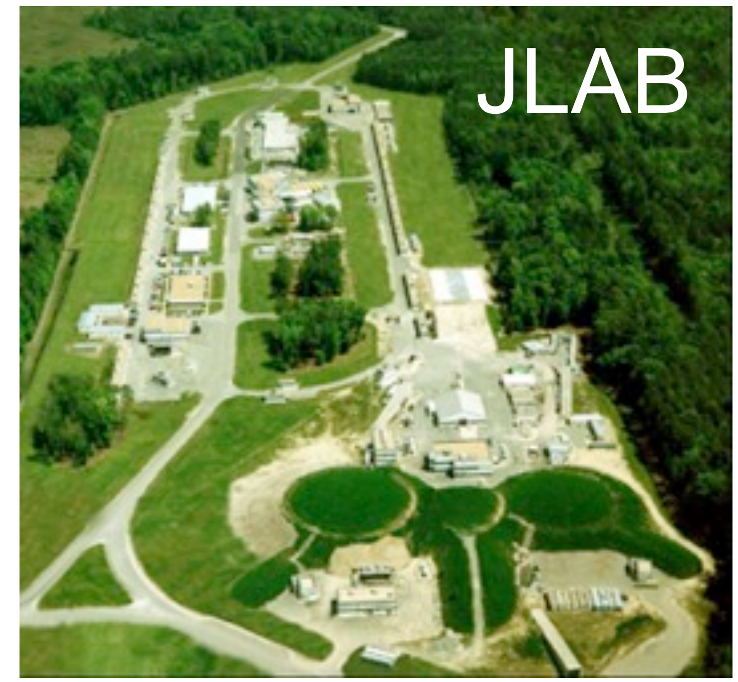
The Equation of State of Neutron Rich Matter

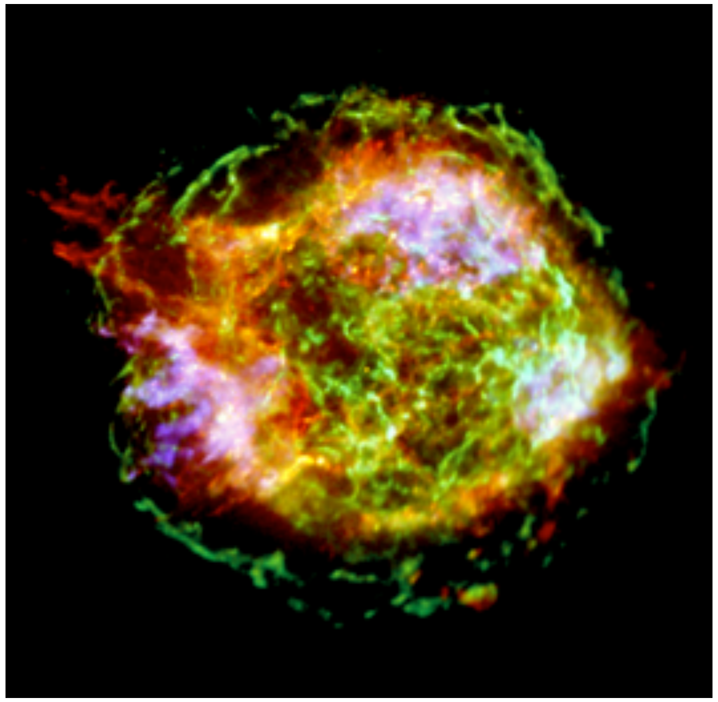
- Pb Radius Experiment (PREX) measures neutron radius of ^{208}Pb.
- Measurements of neutron star radii and masses in radio, visible, X-rays.
- Molecular dynamics simulations of the strength of NS crust and gravitational waves.
- Neutrino probes of dense matter and a new equation of state for supernova simulations.

C. J. Horowitz, Indiana University
NPPD, Glasgow, Scotland, Apr. 2011

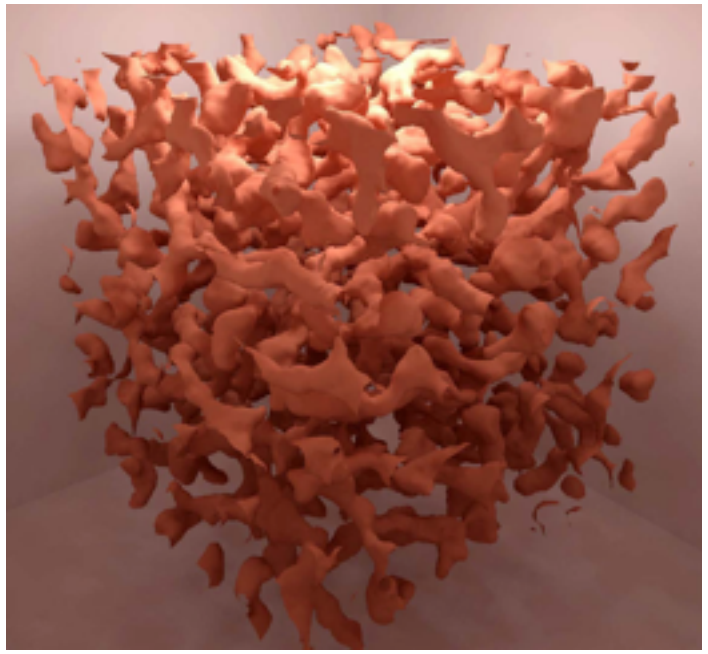


Neutron Rich Matter

- 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 the 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...*
- *Focus on simpler liquid, solid, and gas phases.*



Supernova remanent Cassiopea A in X-rays

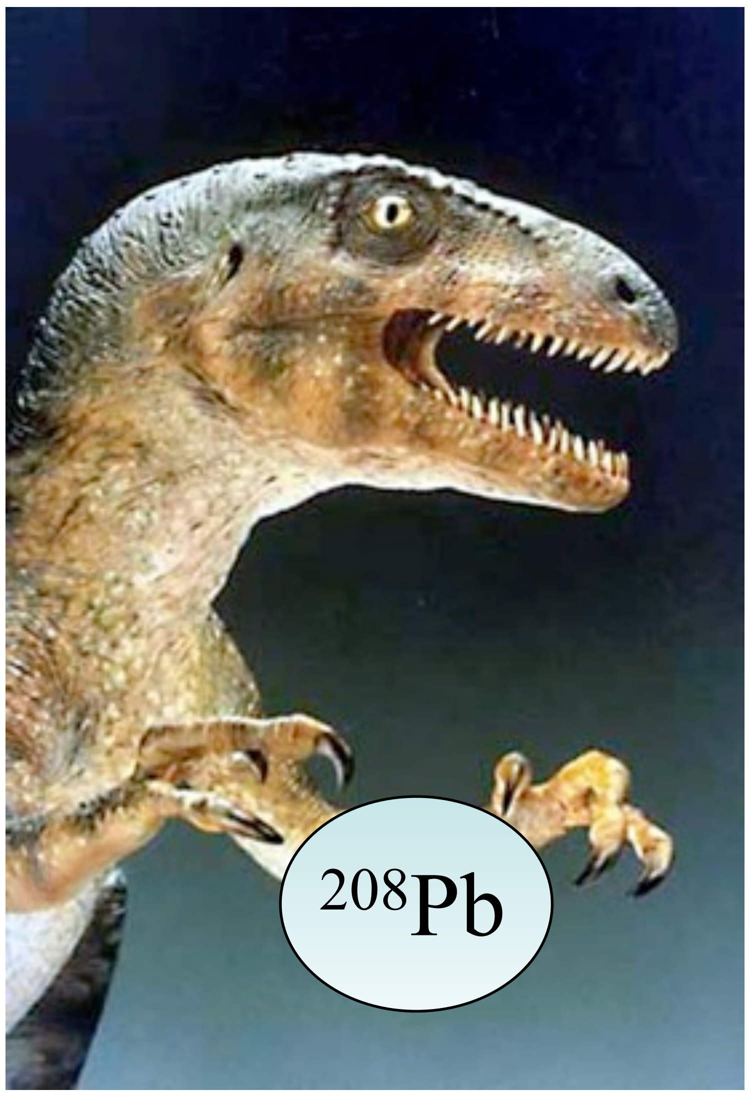


MD simulation of Nuclear Pasta with 100,000 nucleons

Probes of Neutron Rich Matter

- **Multi-Messenger Astronomy:** "seeing" the same event with very different probes should lead 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. However one can also study vapor phase be evaporating nucleons.
  - Electroweak measurements, Heavy ion collisions, Radioactive beams of neutron rich nuclei...
- **Computational:** Important theoretical and computational advances aid study of n rich matter.
  - Chiral effective field theory depends on important and poorly known *three neutron forces*.
  - Large scale computations: Molecular Dynamics, Monte Carlo, No core shell model, coupled cluster...

Pb Radius Experiment (PREX)



Provides a precise laboratory probe of neutron rich matter.

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

This has many implications for nuclear structure, astrophysics, atomic parity violation, and low energy tests of the Standard Model.

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

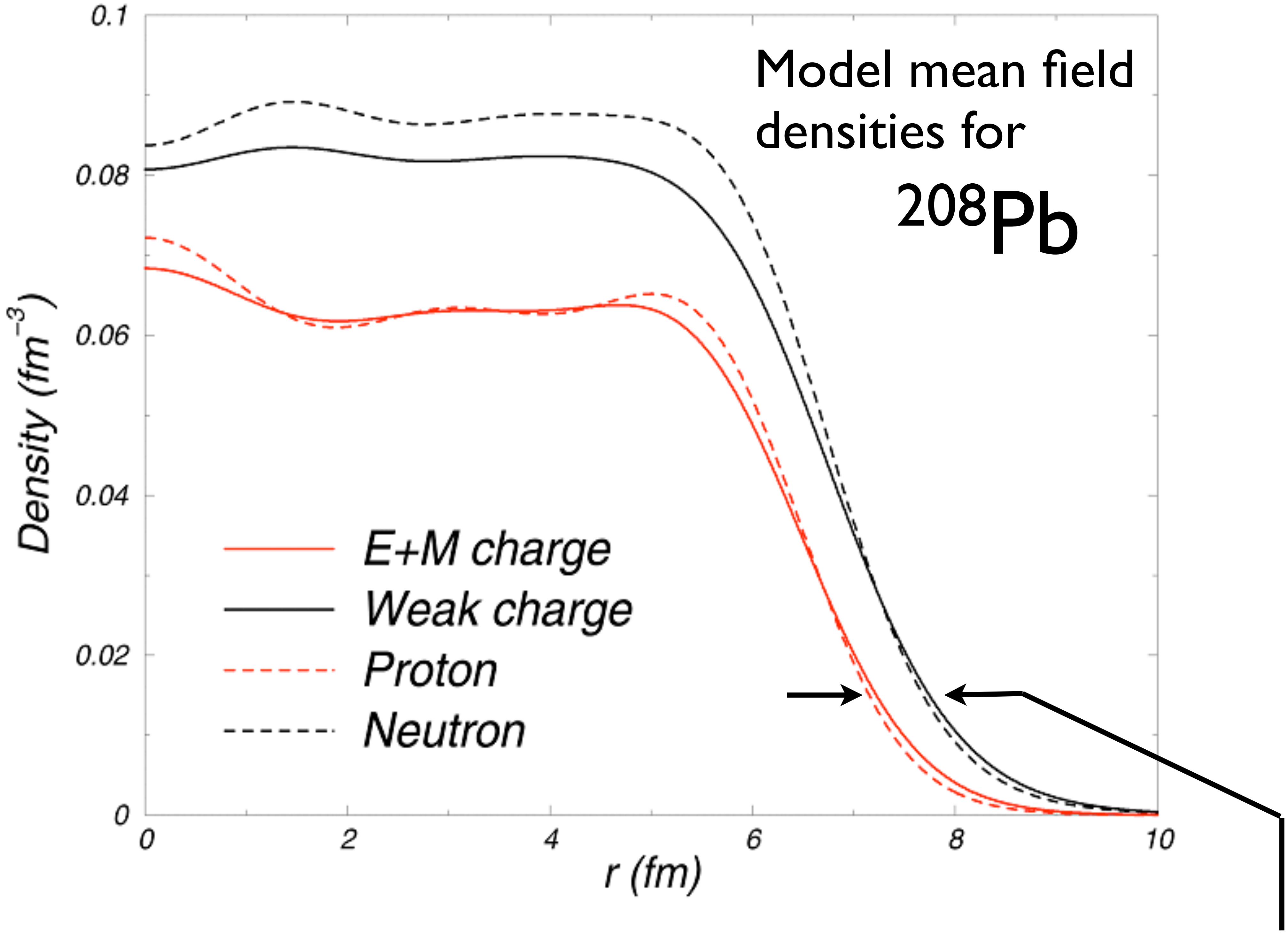
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

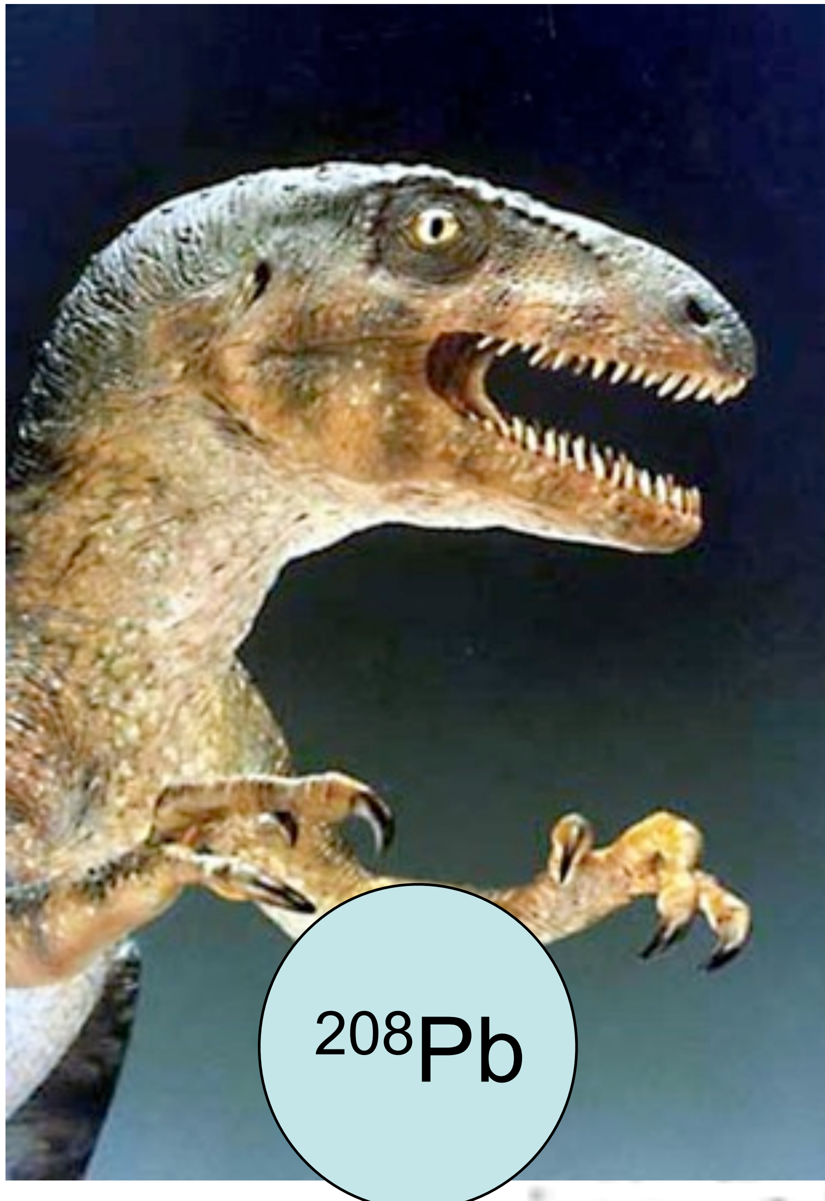
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

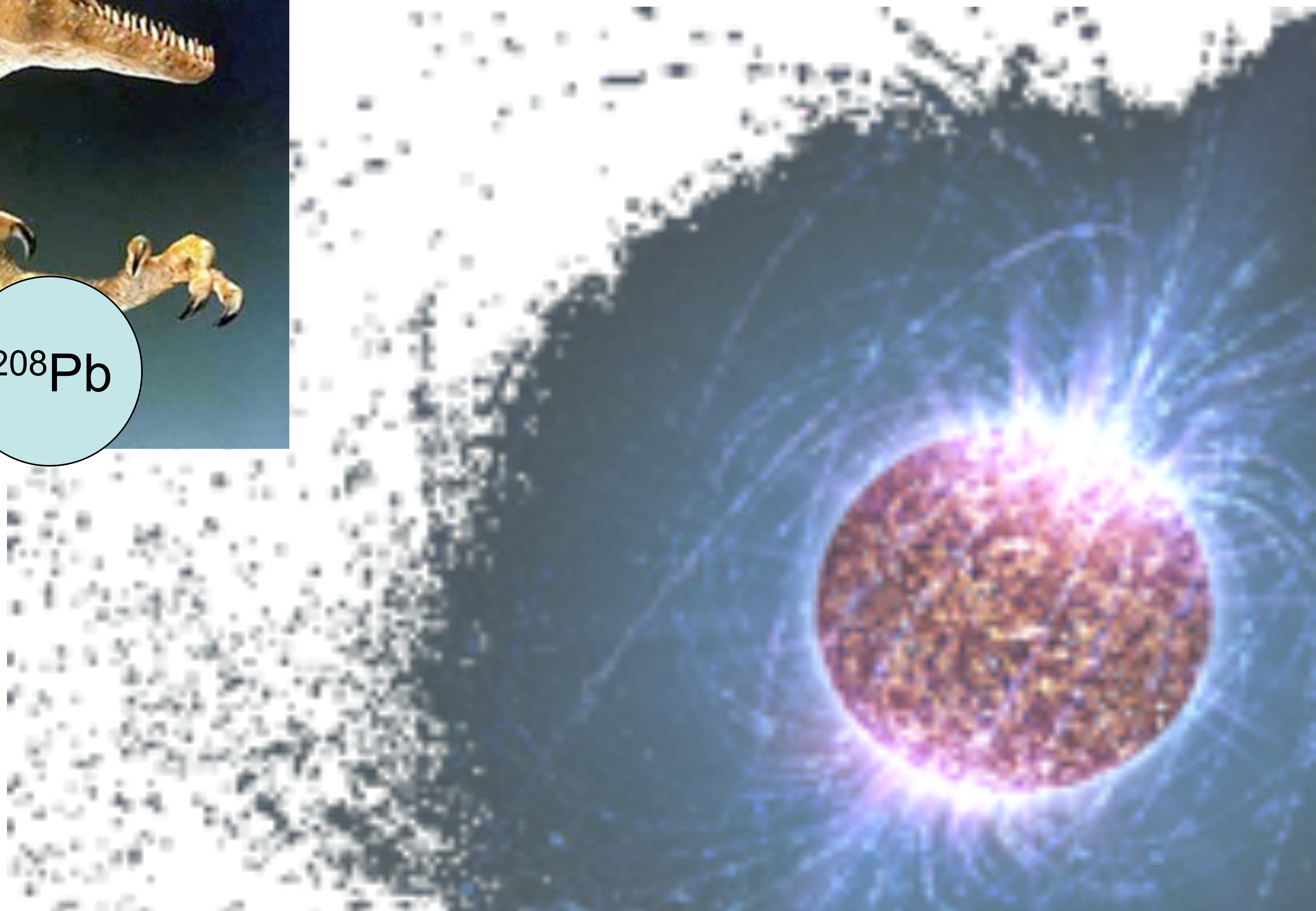
- PREX aims to measure A_{pv} for 1.05 GeV electrons scattering from ^{208}Pb at 5 degrees to 3%. This gives neutron radius to 1% (+/- 0.05 fm).
- Note A_{pv} ~ 0.5 ppm.
  - Donnelly, Dubach, Sick first suggested using PV to measure neutrons.



- PREX measures how much neutrons stick out past protons (neutron skin).
- Experiment ran April to June 2010. High quality data were collected, although statistics were less than originally planned. First results should be announced at April APS meeting.

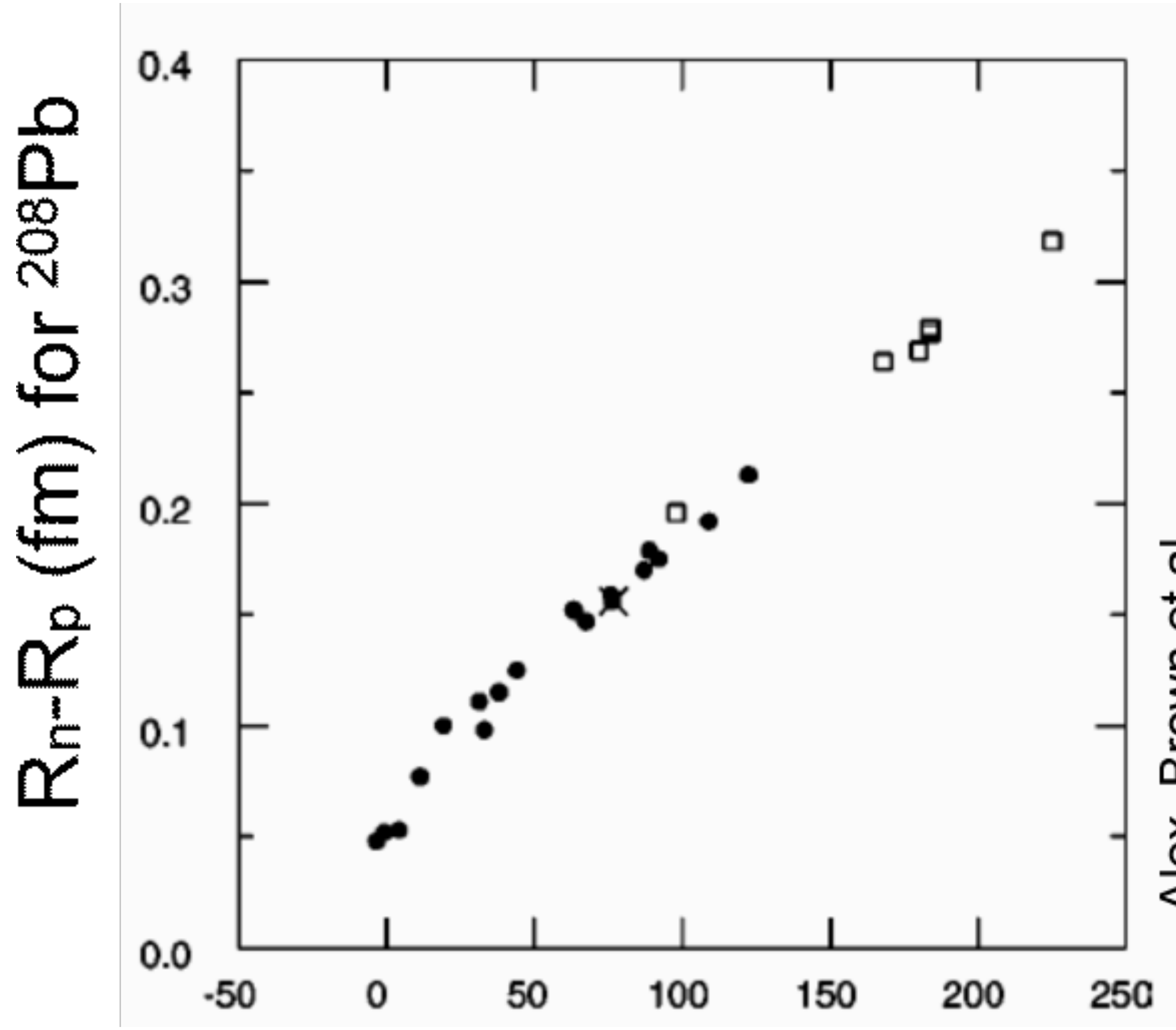
PREX and Neutron Stars





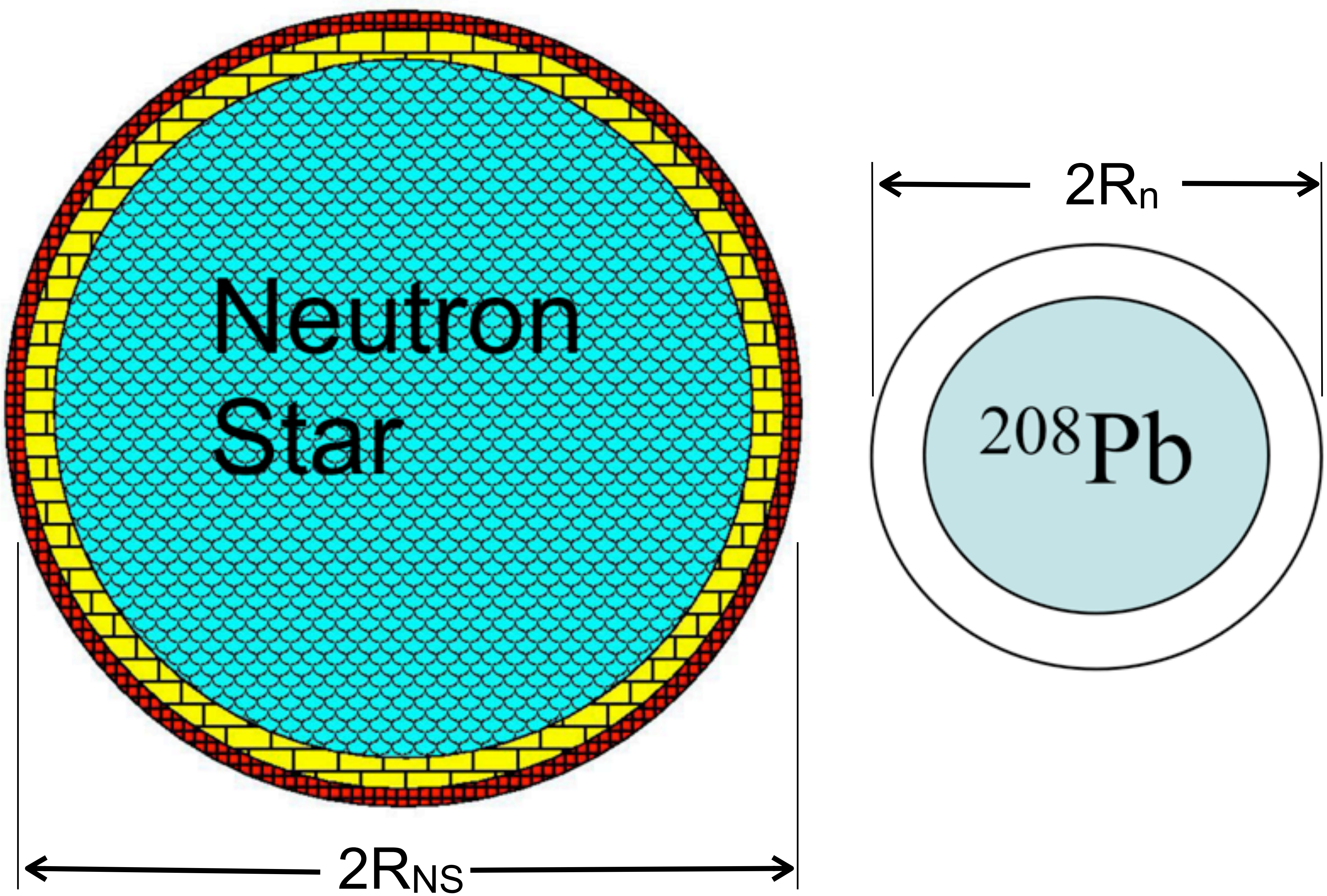
^{208}Pb radius and Equation of State

- Pressure forces neutrons out against surface tension. A large pressure gives a large neutron radius.
- Measuring R_n in ^{208}Pb constrains the pressure of neutron matter at some subnuclear density ~0.1 fm^{-3}.



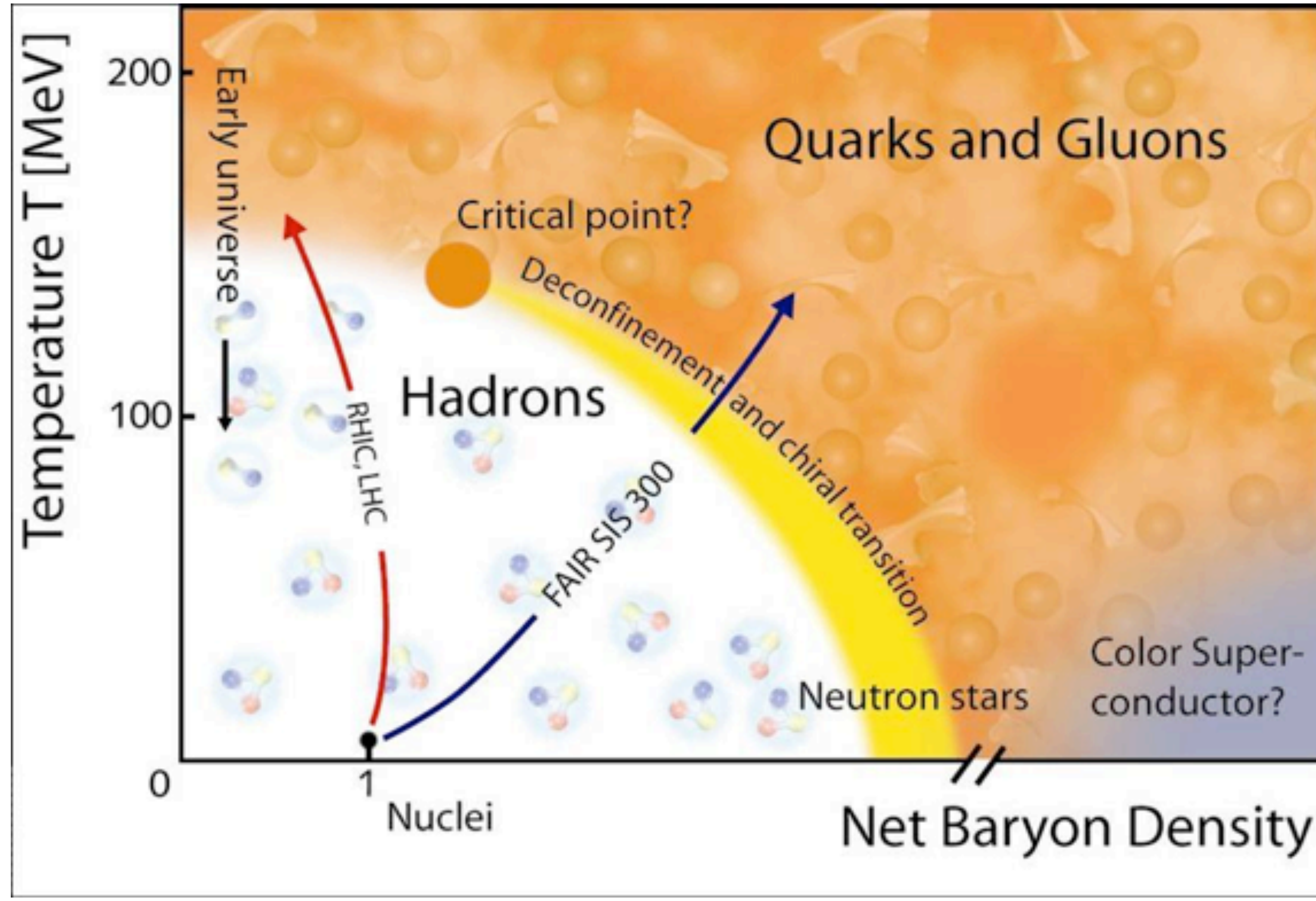
Neutron matter P (MeV/fm^3) at a density of 0.1 fm^{-3}.

Neutron Star radius versus ^{208}Pb Radius



Pb Radius vs Neutron Star Radius

- The ^{208}Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above. Central density of NS few to 10 x nuclear density.
- If Pb radius is relatively large: EOS at low density is stiff with high P. If NS radius is small than high density EOS soft.
  – This softening of EOS with density could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, color super-conductor…



– In fact, observations (see below) suggest the opposite. EOS may be soft at low density and stiff at high density. This greatly reduces room for softening from a high density phase transition.

J. Piekarewicz, CJH

Observing Neutron Star Radii, Masses

- Deduce surface area from luminosity, temperature from X-ray spectrum.

$$L_\gamma = 4\pi R^2 \sigma_{SB} T^4$$

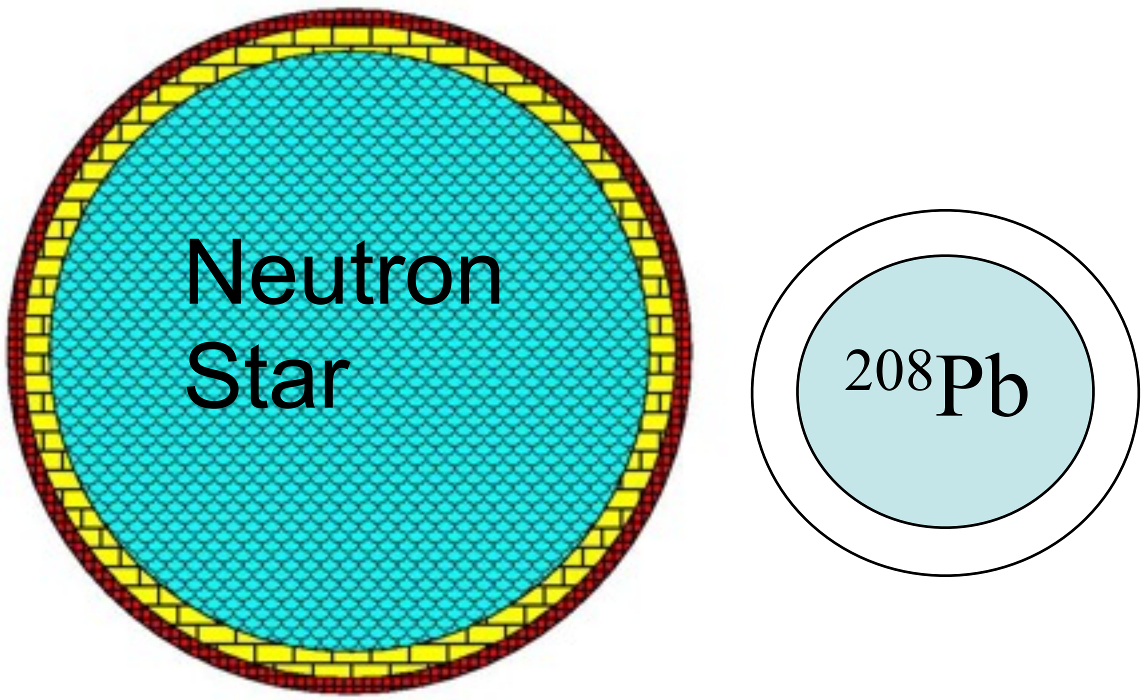
- Complications:
  - Need distance (parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
- Steiner, Lattimer, Brown [ArXiv: 1005.08111] combine observations of 6 NS in 2 classes: X-Ray bursts and NS in globular clusters,

Observations favor stiff high density EOS with ~2 M_{sun} maximum NS mass.

- EOS is soft at low density so 1.4 M_{sun} star has 12 km radius.
- Predict ^{208}Pb neutron skin: R_n-R_p=0.15+/- 0.02 fm.
- F. Ozel et al. get smaller radii.

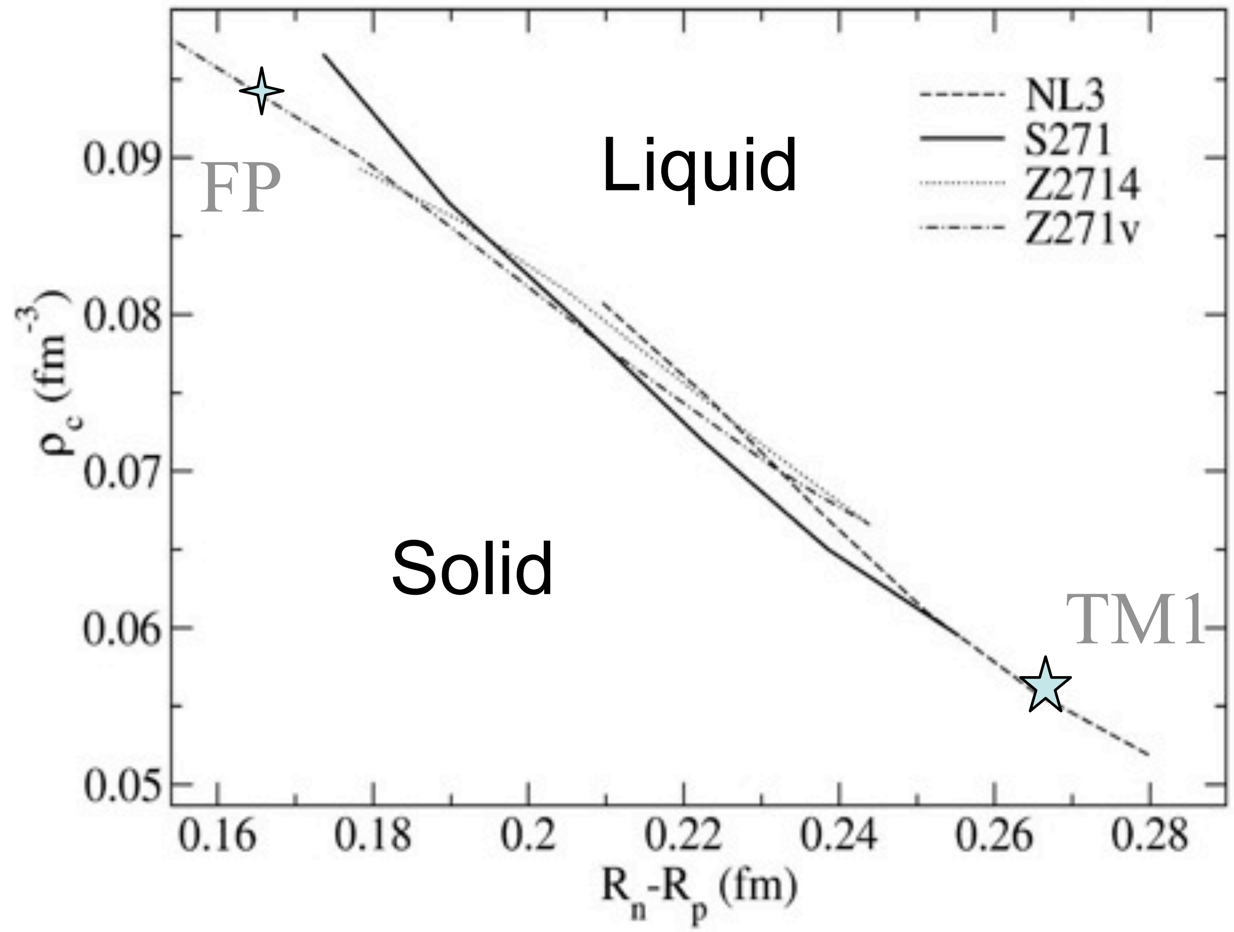
- Radio observations of PSR J1614 find M=1.97+/-0.04 M_{sun}! From binary with 0.5 M_{sun} WD, see relativistic Shapiro delay.
  -- P. Demorest et al., Nature **467** (2010) 1081.
- All soft high density EOS including many with exotic high density phases are ruled out.

Neutron Star Crust vs ^{208}Pb Neutron Skin



- Neutron star has solid crust (yellow) over liquid core (blue).
- Nucleus has neutron skin.
- Both neutron skin and NS crust are made out of neutron rich matter at similar densities.
- Common unknown is EOS at subnuclear densities.

Liquid/Solid Transition Density



- Thicker neutron skin in Pb means energy rises rapidly with density-> Quickly favors uniform phase.
- Thick skin in Pb->low transition density in star.

CJH, J. Piekarewicz, PRL**86** (2001) 5647

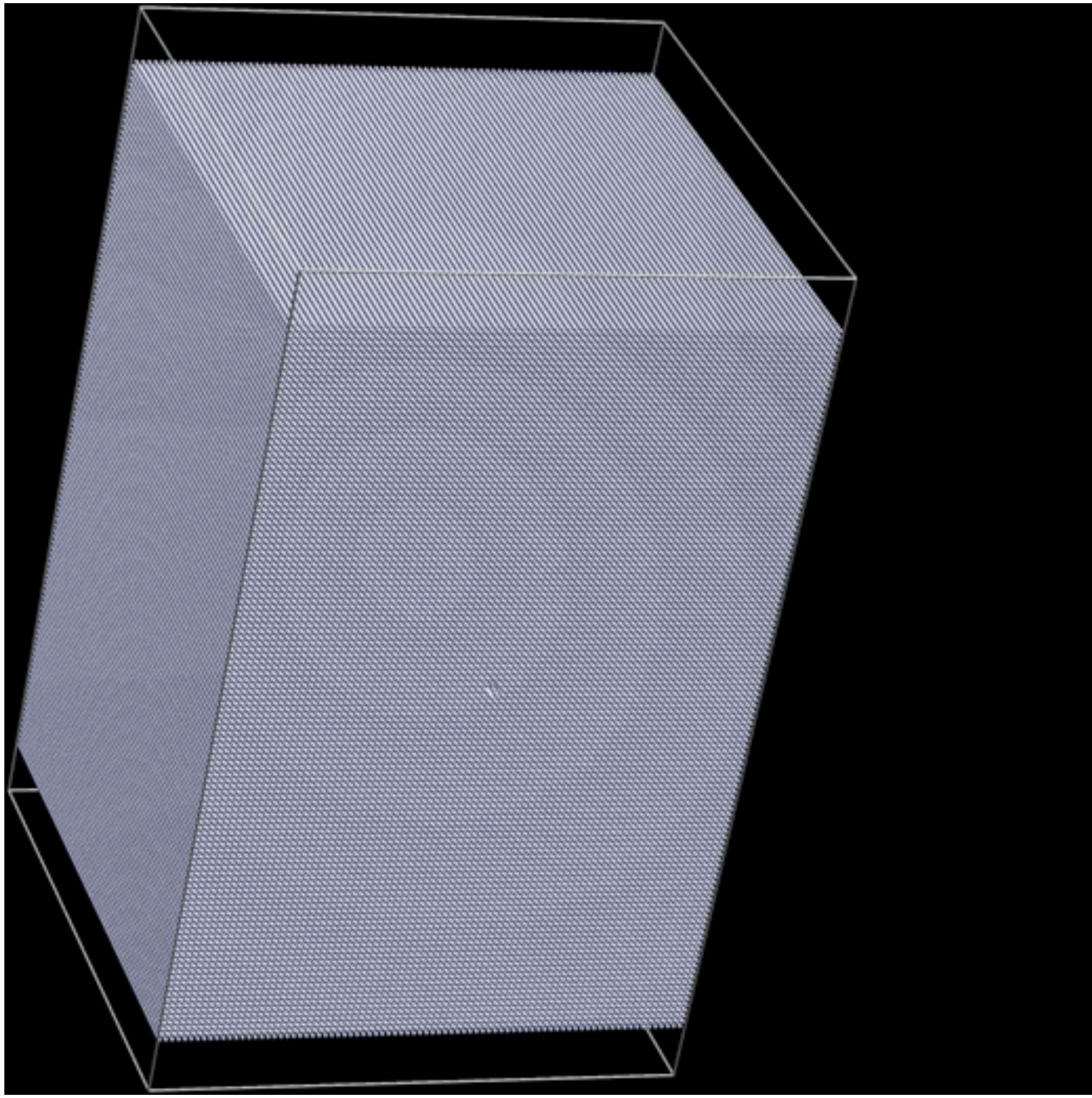
Neutron Star Crust and Gravitational Waves

- Consider a large mountain (red) on a rapidly rotating neutron star. Gravity from the mountain causes space-time to oscillate, radiating gravitational waves. Fundamental question: *how do you hold up the mountain?*
- Strong GW source (at LIGO, VIRGO frequencies) places extraordinary demands on neutron rich matter, *and stress matter to limit.*
  -- Put a mass on a stick and shake vigorously.
  -- May need both a large mass and a strong stick.
  -- Let me talk about the strong stick.

LIGO Hanford

Neutron Star Quadrupole Moments and Gravitational Waves

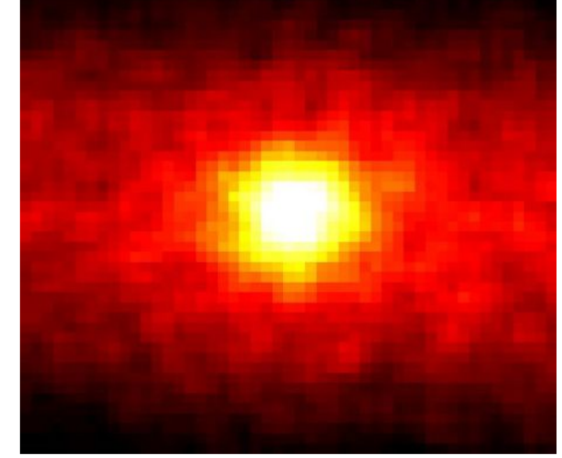
- Very active ongoing/ future searches for continuous GW at LIGO, Virgo ... from mountains.
- How big can the quad. moment be? This depends on the strength of the crust (before mountain collapses under extreme gravity of a NS).
- We perform large scale MD simulations of the crust breaking including effects of defects, impurities, and grain boundaries...
- We find neutron star crust is the strongest material known. *It is 10 billion times stronger than steel.*
- Very promising for GW searches. Large enough mountains are stable.



Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

CJH, Kai Kadau, Phys Rev Let. **102**,191102 (2009)

Neutrino probes of neutron-rich matter



Sun in neutrinos

- New underground dark matter, solar nu,... experiments will be very sensitive to nu from the next galactic supernova (SN).
- Example: ton scale dark matter detectors very sensitive to SN neutrinos via nu-nucleus elastic scattering. Provides info on mu/tau nu spectra not available in Super-K. [CJH, K. Coakley, D. McKinsey, PRD**68**(2003)023005]
- Neutrinos are emitted from the low density $\sim 10^{11}$ g/cm^3 neutrinosphere region. This gas phase can be described with a Virial expansion based on NN, N-alpha,... elastic scattering phase shifts. [CJH, A. Schwenk, NPA**776**(2006)55]
- Virial expansion gives model independent EOS, composition (nucleon, alpha, ^{3}H, ^{3}He, ...), and long wavelength neutrino response. Light nuclei important for electron-neutrino spectrum.

Neutrinos and r-process Nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Here seed nuclei rapidly capture many neutrons. The present best site for the r-process is the neutrino driven wind in core collapse SN.
- Nucleosynthesis depends on ratio of neutrons to protons, this is set by capture rates that depend on neutrino / anti-neutrino energies

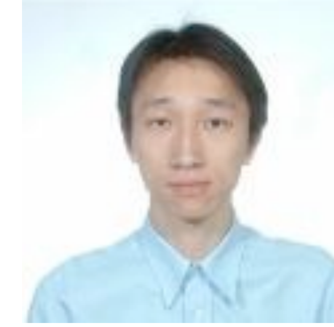
$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

$$\Delta E = \langle E(\bar{\nu}_e)\rangle - \langle E(\nu_e)\rangle$$

- Measure ΔE, difference in average energy for antineutrinos and neutrinos. If ΔE is large, wind will be neutron rich. If ΔE is small, wind will be proton rich and likely a problem for r-process. Hint of problem from SN1987a -- PRD**65** (2002) 083005
- SN is best site but simulations find too few neutrons, entropy is too low, time scale is wrong.

Searching for El Dorado with supernova neutrinos

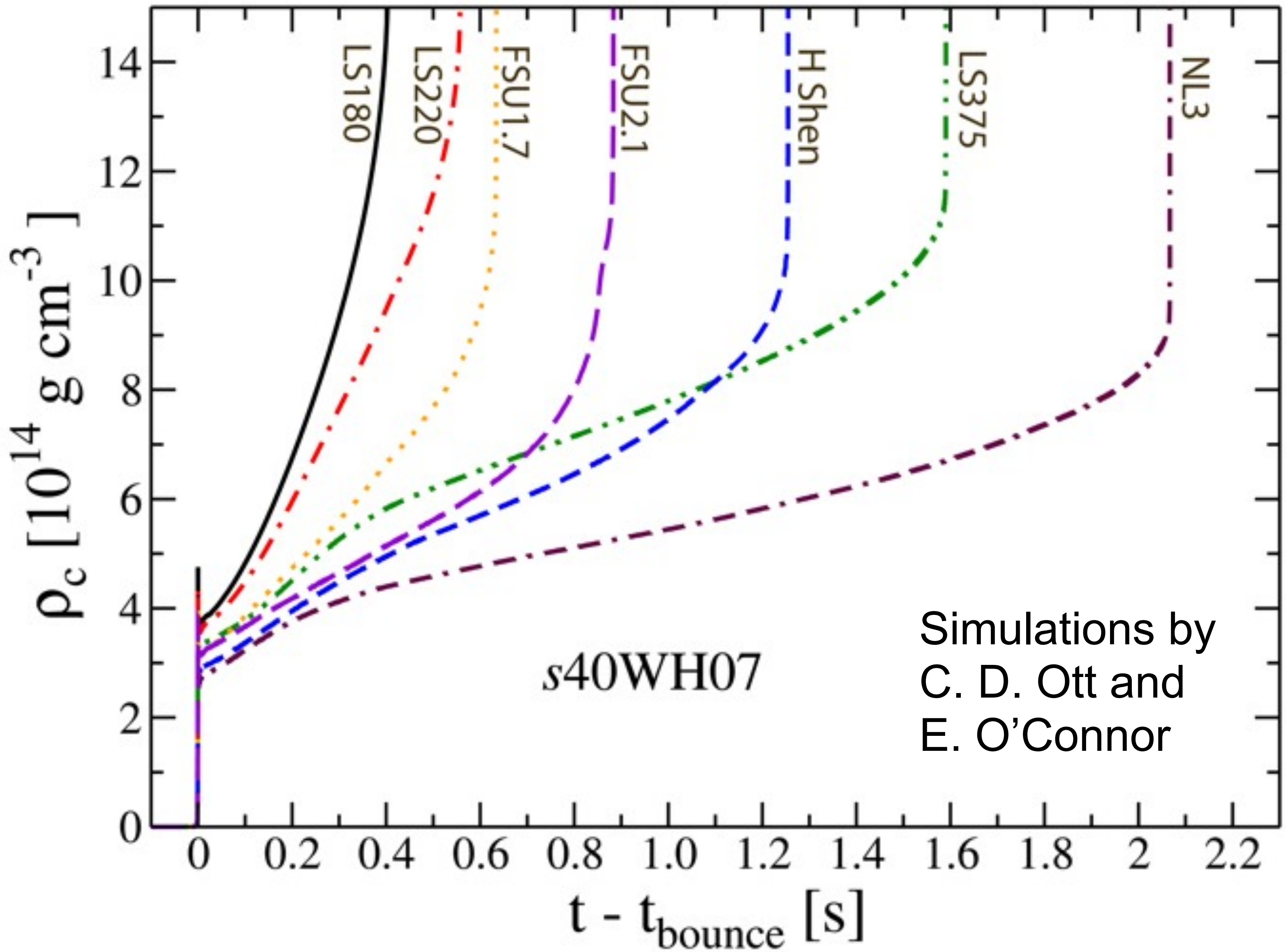
New Equations of State (EOS) for Supernova Simulations



Gang Shen

- The EOS ---pressure as a function of density, temperature, and proton fraction--- is an important ingredient for SN and neutron star merger simulations. Previously only LS and H. Shen EOS in widespread use.
- At low density we use a Virial expansion with nucleons, alphas, and thousands of heavy nuclei. At high density we use relativistic mean field calculations in a spherical Wigner-Seitz approximation. Full thermodynamically consistent EOS table took 100,000+ CPU hours.
- Our EOSs are exact at low density and contain more detailed composition information for calculating neutrino interactions than LS or H. Shen.
- Large equation of state tables are available for download to be used in simulations of supernovae, proto-neutron star evolution, neutron star mergers, black hole formation ...
  – http://cecelia.physics.indiana.edu/gang_shen_eos

Collapse of 40 solar mass star to black hole



- Central density (diverges when black hole forms) vs time after core bounce for different EOSs. Neutrino signal ends when BH forms.
- Our very stiff (NL3) and softer (FSU1.7, FSU2.1) EOSs give longer times than Lattimer Swesty (LS180) EOS.

Conclusions

- **Multi-messenger motherhood (weak form)**: Combine astronomical observations using photons, gravitational waves, and neutrinos to fundamentally advance our knowledge of the heavens.

- **Multi-messenger motherhood (strong form):** Combine astronomical observations using photos, GW, and neutrinos, with laboratory experiments on nuclei, heavy ion collisions, radioactive beams... and new computational tools such as UNEDF to fundamentally advance our knowledge of the heavens, the dense phases of QCD, the origin of the elements, and of neutron rich matter.

Neutron Rich Matter

- Can be studied in lab. with radioactive beams and in Astrophysics with X-rays, neutrinos, and gravitational waves.
- PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb. This has implications for nuclear structure, astrophysics, and atomic parity violation.
- We performed large scale MD simulations of solids in white dwarfs and neutron stars.
- New equations of state are available for Supernova simulations.
- Collaborators D. Berry, E. Brown, A. Chugunov, K. Kadau, J. Piekarewicz Students: L. Caballero, H. Dussan, J. Hughto, A. Schneider and G. Shen.
- Supported in part by DOE and State of Indiana.