Neutron skin measurements and its constraints for neutron matter

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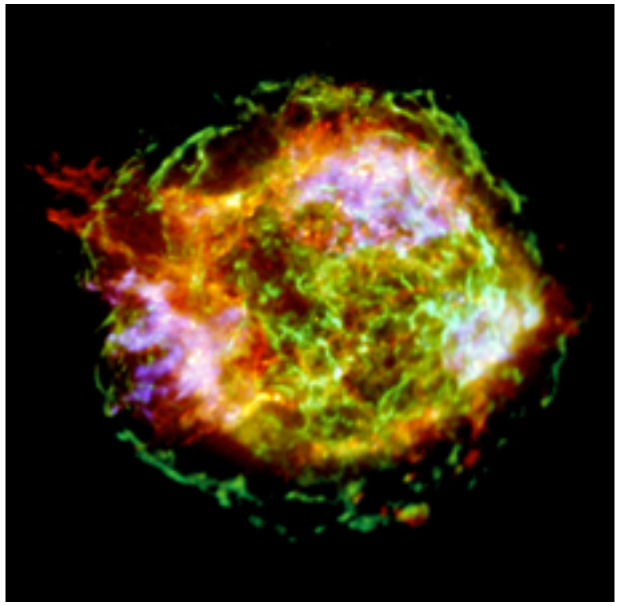
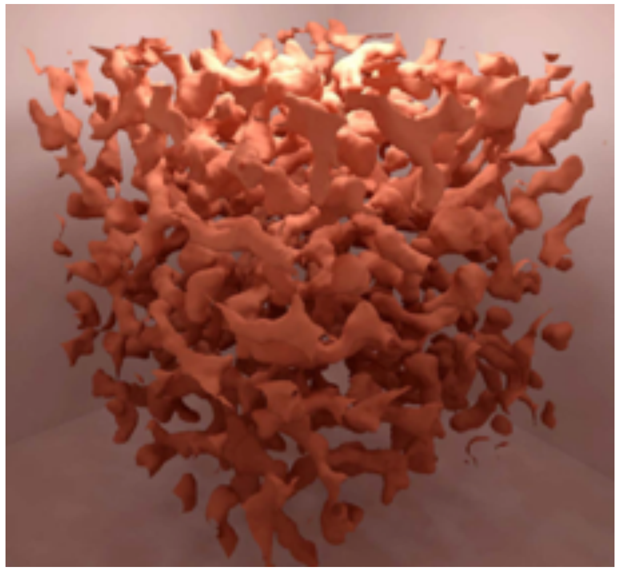
INT, Seattle, 2016

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?
- n rich matter over large range of density and T can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor (T_c=10^{10} K), superfluid, color superconductor* *-> Phases of dense matter*



Supernova remanent Cassiopea A in X-rays



MD simulation of Nuclear Pasta with 100,000 nucleons

r-process nucleosynthesis

- Half of heavy elements, including gold and uranium, made in r-process where seed nuclei rapidly capture many neutrons.

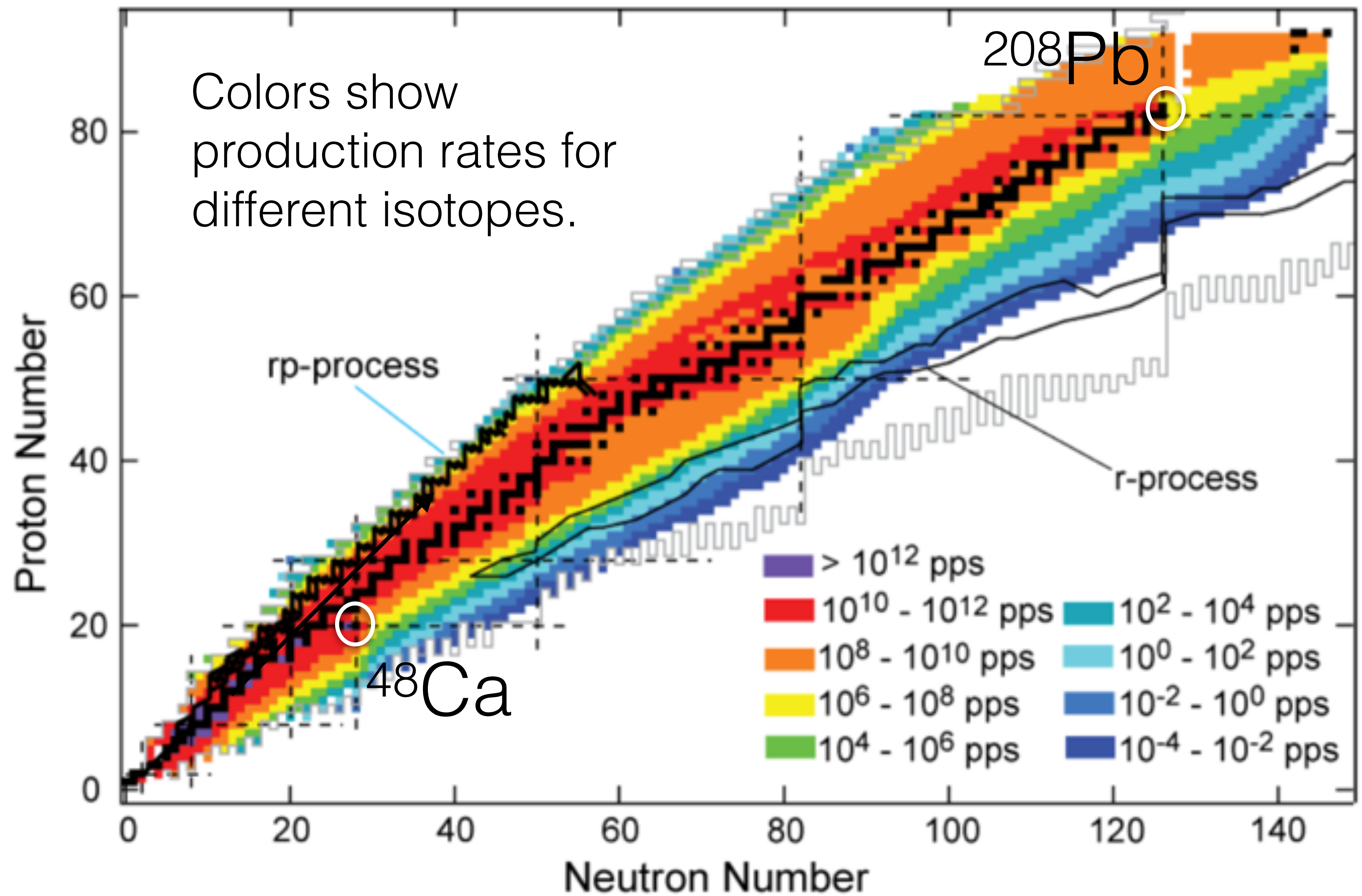
- **Follow the nuclei**: Facility for Rare Isotope Beams (FRIB) will produce many of the very n rich nuclei involved in the r-process.

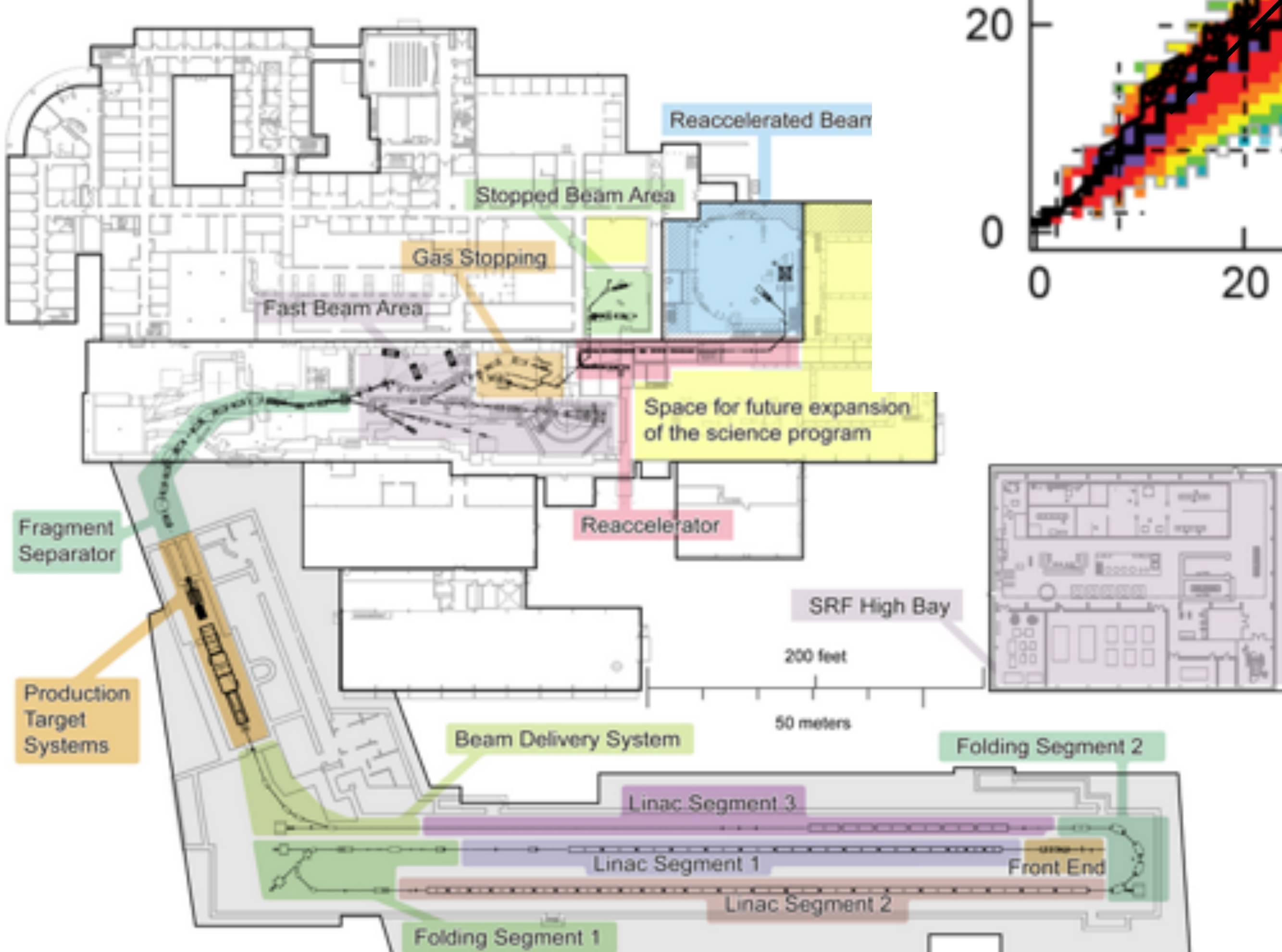
- **Follow the neutrons** needed for r-process:
  — Neutrinos during a supernova eject material. Antineutrinos capture on protons to make neutrons, neutrinos capture on n to make p. Measure detailed antineutrino spectra and detailed neutrino spectra from next galactic SN.
  — Gravity during violent neutron star mergers can eject neutron rich matter. LIGO is directly observing merger rate.

- **Multimessenger:** If neutrinos make the neutrons you should observe the neutrinos, if gravity then observe gravitational waves. Nuclear experiment provides an additional "messenger" to study neutron rich matter.

Facility for Rare Isotope Beams

- Intense radioactive beam accelerator that can produce ~80% of all particle bound isotopes with Z < 90.
- Also GSI-FAIR, RIBF, GANIL, ISAC at TRIUMF, …



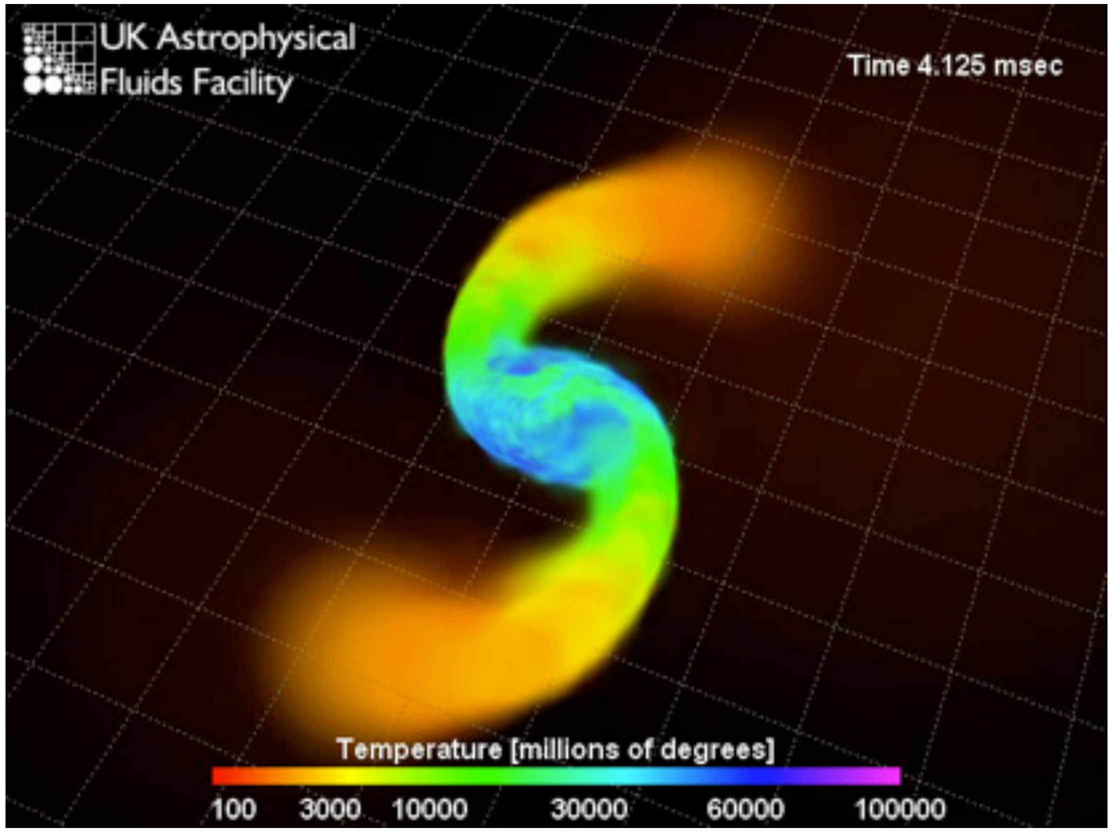


- FRIB can measure masses, half-lives, … of many neutron rich nuclei involved in r-process.
- Help infer r-process conditions from measured abundances.

Neutron Star Mergers and r-process

Ejecta during NS mergers can be so neutron rich that simulations find a robust r-process.

- Possible Kilonova -> radioactive heating of r-process material.
- Observation of ancient dwarf galaxy with r-process elements consistent with a single NS merger [Nature 531, 610 (2016)].

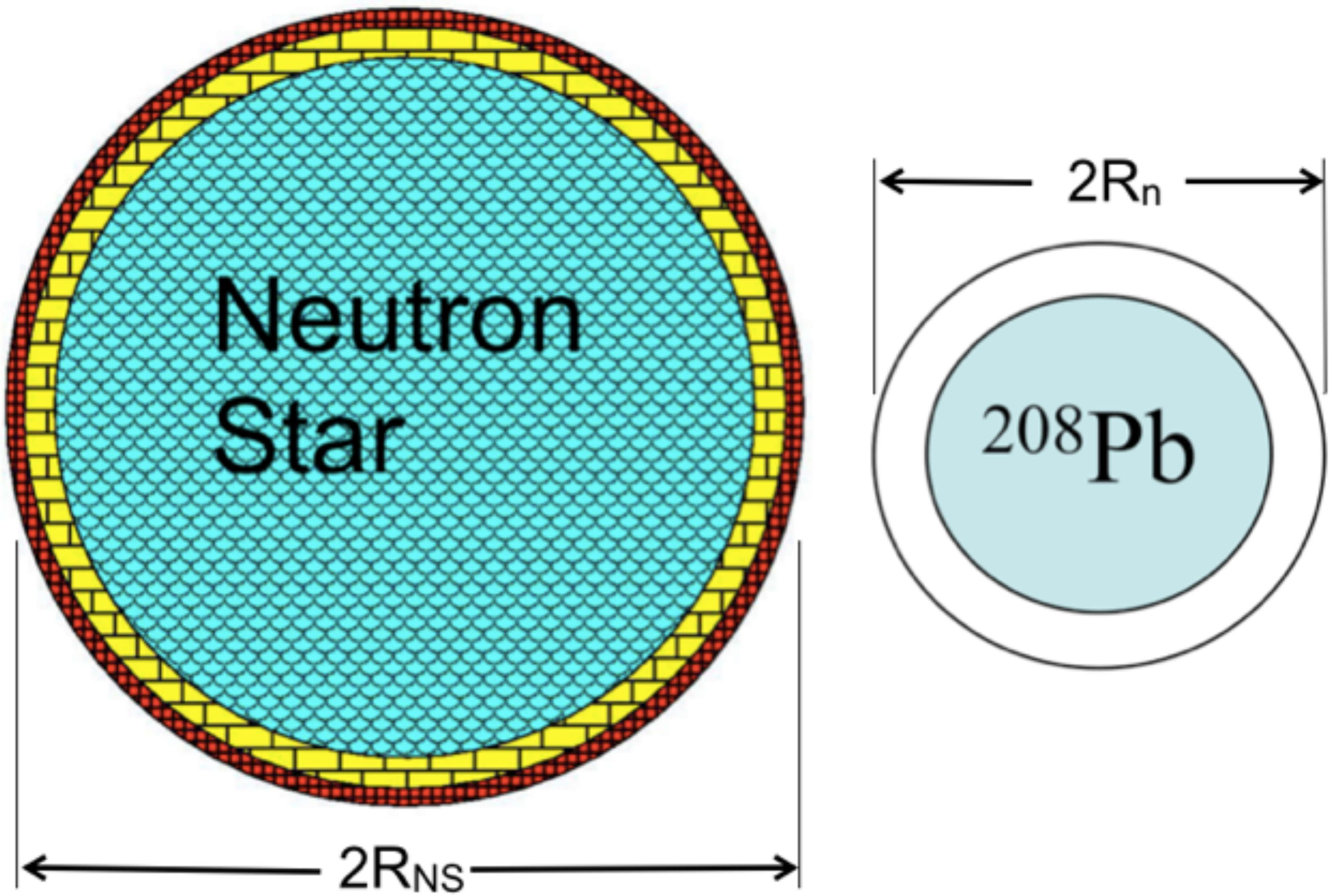


Stephan Rosswog, Richard West.

- Yield of r-process elements: **merger rate X amount of material ejected per merger**.
- LIGO is directly observing **merger rate**. Much GW info: rate, distribution of NS masses, binary populations…
- **Material ejected per merger** depends on mass ratio, …,EOS. **Ejecta components:** tidal tails (more for stiff EOS) , dynamical shock ejecta (more for soft EOS), evaporation of accretion disk, neutrino driven winds.

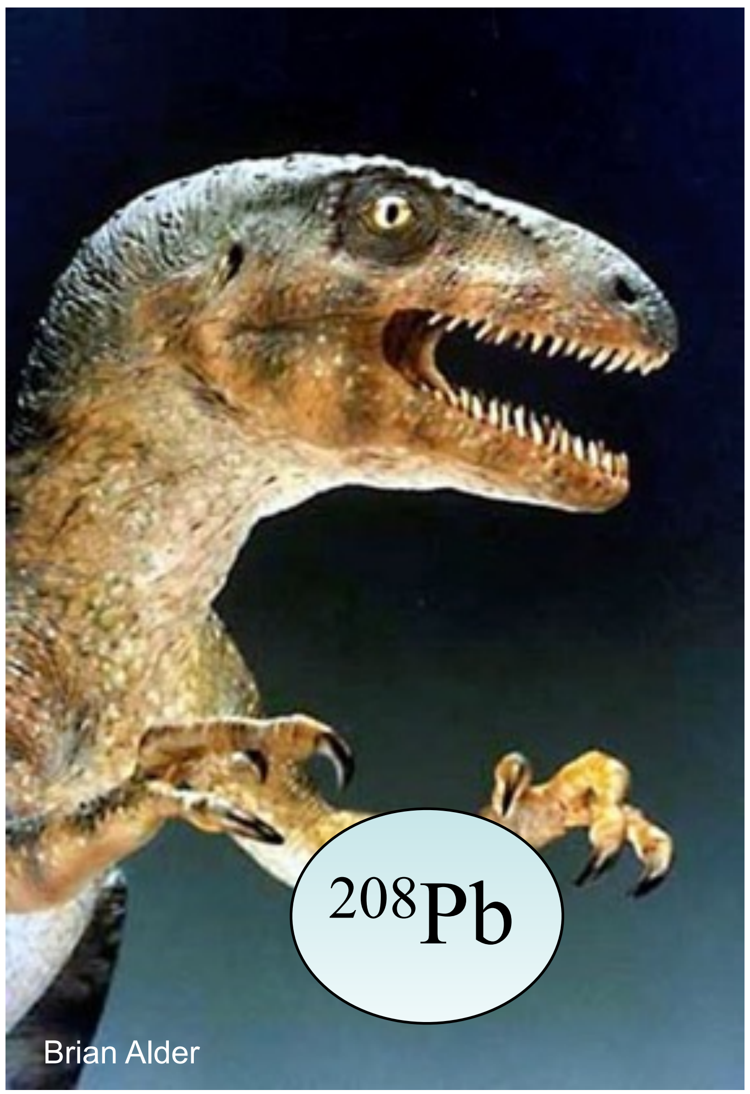
Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb determines P at low densities near ρ_0
- Radius of (~1.4M_{sun}) NS depends on P at medium densities > ρ_0.
- Maximum mass of NS depends on P at high densities.
- These three measurements constrain density dependence of EOS.



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

Lead Radius Experiment (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.

PREX Spokespersons:
K. Kumar, R. Michaels, K. Paschke,
P. Souder, G. Urciuoli

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

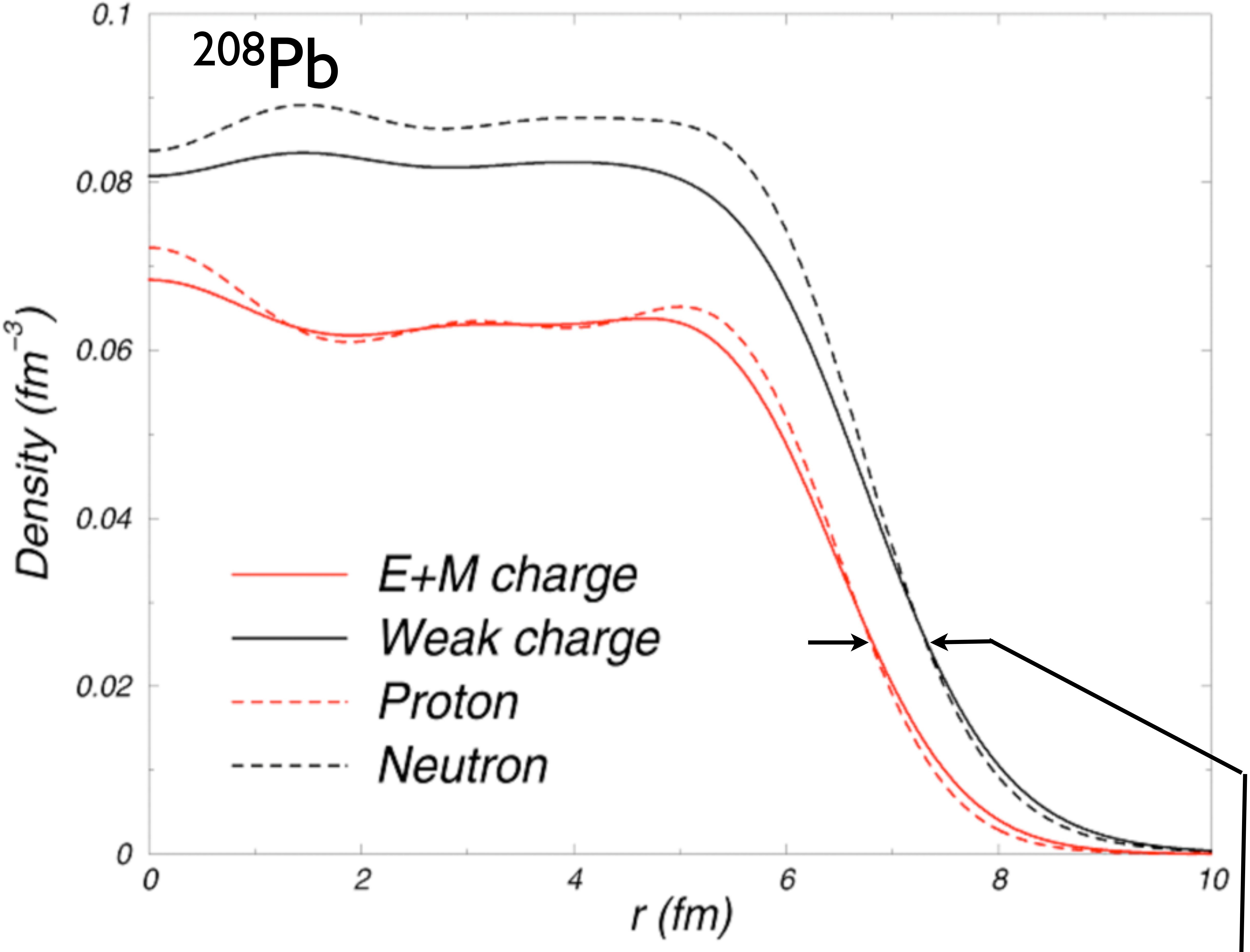
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

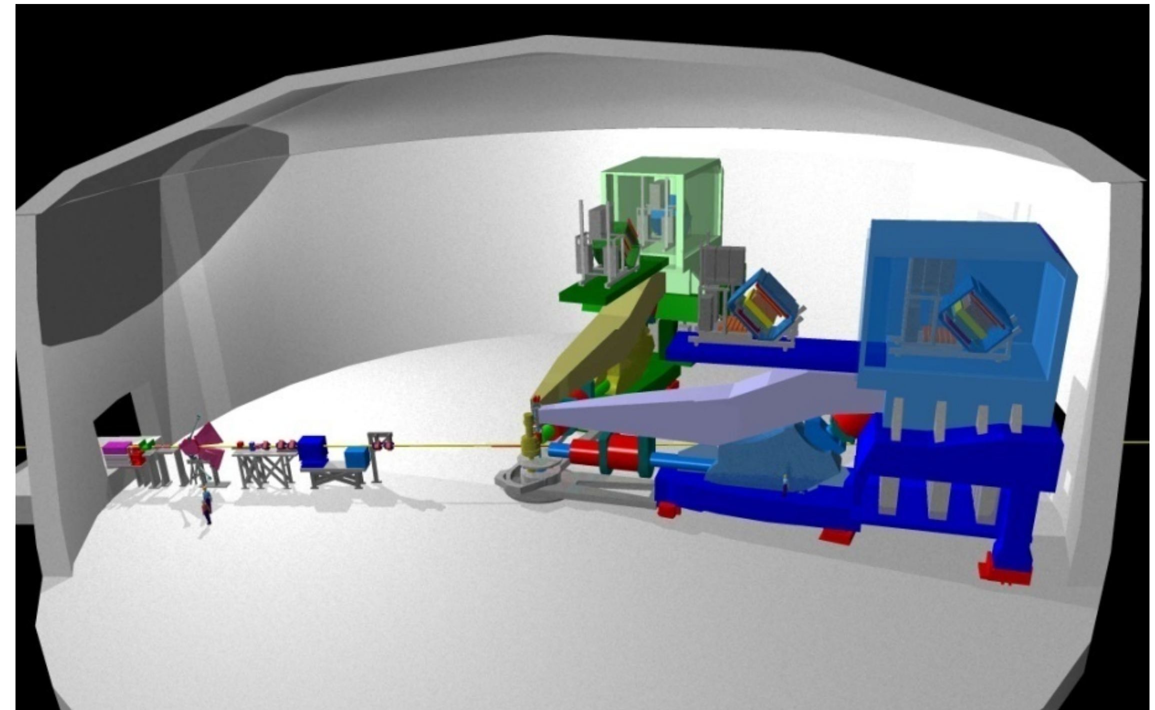
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

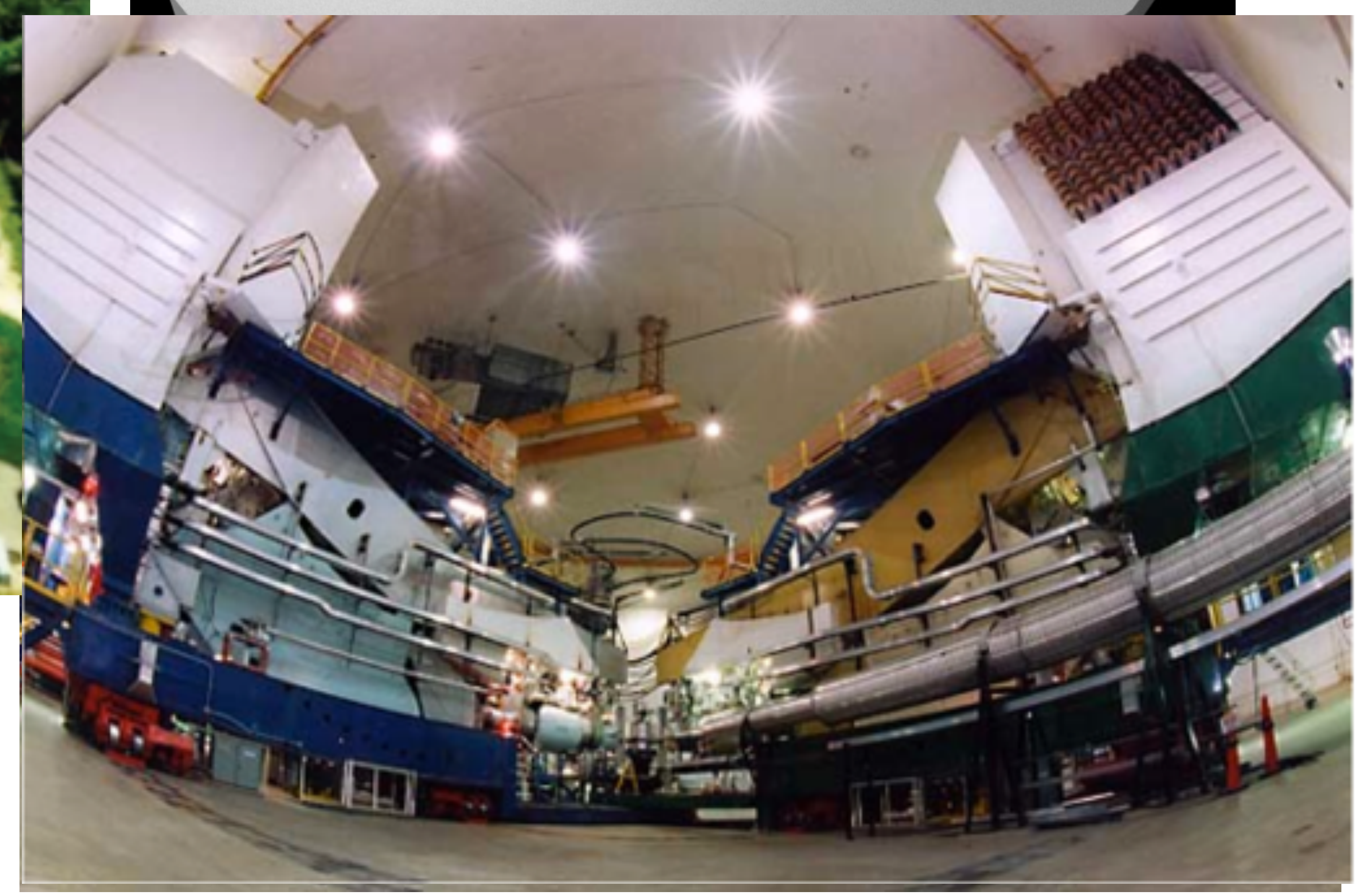
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**
  - What is important is the quality of the systematic error bars!



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

Hall A at Jefferson Lab

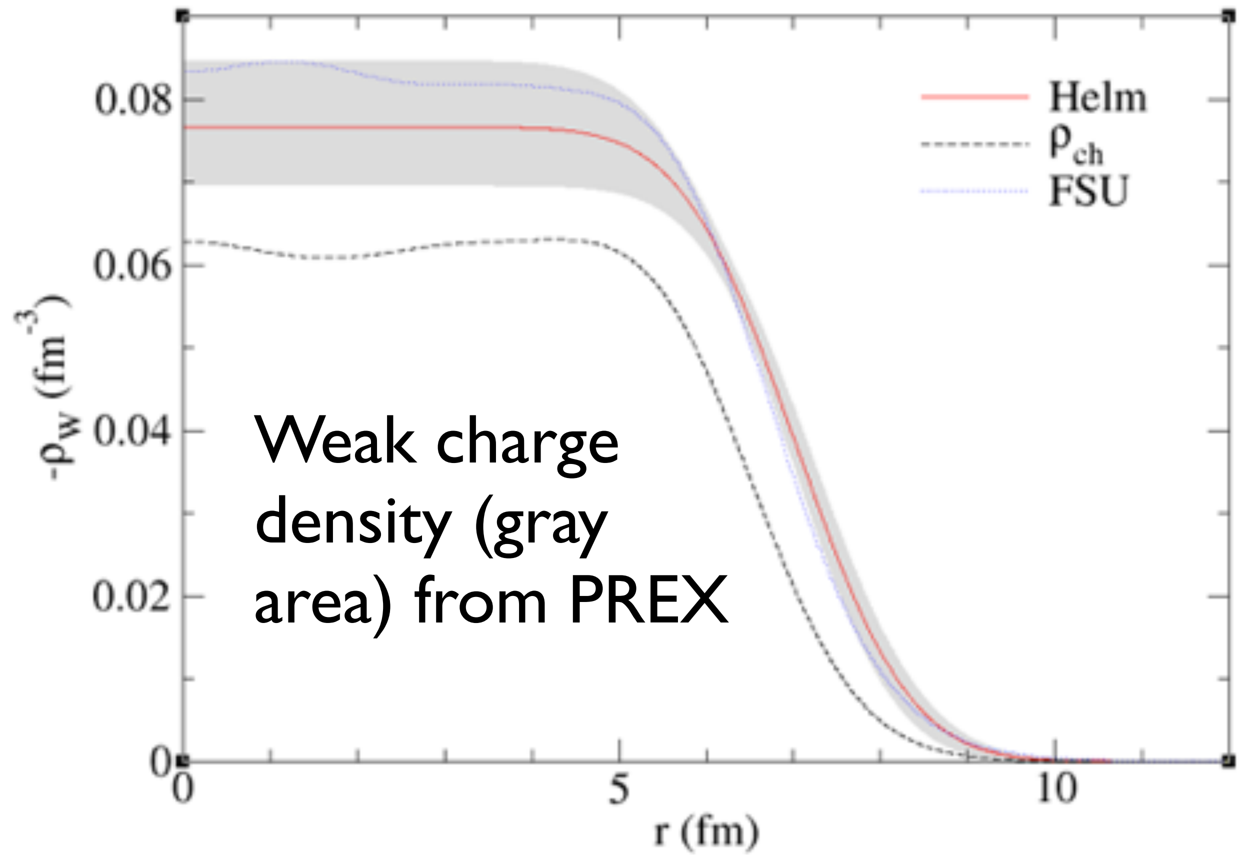




R. Michaels, JLAB

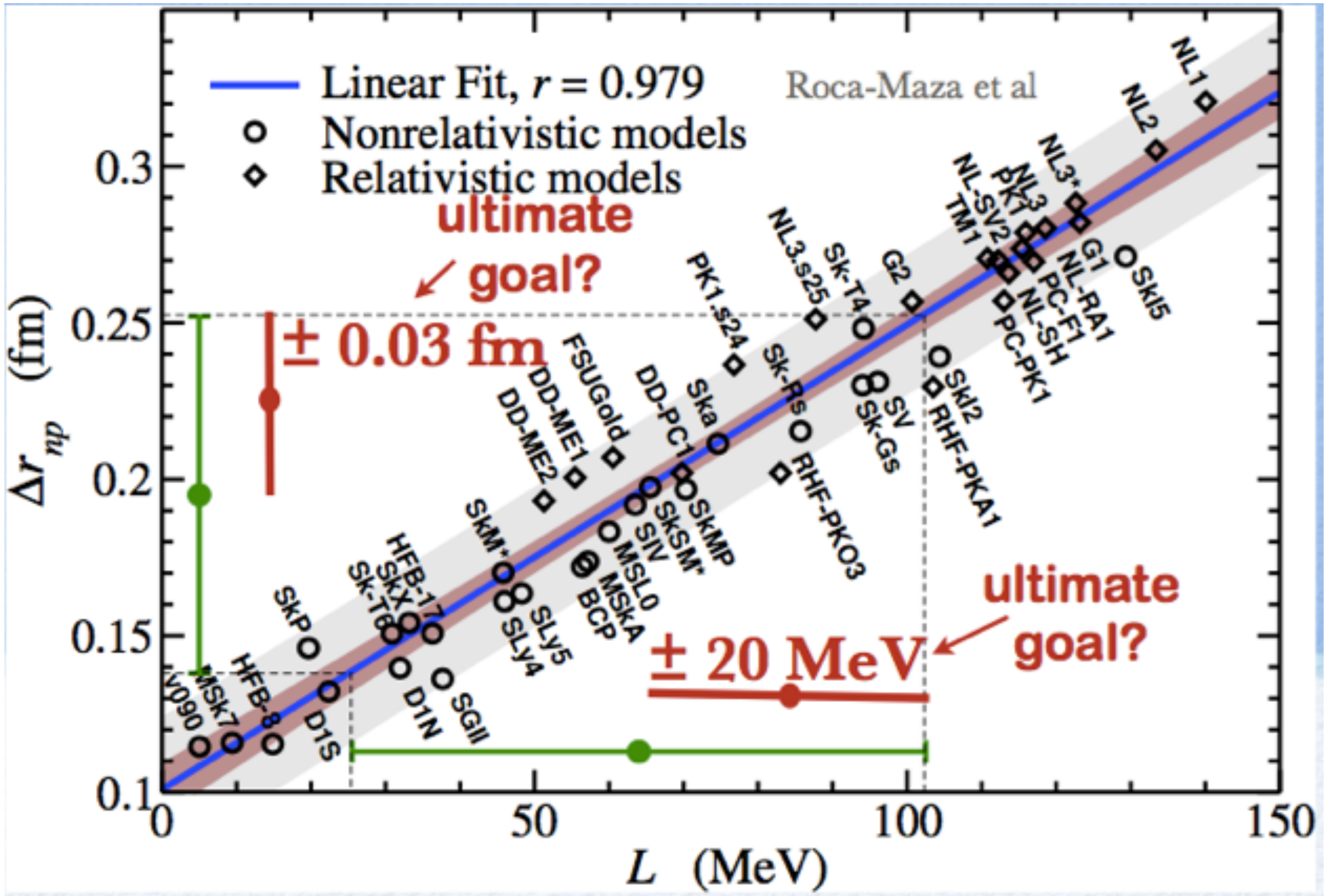
First PREX results

- 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb
- **A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm**
- Determines radius of weak charge density: R_W = 5.83 ± 0.18 ± 0.03 fm
- Compare to charge radius R_{ch}=5.503 fm -->
  $R_W - R_{ch}$ = 0.32 ± 0.18 fm
- Unfold nucleon ff--> neutron skin:
  $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- Phys Rev Let. **108**, 112502 (2012), Phys. Rev. C **85**, 032501(R) (2012)



- Next steps->
  - 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 (but not ^{208}Pb) to relate R_n to three neutron forces.

Density dependence of symmetry energy



- Symmetry energy S(n) is how much E of symmetric matter rises when one goes away from N=Z.

- ^{208}Pb has 44 extra neutrons. Density dep. of S pushes these extra n from center (high density) to surface (low density) giving thicker n skin.

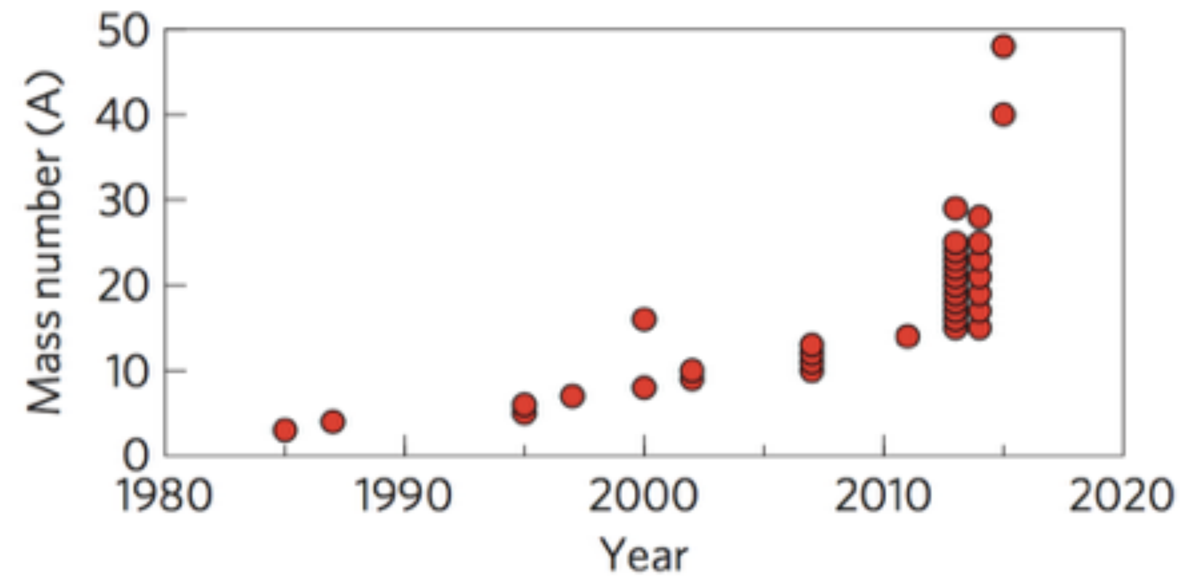
- Strong correlation between L (~dS/dn) and neutron skin.

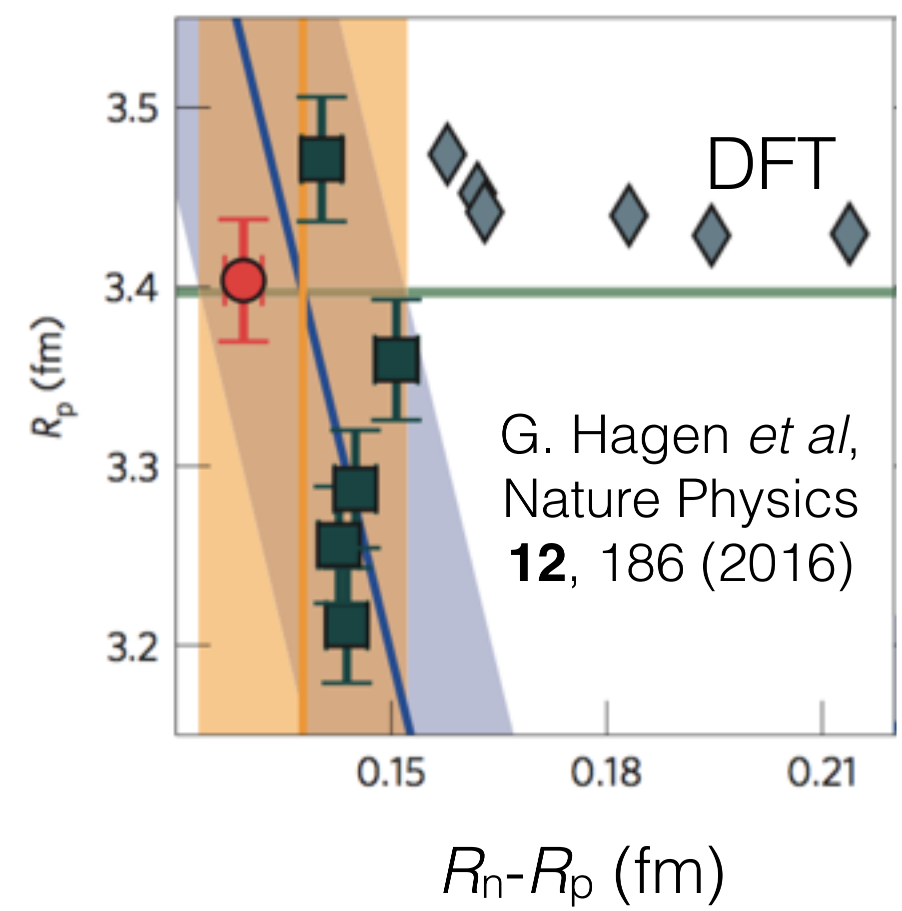
Neutrino cooling of neutron stars

- Direct URCA process: n -> p + e + $\bar{\nu}$ followed by e + p -> n + ν can cool star quickly, but needs large proton fraction to conserve both E and p.
- Proton fraction determined by symmetry energy S.
- If PREX II confirms large PREX R_n-R_p value, S rises rapidly with density, favoring large proton fraction and massive NS will cool rapidly by direct URCA.
- If R_n-R_p is small than direct URCA likely not allowed.
- If some neutron stars are observed with enhanced cooling, and one can rule out direct URCA with small neutron skin measurement, than one can prove that dense matter contains additional hadrons beyond p and n that beta decay to produce the cooling.

Study 3 neutron forces in ^{48}Ca

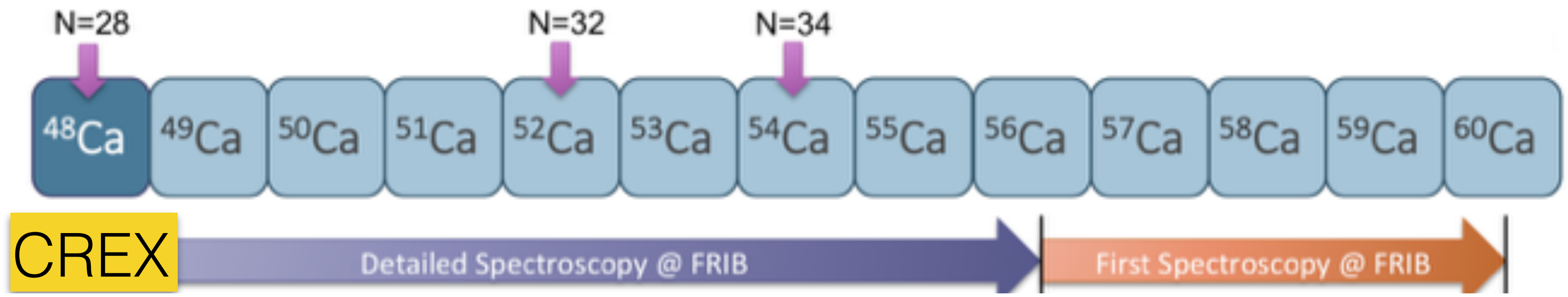
- Large computational advances allow microscopic calculations of structure of medium mass (A=48) nuclei using realistic two nucleon and three nucleon forces from Chiral EFT.
- Coupled cluster calculations by G. Hagen *et al* make sharp prediction R_n-R_p in ^{48}Ca is 0.12 to 0.15 fm.
- Three neutron forces play an important role. Many DFT models predict larger neutron skin.
- Prediction will be directly tested by CREX with goal of R_n to ±0.02 fm.

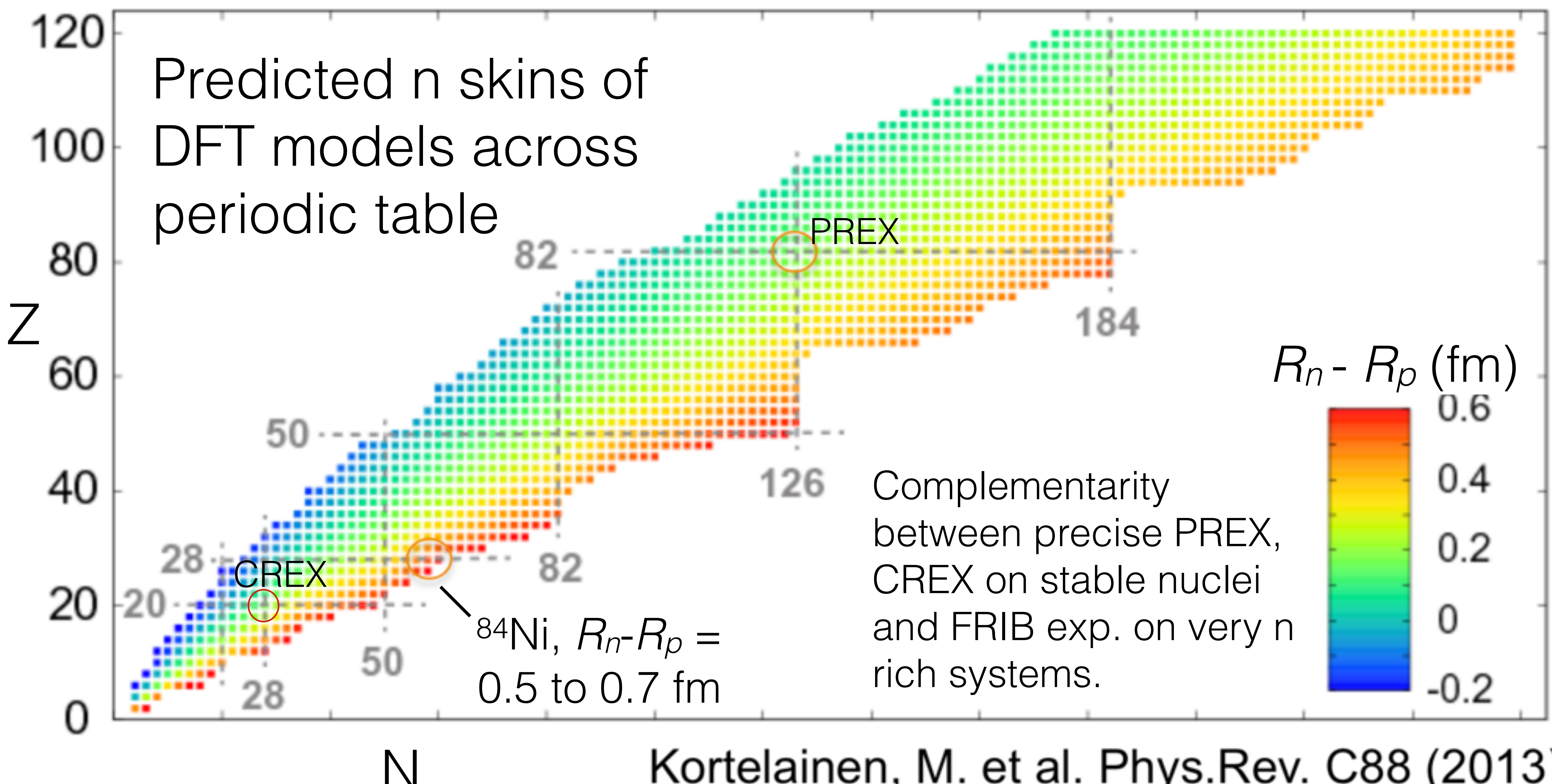




Study more n rich nuclei at FRIB

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





Kortelainen, M. et al. Phys.Rev. C88 (2013)

Neutron skin measurements and its constraints for neutron matter

- In r-process seed nuclei capture many neutrons.
  - FRIB will make very n rich nuclei.
  - Measure spectra of both neutrinos and antineutrinos from SN and gravitational waves from NS mergers to follow n for r-process.
- Parity violating PREX and CREX measure neutron skin of ^{208}Pb, ^{48}Ca and constrain pressure, symmetry energy, and three neutron forces.
- PREX collaboration, Zidu Lin, S. Ban, J. Piekarewicz, R. Michaels, …
- Supported in part by DOE

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