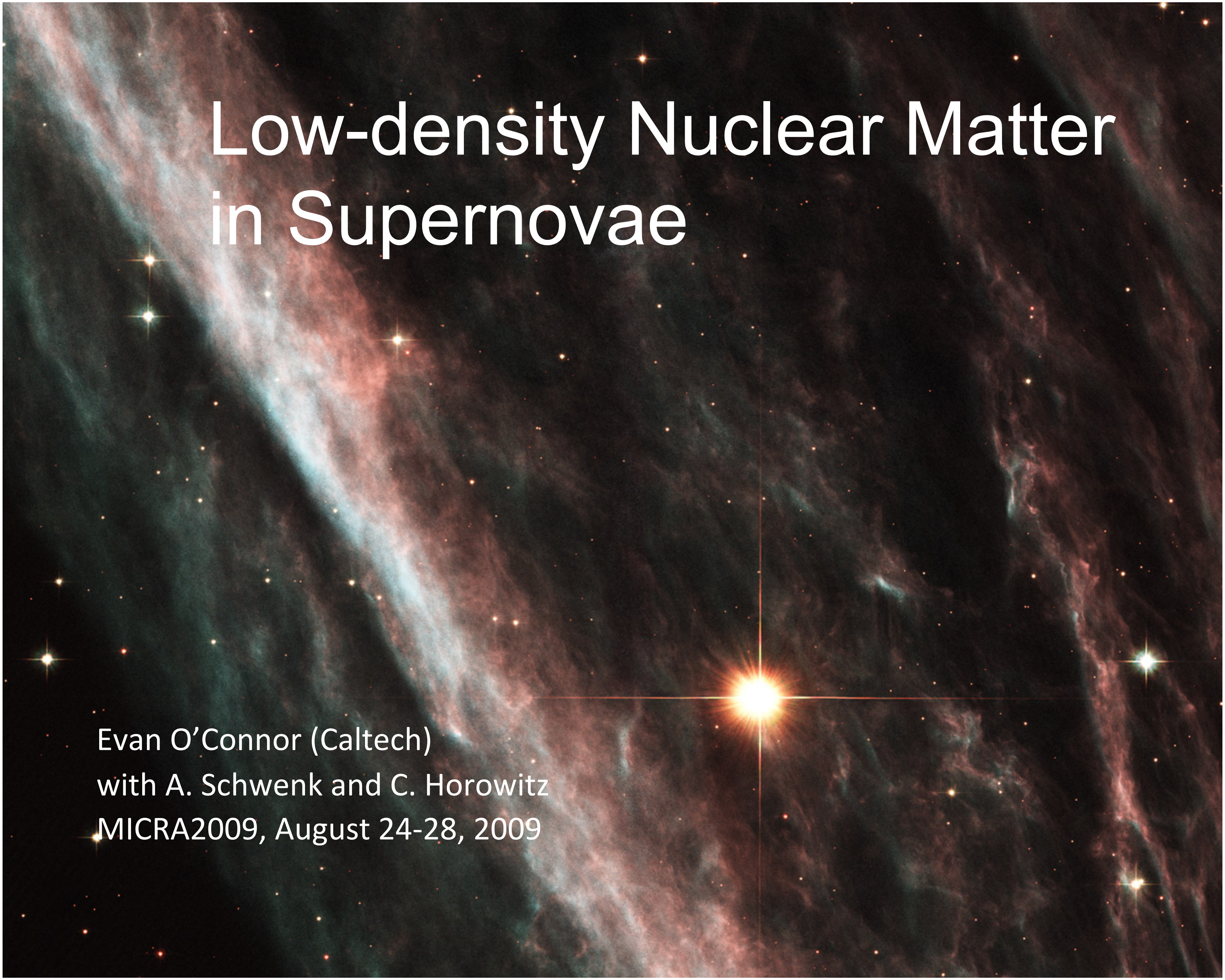

Low-density Nuclear Matter in Supernovae

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Low-density Nuclear Matter in Supernovae

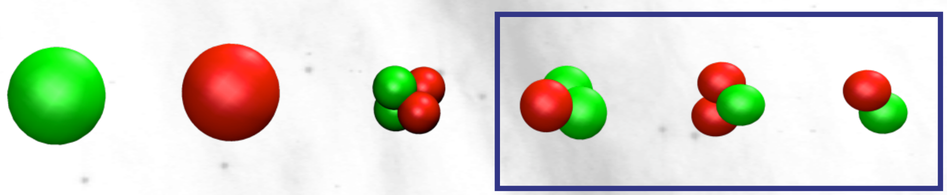
Low density nuclear matter is more then just neutrons, protons and α's

- Why a LDNM EOS for supernovae?
- Describe our systematic low-density approach
- Show presence of light nuclei (A=2,3)
- Connection to Supernovae

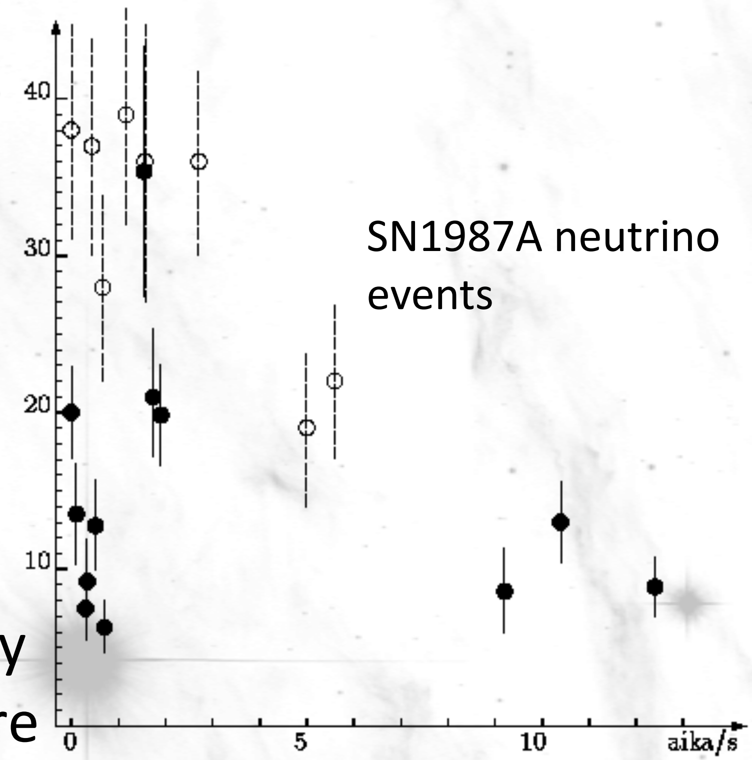
Neutrinosphere

- Surface of last scattering for neutrinos
- $k_B T = \langle E \rangle / 3 \sim 4$ MeV

  $\rho = 1/(\sigma \ell) \sim 10^{(11\text{-}12)}$ g/cm^3
- Composed mainly of low-mass nuclei: neutrons, protons, α particles, **^{2}H**, **^{3}H** and **^{3}He** nuclei



- Neutrino interactions with A=2,3 may be relevant and effect neutrinosphere properties



SN1987A neutrino events

Virial Equation of State

- Expand pressure in fugacities

$$\frac{P}{T} = \sum_i \frac{s_i}{\lambda_i^3} z_i + \sum_{(i,j)} \frac{s_i}{\lambda_i^3} b_{ij} z_i z_j$$

$$z_i = e^{(\mu_i + E_i)/T}$$

$$\lambda_i = \sqrt{2\pi / m_i T}$$

- Solve for unknown chemical potentials (6)
  - assume chemical equilibrium (reduces to 2)

$$\mu_\alpha = 2\mu_n + 2\mu_p$$
$$\mu_{^3\mathrm{H}} = 2\mu_n + \mu_p$$

- Find number density via thermodynamics

$$n_i = z_i \left(\frac{\partial}{\partial z_i} \frac{P}{T} \right)_{V,T}$$

Virial Equation of State

- Initial conditions – density

$$n_b = n_p + n_n + 4n_\alpha + 3n_{^3\mathrm{H}} + 3n_{^3\mathrm{He}} + 2n_\mathrm{d}$$

- Initial conditions – proton fraction

$$Y_p = \frac{n_p + 2n_\alpha + n_{^3\mathrm{H}} + 2n_{^3\mathrm{He}} + n_\mathrm{d}}{n_b}$$

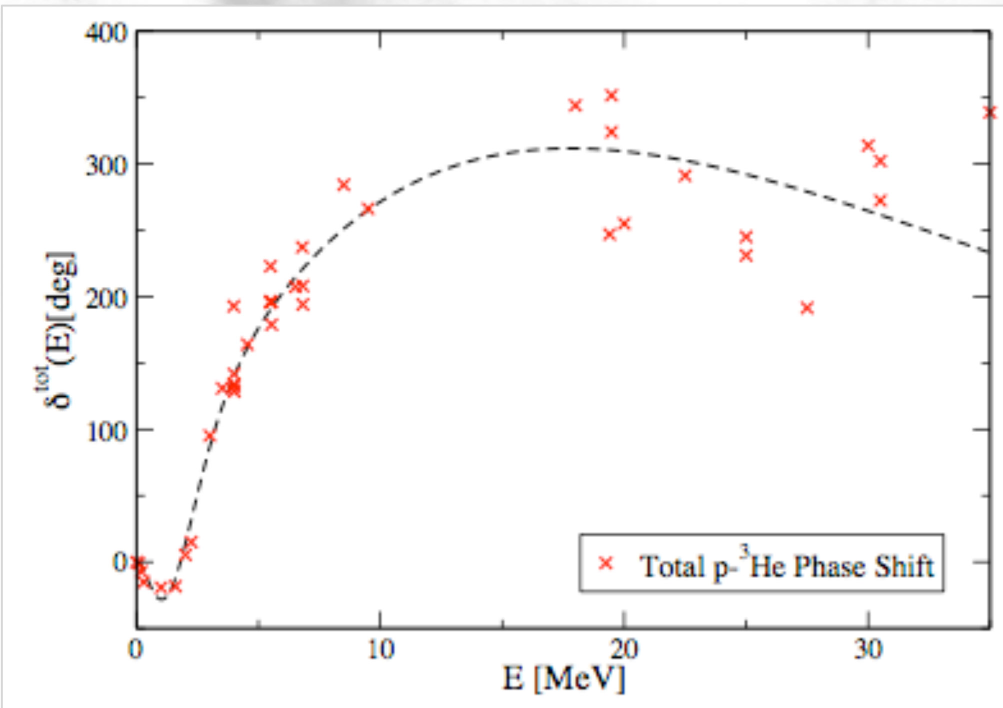
- Calculate other thermodynamic variables:
  - entropy, energy density, compositions

$$s = \left(\frac{\partial P}{\partial T}\right)_\mu \qquad e = Ts + \sum_i n_i\mu_i - P \qquad x_i = \frac{A_i n_i}{n_b}$$

Virial Coefficients

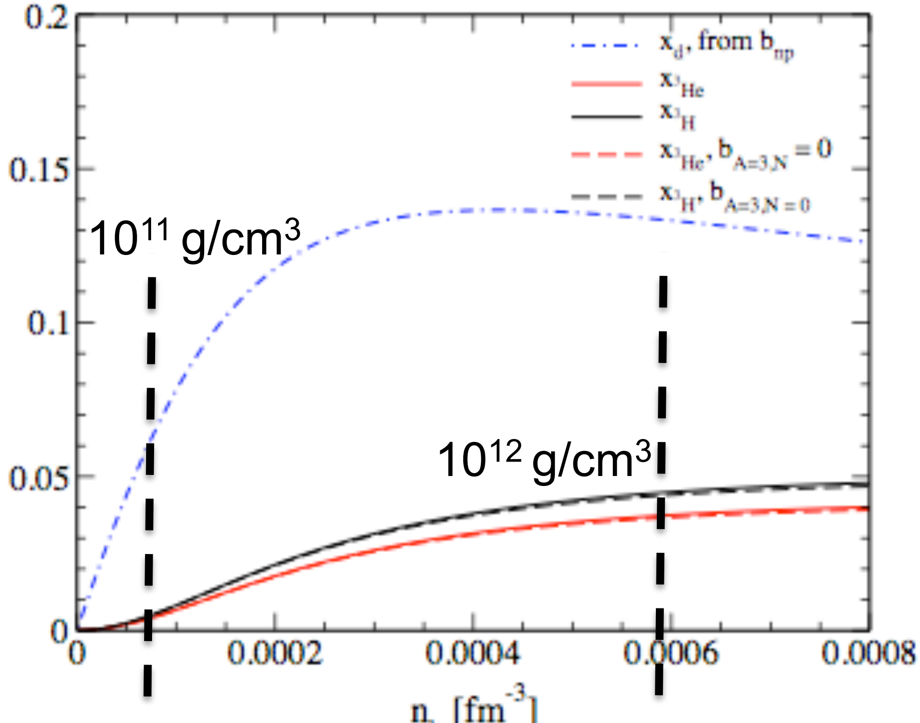
- Second virial coefficients characterize interactions between species, calculated from scattering phase shifts, allows model-independent prediction of EOS.

$$b_2(T) = -\frac{2\,\delta_{tot}(0)}{3\sqrt{3}\pi} + \frac{\sqrt{4/3}}{4\pi T}\int_0^\infty dE\, e^{-3E/4T}\,\delta_{tot}(E)$$

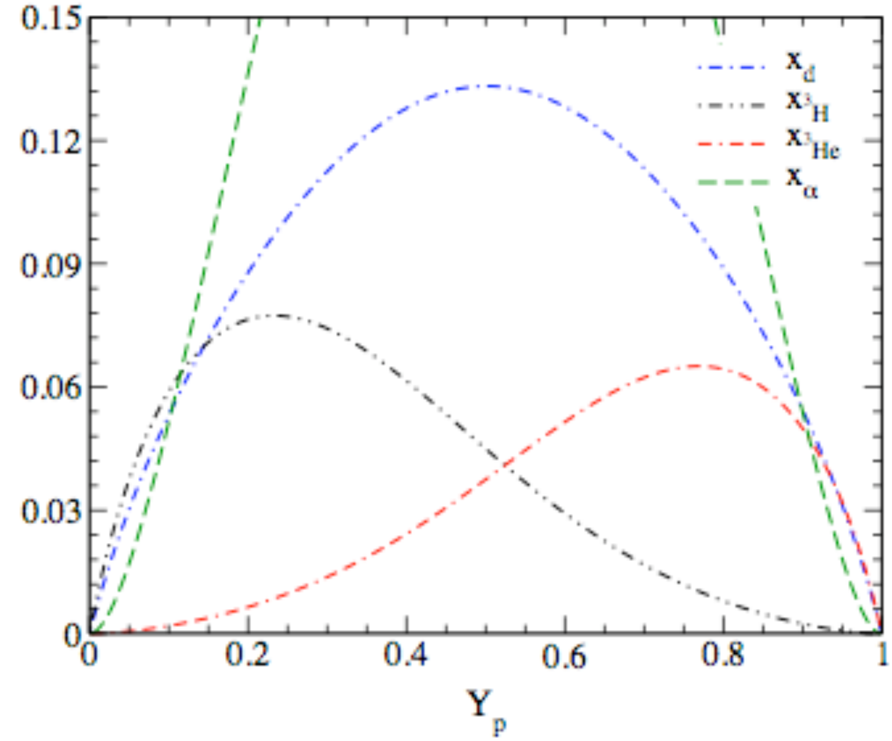


Compositions

- A=2,3 nuclei are present at neutrinosphere conditions
  - rivals α mass fraction, formed at expense of α's in symmetric matter and n's and p's at low Y_p



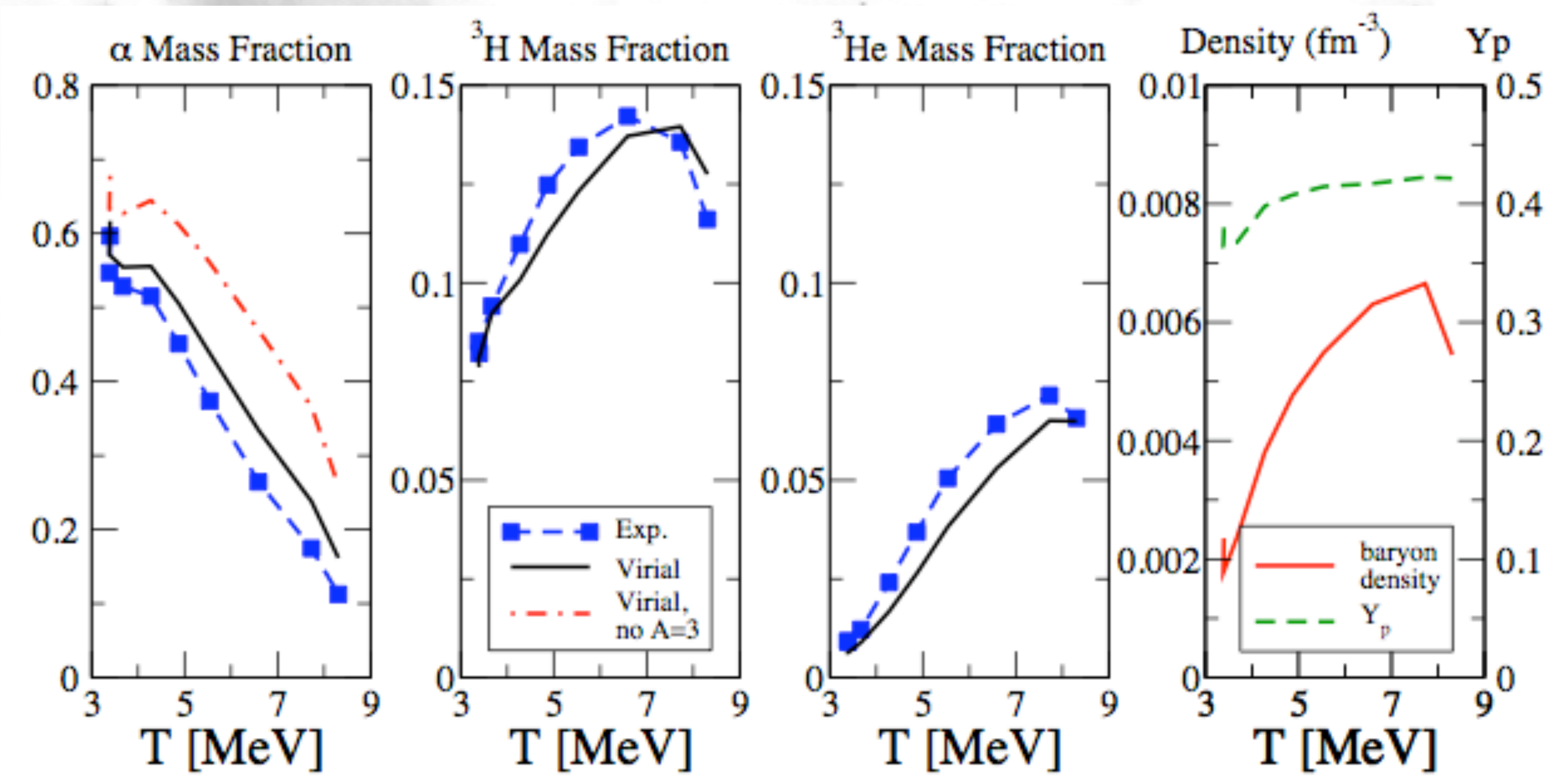
T = 4 MeV Y_p = 0.5



T = 4 MeV n_b = 10^{12} g/cm^3

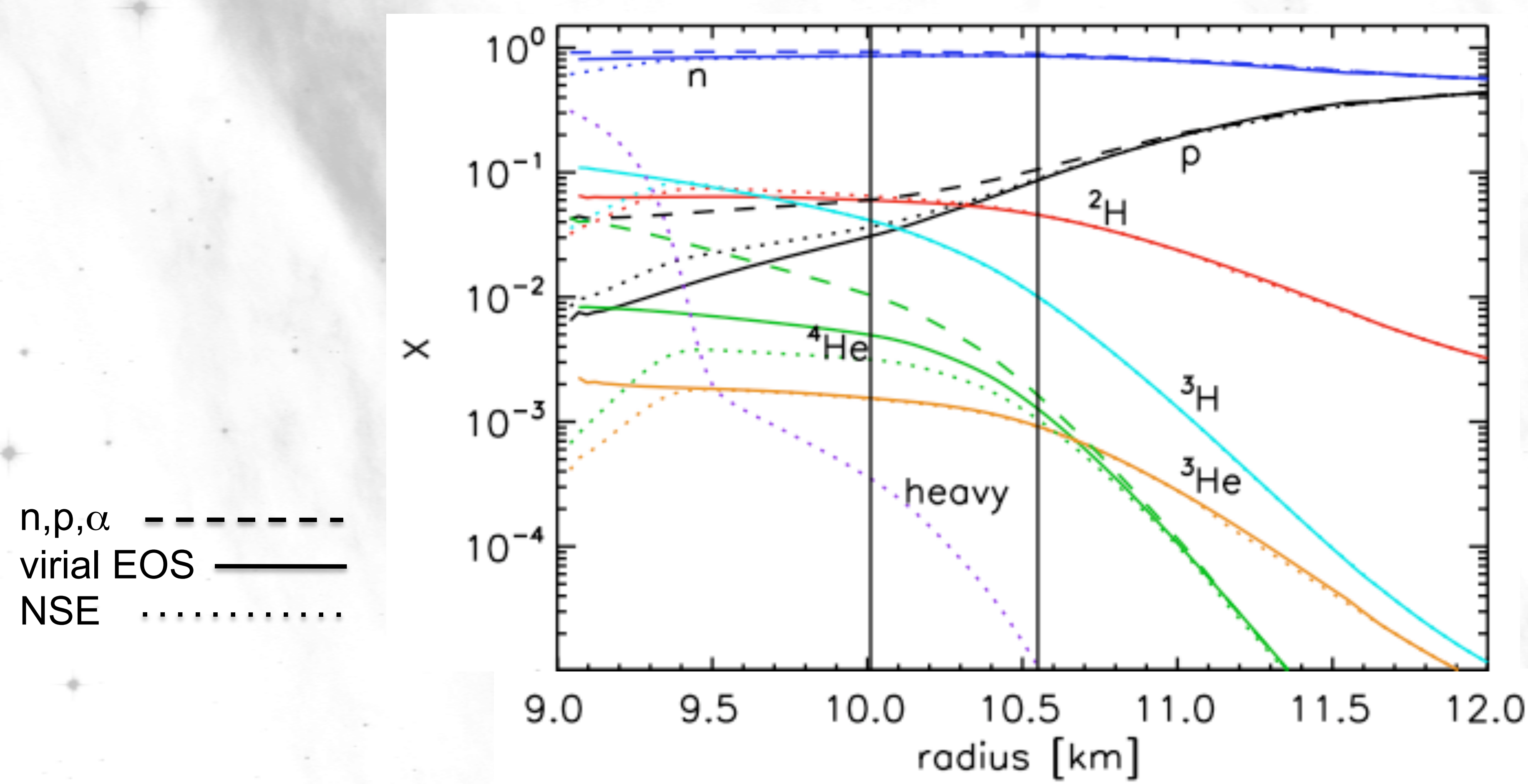
Compositions

- Compare virial EOS predictions with experimental heavy ion collisions, *Kowalski et al. (2007)*.



Supernova Neutrinos *Arcones et al. (2008)*

- Radial profile of 15 Solar mass supernova 2 seconds post-bounce, *Arcones et al. (2007)*. Compositions shown with 3 different EOSs



Supernova Neutrinos *Arcones et al. (2008)*

- Using different compositions (with standard ν-interactions + A=3 ν-interactions) we can calculate the properties of the neutrinosphere to see the effect of A=2,3 nuclei.

t		$R_{\bar{\nu}_e}$ [km]	$T_{\bar{\nu}_e}$ [MeV]	Y_e^w	$\langle \epsilon_{\bar{\nu}_e} \rangle$ [MeV]
t = 2 sec	A	10.01	8.14	0.514	25.64
	B	9.977	8.30	0.507	26.16
	C	10.00	8.17	0.513	25.73
	D	9.979	8.29	0.509	26.12
t = 10 sec	A	9.041	6.94	0.431	21.86
	B	9.039	7.02	0.427	22.12
	C	9.063	6.49	0.456	20.44
	D	9.065	6.45	0.458	20.32

A: n,p,α EOS
B: hybrid (npα-NSE)
C: NSE EOS
D: virial EOS

At early times post-bounce neutrino opacities are decreased allowing the antineutrinos to decouple earlier with a higher average energy

Light nuclei at late times increase antineutino opacity, decreasing average energy and increasing wind Y_e

Summary

- The virial EOS allows for a systematic calculation of properties of low density nuclear matter, deriving interaction terms directly from experiment.
- Light nuclei (A=2,3) are present in relatively high amounts (10%) in the neutrinosphere of SNe and have an influence on neutrinosphere properties (through neutrino interactions) although more on the 1-3% level.