Low density nuclear matter in Core-Collapse Supernova

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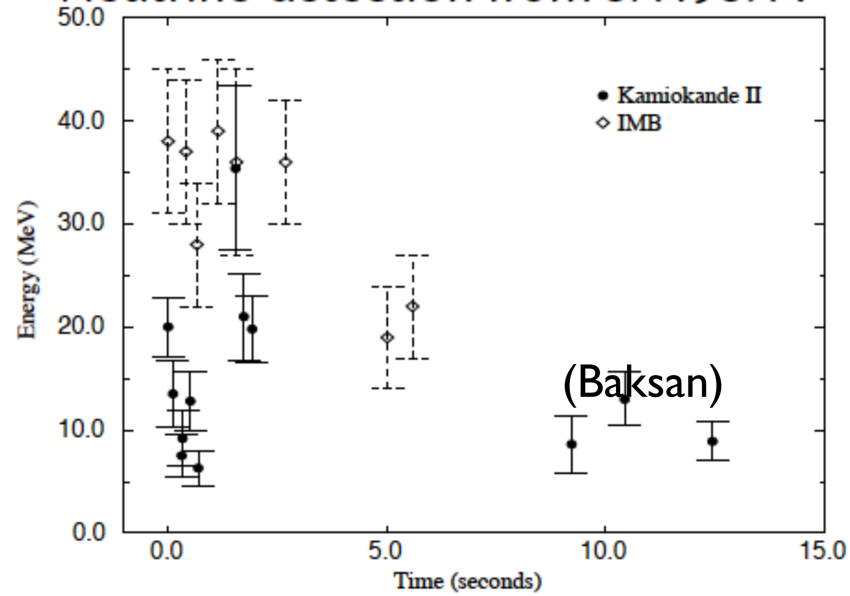
Background

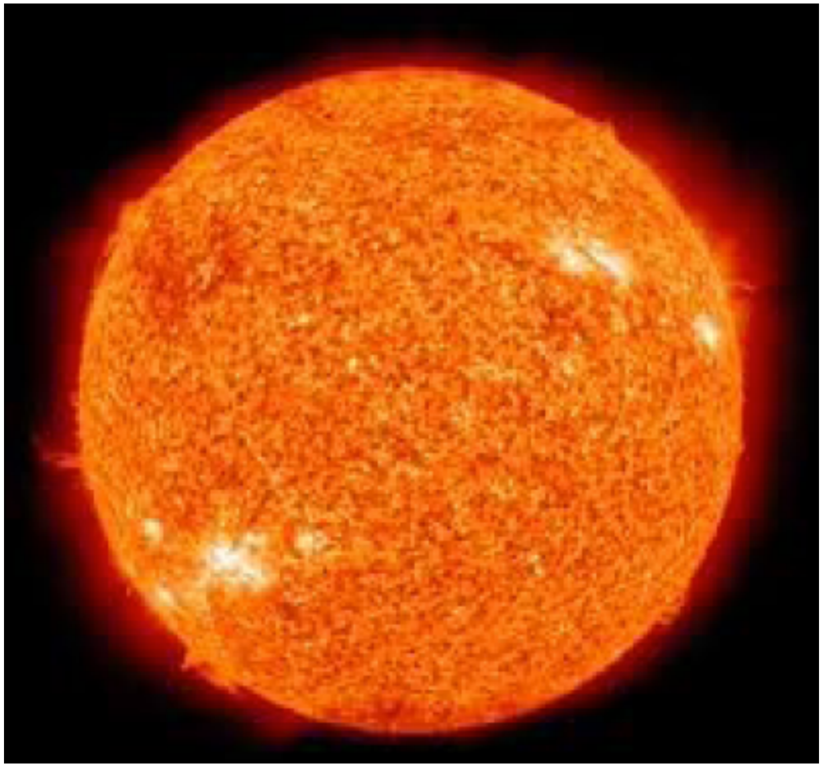
- Core collapse supernova: end of nuclear burning in M>8 Msun star
- Neutrinos carry information on the nuclear eos inside star
- Only ν observation - SN1987A
  - Time ~ 20 s
  - Energy ~ 10^{53} ergs
- Neutrino spectra from proto-neutron star (PNS) atmosphere determined by low density nuclear physics
- Caveat: neutrino flavor oscillations in the outer region complicate the interpretation

Neutrino detection from SN1987A



Neutrino-sphere

- Solar photo-sphere
  - Last scattering site of photon
  - A (quasi-static) layer about 100 km thick (compared to the 700,000 km radius of the Sun).
- Neutrino-sphere(s)
  - Last scattering site of neutrinos in proto-neutron star: $\sim 10^{12}$ g/cm^3, 5 MeV
  - Different for 6-flavor neutrinos
  - Evolve with time (~1 min)

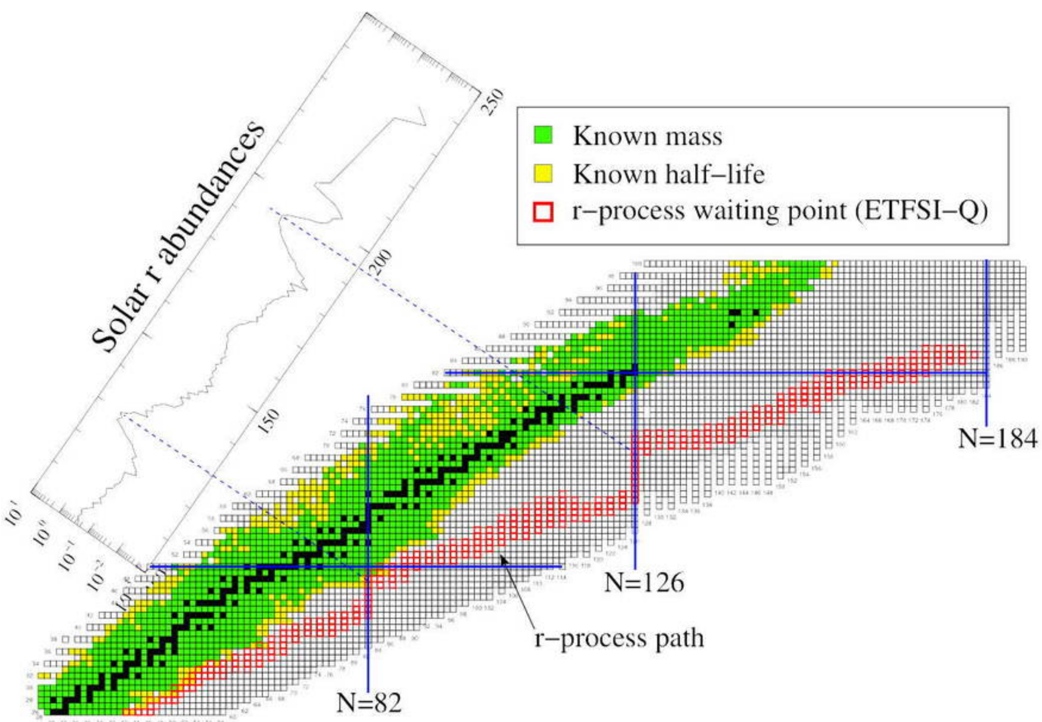


- Conditions can be realized in Heavy ion collision exp.

(Natowitz, this symposium)

r–process in PNS

- r-process (> iron) elements, rapid capture of seed nuclei on free neutrons, have unknown origin(s).
- Sites: PNS nu-driven wind, or neutron star mergers ejecta
- Neutrino spectra from PNS are key input for r-process: set electron (p) fraction in the wind



$$\nu_e + n \rightarrow p + e^-$$

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

- Setting the electron fraction:

$$Y_e \approx \frac{\lambda_{\nu_e}^{-1}}{\lambda_{\nu_e}^{-1} + \lambda_{\bar{\nu}_e}^{-1}} \approx \underbrace{\left(1 + \frac{\dot{N}_{\bar{\nu}_e}}{\dot{N}_{\nu_e}} \frac{(\varepsilon_{\bar{\nu}_e} - \Delta)^2}{(\varepsilon_{\nu_e} + \Delta)^2}\right)^{-1}}_{\text{Neutrino Spectra}}$$

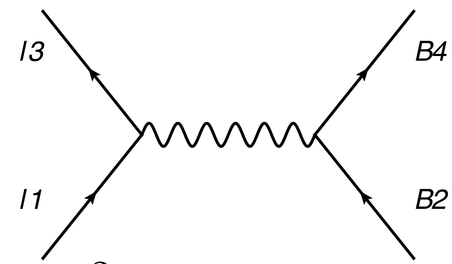
Neutrino-nucleon scattering

- Neutrinos couple to nuclear (isospin) density and (isospin) spin density responses:

V-A theory: $j^\mu(x) = \bar{\psi}(x)\gamma^\mu(C_V - C_A\gamma_5)(\tau_j)\psi(x)$

Non Relativistic limit: $\rightarrow C_V\psi^+(\tau_j)\psi\delta^{\mu 0} - C_A\psi^+\sigma^i(\tau_j)\psi\delta^{\mu i}$

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta dE_3} = \frac{G_F^2}{4\pi^2}E_3^2(1-f_3(E_3))$$
$$\times[C_V^2(1+\cos\theta)S_\rho(q_0,q) + C_A^2(3-\cos\theta)S_\sigma(q_0,q)]$$



- Free Fermi gas response functions:

$$S_{\rho,\sigma}(q_0,q) = \frac{1}{2\pi^2}\int d^3p_2\delta(q_0+E_2-E_4)f_2(1-f_4),$$

Dispersion $E_i(p) = M_i + p^2/2M_i$

same for n, p; response is peaked around $q_0 \sim 0$.

Neutrinos response in mean field

- Mean field models capture most important nuclear physics around normal nuclear density .
- Dispersion relation of quasi-particle from EOS:

$$E_i(k) = \sqrt{k^2 + M^{*2}} + U_i,$$
$$U_n - U_p = 40\frac{n_n - n_p}{n_0}\text{MeV}$$

- ν_e response function is peaked at

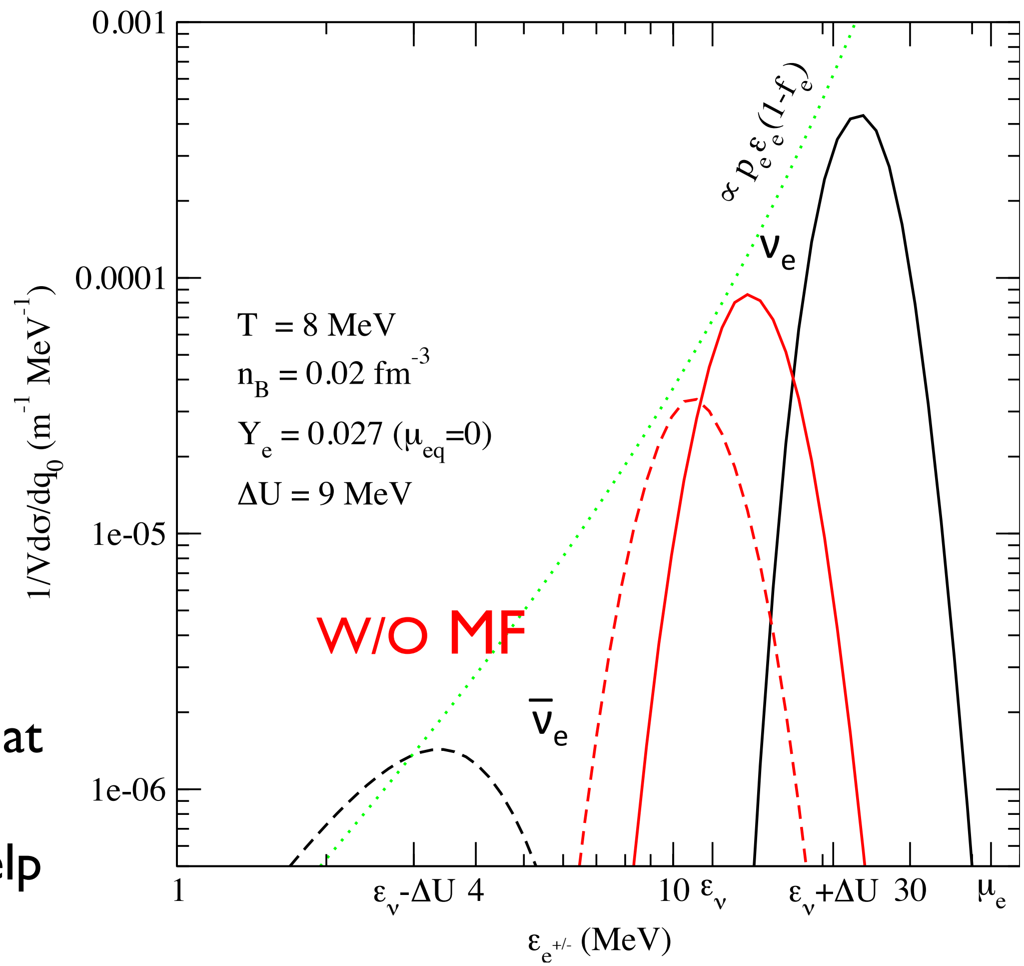
$$q_0 \approx U_n - U_p$$

~ nuclear symmetry energy

- Un−Up > 0:

ν_e decouple at lower temp., while $\bar{\nu}_e$ at higher temp. May reduce electron fraction in neutrino driven wind – help r-p nucleosynthesis

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

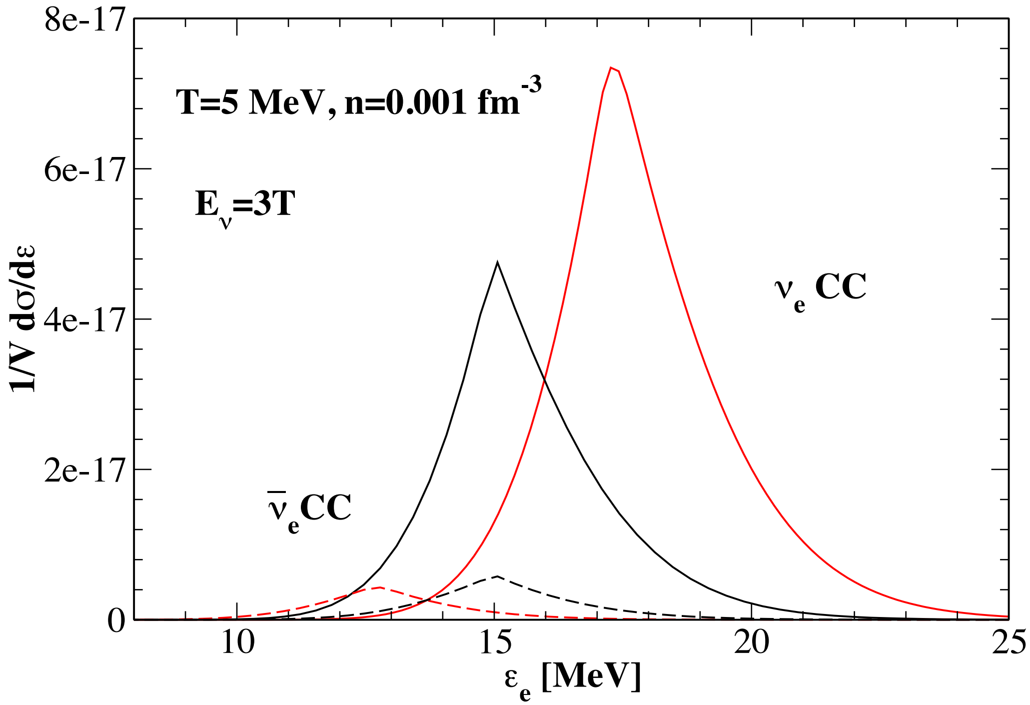


[Roberts et al (2012)]

Neutrino response in virial expansion of nucleon+deuteron

- Virial EOS of n, p: $$P = \frac{2T}{\lambda^3}\{z_n + z_p + (z_n^2 + z_p^2)b_n + 2z_p z_n b_{pn}\},$$
  - 2^{nd} virial coeff. b_n, b_{pn} from mod. ind. scattering phase shifts
  - dominant for matter around neutrino-sphere
- Single particle energy (MF) shift:

$$U_n = \mu_n - \mu_n^f = -\lambda^3 T(n_n \hat{b}_n + n_p b_{pn}) + O(n_i^2)\,.$$



- W/O MF shift: dσ ~ density of n or p
- W MF shift

[Horowitz, Shen, O'Connor, Ott, 2013]

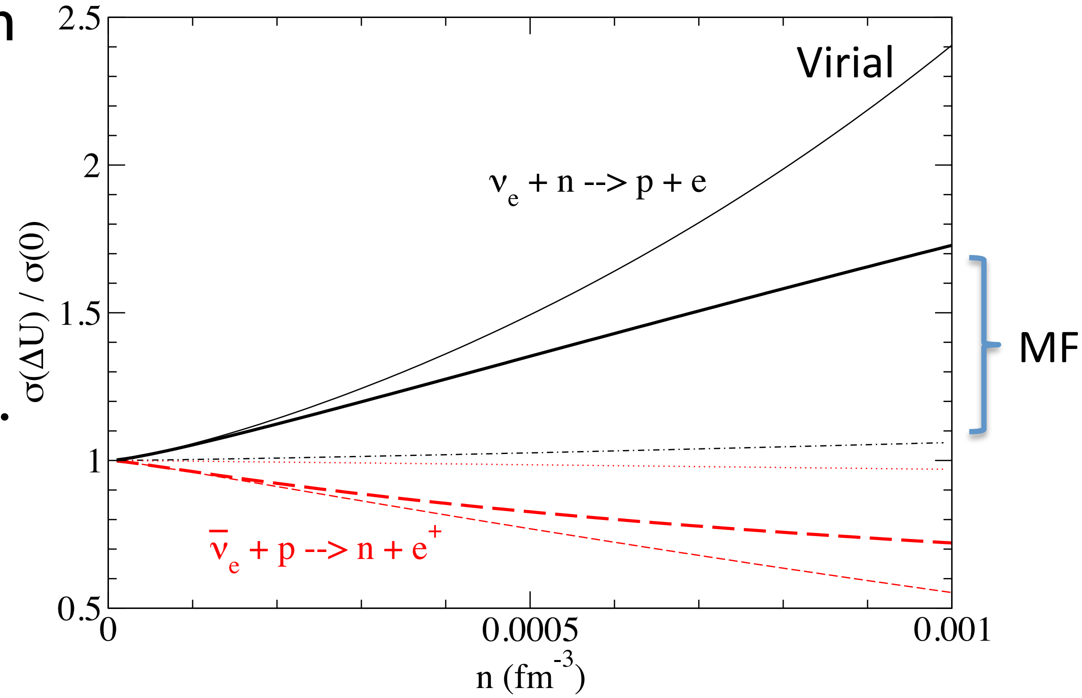
Neutrino response in virial expansion of nucleon+light nuclei

- ratio of cross sections

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

- effect due to n-p correlation (deuteron) larger than mean field.
- may reduce electron fractions in neutrino driven wind compared to mean field.

- Next to explore: higher order terms; momentum dependence of Ui.



[Horowitz, Shen, O'Connor, Ott, 2013]

Neutrino sphere in virial expansion

- Grand partition function

$$\frac{\log Q}{V} = \frac{P}{T} = \frac{2}{\lambda_n^3}[z_n + z_p + (z_p^2 + z_n^2)b_n + 2z_p z_n b_{pn}]$$
$$+\frac{1}{\lambda_\alpha^3}[z_\alpha + z_\alpha^2 b_\alpha + 2z_\alpha(z_n + z_p)b_{\alpha n}]$$
$$+\sum_i \frac{1}{\lambda_i^3} z_i \Omega_i$$

- ➢ nucleon-nucleon
- ➢ nucleon-alpha
- ➢ nuclei

1. Light species: nucleon and alpha — Horowitz & Schwenk '05
2. Heavy species: 8980 nuclei — FRDM mass table: Moller et al '97. Δ_{rms} ~ 0.6 MeV

Chemical equilibrium ------ $\mu_i = Z\mu_p + N\mu_n \quad z_i = z_p^Z z_n^N e^{(E_i - E_i^C)/T}.$

Coulomb correction ------ $E_i^C = \frac{3}{5}\frac{Z_i^2\alpha}{r_A}[-\frac{3}{2}\frac{r_A}{r_i} + \frac{1}{2}(\frac{r_A}{r_i})^3]$

Nuclear partition function Ω_i ---- Fowler, Engelbrecht & Woosley, '78

Nuclei spacing

$$\frac{4}{3}\pi r_i^3 (\sum_j Z_j n_j) = Z_i$$

3. Solving: z_n, z_p, r_i:

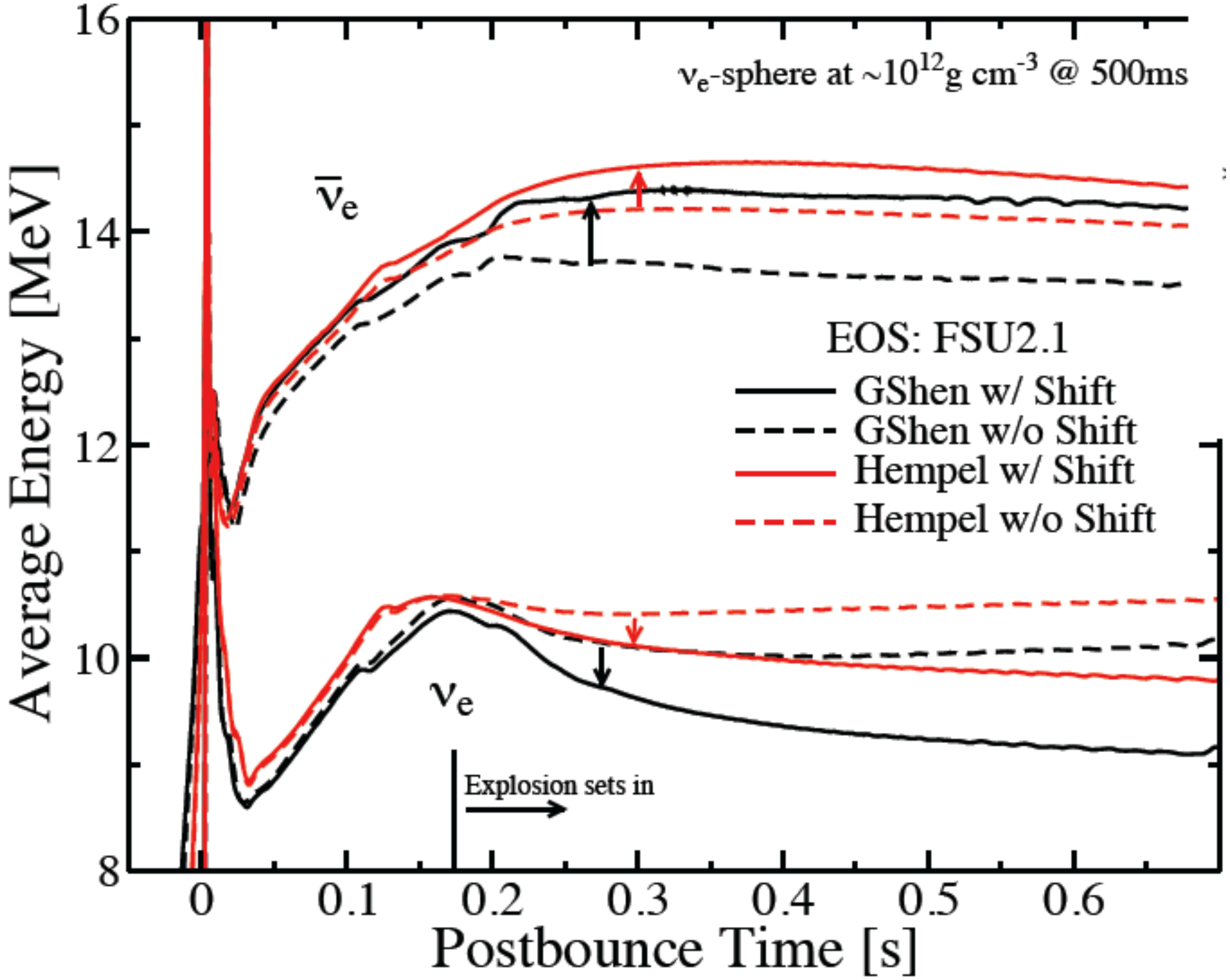
$n_B = n_n + n_p + 4n_\alpha + \sum_i A_i n_i$ = Baryon

$Y_P = (n_p + 2n_\alpha + \sum_i Z_i n_i)/n_B$ = Charge

4. Mass fraction: $X_a = A_a n_a / n_B$

[EOS: Shen, Horowitz, Teige, 2010]

Neutrino spectra from eos in virial expansion



Evan O'Connor, Carly Berard 2013. Preliminary.

- black: virial; red: NSE.
- Preliminary early time result sees larger shifts in both spectra in virial eos.

Summary & Outlook

- Nuclear matter property at low density in core collapse supernova could be determined in a controlled way. It is also possible to be realized in heavy ion collision exp.
- Neutrino spectra from PNS can be determined from EOS at low density, in a controlled method: a way to predict the messenger (neutrino).
- It is key input for r-process nucleosynthesis in supernova wind.

Thank you !