Thermonuclear Supernovae
Stellar Explosions in Three Dimensions

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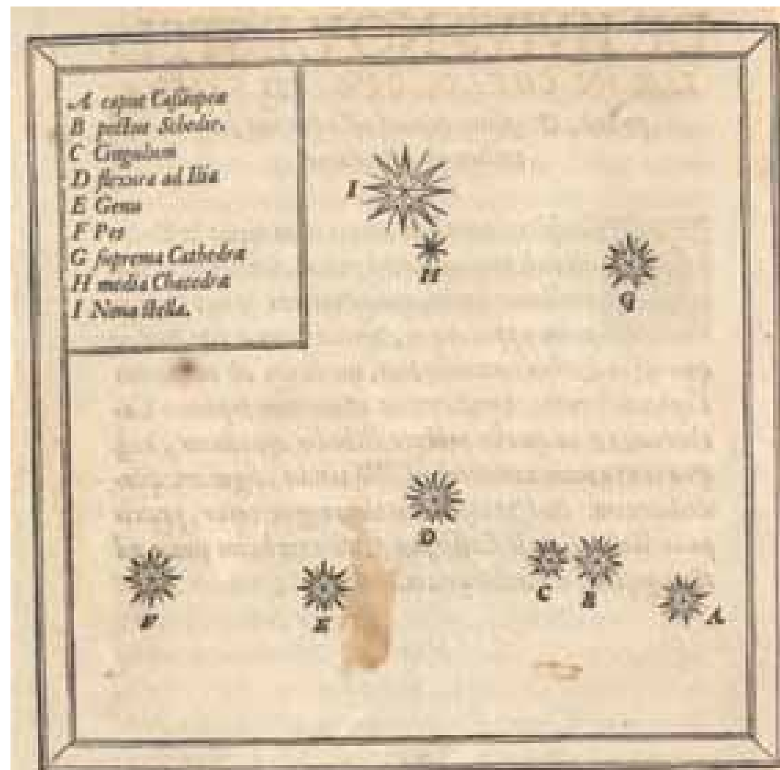
Advanced Simulation and Computing (ASC)
Academic Strategic Alliances Program (ASAP) Center

What Are Type Ia SNe?

- discovery by Tycho de Brahe (Nov 11, 1572)



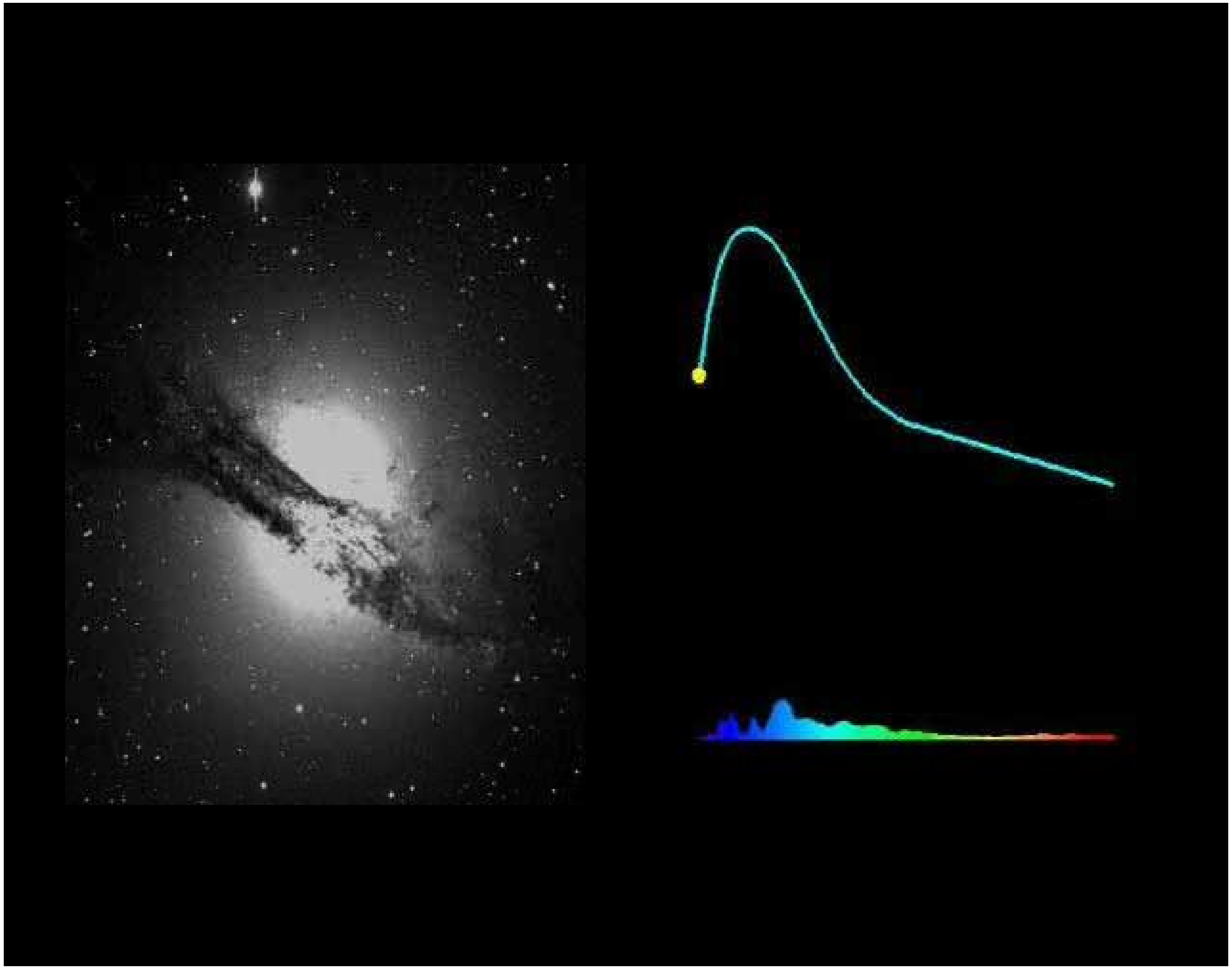
"Stella Nova" (1573), discovery chart

de Brahe's Experience

- $m_v = -4^m$, as bright as Venus

J. Walker (1988)

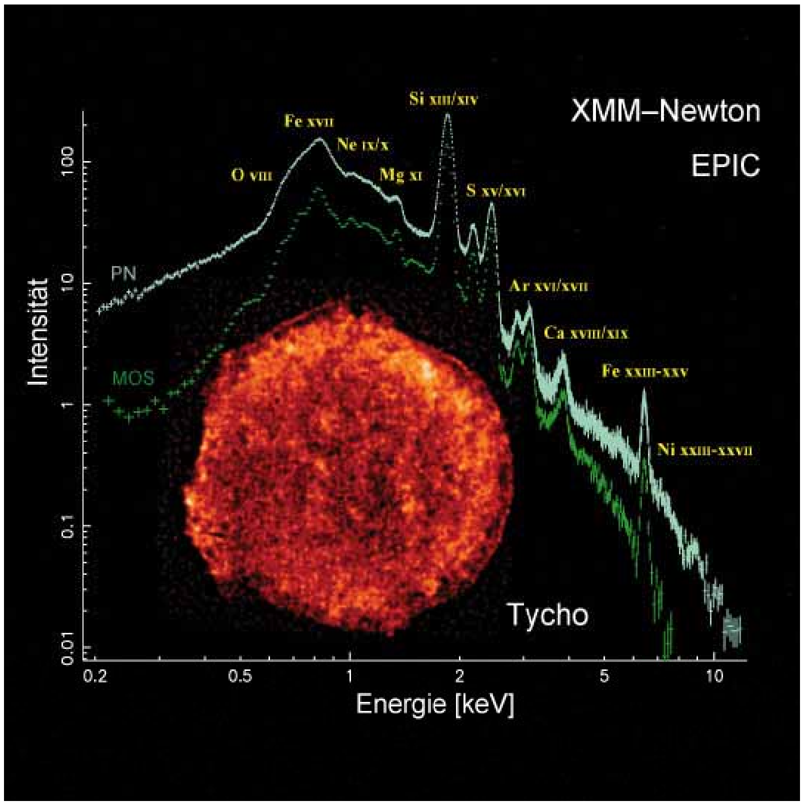
Type Ia SNe Appearance



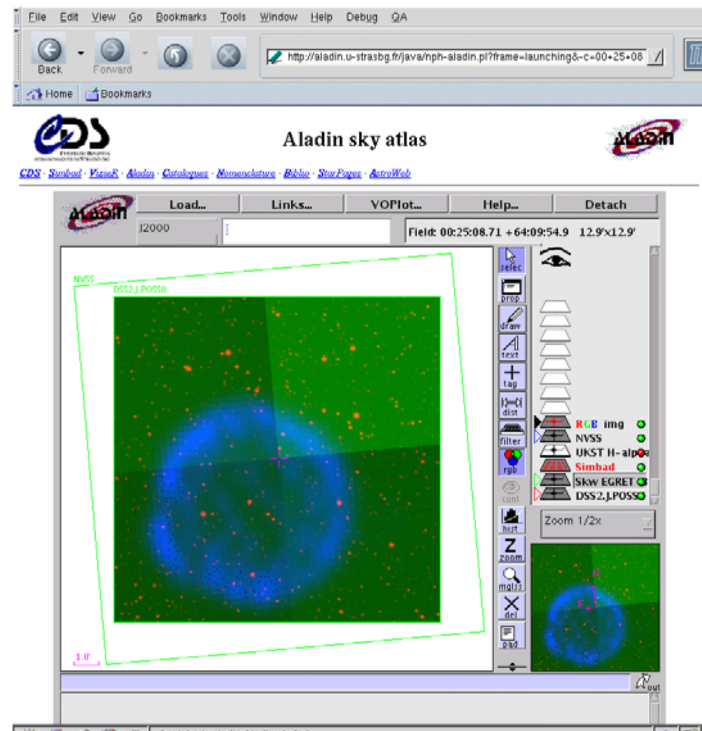
P. Nugent (LBNL)

Tycho Supernova Remnant

- morphology/imagining and spectra



XMM Newton archives



SIMBAD database

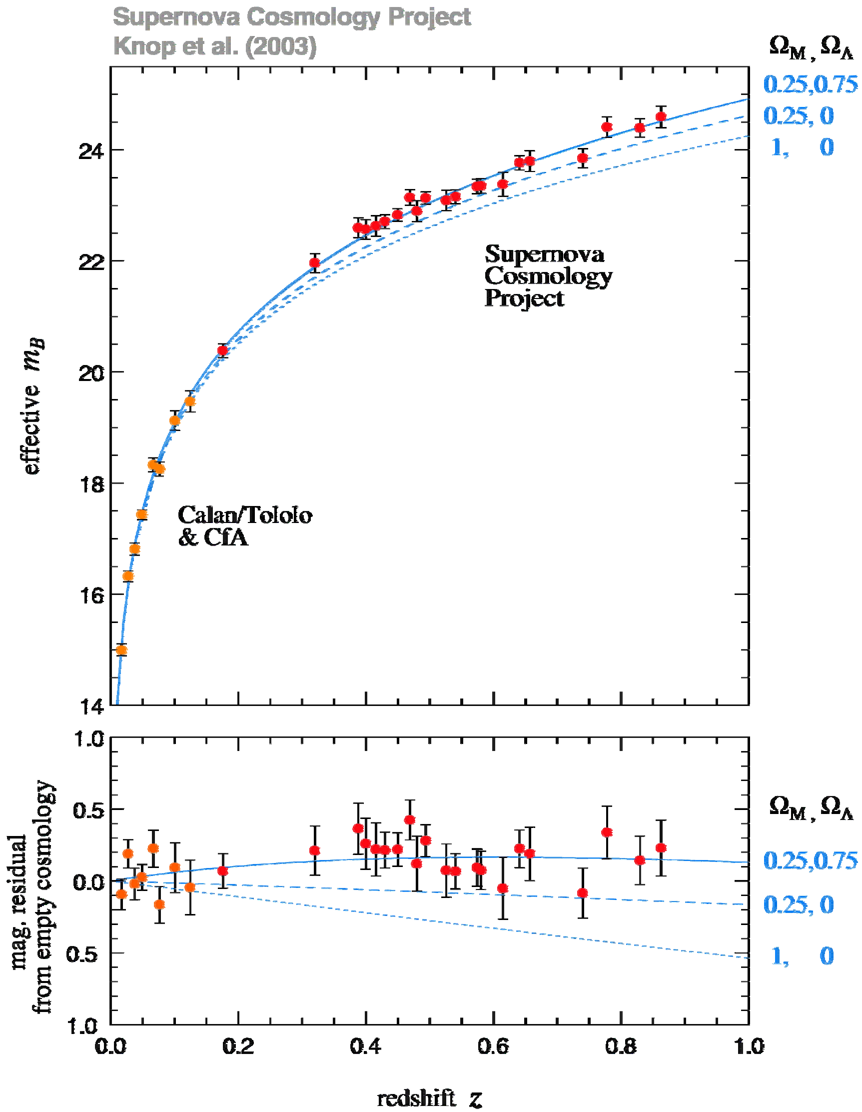
Why Do We Care?

COBE

High-Z Supernova Search Team, HST

- SN Ia are crucial for galactic chemical evolution.
- SN Ia are also crucial for cosmology: probes allowing study of expansion and geometry (Ω_M, Ω_Λ) of the Universe, nature of dark energy
- Provide astrophysical setting for basic combustion problems.

Cosmological Importance



Type Ia supernovae appear *dimmer* in the Universe with non-zero Ω_Λ.

Possible role of host galaxy extinction, environmental and metallicity effects ("population drift" with redshift), different evolutionary channels, intrinsic variations.

Problem Parameters

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Channels for progenitors

- Binary evolution
- Population synthesis

Initial conditions

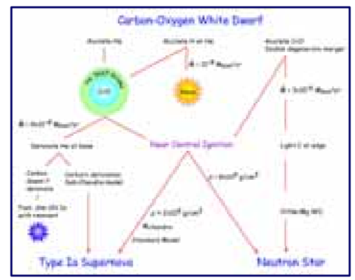
- State of the stellar core
- Metallicity
- Rotation profile
- Magnetic fields

Basic physics

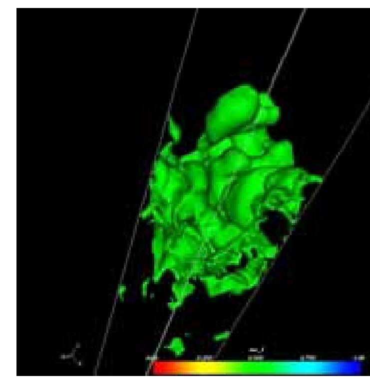
- Flame on intermediate scales
- Unsteadiness
- DDT

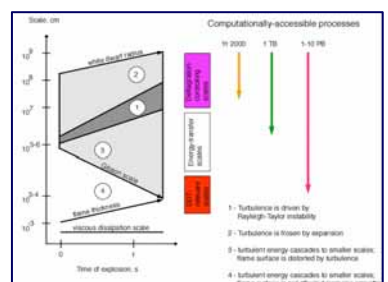
Numerics

- Multiphysics coupling
- Nucleosynthesis postprocessing



F. Timmes


Messer et al. (2004)



A. Khokhlov

What Has Been Done Elsewhere?

1960s

- WD explosion proposed for Type Ia (Hoyle & Fowler)
- 1D detonation model (Arnett)

1970s

- detonation models (several groups)
- deflagration models (Nomoto)

1980s

- improved 1-D deflagration models (Nomoto)
- first 2-D deflagration model (Mueller & Arnett)

1990s

- 2-D and 3-D deflagration models, DDT (Khokhlov)
- non-standard models 2-D He detonations (Livne & Arnett)
- small scale flame turbulence (Niemeyer & Hillebrandt)

2000s

- 3-D deflagration models (NRL, MPA, Barcelona, Chicago)
- 3-D DDT models (NRL)

What Do We Do?

- **Nuclear flames**
  - review Khokhlov's self-regulating mechanism for flame propagation
  - verify numerical implementation
  - reach down to the Gibson scale
  - understand flame surface creation/destruction mechanism
  - understand properties of the turbulent flow field

- **High-resolution integrated multi-physics models**
  - ASC allocations
  - INCITE DOE Office of Science award
    - 2,700,000 SUs on NERSC seaborg
    - targeting very high resolution whole star problems
  - LANL Institutional Computing award
    - 300,000 SUs on pink (2,048 proc Linux cluster)
    - targeting convergence properties at high-resolution for octants

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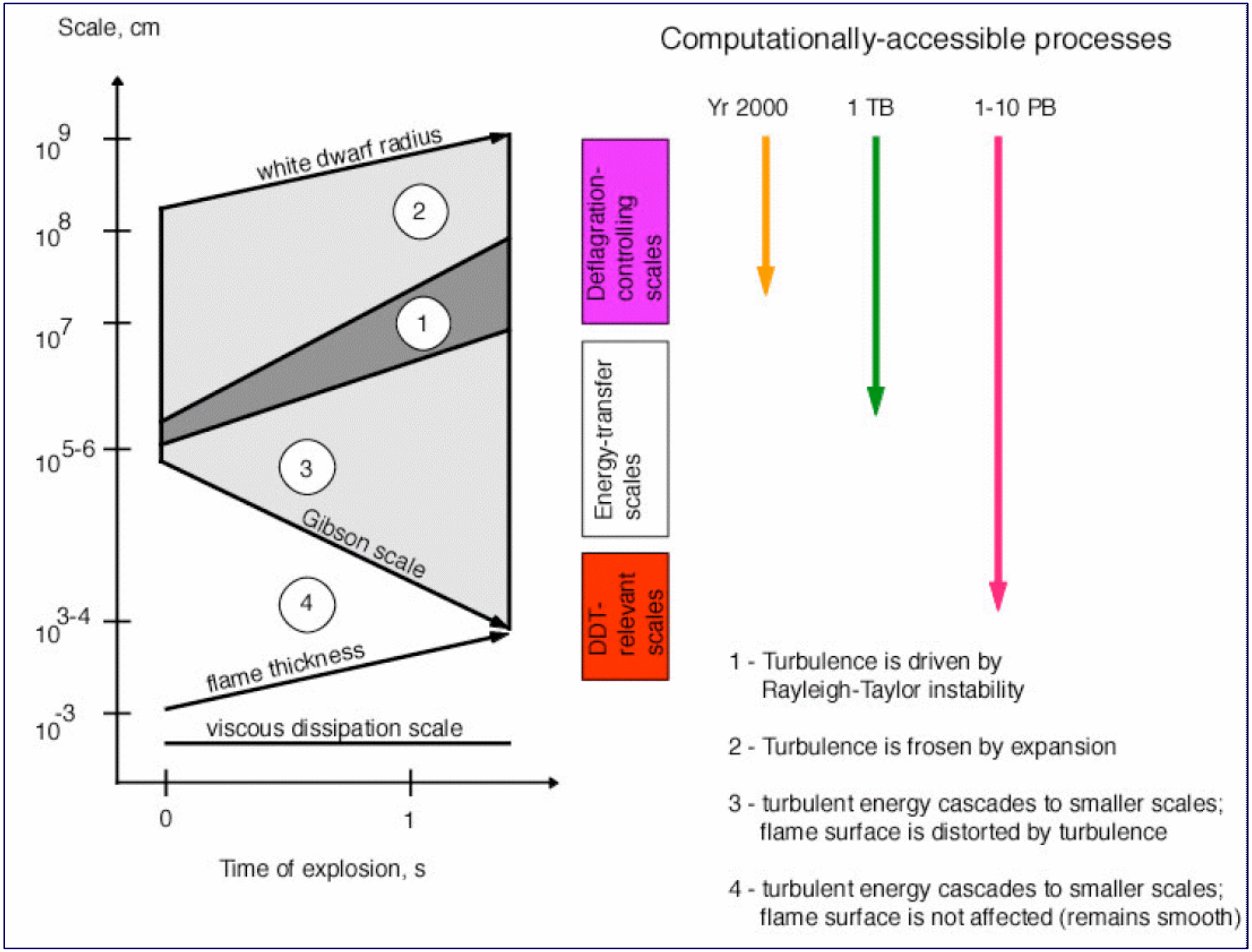
- **Nucleosynthesis**
  - tracer particles to be used for calculation of nucleosynthetic yields
  - required for making direct links to observations
  - another multi-person effort

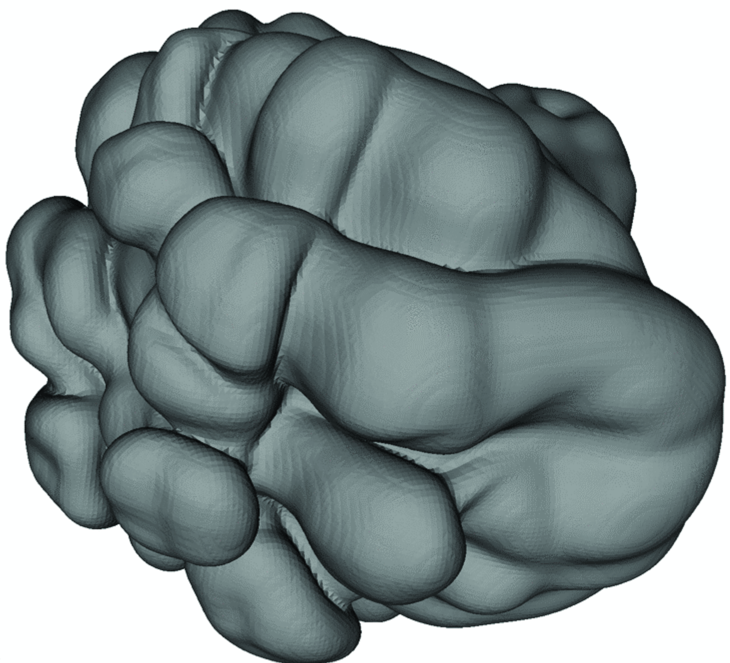
Why Large Scale Simulations?

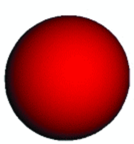


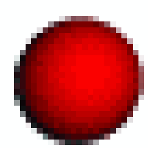
Alexei Khokhlov

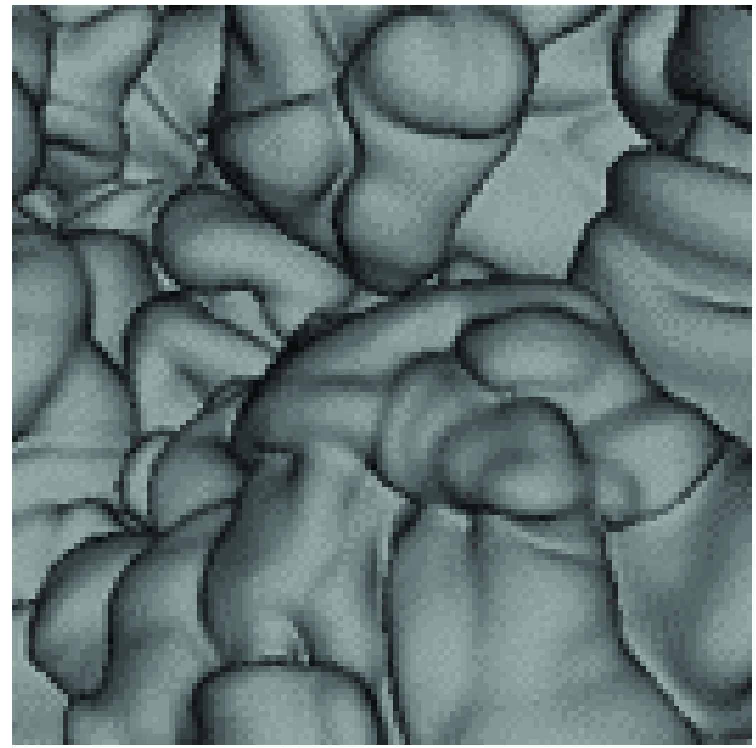
Self-Regulation Of The RT-Unstable Flames

- evolution of the flame surface; r_{ball} = 25 km







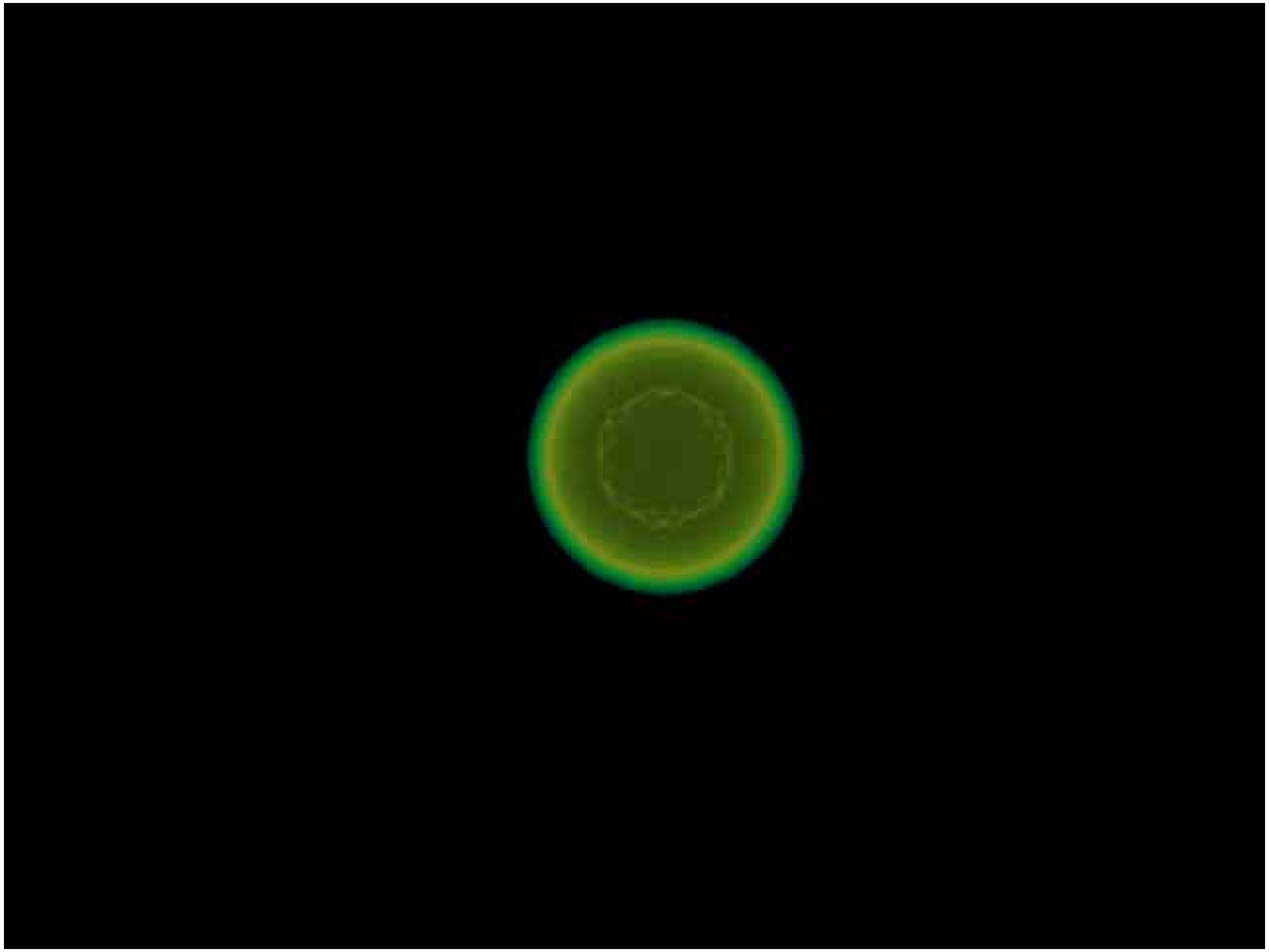


x 280%

t=0.40 s

t=0.75 s

8 km Resolution Central Ignition Whole Star Model



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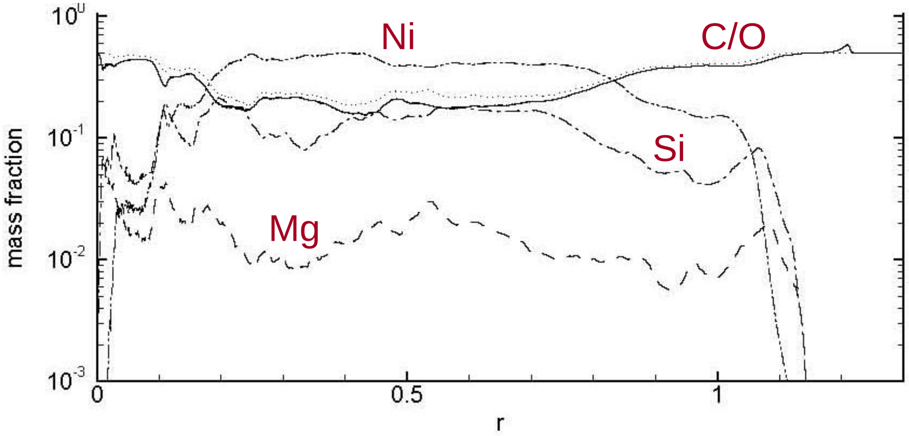
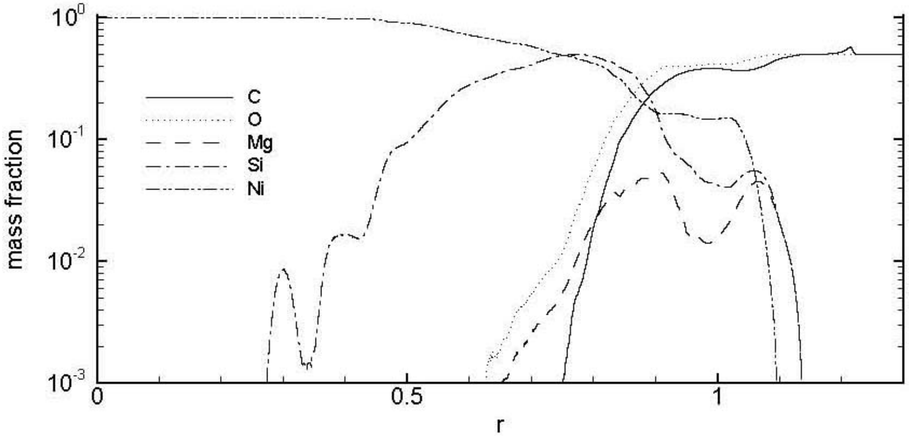
- Two models, 255,000 SUs and 5TB of data per model

Ejecta Composition: Deflagration vs. DDT

Angle-averaged chemical composition



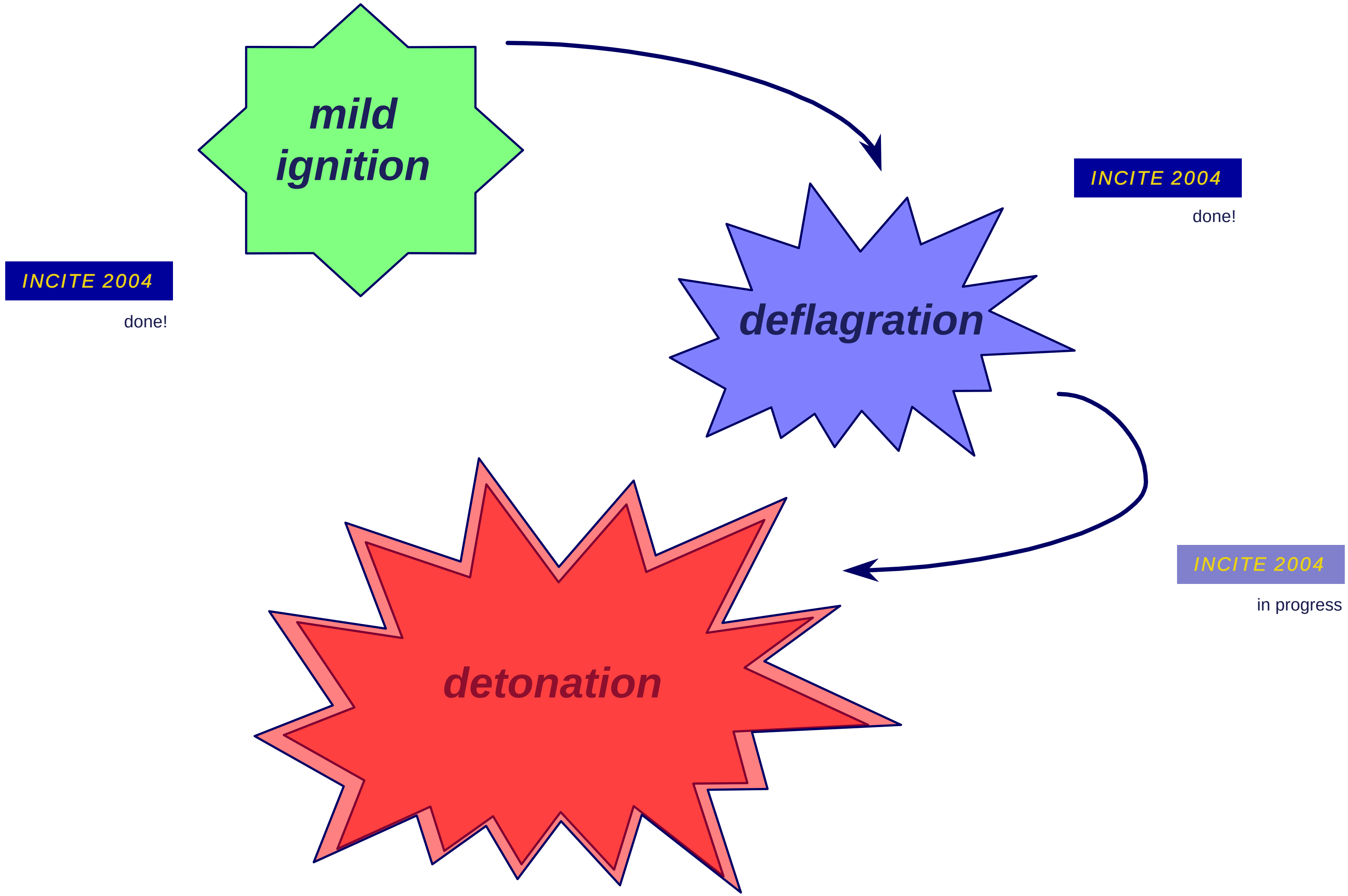
3-D pure deflagration



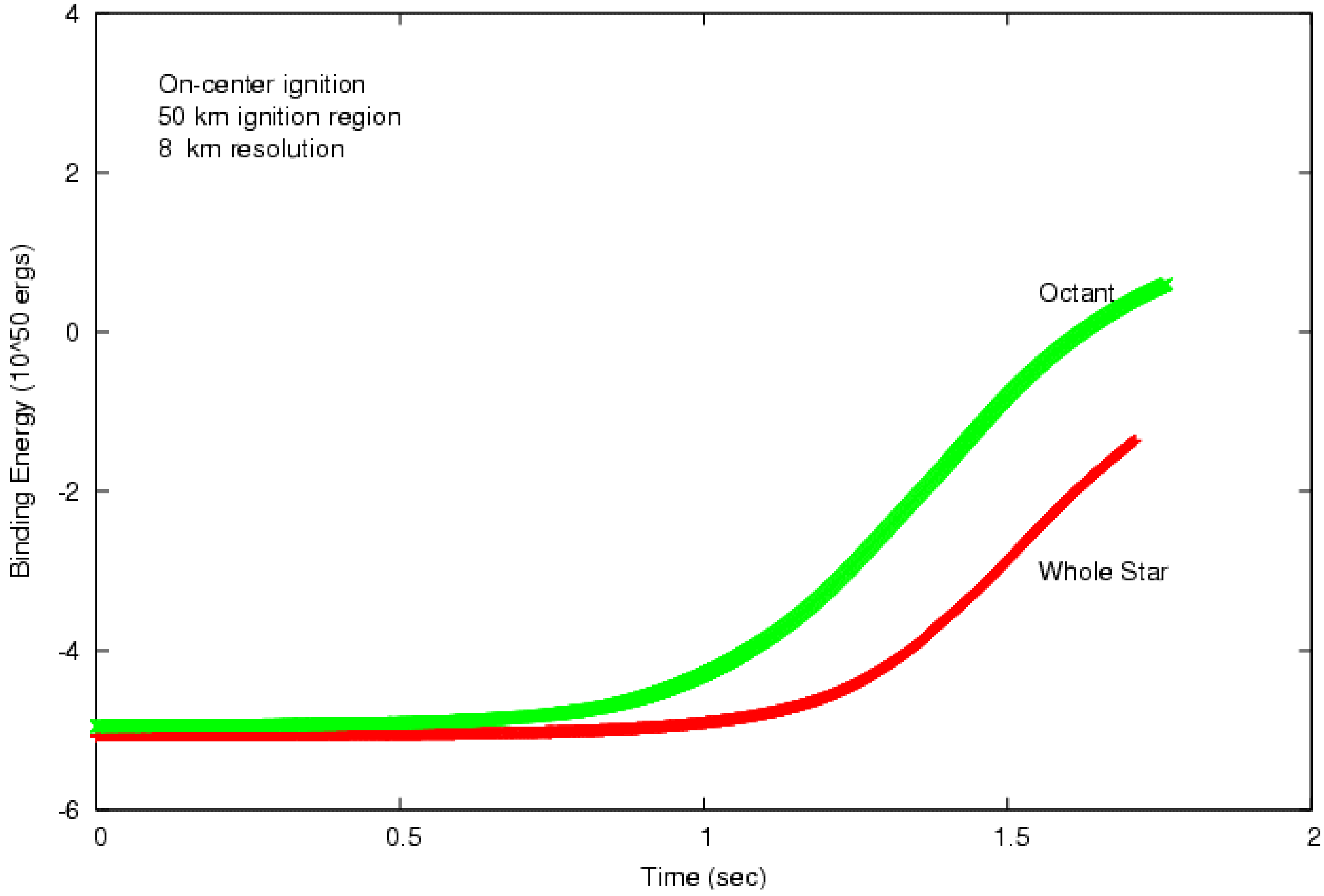
3-D speculative DDT

Gamezo et al. (2003)

Explosive Stage of Thermonuclear Supernova



Explosion Energy: Octants vs. Whole Star Models



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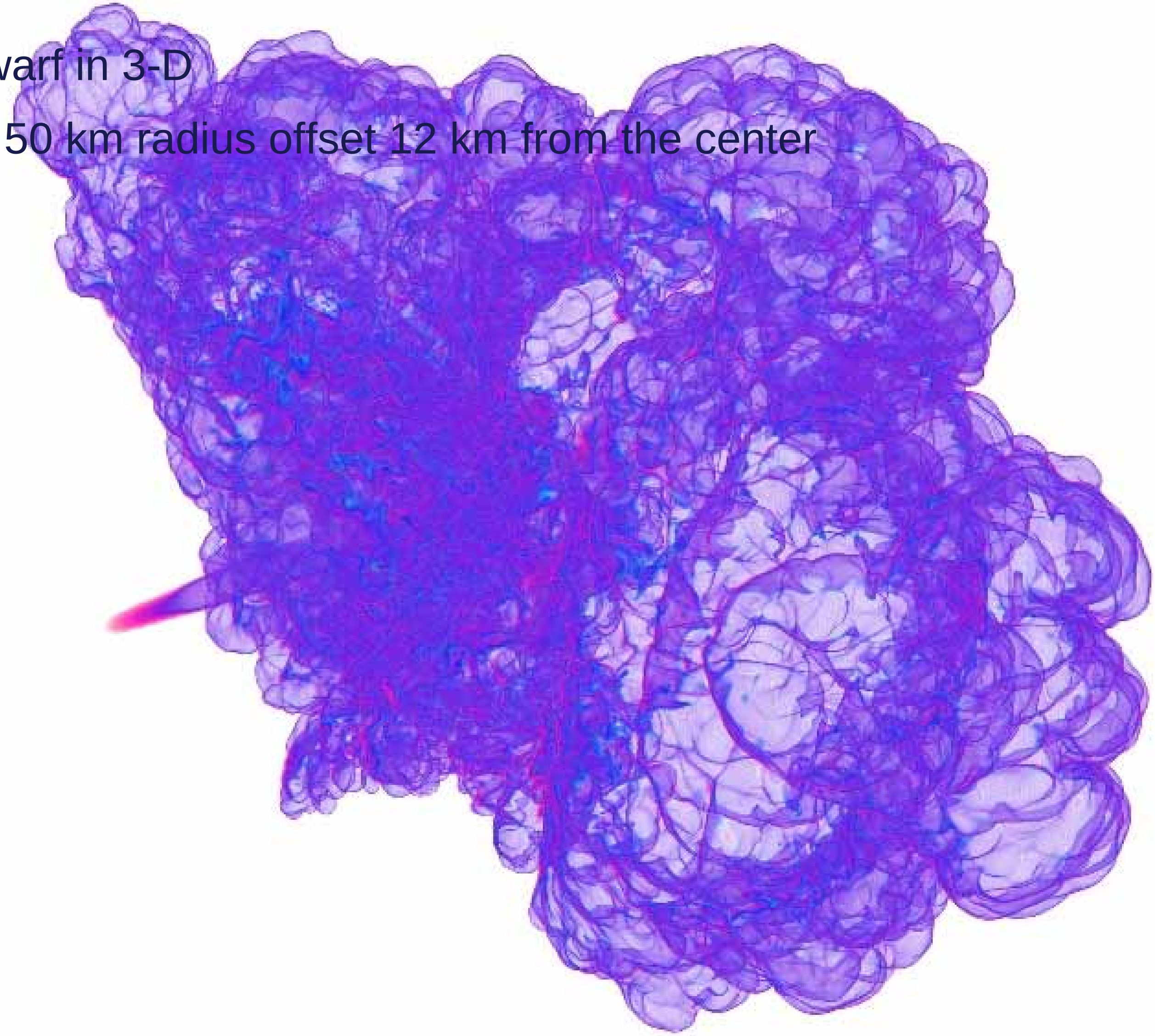
Octants may be nothing more than just 1/8th of the whole story.

Is Location of The Ignition Point Important?

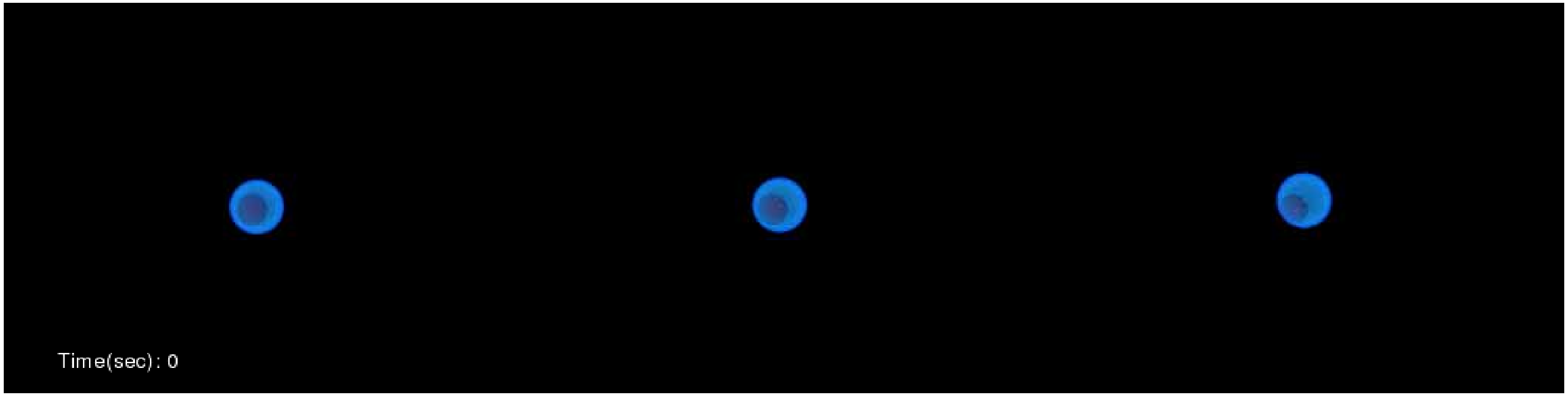
- entire white dwarf in 3-D
- ignition region 50 km radius offset 12 km from the center



Calder et al. (2004)

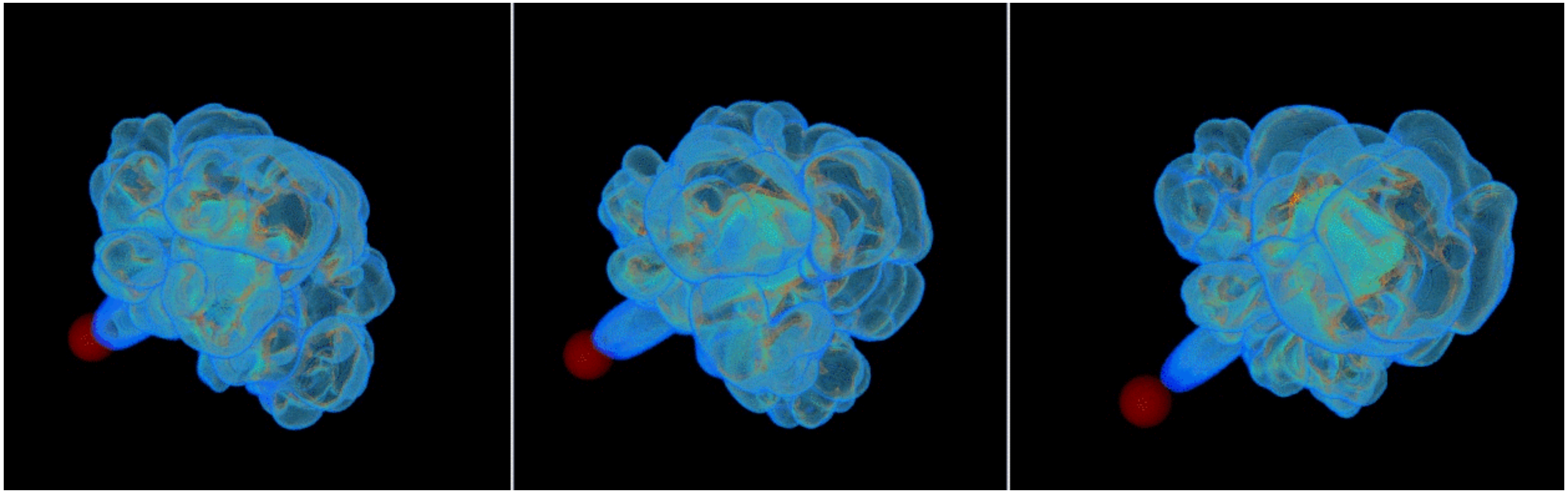
What Does it Mean "Slightly Off-Center"?

Off-center ignition models at 12, 20, and 35 km at 2 km resolution.



Memory Loss of The Initial Conditions

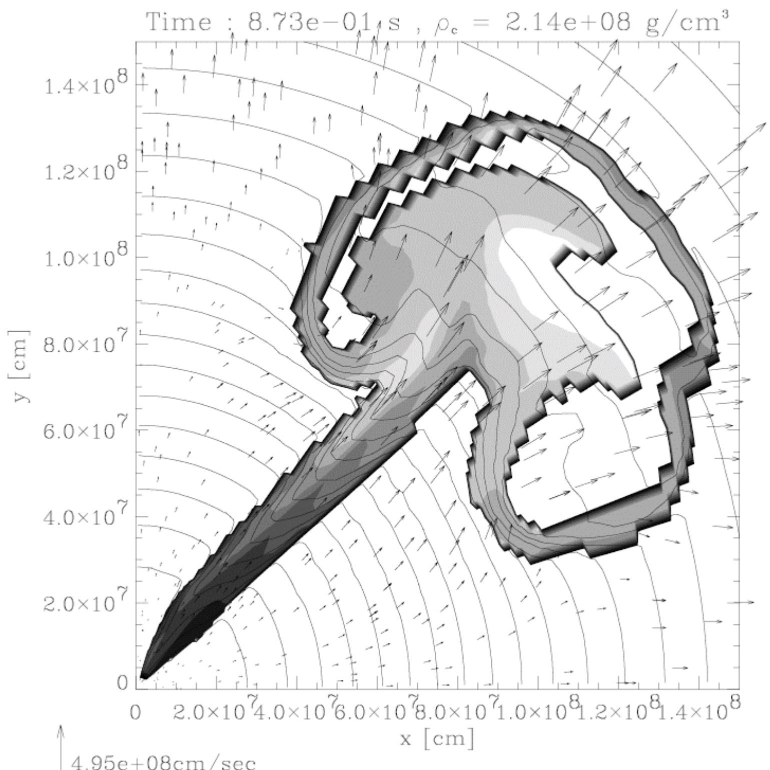
Off-center ignition models at 12, 20, and 35 km at 2 km resolution.



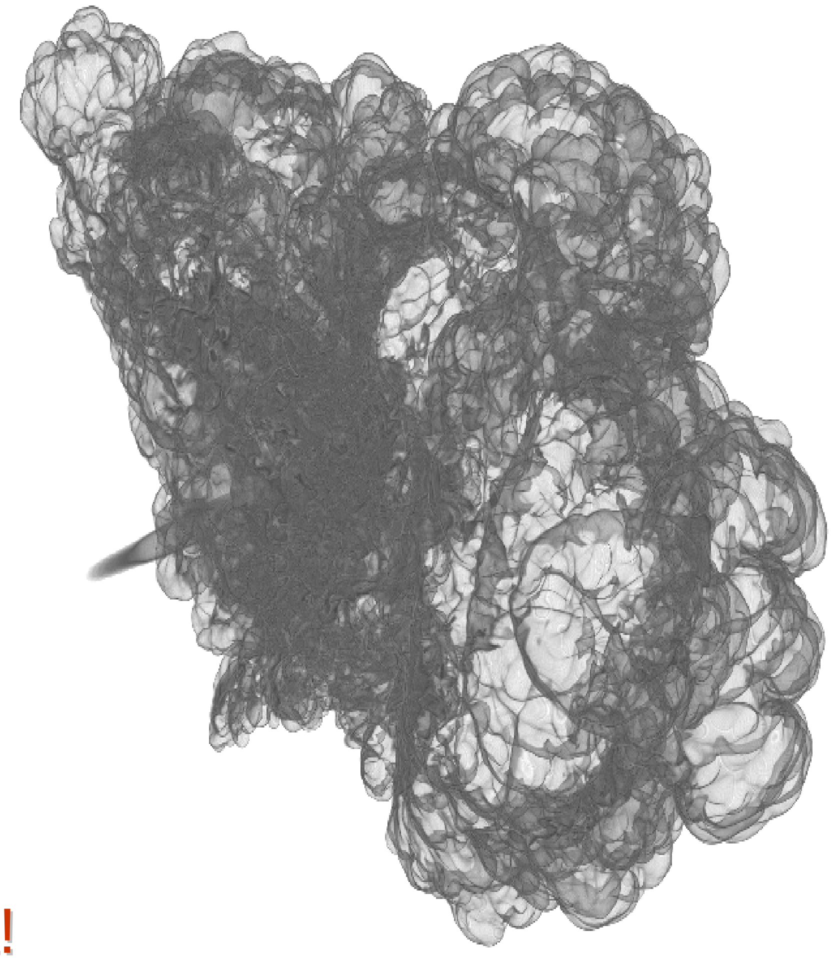
12 km | 20 km | 35 km

Variations in the offset (and initial bubble size) are unlikely to affect early evolutionary phases in any significant way.

8 Years Between, Two Different Methods…



Niemeyer, Hillebrandt, & Woosley (1996)



Calder et al. (2004)

…and virtually the same result!

INCITE Parameter Study of The Initial Conditions

- Single ignition point, 1 km radius, 125 meters resolution
- Impose a dipolar flow field in the core, fixed 200 km radius
- Vary the strength of the dipole: 10, 100, and 200 km/s
- Rotate the dipole to minimize grid imprint
- Vary the initial distance of the bubble from the core: 0 km, 100 km
- Impose temperature limit on the energy deposition to accommodate uncertainty in the model energetics
- Evolve to 0.5 s slowly decreasing maximum resolution
- 12 models in total (about 100,000 SUs each).

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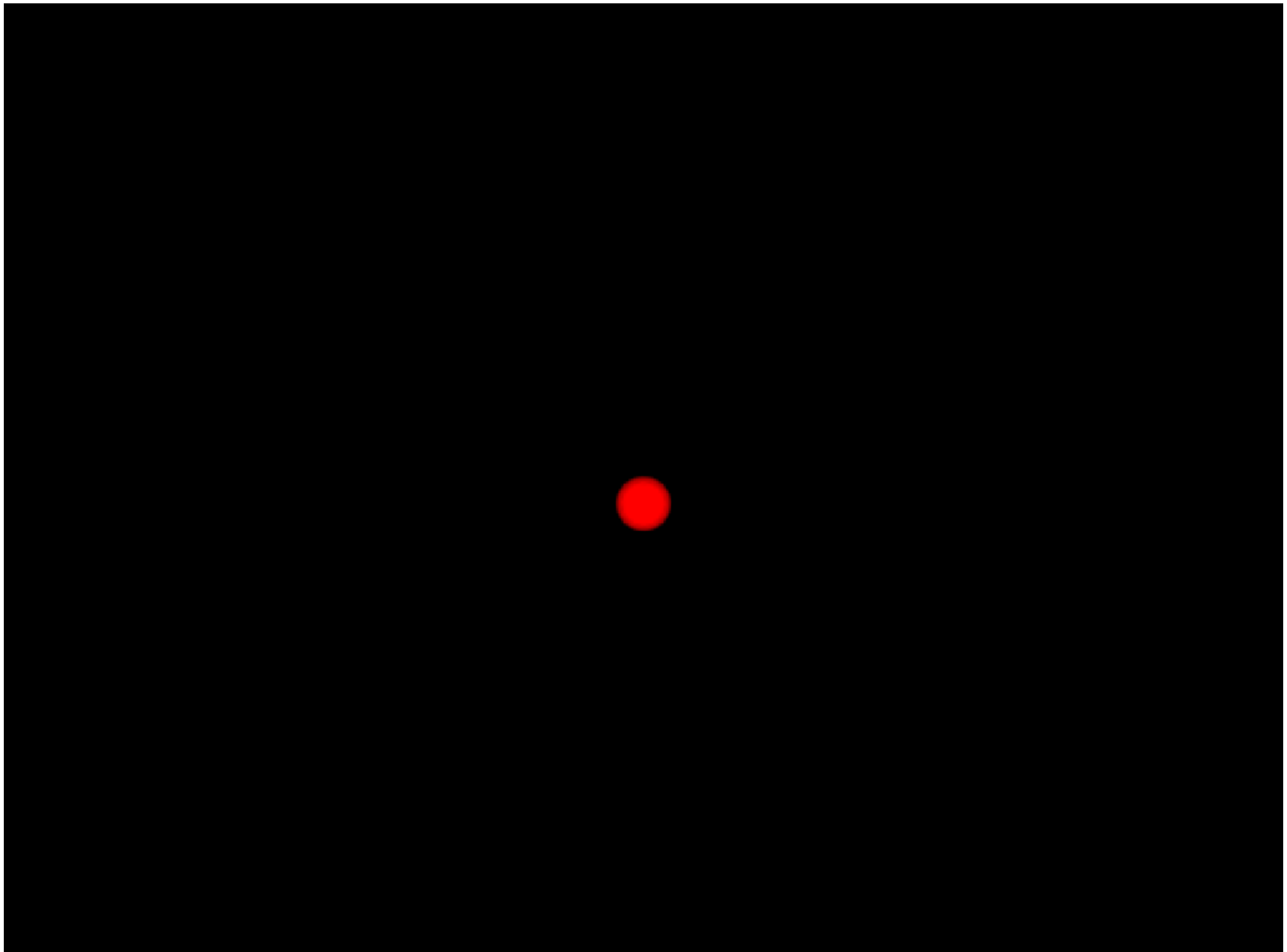
Initial Conditions: Location, Velocity Field

r1y0v10a3030 (central, 10 km/s)



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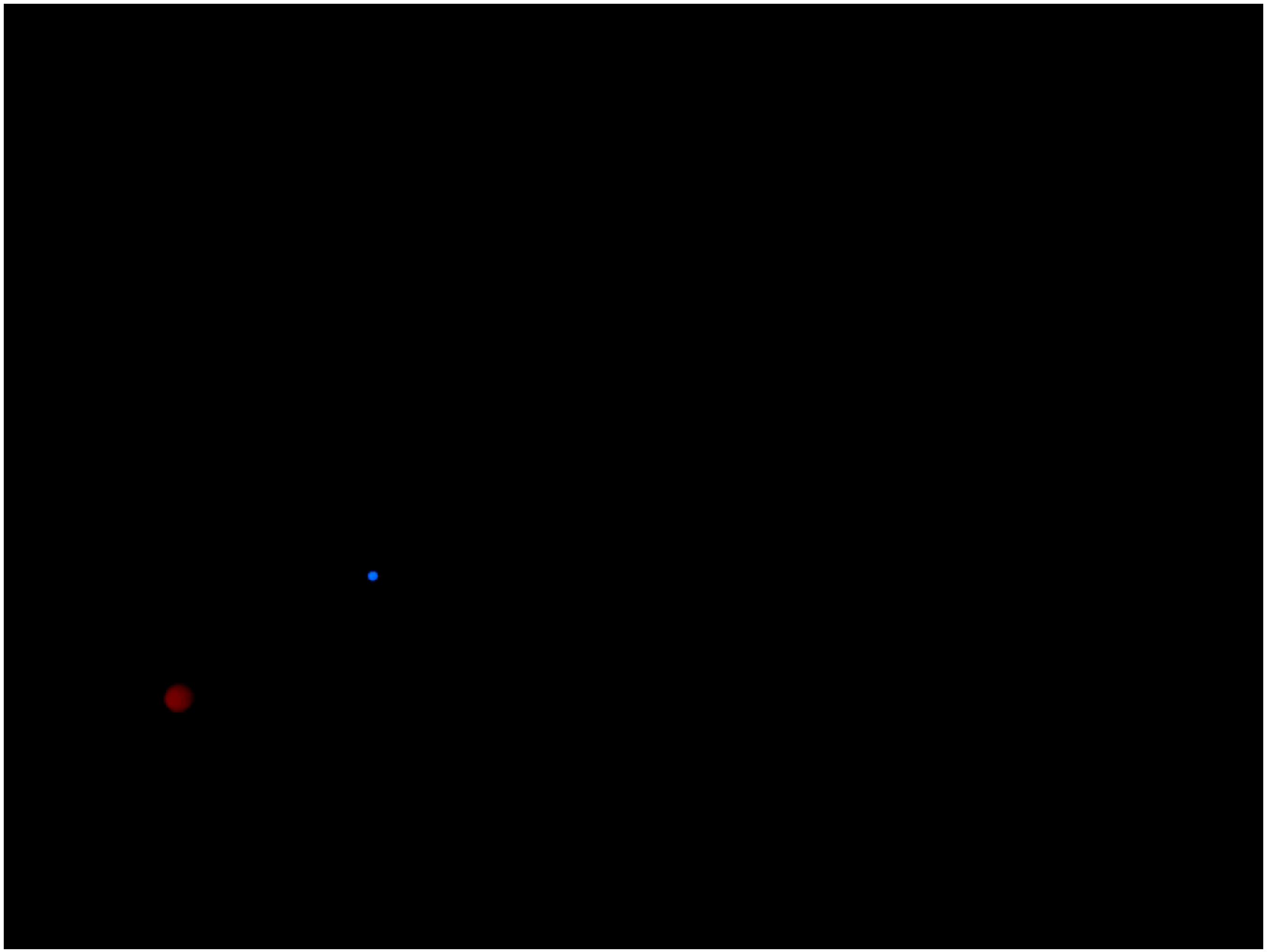
Initial Conditions: Location, Velocity Field

r1y100v100a3030 (outflowing, 100 km/s)



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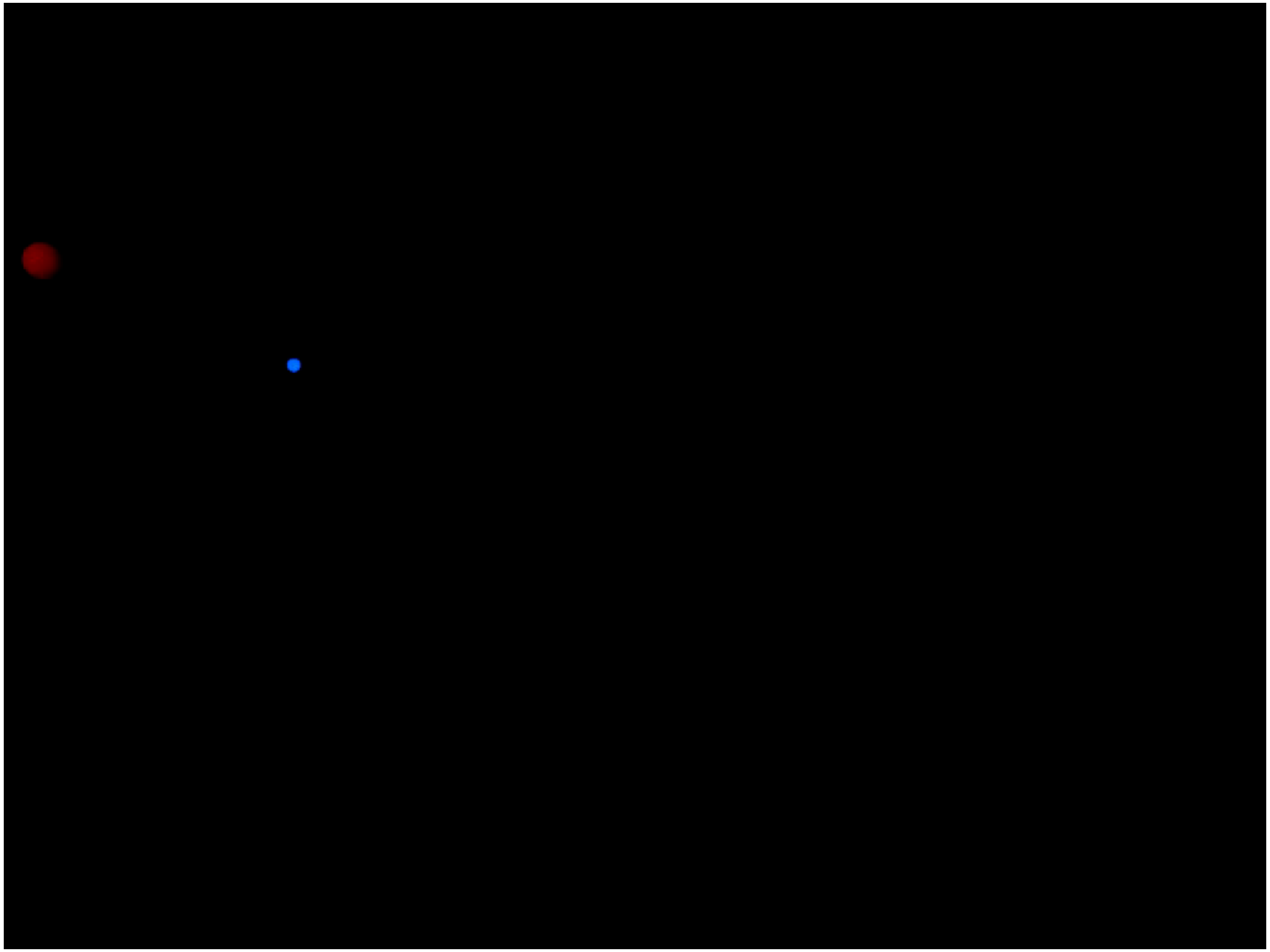
Initial Conditions: Location, Velocity Field

r1y100v100a3030in (inflowing, 100 km/s)



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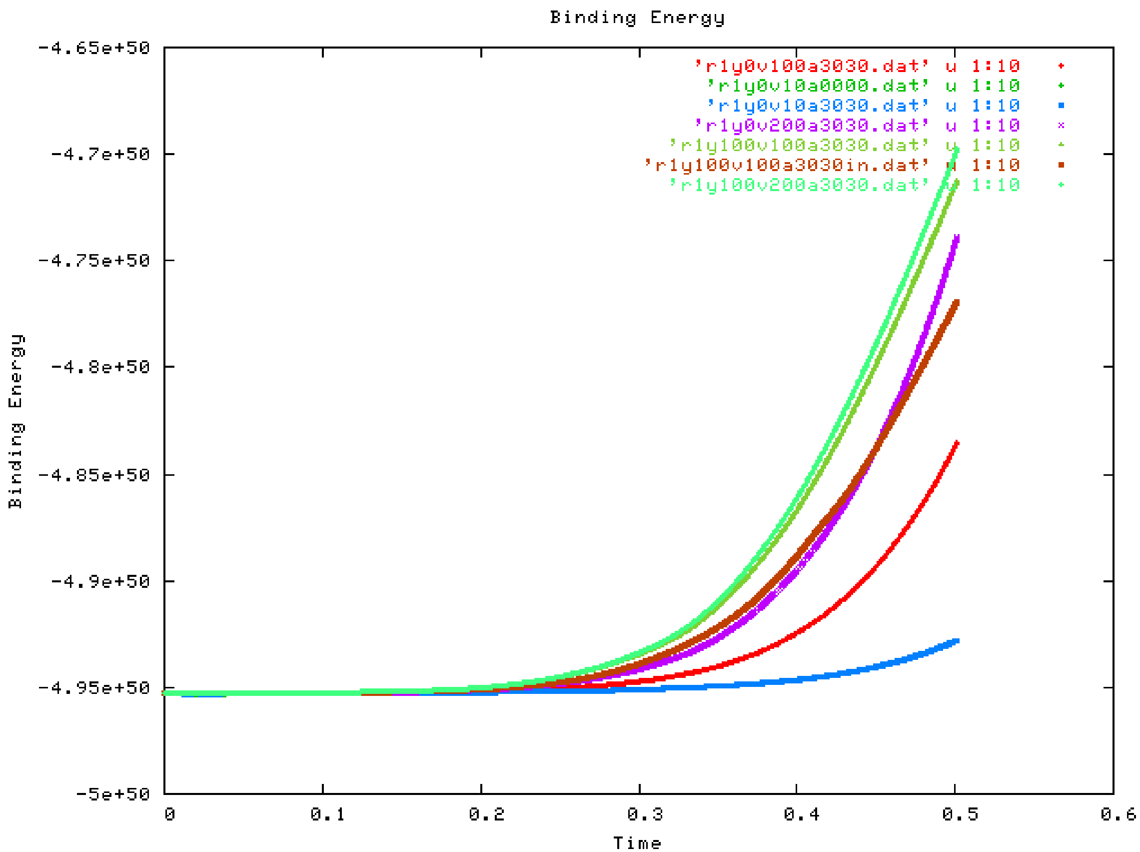
Initial Conditions: Energy Generation



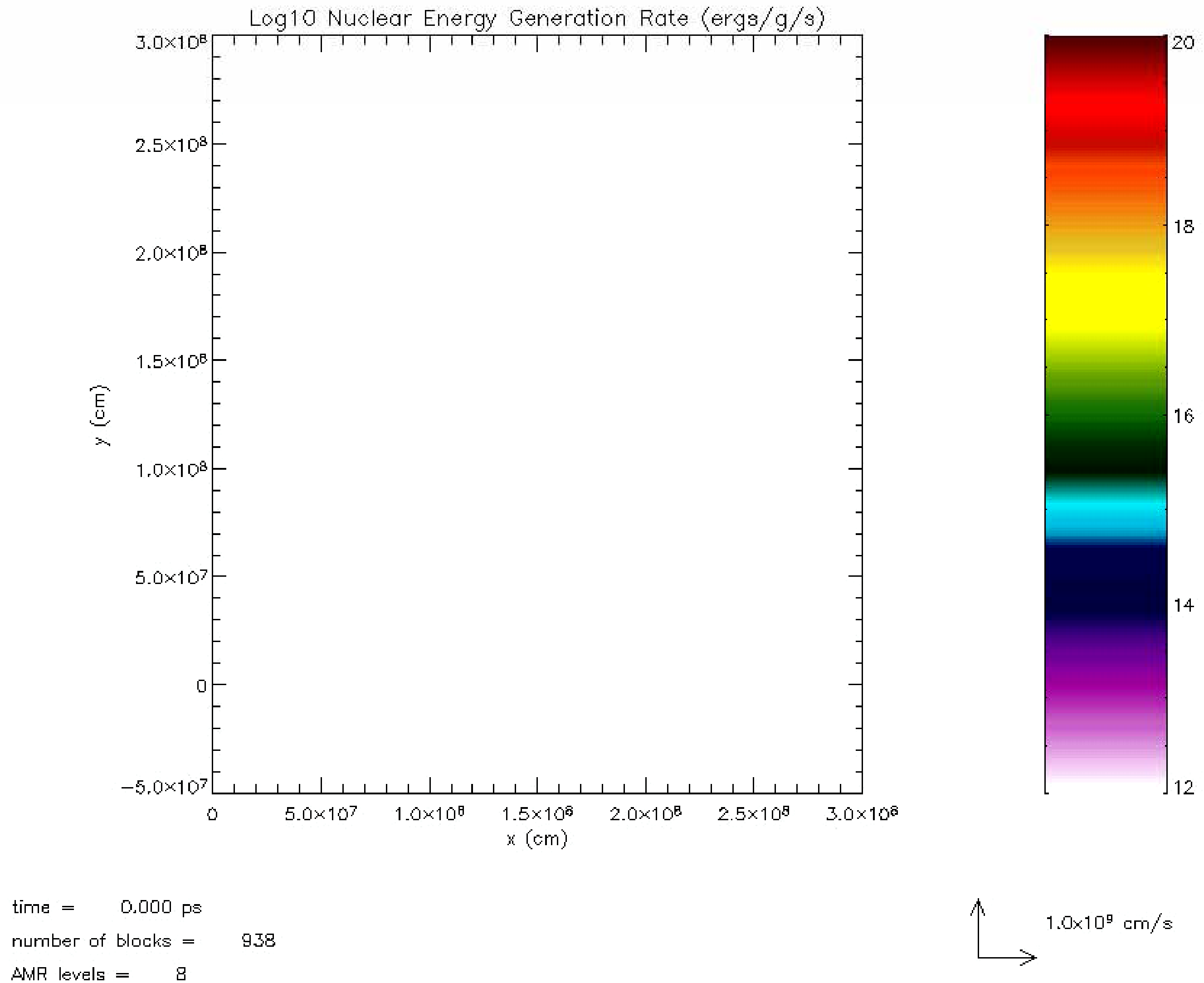
Despite strong variations in the ICs, energetic histories of all models are also similar. The system exhibits *memory loss* of initial conditions.

Initial Conditions: Conclusion

Based on analytic, semi-analytic, and numerical models, the most likely outcome of a mild ignition is the off-center deflagration.

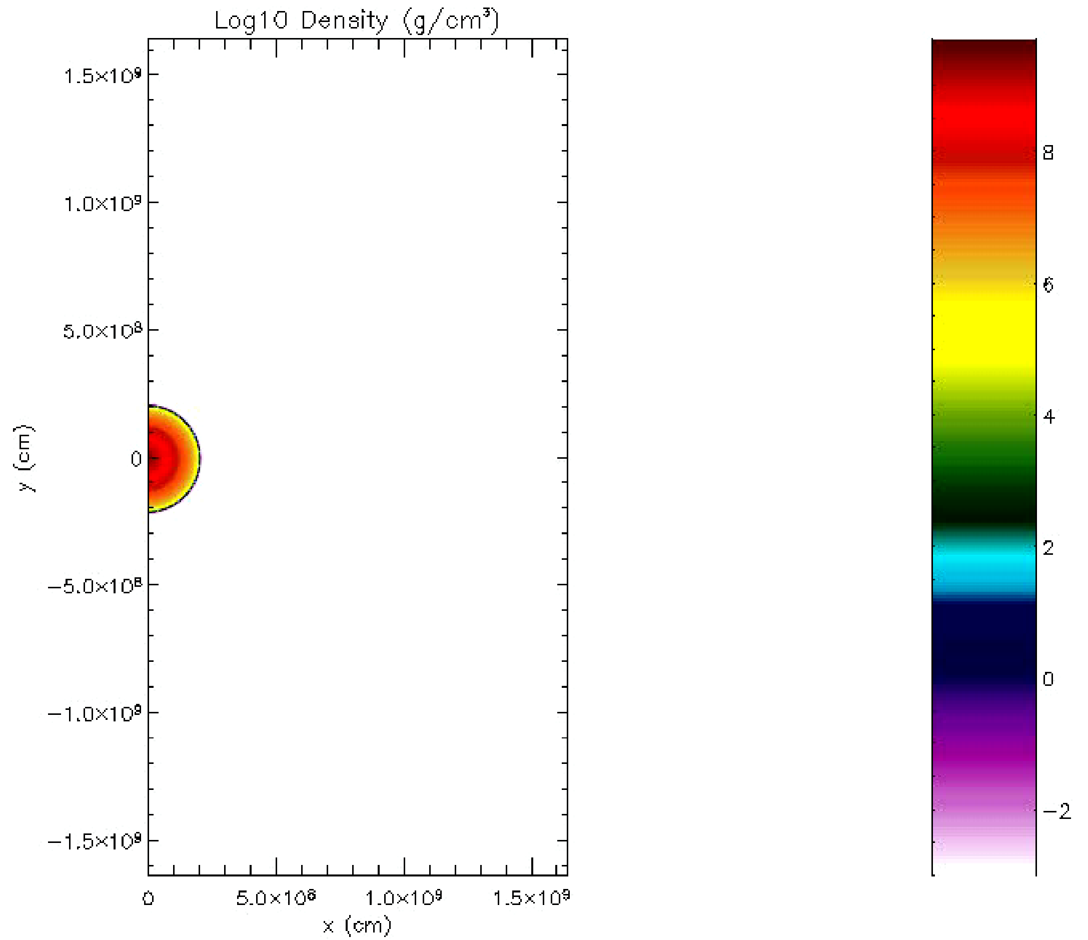
Early Post-burst Evolution in 2-D

- 8 km resolution, ignition 12 km "North", FLASH 03/2004



Post-burst Evolution in 2-D

- in long term bubble burst causes asymmetric matter distribution



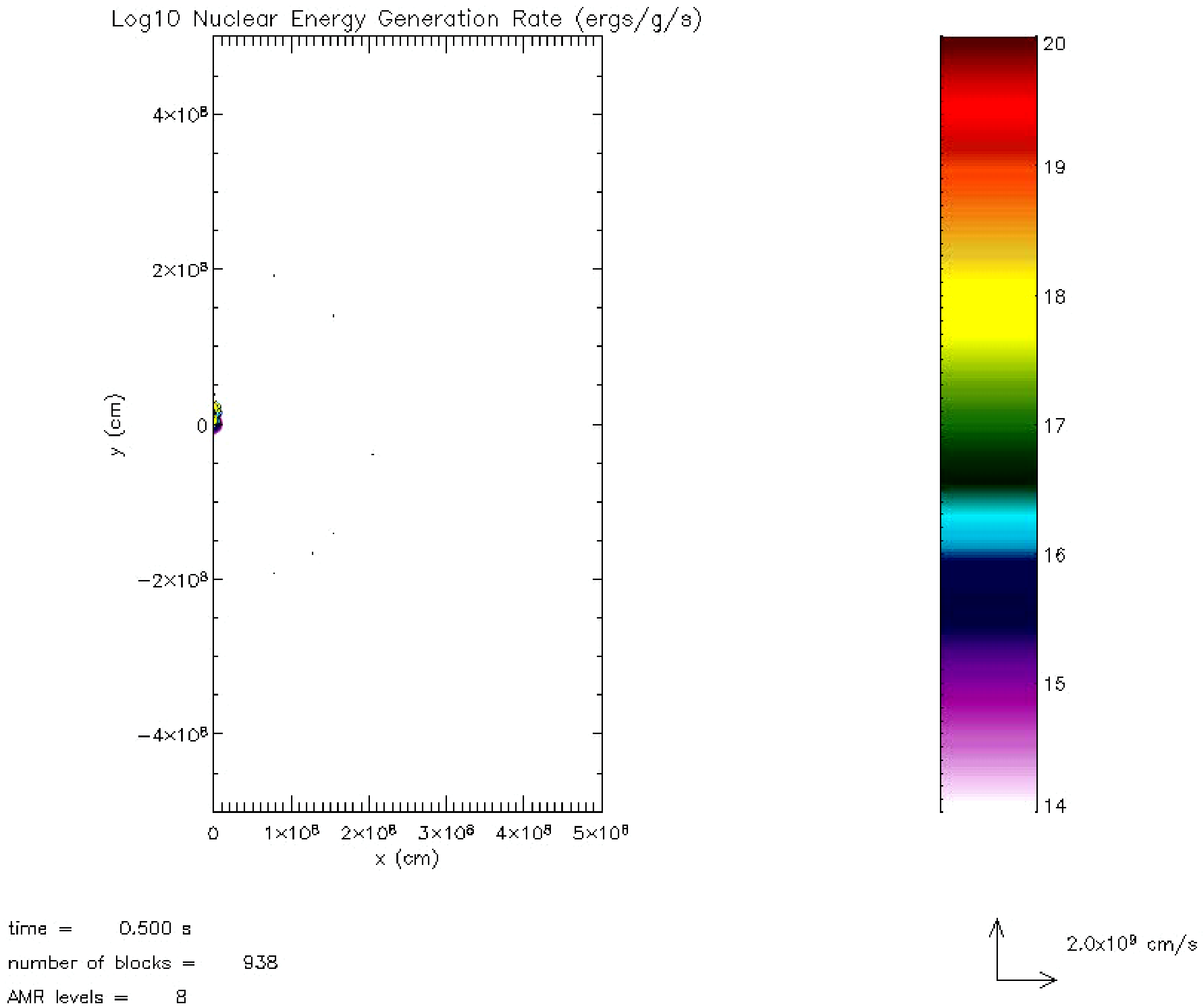
time = 0.000 ps

number of blocks = 938

AMR levels = 8

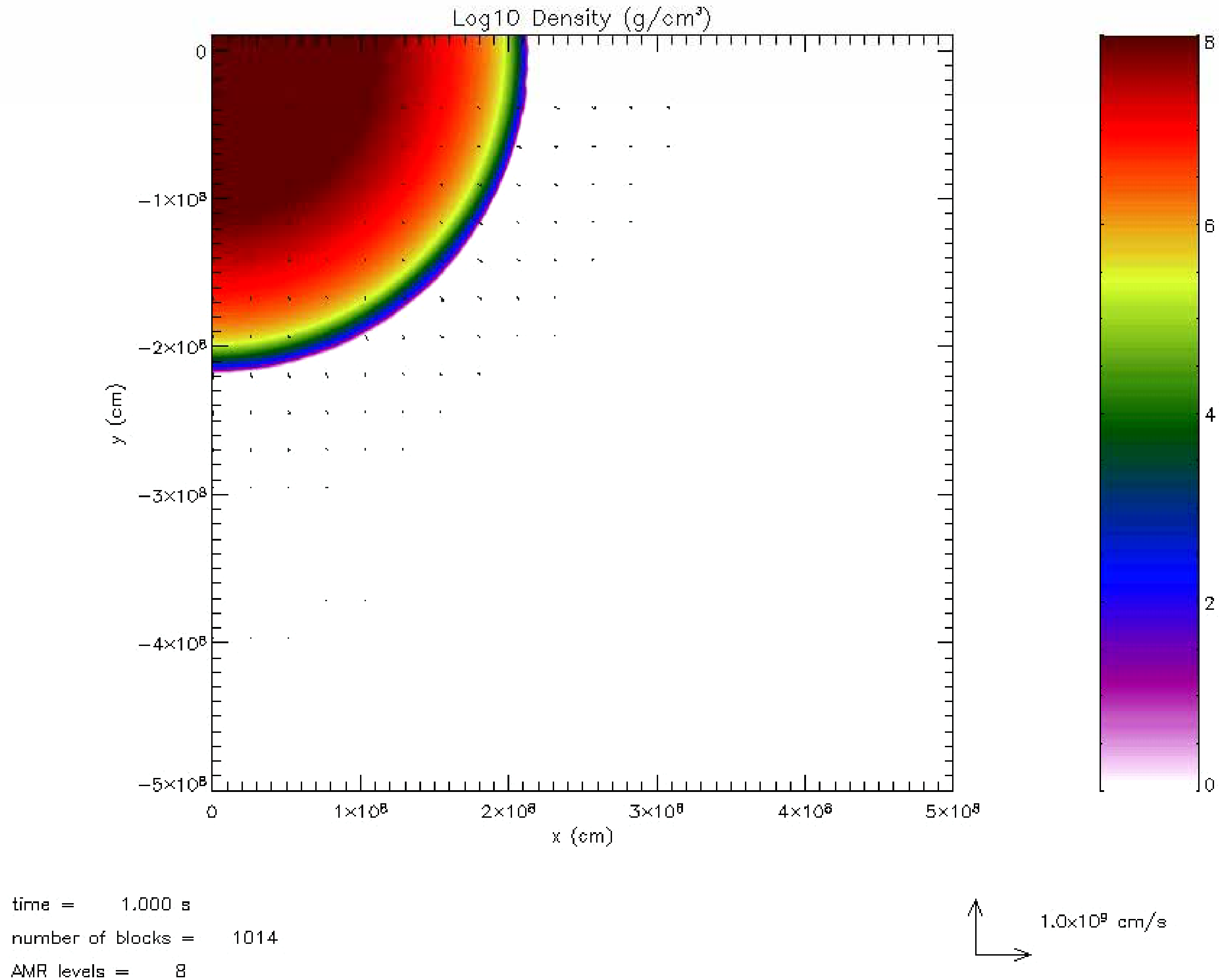
Closer Look Into Post-Burst Evolution

- the surface flow converges at the back side of the star...



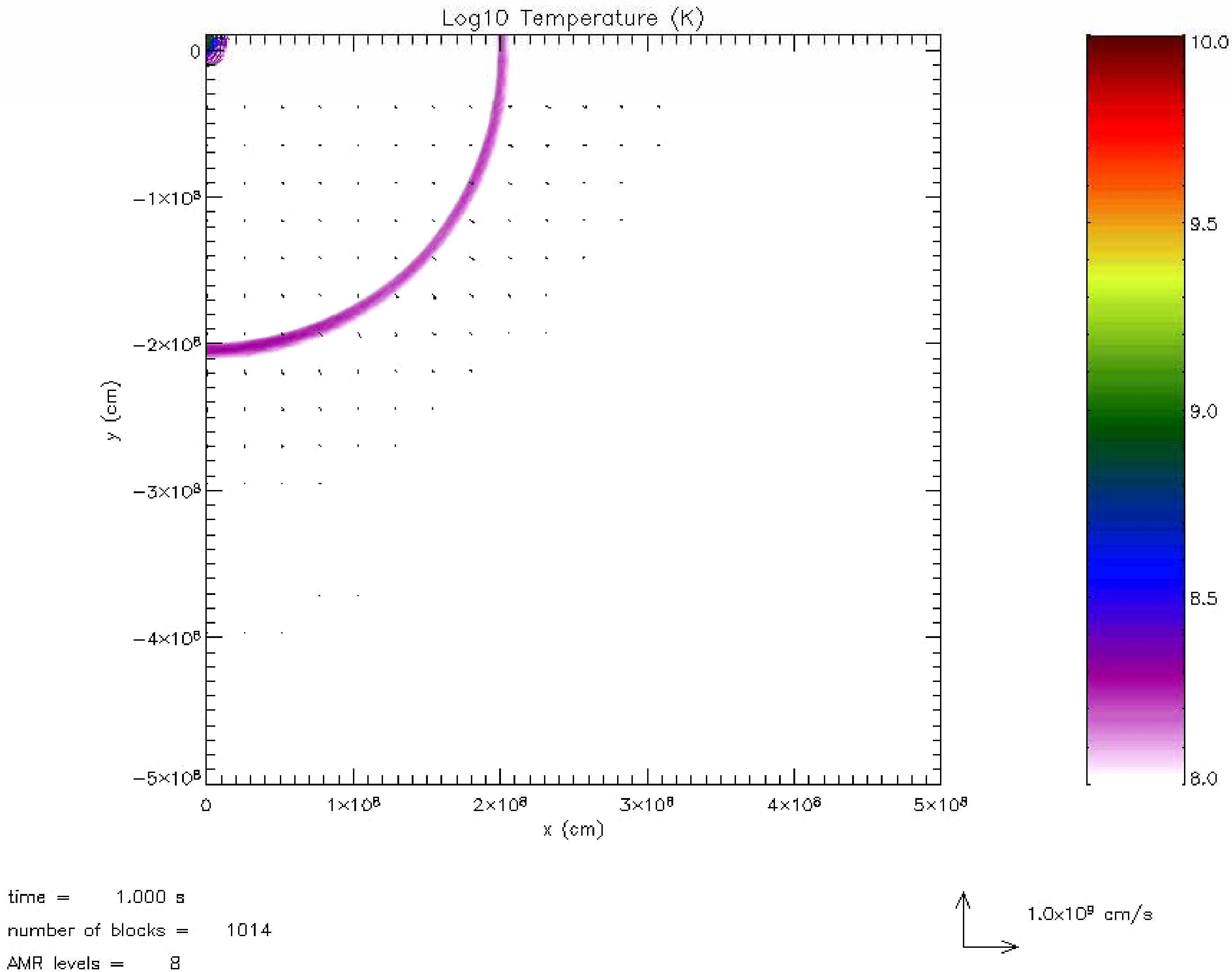
Closer Look Into Post-Burst Evolution

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



“Gravitationally Confined Detonation”

- ...and creates a fusion reactor -

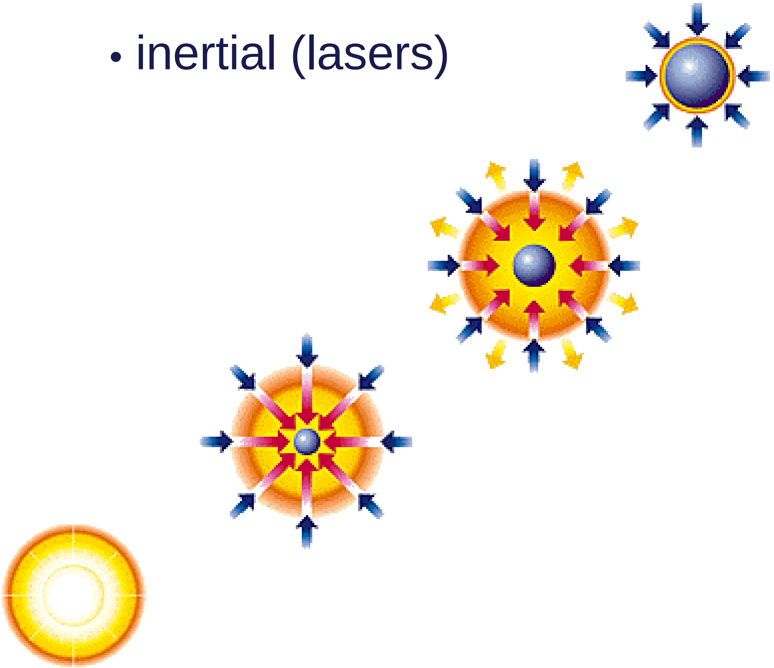


Confined Fusion on Earth

- magnetic (tokamaks)

General Atomics

- inertial (lasers)



Gravitationally Confined Detonations

TYPE IA SUPERNOVA EXPLOSION: GRAVITATIONALLY CONFINED DETONATION

T. Plewa[1,2,3], A. C. Calder[1,2], and D. Q. Lamb[1,2,4]

Submitted to the ApJ

ABSTRACT

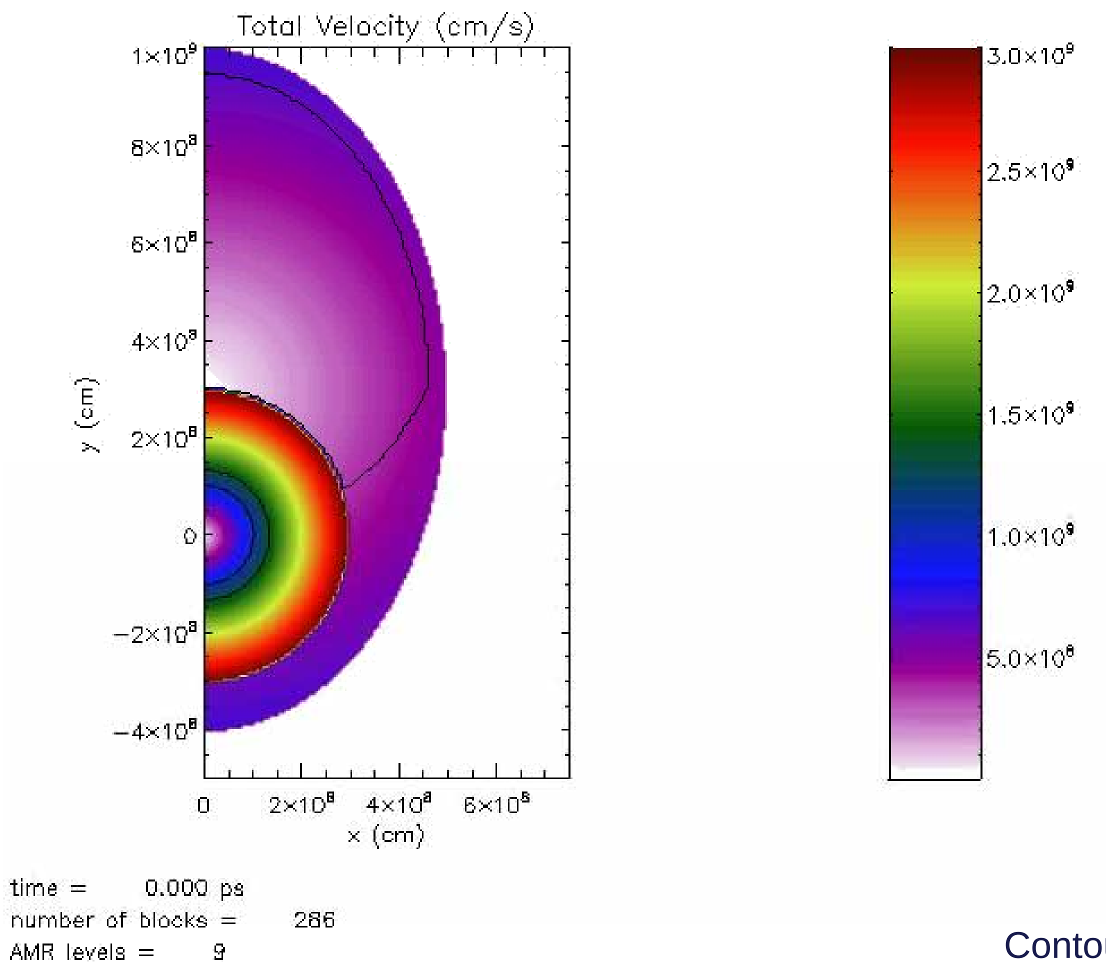
We present a new mechanism for Type Ia supernova explosions in massive white dwarfs. The proposed scenario follows from relaxing the assumption of symmetry in the model and involves a detonation created in an unconfined environment. The explosion begins with an essentially central ignition of stellar material initiating a deflagration. This deflagration results in the formation of a buoyantly-driven bubble of hot material that reaches the stellar surface at supersonic speeds. The bubble breakout forms a strong pressure wave that laterally accelerates fuel-rich outer stellar layers. This material, confined by gravity to the white dwarf, races along the stellar surface and is focused at the location opposite to the point of the bubble breakout. These streams of nuclear fuel carry enough mass and energy to trigger a detonation just above the stellar surface. The flow conditions at that moment support a detonation that will incinerate the white dwarf and result in an energetic explosion. The stellar expansion following the deflagration redistributes stellar mass in a way that ensures production of intermediate mass and iron group elements consistent with observations. The ejecta will have a strongly layered structure with a mild amount of asymmetry following from the early deflagration phase. This asymmetry, combined with the amount of stellar expansion determined by details of the evolution (principally the energetics of deflagration, timing of detonation, and structure of the progenitor), can be expected to create a family of mildly diverse Type Ia supernova explosions.

Subject headings: hydrodynamics — instabilities – stars:interior — supernovae:general — white dwarfs

Astrophys. J. Letters, 612, L37

Spectral Signatures

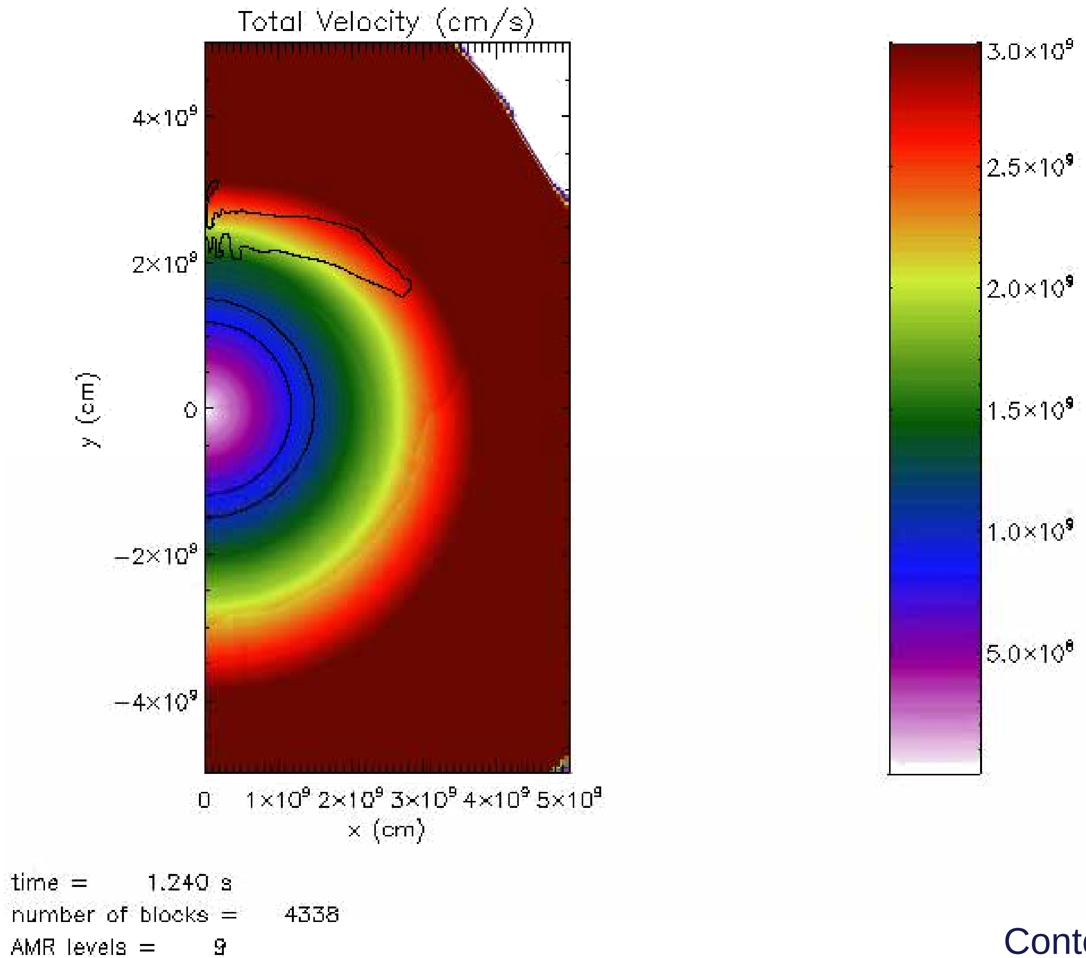
Place a high-density metal-rich matter (blob from a 2-D post-breakout model) in front of the stellar ejecta (adopt standard 1-D W7).



Contour marks $X_{Si} > 0.3$.

Spectral Signatures

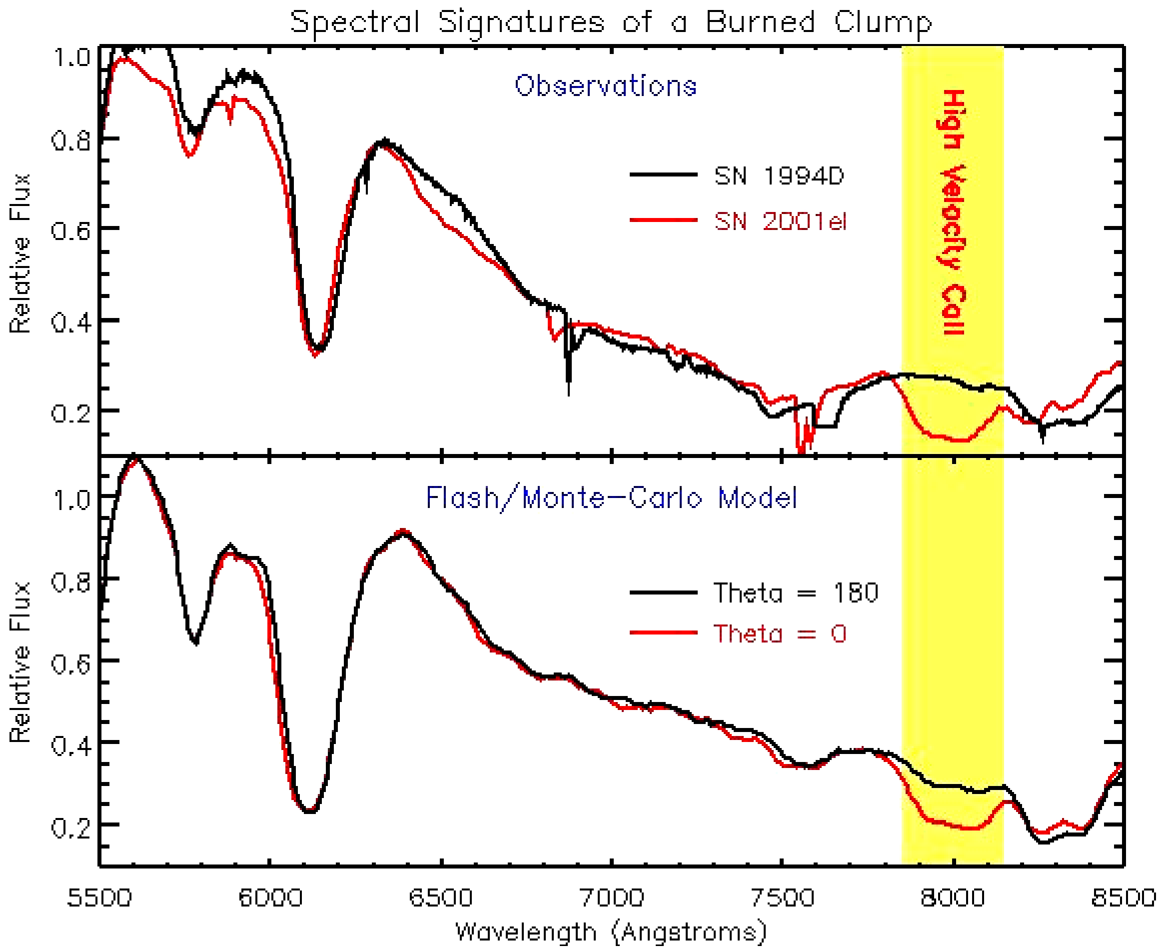
Let ejecta overrun the blob. Follow to free expansion. Notice acceleration of the blob material and presence of significant velocity gradient.



Contour marks $X_{Si} > 0.3$.

Spectral Signatures

Input to the spectrum calculation code (3-D Monte Carlo). Focus on the calcium line.



GCD vs. Classic Delayed Detonation

Characteristics shared with standard DDT models

- mild ignition
- deflagration followed by detonation (by the way, it is **DDT**, actually)
- complete burn
- pre-expansion
- layered ejecta
- modest degree of global asymmetry

Unique features

- accommodates **imperfections in the ICs** (single-bubble deflagration)
- **stellar pre-expansion** is driven by gravity
- **detonation** in unconfined environment
- the three-dimensional input to detonation is in fact **one-dimensional**
- asymmetries resulting in specific **spectral features**

Summary

- We have developed **capability** for studying Type Ia supernovae using integrated multi-physics large-scale computer simulations.

- In our initial work in the INCITE project, we have focused on the dependence of the evolution on the **initial conditions**. We have demonstrated that the most likely outcome is **the off-center deflagration**.

- We have discovered that **nearly central ignition** may naturally lead to **deflagration to detonation transition** due to compression and thermalization of the fuel accelerated by products of the deflagration. The INCITE award will allow us to study complete problem in three dimensions for the first time.

- **Gravitationally Confined Detonation** model
  - displays several main characteristics of observed objects
  - fueled discussion and strengthened importance of the initial conditions
  - detonation in unconfined environment
  - conceptually detonation phase resembles that of ICF
  - natural chain of events, not by-hand, from first principles

Extremely rare case in theoretical astrophysics!

To be continued!