r-Process Nucleosynthesis in the Neutrino Driven Wind?

Luke Roberts (Caltech)

Outline

- Charged current interaction rates in PNS atmospheres
- Secondary heating via acoustic waves in NDWs

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, Vlasov ’14, etc.

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

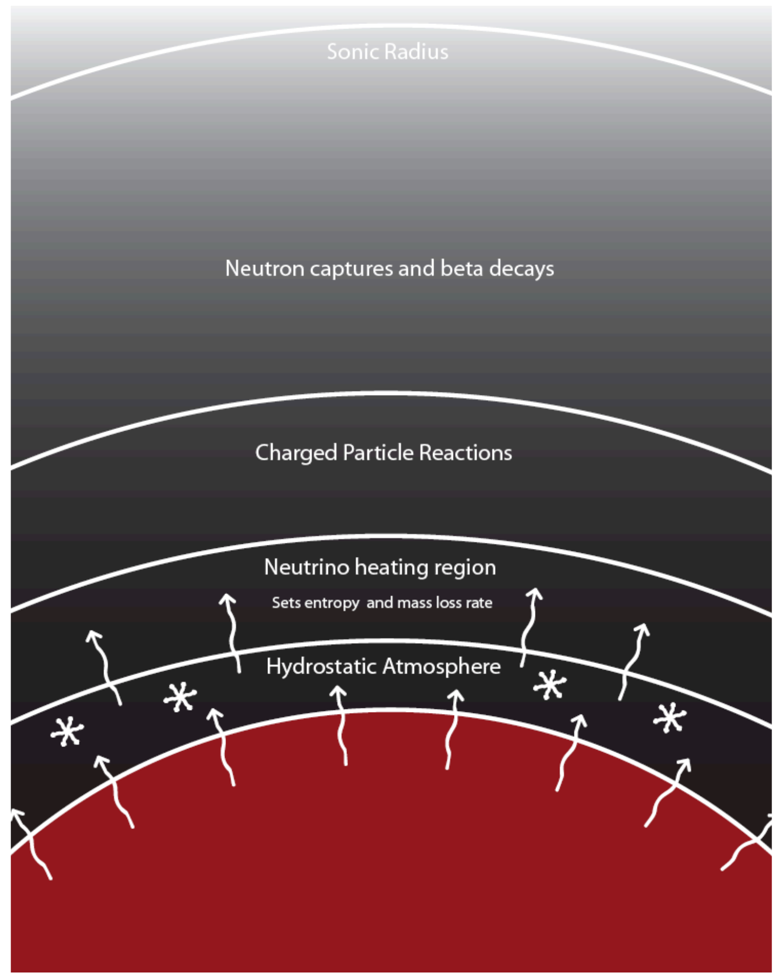
• Drives an outflow from the surface of the neutron star

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

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

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

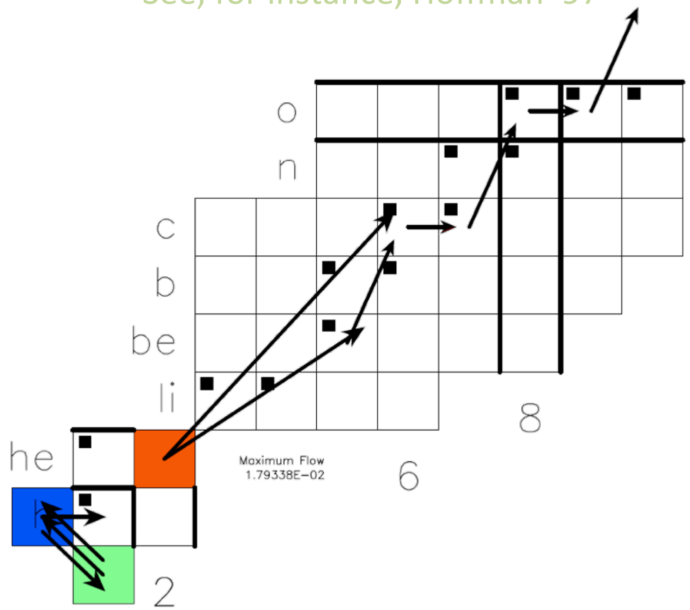
•Possible site to make some interesting nuclei that are not made during normal stellar evolution: *r*-process, light *p* nuclides, N = 50 closed shell nuclei Sr, Y, Zr

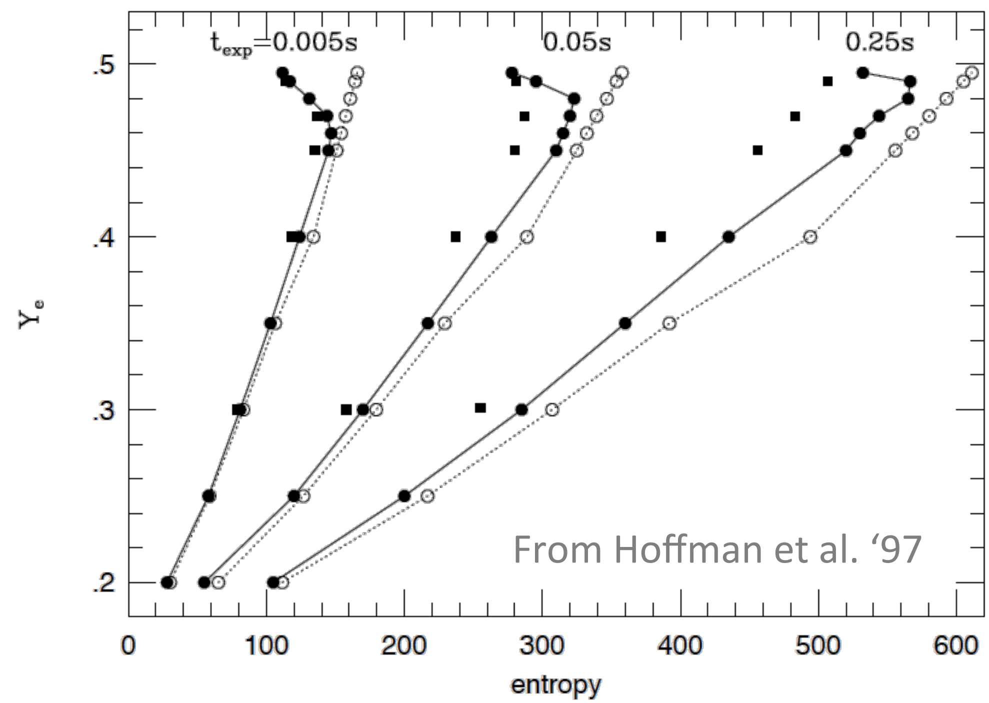


Wind nucleosynthesis:

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

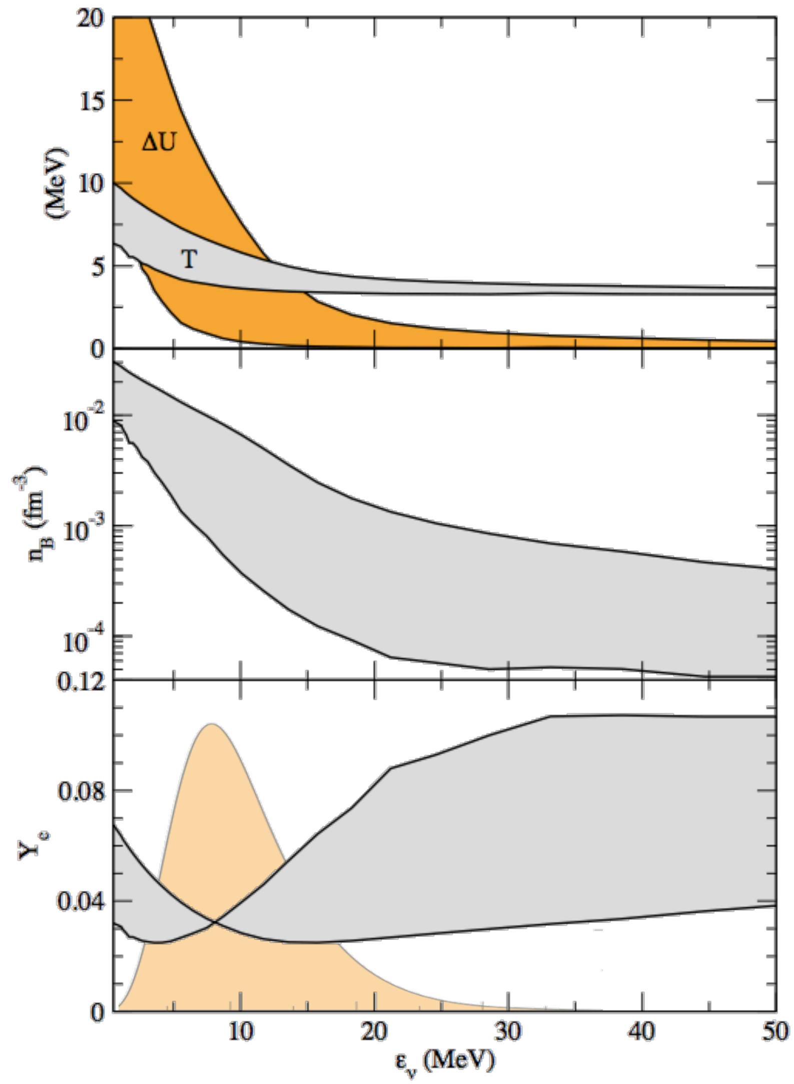
- Setting the neutron to seed ratio:

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

Wind Dynamics

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



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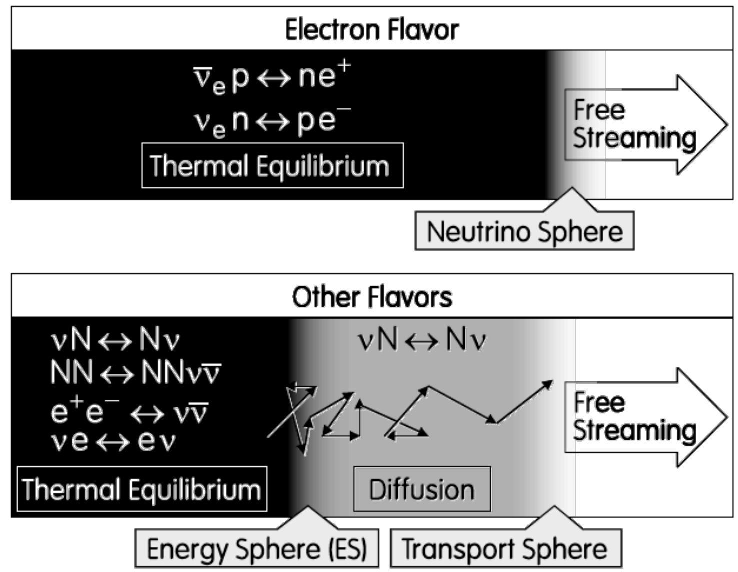
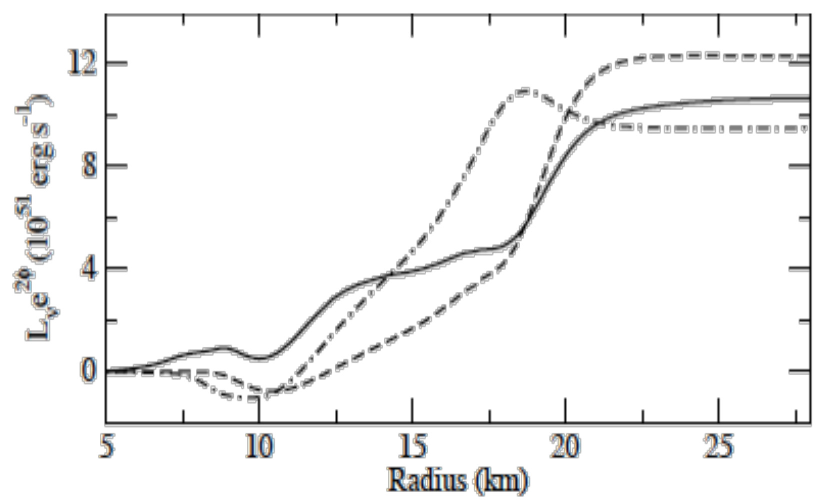


From Raffelt '01



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

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

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

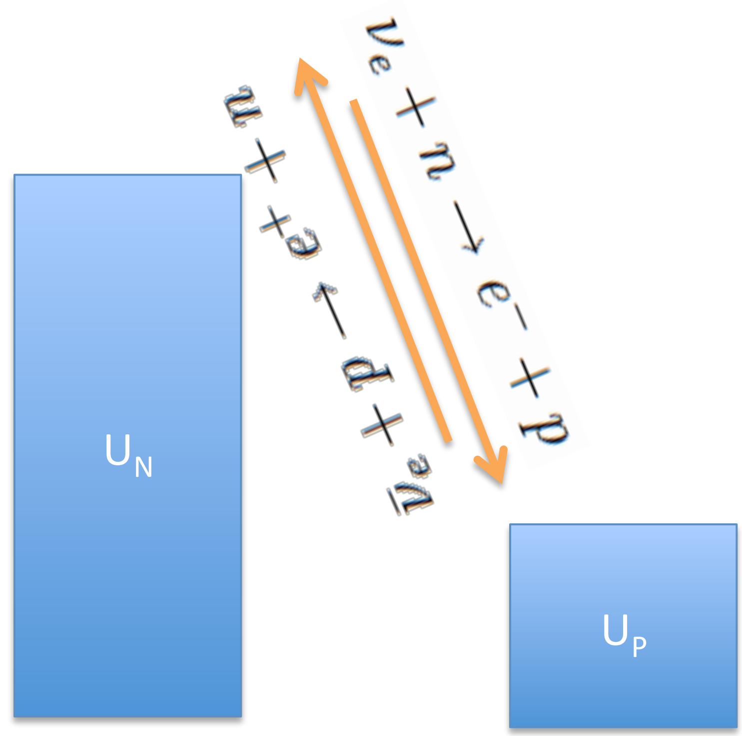
Shifts the peak of the response by

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

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



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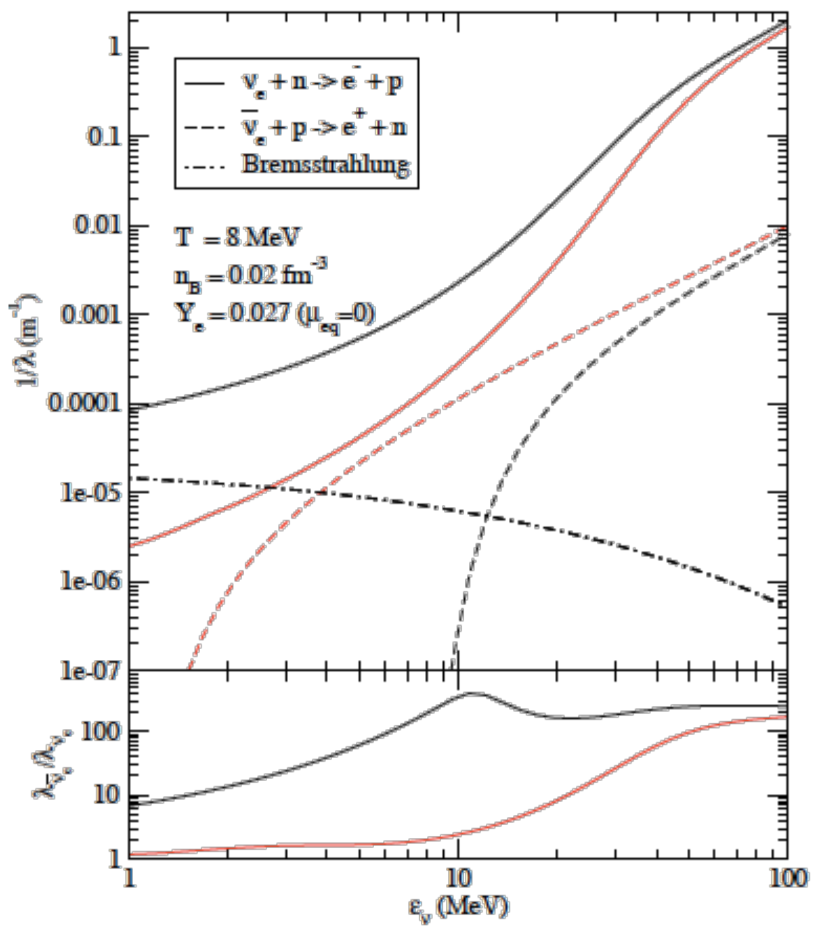
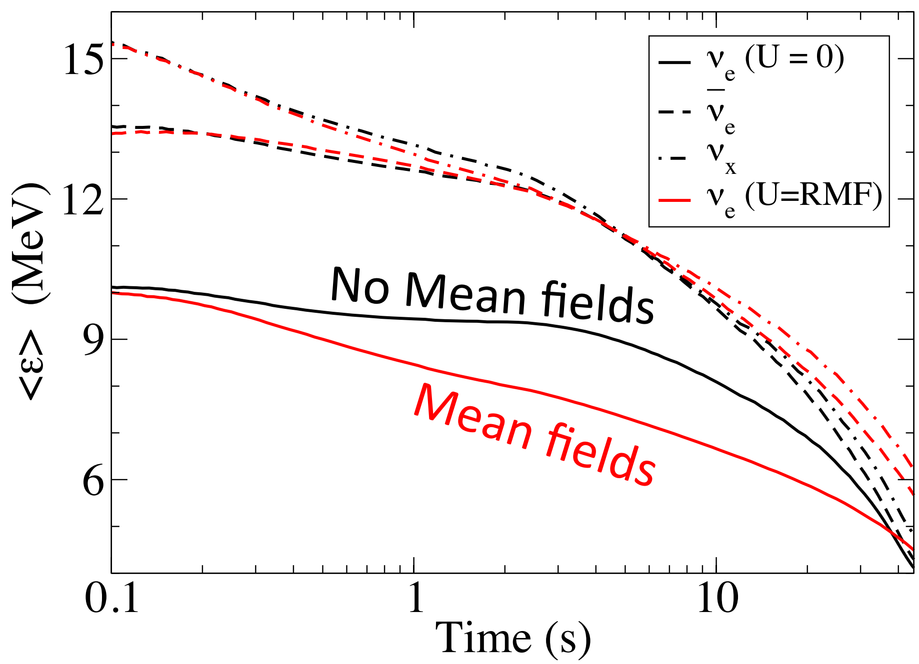


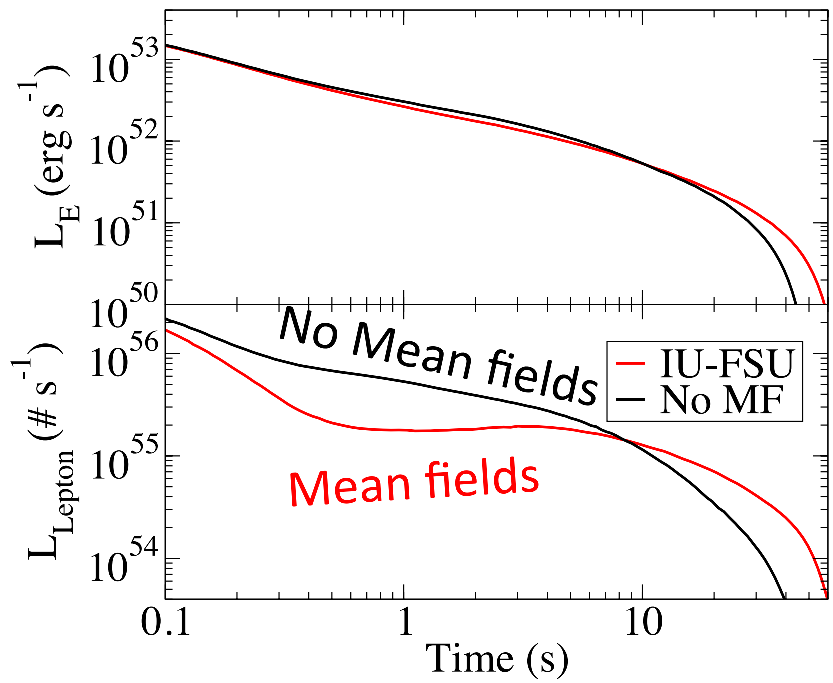
Neutrino emission w/ and w/o Nuclear Interactions

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

Mean fields shift average neutrino energies



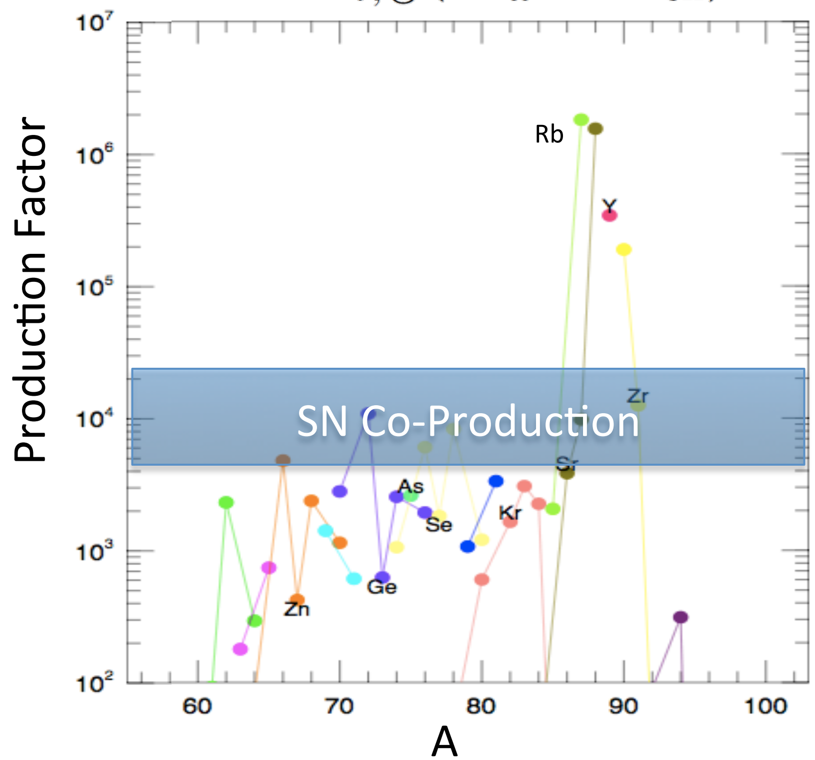
Deleptonization

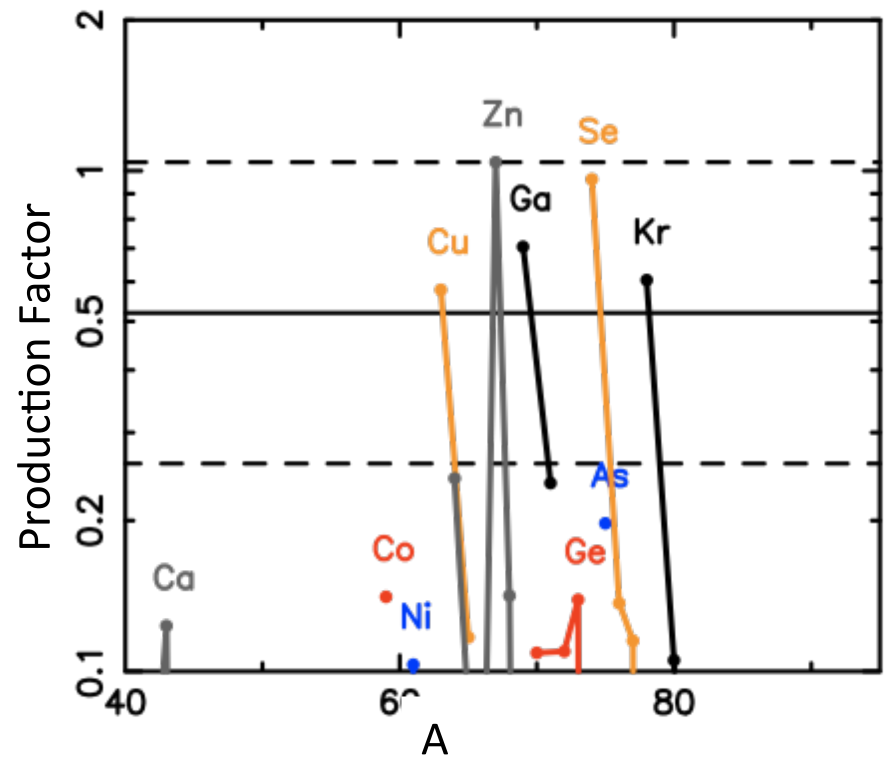


Integrated NDW Nucleosynthesis

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

See also Wanajo (2013)

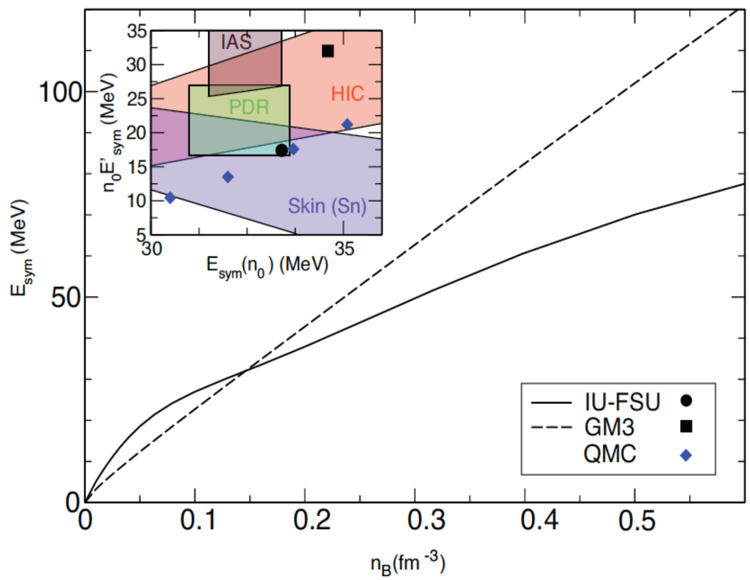




Roberts. '12 neutrino histories. Significant N = 50 closed neutron shell production.

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

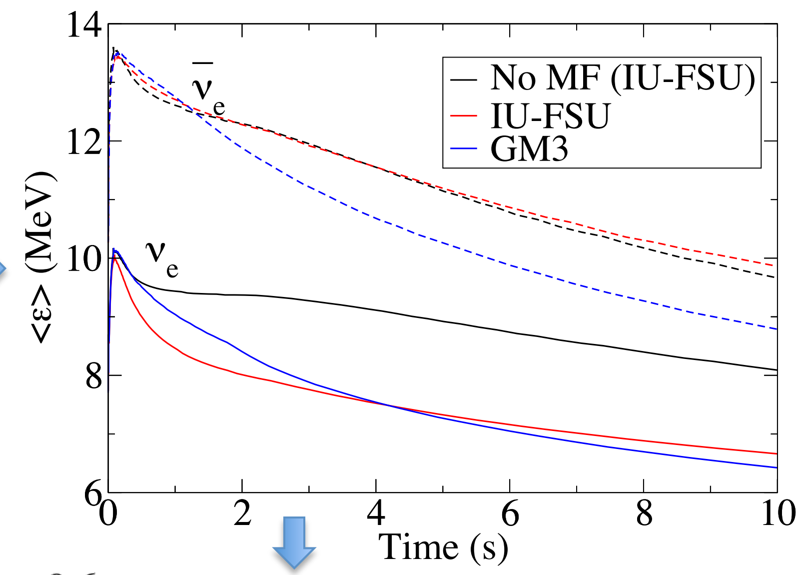
Equation of State Dependence

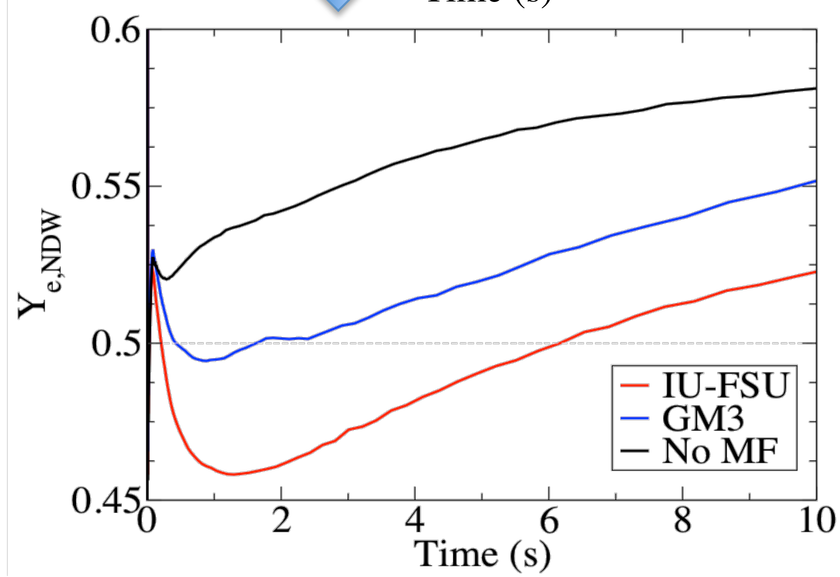


Different equations of state

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

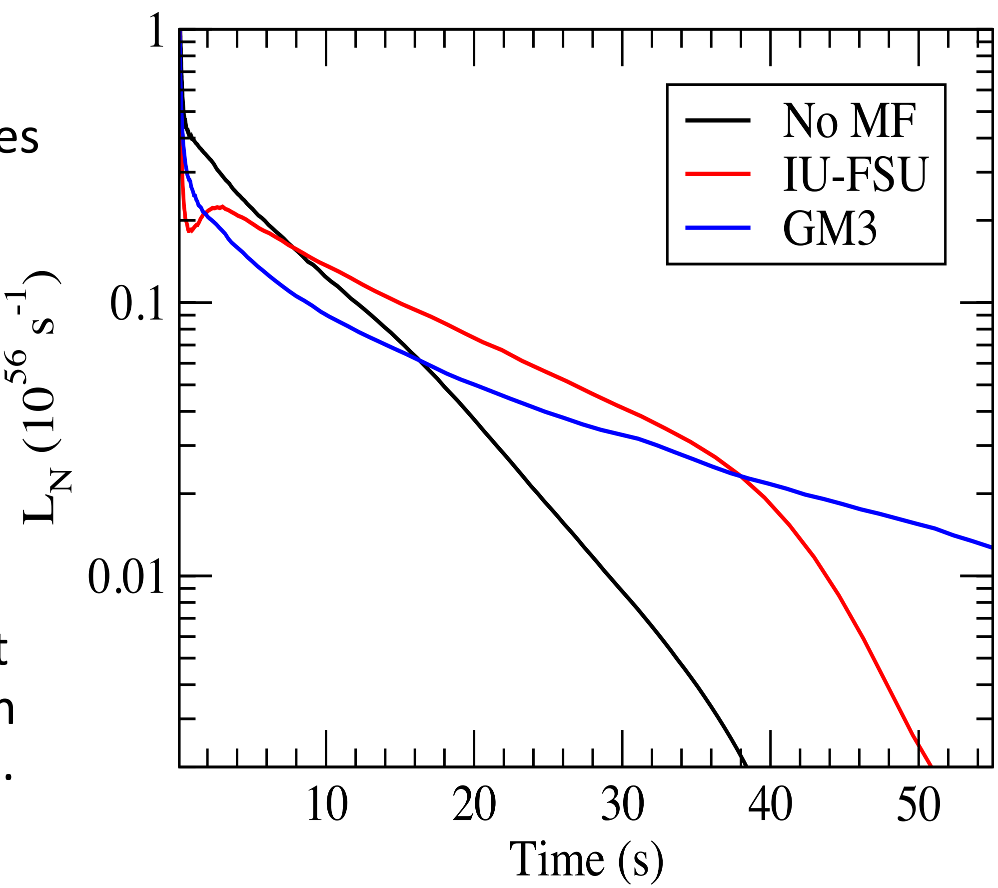
From Horowitz et al. (2012)





The Deleptonization Rate

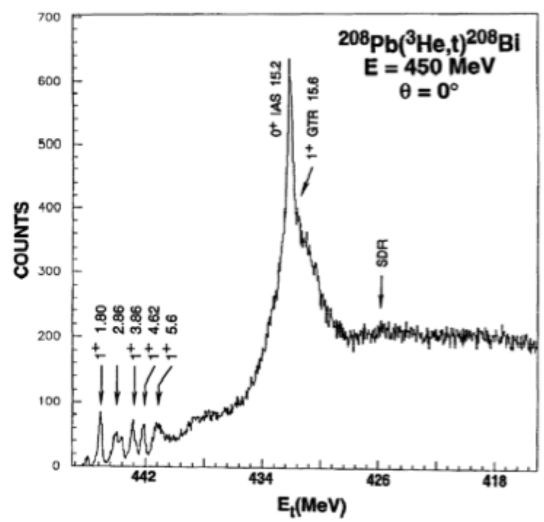
- Asymmetry also effects deleptonization rate of PNS
- Inclusion of mean fields decreases deleptonization rate, which also pushes towards lower electron fraction
- Larger L results in longer deleptonization timescale
- Requires neutrino detectors that can distinguish between electron neutrinos and anti-neutrinos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



What else is still uncertain for charged current rates?

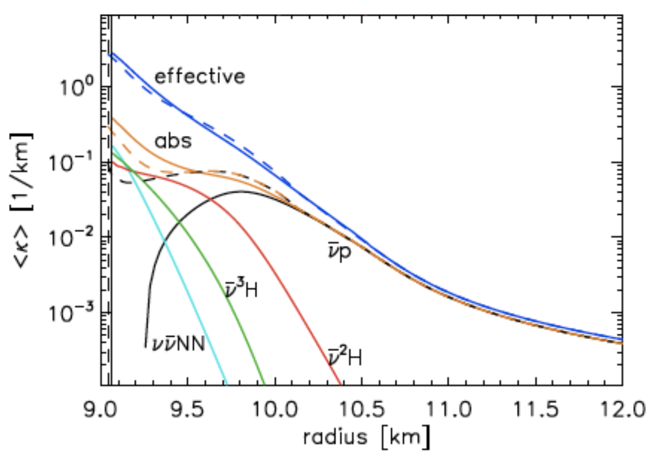
The Gamow-Teller Resonance: Spin-Isospin Collective Mode

Akimune, et al. '94



Light Clusters

Arcones et al. '08

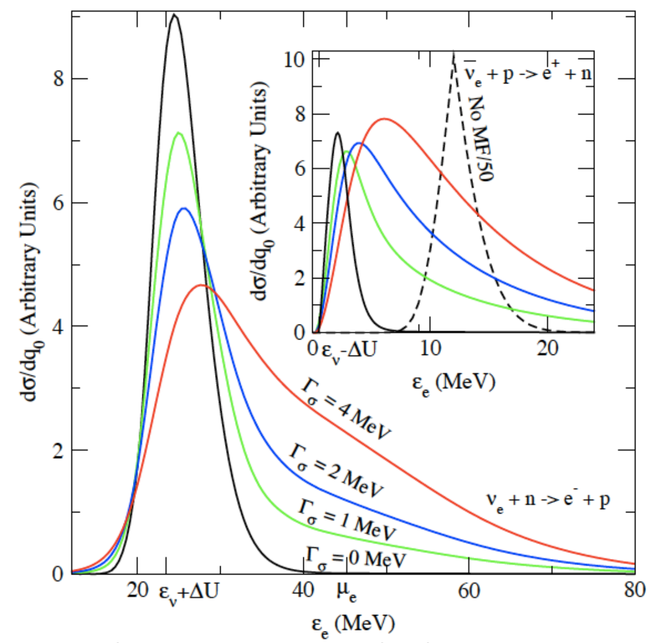


Multi-pair Excitations

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.

Can any *r*-process material be made?

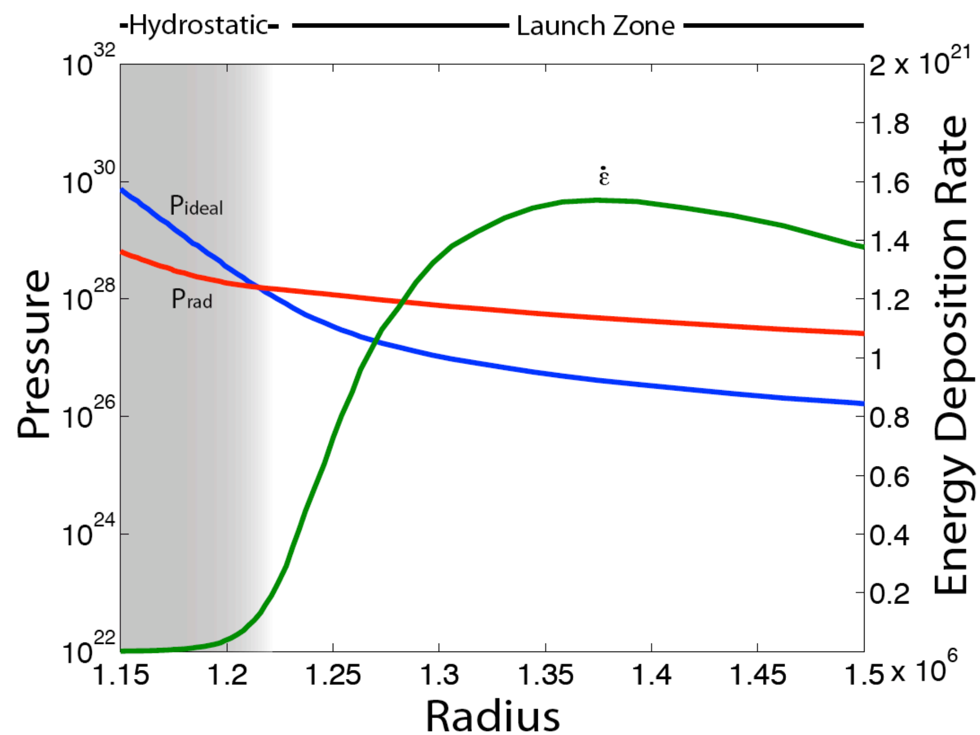
•NDW is not neutron rich enough in the standard scenario to make the *r*-process

•Temperature structure of the protoneutron star atmosphere set by:

$$\dot{q}_e \approx \dot{\varepsilon}_\nu$$
$$\Rightarrow T_{atm} \approx 3\, R_6^{-1/3} L_{\nu,51}^{1/6} T_{\nu,5\,MeV}^{1/3}\, MeV$$

•Secondary energy deposition source doesn't strongly effect atmosphere, deposits energy at lower temperature

• Increases entropy of material, decreases dynamical timescale, conditions more favorable for r-process
(Qian & Woosley '96, Suzuki & Nagataki '05, Metzger et al. '07)



What is the optimal secondary heating rate and damping length?

$$L_{w,c} \approx 10^{47}\,\mathrm{erg\,s^{-1}}\,L_{\nu_e,51}^{5/3}\,\epsilon_{\nu_e,10\mathrm{MeV}}^{10/3}\,R_6^{2/3}\,M_{1.4}^{3}$$

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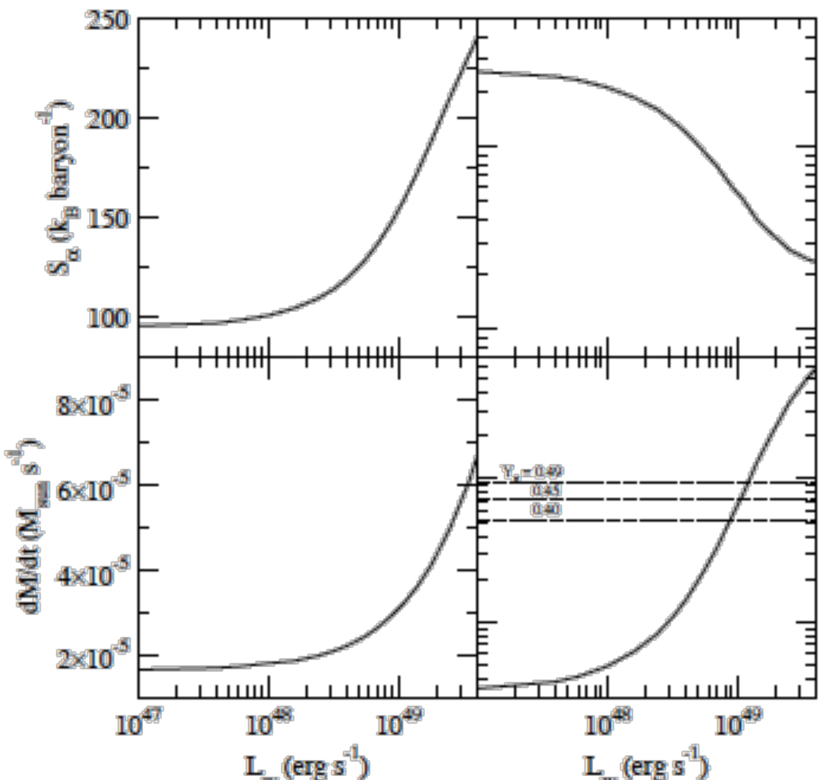
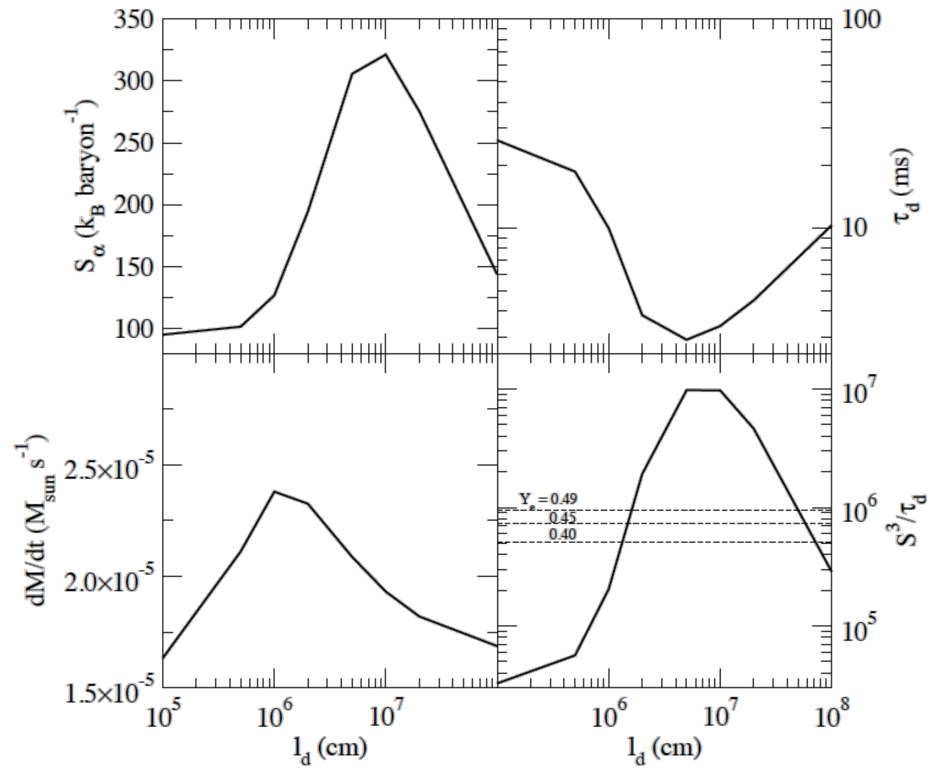




$$\dot{q}_{ext} = \frac{L_0}{4\pi\rho l_d r^2}\exp[(r_0 - r)/l_d]$$

Wave Excitation by Convection

Convection is most efficient at exciting gravity waves:

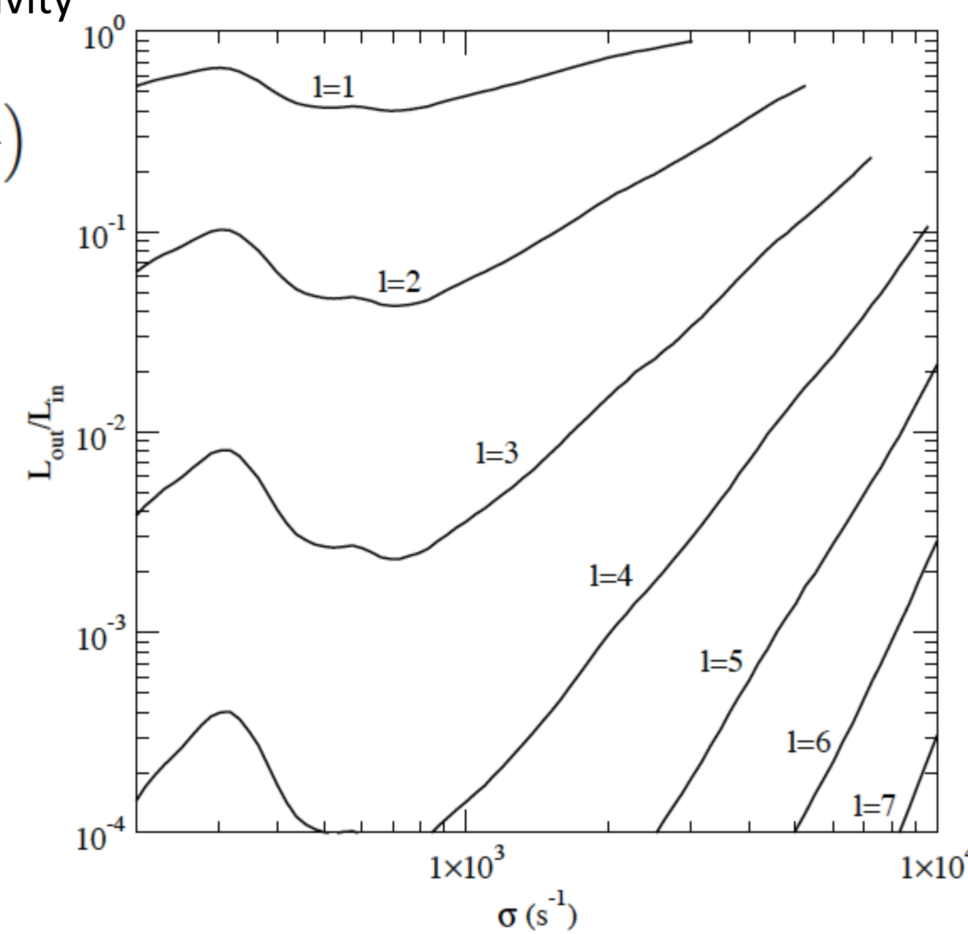
$$L_g \approx M_c L_c \approx 10^{50}\,\mathrm{erg s^{-1}} \left(\frac{r_c}{10^6\mathrm{cm}}\right)^2 \left(\frac{\rho_c}{10^{14}\,\mathrm{g/cc}}\right) \times \left(\frac{v_c}{10^8\mathrm{cms^{-1}}}\right)^4 \left(\frac{c_s}{10^9\mathrm{cms^{-1}}}\right)^{-1}$$

Characteristic frequency of the waves:

$$\omega_g \sim v_c/H_P \sim 10^2 - 10^3\mathrm{s}^{-1}$$

Waves become evanescent and emerge into the acoustic branch, significant damping occurs:

$$L_{w,f}/L_{w,i} \approx \exp\left(-2\int_{r_a}^{r_b} \sqrt{-k_r^2} dr\right)$$



Acoustic Energy Deposition by Weak Shocks

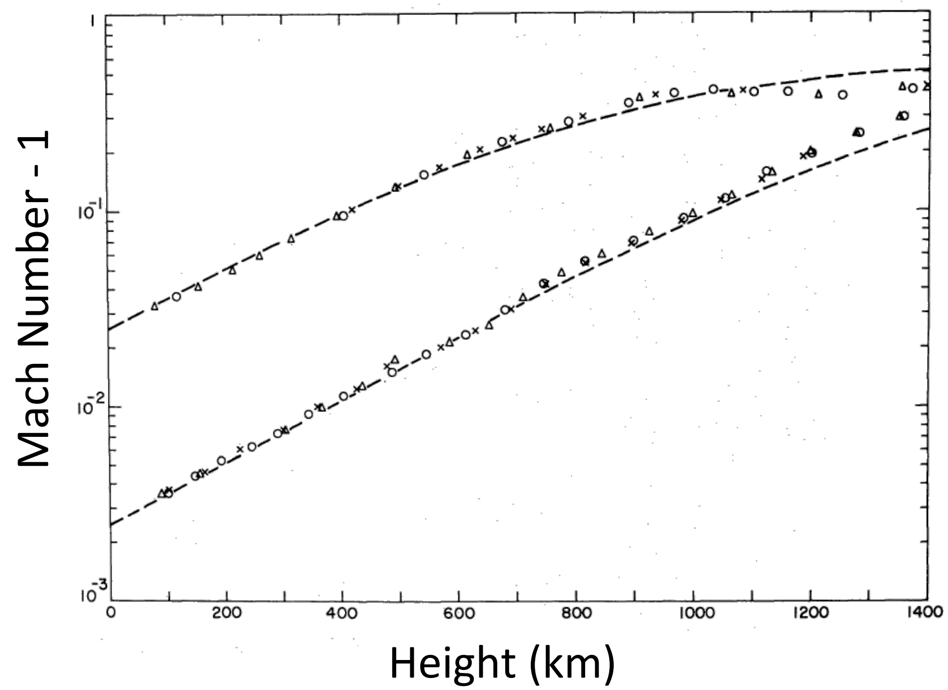
- How do these acoustic waves damp?
- Studied in the context of the solar corona (see Stein & Schwartz '73 for references)
- Steepen into shocks over distance of order the pressure scale height
- Energy loss given by weak shock theory as

$$\nabla \cdot (\mathbf{v_s} \epsilon_s) = -\frac{m}{\pi}\epsilon_s \qquad m = (\gamma+1)\sqrt{\frac{3S}{\gamma P}}$$

$$\partial_t S + r^{-2}\partial_r(r^2 v_g S) \approx -\frac{\gamma+1}{\pi}\omega\sqrt{\frac{3S}{\gamma P}}S$$

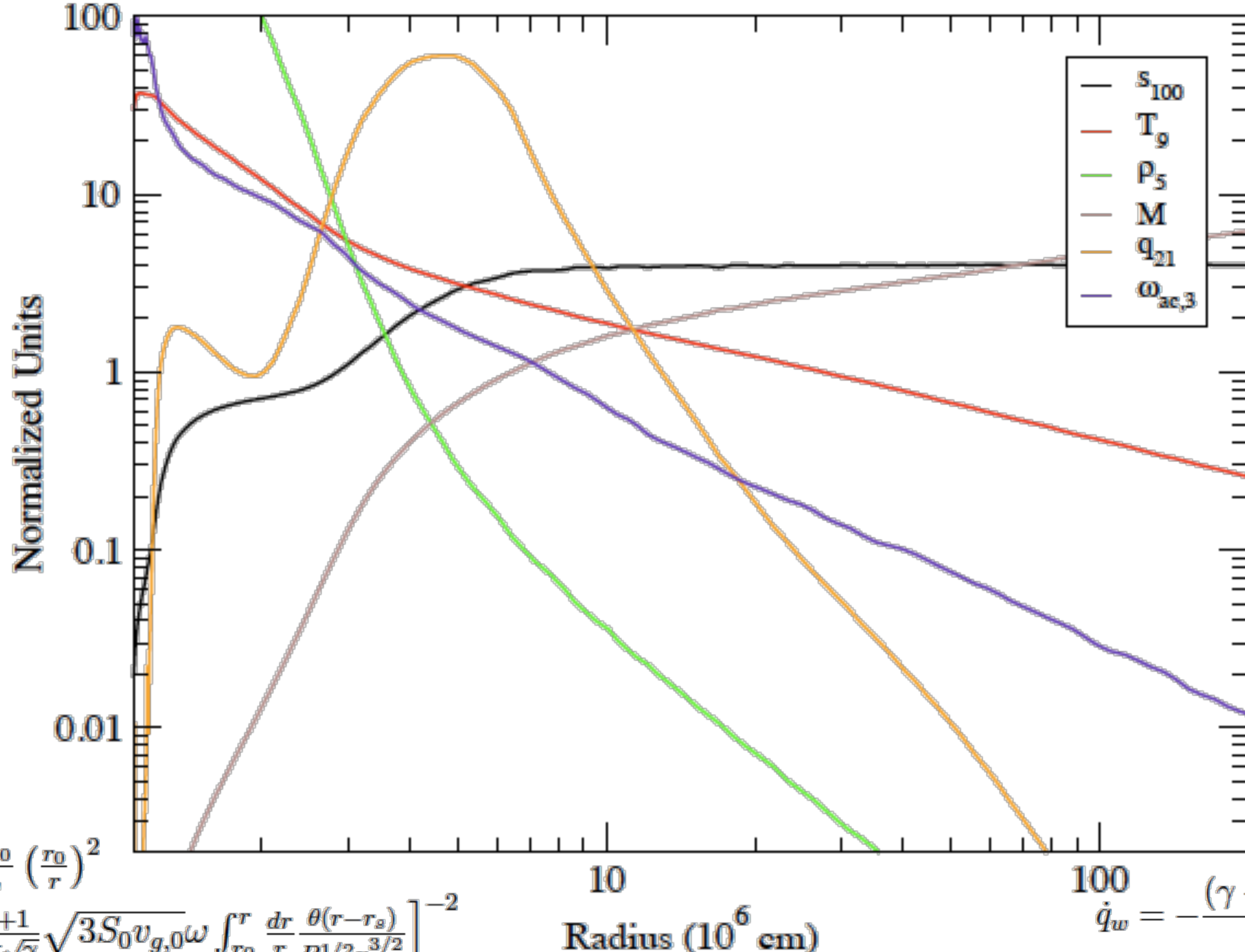
- Results in a damping length

$$l_d \approx 2.6 \times 10^6\,\mathrm{cm}\,\frac{c_{s,9}}{\omega_3}\left(\frac{E}{10S}\right)^{1/2}$$



Stein & Schwartz 1973

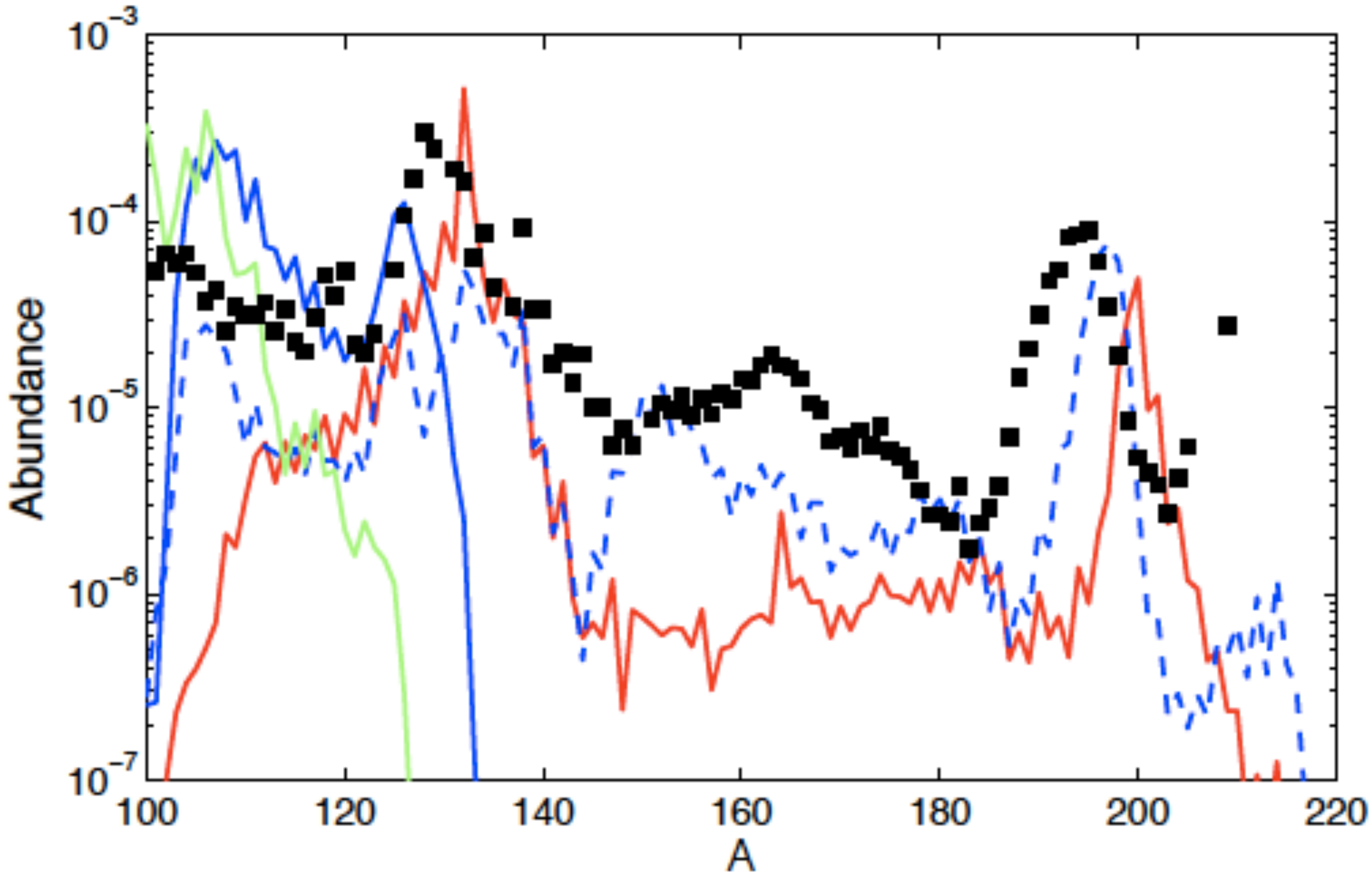
NDW Including Wave Heating



$$S = S_0 \frac{v_{g,0}}{v_g} \left(\frac{r_0}{r}\right)^2 \times \left[1 + \frac{\gamma+1}{2\pi\sqrt{\gamma}} \sqrt{3 S_0 v_{g,0}}\, \omega \int_{r_0}^{r} \frac{dr}{r} \frac{\theta(r - r_s)}{P^{1/2} v_g^{3/2}}\right]^{-2}$$

$$\dot{q}_w = -\frac{(\gamma+1)\omega}{\pi\rho} \sqrt{\frac{3S^3}{\gamma P}}$$

Neutrino/Acoustic Driven Wind Nucleosynthesis



$$L_w = \{1 \times 10^{48},\, 2.5 \times 10^{48},\, 5 \times 10^{48}\}\,\mathrm{erg\,s^{-1}}$$

Summary

- 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
- Deleptonization rate also altered by mean field potentials
- Secondary heating allows for an r-process even in marginally neutron rich winds
- Acoustic power from PNS convection possible source of extra energy