Supernovae

Tomek Plewa

ASC Flash Center, University of Chicago

Konstantinos Kifonidis, Leonhard Scheck,
H.-Thomas Janka, Ewald Müller

MPA für Astrophysik, Garching

Outline

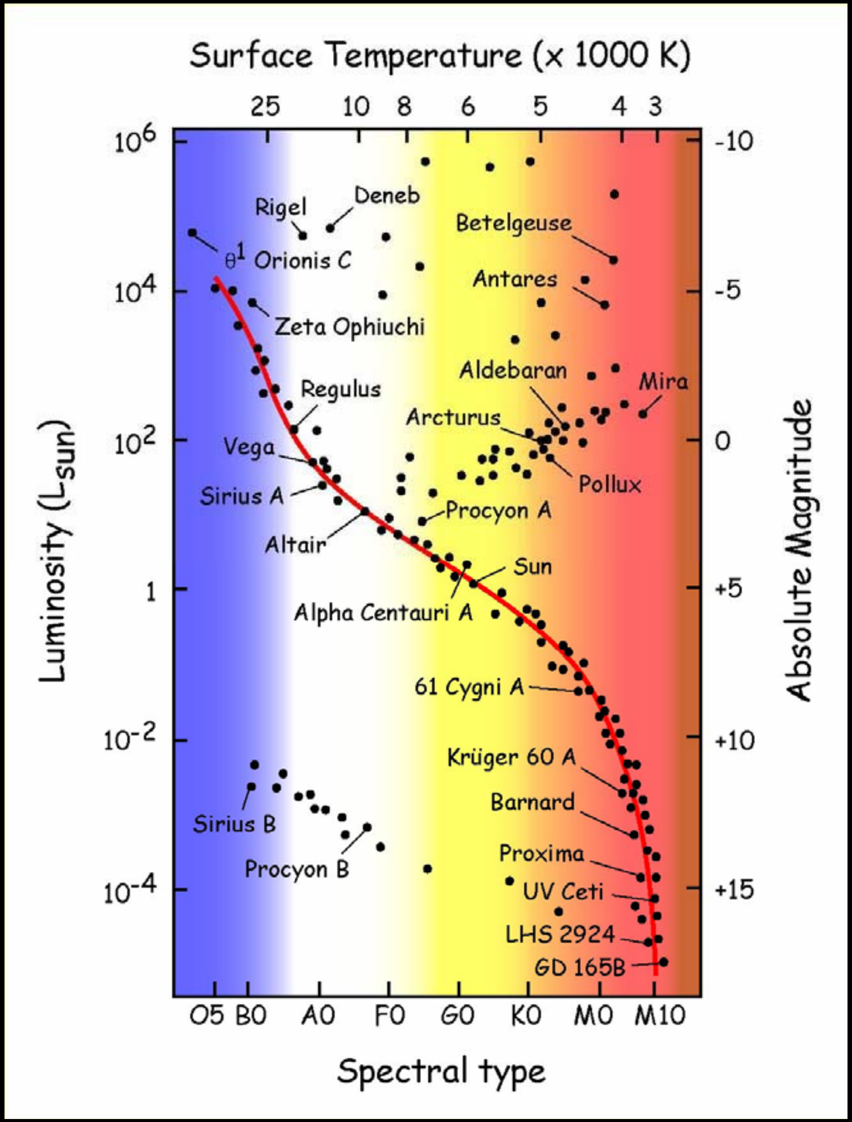
- Non-exotic neutrino-driven supernovae
- Rayleigh-Taylor mixing in normal Type II
- Hydrogen-free case of Type Ib
- Bits from the Labs
- Conclusions

- Non-exotic neutrino-driven supernovae
- Rayleigh-Taylor mixing in normal Type II
- Hydrogen-free case of Type Ib
- Bits from the Labs
- Conclusions

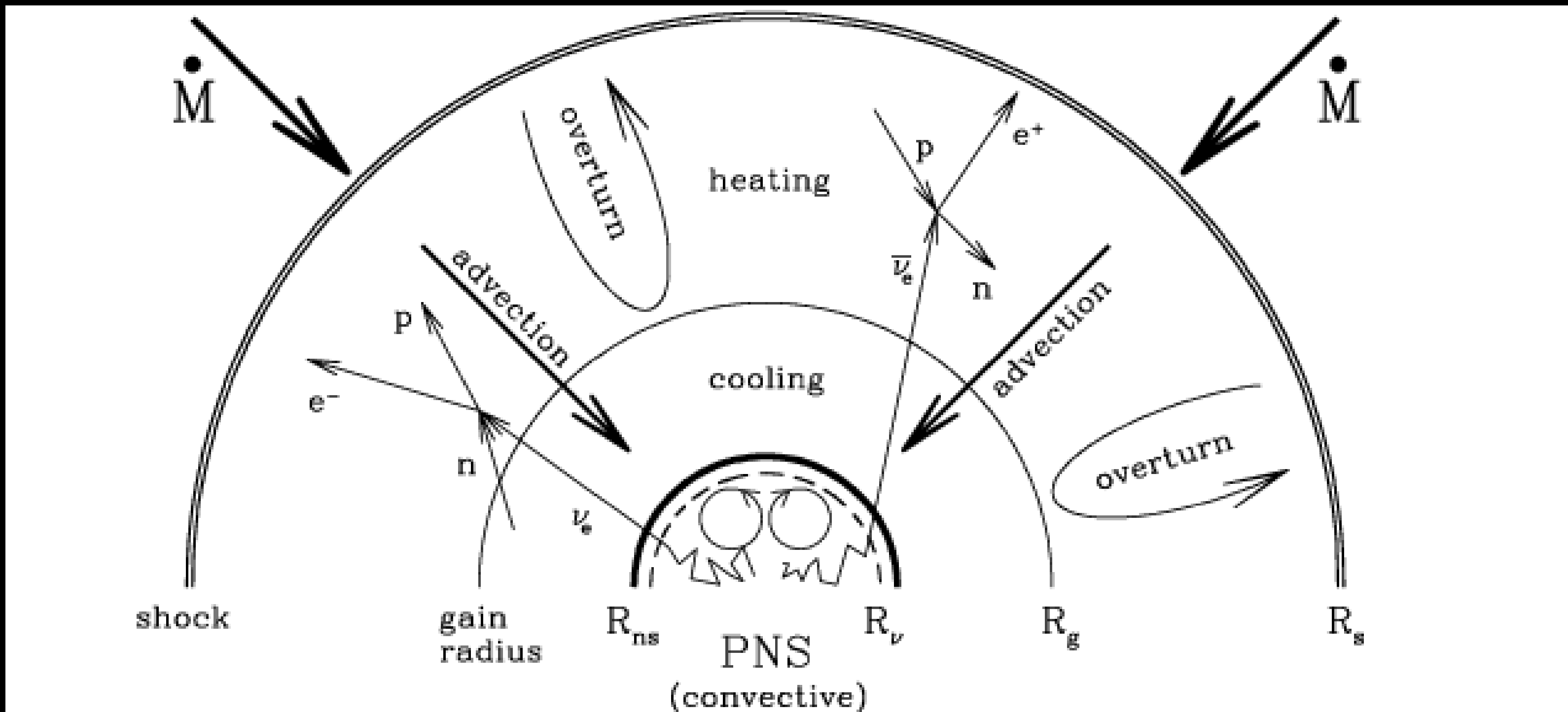
Introduction

- Most core collapse supernovae are *aspherical.*
- Evidence for *strong* ^{56}*Ni mixing*:
  light curves, emission line profiles, early detection of gamma rays in SN 1987A, ...
- Mixing is currently the only source of *detailed observational information* on explosion mechanism.
- *2D/3D hydrodynamic models* required to link theory to observations!

Starz!

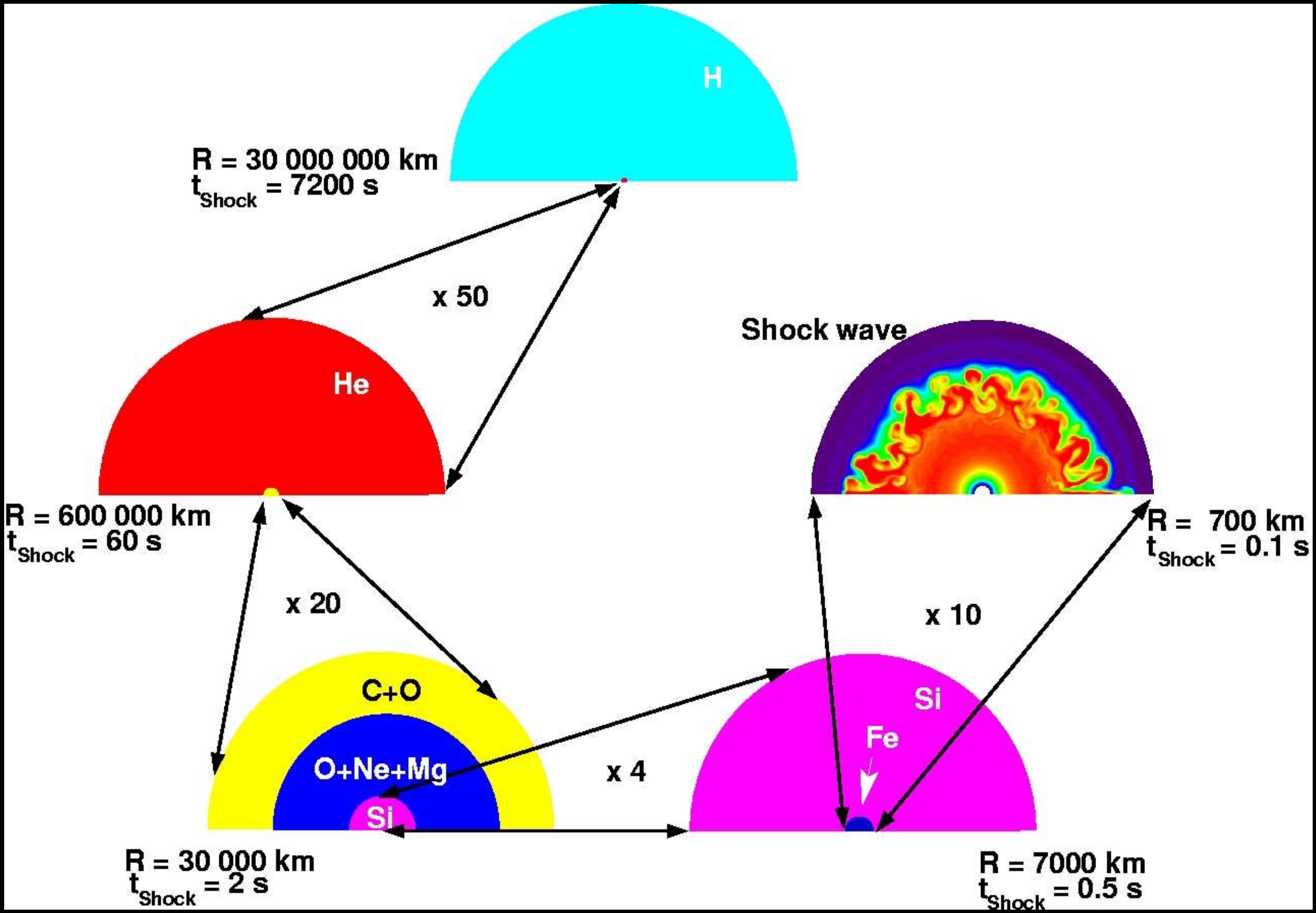

Surface Temperature (x 1000 K)
25 10 8 6 5 4 3
Luminosity (L_sun)
10^6
10^4
10^2
1
10^-2
10^-4
-10
-5
0
+5
+10
+15
Absolute Magnitude
Rigel
Deneb
Betelgeuse
θ1 Orionis C
Antares
Zeta Ophiuchi
Aldebaran
Mira
Regulus
Arcturus
Vega
Pollux
Sirius A
Procyon A
Altair
Sun
Alpha Centauri A
61 Cygni A
Krüger 60 A
Barnard
Sirius B
Proxima
Procyon B
UV Ceti
LHS 2924
GD 165B
O5 B0 A0 F0 G0 K0 M0 M10
Spectral type

The neutrino driven mechanism



Complex multidimensional flow with heating and cooling (Chandrasekhar, Herant, Foglizzo, plus lots of numerical simulations done in the US, Europe, and Japan). Possibly offers the most conservative hydrodynamic mechanism for kicks (requires high-quality hydrodynamic models).

Anatomy of an exploding star



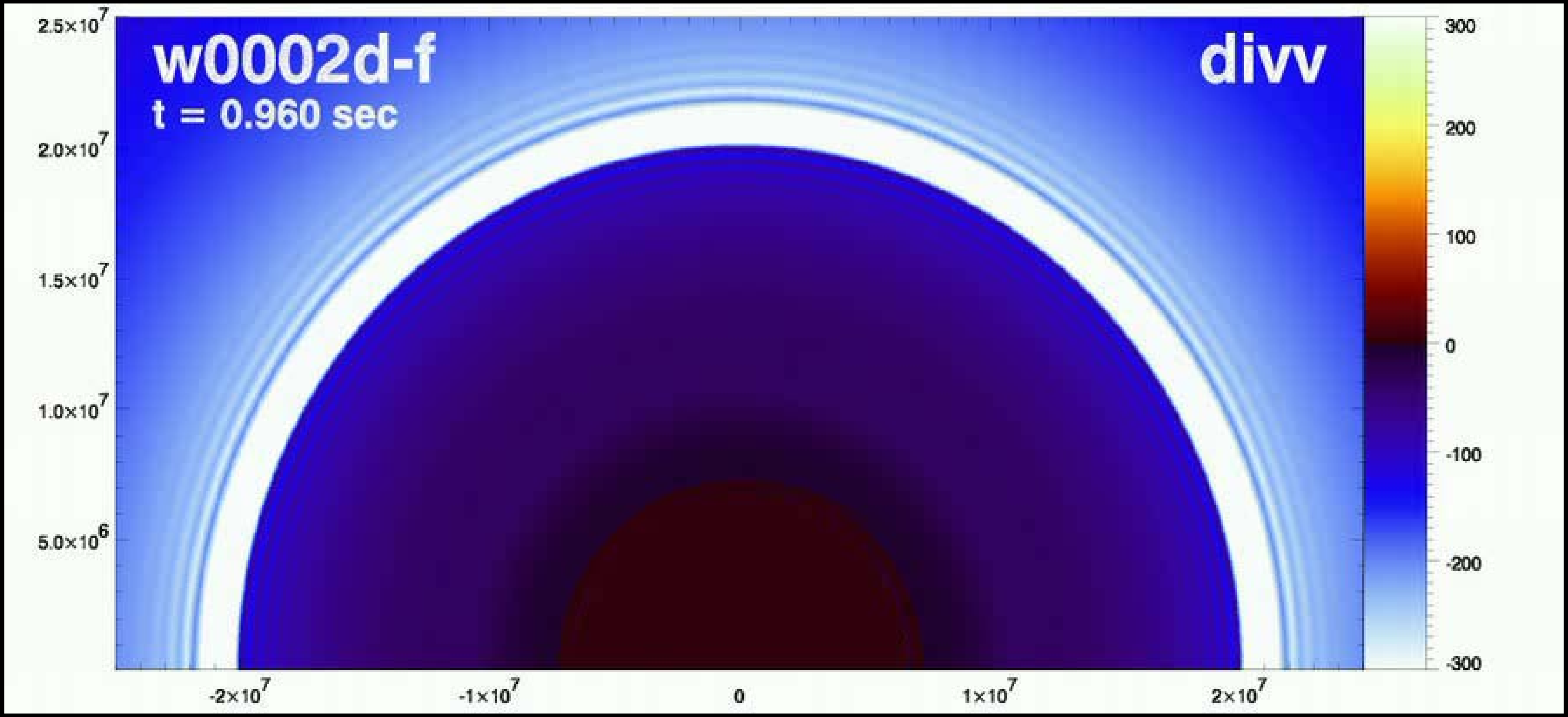
2D hydrodynamic models

- Progenitor: 15 Msol blue supergiant (WPE 88)
- Parameterized neutrino luminosities
  (inner boundary at neutrino sphere, no transport)
- PPM hydro solver + 14 isotope nuclear network
- Selfgravity
- Block Structured Adaptive Mesh Refinement

- Relatively simple, inexpensive physics
- 3072 (2 599 933 per R_*) x 768 zones, remapping

- Non-exotic neutrino-driven supernovae
- Rayleigh-Taylor mixing in normal Type II
  - Done before, why to redo it?
- Hydrogen-free case of Type Ib
- Bits from the Labs
- Conclusions

Neutrino-driven Convection



Entropy, evolution up to 1 s

Numerical sanity

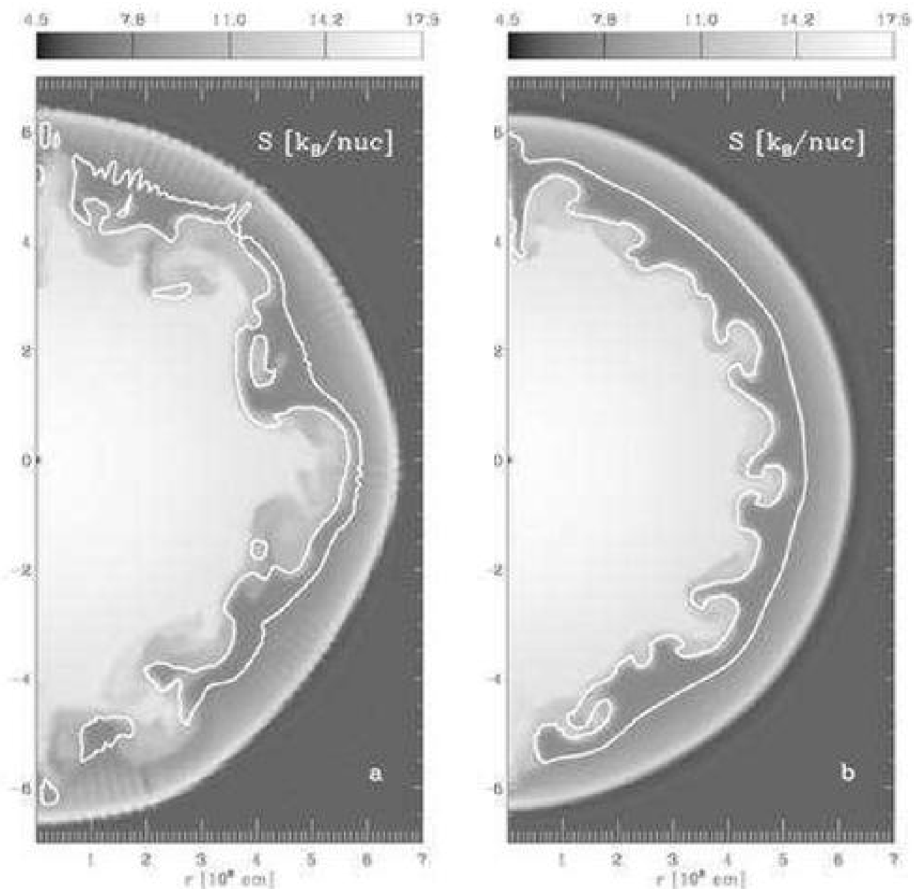
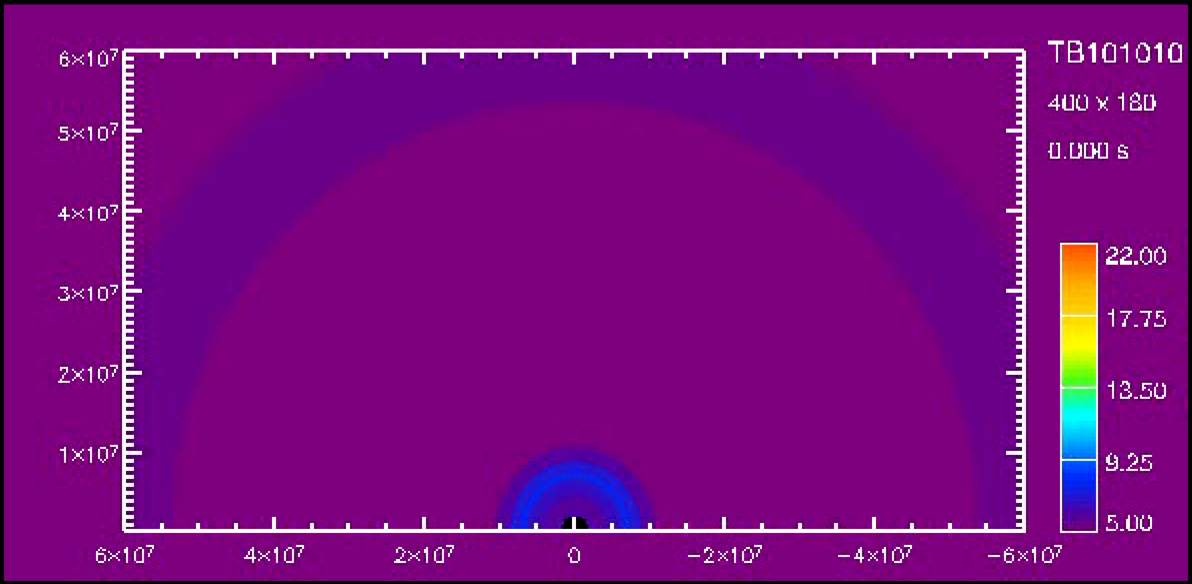


Fig. 1. Entropy (in units of k_B per nucleon) in Model T310 at a timeof 420 ms after core bounce. The white contour line encloses the region where the ^{56}Ni mass fraction is ≥ 20%. a) Calculationperformed with the original PROMETHEUS code showing odd-even decoupling. Note the deformation of the shock. b) Calculition performed with HERAKLES.

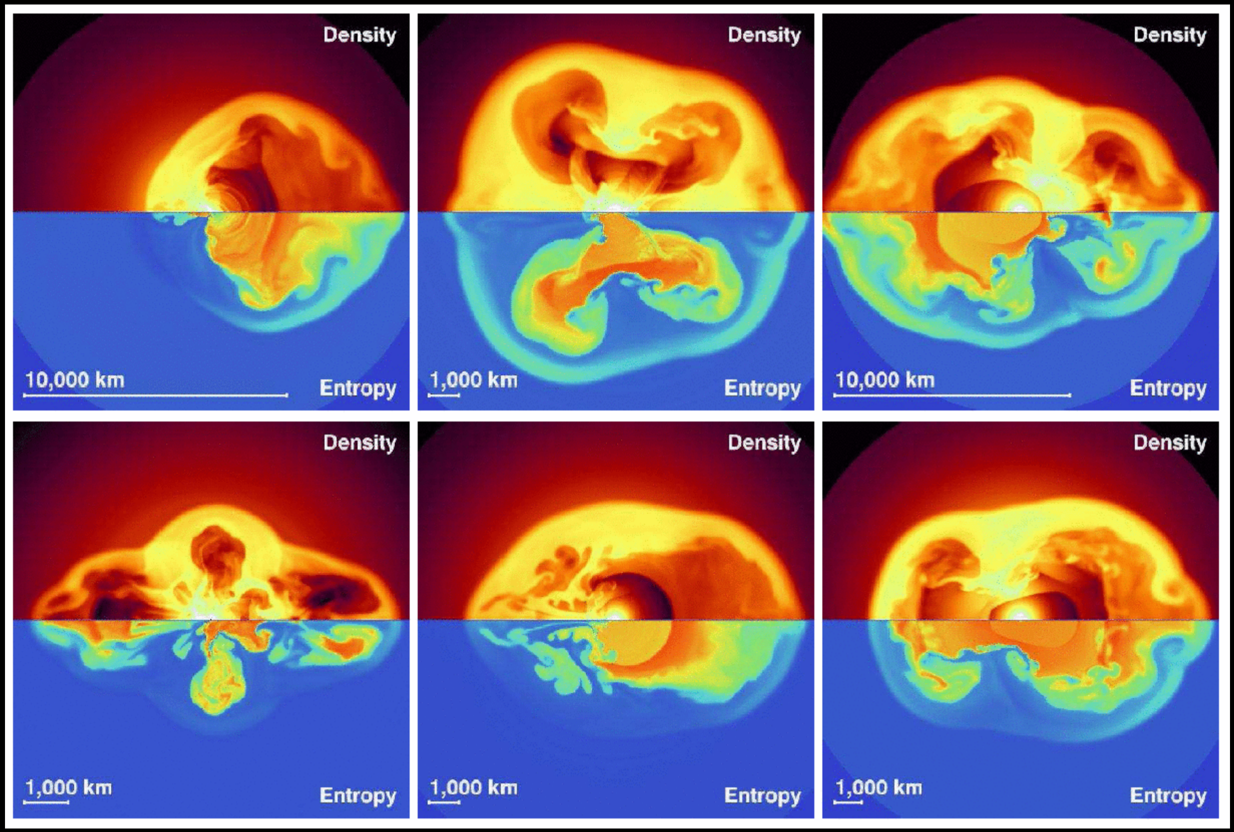
Naturally seeded RT phase.

Model assumptions



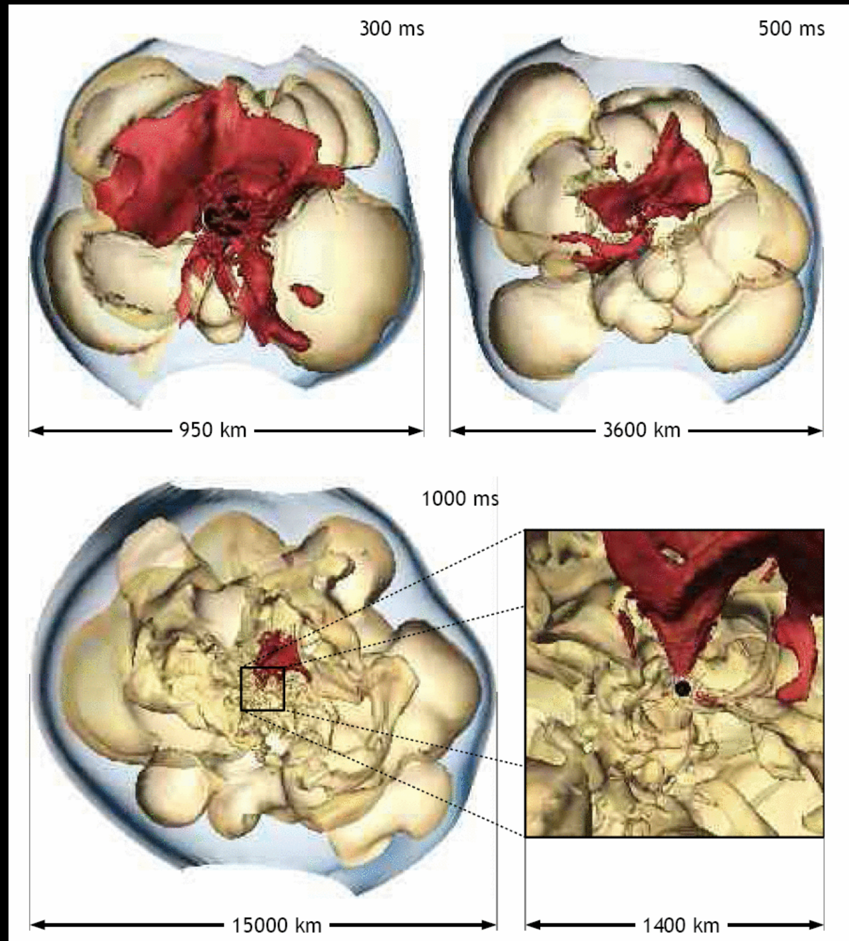
Same total core emission, longer timescale.

Long-term convection



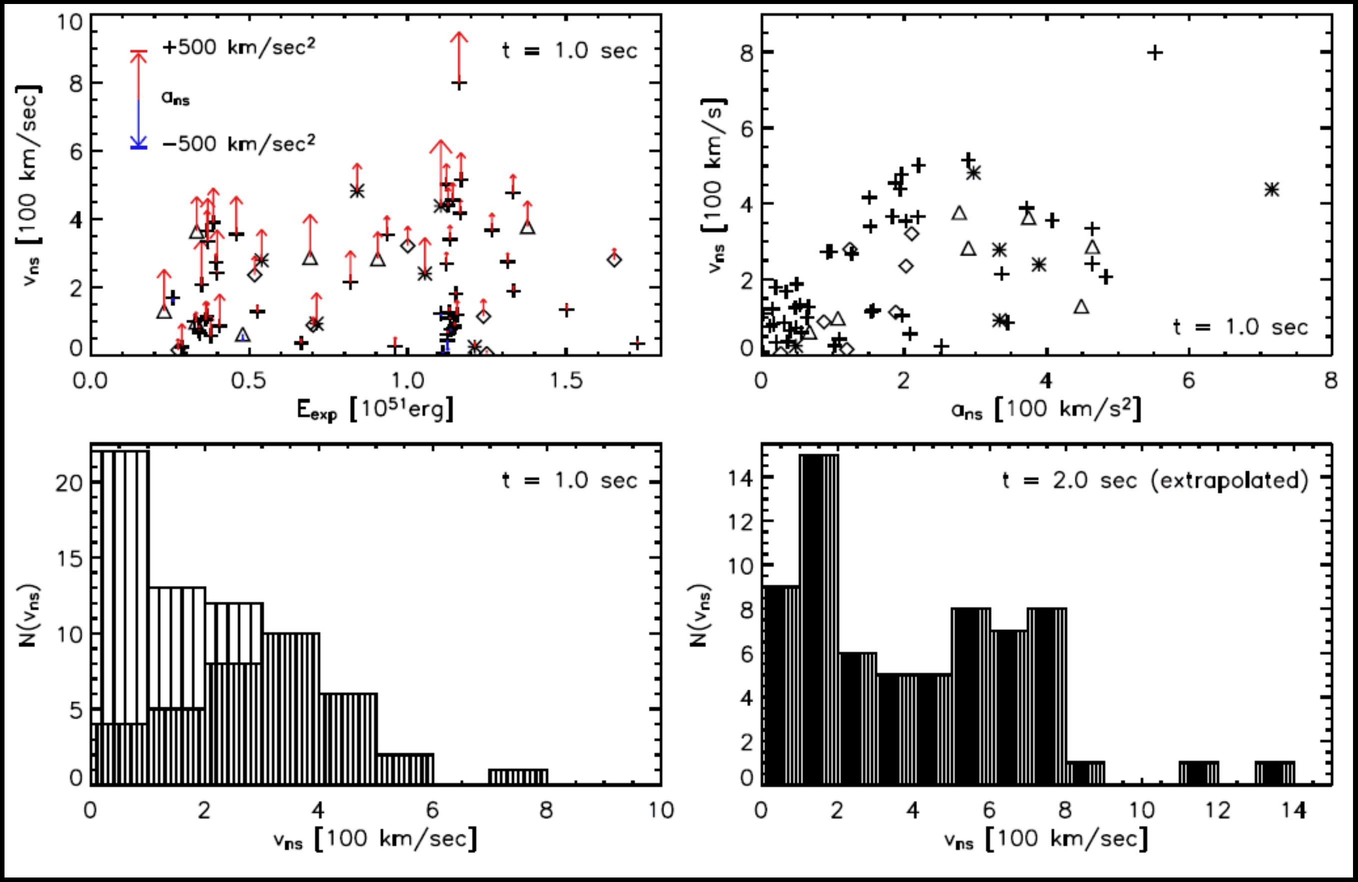
Short wavelength modes are filtered out; m=0,l=1 survives.

Long-term convection in 3D



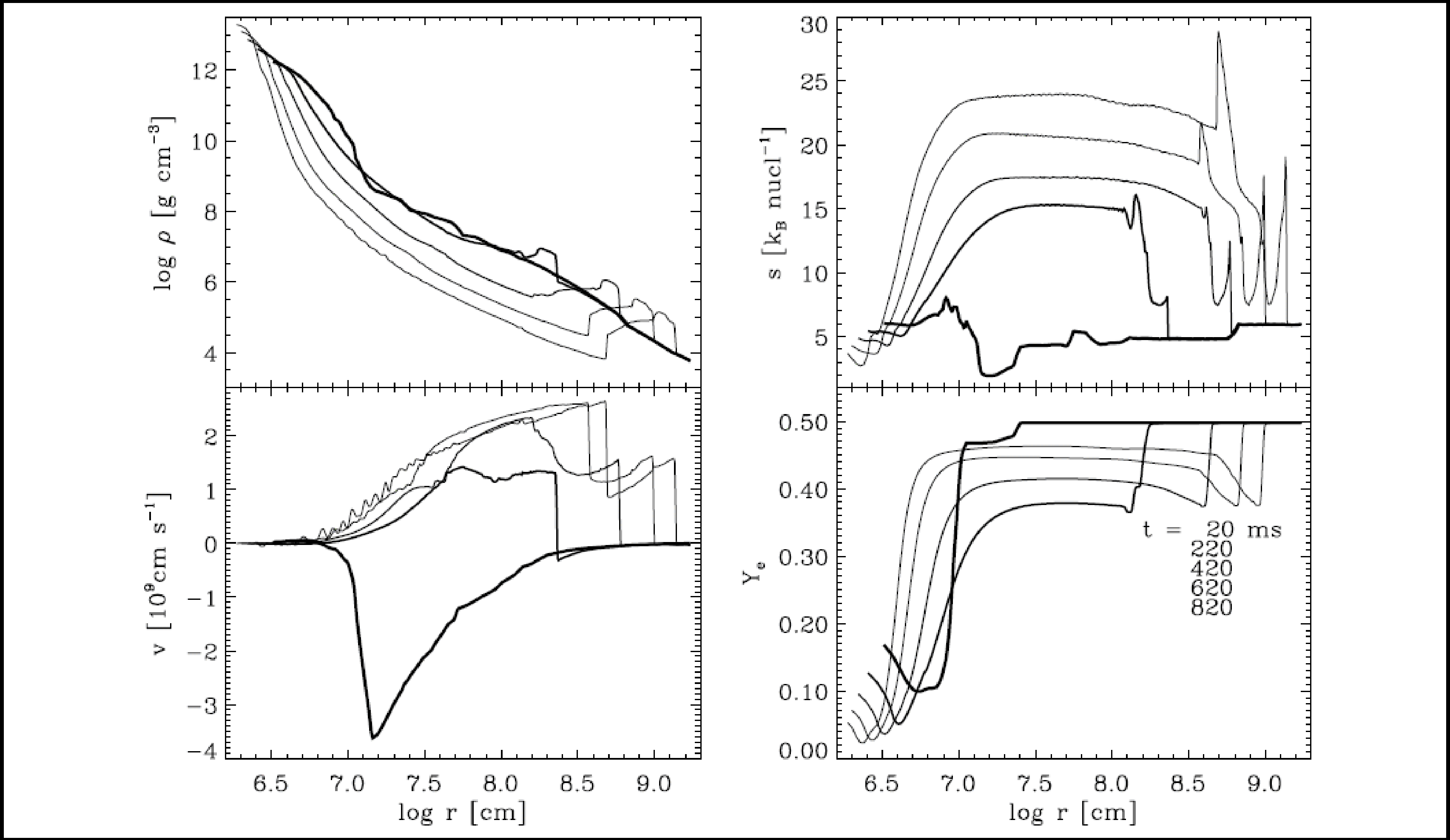
Confirms 2D results (but extremely expensive to obtain).

Pulsar kicks



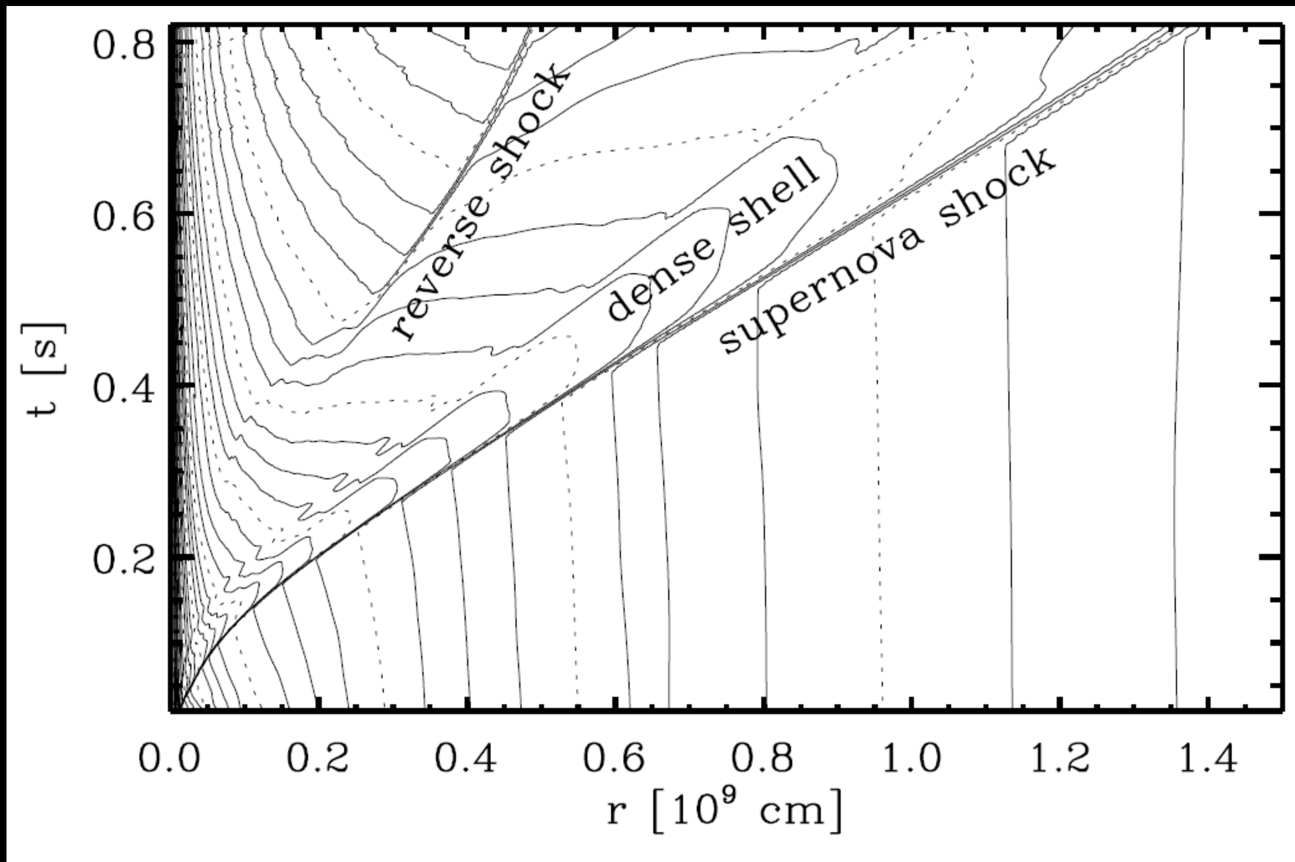
Observed bi-modal distribution and amplitudes recovered.

Post-bounce 1D evolution



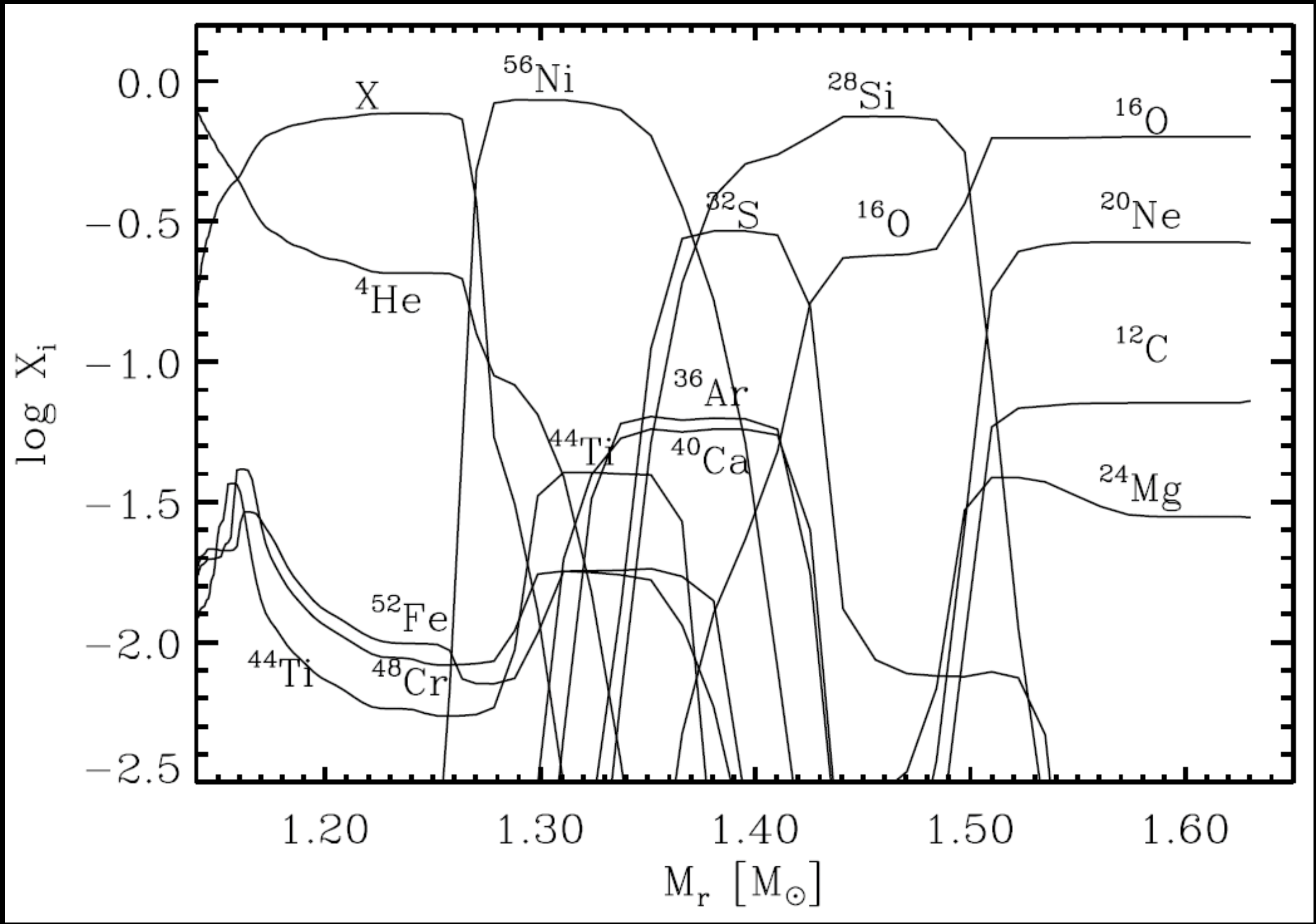
Shock revival after ~300 ms.

Basic 1D structure



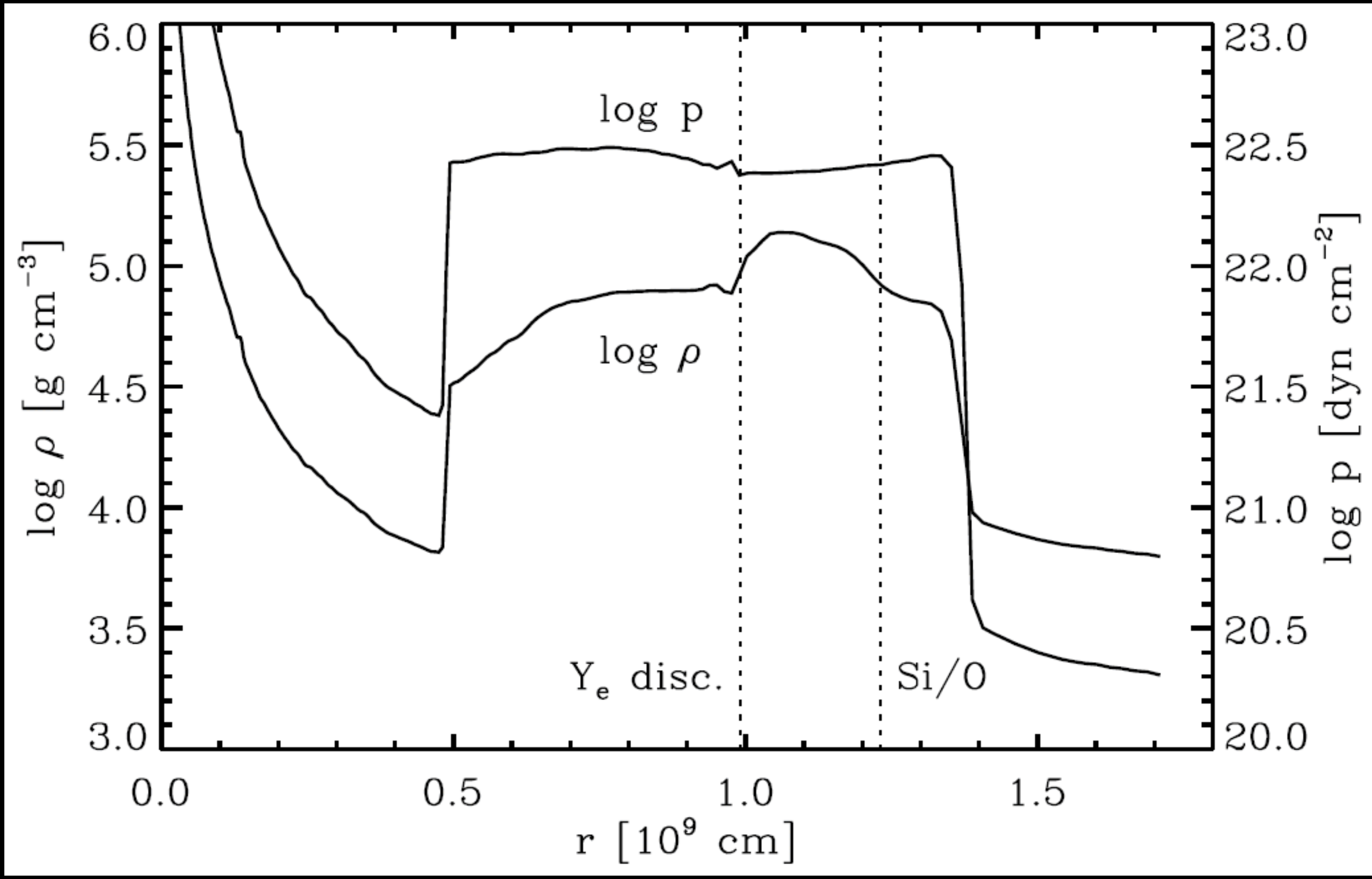
Reverse shock forms after ~300 ms.

Composition of 1D model



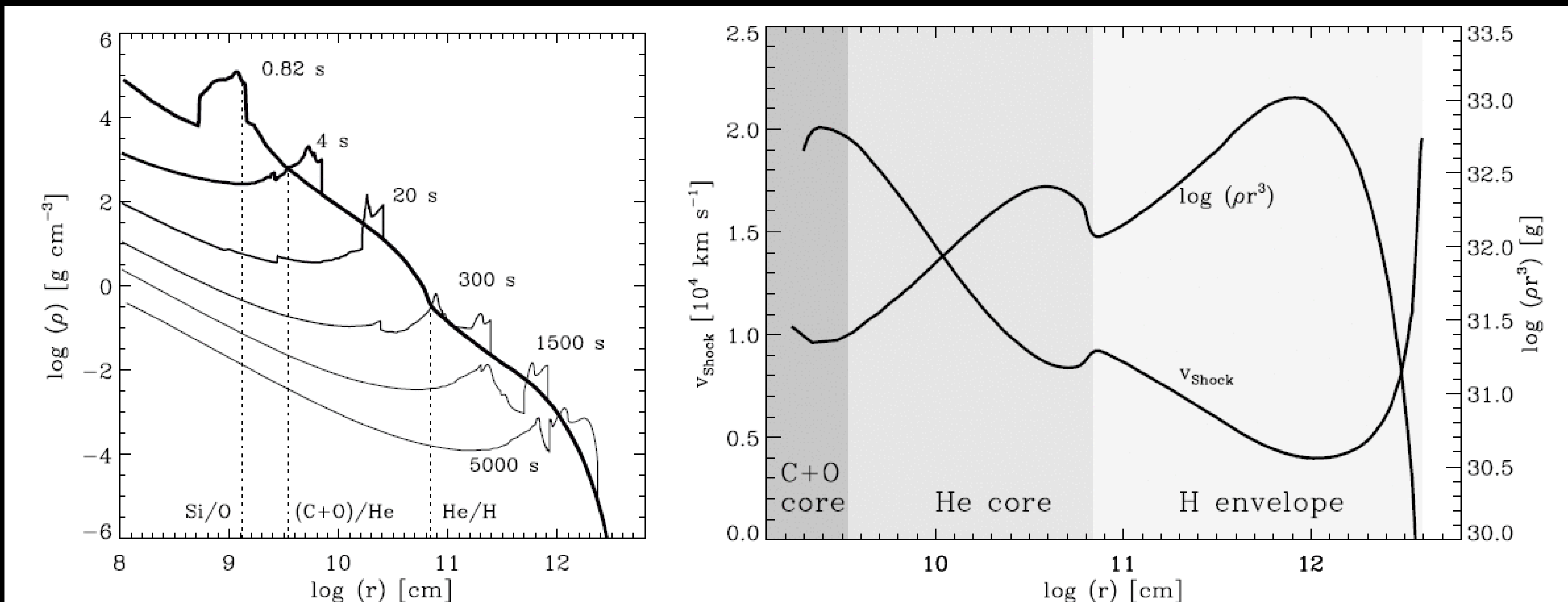
Layered, highly discontinuous, several material interfaces.

Origins of mixing: I



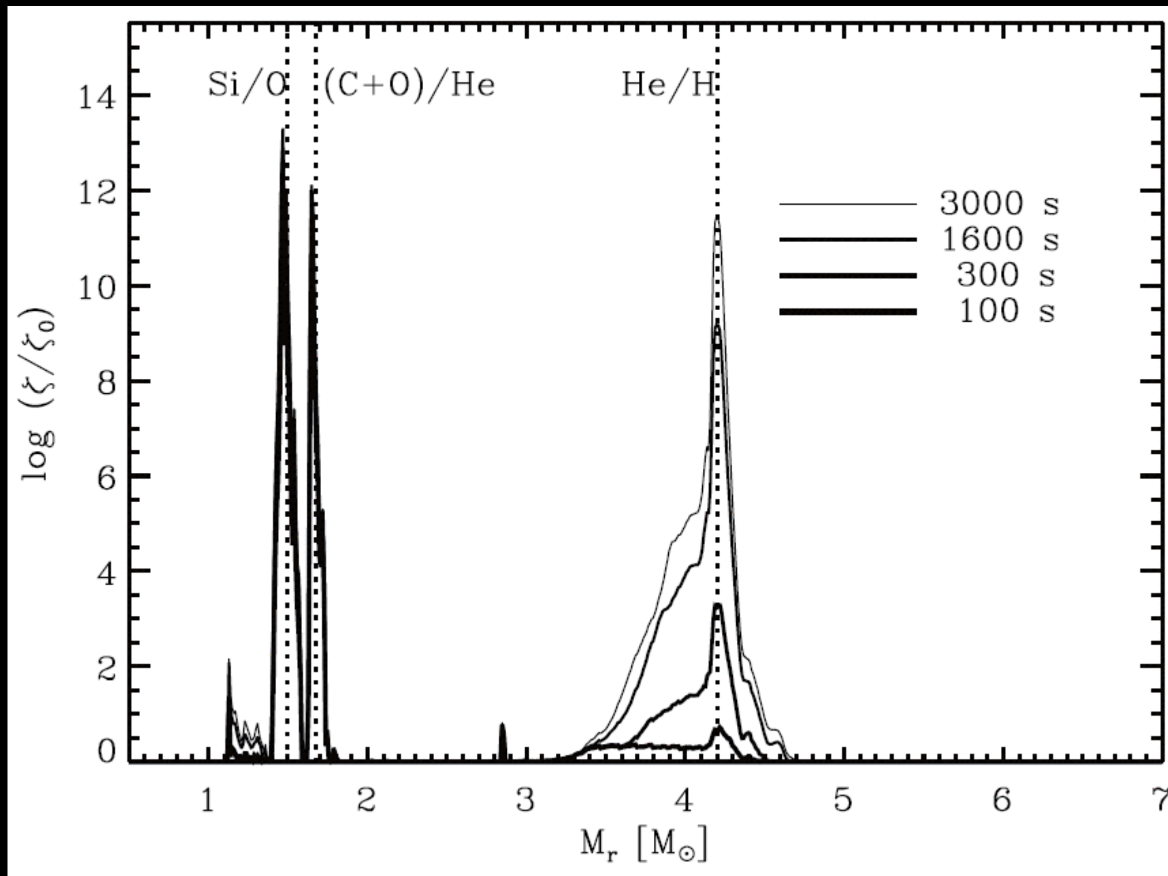
Density and pressure gradients of opposite signs.

Origins of mixing: II



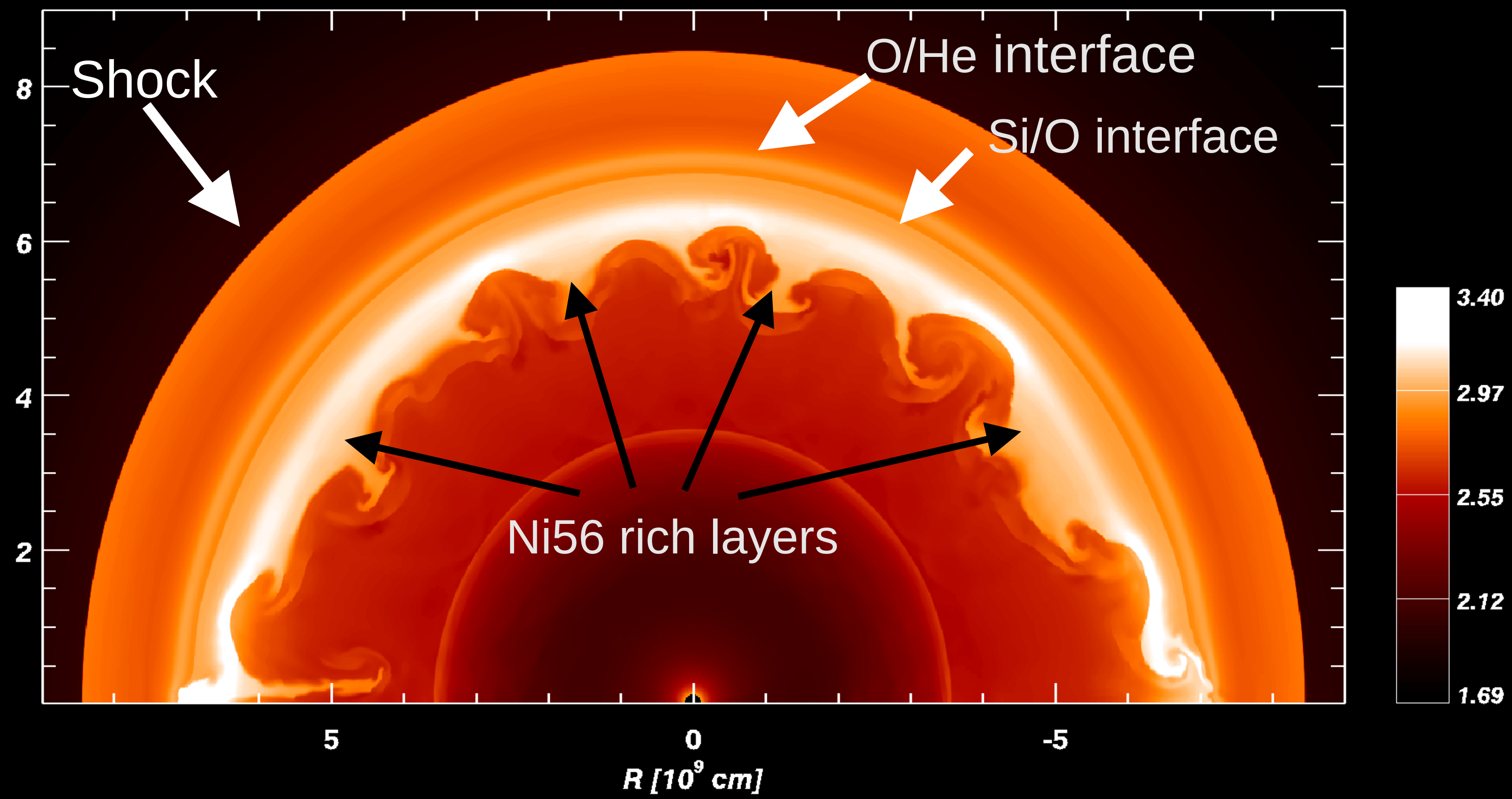
Shock speed deceleration.

Rayleigh-Taylor growth rates

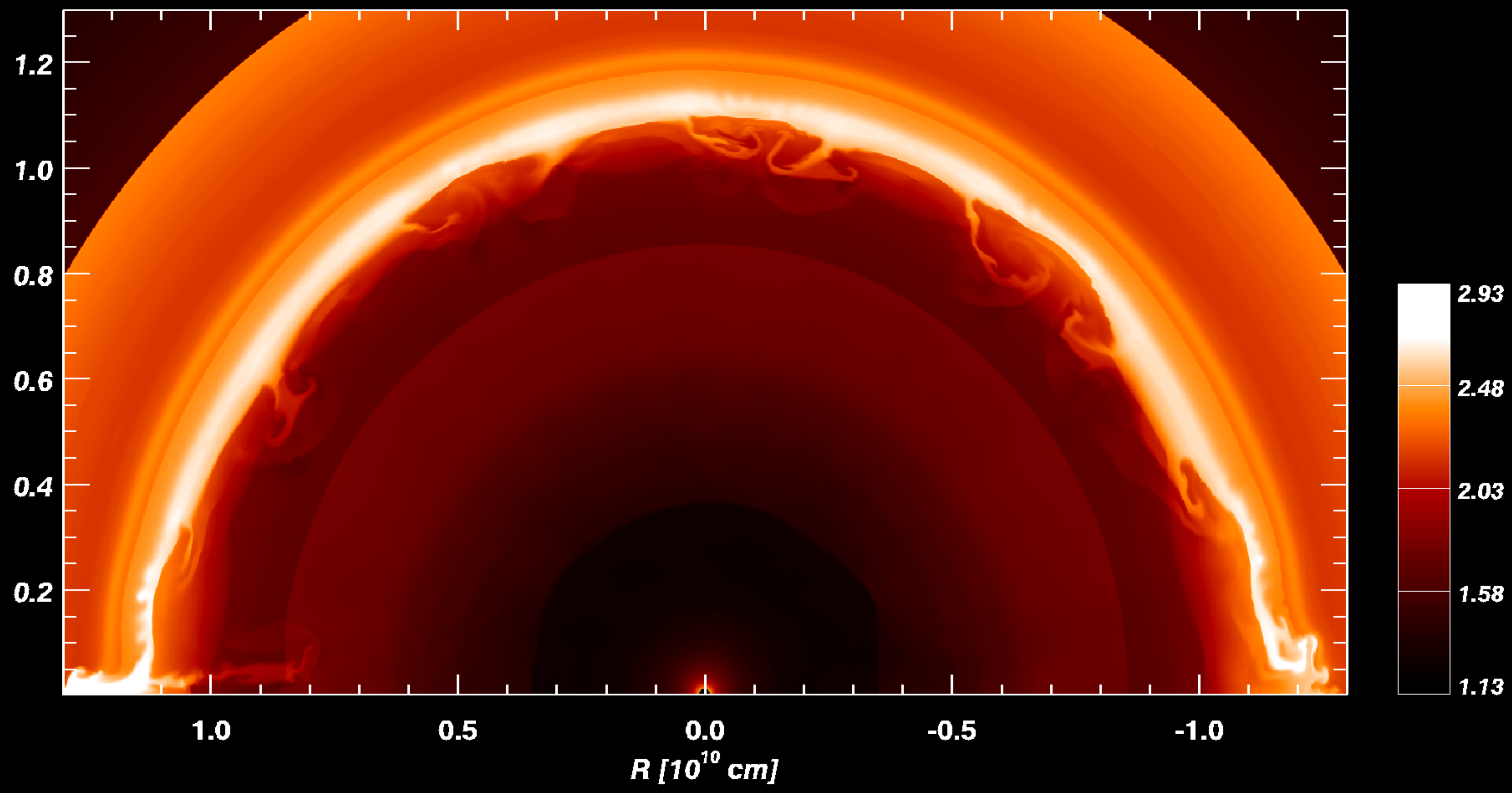


Long-term growth at He/H.

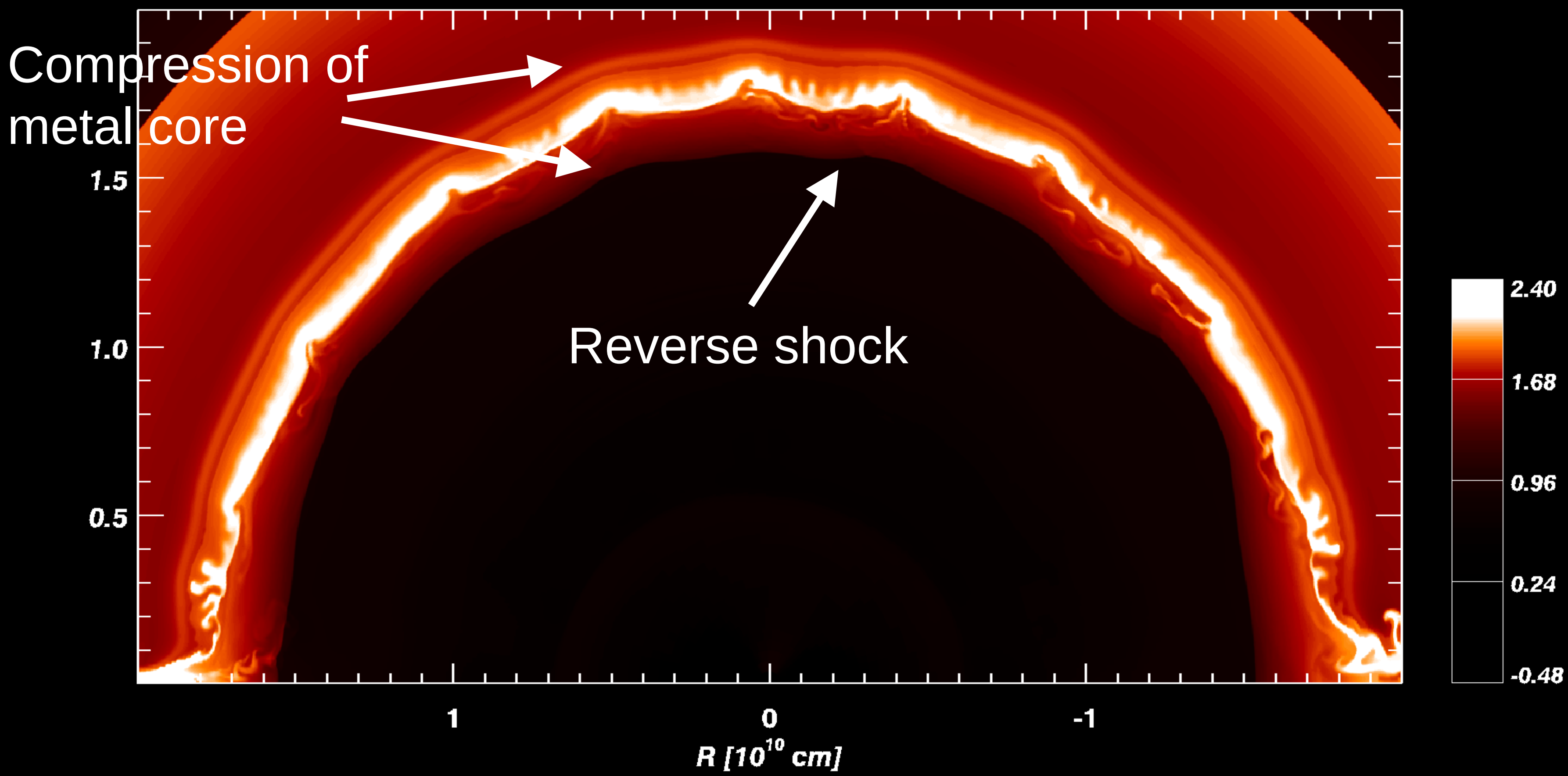
Log (density), 4 s post bounce



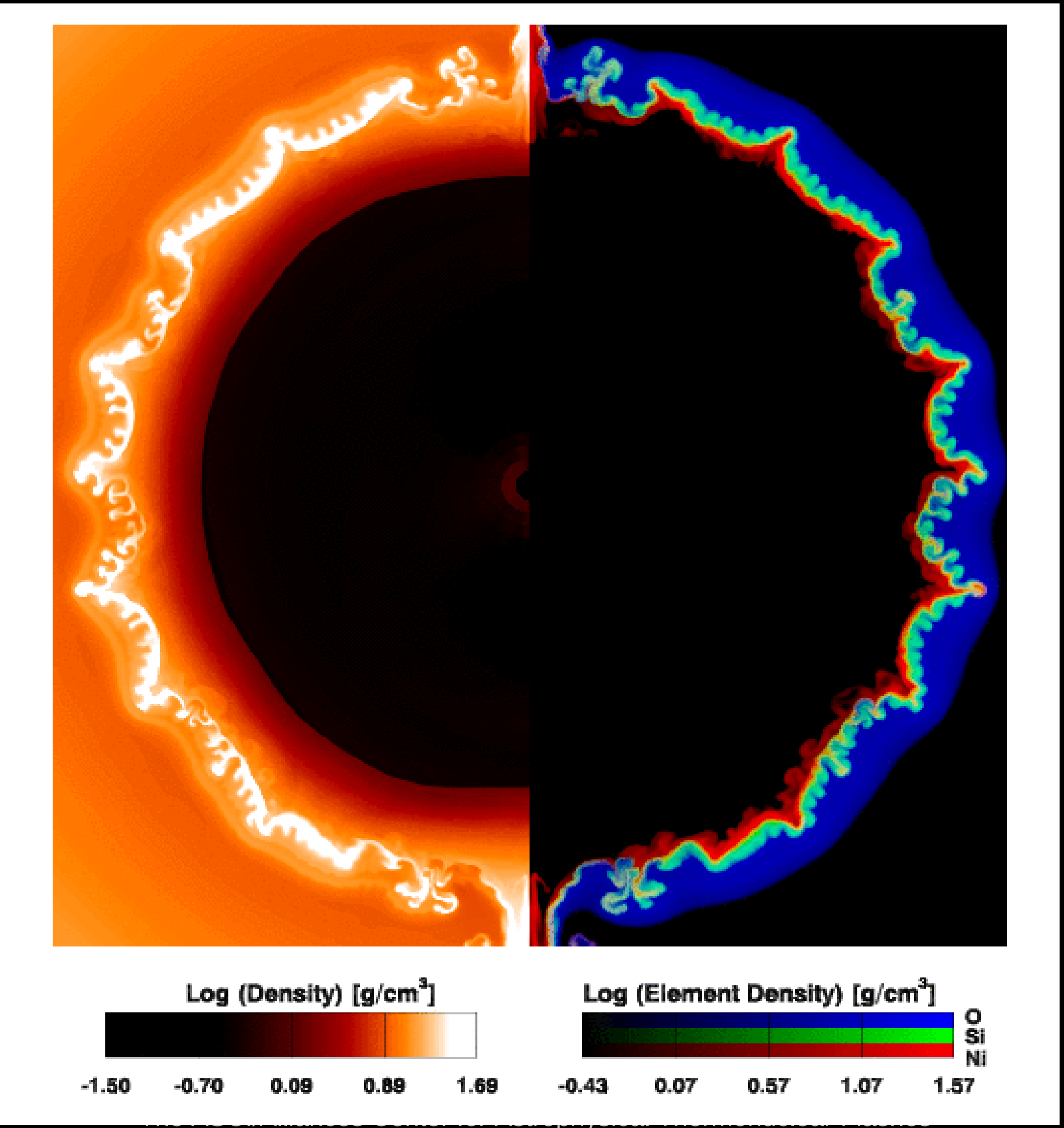
Log (density), 10 s



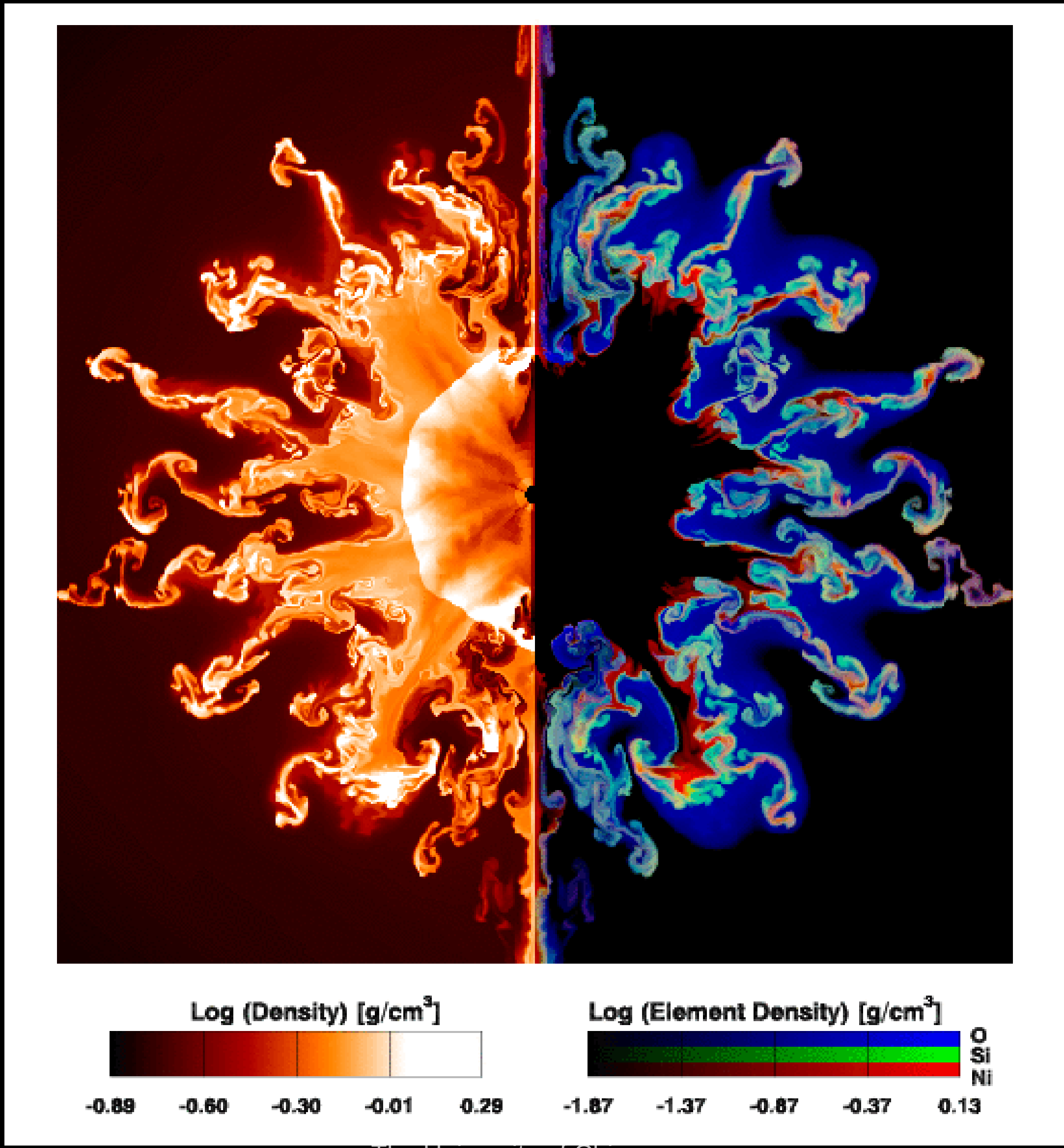
Log (density), 20 s



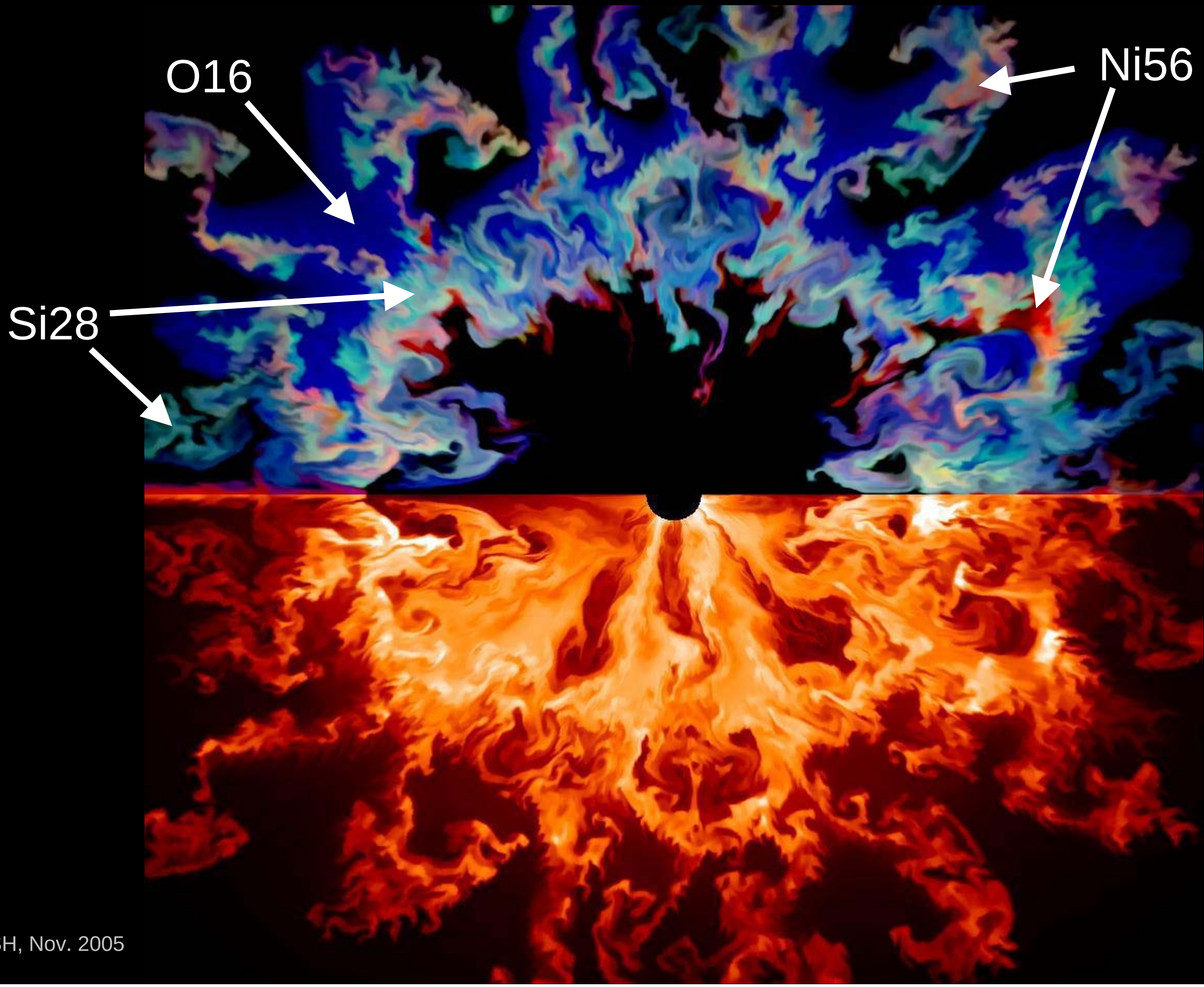
Density + elements, 50 s



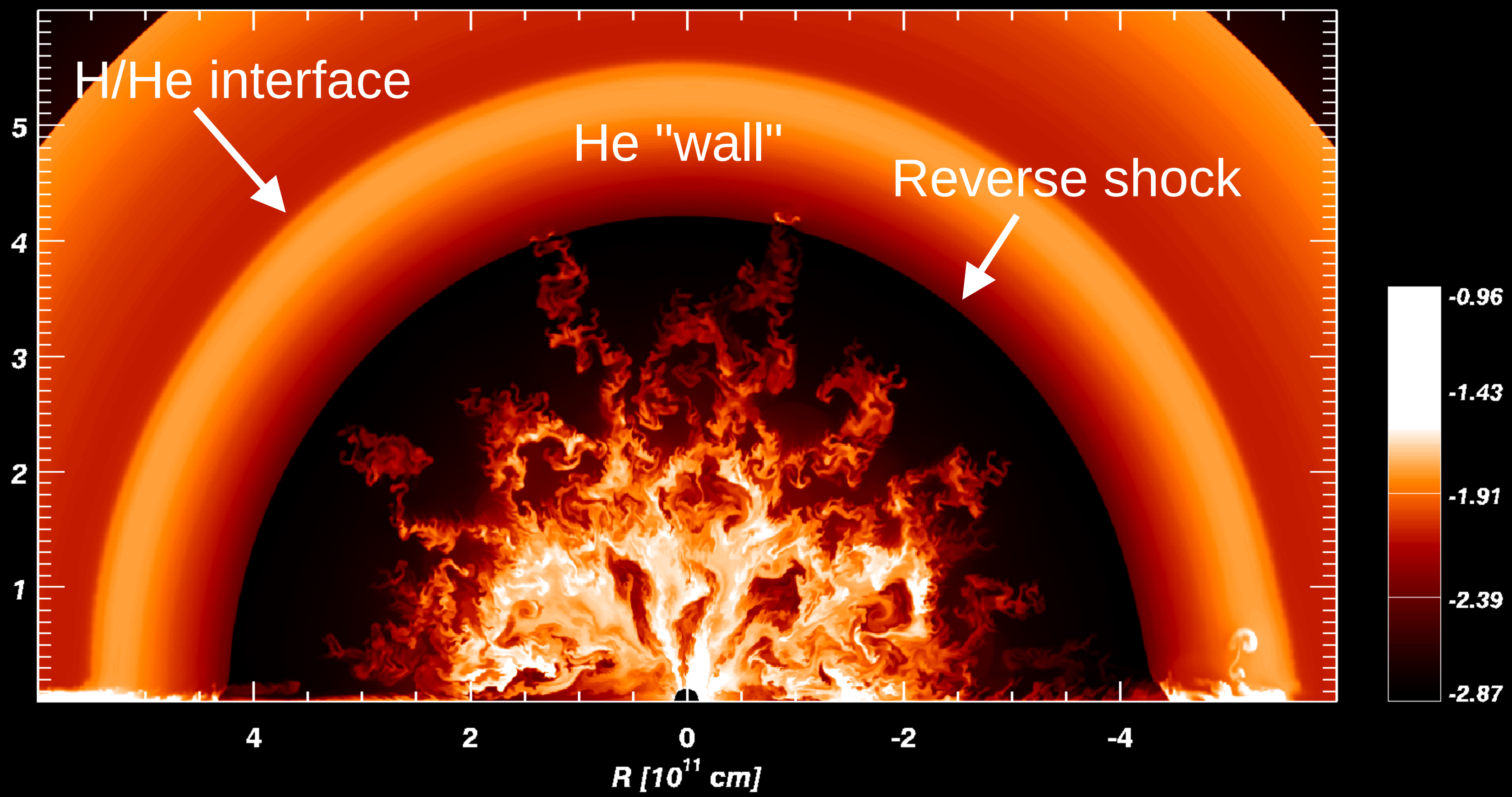
Density + elements, 300 s



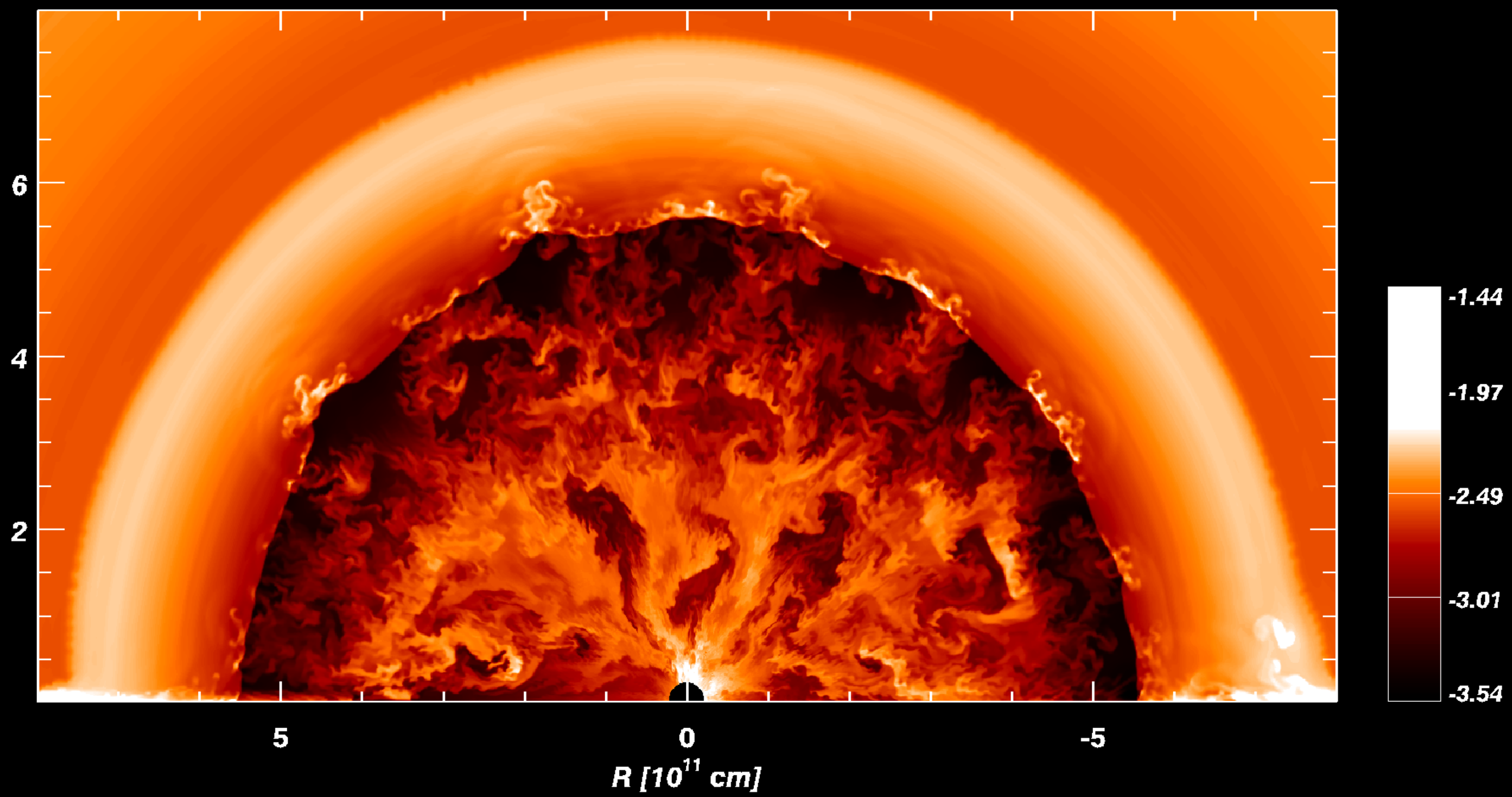
Density + elements, 1170 s



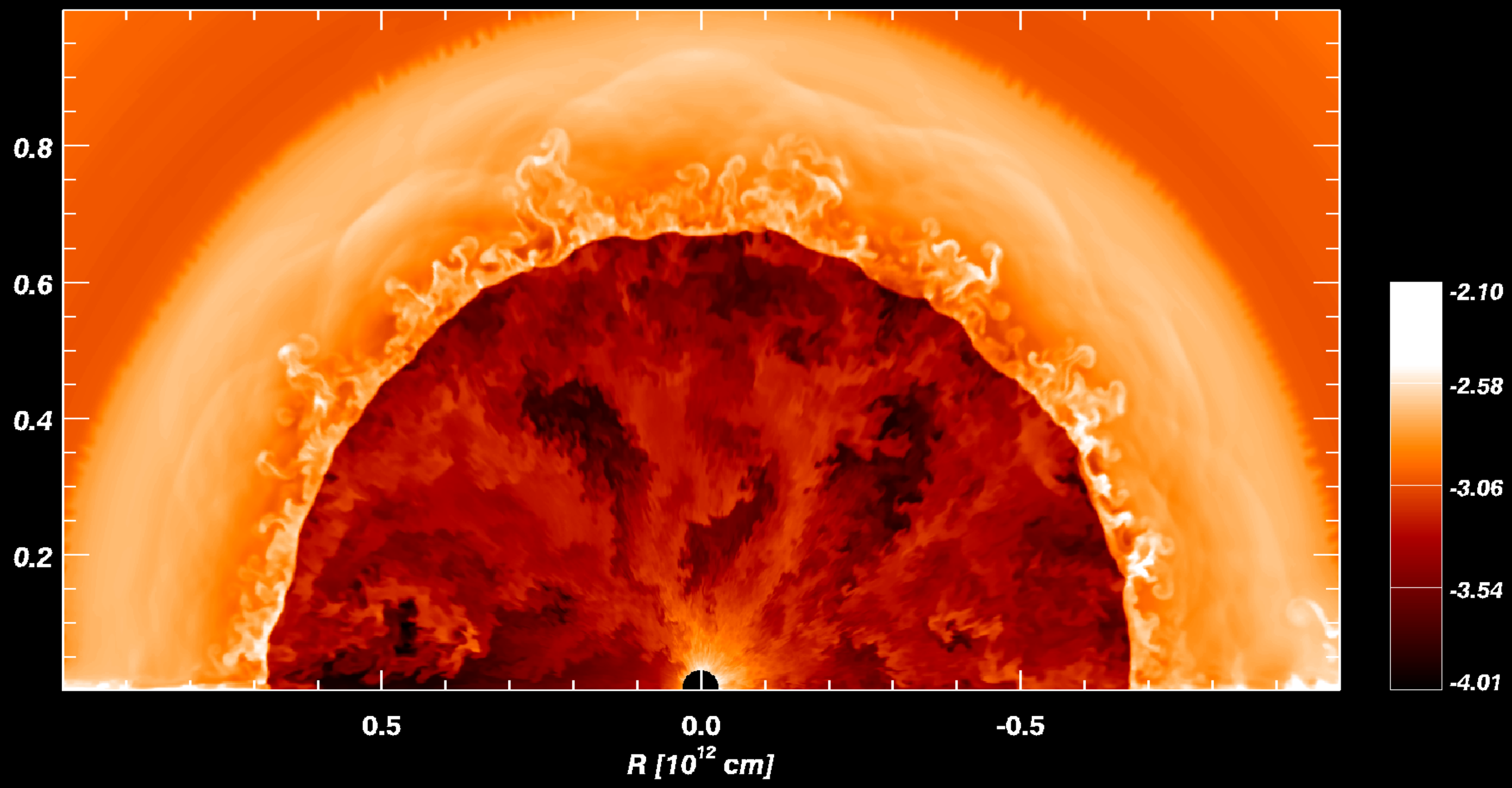
Log (density), 1620 s



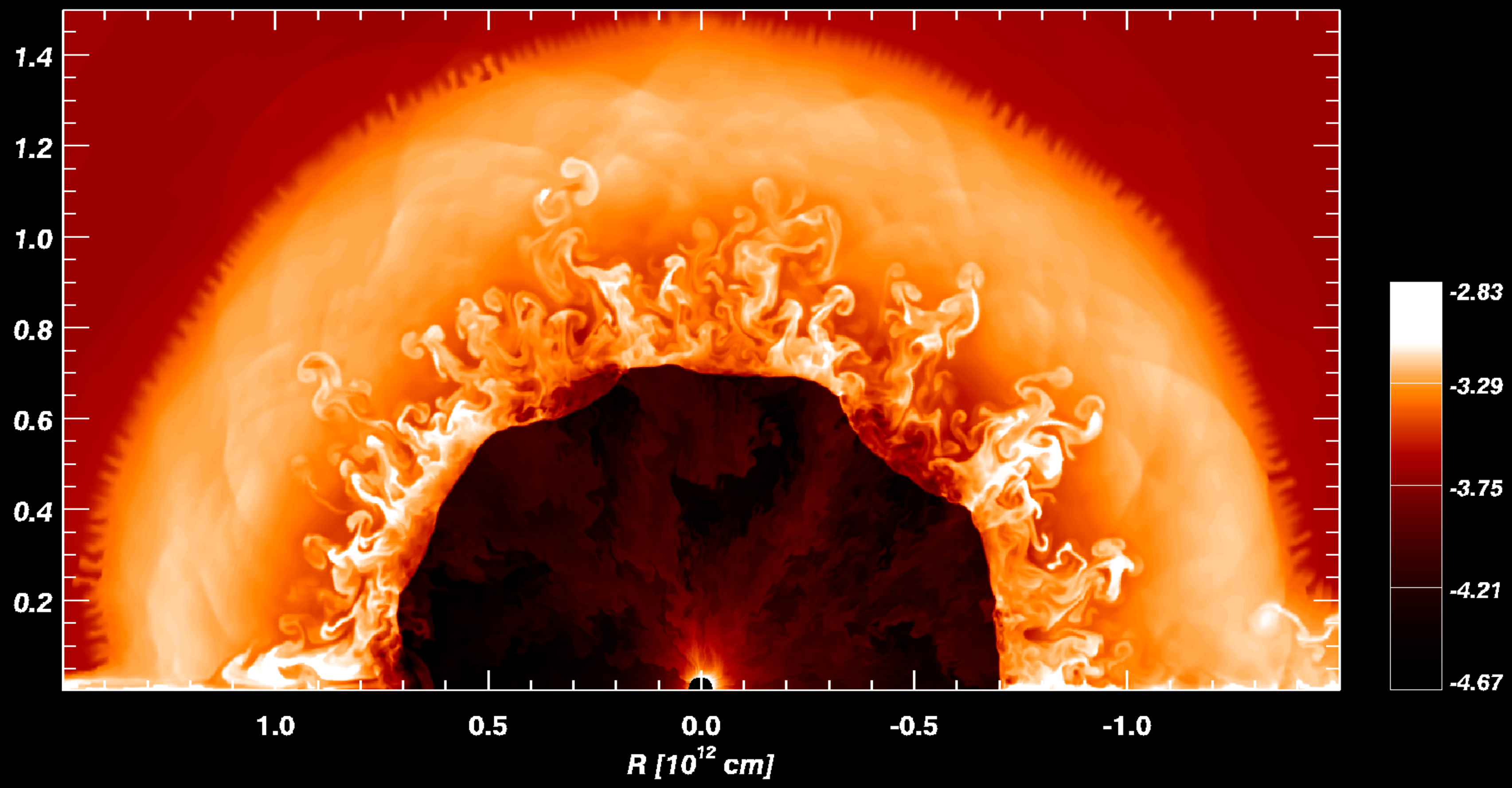
Log (density), 3000 s



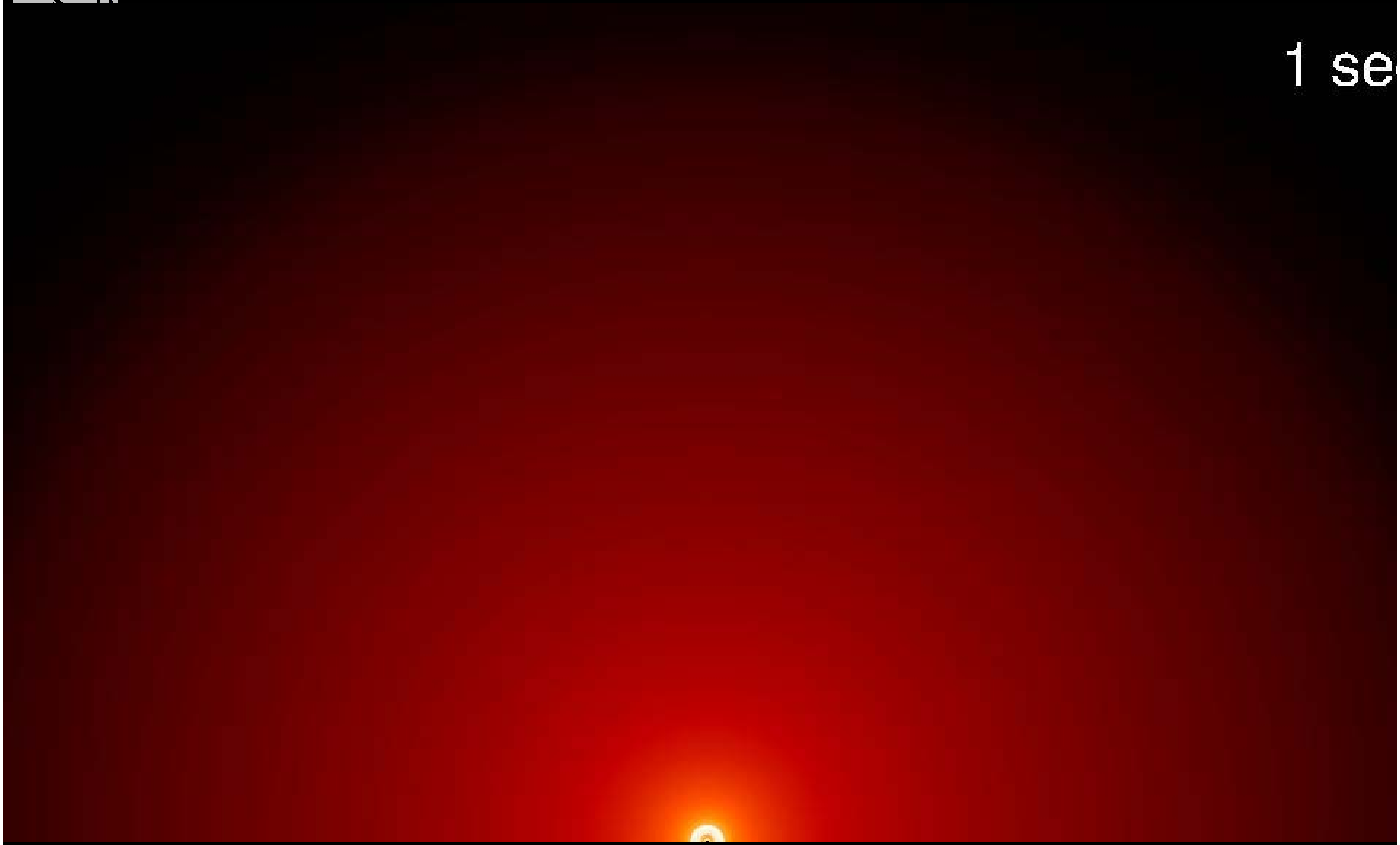
Log (density), 5000 s



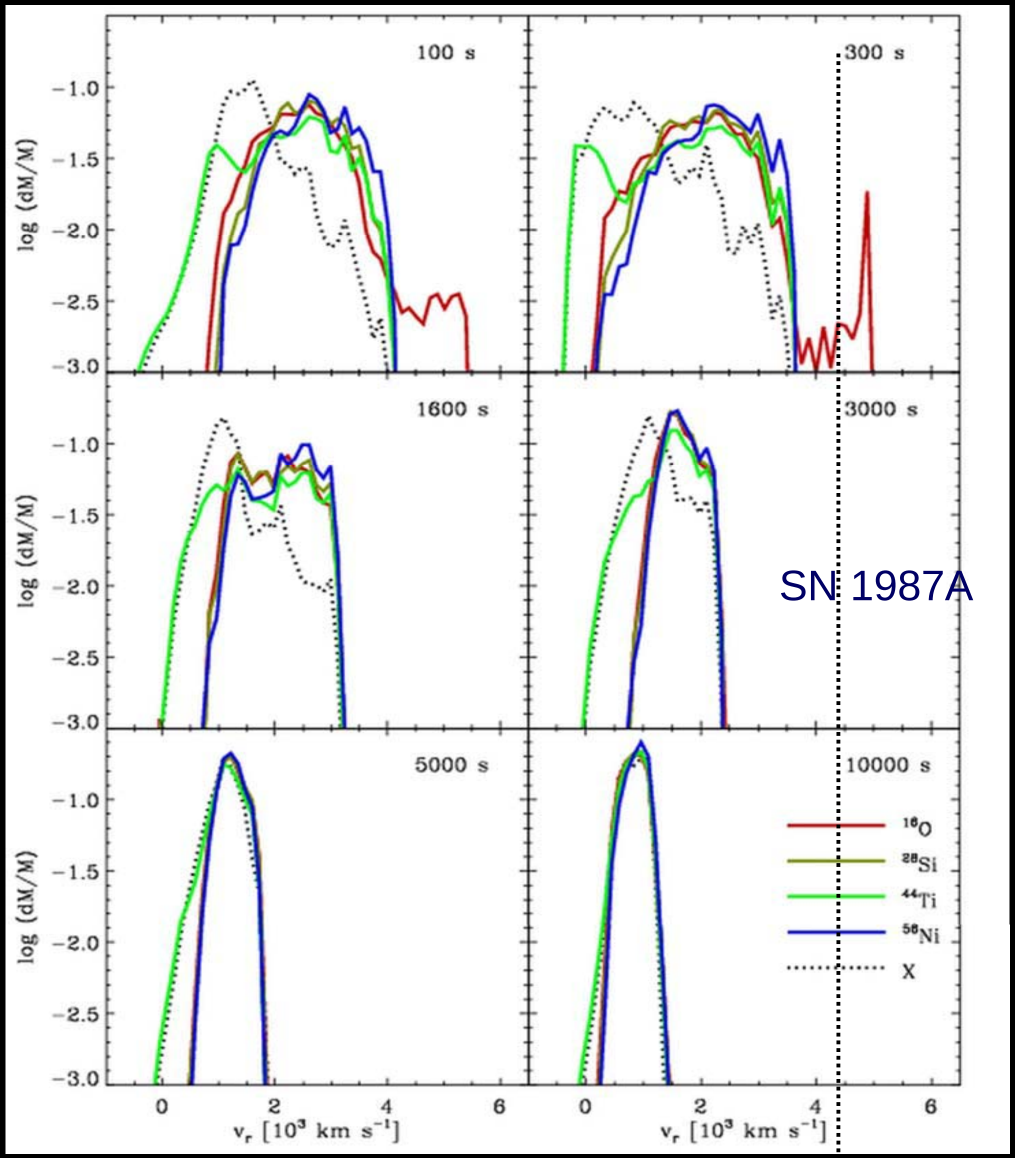
Log (density), 10000 s



Log (density), up to 20,000 s

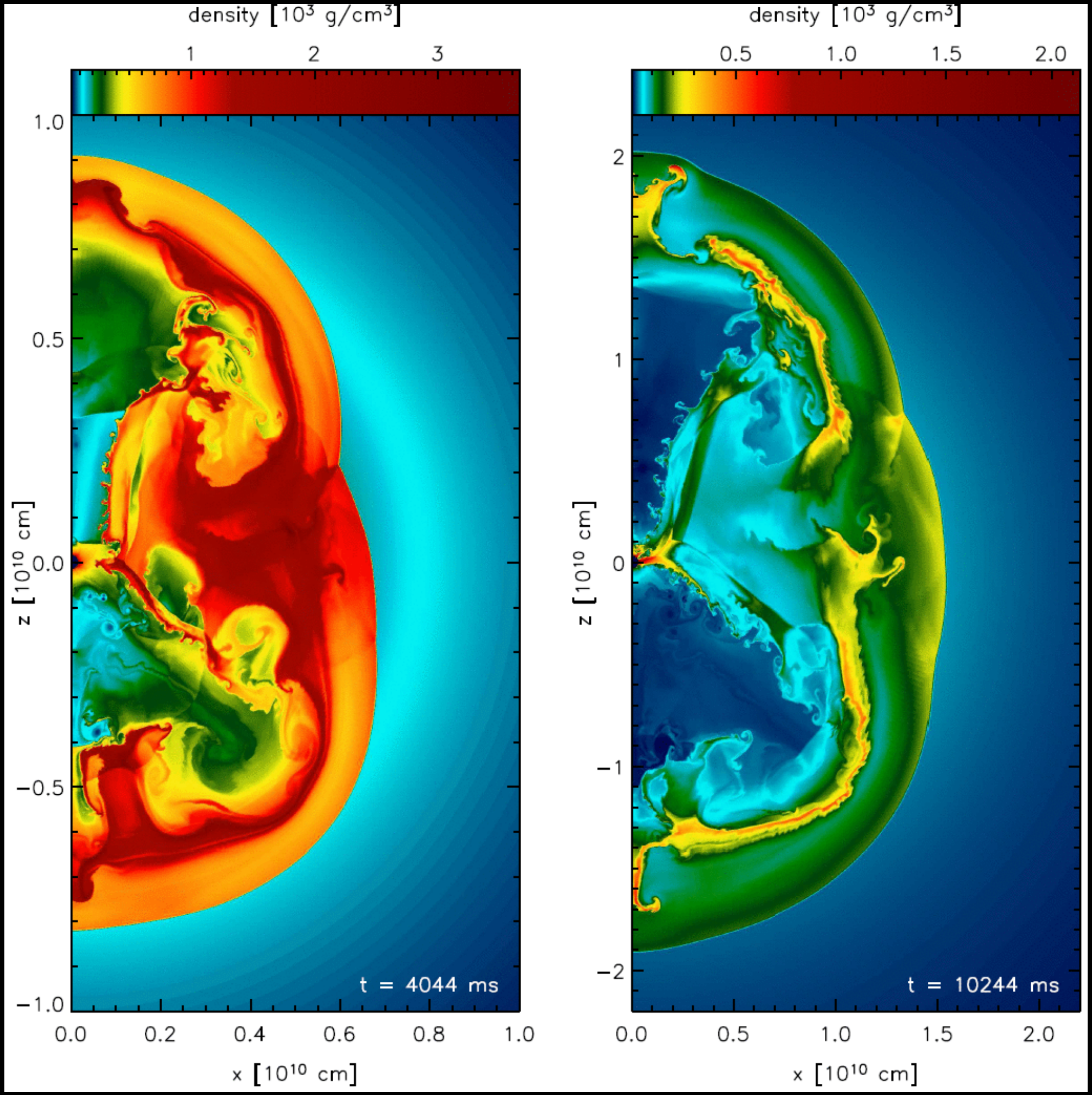


Velocity distributions, Type II model



Kifonidis et al. (2004)

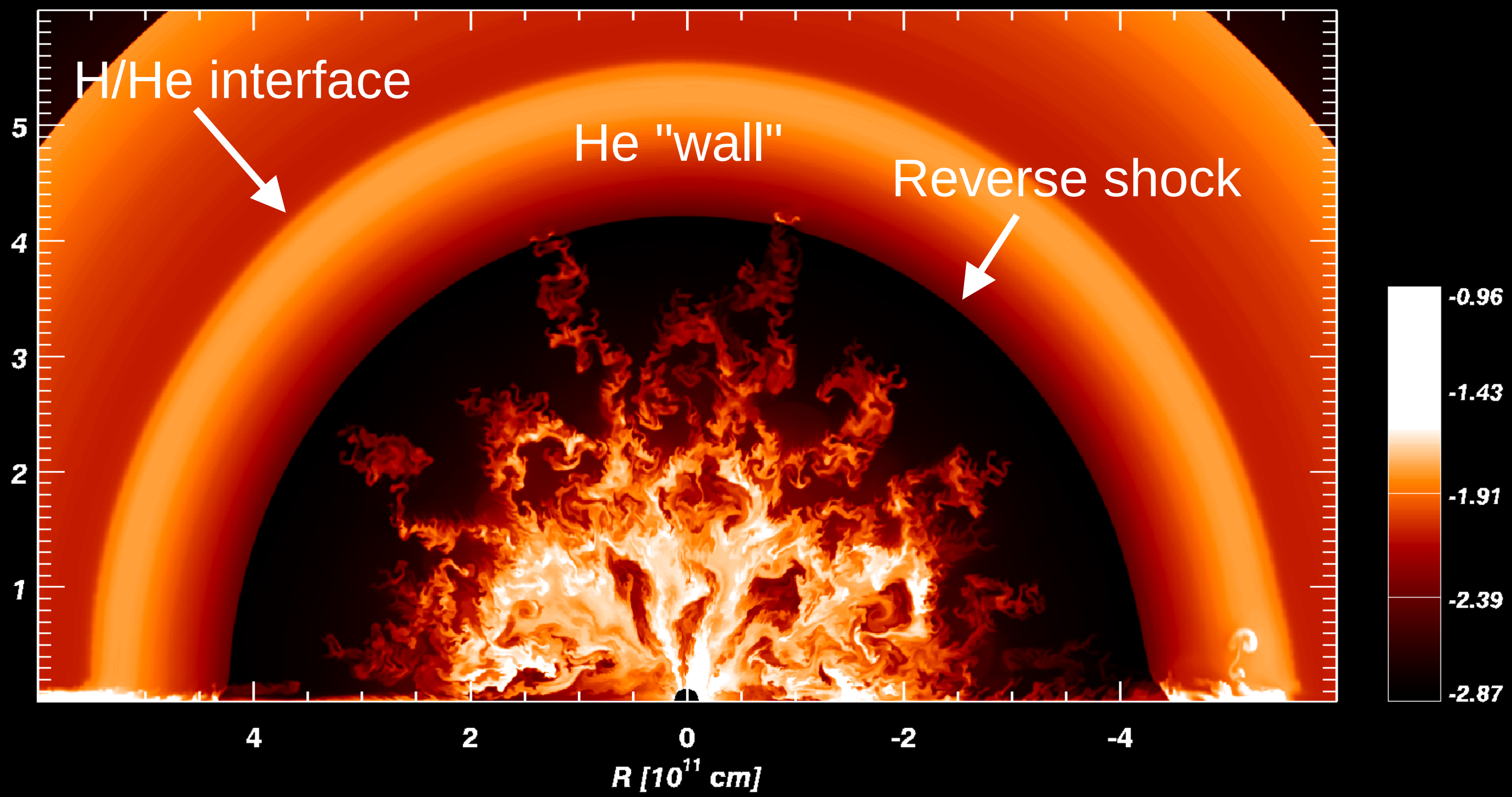
Model ejecta AD2005



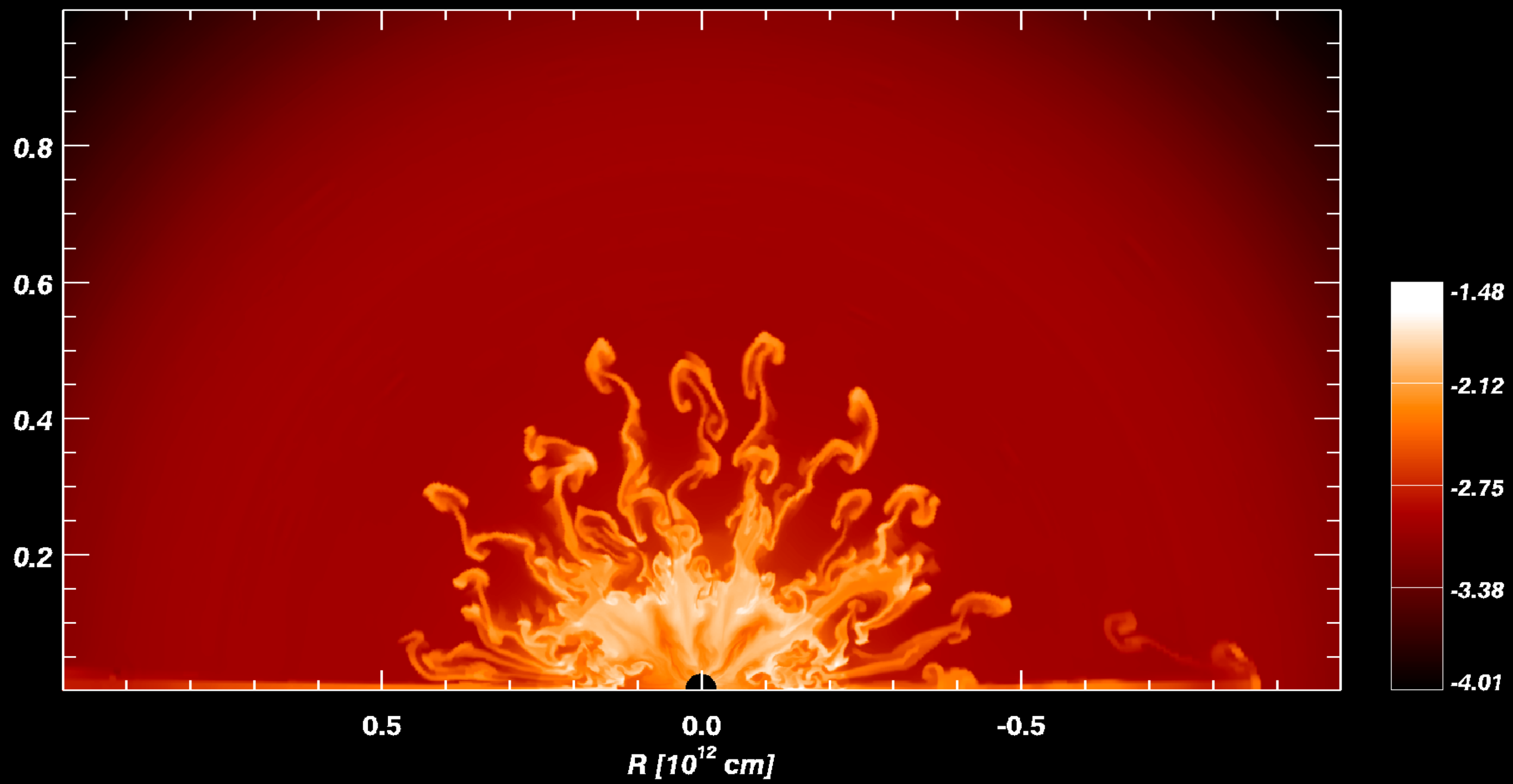
Kifonidis et al. (2006)

- Non-exotic neutrino-driven supernovae
- Rayleigh-Taylor mixing in normal Type II
- Hydrogen-free case of Type Ib
- Bits from the Labs
- Conclusions

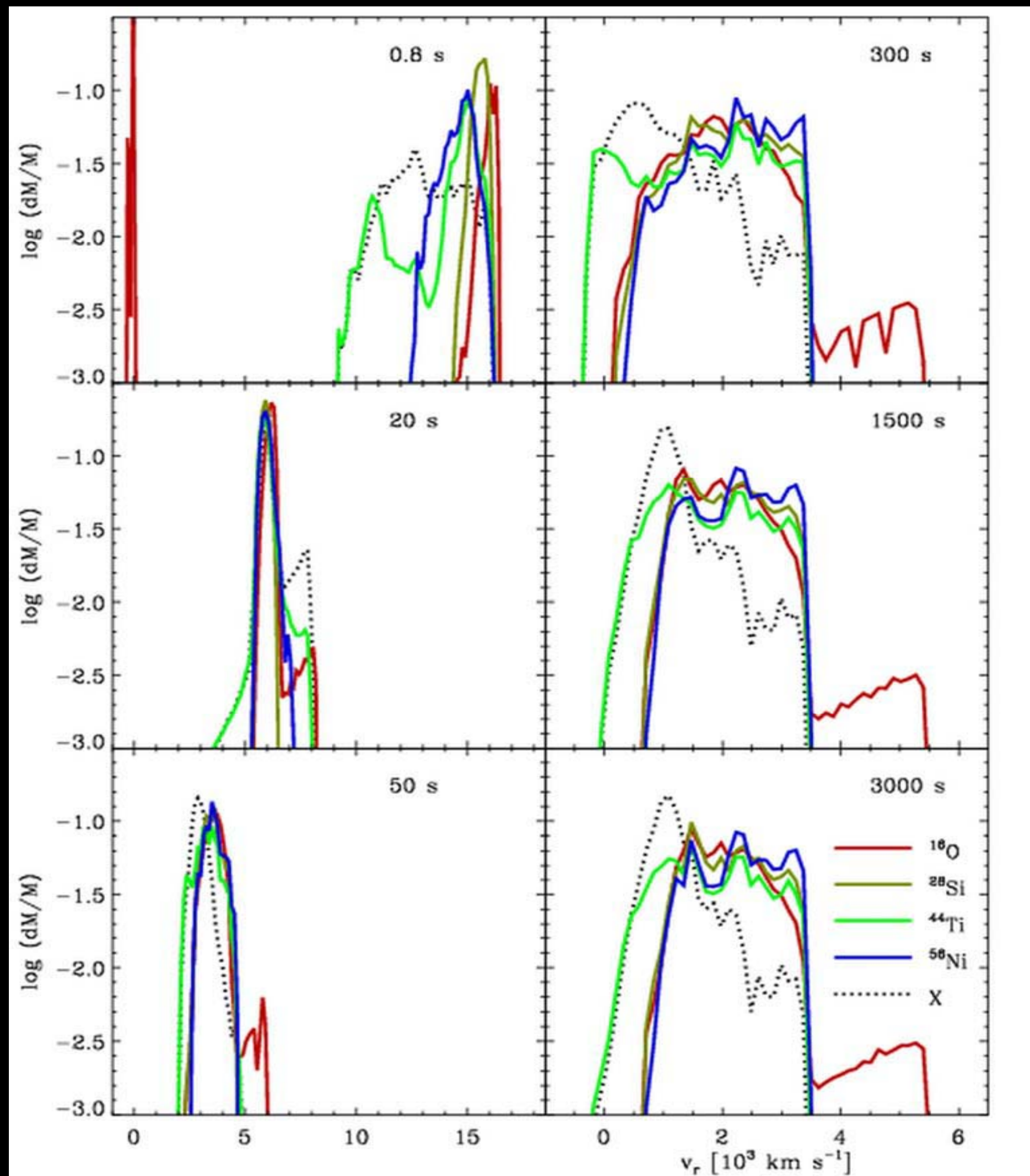
Log (density), Type II model, 1620 s



Log (density), Type Ib model, 1600 s

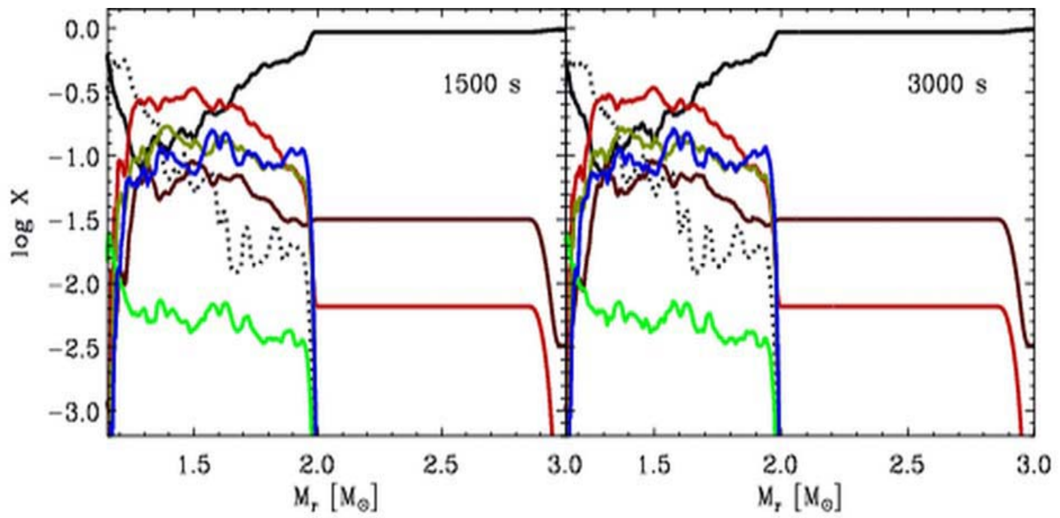


Velocity distributions, Type Ib model

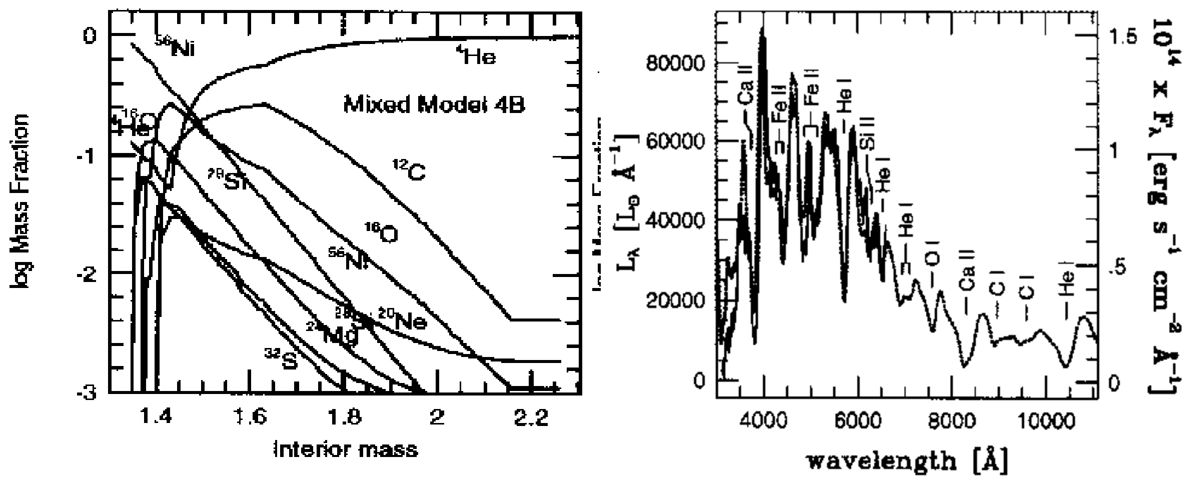


Mixing and spectra of Type Ib SN

This work



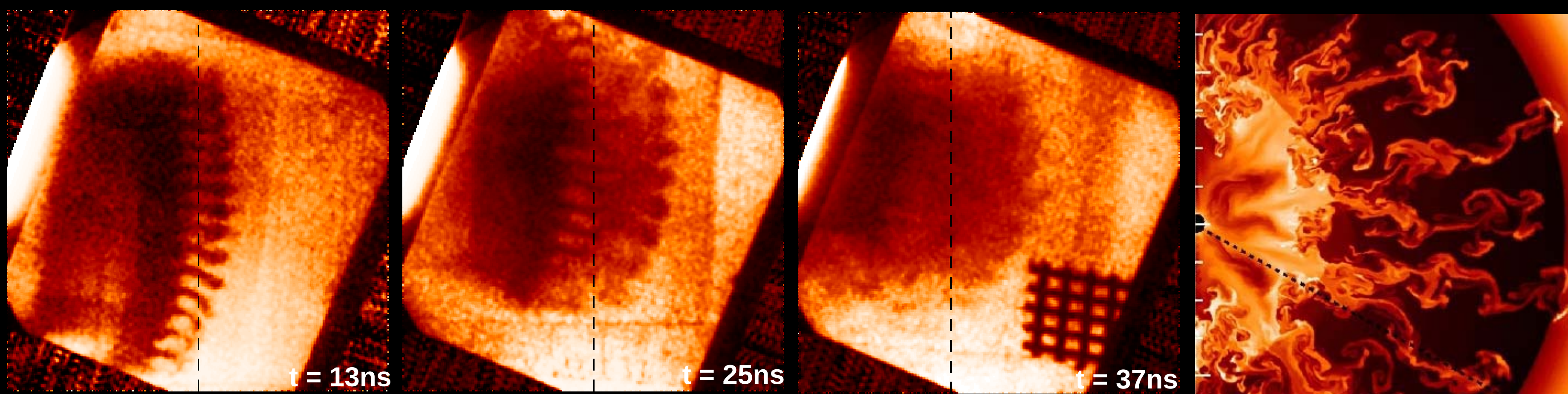
Model 4B of Eastman & Woosley (1997)



- Non-exotic neutrino-driven supernovae
- Rayleigh-Taylor mixing in normal Type II
- Hydrogen-free case of Type Ib
- Bits from the Labs
- Conclusions

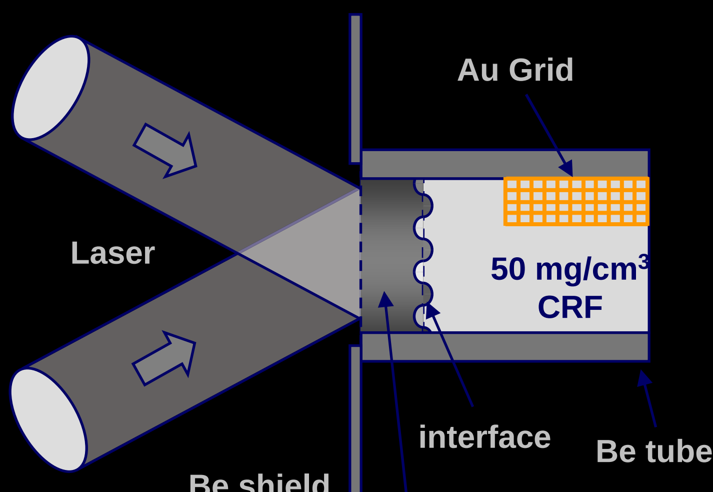
NLUF Supernova Rayleigh-Taylor

Study RM / RT instability-driven transition to turbulence in a planar system at a diagnosable scale.



Kifonidis, Plewa, Janka, & Mueller, 2000, Ap. J. 531, L123

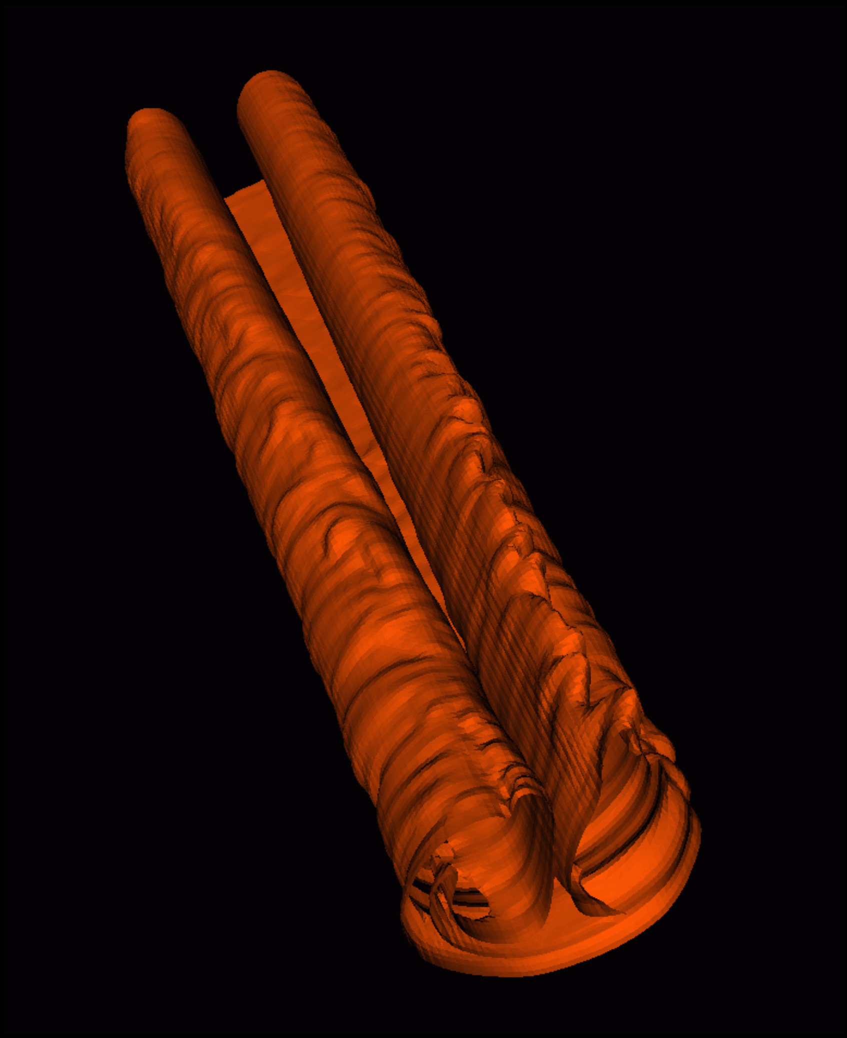
Experiment geometry



Re ~ 10^{10}
Is this turbulence?

Harry Robey et al., LLNL

Shock-cylinder interaction



Chris Tomkins et al., LANL

Conclusions

- Neutrino driven convection seeds Rayleigh-Taylor instability at Si/O and O/He-interfaces. Complex post-shock flow, difficult to model, rich in surprises, not yet fully understood.

- Final ^{56}Ni velocities small compared to SN 1987A.
  The cause: hydrodynamic deceleration at He/H interface!

- Perhaps “non-standard" progenitor models, additional physics (rotation or MHD effects), or possibly simply better treatment of currently considered physics required for SN 1987A.

- Promising mechanism to explain Type Ib spectra
  and light curves!

Discussion