Supernovae, Neutrino-Driven Winds, and Nucleosynthesis

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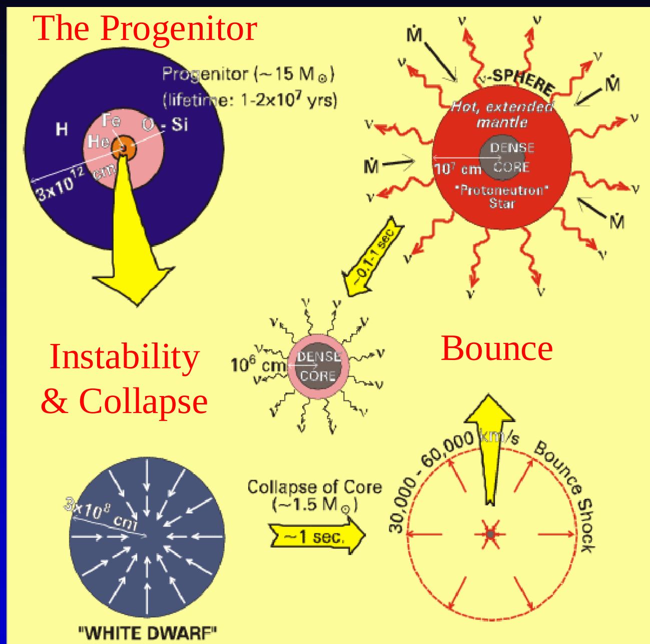
Outline

- Introduction: The Supernova Problem
  - Scales, Important Processes, & Outstanding Questions
- Dynamical Models of Core-Collapse
  - Breakout, Spectra, & Detector Signatures
- Protoneutron Star Winds
  - Neutrino-Driven Outflows & Nucleosynthesis
  - Magnetic Fields
- Summary, Conclusions, & The Future

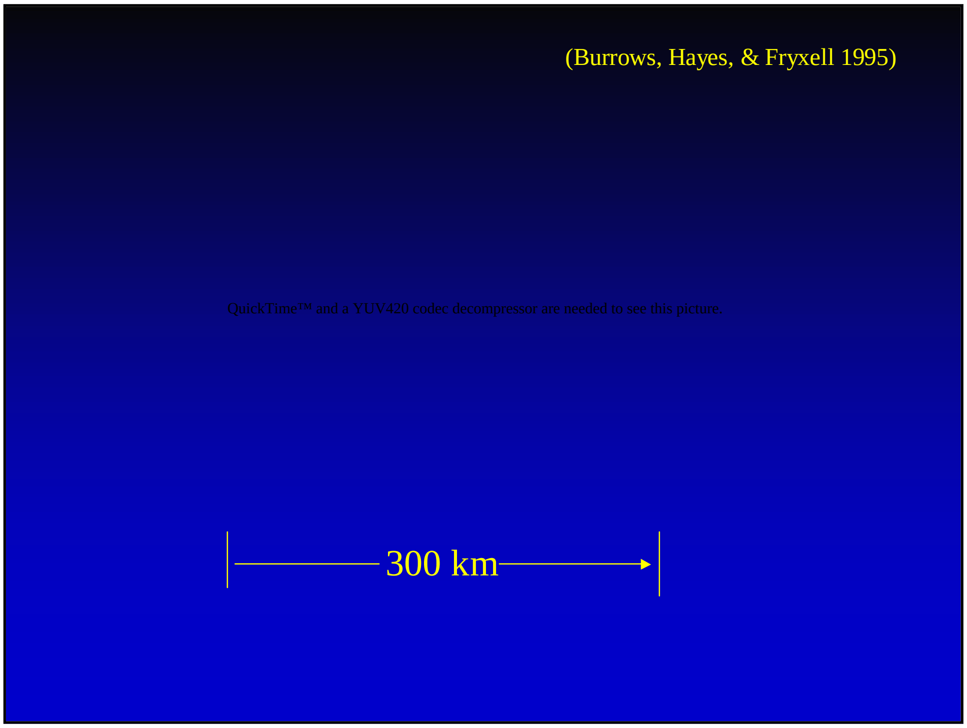


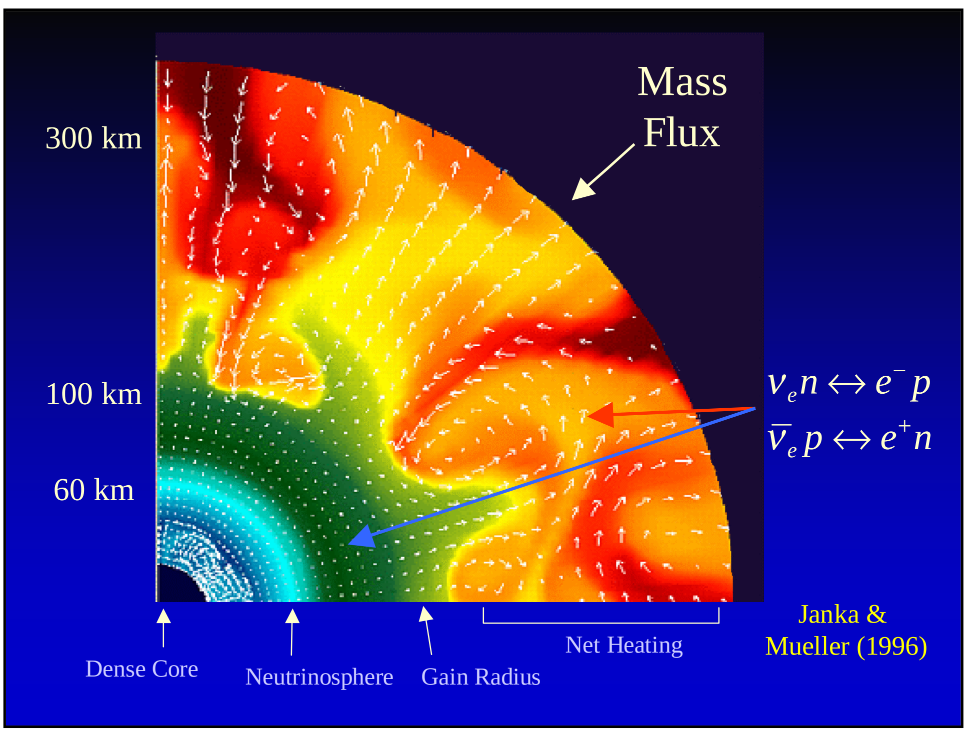
Shock Revival & Explosion (?) ~ 0.5 s

Prompt Shock Stalls (~ ms) R~100 km

Bounce & Shock Formation

- What is a Core-Collapse Supernova?
  - An explosion initiated by a dynamical instability
  - The death of a massive star
  - The birth cry of a neutron star or black hole
  - An agent of chemical and dynamical galactic evolution
- Characteristics of Supernovae:
  - Total kinetic energy: ~10^{51} erg
  - Luminous energy radiated: ~ 10^{49} erg
  - Temperatures: 0.1 – 50 MeV (10 MeV~10^{11} K)
  - Densities: 10^9 – 6 x 10^{14} g cm^{-3}
- Neutrino Production:
  - Neutrino energy radiated: ~ 2-3 x 10^{53} erg
  - Core is opaque to neutrinos of all flavors! $(\nu_e,\bar{\nu}_e)\ (\nu_\mu,\bar{\nu}_\mu)\ (\nu_\tau,\bar{\nu}_\tau)$ $\tau_{\rm Diff} \approx 1{\rm s}$


(Burrows, Hayes, & Fryxell 1995)
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
300 km

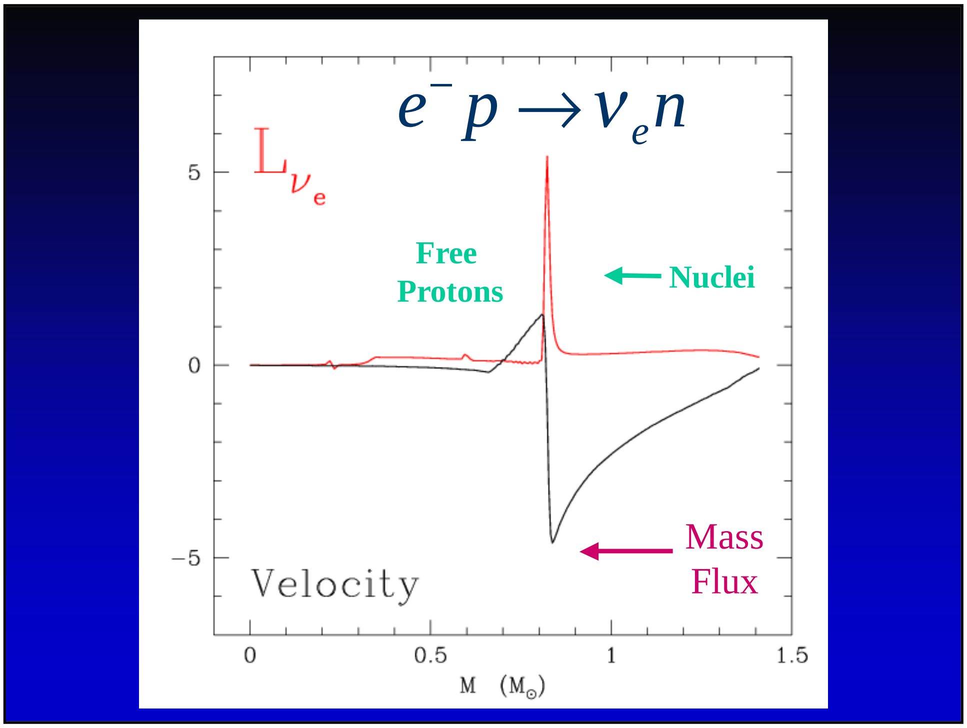

Mass
Flux
300 km
100 km
60 km
$\nu_e n \leftrightarrow e^- p$
$\bar{\nu}_e p \leftrightarrow e^+ n$
Dense Core
Neutrinosphere
Gain Radius
Net Heating
Janka &
Mueller (1996)

Dynamical Models of Supernovae

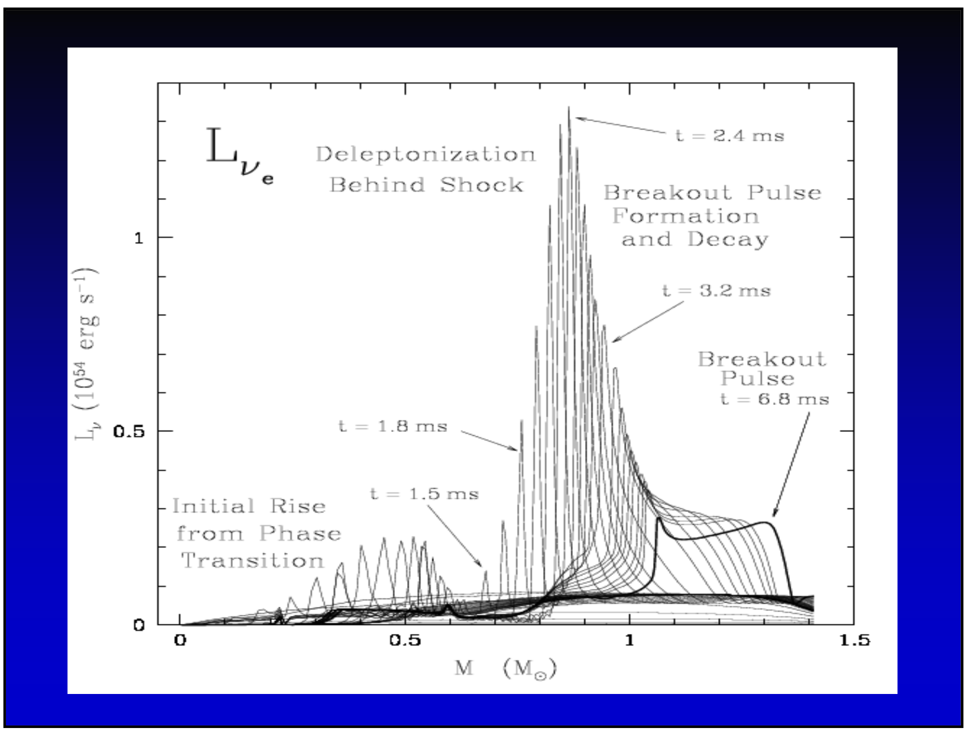
- Ingredients: Thompson et al. '02
  - Hydrodynamics: Newtonian, explicit, artificial viscosity
  - High-density EOS: Lattimer-Swesty, liquid drop model (Lattimer & Swesty 1991)
  - Neutrino Transport: Feautrier technique, tangent-ray, ALI (Eastman & Pinto 1993; Burrows et al. 2000)
  - Microphysics: Neutrino opacities, emission/absorption, new inelastic scattering algorithm, bremsstrahlung

(Rampp & Janka '00, '02; Liebendorfer '00; et al. '01)

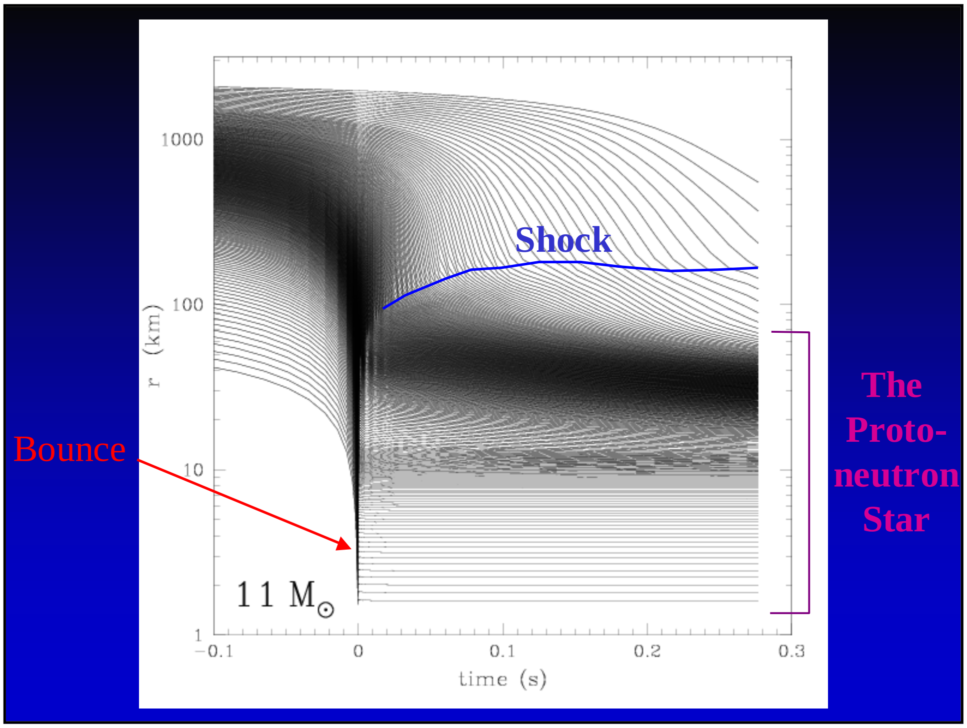
- Tests & Verification

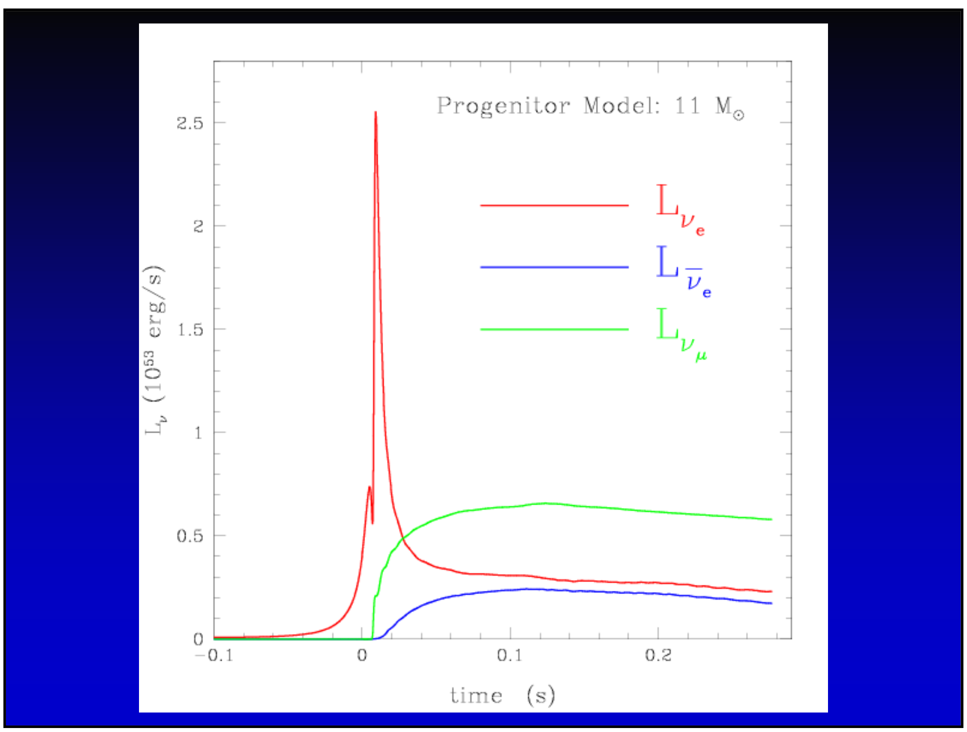


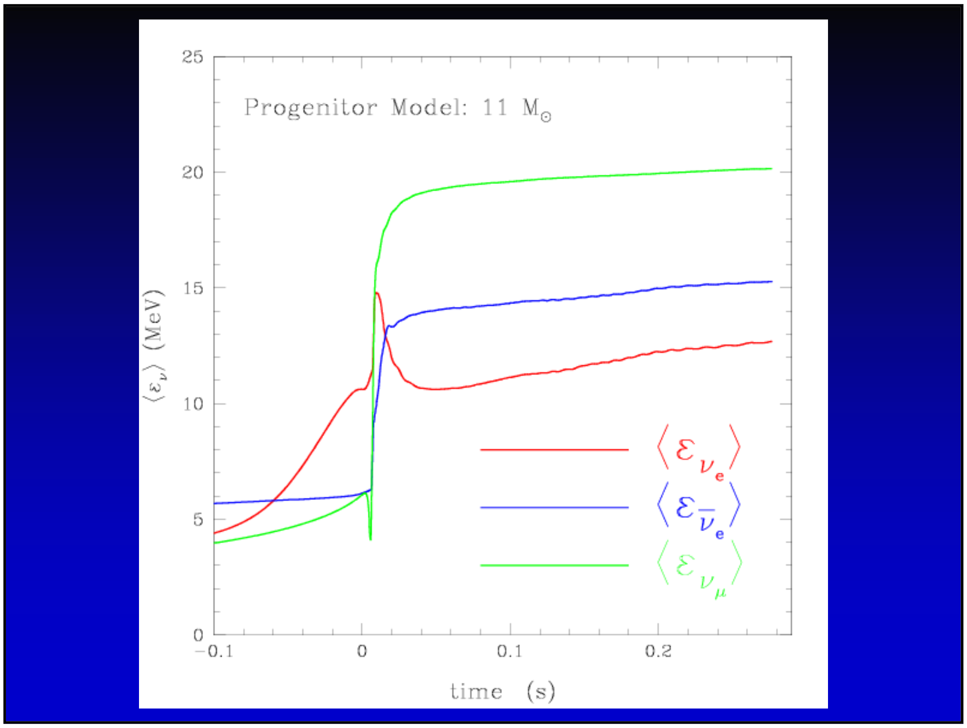
$e^- p \rightarrow \nu_e n$
L_{ν_e}
Free Protons
Nuclei
Mass Flux
Velocity
5
0
−5
0
0.5
1
1.5
M (M⊙)

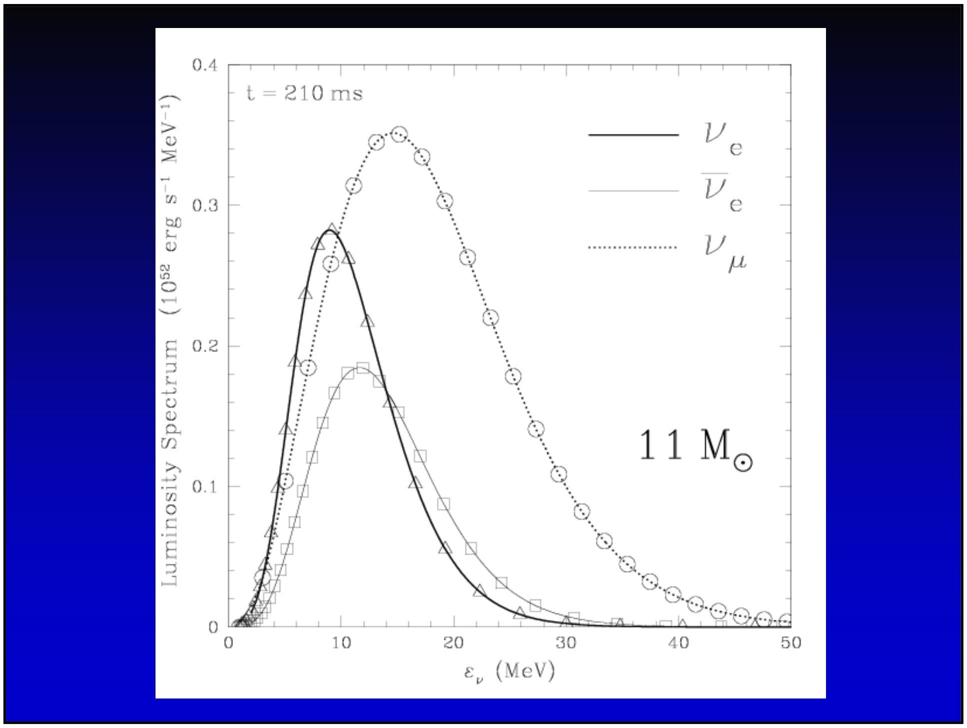


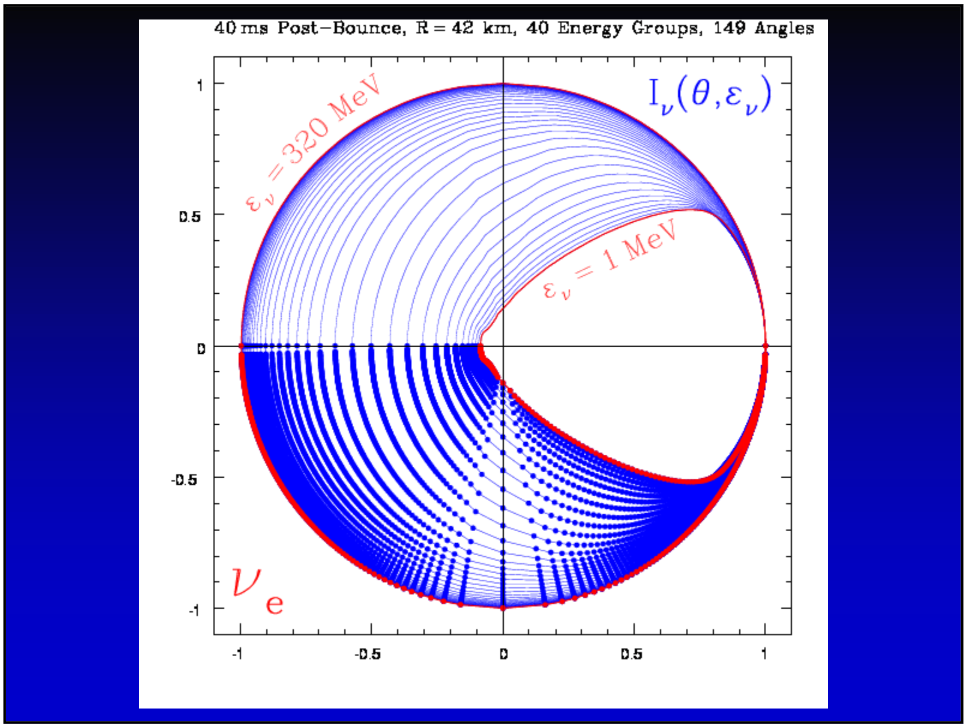
L_{ν_e}
Deleptonization Behind Shock
t = 2.4 ms
Breakout Pulse Formation and Decay
t = 3.2 ms
Breakout Pulse t = 6.8 ms
t = 1.8 ms
t = 1.5 ms
Initial Rise from Phase Transition
L_ν (10^{54} erg s^{-1})
1
0.5
0
0
0.5
1
1.5
M (M⊙)


Shock
Bounce
The Proto-neutron Star
11 $M_\odot$
r (km)
1000
100
10
1
−0.1
0
0.1
0.2
0.3
time (s)


Progenitor Model: 11 $M_\odot$
L_{ν_e}
$L_{\bar{\nu}_e}$
L_{ν_μ}
L_ν (10^{53} erg/s)
2.5
2
1.5
1
0.5
0
−0.1
0
0.1
0.2
time (s)


Progenitor Model: 11 $M_\odot$
$\langle \varepsilon_\nu \rangle$ (MeV)
time (s)
$\langle \varepsilon_{\nu_e} \rangle$
$\langle \varepsilon_{\bar{\nu}_e} \rangle$
$\langle \varepsilon_{\nu_\mu} \rangle$

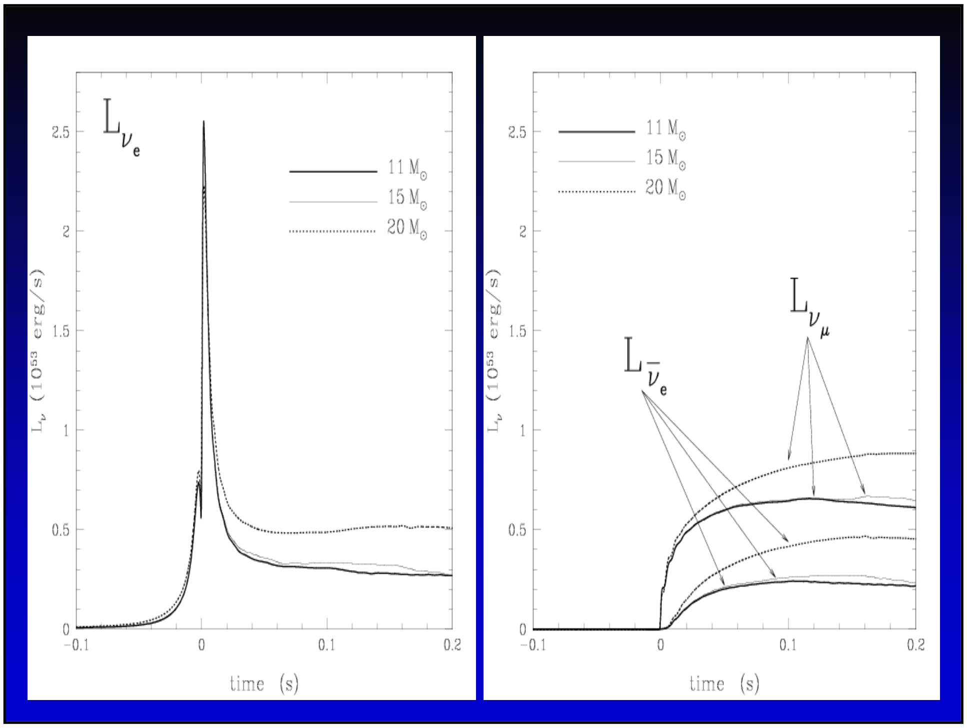

t = 210 ms
ν_e
$\bar{\nu}_e$
ν_μ
11 $M_\odot$
Luminosity Spectrum (10^{52} erg s^{-1} MeV^{-1})
ε_ν (MeV)



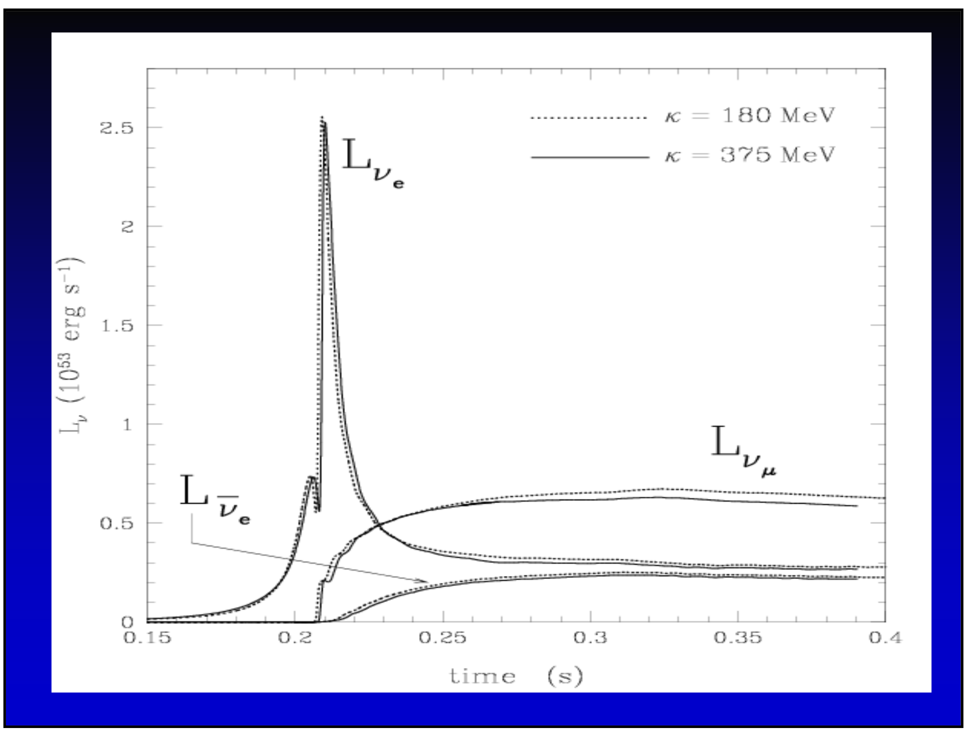
Variations & Detection

- Progenitor Mass: 11, 15, 20, 30, 40, 75 M_{sun}
- Microphysics:
  - Opacities: Neutral-current scattering/10 (Liebendorfer '00)
  - Nucleon-Nucleon Bremsstrahlung (Thompson et al. '00)
  - Inelastic Neutrino Scattering (Bruenn 1985; Thompson et al. '02)
  - Weak Magnetism/Recoil Correction (Horowitz '97, '02)
- Nuclear Compressibility: 180, 220, 375 MeV Modulus
- SK, SNO, ICARUS

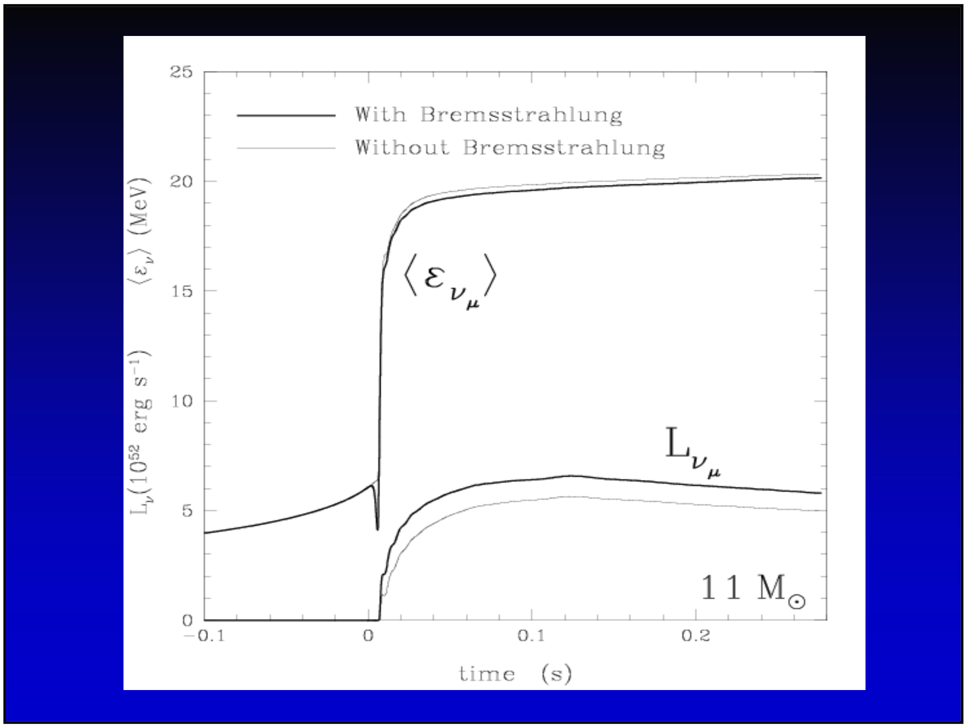
Thompson et al. 2002

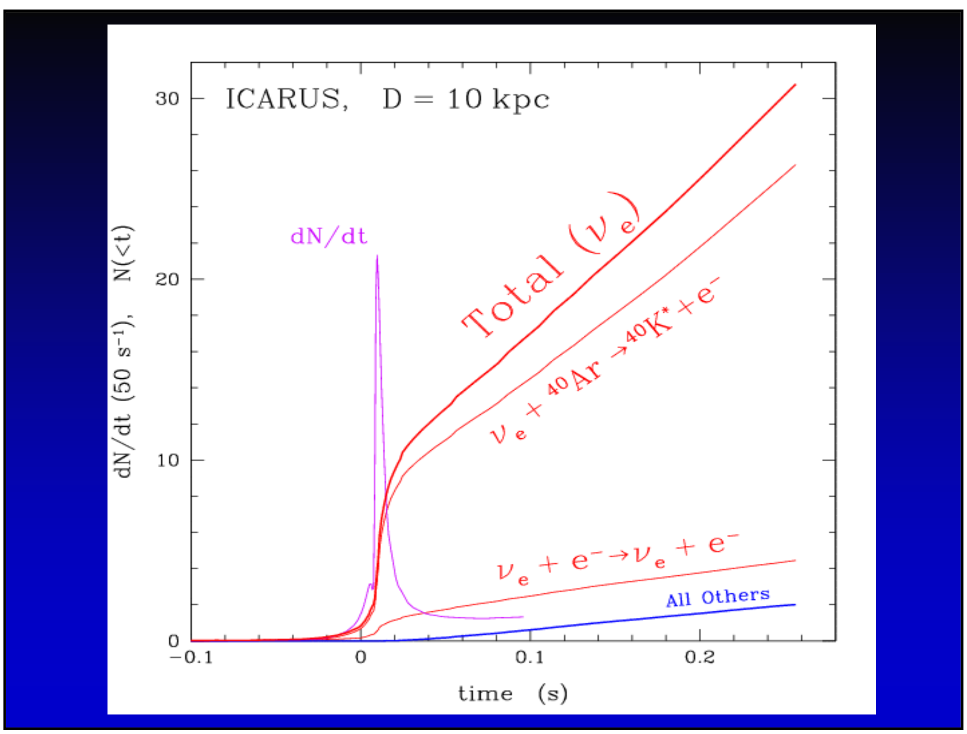


L_{ν_e}
11 $M_\odot$
15 $M_\odot$
20 $M_\odot$
L_ν (10^{53} erg/s)
time (s)
$L_{\bar{\nu}_e}$
L_{ν_μ}



κ = 180 MeV
κ = 375 MeV
L_{ν_e}
$L_{\bar{\nu}_e}$
L_{ν_μ}
L_ν (10^{53} erg s^{-1})
time (s)


With Bremsstrahlung
Without Bremsstrahlung
$\langle \varepsilon_{\nu_\mu} \rangle$
L_{ν_μ}
11 $M_\odot$
$L_\nu(10^{52}$ erg s$^{-1})$ $\langle \varepsilon_\nu \rangle$ (MeV)
time (s)

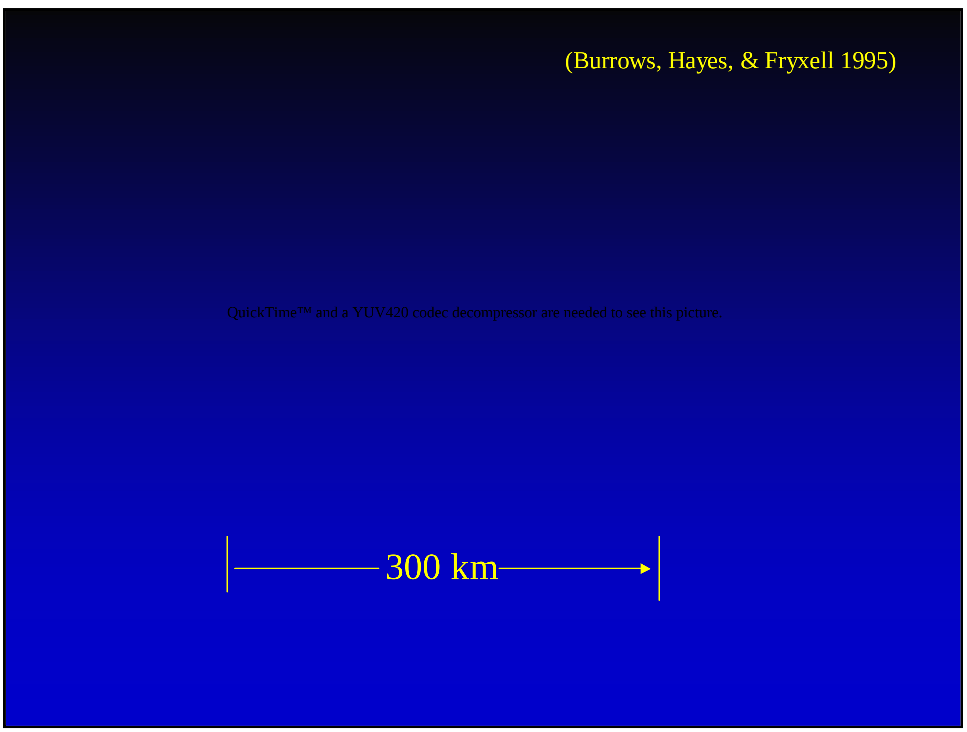

ICARUS, D = 10 kpc
dN/dt
Total (ν_e)
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$
$\nu_e + e^- \rightarrow \nu_e + e^-$
All Others
dN/dt (50 s^{-1}), N(<t)
time (s)

Supernova Model Summary

- Dynamical models constructed
- Precision neutrino spectra calculated for several progenitors

  (AVAILABLE ONLINE! See me!)
- EOS & Opacity variations assessed
- Detector signals calculated

No Explosions in 1D!



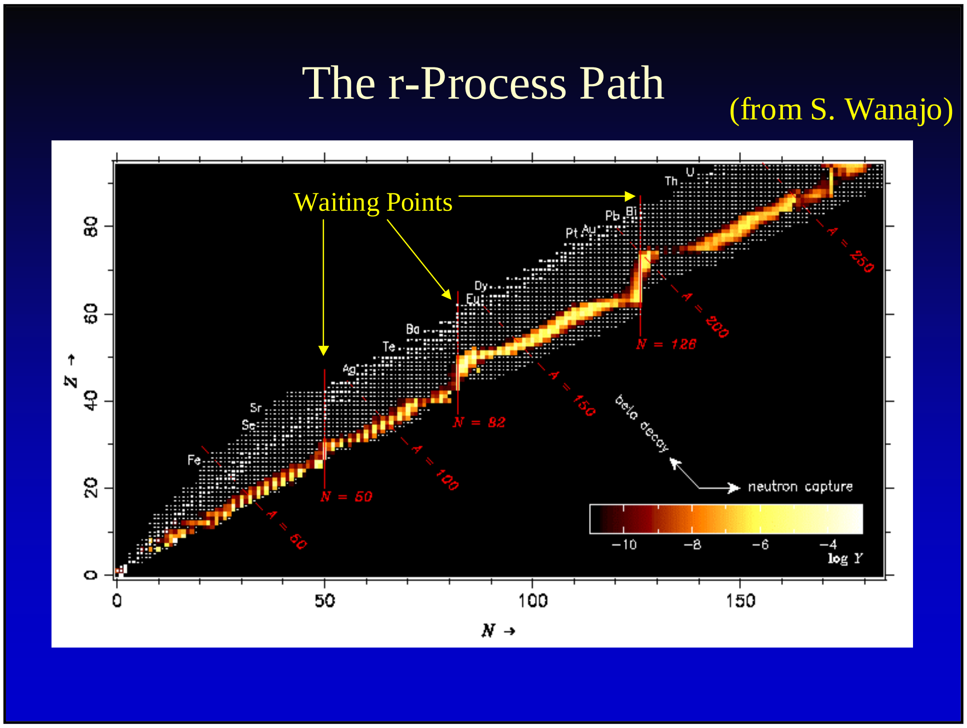
What is the origin of the heavy nuclei we find in nature?

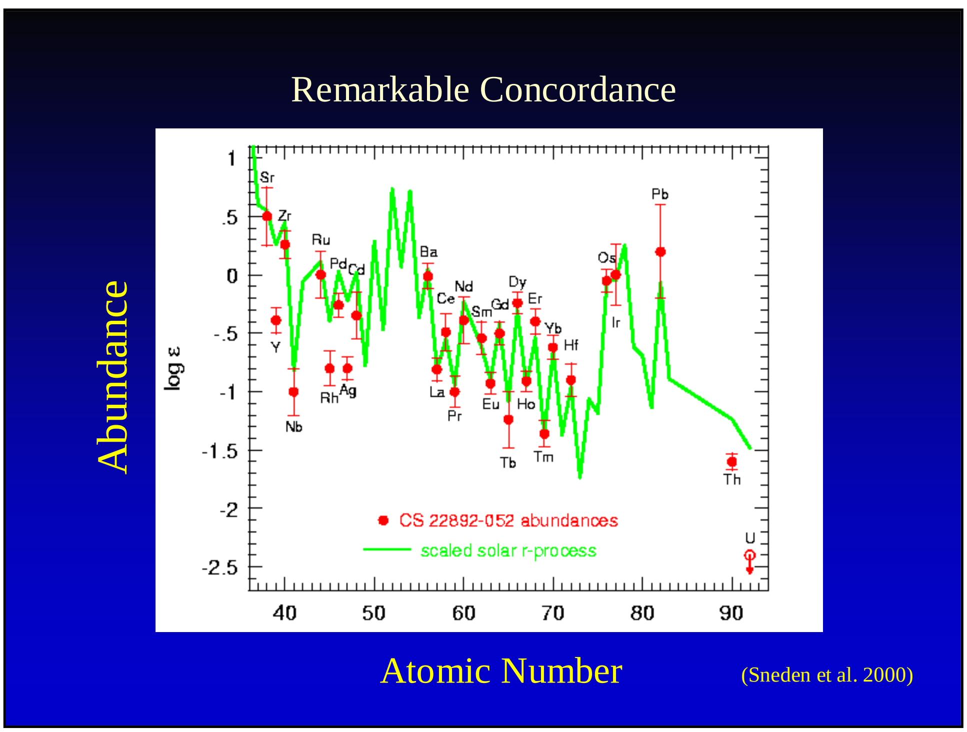
s-Process and r-Process

The Rapid Neutron Capture (r) Process

- Seed nuclei neutron-capture on timescales much shorter than those for beta decay.
- If neutron-to-seed ratio ~ 100:1 $\Rightarrow$ heaviest nuclei.
  - Ratio set by entropy, dynamical timescale, & electron fraction
- The r-process is responsible for roughly half of all nuclei above the iron group.

(Burbidge, Burbidge, Fowler, and Hoyle 1957; Cameron 1957)


The r-Process Path
(from S. Wanajo)
Waiting Points
N = 50
N = 82
N = 126
A = 60
A = 100
A = 150
A = 200
A = 250
beta decay
neutron capture
log Y
Z →
N →


Remarkable Concordance
Abundance
log ε
CS 22892-052 abundances
scaled solar r-process
Atomic Number
(Sneden et al. 2000)

Motivation:

Suggests a universal r-process site that acts early in the chemical enrichment history of the galaxy.

(Burris et al. 2000; Cayrel et al. 2001)

What is the astrophysical site?

Possible Sites:

- Protoneutron Star Winds
  - Rate ~ 1 every 50 yr
  - Required mass ejected ~ 10^{-5}-10^{-6} M_{sun}
- Neutron Star-Neutron Star Mergers
  - Rate ~ 1 every 10^5 yr,
  - Required mass ejected ~ 10^{-1} M_{sun}

  - Both are neutron rich

What are the physical characteristics of neutrino-driven winds?

Are these conditions suitable for a robust r-Process?

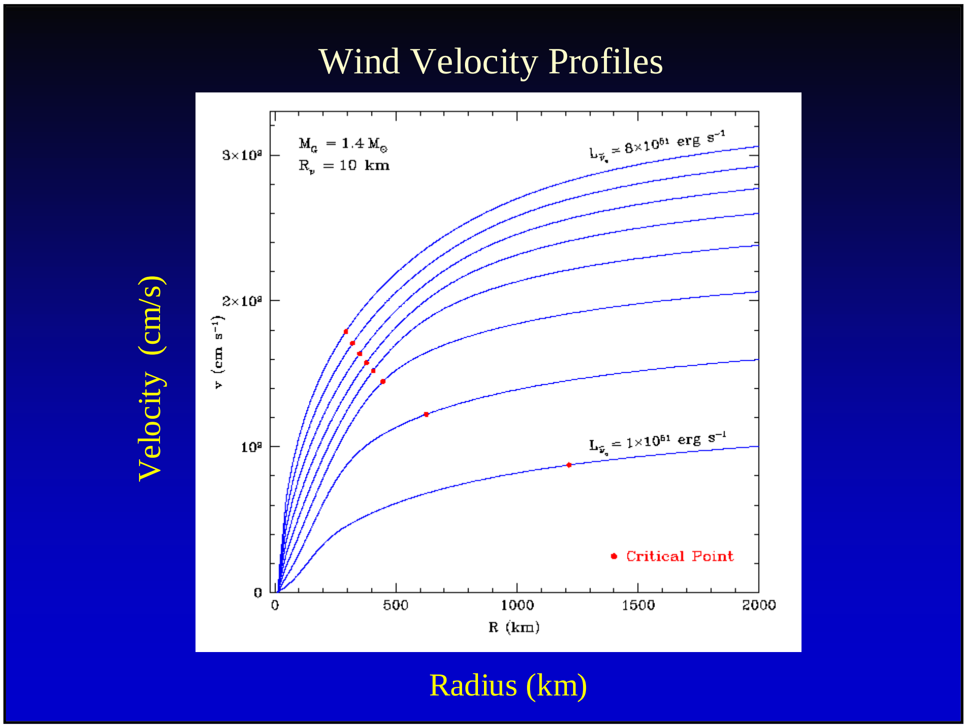
Entropy, dynamical timescale, and electron fraction

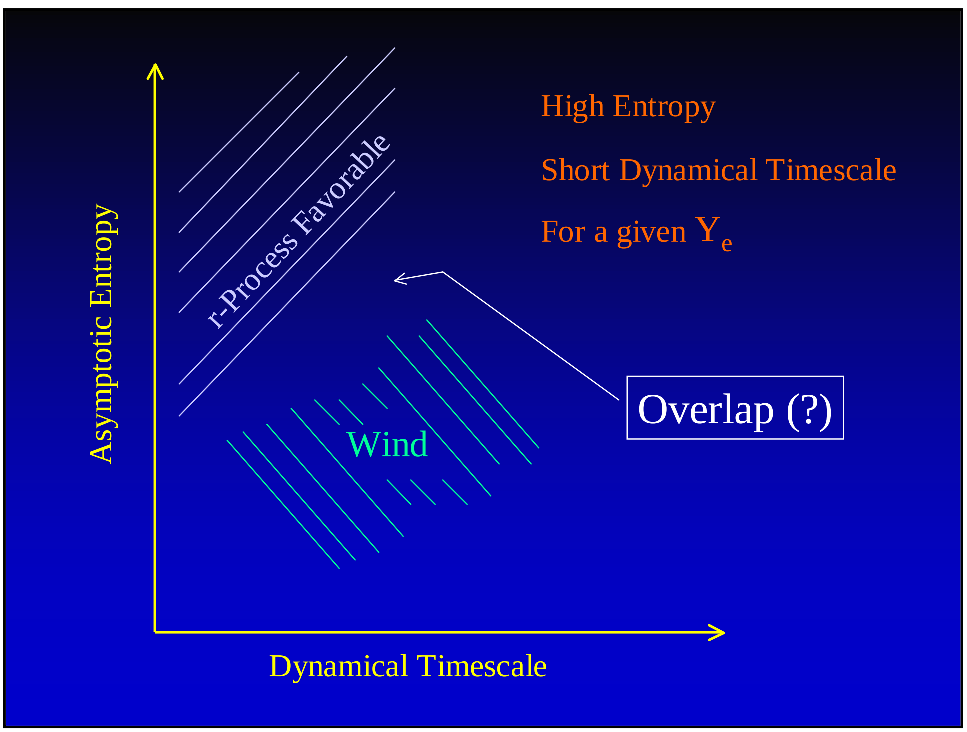
Neutrino-Driven Steady-State Winds

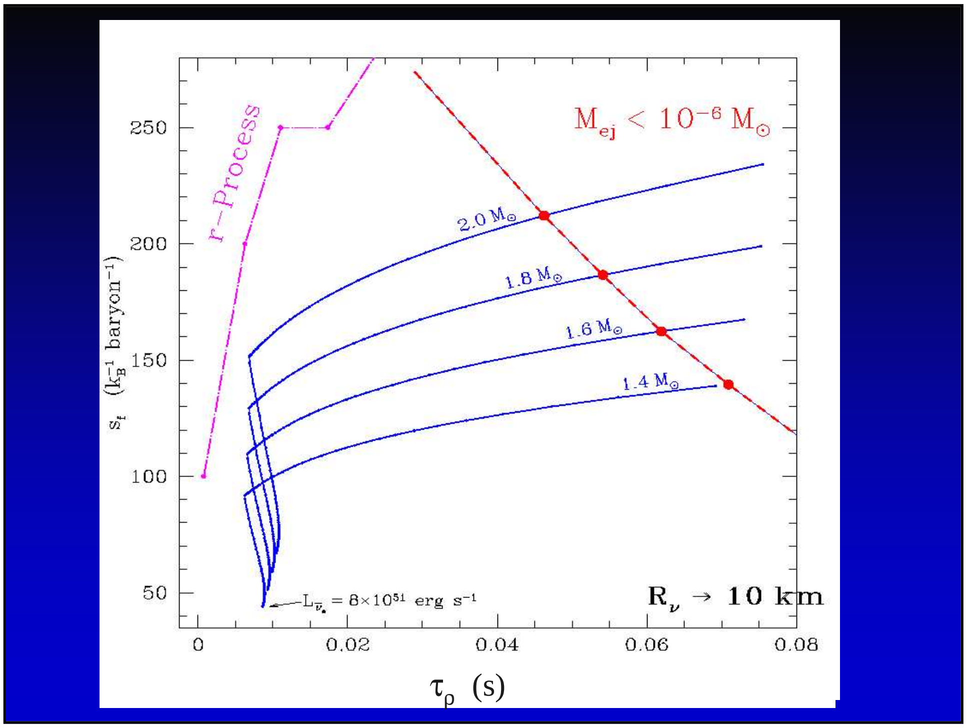
- Physics: eigenvalue problem $\left(\dot{M} = 4\pi r^2 \rho u\right)$
  - Three critical, coupled ODEs for ρ, T, and v
  - Neutrino heating and cooling
  - Electron fraction (Y_e) evolution
  - General Relativity, Schwarzschild metric
  - EOS: Arbitrary lepton degeneracy and relativity

Thompson, Burrows, & Meyer 2001

(Paczyński & Prószyński 1986; Duncan et al. 1986)


Wind Velocity Profiles
$M_G = 1.4\,M_\odot$
$R_\nu = 10$ km
$L_{\bar{\nu}_e} = 8\times10^{51}$ erg s^{-1}
$L_{\bar{\nu}_e} = 1\times10^{51}$ erg s^{-1}
Critical Point
3×10^9
2×10^9
10^9
0
v (cm s^{-1})
0
500
1000
1500
2000
R (km)
Velocity (cm/s)
Radius (km)

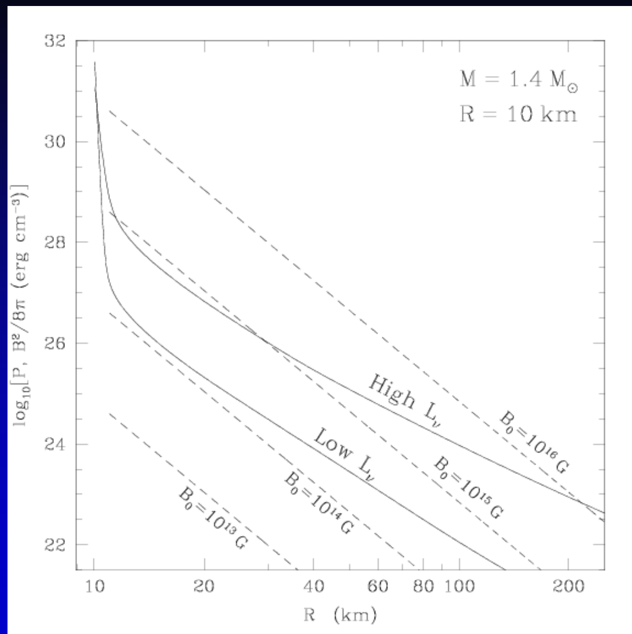

High Entropy
Short Dynamical Timescale
For a given Y_e
r-Process Favorable
Wind
Overlap (?)
Asymptotic Entropy
Dynamical Timescale



Transonic neutrino-driven winds from 1.4M_{sun} R=10km neutron stars fail to produce 3rd-peak r-process nucleosynthesis

Qian & Woosley '94; Otsuki et al. '00;
Thompson et al. '01; Wanajo et al. '01;
Sumiyoshi et al. '00; but, see Terasawa et al. '02

What about magnetic fields and rotation?



Closed Loops, Trapping, and Entropy Amplification

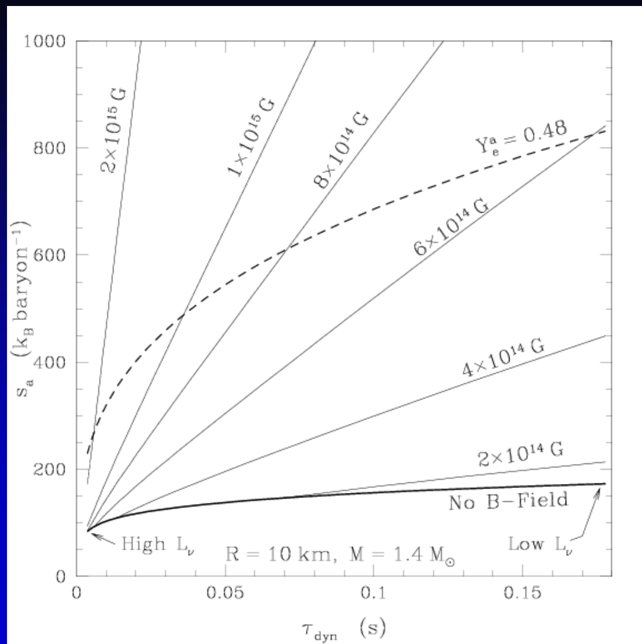
- Closed loops trap matter, but not permanently
- Trapping Timescale:

  $\tau_{Trap} \approx [B^2/8\pi - P]/[q\rho]$

- Entropy Enhancement:

  $\Delta s \approx \tau_{Trap} q / T$

Thompson 2003



Magnetic Protoneutron Star Winds

- Neutrino-driven winds from PNSs with magnetar-like field strengths are magnetically dominated.
- In regions where the field dominates P, closed loops will form.
- These loops may trap matter temporarily, leading to higher asymptotic entropy.
- This entropy enhancement may be sufficient for robust r-process nucleosynthesis.

Some Open Questions

- Complex field topologies
- MHD instabilities
- Convection & Rotation - footpoint motion
- Spindown

The Future

- Dynamical models of explosion, wind emergence, and evolution (reverse shocks, fallback, etc)
- 2D & 3D models of neutrino-driven magnetohydrodynamic protoneutron star winds.

The End

The Fundamental Equations

$$\frac{dv}{dr}=\frac{v}{2r}\left[\frac{v_e^2}{y^2}\left(\frac{1-c_s^2/c^2}{c_s^2-v^2}\right)-4c_s^2\left(\frac{1-v^2/c^2}{c_s^2-v^2}\right)\right]+\frac{D}{C_V T}\frac{\dot{q}}{y}\left(\frac{1-v^2/c^2}{c_s^2-v^2}\right)$$

$$\frac{d\rho}{dr}=\frac{2\rho}{r}\left(\frac{v^2-v_e^2/4y^2}{c_s^2-v^2}\right)+\frac{\rho}{vy}\frac{D}{C_V T}\frac{\dot{q}}{c_s^2-v^2}$$

$$\frac{dT}{dr}=\frac{2}{r\rho}\frac{D}{C_V}\frac{P+\varepsilon}{c^2}\left(\frac{v^2-v_e^2/4y^2}{c_s^2-v^2}\right)+\frac{\dot{q}}{C_V\,(vy)}\left(\frac{(1-D/c^2)c_T^2-v^2}{c_s^2-v^2}\right)$$

where $D=c^2\,\frac{T}{\varepsilon+P}\left.\frac{\partial P}{\partial T}\right|_\rho$ and $y=\gamma\left(1-2GM/rc^2\right)^{1/2}$

Example: Neutrino-Electron Scattering

$$\dot{q}_{\nu_i e} = c n_e n_{\nu_i} \langle \sigma_{\nu_i e} \omega_{\nu_i e} \rangle = \int c \frac{dn_e}{d\varepsilon_e} d\varepsilon_e \frac{dn_{\nu_i}}{d\varepsilon_{\nu_i}} d\varepsilon_{\nu_i} \sigma_{\nu_i e} \omega_{\nu_i e}$$

$$\omega_{\nu_i e} \approx \frac{1}{2}\left(\varepsilon_{\nu_i} - 4T\right) \qquad \sigma_{\nu_i e} \approx \kappa_i T \varepsilon_{\nu_i}$$

(Bahcall 1964) (Tubbs and Schramm 1975)

$$\dot{q}_{\nu_i e} \approx \frac{c}{\rho}\left[\frac{T^3}{(\hbar c)^3}\frac{F_2(\eta_e)}{\pi^2}\right]\frac{L_\nu}{4\pi R^2 c \langle \varepsilon_\nu \rangle}\Phi^4 \, 2\Xi(r) \qquad \text{erg g}^{-1}\text{s}^{-1}$$

$$\times \left[\frac{\kappa}{2}\langle \varepsilon_\nu \rangle \frac{F_4(\eta_\nu)}{F_3(\eta_\nu)} T \left(\langle \varepsilon_\nu \rangle \Phi \frac{F_2(\eta_\nu)}{F_3(\eta_\nu)} - 4T \frac{F_3(\eta_\nu)}{F_4(\eta_\nu)}\right)\right]$$

(Also Tubbs 1975; Janka 1999; Salmonson and Wilson 1999)

Neutrino Interactions: Heating and Cooling $(\dot{q})$

- Charged Current : $\nu_e n \leftrightarrow e^- p$ and $\bar{\nu}_e p \leftrightarrow e^+ n$
  also affect Y_e evolution
- Scattering : $\nu_i e^{-,+} \leftrightarrow \nu_i e^{-,+}$ and $\nu_i n,p \leftrightarrow \nu_i n,p$
- Pair Processes : $e^- e^+ \leftrightarrow \nu_i \bar{\nu}_i$

Tools:

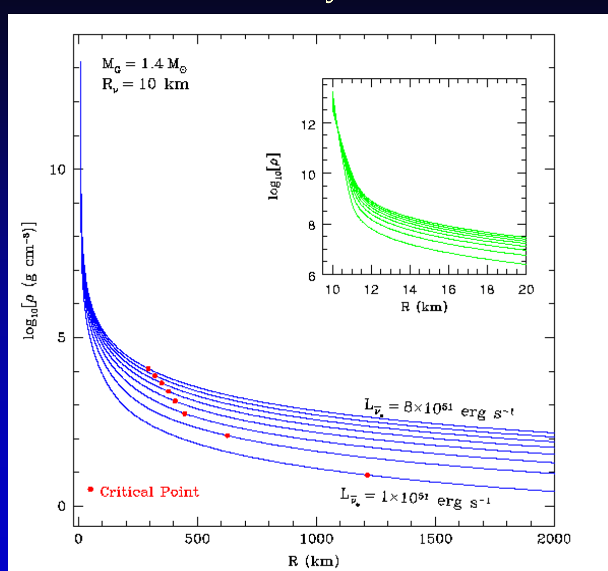
- Algorithm:
  - 2-point boundary value problem
  - Relaxation on adaptive radial mesh
    (London and Flannery 1982)
- Physical BCs:
  - Optical depth
  - Triple Newton-Raphson
  - Sonic Point ($v = c_s$)

$$\tau_{\nu_e}(R) = \frac{2}{3} = \int_R^\infty \kappa\rho \, dr$$

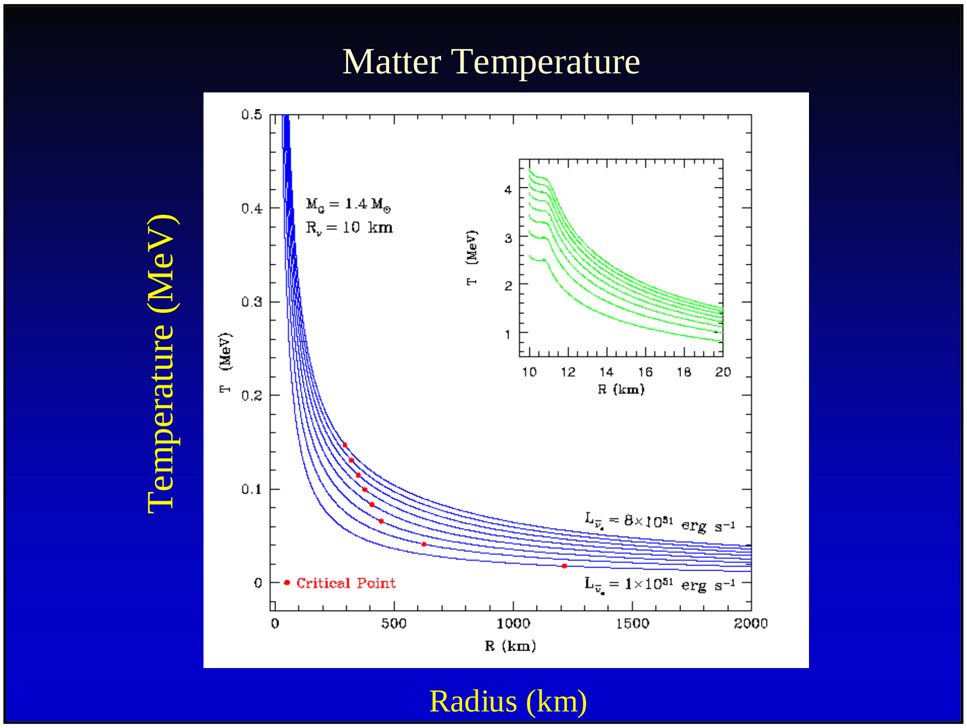
$$\dot{q}(R) = 0; \quad \left.\frac{dY_e}{dr}\right|_R = 0$$

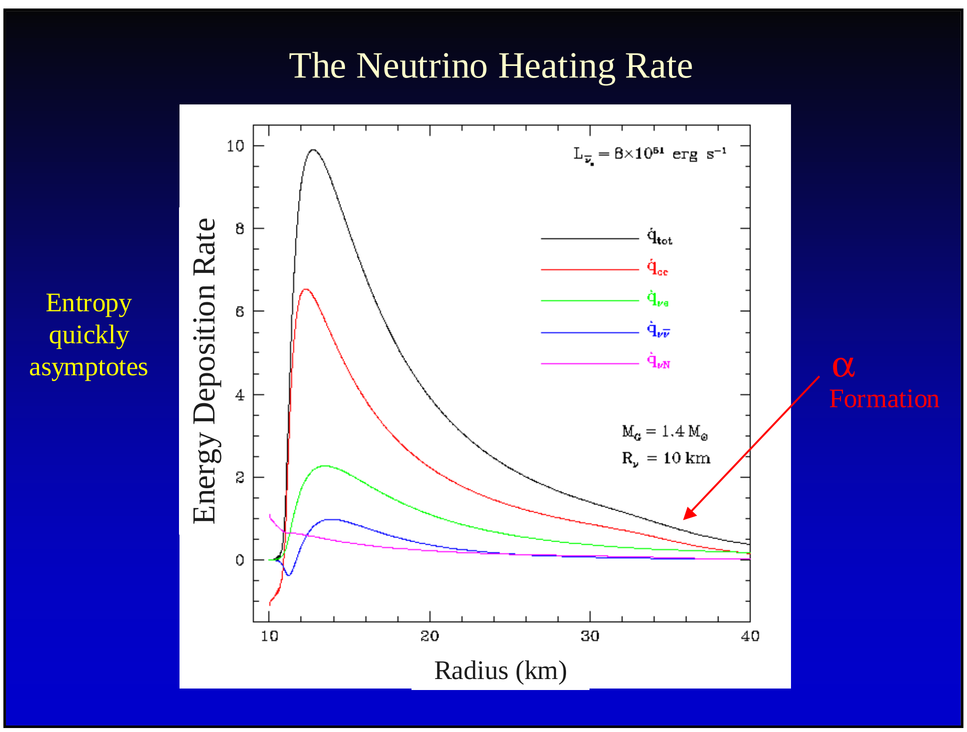
Mass Density Profiles

Density (g/cc)

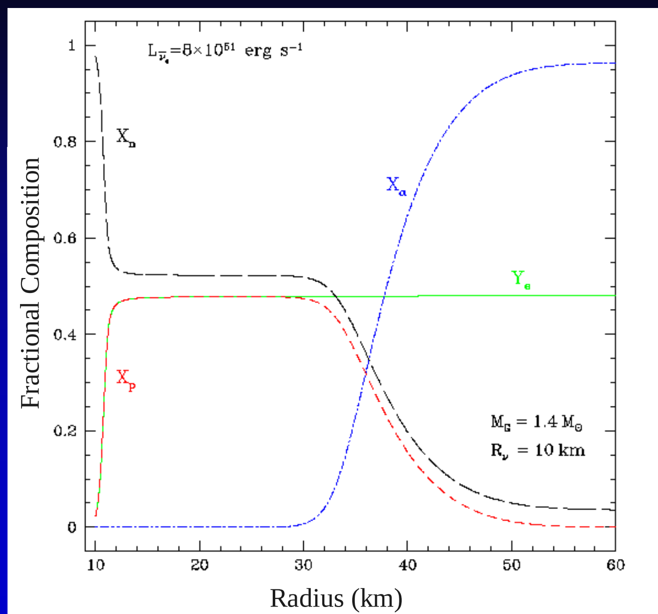


Radius (km)


Matter Temperature
Temperature (MeV)
Radius (km)
$M_G = 1.4\,M_\odot$
$R_\nu = 10$ km
Critical Point
$L_{\bar{\nu}_e} = 8\times10^{51}$ erg s^{-1}
$L_{\bar{\nu}_e} = 1\times10^{51}$ erg s^{-1}
T (MeV)
R (km)


The Neutrino Heating Rate
Entropy quickly asymptotes
Energy Deposition Rate
Radius (km)
$L_{\bar{\nu}_e} = 8\times10^{51}$ erg s^{-1}
$\dot{q}_{tot}$
$\dot{q}_{cc}$
$\dot{q}_{\nu e}$
$\dot{q}_{\nu\bar{\nu}}$
$\dot{q}_{\nu N}$
$M_G = 1.4\,M_\odot$
$R_\nu = 10$ km
α Formation

Composition



$Y_e^a \sim 0.48$

Dynamical Timescale

- Increased by including GR
  - Redshift
  - Bending of null geodesics
- Not constant, evolves in radius

$$\tau_\rho \propto L_\nu^{-0.75} \langle \varepsilon_\nu \rangle^{-2.6}$$

Thompson, Burrows, & Meyer 2001

Asymptotic Y_e

is set by ratio of luminosities and magnitude of energies.

$$Y_e^a \approx \frac{\Gamma_{\nu_e n}}{\Gamma_{\nu_e n} + \Gamma_{\bar{\nu}_e n}} \approx \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\langle \varepsilon_{\bar{\nu}_e} \rangle - 2\Delta + 1.2\Delta^2 / \langle \varepsilon_{\bar{\nu}_e} \rangle}{\langle \varepsilon_{\nu_e} \rangle + 2\Delta + 1.2\Delta^2 / \langle \varepsilon_{\bar{\nu}_e} \rangle}\right)^{-1}$$

$Y_e^a > 0.45$ (Qian et al. 1993)

Asymptotic Entropy

- Increased 20-30 units by GR: more compact
- Important Feedbacks
  - Cannot arbitrarily increase net heating
  - Broader deposition profile increases s.

$$s_a \propto L_\nu^{-0.15} \langle \varepsilon_\nu \rangle^{-0.4}$$

Modeling Evolution with Steady-State Winds

- Posit $L_\nu(t)$, R(t), and $\varepsilon_\nu(t)$
- Calculate mass ejected

$$M_{\mathrm{ejected}}(t) = \int_0^t \dot{M}(t')\,dt'$$

- Timescales:
  - Sound crossing time
  - Escape time
  - Luminosity decay time

$$\tau_{sound}, \tau_{escape} << \tau_{decay}$$

Assessing the Wind's Potential for r-Process Nucleosynthesis

What is the neutron-to-seed ratio in the wind?

- Entropy
  - asymptotes in ~100 km
- Y_e
  - asymptotes in ~10 km
- Dynamical Timescale
  - sets slope of density profile

$$\tau_\rho = \frac{1}{(v y)} \left| \frac{1}{\rho} \frac{\partial \rho}{\partial r} \right|^{-1}_{T=0.5\,\mathrm{MeV}}$$