Thermonuclear Supernovae: Gravitationally Confined Detonation

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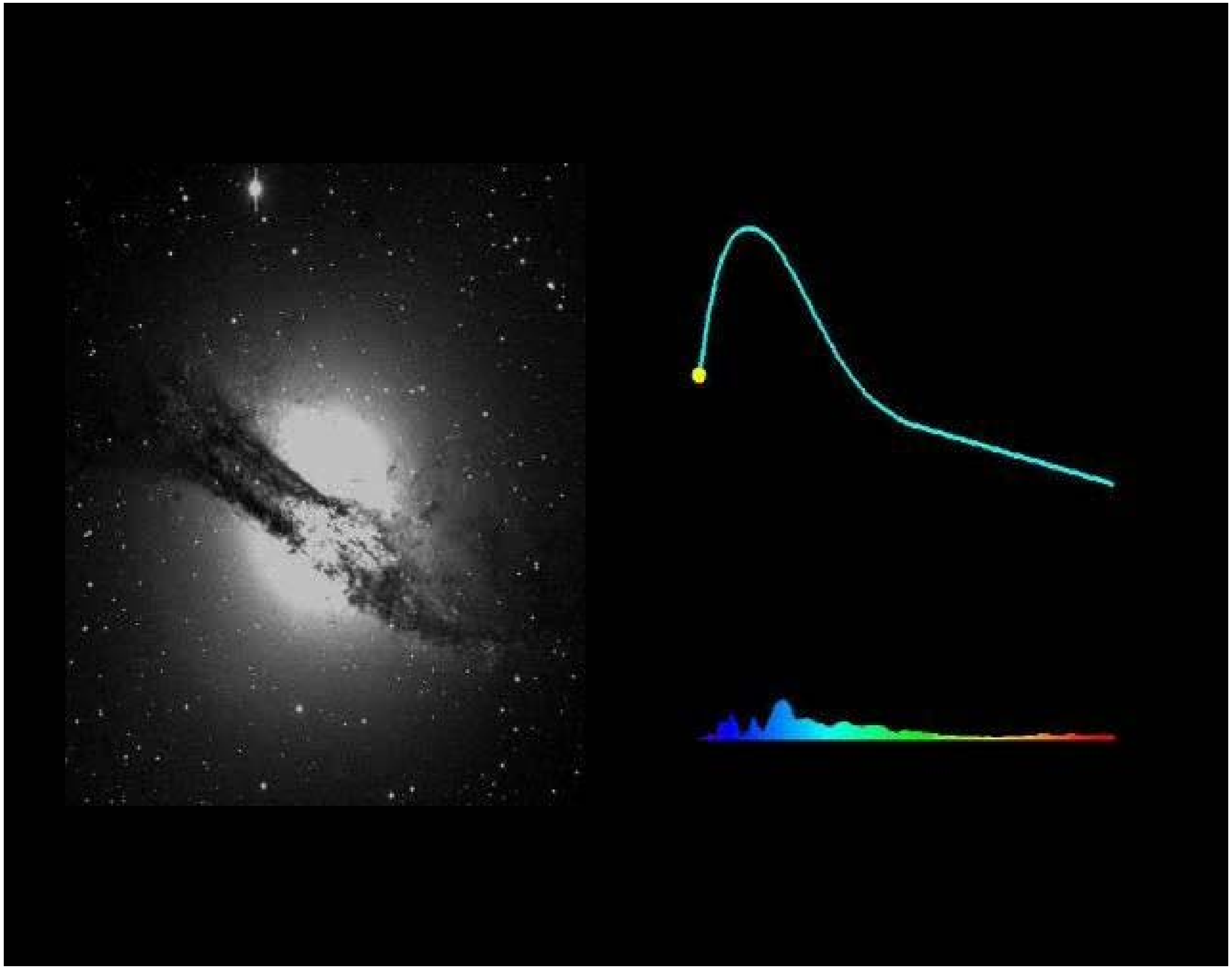
Flash Center

JINA SN Ia Workshop, KITP, UCSB

Type Ia SNe Appearance



P. Nugent (LBNL)

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.

Problem Parameters

Channels for progenitors

- Binary evolution
- Population synthesis

Initial conditions

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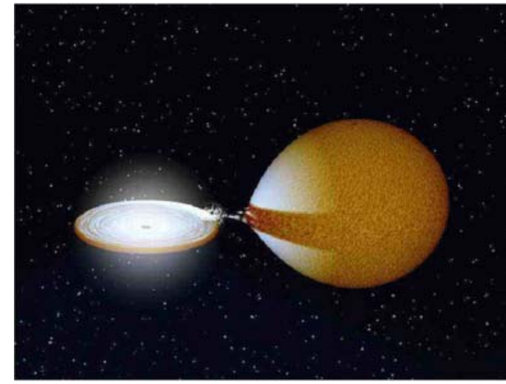
- State of the stellar core
- Metallicity
- Rotation profile
- Magnetic fields

Basic physics

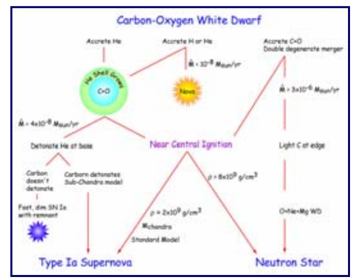
- Flame on intermediate scales
- Unsteadiness
- DDT

Numerics

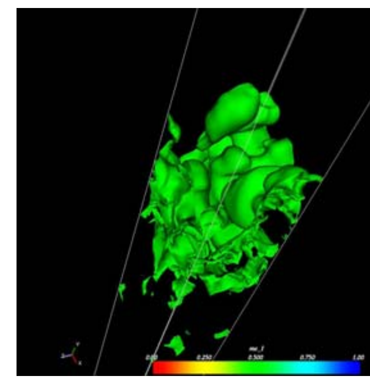
- Multiphysics coupling
- Nucleosynthesis postprocessing



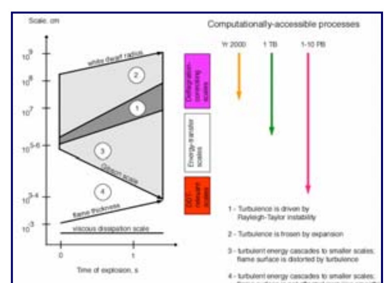
R. Hynes (2000)



F. Timmes



Messer et al. (2005)



A. Khokhlov

What Do We Do?

DOE ASC Alliance Center, University of Chicago

- 5 groups
- ~10 staff members, ~10 postdocs
- 7.5 years of research, 2.5 years still to go
- follow-up program

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) &= -\nabla P + \mathbf{f}, \\
\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\mathbf{v}] &= \mathbf{v} \cdot \mathbf{f} + q\rho\dot{\Phi}, \\
\frac{\partial \rho \phi}{\partial t} + \nabla \cdot (\rho \phi \mathbf{v}) &= \rho \dot{\Phi}, \\
\dot{\Phi} &= \kappa \nabla^2 \phi + R(\phi), \\
\rho E &= \rho e + \frac{\rho \mathbf{v}\mathbf{v}}{2}, \\
e &= e(\rho, P)
\end{aligned}
$$

I. Astrophysics program

- compact objects w/strong gravity
- realistic stellar EOS
- thermonuclear combustion
- turbulent flows
- shock waves

II. Code development

- FLASH
- parallel, multi-physics, adaptive mesh refinement hydrocode
- new hydro modules under development

III. Verification & Validation

- verification (correctness of formal solution)
- validation (physics models, requires real lab experiments)

What Others Has Done?

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)

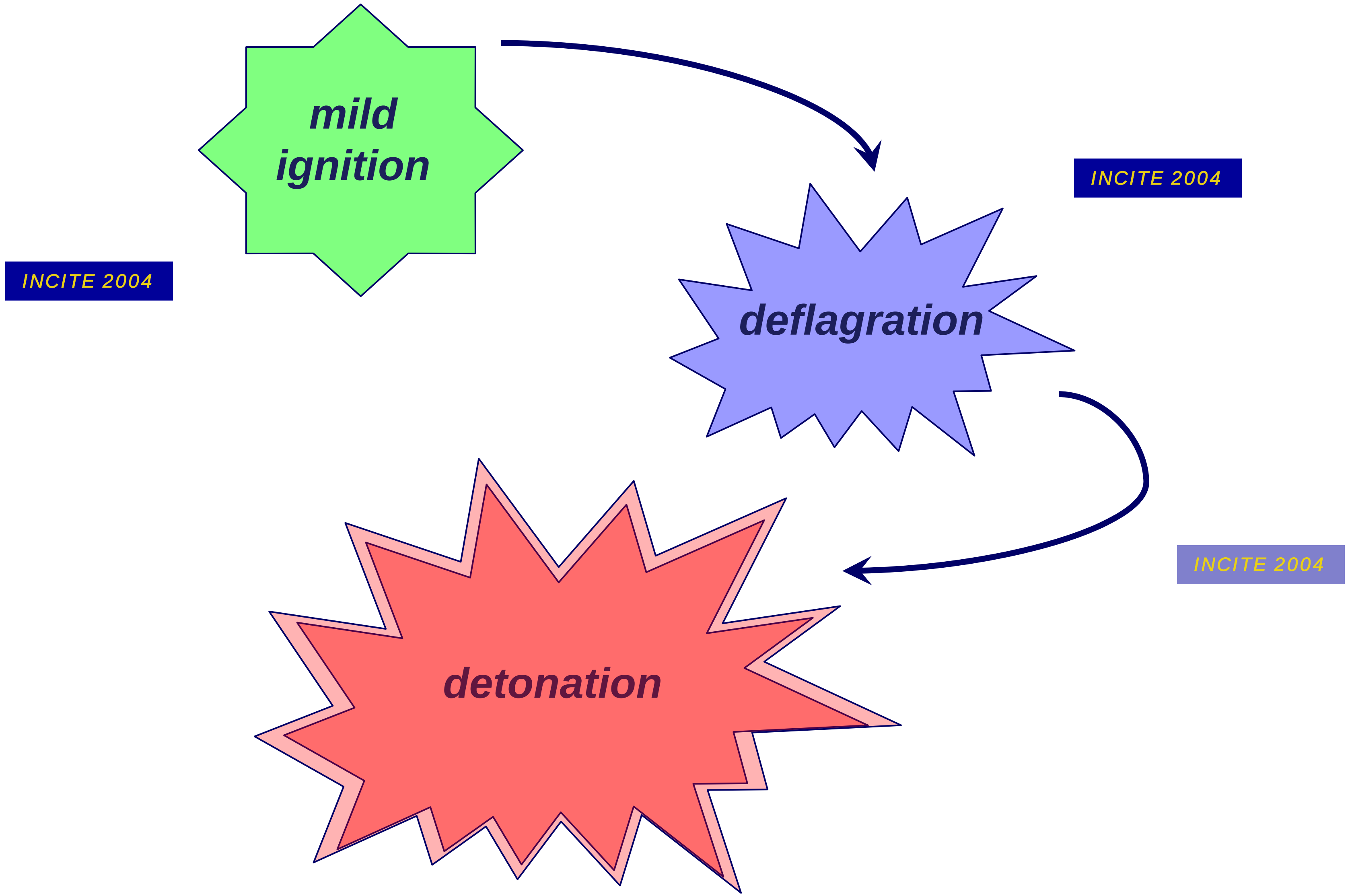
1990s

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

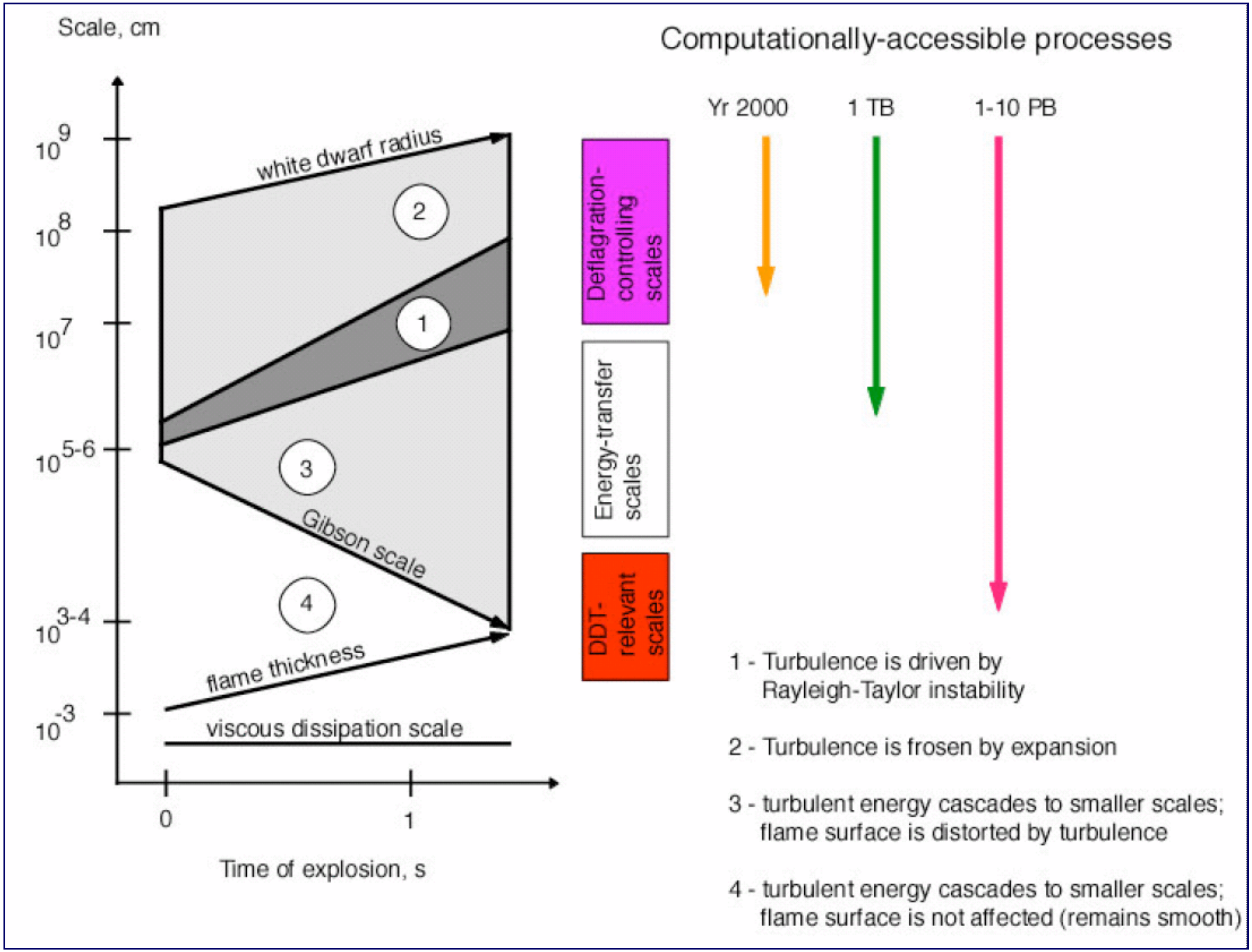
2000s

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

Explosive Stage of Thermonuclear Supernova

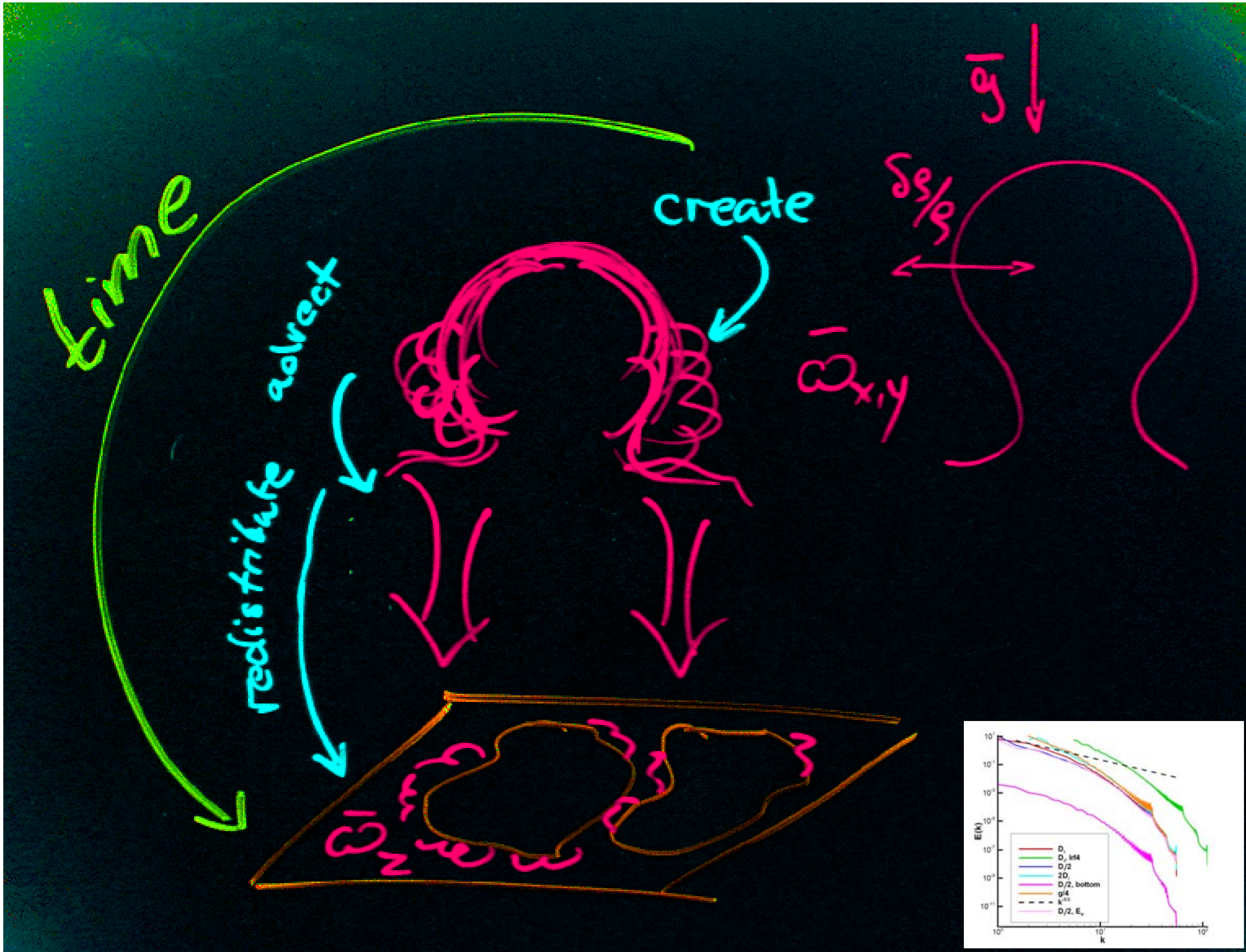


Why Large Scale Simulations?



A. Khokhlov (2003)

RT-driven Turbulence

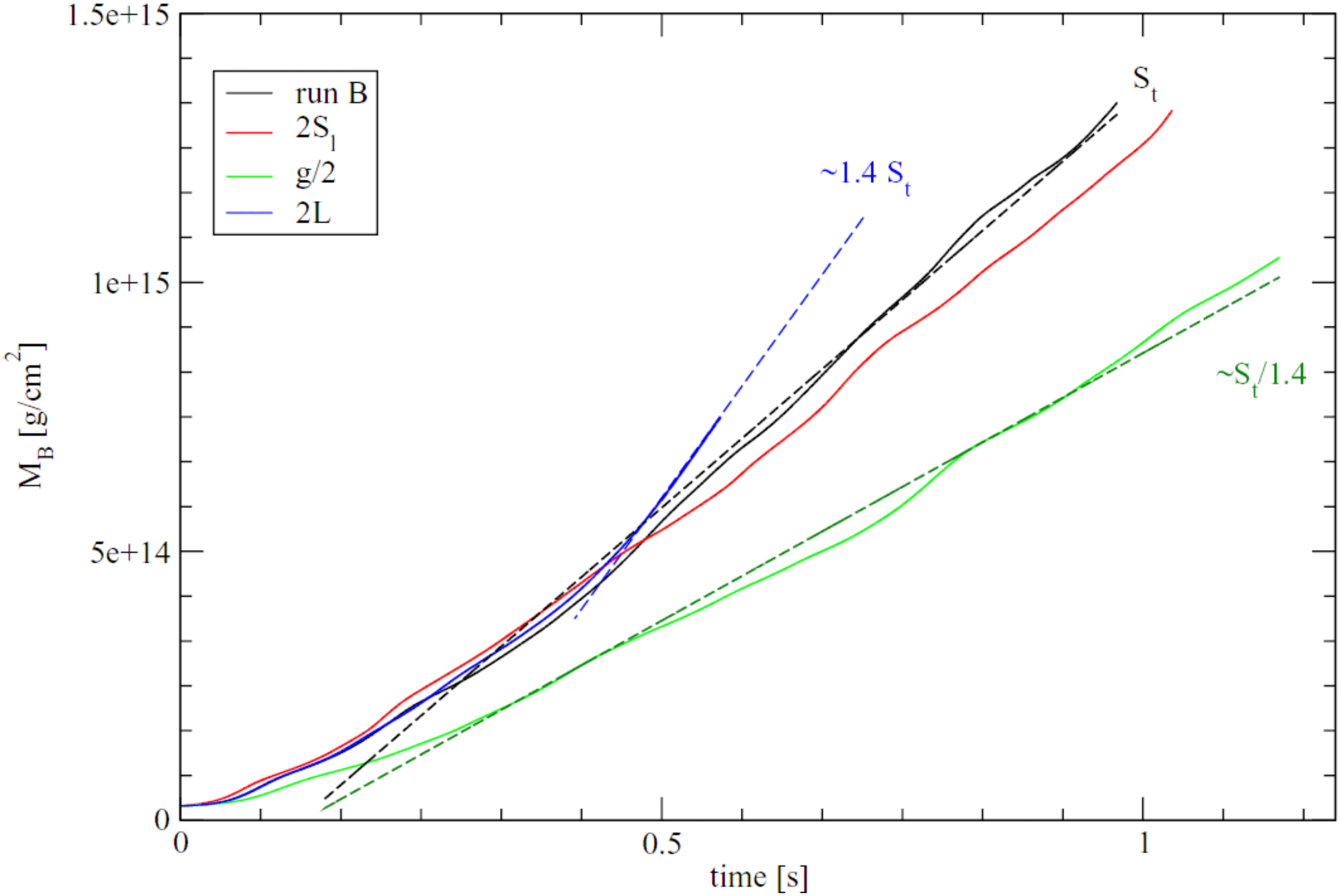


Zhang et al. (2005)

Supernova Turbulent Combustion

Steady-state turbulent flame speed does not depend on small-scale physics:

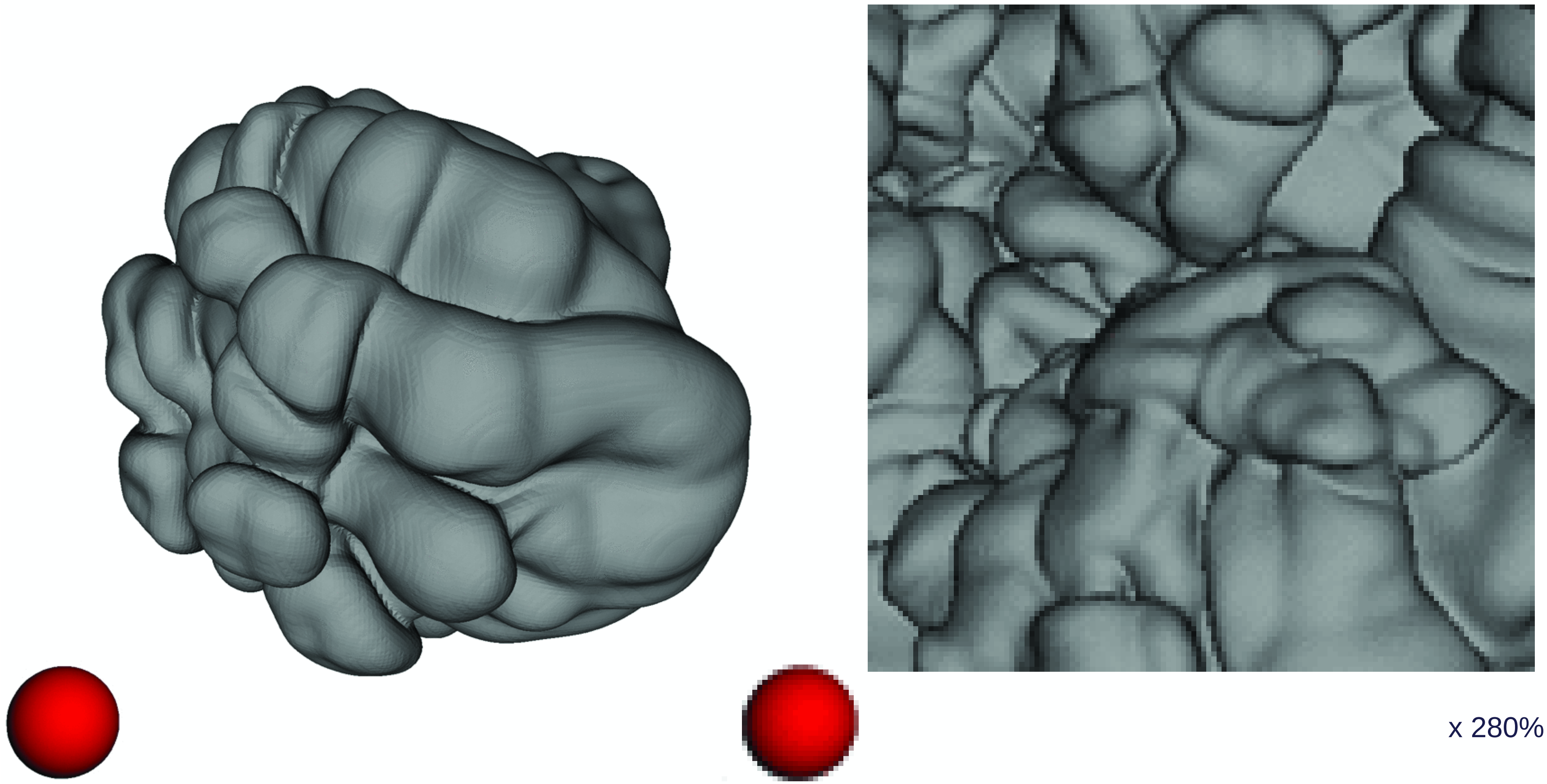
$$S_t = \alpha\sqrt{gLA}$$



Khokhlov (1995)

Messer et al. (2005)

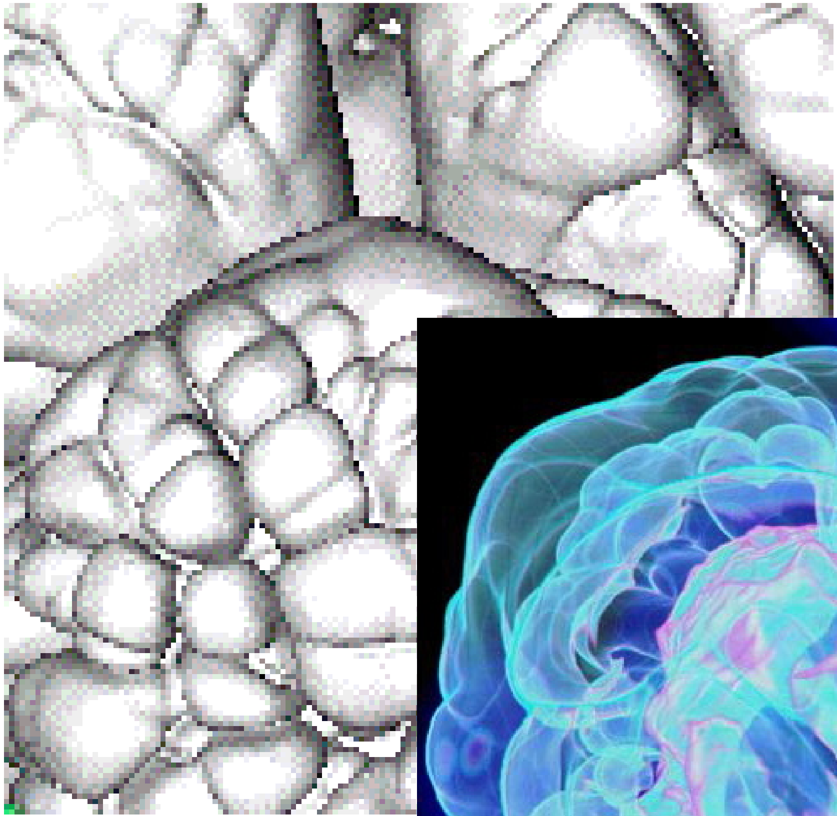
- evolution of the flame surface; r_{ball} = 25 km



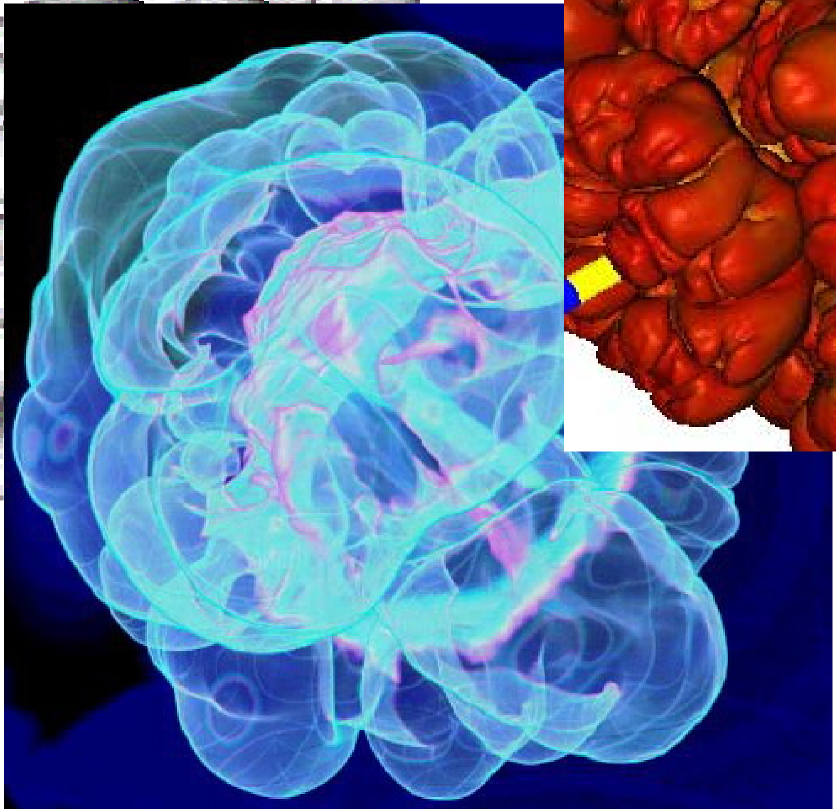
t=0.40 s

t=0.75 s

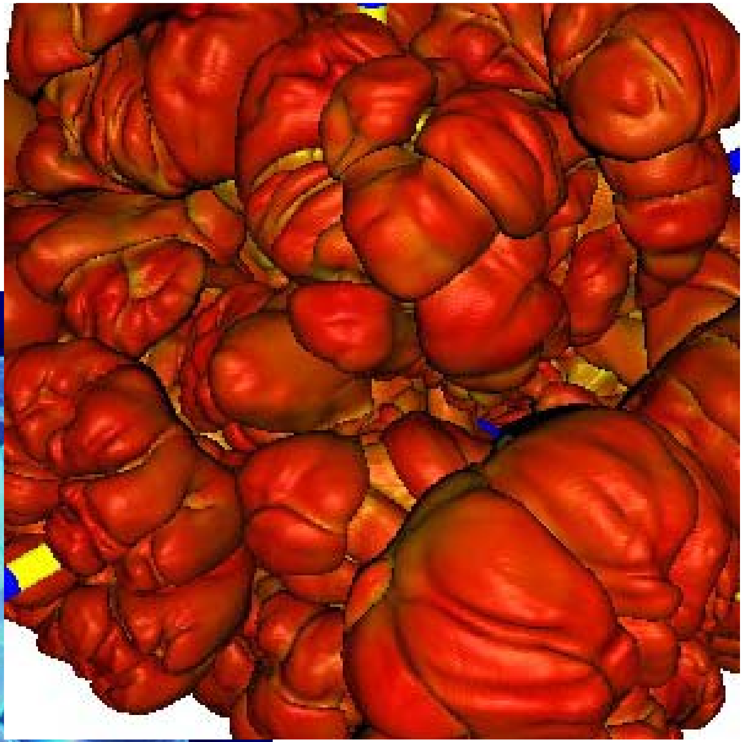
Deflagration Model: Flame Morphology



Gamezo et al. (2002)

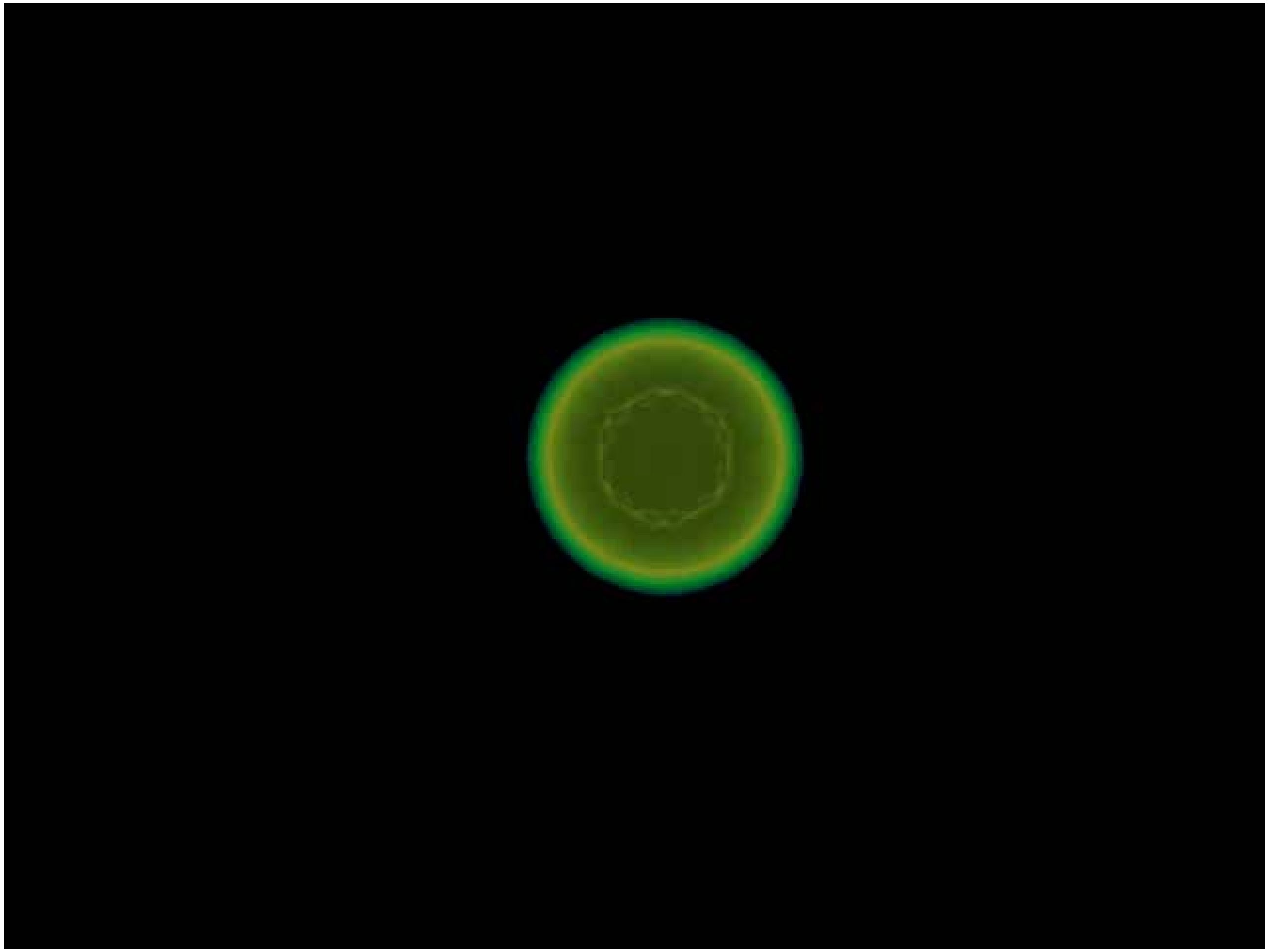


FLASH (2003)



Reinecke et al. (2002)

8 km Resolution Central Ignition Whole Star Model



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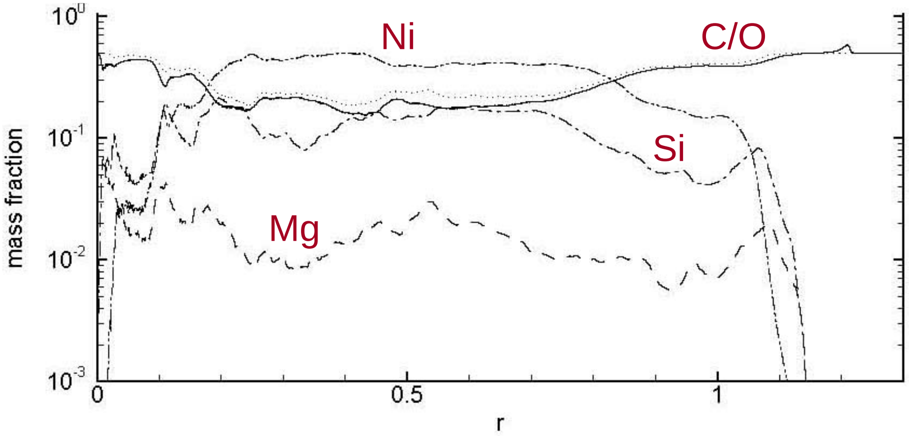
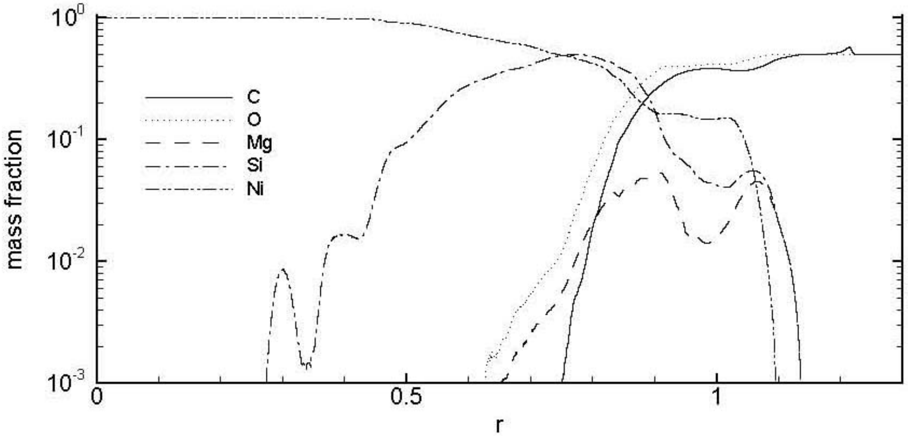
- Two models, 255,000 SUs and 5TB of data per model

Ejecta Composition: Deflagration vs. DDT

Angle-averaged chemical composition



3-D pure deflagration

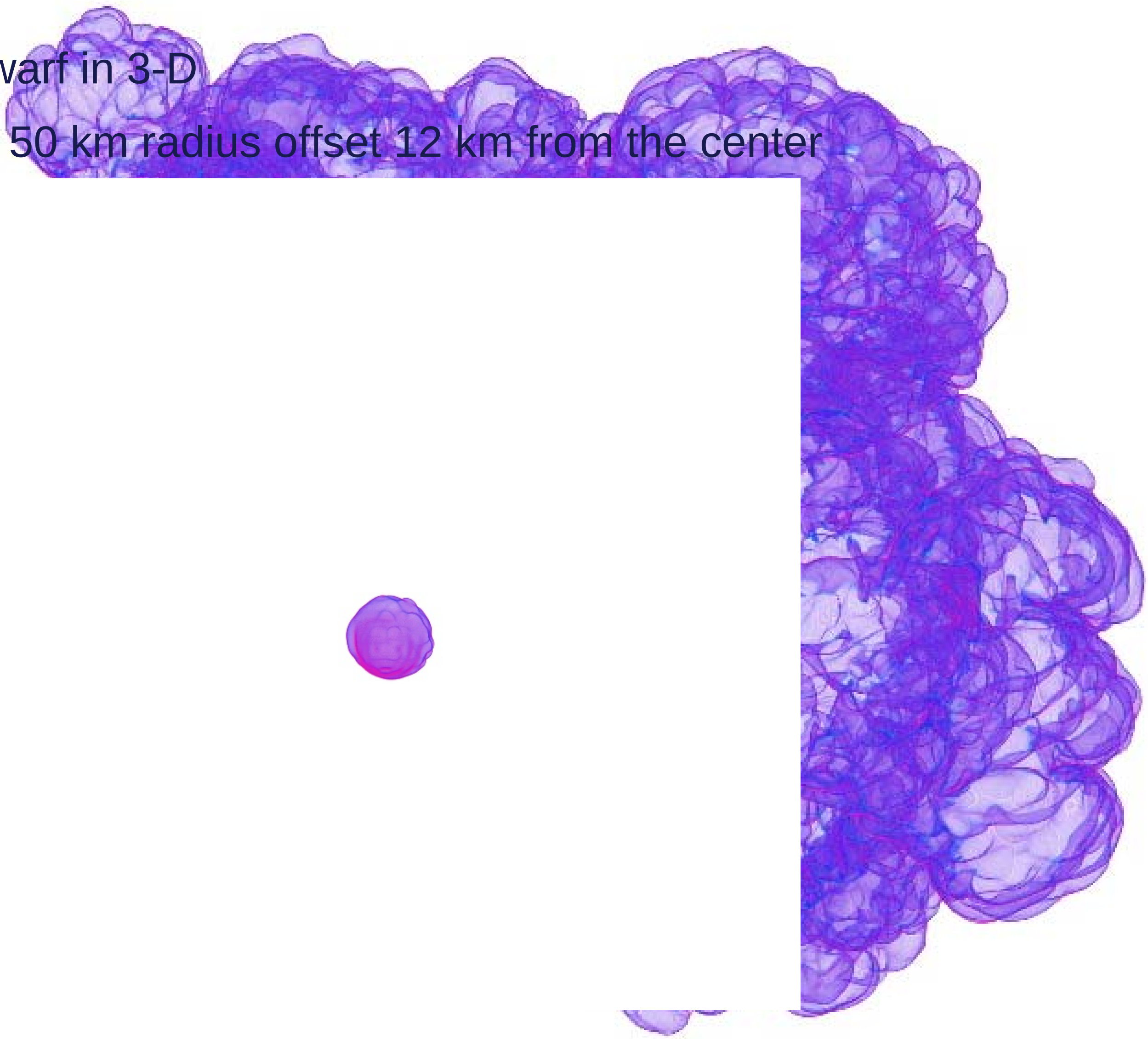


3-D speculative DDT

Gamezo et al. (2003)

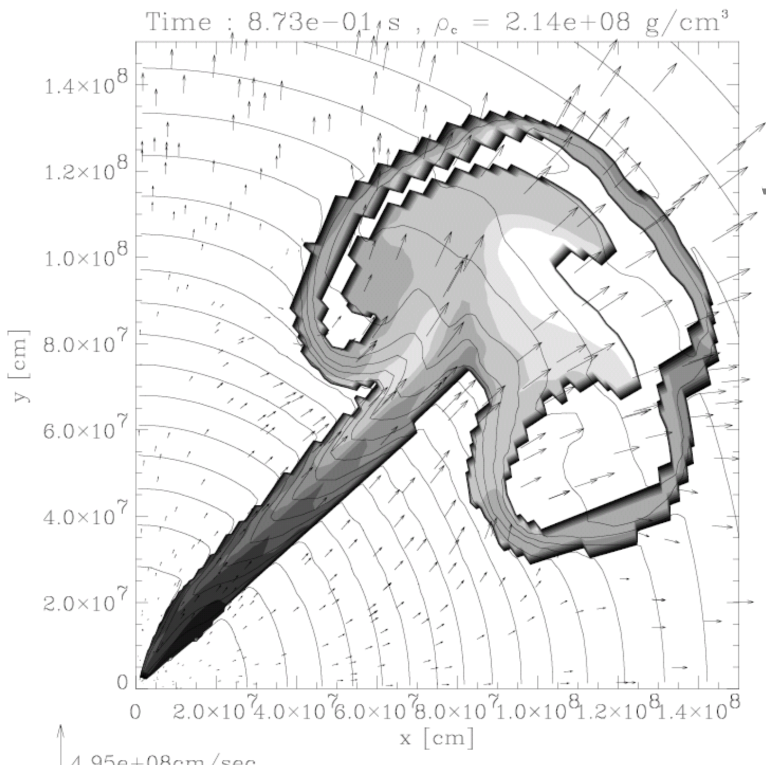
Is Location of The Ignition Point Important?

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

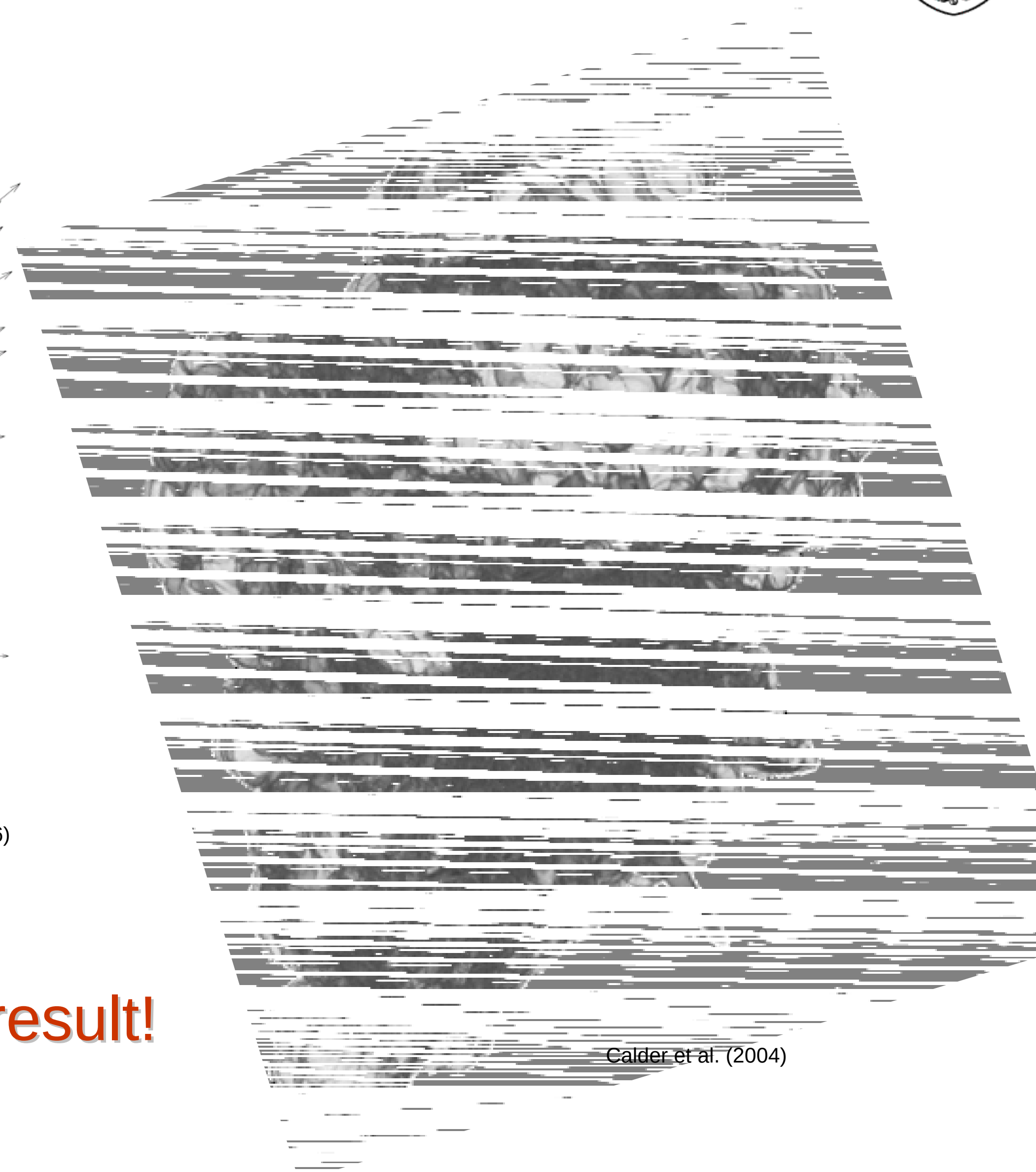


Calder et al. (2004)

8 Years Between, Two Different Methods…



Niemeyer, Hillebrandt, & Woosley (1996)

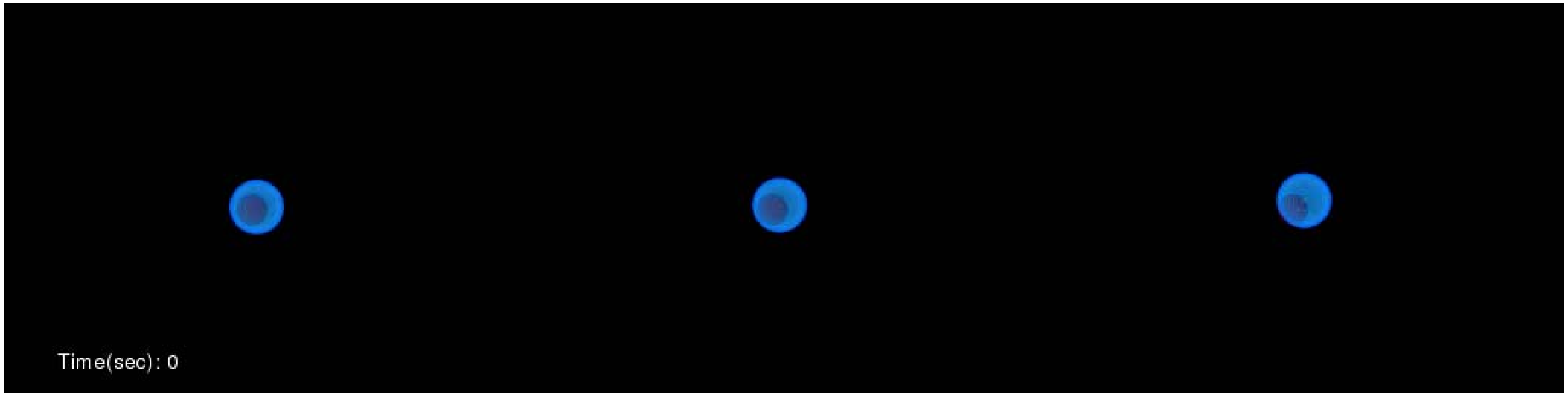


Calder et al. (2004)

…and virtually the same result!

What Does It Mean "Slightly Off-Center"?

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



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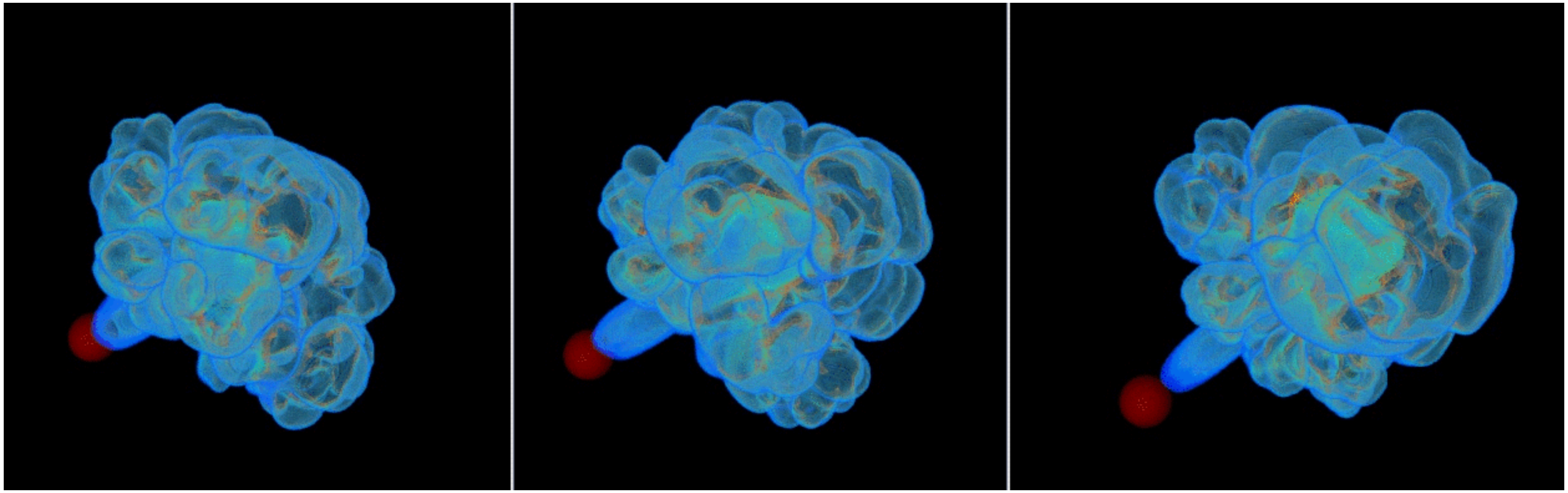
Memory Loss of The Initial Conditions

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

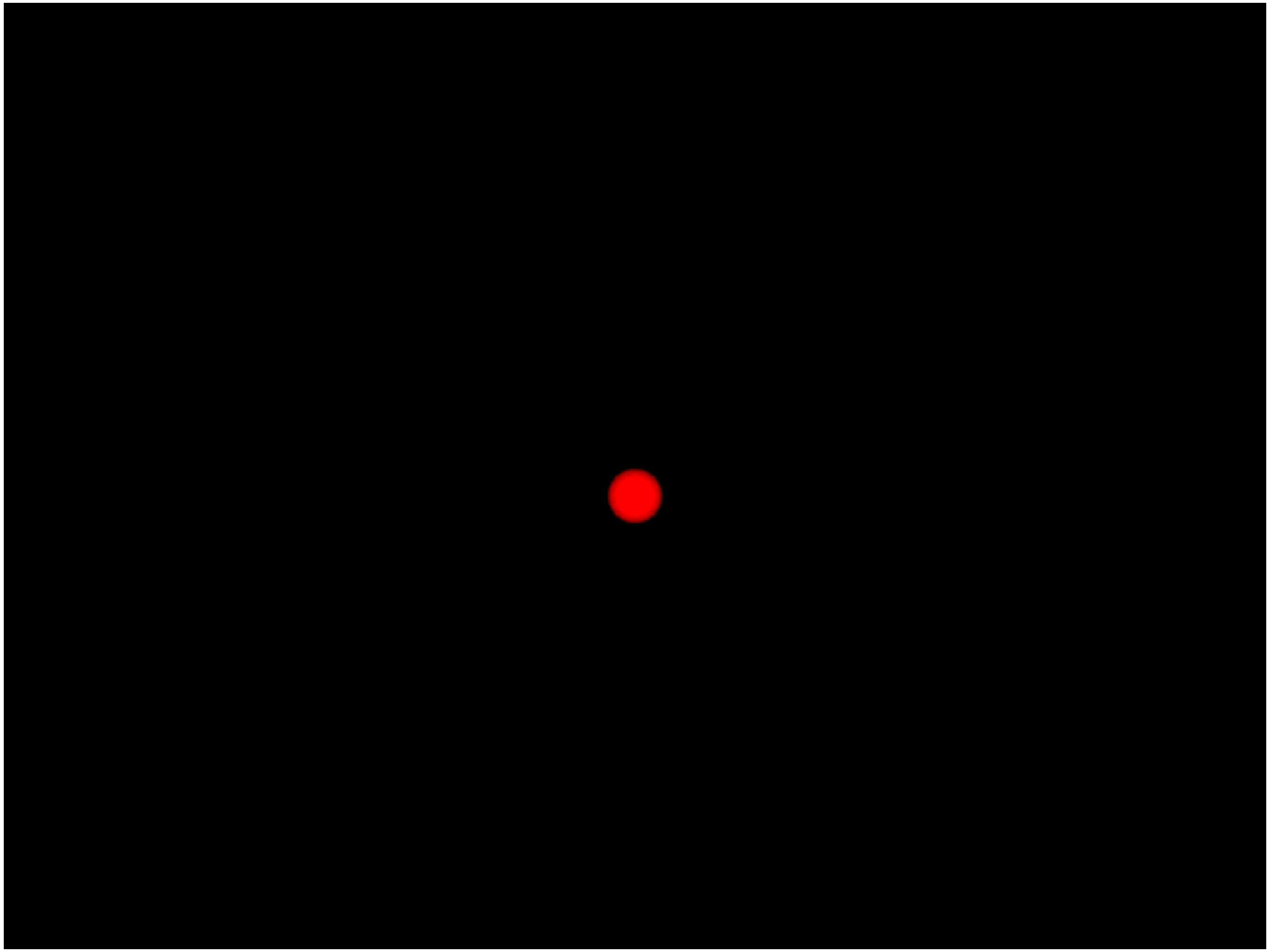


12 km 20 km 35 km

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

Initial Conditions: Location, Velocity Field

r1y0v10a3030 (central, 10 km/s)



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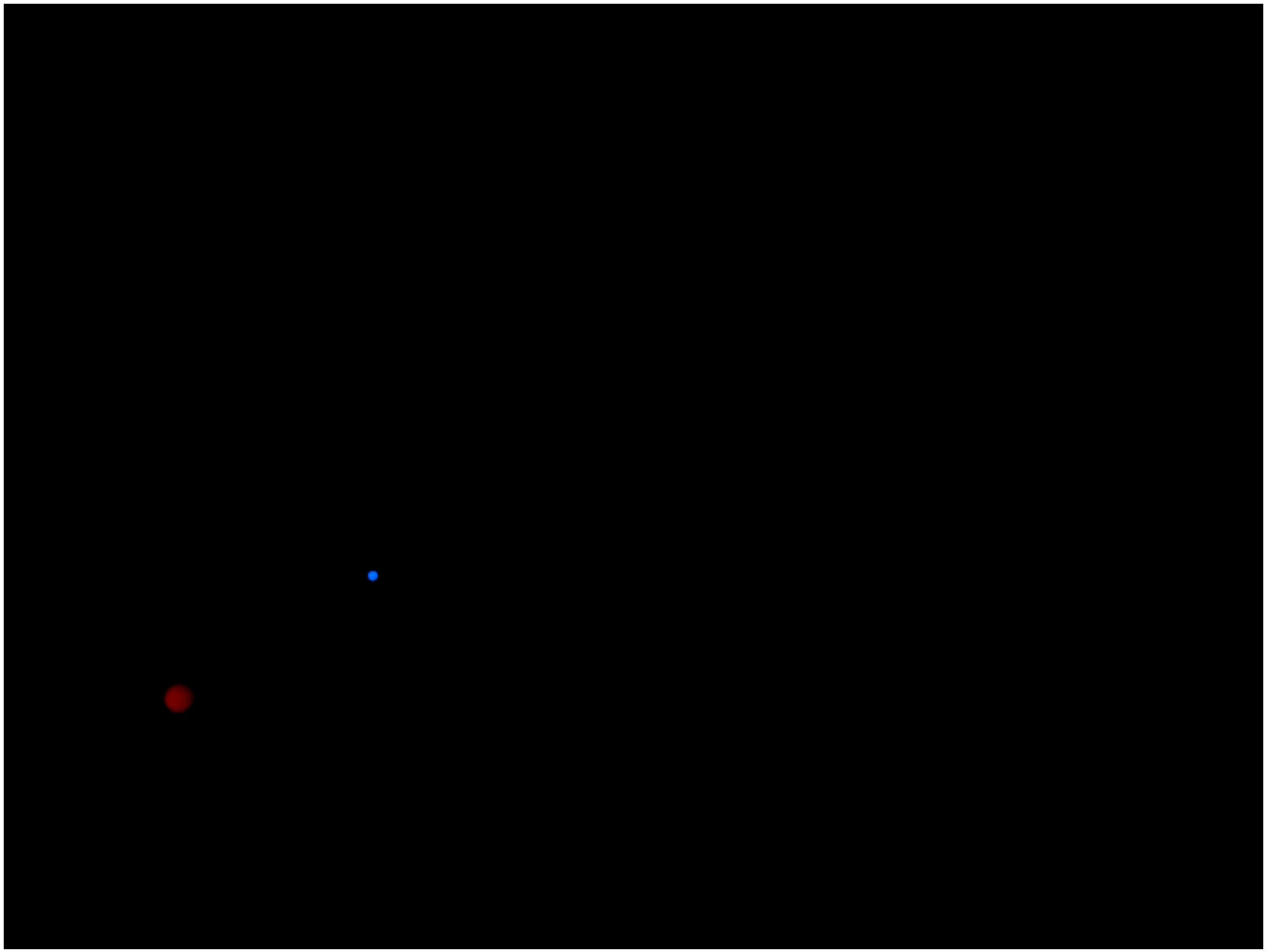
Initial Conditions: Location, Velocity Field

r1y100v100a3030 (outflowing, 100 km/s)



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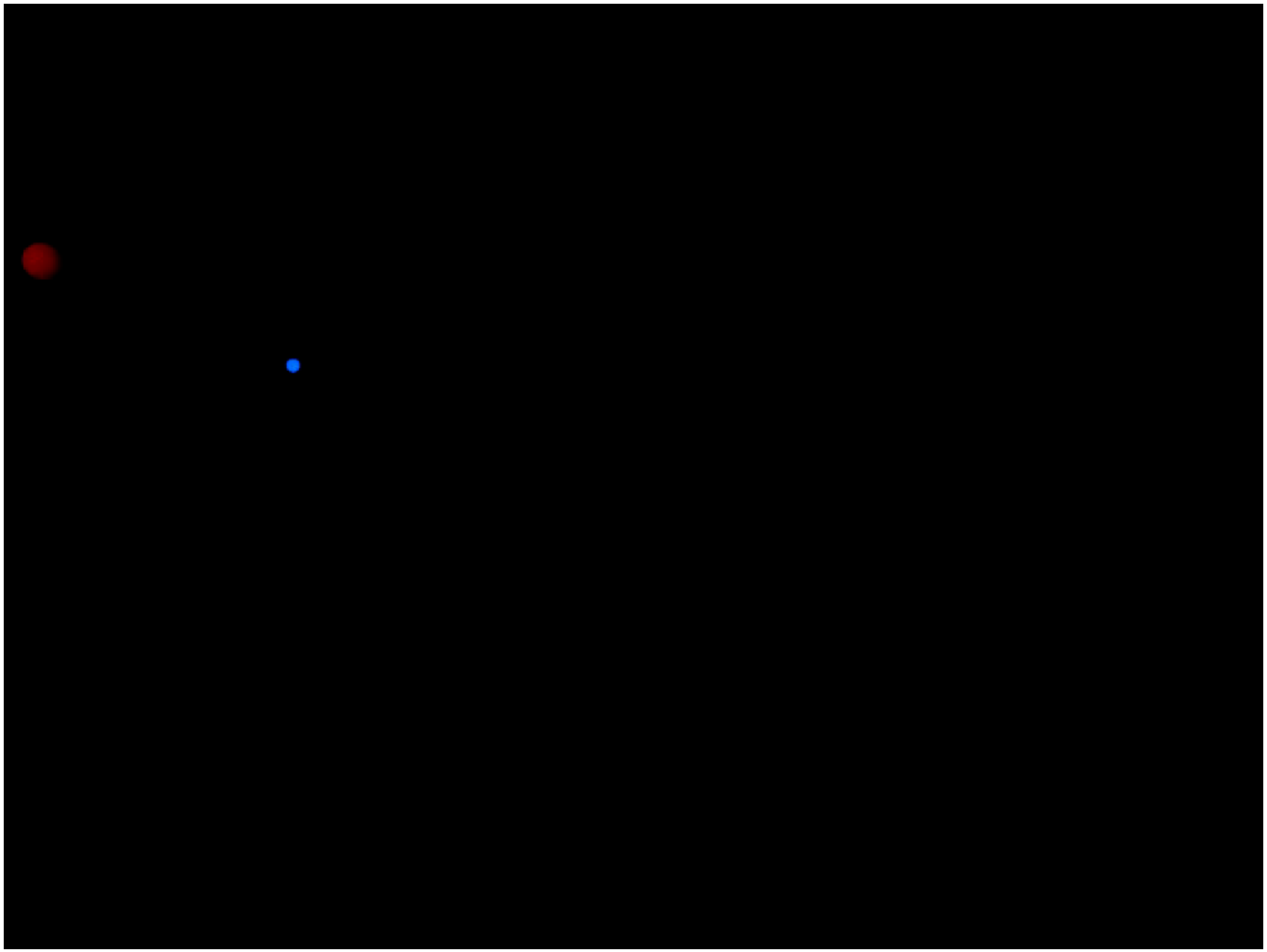
Initial Conditions: Location, Velocity Field

r1y100v100a3030in (inflowing, 100 km/s)



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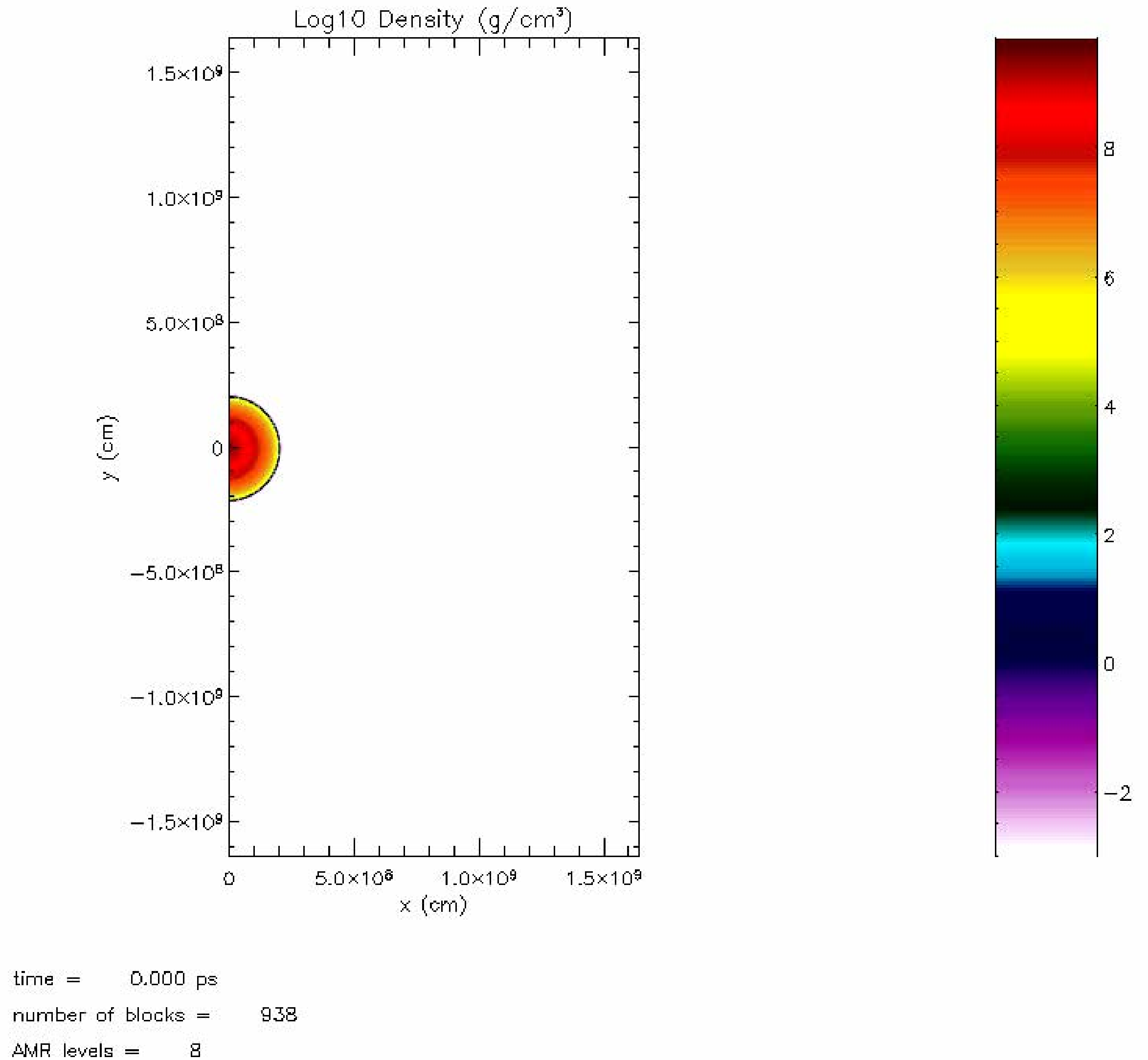
Initial Conditions: Conclusion

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

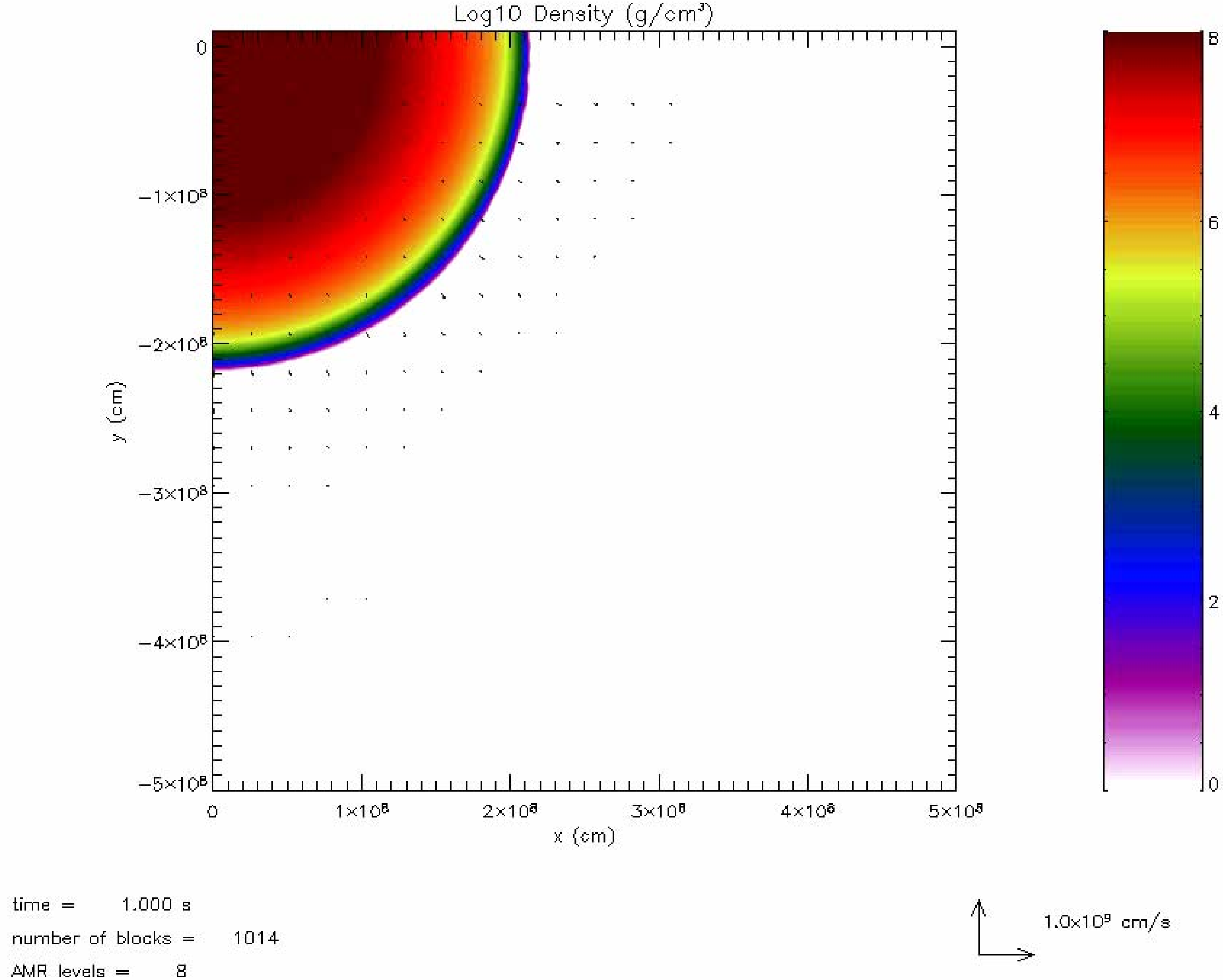
Post-burst Evolution in 2-D (C→Ni)

- in long term bubble burst causes asymmetric matter distribution



Gravitationally Confined Detonation (C→Ni)

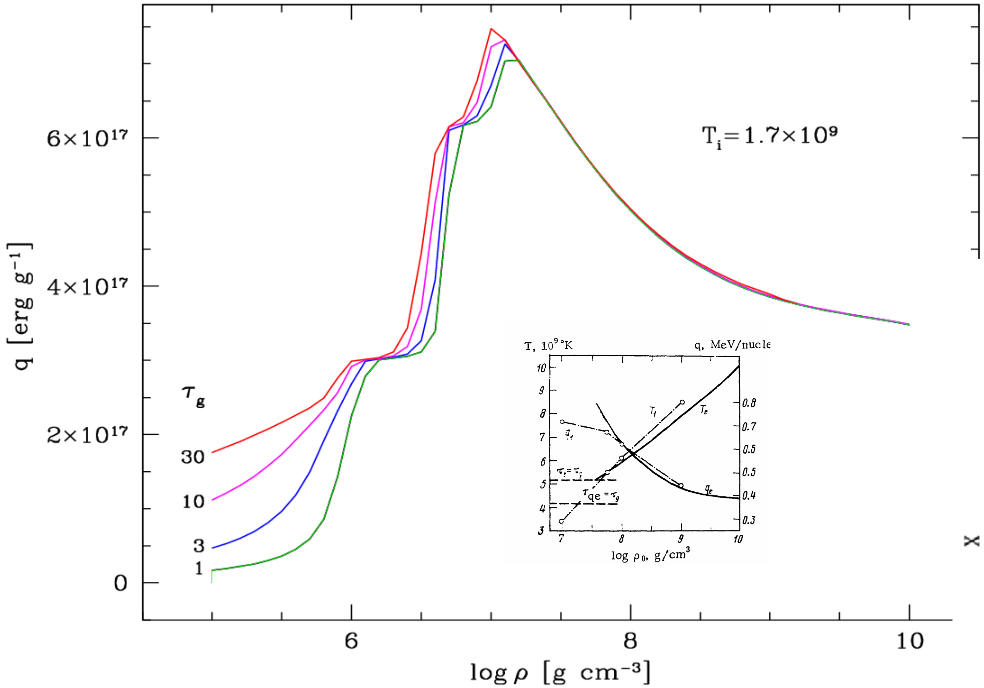
- ...collides, energy is converted into heat, density increases...

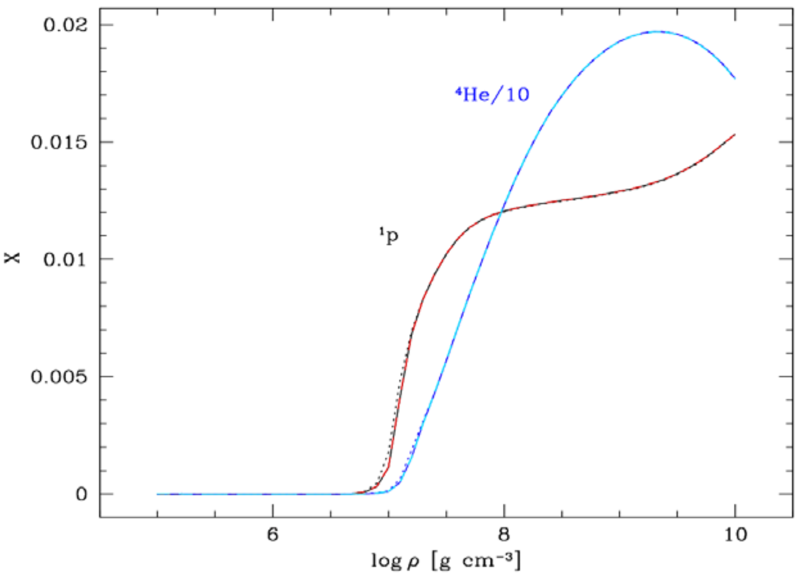


NSE-limited Energy Release C/O Explosive Burn

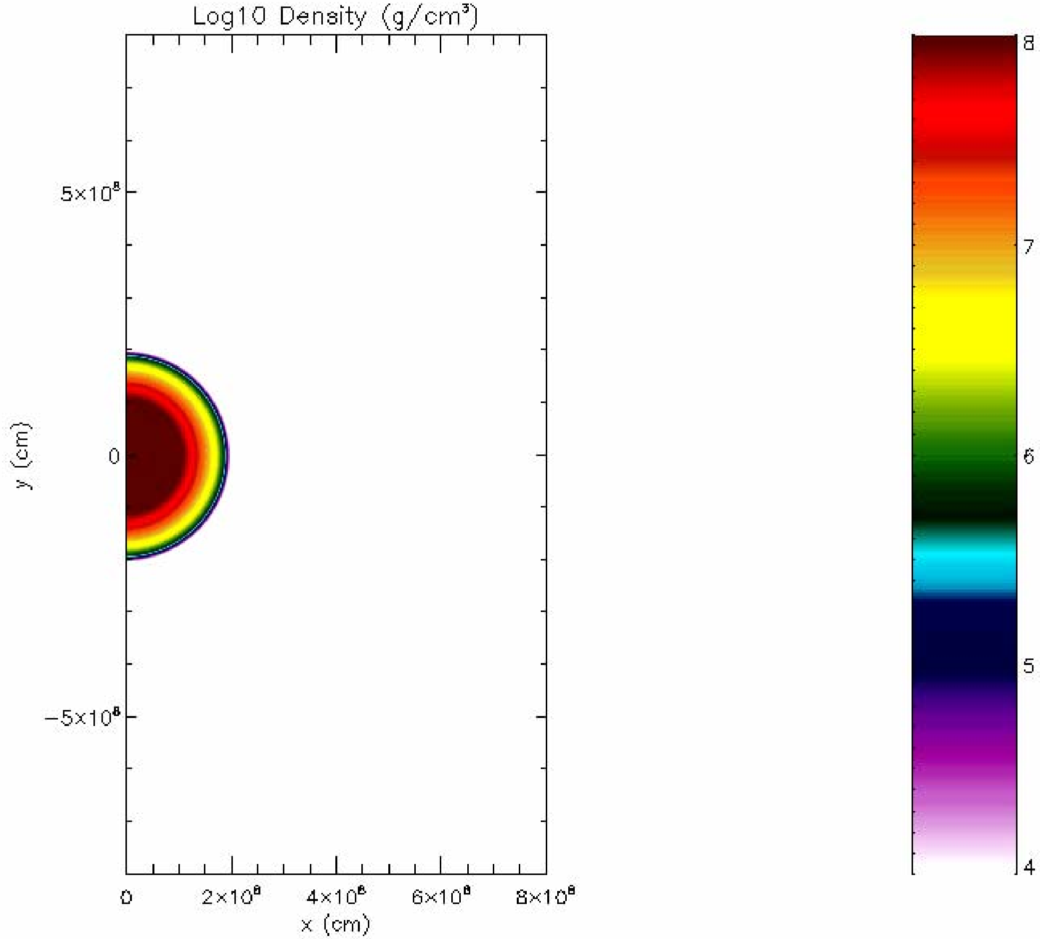
$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\mathbf{v}] = \mathbf{v} \cdot \mathbf{f} + q\rho\dot{\Phi}$$

torch 47 isotopes network





Gravitationally Confined Detonation (NSE-limited)

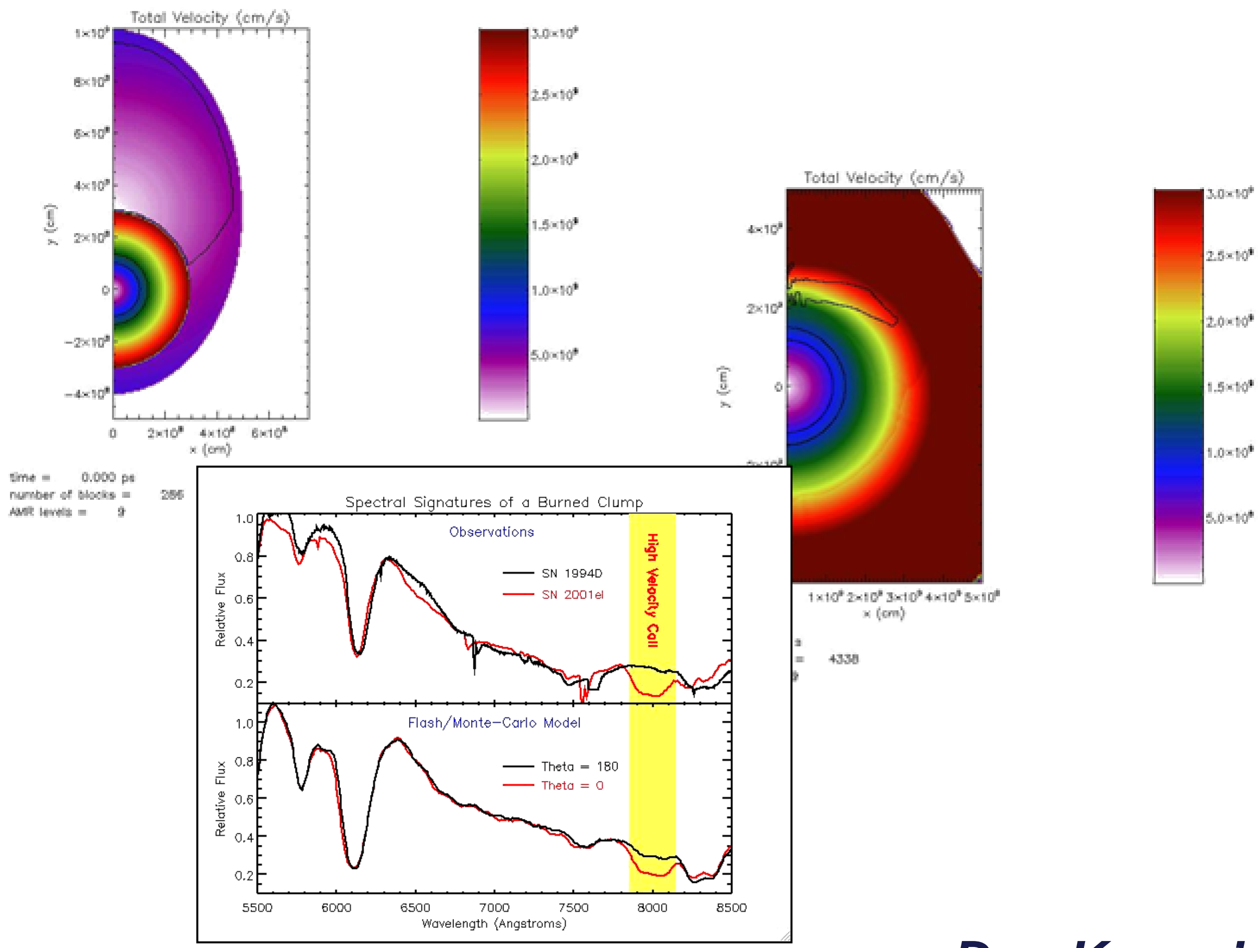


time = 0.000 ps

number of blocks = 1178

AMR levels = 9

GCD Spectral Signatures



Dan Kasen's talk…

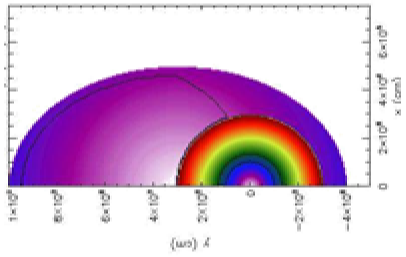
GCD vs. Classic DDT

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

Gravitationally Confined Detonation model

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

Extremely rare case in theoretical astrophysics!

To be continued!