Microphysical aspects of Core-Collapse Supernovae

EOC & Ott ApJ 730 70 (2011)
Dasgupta et al. (2011) arXiv:1106:1167

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INT –August 4 2011

Outline

Part 1:

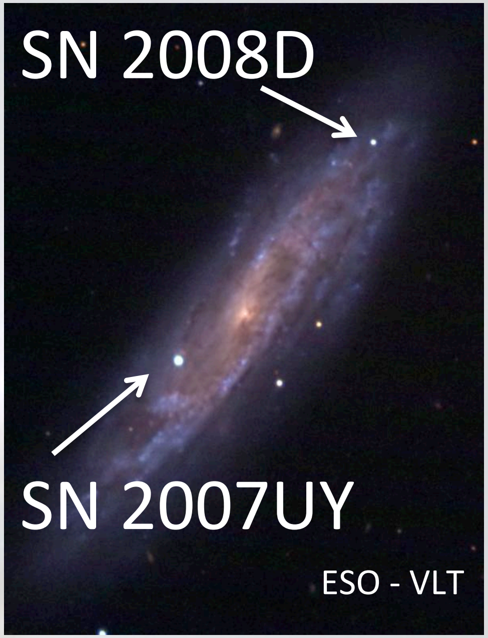
- Supernovae: Core-Collapse Supernovae: Failed Supernovae
- Failed Supernova results (**EOC** & Ott, ApJ, 670 70 (2011))
    - Connection to EOS
    - Prediction of what stars make black holes

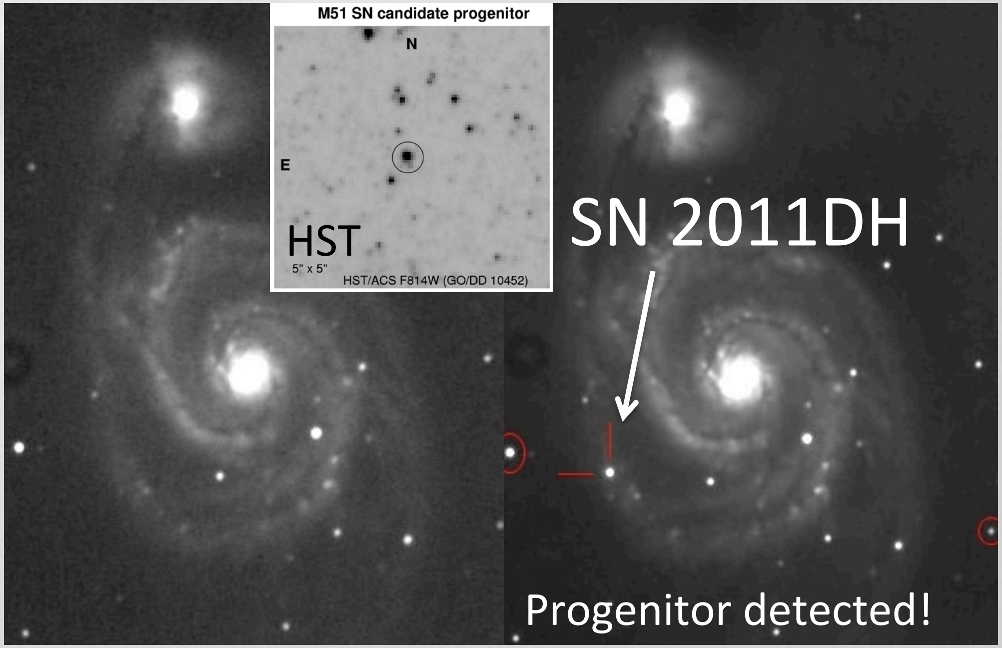
Part 2:

- Role of Collective Neutrino Oscillations on Core-Collapse Supernova Mechanism (Dasgupta, B., **EOC**, Ott, C.D., arXiv:1106.1167)

Supernovae

- Cosmic explosion marking the end of a star’s life.
- Type Ia:
  - thermonuclear explosion of white-dwarf like object
  - `standard’, wide use in cosmology as distance measures
- Type Ib, Ic, II:
  - results from the core collapse of the iron core in a massive star
  - $M_{ZAMS} > 8\text{-}10\ M_{sun}$

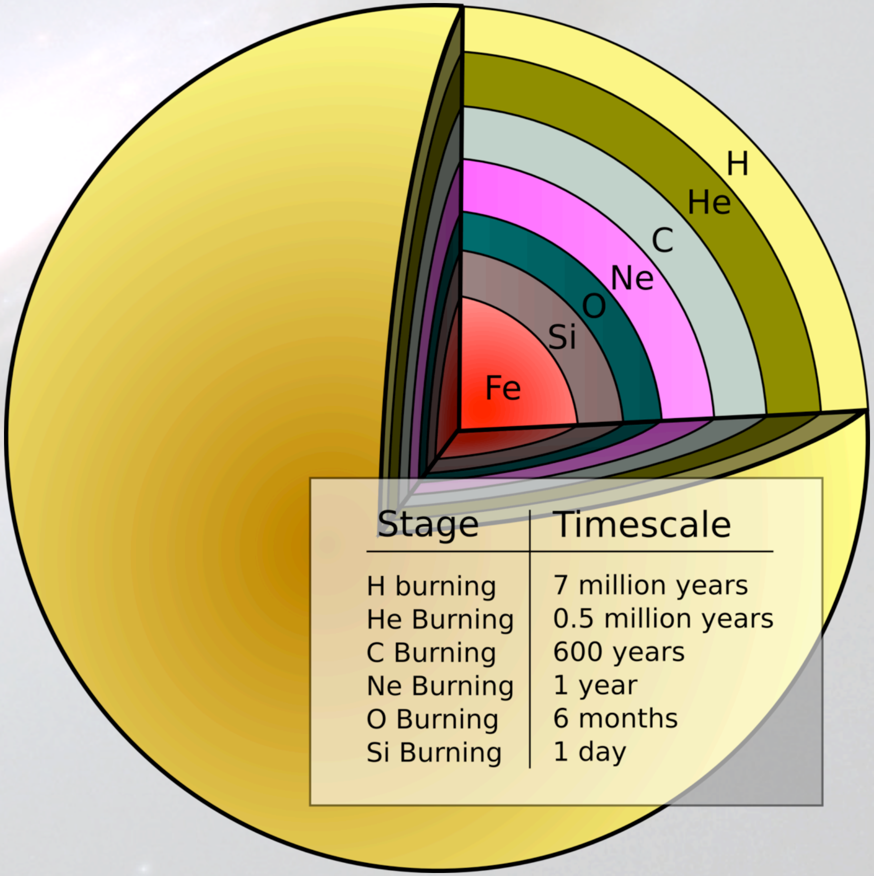




Stephane Lamotte & Marc Deldem June 2 2011

Stellar Collapse: Building the Core

- Stars spend most of their lives burning hydrogen.
- The product – Helium – settles in the core and will burn when temperatures increase sufficiently.
- For massive stars (M > 8-10M_{sun}), the process continues through Carbon, Oxygen, … , up to Iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron core builds up in center of star.



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

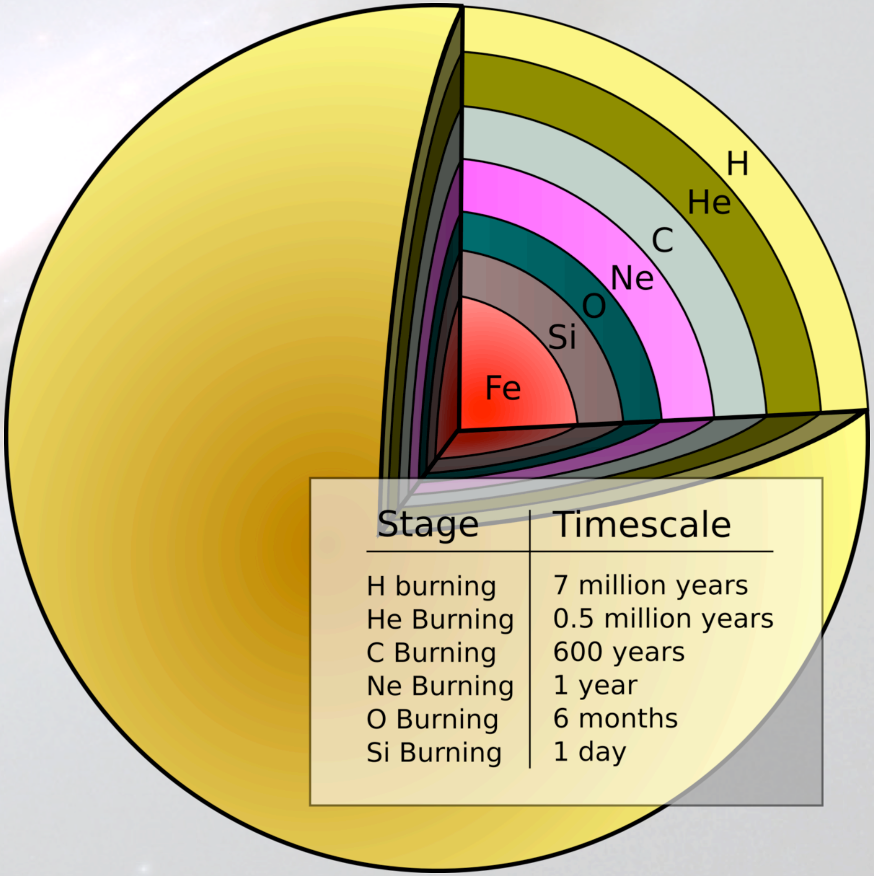
A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).

Stellar Collapse: Stability of the Core

- Stars are, for the majority of the time, in hydrostatic equilibrium because the radiation pressure of the photons from nuclear reactions balance gravity.
- Iron cores however are supported by electron degeneracy pressure, much like a white dwarf, there is a maximum mass that electron degeneracy pressure can support.

$$M_{\max}^{T=0} = 5.83 M_{sun}\, Y_e^2 \xrightarrow{^{56}Fe} 1.26 M_{sun}$$

$$M_{\max} = M_{\max}^{T=0}\left[1+\left(\frac{\pi T}{\varepsilon_F}\right)^2\right]$$



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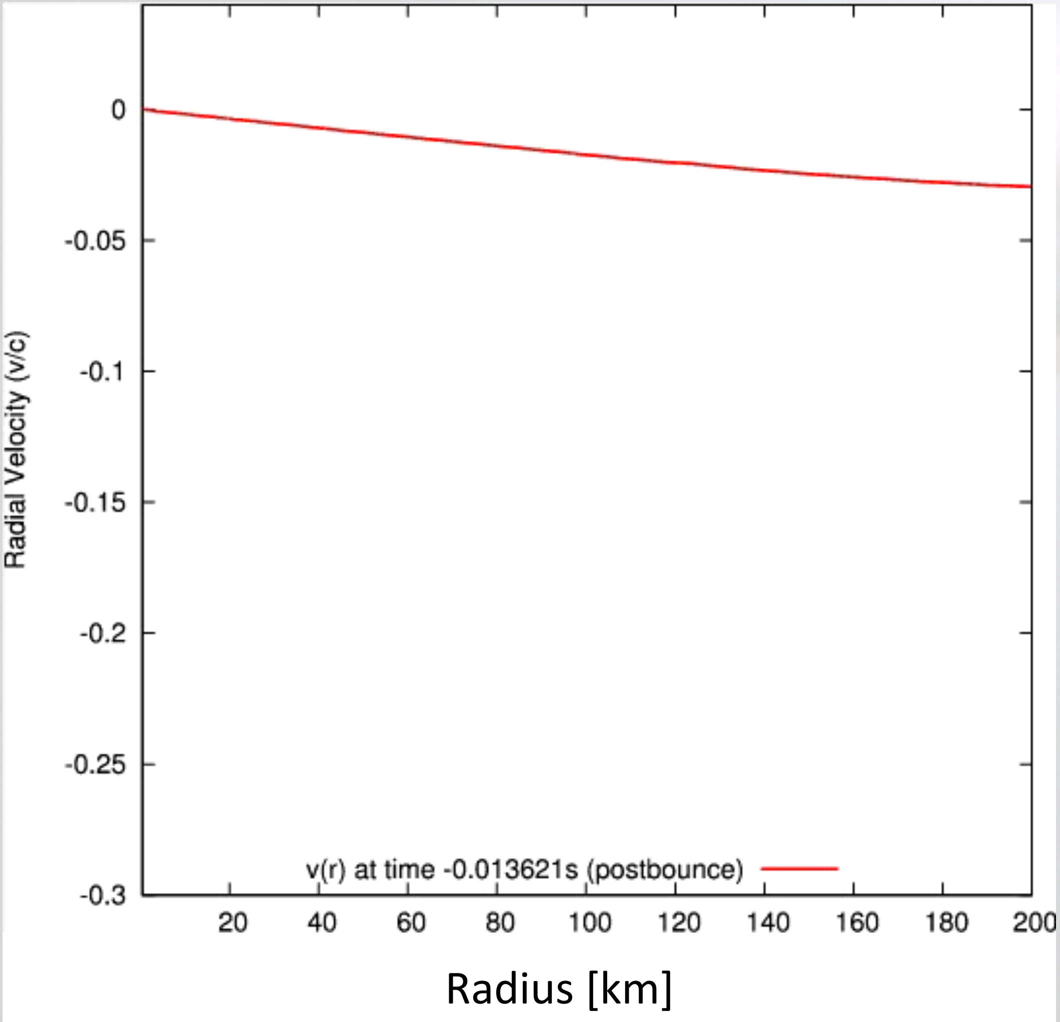
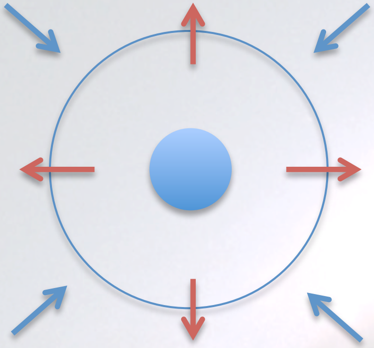
Stellar Collapse: Collapse of the Core



- Iron core begins to collapse and divides into:
  - homologously collapsing inner core ($V \alpha r$)
  - supersonically infalling outer core
- Collapse continues until nuclear matter interactions balance gravity, when densities approach $\rho_{nuc} \sim 2x10^{14}$ g/cm^3
- Supersonically infalling material must come to rest on the surface of the PNS via a shock. Kinetic energy of inner core propels shock to large distances, initially, 100-150km

Supernovae & Stellar Mass Black Holes



Shock fails to be reenergized
Black hole forms ~seconds

Part 1

No rotation, all
material ends up
in black hole

Collapsar Type I:
high rotation,
may leads to GRB

Part 1 & 2

Shock is reenergized by a as-of-yet uncertain
mechanism, explodes in supernova

Fallback may lead
to black hole

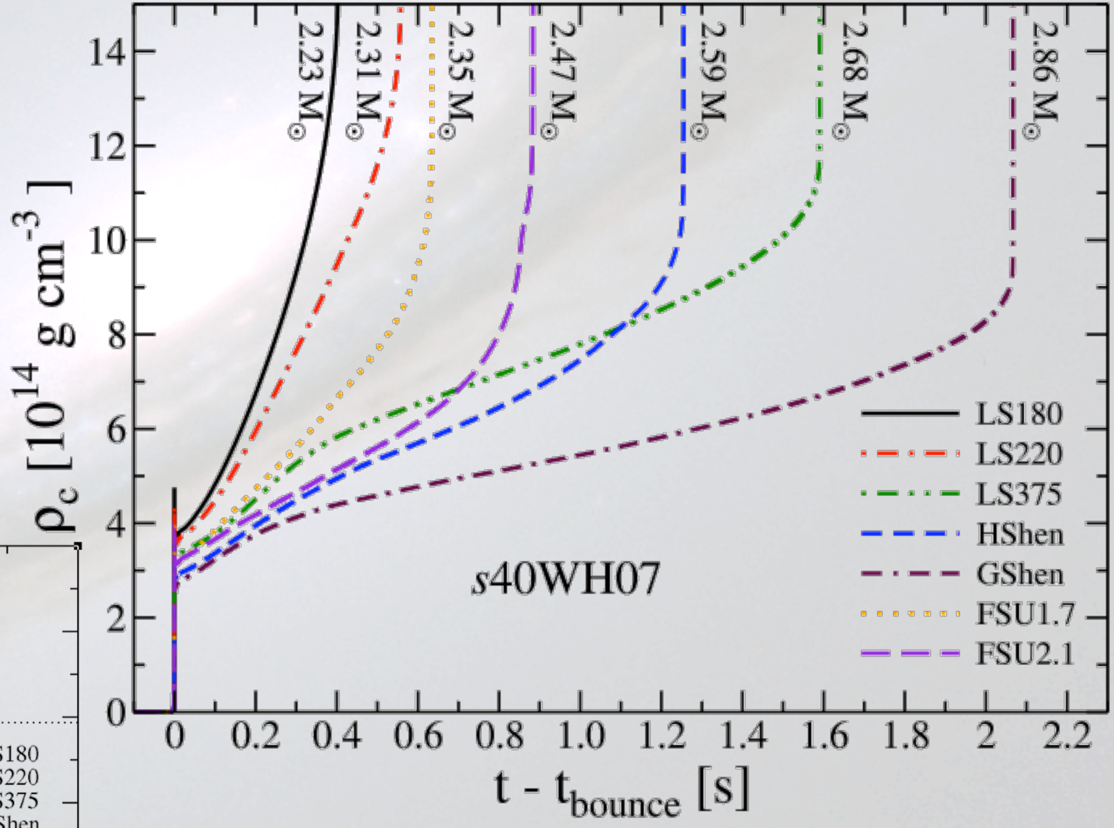
If sufficient rotation, Collapsar
Type II: may lead to GRB

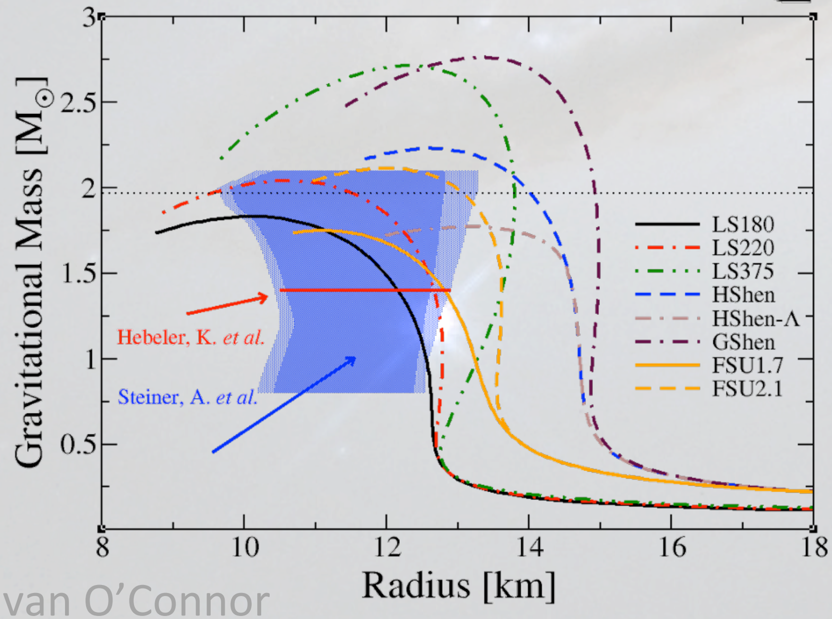
Most common
channel with neutron
star remnant

Black Hole formation dependence on EOS

- EOS stiffness at both low and high densities plays a role in black hole formation
- Hot PNS adds thermal support

Central Density

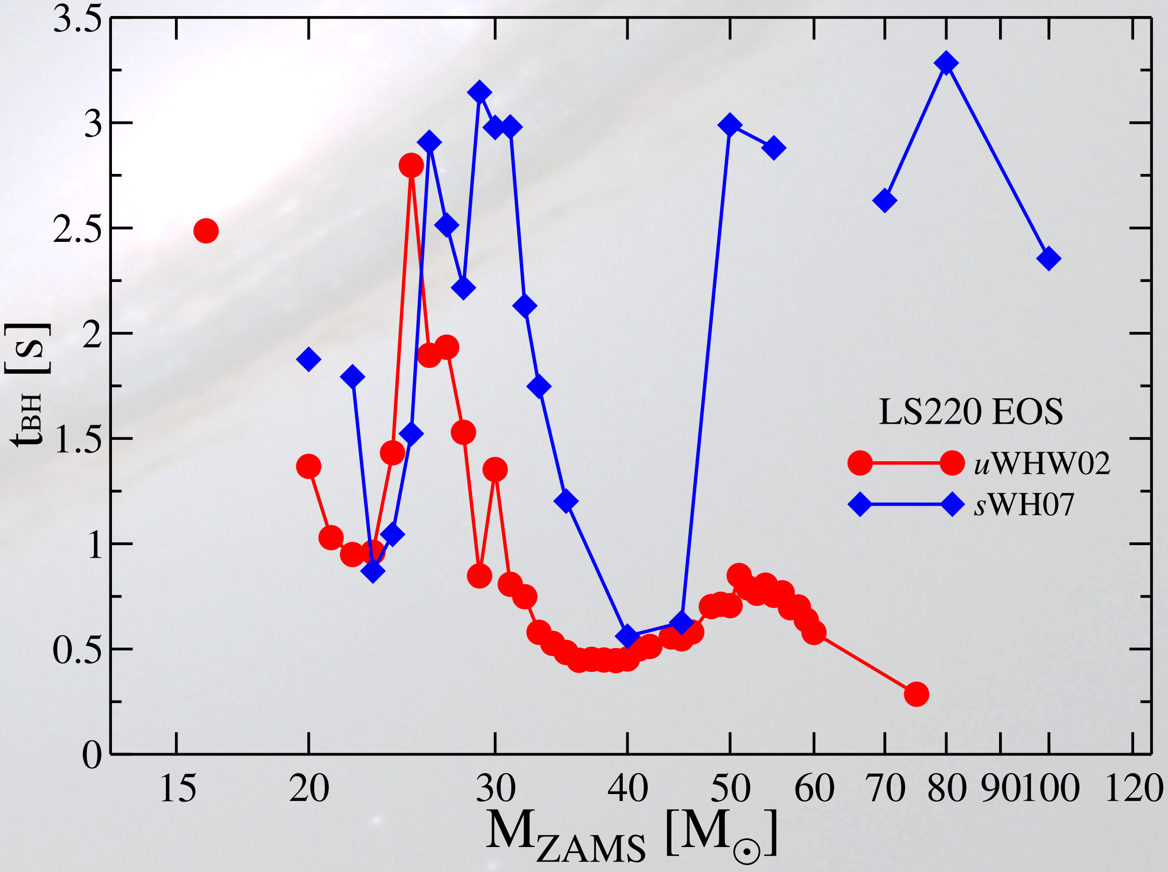




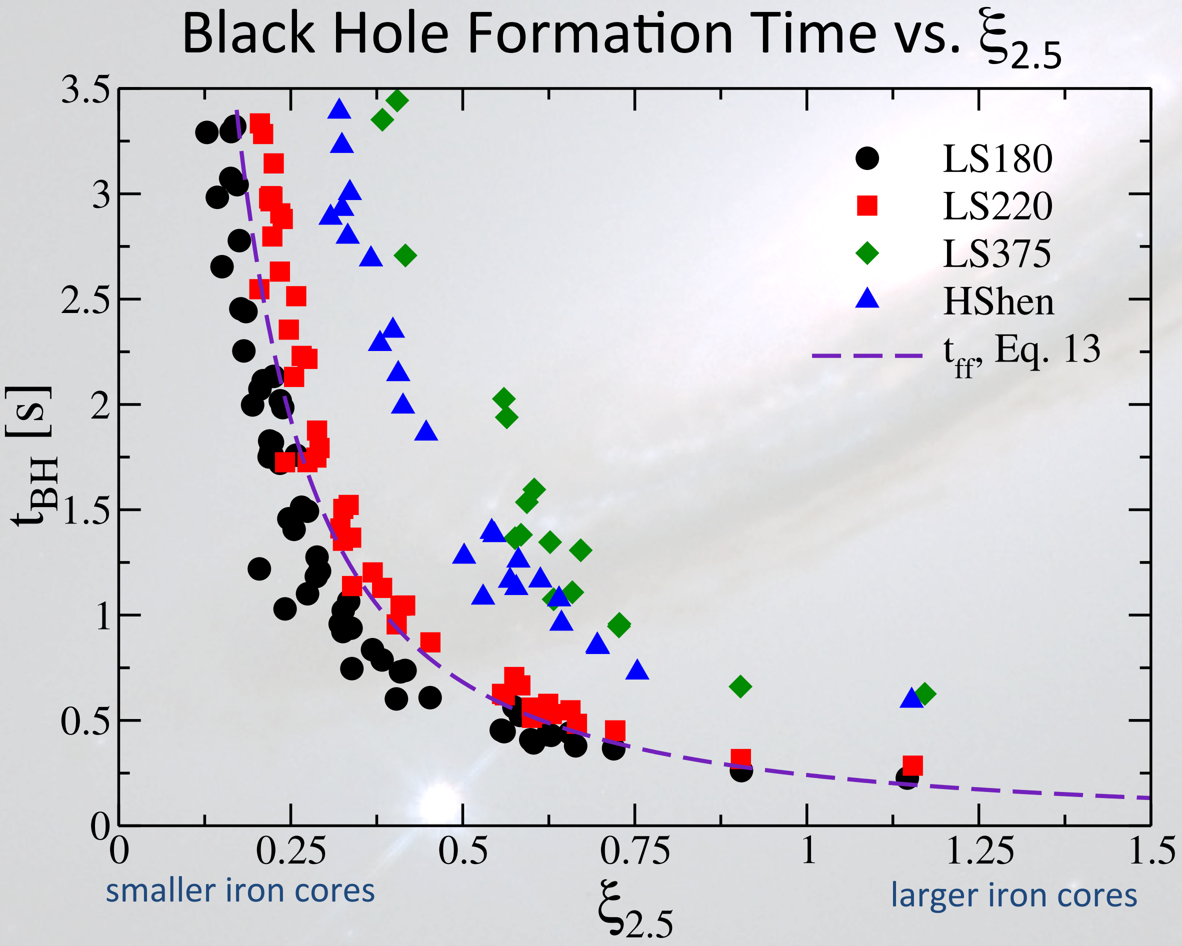
Black Hole Formation Times

- Stellar evolution complicates the connection between ZAMS and BH formation properties
- ZAMS is not the best tracer of BH formation properties, e.g. mass loss

Black Hole Formation Time vs ZAMS Mass



Black Hole Formation Times


Black Hole Formation Time vs. $\xi_{2.5}$

smaller iron cores

larger iron cores

- $\xi_{2.5}$ is a measure of the compactness of the progenitor's inner 2.5 solar masses

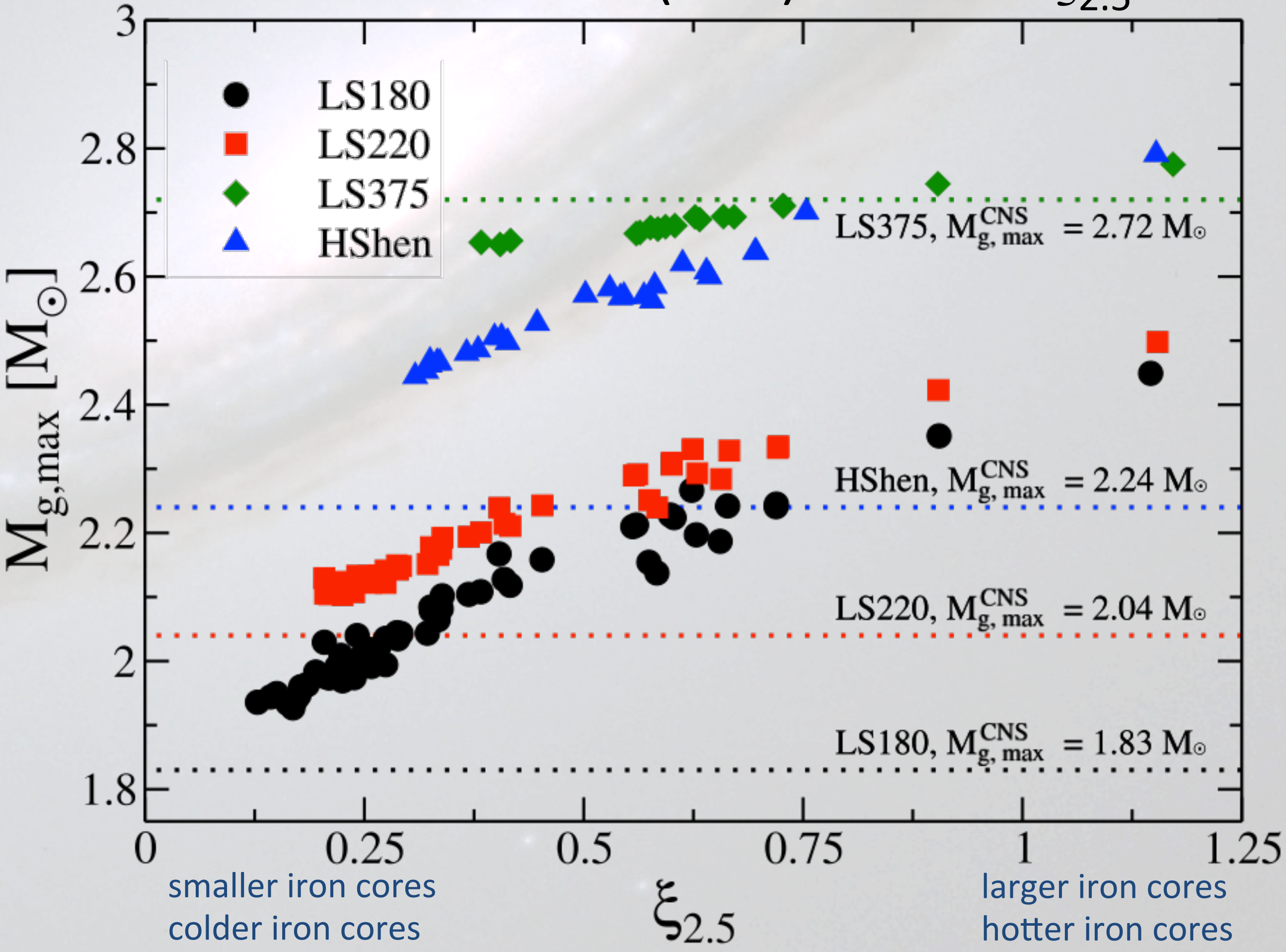
$$\xi_{2.5} = \frac{2.5 M_{sun} / M_{sun}}{R_{2.5 M_{sun}} / 1000 km}$$

- BH formation time set by progenitor structure and EOS
- Of course, many will explode in nature...

Black Hole Formation in failing CCSNe

- The mass of the PBH is higher for progenitors with higher $\xi_{2.5}$
- High $\xi_{2.5}$ models have higher temperatures and thermal support increases PBH mass above cold NS value

Proto-Black Hole (PBH) Mass vs. $\xi_{2.5}$

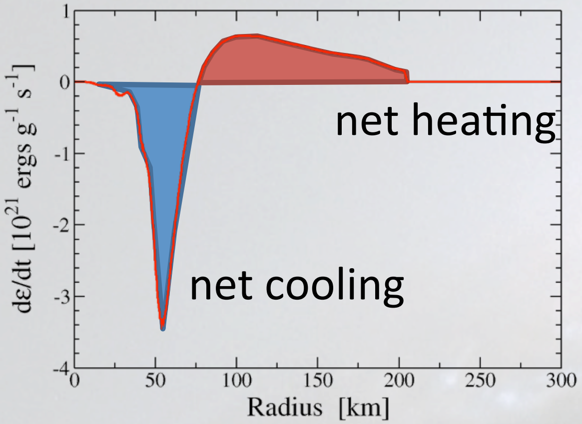


smaller iron cores
colder iron cores

larger iron cores
hotter iron cores

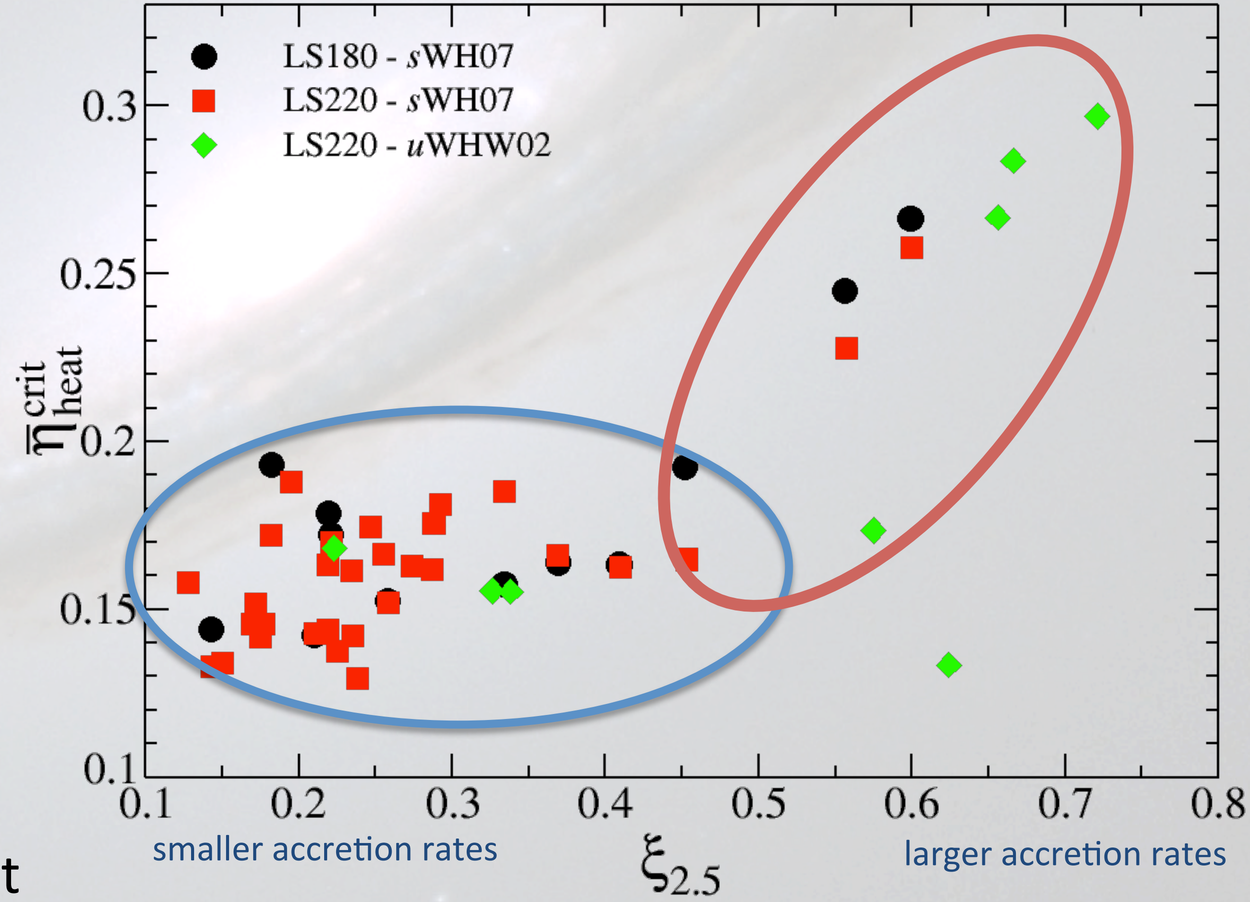
Artificially driven CCSNe explosions

- We artificially drive explosions by increasing neutrino heating



- For models with $\xi_{2.5}$ < 0.45, the critical heating efficiency is roughly constant at 16%
- For high $\xi_{2.5}$, the amount of neutrino heating needed increases.

Heating Efficiency of critically exploding models

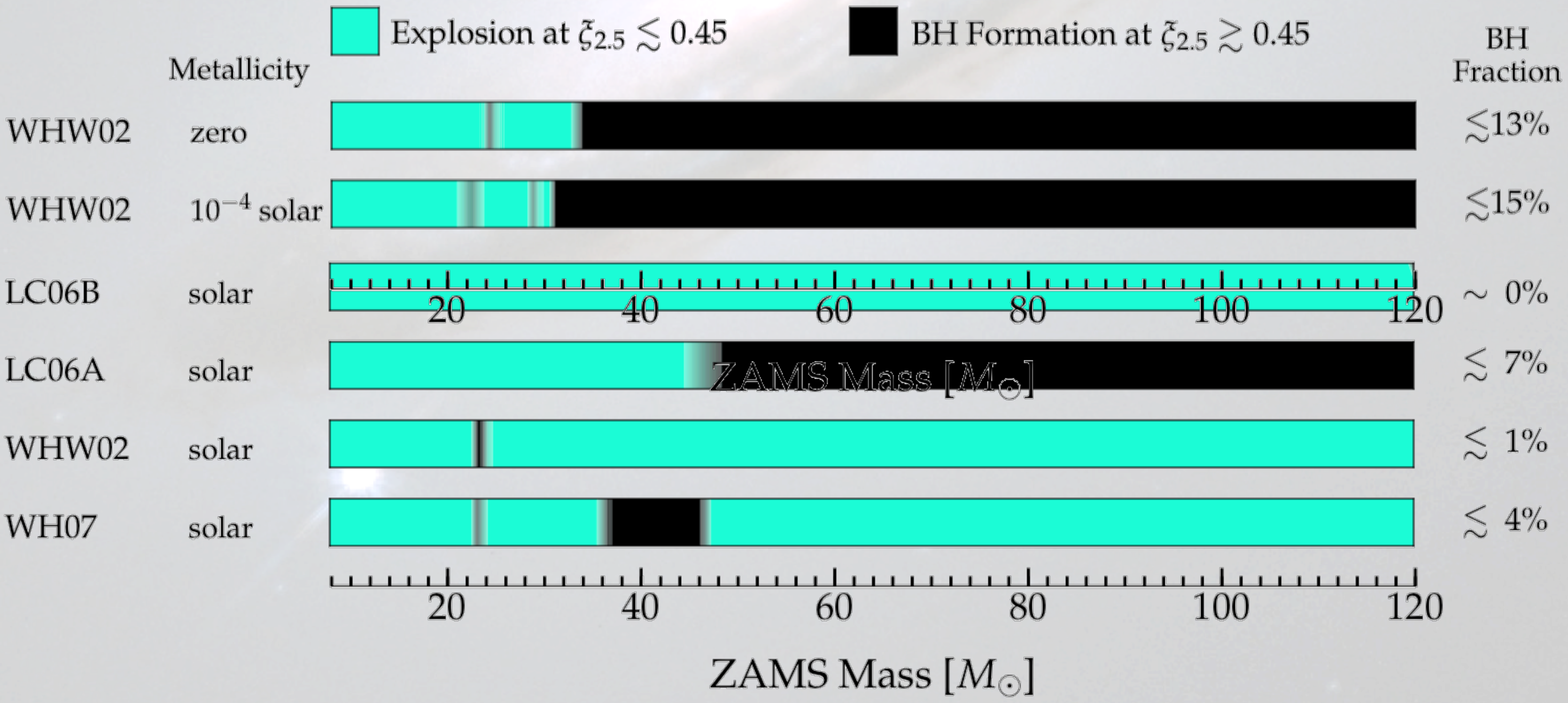


- η_{heat} typical in 1D simulations with full transport: ~6%
- ~10 - 15% actually needed for explosion in 1D
- ~5 - 10% needed for explosion in 2D? 3D??

Black Hole Formation in failing CCSNe

For:

- for soft-moderately soft EOS (LS180-LS220)
- assuming 1D & using neutrino leakage scheme
- Salpeter IMF ($Ndm = M^{-2.35}dm$) between 8 M_{sun} and 150 M_{sun}



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Question: How can we revive the core-collapse supernova shock?

Answer: ??

1. Increased dimensionality (Nordhaus et al. 2010) may be enough to get robust explosion.
2. May be missing some crucial microphysics which could naturally increase the heating rate?

Outline:

- Formalism neutrino oscillations
- Neutrino heating in the postshock region
- Influence of collective neutrino oscillations on shock revival + prospects of this mechanism

Neutrino Oscillations

$$|\,\nu_{\rm mass}\,\rangle = U_M\,|\,\nu_{\rm flavour}\,\rangle$$

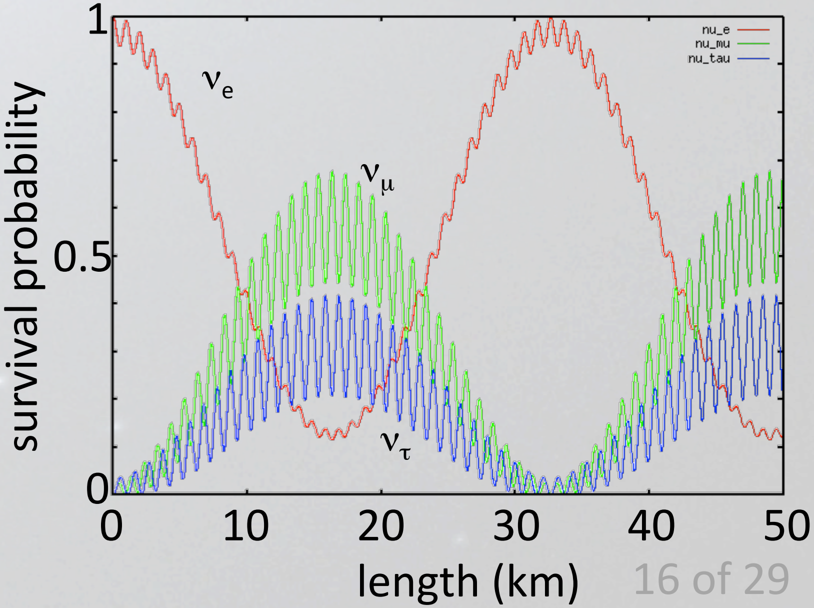
$$U_M = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$|\,\nu_{\rm mass}(t)\,\rangle = e^{-i\mathcal{H}t}\,|\,\nu_{\rm mass}\,\rangle$$

$$|\,\nu_{\rm flavour}(t)\,\rangle = U_M^{-1}\,|\,\nu_{\rm mass}(t)\,\rangle$$

- *Vacuum Oscillations*

$$\begin{pmatrix} |\,\nu_1(t)\rangle \\ |\,\nu_2(t)\rangle \\ |\,\nu_3(t)\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\Delta m^2_{21}t/2E} & 0 \\ 0 & 0 & e^{-i\Delta m^2_{31}t/2E} \end{pmatrix} \begin{pmatrix} |\,\nu_1(0)\rangle \\ |\,\nu_2(0)\rangle \\ |\,\nu_3(0)\rangle \end{pmatrix}$$



Neutrino Oscillations

- *Matter Oscillations*

Matter introduces extra potential in Hamiltonian due to forward scattering of electrons and neutrinos, the MSW potential:

$$\mathcal{H}_{\mathrm{matter}} = \sqrt{2}G_{\mathrm{F}}(N_{e^-} - N_{e^+})$$

- *Collective Oscillations*

High neutrino densities in the core-collapse supernova environment leads to appreciable neutrino-neutrino forward scattering

$$\mathcal{H}_{\mathrm{collective}} = G_{\mathrm{F}} \boxed{\frac{R_{\nu_e}^2}{2r^2 - R_{\nu_e}^2}} \boxed{\int \frac{R_{\nu_e}^2}{r^2}[\Phi_{\nu_e} - \Phi_{\bar{\nu}_e}]dE}$$

interaction angle closes ~1/r^2

differential neutrino number density ~1/r^2

Neutrino Oscillations

- Hamiltonians give equations of motion of the system

$$\mathcal{H}_{\rm vacuum} = -\frac{|\Delta m^2_{31}|}{2E} \qquad \mathcal{H}_{\rm matter} = \sqrt{2}G_{\rm F}(N_{e^-} - N_{e^+})$$

$$\mathcal{H}_{\rm collective} = G_{\rm F}\frac{R^2_{\nu_e}}{2r^2 - R^2_{\nu_e}}\int \frac{R^2_{\nu_e}}{r^2}[\Phi_{\nu_e} - \Phi_{\bar{\nu}_e}]dE$$

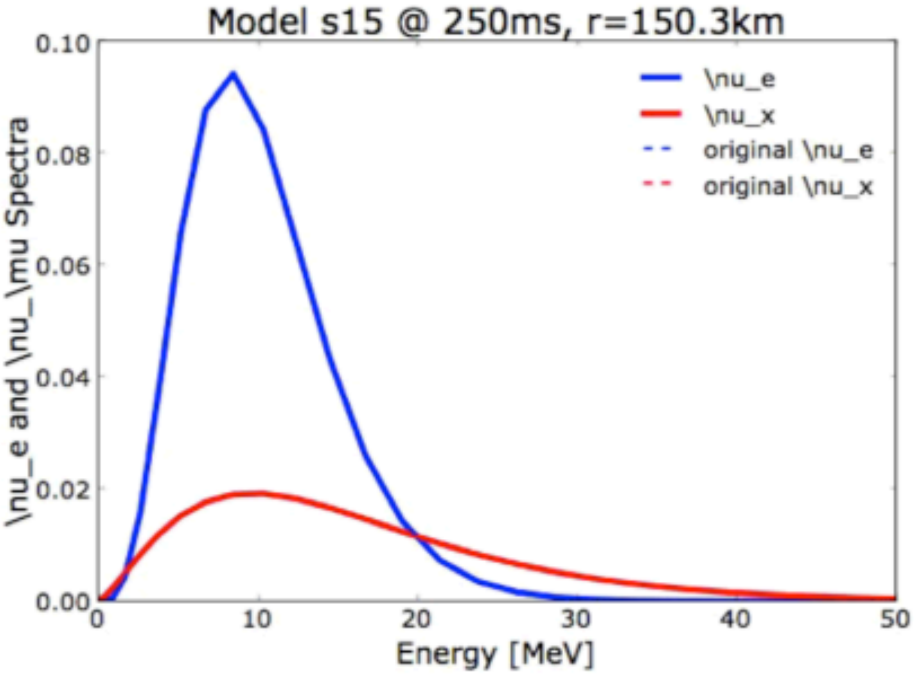
$$\frac{\partial \Phi_\nu}{\partial t} = -\frac{i}{\hbar}[+\mathcal{H}_{\rm vacuum} + \mathcal{H}_{\rm matter} + \mathcal{H}_{\rm collective}, \Phi_\nu]$$

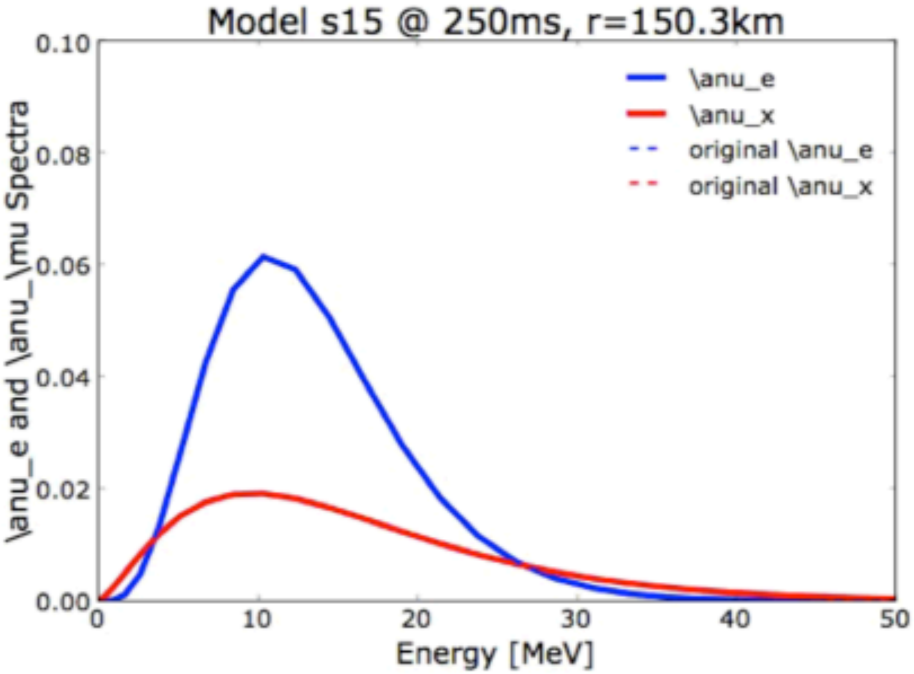
$$\frac{\partial \Phi_{\bar{\nu}}}{\partial t} = -\frac{i}{\hbar}[-\mathcal{H}_{\rm vacuum} + \mathcal{H}_{\rm matter} + \mathcal{H}_{\rm collective}, \Phi_{\bar{\nu}}]$$

- Evolution is complicated due to non-linear coupling of neutrino and antineutrino fields

Neutrino Evolution

- As an example of oscillations, here is a movie showing the evolution of the ν spectra from the ν-sphere out in radius
- Inverted hierarchy, $\Delta m^2_{13} = -\ 2.6\times10^{-3}\mathrm{eV}^2$, $\theta_{13}=0.001$
- Will describe core-collapse simulations in more detail





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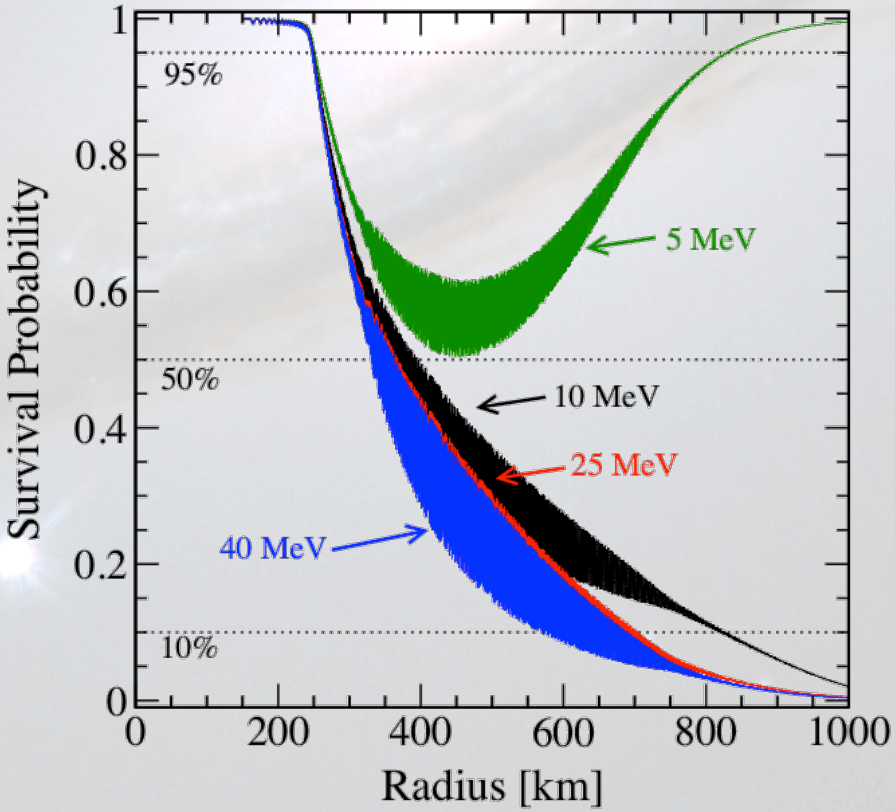
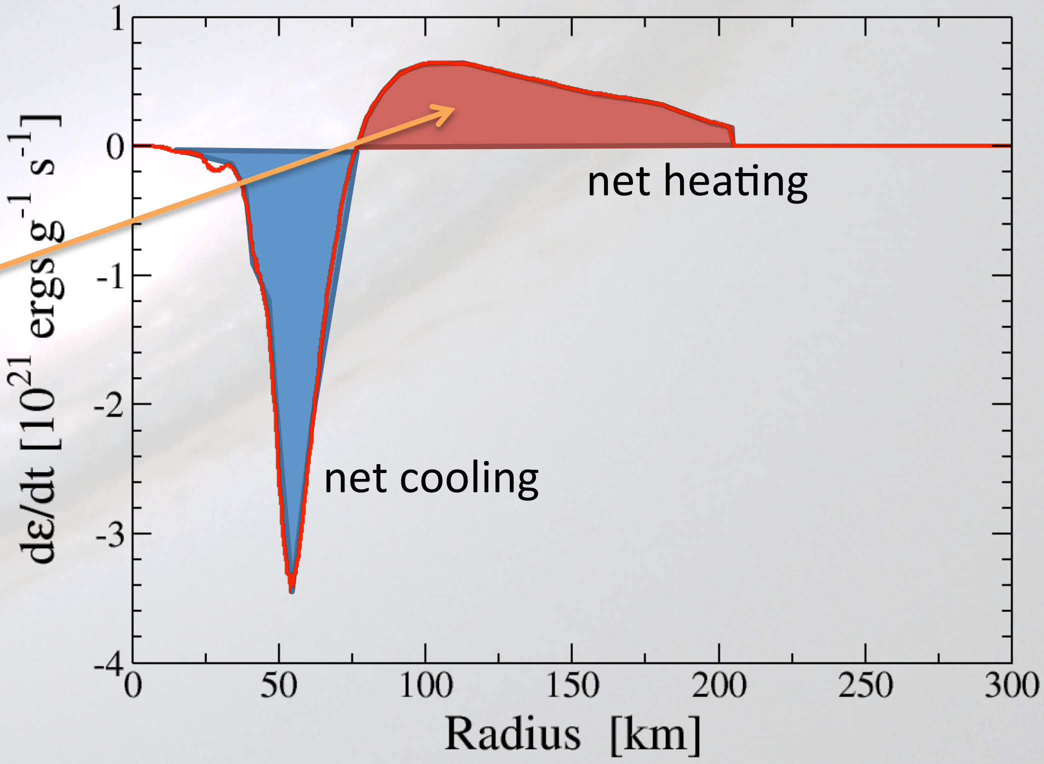
Dasgupta et al. (2011)



Theory of Neutrino Heating

- Neutrinos diffusing from core have a net energy deposition in the postshock region, the so called `gain region’
- The neutrino mechanism works by having sufficient heating in the gain region to reenergize the shock



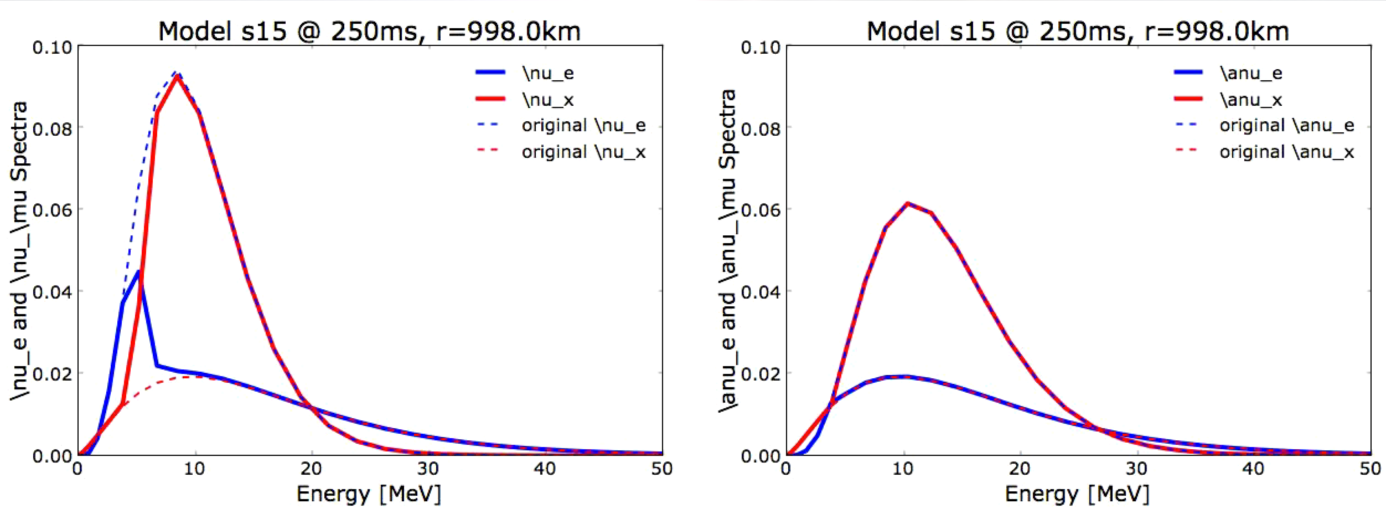
$$\mathcal{H} = \sum_{\nu_e,\bar{\nu}_e} \int_{r_g}^{r_s} dr\, 4\pi r^2 n_i \int_0^\infty d\epsilon\, \sigma_{\nu_i}(\epsilon)\, \frac{\epsilon d\Phi_{\nu_i}}{d\epsilon}$$

$$\sim \hat{\sigma}\left[\langle\epsilon^2_{\nu_e}\rangle \mathcal{L}_{\nu_e} c_N + \langle\epsilon^2_{\bar{\nu}_e}\rangle \mathcal{L}_{\bar{\nu}_e} c_P\right]$$

Hypothosis: Oscillations Enhance Heating

$$\mathcal{H} \sim \hat{\sigma}\left[\langle\epsilon^2_{\nu_e}\rangle\mathcal{L}_{\nu_e}c_N + \langle\epsilon^2_{\bar{\nu}_e}\rangle\mathcal{L}_{\bar{\nu}_e}c_P\right]$$

- Collective oscillations will raise the mean squared energy of the electron neutrinos from the original values to that of the μ and τ's



- In this example, the final spectra would increase $\mathcal{H}$ by 20% if occurring before the gain region

- However, we must determine *where* oscillations begin

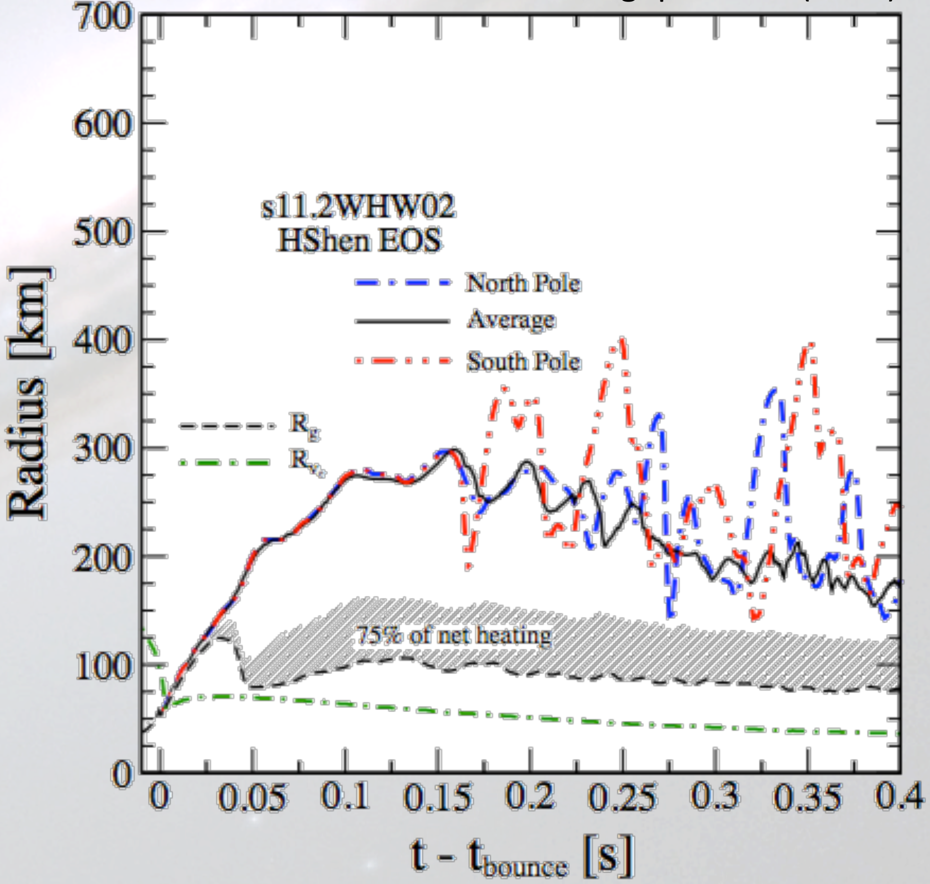
Simulations with `VULCAN/2D`

Livne, E. 1993, Burrows, A. et al. 2006

- Use 11.2 Msun progenitor from Woosley et al. 2002 and the Shen, H. et al. 1998 EOS

- Extract neutrino spectra at ν-sphere and run through dynamical neutrino evolution taking into account collective oscillations

Dasgupta et al. (2011)



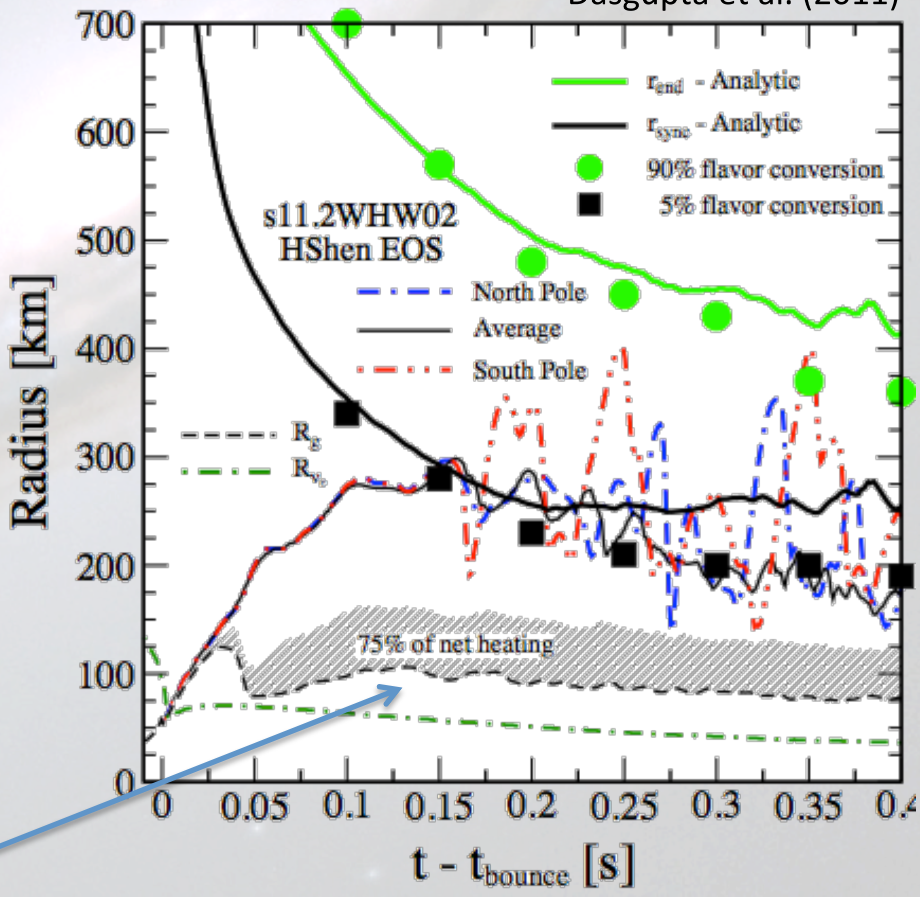
Simulations with `VULCAN/2D`

Livne, E. 1993, Burrows, A. et al. 2006

- Oscillation radii are large due to high neutrino luminosities and large neutrinosphere radii

- Even though oscillations begin inside shock, not complete until well outside.

- Significant heating will occur only if oscillations occur before gain radius



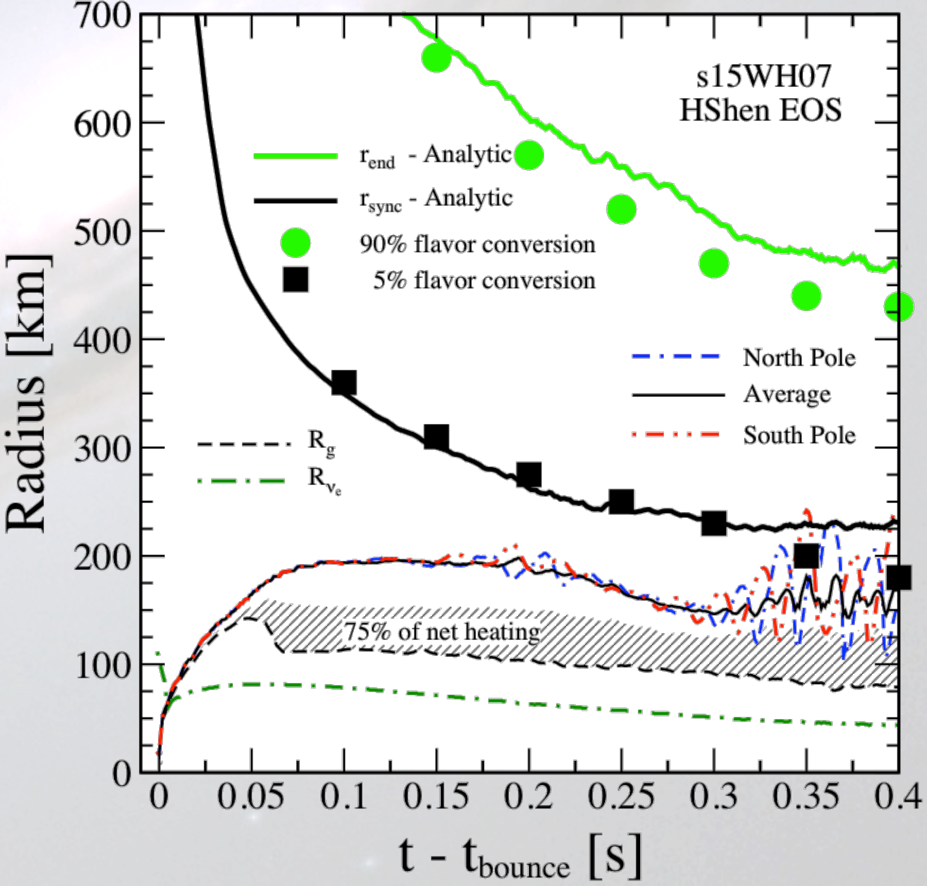
Dasgupta et al. (2011)

Simulations with `VULCAN/2D`

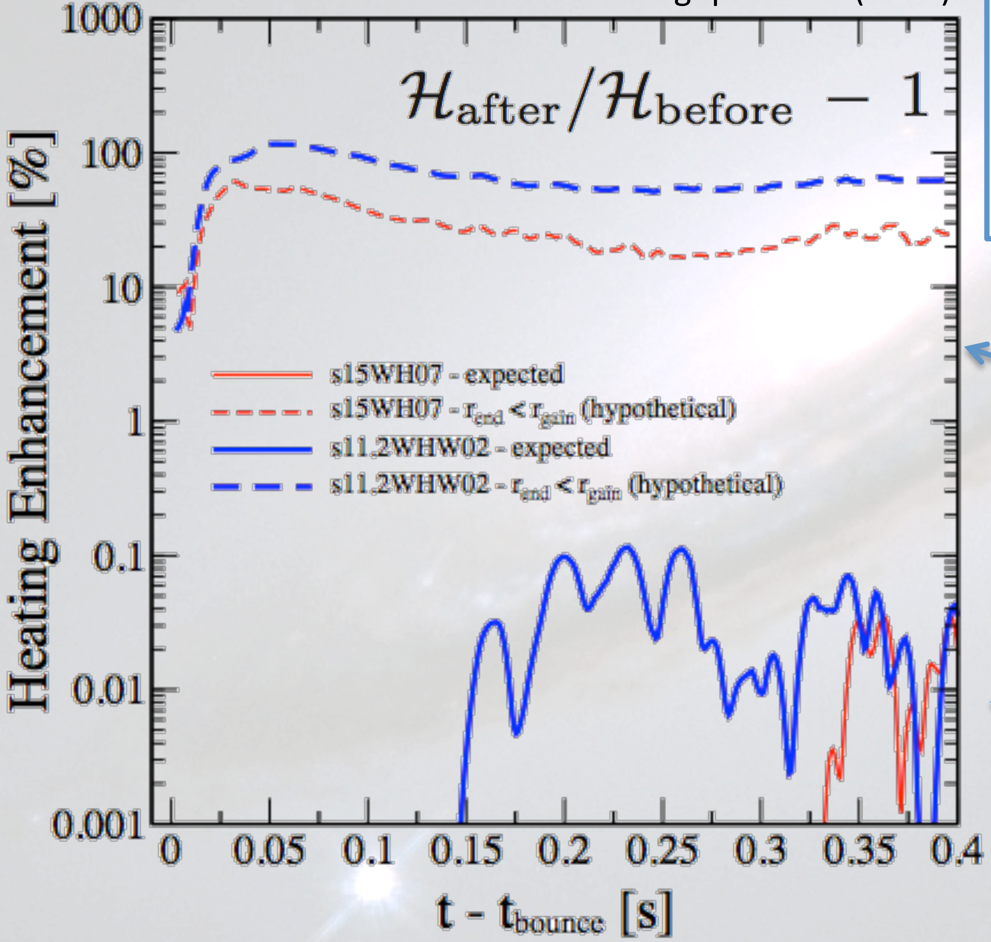
Livne, E. 1993, Burrows, A. et al. 2006

- Use 15 Msun progenitor from Woosley *et al.* 2007 and the Shen, H. *et al.* 1998 EOS
- Higher accretion rates suppress SASI and keep shock at lower radii
- Neutrino oscillations occur at roughly same location as 11.2 model, little affect on heating

Dasgupta et al. (2011)



Expected Heating Enhancement



Dasgupta et al. (2011)

$$
\begin{aligned}
\mathcal{H}_{\rm after} \sim \mathcal{H}_{\rm before} & \\
& + \hat{\sigma}\left[\langle \epsilon^2_{\nu_x}\rangle \mathcal{L}^{\rm ns}_{\nu_x} - \langle \epsilon^2_{\nu_e}\rangle \mathcal{L}^{\rm ns}_{\nu_e}\right] c^O_N \\
& + \hat{\sigma}\left[\langle \epsilon^2_{\nu_x}\rangle \mathcal{L}^{\rm ns}_{\nu_x} - \langle \epsilon^2_{\bar{\nu}_e}\rangle \mathcal{L}^{\rm ns}_{\bar{\nu}_e}\right] c^O_P \\
& + \hat{\sigma}\langle \epsilon^2_{\nu_e}\rangle^\star \left[\langle \epsilon_{\nu_e}\rangle^\star (\mathcal{N}^{\rm ns}_{\nu_e} - \mathcal{N}^{\rm ns}_{\bar{\nu}_e})\right] c^O_N
\end{aligned}
$$

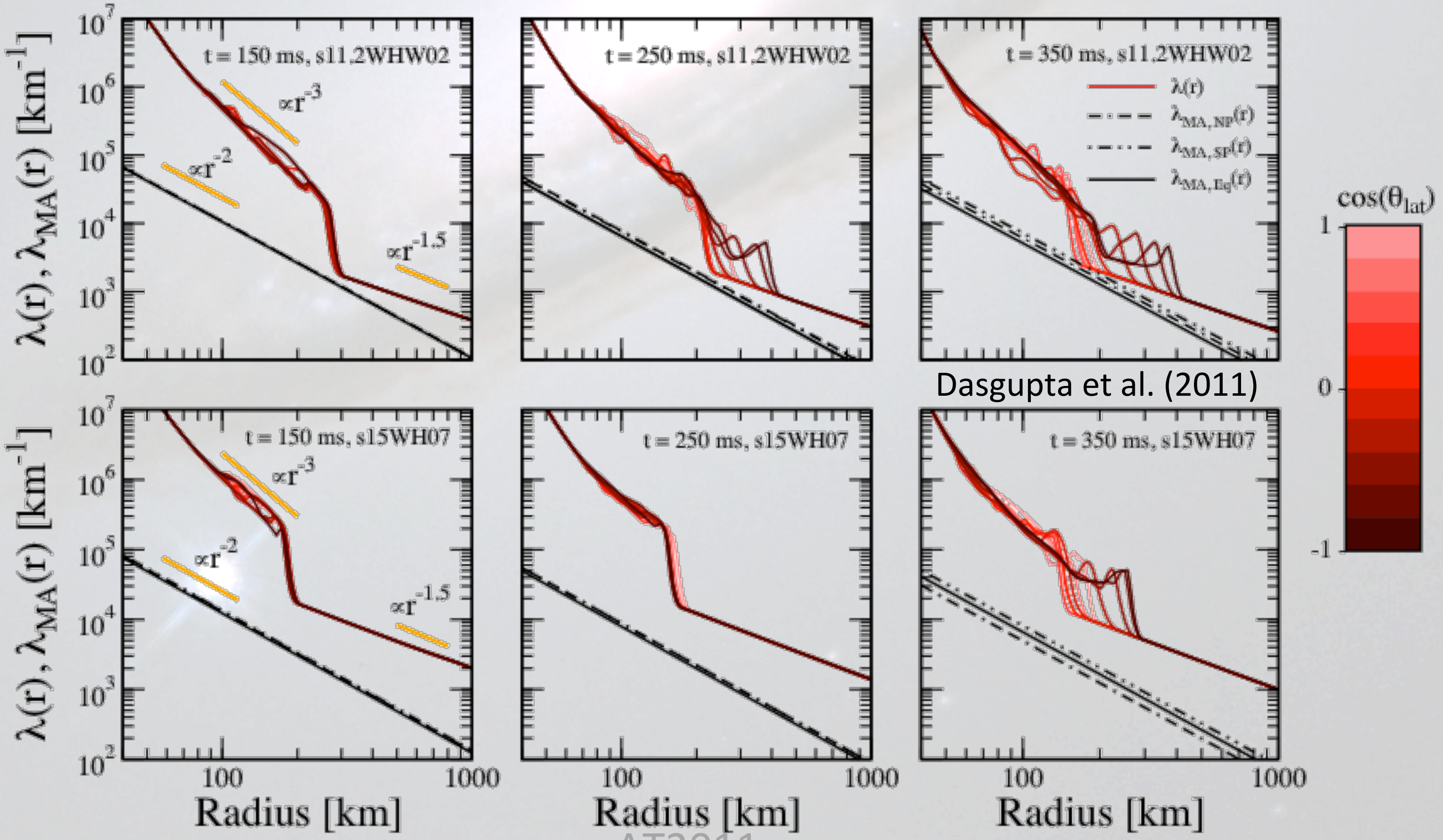
- Hypothetical situation where oscillations complete before gain radius (Suwa et al. 2011)
- Actual heating enhancement is much less, < 1%

Take home message, collective neutrino oscillations do not help explode CCSNe

Multiangle suppression of Oscillations

(see also Chakraborty et al. 2011ab)

- In single angle approximation one can \`rotate' away the matter potential
- Recent developments in multiangle collective oscillations (Esteban-Pretel et al. 2008) leads to a suppression of oscillations until the $n_e < n_\nu$
- Estimate the effect by looking at MSW potential vs. collective potential



Dasgupta et al. (2011)

Should we expect this to be relevant in improved models/EOS/codes/dimensions/neutrinos…?

- Models with higher accretion rates not only suppress SASI but lead to higher ν-sphere radii and neutrino densities. We chose low mass-range models for this reason (…O-Ne-Mg?)

$$r_{\rm sync} \;\propto\; \sqrt{R_{\nu_e}}\left(\Phi_{\nu,\bar{\nu}} R_{\nu_e}^2\right)^{1/4}$$

- Different EOS do not significantly change R_ν or $\Phi_{\nu\nu}$
- 3D may lead to larger shock radii, however need to get oscillations deep down below gain radius to see significant effect – that's hard

Should we expect this to be relevant in improved models/EOS/codes/dimensions/neutrinos…?

Note: here neutrino evolution means the collect oscillation evolution

- Results here in single-angle approximation, multiangle may lead to larger swap radii:
  - multiangle matter effects (Chakraborty et al. 2011)
  - multiangle treatment of neutrino evolution

- If $\Phi_{\nu e} \sim \Phi_{\bar{\nu} e}$ then multiangle decoherence, spectra equilibrate
- Full Boltzmann treatment of neutrino oscillations (lingering matter effects)

- Some as-of-yet unknown collective neutrino physics

- Collective neutrino Oscillations still will influence observed signal and may have consequences on r-process (Duan *et al.* JoPG, 38 035201 (2011), Martínez-Pinedo, arXiv:1105.5304)