Core-collapse Supernove through Cosmic Time…

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Why study supernovae?

Why do some stars explode?

What leads up to the collapse?

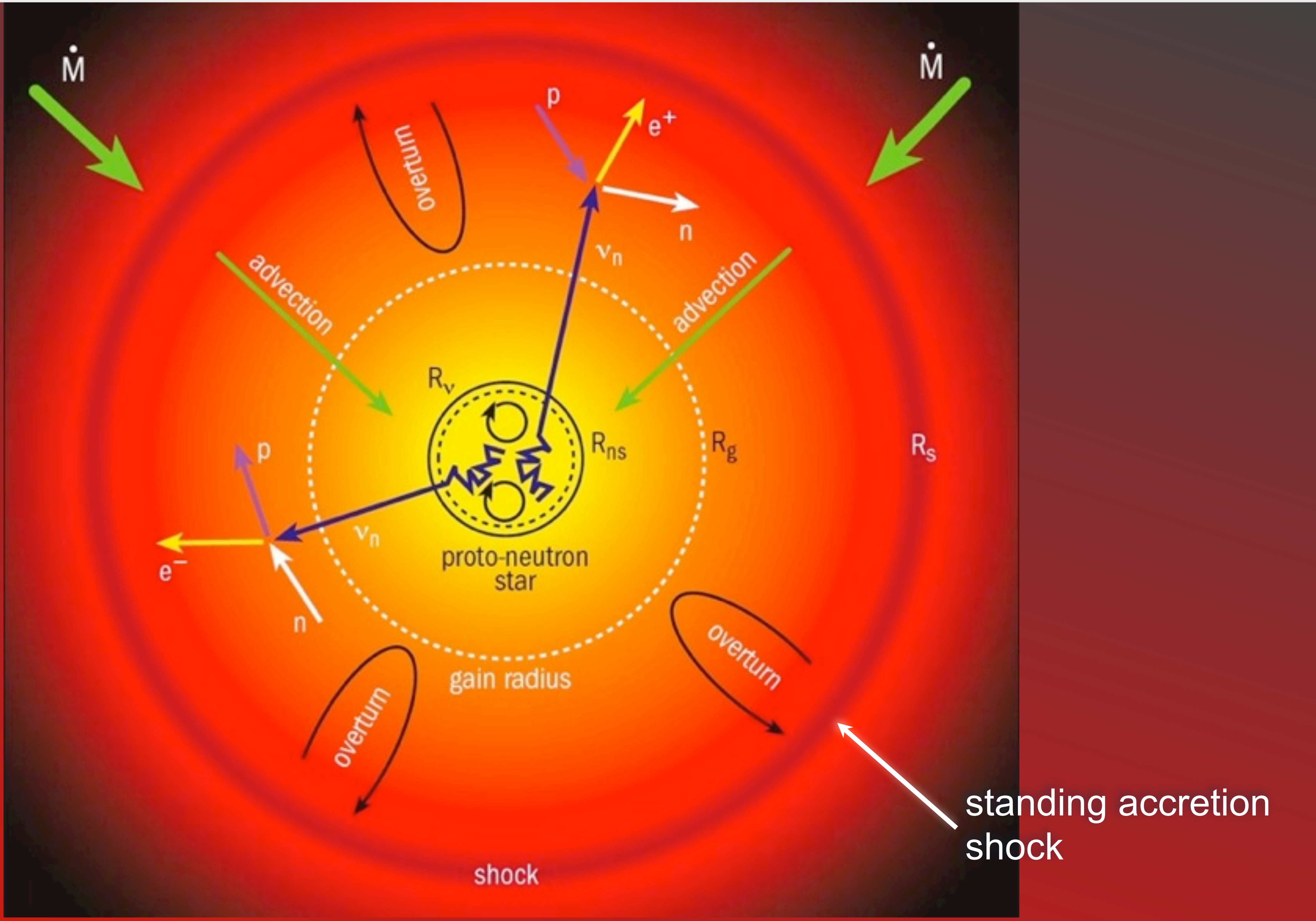
How does collapse of the core result in an explosion?

SN 1987A in LMC

Study exotic physics (nuclear matter, neutrinos, GR) and signals (neutrino, GW)

Understand the generation of elements and their ejection.

Reviving stalled shock with neutrino heating



Adapted from Hillebrandt, Janka, & Müller, 2006, Sci. Am 295, 4, 42

Ingredients

Matching the physical conditions to numerical inputs to reflect the physical fidelity of the system.

Supernovae	Simulations
Pre-supernova stellar history	Stellar evolution models
General Relativity	Full/Approximate/Newtonian
Fluid dynamics & Instabilities	Grids/Resolution/Symmetry
Equation of State	Nuclear/Electron/Network
Neutrino Transport	Relativity/Moments/Spectral/ Ray-by-Ray
Neutrino-matter interactions	Which ones are needed?

CHIMERA

CHIMERA has 3 “heads”

* Spectral Neutrino Transport (MGFLD-TRANS, Bruenn) in Ray-by-Ray Approximation using modern neutrino opacities
* Shock-capturing Hydrodynamics (VH1 [PPM], Blondin)
* Nuclear Kinetics (XNet, Hix & Thielemann)

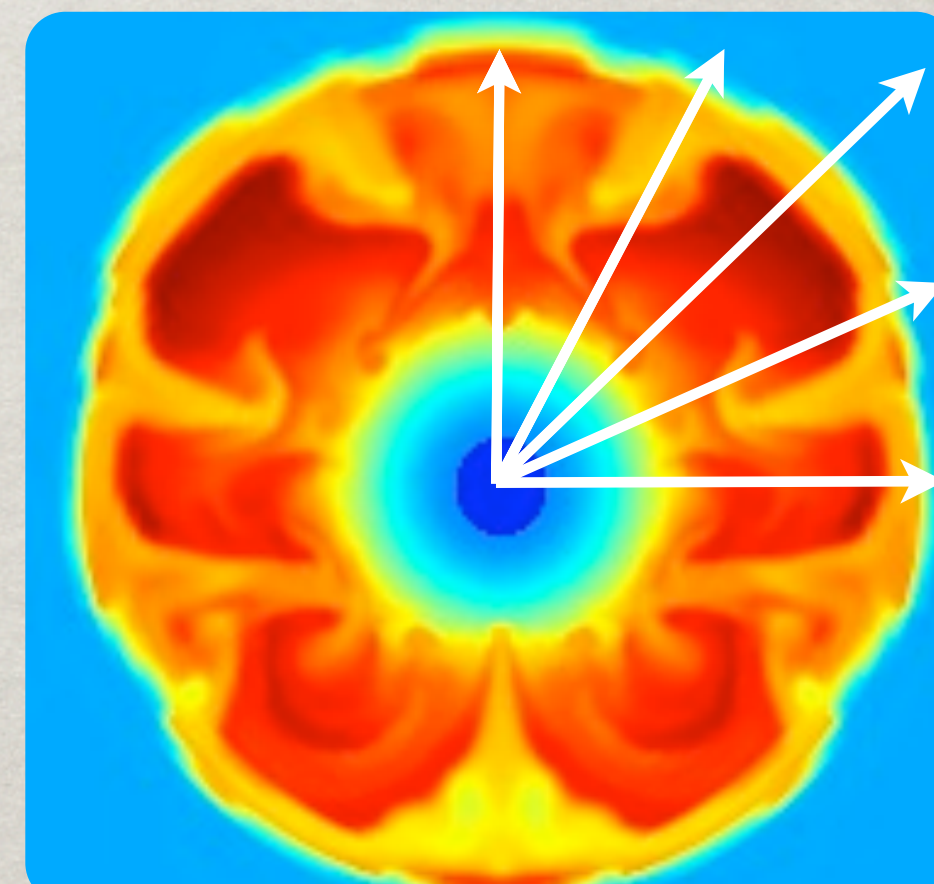
Multipole gravity w/ Spherical GR correction

Equations of State:

Lattimer-Swesty (K=220 MeV)

Cooperstein/BCK: $\rho<10^{11}$ g/cm^3

[Results: Bruenn et al 2006, 2009, 2013]



Ray-by-Ray Approximation

Chimera numerics

Multi-physics: operator split

540 (radial) x 180 (latitude) x180 (longitude) spherical-polar grid w/ inner core (8 km) in spherical symmetry.

2-degree phi resolution

Fixed d(cos theta) resolution (~8 deg at pole, to ~2/3 deg at equator)

[fixed solid angle]

Hydrodynamics: dimensional split, needs transposes

Transpose: MPI_AllToAll on 180 sub-communicators

32400 MPI ranks (4050 XK7 nodes, 8 tasks/node, 2 OpenMP threads)

Each MPI task computes one independent, transport solve using local data.

Dimension changes revival

Key result from many previous studies: 1D does not explode, 3D may be favorable, or not.

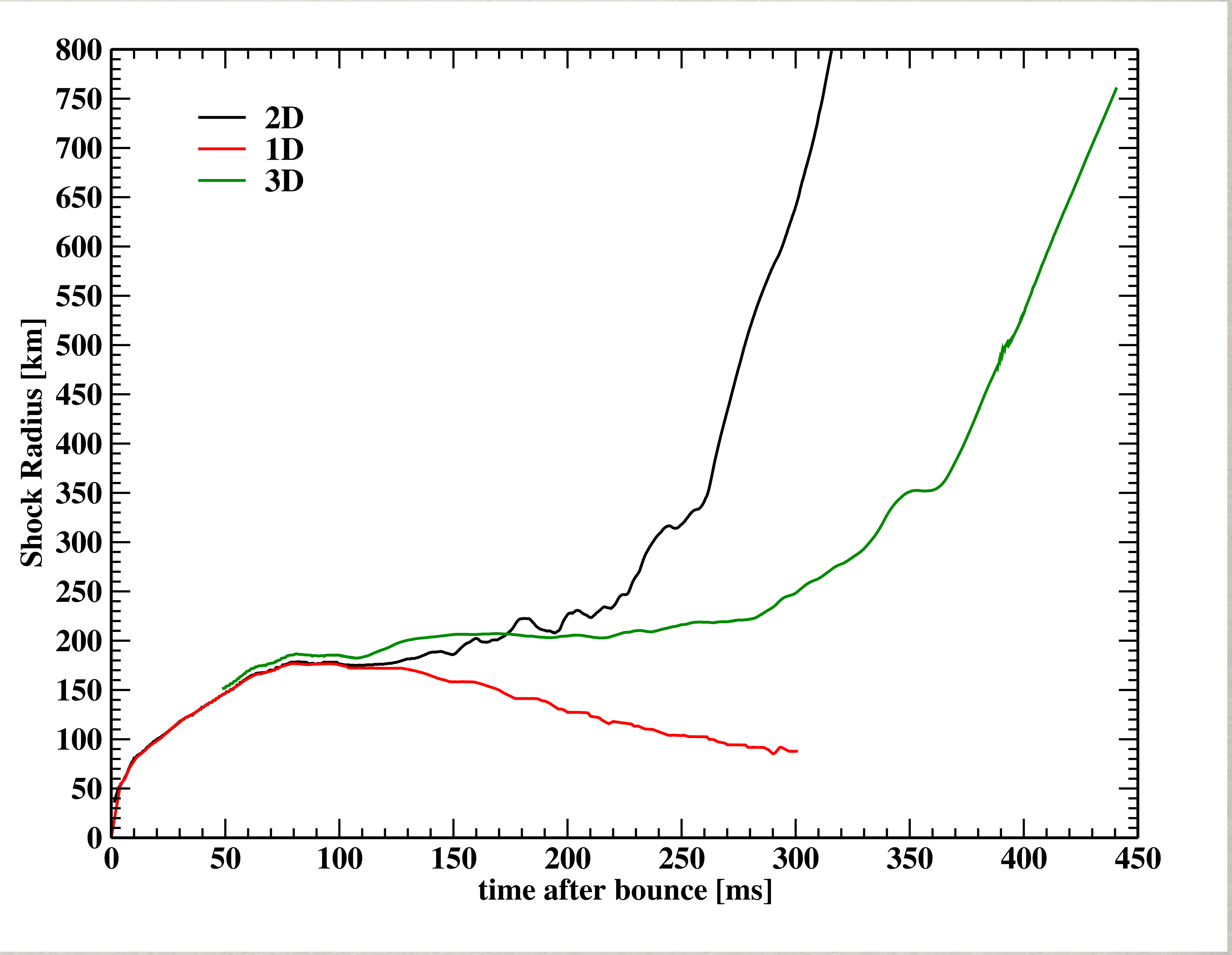
Chimera result:

15 M_sun star.

1D: Fails!

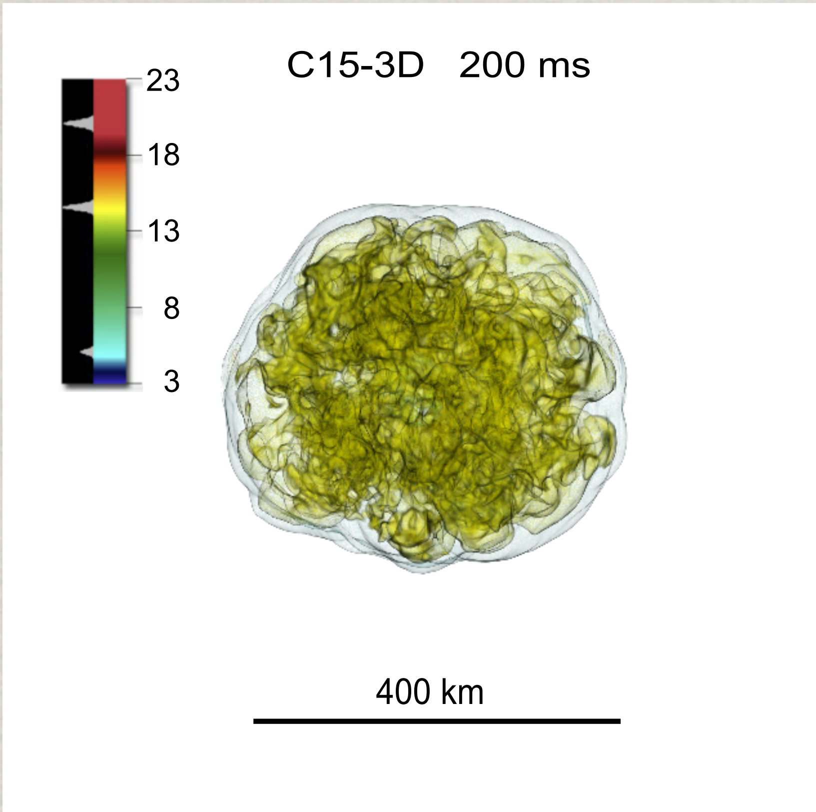
2D: short wait, rapid expansion

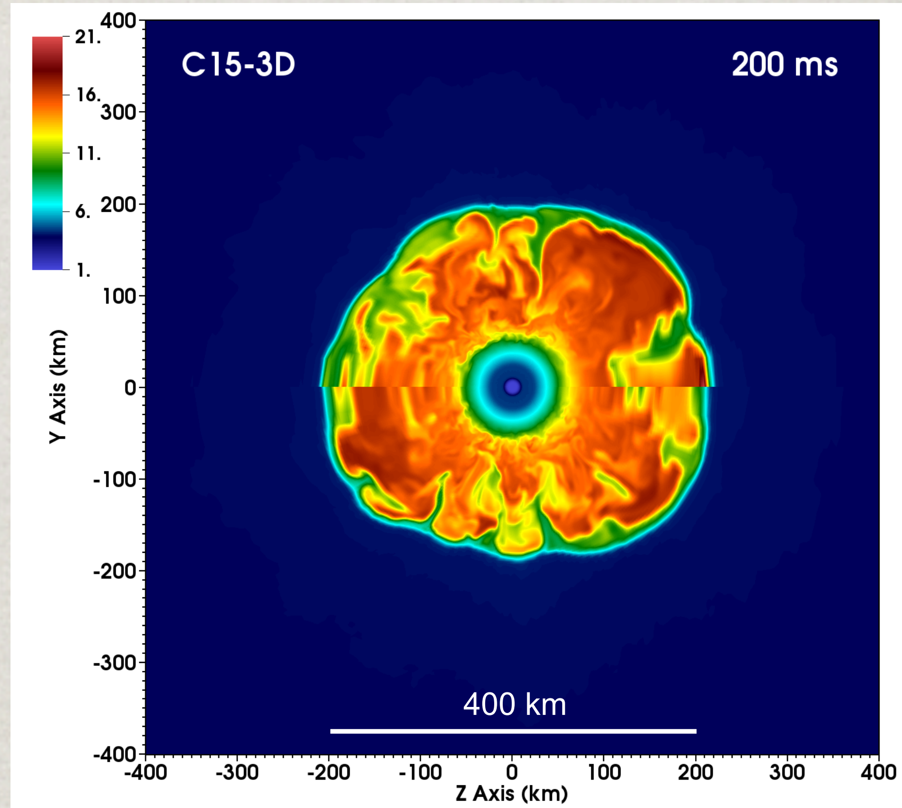
3D: longer delay, less vigorous?

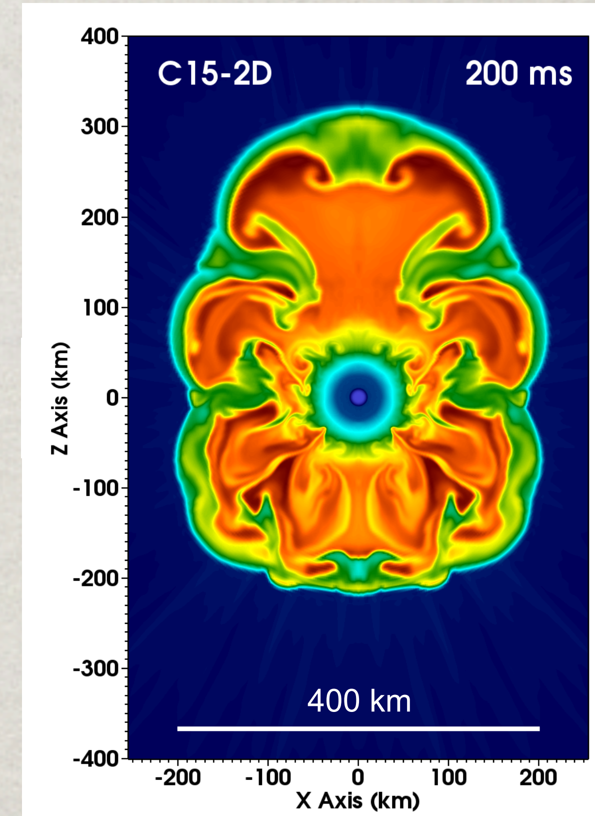


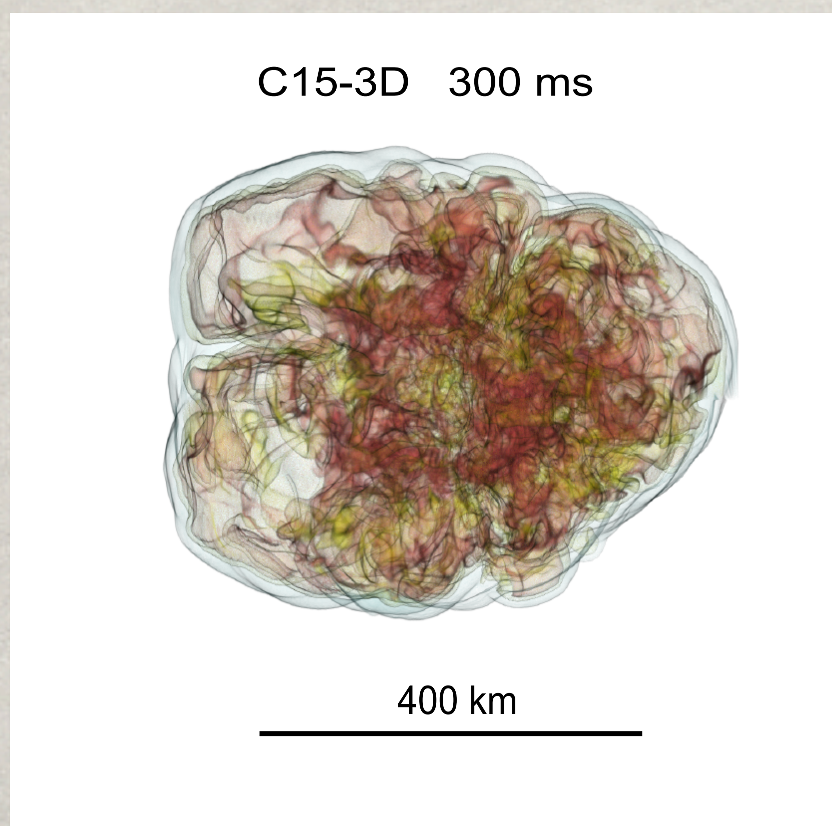
Lentz et al., to be submitted shortly...

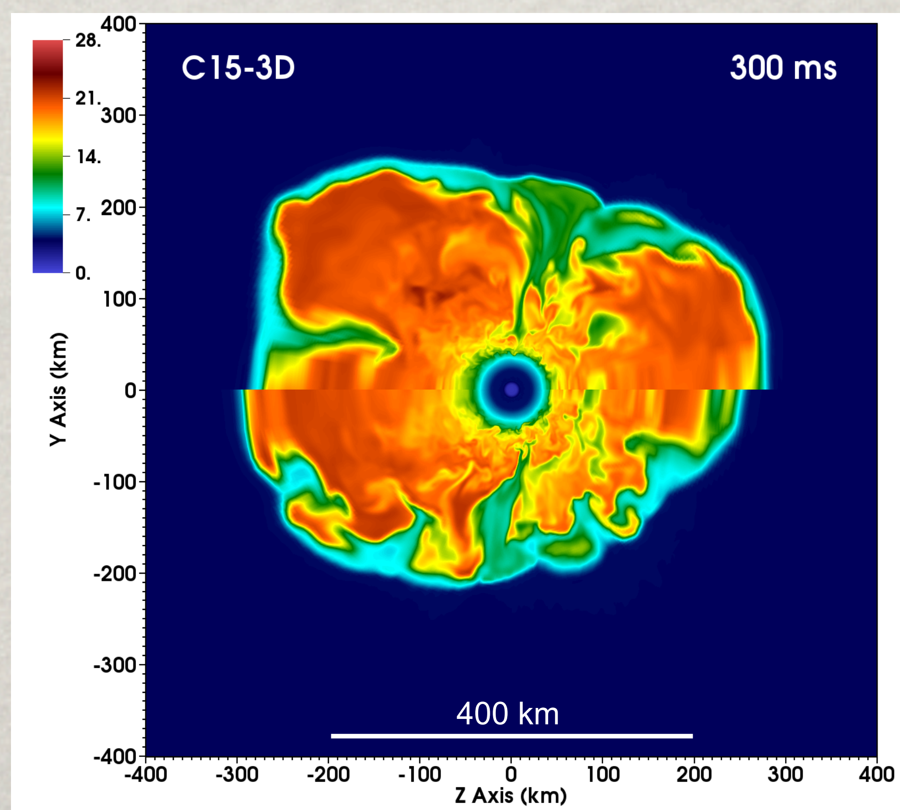
Comparison Images

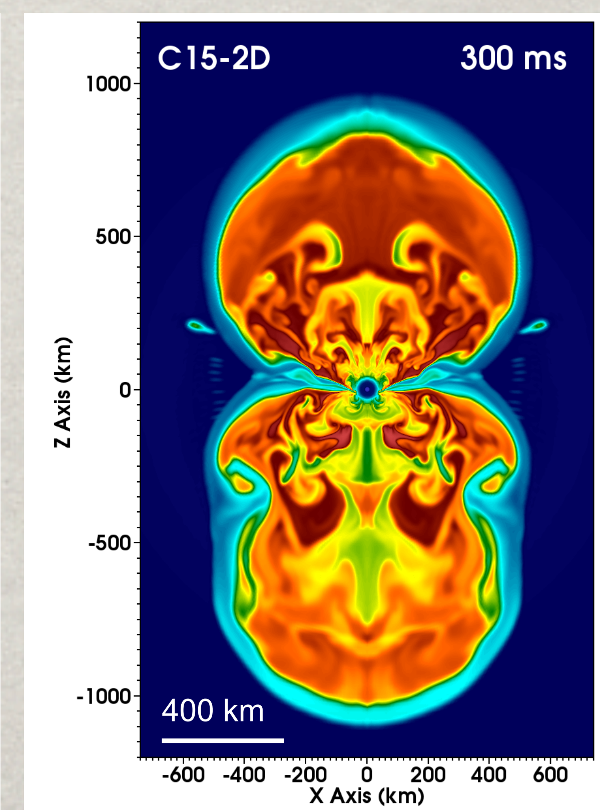












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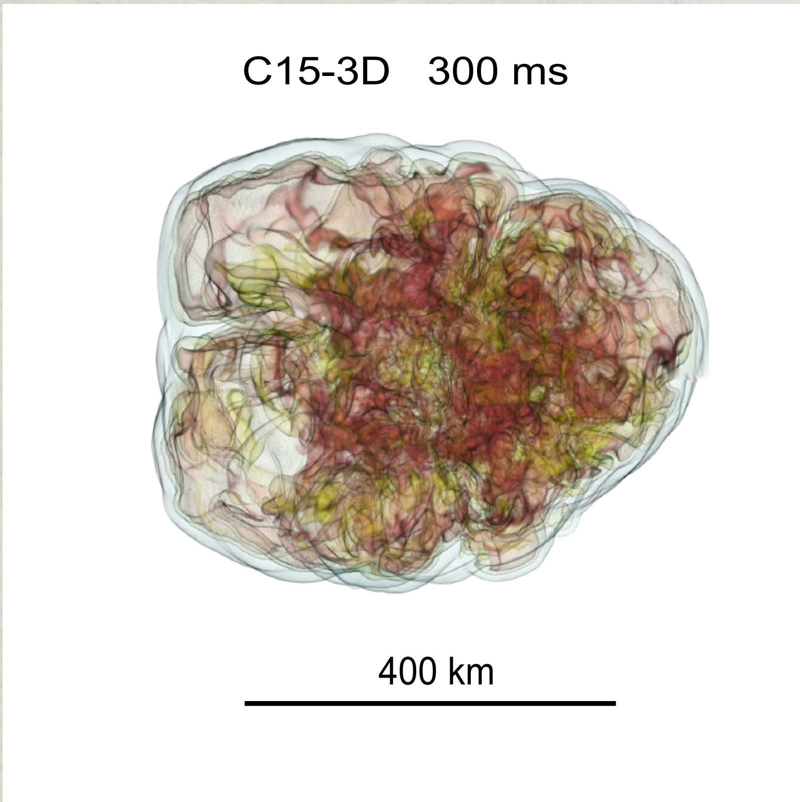
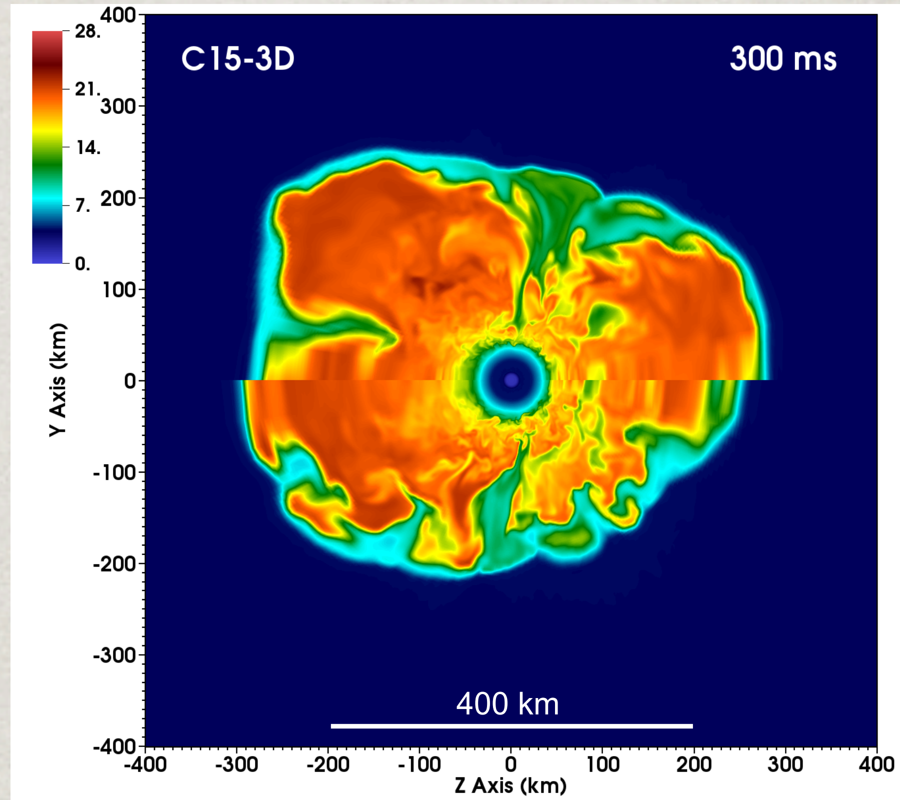
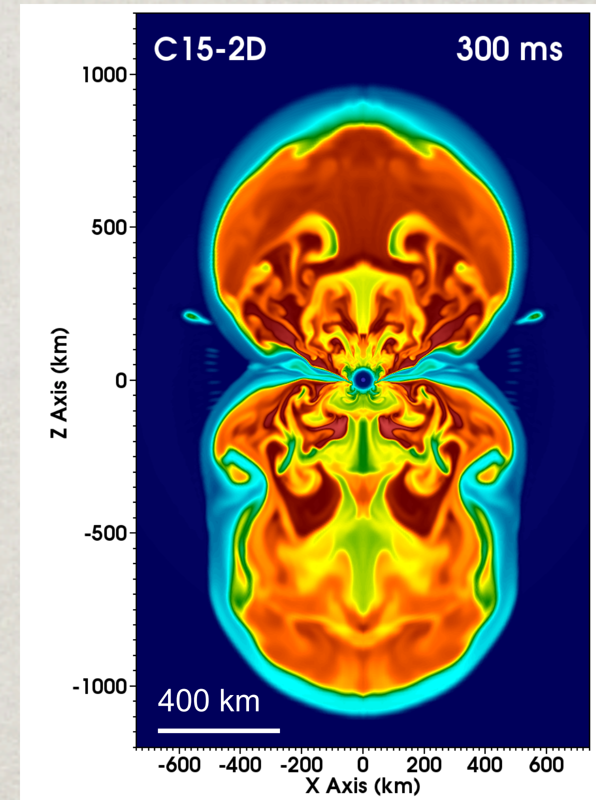
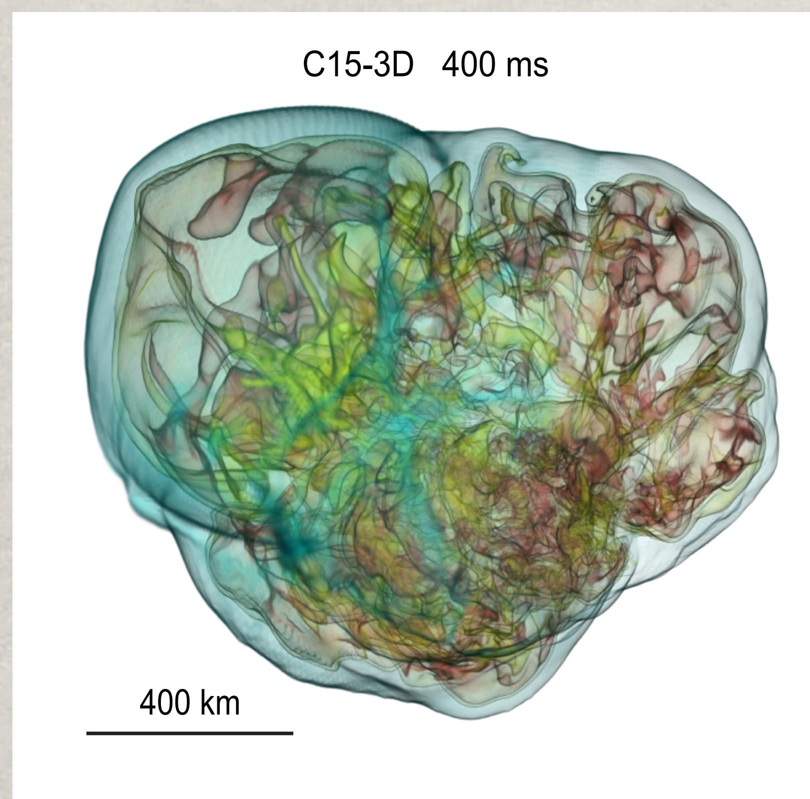
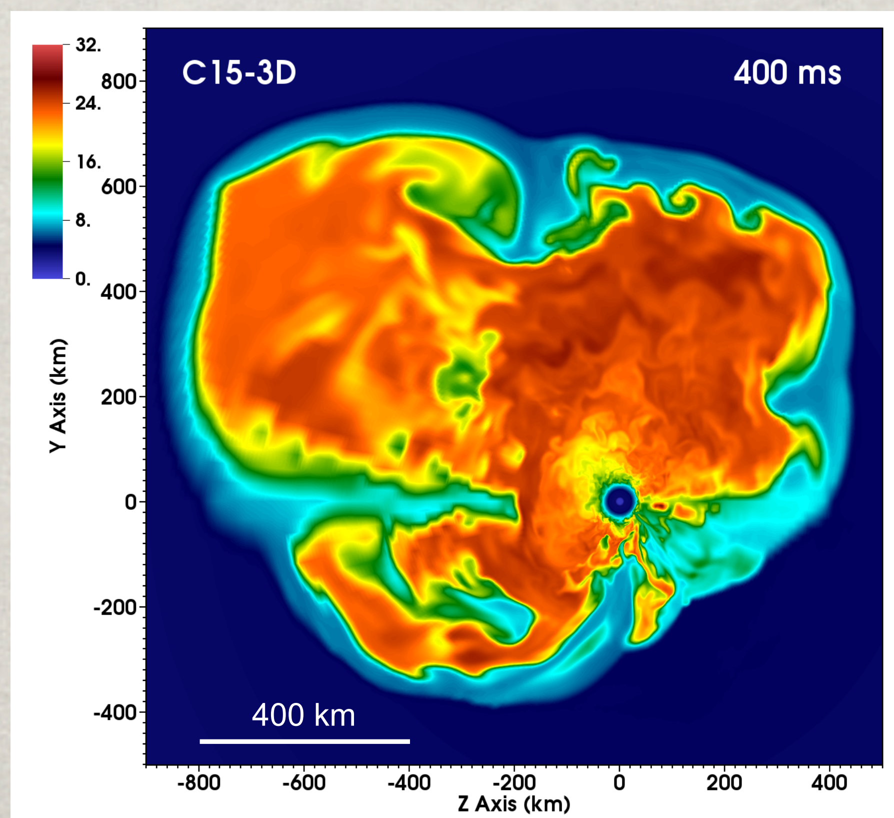
More...

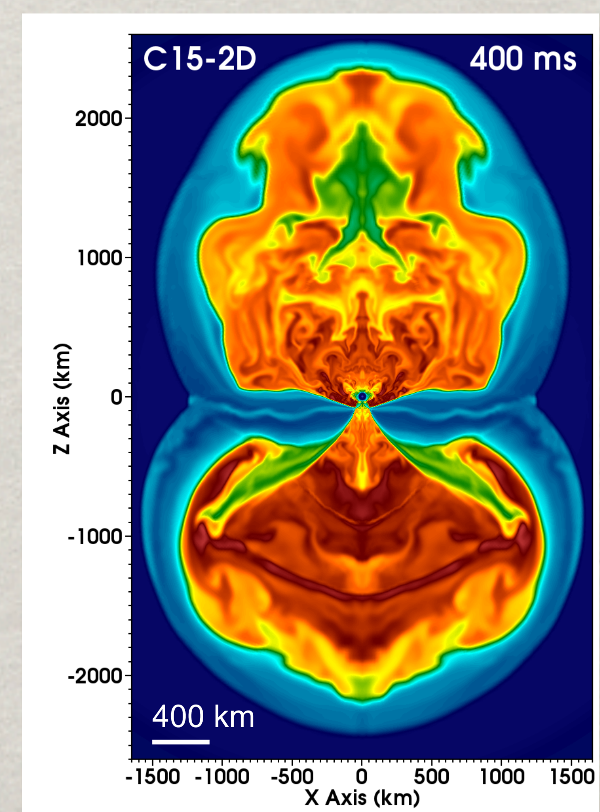












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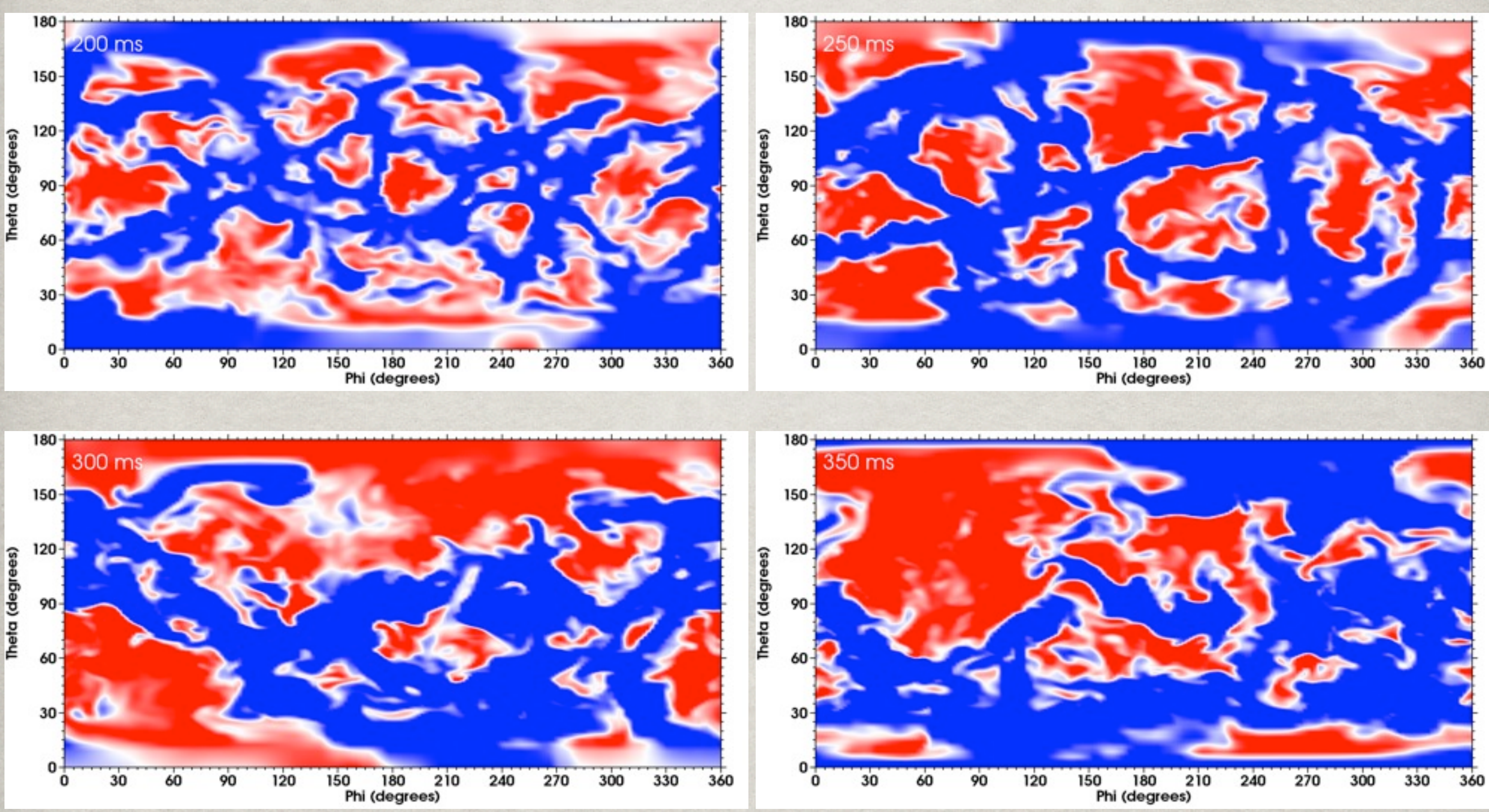
Shock Revival in 3D

Yellow/green, Red: hot plumes; blue =~ shock

Lentz et al., to be submitted shortly...

Plume sizes

Preceding shock revival, plume size grows



Radial velocity, 150 km radius shell

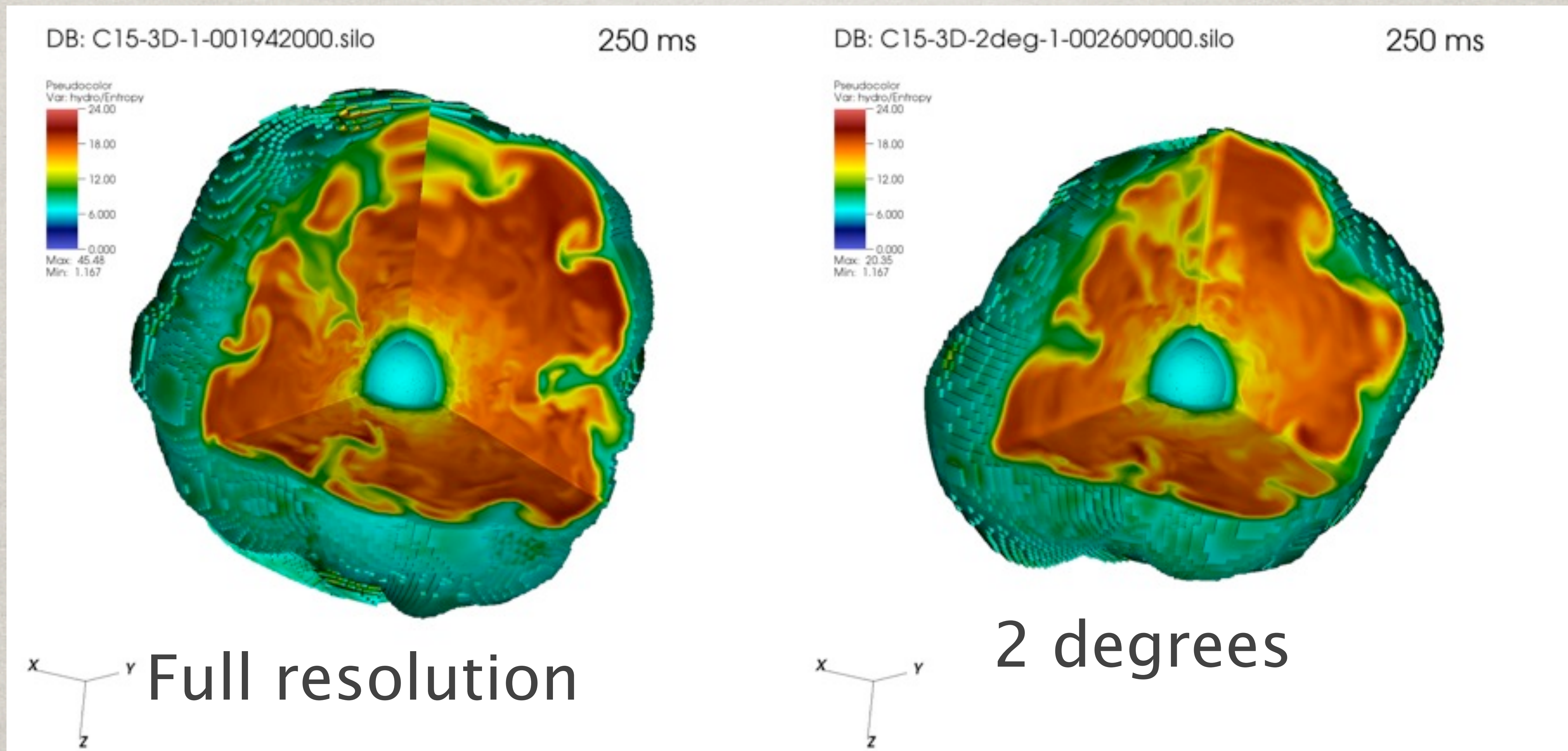
Rising flows in red, sinking in blue

Lentz et al., to be submitted shortly...

Resolution

Initial work on Blue Waters: examine impact of resolution

Low resolution make flows more viscous, terminates turbulent cascade, dissipates small features, etc

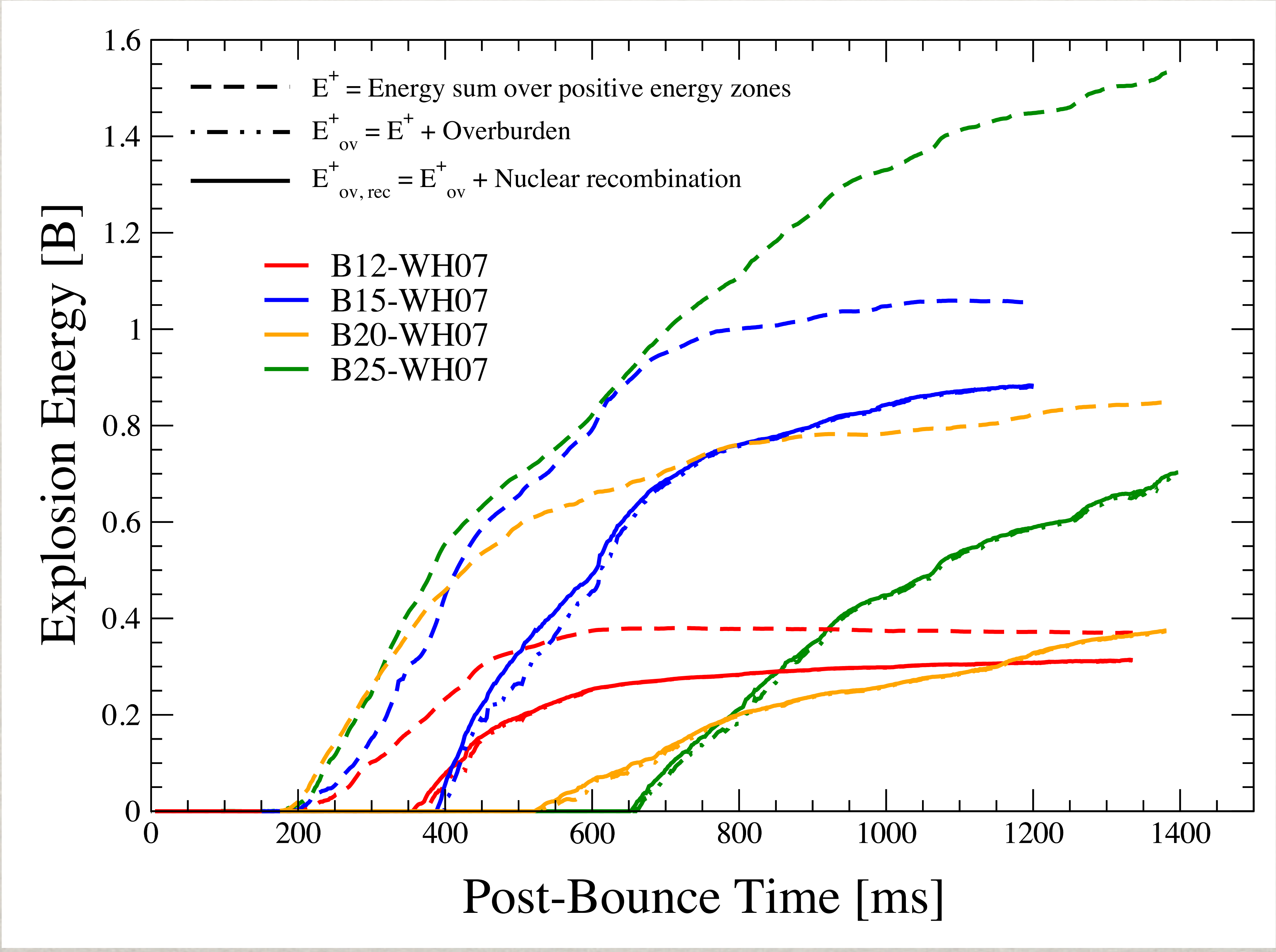


Time to Develop Explosion

4 2D simulations covering mass range (12, 15, 20, & 25 solar masses).

Shock revival at ~200–250 ms, but full saturation of explosion much longer.

Similar times required for quieting neutrino and GW signals.

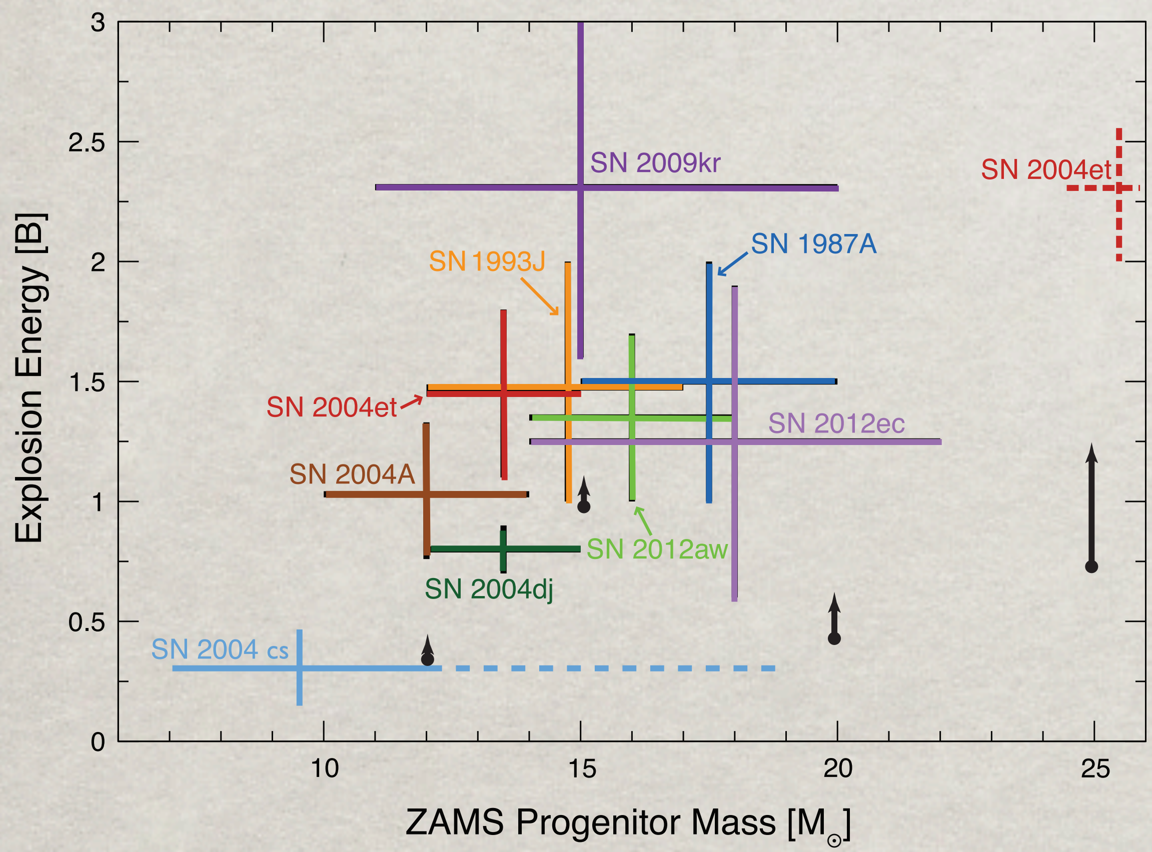


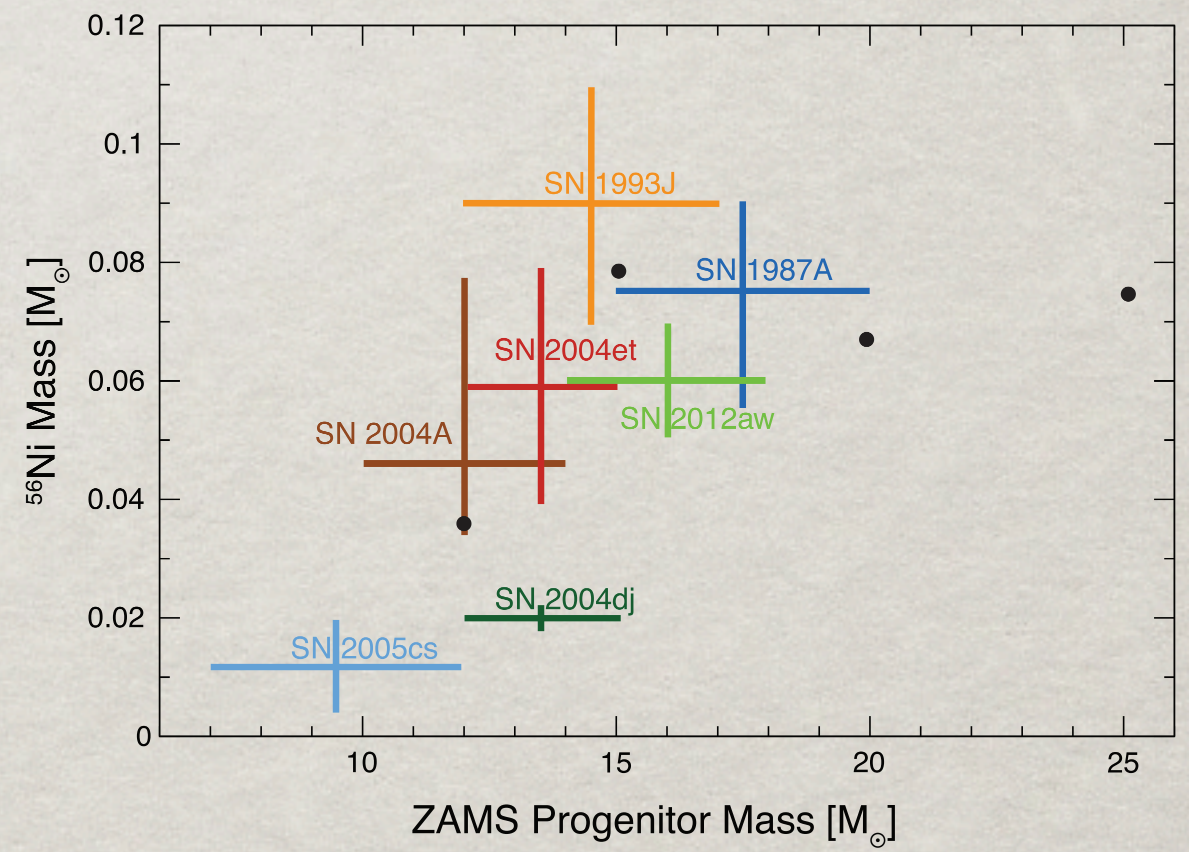
(Bruenn et al. 2014, ApJ, subm.)

2D Comparison to Obs.

Explosion energies (circles with arrows) fall in range of measured values from observed supernovae.

Arrows indicate 1 sec. continued growth at ending rate.





(Bruenn et al. 2014, ApJ, subm.)

PRAC project

Goals:

Similar coverage in mass for 3D simulations.

Long runs to determine energy, signals, and ejecta properties. (1+ second)

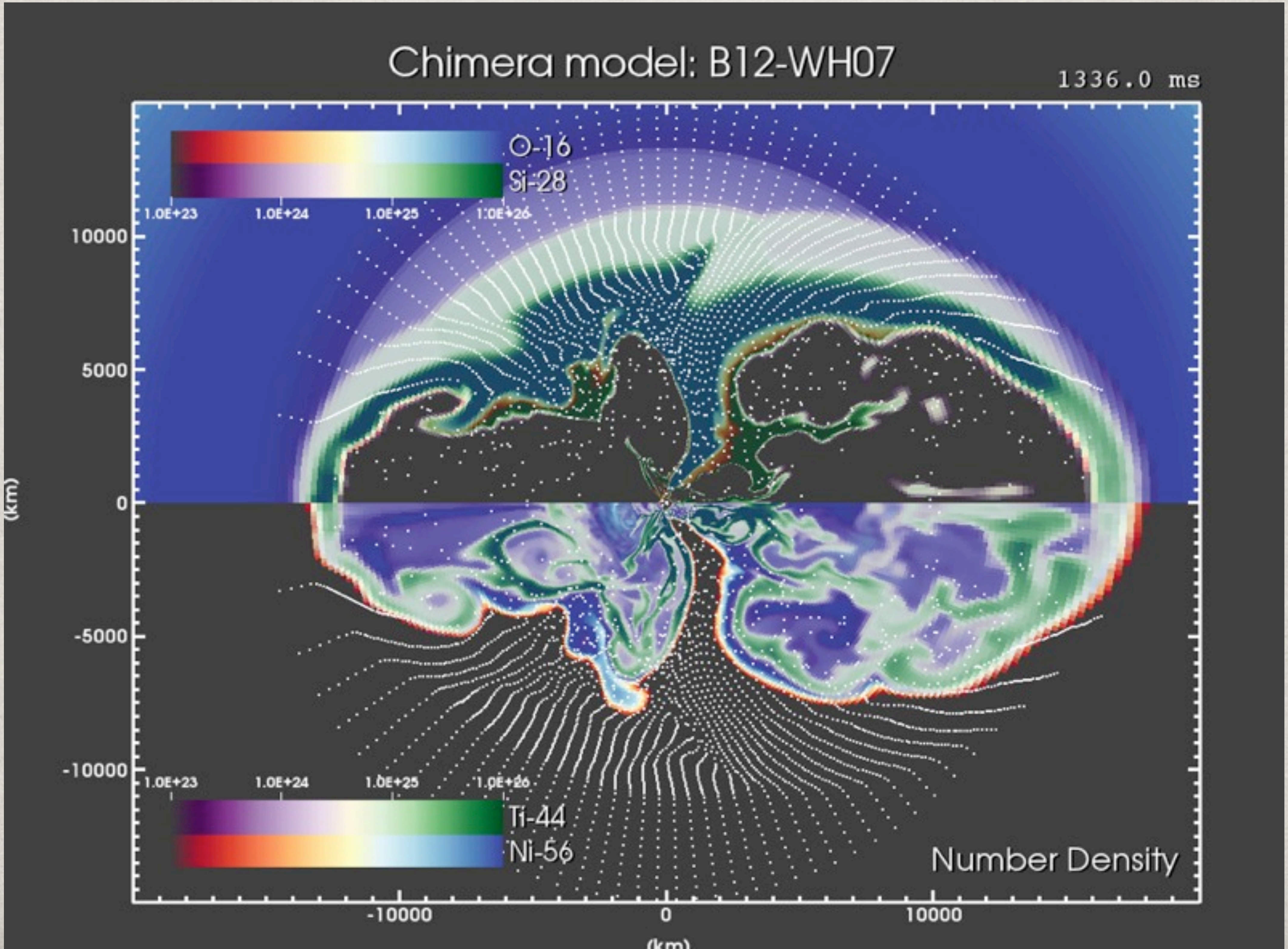
Develop “library” of simulations covert possible behaviors.

Special goal:

Compute nucleosynthesis (elemental & isotopic) yields of CCSNe and calibrate other models used to study the chemical evolution of galaxies.

2D Nucleosynthesis

Recent measurements (Boggs et al. 2015, Science) show asymmetries in Ti-44 distribution in SN 1987A. Our simulations are also clearly asymmetric in Ti-44 (Harris et al, in prep.)



Prac details

Design goals:

3 x 3 grid: 3 heavy element abundance levels (zero or primordial, low, solar) with 3 progenitor masses each.

1+ second simulation time

1-degree Yin-Yang grid (pole-free; less restrictive CFL time steps)