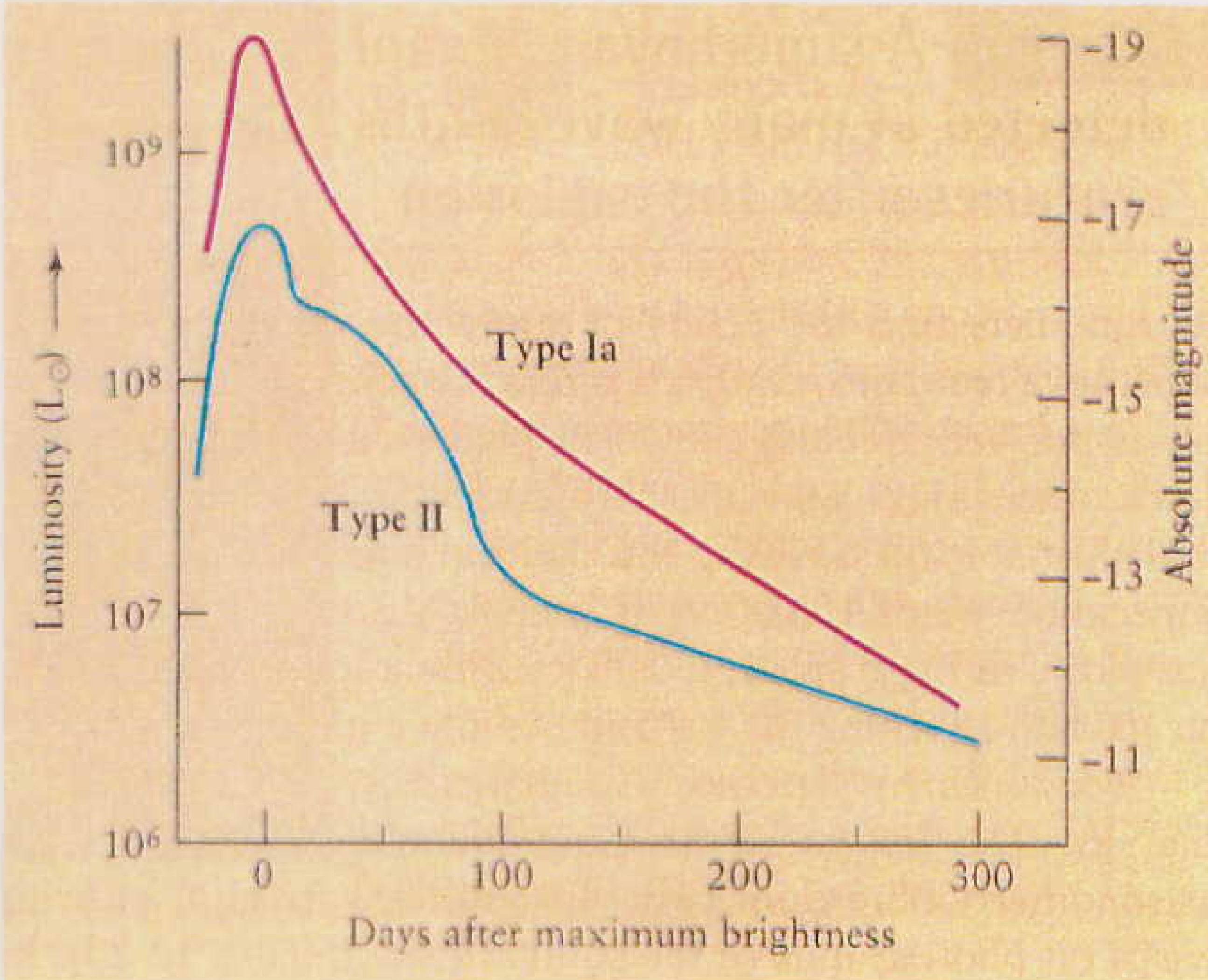
Physical Sciences 120
Winter 2005

*Origin of the Universe,
and How We Know*

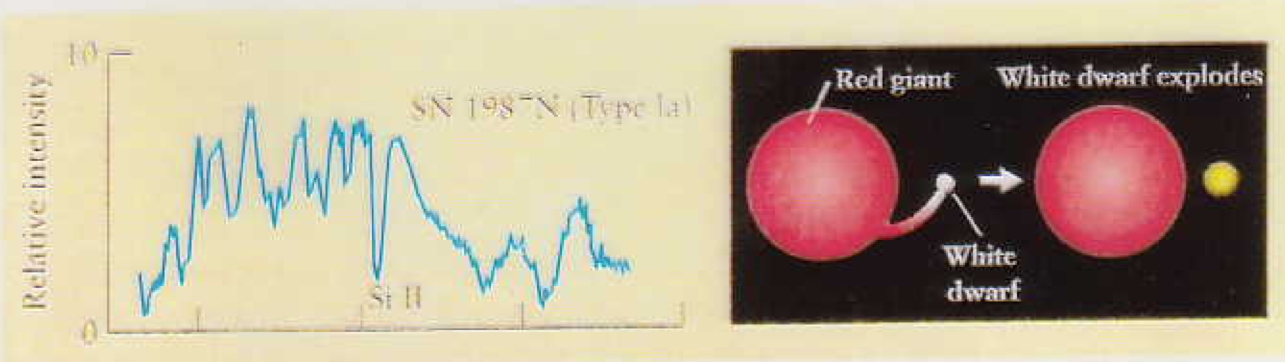
Don Q. Lamb

Lecture 22

TYPE Ia SUPERNOVAE



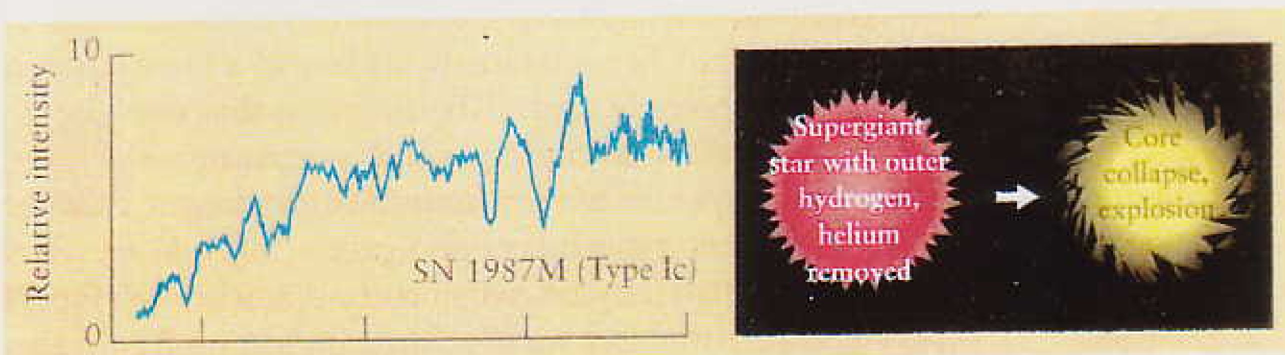
Luminosity ($L_\odot$)
10^9
10^8
10^7
10^6
Type Ia
Type II
0
100
200
300
Days after maximum brightness
-19
-17
-15
-13
-11
Absolute magnitude


10
0
Relative intensity
SN 1987N (Type Ia)
Si II
Red giant
White dwarf explodes
White
dwarf

a


10
0
Relative intensity
SN 1984L (Type Ib)
He I
Supergiant
star with outer
hydrogen
removed
Core
collapse,
explosion

b


10
0
Relative intensity
SN 1987M (Type Ic)
Supergiant
star with outer
hydrogen,
helium
removed
Core
collapse,
explosion

c


10
0
Relative intensity
SN 1992H (Type II)
H_α
400
600
800
1000
Wavelength (nm)
Supergiant
star with
outer layers
largely intact
Core
collapse,
explosion

d

PHY. SCI. 120

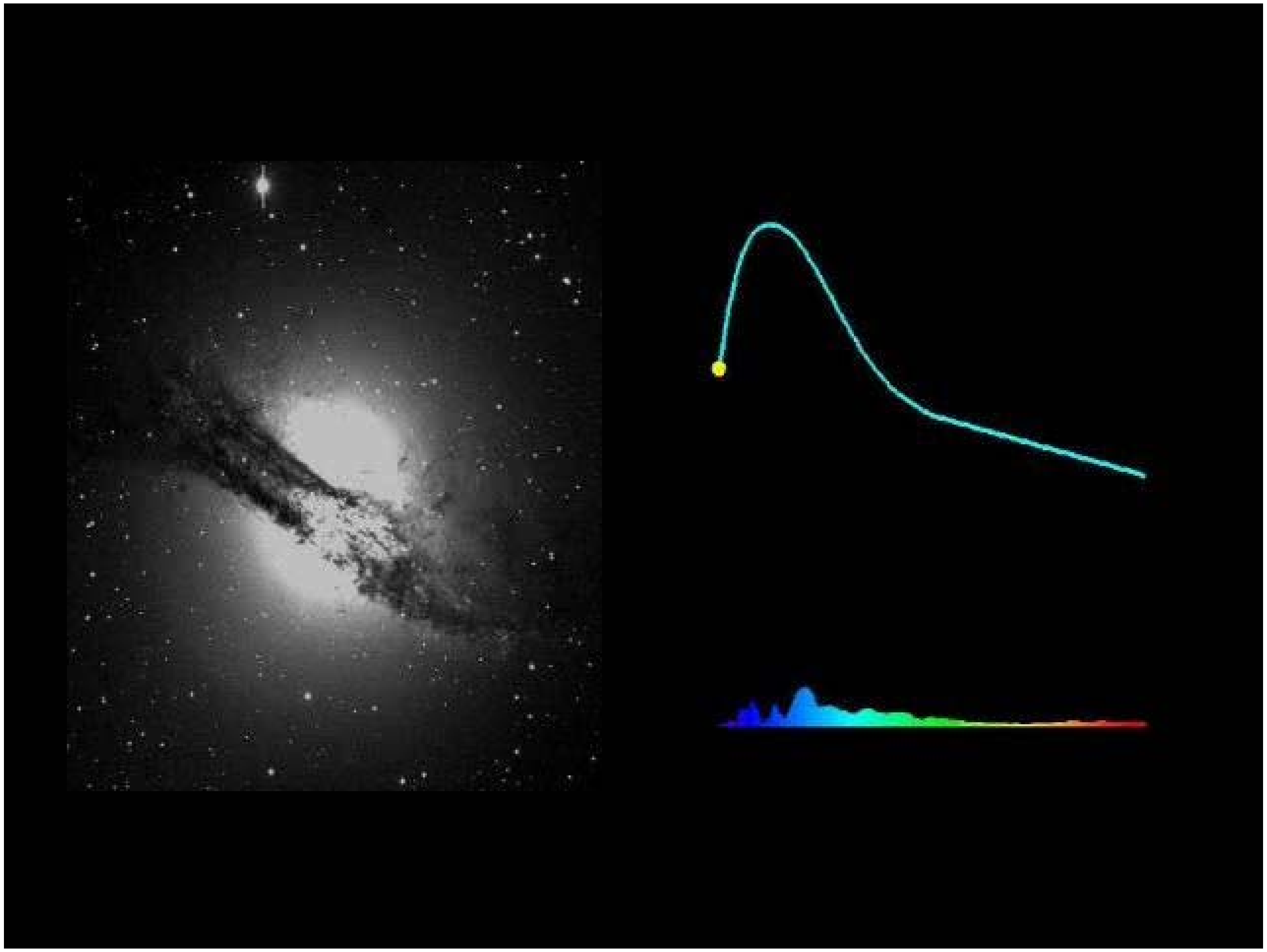
Spring Quarter 2004

TABLE

Properties of Supernovae

Property	Type Ia	Type Ib	Type Ic	Type II
Energy Source	Nuclear	Gravity	Gravity	Gravity
Total Energy (ergs)	3×10^{51}	3×10^{53}	3×10^{53}	3×10^{53}
Fraction of Energy in ν's	≈ 0	≈ 0.1	≈ 0.1	0.99
Fraction of Energy in KE	≈ 1	≈ 1	≈ 1	10^{-2}
Fraction of Energy in Light	3×10^{-3}	3×10^{-3}	3×10^{-3}	3×10^{-3}
H in Spectrum (Yes/No)	No	No	No	Yes
He in Spectrum (Yes/No)	No	Yes	No	Yes
Si in Spectrum (Yes/No)	Yes	No	No	No
Progenitor Star	White Dwarf	$20 - 60\ M_\odot$ Star	$20 - 60\ M_\odot$ Star	$10 - 60\ M_\odot$ Star
Remnant	None	Black Hole	Black Hole	Neutron Star or Black Hole

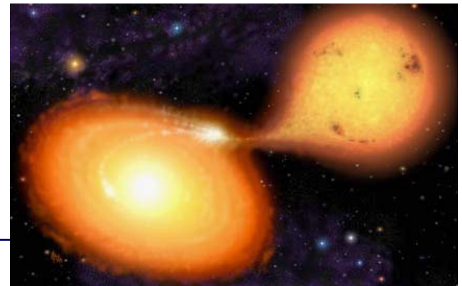
Type Ia Supernova



Supernova Cosmology Project

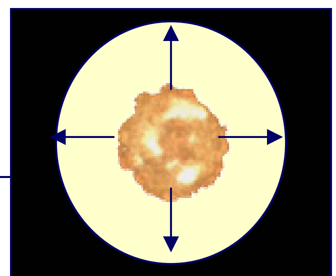
Type Ia Supernovae

Image copyrighted by Mark A. Garlick



Accretion

$>10^8$ yr

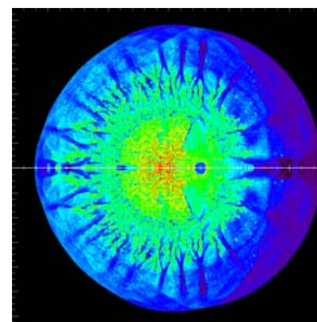


Smoldering

Subsonic convection in core of white dwarf

~1000 yr

Ignition



Flame

- Initial deflagration
- DDT or expansion/recollapse

~seconds

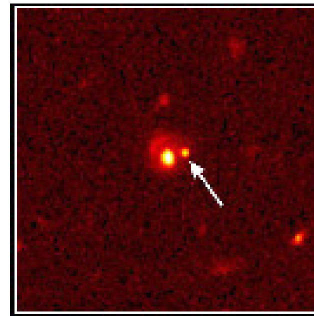


Image credit P. Garnavich/CfA

Lightcurve

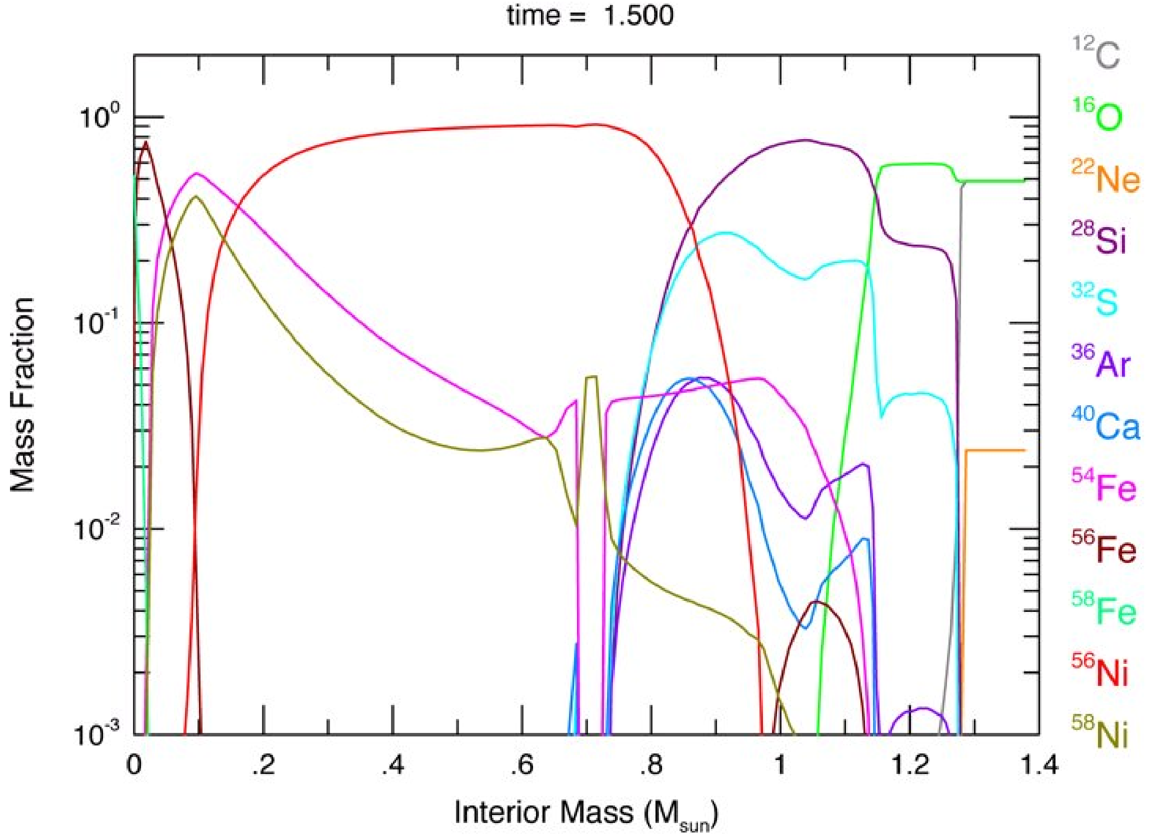
Free expansion of envelope

Some Key Questions Re Type Ia SNe

- Results of simulations are sensitive to initial conditions (center/off center ignition, single/multiple ignition points,…), yet Type Ia SN phenomenon appears robust and observed Type Ia SNe are relatively similar—how does this happen?
- What produces the range of Ni masses that are observed in Type Ia SNe and that may be the origin of the Phillips relation?
- How does a detonation occur in a medium that has no walls (i.e., that is gravitationally confined)?
- Why do 1-D models do better than 2-D models and much better than 3-D models?

Yields for Pre-Expanded White Dwarf

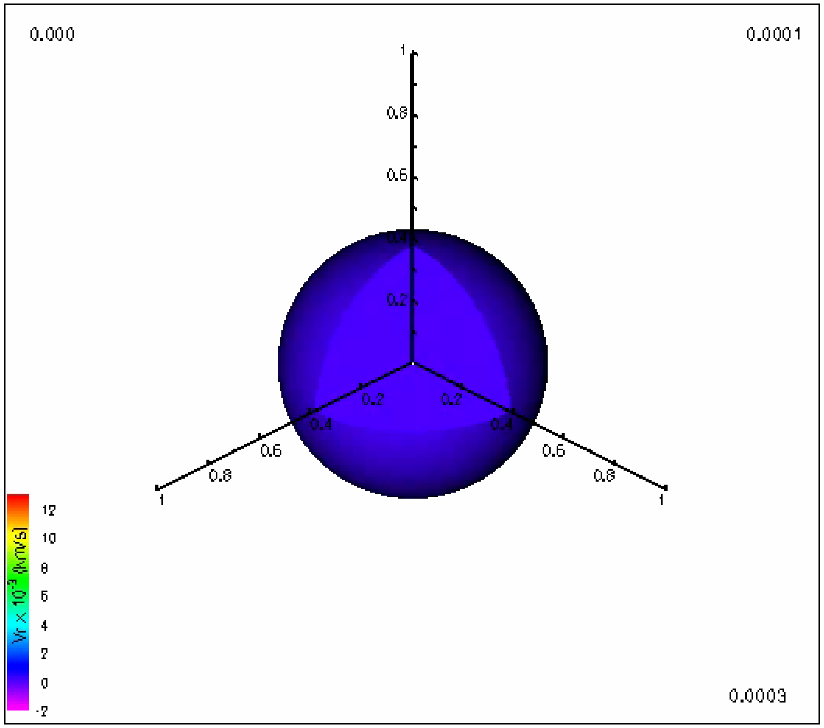
- Ironically, 1-D fast deflagration of artificially pre-expanded massive white dwarf matches observed abundances and spectra, while 2-D central ignition models do worse; 3-D central ignition models do still worse—why?



W7 model of Nomoto, Thielemann, & Yokoi (1984)

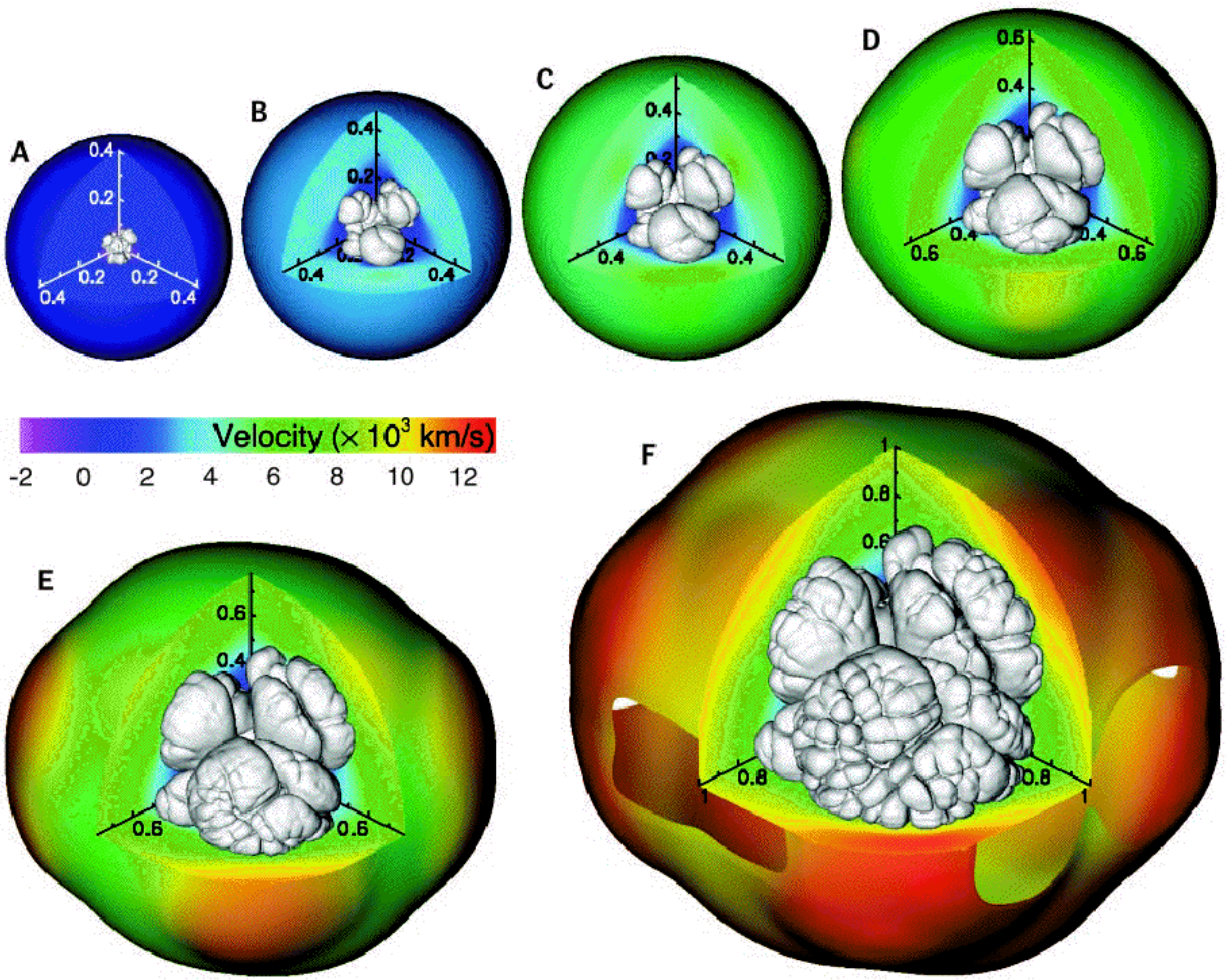
Simulations of Type Ia SN Deflagration Phase

Gamezo, Khokhlov, Oran, Chtchelkanova, Rosenberg (2002)



Simulations of Type Ia Deflagration Phase

Gamezo, Khokhlov, Oran, Chtchelkanova, Rosenberg (2002)



Simulations of Type Ia SN Deflagration Phase

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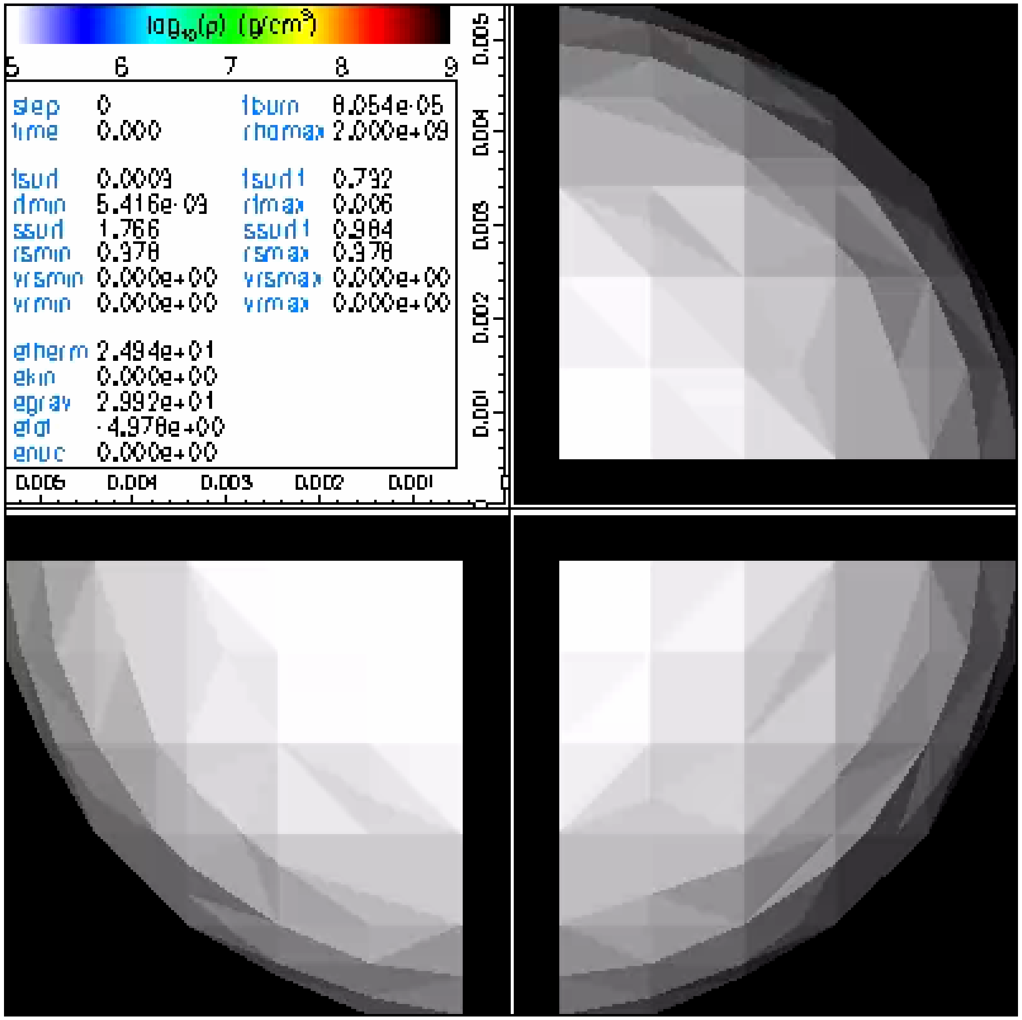
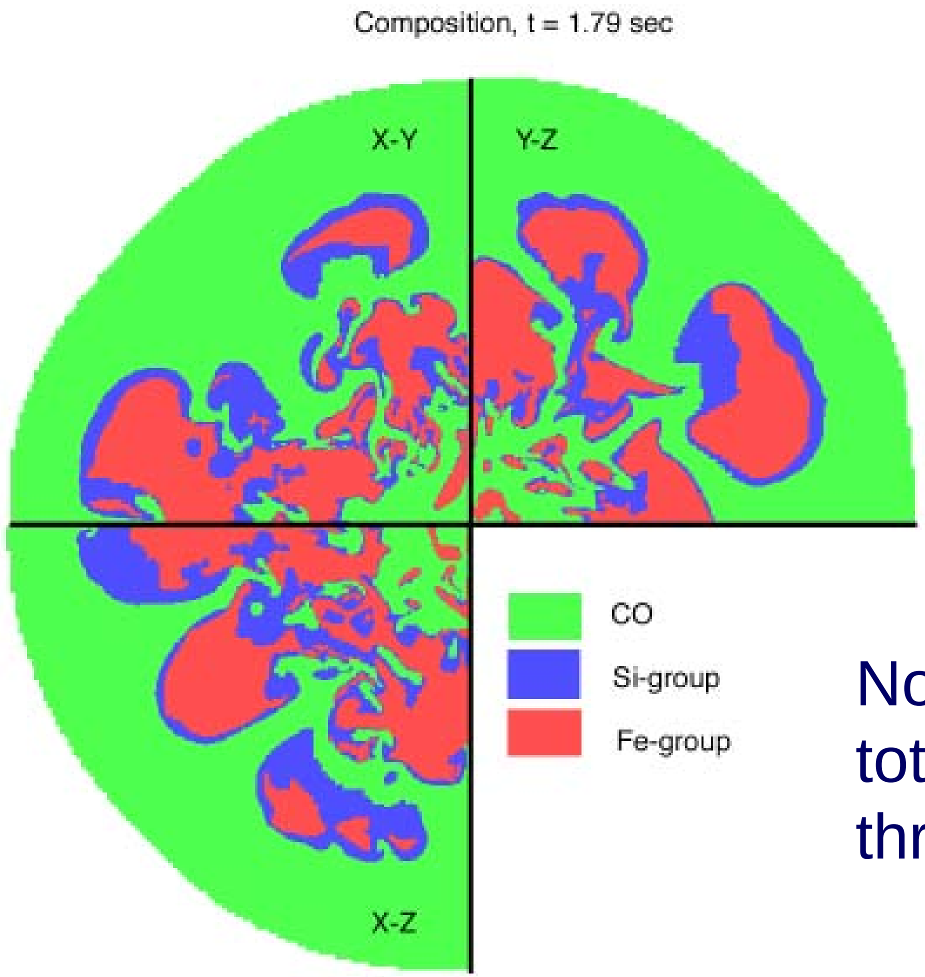


Difficulties With a 3-D Deflagration Model

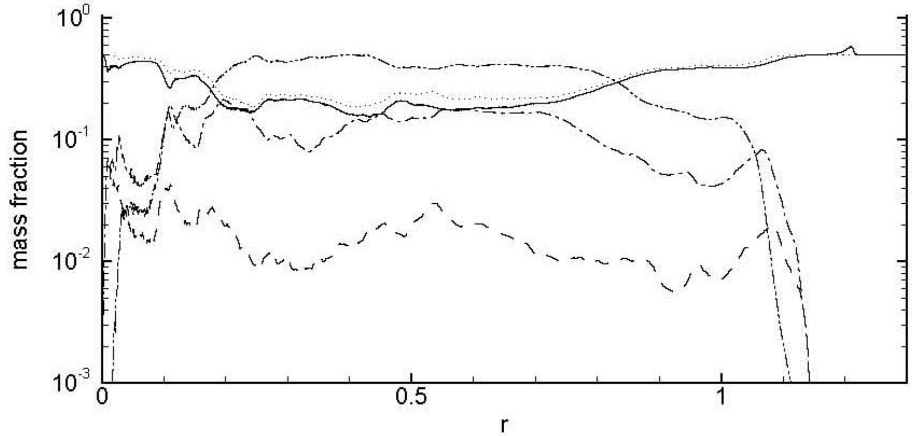


Energy of explosion
Is too small

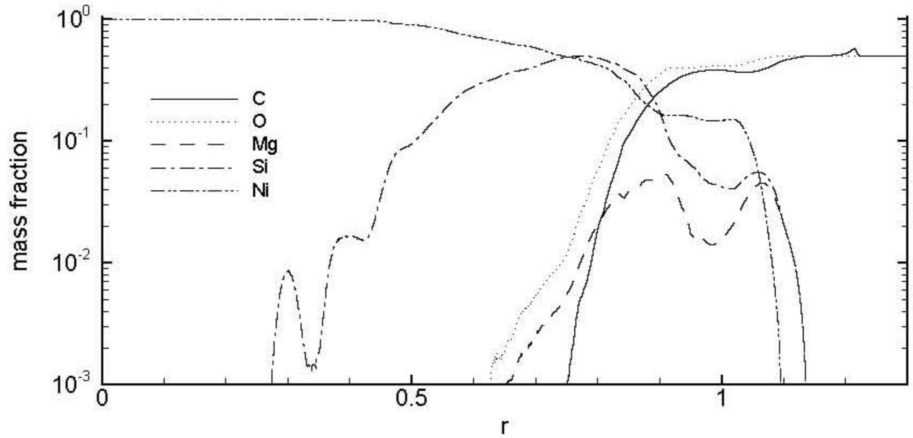
No composition stratification:
total mixing of Ni, Si, C+O
throughout the star

Effects of Delayed Detonation

Angle-averaged chemical composition:



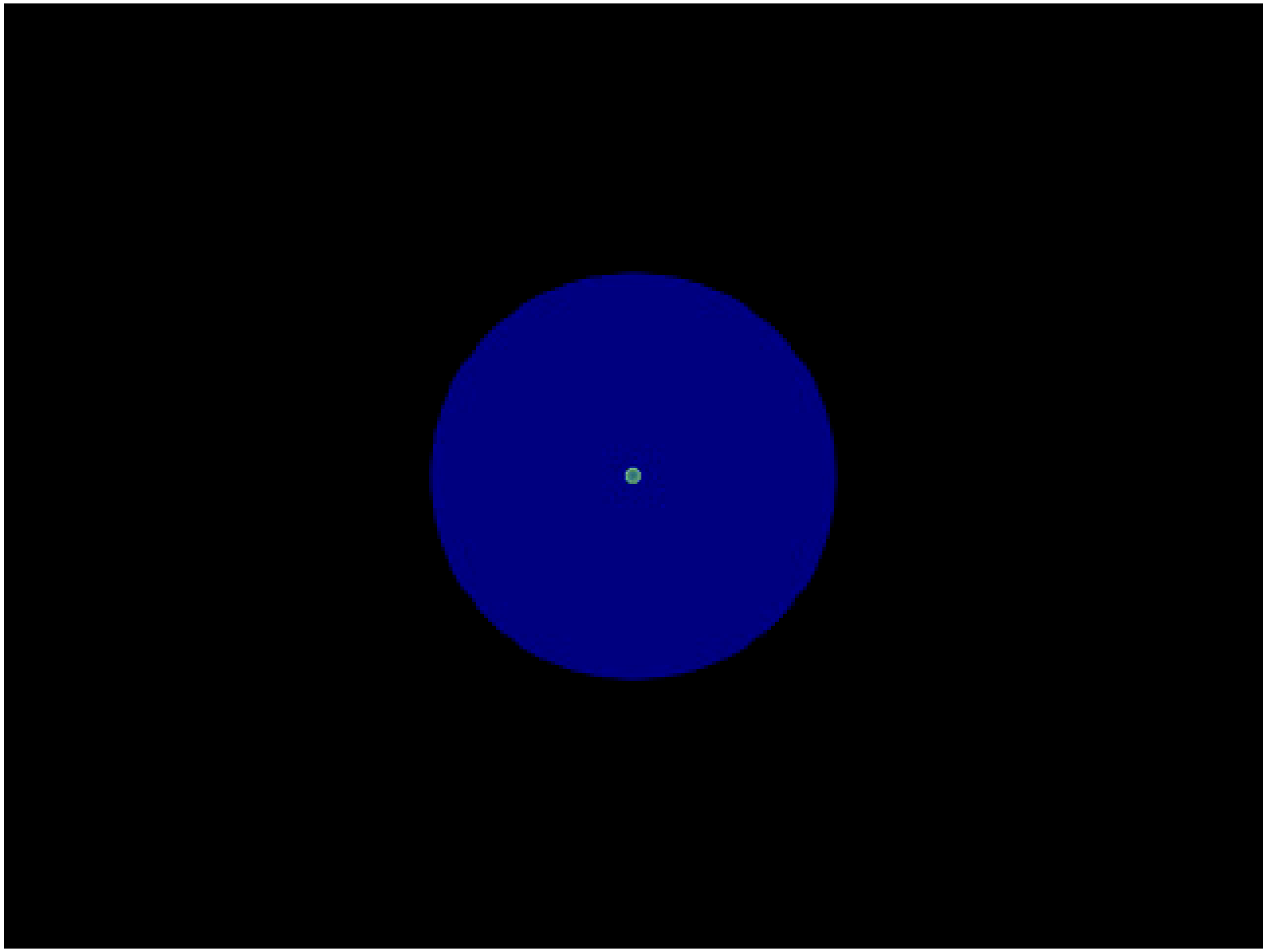
3-D Deflagration



3-D Deflagration followed by detonation

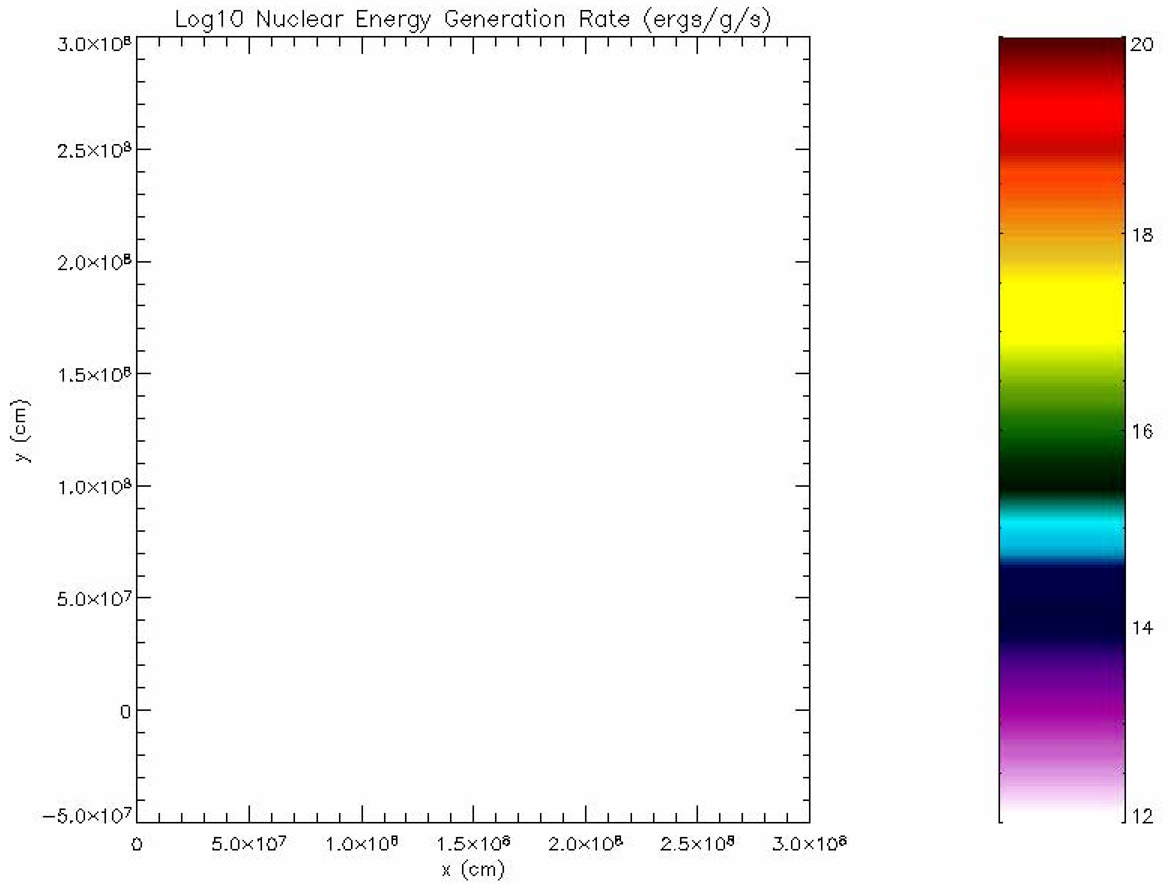
Off-center Deflagration Simulation

Calder, Vladimirova, Plewa, Lamb, Robinson & Truran (2003)



2-D *FLASH* Simulation of SO-CI Model

Slightly off-center ignition (12 km "North")…



time = 0.000 ps

number of blocks = 938

AMR levels = 8

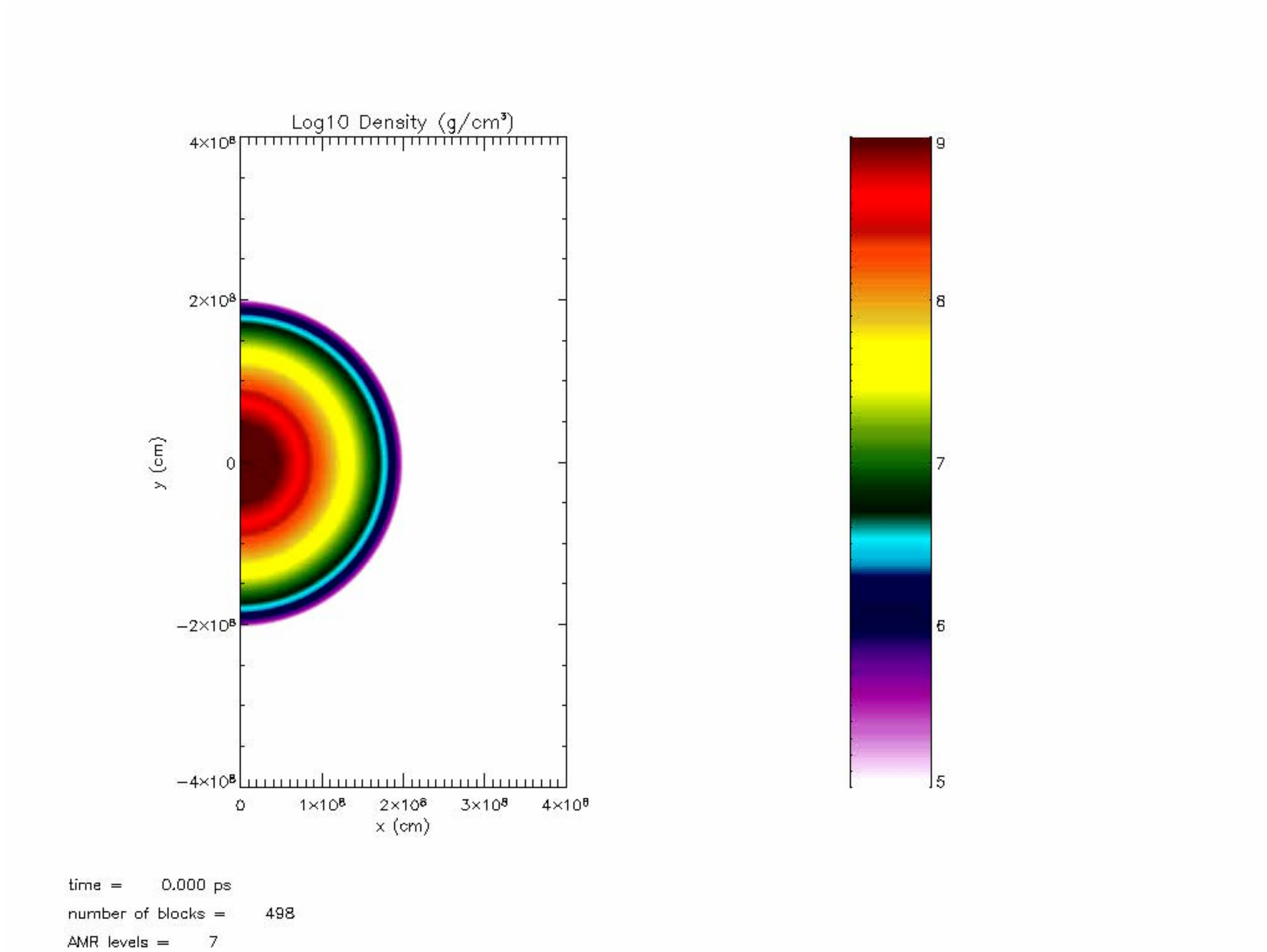
1.0×10^9 cm/s

Plewa, Calder, and Lamb (2004)

The University of Chicago

Post-Breakout Evolution in 2-D

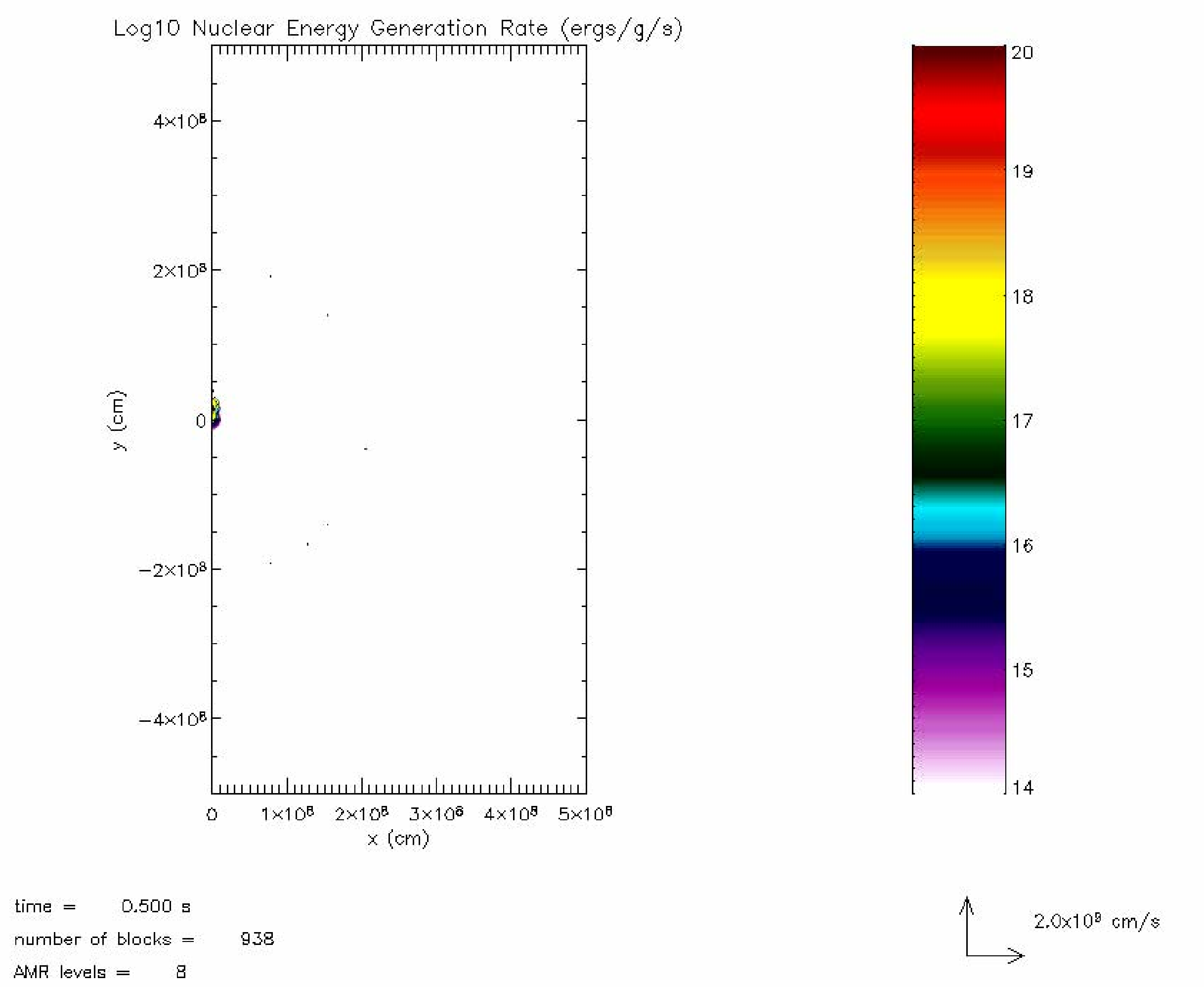
Bubble rises, breaks out, and hot bubble material flows over the surface of the star…



Plewa, Calder, and Lamb (2004)

Closer Look at Post-Breakout Evolution

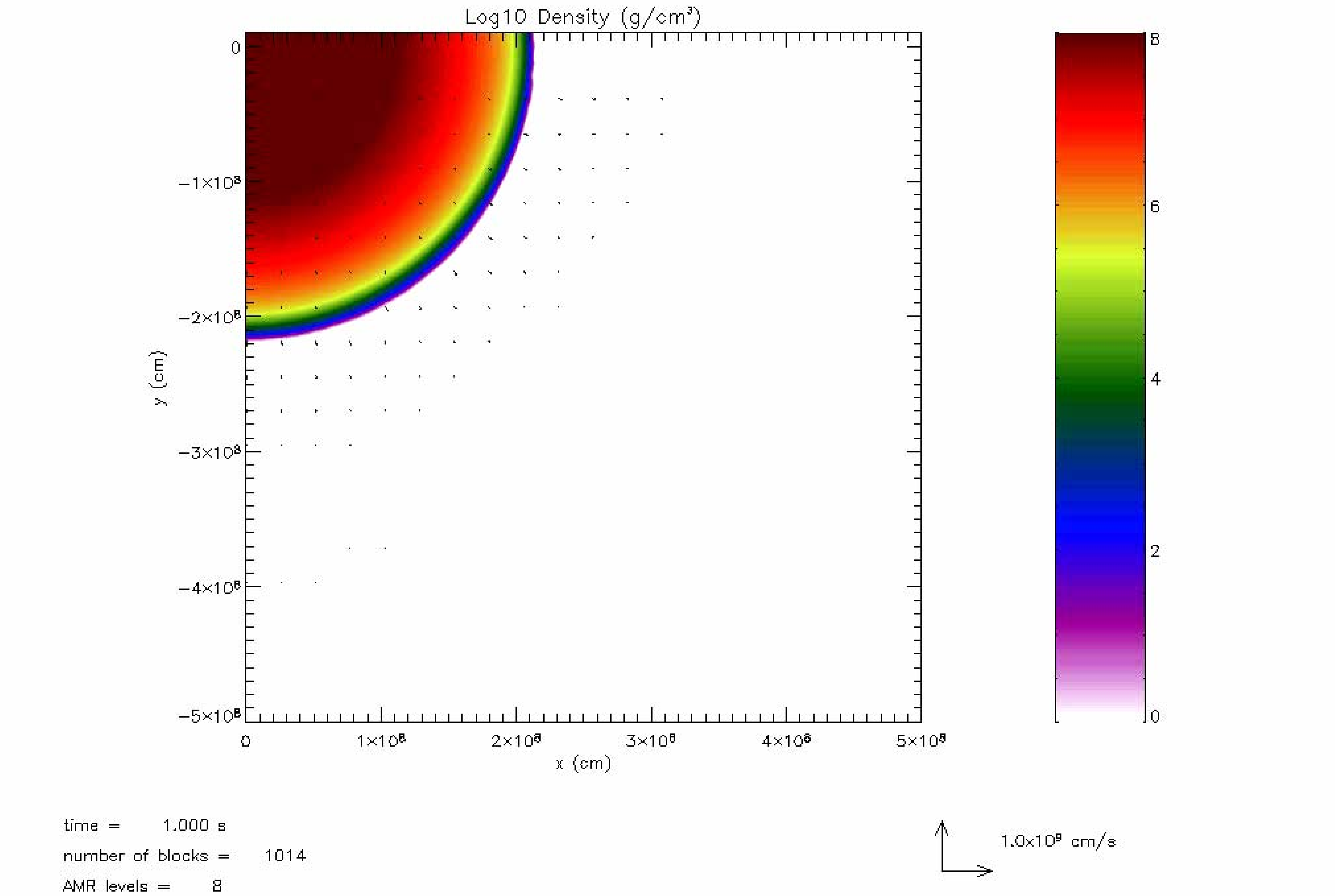
Hot bubble material converges at opposite point on surface of star...



Plewa, Calder, and Lamb (2004)

Closer Look at Post-Breakout Evolution

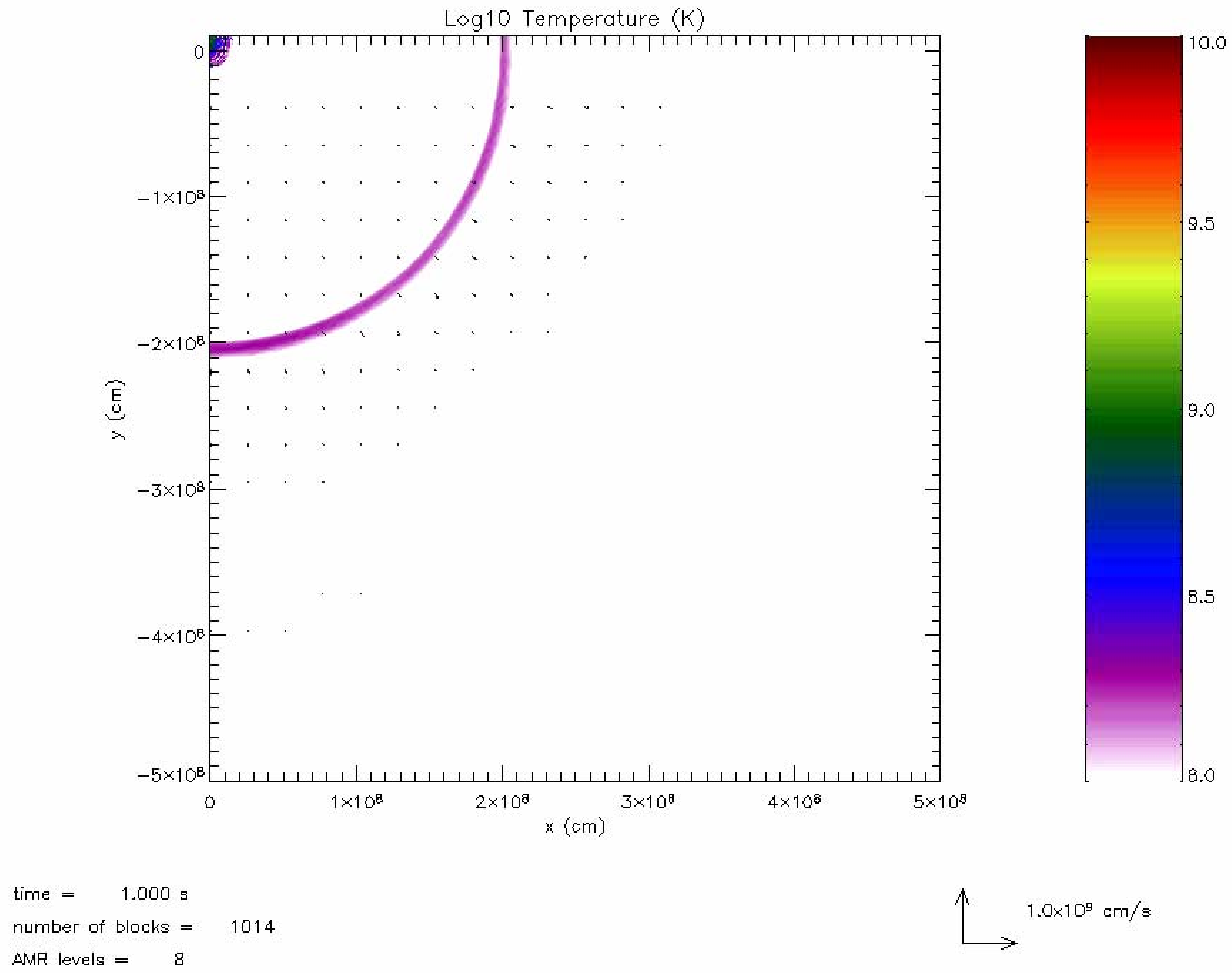
...collides, energy is converted into heat, density increases...



Plewa, Calder, and Lamb (2004)

"Gravitationally Confined Detonation"

...and creates a "gravitationally confined detonation"



Plewa, Calder, and Lamb (2004)

New Type Ia SN Mechanism

- Large-scale, 3-D, multi-physics simulations of entire star show that any off-center ignition (even slightly off-center) creates hot bubble of material that rises rapidly to surface of white dwarf
- As bubble breaks through surface, hot material flows across surface of star at high velocity, pushing material in the surface layers of the star ahead of it
- Flow converges at opposite point on surface of star; resulting compression raises density and temperature of material, initiating detonation
- First model of Type Ia SN in which detonation occurs “naturally” (i.e., without being put in by hand)
- Pre-expansion of star occurs while hot bubble material is flowing across surface of star, so that when detonation occurs, density of star has decreased enough that both Ni and intermediate mass elements are produced

GCD vs Classic Delayed Detonation Models

- Characteristics shared with standard DDT models:
  - —*mild ignition, deflagration phase followed by detonation and incineration*
  - —*pre-expansion, layered ejecta, modest degree of global asymmetry*

- Unique features:
  - —*accommodates* ***variations in the initial conditions*** *(single-bubble deflagration)*
  - —***stellar pre-expansion*** *is driven by decrease in gravity, not increase in pressure (i.e., heating due to energy released by nuclear burning)*
  - —*timescale for* ***pre-expansion*** *determined by the time the surface wave travels around the star (1 second after burst)*
  - —***detonation*** *occurs in gravitationally confined material via colliding shocks*
  - —*star at time of detonation is nearly spherically symmetric (i.e.,* ***1-D)***

Key Questions Re Type Ia SNe Revisited

- How does insensitivity to initial conditions happen?

  —*off-center ignition accommodates some variations in initial conditions, but more study definitely needed*

- What produces the range of Ni masses that are observed in Type Ia SNe and that may be the origin of the Phillips relation?

  —*variation in initial conditions of off-center ignition produces range in masses of hot bubble, range in amounts of pre-expansion, and therefore range in amounts of Ni, but more study definitely needed*

- How does a detonation occur in a medium that has no walls (i.e., that is gravitationally confined)?

  —*gravitationally confined detonation (colliding shocks in focused flow of hot material across white dwarf surface), but more study definitely needed*

- Why do 1-D models do better than 2-D models and much better than 3-D models?

  —*bubble burns only a few percent of M_{WD},producing a pre-expanded star that is nearly spherically symmetric when detonation occurs; i.e., mimics 1-D model!*