A New Mechanism for Core-Collapse Supernova Explosions

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Current Status of the Neutrino Mechanism

- Direct mechanism always fails: "Bounce Shock" doesn't work
- Spherically-symmetric neutrino mechanism might work for O/Ne/Mg cores (e.g., 10.8-solar-mass model: Kitaura et al. 2005), powered by neutrino-driven wind, but underenergetic: ~10^{50} ergs
- 11.2-solar-mass model of WHW (2002) might explode by the convective (2D) neutrino-driven mechanism (Buras et al. 2005b), aided by density cliff, but underenergetic: >10^{49} ergs (mantle binding?), other progenitors very problematic (fizzle, but 3D??)
- Accretion-Induced Collapse (AIC): neutrino-driven wind mechanism; underenergetic as well (Dessart et al. 2006)
- Pulsar birth spins are low, making rotational, MHD jet mechanisms unlikely in the generic case, but hypernovae and GRBs (<1% of core collapses)
- What is left?

Key Ingredients of New Mechanism

- Neutrino-driven convection early on
- After ~200+ ms, another instability is manifest (Advective-Acoustic Instability/SASI?/Foglizzo/Blondin)
- Nested/secondary shock wave is generated during vigorous, large-scale oscillation: multiple shocks and shock interactions! Funnels accretion!
- Entropy grows due to cycles of shocking and neutrino heating
- Vigor/Mach-#/Entropy of inner turbulence increases
- An l=1 g-mode is excited by the accretion funnels and radiates sound!
- Sound waves generated in core power the supernova explosion: Acoustic power and momentum flux!

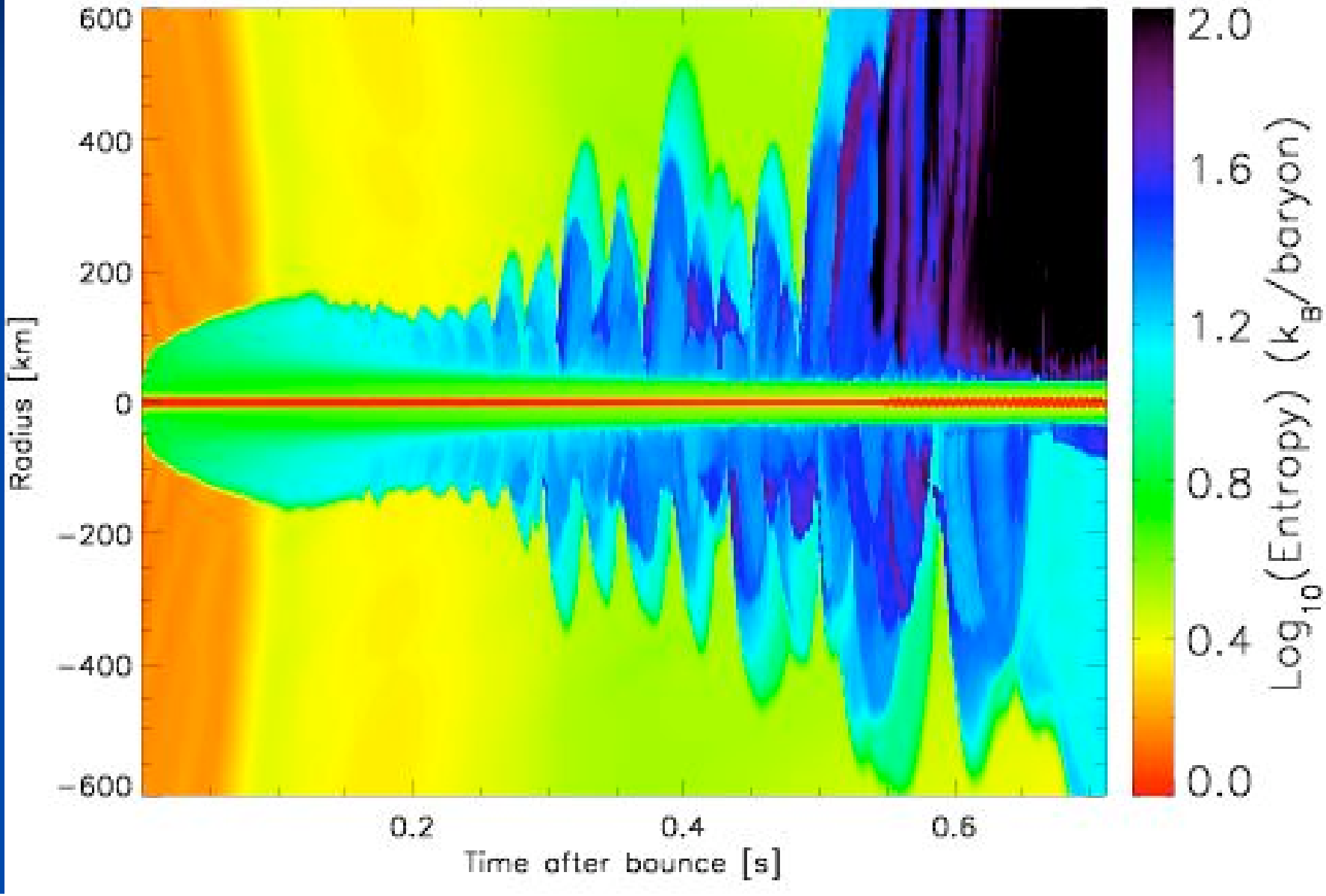
Key Ingredients of New Mechanism (cont.)

- Unlike neutrinos, Sound waves are almost completed "absorbed" by matter
- Sound pulses steepen into shock waves; transfer energy from inside to shock ("absorbed"), converting gravitational energy into mantle energy and momentum
- Explosion ensues late, after ~550+ ms (11-solar mass model)
- Progenitor mass dependence?? Large entropies generated acoustically: **r-process**
- Core is a transducer; self-excited oscillator; capacitor

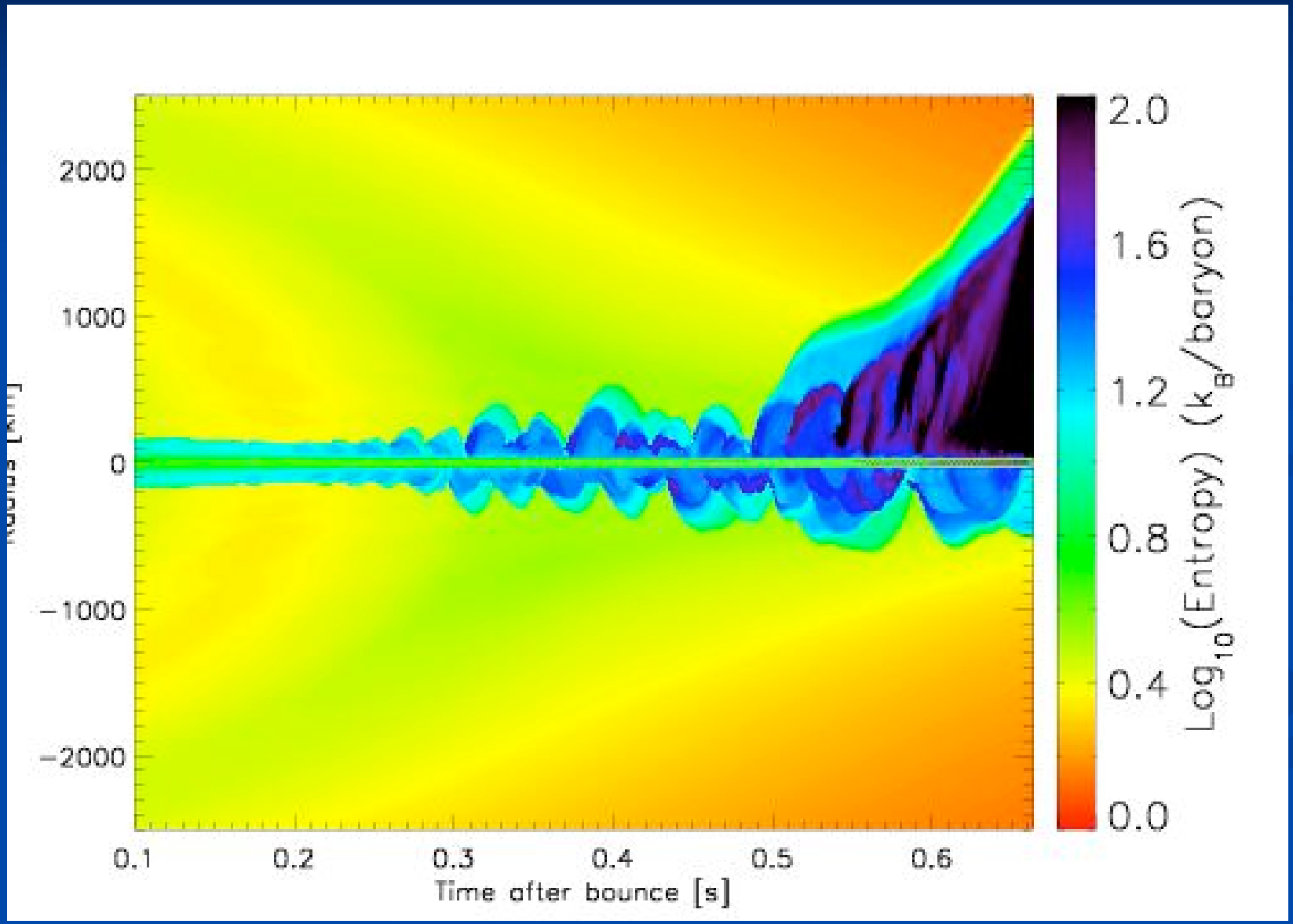
VULCAN/2D Multi-Group,Multi-Angle, Time-dependent Boltzmann/Hydro (6D)

- 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
- 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. (2005), Ott et al. (2005), submitted

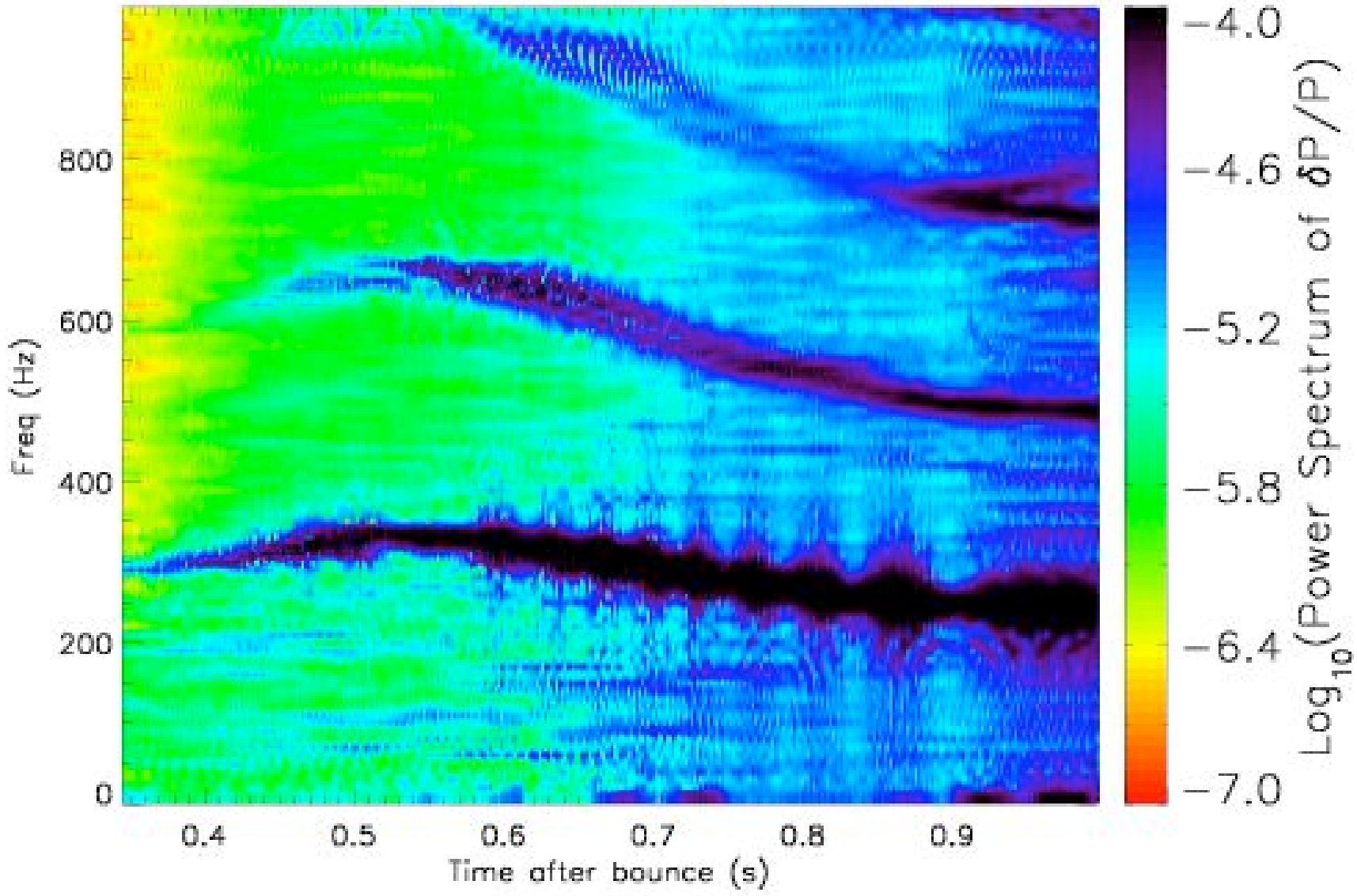
Inner 600-km Look at the Advective-Acoustic Instability



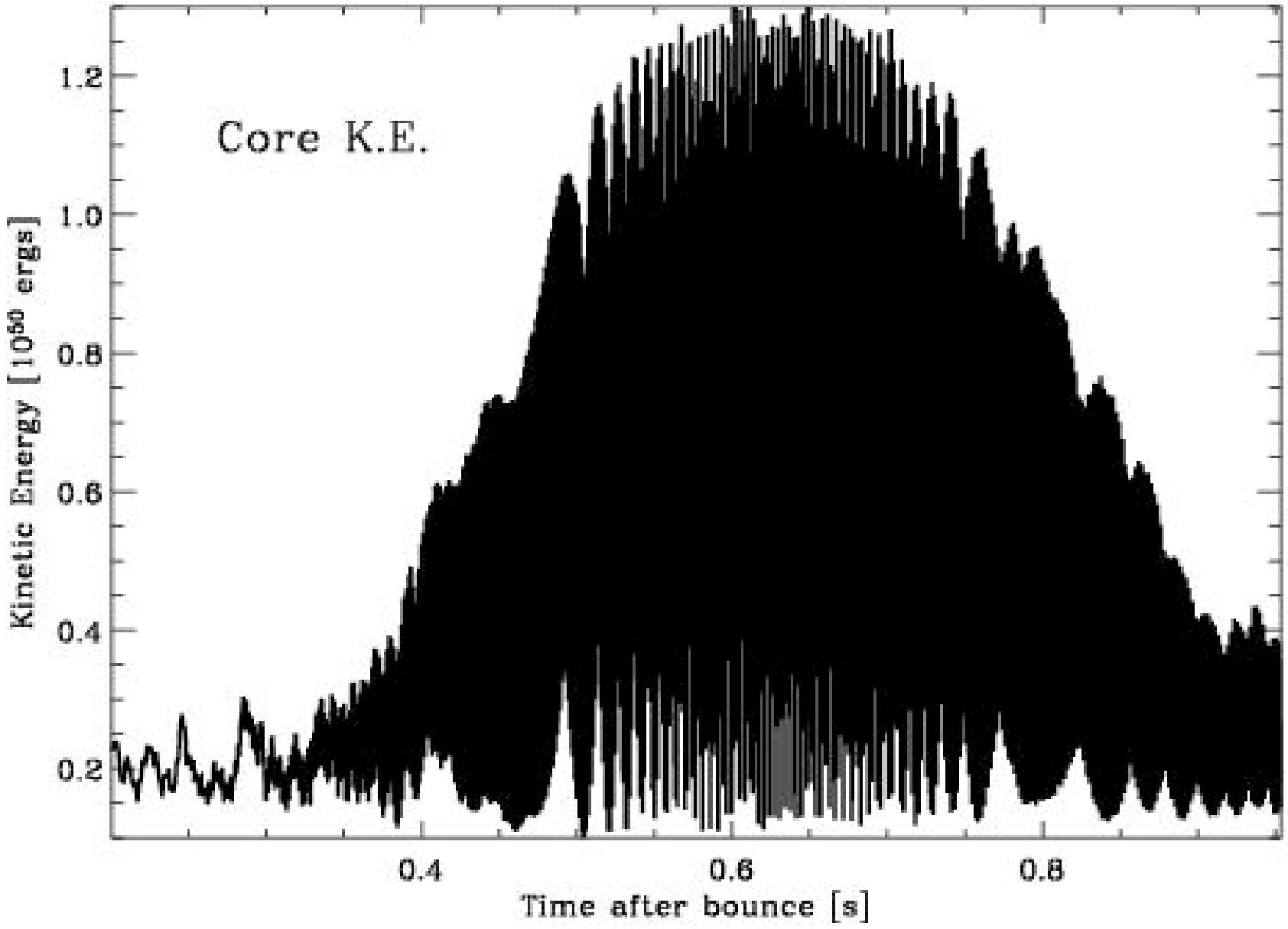
Entropy Profile along Pole versus Time after Bounce

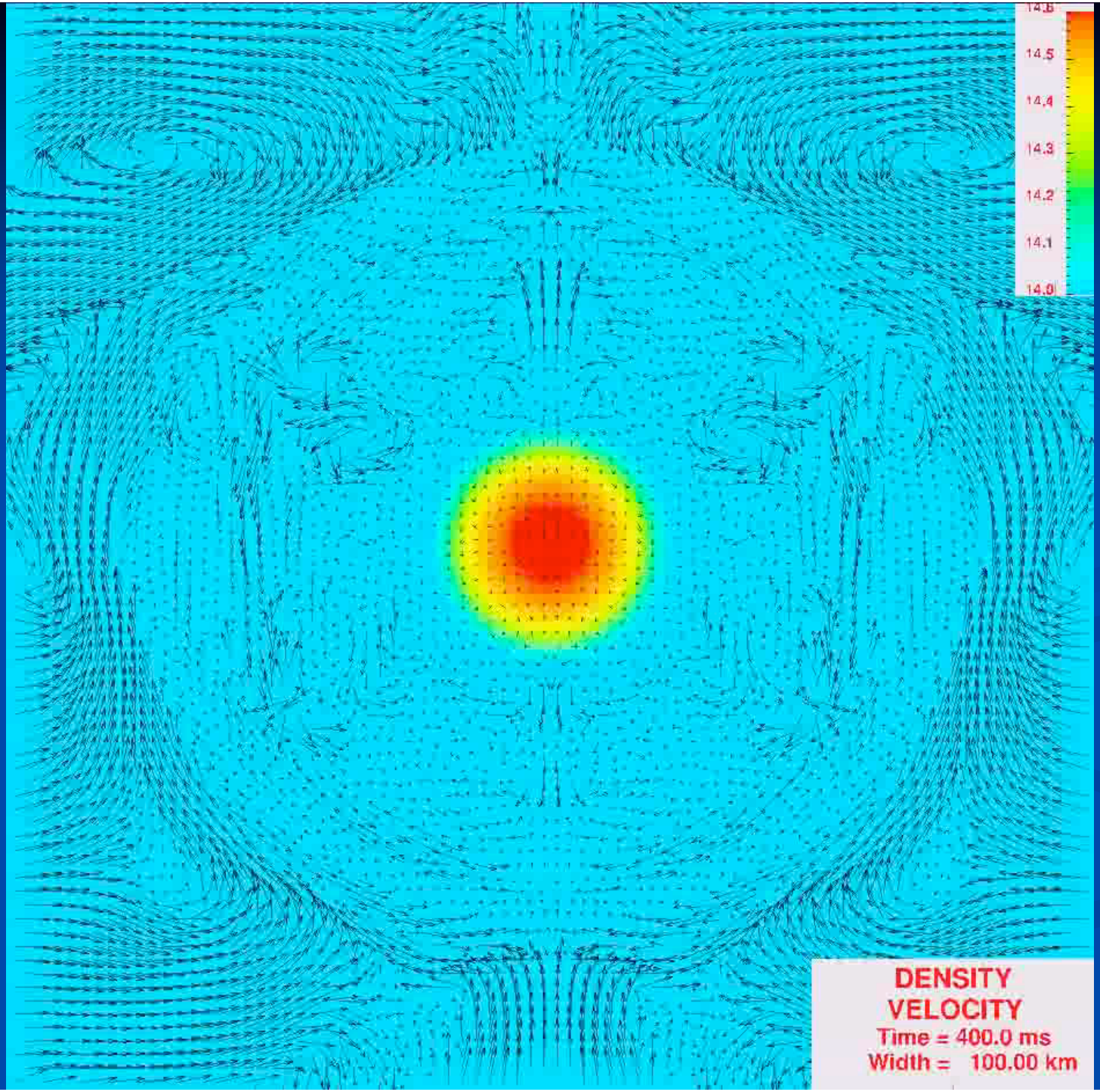


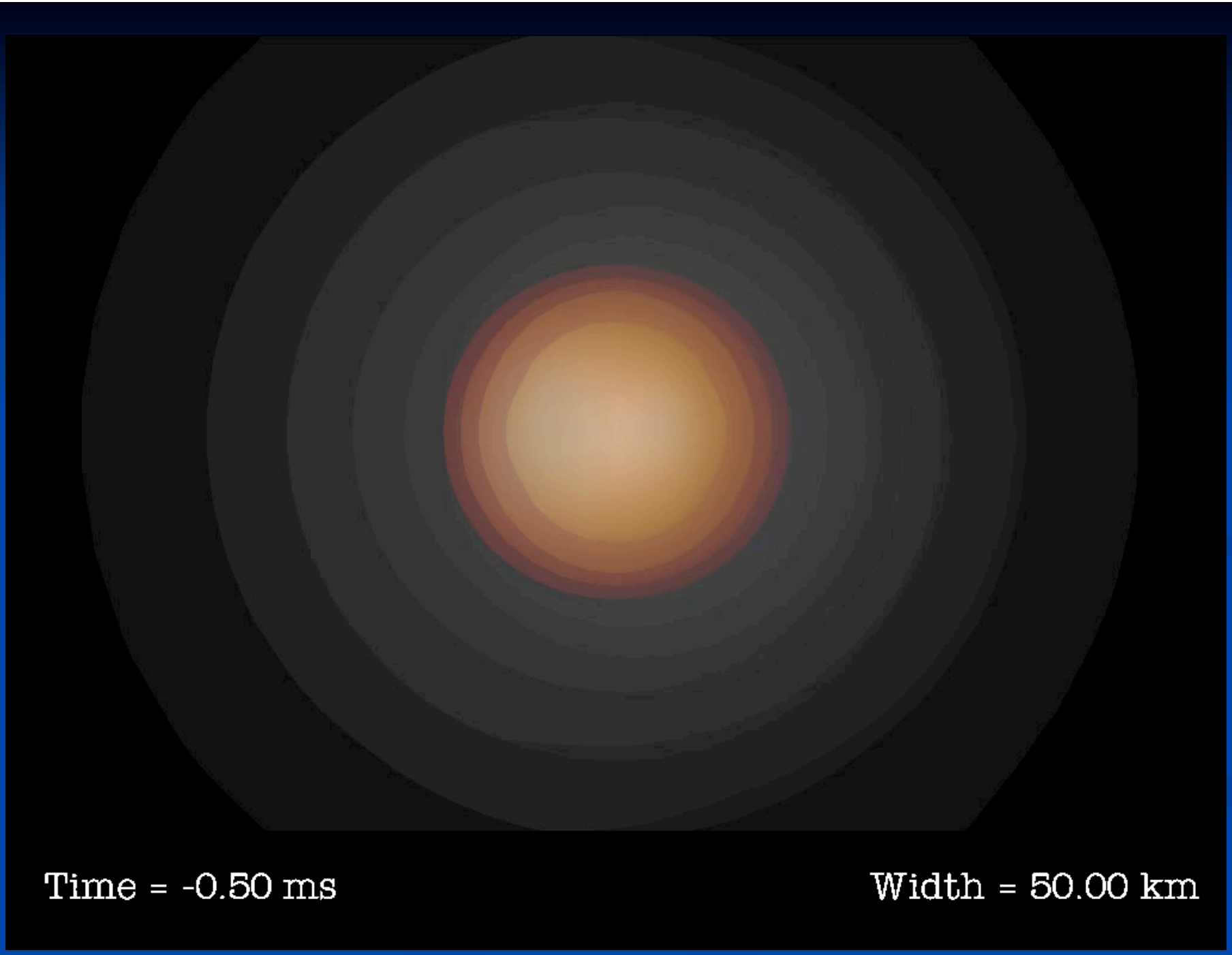
Frequency-Time Evolution of Pulsating Core at 30 km



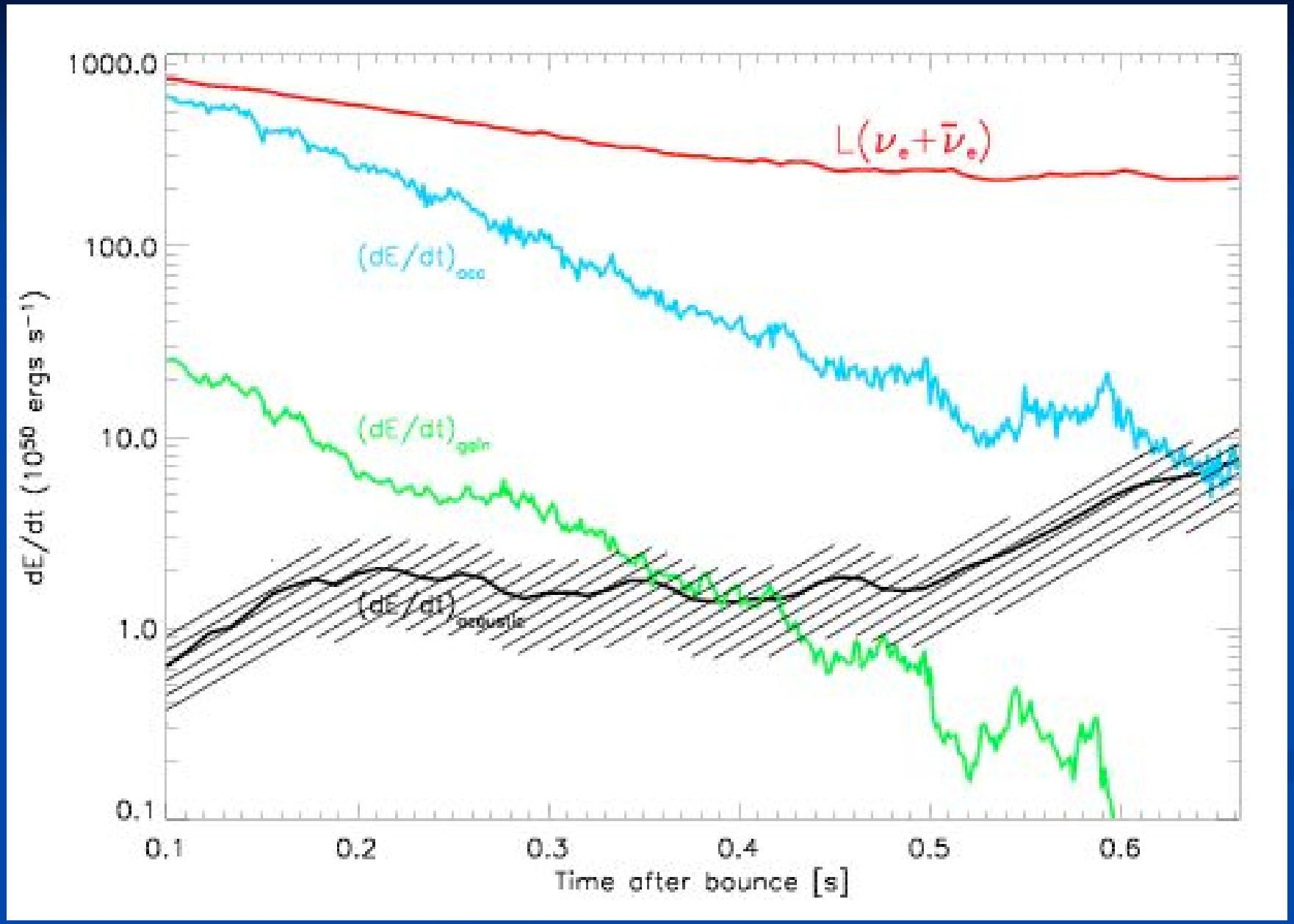
Evolution of Core Kinetic Energy: 11 solar-mass Progenitor

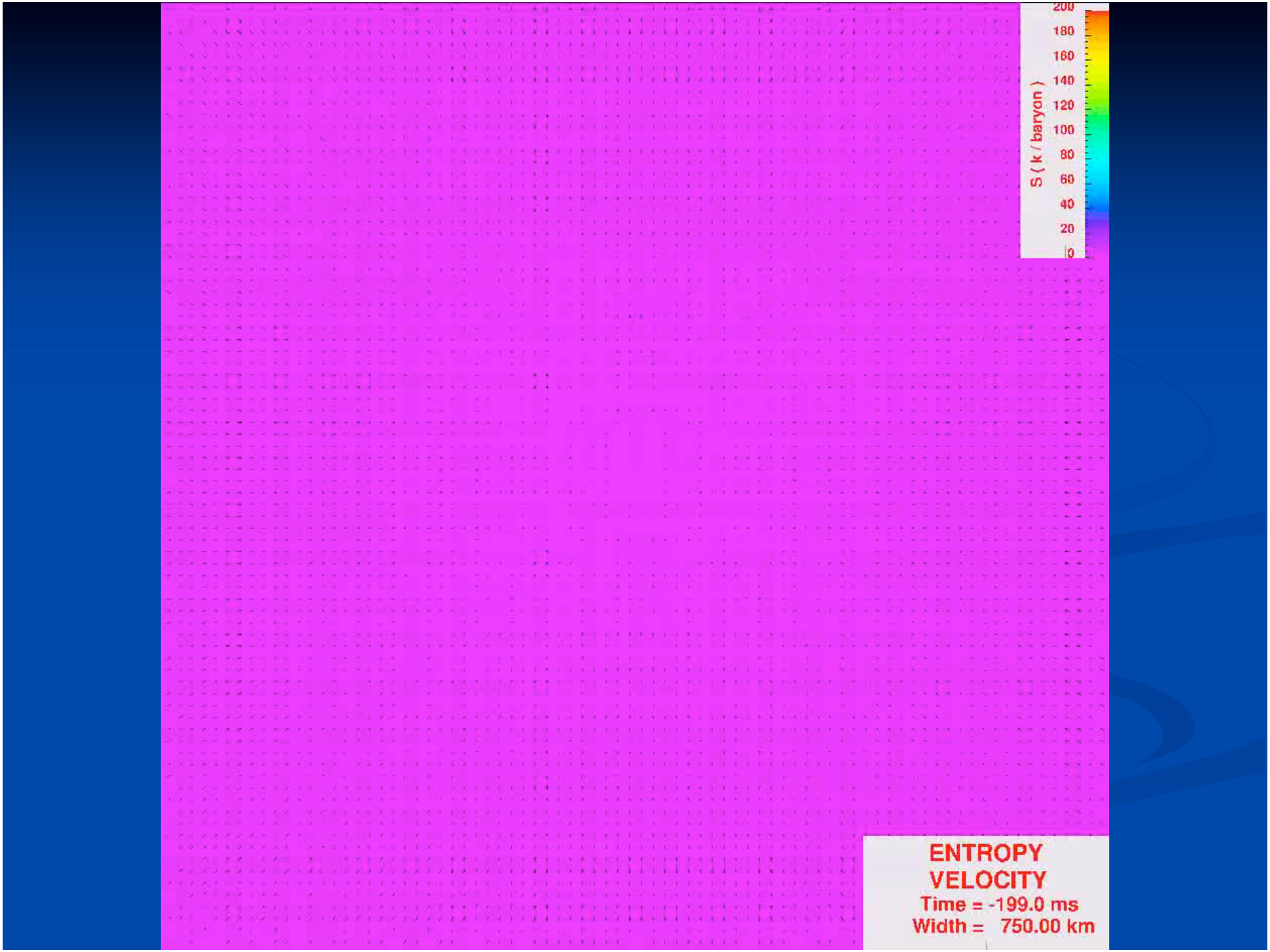



14.5
14.4
14.3
14.2
14.1
14.0
DENSITY
VELOCITY
Time = 400.0 ms
Width = 100.00 km

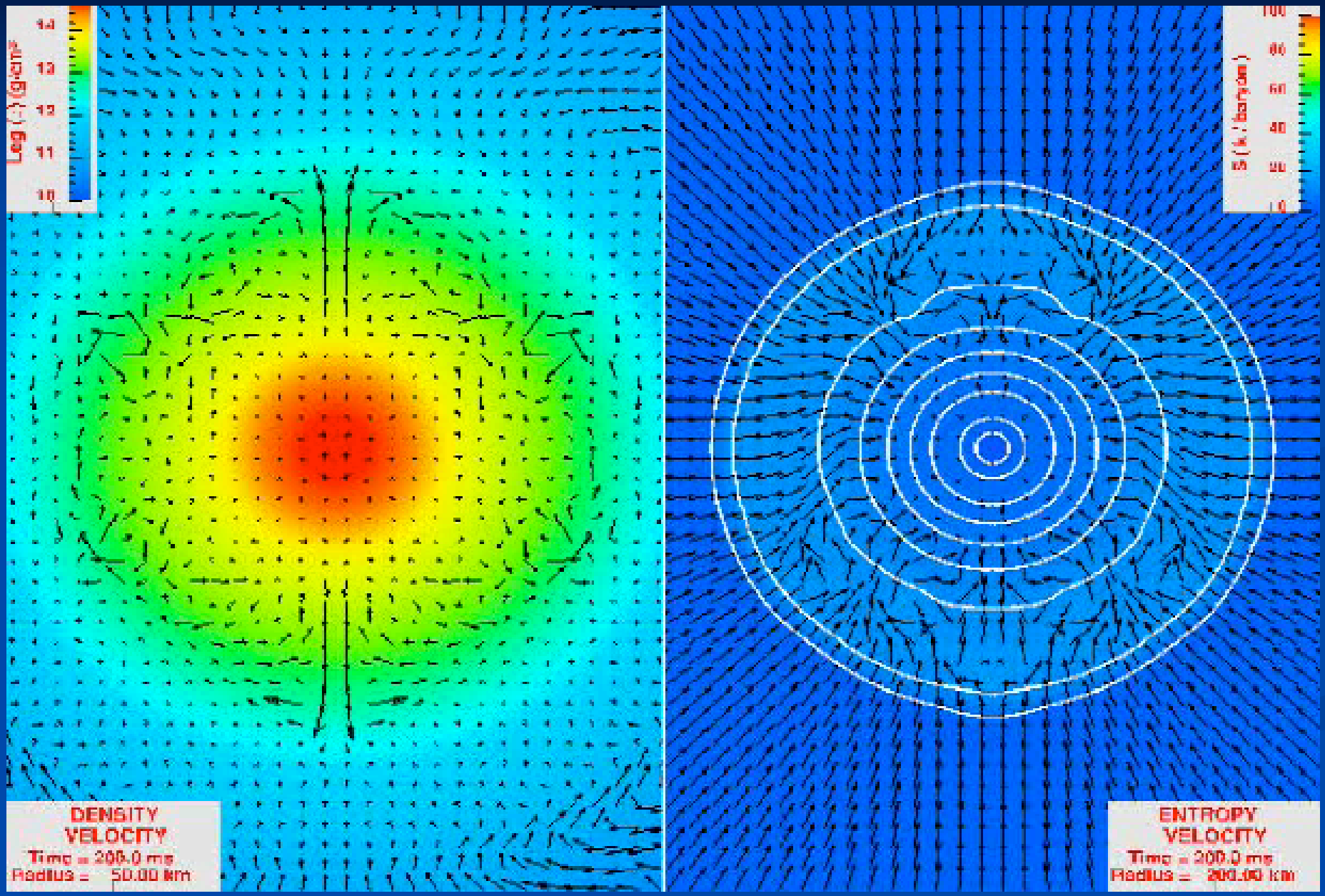

Time = -0.50 ms
Width = 50.00 km

Power Comparisons: 11 Solar-Mass model




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

25 Solar Mass Progenitor: Core Oscillation and Shock Evolution



Why was this Mechanism missed before?

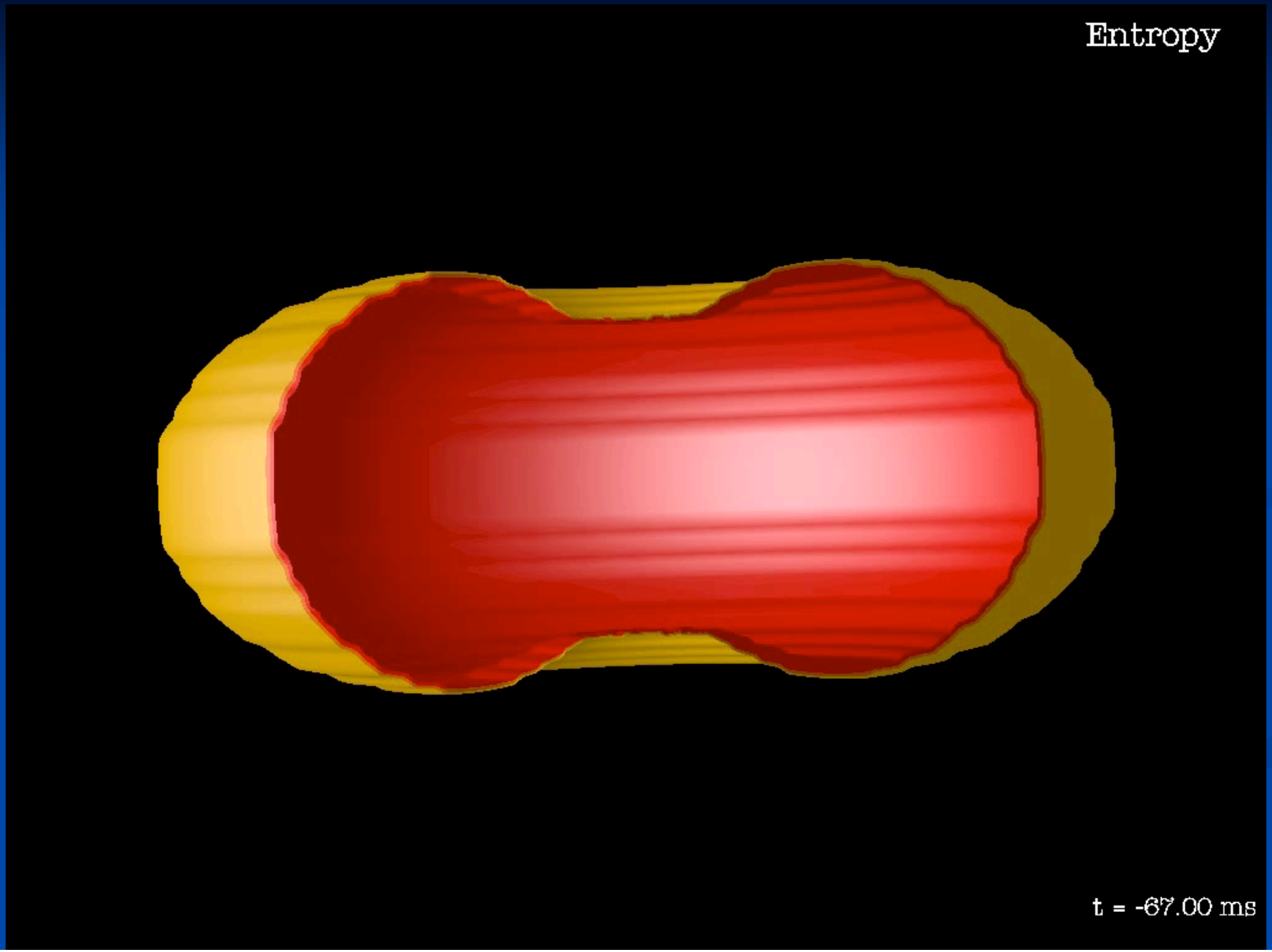
- Most calculations were stopped after 200-300 ms
- Other grid-based codes excised the core, did the calculations on a 90^{o} wedge, or followed the core in 1D, completely suppressing core oscillations
- One key was the computational liberation of the core to execute its natural multi-dimensional motions
- 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): VULCAN/2D is unique in all these features

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

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

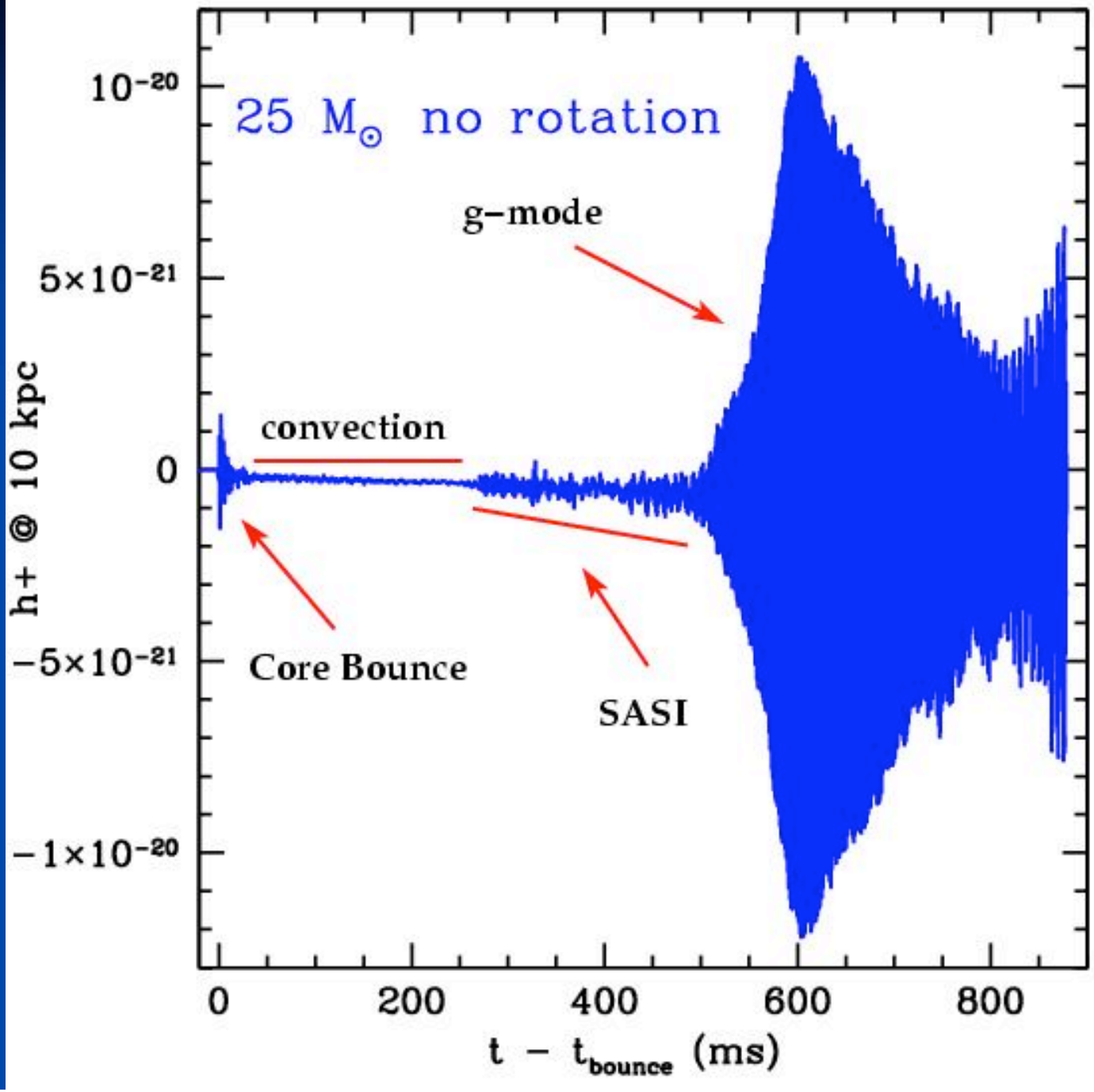
Rapid Rotation!

AIC: 1.92 solar masses:



Gravitational Radiation from Supernovae

Ott et al. (2005)

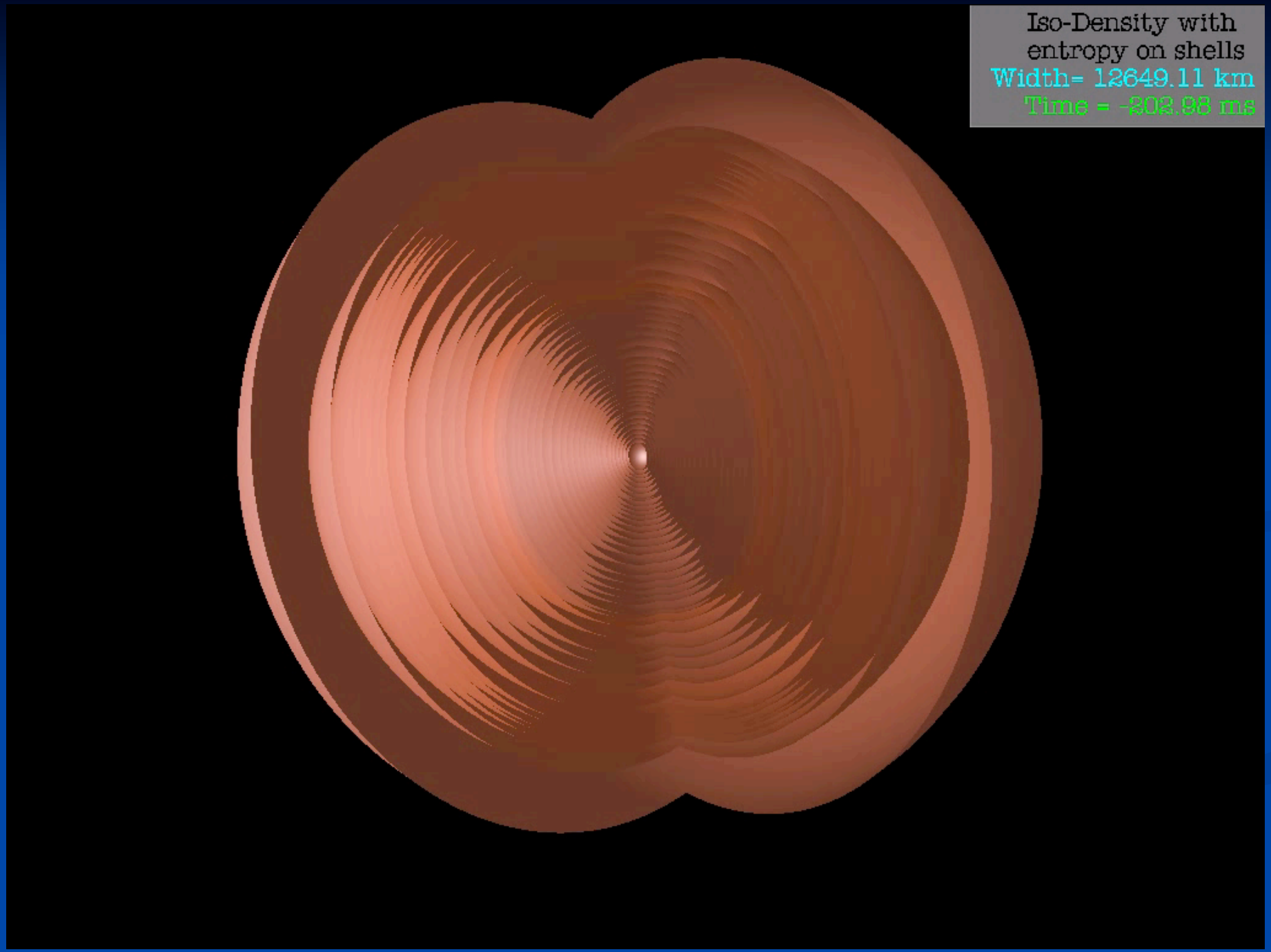

25 M⊙ no rotation
g–mode
convection
Core Bounce
SASI
h+ @ 10 kpc
10⁻²⁰
5×10⁻²¹
0
−5×10⁻²¹
−1×10⁻²⁰
0
200
400
600
800
t − t_bounce (ms)

Summary of Salient Features of New Mechanism

- Neutrino-driven convection starts early; Neutrino mechanism inadequate?
- Delayed onset of Advective-Acoustic/SASI Instability
- Nested/multiple shock waves; Entropy grows due to cycles of shocking and neutrino heating: Sets the Stage, but SASI not the agency of explosion
- Core l=1 g-modes are excited by turbulence and funnel accretion, which persists
- Core Oscillation radiates acoustic power (damping mechanism)
- Acoustic radiation by core oscillation deposited in matter exceeds neutrino heating after ~350-400 ms

Summary of Salient Features of New Mechanism (cont.)

- Excitation by funnel accretion continues as long as it is needed to explode mantle
- A natural means by which the supernova explosion is self-regulating
- Explosion driven by Acoustic power radiated by Core Oscillations
- Sound pulses steepen into multiple, nested shock waves; r-process entropies possible
- Unipolar explosion ("early"): simultaneous explosion and accretion; symmetry breaking
- Self-excitation of core oscillation; core is transducer, storage battery
- Much left to do, verify, falsify, and test (!)

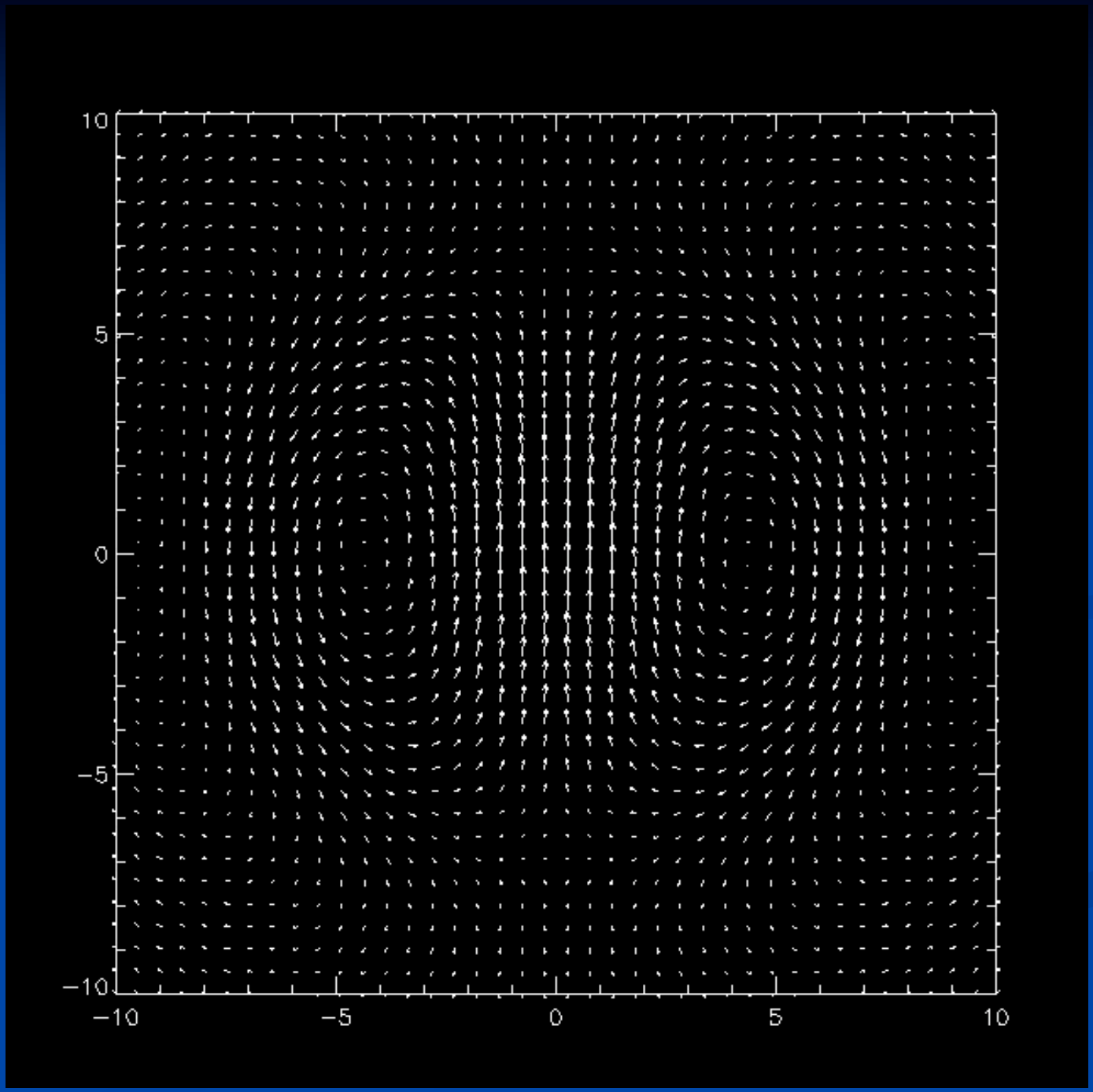

Iso-Density with
entropy on shells
Width= 12649.11 km
Time = -202.98 ms

Core-Collapse Supernovae: The Future

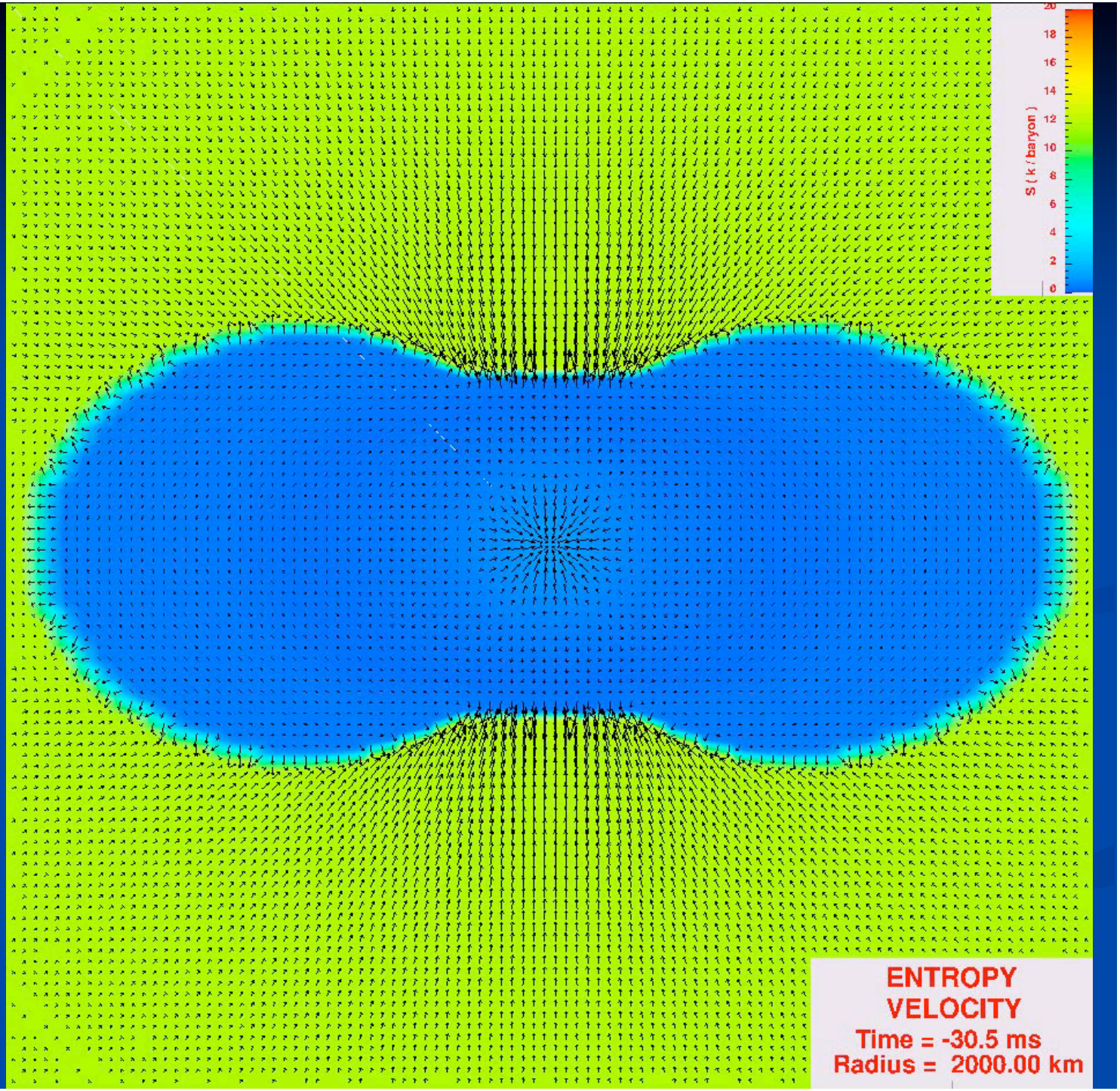
- Sound wave generation and propagation: new way of transferring energy and momentum from core to shock
- Instabilities and Convection are generic: Neutrino-driven, Advective/Acoustic-SASI
- High Entropies possible (r-process)
- Multi-D radiation hydrodynamics
- Is there an important role for Rotation?
- Is there a role for Magnetic fields? Pulsar fields?
- Viscosity? viscous heating and angular momentum transport
- Equation of state?
- Neutrino rates?
- Systematics with progenitor: kicks, r-process, SN energy, BH of observables/diagnostics?
- GRB/hypernova/SN connections!

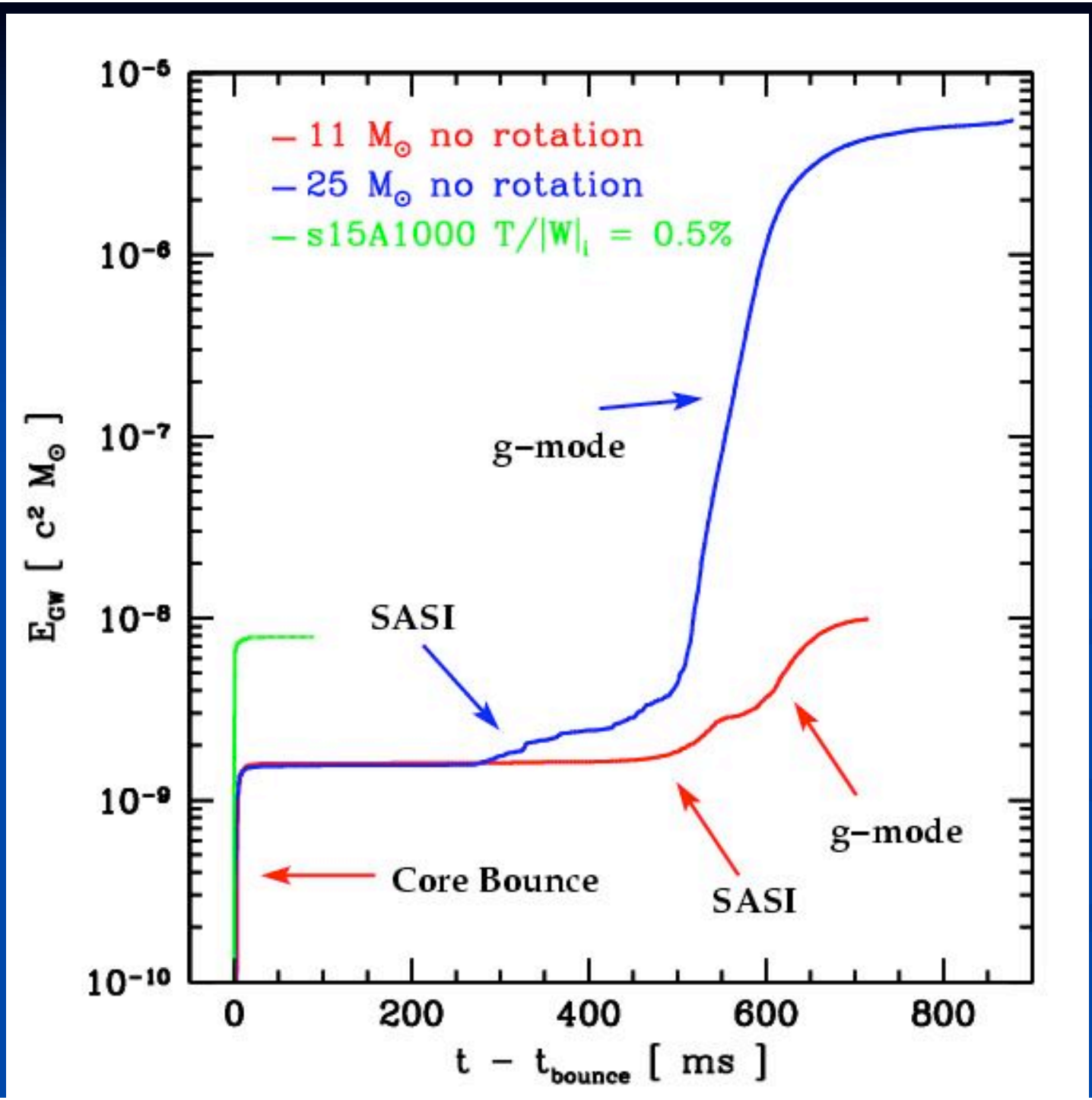
Analytic l=1

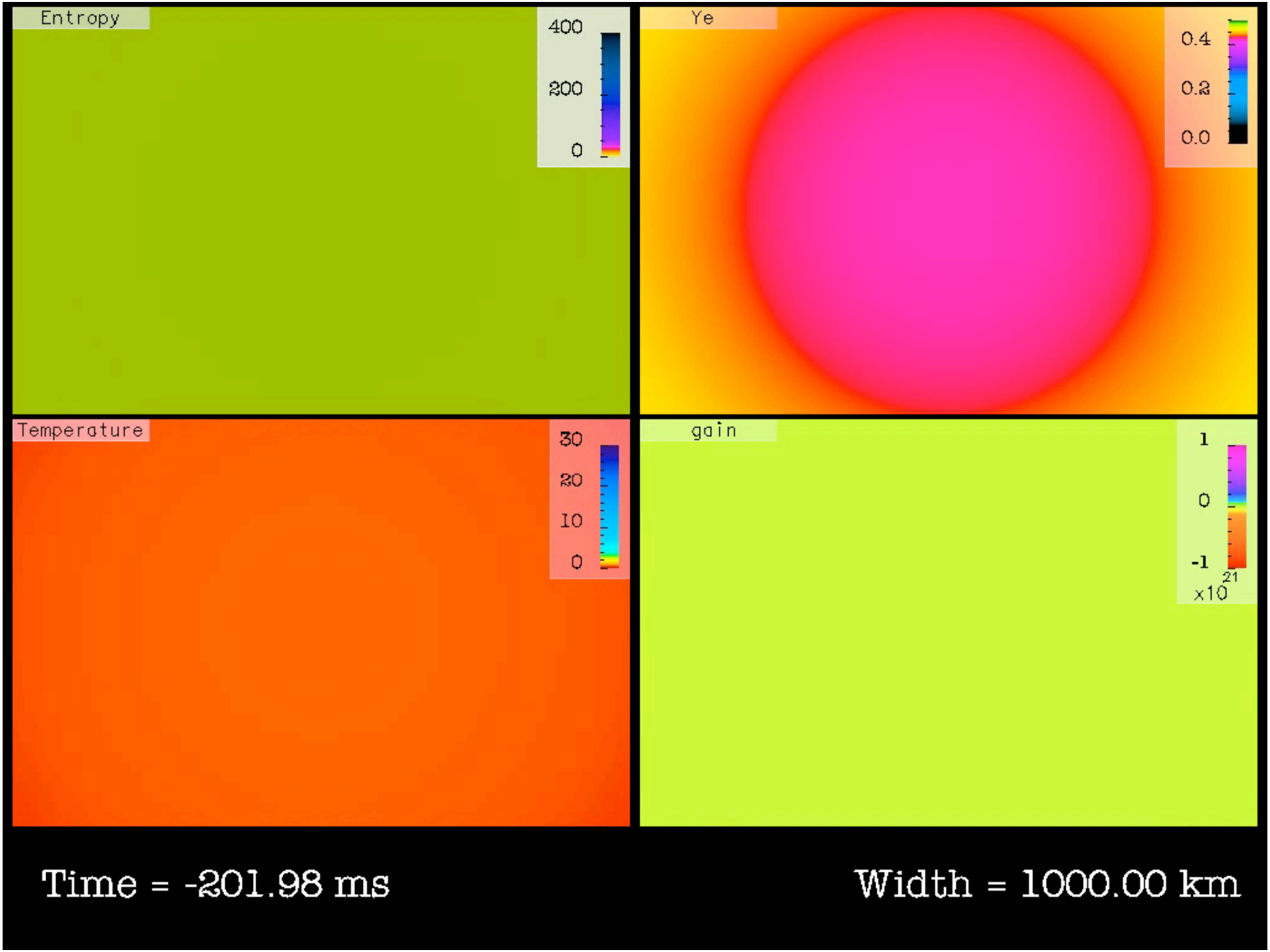
g-mode oscillation:



AIC: 1.92 solar masses:
Entropy




– 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


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