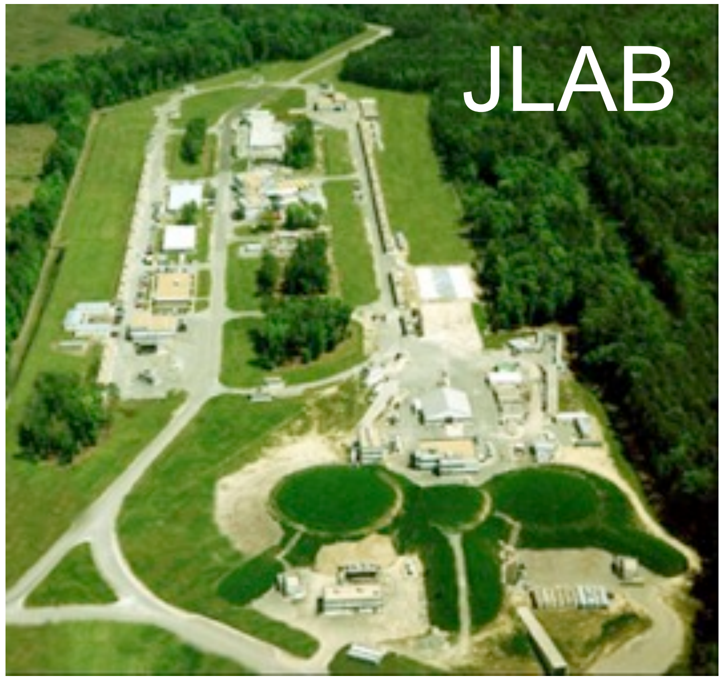
Neutron Rich Matter and Supernovae

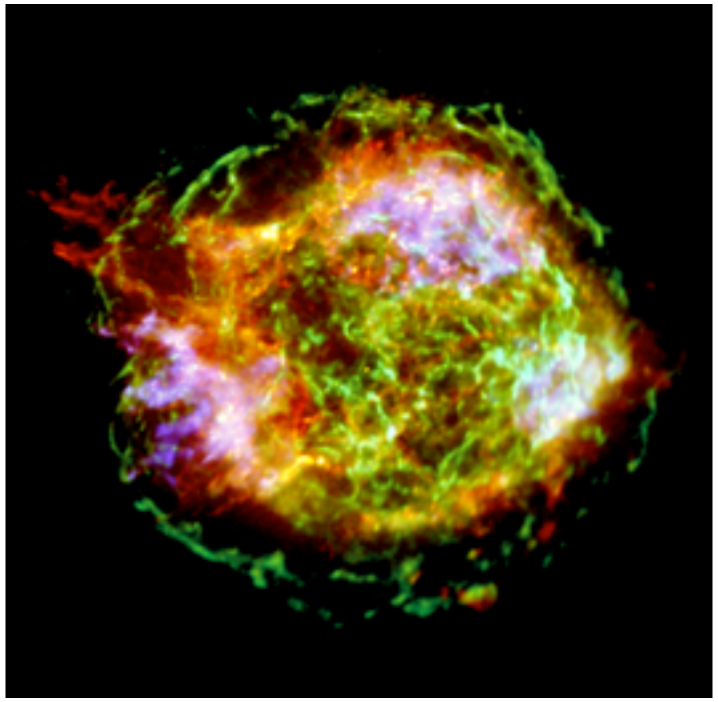
- Pb Radius Experiment (PREX) measures neutron radius of ^{208}Pb, many implications for n rich matter.
- Observations of neutron star radii and masses constrain equation of state of n rich matter.
- Neutrinos in supernovae come from a low density, neutron rich, nearly unitary gas. Virial expansion describes properties of this gas.



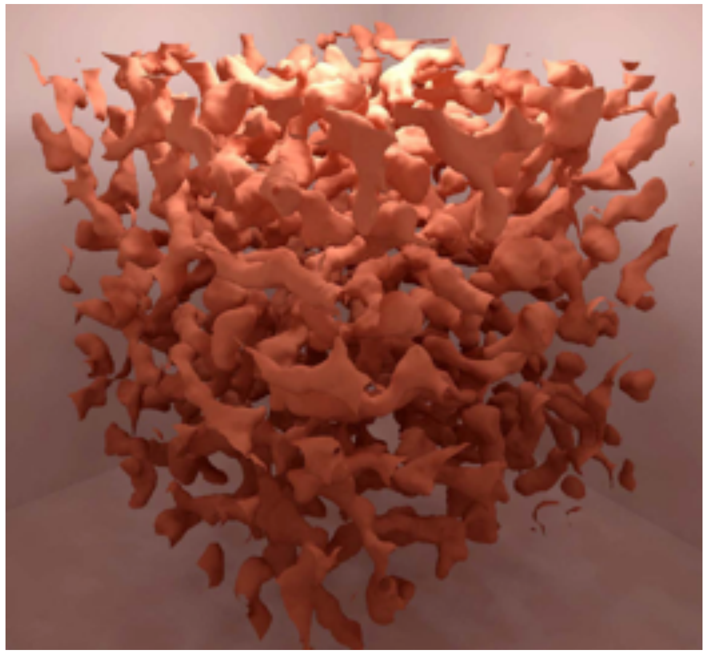
C. J. Horowitz, Indiana University
Cold Atoms, INT, May 2011

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 here on simpler gas, liquid, and solid phases.*



Supernova remanent Cassiopea A in X-rays

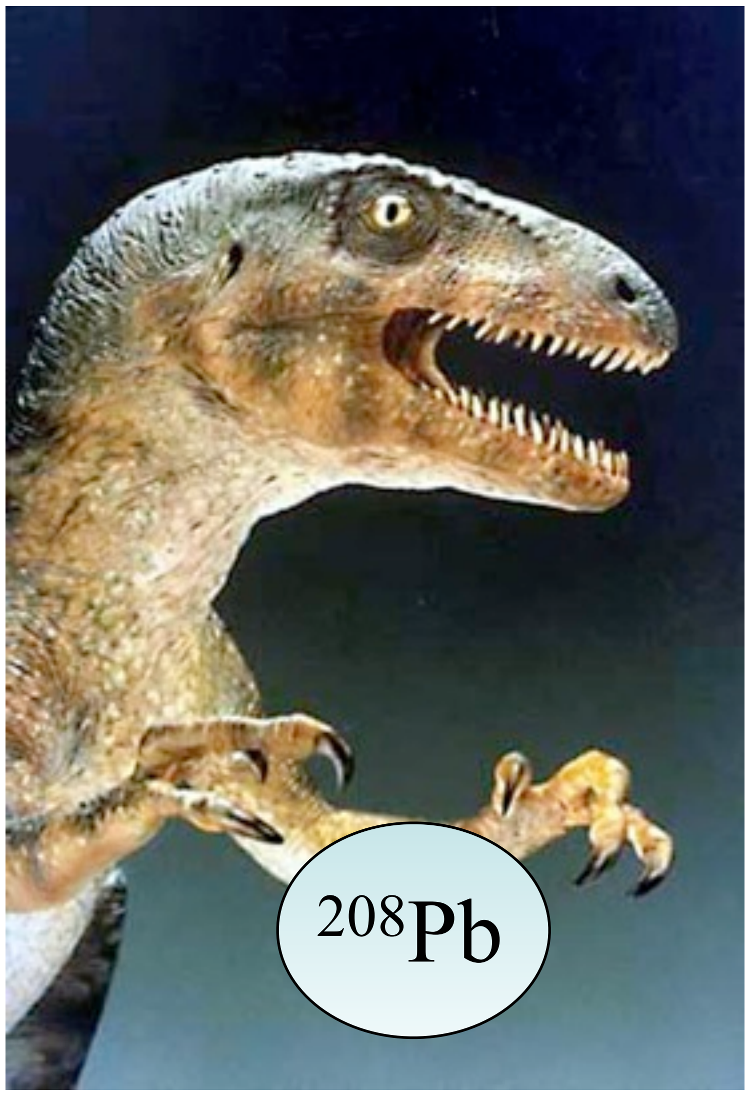


MD simulation of Nuclear Pasta with 100,000 nucleons

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.

Spokespersons: K. Kumar, P. Souder, R. Michaels, 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

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

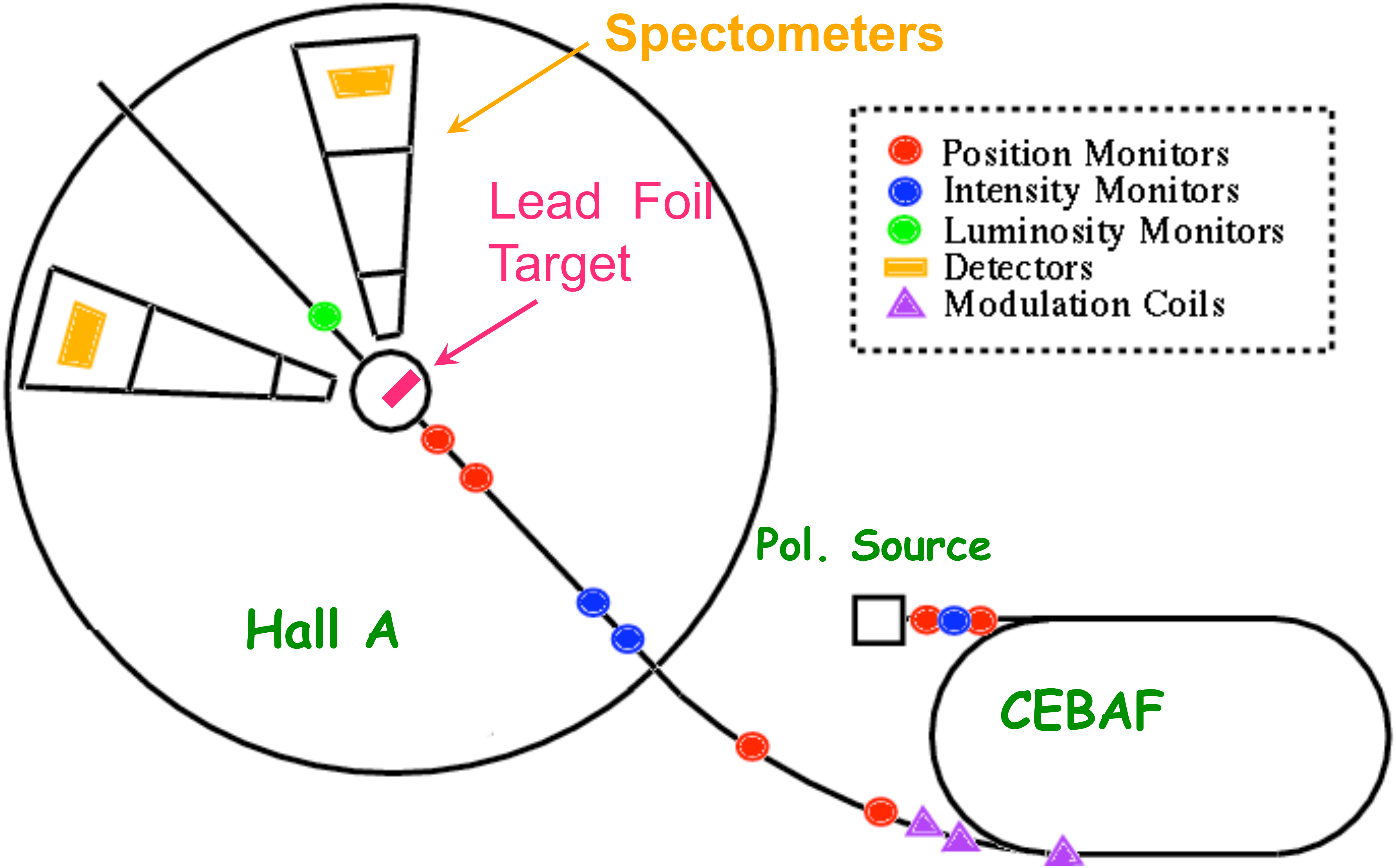
- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

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

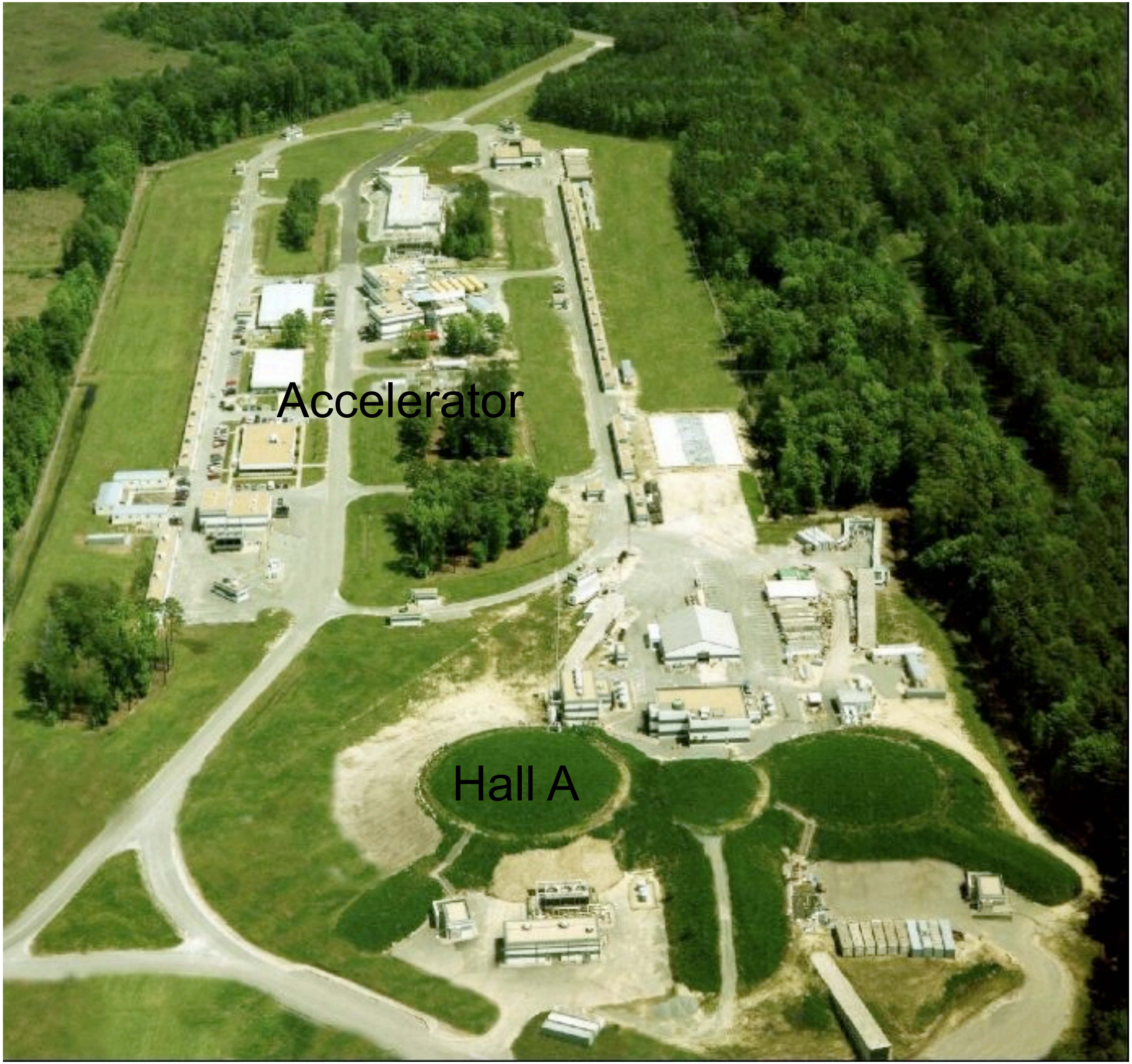
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

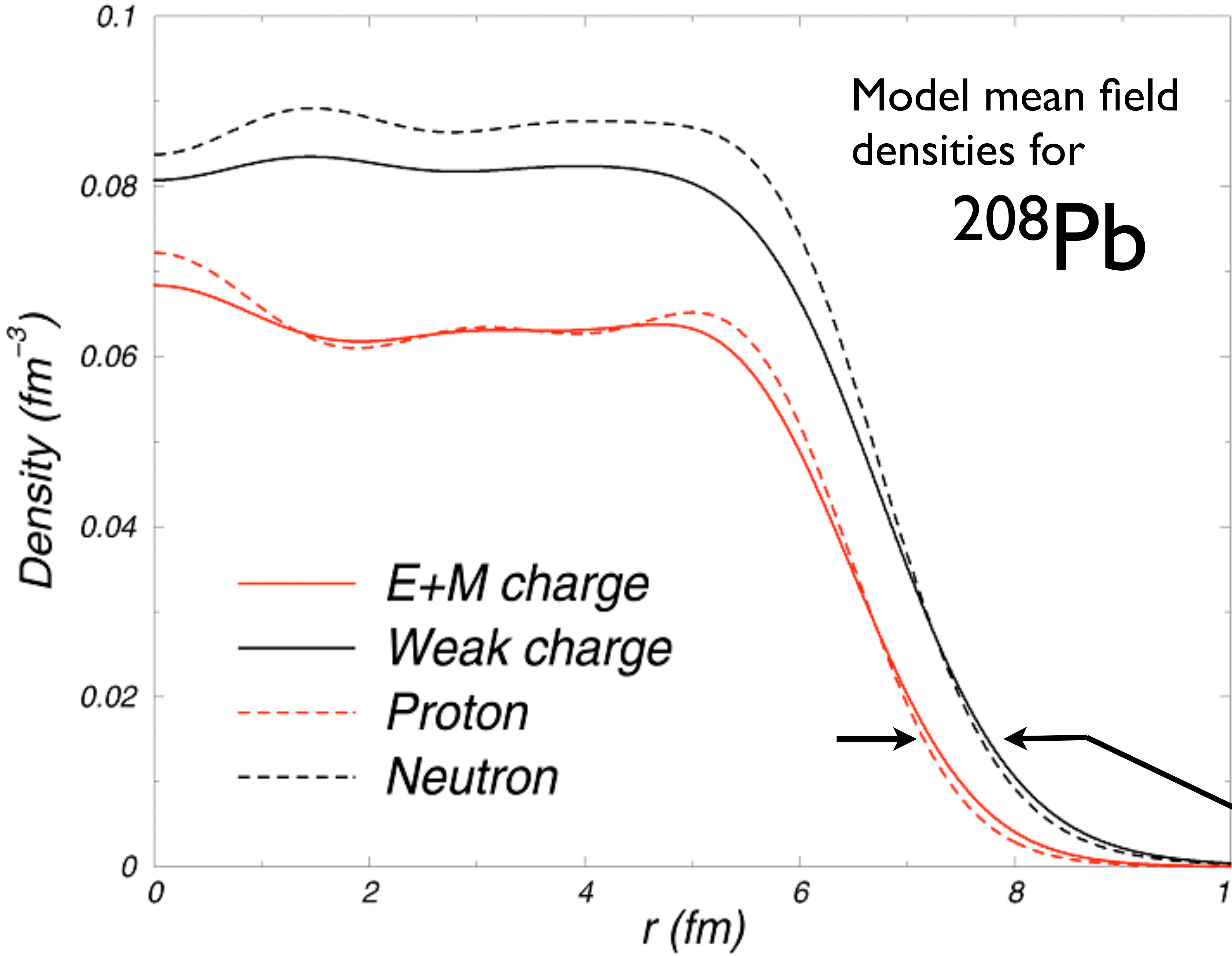
- Coulomb distortions important but accurately calculated.
- PREX measure A_{pv} for 1.05 GeV electrons scattering from ^{208}Pb at 5 degrees. Goal measure A_{pv} to 3%, gives neutron radius R_n to 1% (+/- 0.05 fm).
  - Donnelly, Dubach, Sick first suggested PV to measure neutrons.

PREX in Hall A at JLab



R. Michaels

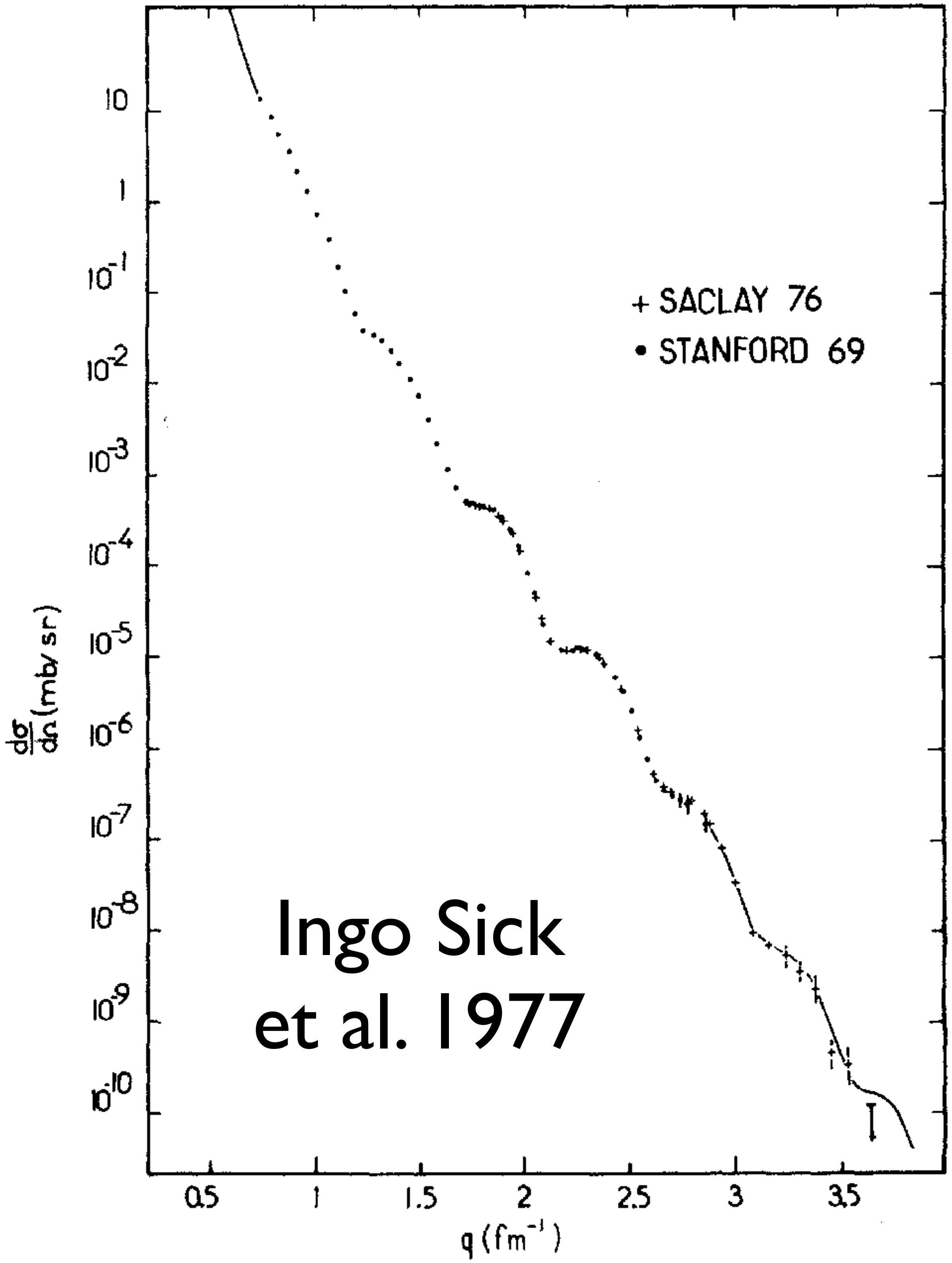

Accelerator
Hall A



PREX

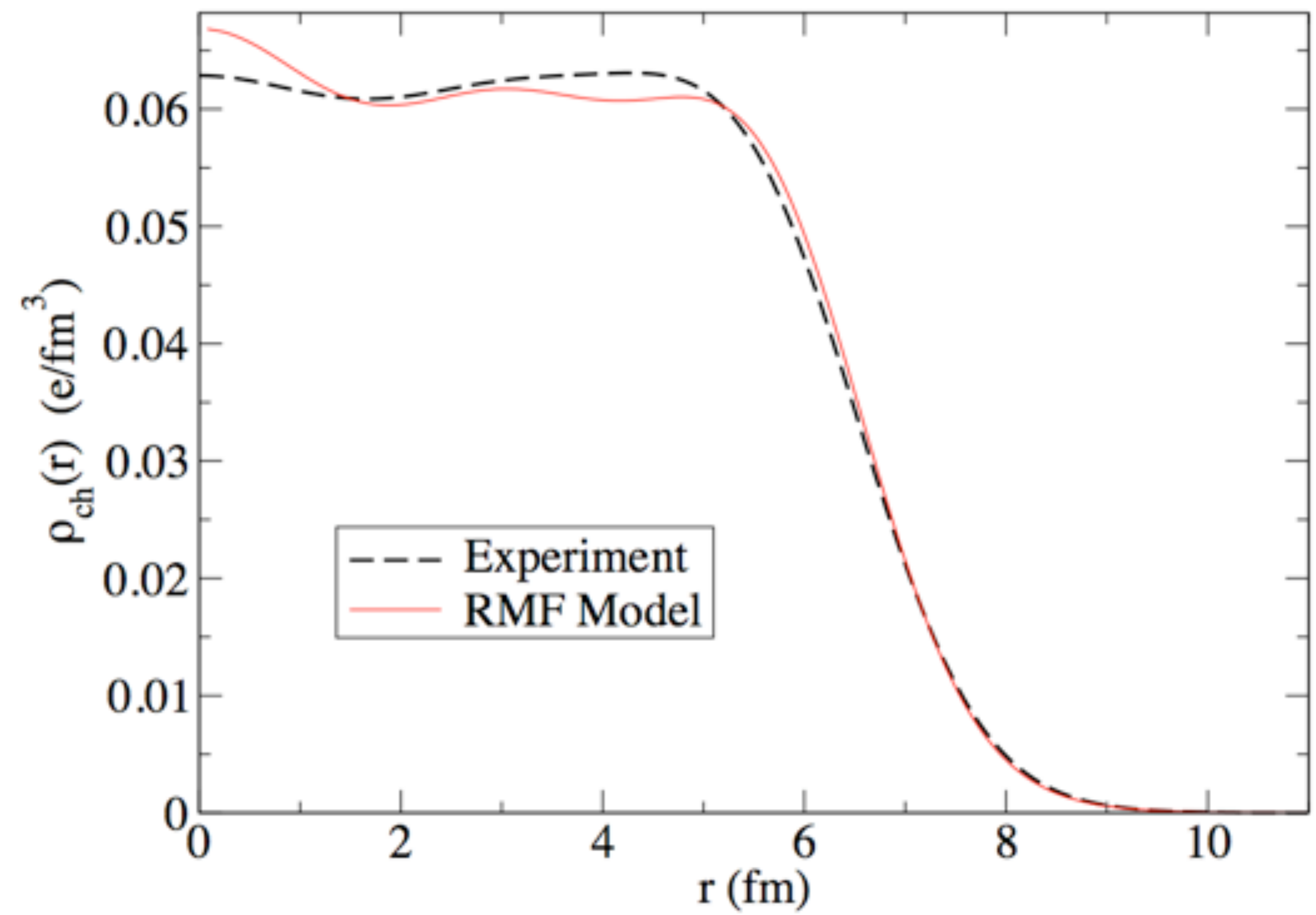
Spokespersons:
K. Kumar
P. Souder
R. Michaels
G. Urchiuli

- PREX measures how much neutrons stick out past protons (neutron skin).
- First result announced April 30, 2011. Measured parity violating asymmetry: A_{pv} = +0.6571 ± 0.0604 ± 0.0130 ppm implies: R_n-R_p=$0.34^{+0.15}_{-0.17}$ fm
- Plan to run again to obtain more statistics and reach 1% error +/-0.05 fm for R_n.



Cross section measured over 12 orders of magnitude.

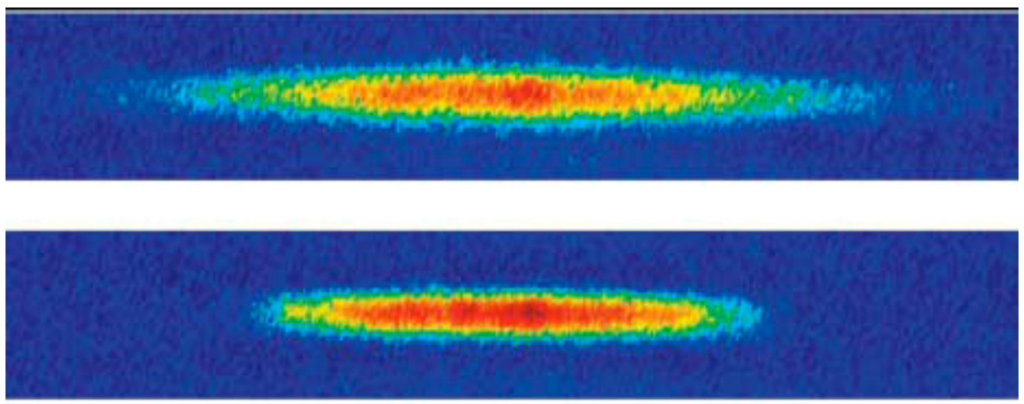
Charge Density of ^{208}Pb, accurately measured in elastic electron scattering.



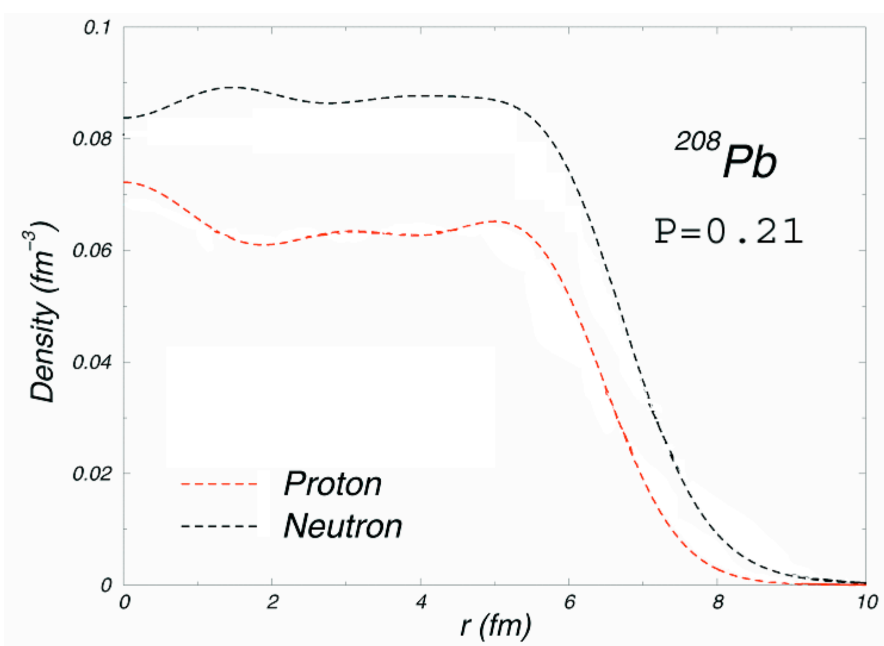
These elastic charge densities ***are*** our picture of the atomic nucleus!

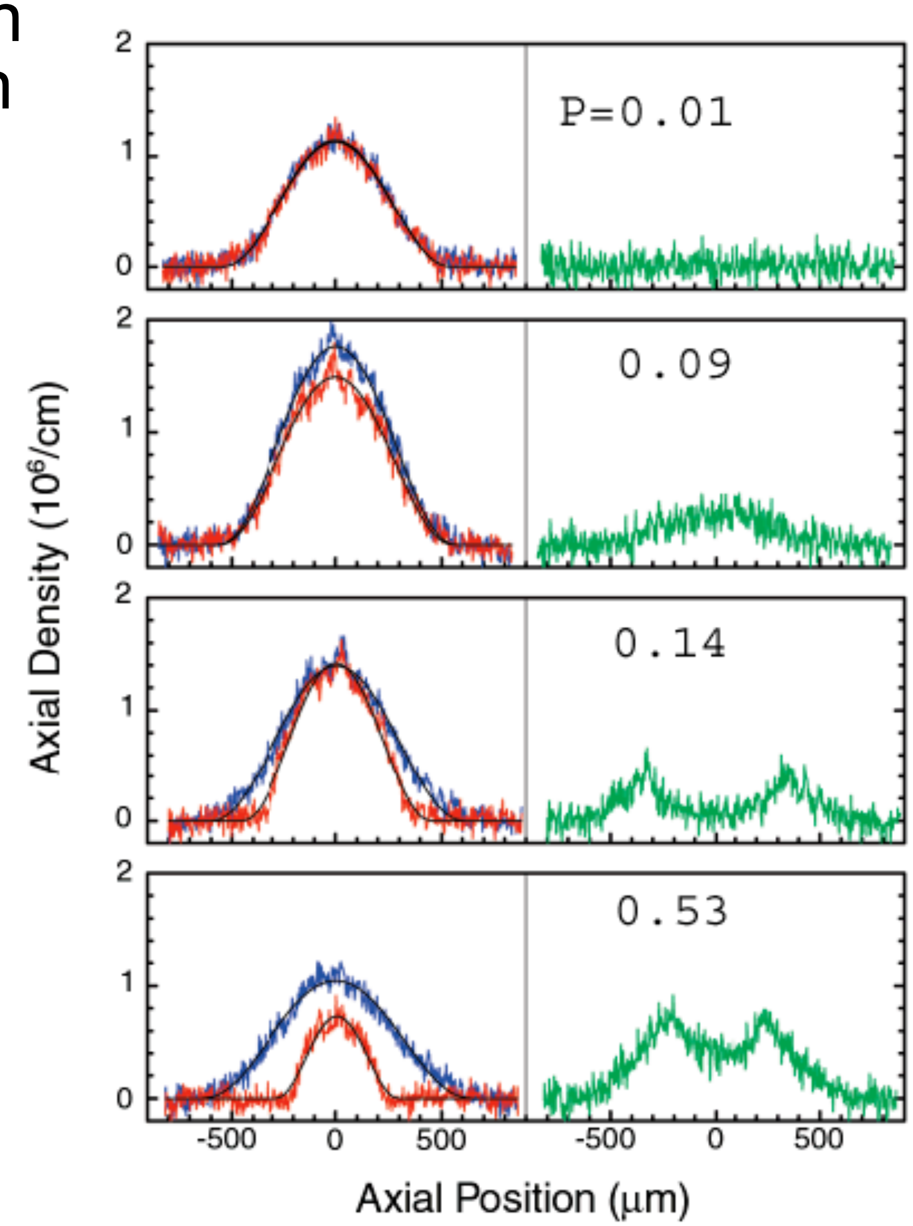
Spin Skins in Cold Atom Systems

- Fermions in asymmetric trap. Call spin up ^{6}Li atoms "neutrons" and spin down "protons". P=(N-Z)/(N+Z)



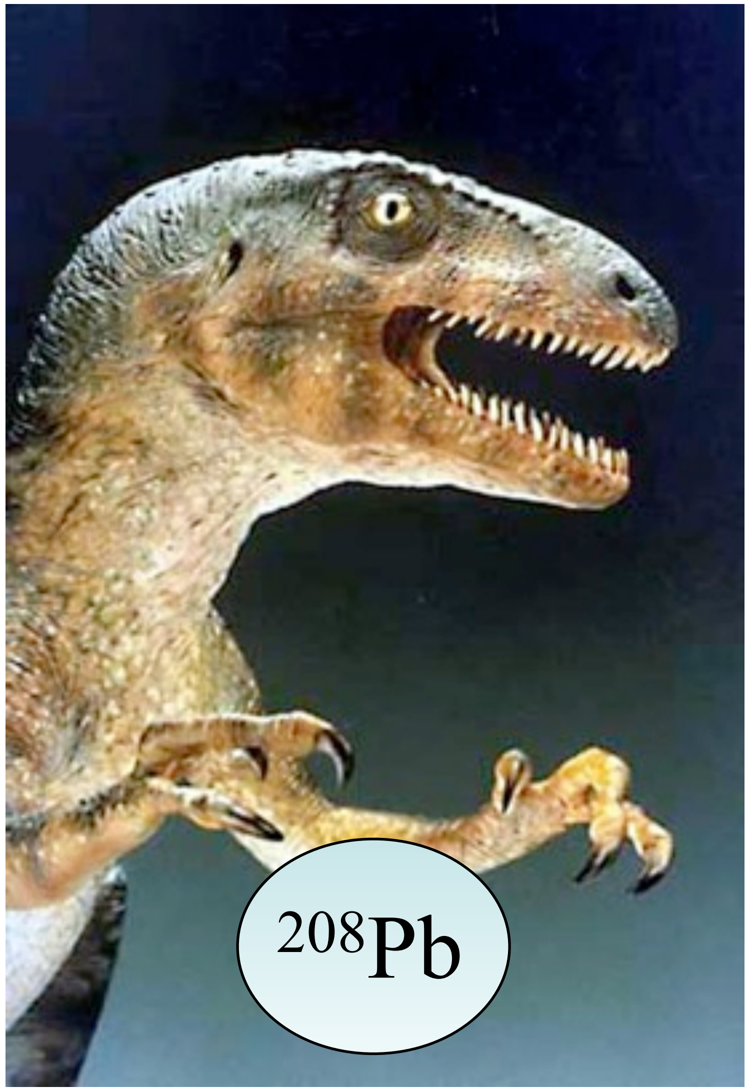
Neutrons (top) and protons for P=0.14



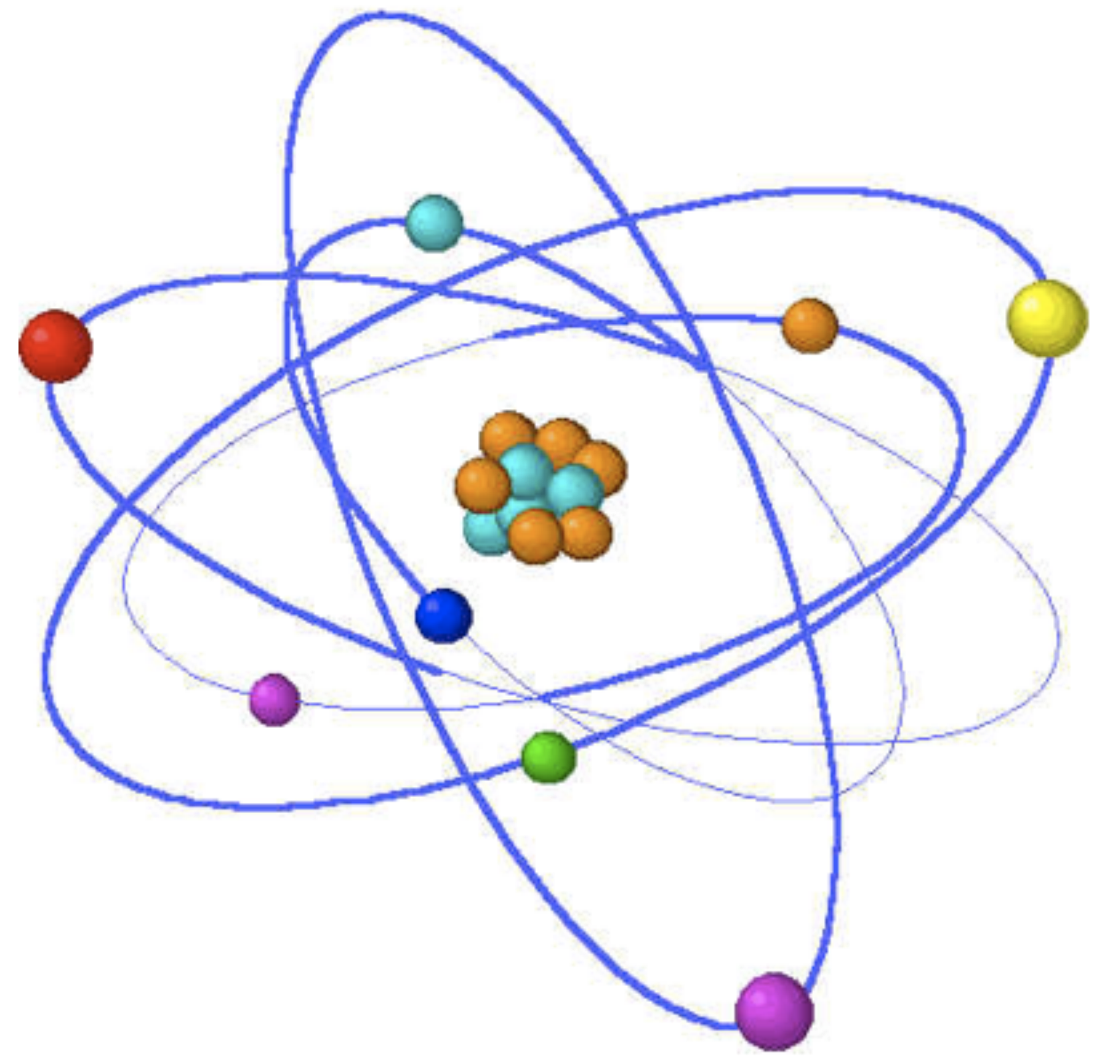


G. Partridge et al, Science **311**('06) 503

Attractive interaction (zero E bound state) for unlike spins, no interaction for like spins.



PREX and Atomic Parity Violation



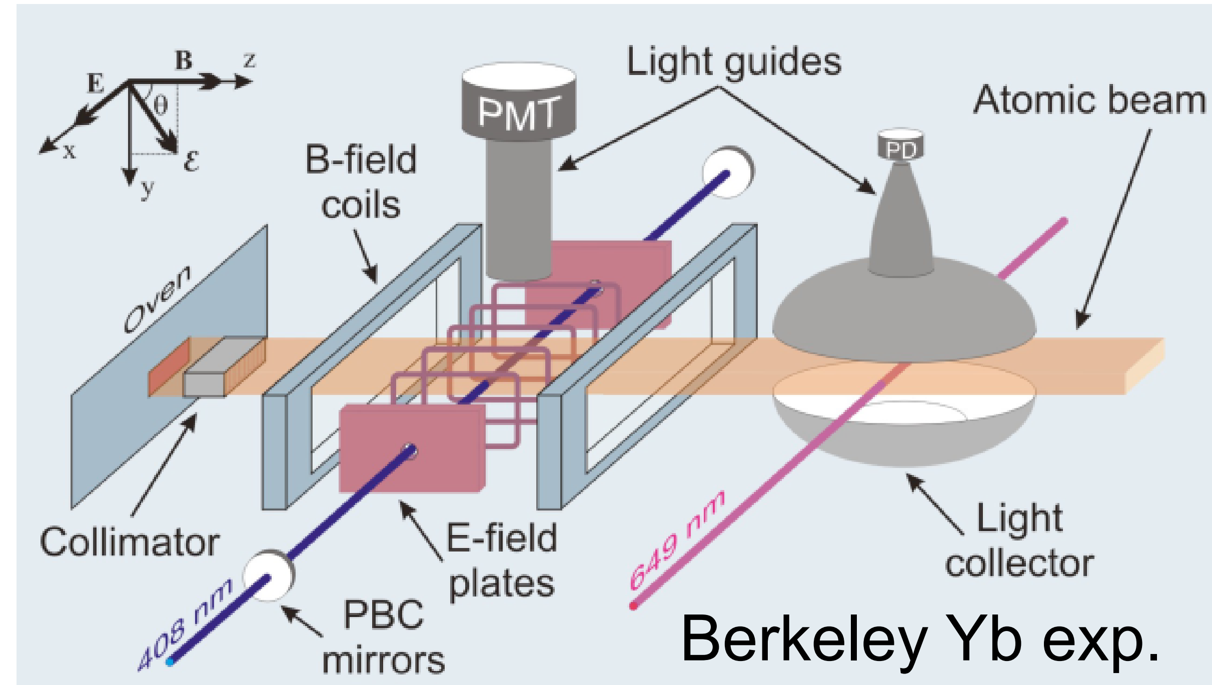
Atomic Parity Violation

• Atomic PV depends on overlap of electrons with neutrons in nucleus.

• Cs experiment good to 0.3%. Not limited by R_n but future 0.1% exp would need R_n to 1%

• Measurement of R_n in ^{208}Pb constrains nuclear theory for R_n in other atomic PV nuclei.

• Combine neutron radius from PV e scattering with an atomic PV exp for best low energy test of standard model.



• Recent Atomic PV Progress:

• Improved atomic theory for Cs.

• First PV results from Berkeley Yb experiment.

• Start of TRIUMF program for laser trapped radioactive Fr.

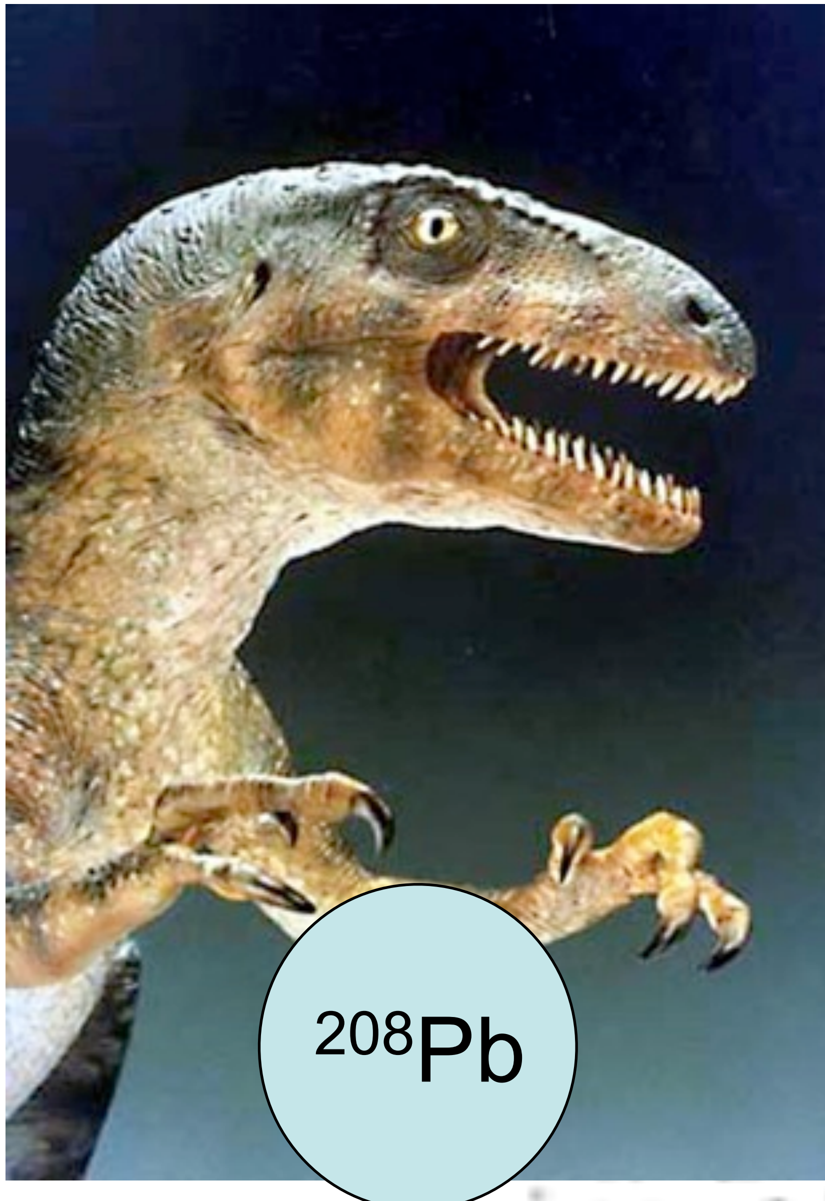
• KVI program on PV in Ra+.

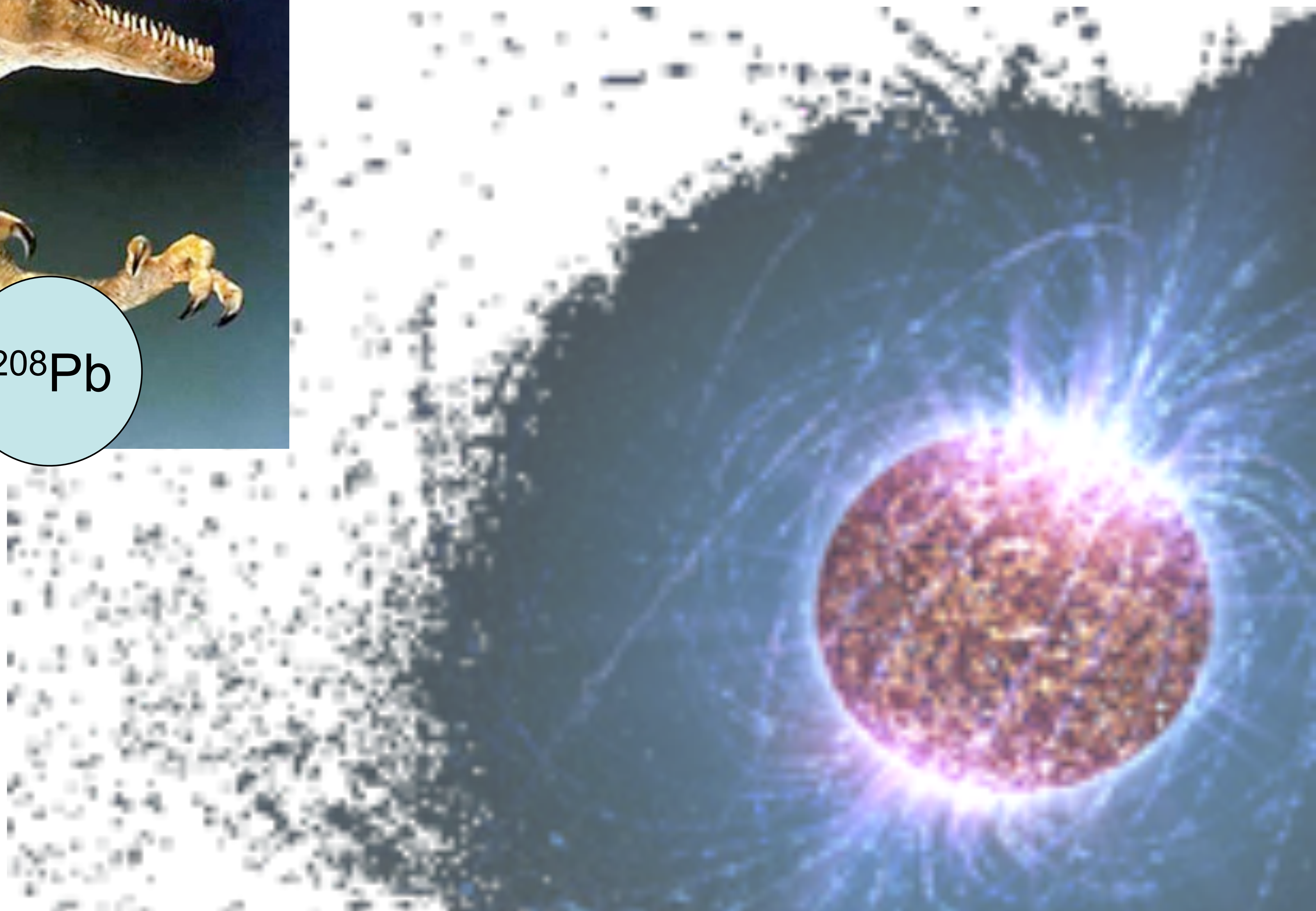
The size of ^{208}Pb

- Charge radius: R_{ch} = 5.50 fm (well measured)
- Point proton radius: R_p = 5.45 fm (- proton size)
- PREX: A_{pv} = +0.6571 ±0.0604 ±0.0130 ppm
- Point neutron radius: $R_n = 5.79^{+0.15}_{-0.17}$ fm
- Skin thickness: R_n-R_p = $0.34^{+0.15}_{-0.17}$ fm (two sigma measurement of skin, two+ sigma verification of coulomb distortions)

- [Proton radius puzzle: r_p=0.877 fm in e-p system and 0.8418(7) fm in mu-p system.]

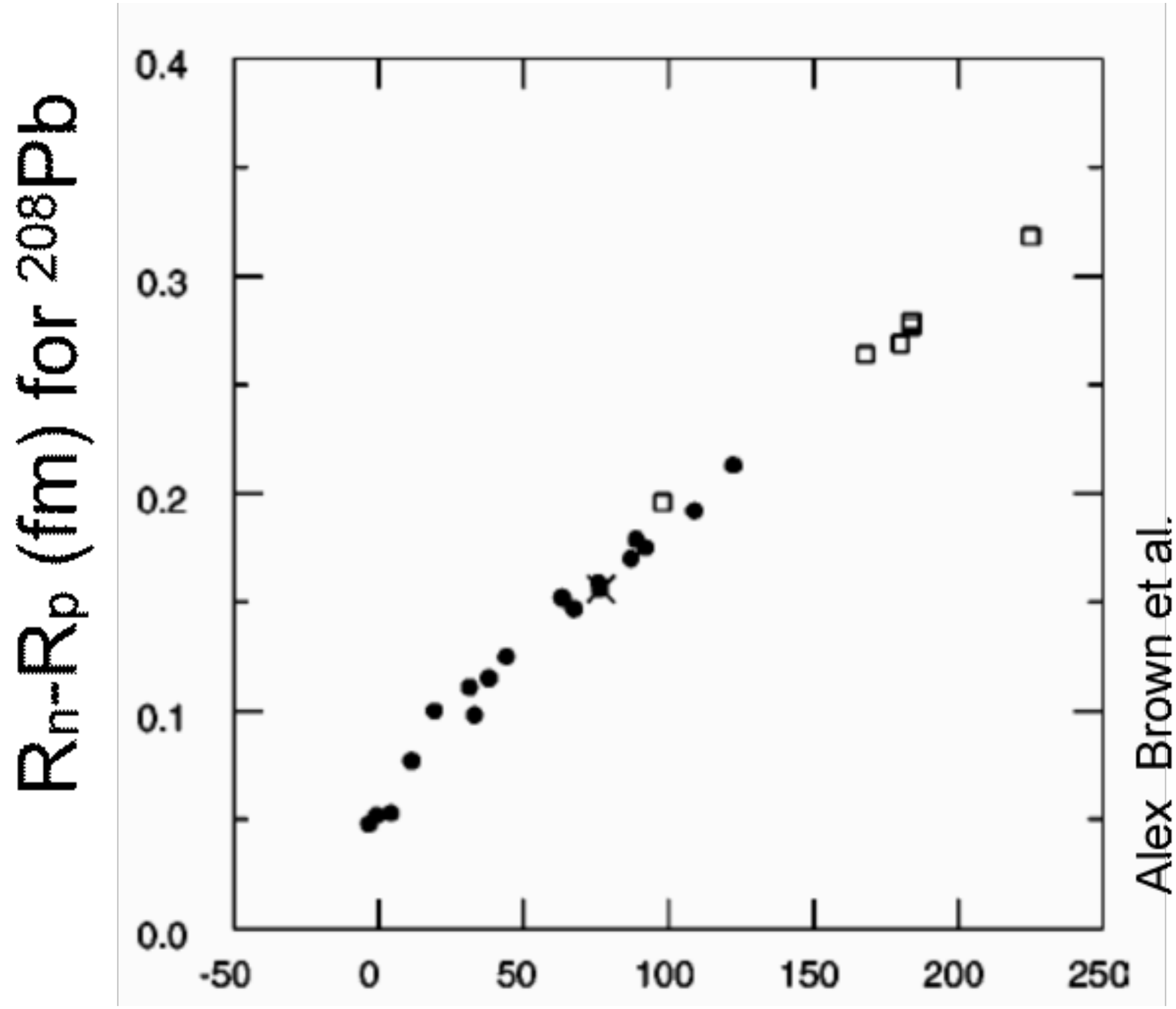
PREX and Neutron Stars





^{208}Pb radius and equation of state

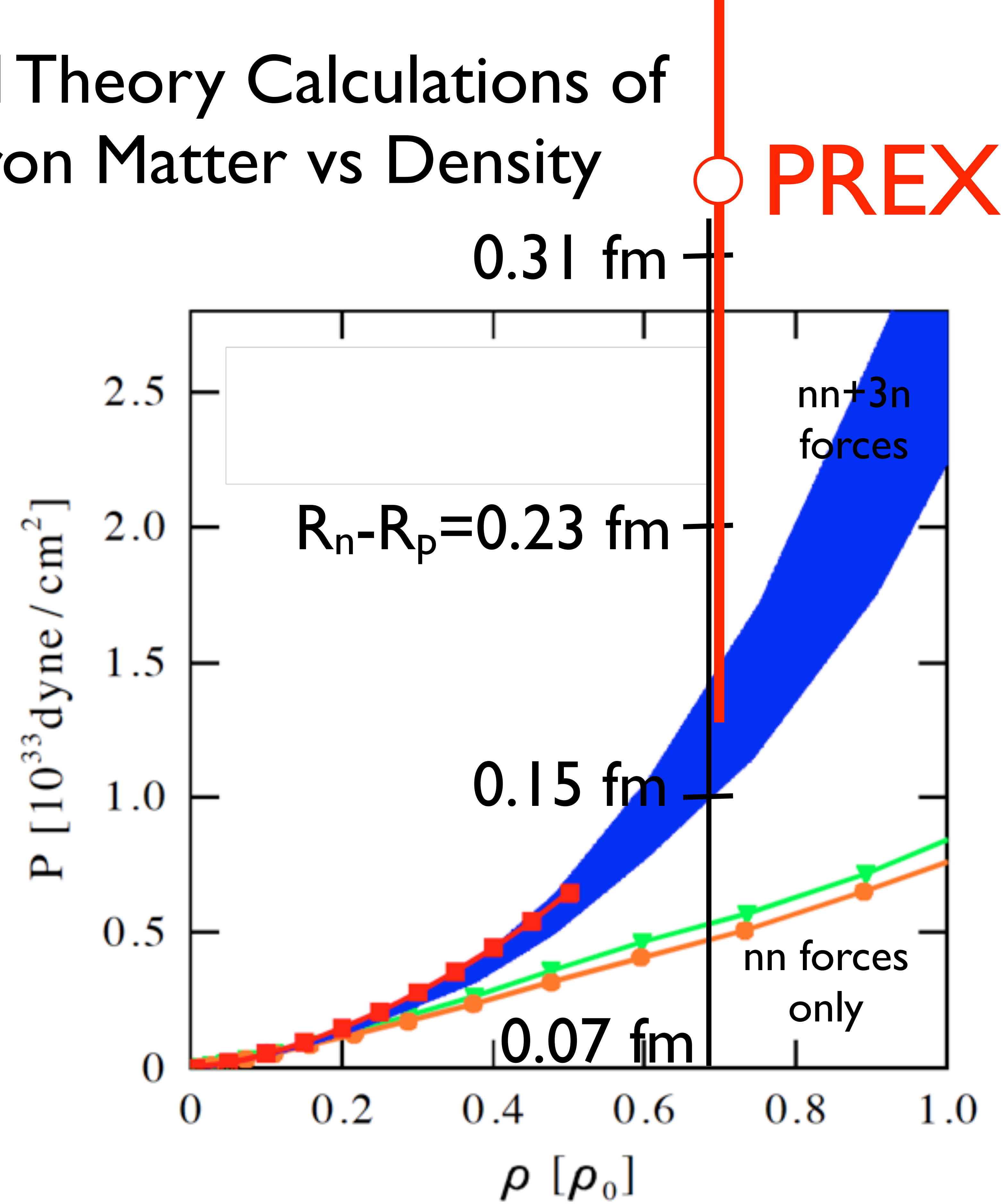
- Pressure of neutron matter forces neutrons out against surface tension. A large pressure gives a large neutron radius.
- Measuring R_n in ^{208}Pb constrains the pressure of neutron matter at $\sim 2/3\rho_0 = 0.1\ fm^{-3}$.



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

Chiral Effective Field Theory Calculations of Pressure of Neutron Matter vs Density

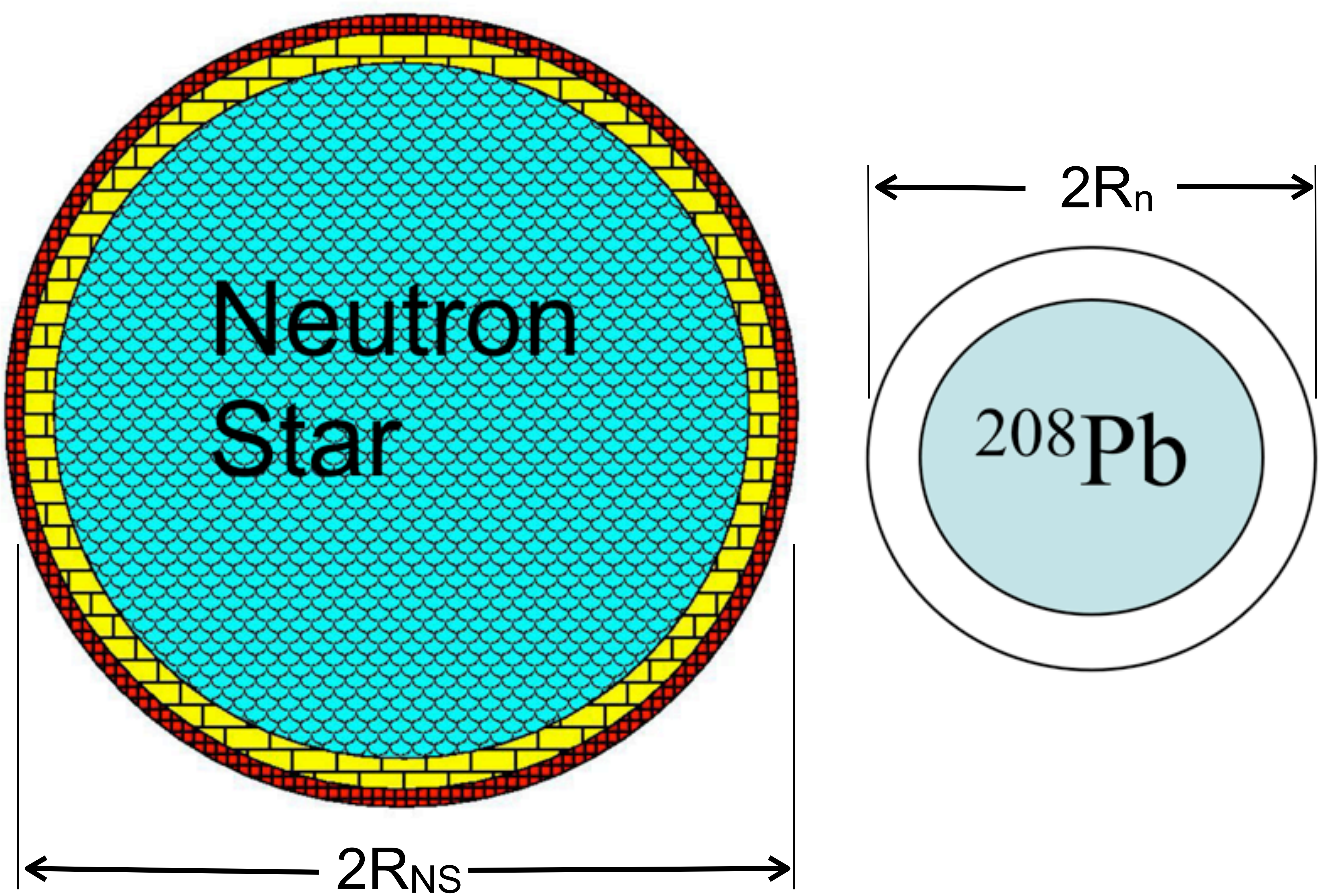
- A. Brown found strong correlation between pressure of neutron matter at a density of $0.66\rho_0$ and R_n-R_p in ^{208}Pb (see vertical black scale)
- Chiral EFT calc. by Hebeler et al. with only two n forces are green and brown while blue band shows results including 3 neutron forces. PRL **105**, 161102 (2010)
- PREX agrees with results including 3n forces. Hebeler et al. predict R_n-R_p=0.14 to 0.2 fm.



A Neutron Star is Newton's 10 km Apple

- In astrophysics and in the laboratory it is the same neutrons, the same strong interactions, the same neutron rich matter, and the same equation of state. A measurement in one domain has important implications in the other domain.

Neutron Star radius versus ^{208}Pb Radius



Observing Neutron Star Radii, Masses

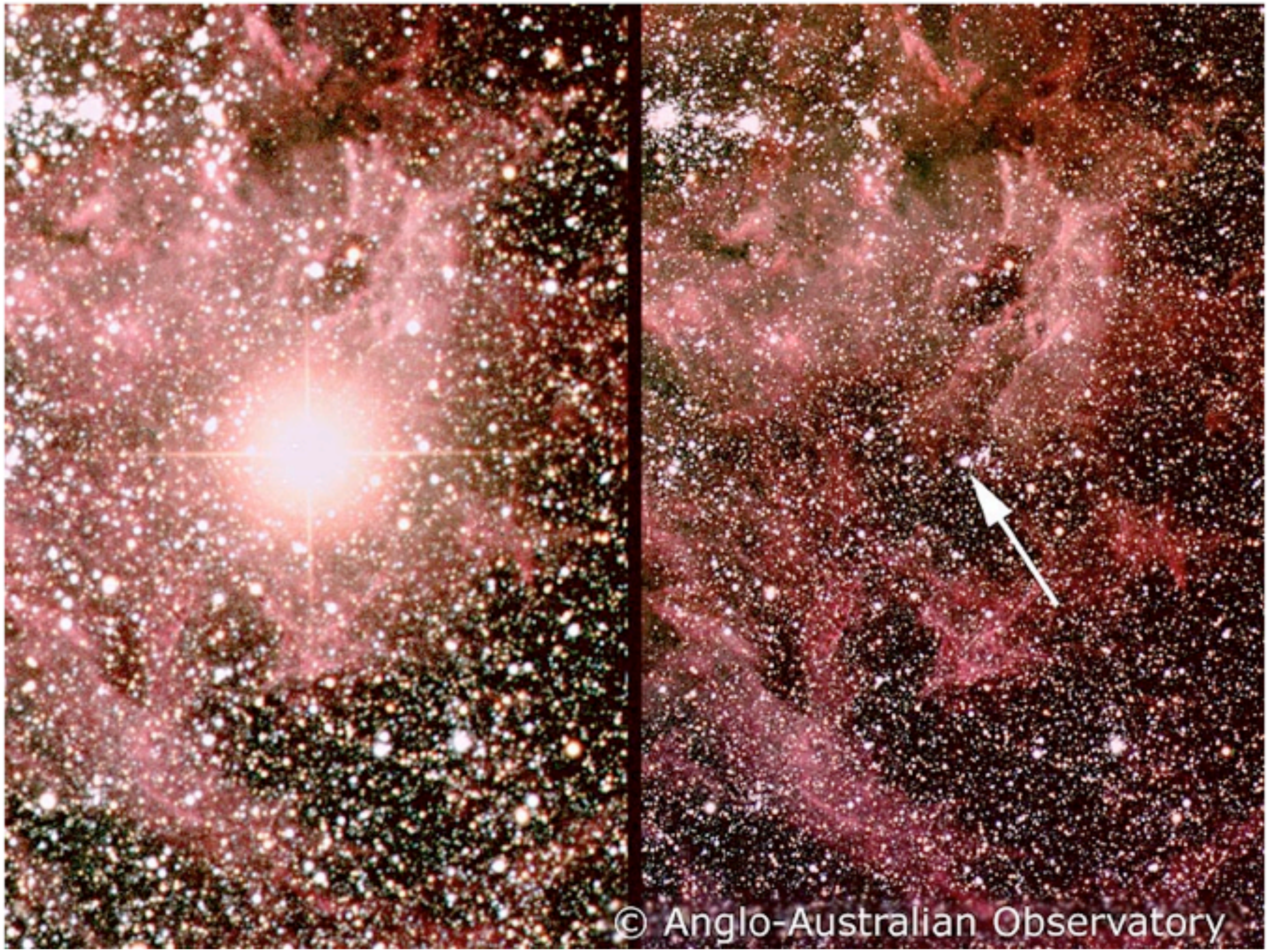
- Deduce surface area from luminosity, temperature from X-ray spectrum.

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

- Complications:
  - 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: 1005.0811] combine observations of NS in X-Ray bursts and globular clusters and deduce
  - 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.
  - PREX R_n-R_p=0.34 +.15 -.17 fm

- Important to test this model dependent extraction of EOS with accurate PREX measurement.
  - Depends on assumptions about X-ray bursts.
  - F. Ozel et al. get ~10 km radius.
- 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.
- Real progress on EOS of cold dense matter is being made with astro-physical observations.

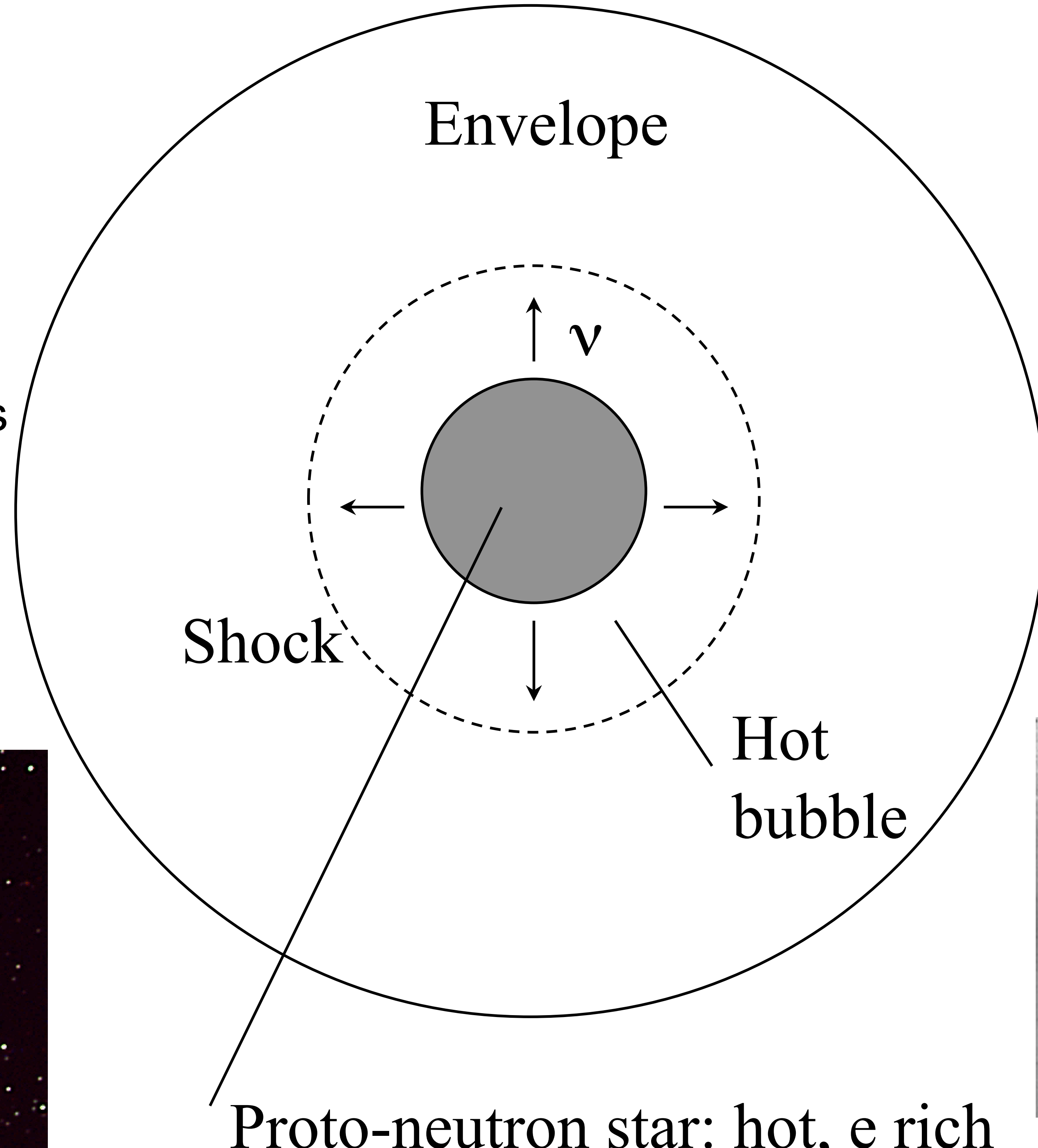
Supernova neutrinos and neutron rich matter



SN1987A

Core Collapse Supernova

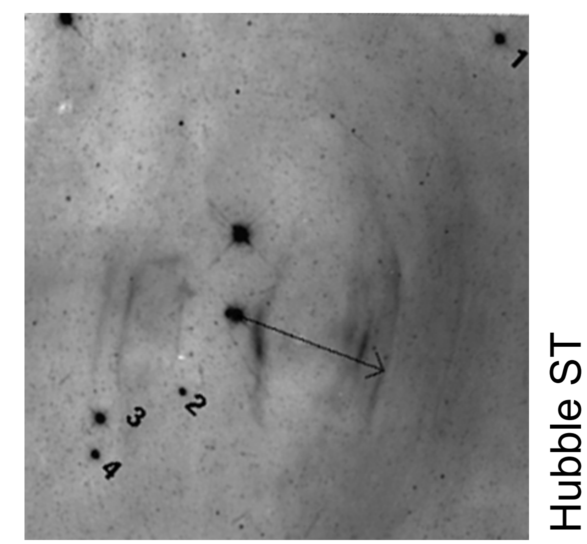
Core of massive star collapses to form proto-neutron star. νs form neutron star energizes shock that ejects outer 90% of star.



July 5, 1054

Crab nebula

Crab Pulsar



Supernova: conversion of up to $0.2M_{sun}c^2$ into 10^{58} neutrinos.

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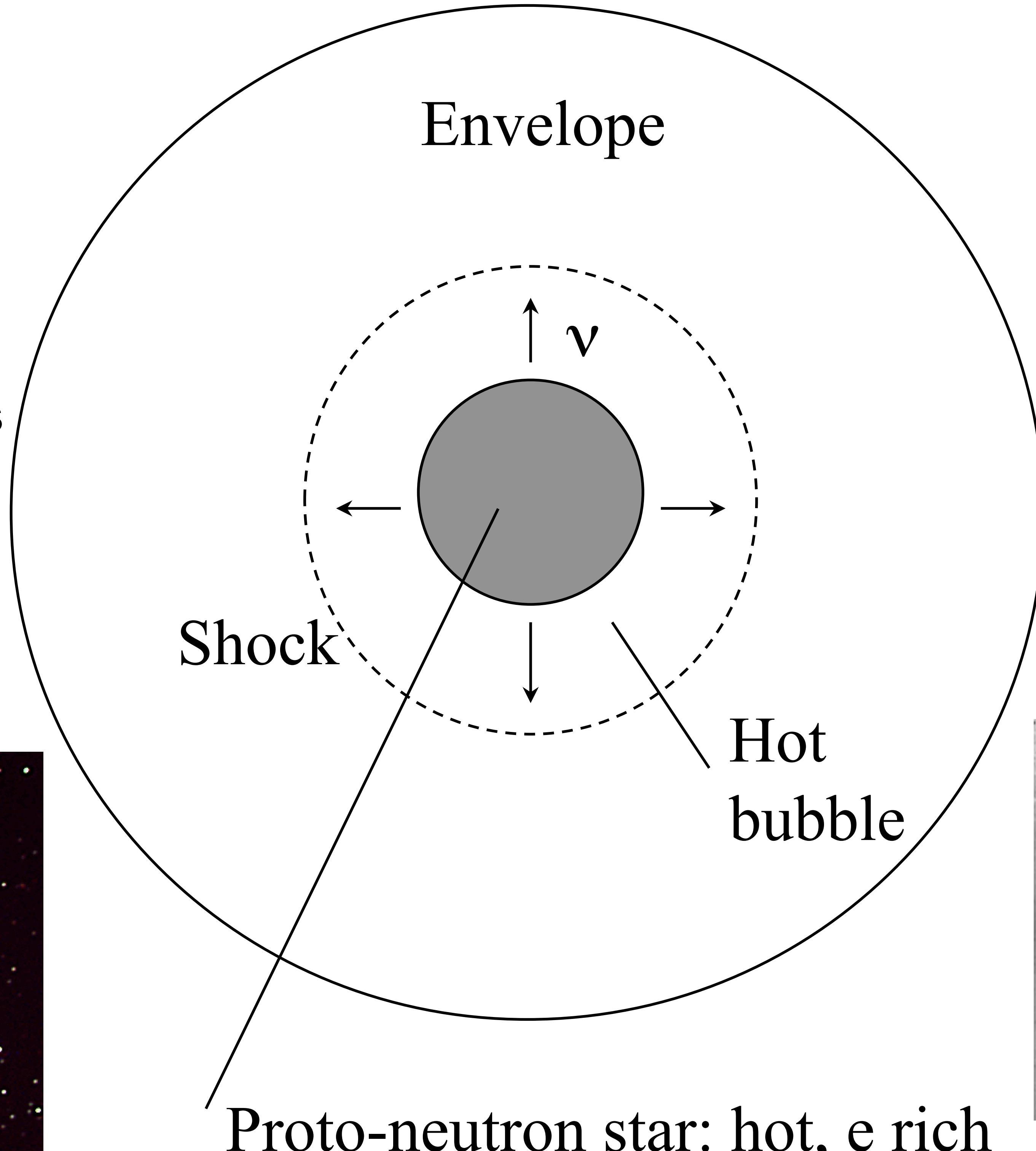

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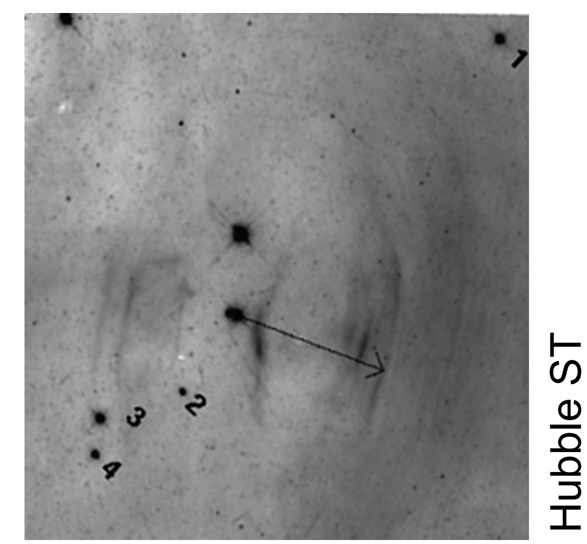

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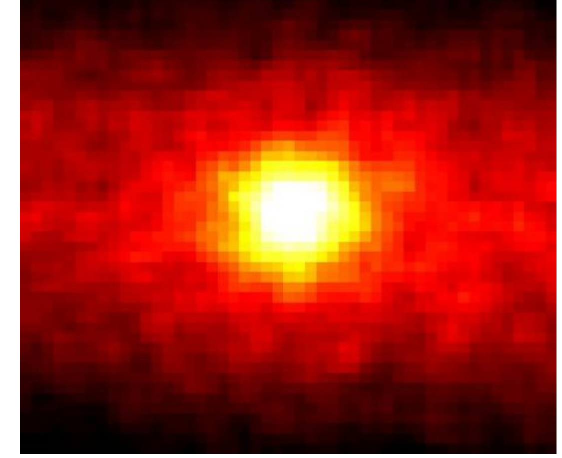
Neutrino probes of neutron-rich matter



Sun in neutrinos

- New underground dark matter, solar nu,... experiments will be very sensitive to nu from the next galactic supernova (SN).
  - About 20 neutrino events from SN1987a.
  - Expect 10,000 + events from next galactic 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 nearly unitary gas can be described with a Virial expansion. [CJH, A. Schwenk, NPA**776**(2006)55]

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

Virial expansion for neutron matter

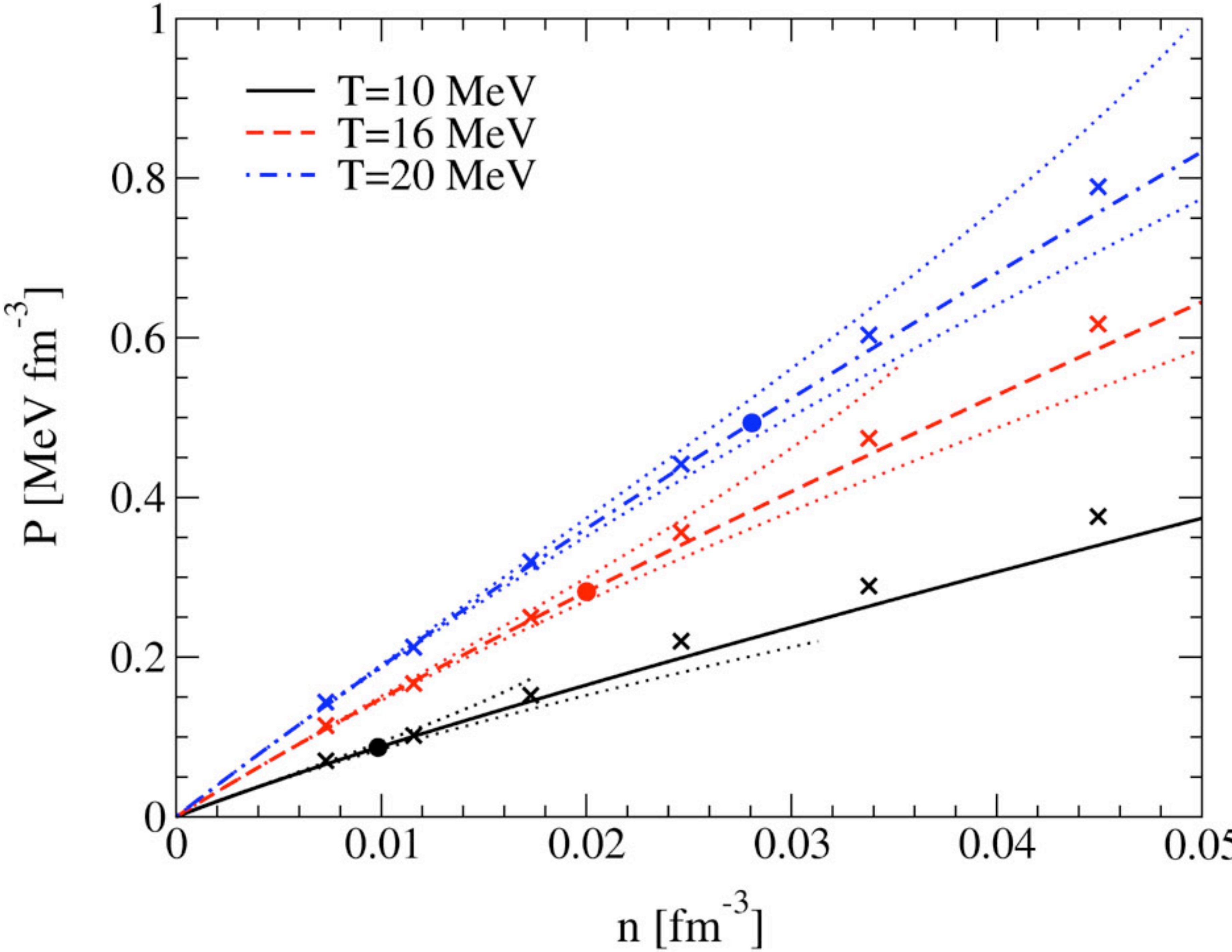
- Assume: system in gas phase and has not undergone a phase transition with increasing density or decreasing T and that the fugacity $z=e^{\mu/T}$ with μ the chemical pot is small.
- Expand pressure in powers of z :

  $P=2T/\lambda^3[z+b_2z^2+b_3z^3+\ldots]$,

  Here λ=thermal wavelength=$(2/mT)^{1/2}$
- 2^{nd} virial coef. $b_2(T)$ from 2 particle partition function which depends on density of states determined from phase shifts:

$$b_2 = 2^{1/2}\sum_B e^{E_B/T} + \frac{2^{1/2}}{\pi}\int_0^\infty dk\, e^{-E_k/2T}\sum_l (2l+1)d\delta_l(k)/dk \pm 2^{-5/2}$$

Neutron matter Equation of State



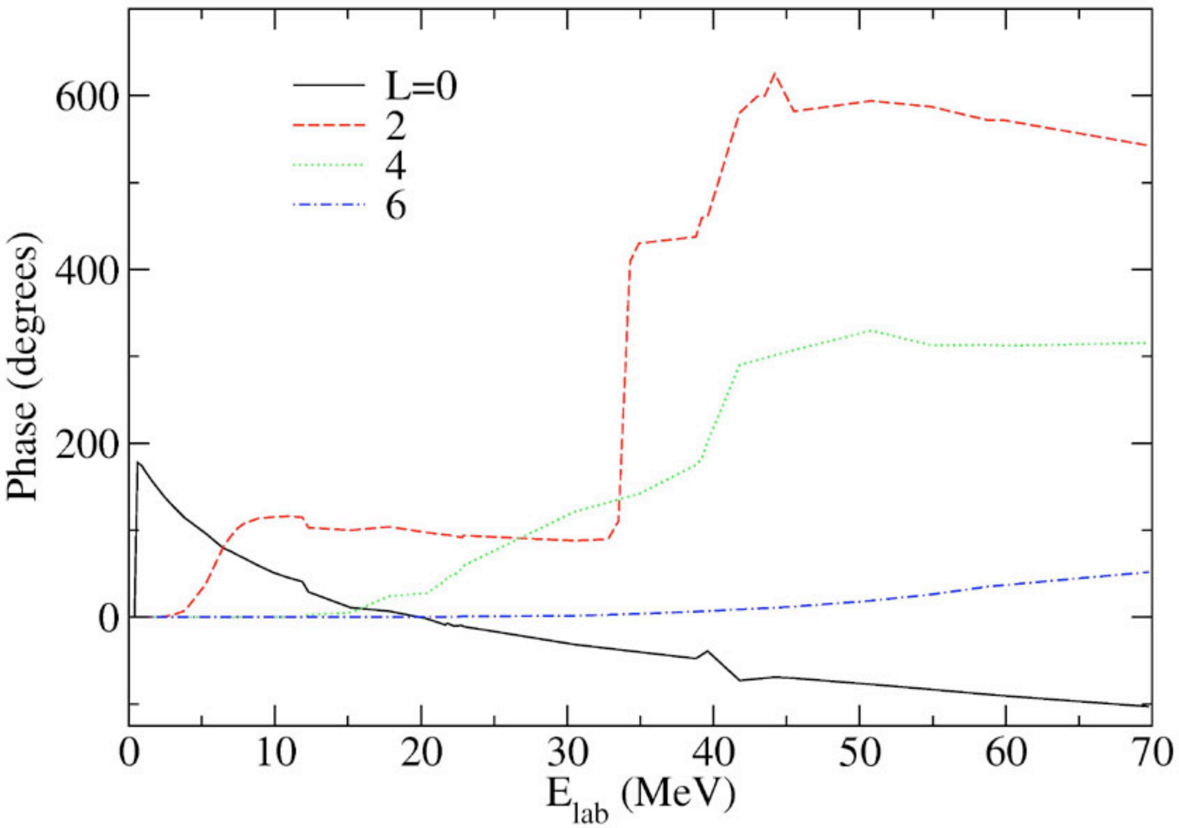
Error bars (dotted) from estimate of b_3

Crosses from microscopic FHNC calc. by Friedman + Pandharipande

Nuclear Matter: *n*, *p*, α system

$$\frac{P}{T} = \frac{2}{\lambda^3}[z_p + z_n + (z_n^2 + z_p^2)b_n + 2z_n z_p(b_{nuc} - b_n)] + \frac{1}{\lambda_\alpha^3}[z_\alpha + z_\alpha^2 b_\alpha + z_\alpha(z_p + z_n)b_{\alpha n}]$$

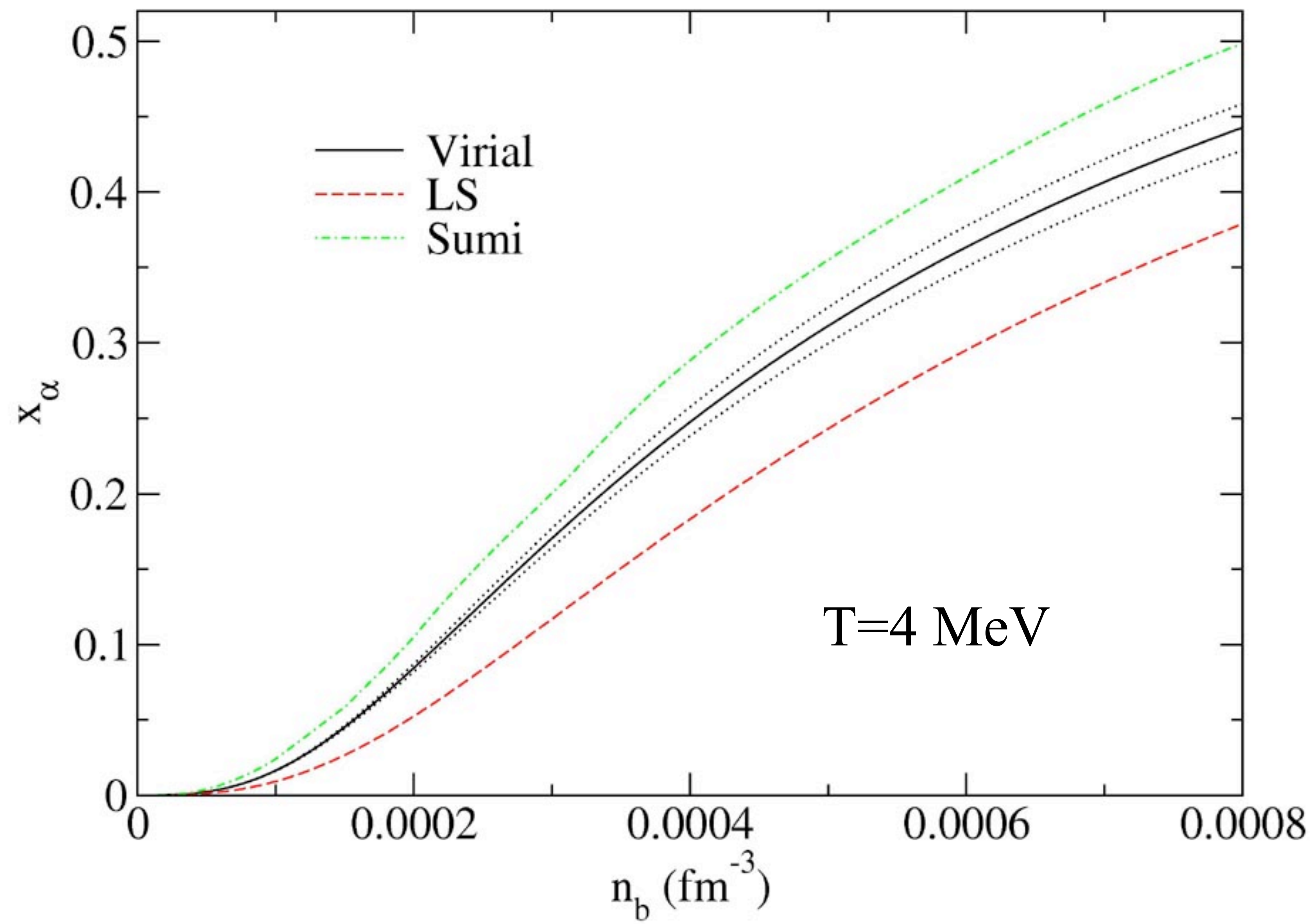
- Need four virial coefficients:
  - b_n for neutron matter,
  - b_{nuc} for symmetric nuclear matter,
  - b_α for alpha system,
  - $b_{\alpha n}$ for interaction between an α and N.
- Virials from NN, Nα and $\alpha\alpha$ elastic scattering phase shifts.



$\alpha-\alpha$ Elastic Phase Shifts

Nuclear Vapor has large α Fraction

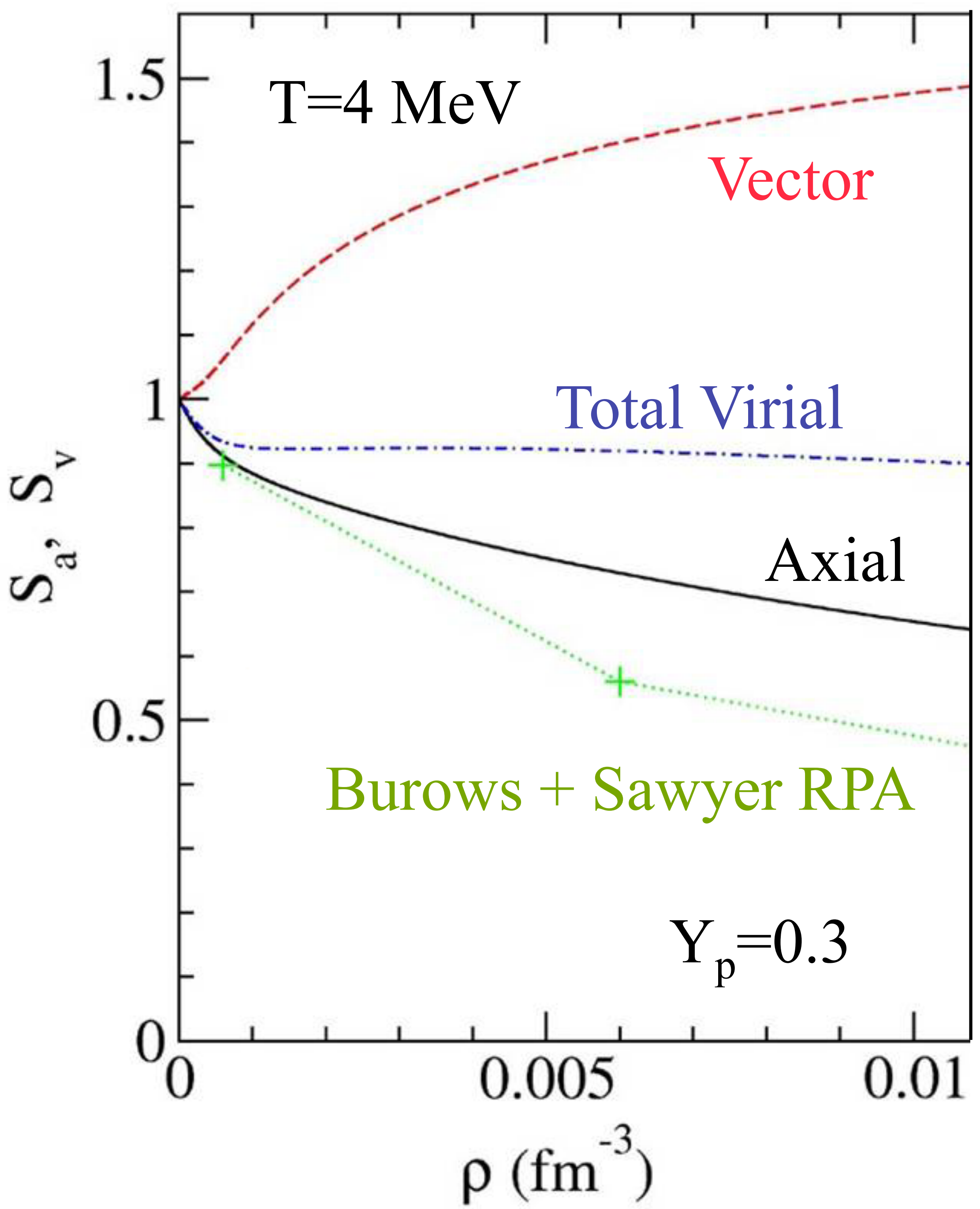
- α particle mass fraction in nuclear matter vs density.
- Virial expansion gives model independent compositions.
- Lattimer Swesty EOS is dashed.
- Sumi is an EOS based on a rel. mean field interaction (dot-dashed).



- Most SN simulations used LS EOS -- had error in alpha concentration

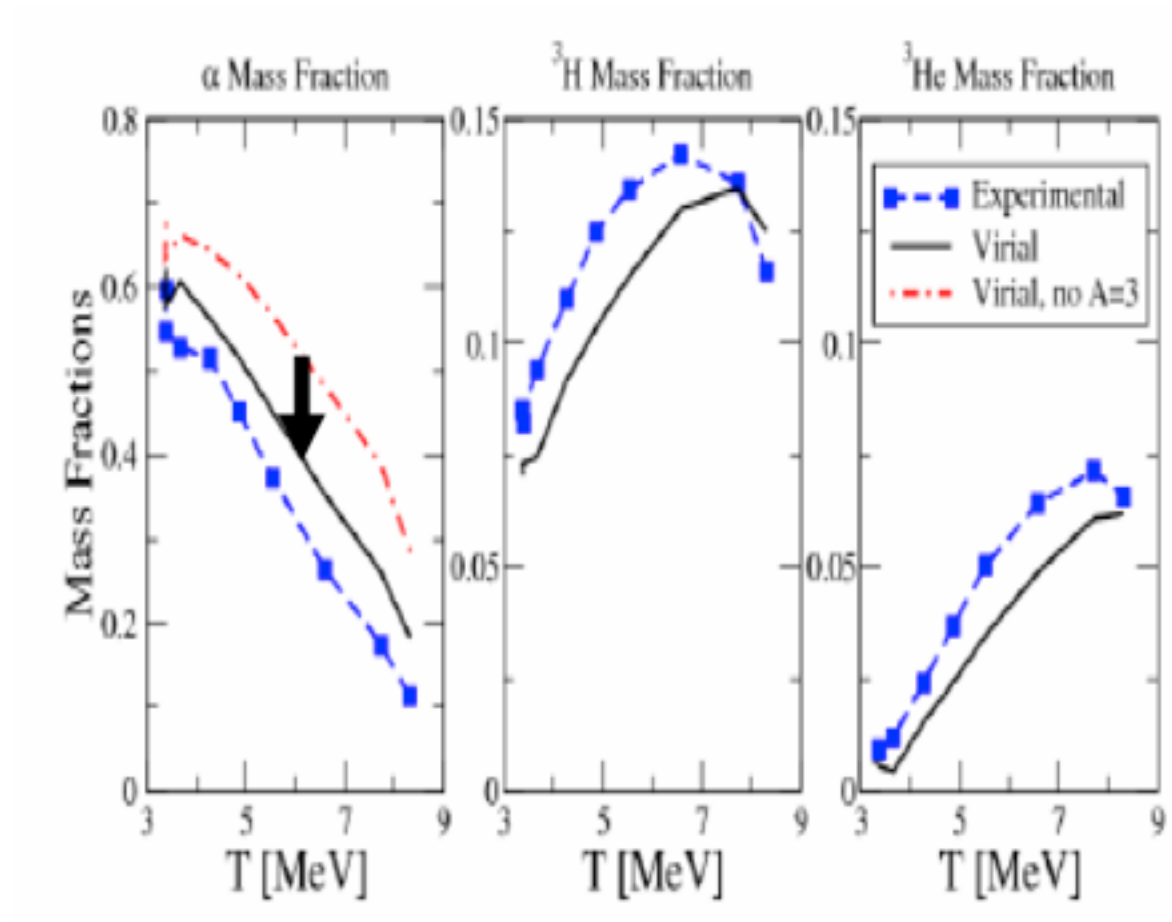
Neutrino Response

- ν neutral current cross section
  $d\sigma/d\Omega = (G^2E_\nu{}^2/16\pi^2)[$
  $(1+\cos\theta)S_v + g_a{}^2(3-\cos\theta)S_a\,]$
- Vector response is static structure factor $S_v=S(q)$ as $q\rightarrow 0$
  $S(0)=T/(dP/dn)$
- Axial or spin response from spin polarized matter.
  $S_a=(1/n)\, d/dz_a\, (n_+ - n_-)\, |_{n_+=n_-}$
- Typical RPA calculations neglect alpha particles.
- *Virial expansion provides model independent results for EOS, composition, and ν response of low density neutron rich matter.*

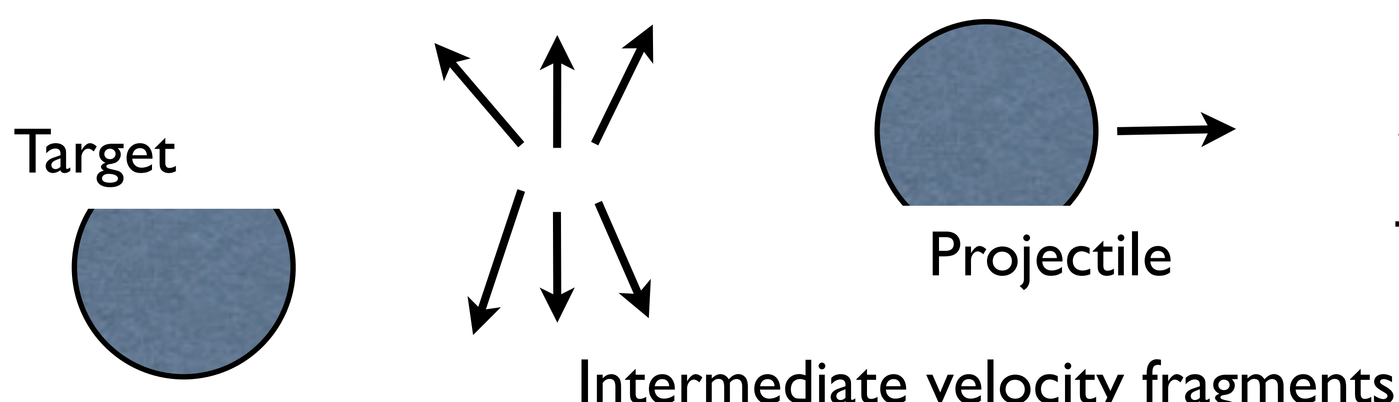


Recreating Neutrinosphere on Earth

- Neutrinos from neutrinosphere: warm, low density gas (T~4 MeV, ~10^{11} g/cm^3)
- Neutron rich system with some light nuclei ^{4}He, ^{3}He, ^{3}H... Light nuclei reduce anti-nu-e, but not nu-e, opacity--> important for ΔE.
- Can study neutrinosphere like conditions with heavy ion collisions in lab. and measure composition of light nuclei. [example J. Natowitz, Texas A&M]
- Neutron-neutron scattering length is very long--> nearly universal unitary gas. Can simulate neutrinosphere like systems with trapped cold atoms. Probe spin response important for neutrino interactions.



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.

Neutron Rich Matter and Supernovae

- 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.
  - First result: R_n-R_p(^{208}Pb)=0.34$^{+.15}_{-.17}$ fm.
  - This has implications for nuclear structure, astrophysics, and atomic parity violation.

- Supernova neutrinosphere described by Virial expansion: model independent EOS, composition, neutrino response.
- Collaborators: A. Schwenk, S. Ban, R. Michaels, J. Piekarewicz ... Students: L. Caballero, H. Dussan, J. Hughto, A. Schneider, and G. Shen.
- Supported in part by DOE and State of Indiana.