Emerging Themes in the Theory of Core-Collapse Supernova Explosions

Supported by:
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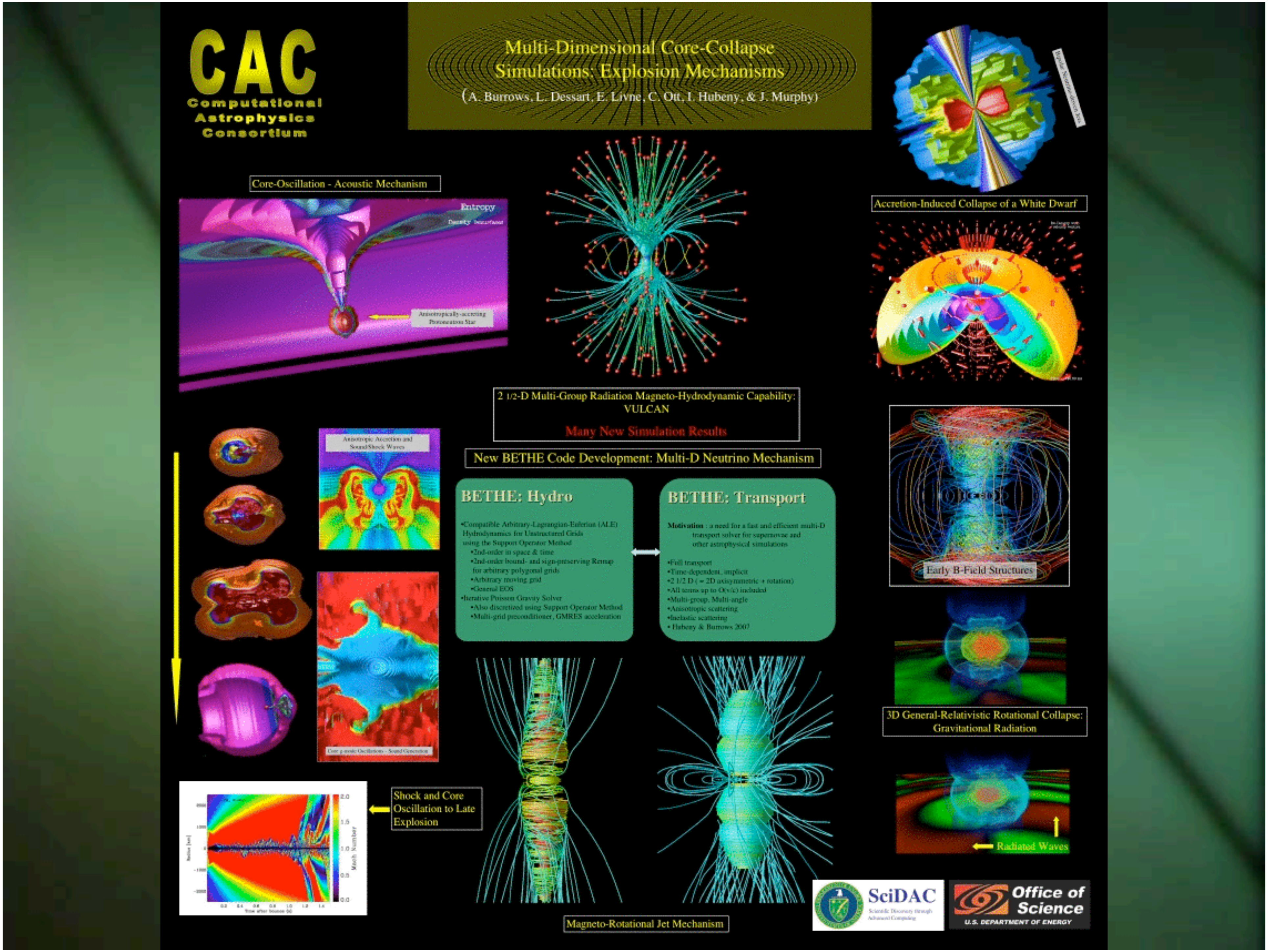
CAC
Computational
Astrophysics
Consortium
Multi-Dimensional Core-Collapse
Simulations: Explosion Mechanisms
(A. Burrows, L. Dessart, E. Livne, C. Ott, I. Hubeny, & J. Murphy)
Core-Oscillation - Acoustic Mechanism
Entropy
Anisotropically-accreting
Protoneutron Star
Accretion-Induced Collapse of a White Dwarf
2 1/2-D Multi-Group Radiation Magneto-Hydrodynamic Capability:
VULCAN
Many New Simulation Results
Anisotropic Accretion and
Sound/Shock Waves
New BETHE Code Development: Multi-D Neutrino Mechanism
BETHE: Hydro
•Compatible Arbitrary-Lagrangian-Eulerian (ALE)
Hydrodynamics for Unstructured Grids
using the Support Operator Method
•2nd-order in space & time
•2nd-order bound- and sign-preserving Remap
for arbitrary polygonal grids
•Arbitrary moving grid
•General EOS
•Iterative Poisson Gravity Solver
•Also discretized using Support Operator Method
•Multi-grid preconditioner, GMRES acceleration
BETHE: Transport
Motivation : a need for a fast and efficient multi-D
transport solver for supernovae and
other astrophysical simulations
•Full transport
•Time-dependent, implicit
•2 1/2 D (= 2D axisymmetric + rotation)
•All terms up to O(v/c) included
•Multi-group, Multi-angle
•Anisotropic scattering
•Inelastic scattering
• Hubeny & Burrows 2007
Early B-Field Structures
3D General-Relativistic Rotational Collapse:
Gravitational Radiation
Radiated Waves
Shock and Core
Oscillation to Late
Explosion
Mach Number
Time after bounce [s]
Magneto-Rotational Jet Mechanism
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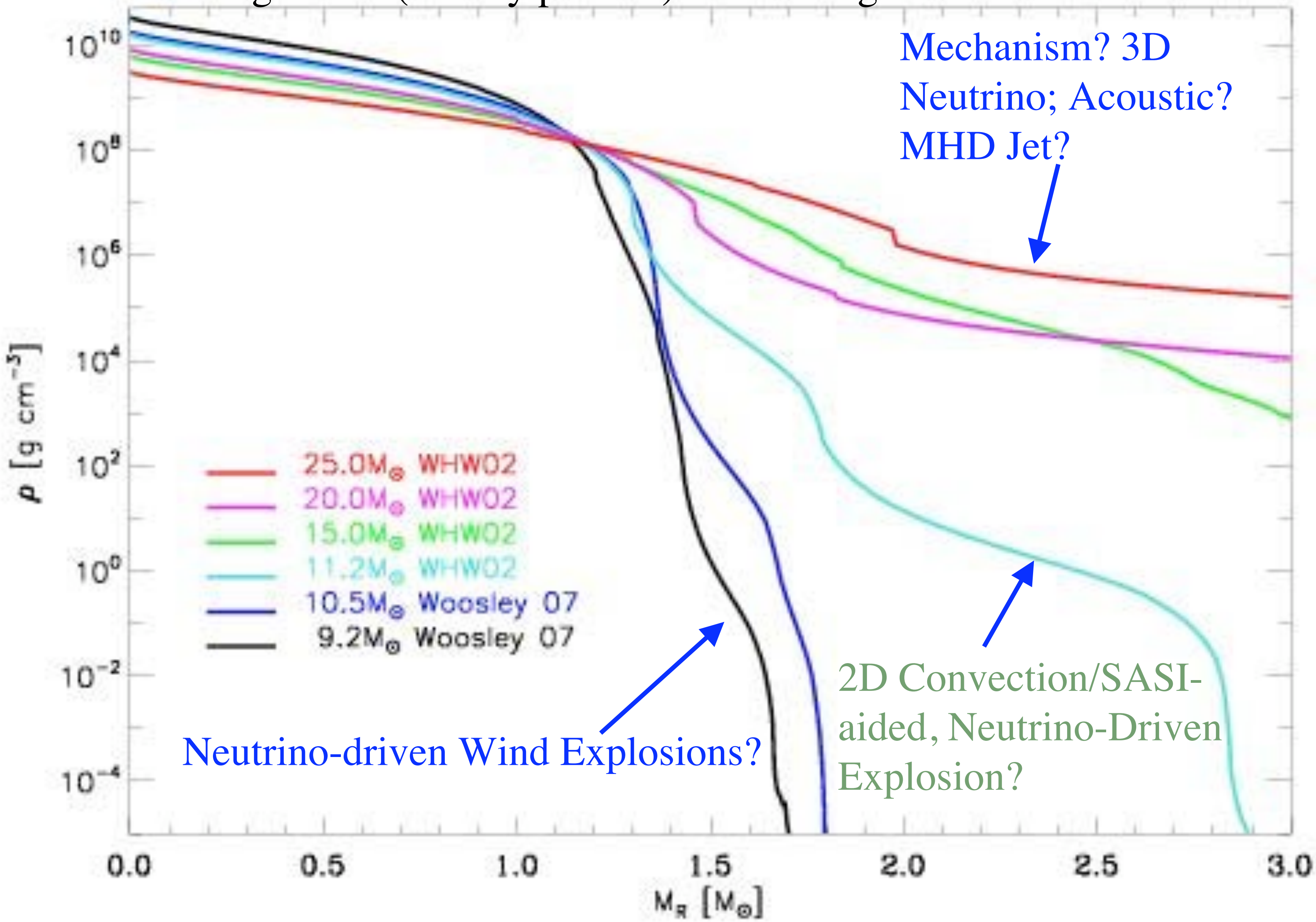
Some Pressing Issues in Core-Collapse Supernova Theory

- Mechanism of Explosion:
  - Neutrino mechanism
  - MHD mechanism
  - Acoustic mechanism
- Neutrino-driven Convection vs. SASI?
- 1D vs. 2D (VULCAN) vs. 3D (CASTRO!)
- Pulsar Kicks (proper motions), B-fields?
- Blast Morphology (Jets?)
- Pulsar Spins?
- Connection with GRBs and Hypernovae?

Density Profiles of Supernova Progenitor Cores

Progenitors (density profiles) Make a Big Difference!



Mechanisms of Explosion

- Direct Hydrodynamic Mechanism: always fails?
- Neutrino-Driven Wind Mechanism, ~1D (Burrows 1987) Lowest-mass massive stars, ~spherical (e.g., 8.8 solar masses, Kitaura et al. 2006, Burrows, Dessart, & Livne 2007)
- Convection/SASI-aided (Burrows et al. 1995; Blondin et al. 2003) Neutrino-Driven Wind Mechanism, 2D (e.g., 11.2 solar masses, Buras et al. 2006)
- Neutrino-Driven Jet/Wind Mechanism, Rapidly rotating AIC of White Dwarf (Dessart et al. 2006)
- Acoustic Power Mechanism (after delay), all progenitors explode (Burrows et al. 2006,2007a) (Weinberg & Quataert 2008 ?)

Mechanisms of Explosion (cont.)

- Convection/SASI-aided Neutrino mechanism? Nuclear-burning aided?? Inelastic scattering?? (Mezzacappa et al. 2006; Marek & Janka 2009; Bruenn et al. 2009; Murphy & Burrows 2008)
- MHD Jet Explosions - requires rapid rotation (e.g., Burrows et al. 2007b)
- The Key feature of almost all mechanisms is the Breaking of Spherical Symmetry (and simultaneous accretion during early explosion)

Multi-D: Simultaneous Explosion and Accretion is the Key?

- Neutrino Mechanism: Anisotropic l=1 explosion --> lower ram pressure at head, larger neutrino heating region, while accretion elsewhere maintains neutrino luminosity to drive the explosion (2D vs. 3D?)
- MHD-Rapid rotation: Explosion along poles, accretion of free rotational energy at equator (engine)
- Acoustic Mechanism: Explosion in one direction, accretion funnels from another, powering oscillation to maintain acoustic power

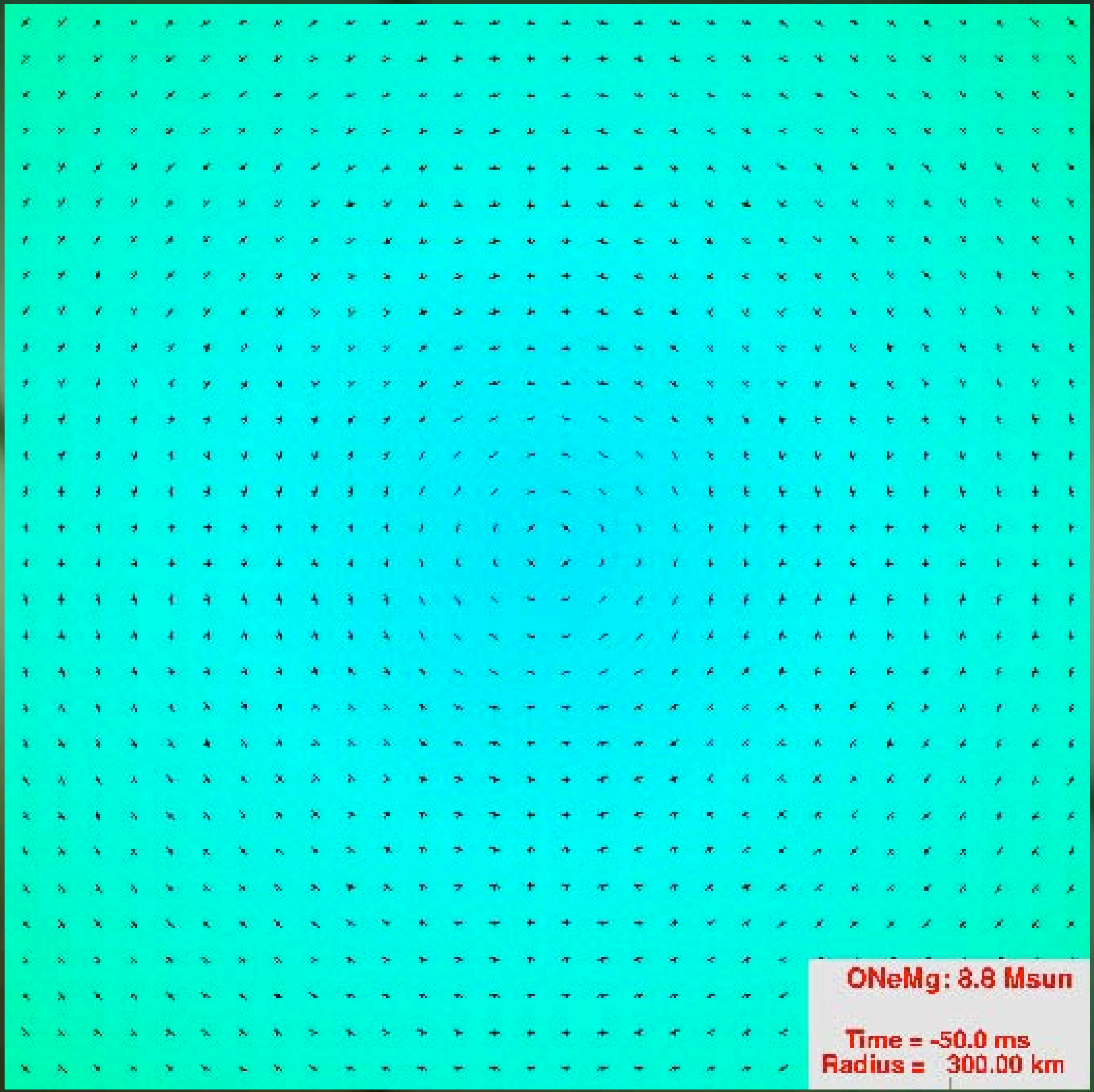
Neutrino-Driven Wind Explosions: Low Mass Progenitors

8.8-Solar mass Progenitor of Nomoto: Neutrino-driven Wind Explosion

First shown by Kitaura et al. 2006

Burrows, Dessart, & Livne 2007;

Burrows 1987

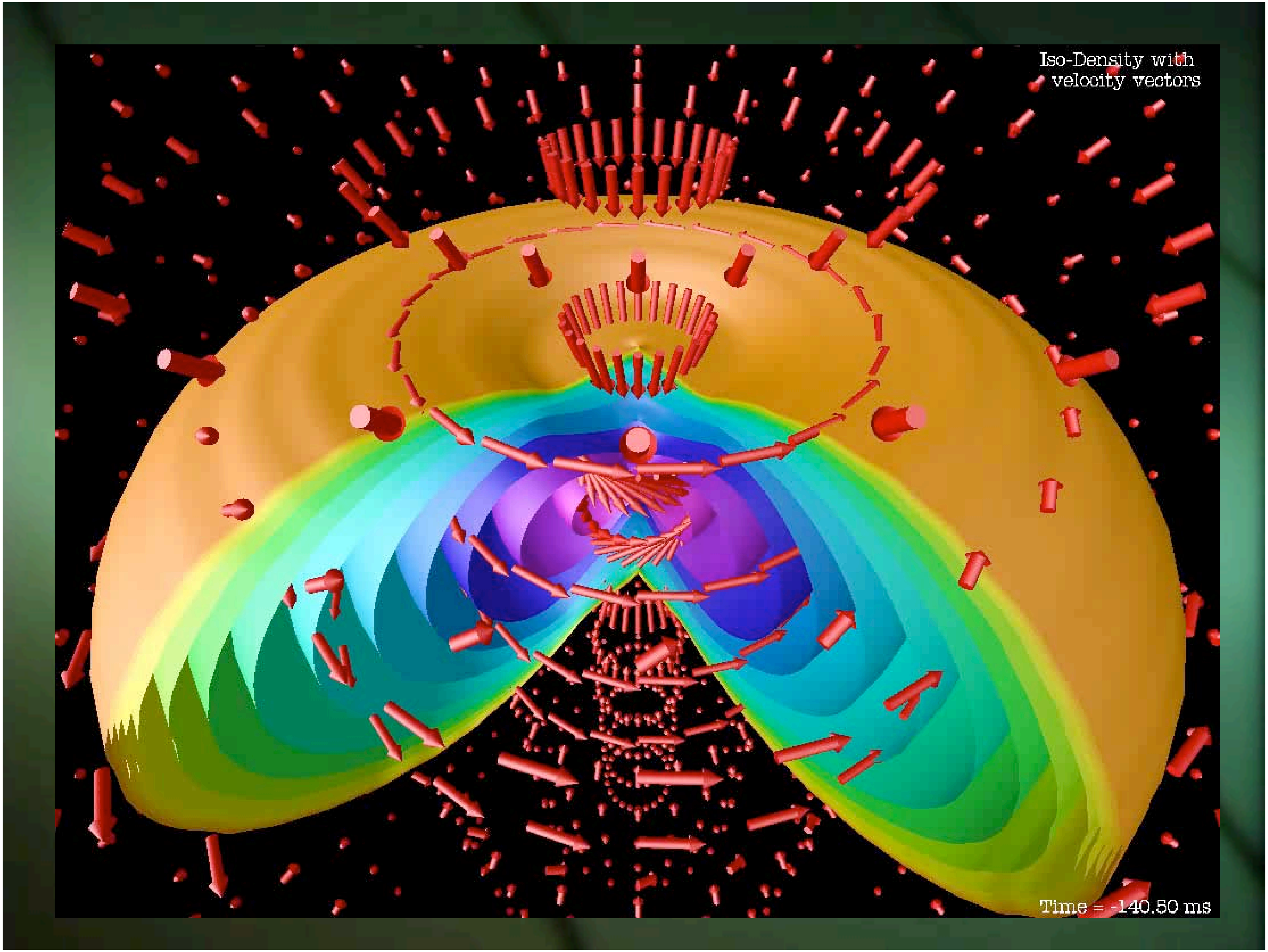


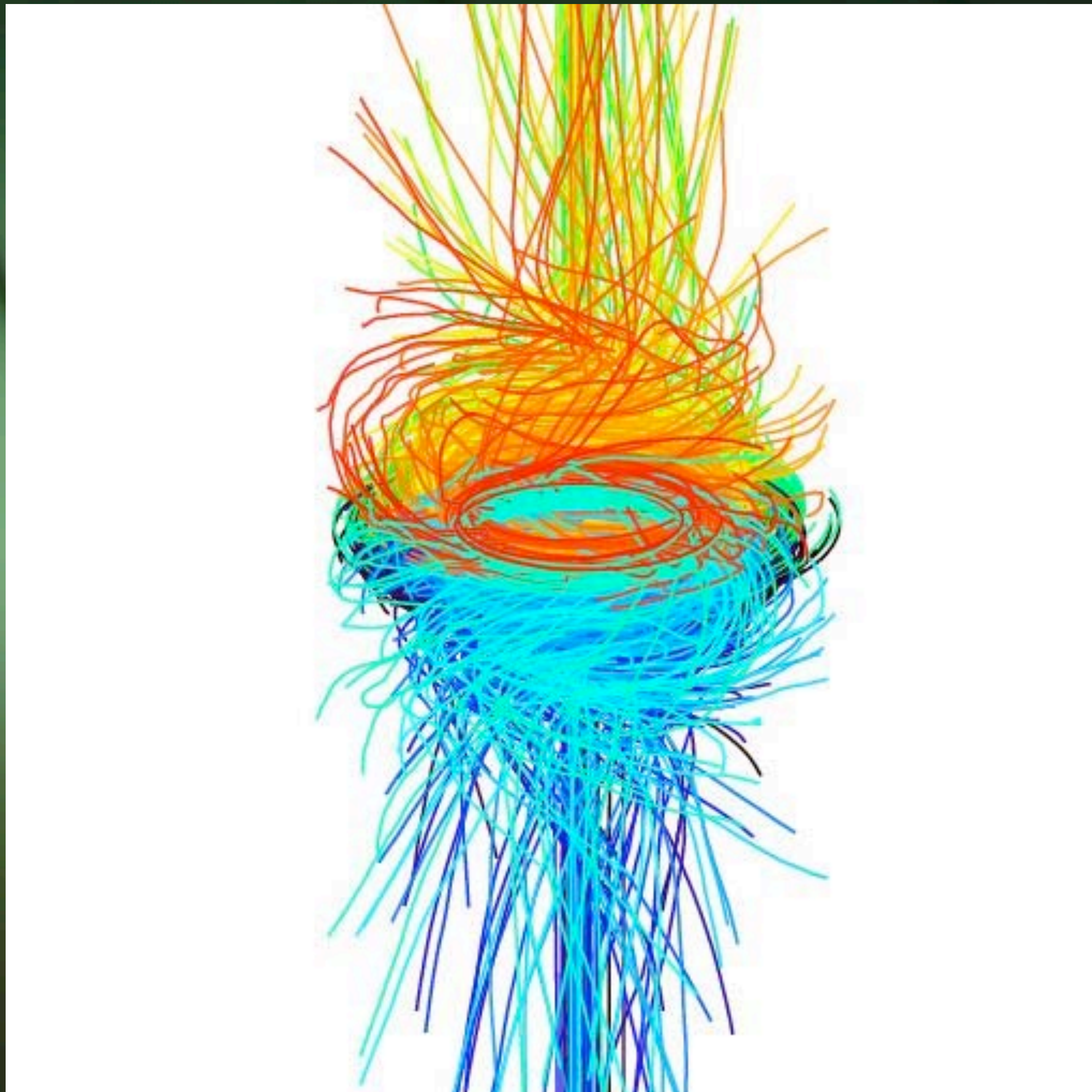
NOTE WIND THAT FOLLOWS

Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

Dessart, Burrows, Ott, Livne, Yoon, & Langer 2006

Rapid Rotation!

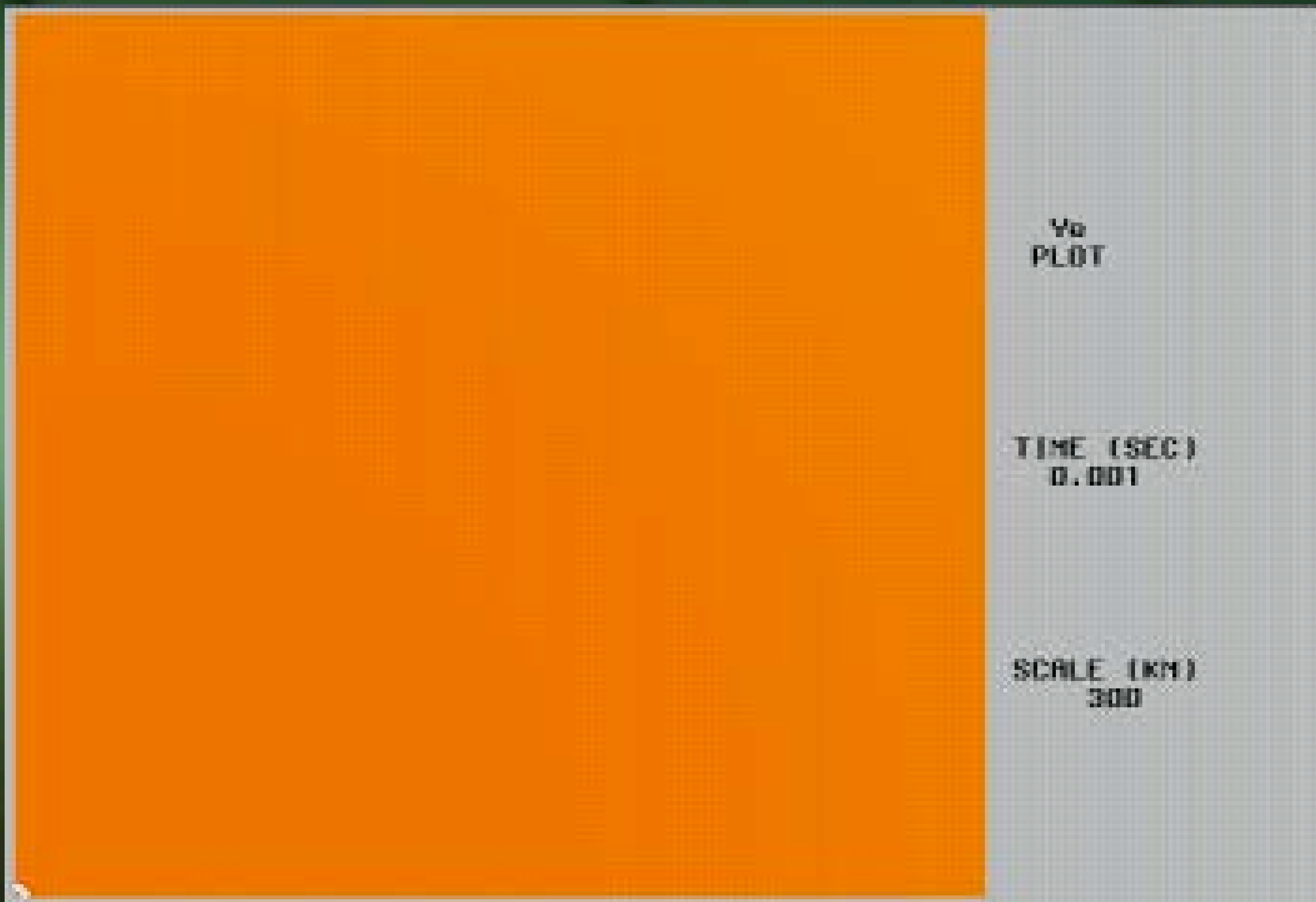

Iso-Density with
velocity vectors
Time = -140.50 ms



2D Radiation-Hydro Simulations of Massive-star Core Collapse

BURROWS, HAYES, & FRYXELL (1995)

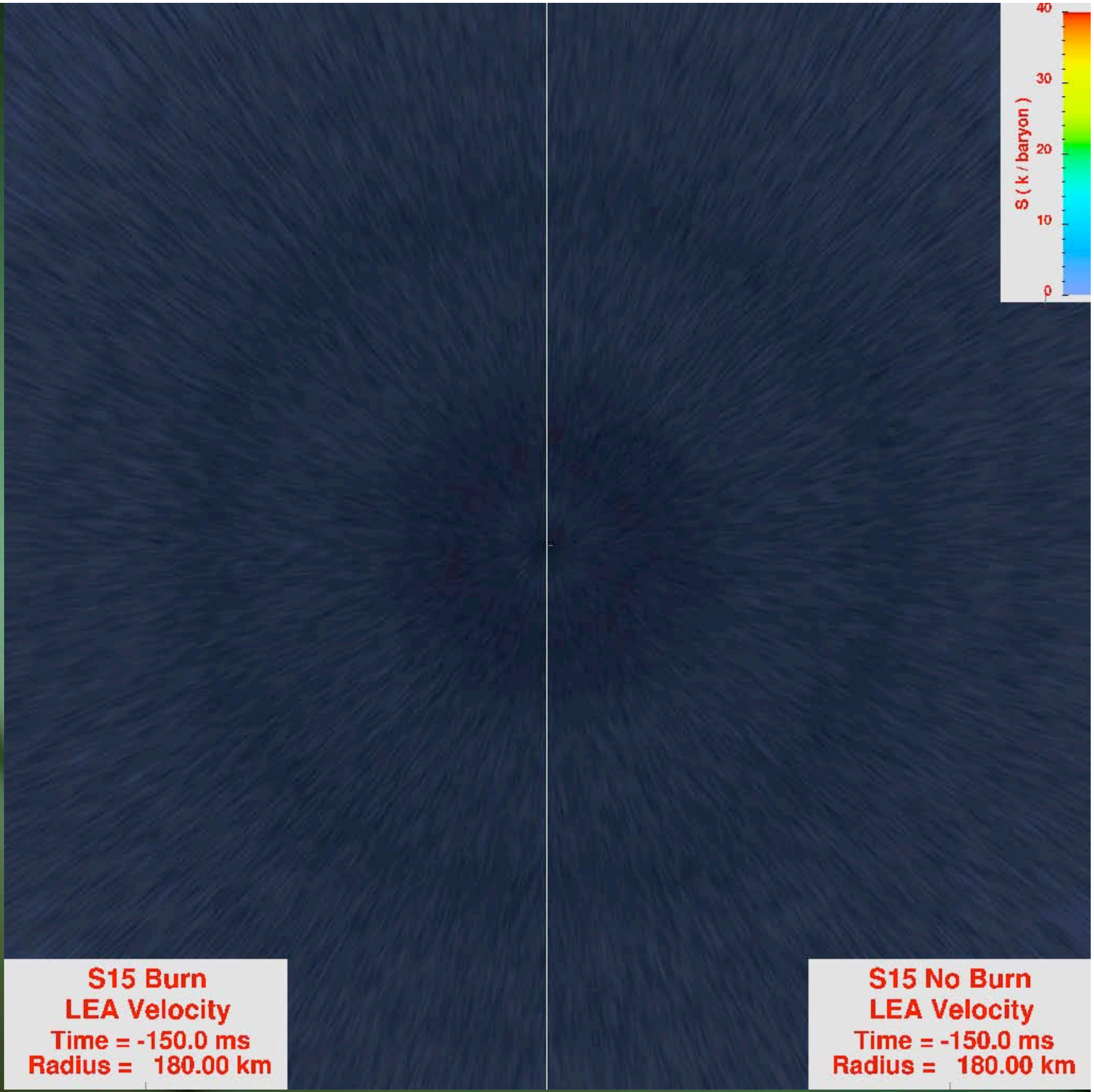
“SASI” in 1995



Neutrino-driven Convection (on a 90^{o} wedge); Terminal PNS wind

Neutrino-driven Convection-SASI in 2D

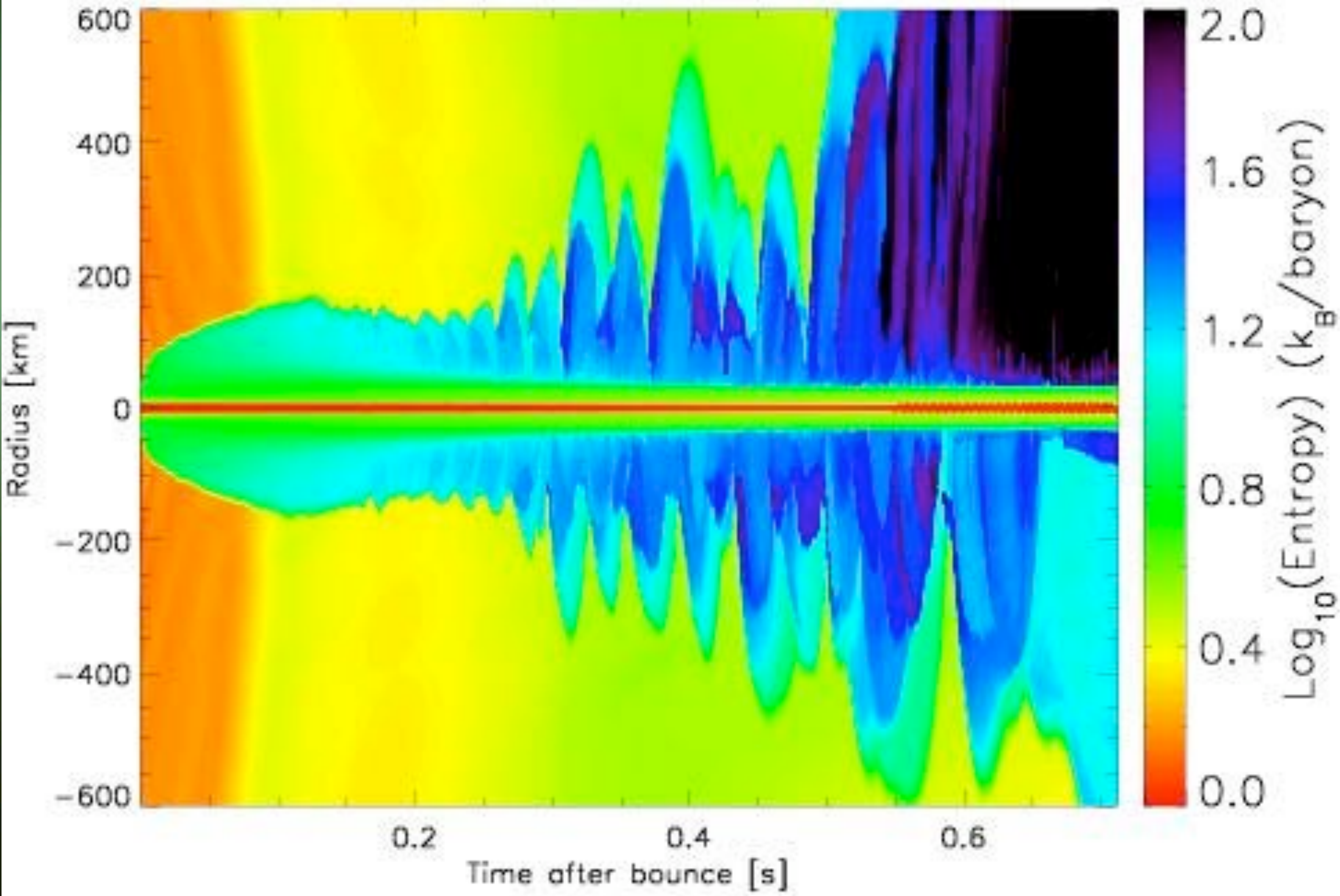
ν-driven convection dominates (e.g., see Fernandez and Thompson 2009)



With and Without Burning

Core Oscillation/Acoustic Power Mechanism

Inner 600-km Look at the Advective-Acoustic Instability



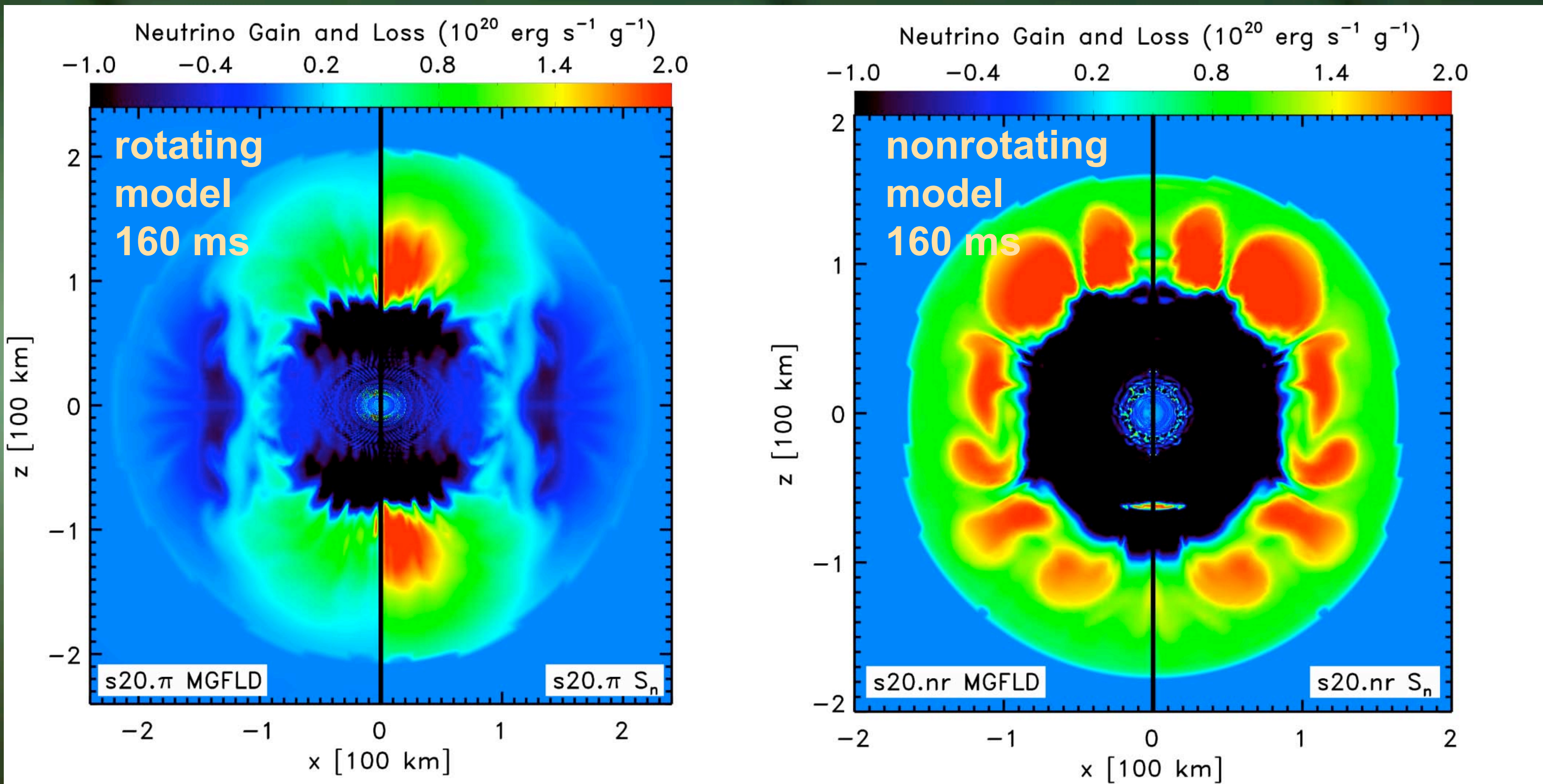
Key Features of Acoustic Mechanism

- "A Tale of Two Instabilities"
- Shock Instability (SASI) after bounce (30-80 Hz)
- Rapid core oscillation progressively excited: l=1 g-mode (~300 Hz), first by turbulence (that grows with time), then non-linearly by anisotropic downflowing plumes/streams
- Core oscillation generates sound waves that propagate outward
- Acoustic power and momentum explode the star
- Hybrid acoustic/neutrino model?
- Self-excited oscillations (very non-linear); transducer
- All models explode, but "late" (0.5-1.0 seconds after bounce
- Fundamentally aspherical explosions: unipolar?
- R-process nucleosynthesis?

Multi-Angle, Multi-group, Time-Dependent Transport in 2D SN Simulations

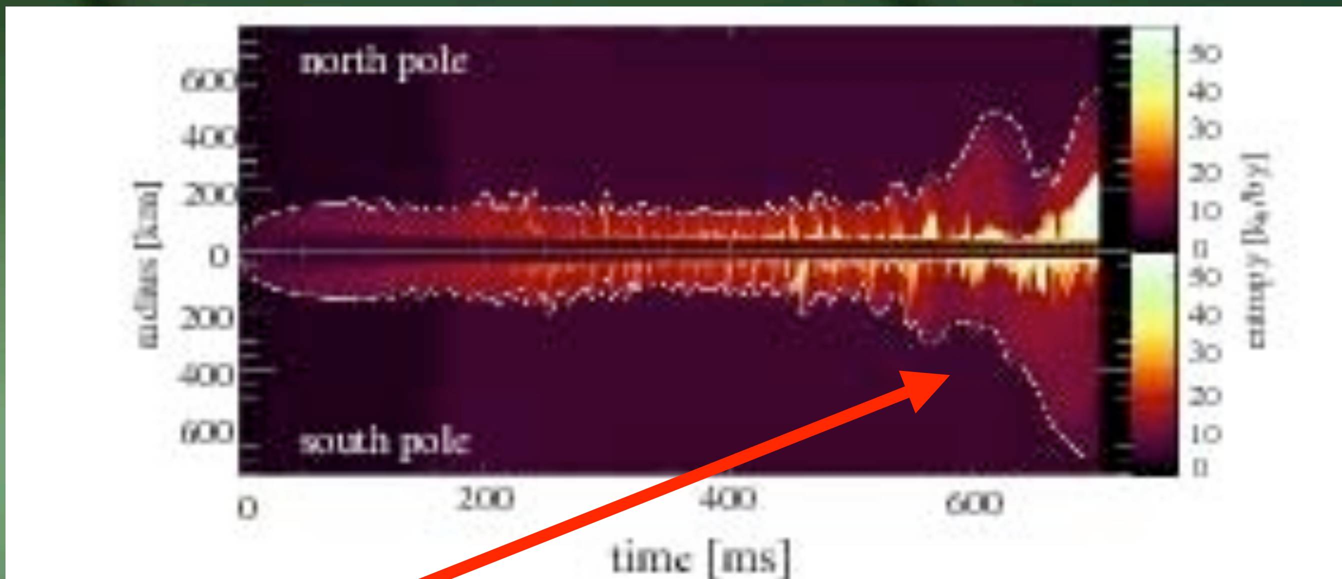
Ott et al. 2008

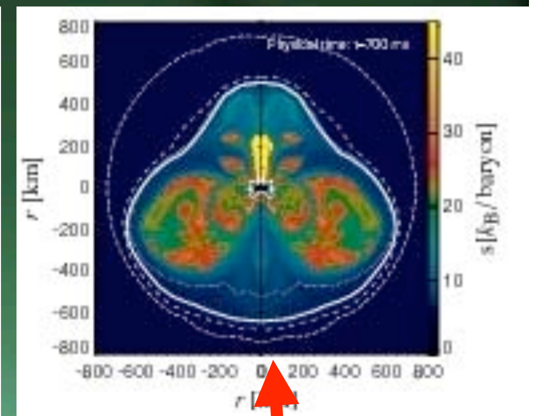
Neutrino Energy Deposition



- s20.nr: Little difference between MGFLD and S_n at 160 ms after bounce.
- s20.π: Large (factor ~3) polar differences in specific heating rates.
  - (only ≈ 2% difference; S_n gain < MGFLD gain!)

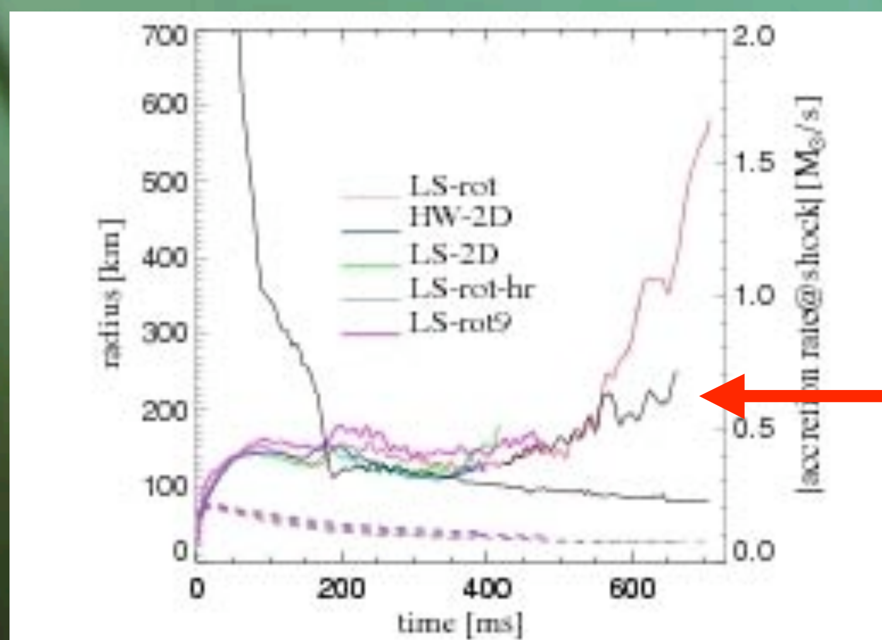
Marek & Janka 2009: 15 solar-mass model with soft (180 MeV) EOS, 1D "ray-by-ray" transport, 2D hydro:





Long delay, weak explosion (?)

R_{shock} to ~600 km

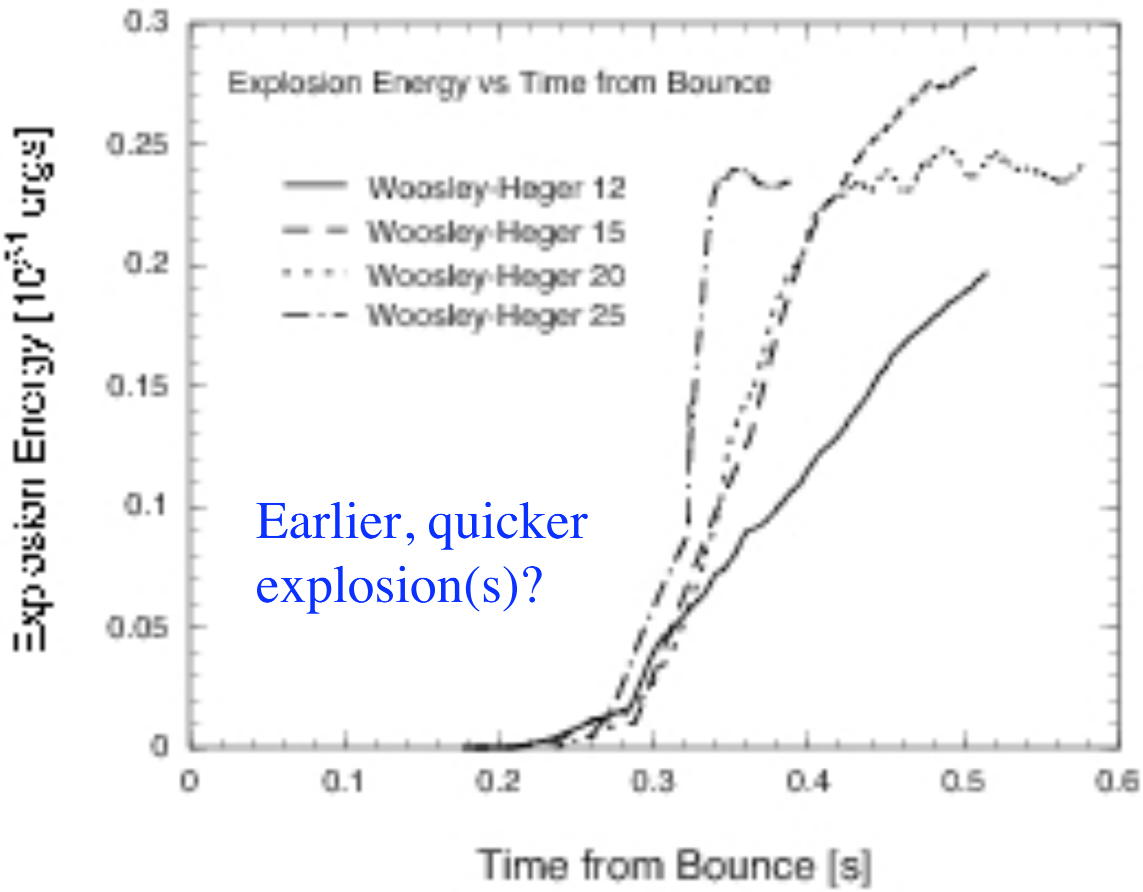


Higher-resolution, stiffer EOS - don't explode??

GR?

Higher-resolution. Smaller radius

Bruenn, Mezzacappa et al. 2009 with soft EOS, 1D “ray-by-ray” transport, 2D Hydro:

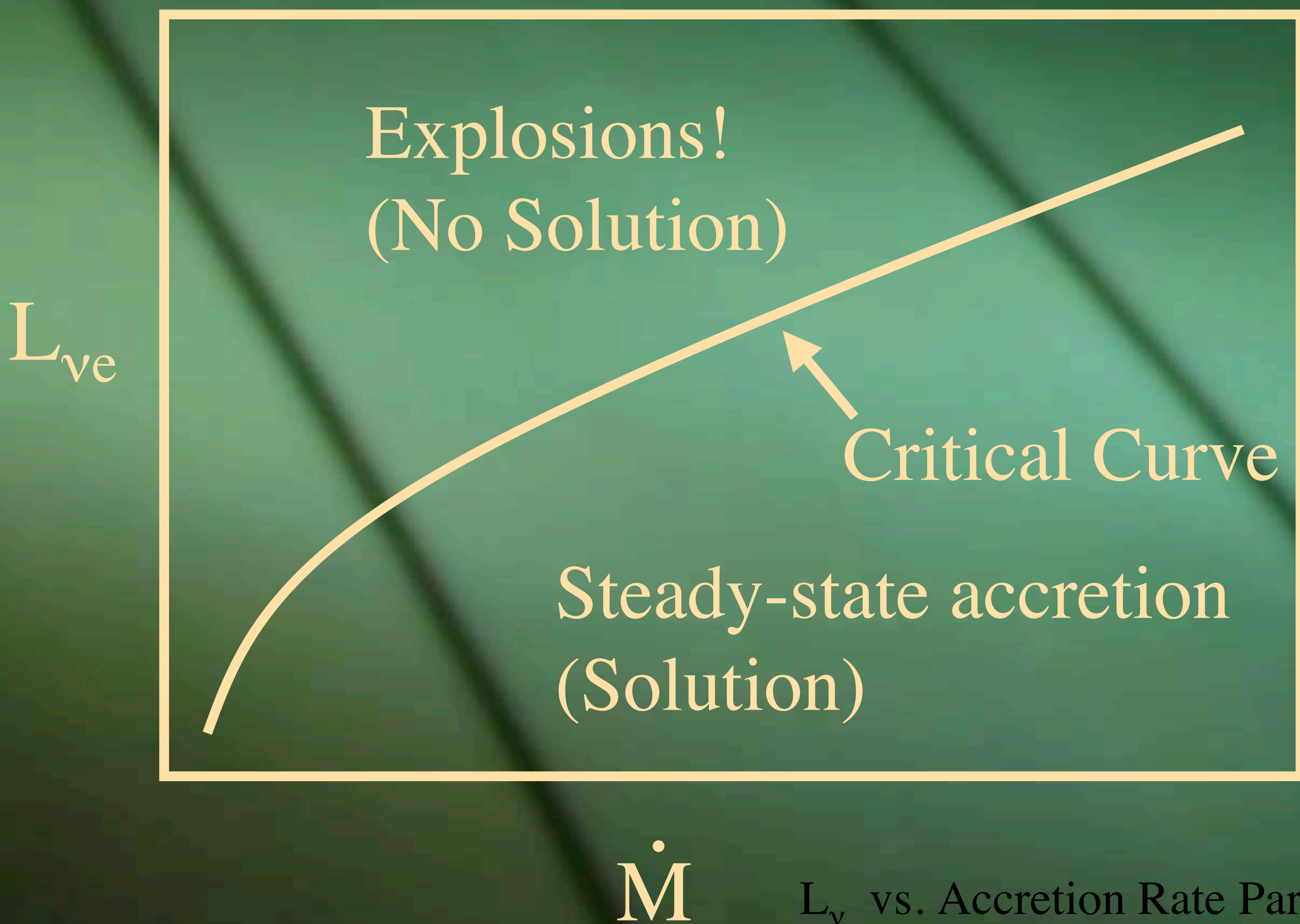


What is the difference?, What’s new? Inelastic scattering??, nuclear burning? …

FIGURE 3. Explosion energies as a function of post-bounce time.

Burrows & Goshy ‘93; Murphy & Burrows 2008

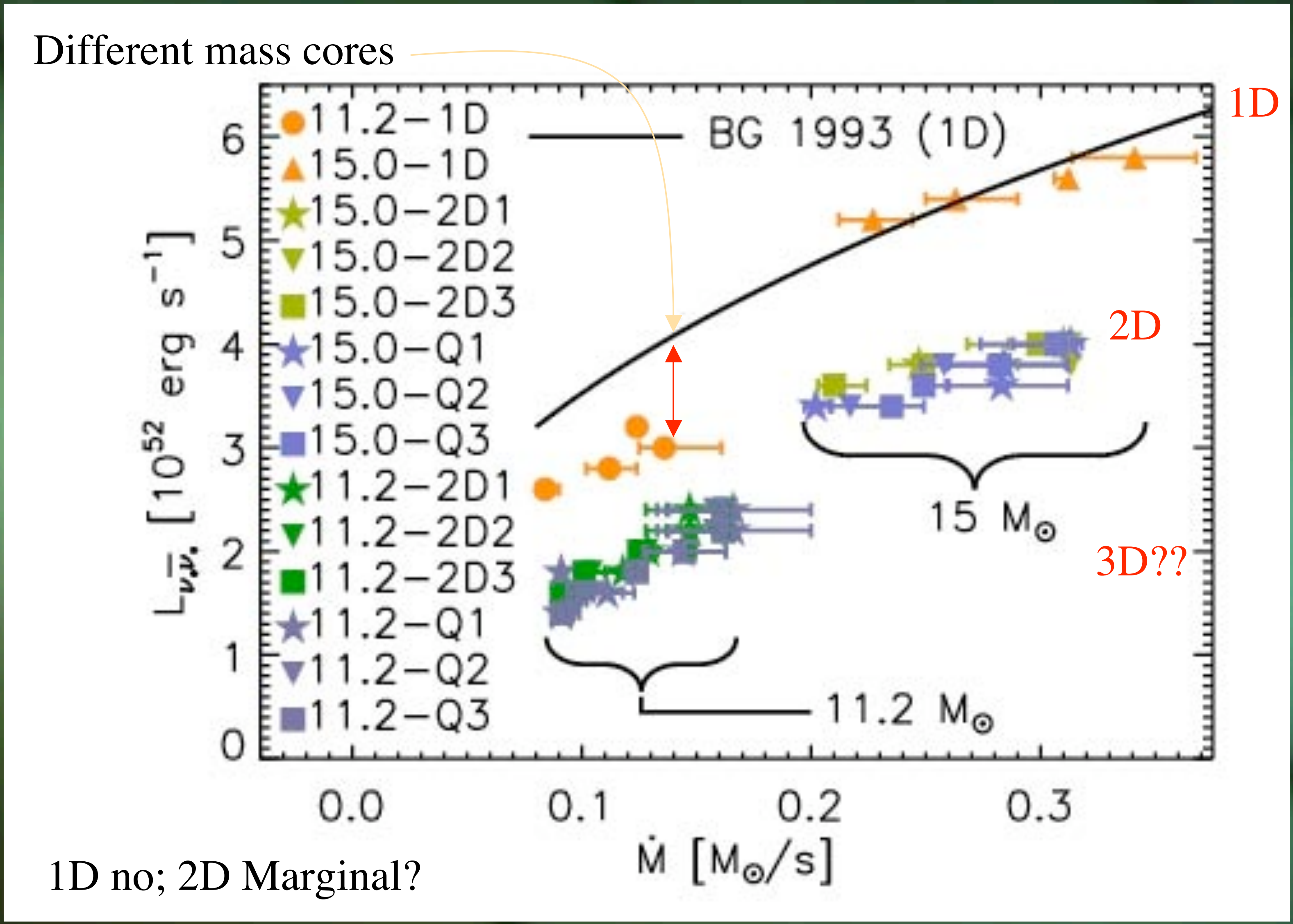
Critical Condition for Neutrino Mechanism:
Dimension-dependent



L_ν vs. Accretion Rate Parameter Study

How do the critical luminosities differ between 1D and 2D?

Critical Curve for Neutrino Mechanism: 1D versus 2D



See Jeremiah's poster!

Murphy & Burrows 2008

Limitations of the VULCAN/2D Simulations

- Doppler shift terms not included in transport
- Inelastic redistribution not included (though subdominant), though could be
- No good development path to 3D

(but …)

Limitations of the ORNL Simulations

- Transport in 1D ("ray-by-ray"): Not Multi-D
- Soft (180 MeV) Nuclear EOS (but measurements?)
- Energy conservation to only ~0.5 Bethes
- Core must stay at grid center (kicks?, acoustic mechanism?)
- Role of Nuclear Burning at Shock?
- Large Stalled Shock Radius ?

Limitations of the MPIA Simulations

- Transport in 1D ("ray-by-ray"): Not Multi-D
- Soft (180 MeV) Nuclear EOS (but measurements?)
- Core must stay at grid center (kicks?, acoustic mechanism?)
- (ORNL and MPIA 15-solar-mass explosion simulations very discrepant)

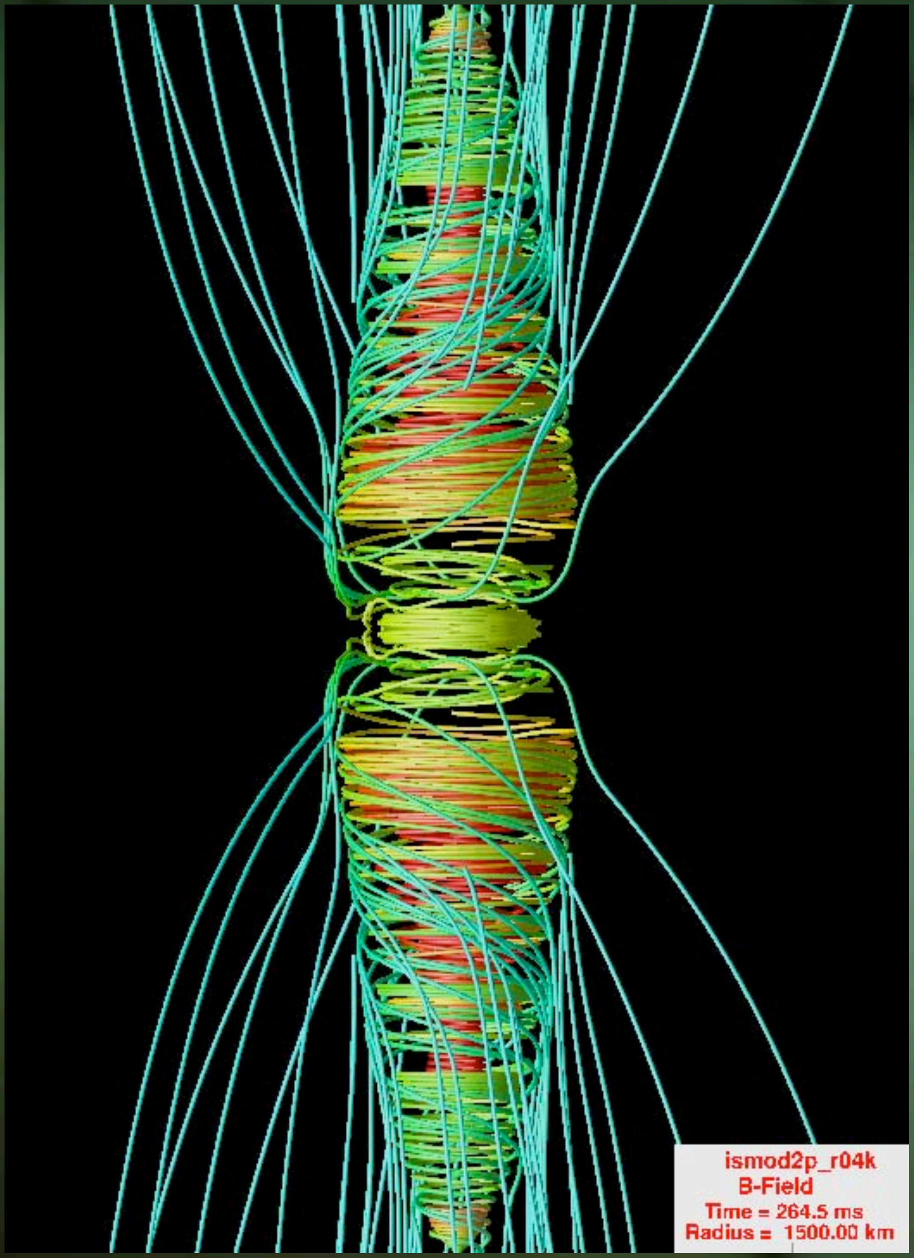
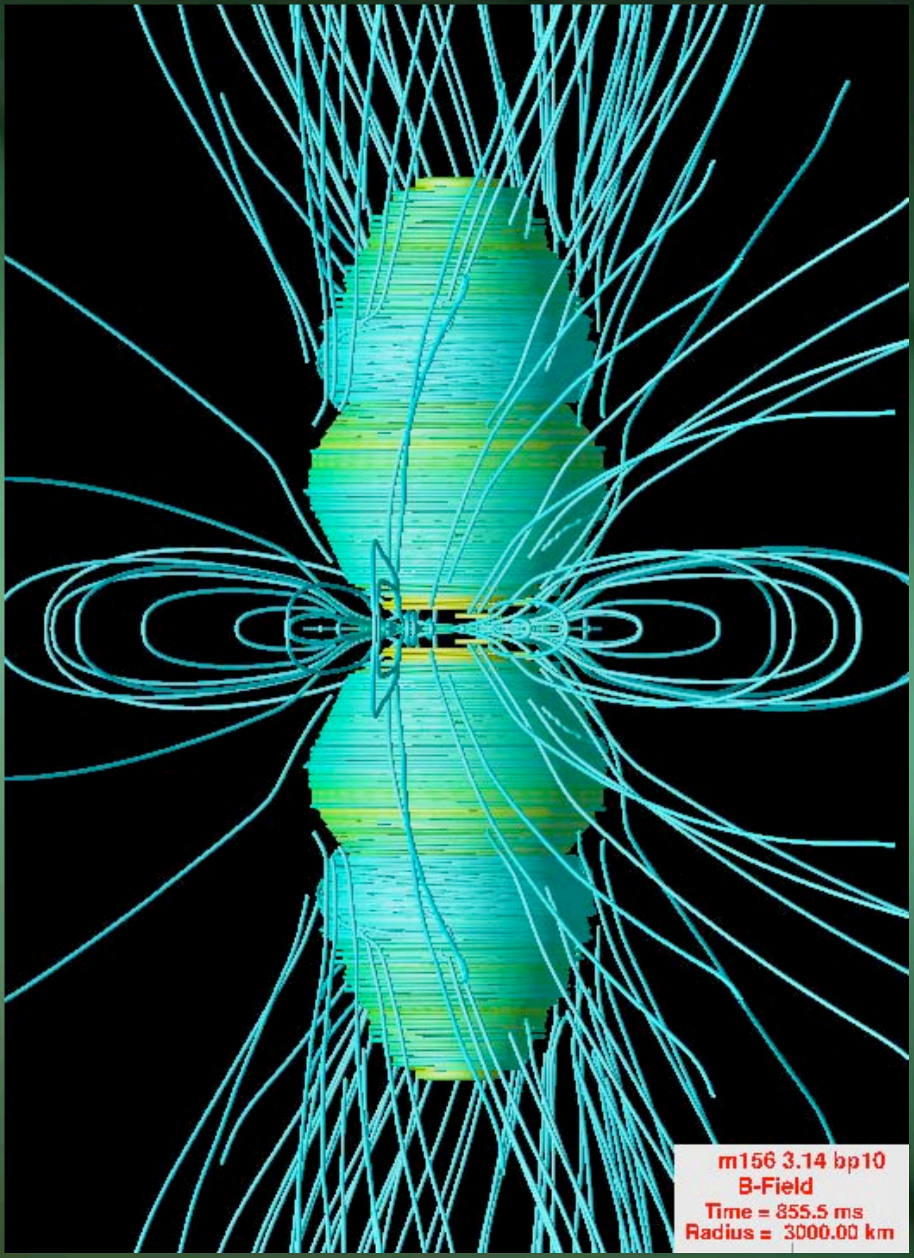
2D Radiation-Hydro Simulations

Verdict: Marginal, Ambiguous, at best (but 3D….?)

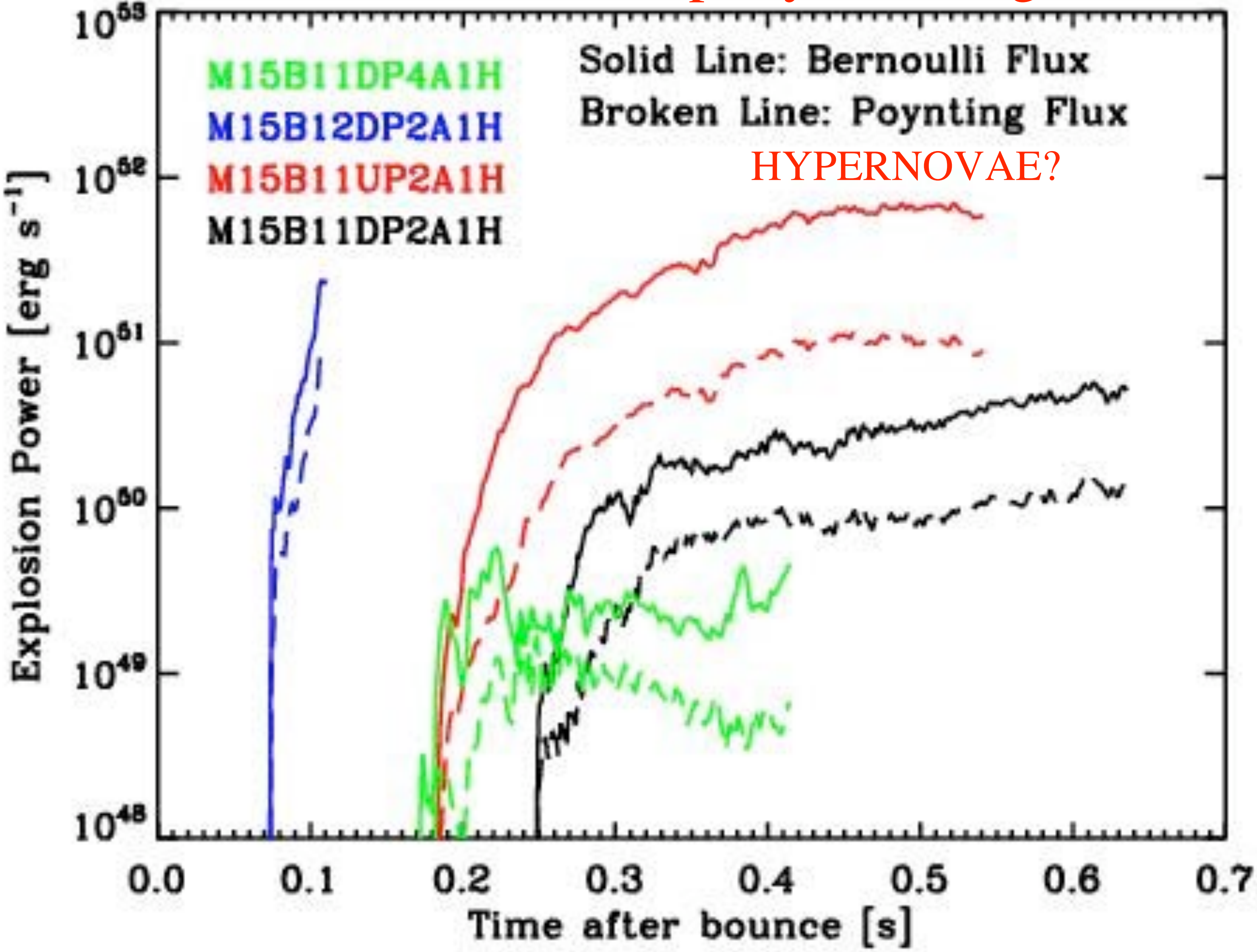
MHD Jets and RMHD Simulations of Core Collapse: *Rapid Rotation Required*

Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007

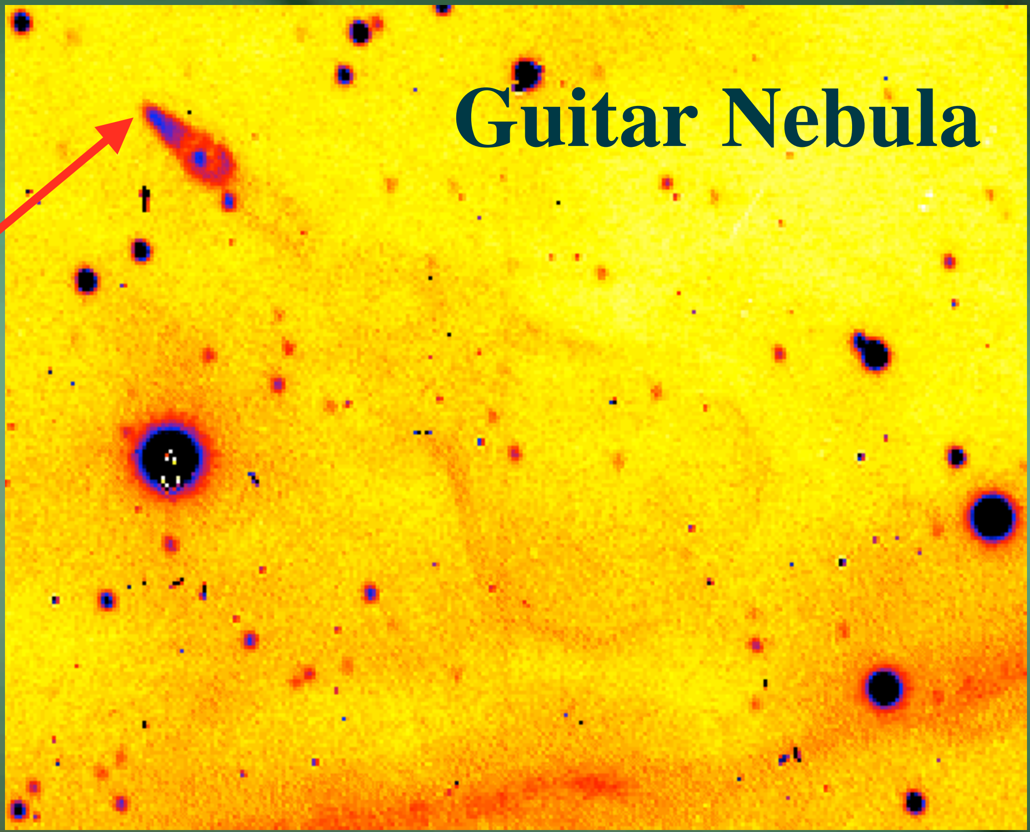
Rotation Winding, the MRI and B-field Stress effects


ismod2p_r04k
B-Field
Time = 264.5 ms
Radius = 1500.00 km

m156 3.14 bp10
B-Field
Time = 855.5 ms
Radius = 3000.00 km

MHD Jet Powers for Rapidly-Rotating Cores

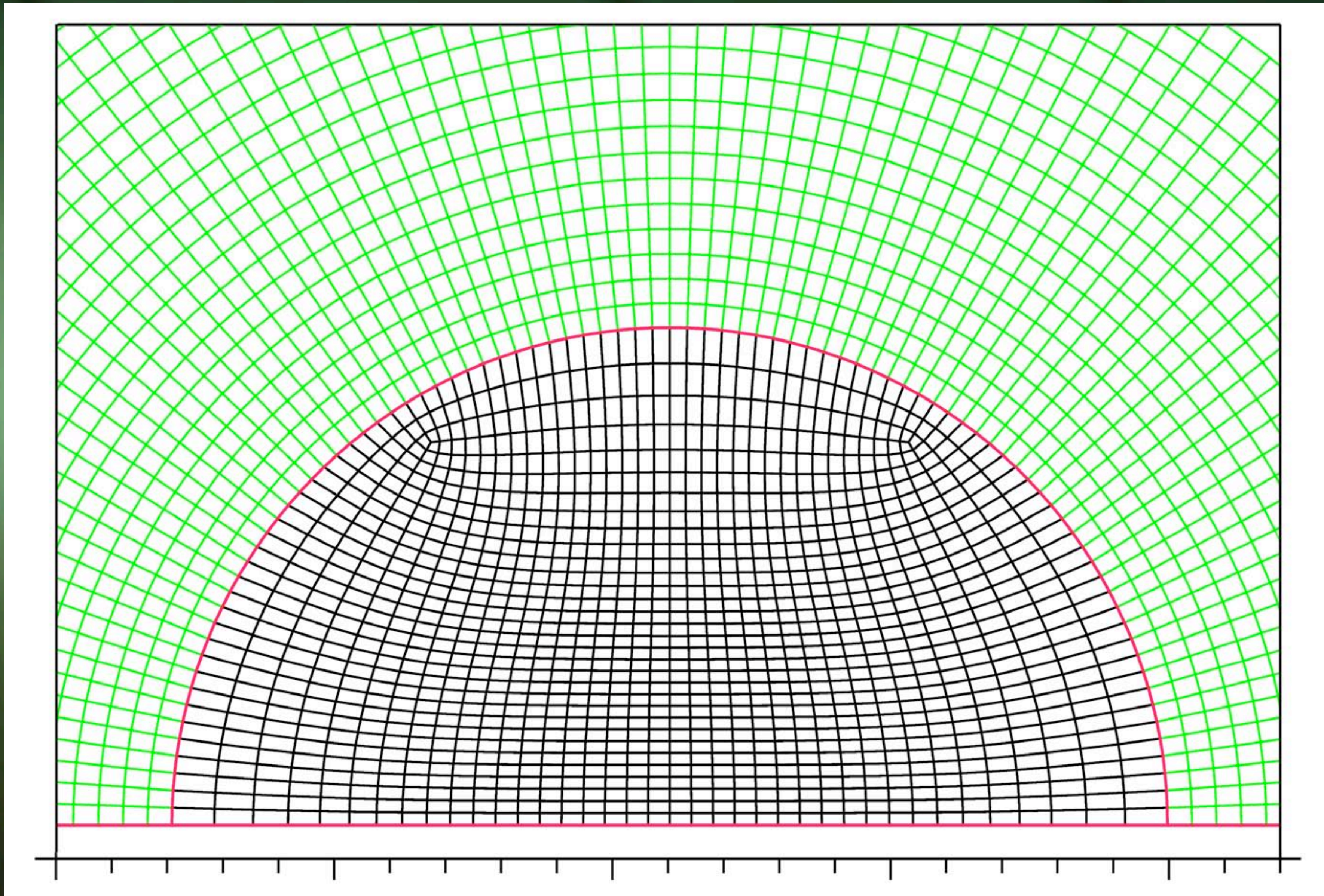


Pulsar Recoil: A Generic Feature

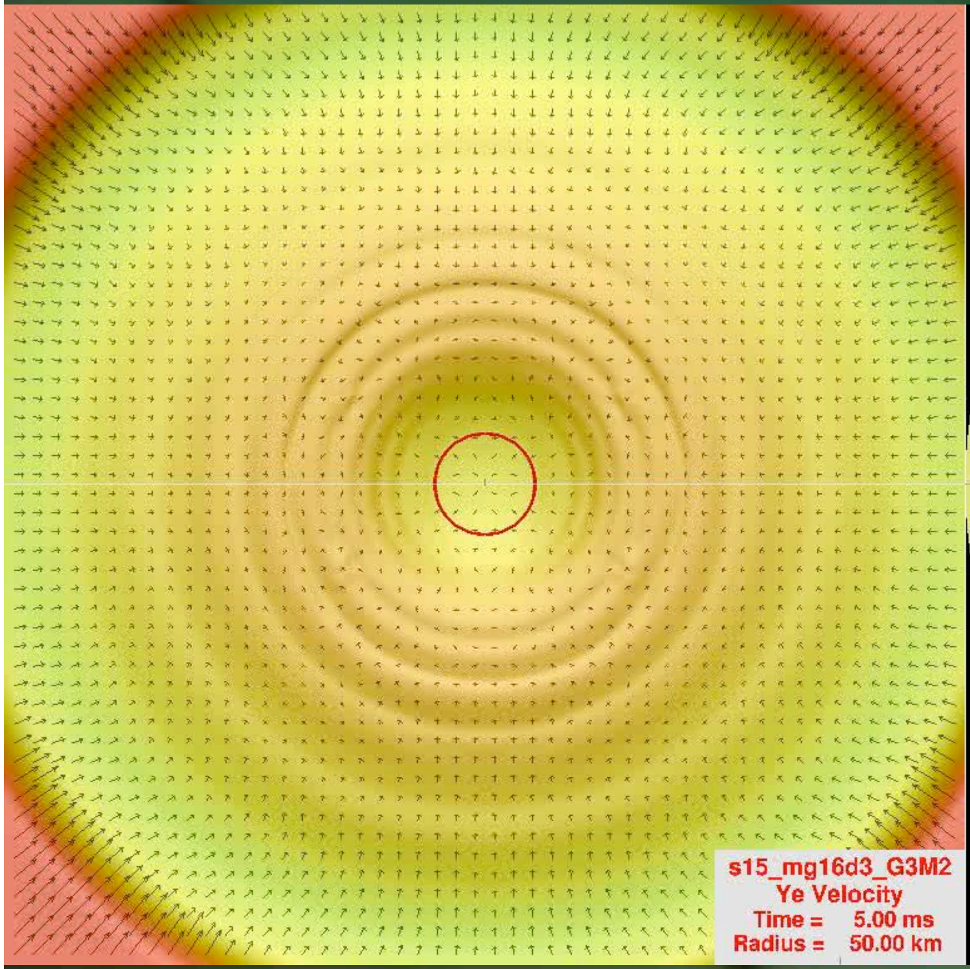


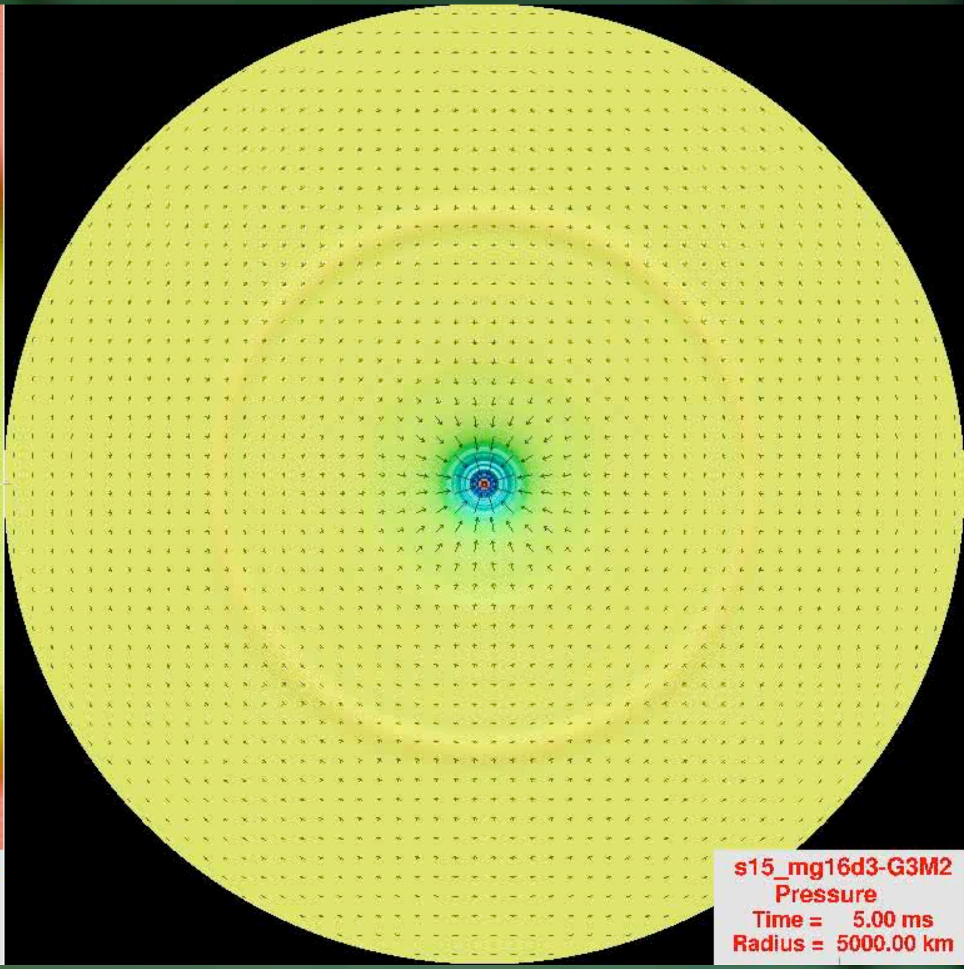
Pulsar Kicks:
Pulsar B2224+65
and Bow Shock
$V \geq 1000$ km s^{-1}

Cordes, Romani, Lundgren ‘93



The Origin of Pulsar Kicks in Hydrodynamic (and neutrino?) Recoil

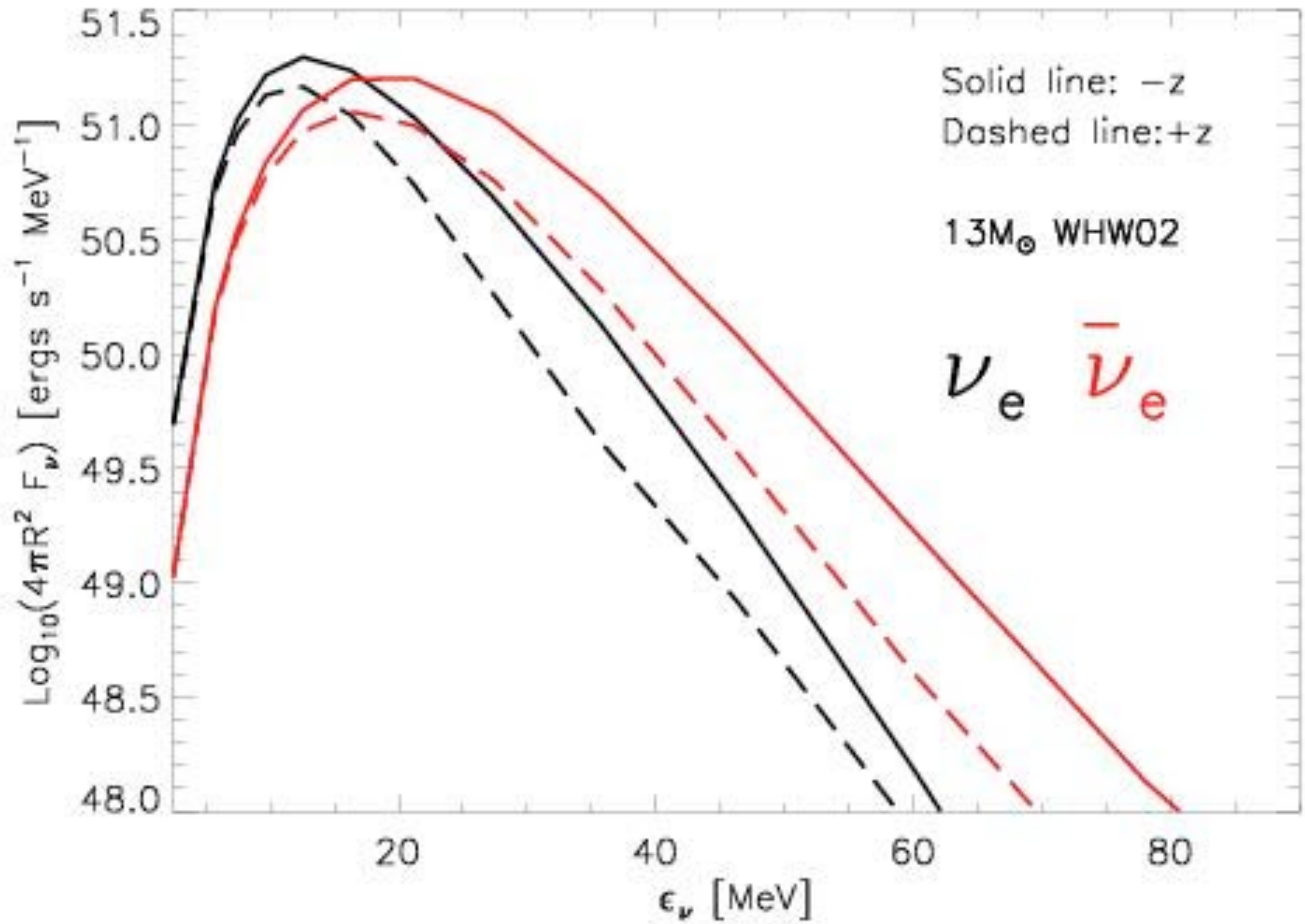




Acceleration ~ 500 km/s^2

Nordhaus, Burrows, & Ott 2009

Top-Bottom Asymmetry in Neutrino Luminosity after Explosion: Kicks!



3D - Crucial Next Step

CASTRO!

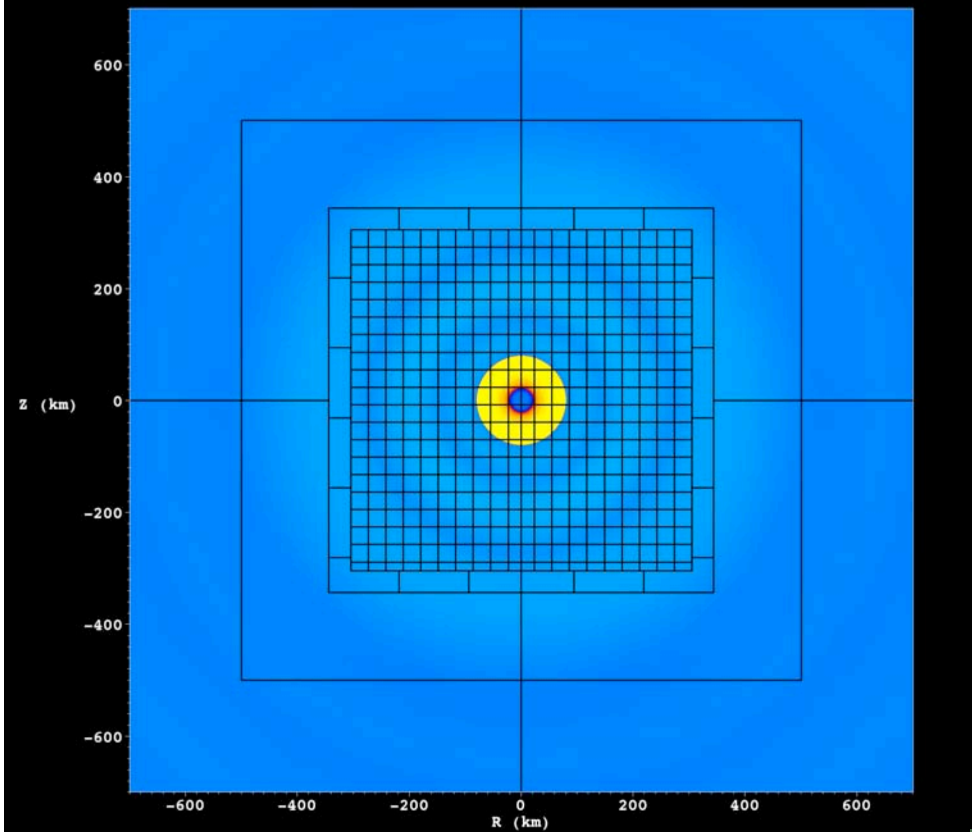
(J. Bell; A. Almgren; L. Howell; M. Singer; A. Burrows; J. Nordhaus)
(Using a MGFLD variant of Hubeny/Burrows scheme)

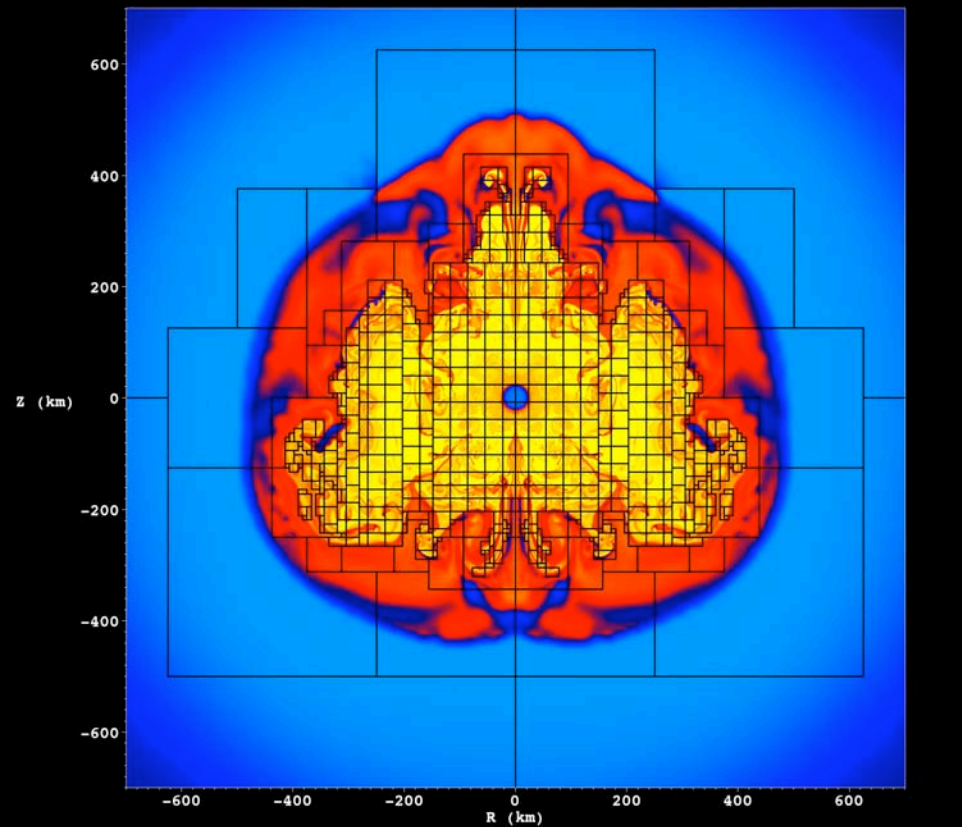
See Jason Nordhaus' poster

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 mixed-frame method of Hubeny & Burrows (2007), 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
- Developers: John Bell, Ann Almgren, Louis Howell, Mike Singer, Jason Nordhaus, Adam Burrows - LBNL, LLNL, Princeton

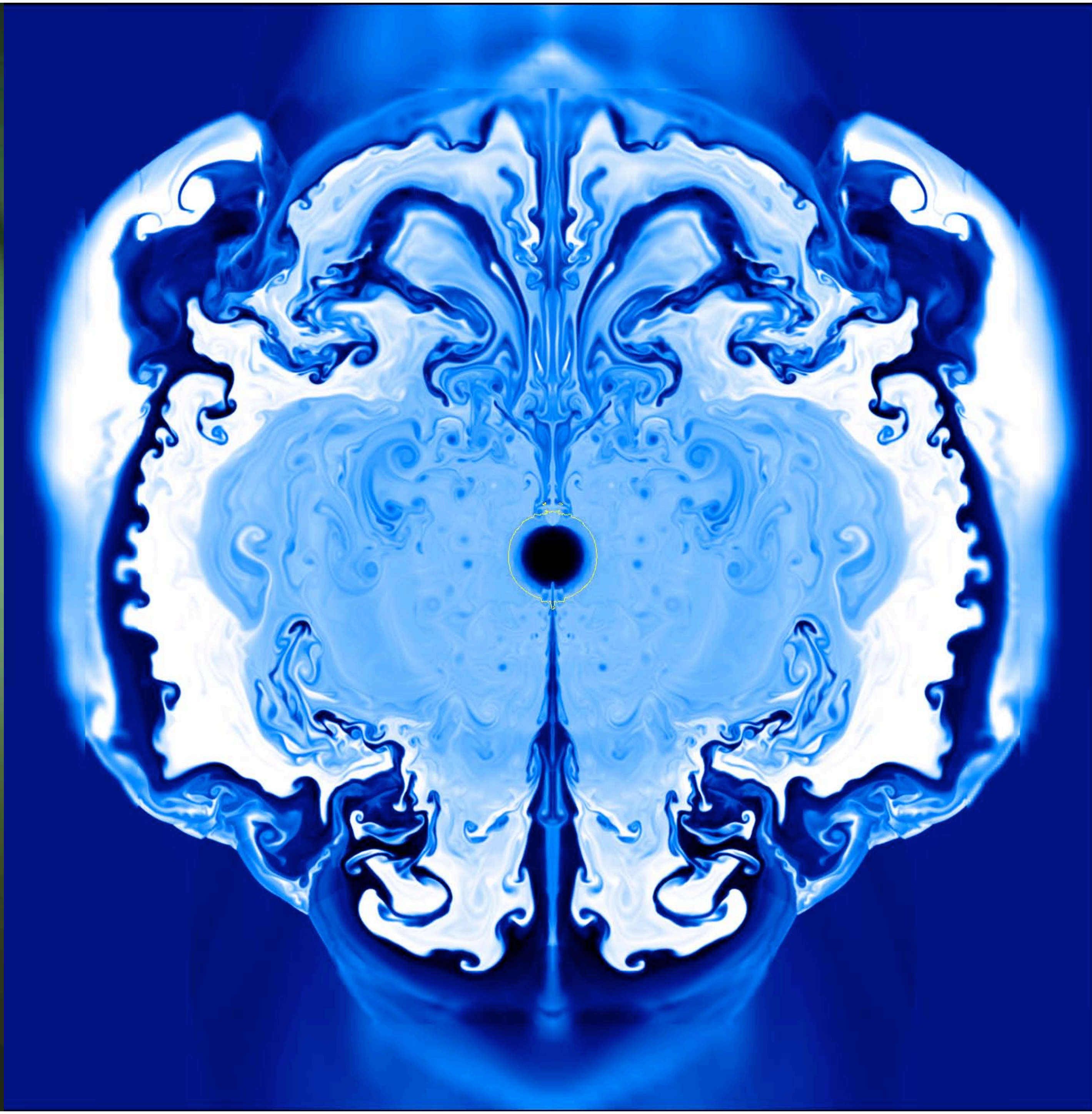
Sample Block Grid Structures of CASTRO: Pre-collapse, Post-bounce



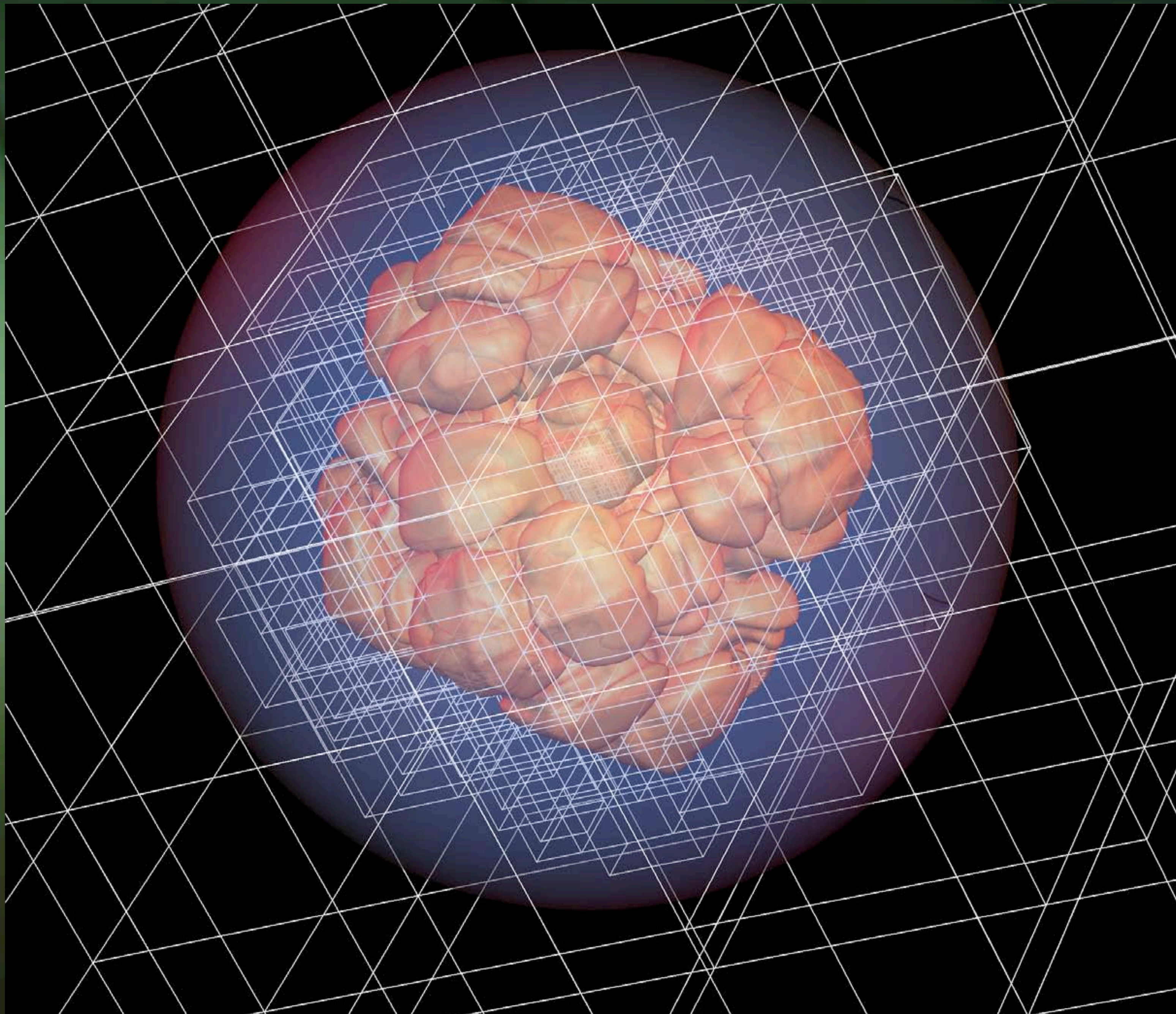


See Jason's poster!

2D:

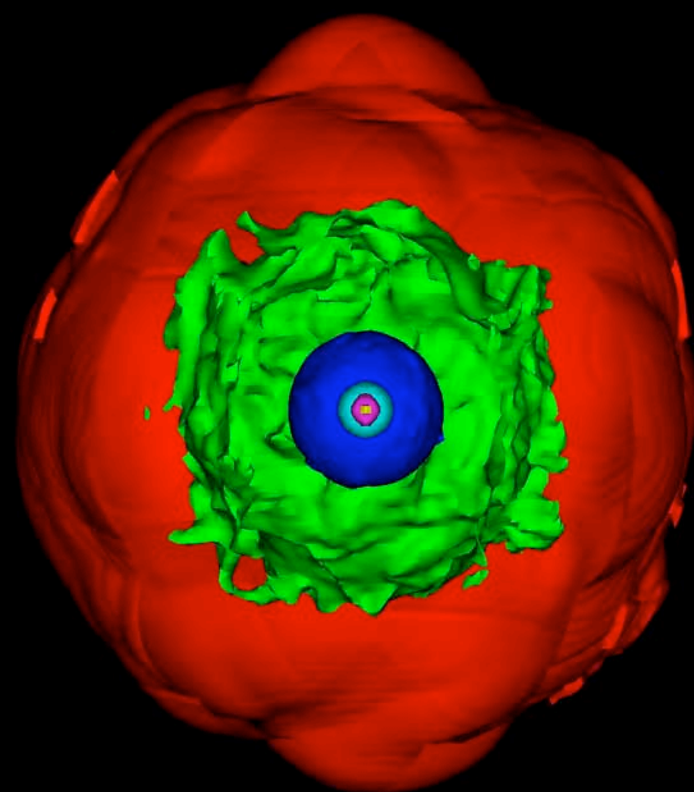


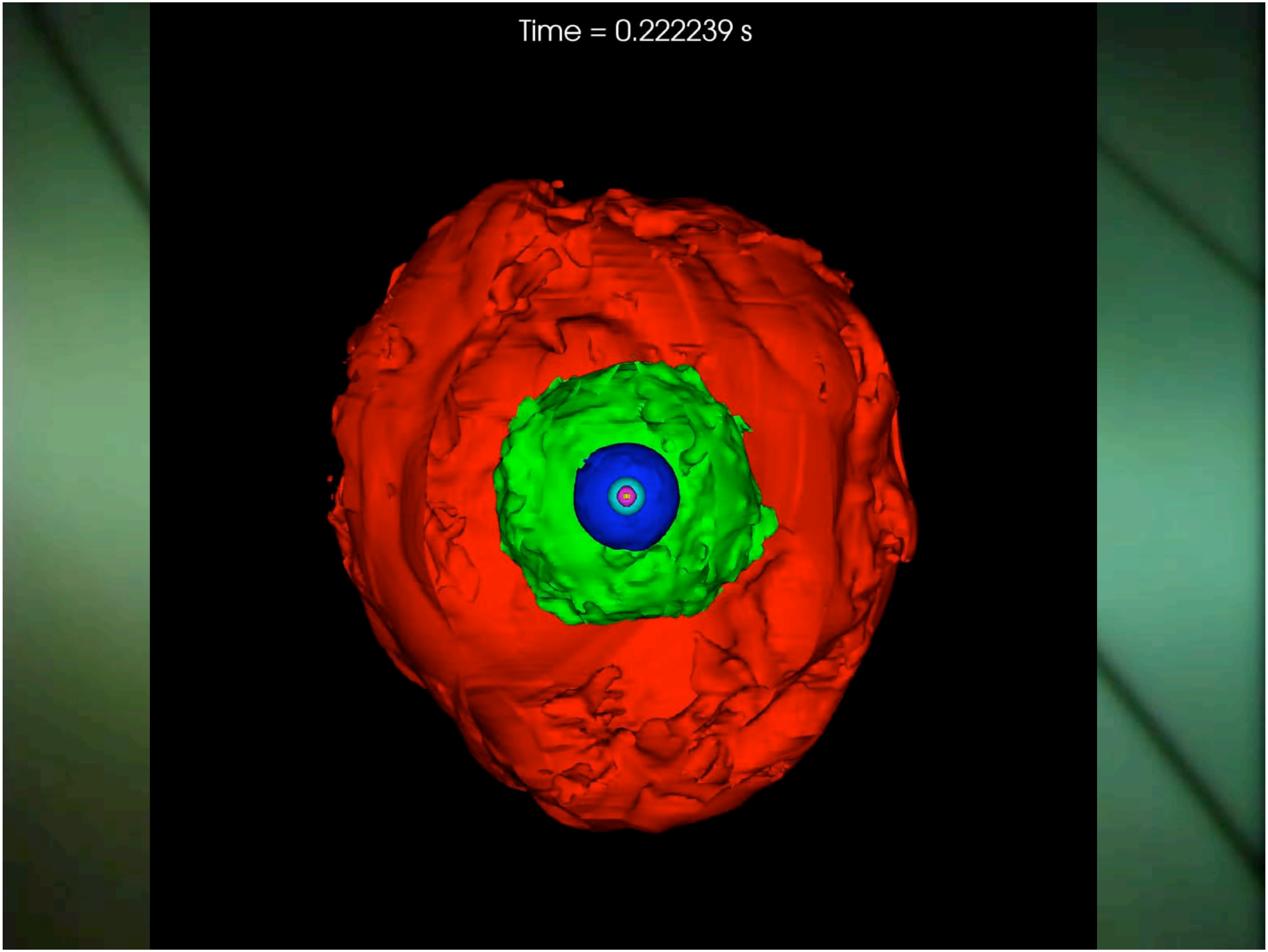
CASTRO 3D AMR Mesh: Explosion Model



Time = 0.098226 s

No Neutrino heating, stalled shock test

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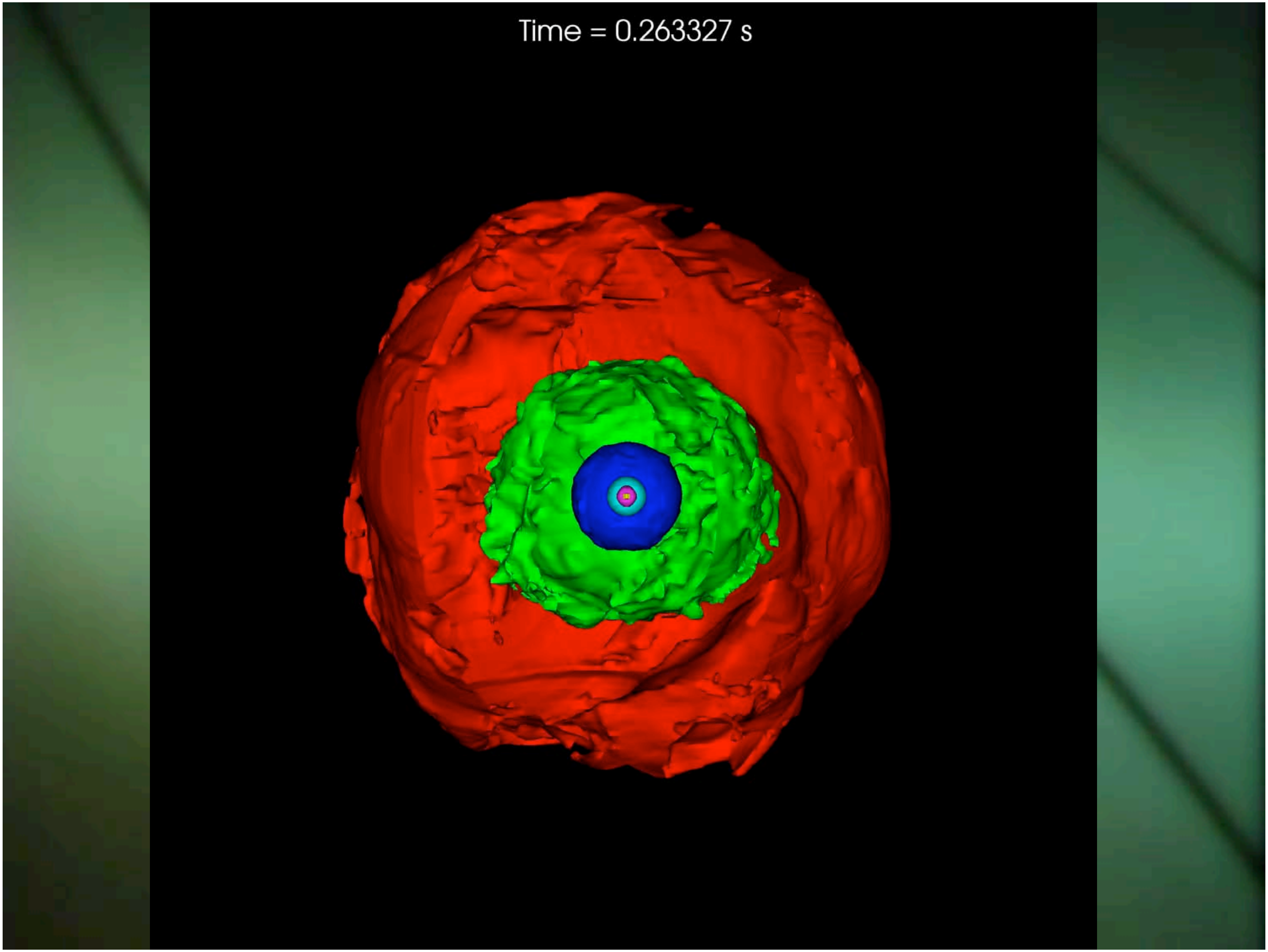
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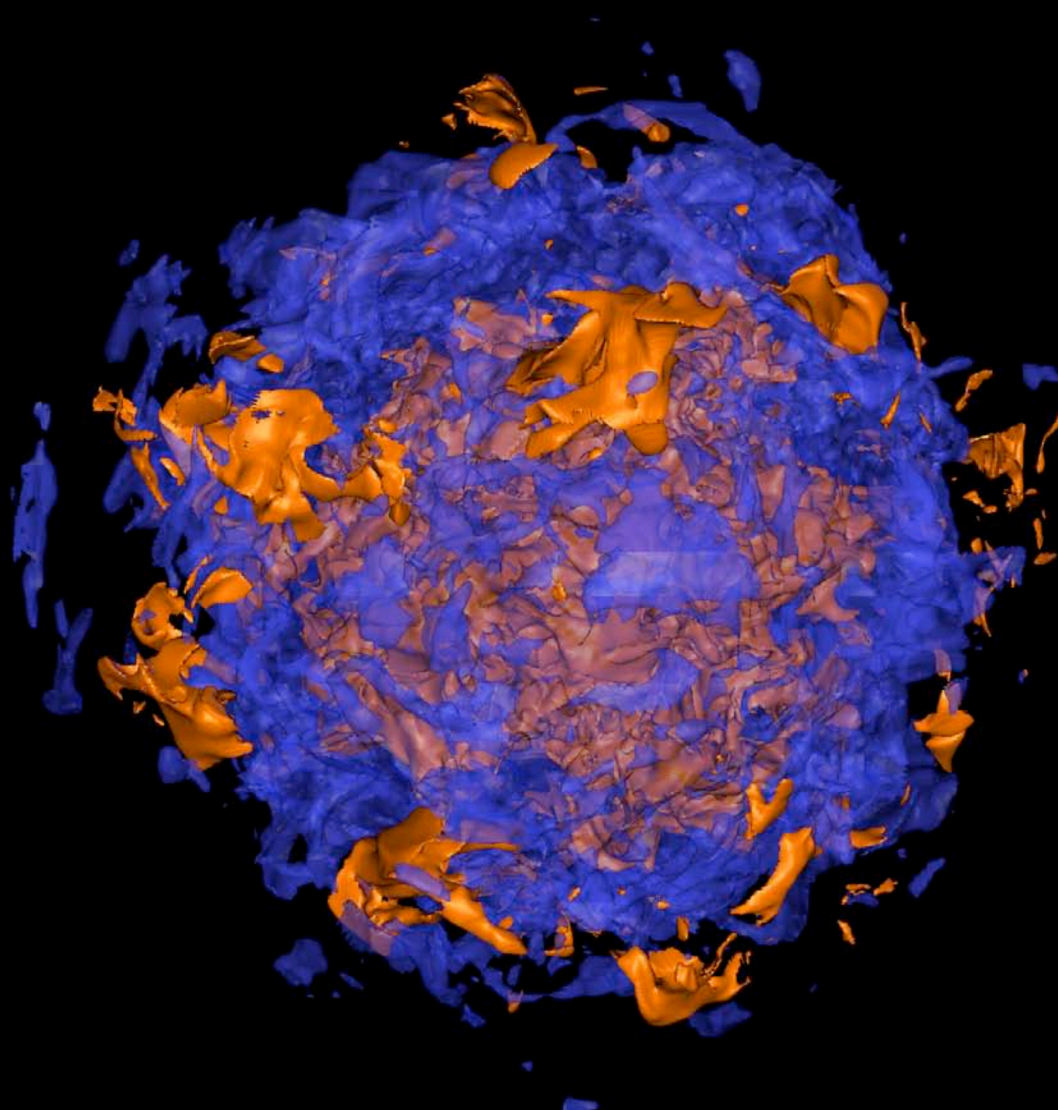
CASTRO 3D AMR No-Explosion Model



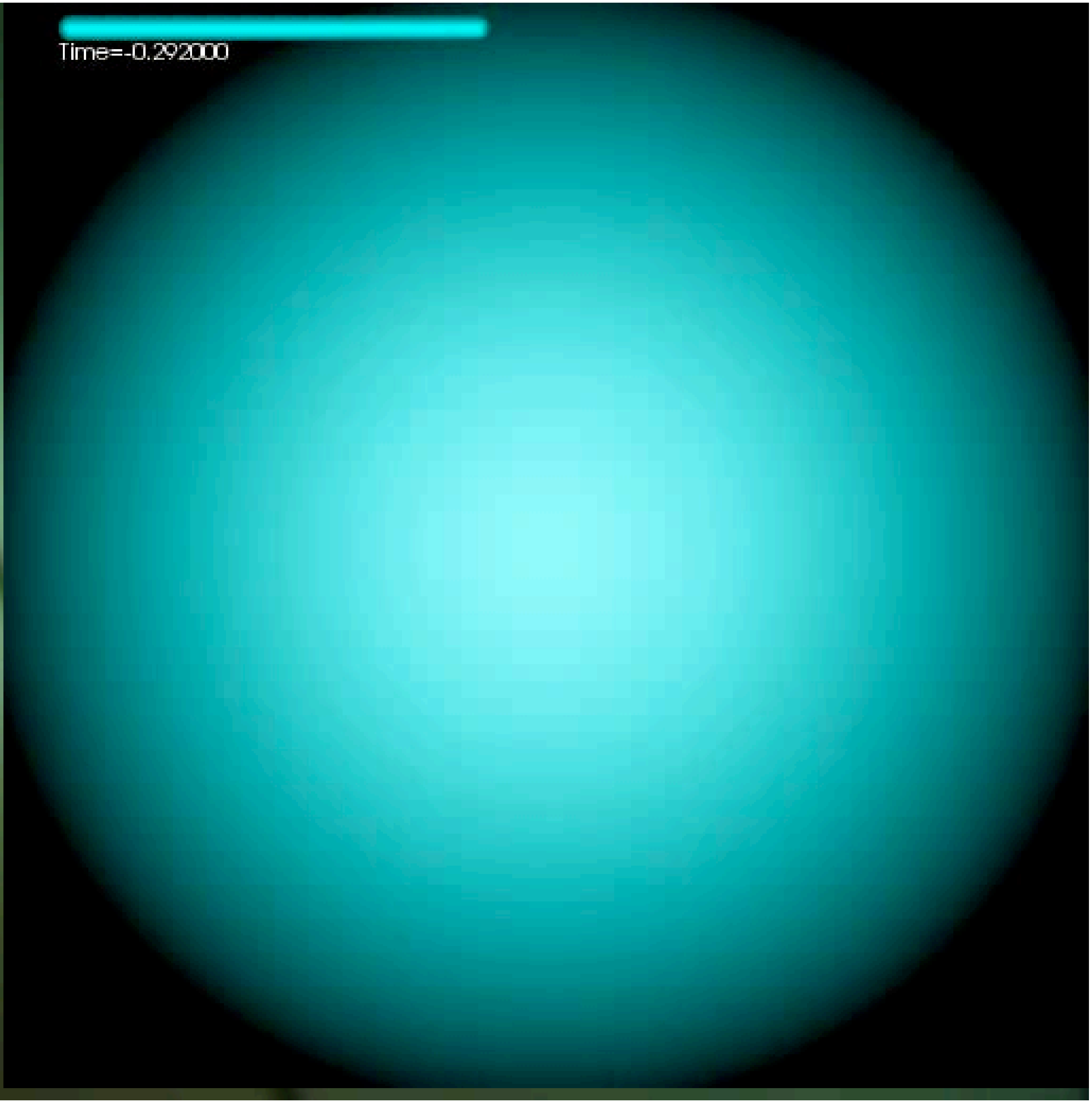
Entropy:

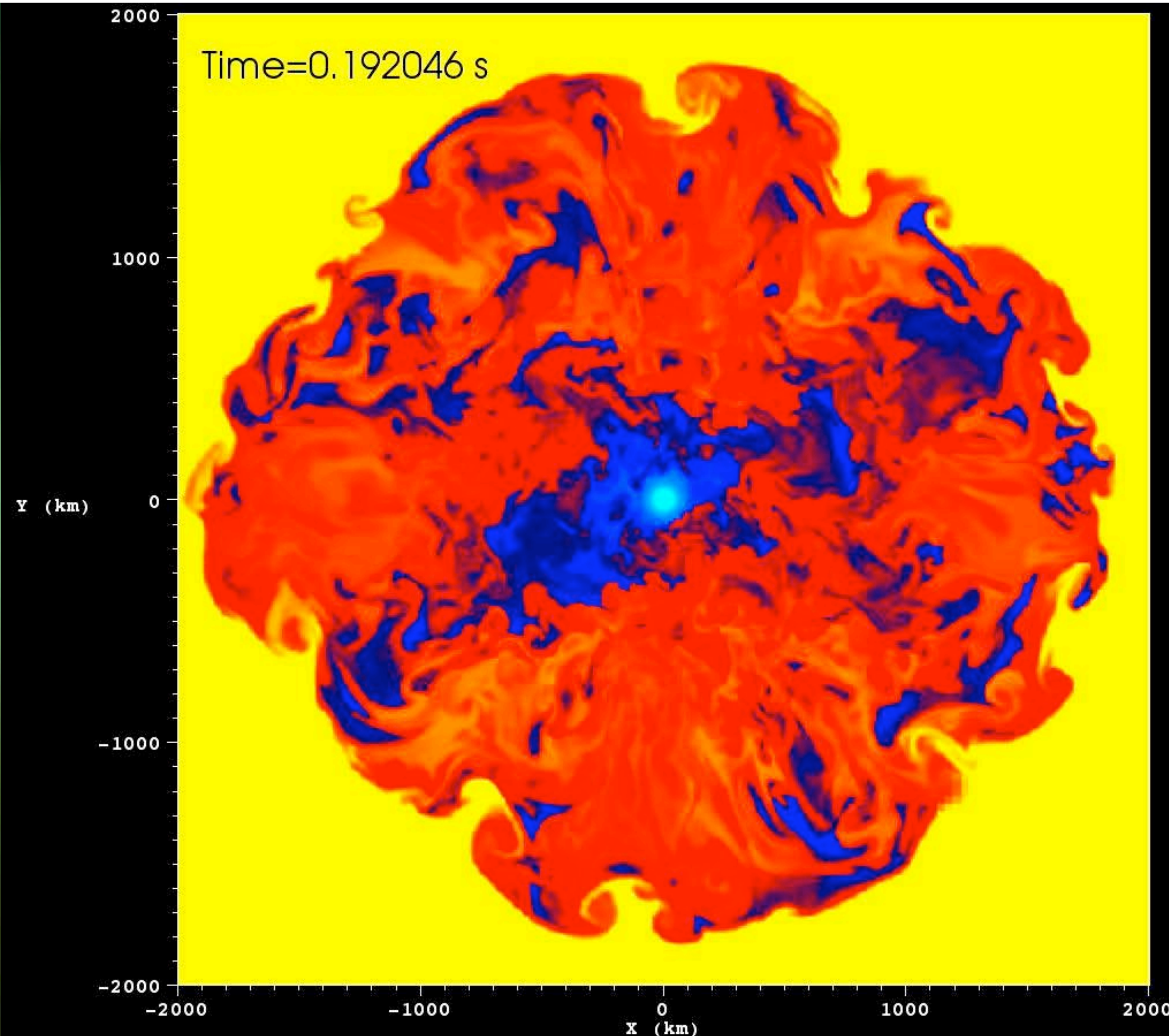
CASTRO 3D AMR Core-Collapse -- No Explosion Model

Little evidence of fast induced rotation; (see also Iwakami et al. 2009);

Blondin and Mezzacappa 2007?:

A bit of rotation (on the outside), but…

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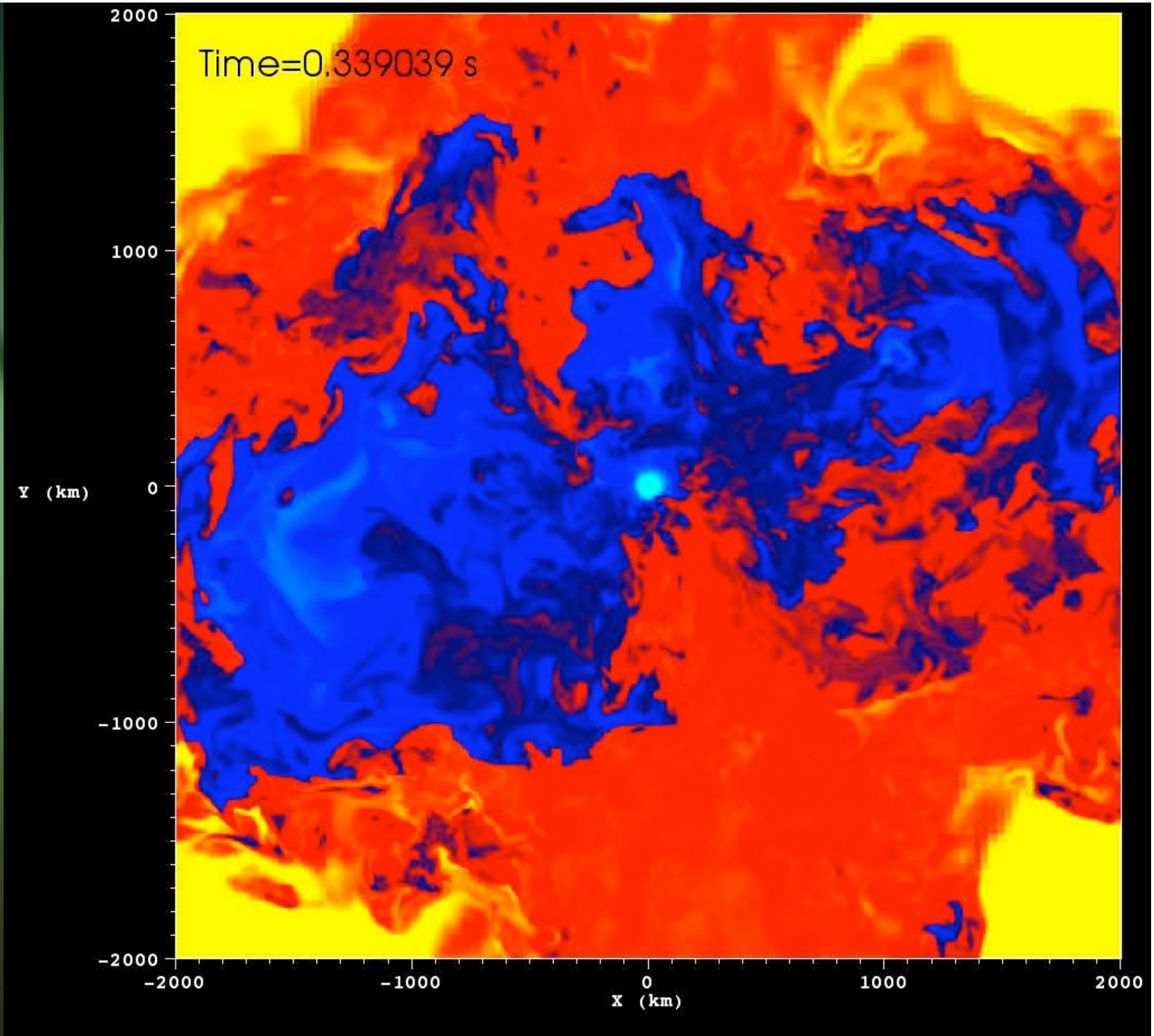
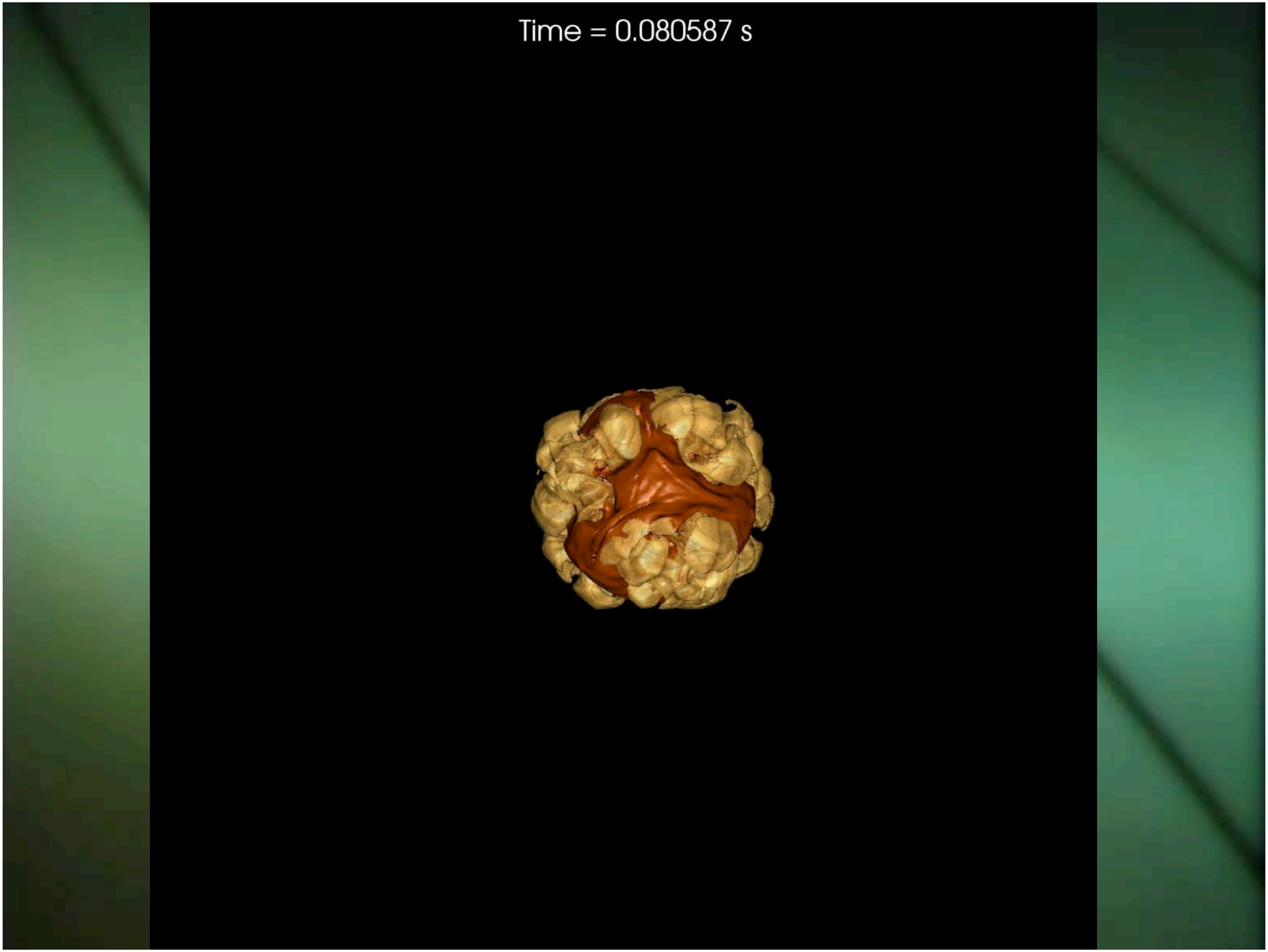
2000
1000
0
-1000
-2000
Y (km)
-2000
-1000
0
1000
2000
X (km)

CASTRO 3D AMR Core-Collapse -- Explosion Model

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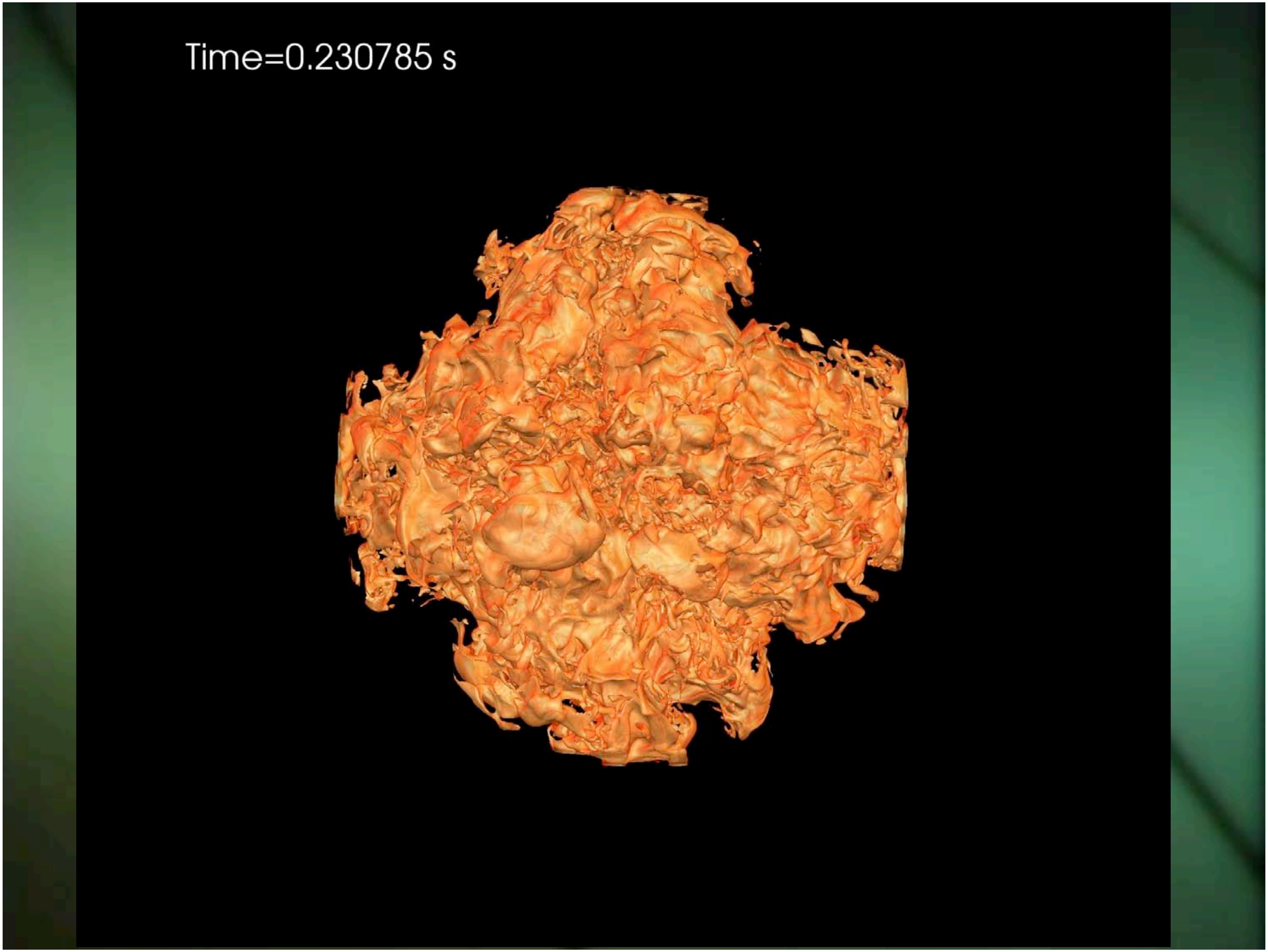
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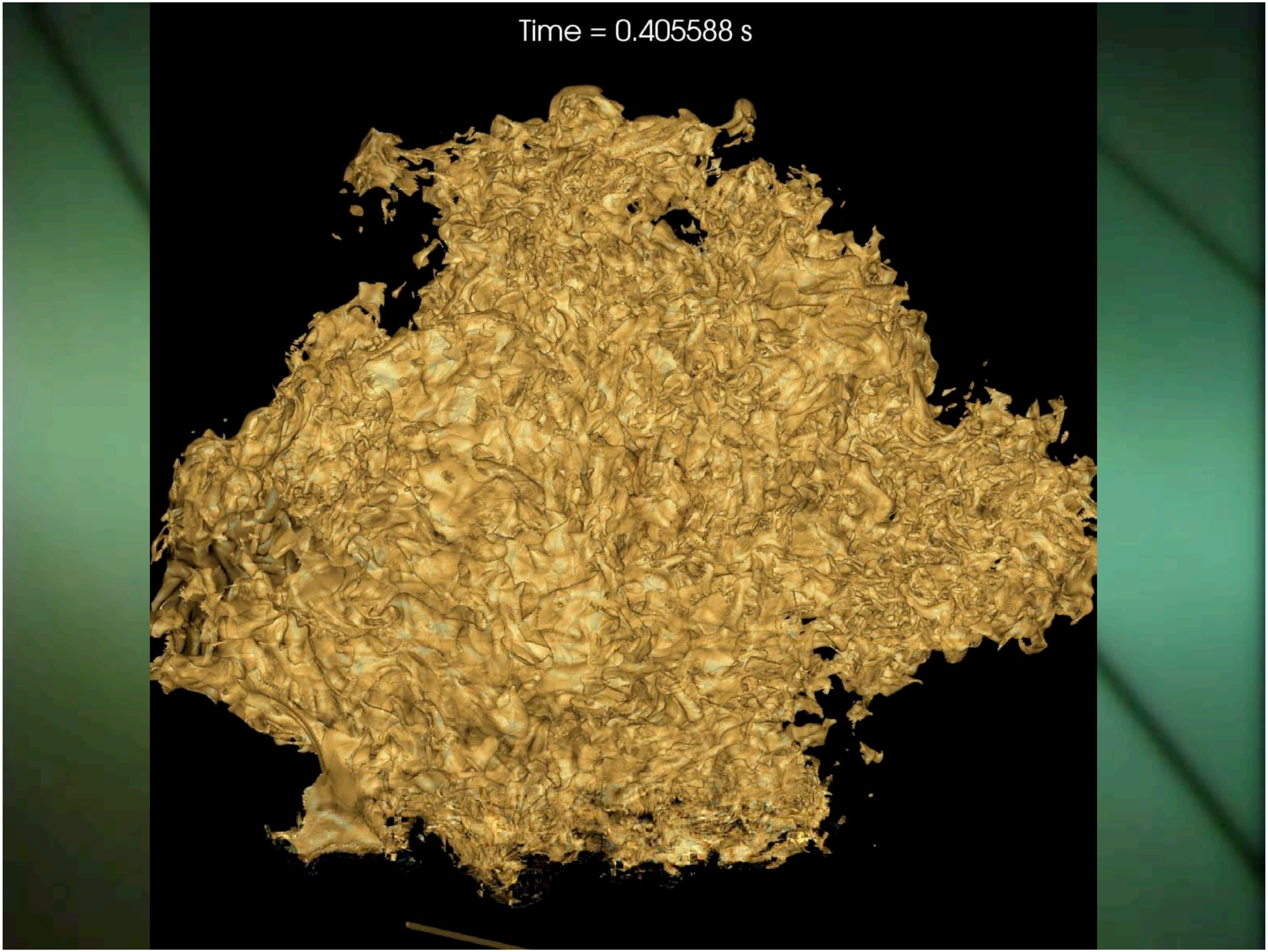
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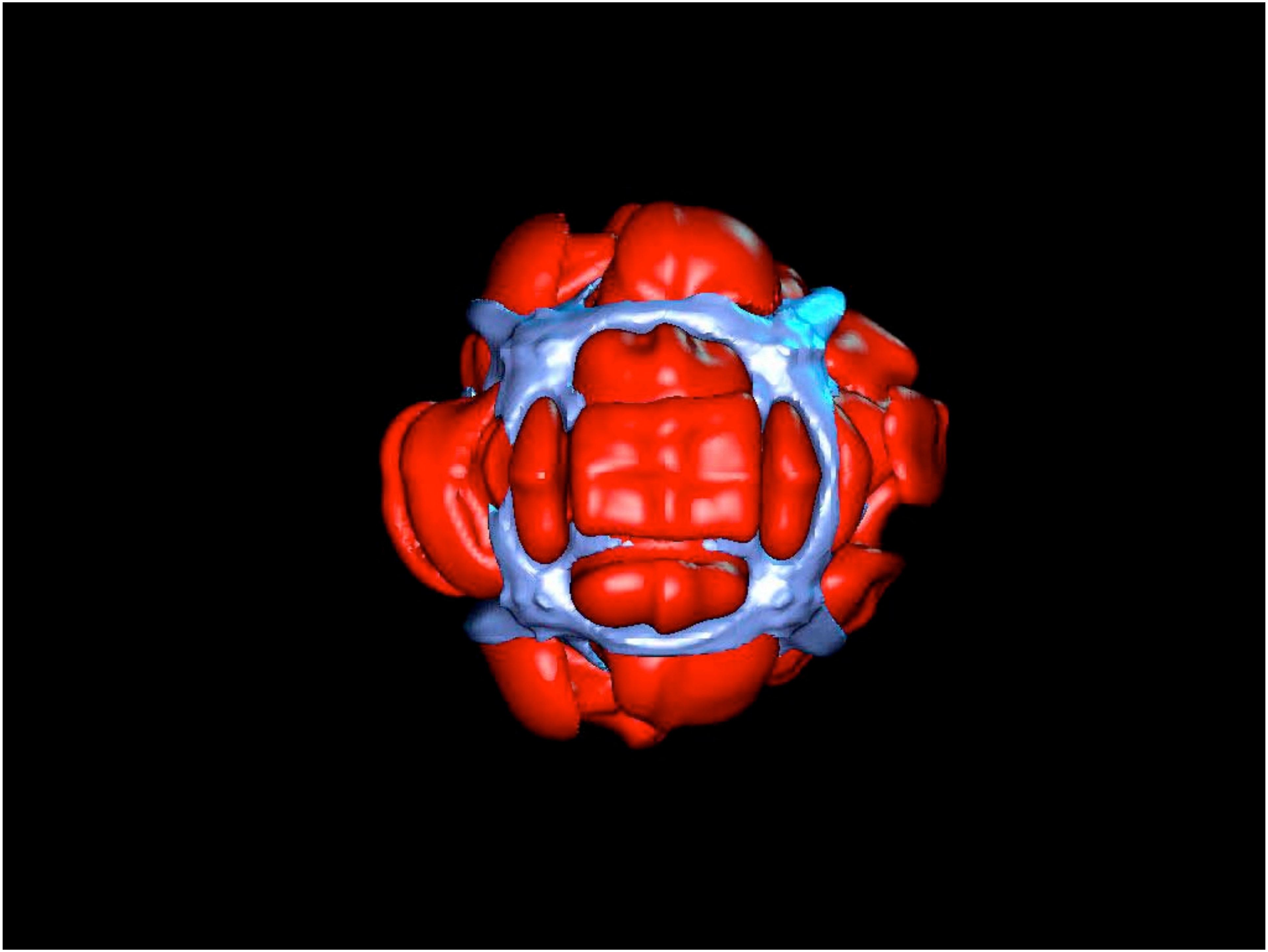
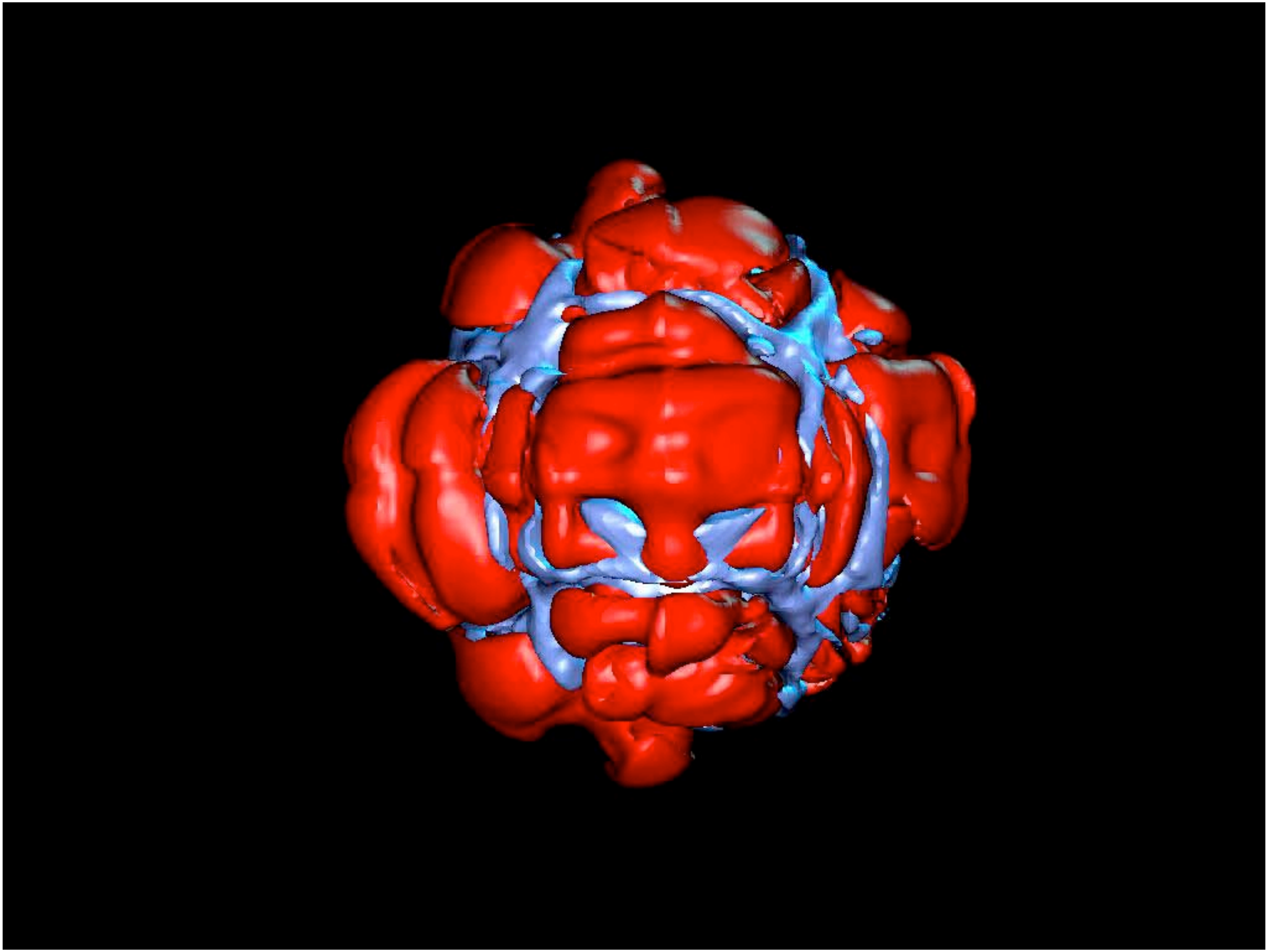
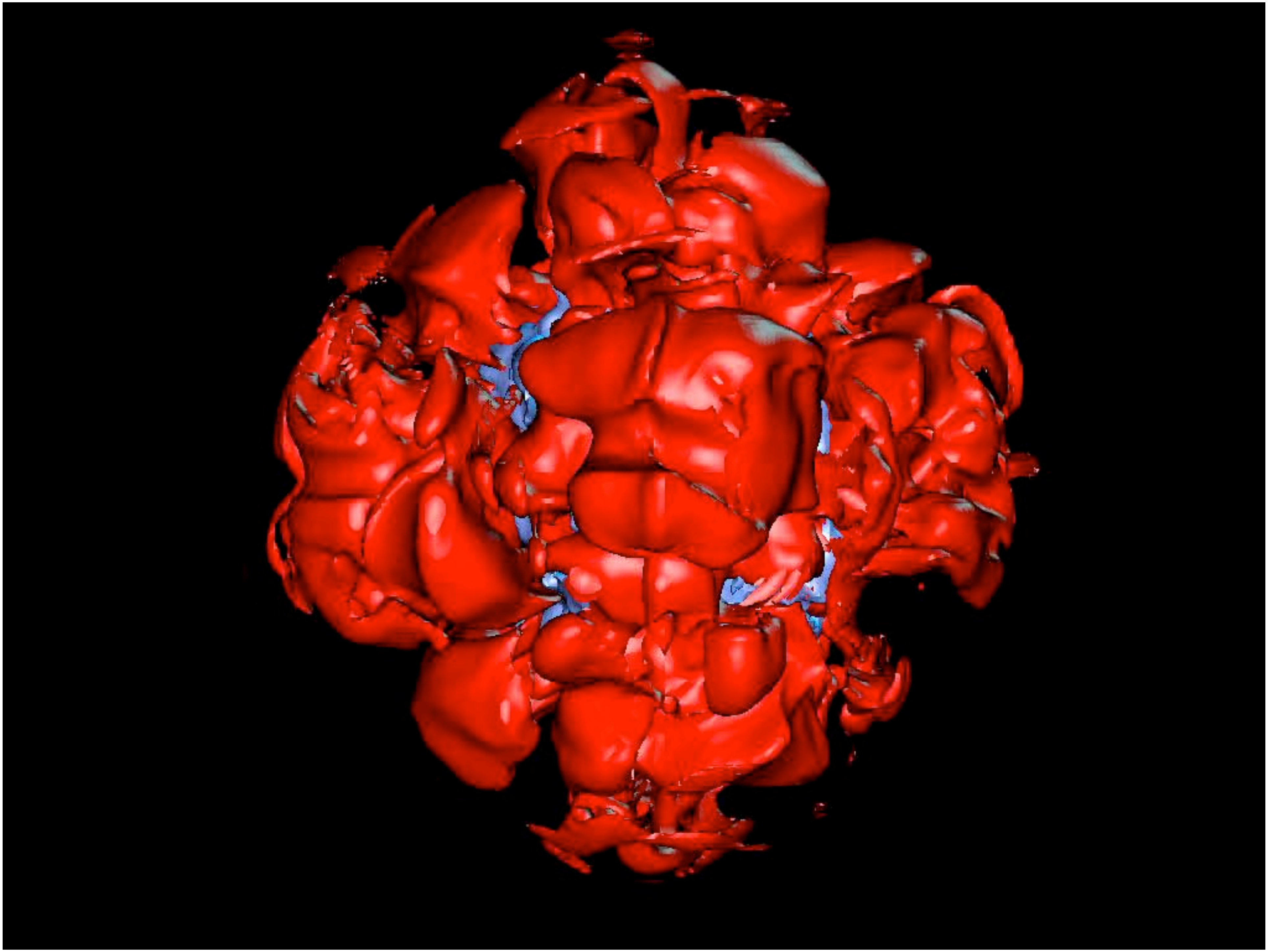
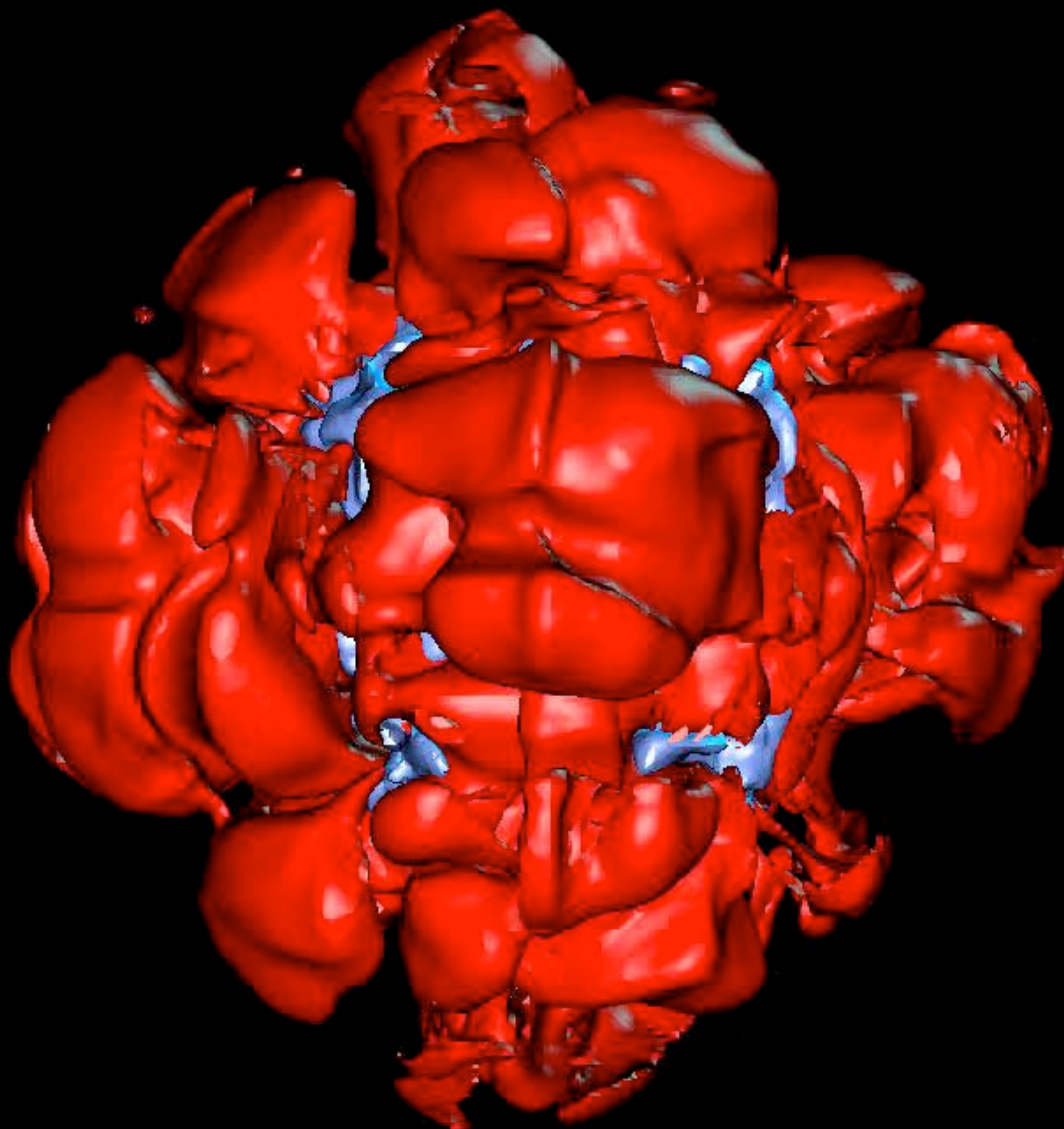
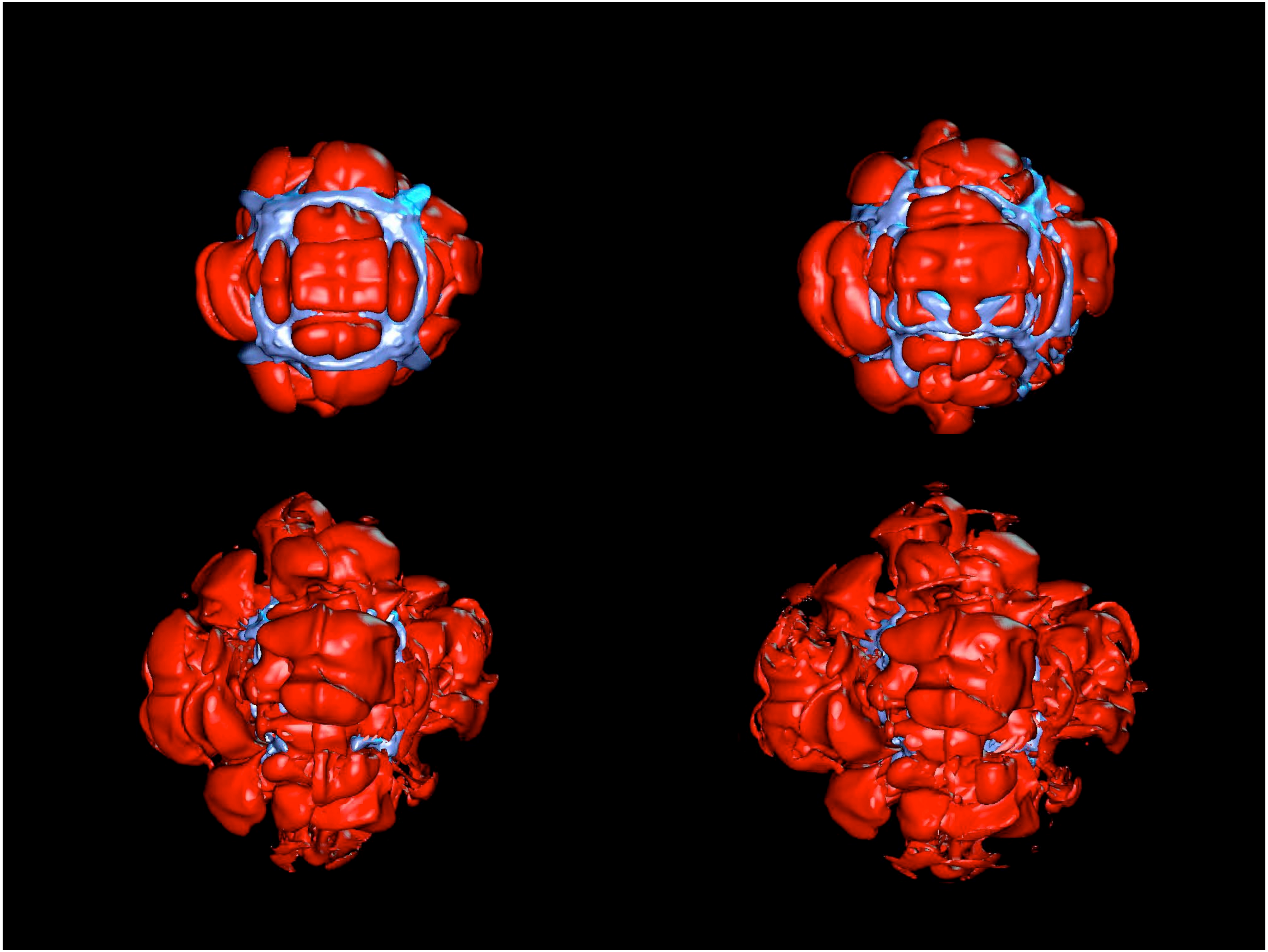


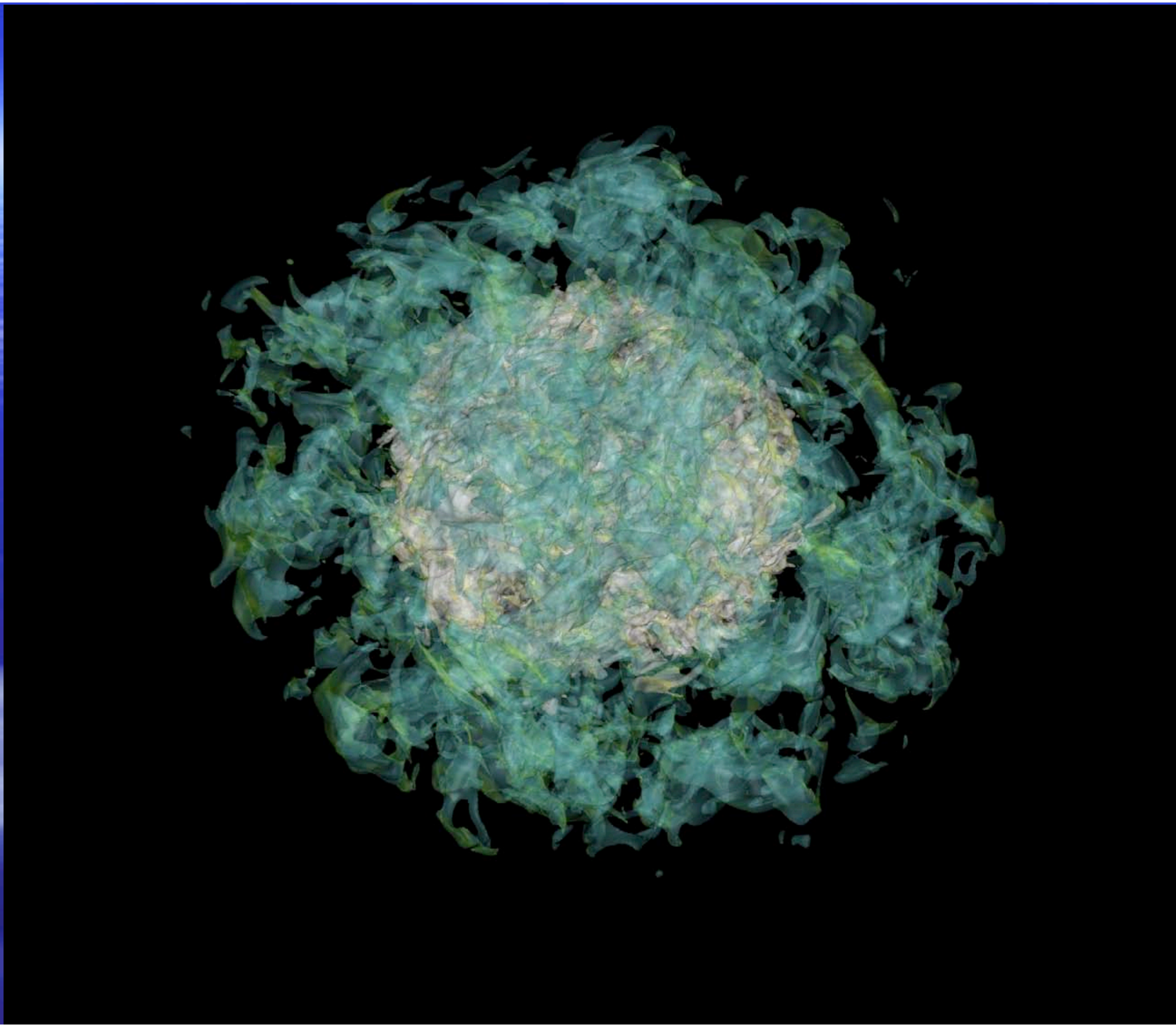


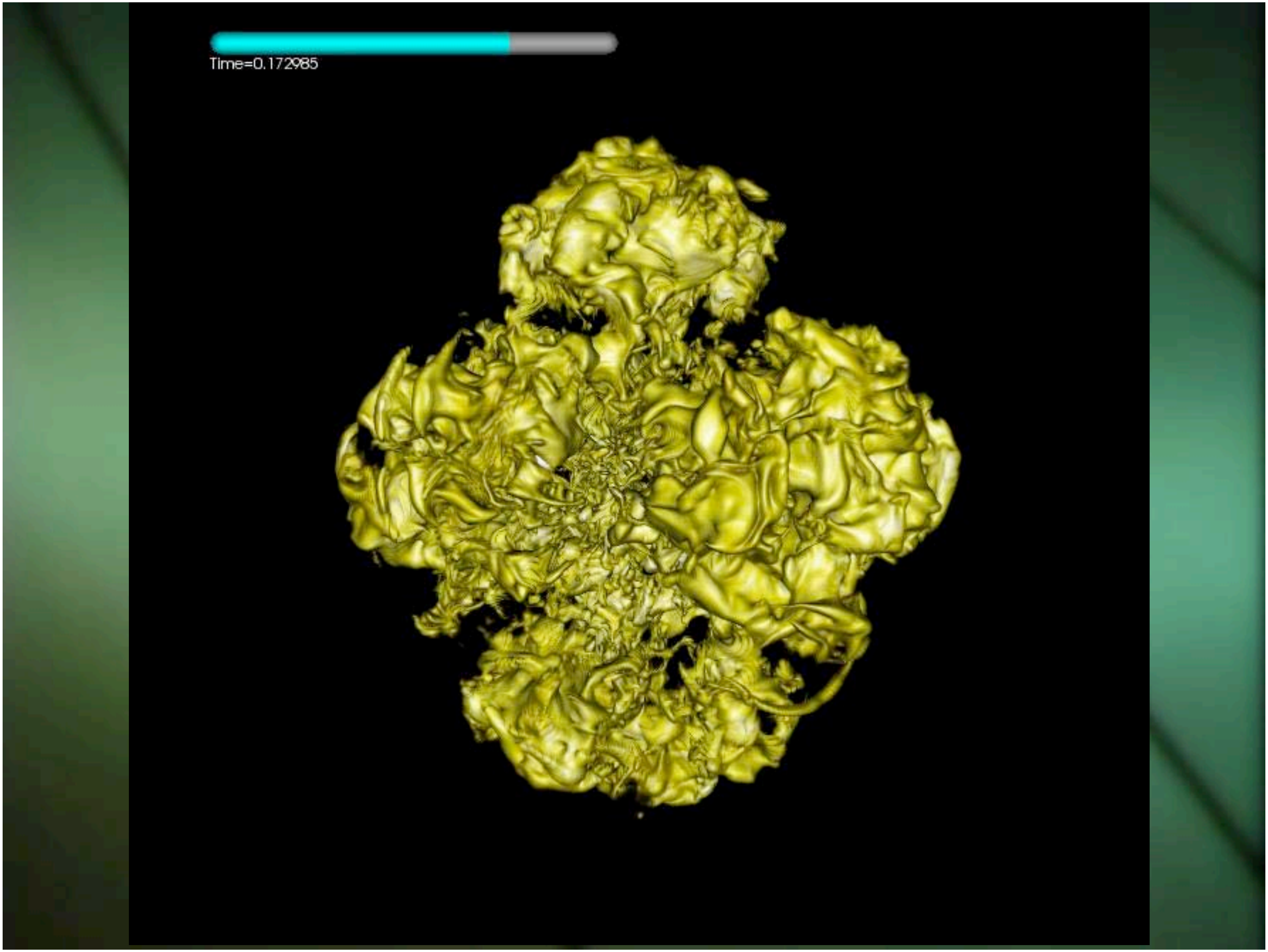


CASTRO 3D AMR Neutrino-driven Explosion Model





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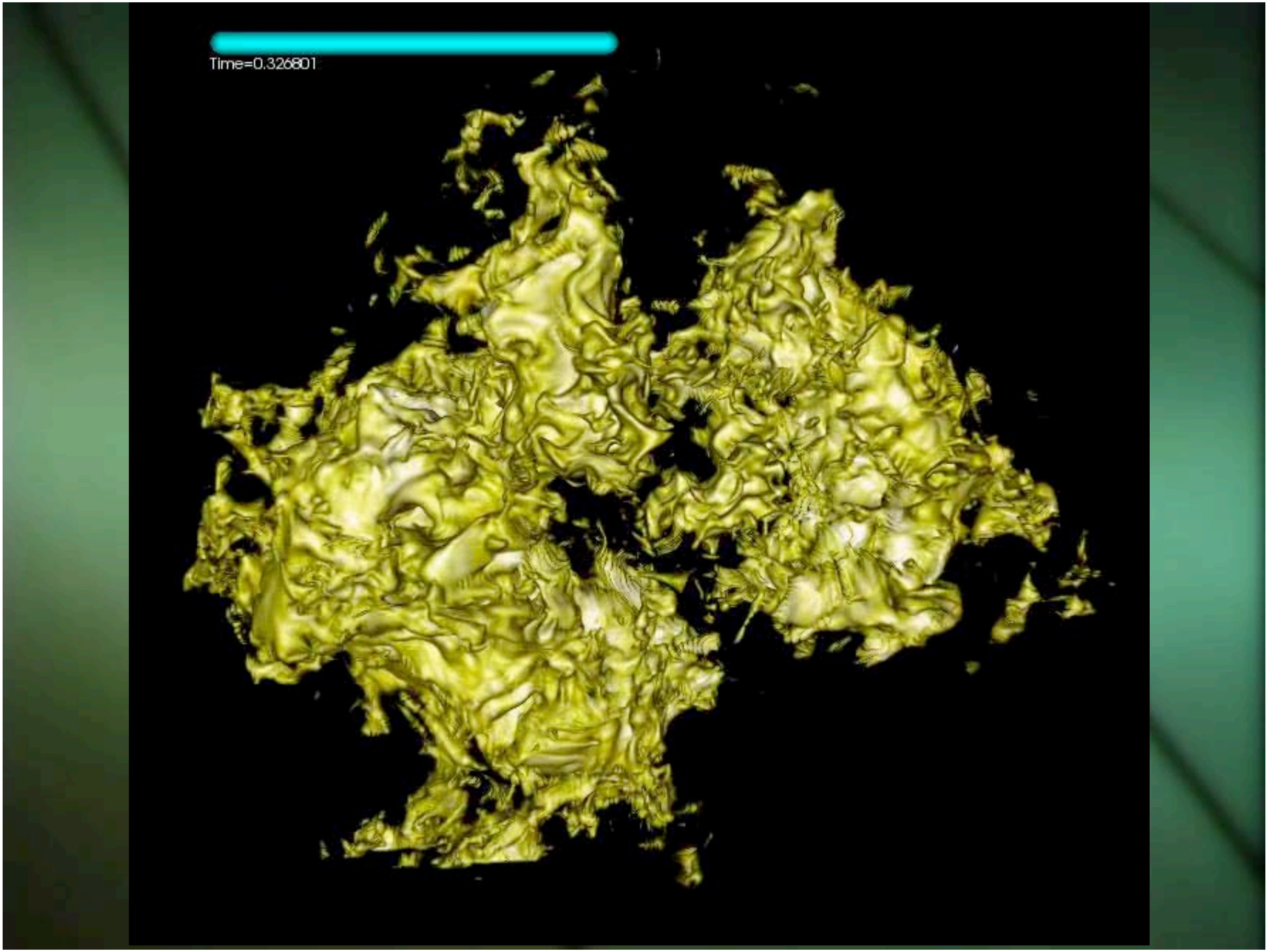
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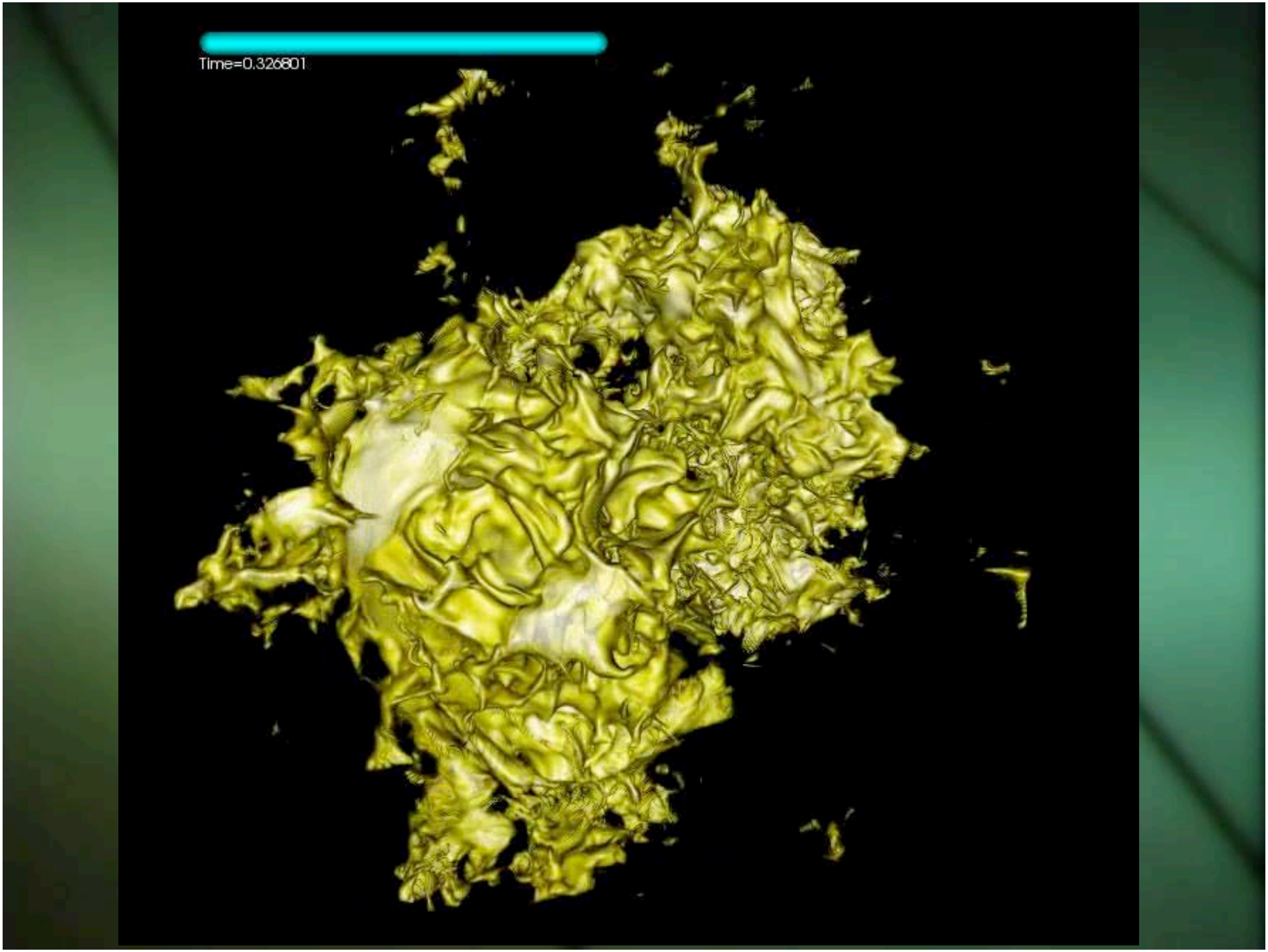
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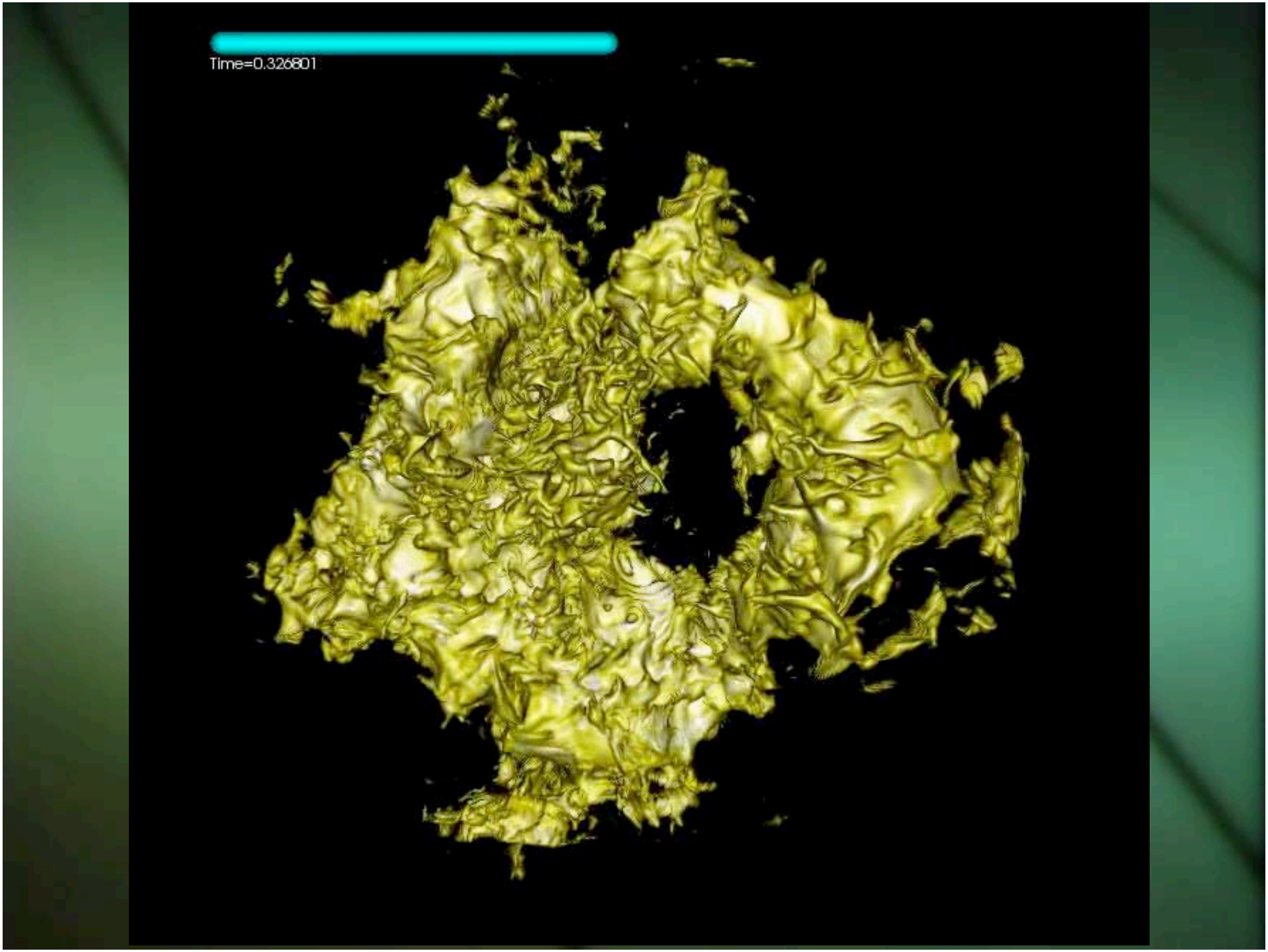
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Core-Collapse Theory: A Status Summary

- Multi-D is Key Enabler of explosion for all viable mechanisms
- Progenitor structure crucial
- Multi-D allows simultaneous explosion and accretion (not possible in 1D)
- Neutrino mechanism: 3D(?) > 2D > 1D - Critical condition
- Neutrino Mechanism marginal/ambiguous in 2D; Need to go to 3D !?
- Neutrino-driven convection > SASI
- Pulsar Kicks are Simple Recoils in Multi-D context
- MHD explosion models require rapid rotation (rare); hypernovae? < 2×10^{52} ergs
- GRBs may be preceded by Non-Rel. precursor jets launched during PNS phase