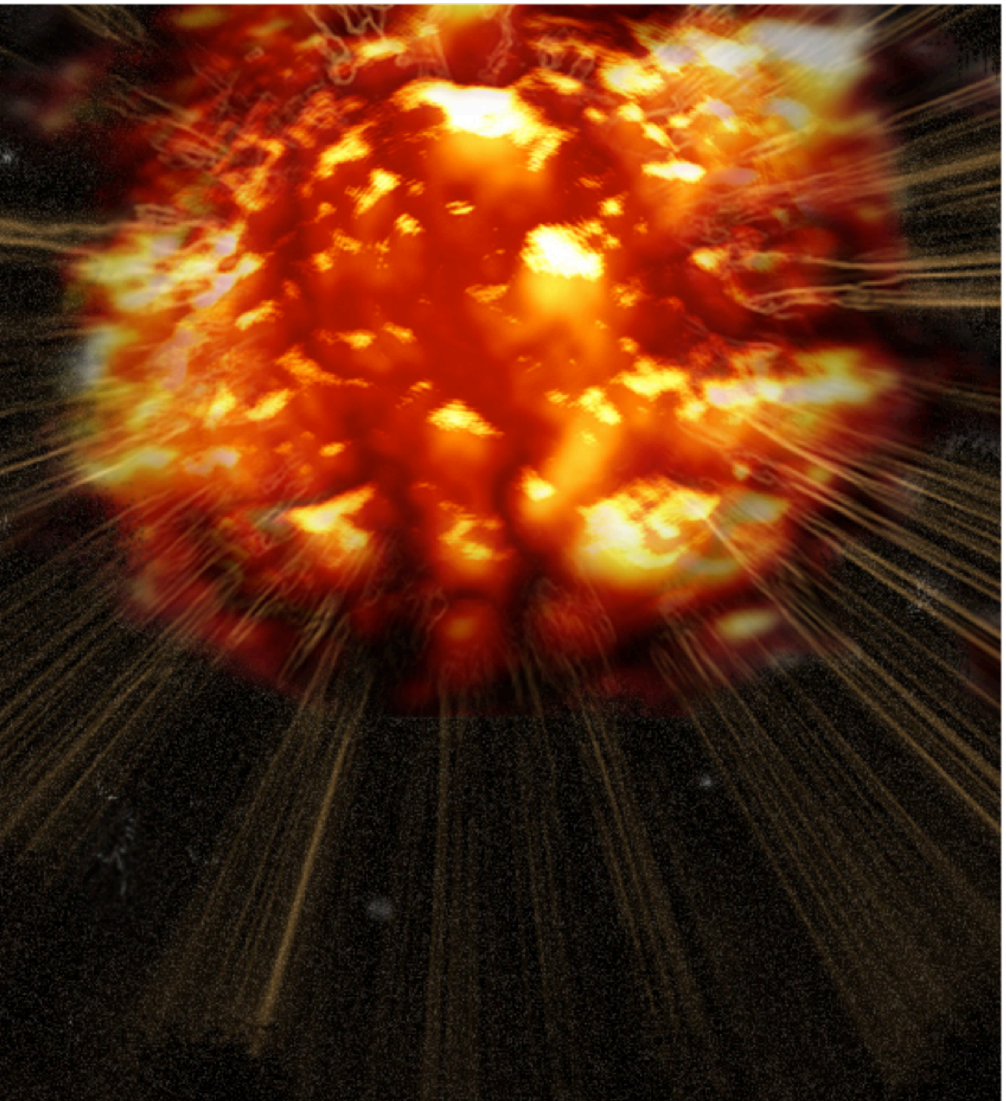
# Black Hole Formation in Failing CCSN



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with Christian Ott

# Outline

Many input parameters influence black hole formation properties in CCSN, but some properties seem universal.

- Supernovae
  - The Black Hole Connection
  - Motivation & Justification
- Simulation Details
  - GR, Hydrodynamics
- Results
  - Black Hole Formation

# Core-Collapse Supernovae

- One of the brightest astrophysical phenomena in the universe, collapse of the electron degenerate iron core of a massive star liberates ~$10^{53}$ ergs, 99% in neutrinos.

- Remaining energy goes into explosion of star: this mechanism is not fully understood – neutrinos, multi-D, …

- There is theoretical evidence (and astrophysical implications) that more massive stars (a) do not explode in a supernova, or (b) explode but very weakly. *Fryer & Kalogera (2001)*, *Heger et al. (2003)* among others.

AAO, SN1987A

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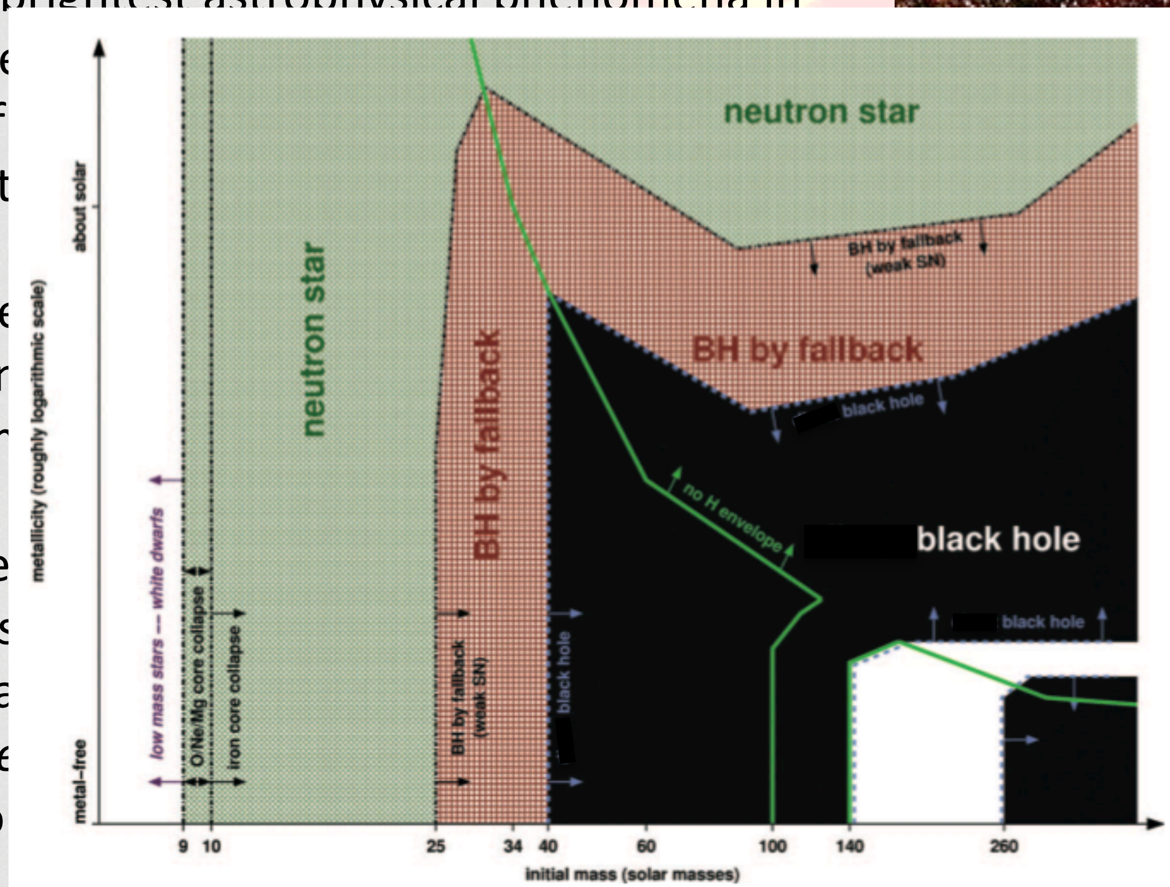
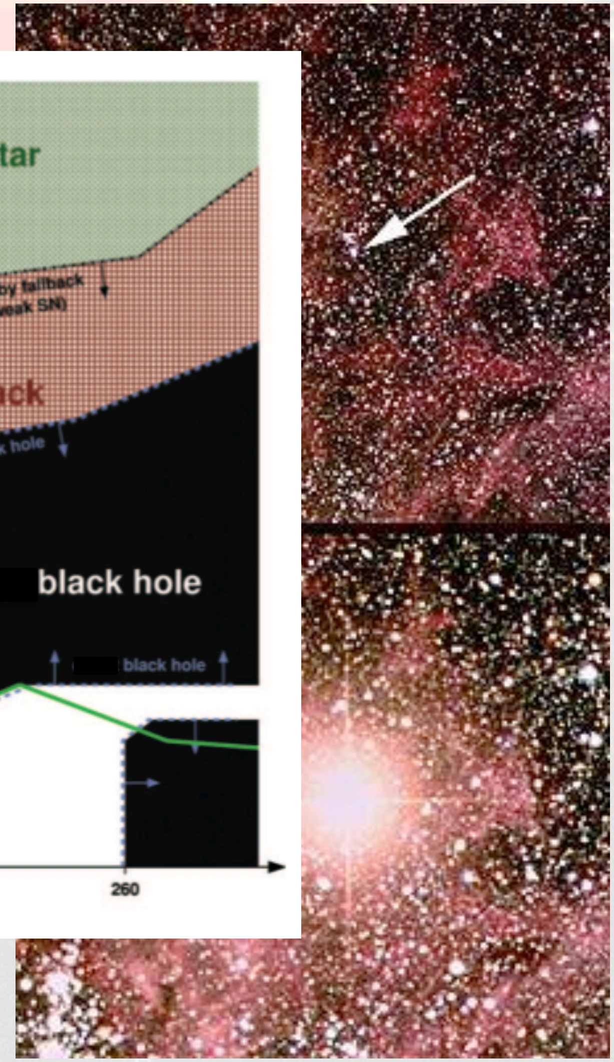


AAO, SN1987A

# Justification for 1D

- Multiple dimensions give rise to rich physics, all of which are crucial in understanding stellar collapse, supernovae and black hole formation.

- But multi-D simulations are computationally expensive. The 1D simulations presented take ~1-2 days (on 1 core): 3D simulations would take months (on multiple cores).

- Want to systematically explore all available models & parameters which will lead to limiting and interesting cases in black hole formation, give insight into future multi-D black hole formation simulations while also allowing for easy testing of new technologies such as EOSs & neutrino leakage/heating/transport.

# 1D GR Hydrodynamic Code

- We adopt the GR-Hydro formalism of *Romero et al. 1996*: Radial Gauge, Polar Slicing (RGPS), where the shift vector is taken as $\beta^i = 0$, and metric is given below:

$$\left\| g_{\mu\nu} \right\| = \begin{bmatrix} -\alpha^2 & & & \\ & X^2 & & \\ & & r^2 & \\ & & & r^2 \sin^2(\theta) \end{bmatrix}$$

$$X = \left(1 - \frac{2m(r)}{r}\right)^{-1/2}$$

$$\alpha = \exp(\phi)$$

- Using the stress-energy tensor for a relativistic perfect fluid,

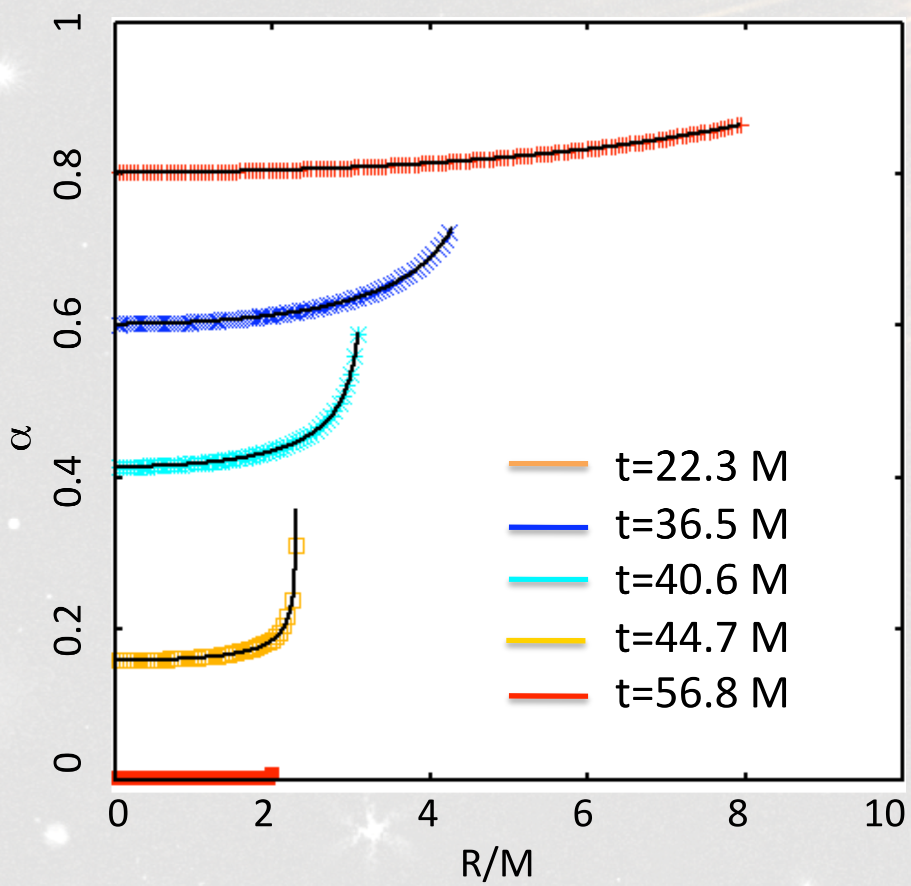
$$T^{\mu\nu} = \rho h u^\mu u^\nu + g^{\mu\nu} P$$

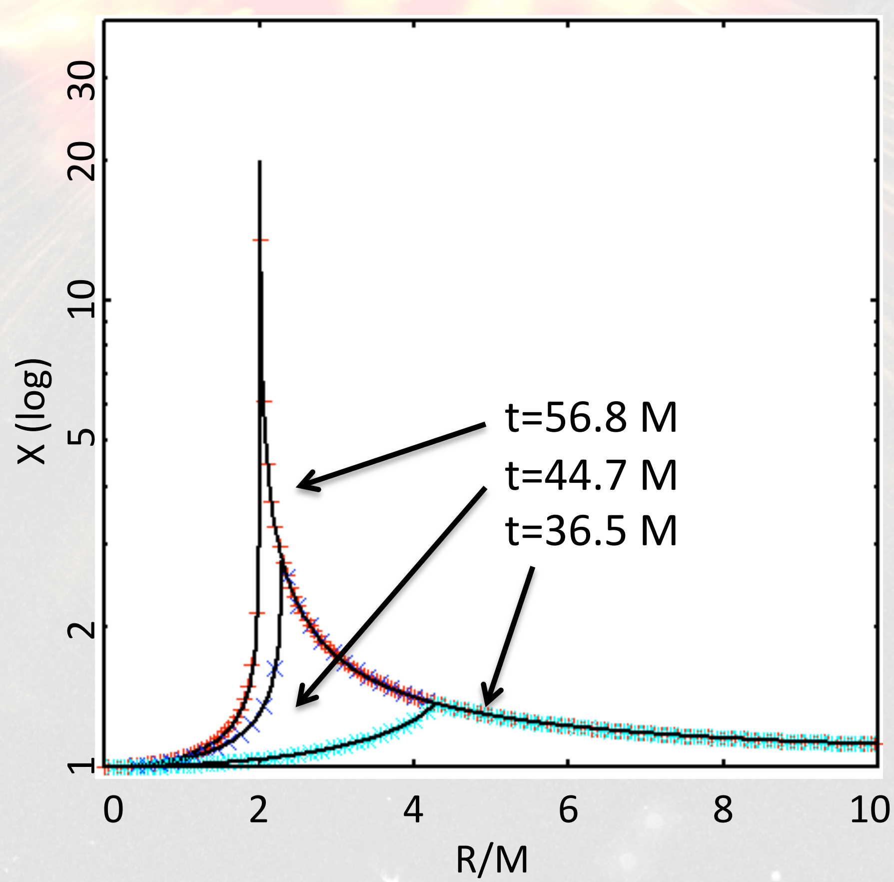
- Einstein's equations then give equations for metric in terms of fluid variables
  - Eulerian hydrodynamics, 2nd order RK, PPM reconstruction & HLLE flux solver to evolve fluid variables (D, $S_r$, $\tau$)

$$\frac{\partial \vec{u}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\frac{r^2\alpha}{X}\vec{f}(\vec{u})\right] = \vec{s}(\vec{u})$$

# Oppenheimer-Snyder Collapse

OSC is the gravitational collapse of a spherical dust ball (P=0). It is one of the only analytic solutions available in GRHydro



# CCSNe Physics

- Implemented physics:
  - Finite temperature EOSs (Shen, LS)
  - Neutrino leakage, *Ruffert et al. (1996)*.

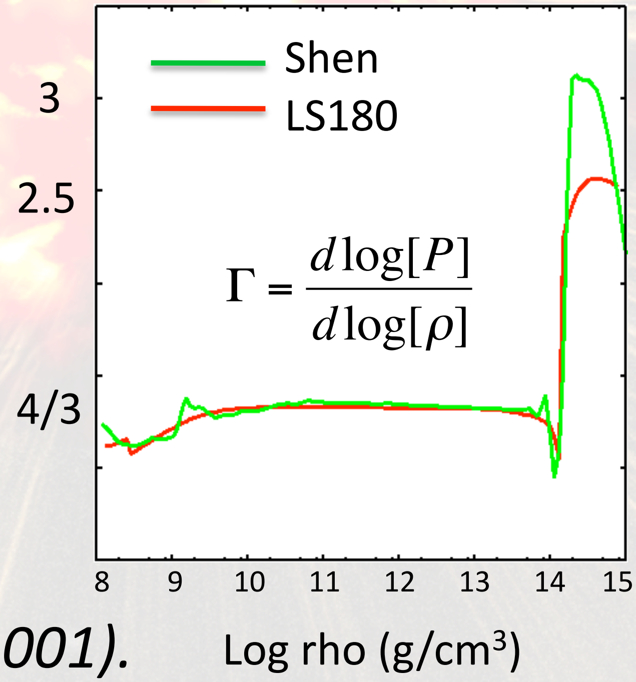
$$\nu + N \rightarrow \nu + N \qquad e^+ e^- \rightarrow \nu\bar{\nu}$$

$$\bar{\nu}_e + p \leftrightarrow n + e^+ \qquad \nu_e + n \leftrightarrow p + e^-$$

  - Neutrino heating scheme, based *Janka (2001).*

$$Q^+_{\nu_e/\bar{\nu}_e} \propto X_{n/p} \left\langle \varepsilon_\nu^2 \right\rangle \frac{L_{\nu_e/\bar{\nu}_e}}{4\pi r^2} \left\langle \frac{1}{F} \right\rangle$$

  - Pre-supernova models from various groups



# CCSNe Physics

- Implem
  - Finit
  - Neut

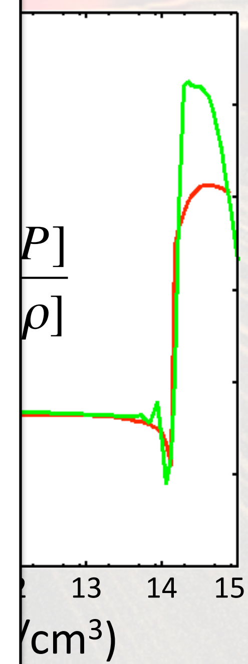
$\nu +$

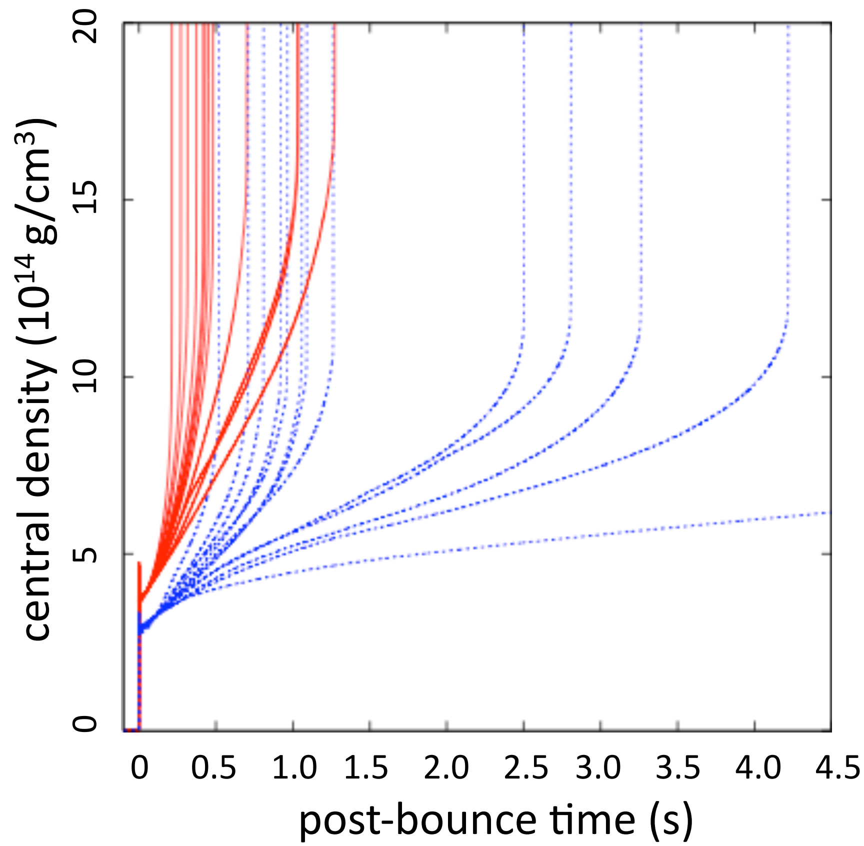
$\bar{\nu}_e$ -

  - Neut

$Q^+_{\nu_e}$

  - Pre-s

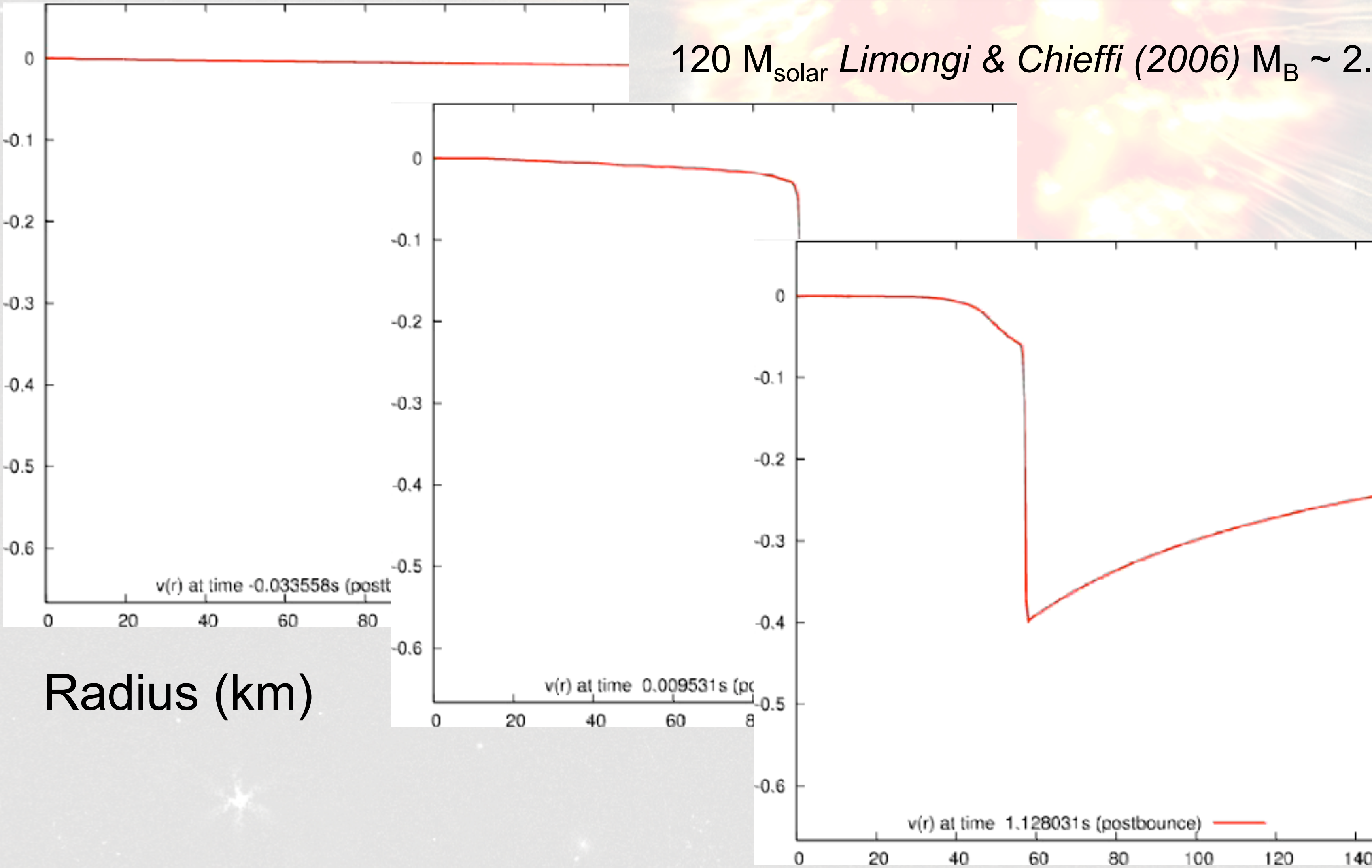


# Black Hole Formation

120 $M_{solar}$ *Limongi & Chieffi (2006)* $M_B$ ~ 2.5

Radial Velocity (1/c)




Radius (km)

# EOS Comparison

- Stellar Model: Woosley & Weaver (1995) 40 $M_{solar}$, $Z_{solar}$,

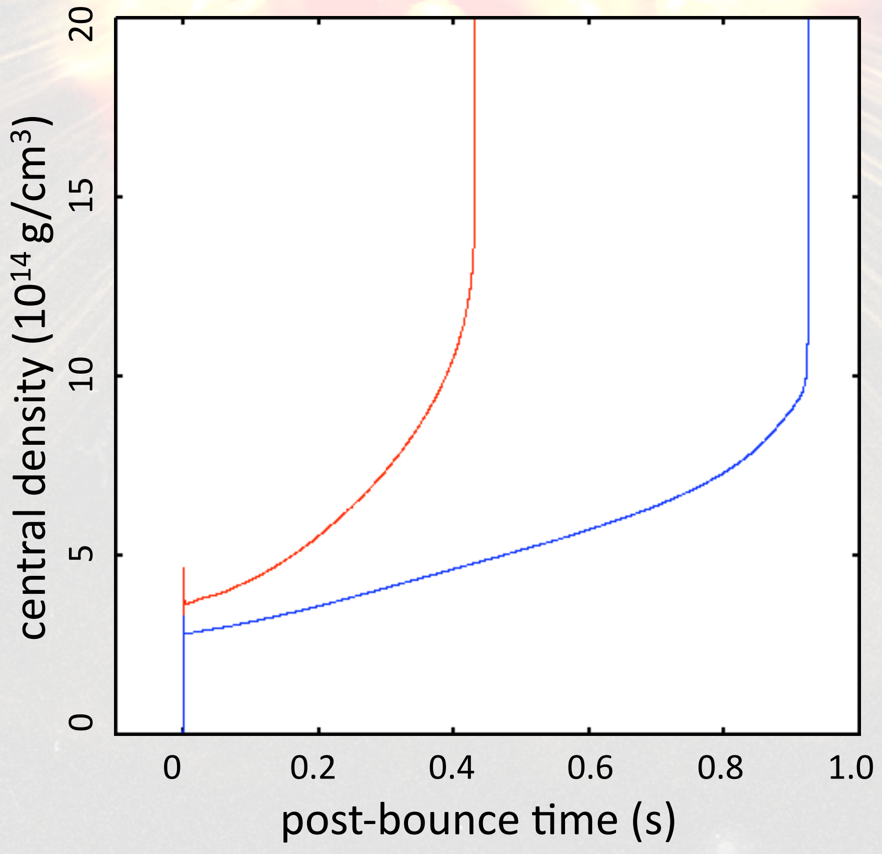
LS (K=180 MeV)
Shen

- $t_{BH,LS}$ = 430ms
- $t_{BH,Shen}$ = 923ms

- Previous Studies

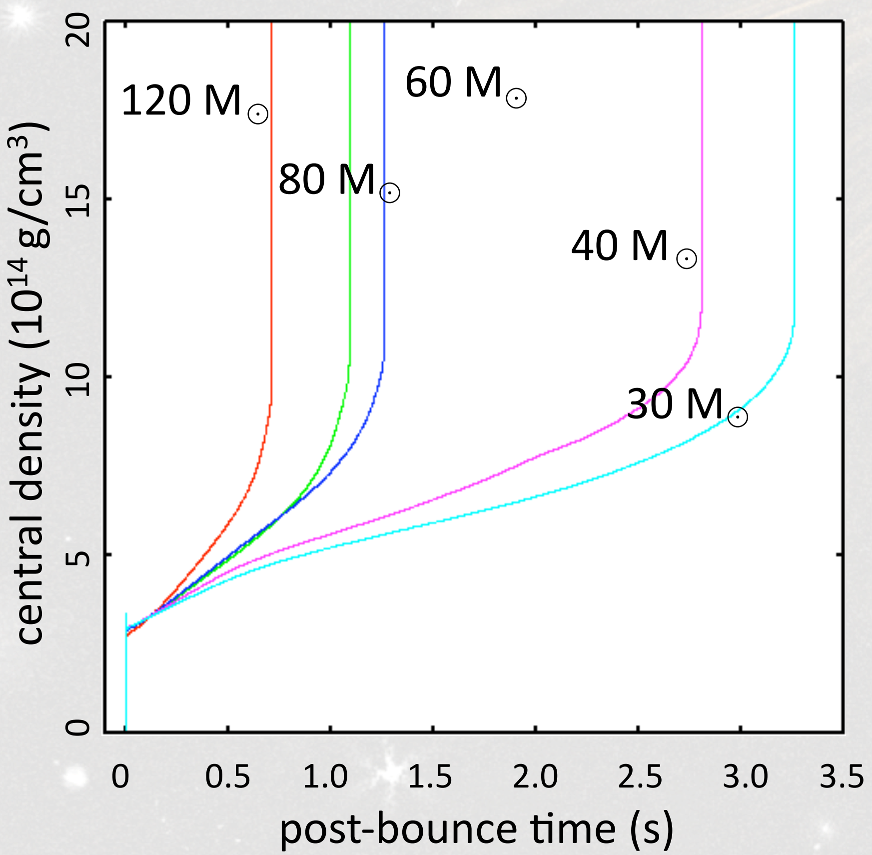
  Fischer et al. (2009) 436ms,~1400ms

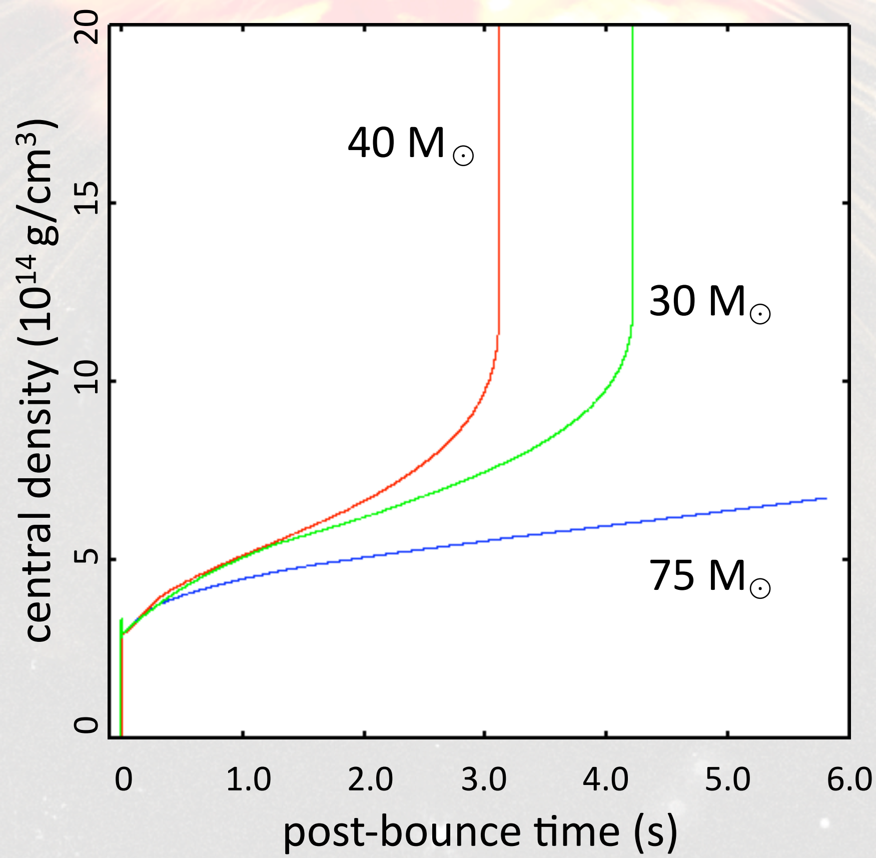
  Sumiyoshi et al. (2007) 560 ms, 1340ms



# Stellar Evolution

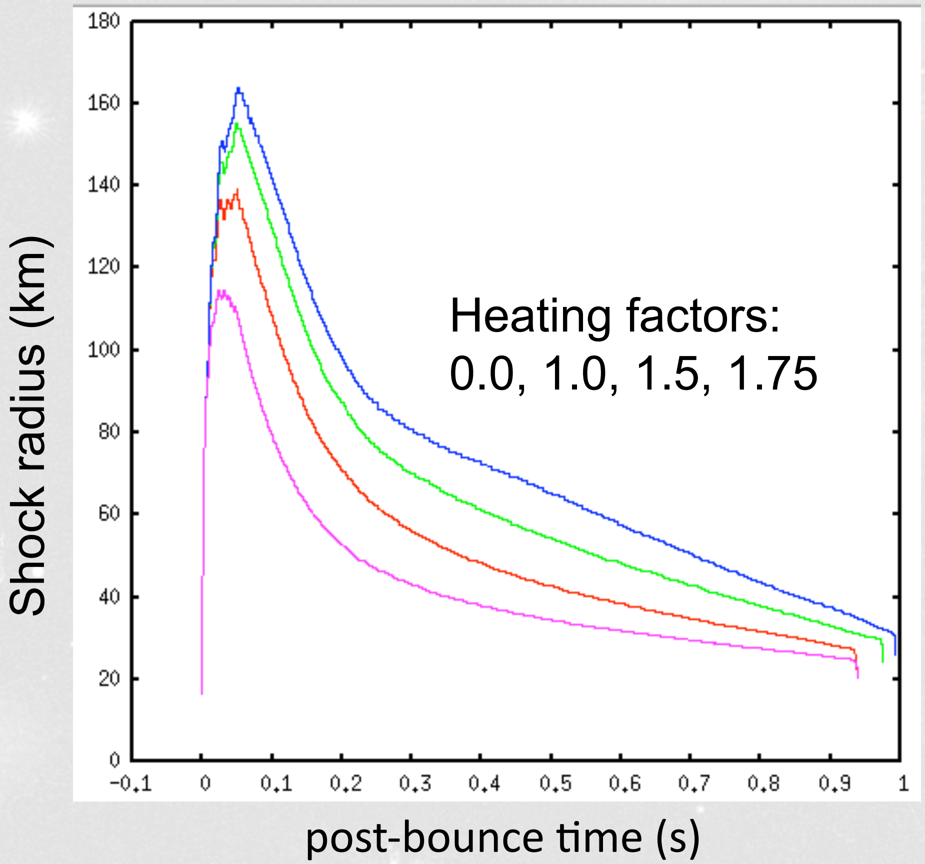
- 5 Models from Limongi & Chieffi (2006) & 3 from Woosley, Heger & Weaver(2002):
  - Masses 30 $M_\odot$ – 120 $M_\odot$ - Solar metallicity -Shen EOS - mass loss

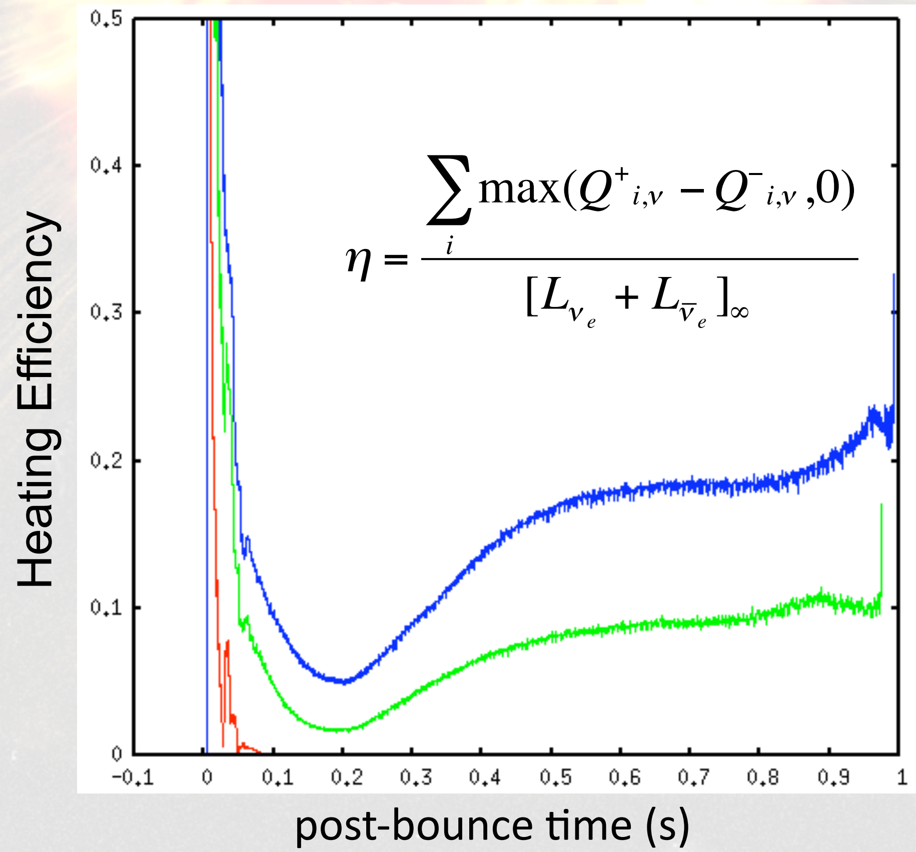


# Neutrino Heating

- Stellar Model: *Woosley & Weaver (1995)* $40M_{solar}$, $Z_{solar}$, Shen EOS



# Summary

- By simulating in 1D, we can systematically study the effect of progenitor mass, metallicity, and theoretical unknowns such as EOS, neutrino physics, stellar evolution.

- We find:
  - There is no direct black hole formation, a PNS always forms at bounce and a black hole may form on an accretion timescale.
  - The nuclear EOS determines universal properties of failing CCSNe. Softer EOSs collapse to BHs earlier.
  - Presupernova stellar structure strongly affects the post-bounce evolution of collapsing stars. Current stellar evolutionary calculations by different groups do not yet produce consistent precollapse models.