Charged Current Interactions in Proto-Neutron Star Atmospheres and the Symmetry Energy

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Core Collapse Supernovae

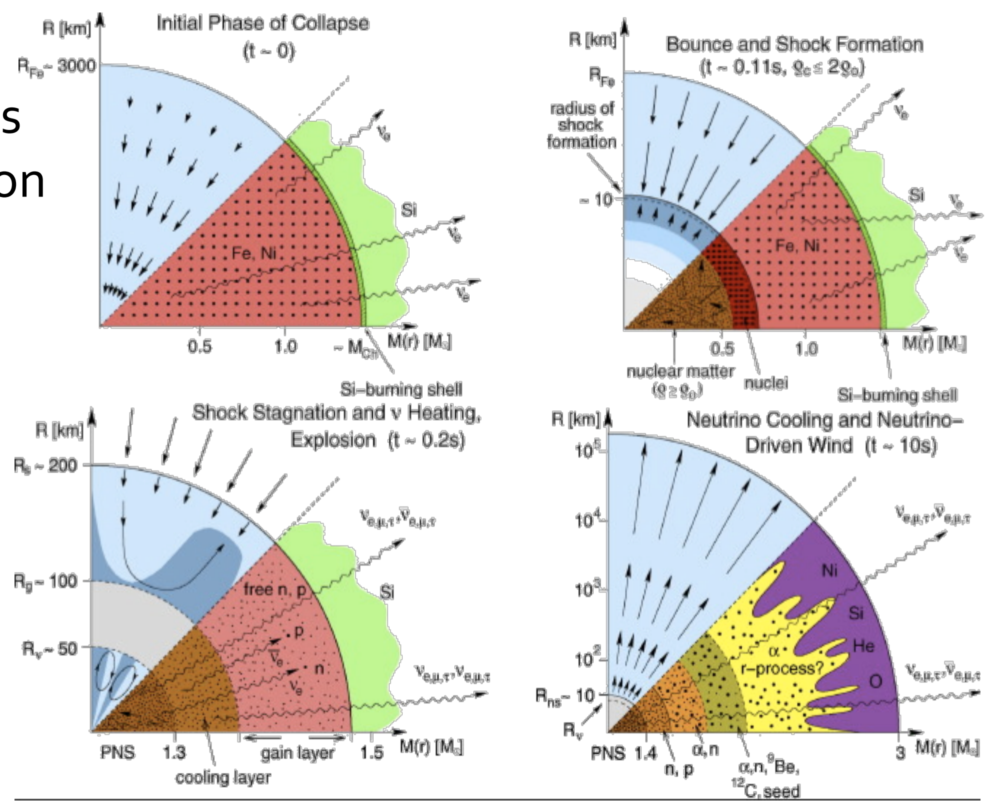
- Stars with M >~ 9 M_{sun} burn their core to Fe
- Core exceeds a Chandrasekhar mass → supersonic collapse outside of homologous core → bounce shock after ~2 x saturation density
- Gravitational binding energy of compact remnant:

$$\frac{GM_{NS}^2}{R_{NS}} \sim 3 \times 10^{53}\, erg$$

- Binding energy of stellar envelope:

$$\sim 10^{51}\, erg$$

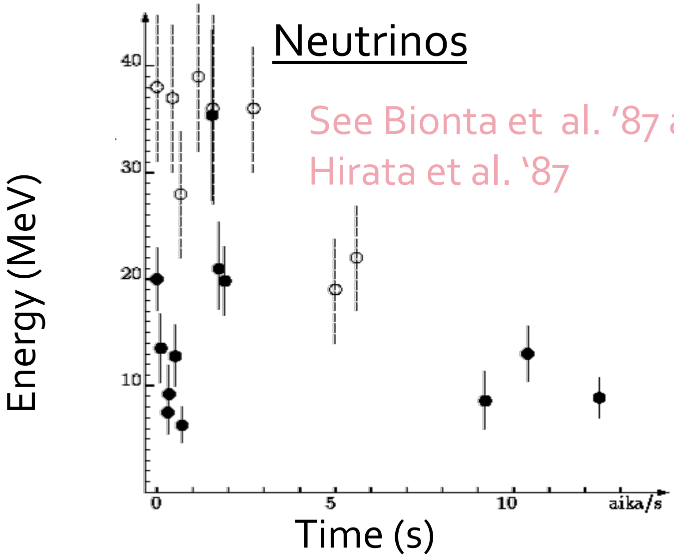
- Details of coupling somewhat uncertain
- After explosion, leave hot dense remnant



From Janka et al. '07

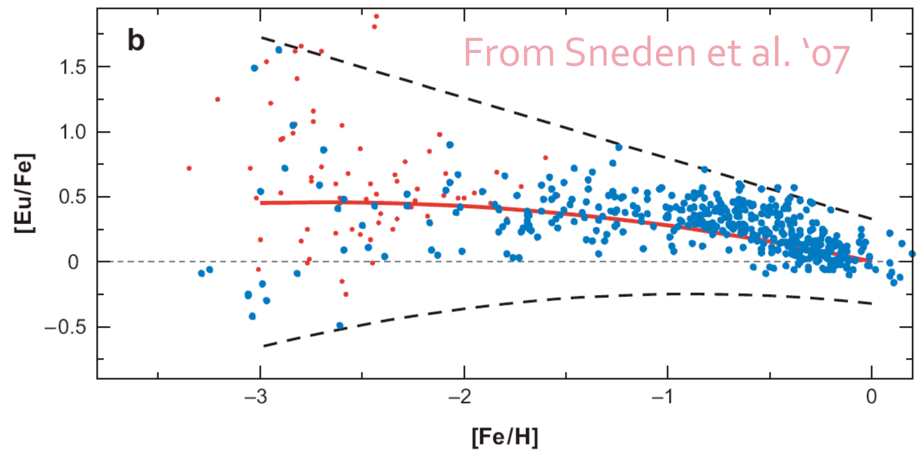
Core Collapse Supernovae: Multi-Messenger Events

Neutrinos

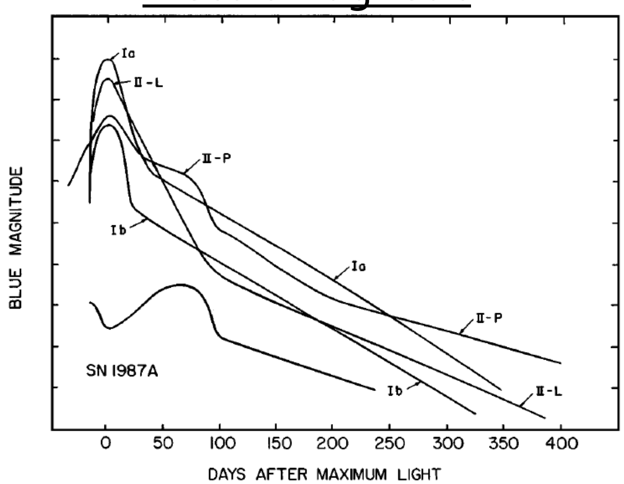


See Bionta et al. '87 and Hirata et al. '87

Nucleosynthesis

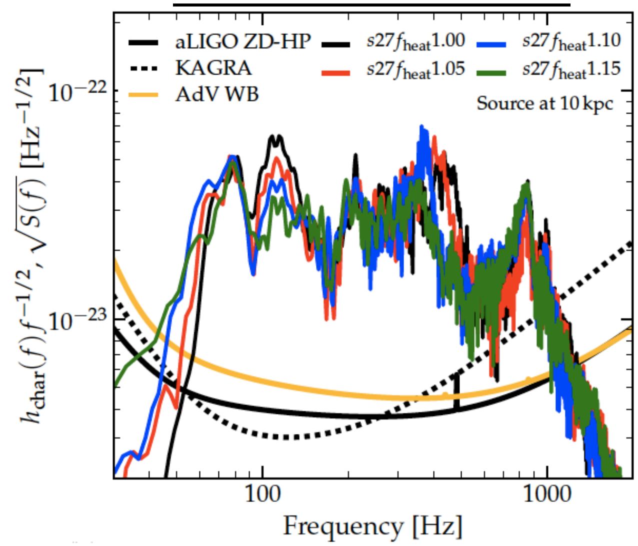


Electromagnetic



From Filippenko '97

Gravitational Waves



From Ott et al. '12

Outline

- Proto-neutron star neutrino emission and nucleosynthesis in the innermost regions of supernovae
- Models of PNS neutrino emission
- Charged current interaction rates in PNS atmospheres
- Predictions for NDW compositions

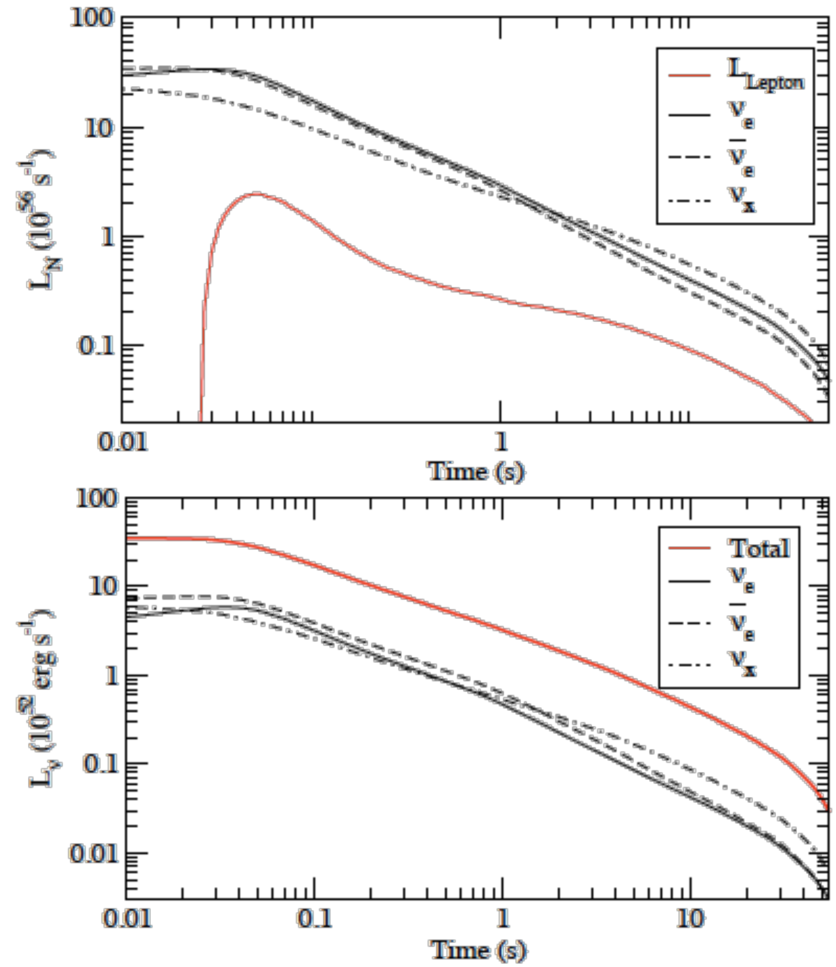
Proto-Neutron Star Neutrino Emission

See e.g. Burrows & Lattimer '86, Huedepohl et al. '10, Fischer et al. '10, LR '12

- Majority of neutrinos emitted during CCSN come from cooling phase
- Late time neutrinos are emitted from regions near nuclear saturation density
- Kelvin-Helmholtz evolution of the neutron star mediated by neutrinos

$$L_{\nu,tot} \sim 4\pi R^2 \sigma_\nu T_{eff}^4 \sim 10^{52}\ ergs\ s^{-1}$$

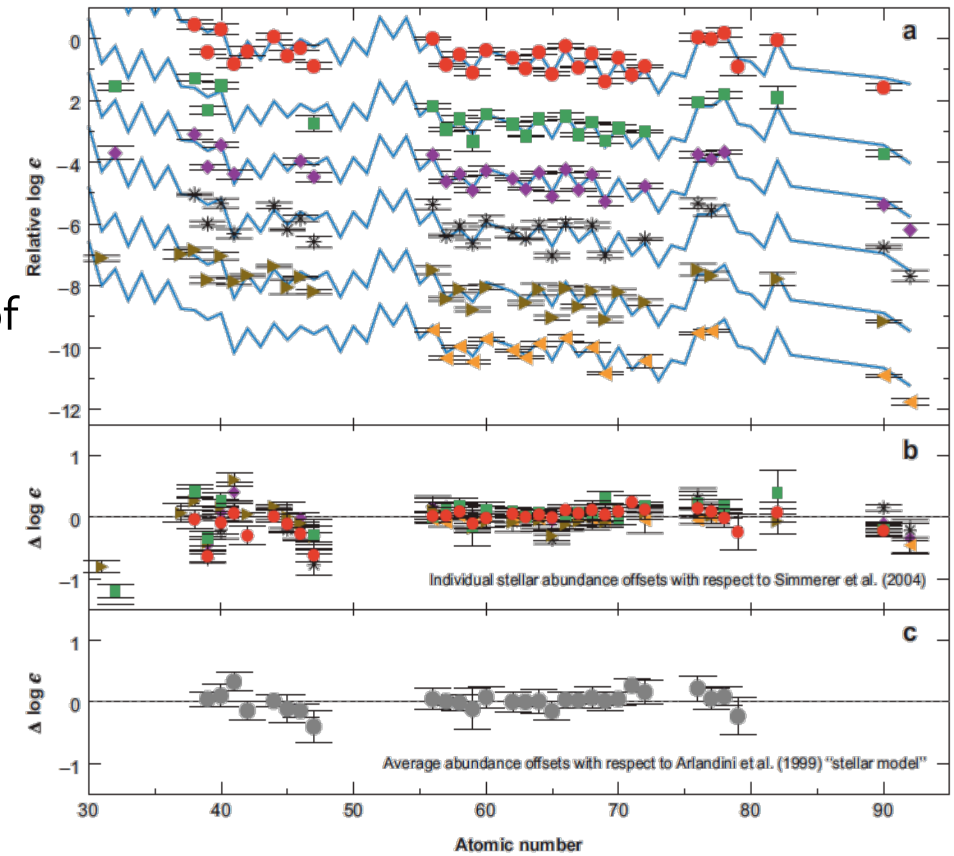
$$\tau_{KH} \sim \frac{3GM_{NS}^2}{5RL_{\nu,tot}} \sim 25\ s$$



What can we learn from supernova neutrinos?

- Supernova explosion mechanism
  - Neutronization burst
  - Duration of accretion phase
  - ...
- Properties of high density matter
  - Phase transitions at high densities
  - Sub saturation density properties of nuclear matter
  - ...
- Neutrino properties
  - Neutrino mass hierarchy
  - Collective Oscillations
  - ...
- Nucleosynthesis
  - Neutrino driven wind
  - Neutrino induced nucleosynthesis
  - ...

Heavy elements in low metallicity halo stars



From Sneden et al. '08

The Neutrino Driven Wind

See Duncan et al. ‘86,Woosley et al. ’94, Takahashi et al. ‘94, Thompson et al. ’01, Metzger et al. ‘07 Arcones et al. ’08, LR et al. ’10, Fischer et al. ‘10, Huedepohl et al. ‘10 etc.

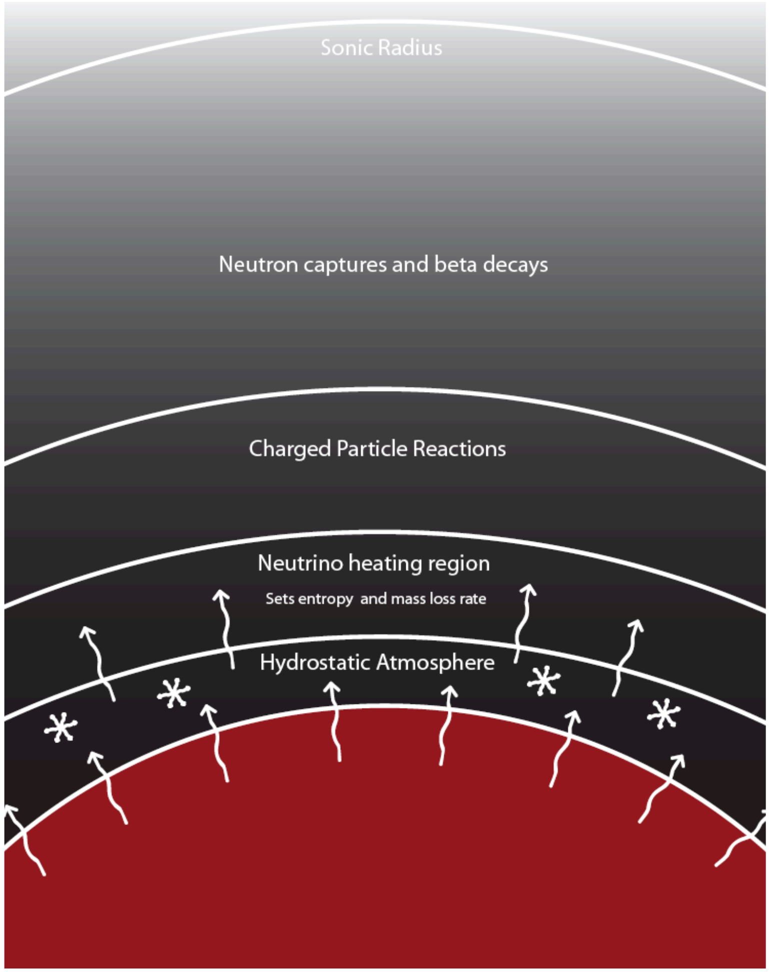
• As neutrinos leave the PNS, they deposit energy in material at the neutron stars surface

• Drives an outflow from the surface of the neutron star

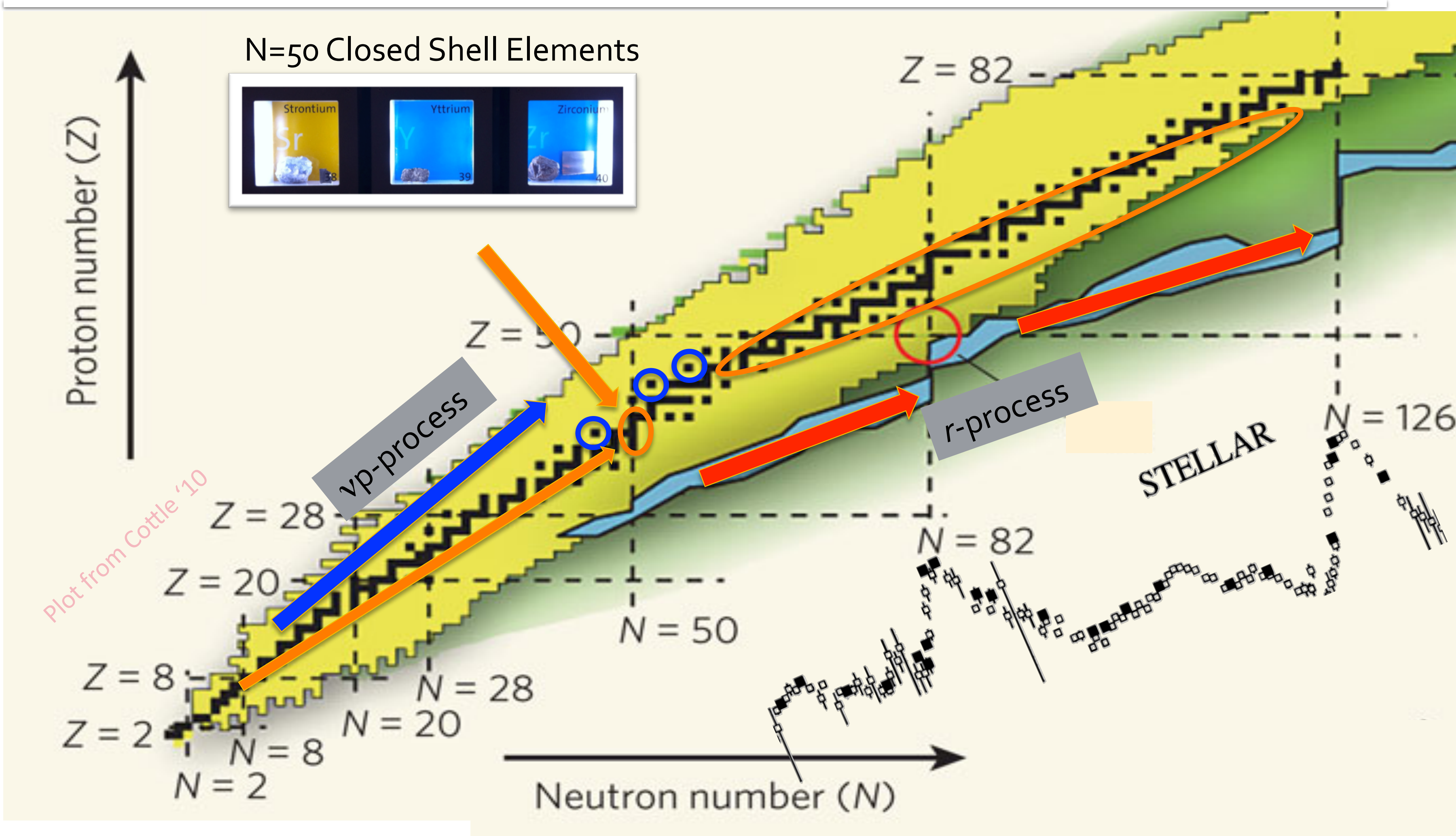
• Electron fraction is determined by the neutrino interactions, some neutrons turned into protons and vice-versa

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

•Possible site to make some interesting nuclei that are not made during normal stellar evolution: *r*-process, light *p* nuclides, N = 50 closed shell nuclei Sr, Y, Zr

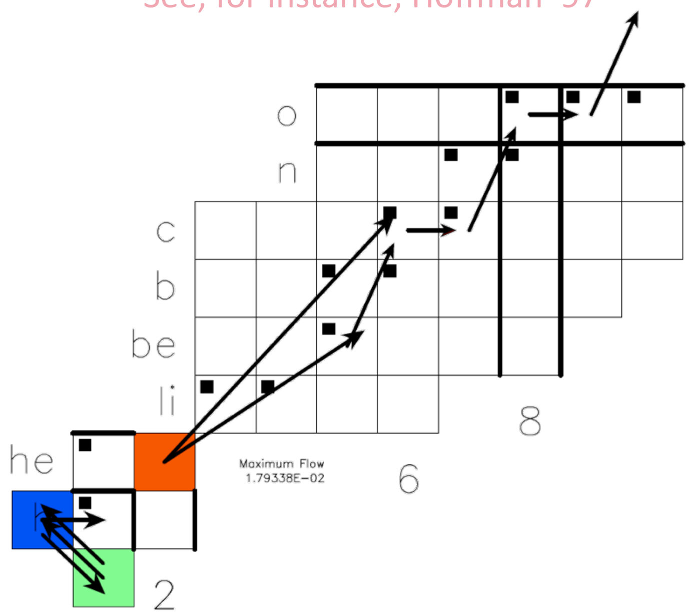


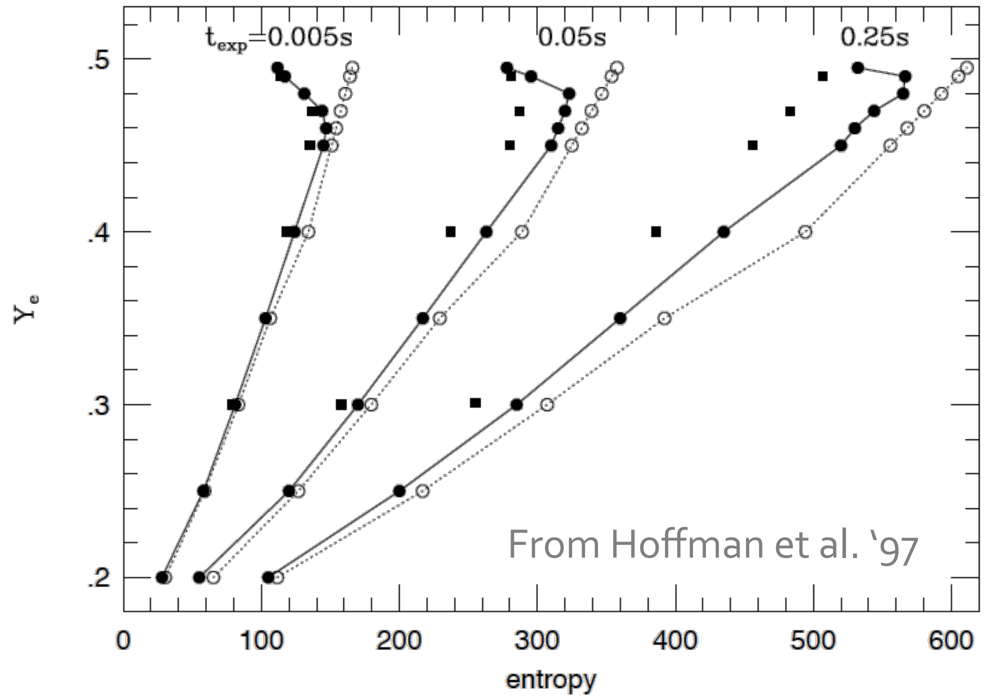
Different Modes of Nucleosynthesis



Wind nucleosynthesis:
The important parameters

See, for instance, Hoffman '97





- Setting the electron fraction:

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

Neutrino Properties

- Setting the neutron to seed ratio:

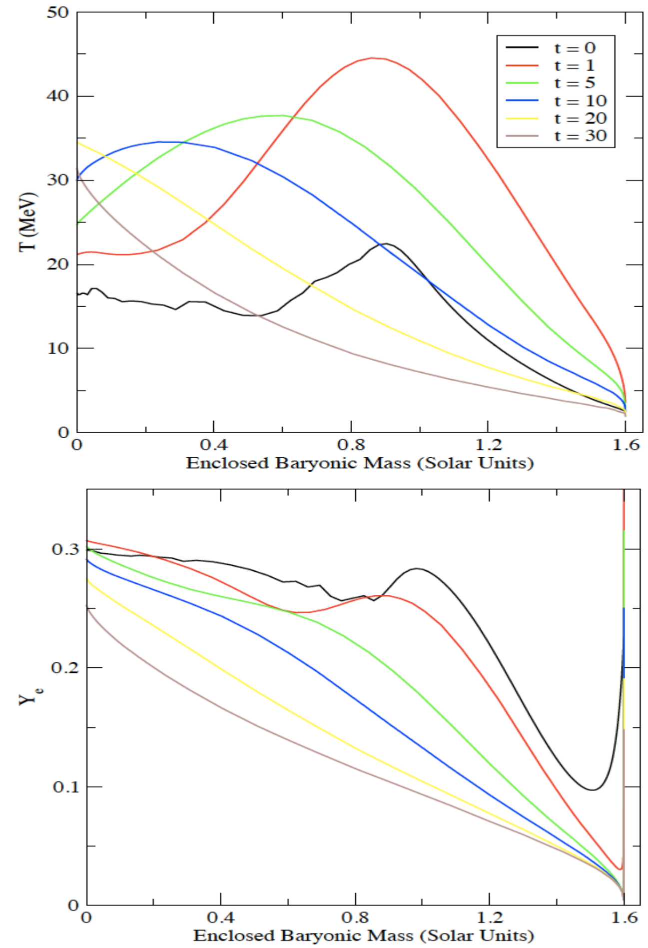
$$\frac{dY_{seed}}{dt} \approx \frac{dY_{^{12}C}}{dt} \propto \rho^3 Y_\alpha^3 Y_n \Rightarrow \frac{N_n}{N_{seed}} \propto (1 - 2Y_e) \frac{S_f^3}{\tau_{dyn}}$$

Wind Dynamics

Ingredients for Modeling PNSs

See e.g. Burrows & Lattimer ’86, Huedepohl et al. ‘10, Fischer et al. ’10, LR ‘12

- Neutron star structure
- Boltzmann neutrino transport
- Nuclear equation of state
- Neutrino opacities



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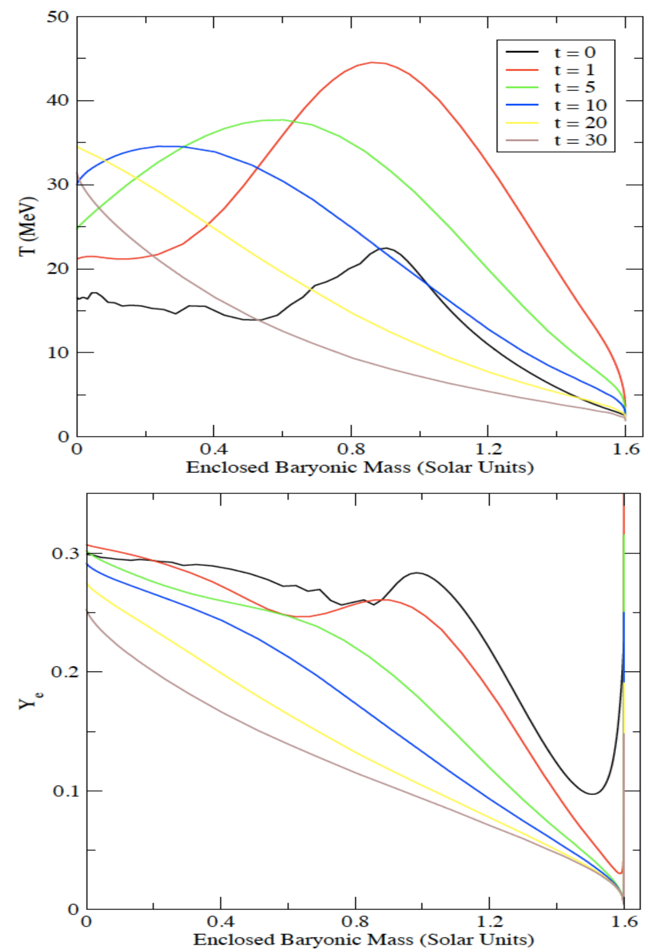
Need to be constrained by experiment!



Moment Approach to Transport

Simplify the formalism and make the problem simple

- Assume spherical symmetry: distribution only depends on *r* and μ

$$w^n = \frac{\omega^3}{(2\pi)^2} B_n \int_{-1}^{1} d\mu P_n(\mu) f(\omega, \mu)$$

- Transform to energy at infinity to obviate GR red shift corrections

$$\frac{\partial w^i}{\partial x} \rightarrow \frac{\partial w^i}{\partial x} + \frac{\partial \nu}{\partial x}\frac{\partial w^i}{\partial \nu}$$

- Truncate infinite hierarchy of moments after second moment

$$\frac{\partial w^0/n_B}{\partial t} + \frac{w^0}{n_B} e^{\phi} \left(\frac{\Theta}{3} + g_2 \frac{3}{2}\sigma \right) + \frac{\partial}{\partial a}\left(4\pi r^2 e^{\phi} w^1\right)$$
$$- \frac{e^{\phi}}{n_B} \frac{\partial}{\partial \nu} \nu \left[\left(\frac{\Theta}{3} + g_2 \frac{3}{2}\sigma \right) w^0 \right] + \frac{\nu}{n} \frac{\partial \phi}{\partial t} \frac{\partial w^0}{\partial \nu} = e^{\phi} \frac{s^0}{n_B}$$

- Use energy integrated formalism to reduce number of energy groups required and correctly capture neutrino Fermi surface

$$N_g = \int_{\omega_{g,L}}^{\omega_{g,U}} \frac{d\omega}{\omega} w^0$$

→

$$\frac{\partial}{\partial t}\left(\frac{N_g}{n_B}\right) + \frac{\partial}{\partial a}\left(4\pi r^2 e^{\phi} F_g\right)$$
$$- \frac{e^{\phi}}{n_B} \left(\frac{\Theta}{3} + g_2 \frac{3}{2}\sigma - e^{-\phi} \frac{\partial \phi}{\partial t} \right) w^0 \Big|_{\nu_L}^{\nu_U} = e^{\phi} \frac{S_g^0}{n_B}.$$

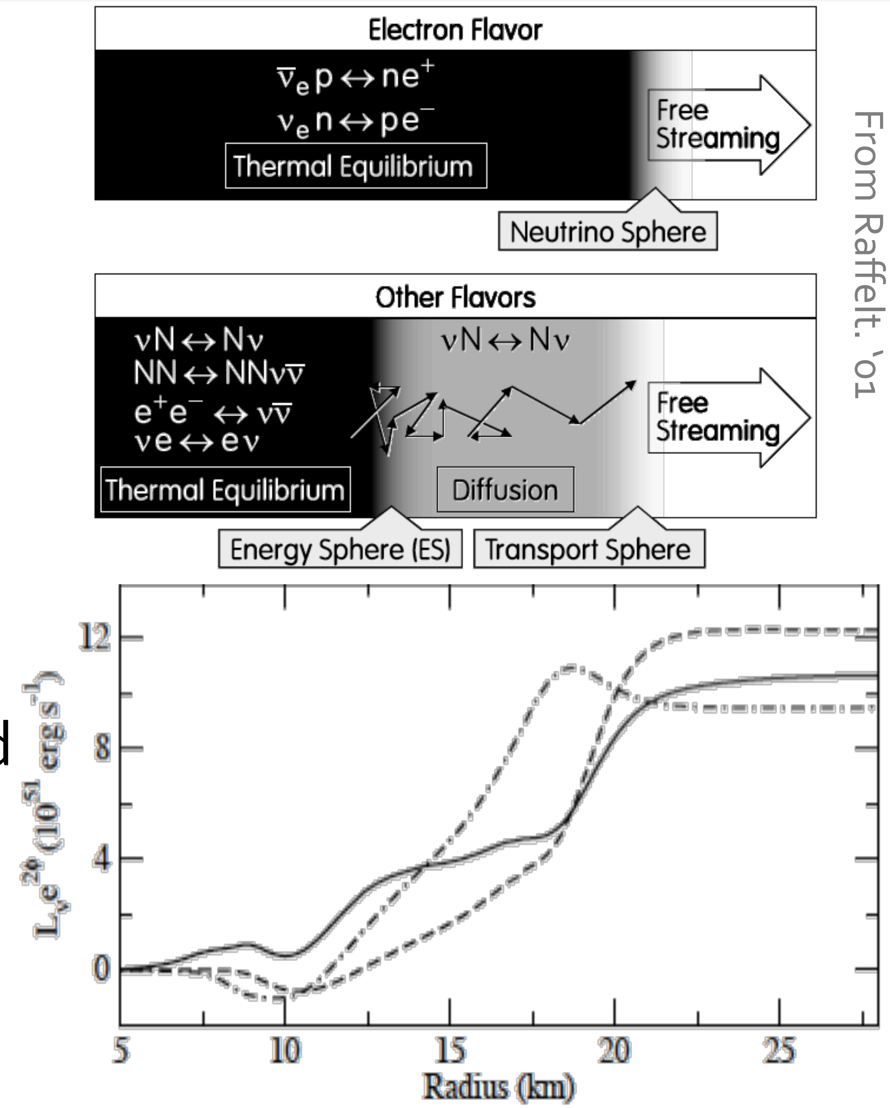
Input Physics:

Neutrino Opacities Consistent with Underlying EoS

Reaction	Details & References
$\nu + N \leftrightarrow \nu + N$	Relativistic, inelastic, weak magnetism corrections, mean field (Reddy et al. '98, Horowitz & Perez-Garcia '03)
$\nu + e^- \leftrightarrow \nu + e^-$	Ultra-relativistic, inelastic (Yueh & Buchler '77, etc.)
$\nu + \bar{\nu} + N + N \leftrightarrow N + N$	Non-relativistic, One-pion exchange, uncertain (Hannestad & Raffelt '98)
$\nu + \bar{\nu} \leftrightarrow e^- + e^+$	Ultra-relativistic (Bruenn '85)
$\nu_e + n \leftrightarrow e^- + p$	Relativistic, weak magnetism corrections, mean field (Reddy et al. '98)
$\bar{\nu}_e + p \leftrightarrow e^+ + n$	Relativistic, weak magnetism corrections, mean field (Reddy et al. '98)

What Determines the ν_e Spectra?

- "Neutrino sphere" is not well defined, energy dependent, range of densities and temperature
- Both charged and neutral current reactions important to ν_e and anti-ν_e decoupling radii
- Charged current rates introduce asymmetry between neutrinos and antineutrinos
- What effects the charged current interaction rates?



From Raffelt, '01

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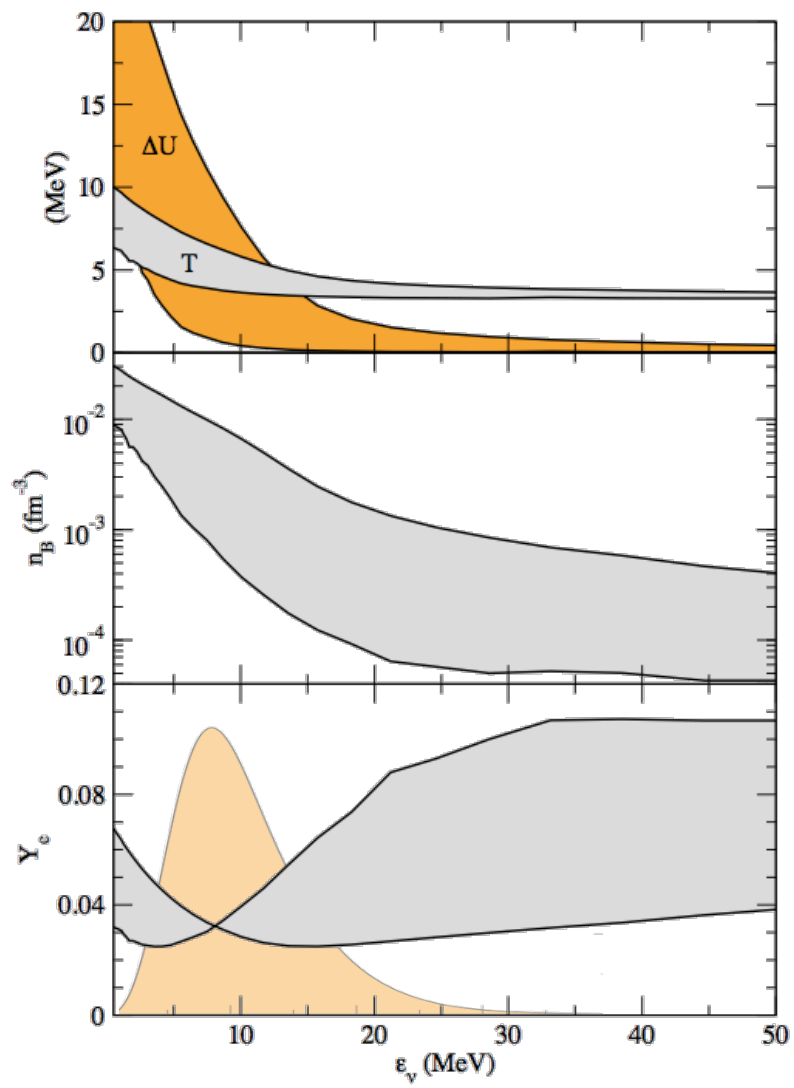


Charged Current Interaction Rates

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

Differential cross-section: (e.g. Reddy et al. 1998, Burows & Sawyer 1999)

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta dE_e} = \frac{G_F^2\cos^2\theta_c}{4\pi^2} p_e\, E_e\,(1 - f_e(E_e))$$

$$\times\left[(1+\cos\theta)S_\tau(q_0,q) + g_A^2(3-\cos\theta)S_{\sigma\tau}(q_0,q)\right]$$

Final electron/positron phase space

Response functions of nuclear medium

Free gas response: $S_{\rm F}(q_0,q) = \frac{1}{2\pi^2}\int d^3p_2\delta(q_0+E_2-E_4)f_2(1-f_4)$

PNS Atmosphere phase space:

$$p_{e^-}E_{e^-}(1-f_{e^-}) \approx (E_\nu - q_0)^2\exp\left(\frac{E_\nu - q_0 - \mu_{e^-}}{T}\right)$$

$$p_{e^+}E_{e^+}(1-f_{e^+}) \approx (E_\nu - q_0)^2$$

Charged Current Interaction Rates in Medium

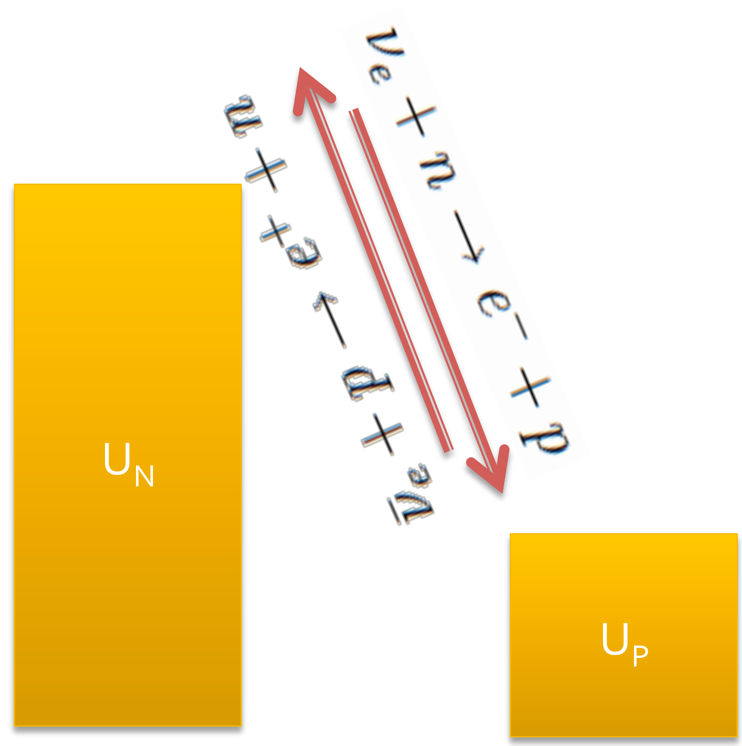
Nucleons are in an interacting medium, mean field approximation assumes density dependent mean fields, which alter nucleon dispersion relations:

$$E_i(k) = \sqrt{k^2 + M^{*2}} + U_i$$

Changes the energy transfer to the final state nucleon by

$$q_0 \;\longrightarrow\; \tilde{q}_0 = q_0 + U_2 - U_4$$

e.g. Reddy et al. 1998, Horowitz & Perez-Garcia 2003, LR, Reddy & Shen 2012



The Nucleon Response

Nucleons are in an interacting medium, mean field approximation assumes density dependent mean fields, which alter nucleon dispersion relations:

$$E_i(k) = \sqrt{k^2 + M^{*2}} + U_i$$

Changes the energy transfer to the final state nucleon by

$$q_0 \;\rightarrow\; \tilde{q}_0 = q_0 + U_2 - U_4$$

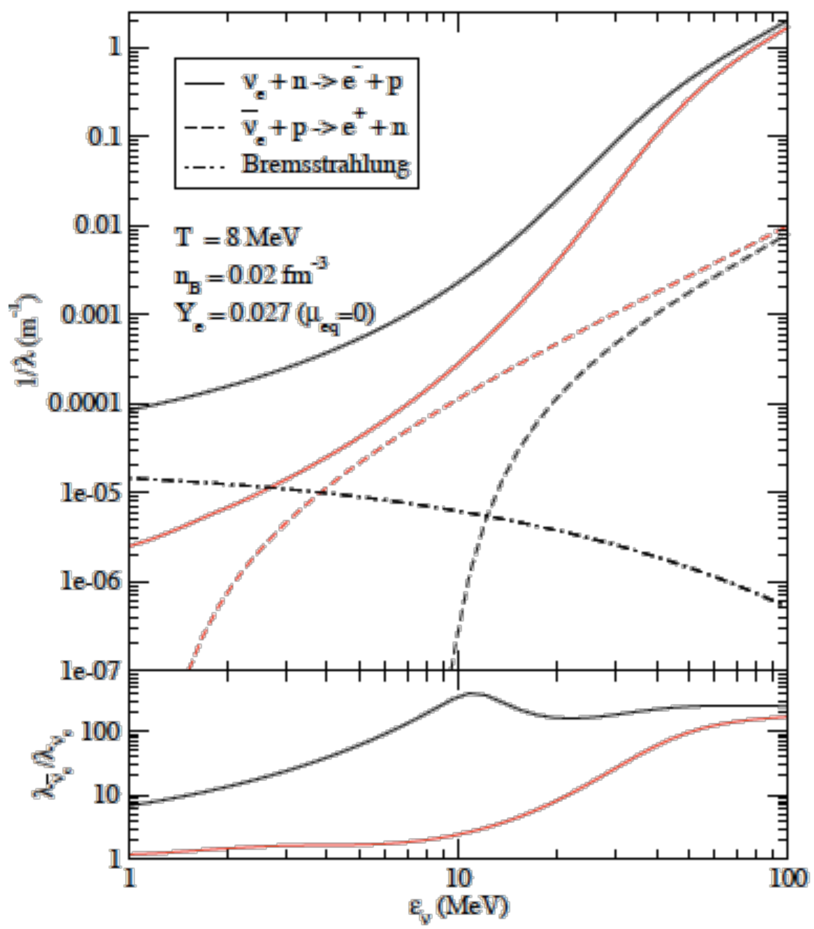
Shifts the peak of the response by

$$\Delta U = U_n - U_p \approx 40 \times \frac{(n_n - n_p)}{n_0}\ \mathrm{MeV}$$

Exponential increase in available phase space

$$\frac{\lambda^{-1}(\Delta U)}{\lambda^{-1}(\Delta U = 0)} \approx \frac{(\varepsilon_\nu + \Delta U)^2}{\varepsilon_\nu^2} \exp(\Delta U / T)$$

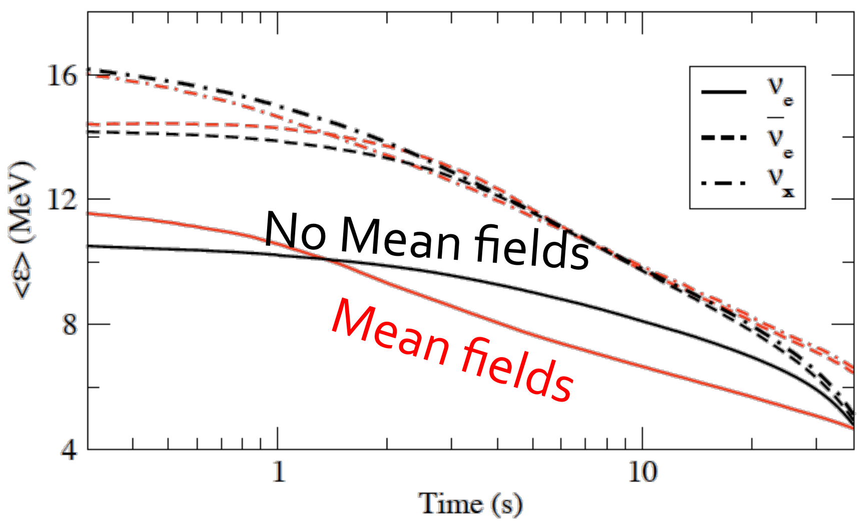
e.g. Reddy et al. 1998, Horowitz & Perez-Garcia 2003, LR, Reddy & Shen 2012



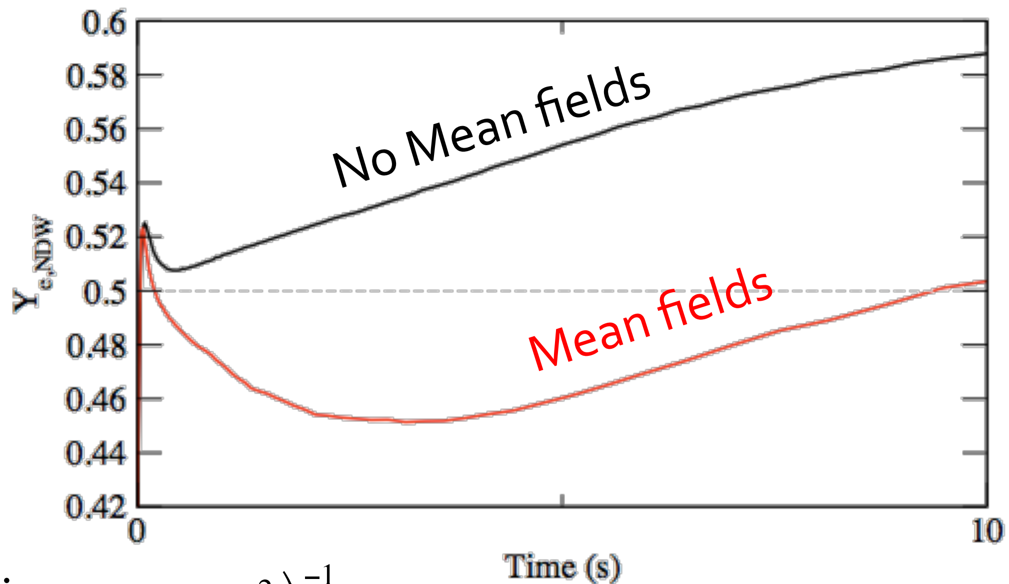
Neutrino emission w/ and w/o Nuclear Interactions

See LR '12 and Martinez-Pinedo et al. '12

Mean fields shift average neutrino energies



Neutrino driven wind electron fractions

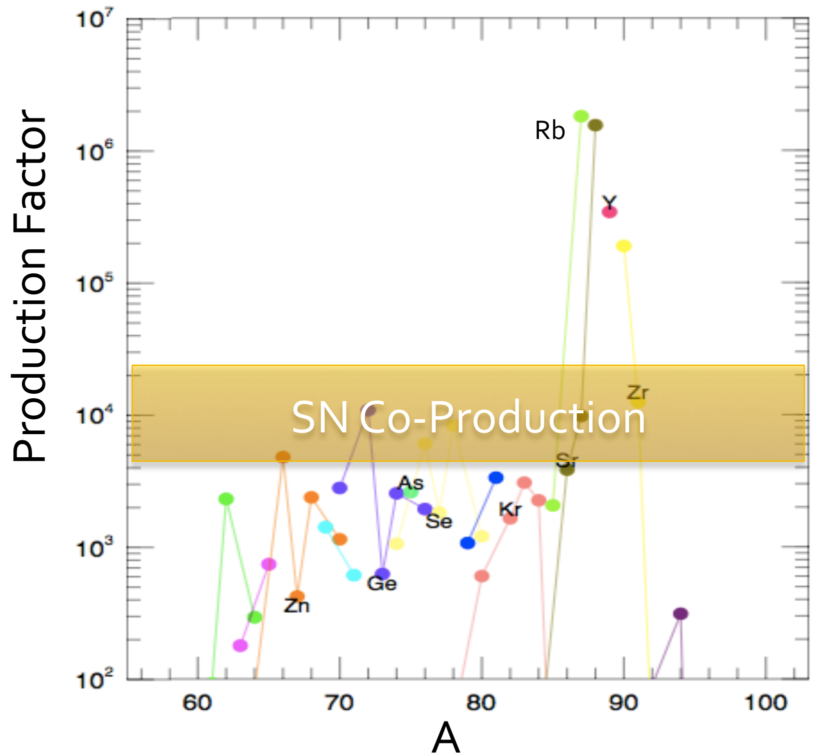


$$Y_e \approx \left(1 + \frac{\dot{N}_{\bar{\nu}_e}}{\dot{N}_{\nu_e}} \frac{(\varepsilon_{\bar{\nu}_e} - \Delta)^2}{(\varepsilon_{\nu_e} + \Delta)^2}\right)^{-1}$$

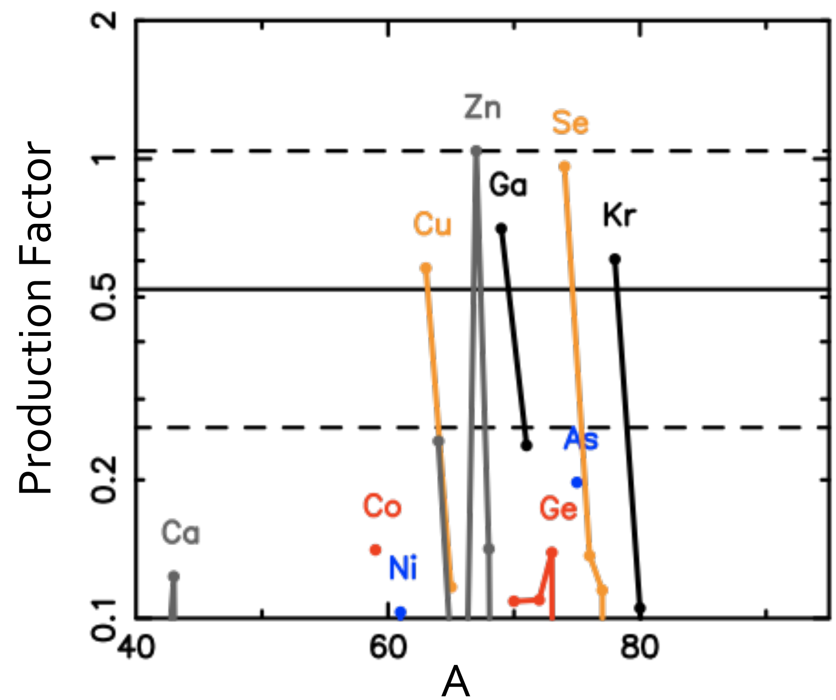
Integrated Wind Nucleosynthesis

$$P_i = \frac{X_{i,w} M_w}{X_{i,\odot}(M_w + M_{sn})}$$

See also recent pre-print by Wanajo (arXiv:1305.0371)

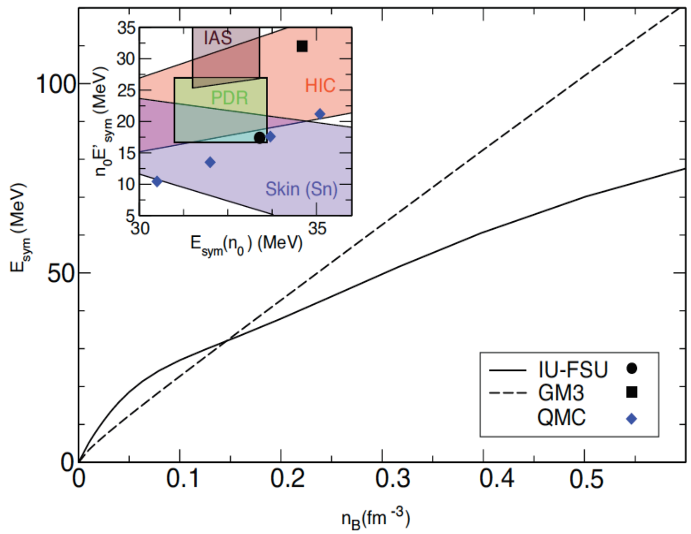


Roberts. '12 neutrino histories. Significant N = 50 closed neutron shell production, back to the same old problem.



Huedepohl et al. '10 neutrino histories. Very little nucleosynthesis. 7.5 M_{sun} ejected.

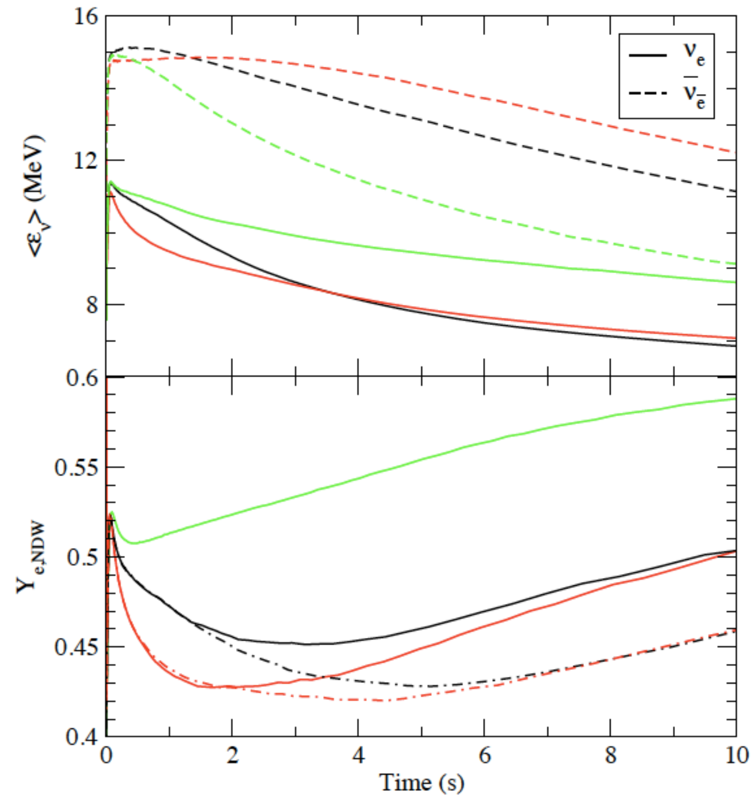
Equation of State Dependence



Different equations of state

Model	ΔU (MeV)
Lowest order virial, Eq. (21)	3.85
Virial $\mu_i - \mu_i^f$, Eq. (31)	2.27
Mean field model GM3, Eq. (36)	0.23
Mean field model IUFSU [24]	1.11

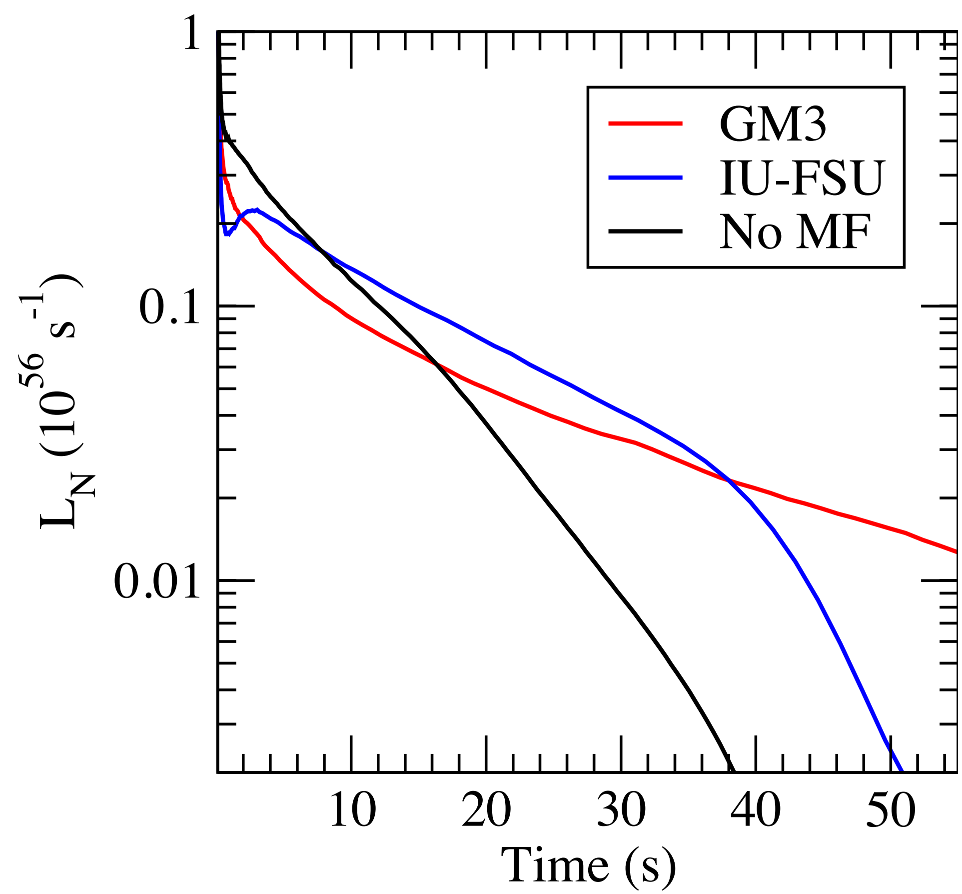
From Horowitz et al. (2012)



Different spectra and wind electron fractions

The Deleptonization Rate

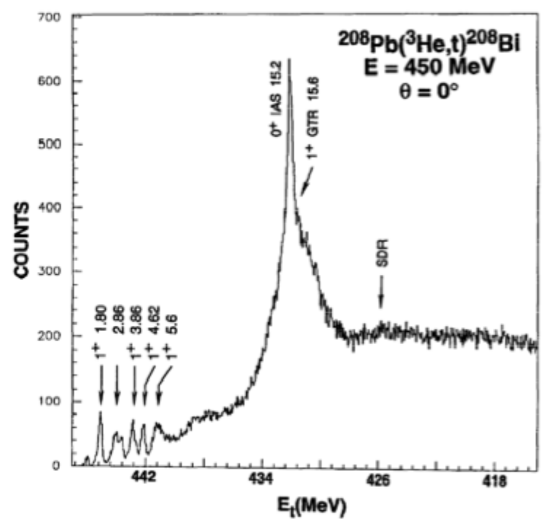
- Asymmetry also effects deleptonization rate of PNS
- Inclusion of mean fields increases deleptonization timescale
- Larger L results in longer deleptonization timescale
- Requires neutrino detectors that can distinguish between electron neutrinos and anti-neutrinos (i.e. Liquid Ar detectors)



What else is still uncertain for charged current rates?

The Gamow-Teller Resonance: Spin-Isospin Collective Mode

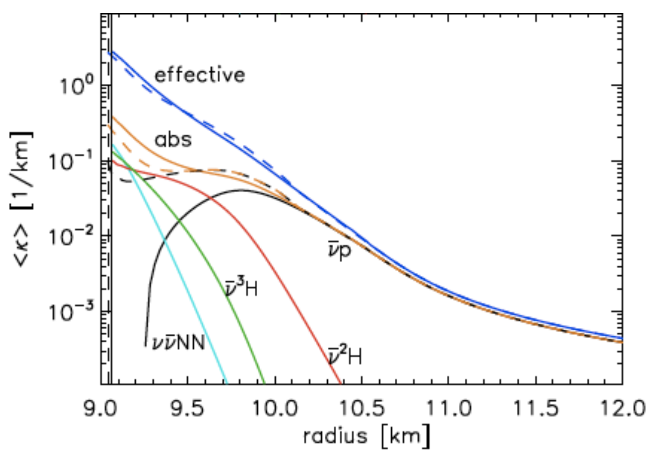
Akimune, et al. '94



Nuclear Pasta?

Light Clusters

Arcones et al. '08

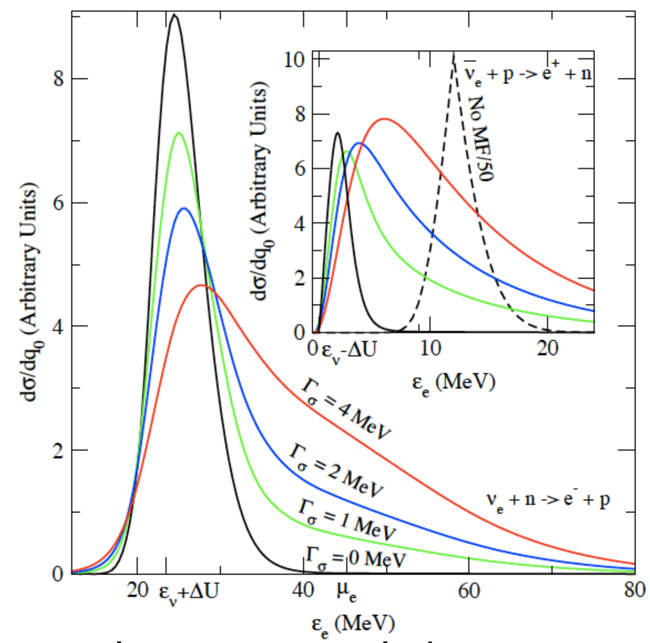


Multi-pair Excitations

Lykasov, Olsson, Pethick (2005)

Lykasov, Pethick, Schwenk (2006)

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



Relax two particle kinematic restrictions allowing for larger energy transfers to the final state leptons.

Summary

- Nailing spectra most important part of understanding NDW nucleosynthesis
- Uncertainties in ν_e and anti-ν_e neutrino emission from PNSs
- The importance of the nuclear MF potentials to PNS charged current interactions, moving back to being neutron rich
- Expected nucleosynthesis depends on the EoS, specifically the nuclear symmetry energy