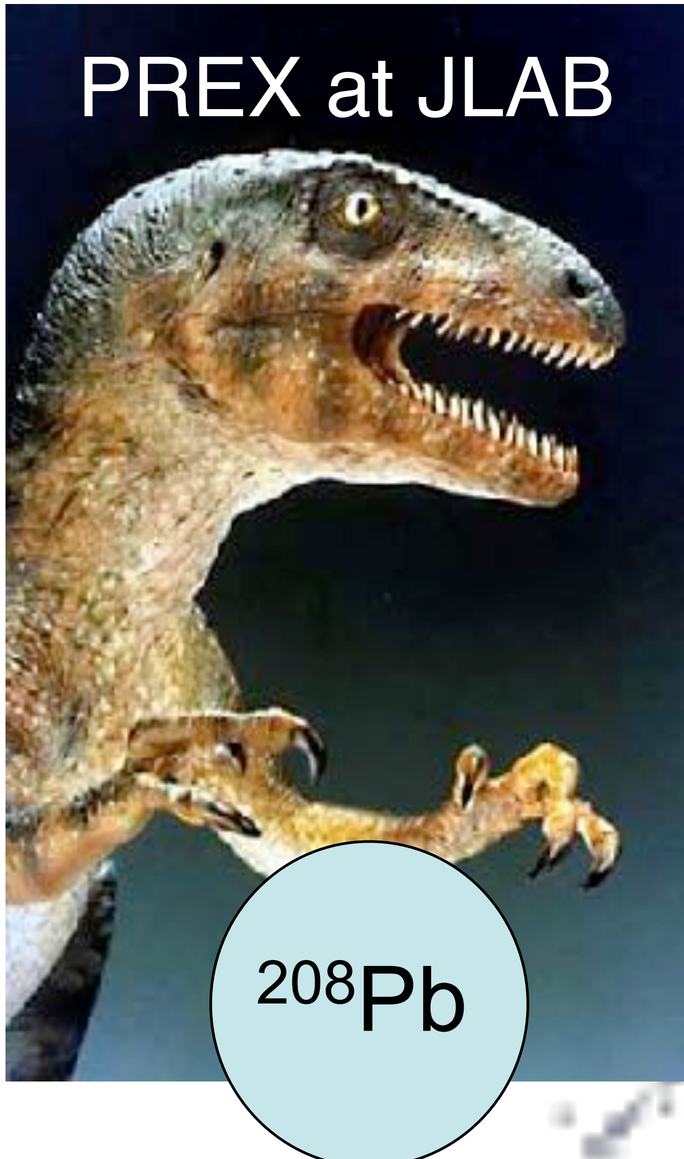
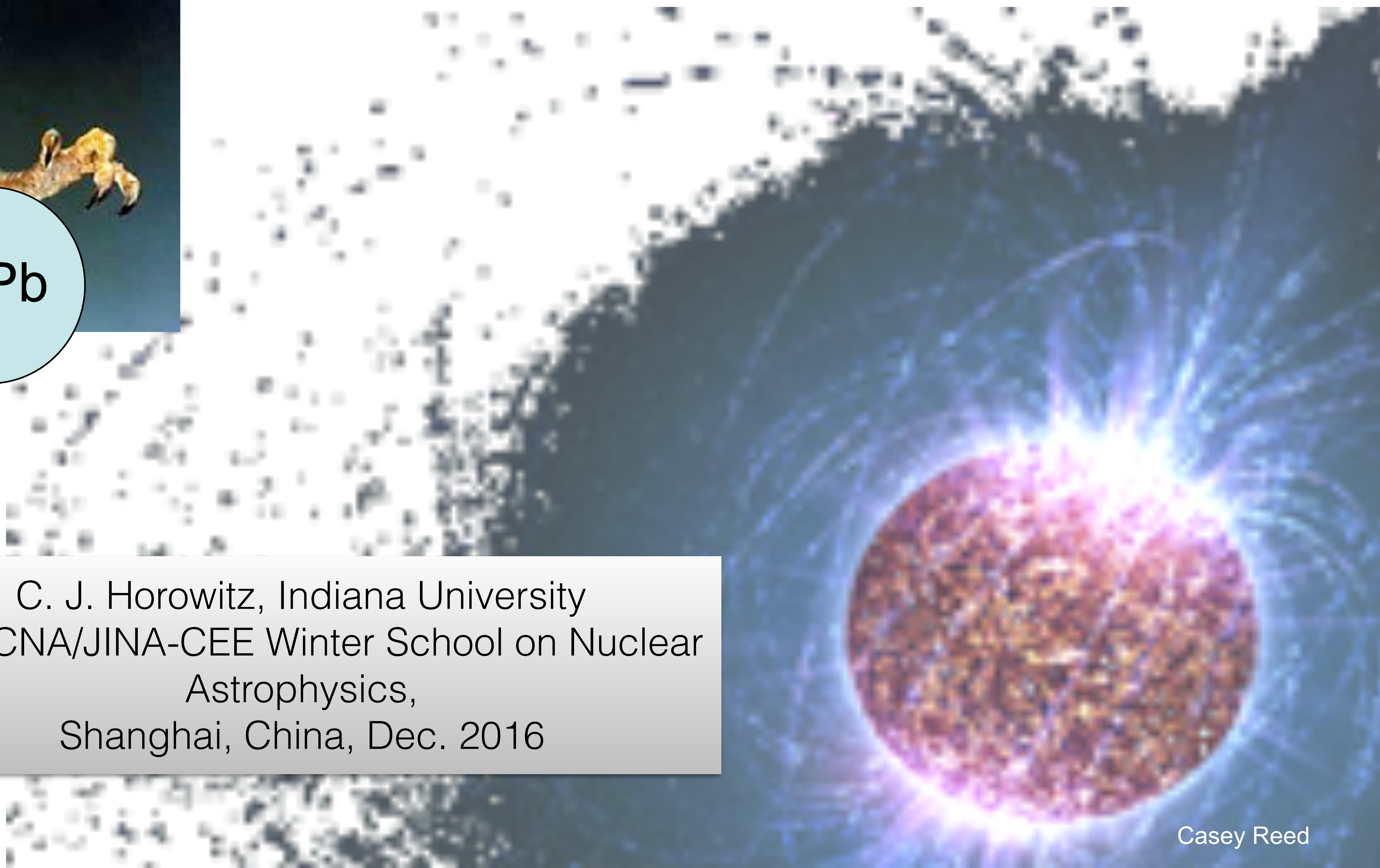


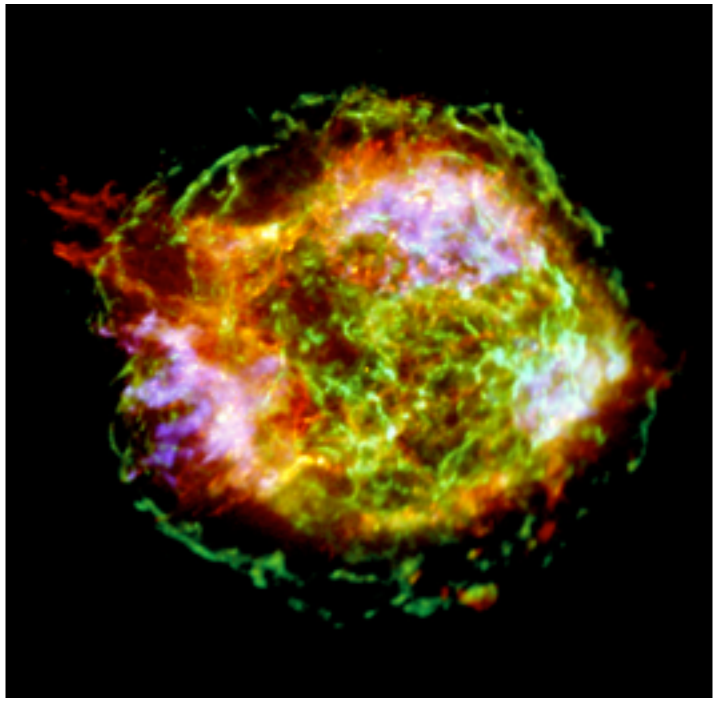
Laboratory and Astronomical Observations of Neutron Rich Matter



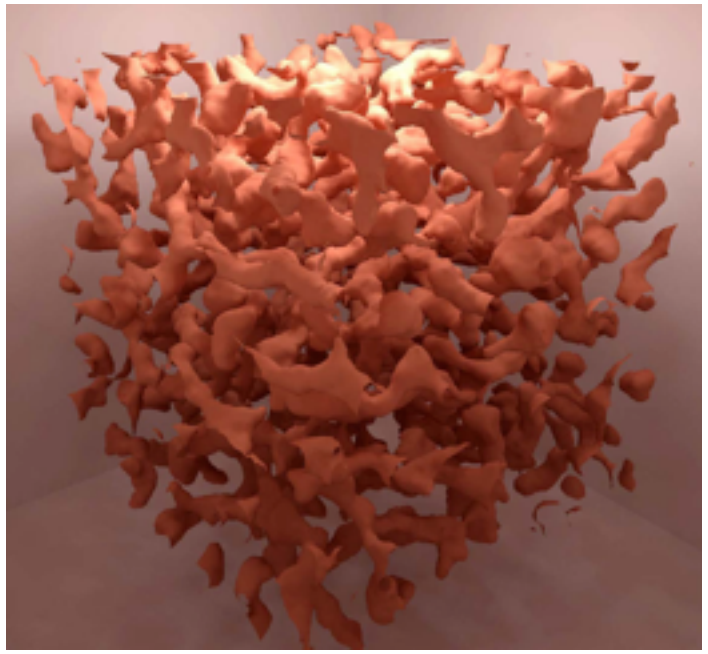
C. J. Horowitz, Indiana University
Joint CNA/JINA-CEE Winter School on Nuclear Astrophysics,
Shanghai, China, Dec. 2016

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 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, superfluid, color superconductor...*



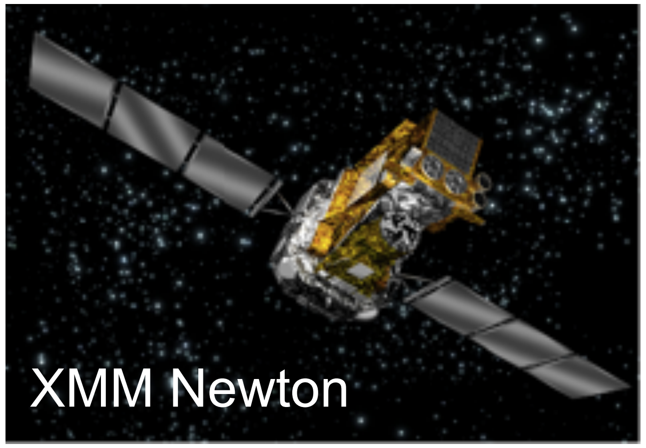
Supernova remanent Cassiopea A in X-rays

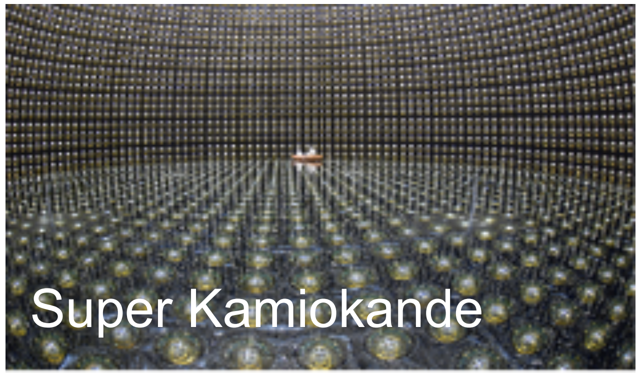


MD simulation of Nuclear Pasta with 100,000 nucleons

Probes of Neutron Rich Matter

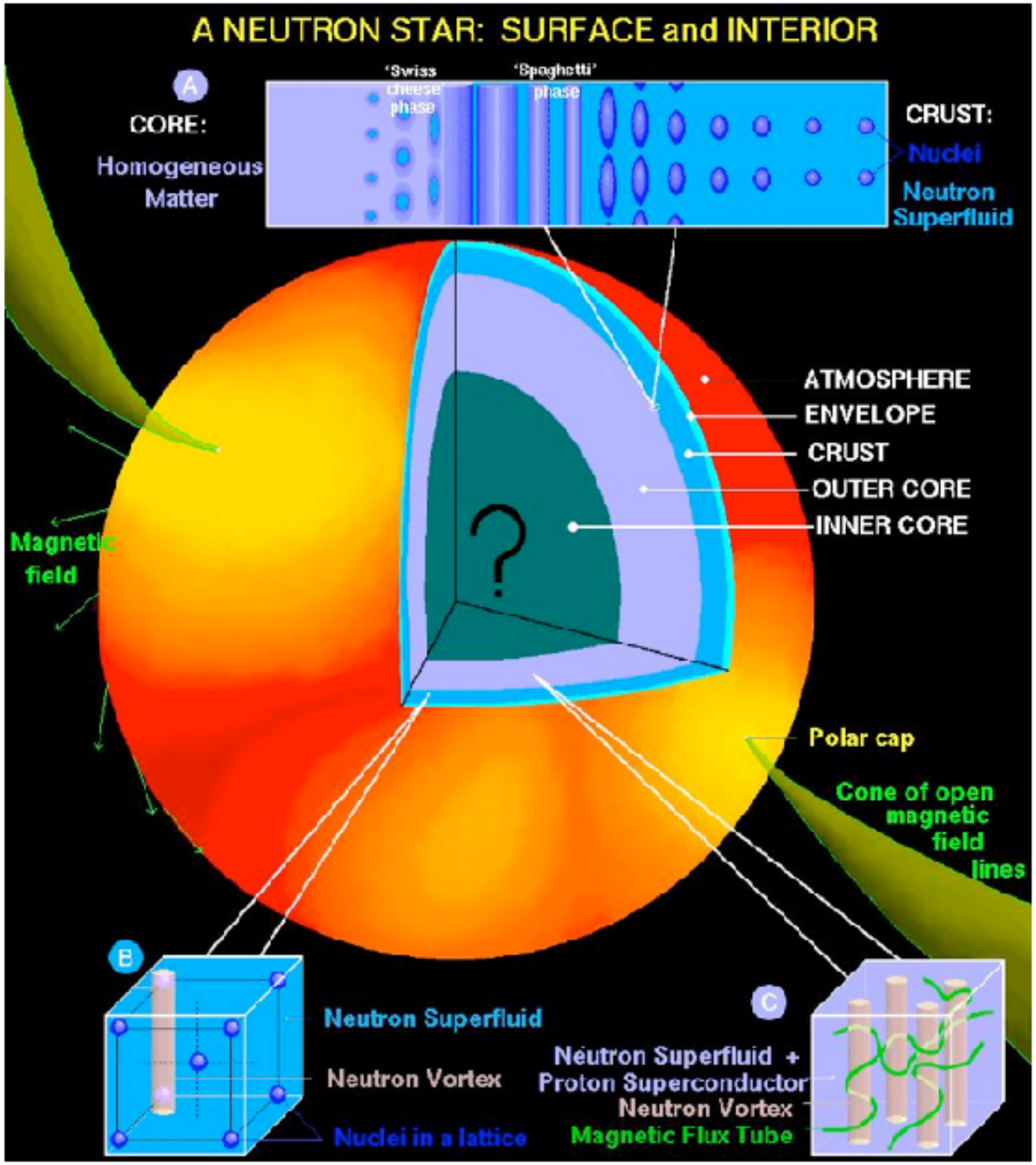
- **Multi-Messenger Astronomy:** "seeing" the same event with very different probes should lead to fundamental advances. Often ***photons*** from *solid* neutron star crust, supernova ***neutrinos*** from low density *gas*, and ***gravitational waves*** from energetic motions of *liquid* interior of 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:**
  – Chiral effective field theory (and MC calc. with phenomenological NN and NNN forces) depends on important and poorly known *three neutron forces*.
  – Chiral expansion does not converge at high densities. This strongly limits first principle calculations.
- Increases importance of laboratory experiments and astrophysical observations.





Neutron stars

- Neutron stars are formed from the collapse of a massive star in a supernova explosion.
- Mass ~1.4 M_{sun}, Radius ~10 km
- Solid crust ~ 1km thick (~10^{12} g/cm^3) over liquid outer core of neutron rich matter(~10^{15} g/cm^3).
- Possible exotic phase in center: de-confined quark matter, strange matter, meson condensates, color superconductor...
- Structure determined by Equation of State (pressure vs density) of n rich matter.
- Figure: **Dany Page,** UNAM



Equation of state

- Neutron star structure is determined by the equation of state: pressure as a function of energy density.
- $P = -dE/dV = -d(E/A)/d(V/A) = n^2 d(E/A)/dn$, V=volume.
- Here the baryon density $n=(A/V)$. [particles/fm^3]
- The energy density is $\epsilon=E/V=(E/A)n$. [MeV/fm^3]
- The mass density is $\rho=\epsilon/c^2$. [g/cm^3] Note that E includes rest mass mc^2. (In nonrel. limit $\rho=mn$)
- Calculate both $\epsilon(n)$, $P(n)$ and tabulate **$P=P(\epsilon)$** **which is the equation of state.**

NS hydrostatic equilibrium

- As you go deeper into a NS pressure p rises because of weight of material above you.

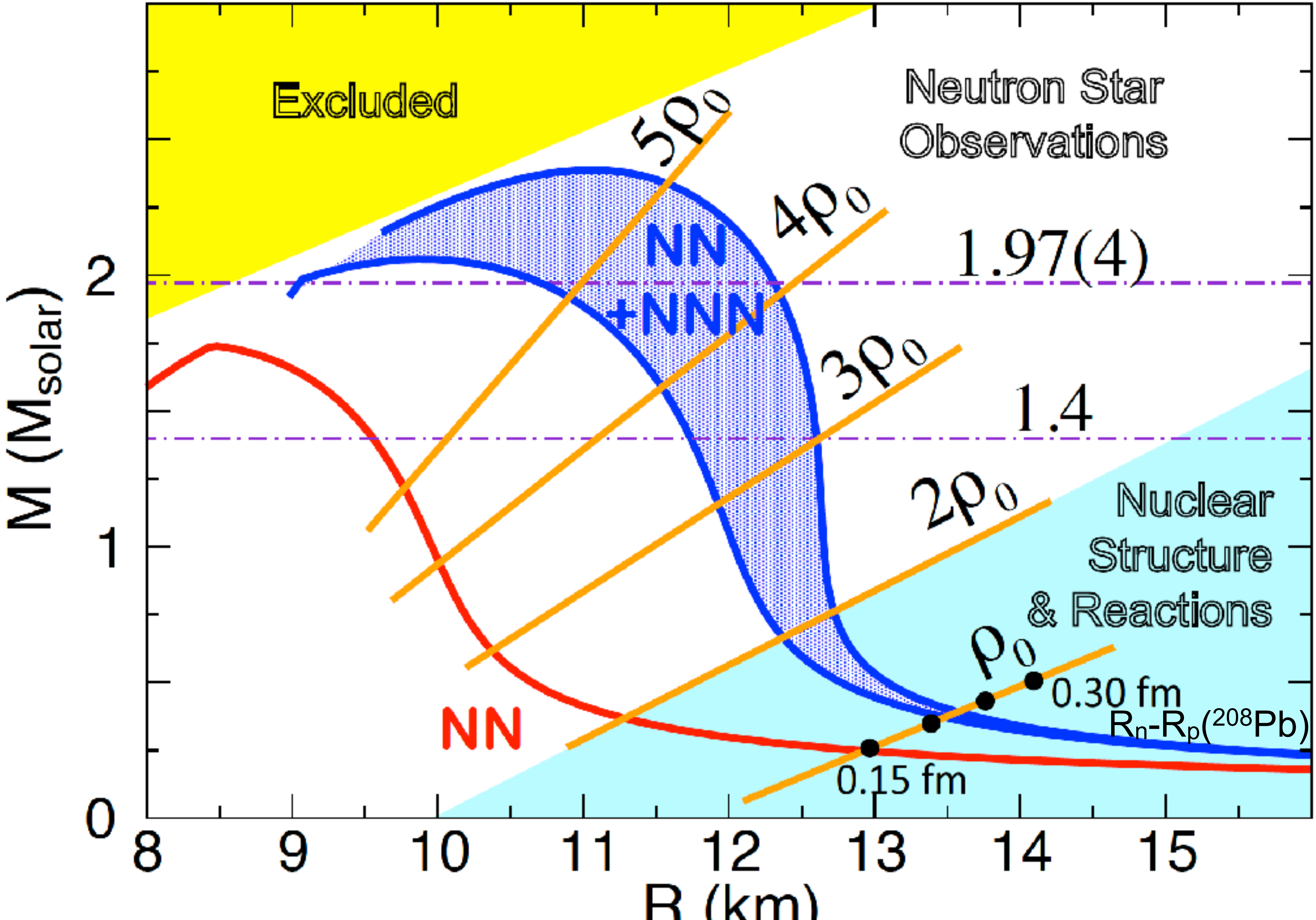
$$
\begin{aligned}
\frac{dp}{dr} &= -\frac{G\rho(r)\mathcal{M}(r)}{r^2} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2 r^2} \\
\frac{d\mathcal{M}}{dr} &= 4\pi r^2 \rho(r) = \frac{4\pi r^2 \epsilon(r)}{c^2} \\
\mathcal{M}(r) &= 4\pi \int_0^r r'^2 dr' \rho(r') = 4\pi \int_0^r r'^2 dr' \epsilon(r')/c^2
\end{aligned}
$$

- Above assumes Newtionian gravity. See NS for undergraduates R. R. Silbar, S. Reddy, Am. J. Phys. **72** (2004) 892

TOV Equation

$$\frac{dp}{dr} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2r^2}\left[1+\frac{p(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{\mathcal{M}(r)c^2}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2r}\right]^{-1}$$

- First two terms in brackets are special relativistic corrections while last term is a GR correction from the curvature of space.
- All three terms act to increase p in star. Effects are nonlinear, eventually gravity wins and star will collapse to black hole —> maximum mass for NS.
- For given EOS p=p(ϵ) guess central p and ϵ(p). Integrate p outward from r=0 until p=0. This gives radius and mass of star. Repeat for different central p to determine mass of NS as a function of radius.

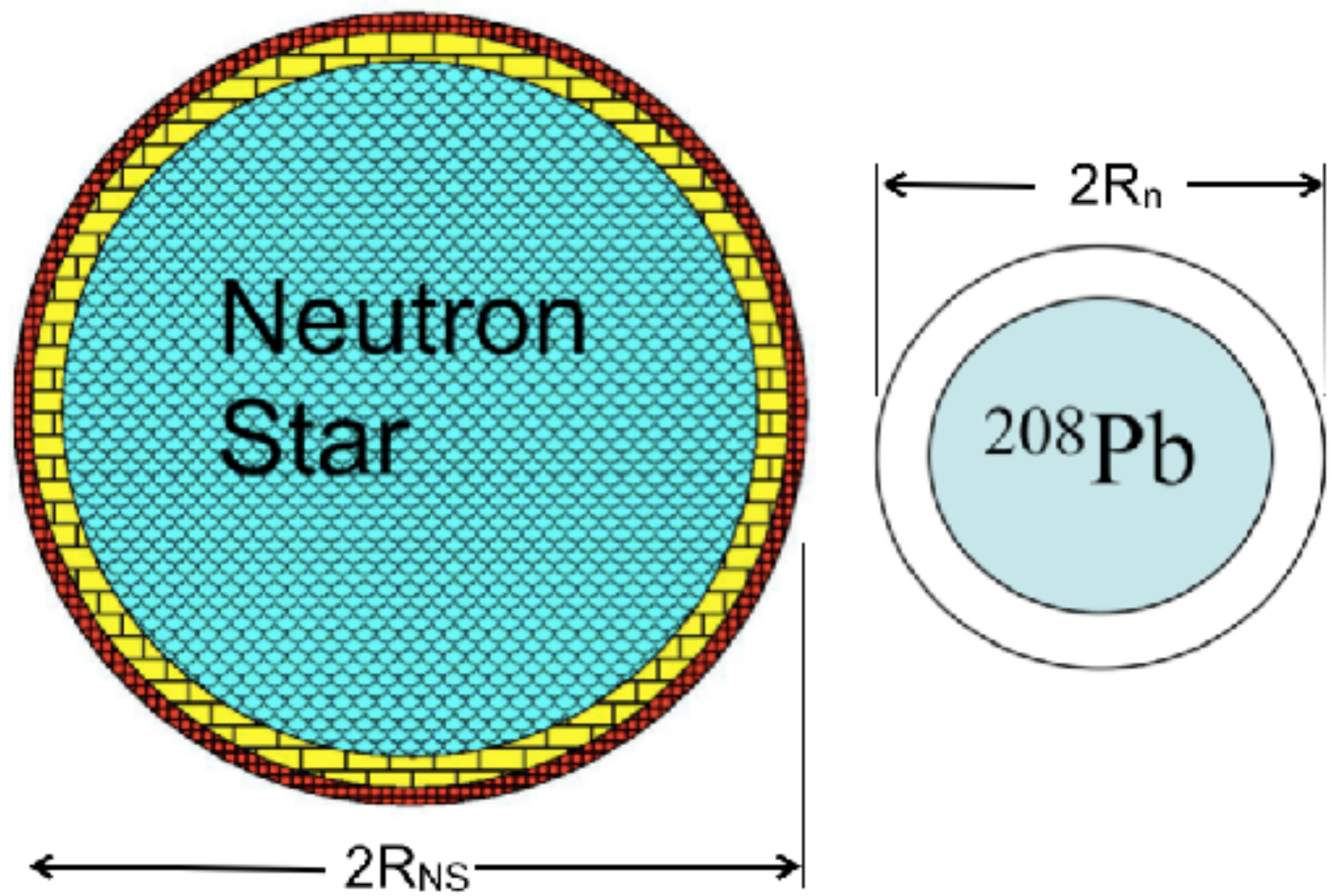


Gandolfi, Carlson, Reddy

Equation of state and Radii

- Neutron radius of heavy nucleus determines:
  - Equation of state (pressure vs density) of neutron matter.
  - Density dependence of symmetry energy.
- Radius of a neutron star:
  - Also determined by equation of state of neutron matter.
  - Can be measured with X-ray observations.

Neutron Star radius versus ^{208}Pb Radius

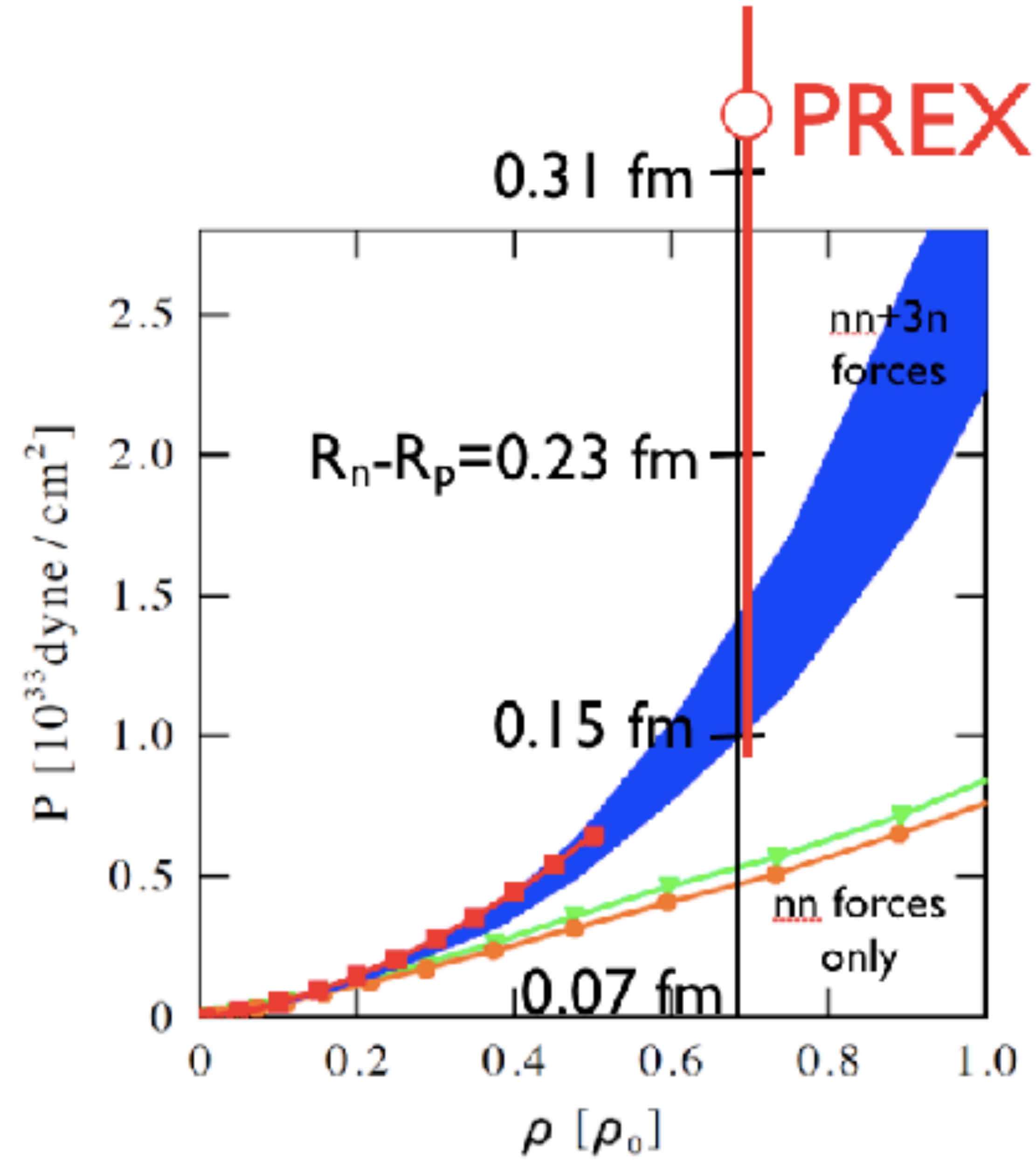


Neutron star is 18 orders of magnitude larger than ^{208}Pb nucleus but both radii determined by same strong interaction physics.

Pb Radius vs Neutron Star Radius

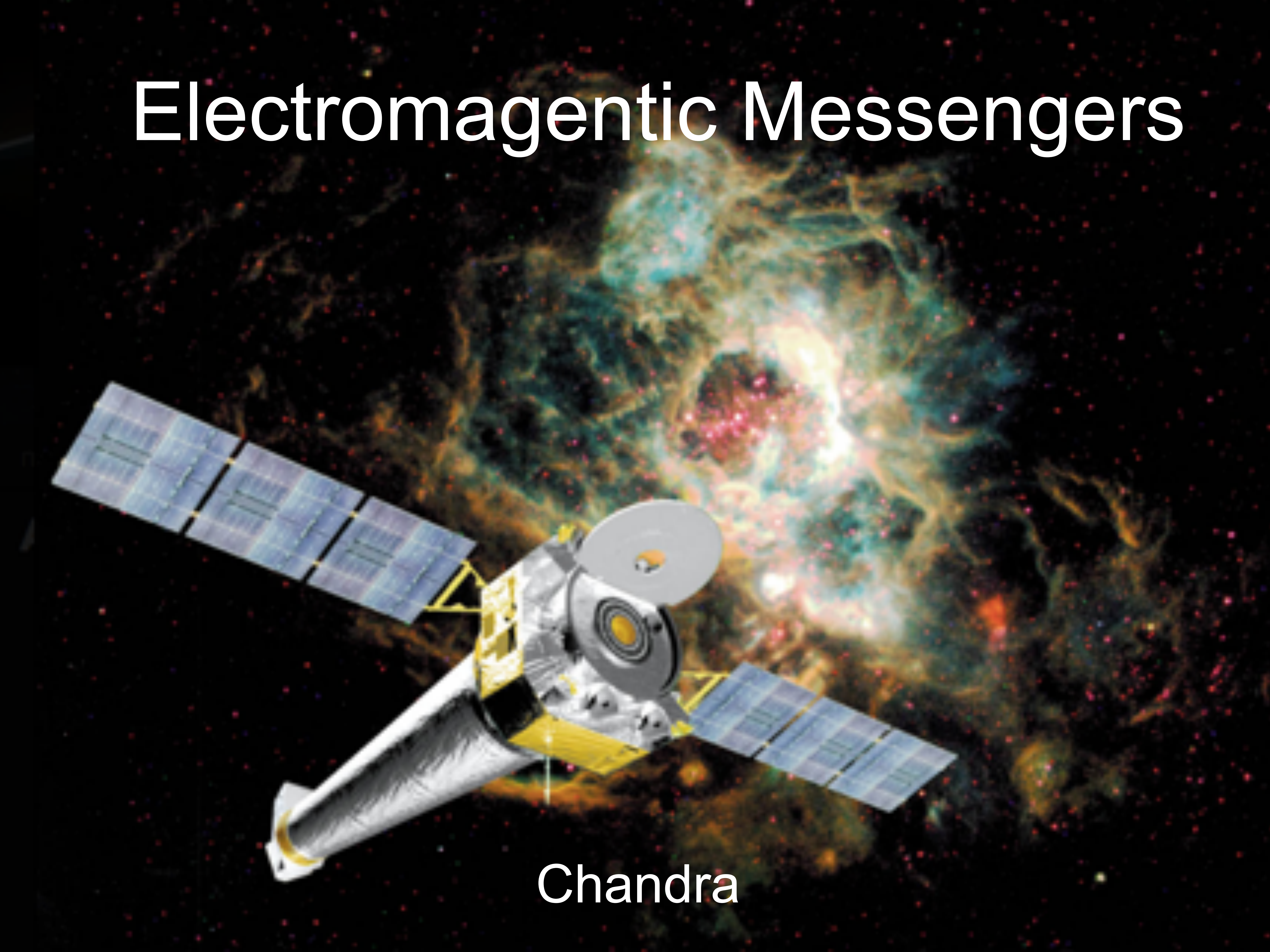
- The ^{208}Pb radius constrains the pressure of neutron matter at subnuclear densities. Typel + Brown find sharp correlation between P at 2/3 ρ_0 and R_n.
- The NS radius depends on the pressure at nuclear density and above. Central density of NS few to 10 x nuclear density.
- *Pb radius probes low density, NS radius medium density, and maximum NS mass probes high density equation of state.*
- An observed softening of EOS with density (smaller increase in pressure) could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, or a color superconductor…

J. Piekarewicz, CJH



Chiral EFT calc. of pressure P of neutron matter by Hebeler et al. including three *neutron* forces (blue band) agree with PREX results but two nucleon only calculations yield smaller P.

Electromagentic Messengers



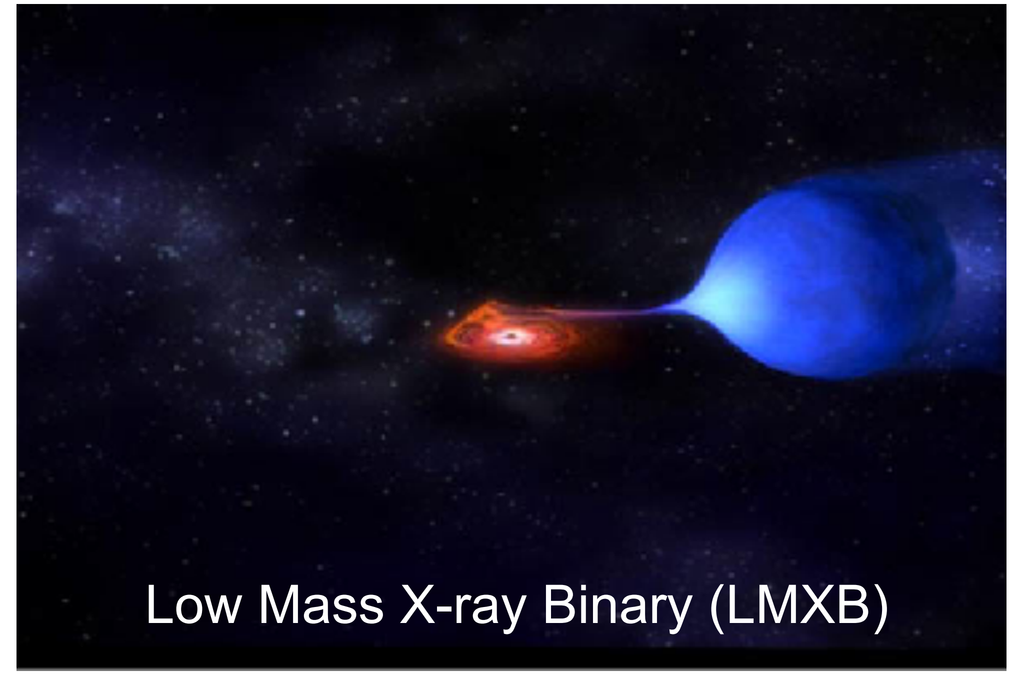
Chandra

X-ray observations of NS 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.
- NS in globular clusters: expect simple nonmagnetic hydrogen atmospheres and know distance.
- X-ray bursts: NS accretes material from companion that ignites a runaway thermonuclear burst.

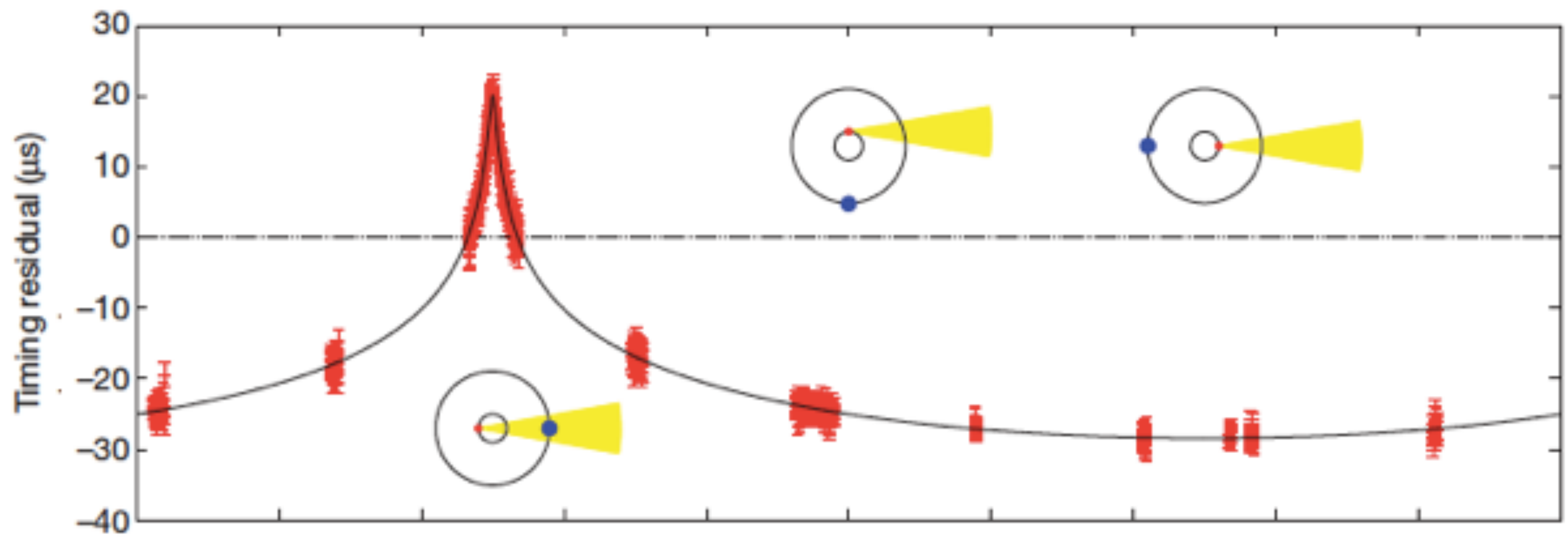

Low Mass X-ray Binary (LMXB)

- Eddington luminosity: when radiation pressure balances gravity --> gives both M and R!
- Steiner, Lattimer, Brown combine X-ray observations --> 1.4 M_{sun} star has ~ 12 km radius.
- However important uncertainties may remain in extracted radii. Suleimanov and Poutanen use more sophisticated atmosphere models and find larger radii.

Discovery of $2M_{sun}$ Neutron Star

Demorest et al: PSR J1614-2230 has 1.97+/- 0.04 M_{sun}.

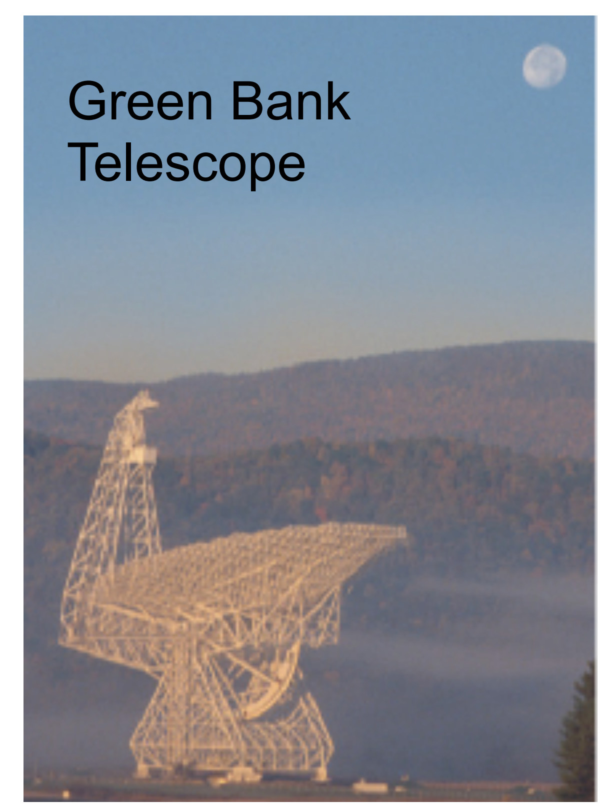
Delay in pulse arrival



NS + White Dwarf Binary

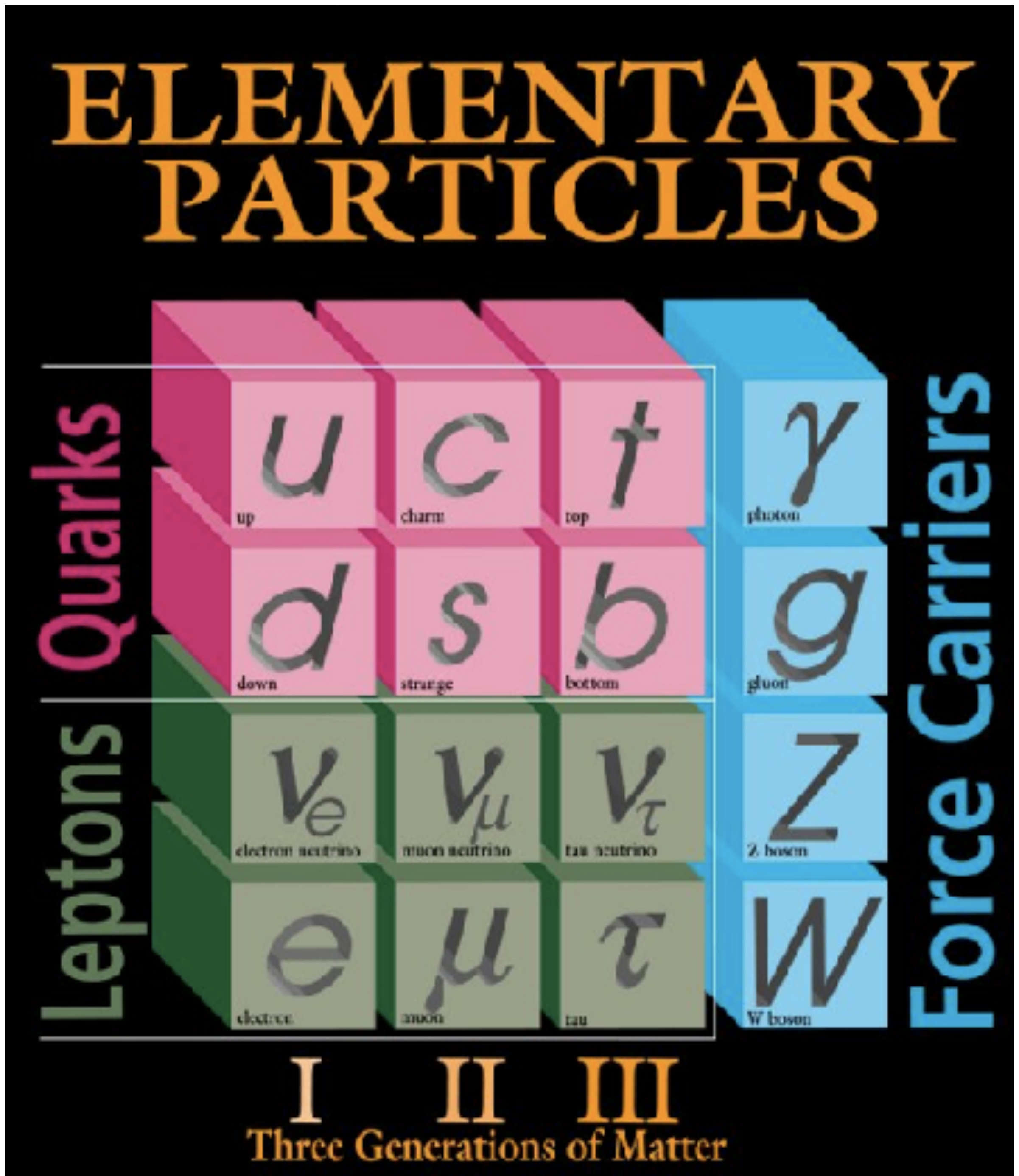
Orbital phase

- The equation of state of neutron rich matter (pressure vs density) at high densities must be stiff enough (have a high enough p) to support this mass against collapse to a black hole. *All soft EOS are immediately ruled out!*
- *However this does not tell composition of dense matter be it neutron/ proton, quark, hyperon...*
- *NS cooling (by neutrinos) sensitive to composition.*



Five-hundred-meter Aperture Spherical radio Telescope

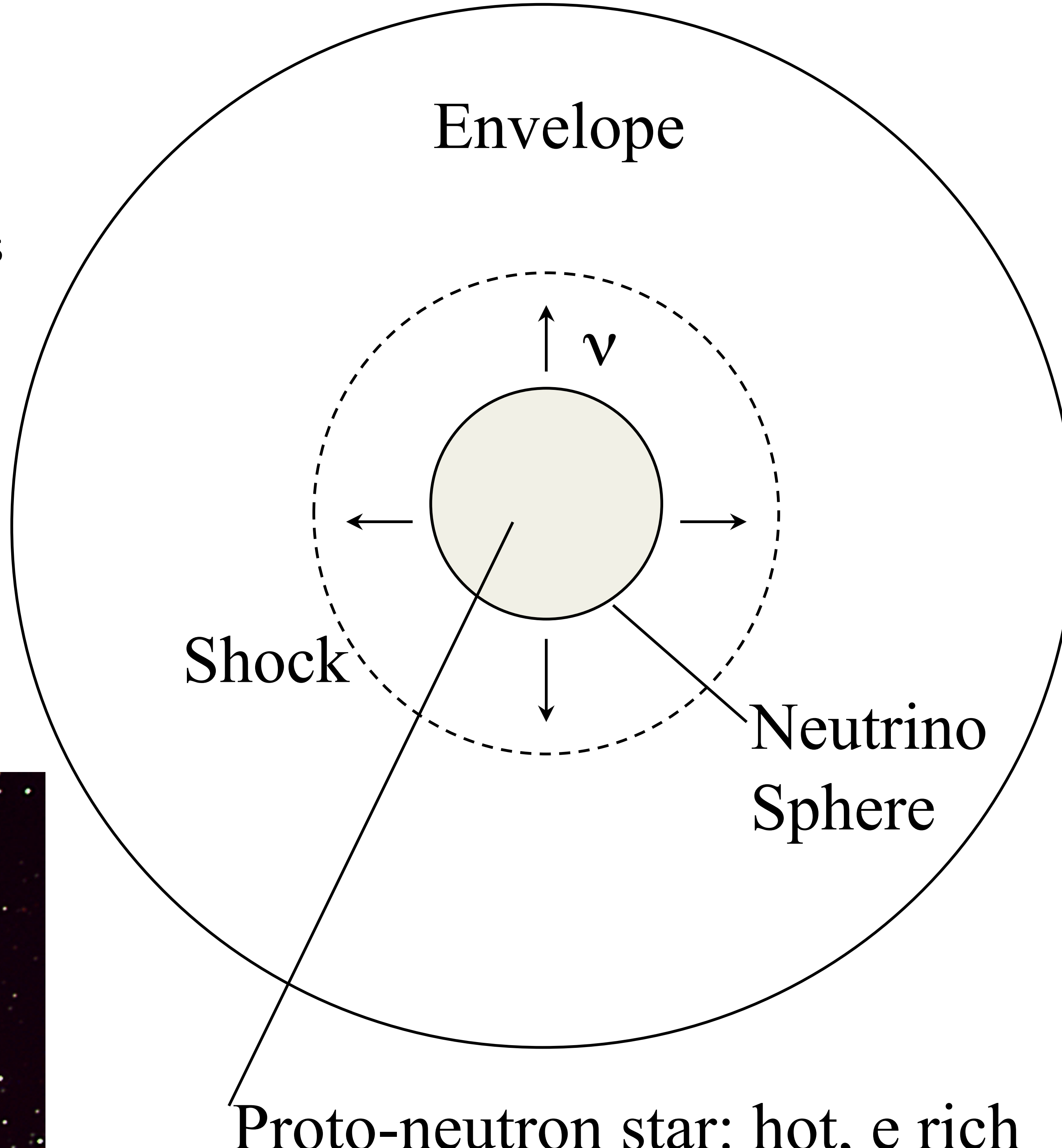
Neutrino messengers



- All three flavors of neutrinos and their antineutrinos (electron, mu, tau) are radiated in core collapse supernovae.
- **Neutrinos cary unique flavor information all the way to earth.**
- Note, neutrinos are somewhat forgetful messengers because of oscillations.

NS Born in Core Collapse Supernovae

Core of massive star collapses to form proto-neutron star. νs form neutron star energizes shock that ejects outer 90% of star.



July 5, 1054

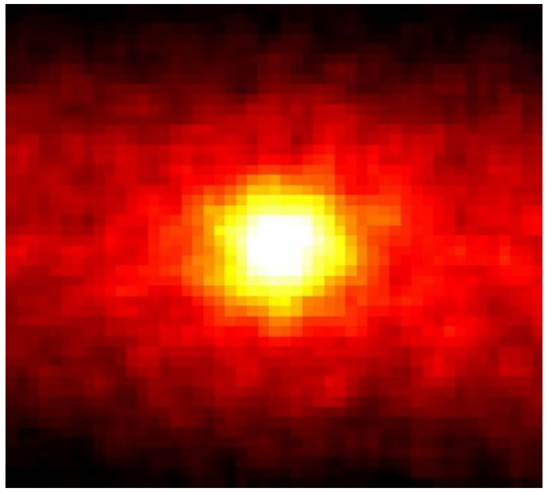
Crab nebula

Crab Pulsar

Hubble ST

Astrophysical Neutrinos

- Much progress with **solar neutrinos** over last decade documenting neutrino oscillations and confirming solar model.
- Core collapse supernovae radiate gravitational binding energy of NS, $\sim 3/5GM^2/R = 0.1$ to $0.2\ M_{sun}c^2$ in 10^{58} neutrinos of ~ 10 MeV each.


Sun in neutrinos

- Historic first detection of ~20 **supernova neutrinos** from SN1987A (detection efficiency 10^{-57}).
- New underground dark matter, solar nu,... experiments will be sensitive to nu from the next galactic supernova (SN).
- Example: ton scale dark matter detectors sensitive to SN neutrinos via nu-nucleus elastic scattering. [CJH, K. Coakley, D. McKinsey, PRD**68**(2003)023005]
- Expect ten thousand or more events from next galactic SN!

Neutrino Spectra

- The stronger the neutrino interactions, the longer a neutrino stays in thermal equilibrium with matter to lower densities and temperatures, and the lower is the emitted neutrino energy.
- Mu and tau neutrinos have only neutral current reactions (not enough energy to make muons) and so decouple at highest energies.
- Electron antineutrinos capture on protons while neutrinos capture on neutrons. Matter is neutron rich so neutrinos have large opacity. Therefore electron neutrinos are emitted with lowest energy.
- Expect order E(mu, tau) > E(anti-nu$_e$) > E(nu$_e$).

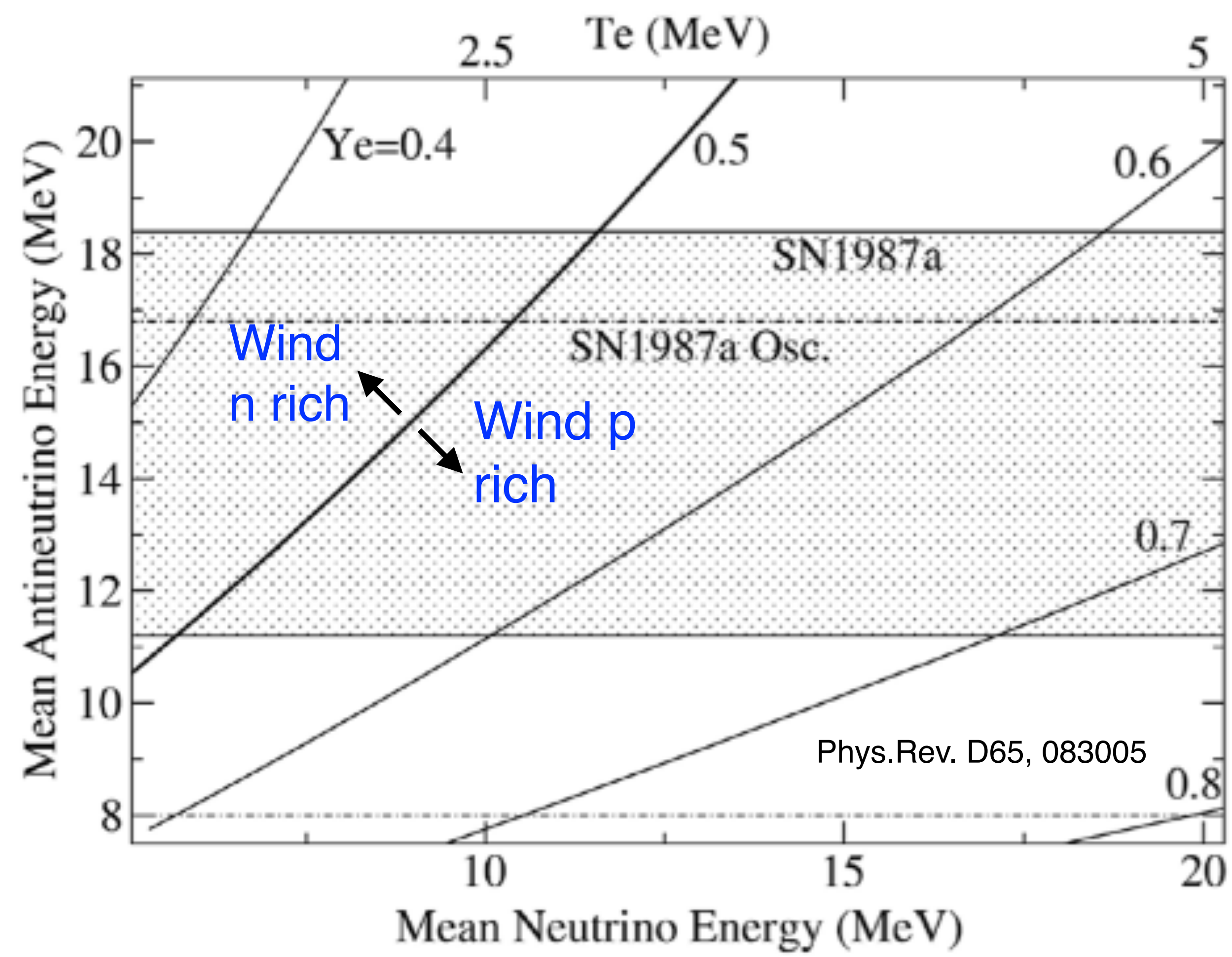
Deep Underground Neutrino Experiment

- Neutrino driven wind in a Supernova is an important nucleosynthesis site.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and antineutrino energies.

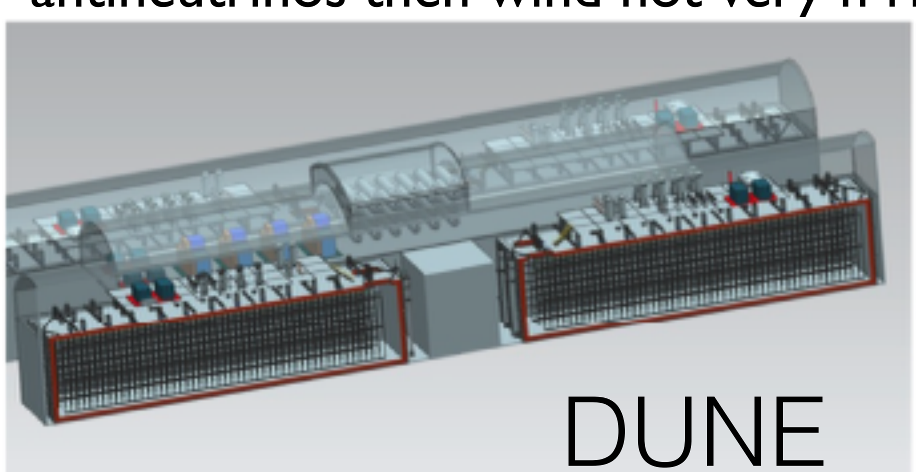
$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

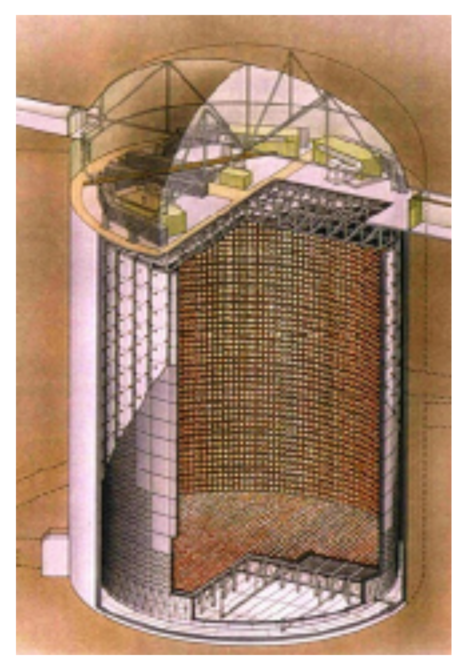
- Measure spectrum of both **antineutrinos** and **neutrinos** from next galactic SN.
- Super Kamiokande is large H_2O detector good for **antineutrinos**.
- DUNE will be large liquid Ar detector that should measure **neutrino** spectrum well. If neutrinos are not much colder than antineutrinos then wind not very n rich.

Super K H_2O



DUNE liquid Ar





Super K

Present SN simulations find too few neutrons for (main or 3rd peak: Au, U) r-process.

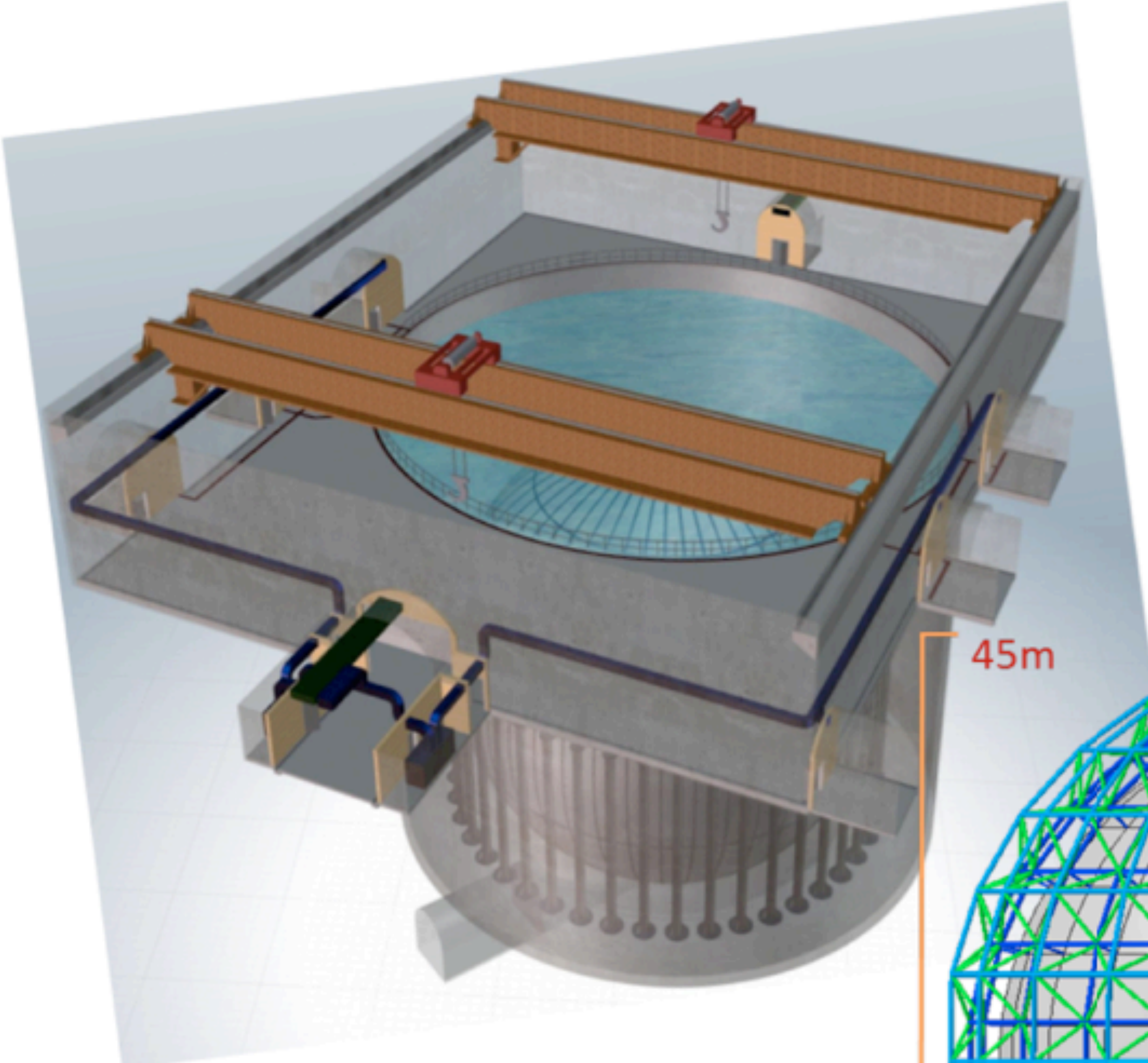
Likely that main r-process occurs in neutron star mergers. Expect gravitational wave observations.

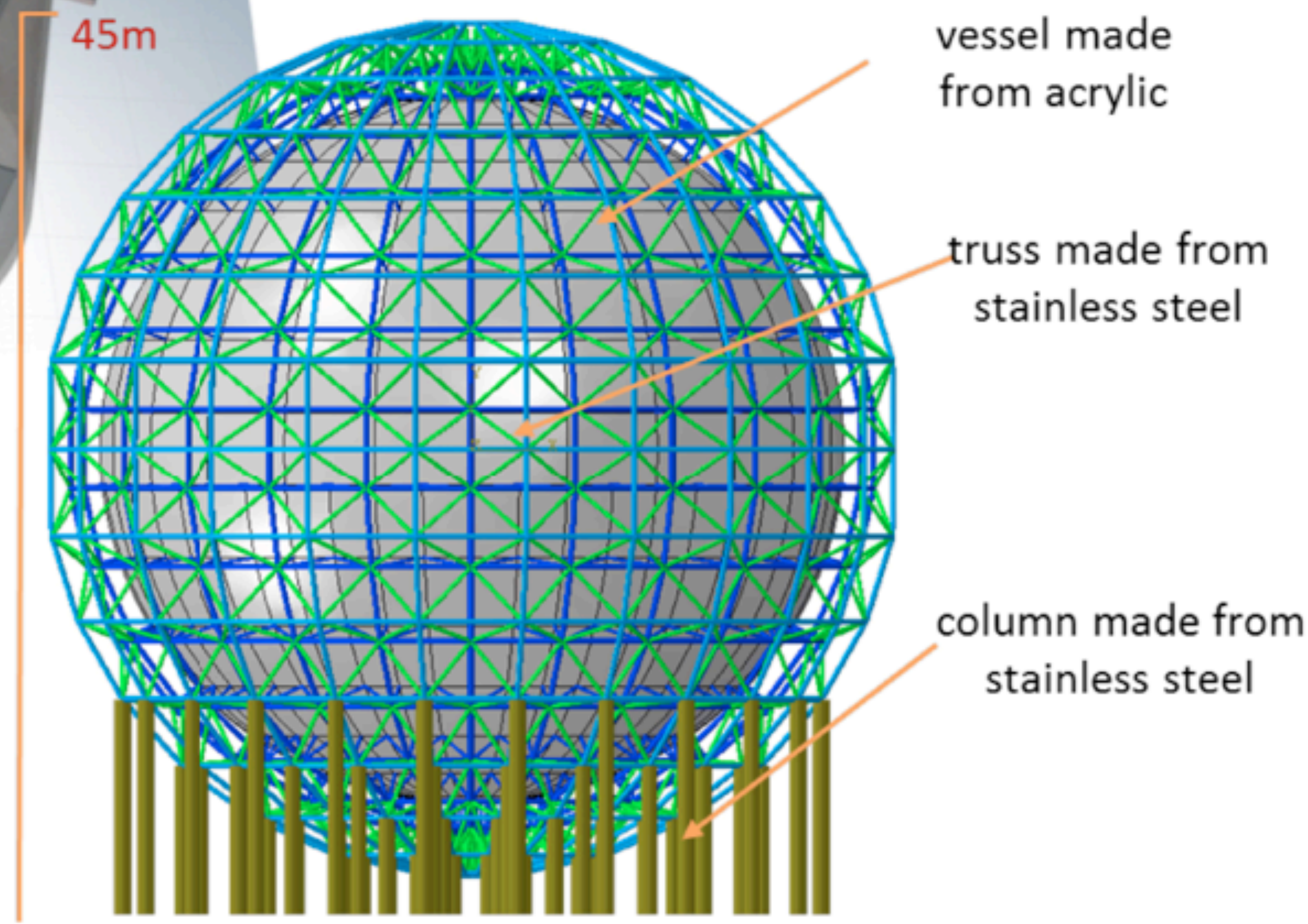
JUNO detector

35m diameter

20kt of liquid scintillator

15,000 PMTs





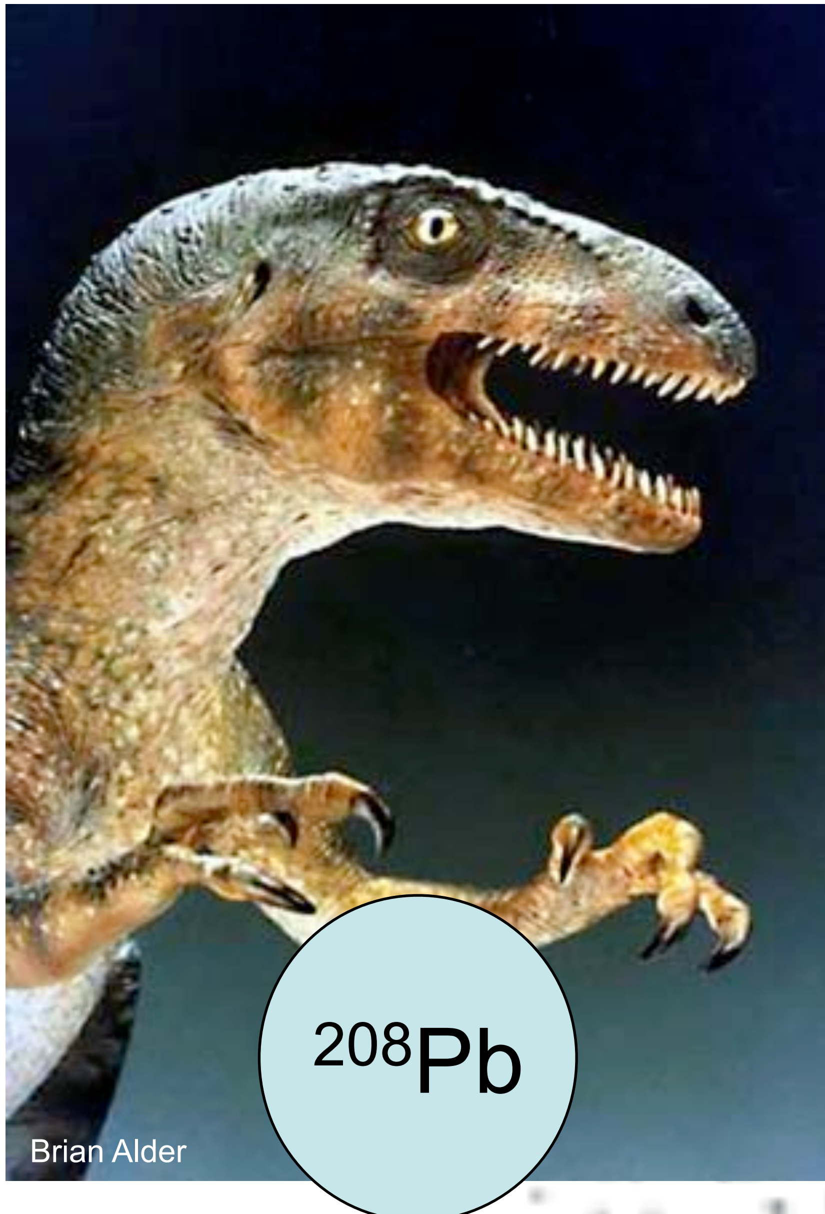
Supernova Neutrinos

- Many thousands of events for a galactic SN.
- Electron antineutrinos in Super-K, JUNO, …
- Electron neutrino spectra in DUNE (liquid Ar).
- Mu and tau neutrinos and antineutrinos via nu_x+p —> nu_x+p elastic scattering in JUNO.

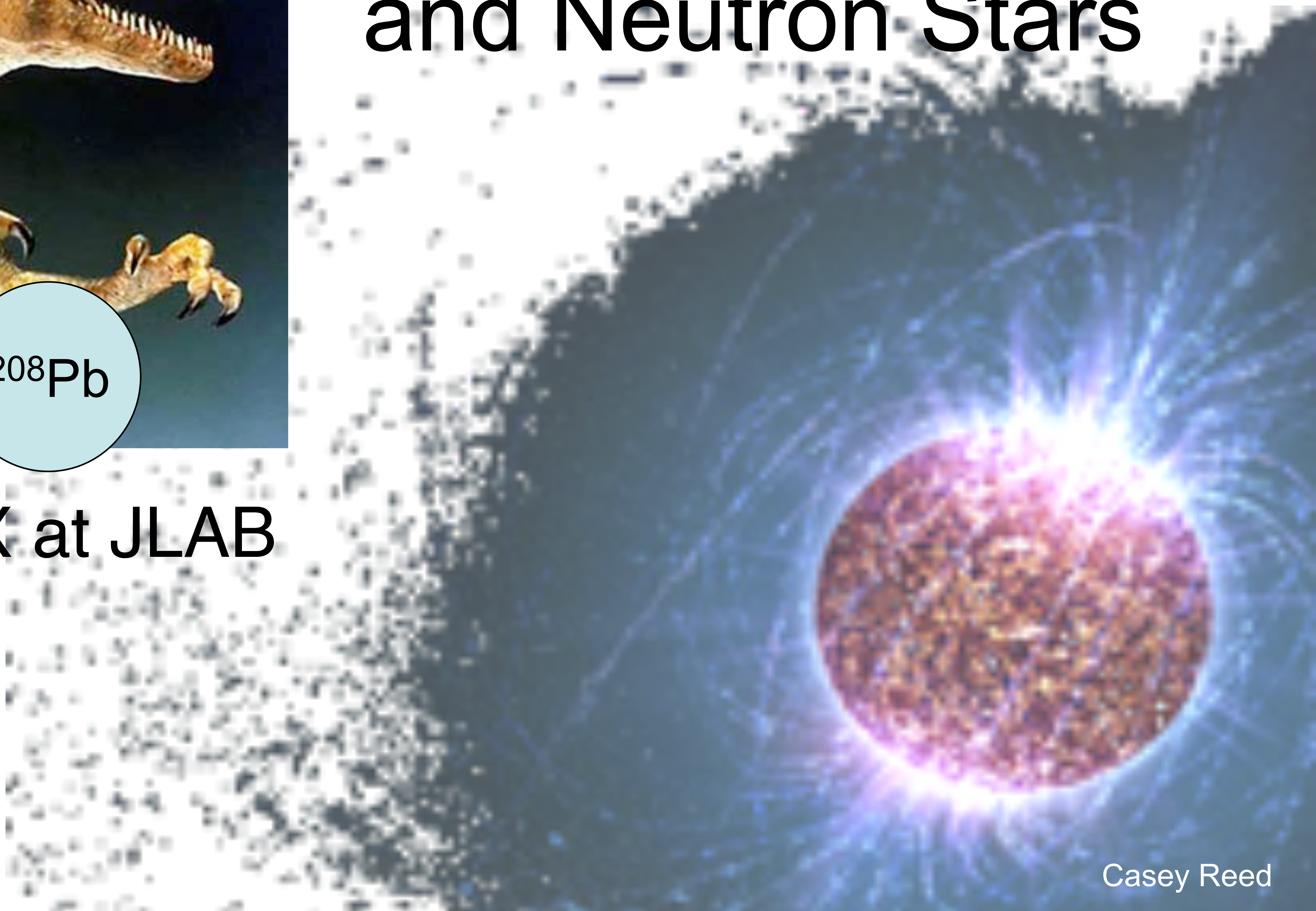
Site of main r-process

- Could be core collapse supernovae —> Neutrino observations from next galactic SN will provide fundamental information.
- Could be neutron star mergers —> Gravitational wave observations from LIGO are directly determining the merger rate.

Laboratory Measurements and Neutron Stars



PREX at JLAB

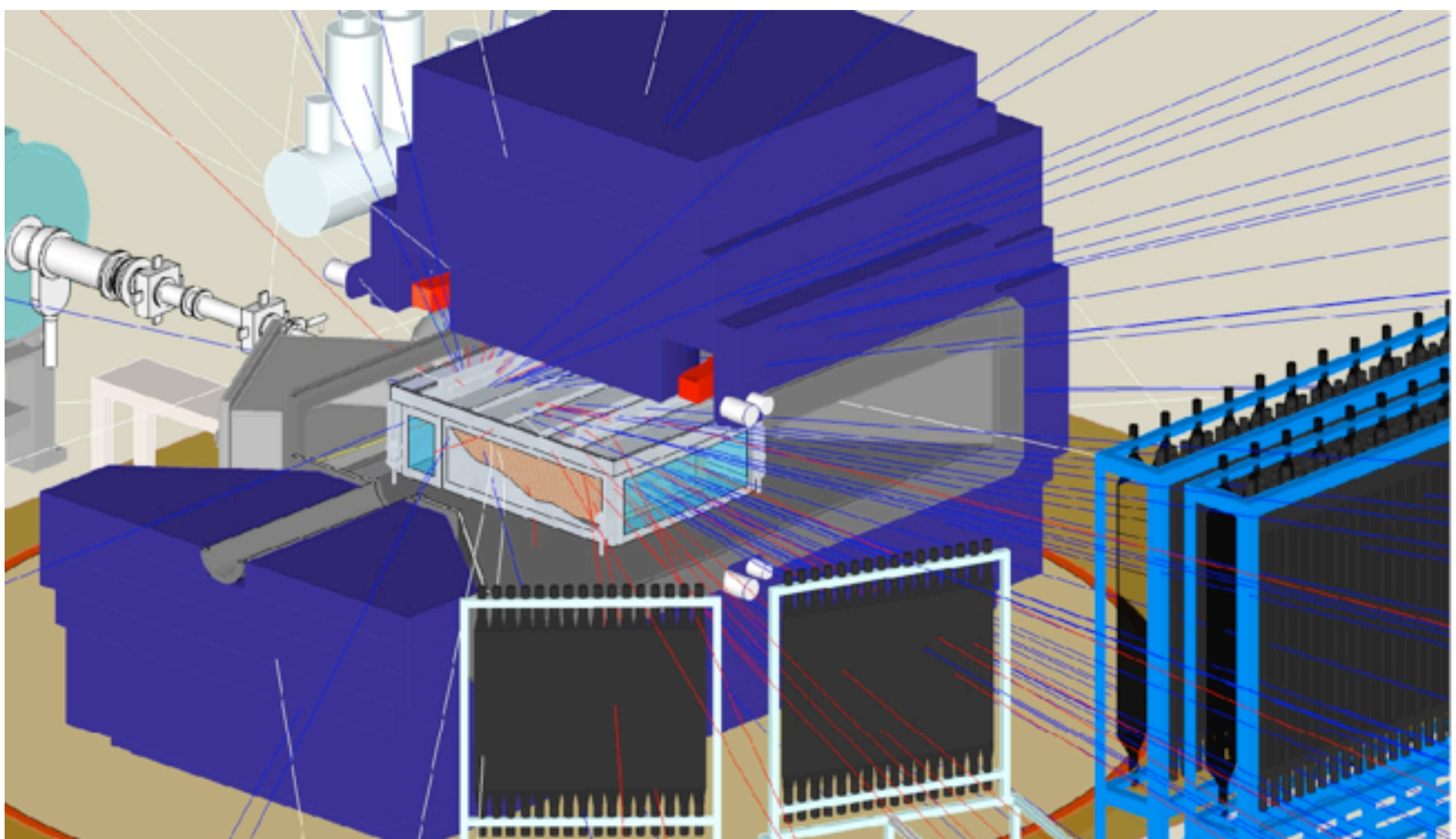


Symmetry Energy S(ρ)

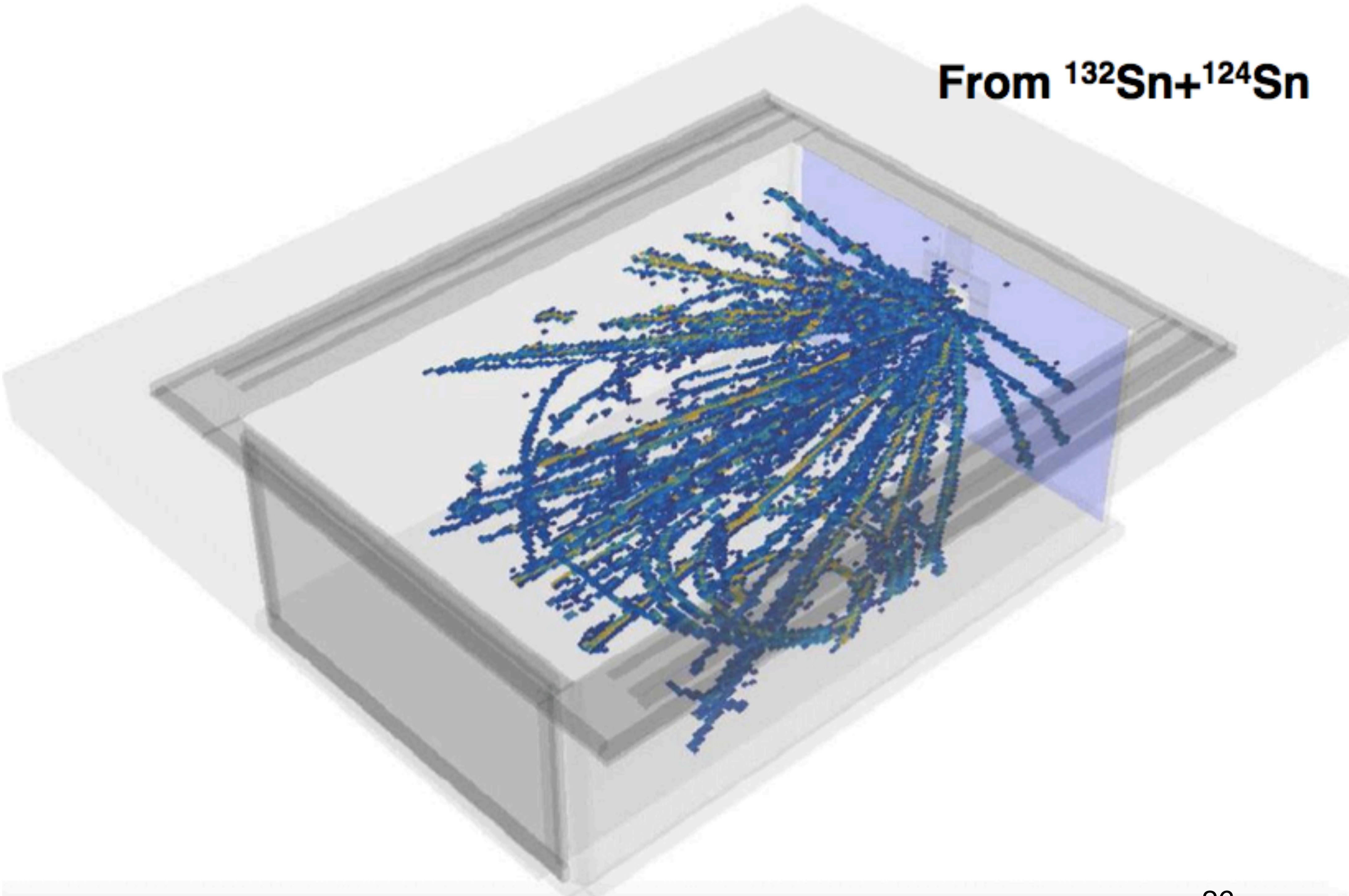
- Describes how energy of nuclear matter rises with increasing neutron excess.
- Important for extrapolating laboratory measurements to very neutron rich systems in astrophysics.
- *S(ρ) at high densities ($\rho>\rho_0$) is the single laboratory observable most closely related to the structure of neutron stars.*
- Heavy ion collisions, with radioactive beams, can produce high density n rich matter in the laboratory.

Samurai TPC and S(ρ) at $\rho > \rho_0$

- Determining S(ρ) from HI exp. may depend on transport models. Look at pion production and π^+/π^- ratios, n/p flow…
- Experimental program underway at RIKEN RIBF using SAMURAI magnet and time projection chamber (TPC). Exp. with ^{108}Sn, ^{132}Sn beams 2016



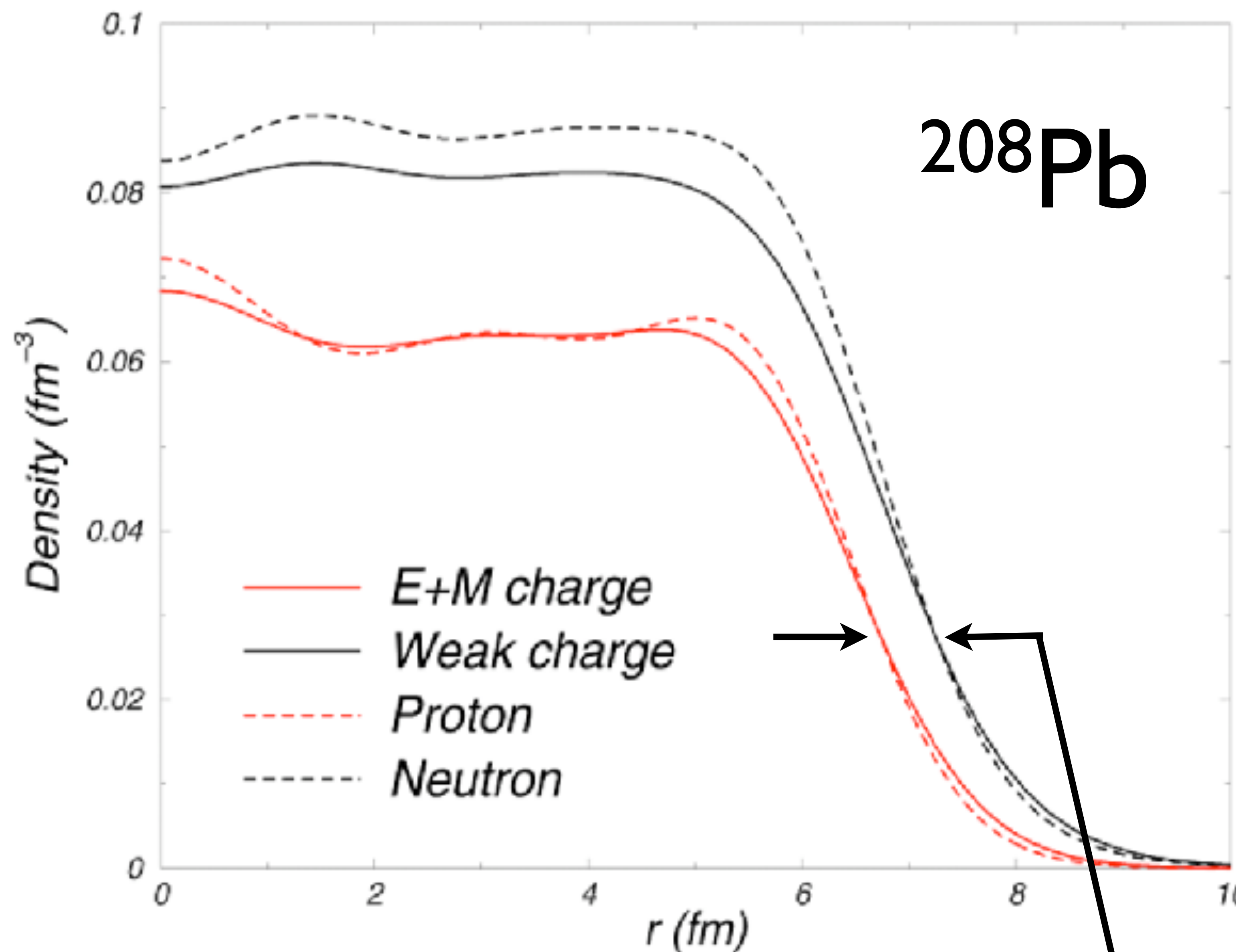
First results in a year



Event from Tetsuya MURAKAMI talk

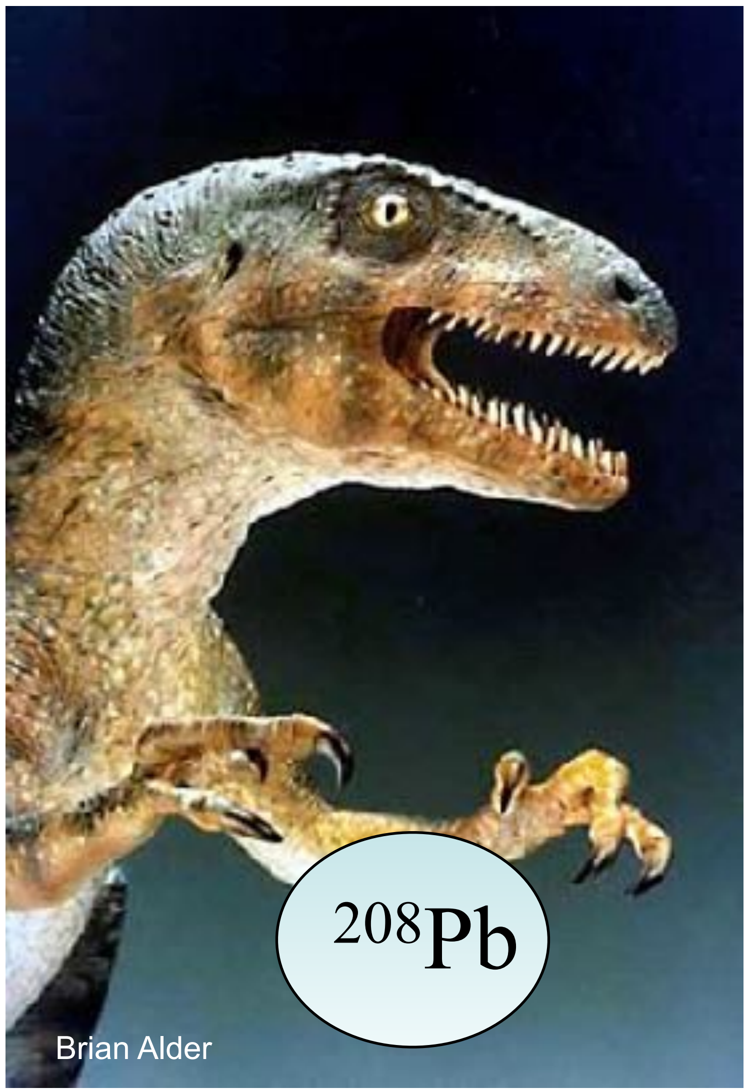
Neutron skins and dS/dρ

- Cleanest way to get dS/dρ is to measure neutron skin thickness.
- ^{208}Pb has 44 more n than p. If extra n are in the center they will cost S(ρ) at relatively high ρ. But if extra n are in the surface they will only cost S(ρ) at low surface densities.
- The density dependence of S (dS/dρ) will push n out to the surface and give a thick n skin.



Measure how much neutrons stick out past protons

Laboratory probe 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

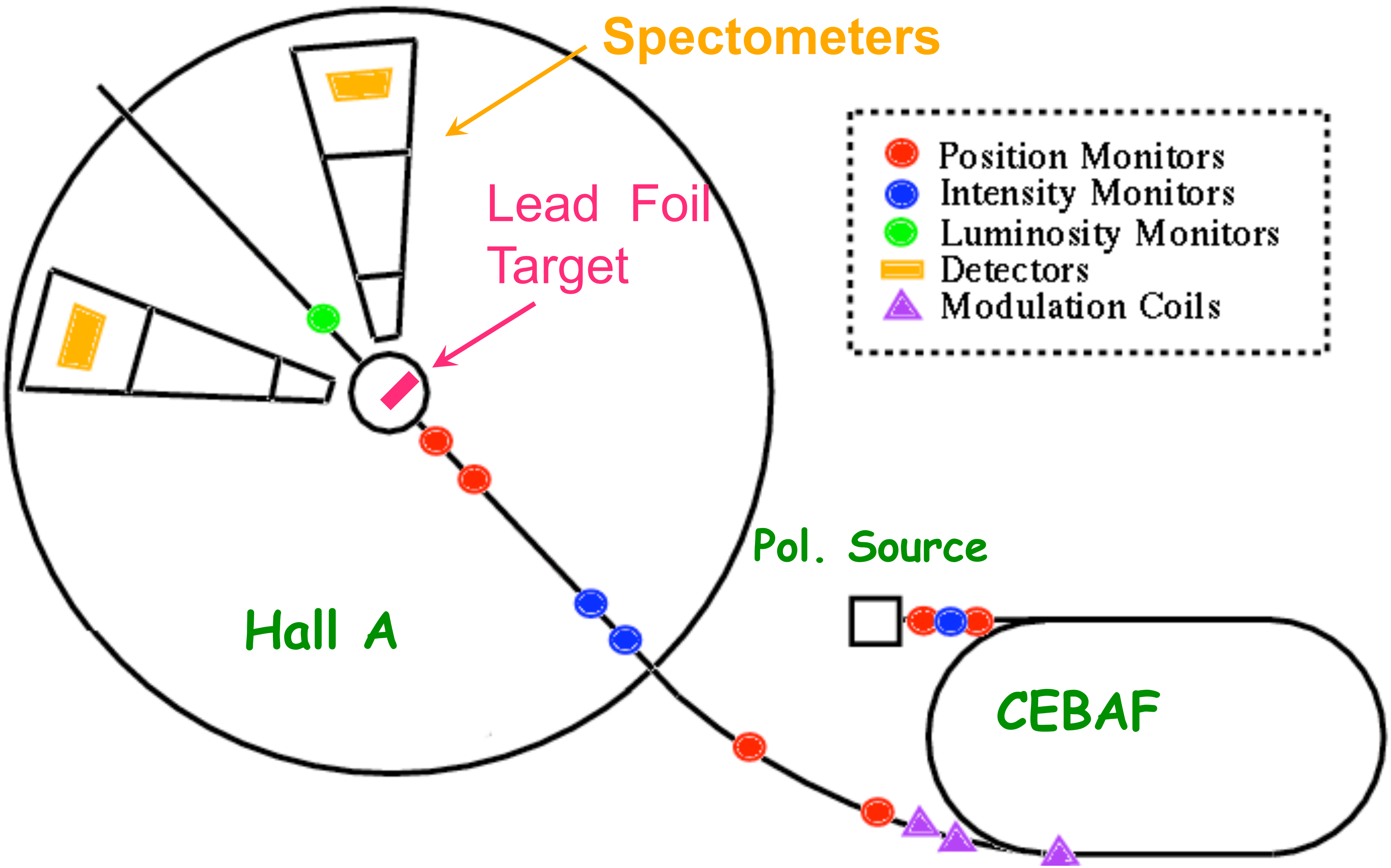
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

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

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

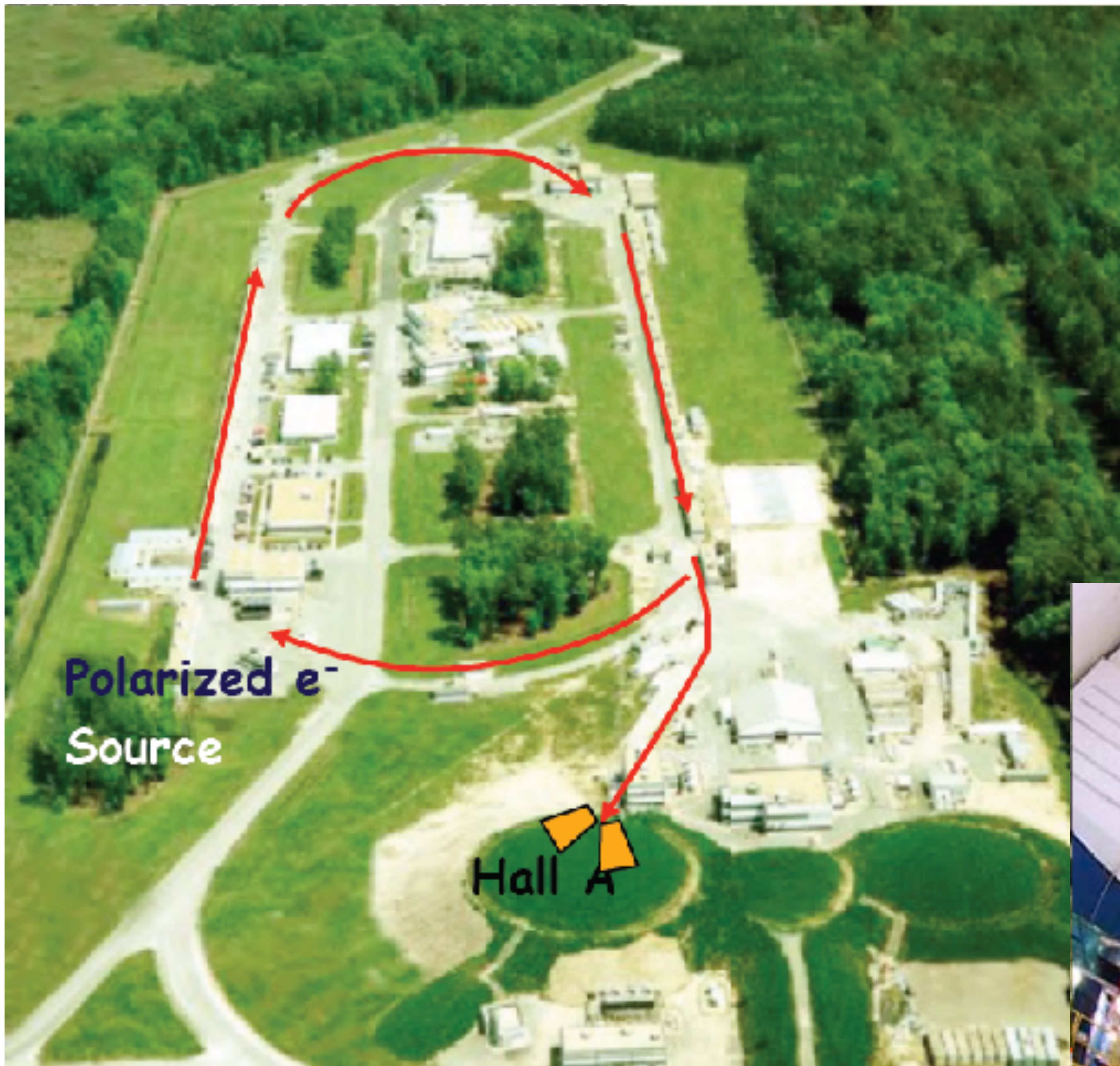
–Donnelly, Dubach, Sick

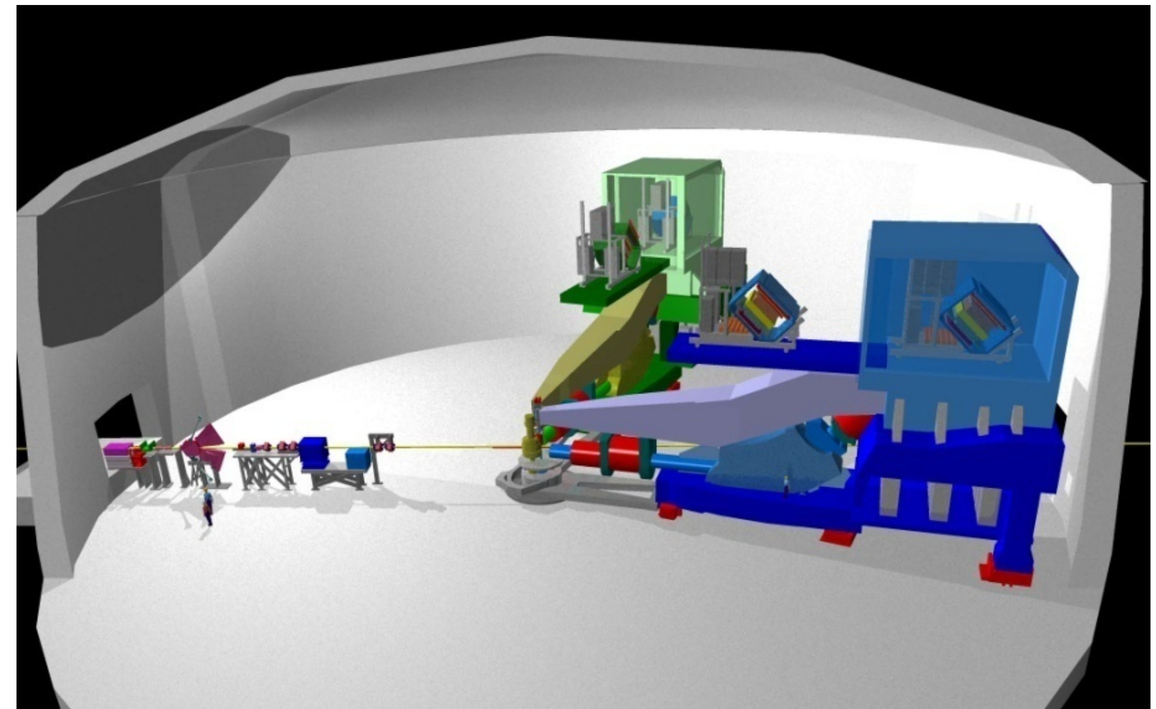
PREX in Hall A at JLab

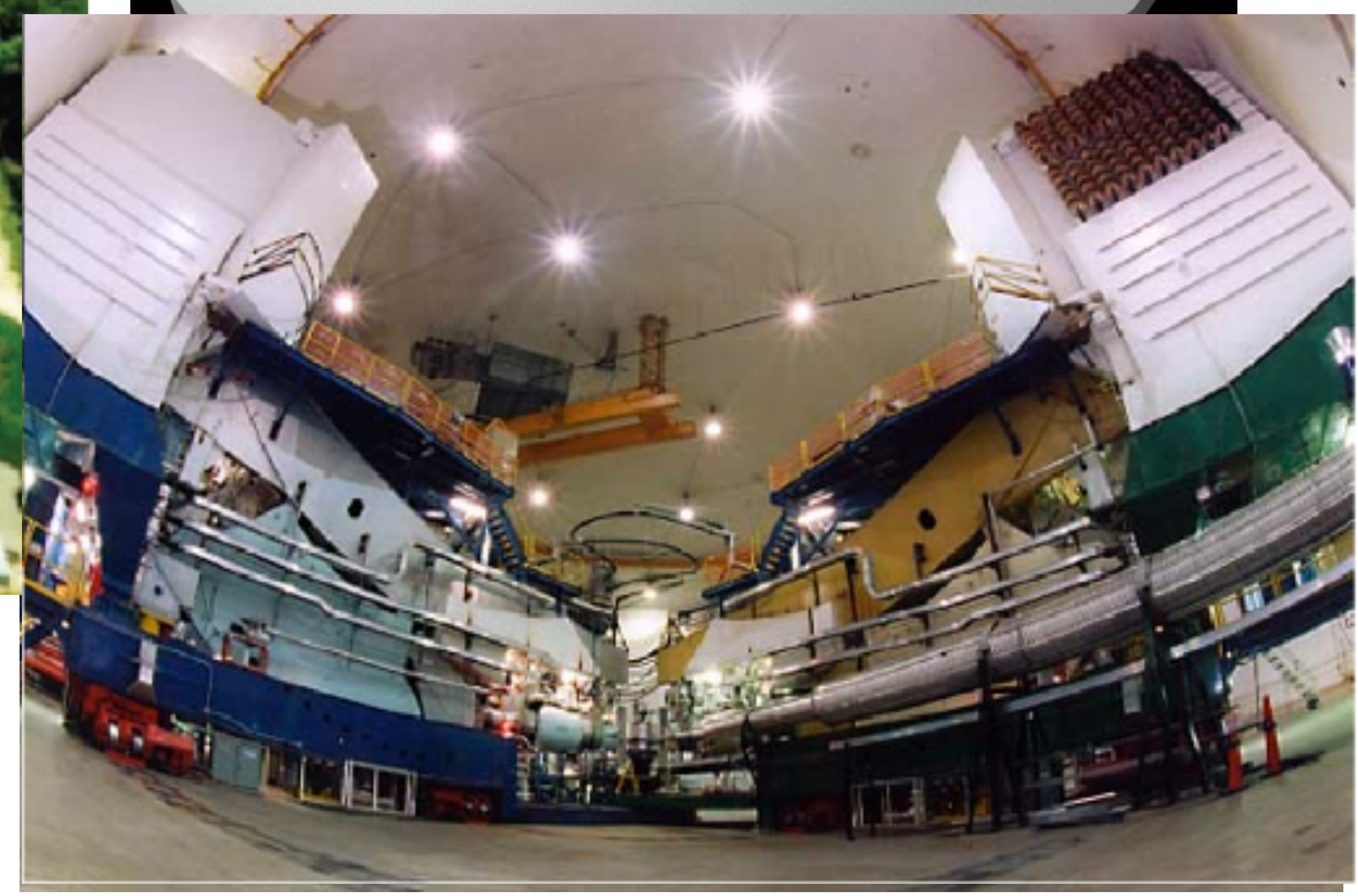


R. Michaels

Hall A at Jefferson Lab



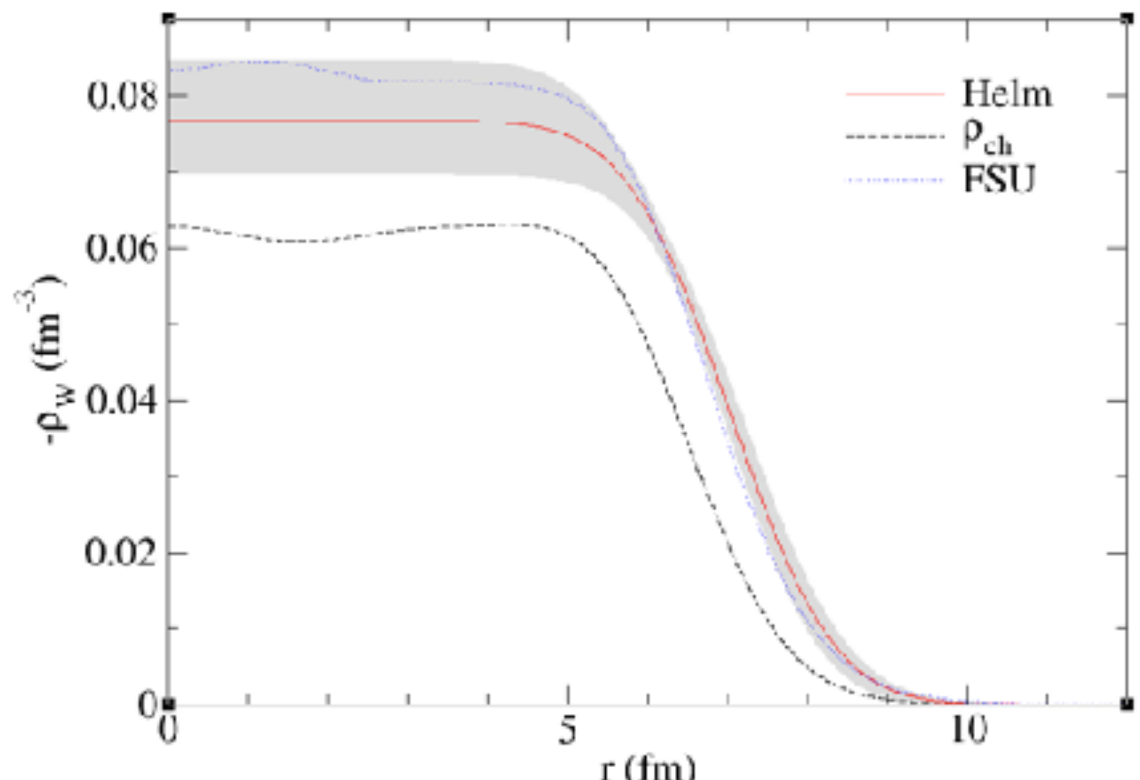




R. Michaels, JLAB

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**
- Weak form factor at q=0.475 fm^{-1}:
  $F_W(q) = 0.204 \pm 0.028$
- Radius of weak charge distr.
  $R_W = 5.83 \pm 0.18 \pm 0.03$ fm
- Compare to charge radius R_{ch}=5.503 fm --> Electroweak skin:
  $R_W - R_{ch} = 0.32 \pm 0.18$ fm
- First observation that weak charge density more extended than (E+M) charge density --> weak skin.
- 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)



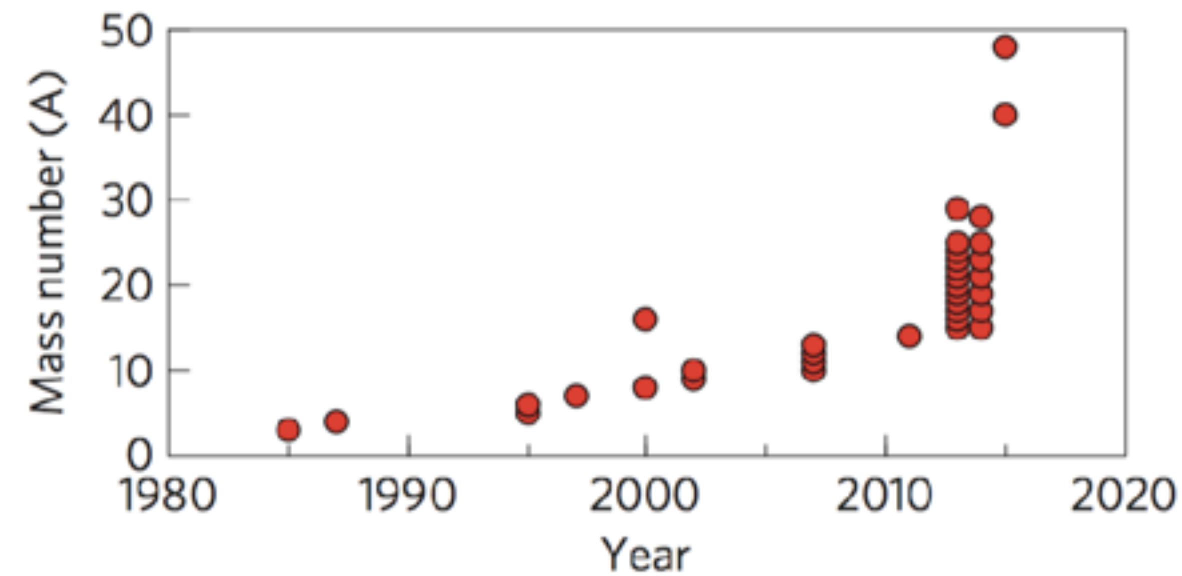
Helm model weak charge density (gray area) consistent with PREX results.

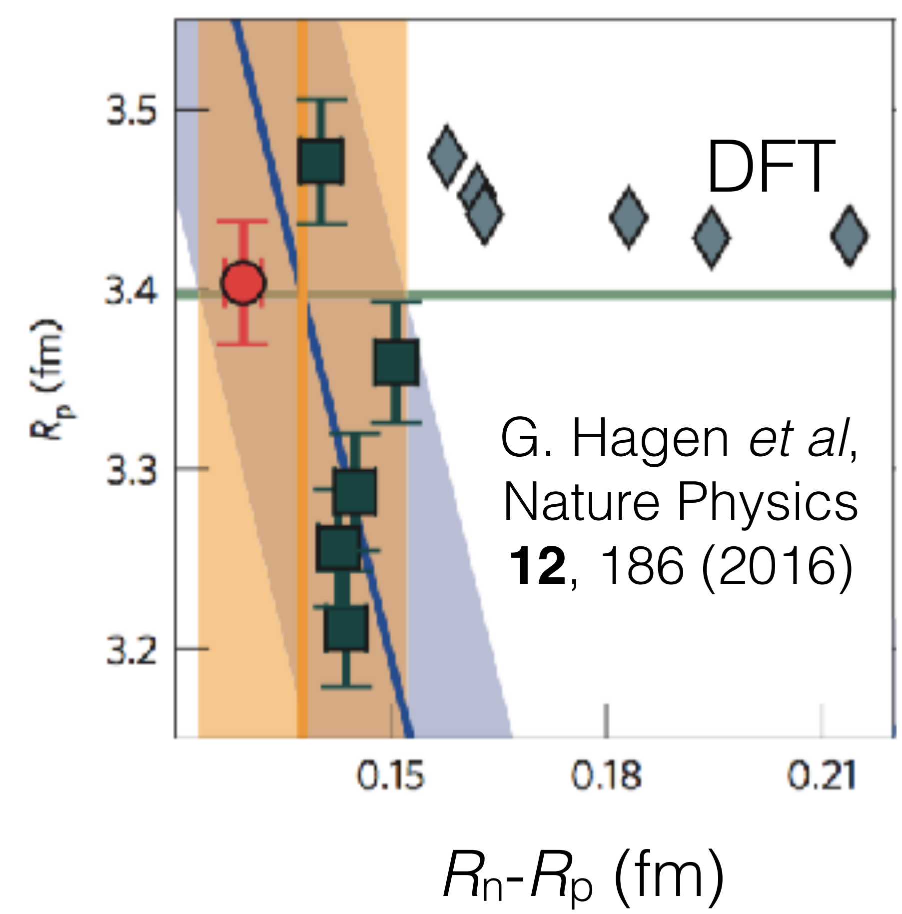
Next Steps

- PREX-II: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm. Will large R_n-R_p be confirmed?
- 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.

Study 3 neutron forces in ^{48}Ca

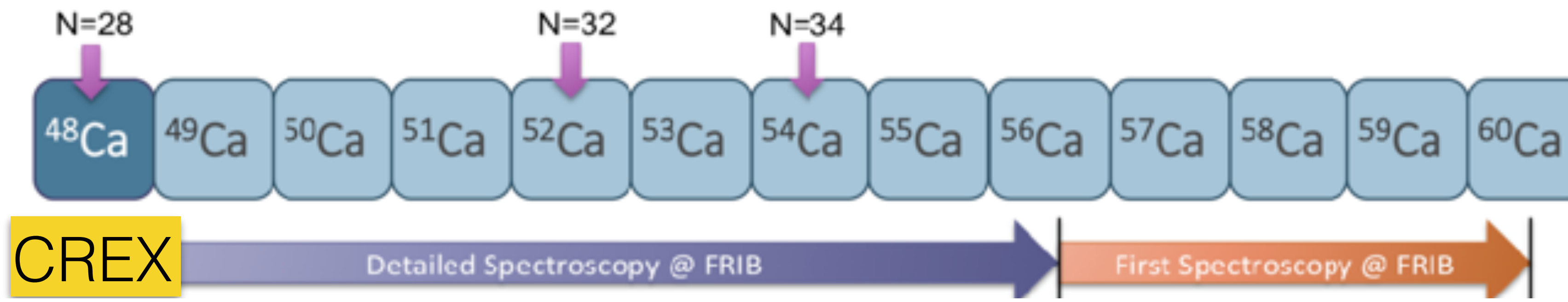
- Large computational advances allow microscopic calculations of structure of medium mass (A=48) nuclei using realistic two nucleon and three nucleon forces from Chiral EFT.
- Coupled cluster calculations by G. Hagen *et al* make sharp prediction R_n-R_p(^{48}Ca) = 0.135 ±0.015 fm.
- Three neutron forces 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.

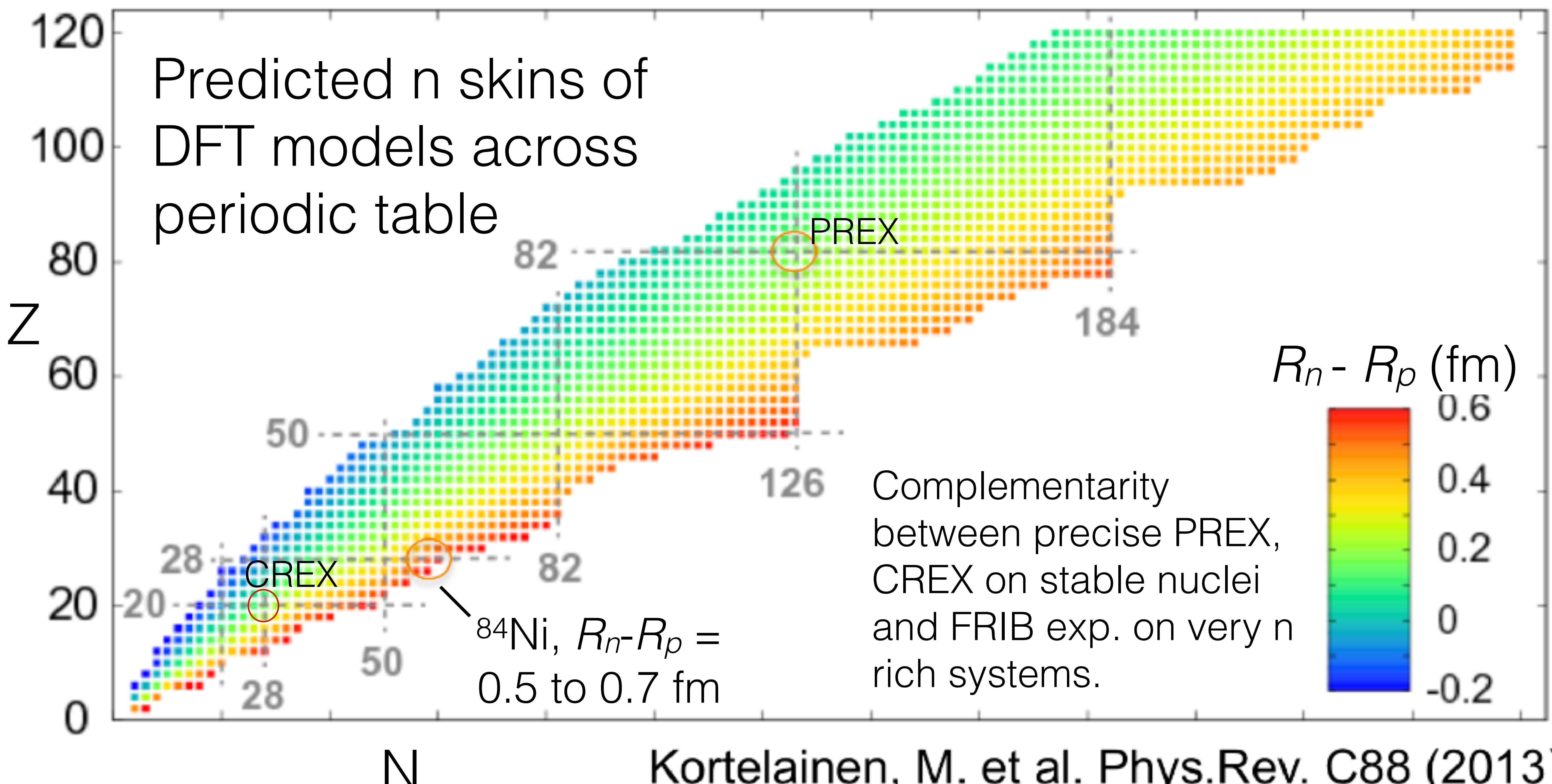




Study more n rich nuclei at FRIB

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

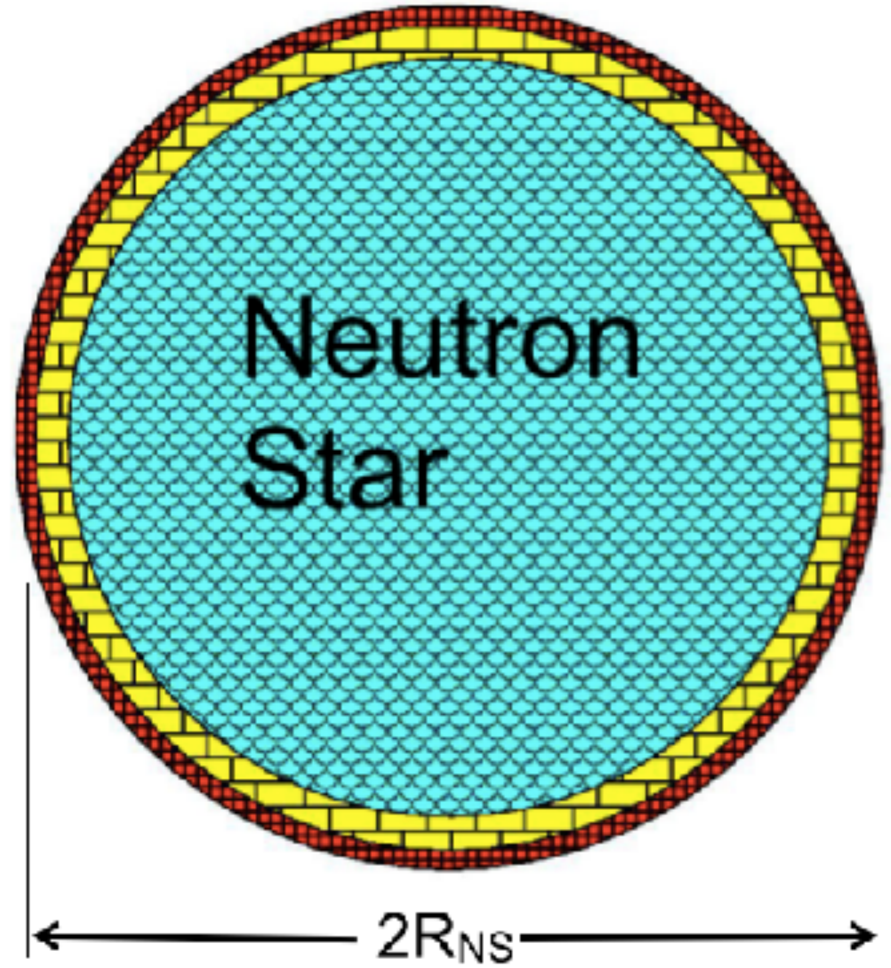


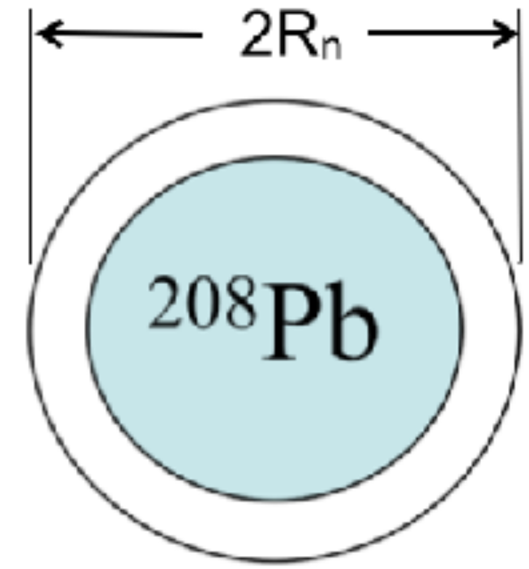


Kortelainen, M. et al. Phys.Rev. C88 (2013)

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 ($\sim 1.4 M_{sun}$) 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.





$R_{NS} \sim 3L_{LIGO}$

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

PREX II: $R_n(^{208}\text{Pb})$ to ±0.06 fm
CREX: $R_n(^{48}\text{Ca})$ to ±0.02 fm or $\sim 5\Delta L_{LIGO}$

Laboratory and Astronomical Observations of n Rich Matter

- Parity violating PREX and CREX measure neutron skin of ^{208}Pb, ^{48}Ca and constrain pressure of neutron rich matter near nuclear density, density dependance of the symmetry energy, and three neutron forces.
- Neutron star radius constrains pressure of neutron rich matter at medium densities ~2 nuclear density.
- Maximum mass of a neutron star constrains pressure at high densities.
- Supported in part by DOE

C. J. Horowitz, horowit@indiana.edu, Indiana University, Dec. 2016
Joint CNA/JINA-CEE Winter School on Nuclear Astrophysics, Shanghai, China

TALENT Classes

- Training in Advanced Low Energy Nuclear Theory (TALENT) teaches three week advanced classes in nuclear theory / astrophysics in North America and Europe.
- Example in 2015 “Nuclear and neutrino physics and astrophysics of neutron stars and supernovae” was taught at the INT in Seattle.
- Check web site for this years classes.
- Should TALENT be expanded to teach classes in China?