Simulating core-collapse supernovae with Chimera

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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?

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

Understand the generation of elements and their ejection.

← SN 1987A in LMC

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

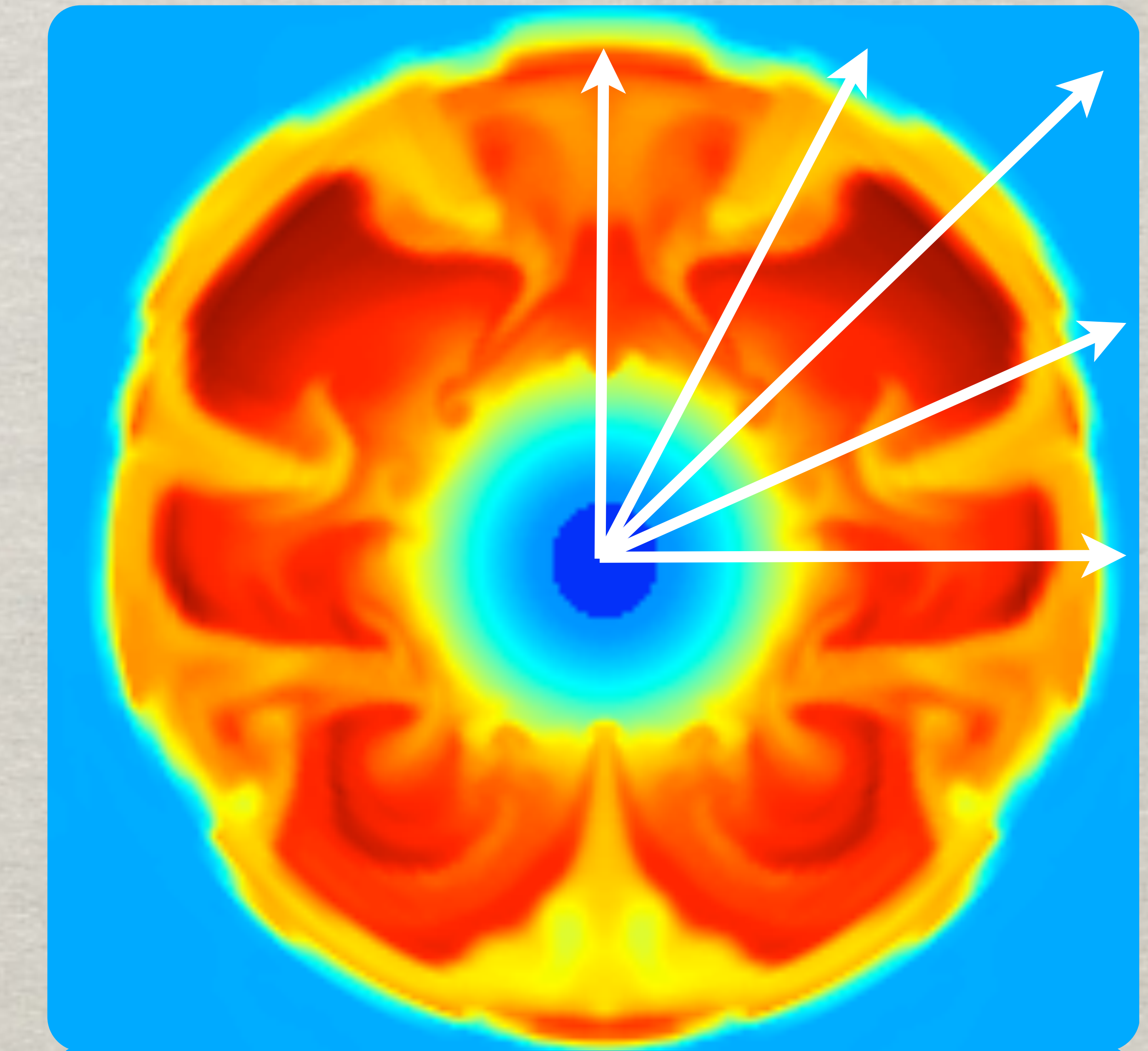
Equations of State:

Lattimer-Swesty (K=220 MeV)

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

Passive Lagrangian Tracers for post-processing

Bruenn et al. (2018), arXiv:1809.05608



Ray-by-Ray Approximation

Model History

Series-A: Bruenn+2009 (J. Phys. Conf. Ser, 46, 393), Yakunin +2010 (C.Q.Grav, 27, 4005)

Series-B: Bruenn+2013 (ApJL, 767, L6), Bruenn+2016 (ApJ, 818, 123)

Series-C: Lentz+2015 (ApJL, 807, L31)

Series-D: multiple studies

- 2D solar metal stars (Bruenn+ in prep.)
- 2D zero metal stars (Huk, Hix, Lentz, + in prep.)
- 2D with large (160-species) network (Harris+ in prep.)
- 3D Wedge turbulence study (Casanova+ in prep.)
- **Multiple 3D simulations with Yin-Yang grid**

Series-E: 2D study of nuclear equation of state (Landfield, 2018, UTK Ph.D., paper: in prep.)

You can guess what series comes next...

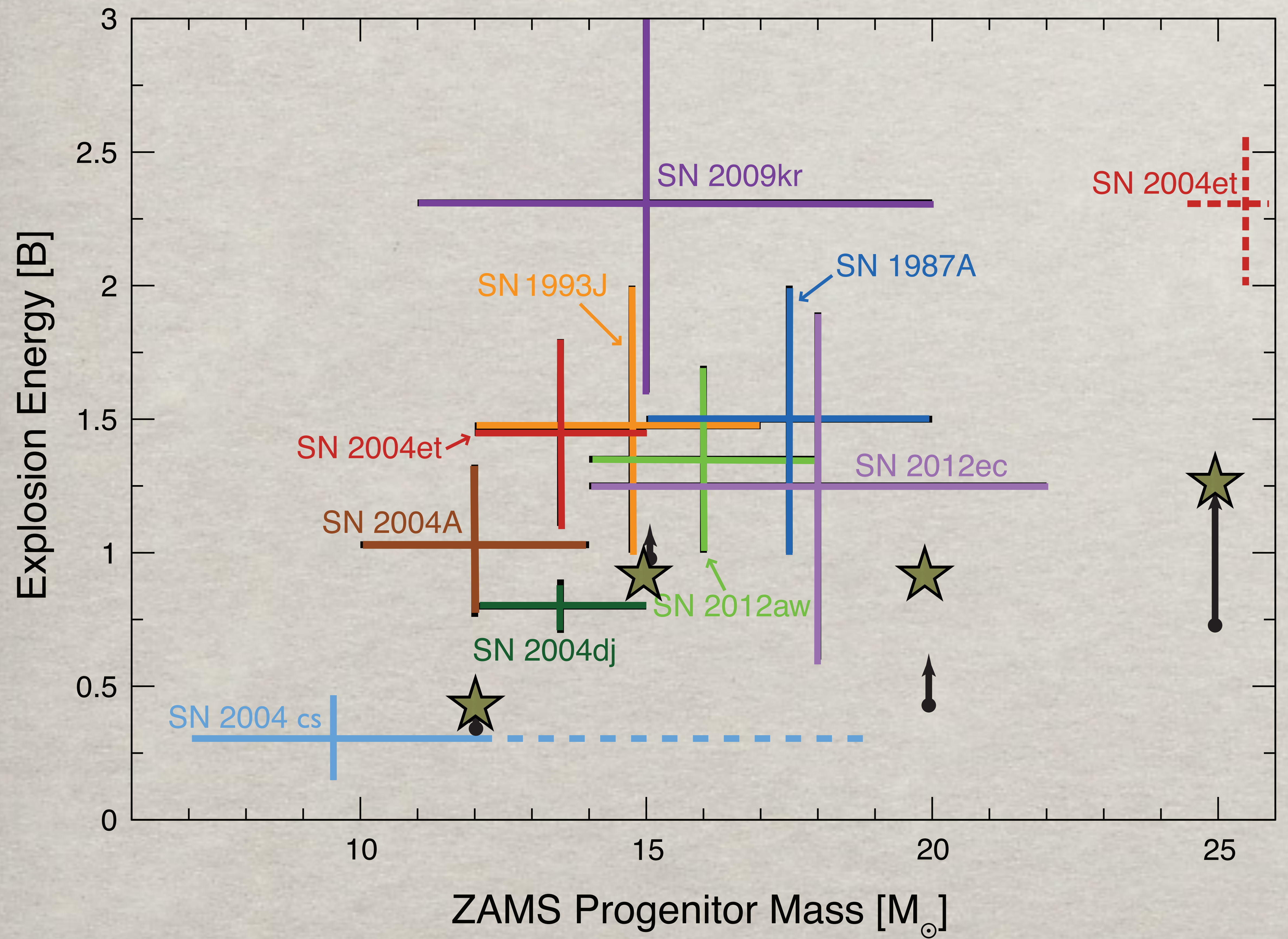
- Improved microphysics (SFHo EoS, ...)

B-series

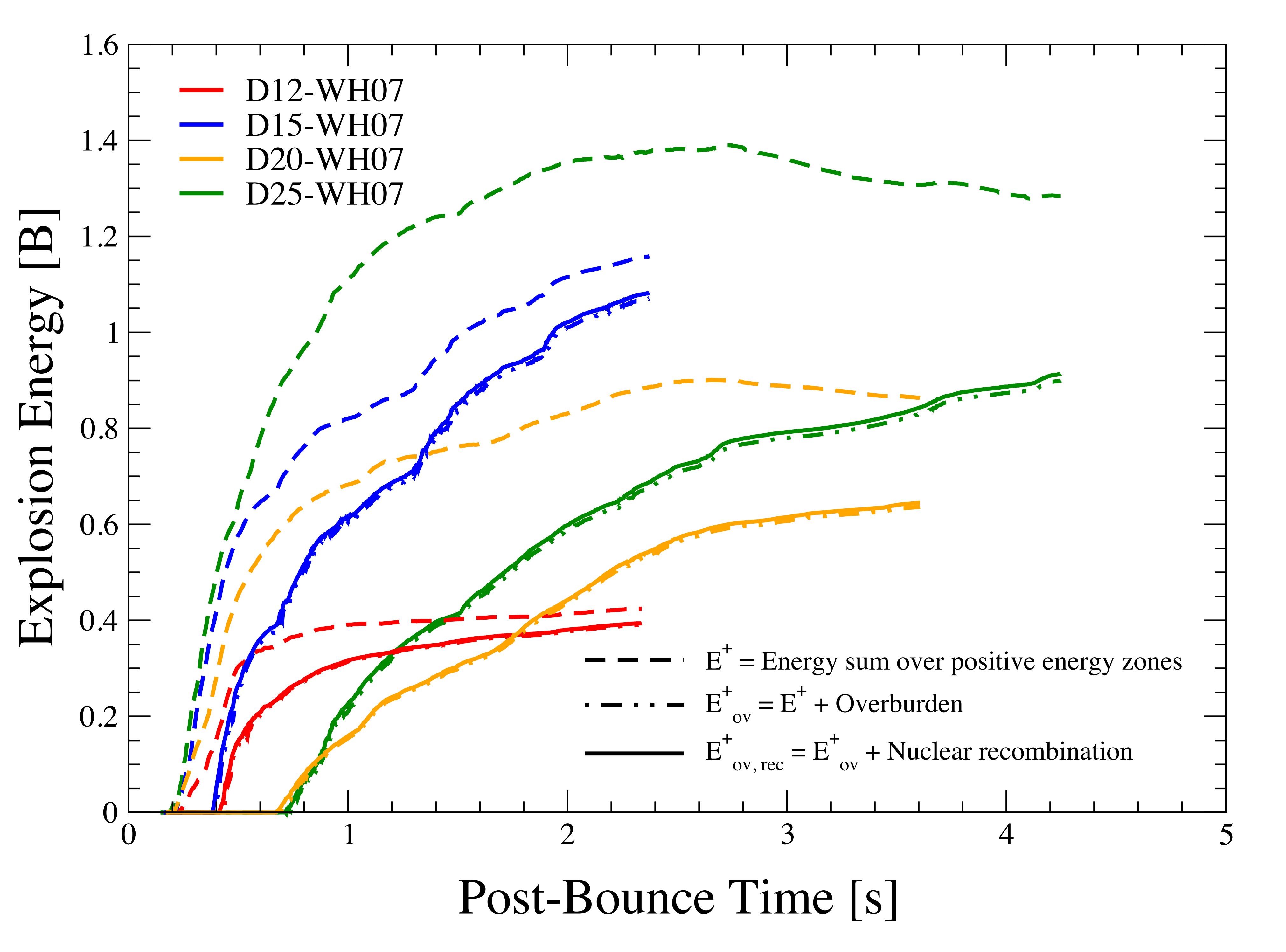
12-25 M$_\odot$ Woosley & Heger (2007) progenitors, run 0.8-1.4 sec.

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

Arrows indicate 1 sec. additional growth at ending rate. (Stars show D-series equiv.)

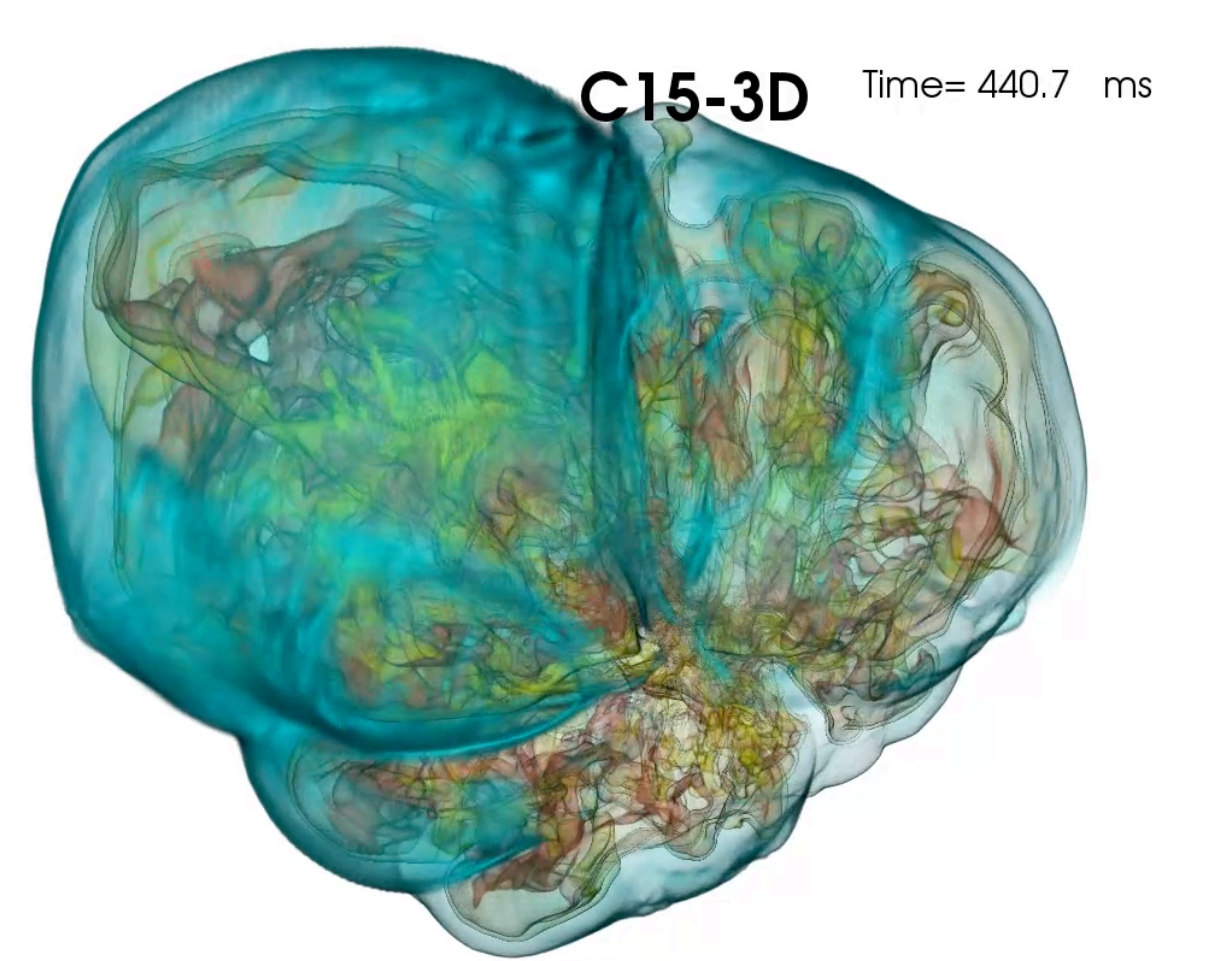


(Bruenn et al. 2014, ApJL, 767, L6)



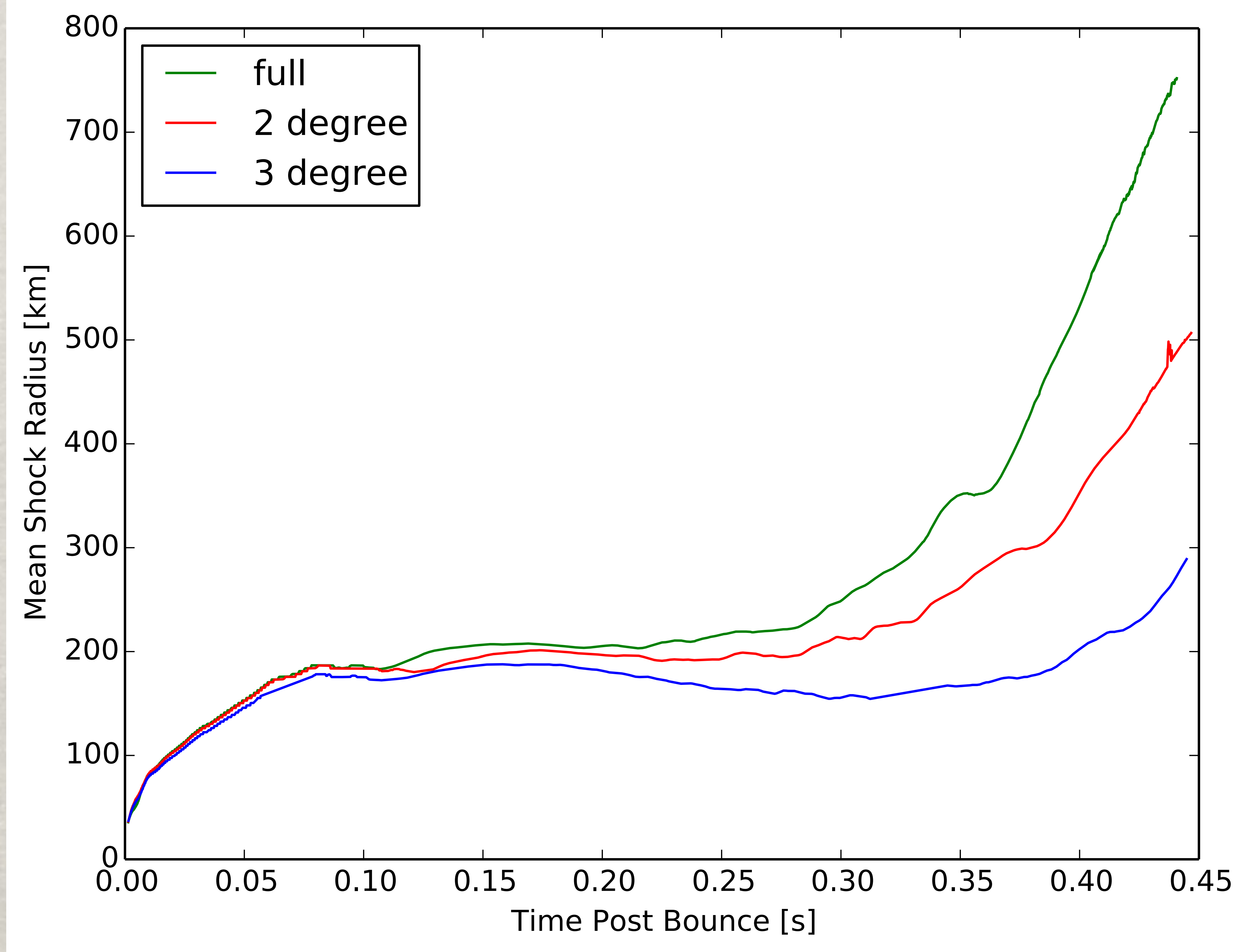
★ D-series, same models (Bruenn et al., in prep.)

C-series



Lentz et al., (2015), ApJL, 807, L31

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



Shock organized into large plumes, main plume opposite main inflow. (left)

Lower resolution models (above) delays shock relaunch. (Lentz+ in prep.)

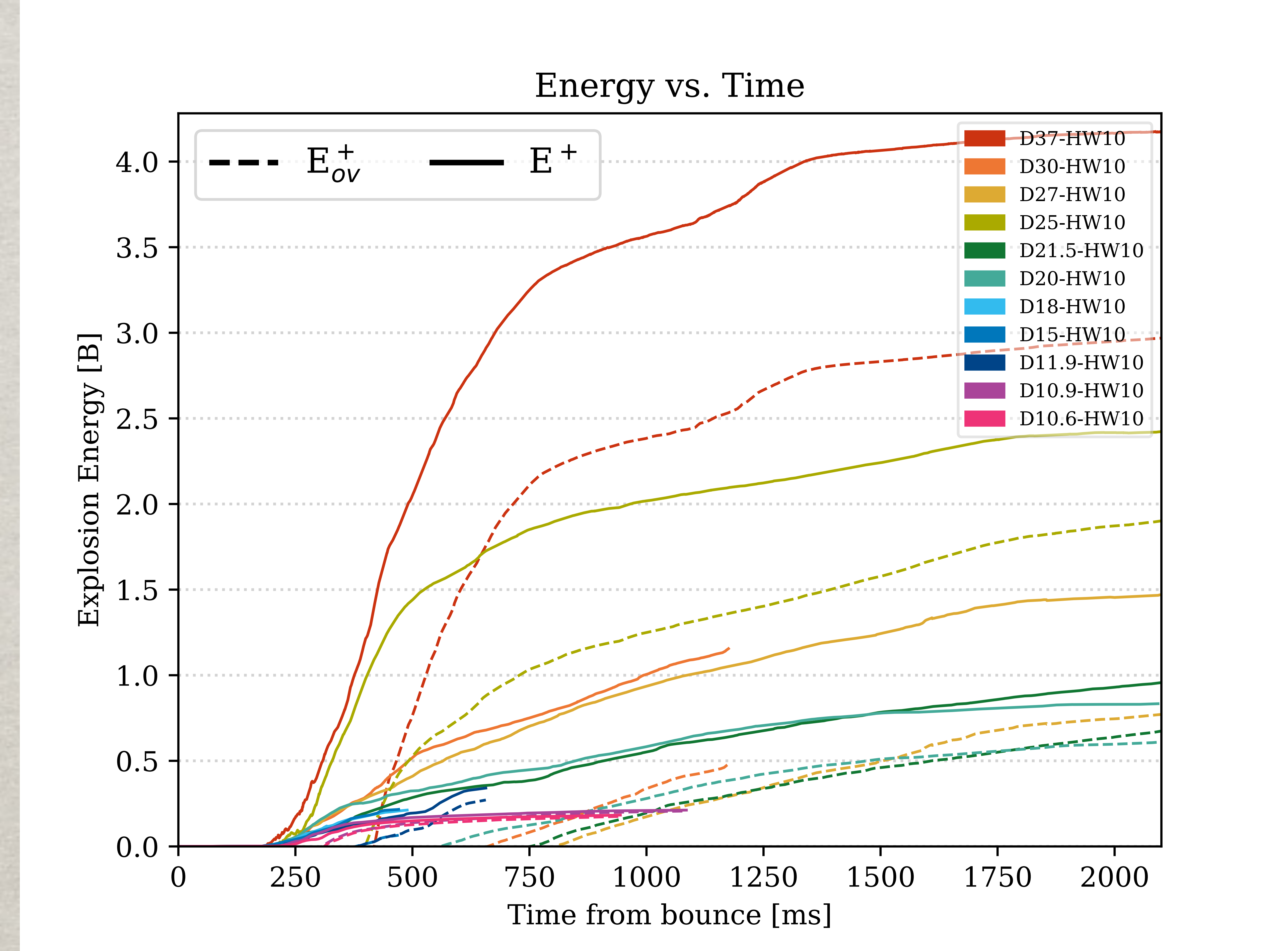
D-series (2D zero metal)

Heger & Woosley (2010)

Large Explosion energies correlated to large Proto-NS

Accretion/reheating engine seems more efficient.

Most of these are still running...



Huk, Hix, Lentz, et al., in prep.

Proto-NS ($M_\odot$)

D37-HW10: 2.23

D30-HW10: 1.80

D27-HW10: 1.81

D25-HW10: 2.08

D21.5-HW10: 1.69

D20-HW10: 1.62

D18-HW10: 1.52

D15-HW10: 1.46

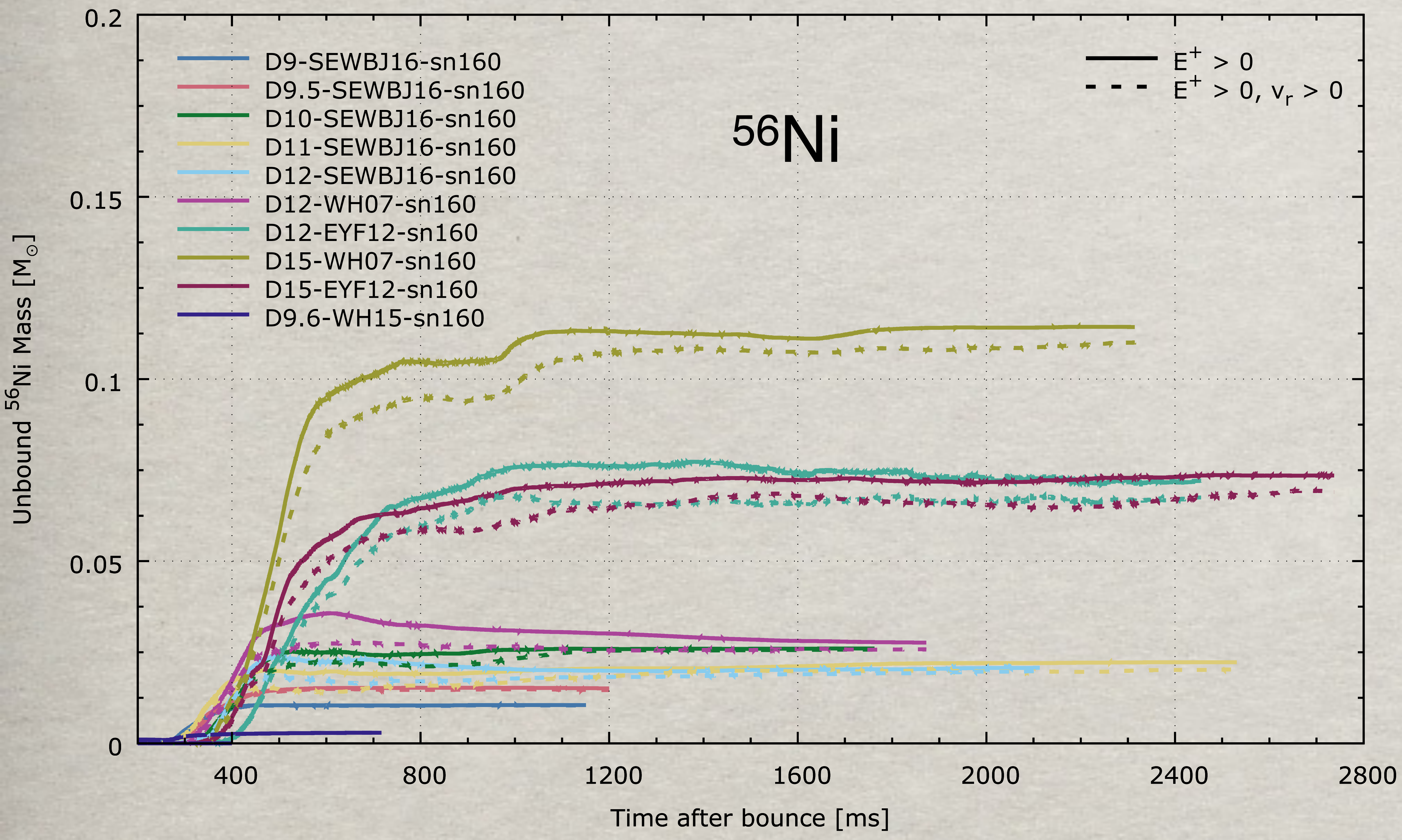
D11.9-HW10: 1.44

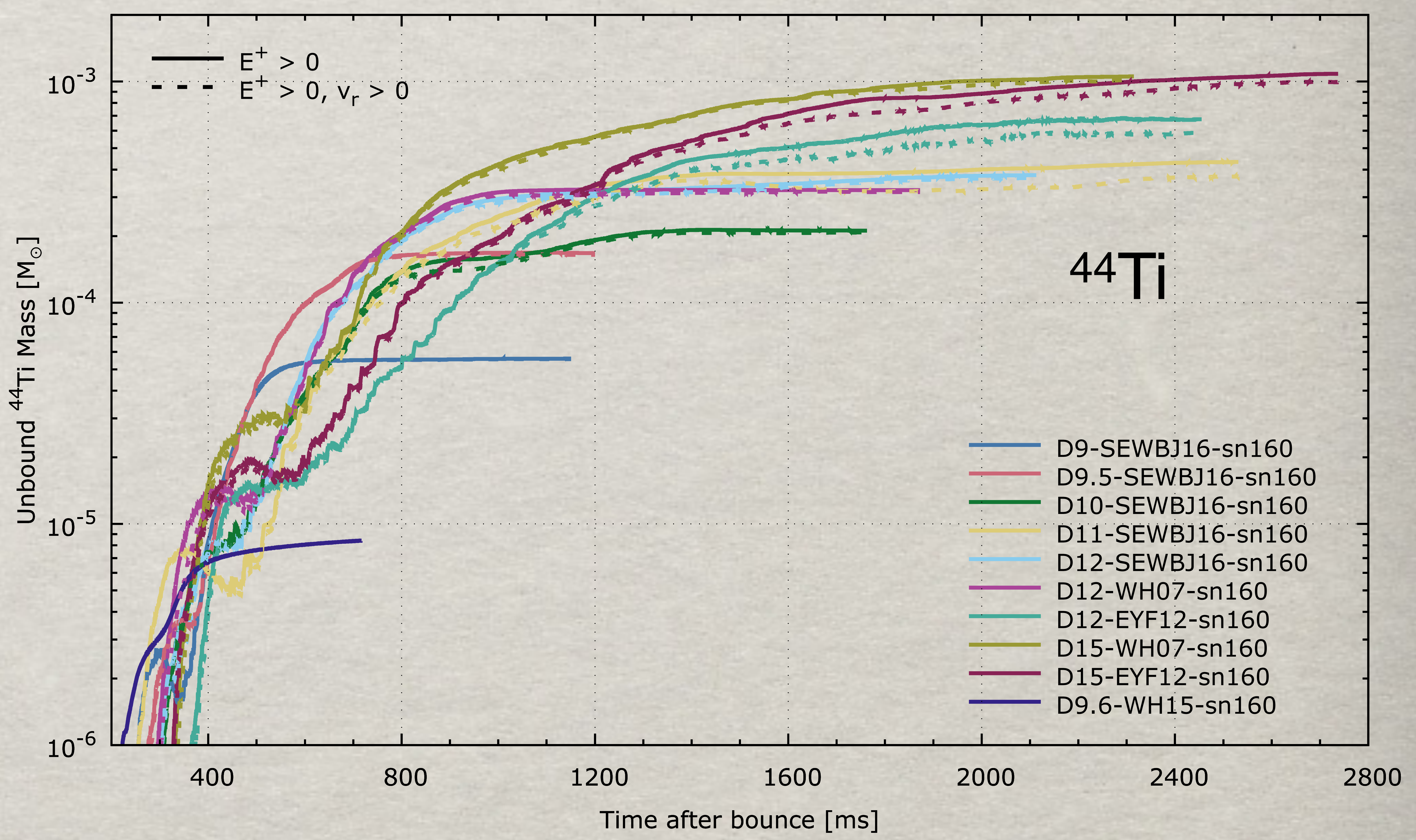
D10.9-HW10: 1.39

D10.6-HW10: 1.36

D10.3-HW10: 1.36

D-series: 2D large network





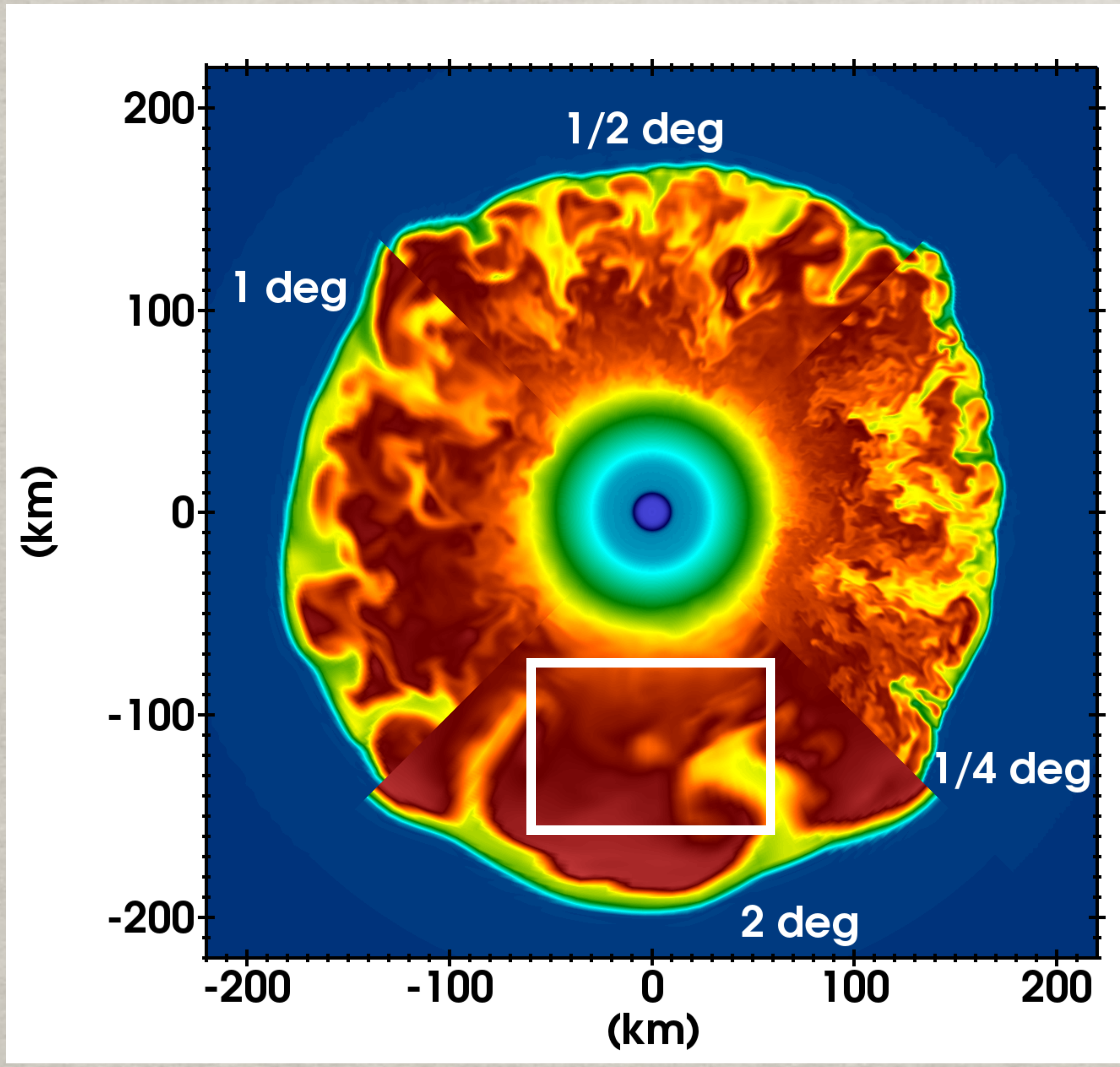
- Group of 2D models with 160-species network
- 9-15 M☉, various stellar evolution sources
- Run to late times (until shock reaches He-shell)
- Harris et al., in prep.

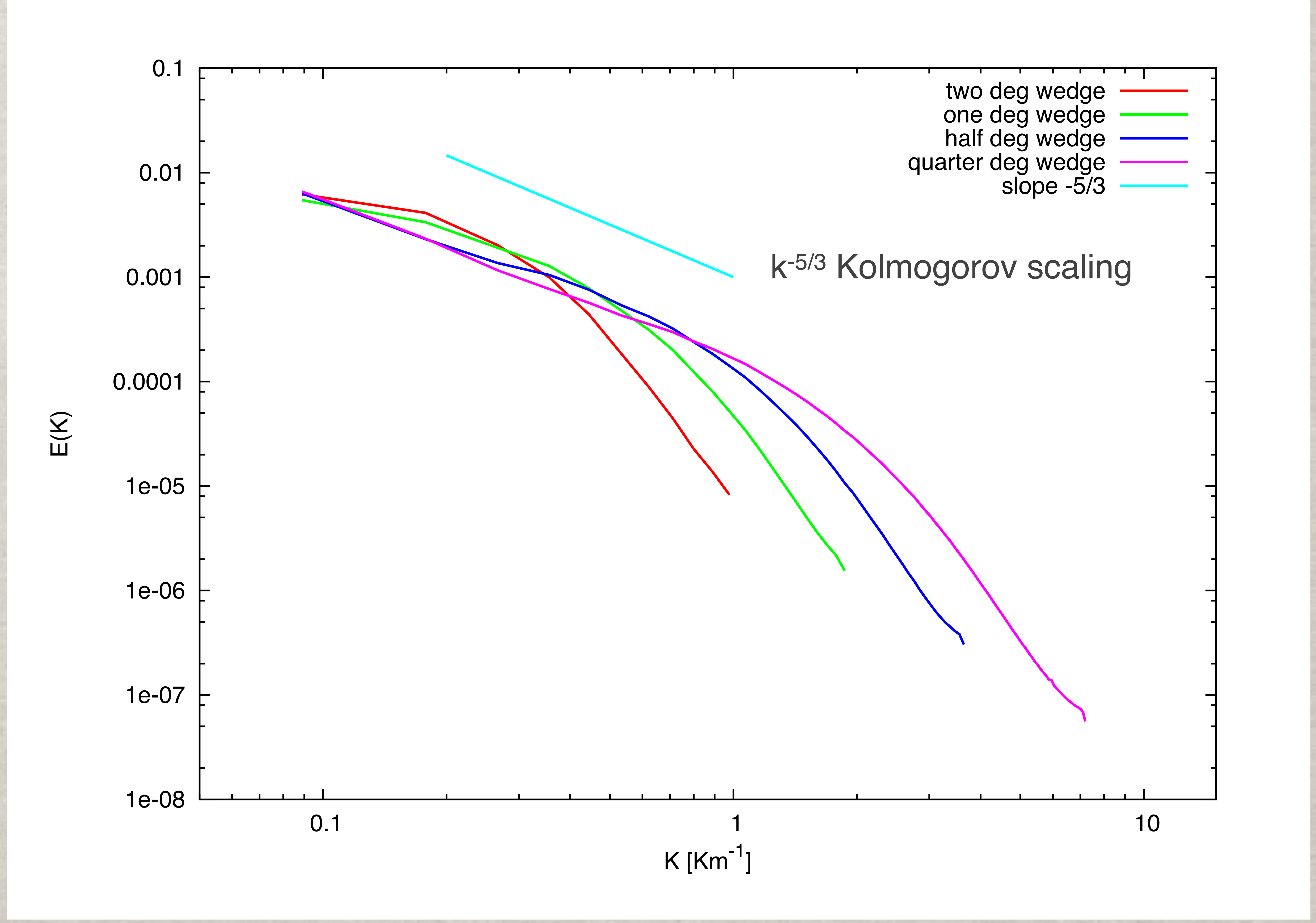
D-series: 90-degree 3D

How does resolution affect 3D simulations? Particularly turbulence.

90-degree 3D wedge. Periodic in theta and phi. 2-, 1-, 1/2-, and 1/4-degree models

Full physics (self-gravity, EoS, neutrino transport) WH07 15 $M_\odot$ progenitor

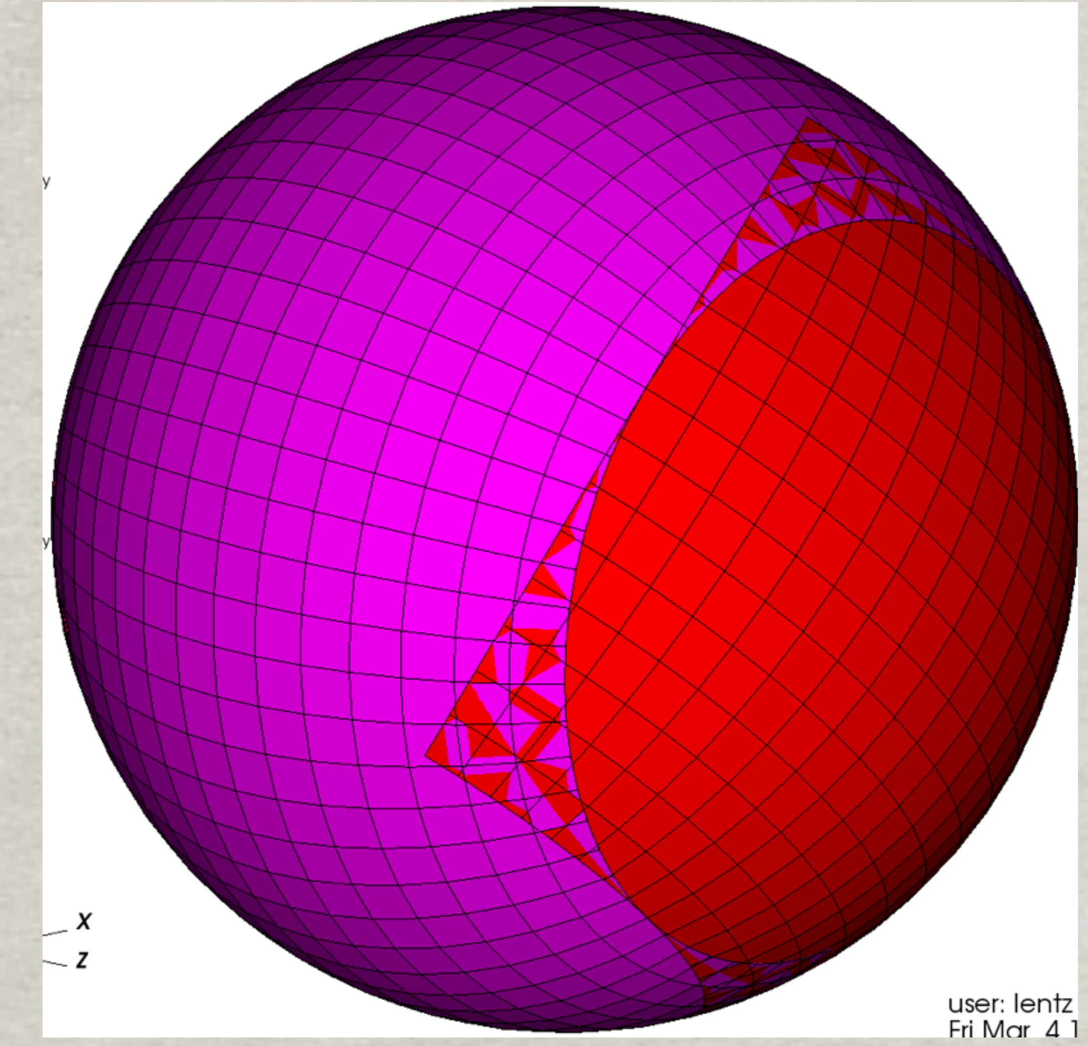


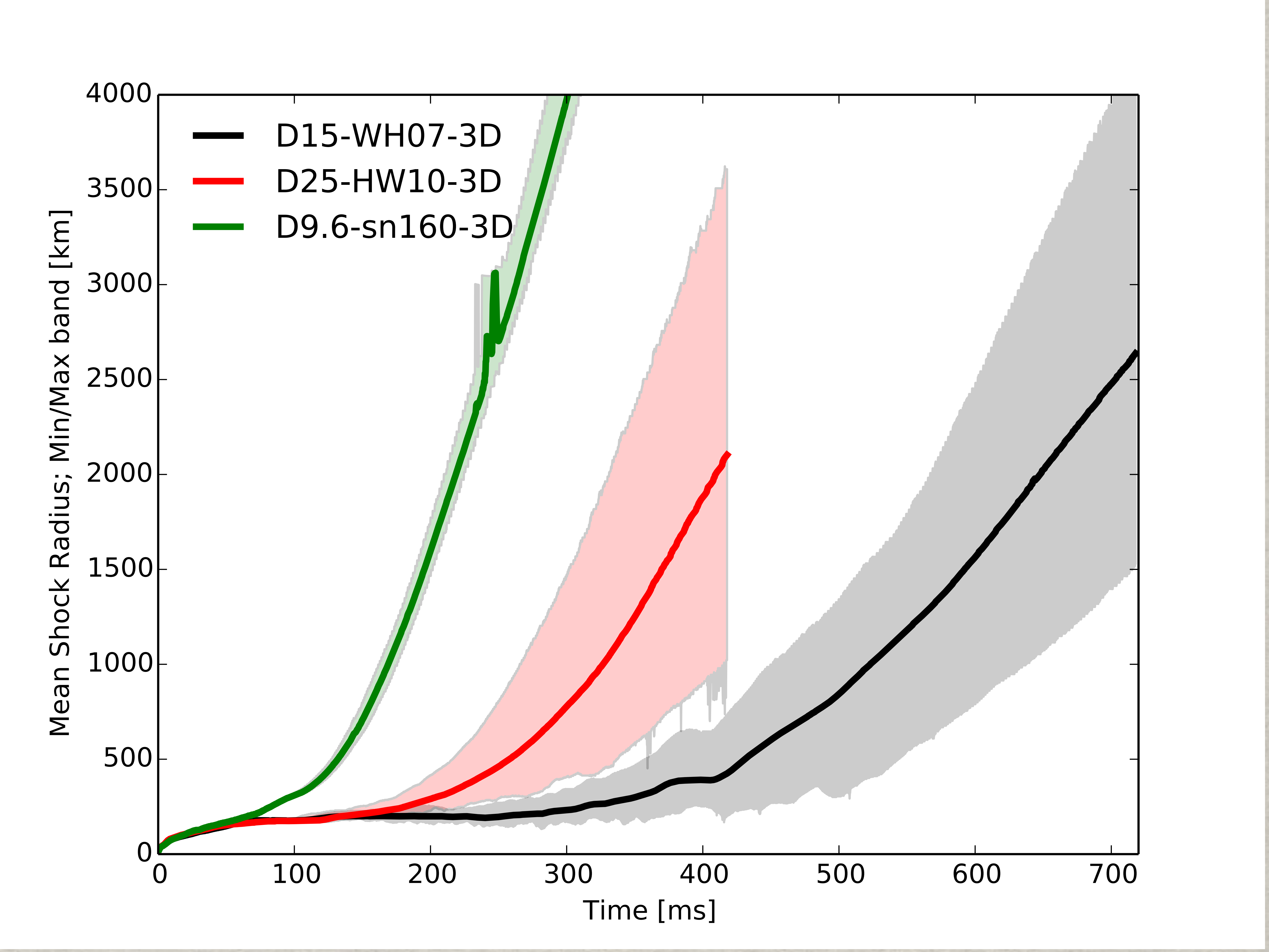


Casanova et al., in prep.

D-series in 3D

1-degree Yin-Yang grid





Mean shock + min/max band

9.6 $M_\odot$**:** Low-mass w/ low density outside Fe-core (Heger, zero metal)

15 $M_\odot$**:** (Woosley & Heger 2007, solar)

25 $M_\odot$**:** (Heger & Woosley 2010, zero metal. Large Fe-core.

3 Models - 3 Histories

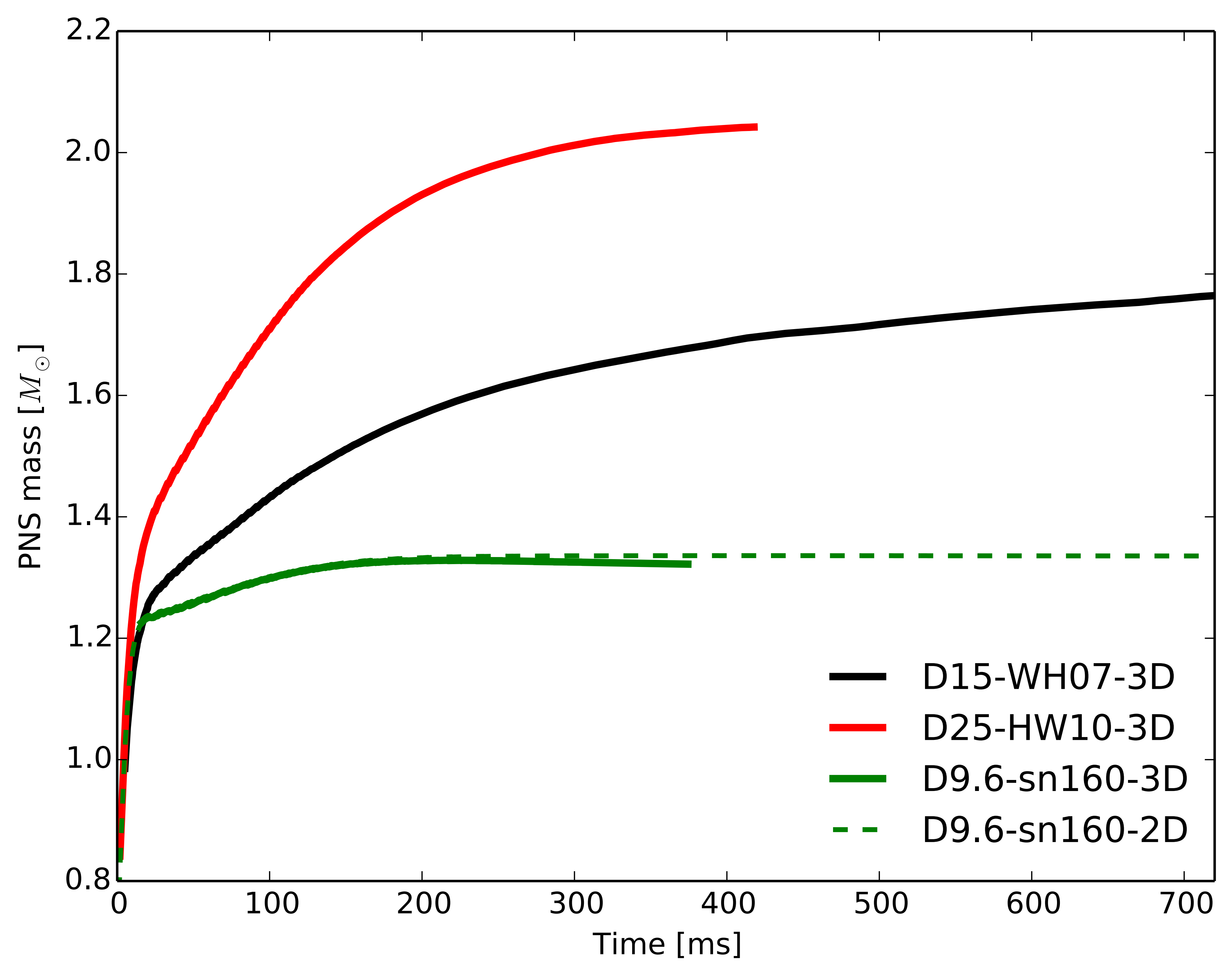
Diagnostic energies -->

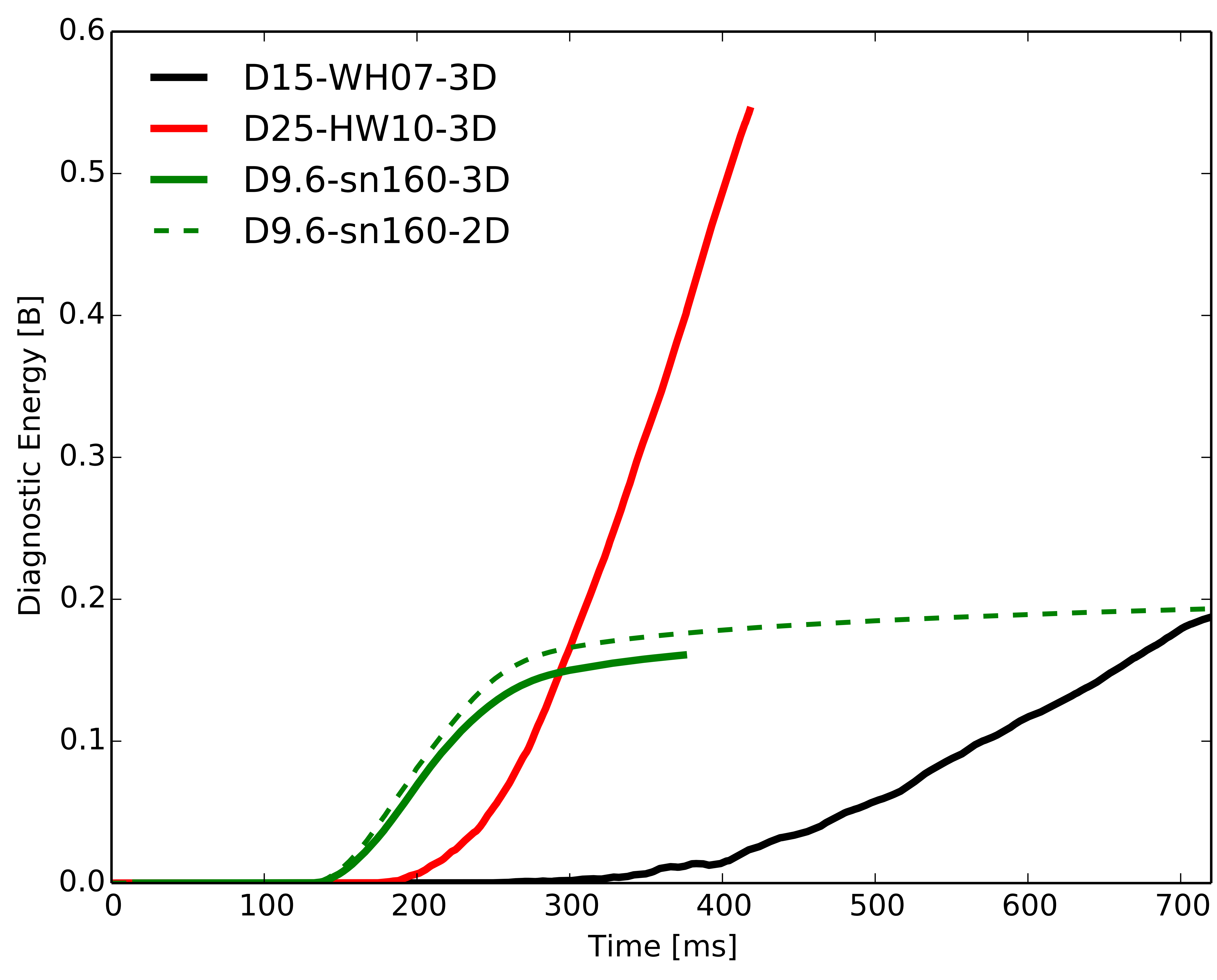
15: Grows slowly after shock launch

25: Rapid growth in explosion energy

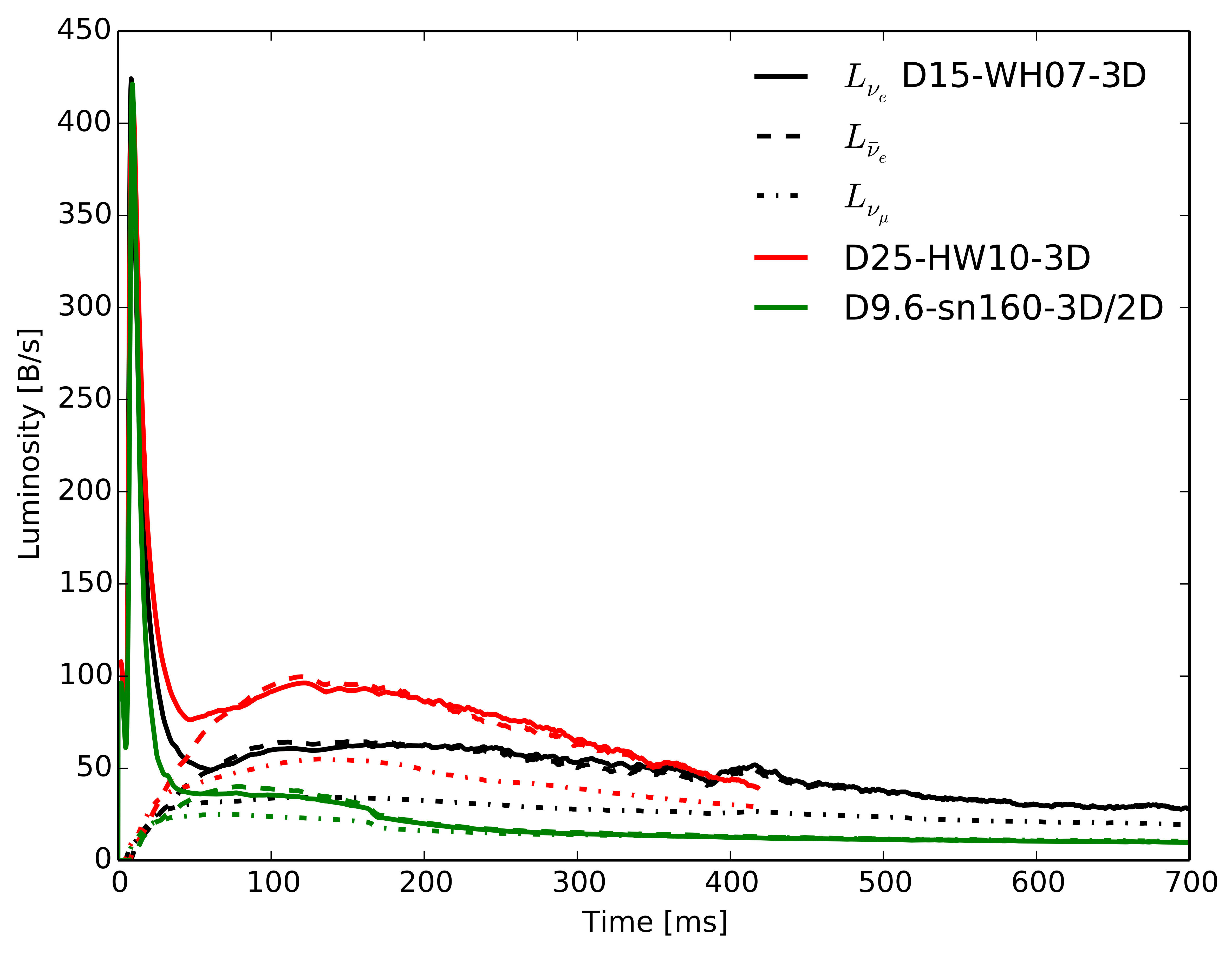
9.6: Explosion is very quick to start and to saturate

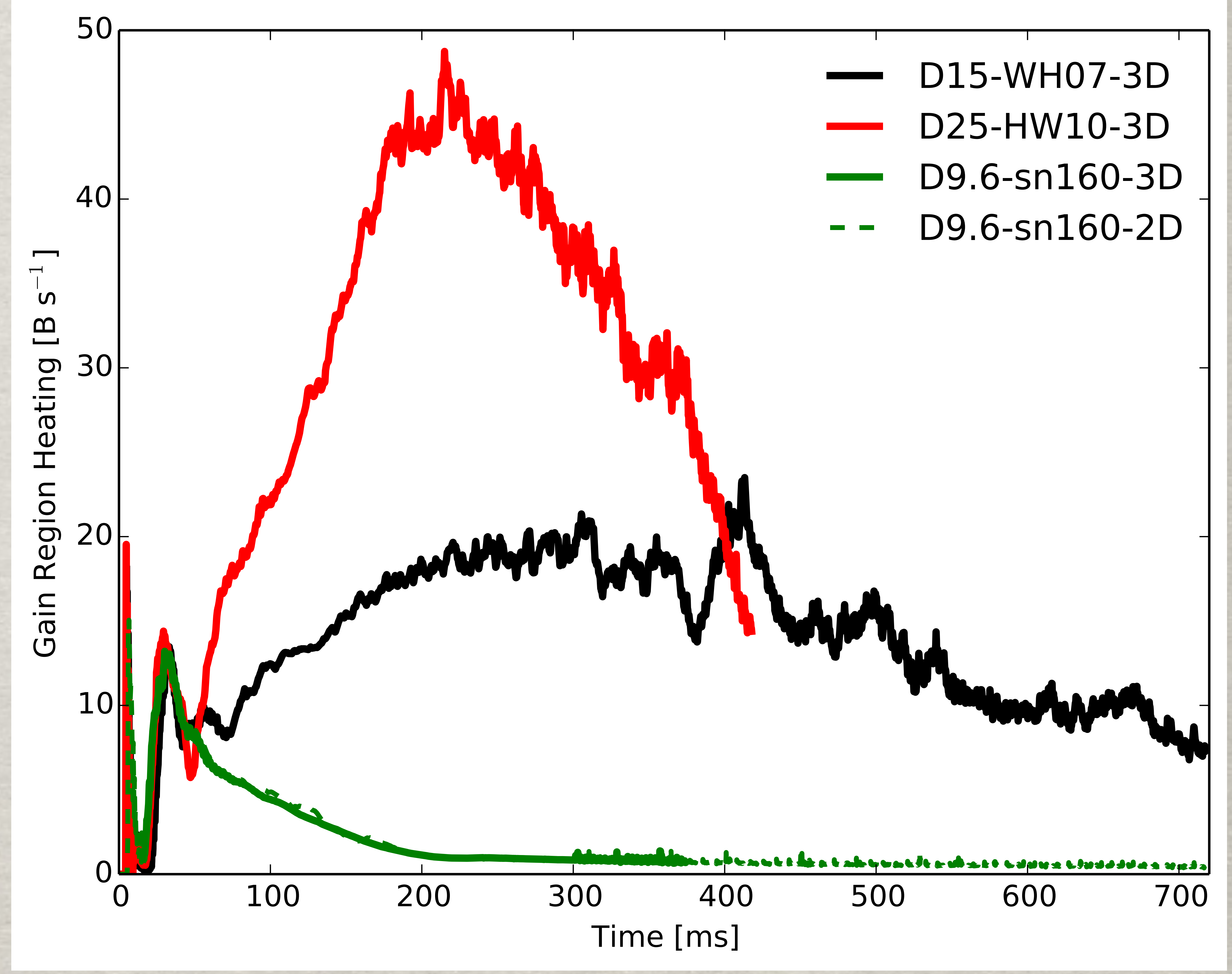
NS Mass growth





Neutrinos & Heating



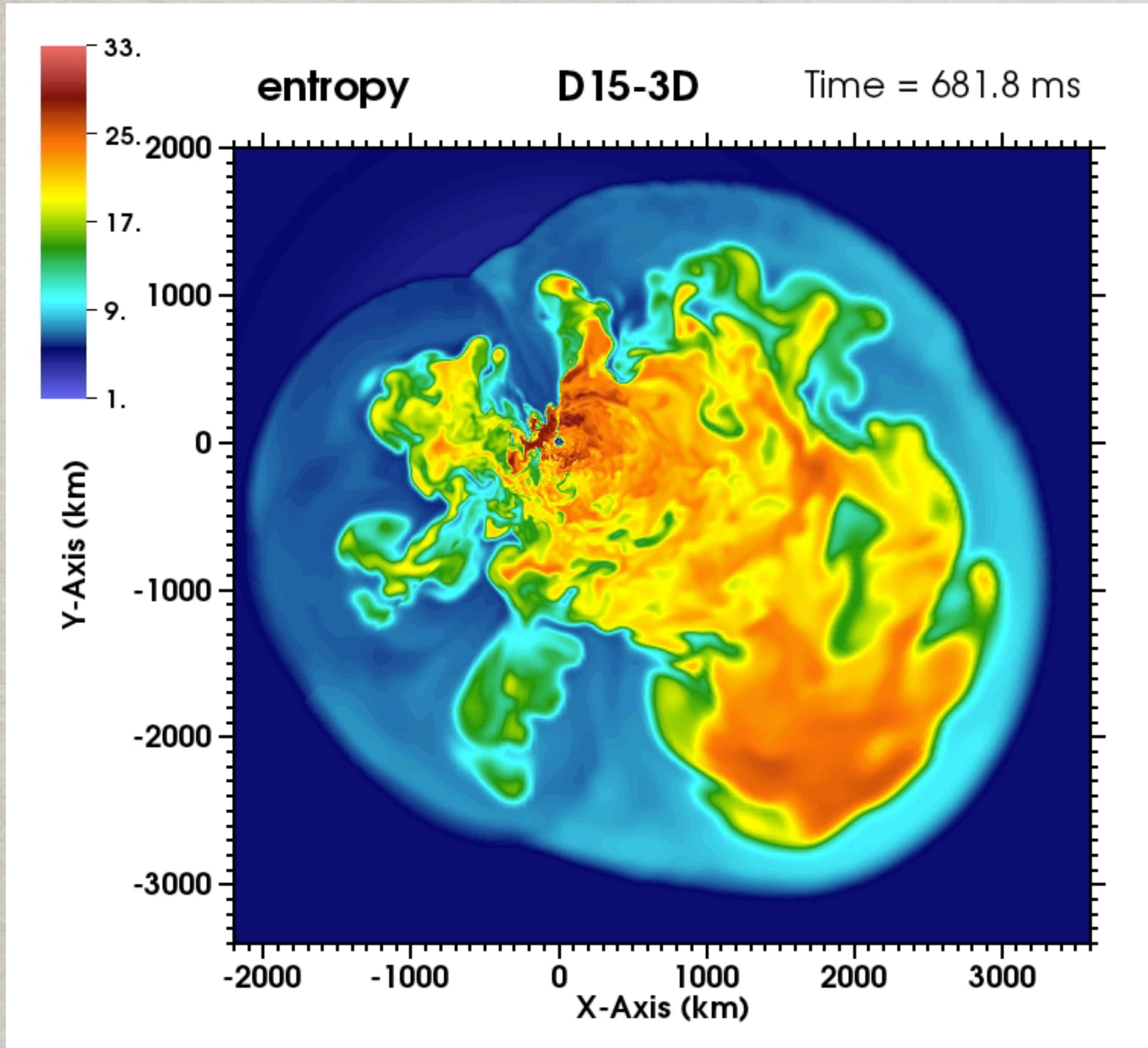


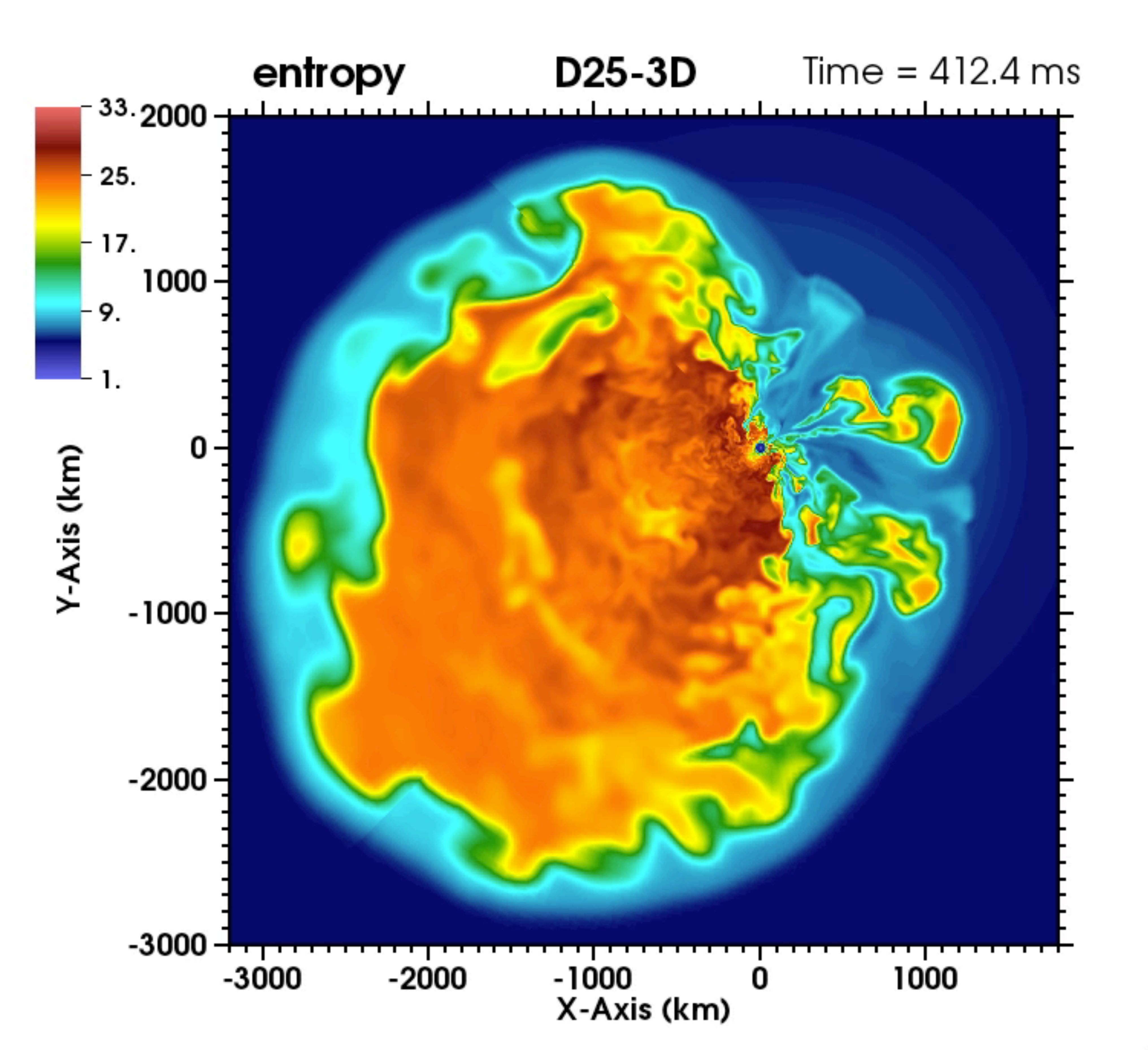
Luminosity correlates to PNS mass in few 100 ms after breakout

D9.6 heating fades quickly (thus low expl. energy)

D15 heating similar to C15-3D; **D25** heating very strong after breakout

3D in motion





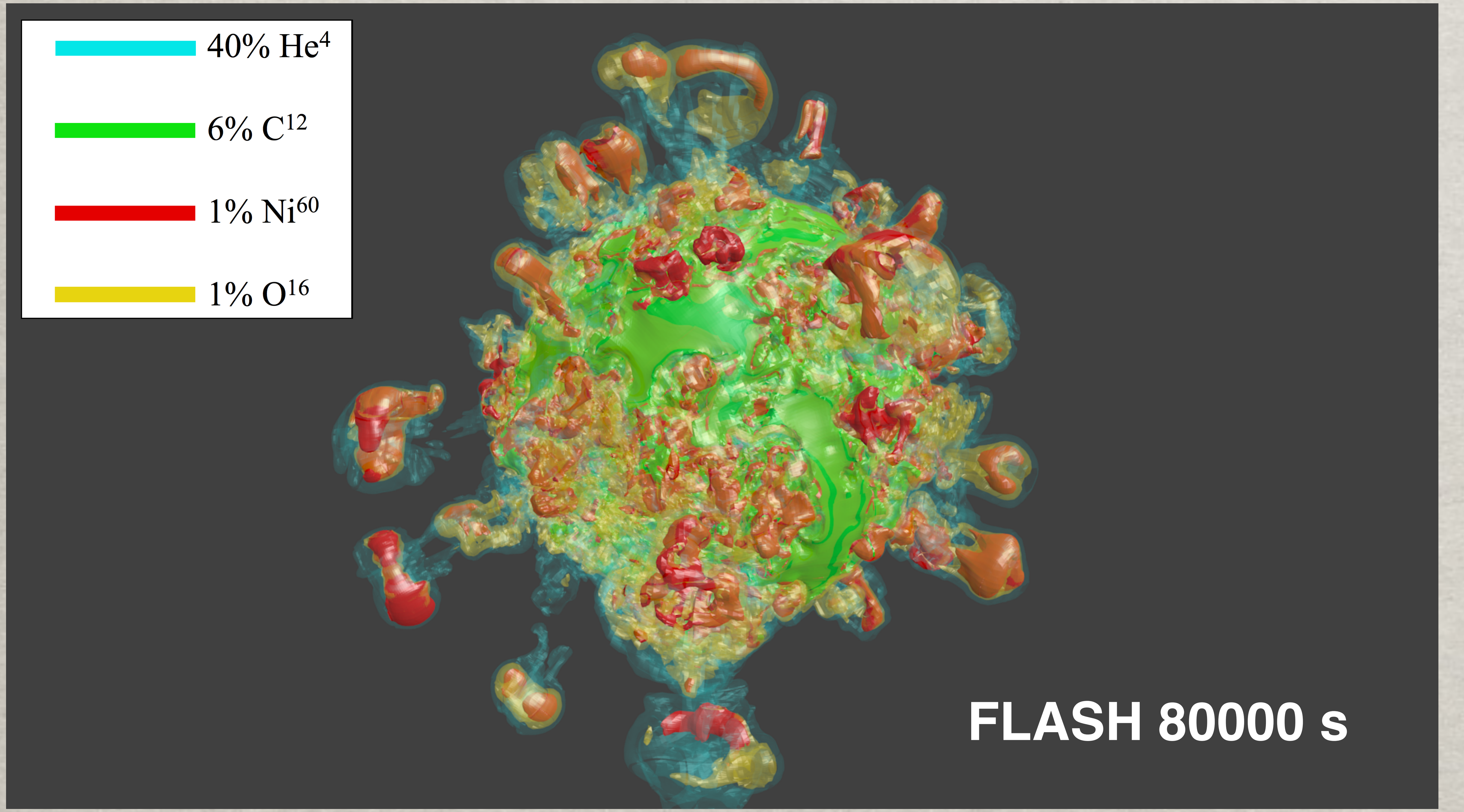
Entropy slice, 20 ms frame interval

Both models form a large outflow (just like C15-3D model) and primary inflow from opposite end.

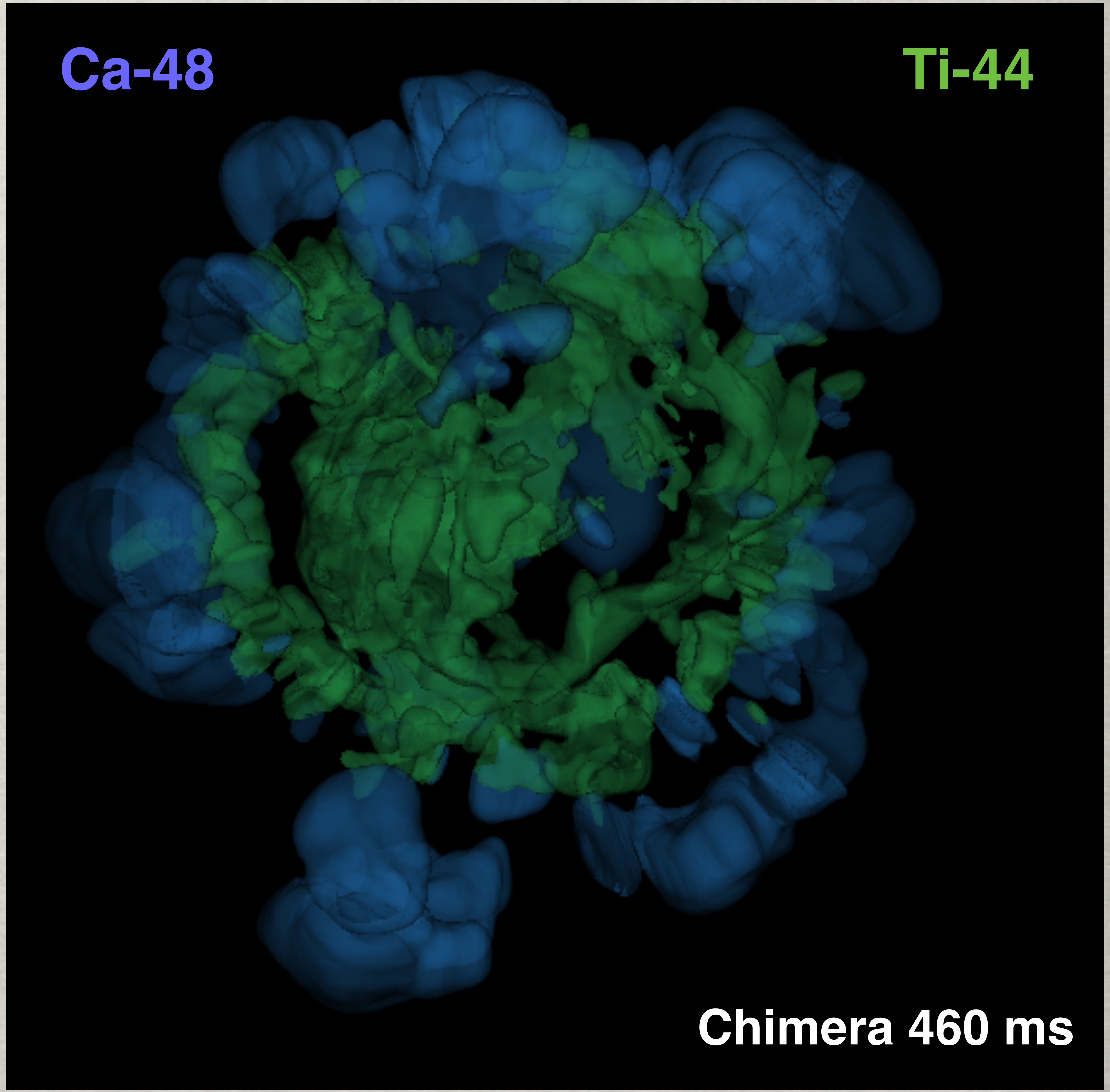
9.6 M⊙, zero metal, 160-nuc. net

Right: Low densities outside Fe-core triggers rapid neutrino-driven explosion with low Ye layer behind shock, creates neutron-rich isotopes (460 ms).

Below: Transferred to FLASH hydro to star surface (~1 AU), develops large plumes enveloped in He & embedded in H, 80000 s (22 hr).



Sandoval et al., in prep



Lentz, Hix, Harris et al, in prep

Series-E: Nuclear EoS in 2D

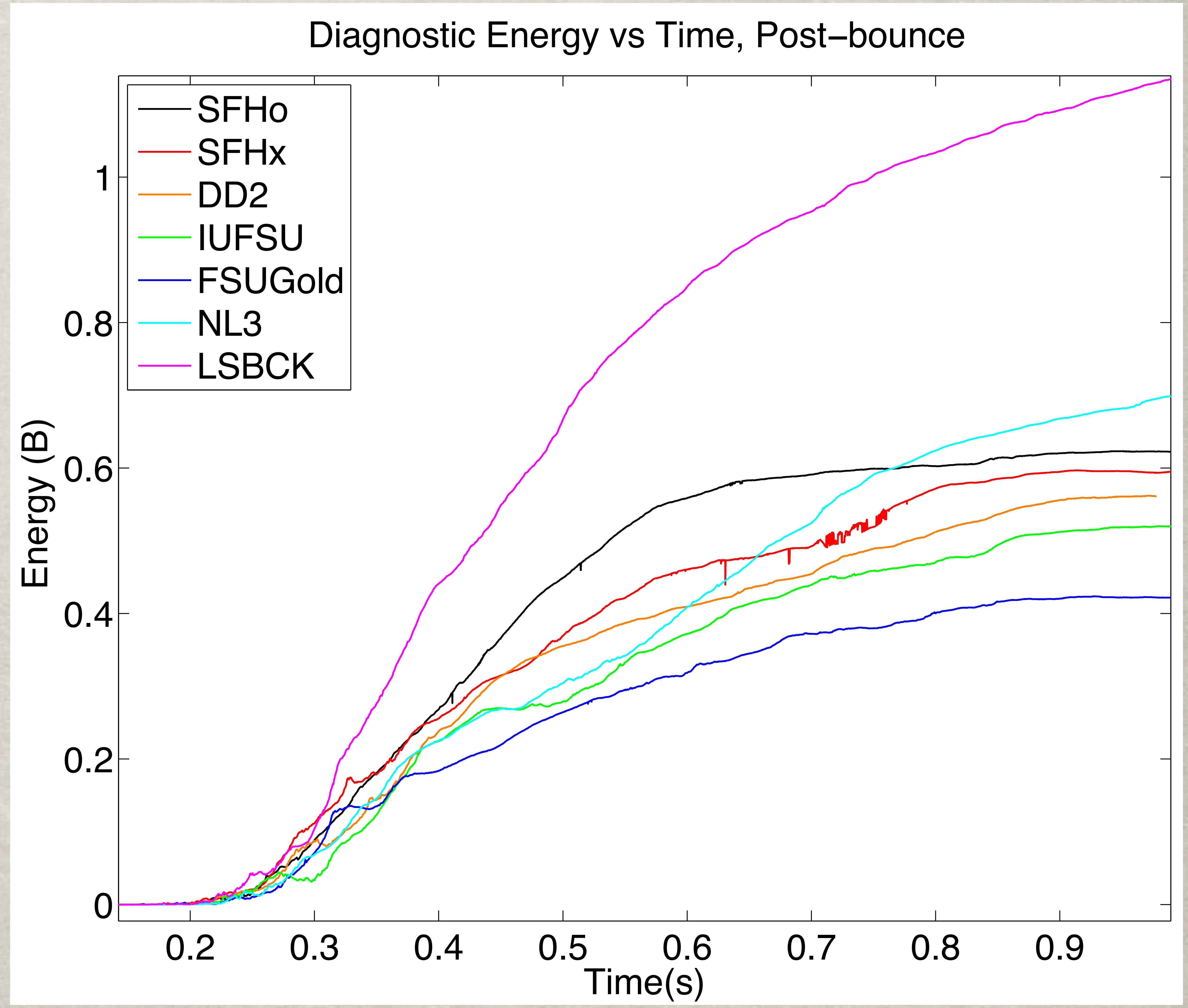
Dense nuclear Equation of State regulates nature of core bounce and neutrino emissions during shock revival.

Newer Equations of State use different numerical methods and are constrained by experimental and theoretical nuclear physics and measurements of neutron stars.

The old "standard" (Lattimer-Swesty-220) is the outlier.

2D models of 15 $M_\odot$ WH07 progenitor

Ryan Landfield (UTK Ph.D., 2018)



Concluding thoughts

We have a lot of simulation data that we are working to analyze. Buried in that data is a lot of interesting behaviors and physics; some of which we've found; some of that I shared today.

Supernova modeling with Chimera continues to proceed in 2D and 3D with improving microphysics and a widening range of pre-supernova progenitors.

Coming in the near future is multidimensional pre-supernova evolution (Chloe Keeling-Sandoval, Ph.D. project).

In addition to reporting on explosion simulations we are also working on neutrino signals, gravitational wave signals, nucleosynthesis, and disruptions of supernova progenitors.