Type Ia Supernovae:
Turbulent Nuclear Combustion at High Resolution

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Type Ia Supernovae

Spectral Classification
“I” – weak hydrogen
“a” – strong silicon

Type Ia Supernovae (SNe Ia)

Thermonuclear explosions of C/O white dwarfs – objects about 35% more massive than the Sun, crammed into a sphere the size of the Earth.

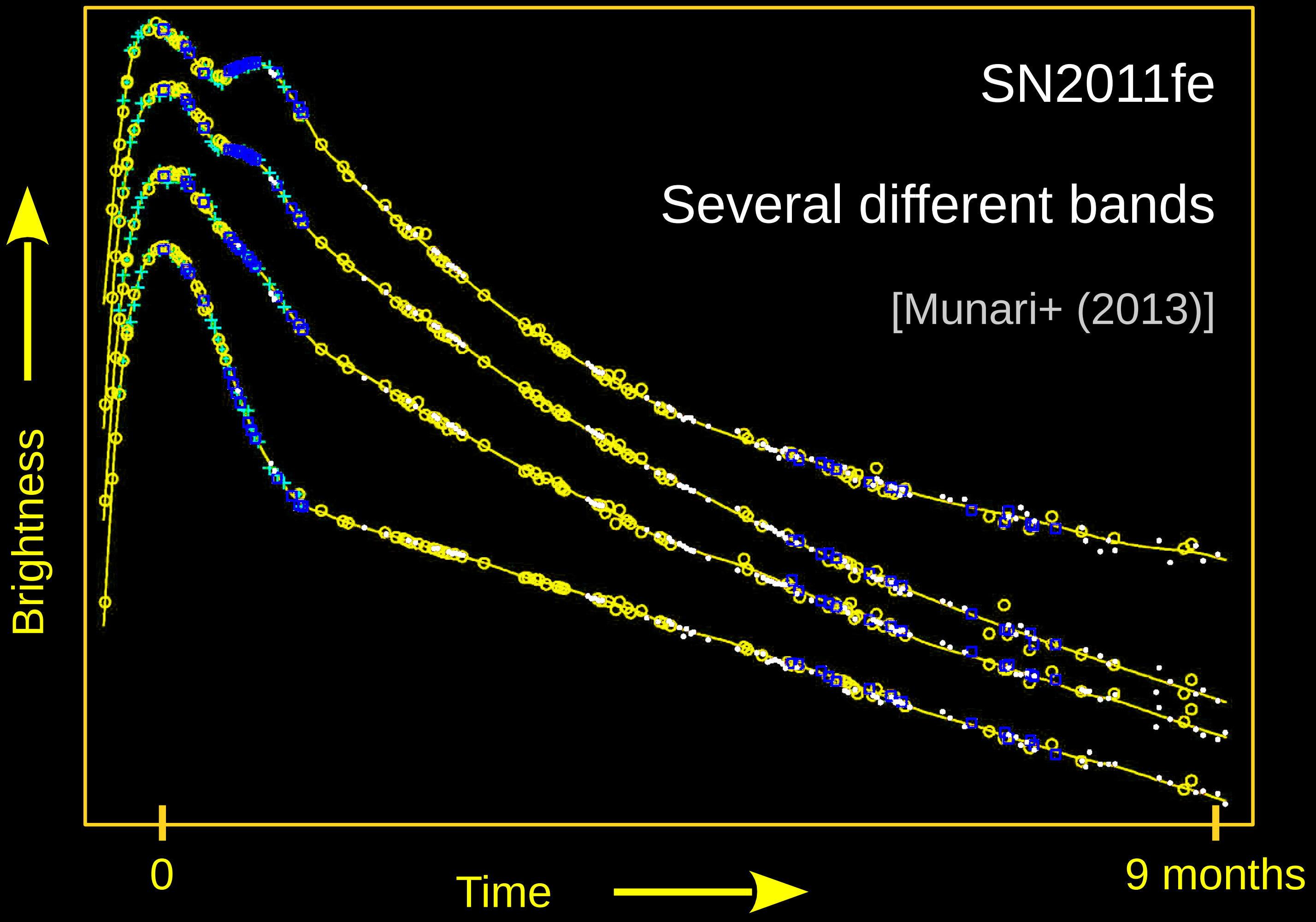
$\rho_c \sim 2 \times 10^9$ g cm^{-3}

SNe Ia

Outshine entire galaxy for months

SN1994D

SNe Ia – Lightcurve



SN2011fe

Several different bands

[Munari+ (2013)]

Powered by radioactive decay of heavy isotopes ($^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$)

Why it Matters

Why it Matters in General

Stars convert H/He into heavier elements up to Fe.

Supernovae, in general, release this material to the rest of the galaxy.

“*We are all starstuff.*” – Carl Sagan

Why it Matters in Particular

The supernova process itself produces even heavier elements.

SNe Ia produce a lot (~ 0.5 M_{sun}) of “iron-group elements” – Fe, Co, Ni – and to a lesser extent, “intermediate-mass elements” – Si, S, Ca

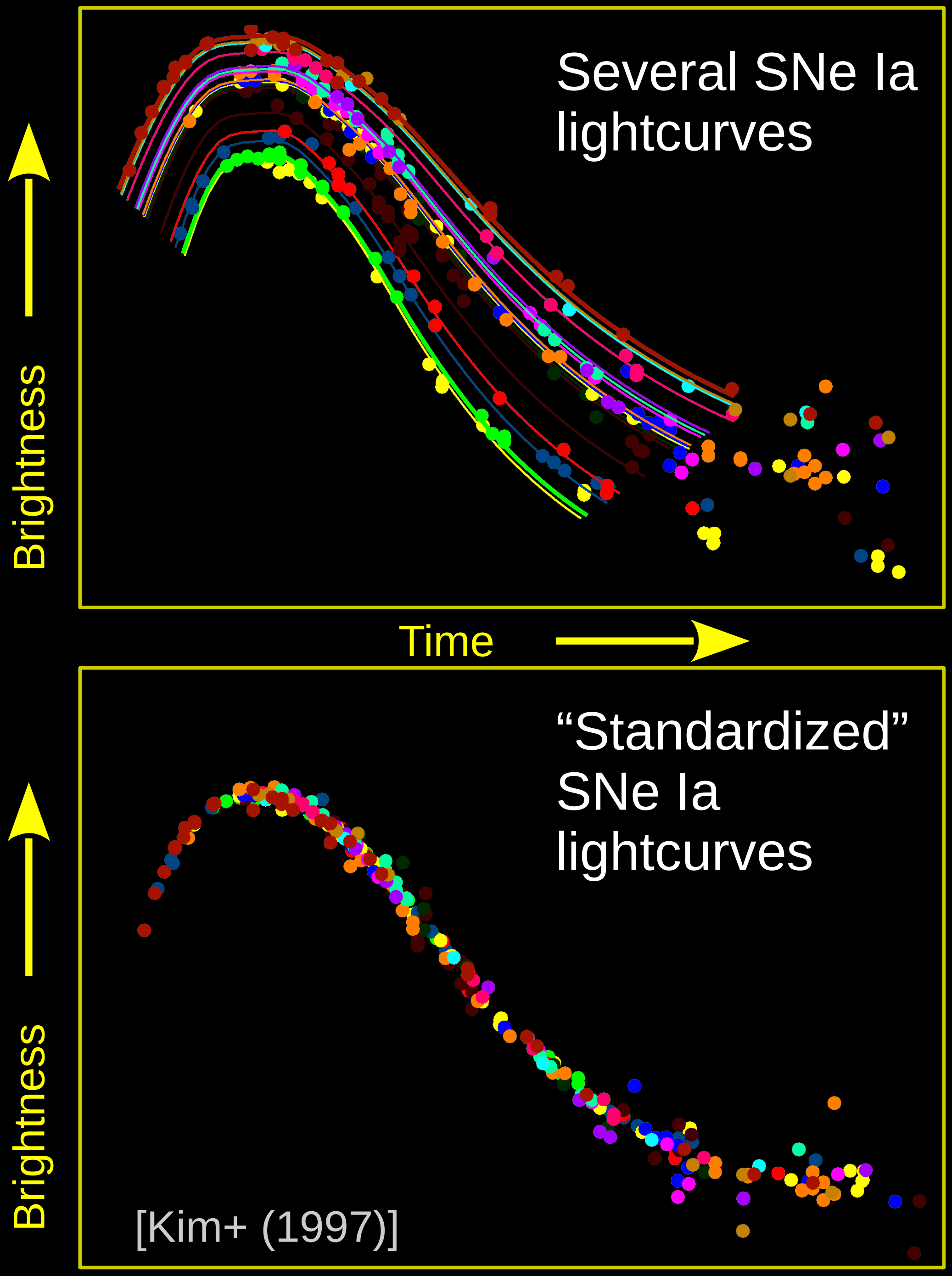
Why it Matters in Cosmology

“Broader is brighter” – Phillips' Relation

“Standardization” allows for distance measure

2011 Nobel Prize in Physics:
Perlmutter, Schmidt, and Riess

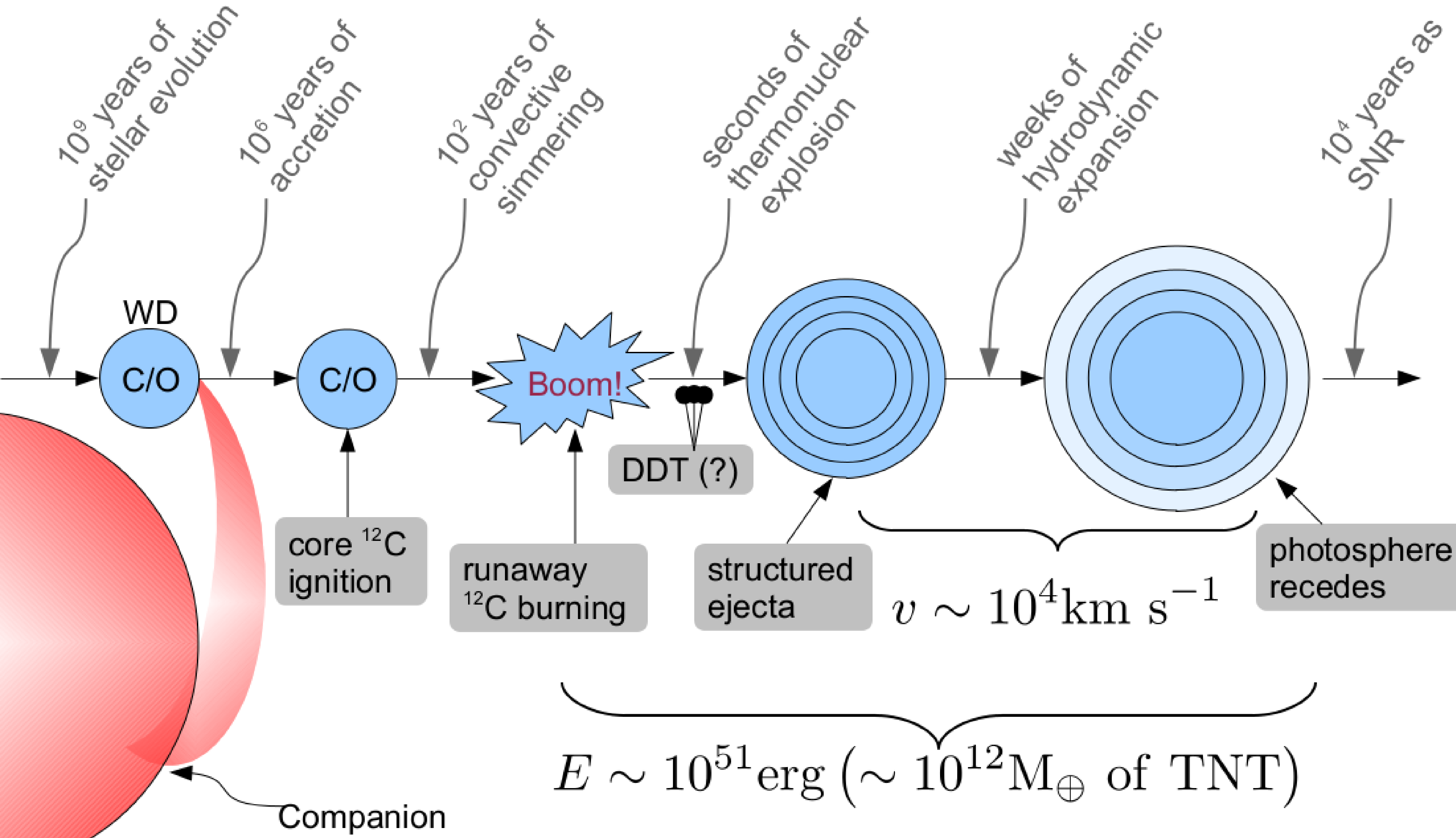
“for the discovery of the accelerating expansion of the Universe through observations of distant supernovae.”



[Kim+ (1997)]

Key Challenges

Single Degenerate Model



10^9 years of stellar evolution

10^6 years of accretion

10^2 years of convective simmering

seconds of thermonuclear explosion

weeks of hydrodynamic expansion

10^4 years as SNR

WD

C/O

C/O

Boom!

core ^{12}C ignition

runaway ^{12}C burning

DDT (?)

structured ejecta

photosphere recedes

$$v \sim 10^4 \mathrm{km\ s}^{-1}$$

$$E \sim 10^{51} \mathrm{erg} \left(\sim 10^{12} \mathrm{M}_\oplus \text{ of TNT}\right)$$

Companion

Key Challenges

Linking together different phases of the evolution involves coupling different physics and, sometimes, different algorithms/solvers.

Key Challenges

The simmering phase is quite subsonic ($M \sim 0.05$).

Map between "Low Mach" code (Maestro) and compressible code (Castro)

The flame propagation (TNR) is mildly subsonic ($M \sim 0.2$).

Runaway ignition occurs once, in a small region ($r < 2$ km).

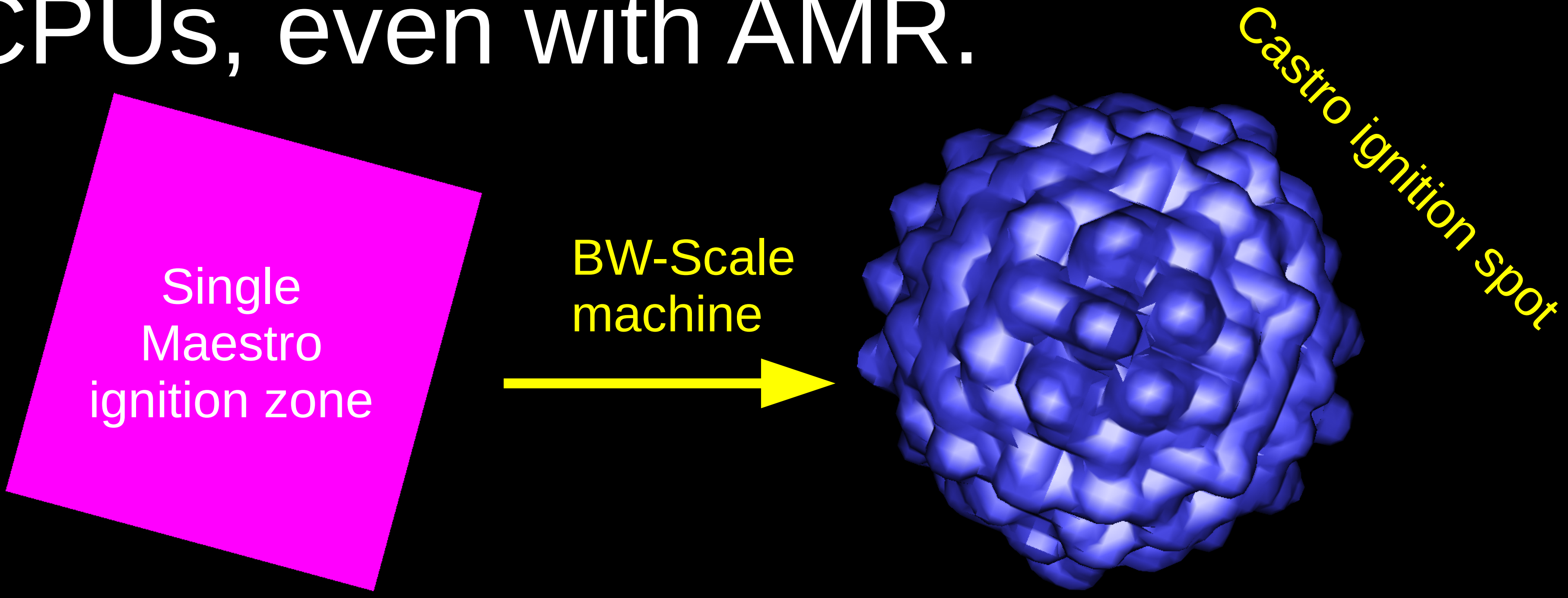
At ignition, the flame is incredibly thin ($l < 1$ mm).

High resolution and approximate model for the flame

Why Blue Waters?

Why Blue Waters?

Simulating a full star (r ~ 10^3 km) while resolving the initial ignition point (r ~ 2 km) requires a lot of CPUs, even with AMR.



Single Maestro ignition zone

BW-Scale machine

Castro ignition spot

Initially 5 levels of AMR – effective resolution $36{,}864^3$ (135 m/zone)

Typical run – 4096 MPI tasks, 16 OMP threads/task, 2 MPI tasks per node: 65,536 core modules

Why Blue Waters?

Such high resolution implies large checkpoint (~200 GB) and viz (~ 100 GB) files.

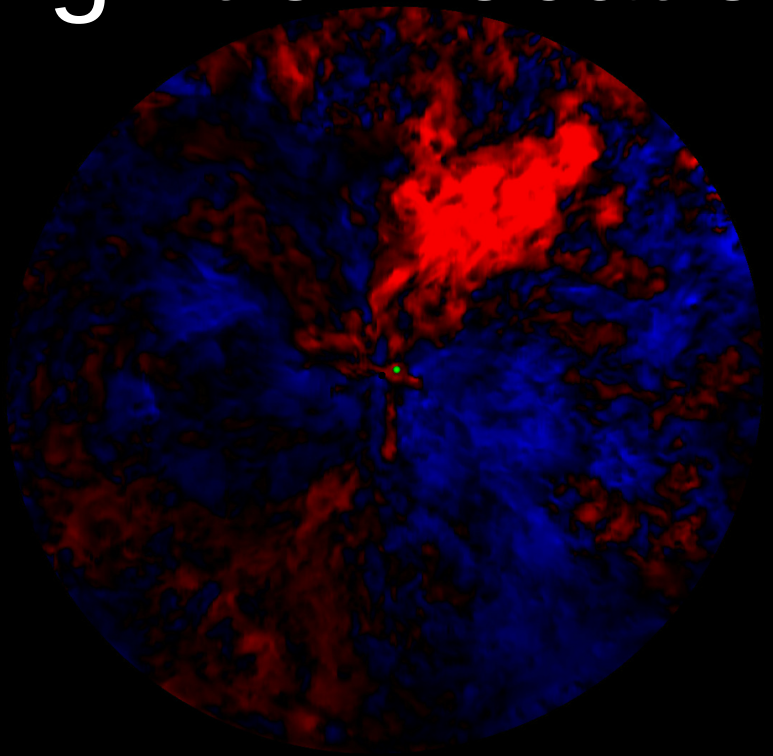
Dumped every couple of hours, we generated several 10's of TB of data (spread over multiple machines). By far, I/O on BW was superb.

*Globus Online

Accomplishments

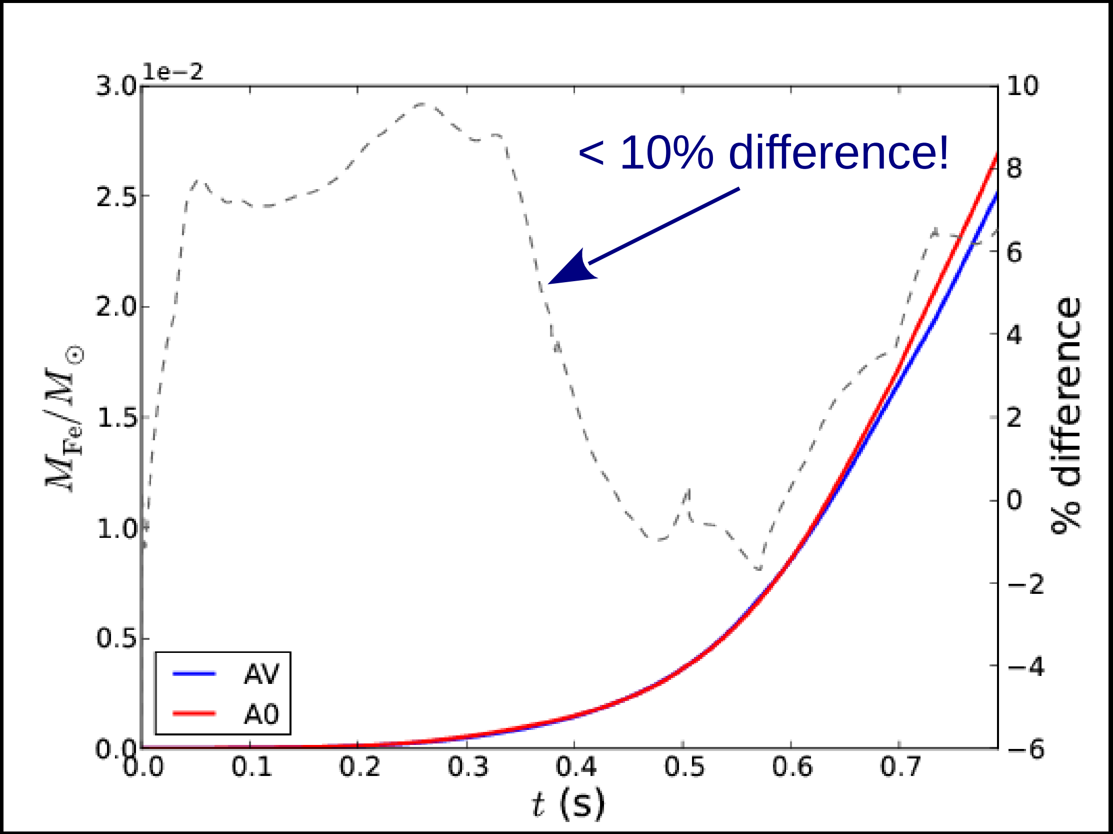
Accomplishments

First simulation to include a realistic convective flow field...but it has little effect for *typical* (40 km off-center) ignition locations.



[Nonaka+ (2012)]

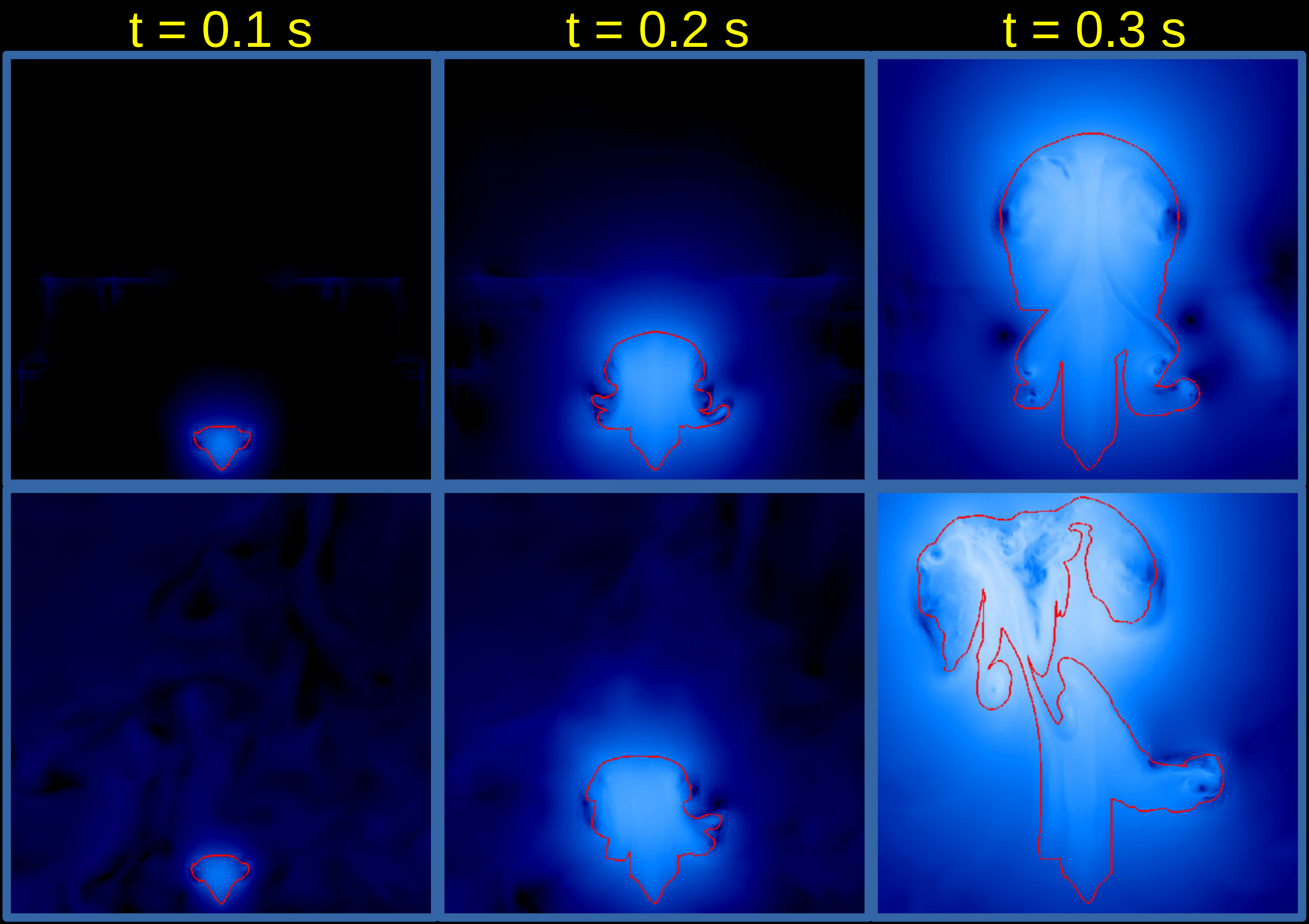
Typical convective pattern



< 10% difference!

Accomplishments

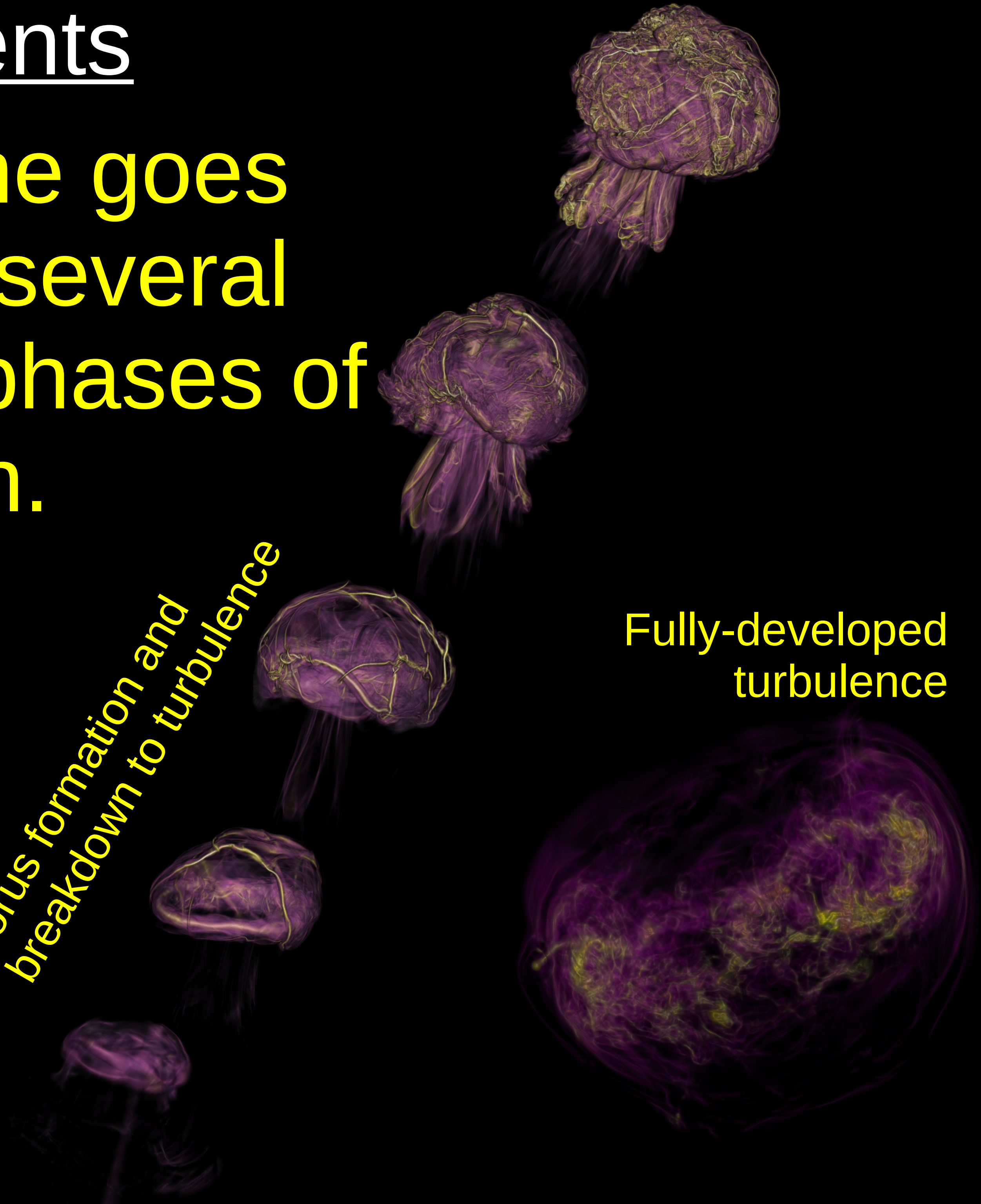
However, if one artificially moves the ignition closer to the center (10 km)...



Accomplishments

The flame goes through several distinct phases of evolution.

Flame surface – laminar burning



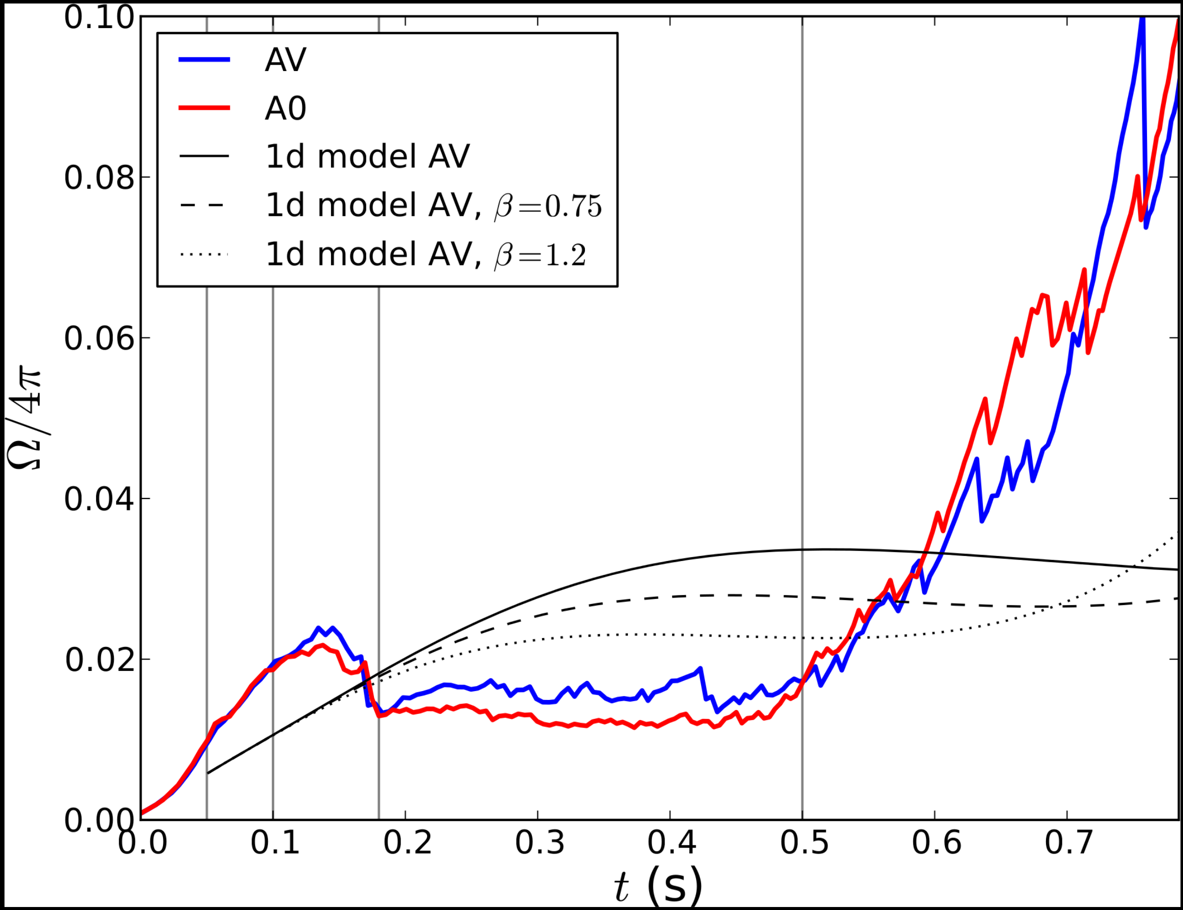
Torus formation and breakdown to turbulence

Fully-developed turbulence

Accomplishments

The flame goes through several distinct phases of evolution.

Can be characterized by solid angle of buoyant flame



Implications

Implications of our Calculations

- Explosions are asymmetric
- Relatively little mass burned via flame
- Yields faint transient events
- Subsequent transition to detonation would produce extremely bright event