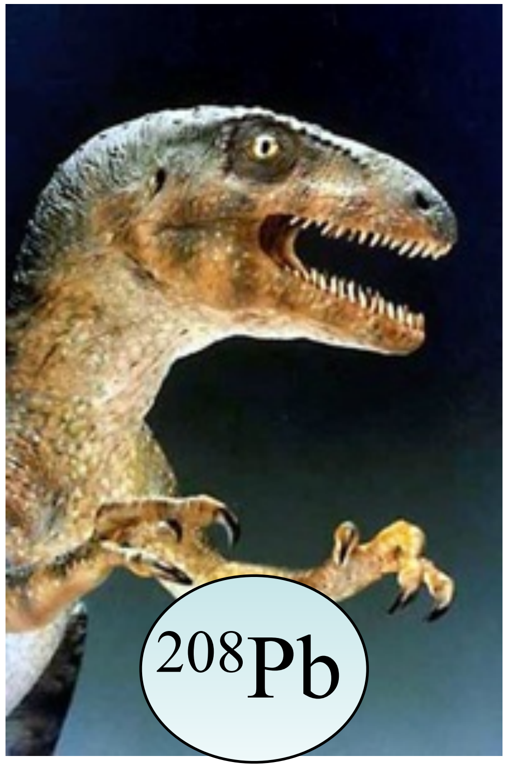
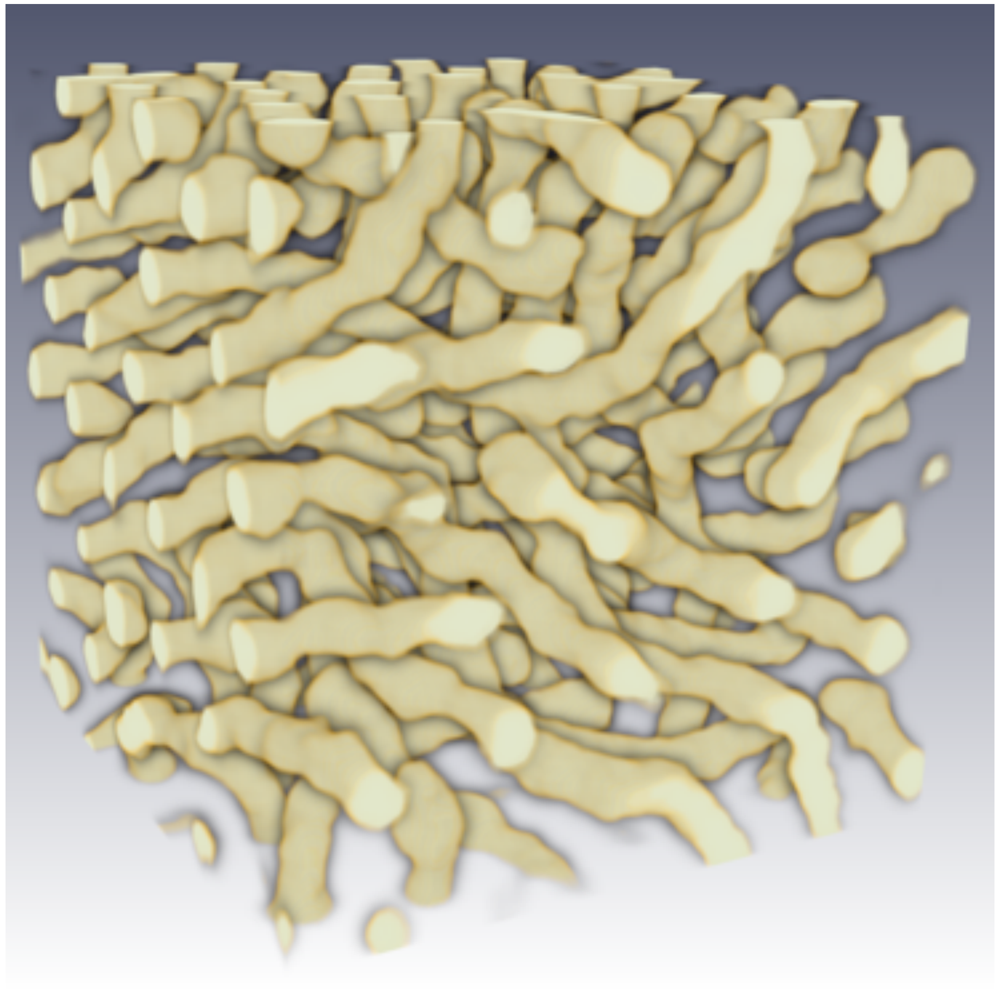
# Neutron rich matter



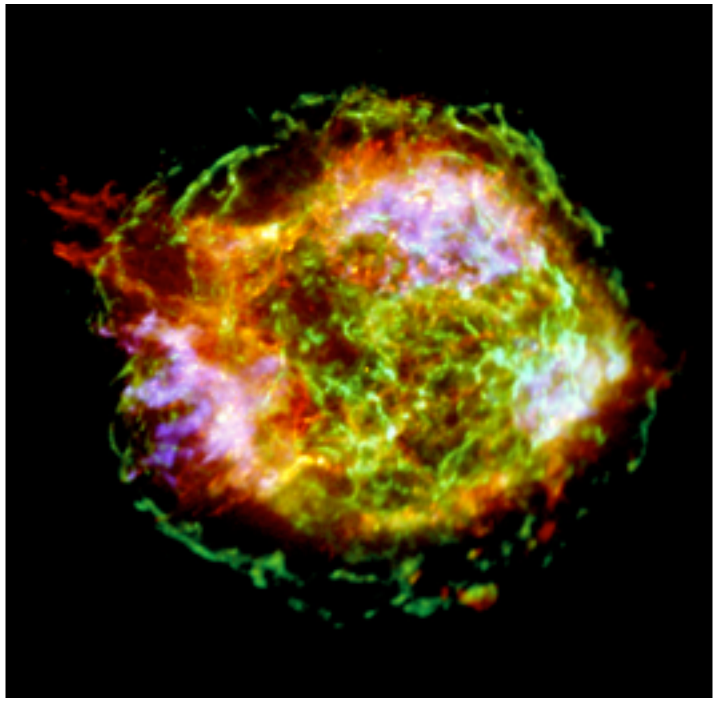

C. J. Horowitz, Indiana University



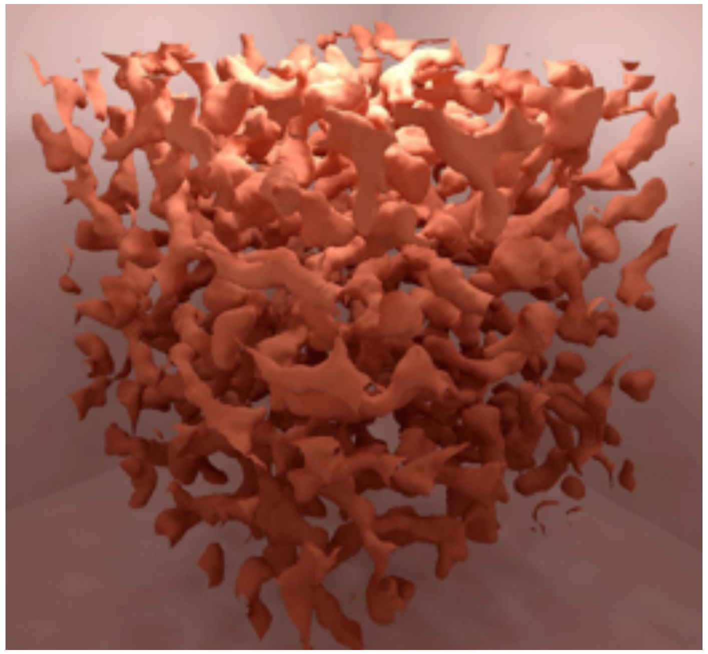
Supernovae and Gamma-Ray Bursts, Yukawa Inst., Kyoto, Oct. 2013

# 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



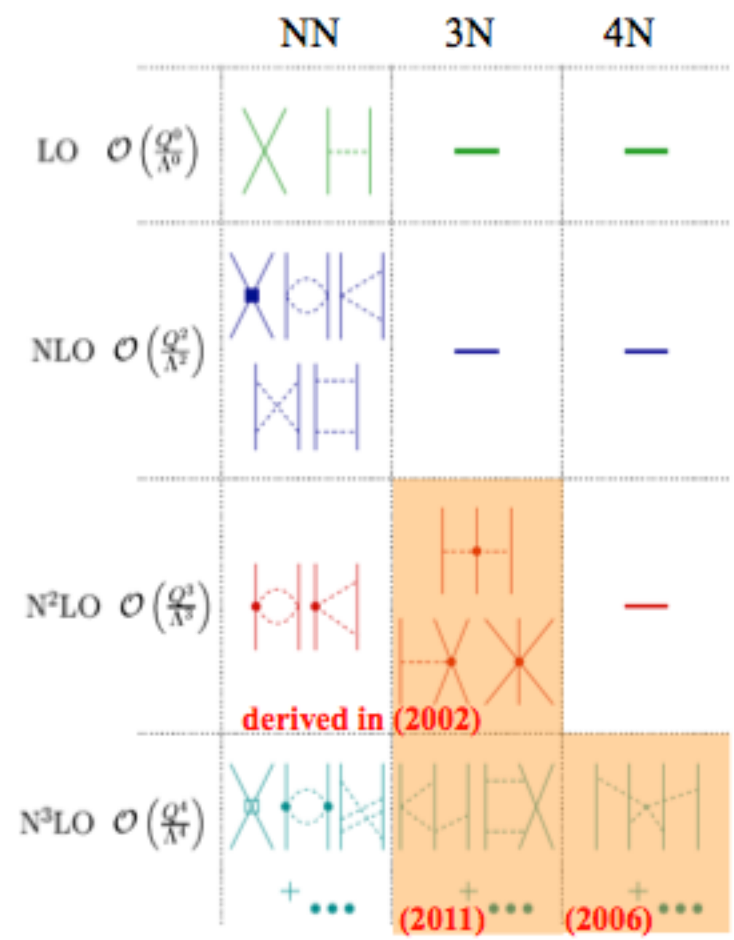
MD simulation of Nuclear Pasta with 100,000 nucleons

# Neutron rich matter

- **Theory:** chiral effective field theory.
- **Experiment:** neutron skin thickness of $^{208}$Pb, and $^{48}$Ca via parity violating electron scattering.
- **Low density nonuniform matter:**
  - –Formation of nuclear pasta.
  - –Neutrinosphere region in core collapse SN.

# 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 ~1/2$\rho_0$ to ~$\rho_0$.
  - –At higher densities chiral expansion may not converge.
  - –At lower densities matter is nonuniform.

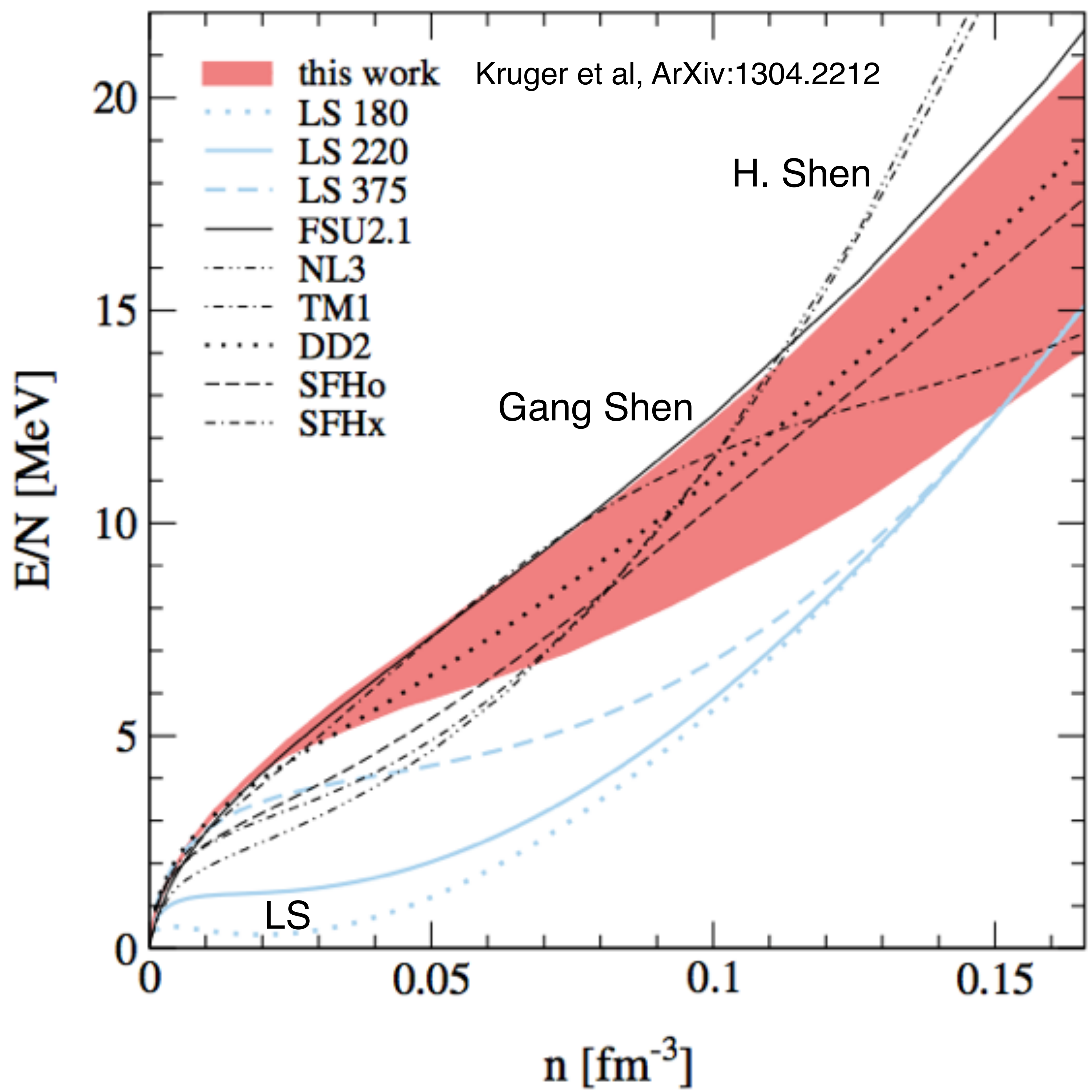



A. Schwenk

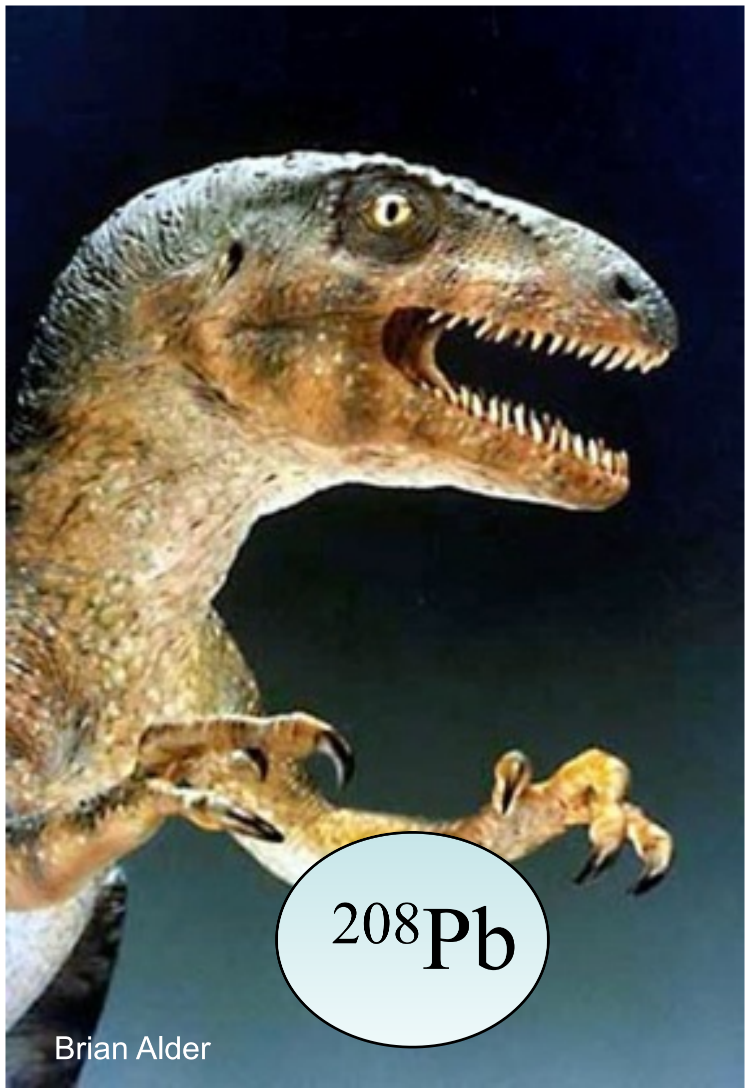
- All hadronic calculations of nuclear matter, for densities above $\rho_0$, may have large uncertainties in three and more nucleon forces.

# 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).



# 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

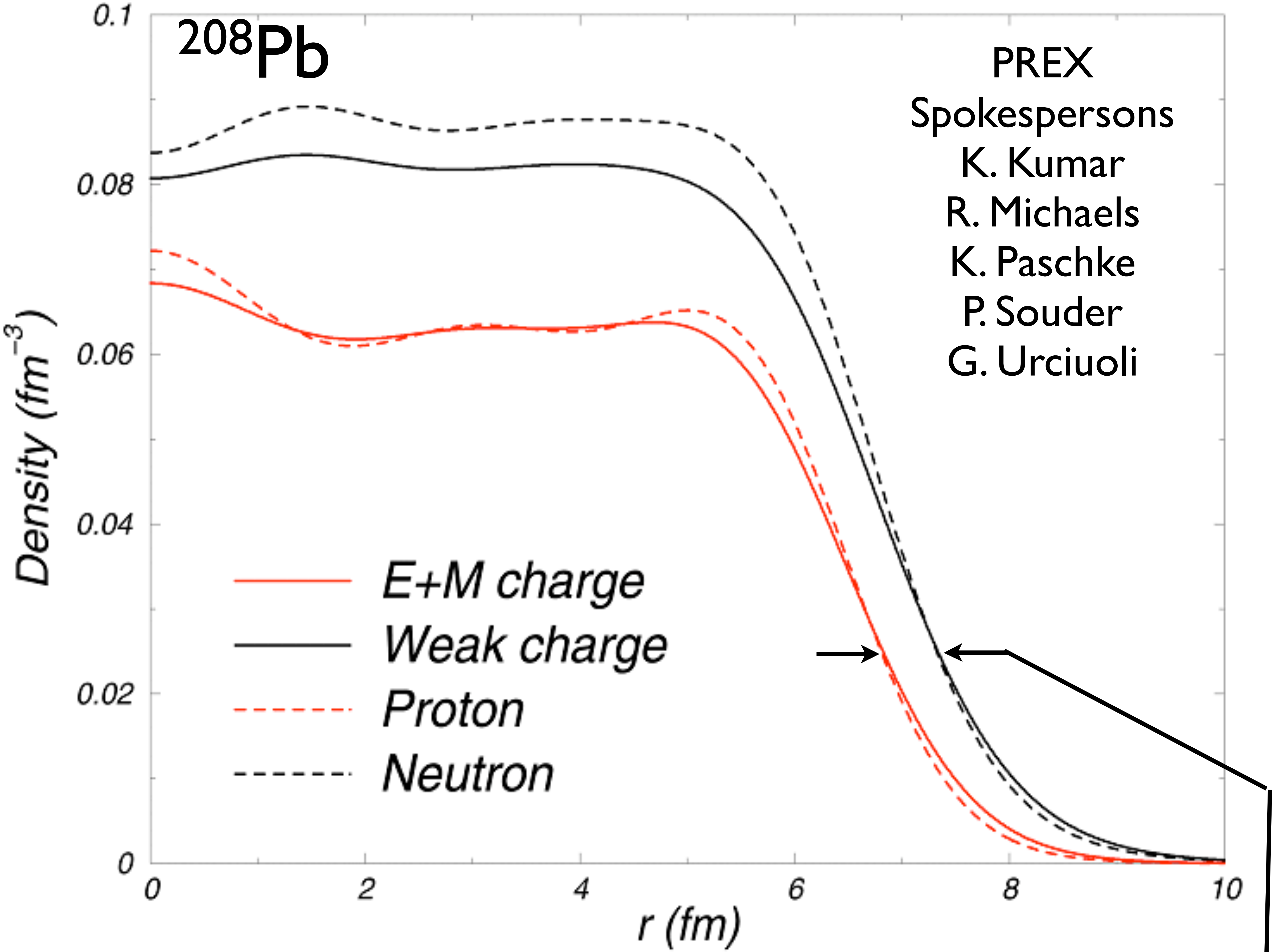
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\rm ch}(Q^2)}$$

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

- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**
  - Donnelly, Dubach, Sick first suggested PV to measure neutrons.

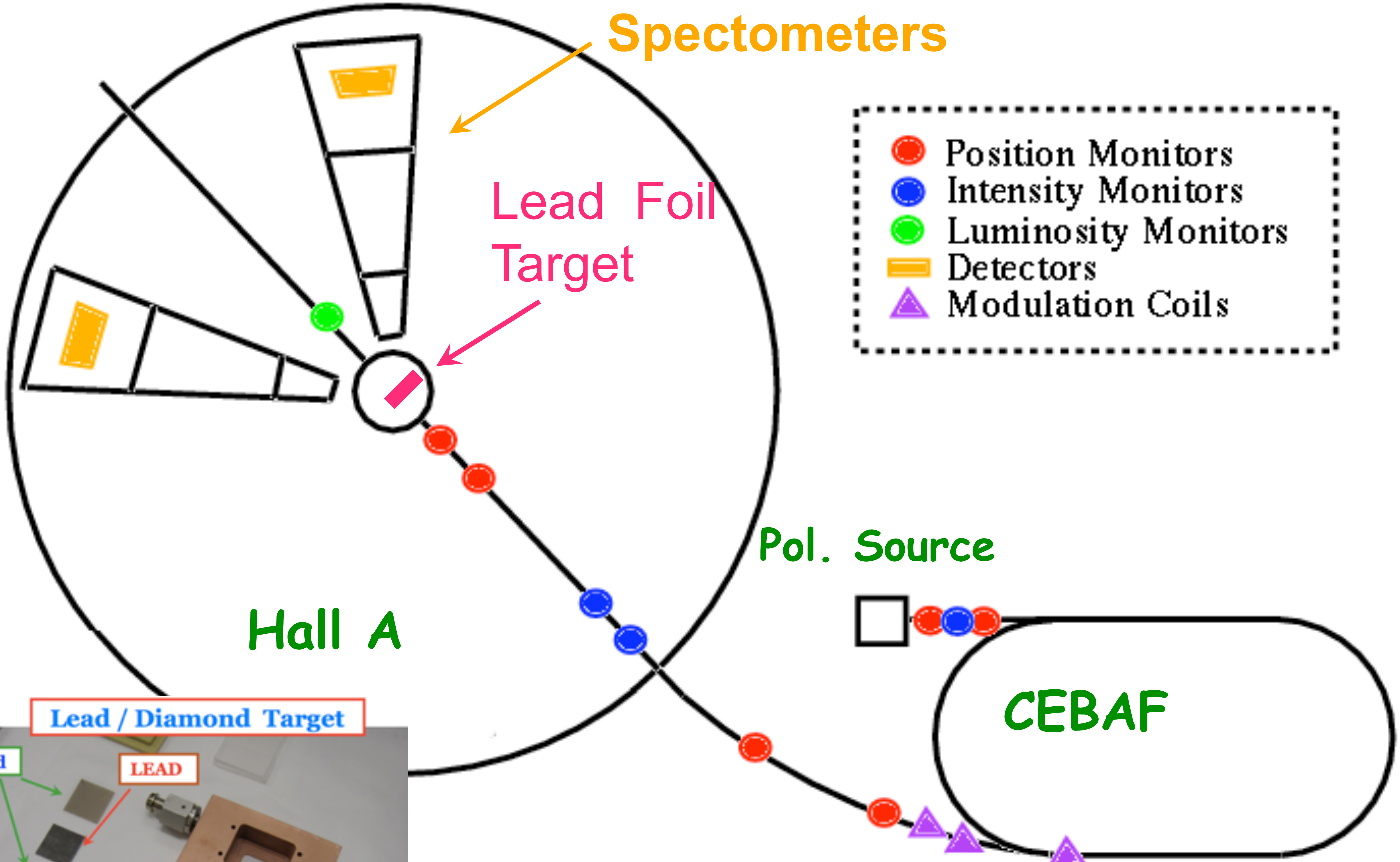
# Neutron radii from proton scattering

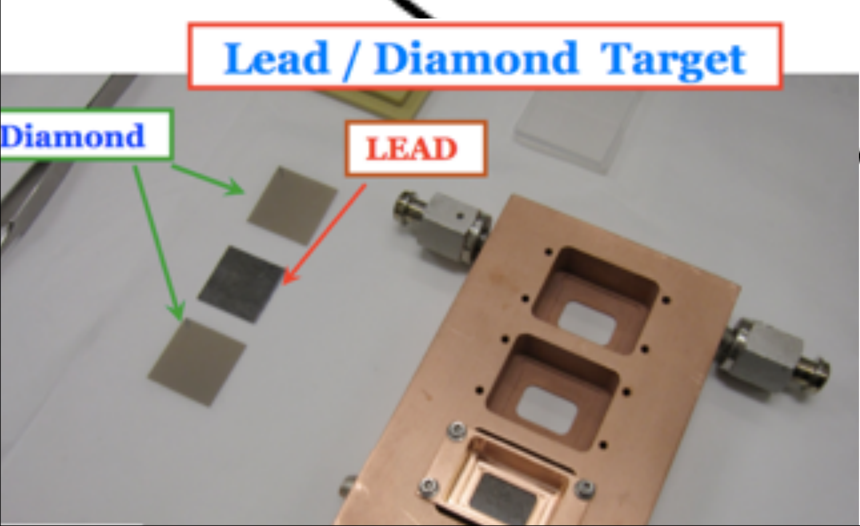
- Tamii et al. extract the electric dipole polarizability of $^{208}Pb$ using small angle proton scattering.
  - Claim $R_n$-$R_p$ = $0.156^{+0.025}_{-0.021}$ fm based on a *model dependent* correlation between polarizability and skin.
  - Fattoyev et al show that models with *a larger range of $R_n$-$R_p$* are consistent with polarizability (PRL**111**, 162501).
- Many *model dependent* extractions of neutron densities from proton elastic scattering. For example Terashima et al. (PRC77, 024317) modify NN amplitudes until $^{58}Ni$ has small $R_n$-$R_p$ and then use amplitudes to extract $R_n$-$R_p$ for Sn isotopes. Note, this procedure may depend on energy and nucleus.




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

# PREX in Hall A at JLab

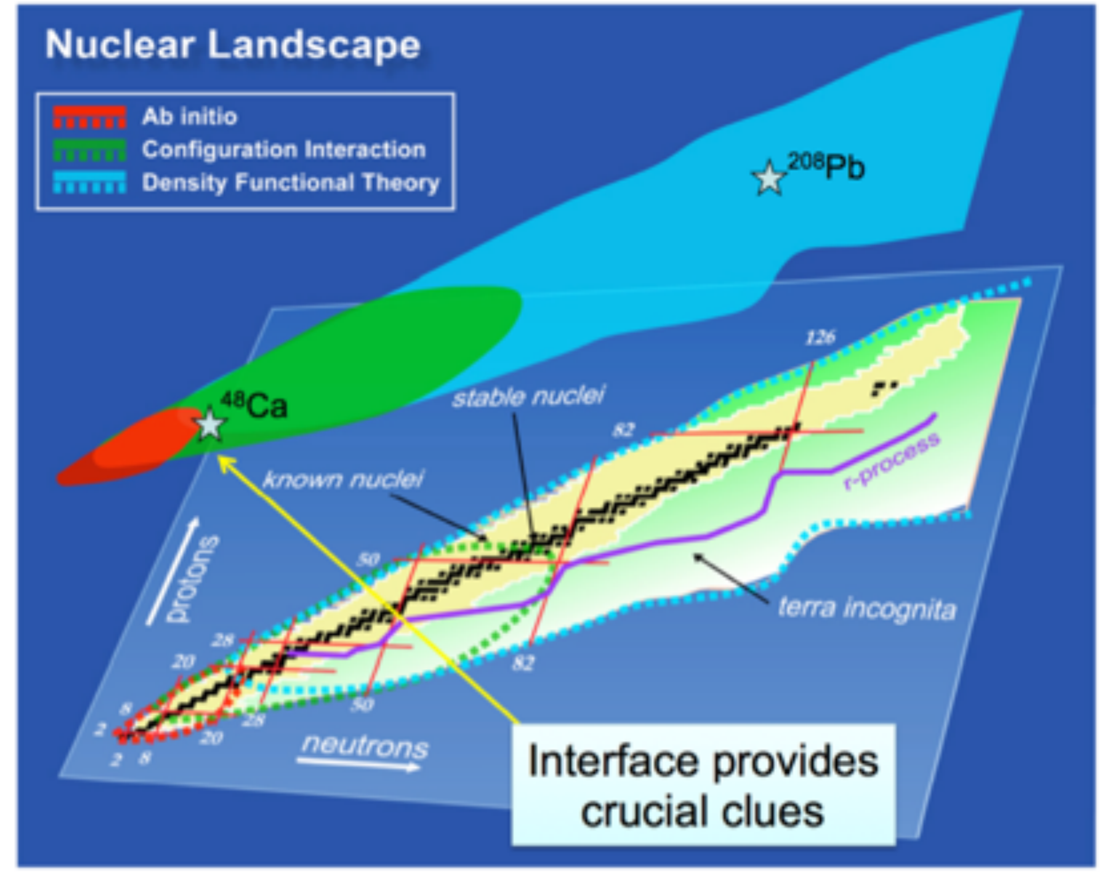


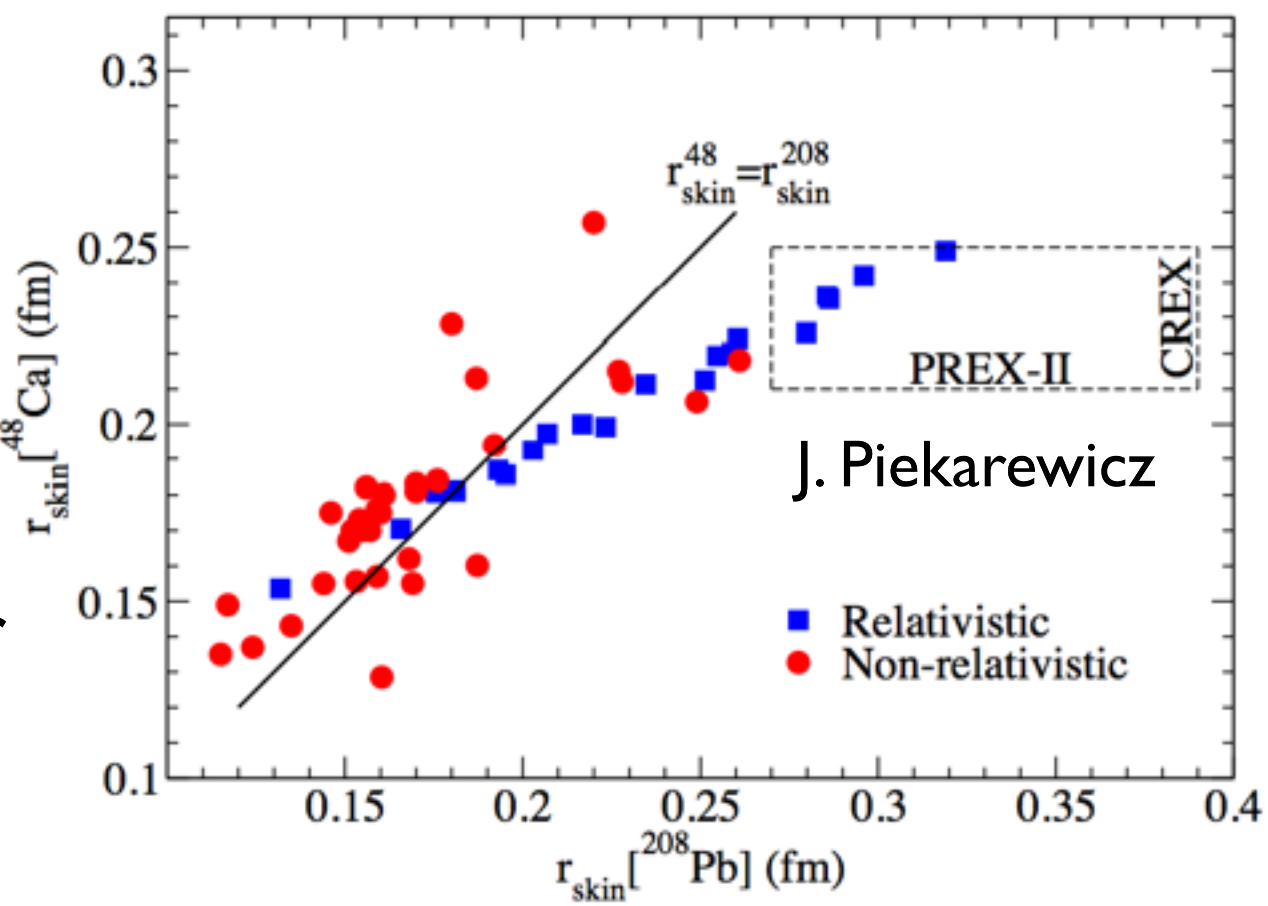




R. Michaels

# First PREX result and future plans

- 1.05 GeV electrons elastically scattering at ~5 deg. from $^{208}$Pb.
- $A_{PV}$=0.66±0.06(stat)±0.014(sym) ppm
- Neutron skin: $R_n$-$R_p$=$0.33^{+0.16}_{-0.18}$ fm
- Future plans: **PREX-II** (approved 25 days) Run $^{208}$Pb again to accumulate more statistics. Goal: $R_n$ to ±0.06 fm.
- **CREX**: Approved follow on for $^{48}$Ca with goal: $R_n$ to ±0.02 fm.
- Lighter $^{48}$Ca allows coupled cluster calculations to relate $R_n$ to three neutron forces. Important isovector observable to bridge ab initio and density functional descriptions.

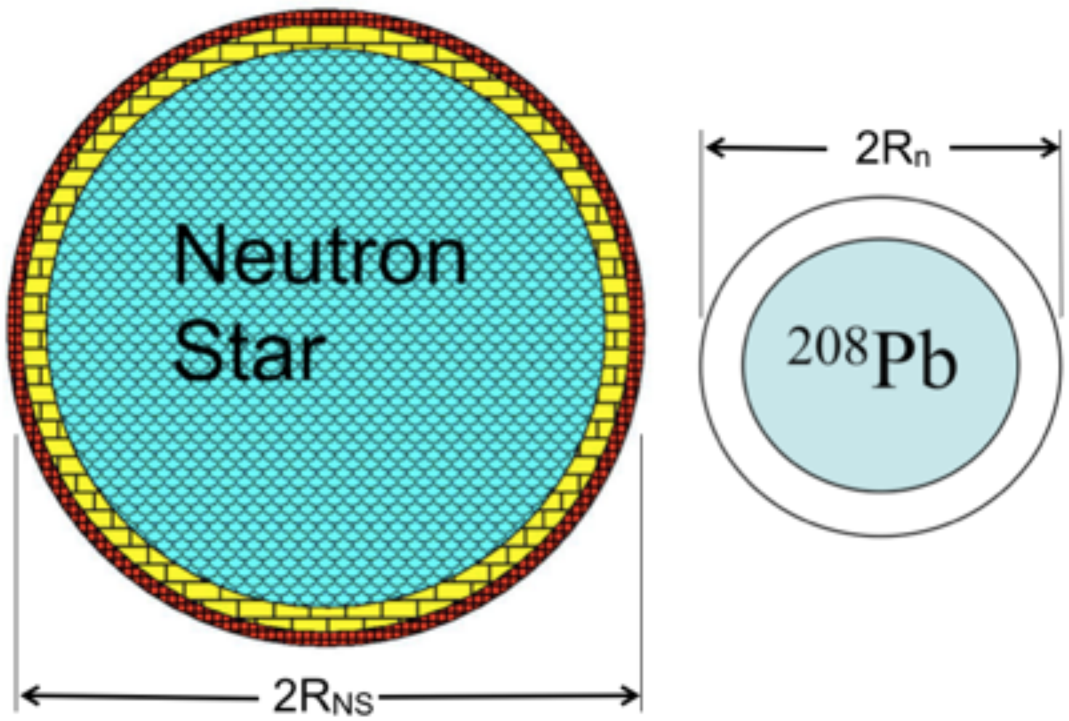


# Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension ==> $R_n$-$R_p$ of $^{208}$Pb determines P at low densities of about $2/3\rho_0$ (average of surface and interior $\rho$).
- Radius of ($\sim$1.4$M_{sun}$) NS depends on P at medium densities of $\rho_0$ and above.
- Maximum mass of NS depends on P at high densities.

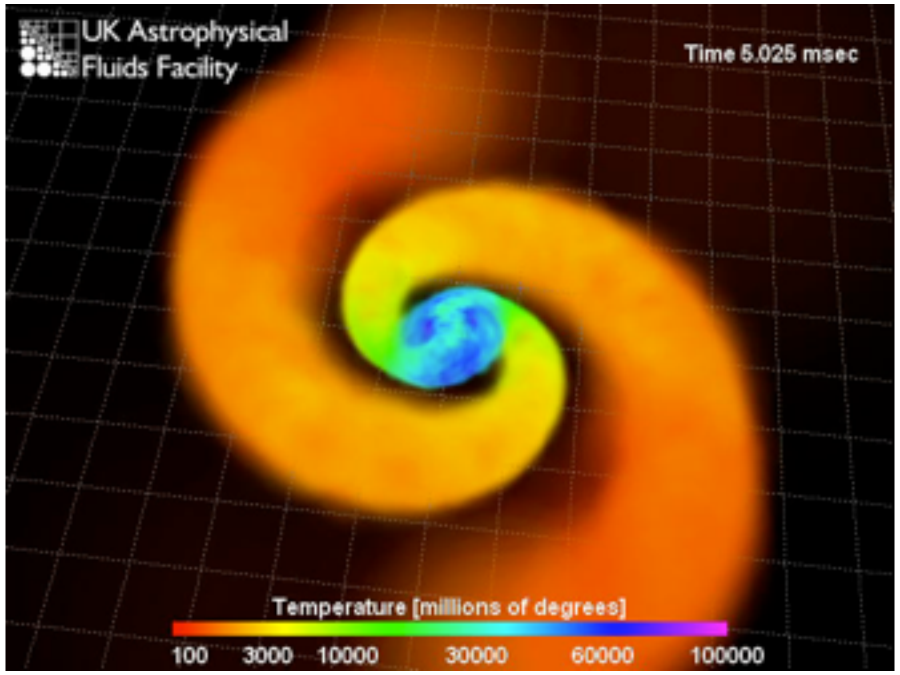
Neutron Star radius versus $^{208}$Pb Radius




- These three measurements constrain density dependence of EOS and possible pressure changes from phase transitions.

# Low Density Nonuniform Matter

- Half of heavy elements (including gold) made in r-process.
- **What makes all of the neutrons?**
  - **Neutrinos:** ratio of n/p in supernova $\nu$ driven wind set by rates of $\nu$ capture.
  - **Gravity:** compresses matter until electron capture drives it n rich. Tidal forces during NS mergers can eject n-rich material.
- Follow fluid element in tidal tail as it decompresses (next pages).
- Matter ejecta so n rich that it undergoes robust r-process!




- r-process yield depends on:
  - How much material is ejected in a merger? Better numerical relativity simulations.
  - What is merger rate? Advanced LIGO will soon directly observe rate.

Simulation by Stephan Rosswog, University of Leicester. Visualisation by Richard West, UKAFF.

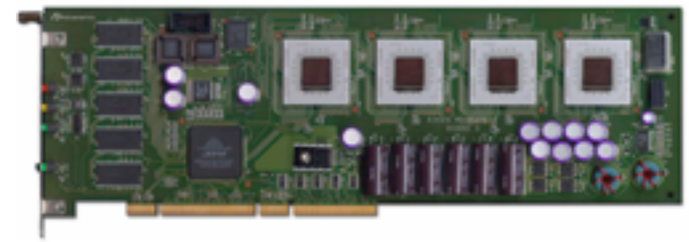
# Nuclear Pasta Formation

- During NS merger tidal excitation decreases density: uniform nuclear matter -> nuclear pasta -> nuclei + n -> r-process. **Decompression pasta** (ms time scale, low $Y_p$).
- Gravitational collapse during SN increases density: ~ Fe nuclei -> nuclear pasta -> uniform nuclear matter -> neutron star. **SN pasta** (ms time scale, high $Y_p$).
- **Cooling pasta** as protoneutron star cools.
- Accretion, slow cooks new pasta on accretion time scales (thousands of years??). **Accreted pasta**.
- Pasta formation involves phase transitions between very different shapes. *Cooking pasta is not so simple!*


We have started on pasta microphysics: thermal/ electrical conductivity, shear viscosity, neutrino opacity, dynamical response...

# (Semi)classical pasta model

- Charge neutral system of n, p, and e. [e provide screening length $\lambda$ for Coulomb.]
- Thermal wave length of heavy clusters much shorter than inter cluster spacing: semi-classical approx. should be good.
- n, p interact via 2-body pot: $H = K + \Sigma_{i<j}\, v(r_{ij})$
  $v(r) = a\, \mathrm{Exp}[-r^2/\Lambda] + b_{ij}\, \mathrm{Exp}[-r^2/2\Lambda] + e_i e_j\, \mathrm{Exp}[-r/\lambda]/r$
- Parameters a, $b_{pp}=b_{nn}$, $b_{pn}$, $\Lambda$ fit to binding E and saturation density of nuclear matter, reasonable symmetry E...
- Simple model allows large MD simulations with 300,000+ nucleons, long simulation times $10^7$ + fm/c.
- Also QMD simulations by Watanabe et al, Quantum calculations by W. Newton ...



MDGRAPE-2 boards in past


Presently run on about 1000 cores for ~ few weeks


Porting to GPU based machines such as IU's new Big Red II

# Simulation of pasta formation. ArXiv:1307.1678

51200 nucleons,
$Y_p$=0.4,
T=1 MeV,
$\lambda$=10 fm,
$\xi$=2x$10^{-8}$ c/fm,
$L_0$=80 fm
$L=(1+\xi t)L_0$

$n = 0.1000\mathrm{fm}^{-3}$

Andre Schneider

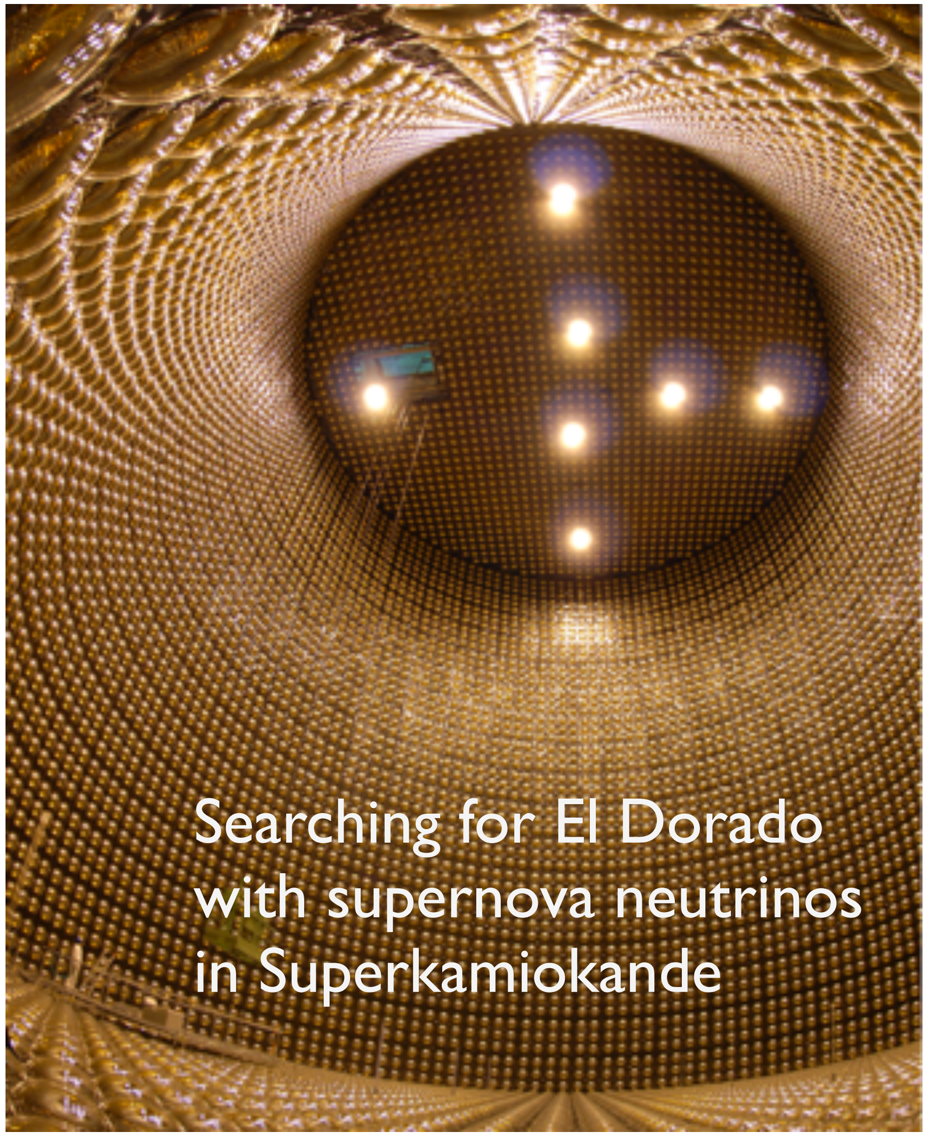
# SN neutrinos and r-process nucleosynthesis

- Important possible site for the r-process is the neutrino driven wind in core collapse supernovae.
- Ratio of neutrons to protons in wind 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.

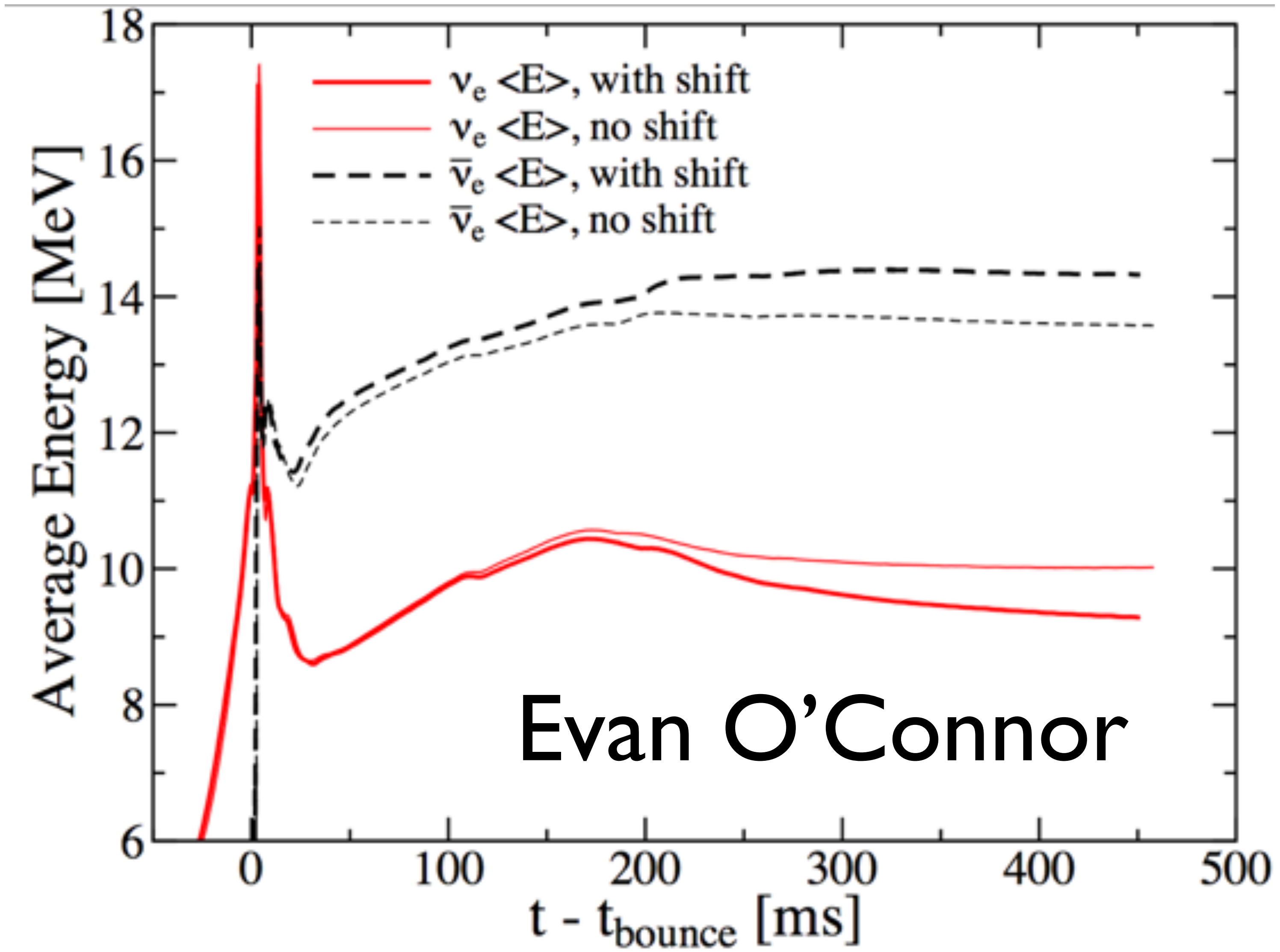



Measure energy of both anti-nu (SK) and neutrinos (liquid argon?).

**Present SN simulations find too few neutrons.**

# 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.
- Electron antineutrinos capture on protons while neutrinos capture on neutrons. Matter is neutron rich so neutrinos have larger opacity. Therefore electron neutrinos (red) are emitted with lower energy than antineutrinos (black).




- Binding energy shift (see below) increases antineutrino and decreases neutrino energies leading to a larger $\Delta E$.

# Binding Energy shift

- Proton in n rich matter more bound than n because of symmetry energy.
- Energy shift can be calculated exactly with virial expansion (with A. Schwenk). Find it is much larger than in some mean field models because of cluster formation.

$$\Delta U = U_n - U_p = \lambda^3 T(n_n - n_p)(b_{pn} - \hat{b}_n)$$

- Neutrino absorption cross section is increased by energy shift which increases energy and phase space of outgoing electron: $\nu_e$+n -> p+e

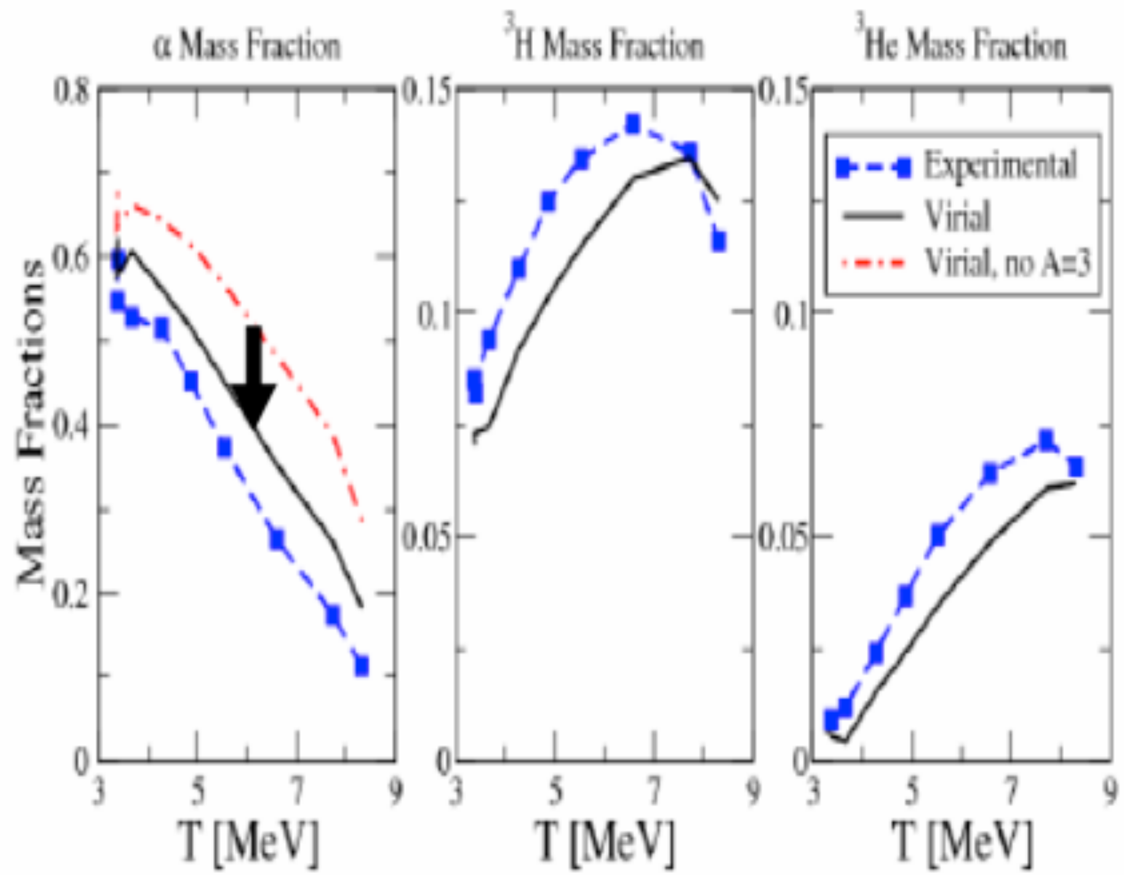
$$\frac{\sigma_{\nu_e}(\Delta U)}{\sigma_{\nu_e}(0)} = \frac{(E_\nu + \Delta U)^2[1 - f(E_\nu + \Delta U)]}{E_\nu^2[1 - f(E_\nu)]}.$$

- Effect opposite for anti-neutrino absorption and reduces cross section increasing E(anti-nu).
- Increases ΔE and makes wind somewhat more neutron rich. Probably not enough for r-process, but still important for nucleosynthesis!

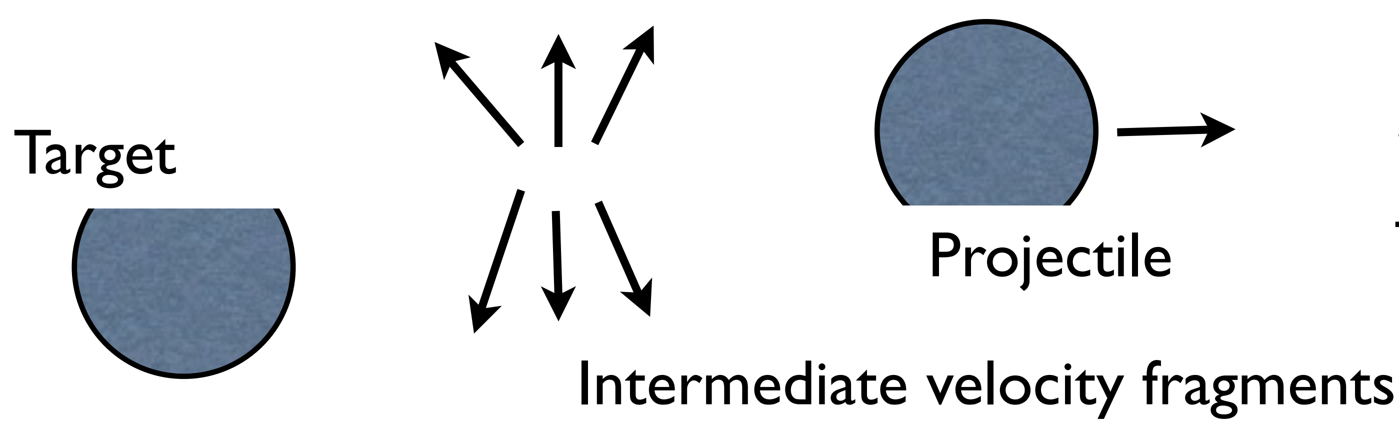
Idea due to L. Roberts, my work with G. Shen, C. Ott, E. O'Connor

# Recreating Neutrinosphere on Earth

- Much of the "action" in core collapse supernovae happens near the neutrinosphere at LOW densities where the matter may be nonuniform.
- Neutrinosphere where mean free path is size of system R~10 km = $(\sigma\rho)^{-1}$ --> warm, low density gas (T ~ 5 MeV, density ~$\rho_0$/100 )
- Properties of neutrinosphere matter (for example composition of light clusters 4He, 3He, 3H…) important for emitted neutrino spectra and nucleosyntheis of SN.
- Can study neutrinosphere like conditions with heavy ion collisions in lab.




Composition of intermediate velocity fragments in HI collisions: Data (blue squares) Kowalski et al, PRC **75**, 014601(2007). Our virial EOS is black.

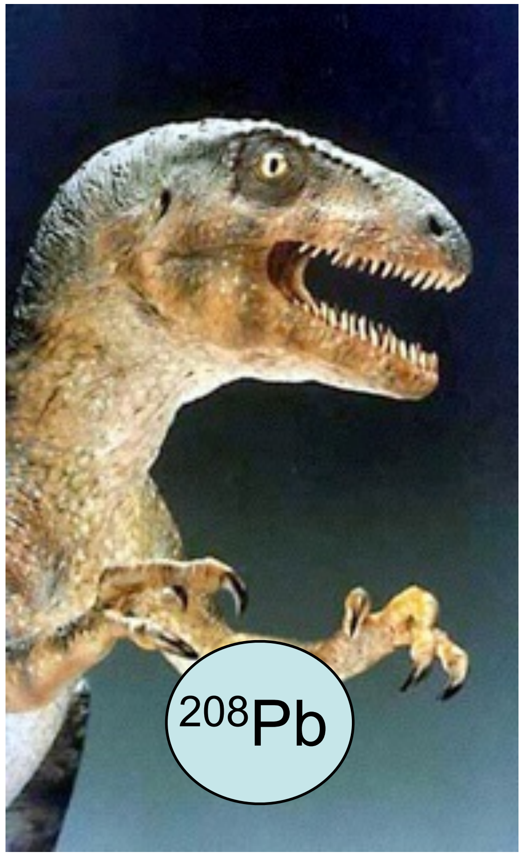



In a peripheral HI collision, intermediate velocity fragments from warm low density region.

# Femtonova collaboration

- Recreate neutrinosphere conditions with heavy ion collisions using radioactive beams.
- By comparing collisions with proton rich and neutron rich systems, extrapolate to very neutron rich neutrinosphere conditions.
- Measure composition, symmetry energy, equation of state,... of neutrinosphere matter.
- Allow more robust predictions of neutrino spectra and nucleosynthesis for core collapse SN.
- Workshop at ECT* in Trento, Italy, April 7-11, 2014.
- New members (HI experimentalists, astrophysicists, neutrino physicists…) welcome

# Neutron Rich Matter




- Can be studied in lab. with radioactive beams and in Astrophysics with X-rays, neutrinos, gravitational waves.
- PREX uses parity violating electron scattering to accurately measure the neutron radius.
  - First result: $R_n$-$R_p$($^{208}$Pb)=$0.33^{+.16}_{-.18}$ fm.
  - Plan to get more statistics for $^{208}$Pb, also 2nd expt. on $^{48}$Ca.
  - Many implications for astrophysics...

- Collaborators: D. Berry, M. Gorchtein, R. Michaels, J. Piekarewicz, G. Shen... Students: C. Briggs, J. Hughto, A. Schneider.
- Supported in part by DOE.