Numerical Simulations of Astrophysical Explosions

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Supported by:
SciDAC
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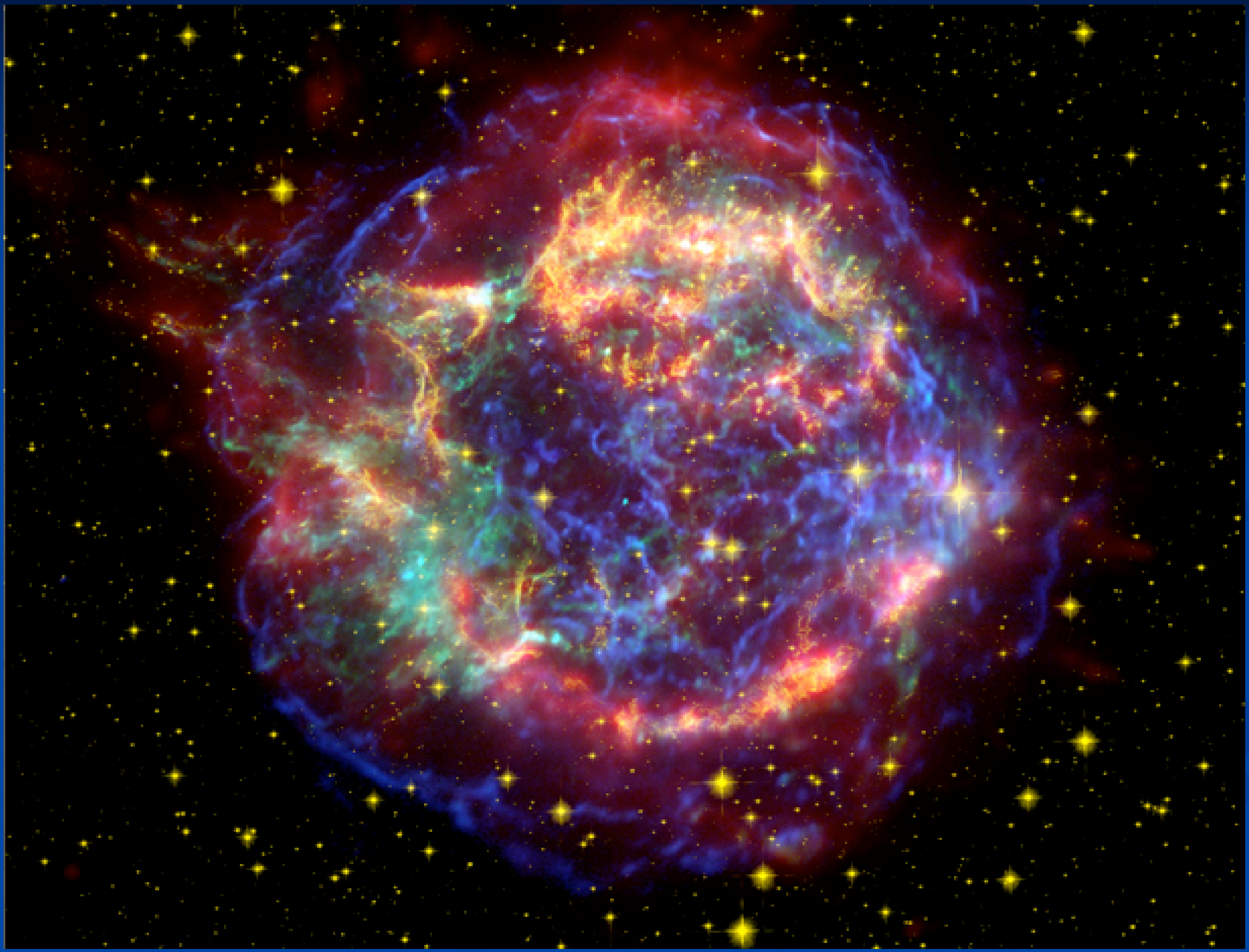
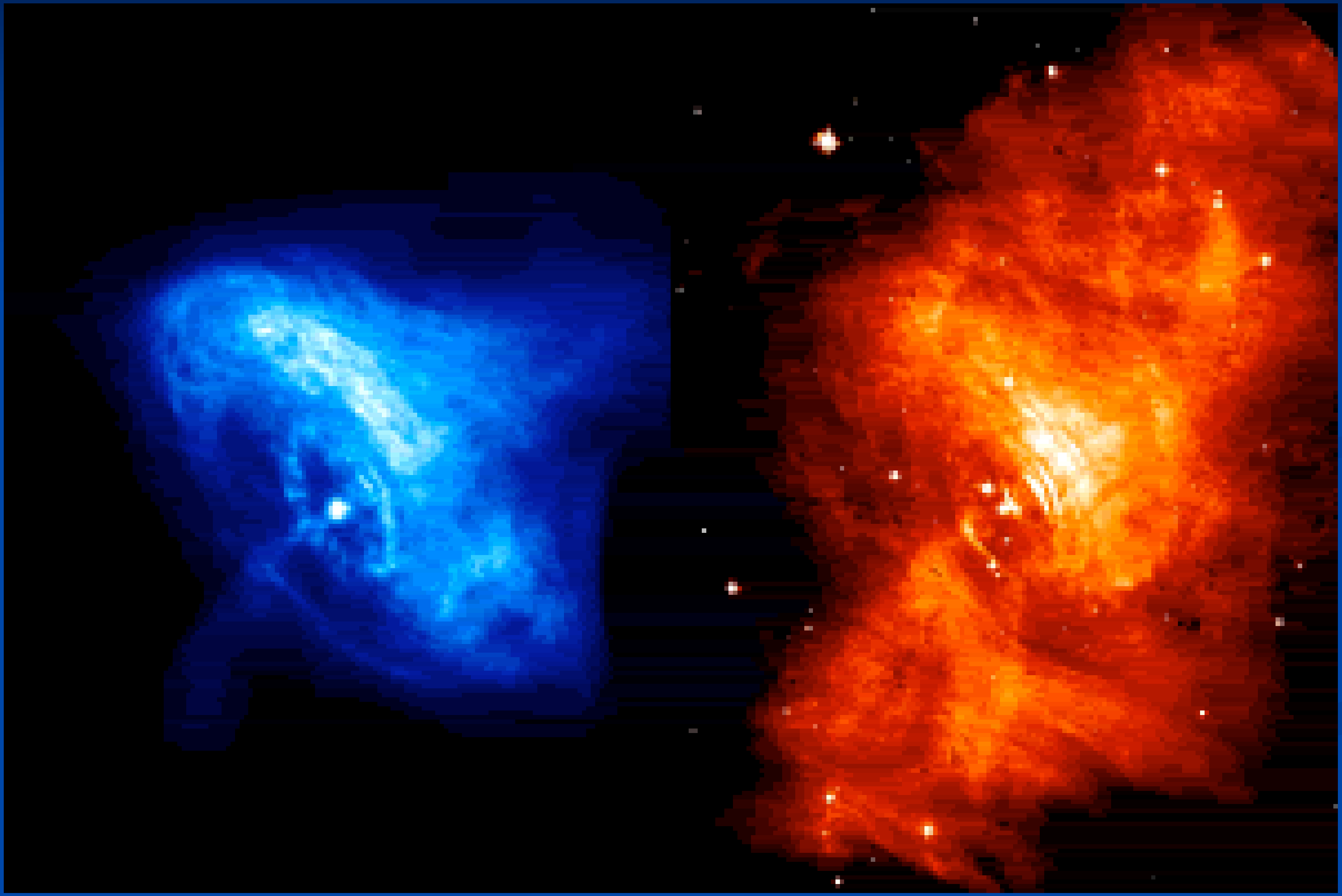
Core-Collapse Supernovae - The Deaths of Massive Stars

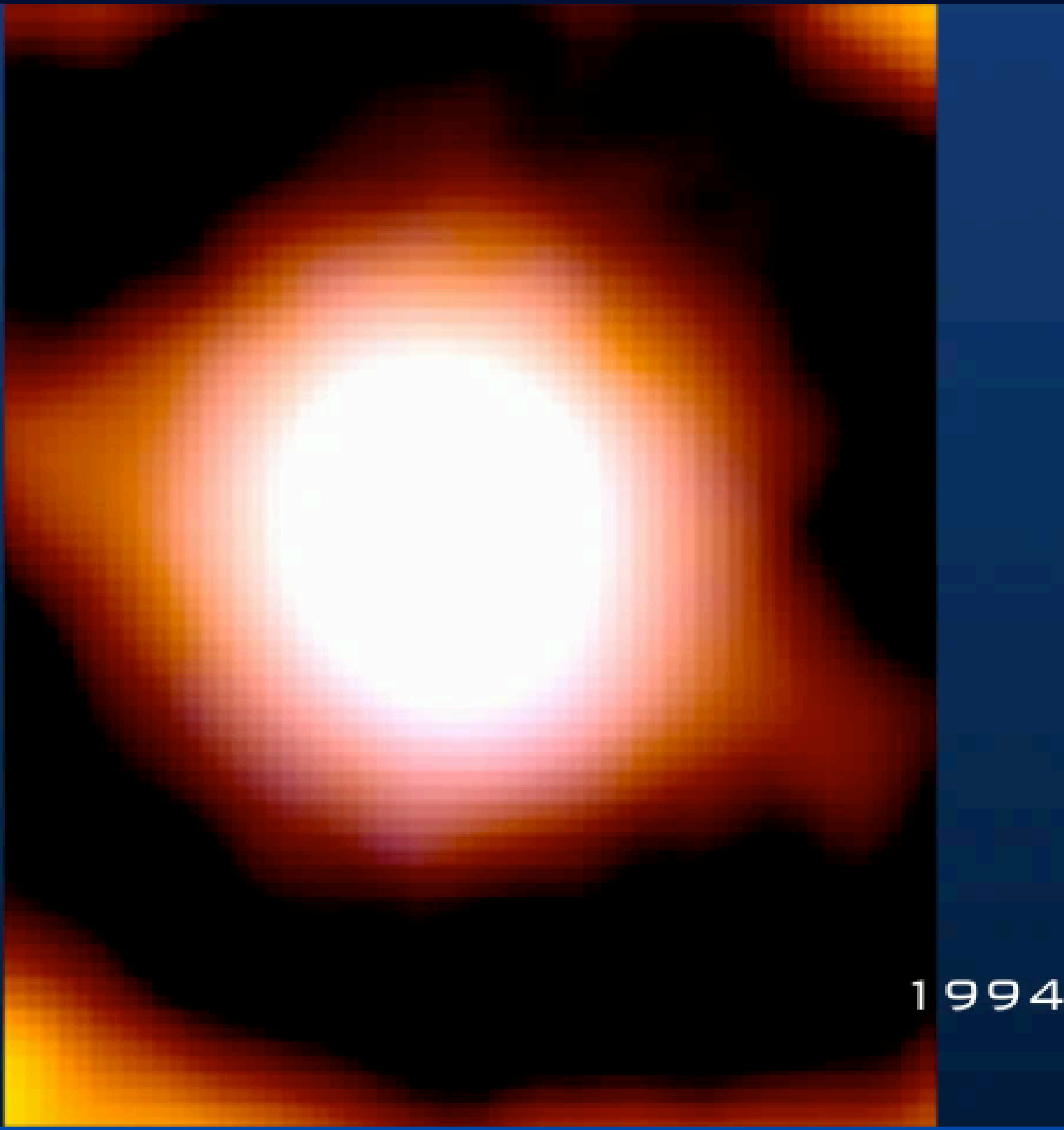
Supernova Remnant Cas A in X-rays



Crab Pulsar (Neutron Star): The Movie

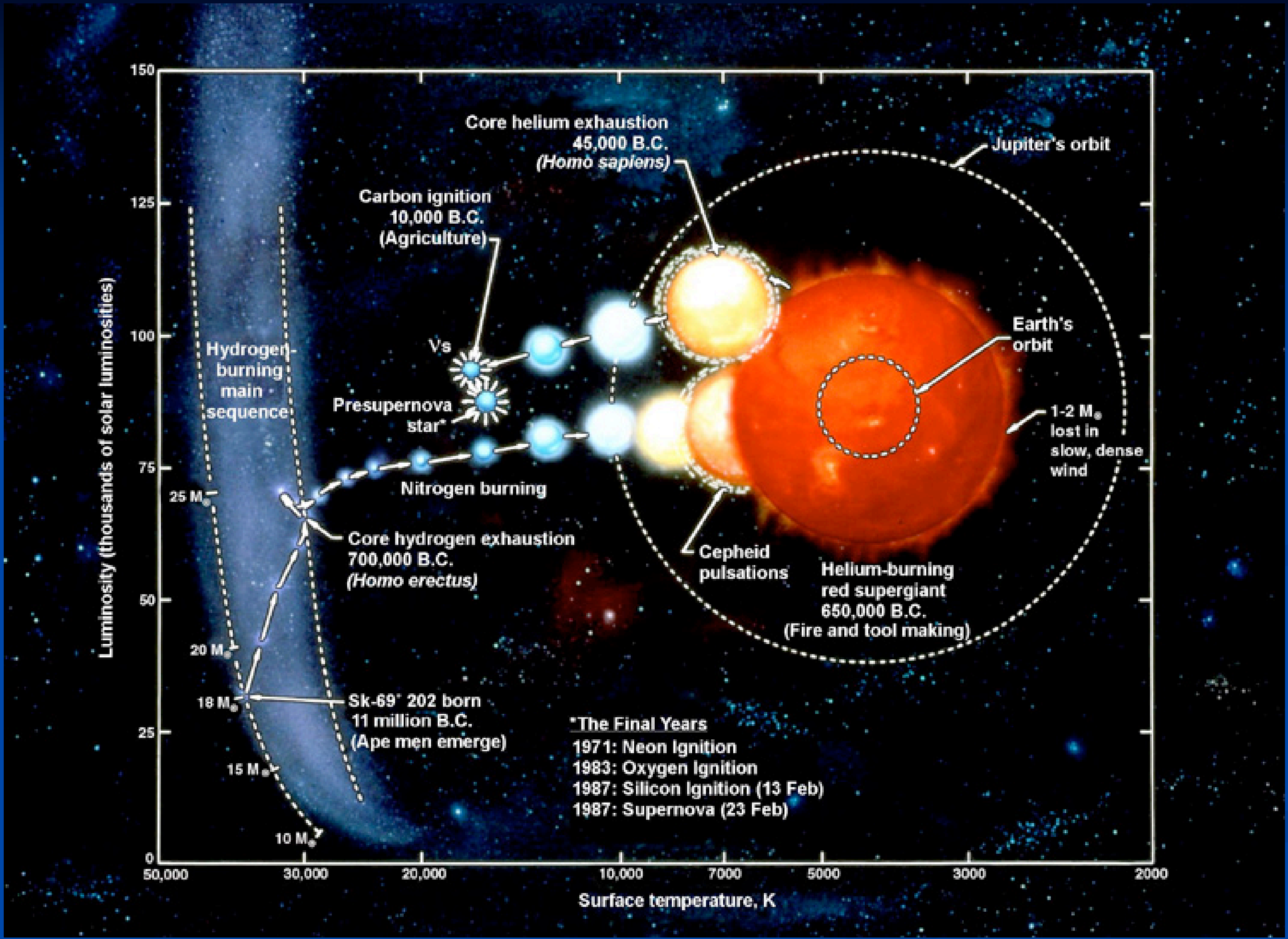


SN1987a (Pete Challis)



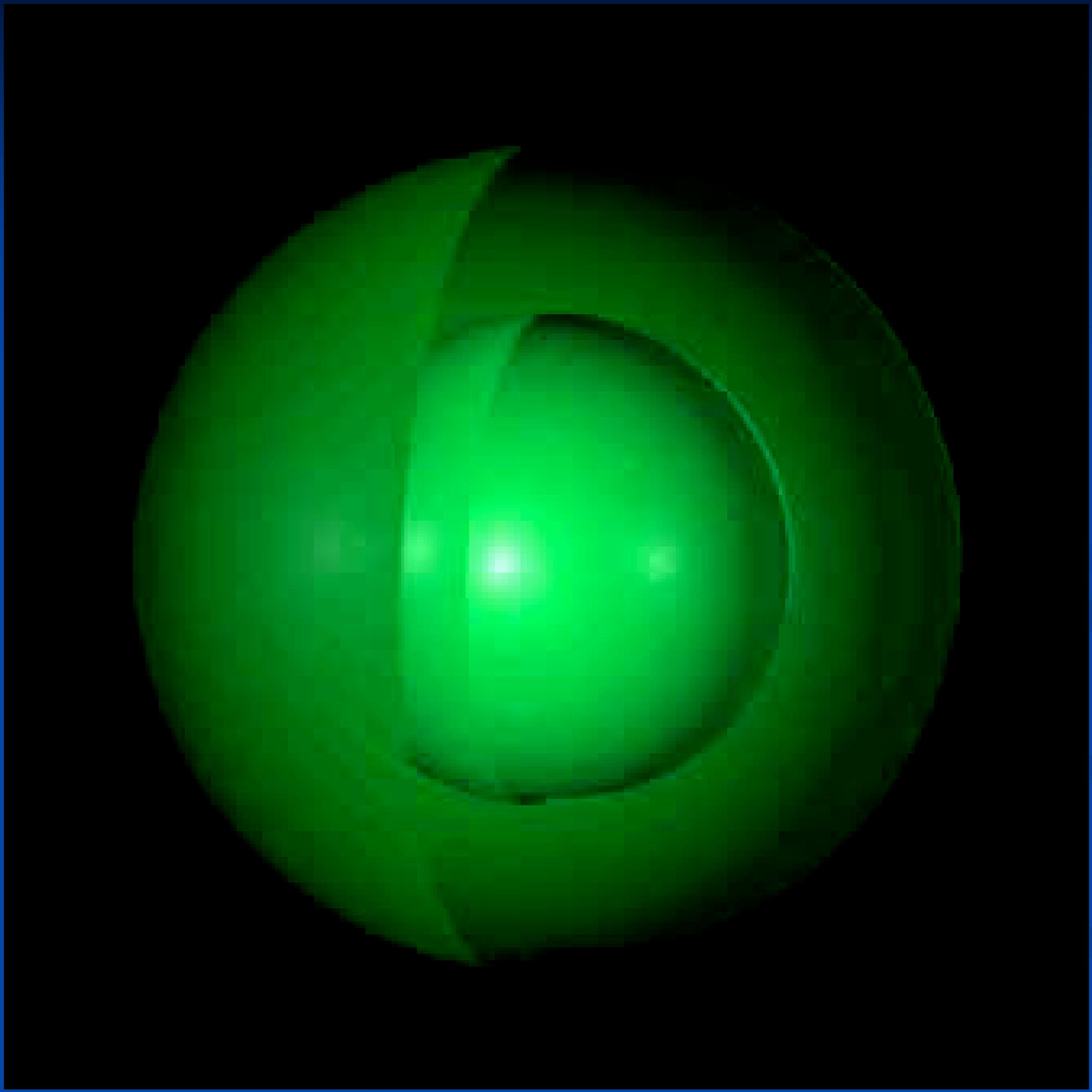
Important Questions in Supernova Theory

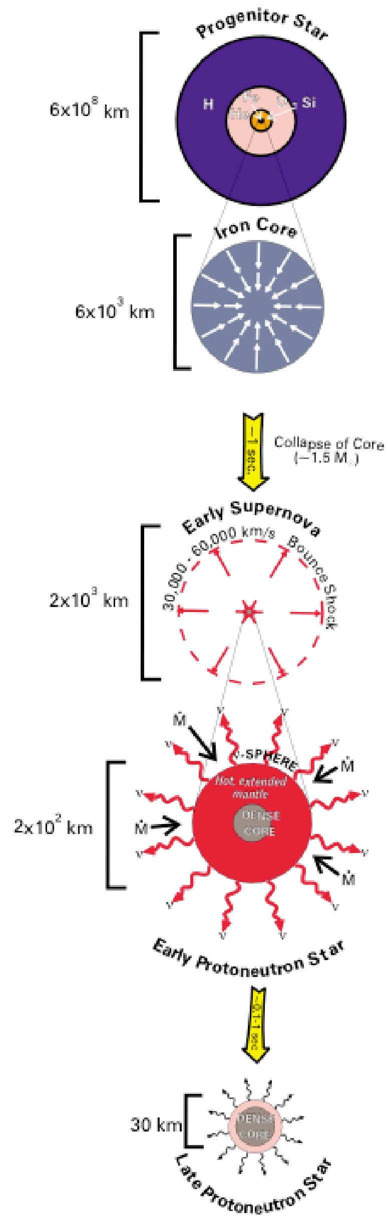
- Mechanism of explosion?
- Pulsar Kicks (proper motions)?
- Nucleosynthesis: Nickel, etc. Yields?
- R-process site?
- Blast Morphology (and polarization)?
- Pulsar Spins?
- Pulsar/AXP/Magnetar B-fields?
- Black Hole formation?
- Systematics with progenitor (and role of rotation/magnetic fields)?
- Connection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



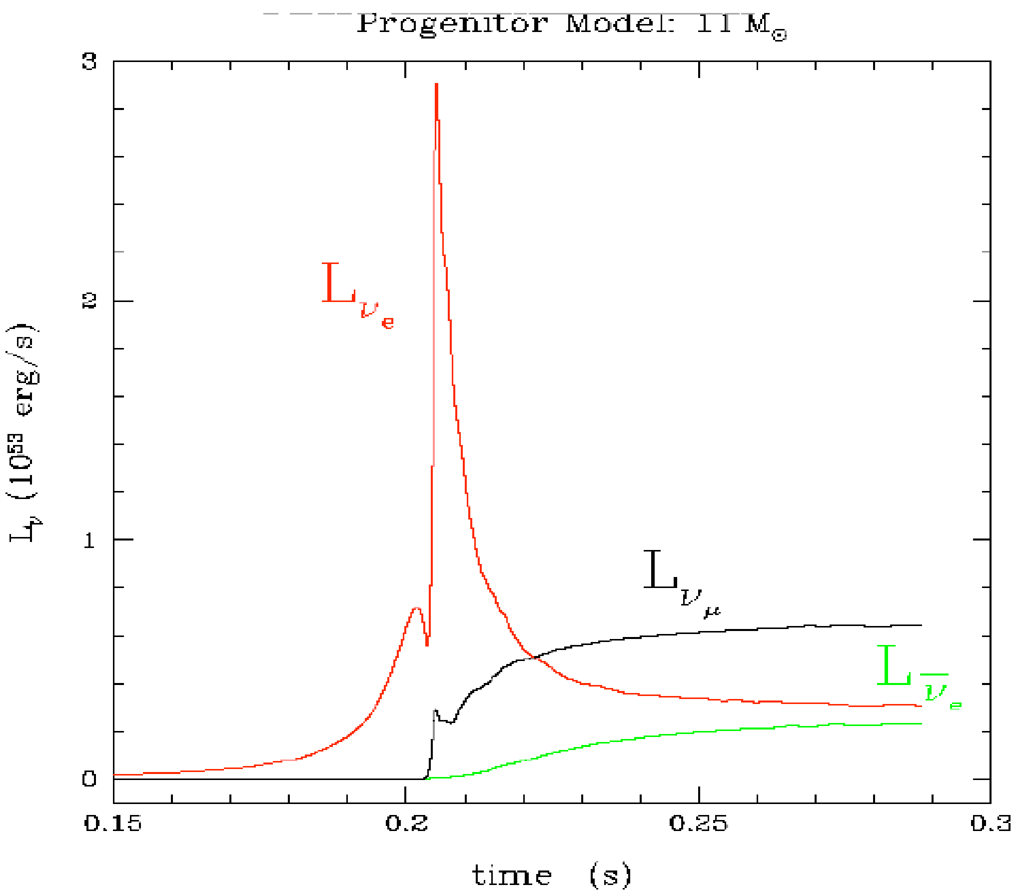
Courtesy of Tom Weaver

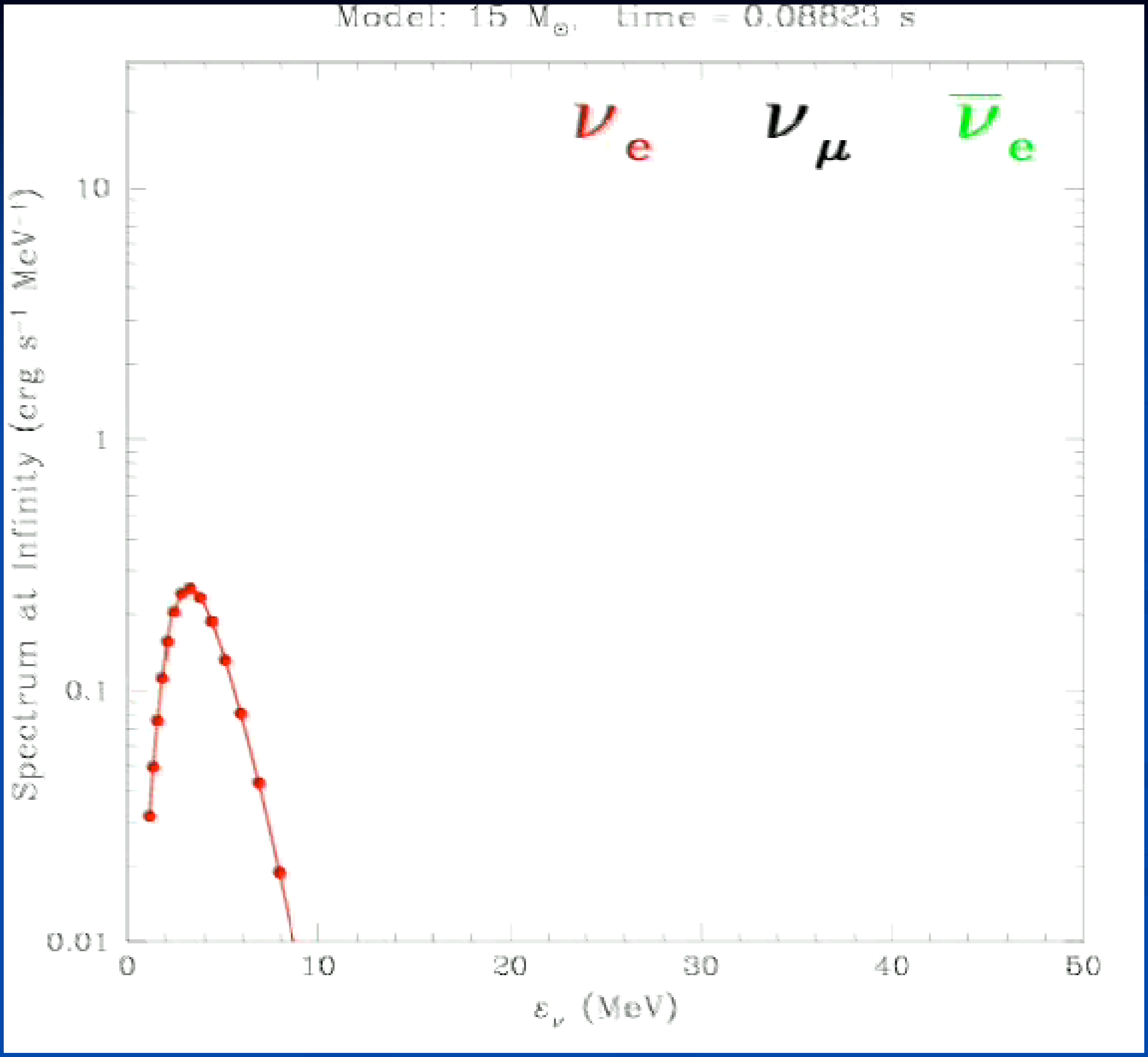
Onion Skin Structure: The Mote in the Eye of the Storm




Progenitor Star
6x10^8 km
H
Si
Iron Core
6x10^3 km
Collapse of Core
Early Supernova
30,000 - 60,000 km/s
Bounce Shock
2x10^3 km
ν-SPHERE
Hot, extended mantle
DENSE CORE
2x10^2 km
Early Protoneutron Star
30 km
DENSE CORE
Late Protoneutron Star

Breakout Burst of Neutrinos: Precision Boltzmann Transfer





Model: 15 $M_{\odot}$, time = 0.08823 s
ν_e
ν_μ
$\bar{\nu}_e$
Spectrum at Infinity (erg s^{-1} MeV^{-1})
10
1
0.1
0.01
0
10
20
30
40
50
ε_ν (MeV)


Flux Vectors
ν_e
21.01 MeV
$\Omega = 0$
Time = -194.5 ms
Distance = 250.0 km
Entropy
0
200
400
600
800
1000
1200

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)
- SASI-aided (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)
- Nuclear-burning aided? (Mezzacappa et al. 2006)
- MHD Jet Explosions (e.g., Burrows et al. 2007b)
- The Key feature of almost all mechanisms is the **Breaking of Spherical Symmetry**

Current Status of the Neutrino Mechanism

- Spherically-symmetric neutrino mechanism might work for O/Ne/Mg cores (e.g., 8.8-solar-mass model: Kitaura et al. 2006), powered by neutrino-driven wind, but underenergetic: ~10^{50} ergs
- 11.2-solar-mass model of WHW (2002) might explode by the convective/SASI (2D) neutrino-driven mechanism (Buras et al. 2006), aided by density cliff, but underenergetic: >10^{49} ergs (mantle binding?), other progenitors very problematic (fizzle, but 3D??)
- Accretion-Induced Collapse (AIC): neutrino-driven jet/wind mechanism; underenergetic (~ few x 10^{50} ergs) as well (Dessart et al. 2006)
- Note: Janka's recent 15 solar mass model? Neutrino-driven, long timescale (580 ms)
- 3D may be needed to explode other/most progenitors

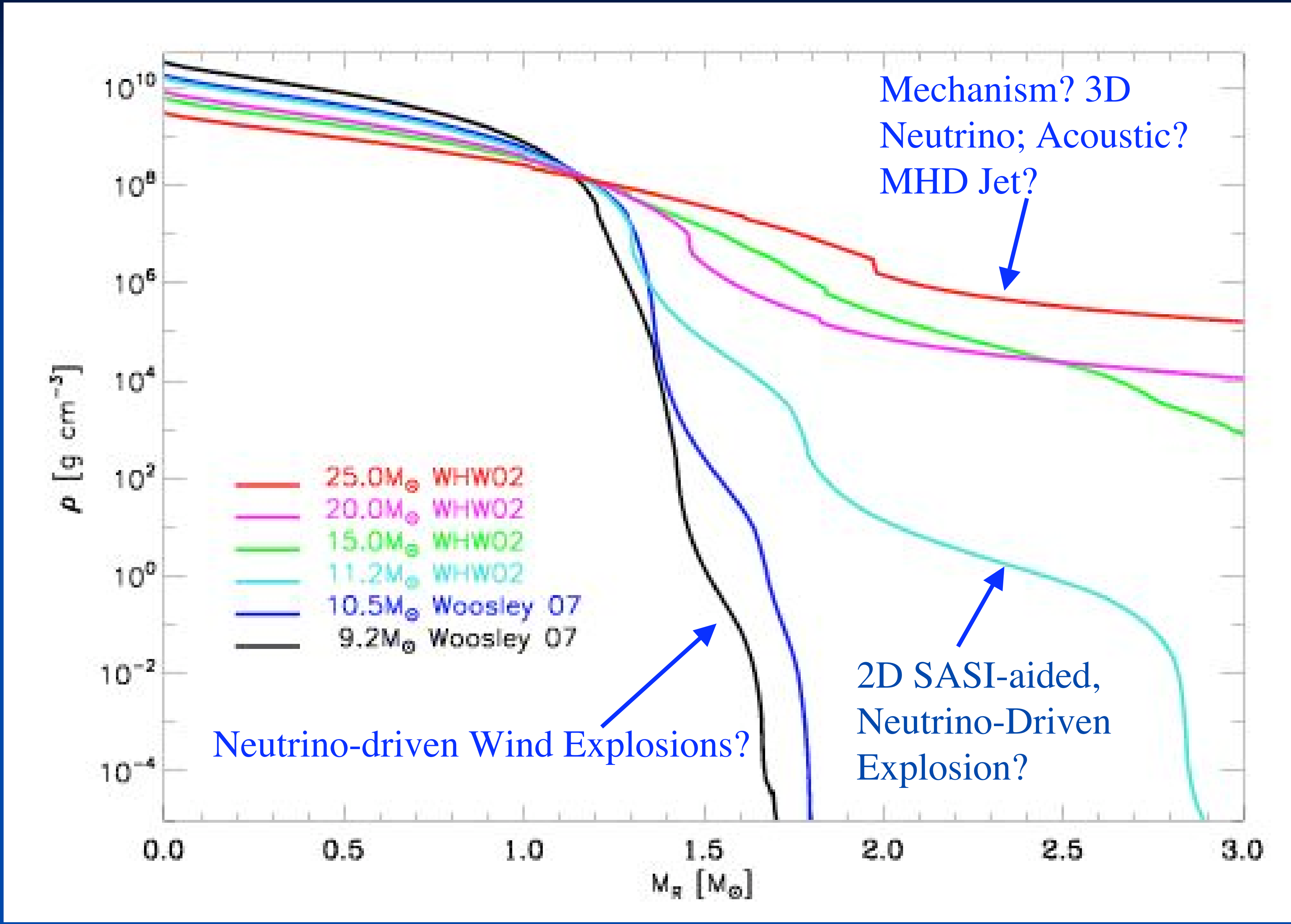
Issues/Problems

- Neutrino-driven wind explosions are "under-energetic": ~0.05 to 0.2 Bethes, or don't work (in 2D): What of M > ~12 solar masses?
- 3D effects may be needed to save the day for the neutrino mechanism for most progenitors and to achieve ~1 Bethe energies (last chance?); but note Janka's 15 solar mass model, this meeting ; Better and Multi-D Neutrino Transport?
- Long delay for Core-oscillation/Acoustic mechanism: Does something else precede it? Can the core modes achieve the required amplitudes?
- MHD Jets: Rapid Rotation necessary

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

- 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; MHD
- Axially-symmetric; Rotation
- Flux-conservative; smooth matching to diffusion limit
- Velocity-dependent terms: advection included (DI/dt), but not yet Doppler/Aberration terms
- Parallelized in energy groups; almost perfect parallelism
- Energy redistribution: explicit
- New Implicit Hydro version
- Livne, Burrows et al. (2004), Ap.J., 609, 277
- Walder et al. (2005), Ap.J., 626, 317; Ott et al. (2004) Ap.J., 600, 834
- Burrows et al. (2006), Ott et al. (2005); Dessart et al. 2005ab

Density Profiles of Supernova Progenitor Cores



Neutrino-Driven Wind Explosions: Low Mass and AIC

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

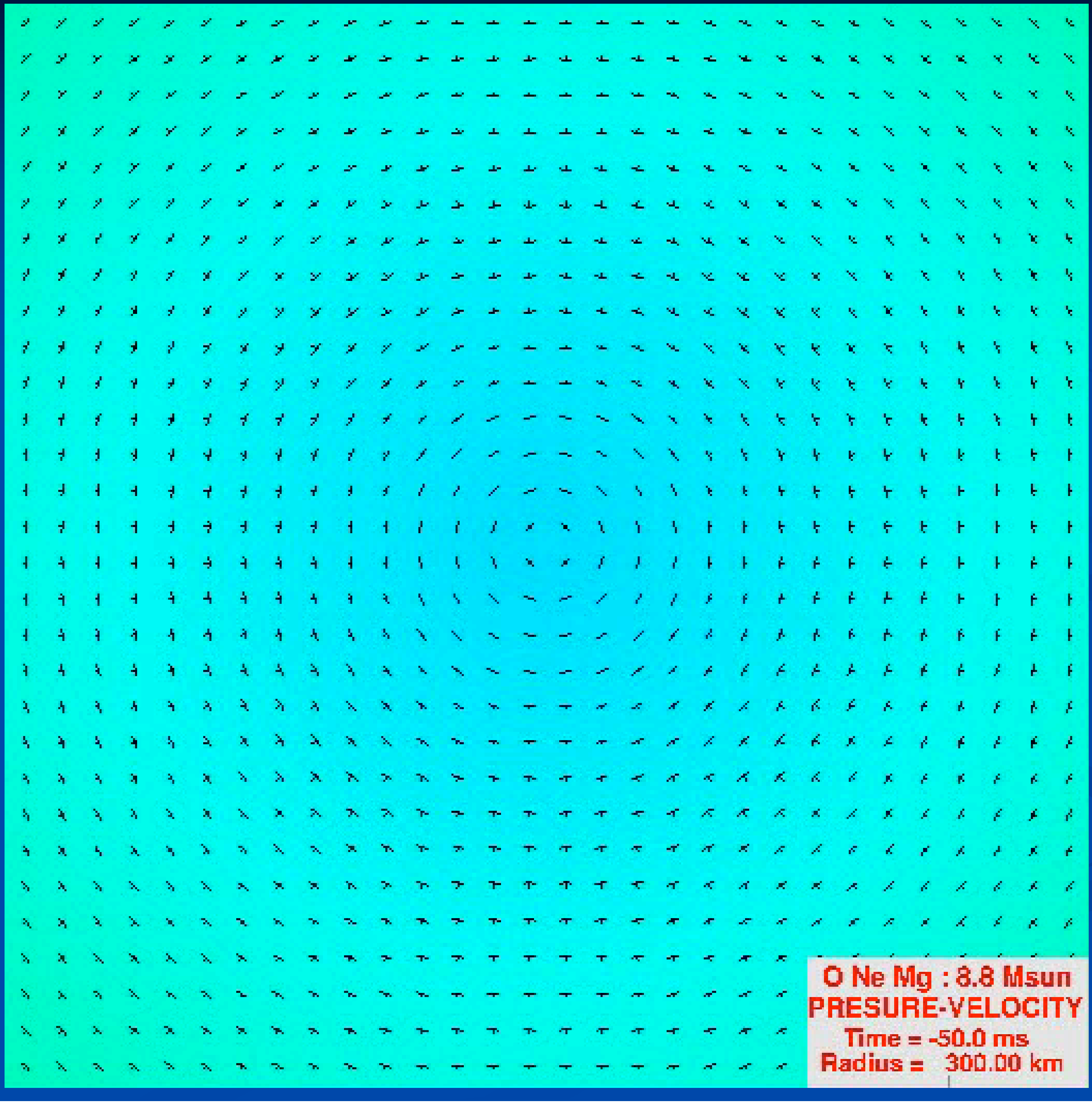
First shown by Kitaura et al. 2006

NOTE WIND THAT FOLLOWS:

TWO SHOCKS!

Dessart, Burrows et al. 2007;

Burrows 1987

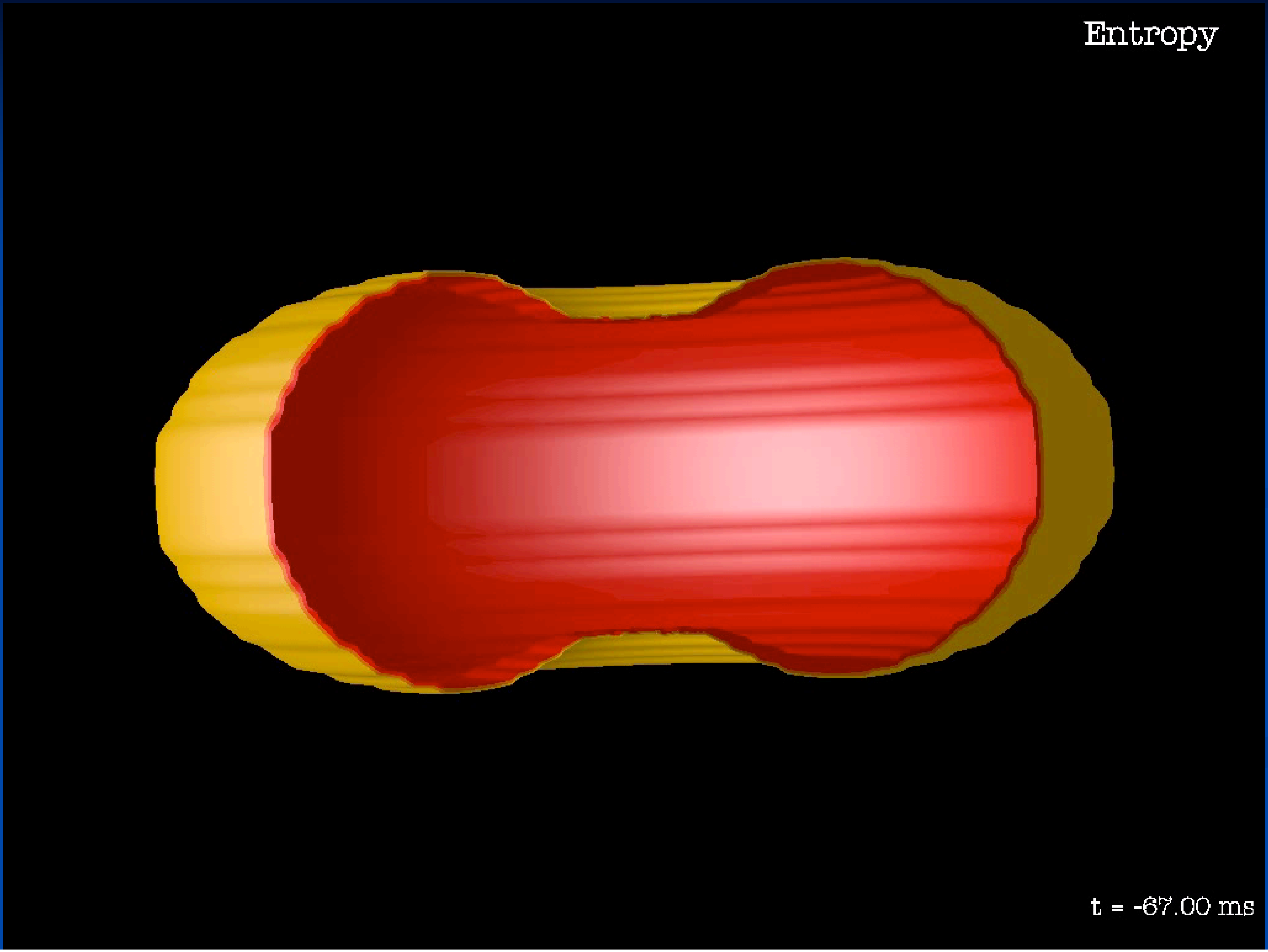


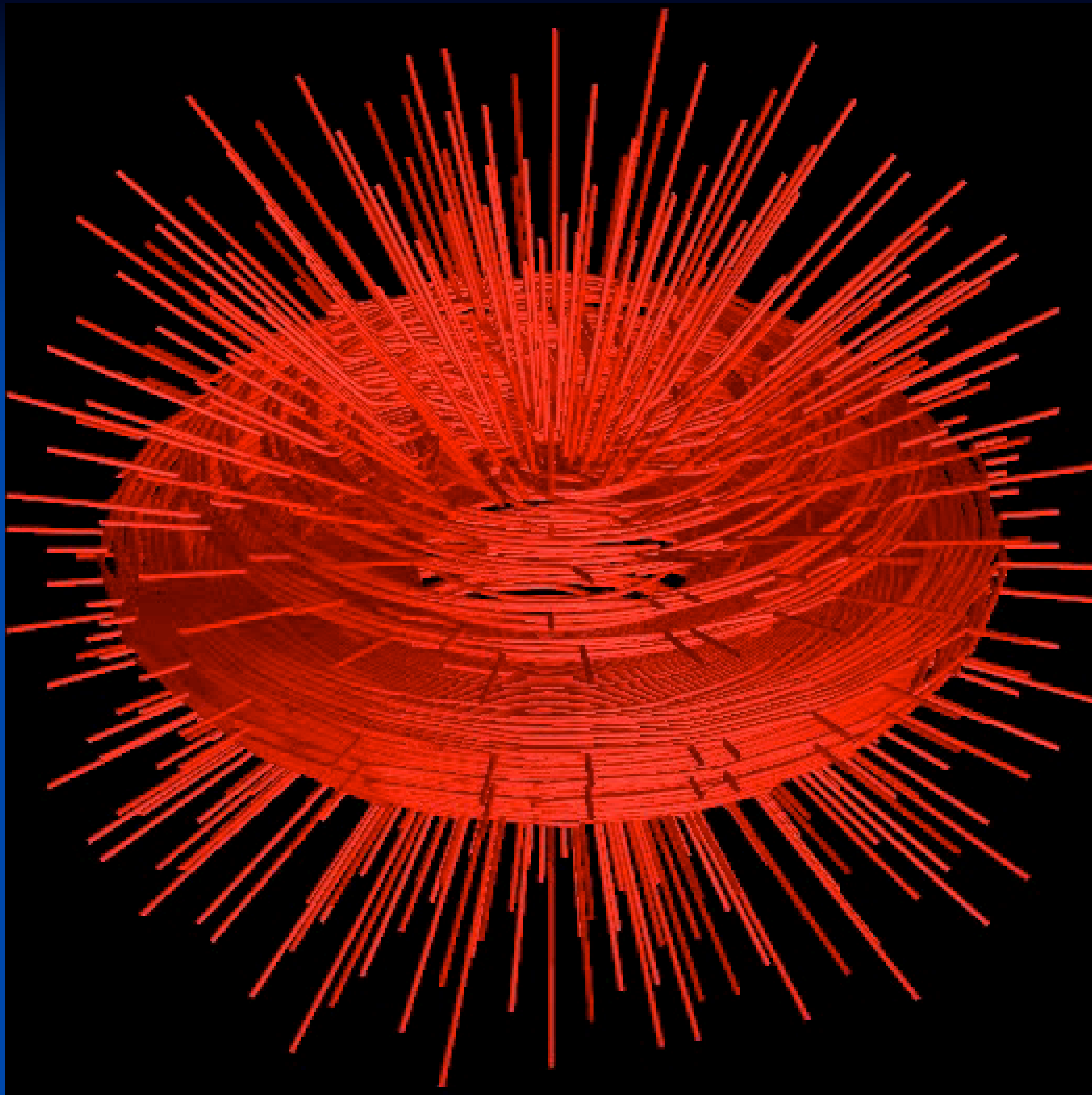
Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

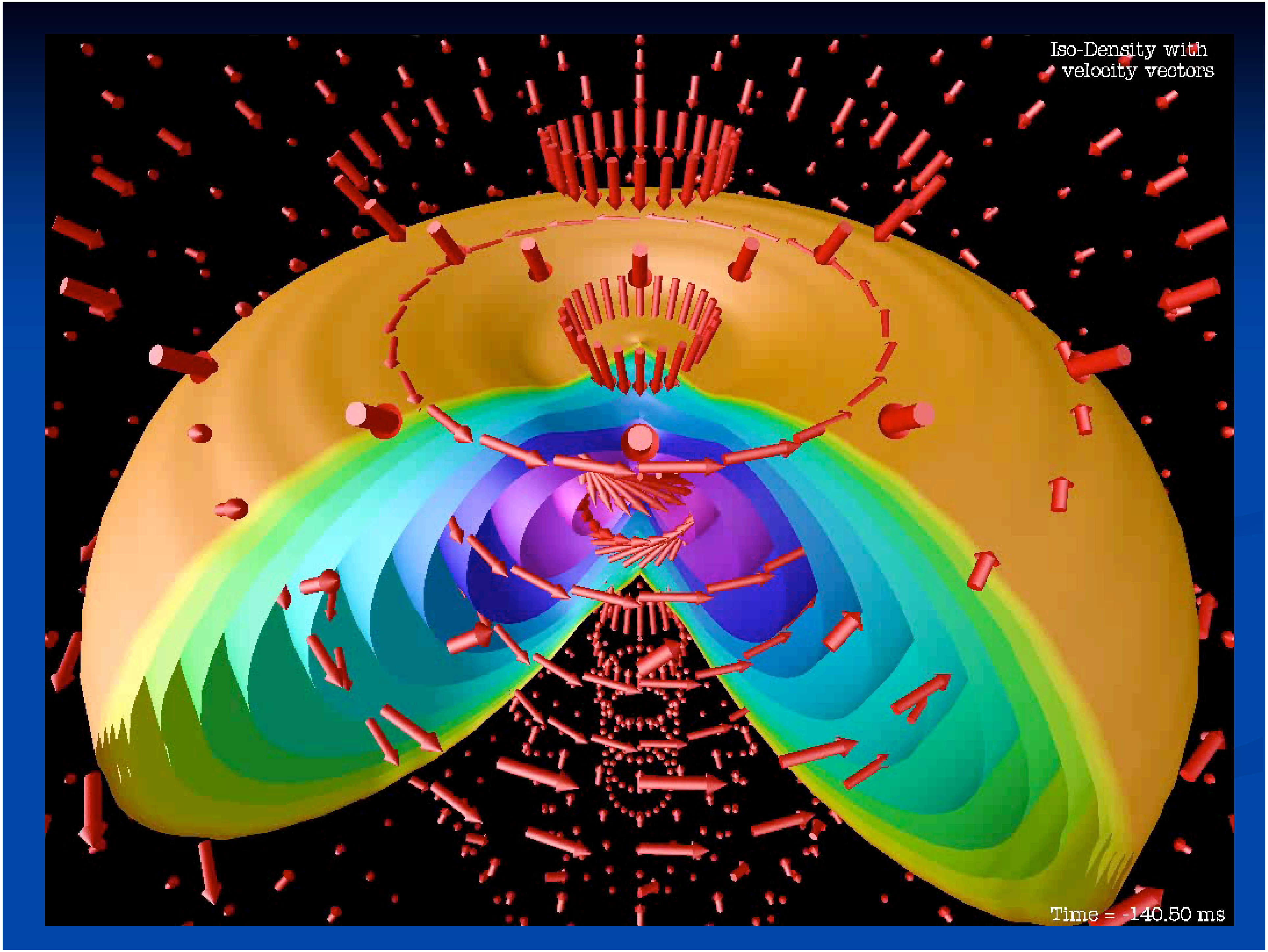
Dessart, Burrows, Ott, Livne, Yoon, & Langer 2006

Rapid Rotation!

AIC: 1.92 solar masses:



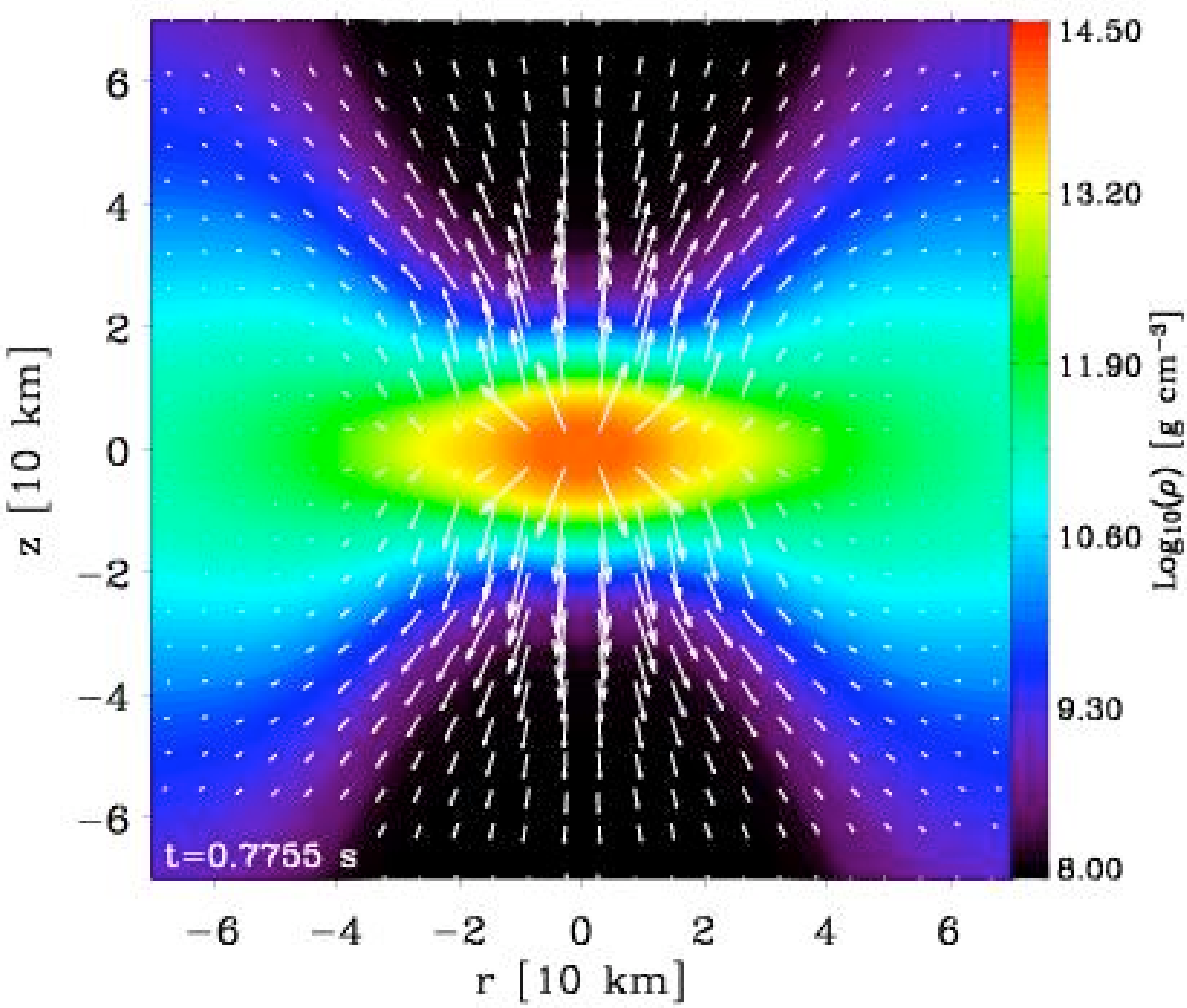



Iso-Density with
velocity vectors
Time = -140.50 ms

Anisotropic Neutrino Fluxes due to Rotation

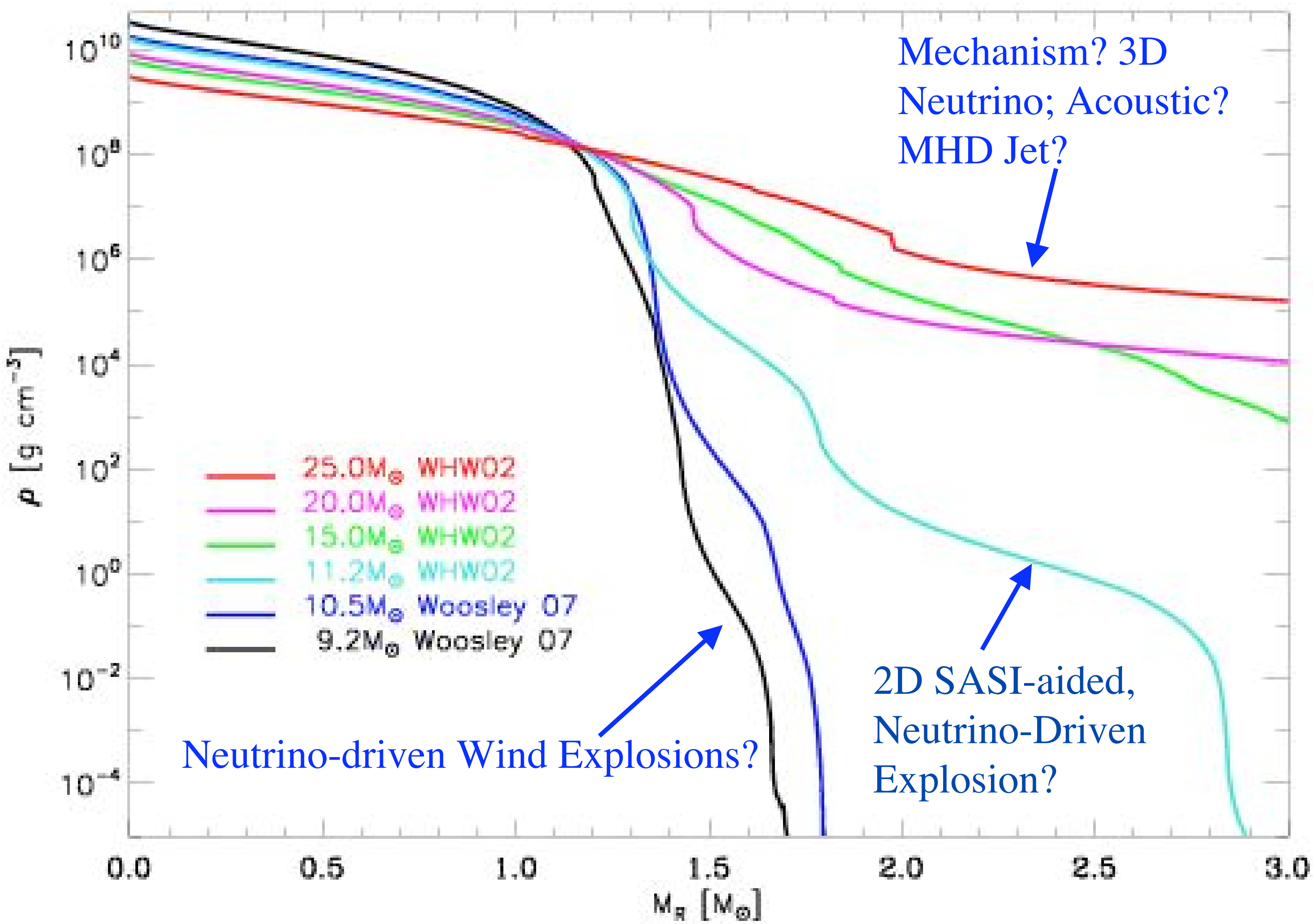
2D Electron Neutrino Fluxes for 1.92 solar mass AIC model:

Rapid Rotation!

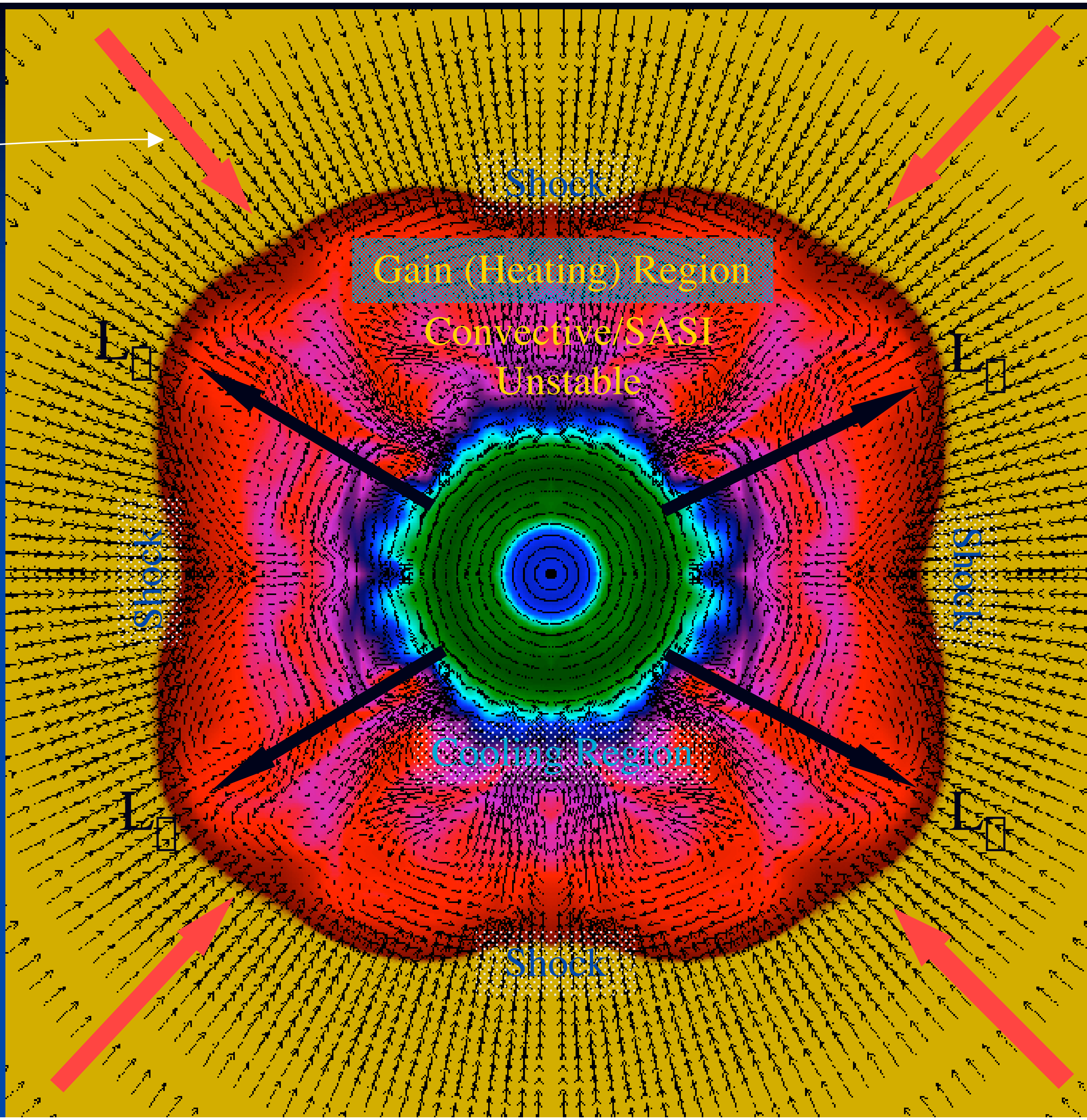


AIC
with
MHD

Density Profiles of Supernova Progenitor Cores



$\dot{M}$



L_ν vs. $\dot{M}$

τ_{adv} vs. τ_ν

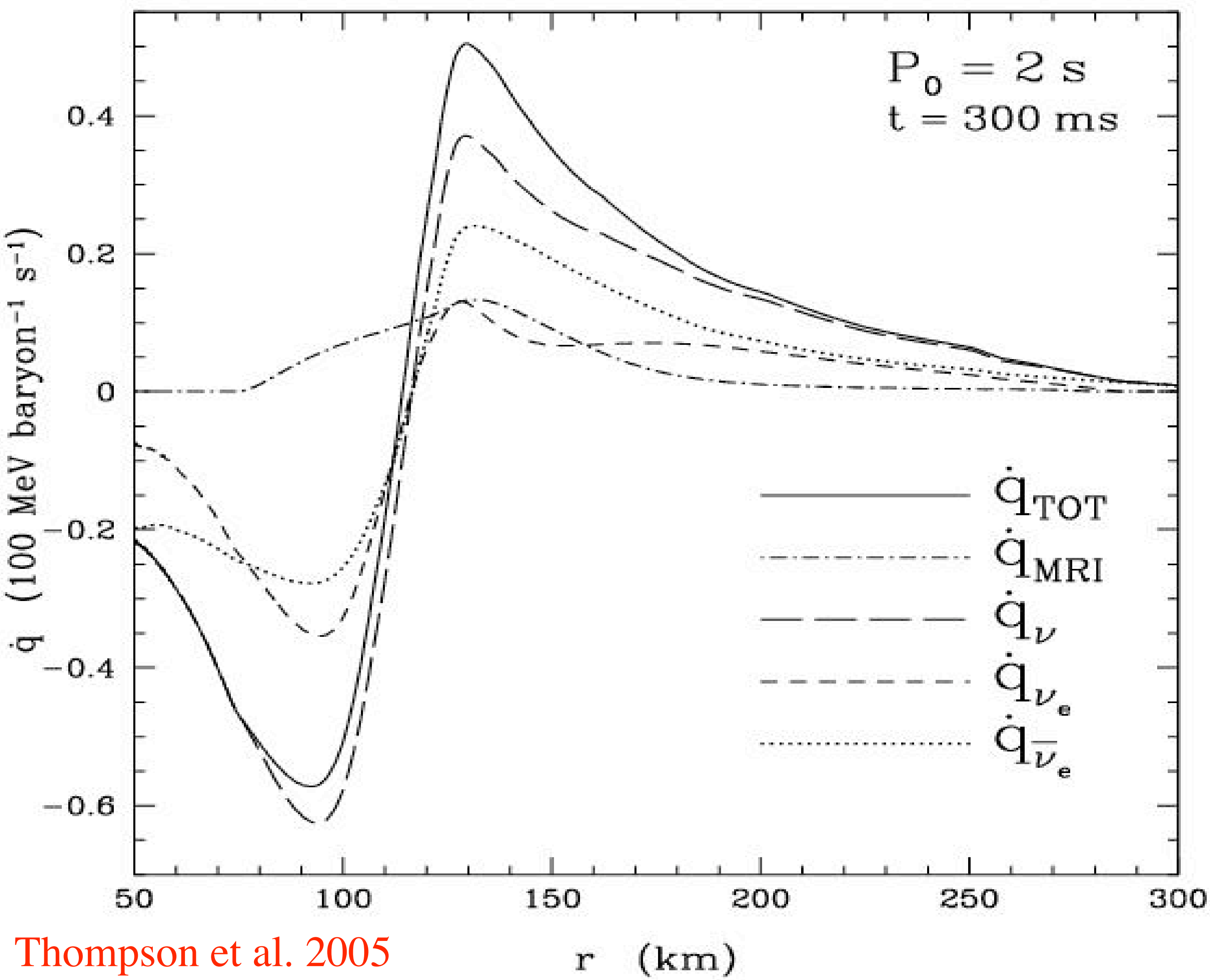
(TQB 2005)

τ_{adv} :

2D/3D > 1D

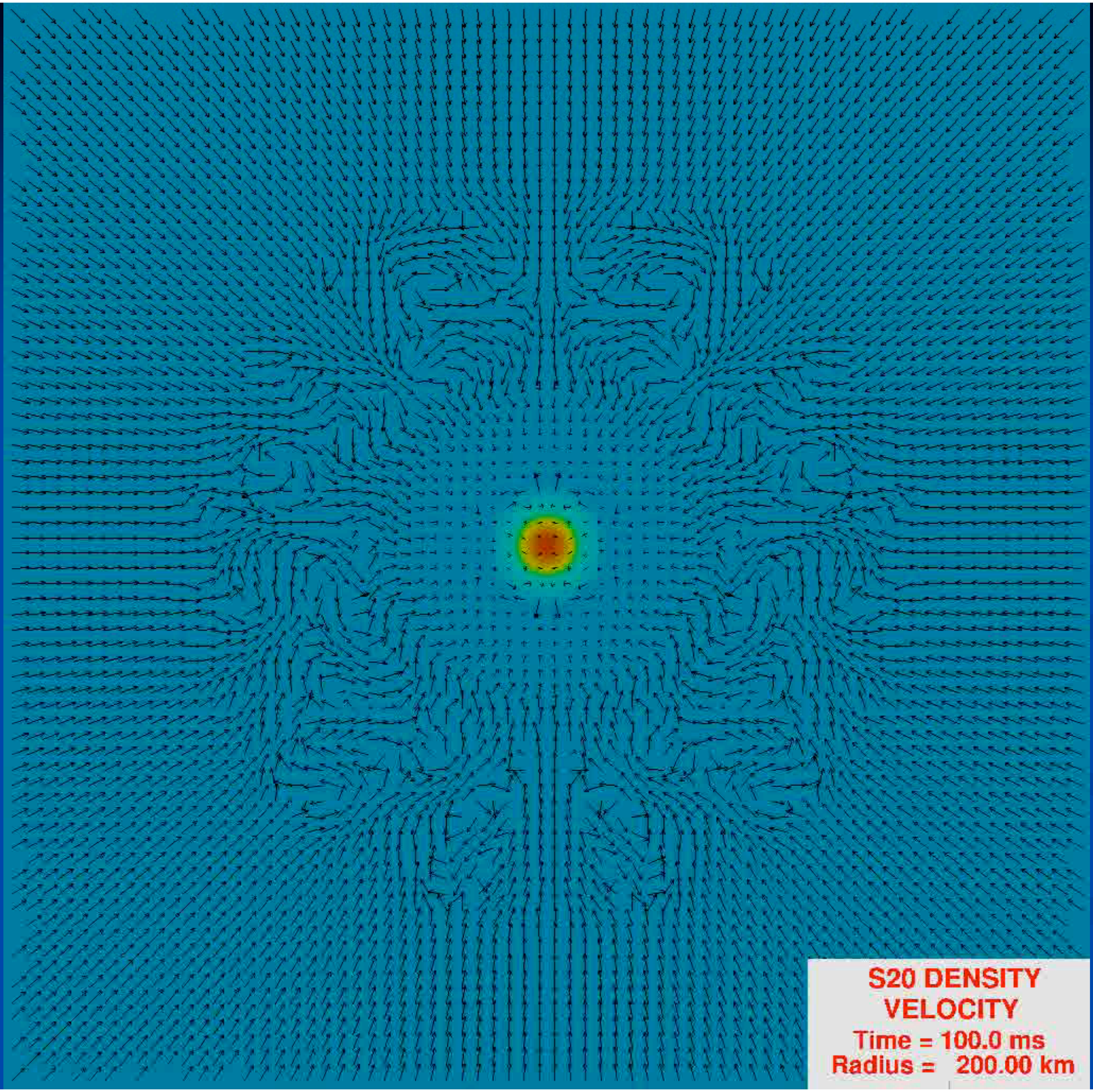
What happens in 3D?

Heating and Cooling; The Effect of an Extra Source



Thompson et al. 2005

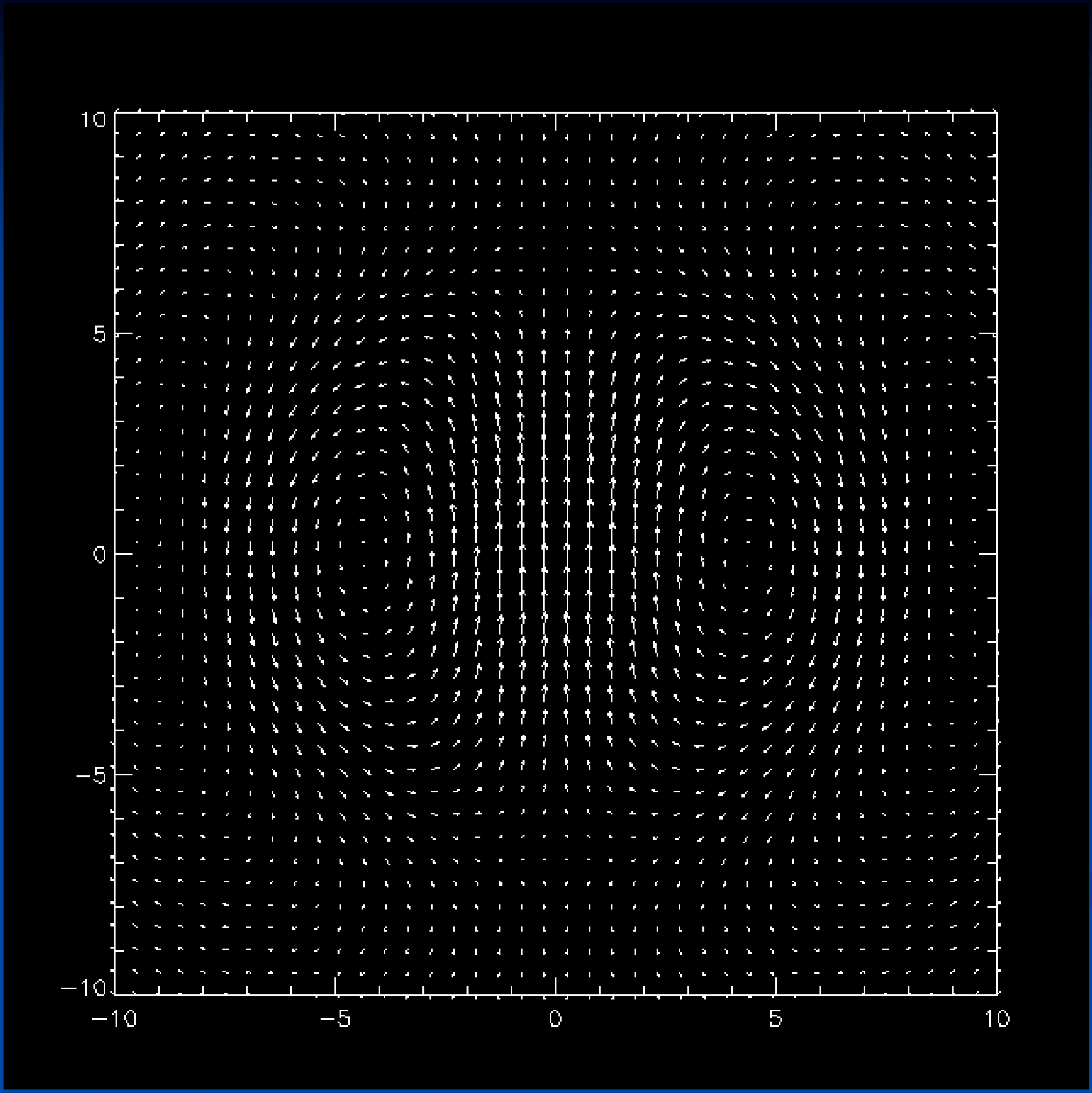
But,
in
3D?

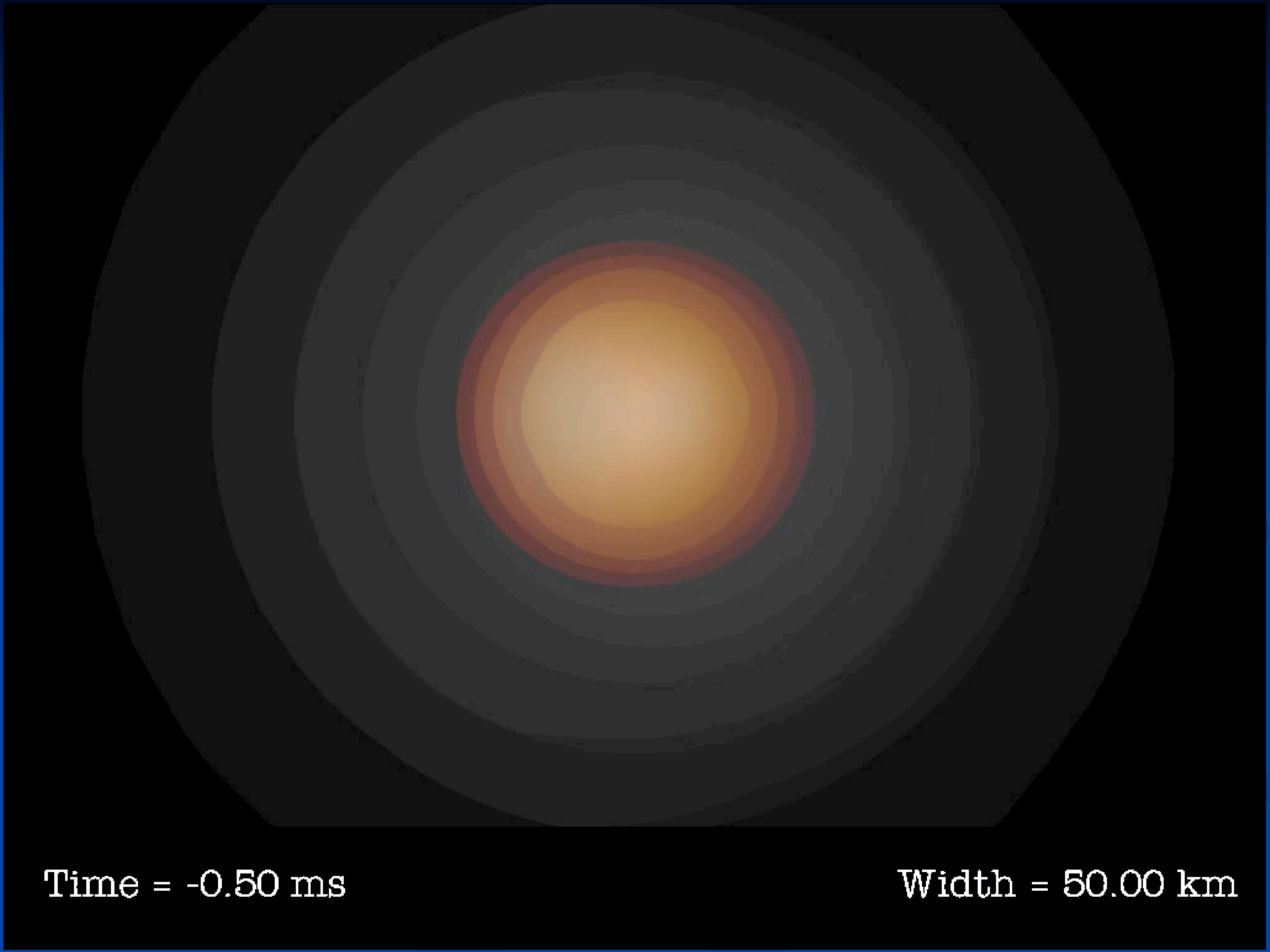


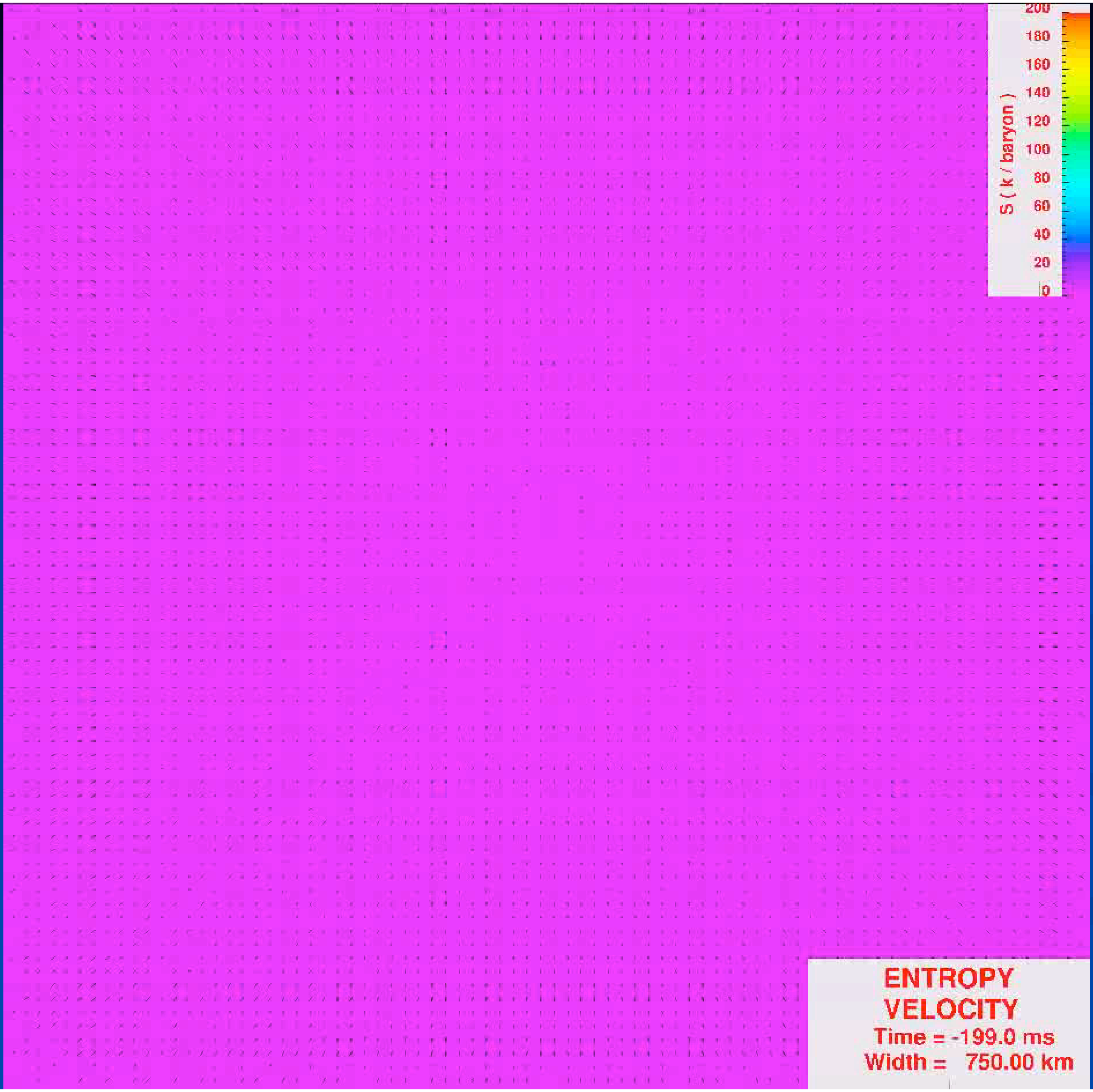
Core Oscillation/Acoustic Power Mechanism

Analytic l=1

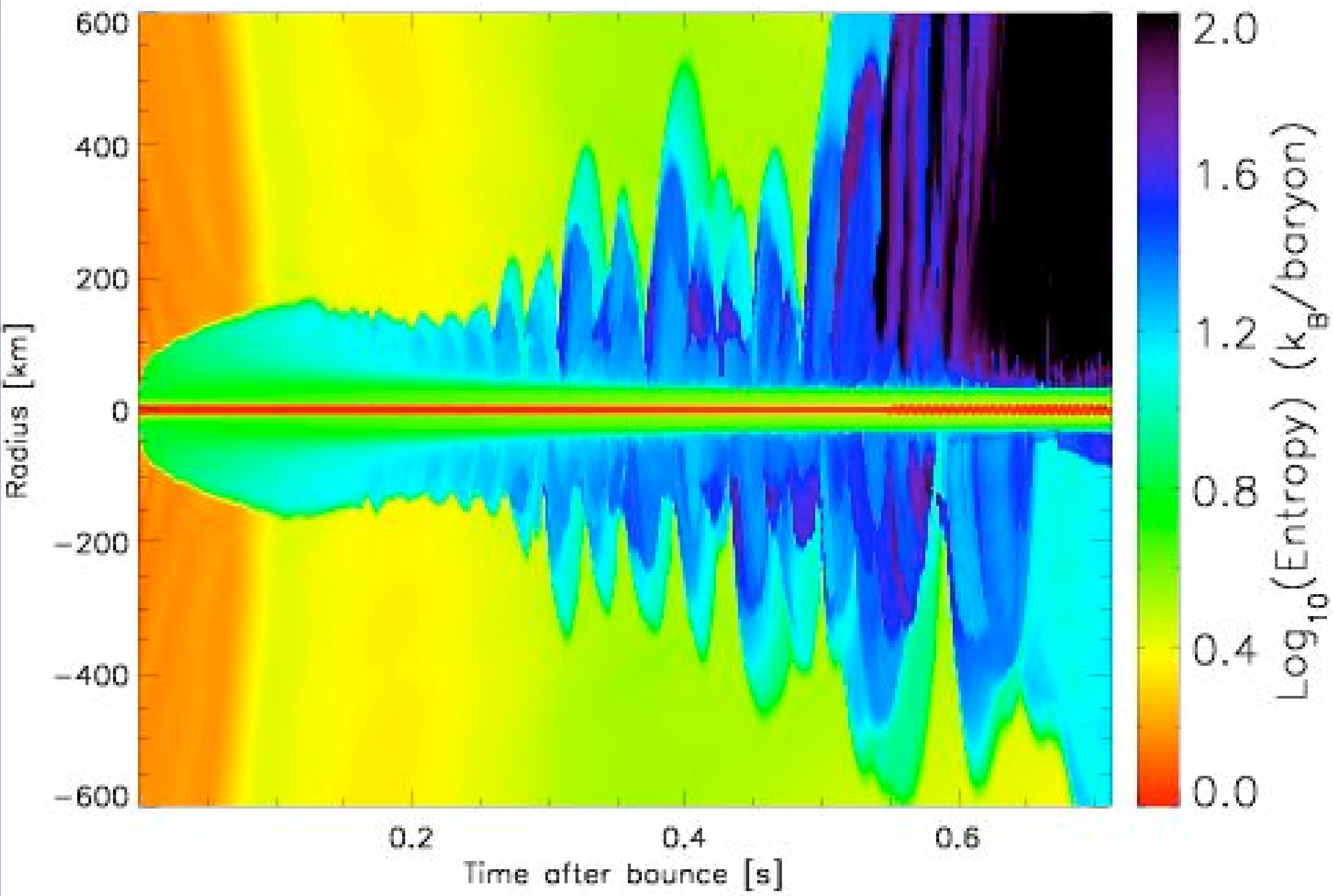
g-mode oscillation:

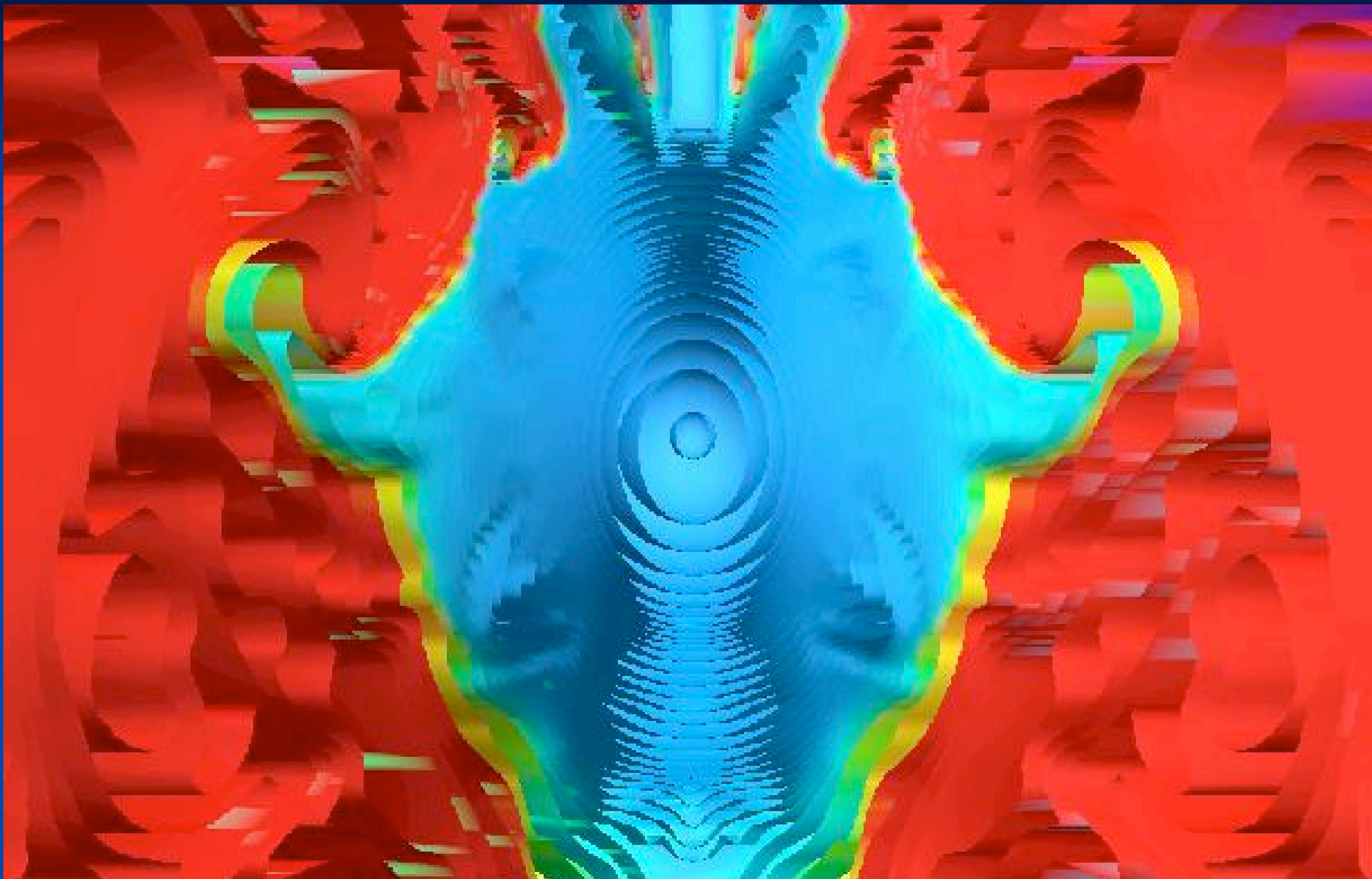



Time = -0.50 ms
Width = 50.00 km

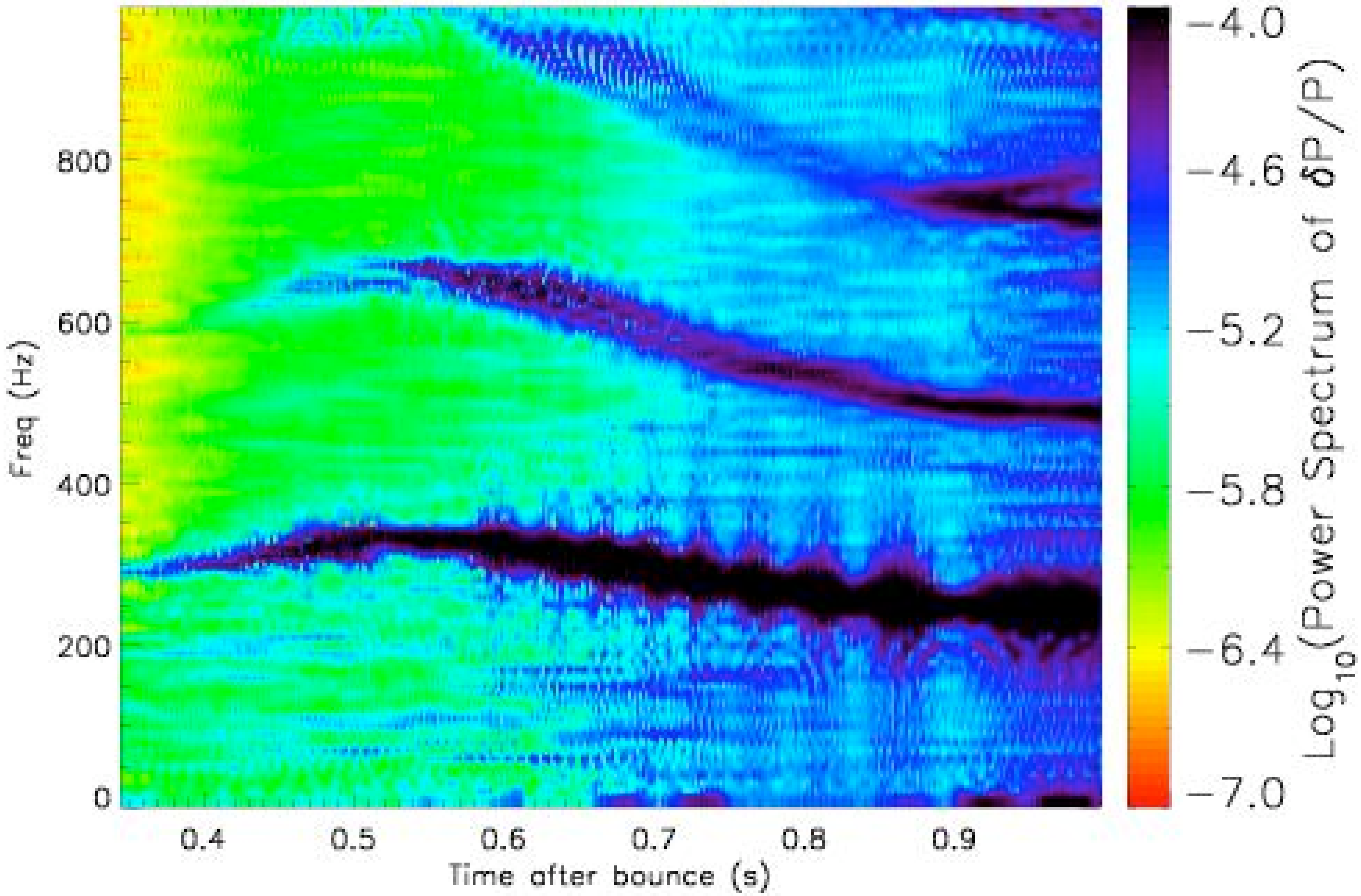

S (k / baryon)
200
180
160
140
120
100
80
60
40
20
0
ENTROPY
VELOCITY
Time = -199.0 ms
Width = 750.00 km

Inner 600-km Look at the Advective-Acoustic Instability

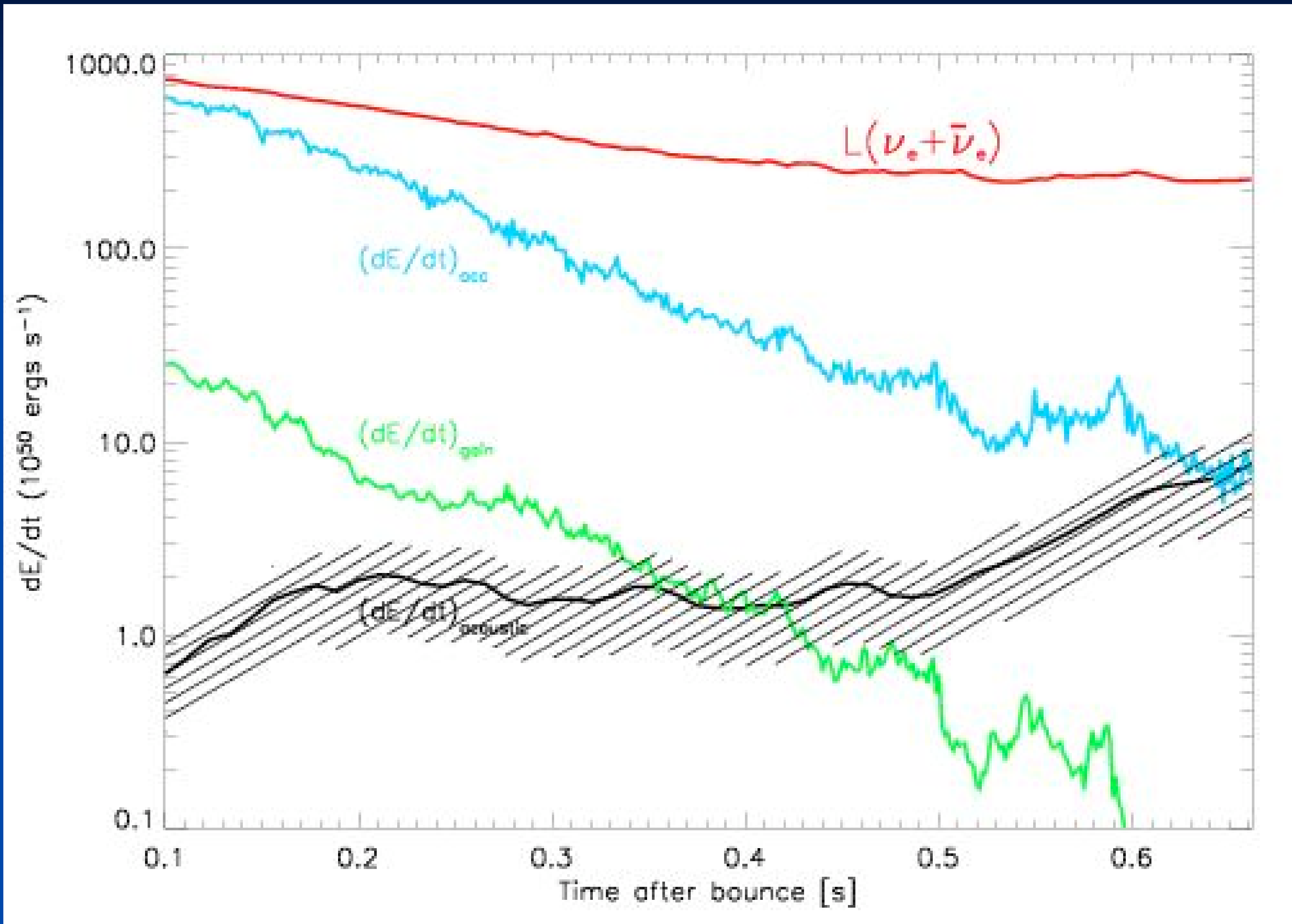




Frequency-Time Evolution of Pulsating Core at 30 km



Power Comparisons: 11 Solar-Mass model

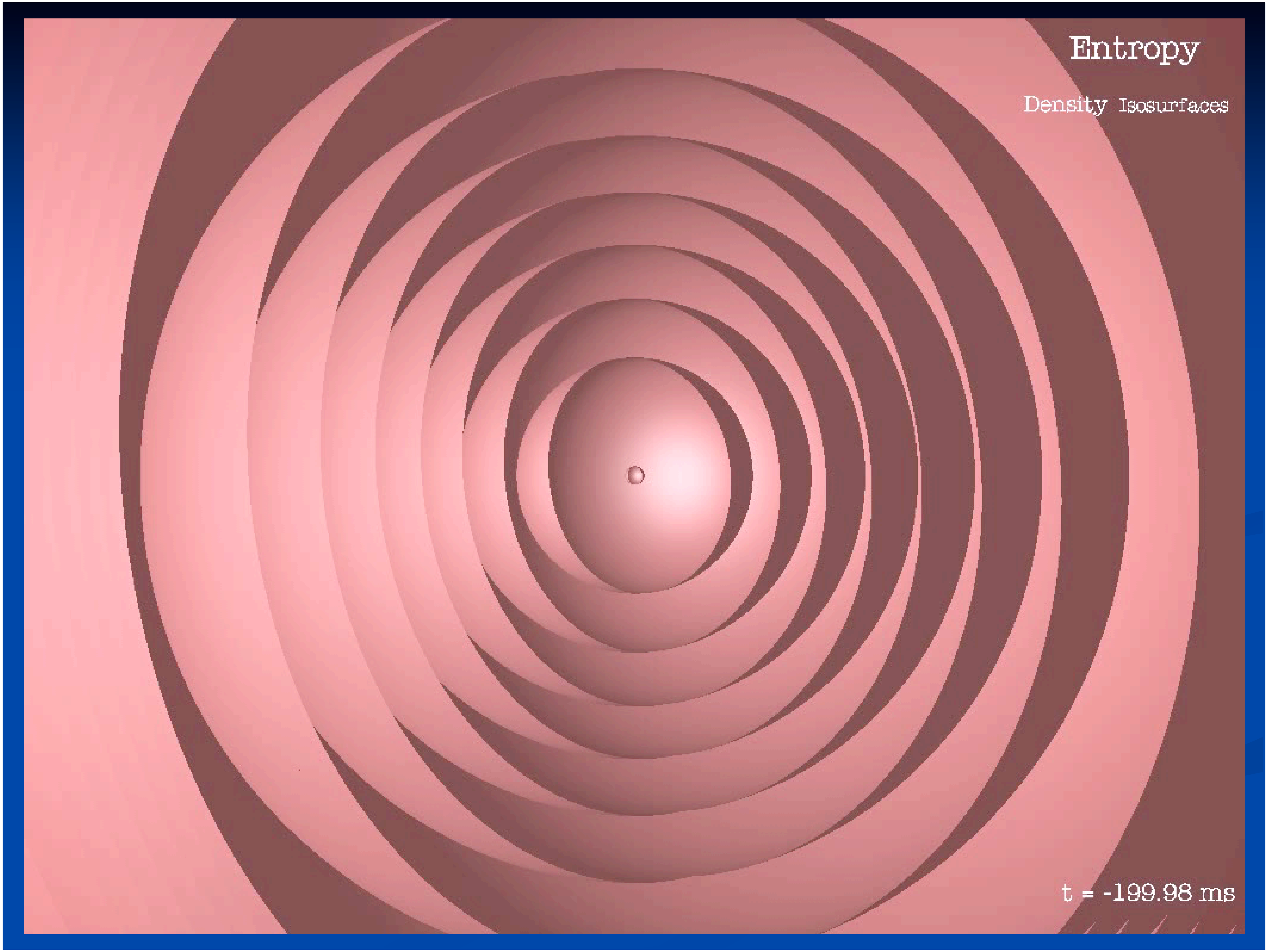


Key Features of Acoustic Mechanism

- "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?
- Recoil: Natural mechanism for pulsar kicks?

Computational Context Needed to Explore Acoustic Mechanism

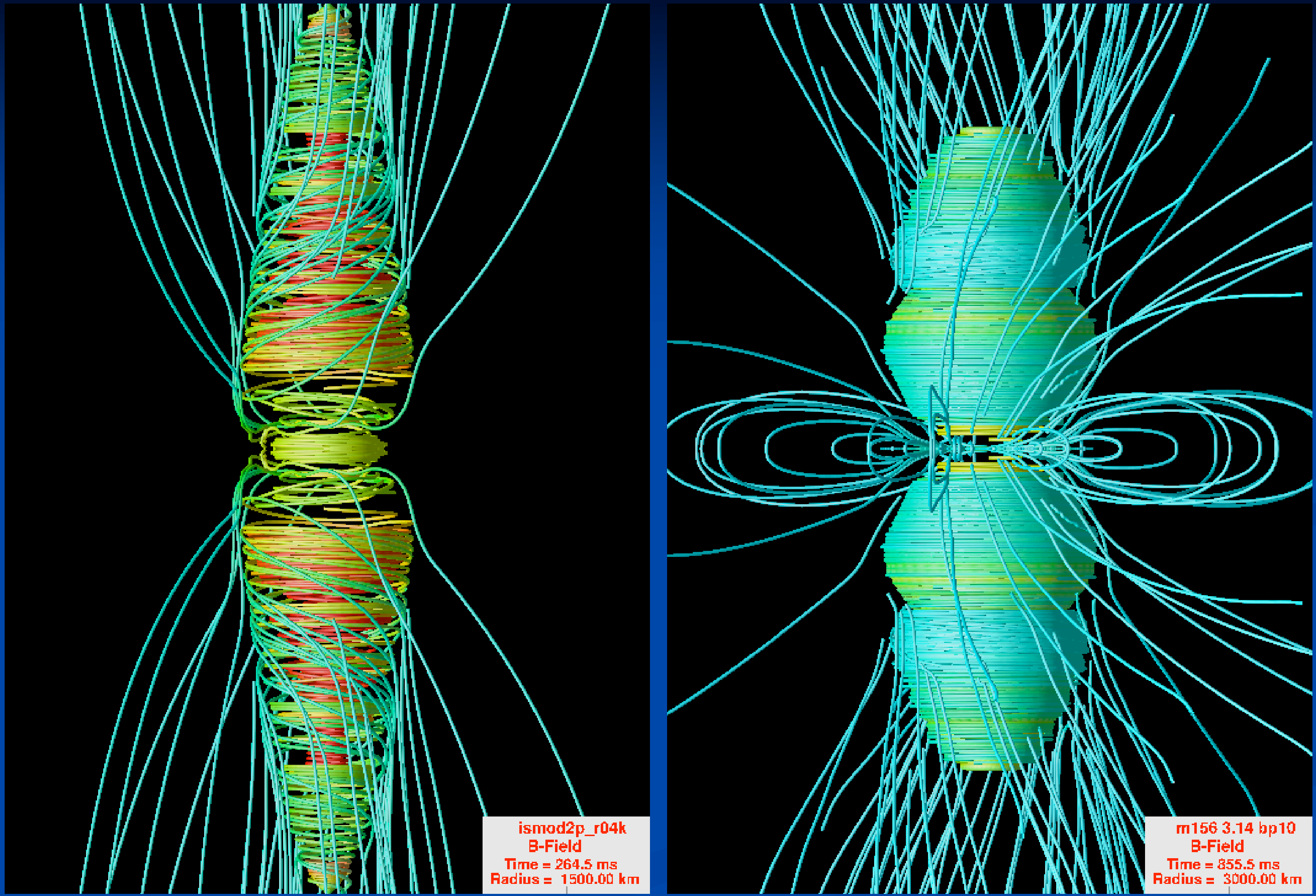
- Most calculations were stopped after 200-300 ms
- Other grid-based codes excised the core, did the calculations on a 90^{o} wedge, or followed the core in 1D, completely suppressing core oscillations
- One key was the computational liberation of the core to execute its natural multi-dimensional motions
- Another key was patience to perform the calculations to very "late" times
- Crucial capabilities: 1) Momentum conservation, 2) "Cartesian-like" grid in the core (Courant condition), 3) High-precision gravity solver, 4) Moving grid (to maintain high-resolution under core)
- But, are the g-mode amplitudes large enough to explode the star?

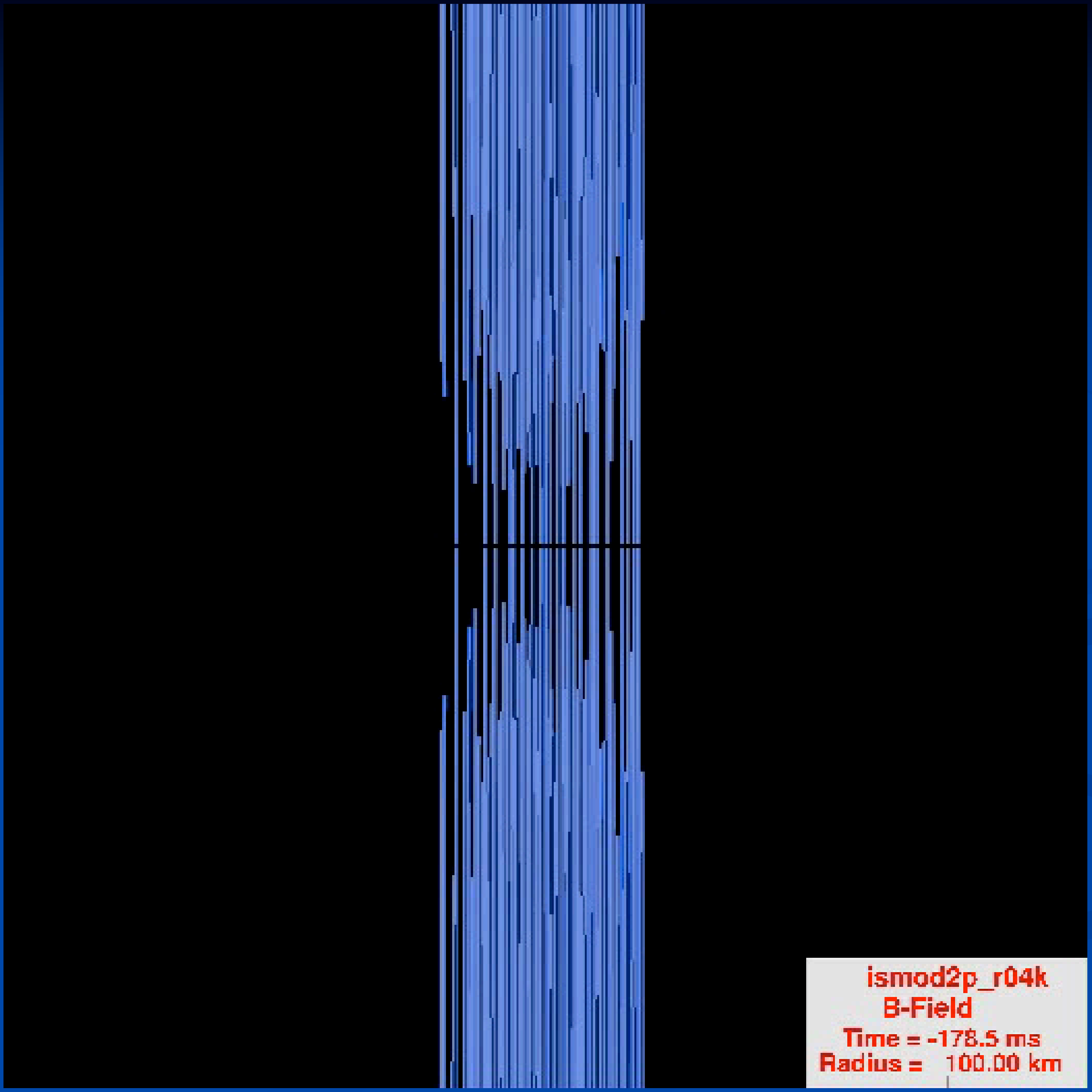

Entropy
Density Isosurfaces
t = -199.98 ms

MHD Jets and RMHD Simulations of Core Collapse: Rapid Rotation

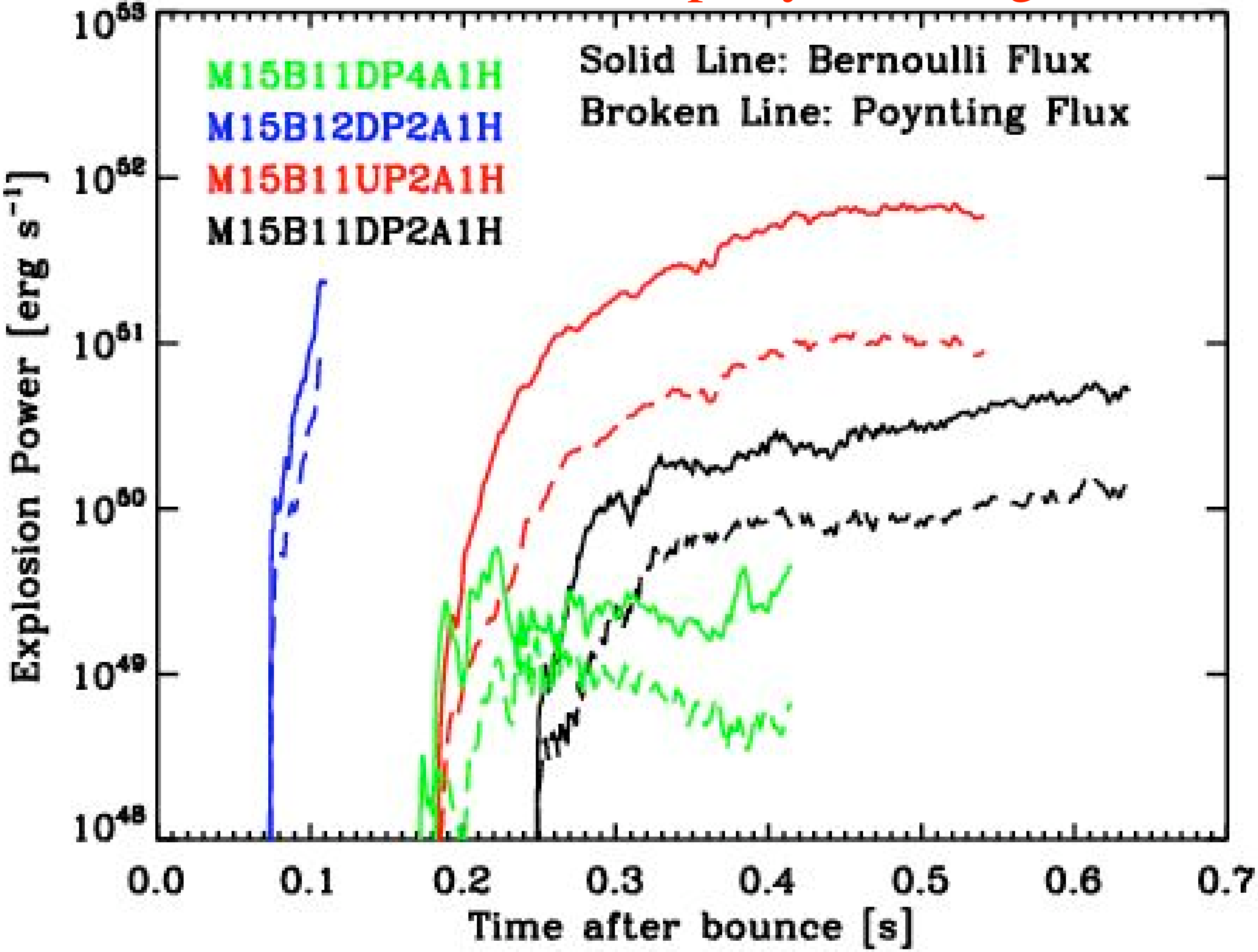
Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007

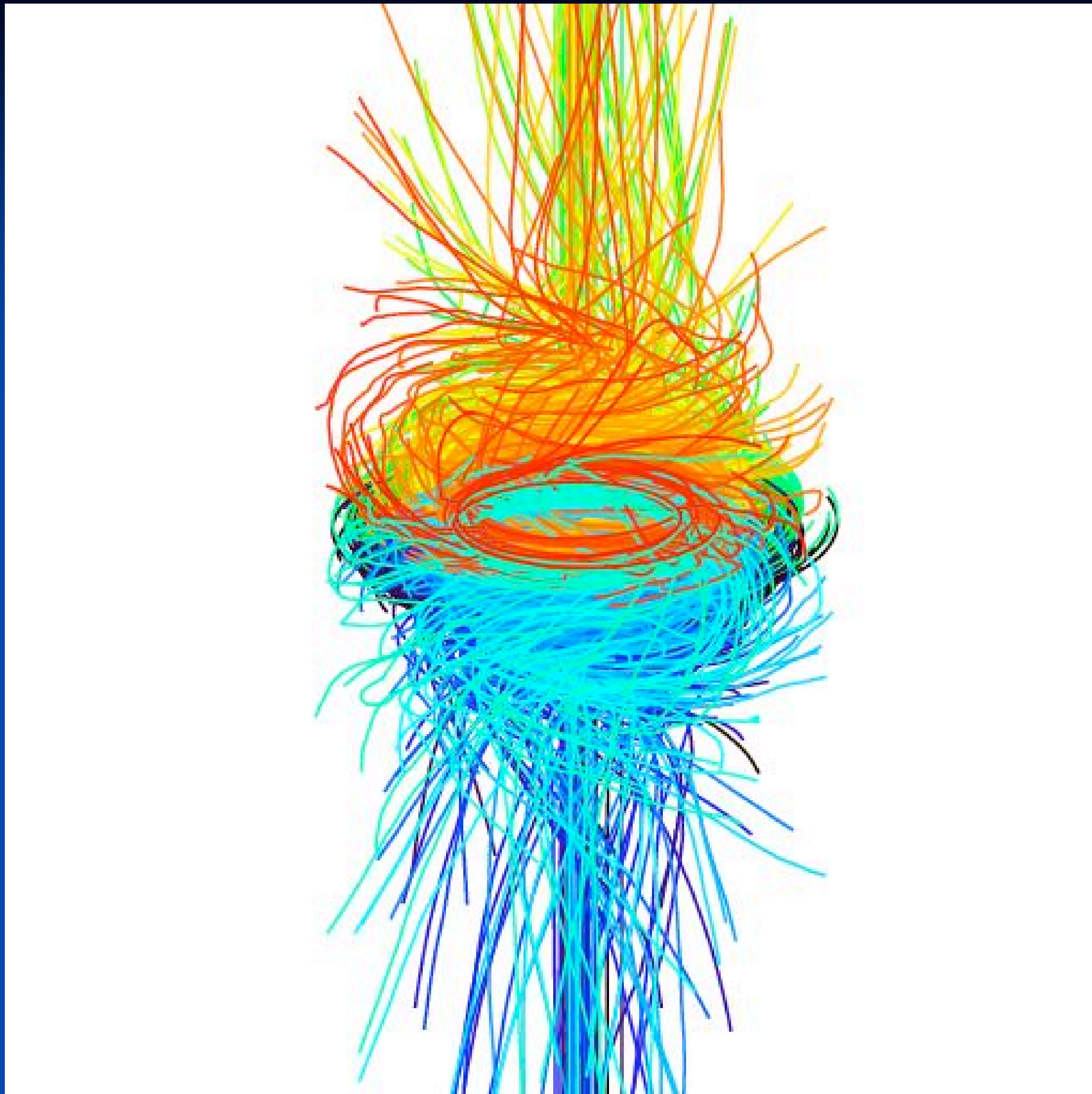
Rotation Winding, the MRI and B-field Stress effects

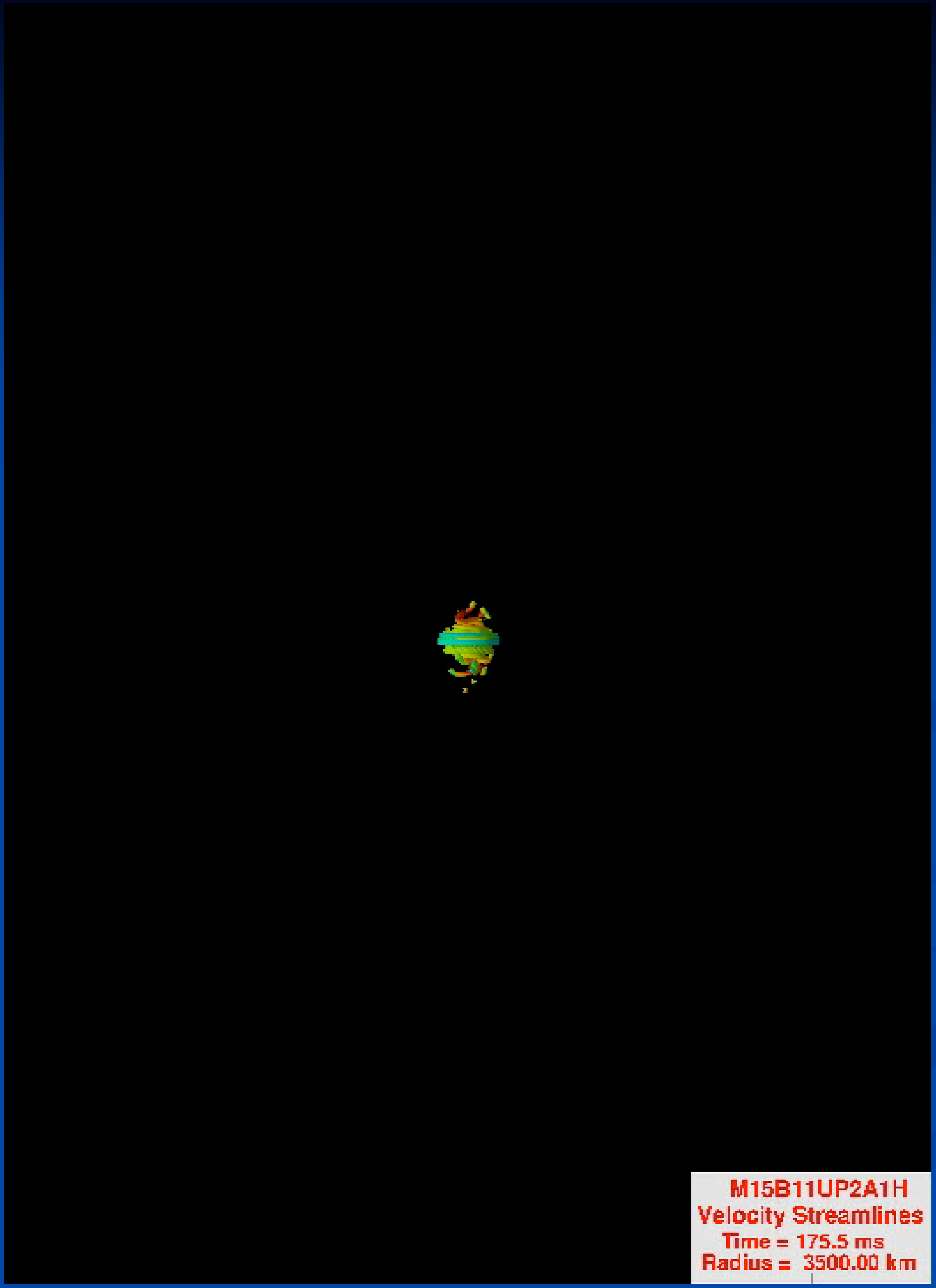

ismod2p_r04k
B-Field
Time = 264.5 ms
Radius = 1500.00 km
m156 3.14 bp10
B-Field
Time = 855.5 ms
Radius = 3000.00 km

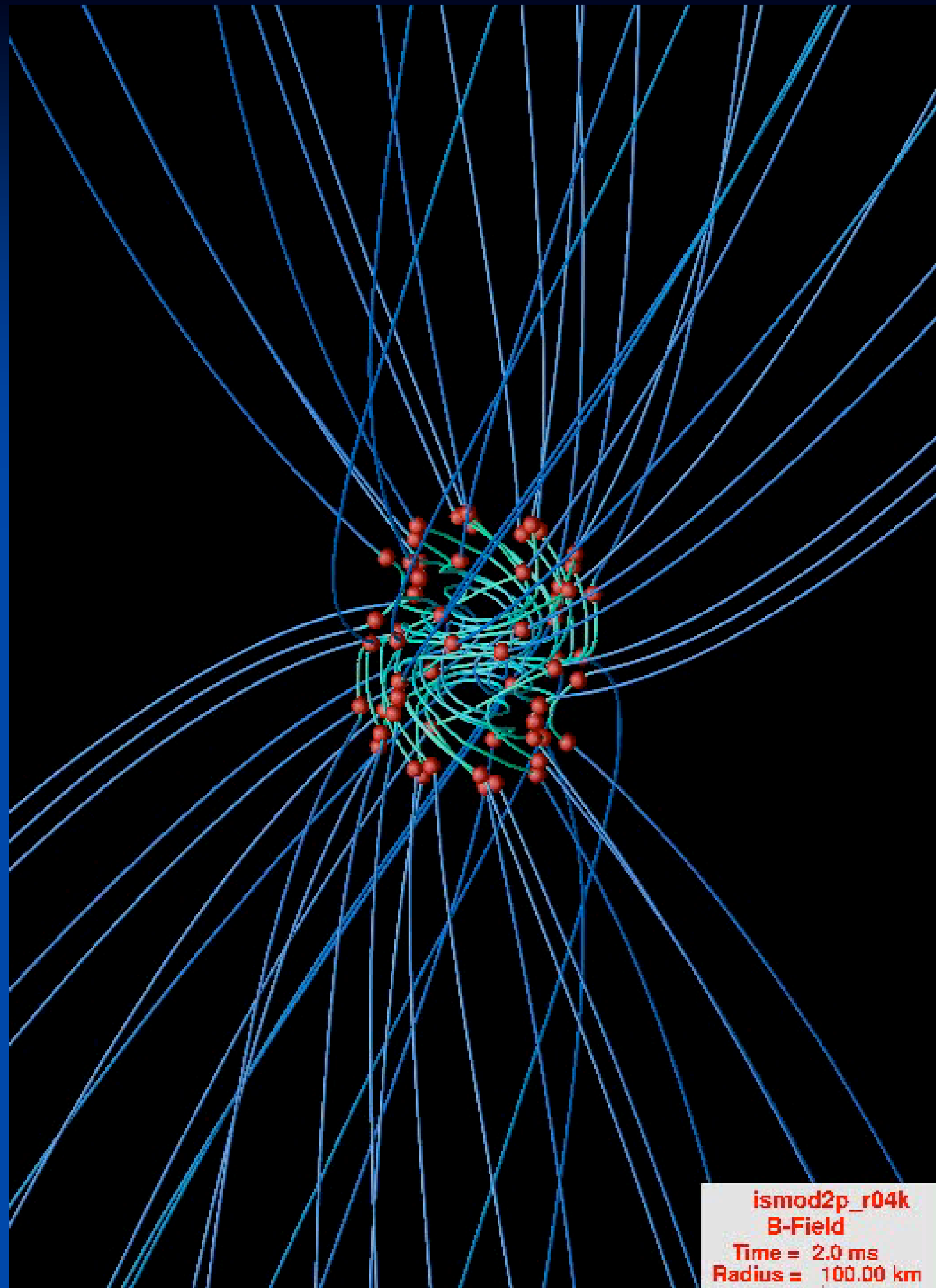

ismod2p_r04k
B-Field
Time = -178.5 ms
Radius = 100.00 km

MHD Jet Powers for Rapidly-Rotating Cores






M15B11UP2A1H
Velocity Streamlines
Time = 175.5 ms
Radius = 3500.00 km


ismod2p_r04k
B-Field
Time = 2.0 ms
Radius = 100.00 km

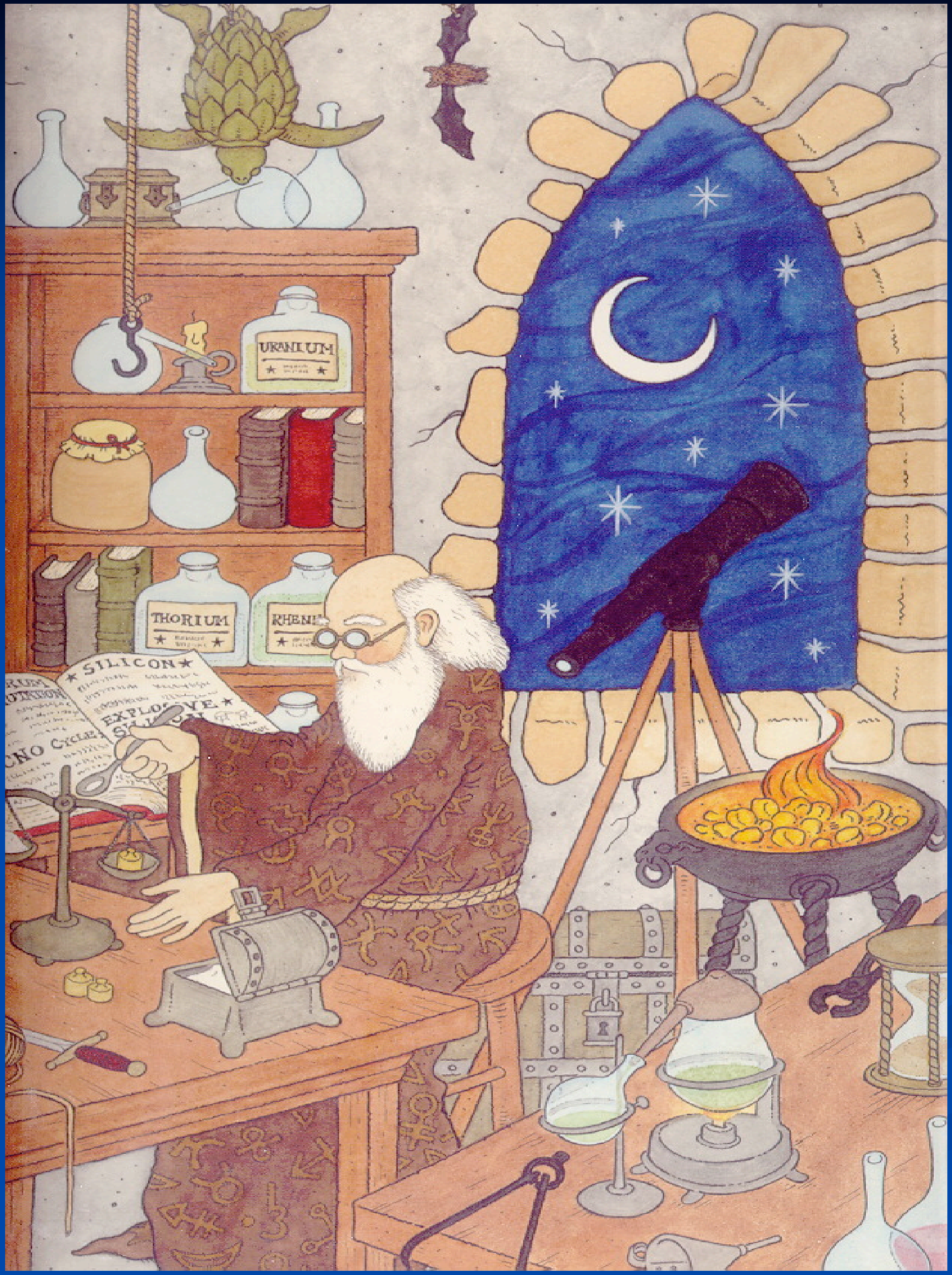
Questions: MHD Jets

- Initial models: Spin rates and B-fields?
- 3D simulations?
- MRI?
- Dynamo?
- Whither Pulsars/Magnetars? Final spins and B-fields? Spindown?
- Hypernova/GRB connection?
- Secondary MHD Jets/low-energy explosion after other main explosion?

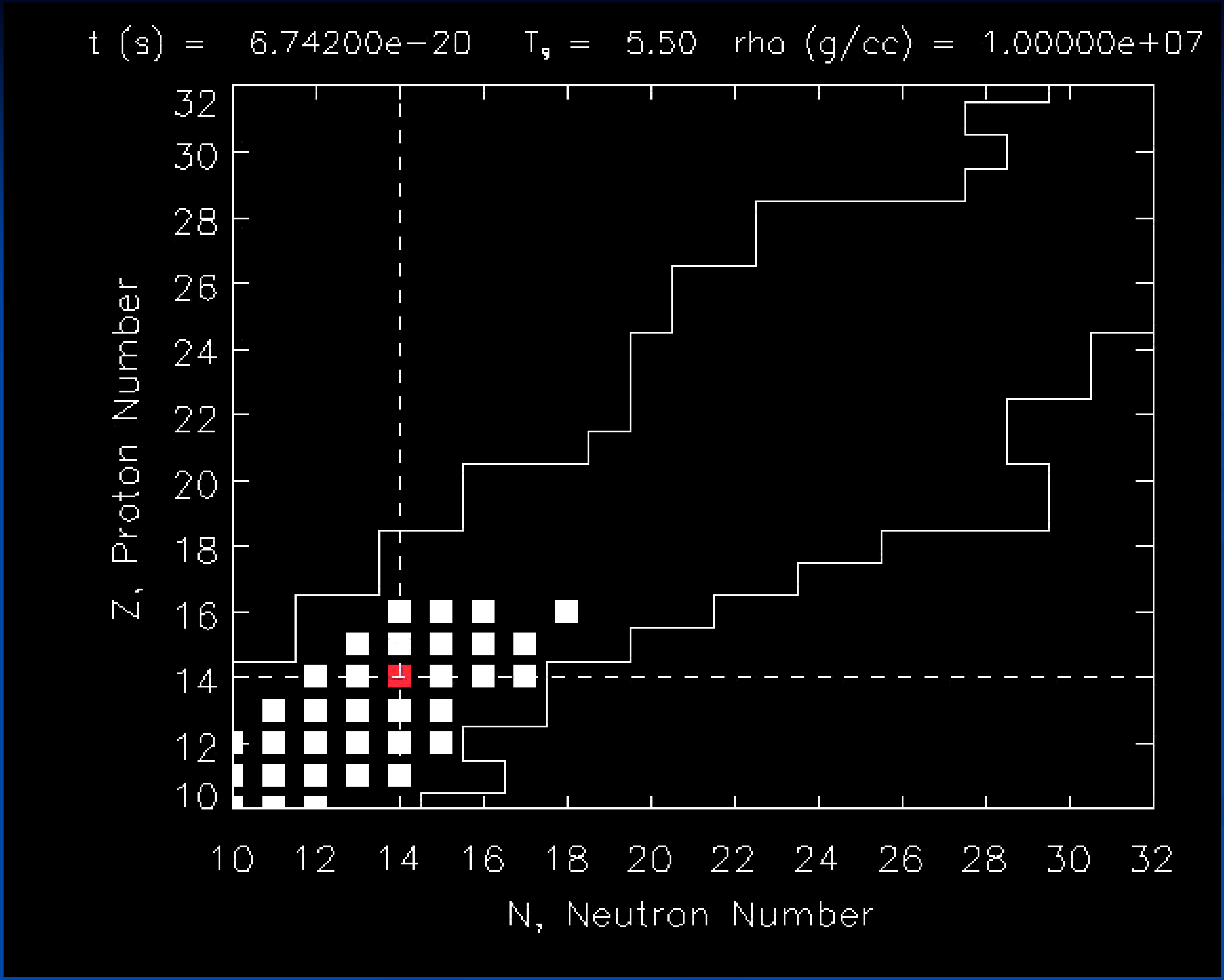
Core-Collapse Supernovae: The Future

- Numerous Explosion Mechanisms identified: Neutrino-Wind, Neutrino/SASI, Acoustic/Core-oscillation, MHD Jet, Hybrids
- Symmetry-breaking, instabilities frequently the key to explosion: Simultaneous accretion and explosion
- Multi-D (2D and 3D) radiation hydrodynamics: 3D effects?
- Is there an important role for Rotation?
- Is there a role for Magnetic fields? Pulsar/Magnetar fields?
- Viscosity? viscous heating and angular momentum transport
- Equation of state?
- Neutrino physics, rates, neutrino oscillations?
- Systematics with progenitor: kicks, r-process, SN energy, BH of observables/diagnostics?
- GRB/hypernova/SN connections!

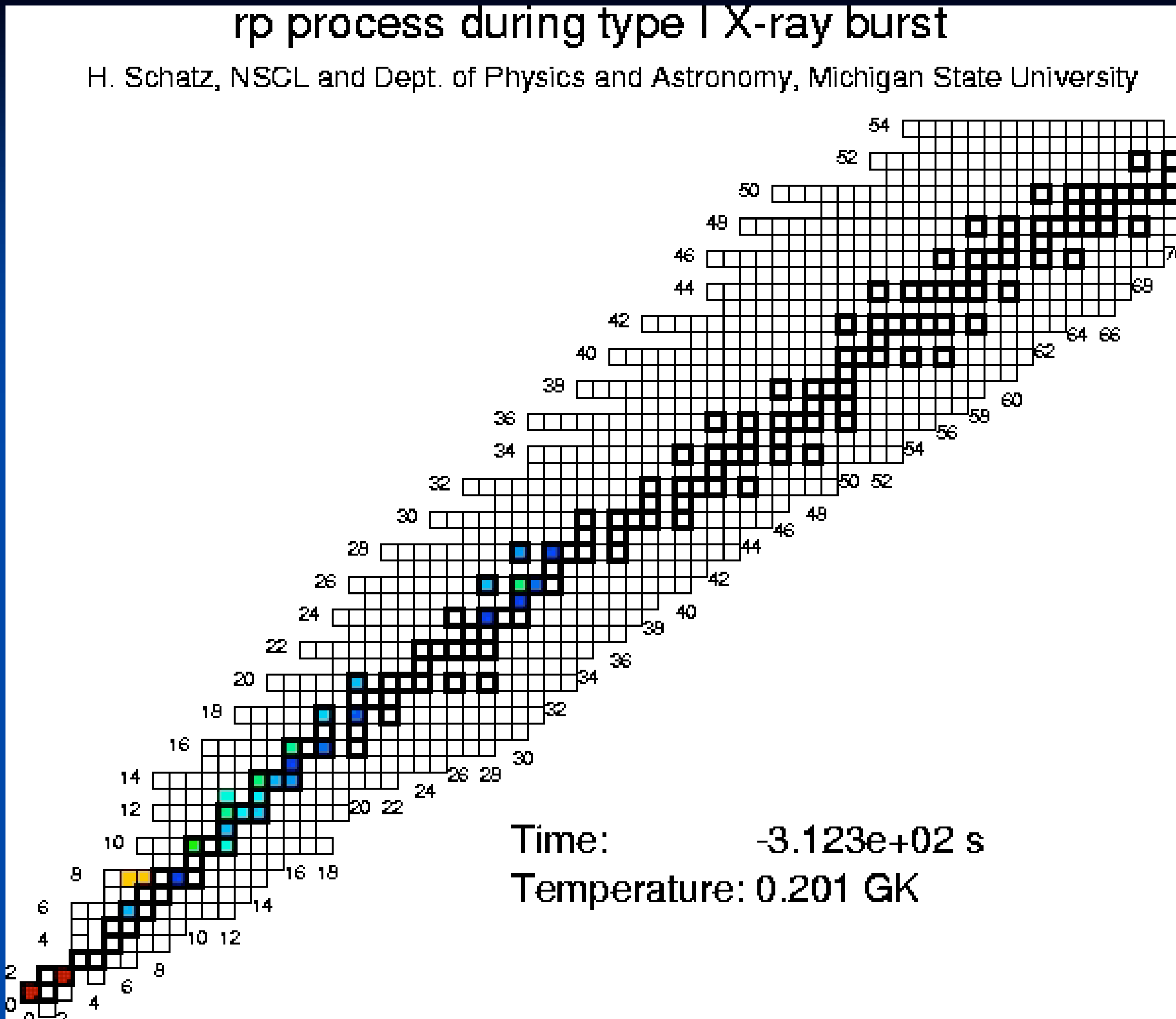
Nucleosynthesis



Courtesy of
Stan Woosley



t (s) = 6.74200e-20 T9 = 5.50 rho (g/cc) = 1.00000e+07
Z, Proton Number
N, Neutron Number
32
30
28
26
24
22
20
18
16
14
12
10
10 12 14 16 18 20 22 24 26 28 30 32



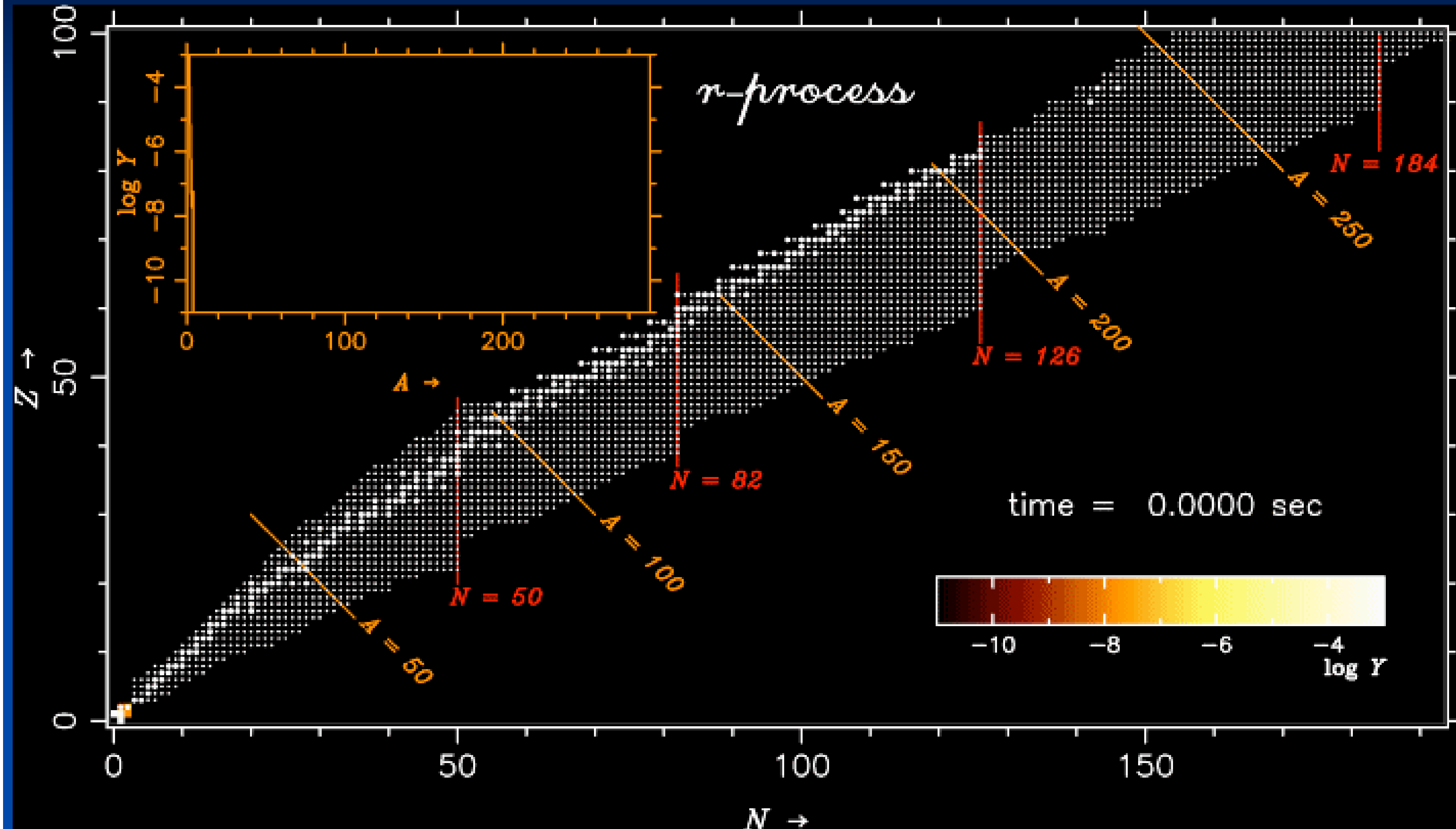
Z

N

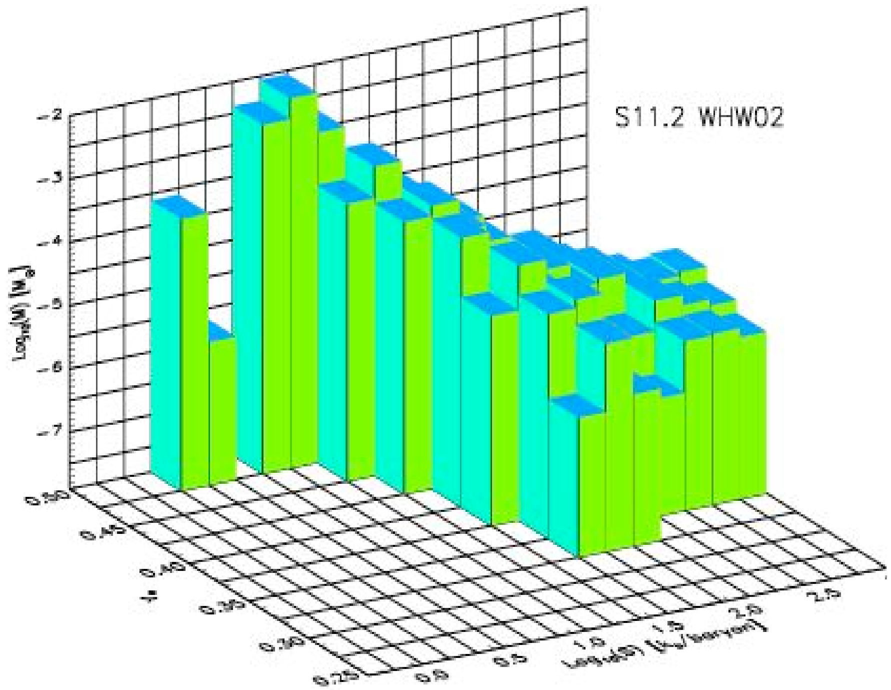
Creating Isotopes in X-ray Bursts

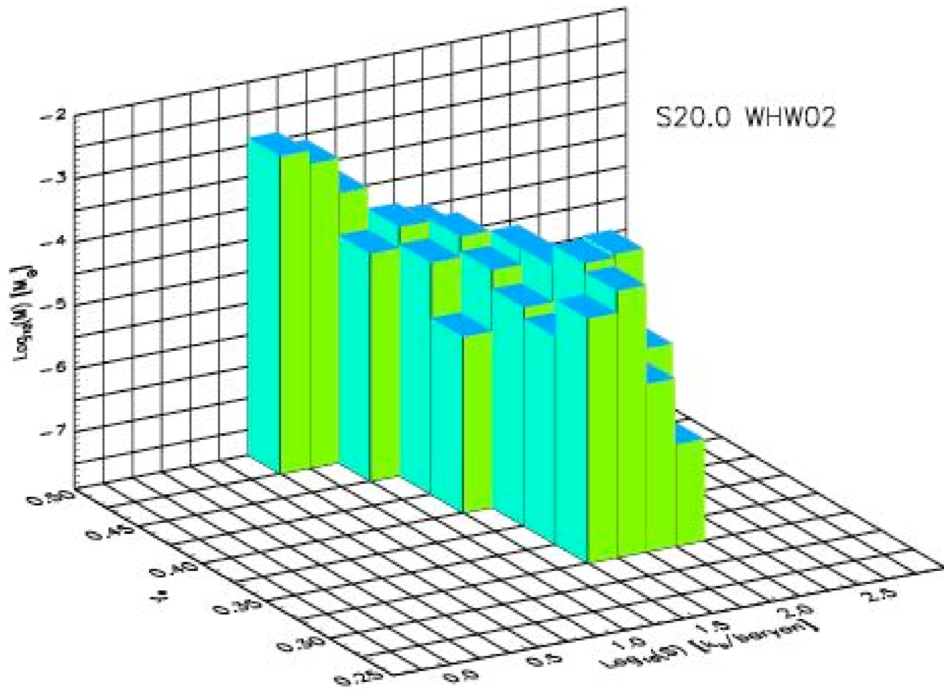
“R-process” Nucleosynthesis?

Transmutation by Rapid Neutron Addition



Ejecta mass versus Entropy and Y_e for Acoustic Mechanism: R-process?





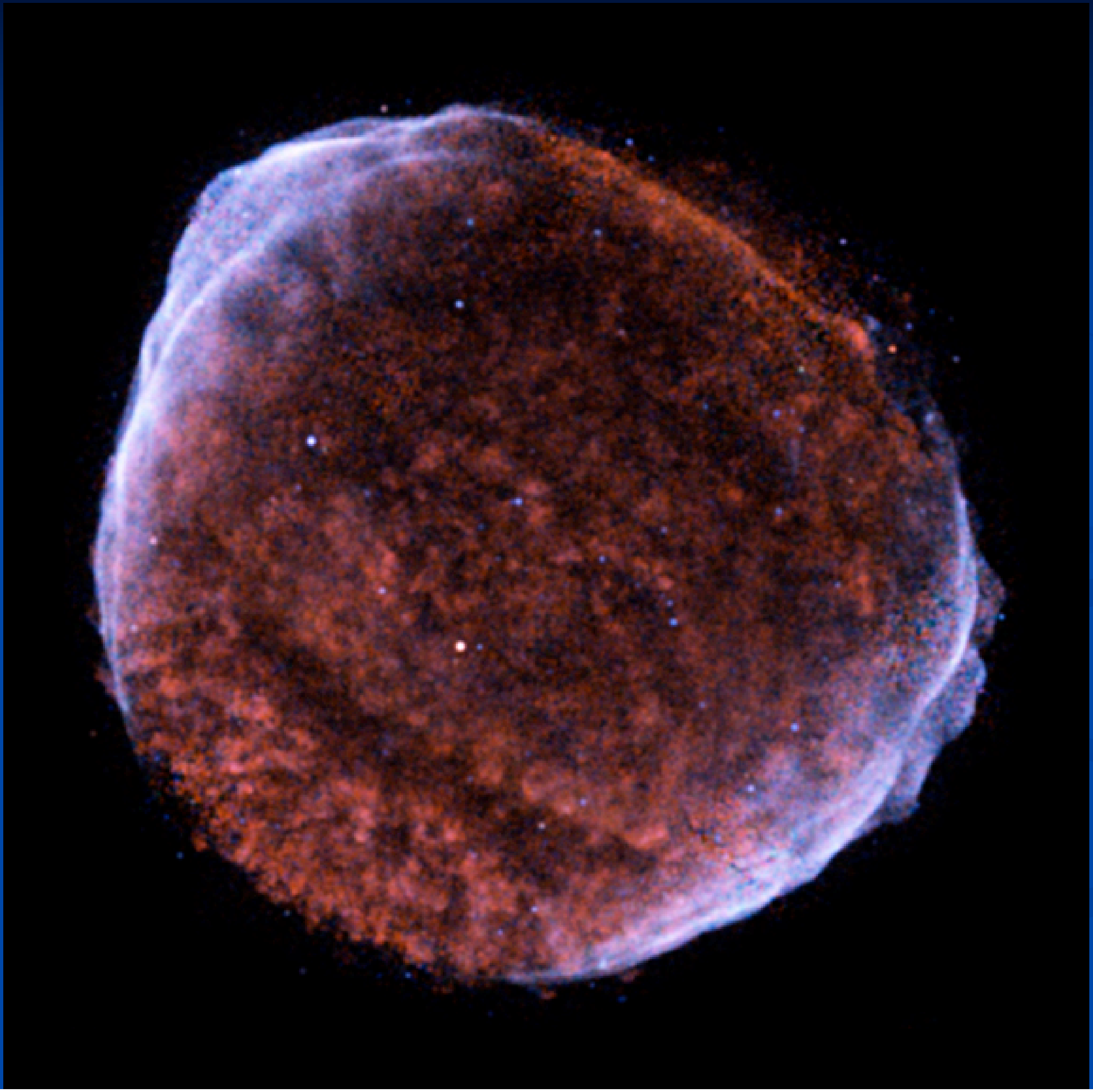
M (s > 300): 1.25 x 10^{-4} $M_\odot$?

M (s > 100): 1.07 x 10^{-5} $M_\odot$?

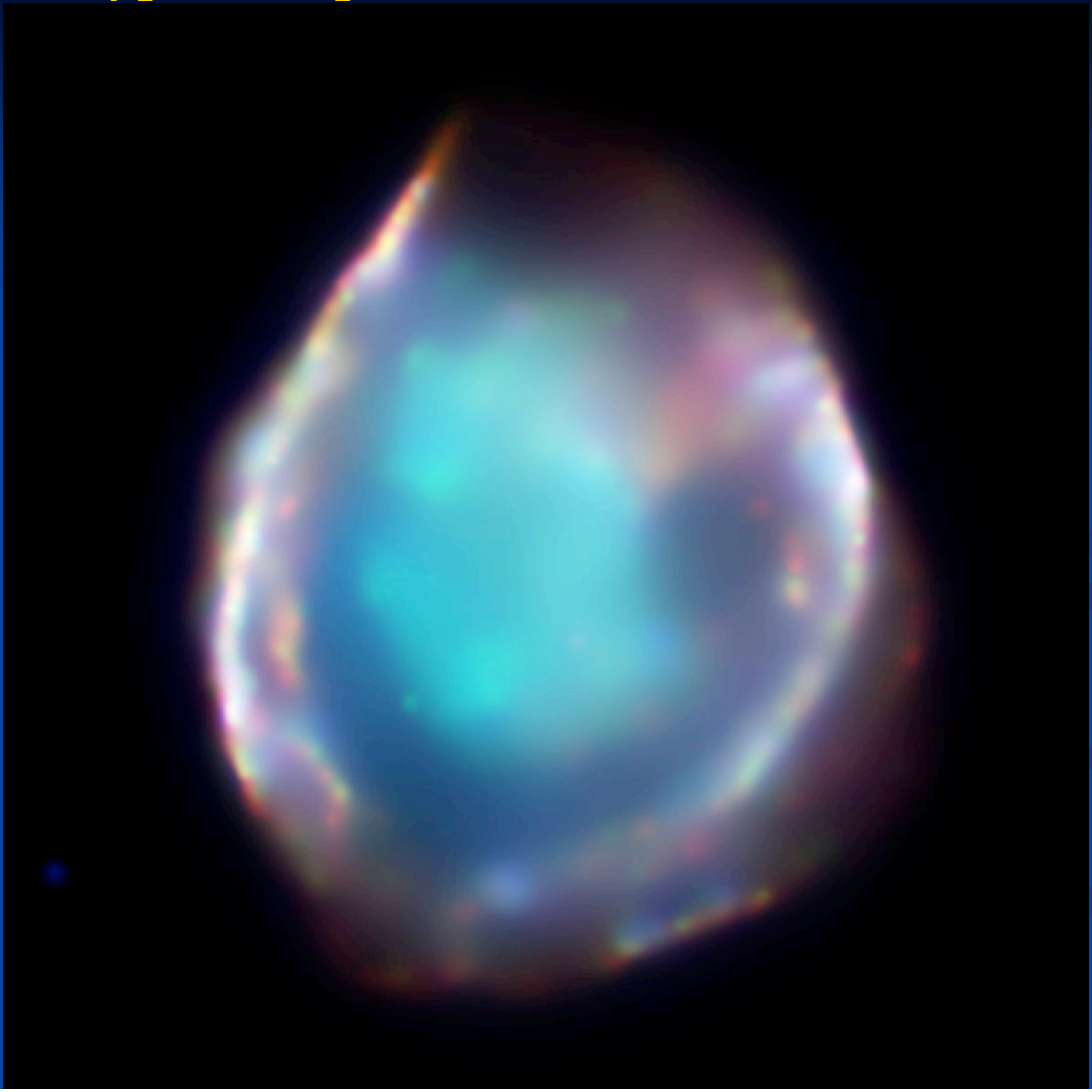
Very Preliminary!!!

Type Ia (Thermonuclear) Supernova Explosions

Type Ia: SN1006 (in X-rays)



Type Ia Supernova Remnant: DEM171



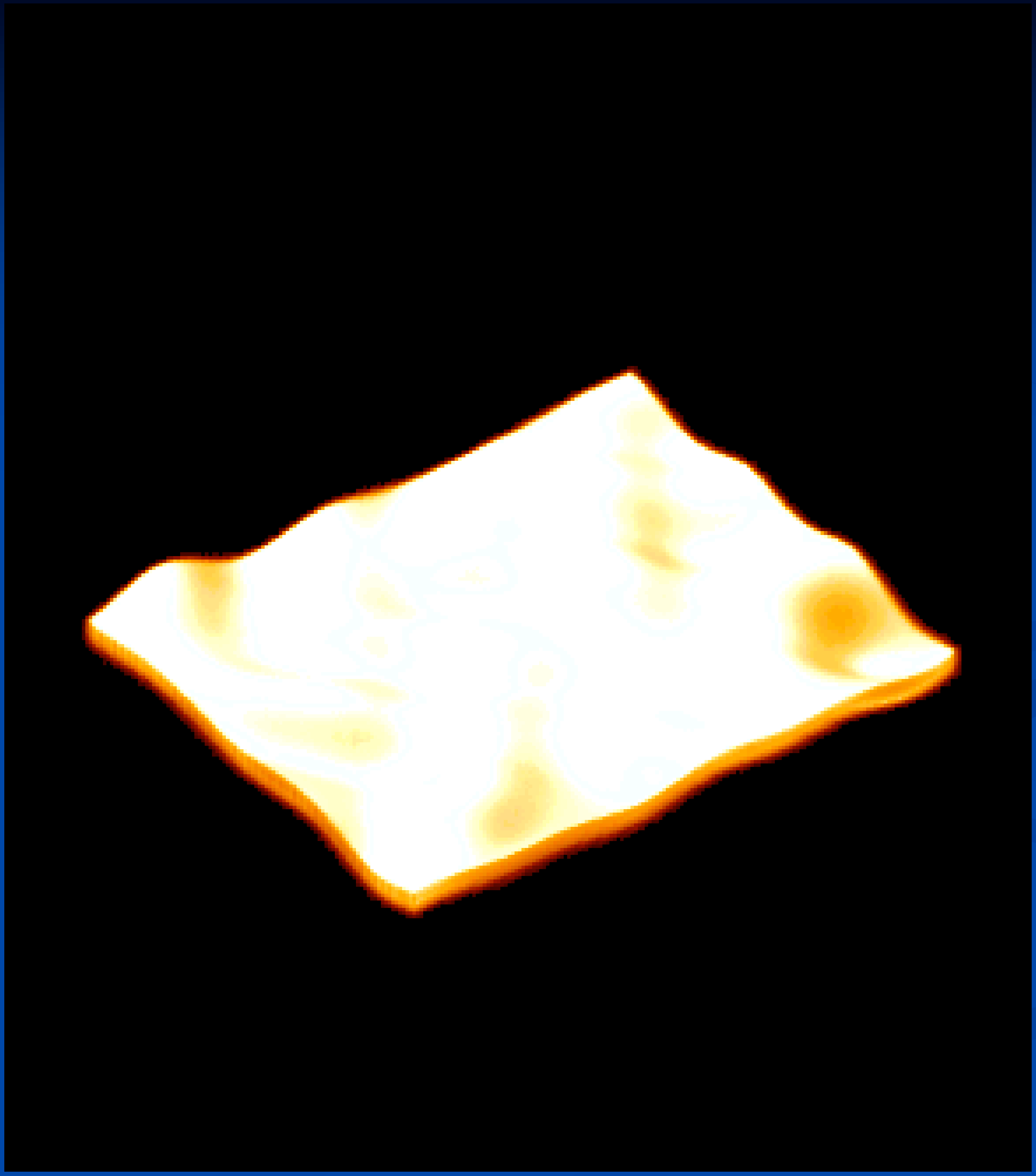
Type Ia Supernova Facts

- Thermonuclear Explosion of the entire accreting C/O White Dwarf; Explosion lasts ~1 second
- Emits mostly Optical and Infrared light
- Used as a primary yardstick for the Cosmology. Can be seen across the Universe: Indicates the Universe is Accelerating
- Significant element production and ejection: Iron (radioactive Nickel), Ca, Si, S, Ar, …
- Light lasts months; Peak Luminosity ~ 10^{21} Megatonnes of TNT/second (very bright)
- Complete disassembly; Energy > 10^{28} Mtonnes of TNT

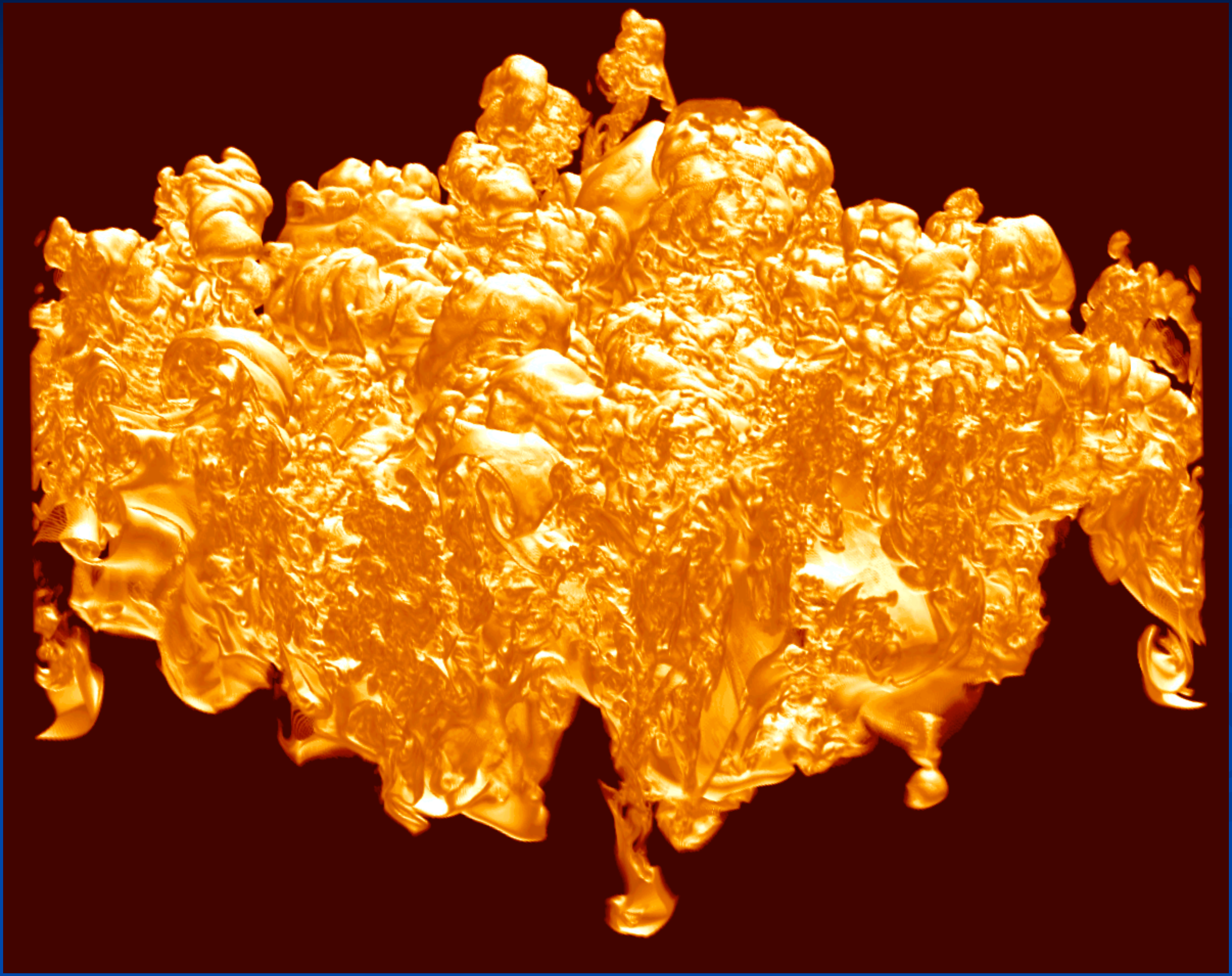
Type Ia Flame:

The Start:

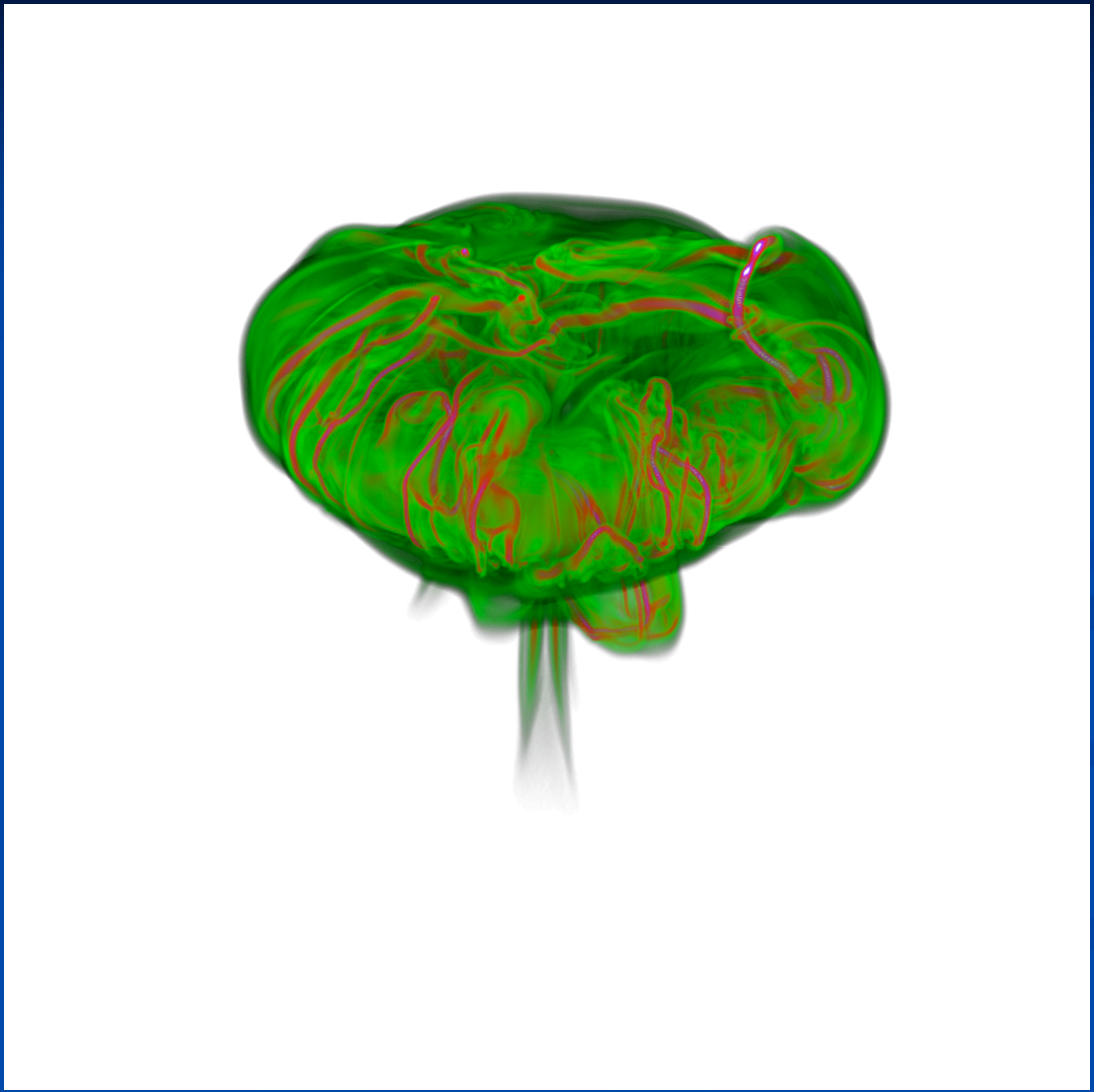
On Small Scales near the center of the star

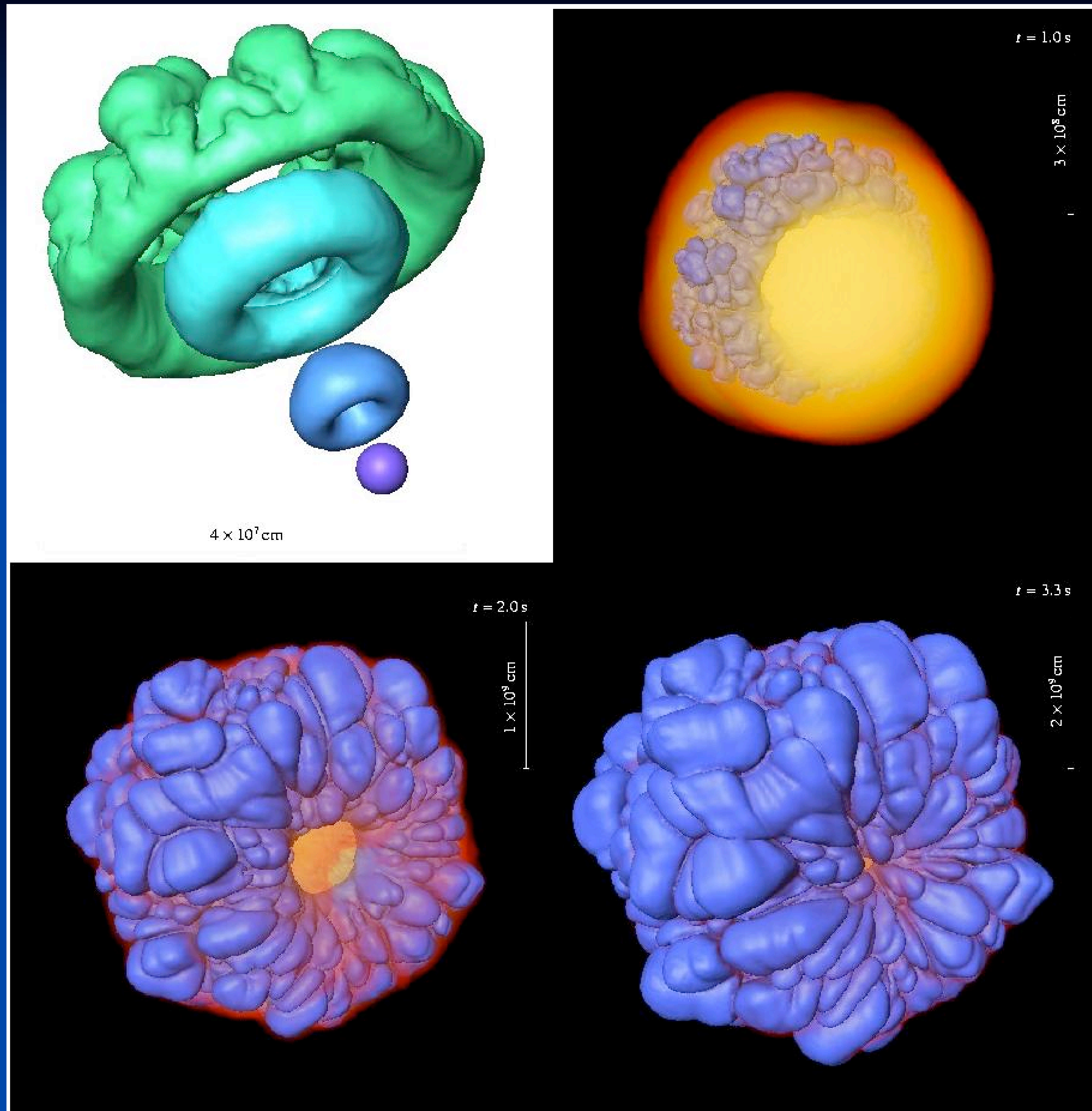


Turbulent Thermonuclear Flame Front

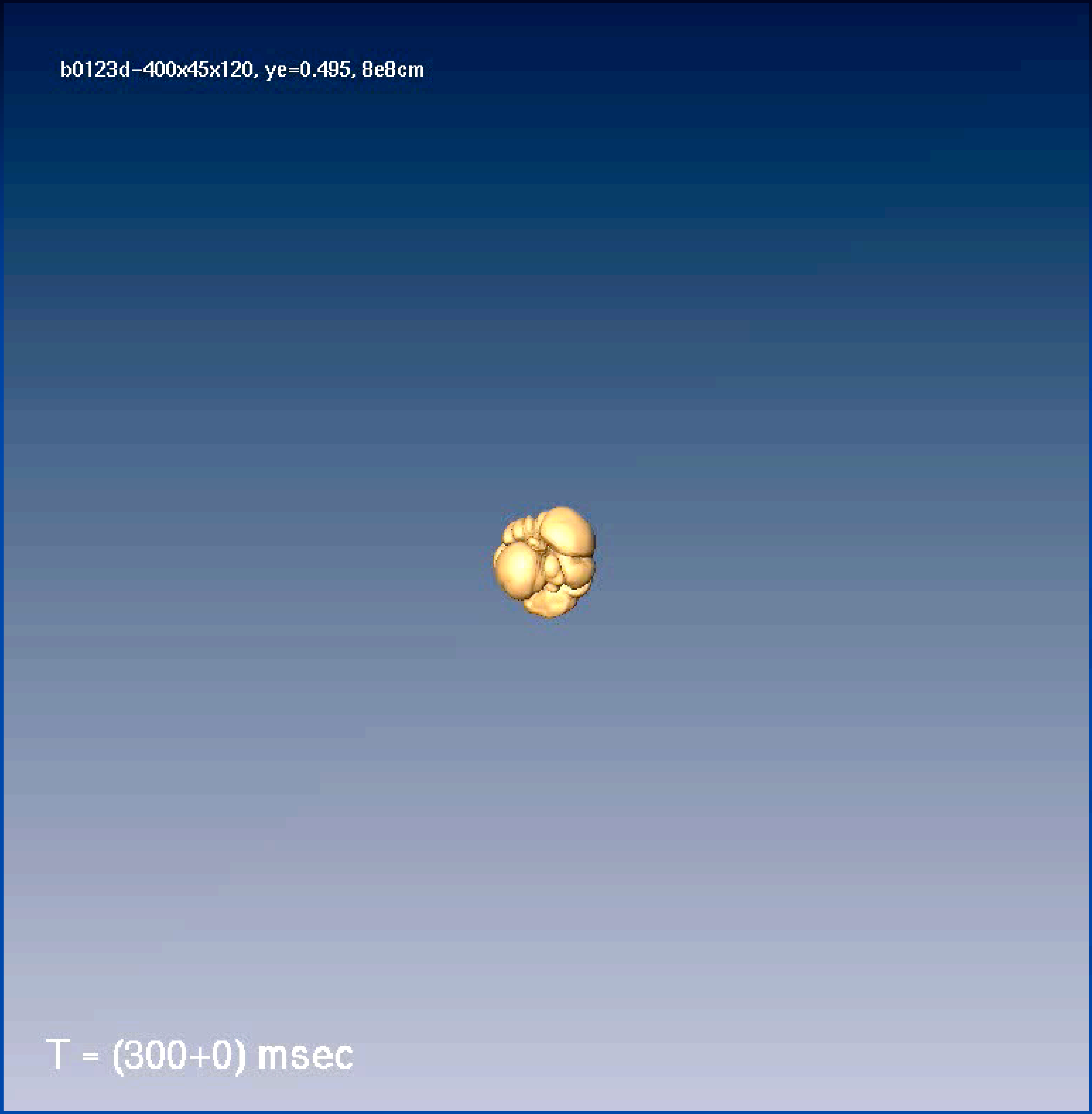


Burning Bubble of Thermonuclear (C/O) Fuel





4 × 10⁷ cm
t = 1.0 s
3 × 10⁸ cm
t = 2.0 s
1 × 10⁹ cm
t = 3.3 s
2 × 10⁹ cm


b0123d-400x45x120, ye=0.495, 8e8cm
T = (300+0) msec

White Dwarf Deflagration

Resolution: 6 km

Initial Bubble Radius: 25 km

Ignition Offset: 100 km

Variable 1: Density [1.5e+07 - 2.0e+07]

Variable 2: Reaction Progress [0.0 - 1.0]

White Dwarf Deflagration

Resolution: 6 km

Initial Bubble Radius: 25 km

Ignition Offset: 100 km

Variable 1: Density [1.5e+07 - 2.0e+07]

Variable 2: Temperature: [1.5e+09 - 4.0e+09]

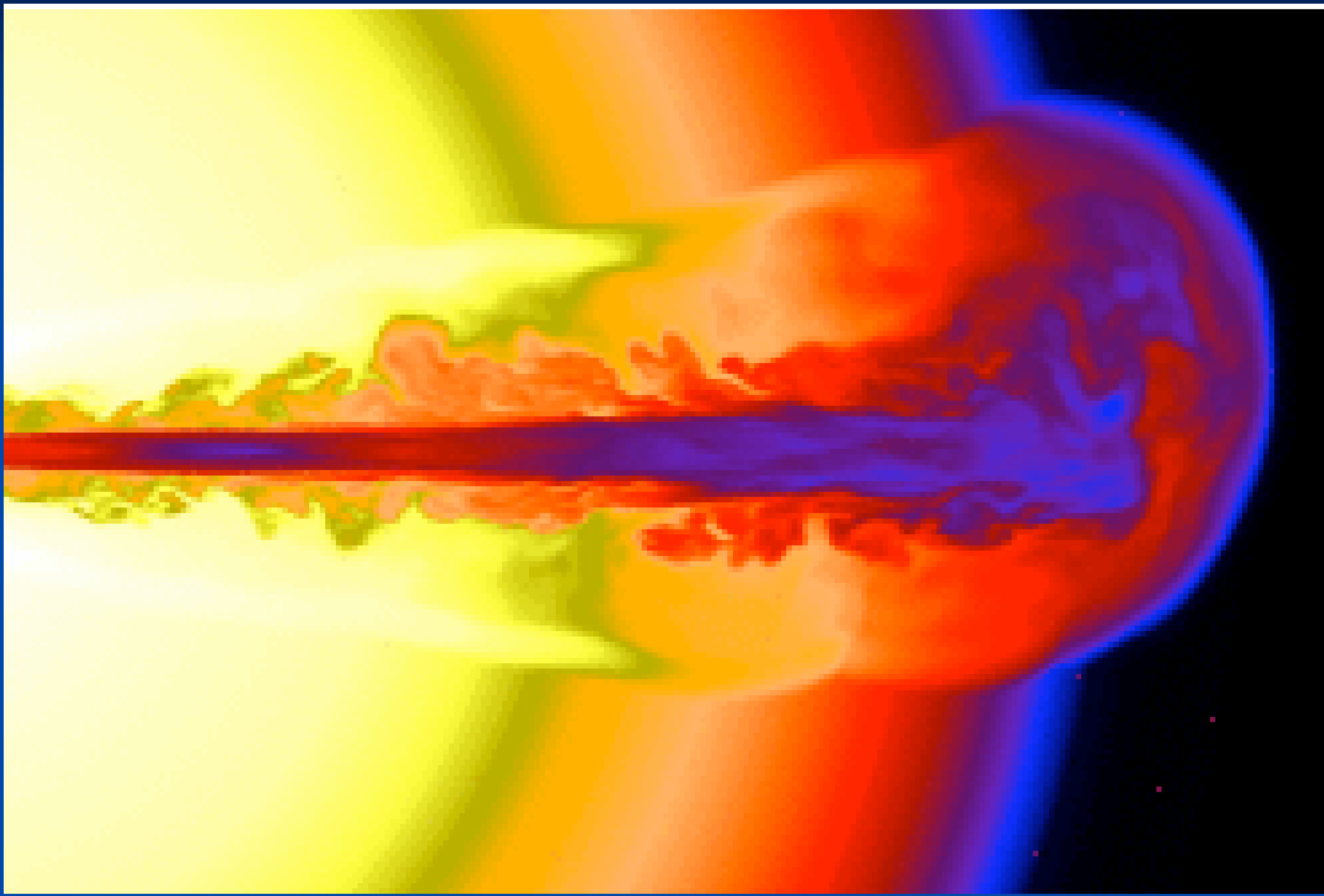
Gamma-ray Bursts: Two Varieties: Collapsars and Neutron Star Binary Inspirals??

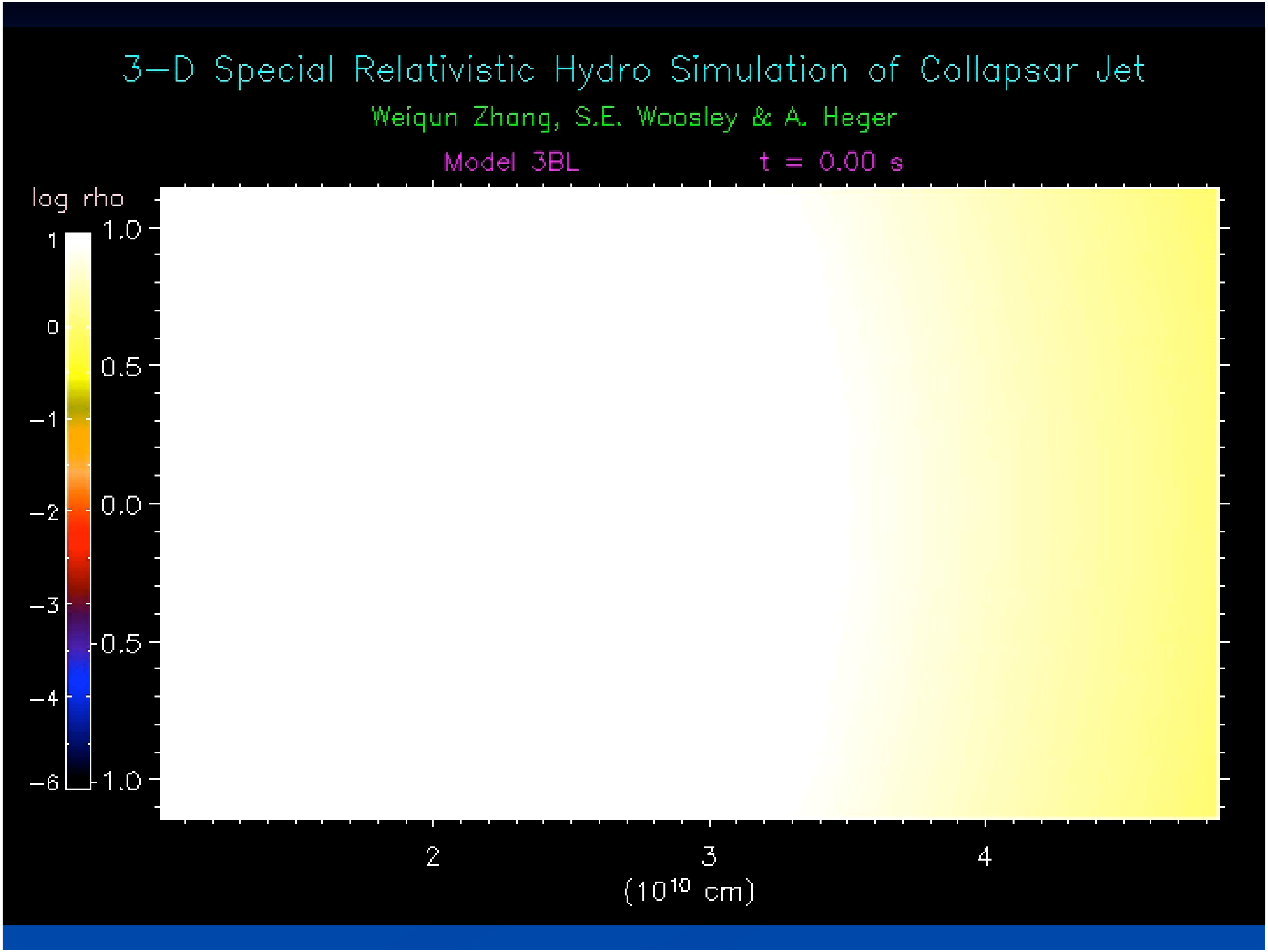
Gamma-Ray Burst (GRB) Facts : I

- Relativistic Narrow Jet from a small subset of core collapses; Rapidly rotating black hole formed: Collapsar model? Long-duration/"soft" □ray spectrum; See one per day
- Emits mostly Gamma-rays (~10 seconds), but afterglows in radio, X-ray, optical, etc. last weeks
- A "Hypernova" is concurrent!
- Birth of Black holes?
- Significant element production and ejection: Oxygen, Iron (radioactive Nickel), Ca, Si, S, Ar, C, ….
- Peak □ray Luminosity ~ 10^{27} Megatonnes of TNT/second; Energy ~ 10^{28} Mtonnes of TNT

SWIFT Satellite Observes a GRB

Collapsar/GRB Jet Breakout of Star




3-D Special Relativistic Hydro Simulation of Collapsar Jet
Weiqun Zhang, S.E. Woosley & A. Heger
Model 3BL
t = 0.00 s
log rho
1
0
−1
−2
−3
−4
−6
1.0
0.5
0.0
−0.5
−1.0
2
3
4
(10^10 cm)

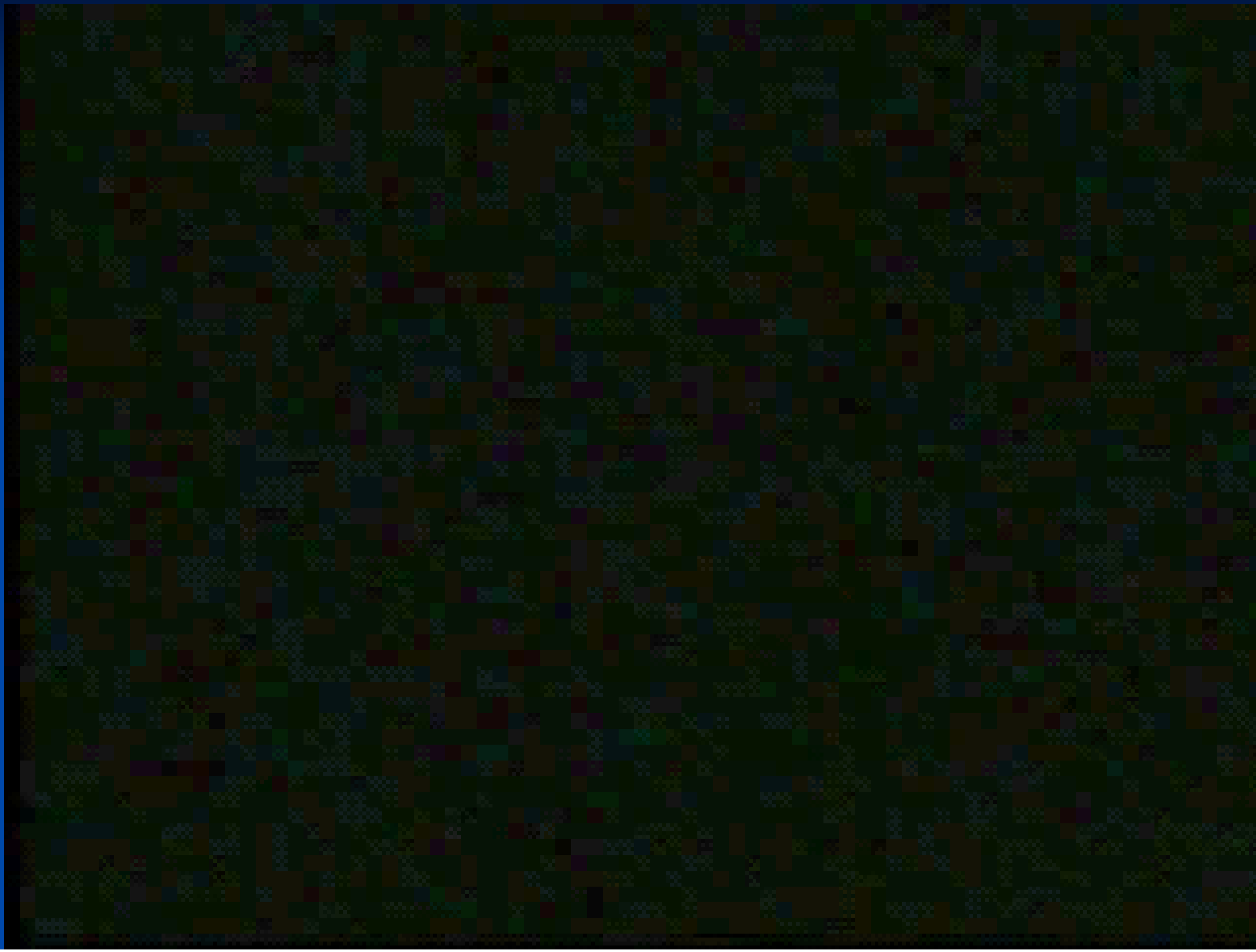
Animation of a Collapsar/GRB Jet Explosion

Animation of a Long-Soft Gamma-Ray Burst

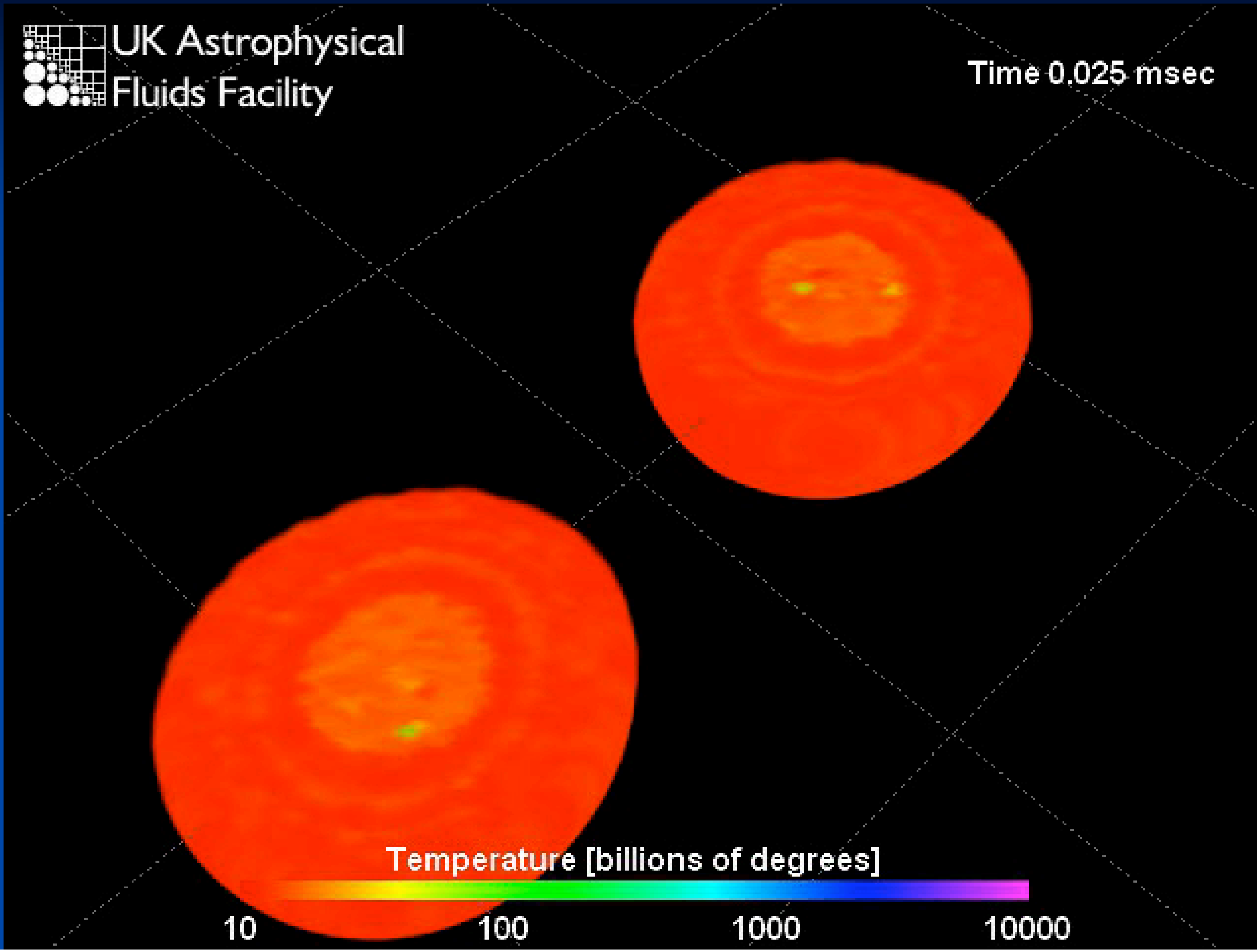
Gamma-Ray Burst (GRB) Facts : II

- Relativistic Narrow Jet from merging neutron star binary? Short-duration/"hard" □ray spectrum
- Emits mostly Gamma-rays (< 1 second)
- Birth of a Black hole?
- Little element production and ejection, but r-process??
- Peak □ray Luminosity ~ 10^{27} Megatonnes of TNT/second; Energy ~ 10^{28} Mtonnes of TNT
- LIGO gravitational wave source??

Formation of an Isolated Millisecond Pulsar

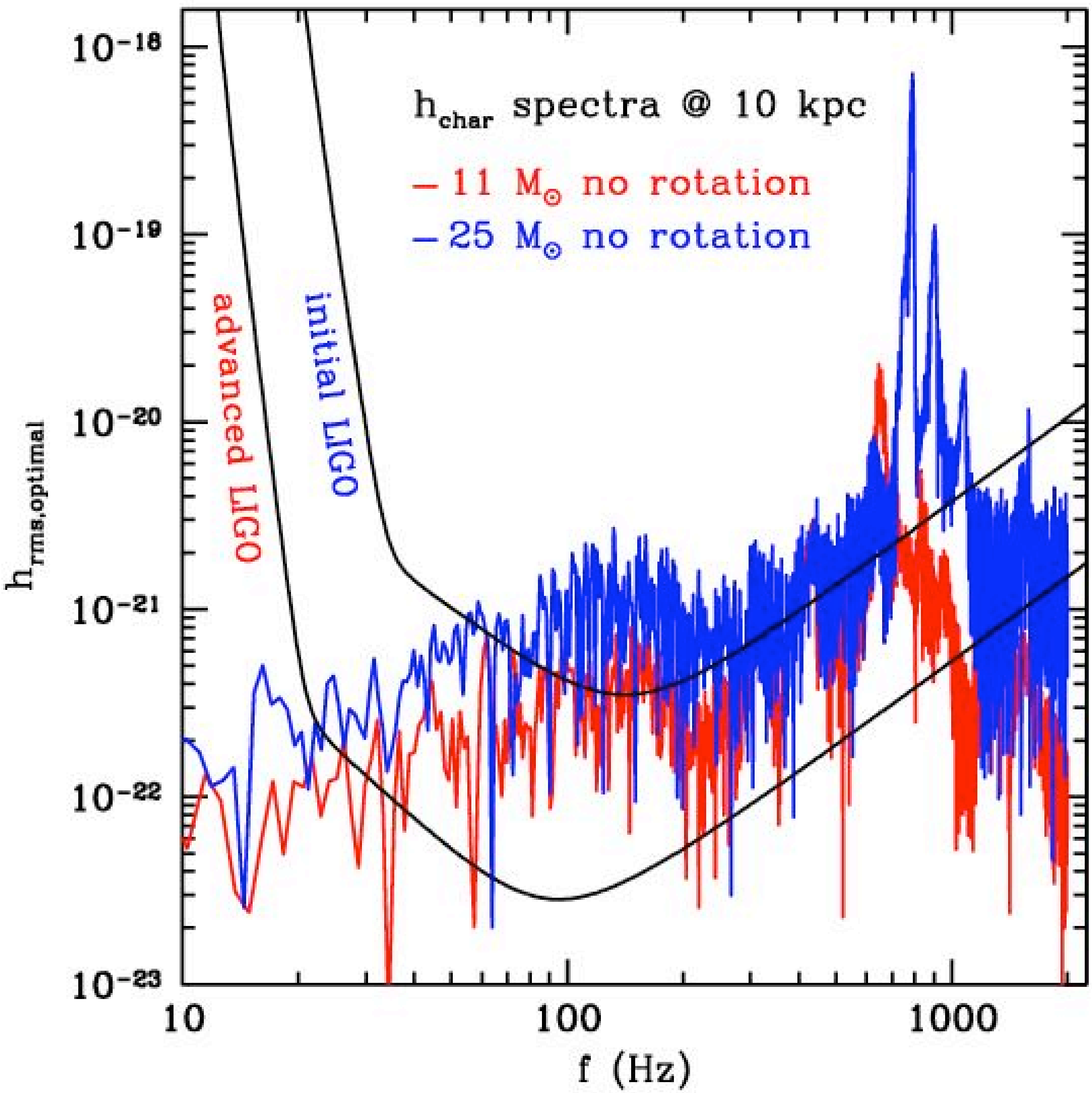


Merging Neutron Stars

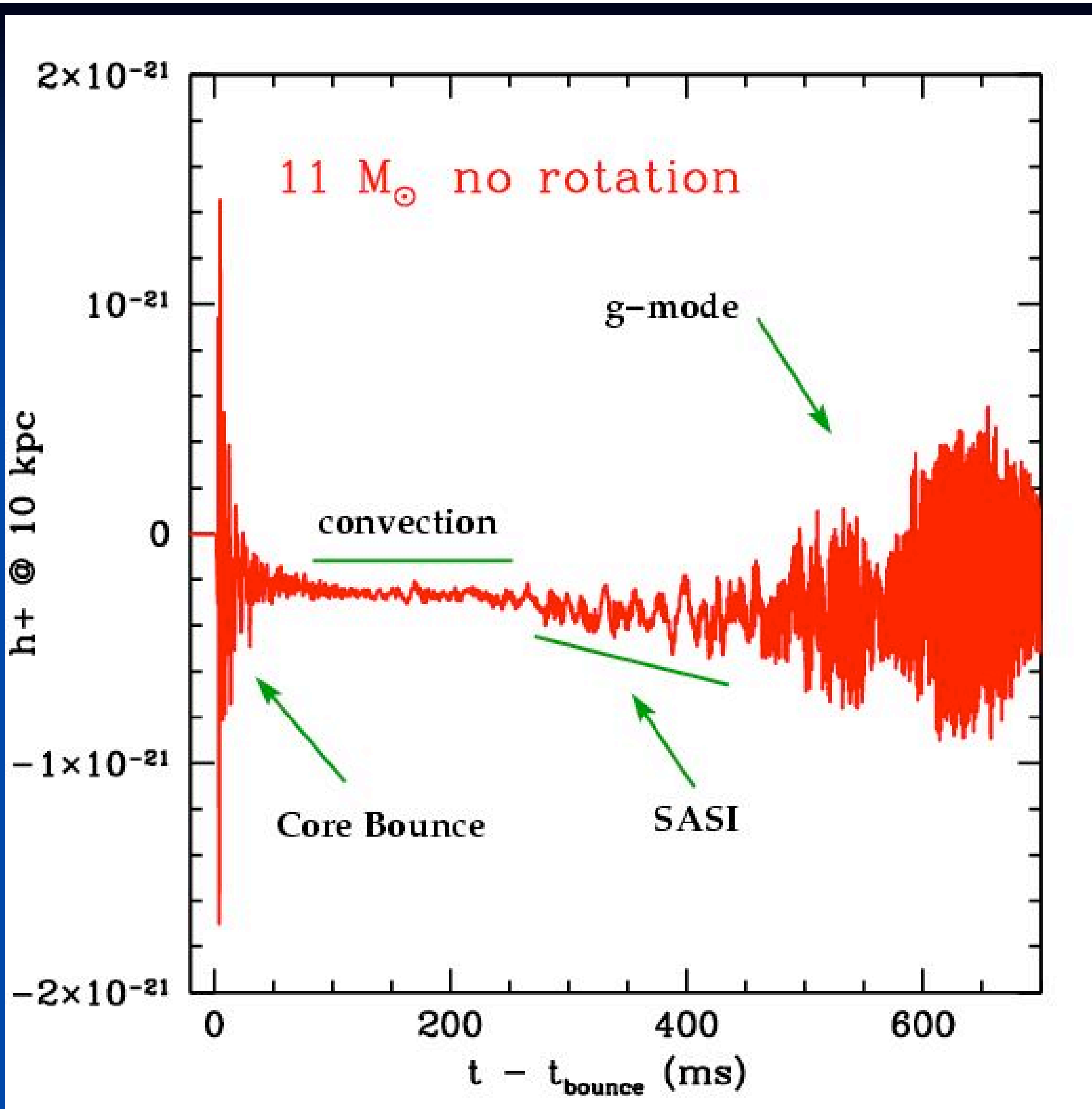


Gravitational Radiation from Supernovae

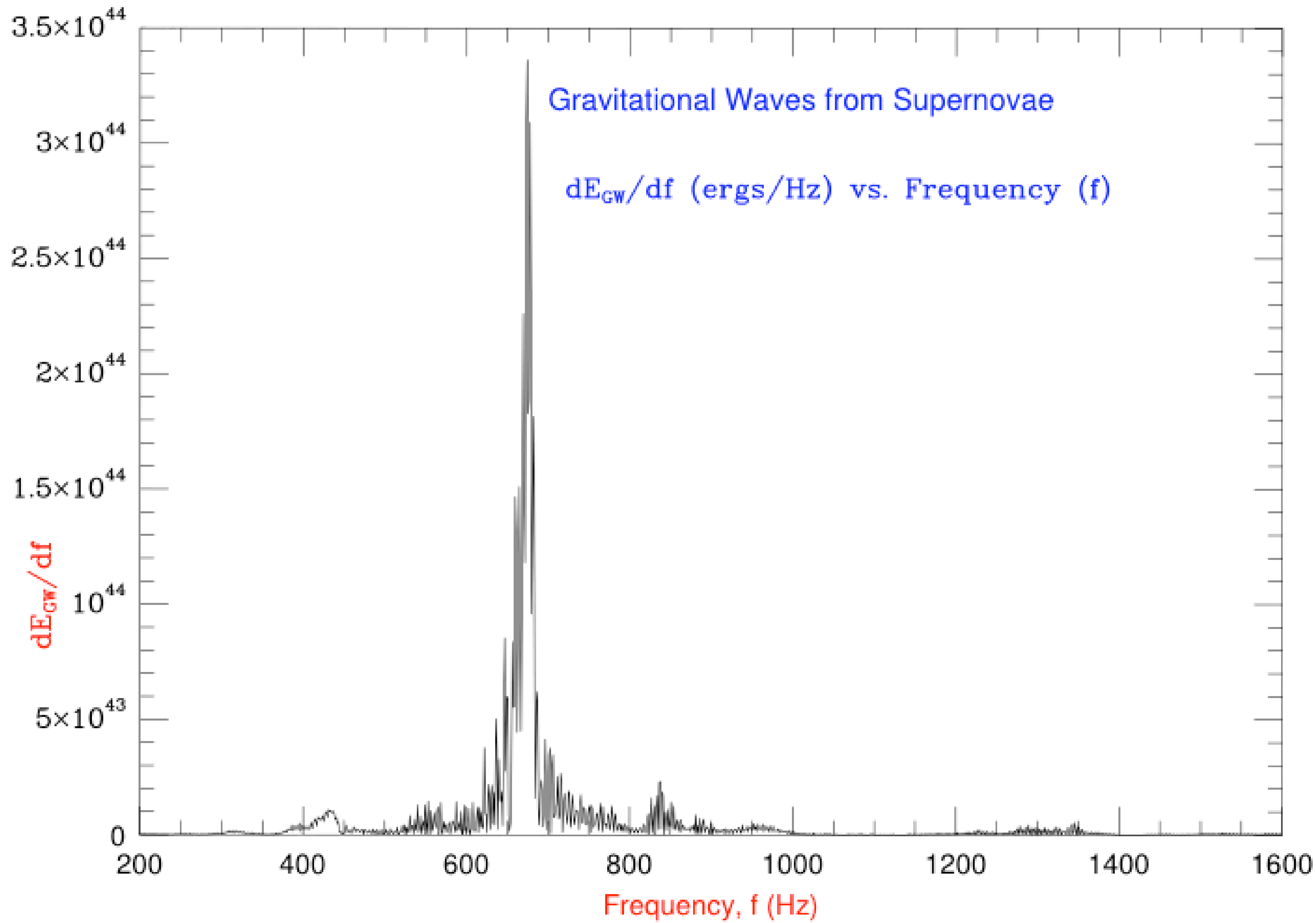
Ott et al. (2004,2006)



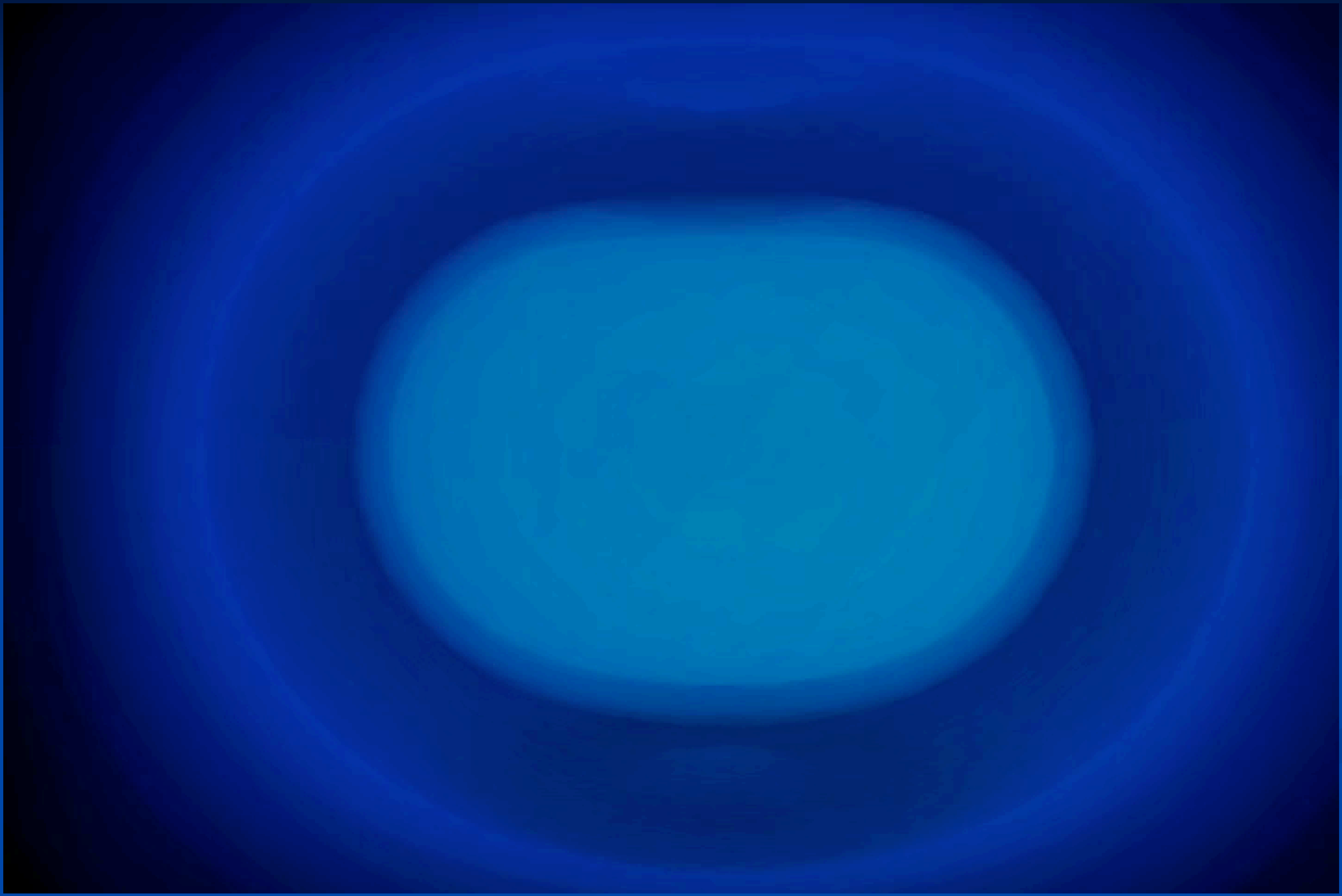
h_{char} spectra @ 10 kpc
– 11 $M_\odot$ no rotation
– 25 $M_\odot$ no rotation
advanced LIGO
initial LIGO
$h_{rms,optimal}$
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
100
1000
f (Hz)



11 M⊙ no rotation
g−mode
convection
Core Bounce
SASI
2×10⁻²¹
10⁻²¹
0
−1×10⁻²¹
−2×10⁻²¹
h+ @ 10 kpc
0
200
400
600
t − t_bounce (ms)

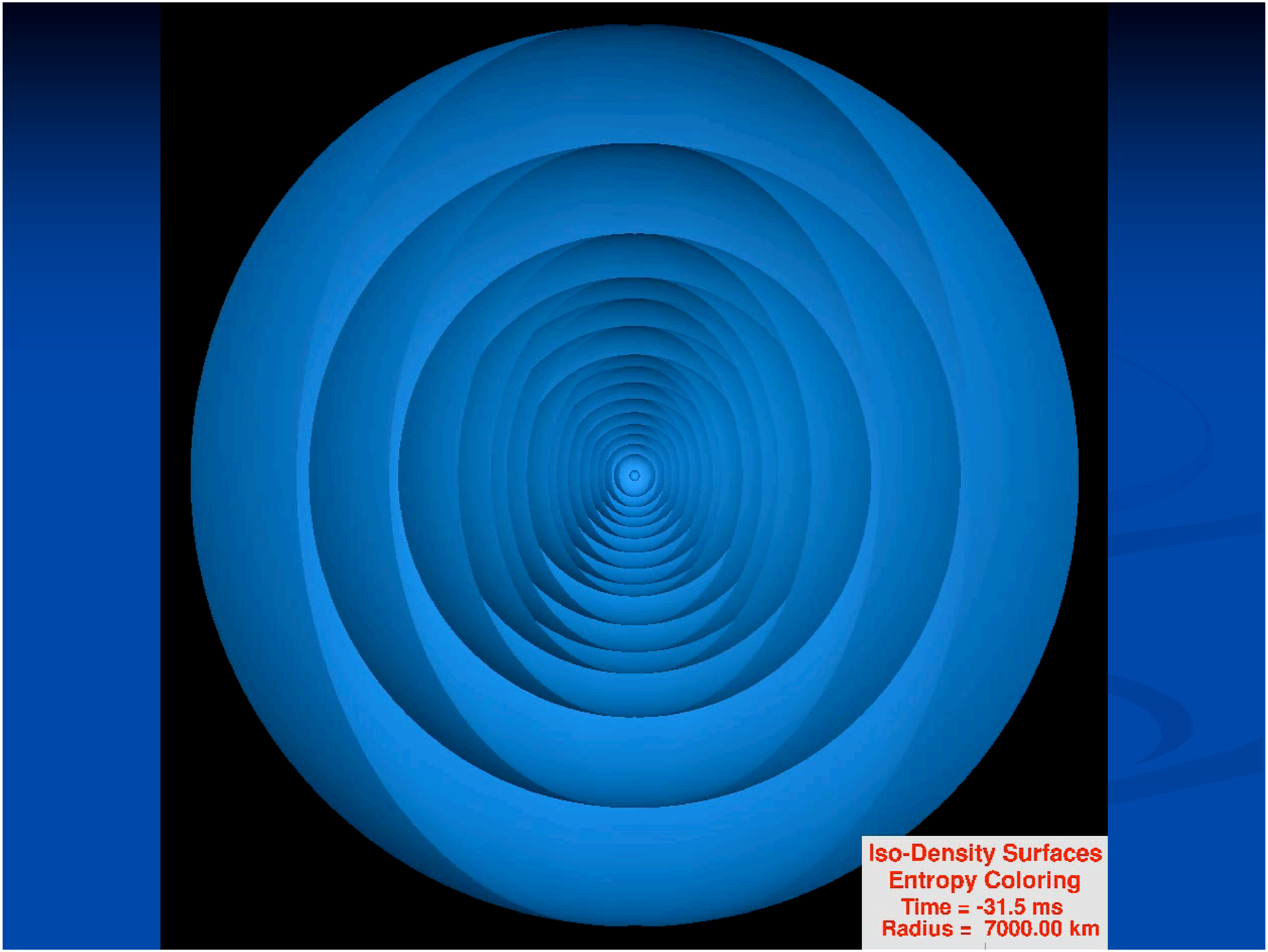


Gravitational Waves from Supernovae
dE_GW/df (ergs/Hz) vs. Frequency (f)
3.5×10^44
3×10^44
2.5×10^44
2×10^44
1.5×10^44
10^44
5×10^43
0
dE_GW/df
200
400
600
800
1000
1200
1400
1600
Frequency, f (Hz)

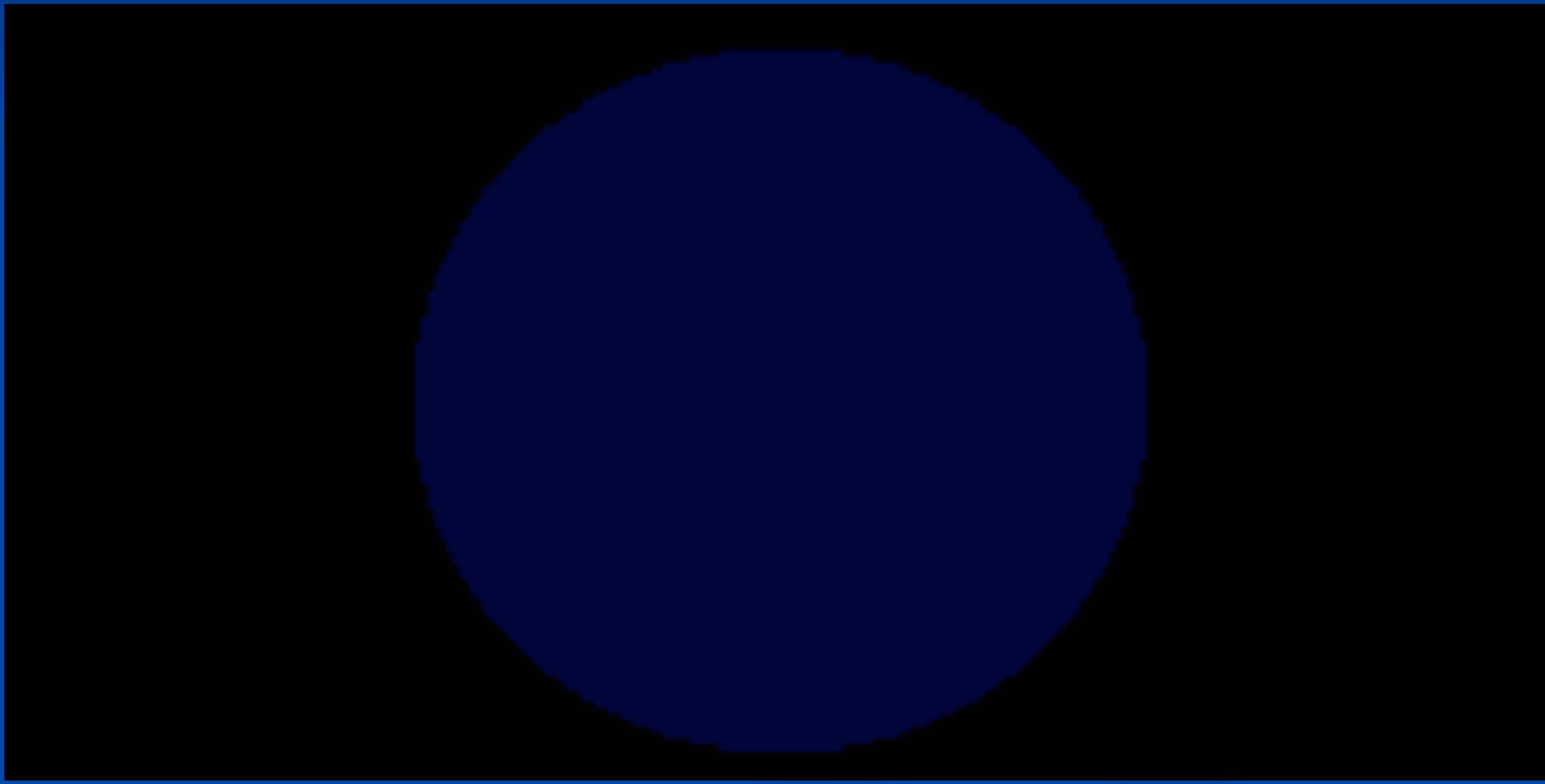


3D; GR; C. Ott et al.

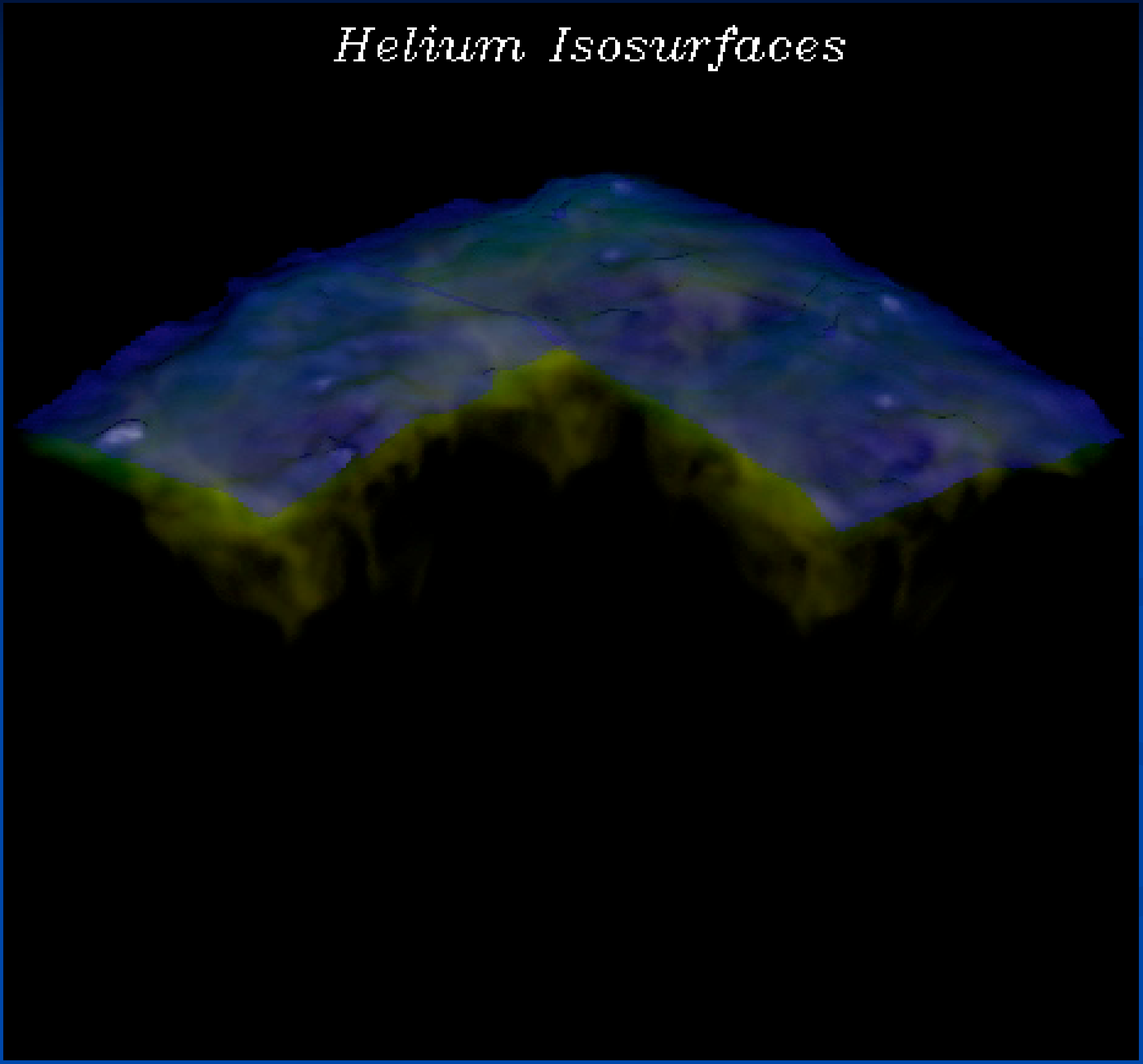
Fin

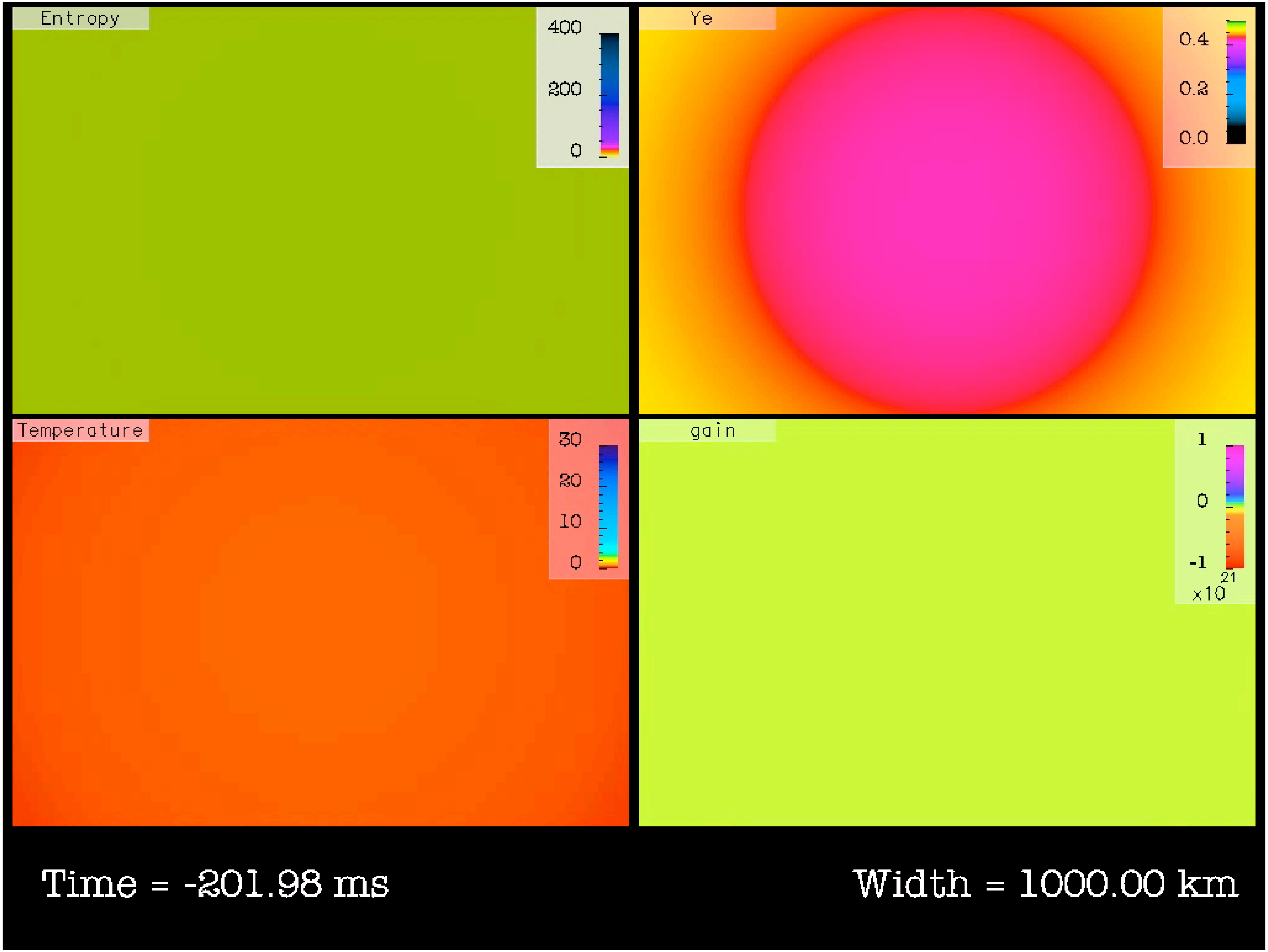

Iso-Density Surfaces
Entropy Coloring
Time = -31.5 ms
Radius = 7000.00 km

Flame Propagation on a Neutron Star



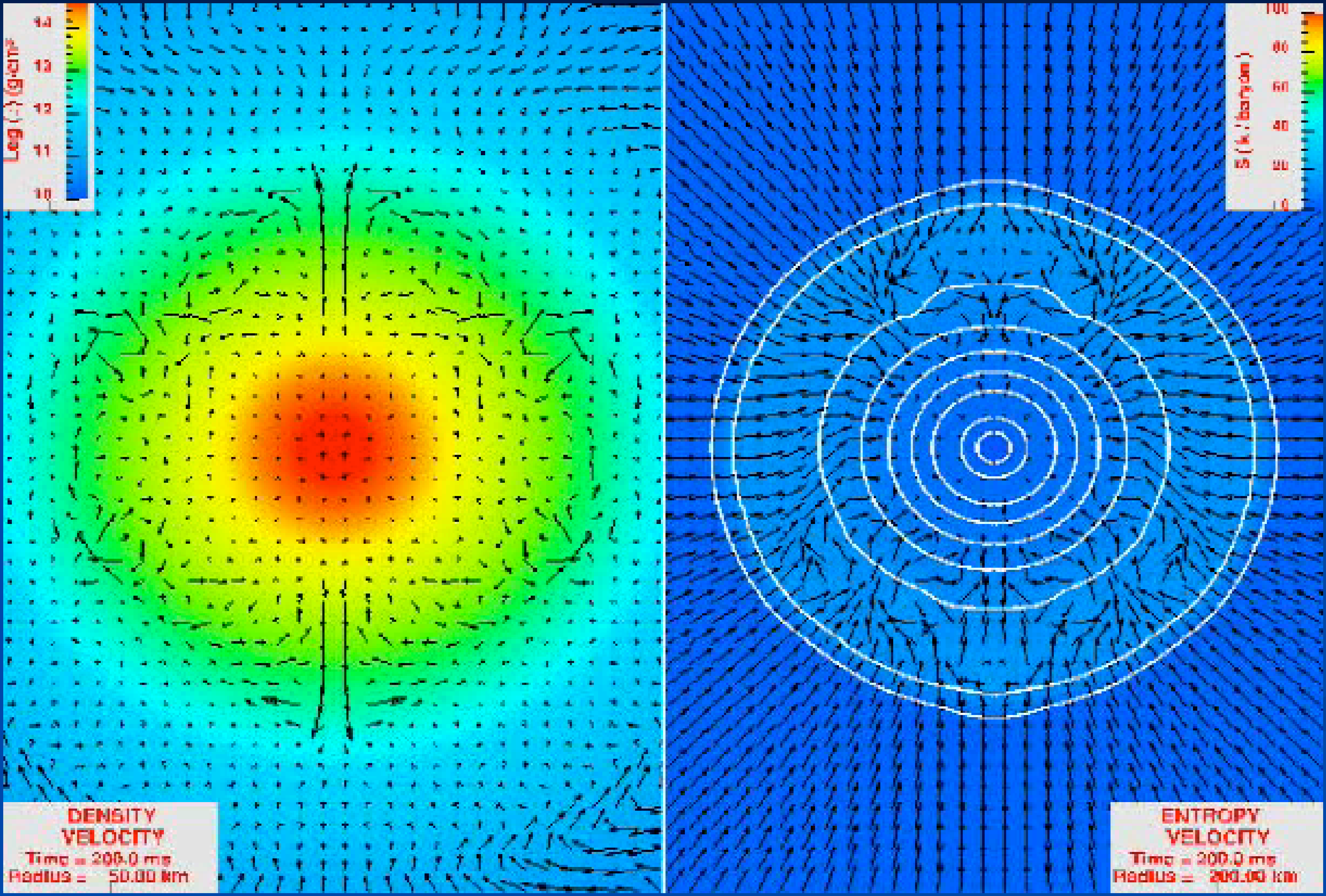
Casey Meakin: 3D Convection Studies



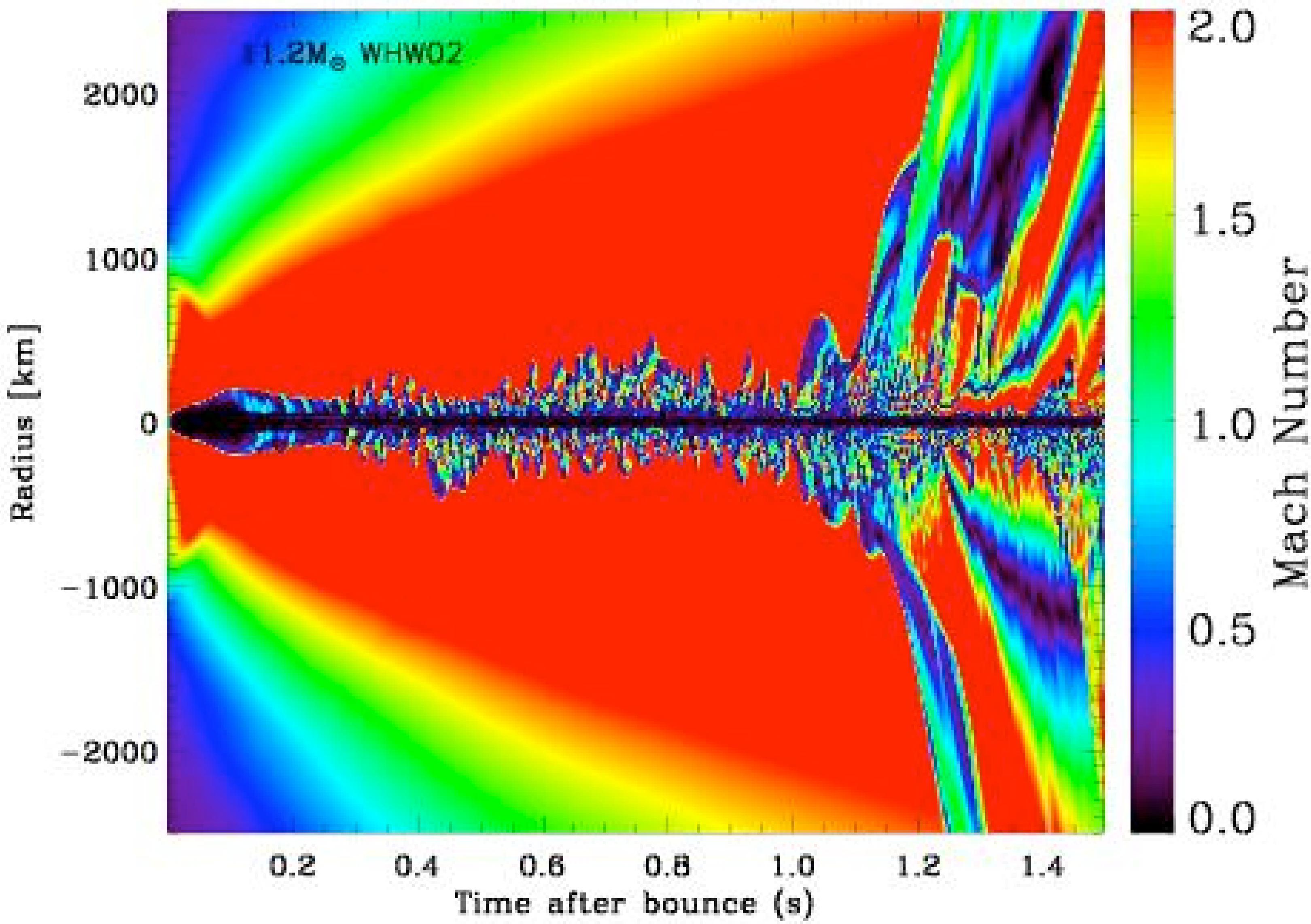


Entropy
400
200
0
Ye
0.4
0.2
0.0
Temperature
30
20
10
0
gain
1
0
-1
x10^21
Time = -201.98 ms
Width = 1000.00 km

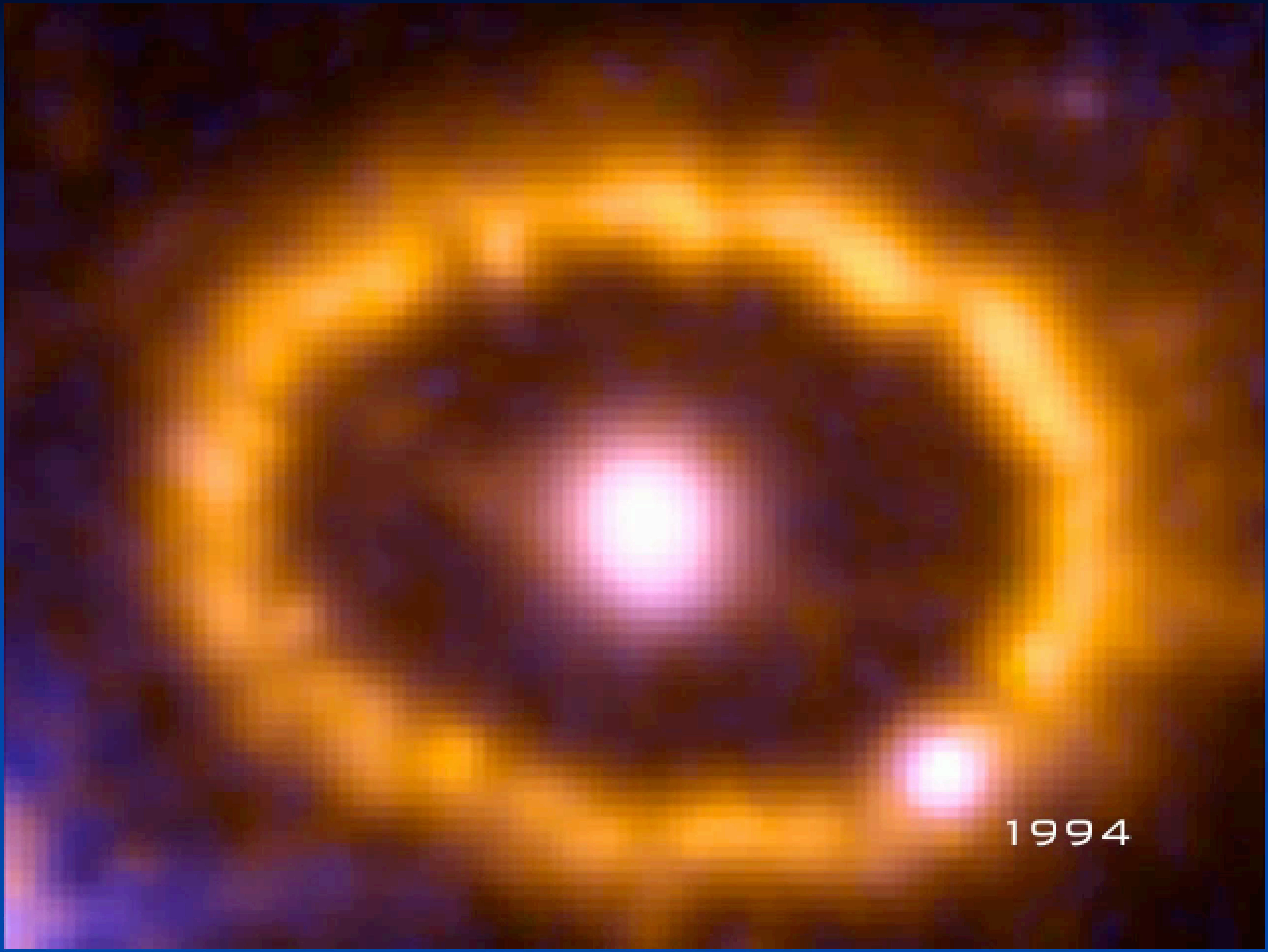
25 Solar Mass Progenitor: Core Oscillation and Shock Evolution



Mach Number along axis versus Time

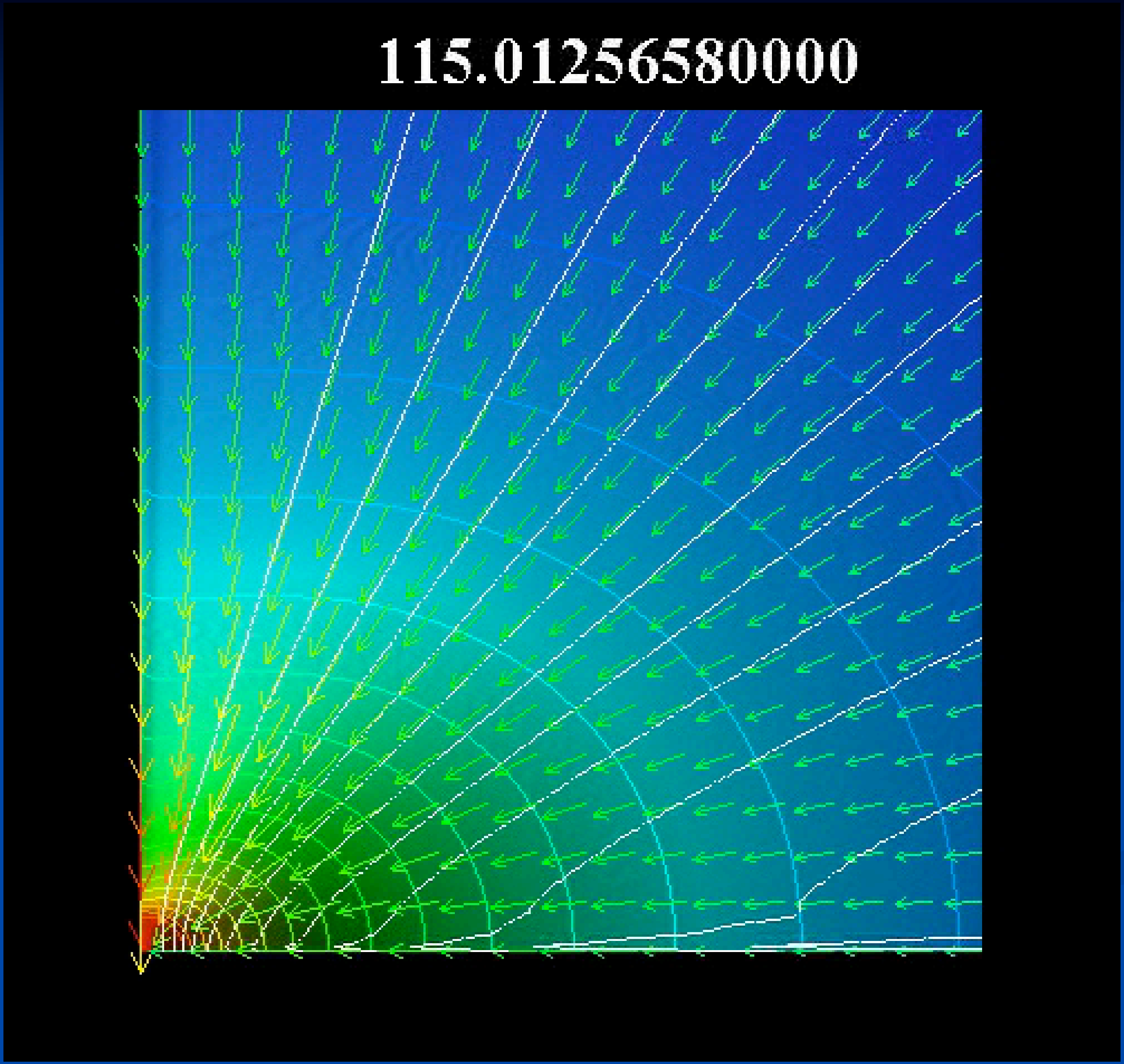


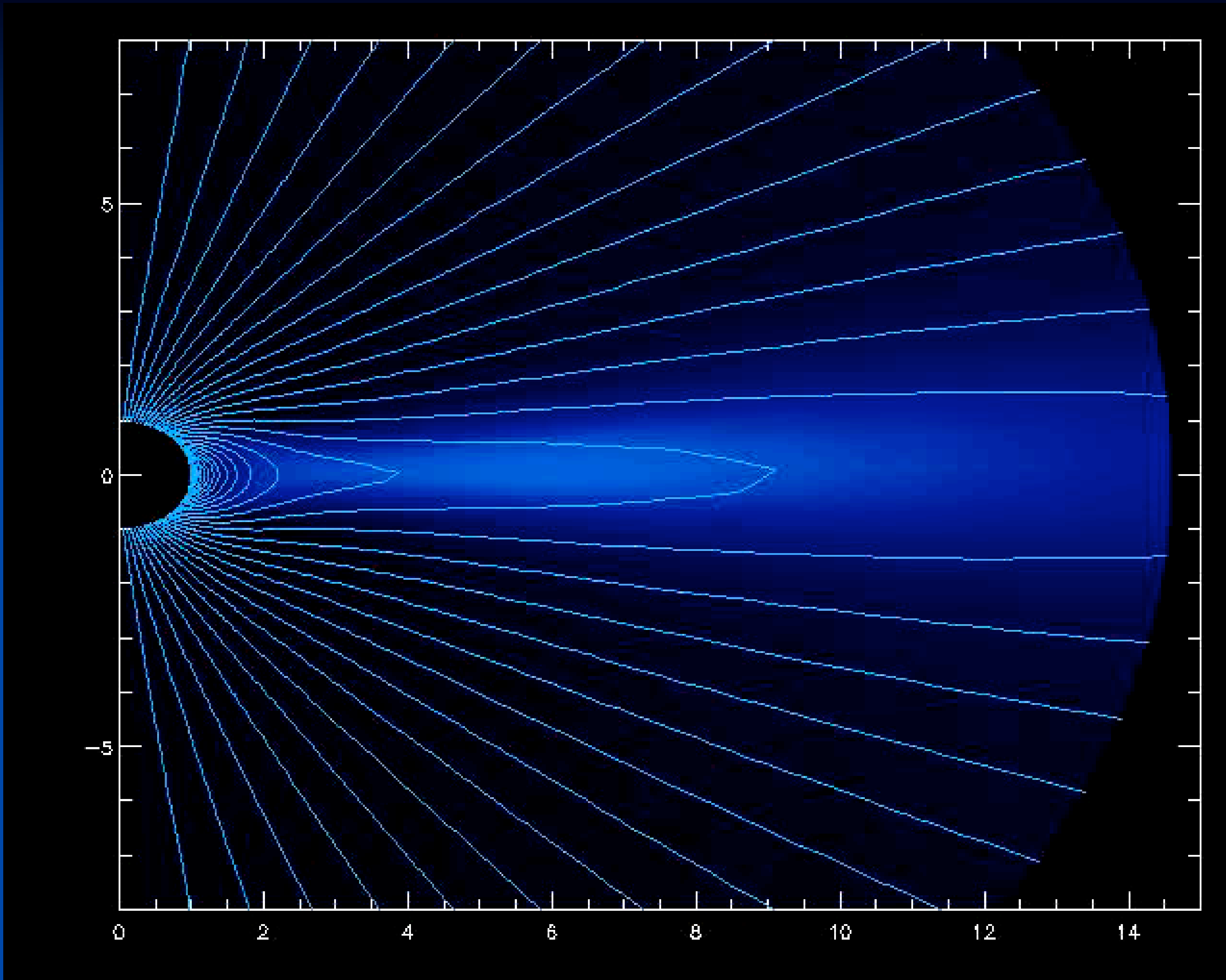
SN1987a (Pete Challis)



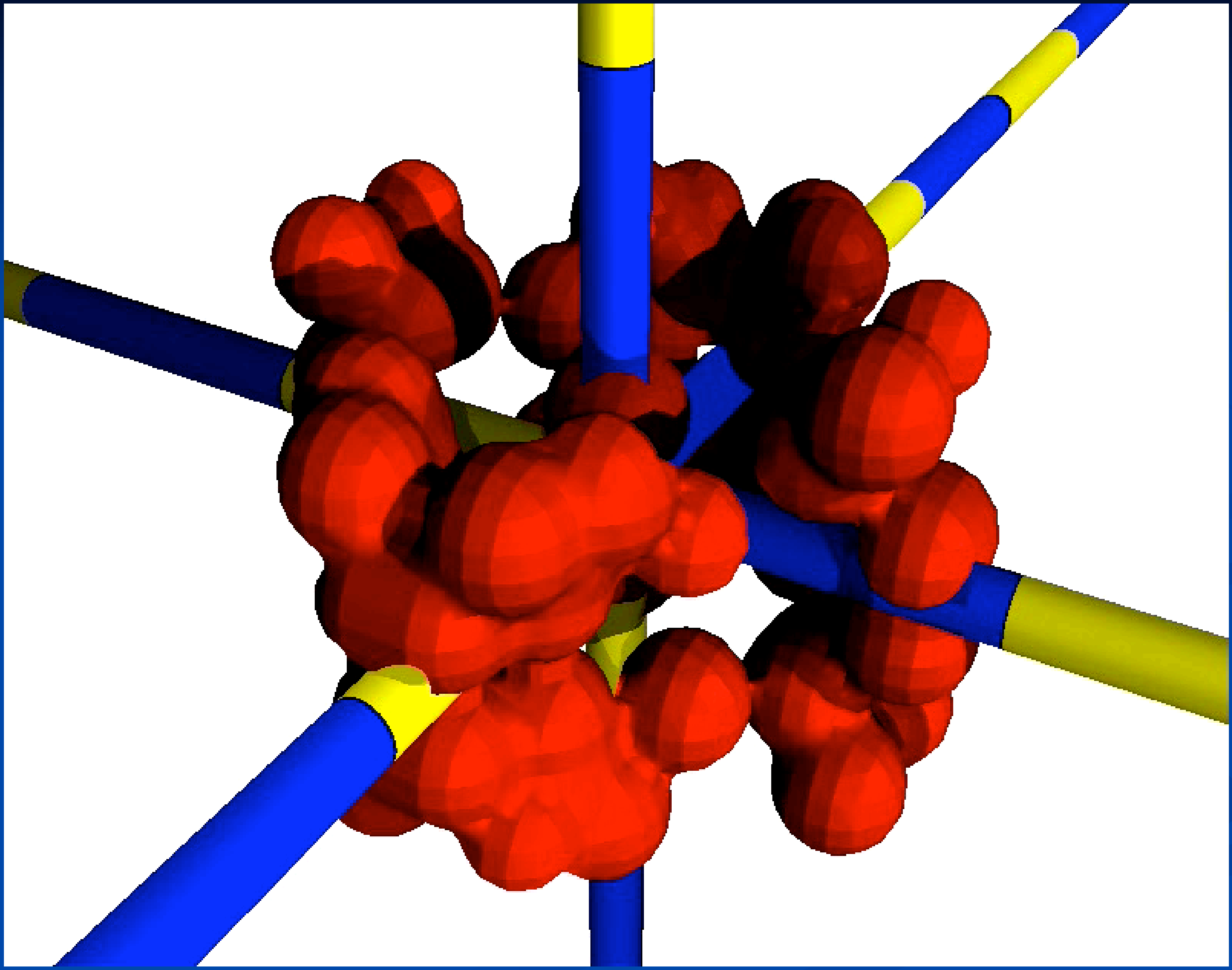
Shibata et al. 2007

(33 ms of post-bounce evolution)





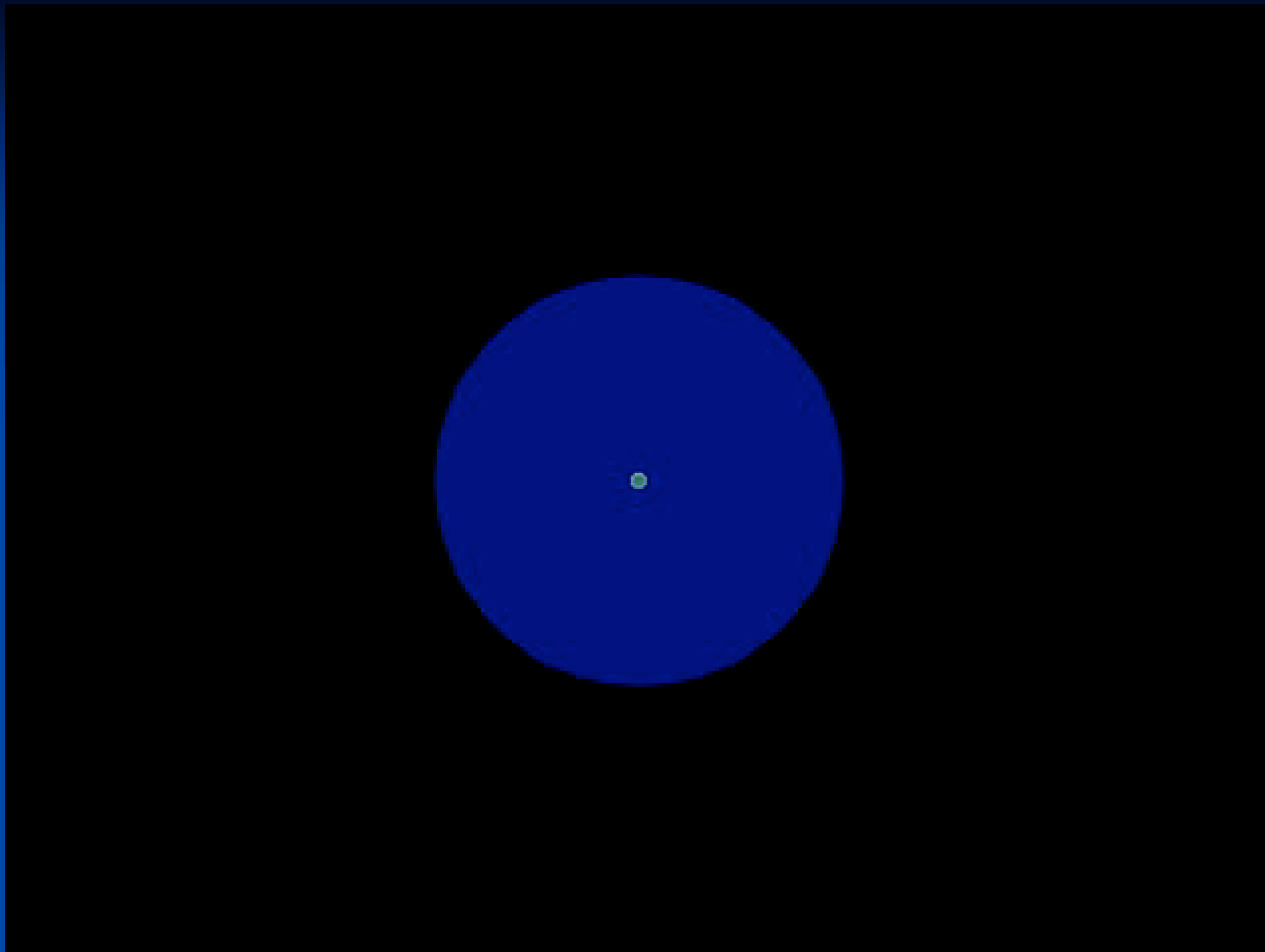
5
0
−5
0
2
4
6
8
10
12
14



MPA Type Ia Simulation

Summary of Salient Features of Acoustic Mechanism

- All Explosions are Fundamentally Aspherical
- Core l=1 g-modes are excited by turbulence and funnel accretion, which persists
- Explosion driven by Acoustic power radiated by Core Oscillations and by neutrino heating (which dominates?)
- Sound pulses steepen into multiple, nested shock waves; r-process entropies possible?
- "Unipolar" / asymmetric-wind explosion: simultaneous explosion and accretion; symmetry breaking is fundamental
- Self-excitation of core oscillation; core is transducer, storage battery?
- Natural mechanism for pulsar proper motions, supernova polarizations, and observed debris morphologies?



Flash Center, Off-Center Single-point Ignition