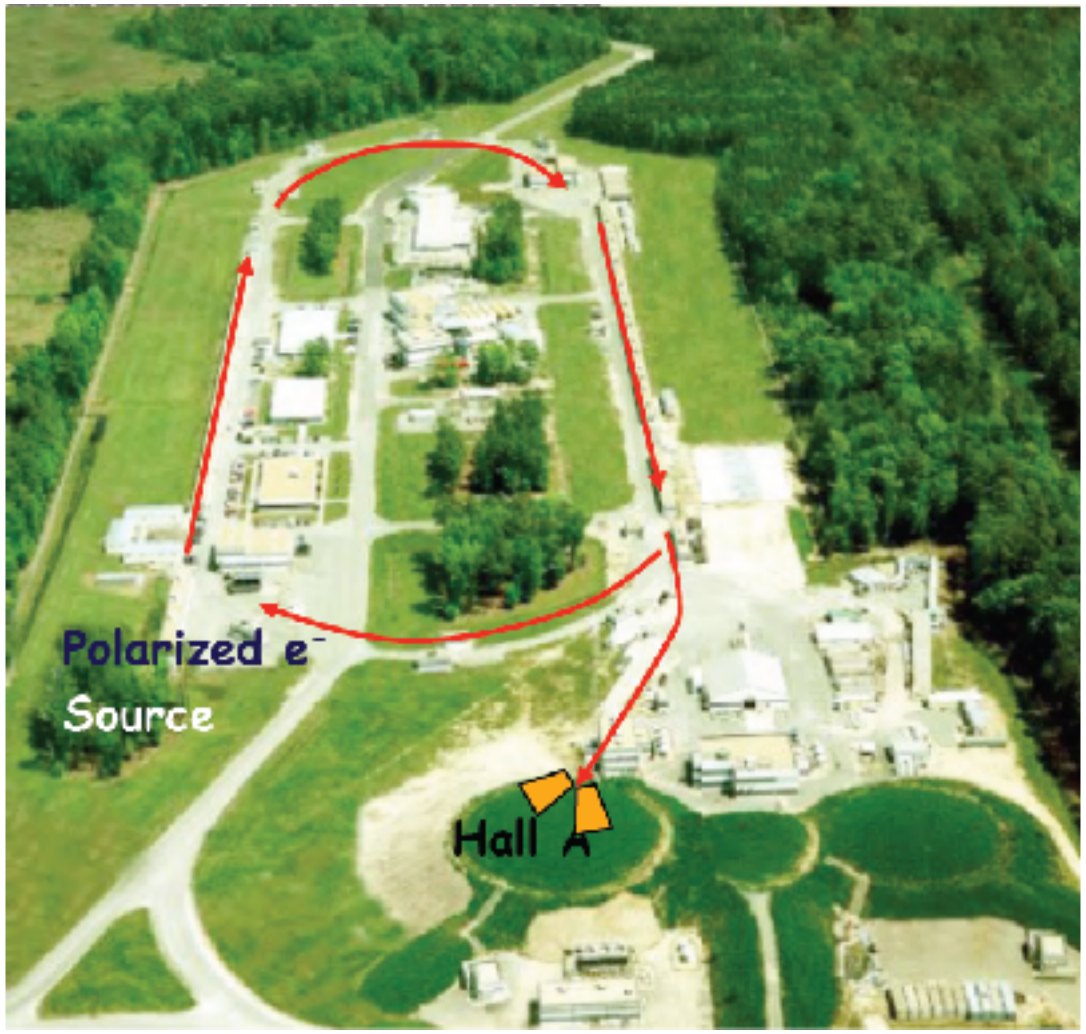
- A_{pv} from interference of photon and Z^0 exchange.
- Determines weak form factor

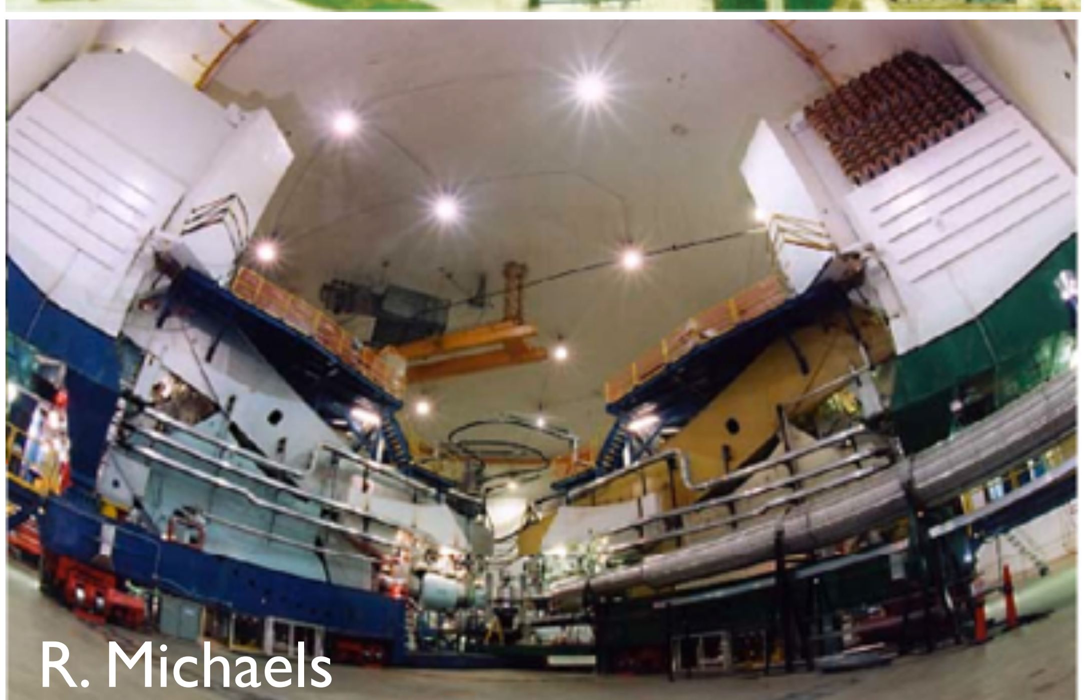
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

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

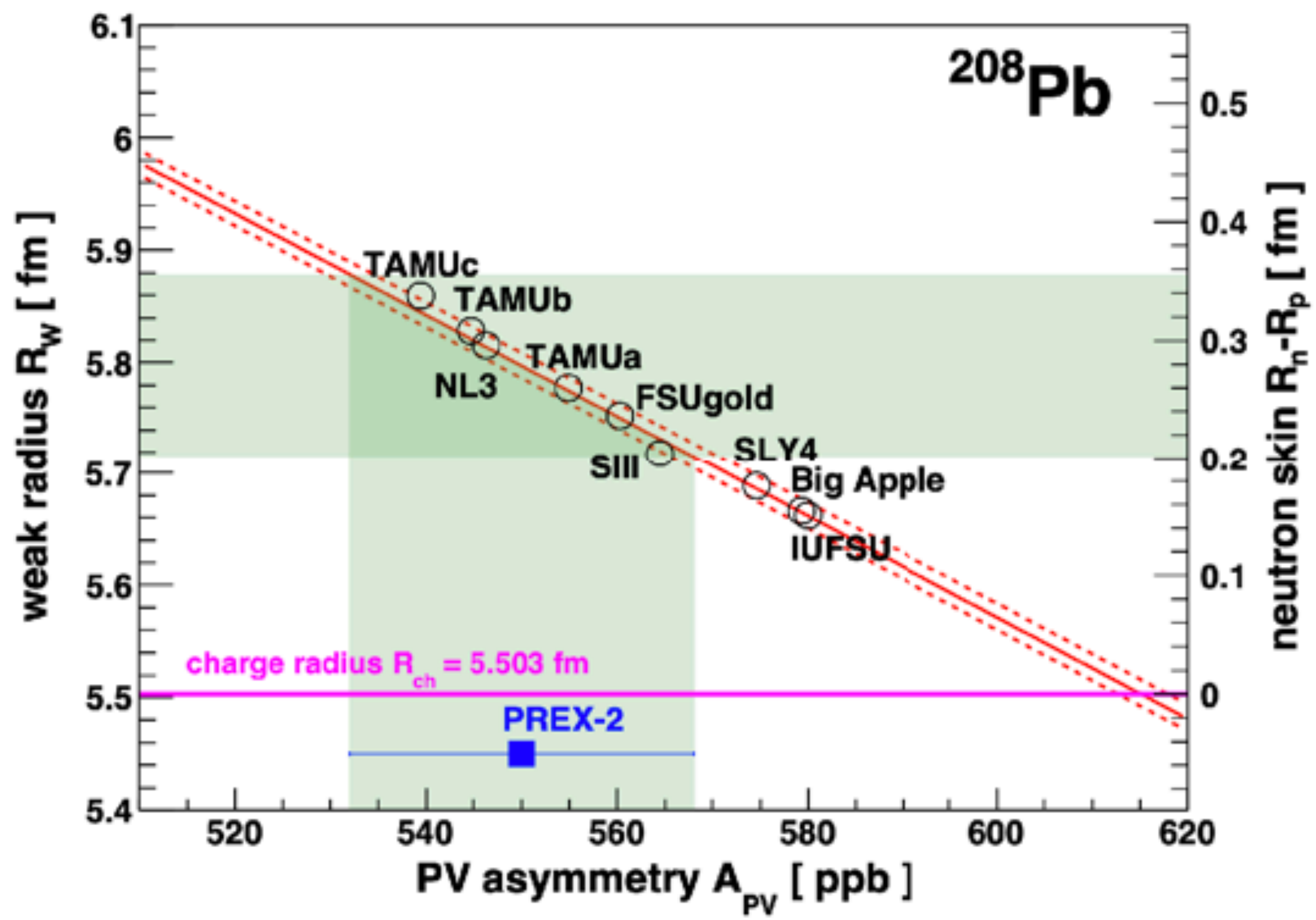
$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L - \sigma_R} \approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

PREX in Hall A at Jefferson Lab





- One GeV e scattered at ~ 5 deg.
- R_W=5.800 +/- 0.075 fm
  [R_{ch}=5.503 fm]
- R_n-R_p=0.283 +/- 0.071 fm



PREX Errors

- Measure: A_{PV}=550 +/- 16(stat) +/- 8(sys) parts per billion

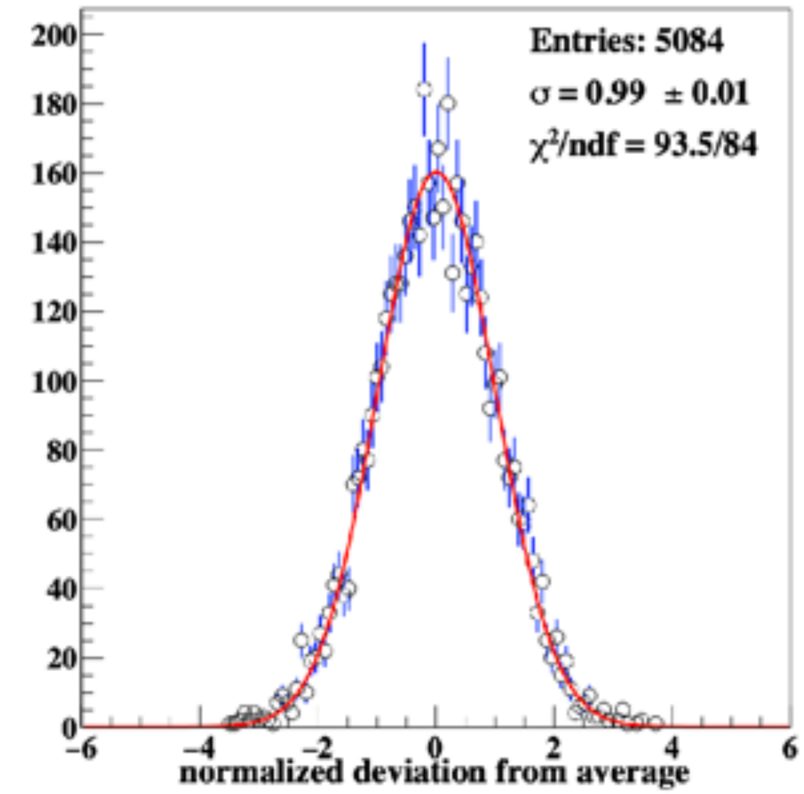
- **Statistics**: dominates (lots more beam time hard)

- **Systematics**: often from helicity correlated beam properties. Measure constantly and feedback as necessary. Much experience with other parity experiments, very high quality of JLAB beam helps a lot. Paul Souder spent 3+ decades reducing systematic errors in parity experiments!

- **Model**: Need very modest assumptions about surface thickness to extract weak radius (because Q^2 finite)

- R_W=5.800 +/- 0.074 (exp) +/- 0.013 (model) fm

- Any question about model error, use form factor: $F_W(<Q^2>)$=0.368 +/- 0.013 (exp)

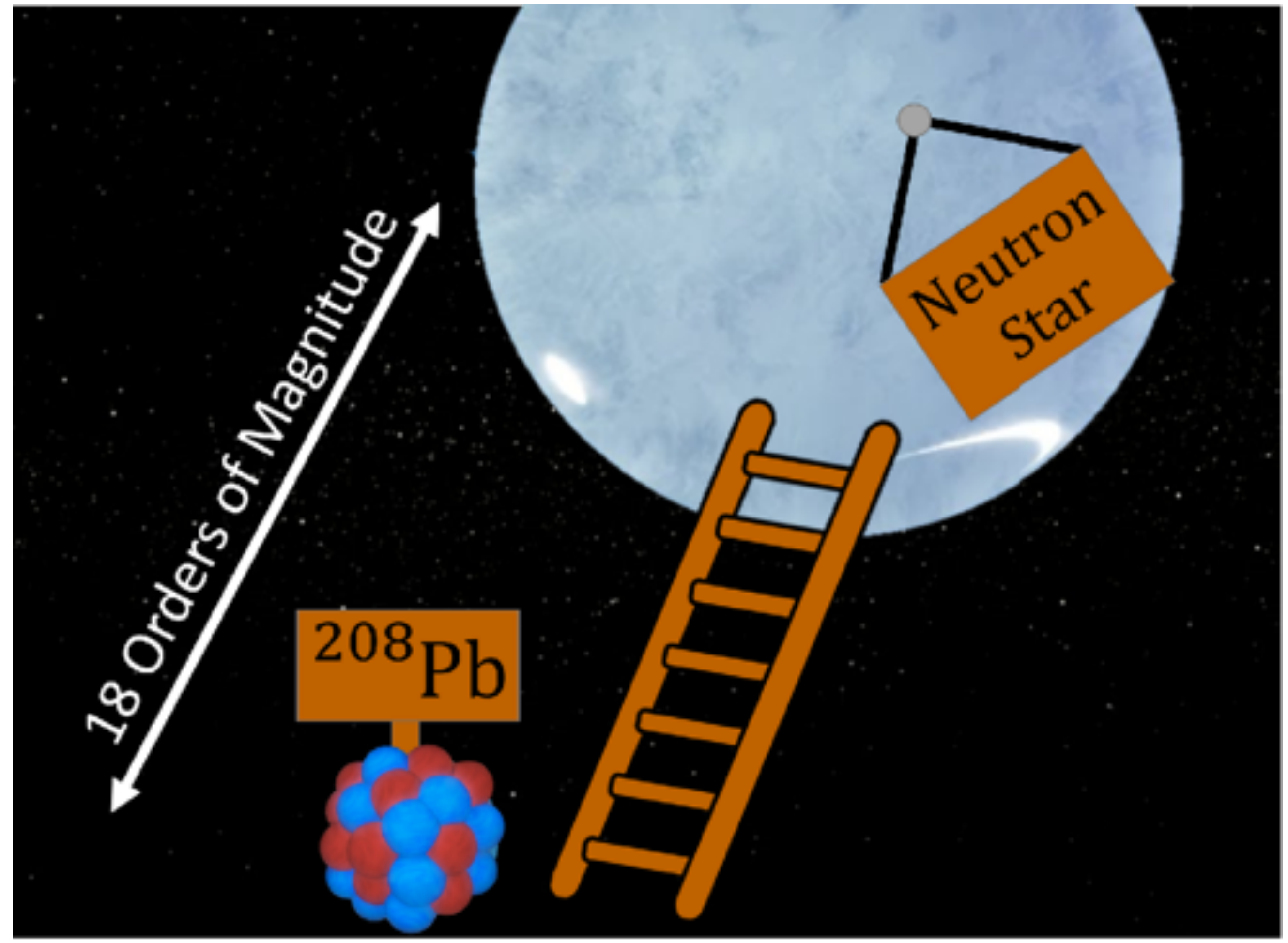


A_{PV} from 5 min beam runs show nearly perfect gaussian!

Theory error from uncertainties in radiative corrections very small!

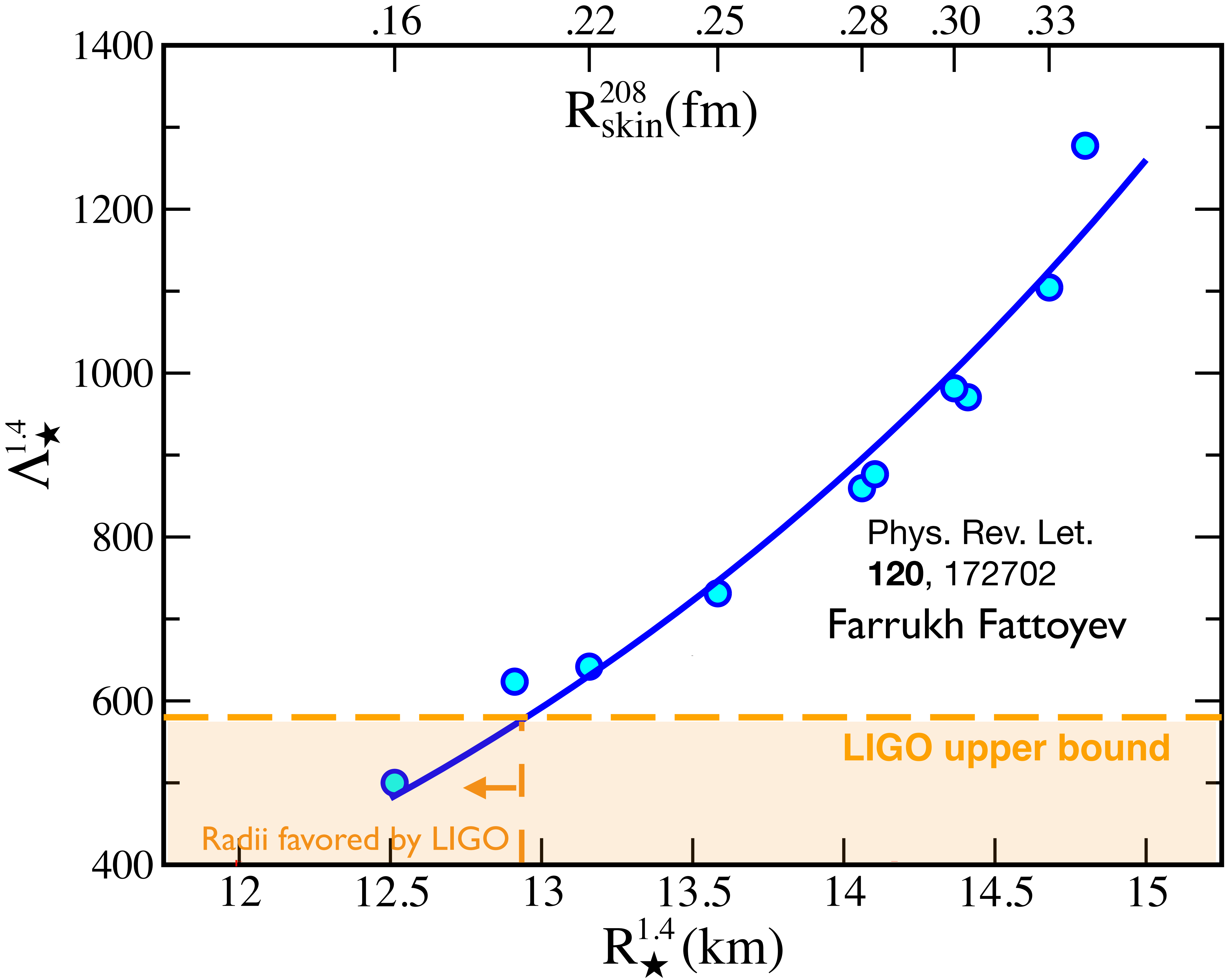
Radii of ^{208}Pb and Neutron Stars

- 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 determines P near nuclear density and has important implications for the structure of neutron stars.

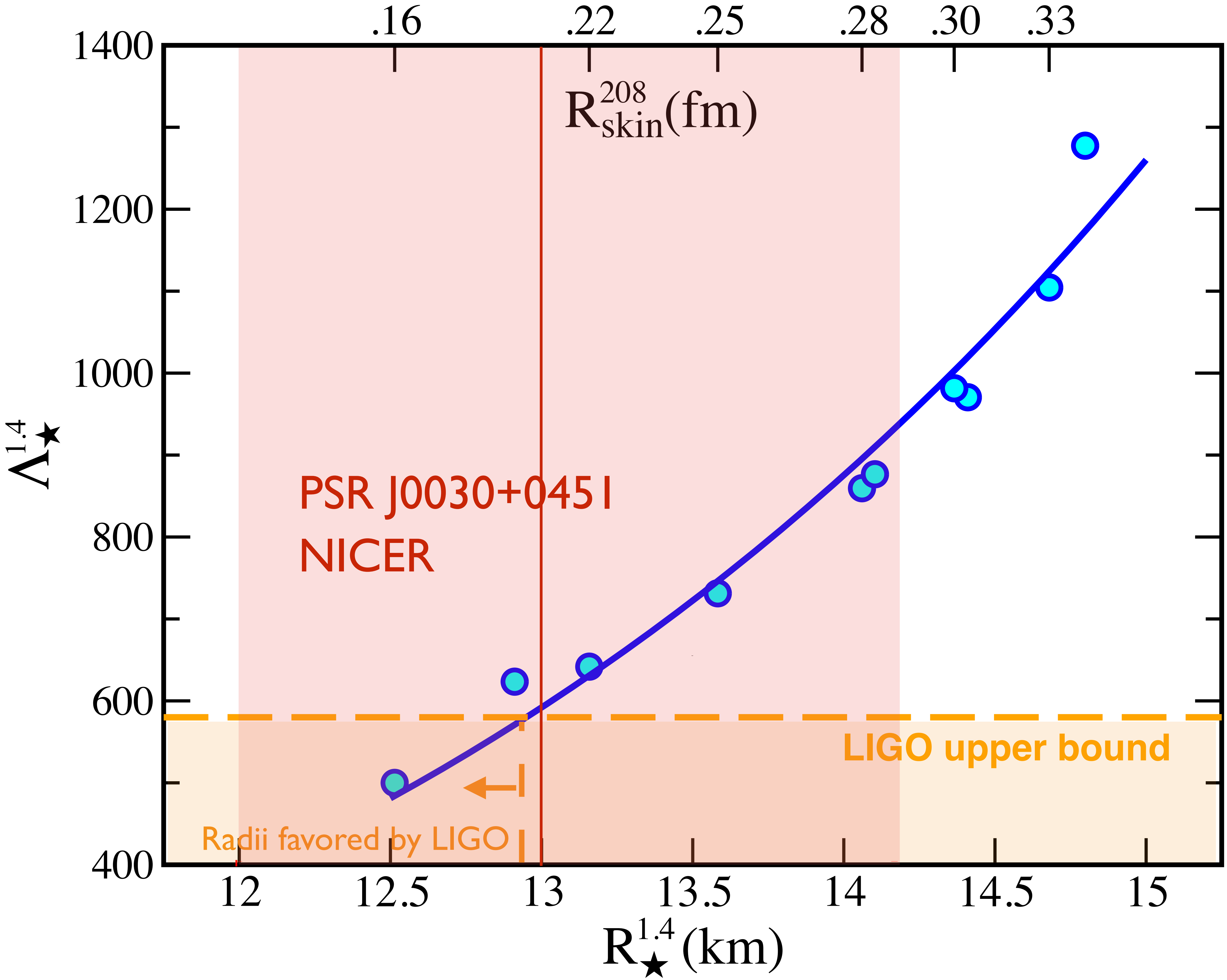


Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

Pressure is force/area. Measure force with spring (surface tension) and ruler (PREX).



.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)
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$\Lambda^{1.4}_{\star}$
PSR J0030+0451
NICER
LIGO upper bound
Radii favored by LIGO
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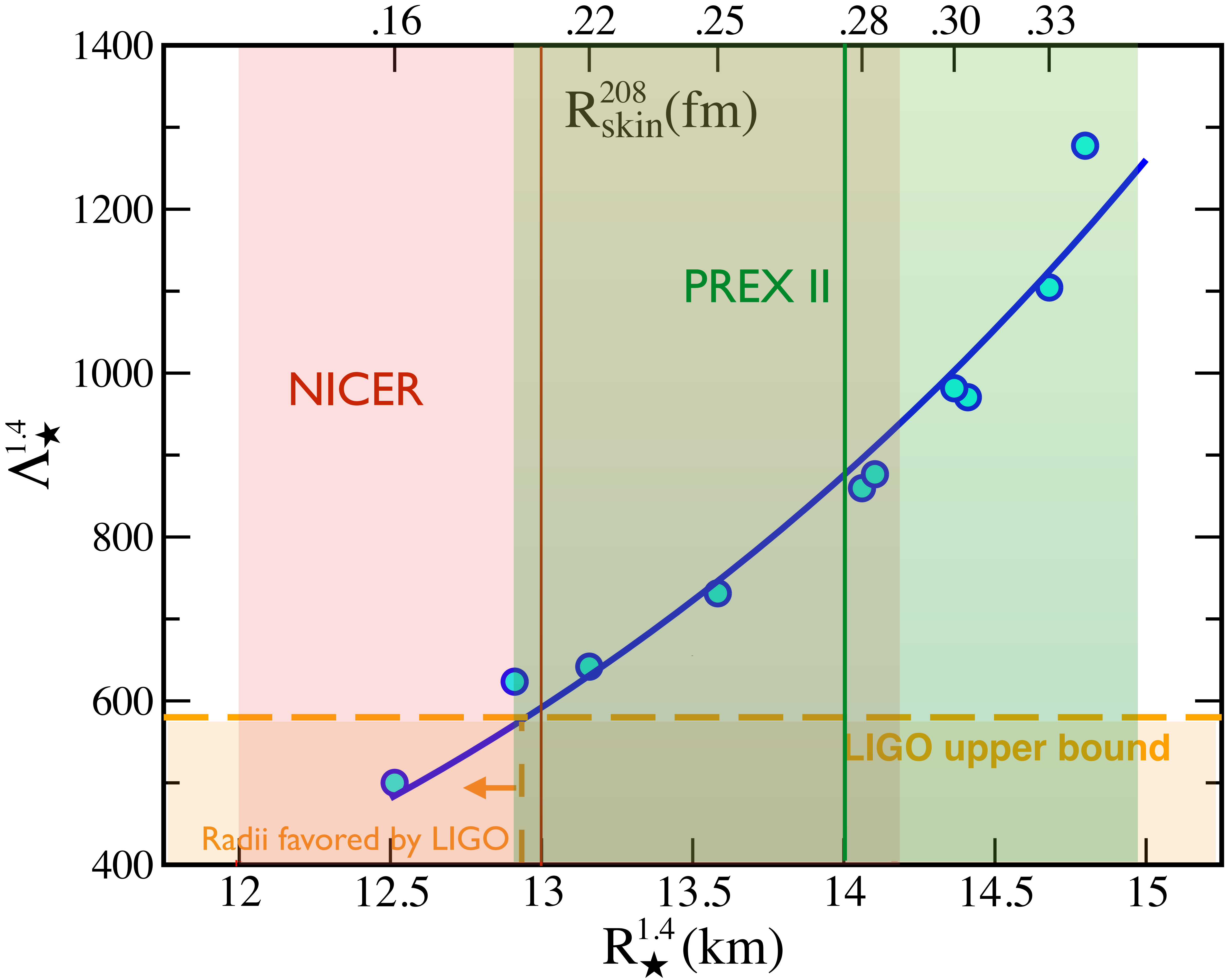
$R^{1.4}_{\star}$(km)



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

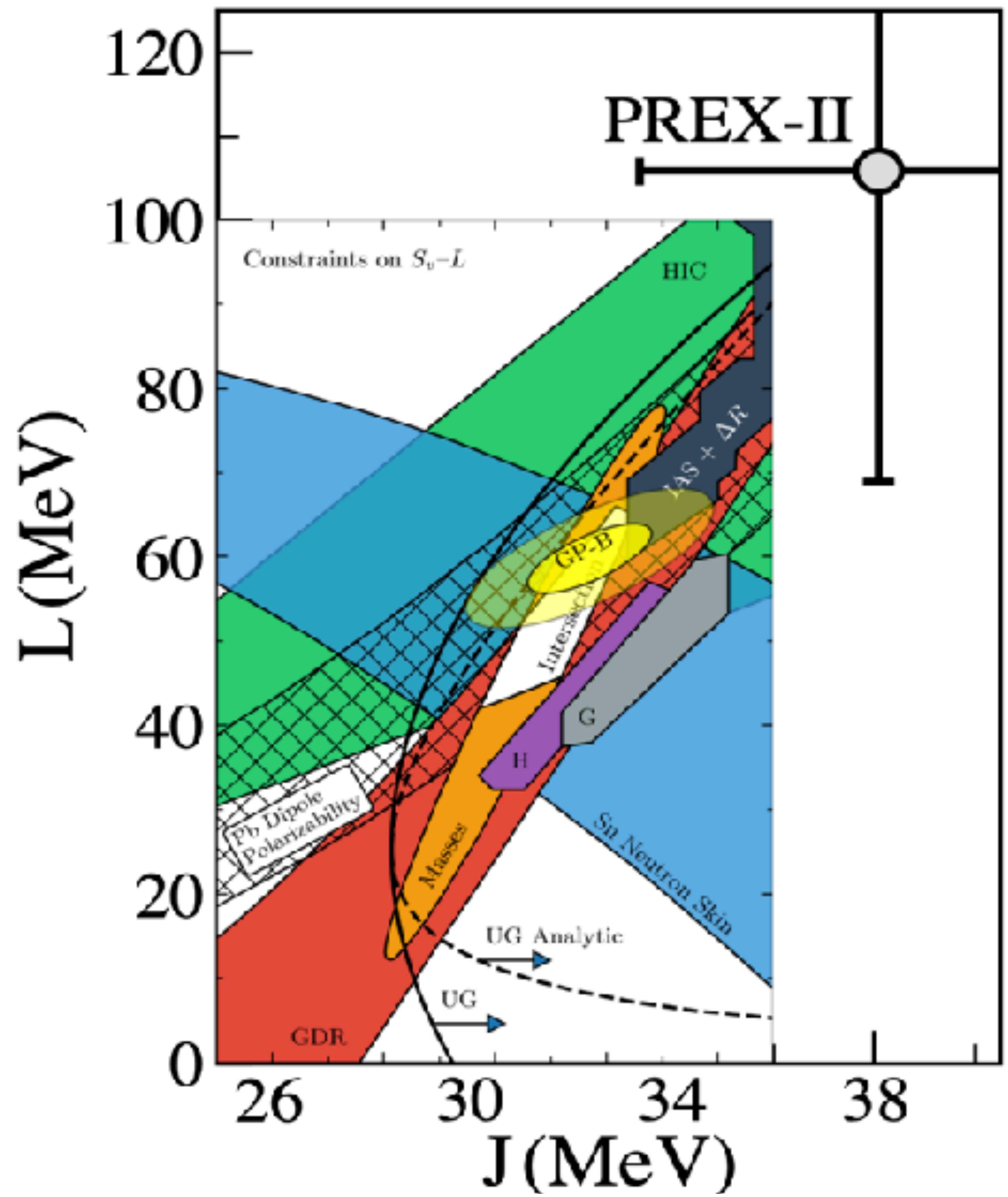
Symmetry Energy

- Symmetry energy S(n) describes increase in E of nuclear matter as one goes away from equal numbers of n and p.

- If S increases rapidly with density n it will push 44 extra n in ^{208}Pb out into low density surface increasing n skin thickness.

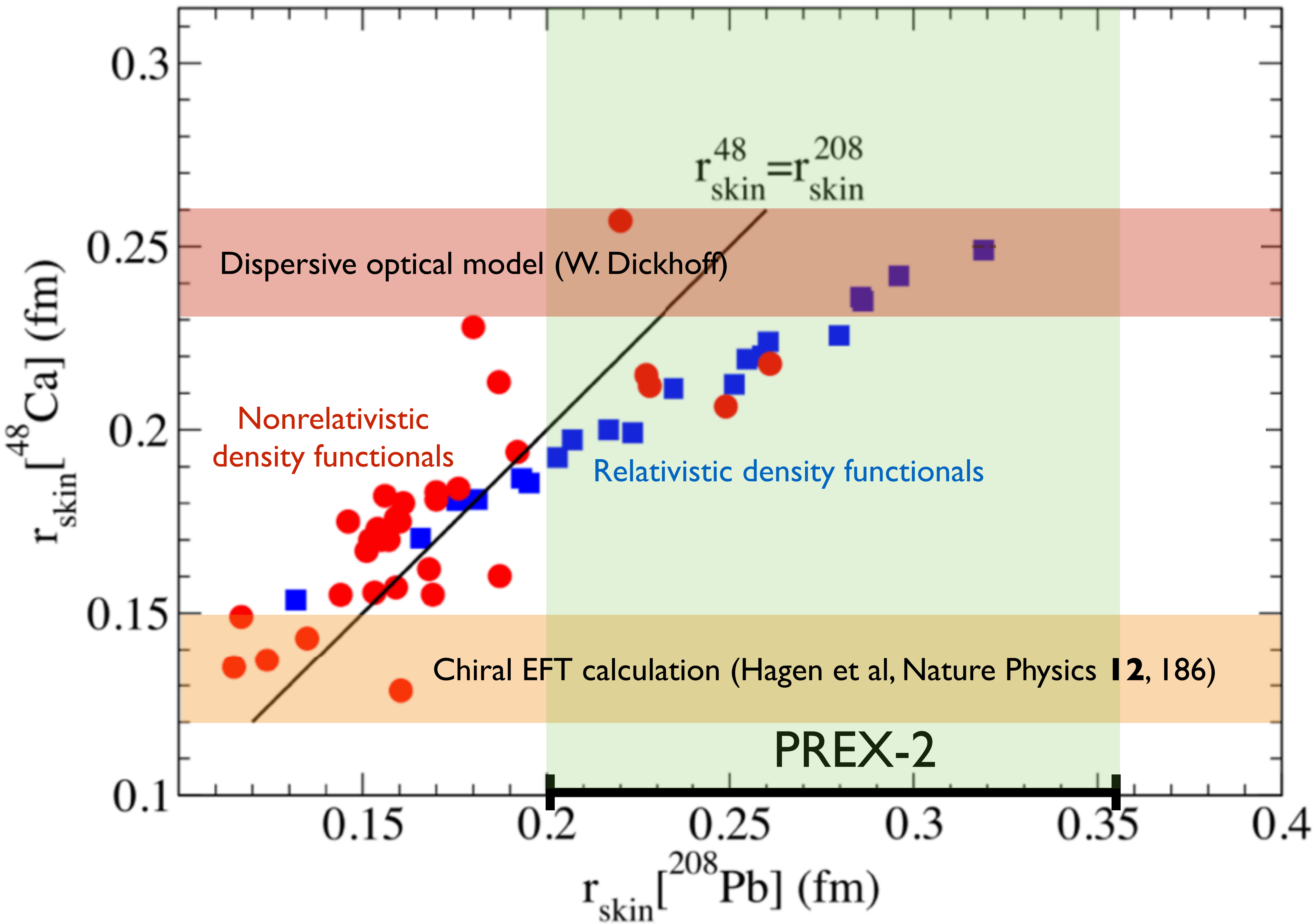
- L describes density dependence of S. J is S at n_0.

- PREX-2: L = 110 +/- 36 MeV



CREX and Chiral EFT

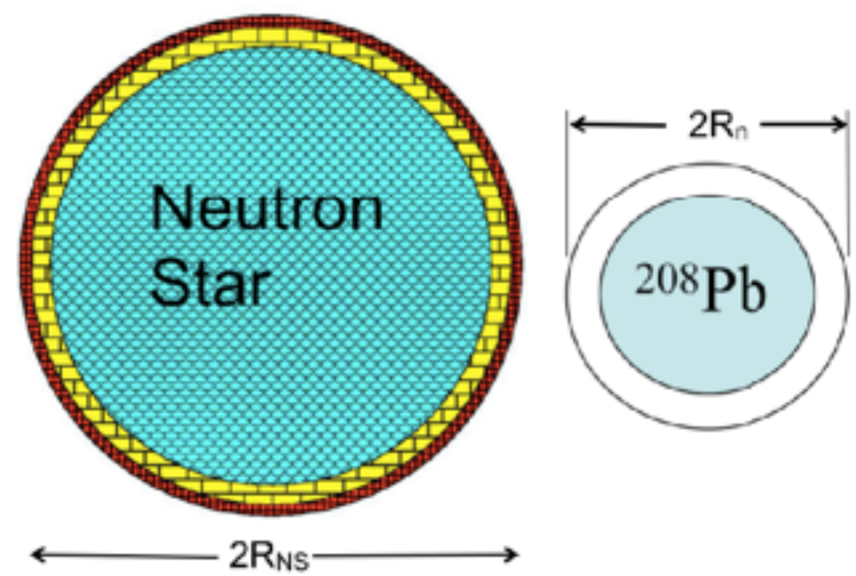
- Chiral EFT expands 2, 3, … nucleon interactions in powers of momentum transfer over chiral scale.
- **Three neutron forces** are hard to directly observe. They increase the pressure of neutron matter and the neutron skin thickness of both ^{208}Pb and ^{48}Ca.
- Only stable, neutron rich, closed shell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



Dispersive optical model (W. Dickhoff)
Nonrelativistic density functionals
Relativistic density functionals
Chiral EFT calculation (Hagen et al, Nature Physics 12, 186)
PREX-2
$r^{48}_{skin}=r^{208}_{skin}$
$r_{skin}[^{48}Ca]$ (fm)
$r_{skin}[^{208}Pb]$ (fm)
0.1
0.15
0.2
0.25
0.3
0.35
0.4

PREX-2 experiment and neutron rich matter in the laboratory

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke, G. Urciuoli…
- NS deformability vs ^{208}Pb skin: **Farrukh Fattoyev**, Jorge Piekarewicz
- Graduate student: **Brendan Reed**



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