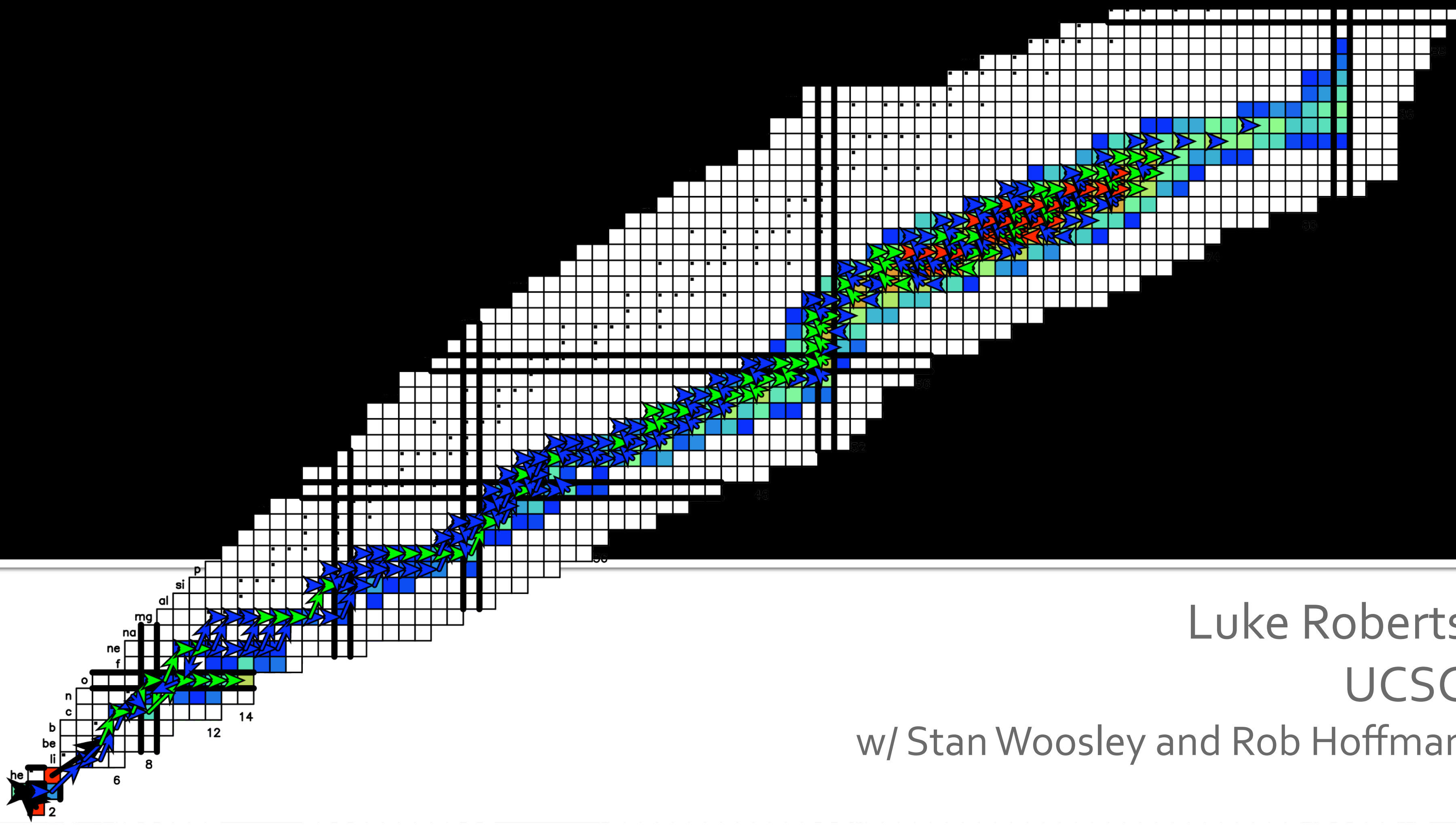
Nucleosynthesis in Neutrino Driven Winds



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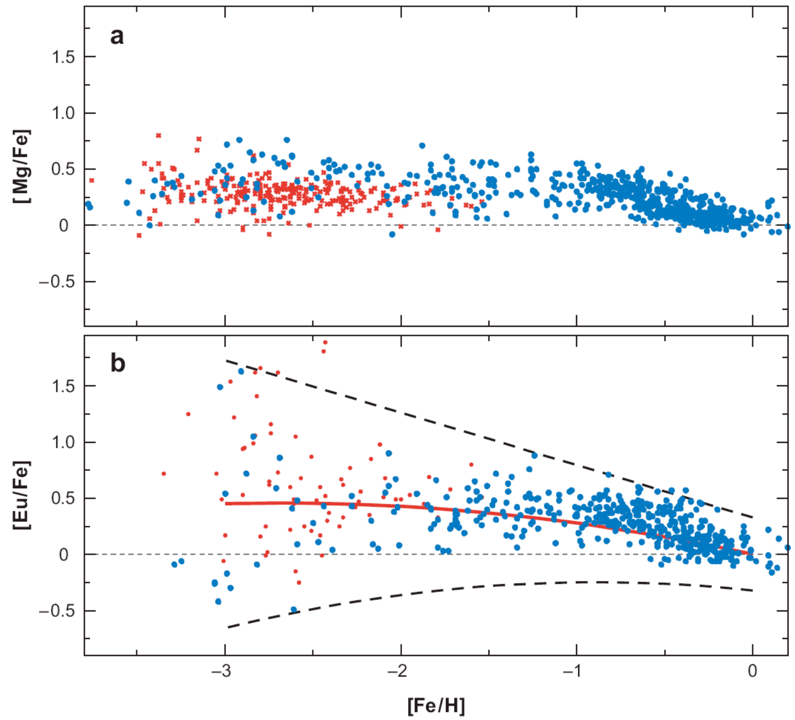
w/ Stan Woosley and Rob Hoffman

Overview

- Neutrino Driven Wind Models
- Integrated Nucleosynthesis
  - 2 Models
  - Effects of varying neutrino luminosities
- Secondary heating source
  - Neutron to seed ratio variation
  - Acoustic power

Wind Nucleosythesis

- Initial studies found wind to be promising r-process site (Woosley et al. 1994)
- Wind nucleosynthesis determined by $Y_{e,}$ s, and t_{dyn}
- Proton rich wind may also contribute to nucleosynthesis
- How does standard NDW nucleosynthesis fit in the context of full stellar models?



Sneden et al. 2007

Wind nucleosynthesis:
Setting the neutron to seed ratio

- Neutron and alpha particle abundances after nucleon recombination:

$$Y_n = (1 - 2Y_e)$$

$$Y_\alpha = Y_e / 2$$

- Rate of seed production given by:

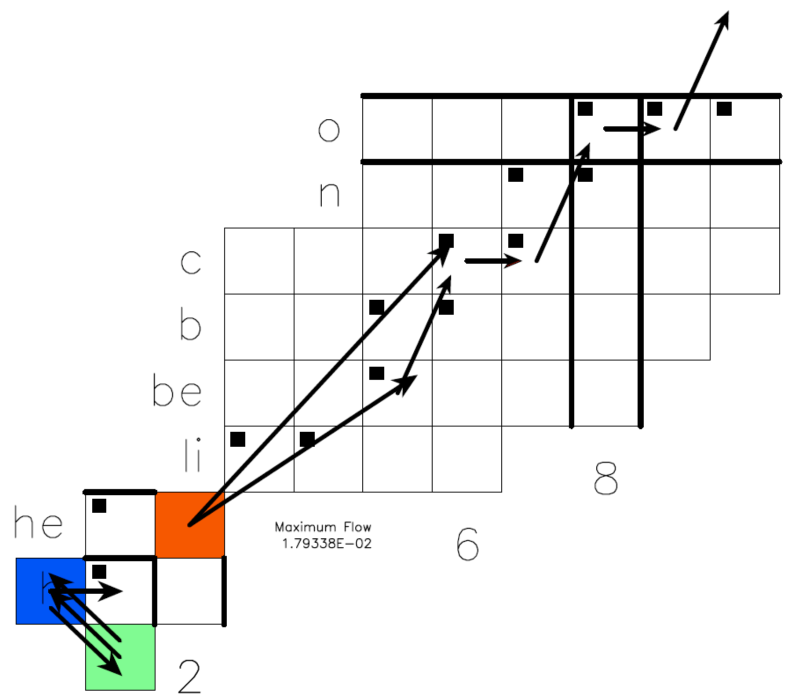
$$\frac{dY_{seed}}{dt} \approx \frac{dY_{^{12}C}}{dt} \propto \rho^3 Y_\alpha^3 Y_n$$

- Giving a neutron to seed ratio:

$$Y_{seed} \propto S_f^{-3} \left(\tfrac{Y_e}{2}\right)^3 Y_n \tau_{dyn}$$

$$\Rightarrow \frac{N_n}{N_{seed}} + 10 \propto \frac{S_f^3}{\tau_{dyn}}$$

Hoffman et al. (1997)



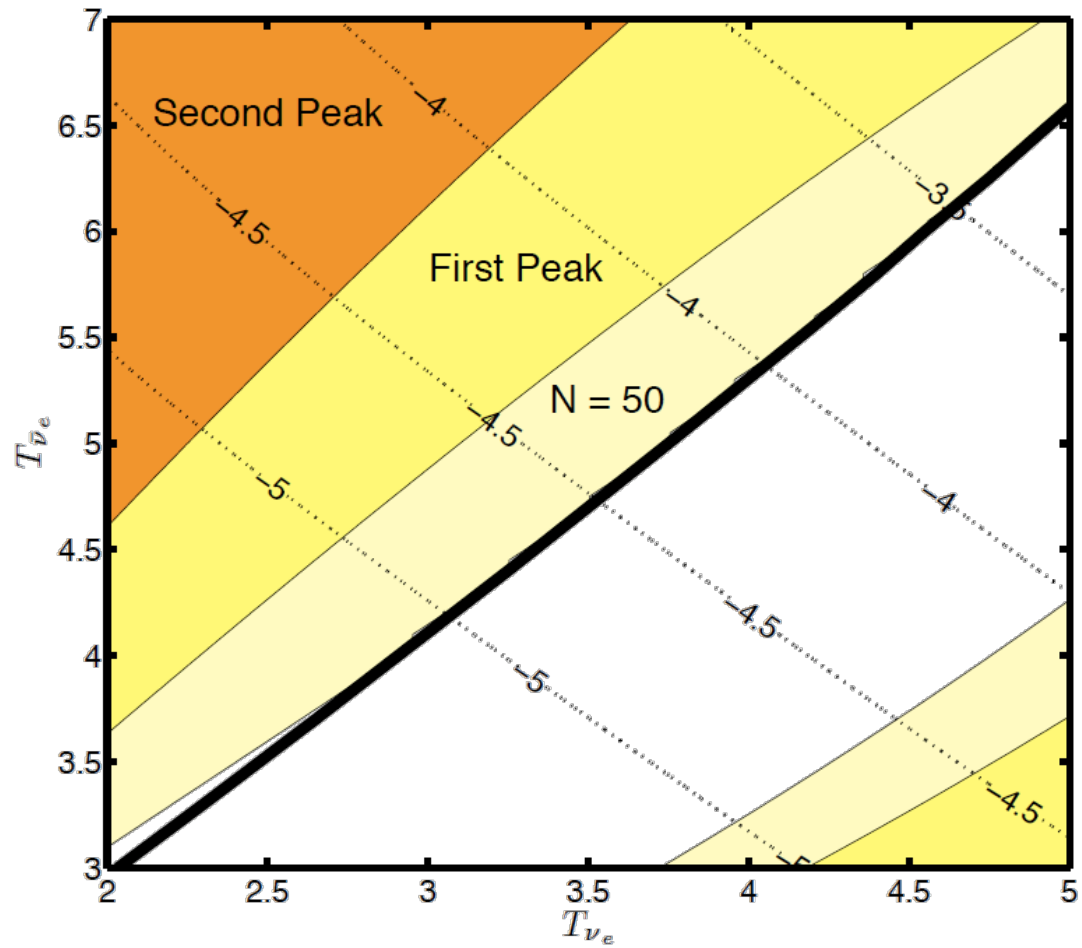
Wind nucleosynthesis:
Analytic Predictions

- Assuming

$$L_\nu \propto \langle T_\nu \rangle^4$$

- Large neutrino anti-neutrino asymmetry required in "standard model"

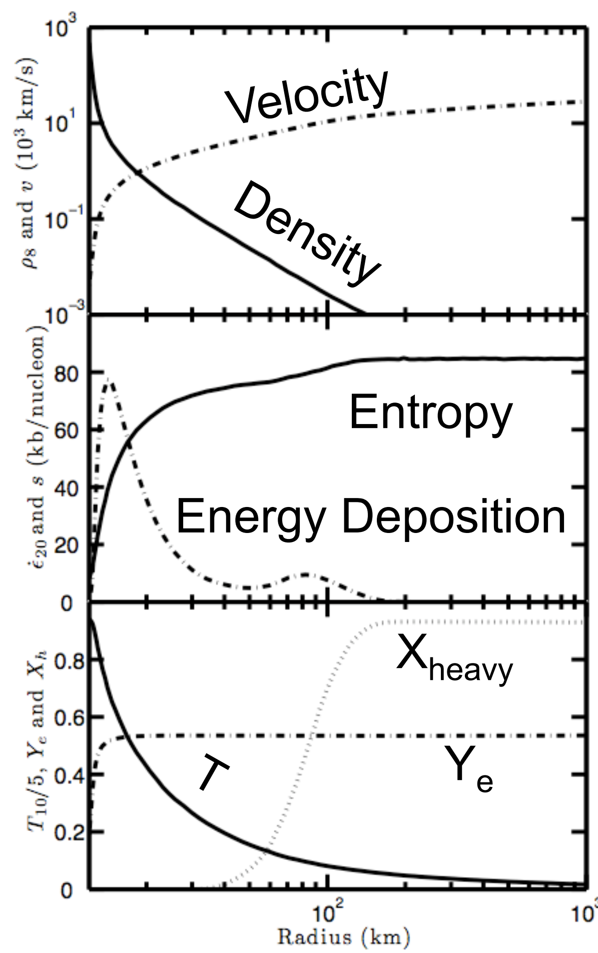
- Likely in N=50 Regime



Neutrino driven wind models

Kepler massive stellar evolution code (cf. Weaver, Zimmerman, & Woosley 1978)

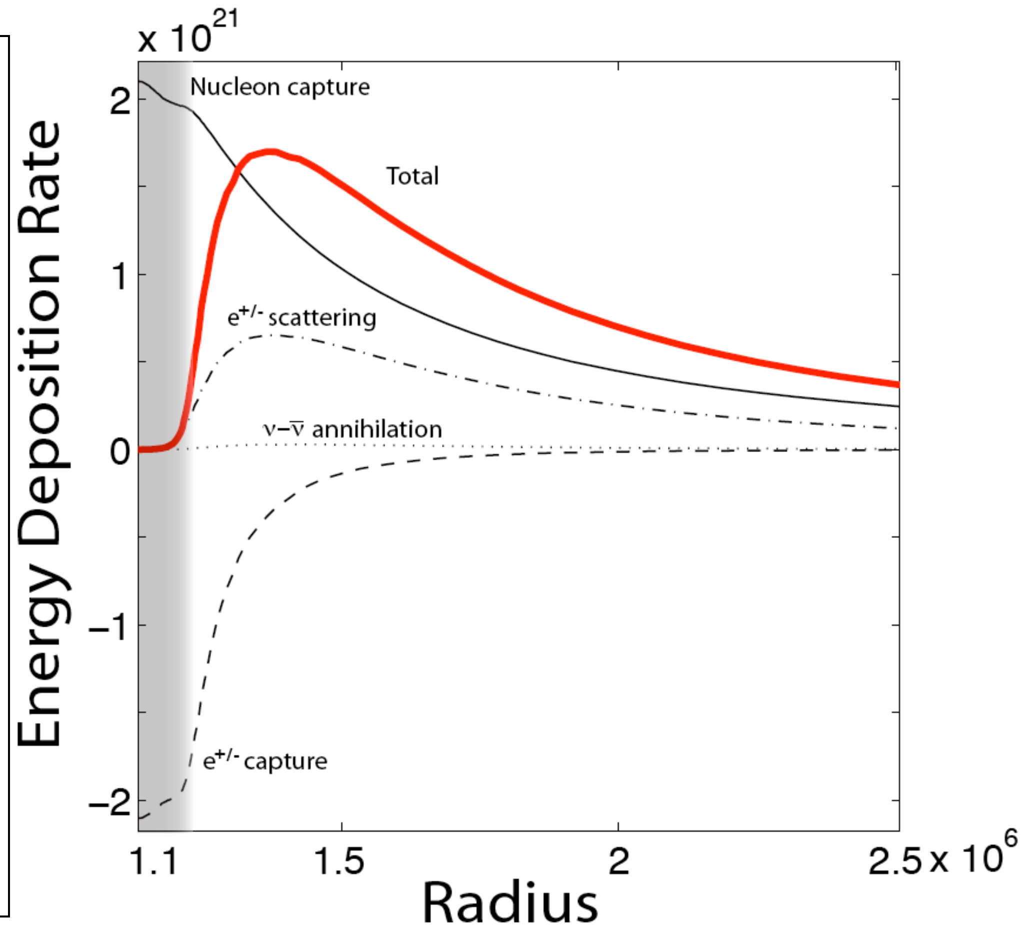
- Spherically symmetric
- Implicit Lagrangian hydrodynamics
- Nuclear network for energy generation
- Adaptive nuclear network for nucleosynthesis to ~3000 isotopes
- Thermal neutrino losses
- Integrates ejected nucleosynthesis as mass flows off the grid
- Post Newtonian corrections to gravitational potential



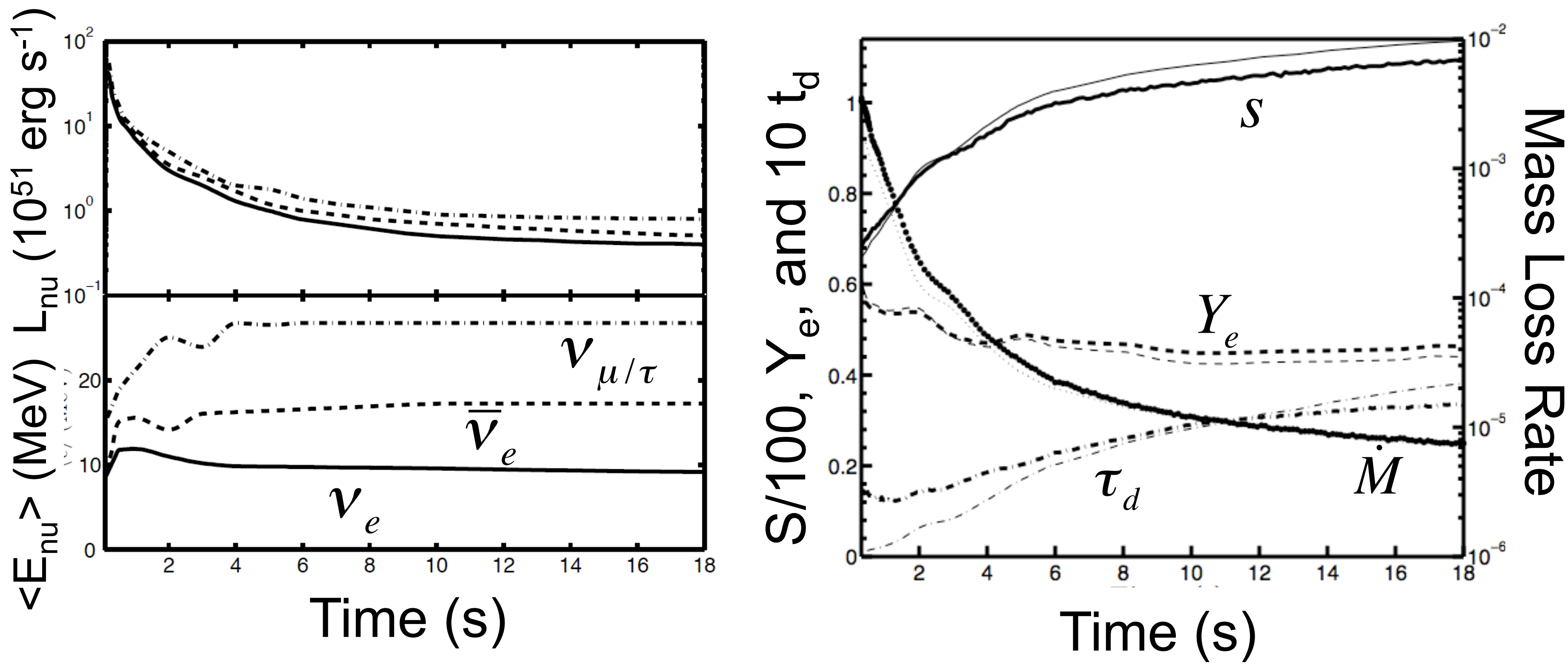
Neutrino driven wind models

Kepler updates for wind models

- New neutrino interaction rates
  - Coupled to both reaction networks
  - Nucleon capture rates include first order corrections in the nucleon mass
  - Gravitational redshifts
- "Lightbulb" transport approximation
  - Includes bending of null geodesics in Schwarzschild geometry
  - Different neutrino sphere radii
- Mass recycling
- Artificial energy deposition



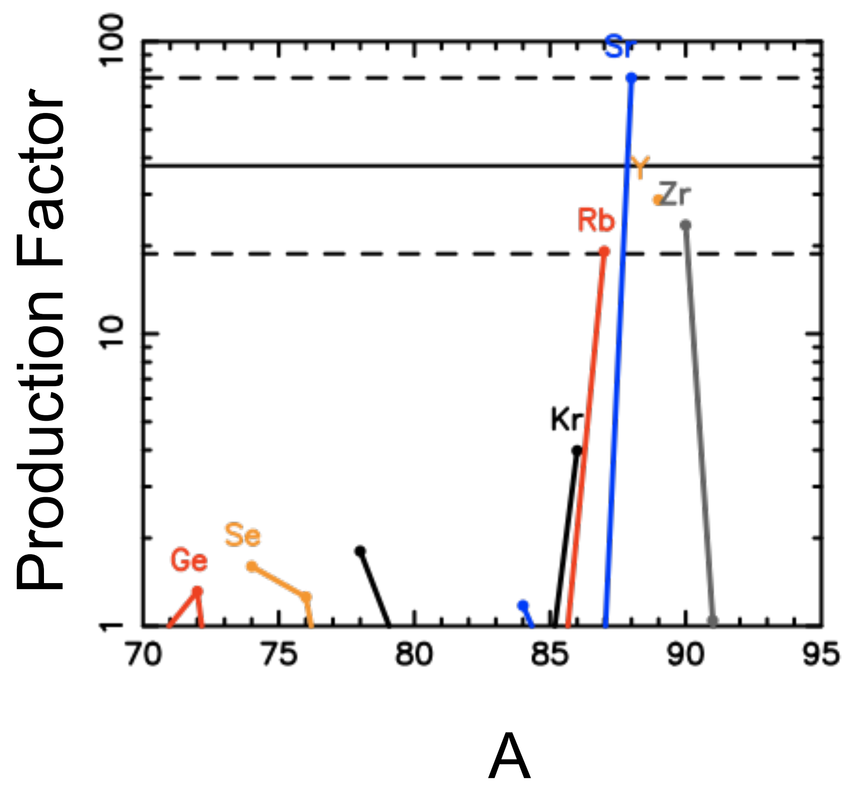
20 Msun Progenitor: NDW Evolution



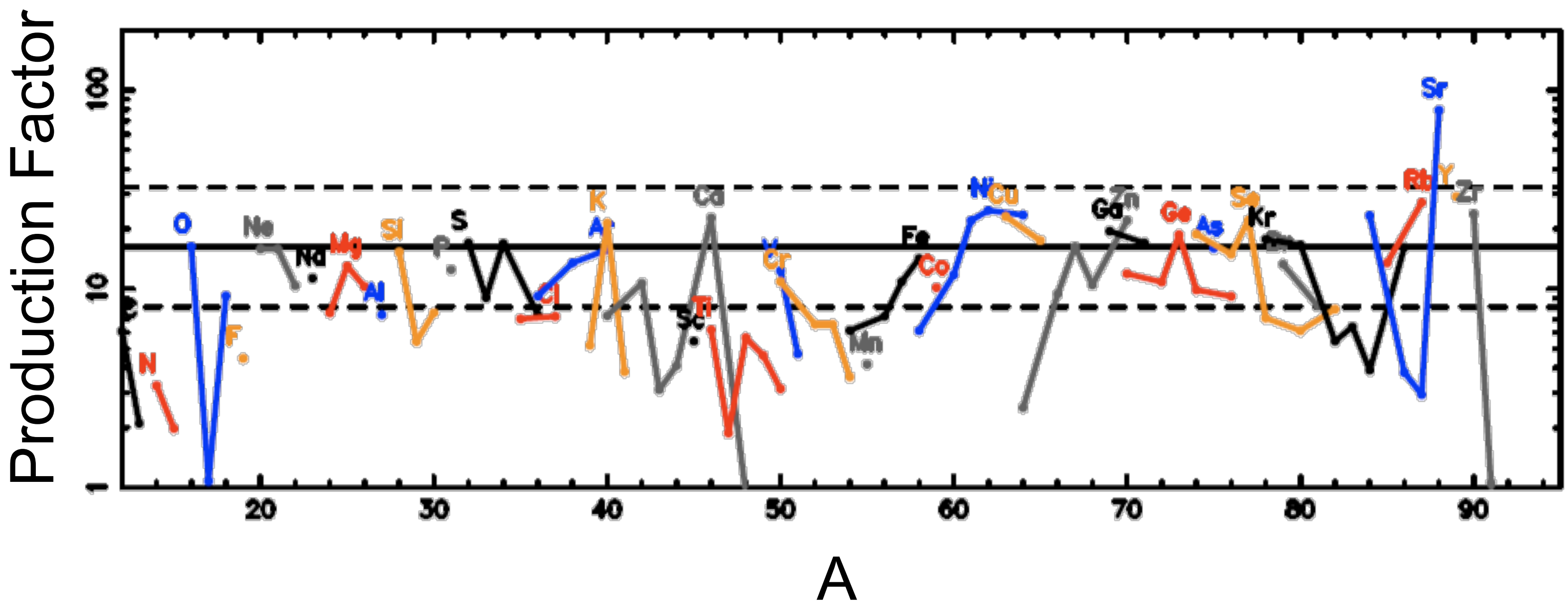
Luminosity histories from Woosley et al. (2004)
Original models had successful r-process, but entropies were too high

20 Msun Progenitor: Nucleosynthesis

- Total ejected mass: 18.4 Msun
- No significant p-process production
- Reverse shock doesn't affect nucleosynthesis

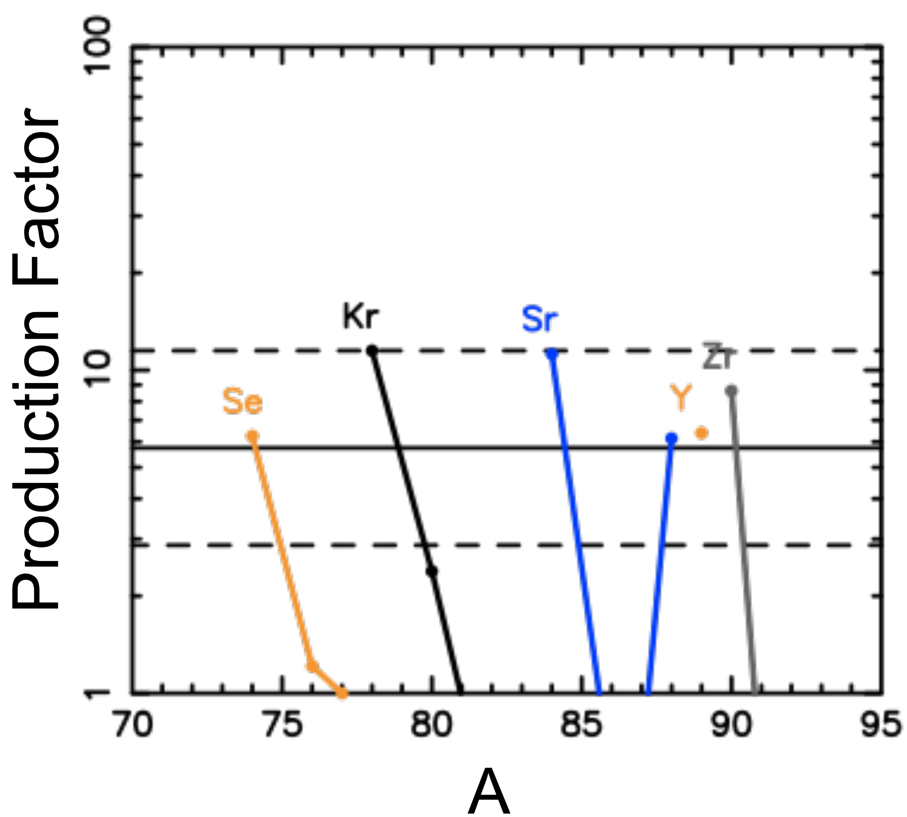


Combined Production Factors

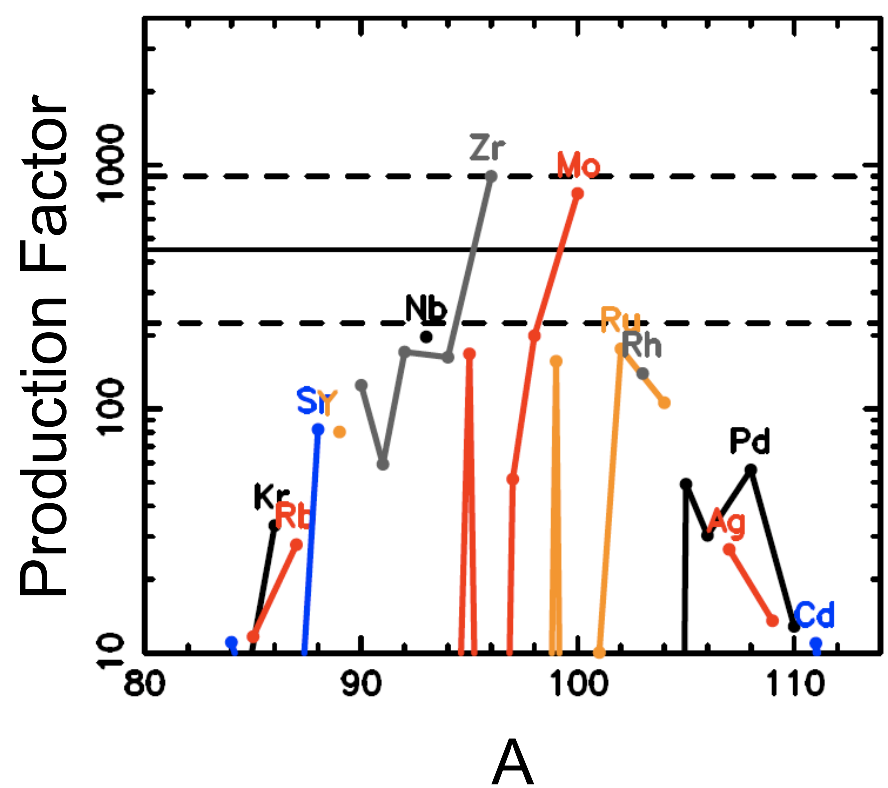


Integrated wind yields combined with yields from 20 Msun model of Woosley & Weaver (1995)

Varying Neutrino Luminosities



Anti-neutrino energy reduced by 15%



No weak magnetism corrections

Neutrino driven winds:

Time dependent models

t_{bounce} (ms)	$\dot{M}$ ($M_\odot$ s^{-1})	τ_{dyn} (ms)	S_f $k_B$baryon^{-1}	Y_e
0.5	9.1×10^{-4}	5.0	80	0.55
1.0	3.0×10^{-4}	6.6	83	0.50
1.5	1.6×10^{-4}	8.1	87	0.50
2.0	5.0×10^{-5}	13.1	94	0.49
3.0	2.6×10^{-5}	18.1	98	0.45
3.8	1.5×10^{-5}	24.4	102	0.42
5.3	6.7×10^{-6}	36.4	104	0.44
7.1	4.2×10^{-6}	47.9	107	0.45
9.9	2.6×10^{-6}	66.1	117	0.39

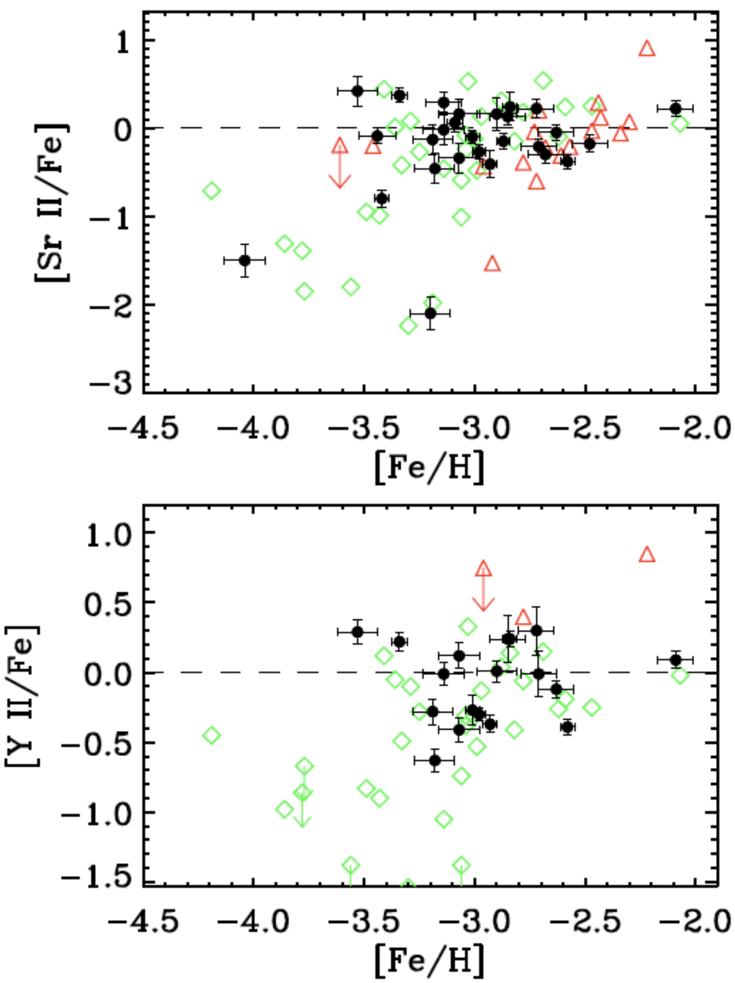
Without neutrino interaction corrections

t_{bounce} (ms)	$\dot{M}$ ($M_\odot$ s^{-1})	τ_{dyn} (ms)	S_f $k_B$baryon^{-1}	Y_e
0.5	7.9×10^{-4}	5.1	73	0.60
1.0	2.6×10^{-4}	7.0	80	0.56
1.5	1.4×10^{-4}	8.7	84	0.56
2.0	4.5×10^{-5}	14.5	92	0.55
2.8	2.6×10^{-5}	18.7	97	0.51
3.8	1.2×10^{-5}	27.4	100	0.48
5.2	5.9×10^{-6}	39.8	110	0.49
7.0	3.7×10^{-6}	52.1	113	0.50
10.0	2.1×10^{-6}	73.87	117	0.45

With neutrino interaction corrections

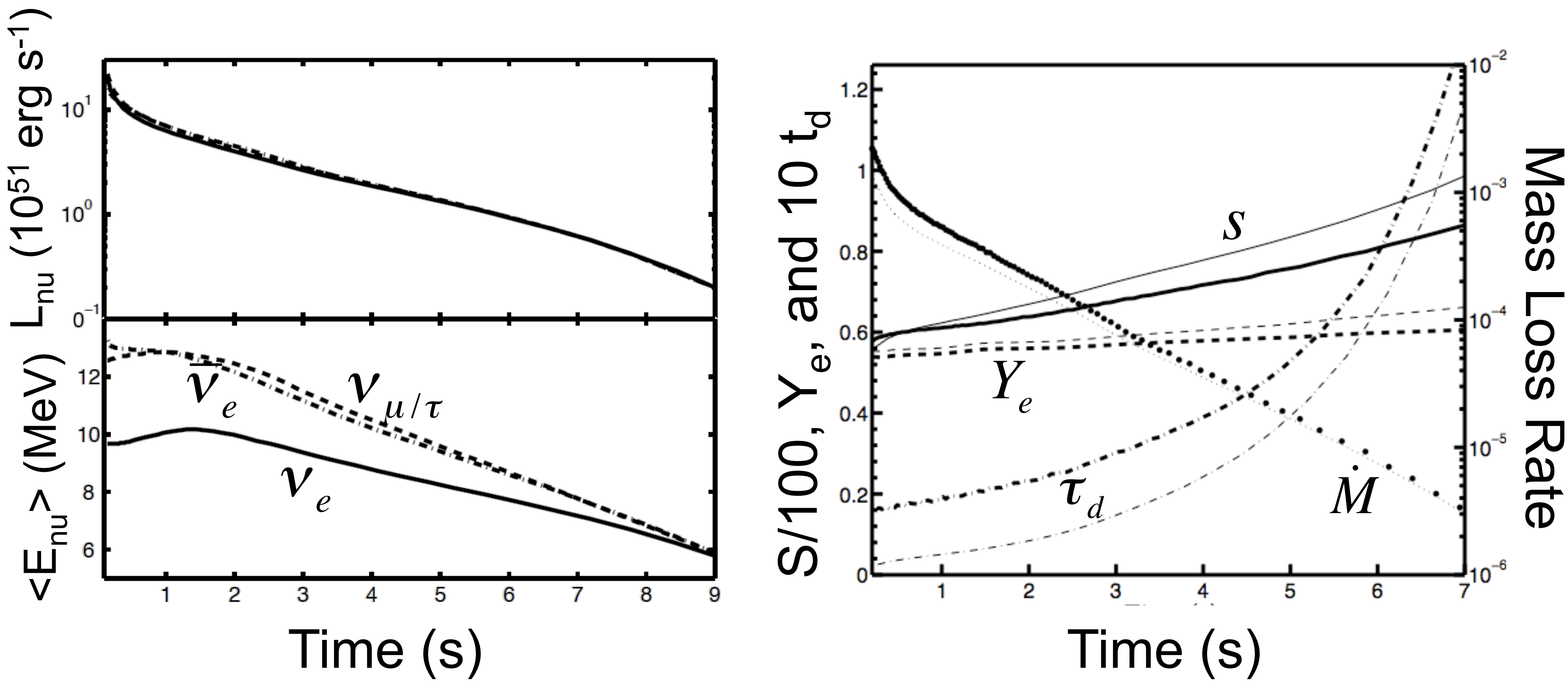
Chemical Evolution of N=50 Elements

- Fall off at low metallicity
- Inconsistent with NDW nucleosynthesis predictions
- [Sr/Fe]=0.8 in 20 Msun model
- Evidence for increased SN fallback at low metallicity?



Lai et al. (2008)

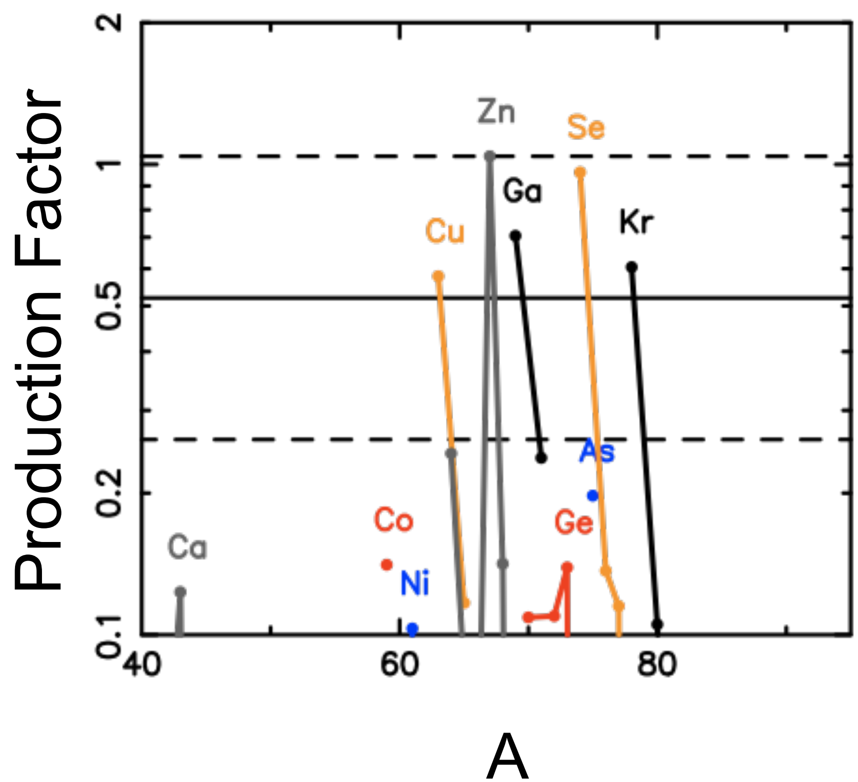
8.8 Msun Wind Evolution



Luminosity histories from Huedepohl et al. (2009)
Proton rich throughout, nup-process?

8.8 Msun Progenitor Yields

- Total ejected mass: 7.4 Msun
- All weighted production factors at or below one
- No significant p-process production
- Reverse shock not expected to be strong, doesn't affect nucleosynthesis



Neutron star atmosphere

- Temperature structure of the protoneutron star atmosphere set by:

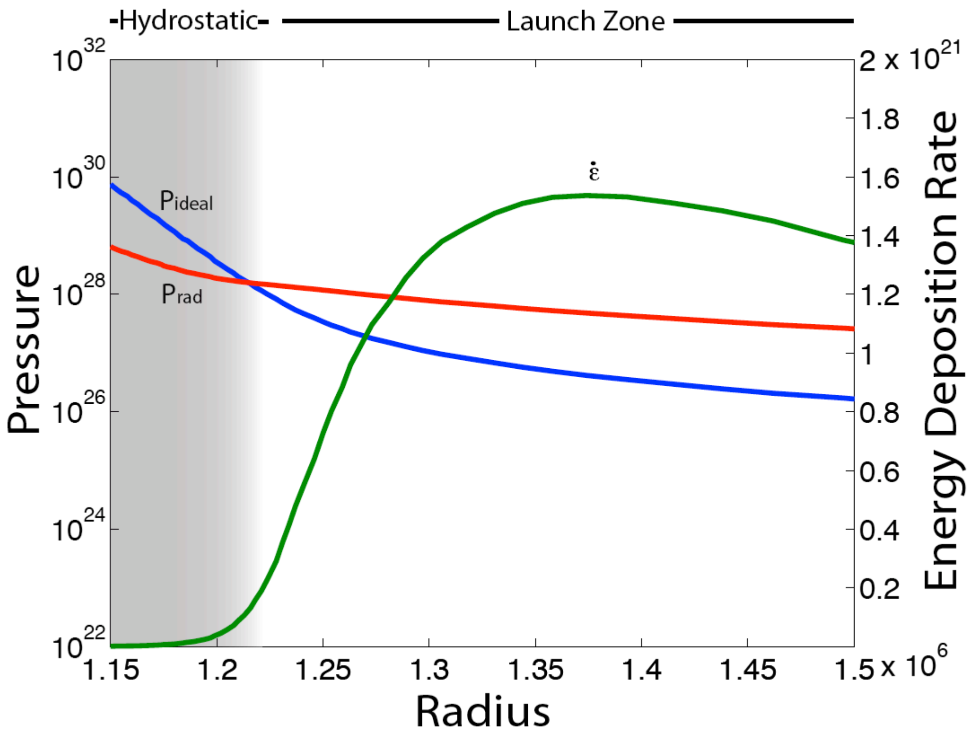
$$\dot{q}_e \approx \dot{\varepsilon}_\nu$$

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

- Mass loss rate set near surface

- Volumetric energy deposition source doesn't effect atmosphere, deposits energy after mass loss rate is set

- Increases entropy of material, decreases dynamical timescale, conditions more favorable for r-process
(Qian & Woosley 96, Suzuki & Nagataki 05)



Secondary Energy Deposition

- Volumetric energy deposition source with constant damping:

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

- Optimal damping length:

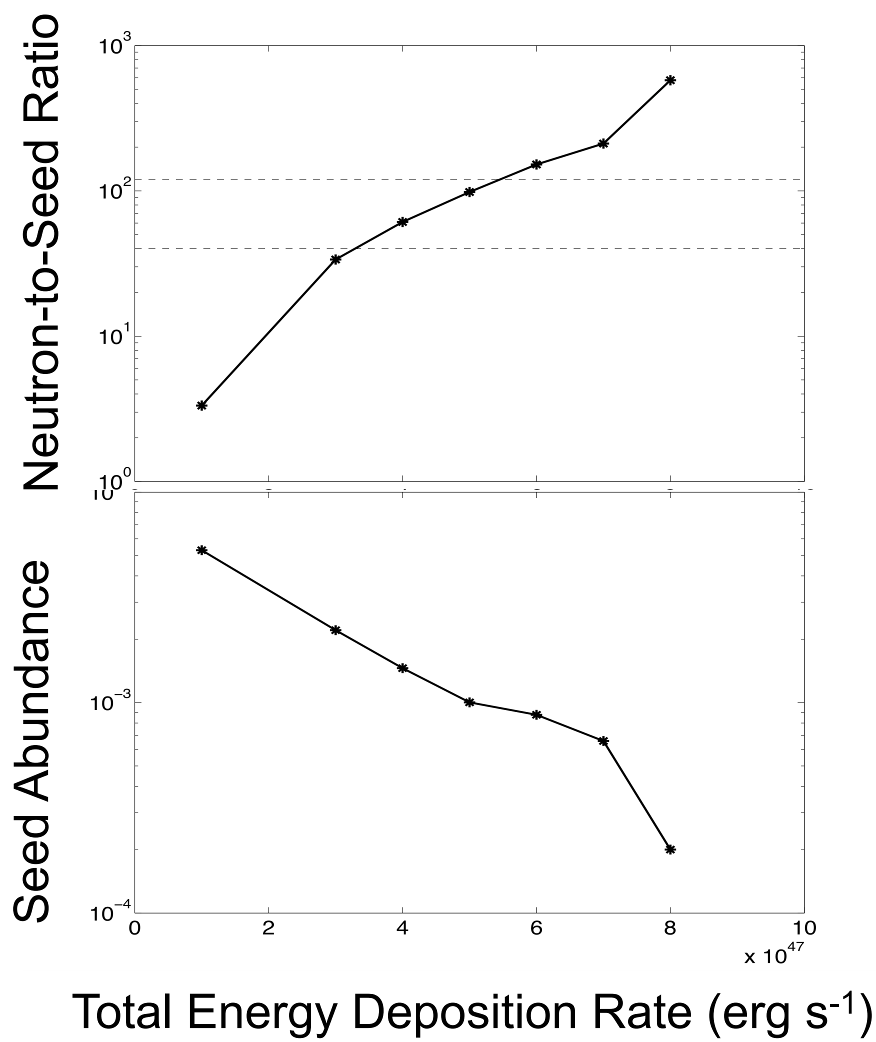
$$l_d \approx 10^6 cm$$

(see Suzuki & Nagataki 2005)

- Conditions at 10 sec in Woosley (1994) model:

$$Y_e = 0.44$$

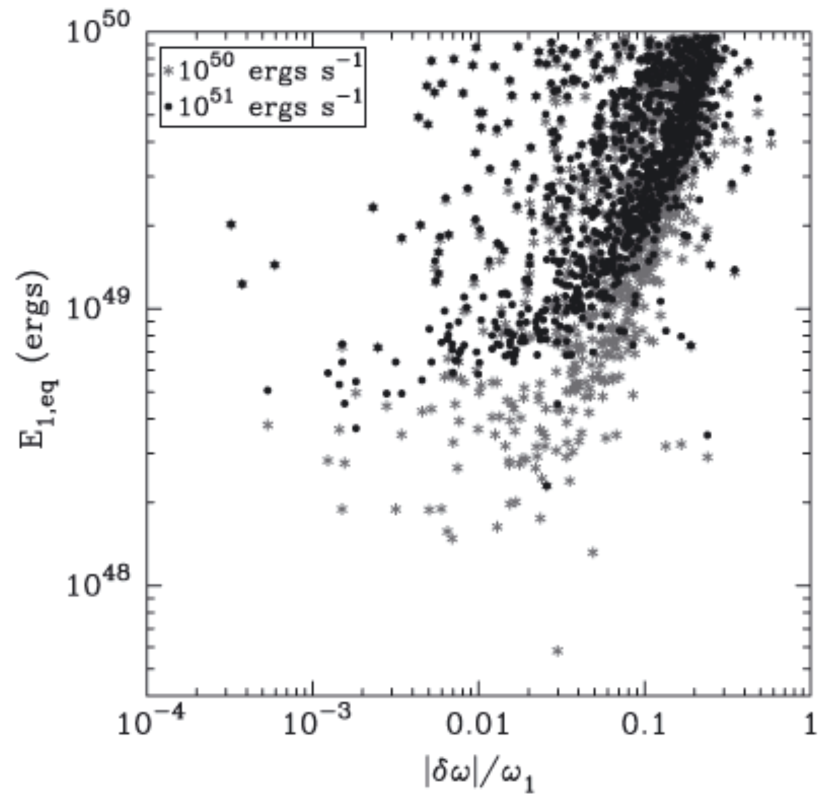
- Is this reasonable?



Acoustic Power

- Suzuki & Nagataki argue it is reasonable for high magnetic fields, give Alfven waves and non-linear damping
- Other possibility, purely acoustic power (Qian & Woosley 1996, Burrows et al 2007)
- Neutrino damped PNS oscillations (Weinberg & Quatert 2008)
- l=1 oscillations have intensity of (see Landau & Lifshitz)

$$L_0 \approx 4\times10^{47} erg\, s^{-1} \times\left(\frac{E_1}{10^{48} erg}\right)\left(\frac{1.4 M_{sun}}{M_{NS}}\right)\left(\frac{\rho}{10^{12} g/cc}\right) \times\left(\frac{10^9 cm/s}{c_s}\right)^3\left(\frac{R_{NS}}{10^6}\right)^6\left(\frac{\omega}{1000\ hz}\right)^4 \times\frac{1}{1+(\omega R/c_s)^4/4}$$



Weinberg & Quatert 2008

- Q-factor < 1
  - Must be driven by accretion

Acoustic Energy Deposition via Weak Shocks

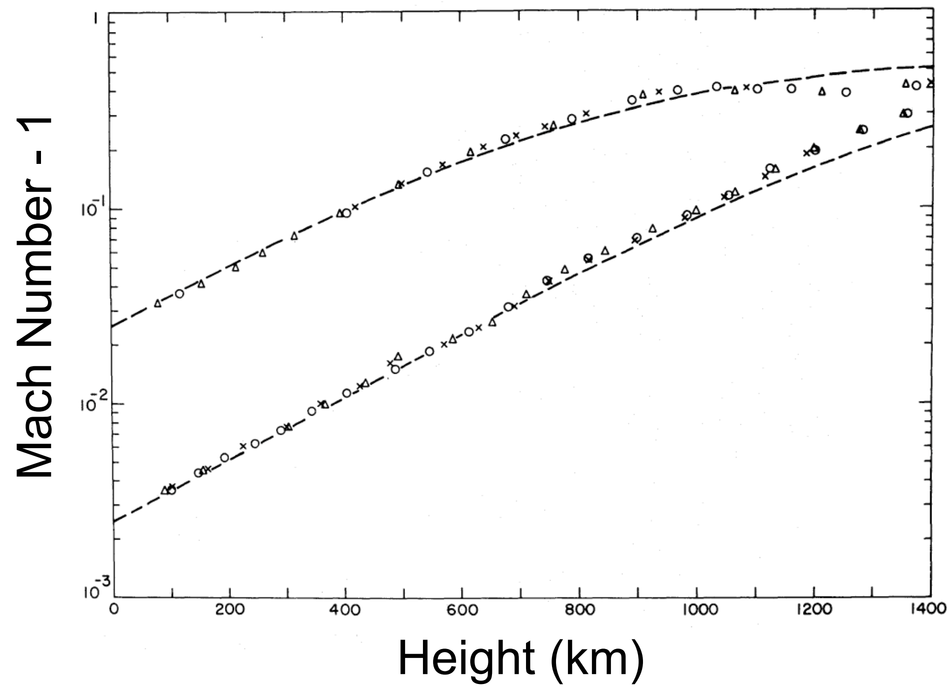
- How do these acoustic waves damp?
- Studied in the context of the solar corona (see Stein & Schwartz 1973for references)
- Steepen into shocks over distance of order the pressure scale height
- Energy loss given by weak shock theo as

$$\Delta s = \frac{2\gamma(\gamma-1)c_v}{3(\gamma+1)^2} m^3$$

$$\frac{dE_s}{dt} = -\rho T c_s \Delta s (1 + m/2)$$

- Results in a damping length

$$l_d \approx 2.6 \times 10^6 \ cm \times \left(\frac{T}{MeV}\right)^{1/2} \left(\frac{s}{100}\right)^{1/2} \left(\frac{1000 \ hz}{\omega_0}\right)^{1/2} \left(\frac{P}{3\varepsilon_w}\right)^{1/2}$$



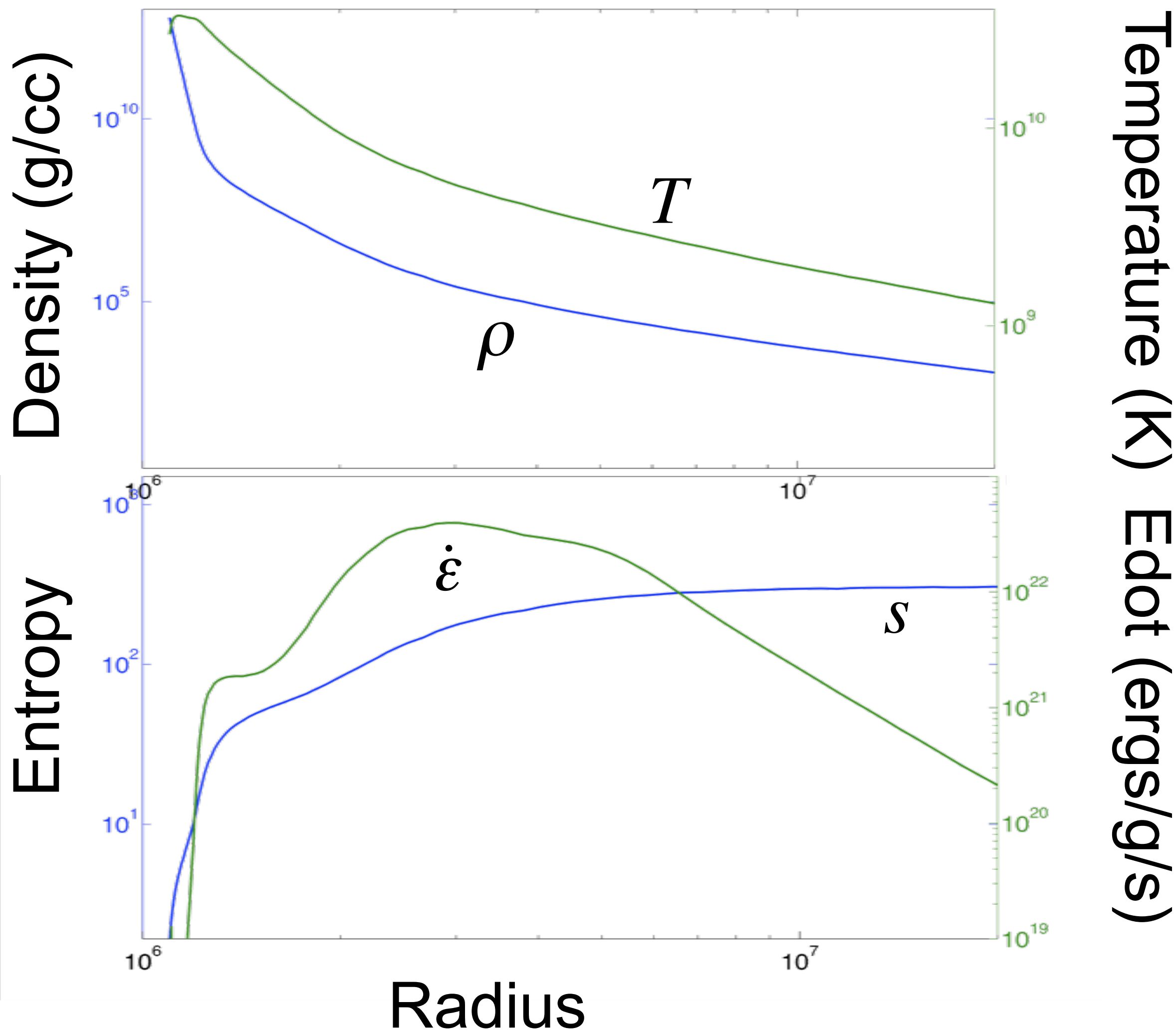
Stein & Schwartz 1973

Wind Structure w/ Extra Energy Deposition

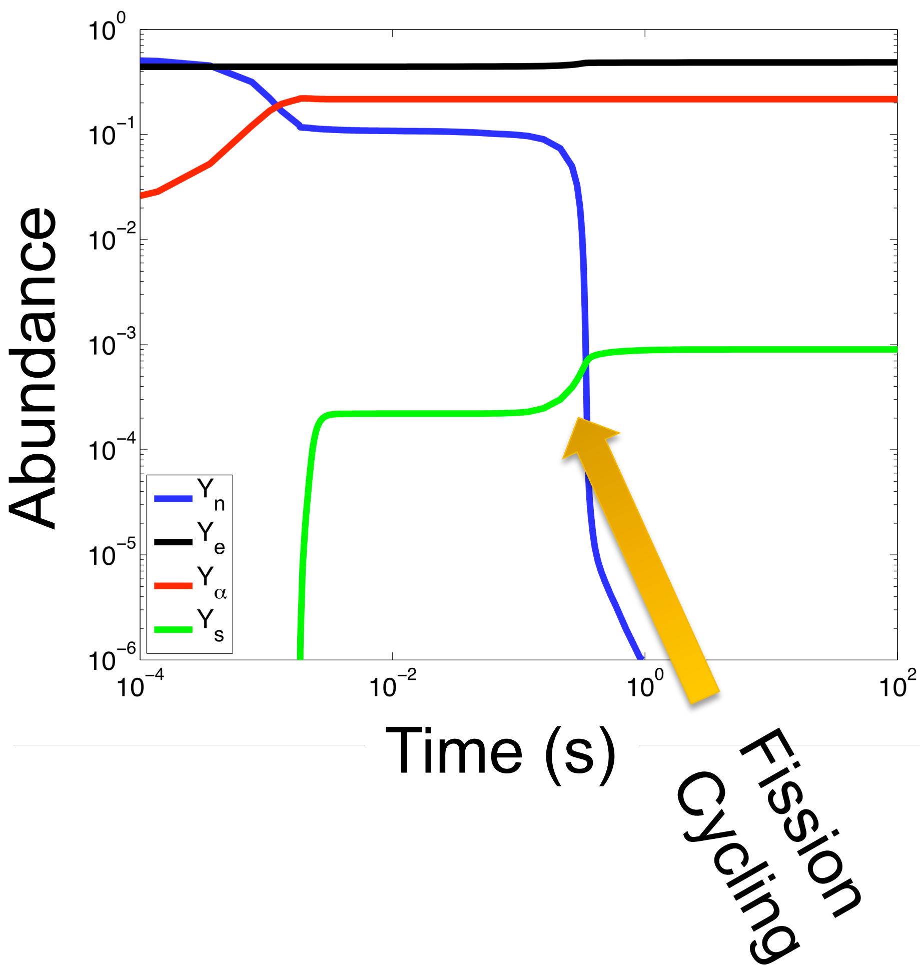
- Self consistent acoustic energy input based on weak shock damping length

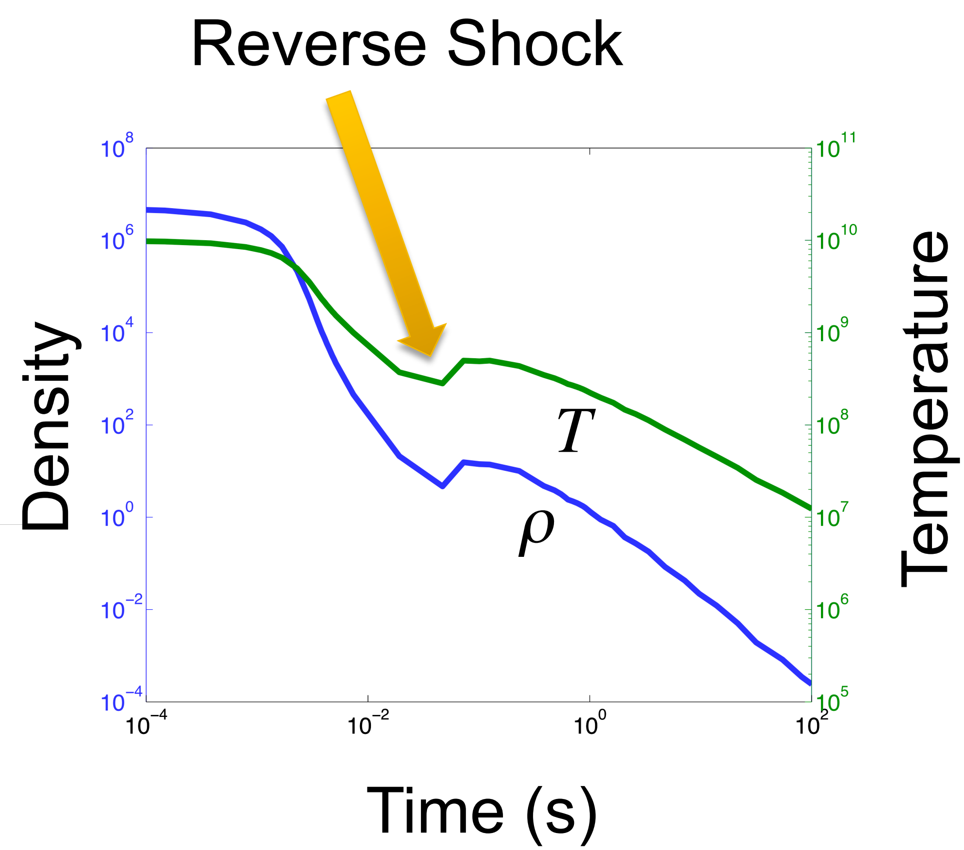
$$\partial_t S + r^{-2}\partial_r(r^2 v_g S) = -\frac{\sqrt{3}}{\pi}\gamma(\gamma-1)c_v\rho T\omega\frac{S^{3/2}}{P^{3/2}}$$

- Atmosphere temperature still set by neutrino fluxes
- Final entropy 285
- Dynamical timescale ~2 ms

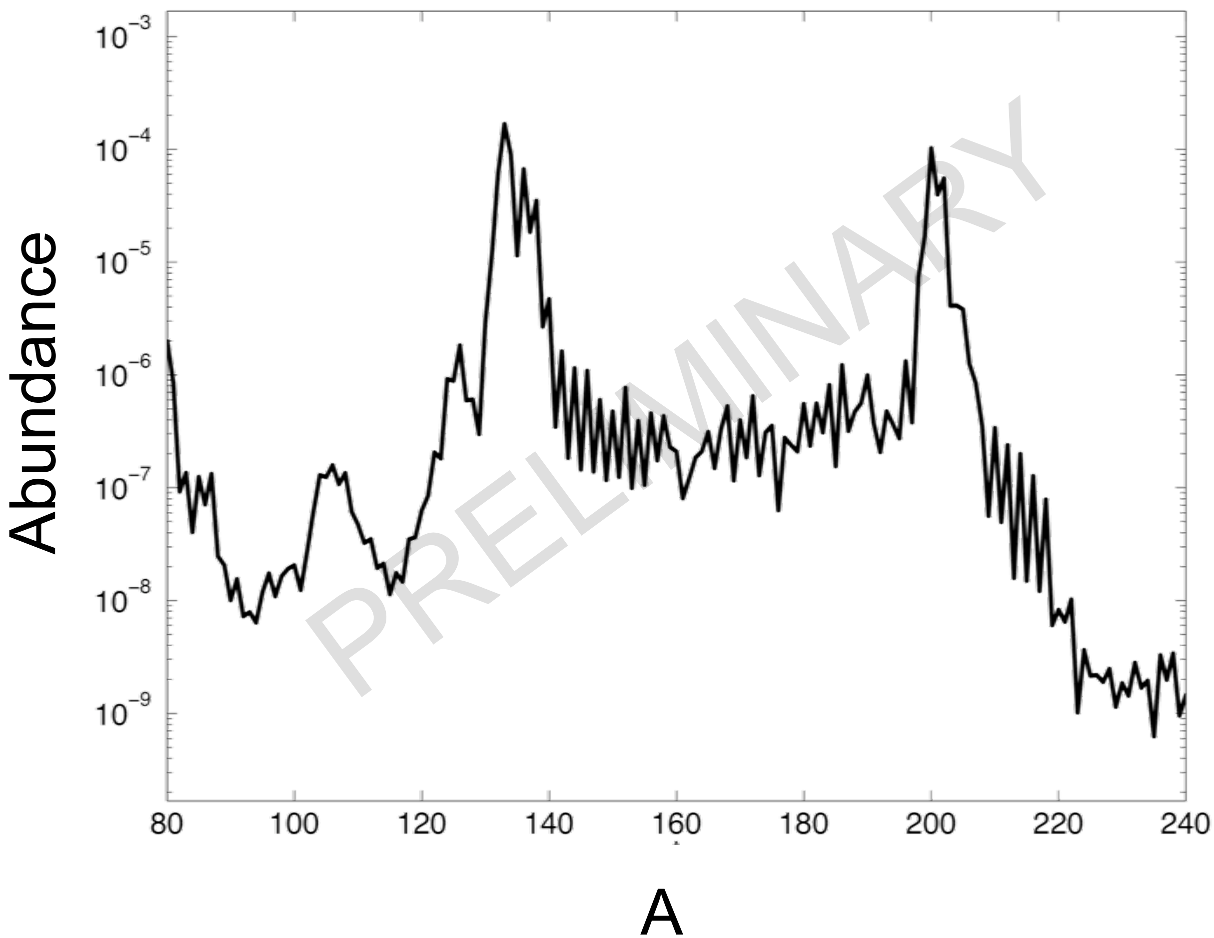


Time Evolution





Final Abundances



Summary

- Integrated NDW Nucleosynthesis
  - Low mass progenitor wind does not contribute significantly
  - Higher mass progenitor consistent with yields from the full star
  - Sensitive to uncertain neutrino spectra
  - Evolution of N=50 closed shell elements may trace fallback history
  - See arXiv:1004.4916
- Secondary Energy Deposition
  - Get high neutron to seed ratios for reasonable amount of energy deposition
  - sound waves from PNS oscillations → weak shocks
  - Volumetric energy deposition at correct radius for r-process