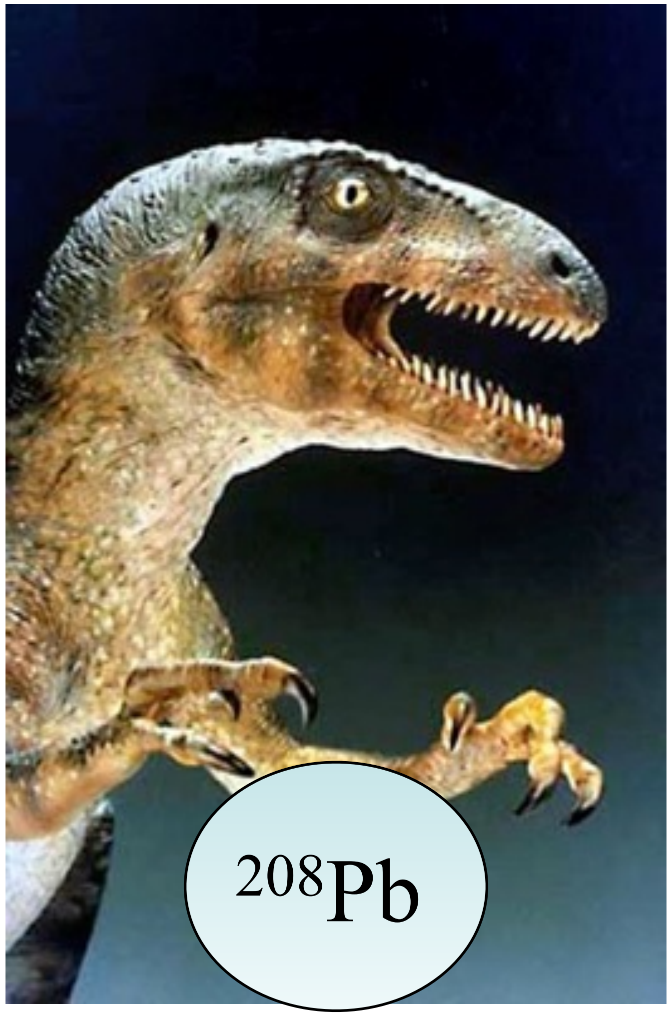
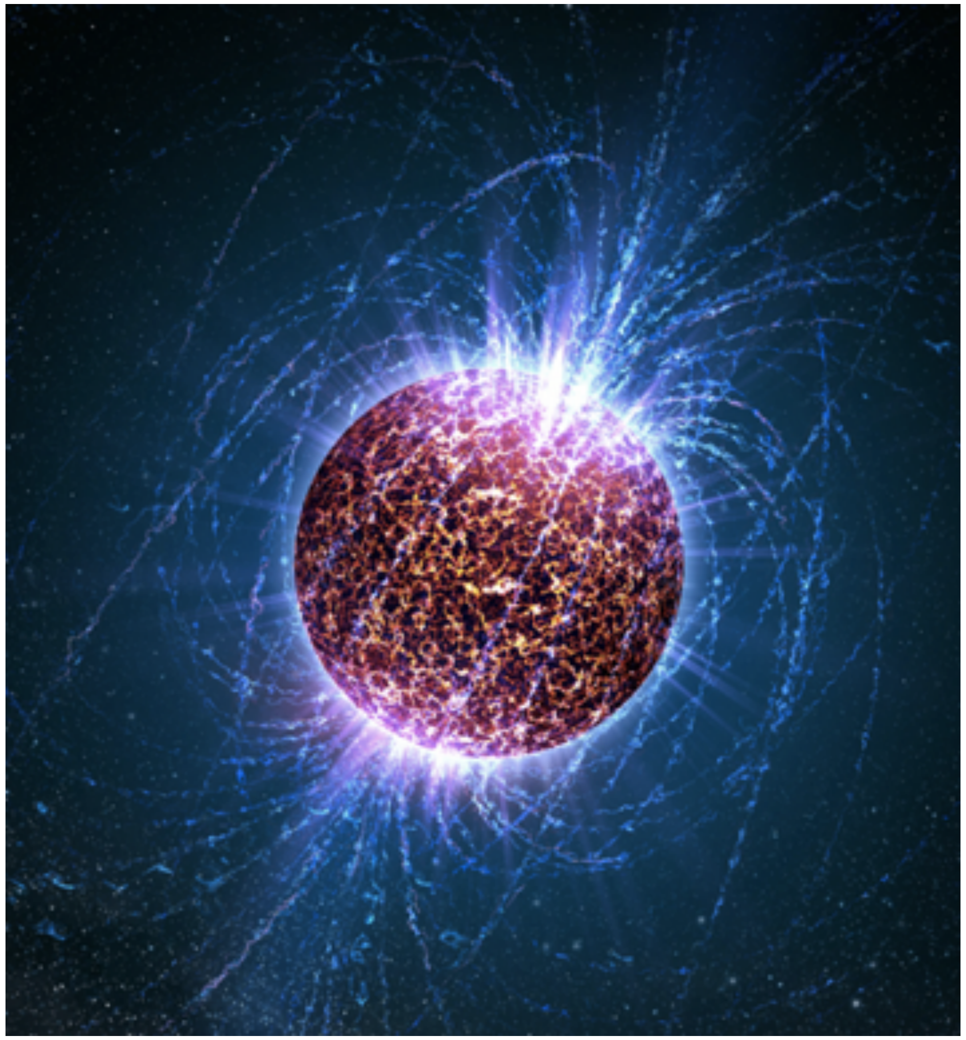
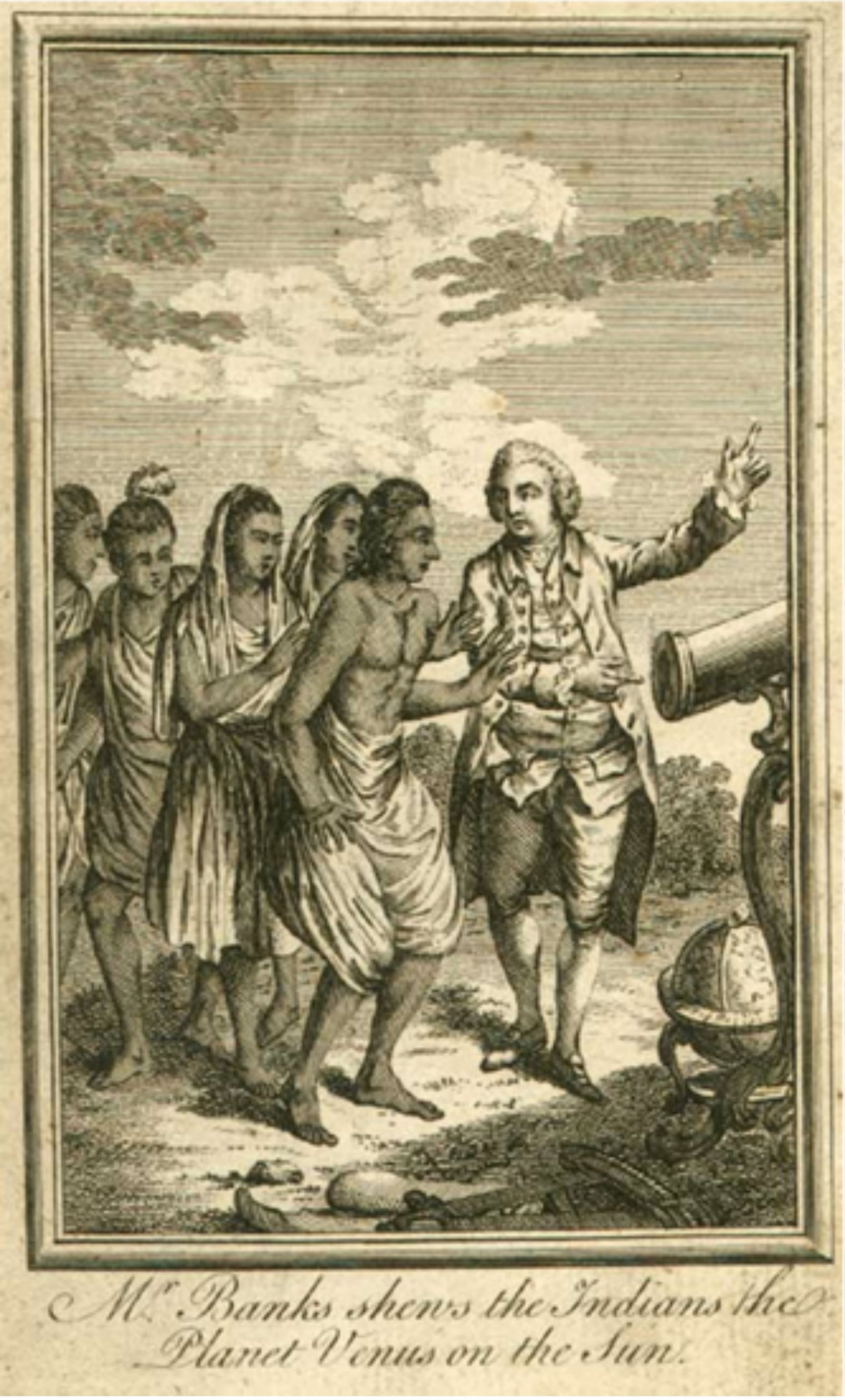
Neutron rich matter and the equation of state of cold dense QCD





C. J. Horowitz, Indiana University,   BEST collaboration meeting, May 2016

Transit of Venus from Point Venus Tahiti



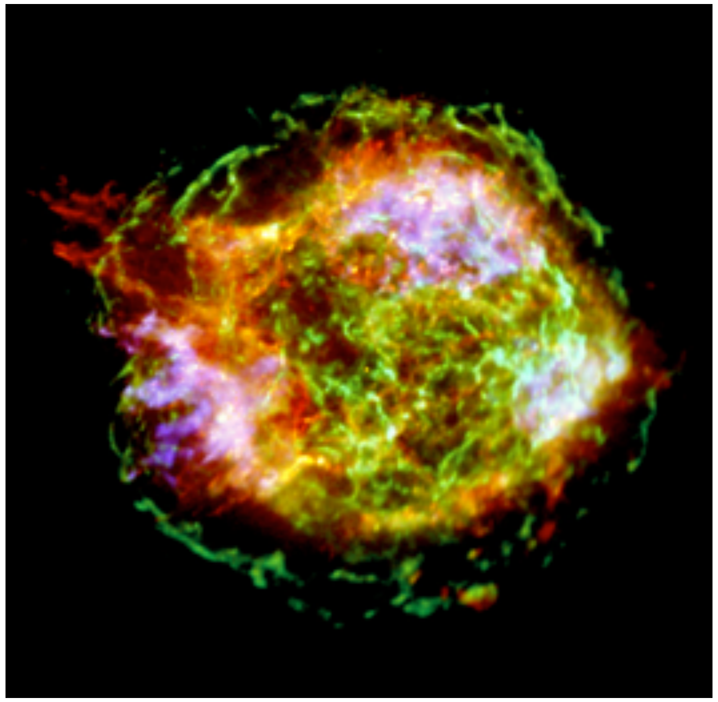
Mr. Banks shews the Indians the Planet Venus on the Sun.

1769

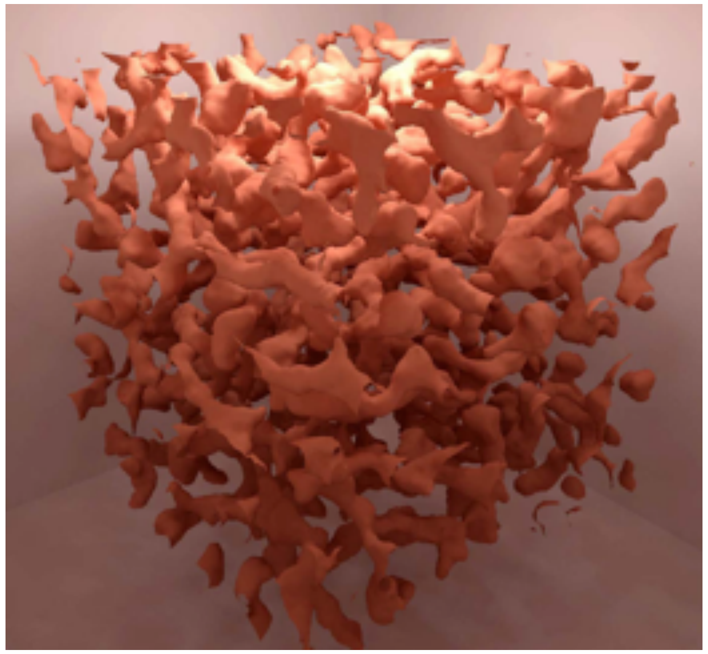
2012

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



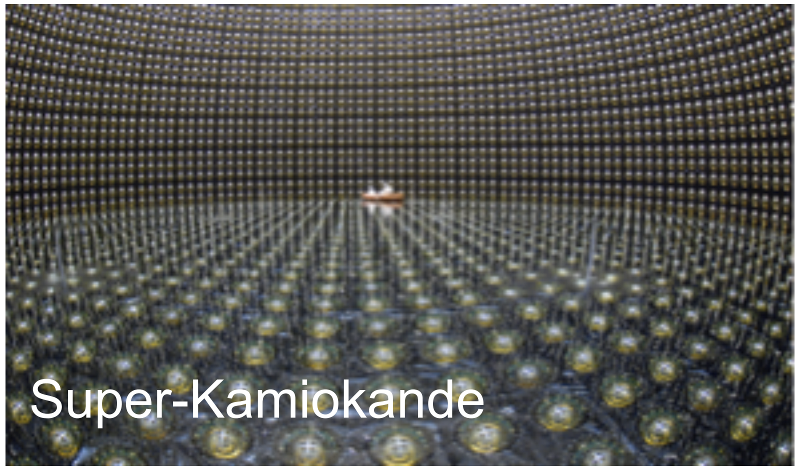
MD simulation of Nuclear
Pasta with 100,000 nucleons

Study n rich matter

- **Laboratory Experiments:** neutron skin thickness of ^{208}Pb, via parity violating electron scattering.
- **X-ray observations** of neutron star radii.
- **Supernova neutrinos,** n rich matter, and nucleosynthesis.
- **Gravitational wave observations** of neutron star mergers.


JLAB


Chandra


Super-Kamiokande


VIRGO

r-process nucleosynthesis

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

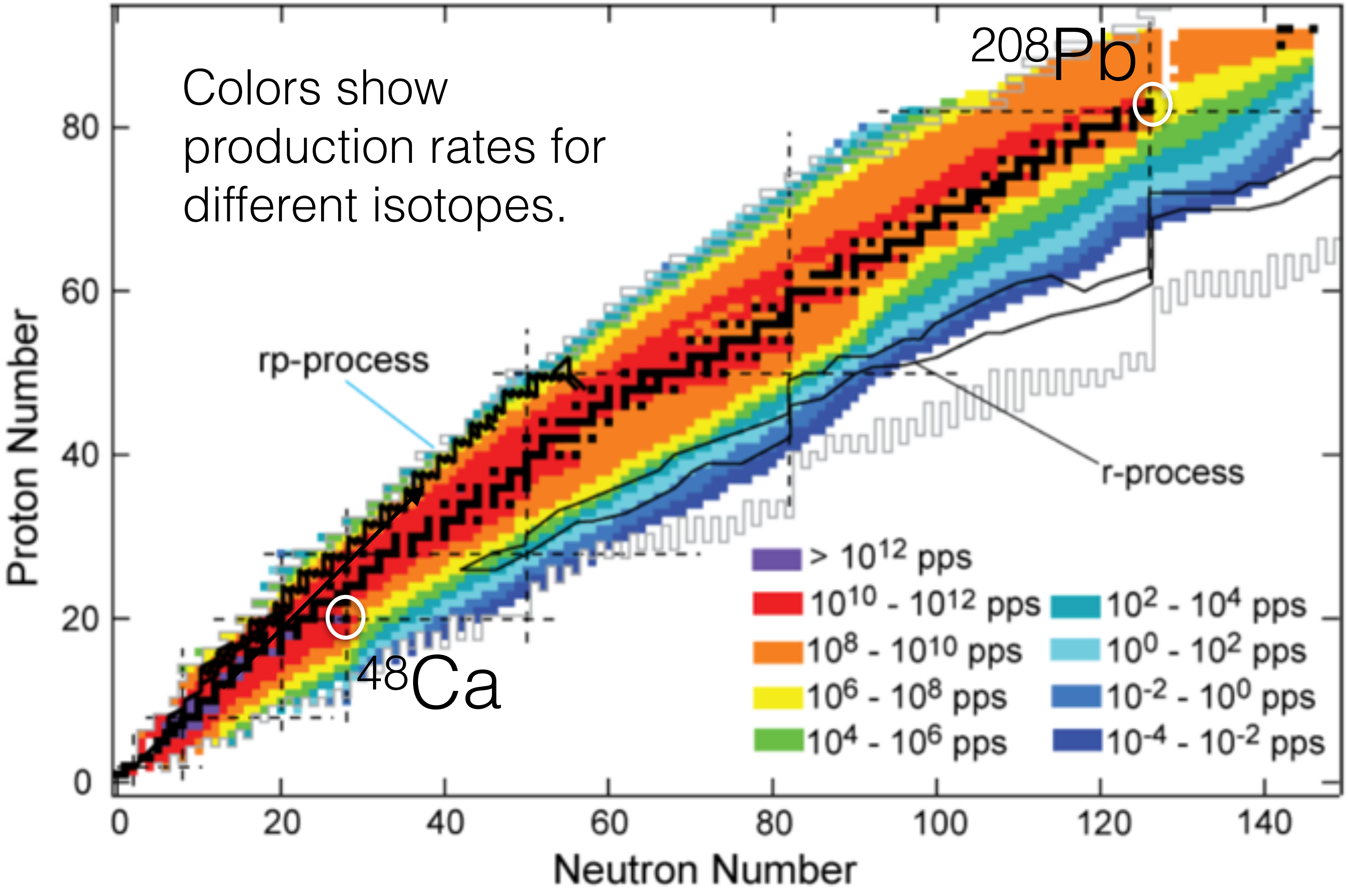
- **Follow the nuclei**: Facility for Rare Isotope Beams (FRIB) will produce many of the very n rich nuclei involved in the r-process.

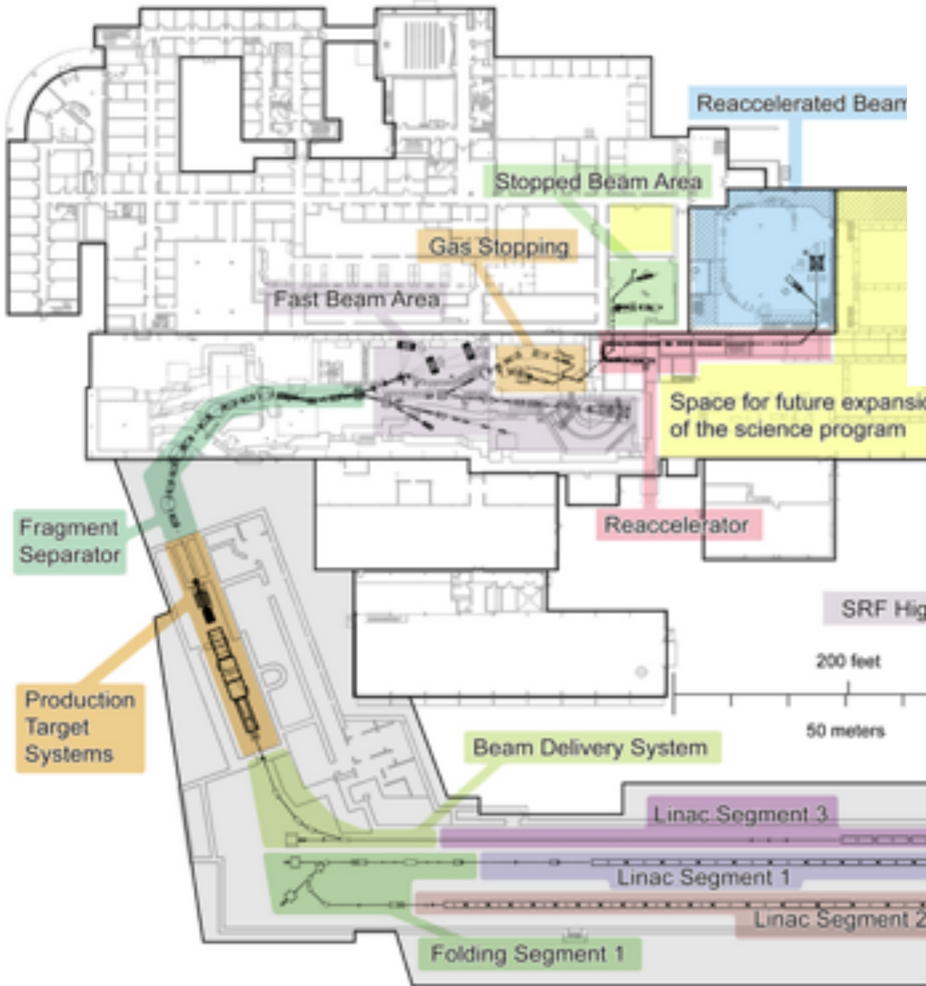
- **Follow the neutrons** needed for r-process:
  — Neutrinos during a supernova eject material. Antineutrinos capture on protons to make neutrons, neutrinos capture on n to make p. Measure detailed antineutrino spectra and detailed neutrino spectra from next galactic SN.
  — Gravity during violent neutron 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

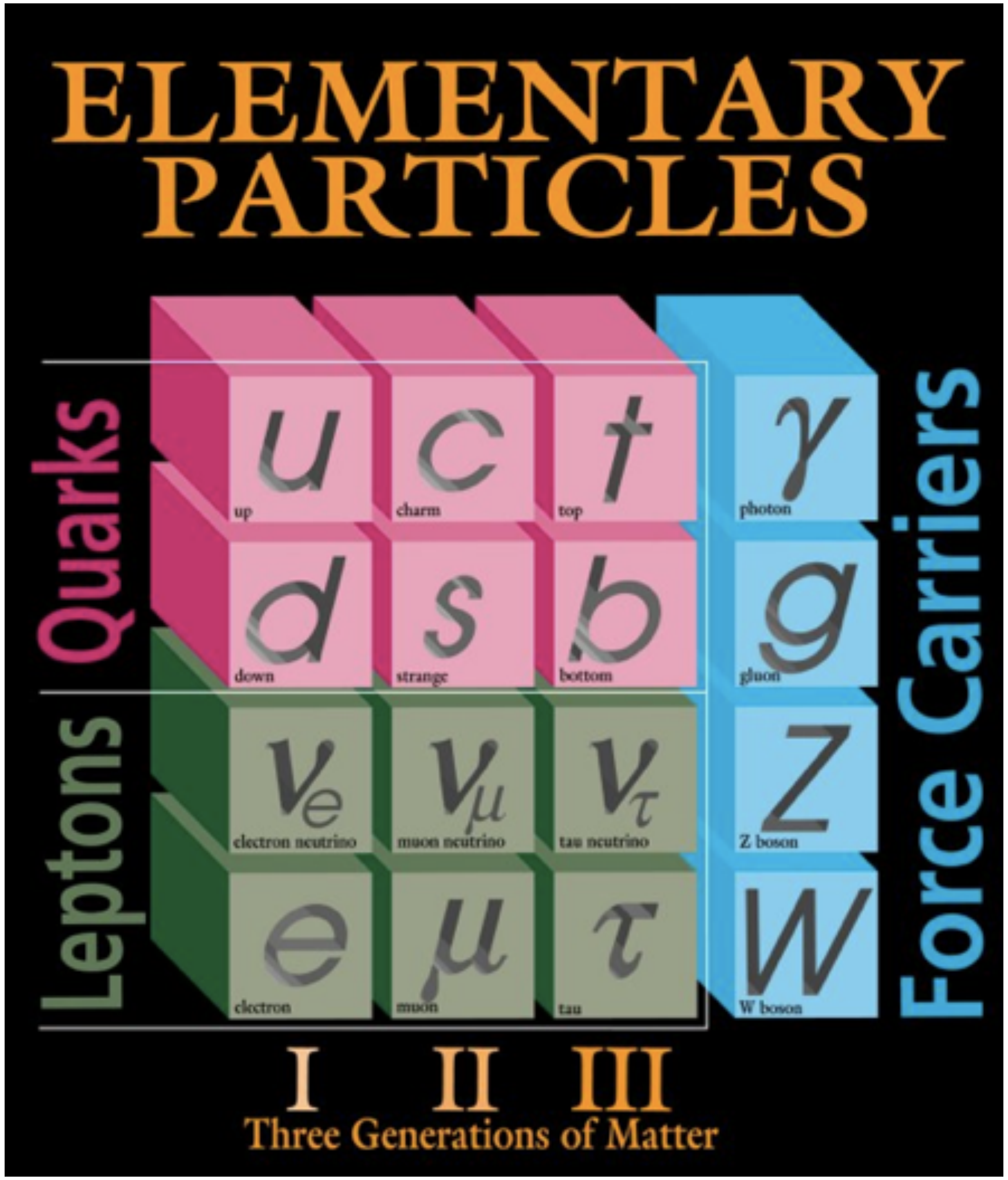
- Intense radioactive beam accelerator that can produce ~80% of all particle bound isotopes with Z < 90.
- Also GSI-FAIR, RIBF, GANIL, ISAC at TRIUMF, …





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

Neutrino messengers



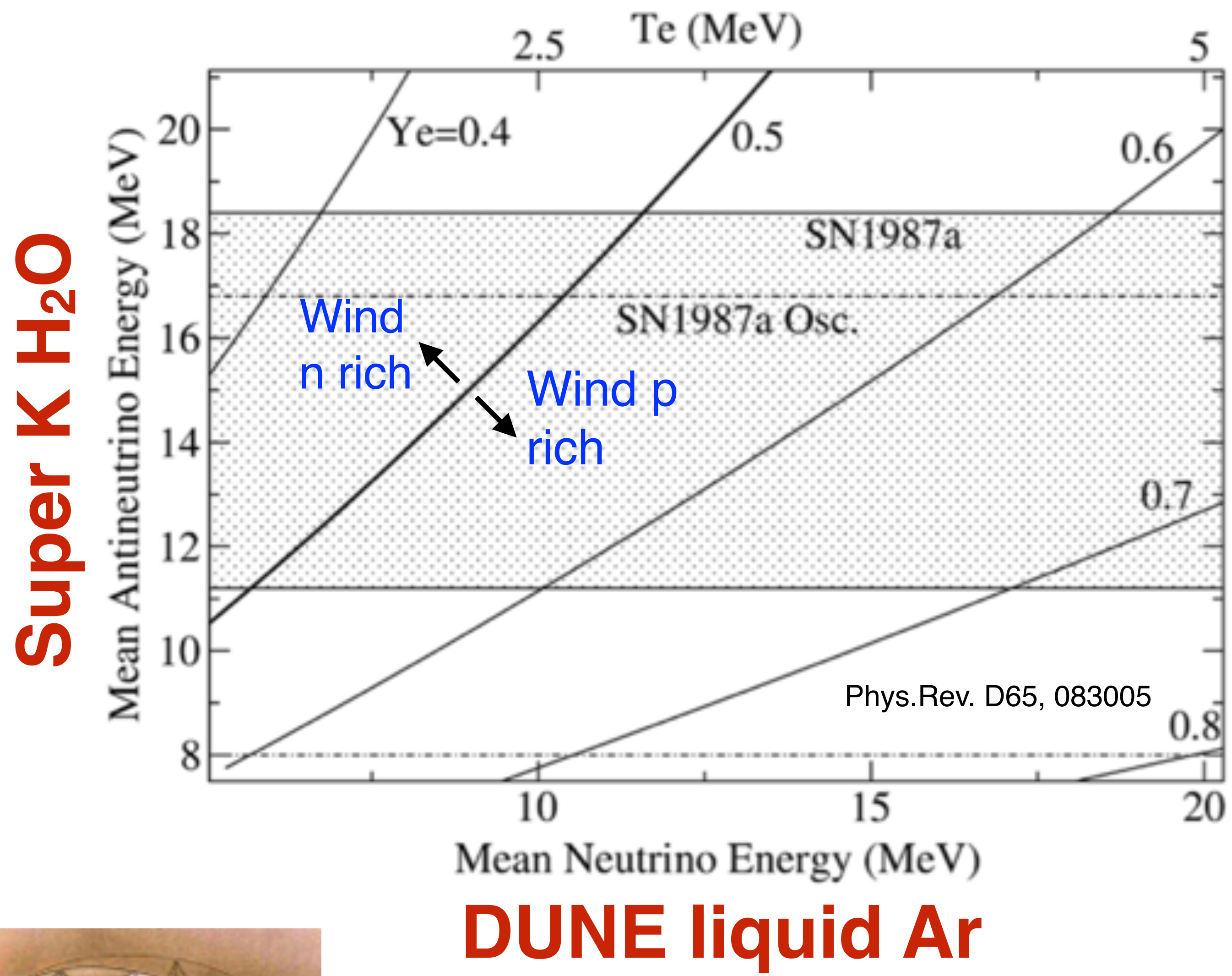
- All three flavors of neutrinos and their antineutrinos (electron, mu, tau) are radiated in core collapse supernovae.
- **Neutrinos cary unique flavor information all the way to earth.**
- Note, neutrinos are somewhat forgetful messengers because of oscillations.

Deep Underground Neutrino Experiment

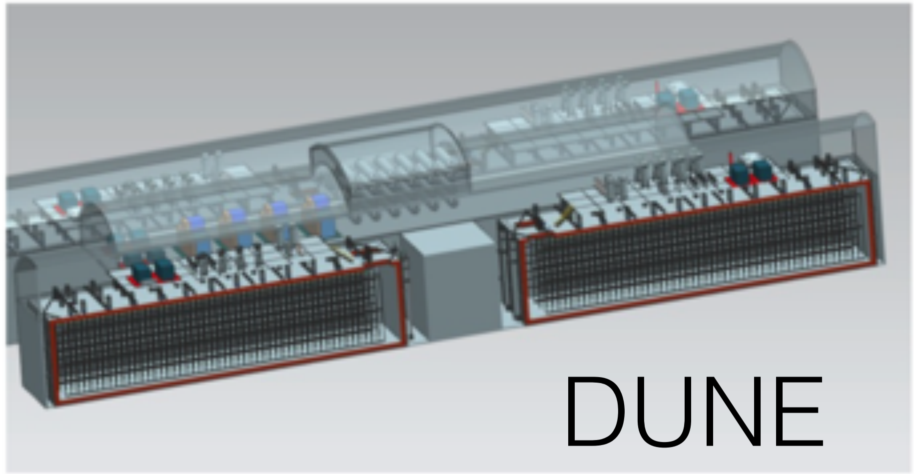
- Neutrino driven wind in a Supernova is an important nucleosynthesis site.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and antineutrino energies.

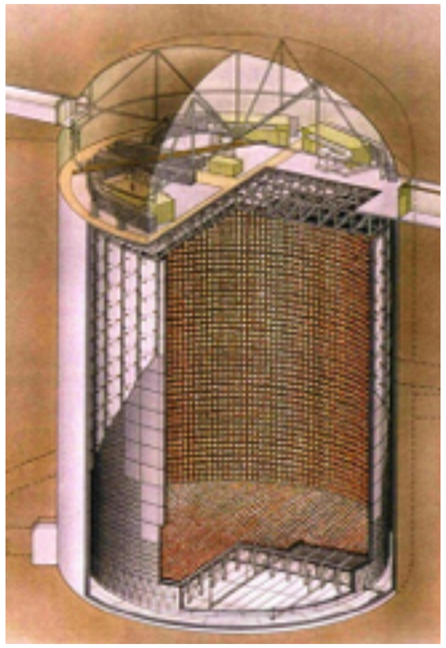
$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

- 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.



Phys.Rev. D65, 083005





Super K

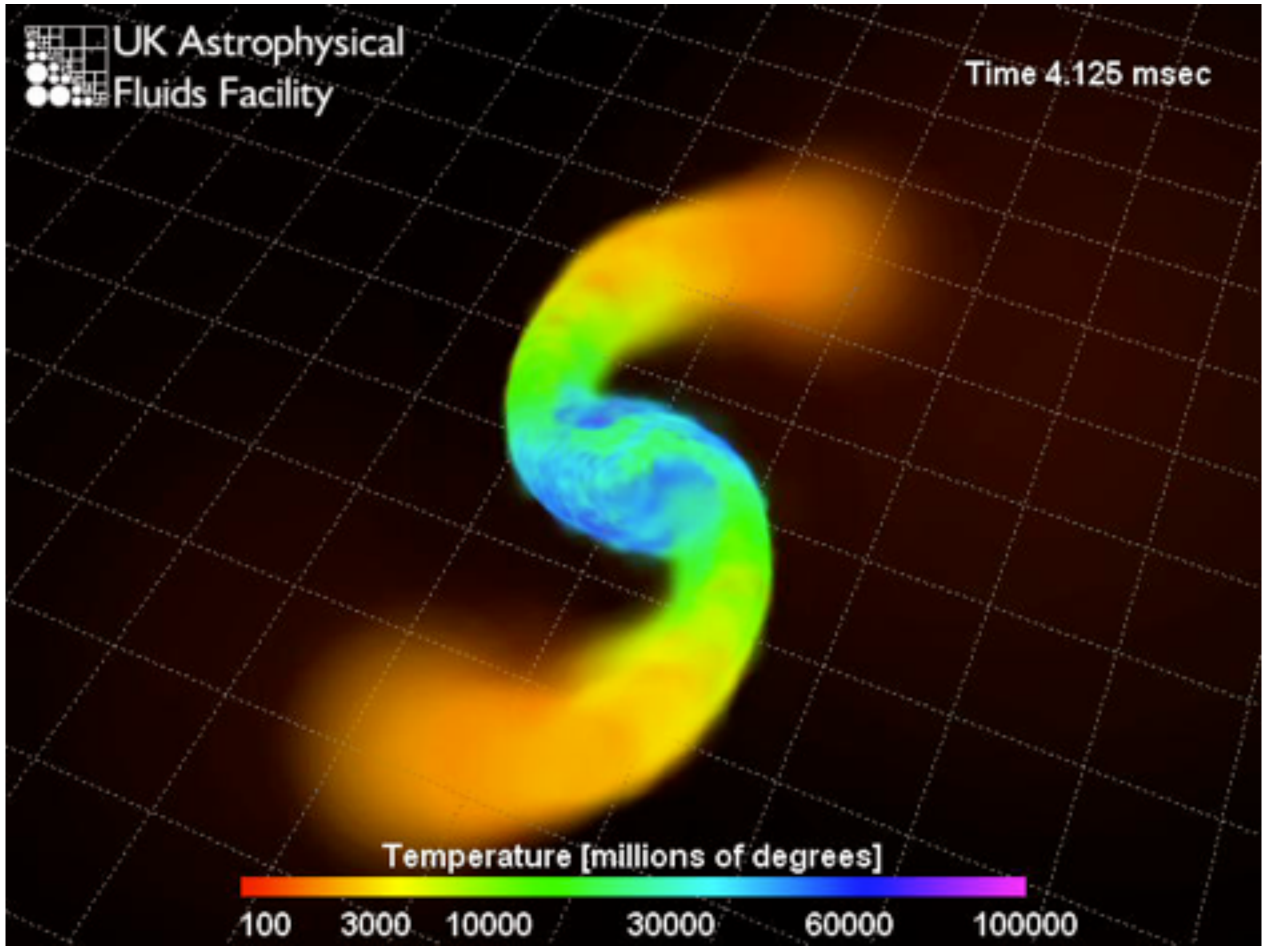
Present SN simulations find too few neutrons for (main or 3rd peak: Au, U) r-process.

Workshop: "Flavor observations with SN neutrinos", INT, Aug. 15-19, 2016.
http://www.int.washington.edu/PROGRAMS/16-61w/

Neutron Star Mergers and r-process

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

- Possible Kilonova from 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)].

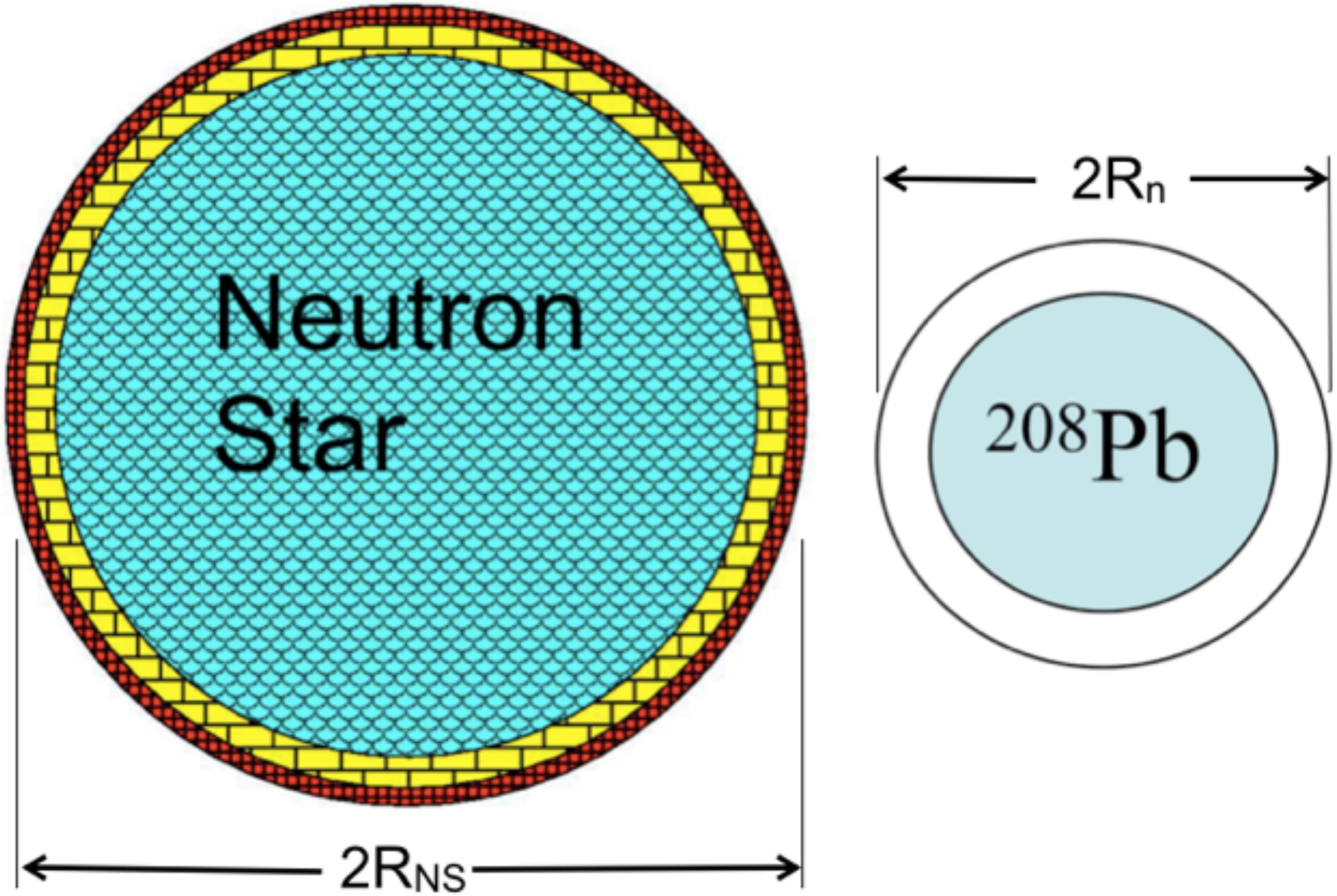


Stephan Rosswog, Richard West.

- Yield of r-process elements: **merger rate X amount of material ejected per merger**.
- LIGO is directly observing **merger rate** (Duncan Brown's talk). Much GW info: rate, distribution of NS masses, binary populations…
- **Material ejected per merger** depends on mass ratio, …, equation of state (pressure vs density of n rich matter).

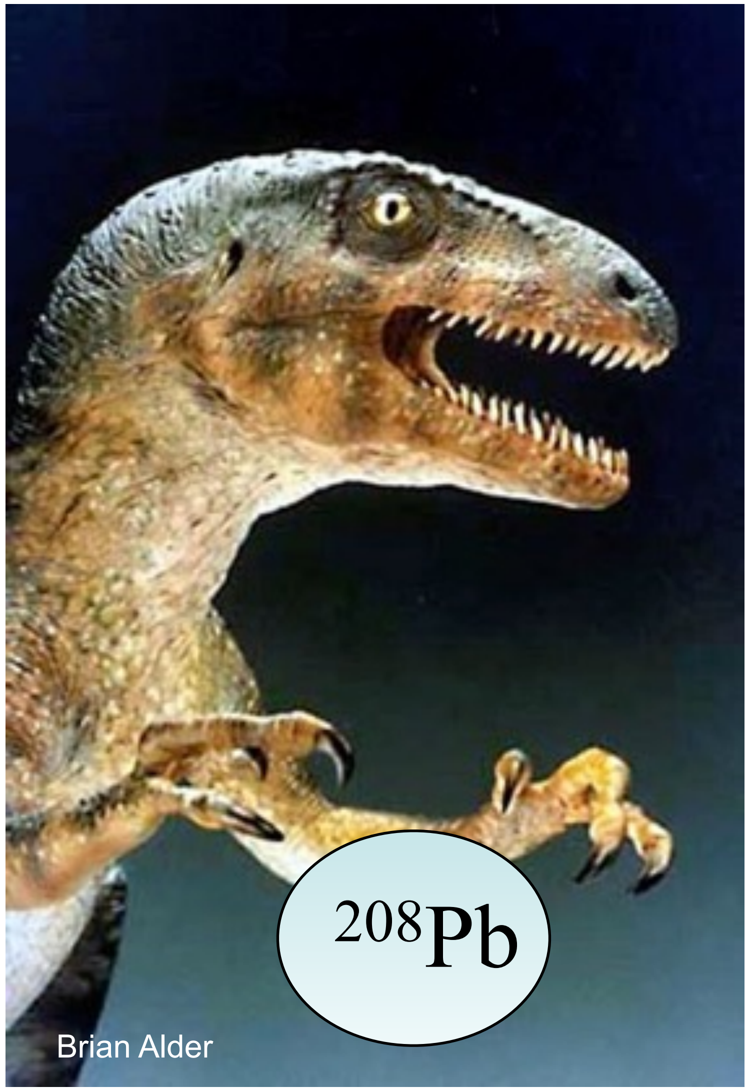
Density Dependence of EOS

- 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.

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

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

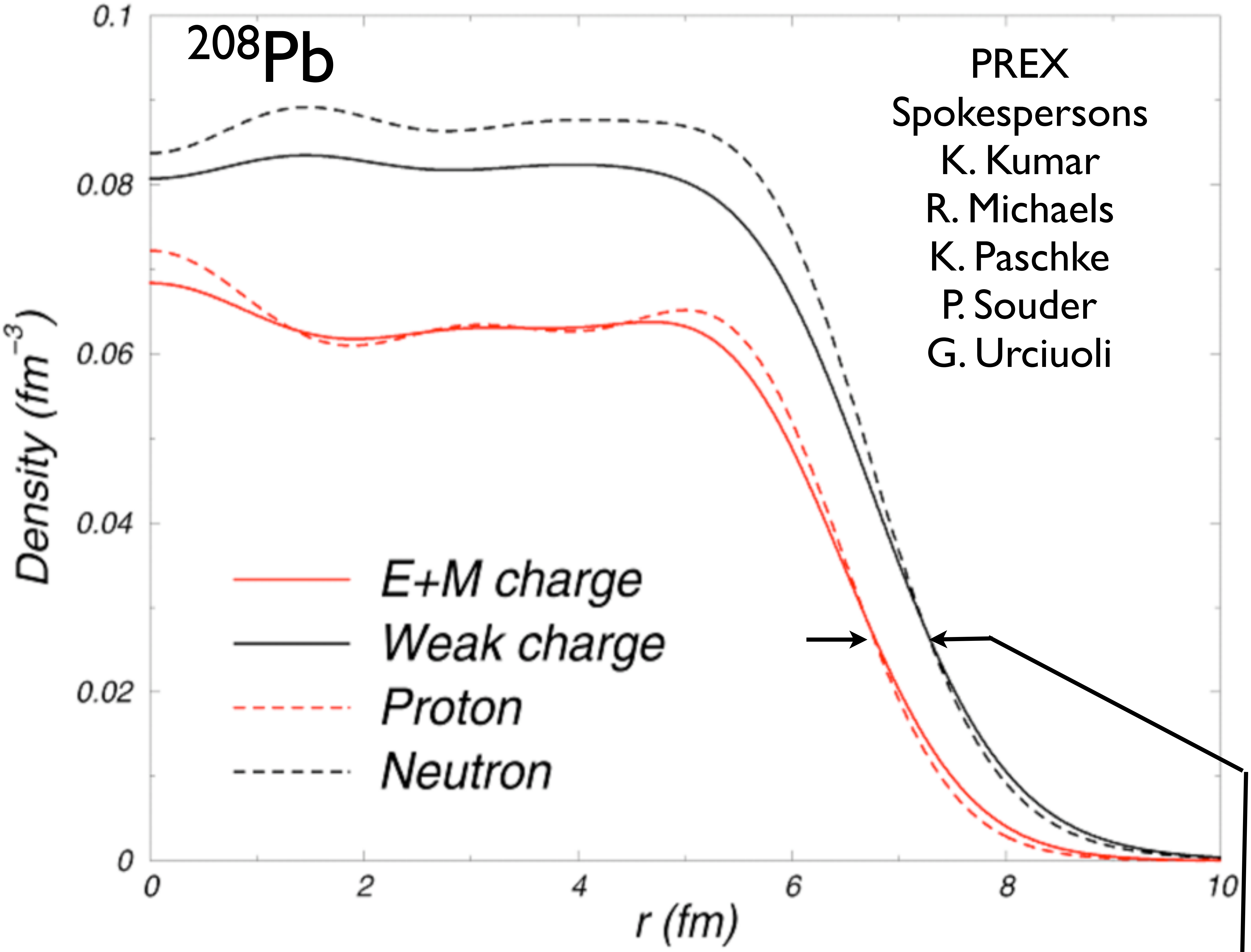
- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

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

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

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

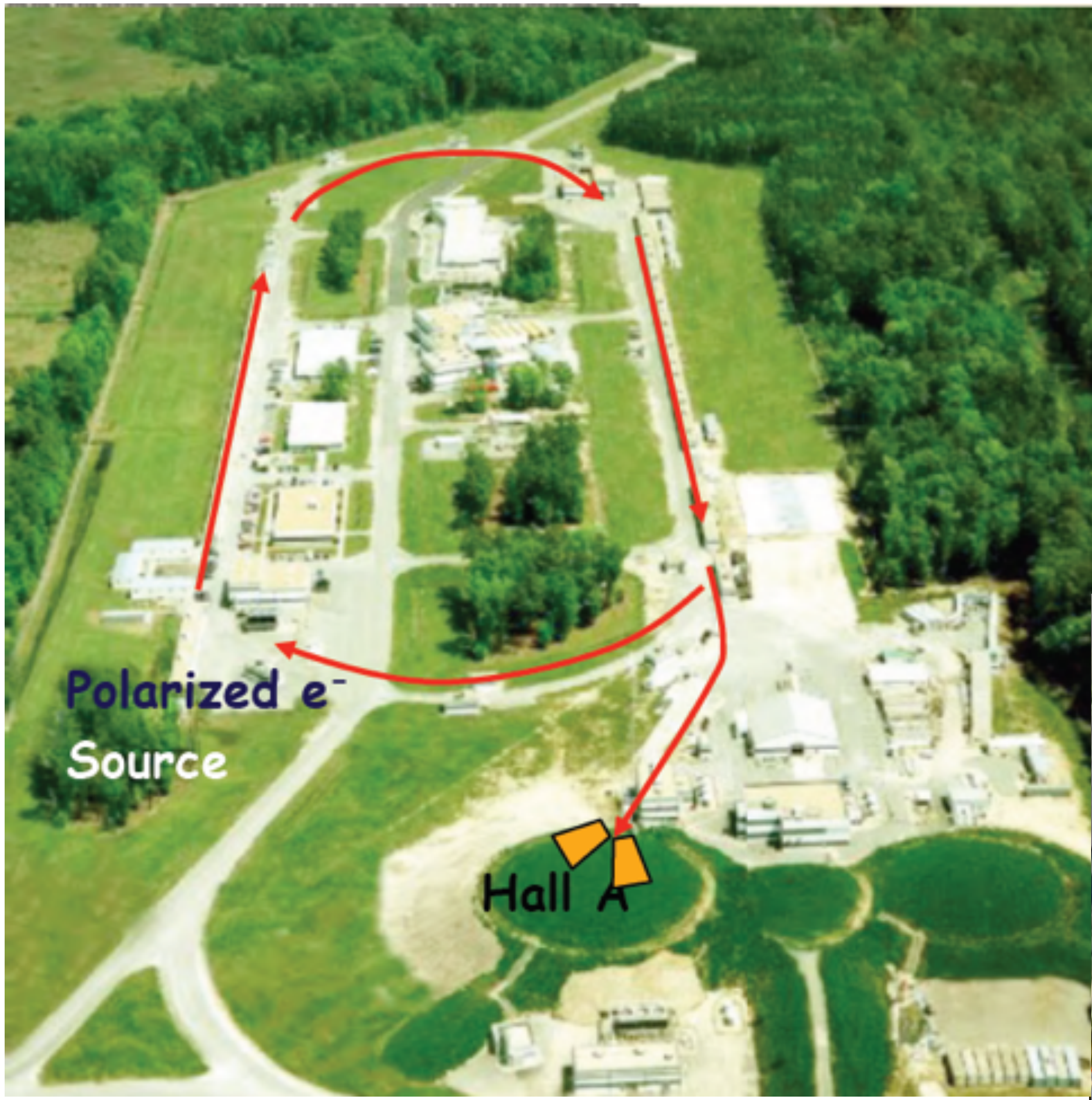
–Donnelly, Dubach, Sick

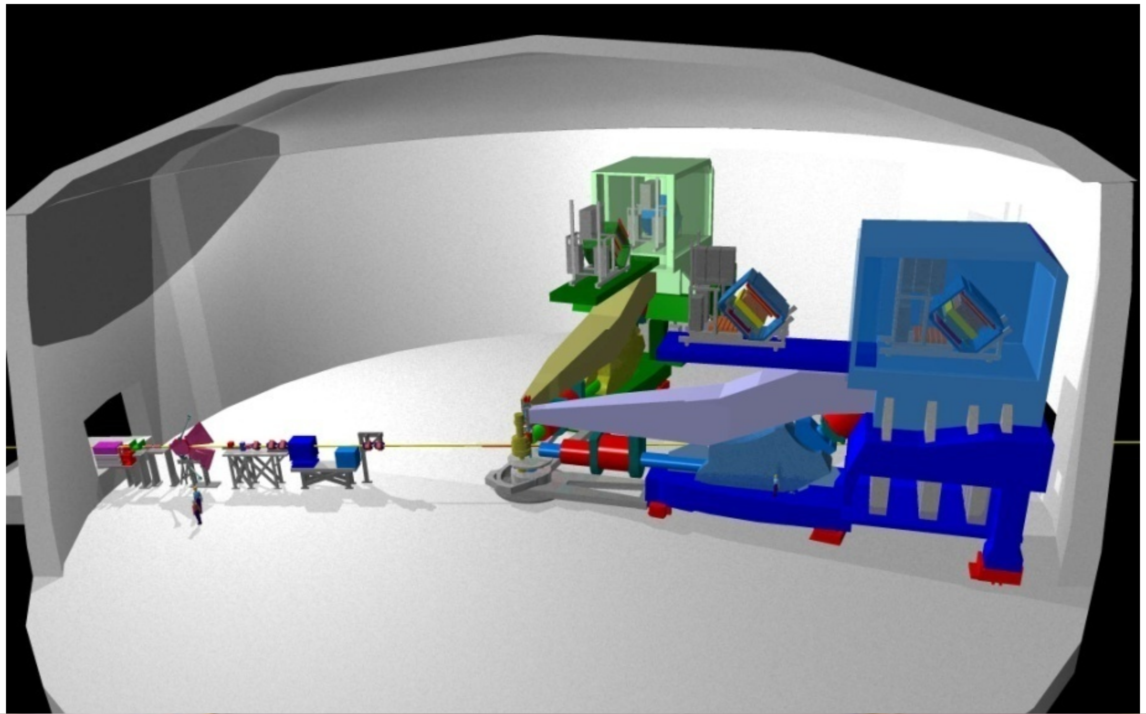


PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

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

Hall A at Jefferson Lab

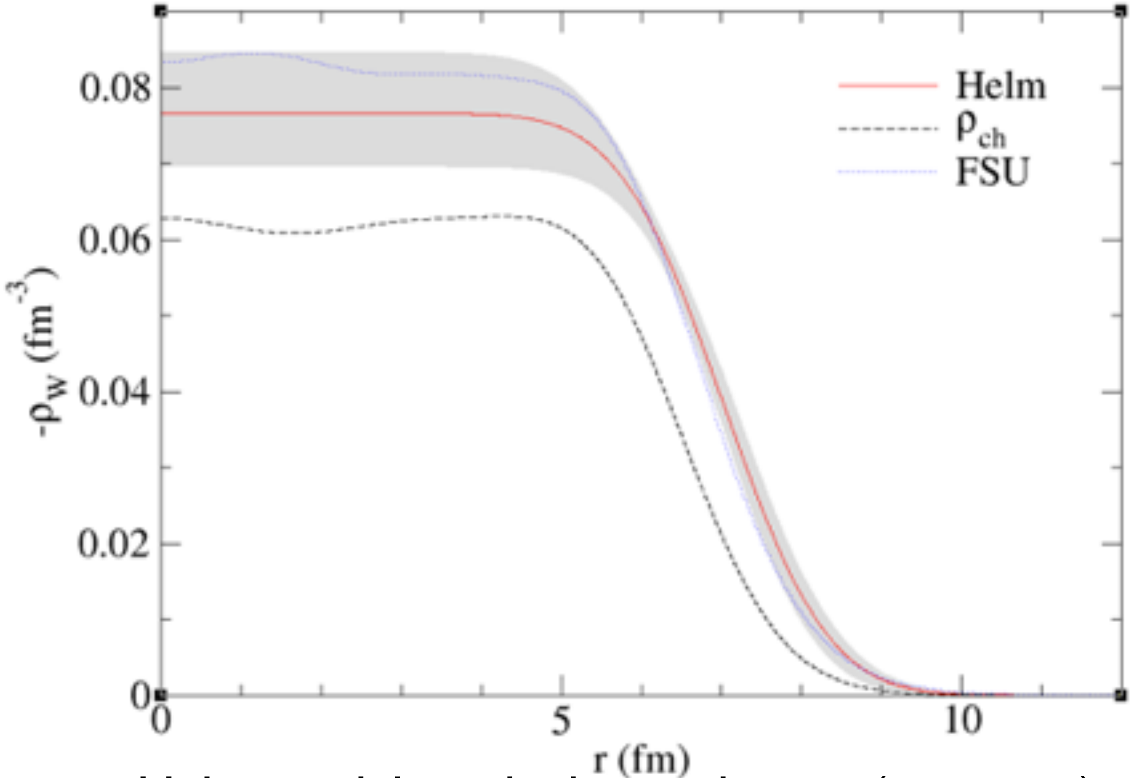




R. Michaels, JLAB

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**
- Weak form factor at q=0.475 fm^{-1}:
  $F_W(q)$ = 0.204 ± 0.028
- Radius of weak charge distr.
  R_W = 5.83 ± 0.18 ± 0.03 fm
- Compare to charge radius R_{ch}=5.503 fm --> Electroweak skin:
  $R_W - R_{ch}$ = 0.32 ± 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

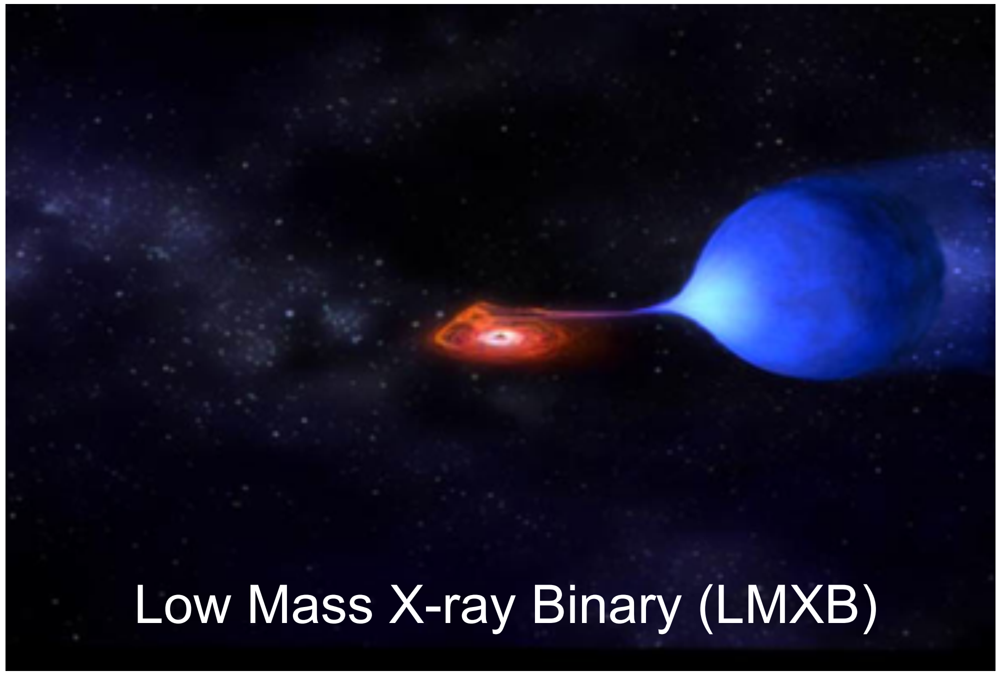
- PREX-II: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm. Will large R_n-R_p be confirmed?
- CREX: Measure R_n of ^{48}Ca to ±0.02 fm. Microscopic calculations feasible for light n rich ^{48}Ca (but not ^{208}Pb) to relate R_n to three neutron forces.

X-ray observations of NS radii, masses

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

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

- Complications:
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Need accurate distance to star.
  - 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.
- Eddington luminosity: when radiation pressure balances gravity --> gives both M and R.

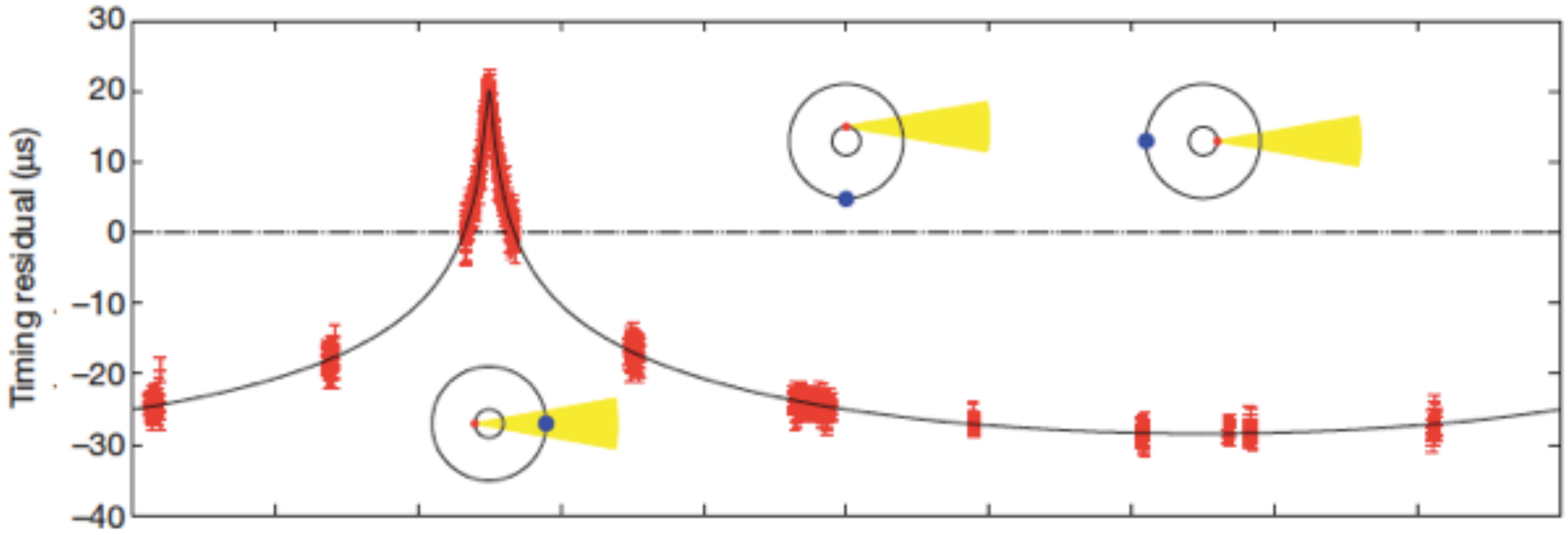
Quiescent NS in Globular Clusters: Guillot et al., arXiv:1302.0023

- Considers five LMXB in M13, M28, NGC6304, NGC6397, Omega Cen.
- Simple assumptions:
  - Nonmagnetic hydrogen atmospheres: no evidence for B field, heavier elements should rapidly sink, one companion star observed to have H envelope.
  - Spherically symmetric: no observed pulsations.
  - All observed stars have approximately the same radius (independent of mass): consistent with most EOS, greatly improves statistics.
  - Distance to stars known: Globular cluster distances good but perhaps not perfect, *Gaia should give ~ perfect distances soon.*
  - Interstellar absorption from X-ray data.
- Result $R = 9.1^{+1.3}_{-1.5}$ km (90%-confidence).

Discovery of $2M_{sun}$ Neutron Star

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

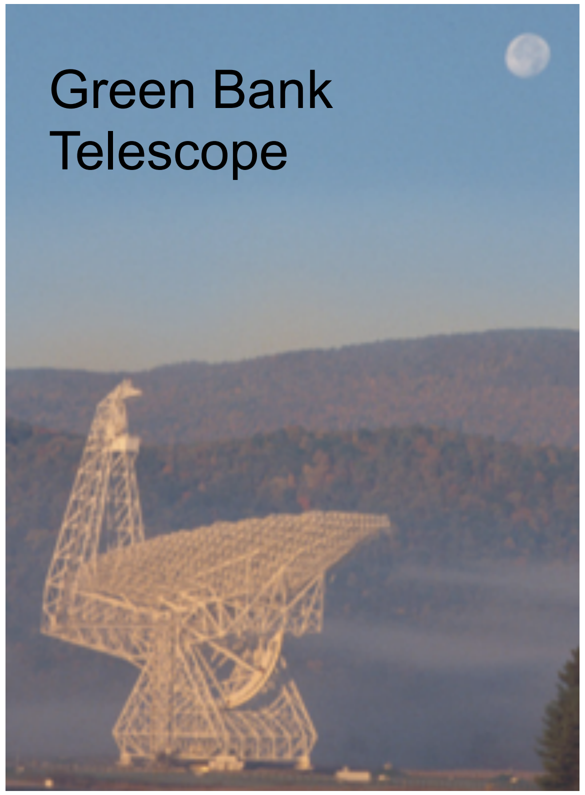
Delay in pulse arrival



NS + White Dwarf Binary

Orbital phase

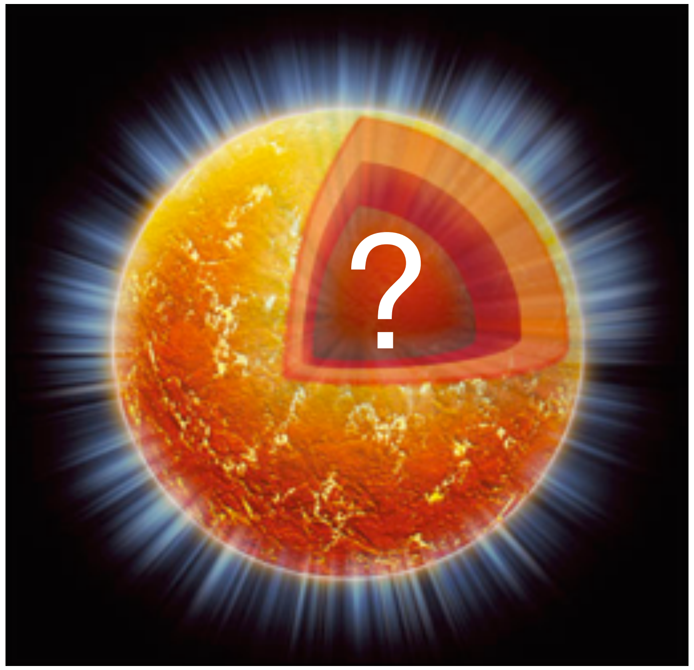
- The equation of state of neutron rich matter (pressure vs density) at high densities must be stiff enough (have a high enough p) to support this mass against collapse to a black hole. *All soft EOS are immediately ruled out!*
- *However this does not tell composition of dense matter be it neutron/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



Green Bank Telescope

What are neutron stars made of?

- They are made of **strongly interacting stuff.** The strong interactions produce high pressures that support $2M_{sun}$ NS.
- Mass and radius measurements alone, determine the pressure, but do not directly determine the composition.
- Could be strongly interacting quarks or strongly interacting nucleons (hadrons) but not nearly free quarks.
- Example: what is the role of hyperons (baryons with strange quarks)?
  - Hyperon-nucleon 2-body forces are attractive to fit energies of hyper-nuclei. These attractive 2-body forces suggest hyperons should significantly reduce the pressure, in apparent conflict with observations of $2M_{sun}$ stars.
  - Solution likely involves repulsive three-body forces that increase pressure. Do these 3-body forces prevent the appearance of hyperons or just increase the pressure of matter with hyperons?
- **Observations of NS cooling** provide additional information on composition because NS cool by neutrino emission from their dense interiors. [See talk by S. Reddy]

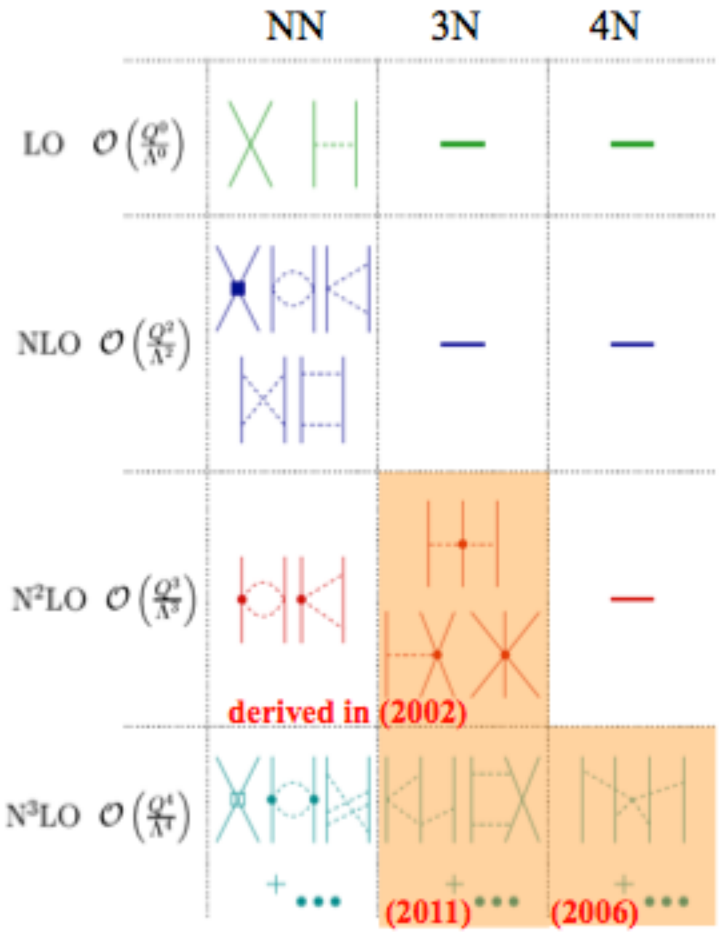


Neutrino cooling of neutron stars

- Direct URCA process: n->p+e+anti-nu followed by e+p->n+nu. Cools star quickly but it needs a large proton fraction to conserve both E and momentum.
- Proton fraction determined by symmetry energy S. This says how energy of nuclear matter rises when one goes away from N=Z.
- If S in interior >> S in surface, 44 extra n in ^{208}Pb pushed to surface and R_n-R_p large.
- If PREX II confirms PREX large 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.

Chiral Effective Field Theory

- Expands interactions in powers of momentum over chiral scale.
- Predicts properties of ***uniform*** nuclear matter at ***low*** densities.
- Many body perturbation theory calculations now being improved with coupled cluster calculations by G. Hagen et al.
- Note that calculations of nuclear matter may only be applicable over a limited density range from ~1/2ρ_0 to ~ρ_0.
    - At higher densities chiral expansion may not converge.
    - At lower densities matter is nonuniform.

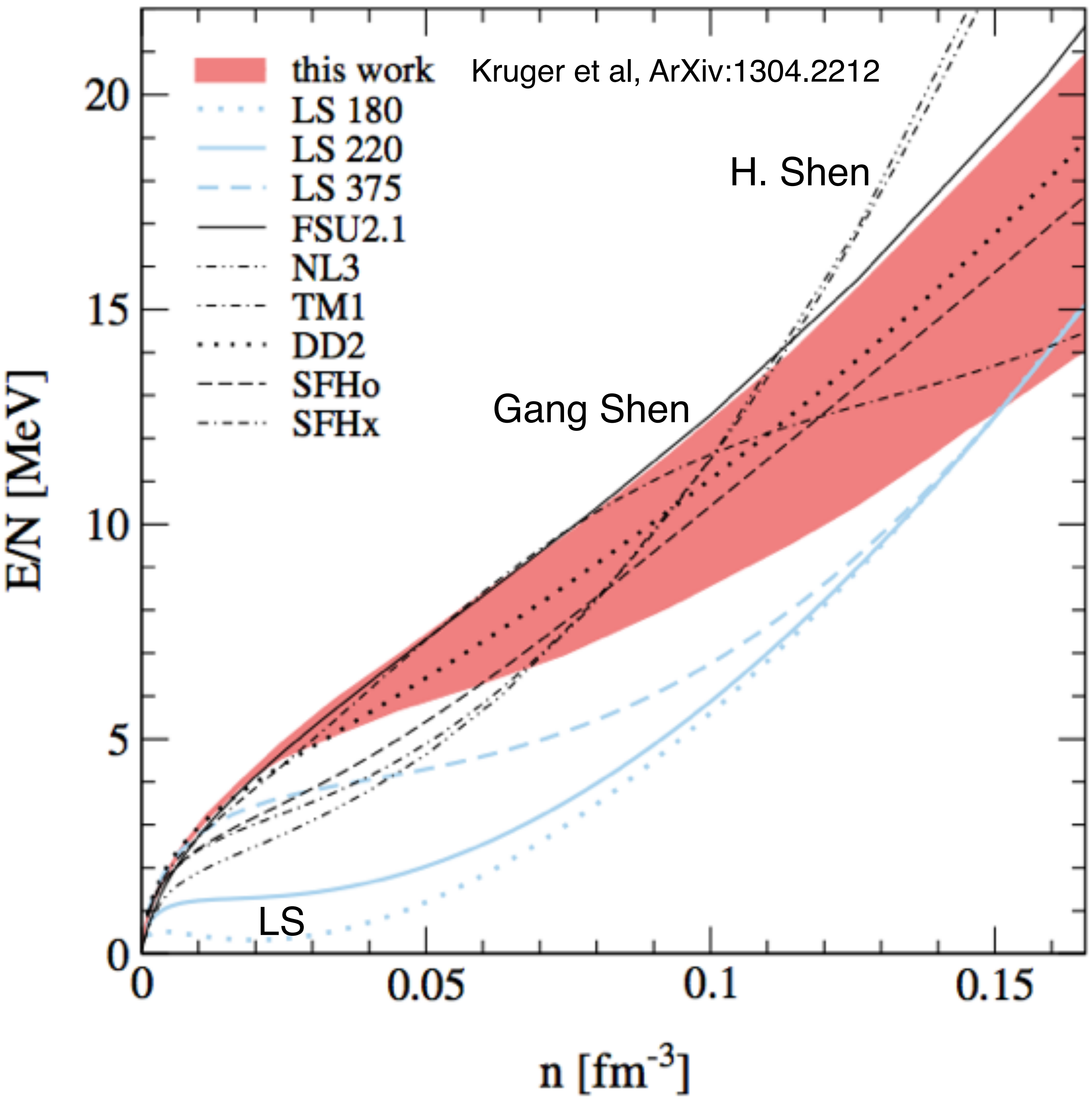


A. Schwenk

- All hadronic calculations of nuclear matter, for densities above ρ_0, may have large uncertainties in three and more nucleon forces.

Energy of Neutron Matter at N3LO

- Supernova EOS of Lattimer-Swesty (LS180 or LS220) has too low neutron matter energy at low densities.
- H. Shen EOS based on RMF (TM1) has E increase too fast with density.
- Gang Shen EOS (FSU2.1) based on extensive mean field calculations using FSUgold interaction stiffened at high densities to support $2.1M_{sun}$ NS consistent with chiral calculations PRC**83**,065808 (2011).



Neutron rich matter and the equation of state of cold dense QCD

- Parity violating PREX experiment measures neutron skin of ^{208}Pb, constrains pressure of neutron rich matter near nuclear density n_0=0.16 fm^{-3}.
- X-ray observations help measure radius of NS and this constrains pressure at medium densities.
- Maximum mass of NS (>=2Msun) implies pressure at high densities is large ==> Neutron star matter is strongly interacting.
- Supported in part by DOE

C. J. Horowitz, horowit@indiana.edu, BEST meeting, May, 2016