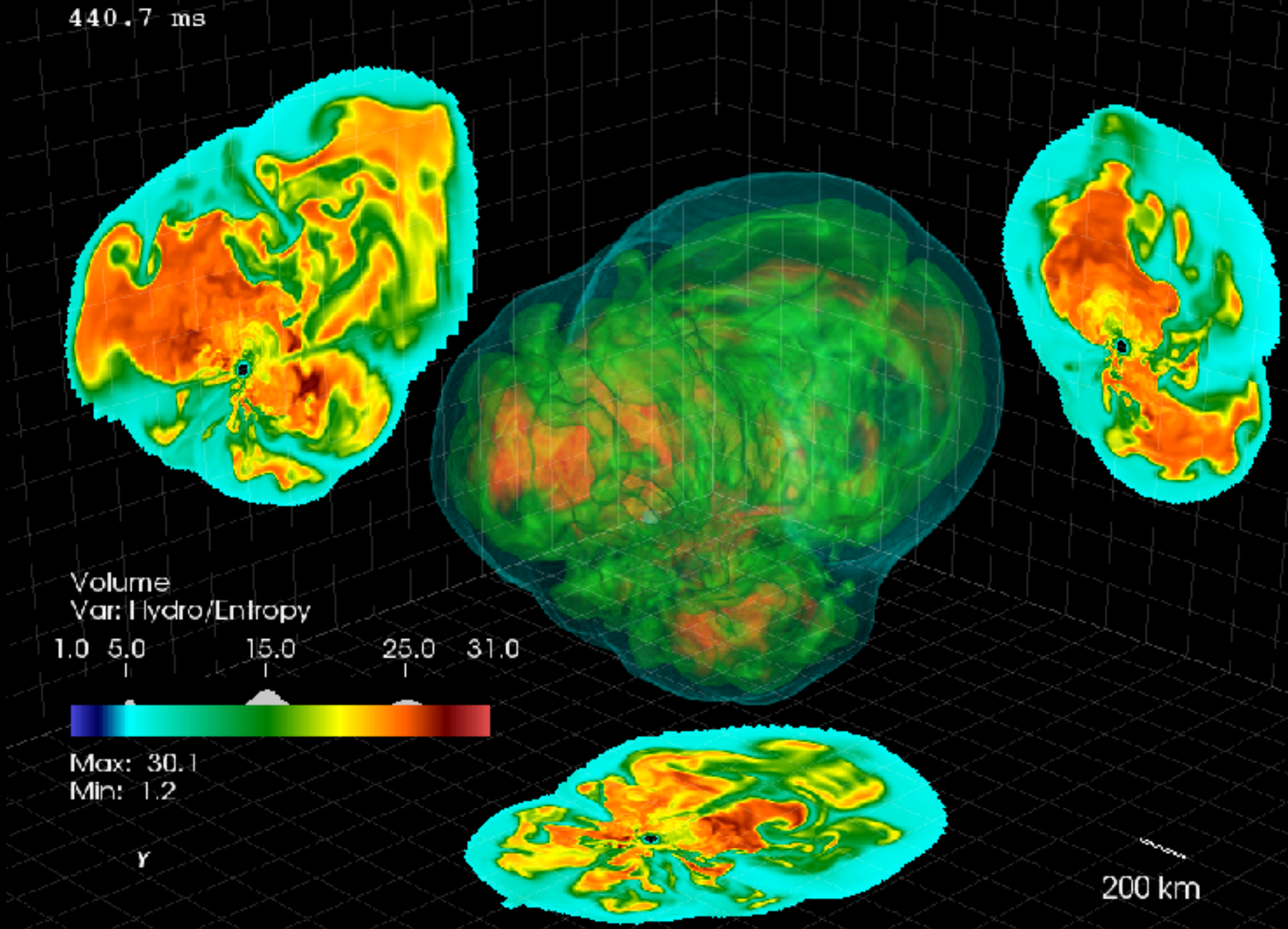
Recent Progress with CHIMERA



William Raphael Hix (ORNL/U. Tennessee)

Blondin, Bruenn, Harris, Lentz, Marronetti, Messer, Mezzacappa (Florida Atlantic U., NC State U., ORNL, UT, NSF)

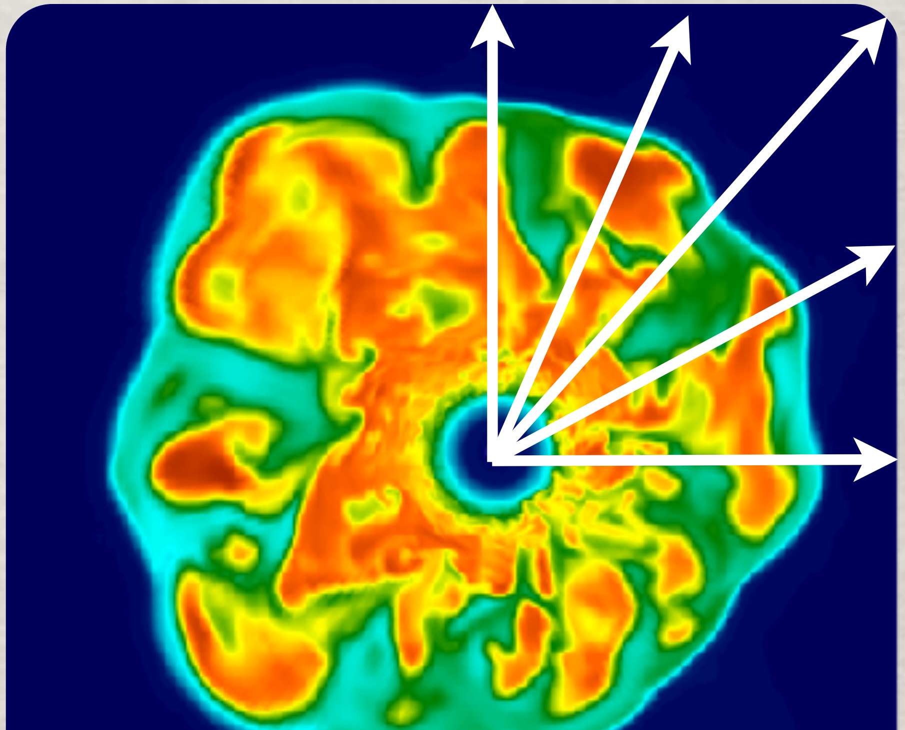
CHIMERA

CHIMERA has 3 “heads”

- Spectral Neutrino Transport (MGFLD-TRANS, Bruenn) in Ray-by-Ray Approximation
- Shock-capturing Hydrodynamics (VH1, Blondin)
- Nuclear Kinetics (XNet, Hix & Thielemann)
- Plus Realistic Equations of State, Newtonian Gravity with Spherical GR Corrections.

Models use a variety of approximations

- Self-consistent models, like CHIMERA, use full physics to the center.
- Leakage & IDSA models simplify the transport.
- Parameterized models replace the core with a specified neutrino luminosity.



Ray-by-Ray Approximation

TEAMS progress

Under TEAMS, CHIMERA is charged with exploring the potential for the r- or p-process in three scenarios,

1) PNS wind:

We have a growing set of D-series 2D models run until the PNS wind begins. Limitation is outer boundary limited to density > 100 g cm^{-3}, which is being addressed by replacing BCK EoS with Helmholtz.

2) Epstein, Colgate & Haxton Mechanism:

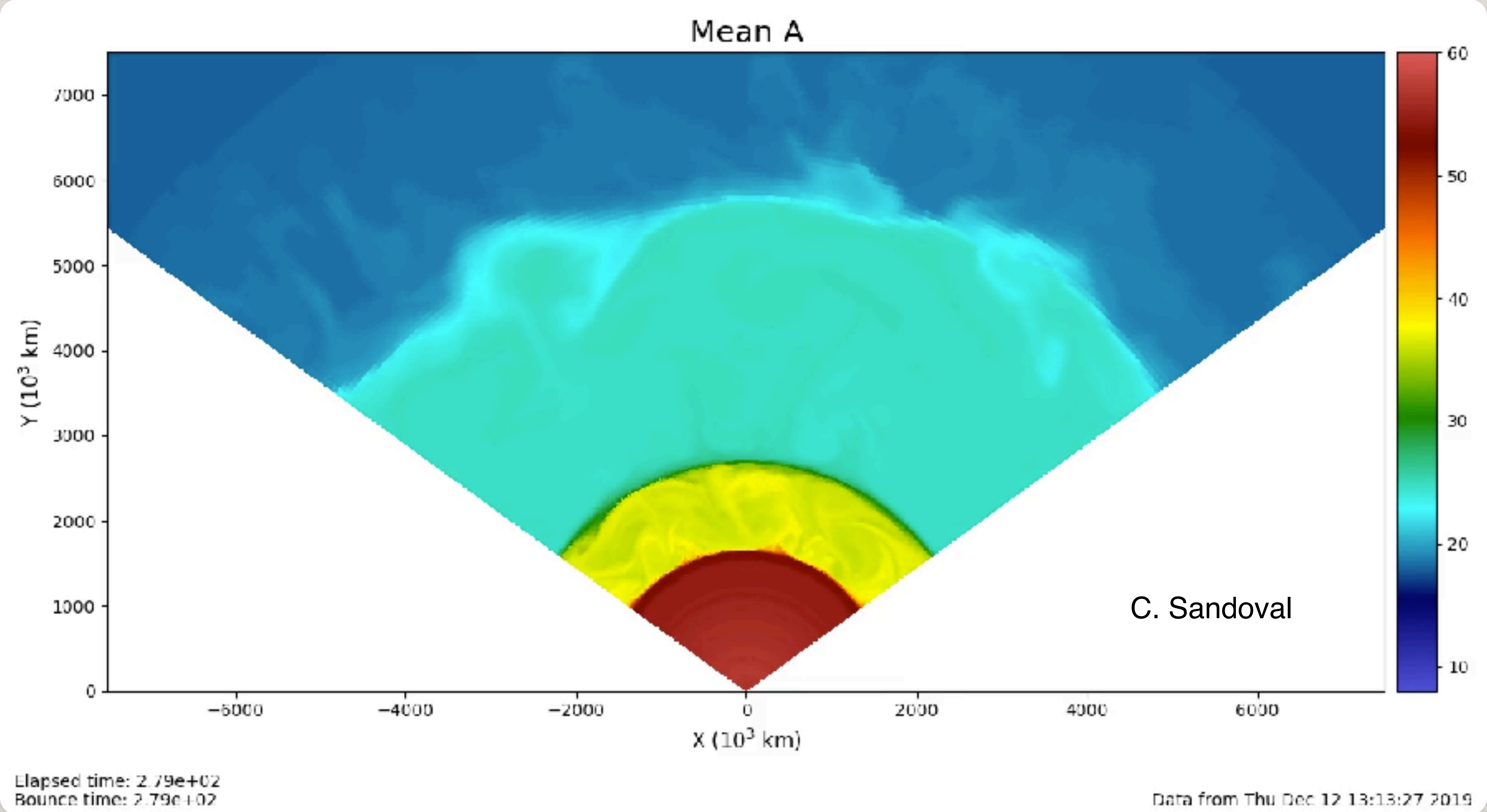
Outer boundary of 2D CHIMERA models falls in the (inner) helium layer, thus these same simulations can explore the ECH mechanism.

3) ONeMg core-collapse:

We are exploiting CHIMERA's large network capability in a number of iron core-collapse supernova simulations (e.g. D9.6-Hpr). Need to explore species needed for ONeMg core-collapse and include neutrinos in network.

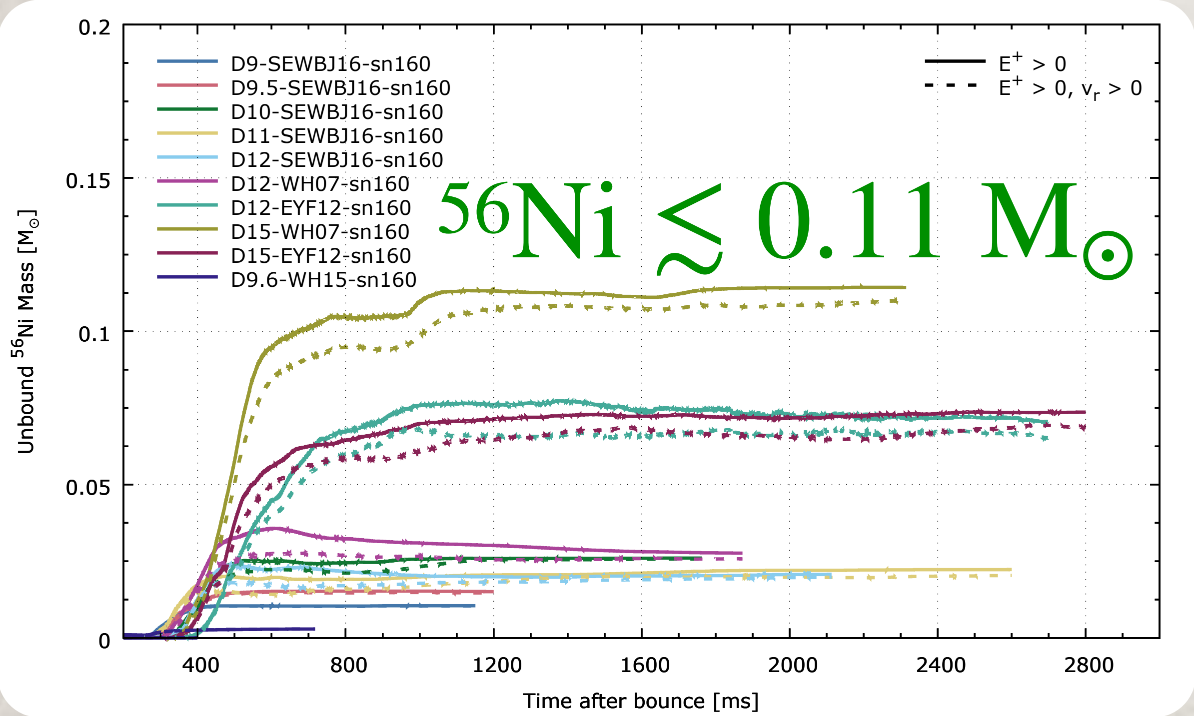
Making Progenitors

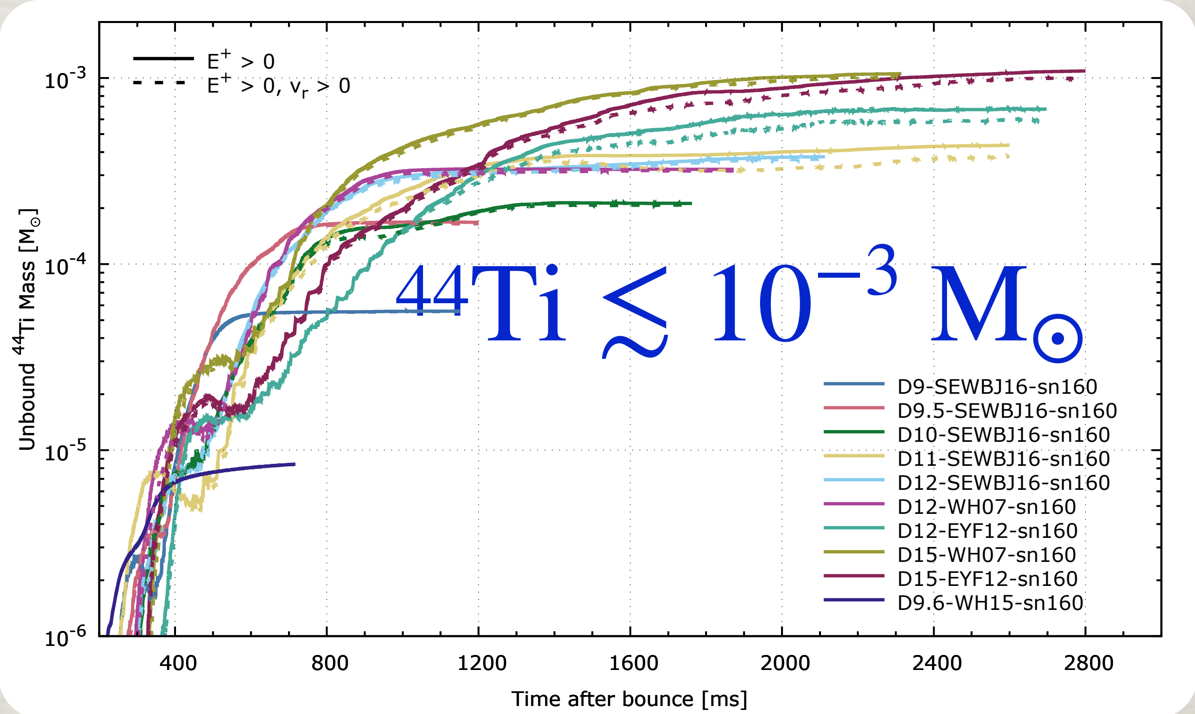
The project to model convective shell burning has added capabilities (e.g. Helmholtz EOS) to Polaris which will be useful to the ECH and ONeMg investigations once they are back ported to CHIMERA.

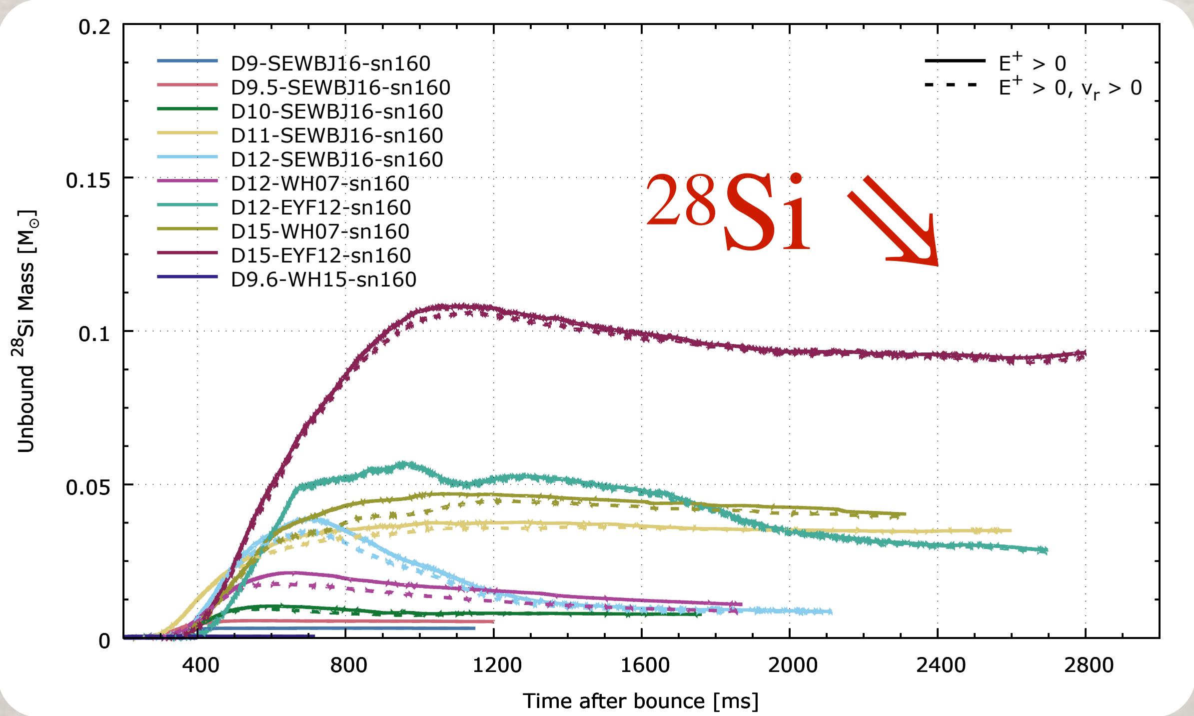


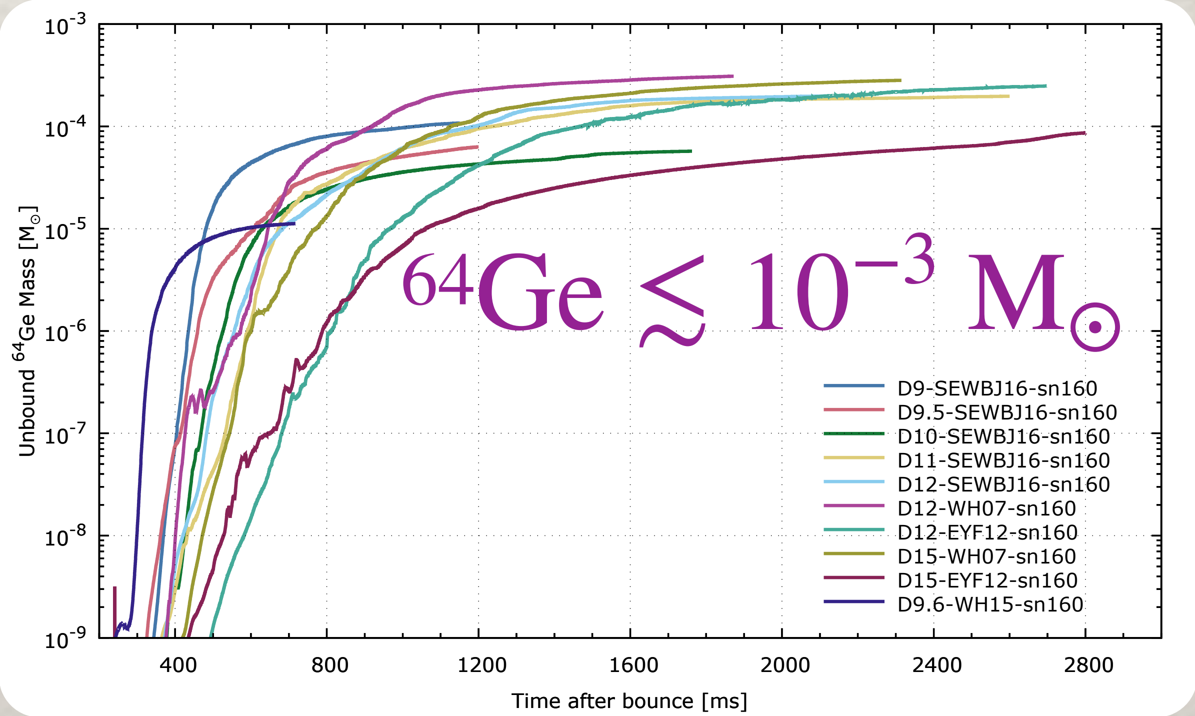
Realistic Network Models

Computation of CCSN models with fully coupled networks of sufficient size for O, Si burning and NSE freezeout is possible.



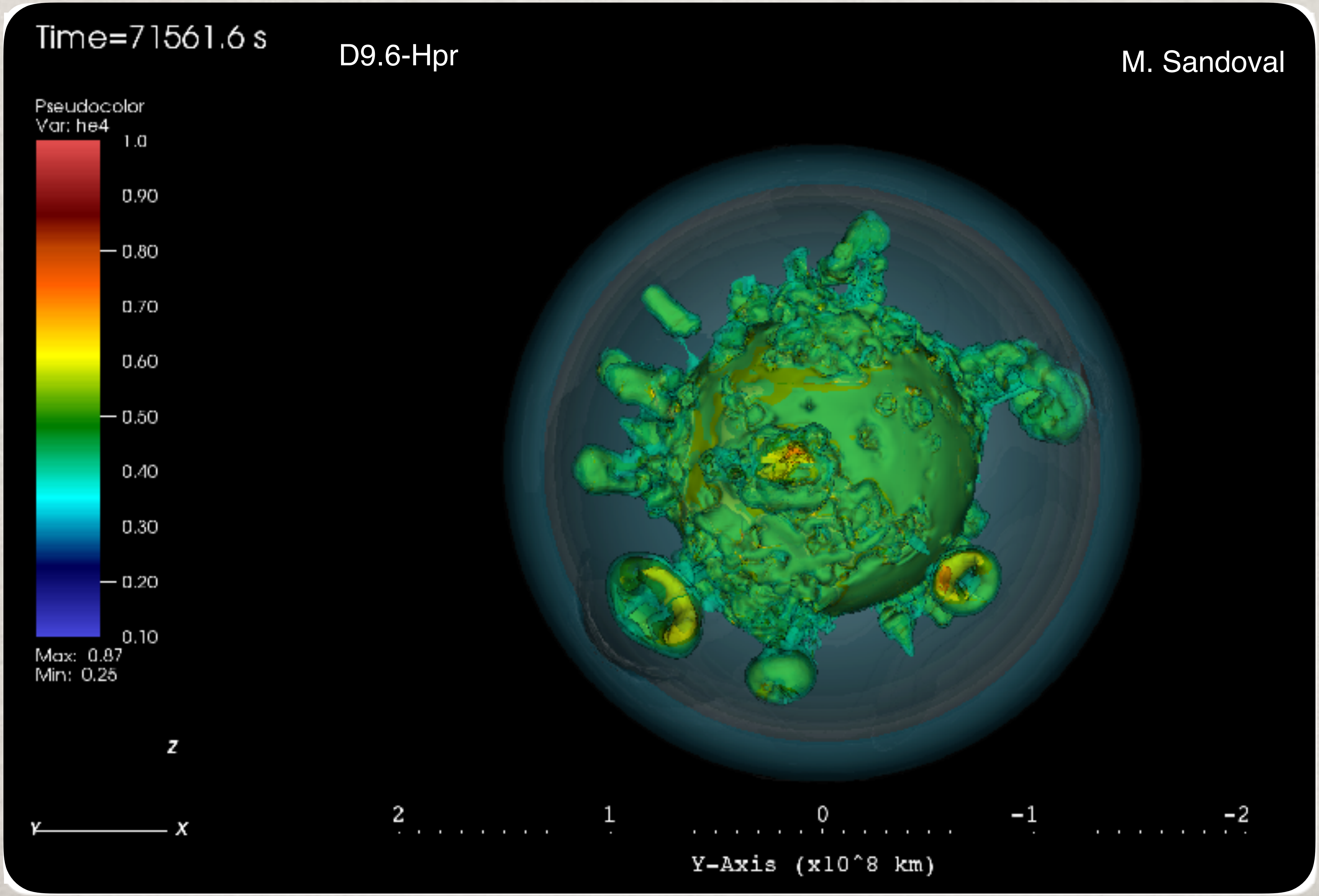






Extended Running

One possibility for exploring the ECH mechanism is to use our extended running capability in FLASH.



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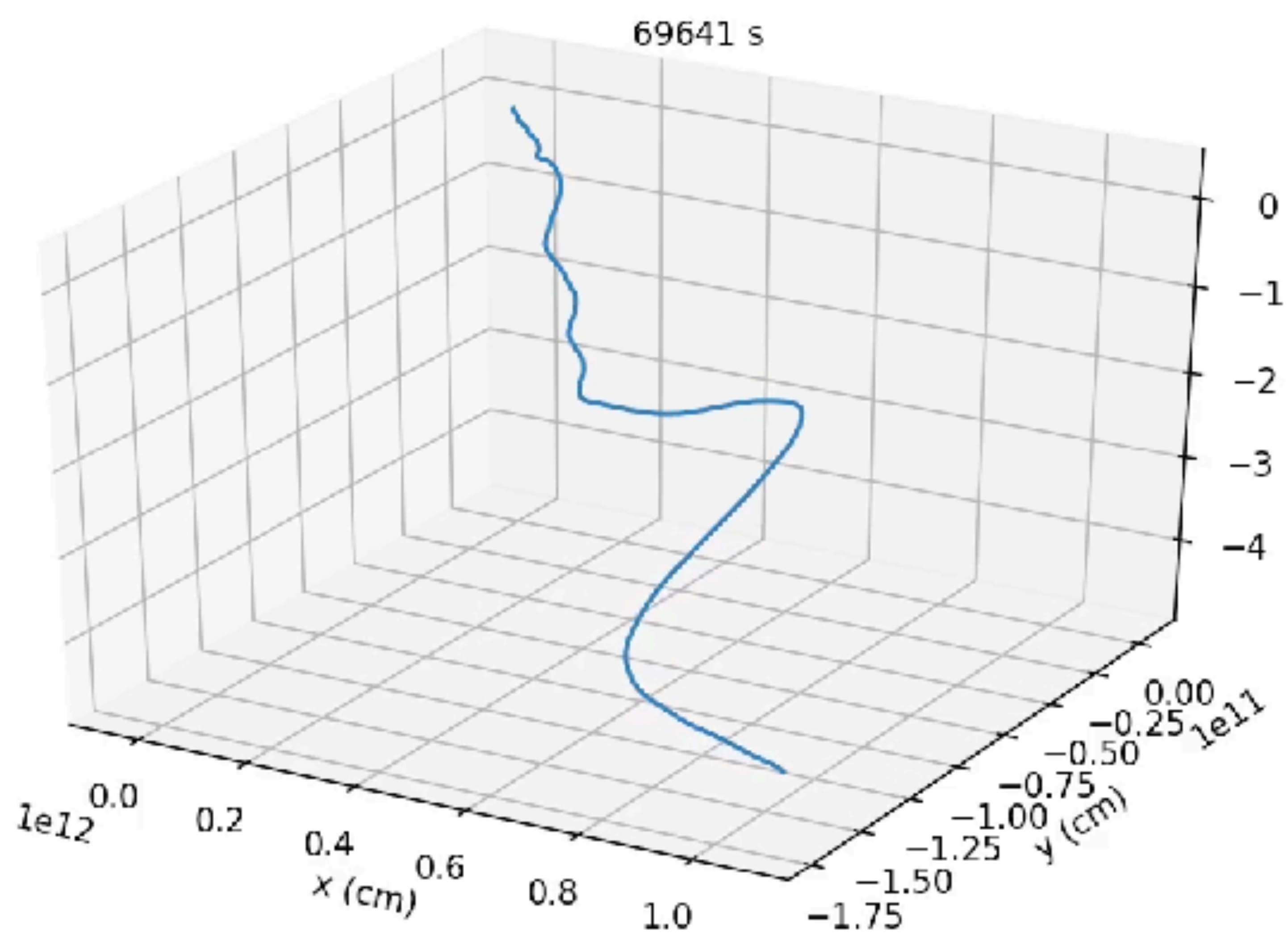


A, B, C, D, E…

CHIMERA remains a work in progress, improving over time.

To differentiate our models to reflect this code development, we describe series of models with a common codebase.

The A series consisted of axisymmetric (2D) models 2009–2010.

The B series (e.g. Bruenn et al. 2016), improved NSE-nonNSE transition with detailed NSE composition at low density, switch to Lattimer-Swesty EoS with K=220 MeV, …

C series (e.g. Lentz et al. 2015) includes further improvements in the NSE-nonNSE transition and neutrino transport in the shock, …

D series further refines neutrino transport in the shock, introduces Yin-Yang grid…

E series develops tabular EOS (e.g. SFHo, SFHx, …)

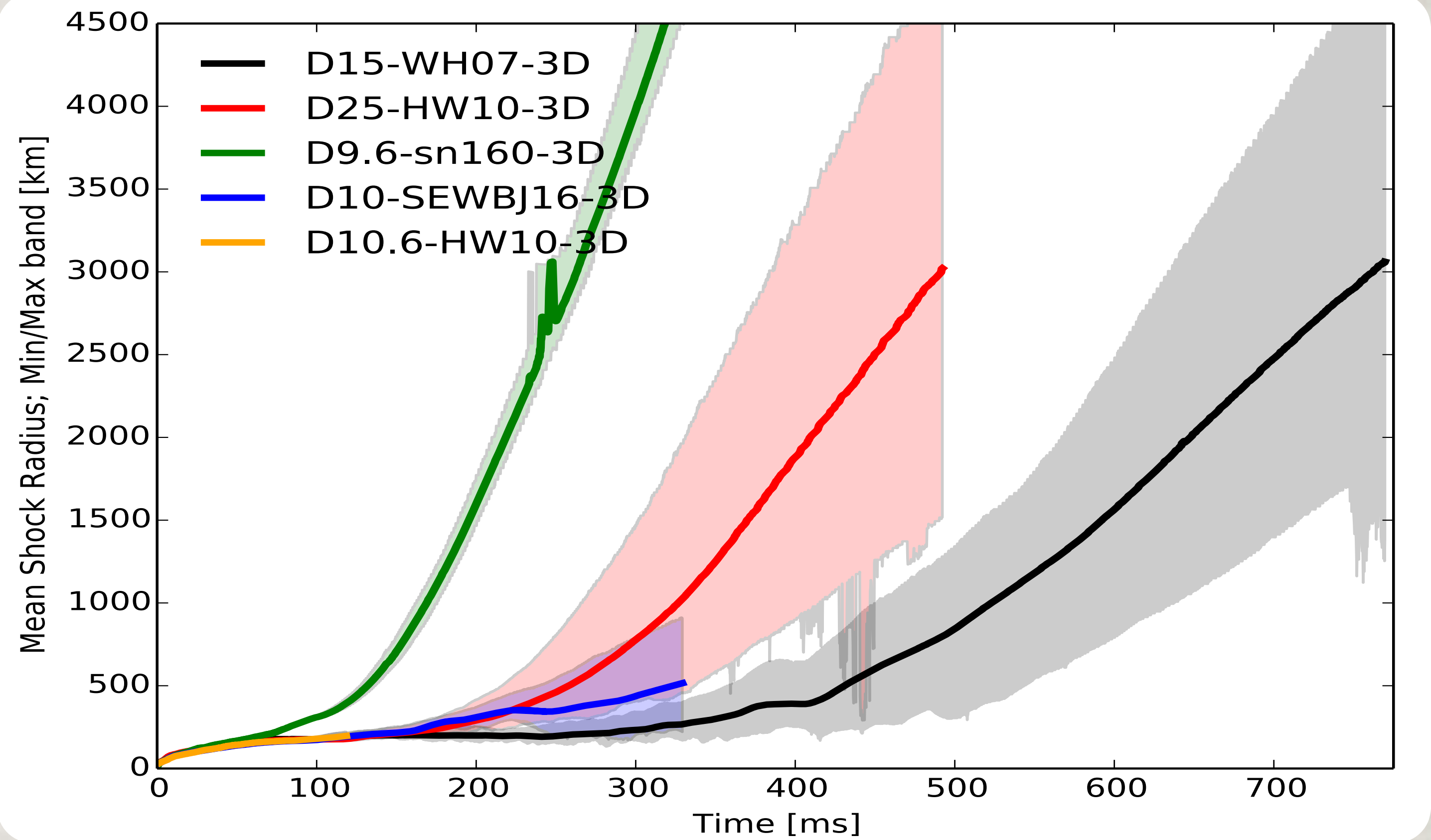
F, G, etc. will come.

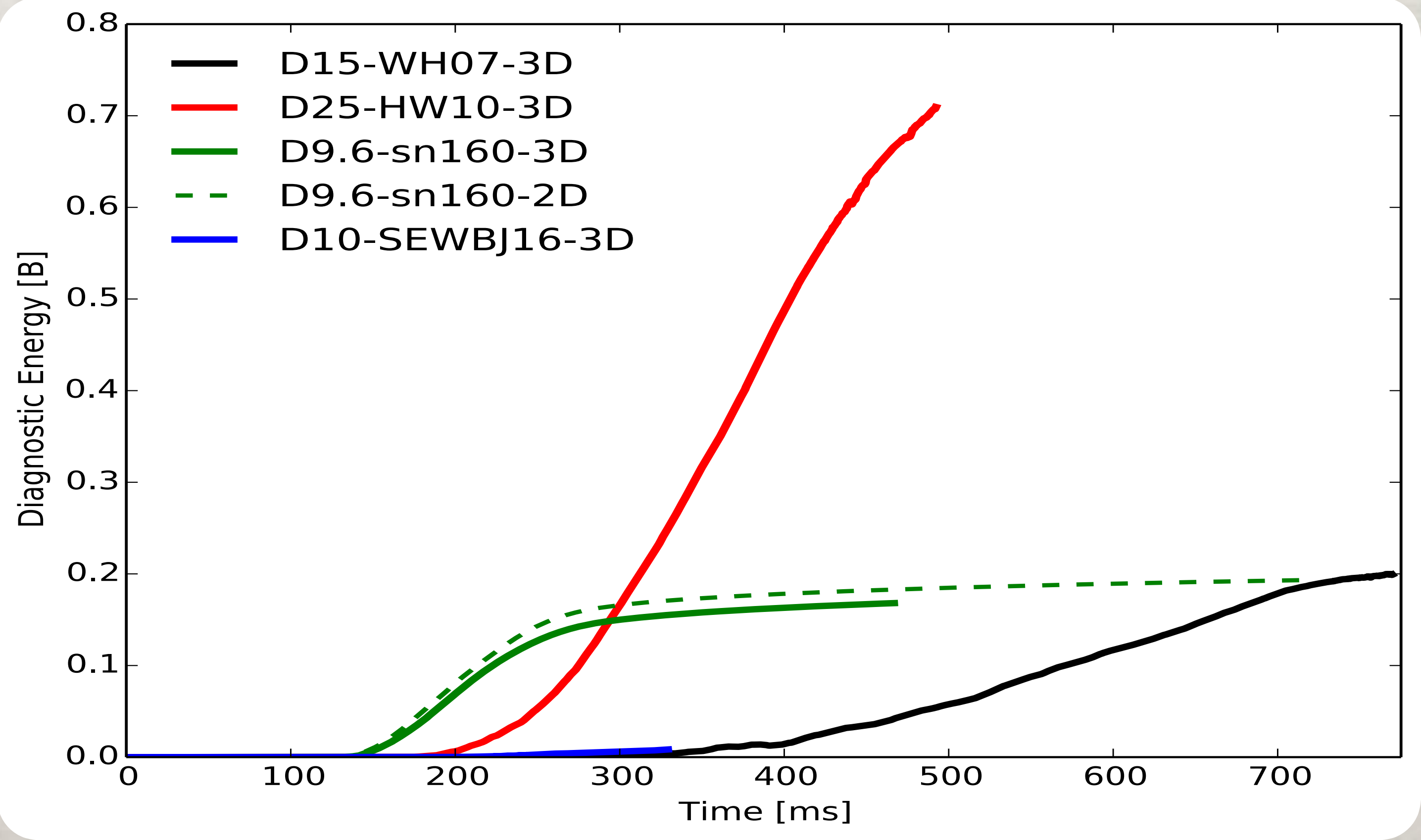
3D Progress

Last year, we ran 5 3D models as part of the D-series with ~1° resolution in latitude & longitude and 540-720 adaptive radial zones.

Progenitors are 9.6, 10.6 & 25 $M_\odot$ zero metals and 10 & 15 $M_\odot$ solar metals.

Only D15-WH07 and D9.6-Hpr reached saturated explosion energies before allocation expired.





Mother of Side Tracks

We recently published an extensive methods paper documenting CHIMERA through the C-series.

The Astrophysical Journal Supplement Series, 248:11 (94pp), 2020 May
https://doi.org/10.3847/1538-4365/ab7aff

CrossMark

CHIMERA: A Massively Parallel Code for Core-collapse Supernova Simulations

Stephen W. Bruenn[1], John M. Blondin[2], W. Raphael Hix[3,4], Eric J. Lentz[3,4,5], O. E. Bronson Messer[3,4,6], Anthony Mezzacappa[4,5], Eirik Endeve[4,5,7], J. Austin Harris[3,6], Pedro Marronetti[8], Reuben D. Budiardja[4,6], Merek A. Chertkow[4], and Ching-Tsai Lee[4]

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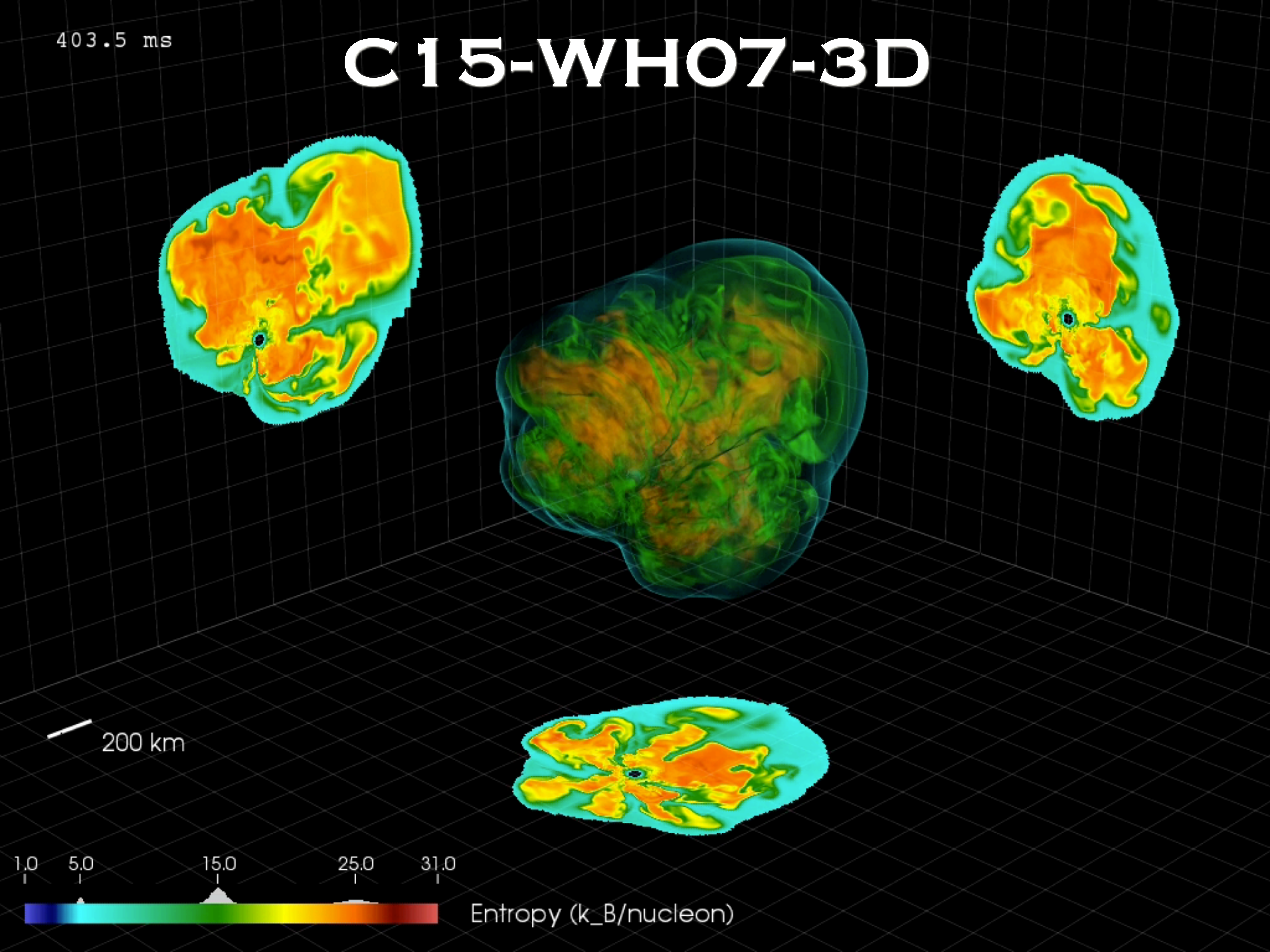
In the spirit of Bruenn (1985), the paper provides a detailed look at the inner workings of CHIMERA and a log of the issues we have encountered and dealt with during its development.

The gestation process was, naturally, effortless.

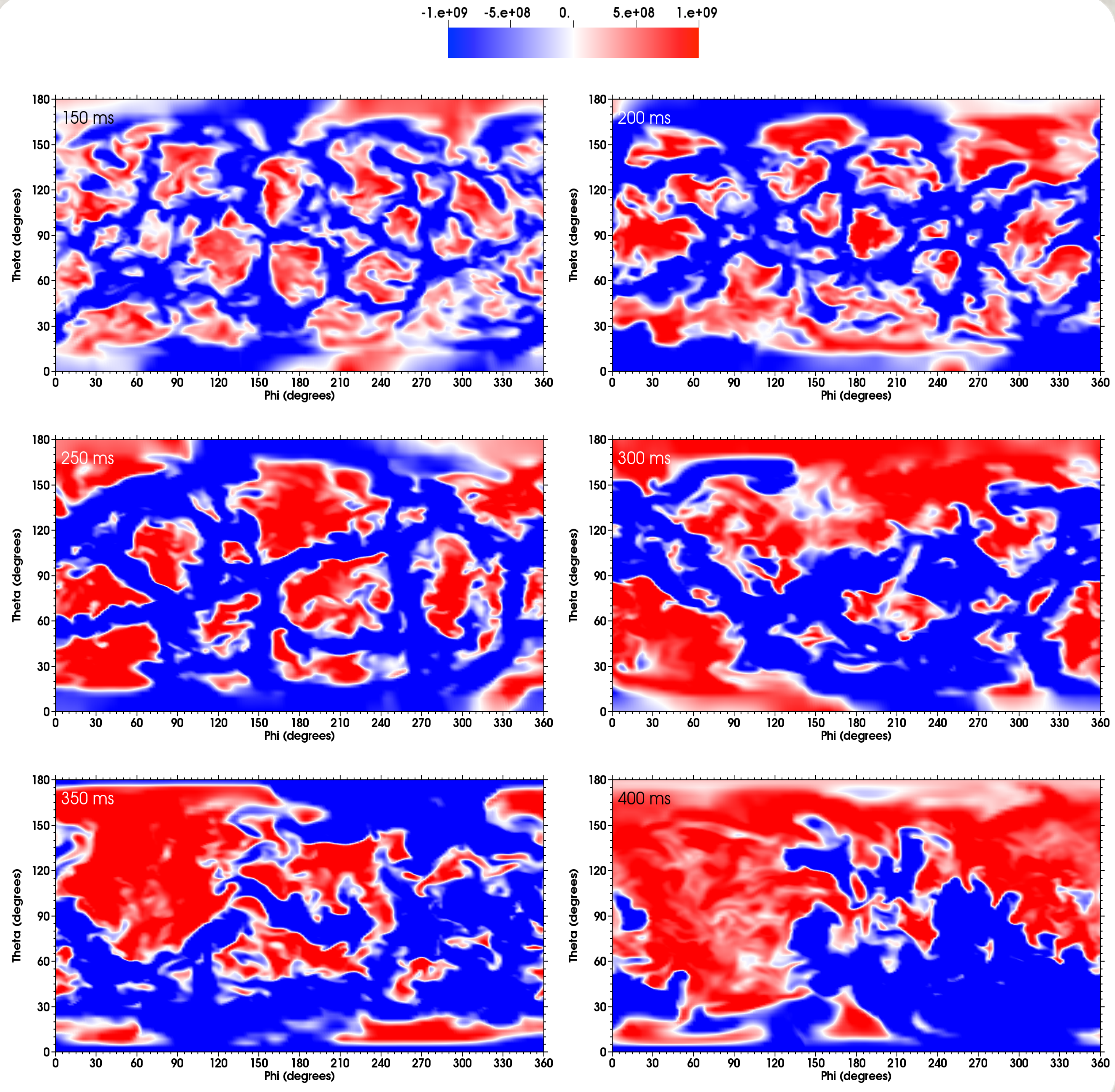

403.5 ms
C15-WH07-3D
200 km
1.0
5.0
15.0
25.0
31.0
Entropy (k_B/nucleon)

Growing Plumes

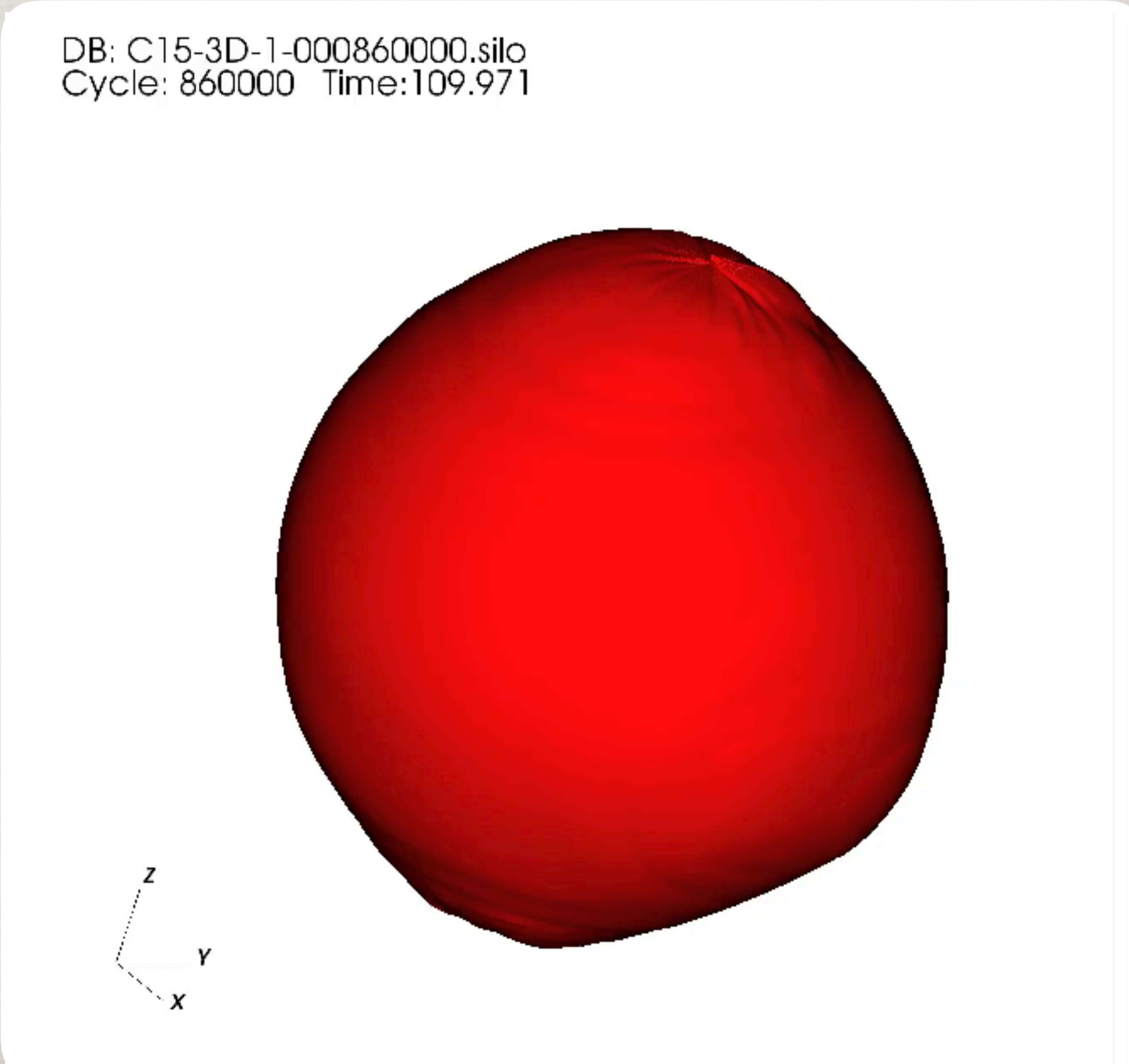
The explosion in 3D (as well as 2D) is preceded by the progress to fewer, larger plumes, see Fernandez (2015).

However, in 2D this progress is very rapid.

These larger plumes allow neutrino heating to do work on the shock.



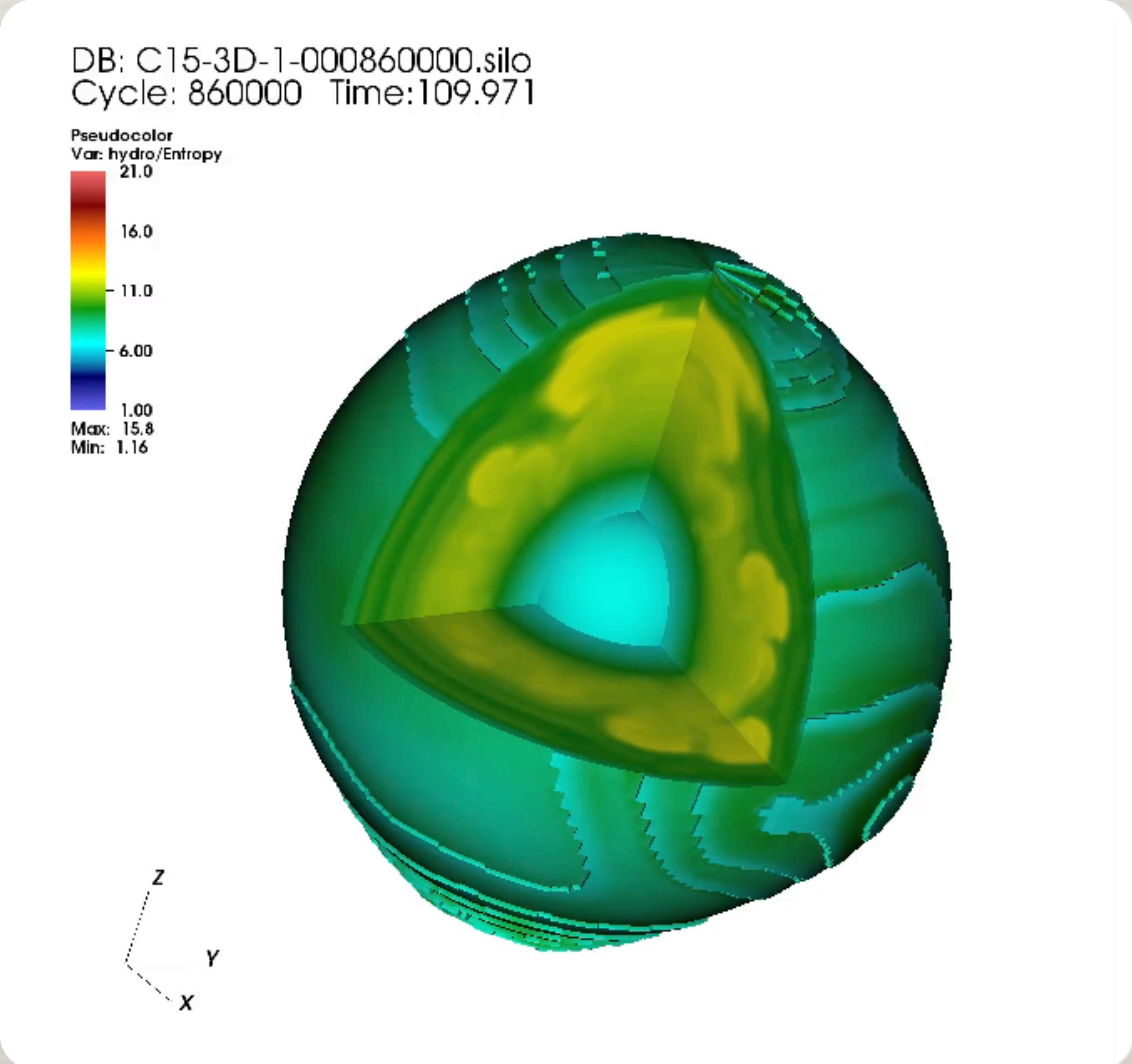
Plume Punching



Plume Punching

Rising plumes pushing out the shock, slowly increasing the volume of the heating region.

Larger plumes are more effective, so the process accelerates as the plumes grow to large scale.

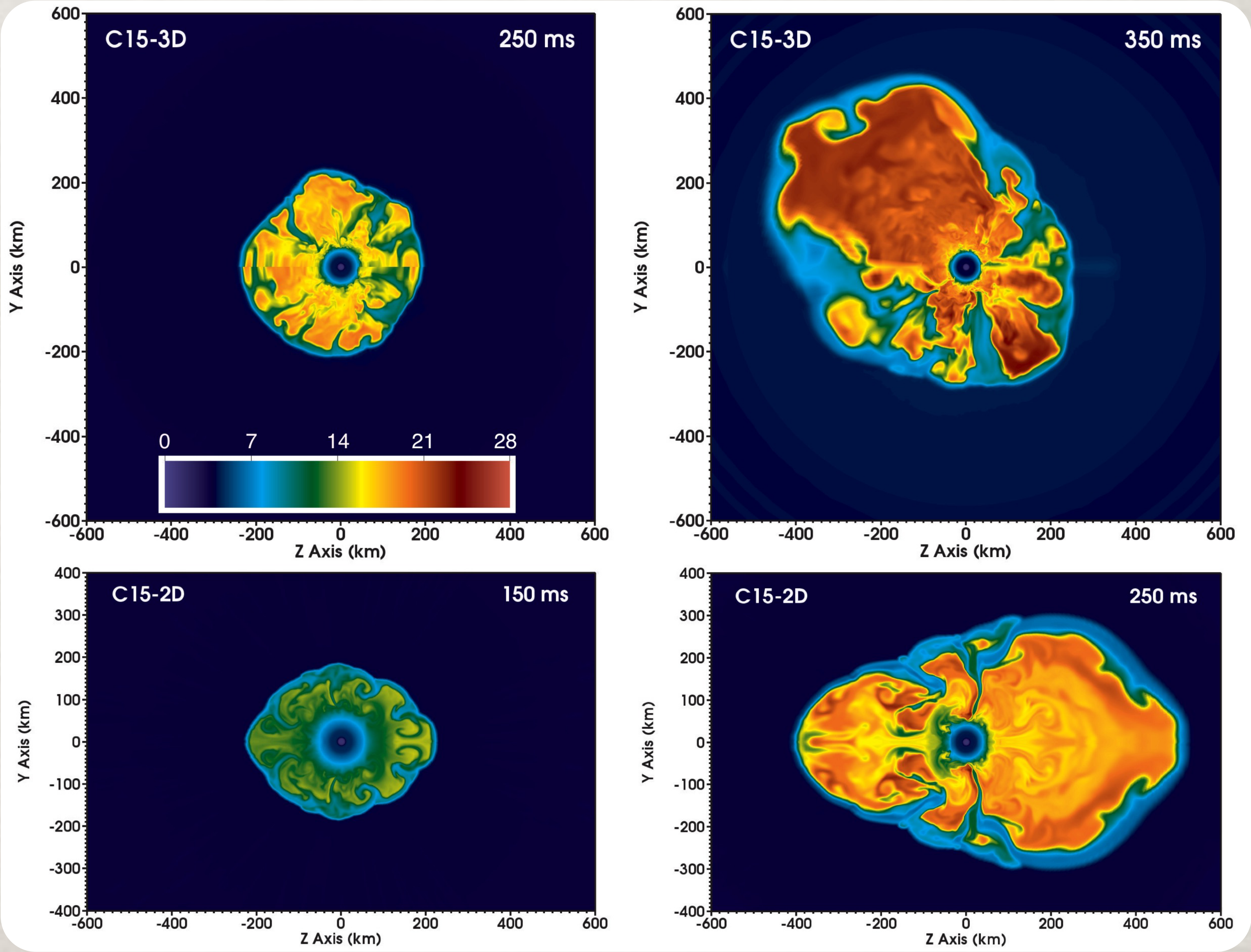


2D Acceleration

The Rayleigh-Taylor Instability, driven in CCSN by neutrino heating, favors large scale plumes, regardless of dimensionality.

In 2D, the turbulent cascade also favors organizing small scale motion into larger scale flows.

However, in 3D, the cascade favors tearing apart large scale flows. Thus in 3D, R-T requires more time and more heating to develop.



This implies that successful 2D models will tend to have lower entropy in the heating regions.

Low Resolution grows Large Plumes

To test the impact of resolution, we ran a set of D15-WH07 models on a 3D 90° × 90° wedge at resolutions of 2°, 1°, ½° & ¼°.

The setup is similar to Radice, Ott, Abdikamalov … (2016), but with a fully self-consistent model.

IOP Publishing Physica Scripta
Phys. Scr. 95 (2020) 064005 (10pp) https://doi.org/10.1088/1402-4896/ab7dd1

On the character of turbulent-like flows in self-consistent models of core-collapse supernovae

Proceedings of the 6th International Conference 'Turbulent Mixing and Beyond'

Jordi Casanova[1], Eirik Endeve[2,3,4], Eric J Lentz[1,2,3], O E Bronson Messer[1,2,5], W Raphael Hix[1,2], J Austin Harris[1,5] and Stephen W Bruenn[6]

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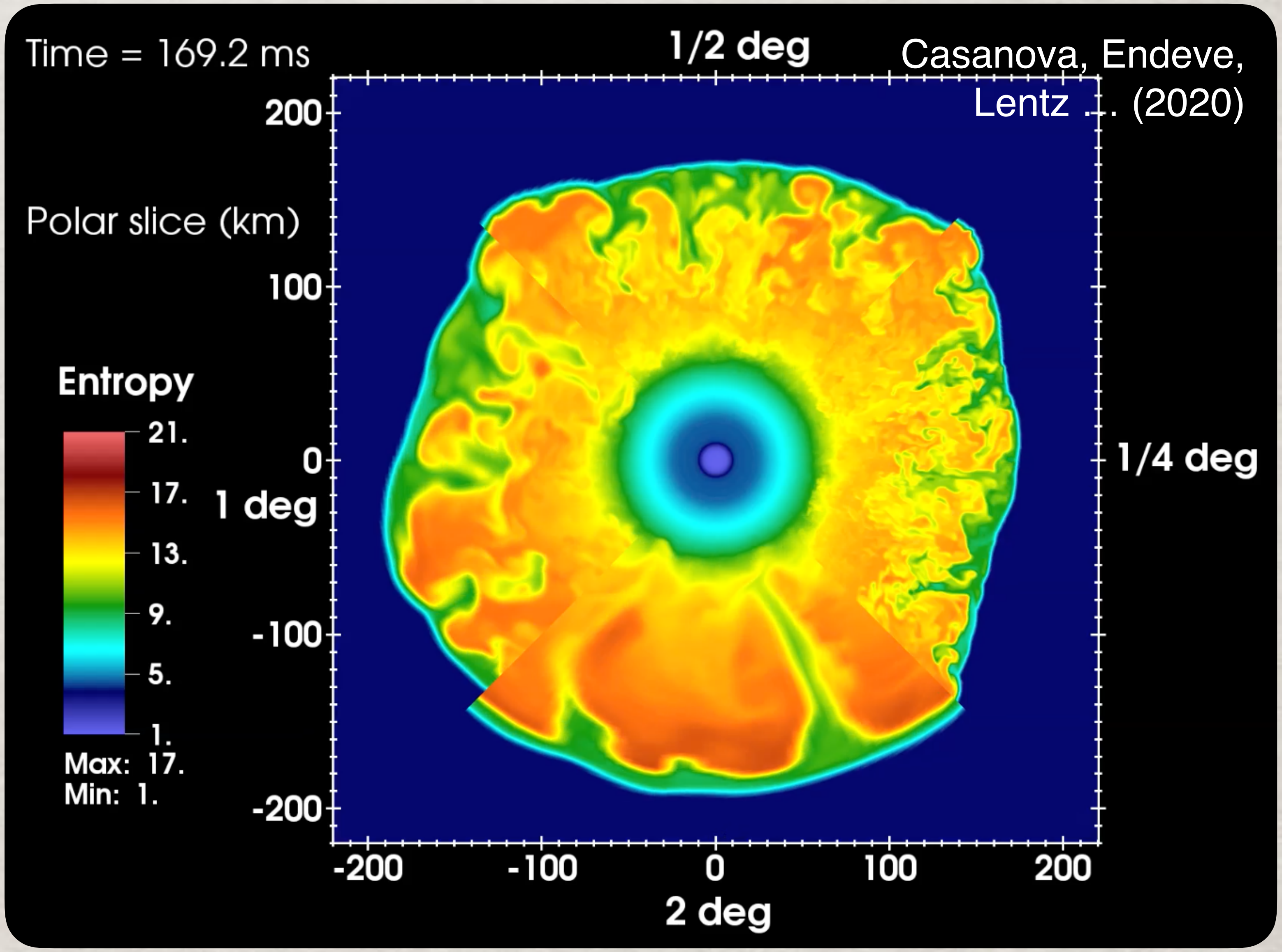
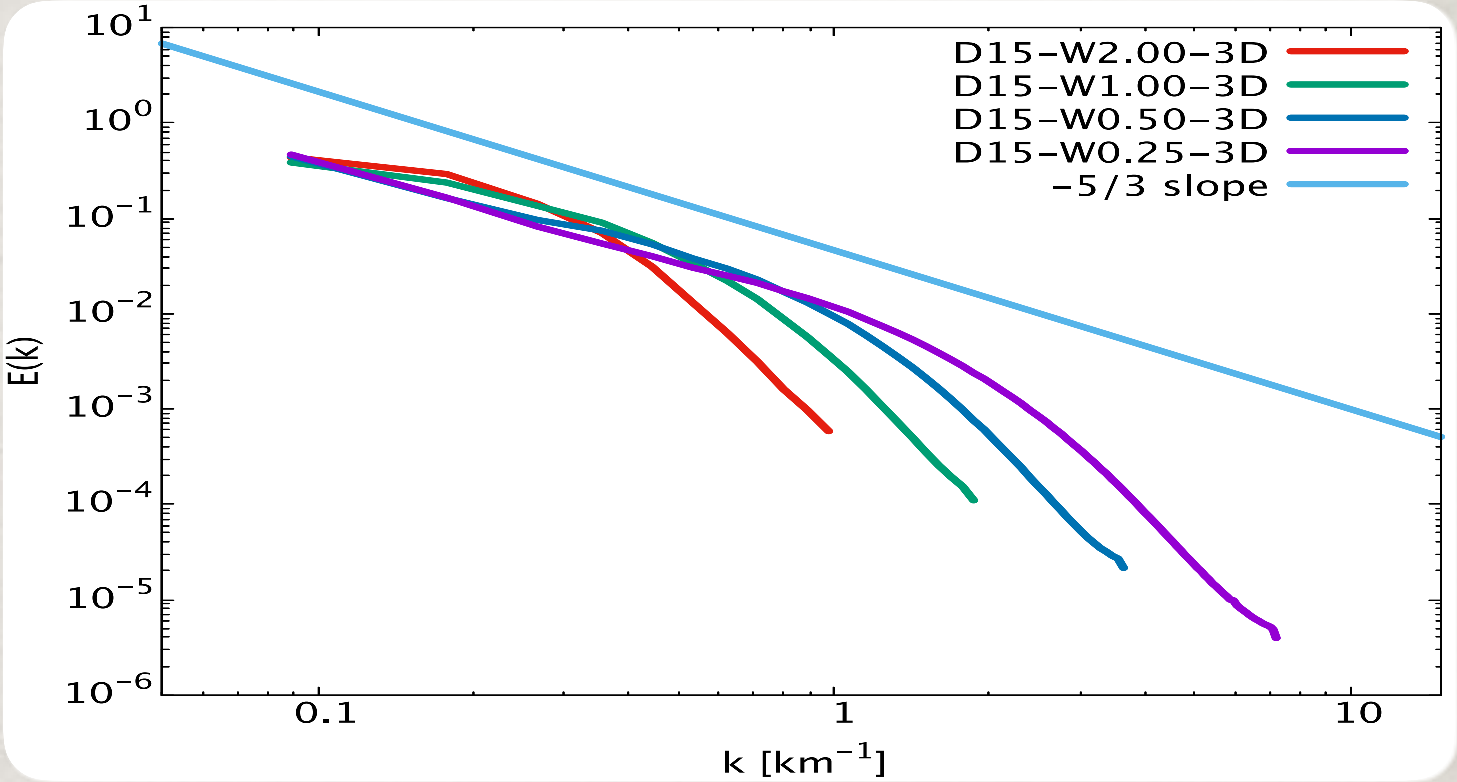
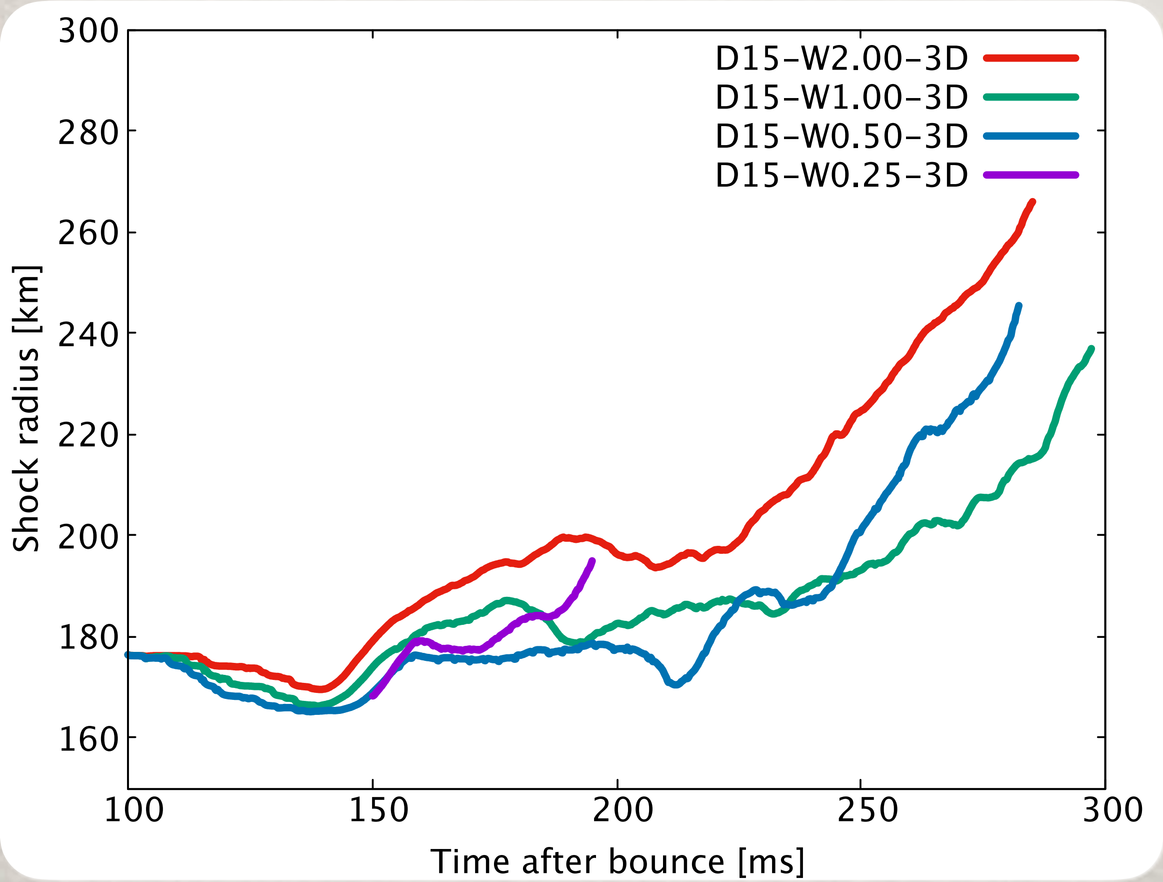


Clearly lower resolution, like 2D, artificially favors large scale convective features. Visually, resolutions > ½° are distinct from those ≤ ½° and seem to have progressed farther toward explosion.

Excess Power

The effect of the turbulent cascade is to remove power from large scales (small wavenumber k) in favor of smaller scale features and ultimately dissipation as heat.





Kolmogorov predicts $k^{-5/3}$ scaling, which the higher resolution models achieve, though spanning only one decade due to computational cost.

Lower resolution models exhibit an earlier liftoff of the stalled shock.

Testing the EoS

CHIMERA was built around a combination of Lattimer & Swesty (1991; LS) in the PNS ($\rho > 10^{11}$ g cm^{3}) and Baron, Cooperstein, and Kahana (1985; BCK).

For his dissertation project, Ryan Landfield implemented a tabular EoS interface in CHIMERA (WeakLib).

For the E-series of models, he used this revised version of CHIMERA to examine the impact of 7 EoSs, LS-BCK and 6 from CompOSE.

The CompOSE EoSs are based on the statistical model of Hempel & Schaffner-Bielich (2010) with different interactions.

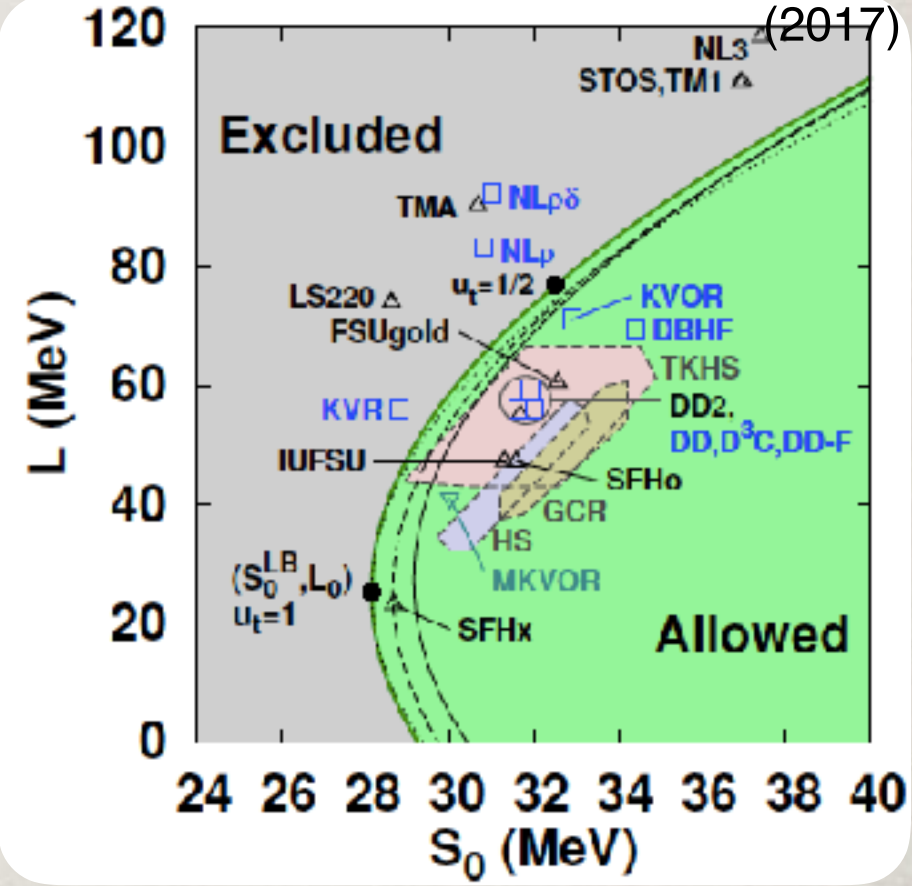
SFHo & SFHx use interactions from Steiner, Hempl & Fischer (2013). DD2 is based on Typel, Röpke, Klähn, Blaschke & Wolte (2010). NL3 is based on Lalazissis, König & Ring (1997). FSUGold is based on Todd-Rutel & Piekarewicz (2005). IUFSU is based on Fattoyev, Horowitz, Piekarewicz & Shen (2010).

Choosing an EoS

This wide variety of EoSs available represents a sea change from the 1990s, when only 3 EoSs were available.

Each EoS results in different key parameters like the saturation density (ρ_s), the incompressibility (K), the saturation energy (S_0), slope of the symmetry energy with respect to density (L). etc.

Tews, Lattimer, Ohnishi, & Kolomeitsev (2017)



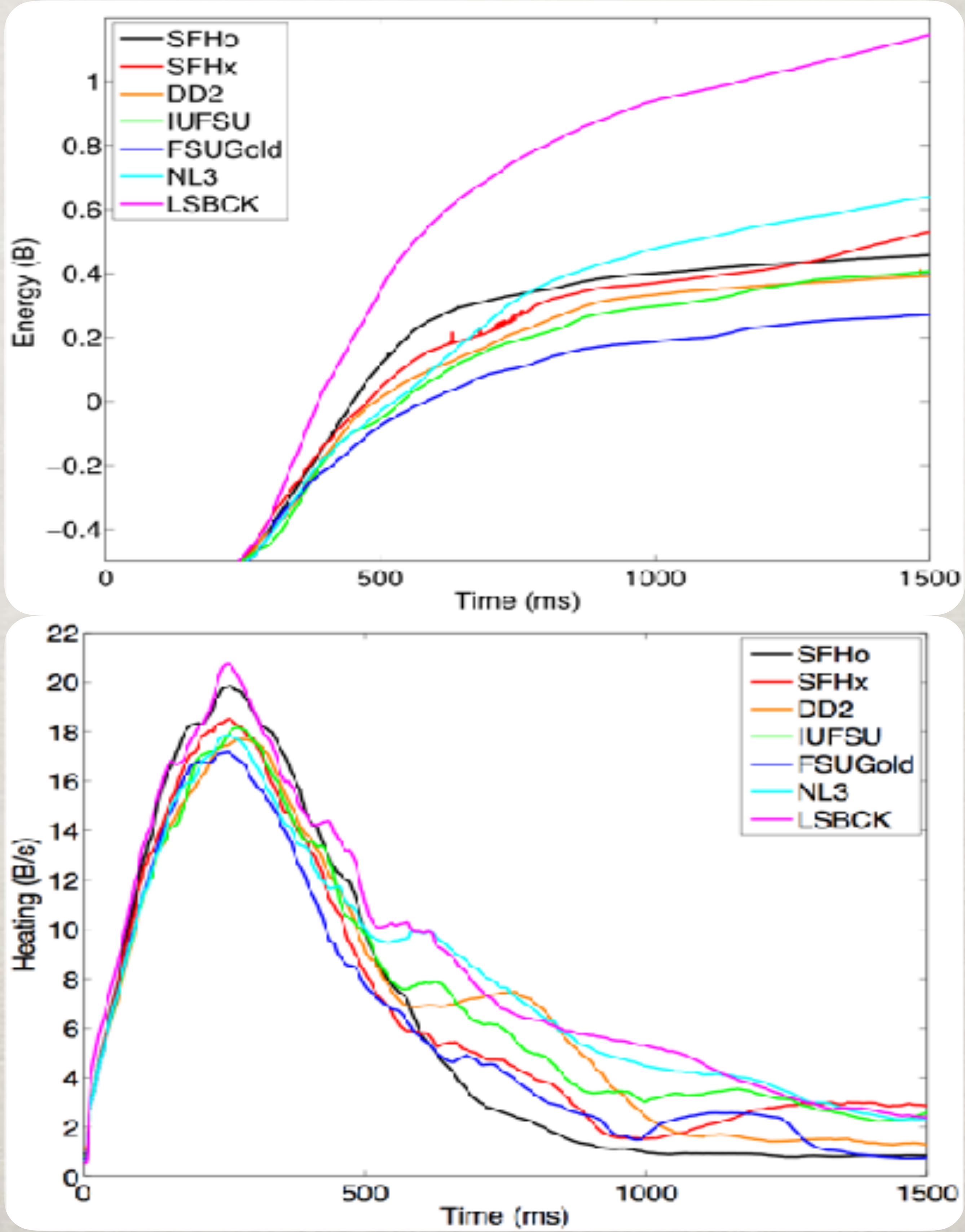
	SFHo	SFHx	DD2	IUFSU	FSUGold	NL3	LSBCK
$\rho_s (\times 10^{14}$ g cm$^{-3})$	2.629	2.660	2.476	2.567	2.461	2.461	2.574
E_0 (MeV)	16.19	16.16	16.02	16.39	16.27	16.24	16.0
K (MeV)	245.4	238.8	242.7	231.3	229.5	271.5	220
K' (MeV)	-467.8	-457.2	168.7	-290.3	-523.9	202.6	243.2
J (MeV)	31.57	28.67	31.67	31.29	32.56	37.39	29.3
L (MeV)	47.10	23.18	55.03	47.20	60.43	118.49	74
K_{sym} (MeV)	-205.4	-40.0	-93.2	28.5	-51.4	100.8	64.9
M_{max} $M_\odot$	2.06	2.13	2.42	1.95	1.74	2.79	2.06
$R_{M_{max}}$ (km)	10.32	10.77	11.90	11.31	10.95	13.40	10.67
$R_{1.4}$ (km)	11.9	12.0	13.2	12.7	12.6	14.8	12.71

More choices requires more knowledge to choose correctly, fortunately we can rely on experts.

Impact of the EoS

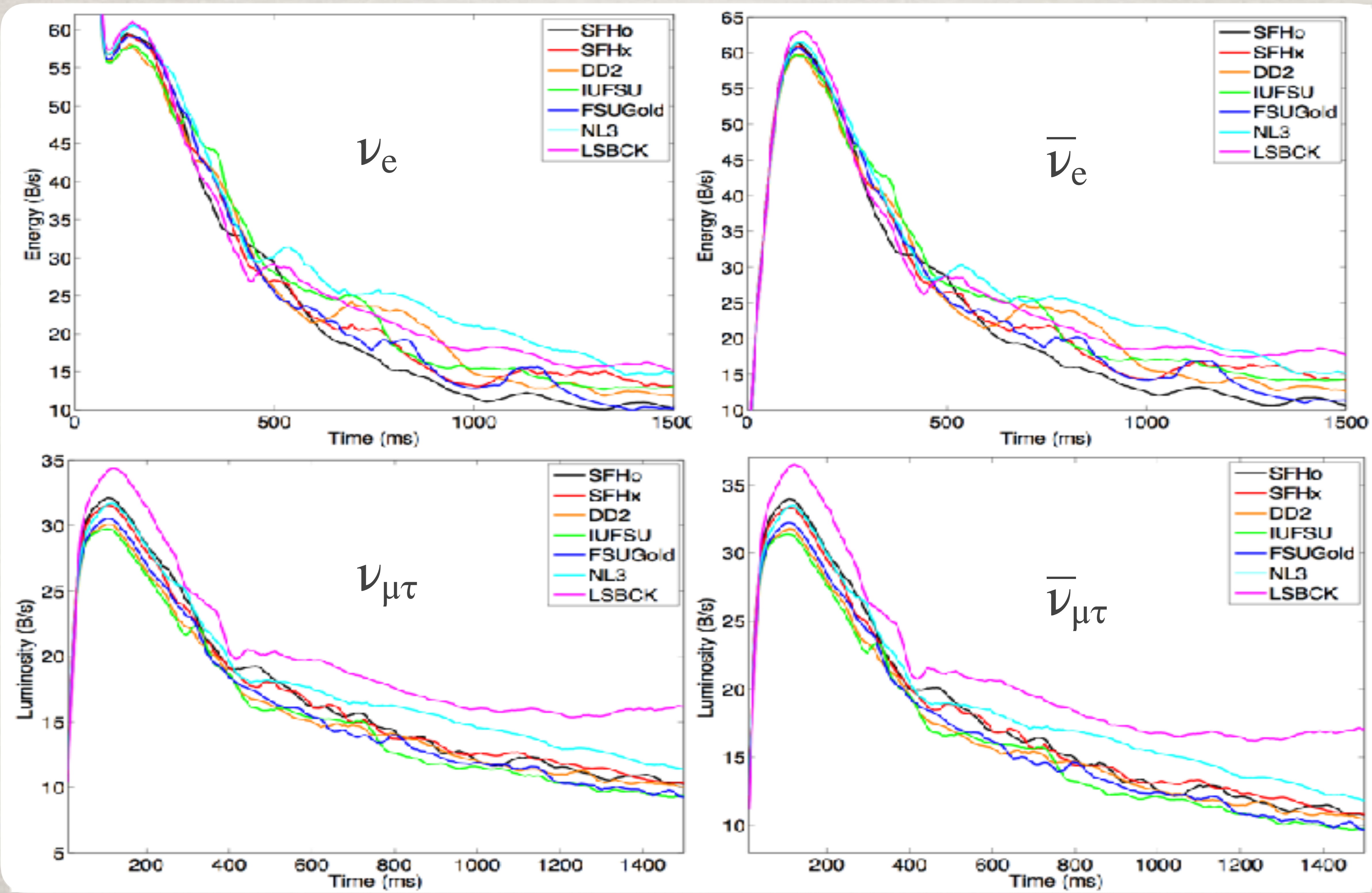
The impact of the nuclear Equation of State in Core-Collapse Supernovae is many-fold. In addition to determining the size and structure of the proto-neutron star, it determines the composition which affects the opacities which go into the neutrino transport.

Hence, we turn to simulations to gauge the impact. These reveal that the LS-BCK EoS produces the largest explosion energy as a result of the largest neutrino heating.



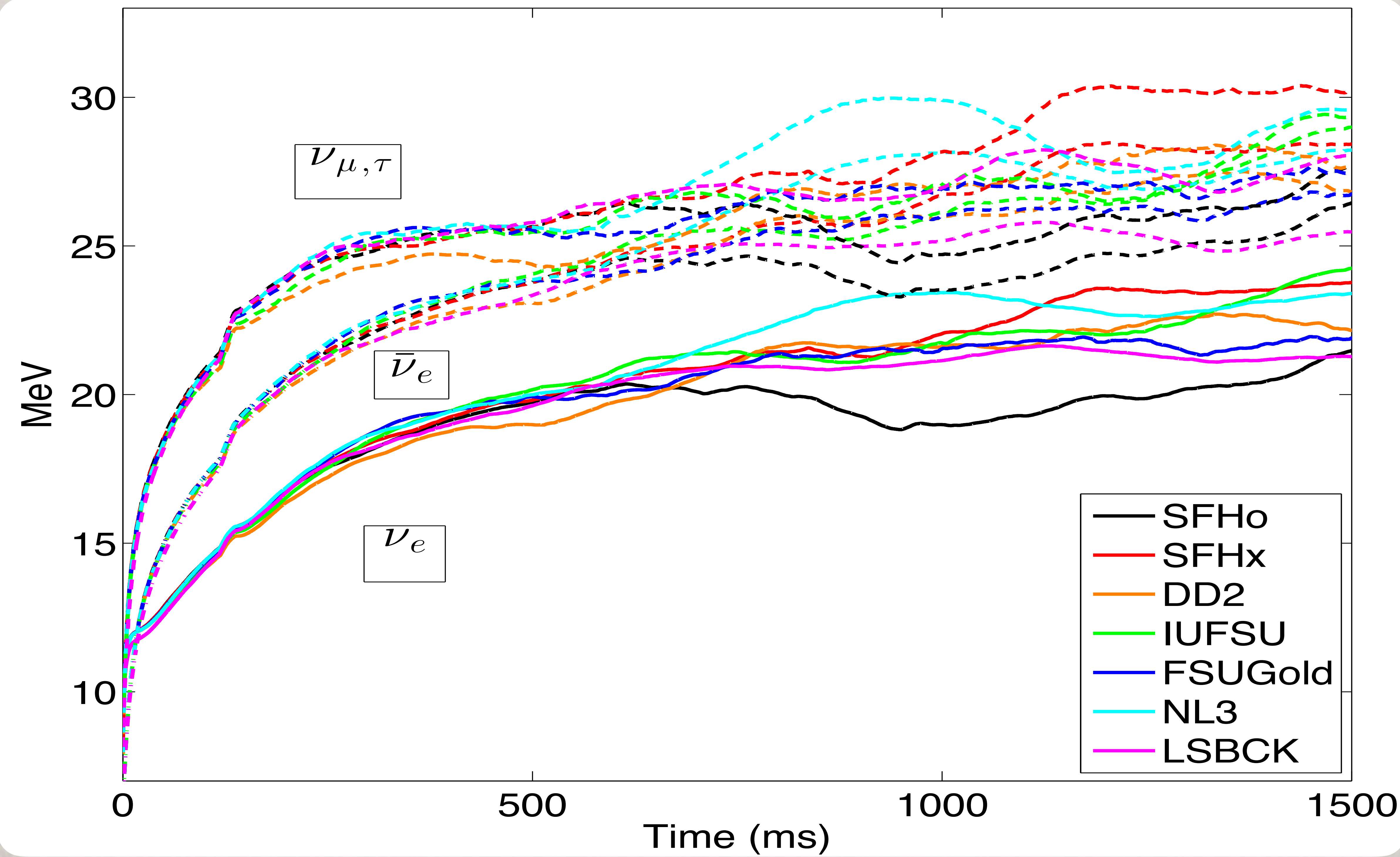
Neutrino power

We find that the LS-BCK model exhibits the highest luminosities.



RMS Energies

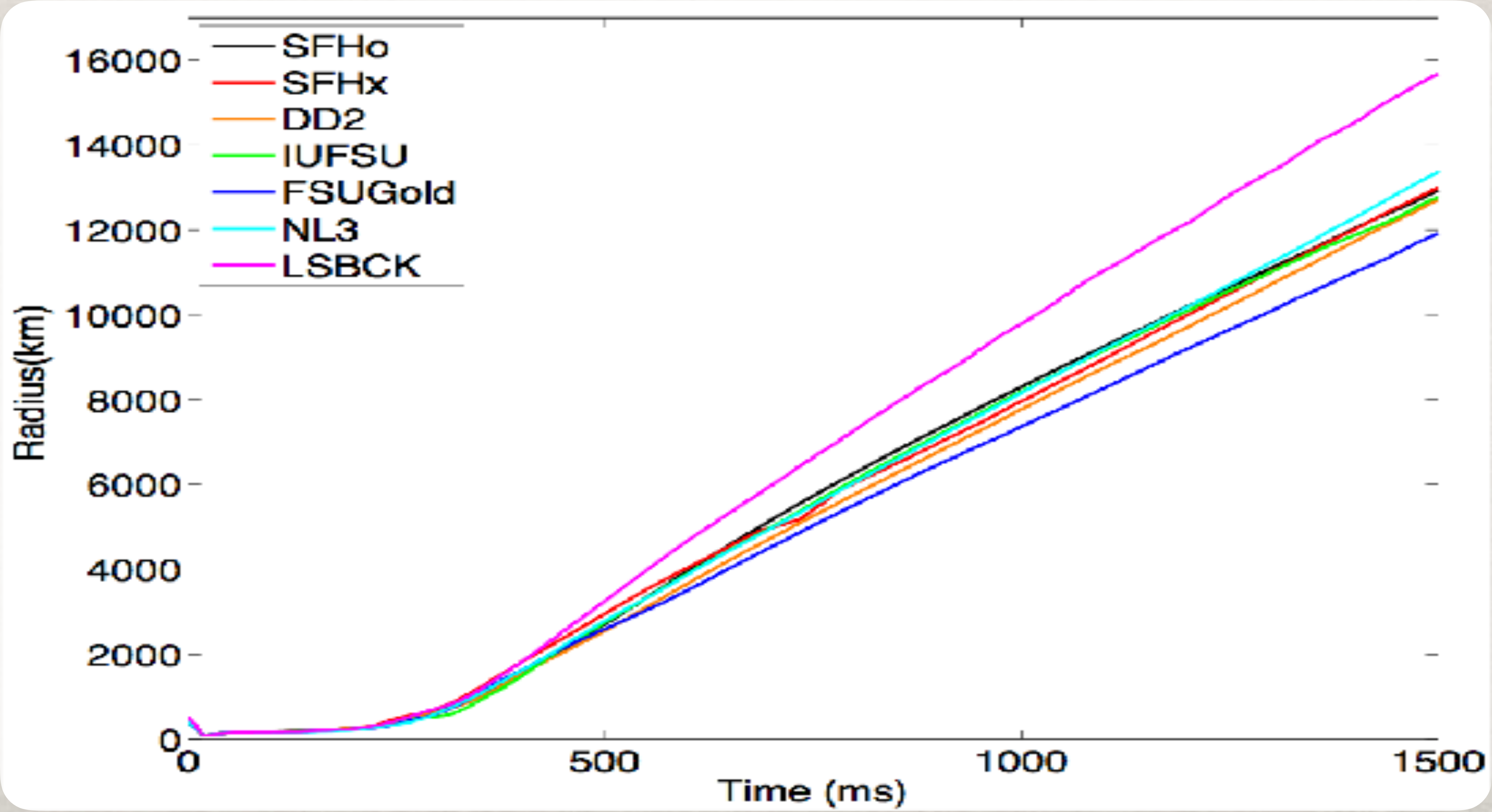
While the LS-BCK model does exhibit the highest μ/τ neutrino RMS energies, its electron flavor RMS neutrino energies tend to be low.



Choice for the Future

With LS-BCK very strongly favoring explosion as a result of its higher luminosity, it is clearly the outlier among the EoSs studied.

Among the EoS based on Hempel & Schaffner-Bielich (2010), NL3 is the most favorable to explosion, due to enhanced luminosity at later times, which FSUGold is the least favorable.



Conclusions

To compare to observables, models must self-consistently treat the explosion mechanism while running to times > 1-2 second after bounce (>3-4 seconds for massive CCSN) for uncertainties in the explosion energy, mass cut, PNS wind, etc. to become tractable.

To prevent artificial acceleration of the explosion, simulations must be 3D and should have resolutions in latitude and longitude ≤ 1°.

Full 3D simulations, run to times sufficient for the explosion to fully develop are possible, but very computationally expensive. Securing sufficient computing resources for a multitude of models, at sufficient resolution, run to these late times are an ongoing challenge.

Equations of state that obey modern nuclear physics constraints tend toward weaker explosions than our old standby EoSs.