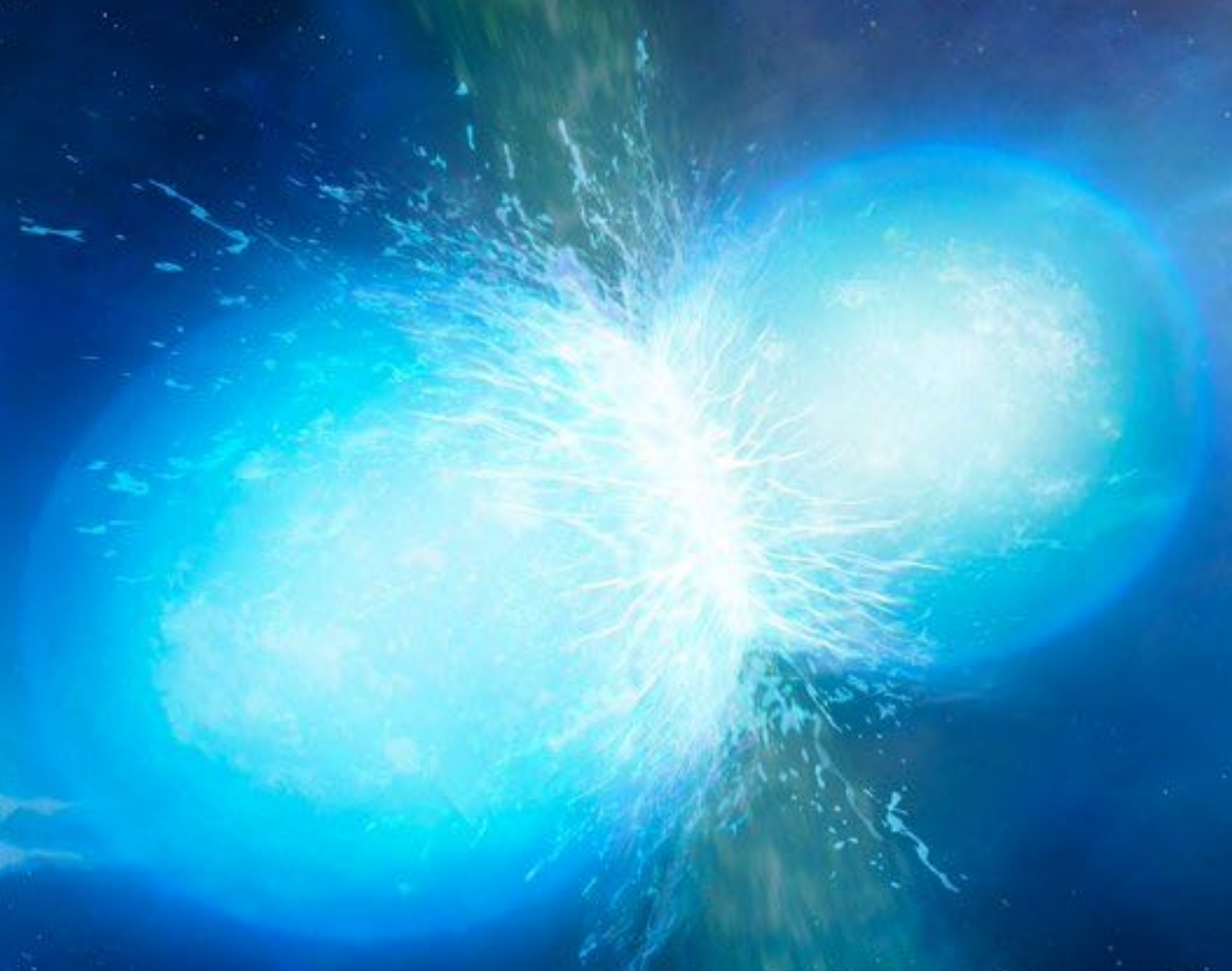
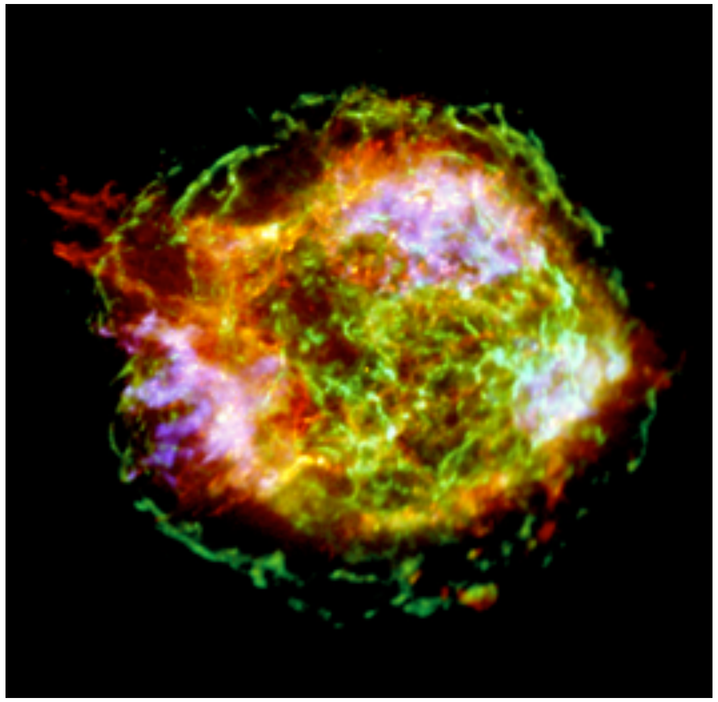
Neutron skins of nuclei vs neutron star deformability



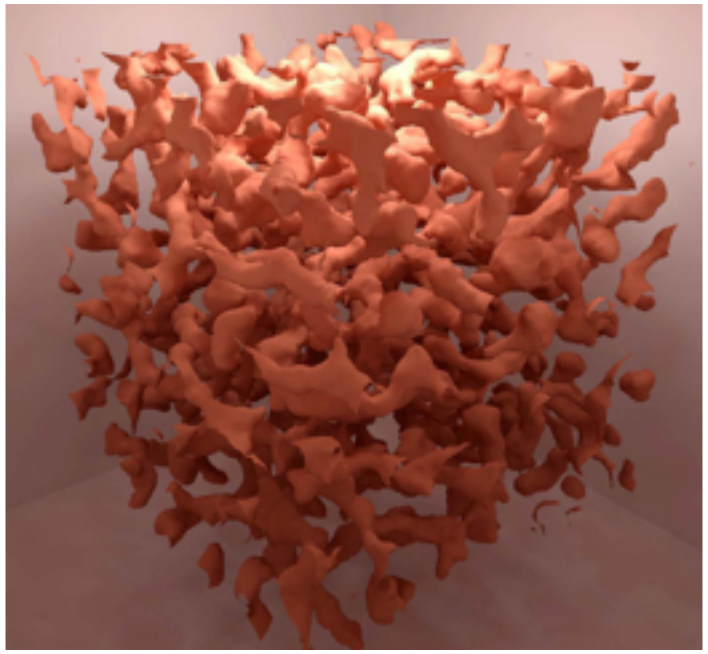
Chuck Horowitz, Indiana U., INT, Mar. 2018

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...*

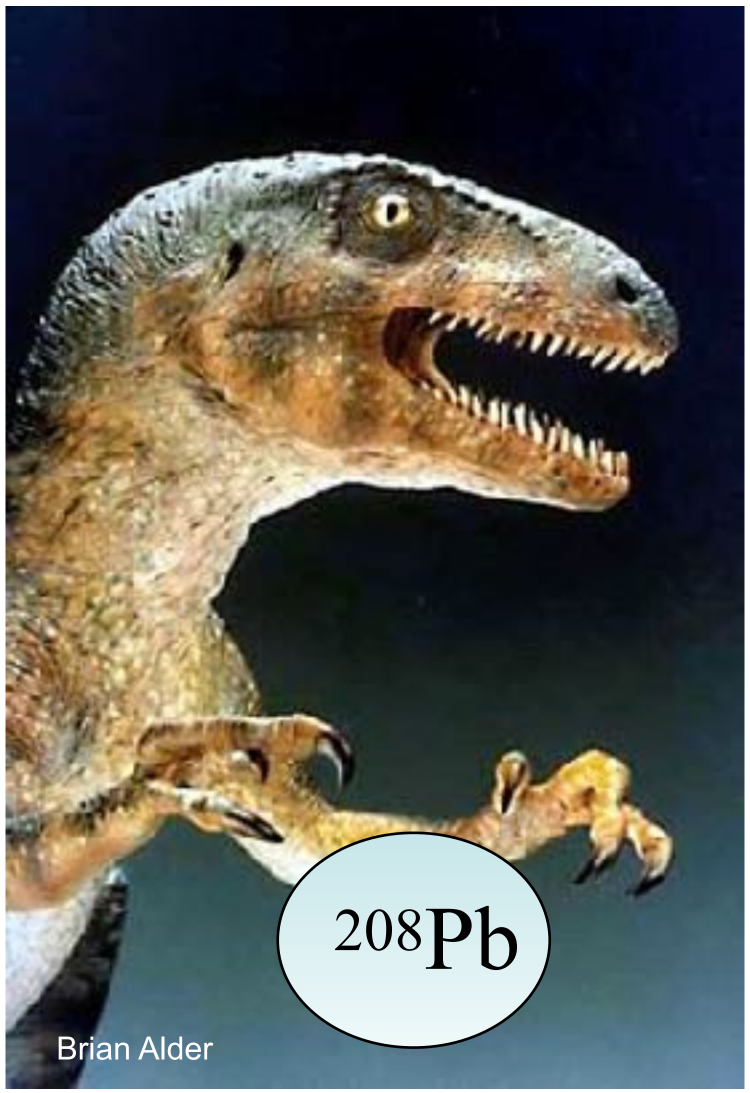


Supernova remanent Cassiopea A in X-rays



MD simulation of Nuclear Pasta with 100,000 nucleons

Laboratory probes of neutron rich matter



PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.

This has important implications for neutron rich matter and astrophysics.

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

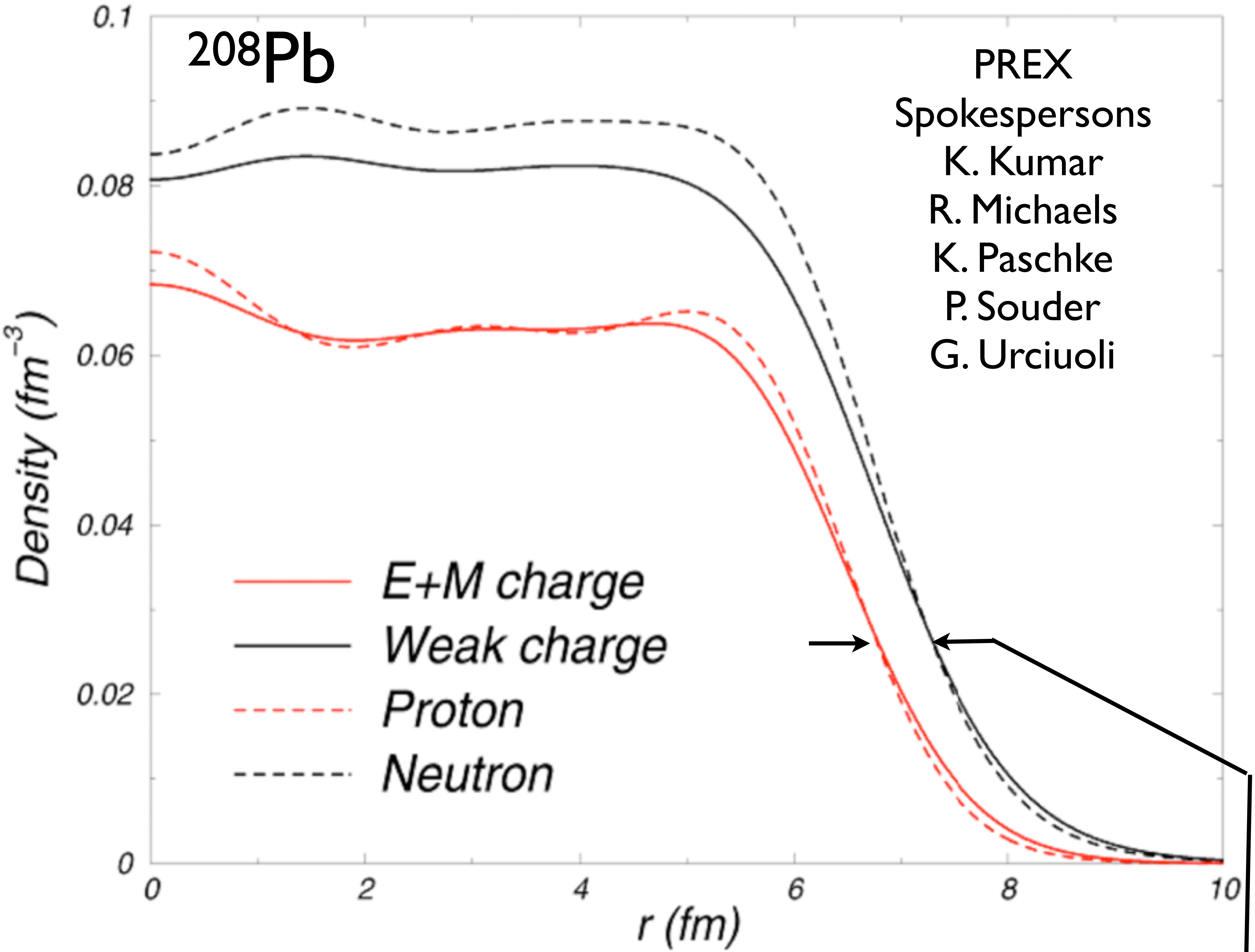
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

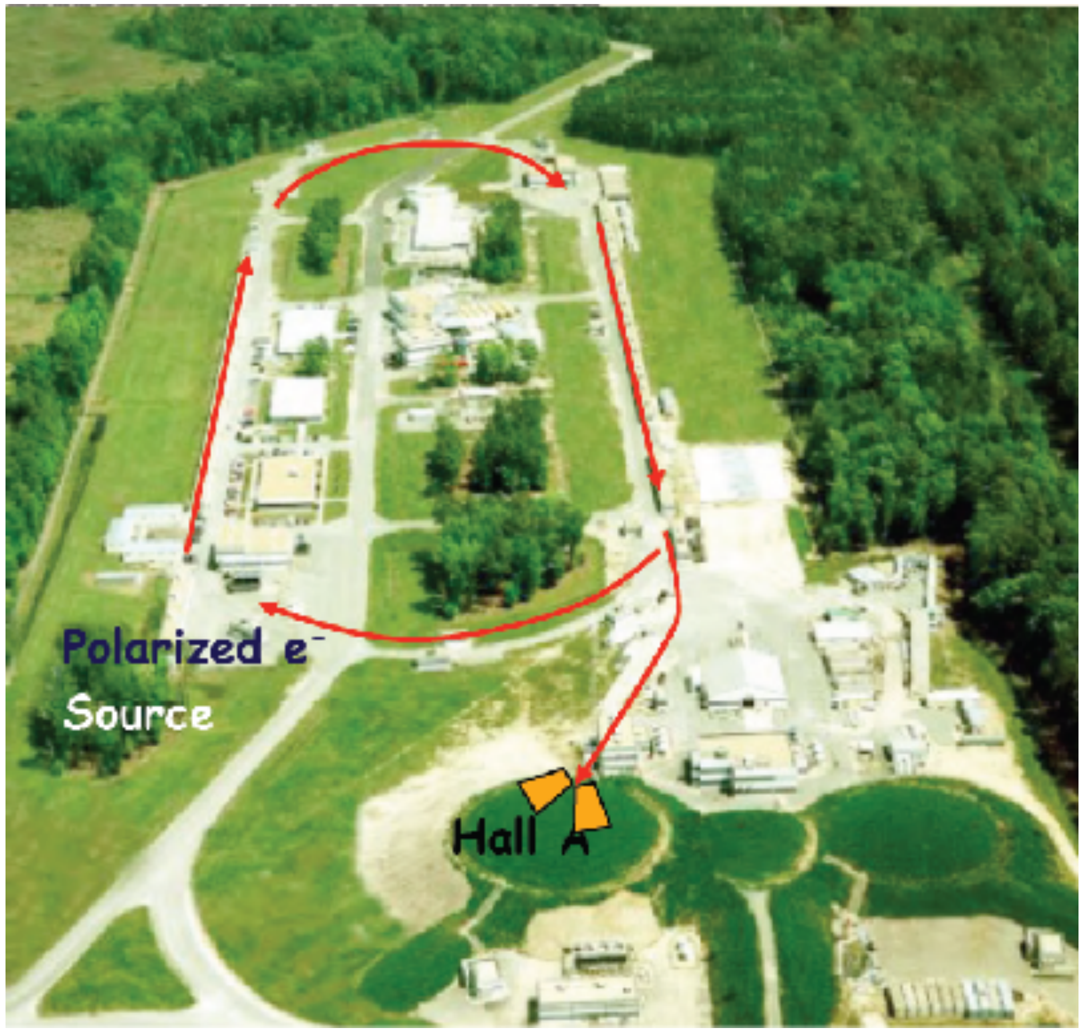
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

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



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

PREX in Hall A 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.

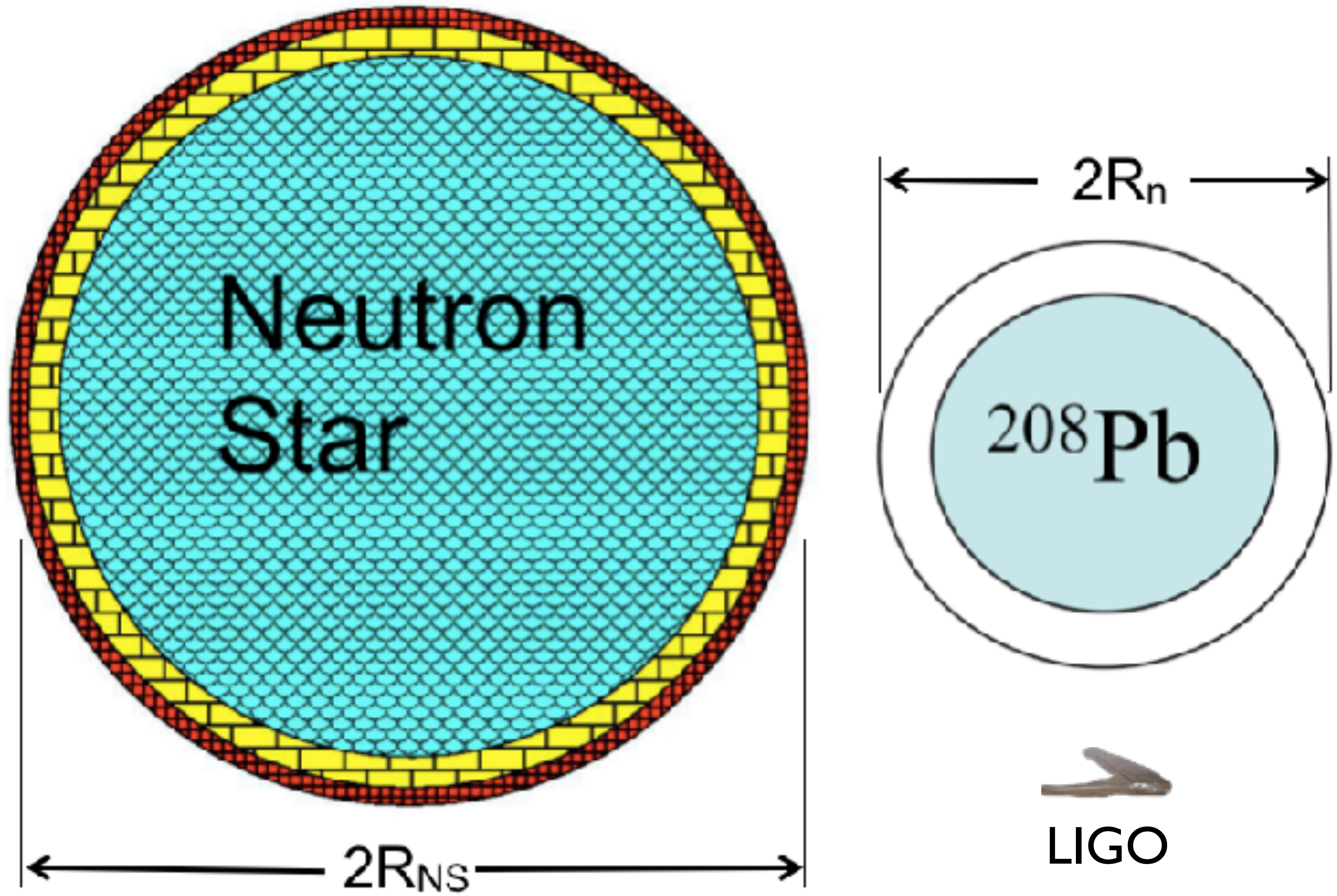
- Next run (plan is 2019)

- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm.

- **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*.

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.

Polarizability of giant nuclei

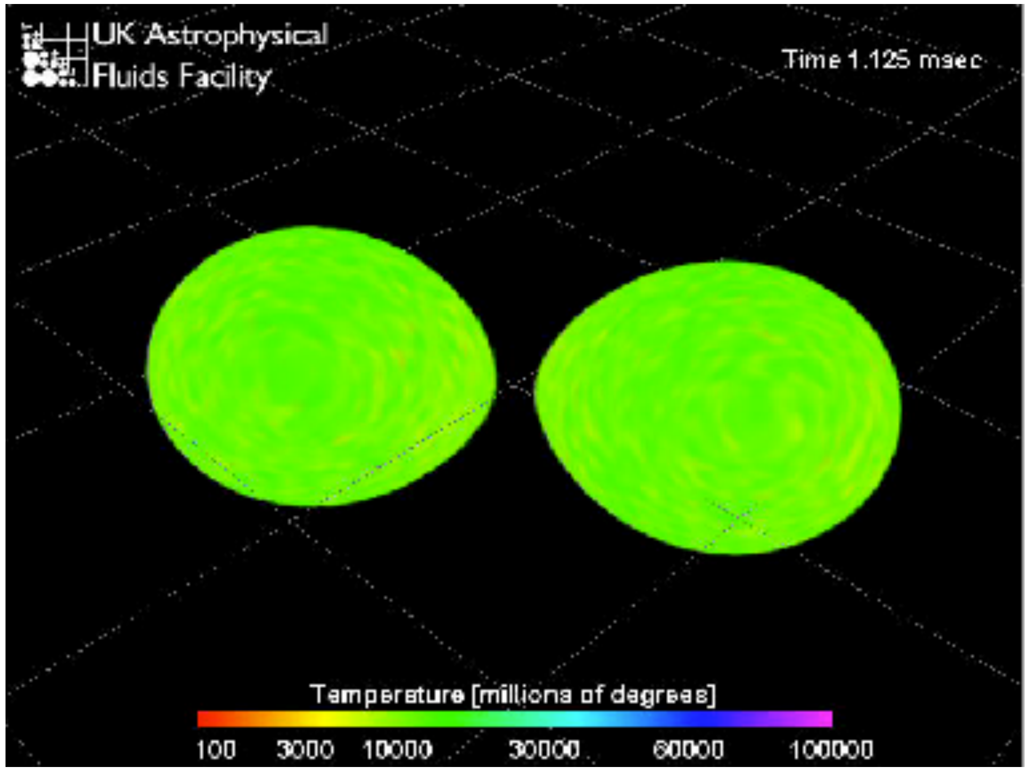
- Electric dipole polarizability of an atom scales as R^3.

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

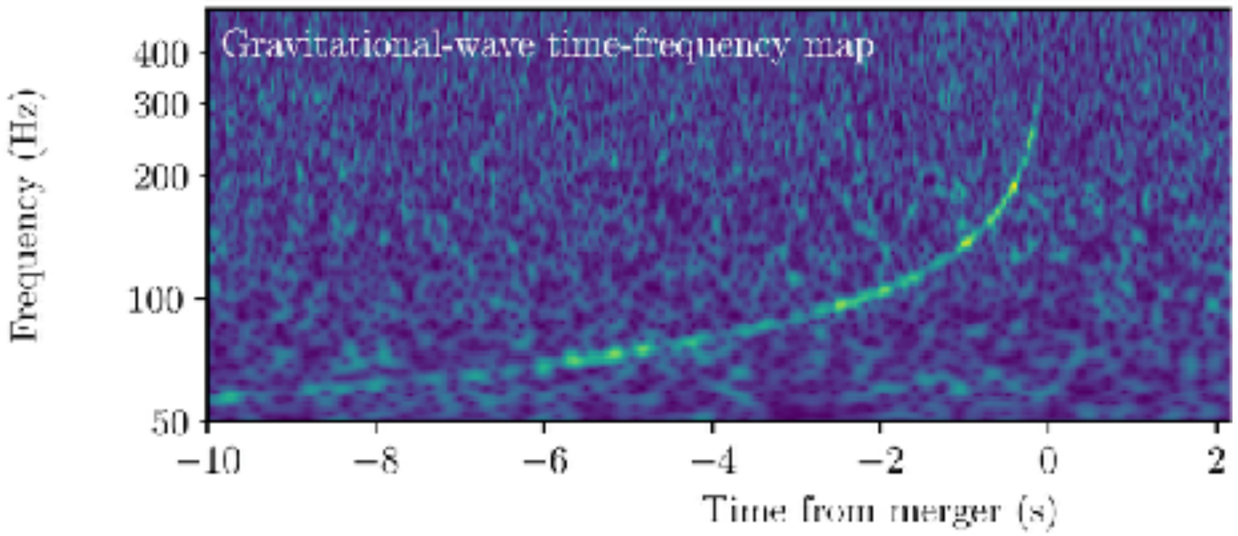
- Mass quadrupole polarizability of a neutron star scales as R^5.

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

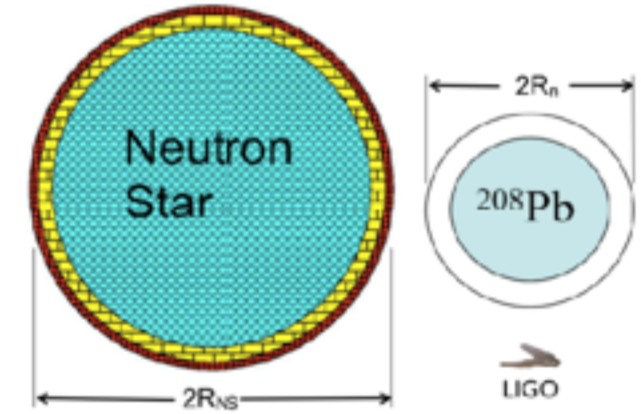
- LIGO is sensitive to increase in orbital frequency as system loses energy to both gravitational waves and internal excitation of neutron stars. GW170817 data place limits on polarizability (deformability) of NS and hence limits on NS radius.



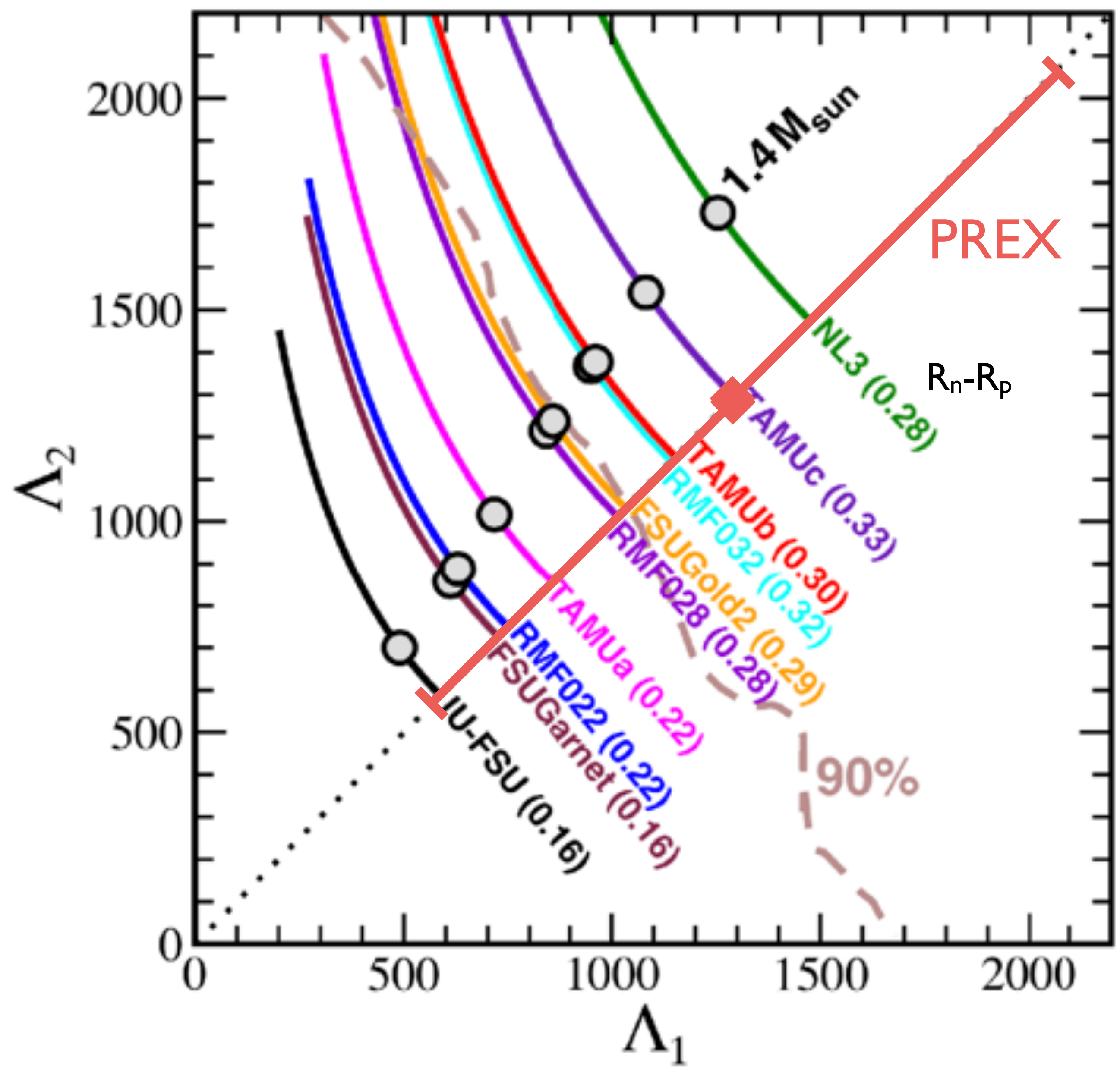
Stephan Rosswog, Richard West



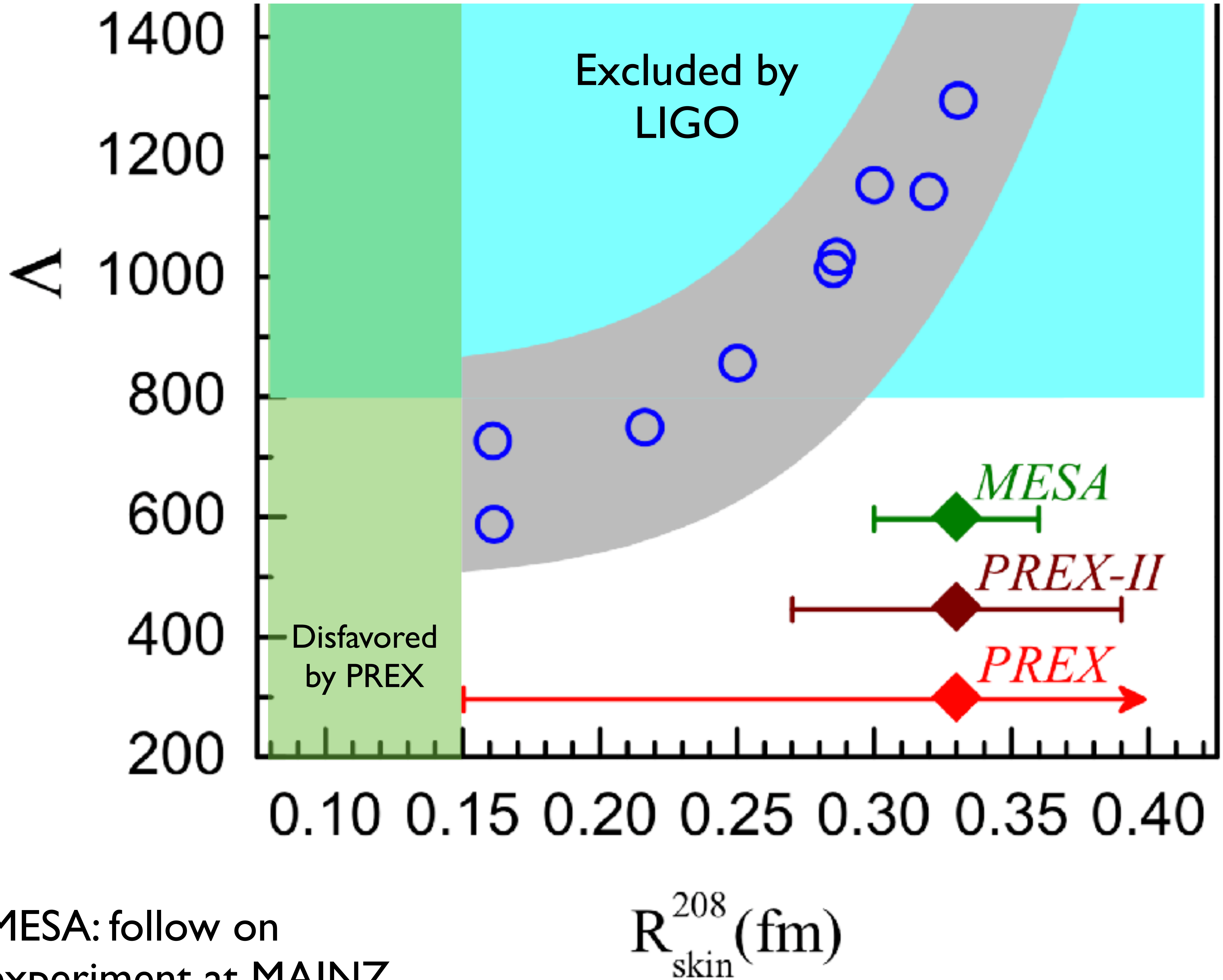
NS deformability and neutron skin of ^{208}Pb



- EOS with high pressure give thick n skin for ^{208}Pb and large deformability for a NS.
- Several relativistic mean field EOS curves with R_n-R_p (^{208}Pb) listed in fm.
- GW170817 rules out stiff EOS with neutron skins greater than about 0.29 fm.
- PREX R_n-R_p= $0.33^{+0.16}_{-0.18}$ fm. Central value ruled out. *PREX lower limit R_n-R_p=0.15 fm gives lower limit for Λ>500.*



GW170817 allowed region to lower left of 90% line. F. Fattoyev et al. ArXiv: 1711.06615



MESA: follow on experiment at MAINZ

F. Fattoyev et al. ArXiv:1711.06615

Density dependence of EOS

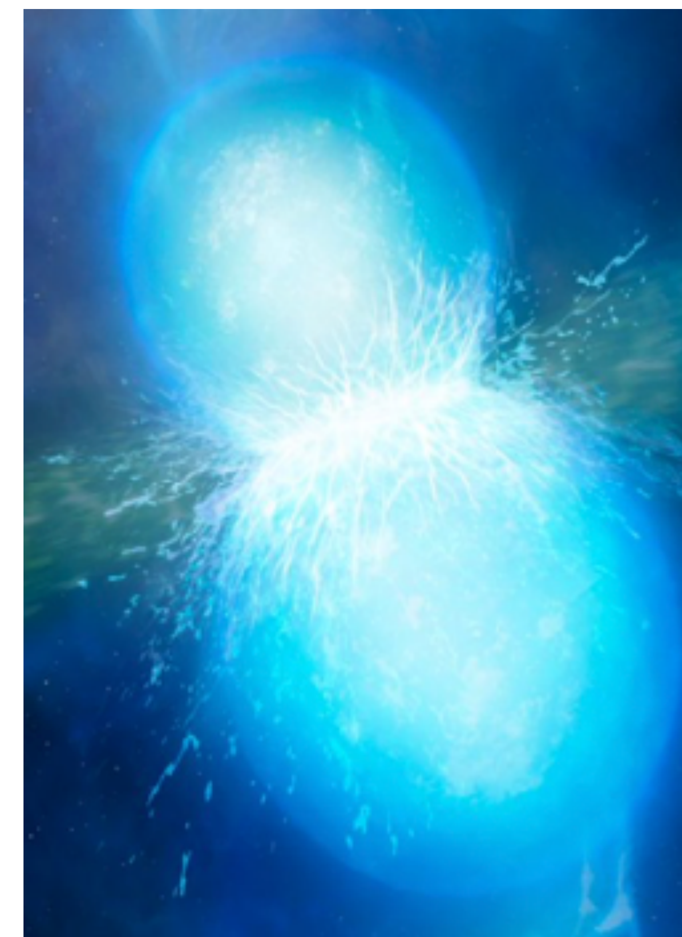
- Neutron skin of nucleus: sensitive to EOS at around 0.7 nuclear density n_0.
- NS radius or deformability: Most sensitive to EOS at around $2n_0$.
- Maximum mass of NS or fate of remnant: sensitive to EOS at high densities.

FRIB TA Summer school: "Neutron star mergers for non-experts: GW170817 in the multi-messenger astronomy and FRIB eras"

- The FRIB Theory Alliance will offer a summer school May 16-18, 2018 at the Facility for Rare Isotope Beams (FRIB) in East Lansing, MI.

- The school is intended for an inclusive audience of graduate students, post docs, and more senior researchers working in nuclear physics, astrophysics, astronomy, and related areas.

- Lecturers: Brian Metzger (Columbia), C. J. Horowitz (Indiana), Katerina Chatziioanno (CITA), David Radice (Princeton), Luke Roberts (MSU), Hendrik Schatz (MSU).



- You are all invited! https://indico.fnal.gov/event/15789/

Apply be April 1

Neutron skins of nuclei vs neutron star deformability

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke…
- NS deformability vs ^{208}Pb skin: **Farrukh Fattoyev**, J. Piekarewicz.
- Graduate students: Zidu Lin (2018), Hao Lu (Astronomy), Jianchun Yin, Zack Vacanti. Also Matt Caplan (2017) now CITA fellow at McGill, Andre Schneider (2013) now at Caltech.

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C. J. Horowitz, horowit@indiana.edu, First multi-messenger observations of a neutron star merger and its implications for nuclear physics, INT, Mar. 2018