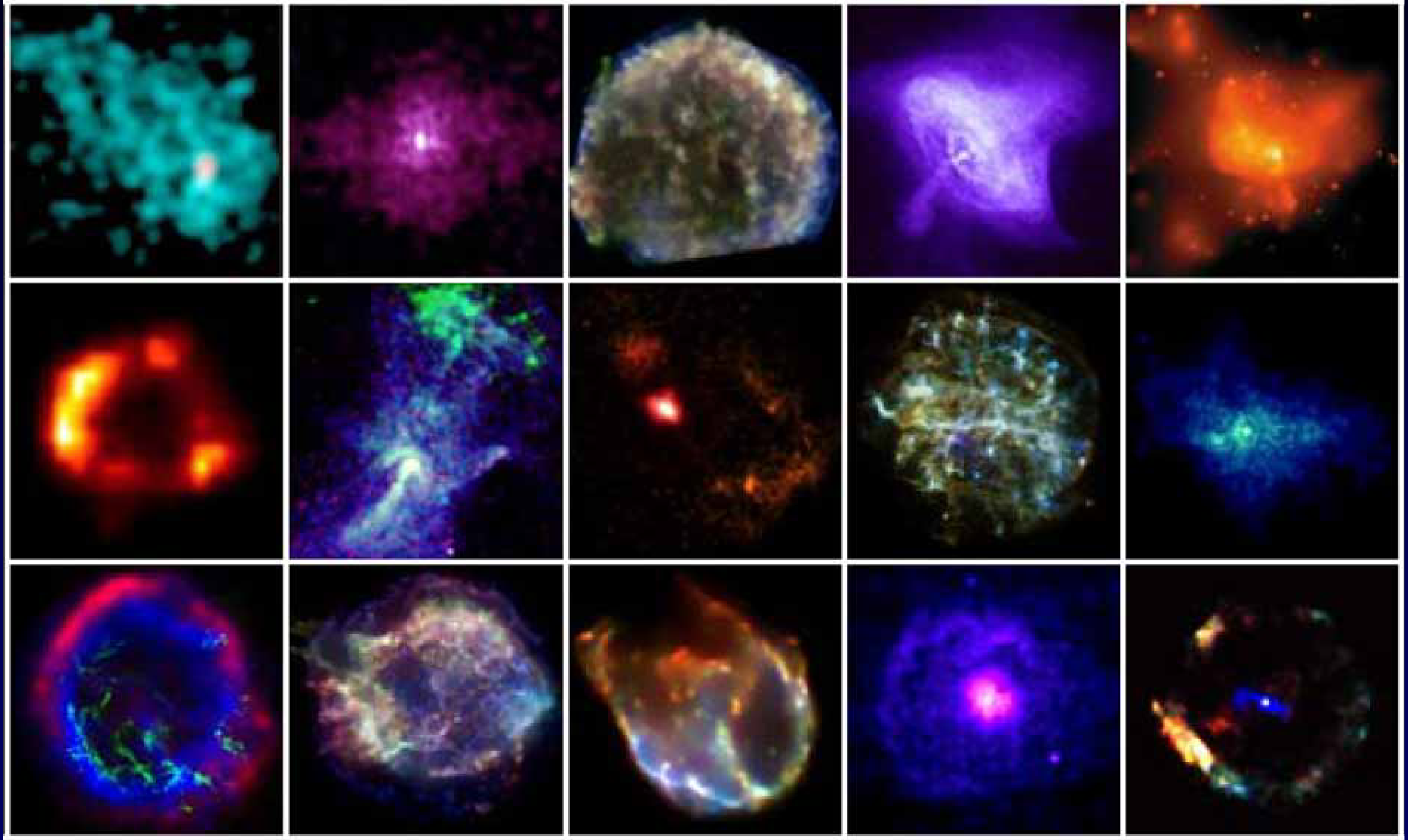
The Role of Nuclear Electron Capture during Stellar Core Collapse



Hix, Messer, Mezzacappa, Liebendörfer
Langanke, Martínez-Pinedo, Sampaio, Juodagalvis, Dean

Effects of Nuclear Electron Capture during Core Collapse

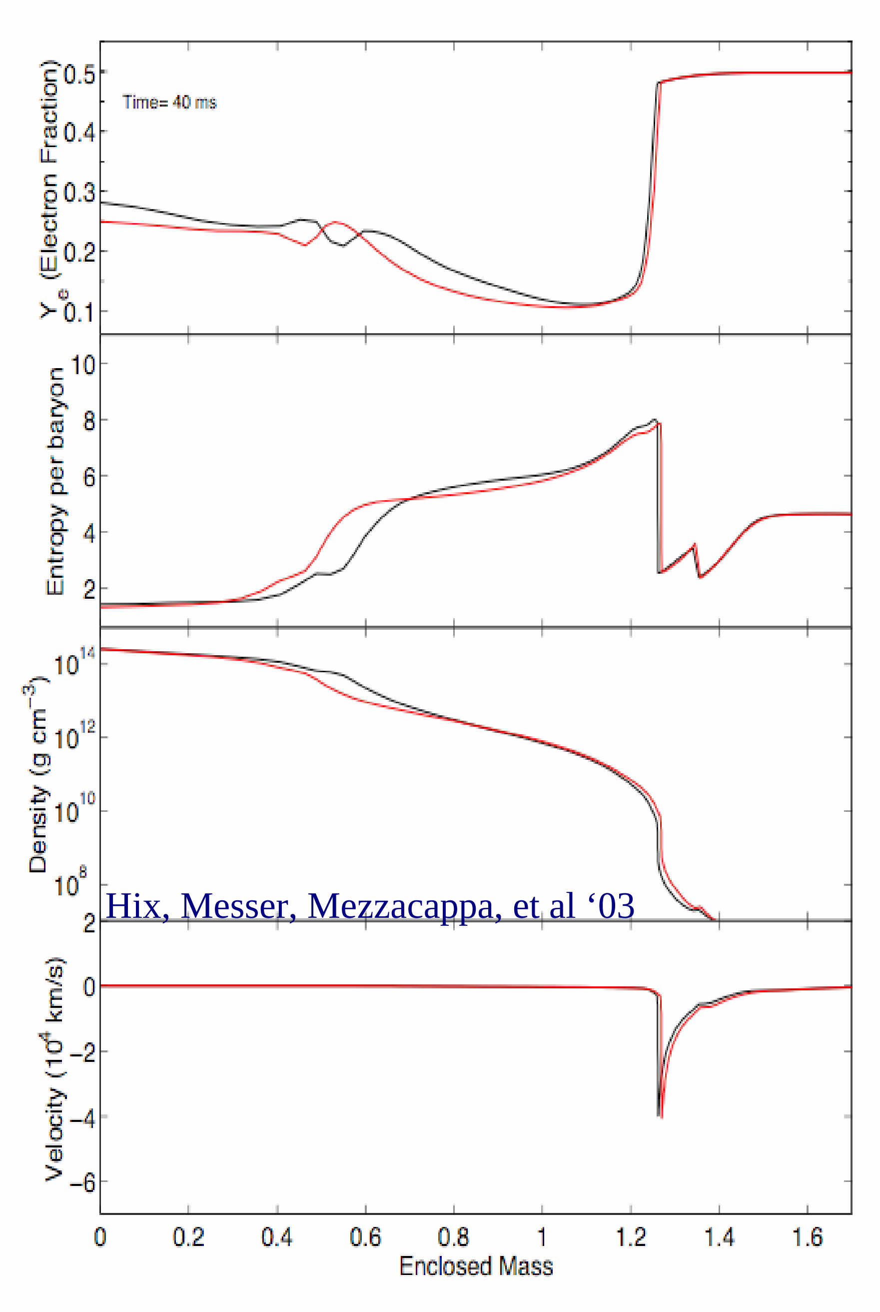
There are 2 separate effects.

1) Continuation of nuclear electron capture at high densities results in lower interior Y_e.

2) SMD rates result in less electron capture at low densities.

Initial mass interior to the shock reduced by ~20%.

Shock is ~15% weaker.



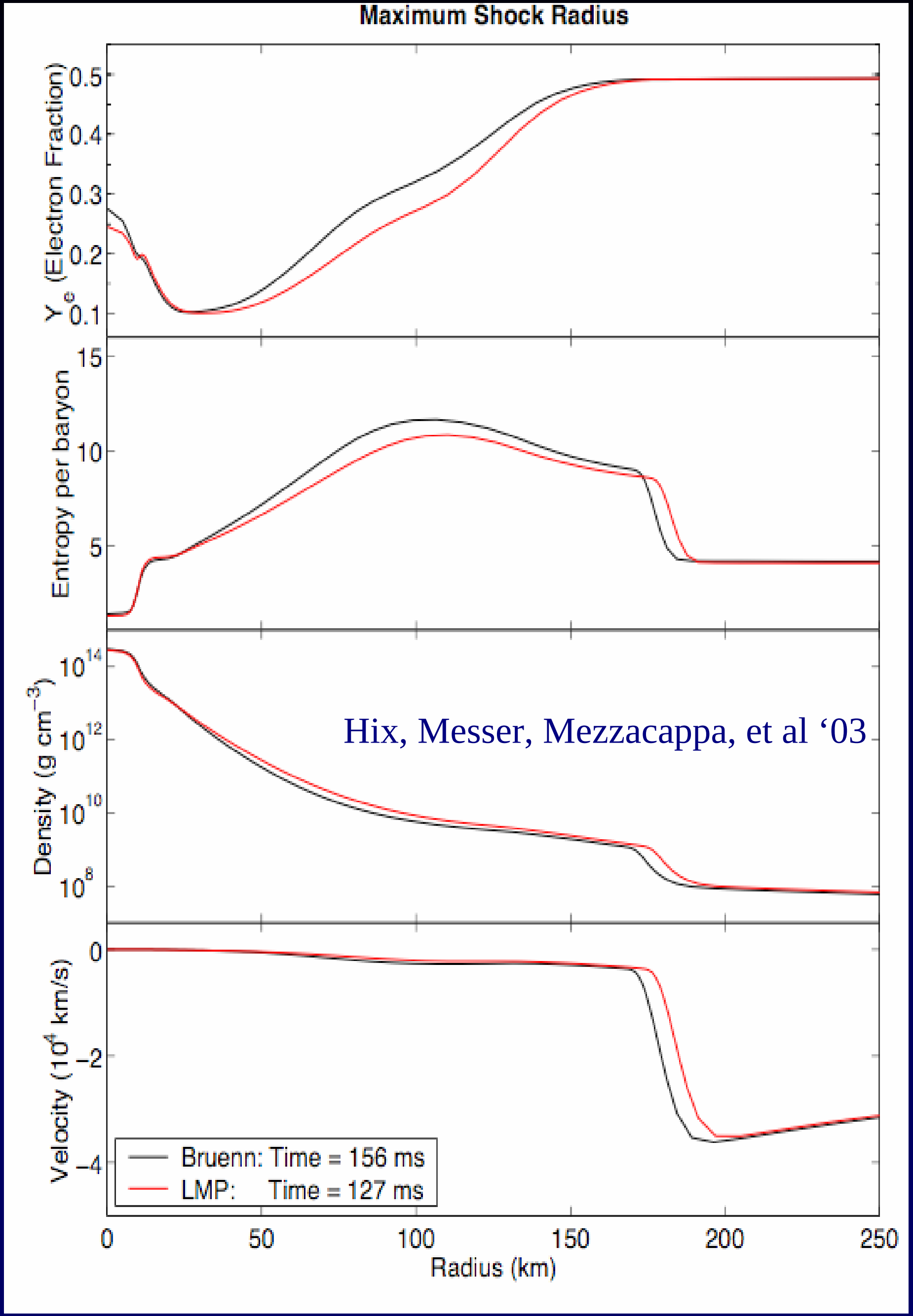
Hix, Messer, Mezzacappa, et al ‘03

Effects on Shock propagation

Gradients which drive convection are altered.

“Weaker” shock is faster.

Maximum excursion of the shock is 10 km further and 30 ms earlier.

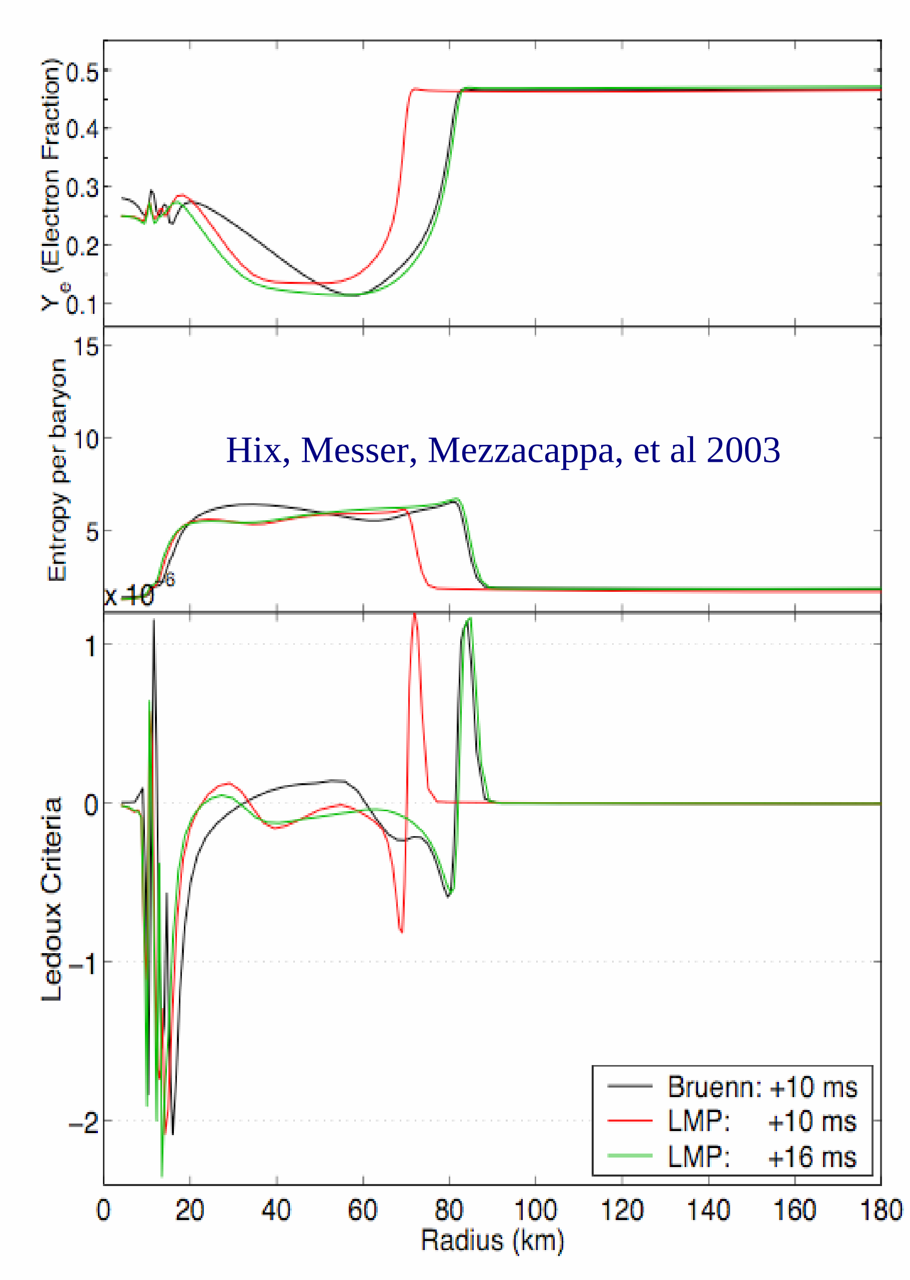


Hix, Messer, Mezzacappa, et al ‘03

PNS Convection

Fluid instabilities which drive convection result from complete neutrino radiation-hydrodynamic problem including nuclear interactions.

Updated nuclear e^- capture restricts PNS convection to smaller, deeper region.


Hix, Messer, Mezzacappa, et al 2003

Changes in Neutrino Emission

ν_e burst slightly delayed and prolonged.

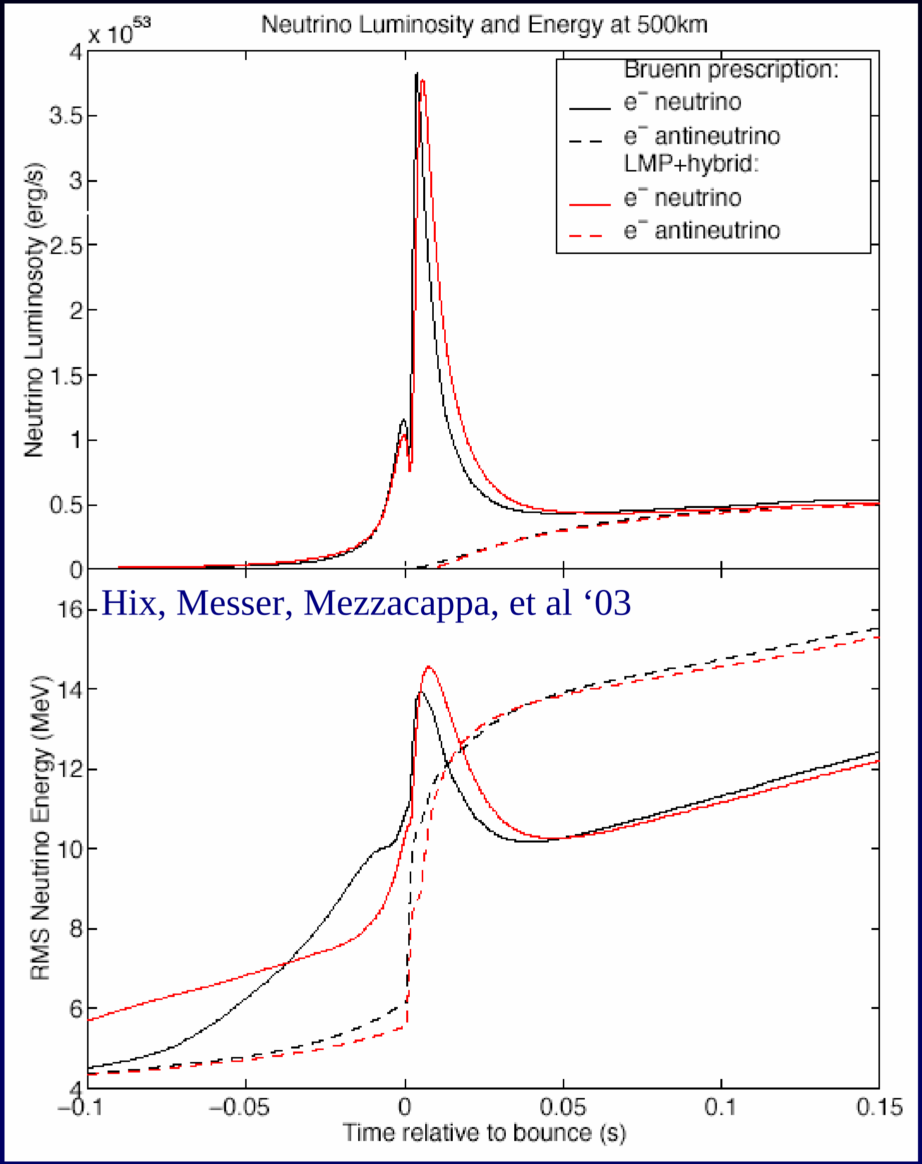
Other luminosities minimally affected (~1%).

Mean ν Energy altered:

  1-2 MeV during collapse

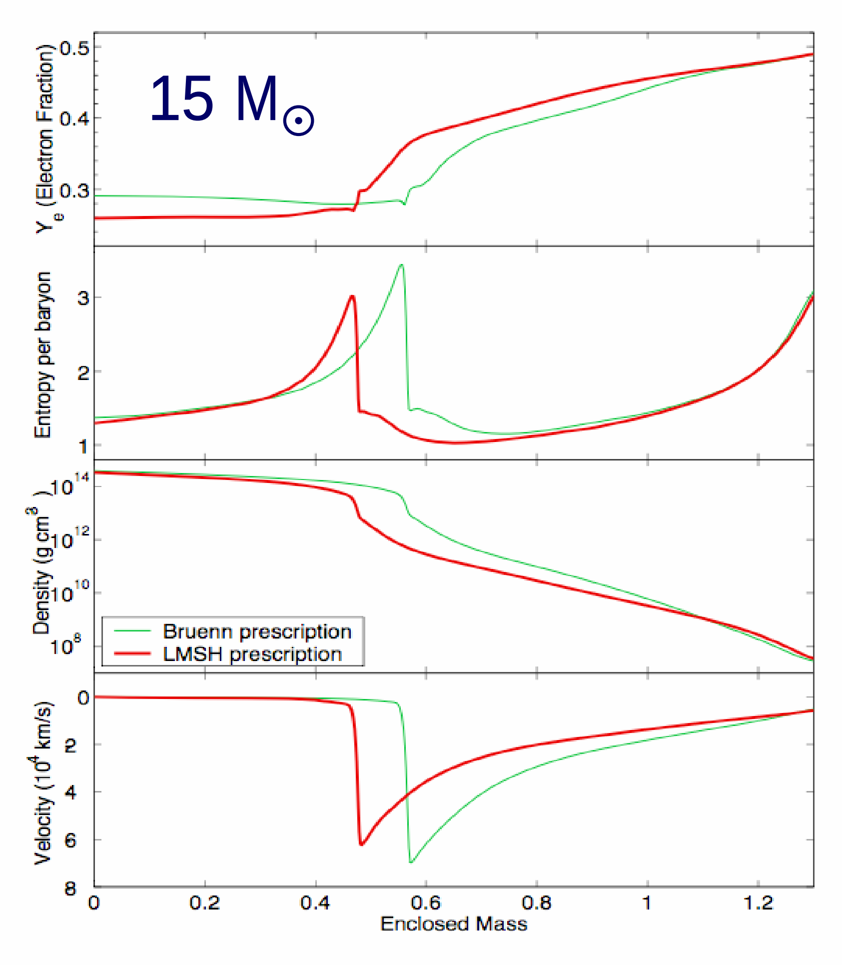
  ~1 MeV up to 50ms after bounce

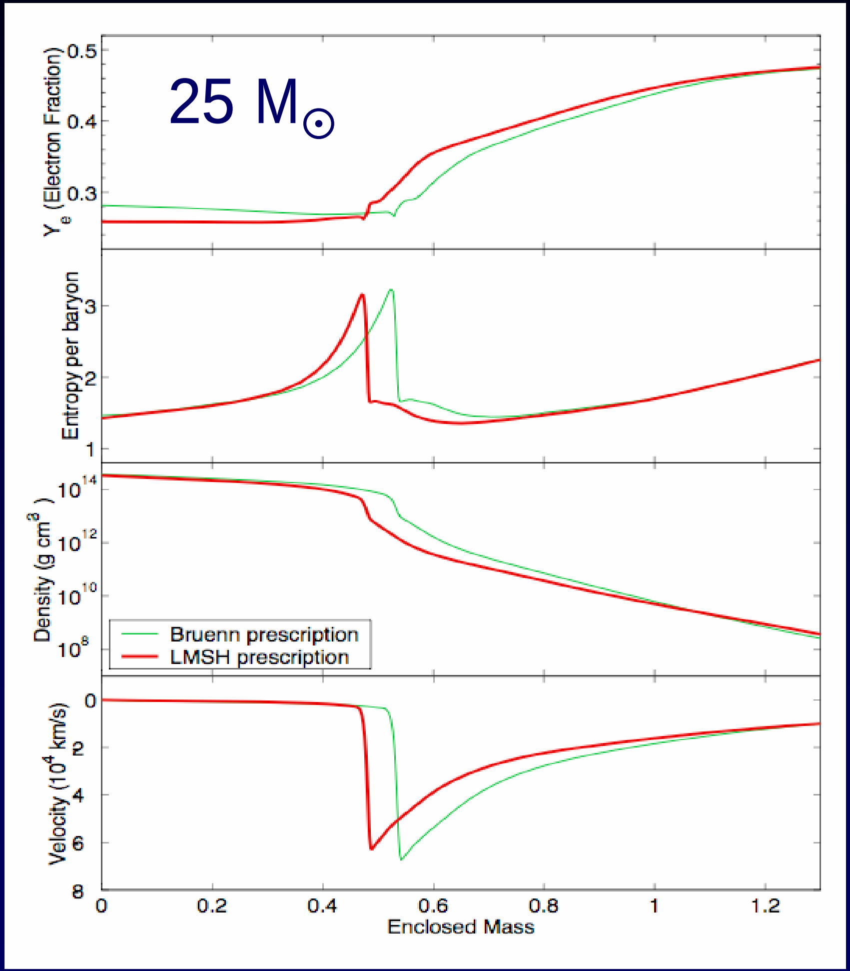
  ~.3 MeV at late time



Hix, Messer, Mezzacappa, et al ‘03

The impact of stellar mass





Higher mass cores have higher initial entropy.

Effects of nuclear electron capture are reduced but comparable (1/2 to 2/3).

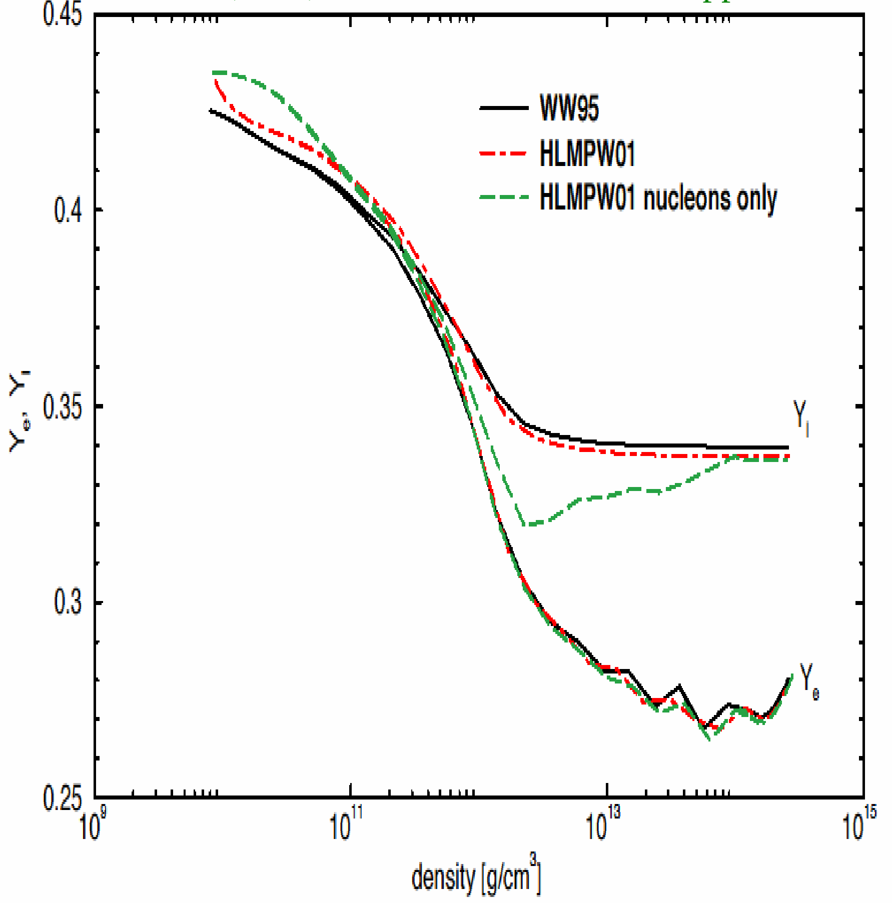
Electron Capture Feedback

Continued e^-/ν capture on nuclei not only changes the amount of capture but also breaks a feedback loop.

When e^- capture on protons dominates, there is a strong self regulation because Y_p (and therefore dY_e/dt) is a strong function of Y_e. This washes out differences in Y_e.

Example:

e^- capture on protons during collapse erases differences between progenitors with improved e^- capture rates.

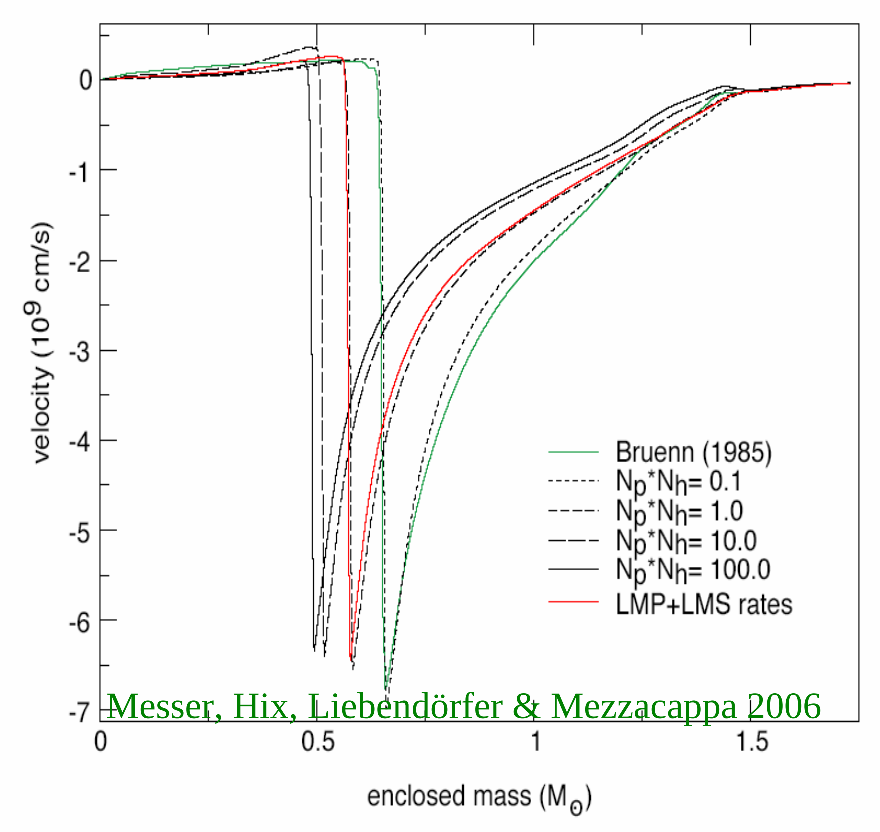

Messer, Hix, Liebendörfer & Mezzacappa 2006

Testing the Sensitivity

Used Bruenn (1985) as a reproducible starting point.

Replaced quenching term with parameter $(N_p N_h)$ = 0.1-100

Changes from current electron capture rate of a factor of 10 move shock formation by ~0.1 solar mass.



Messer, Hix, Liebendörfer & Mezzacappa 2006

$$j_{nuclear} = \frac{2}{7}\frac{(2\pi)^4 G_F^2}{\pi h^4 c^4} g_A^2 \frac{\rho X_H}{m_B A} N_p(Z) N_h(N) (E+Q')^2 \left[1-\left(\frac{M_e}{E+Q'}\right)^2\right]^{1/2} F_e(E+Q'), \quad (1)$$

where

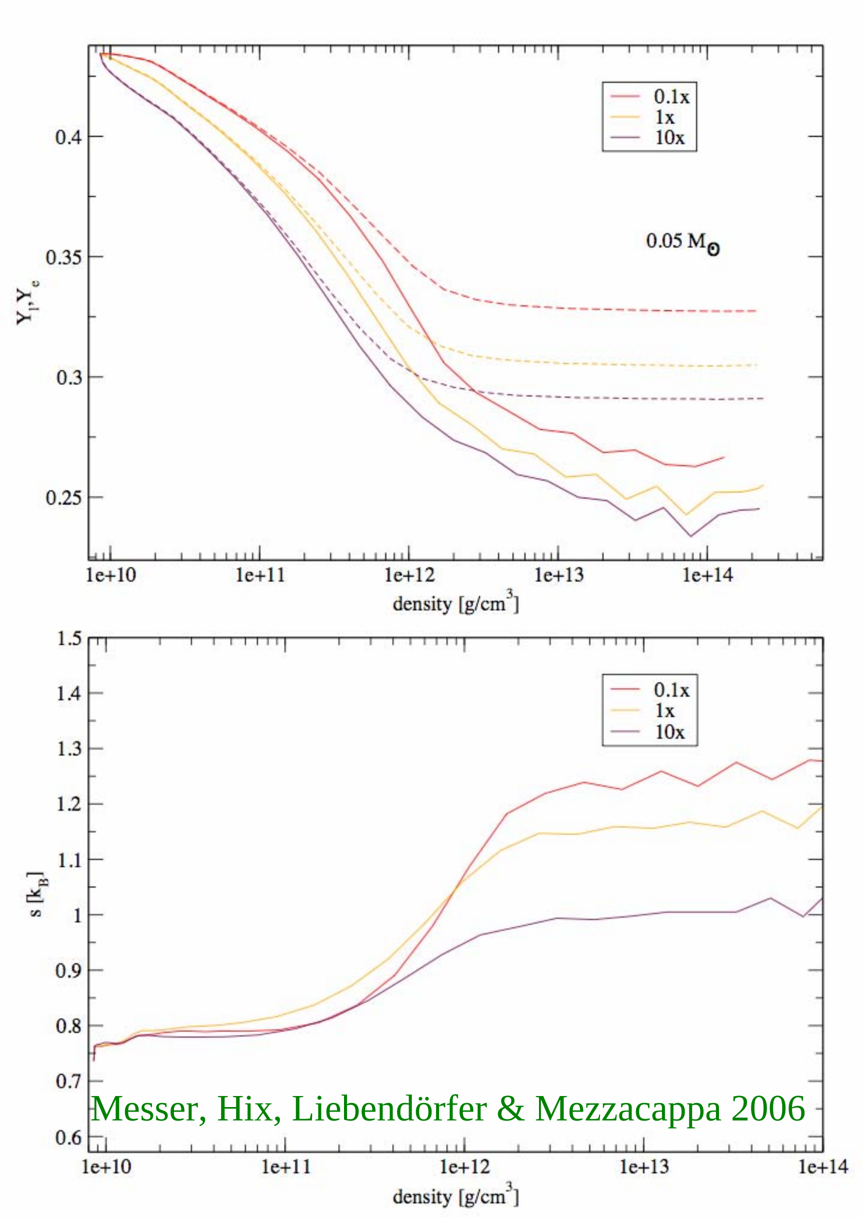
$$N_p(Z) = \begin{cases} 0 & Z < 20 \\ Z-20 & 20 < Z < 28 \\ 8 & Z > 28 \end{cases} \quad \text{and} \quad N_h(N) = \begin{cases} 6 & N < 34 \\ 40-N & 34 < N < 40 \\ 0 & N > 40\,. \end{cases} \quad (2)$$

Determining Y_e and Entropy

Change in lepton abundance ($Y_l=Y_e+Y_\nu$) occurs gradually over 2+ decades of density up to ~3×10^{12} g/cm^3.

Change in Y_e after equilibration is due to thermodynamic changes altering emission/absorption balance.

Entropy is flat until appreciable Y_ν is achieved allowing significant neutrino capture and heating then flattens after equilibration.



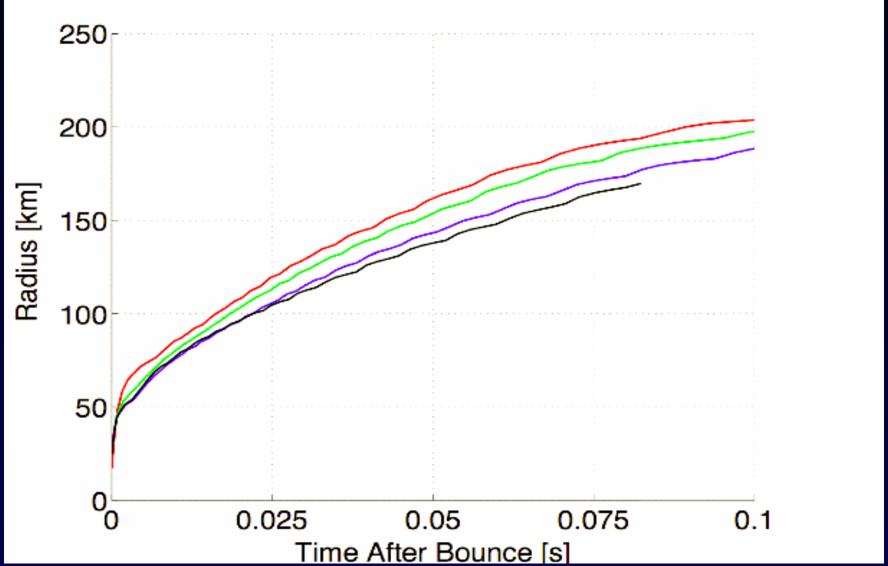
Messer, Hix, Liebendörfer & Mezzacappa 2006

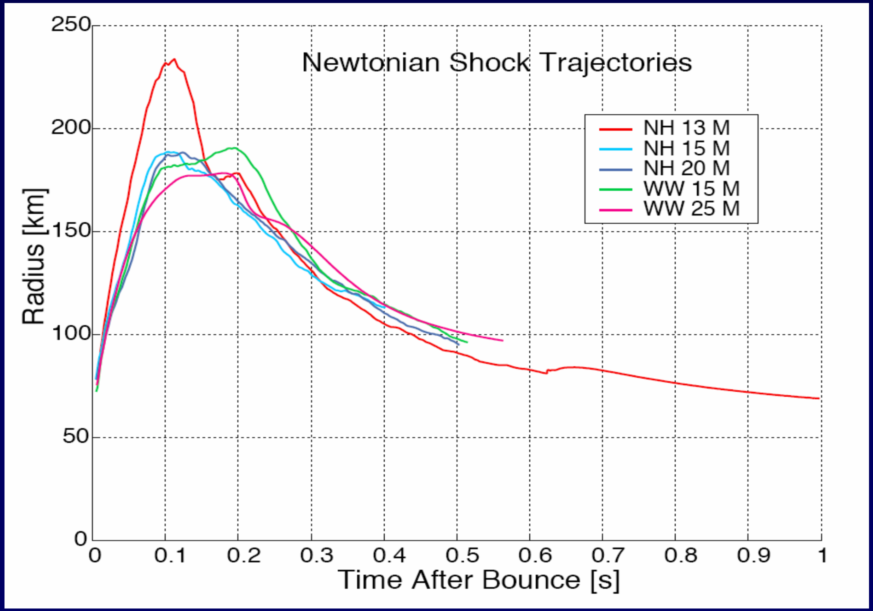
Explosive Effects

Effects of electron capture on core collapse are clear.

However, collapse and explosion are separated by a “pause”.

Thus the long term impact on the supernova explosion is an open question.



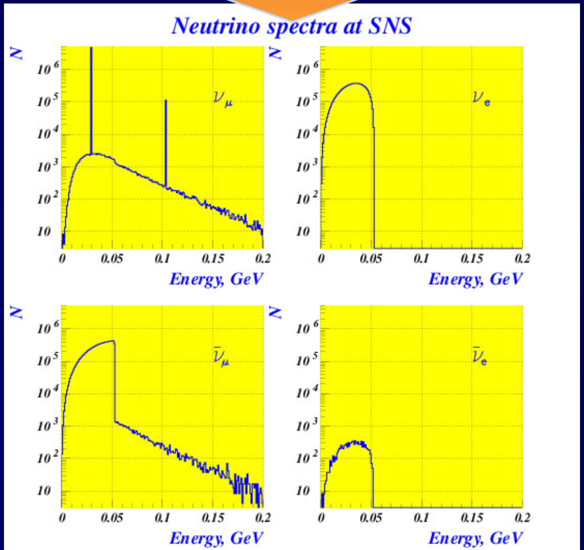


However effects on shock propagations bridge at least part of the “pause” and are significant.

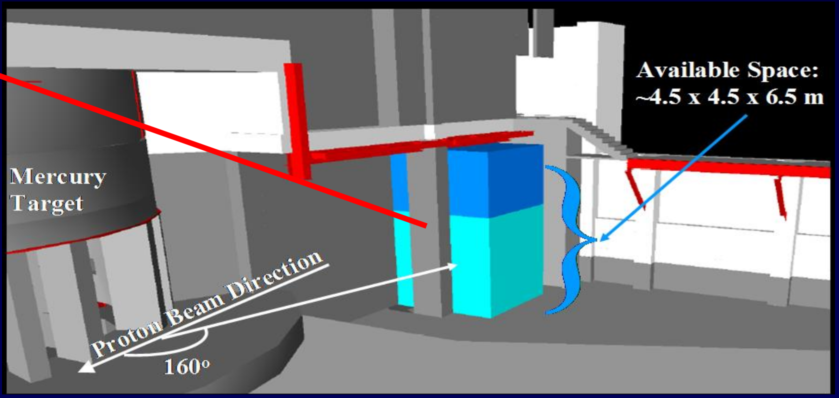
Theory is nice, but … experimental verification is needed

Spallation Neutron Source

~10^{15} ν sec^{-1}


Neutrino spectra at SNS

ν-SNS an experimental program to study neutrino cross sections in the region of interest for astrophysics



2 universal ~ 20 tones detectors located 20 meters from the SNS target

Segmented detector for solid targets

^{51}V, ^{27}Al, ^{9}Be, ^{11}B, ^{52}Cr, ^{56}Fe, ^{59}Co, ^{209}Bi, ^{181}Ta

Homogeneous detector for **Liquid targets**

^{2}d, ^{12}C, ^{16}O, ^{127}I

Summary

Recent advances in nuclear structure theory have changed our understanding of electron capture at finite temperature in heavy nuclei.

Modern treatment of nuclear electron capture significantly changes during core collapse and probably supernova evolution.

Better structure theory and experiment are needed to test the rates we've used.

Full understanding of the impact of nuclear electron capture (and all other physics) awaits exploding multi-dimensional models with accurate neutrino transport.