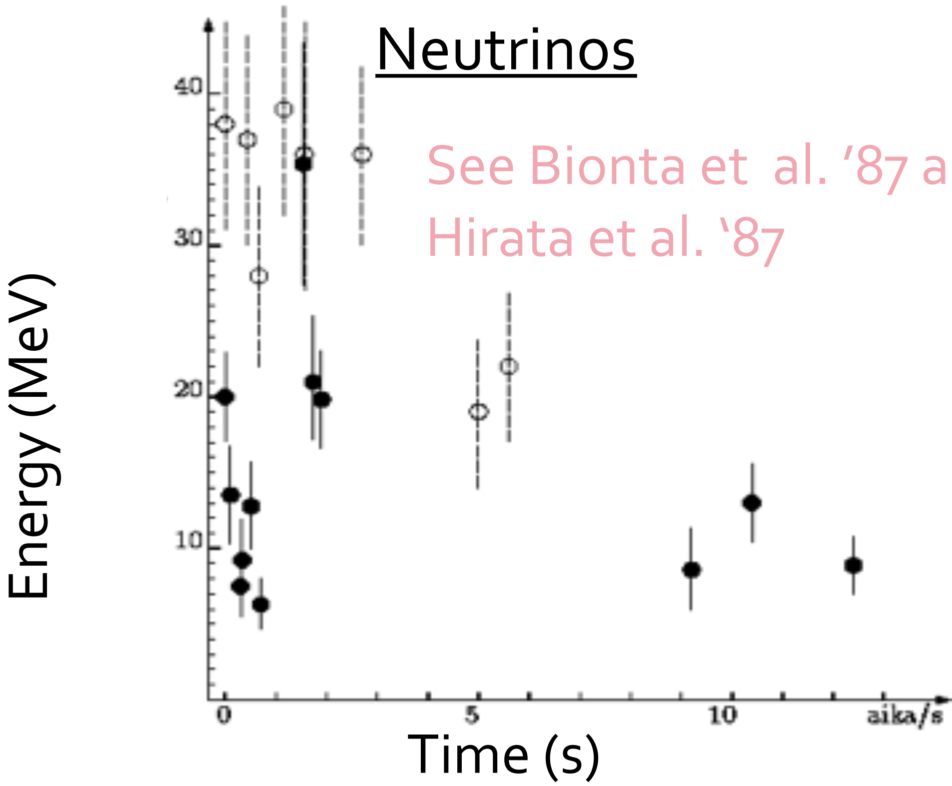
Three Dimensional Radiation Hydrodynamics Simulations of Core Collapse Supernovae

Luke F. Roberts

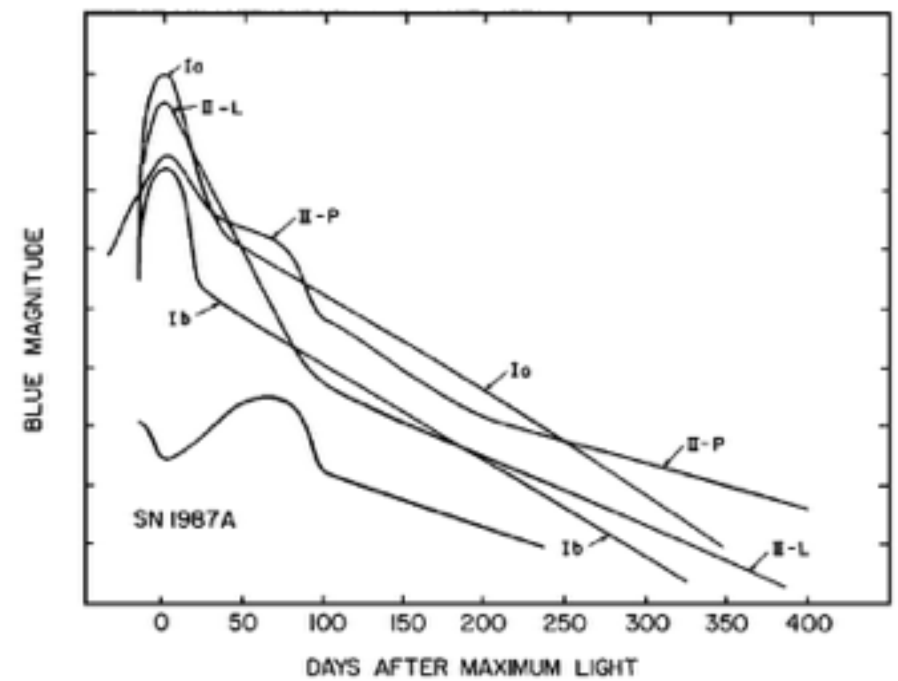
TAPIR, Caltech

Core Collapse Supernovae: Multi-messenger events

Neutrinos

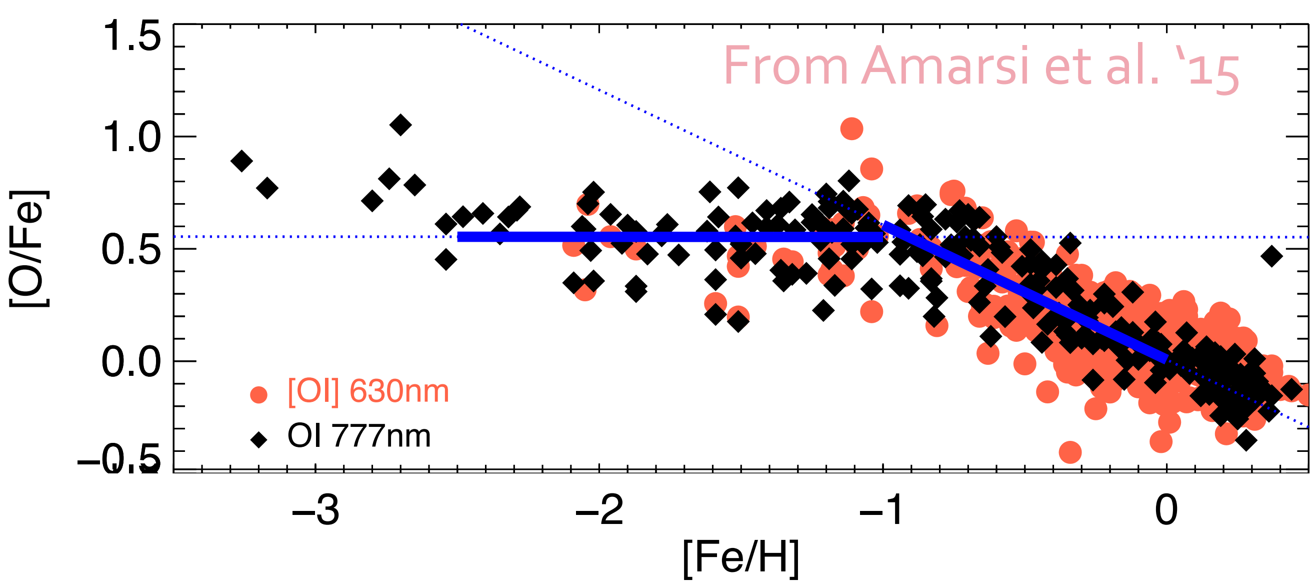


Electromagnetic

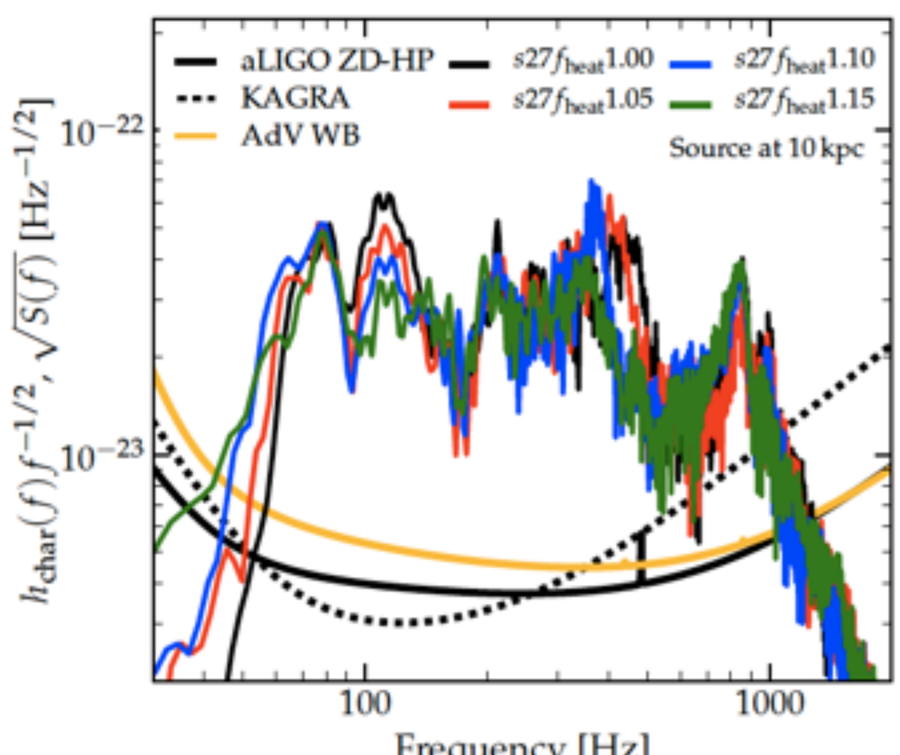


From Filppenko '97

Nucleosynthesis

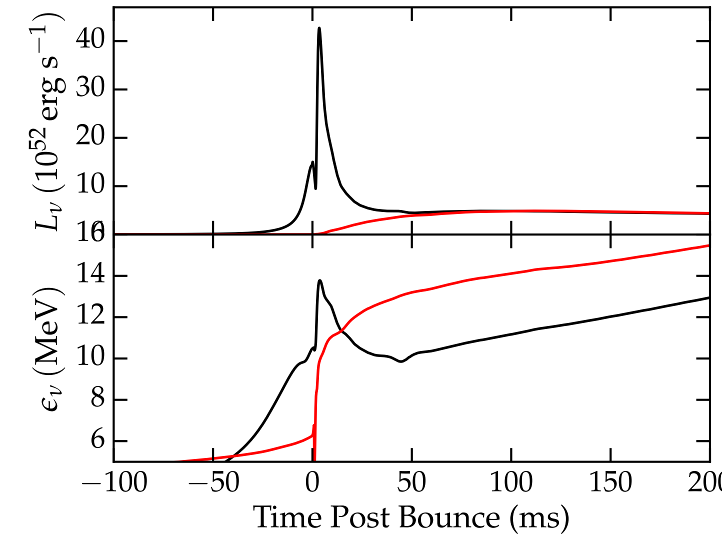


Gravitational Waves



From Ott et al. '12

Core Collapse



- Stars with M >~ 9 M_{sun} burn their core to Fe

- Core exceeds a Chandrasekhar mass ➡ supersonic collapse outside of homologous core ➡ bounce shock after ~2 x saturation density

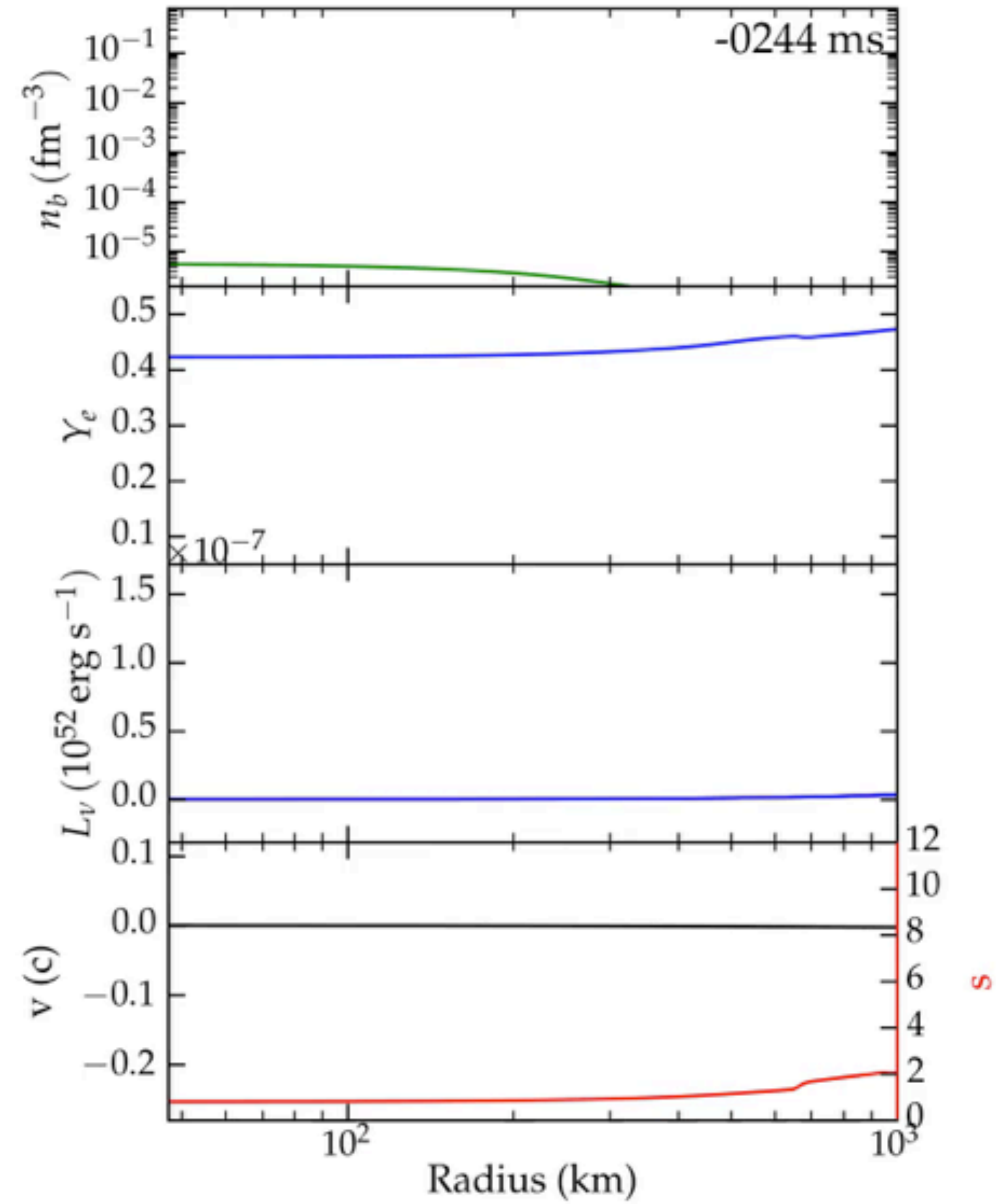
- Gravitational binding energy of compact remnant:

$$\frac{GM_{NS}^2}{R_{NS}} \sim 3\times 10^{53}\, erg$$

- Binding energy of stellar envelope:

$$\sim 10^{51}\, erg$$

- No Explosions by the neutrino mechanism in spherical symmetry (e.g. Liebendorfer ’00)



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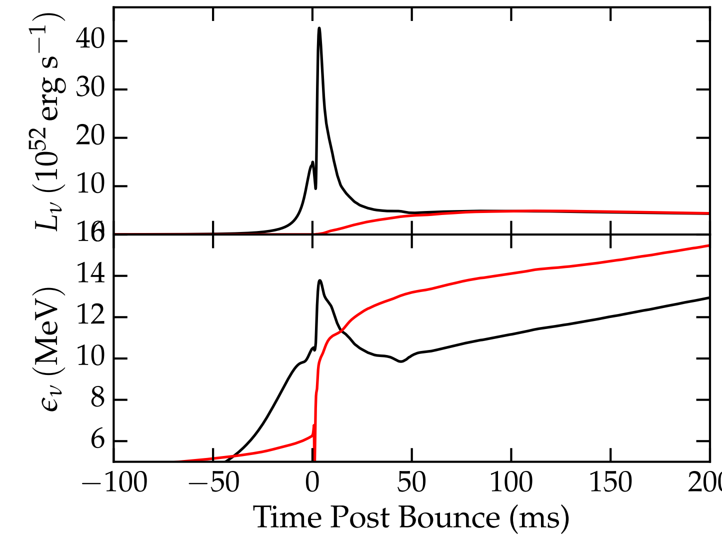

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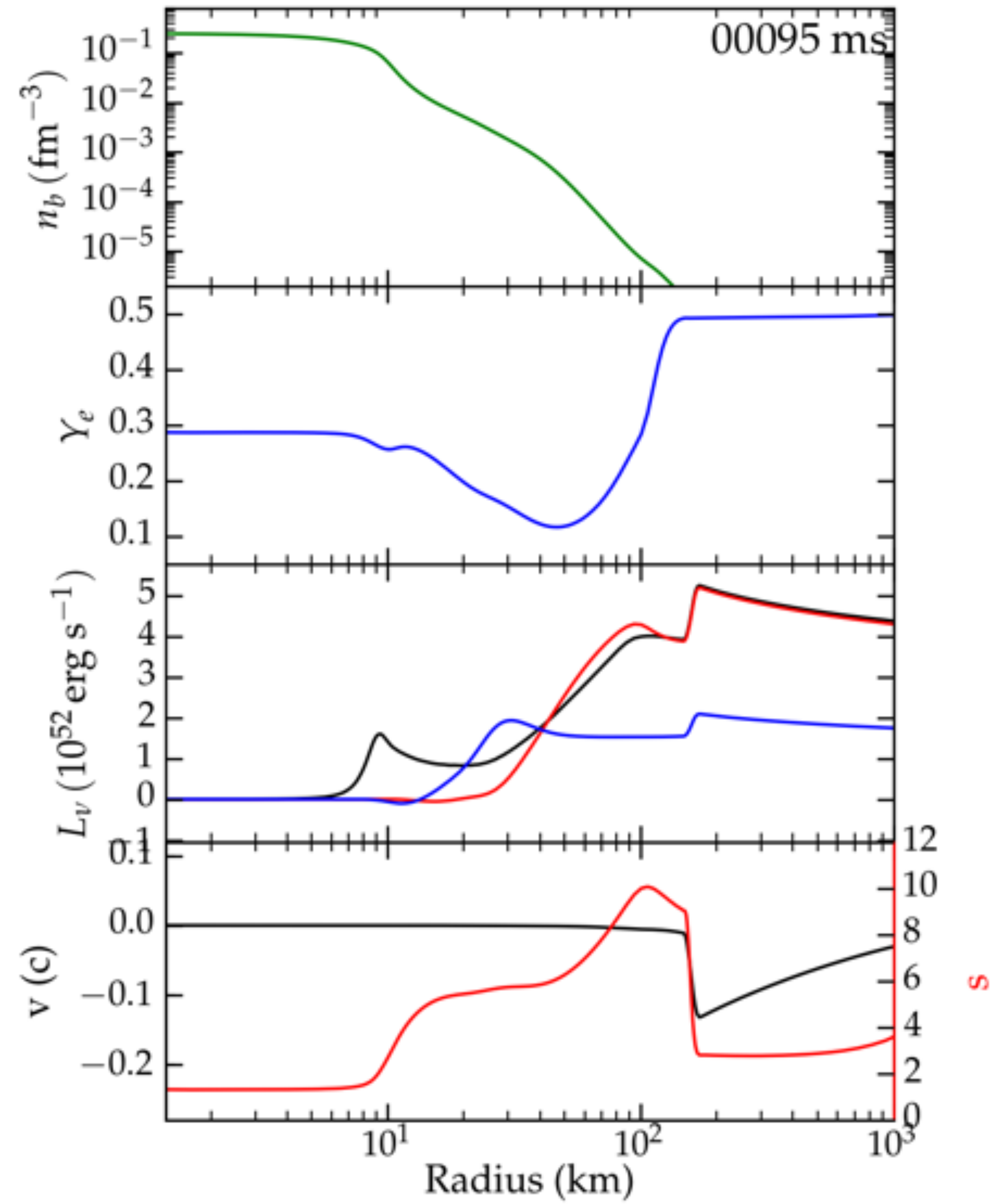


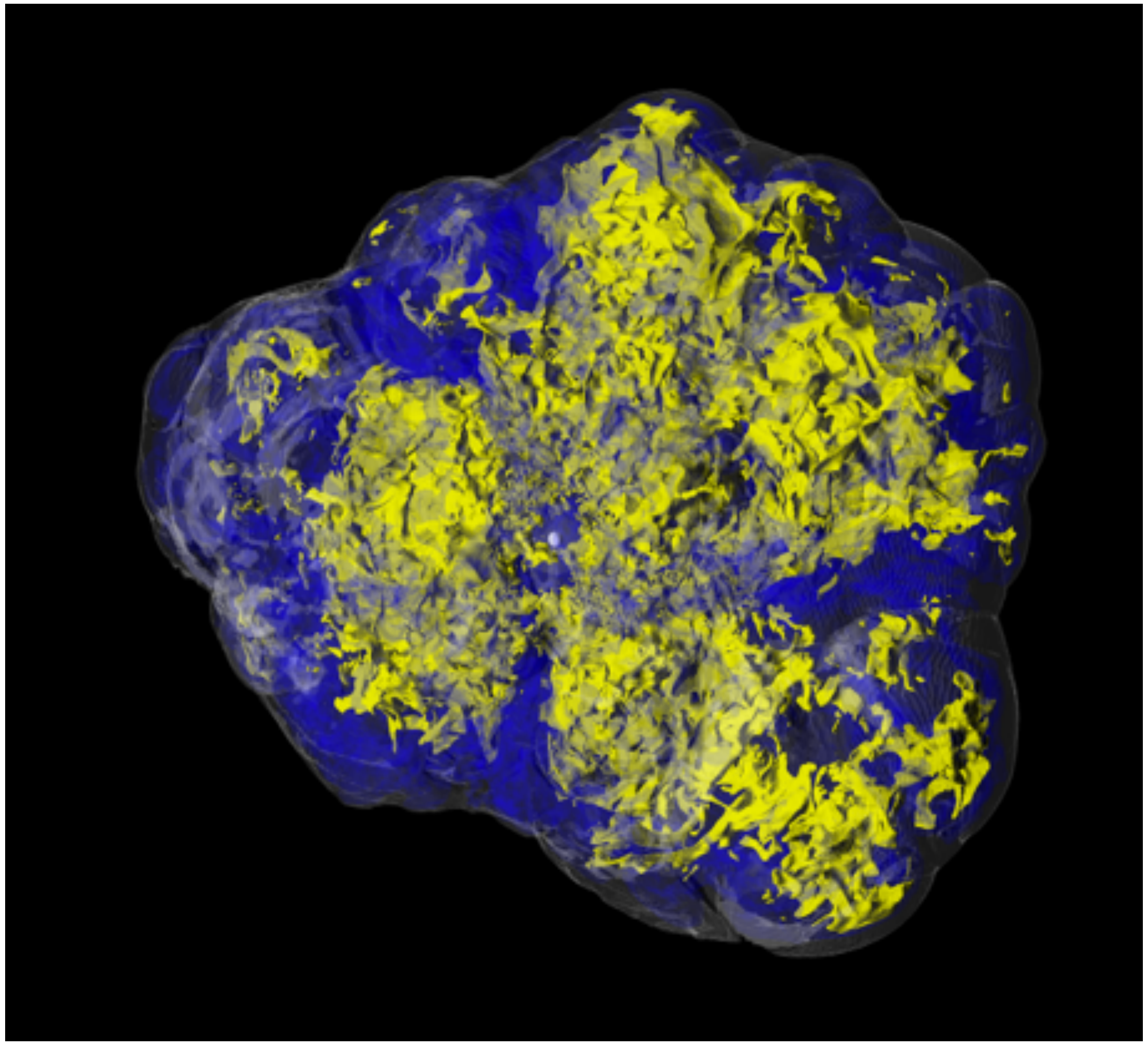
Post Bounce Evolution of CCSNe

- Hydrodynamic instabilities in the region behind the shock can provide increased post shock pressure and transport extra energy

- In axial symmetry, this enhances the efficiency of neutrino energy deposition and results in successful explosions (Mueller et al. ’12, Bruenn et al. ’13)

- Does the neutrino mechanism work in 3D? Lentz et al. ’15 and Melson et al. ‘15 find it works for some progenitor stars using ray-by-ray transport

- How does this depend on input physics and numerics?



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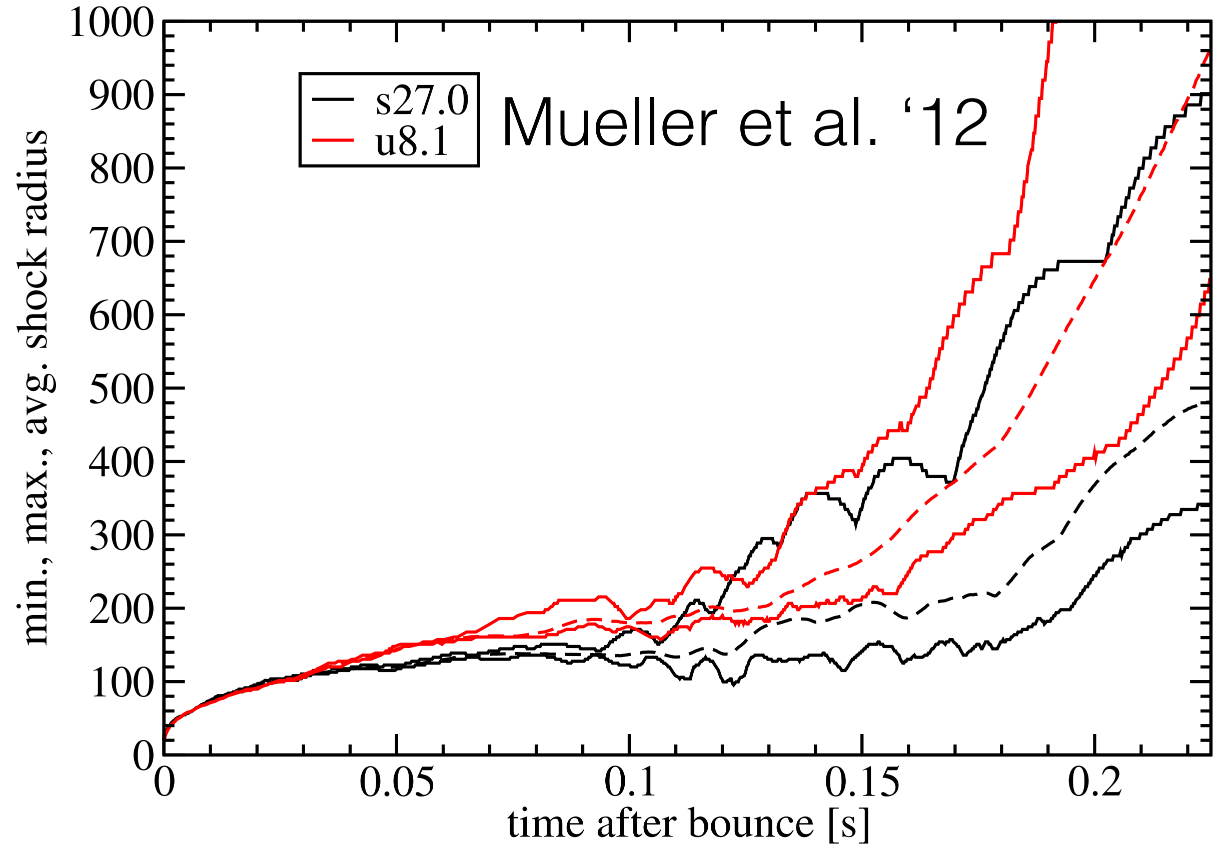

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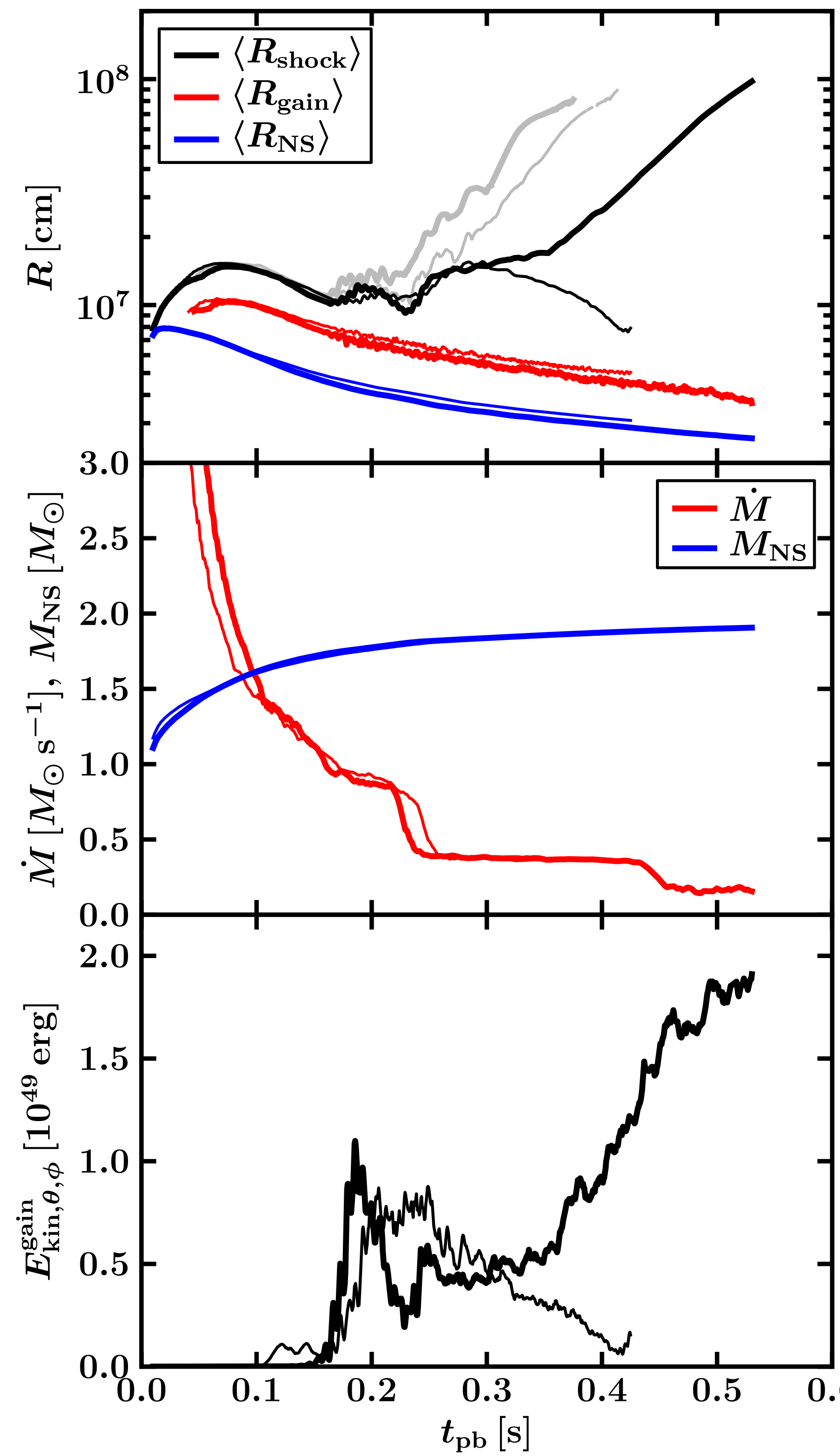

Melson et al. '15

Two Moment Neutrino Transport

Boltzmann Equation:

$$\frac{\partial x^\alpha}{\partial \tau}\frac{\partial f(x^\mu, p^\mu)}{\partial x_\alpha} + \frac{\partial p^i}{\partial \tau}\frac{\partial f(x^\mu, p^\mu)}{\partial p_i} = \tilde{S}(x^\mu, p^\mu)$$

Take angular moments of the neutrino distribution function:

$$M^{A_k}_{(\nu)} = \int dV_p \frac{p^{\alpha_1}...p^{\alpha_k}}{(-p_\mu u^\mu)^{k-2}} f(p^\beta, x^\beta)\delta(\nu + p_\delta u^\delta)$$

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Get conservation equations for projections of the rest frame energy dependent stress tensor:

$$M^{\alpha\beta}_{(\nu)\ ;\beta}$$

$$\partial_t \tilde{E} + \partial_j\left(\alpha \tilde{F}^j - \beta^j \tilde{E}\right) + \partial_\nu\left(\nu\alpha n_\alpha \tilde{M}^{\alpha\beta\gamma} u_{\gamma;\beta}\right) = \alpha\left[\tilde{P}^{ij}K_{ij} - \tilde{F}^j\partial_j \ln\alpha - \tilde{S}^\alpha n_\alpha\right]$$

$$\partial_t \tilde{F}_i + \partial_j\left(\alpha \tilde{P}^j{}_i - \beta^j \tilde{F}_i\right) - \partial_\nu\left(\nu\alpha\gamma_{i\alpha} \tilde{M}^{\alpha\beta\gamma} u_{\gamma;\beta}\right) = \alpha\left[\frac{\tilde{F}_k\partial_i\beta^k}{\alpha} - \tilde{E}\partial_i \ln\alpha + \frac{\tilde{P}^{jk}}{2}\partial_i\gamma_{jk} + \tilde{S}^\alpha\gamma_{i\alpha}\right]$$

Two Moment Neutrino Transport

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$$\frac{\partial x^\alpha}{\partial \tau}\frac{\partial f(x^\mu, p^\mu)}{\partial x_\alpha} + \frac{\partial p^i}{\partial \tau}\frac{\partial f(x^\mu, p^\mu)}{\partial p_i} = \tilde{S}(x^\mu, p^\mu)$$

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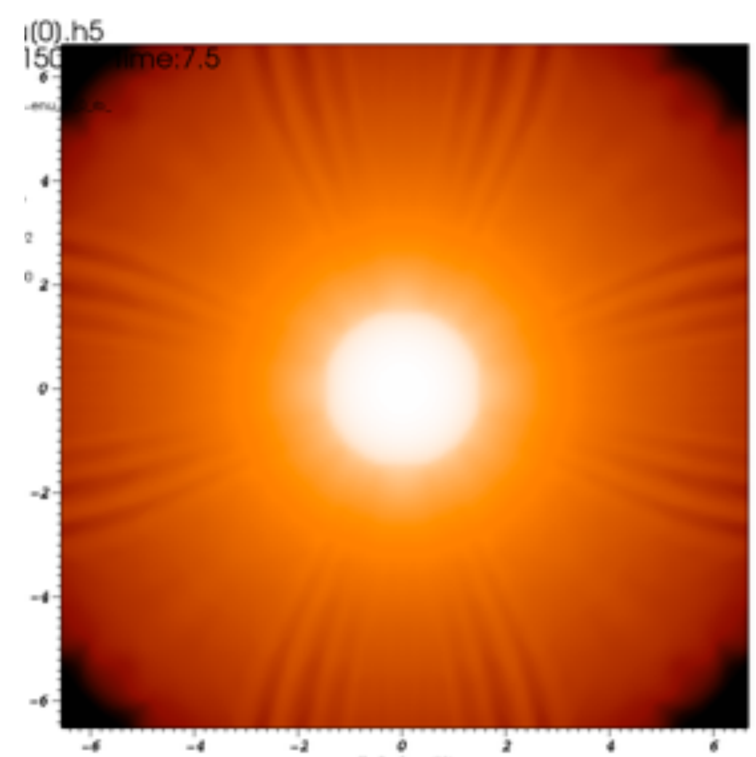
Amenable to finite volume techniques



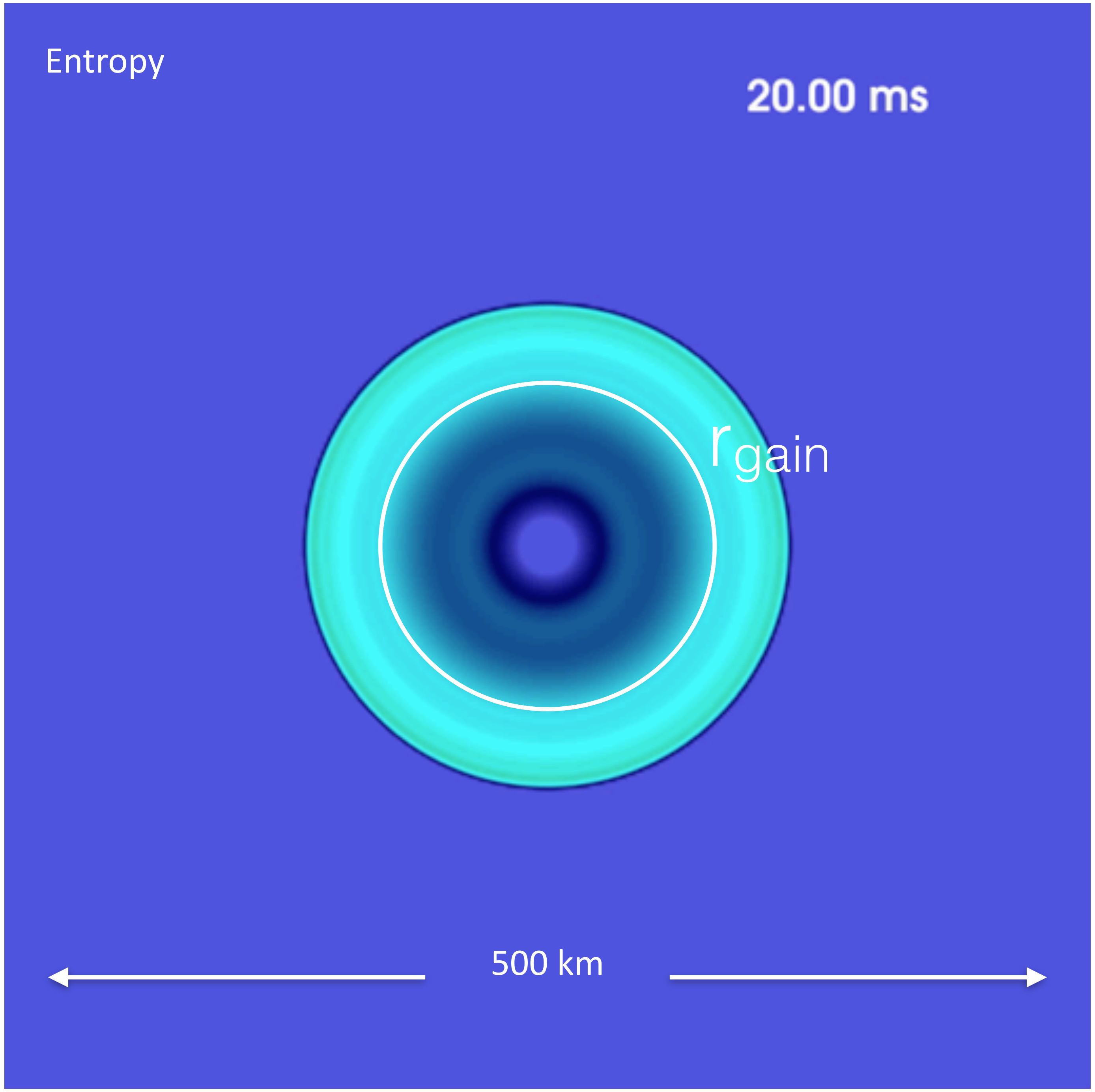
Still need to specify neutrino stress tensor:

$$P^{\alpha\beta}_{(\nu)} = \frac{3\chi(\xi) - 1}{2}P^{\alpha\beta}_{(\nu),thin} + \frac{3(1-\chi(\xi))}{2}P^{\alpha\beta}_{(\nu),thick}$$

Neutrino Interactions

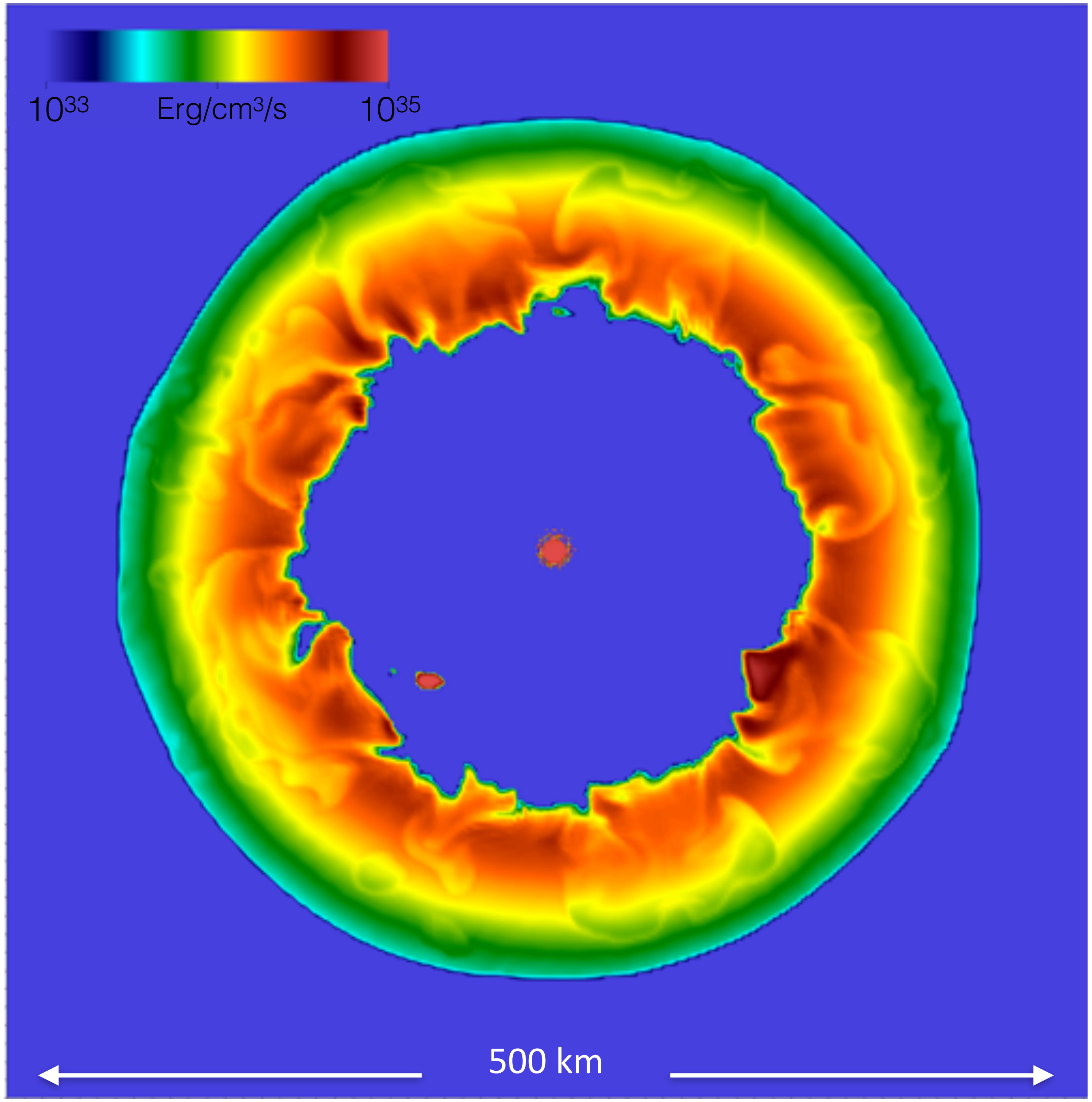
Reaction	Details & References
$\nu + N \leftrightarrow \nu + N$	Inelastic, non-interacting (Bruenn '85)
$\nu + e^{-} \leftrightarrow \nu + e^{-}$	Ultra-relativistic, **elastic** (Yueh & Buchler '77, etc.)
$\nu + \bar{\nu} + N + N \leftrightarrow N + N$	Non-relativistic, One-pion exchange, uncertain (Hannestad & Raffelt '98)
$\nu + \bar{\nu} \leftrightarrow e^{-} + e^{+}$	Ultra-relativistic (Bruenn '85)
$\nu_e + n \leftrightarrow e^{-} + p$	Inelastic, non-interacting, degeneracy (Bruenn '85)
$\bar{\nu}_e + p \leftrightarrow e^{+} + n$	Inelastic, non-interacting, degeneracy (Bruenn '85)

Post Bounce Evolution of CCSNe



LR et al. in prep

Neutrino Heating Rate



Conclusions

- M1 provides a reasonably good method for radiative transfer in quasi-spherical situations
- Long term evolution of post-bounce CCSNe evolution without any imposed symmetries
- Shock runaway occurs in many models, but have not quantified predicted explosion energies
- Significant dependence on resolution and assumed symmetries
- More detailed analysis of post-shock flow required