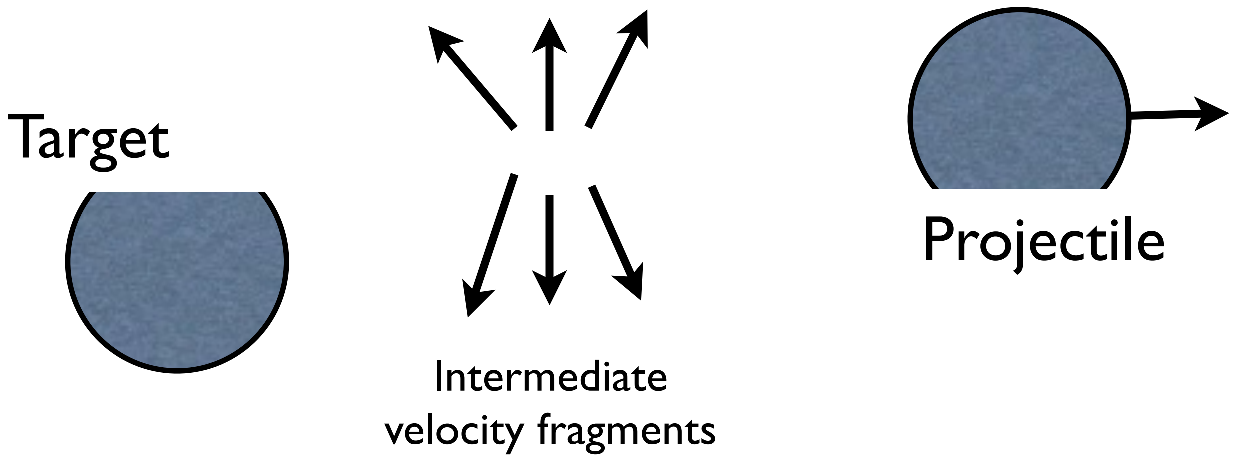
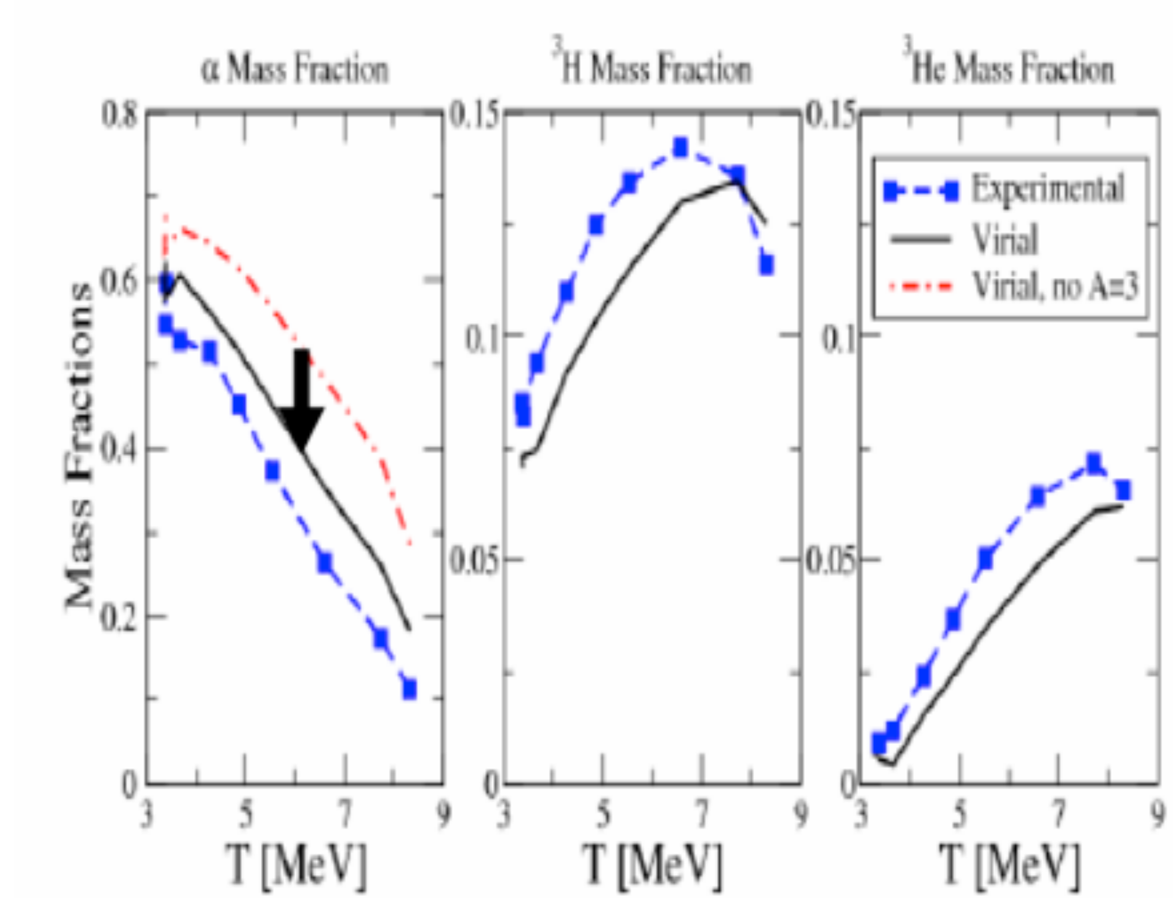
Simulating the supernova neutrino-sphere with heavy ion collisions

- Core collapse SN dominated by neutrinos. Much of the "action" occurs near the neutrinosphere that is composed of warm low density neutron rich gas of nucleons and light nuclei. Not a free gas!
- Study in the laboratory the equation of state, symmetry energy, composition, and neutrino response … of neutrinosphere material.
  - Recreating ~5+ MeV temperature is straight forward.
  - Recreating low densities occurs as system expands but it may be difficult to measure the density.
  - Recreating the very neutron rich conditions is harder. Perform HI collisions with proton rich and then neutron rich radioactive beams and extrapolate to very neutron rich conditions.

Recreating Neutrinosphere on Earth

In a peripheral HI collision at say 30 MeV/A, study intermediate velocity fragments that come from warm low density region.





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

- Describe system with virial expansion, valid at low density and or high temperature. Pressure is expanded in powers of $z=e^{\mu/T}$ (with μ the chemical pot) $P=2T/\lambda^3[z+b_2z^2+\ldots]$. Here λ=thermal wavelength=$(2\pi/mT)^{1/2}$, 2nd virial coef. $b_2(T)$ from phase shifts.

Symmetry Energy shift

- Proton in n rich matter more bound than neutron because of symmetry energy.
- Symmetry energy at low density 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.
- Neutrino absorption cross section increased by energy shift which increases energy and phase space of outgoing electron-> lowers E(nu).
- Consider $\boldsymbol{\nu}_e$ + n -> p + e

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

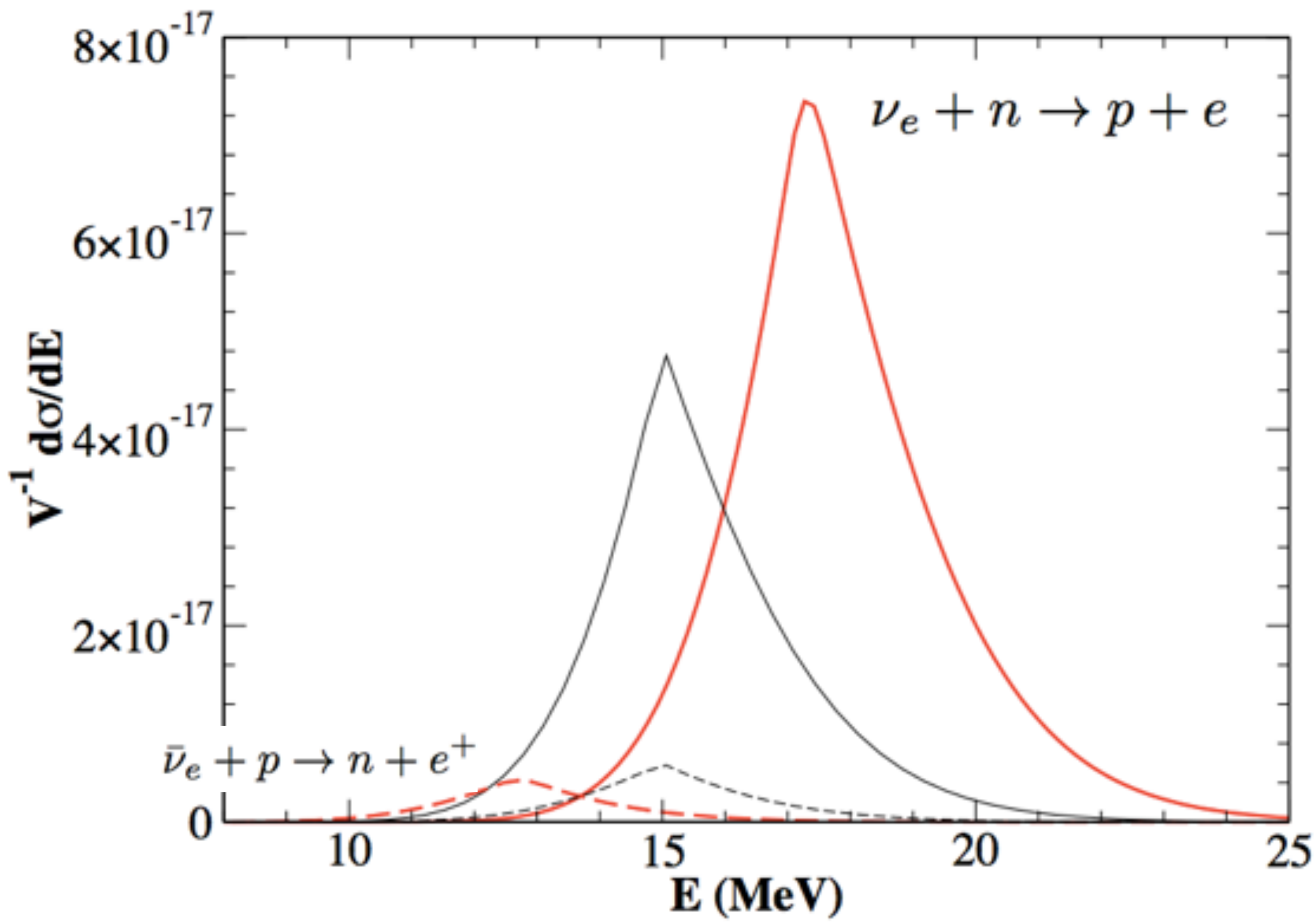
$$\frac{\sigma_{\nu_e}(\Delta U)}{\sigma_{\nu_e}(0)} = \frac{(E_\nu + \Delta U)^2[1 - f(E_\nu + \Delta U)]}{E_\nu^2[1 - f(E_\nu)]}.$$

- 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 symmetry energy is relevant.

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

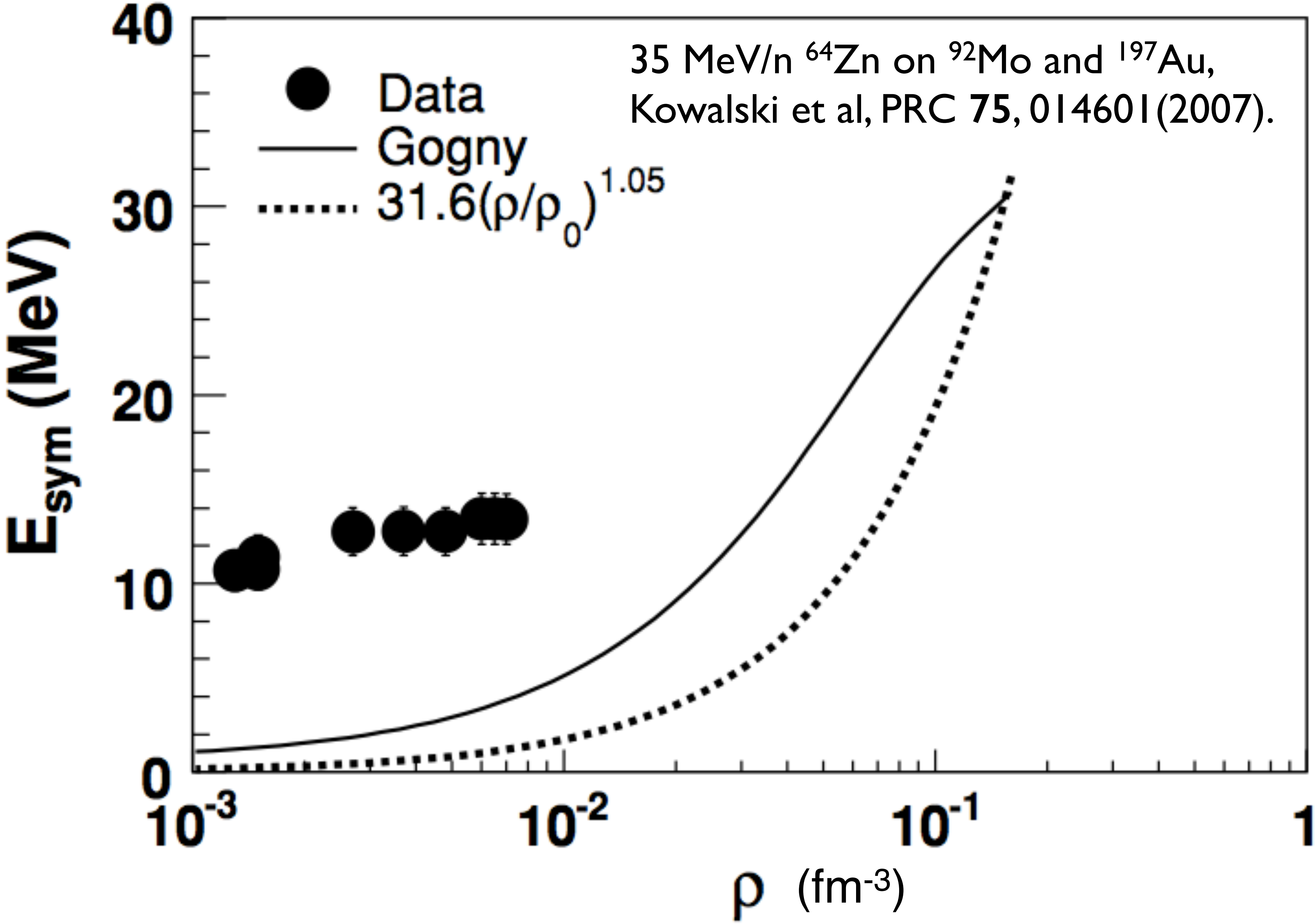
Neutrino and antineutrino cross sections

- Cross section for neutrino (anti-neutrino) absorption solid (dashed) vs energy of outgoing charged lepton without (black) and with (red) energy shift. E_{nu}=15 MeV, T=5 MeV and n=0.001 fm^{-3}.



- Effect decreases energy of emitted neutrinos because larger cross section keeps them in equilibrium to lower densities and temperatures.

- This change in neutrino spectra leads to a neutrino driven wind that is somewhat more neutron rich. However, probably still not neutron rich enough for the main r-process.



Symmetry energy from isoscaling analysis of ratio of yields of light clusters with different N/Z values. The temperature varies from about 4 MeV (lowest density) to 10 MeV (highest density)

Neutrino Interactions

- Neutral current cross section in medium modified by vector (density) S_v and axial (spin) S_a response functions.

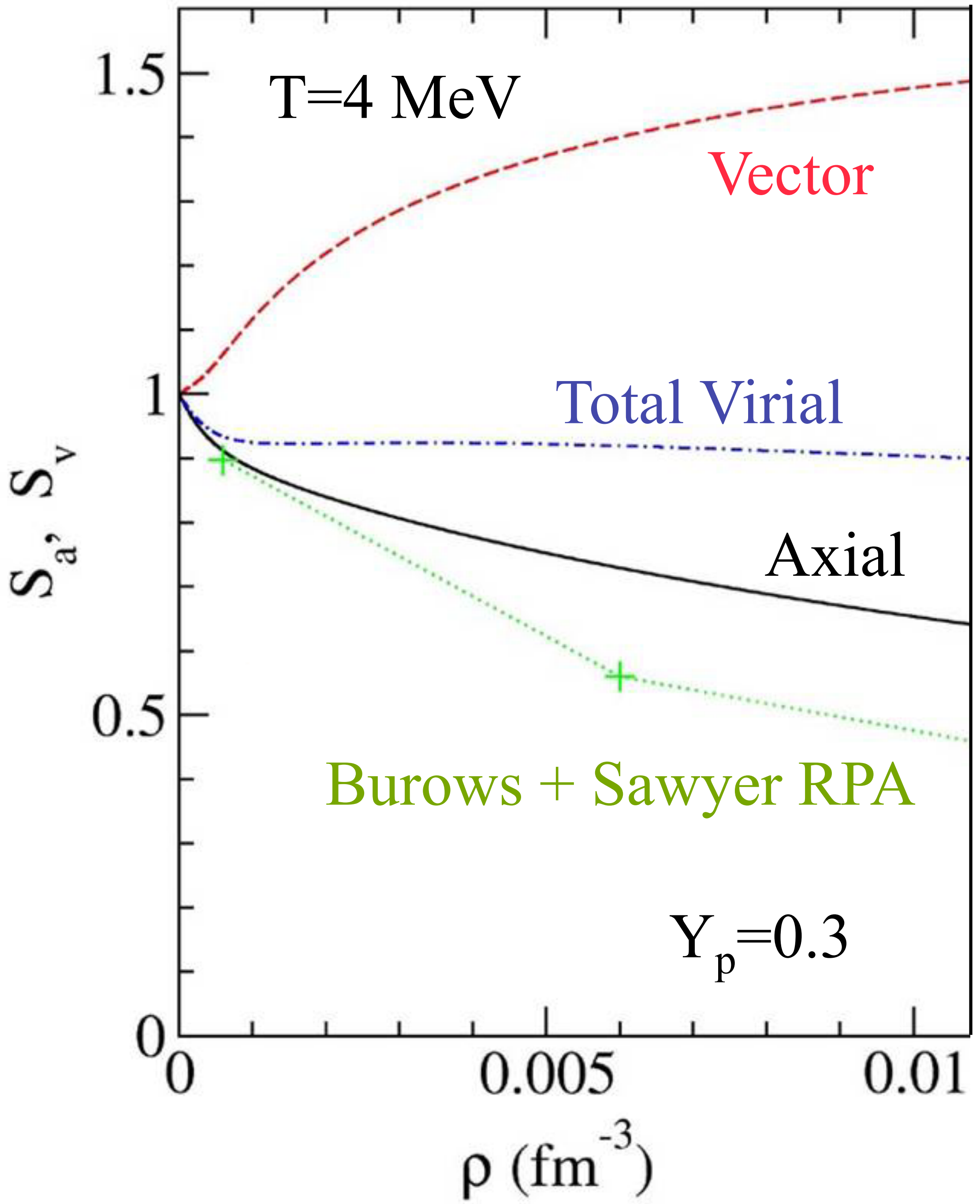
$$\frac{1}{N}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\left(g_a^2\,(3-\cos\theta)S_a(q) + (1+\cos\theta)S_v(q)\right)$$

- Formation of light clusters such as ^{4}He enhances vector response because of attractive interactions. Present state of the art in SN simulations is RPA in nucleon degrees of freedom. This ignores cluster formation and underestimates vector response.

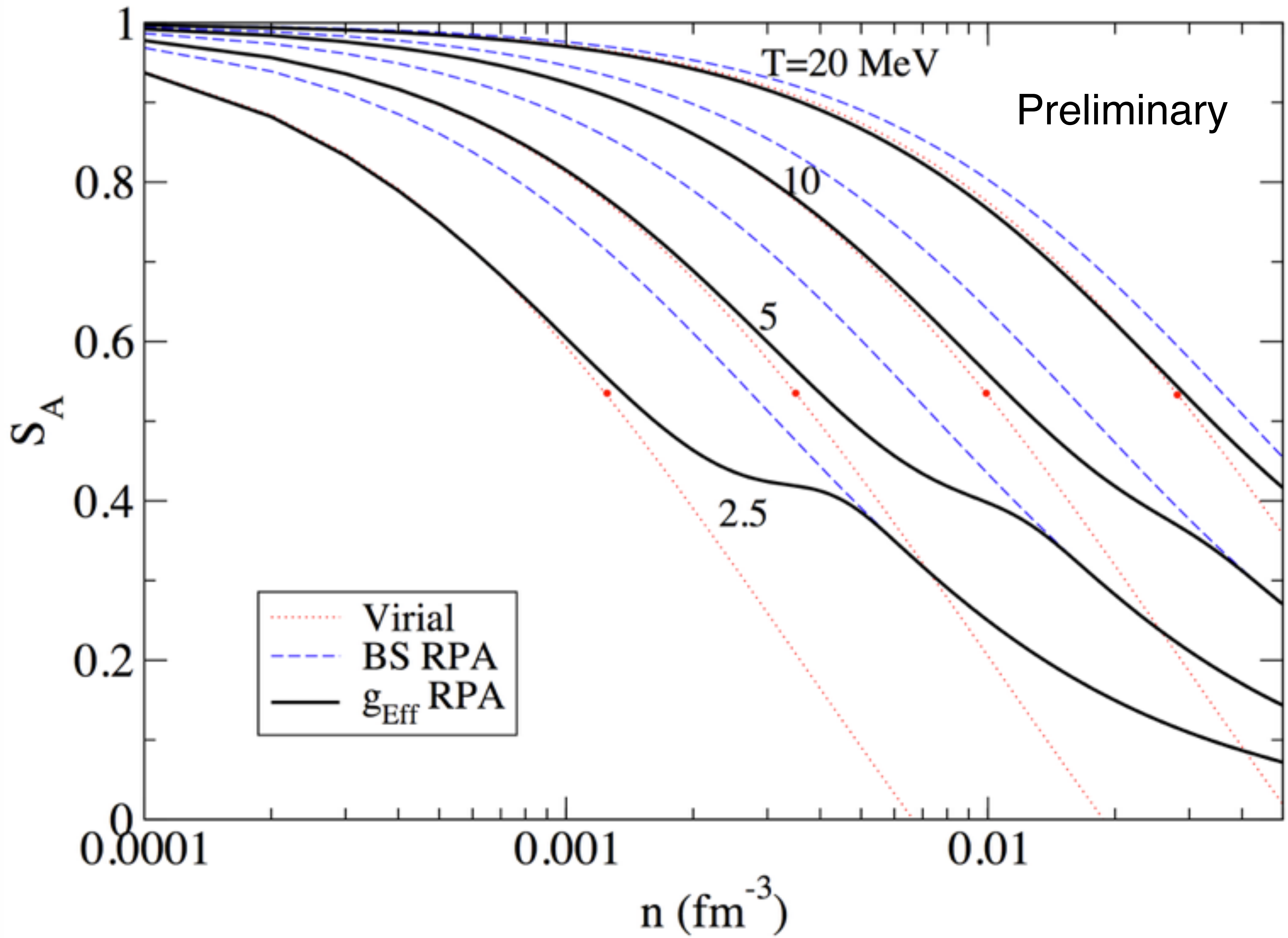
$$S_v = 1 + \left(\frac{4}{\lambda^3}\right)\frac{z_n^2 b_n + 16 z_n z_\alpha b_{\alpha n} + 16 z_\alpha^2 b_\alpha}{n_n + 4n_\alpha}$$

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.*



Axial response of neutron matter



$$S_A = 1 + \frac{4}{\lambda^3}\frac{(z_p^2 + z_n^2)b_a - 2z_p z_n b_{pn}^a}{n_n + n_p}$$

Neutrino Atmospheres

- There are important corrections to the neutrino interactions of free nucleons for neutrinosphere conditions. These are from nucleon-nucleon interactions.
- These corrections can be calculated (at low density), in a model independent way with the virial expansion, and tested with heavy ion collisions in the laboratory.
- This should give ***more reliable*** neutrino atmospheres for predicting neutrino spectra, explosion mechanism, and nucleosyn.

Femtonova

- Use Heavy Ion collisions to simulate neutrinosphere region of core collapse supernovae.
- Measure EOS, composition, symmetry energy, neutrino response … of warm, low density, neutron rich matter.
- Experiments with both stable and radioactive beams allow extrapolation to very neutron rich conditions.
- Virial expansion at low density and or high T provides model independent EOS, composition, neutrino response functions …
- Supported by DOE DE-FG02-87ER40365 and DE-SC0008808 (NUCLEI SciDAC Collaboration).
- With L. Caballero, E. O'Connor, A. Schwenk,