Setting the stage: Neutrinos

C. J. Horowitz, Indiana University
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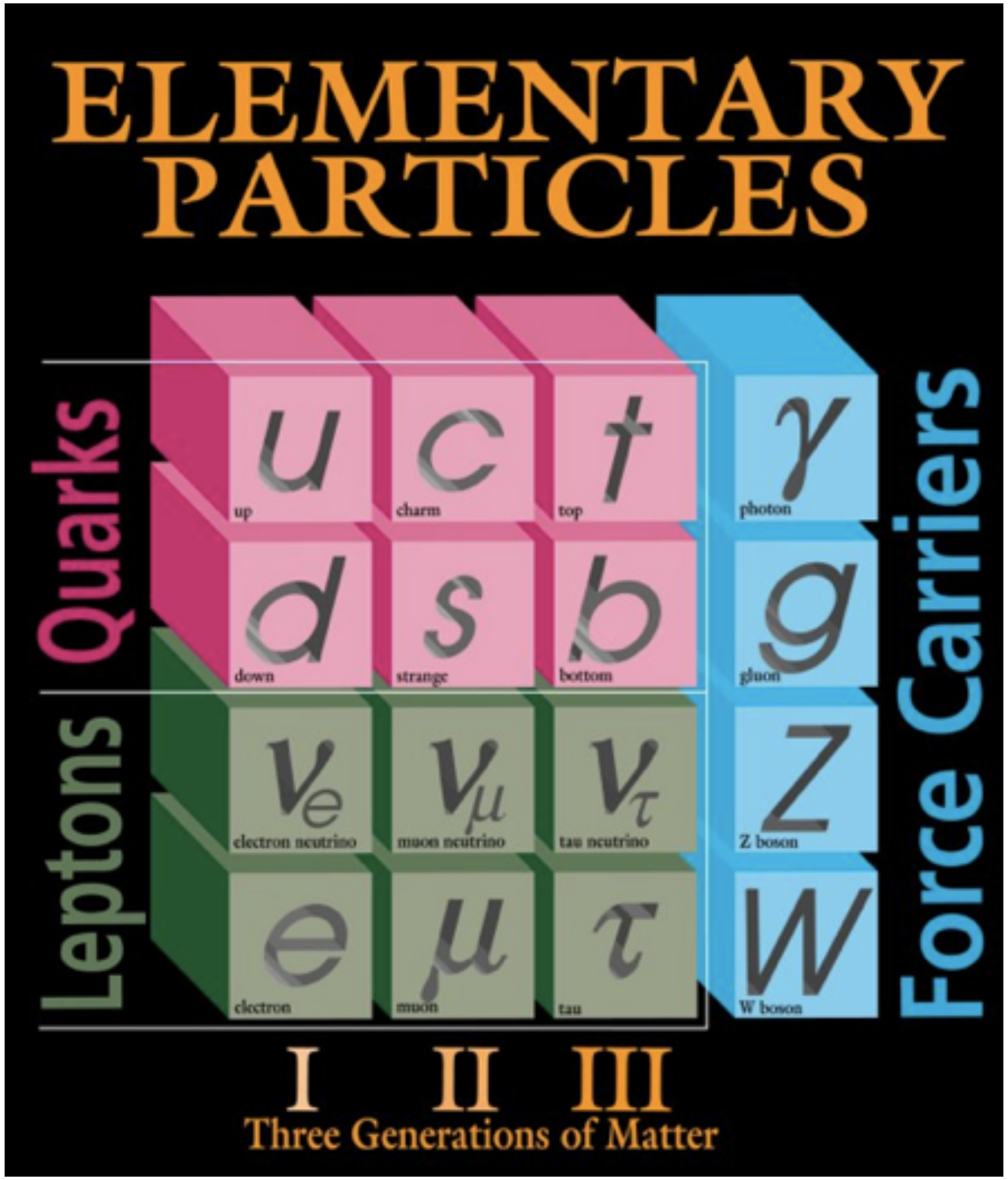
Neutrino Interactions

- Introduction and weak magnetism
- SN neutrino detectors
- Medium modifications:
  - Symmetry energy shift for charged currents
  - Correlation corrections for neutral currents

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.

- Flavor information important for nucleosynthesis, oscillations, and other fundamental symmetry tests.

SN Quantum Numbers

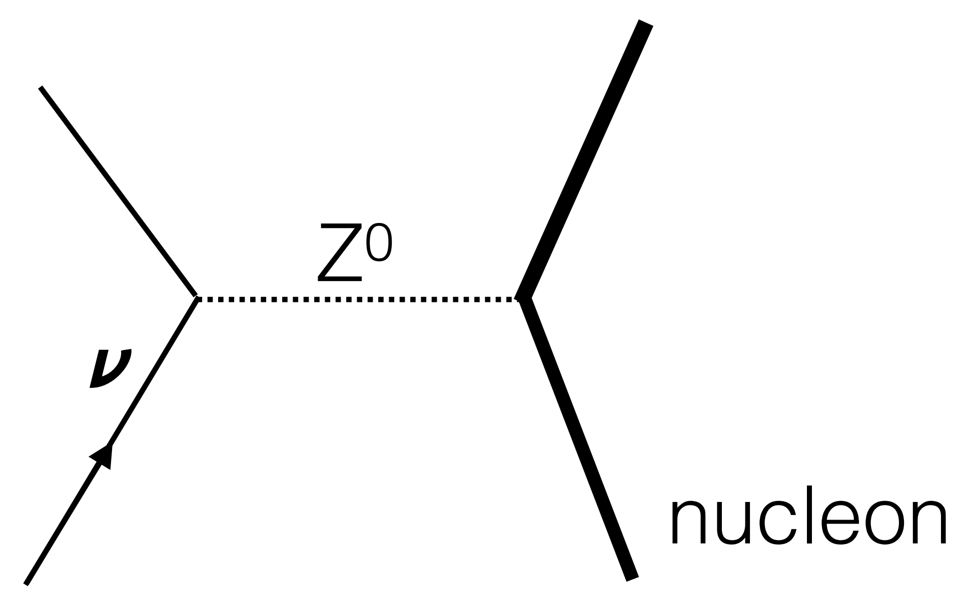
- Core collapse SN involve astronomical changes in numbers of second and third generation particles.

	Pre SN core	SN	Neutron star
Neutrinos	$3/5GM^2/R$ / (10-20 MeV)	10^{58}	
Baryon #	10^{57}	10^{57}	10^{57}
Electron #	10^{57}	—>	10^{56}
Muon #	0	—>	10^{55}
Tau #	0	10^{54}	0
Strangeness	0	—>	?

- Tau neutrinos produced in pairs but antineutrinos have longer mean free paths and diffuse faster leaving star tau neutrino rich.

Weak magnetism

- Neutrino cross sections are about 10% larger than antineutrino cross sections at SN energies.
- If nucleon does not recoil, time reversal symmetry gives equal cross sections.
- Difference is recoil order E_ν/M but with a large coefficient involving nucleon magnetic moment.
- Charge conjugation violation implies P violation if CP approximately conserved.
- $\sigma = \sigma_0 [1 \pm \xi \, G_A(F_1+F_2) \, (E_\nu / M)]$
- Consider four neutrino transport: ν_e, anti-ν_e, ν_x and anti-ν_x. $E(\nu_x) < E(\text{anti-}\nu_e)$?
- Important for nucleosynthesis.



Supernova Neutrino Detectors

- Detect full flavor content of neutrino signal from next galactic SN and measure independently the spectra of (1) electron anti-neutrinos, (2) electron neutrinos, and (3) mu and tau neutrinos.

- About 20 electron-anti-neutrinos observed from SN1987a. Many SN detectors best for anti-ν_e.

Detection reactions

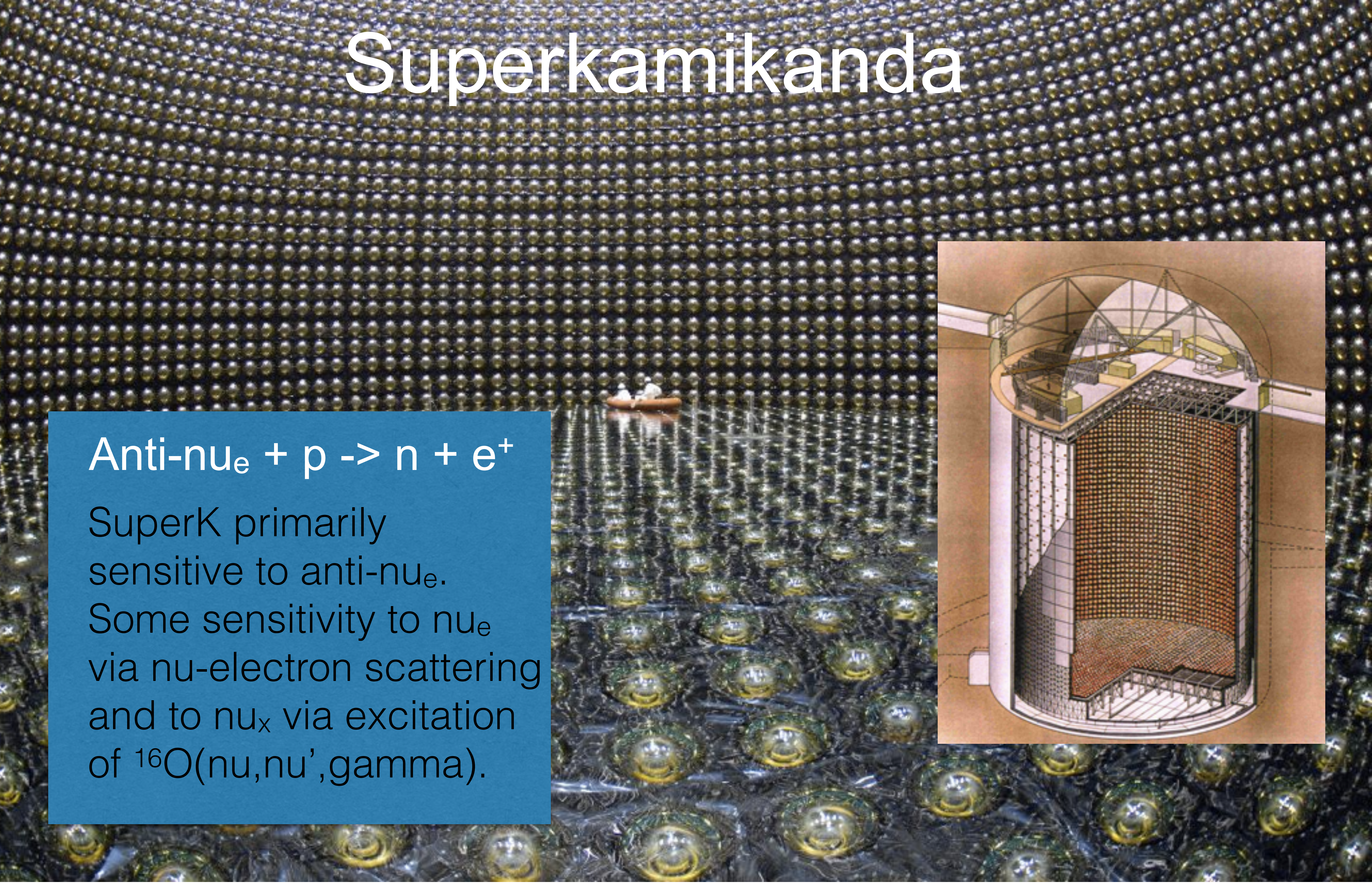
	Channel	Observable(s)	Interactions
	$\nu_x + e^- \rightarrow \nu_x + e^-$	C	17/10
Super Kamikande	$\bar{\nu}_e + p \rightarrow e^+ + n$	C, N, A	278/165
	$\nu_x + p \rightarrow \nu_x + p$	C	682/351
	$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}^{(*)}$	C, N, G	3/9
	$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}^{(*)}$	C, N, G, A	6/8
	$\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}^*$	G	68/25
	$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$	C, N, G	1/4
	$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$	C, N, G	7/5
	$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$	G	50/12
DUNE	$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	C, G	67/83
	$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	C, A, G	5/4
	$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$	N	144/228
	$\nu_x + {}^{208}\mathrm{Pb} \rightarrow \nu_x + {}^{208}\mathrm{Pb}^*$	N	150/55
Dark matter detectors	$\nu_x + A \rightarrow \nu_x + A$	C	9,408/4,974

per kiloton for SN at 10 kpc

K. Scholberg

Important to measure spectrum of all three components: electron neutrinos, electron antineutrinos, and nu-x.

Superkamikanda



Anti-nu_e + p -> n + e^+

SuperK primarily sensitive to anti-nu_e. Some sensitivity to nu_e via nu-electron scattering and to nu_x via excitation of ^{16}O(nu,nu’,gamma).

- 32 kilotons of very clear water. Many large phototubes see light from e^+. Of order 10,000 events for galactic SN

Deep Underground Neutrino Experiment

- Send neutrino and antineutrino beams from Fermilab (near Chicago) 1300 km to a large (34 kt) liquid Ar detector in the Homestake gold mine in South Dakota. Main goal: observe CP violation in neutrino oscillations.

- Powerful supernova detector that should be able to measure **electron neutrino** energies very well.

- Combine anti-nu spectra from Super K with nu spectra from DUNE to predict composition of neutrino driven wind and likely strongly disfavor r-process in wind.

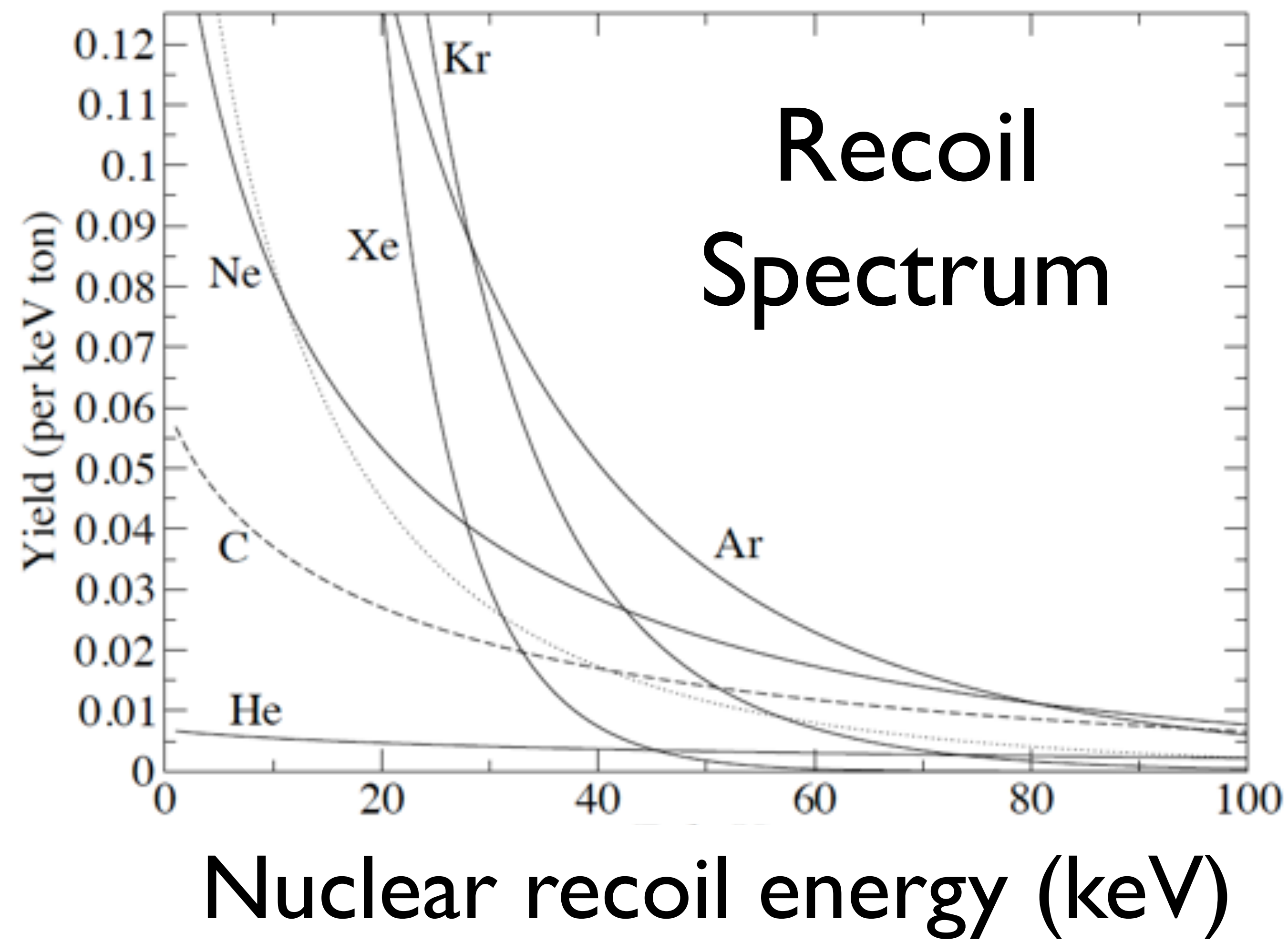
Can Measure total E via Neutrino-Nucleus Elastic Scattering

- Most of SN energy in mu and tau neutrinos. Need to measure spectrum of nu_{mu}, nu_{tau}.
- Spectrum of nuclear recoils in nu-A elastic scattering provides direct info on nu_x spectrum. Important info not in anti-nu_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

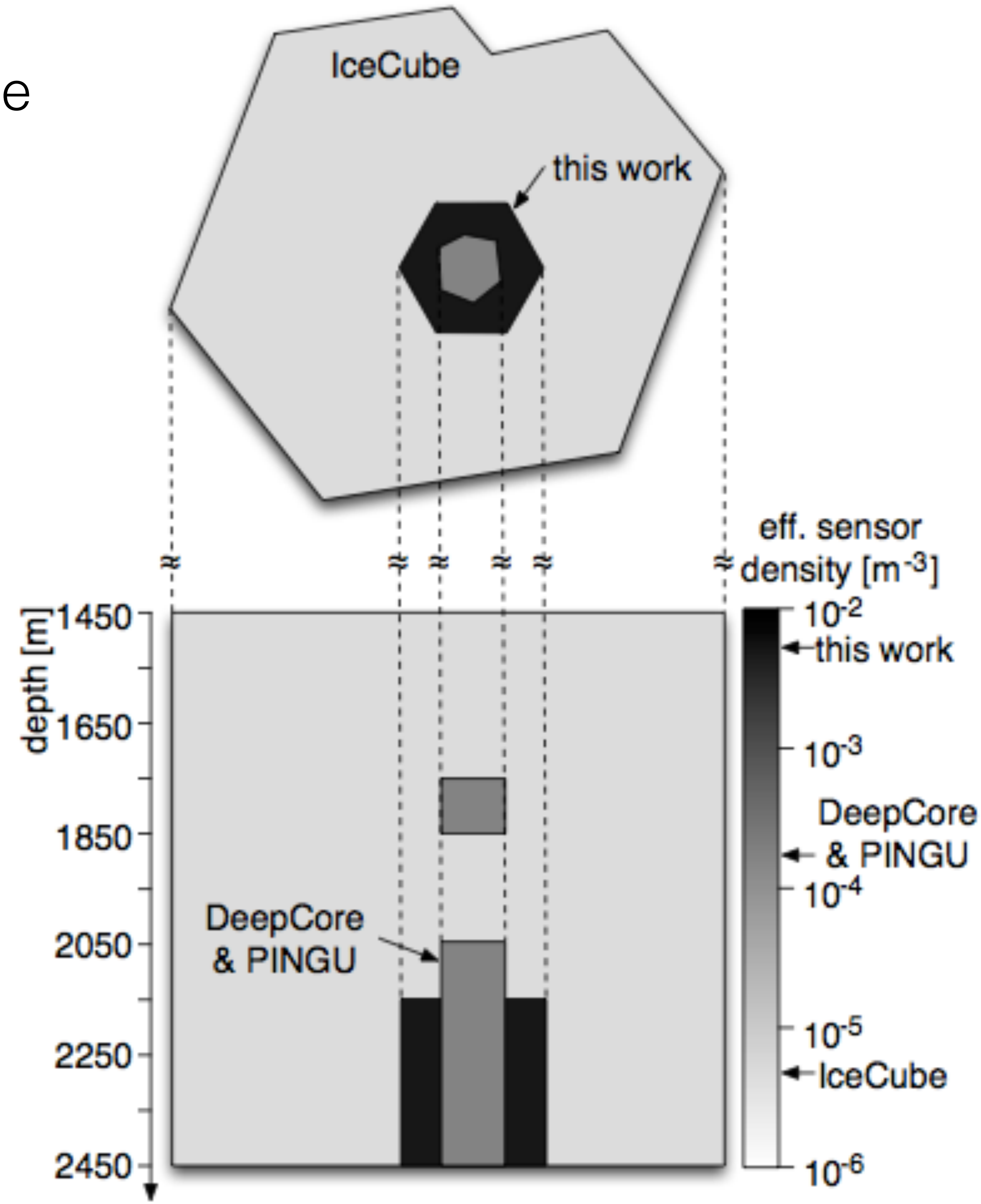


- Yield goes up with mass number while spectrum moves to lower recoil energies.

Important to measure spectrum of all three components: anti-nu_e, nu_e, and nu_x. Coherent good for nu_x!

Detecting extra-galactic supernova neutrinos in the Antarctic ice (10 Megaton detector)

- Preliminary idea to instrument inner region of IceCube to obtain 10 MeV threshold and 10 Mt effective volume.
- Issues with cost, photodetectors, and noise.
- See SN to 10 Mpc with rate of 1 to 4 per year.
- Boser et al, arXiv:1304.2553
- Coincident with GW signal.
- What do you learn from handful of events?
- What else can this detector do?

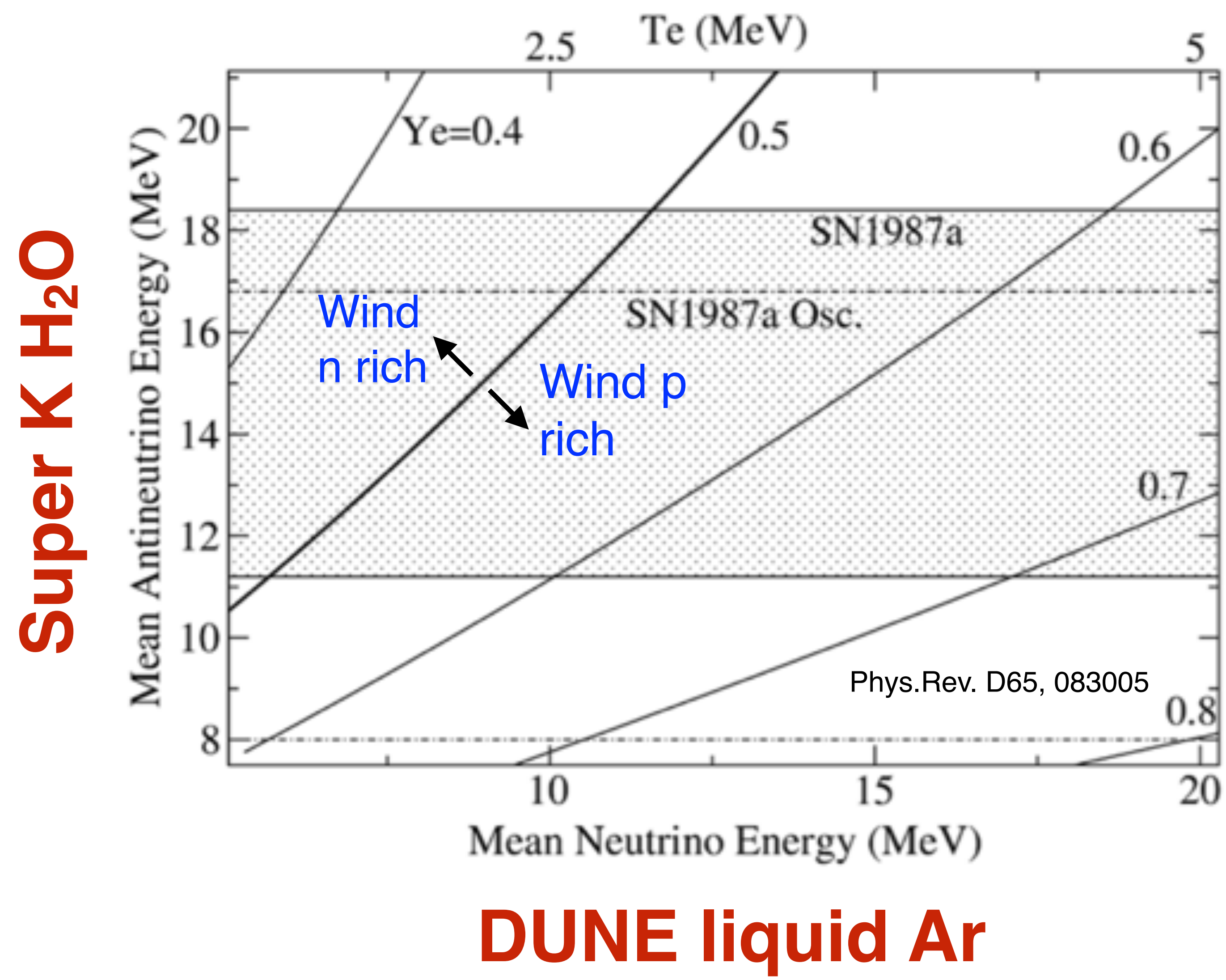


SN neutrinos and r-process nucleosynthesis

- Important site for the r-process is the neutrino driven wind in SN.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

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

- Measure difference in average energy of **antineutrinos** and **neutrinos**. If large, wind will be neutron rich. If it is small, wind will be proton rich and likely a problem for r-process.
- Composition (Y_e) of wind depends on anti-neutrino energy (Y-axis) [results from ~20 SN1987A events shown] and energy of neutrinos (X-axis). Energy of neutrinos, not yet measured, depends on properties of n rich gas (nu-sphere).



Present SN simulations find too few neutrons for (main or 3rd peak: Au, actinides) r-process. Suggests this is not r-process site.

There's gold in them there galaxies!

- Prospecting the universe with ghost particles (neutrinos) and oscillations of space-time (gravitational waves).

Neutrinosphere and nearly unitary gas

- Neutrinosphere is at subnuclear densities (~ 1/100 of n_0) but it is not a free nucleon gas.

- Neutron-neutron scattering length is very long, comparable to or greater than average distance between nucleons at neutrinosphere density.

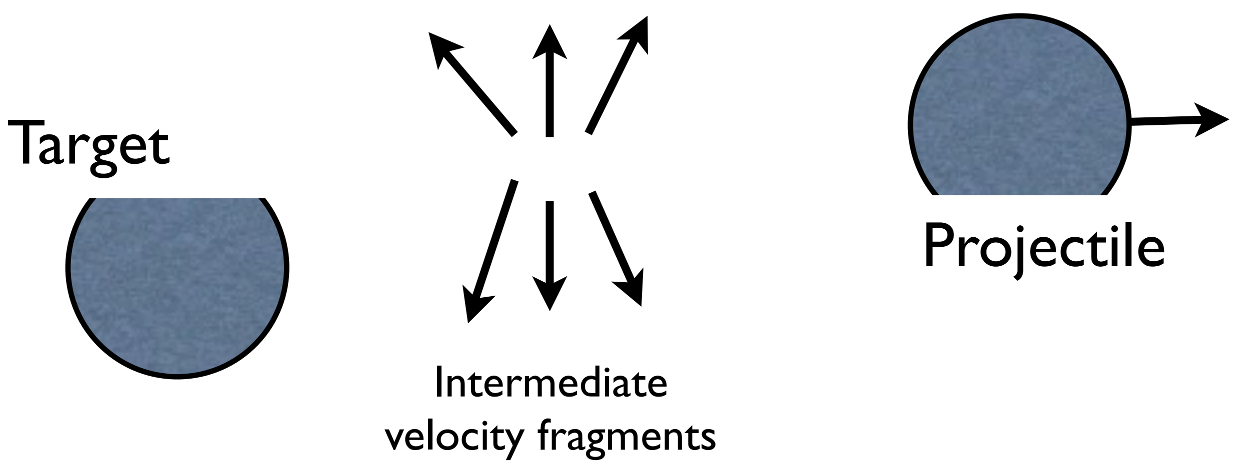
- Can be significant symmetry energy shift (for charged current) and correlation (for neutral current) corrections to neutrino interactions even at "low" densities.

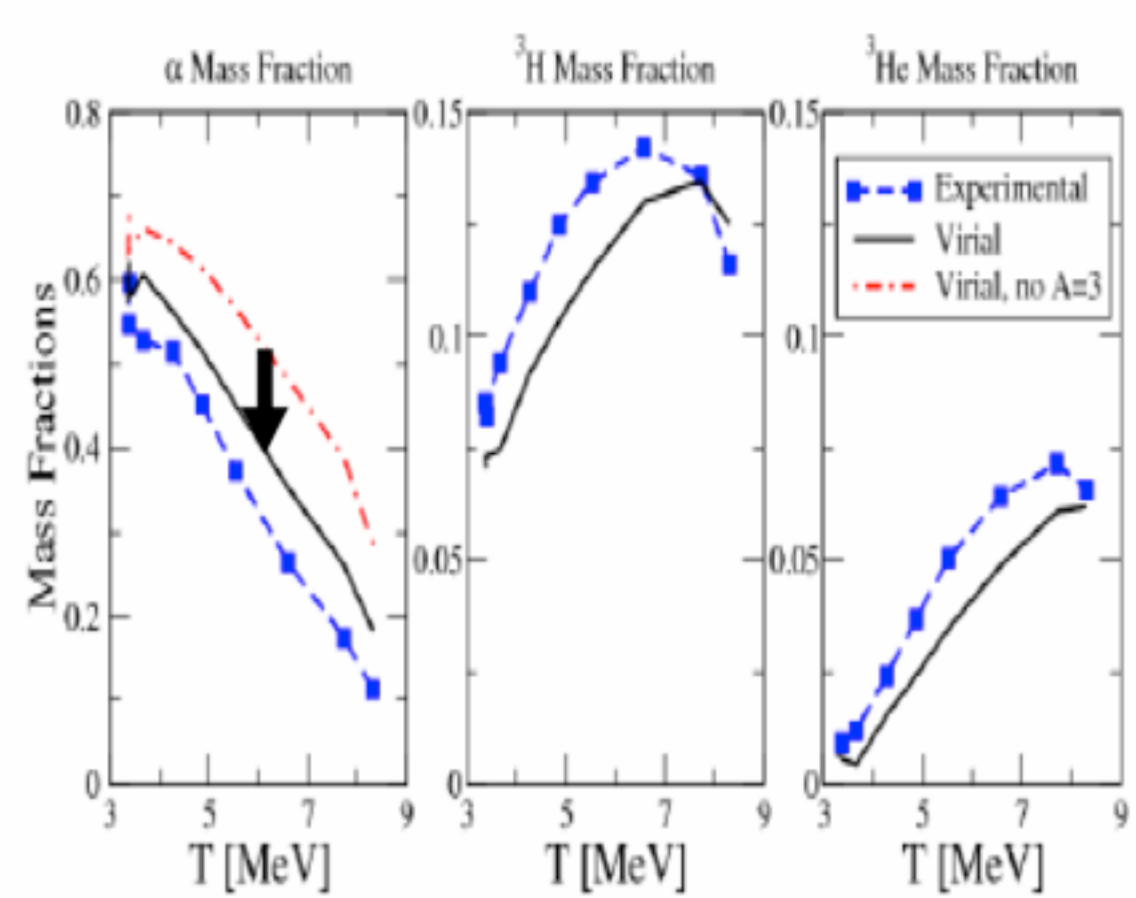
Simulating the supernova neutrino-sphere with heavy ion collisions

- 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

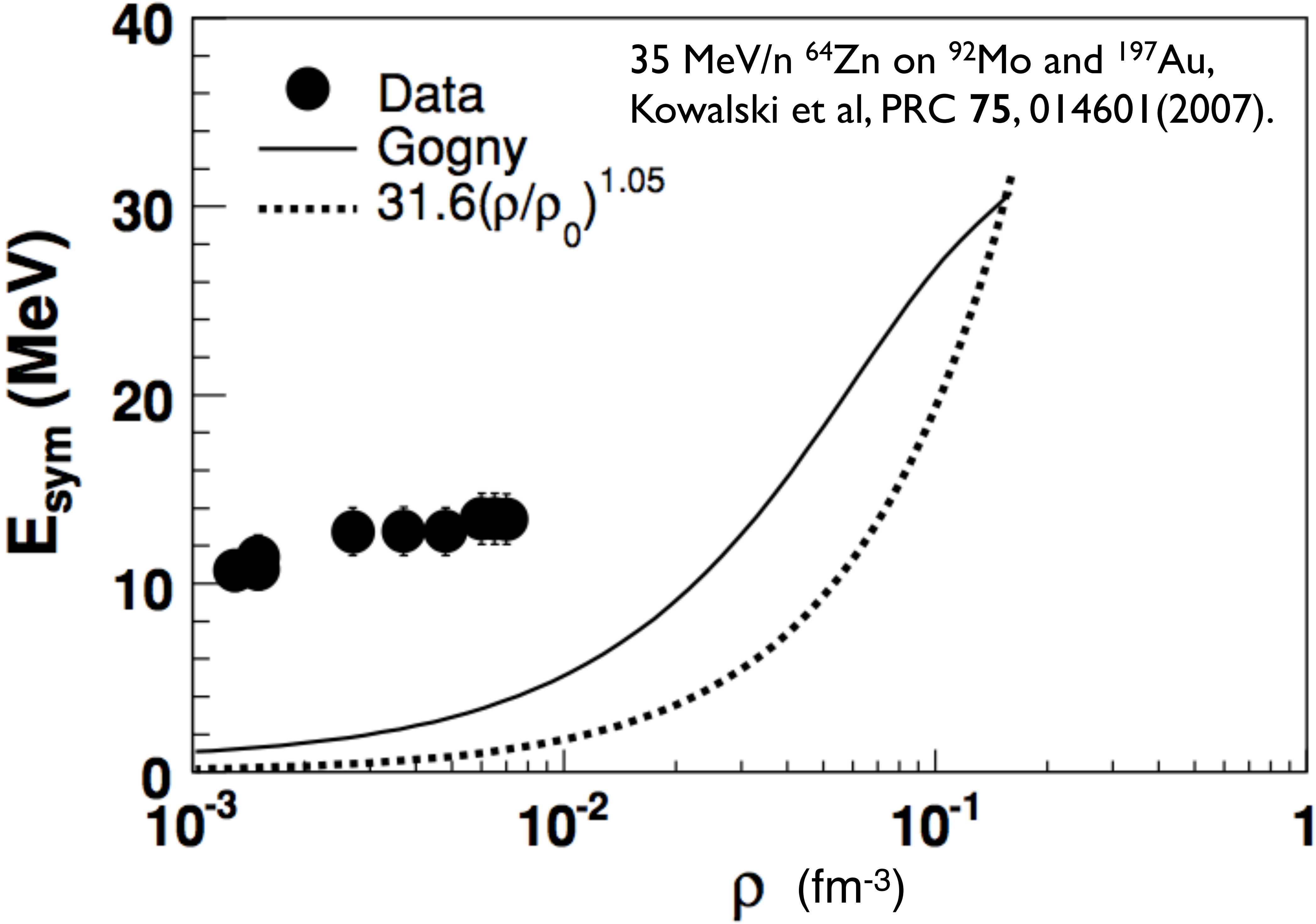
In a peripheral HI collision at say 30 MeV/A, study intermediate velocity fragments that come from warm low density region.





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 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)

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

Correlation corrections

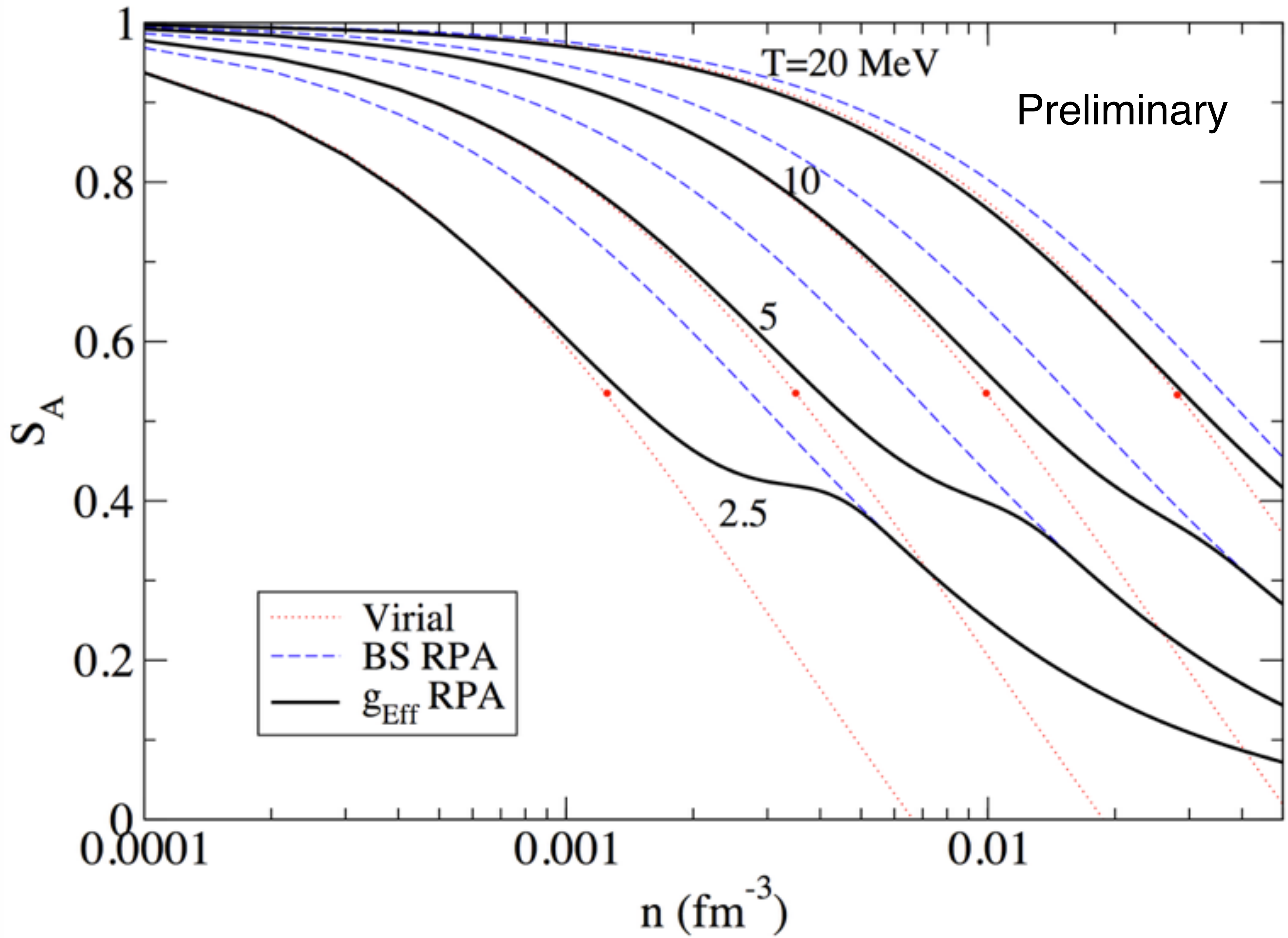
- Neutral current cross sections modified by vector (density) S_v and axial (spin) S_a response functions.

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

- 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.

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

Axial response of neutron matter



L. Caballero
Evan O'Connor
A. Schwenk

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

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 opacities and neutrino atmospheres for predicting neutrino spectra, explosion mechanism, and nucleosyn.

Neutrino Oscillations

- Fundamental, complicated, and rich.
- Nonlinear problem, neutrino self-interactions depend on background nu flavors.
- Shock breakout burst, clean source of nu_e to probe new oscillations such as neutrino to antineutrino that could be resonantly enhanced.
- Probably determine neutrino mass ordering in terrestrial experiments.
- Use SN to probe for new physics such as sterile neutrinos.

Neutrinos

- Important to measure well electron neutrino (DUNE), electron antineutrino (SuperK) and nu_x spectra from next galactic SN.
- Large n-n scattering length implies significant symmetry energy (charged current) and correlation (neutral current) corrections to nu interactions near neutrinosphere.
- Use Heavy Ion collisions to simulate neutrinosphere and measure EOS, light cluster composition, symmetry energy, neutrino response … of warm, low density, neutron rich matter.
- Supported by DOE DE-FG02-87ER40365 and DE-SC0008808 (NUCLEI SciDAC Collaboration).