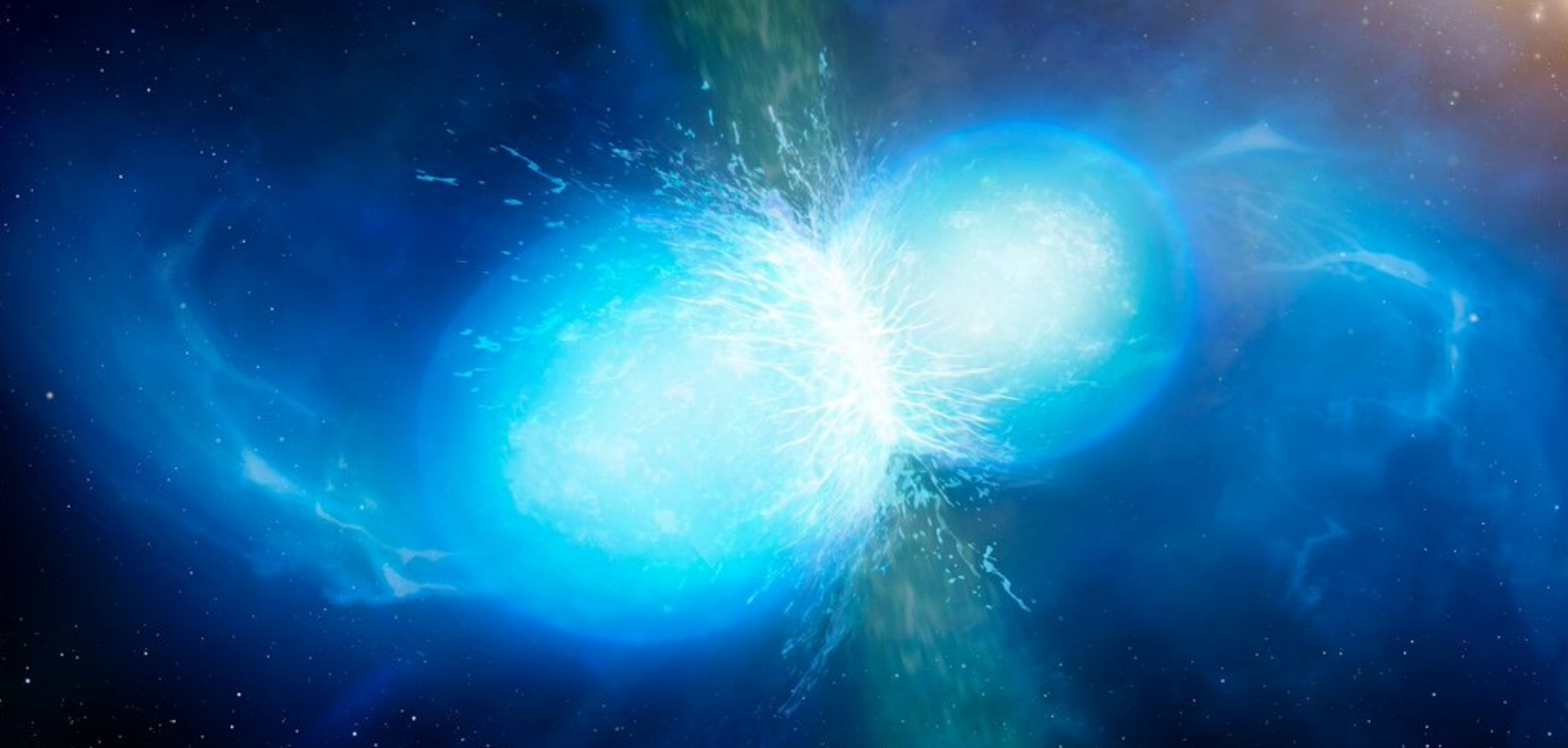
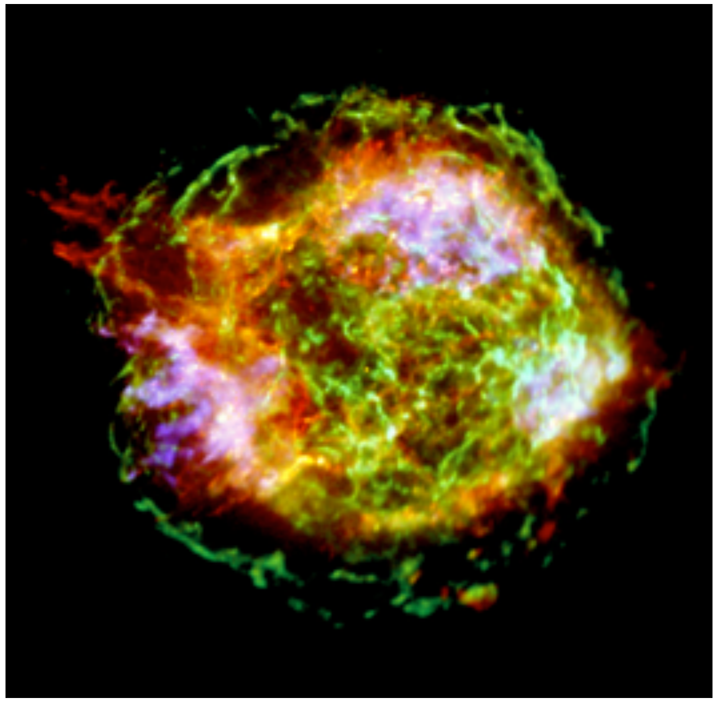
Neutron stars, neutron star mergers, and neutron rich matter



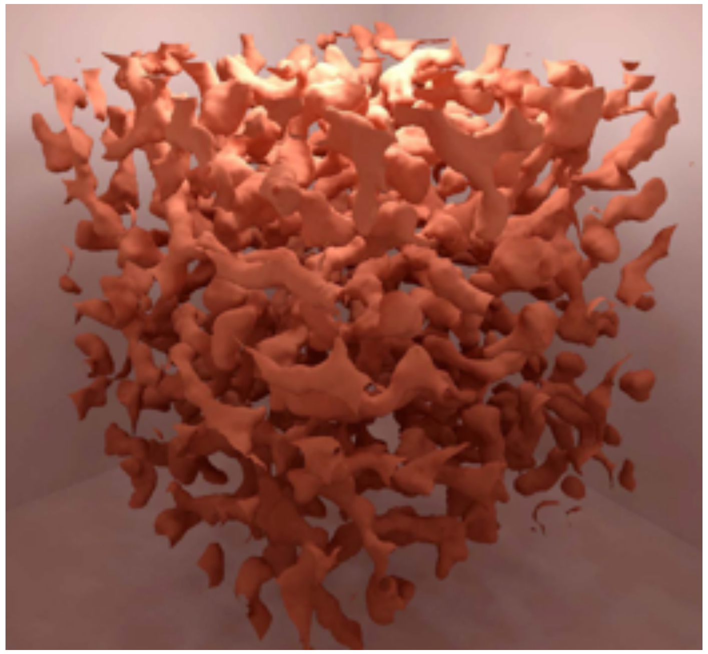
Chuck Horowitz, Indiana U., Ariel, TRIUMF, July 2018

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...*



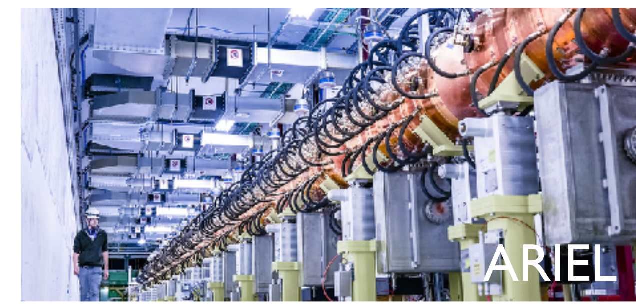
Supernova remanent Cassiopea A in X-rays

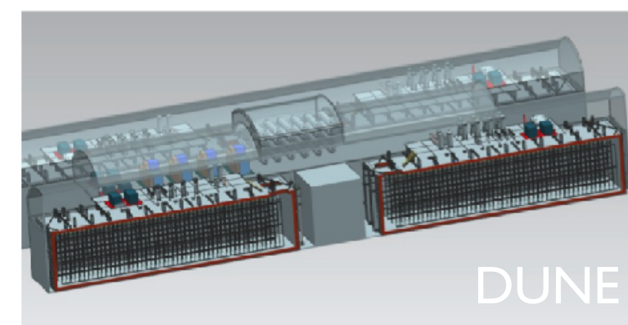


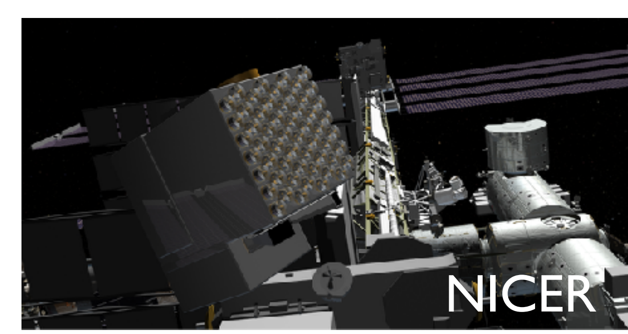
MD simulation of Nuclear Pasta with 100,000 nucleons

Probes of Neutron Rich Matter

- **Multi-Messenger Astronomy:** "seeing" the same event with very different probes is leading to fundamental advances. Often ***photons*** from *solid* neutron star crust, supernova ***neutrinos*** from low density *gas*, and ***gravitational waves*** from energetic motions of *liquid* interior of neutron stars.
- **Laboratory:** Nuclei are liquid drops so most experiments probe liquid n rich matter.
  – Electroweak measurements, Heavy ion collisions, Radioactive beams of neutron rich nuclei...
- **Computational:**
  – Chiral effective field theory (and MC calc. with phenomenological NN and NNN forces) depends on important and poorly observed *three neutron forces*.
  – Chiral expansion does not converge at high densities. This strongly limits microscopic calculations.
- Increases importance of laboratory experiments and astrophysical observations.

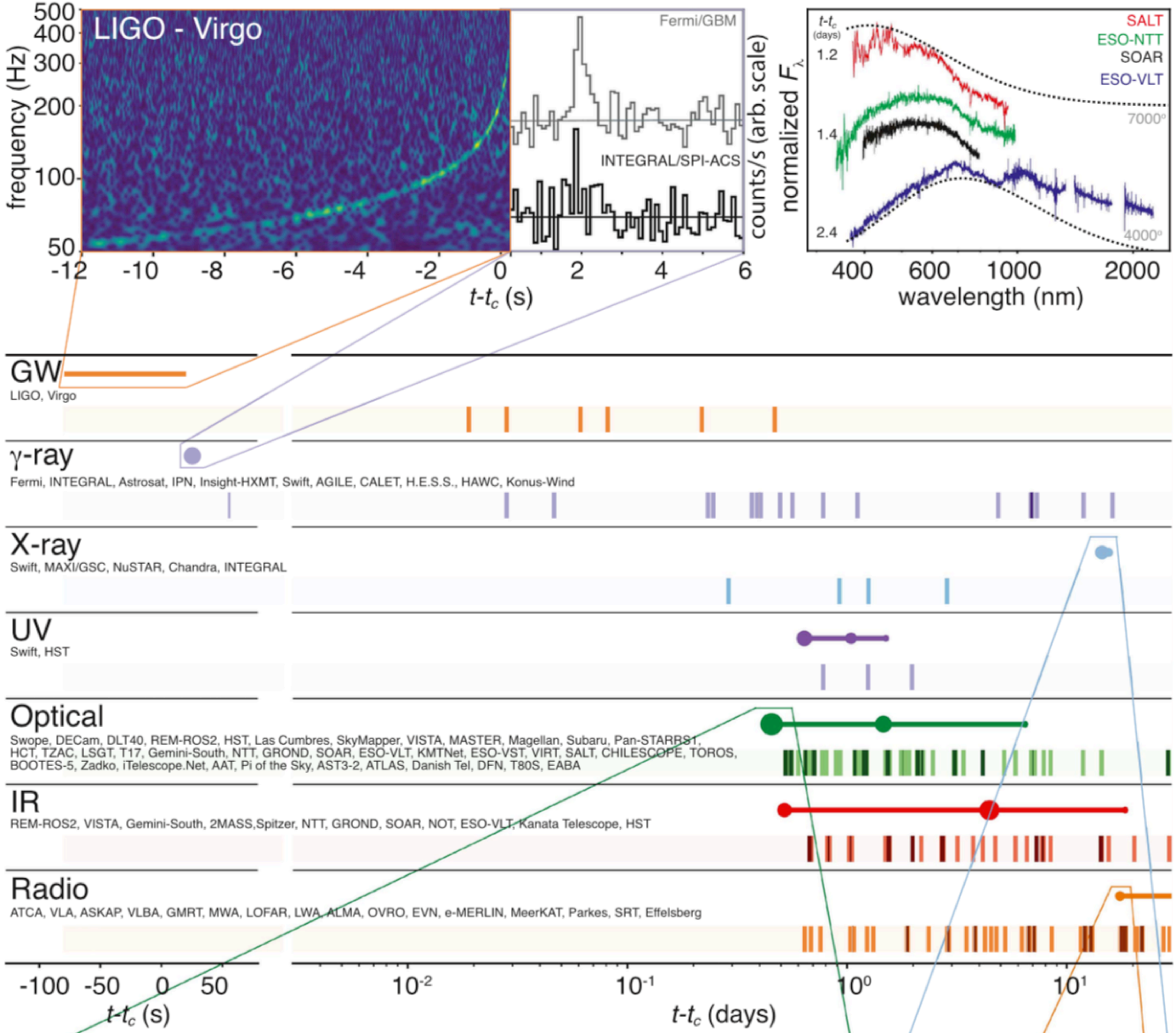






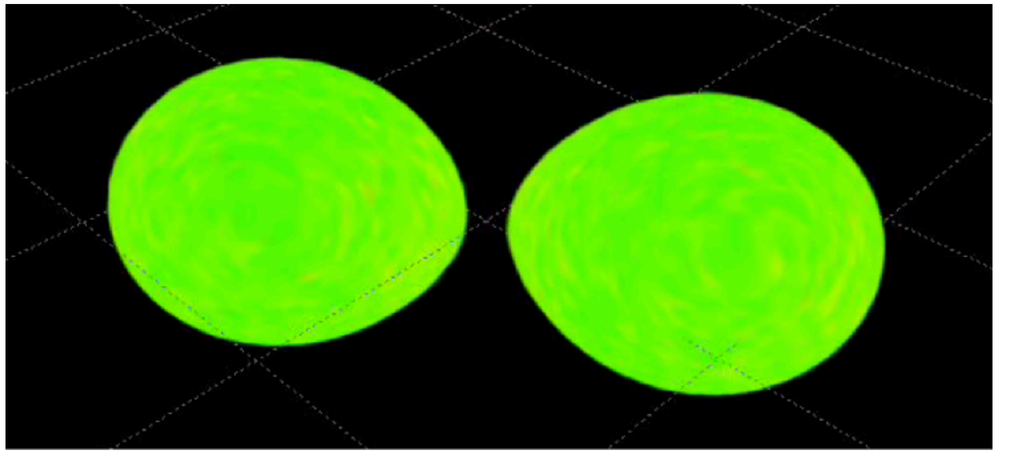
Spectacular event GW170817

- On August 17, 2017, the merger of two neutron stars was observed with gravitational waves (GW) by the LIGO and Virgo detectors.
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observations detected this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.
- Focus here on implications for equation of state of neutron rich matter. Others will discuss implications for r-process nucleosynthesis.



LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
t-t_c (days)
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)

Tidal deformability of NS



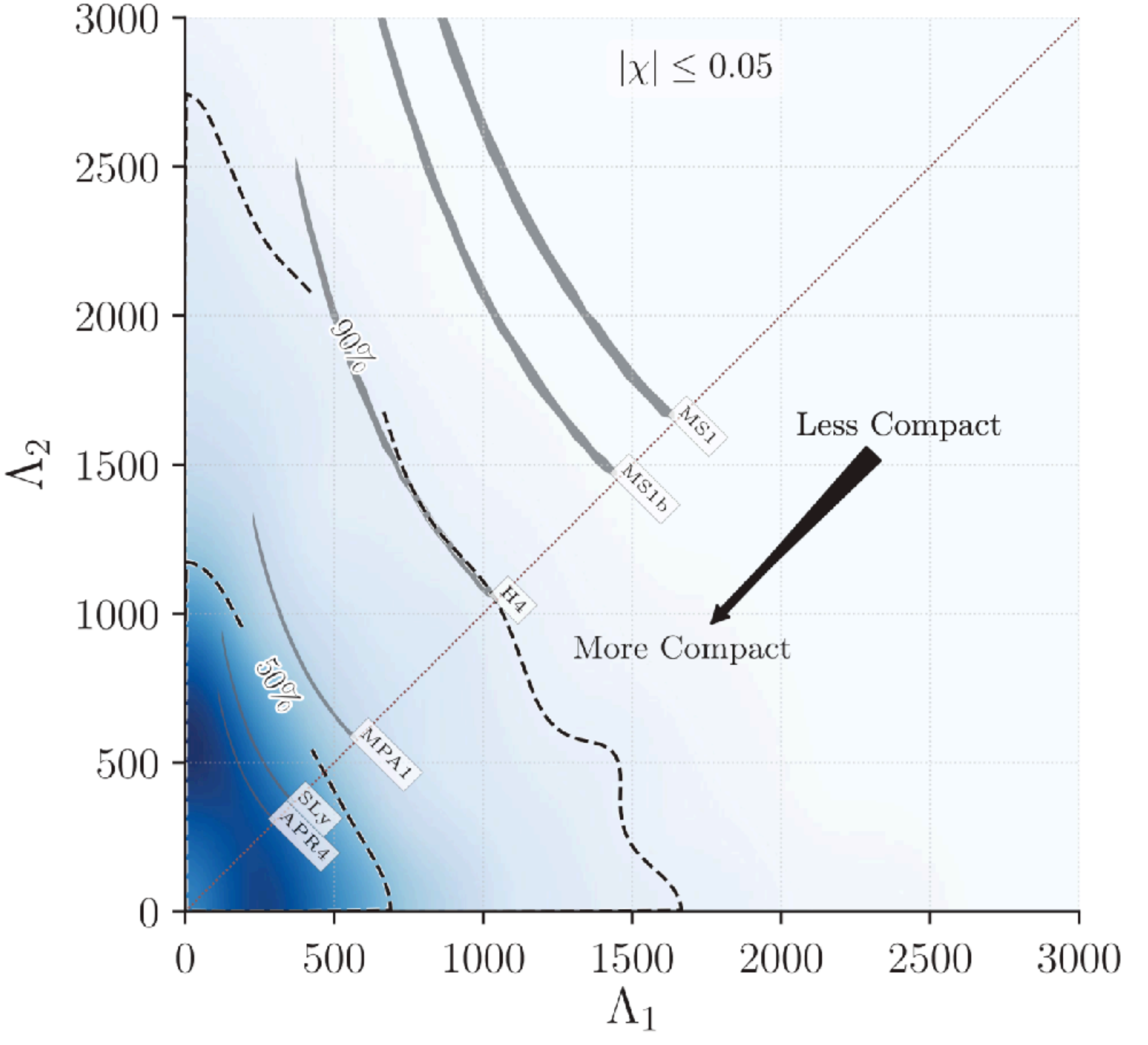
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom ~R^3.

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

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

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

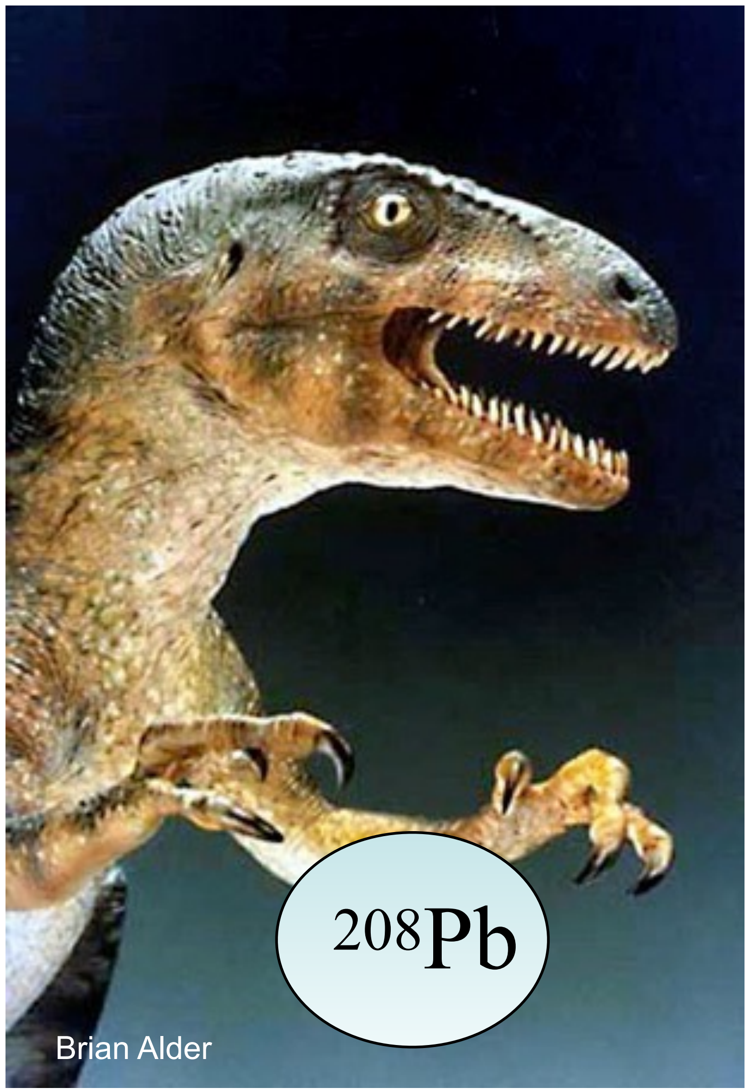
- GW170817 observations set upper limits on Λ_1 and Λ_2.



Equation of state of neutron rich matter

- EOS gives pressure P as a function of density ρ for neutron rich matter: $P=P(\rho)$. This depends on the strength of interactions in dense matter.
- **Low density:** nuclear structure observables including ***neutron skin*** thickness probe EOS near nuclear density. [Nuclear density ~ 3×10^{14} g/cm^3]
- **Medium density:** NS radius or ***deformability*** probe EOS at about twice nuclear density.
- **High density:** maximum NS mass or ***fate*** of merger remnant probes EOS at high densities.

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

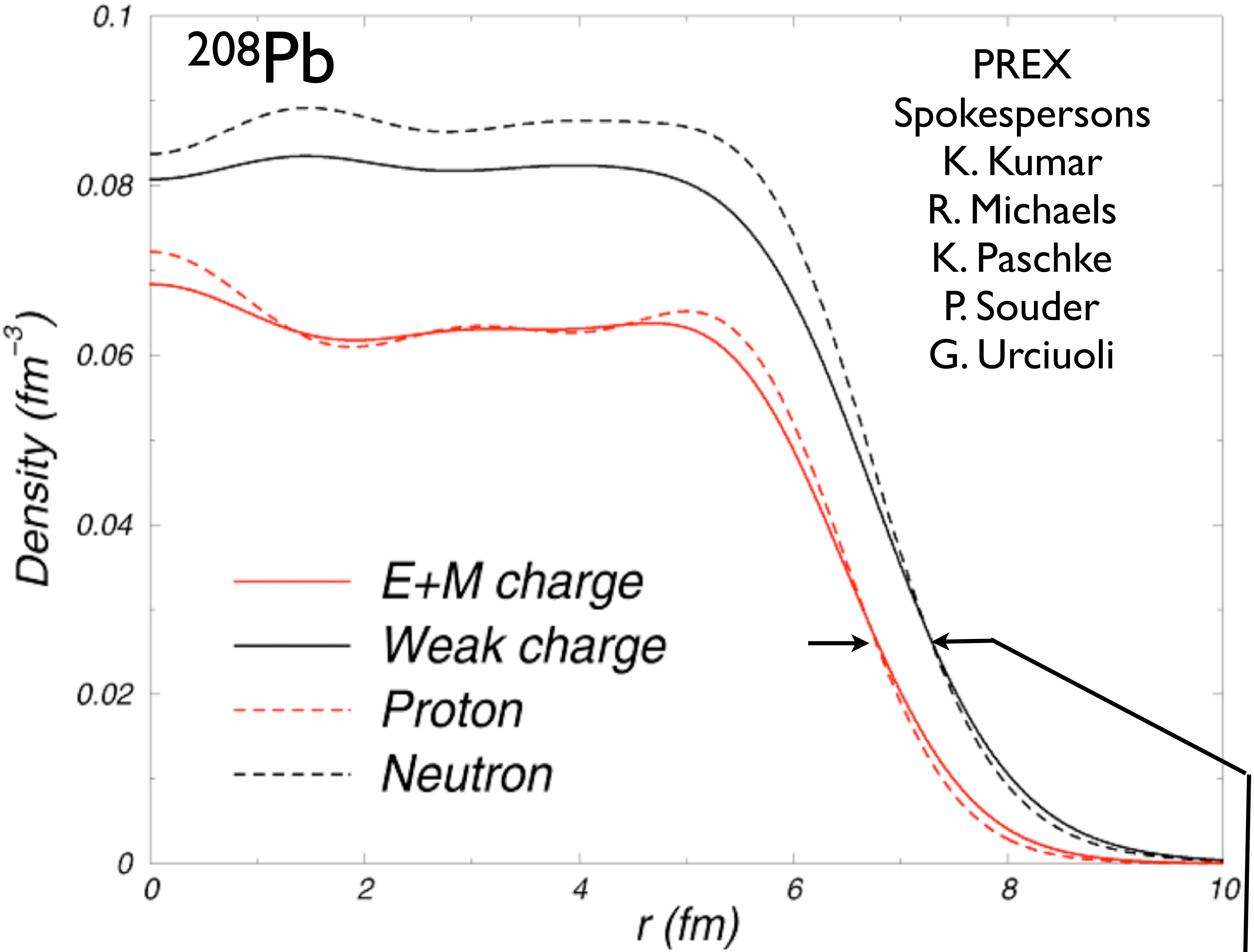
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

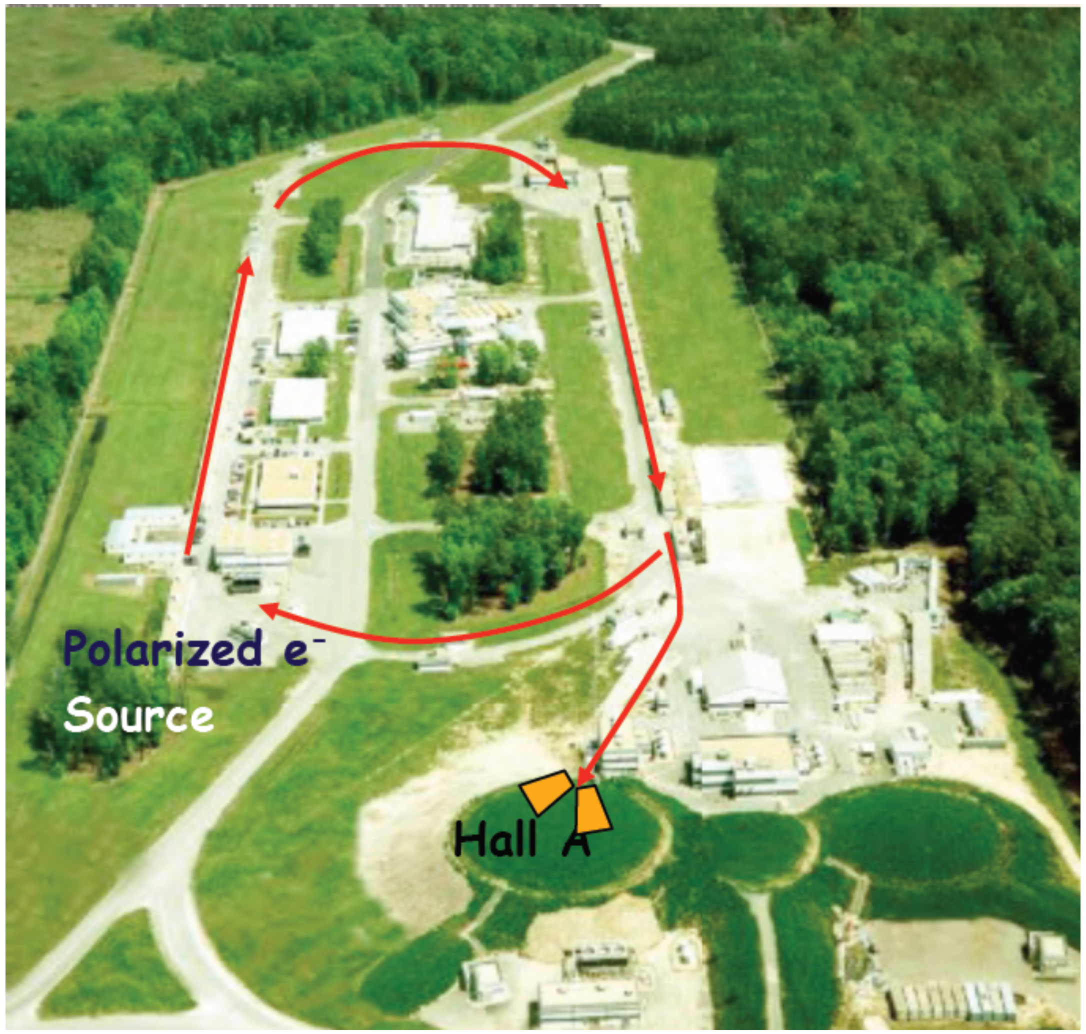
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

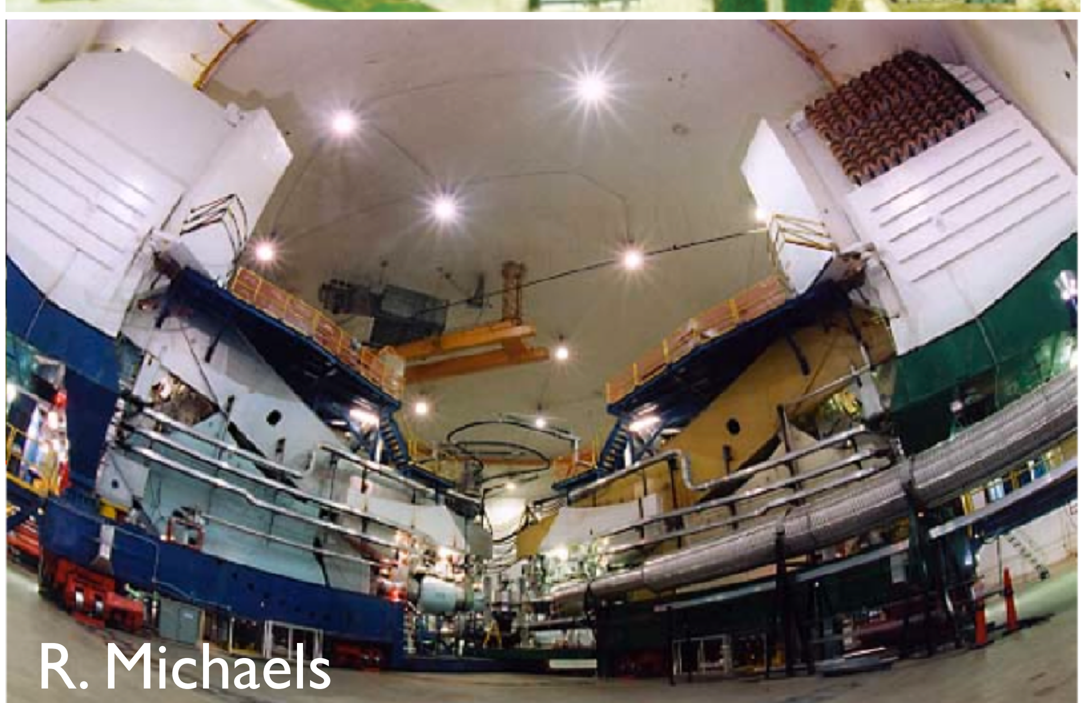
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**



- 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 ± 0.060(stat) ± 0.014(sym) ppm

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

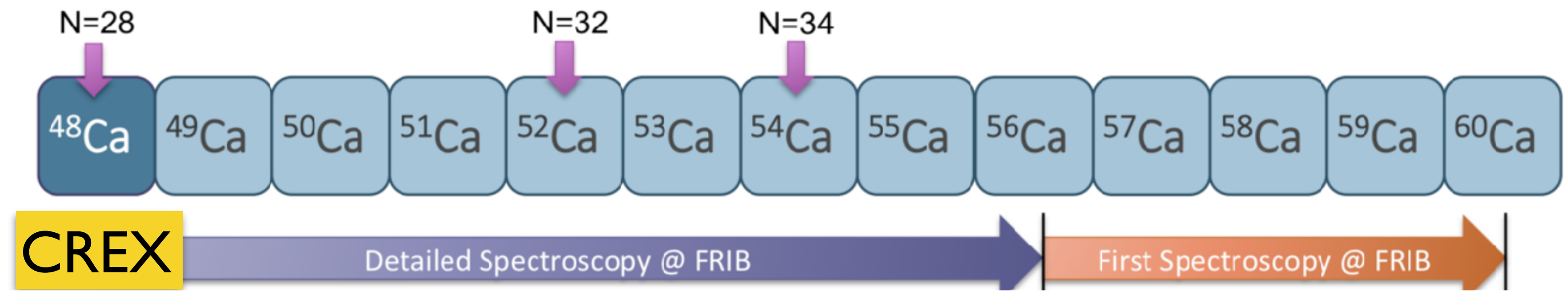
- Next runs (Scheduled for 2019)

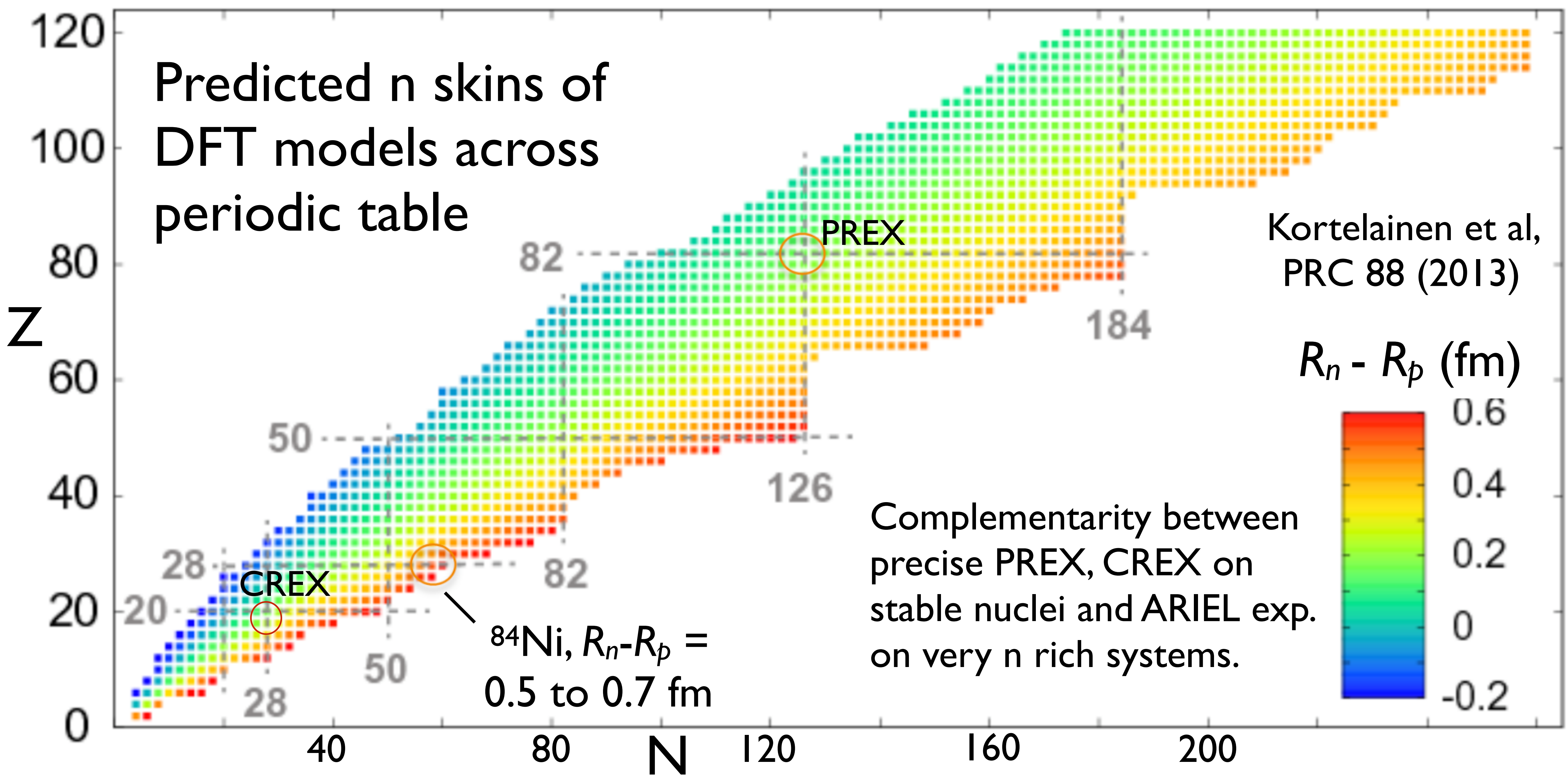
- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm.

- **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*.

Study more n rich nuclei at ISAC/ARIEL

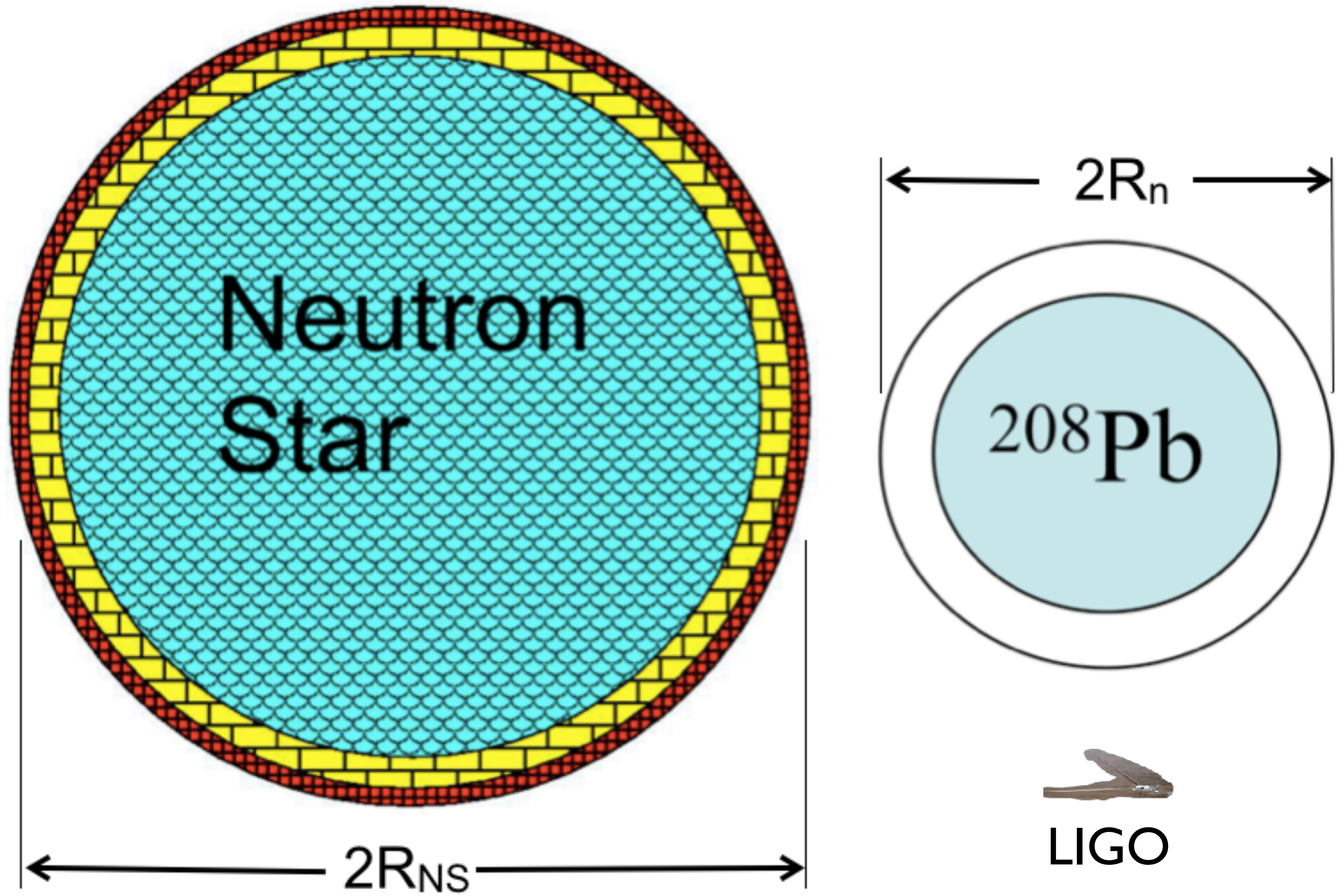
- ^{40}Ca (Z=N=20) is stable. FRIB can make ^{60}Ca (N=40)





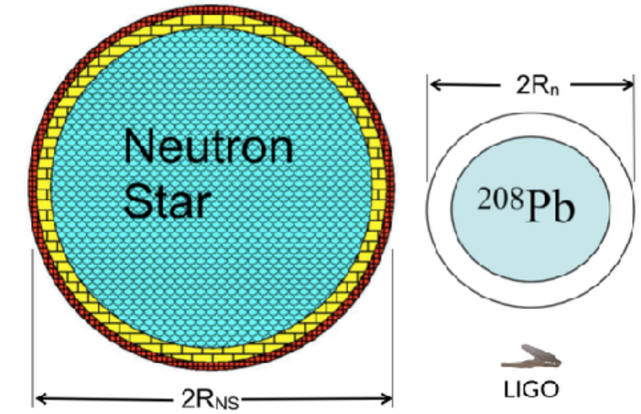
Radii of ^{208}Pb and Neutron Stars

- 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.

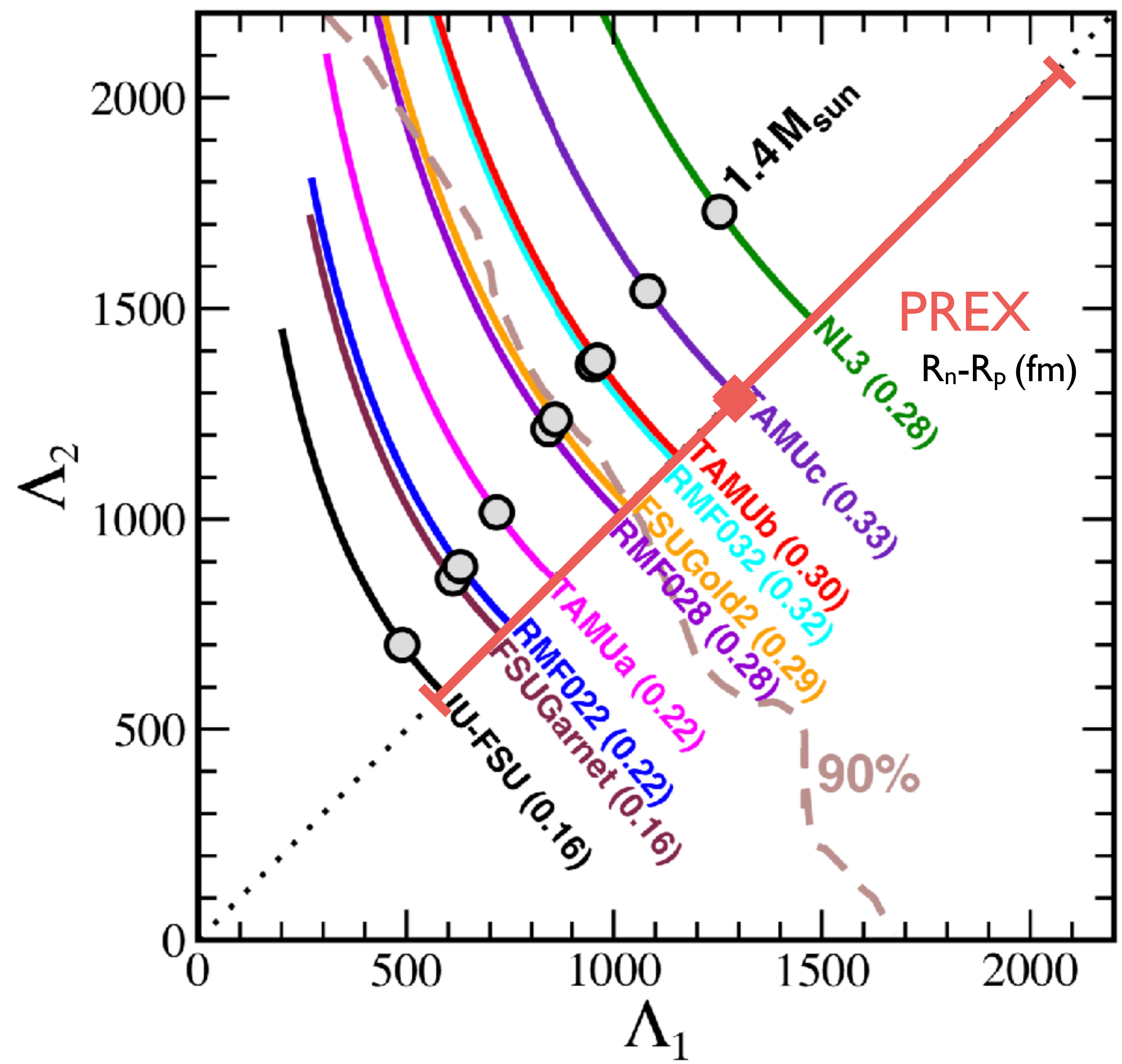


Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

NS deformability and neutron skin of ^{208}Pb



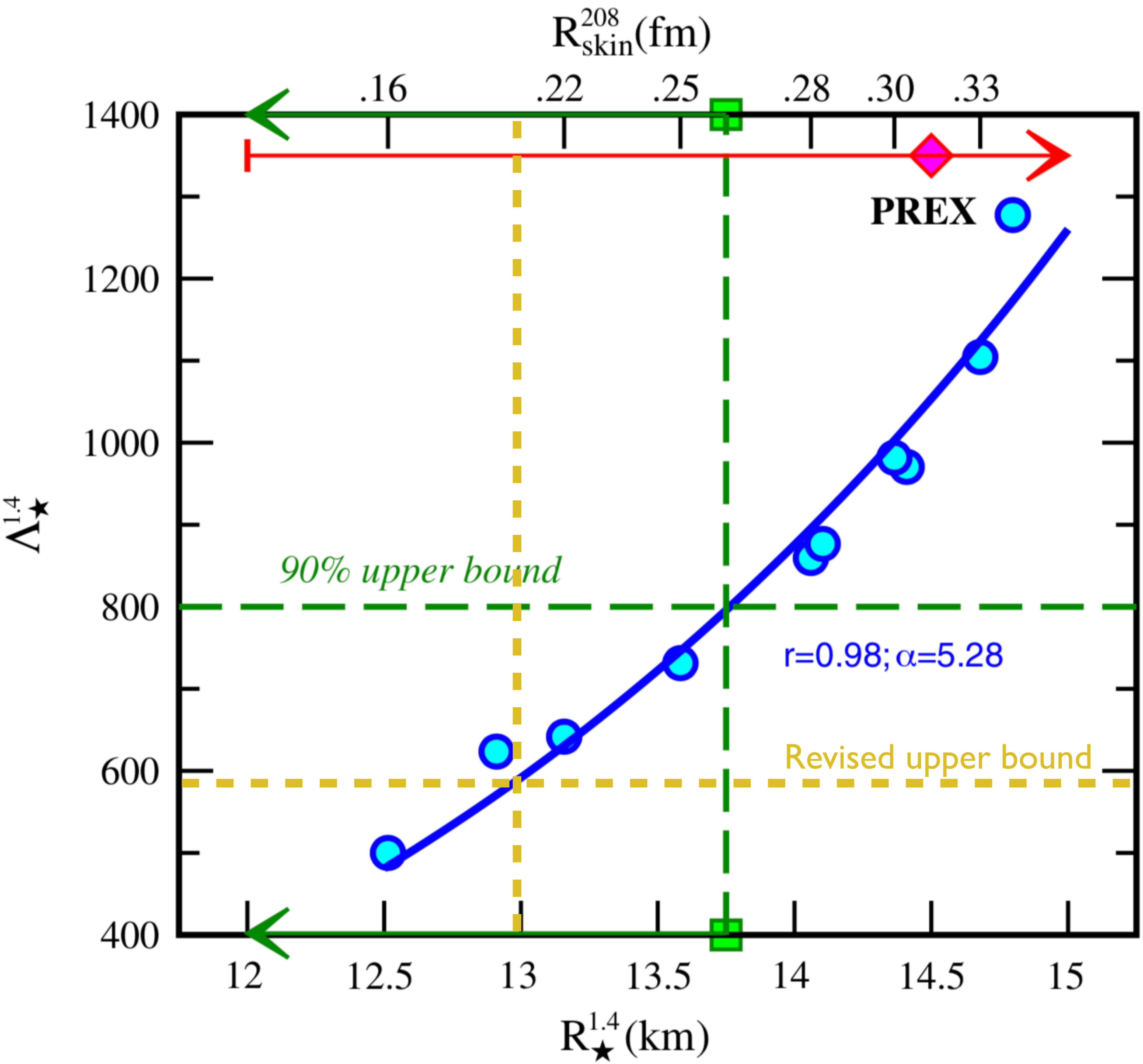
- EOS with high pressure give thick n skin for ^{208}Pb and large deformability for a NS.
- Several relativistic mean field EOS curves with R_n-R_p (^{208}Pb) listed in fm.
- GW170817 rules out stiff EOS with neutron skins greater than about 0.29 fm.
- PREX R_n-R_p= $0.33^{+0.16}_{-0.18}$ fm. Central 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. Phys. Rev. Let. **120**, 172702 (2018).

Deformability Λ of $1.4M_{sun}$ NS now less than 590 (Yellow dashed). ArXiv: 1805.11581

This suggests radius of a NS R < 13 km and $R_{skin}(^{208}Pb)$ < 0.21 fm

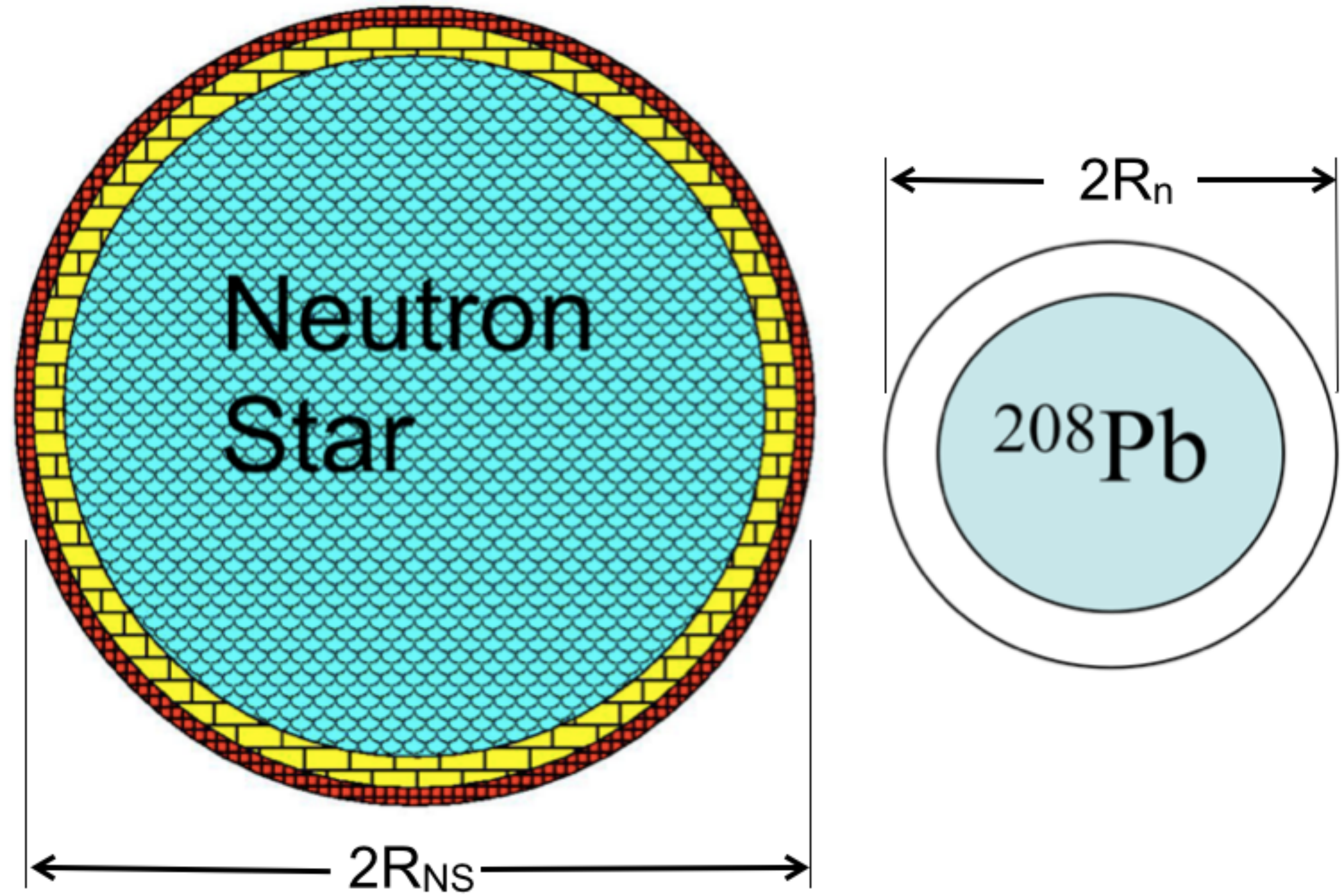


NS merger zoo

- **Multi-messenger astronomy may have started with a bang, but it is just getting going!**
- Expect observation of many more NS mergers when LIGO reaches full design sensitivity.
- Other mergers may be different from GW170817 (~2.75M_{sun})
- Merger of massive NS (say 1.6+1.6 M_{sun}?) could lead to a prompt collapse and little ejected mass. Perhaps a "dud" with out much nucleosynthesis or E+M fireworks.
- Merger of low mass NS (say 1.2+1.2 M_{sun}?) could produce longer lived SMNS and very bright E+M fireworks??
- In general the lower the total mass (or chirp mass) the longer lived the remnant and perhaps the brighter the kilonova. Could be sensitive to modest changes in total mass.

Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb determines P at **low densities** ~0.7ρ_0
- Radius or deformability Λ of (~1.4M_{sun}) NS depends on P at **medium densities** ~2ρ_0.
- Maximum mass of NS depends on P at **high densities** (fate of merger remnant).
- Three measurements constrain density dependence of EOS.



If PREX II finds a thick ^{208}Pb skin and high pressure, while NS radius or deformability appears small: this could suggest a softening of the EOS (lowering of P with increasing density) from a phase transition — perhaps from hadronic to quark matter.

Neutron stars, neutron star mergers, and neutron rich matter

- 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), Jianchun Yin, Zack Vacanti. Also Matt Caplan (2017) now CITA fellow at McGill, Andre Schneider (2013) now at Caltech.

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NUCLEI Nuclear Computational Low-Energy Initiative

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