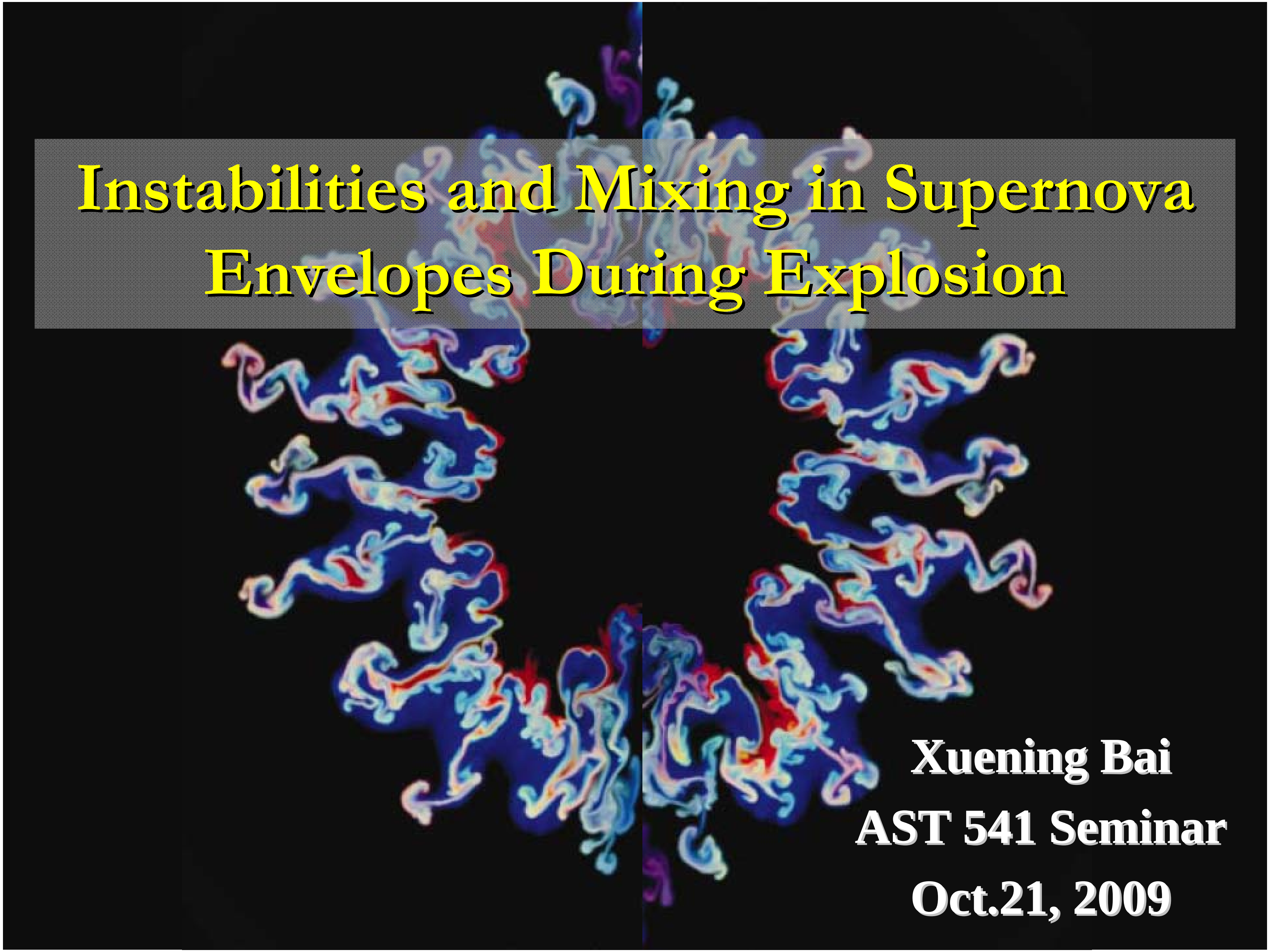


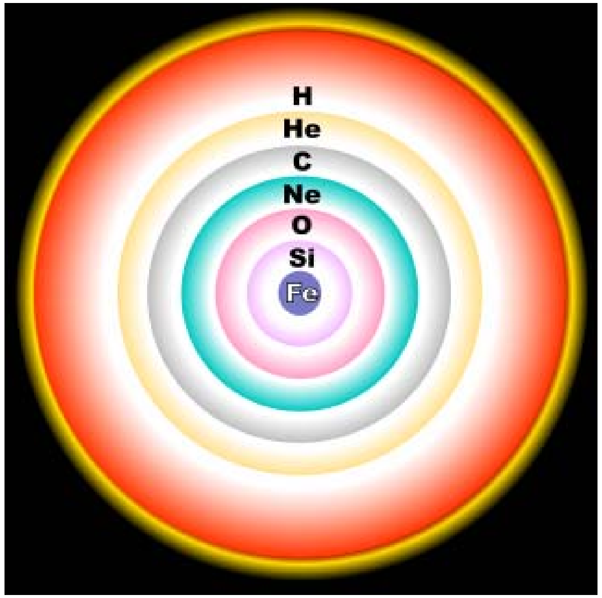
Instabilities and Mixing in Supernova Envelopes During Explosion

Xuening Bai
AST 541 Seminar
Oct.21, 2009

Outline

- Overview
- Evidence of Mixing
  - SN 1987A
  - Evidence in supernova remnants
- Basic Physics
  - Rayleigh-Taylor Instability
  - Richtmyer-Meshkov Instability
- Numerical Simulations
  - Early 2D simulations
  - Recent 2D simulations
  - First 3D simulation
- Summary

Overview



- Core-collapse: before and after

  Length scale: Fe core (3000km) -> PNS (60km)

  Stellar onion (>10^12cm)

  Time scale: Core collapse (0.5s)

  Envelope response (>1h)

- Macroscopic/microscopic mixing

  Macroscopic: mixing of bulk material, leads to inhomogeneity

  time scale: dynamical

  Microscopic: mixing in inter-particle scale, leads to homogeneity

  time scale: >10^5 yrs

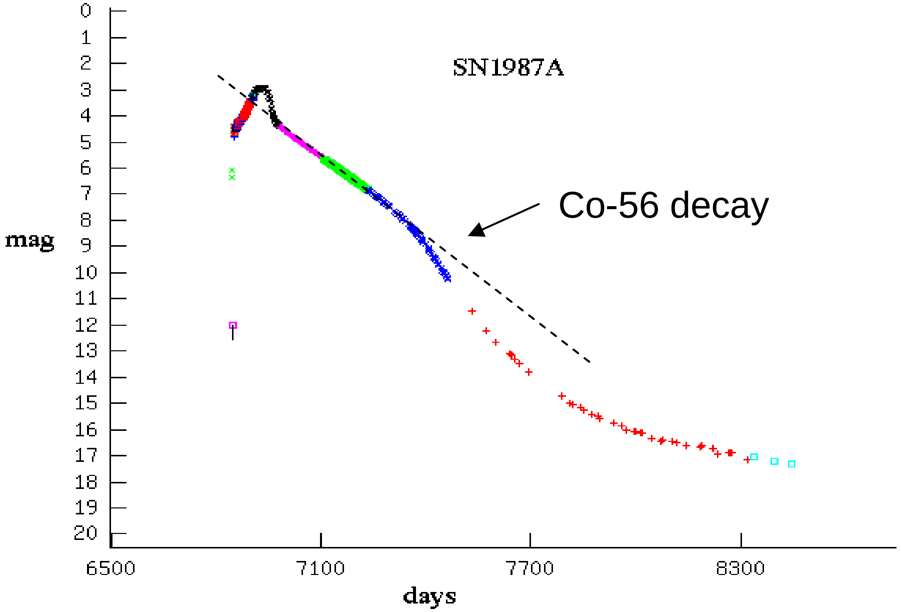
- Scientific interest

  probe the structure of the progenitor star / constrain explosion model

Observational Evidence of Mixing in Supernova Explosions

SN 1987A in the LMC

© Anglo-Australian Observatory



Co-56 decay

Exploded: Feb.23, 1987 (roughly type II-P)

Progenitor: Sk -69° 202a (B3 I supergiant)

Puzzle: A blue supergiant rather than red

Cause: extensive mass loss and low metalicity

Substantial mixing of Co-56 is required to explain the smoothness of the light curve

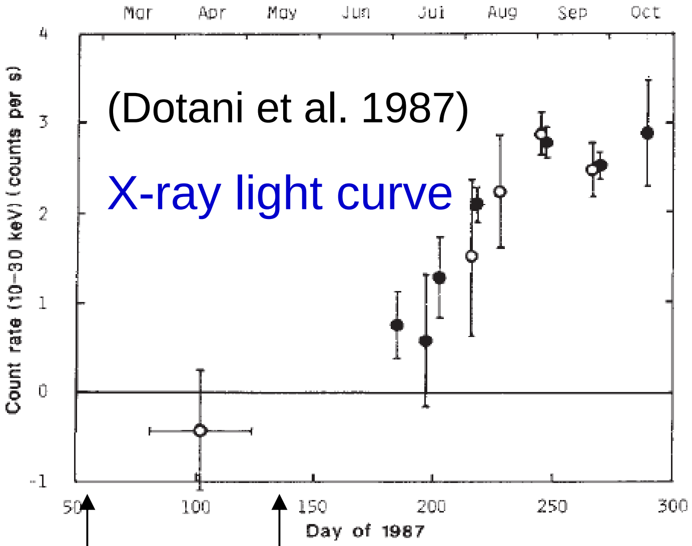
(Arnett et al. 1989)

Best-fit model for the progenitor:

Mass as M.S.:	$19 \pm 3 \ M_\odot$
He core mass:	$6 \pm 1 \ M_\odot$
H envelop mass:	$5\text{–}10 \ M_\odot$
Stellar radius:	$3(\pm 1) \times 10^{12}$ cm

(Woosley 1988)

SN 1987A: X-ray and gamma-ray light curves



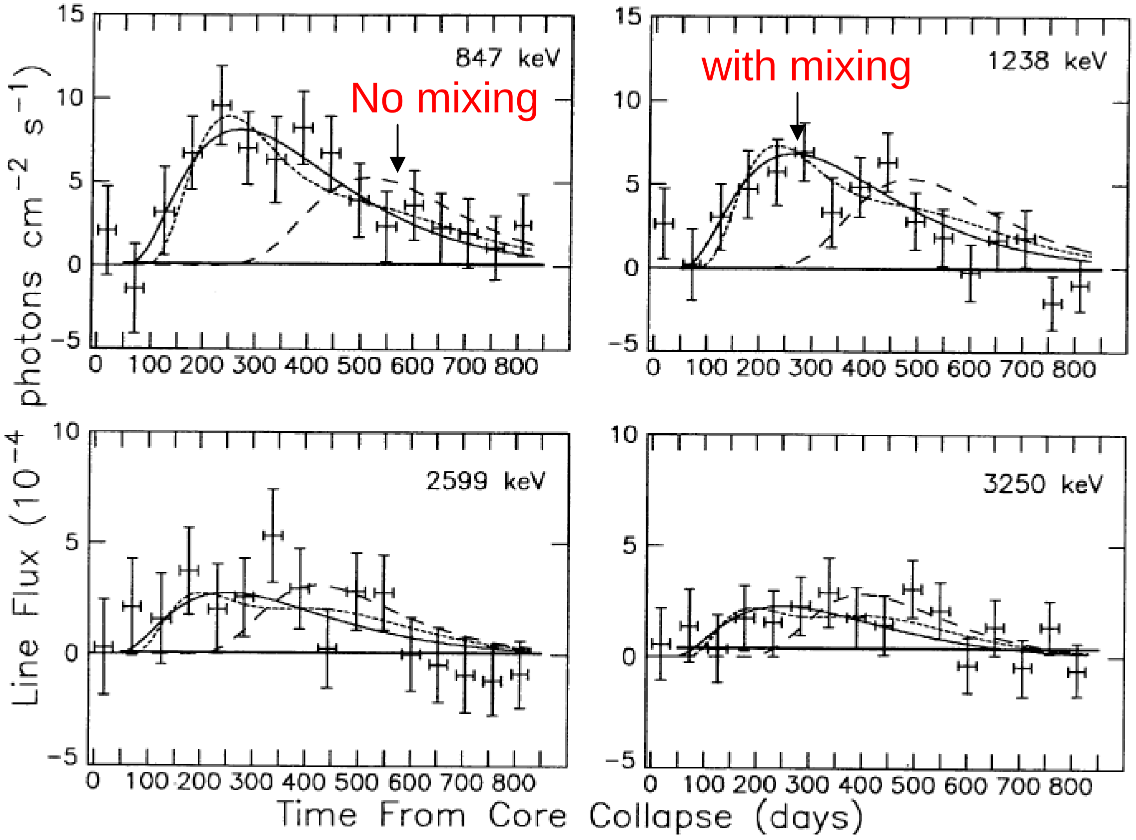
(Dotani et al. 1987)

X-ray light curve

explosion

Peak brightness

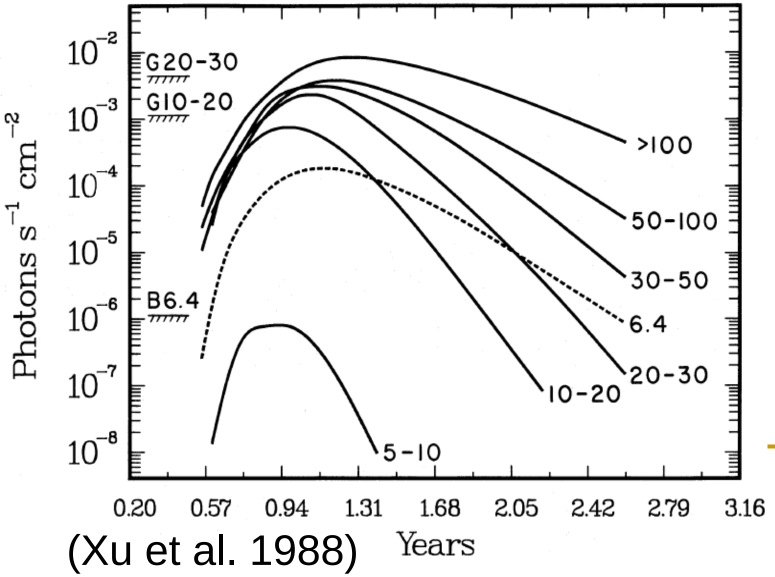
gamma-ray light curve



No mixing

with mixing

(Leising & Share, 1990)

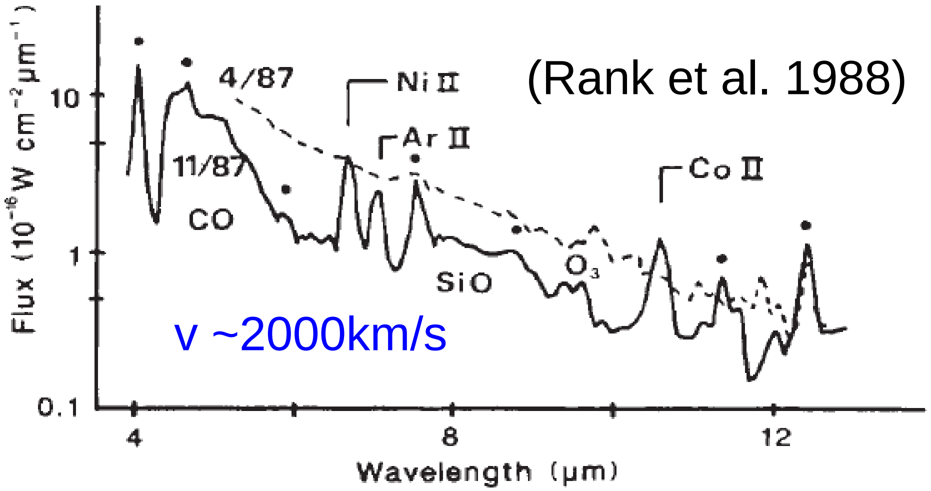


(Xu et al. 1988)

Earlier than expected hard X-ray

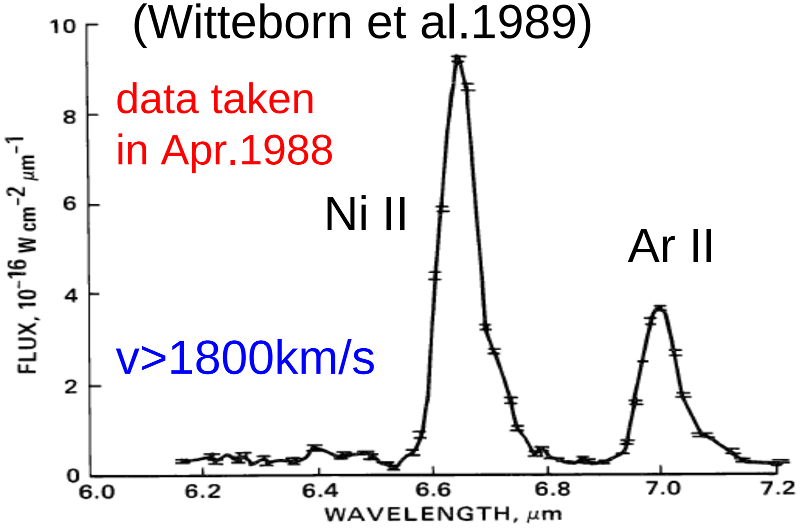
Mixing of Co56 required for gamma-ray light curves

SN 1987A: Spectra of heavy elements



(Rank et al. 1988)

v ~2000km/s



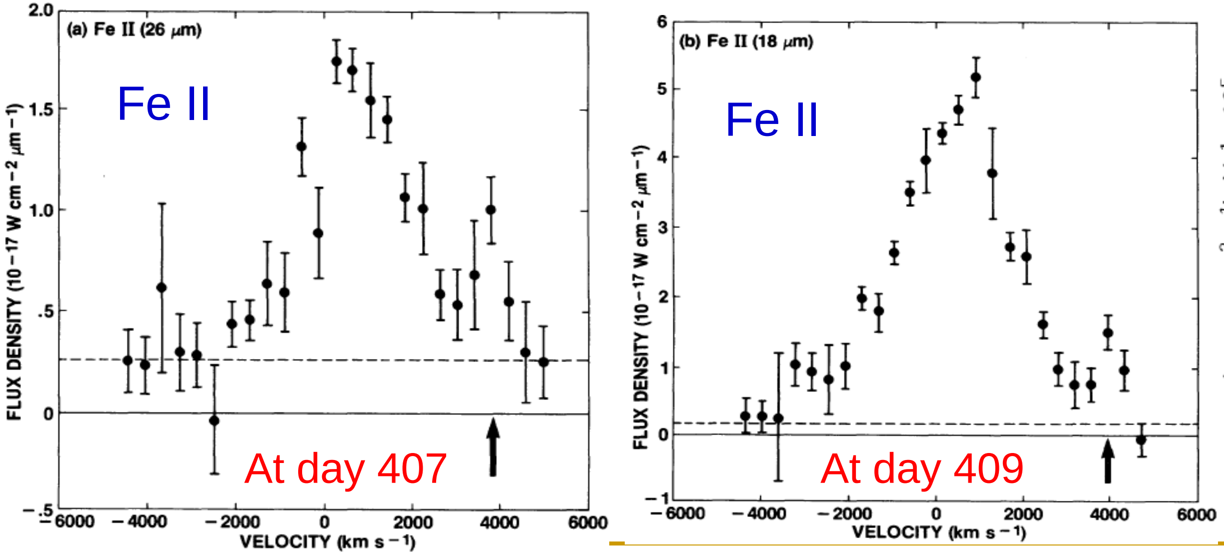
(Witteborn et al.1989)

data taken in Apr.1988

Ni II

Ar II

v>1800km/s



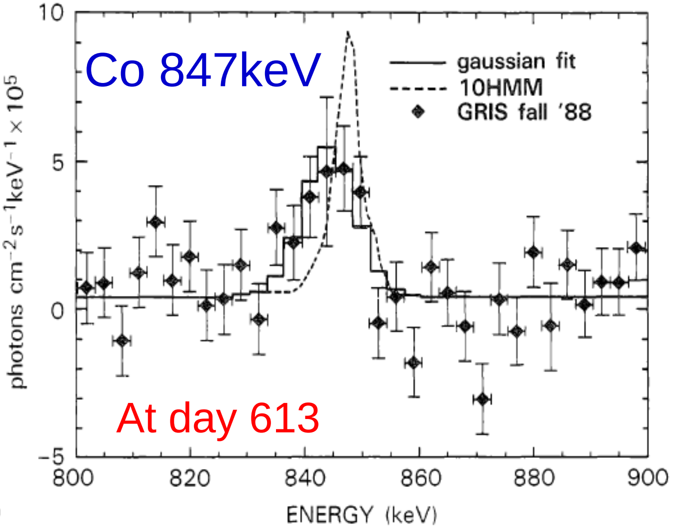
Fe II

At day 407

Fe II

At day 409

(Haas et al. 1990)



Co 847keV

At day 613

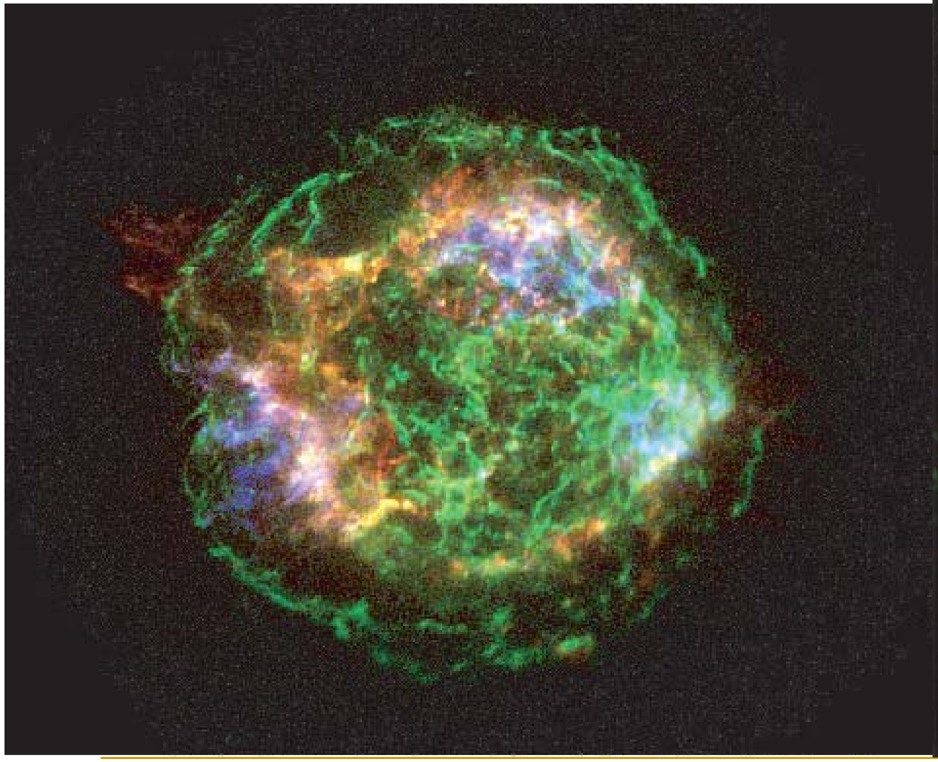
(Tueller et al. 1990)

Evidence of Mixing: Supernova Remnant

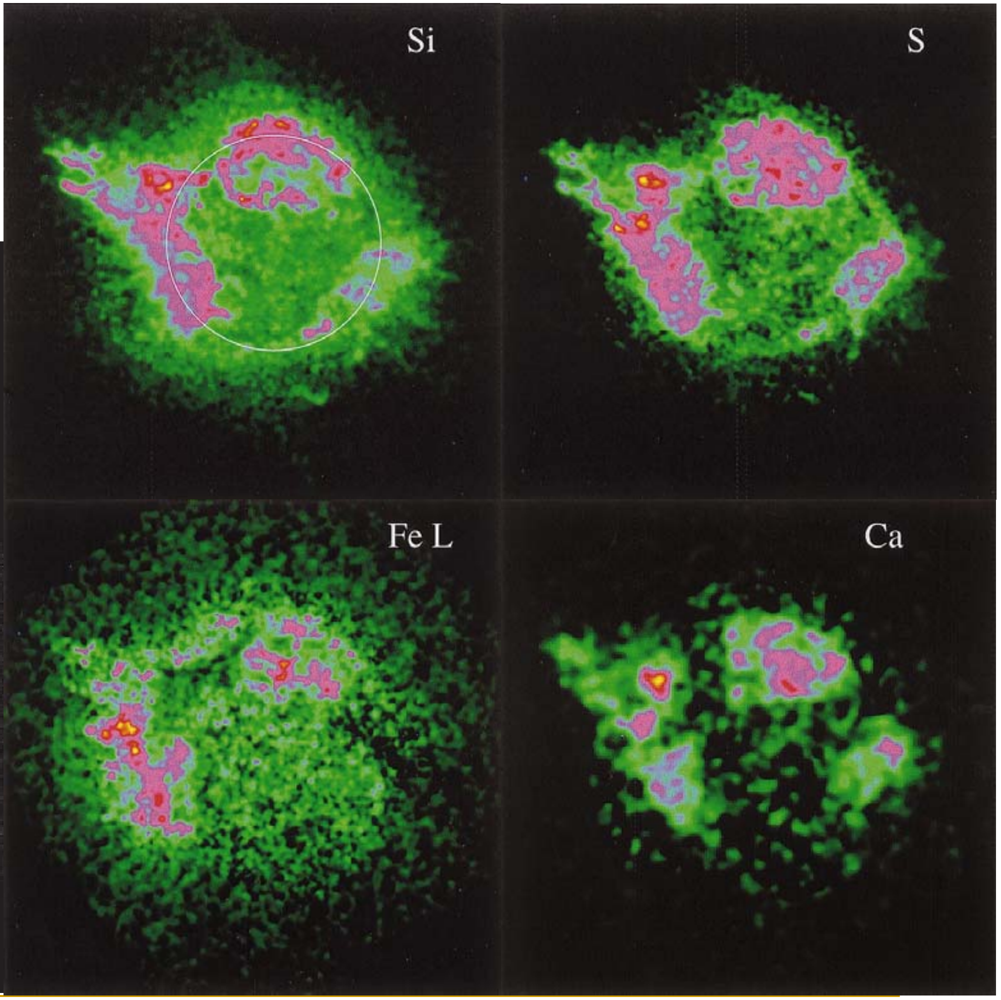
SNR Cassiopeia A

Exploded at year 1681(+/-19)

Type: IIb (Krause et al. 2008)



(Hwang et al. 2004)



(Hwang et al. 2000)

Basic Physics: Fluid Instabilities

Basic physics: Rayleigh-Taylor instability

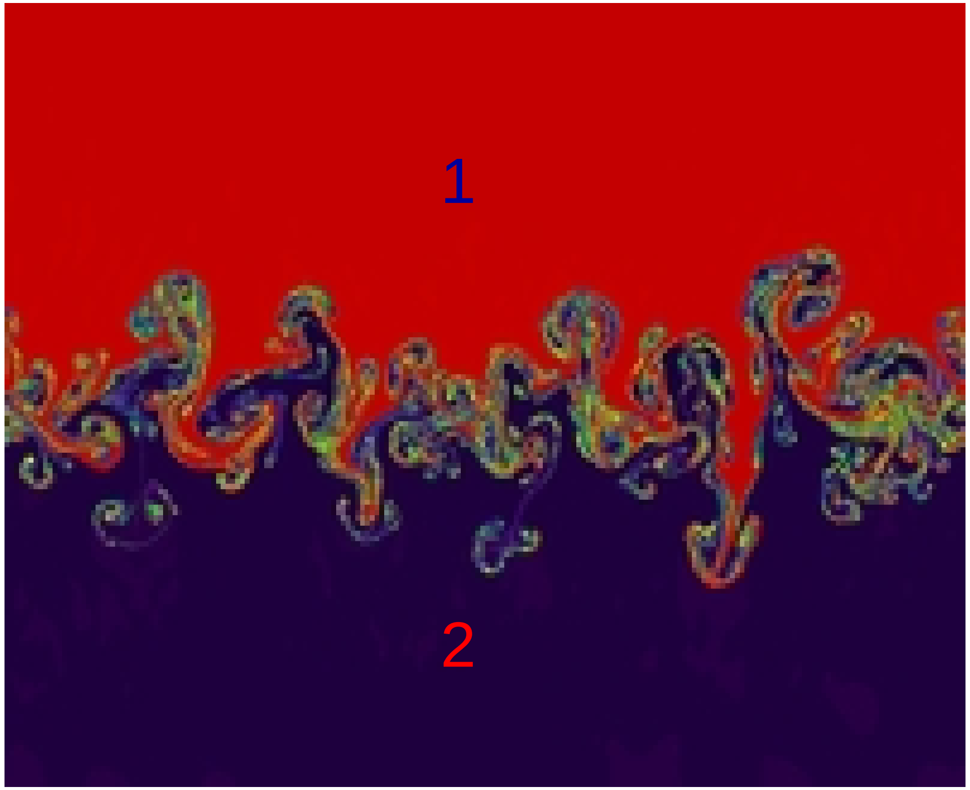
Stability of the interface of two incompressible fluids under constant acceleration normal to the interface:

$$\omega = \sqrt{kg\frac{\rho_2 - \rho_1}{\rho_1 + \rho_2}}$$

Unstable when heavy fluid is on top.

Small scale grows fastest.

Magnetic field/surface tension stabilize it.



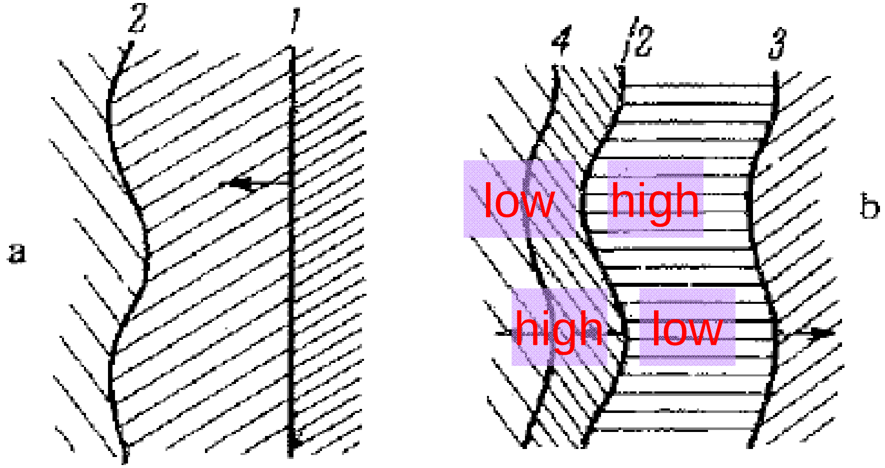
Generalization:

The interface is unstable when pressure and density gradient are in opposite sign.

(Chevalier 1976)

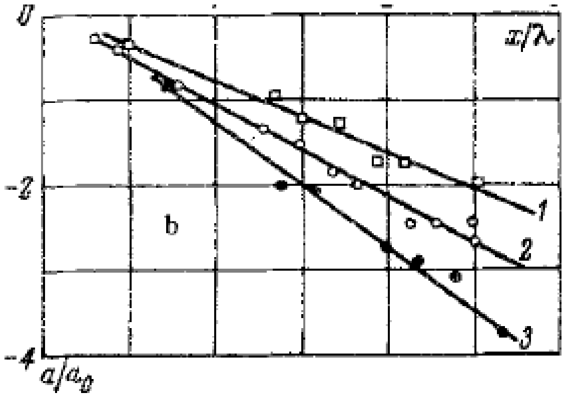
Basic physics: Richtmyer-Meshkov instability

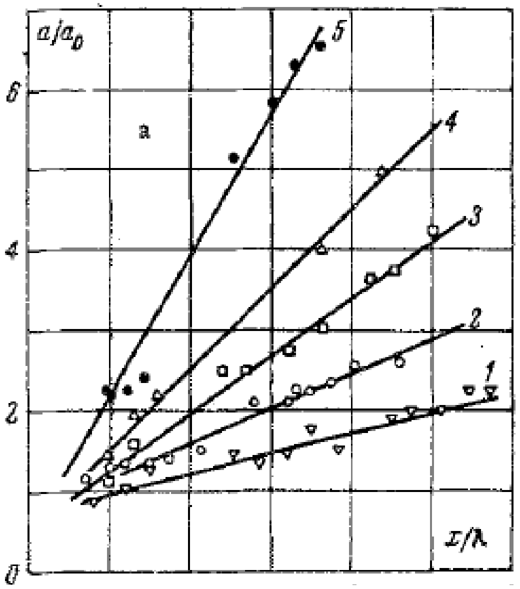
Stability of the interface of two fluids under impulsive acceleration:

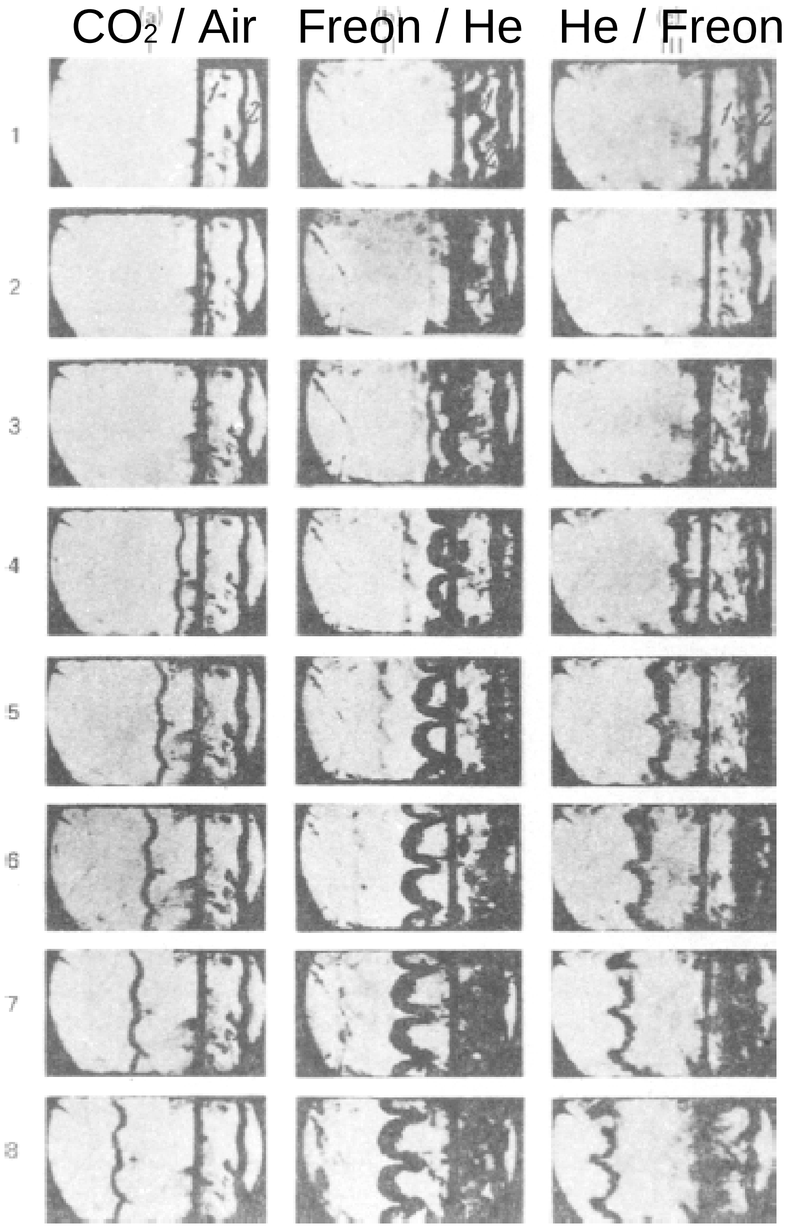


Always unstable!

Linear growth!





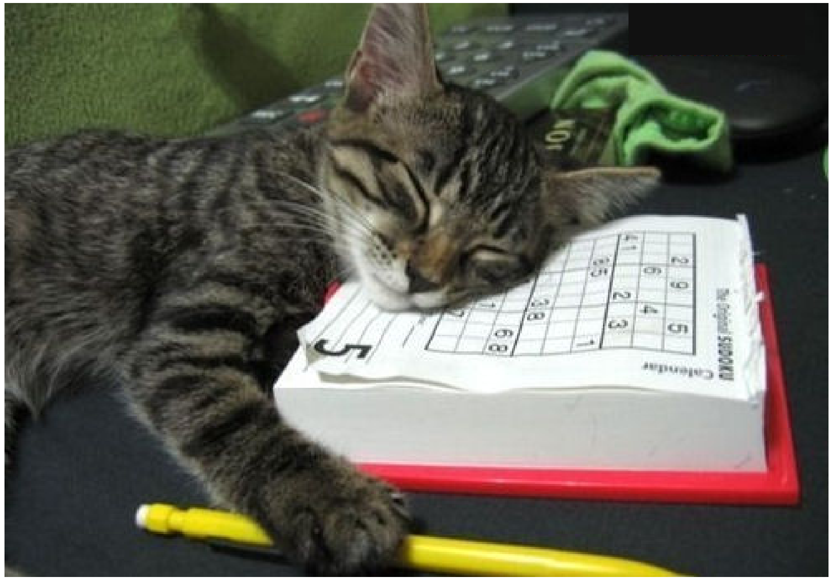


Numerical Simulations of Mixing in Supernova Explosions

Numerical Simulation: General Issues

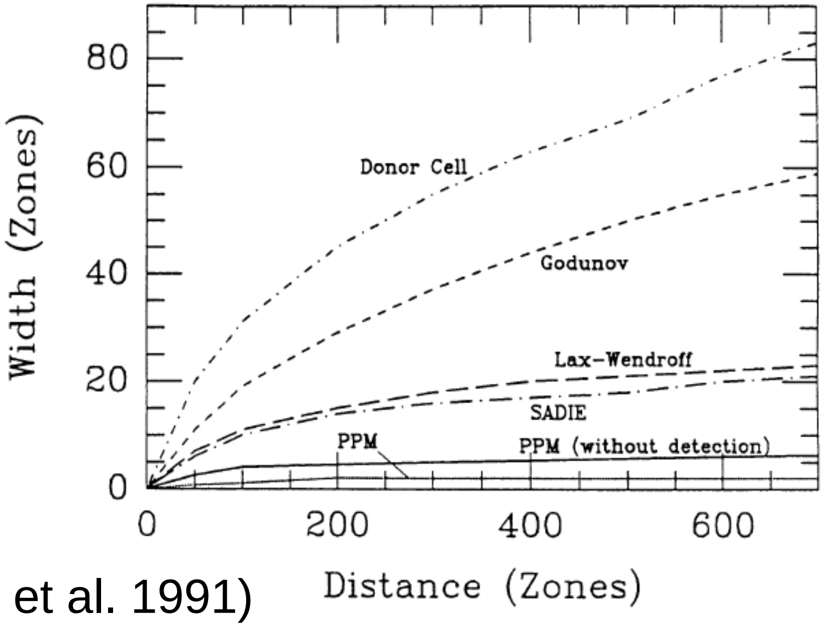
Physical ingredients

- Stellar evolution
- Hydrodynamics
- Gravity
- Thermodynamics
- Neutrino transport
- Nuclear reactions



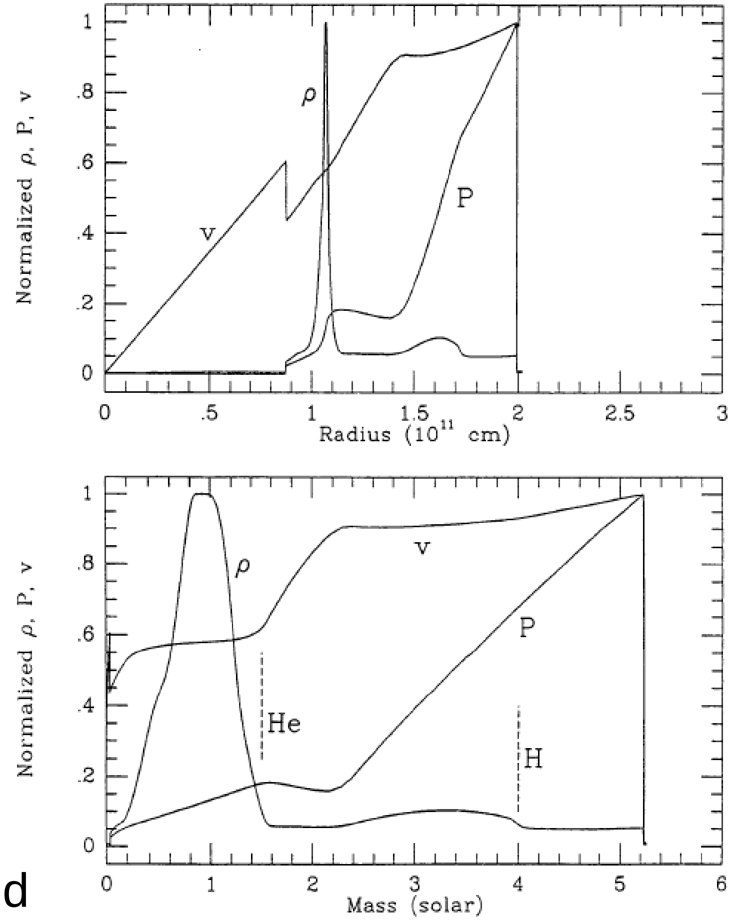
Numerical Issues

- Shock capturing
- Numerical mixing at contact discontinuities
- Time scales (millisecond – several hours)
- Spatial scales (10^8cm – 10^12cm)



(Fryxell et al. 1991)

Early 2D Numerical Simulations



Presupernova model:

Post-C burning star of 15 $M_\odot$

Metalicity = 1/4 solar

Radius $R = 3 \times 10^{12}$ cm

Mass inside the H shell: 4 $M_\odot$

Initial Explosion:

Stellar model from 0~0.1R mapped to 1D grid

Point injection of 1.0×10^{51} ergs explosion energy

Evolve until blast wave reaches the grid boundary

Mixing Calculation:

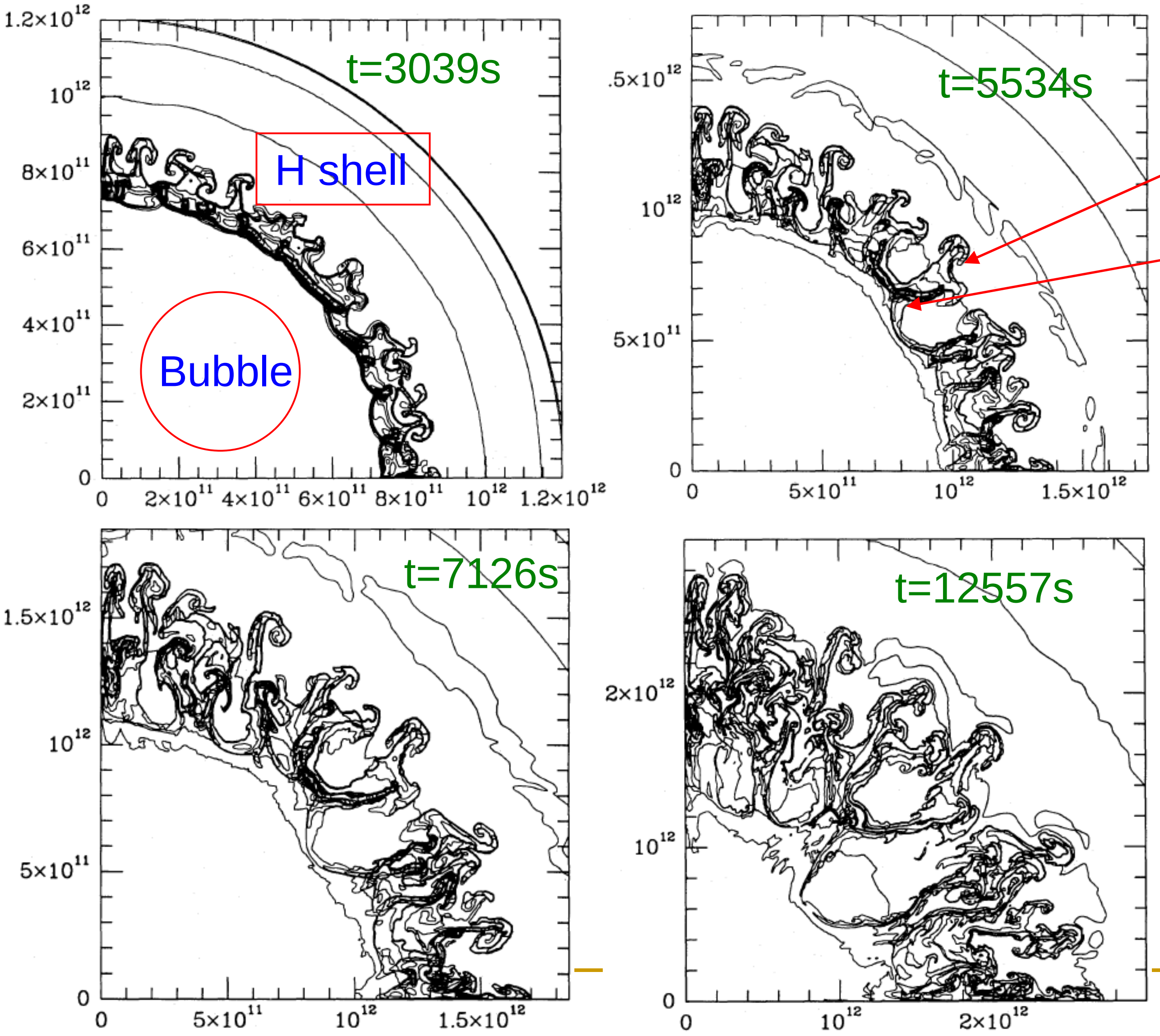
1D grid + the rest star mapped to 2D cylindrical grid

Seed initial perturbations.

Continue to evolve after shock break out.

(Fryxell et al. 1991)

Early 2D Numerical Simulations



Two interfaces are unstable to RTI:

H/He interface

He/CO interface

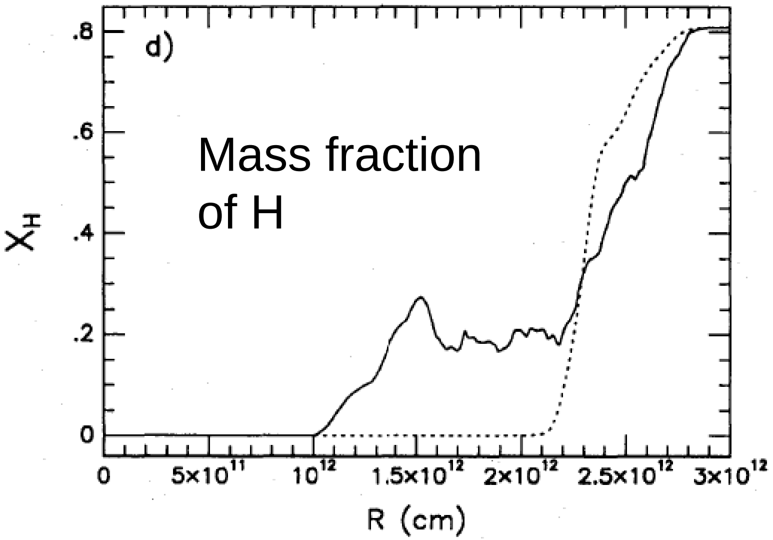
Metals are mixed to the envelope => larger velocity dispersion

H is mixed inward => smaller velocity

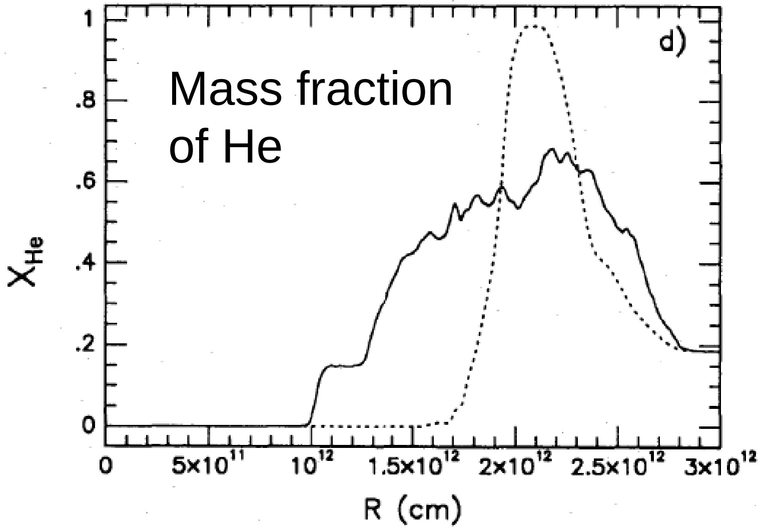
Co/Ni penetrate outward => earlier than expected X-ray/gamma-ray

(Muller et al. 1991)

Early 2D Numerical Simulations

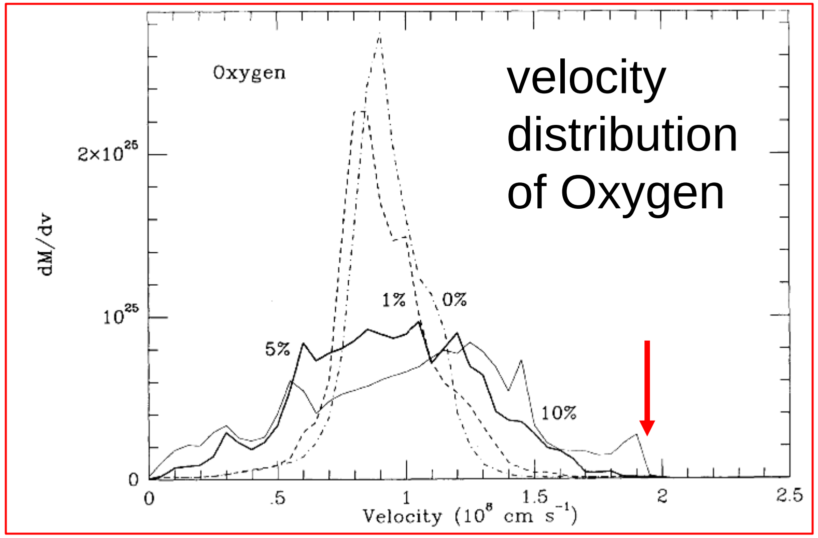


Mass fraction of H

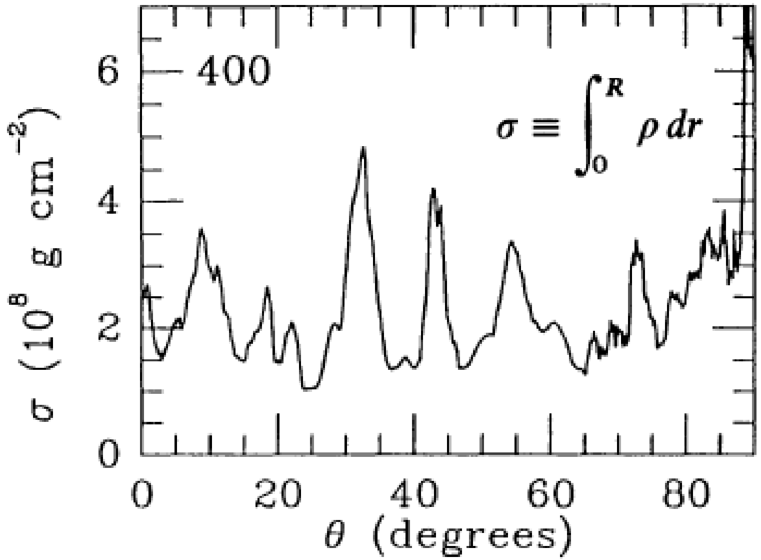


Mass fraction of He

(Muller et al. 1991)



velocity distribution of Oxygen



(Fryxell et al. 1991)

Recent 2D Numerical Simulations

Initial Condition:

- Presupernova model from Woosley et al. (1988)
- 20 ms after core bounce from Bruenn (1993)
- Random perturbation (0.1%) added to velocity

First second: neutrino-hydrodynamics calculation

- Isotropic neutrino injection from retreating inner boundary (60km to 15km)
- Simple (but non-trivial) treatment neutrino transport
- Nuclear reaction network: 32 species, 141 reactions
- Self-gravity (2D) with general-relativistic corrections (1D)

Beyond first second: hydrodynamic calculation (to 20000s)

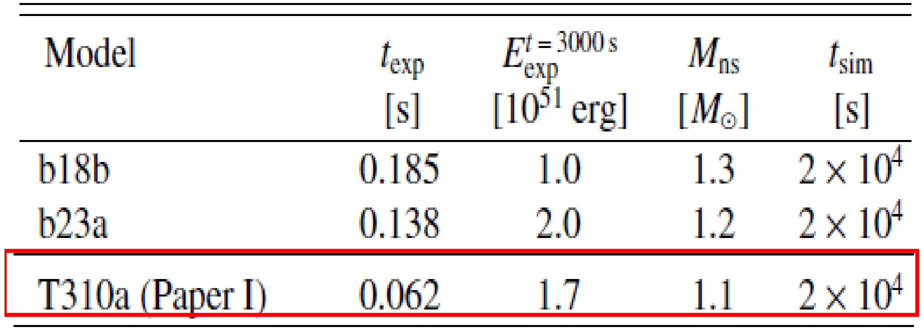
- Transmitting boundary condition at (moving) inner and outer boundary
- Adaptive mesh refinement with zooming algorithm to achieve high resolution
- No neutrinos / Same nuclear network / Self-gravity in 1D (radial)

Miscellaneous

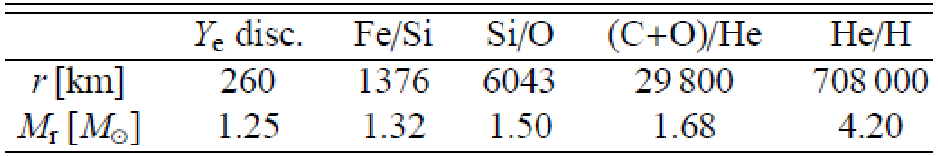
- 2D polar coordinate / Non-equidistant radial zones / EoS from e, photon, pairs, & 14 nuclei
- Advanced hydro solver, especially improvement to resolve grid-aligned shock

(Kifonidis et al. 2003, 2006)

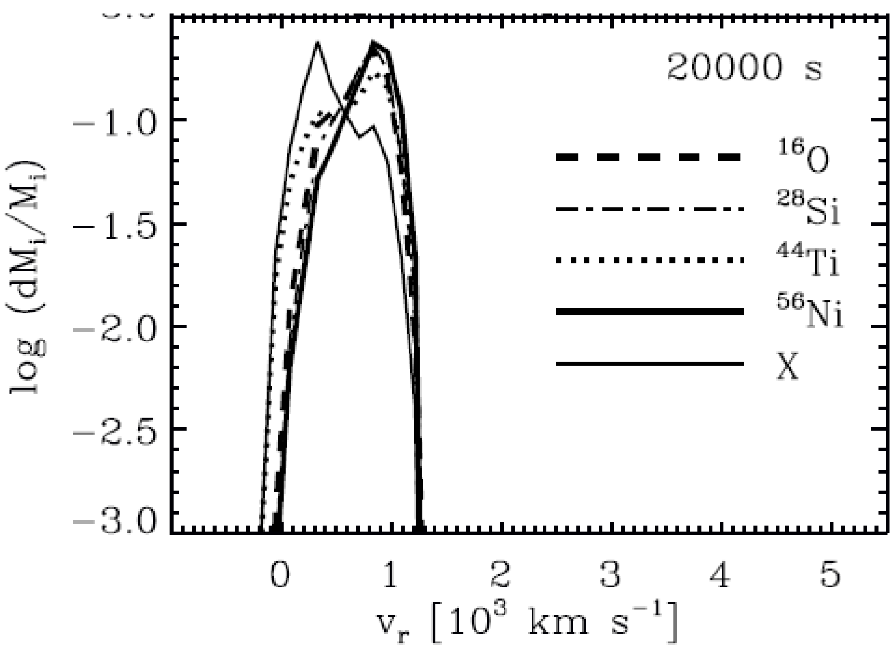
Recent 2D Numerical Simulations



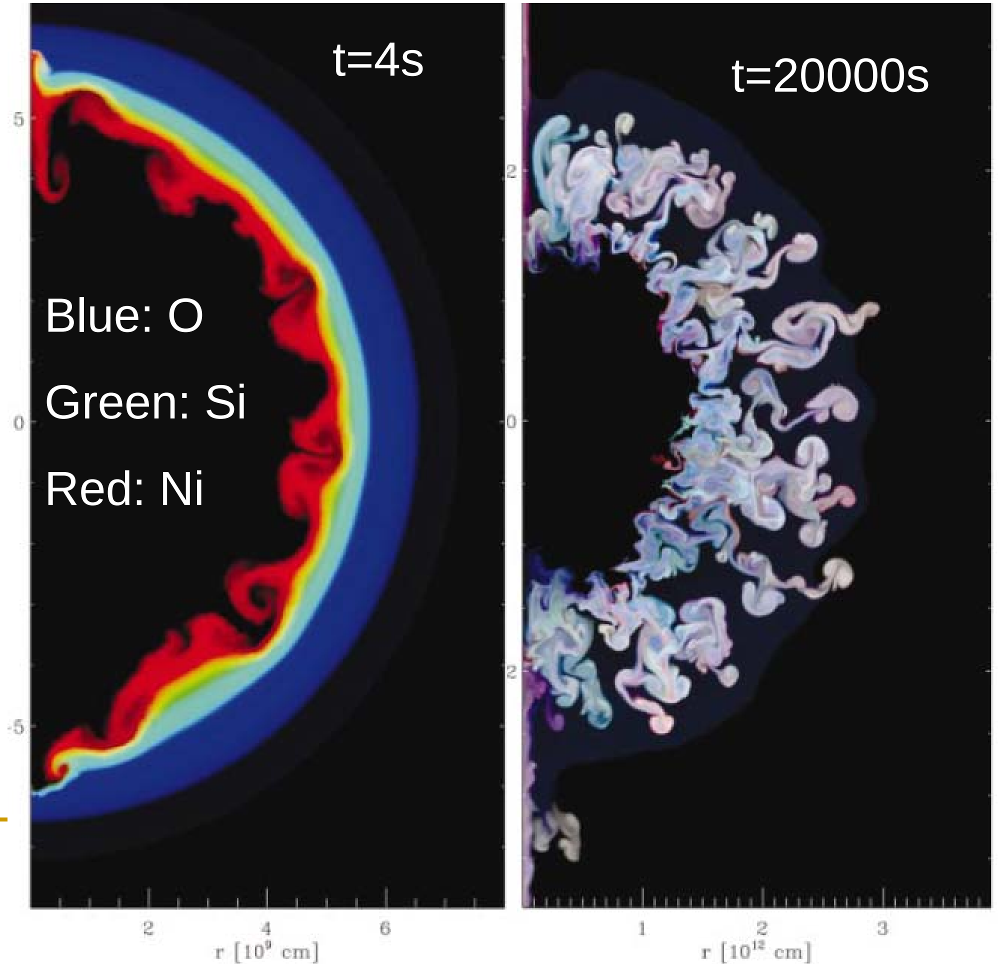
Model	$t_{\rm exp}$ [s]	$E_{\rm exp}^{t=3000\,{\rm s}}$ [10^{51} erg]	$M_{\rm ns}$ [$M_\odot$]	$t_{\rm sim}$ [s]
b18b	0.185	1.0	1.3	2×10^4
b23a	0.138	2.0	1.2	2×10^4
T310a (Paper I)	0.062	1.7	1.1	2×10^4



	Y_e disc.	Fe/Si	Si/O	(C+O)/He	He/H
r [km]	260	1376	6043	29 800	708 000
M_r [$M_\odot$]	1.25	1.32	1.50	1.68	4.20



(Kifonidis et al. 2003)



t=4s

t=20000s

Blue: O

Green: Si

Red: Ni

Recent 2D Numerical Simulations

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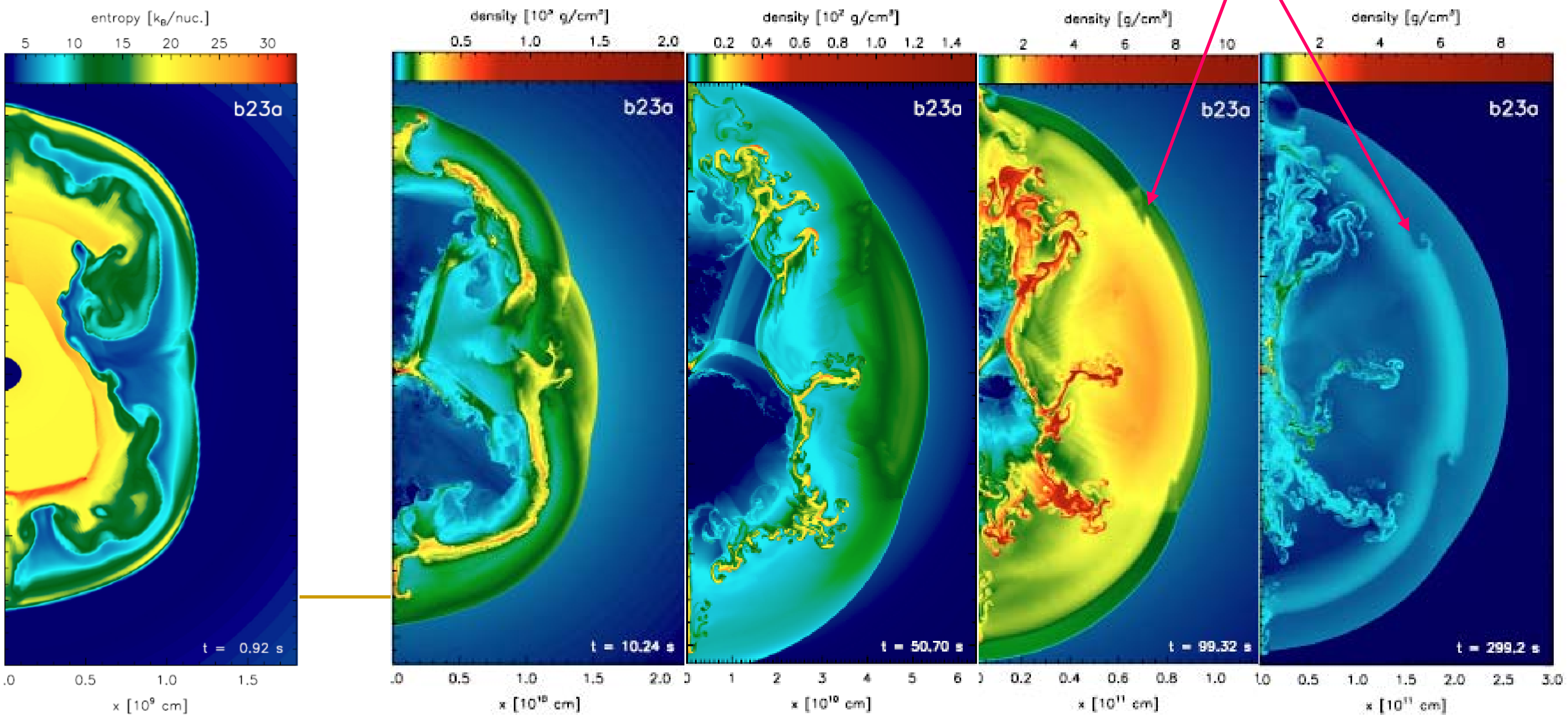
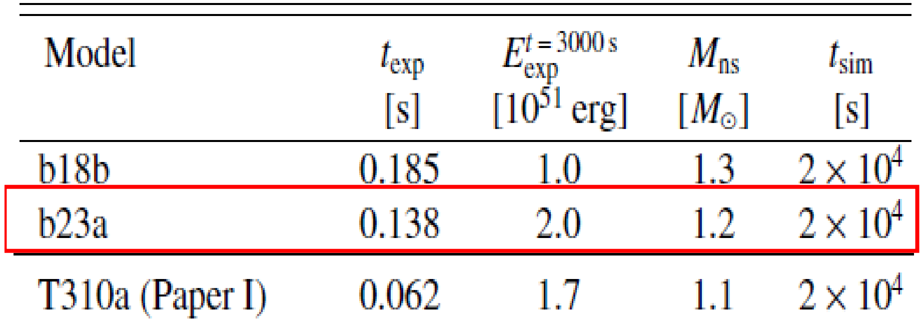
(Kifonidis et al. 2006)

development of RMI from H/He interface



Recent 2D Numerical Simulations



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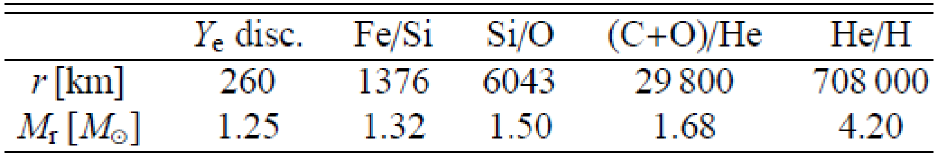

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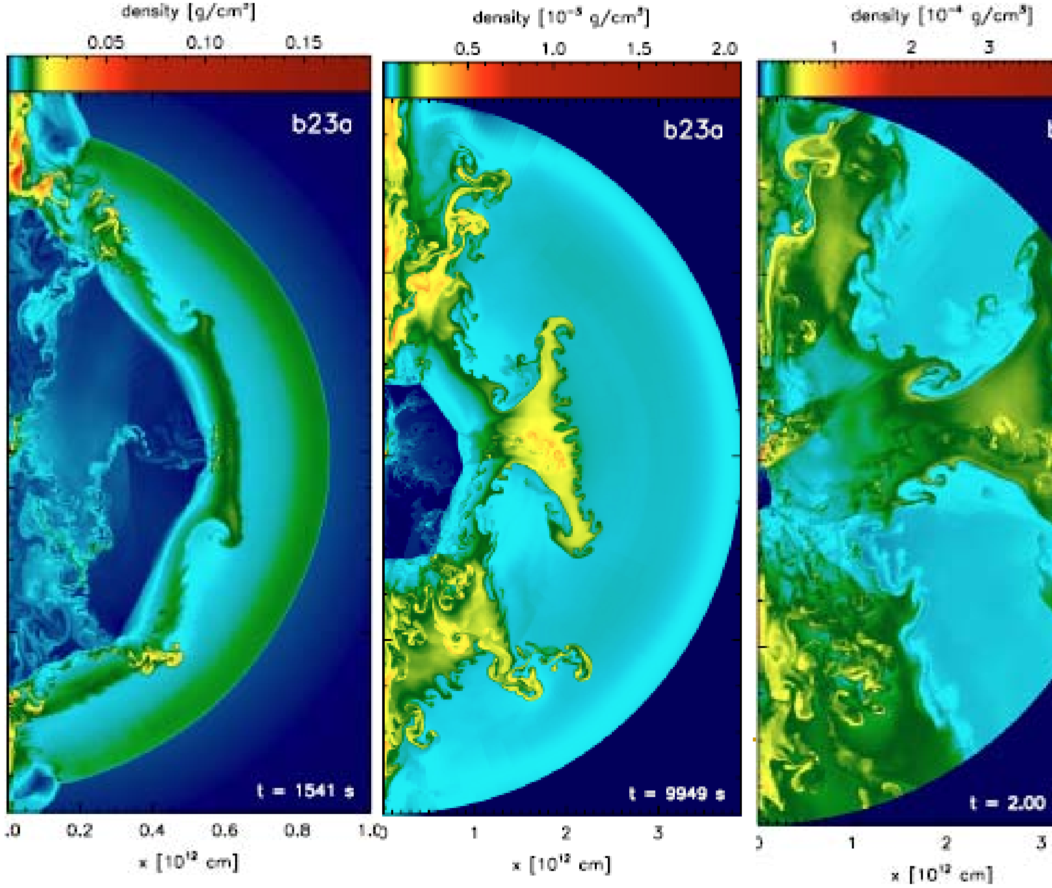
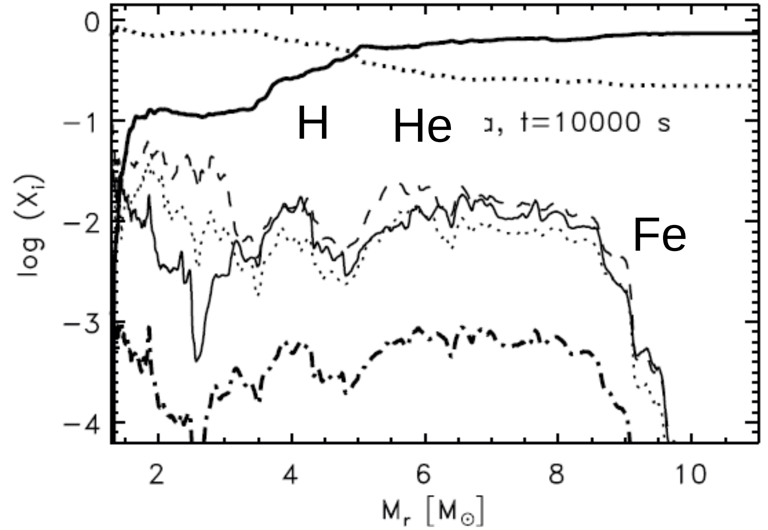
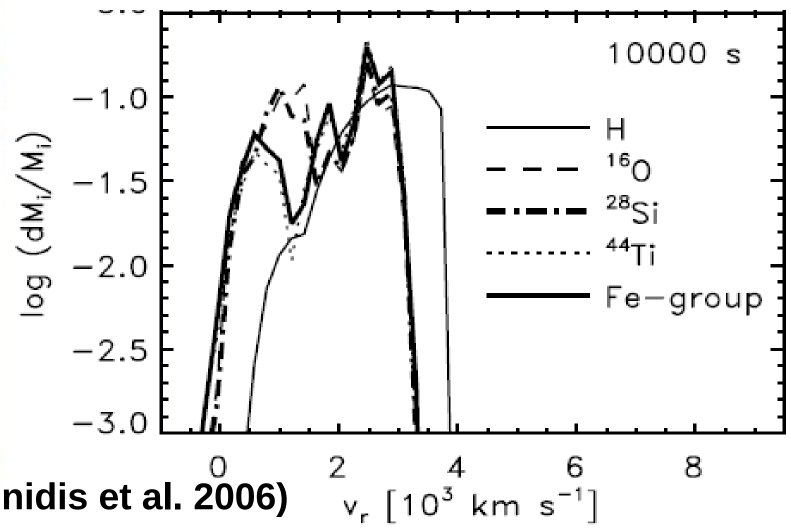
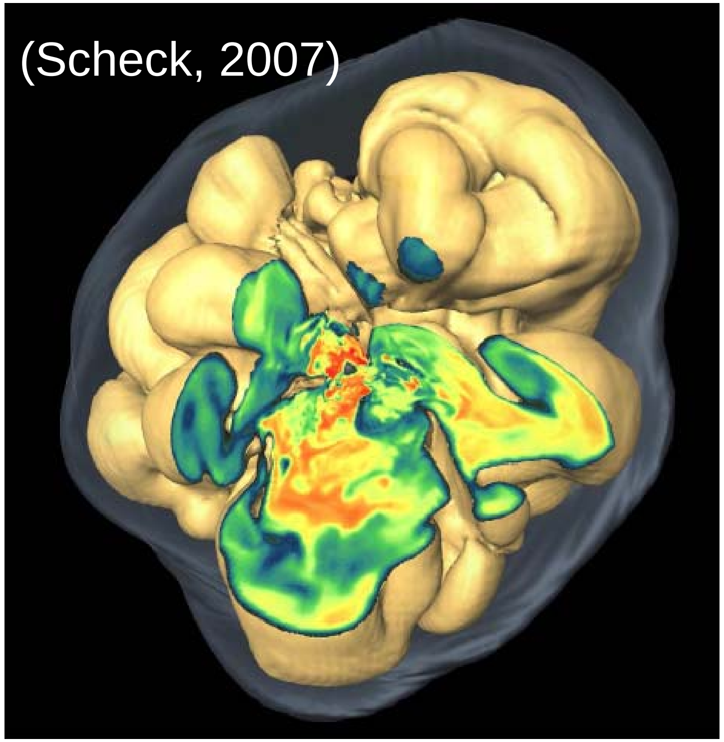




(Kifonidis et al. 2006)



First 3D Numerical Simulation



Initial condition:

Presupernova model from Woosley et al. (1988)

3D simulation of neutrino-driven explosion at 0.5s →

2D runs initialized from different meridional slices

Boost explosion energy to 1e51erg

Input physics:

First 0.5 second similar to the previous 2D model

Neglect nuclear reactions

No self-gravity

Slightly simplified EoS, especially, no Si

Computational method:

3D spherical polar coordinates / Resolution 1200x180x360 (no AMR)

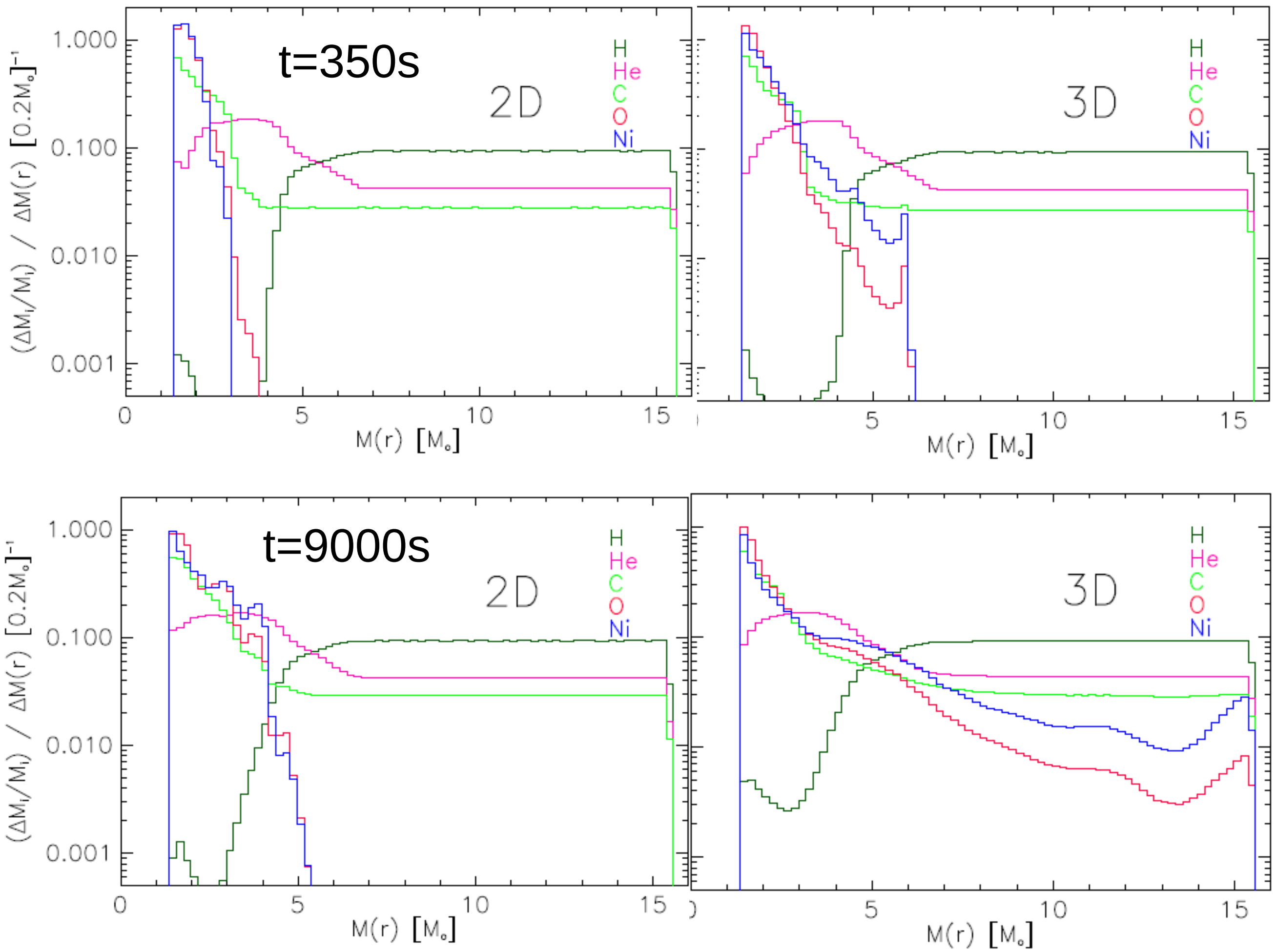
Logarithmic radial spacing with $dr/r \sim 0.01$

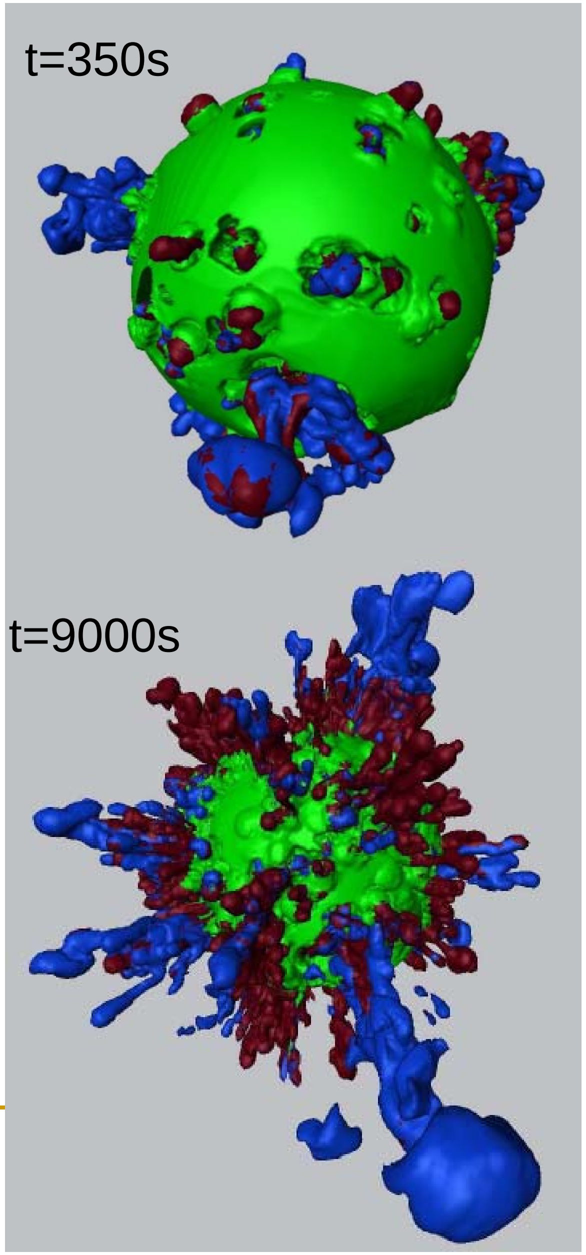
Inner/outer bourndary at 200km/3.9e12cm; Inner/outer BCs are reflecting/outflow

(Hammers et al. 2009)

First 3D Numerical Simulation

Mass distribution of elements

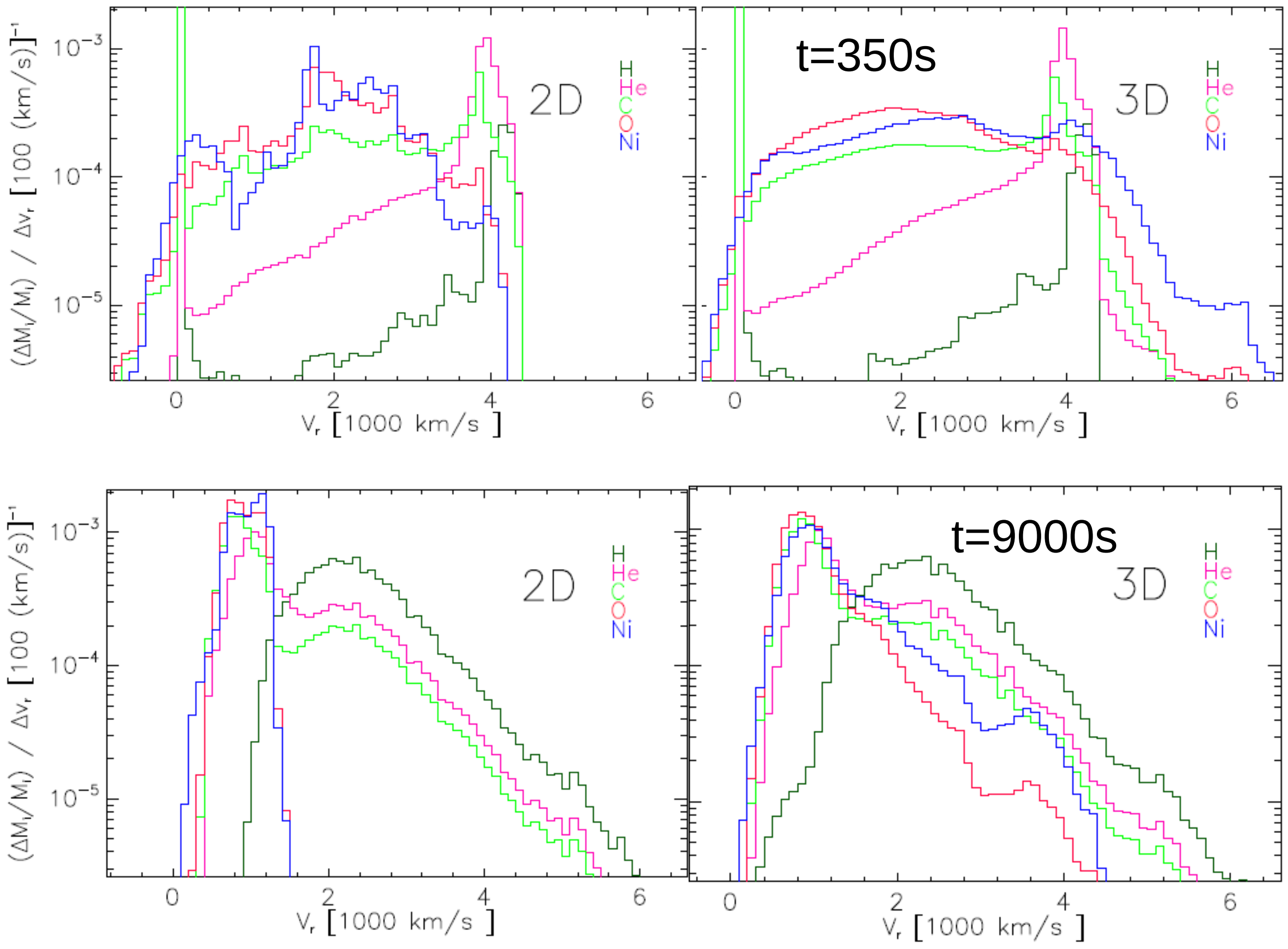




(Hammers et al. 2009)

First 3D Numerical Simulation

Velocity distribution of elements



Significant higher velocity in 3D early on

Rayleigh-Taylor instability grows faster in3D

Metal-rich clumps decelerates less in 3D

Less “drag” experienced by “spheres” than by “torus”

(Hammers et al. 2009)

Summary

- There are plenty of observational evidences of asymmetry and mixing in supernova explosions
- Rayleigh-Taylor instability and Richtmyer-Meshkov instability are important sources of mixing in supernova envelopes
- Multi-dimensional approach with all relevant physics, a capable code and sufficient computational power are essential to study the mixing problem of supernova explosion

- In 2D calculations, low-mode oscillations in the neutrino-driven phase appear to be essential to reproduce observational data
- The first 3D simulation shows that outward mixing of heavy elements and inward mixing of hydrogen is more efficient than in 2D

- We are approaching the reality, but still lack global agreement

Main References

- Arnett, D., Bahcall, J., Kirshner, R., Woosley, S.E., 1989, ARA&A, 27, 629
- Fryxell, B., Muller, E., Arnett, D., 1991, ApJ, 367, 619
- Hammer, N.J., Janka, H.-Th., Muller, E., 2009, arxiv:0908.3474
- Kifonidis, K., Plewa, T., Janka, H.-Th., Muller, E., 2003, A&A, 408, 621
- Kifonidis, K., Plewa, T., Scheck, L., Janka, H.-Th., Muller, E., 2003, A&A, 453, 661
- Muller, E., Fryxell, B., Arnett, D., 1991, A&A, 251, 505
- Scheck, L., Kifonidis, K., Janka, H.-T., Muller, E., 2006, A&A, 457, 963