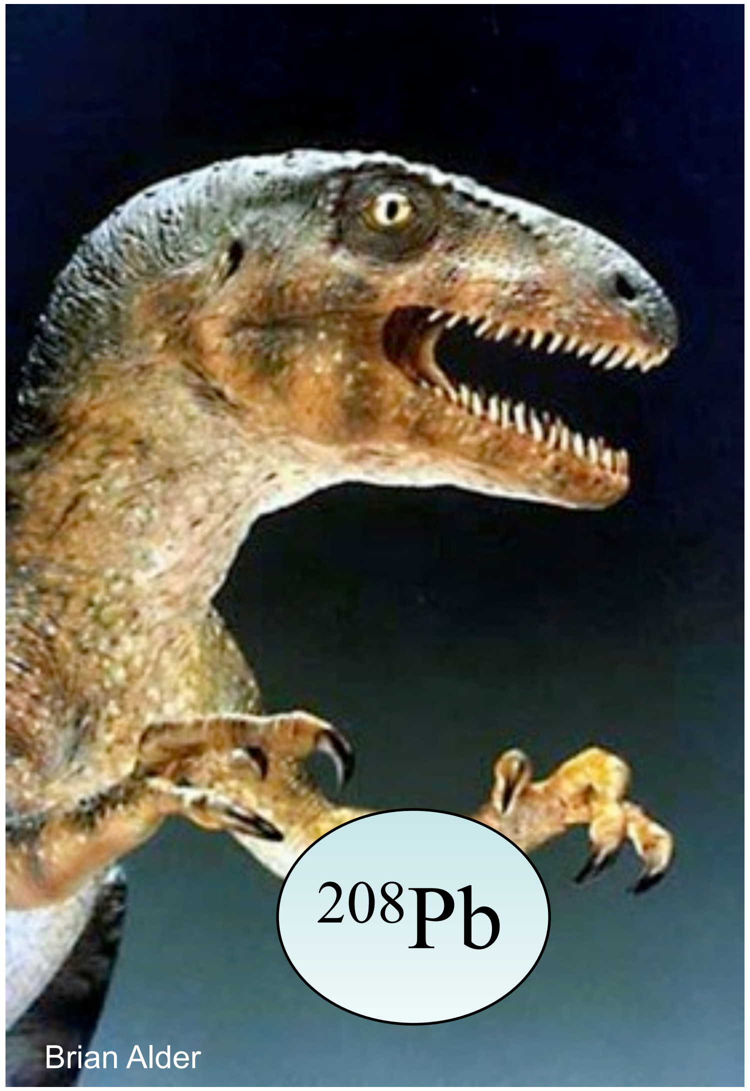
Multi-messenger observations of neutron rich matter



Introduction: neutron rich matter can be *probed* in many ways.

Laboratory: PREX at JLab uses parity vio. to measure neutron radius of ^{208}Pb.

Gravitational waves:

- Neutron star mergers and equation of state.
- NS mountains and crust strength.
- r-modes and shear/bulk viscosity.

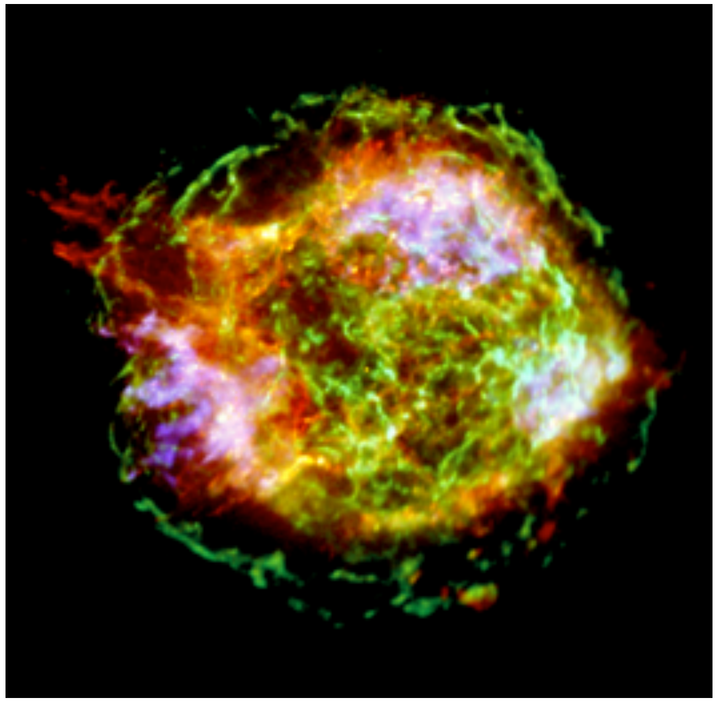
Supernova neutrinos:

- Importance for nucleosynthesis.
- Model independent EOS and neutrino opacities near neutrinosphere from virial expansion.

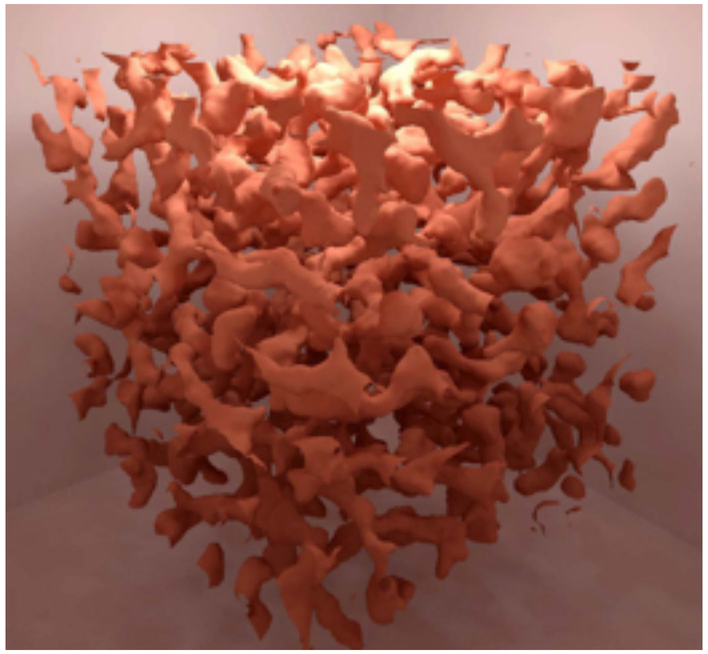
C. J. Horowitz, Indiana U., Core-Collapse Supernovae, INT, Jul. 2012

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 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...*
- *Review article: Multi-messenger observations of neutron rich matter, Int. J. Mod. Phys. E 20 (2011) 1.*



Supernova remanent
Cassiopea A in X-rays



MD simulation of Nuclear
Pasta with 100,000 nucleons

Laboratory probe of neutron rich matter

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

- *Electroweak reaction is free from most strong interaction uncertainties.*

- 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, -1.

--> Weak interactions, at low Q^2, probe neutrons.

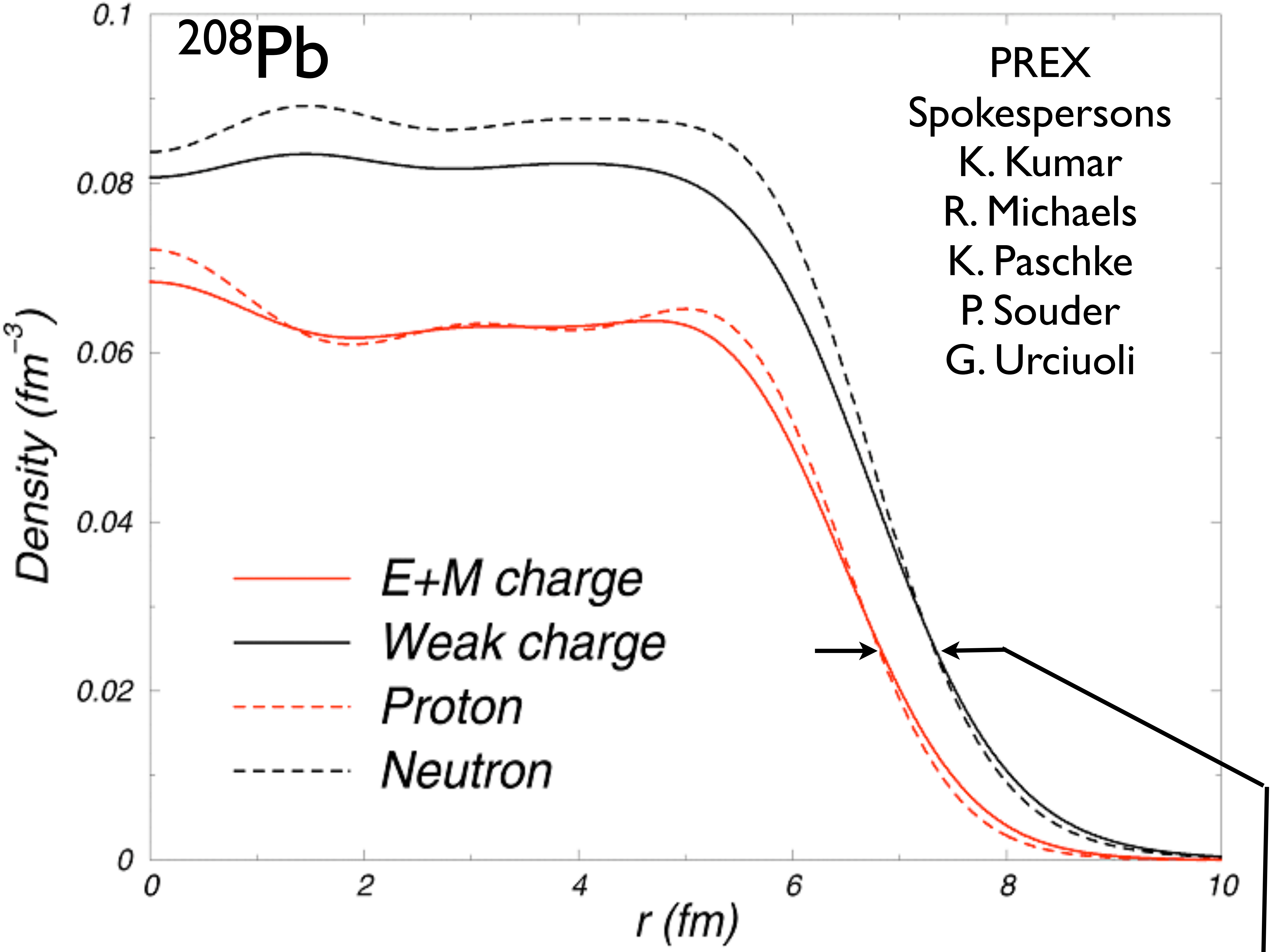
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

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

For 1 GeV e scattering at ~5 deg, A_{pv} ~ 0.5ppm

PREX History

- Electron scattering workshop, INT 1997

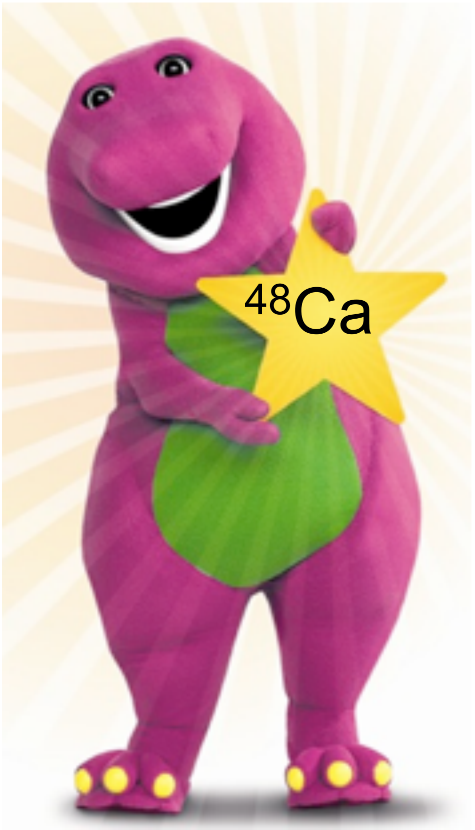


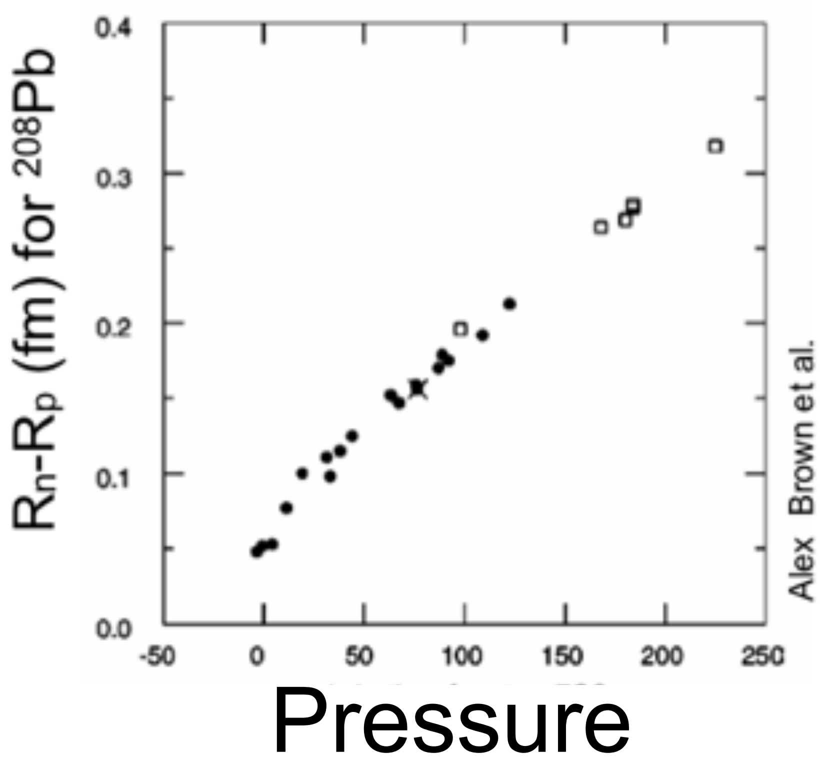
PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

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

PREX measurements

- PREX-I: A_{PV}=0.66±0.06(stat)±0.014 (sys) ppm --> $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- PREX-II (approved for 25 days) Run ^{208}Pb again to accumulate more statistics. Goal: R_n to 1%, ±0.06 fm.
- CREX: ^{48}Ca conditionally approved.
  - Microscopic coupled cluster and no-core shell model calculations can directly relate R_n (^{48}Ca) to three neutron forces.
  - Goal: R_n to ±0.03 fm.
- Implications of ^{208}Pb neutron radius. Pressure forces neutrons out against surface tension. Alex Brown finds correlation between R_n in ^{208}Pb and P of neutron matter at 2/3 nuclear density.

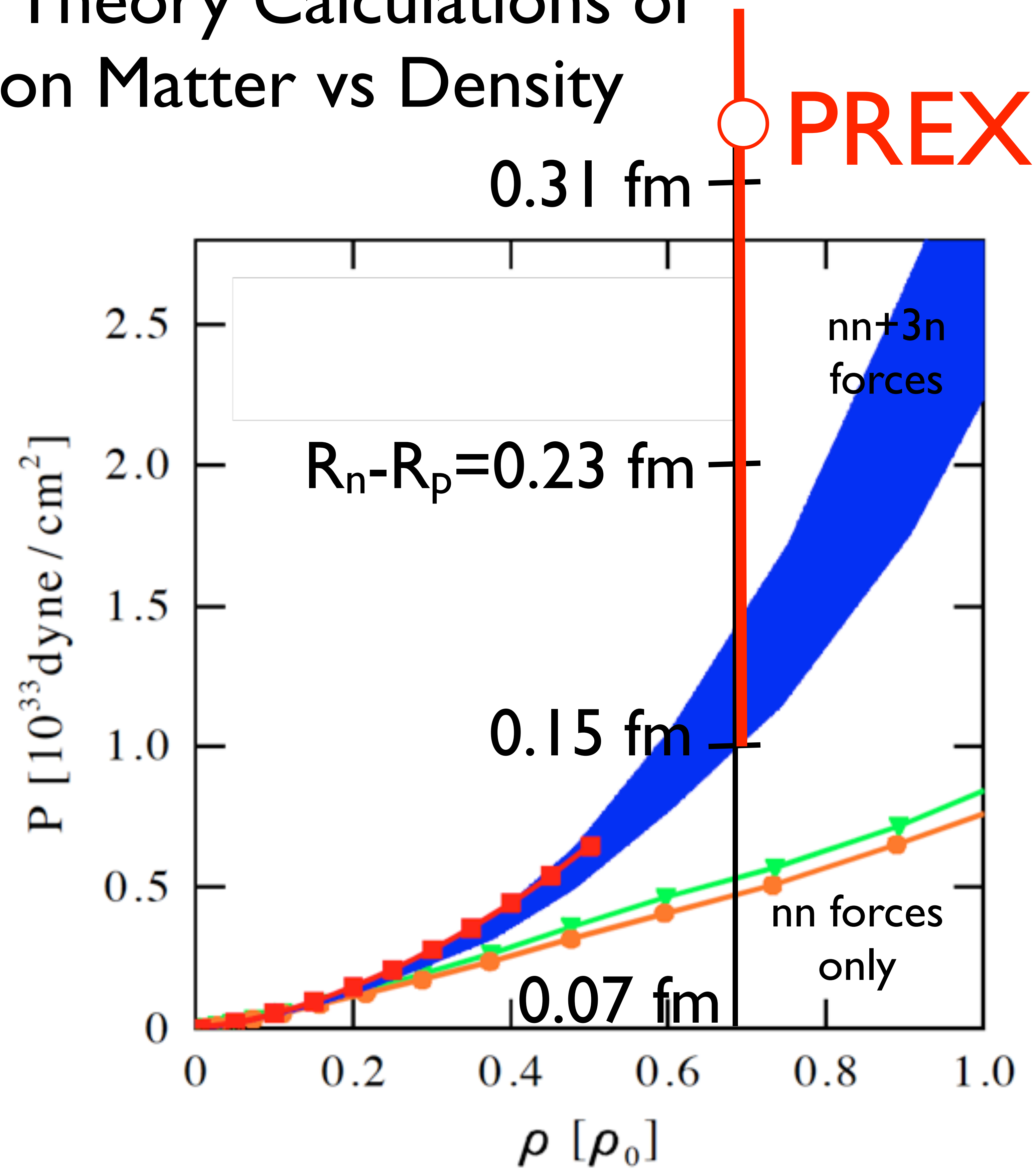




Chiral Effective Field Theory Calculations of Pressure of Neutron Matter vs Density

- Chiral EFT calc. of pressure of neutron matter by Hebeler et al. including three *neutron* forces (blue band) PRL**105**, 161102 (2010)

- PREX agrees with results including 3n forces. Three *neutron* forces are very interesting, unconstrained. Some information on 3 *nucleon* forces in ^{3}H, ^{3}He...

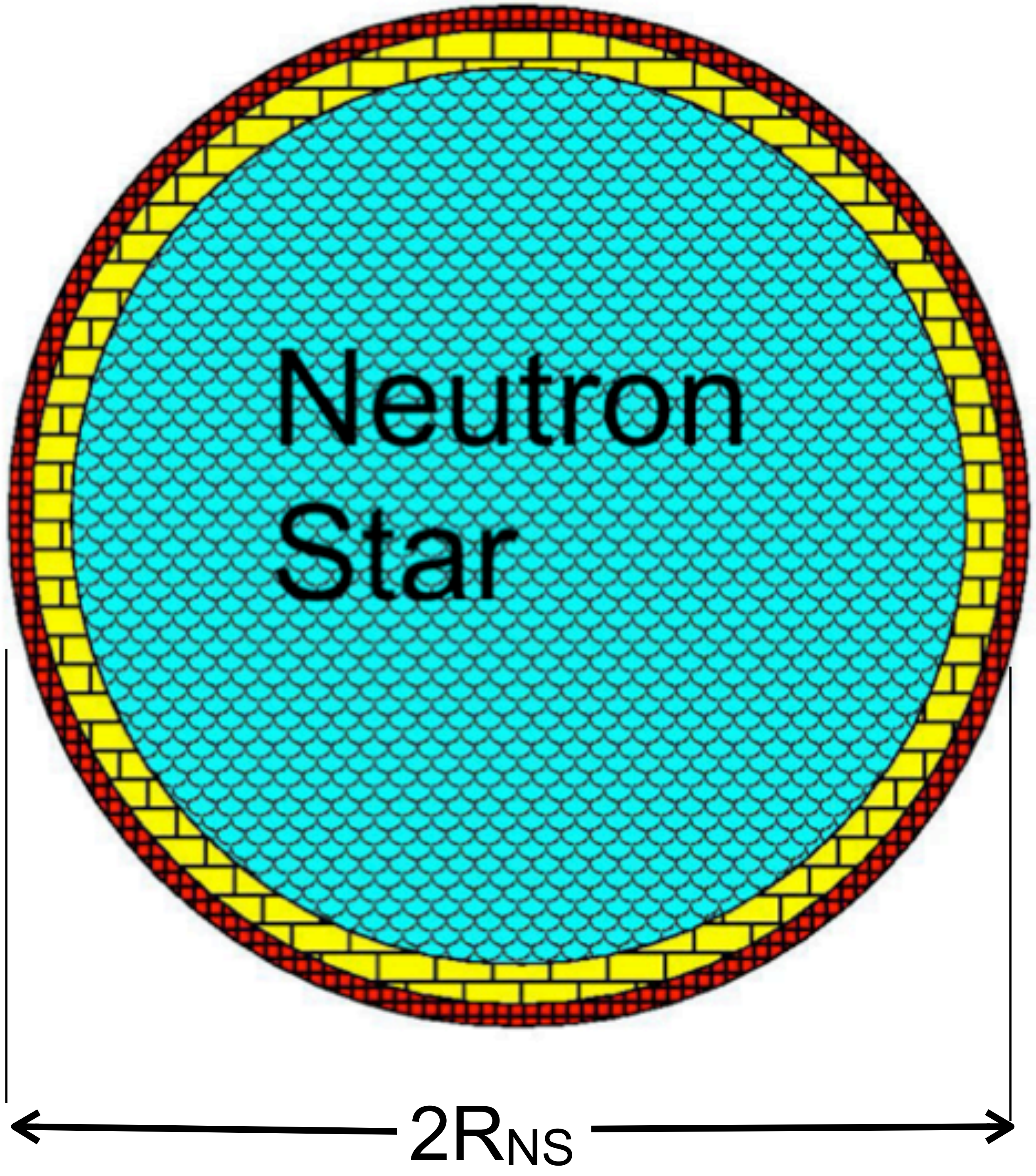


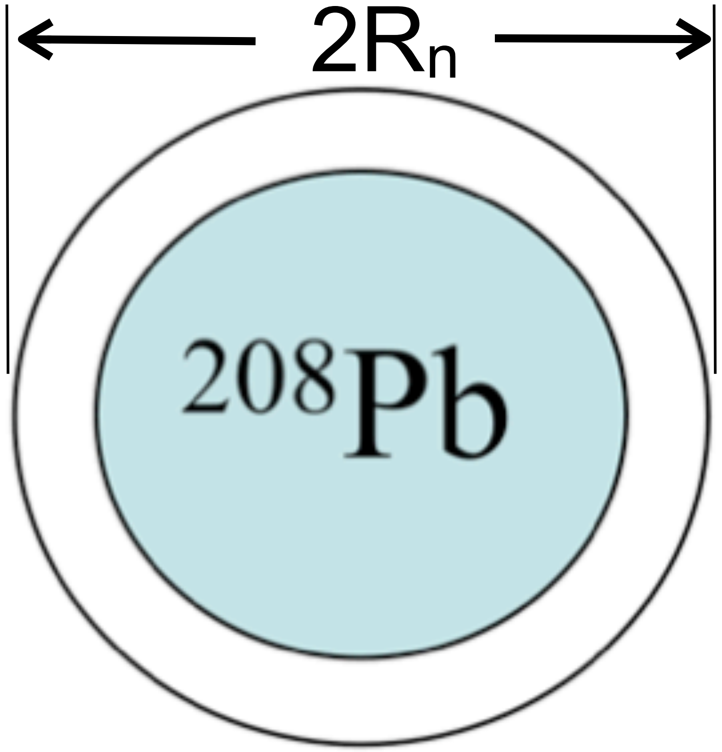
Both lab and heavens made of same “stuff”

- For Newton the stuff was mass. In 19th century it was chemical elements. Observation that spectral lines are the same in lab and in space created astrophysics.
- Today the stuff is neutron rich matter. In astrophysics and in the laboratory it has the same neutrons, the same strong interactions, and the same equation of state.
- A measurement in one domain (astronomy or the lab) has important implications in the other domain.

Neutron Star radius vs ^{208}Pb Radius

^{208}Pb radius depends on pressure near nuclear density. NS radius depends on pressure at nuclear density and above. Look for strong density dependence of EOS, could signal phase transition.

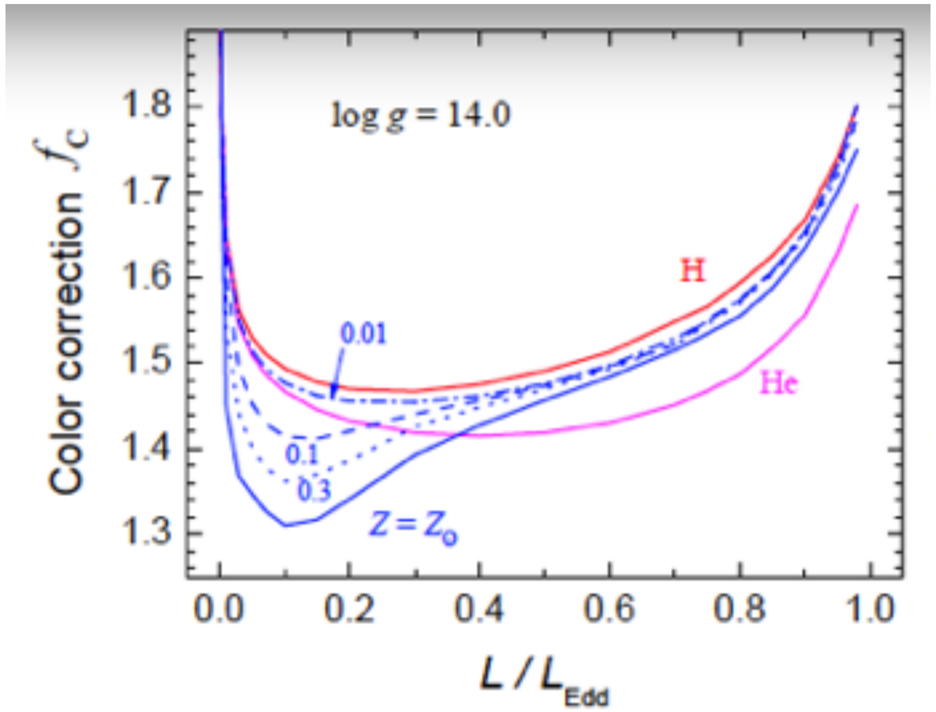




Present NS radius measurements have important uncer. from atmosphere model, X-ray burst model...

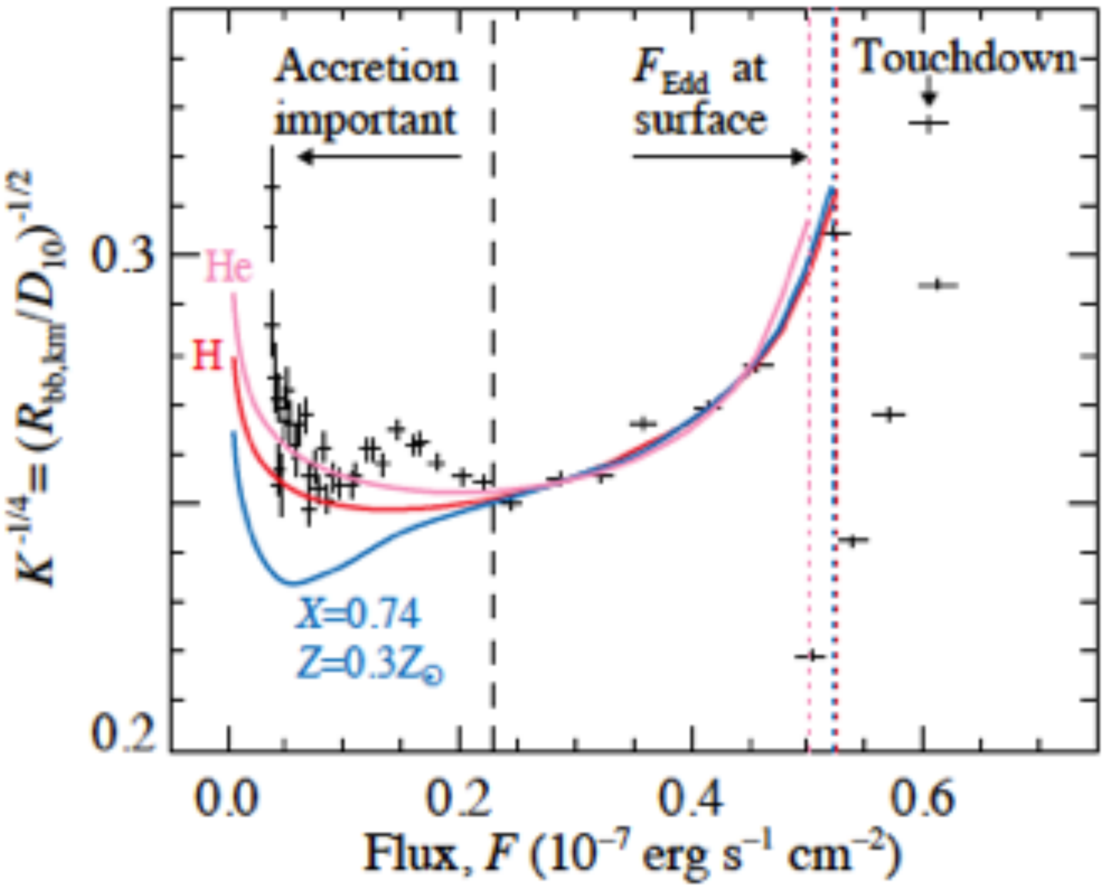
Model atmospheres of X-ray bursting neutron stars

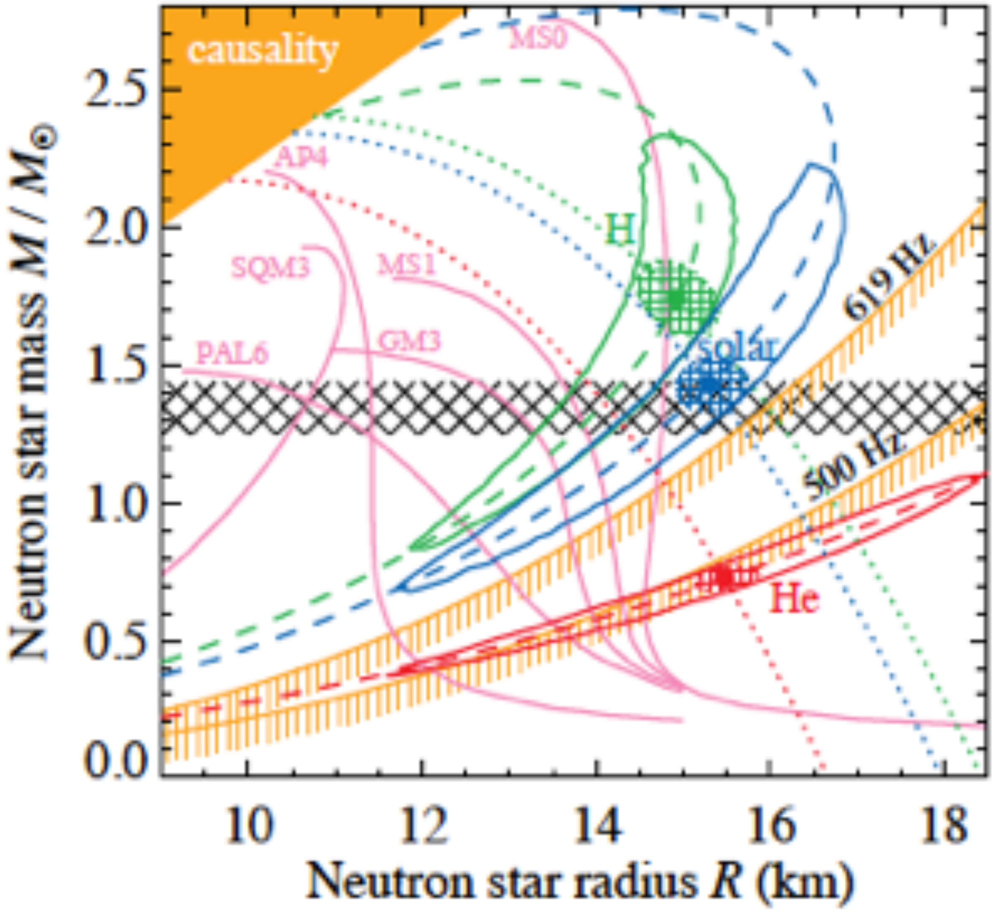
V. Suleimanov[*,†], J. Poutanen[**], M. Revnivtsev[‡] and K. Werner[*]



Model atmospheres determine non-black body correction f_C. This depends on luminosity and composition. Apply to 4U 1724-307 and find large ~15 km radius.

- arXiv:1010.0151



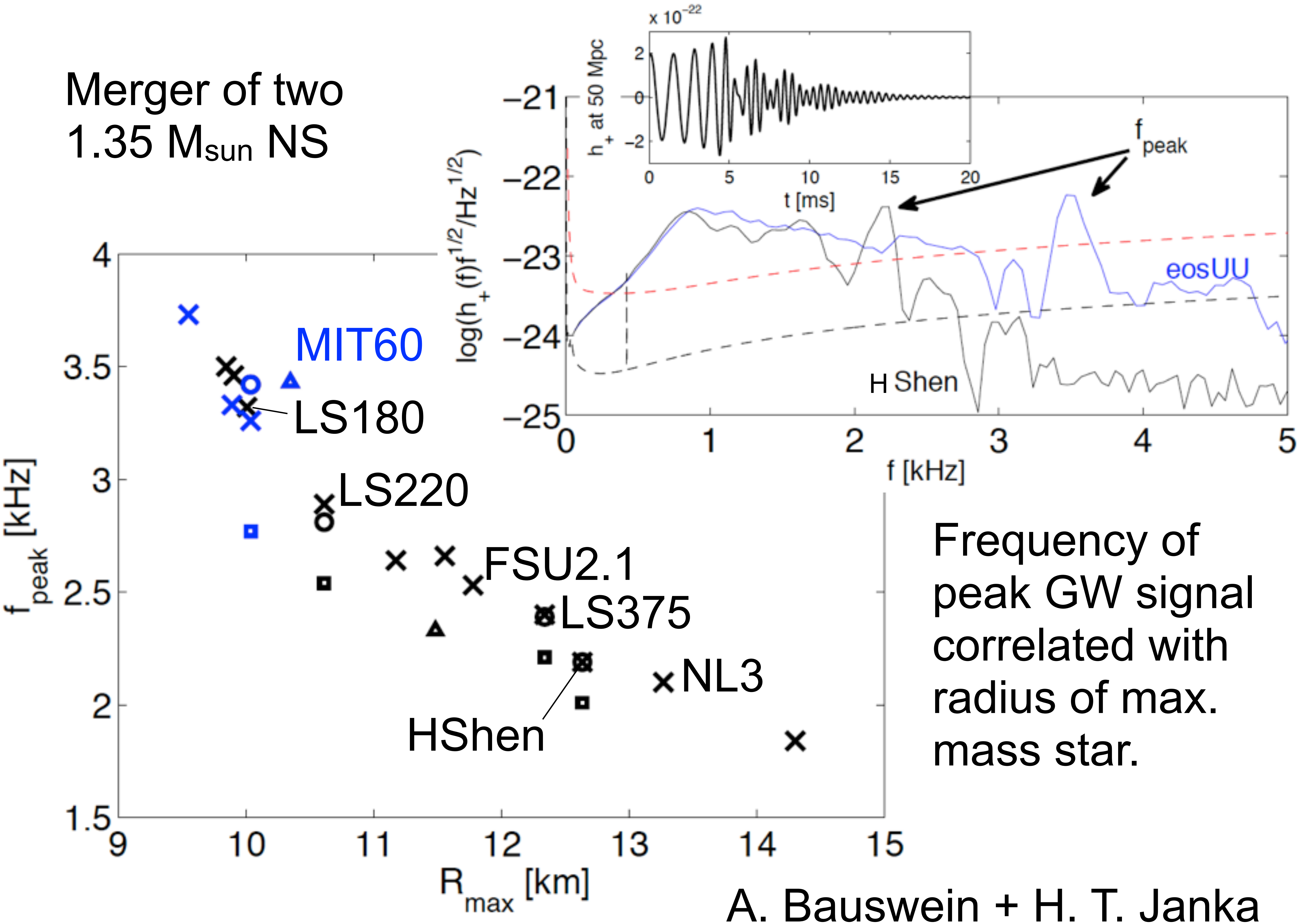


Gravitational Waves and neutron rich matter

- Data analysis groups: modeled bursts such as NS mergers (and EOS).
- Un-modeled bursts such as Magnetar giant flares?
- Continuous GW signals from mountains (mechanical properties: shear modulus/ breaking strain) or collective r-modes (shear and bulk viscosities).

Gravitational Waves from NS mergers and EOS

Merger of two
1.35 M_{sun} NS



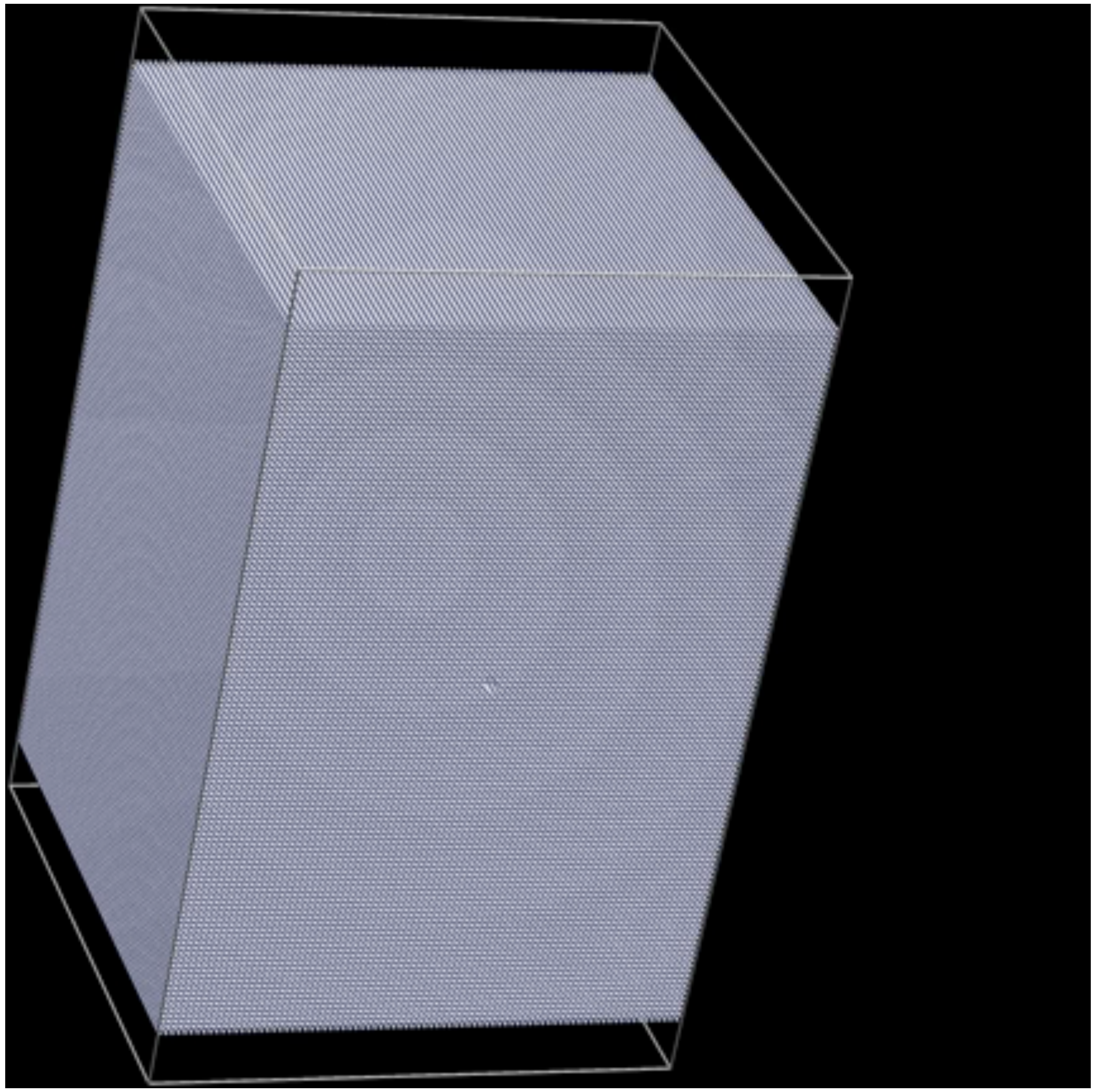
Frequency of peak GW signal correlated with radius of max. mass star.

A. Bauswein + H. T. Janka

Gravitational Waves from NS mountains

- A mountain on a rapidly rotating NS efficiently radiates GW.
- Maximum size of a mountain depends on strength of neutron star (NS) crust.
- We perform large scale MD simulations of the crust breaking including effects of defects, impurities, and grain boundaries...
- We find NS crust is strongest material known: *10^{10} times stronger than steel.* It can support few cm tall mountains!
- Ongoing and near future searches for weak continuous GW signals by coherently integrating for long times. Computationally very intensive!
- Our strong crust can support ellipticities $\epsilon=(I_1-I_2)/I_3$ up to 10^{-5}, best observations now $< 10^{-7}$ so mountains are detectable!

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

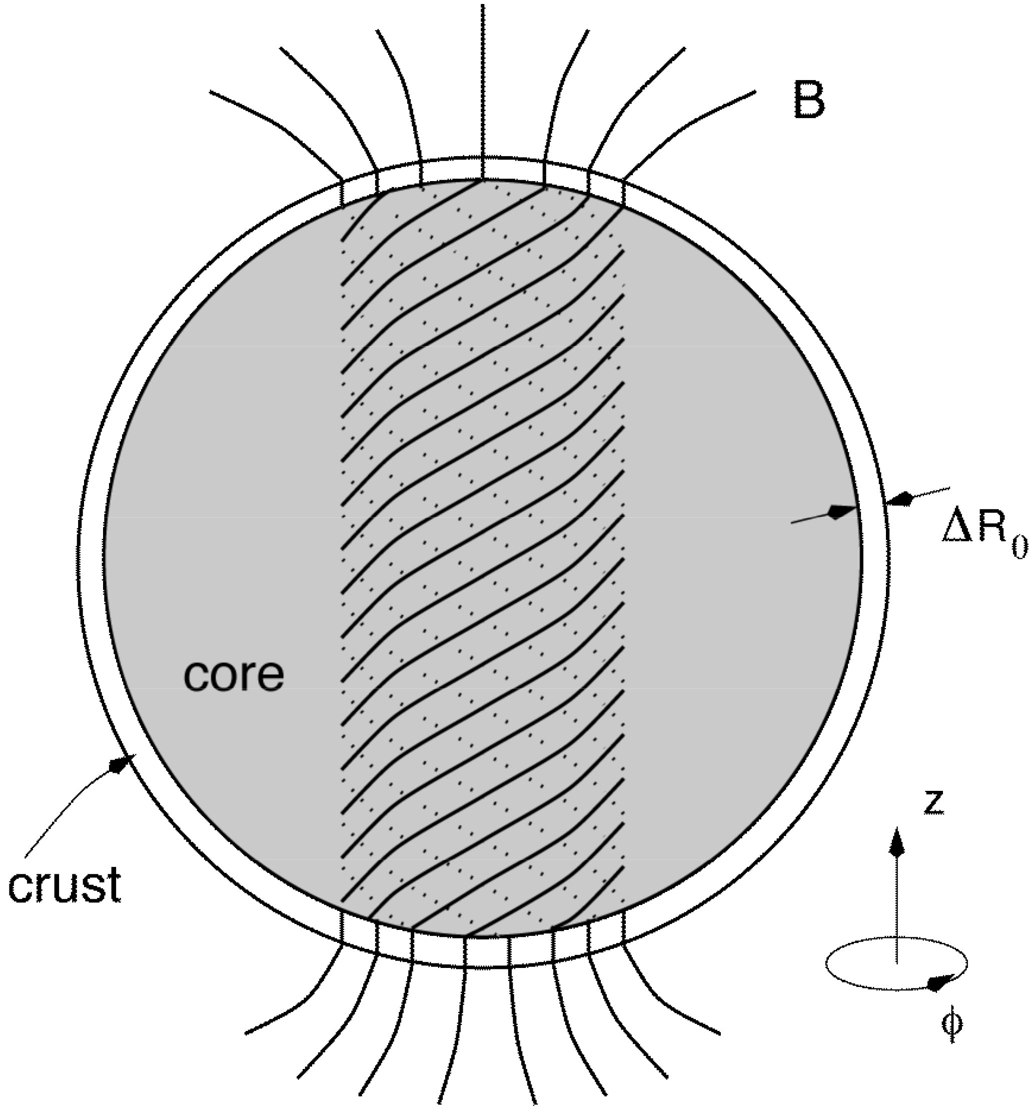


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

Crust breaking and Magnetar Flares

- Crust breaking likely associated with giant flares. Twisted B field breaks crust allowing magnetic field to reconnect (or field reconnects and breaks crust.)
- ***Very strong crust helps explain very large giant flare energies.***
- Further work on crust breaking:
  - How old are the hills? With A. Chugonov fit phenomenological model of breaking to simulation results and extrapolate model to very long times. Within model, mountains can last a long time.
  - Include strong B field in simulations: Joe Hughto.
  - Breaking strain of nuclear pasta: Andre Schneider.

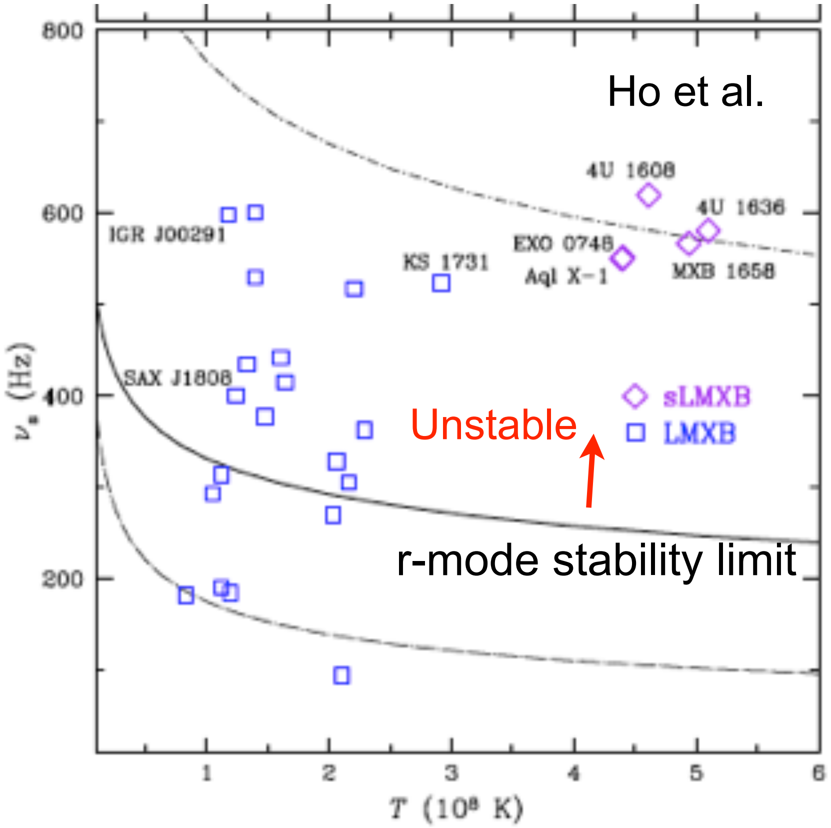
SGR 1806-20 on 27 Dec 2004 radiated ~ 4×10^{46} erg of gamma rays in 0.2 sec.



Thompson + Duncan

Rapidly rotating NS and r-modes

- r-modes: class of oscillation where restoring force is Coriolis force. May be unstable to GW radiation.
- GW radiation from r-modes potentially observable in LIGO.
- r-mode unstable if rate energy gained from GW radiation (tapping rotational E) greater than rate E lost from shear and bulk viscosities.
- Many calculations of **shear viscosity** of neutron rich matter, nuclear pasta (complex shapes), crust core boundary layer... and **bulk viscosity** of neutron rich matter, hyperons, quark matter,...
- *Dissipation from all of these sources does not appear to be enough.*



- **r-mode problem:** many observed NS are rotating so fast (above solid line) that they appear to be unstable to r-mode oscillations that would likely rapidly spin them down. --- Ho, Andersson, Haskell, PRL**107,** 101101(2011).

Dark matter in neutron stars

- If dark matter is weakly interacting massive particles (WIMPs) they will collect in neutron stars.
- Shear viscosity η_W of WIMP gas of density n_W is

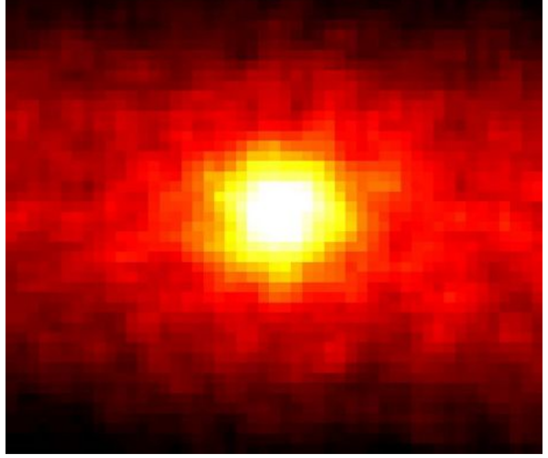
$$\eta_W = \frac{1}{3}(3kTM_W)^{1/2}\lambda_W n_W$$

- WIMP-nucleon cross sections near present CDMS, XENON100 exp. limits may allow WIMP mean free path λ_W < size of star.
- η_W will exceed shear viscosity of conventional neutron rich matter if the number fraction of WIMPS to baryons $X_W = n_W/n_B > 10^{-10}$.

- *We speculate that WIMPs may enhance shear viscosity enough to solve r-mode problem.*
- Observations of NS spins may provide indirect information on dark matter.
  - Young NS with little dark matter unstable to r-modes can't spin fast
  - Old stars with more dark matter can spin fast. Indeed many old millisecond pulsars.
  - NS may be able to spin fastest in regions of galaxy with high dark matter density. Indeed fastest known NS near galactic center.

--- ArXiv:1205.3541

Neutrino probes of neutron-rich matter


Sun in neutrinos

- Supernova neutrinos carry unique flavor information (some what complicated by oscillations) that may be closely related to nucleosyntheis.
- 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 neutrino-sphere region. This gas phase can be described with a Virial expansion [CJH, A. Schwenk, NPA**776**(2006)55] and studied in the lab with HI collisions.

Total Energy in Neutrinos

- Binding E of neutron star ~ 3/5 GM^2/R is observable!
- If all else fails, gives distance to SN. I will assume distance known from E+M observations.
- If E large, big astrophysics implications: made massive and or very small object.
- If E small, big particle physics implications: new particles are carrying some of the energy.
- If E ~ correct: gives mass of neutron star. Neutron star mass important diagnostic for explosion mechanism and mass cut for nucleosynthesis.

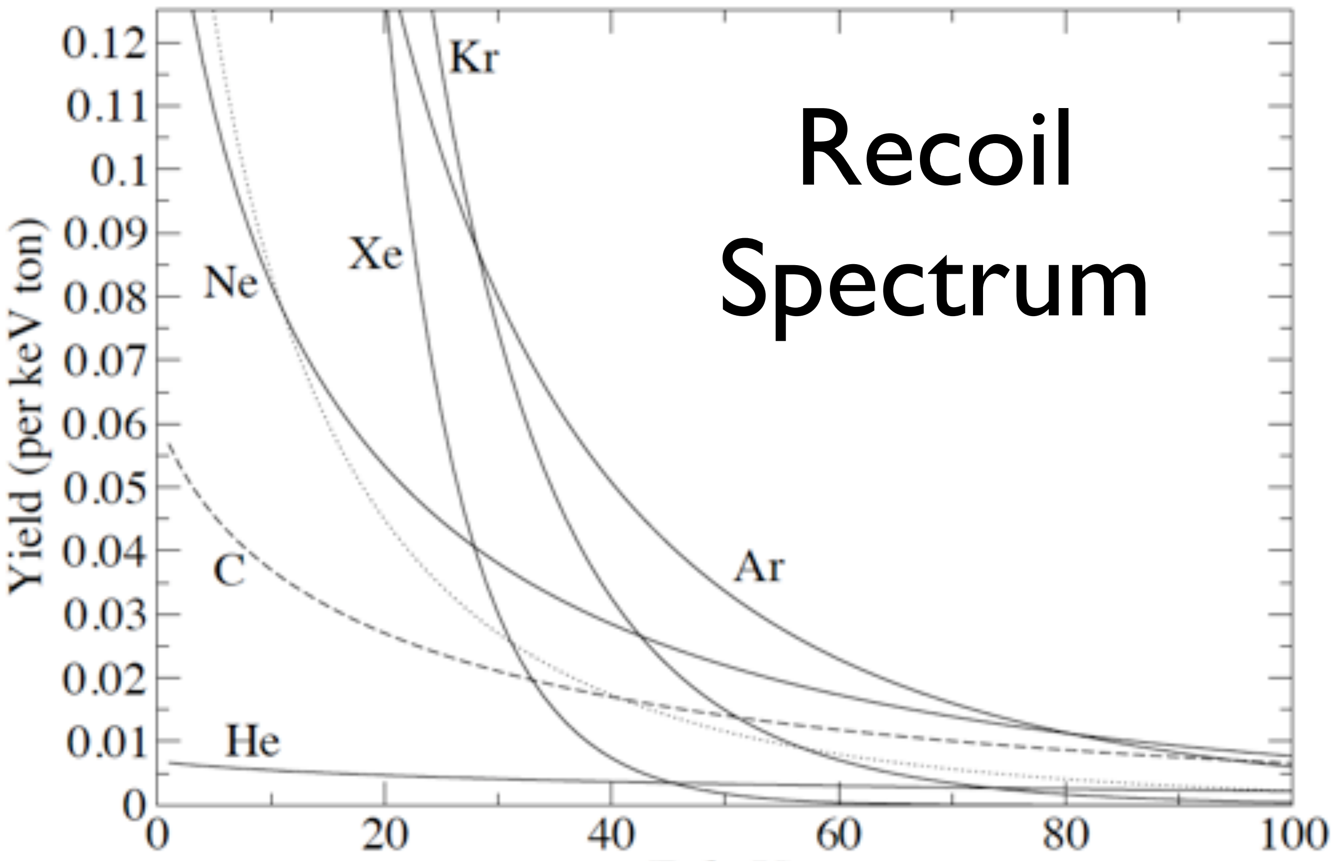
Can Measure total E via Neutrino-Nucleus Elastic Scattering

- Most of SN energy in mu and tau neutrinos. Need to measure spectrum of ν_μ, ν_τ.
- Spectrum of nuclear recoils in ν-A elastic scattering provides direct info on ν_x spectrum. Important info not in anti-ν_e spectrum. Results blind to (active) oscillations.
- Very large yield for nu-nucleus elastic, can be *tens of events per ton*, for SN at 10 kpc, instead of *hundreds of events per kiloton* for conventional detector. Because of (1) very large coherent cross section, (2) sensitive to all six flavors of neutrinos and antineutrinos, and (3) most detector mass is active.
- Need very low energy threshold for nuclear recoils.
- Background is less of a problem for SN, than for dark matter searches, because only interested in about 10 seconds of data.

Elastic scattering Yield, Spectrum

Yield, in events per ton for a SN at 10 kpc, and average nuclear recoil energy.

Target	Yield	<E>
^{20}Ne	4	46 keV
^{40}Ar	9	21
^{76}Ge	19	10
^{132}Xe	31	5

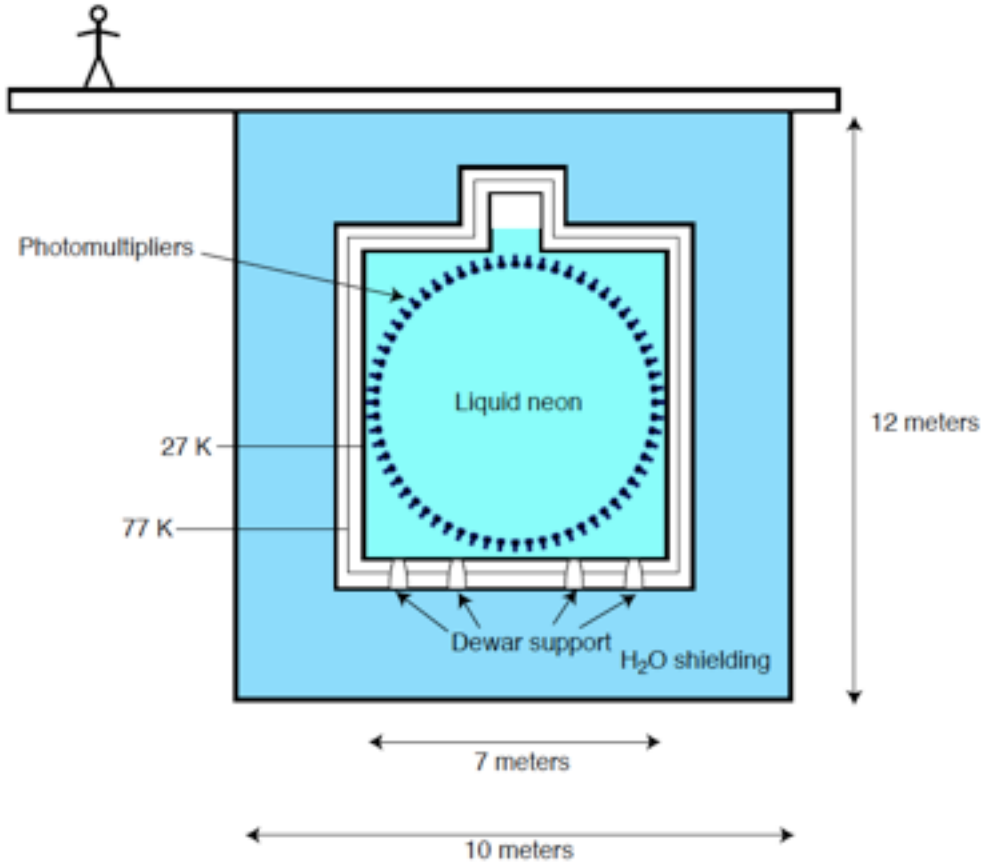


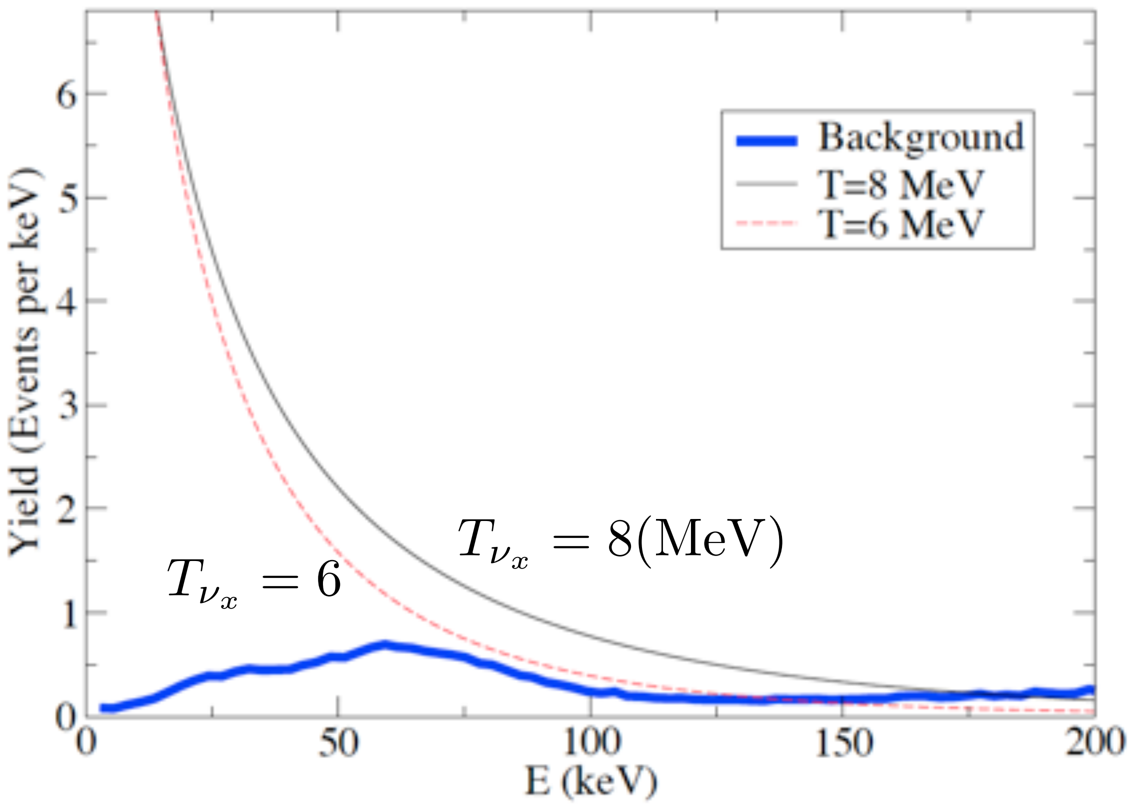
Recoil Spectrum

Nuclear recoil energy (keV)

- Yield goes up with mass number while spectrum moves to lower recoil energies.

Example: Liquid Ne CLEAN Detector





- Monte Carlo simulation of 100 ton CLEAN solar neutrino detector. Spectrum shows sensitivity to temperature of mu and tau neutrinos (nu_x). Note, spectrum of nu_e fixed.
- Solid blue line is all background activity in detector during 10 seconds. Most is at surface and can be separated from signal.
- Observe neutrino-nucleus elastic scattering in the laboratory! For example at SNS.

--- D. Mckinsey, K. Coakley, CJH, PRD **68** (2003) 023005

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

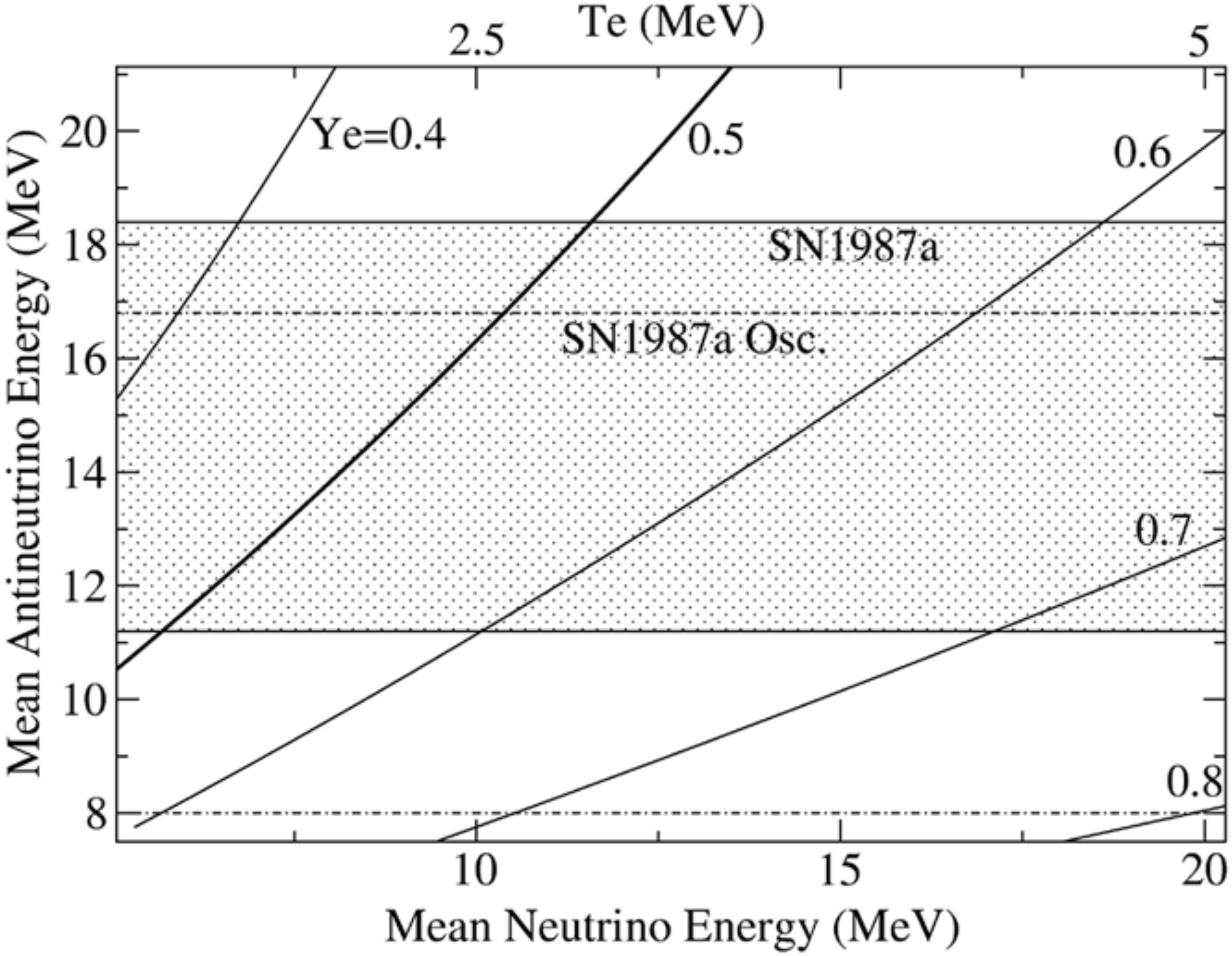
$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

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

- 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. Alternative site is NS mergers.

Searching for El Dorado with supernova neutrinos

n/p ratio in ν-driven wind

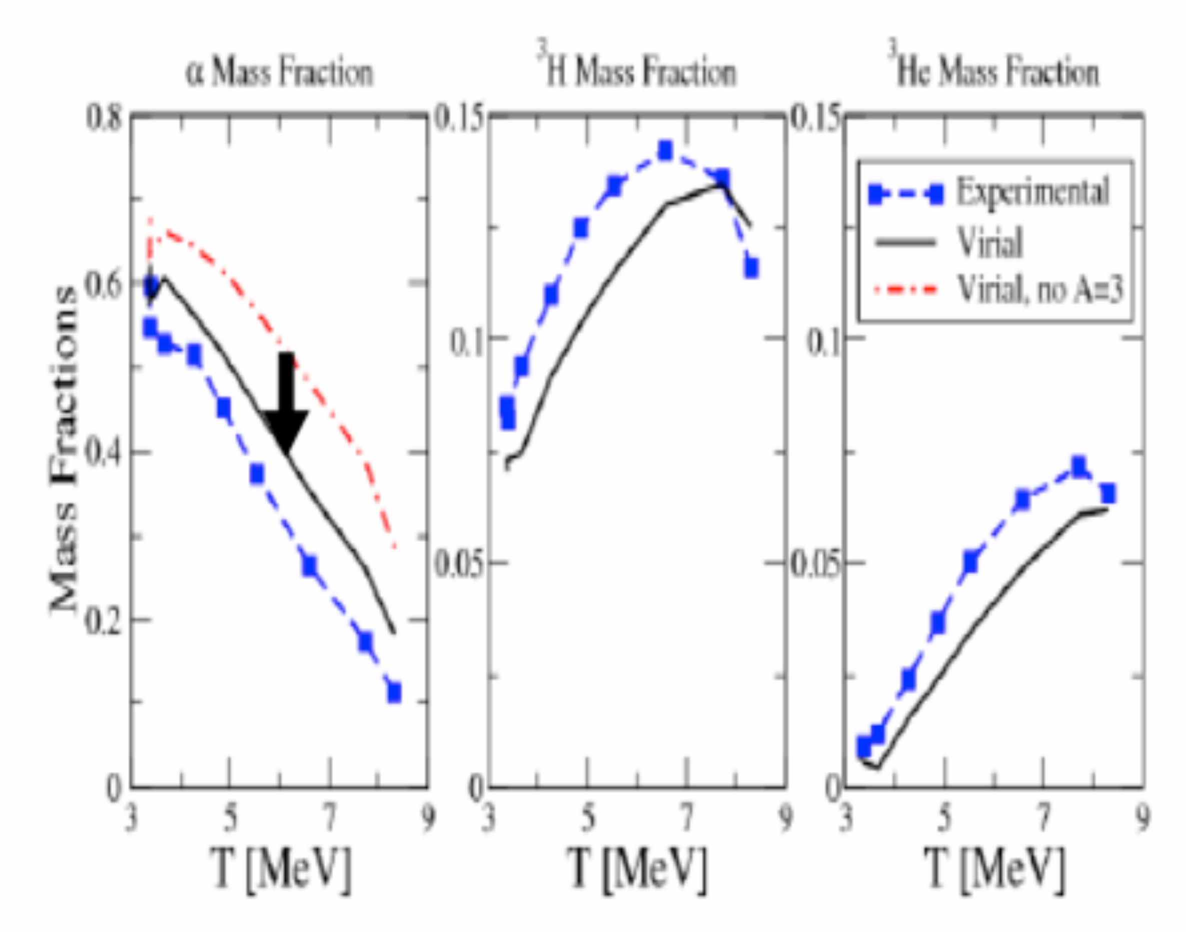


For wind to be neutron rich must be above dark Y_e=0.5 line and below SN1987A limit line. This requires cold ν_e temperatures, top scale.

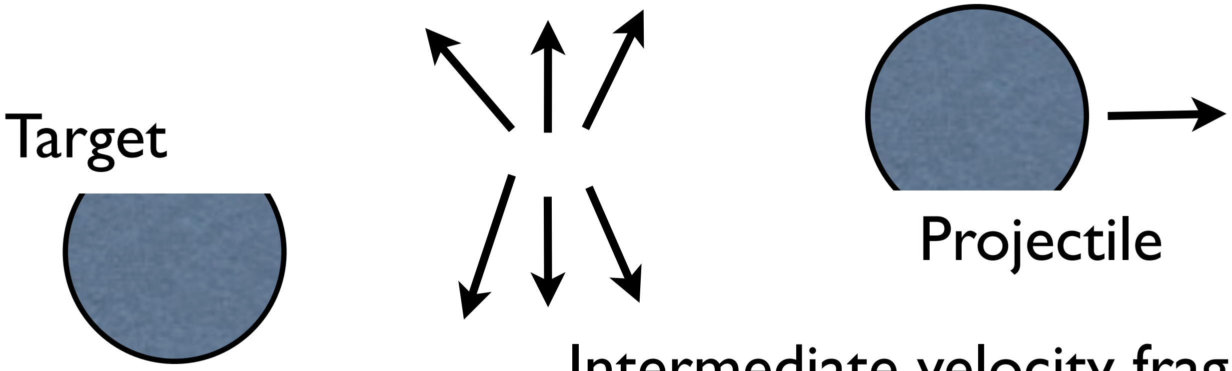
Very important to measure ν_e energy in galactic SN
If wind not r-process site, still need Y_e for nucleosyn.

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.



Target

Projectile

Intermediate velocity fragments

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

Virial Expansion

- Assume (1) system in gas phase and has not undergone a phase transition with increasing density or decreasing temp. (2) fugacity $z=e^{\mu/T}$ with μ the chemical pot is small.
- Expand pressure in powers of z :

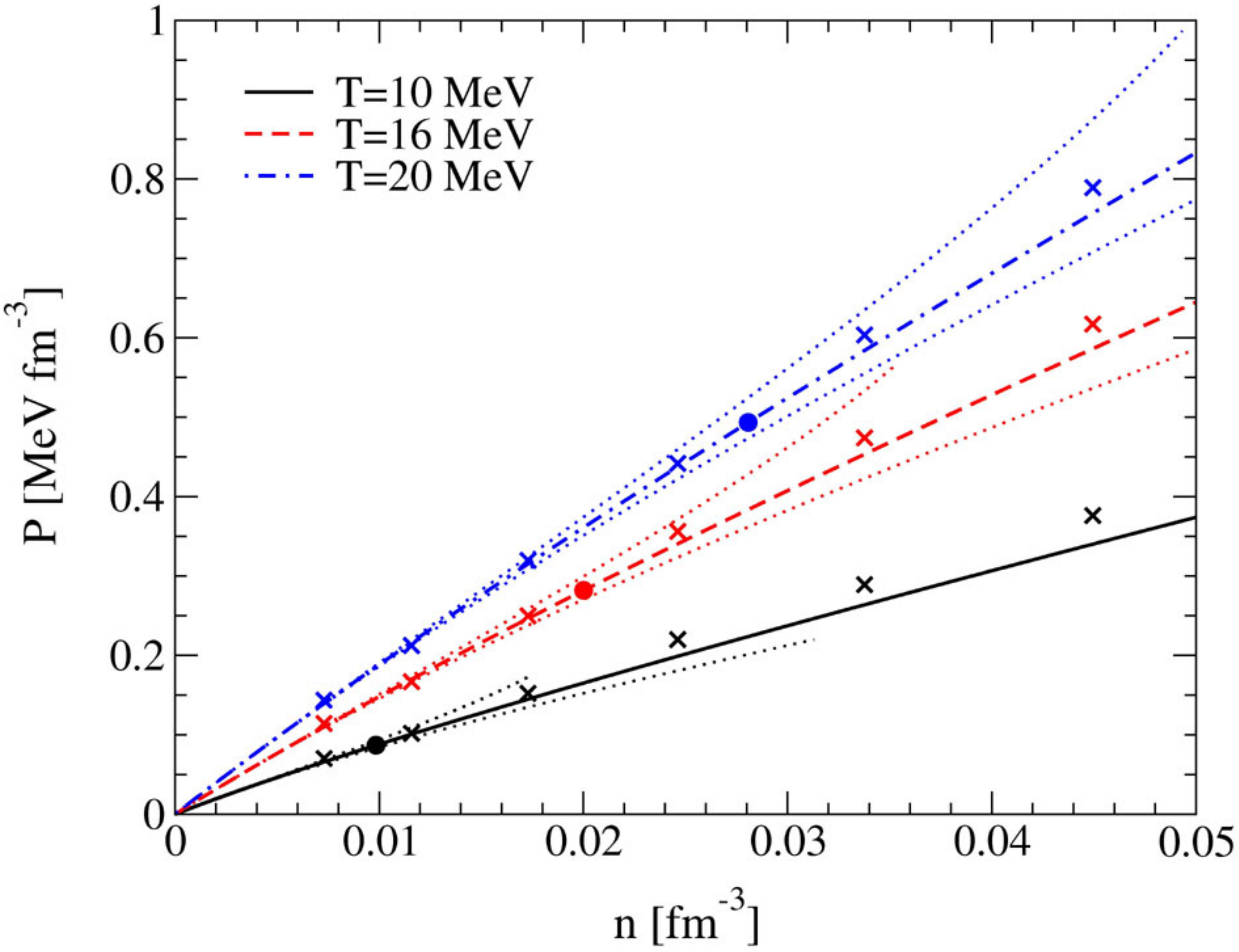
  $$P=2T/\lambda^3[z+b_2z^2+b_3z^3+\ldots],$$

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

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

with A. Schwenk

Neutron matter Equation of State



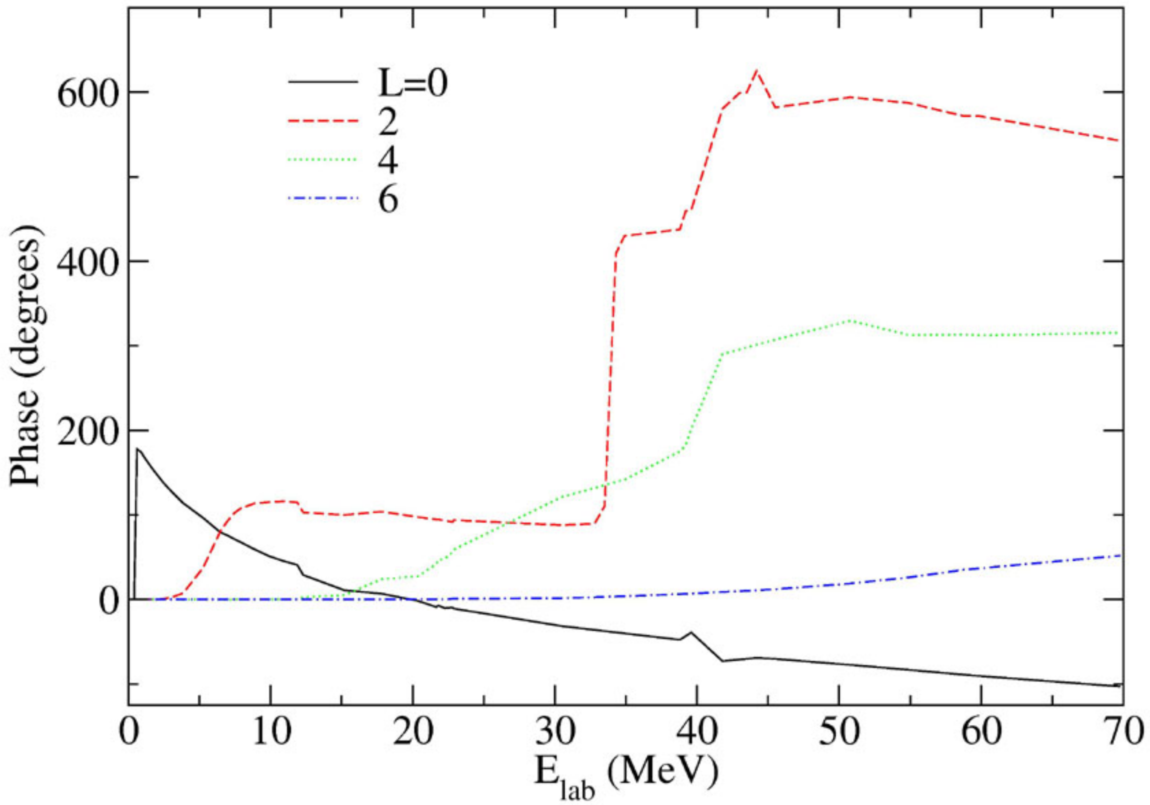
Error bars (dotted) from estimate of b_3

Crosses from microscopic FHNC calc. by Friedman + Pandharipande

Nuclear Matter: *n*, *p*, α system

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

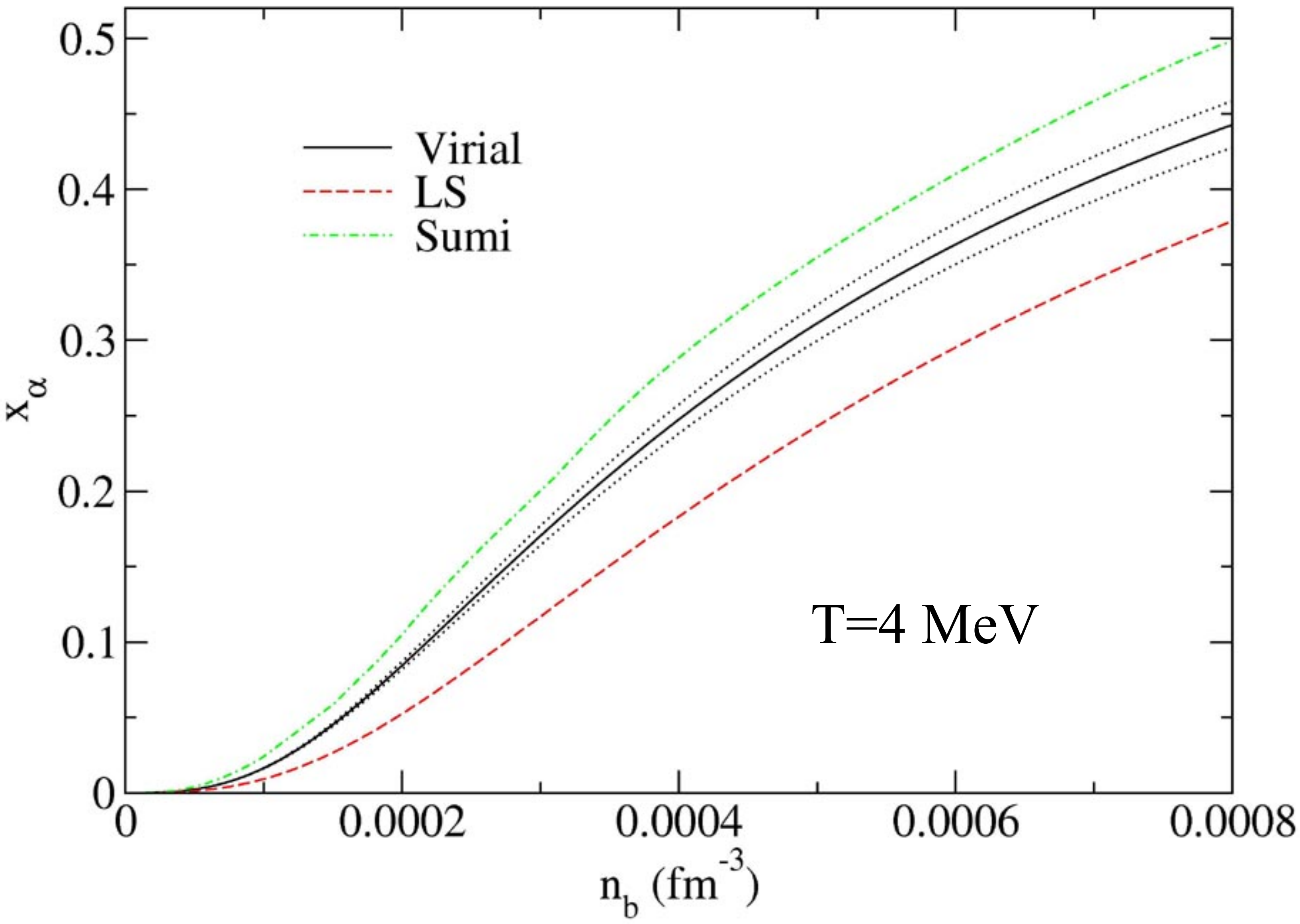
- Need four virial coefficients:
  - b_n for neutron matter,
  - b_{nuc} for symmetric nuclear matter,
  - b_α for alpha system,
  - $b_{\alpha n}$ for interaction between an α and N.
- Virials from NN, Nα and $\alpha\alpha$ elastic scattering phase shifts.



$\alpha-\alpha$ 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

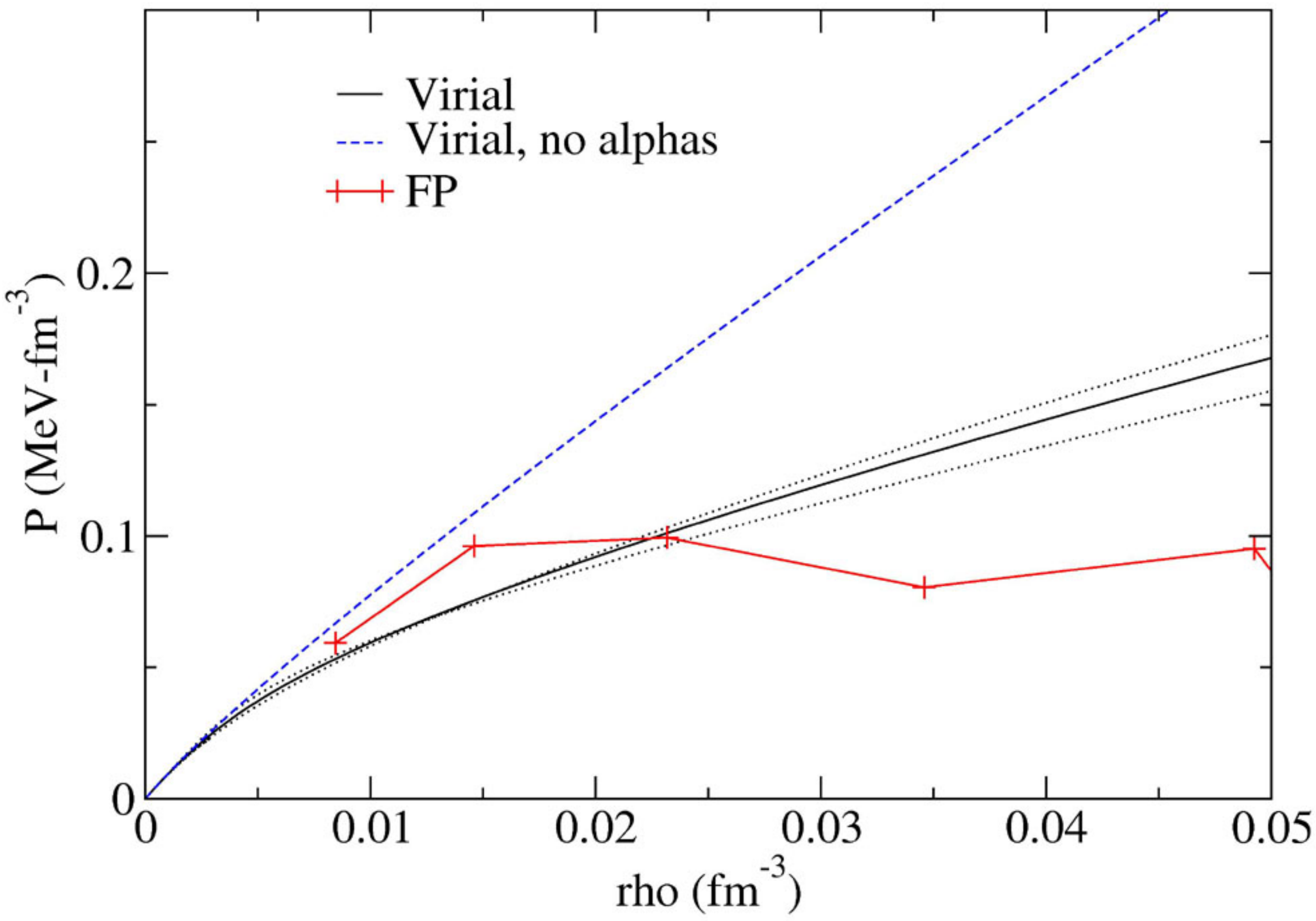
Pressure of Nuclear Matter

- Conventional microscopic approaches fail because of cluster (alpha) formation.
- Variational wave-function

  $\Psi=\Pi_{i<j} f(r_{ij})\Phi$

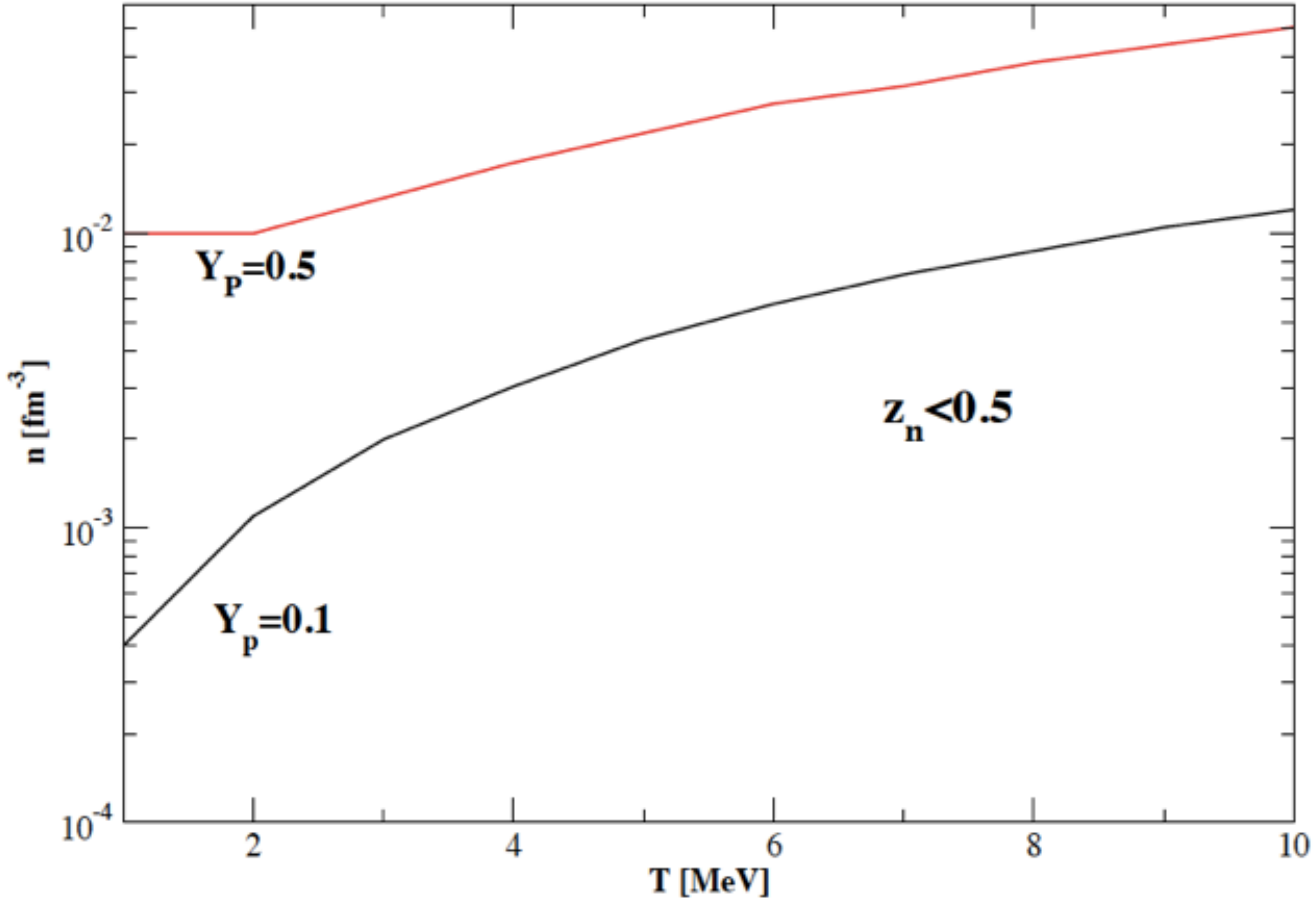
  can only describe a single cluster.

  Friedman +Pandharipande calc. (FP) based on NN+3N pot. and FHNC approximation.



Pressure of symmetric nuclear matter at a temperature of T=10MeV.

Range of Validity of Virial



- Virial good at density, T to lower right of lines. For T=4 MeV, Y_P=0.1, Virial good to ~ 3×10^{12} g/cm^3. Directly covers neutrino-sphere region until very late times.

Neutrino Response

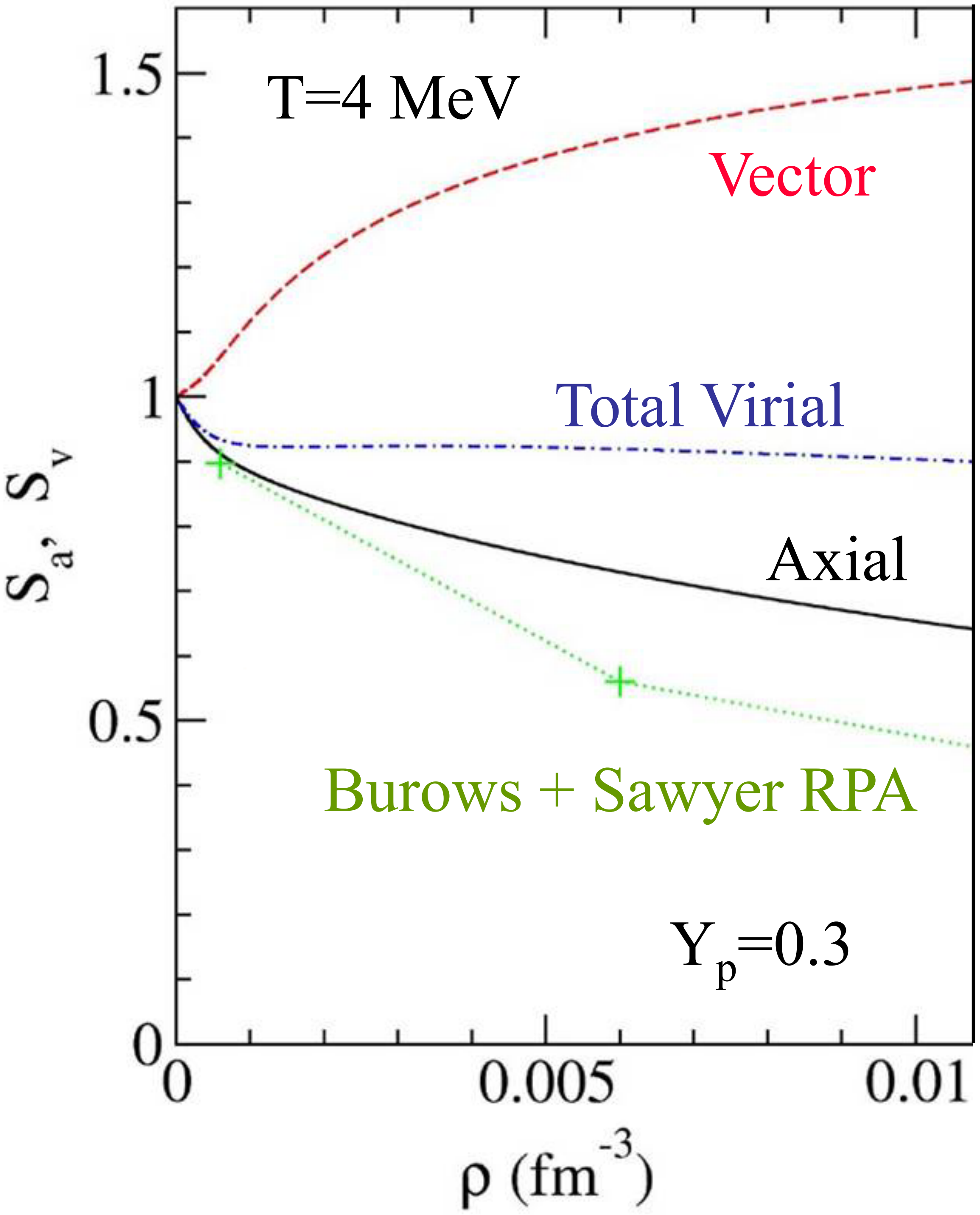
- ν neutral current cross section

  $d\sigma/d\Omega = (G^2E_\nu{}^2/16\pi^2)[$

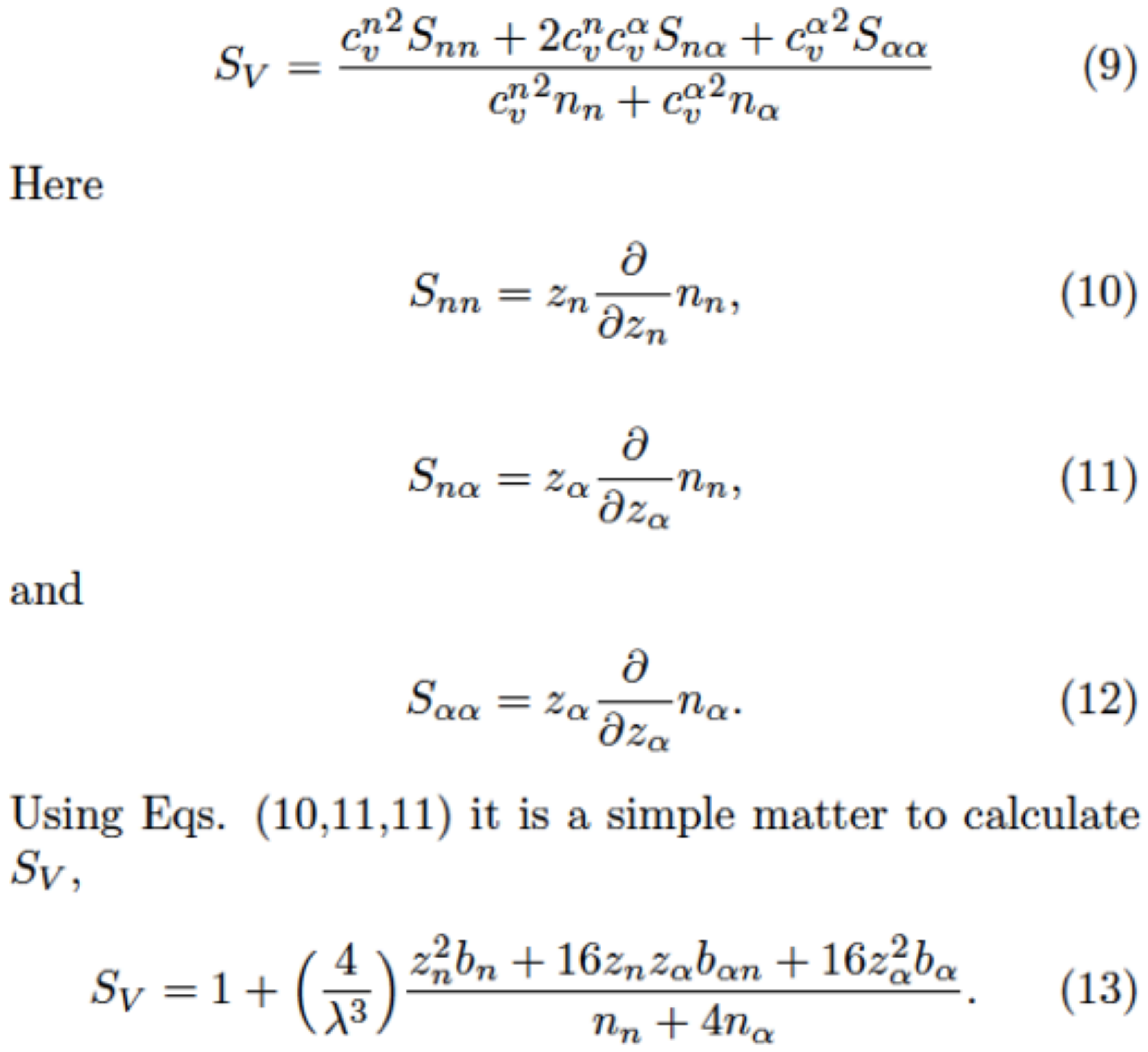
  $(1+\cos\theta)S_v + g_a{}^2(3-\cos\theta)S_a\,]$
- Vector response is static structure factor S_v=S(q) as q→0

  $S(0)=T/(dP/dn)$
- 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.*



Vector response of nucleon + alpha system



$$S_V = \frac{c_v^{n2} S_{nn} + 2c_v^n c_v^\alpha S_{n\alpha} + c_v^{\alpha 2} S_{\alpha\alpha}}{c_v^{n2} n_n + c_v^{\alpha 2} n_\alpha} \tag{9}$$

Here

$$S_{nn} = z_n \frac{\partial}{\partial z_n} n_n, \tag{10}$$

$$S_{n\alpha} = z_\alpha \frac{\partial}{\partial z_\alpha} n_n, \tag{11}$$

and

$$S_{\alpha\alpha} = z_\alpha \frac{\partial}{\partial z_\alpha} n_\alpha. \tag{12}$$

Using Eqs. (10,11,11) it is a simple matter to calculate S_V,

$$S_V = 1 + \left(\frac{4}{\lambda^3}\right) \frac{z_n^2 b_n + 16 z_n z_\alpha b_{\alpha n} + 16 z_\alpha^2 b_\alpha}{n_n + 4n_\alpha}. \tag{13}$$

Present RPA responses are qualitatively wrong at low density because of cluster formation.

Virial Expansion

- Describes region near neutrino-sphere in terms of observed nucleon-nucleon, nucleon-alpha, and alpha-alpha elastic scattering phase shifts.
- Provides model independent:
  - EOS (pressure as a function of density, temperature, and Y_p).
  - Composition (fraction of D, ^{3}H, ^{3}He, ^{4}He...).
  - Neutrino response (at long wavelength).
  - Full q, ω dependence of response possible with very small model dependence.

Multi-messenger observations of neutron rich matter

- 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 very attractive.
- Gravitational waves: from NS mergers depend on EOS, from mountains depend on crust strength, and from r-modes depend on bulk/shear viscosities.
- Optimize SN neutrino detectors to determine total E radiated in active neutrinos (measure ν_x spectrum) and <E> in ν_e.
- Much of region near neutrino sphere can be described in a model independent way with the virial expansion.
- K. Kadau, J. Piekarewicz, A. Schwenk, E. O'Connor, G. Shen ...
- Supported in part by DOE.