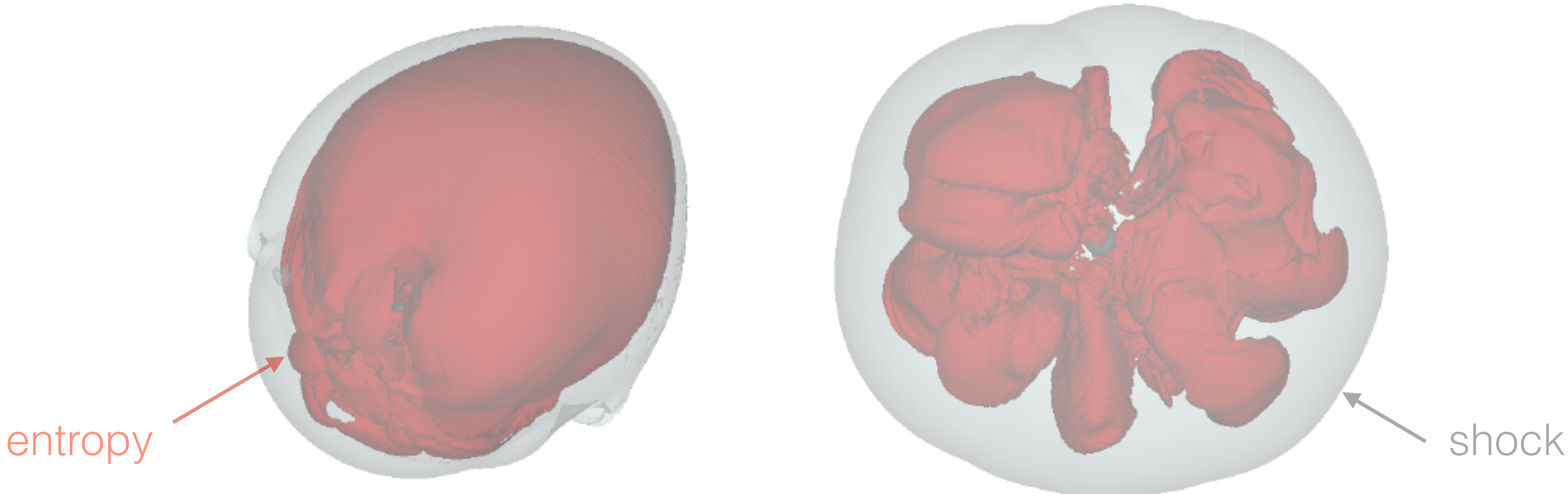

SASI- and Convection-Dominated Core-Collapse Supernovae

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Neutrino Mechanism

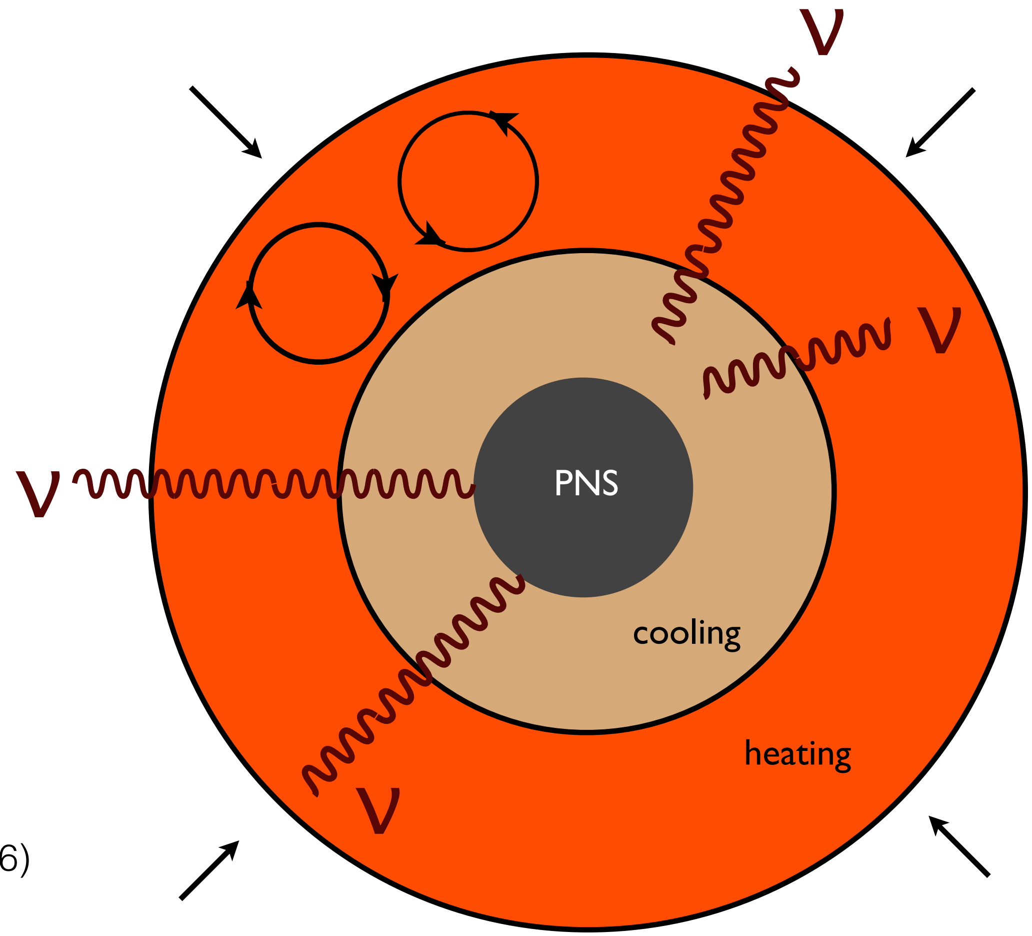
Bethe & Wilson (1985)

- Works in 1D only for lightest progenitors (e-capture SNe)

  e.g., Kitaura et al. (2006)

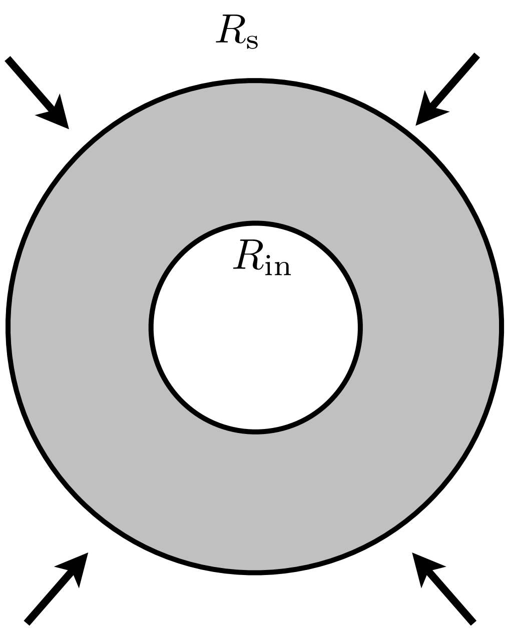
- If iron core formed, need to break spherical symmetry to improve efficiency

  Liebendoerfer et al. 2001, Rampp et al. 2002, Thompson et al. (2002), Sumiyoshi et al. (2006)



Hydrodynamic Instabilities

(region between PNS and shock)



1. Neutrino-Driven Convection

   local, non-oscillatory, heat/buoyancy

   e.g., Bethe (1990), Murphy et al. (2013)

2. Standing Accretion Shock Instability (SASI)

   global, oscillatory, wave cycle

   Blondin et al. (2003), Foglizzo et al. (2007)

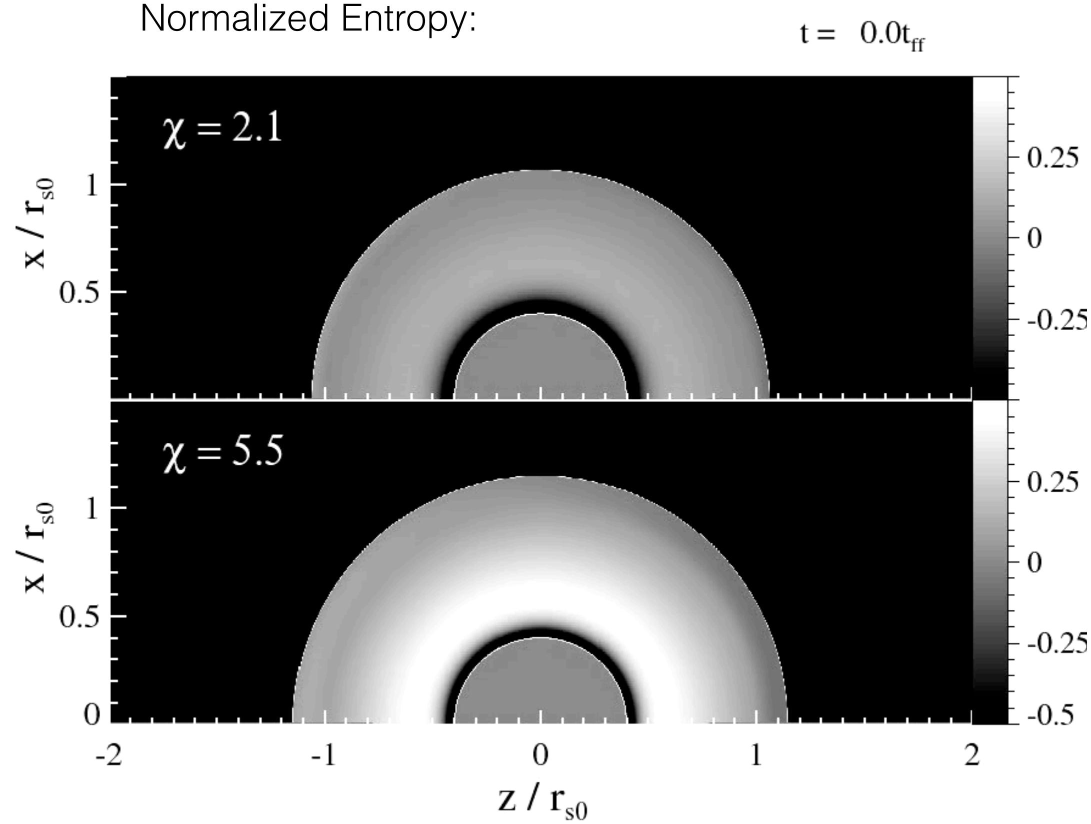
Buoyancy vs. Advection

$$\chi = \int_{\mathrm{gain}} \frac{|\omega_{\mathrm{BV}}|}{|v_r|} \mathrm{d}r$$

$$\chi_{\mathrm{crit}} \simeq 3$$

Foglizzo et al. (2006)

Normalized Entropy:



RF & Thompson (2009)

2D vs. 3D: Kinetic Energy

- 3D no more favorable for explosion than 2D

Hanke et al. (2013) Handy+ (2014)

Dolence+ (2013) Lenz+ (2015)

Abdikamalov+ (2014) Takiwaki+ (2014)

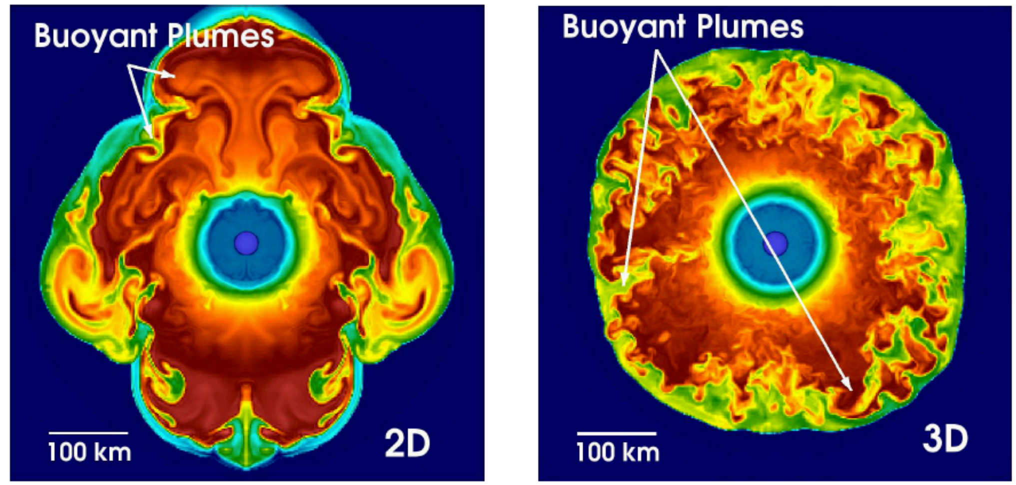
Couch & O'Connor (2014)

- But most studies find that convection dominates

- Kinetic energy on large scales favors explosion

Hanke et al. (2012)

Dimensionality and turbulence:



Murphy+ (2013)

Vorticity equation:

$$\frac{\mathrm{d}\vec{\omega}}{\mathrm{d}t} = (\vec{\omega} \cdot \nabla)\vec{v} - \vec{\omega}(\nabla \cdot \vec{v}) + \frac{1}{\rho^2}\nabla\rho \times \nabla p + ...$$

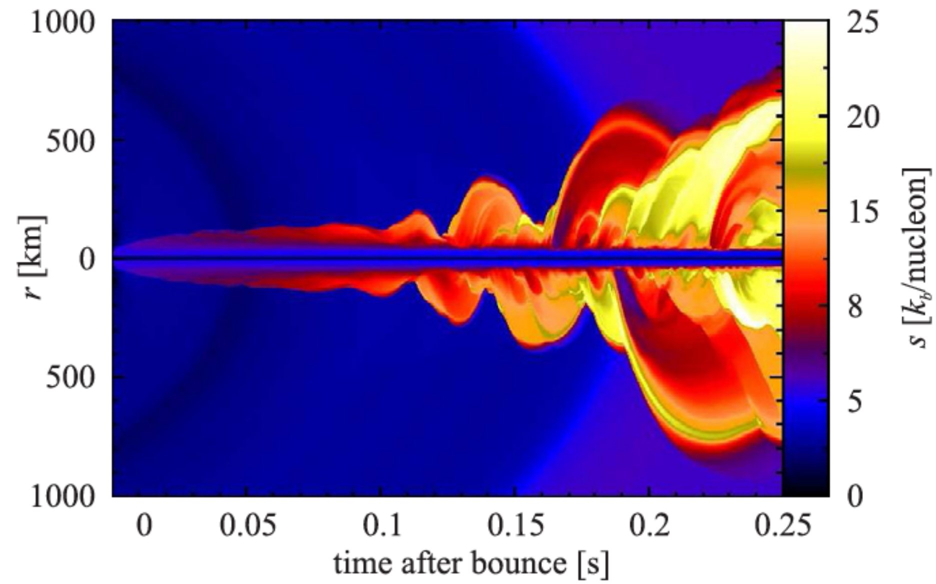
vortex stretching vanishes in 2D
(known for decades by fluid dynamicists)

Diversity of Explosion Paths

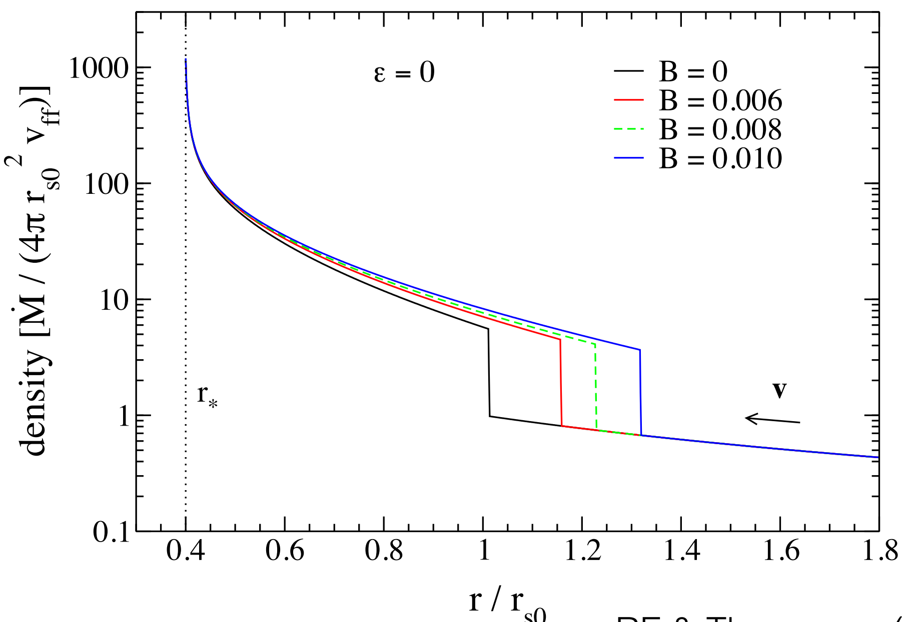
- 27 $M_\odot$ star: first SASI-dominated explosion in a full-physics model (2D) ⟶

Müller, Janka, & Heger (2012)

SASI-dominated explosion (entropy):



Initial density profile for different heating:

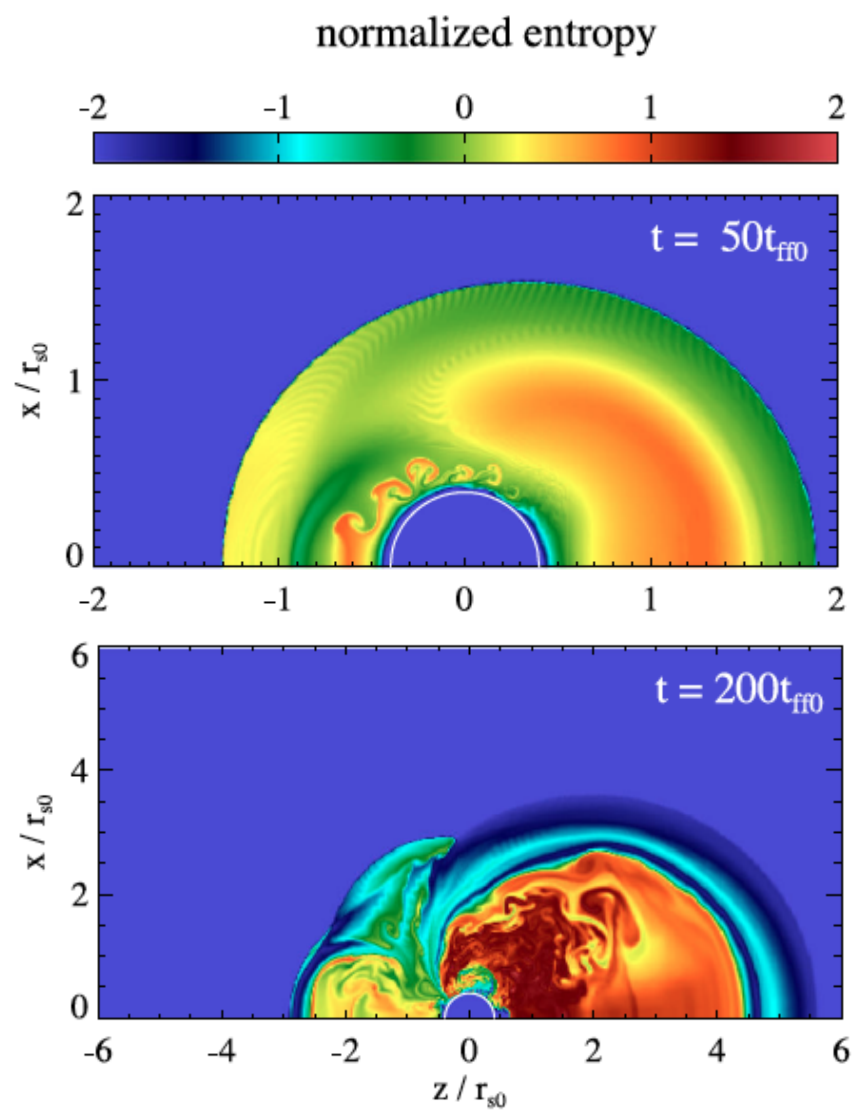


RF & Thompson (2009)

- Parametric setup: tune to obtain explosion in well-defined parameter regime

Parametric 2D Models:

- Turbulence in gain region shares features with full-physics models
- SASI and convection-dominated explosion generate large high-entropy bubbles
- Bubble formation mechanism is the key difference



RF, Müller, Foglizzo & Janka (2009)

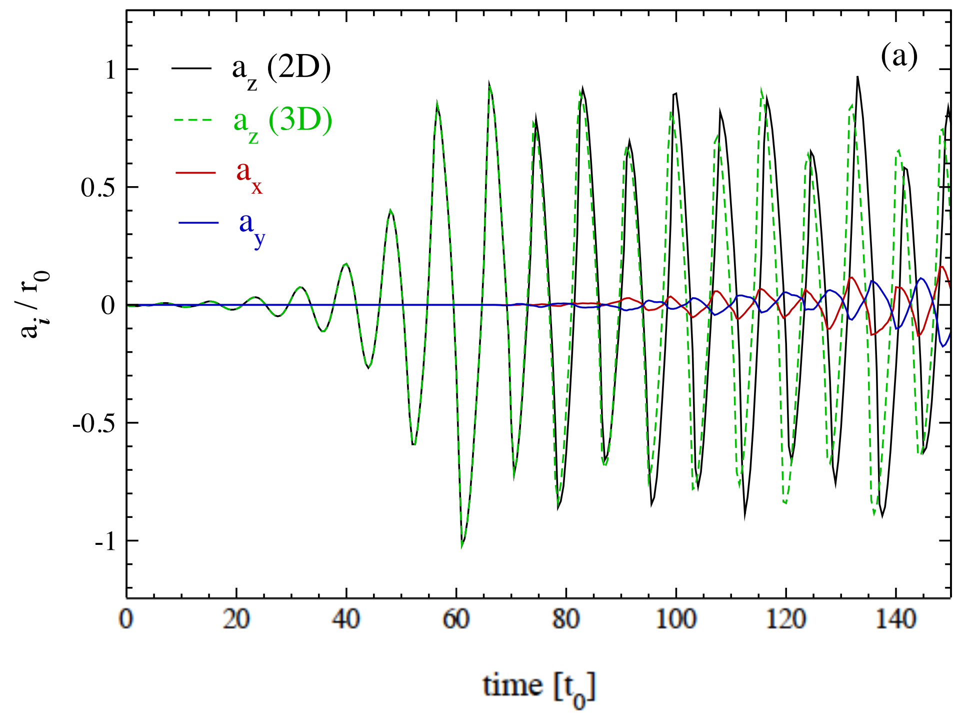
Extension to 3D

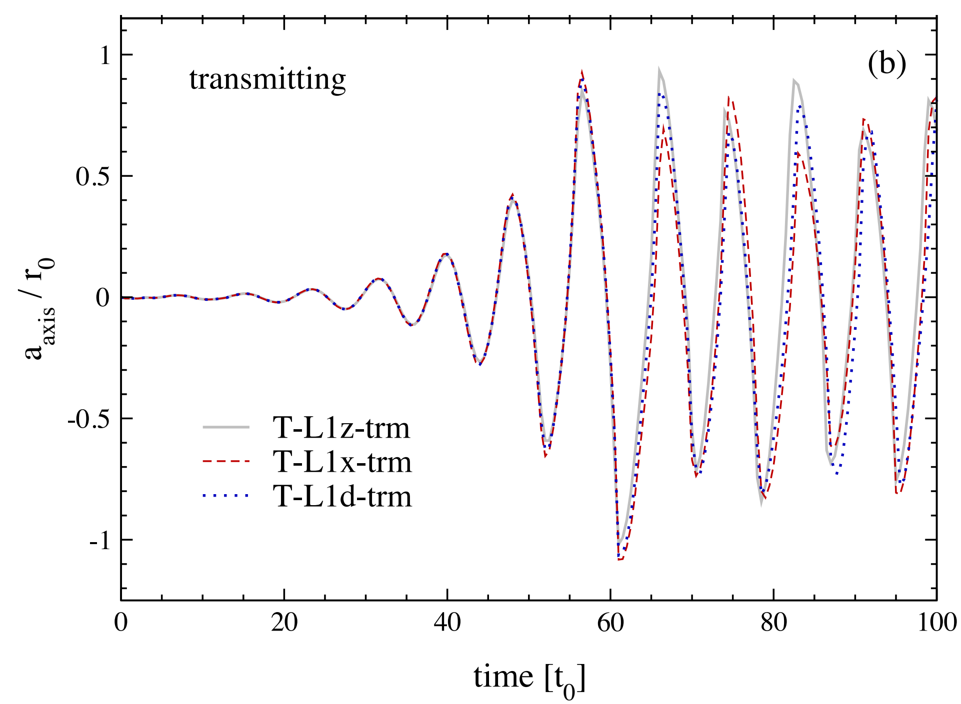
- Extend FLASH3.2 to allow for 3D spherical coordinates (PROMETHEUS-based)

- SASI can be used to test the isotropy of the code in 3D, and consistency with 2D

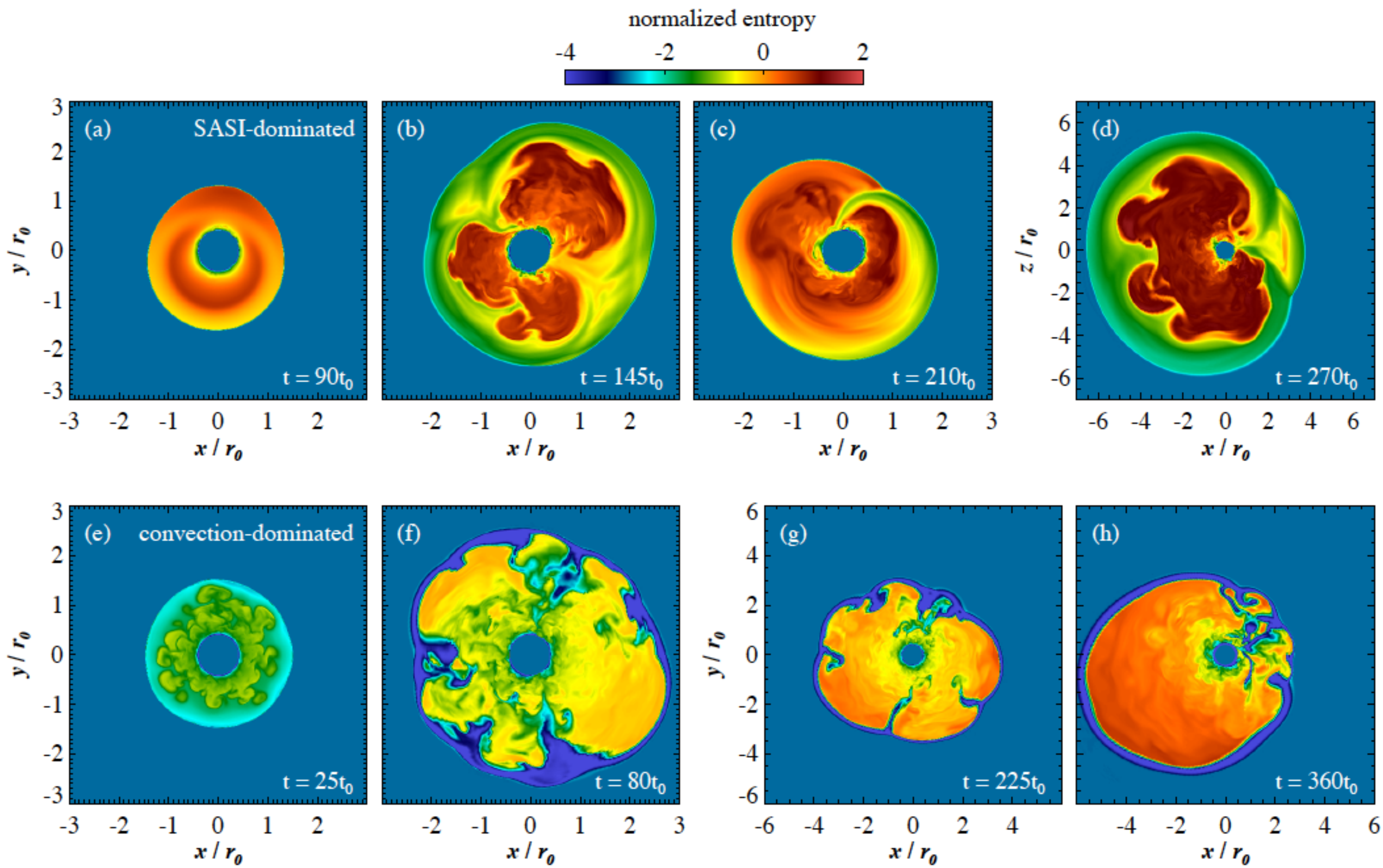
RF (2015)

Shock dipole coefficient:

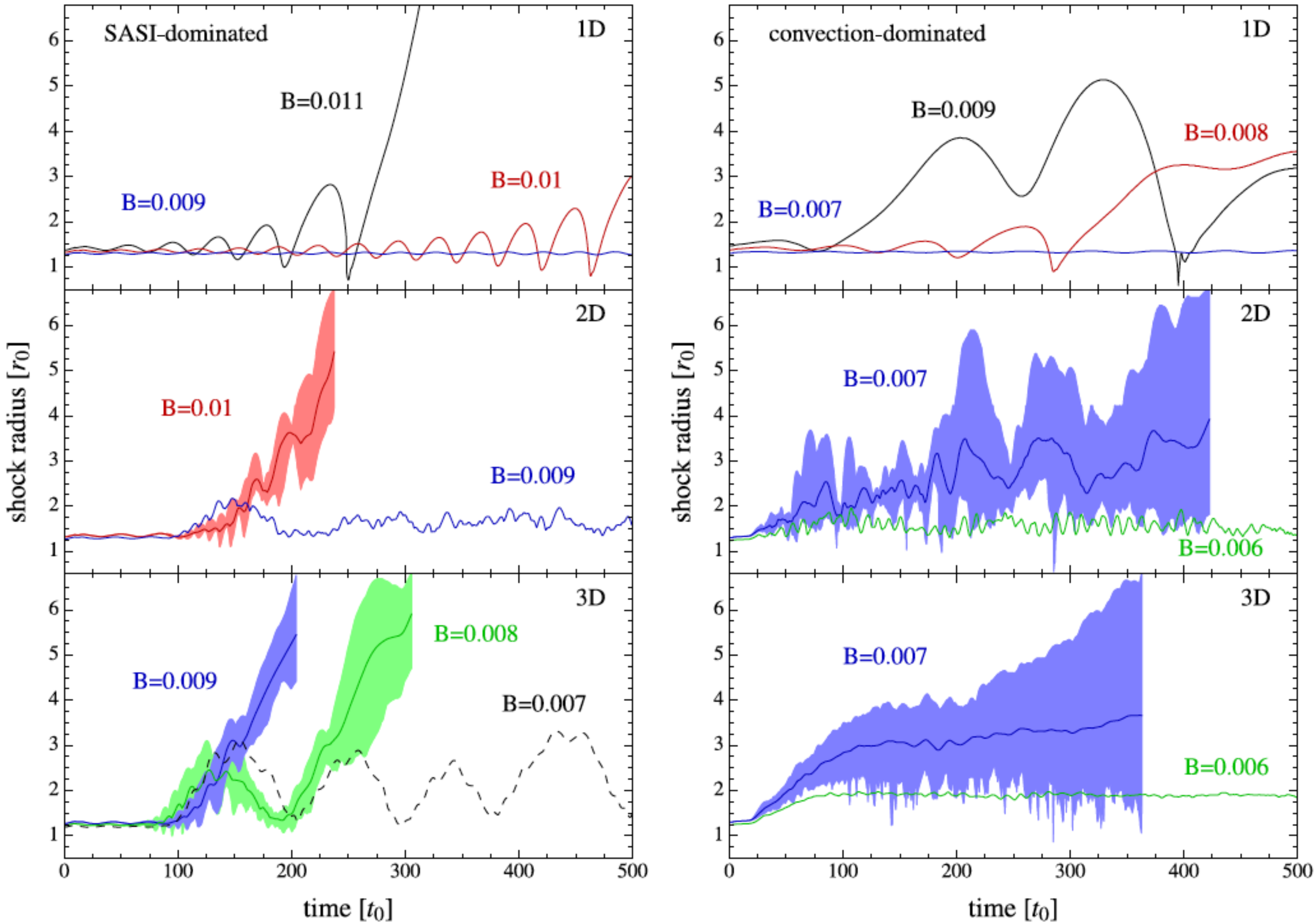




3D: Transition to Explosion



RF (2015)

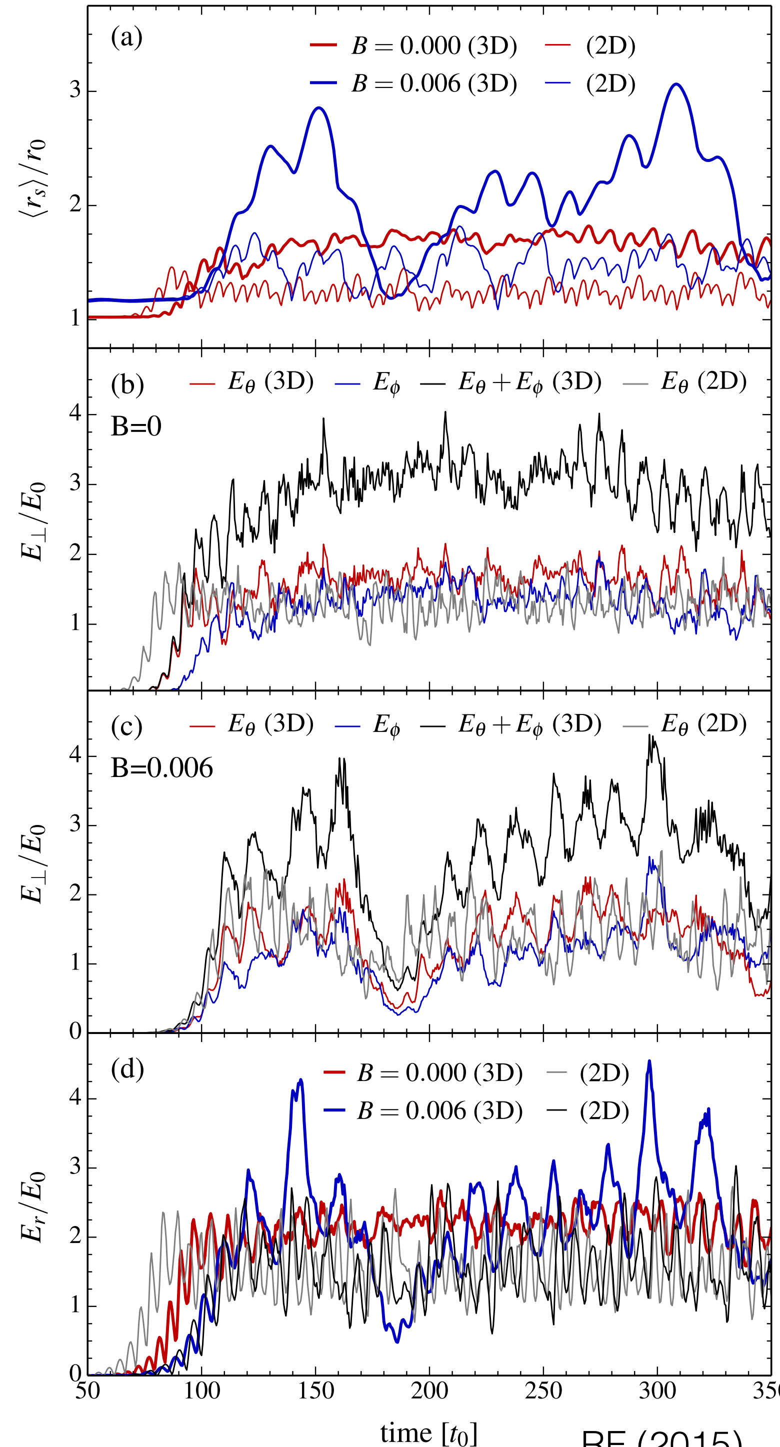


SASI-dominated
1D
B=0.011
B=0.01
B=0.009
2D
B=0.01
B=0.009
3D
B=0.009
B=0.008
B=0.007
convection-dominated
1D
B=0.009
B=0.008
B=0.007
2D
B=0.007
B=0.006
3D
B=0.007
B=0.006
shock radius [r_0]
time [t_0]

RF (2015)

Kinetic Energy

- Spiral modes (3D) provide more transverse kinetic energy than a sloshing mode (2D), even without heating
- With heating: large bubbles are formed, resulting in shock excursions. Larger in 3D



Shock Radius

Transverse KE (no heating)

Transverse KE (with heating)

Radial KE

RF (2015)

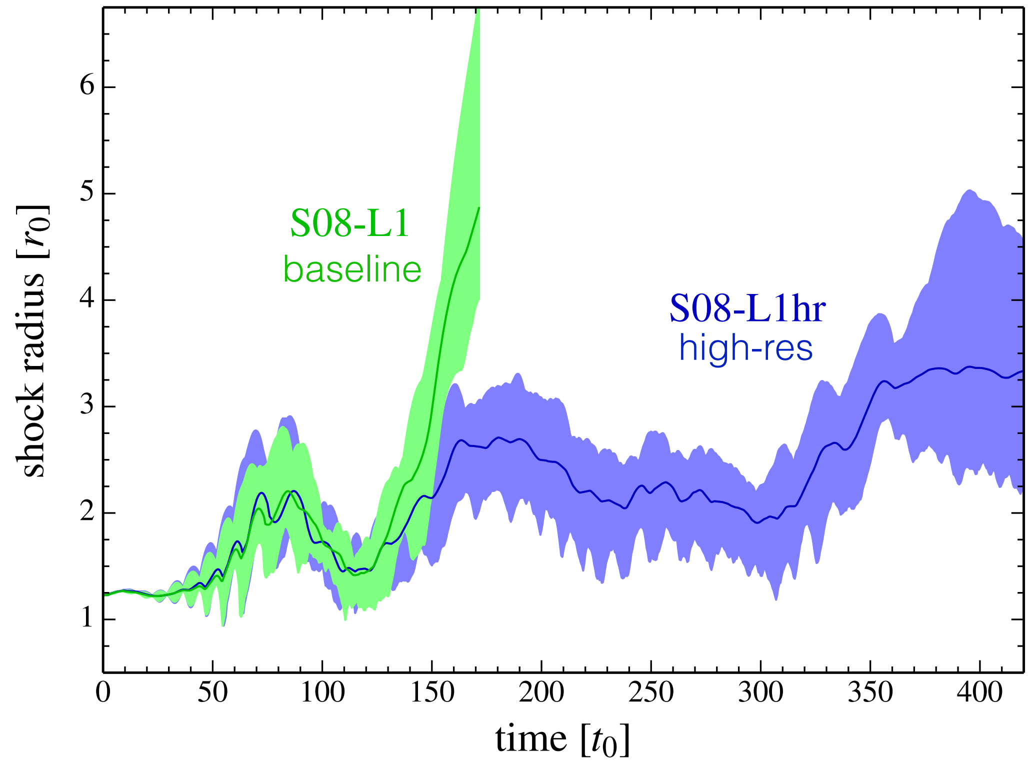
Resolution

- Higher resolution is detrimental for 3D models

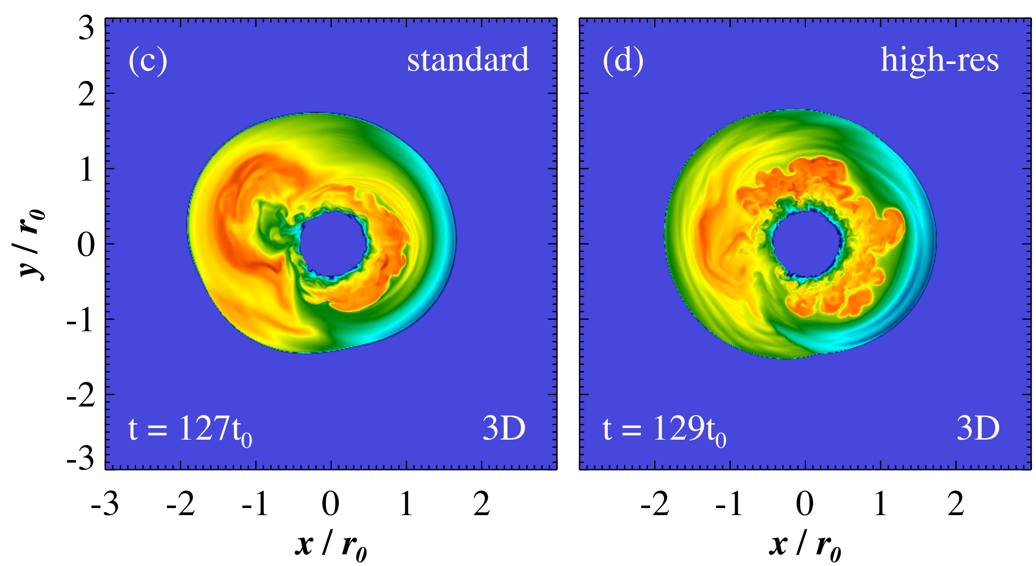
(consistent with previous work)

- Turbulence is more efficient at shredding bubbles

Same parameters except angular resolution:



RF (2015)



Summary

RF (2015), arXiv:1504.07996

1. SASI-dominated explosions are possible in 3D

2. If SASI-dominated, 3D is more favorable than 2D (by up to ~20% in L_ν) because spiral modes generate more kinetic energy than a sloshing mode

3. Convection-dominated models show a much smaller difference between 2D and 3D (as in previous work)

4. Is this parameter space ever achieved in Nature?

Thanks to: