

# The Neutrino Mechanism of Core-Collapse Supernovae

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# Background on Core Collapse SNe

Progenitors: Massive Stars ( $8 - 50? M_{\odot}$ )

Products: Blast wave, neutron star remnant ( $\sim 1.5 M_{\odot}$ )

Energies:

- Neutron star binding energy:  $\sim 3 \times 10^{53}$  erg
- Kinetic energy of ejecta:  $\sim 10^{51}$  erg
- Light-curve energy:  $\sim 10^{49}$  erg

Timescales:

- Core collapse:  $\sim 500$  ms
- Post-Bounce Time to Explosion:  $\lesssim 1$  s
- Core Neutrino Cooling Time:  $\sim 10$  s

# History of the Core-Collapse Problem I

## Pioneering Work

- Chandrasekhar (1935): Iron core must collapse if  $M_c \gtrsim 1.4M_\odot$
- Burbidge, Burbidge, Fowler, Hoyle (1957):
  - ▶ Photodisintegration of iron removes  $8.5 \times 10^{18} \text{ erg g}^{-1} \gg U_{\text{therm}} \sim 3 \times 10^{17} \text{ erg g}^{-1}$
  - ▶ Collapse  $\Rightarrow$  nuclear burning, detonation in outer envelope
- Colgate, White (1966):
  - ▶ Electron capture, nuclear dissociation initiate dynamical collapse
  - ▶ Collapse halted at nuclear densities, shock wave begins as core matter is suddenly decelerated
  - ▶ Nuclear burning won't work
  - ▶ Neutrinos proposed (albeit with much hand waving) as an energy transport mechanism
- Early simulations: bounce shock stalls at  $\sim 100 - 200 \text{ km}$ 
  - ▶ Sapped of pressure by electron capture, neutrino losses

# History of the Core-Collapse Problem II

~ 1970 – present: what happens with the neutrinos?

- Arnett (1967, 1977), Sato (1975): Bounce at low densities ( $\rho \sim 10^{13} \text{ g cm}^{-3}$ )
  - ▶ Relatively low densities  $\Rightarrow$  neutrinos are less trapped
  - ▶ Burst of flux over  $\sim 100\text{ms}$ , radiation pressure ejects envelope?
- Bethe, Wilson (1985): Neutrino heating behind stalled shock
  - ▶ Nuclei do not dissociate on infall  $\Rightarrow$  bounce at  $\rho \approx 2.6 \times 10^{14} \text{ g cm}^{-3}$
  - ▶ Shock energized with  $p\text{d}V$  work, not neutrino pressure
- Recent work (Burrows, Janka, Mezzacappa): full numerical assault
  - ▶ Multi-D simulations (3-D just beginning)
  - ▶ Detailed neutrino transport
  - ▶ General relativity, other secondary physics
- ... but we still can't make it reliably work.
  - ▶ 3-D effects?
  - ▶ Missing physics?
  - ▶ Numerical/resolution effects?

# Neutrino-Matter Interactions I

## Neutrinos are fermions

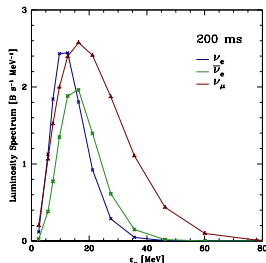
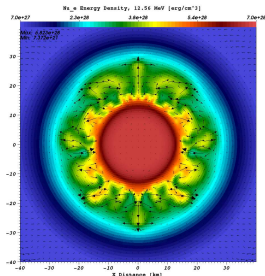
- Trapped electron neutrinos create a degenerate Fermi sea (see figure)
- Stimulated absorption in reactions due to Pauli blocking (stimulated *emission* for photons)

## Neutrino Types:

Electron	$\nu_e$	Anti-Electron	$\bar{\nu}_e$
Muon	$\nu_\mu$	Anti-Muon	$\bar{\nu}_\mu$
Tau	$\nu_\tau$	Anti-Tau	$\bar{\nu}_\tau$

## Typical energies:

Beta Decay Neutrinos	$\lesssim 0.5$ MeV
Solar Neutrinos	$\sim 0.1 - 17$ MeV
Supernova Neutrinos	$\sim 5 - 40$ MeV



# Neutrino-Matter Interactions II

Neutrino-matter cross sections are *very* low

- Thomson electron scattering cross-section:  $\sim 10^{-24}$  cm<sup>2</sup>
- Weak interaction cross sections  $\sim 10^{-42}$  cm<sup>2</sup> for SN energies
- Mean free path  $\sim 100 \left( \frac{10^{15} \text{ g cm}^{-3}}{\rho} \right) \left( \frac{10 \text{ MeV}}{\epsilon_\nu} \right)^2$  cm

Significant Interactions:

Reaction	Neutrino Type	Cross-Section $\sigma$ [ $\times 10^{-42}$ cm <sup>2</sup> ]
$\nu_e + n \leftrightarrow e^- + p$	Electron	$\sim 8 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right)^2$
$\bar{\nu}_e + p \leftrightarrow e^+ + n$	Anti-Electron	$\sim 7 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right)^2$
$\nu_i + p \rightarrow \nu_i + p$	All Species	$\sim 1.7 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right)^2$
$\nu_i + n \rightarrow \nu_i + n$	All Species	$\sim 2.0 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right)^2$
$\nu_i + \mathbf{A} \rightarrow \nu_i + \mathbf{A}$	All Species	$\sim 1.2 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right)^2$
$\nu_i + e^- \rightarrow \nu_i + e^-$	All Species	$\nu_e: \sim 5 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right) \left( \frac{T + \mu_e/4}{10 \text{ MeV}} \right)$ other species: $\sim 1 \left( \frac{\epsilon_\nu}{10 \text{ MeV}} \right) \left( \frac{T + \mu_e/4}{10 \text{ MeV}} \right)$



## Aside: Dynamical Instability for $\gamma \leq \frac{4}{3}$

Consider the simple model shown with equation of motion

$$m \frac{d^2 r}{dt^2} = -\frac{GMm}{r^2} + 4\pi r^2 p, \quad (1)$$

and consider an equilibrium  $r_0, p_0$ , so that

$$\frac{GMm}{r_0^2} = 4\pi r_0^2 p_0. \quad (2)$$

Perturb  $r \rightarrow r_0 + \delta r$ ,  $p \rightarrow p_0 + \delta p$ , linearize (1) to obtain:

$$m \frac{d^2(\delta r)}{dt^2} = -\frac{GMm}{r_0^2} \left(1 - 2\frac{\delta r}{r_0}\right) + 4\pi r_0^2 p_0 + 8\pi r_0 p_0 \delta r + 4\pi r_0^2 \delta p. \quad (3)$$

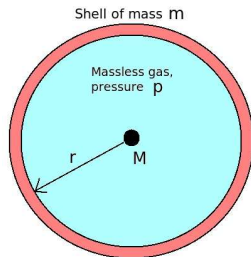
Now use the adiabatic index of the gas to relate  $\delta p$ ,  $\delta r$ :

$$pV^\gamma = \text{constant} \Rightarrow p \propto r^{-3\gamma} \Rightarrow \frac{\delta p}{p_0} = -3\gamma \frac{\delta r}{r_0}. \quad (4)$$

Use the equilibrium condition (2) and the adiabatic relation (4) to obtain

$$\frac{d^2(\delta r)}{dt^2} = \frac{GM}{r_0^3} (4 - 3\gamma) \delta r. \quad (5)$$

$\delta r$  oscillates sinusoidally for  $\gamma > \frac{4}{3}$ , grows or decays exponentially for  $\gamma < \frac{4}{3}$ .



# Stalling of the Shock

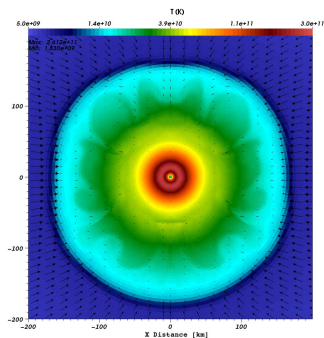
Shock wave propagates out into heavy nuclei with high specific heat

- Shock energy goes into:
  - ▶ electron capture ( $A + e^- \rightarrow A' + \nu_e$ )
  - ▶ excitation of nuclei
  - ▶ dissociation (i.e.  ${}^{56}_{26}\text{Fe} \rightarrow 26p + 30n$ )
- Post-shock pressure falls
- Ram pressure  $p_{\text{ram}} = \rho v^2$  may be more than post-shock pressure

Prompt explosion will only work if ram pressure drops

- Need a steep density gradient?  
8 – 10 $M_{\odot}$  progenitors?

Otherwise,  $p_{\text{ram}} > p_{\text{post-shock}} \Rightarrow$  shock stalls



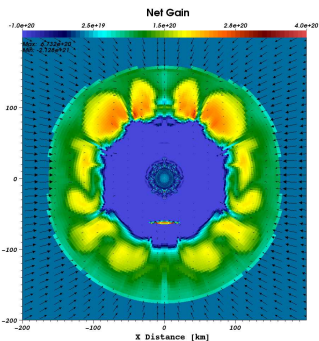
# Reviving the Shock

We need to either increase  $p_{\text{post-shock}}$ , decrease  $p_{\text{ram}}$ , or both, by:

- Depositing additional energy behind the shock,
- Changing the nuclear equation of state (nope: e.g. Burrows & Lattimer 1985),
- Using radiation pressure (nope:  $L_{\text{typ}} \sim 10^{53} \text{ erg s}^{-1} \ll L_{\text{Edd}} \sim 10^{55} \text{ erg s}^{-1}$ ), or
- Using progenitor models with steeper density profiles.

Possible energy sources:

- Nuclear burning (e.g.  $\text{O} \rightarrow \text{Fe}$ )
  - ▶ Releases  $\sim 5 \times 10^{17} \text{ erg g}^{-1} \ll 10^{19} \text{ erg g}^{-1}$   
 $\sim$  gravitational binding energy at 200 km.
  - ▶ For  $10^{51} \text{ erg}$ , need to burn  $1 M_{\odot}$  of oxygen explosively  $\Rightarrow$  need to already have enormous blast wave at large  $R$ .
- $\nu_e + \bar{\nu}_e \rightarrow e^+ + e^- \rightarrow 2\gamma$  (annihilation)?
  - ▶ Most efficient where  $\nu$  cooling is severe
- Delayed neutrino heating: Neutrino Mechanism



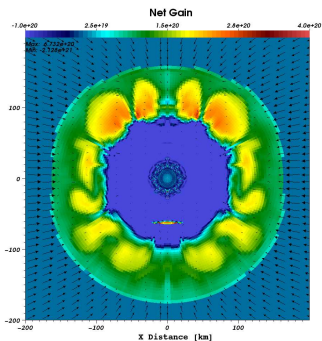
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# Neutrino Cooling

Simplified (neutrino) radiation transport, neglect scattering:

- “ $\frac{\partial I_\epsilon(r)}{\partial r} = \kappa_\epsilon \rho [B_\epsilon(T) - I_\epsilon(r)]$ ”
  - ▶  $B_\epsilon(T)$  is the blackbody function for  $\nu$ 's.
- Integrated over  $\epsilon_\nu$ : “ $\frac{\partial F(r)}{\partial r} = \bar{\kappa} \rho [acT^4 - F(r)]$ ”.
- $\bar{\kappa} \rho acT^4$  is emission from matter (cooling),  $\bar{\kappa} \rho F(r)$  is absorption by matter (heating)

Neutrino cooling density ( $\bar{\kappa} \rho acT^4$ ) dominated by URCA processes:

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

Neutrino energy loss rate per gram is  $\bar{\kappa} acT^4$ :

- $\bar{\kappa} \propto (\epsilon_\nu)^2 \Rightarrow \bar{\kappa} \propto T^2$
- Cooling rate per gram  $\mathcal{C} \propto T^6$
- Numerically,  $\mathcal{C} \approx 1.4 \times 10^{20} \left(\frac{T}{2 \text{ MeV}}\right)^6 \text{ erg g}^{-1} \text{ s}^{-1}$

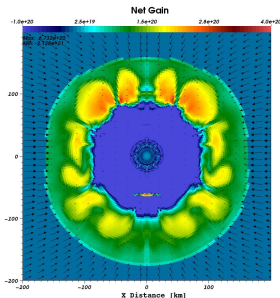
URCA cooling dominates at  $R \lesssim 70 \text{ km}$  where the matter is hot



# Neutrino Heating

Neutrino heating rate per gram ( $\bar{\kappa}F_\nu$ ):

- Most important processes: inverses of URCA
  - ▶  $\nu_e$  capture  $\nu_e + n \rightarrow p + e^-$
  - ▶  $\bar{\nu}_e$  capture  $\bar{\nu}_e + p \rightarrow n + e^+$
- $\bar{\kappa} \propto (\epsilon_\nu)^2 \Rightarrow \bar{\kappa} \propto (T_{\nu_e})^2$
- Heating rate per gram  $\mathcal{H} \propto (T_{\nu_e})^2 \frac{L_\nu}{4\pi r^2}$
- $\mathcal{H} \approx 1.5 \times 10^{20} L_{\nu_e} \left(\frac{100 \text{ km}}{r}\right)^2 \left(\frac{T_{\nu_e}}{4 \text{ MeV}}\right)^2 \text{ erg g}^{-1} \text{ s}^{-1}$ 
  - ▶ Characteristic temperature of the neutrino spectrum  $T_{\nu_e}$  *does not decrease with radius*.



Since cooling falls off at  $T^6$ , faster than heating at  $r^2$ , we have a **gain region** of net  $\nu$  heating

- $\mathcal{H} - \mathcal{C} \approx \left[ 1.5 \times 10^{20} L_{\nu_e} \left(\frac{100 \text{ km}}{r}\right)^2 \left(\frac{T_{\nu_e}}{4 \text{ MeV}}\right)^2 - 1.4 \times 10^{20} \left(\frac{T}{2 \text{ MeV}}\right)^6 \right] \text{ erg g}^{-1} \text{ s}^{-1}$
- Gain region:  $\sim 80 \text{ km} - R_{\text{shock}}$ .

# Will it Work?

Net neutrino heating adds  $\sim 10^{20} \text{ erg g}^{-1} \text{ s}^{-1}$  in the gain region

- Matter gains sufficient energy to become unbound in  $\sim 100 \text{ ms}$ !
- Energy deposition significantly increases  $p_{\text{post-shock}}$

Star blows up, declare victory!

# Will it Work?

Net neutrino heating adds  $\sim 10^{20}$  erg  $\text{g}^{-1}$   $\text{s}^{-1}$  in the gain region

- Matter gains sufficient energy to become unbound in  $\sim 100$  ms!
- Energy deposition significantly increases  $p_{\text{post-shock}}$

Star blows up, declare victory!

But, does matter remain in the gain region long enough?

# Important Quantities, Timescales

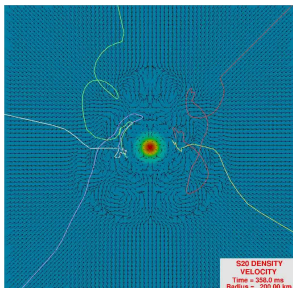
Quantity	Definition	Description
Residence Time	$\tau_{\text{res}}$	Mean dwelling time in the gain region Timescale for gain region to lose energy
Heating Time	$\tau_{\text{q}} \equiv \frac{\int_{\text{gain}} U_{\text{int}}}{\int_{\text{gain}} (\mathcal{H} - \mathcal{C})}$	Characteristic timescale to heat gain region
Heating power	$\mathcal{P} \equiv \tau_{\text{L}\nu}$	Net neutrino energy deposition rate

Burrows & Goshy 1993, Murphy & Burrows 2008

Important dimensionless ratio:  $\frac{\tau_{\text{res}}}{\tau_{\text{q}}}$

- If  $\frac{\tau_{\text{res}}}{\tau_{\text{q}}} > 1$ , net energy (and therefore pressure!) are added to the gain region
  - ▶ If this is sustained, star explodes, declare victory!
- $L_{\nu} - \dot{M}$  relation:  $\frac{\tau_{\text{res}}}{\tau_{\text{q}}} \sim \frac{M_{\text{gain}}}{M} \frac{L_{\nu}}{\int_{\text{gain}} U_{\text{int}}} \sim \frac{L_{\nu}}{M} \frac{m_{\text{p}}}{k_{\text{B}} T_{\text{gain}}}$ .

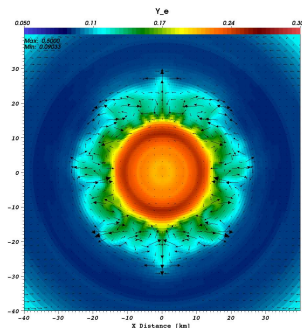
To make the neutrino mechanism explode current progenitor models, we need to increase  $\tau_{\text{res}}$  and/or  $L_{\nu}$ .



# Convection and GR: Increasing $\mathcal{P} \equiv \tau L_\nu$

## Core Convection/Overturn

- Core convection can transport neutrinos out faster
- Potentially increases  $L_\nu$  and therefore  $\mathcal{P}$
- “Neutron fingers”, “lepto-entropy fingers” to dredge up trapped neutrinos? (e.g. Bruenn et al. 2004)
  - ▶ Nope: multi-D simulations show no large-scale overturn (Dessart et al. 2006)
- Convection is present in outer core at early times (see figure), has a modest effect



## General Relativity

- Relativity tends to make the core more compact
  - ▶ Hotter neutrinospheres  $\Rightarrow$  higher  $\langle \epsilon_\nu \rangle$  (bigger cross-sections)  $\Rightarrow$  more heating
  - ▶ But... neutrinos are redshifted as they emerge from the deeper well
- GR seems to give a relatively minor correction to  $\mathcal{P}$ .



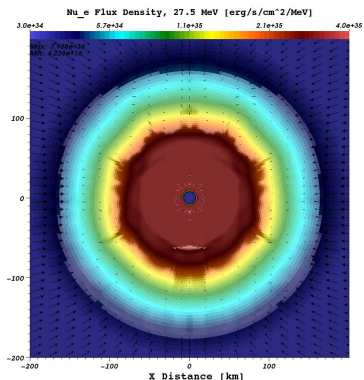
# Neutrino Transport

Solving the full Boltzmann equation for specific intensity is prohibitive.  
Various approximations are made:

- Diffusion artificially transitioning to free-streaming
- Solutions to the full Boltzmann equation along individual rays
- Simplified, discrete multi-angle transport

How much does it matter?

- Do the various approaches systematically over or underestimate neutrino luminosities and/or asymmetries?
- Will these errors be significant in calculating  $\tau$  or  $L_\nu$ ?
- Might these errors have feedbacks with the hydrodynamics, particularly in 2-D and 3-D?



# Summary

Massive star cores become unstable (Chandrasekhar), collapse dynamically, eventually produce Type II SNe.

What happens after collapse to get a huge blast wave?

- Core bounces at  $\rho_{\text{nuc}}$ , shock wave starts, stalls at  $\sim 200$  km?
- How is the shock revived?

Neutrino mechanism: neutrino cooling falls off faster than heating

- Region of net energy deposition from  $\sim 80$  km –  $R_{\text{shock}}$
- Shock is revived (?) by  $p\text{d}V$  expansion of the heated matter

But we're still missing something

- 3-D effects? We'll know very soon.
- Progenitor models? Important, but probably not the whole story
- Numerical methods, subdominant physics (e.g. GR, inelastic neutrino scattering)?  
Can these seemingly subdominant effects turn fizzles into robust explosions?

Nature is very good at blowing up stars. We are not.

# References

Arnett, D. 1967, *CaJPh*, 45, 1621

Arnett, W. D. 1977, *ApJ*, 218, 815

Bethe, H. A., & Wilson, J. R. 1985, *ApJ*, 295, 14

Bruenn, S. W., Raley, E. A., & Mezzacappa, A. 2004, *ArXiv Astrophysics e-prints*

Burrows, A., Dessart, L., & Livne, E. 2007, in *AIPC, Vol. 937, Supernova 1987A: 20 Years After: Supernovae and Gamma-Ray Bursters*, ed. S. Immler, K. Weiler, & R. McCray, 370

Burrows, A., & Goshy, J. 1993, *ApJL*, 416, L75

Burrows, A., & Thompson, T. A. 2002, *ArXiv Astrophysics e-prints*

Colgate, S. A., & White, R. H. 1966, *ApJ*, 143, 626

Dessart, L., Burrows, A., Livne, E., & Ott, C. D. 2006, *ApJ*, 645, 534

Foglizzo, T., Scheck, L., & Janka, H.-T. 2006, *ApJ*, 652, 1436

Janka, H.-T. 2001, *A&A*, 368, 527

Kitaura, F. S., Janka, H.-T., & Hillebrandt, W. 2006, *A&A*, 450, 345

Mazurek, T. J. 1974, *Nature*, 252, 287

Mezzacappa, A. 2001, *NuPhA*, 688, 158

Mezzacappa, A. 2005, *ARNPS*, 55, 467

Murphy, J. W., & Burrows, A. 2008, *ApJ*, 688, 1159

Sato, K. 1975, *PThPh*, 54, 1325

Wilson, J. R. 1971, *ApJ*, 163, 209