What the Emerging Theory of Core-Collapse Supernova Explosions May Say About the Morphology of Their Remnants

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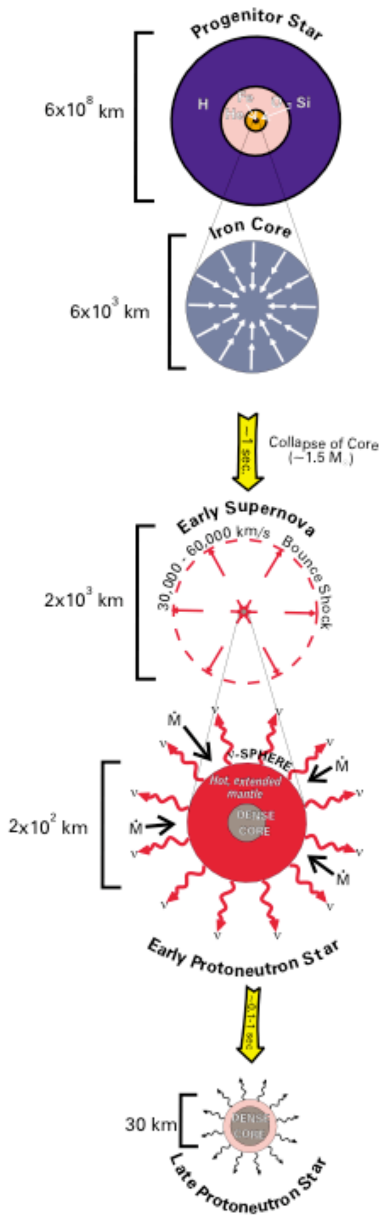
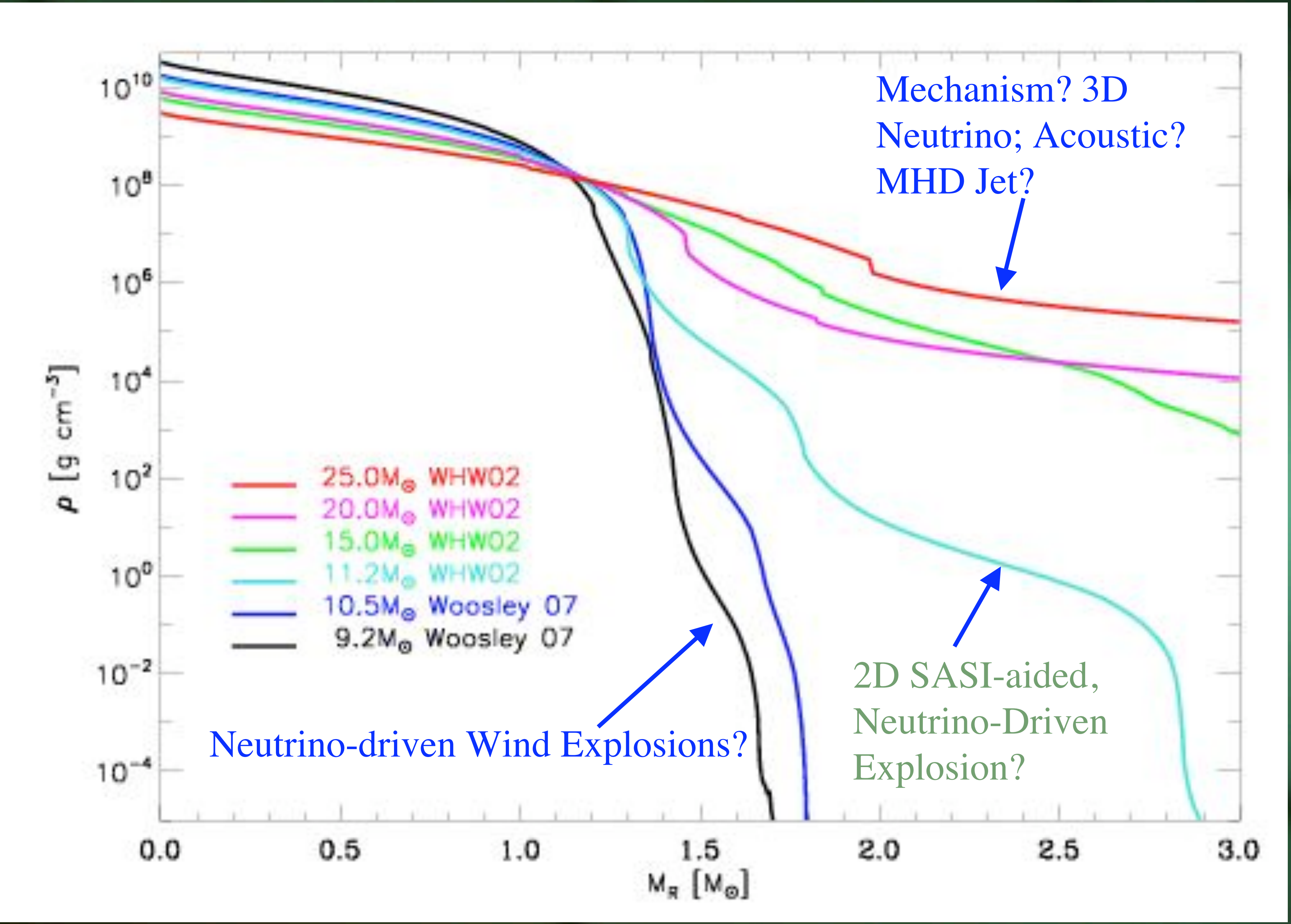
Important Questions in Supernova Theory

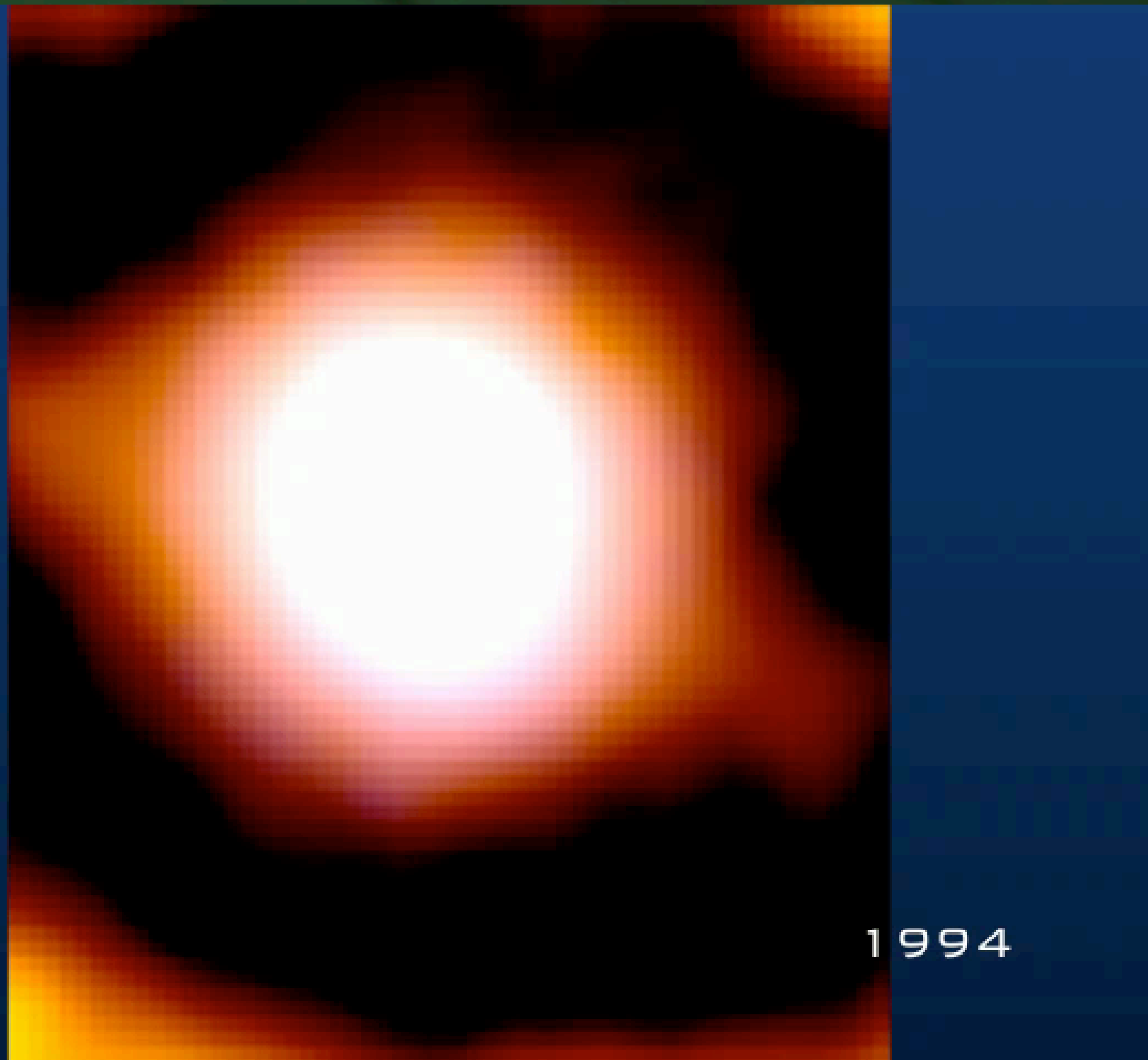
- Mechanism of explosion?
- Pulsar Kicks (proper motions)?
- Nucleosynthesis: Nickel, etc. Yields?
- R-process site?
- Blast Morphology (and polarization)?
- Pulsar Spins?
- Pulsar/AXP/Magnetar B-fields?
- Black Hole formation?
- Systematics with progenitor (and role of rotation/magnetic fields)?
- Connection with GRBs and Hypernovae?


Progenitor Star
6x10⁸ km
H
Si
Iron Core
6x10³ km
~1 sec.
Collapse of Core
(~1.5 M☉)
Early Supernova
30,000 - 60,000 km/s
Bounce Shock
2x10³ km
ν-SPHERE
Hot, extended mantle
DENSE CORE
2x10² km
Early Protoneutron Star
30 km
DENSE CORE
Late Protoneutron Star

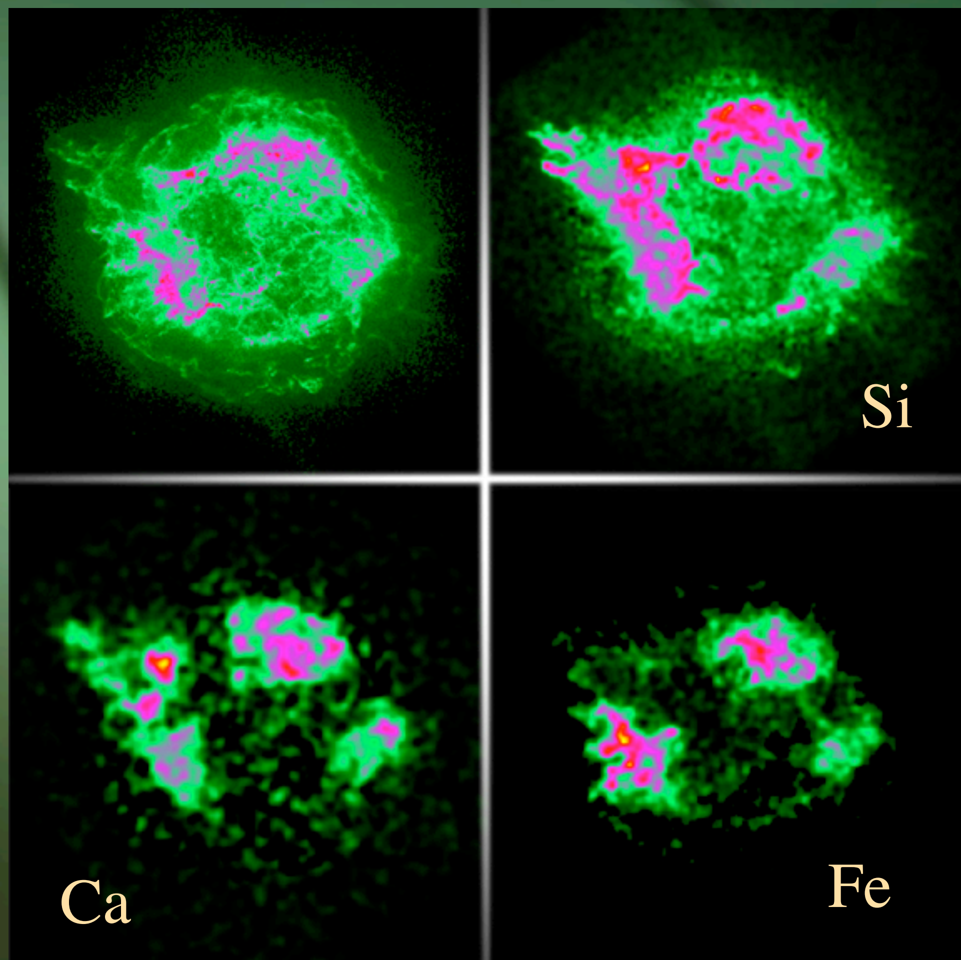
Density Profiles of Supernova Progenitor Cores



SN1987a (Pete Challis)



Observed Asymmetry

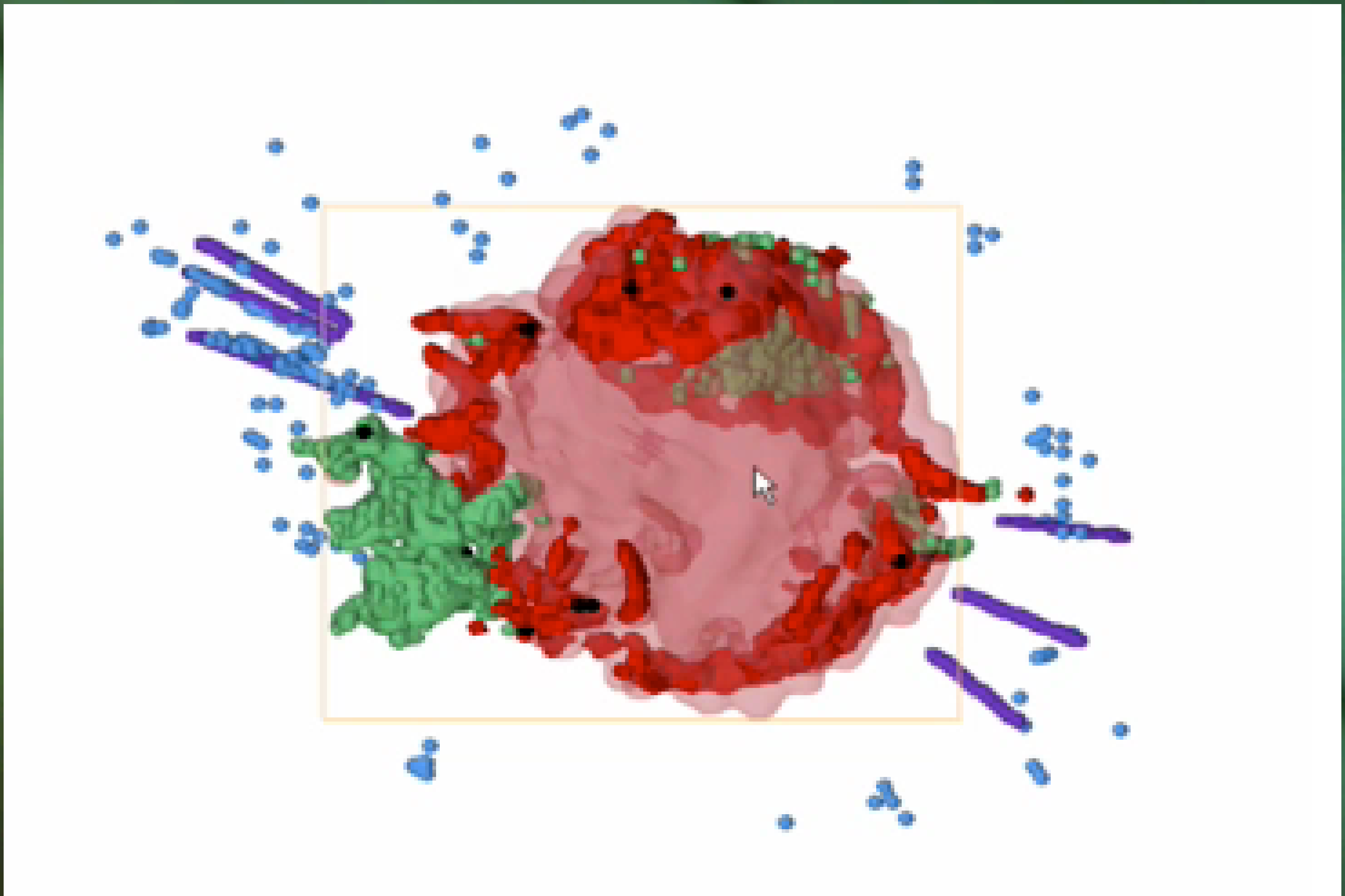


Cas A SN Remnant: Chandra

Element Asymmetries in Cas A Remnant

Fe

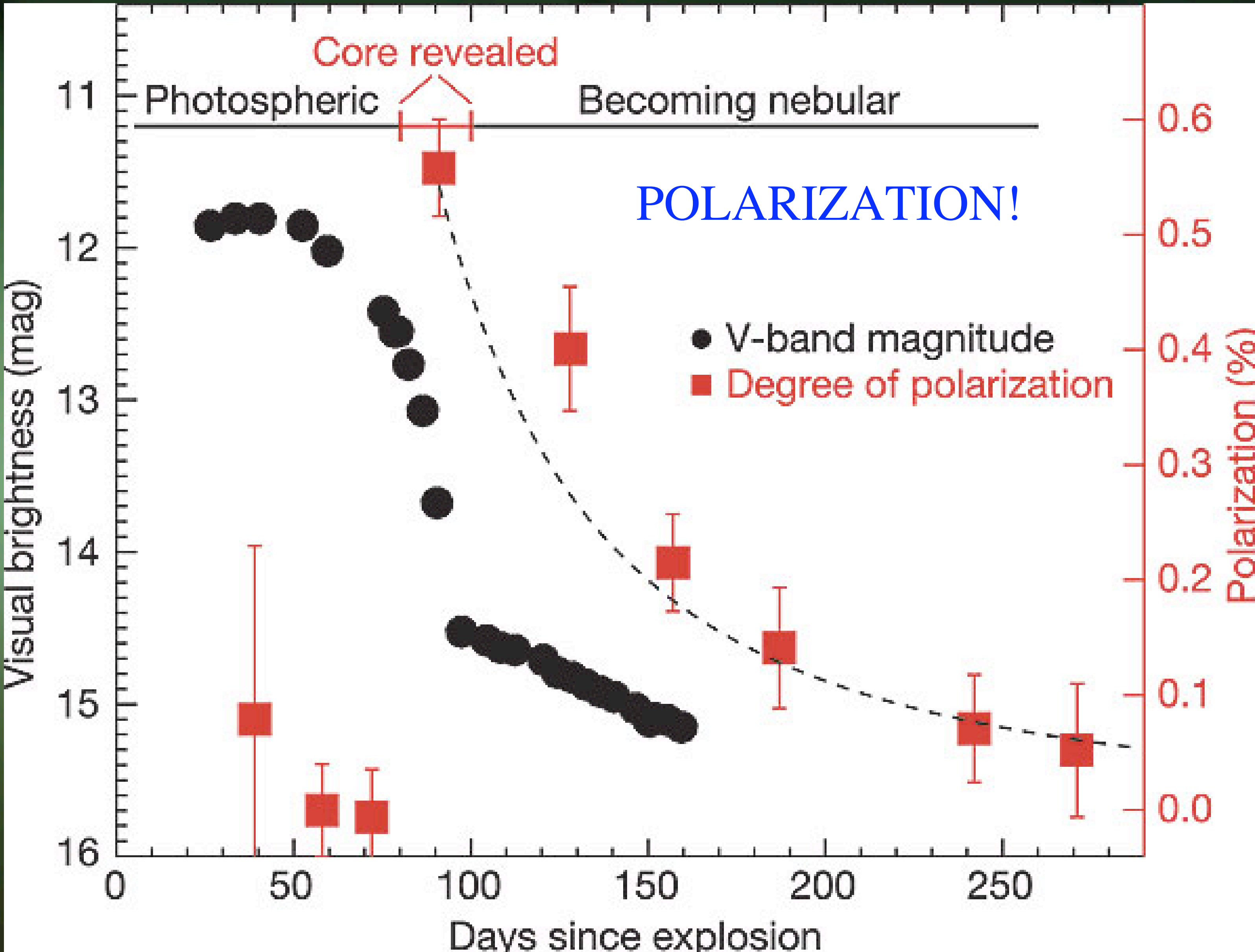
Si



DeLaney et al. 2009

Asymmetries in Supernovae and Remnants (cont.)

- G11.2-0.3 remnant: Dense Fe Ejecta in Near IR - Asymmetrical line profiles (Moon et al. 2008)
- OI Doublet line shapes for many CCSN (e.g., SN 2007gr, SN 2007rz, SN 2007uy, SN 2008ax, SN 2008bo) evidence for asphericities (Milisavljevic et al. 2009)
- Ejecta Asphericity in Type Ib/c (39 SNe): Overall asymmetries in OI in ~39%: Evidence of no "jet" in most (Taubenberger et al. 2008)
- SN 2005bf: Spectropolarimetry = Large Top-bottom Asymmetry in Fe distribution and non-Coplanarity - larger, later (M. Tanaka et al. 2009)



Leonard et al. 2006

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)

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

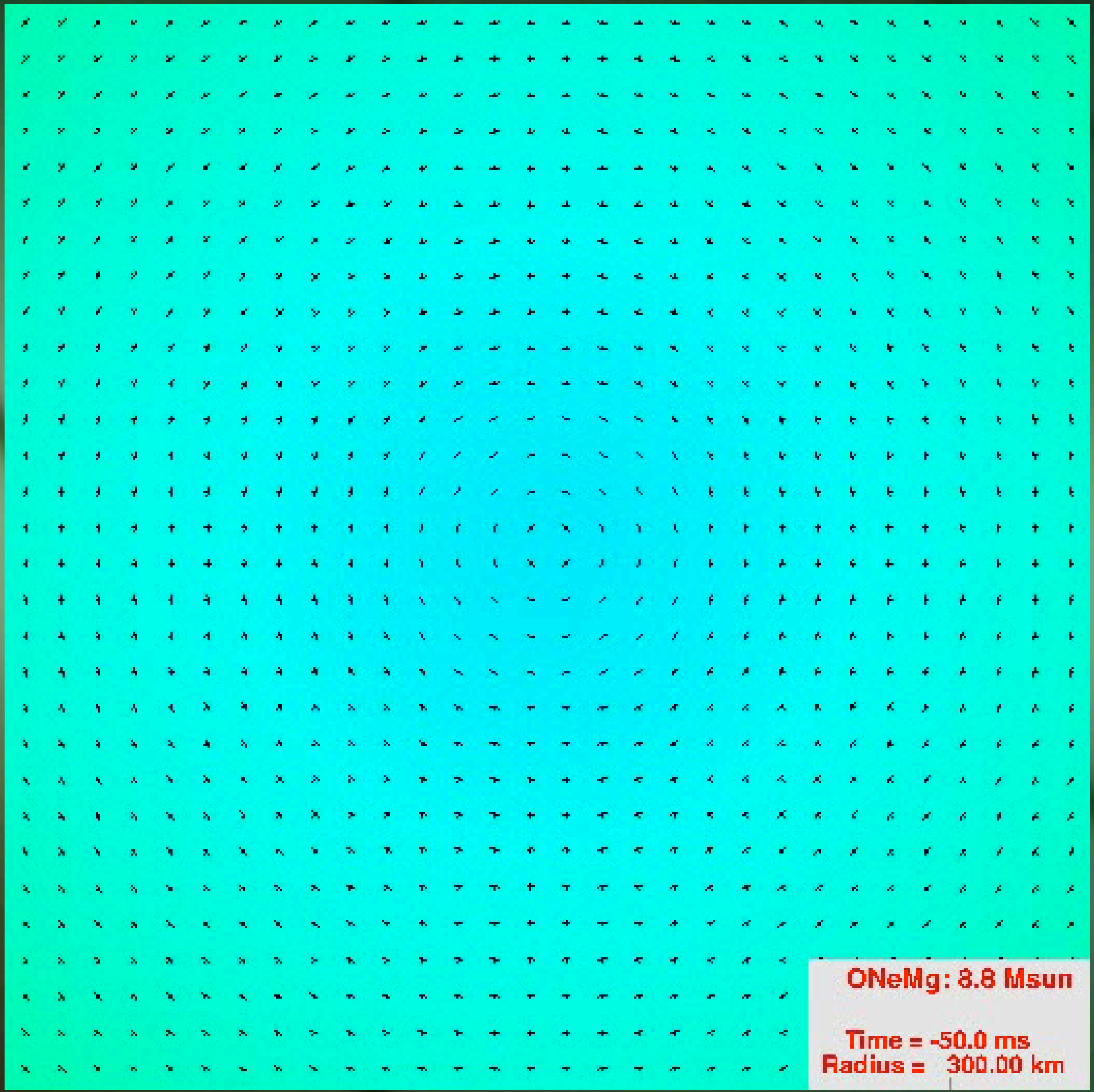
Neutrino-Driven Wind Explosions: Low Mass Progenitors

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

First shown by Kitaura et al. 2006

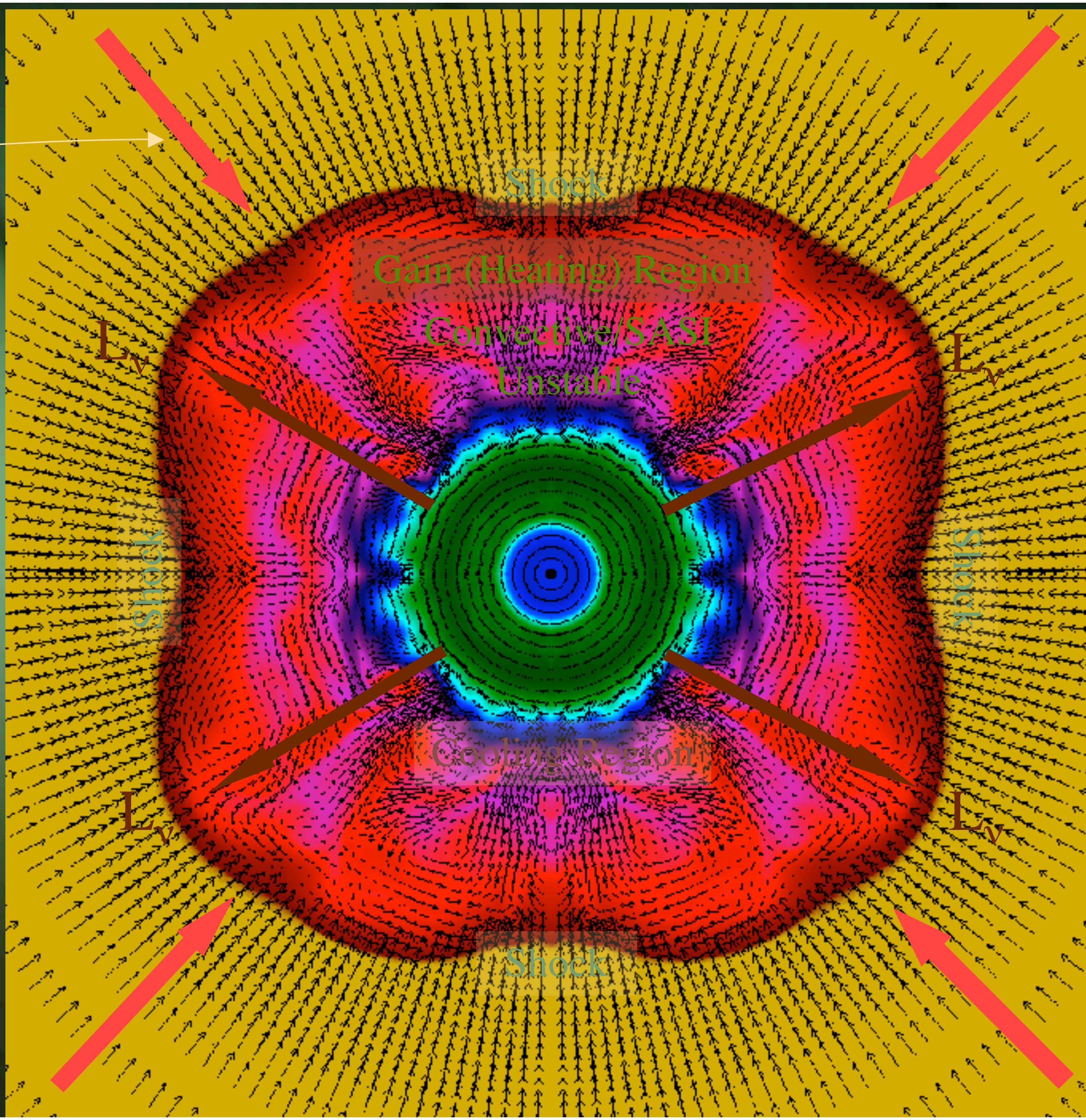
Burrows, Dessart, & Livne 2007;

Burrows 1987



NOTE WIND THAT FOLLOWS

$\dot{M}$



L_ν vs. $\dot{M}$

τ_{adv} vs. τ_H

(TQB 2005)

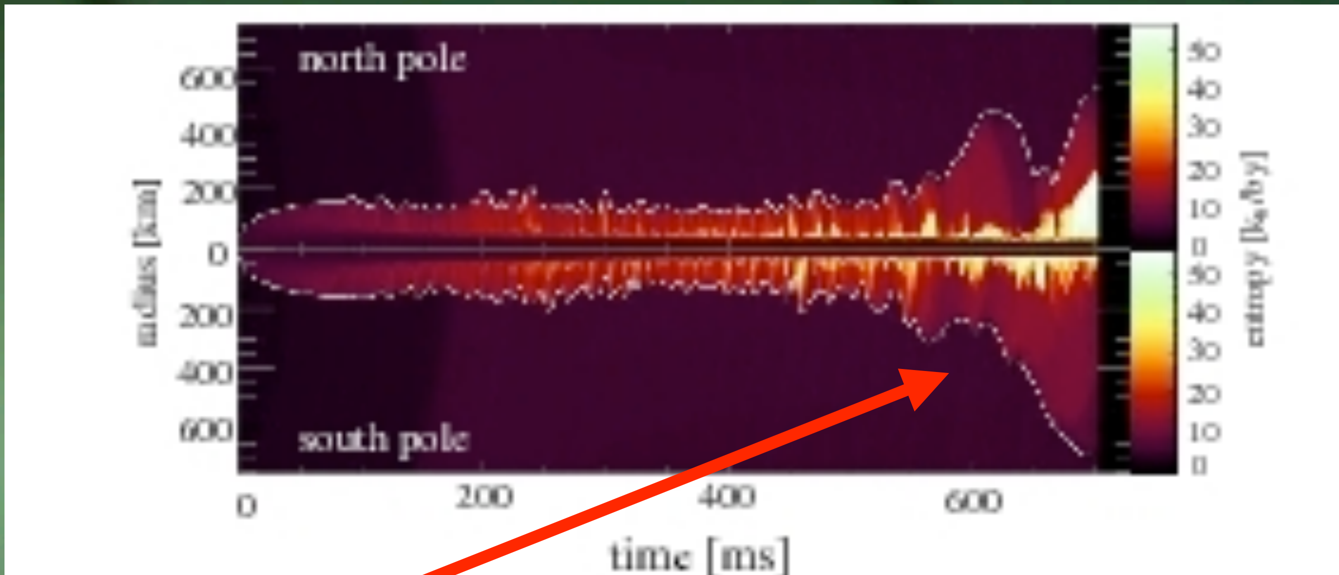
τ_{adv} :

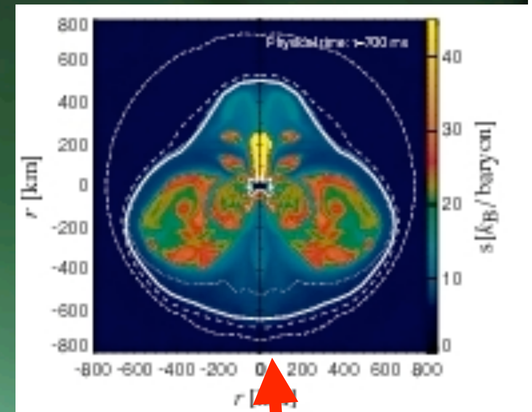
2D/3D > 1D

What happens in 3D?

BURROWS, HAYES, & FRYXELL (1995)

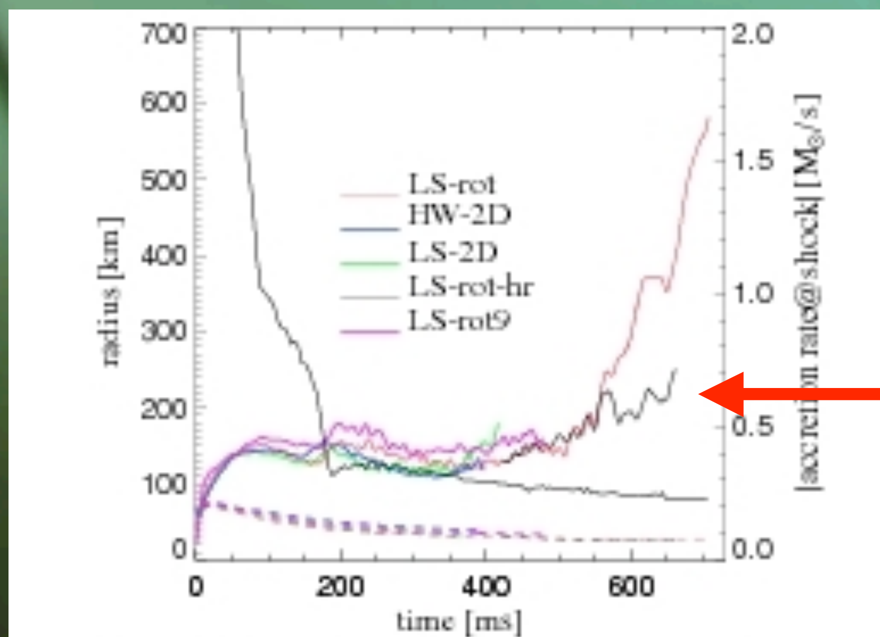
Marek & Janka 2009: 15 solar-mass model with soft (180 MeV) EOS, 1D "ray-by-ray" transport, 2D hydro:





Long delay, weak explosion (?)

R_{shock} to ~600 km

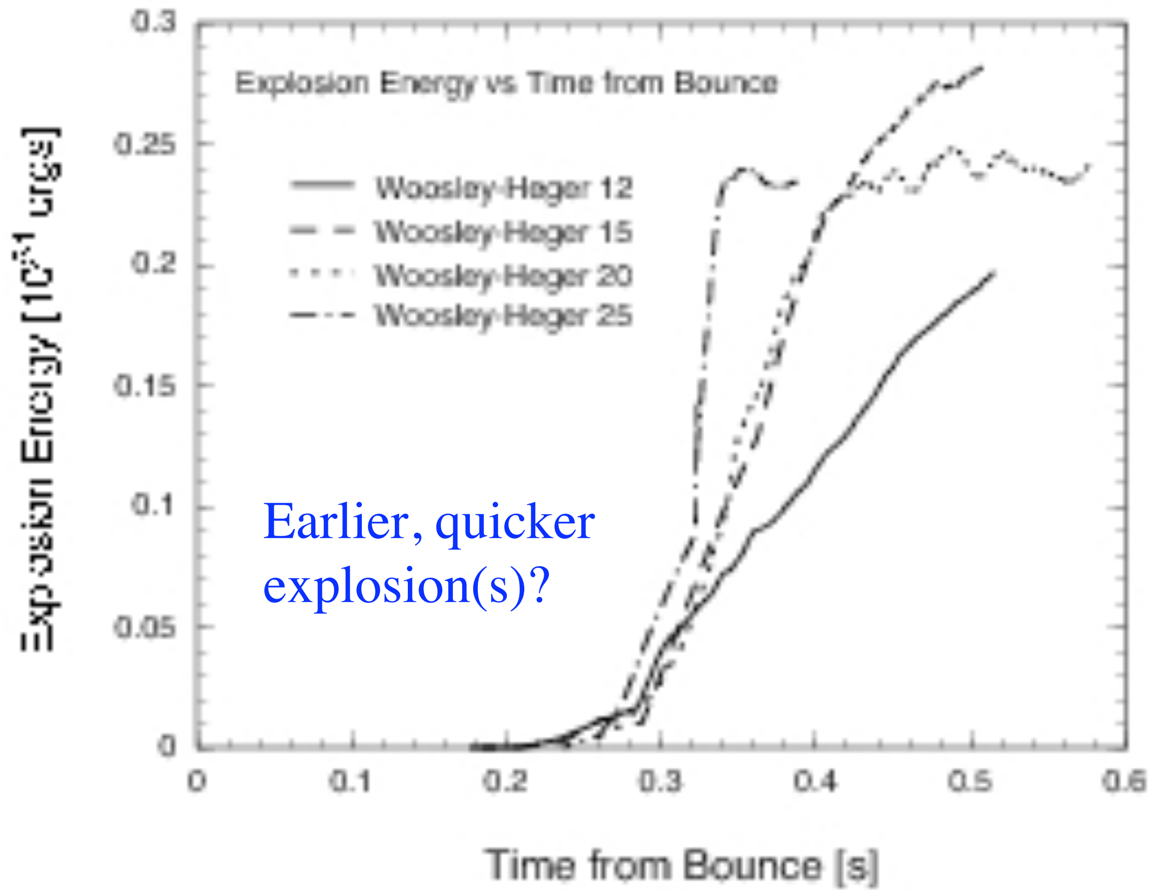


Higher-resolution, stiffer EOS - don't explode??

Higher-resolution. Smaller radius

GR?

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

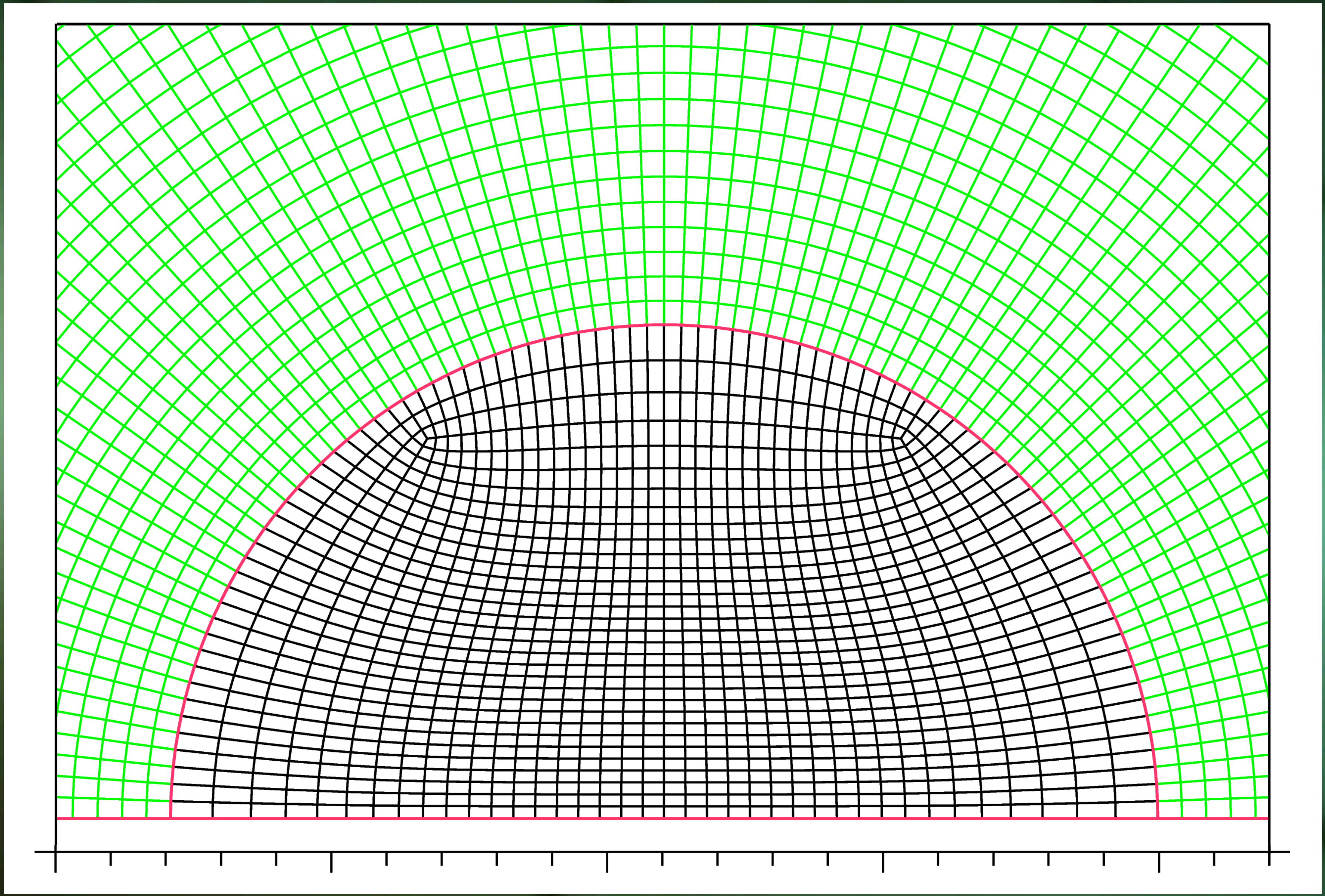


What is the difference?, What’s new? Inelastic scattering??, nuclear burning? …

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

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

- Only code with multi-D 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 (still slow)
- 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



Limitations of the VULCAN/2D Simulations

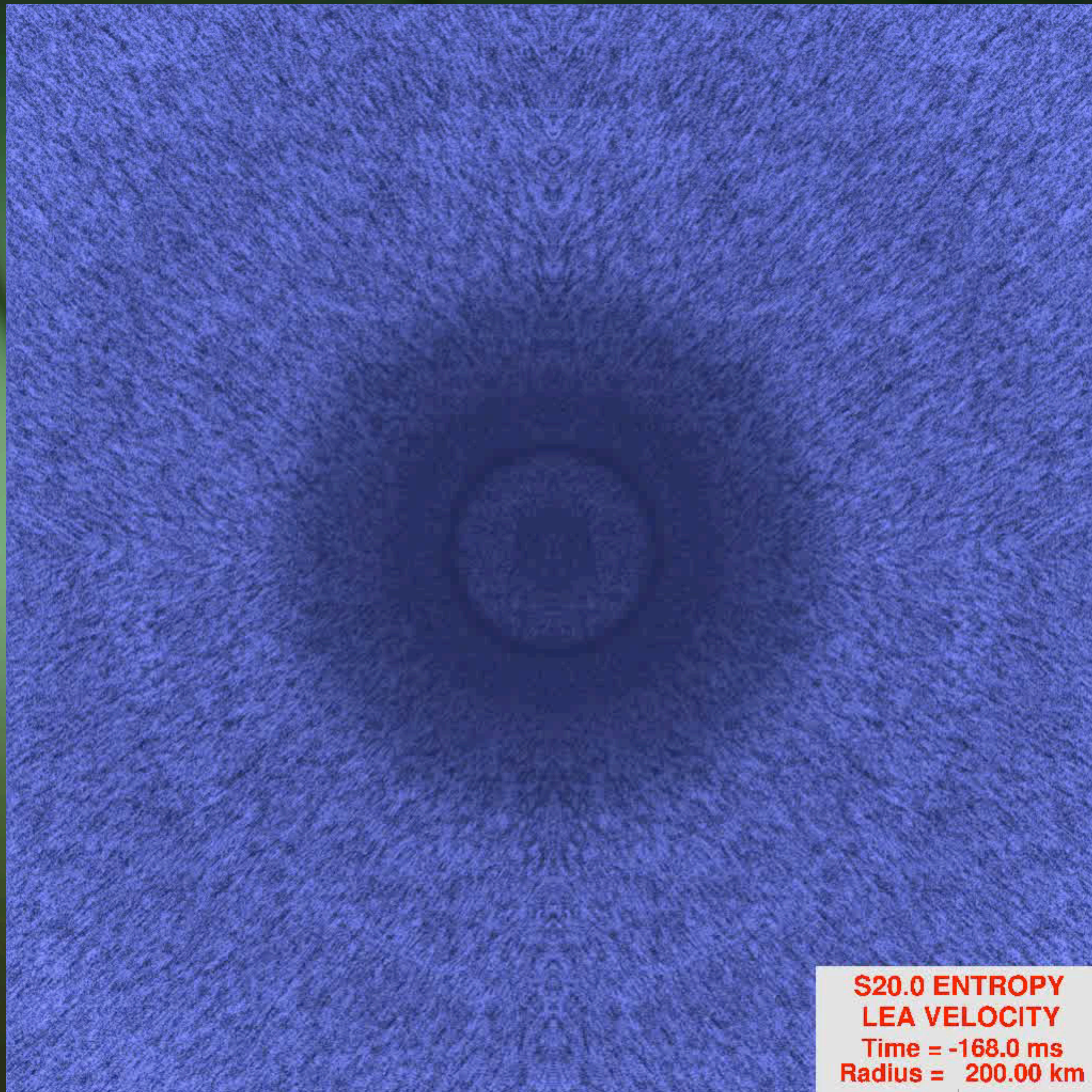
- Doppler shift terms not included in transport
- Inelastic redistribution not included (though subdominant), though could be
- No good (but …) development path to 3D

Limitations of the ORNL Simulations

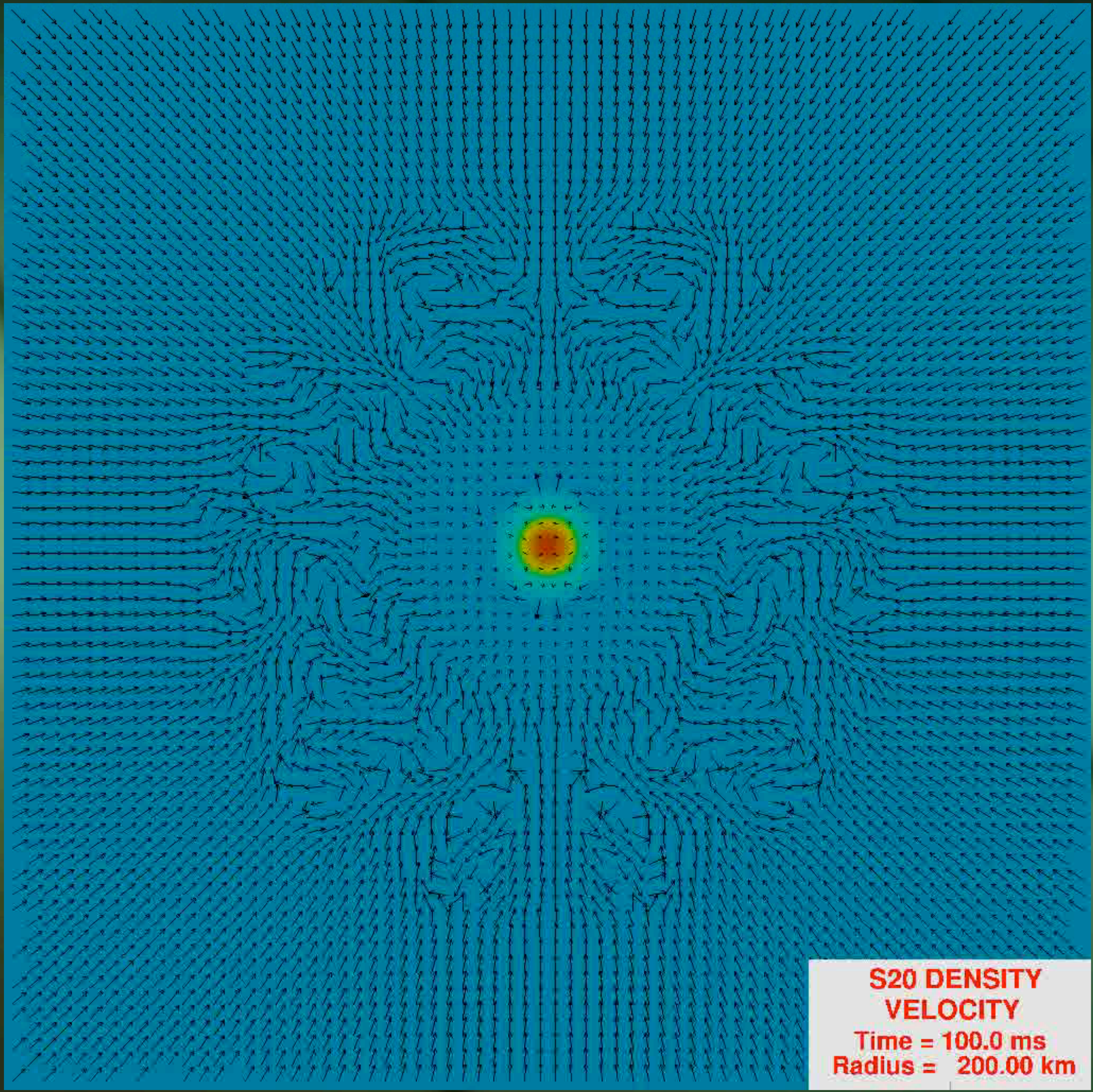
- Transport in 1D ("ray-by-ray"): Not Multi-D
- Soft (180 MeV) Nuclear EOS (but measurements?)
- Energy conservation to only ~0.5 Bethes
- Core must stay at grid center (kicks?, acoustic mechanism?)
- Role of Nuclear Burning at Shock?
- Large Stalled Shock Radius ?

Limitations of the MPIA Simulations

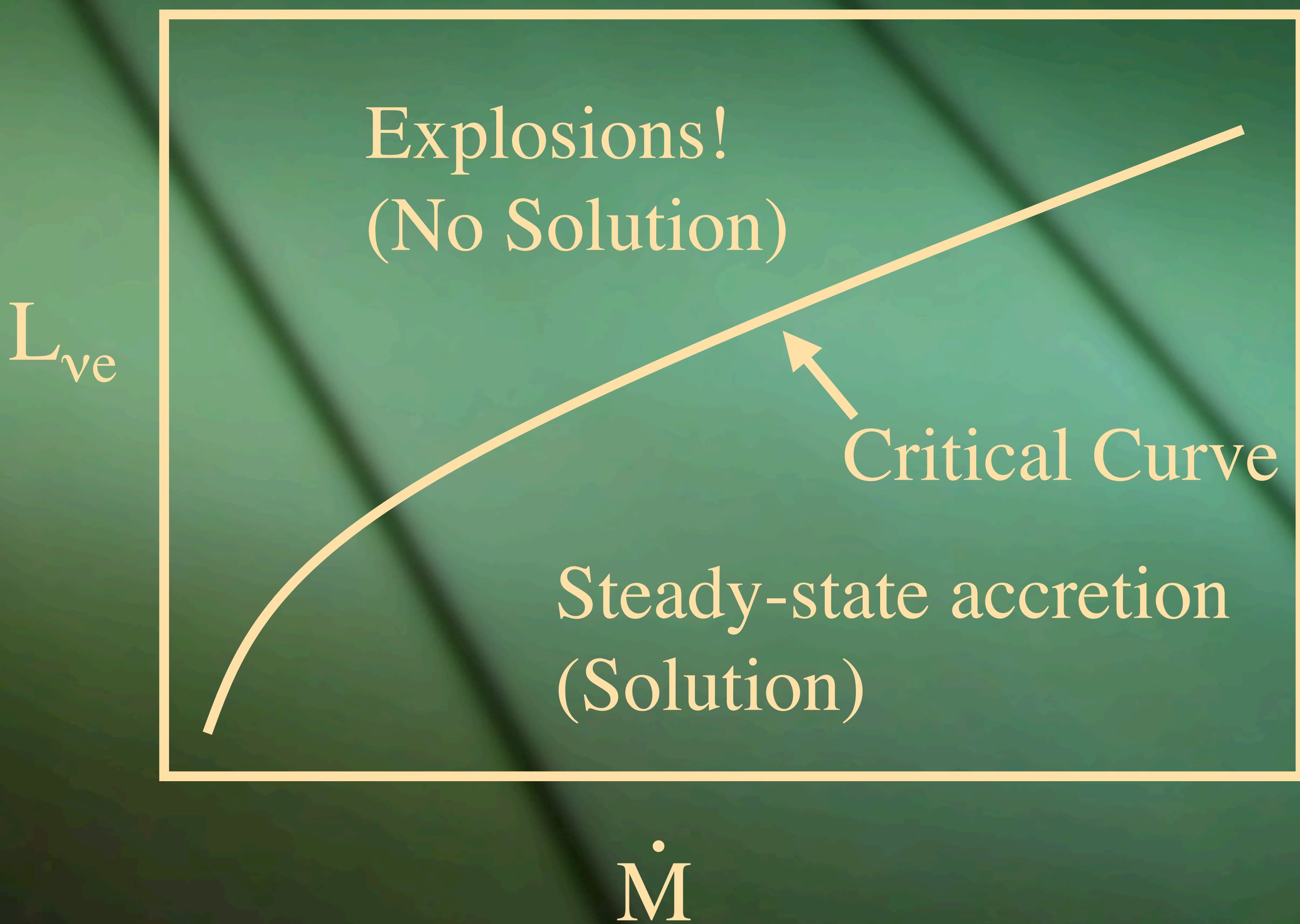
- Transport in 1D ("ray-by-ray"): Not Multi-D
- Soft (180 MeV) Nuclear EOS (but measurements?)
- Core must stay at grid center (kicks?, acoustic mechanism?)
- (ORNL and MPIA 15-solar-mass explosion simulations very discrepant)


S20.0 ENTROPY
LEA VELOCITY
Time = -168.0 ms
Radius = 200.00 km

But,
in
3D?

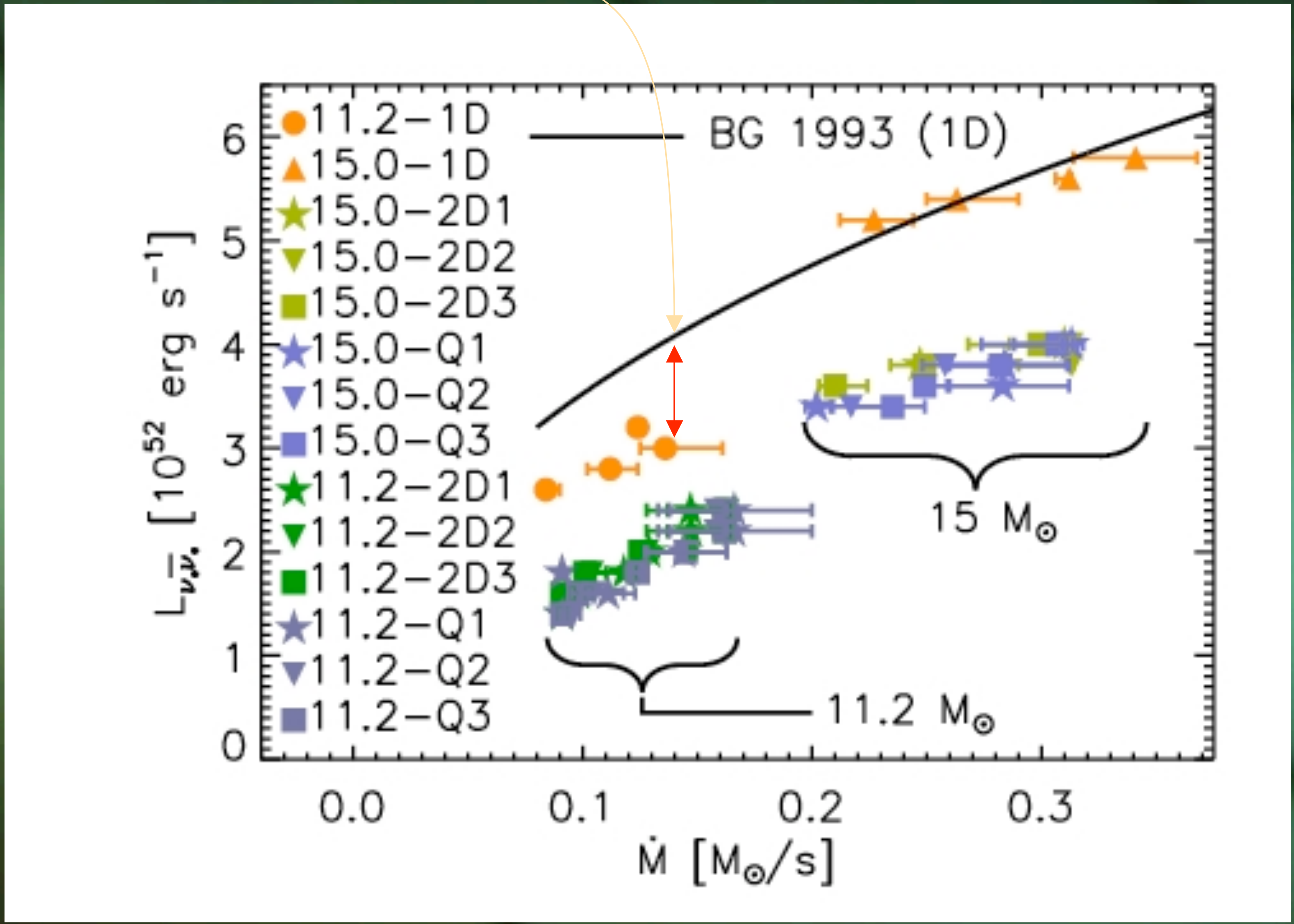


Burrows & Goshy '93; Murphy & Burrows 2008
Steady-state solution (ODE) and Hydrodynamic Parameter Study



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

Shift due to
different mass cores



Murphy & Burrows 2008

3D and the Neutrino Mechanism?

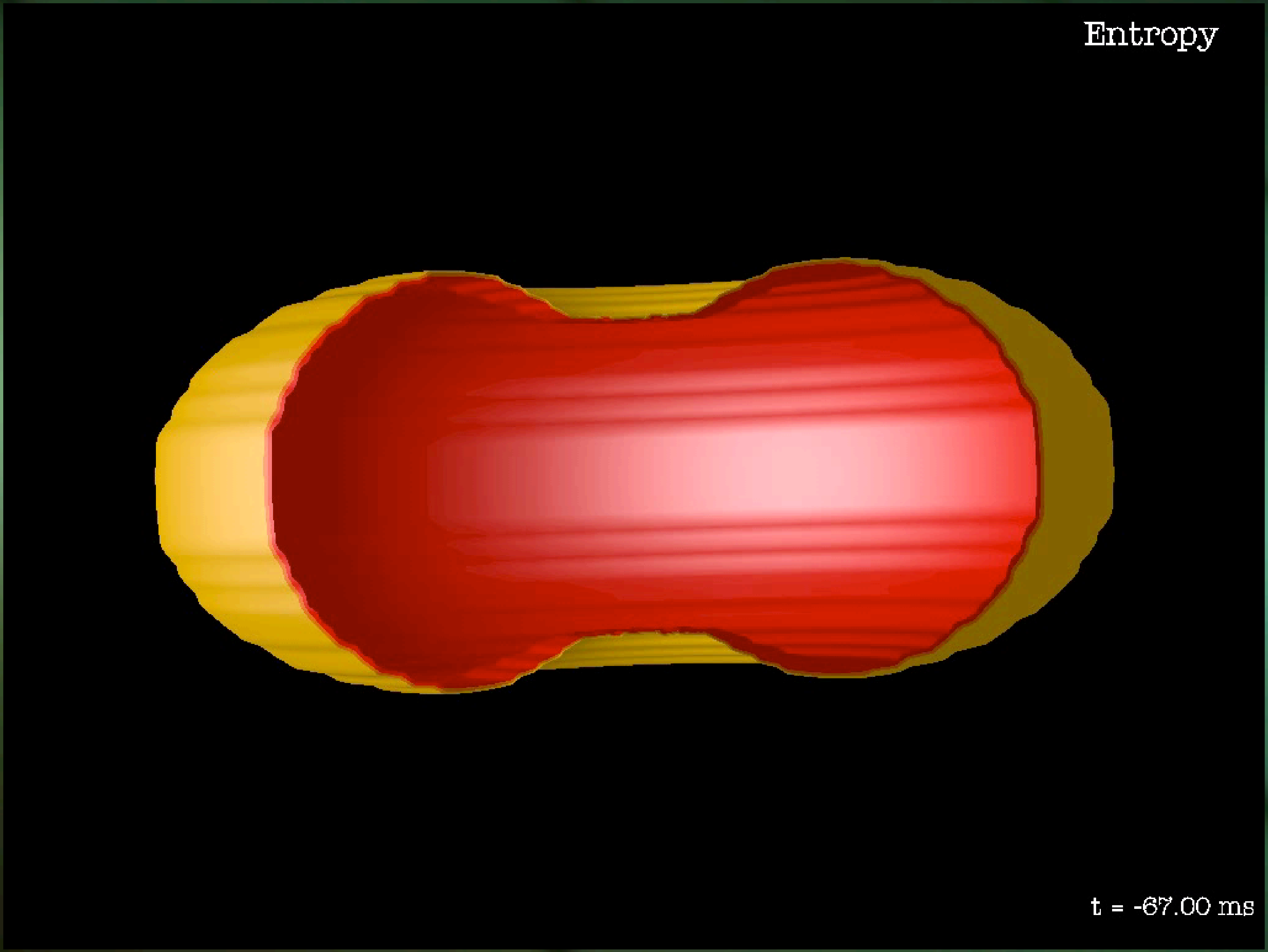
Still Open Question

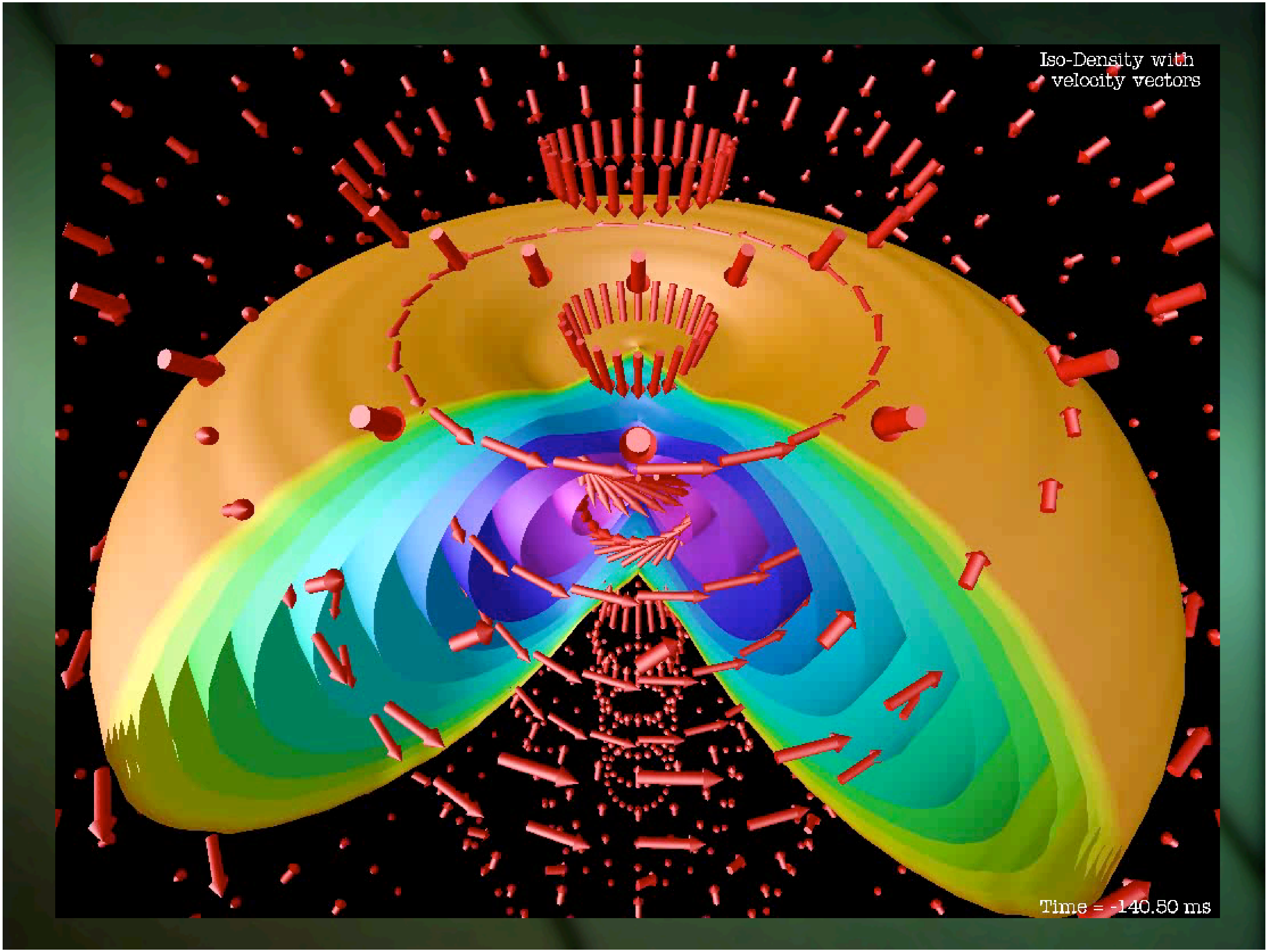
Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

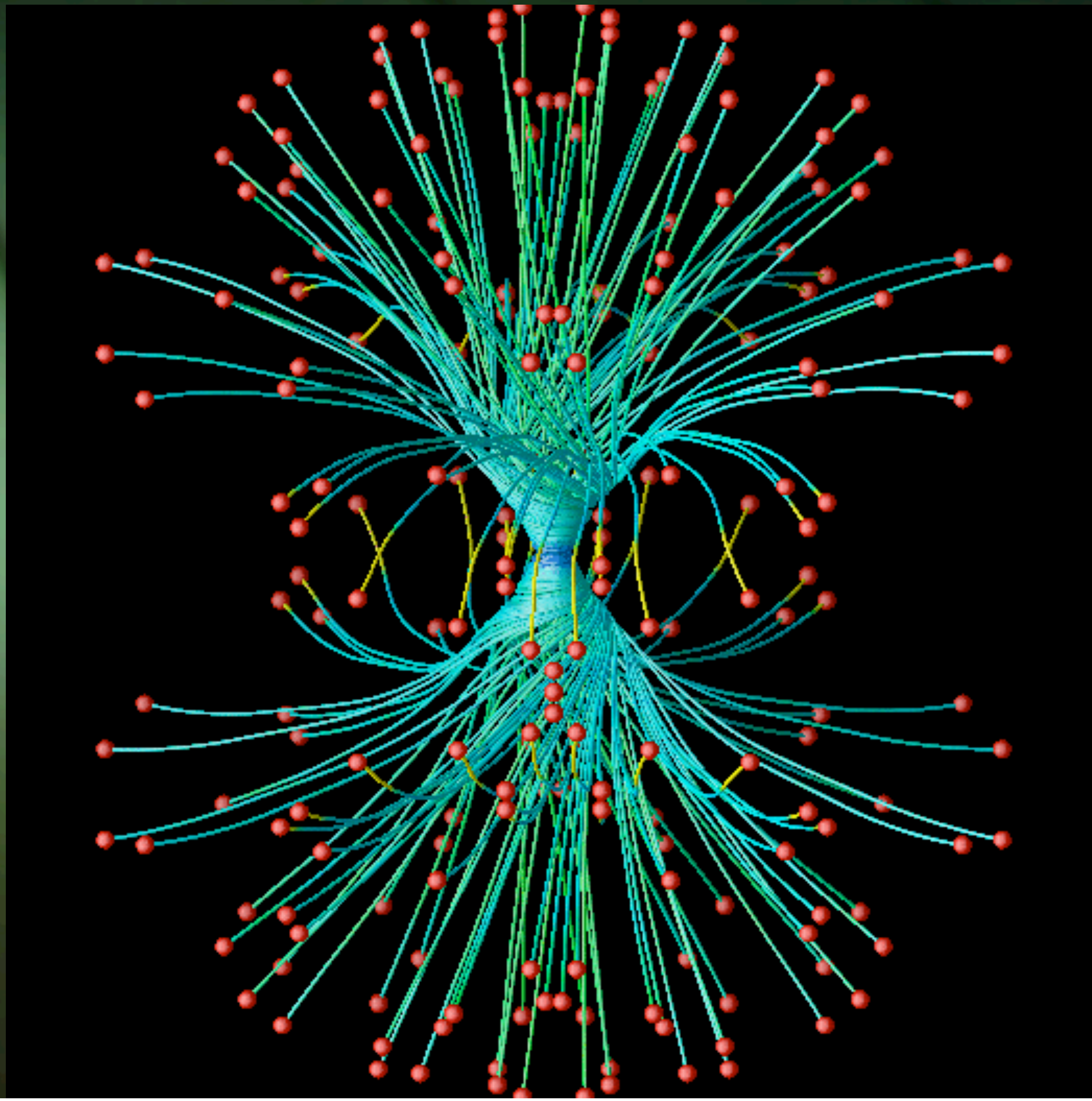
Dessart, Burrows, Ott, Livne, Yoon, & Langer 2006

Rapid Rotation!

AIC: 1.92 solar masses:

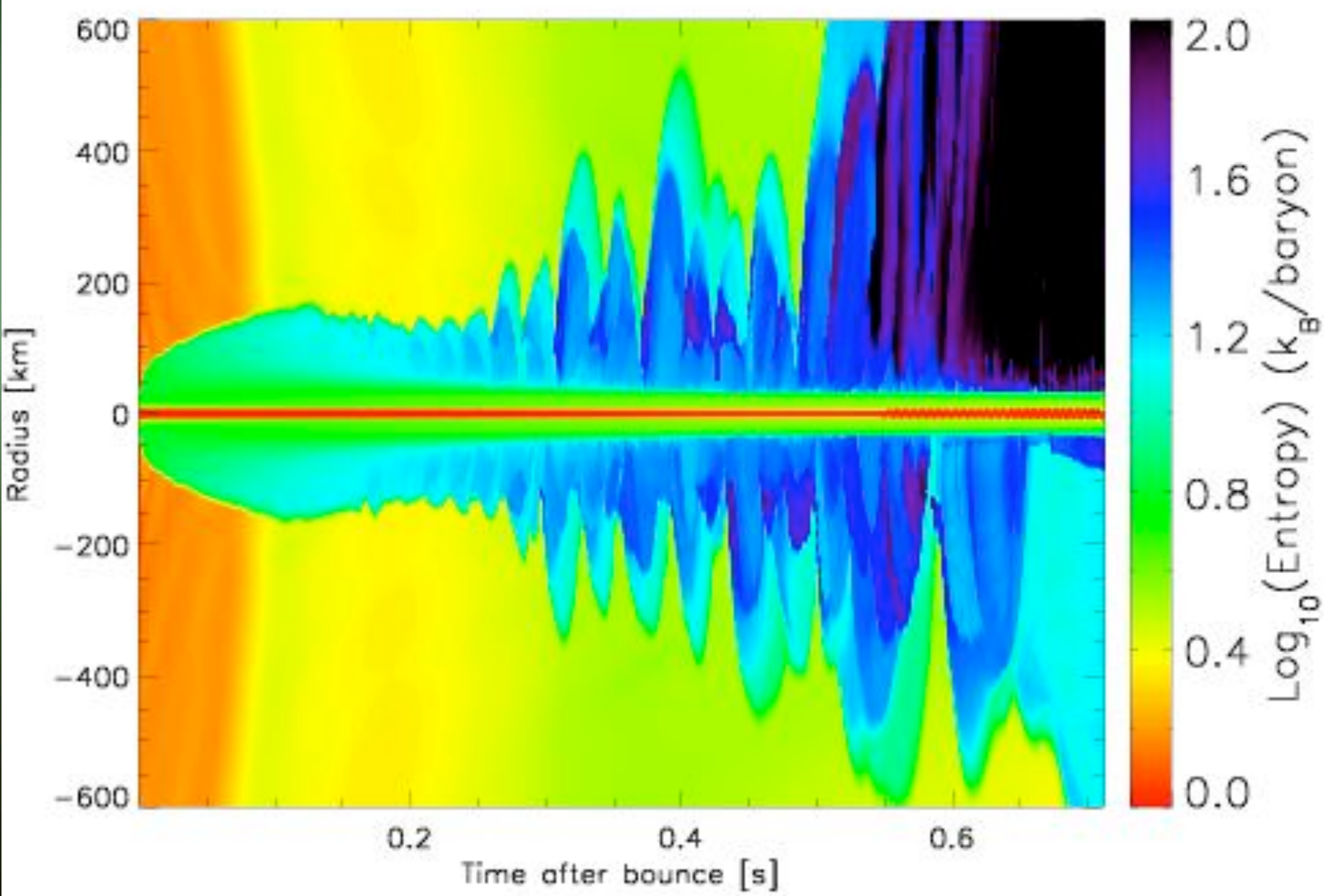


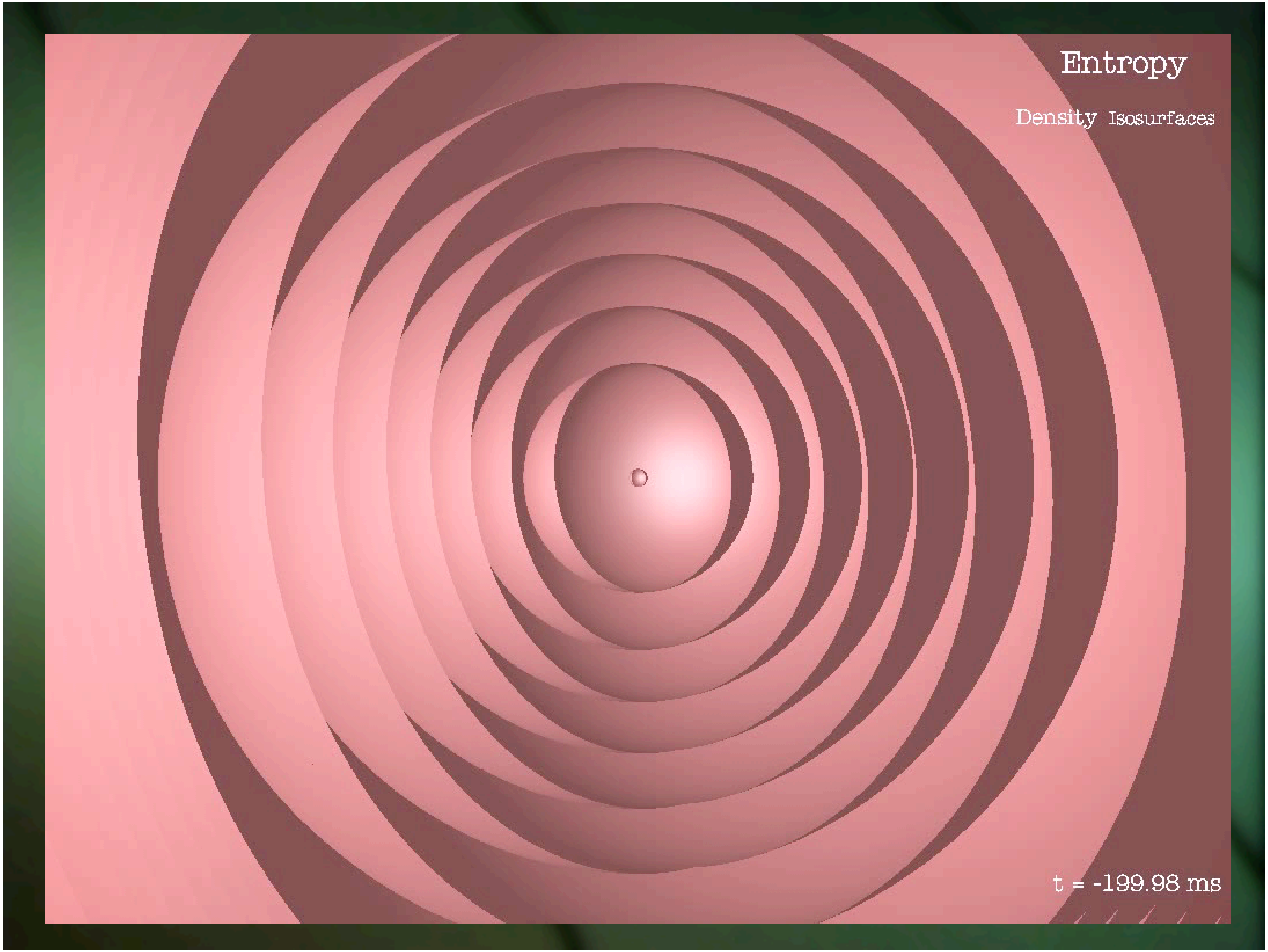

Iso-Density with
velocity vectors
Time = -140.50 ms



Core Oscillation/Acoustic Power Mechanism

Inner 600-km Look at the Advective-Acoustic Instability

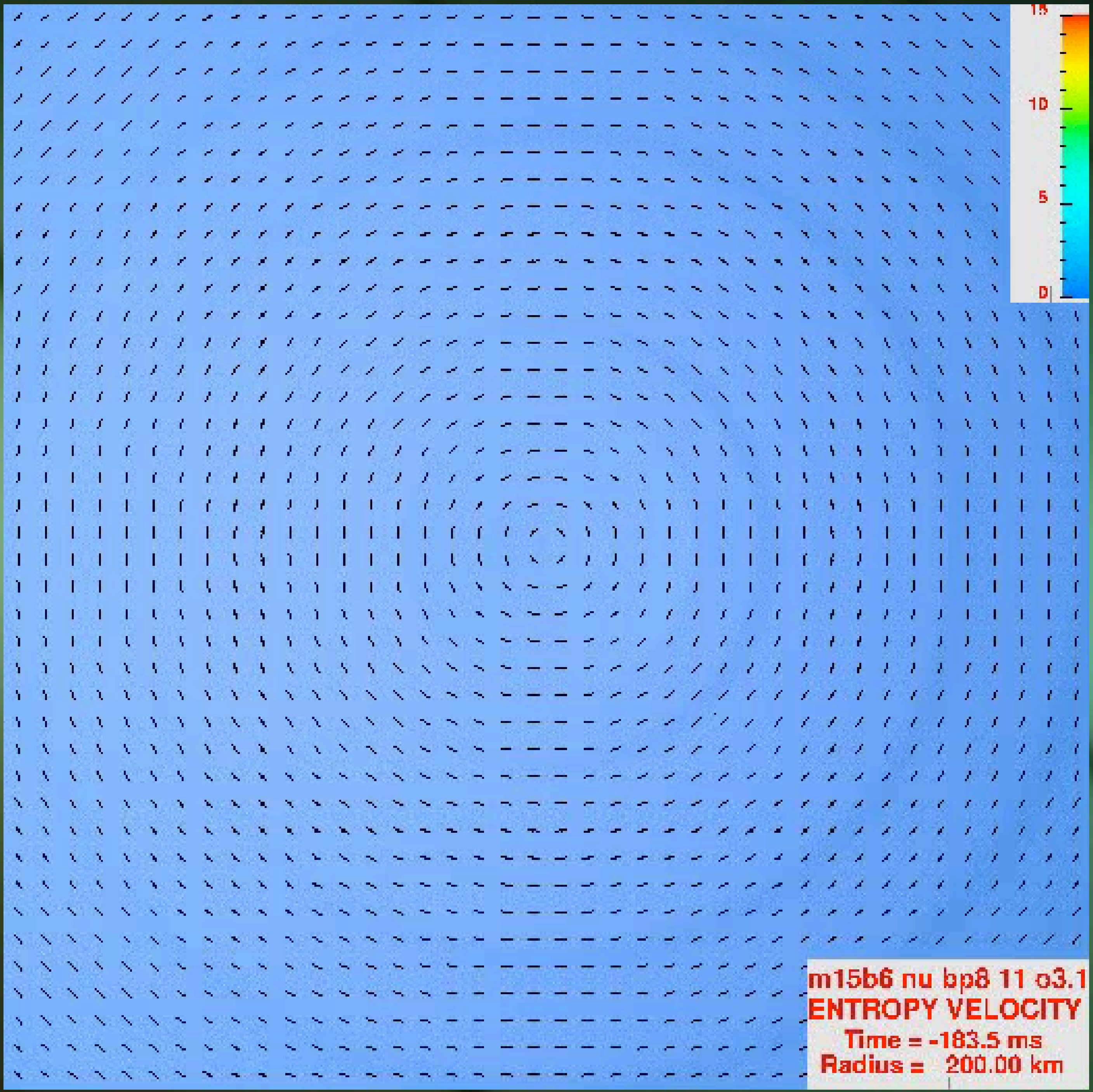



Entropy
Density Isosurfaces
t = -199.98 ms

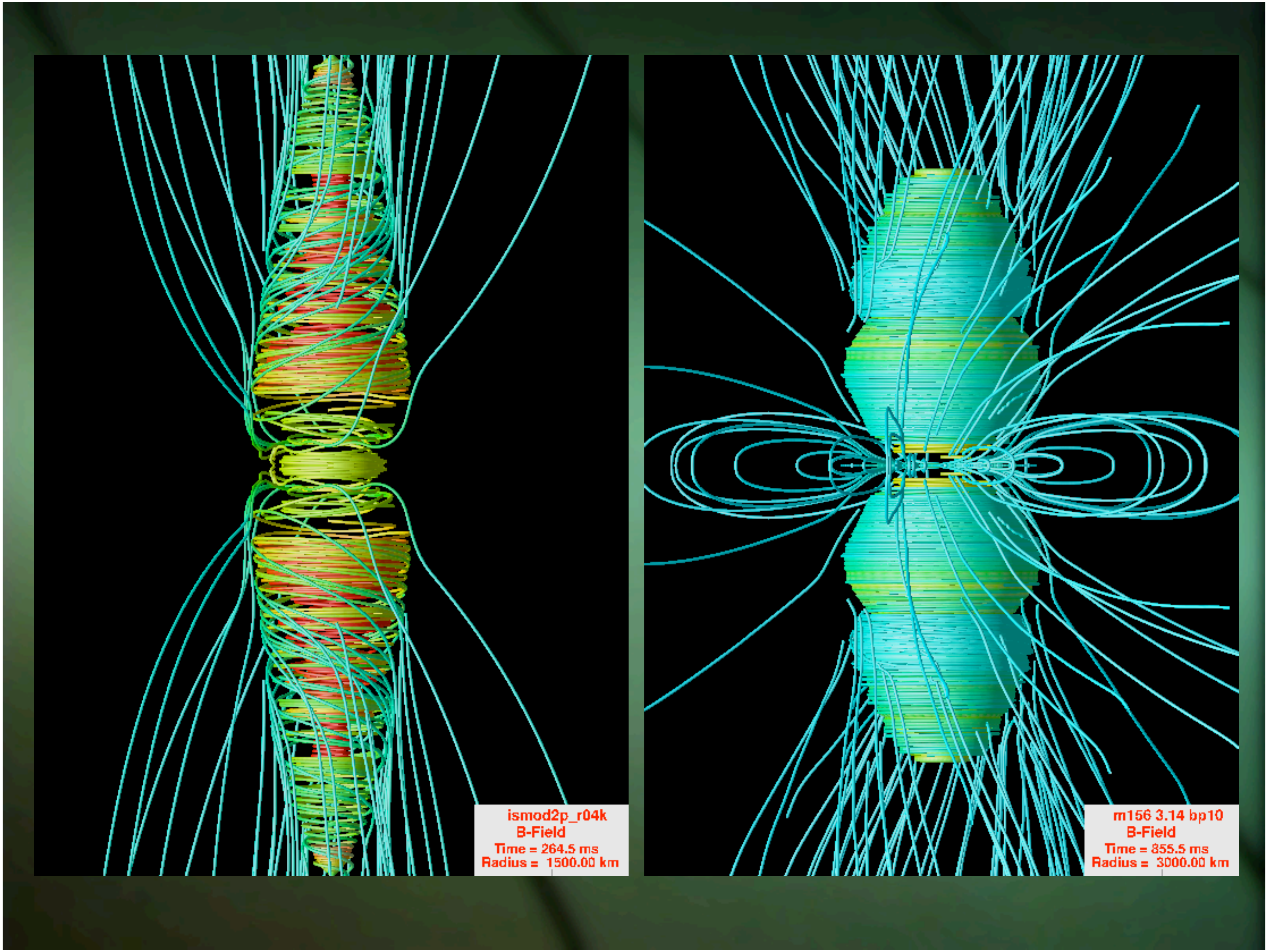
MHD Jets and RMHD Simulations of Core Collapse: Rapid Rotation

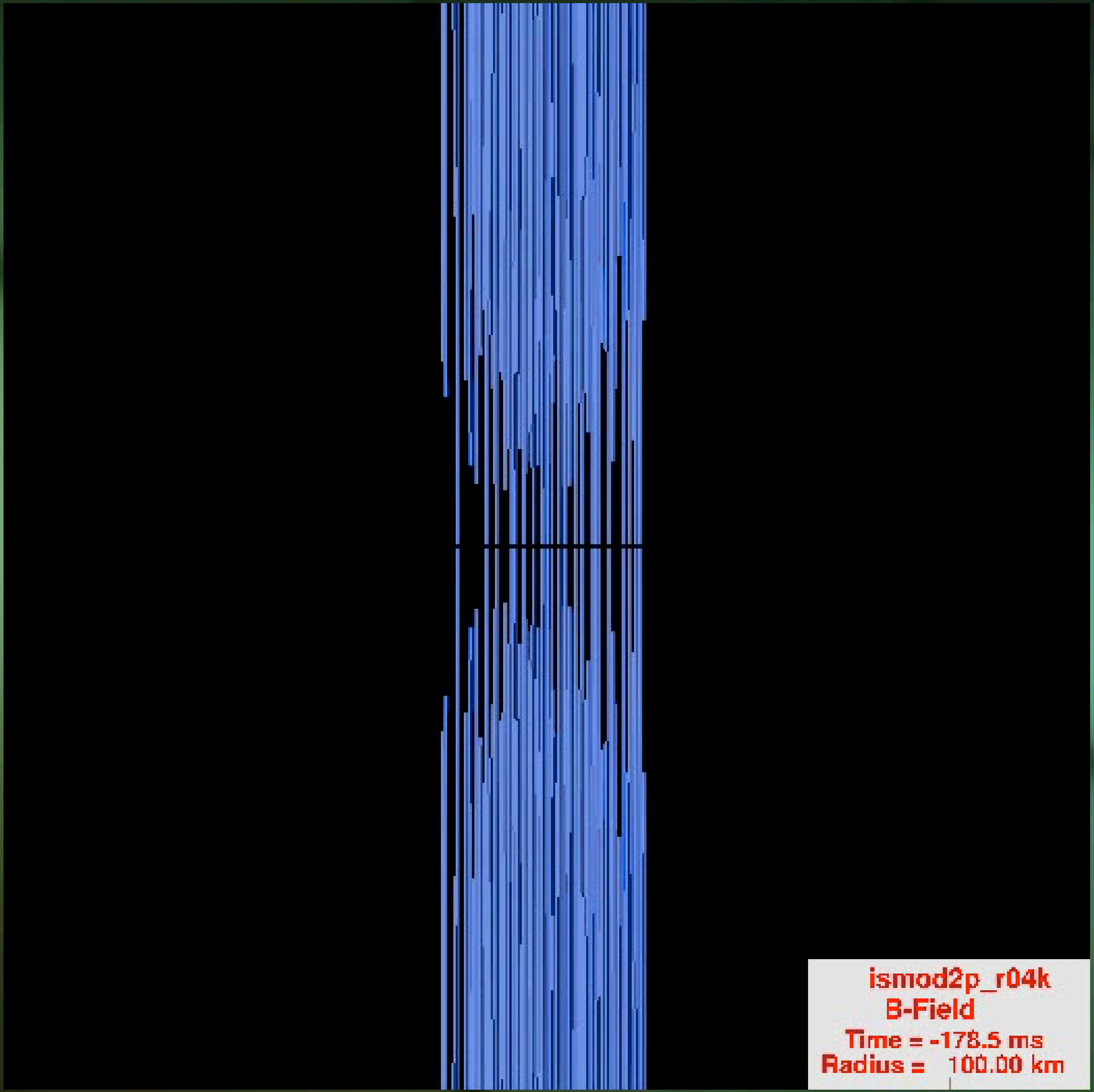
Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007

Rotation Winding, the MRI and B-field Stress effects

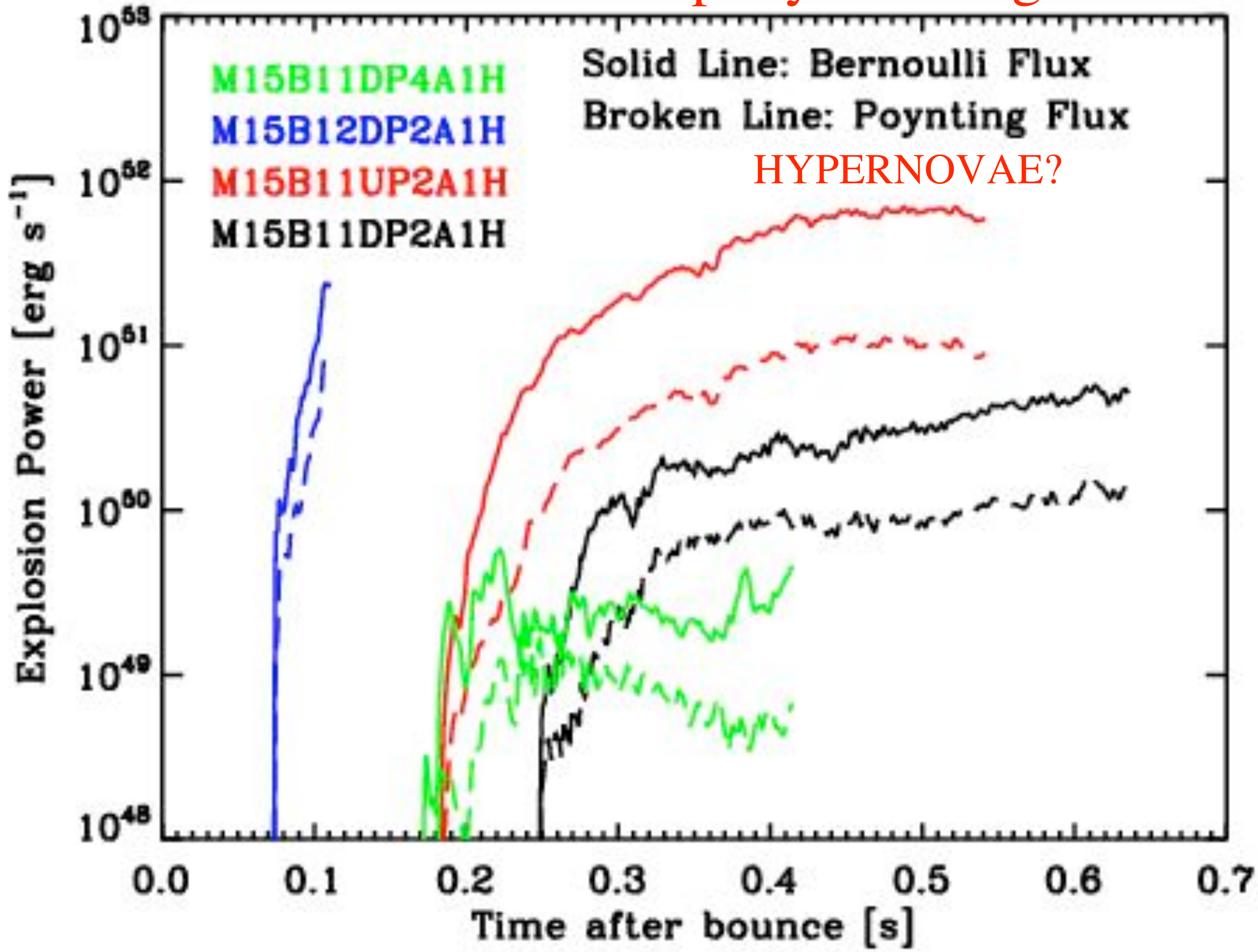


15
10
5
0
m15b6 nu bp8 11 o3.1
ENTROPY VELOCITY
Time = -183.5 ms
Radius = 200.00 km


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

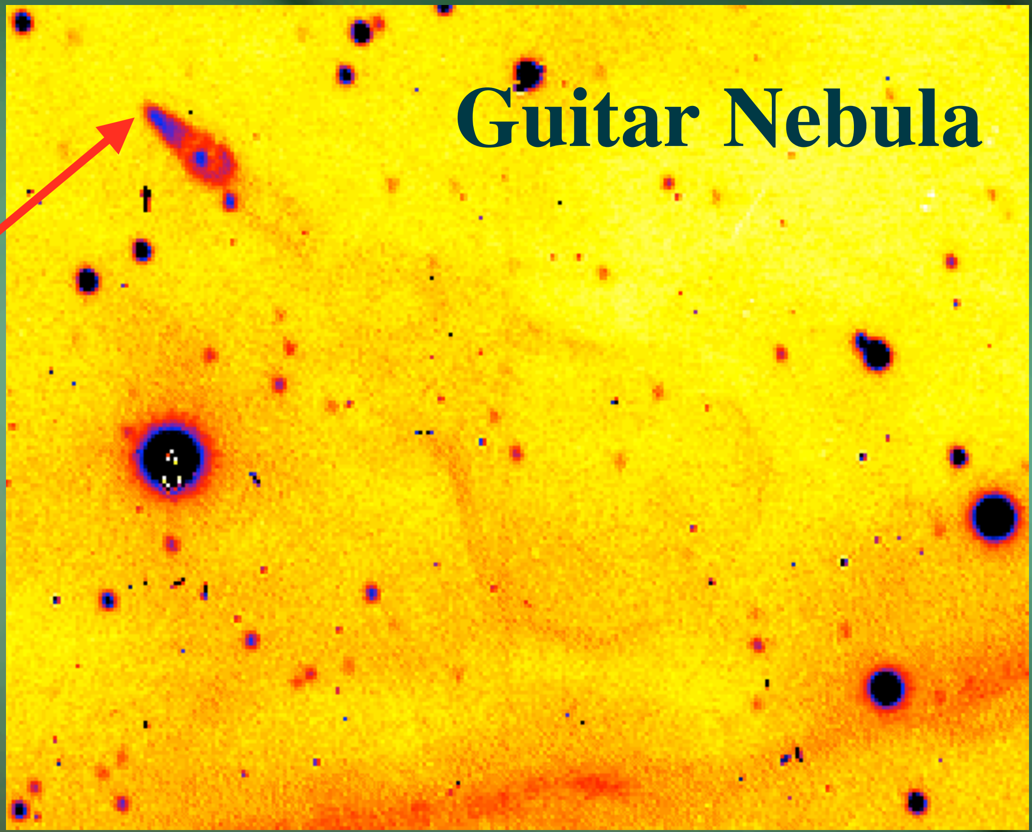

ismod2p_r04k
B-Field
Time = -178.5 ms
Radius = 100.00 km

MHD Jet Powers for Rapidly-Rotating Cores



Pulsar Recoil: A Generic Feature

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

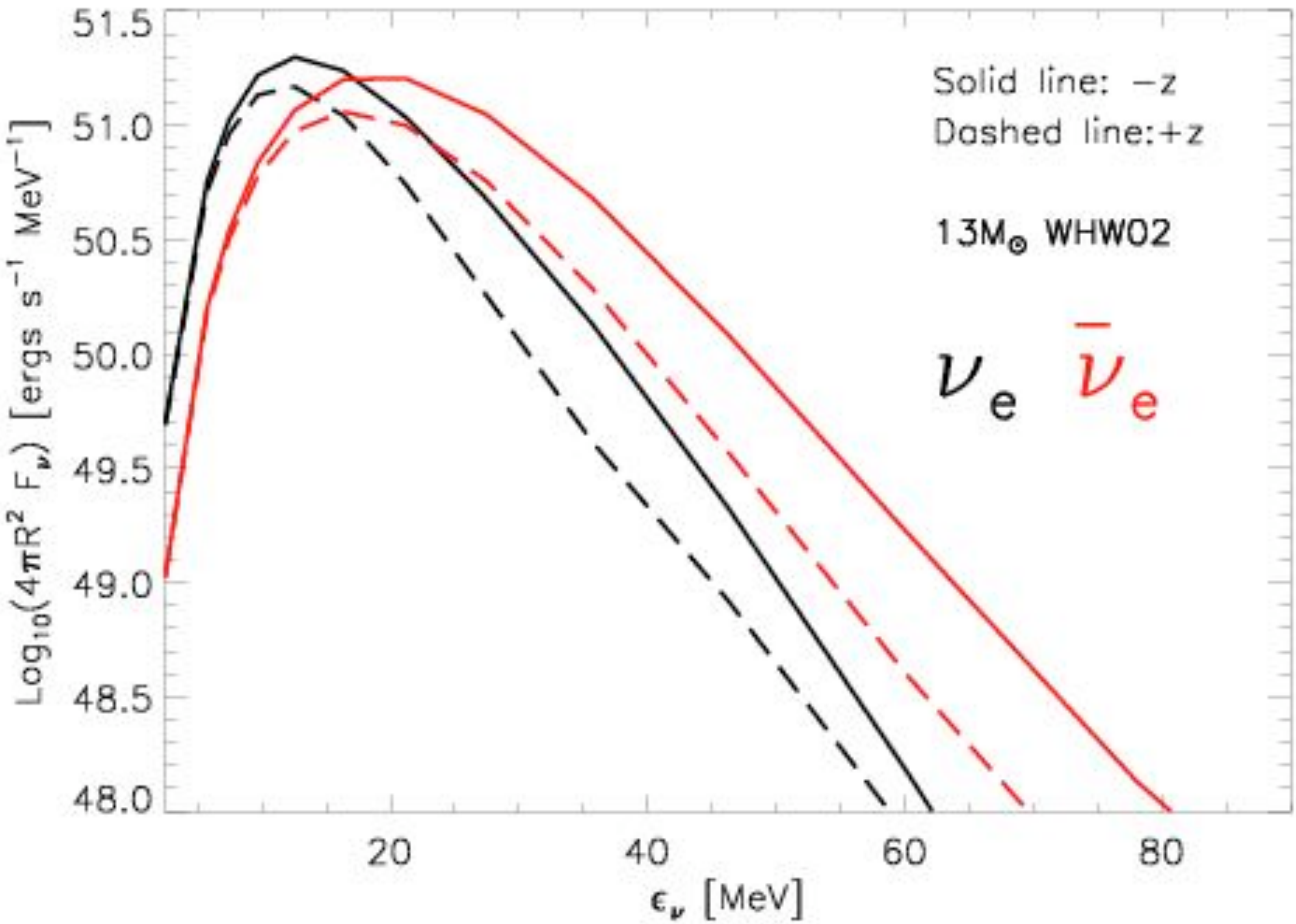


Cordes, Romani, Lundgren '93

Pulsar Kicks

- Puppis A (RX J0822-4300) - 112 ms pulsar, weak field (Pdot) at birth (Gotthelf and Halperin 2008) - evidence against electromagnetic kick
- Puppis A (RX J0822-4300): kick of ~1500 km s^{-1} (transverse) (Winkler and Petre 2007) - asymmetric explosion, imparting ~3 x 10^{49} ergs in kick K.E. - Oxygen knot recoil?
- Supernova kicks and misaligned Be Star Binaries (Martin, Tout, and Pringle 2007)
- Spin-Kick Correlation of Young Pulsars (Ng and Romani 2007)

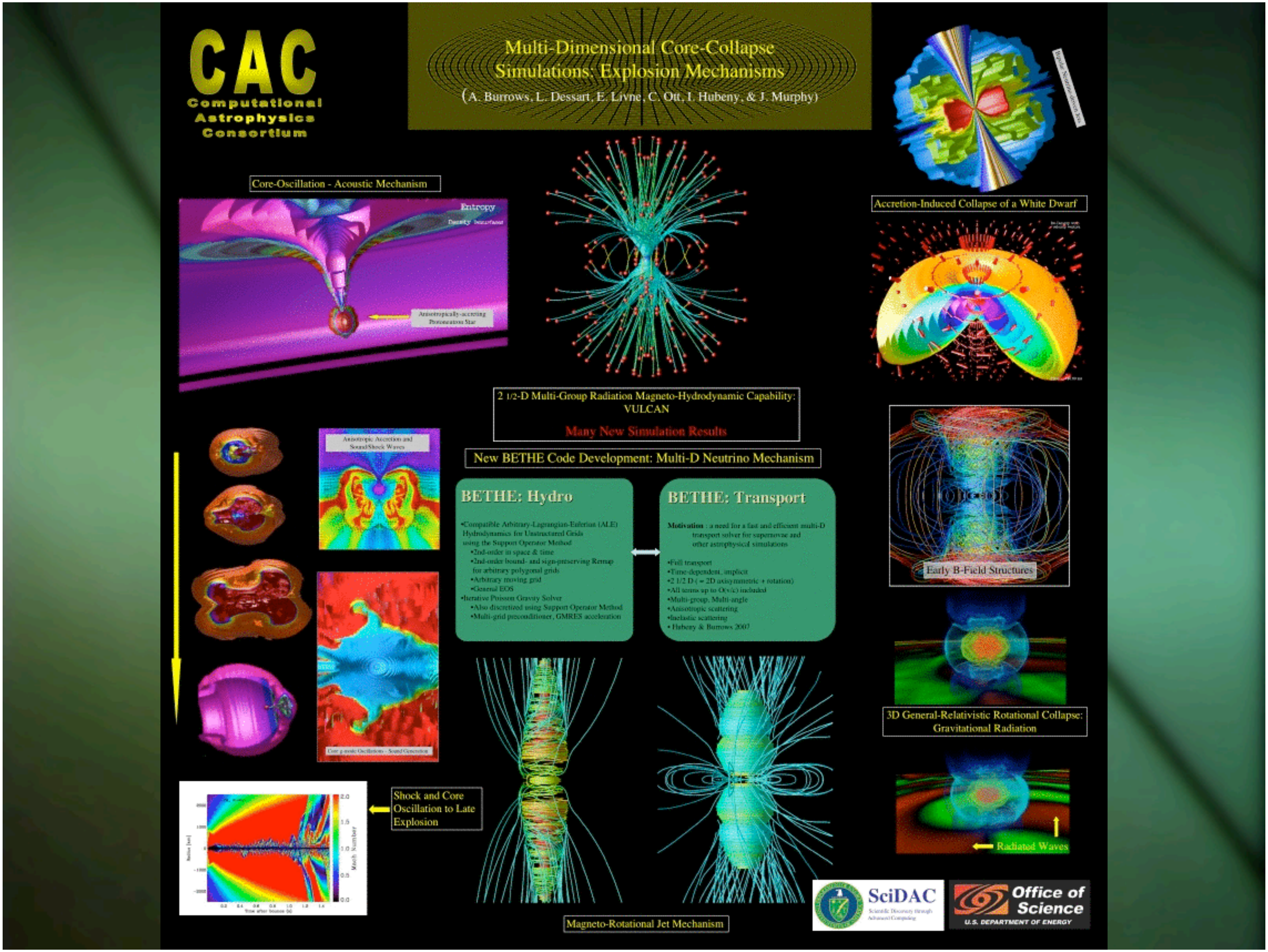
Top-Bottom Asymmetry in Neutrino Luminosity after Explosion: Kicks!



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
- 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

Extra Slides


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
Accretion-Induced Collapse of a White Dwarf
2 1/2-D Multi-Group Radiation Magneto-Hydrodynamic Capability: VULCAN
Many New Simulation Results
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
Magneto-Rotational Jet Mechanism
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