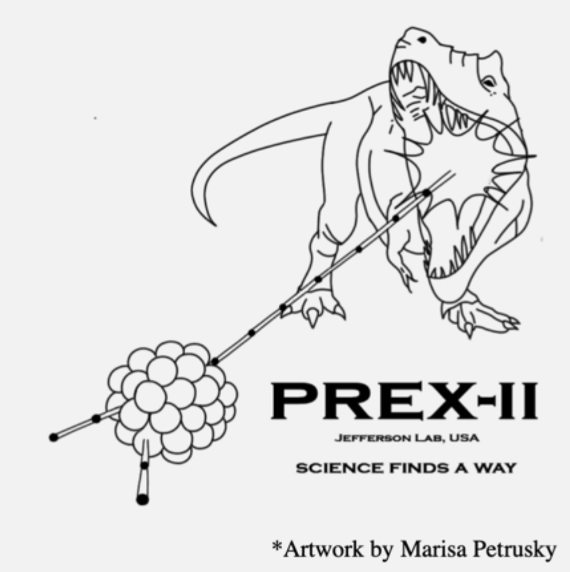
The neutron skin of ^{208}Pb and the structure of neutron stars



Chuck Horowitz, Indiana U. JLAB Hall A, Jan. 2021

U.S. DEPARTMENT OF ENERGY Office of Science

The neutron skin of ^{208}Pb and the structure of neutron stars

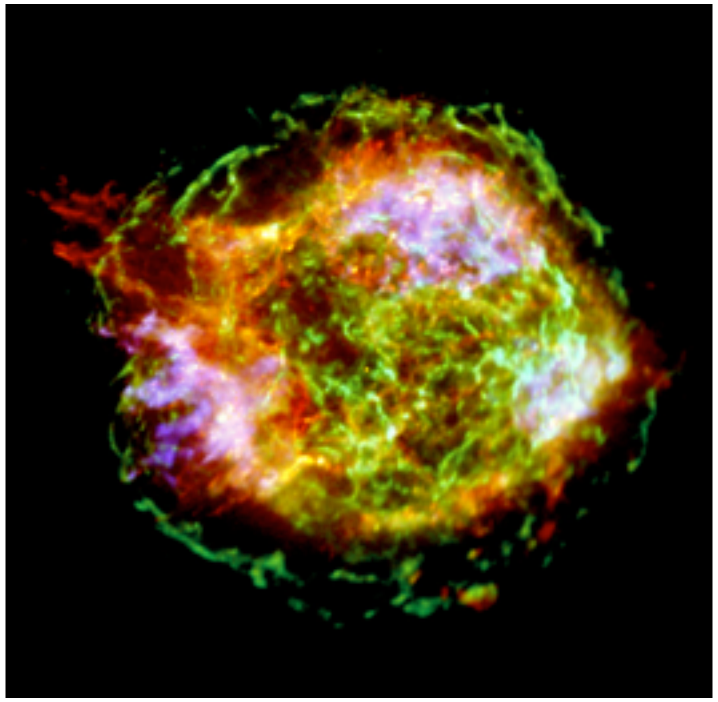
- PREX II experimental results for the neutron skin of ^{208}Pb and the pressure of neutron rich matter.

- Comparison to Laser Interferometer Gravitational-Wave Observatory (LIGO) and X-ray telescope NICER results for the radius and polarizability of neutron stars.

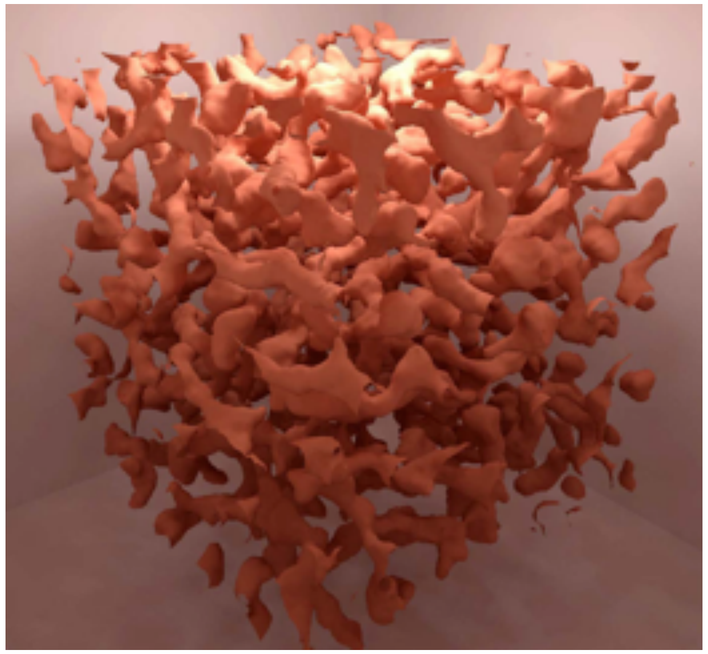
- *Measuring nuclear density* $\boldsymbol{\rho_0}$: the interior weak and baryon densities of ^{208}Pb.

Neutron Rich Matter

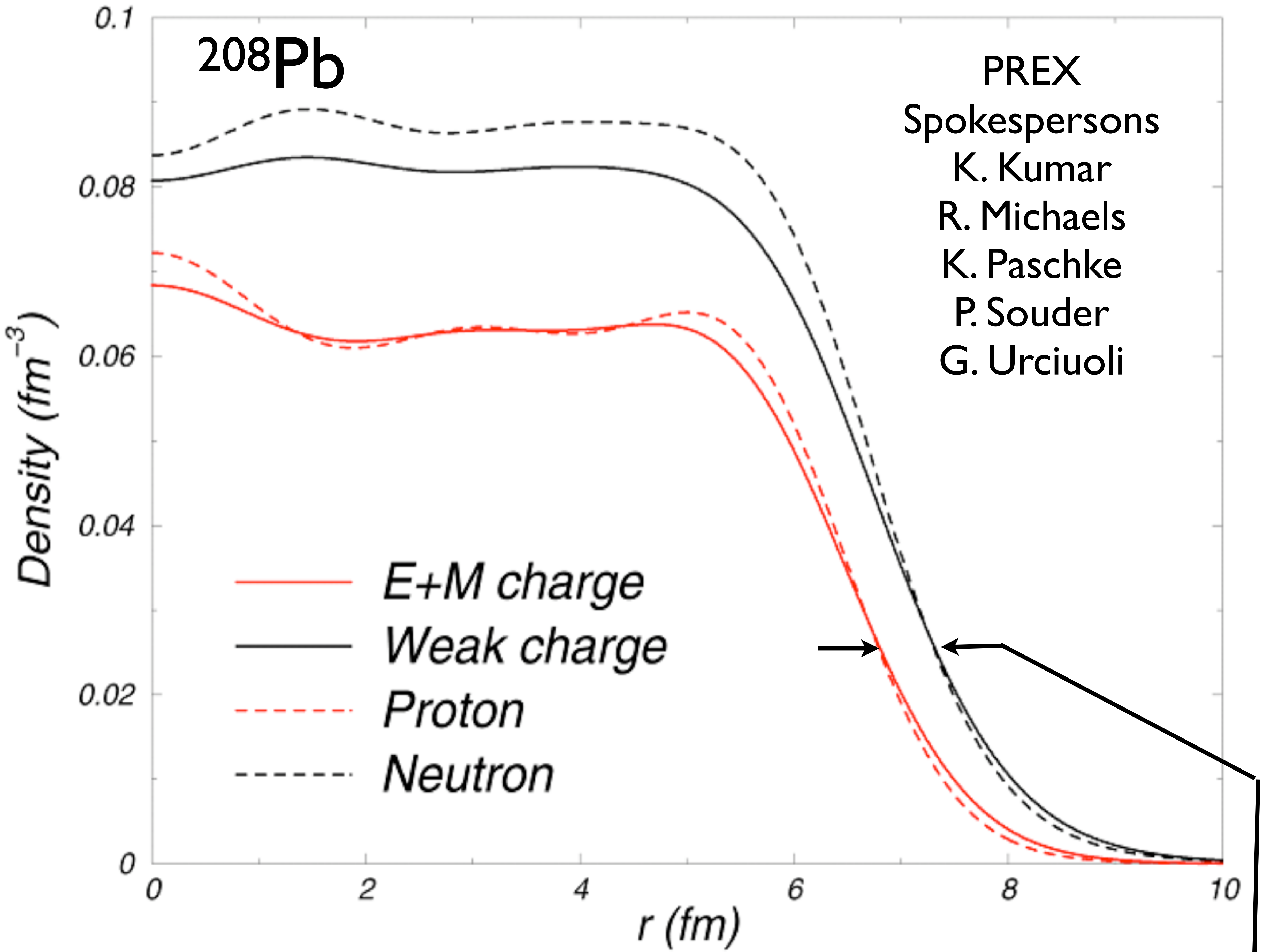
- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did chemical elements come from?
  - What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

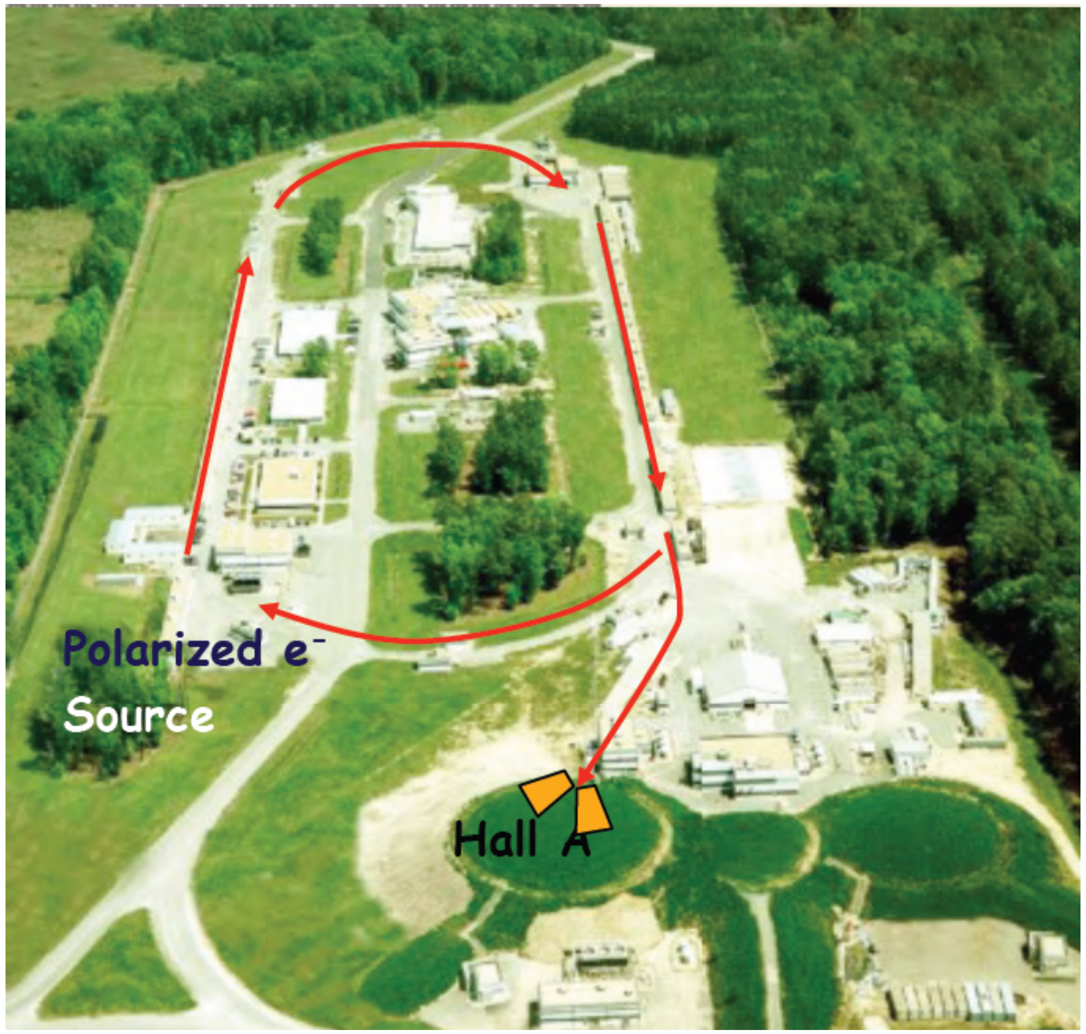
- A_{pv} from interference of photon and Z^0 exchange.
- Determines weak form factor

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

- 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



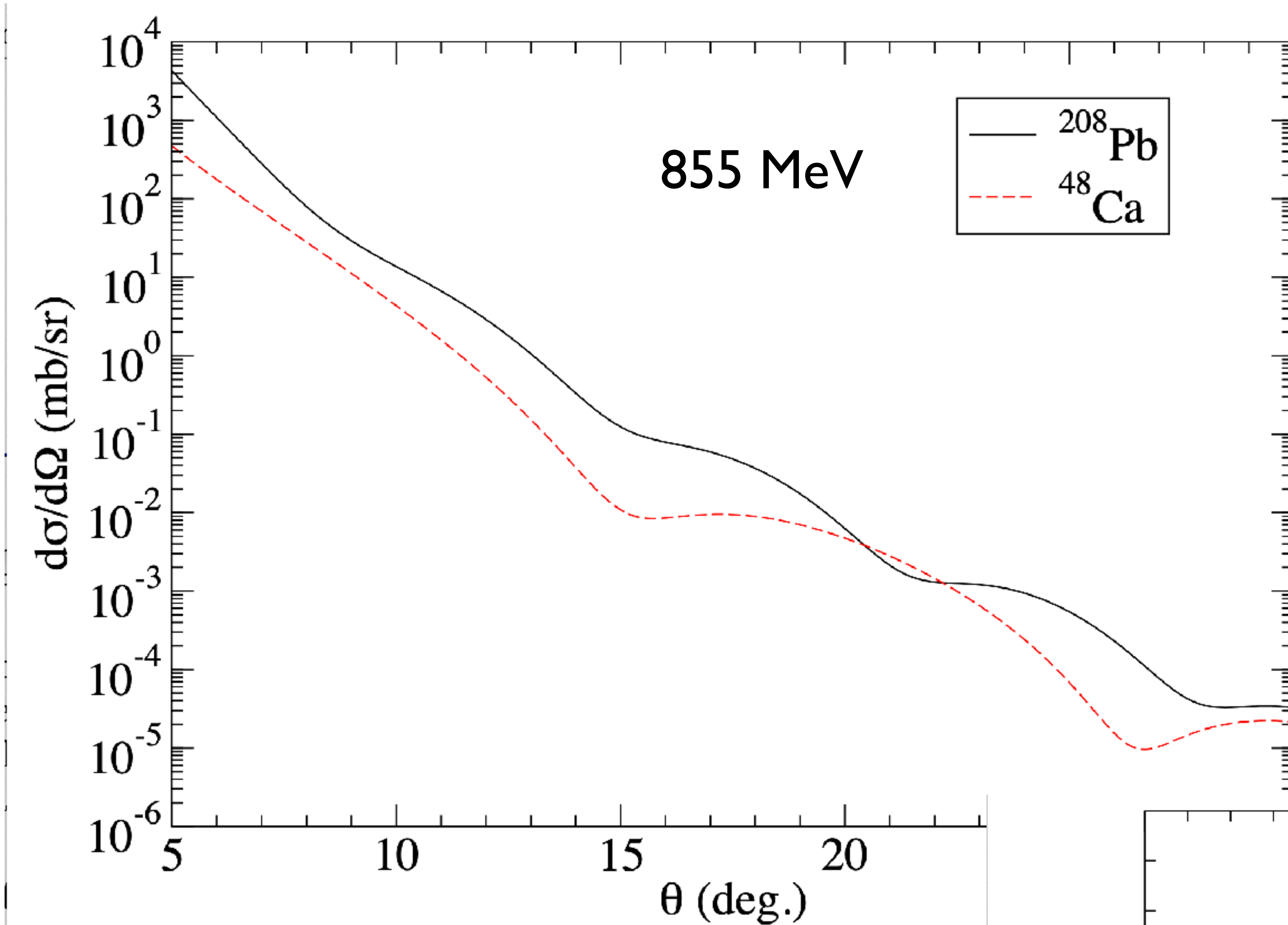
- **PREX**: ran in 2010. 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb

  $A_{PV} = 0.657 \pm 0.060(\text{stat}) \pm 0.014(\text{sym})$ ppm

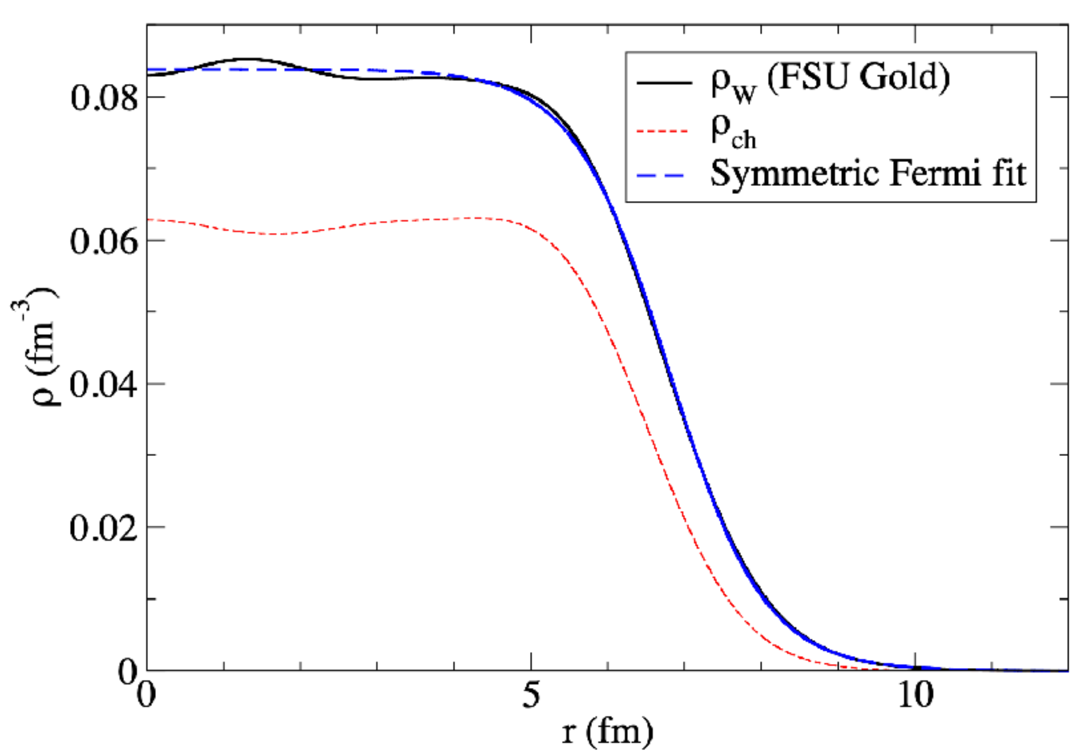
- From A_{pv} I inferred neutron skin:
  $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm.

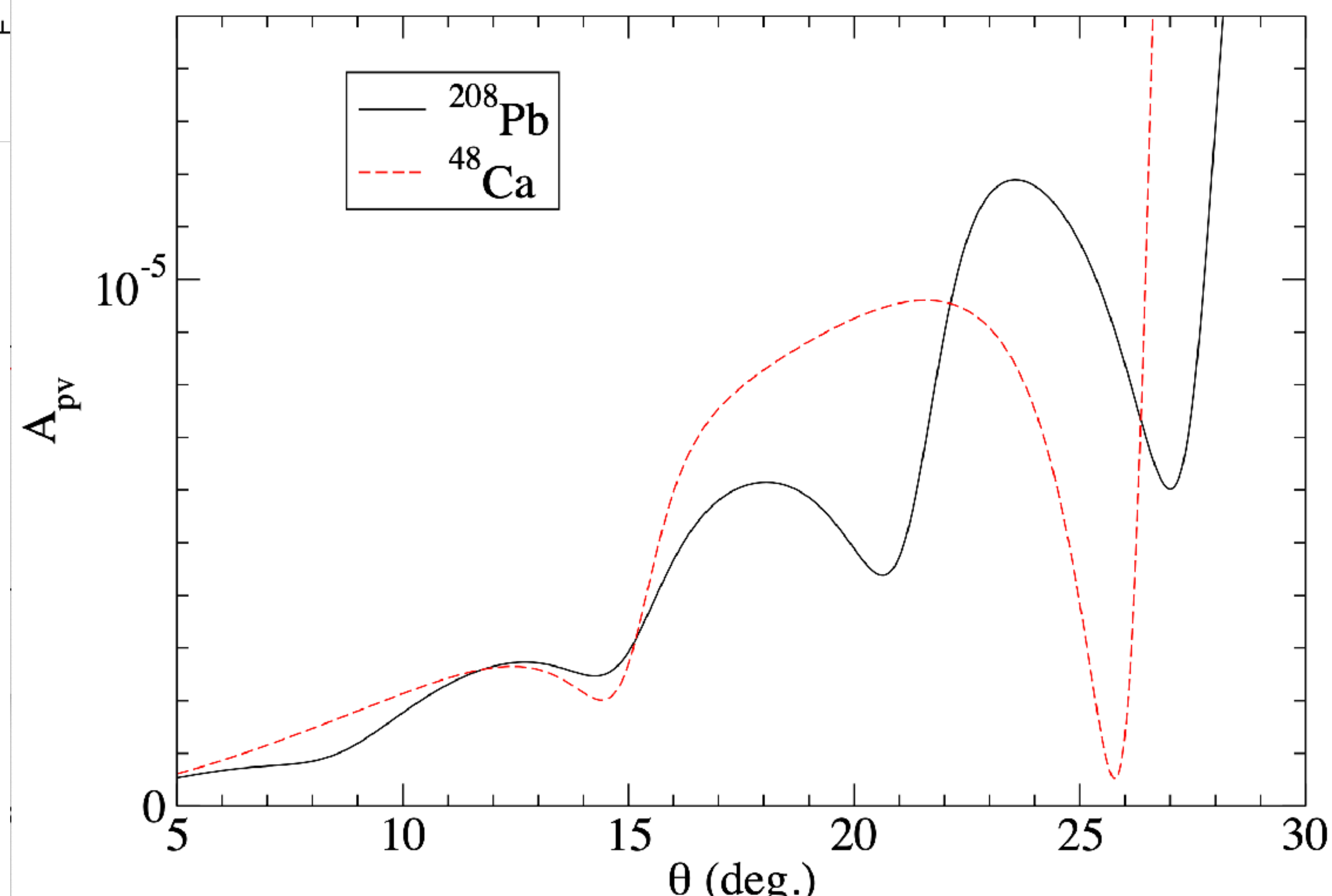
- **PREX-II**: ^{208}Pb with more statistics. Ran during summer of 2019. 950 MeV electrons scattering at about 5 degrees.

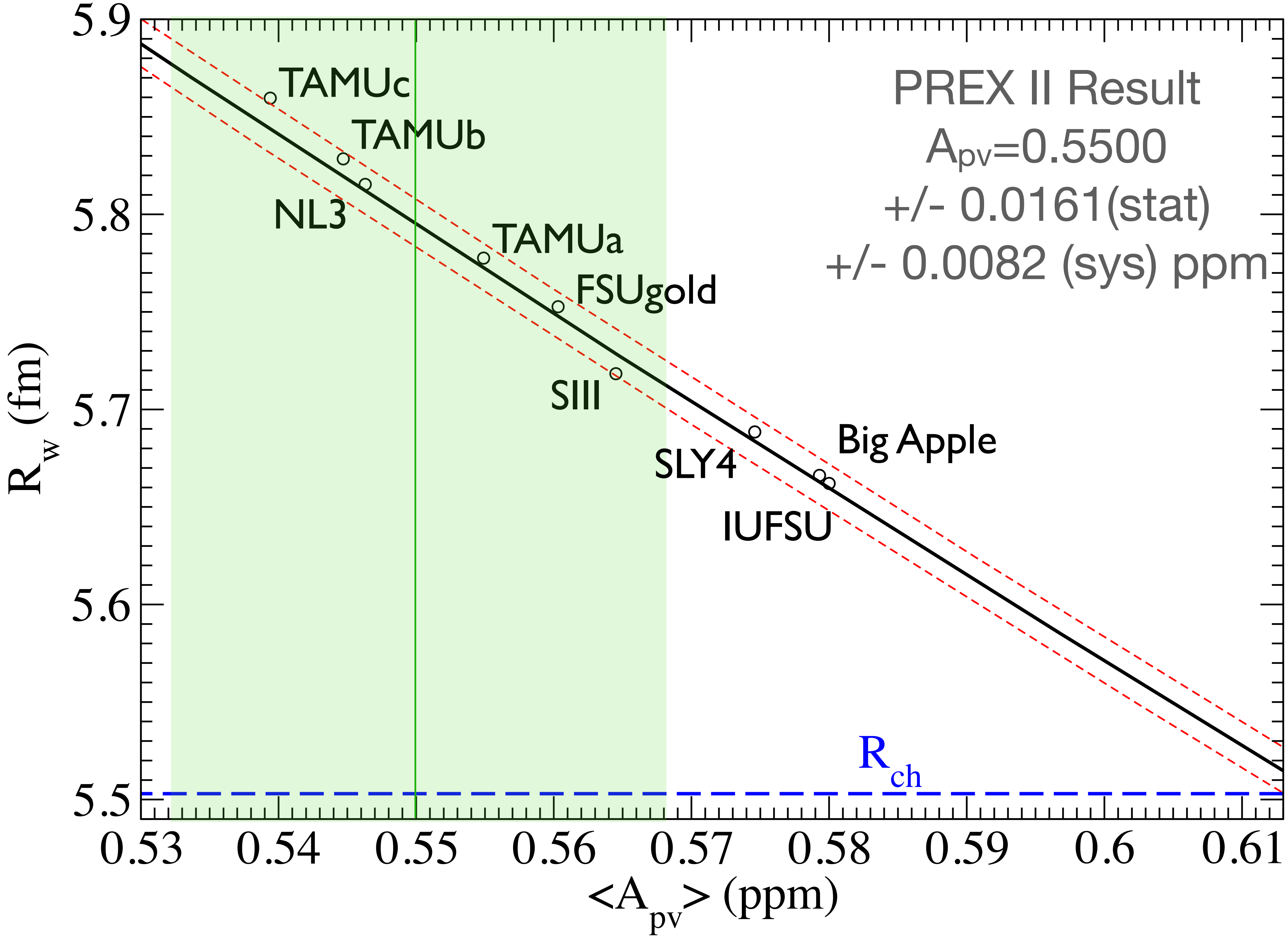
- **CREX**: Measure R_n of ^{48}Ca to ±0.02 fm. Microscopic calculations feasible for light n rich ^{48}Ca to relate R_n to *three neutron forces*. Ran during Fall 2019-Spring 2020 and Summer 2020. Analysis underway, results in a year.



Numerical solution of Dirac equation for electron moving in coulomb plus small weak potentials give cross section and A_{pv}.







PREX II Result
Apv=0.5500
+/- 0.0161(stat)
+/- 0.0082 (sys) ppm
TAMUc
TAMUb
NL3
TAMUa
FSUgold
SIII
SLY4
Big Apple
IUFSU
Rch
Rw (fm)
<Apv> (ppm)
5.9
5.8
5.7
5.6
5.5
0.53
0.54
0.55
0.56
0.57
0.58
0.59
0.6
0.61

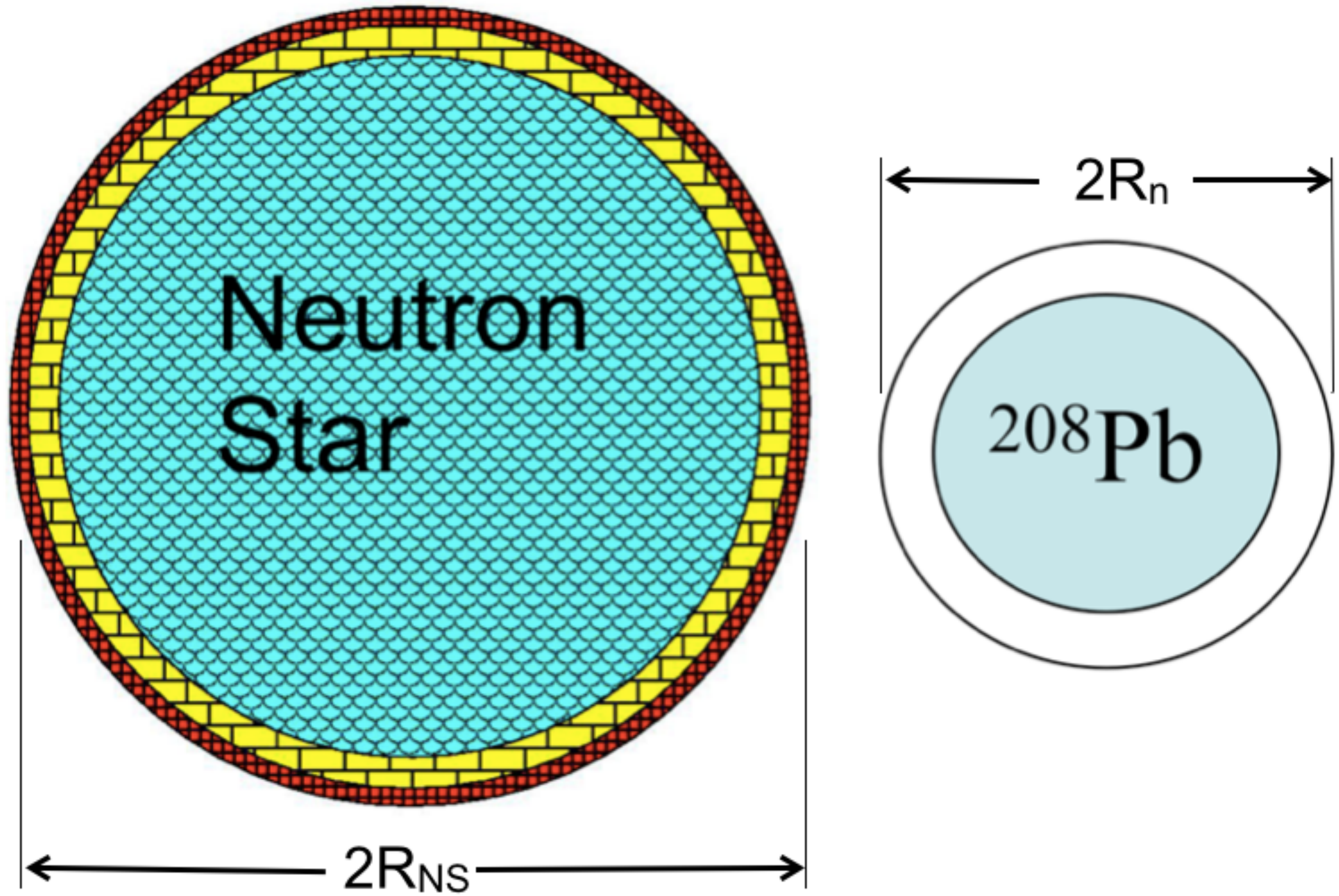
Preliminary results

- $\langle A_{pv} \rangle$=550.0 +/- 18.1 ppb
  - Weak charge of ^{208}Pb: -117.9 +/- 0.3 and numerical coulomb distortions yield->
- 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   PREX II neutron skin
  - Model error (from uncertainty in surface thickness) +/- 0.013 fm
  - Gamma-Z box diagram radiative correction uncertainty +/- 0.006 fm.

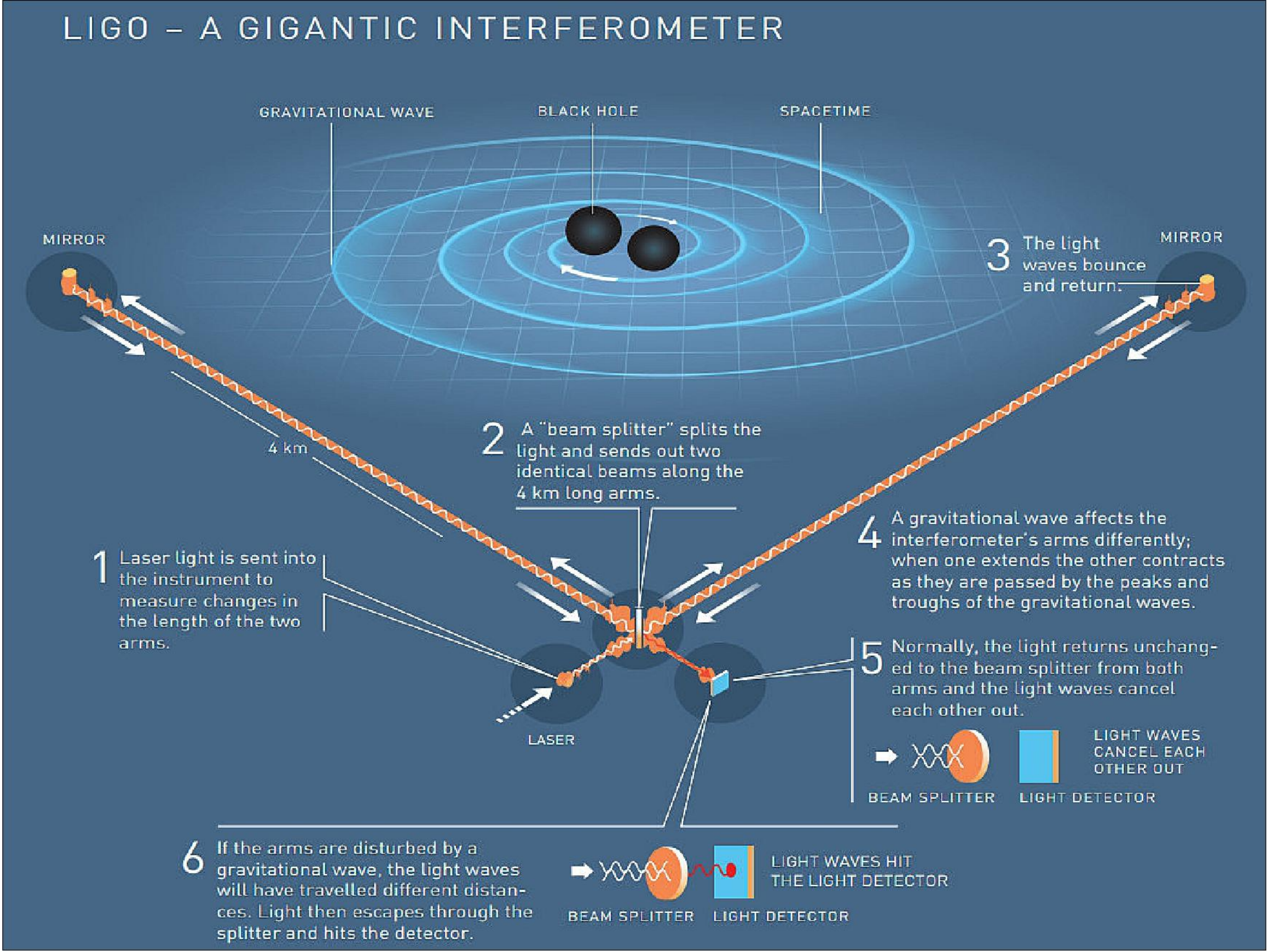
Weak form factor: $F_W(Q^2$=0.00616 GeV^2)=0.3676+/-.0125

Radii of ^{208}Pb and Neutron Stars

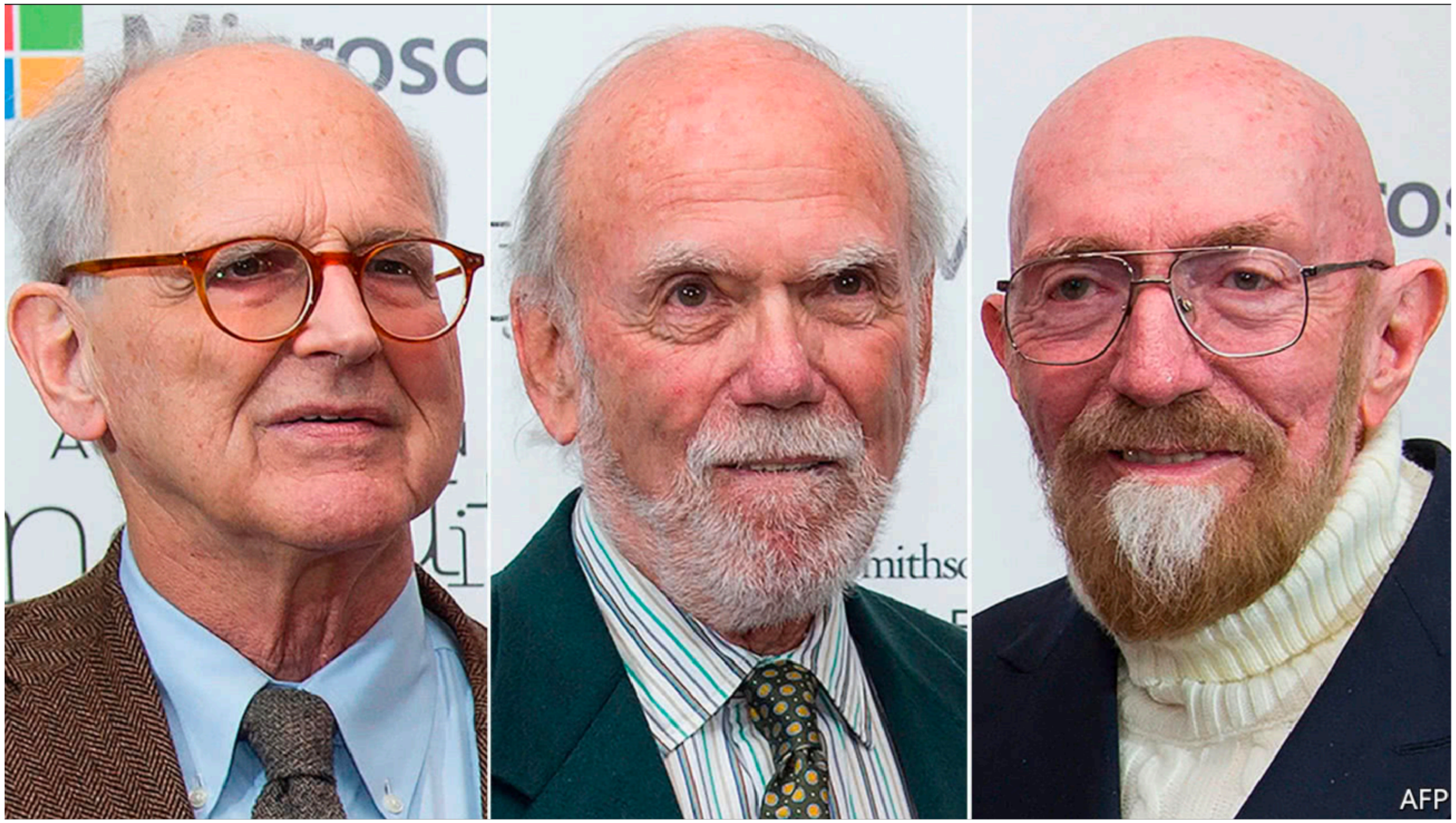
- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



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


LIGO – A GIGANTIC INTERFEROMETER
GRAVITATIONAL WAVE
BLACK HOLE
SPACETIME
MIRROR
MIRROR
3 The light waves bounce and return.
4 km
2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.
1 Laser light is sent into the instrument to measure changes in the length of the two arms.
4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.
5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.
LASER
LIGHT WAVES CANCEL EACH OTHER OUT
BEAM SPLITTER
LIGHT DETECTOR
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.
LIGHT WAVES HIT THE LIGHT DETECTOR
BEAM SPLITTER
LIGHT DETECTOR

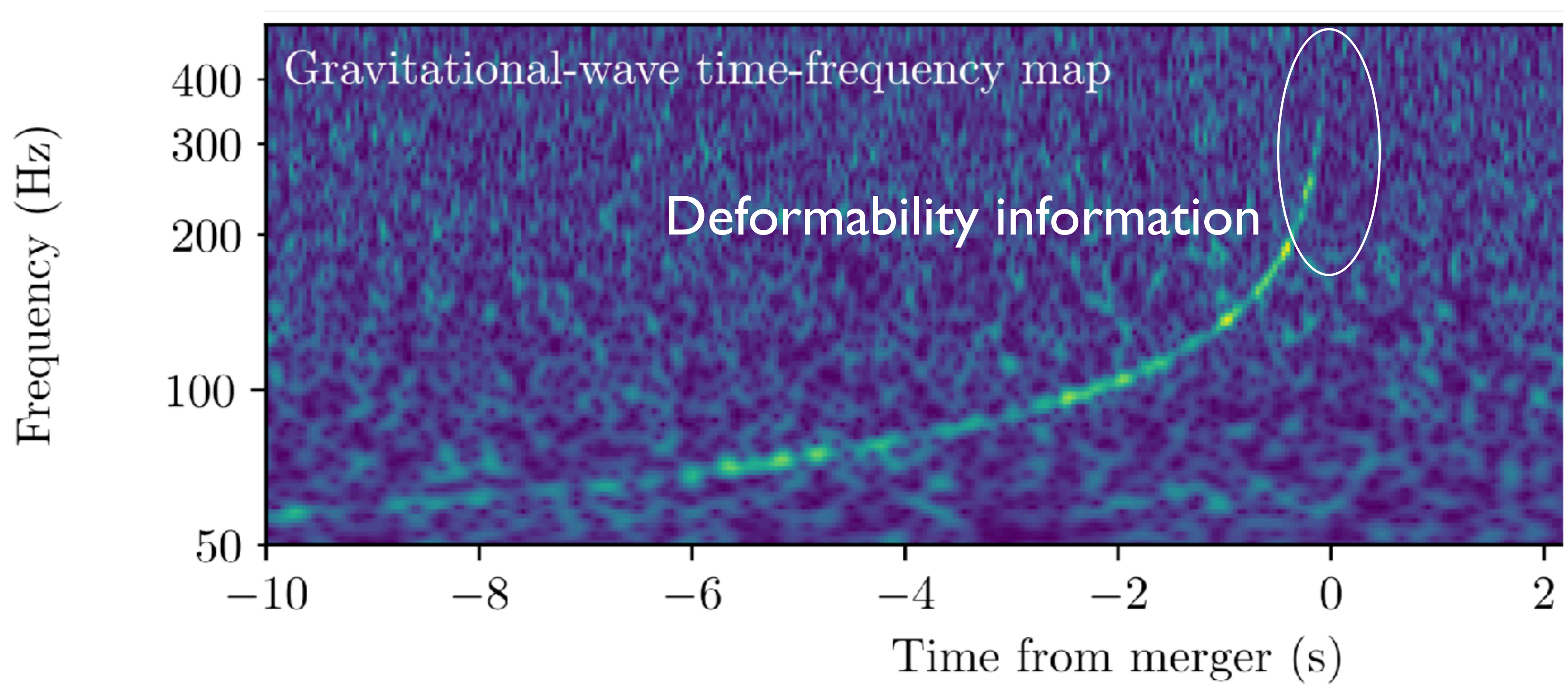
Nobel Prize in Physics 2017



- One half to Rainer Weiss (MIT) and the other half jointly to Barry C. Barish and Kip S. Thorne (Caltech)
- “for decisive contributions to the LIGO detector and the observation of gravitational waves”

Spectacular event GW170817

- On Aug. 17, 2017, the merger of two NS observed with GW by the LIGO and Virgo detectors.
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observed this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.



Merger GW170817: deformability of NS

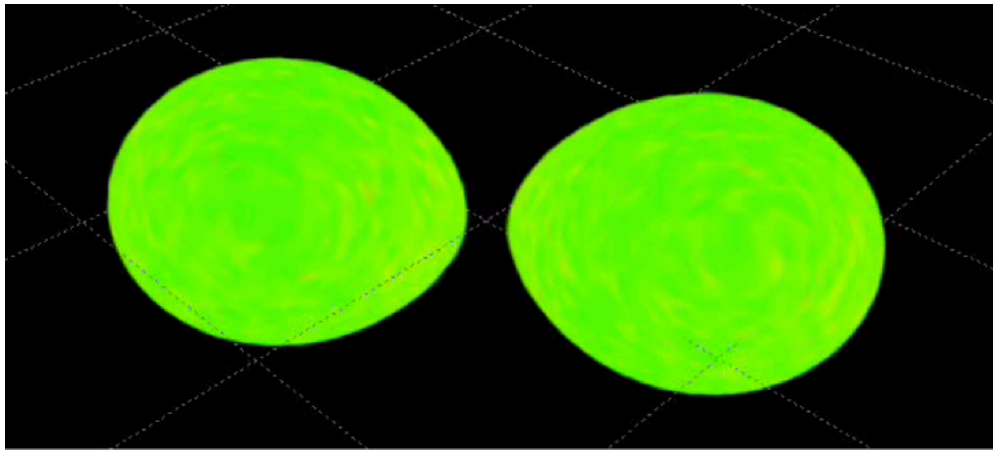
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom ~ R^3.

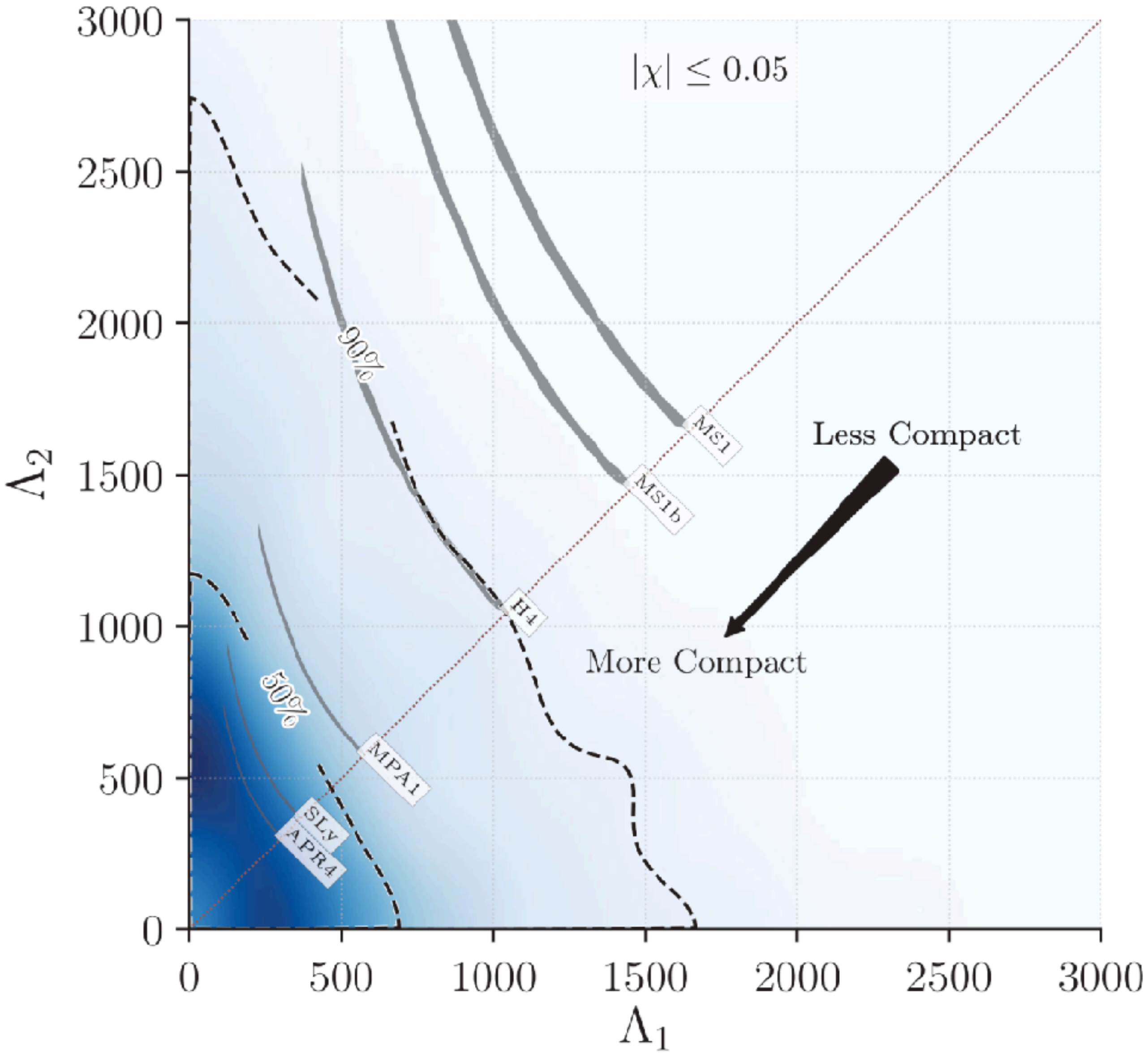
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

- 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 limits on Λ_1 and Λ_2.



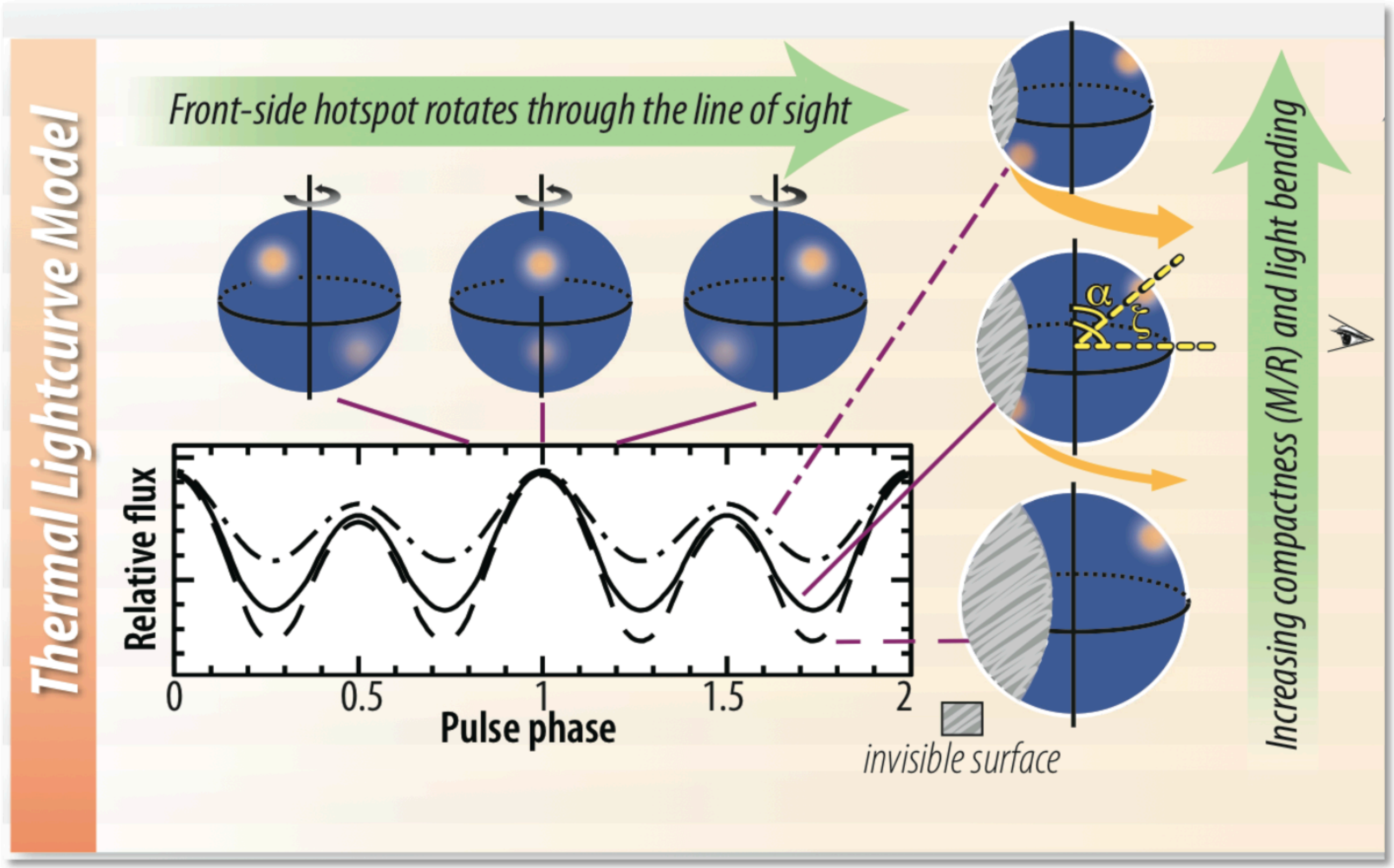



NICER
Neutron star Interior Composition ExploreR
Keith Gendreau, NASA GSFC
Principal Investigator
NASA
GSFC
MIT KAVLI
INSTITUTE

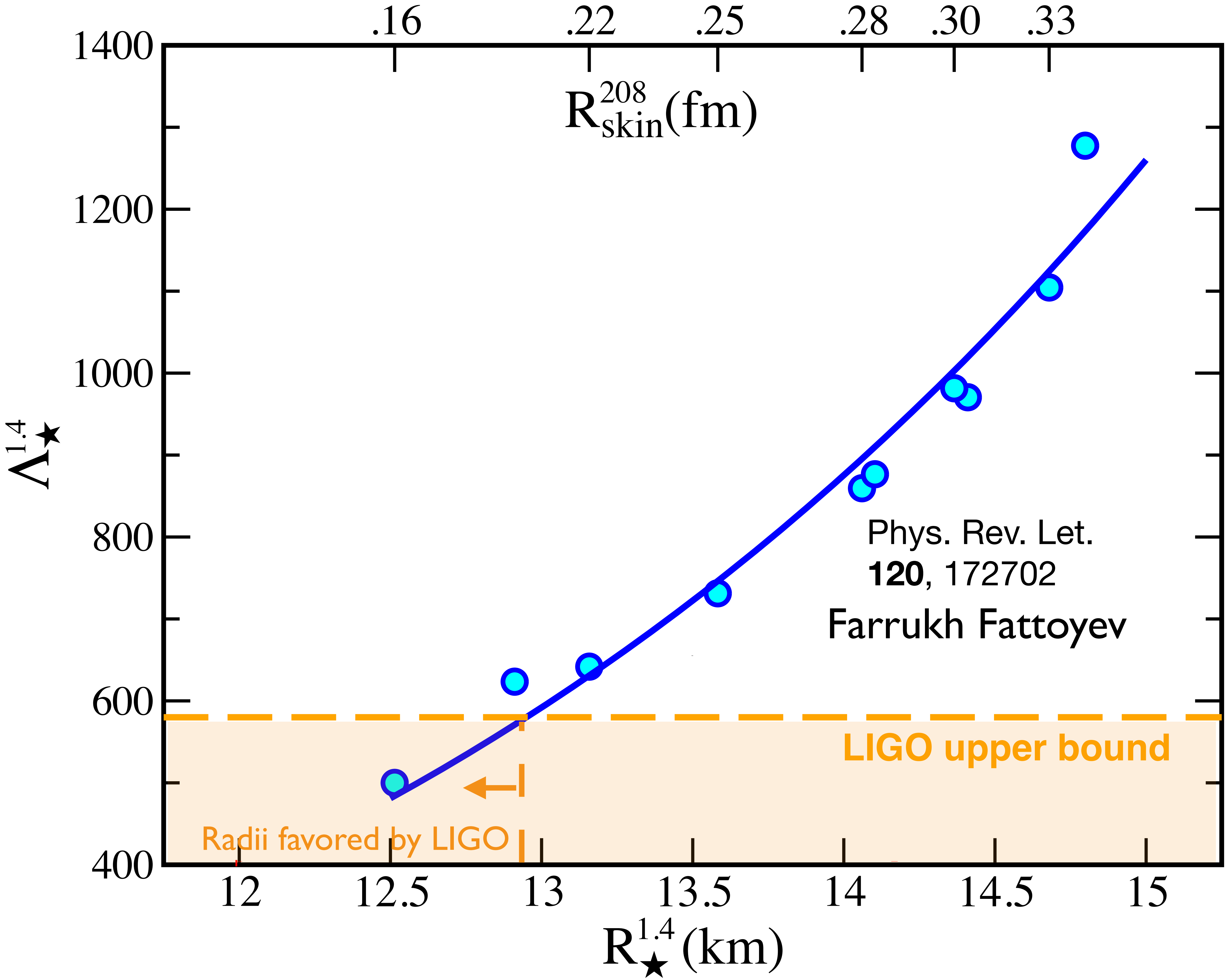
Science Measurements

NICER

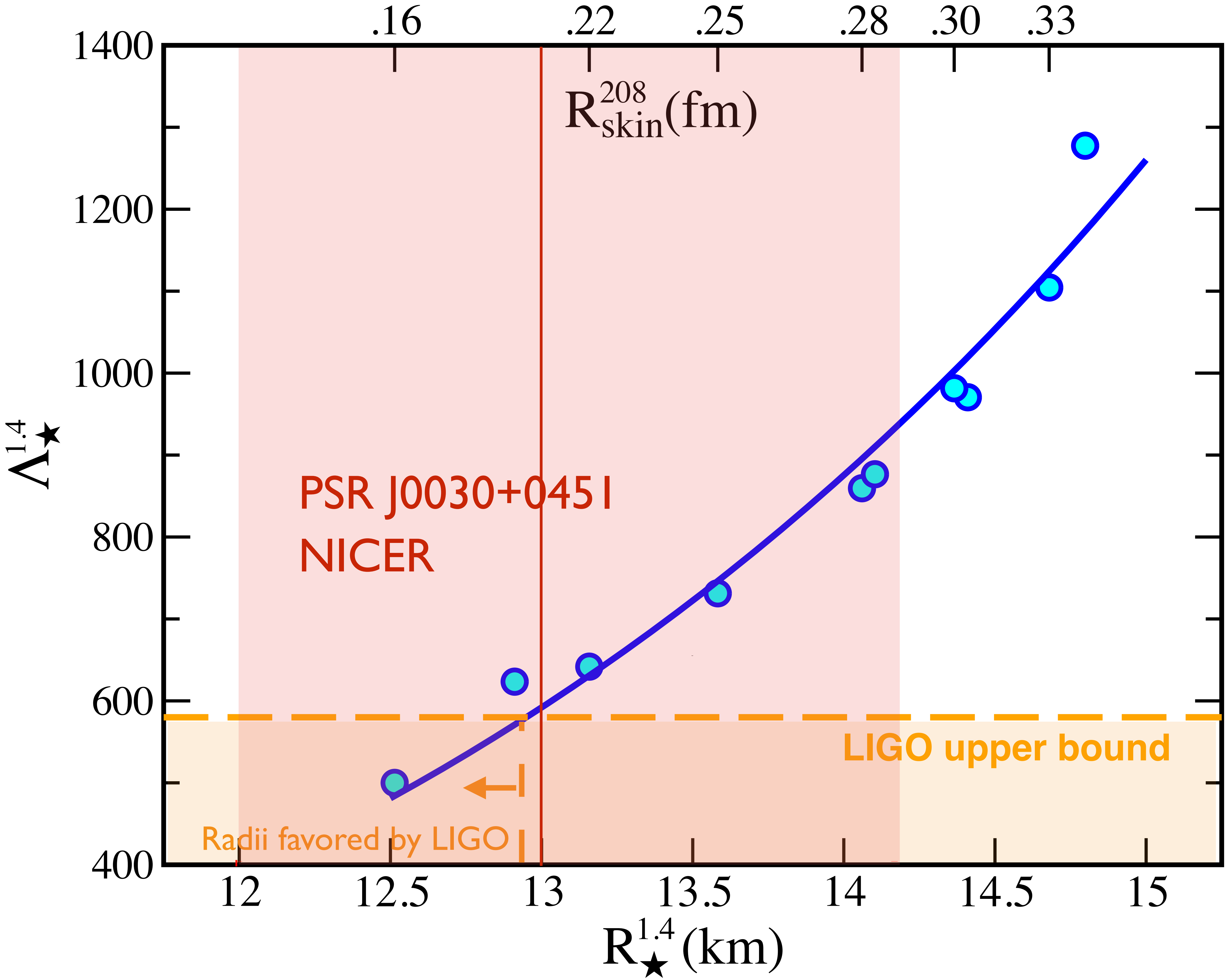
Reveal stellar structure through lightcurve modeling, long-term timing, and pulsation searches



Lightcurve modeling constrains the compactness (*M/R*) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending…



.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_{skin}^{208}(fm)
1400
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$\Lambda_\star^{1.4}$
PSR J0030+0451
NICER
LIGO upper bound
Radii favored by LIGO
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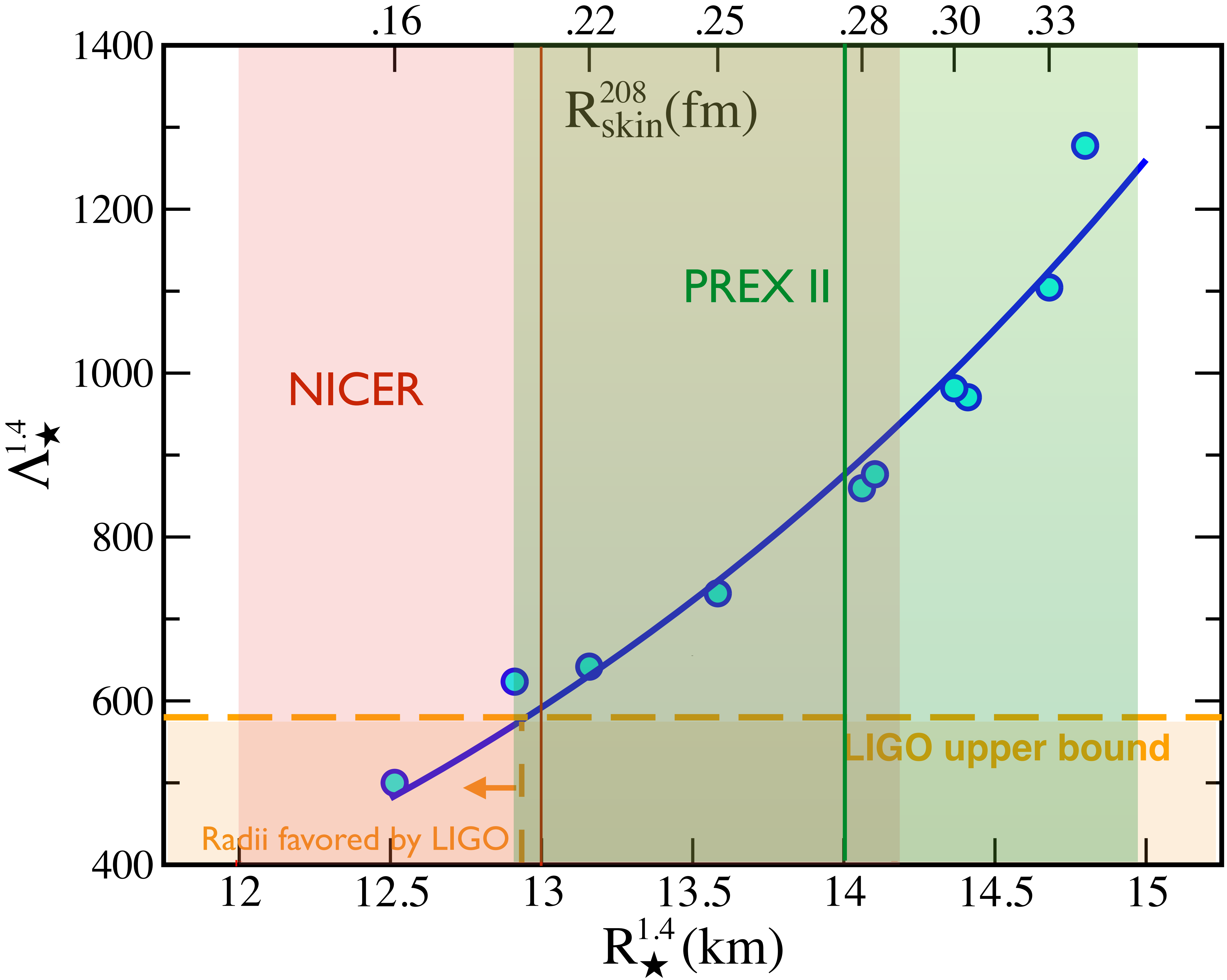
$R_\star^{1.4}$(km)



.16
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R^{208}_{skin}(fm)
PREX II
NICER
LIGO upper bound
Radii favored by LIGO
$\Lambda^{1.4}_{\star}$
$R^{1.4}_{\star}$(km)
1400
1200
1000
800
600
400
12
12.5
13
13.5
14
14.5
15

Radius of 1.4M_{sun} Neutron Star

- LIGO: Small NS deformability suggests R is13 km or less.
- Nicer: R=13 +/- ~1 km
- PREX II: R=13 km or more.
- Simplest solution -> Radius of NS near 13 km and neutron skin in ^{208}Pb near PREX II lower limit: R_n-R_p ~ 0.20 to 0.22 fm.

Nuclear saturation

- 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.
  - Baryon density $\rho_b(r)$ approx constant in interior of heavy nucleus. *Never been directly observed.*
  - ^{40}Ca is largest stable N=Z nucleus, too small to have nearly constant interior density.
  - Have interior charge densities for heavier N>Z systems but not neutron or baryon densities.

PREX II provides first clean measurement of interior baryon density of a heavy nucleus.

Interior weak density of ^{208}Pb

- Two parameter (sym.) Fermi function [see PRC **102** (2020) 044321]

$$\rho_{\mathrm{wk}}(r,c,a)=\rho^0_{\mathrm{wk}}\frac{\sinh(c/a)}{\cosh\left(r/a\right)+\cosh(c/a)}$$

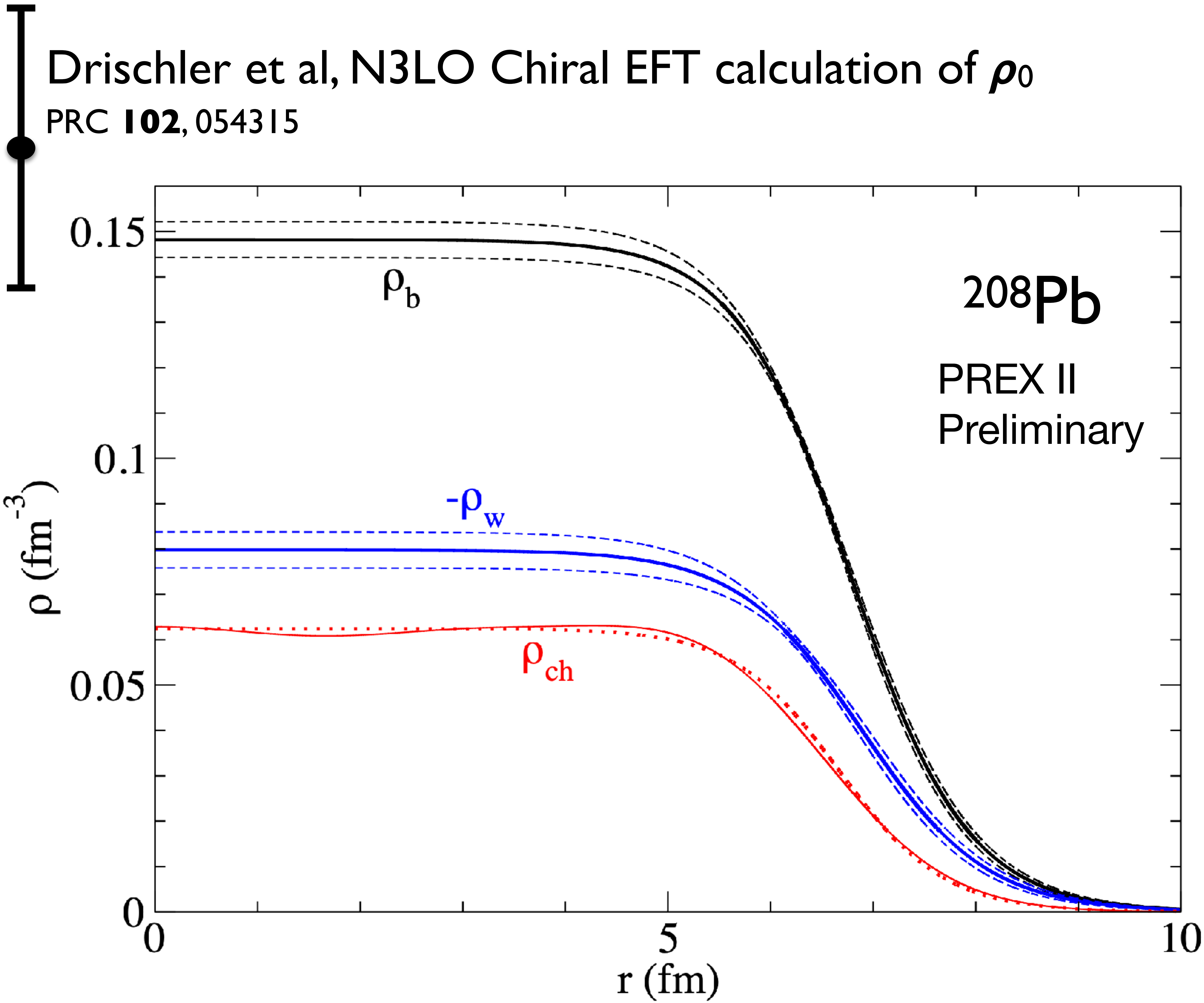
$$R^2_{\mathrm{wk}}=\frac{1}{Q_{\mathrm{wk}}}\int r^2\rho_{\mathrm{wk}}(r)d^3r=\frac{3}{5}c^2+\frac{7}{5}(\pi a)^2$$

$$\rho^0_{\mathrm{wk}}=\frac{27Q_{\mathrm{wk}}}{4\pi(5R^2_{\mathrm{wk}}-4\pi^2a^2)\sqrt{15R^2_{\mathrm{wk}}-21\pi^2a^2}}$$

- Surface thickness parameter *a*: measure with 2nd PV exp at higher Q^2 , feasible at Mainz [PRC **102**, 064308], or take from theory.
- Many nonrel. and relativistic density functionals have *a*=0.605 +/- 0.025 fm

Drischler et al, N3LO Chiral EFT calculation of ρ_0

PRC **102**, 054315



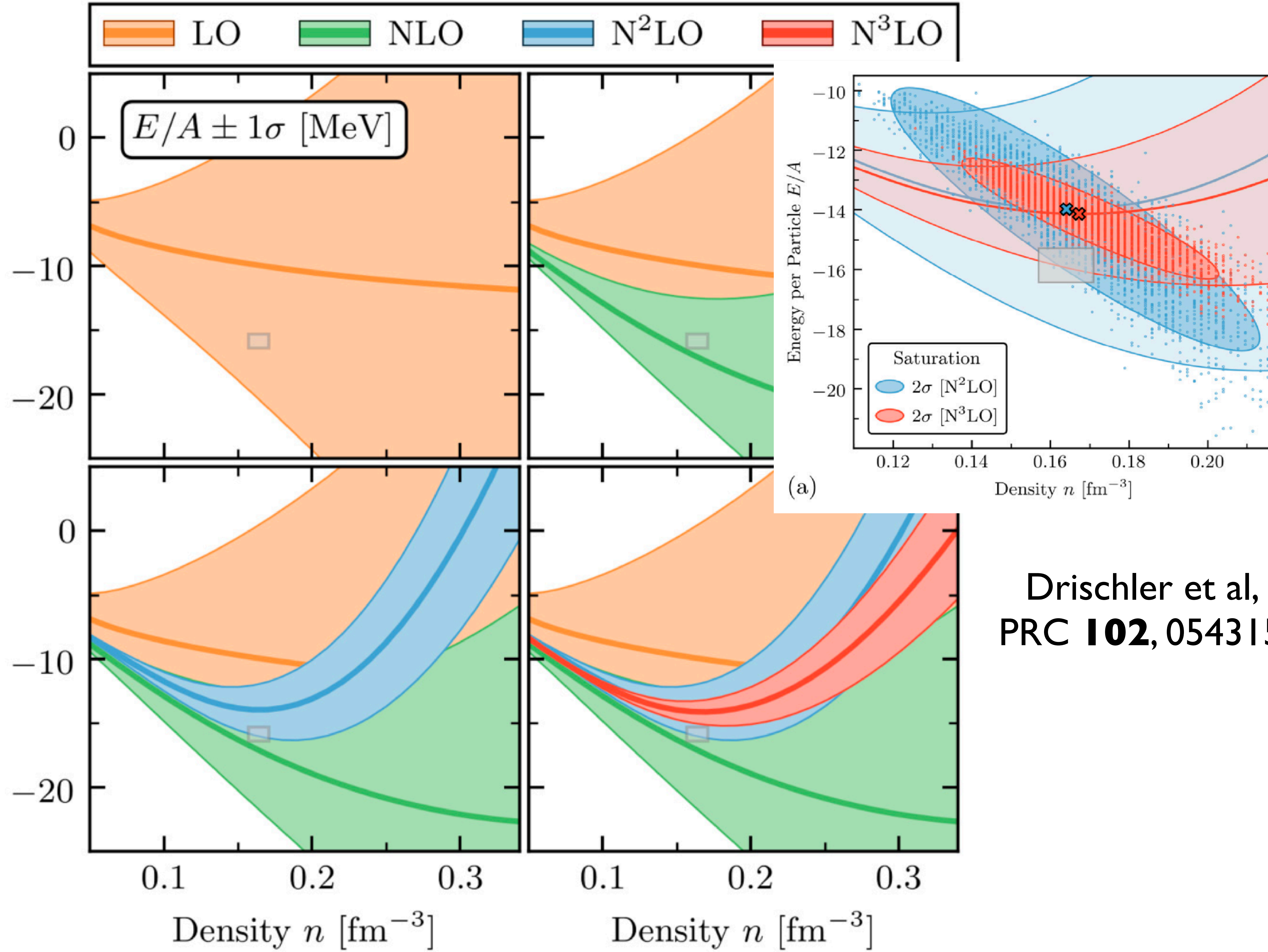
Interior baryon density of ^{208}Pb

- Prex II: R_W=5.795+/-0.082 fm (1.4%) implies
- ρ_W^0=-0.0798+/-0.0039(R_W)+/-0.0013(a) fm^{-3}
- Add known charge density to get baryon density
- ρ_b^0 = 0.1482+/-0.0042 fm^{-3}
- *Fundamental nuclear structure measurement, very closely related to nuclear density $\rho_0 \sim 0.16$ fm^{-3}.*
- *Error is small only* 2.8% ~ (1/2) 3 $\Delta R_W/R_W$

PREX II, preliminary

Chiral EFT and CREX

- Chiral EFT expands 2, 3, … nucleon interactions in powers of momentum transfer over chiral scale.
- Nucleon “hard cores” too small -> calculations with only 2 nucleon forces saturate at too high a density (up to $2\boldsymbol{\rho}_0$)
- Three nucleon forces very important for $\boldsymbol{\rho}_0$.
- **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.
- CREX measures neutron skin in ^{48}Ca. Smaller system allows direct comparison to Chiral EFT calculations and very sensitive to 3 *neutron* forces.



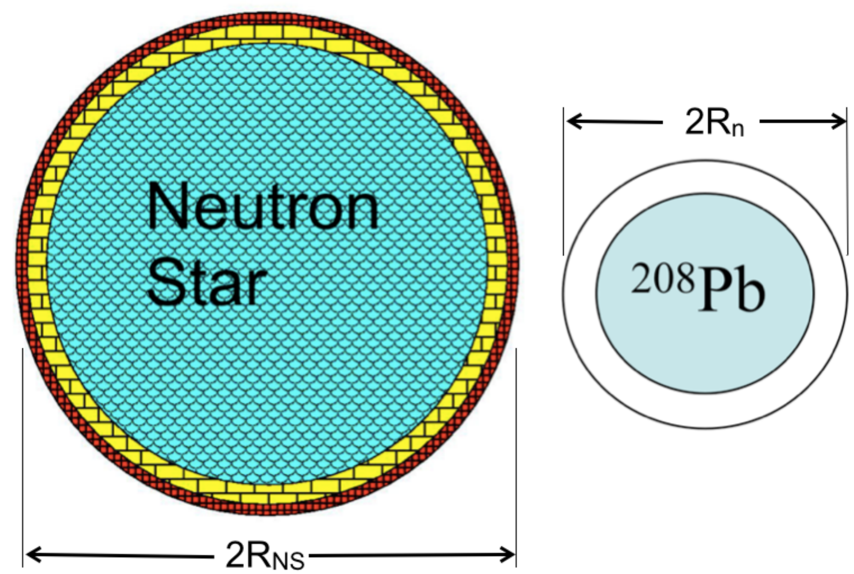
Drischler et al,
PRC **102**, 054315

Parity violation at Mainz

- Can measure surface thickness of ^{208}Pb weak charge density at Microtron.
- 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).

The neutron skin of ^{208}Pb and the structure of neutron stars

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



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JLAB Hall A, Jan. 2021