Numerical Experiments in Core-Collapse Supernova Hydrodynamics

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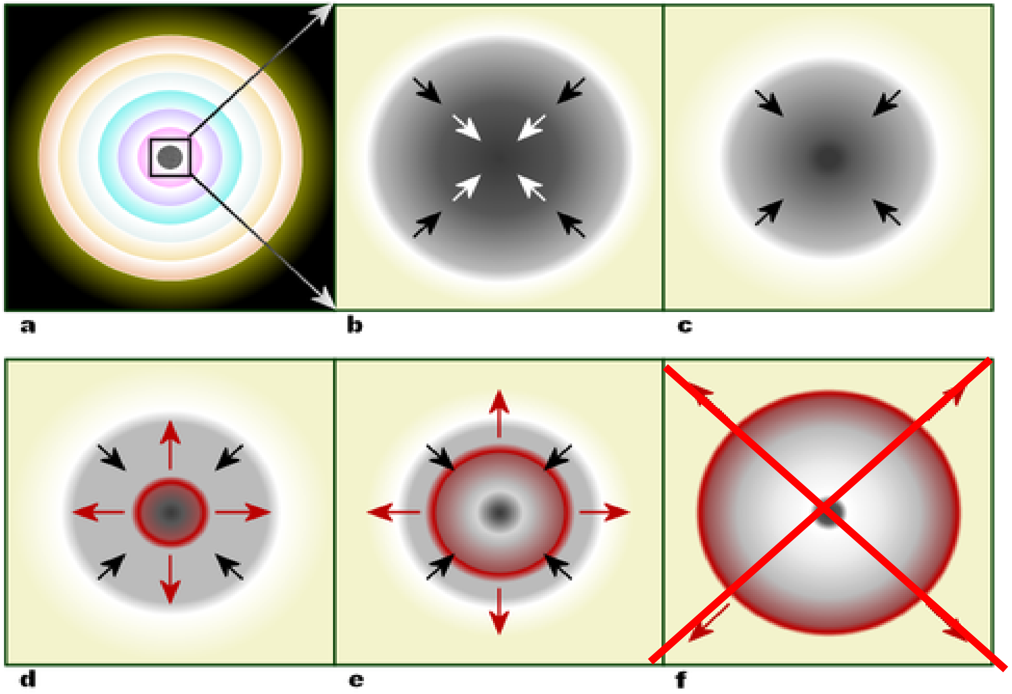
Outline

1) The Explosion Mechanism

2) SASI with **Nuclear Dissociation**

3) Interplay with ν-driven **Convection**

Collapse and Bounce Shock



www.wikipedia.org

- EOS stiffens due to nucleon repulsion: **bounce shock**

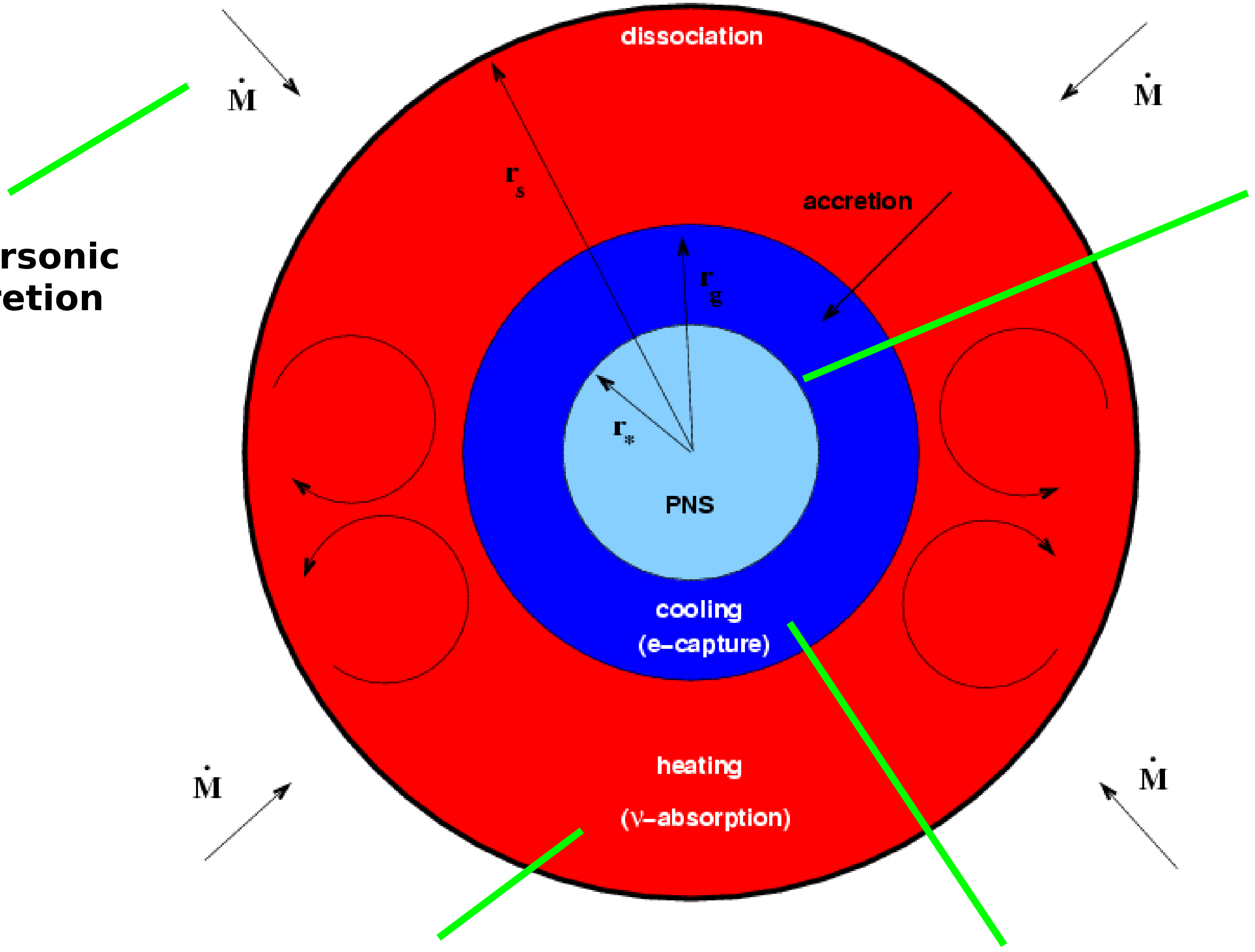
- BUT **stalls** due to nuclear dissociation and neutrino emission

Stalled Shock

Supersonic Accretion

Neutrinosphere

$\tau = 2/3$



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

$$\sim L_\nu \frac{\rho}{r^2}$$

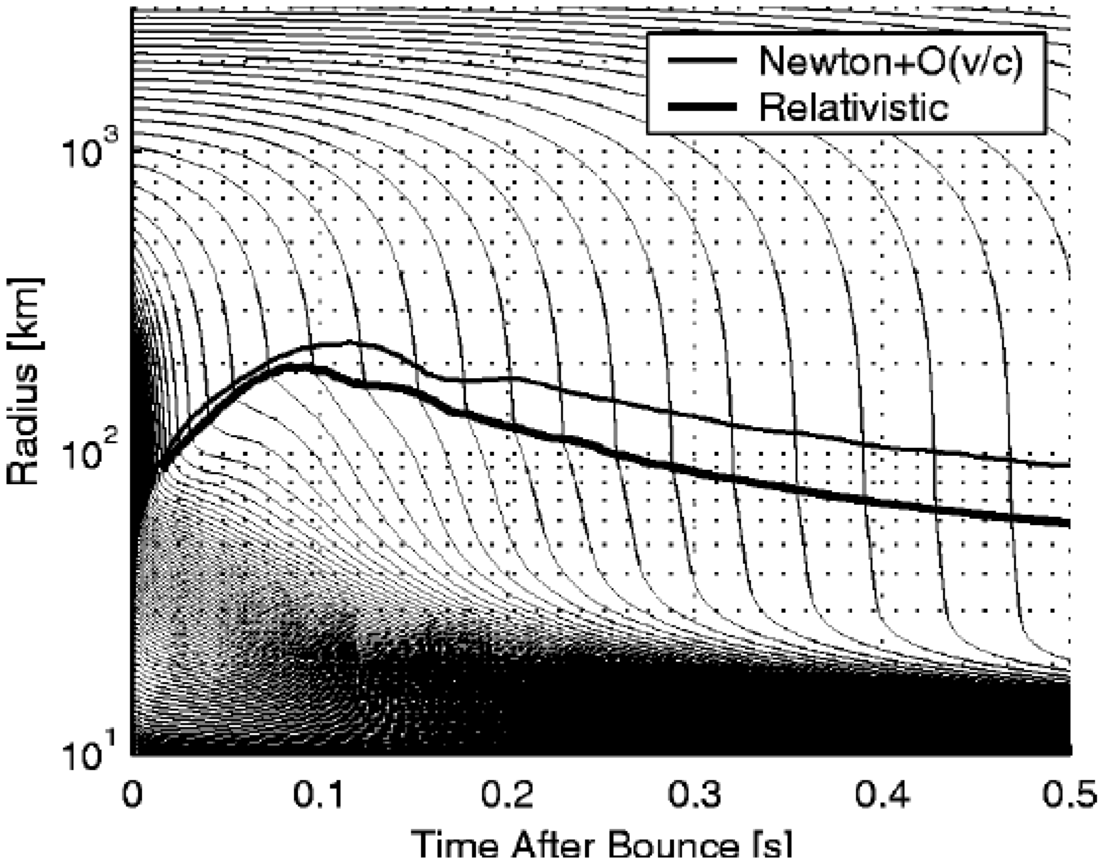
$$e^- + p \rightarrow n + \nu_e$$
$$e^+ + n \rightarrow p + \bar{\nu}_e$$

$$\sim \rho\, T^6$$

Neutrino Mechanism

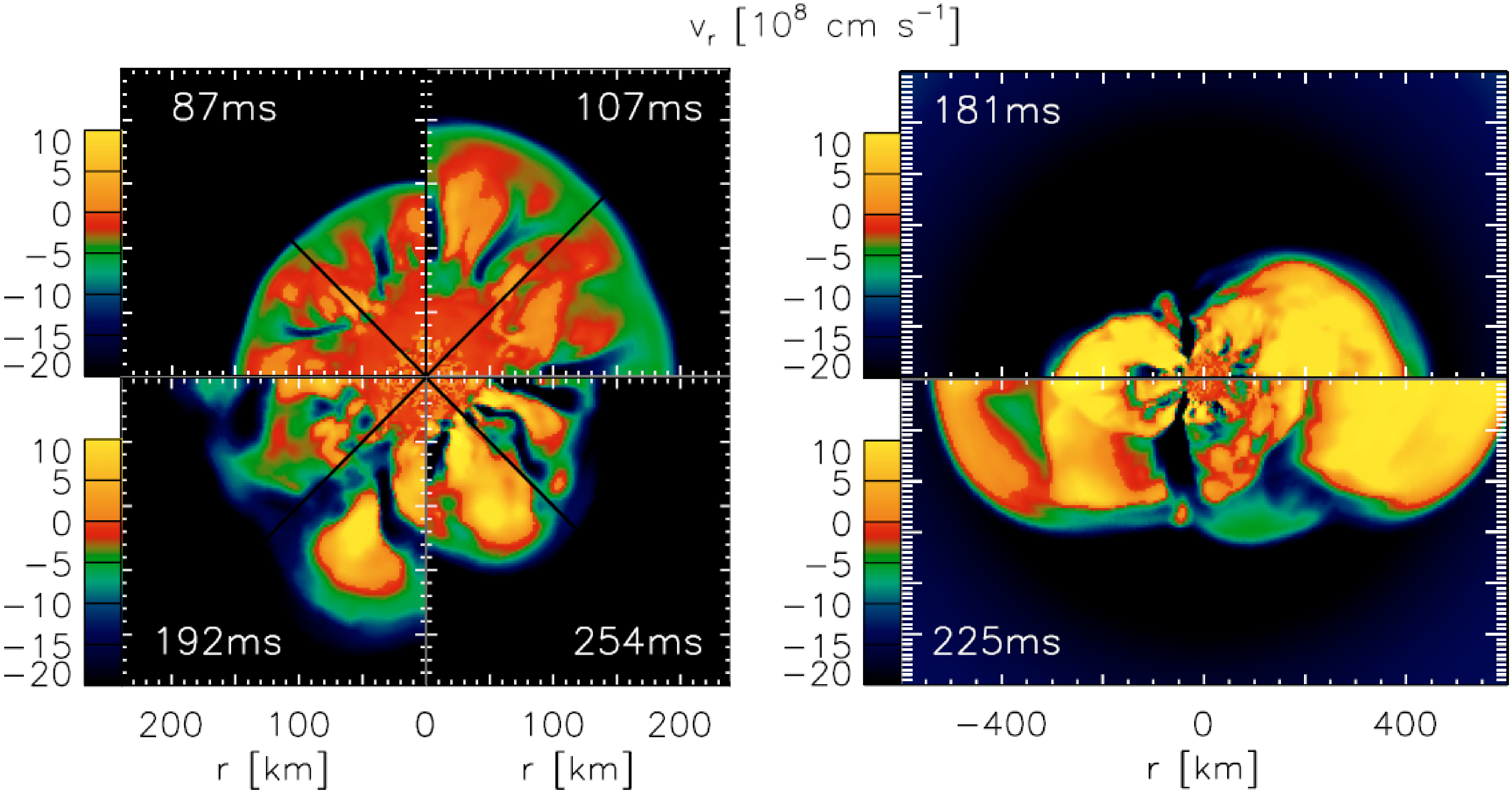
- O-Ne-Mg cores (8-10M_{sun}) **explode** in 1D via neutrino mechanism (Kitaura et al. 2006, Burrows et al. 2007)

- BUT Stars that form iron cores **do not explode in 1D** (Liebendoerfer et al. 2001, Rampp & Janka 2002, Thompson et al. 2003, Sumiyoshi et al. 2005)



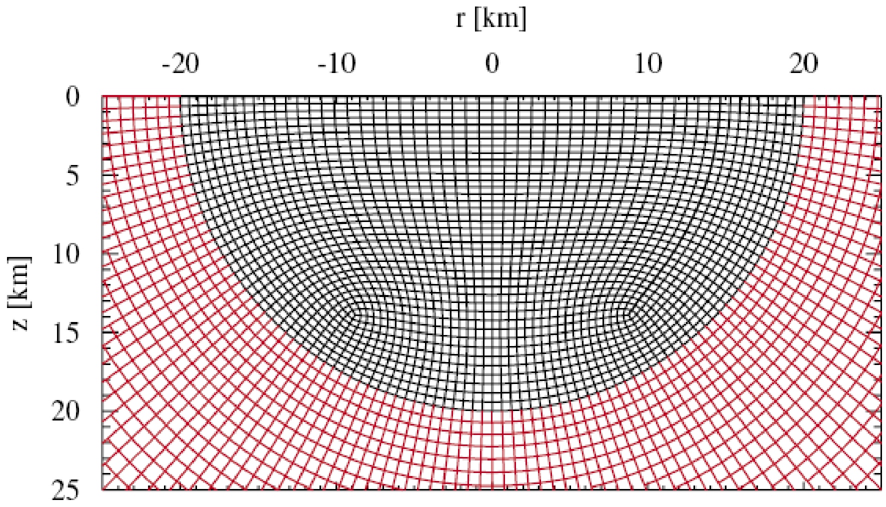
Liebendörfer et al. (2001)

Neutrino Mechanism

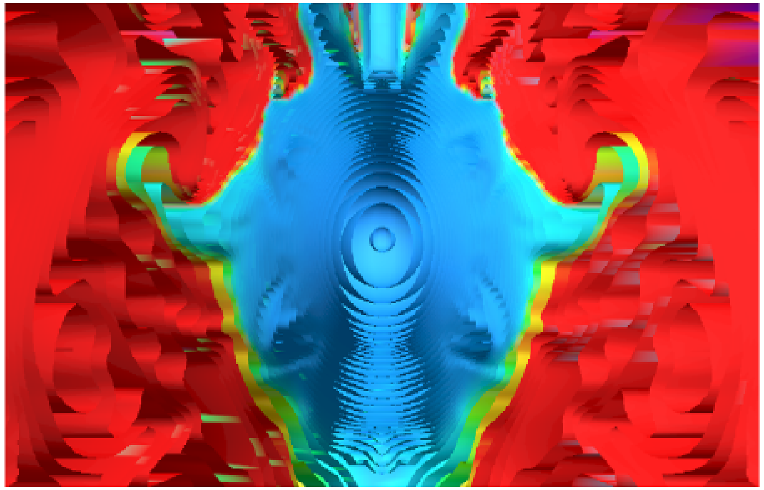


11.2 M_{sun} : Buras et al. (2006)

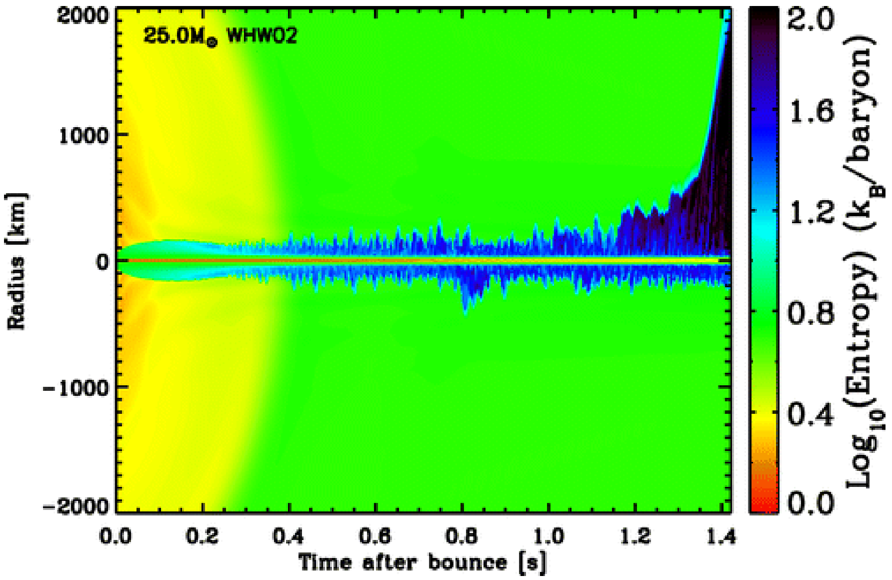
Acoustic Mechanism



Burrows et al. (2007b)



- Anisotropic accretion excites **PNS g-modes**
- Modes dissipated through **acoustic energy**
- Energetic explosions at **late times** (~1s)
- Remains to be confirmed (resolution, dimensionality)



Burrows et al. (2007a)

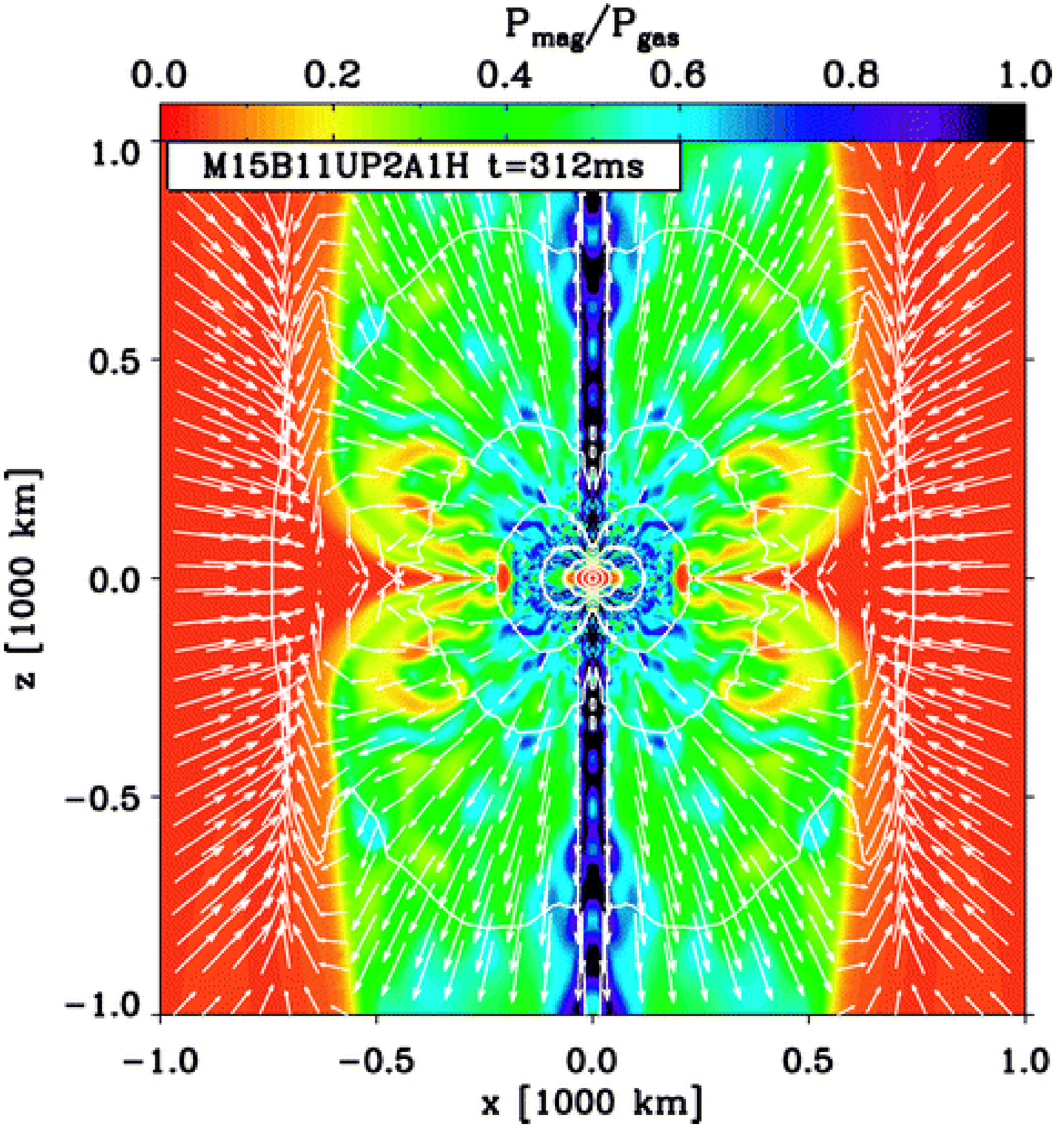
Magnetorotational Mechanism

- Rapid rotation:
  B field amplification
  (Leblanc & Wilson 1970,
  Akiyama 2003)

- **MHD jet** powered explosion (while accreting along the equator)

- Can yield high explosion energy (~1e+52 erg)

- But need **unrealistic initial conditions** with current technology



Burrows et al. (2007c)

Numerical Experiments

Systematic exploration of interplay between

1) **Nuclear dissociation/recombination**
(constant / NSE α,p,n)

2) **Multidimensional hydrodynamics**
(SASI, convection, finite amplitude instability)

3) **Neutrino Heating**

Numerical Setup

2D Time-dependent hydrodynamic simulations with **FLASH 2.5**

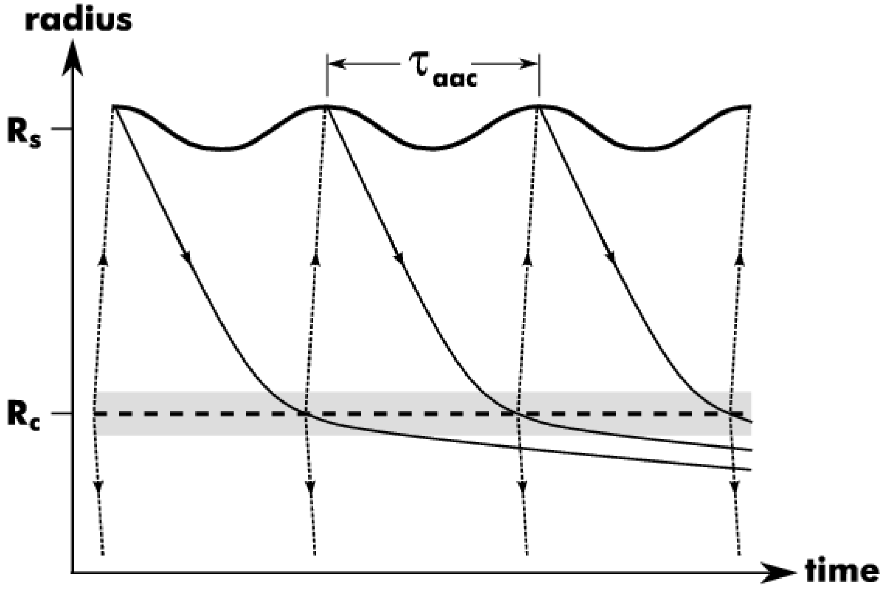
- Ideal gas EOS, γ = 4/3
- Upstream flow adiabatic, constant $\dot{M}$
- Dissociation at shock (simple / NSE)
- Cooling/Heating as source terms
- Hard inner boundary
- Point mass gravity

SASI

Linear phase:

Advective-Acoustic Cycle

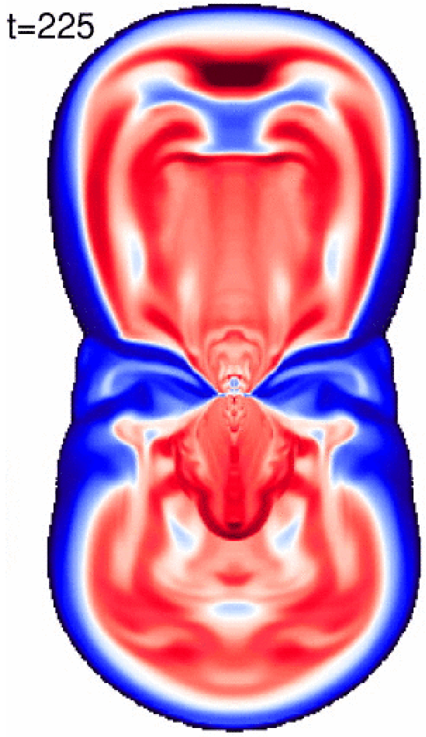
Foglizzo et al. (2007)



Scheck et al. (2008)

Non-linear phase:

Turbulent Kinetic Energy

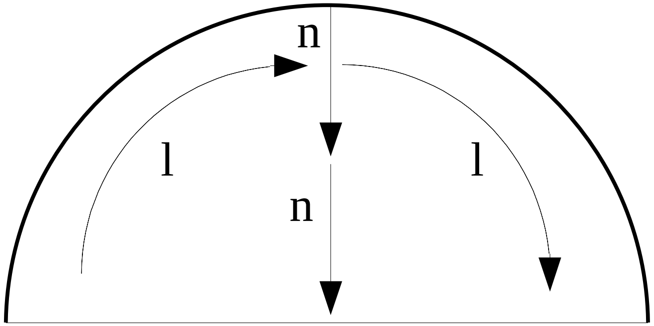


Blondin et al. (2003)

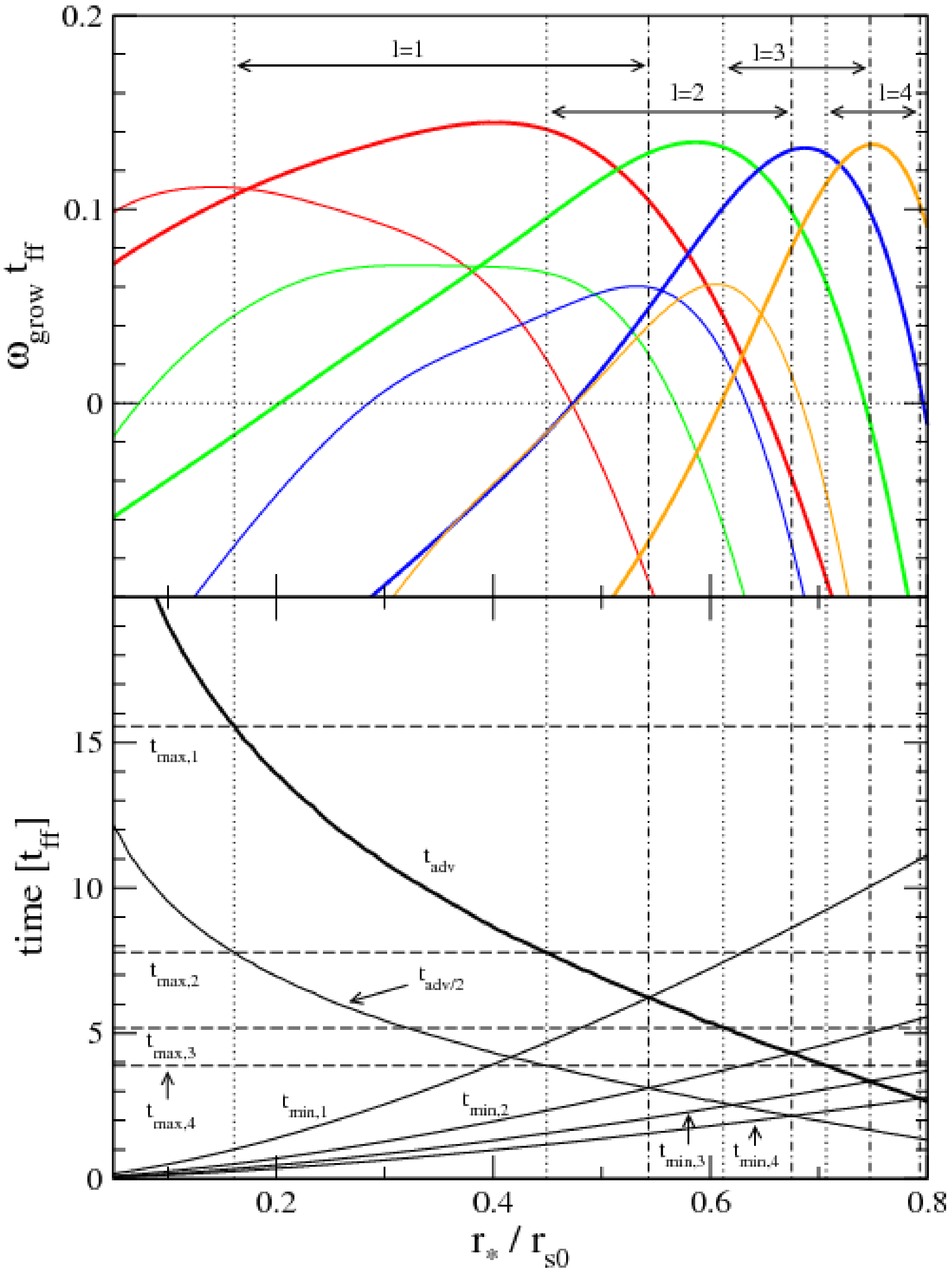
Linear SASI

Peak of growth rate:

$$\frac{t_{SL,min}}{l} < \frac{t_{adv}}{(n+1)} < \frac{t_{SL,max}}{l}$$



l=1 🟥 l=2 🟩 l=3 🟦



$\gamma = 4/3$

RF & Thompson (2009a)

SASI with Nuclear Dissociation

Shock jump conditions (ideal gas):

$$\rho_1 v_1 = \rho_2 v_2$$

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$

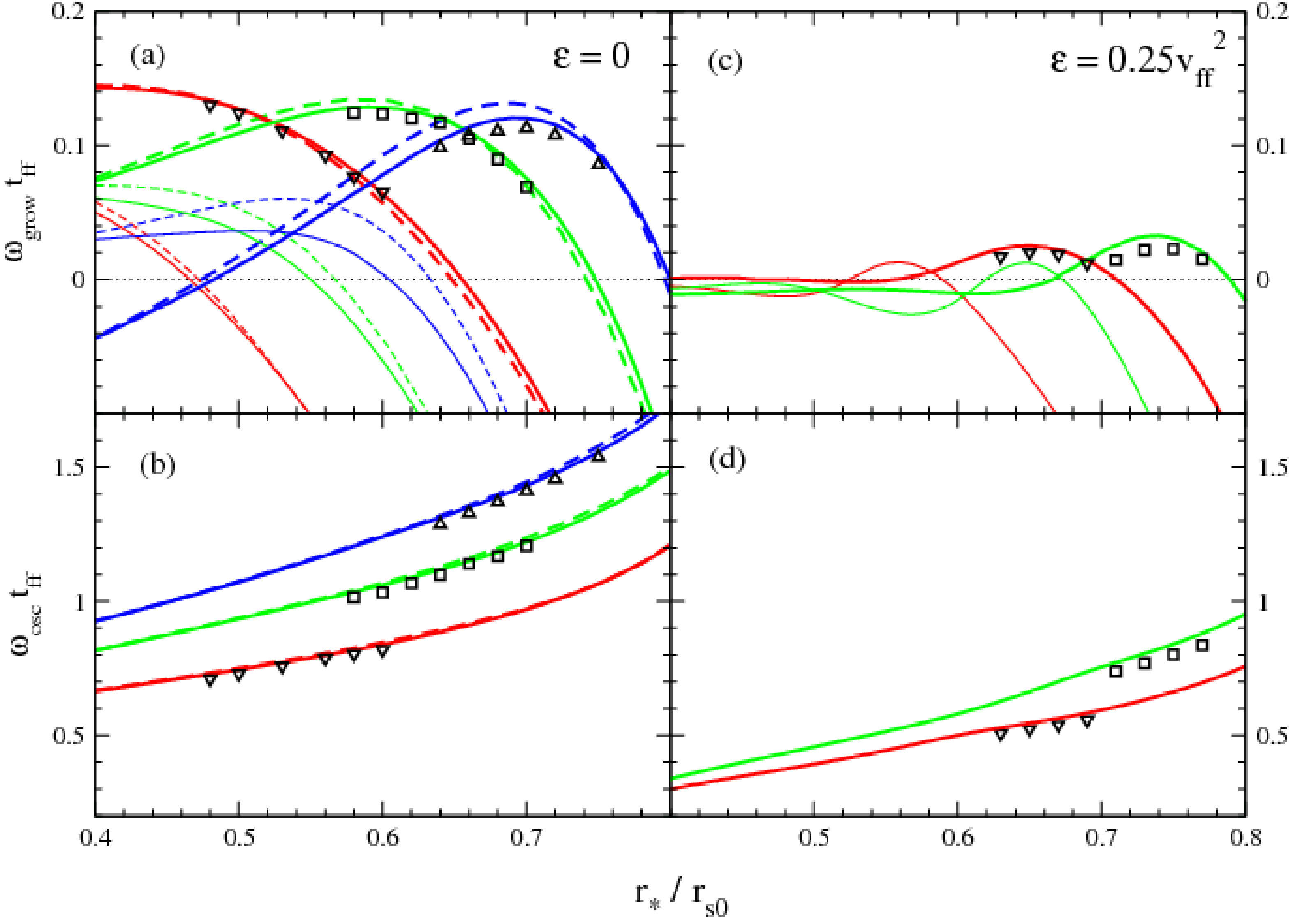
$$\frac{1}{2} v_1^2 + \frac{\gamma}{(\gamma - 1)} \frac{p_1}{\rho_1} = \frac{1}{2} v_2^2 + \frac{\gamma}{(\gamma - 1)} \frac{p_2}{\rho_2} + \boxed{\epsilon}$$

Enhanced **compression factor:**

$$\kappa \equiv \frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)}{(\gamma + M_1^{-2}) - \sqrt{(1 - M_1^{-2})^2 + (\gamma^2 - 1) \frac{2\epsilon}{v_1^2}}}$$

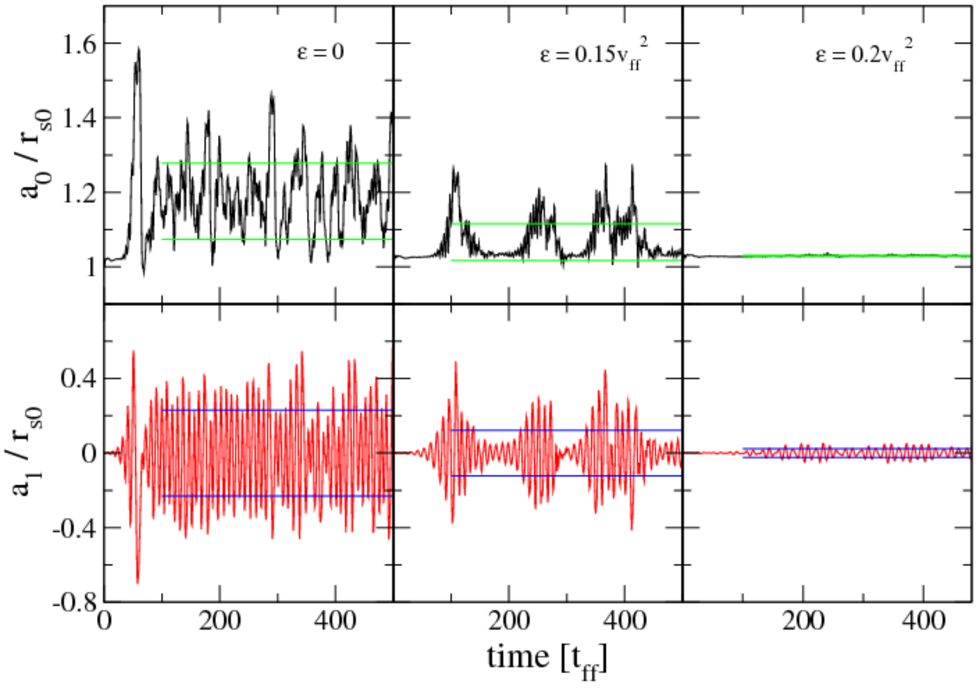
Thompson (2000)

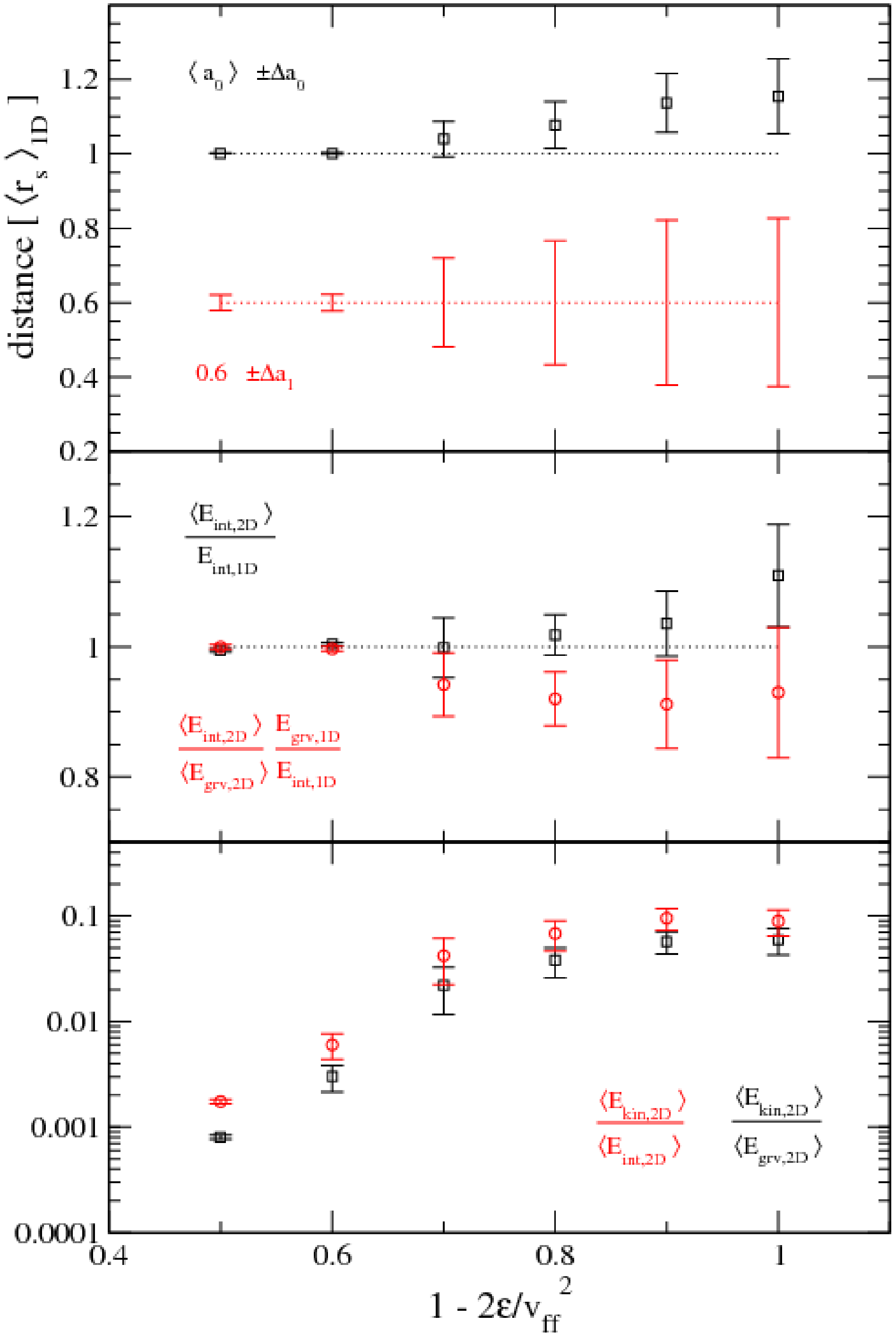
Linear SASI



l=1 — l=2 — l=3 — $\gamma = 4/3$ RF & Thompson (2009a)

Nonlinear SASI





l=0 — l=1 — RF & Thompson (2009a)

- **Saturation Amplitude Reduced**
  (see also Guilet et al. arXiv/0910.3953)

Nonlinear SASI

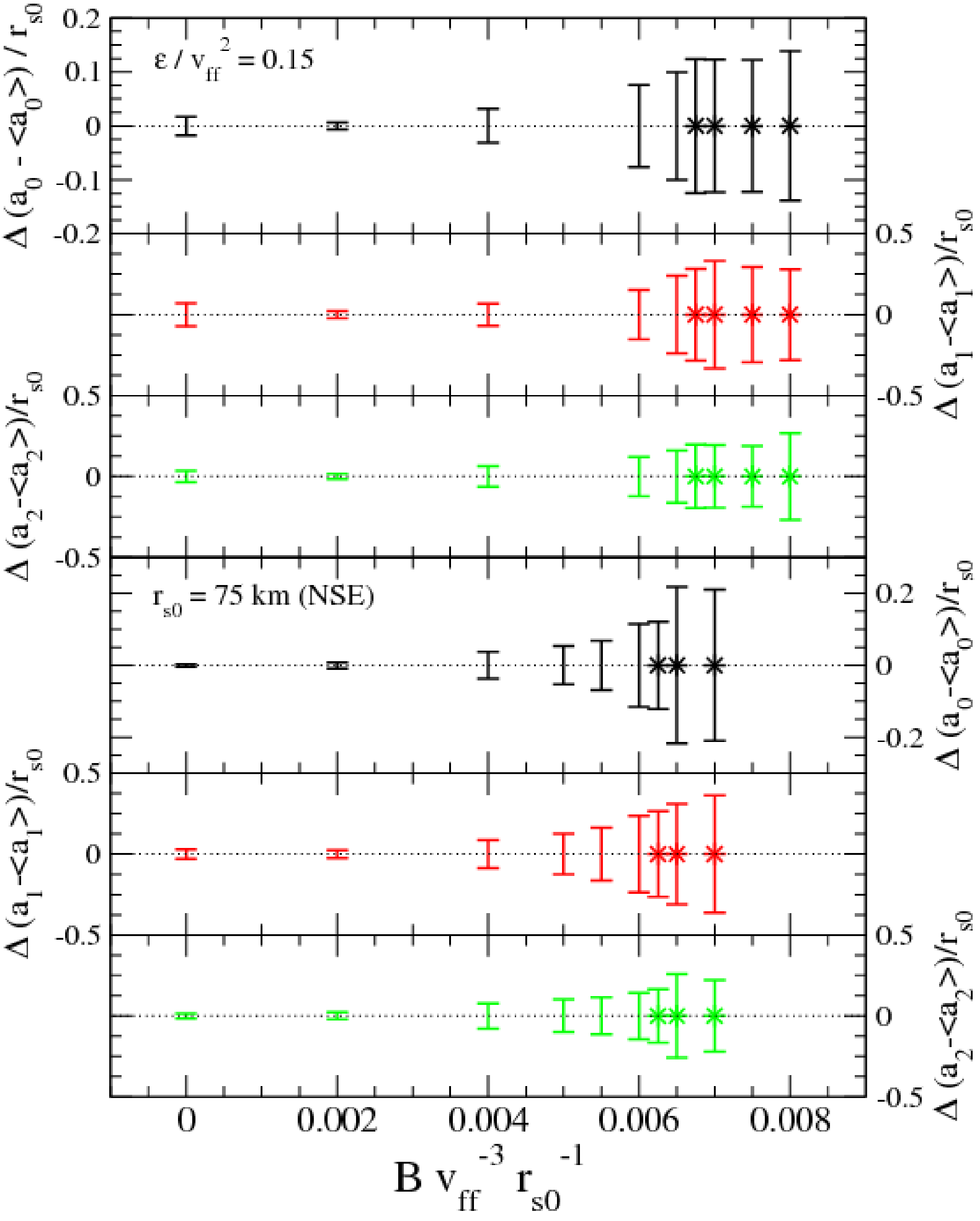
- **Heating**:

$$L_H = \frac{B\rho}{r^2}$$

- Amplitude **increases**

- But **convection** sets in:

  still a SASI?



RF & Thompson (2009b)

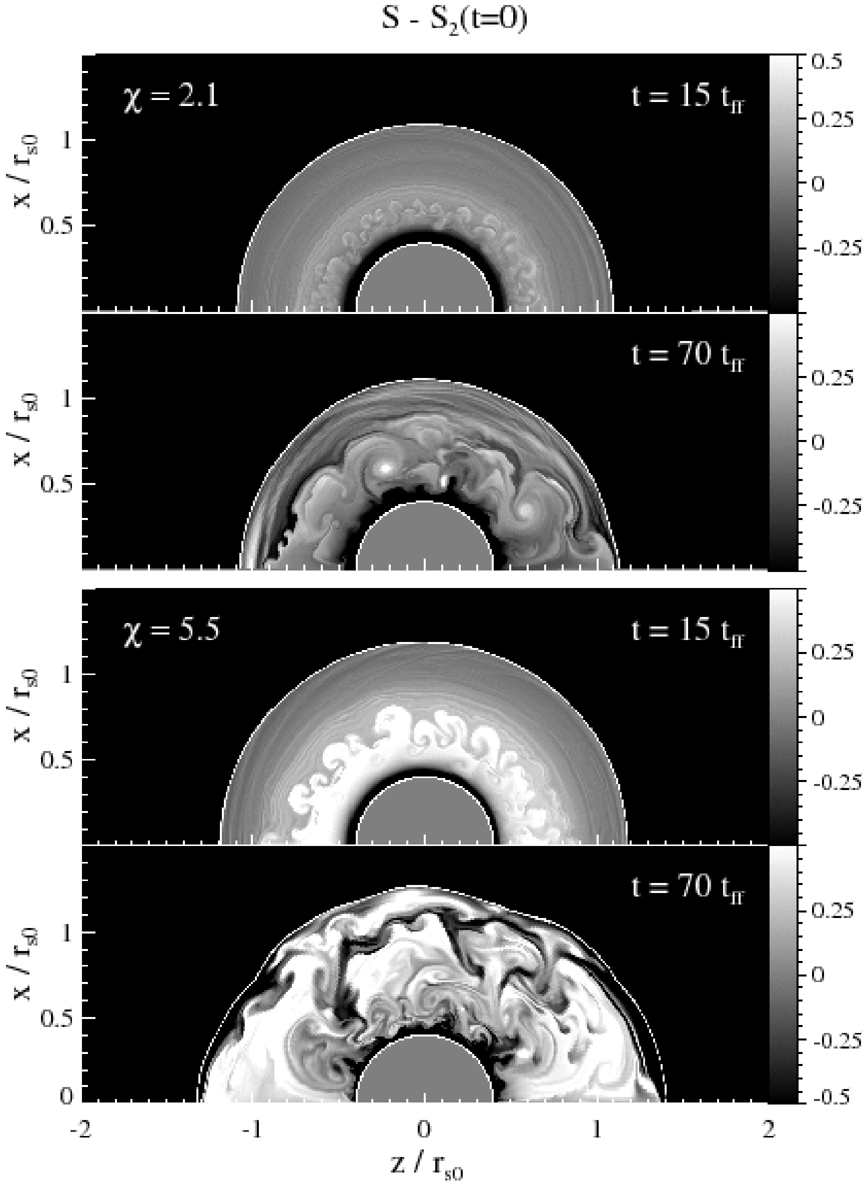
SASI and Heating

- **Advection** vs. **Buoyancy**:

$$\chi \equiv \int_{r_g}^{r_s} |\omega_{BV}| \frac{dr}{|v_r|} > 3$$

Foglizzo et al. (2006)

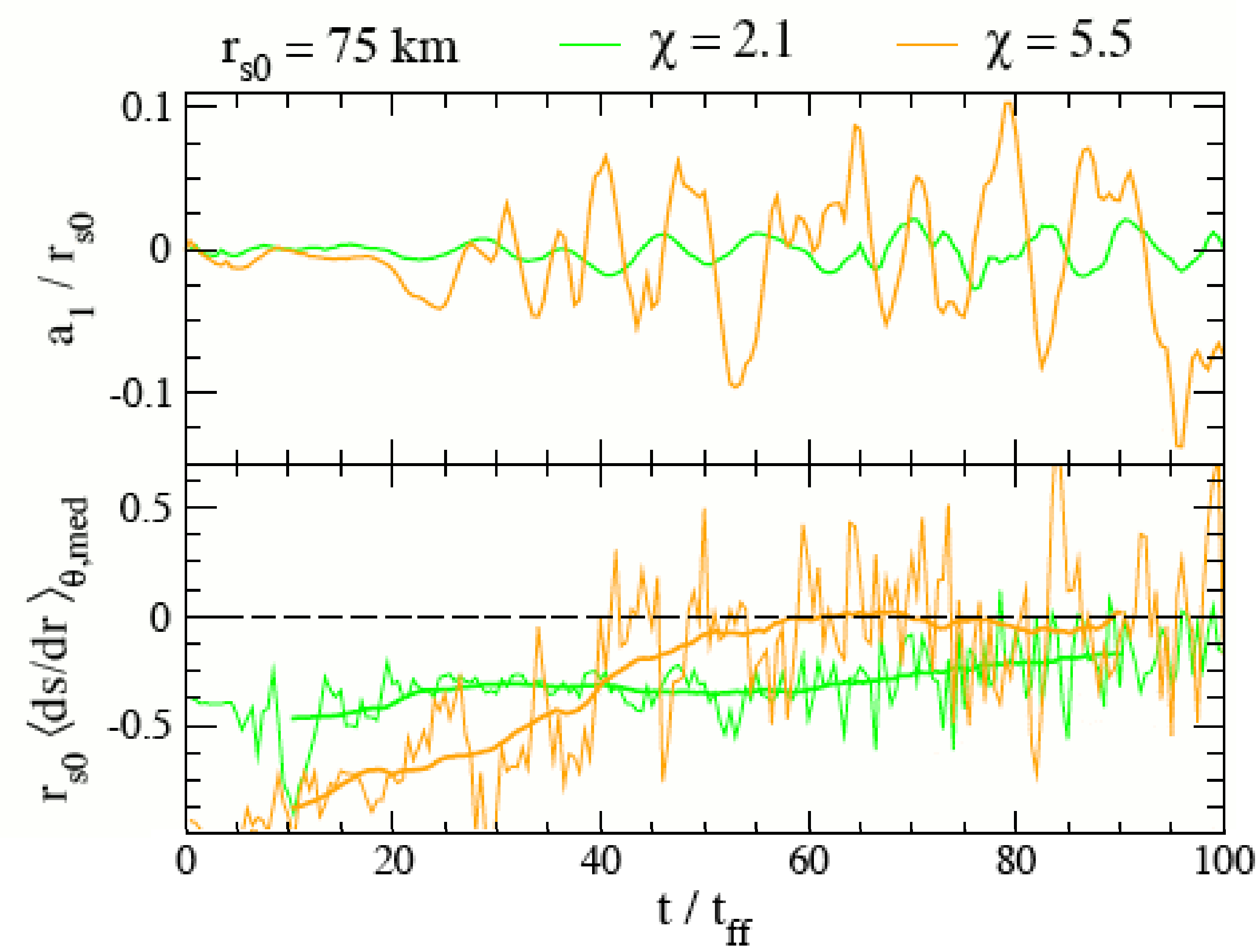
- Scheck et al. (2008): boundary contraction yields large advection velocities at early times



RF & Thompson (2009b)

SASI and Heating

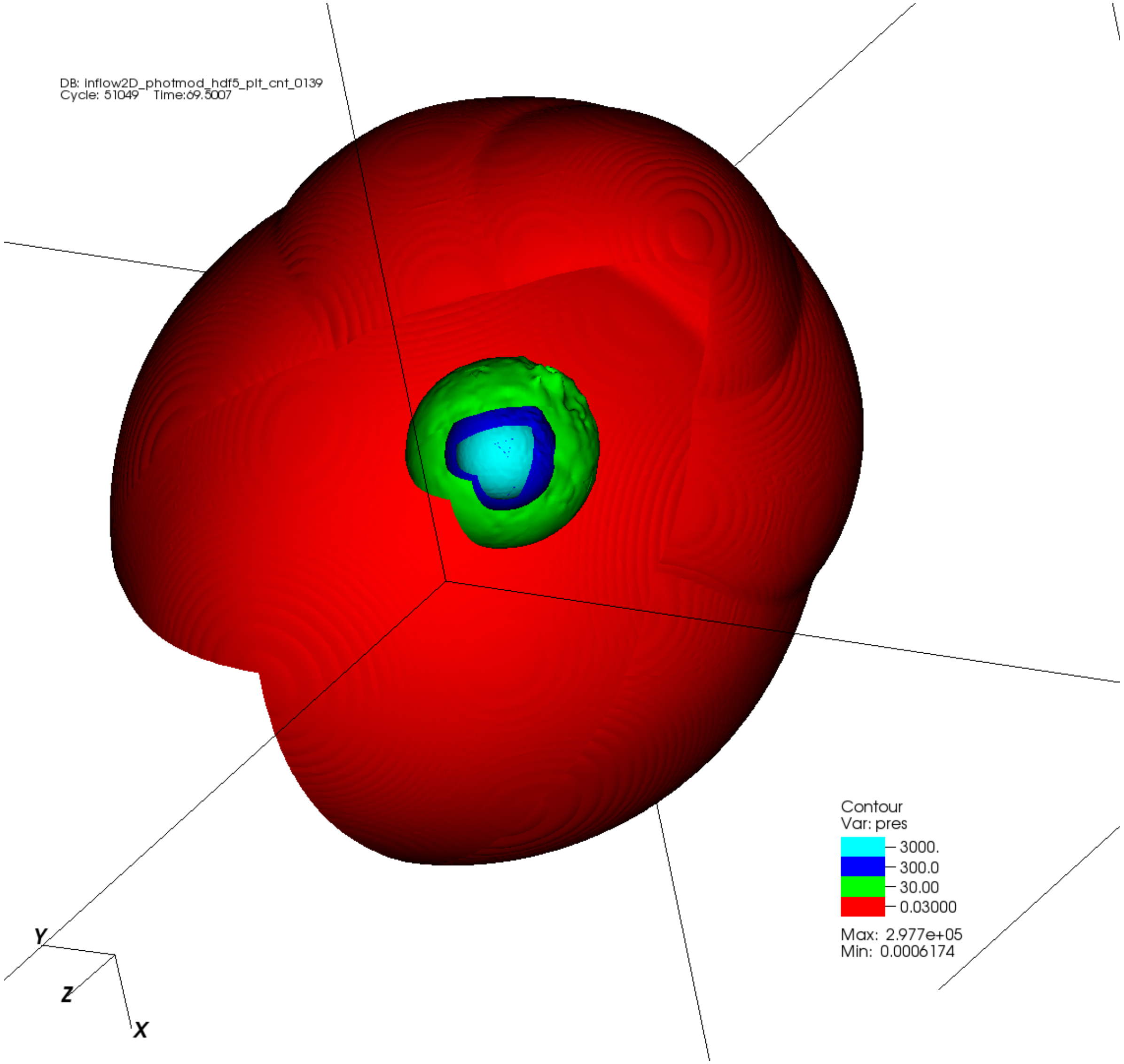
- Onset of convection triggers large amplitude oscillations



RF & Thompson (2009b)

Need 3D!

3D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Summary

1) There is increasing evidence that the explosion mechanism of core-collapse supernovae is **intrinsically multidimensional,** involving large scale hydrodynamic instabilities

2) Nuclear dissociation **decreases linear growth rates** and **saturation amplitude** of SASI

3) **Convection** forces large amplitudes (but is that still the SASI?)

4) Need **3D calculations** to properly understand the dynamics (large scale modes may not dominate)