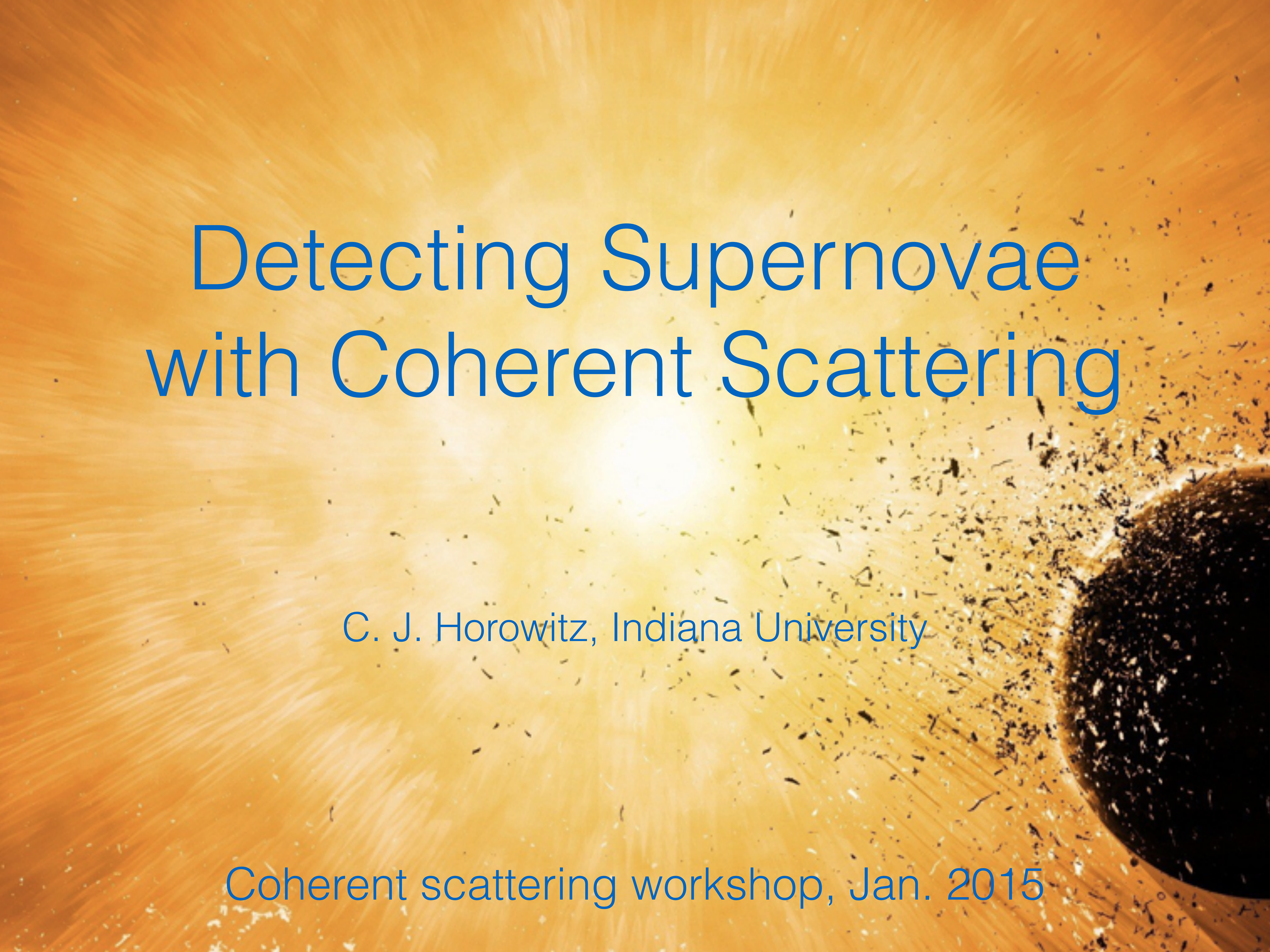
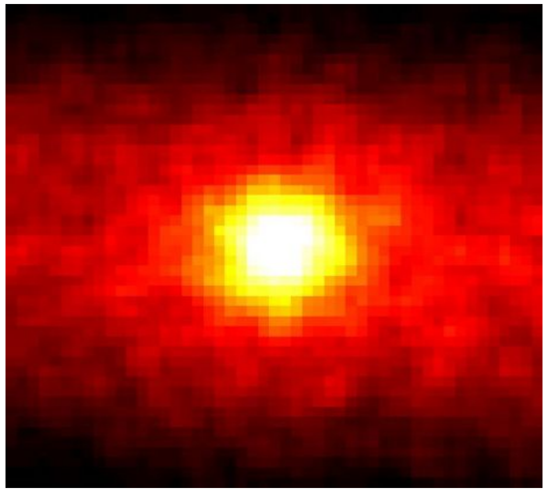


Detecting Supernovae with Coherent Scattering

C. J. Horowitz, Indiana University

Coherent scattering workshop, Jan. 2015

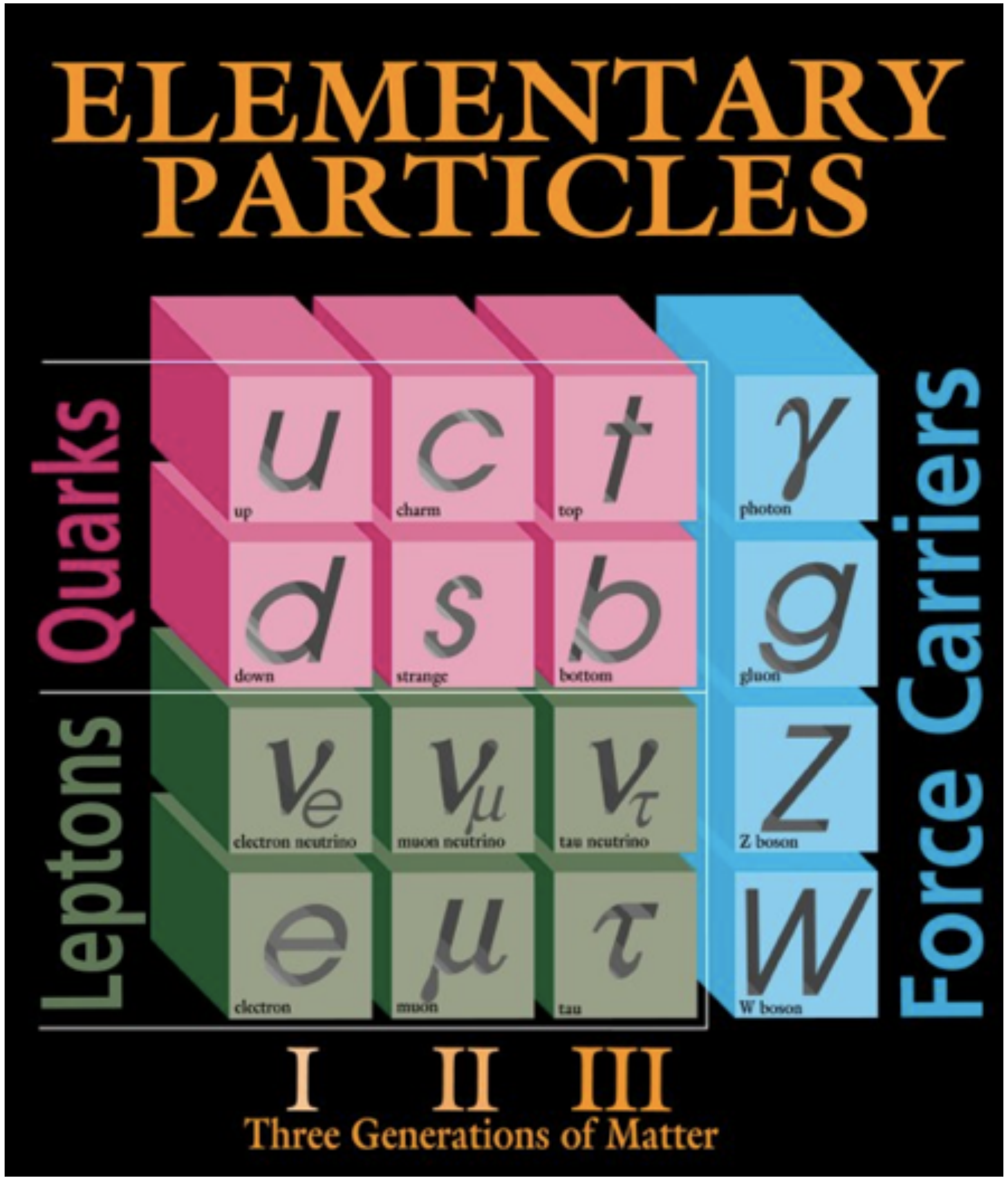
Supernova Neutrinos



Sun in neutrinos

- Core collapse supernova radiates gravitational binding energy of a neutron star ~ 0.2 $M_{sun}c^2$! in 10^{58} neutrinos of about 10 MeV each.
- All three flavors (e, mu, tau) of neutrinos and anti-neutrinos are radiated.
- Historic detection of ~20 **neutrinos** from SN1987A .
- New underground dark matter, solar nu,... experiments will be sensitive to nu from the next galactic supernova (SN).
- Expect ten thousand or more events from next galactic SN!
- Neutrinosphere is region of last scattering where neutrinos decouple. Neutrinos very roughly are emitted with the temperature of neutrinosphere.
- View SN in neutrinos, see neutrinosphere which is a neutron rich gas with T~5MeV (observed from 1987A), and a low density 1/1000 to 1/10 of n_0. Properties of this region important for SN simulations.

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.

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.
- Mu and tau neutrinos have only neutral current reactions (not enough energy to make muons) and so decouple at highest energies.
- Electron antineutrinos capture on protons, nu-bar+p->n+e^+, while neutrinos capture on neutrons, nu+n->p+e. Matter is neutron rich so neutrinos have large opacity. Therefore electron neutrinos are emitted with lowest energy.
- Expect order E(mu, tau) > E(anti-nu_e) > E(nu_e).

SN neutrinos and r-process nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Seed nuclei captures many n and decay. **What makes all the neutrons?**
- **Neutrinos:** 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.

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

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

- 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.

Searching for El Dorado with supernova neutrinos

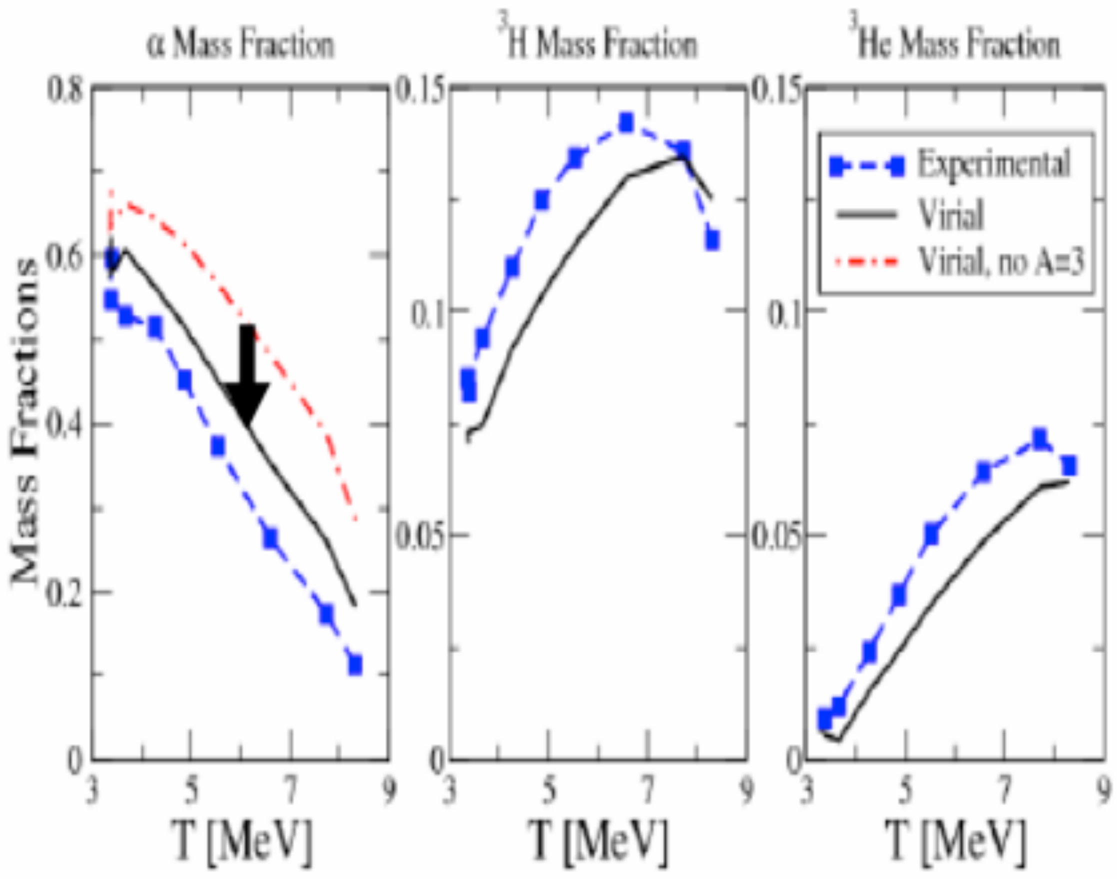
Important to measure energy of both anti-nu (SK) and neutrinos (liquid argon?).

ΔE depends on some nuclear physics including symmetry E at low densities.

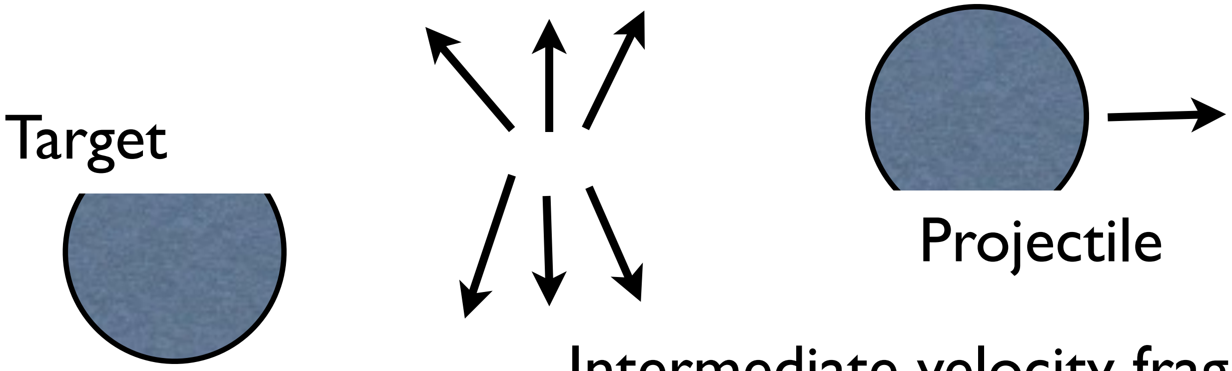
However, present SN simulations find too few neutrons.

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 ~$\rho_0/100$)
- Neutron rich system with some light nuclei ^{4}He, ^{3}He, ^{3}H... anti-neutrinos capture on protons, binding them into light nuclei reduces opacity. Neutrinos capture on plentiful free neutrons. --> important for ΔE.
- Can study neutrinosphere like conditions with heavy ion collisions in lab.



Composition of intermediate velocity fragments in 35 MeV/n ^{64}Zn on ^{92}Mo and ^{197}Au: Data (blue squares) Kowalski et al, PRC **75**, 014601(2007). Virial EOS black



Target

Projectile

Intermediate velocity fragments

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

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

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

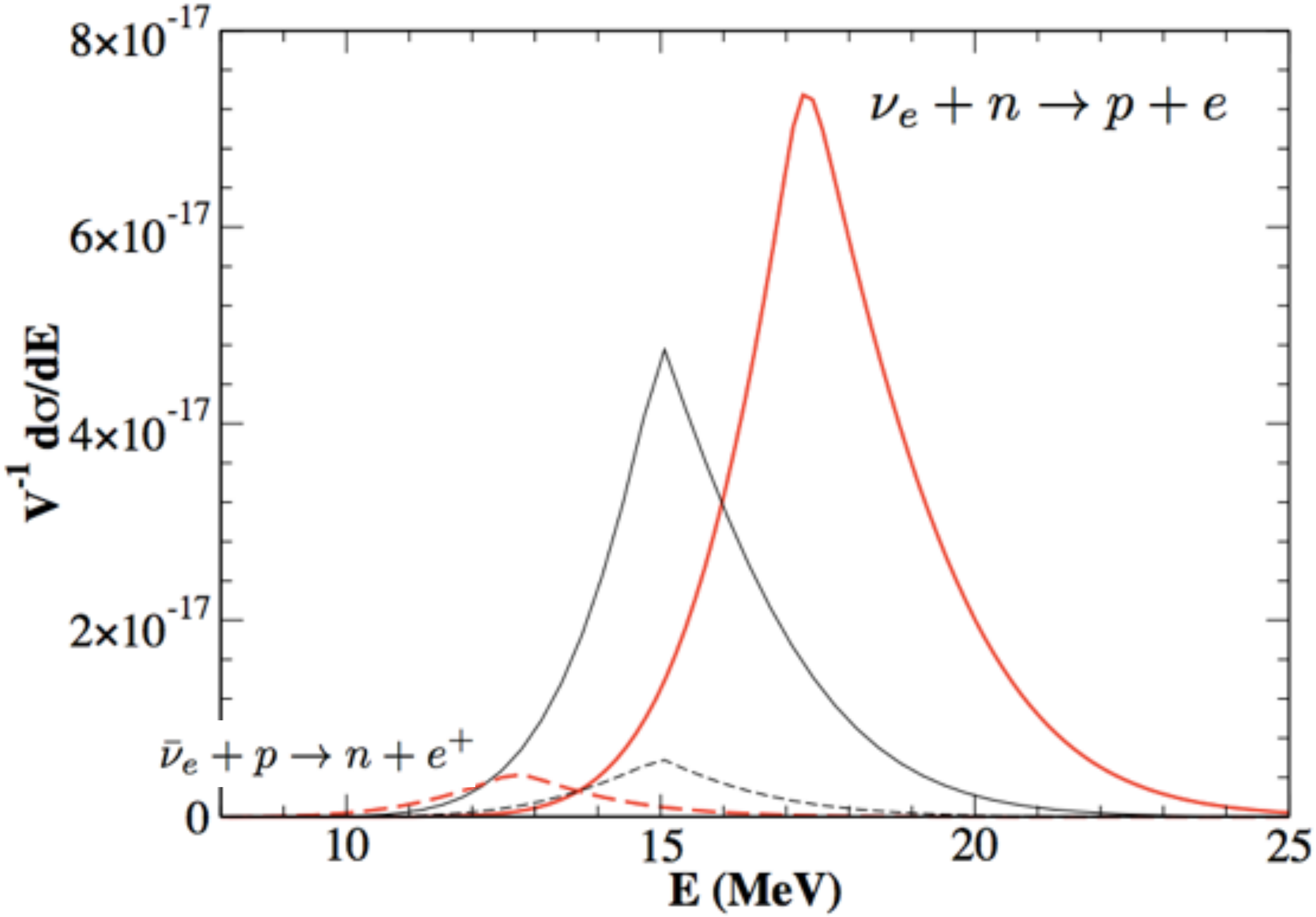
$$\frac{\sigma_{\nu_e}(\Delta U)}{\sigma_{\nu_e}(0)} = \frac{(E_\nu + \Delta U)^2[1 - f(E_\nu + \Delta U)]}{E_\nu^2[1 - f(E_\nu)]}.$$

- 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

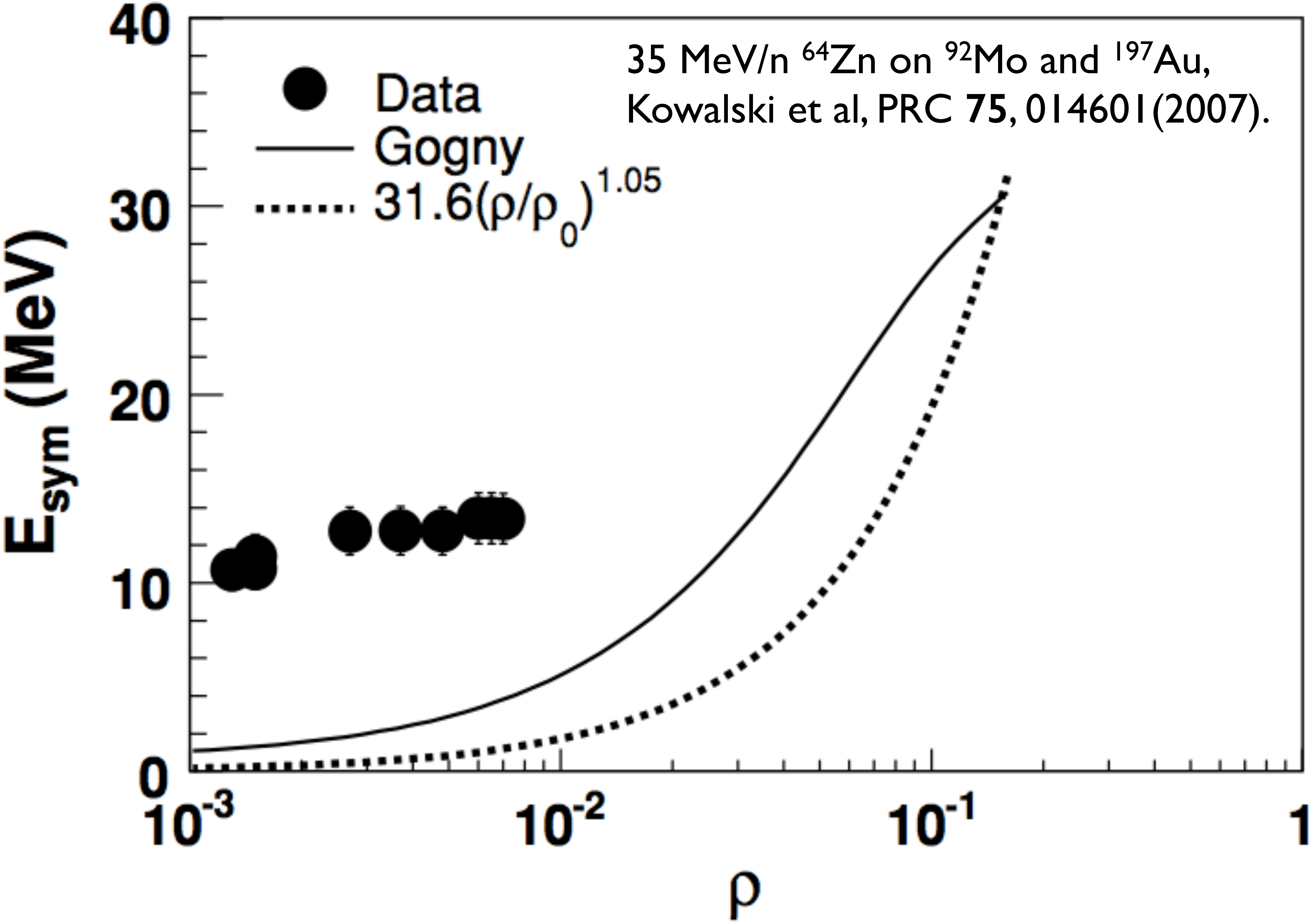
Neutrino and antineutrino cross sections

- 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.


35 MeV/n ^{64}Zn on ^{92}Mo and ^{197}Au, Kowalski et al, PRC **75**, 014601(2007).

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)

SN neutrinos and r-process nucleosynthesis

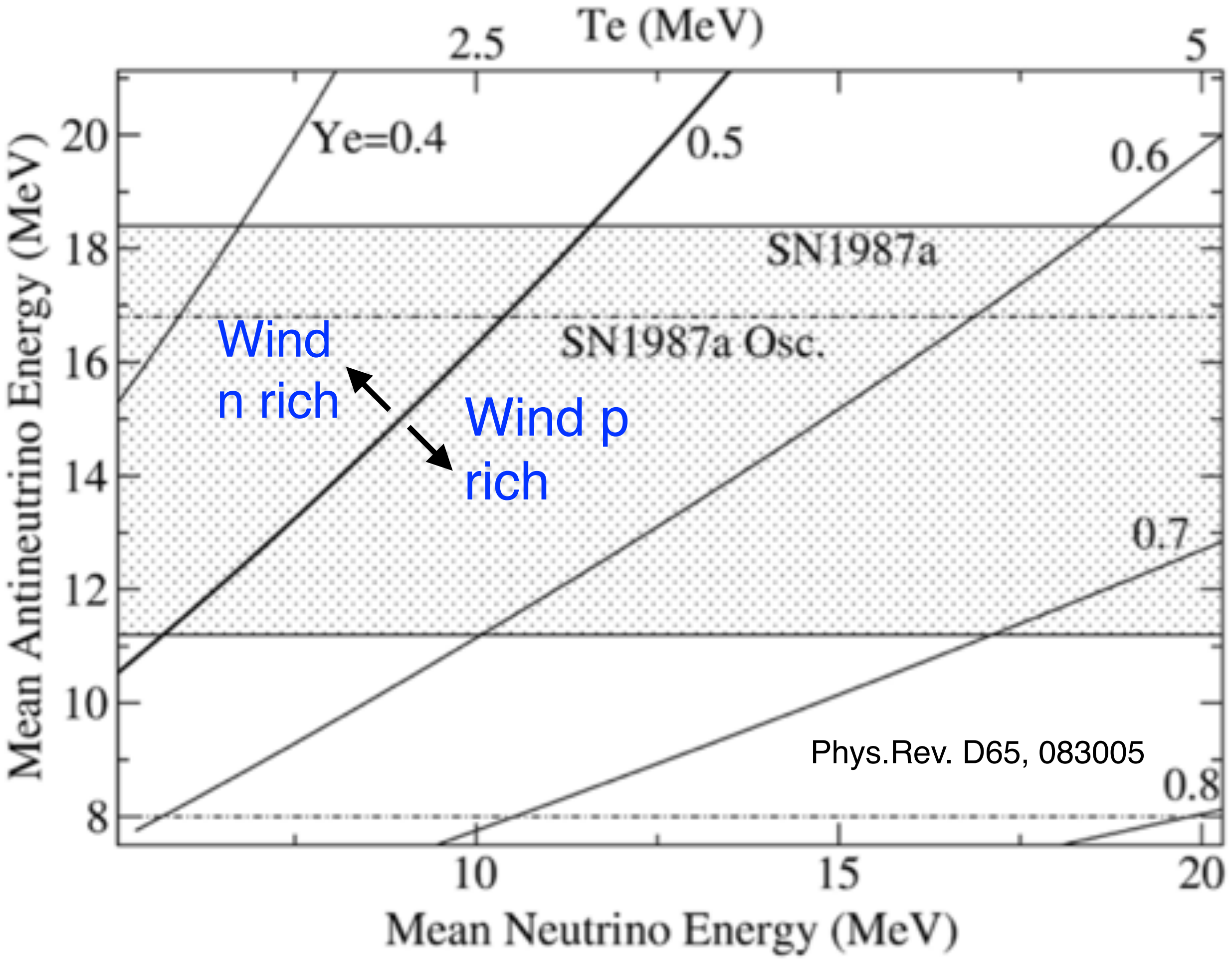
- Important alternative site for the r-process is the neutrino driven wind in core collapse supernovae.

- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino 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).



Phys.Rev. D65, 083005

LBNE measures X axis and Super-K measures Y axis.

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

Detecting the next galactic Supernova!

- Measuring difference between average energy of electron neutrinos and electron antineutrinos is very important for nucleosynthesis, oscillations, and nu detection.
- Measure total energy radiated, in all flavors of (active) neutrinos.
- What detectors are needed and what accuracy is possible?

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. [May measure radius from X-ray observations of NS.] Neutron star mass important diagnostic for explosion mechanism and mass cut for nucleosynthesis.

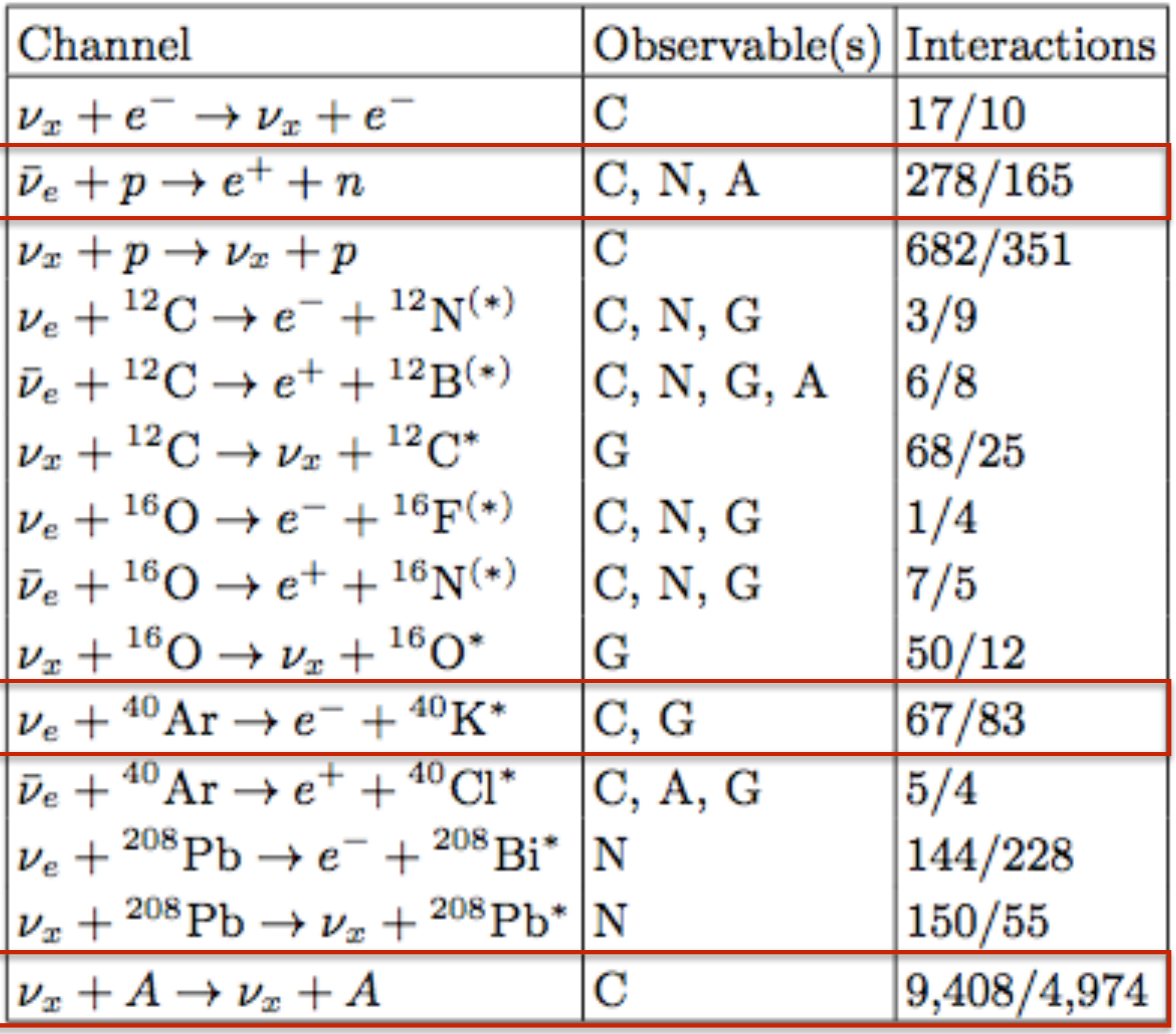
Big differences between simulations of neutrino experiments and supernovae!

- Monte Carlo simulations of the source and detector likely constitute our most detailed knowledge of a laboratory neutrino experiment. [You should believe them!]

- SN simulations likely have astronomical errors! [Example we can’t reproduce observed SN kinetic energies.] Do not assume all features, but one, of a simulation and try to only measure one thing! Be ready for possible big surprises.

- Wild neutrinos are wild for a reason!

Detection reactions



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

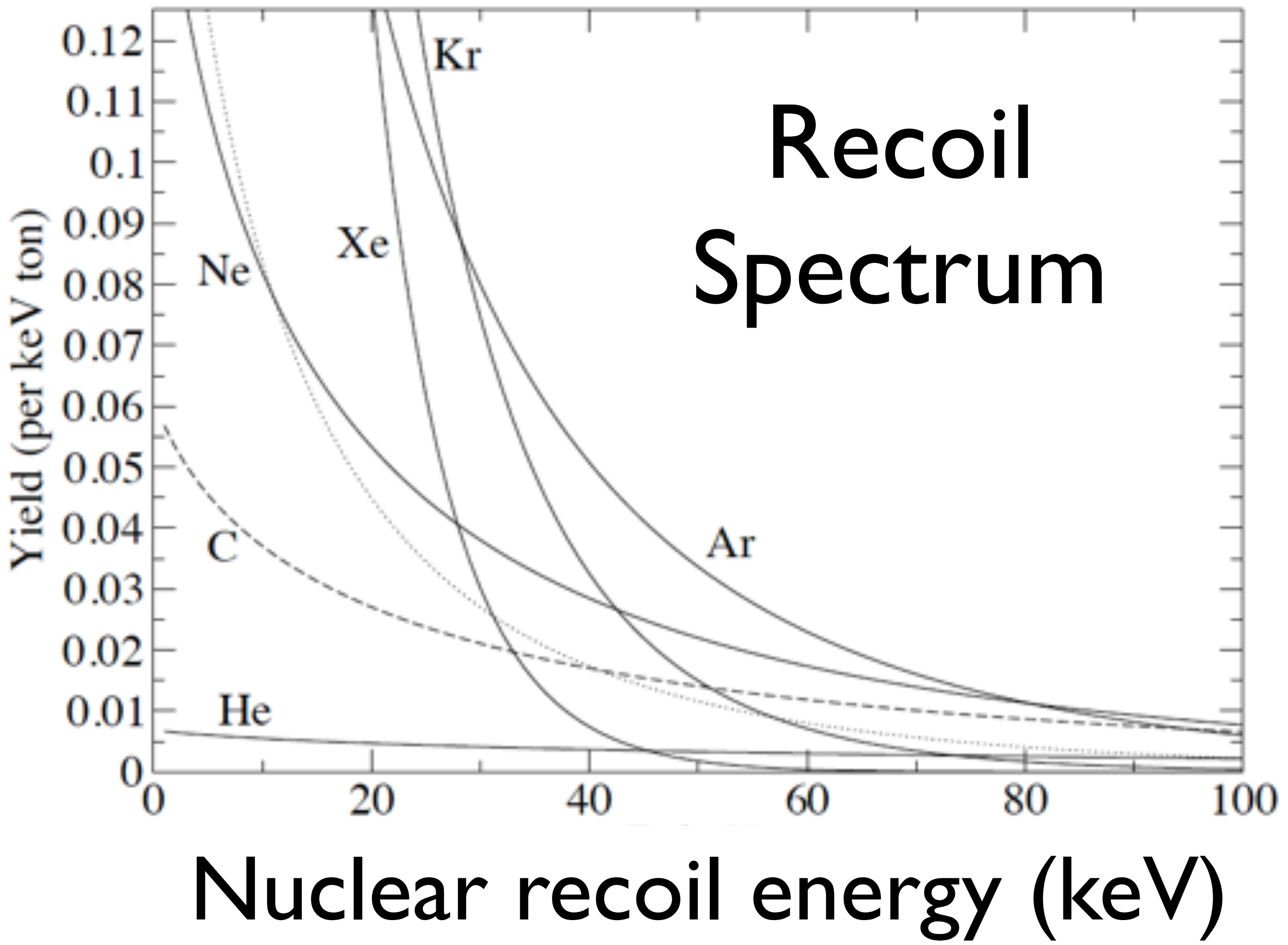
Can Measure total E via Neutrino-Nucleus Elastic Scattering

- 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!

Neutino-Nucleus Elastic Scattering in the Lab.

Cross sec depends on distribution of neutrons in a heavy nucleus.

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{Q_w^2}{4}F(Q^2)^2$$

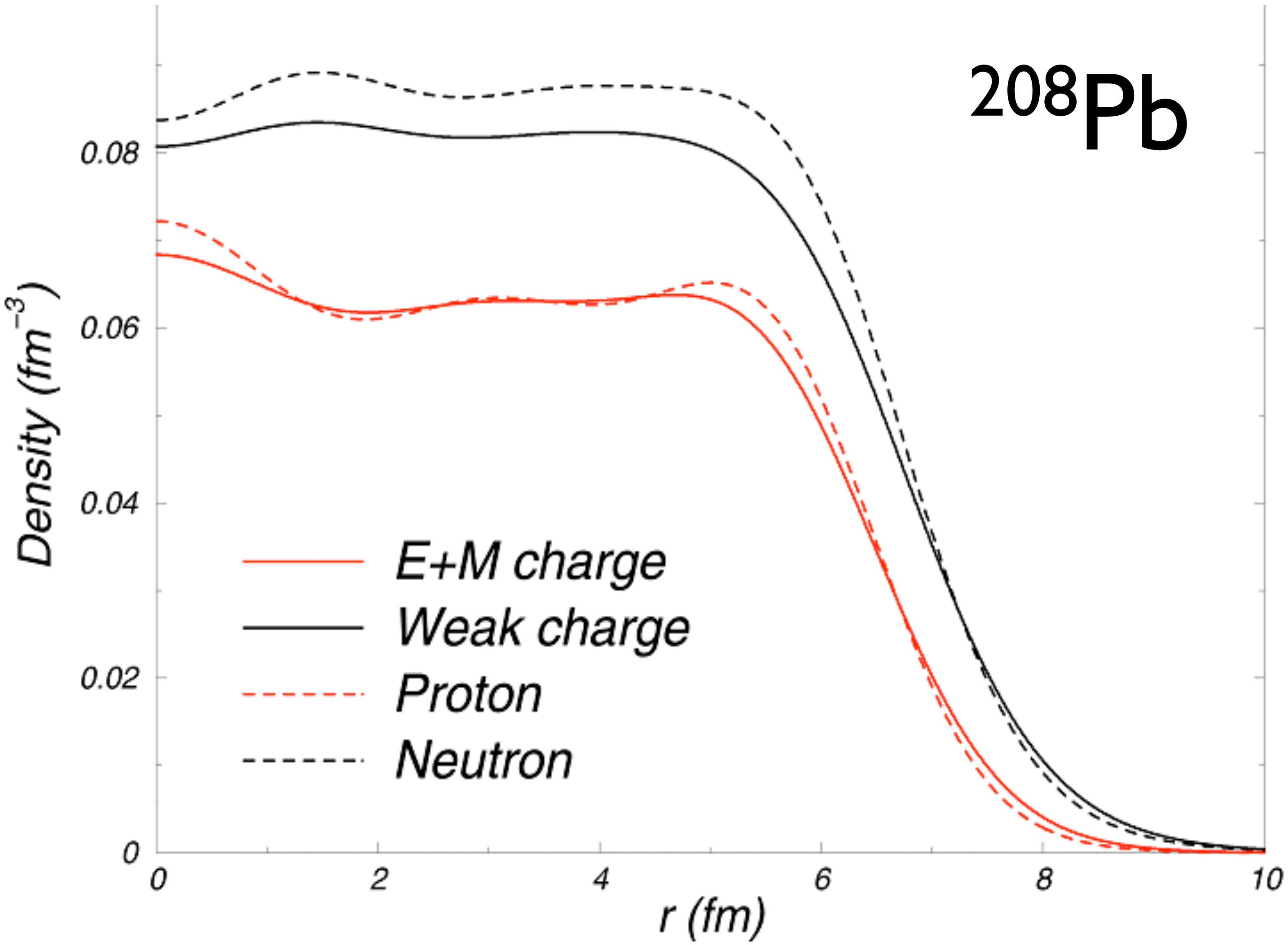
$$Q_W = \int d^3r \rho_W(r)$$

$$= N - (1 - 4\sin^2\Theta_W)Z$$

- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big: $Q_W^n = -1$



Can measure weak form factor.

$$F(Q^2) = \frac{1}{Q_w}\int d^3r \frac{\sin(Qr)}{Qr}[\rho_n(r) - (1 - 4\sin^2\Theta_W)\rho_p(r)].$$

Parity Violation measures same form factor

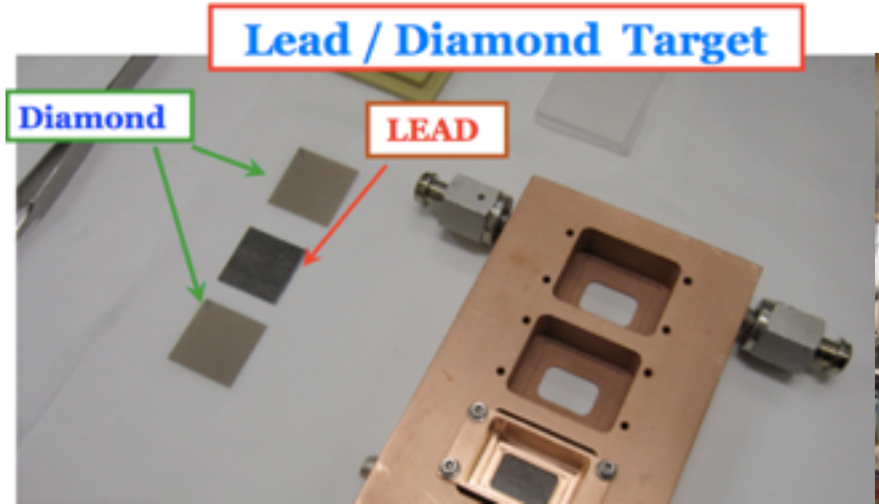
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons.

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

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

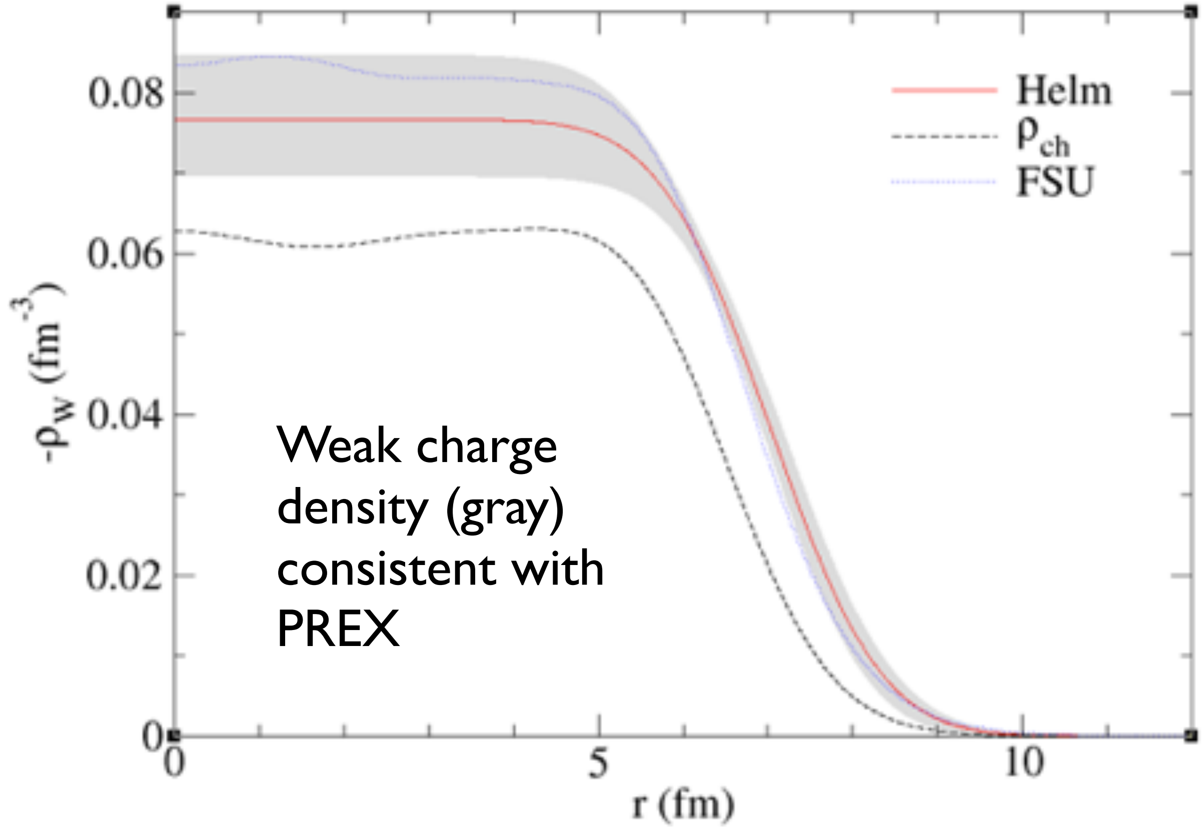
$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\mathrm{ch}}(Q^2)}$$

- PREX ran in 2010 in Hall A at JLAB to measure ^{208}Pb weak form factor and neutron radius.



PREX results from 2010 run

- 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb
- **A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm**
- Weak form factor at Q=0.475 fm^{-1}: F(Q) = 0.204 ± 0.028
- Radius of weak charge distr. to 3%. R_W = 5.83 ±0.18 ±0.03(model) fm
- Compare to charge radius R_{ch}=5.503 fm --> weak skin: $R_W - R_{ch}$ = 0.32 ± 0.18 ± 0.03 fm
- First observation that weak charge density more extended than (E+M) charge density --> weak skin.



Weak charge density (gray) consistent with PREX

- Future plans: **PREX-II** (approved 2016) Run ^{208}Pb again for more statistics. Goal: R_n to 1% (±0.06 fm).
- **CREX**: Approved follow on for ^{48}Ca with goal: R_n to ±0.02 fm. This is 0.5% ! (R_n about 3.6 fm)

Alas, I think it will be very hard for nu scattering to beat PV.

Coherent Catch 22

- Because no one has yet seen coherent scattering (because PACs keep saying no), we can’t accurately measure new physics with this first experiment, so the PAC answer is still no.
- Solution: Just do it! Coherent cross sections are so large they will open up new neutrino technology and allow qualitatively new measurements in future.
- Examples: New sterile osc searches with near and far, flavor blind, coherent detectors.
- Separate Supernova nu_x from anti-nu_x with both nu - p elastic and coherent nu - A detectors. Weak magnetism makes nu - p cross section larger than anti-nu - p while nu - A are equal.