Neutrino-sphere in supernova and symmetry energy

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Outline

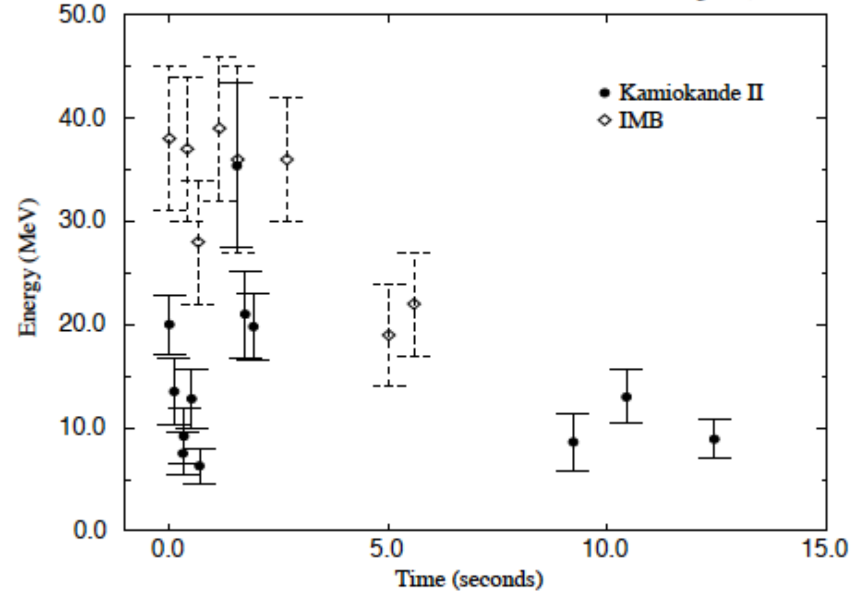
1. Intro. to neutrino-sphere in supernova
2. Equation of state around neutrino-sphere
3. ν-opacity around neutrino-sphere
4. Summary

Neutrino emissions from proto-neutron star

Single Observation – SN1987A

- ν carries away 99% of GR energy in SN explosion
- ν cooling PNS in ~ 1 minute
- Consistent with ~ 20 events / 20 s observed in SN1987A
- $\bar{\nu}_e$ events from Water Cerenkov detectors
- Interpretation of neutrino spectra - nontrivial

Neutrino detection from SN1987A



Neutrino spectra and luminosities important for:

- Neutrino oscillations (collective, MSW, vacuum)
- Nucleosynthesis in neutrino driven wind: ν p-process and r-process

Nuclear physics in PNS

Temperature [MeV]	0 ~ 60 (maybe higher)		
Proton fraction Y_p	0 ~ 0.6 (maybe higher in neutrino driven wind)		
Baryon Density [fm^{-3}]	1E-13	1E-2	1E0
Particle spacing [fm]	~1E5	~10	~1
Phases	Gas	Solid (low T)	Liquid

- Challenge: multi-scale, multi-component, multi-phase
- Covering full parameter space – combination of different methods
- Uncertainty in high density: hyperons, excited baryons, quarks
- Uncertainty in high temperature: meson excitations, etc

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: ~10^{12} g/cm^3, 5 MeV
  - Different for 6-flavor neutrinos
  - Evolve with time! (~1 min)

EOS around neutrino-sphere

Exp: multi-fragmentation in Heavy ion collsion: Natowitz et al

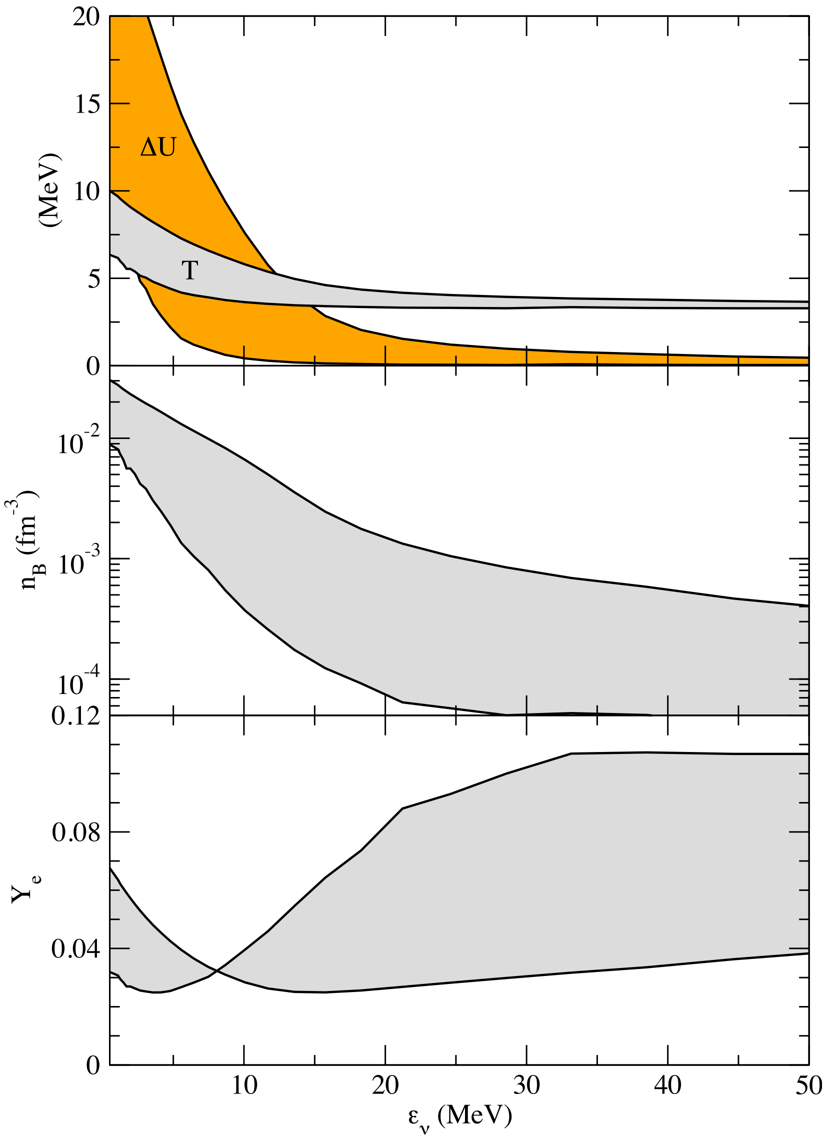
Neutron matter, T=0 (benchmark)

- Chiral EFT: Schwenk, Hebeler, …
- QMC: Carlson, Gezerlis, Gandolfi, …..
- QMC/Chiral EFT: Gezerlis et al

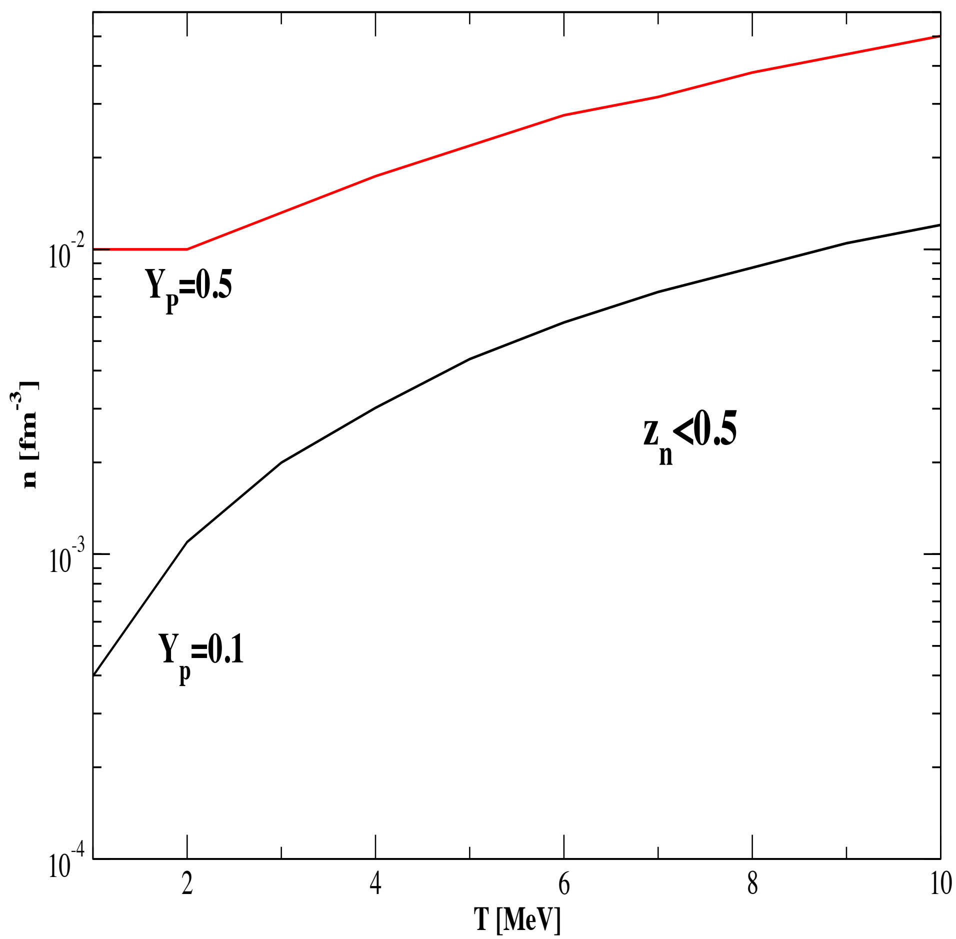
Nuclear matter, finite T

- Statistical method: Röpke, Typel, Wolter, …
- Virial expansion: Horowitz, Schwenk, Shen …

Virial expansion is valid around ν-sphere



Courtesy: Luke Roberts



Virial expansion of n, p to 2nd order

Low density: Ensemble of nucleons and nuclei

- Grand partition function in virial expansion

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

1

➢ nucleon-nucleon

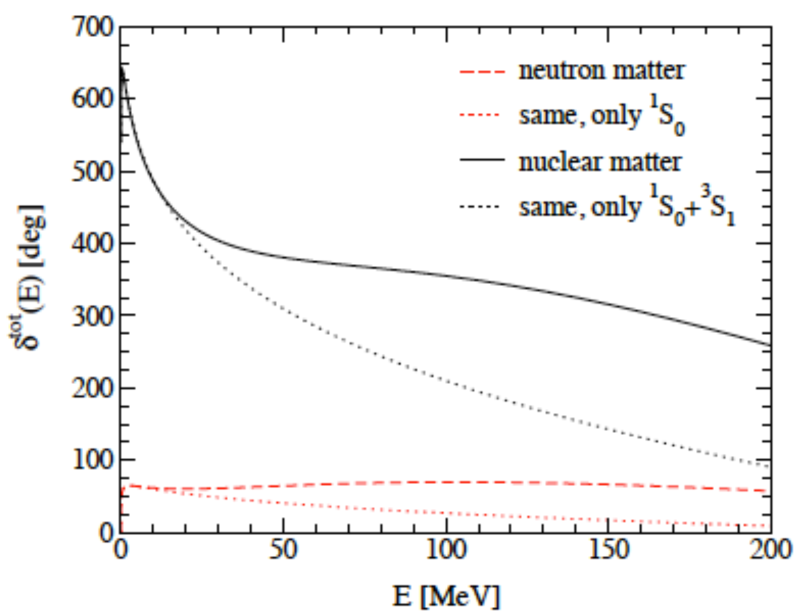
➢ nucleon-alpha

1. Nucleon and alpha: mod. ind. Horowitz, Schwenk '05

2^{nd} virial coef. b_2 determined from elastic scattering phase shifts: model-independent

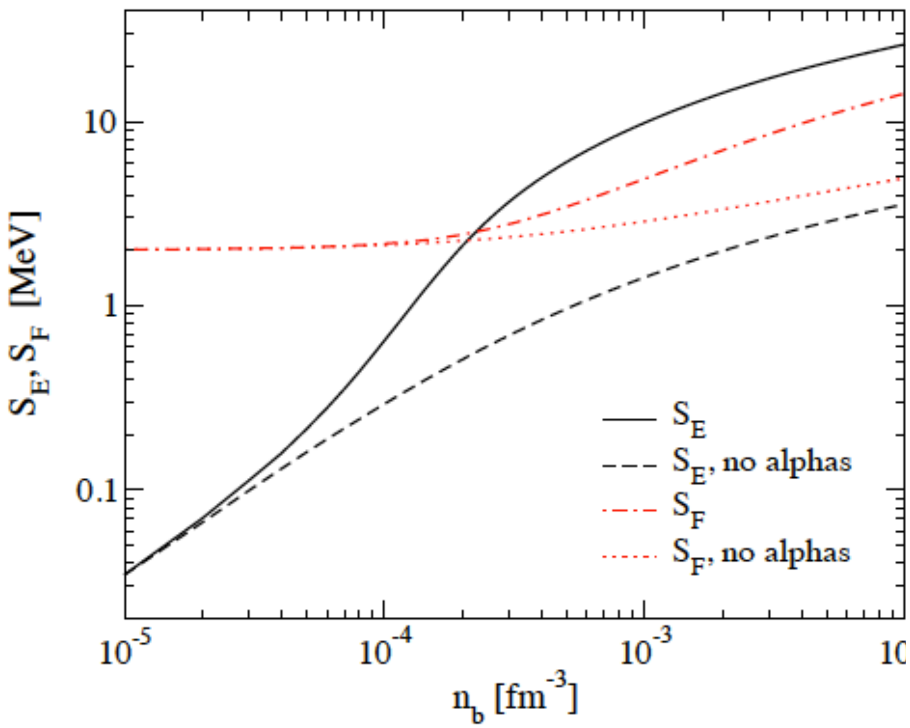
– b_n for n-n (p-p), – b_{pn} for n-p,
– b_α for alpha-alpha, – $b_{\alpha\text{-}n}$ for alpha-n

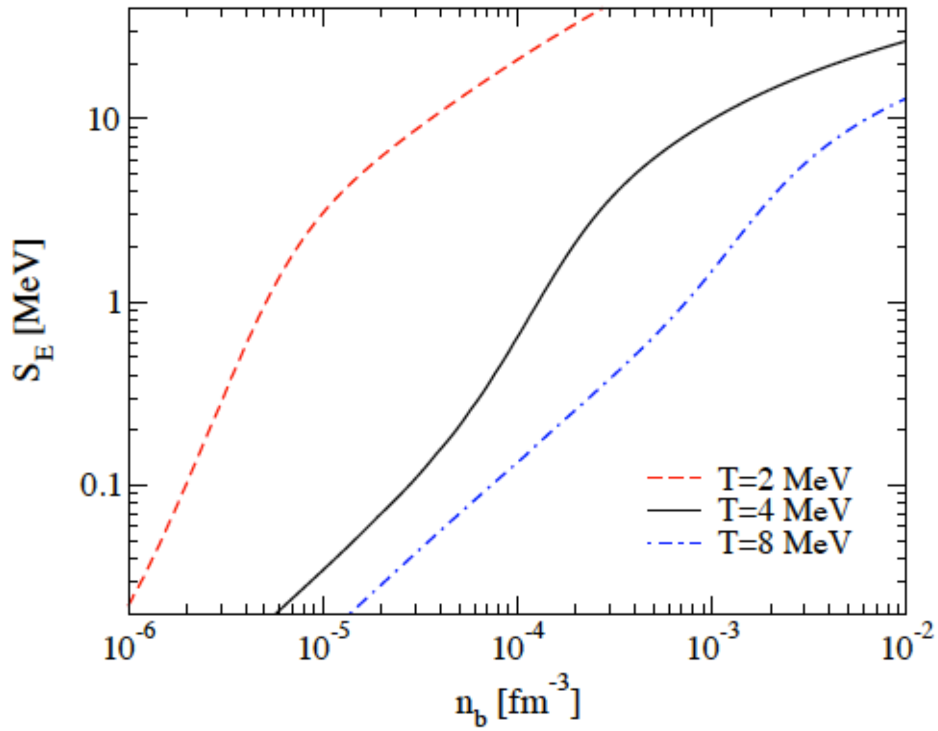
$$b_n(T) = \frac{1}{2^{1/2}\,\pi T}\int_0^\infty dE\, e^{-E/2T}\,\delta_n^{\rm tot}(E) - 2^{-5/2}\,.$$



Symmetry energy at finite T

Horowitz, Schwenk '05





$$S_E = \frac{1}{8}\frac{\partial^2}{\partial {Y_p}^2}\frac{E}{A}\bigg|_{Y_p=1/2}. \qquad S_F = \frac{1}{8}\frac{\partial^2}{\partial {Y_p}^2}\frac{F}{A}\bigg|_{Y_p=1/2}$$

Virial expansion including heavy nuclei

- Grand partition function in virial expansion

Shen, Horowitz, Teige '10

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

- nucleon-nucleon
- nucleon-alpha
- nuclei

1. Nucleon and alpha: mod. ind. — Horowitz, Schwenk '05
2. Heavy species: 8980 nuclei — FRDM mass table: Moller et al '97. $\Delta_{rms} \sim 0.6$ 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 ------ $E_i^C = \frac{3}{5}\frac{Z_i^2\alpha}{r_A}[-\frac{3}{2}\frac{r_A}{r_i} + \frac{1}{2}(\frac{r_A}{r_i})^3]$

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

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

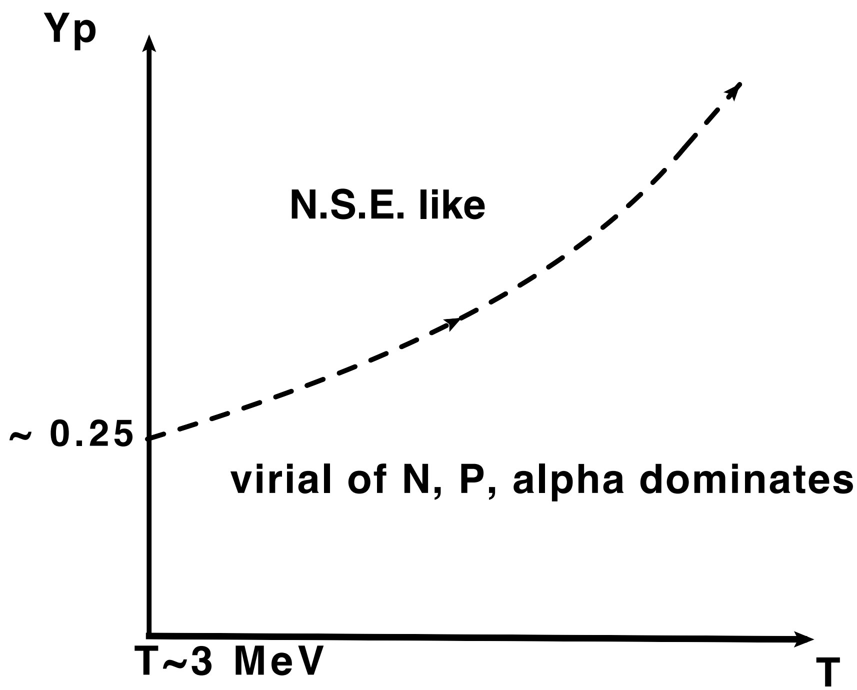
3. Solving: z_n, z_p, r_i:

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

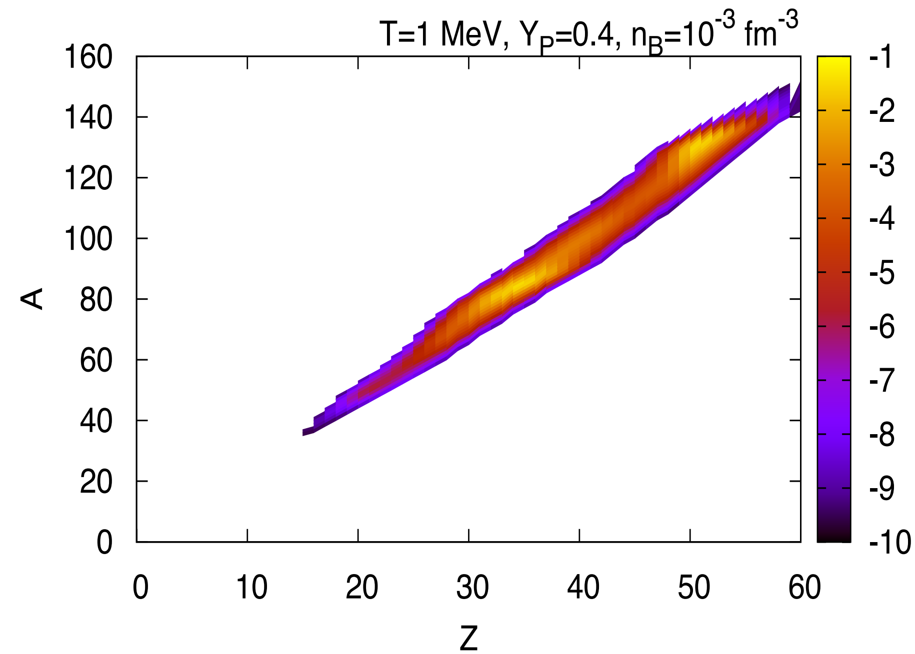
   $Y_P = (n_p + 2n_\alpha + \sum_i Z_i n_i)/n_B$ = Charge

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

- n< 0.1-0.01 n_0
- T< 12 MeV



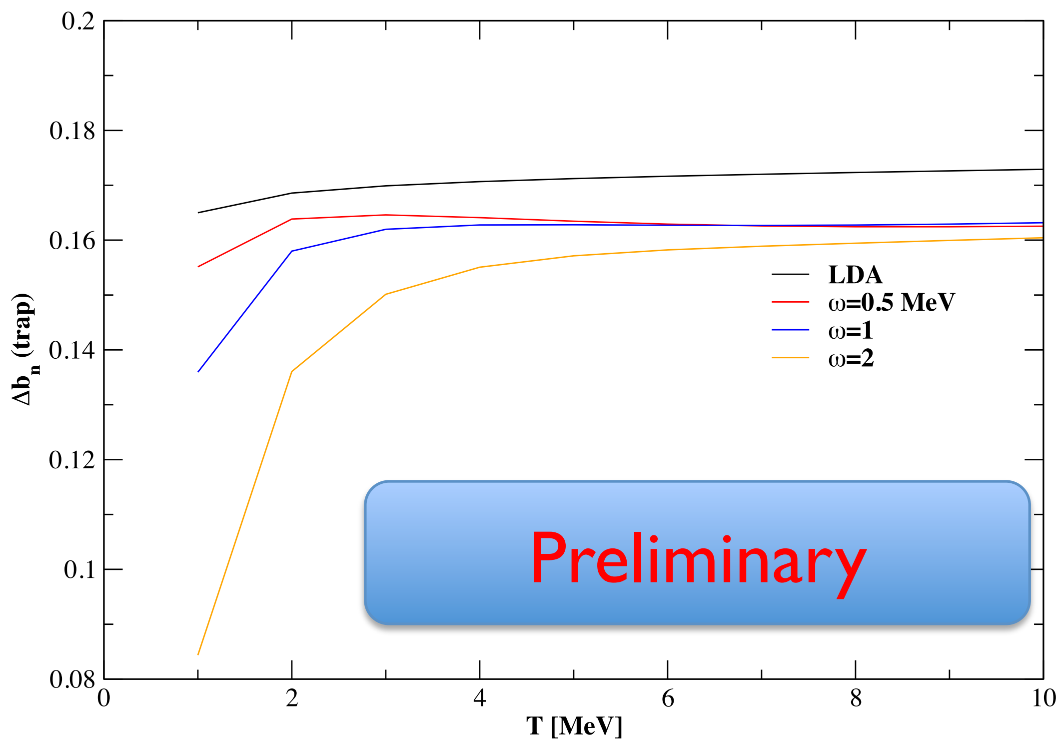
Mass distributions in Virial gas - multi-nuclei distribution

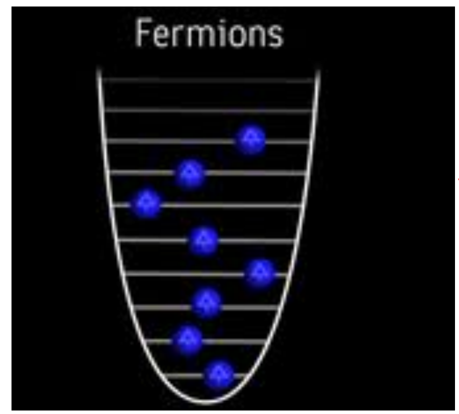


- Exact in low density limit for neutron rich matter
- Match to NSE at large Yp
- Mass 2, 3 nuclei can be included in virial expansion: O'Connor et al, 2008
- To be improved: model dep. on mass table, nuclear partition function – small effect on thermodynamics, unclear on the dynamics (interactions with neutrinos)

Higher order virial coeff: in trap neutron system

$$\frac{\log Q}{V} = \frac{P}{T} = \frac{2}{\lambda_n^3}[z_n + z_p + (z_p^2 + z_n^2)b_n + 2z_p z_n b_{pn}] \quad + b_3 z^3$$





$V_{HO}(\omega)$

- 2^{nd} order: ~5% within determined from exp. phase shift
- for AV18 potential and Chiral potential
- 3^{rd} order: in progress

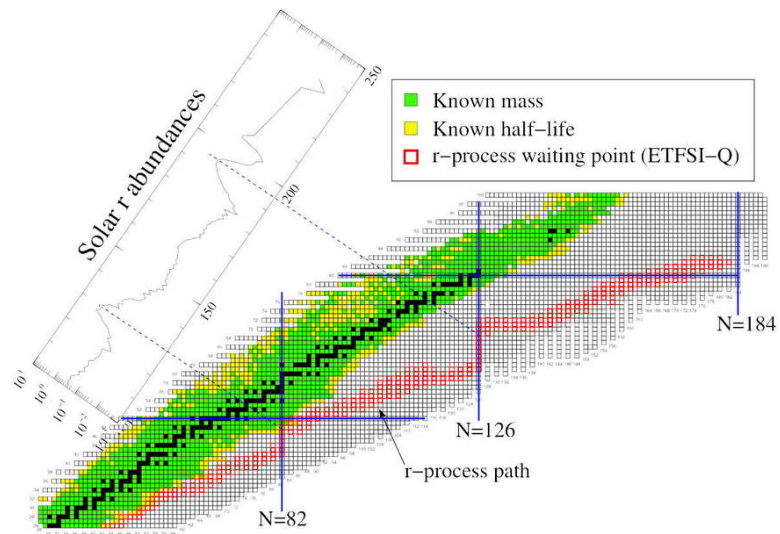
ν-opacity around neutrino-sphere

- Important for neutrino spectra from PNS and key input for r-process: proton (electron) fraction in the wind

- Setting the electron fraction:

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

Neutrino Spectra



- Effect of symmetry energy and light nuclei

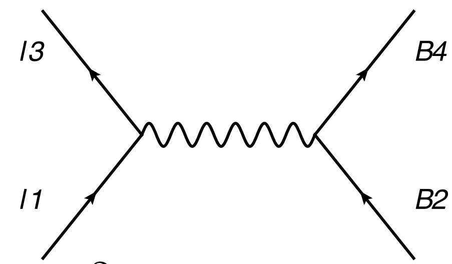
Neutrino-nucleon scattering

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

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: peaked around $q_0 \sim 0$

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

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

Medium correction (I): mean field

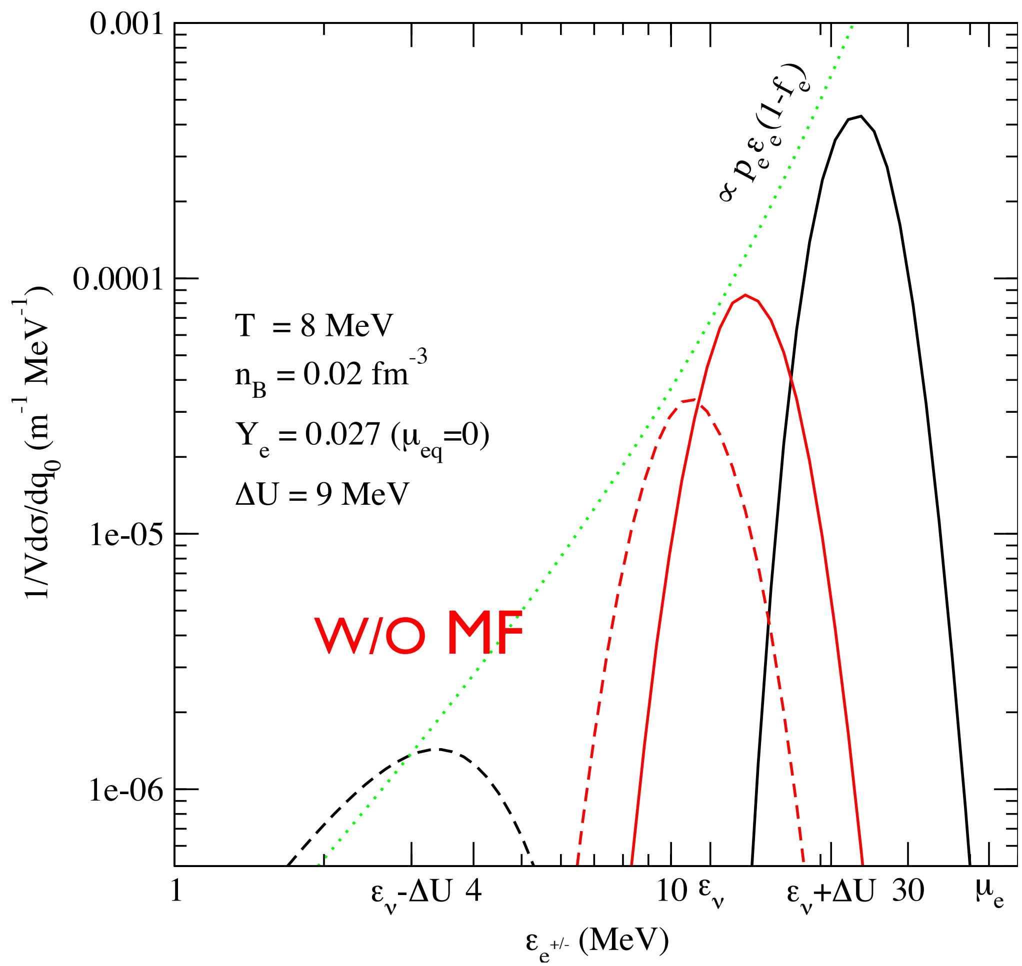
$$\mathrm{Im}\Pi^+ : \ \nu_e + n \rightarrow p + e^-$$
$$\mathrm{Im}\Pi^- : \ \bar{\nu}_e + p \rightarrow n + e^+$$

- Dispersion relation of quasi-particle from EOS:

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

- Response function is peaked around $q_0 \approx U_n - U_p$

- Around neutrino sphere, mean field shift is comparable to temperature.

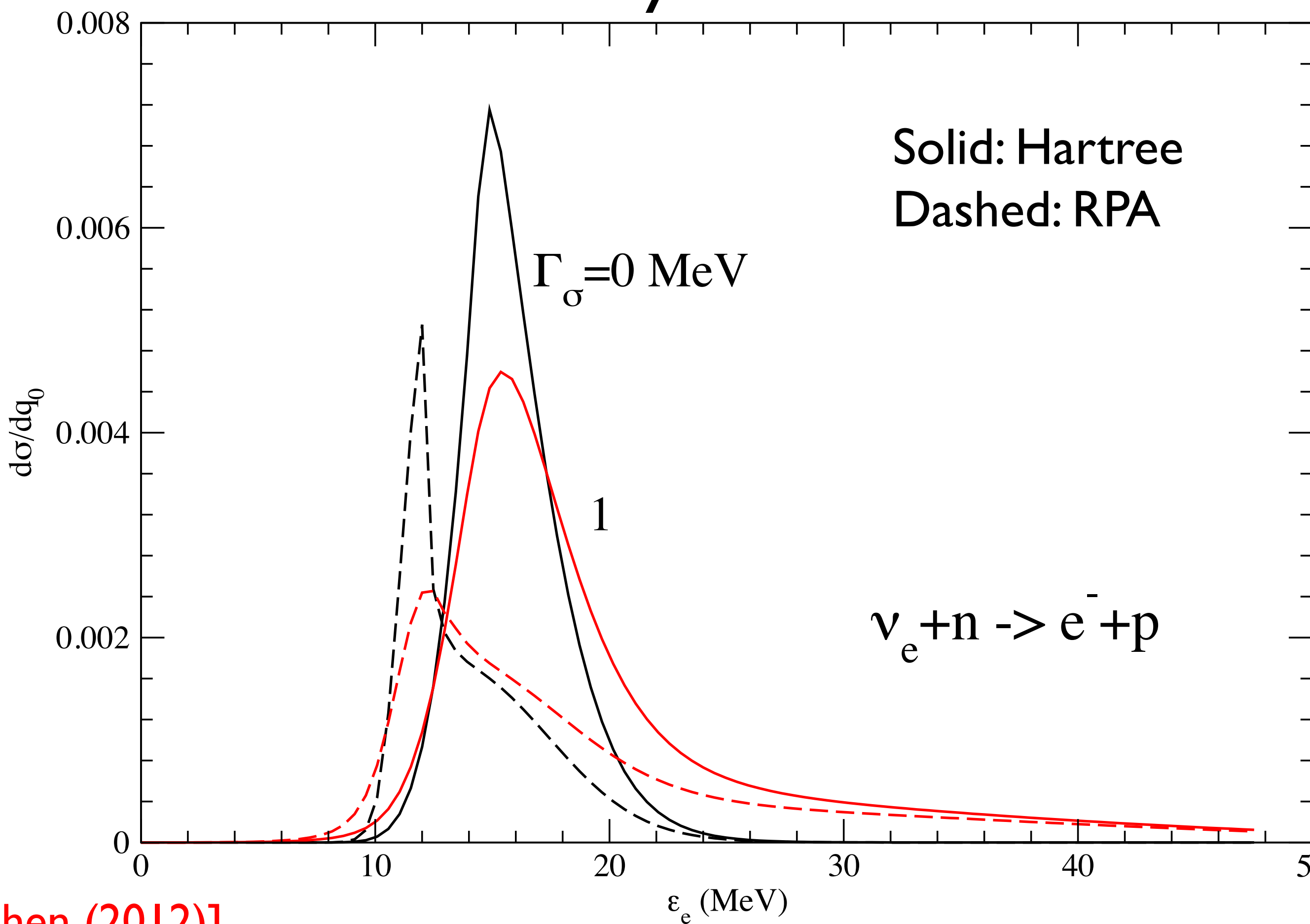


[Roberts, Reddy (2012)]

Roberts (2012)
Martinez-Pinedo et al. (2012)

Medium correction (II)
RPA and beyond

T=8 MeV
N=0.006 fm-3
Ye=0.03
μ_e=30 MeV
E_ν=12 MeV



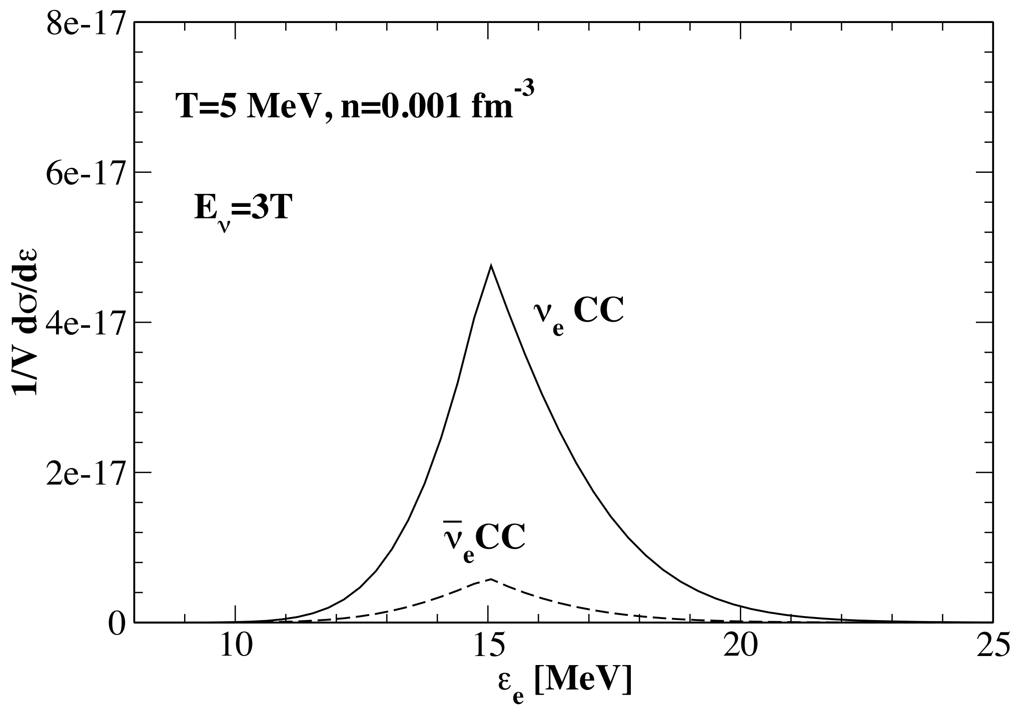
[Roberts, Reddy, Shen (2012)]

- RPA suppresses response and shifts its strength via collective mode. Multi-particle dynamics enhances it.
- Net effect mild suppression. Follow SN trajectory to study details.

Medium corrections (III): light nuclei in virial expansion for MF shifts

- Virial EOS of n, p: $P = \frac{2T}{\lambda^3}\{z_n + z_p + (z_n^2 + z_p^2)b_n + 2z_p z_n b_{pn}\},$
  - 2nd virial coeff. b_n, b_{pn} from mod. ind. scattering phase shifts
  - Suitable 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

Horowitz, GS, O'Connor, Ott, 2012

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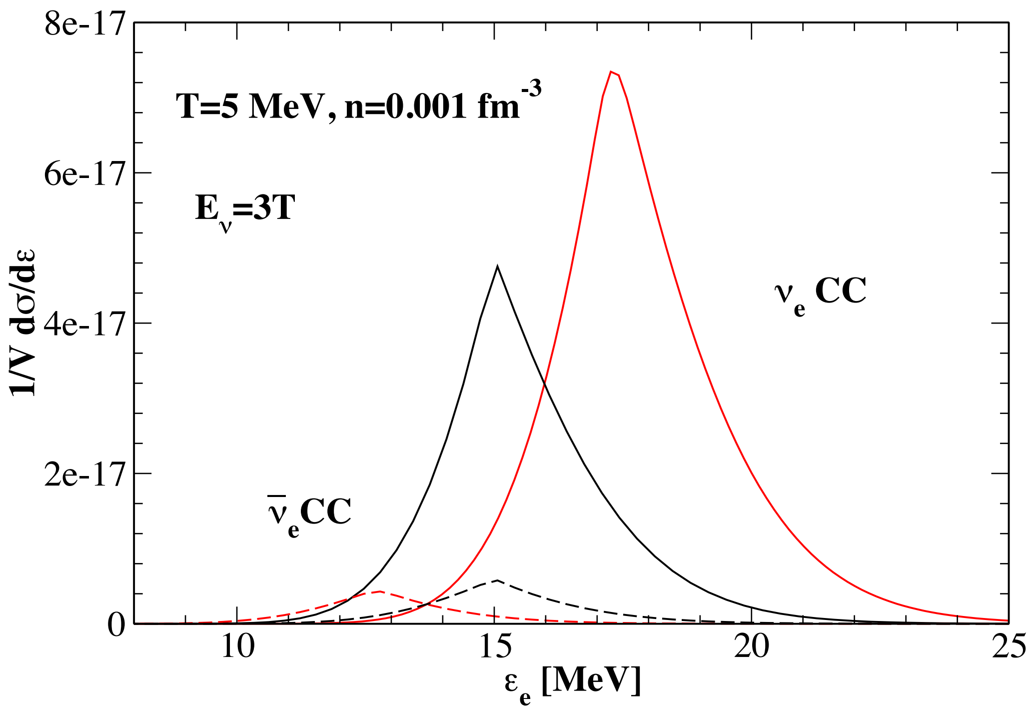


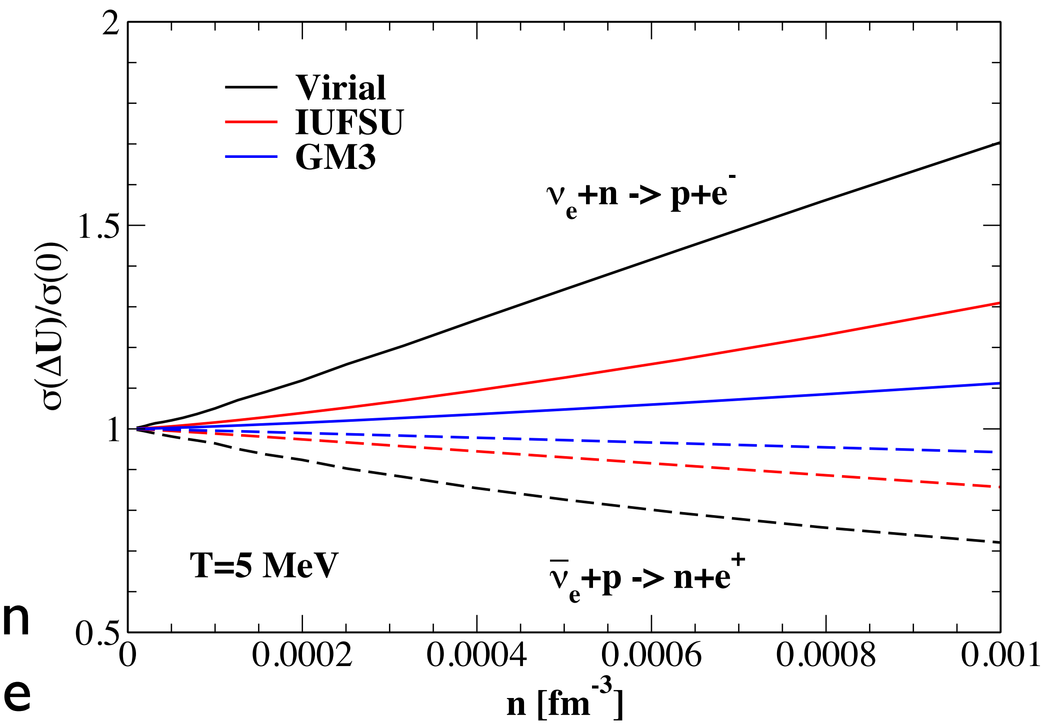
- W/O MF shift: dσ ~ density of n or p
- W MF shift

Horowitz, GS, O'Connor, Ott, 2012

- 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 larger than MF, due to n-p correlation (D)
- May reduce electron fractions in neutrino driven wind compared to MF
- Feedback: larger Y_e in ν-sphere from larger E_{sym}
- Need consistent simulation with EOS and virial response



Z < 0.16

Horowitz, GS, O'Connor, Ott, 2012

Summary

- EOS and neutrino response at neutrino-sphere important for neutrino spectra and r-process in SN
- Strongly related to symmetry energy at sub-nuclear density: nuclear physics known in principle – relatively clean problem !
- Controlled theo. methods possible:
  - 3rd order in virial expansion of nuclear matter (or, extend EFT,QMC to finite T,Yp)
  - eliminate MF model dep. and converge
  - Chiral EFT/QMC: neutrino response ?

- Q: How could exp. help pin down Esym and response function at these densities: fragmentation in HI, etc
- Q: Role of bound states in neutrino response: more light nuclei (especially at late times)