Multi-D Core-Collapse Supernova Explosion Simulations

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Cas A Remnant

Fe

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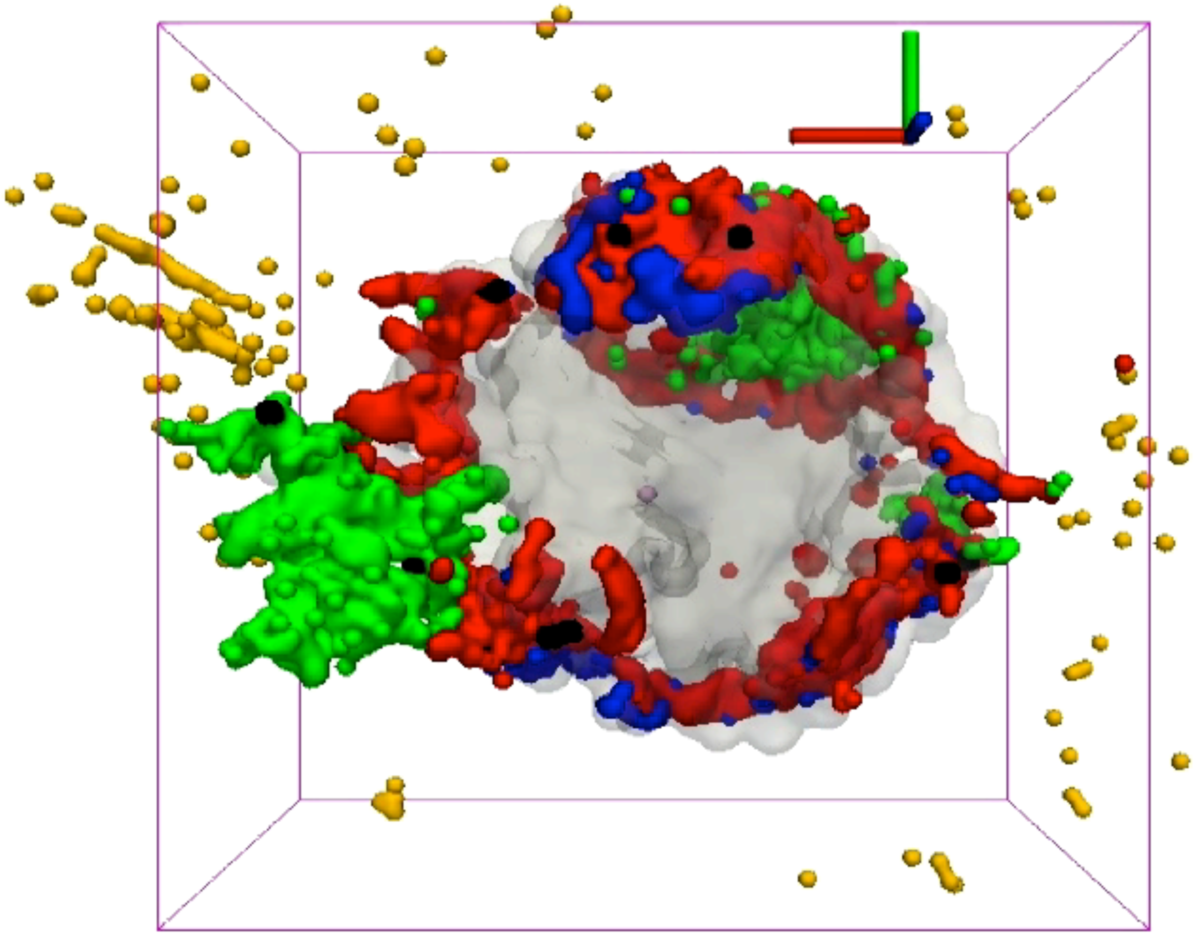
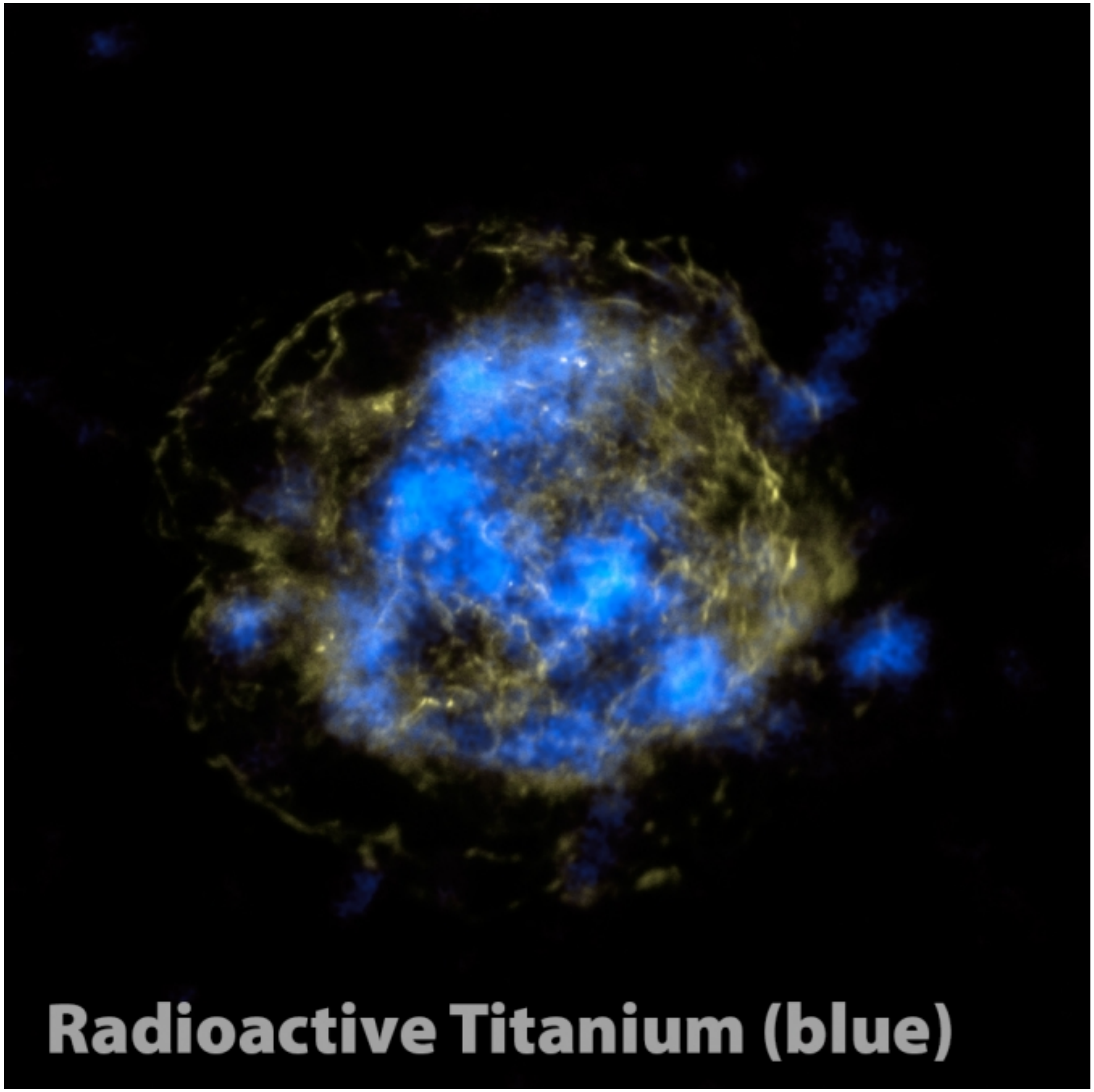
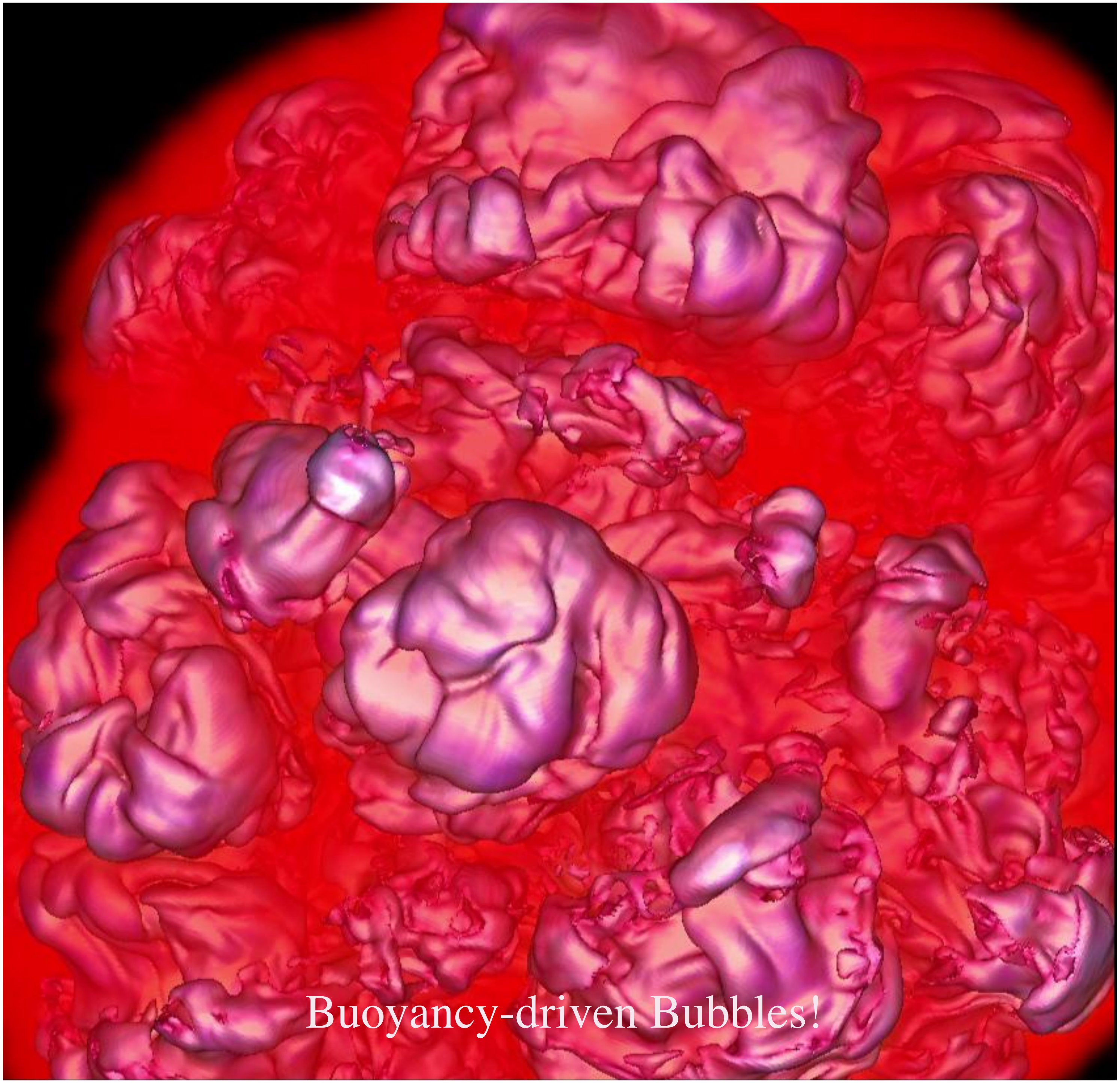


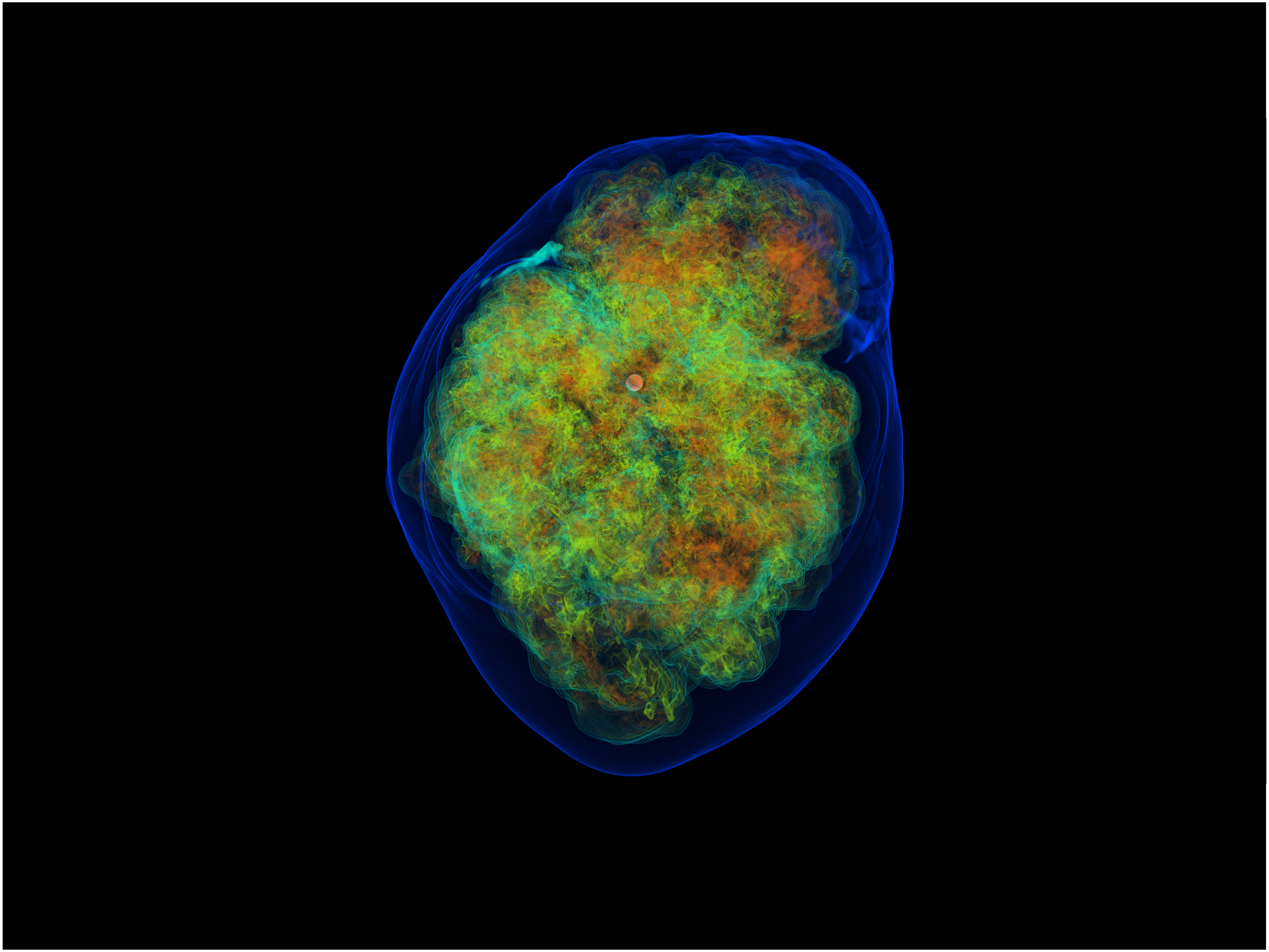
DeLaney et al. 2010

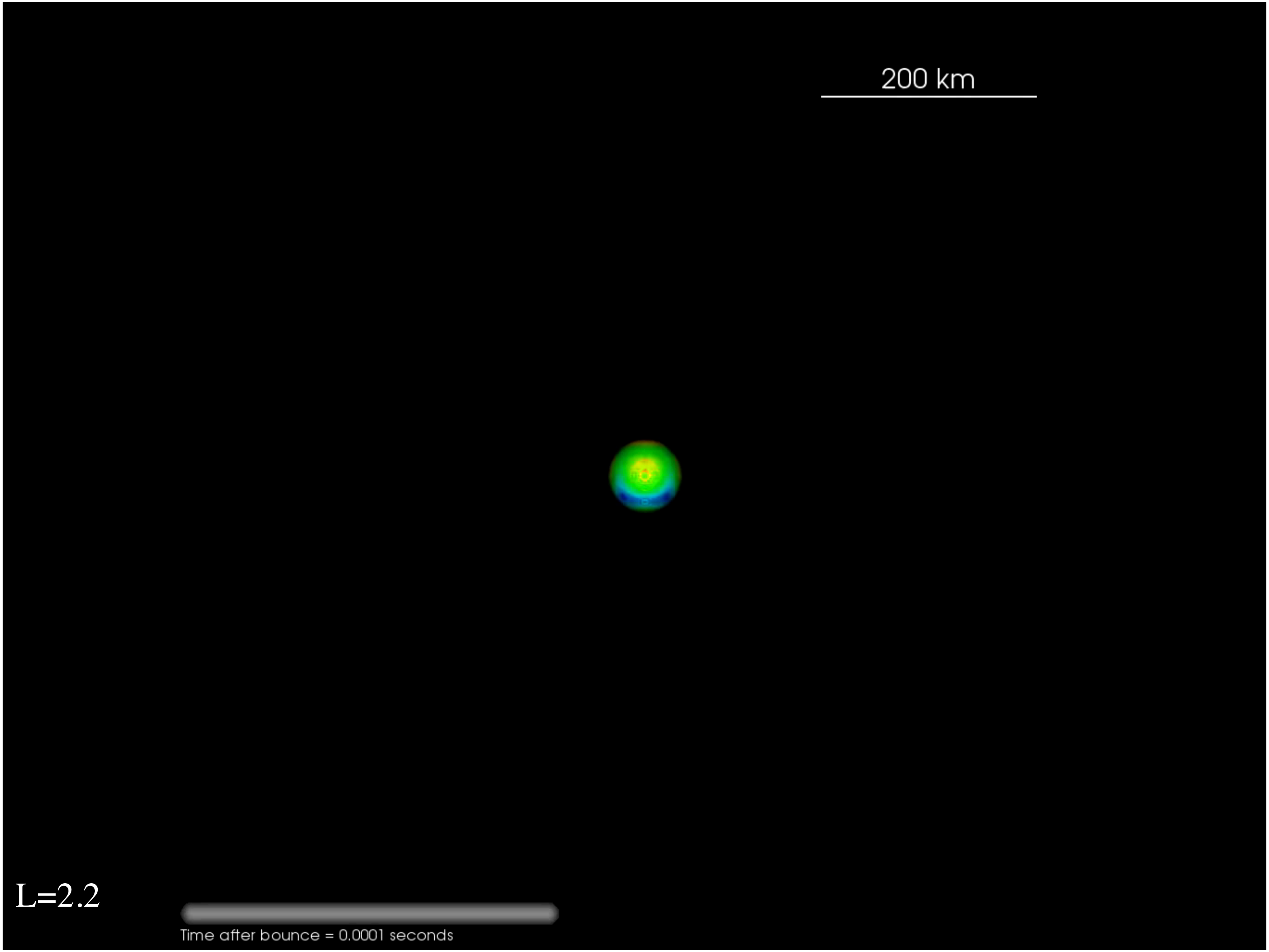
Cas A Remnant in ^{44}Ti



NuSTAR: Grefenstette et al. 2014


Buoyancy-driven Bubbles!




200 km
L=2.2
Time after bounce = 0.0001 seconds

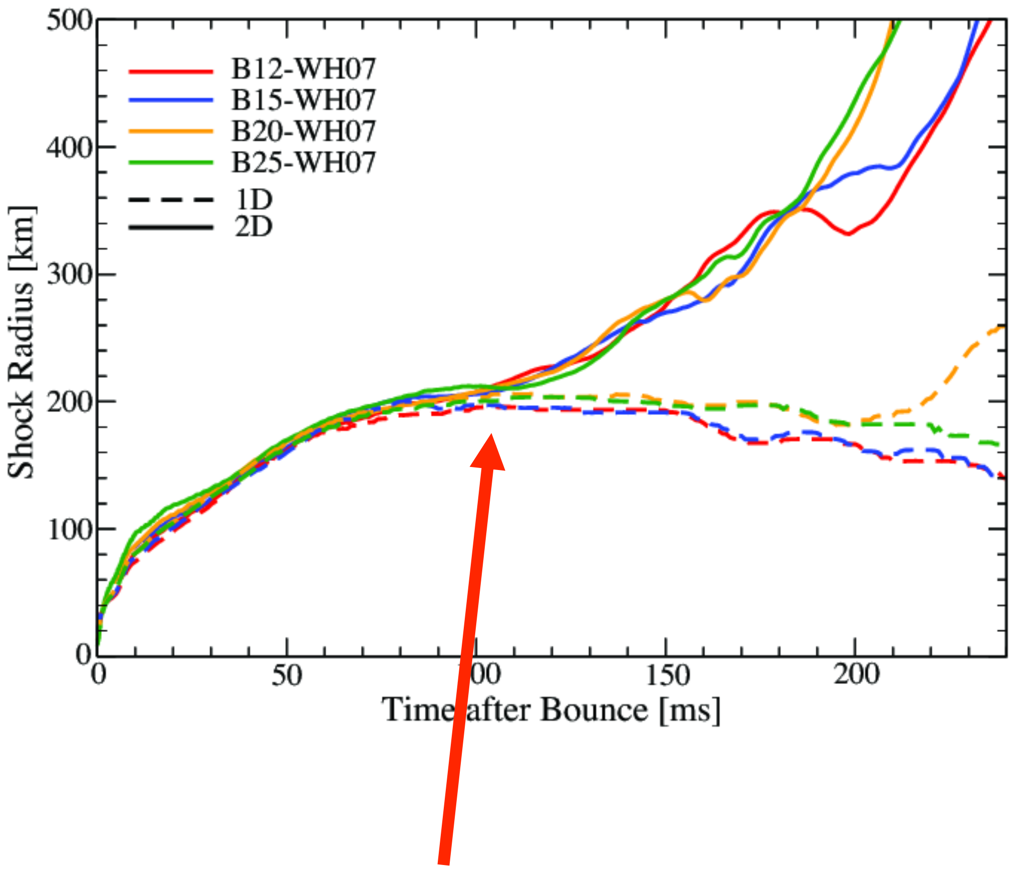
Mechanisms of Explosion

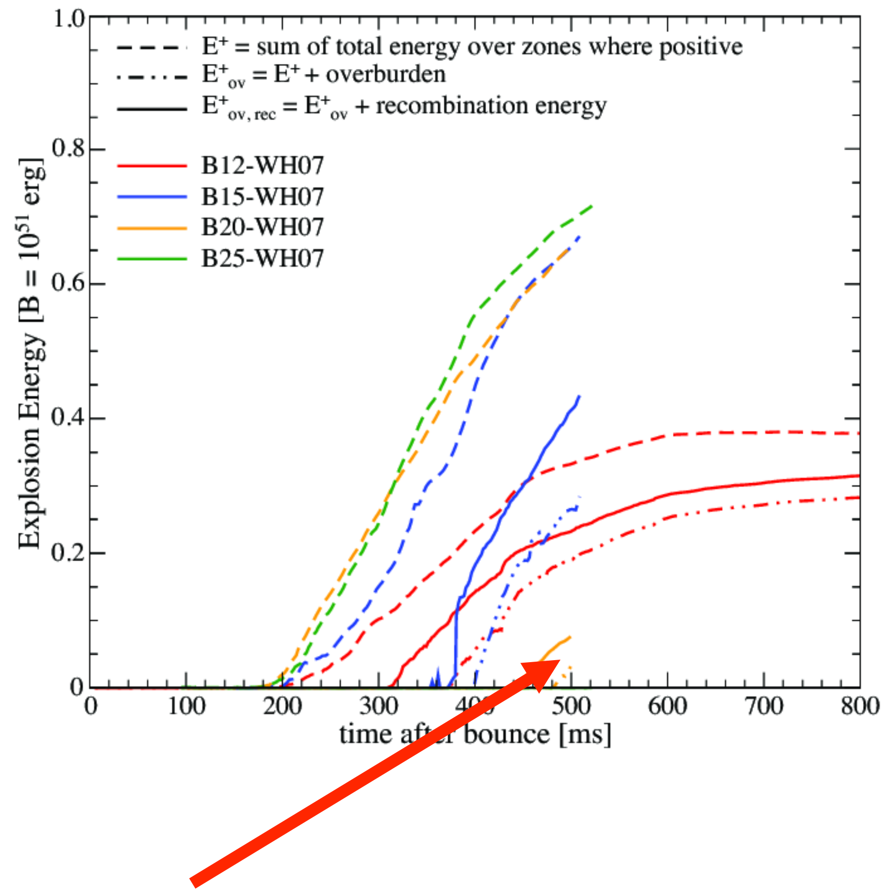
- Direct Hydrodynamic Mechanism: always fails
- Neutrino-Driven Wind Mechanism, ~1D; Low-mass progenitors
- 2D Convection Neutrino-driven (circa 1995-2009)
  ("SASI" not a mechanism, but a shock instability)
- Neutrino-Driven Jet/Wind Mechanism, Rapidly rotating AIC of White Dwarf
- MHD/Rapid Rotation - "Hypernovae"?
- Acoustic Power/Core-oscillation Mechanism? (Aborted if neutrino mechanism works earlier; Weinberg & Quataert ?)
- 3D "Convection" Neutrino-driven Mechanism

Important Ingredients/Physics

- Progenitor Models (and initial perturbations?)
- Multi-D Hydrodynamics (3D)
- Multi-D Neutrino Transport (multi-D) (most challenging aspect)
- Instabilities - Neutrino-Driven Convection (+ SASI?)
- Neutrino Processes - Cross sections, emissivities, etc. (at high densities?)
- General Relativity (May & White; Schwartz; Bruenn et al.; Mueller et al.; Kotake et al.)
- Must do 3D radiation/hydrodynamics – "6D" or 7D (full Boltzmann, not yet)

Bruenn et al. (2014) Explosions -1D "ray-by-ray" transport



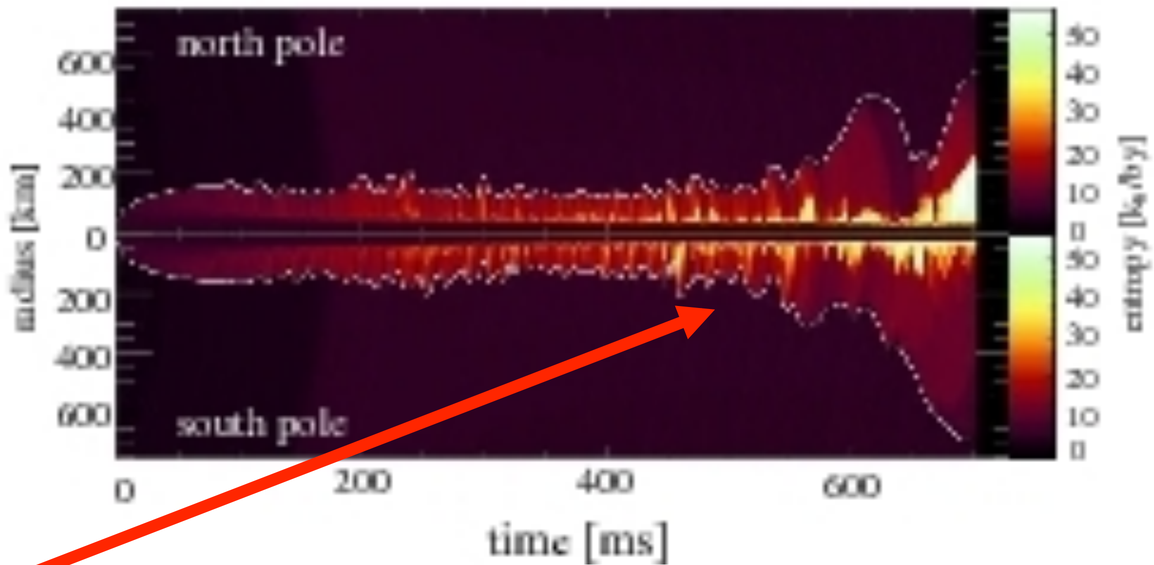


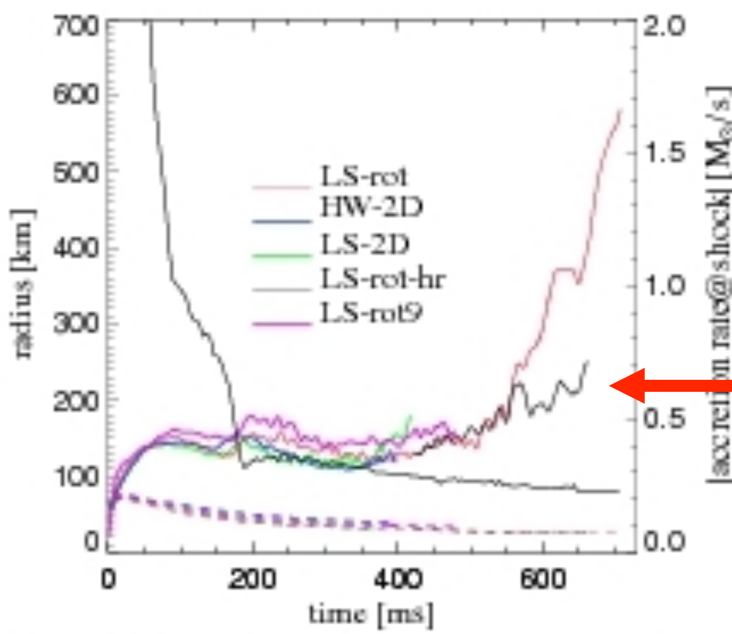
All explode at ~ same time

Sub-energetic, even if they actually explode

Marek & Janka 2009 and Muller, Janka, & Marek 2012:

1D "ray-by-ray" transport, 2D hydro:





Long delay, weak explosion (?)

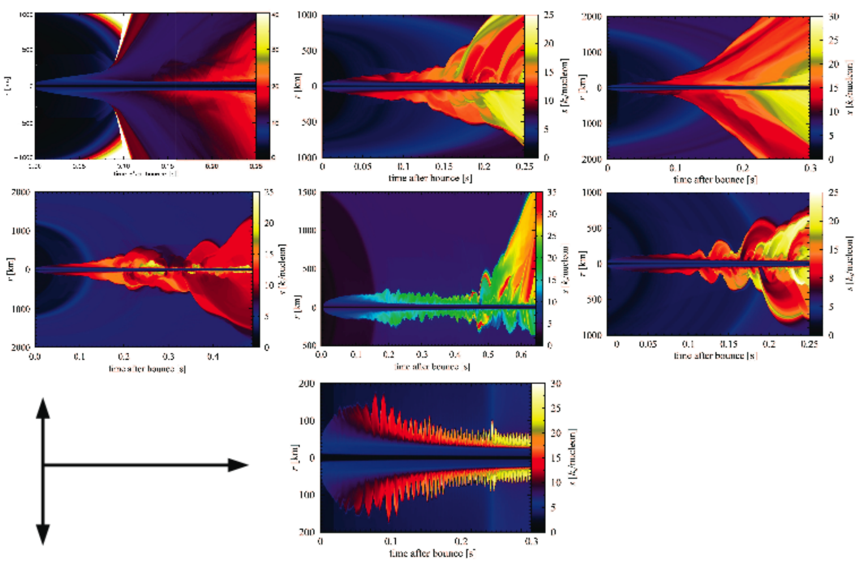
Higher-resolution, stiffer EOS - don't explode?? GR?

Higher-resolution. Smaller radius

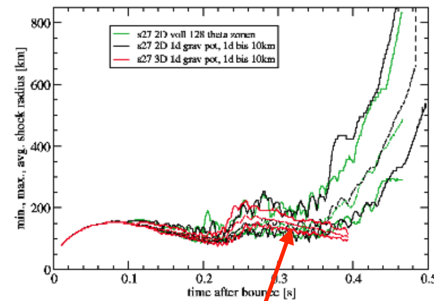
3D not exploding, when 2D did (Muller and Janka 2012/2013; Bruenn et al. 2013)

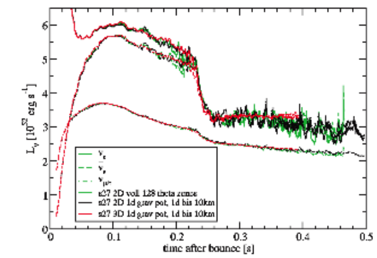
Problems: RbR; 2D vs. 3D turbulent Pressure?

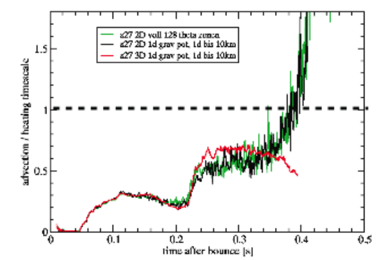
2D



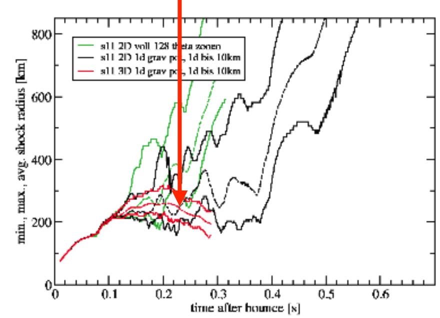
2D vs. 3D

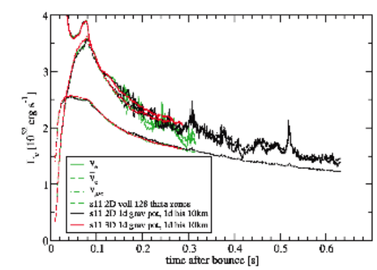


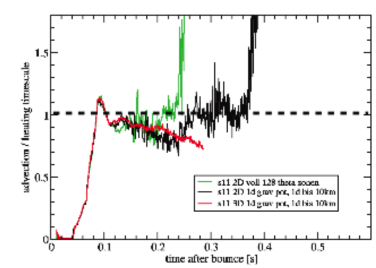




3D?



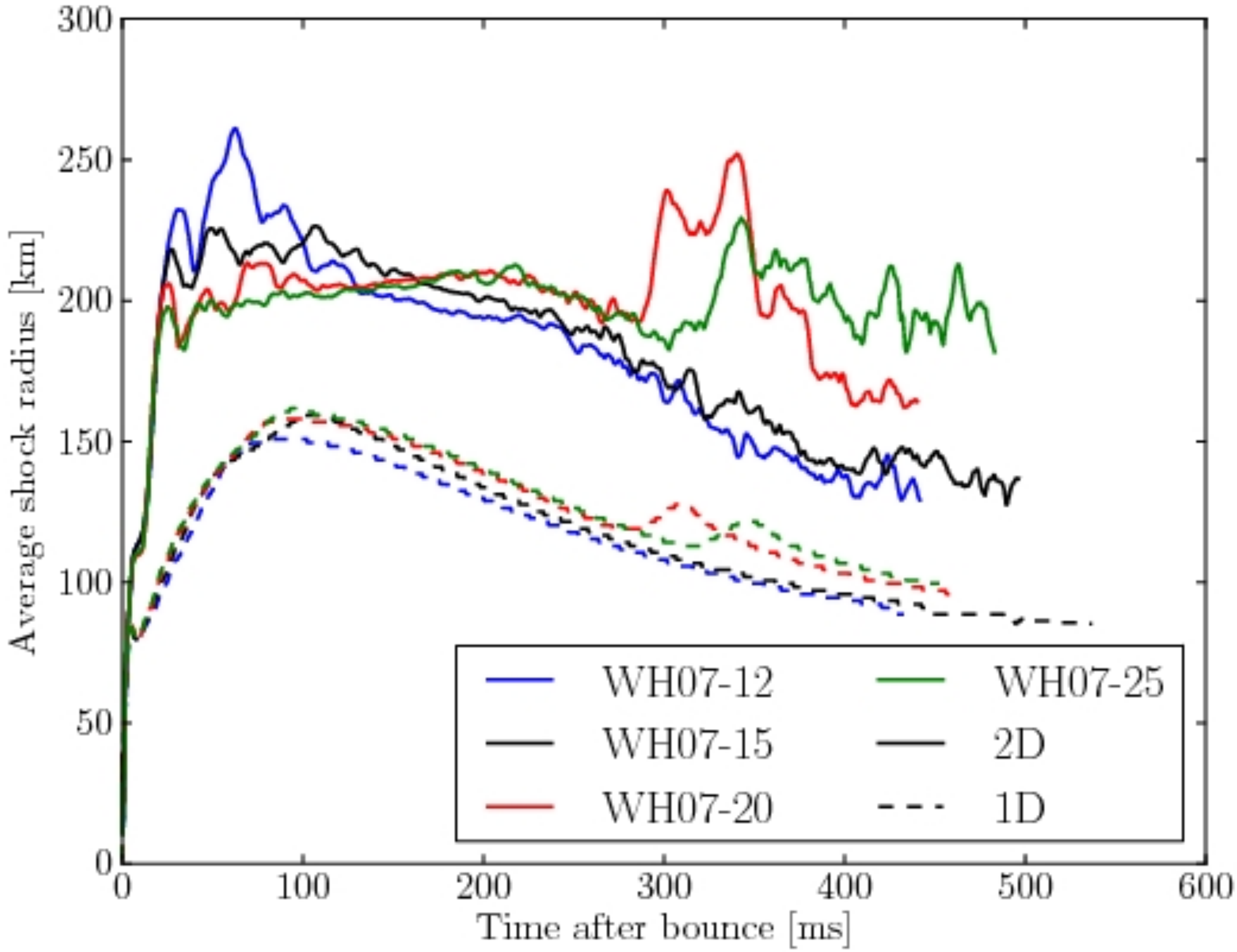




Janka et al. Garching/Monash group

Shock Radii 1D-2D Comparison (Castro): MGFLD with multi-dimensional transport (no ray-by-ray)

Burrows et al. 2013; Dolence et al. 2013

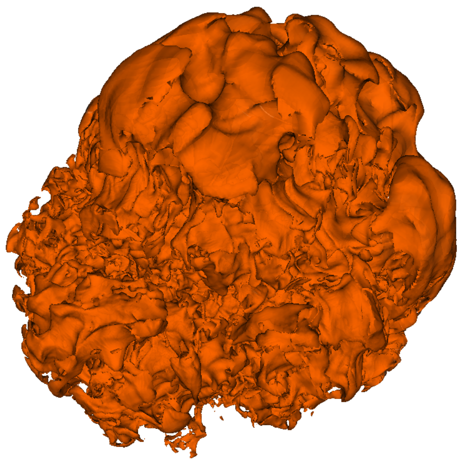


Problems with All Extant 2D and 3D Explosions Models

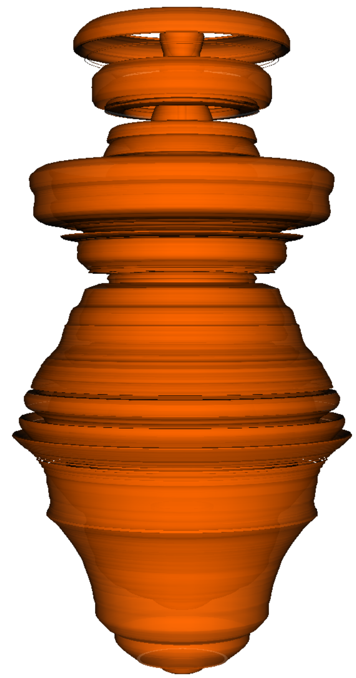
- Ray-by-ray+ Reduced Transport – Doing multiple 1D radial transport solves for a multi-D problem. Errors ~10-100%
- Explosions models are generally underenergetic
- Excising cores , or doing central calculation in 1D
- Low spatial resolution in 2D and 3D – higher resolution can turn an explosion into a dud
- No relativistic transport in multi-D, or fake GR (gravity + redshift (?))
- Multi-angle, multi-group calculations are currently too expensive for 3D
- Groups that say they are incorporating the same physics and methodologies are getting (very) different results in 2D and 3D
- Progenitors only in 1D (one exception) – initial structures and perturbations?

2D and 3D Models are Very Different

3D

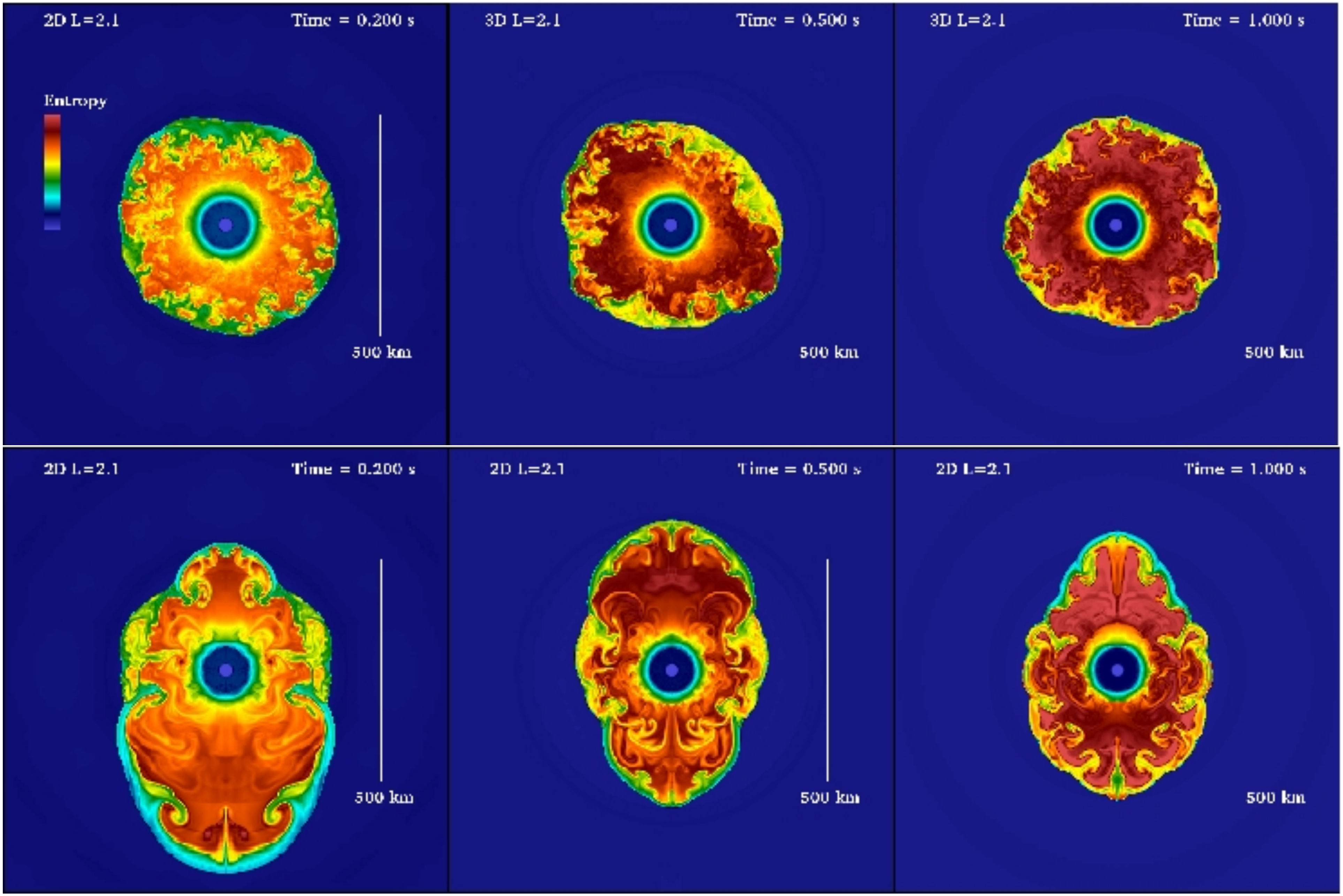


2D

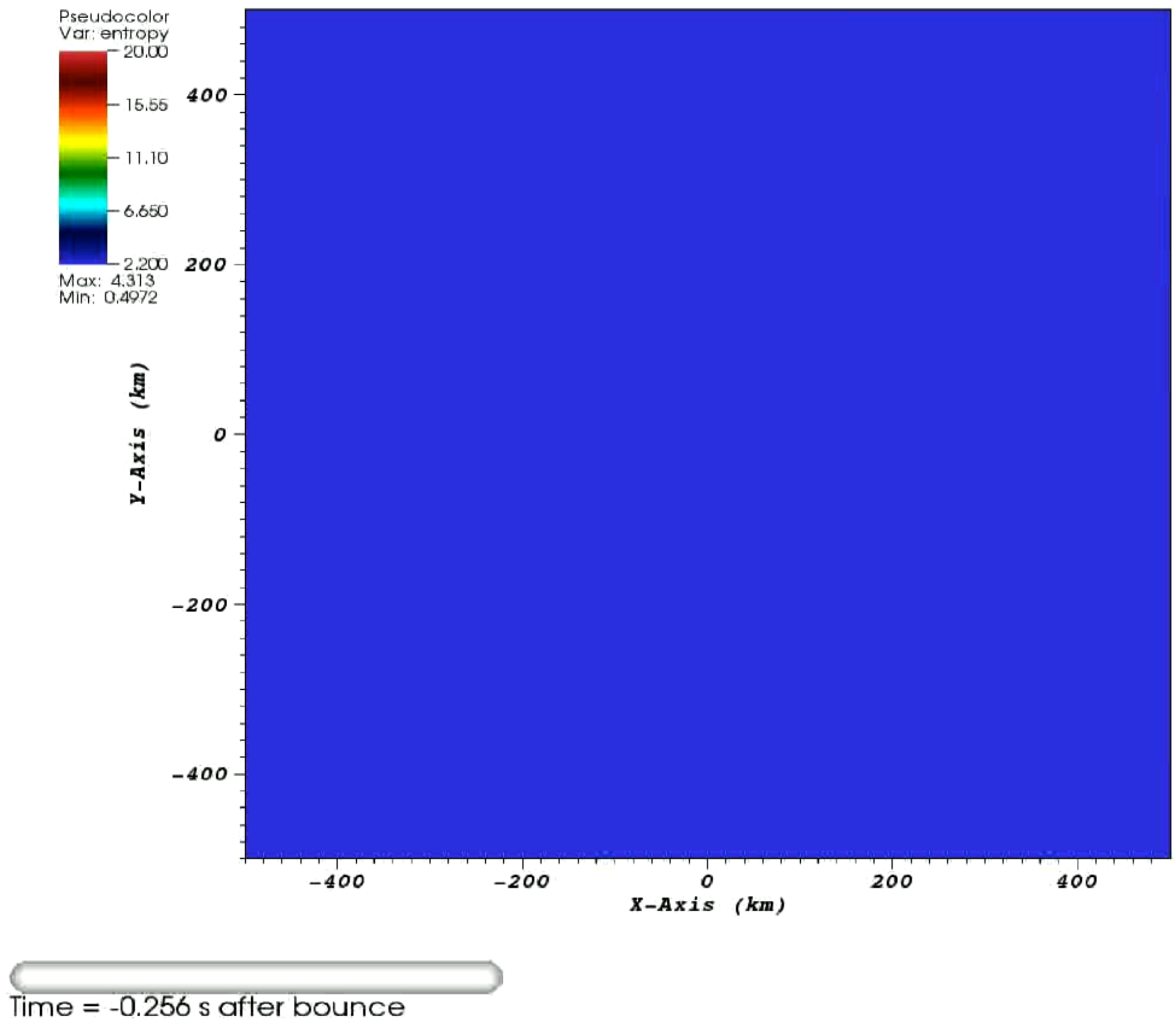


Couch 2012

Comparison of 2D with 3D

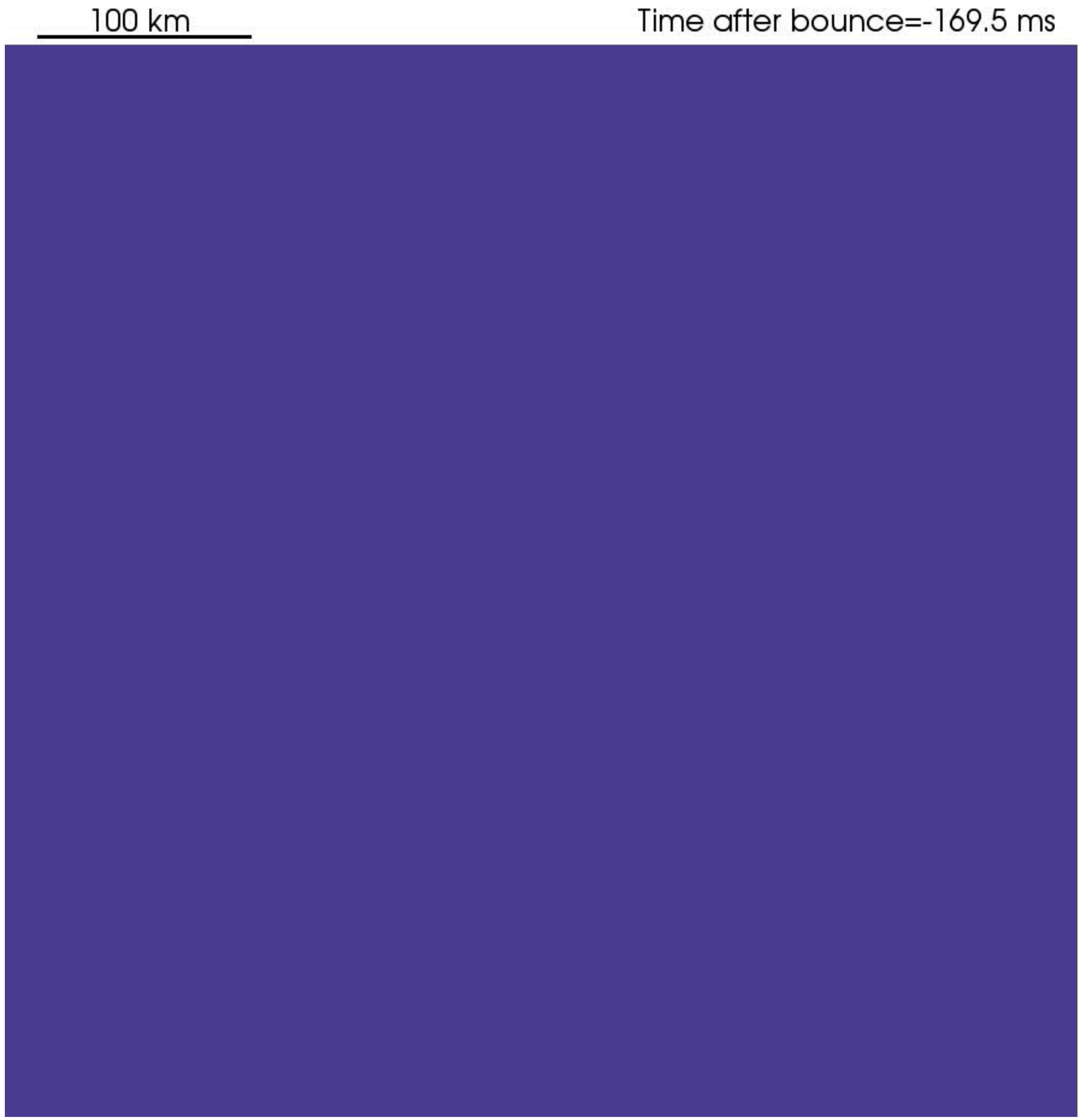


Character of 3D turbulence and Explosion Very Different from those in 2D



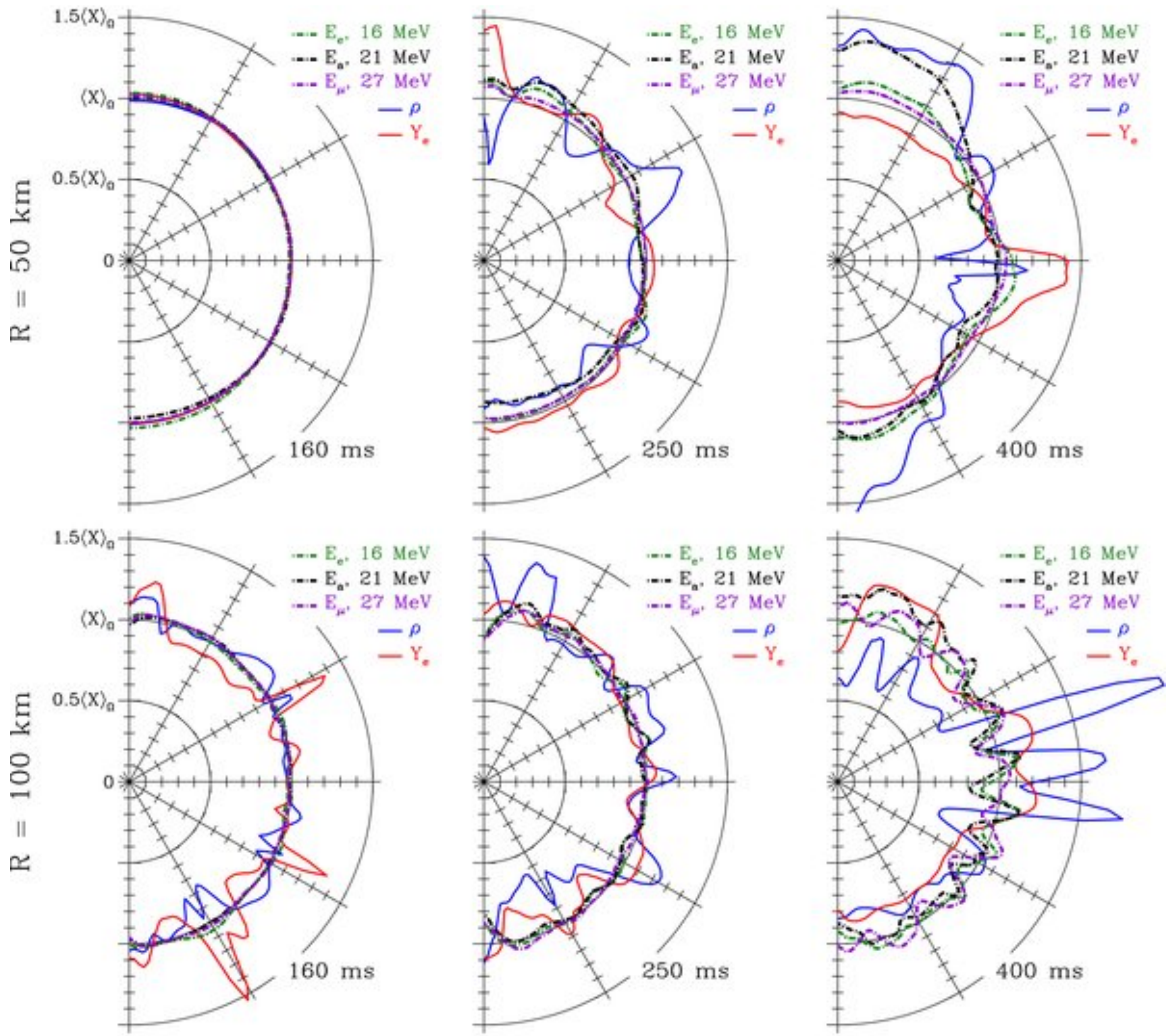
Possible Problems with "Ray-by-ray" Pseudo-Transport

Ray-by-ray May Exaggerate Angular and Temporal Variation in Neutrino Fluxes and Heating



2D (Castro): MGFLD with multi-D Transport (no ray-by-ray)

Brandt et al. 2011 - Multi-Angle, Multi-Group, 2D Transport



Sample Computational Requirements for Future Core-Collapse Supernova Simulations

Platform	Space	Neutrino	$\#f_\nu$	Matrix	Ops./Δt
Current	256x32x64	8x12x14	20 GB	2 TB	$6x10^{12}$
Near-Term	512x64x128	12x24x20	600 GB	200 TB	$2x10^{15}$
Exa-Scale	512x128x256	24x24x24	6 TB	3 PB	$8x10^{16}$
"Full Coupling"	512x128x256	24x24x24	6 TB	80 PB	$4x10^{19}$

Kotake et al. 2012

Cycle and Memory Requirements for Supernova Simulations

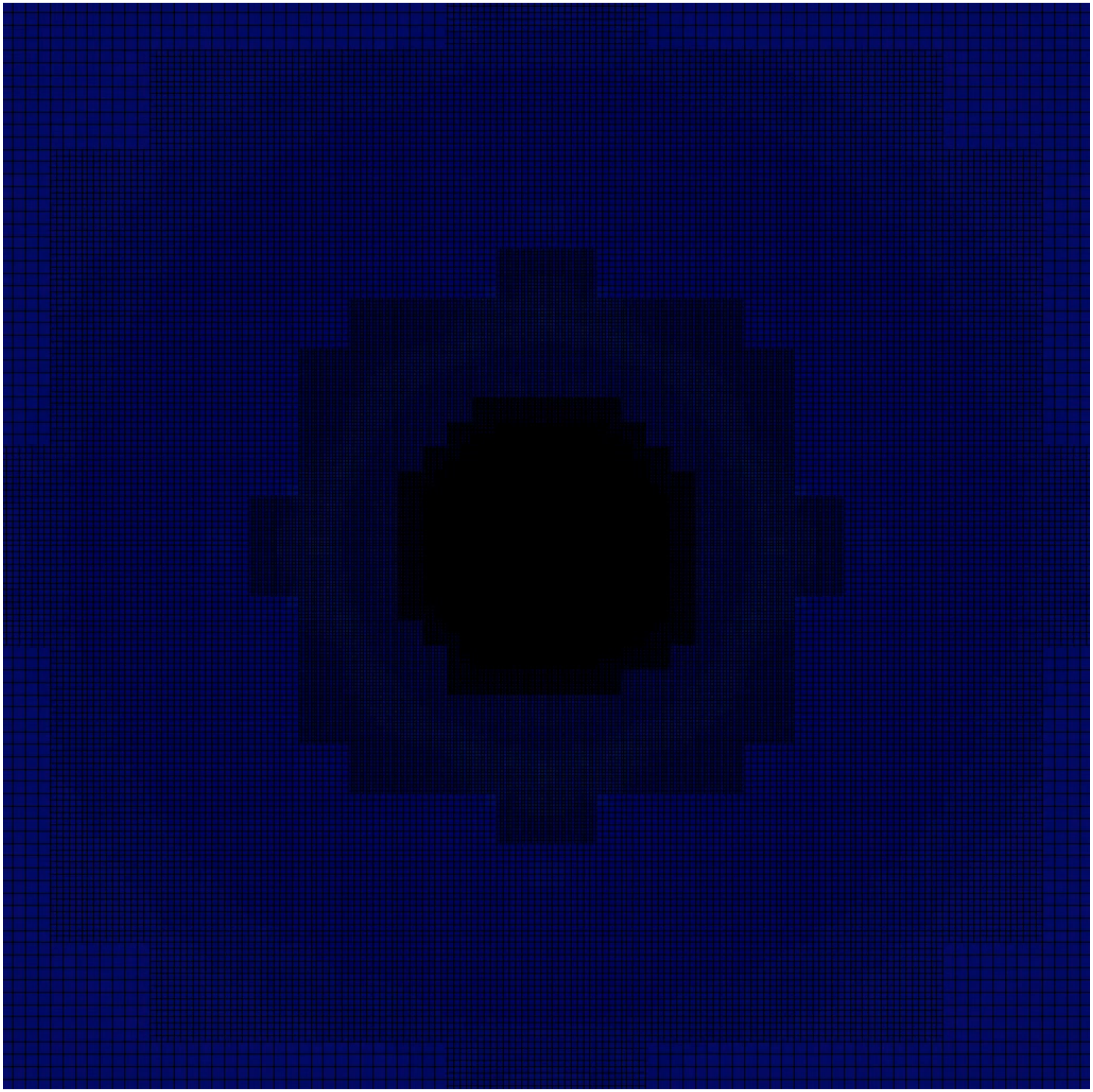
- 1985 (1D) - ~10^{2-3} CPU-hours per run; 10 Gbytes memory
- 1995 (low 2D) - ~10^{5-6} CPU-hours per run; 100 Gbytes memory
- 2005 (medium 2D) - ~10^{6} CPU-hours per run; 10^{2} cores; Tbytes memory
- 2010 (low 3D) - ~10^{6-7} CPU-hours per run; ; Tbytes memory
- 2015 (medium 3D) - ~10^{7-8} CPU-hours per run; ; 0.2-1 Pbytes memory
- 2020 (~heroic 3D) - ~10^{8-9} CPU-hours per run; ; >10 Pbytes memory

VULCAN/2D Multi-Group,Multi-Angle, Time-dependent Boltzmann/Hydro (6D)

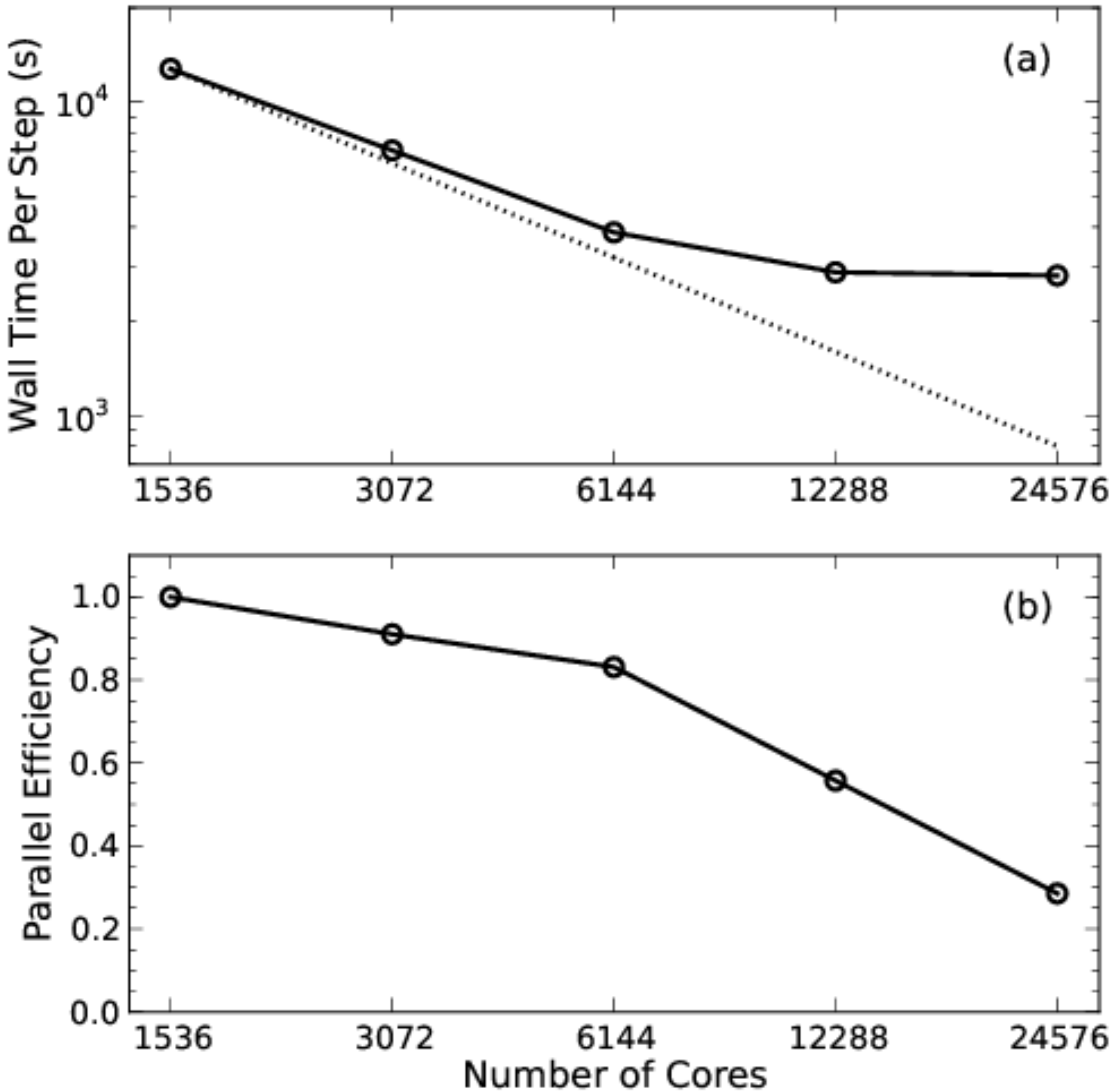
- Only code with multi-D, multi-angle transport used in supernova theory
- Arbitrary Lagrangian-Eulerian (ALE); remapping
- 6 - dimensional (1(time) + 2(space) + 2(angles) + 1(energy-group))
- Moving Mesh, Arbitrary Grid; Core motion (kicks?)
- 2D multi-group, multi-angle, S_n (~150 angles), time-dependent, implicit transport - Ott et al. 2009
- 2D MGFLD, rotating version (quite fast)
- Poisson gravity solver
- Axially-symmetric; Rotation
- MHD version ("2.5D") - div B = 0 to machine accuracy; torques
- Flux-conservative; smooth matching to diffusion limit
- Parallelized in energy groups; almost perfect parallelism
- Livne, Burrows et al. (2004,2007a)
- Burrows et al. (2006,2007b), Ott et al. (2005,2008); Dessart et al. 2005ab, 2006

CASTRO - 3D AMR, Multi-Group Radiation-Hydrodynamic Supernova Code

- 2nd-order, Eulerian, unsplit, compressible hydro
- PPM and piecewise-linear methodologies
- Multi-grid Poisson solver for gravity
- Multi-component advection scheme with reactions
- Adaptive Mesh Refinement (AMR) - flow control, memory management, grid generation
- Block-structured hierarchical grids
- Subcycles in time (multiple timestepping - coarse, fine)
- Sophisticated synchronization algorithm
- BoxLib software infrastructure, with functionality for serial distributed and shared memory architectures
- 1D (cartestian, cylindrical, spherical); 2D (Cartesian, cylindrical); 3D (Cartesian)
- Transport is a conservative implementation of flux-limited diffusion, with v/c terms and inelastic scattering
- Uses scalable linear solvers (e.g., hypre) with high-performance preconditioners that feature parallel multi-grid and Krylov-based iterative methods - challenging!



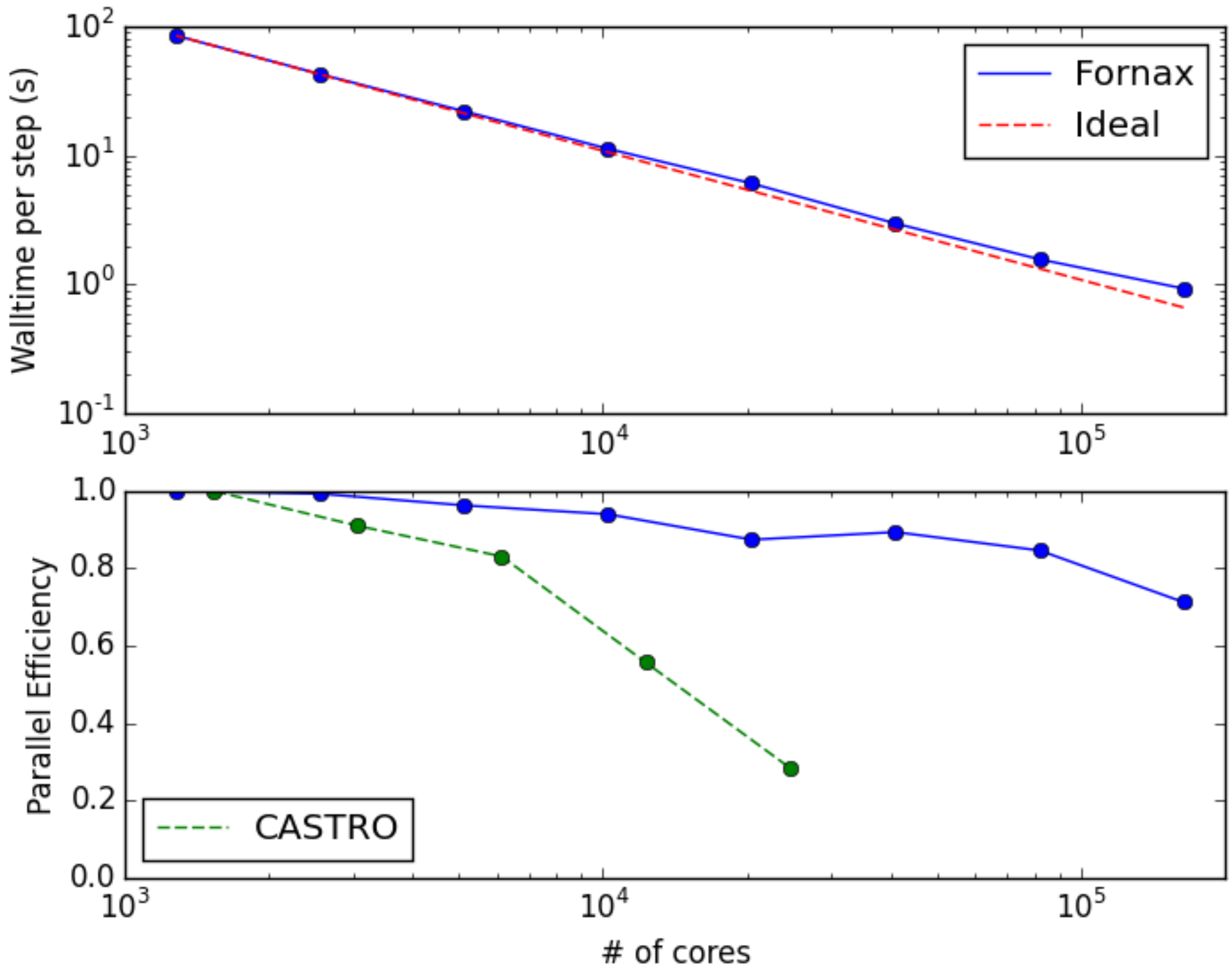
CASTRO Radiation/Hydro: Strong Scaling in 3D

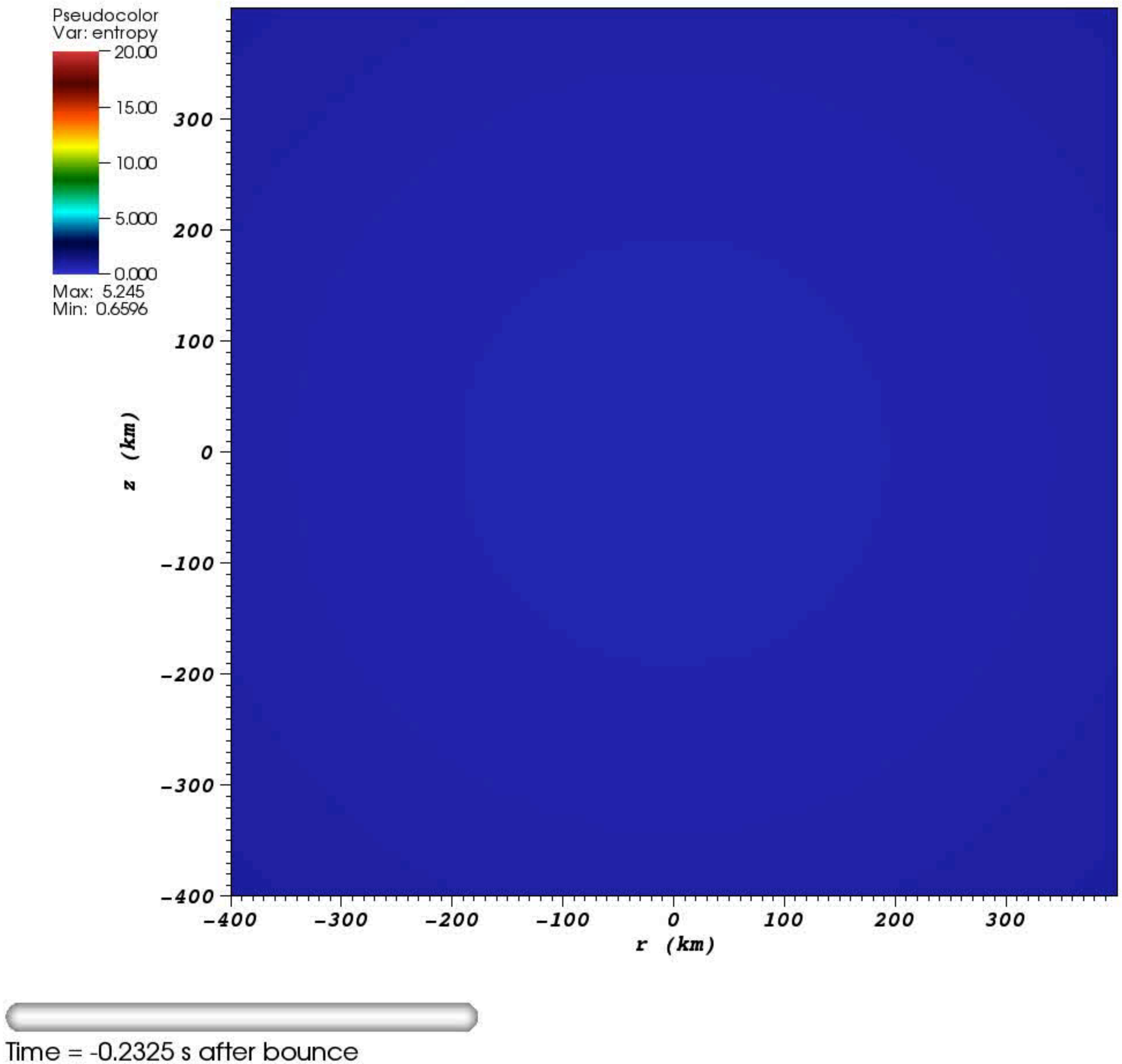


FORNAX: 1D,2D,3D, Multi-Group, Explicit Radiation/Hydrodynamics, ("6"D)

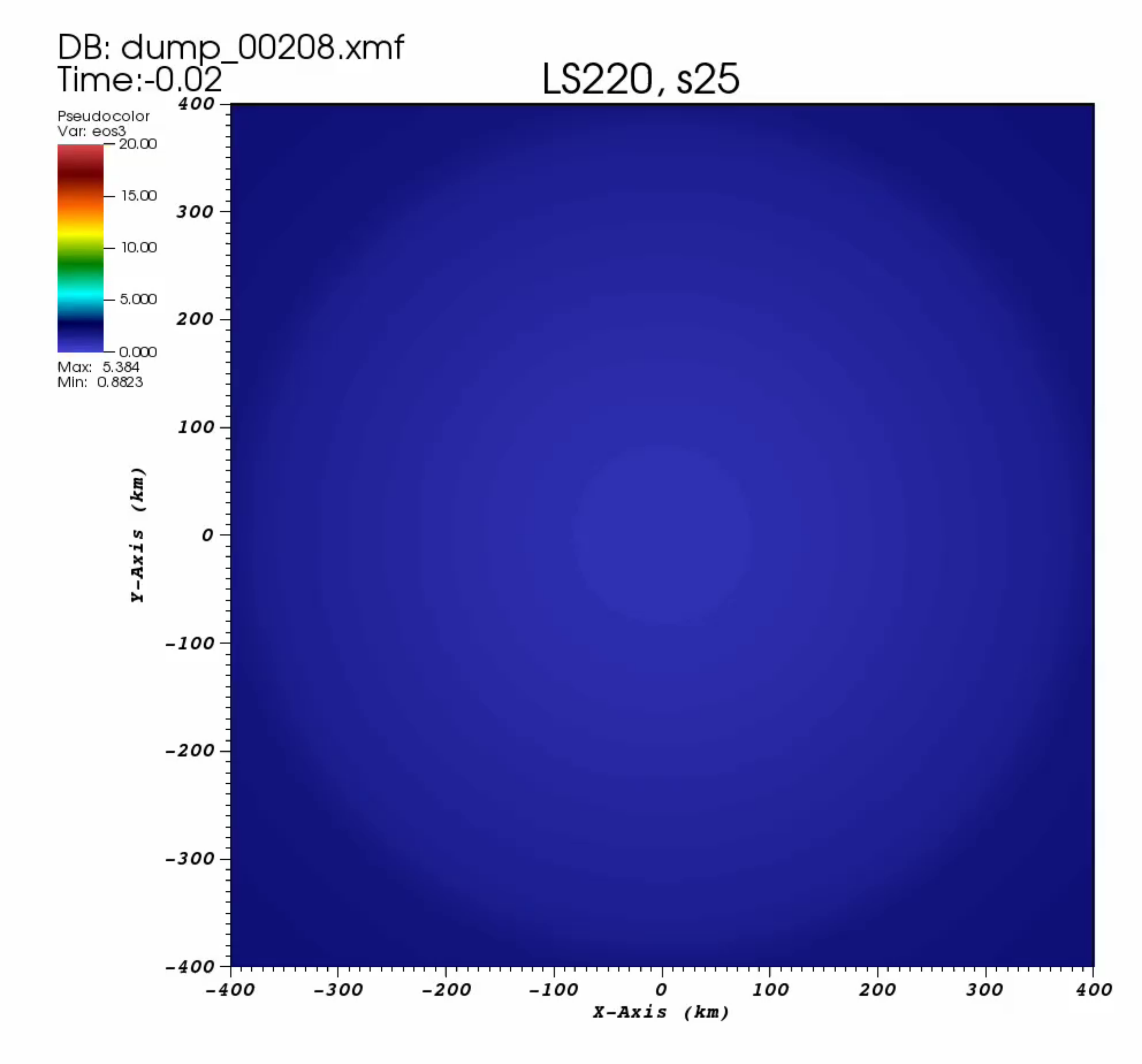
- Solves the Two-Moment Transport Equations, with 2nd and 3rd moment closures (not "ray-by-ray"); second-order accurate in space and time
- Explicit Riemann Godunov-like solution to the Transport operator
- Terms of O(v/c) included in transport
- Implicit solution to the local transport source terms
- Explicit Newtonian hydro; full energy and momentum couplings – HLLC
- Conserves energy, momentum, and lepton number to machine precision
- Very good energy conservation with gravity included
- "6"– Dim. = 1(time) + 3(space) + 1(energy-group) + vector Flux
- Logically spherical coordinates – general metric/covariant formulation
- Multipole Gravity (can include GR-like modifications to the monopole)
- Multi-D calculated to the center - Core refinement ("inverse spider grid") – improves timestepping by many factors (!); static mesh refinement
- For 2D, Axisymmetry – Rotation can be included (conserving angular momentum to machine precision)
- Good strong scaling in core count and scaling in energy group (linear)
- Result: Fast multi-D supernova code (by factor of ~10 x CASTRO)
- Burrows & Dolence 2015 ; Dolence & Burrows 2015

FORNAX: Strong Scaling in 3D





25 solar mass (WH 2007) 2D (Castro): MGFLD with multi-D Transport



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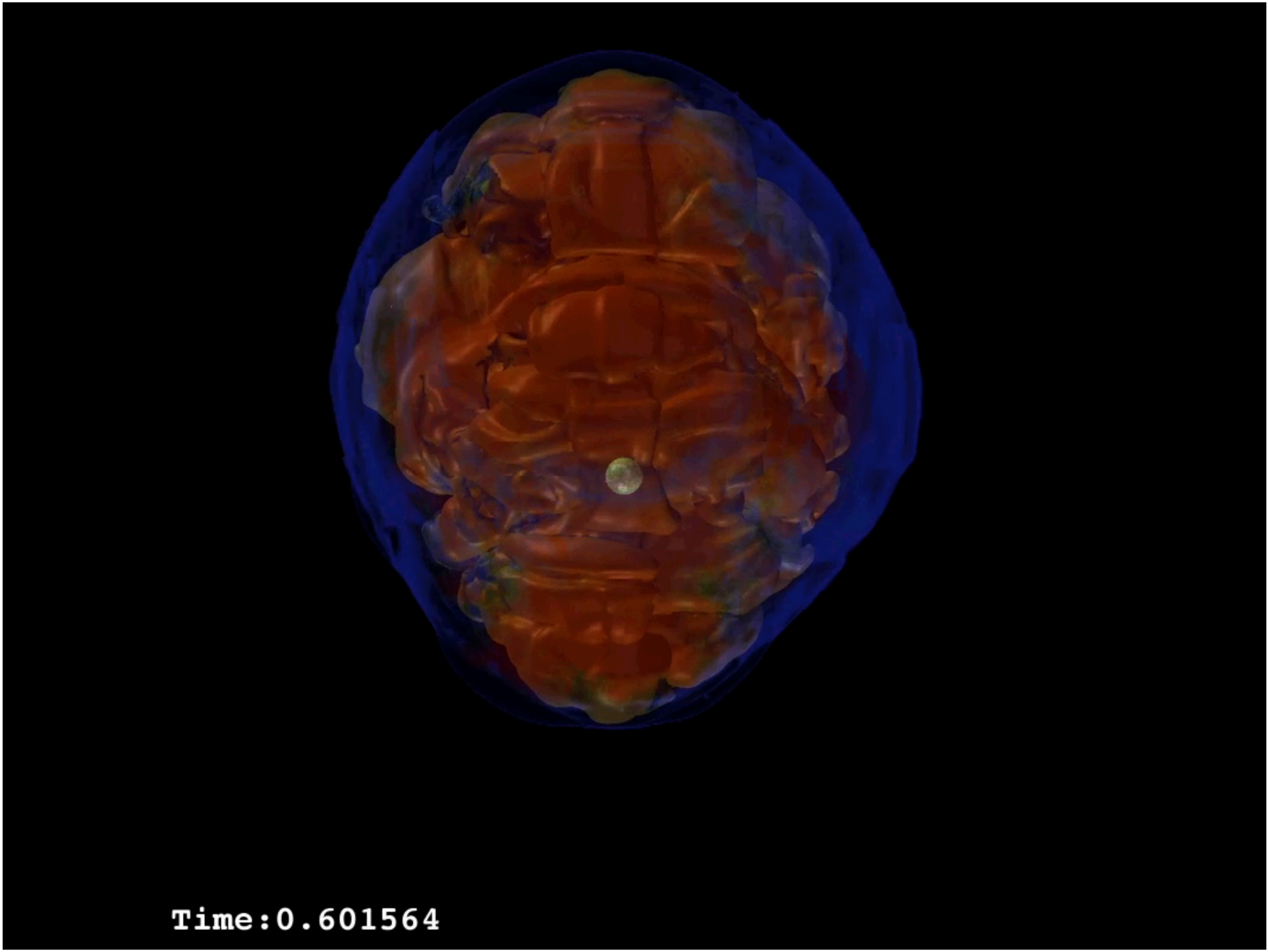
-100
-200
-300
-400
Y-Axis (km)
-400
-300
-200
-100
0
100
200
300
400
X-Axis (km)

Summary: Advantages of Fornax

- No global solves!! – no need for Krylov subspace methods
- Linear scaling with energy group number (not quadratic)
- Almost perfect strong scaling with core count to 100,000 – 200,000 cores
- Speed-up by at least a factor of ~10 over implicit solvers and codes
- Written in covariant form; general coordinate system
- Inverse spider grid – static mesh refinement
- Can include the core without suffering from spherical-coordinate Courant (CFL) time step problem – fully 3D down to the center

Enabled in the supernova problem by the fact that the speed of sound is not far from the speed of light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