Theories of the Explosive Death of Massive Stars

Adam Burrows, Eli Livne, Luc Dessart, Christian Ott (JINA postdoc), Jeremiah Murphy (JINA Fellow)

Supported by:
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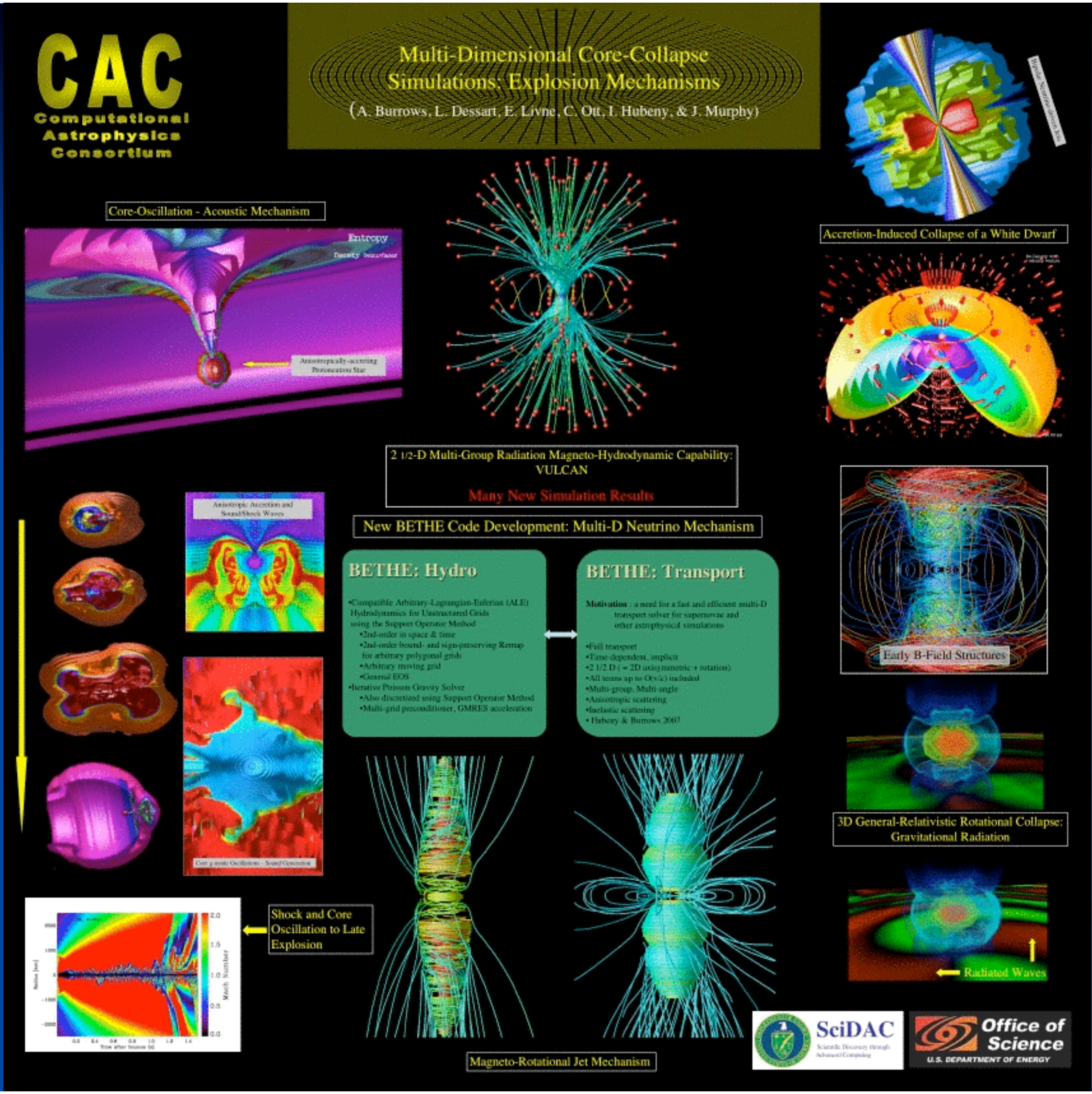
CAC
Computational Astrophysics Consortium
Multi-Dimensional Core-Collapse Simulations: Explosion Mechanisms
(A. Burrows, L. Dessart, E. Livne, C. Ott, I. Hubeny, & J. Murphy)
Core-Oscillation - Acoustic Mechanism
Entropy
Accretion-Induced Collapse of a White Dwarf
2 1/2-D Multi-Group Radiation Magneto-Hydrodynamic 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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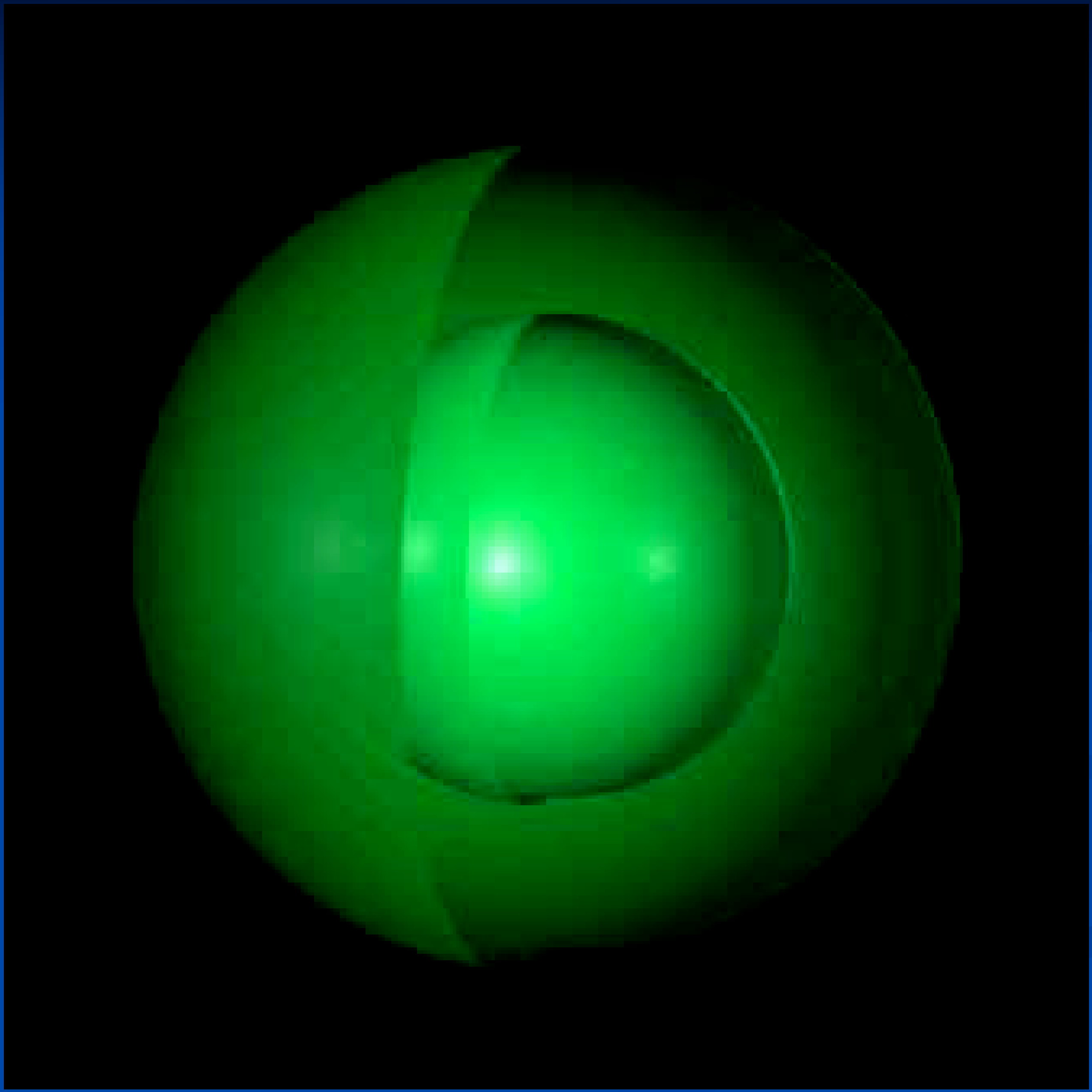
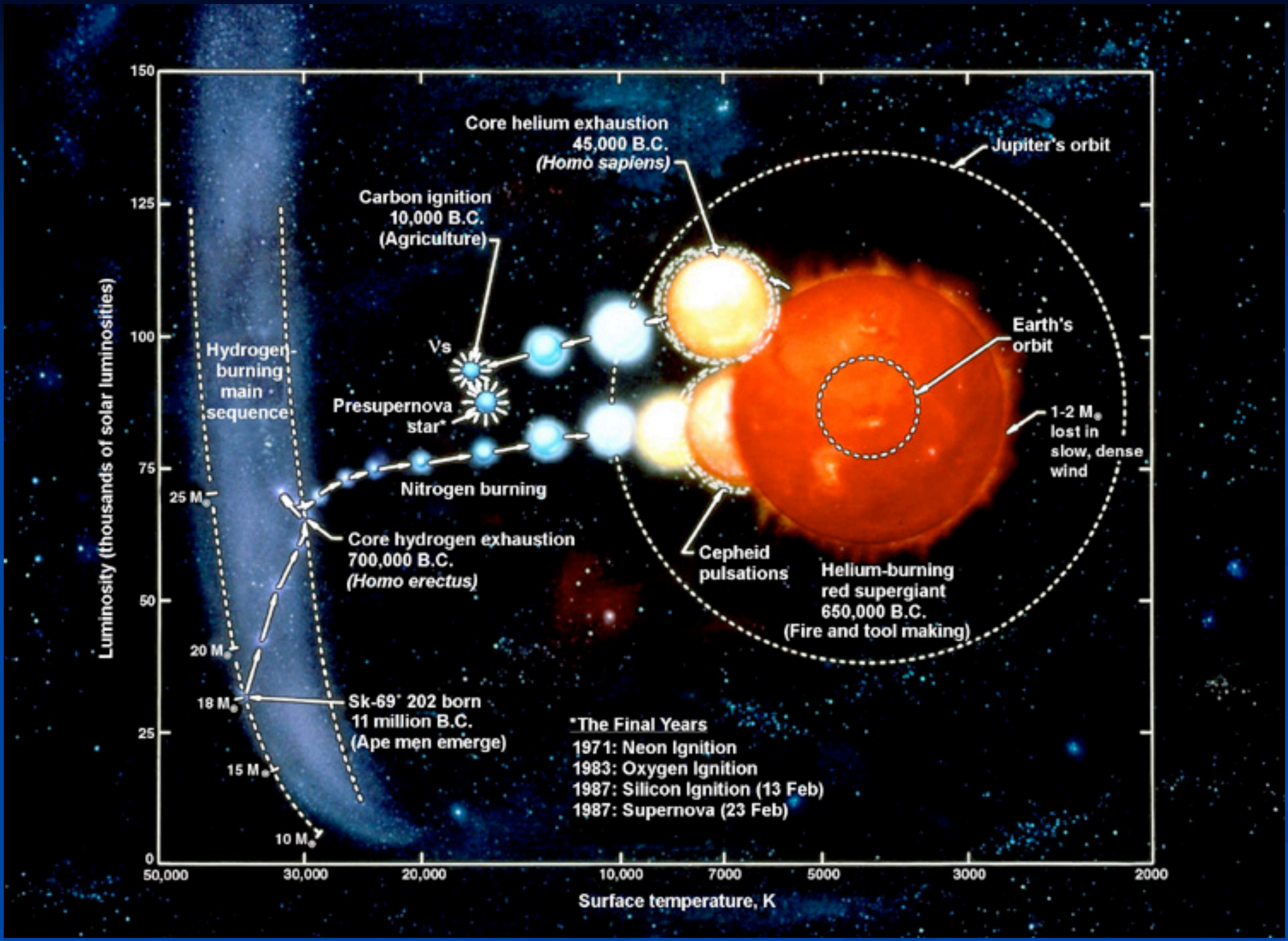
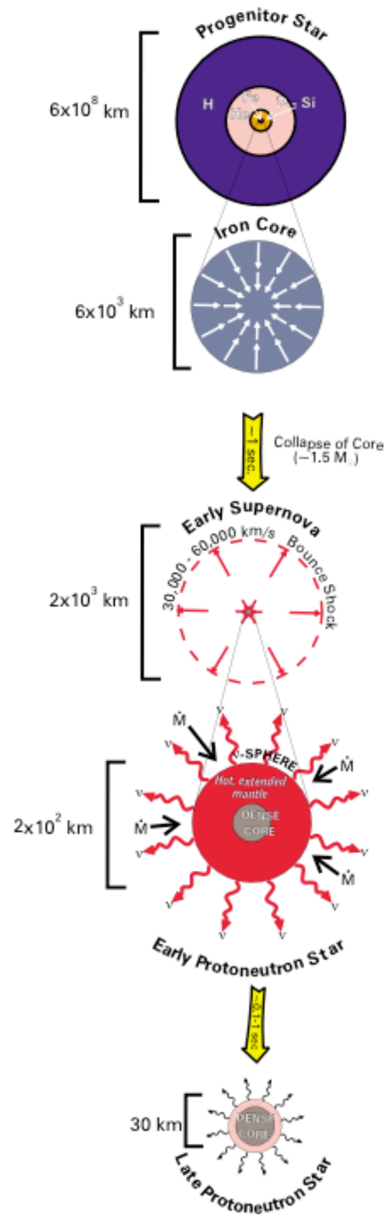
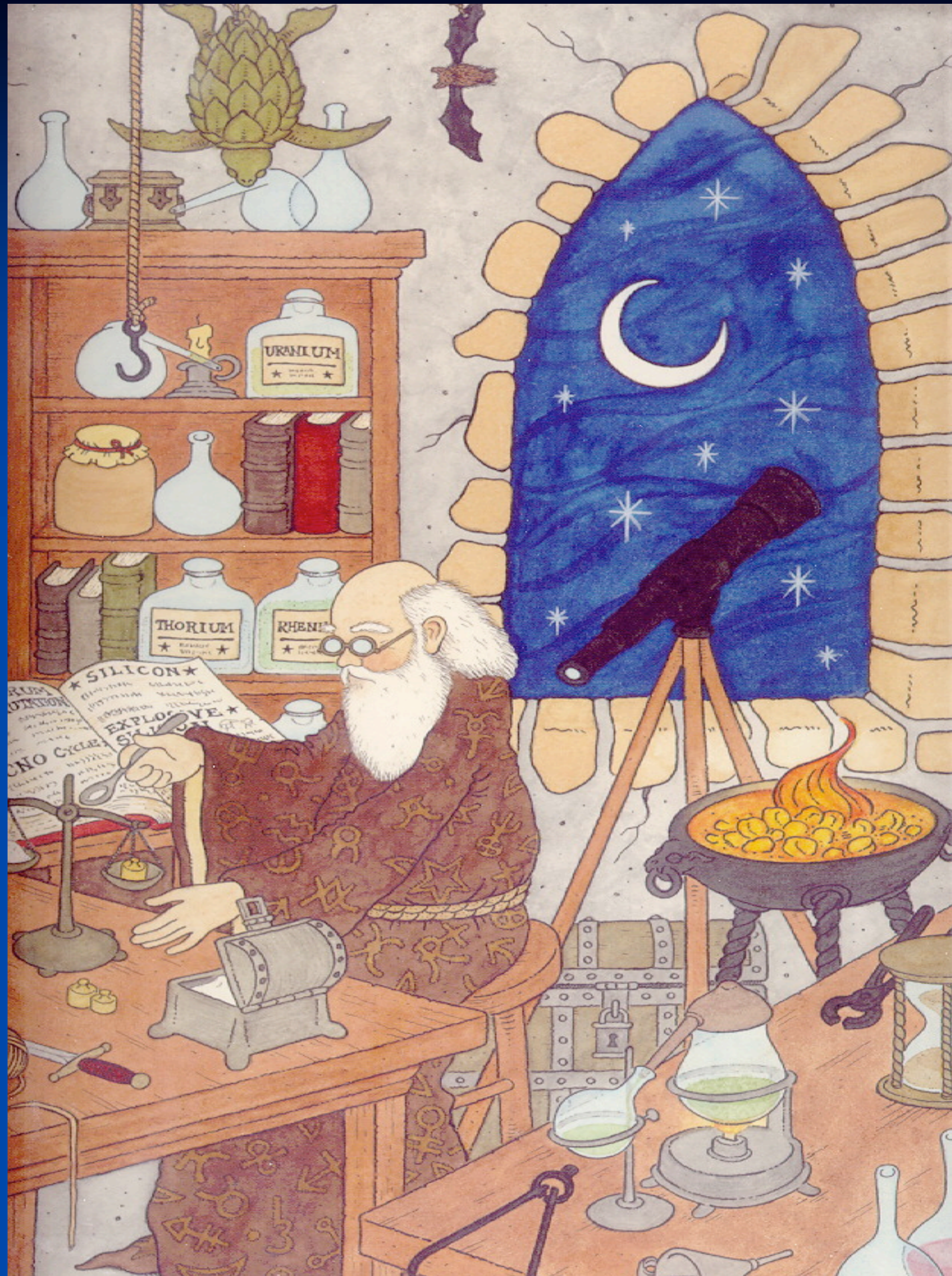
Onion Skin Structure: The Mote in the Eye of the Storm



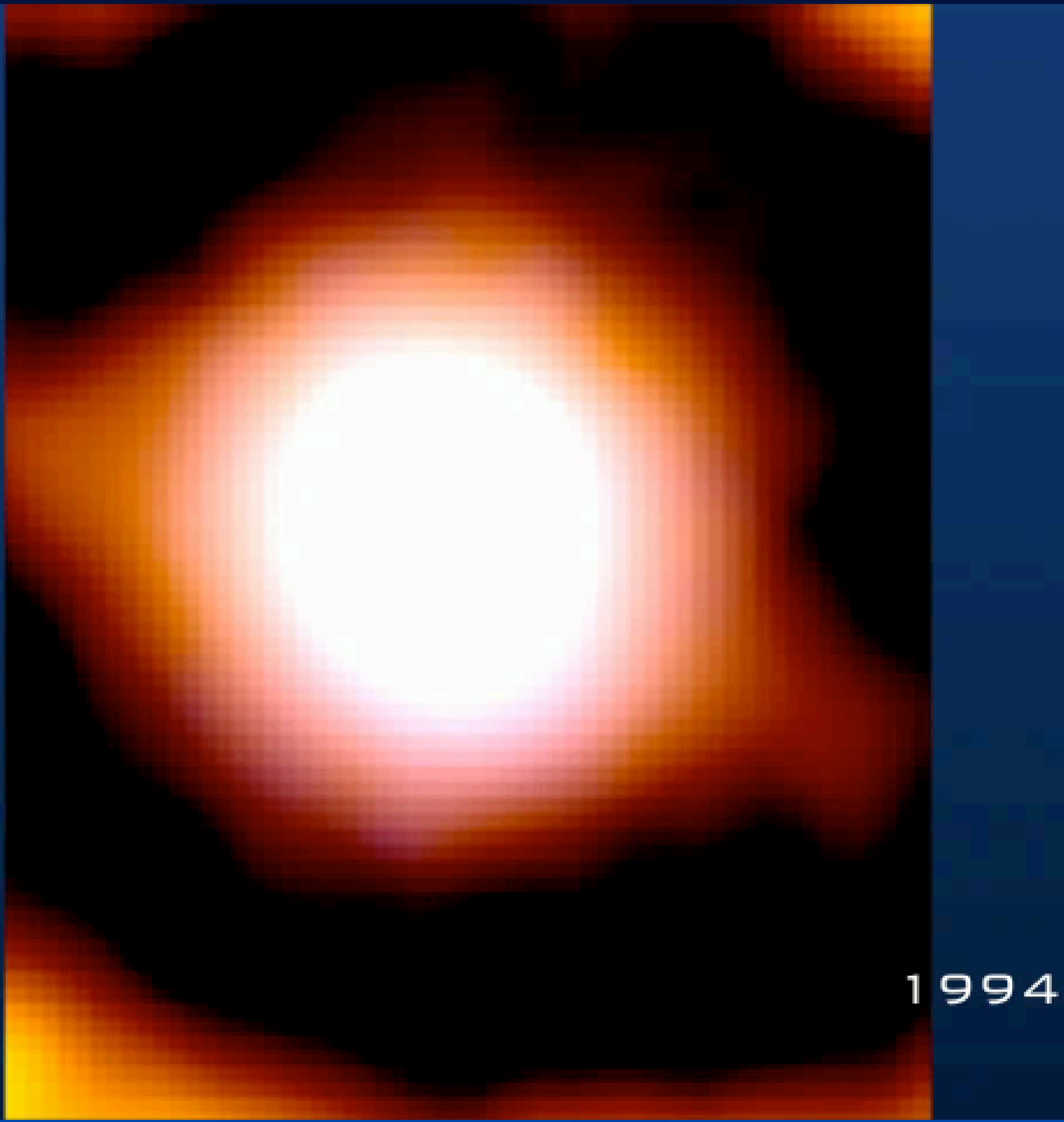


Courtesy of Tom Weaver

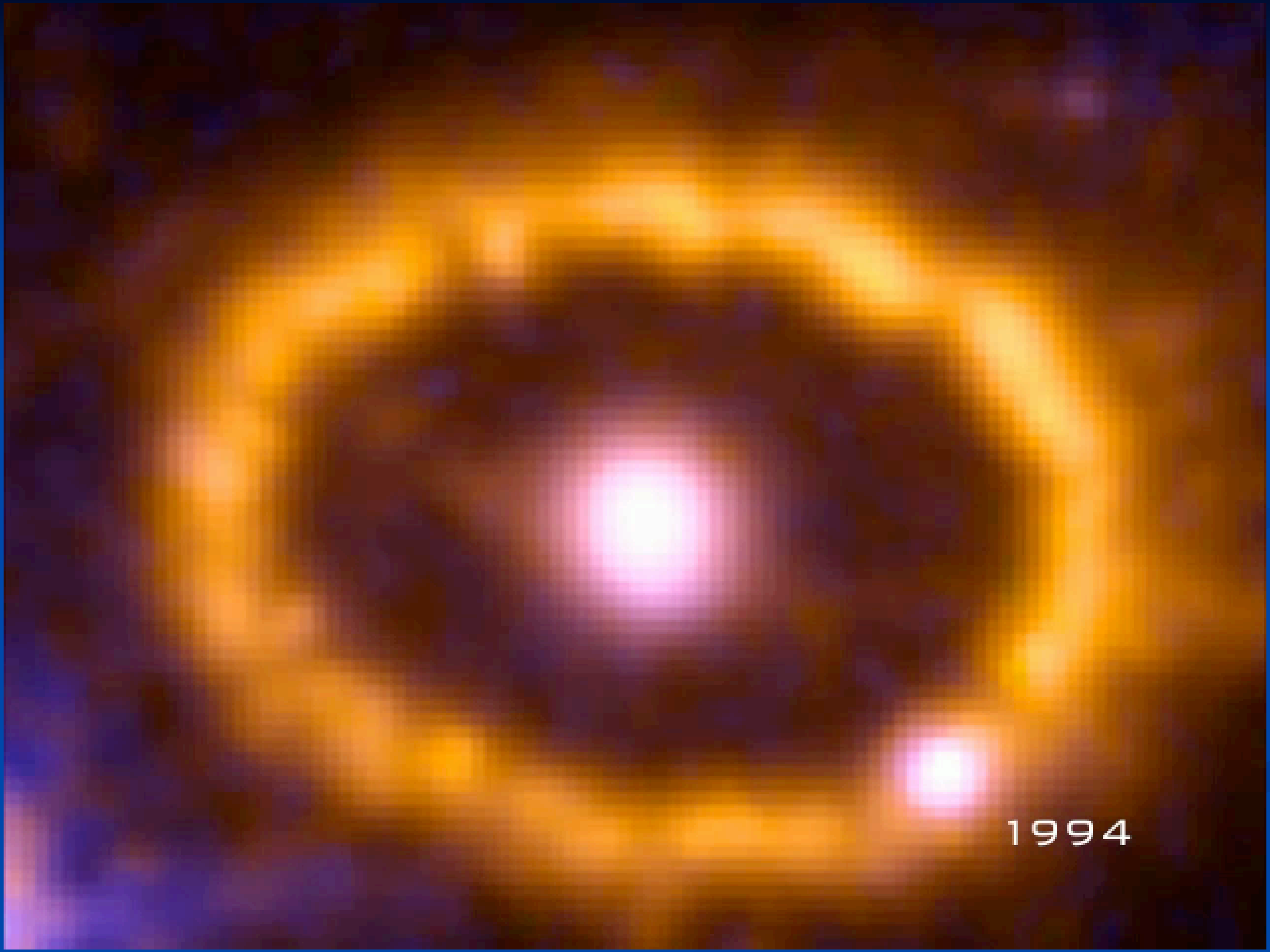

Progenitor Star
6x10^8 km
H
Si
Iron Core
6x10^3 km
~1 sec.
Collapse of Core
(~1.5 M☉)
Early Supernova
30,000 - 60,000 km/s
Bounce Shock
2x10^3 km
ν-SPHERE
Hot, extended mantle
DENSE CORE
2x10^2 km
Early Protoneutron Star
~0.1-1 sec
30 km
DENSE CORE
Late Protoneutron Star


URANIUM
THORIUM
SILICON
CNO CYCLE

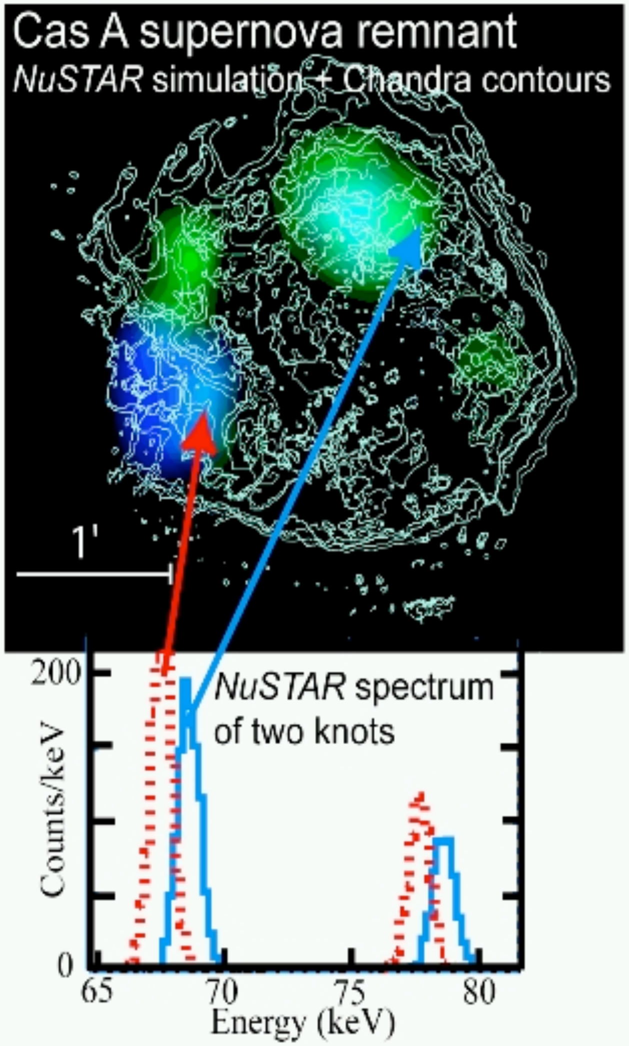
SN1987a (Pete Challis)



SN1987a (Pete Challis)



NuSTAR will map the remnants of recent supernova explosions, testing theories of where the elements are born



NuSTAR will measure and map the ^{44}Ti lines at 68 and 78 keV in historic remnants:
Tycho, Kepler, Cas A and SN1987A

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?

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**

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

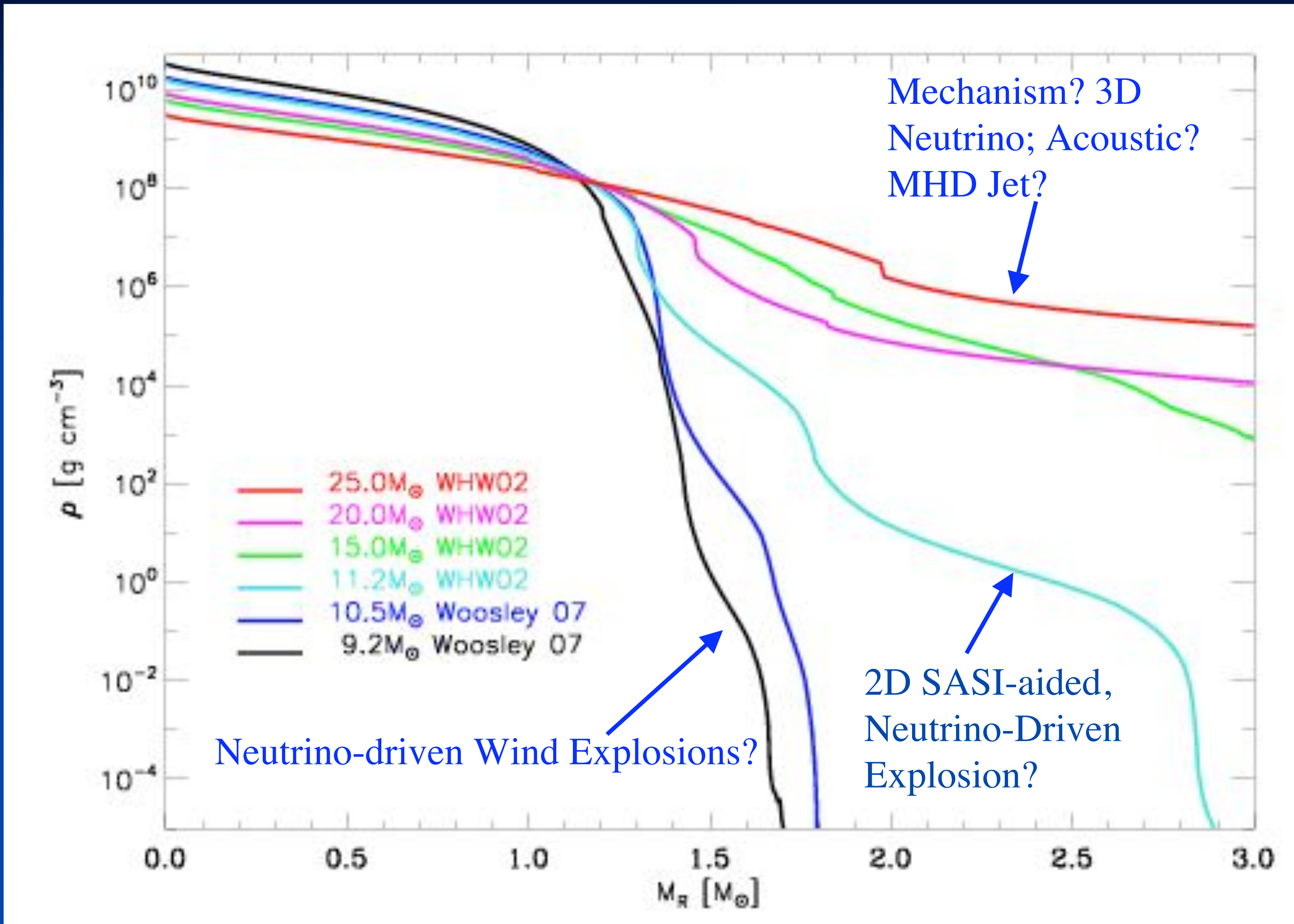
Issues/Problems

- 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; 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
- Axially-symmetric; Rotation
- MHD version ("2.5D") - div B = 0 to machine accuracy; torques
- Flux-conservative; smooth matching to diffusion limit
- Velocity-dependent terms: advection included (DI/dt), but not yet Doppler/Aberation terms
- Parallelized in energy groups; almost perfect parallelism
- Energy redistribution: explicit
- New Implicit Hydro version
- Livne, Burrows et al. (2004,2007)
- Burrows et al. (2006,2007), Ott et al. (2005); Dessart et al. 2005ab

Density Profiles of Supernova Progenitor Cores



Neutrino-Driven Wind Explosions: Low Mass and AIC

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

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

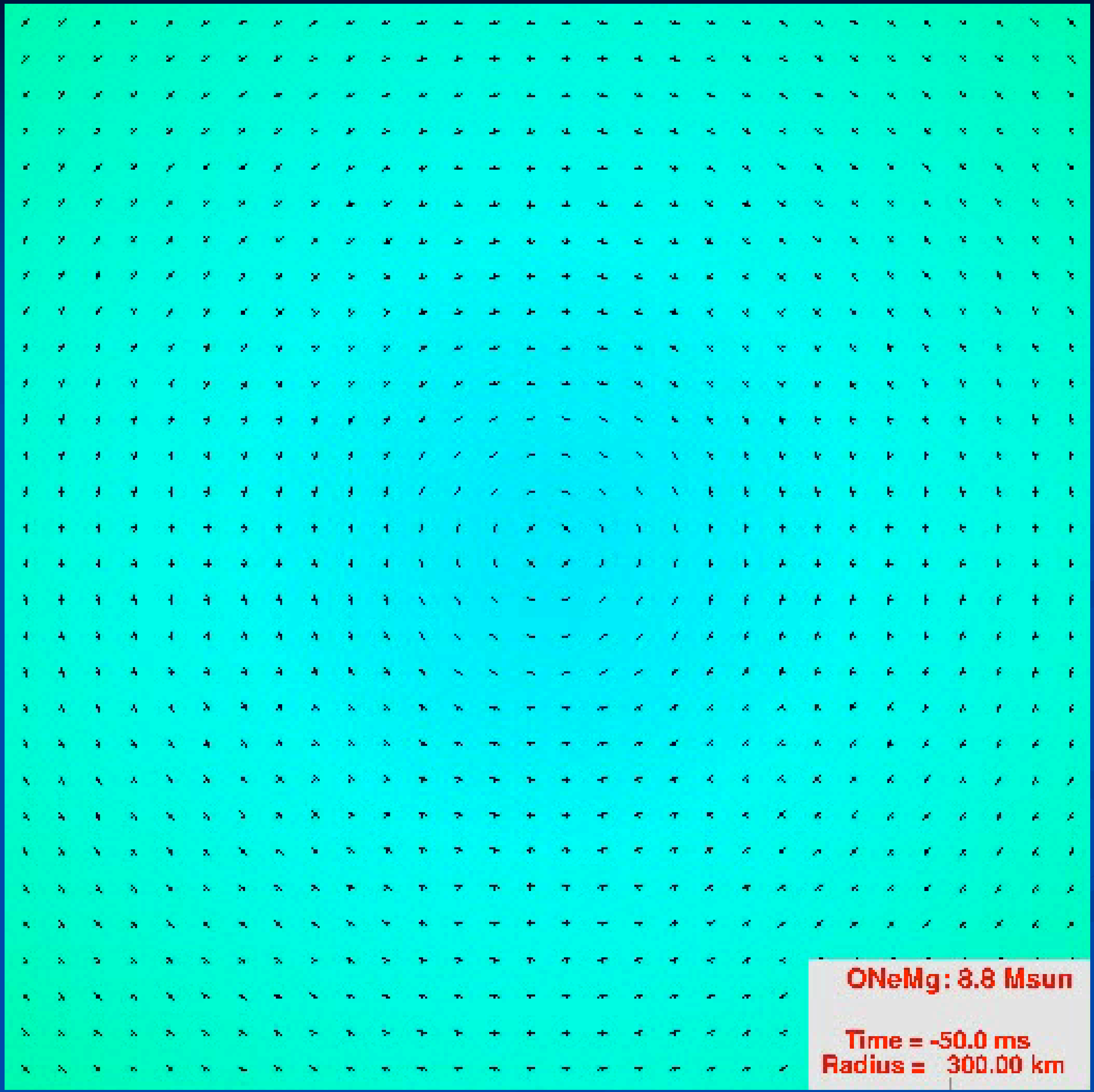
First shown by Kitaura et al. 2006

NOTE WIND THAT FOLLOWS:

TWO SHOCKS!

Dessart, Burrows et al. 2007;

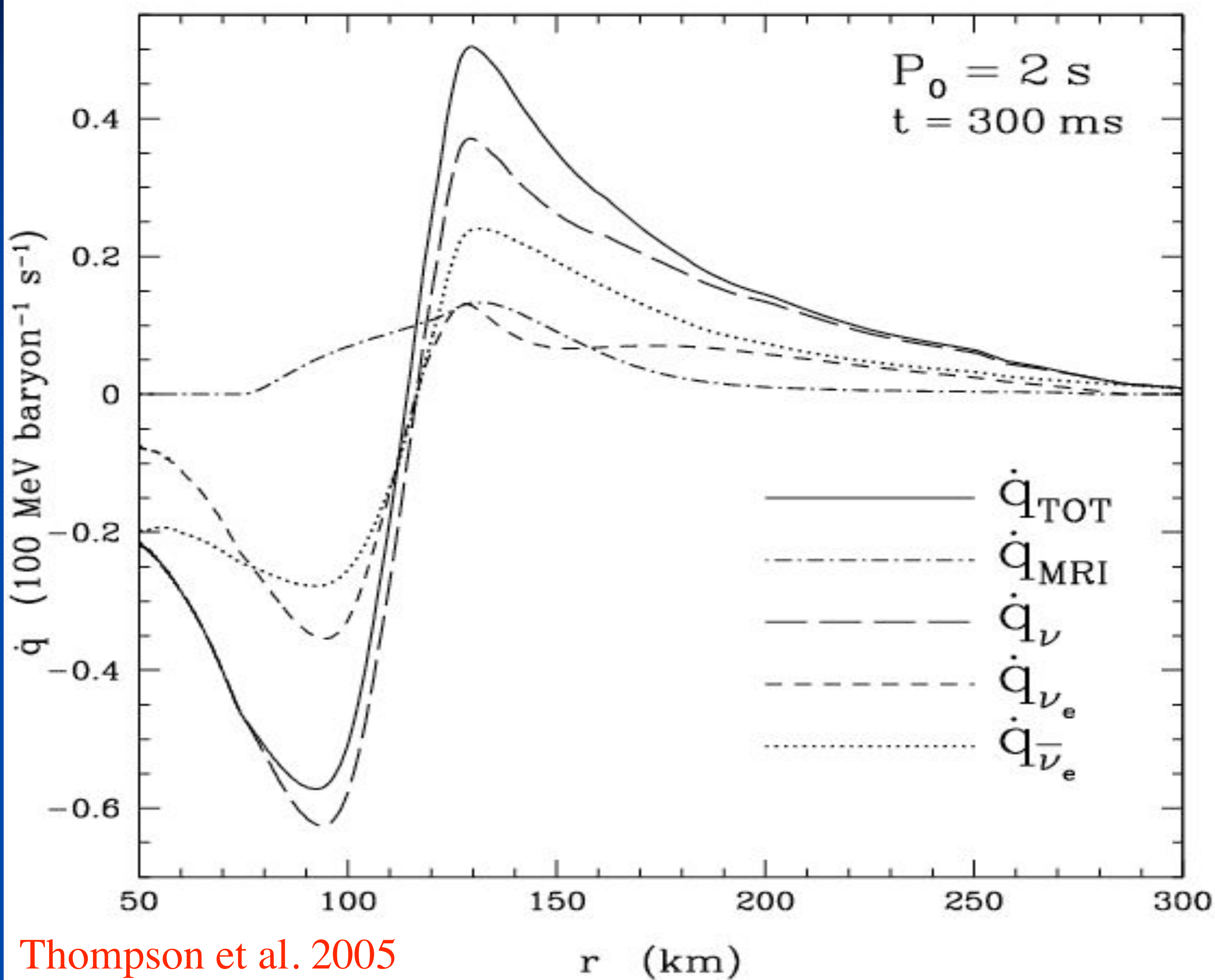
Burrows 1987



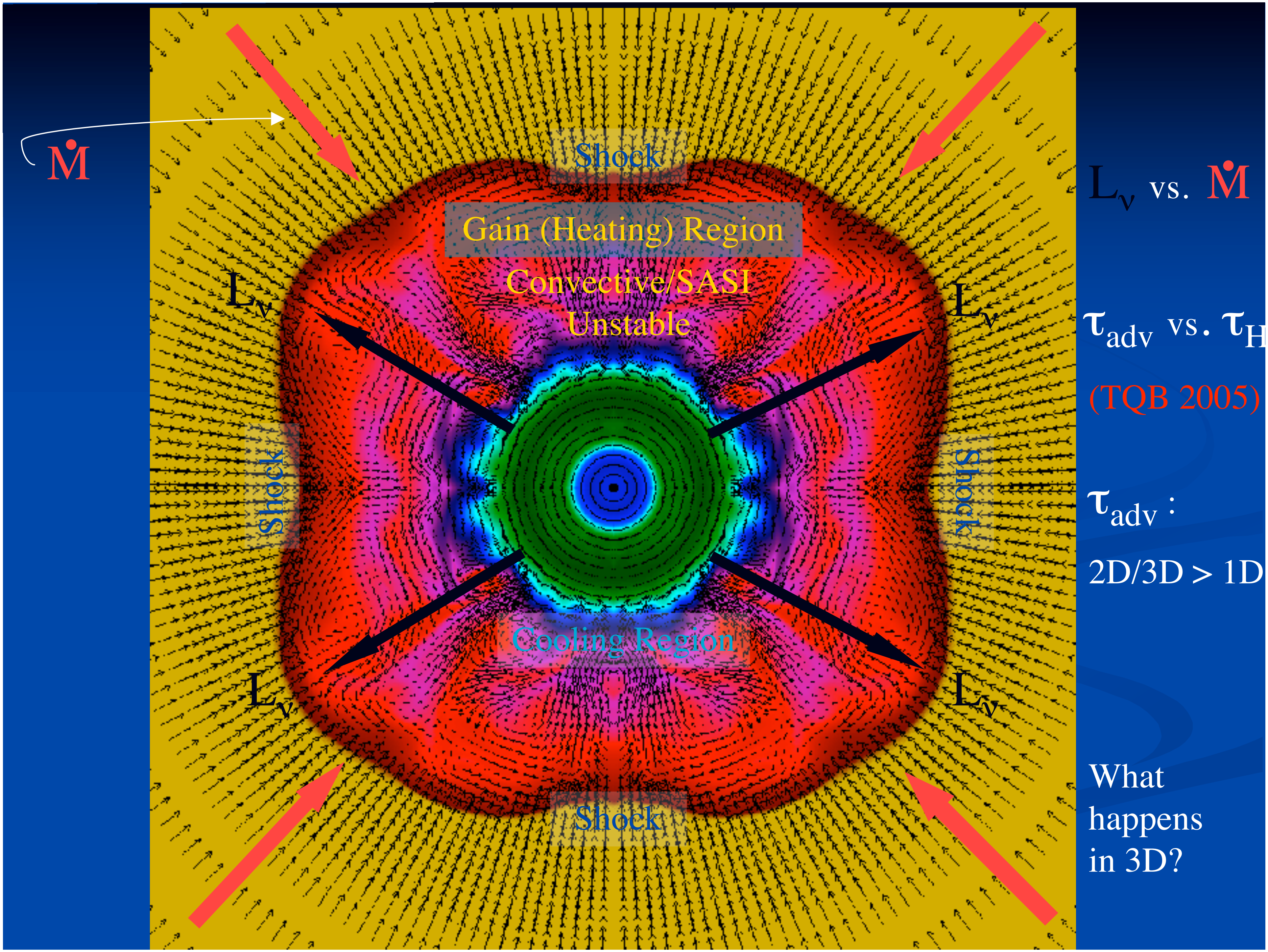
1) What is the Essence of the Neutrino Mechanism

2) How can it "be made" to work?

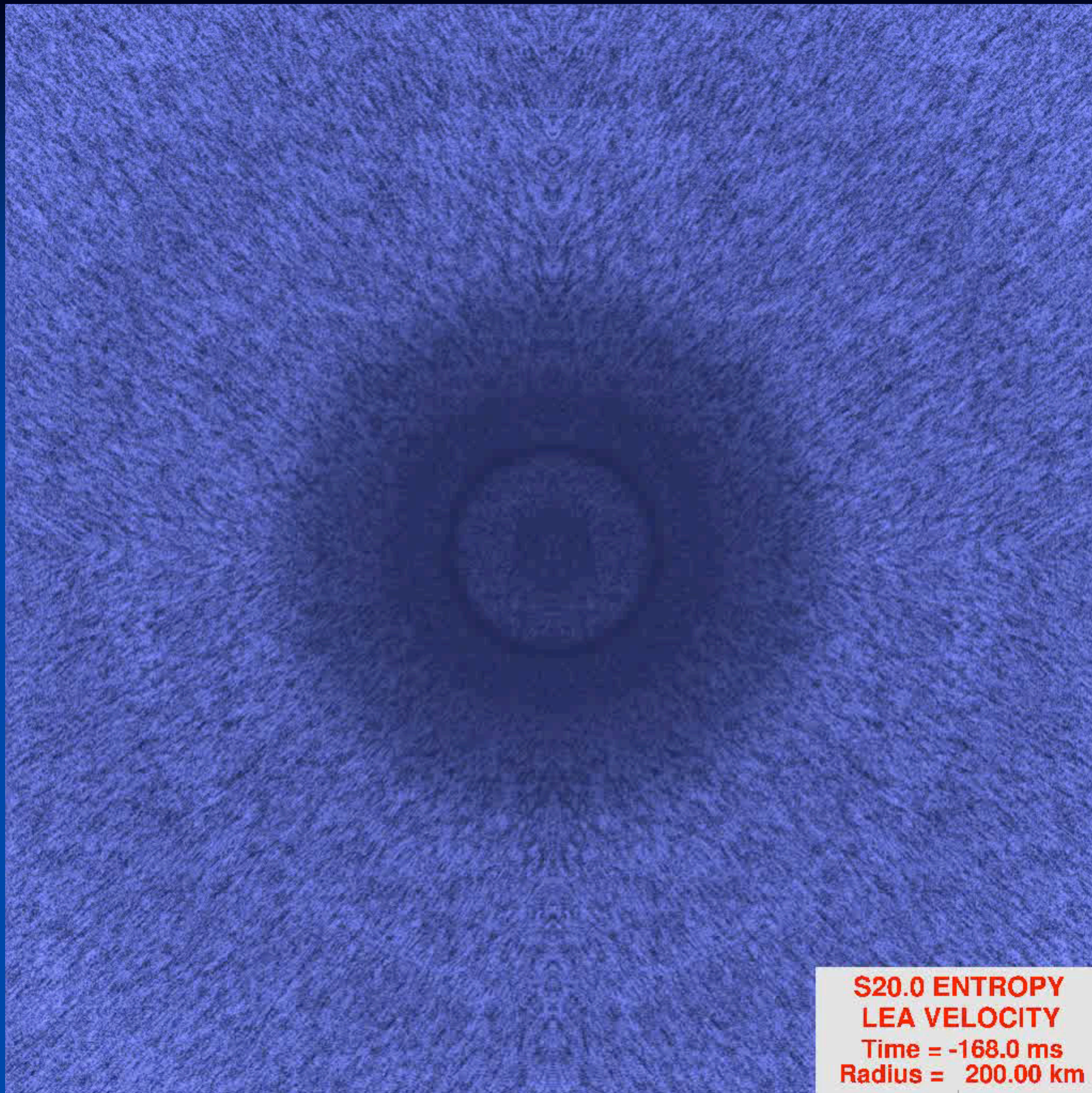
Heating and Cooling; The Effect of an Extra Source



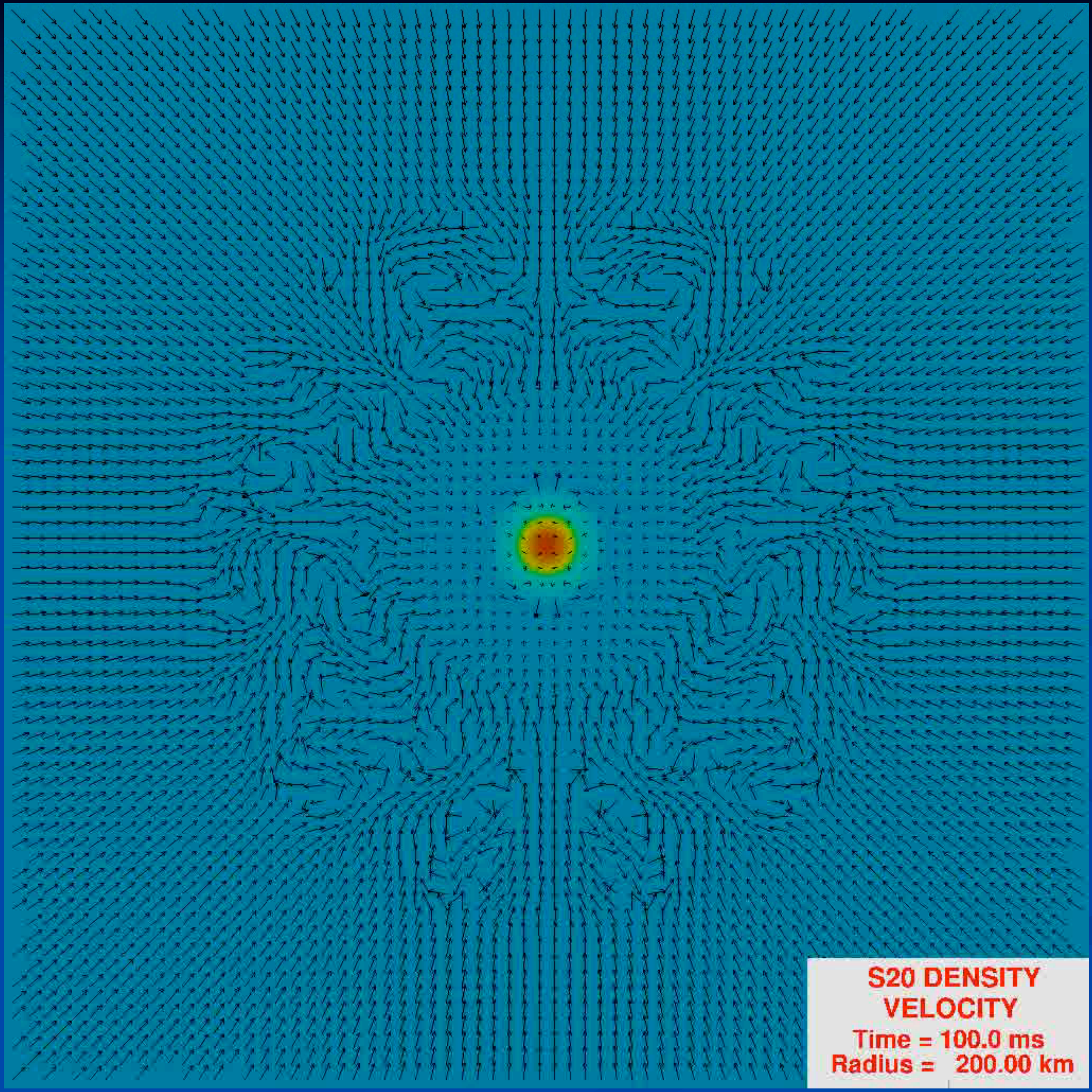
Thompson et al. 2005



$\dot{M}$
Shock
Gain (Heating) Region
Convective/SASI
Unstable
L_ν
L_ν
Shock
Shock
Cooling Region
L_ν
L_ν
Shock
L_ν vs. $\dot{M}$
τ_{adv} vs. τ_H
(TQB 2005)
τ_{adv} :
2D/3D > 1D
What
happens
in 3D?


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

But,
in
3D?



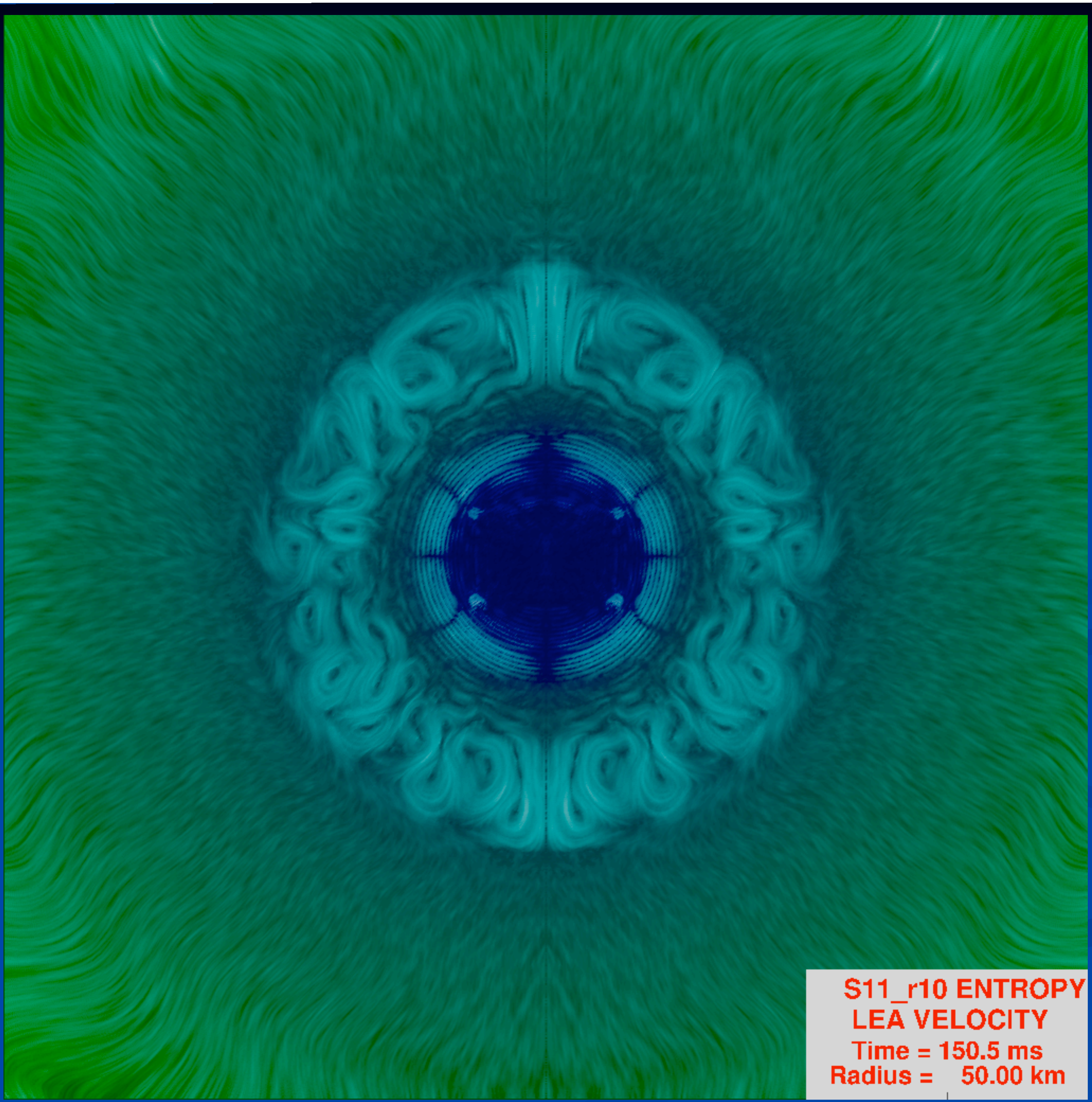
"Protoneutron Star Convection"

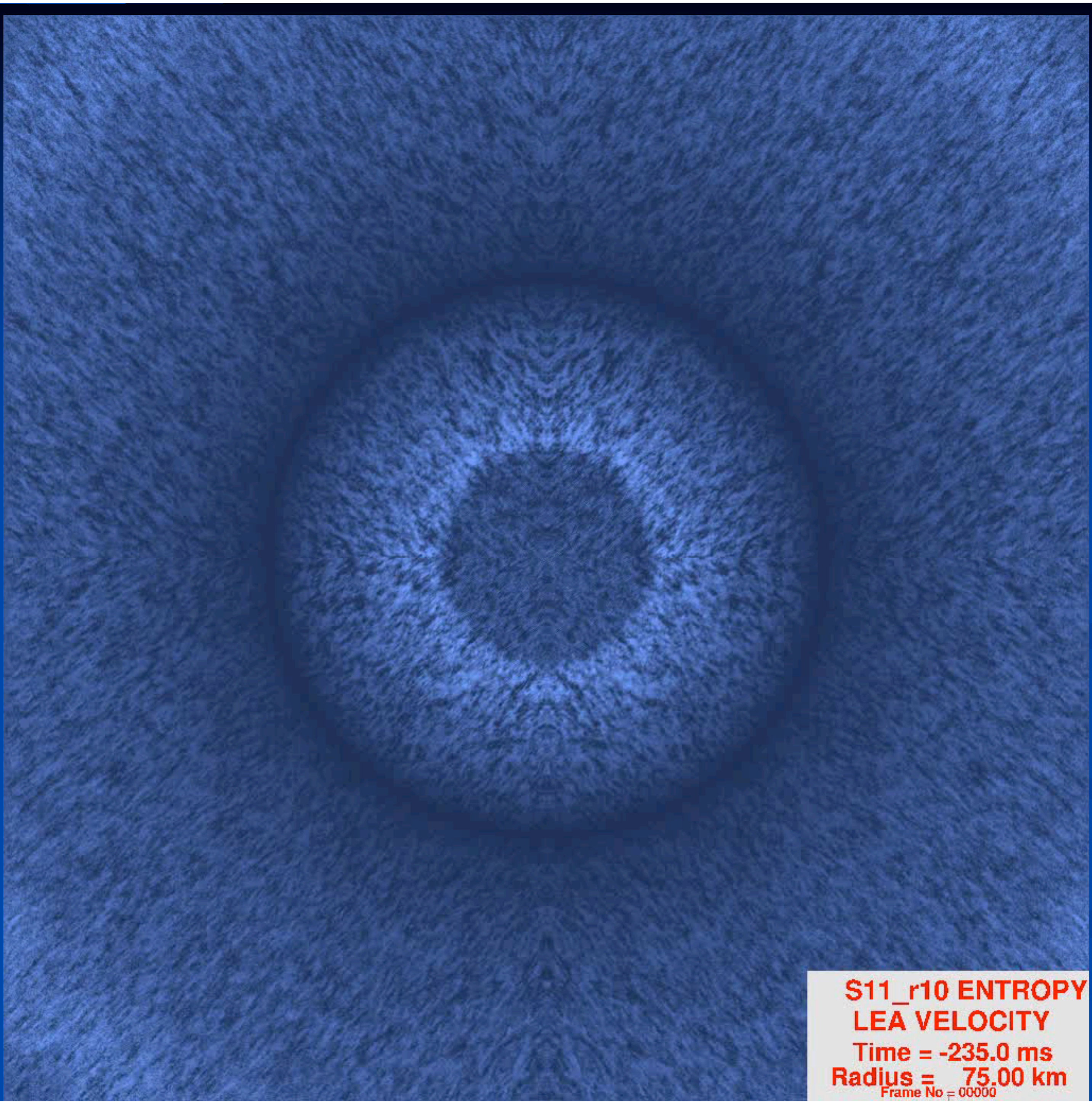
Ledoux (S/Y_e ?) and/or Doubly-Diffusive Convection?

Can it Boost the Driving Neutrino Luminosities?

(Wilson & Mayle 1988; Burrows 1987)

New study by Dessart et al. 2005


S11_r10 ENTROPY
LEA VELOCITY
Time = 150.5 ms
Radius = 50.00 km

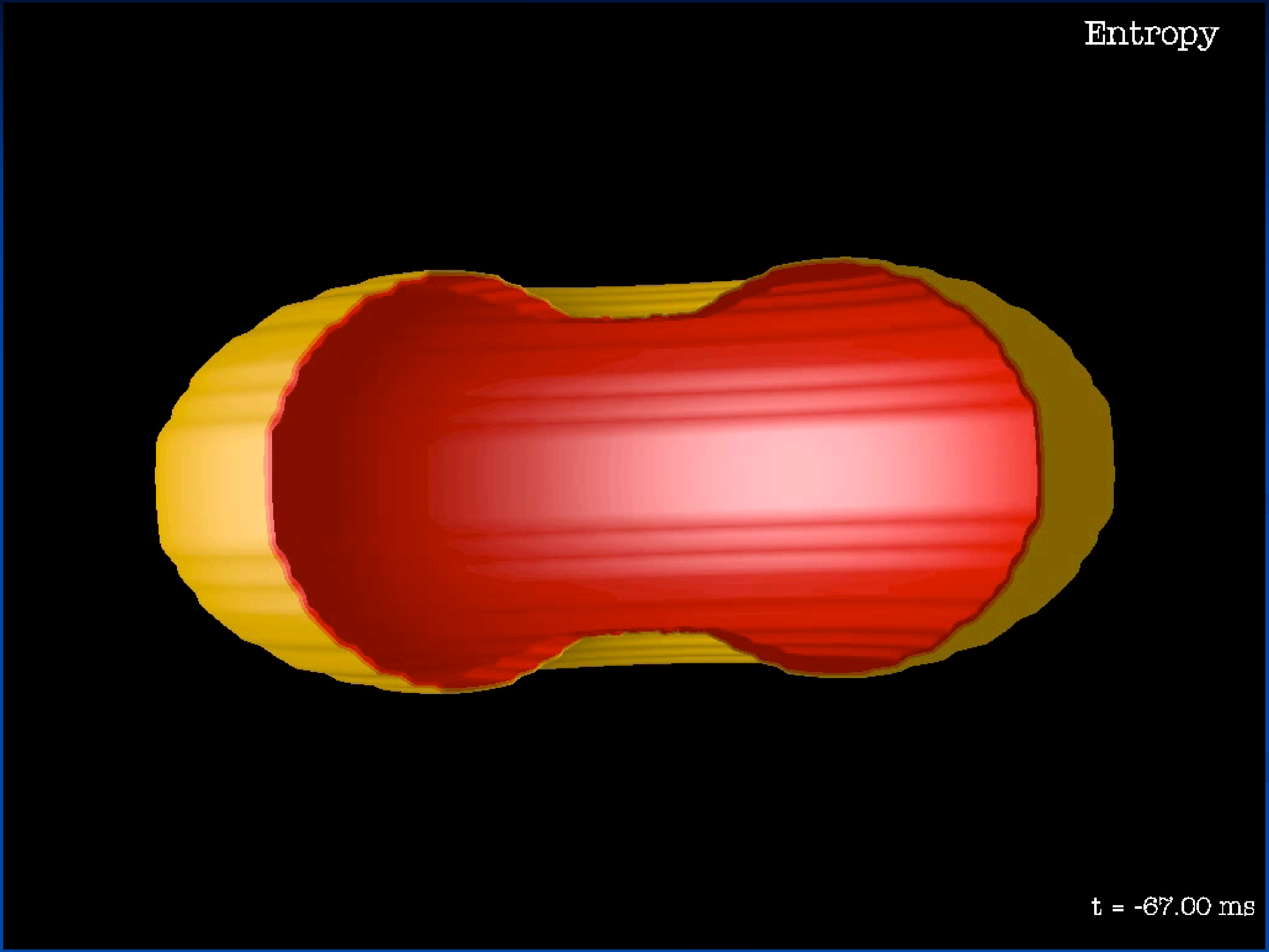

S11_r10 ENTROPY
LEA VELOCITY
Time = -235.0 ms
Radius = 75.00 km
Frame No = 00000

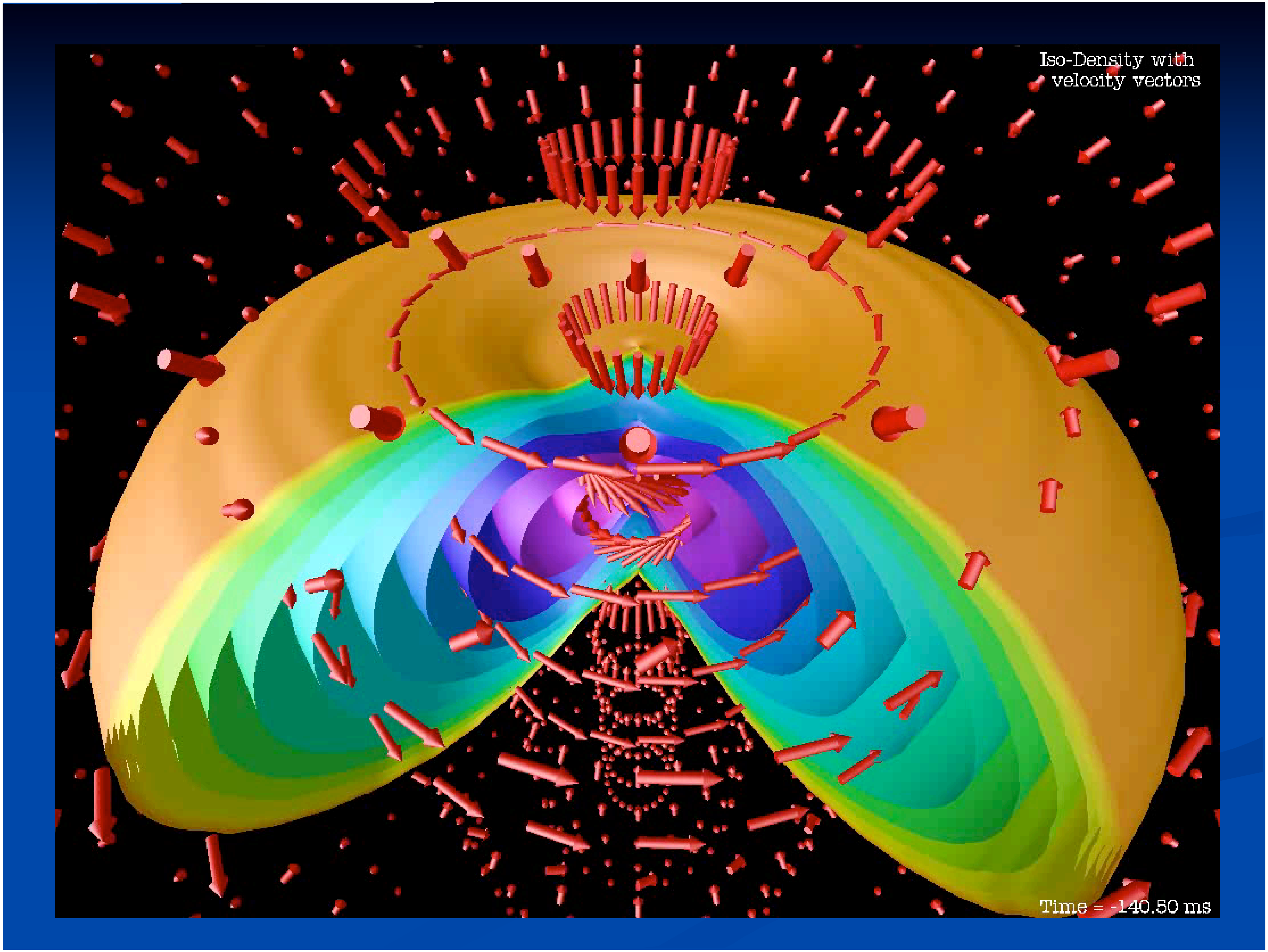
Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

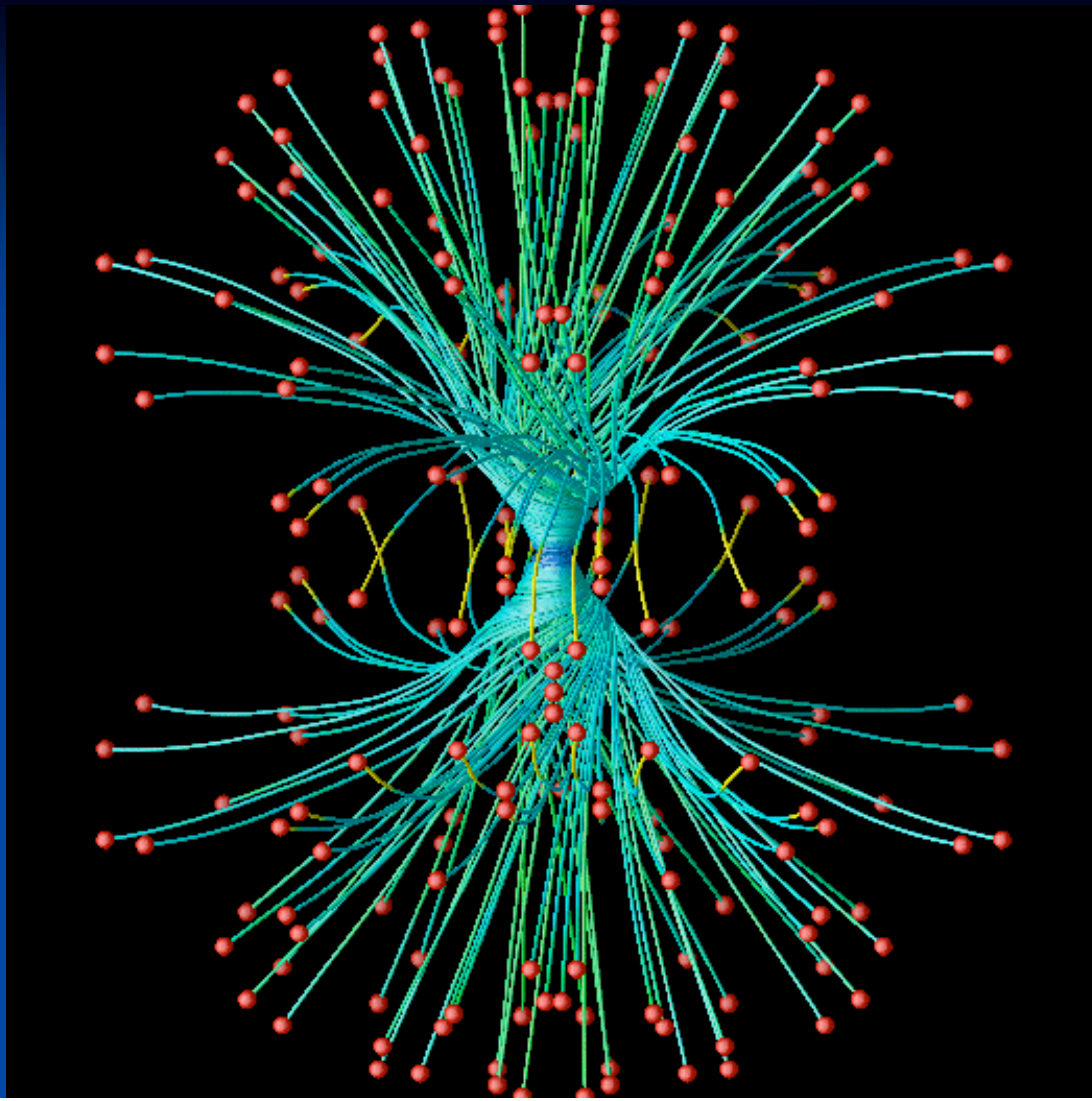
Dessart, Burrows, Ott, Livne, Yoon, & Langer 2006

Rapid Rotation!

AIC: 1.92 solar masses:




Iso-Density with
velocity vectors
Time = -140.50 ms

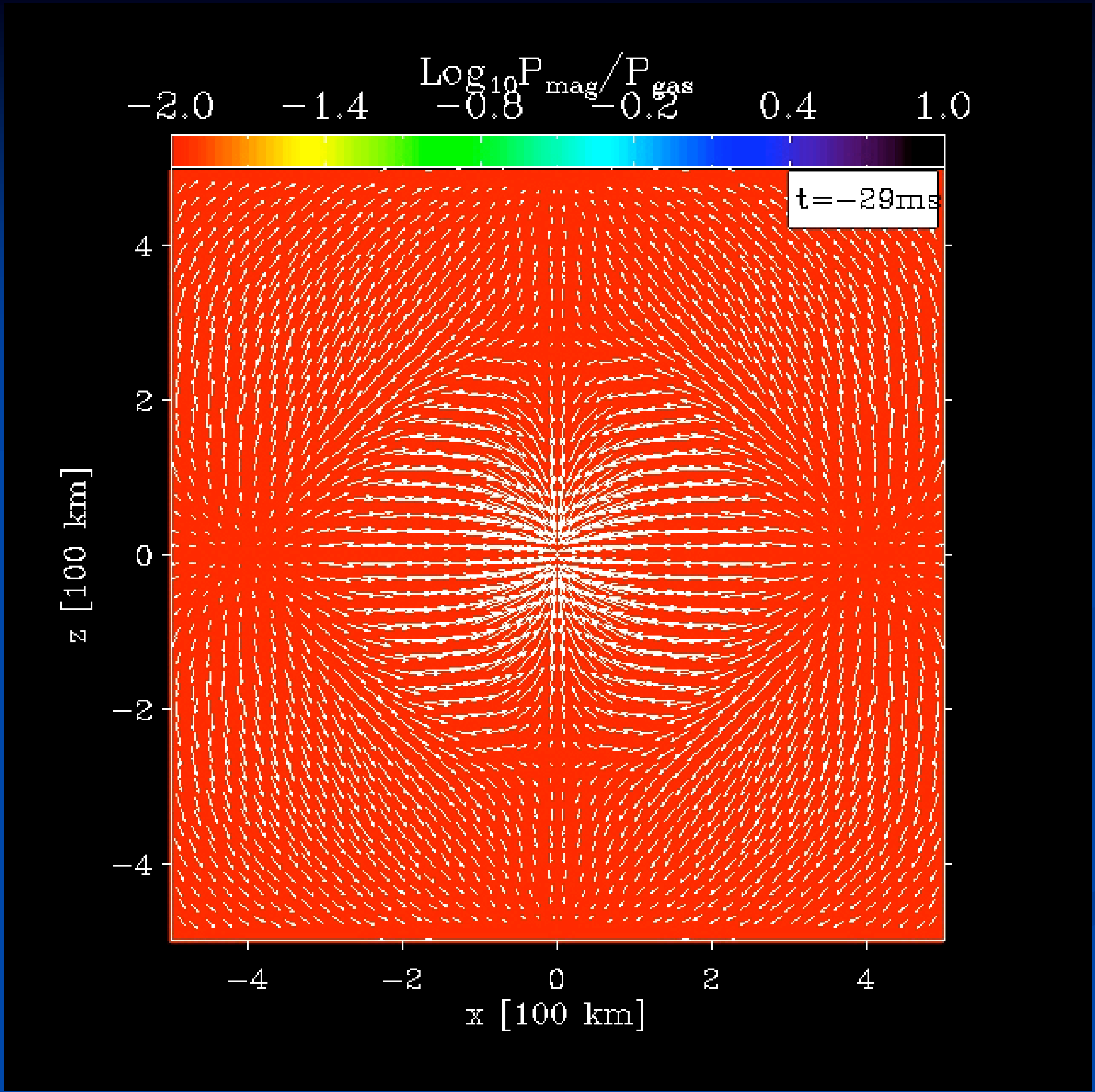


Accretion-Induced Collapse with **Magnetic Fields**

Dessart et al. 2007

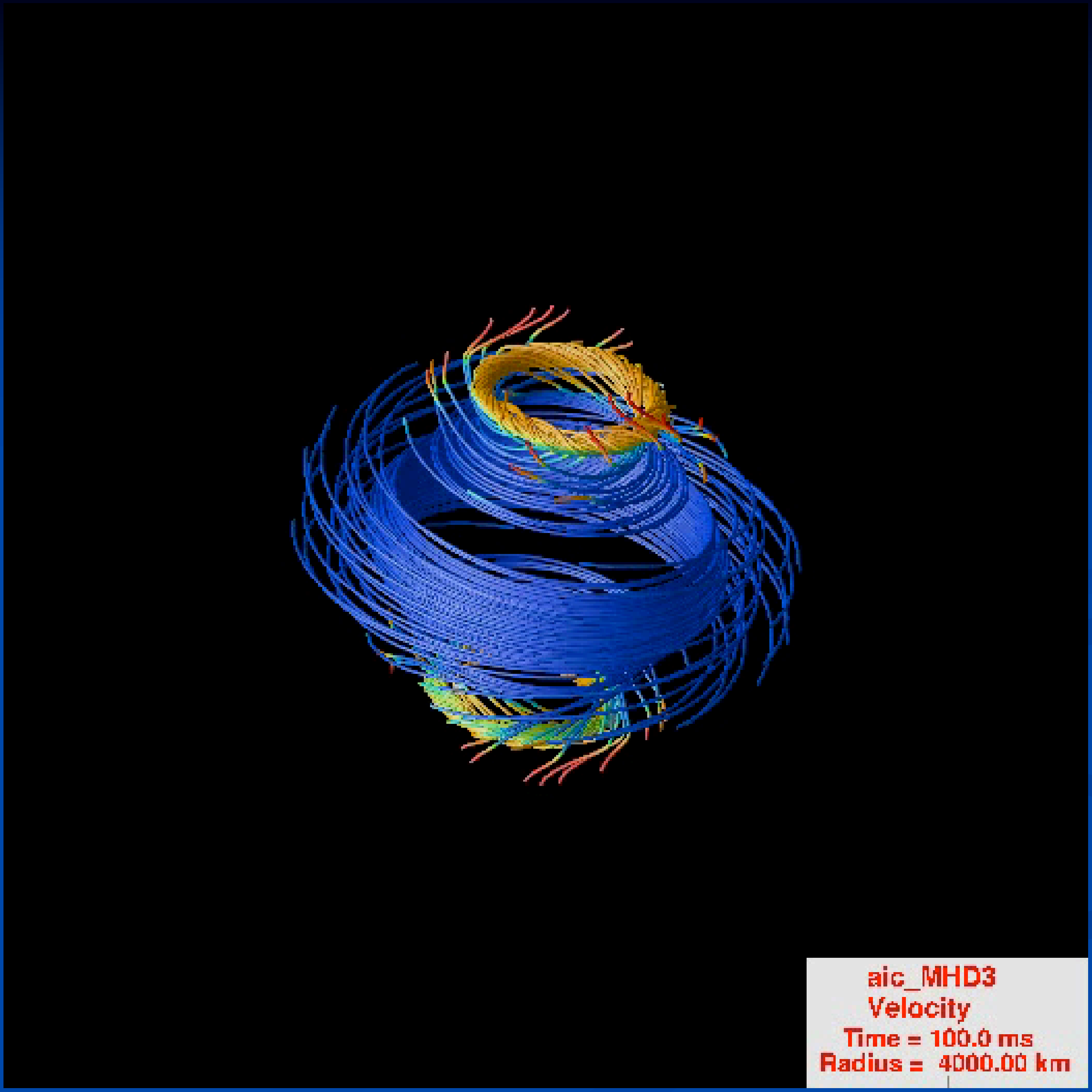
Rapid Rotation!

AIC with MHD

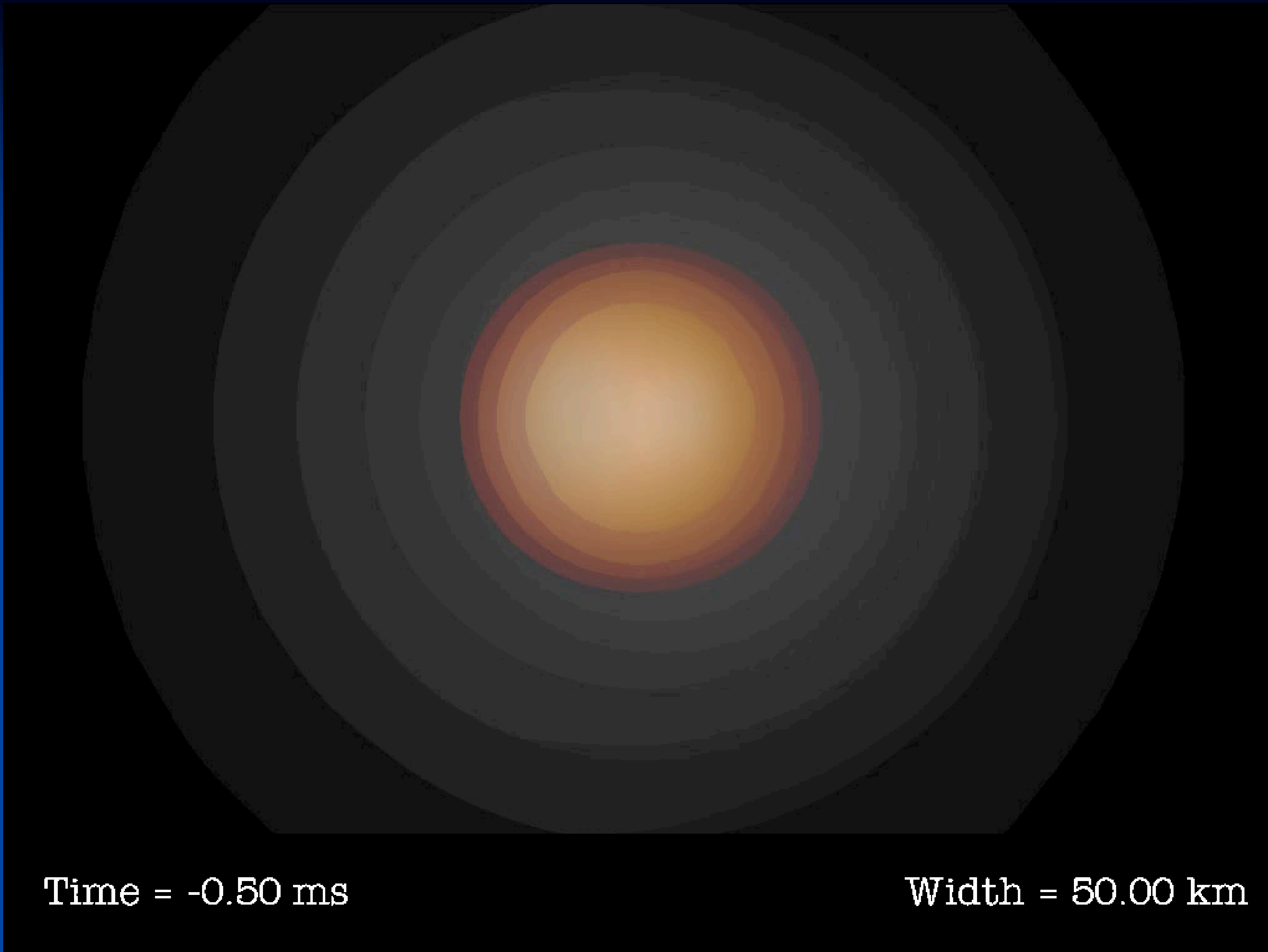


$Log_{10}P_{mag}/P_{gas}$
−2.0
−1.4
−0.8
−0.2
0.4
1.0
t=−29ms
4
2
0
−2
−4
z [100 km]
−4
−2
0
2
4
x [100 km]

AIC
with
MHD

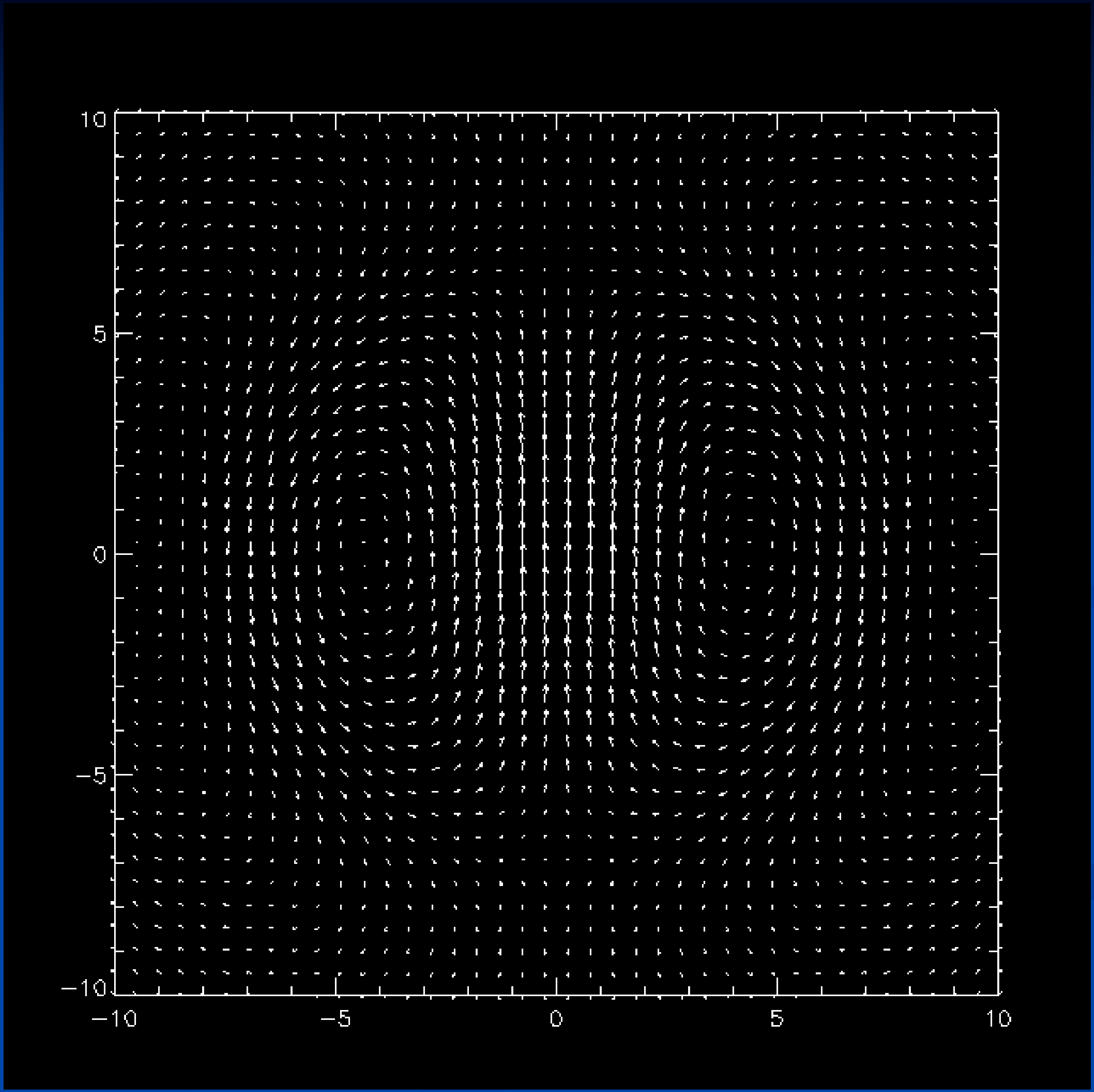


Core Oscillation/Acoustic Power Mechanism

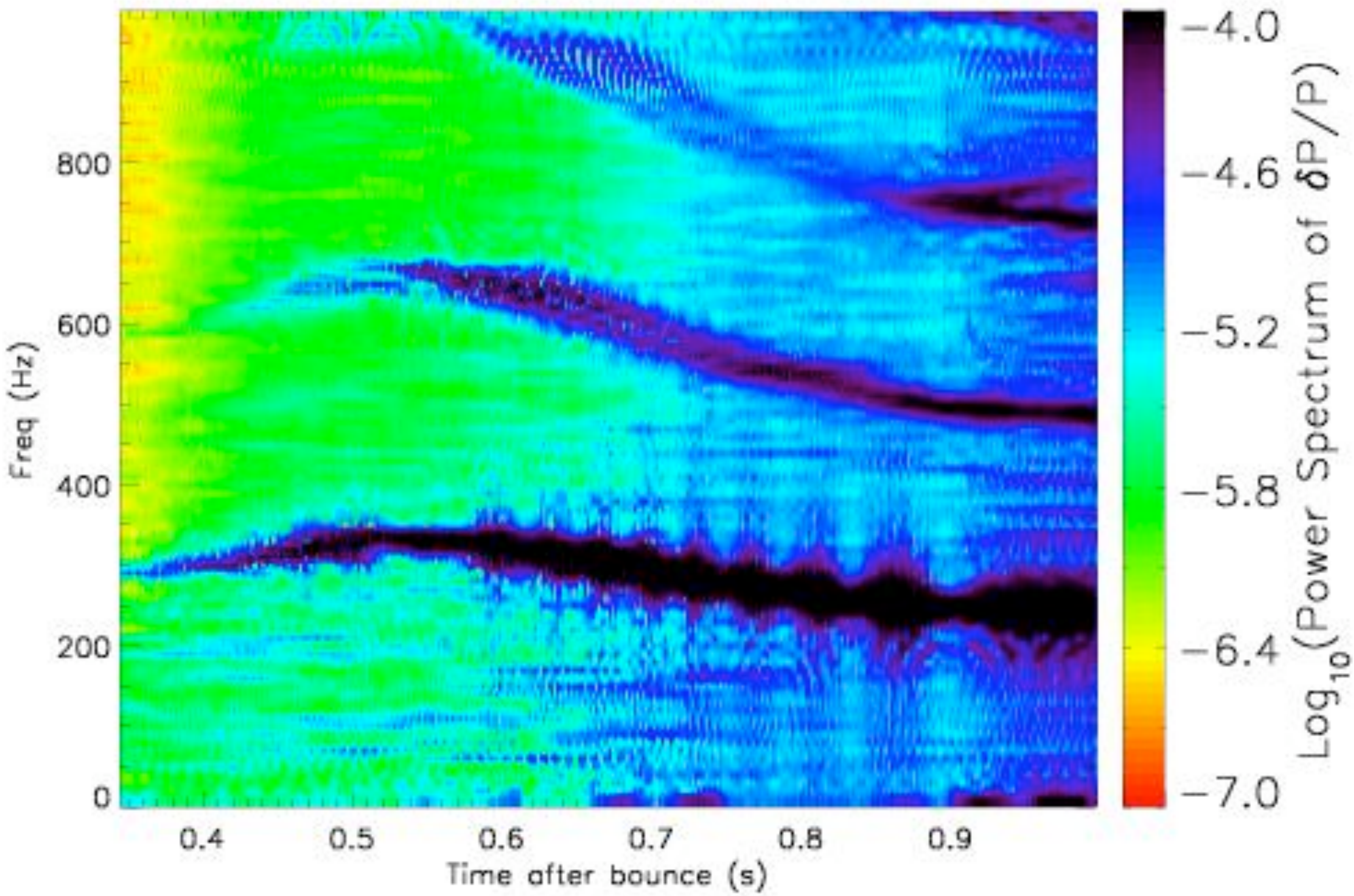

Time = -0.50 ms
Width = 50.00 km

Analytic l=1

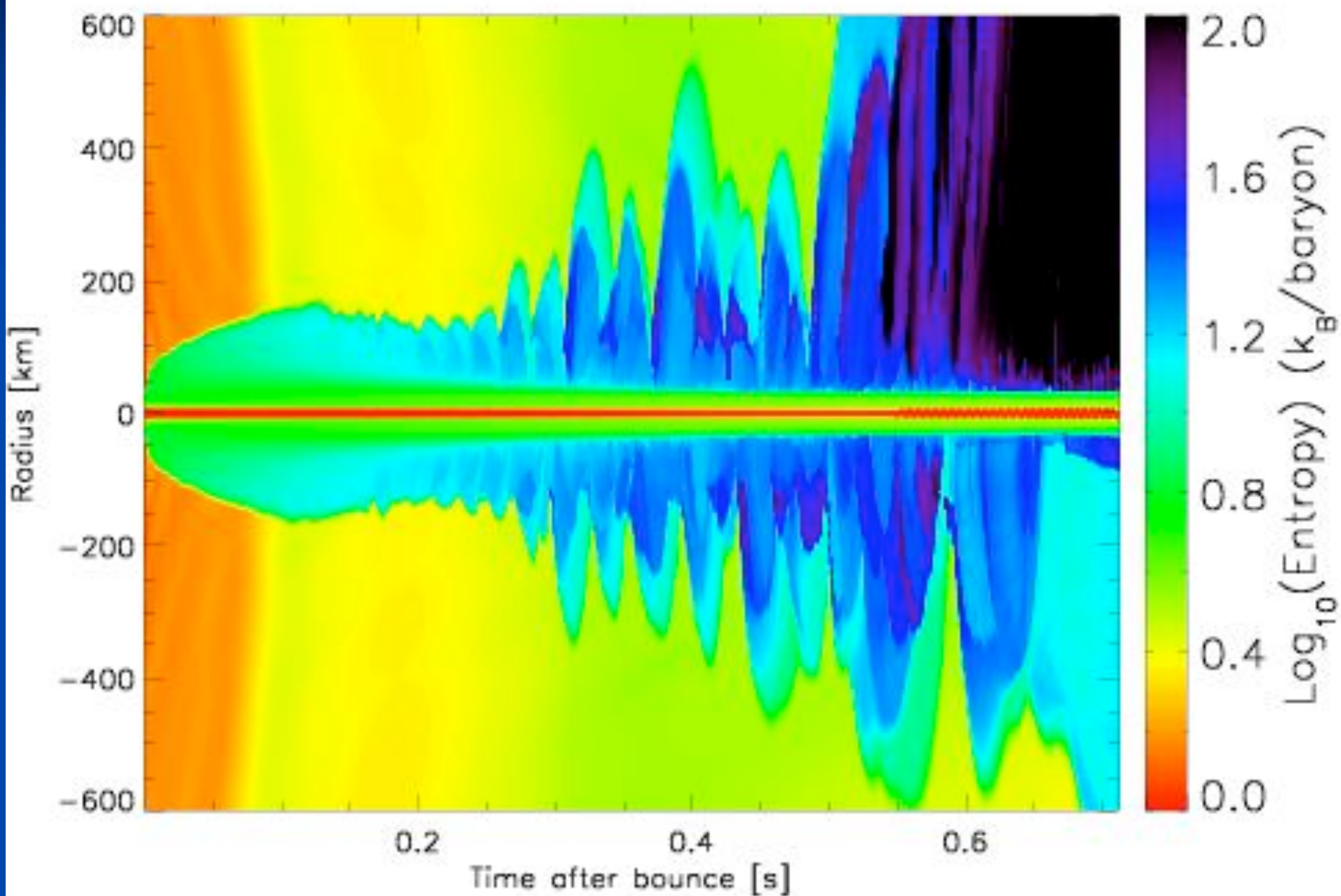
g-mode oscillation:



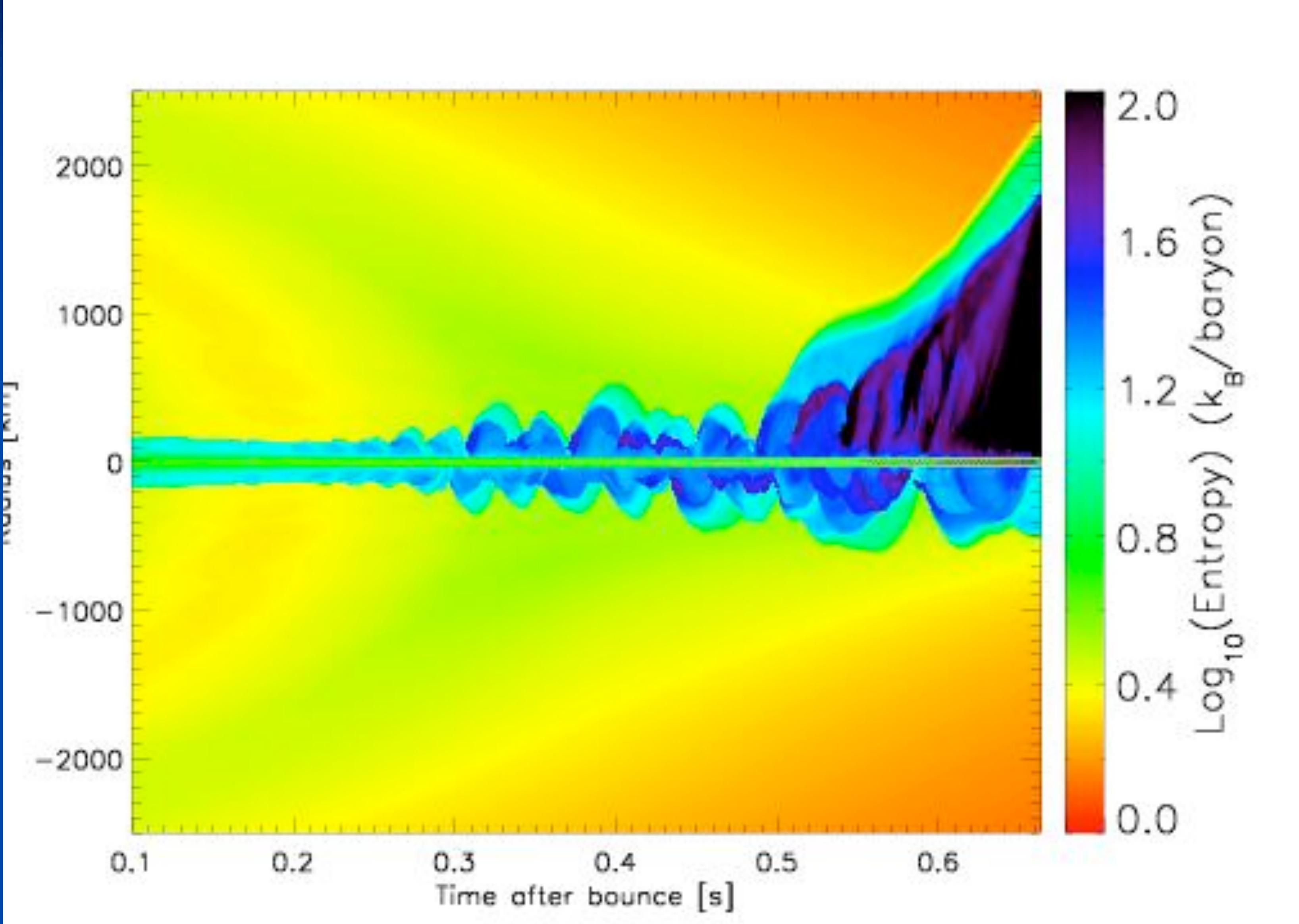
Frequency-Time Evolution of Pulsating Core at 30 km

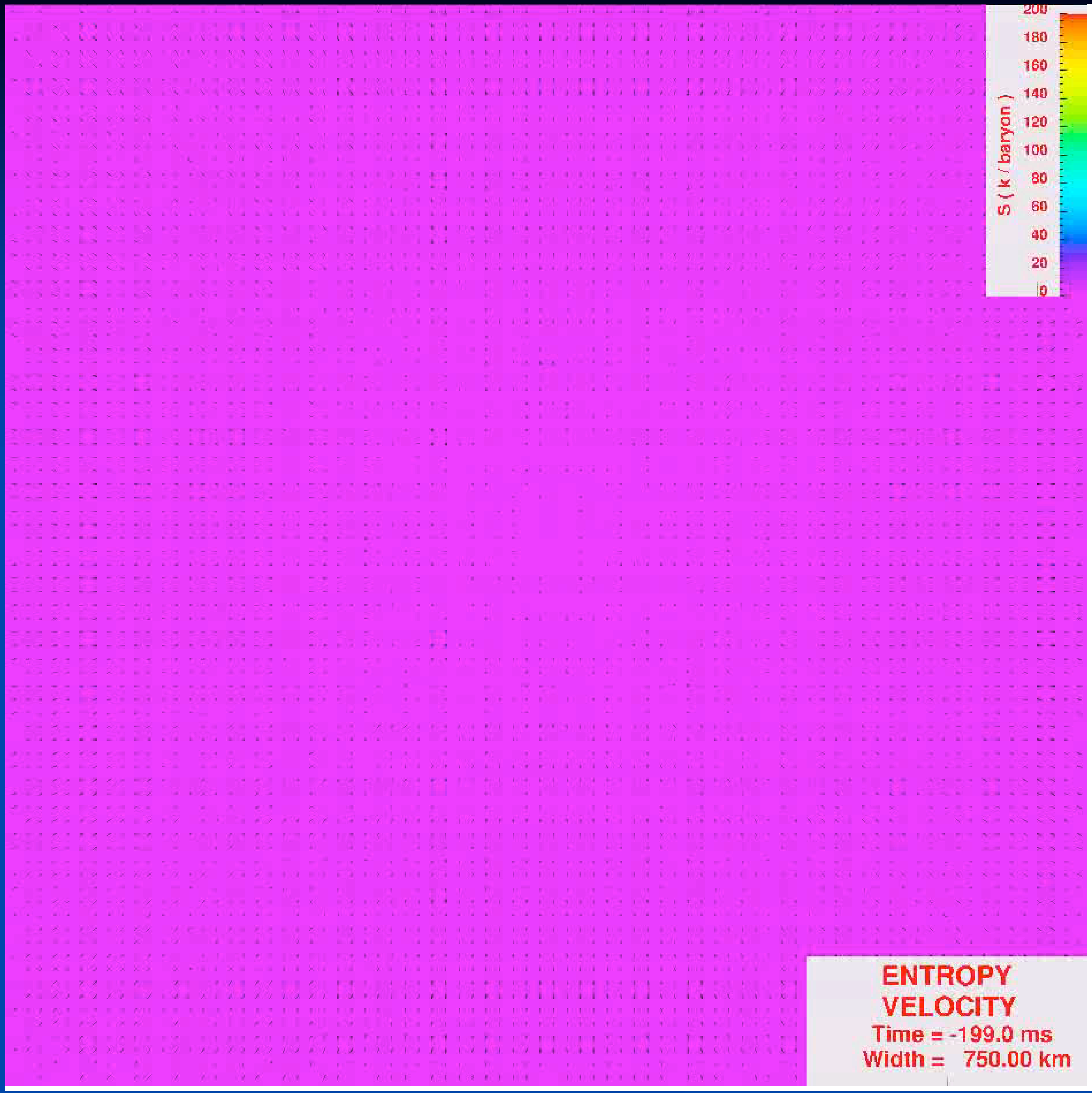


Inner 600-km Look at the Advective-Acoustic Instability

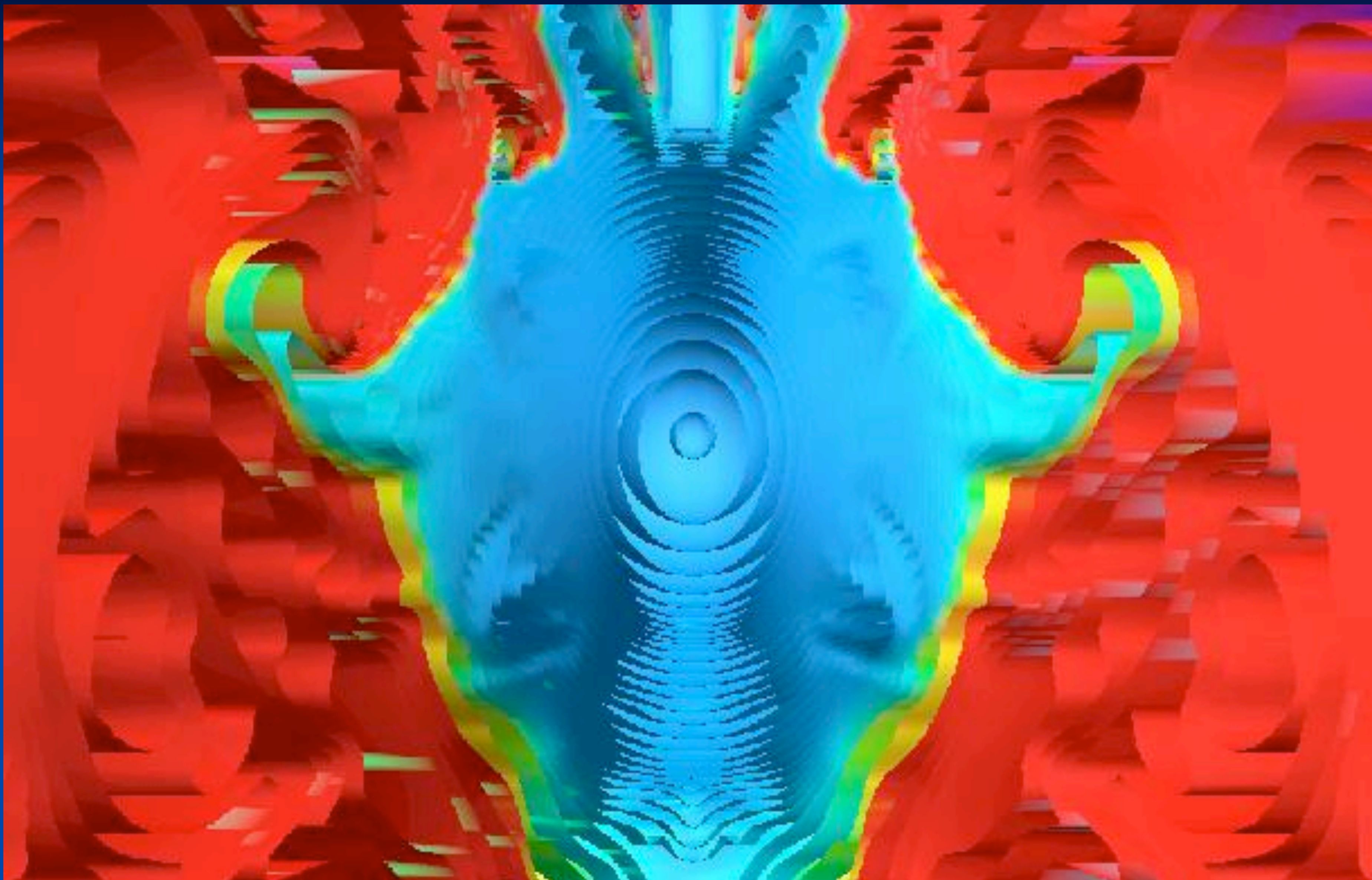


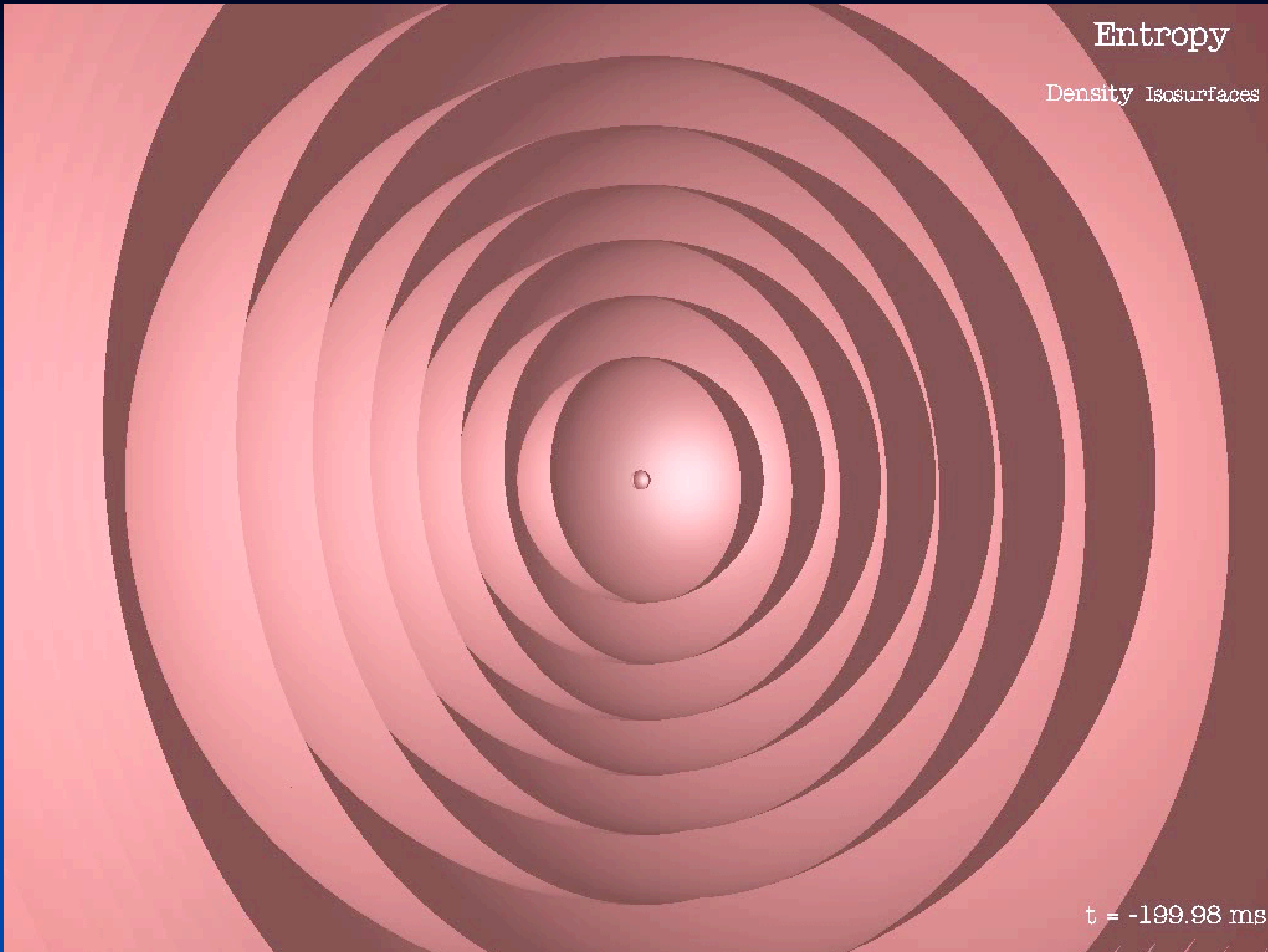
Entropy Profile along Pole versus Time after Bounce



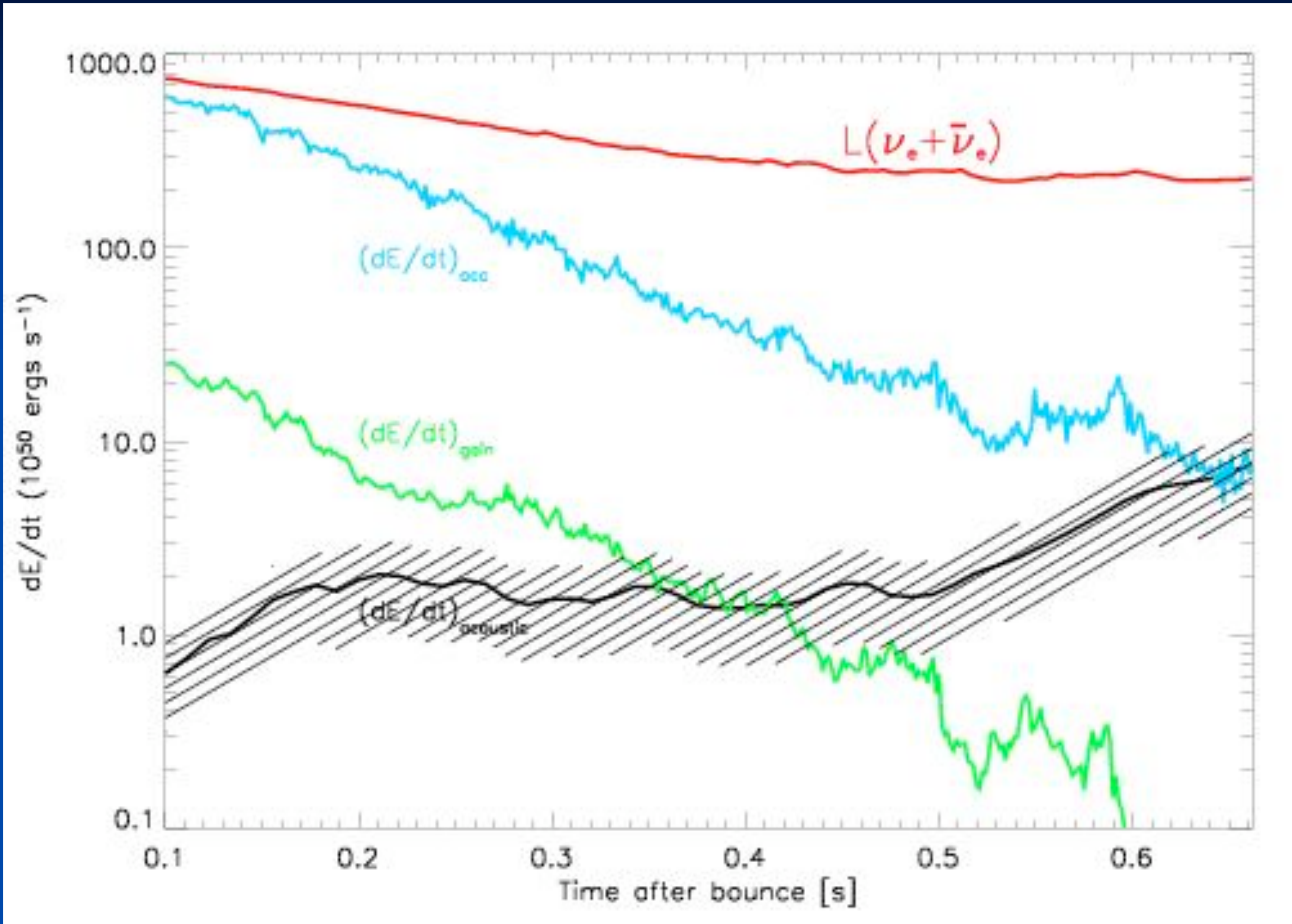


S (k / baryon)
200
180
160
140
120
100
80
60
40
20
0
ENTROPY
VELOCITY
Time = -199.0 ms
Width = 750.00 km




Entropy
Density Isosurfaces
t = -199.98 ms

Power Comparisons: 11 Solar-Mass model



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° 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?

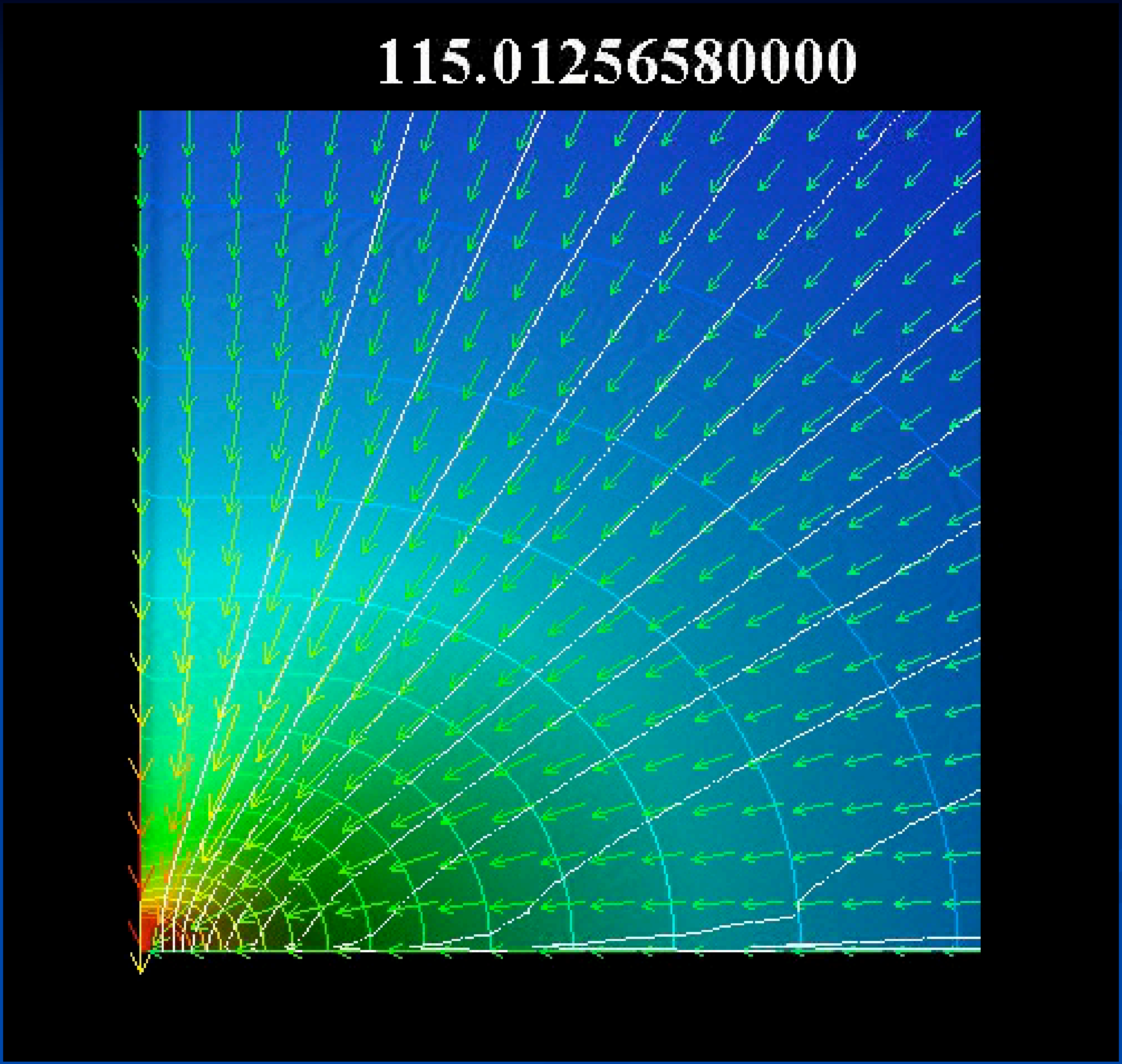
MHD Jets and RMHD Simulations of Core Collapse: Rapid Rotation

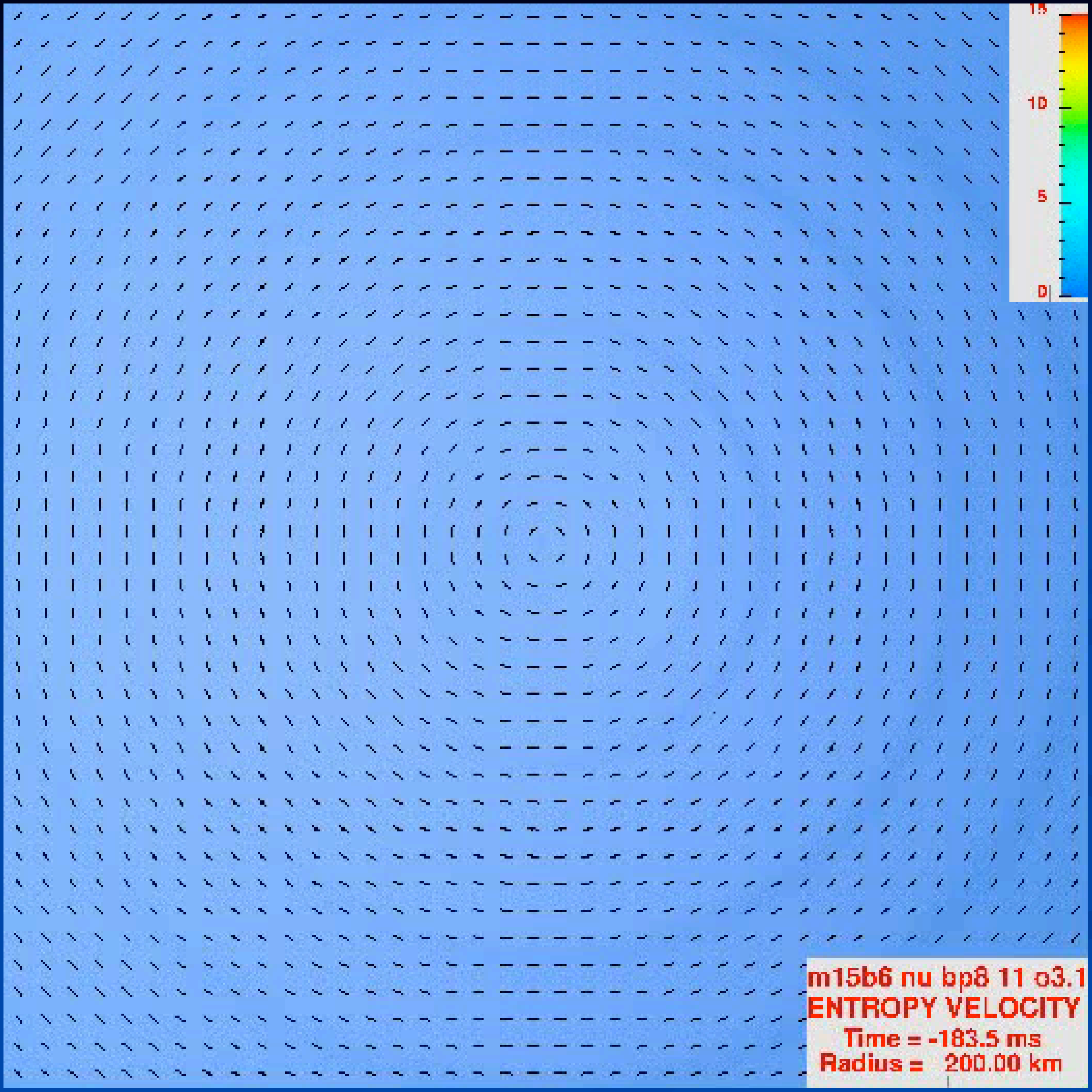
Burrows, Dessart, Livne, Ott, & Murphy 2007; Dessart et al. 2007

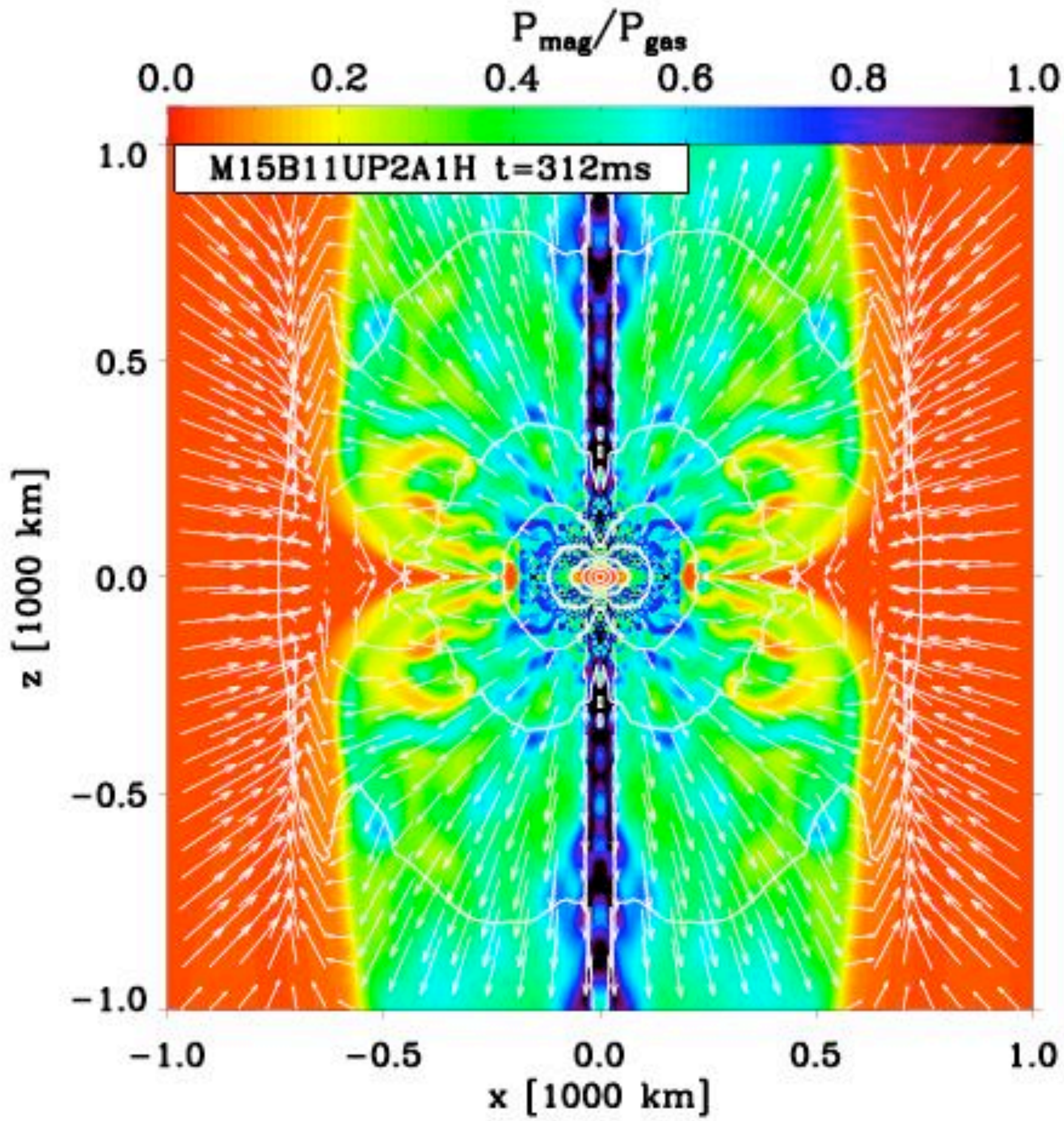
Rotation Winding, the MRI and B-field Stress effects

Shibata et al. 2007

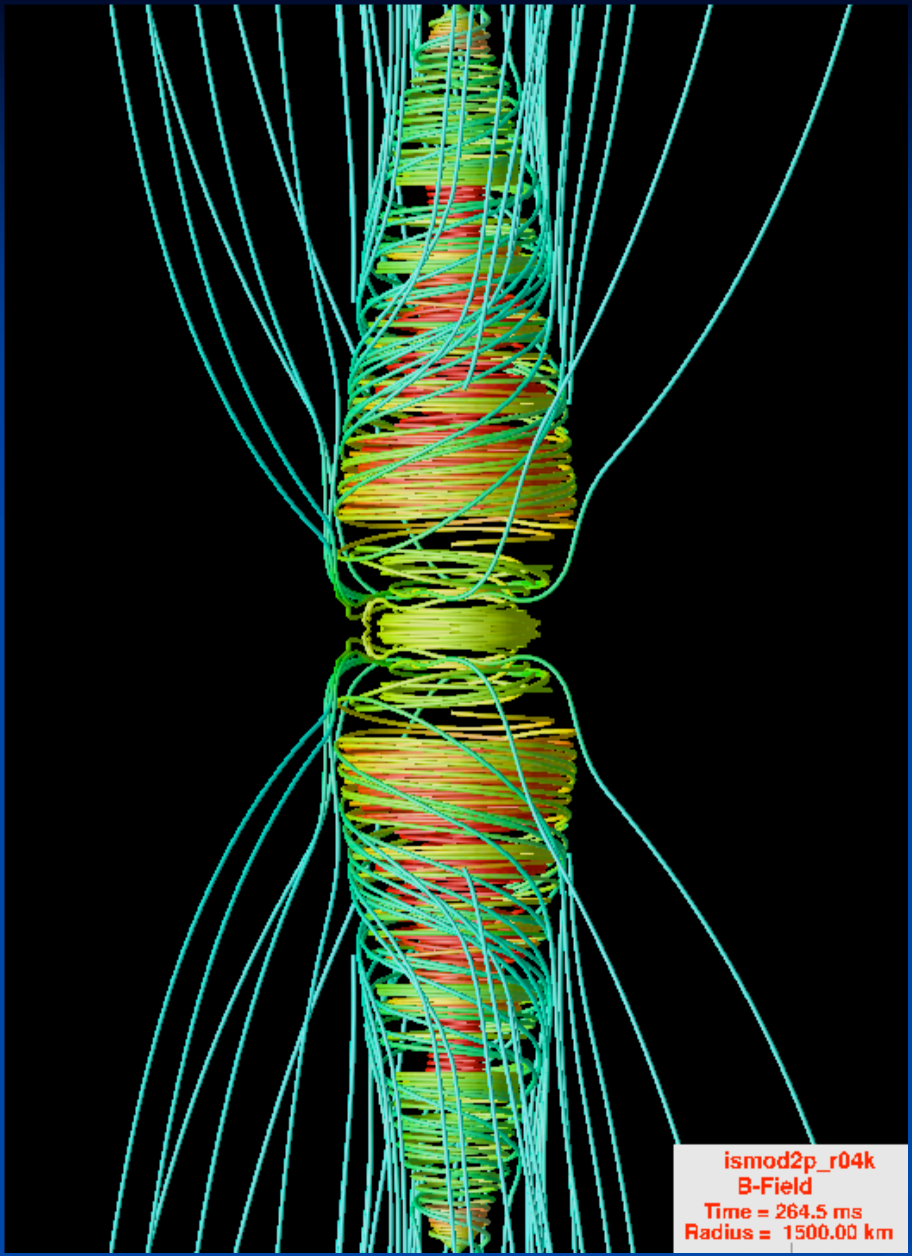
(33 ms of post-bounce evolution)

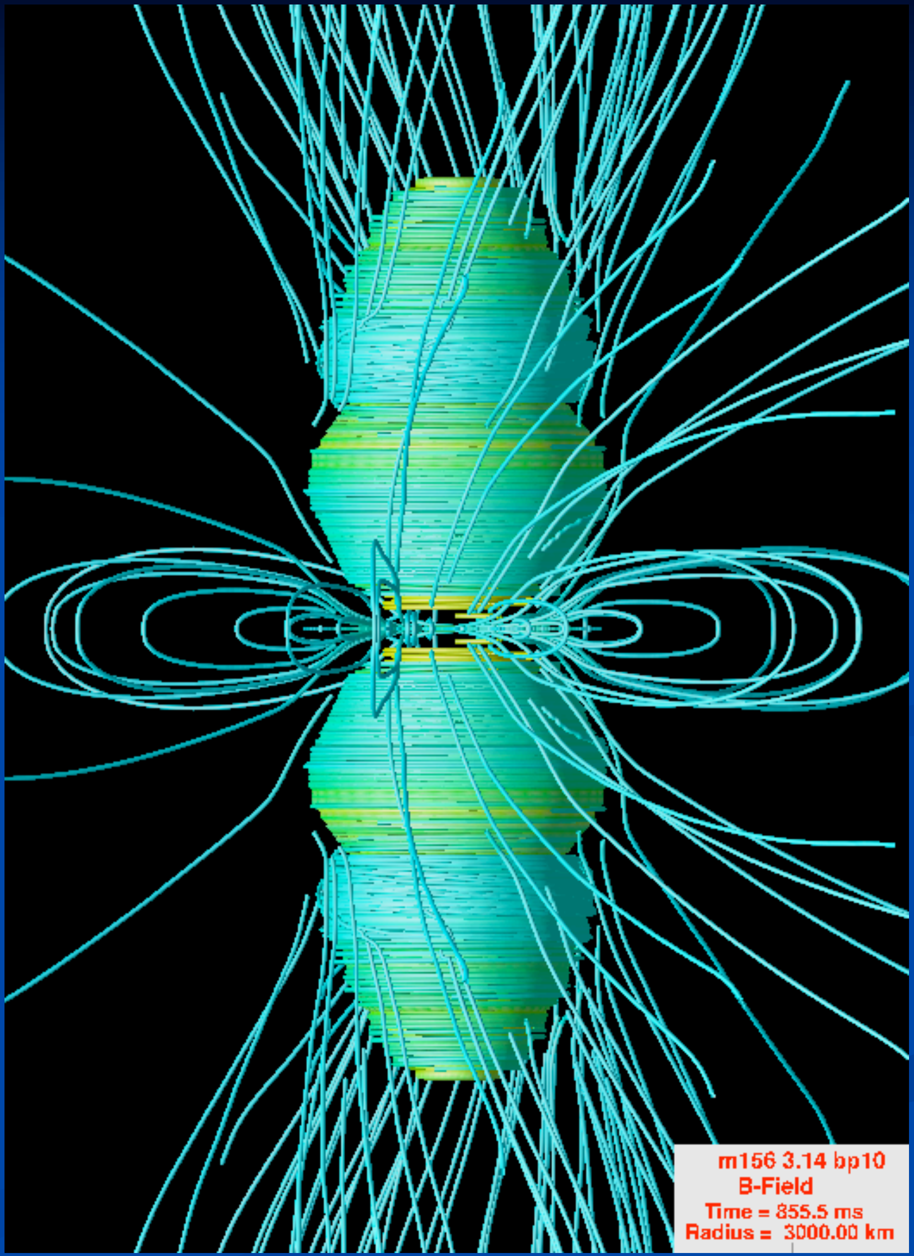


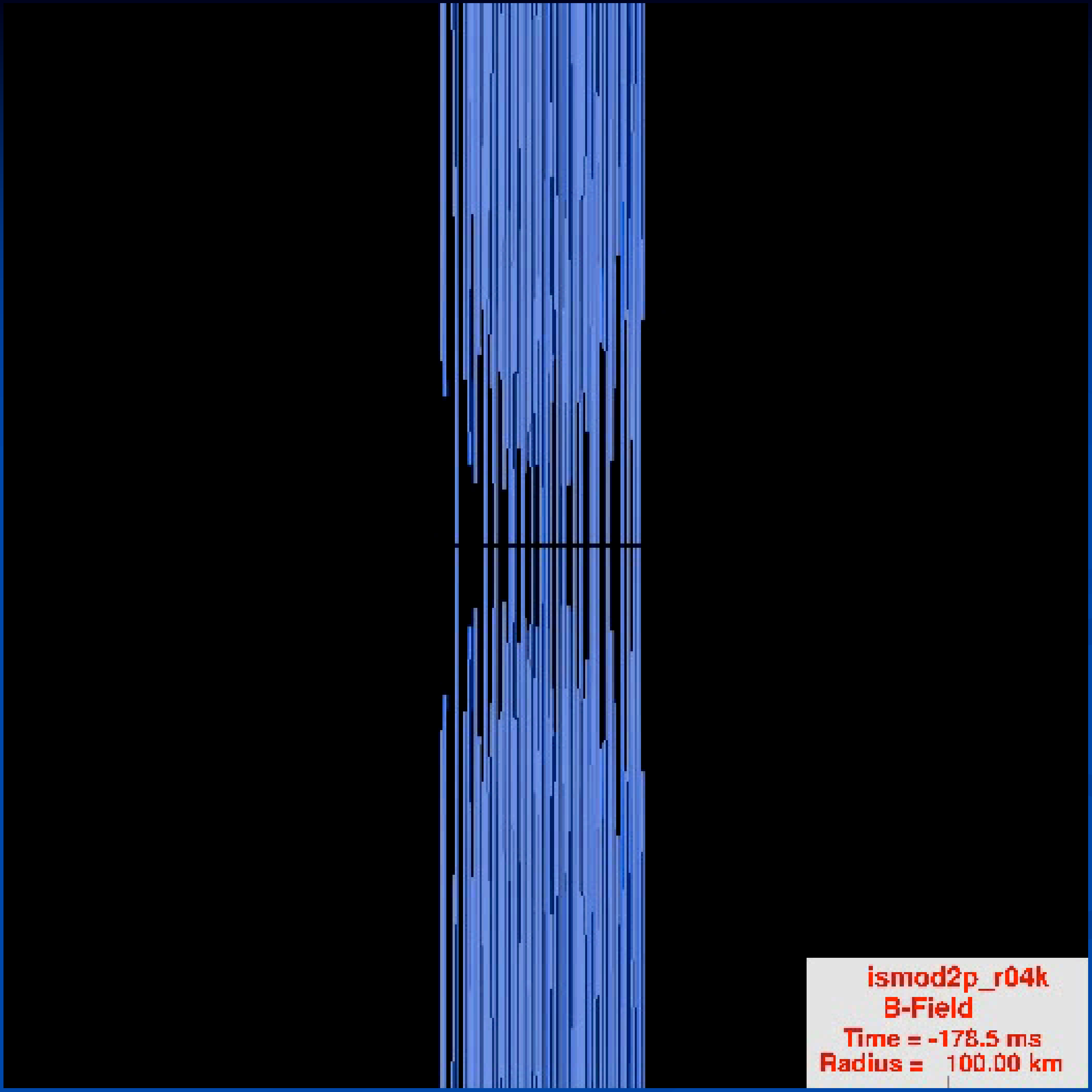

15
10
5
0
m15b6 nu bp8 11 o3.1
ENTROPY VELOCITY
Time = -183.5 ms
Radius = 200.00 km

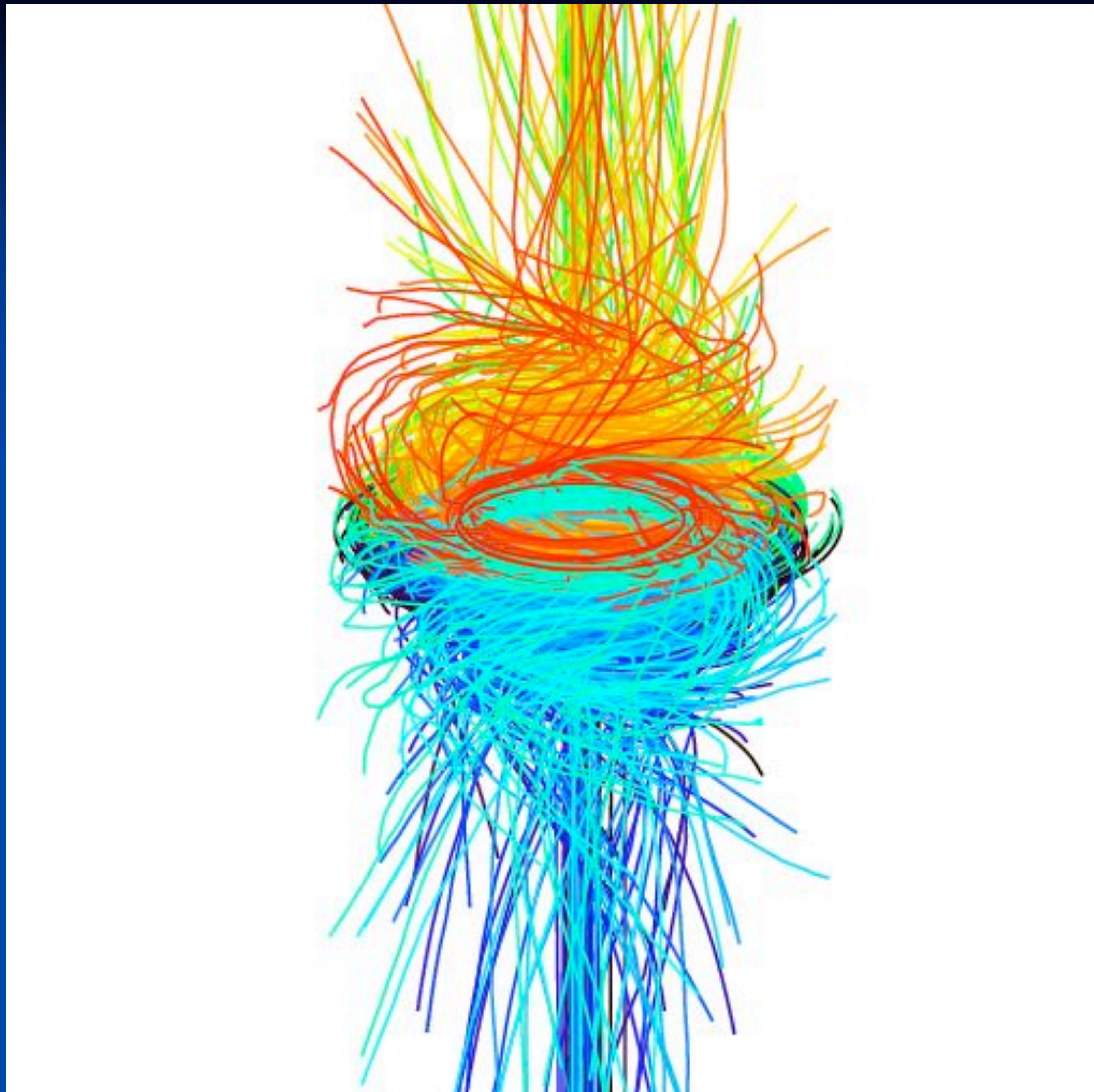


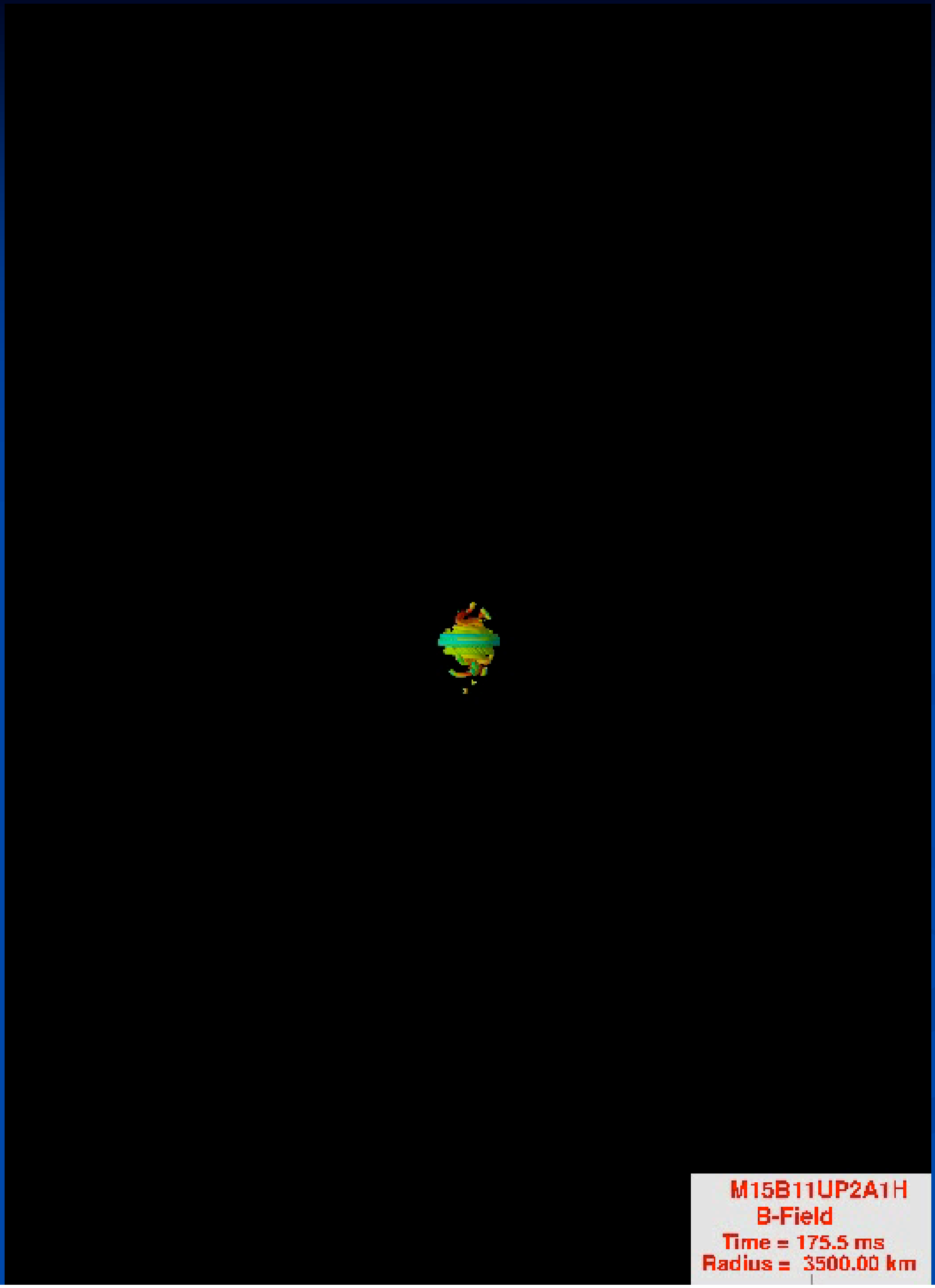
P_{mag}/P_{gas}
0.0
0.2
0.4
0.6
0.8
1.0
M15B11UP2A1H t=312ms
1.0
0.5
0.0
−0.5
−1.0
z [1000 km]
−1.0
−0.5
0.0
0.5
1.0
x [1000 km]


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

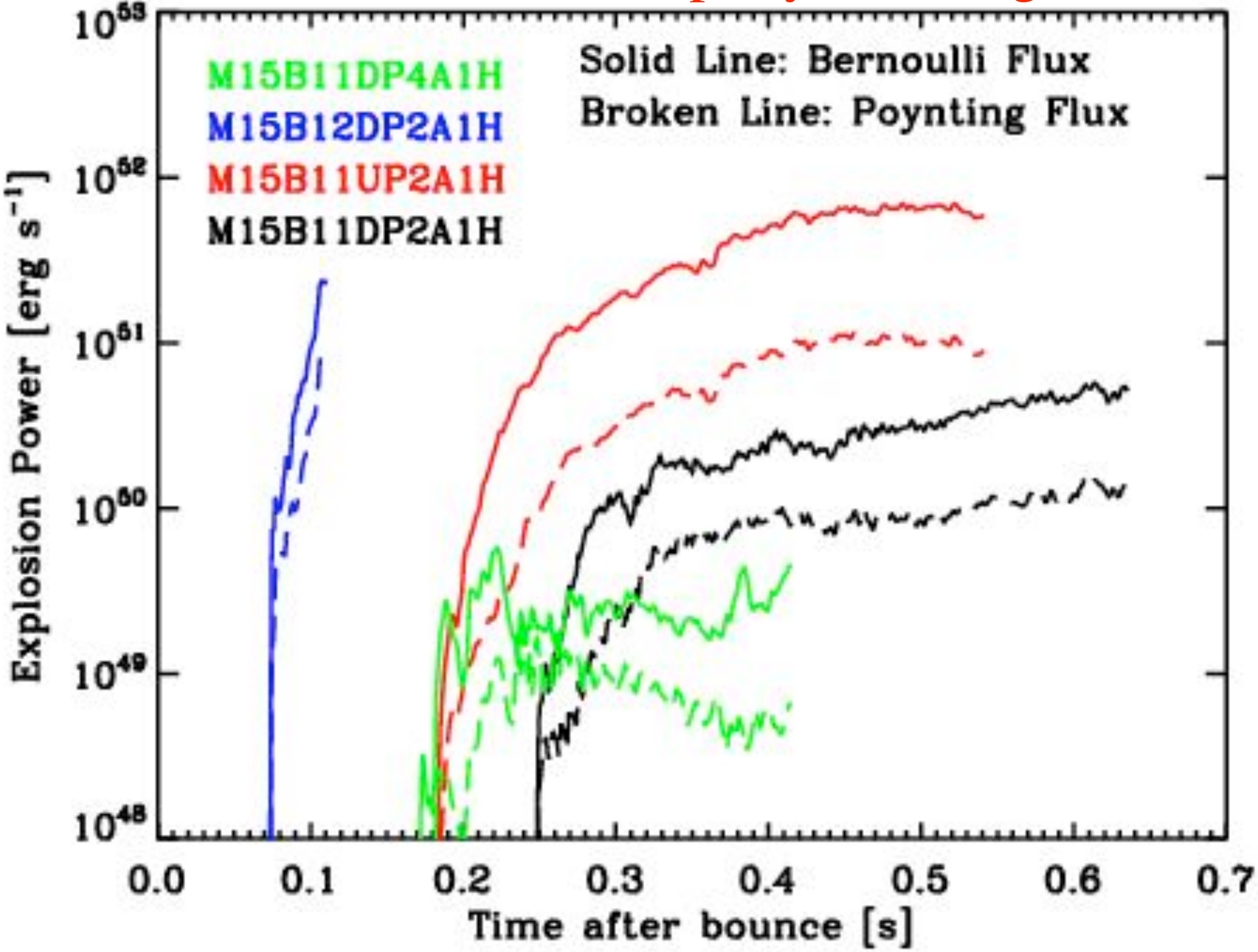

m156 3.14 bp10
B-Field
Time = 855.5 ms
Radius = 3000.00 km


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




M15B11UP2A1H
B-Field
Time = 175.5 ms
Radius = 3500.00 km

MHD Jet Powers for Rapidly-Rotating Cores

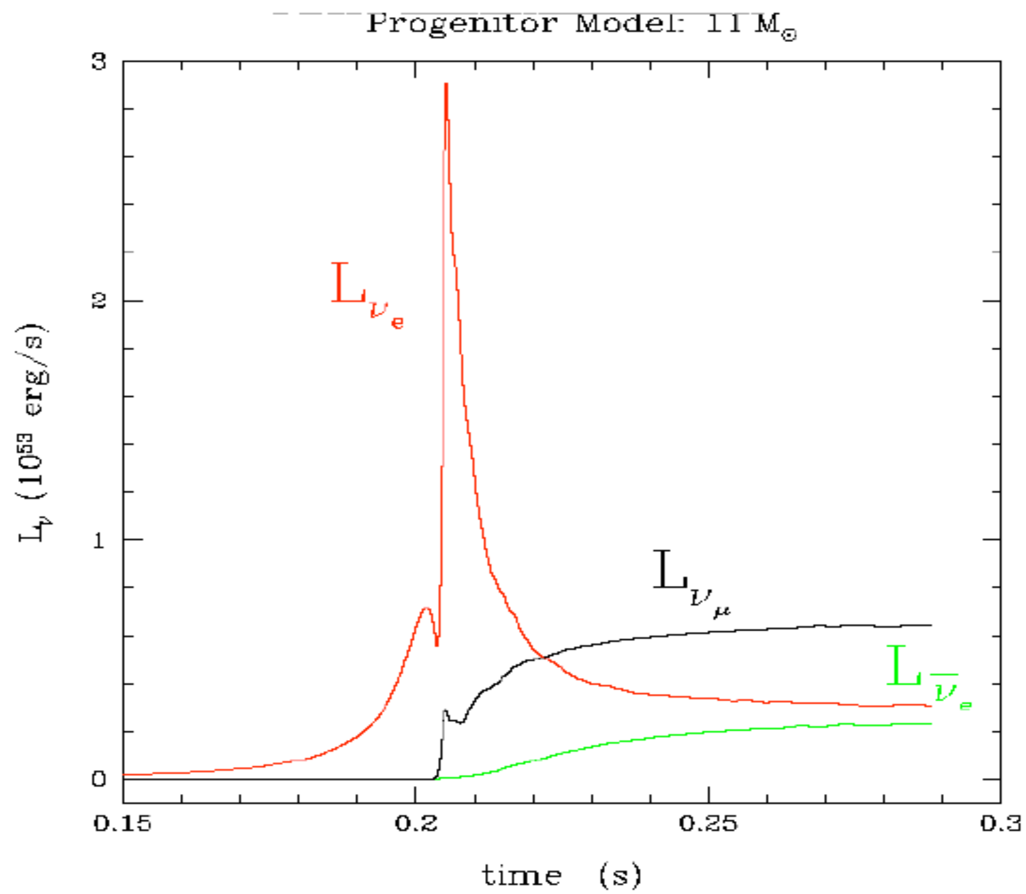


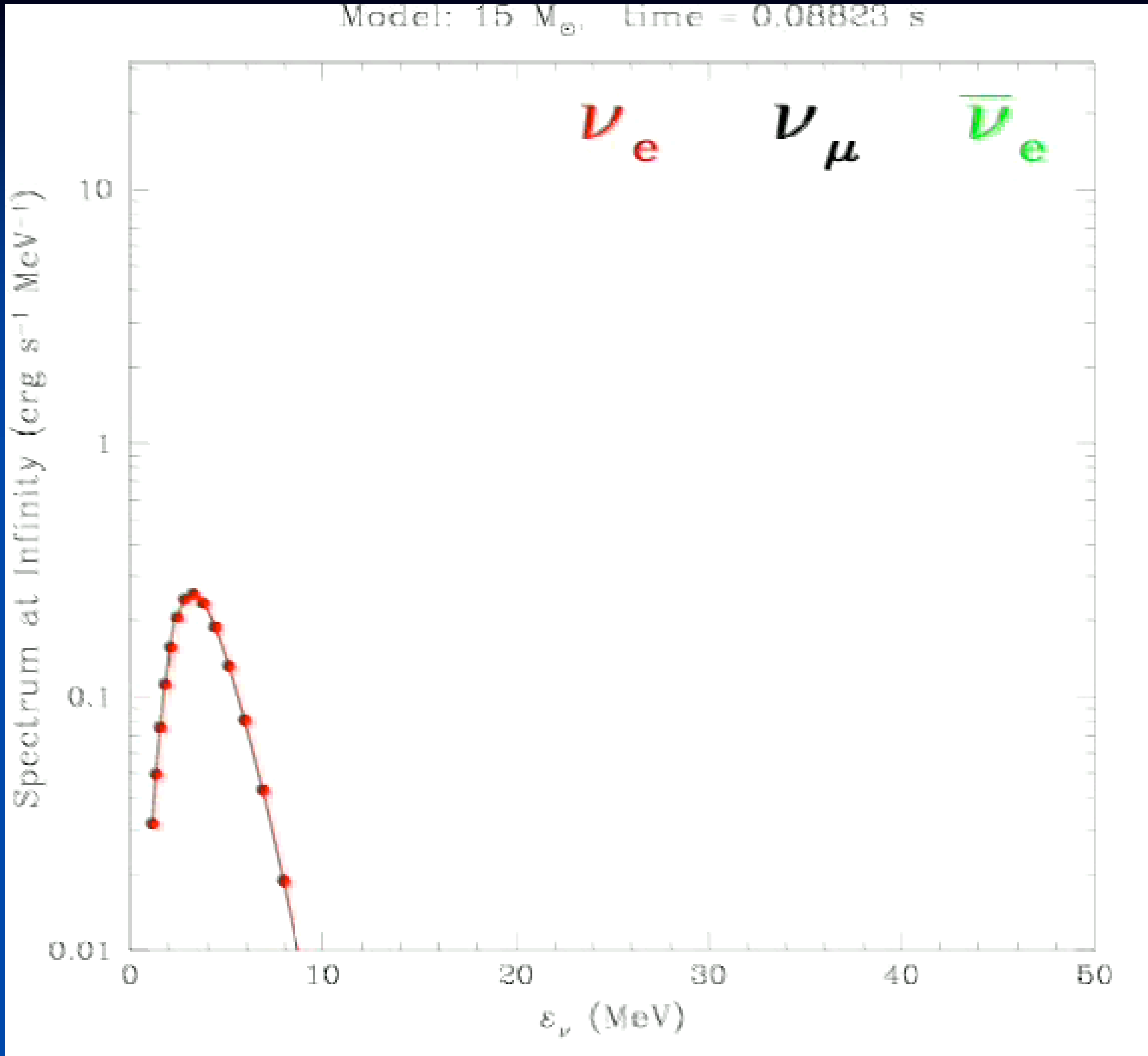
Questions: MHD Jets

- 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?

Neutrino Bursts/Signatures

Breakout Burst of Neutrinos: Precision Boltzmann Transfer





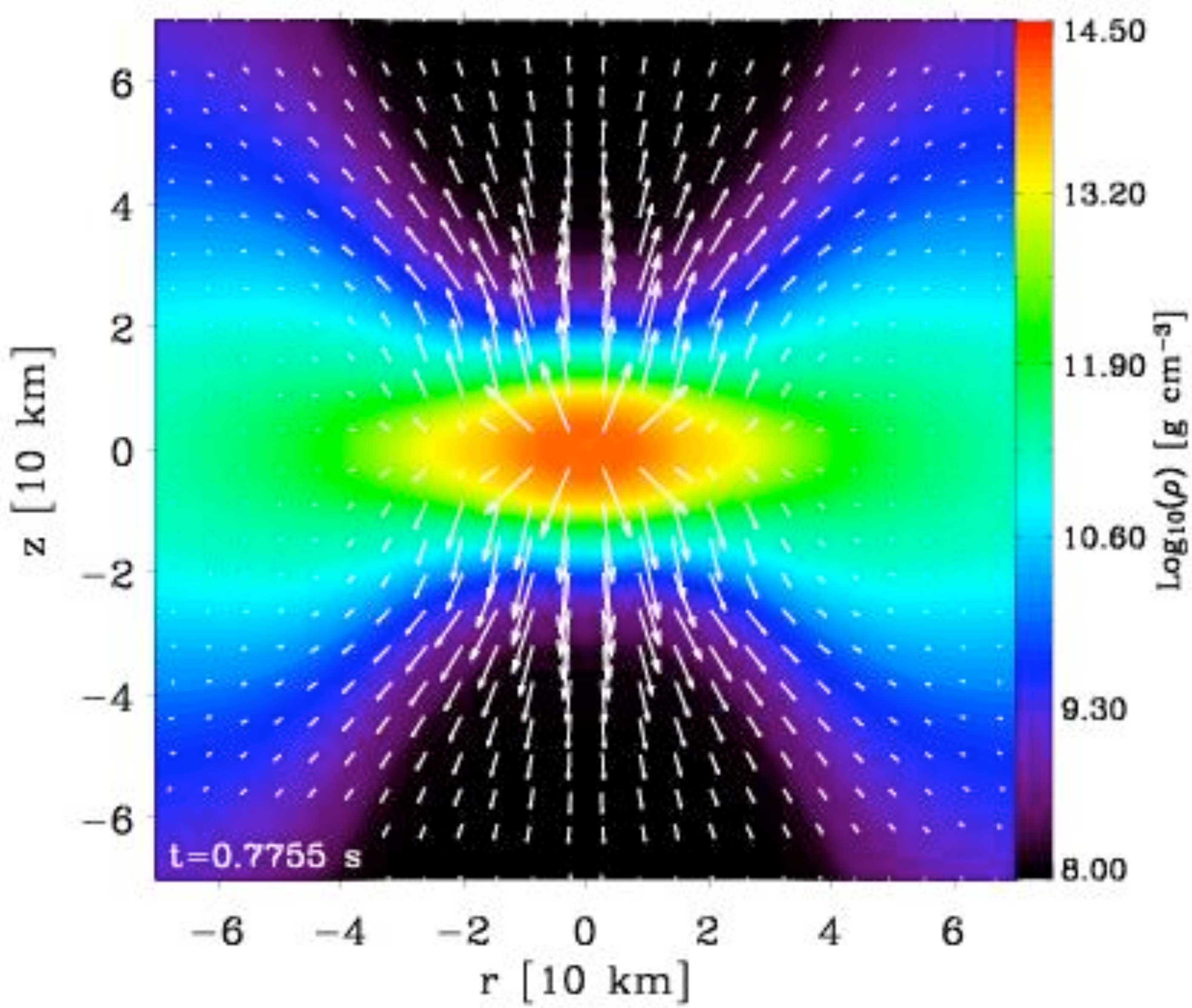
Model: 15 $M_\odot$ time = 0.08823 s
ν_e
ν_μ
$\bar{\nu}_e$
Spectrum at Infinity (erg s^{-1} MeV^{-1})
10
1
0.1
0.01
0
10
20
30
40
50
ε_ν (MeV)


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

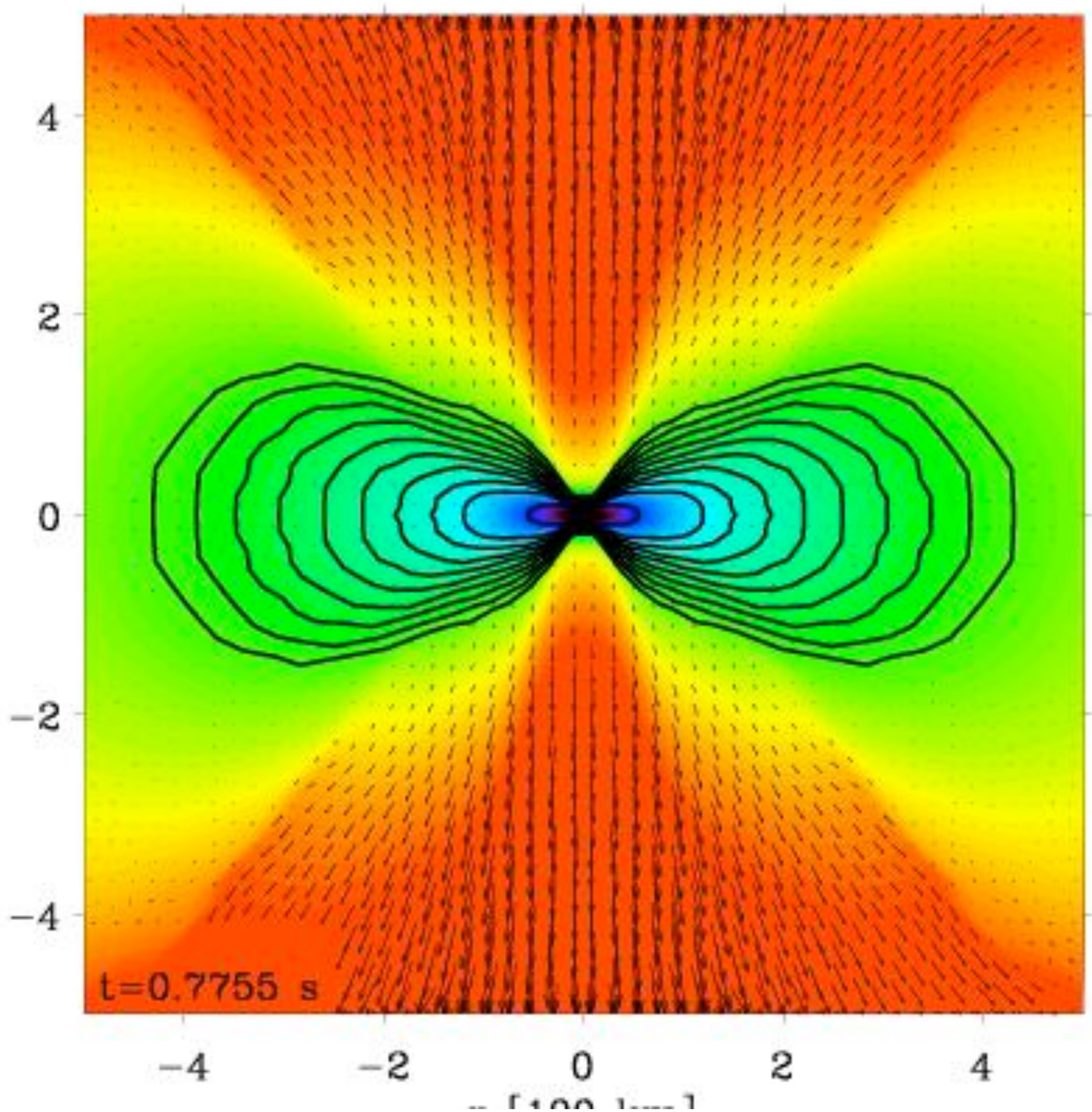
2D Electron Neutrino Fluxes for 1.92 solar mass AIC model:

Rapid Rotation!

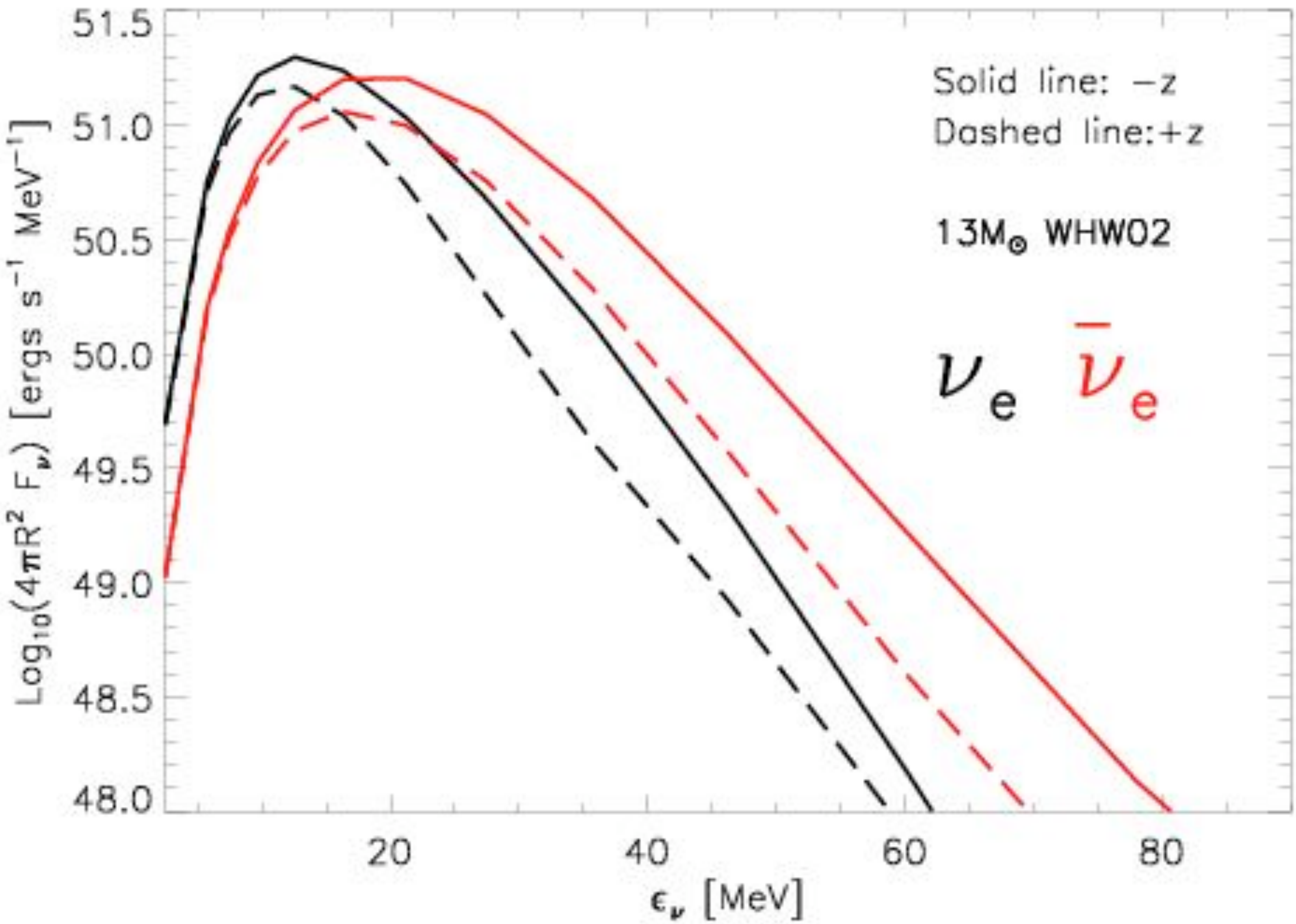
Anisotropic Neutrino Fluxes due to Rotation

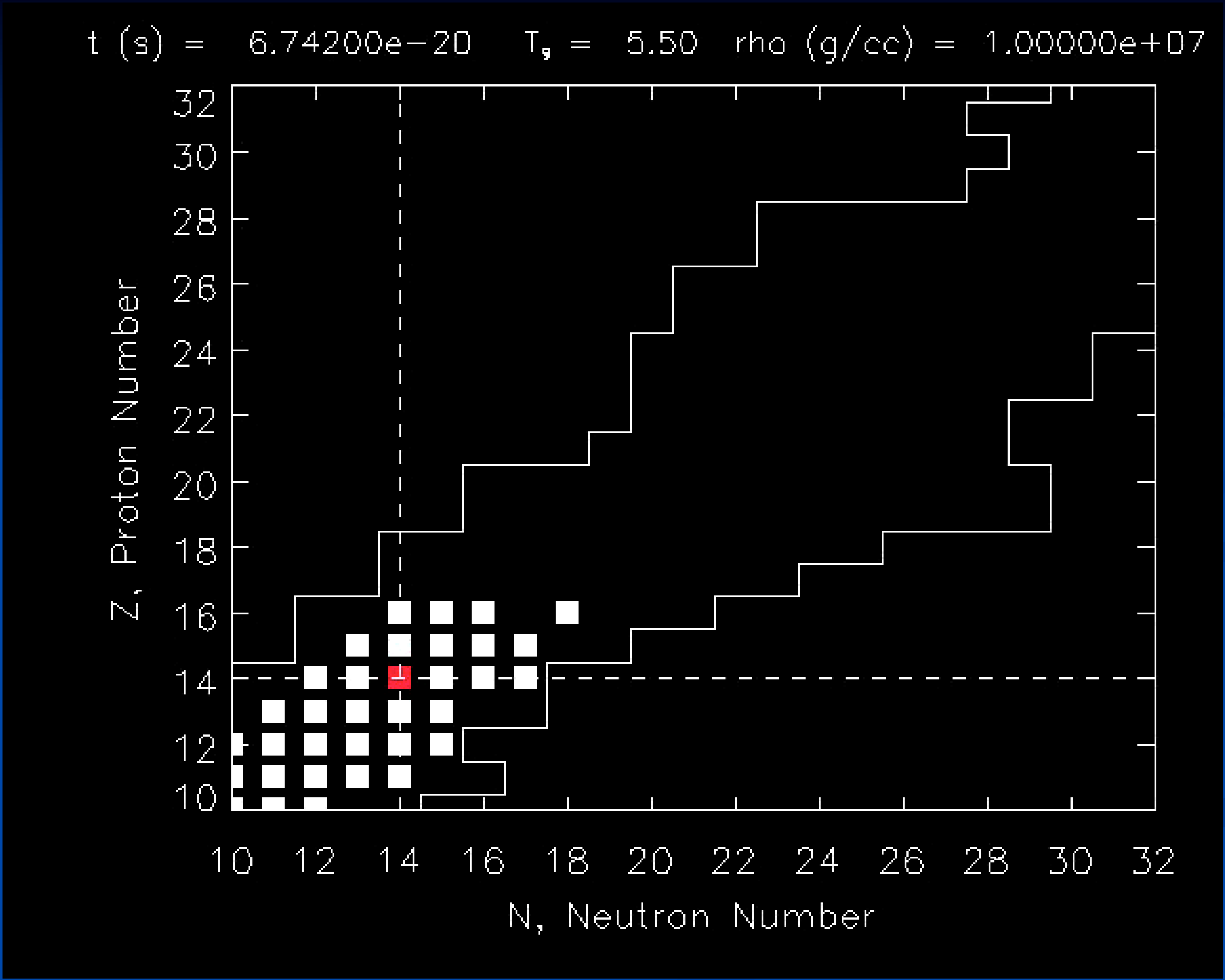


Electron Neutrinospheres for 1.92 solar mass AIC model:



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

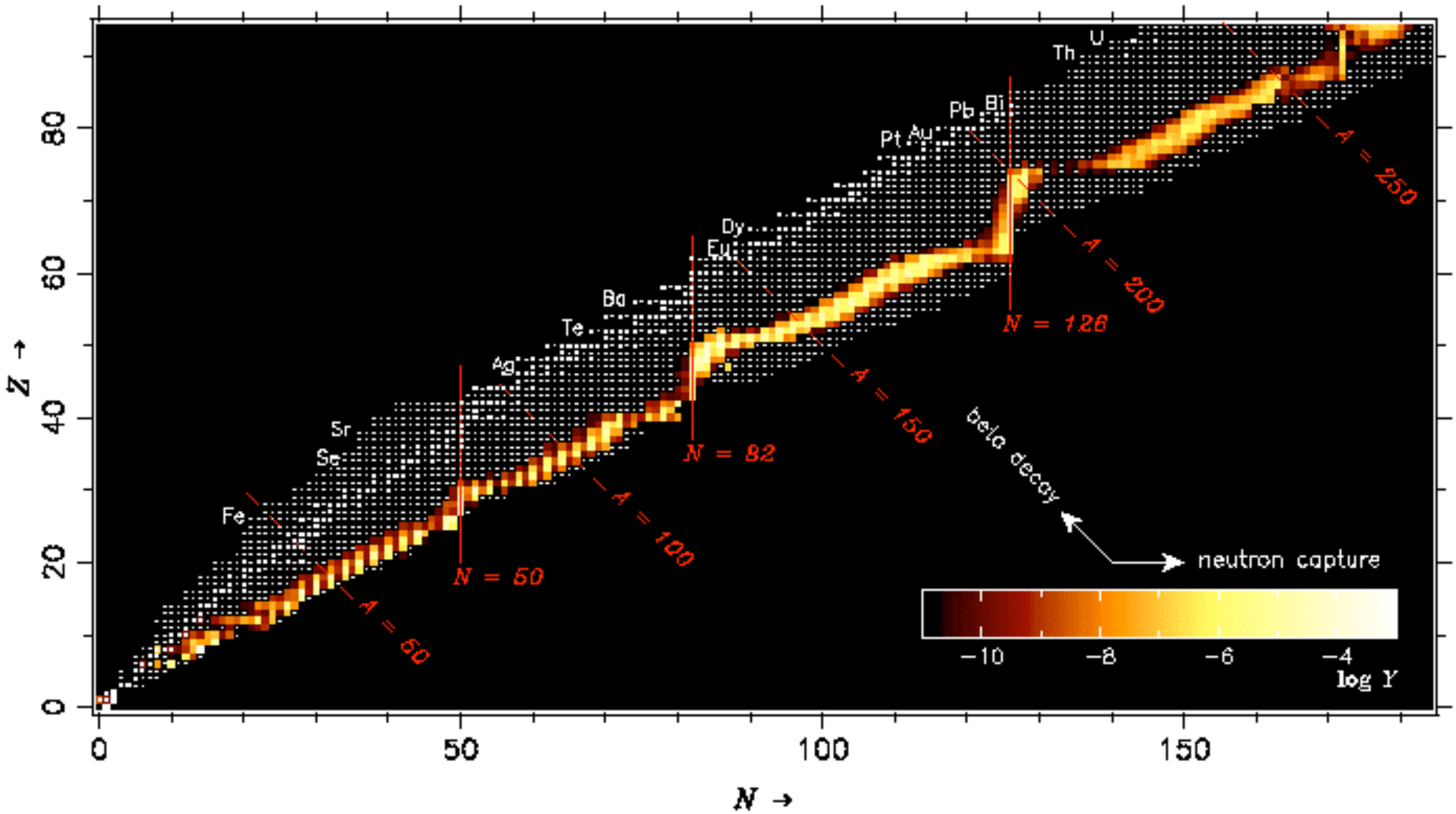




t (s) = 6.74200e-20 T_9 = 5.50 rho (g/cc) = 1.00000e+07
Z, Proton Number
32
30
28
26
24
22
20
18
16
14
12
10
10 12 14 16 18 20 22 24 26 28 30 32
N, Neutron Number

“R-process” Nucleosynthesis?

R-Process Nucleosynthesis



Nucleosynthesis in the r-process

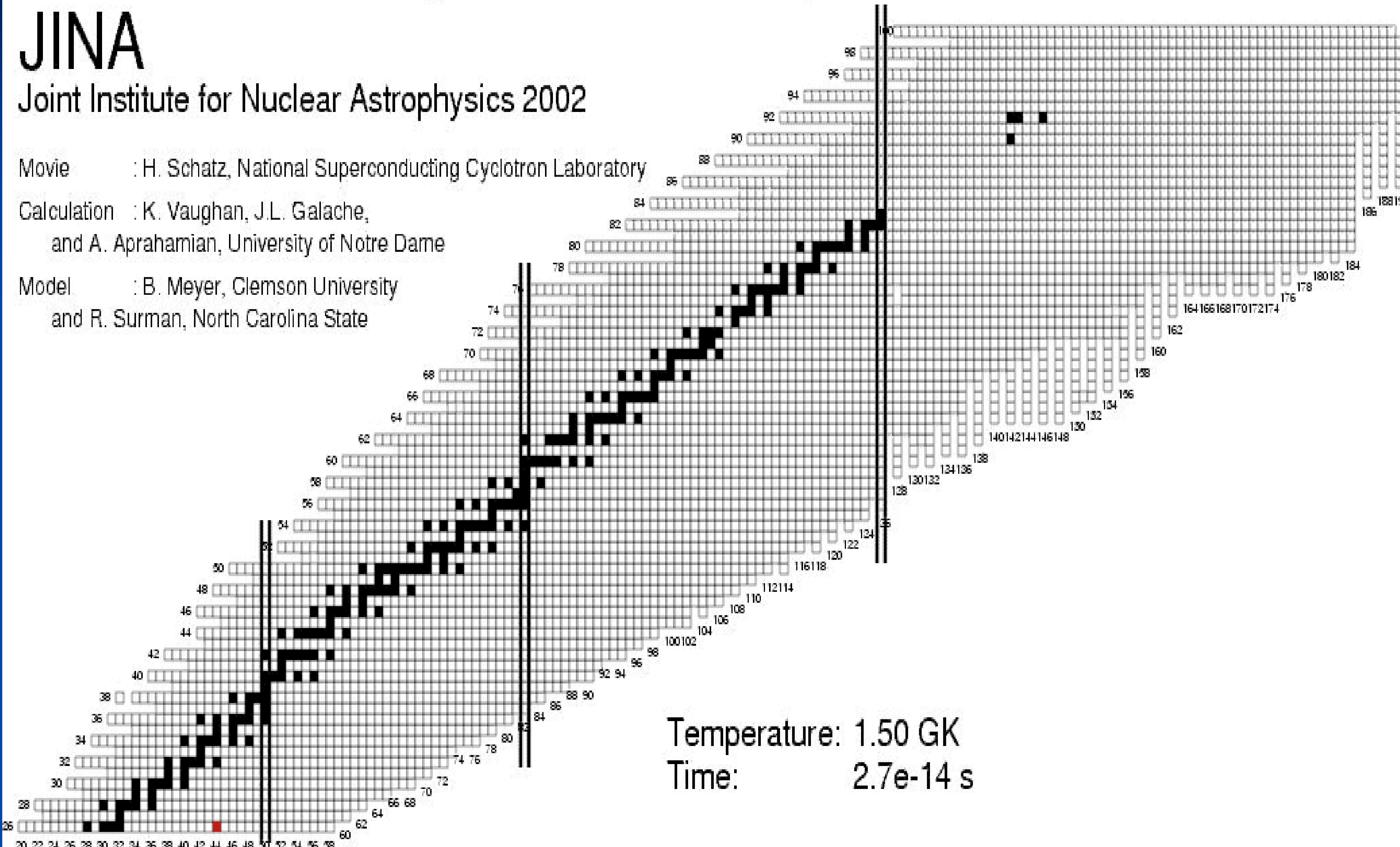
JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame

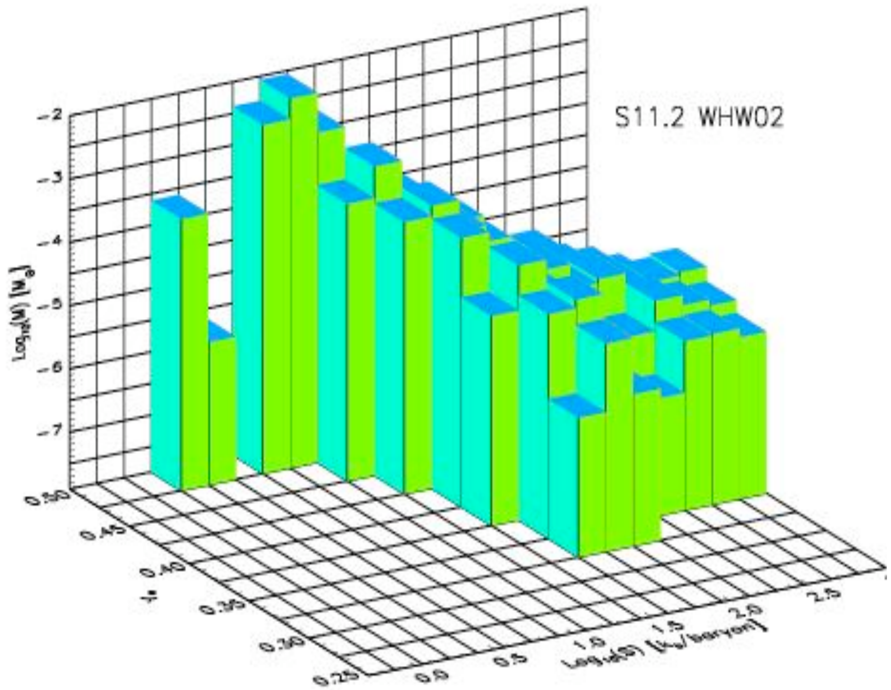
Model : B. Meyer, Clemson University and R. Surman, North Carolina State

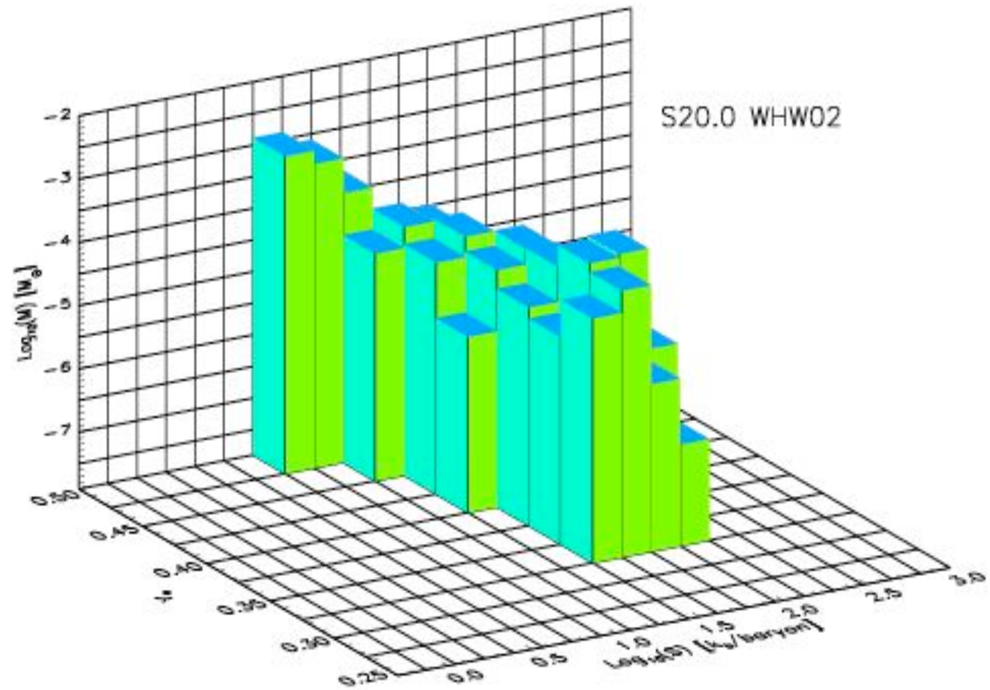


Temperature: 1.50 GK

Time: 2.7e-14 s

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



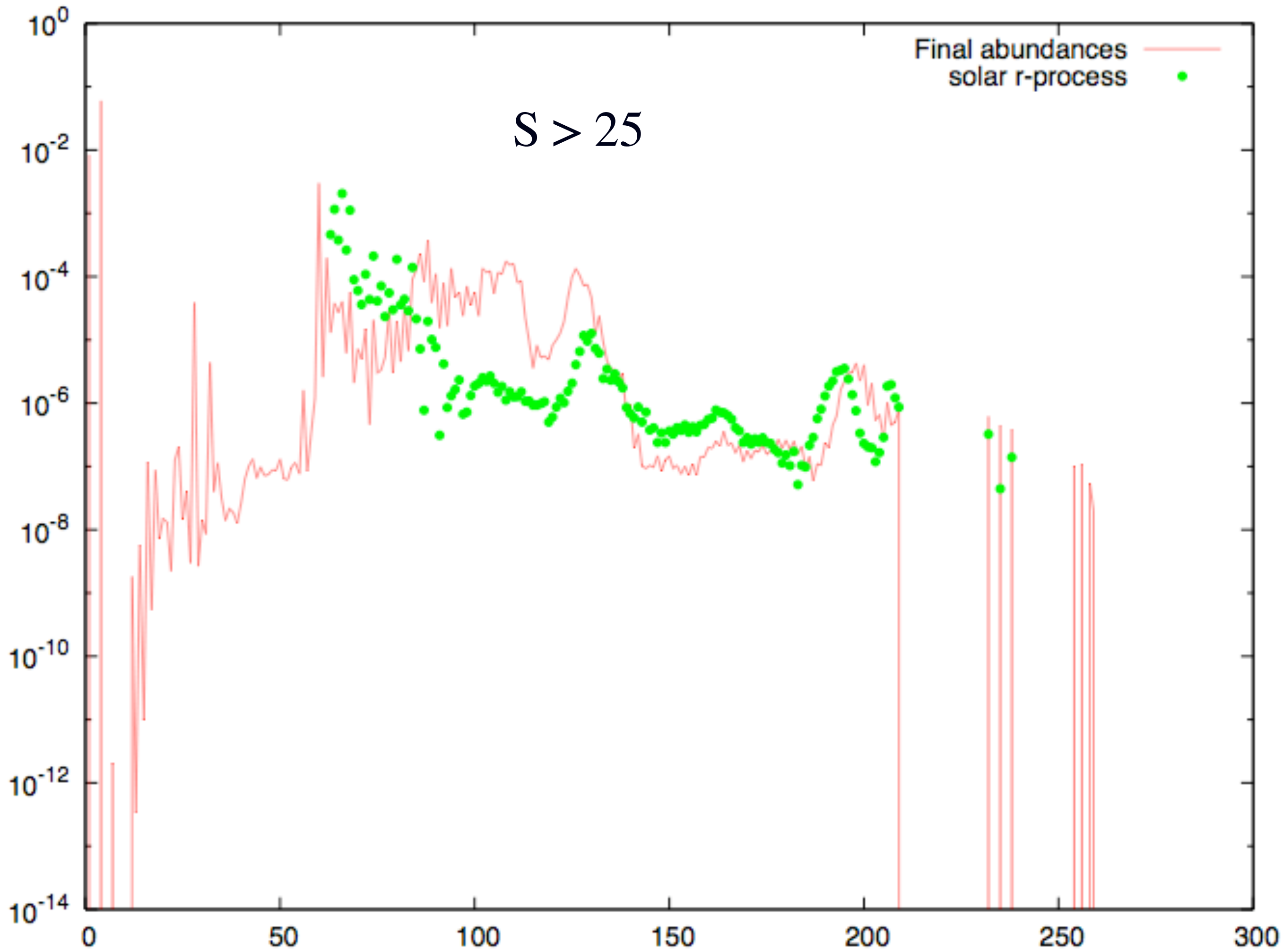


M (s > 300): 1.25 x 10^{-4} $M_\odot$?

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

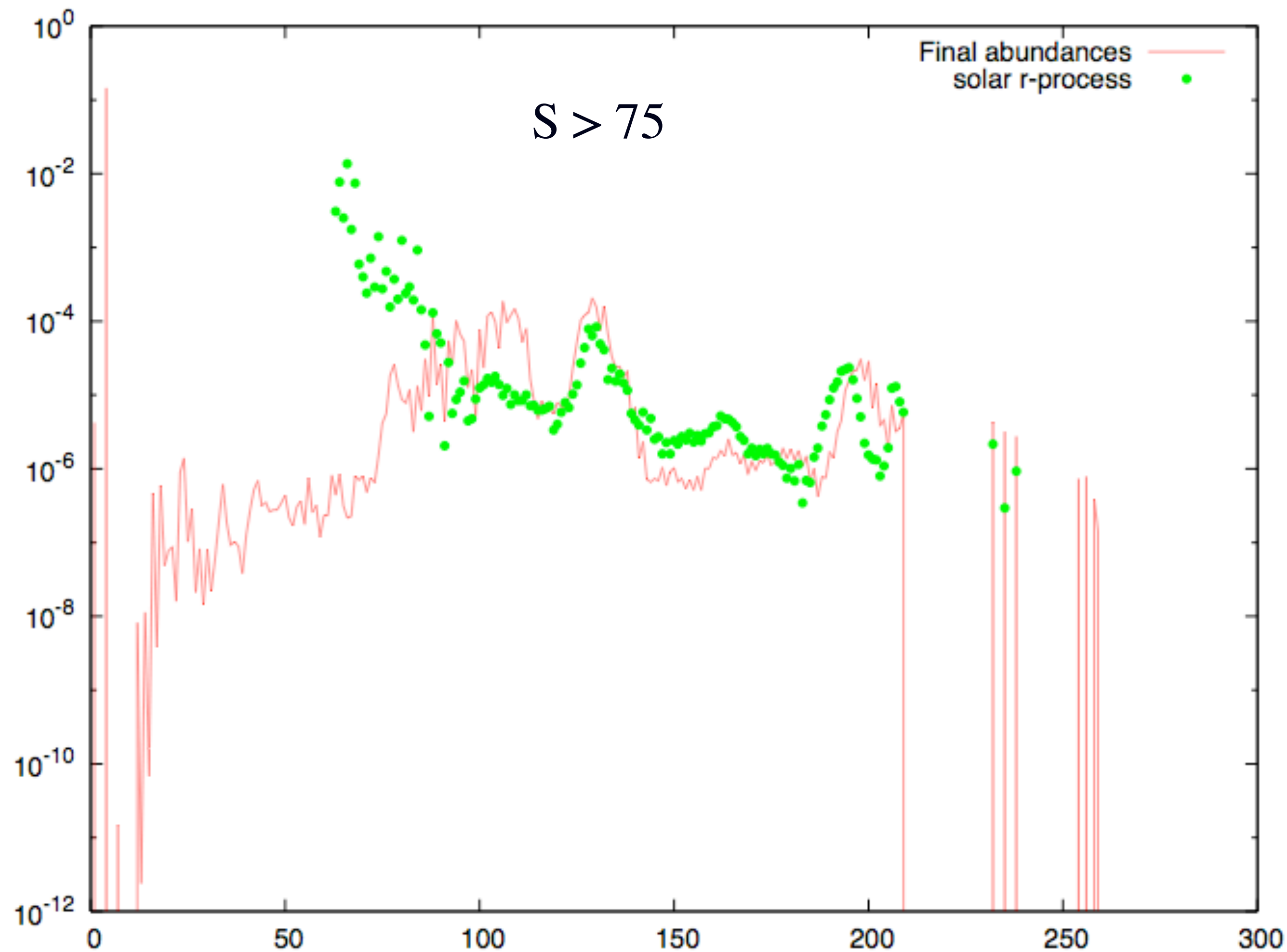
Very Preliminary!!!

Preliminary R-process Calculations for the Long-term Acoustic Mechanism



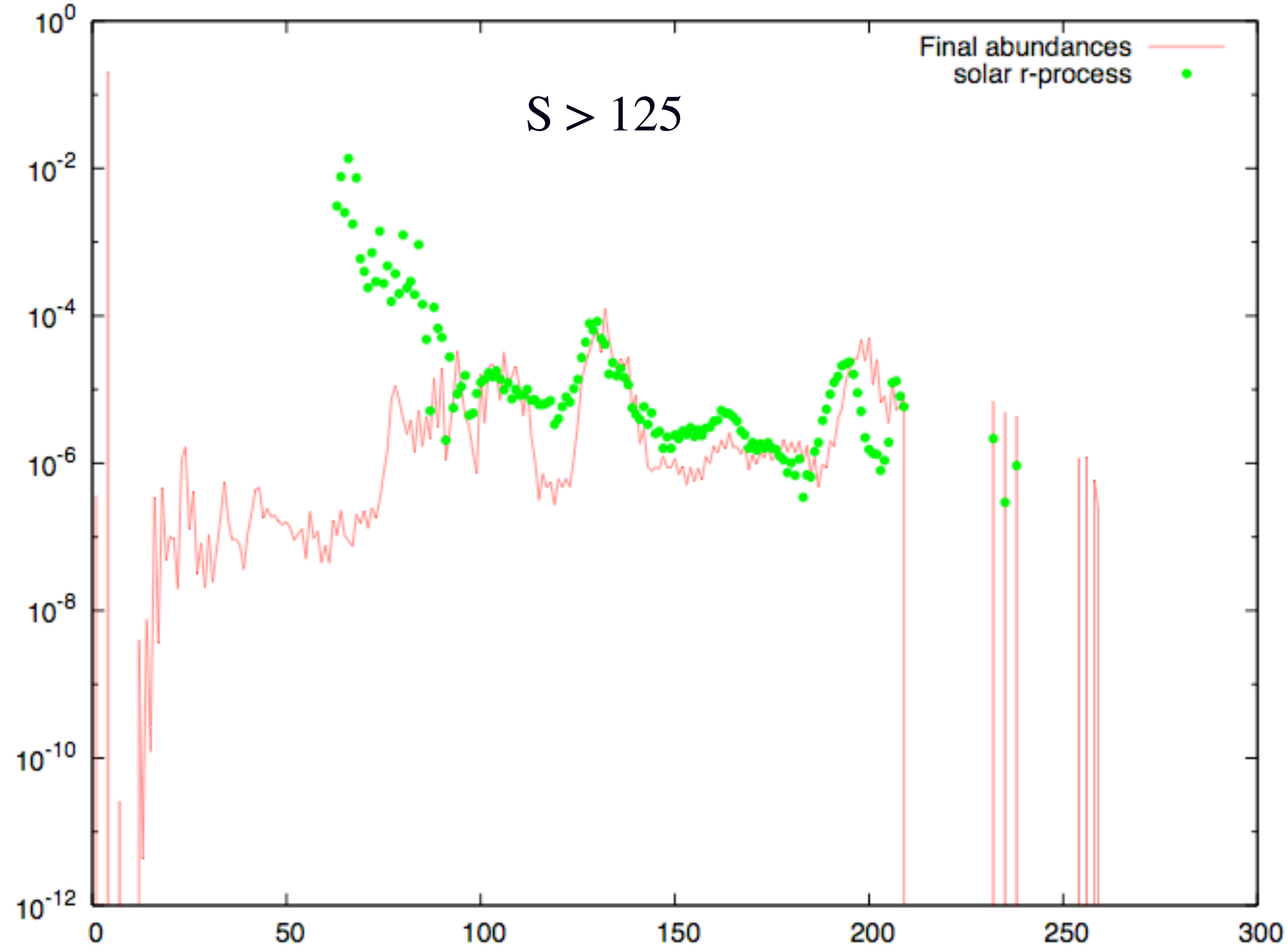
K. Otsuki et al. 2008

Preliminary R-process Calculations for the Long-term Acoustic Mechanism



K. Otsuki et al. 2008

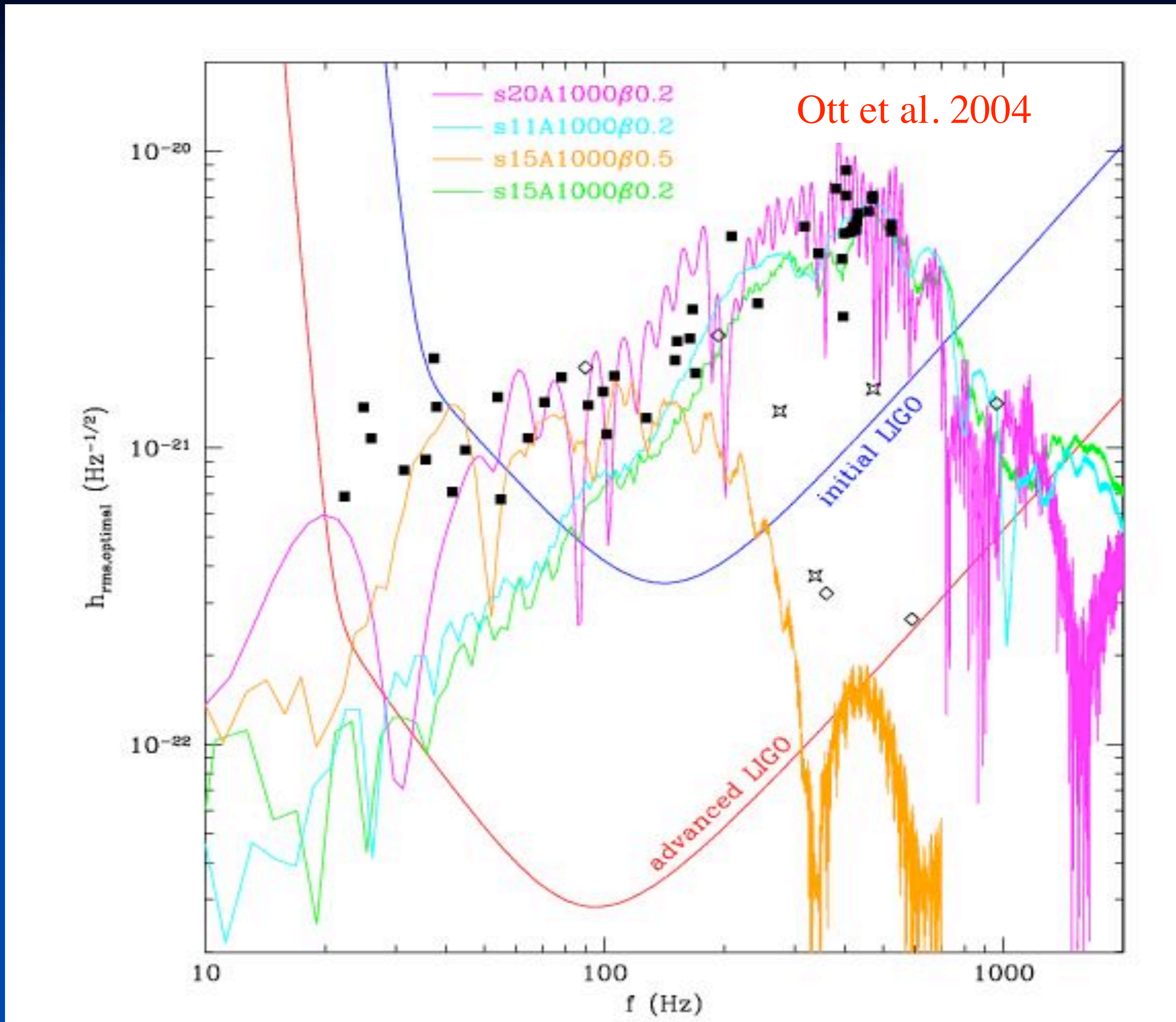
Preliminary R-process Calculations for the Long-term Acoustic Mechanism

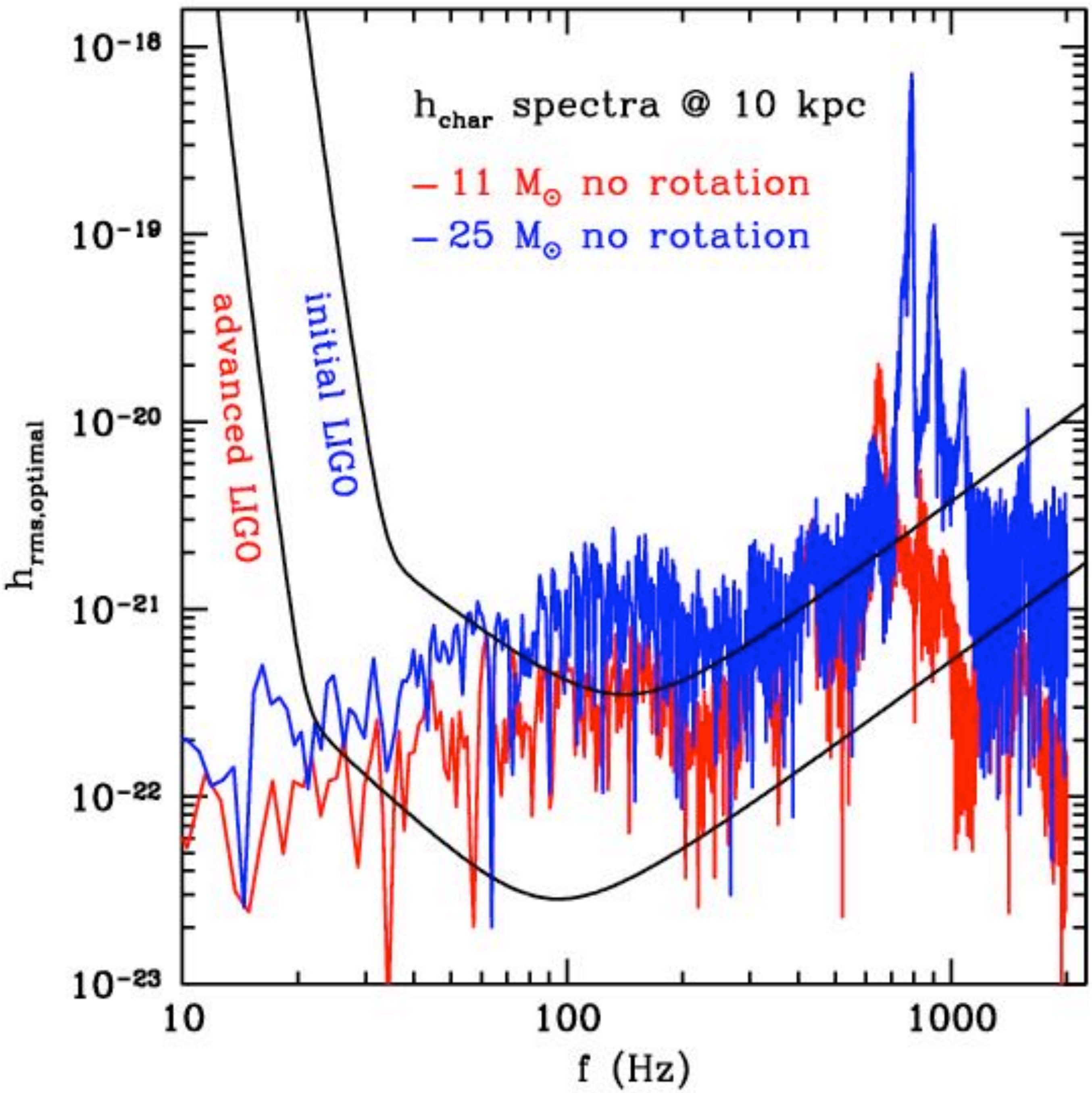


K. Otsuki et al. 2008

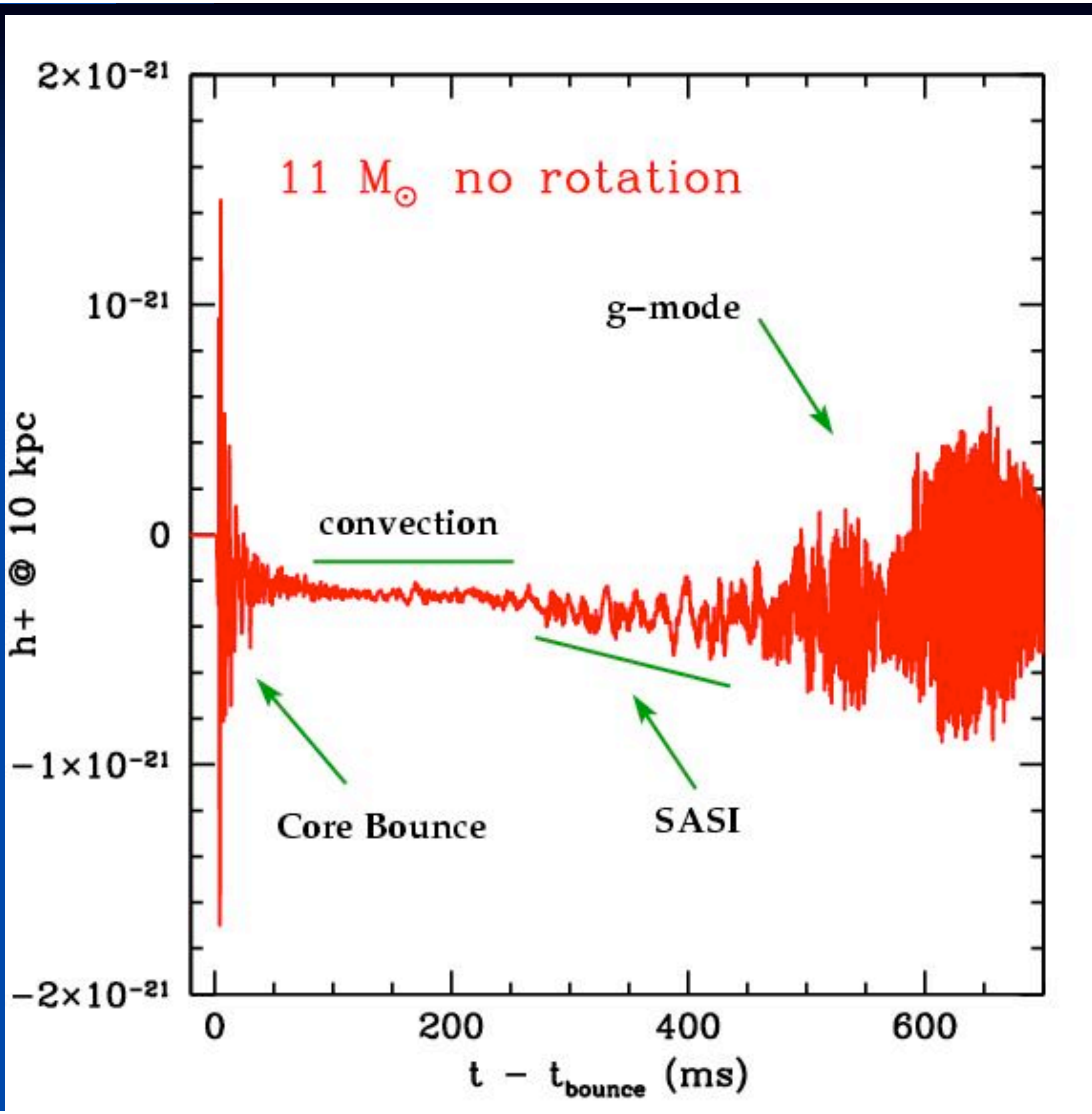
Gravitational Radiation from Supernovae

Ott et al. (2004,2006)

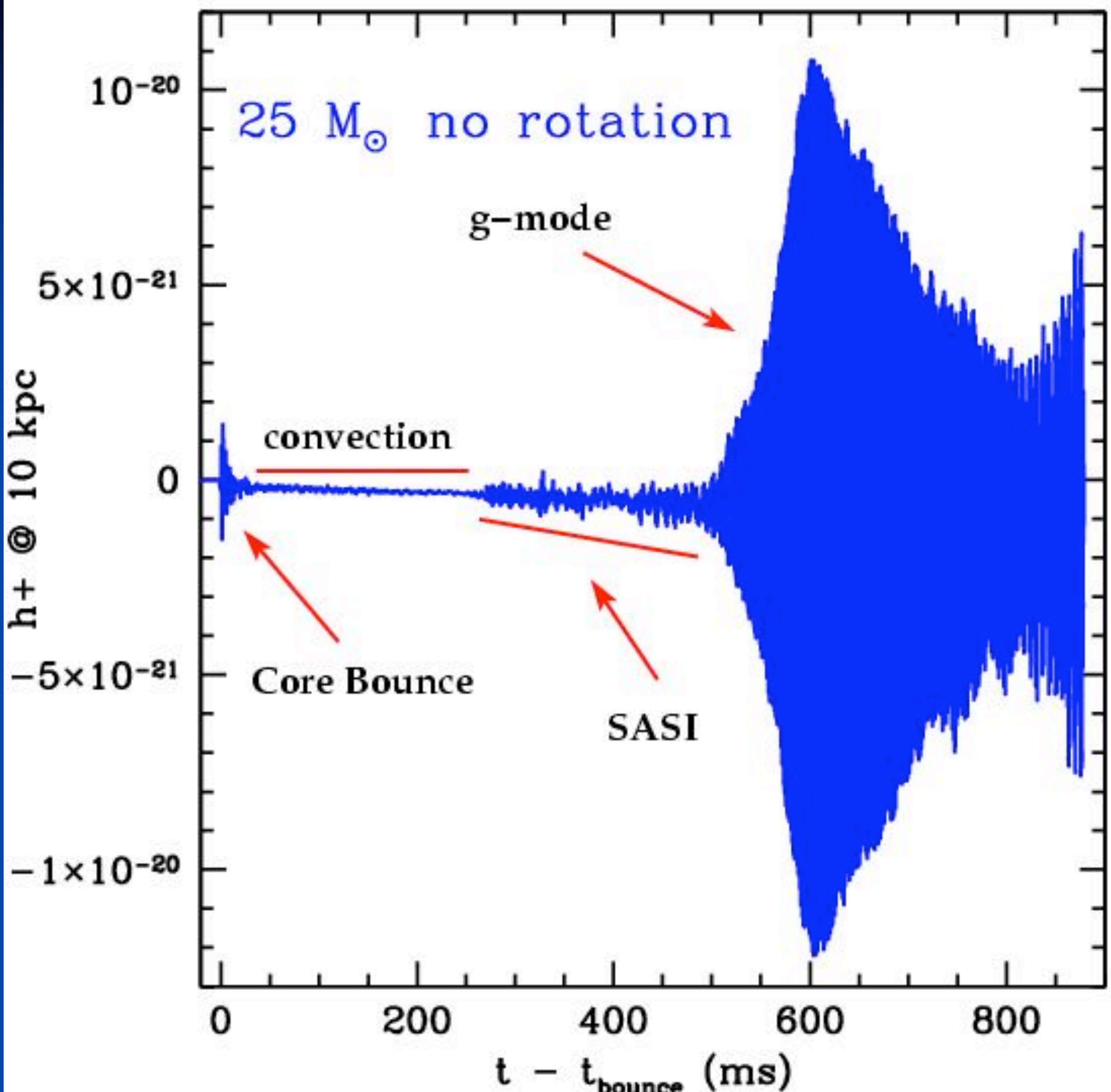

s20A1000β0.2
s11A1000β0.2
s15A1000β0.5
s15A1000β0.2
Ott et al. 2004
initial LIGO
advanced LIGO
h_rms,optimal (Hz^-1/2)
f (Hz)
10^-20
10^-21
10^-22
10
100
1000

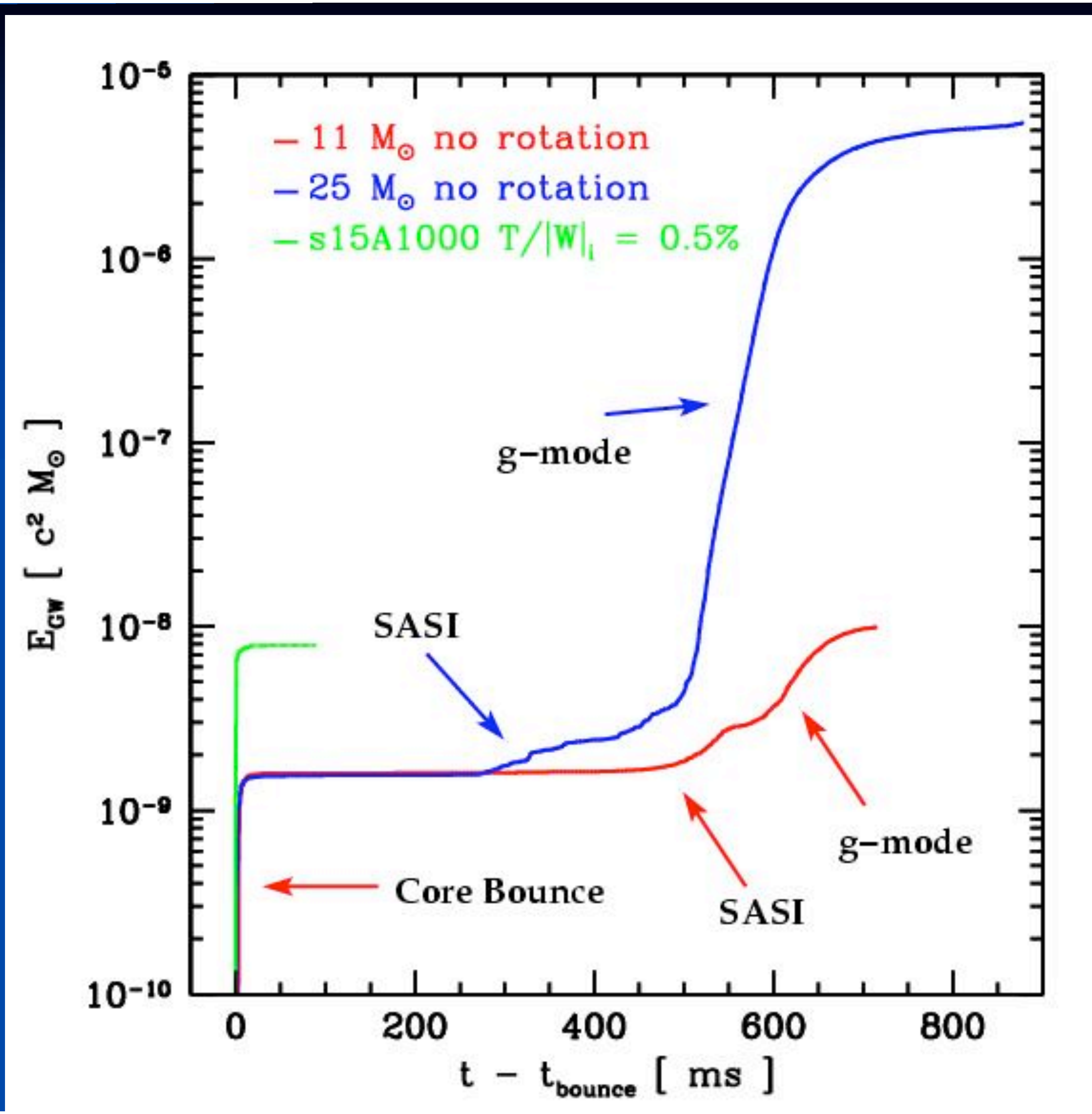


h_char spectra @ 10 kpc
– 11 M⊙ no rotation
– 25 M⊙ no rotation
advanced LIGO
initial LIGO
h_rms,optimal
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10
100
1000
f (Hz)

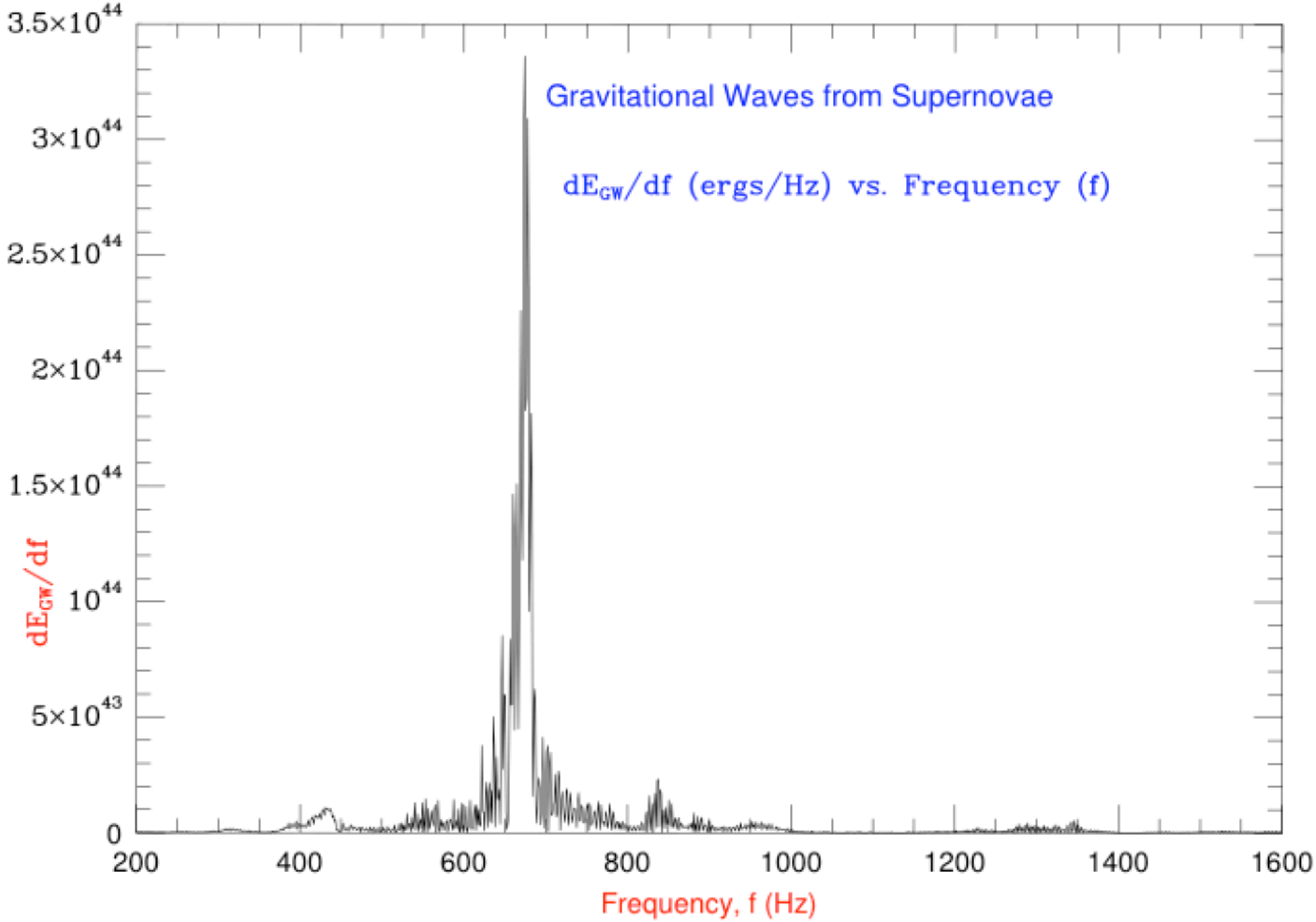


11 M⊙ no rotation
g−mode
convection
Core Bounce
SASI
2×10⁻²¹
10⁻²¹
0
−1×10⁻²¹
−2×10⁻²¹
h+ @ 10 kpc
0
200
400
600
t − t_bounce (ms)

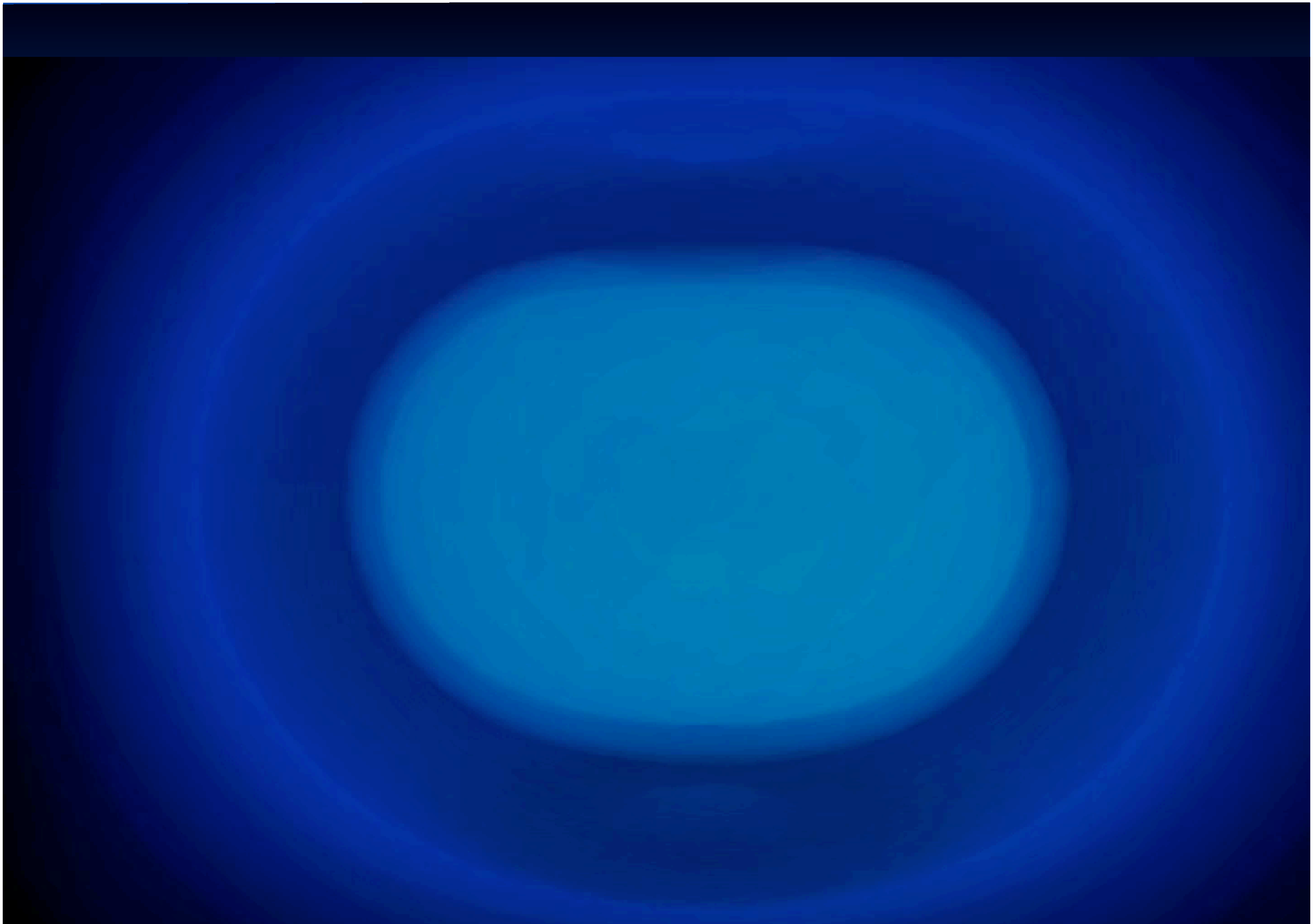

25 $M_\odot$ no rotation
g–mode
convection
Core Bounce
SASI
10^{-20}
5×10^{-21}
0
-5×10^{-21}
-1×10^{-20}
h+ @ 10 kpc
0
200
400
600
800
$t - t_{bounce}$ (ms)



– 11 M⊙ no rotation
– 25 M⊙ no rotation
– s15A1000 T/|W|i = 0.5%
g–mode
SASI
Core Bounce
SASI
g–mode
E_GW [c² M⊙]
t – t_bounce [ms]
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
200
400
600
800



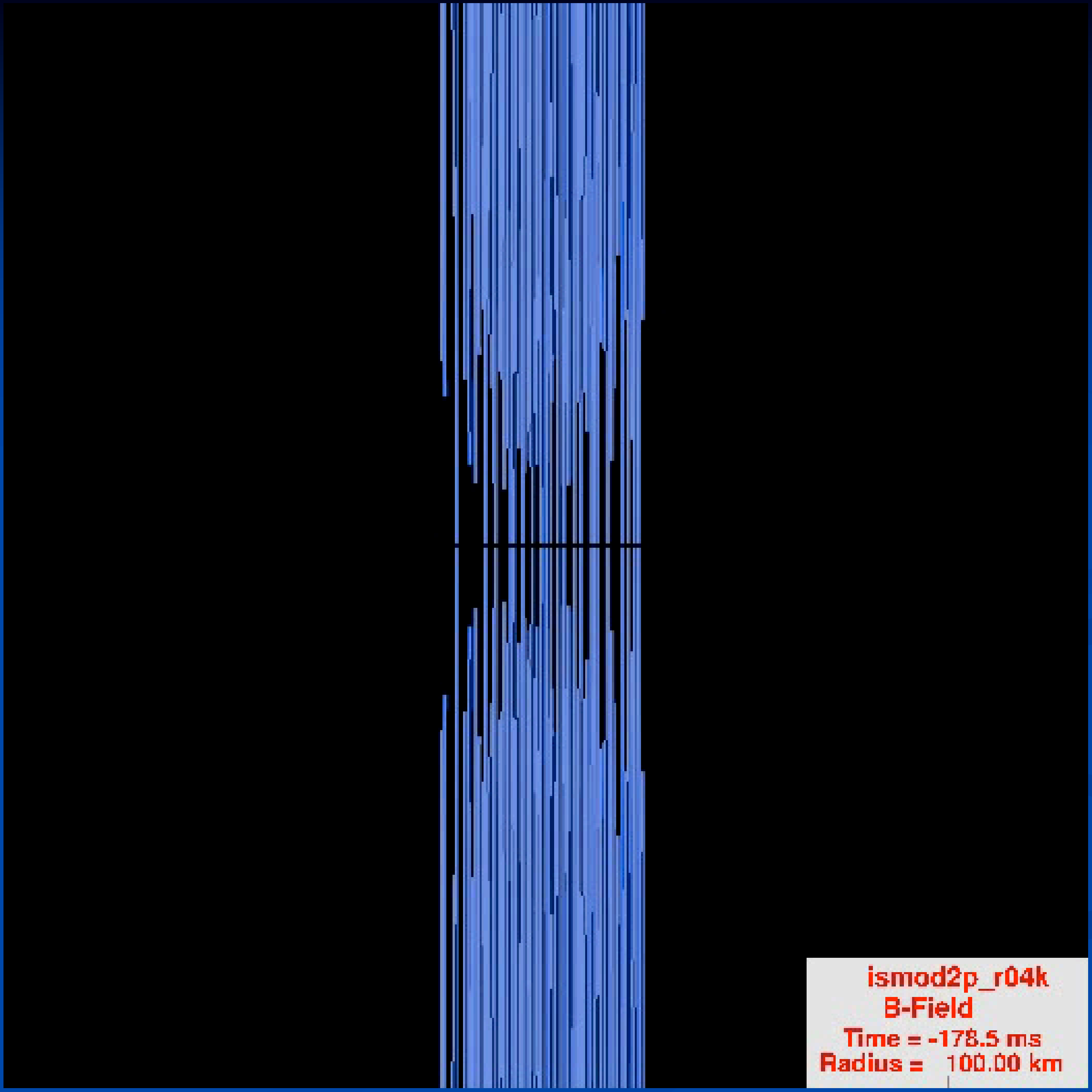
Gravitational Waves from Supernovae
dE_GW/df (ergs/Hz) vs. Frequency (f)
3.5×10^44
3×10^44
2.5×10^44
2×10^44
1.5×10^44
10^44
5×10^43
0
dE_GW/df
200
400
600
800
1000
1200
1400
1600
Frequency, f (Hz)

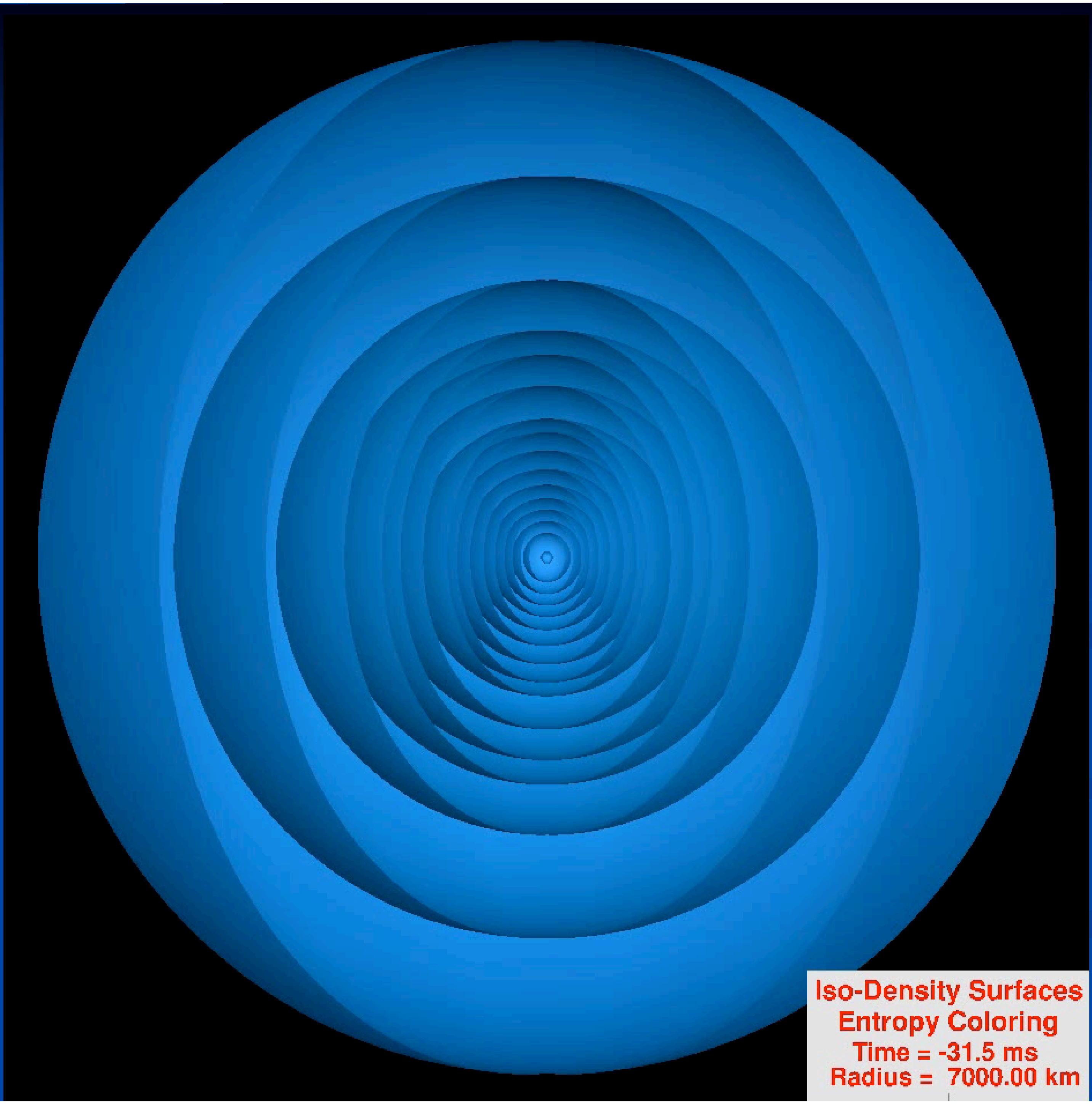


3D; GR; C. Ott et al.

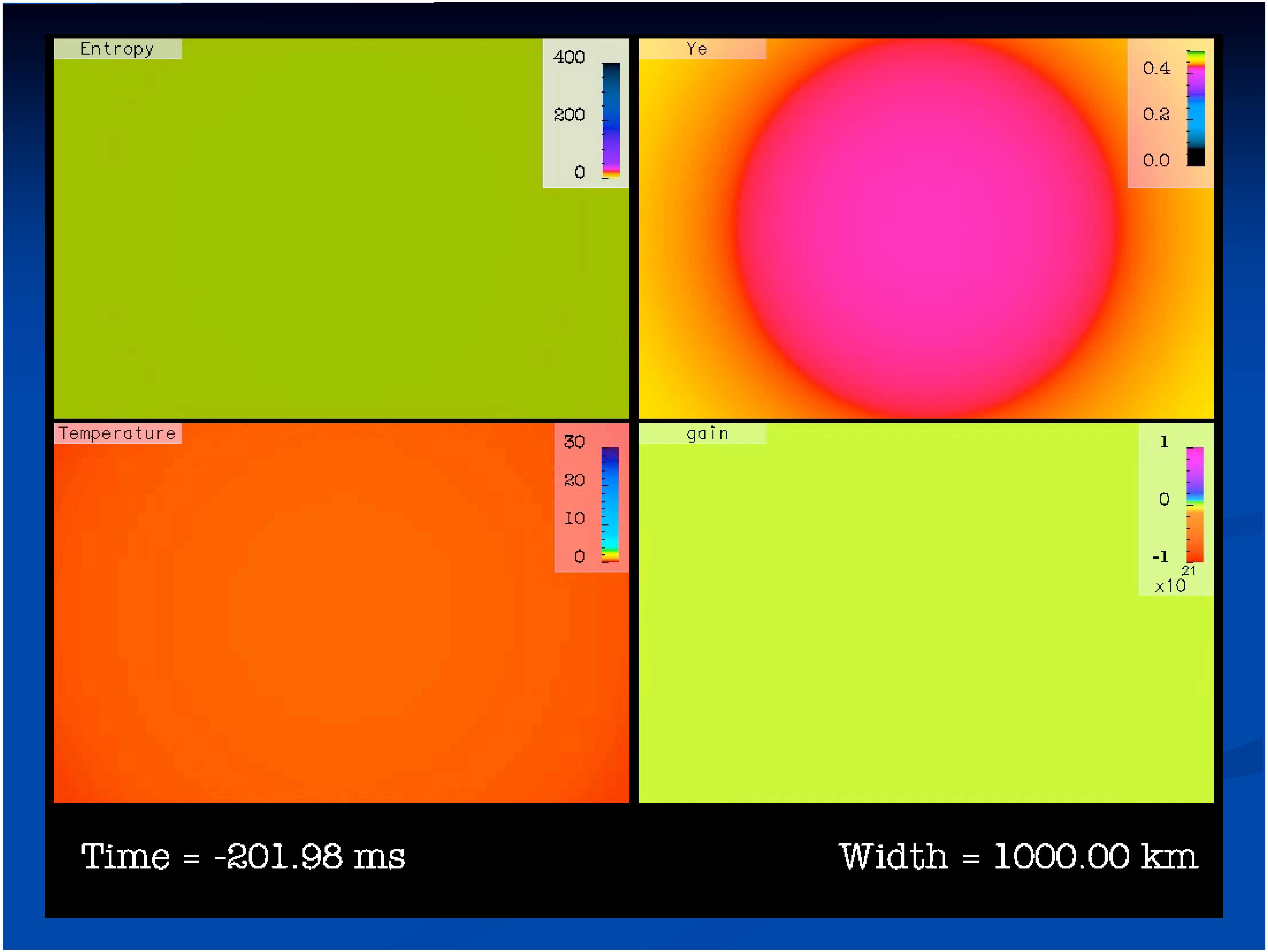
Core-Collapse Supernovae: The Future

- 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!


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


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

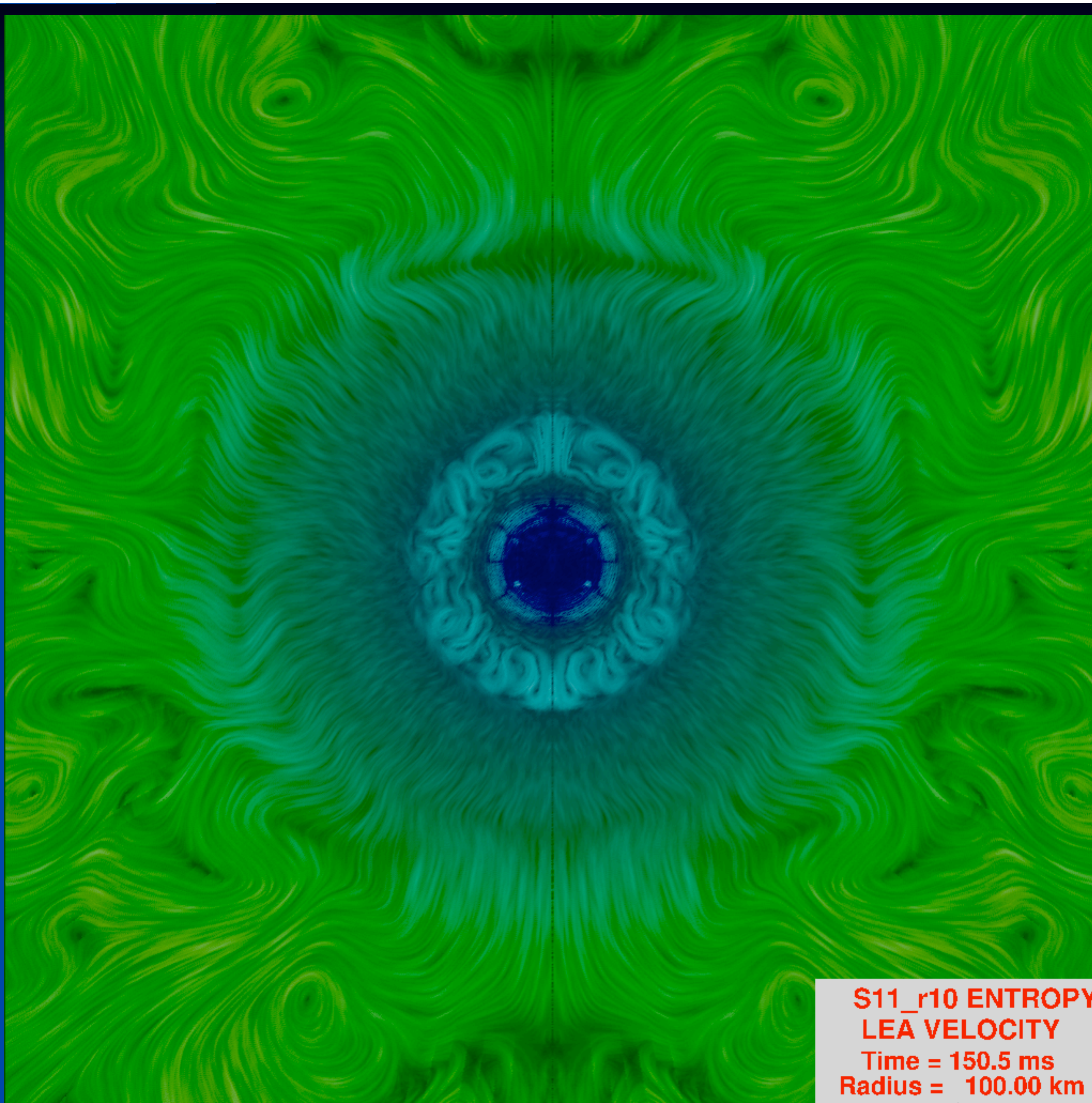
Extra Slides



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

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?


S11_r10 ENTROPY
LEA VELOCITY
Time = 150.5 ms
Radius = 100.00 km

A Boltzmann Formalism for Oscillating Neutrinos

P. Strack and A. Burrows

Phys.Rev.D 71:093004,2005 (hep-ph/0504035) & hep-ph/0505056

Quasi-classical Boltzmann equations

- Wigner density matrix, ensemble-averaging →

$$\mathcal{F} = \langle n_i|\rho|n_j\rangle = \begin{pmatrix} f_{\nu_e} & f_{e\mu} \\ f^*_{e\mu} & f_{\nu_\mu} \end{pmatrix}$$

→ Diagonal elements: real numbers: Phase-Space densities

→ Off-diagonal elements: complex numbers: Macroscopic Overlap densities

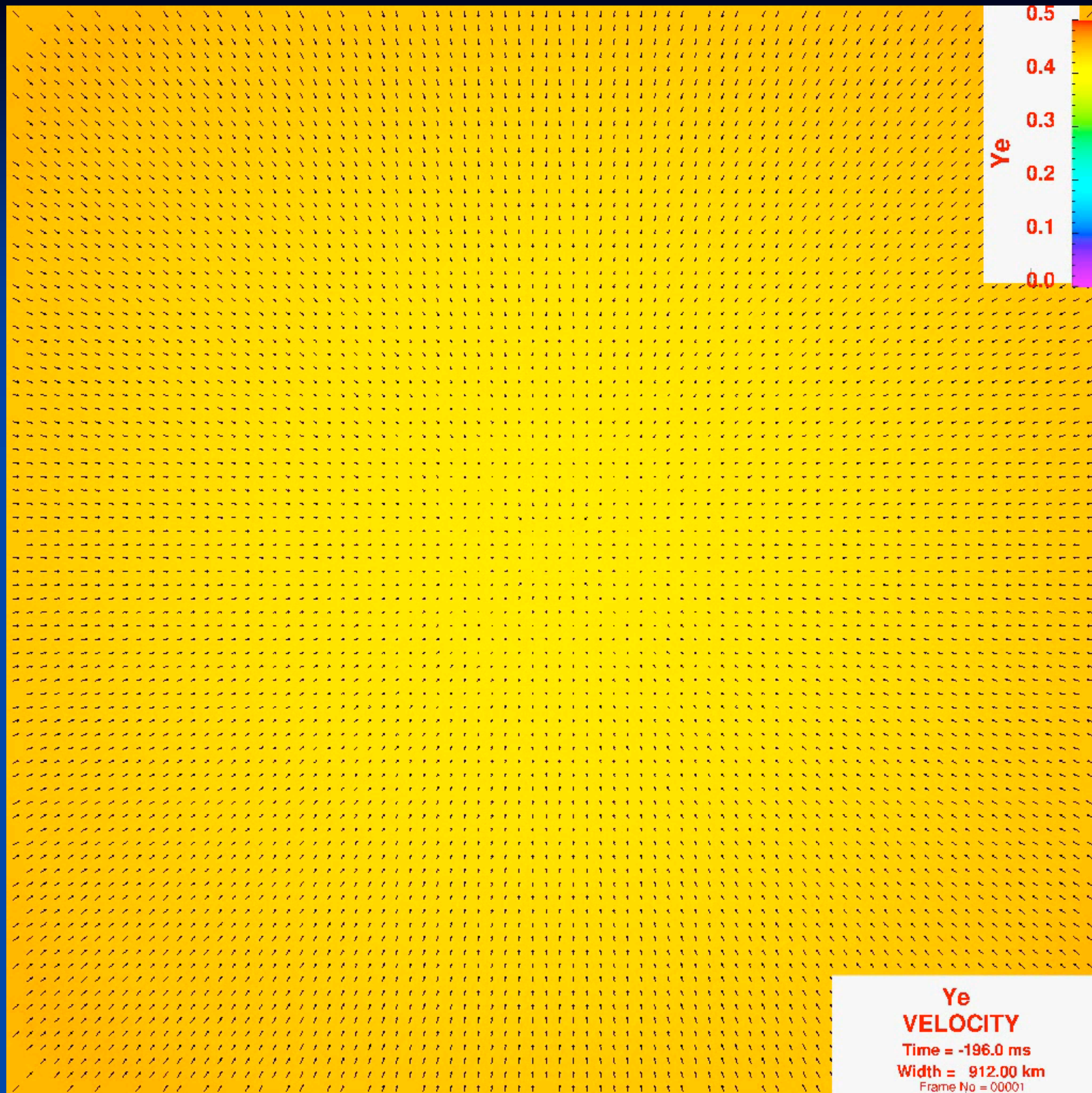
$$f_r = \frac{1}{2}\left(f_{e\mu} + f^*_{e\mu}\right) \quad \text{(Real part)}$$

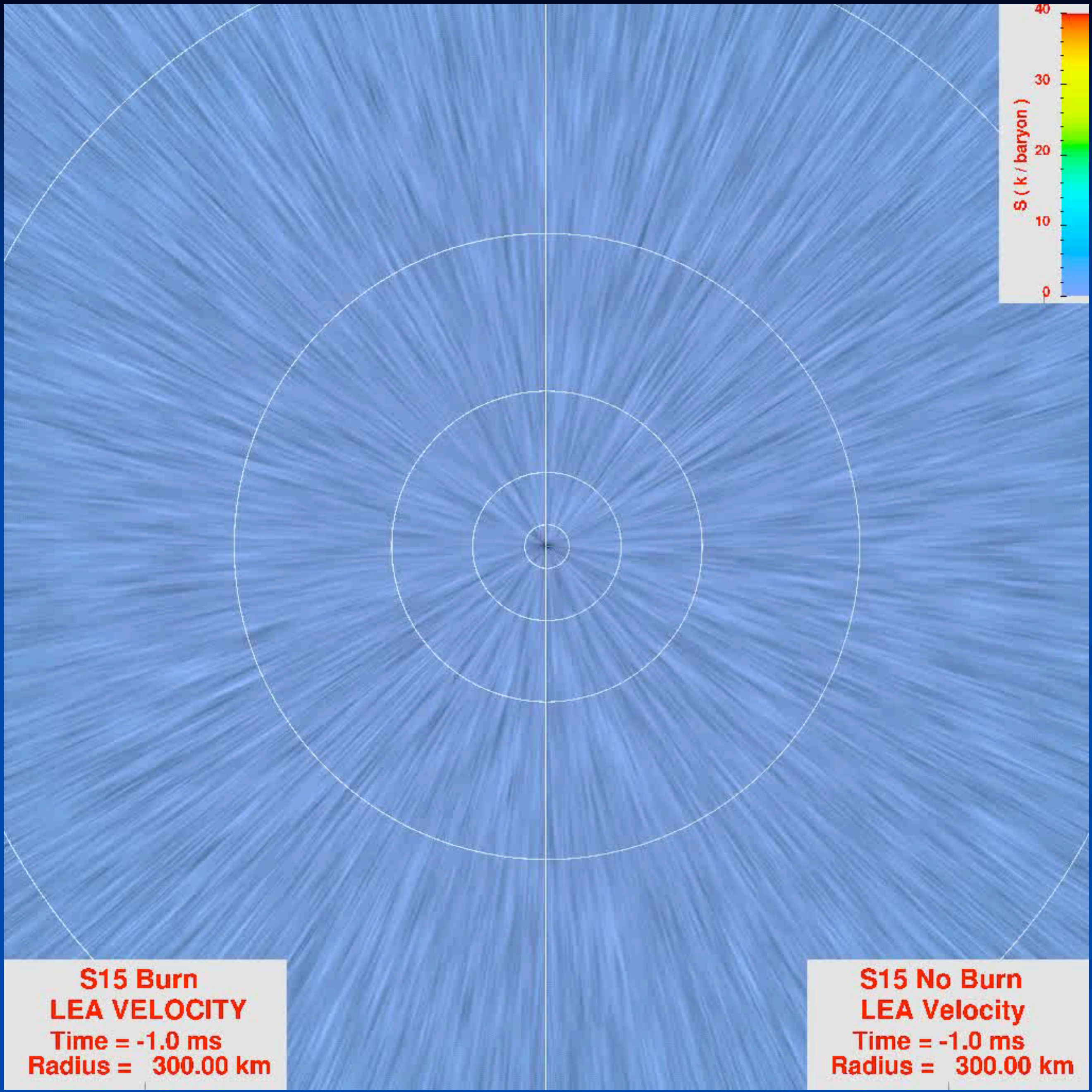
$$f_i = \frac{1}{2i}\left(f_{e\mu} - f^*_{e\mu}\right) \quad \text{(Imaginary part)}$$

$$L = \frac{4\pi\hbar c\varepsilon}{\Delta m^2 c^4}$$

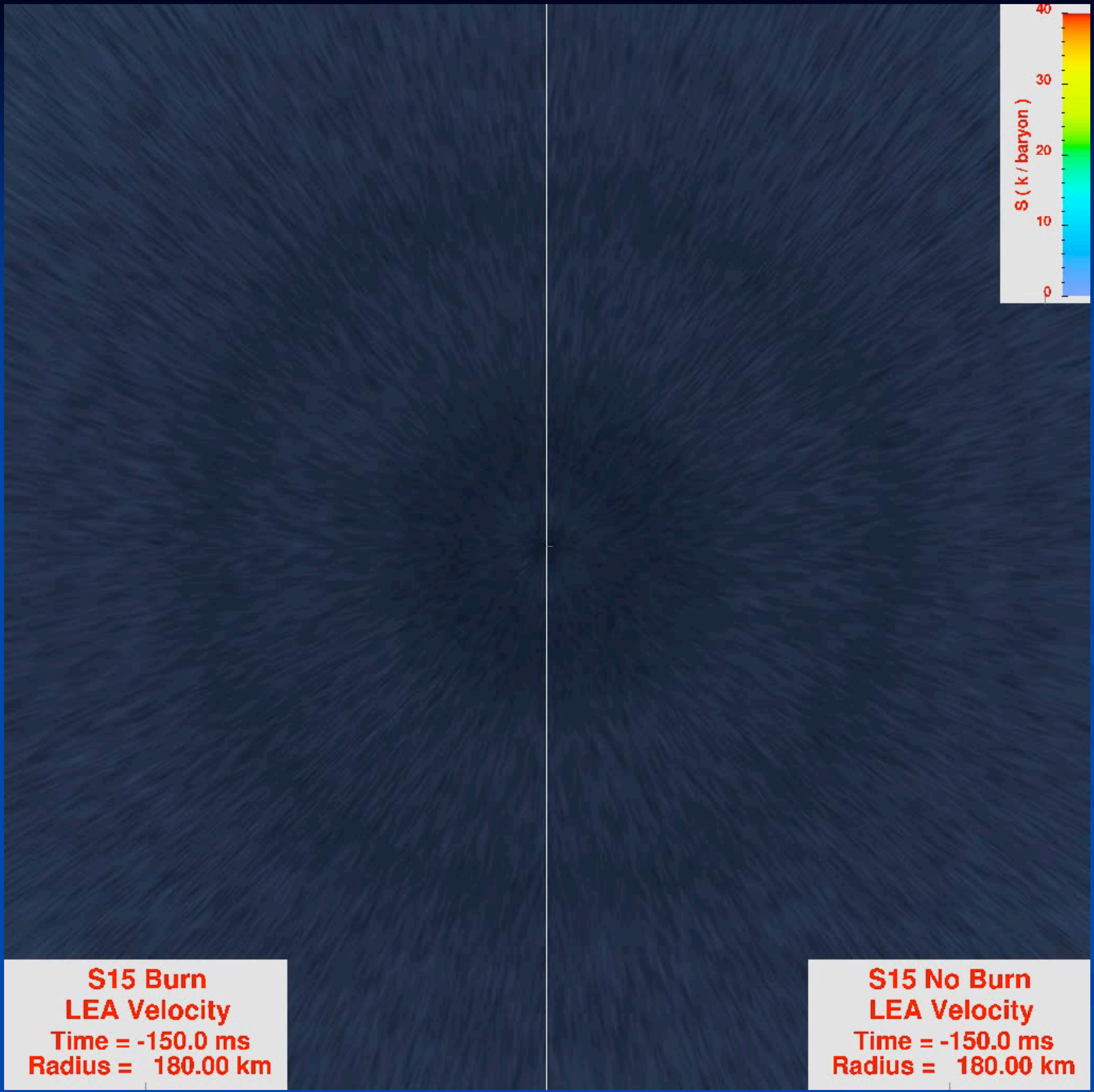
$$A = \left(\frac{L}{\pi c}\right)\frac{2\sqrt{2}G_F}{\hbar}n_e(\mathbf{r})$$

$$\begin{aligned}
\frac{\partial f_{\nu_e}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\nu_e}}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_{\nu_e}}{\partial \mathbf{p}} &= -\frac{2\pi c}{L} f_i \sin 2\theta + C_{\nu_e} \\
\frac{\partial f_{\nu_\mu}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\nu_\mu}}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_{\nu_\mu}}{\partial \mathbf{p}} &= \frac{2\pi c}{L} f_i \sin 2\theta + C_{\nu_\mu} \\
\frac{\partial f_r}{\partial t} + \mathbf{v}\cdot\frac{\partial f_r}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_r}{\partial \mathbf{p}} &= -\frac{2\pi c}{L} f_i \left(\cos 2\theta - A\right) \\
\frac{\partial f_i}{\partial t} + \mathbf{v}\cdot\frac{\partial f_i}{\partial \mathbf{r}} + \dot{\mathbf{p}}\cdot\frac{\partial f_i}{\partial \mathbf{p}} &= \frac{2\pi c}{L}\Big(\frac{f_{\nu_e} - f_{\nu_\mu}}{2}\sin 2\theta + \\
&\quad f_r \left(\cos 2\theta - A\right)\Big)
\end{aligned}$$

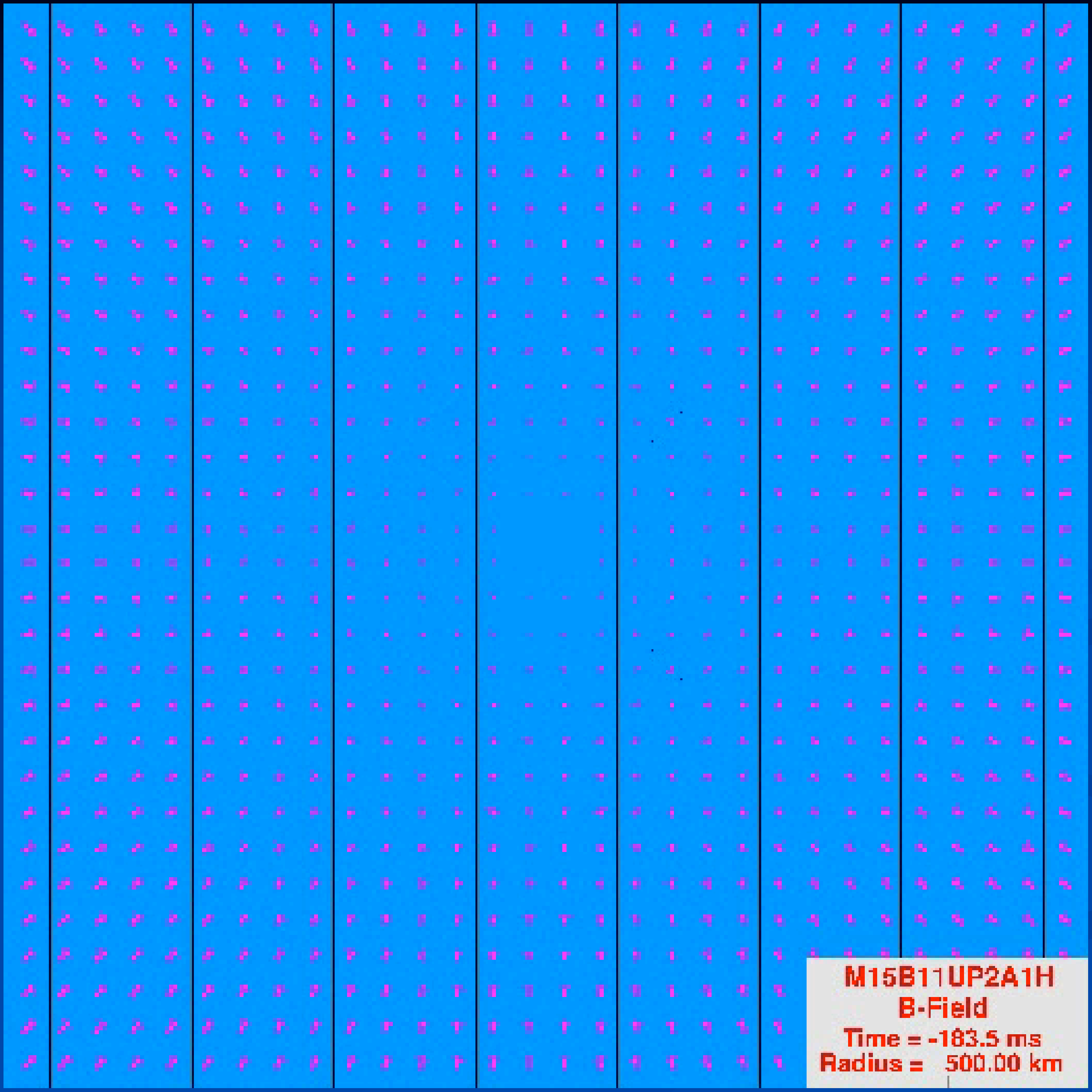

0.5
0.4
0.3
0.2
0.1
0.0
Ye
Ye
VELOCITY
Time = -196.0 ms
Width = 912.00 km
Frame No = 00001

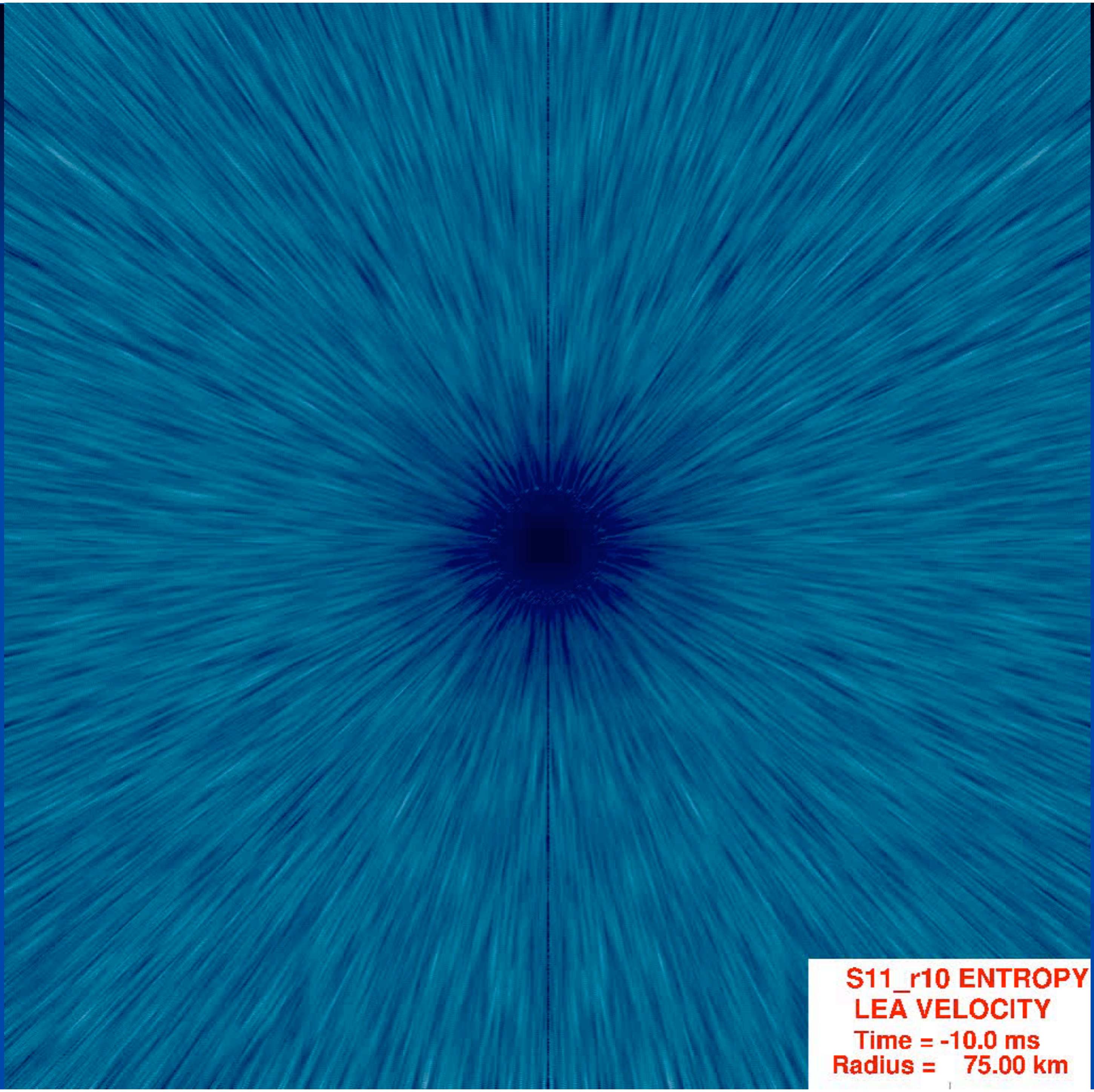


With and Without Burning



With and Without Burning

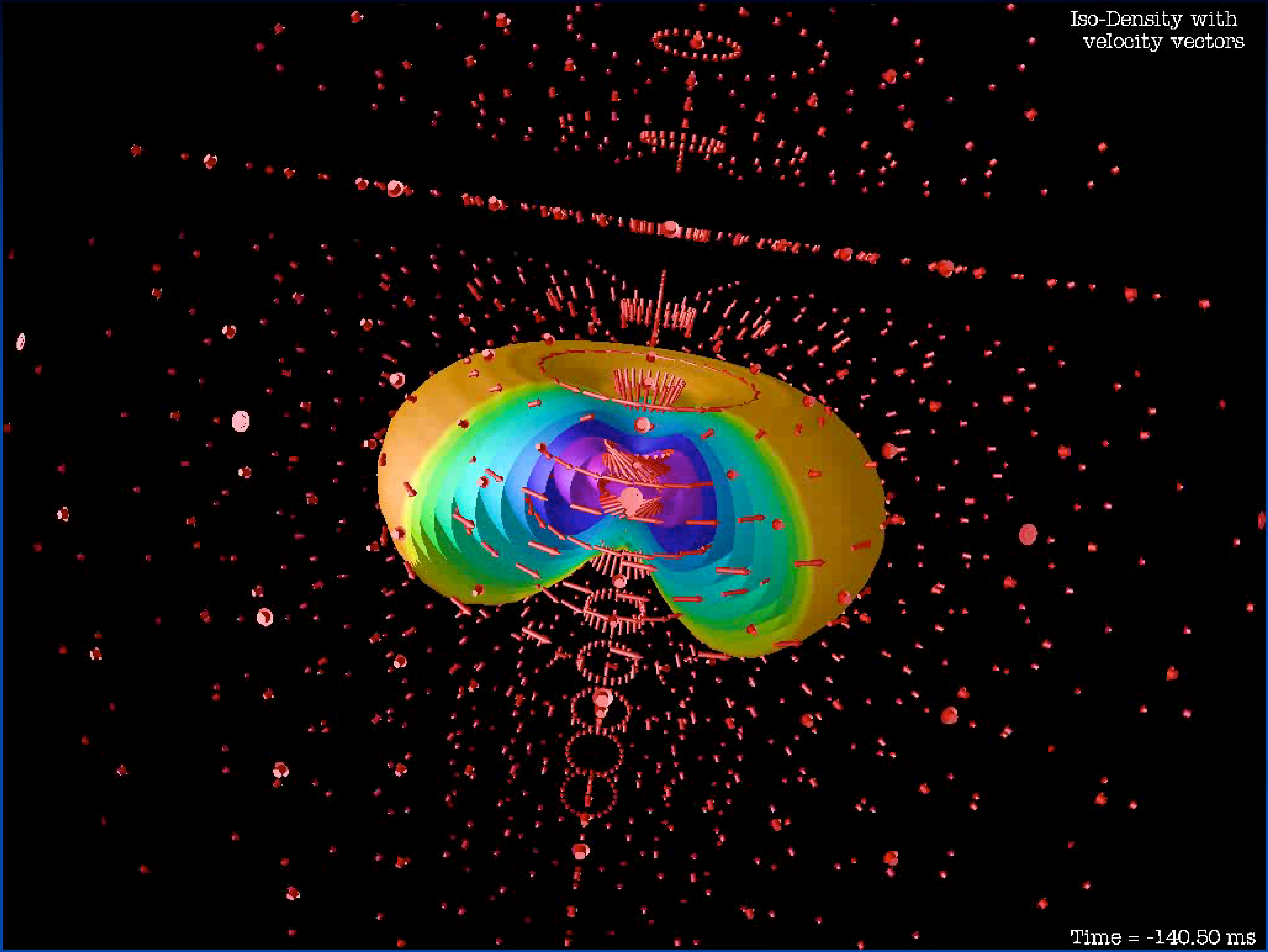

M15B11UP2A1H
B-Field
Time = -183.5 ms
Radius = 500.00 km


S11_r10 ENTROPY
LEA VELOCITY
Time = -10.0 ms
Radius = 75.00 km

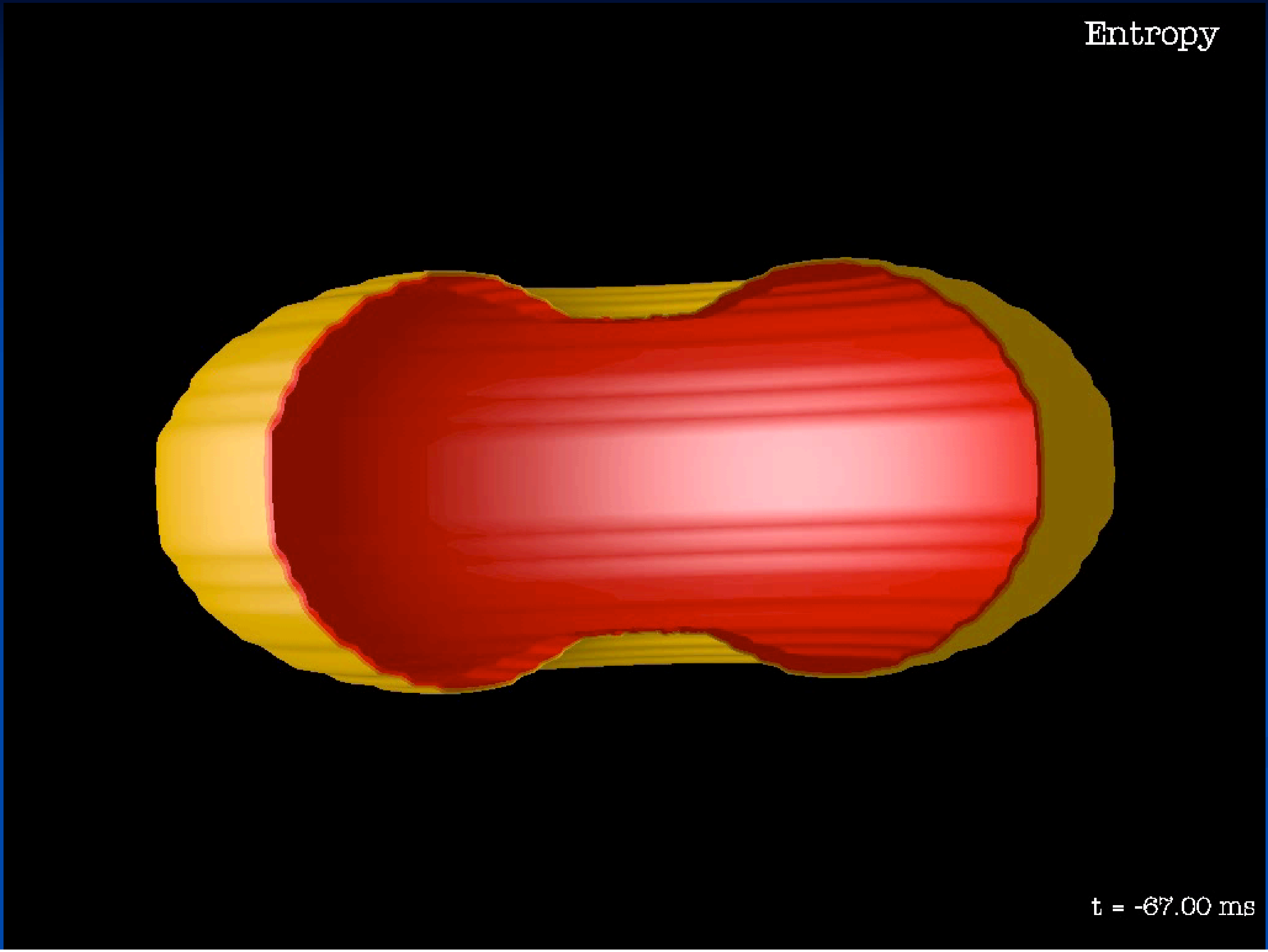
Accretion-Induced Collapse of O-Ne-Mg White Dwarfs

Dessart, Burrows, Ott, Livne, Yoon, & Langer 2005

Rapid Rotation!

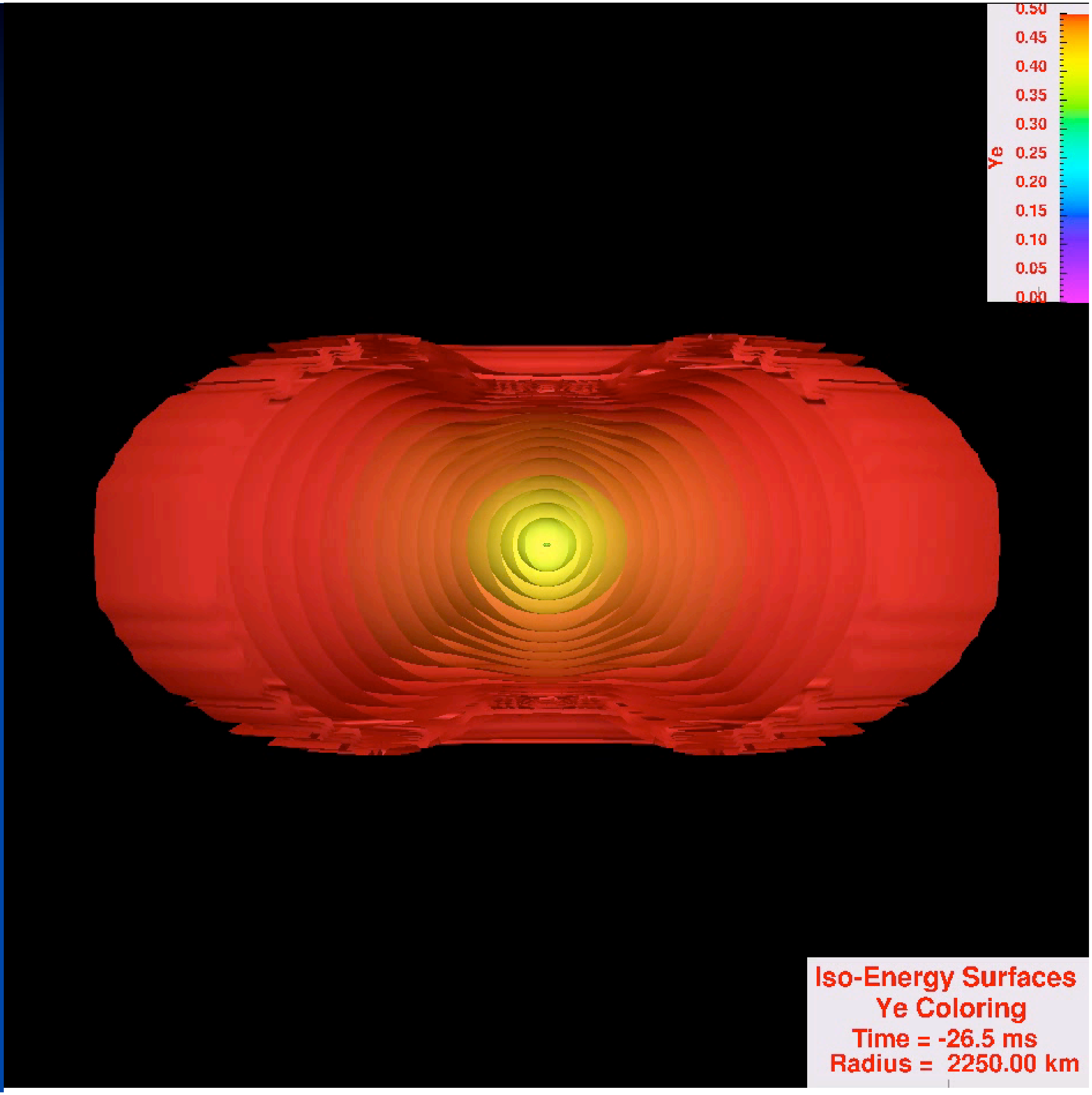

Iso-Density with
velocity vectors
Time = -140.50 ms

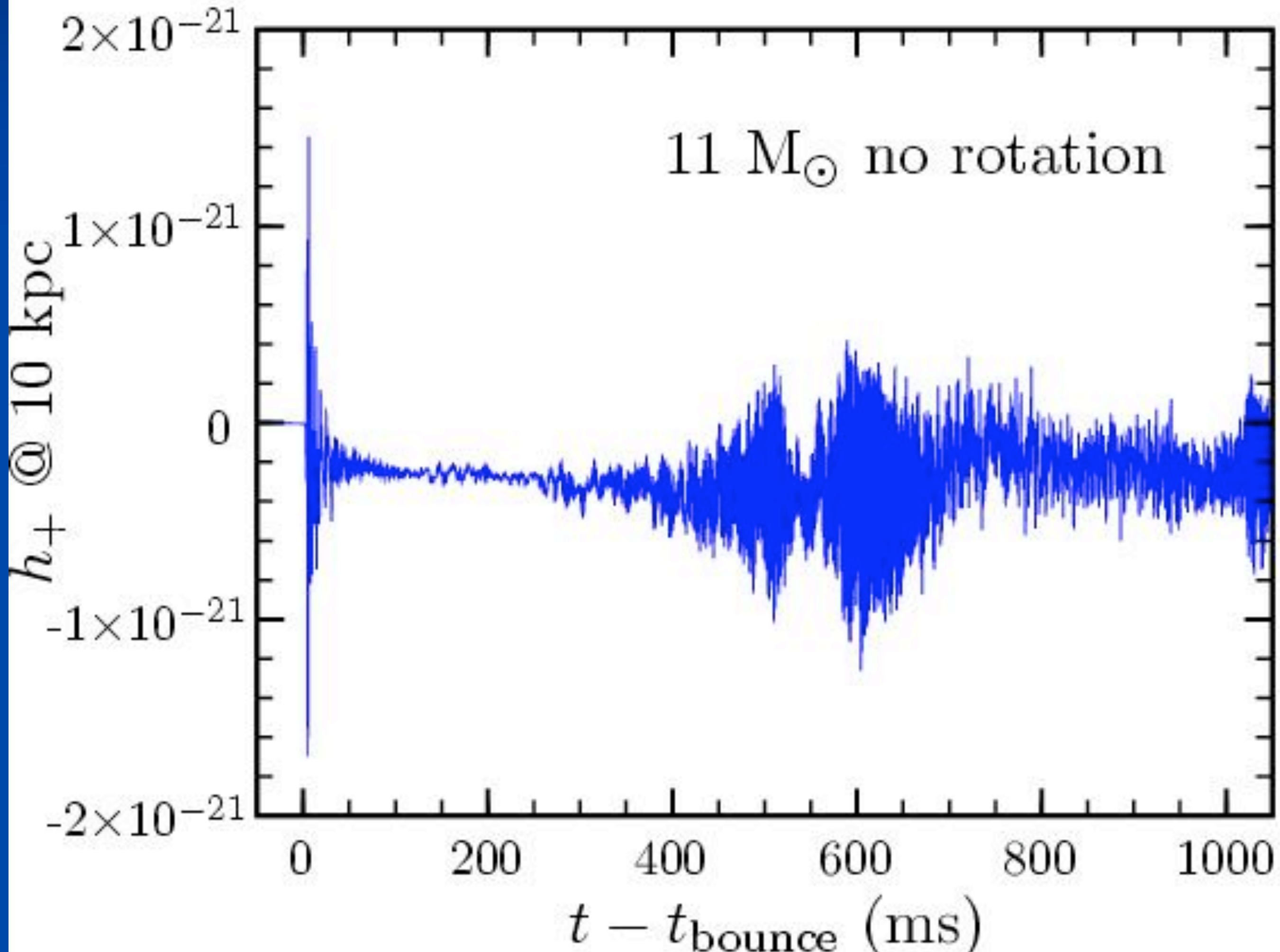
AIC: 1.92 solar masses:



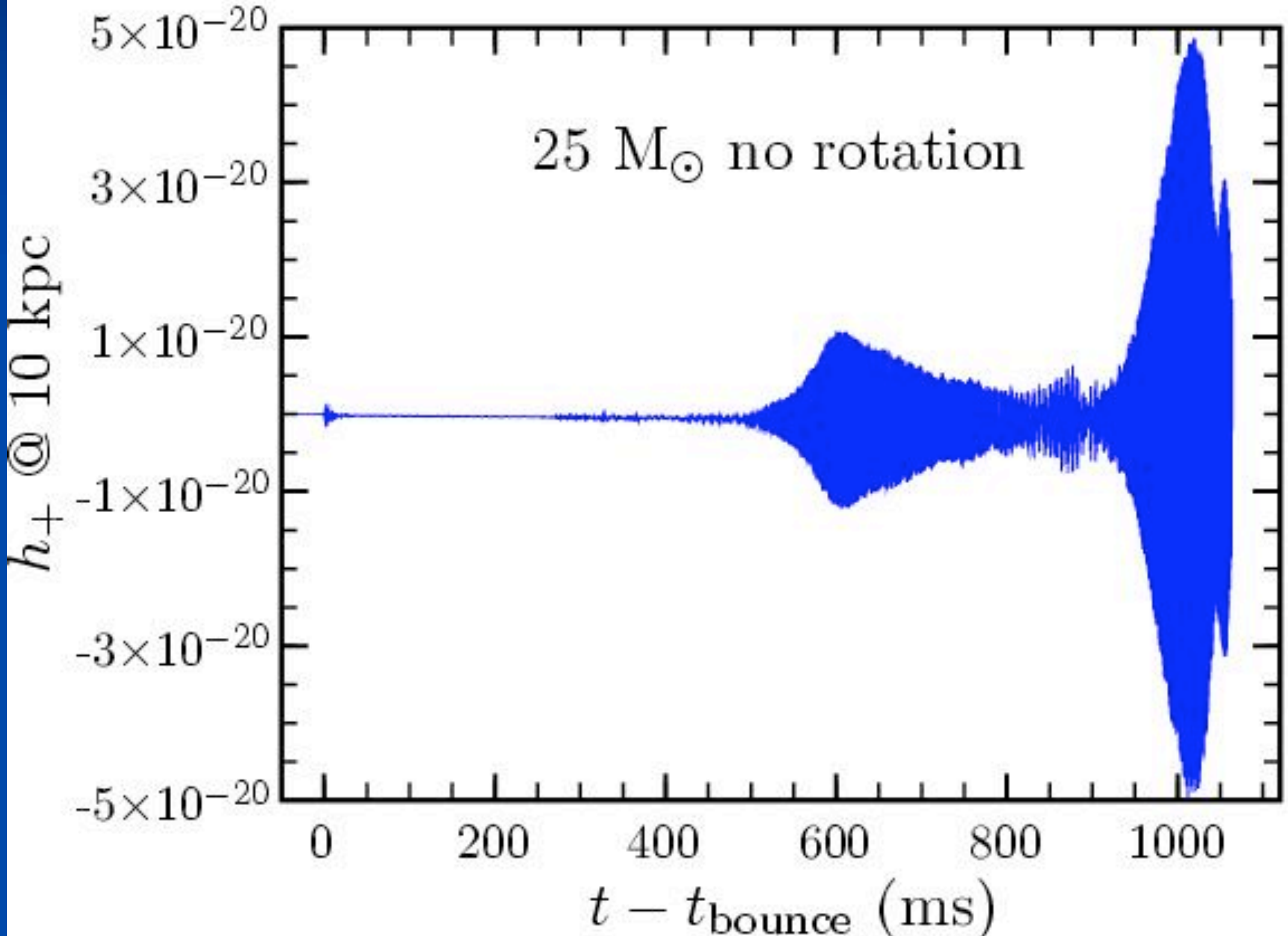
AIC: 1.92 solar masses:

Iso-Energy/Ye coloring



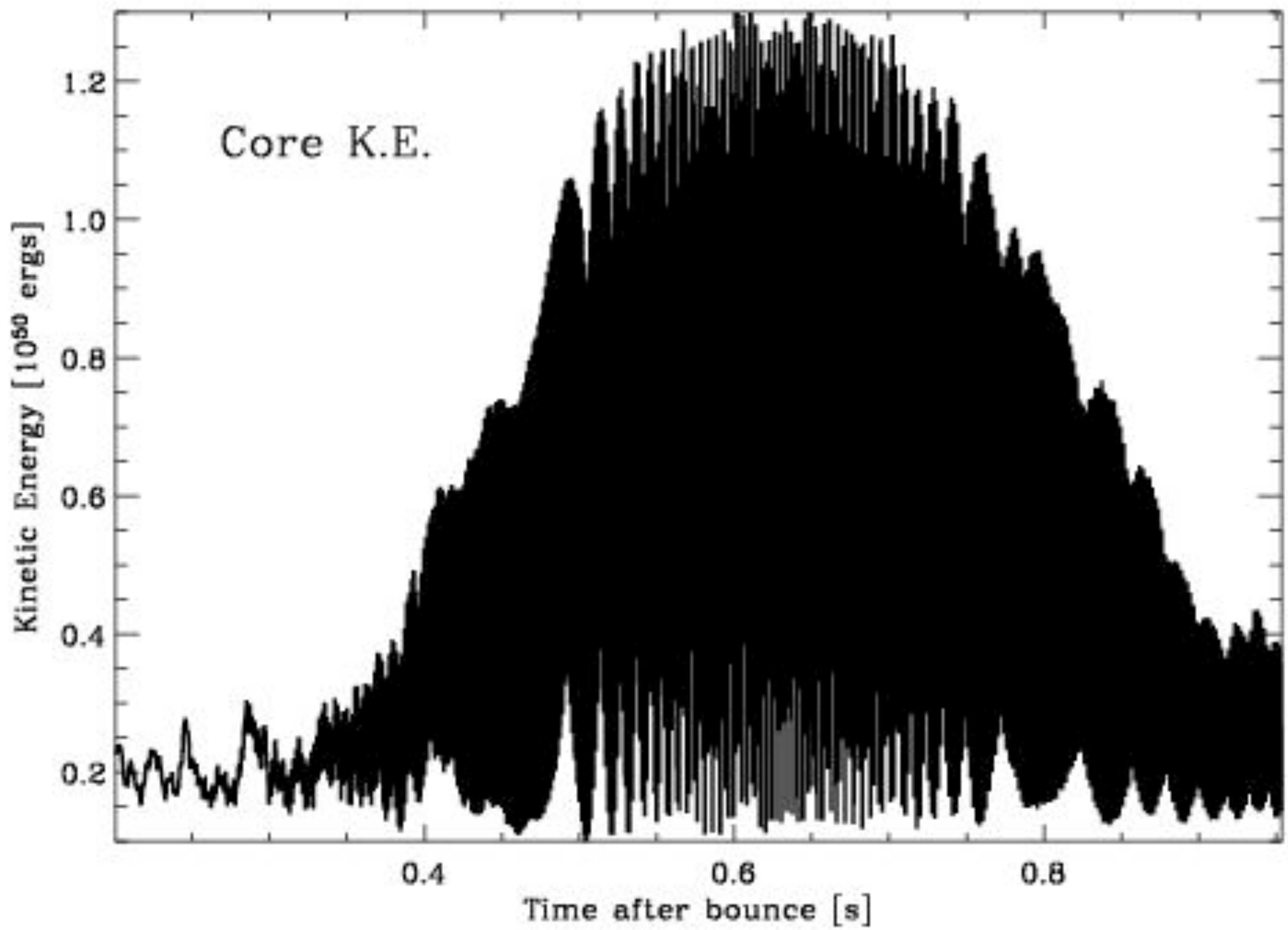


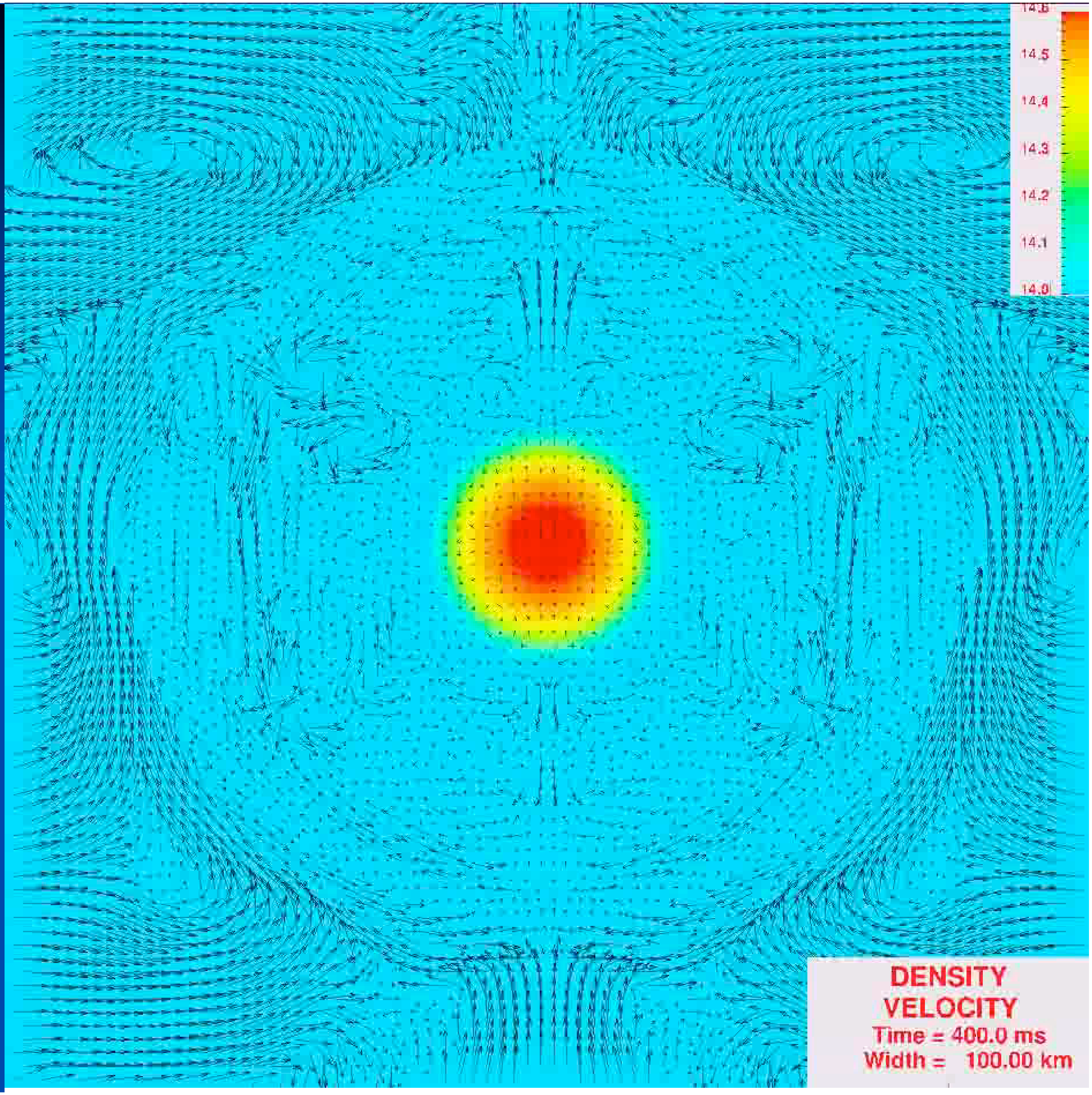
11 M$_\odot$ no rotation
2×10^{-21}
1×10^{-21}
0
-1×10^{-21}
-2×10^{-21}
h_+ @ 10 kpc
0
200
400
600
800
1000
$t - t_{\rm bounce}$ (ms)

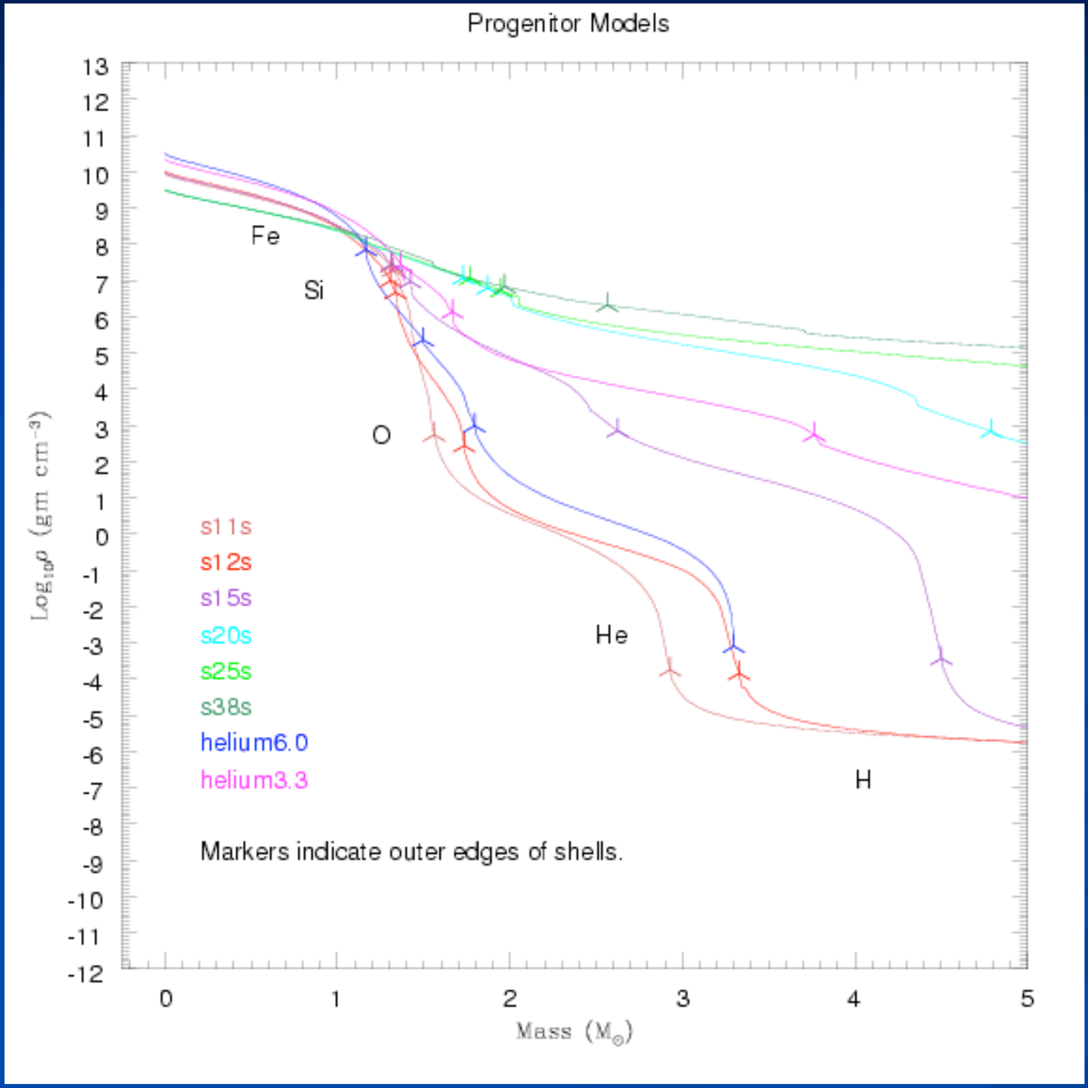


25 M⊙ no rotation
h_+ @ 10 kpc
5×10^{-20}
3×10^{-20}
1×10^{-20}
-1×10^{-20}
-3×10^{-20}
-5×10^{-20}
0
200
400
600
800
1000
$t - t_{\rm bounce}$ (ms)

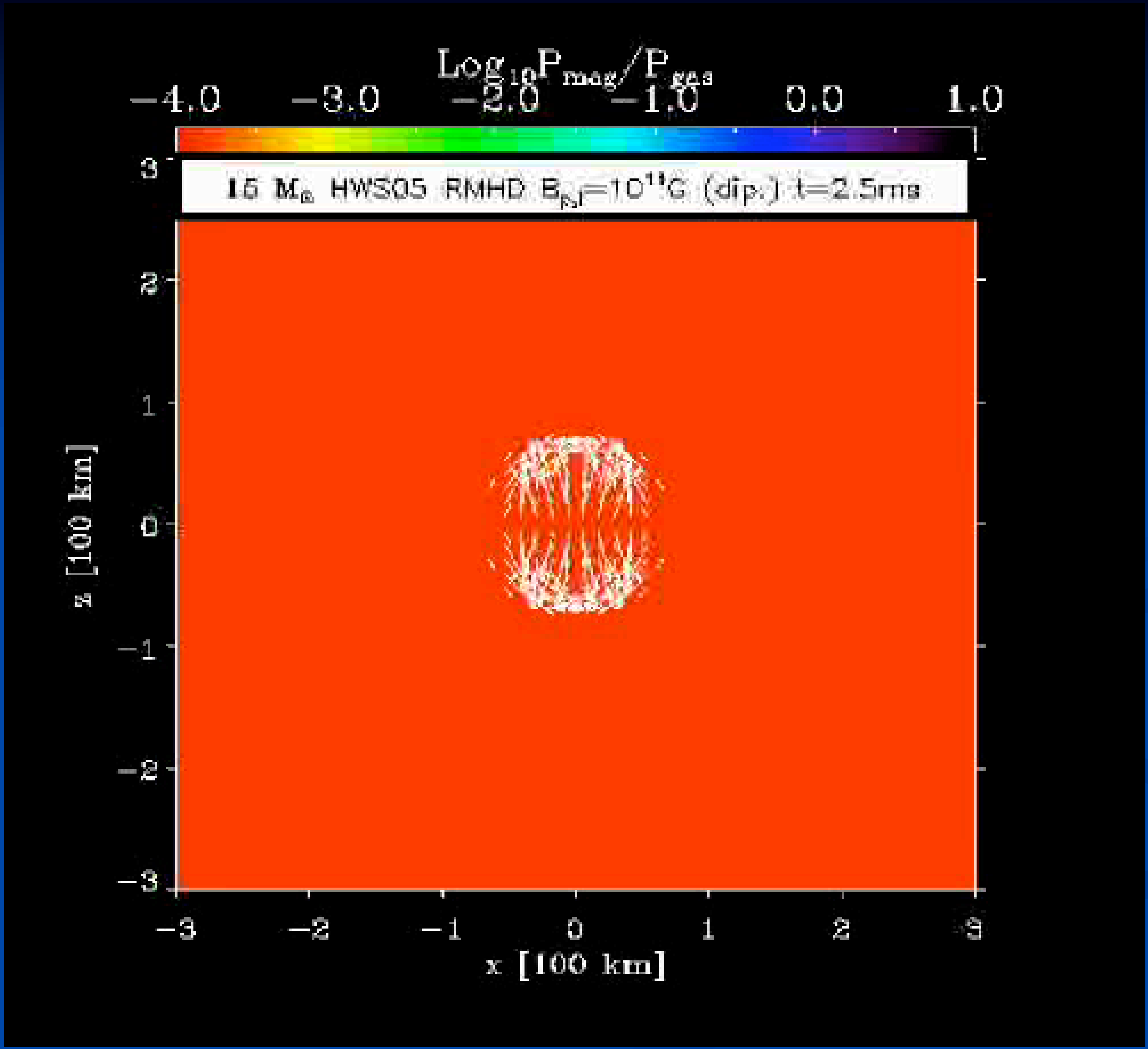
Evolution of Core Kinetic Energy: 11 solar-mass Progenitor




14.6
14.5
14.4
14.3
14.2
14.1
14.0
DENSITY
VELOCITY
Time = 400.0 ms
Width = 100.00 km

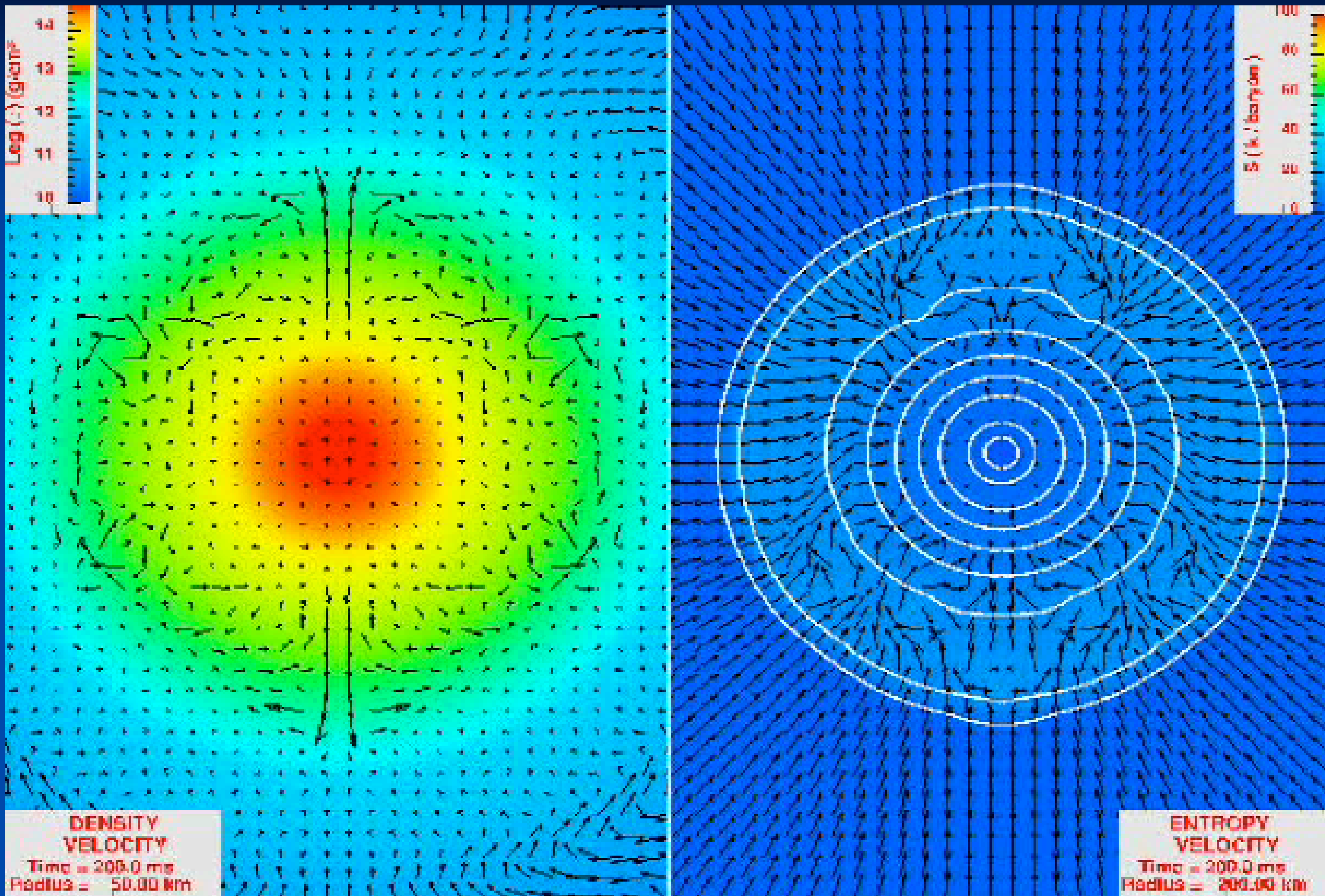


Progenitor Models
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
0
1
2
3
4
5
Mass (M⊙)
Log10ρ (gm cm-3)
Fe
Si
O
He
H
s11s
s12s
s15s
s20s
s25s
s38s
helium6.0
helium3.3
Markers indicate outer edges of shells.

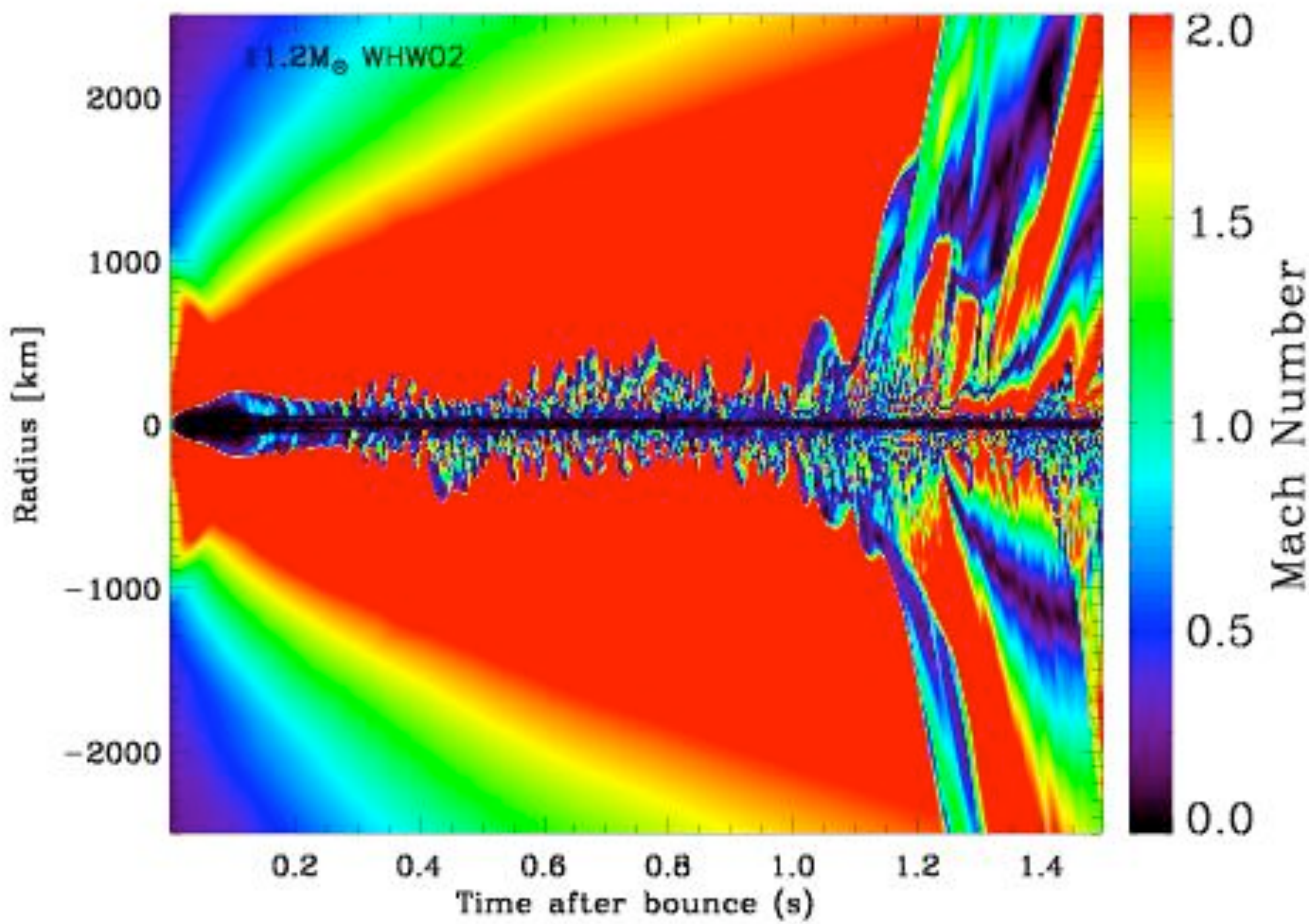


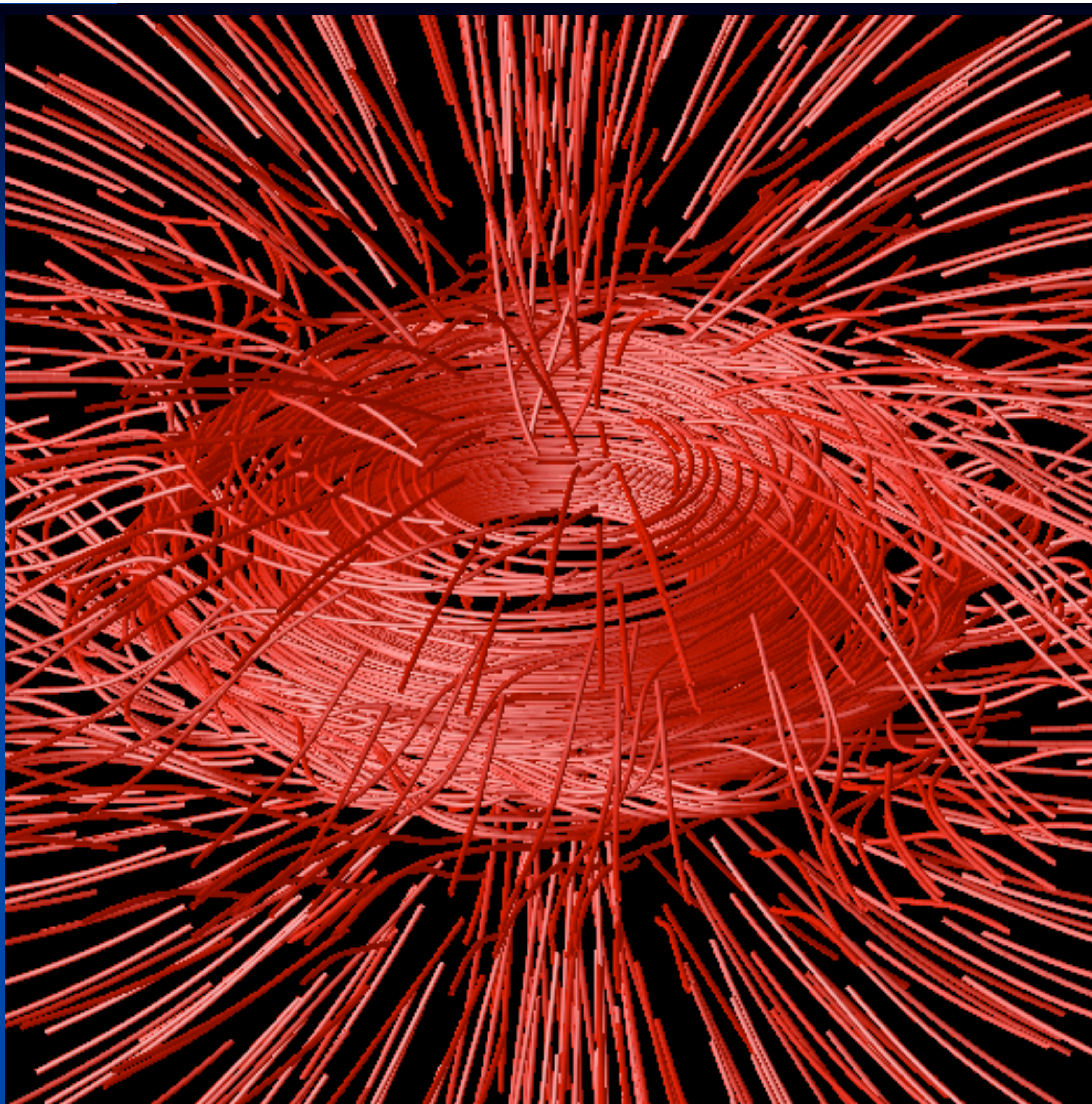
$Log_{10}P_{mag}/P_{gas}$
−4.0 −3.0 −2.0 −1.0 0.0 1.0
15 M☉ HWS05 RMHD $B_{NI}=10^{11}$G (dip.) t=2.5ms
z [100 km]
x [100 km]
−3 −2 −1 0 1 2 3

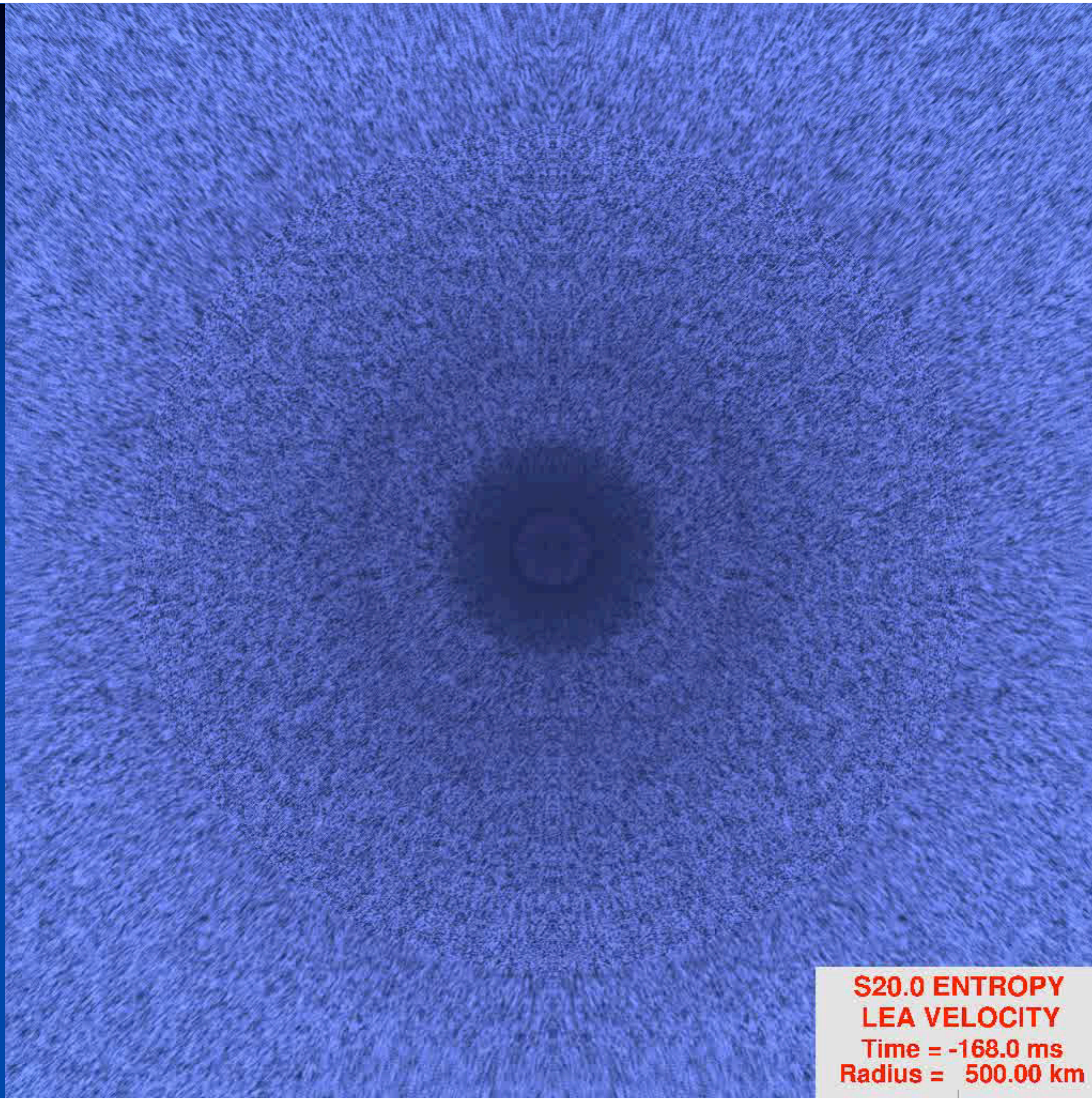
25 Solar Mass Progenitor: Core Oscillation and Shock Evolution

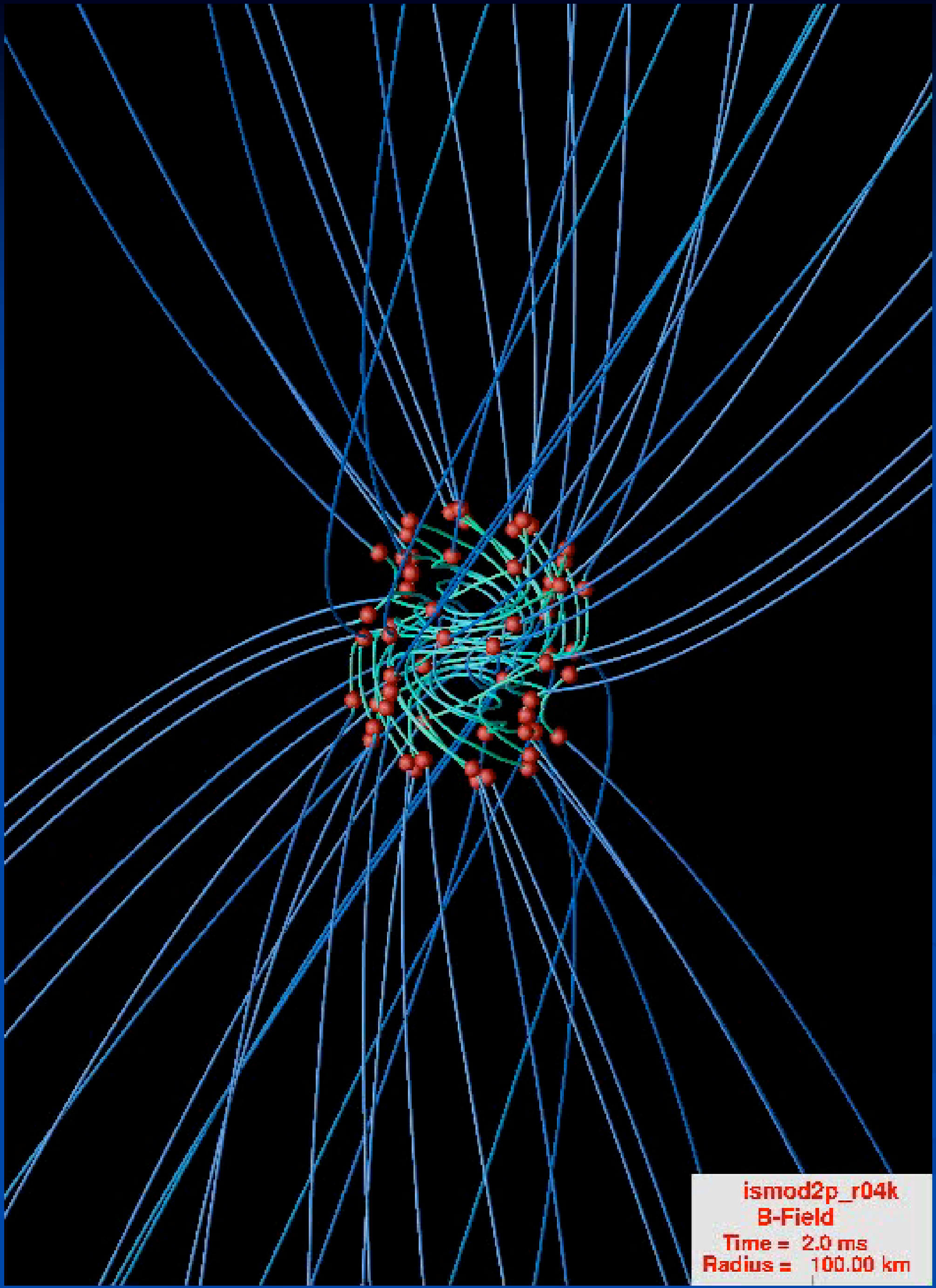


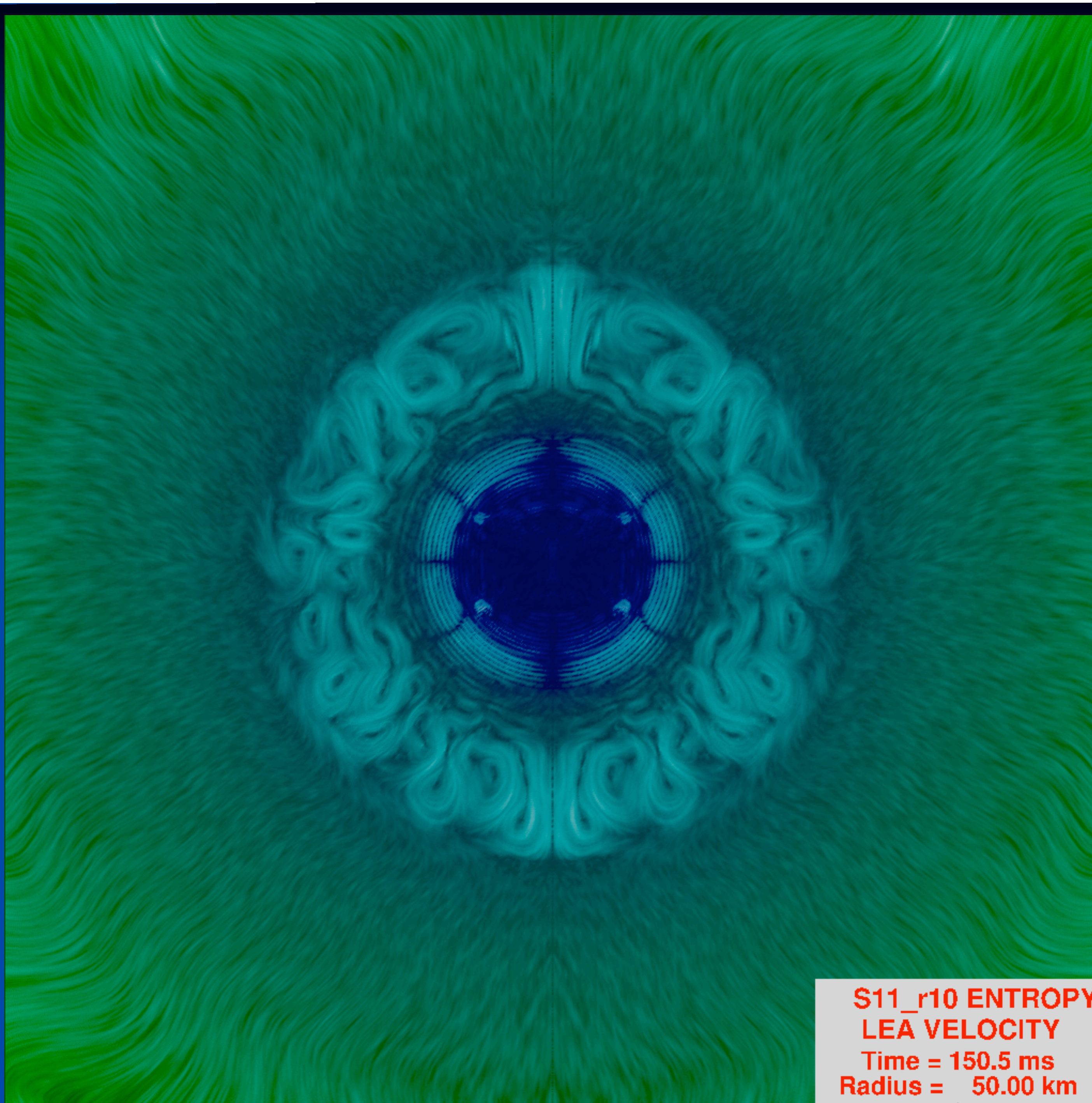
Mach Number along axis versus Time



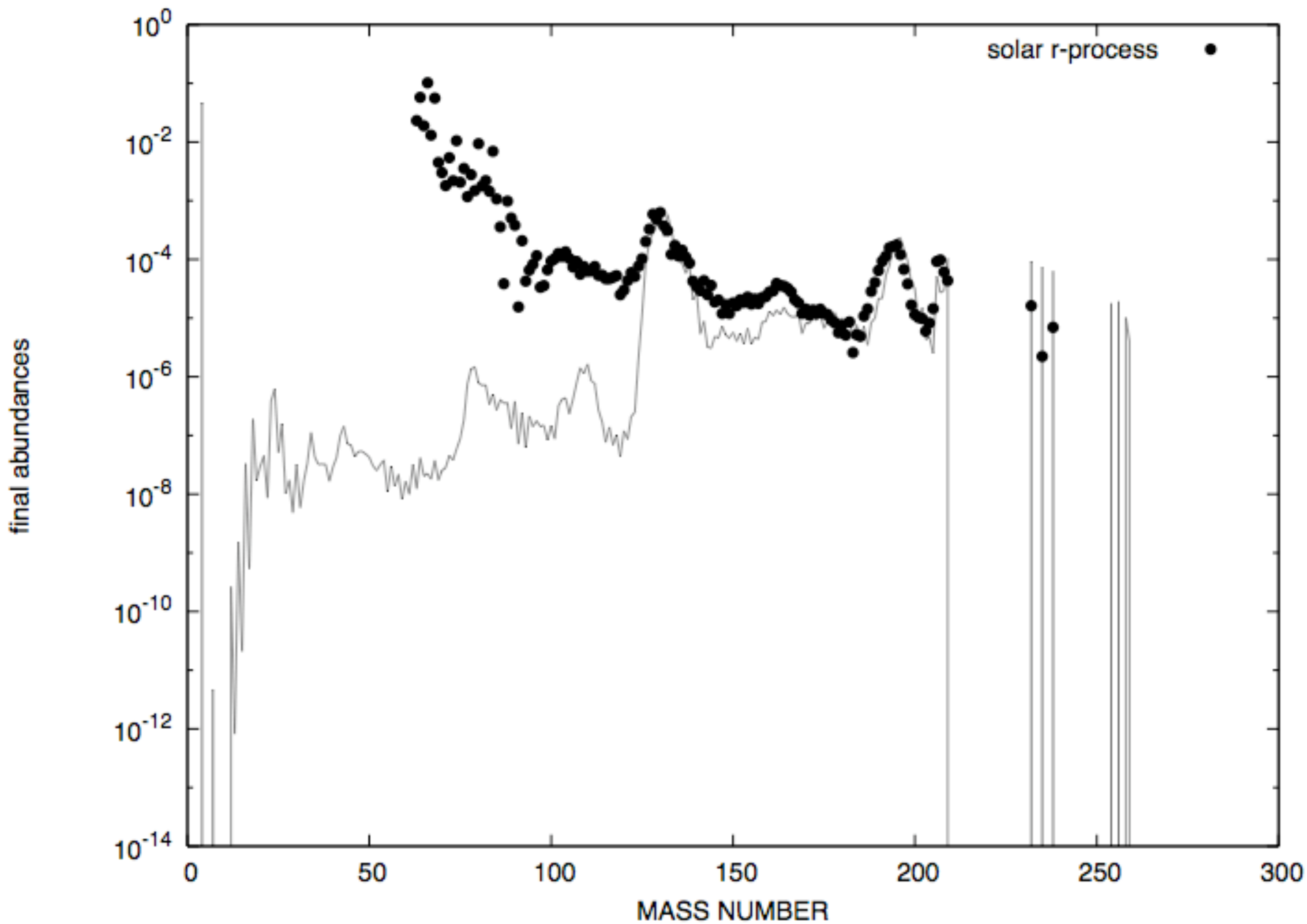



S20.0 ENTROPY
LEA VELOCITY
Time = -168.0 ms
Radius = 500.00 km


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


S11_r10 ENTROPY
LEA VELOCITY
Time = 150.5 ms
Radius = 50.00 km

Preliminary R-process Calculations for the Long-term Acoustic Mechanism



K. Otsuki et al. 2008

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?