New Insights Into Buoyancy-Driven Turbulent Nuclear Combustion from Large-Scale 3D FLASH Simulations

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Mira Early Science Project Conference
Argonne National Laboratory
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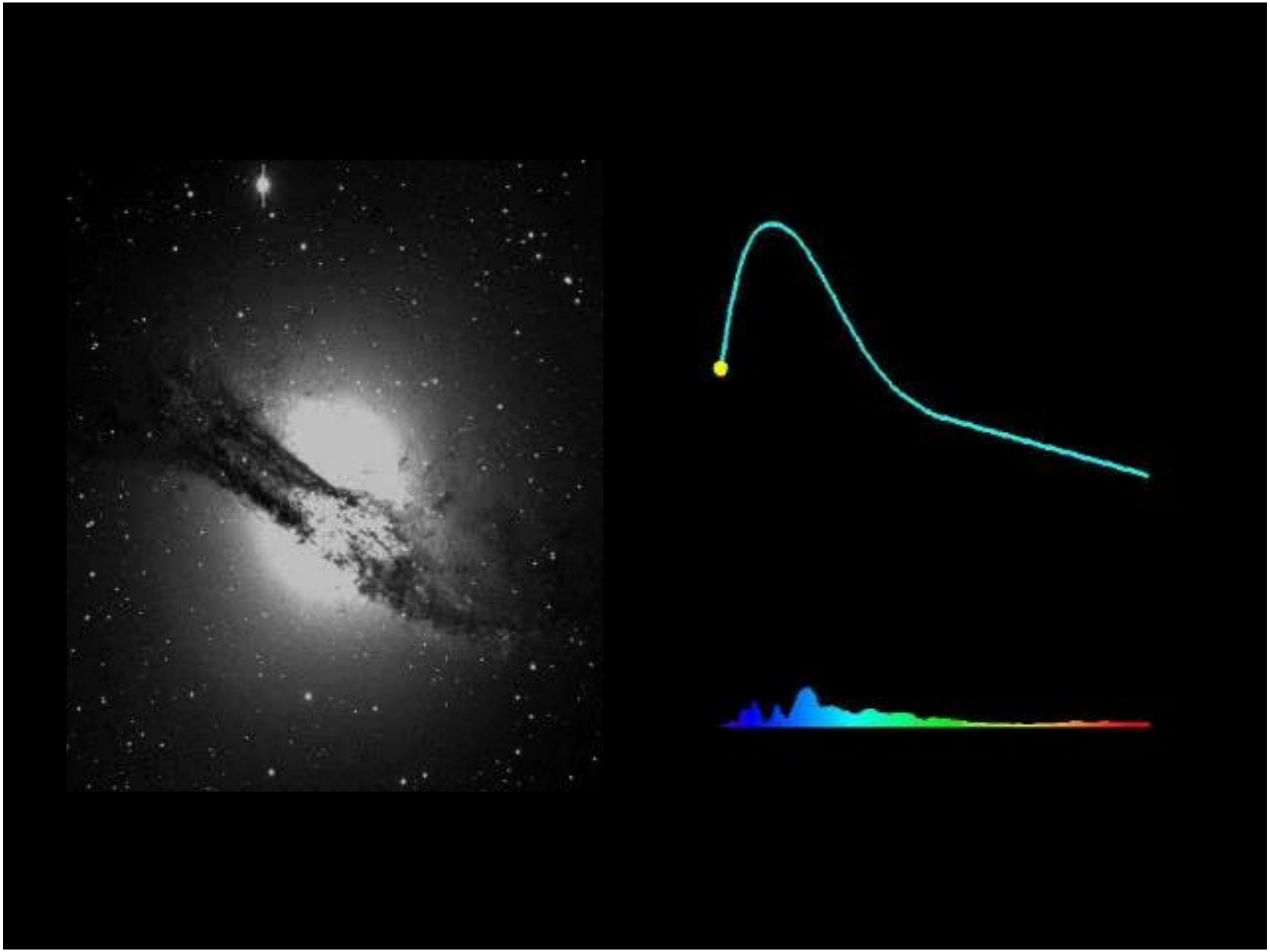
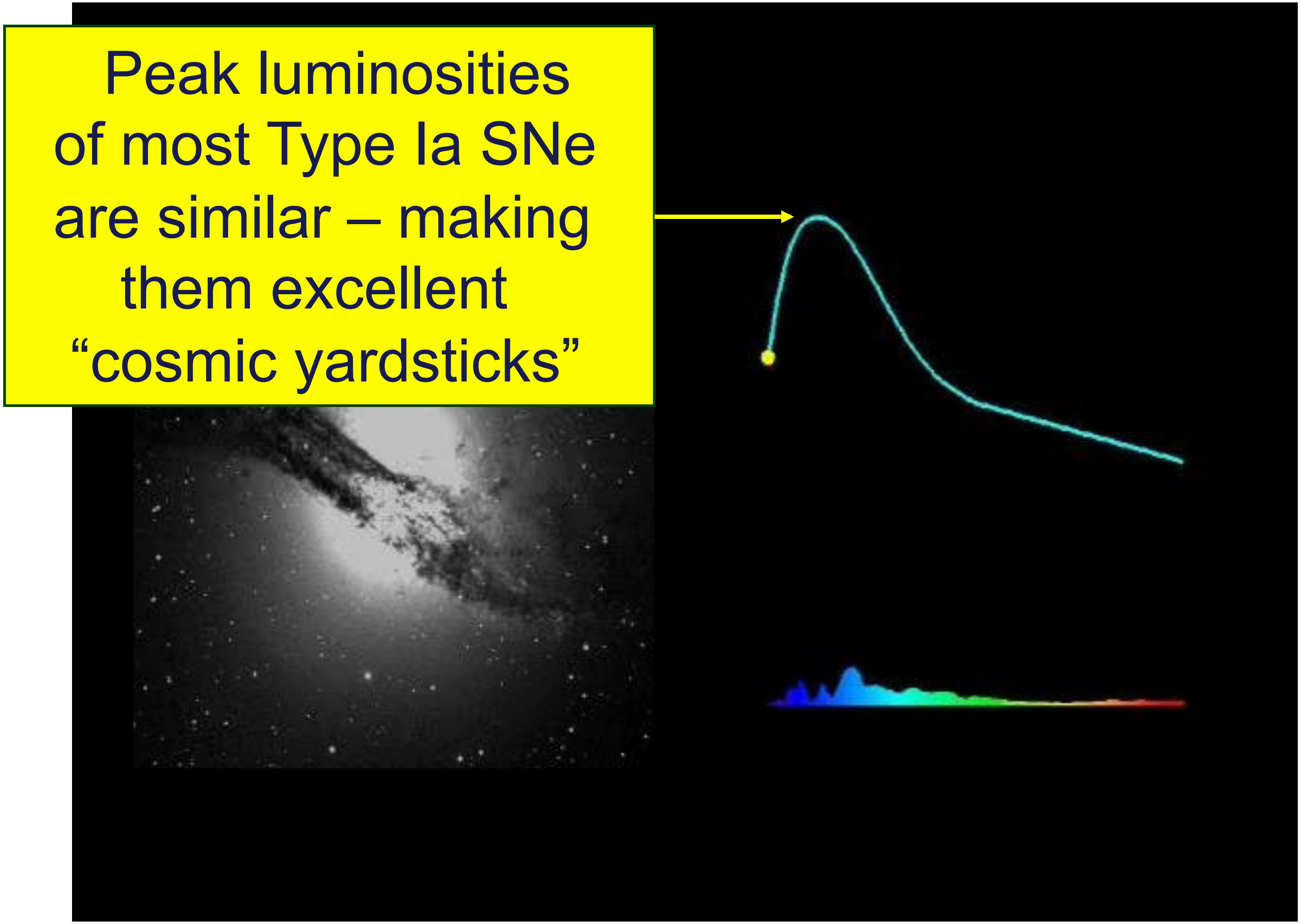
What are Type Ia supernovae?



What are Type Ia supernovae?



Calibration using empirical correlation between peak brightness and duration

Peak brightnesses of Type Ia SNe vary by roughly 1 mag = factor 3

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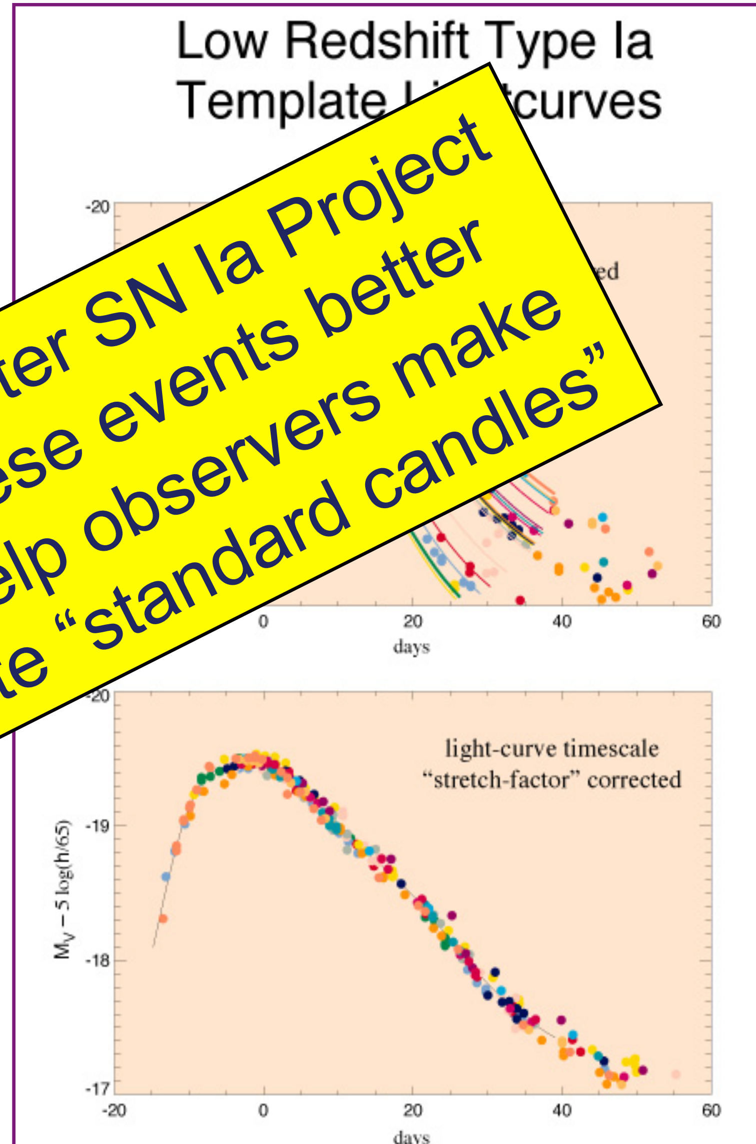
be re   about 15%

Goal of the Flash Center SN Ia Project is to understand these events better and by doing so, help observers make them more accurate “standard candles”



Physics of Type Ia supernovae

Image copyrighted by Mark A. Garlick

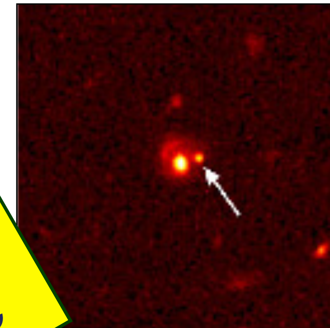


Image credit P. Garnavich/CfA

Accretion
- Stellar binary in which main
  sequence star transfe
  mass onto white

Radioactive decay of ^{56}N heats expanding gas and makes explosion visible

Lightcurve
- E xpansion of star
  tive decay of
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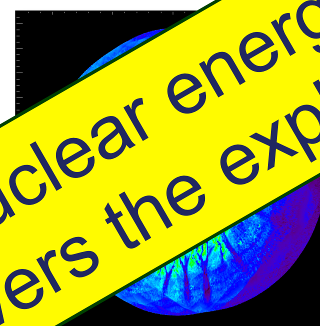
  w, which makes the
  supernova visible



Nuclear energy powers the explosion

~seconds

Smoldering
- Subsonic convection in core of white dwarf
- Heat transport is by electron conduction

1000 yr

Ignition

Flame
- Nuclear burning initially due to laminar flame
- Buoyancy—driven turbulence increases nuclear burning rate
- Transition from deflagration to detonation occurs, causing the star to explode

FLASH is being used for a broad range of problems by groups throughout the world

Munich University Observatory

- FLASH is an finite-volume Eulerian hydro/MHD code with AMR.
- FLASH scales to well over a hundred thousand processors. It uses domain decomposition, mesh replication, and threading to best utilize current platforms.
- FLASH is extremely portable and can run on a variety of platforms from laptops to supercomputing systems such as the IBM BG/P and BG/Q.
- FLASH is composed of interoperable units/modules; particular modules are combined to run individual simulations, which allows for important compile-time optimizations that improve performance.
- FLASH is professionally managed software with daily, automated regression testing on a variety of platforms, version control, coding standards, extensive documentation, user support, and integration of code contributions from external users.
- Nearly 1200 scientists around the world have now used FLASH, and more than 800 papers have been published that directly use it.

the FLASH development, a high performance computing (HPC) cluster of 16 powerful alpha EV67 processors distributed in 4 compaq ES40 (interconnected with a highly efficient Memory Channel II), entirely dedicated to HPC projects (for more information see the SCAN facility homepage).

http://www.astropa.unipa.it/FLASH/ Page 1 of 1

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Quenching cluster cooling flows with recurrent hot plasma bubbles

Claudio Dalla Vecchia[1], Richard G. Bower[1], Tom Theuns[1,2], Michael L. Balogh[1], Pasquale Mazzotta[3] and Carlos S. Frenk[1]

The Center for Astrophysical Thermonuclear Flashes

Simulation of the Deflagration-to-Detonation Model of a Type Ia Supernova

Ignition occurs at 63 points within a 128 km radius sphere whose center is coincident with the center of the star. Hot ash is shown in yellow and the stellar surface in blue.

This work was supported in part by the DOE NNSA ASC ASAP and by the NSF. This work also used computational resources at the ALCF at ANL awarded under the INCITE program, which is supported by the DOE Office of Science.

An Advanced Simulation and Computation (ASC) Academic Strategic Alliances Program (ASAP) Center at The University of Chicago

The Center for Astrophysical Thermonuclear Flashes

Simulation of the Deflagration and Detonation Phases of a Type Ia Supernovae

30 initial bubbles in 100 km radius.
Ignition occurs 80 km from the center of the star.
Hot material is shown in color and stellar surface in green.

This work was supported in part at the University of Chicago by the DOE NNSA ASC ASAP and by the NSF. This work also used computational resources at LBNL NERSC awarded under the INCITE program, which is supported by the DOE Office of Science.

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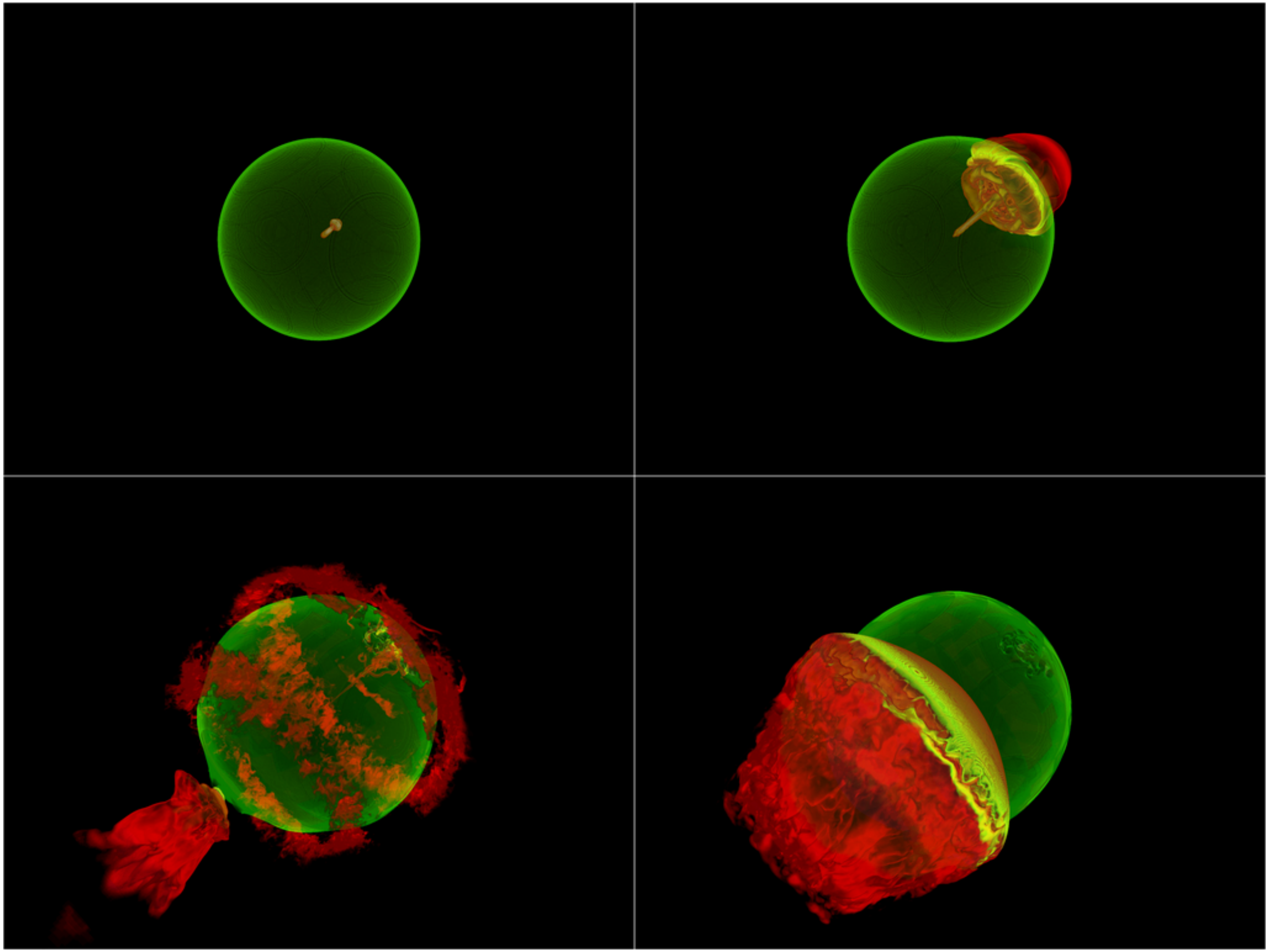
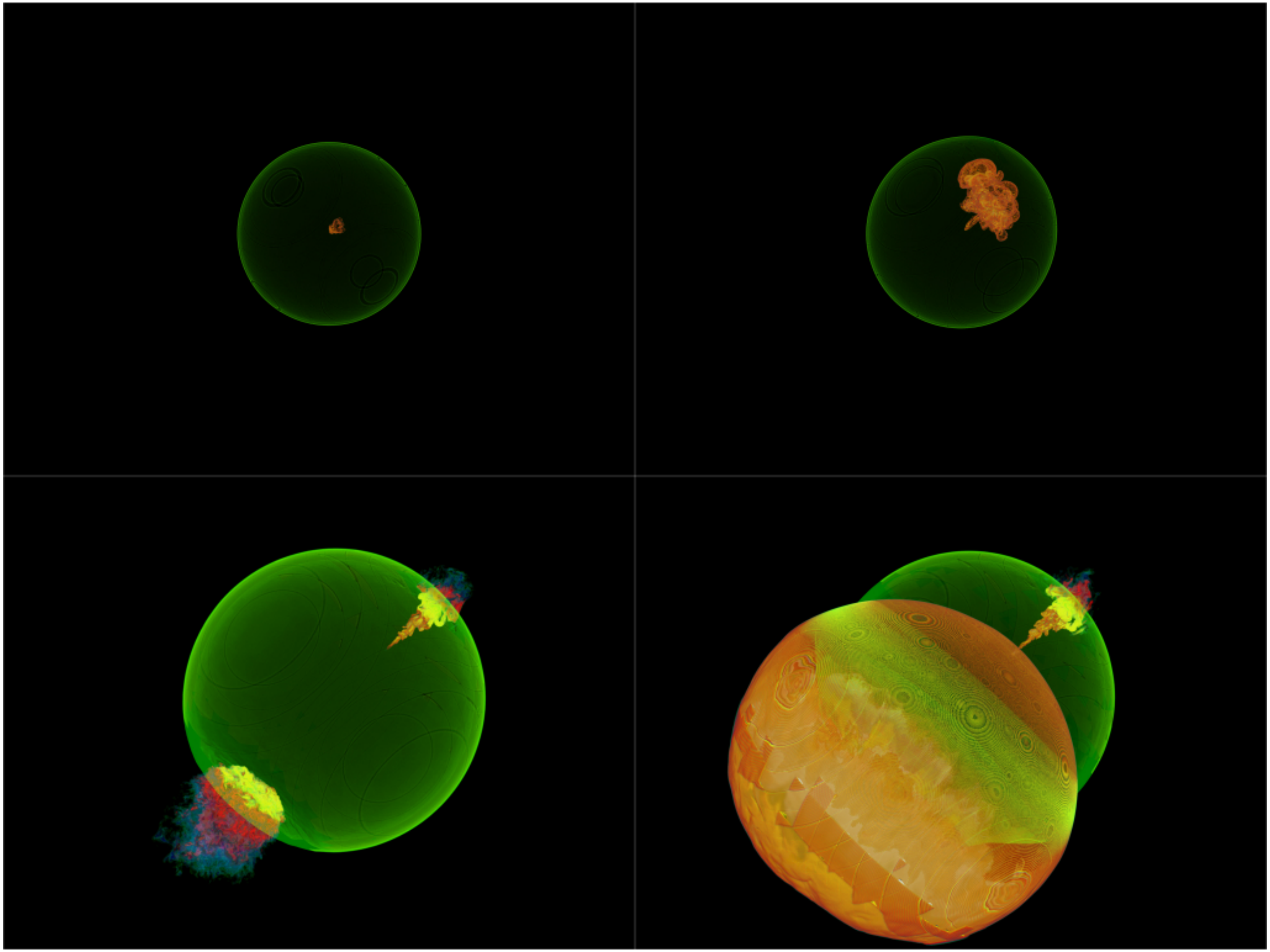
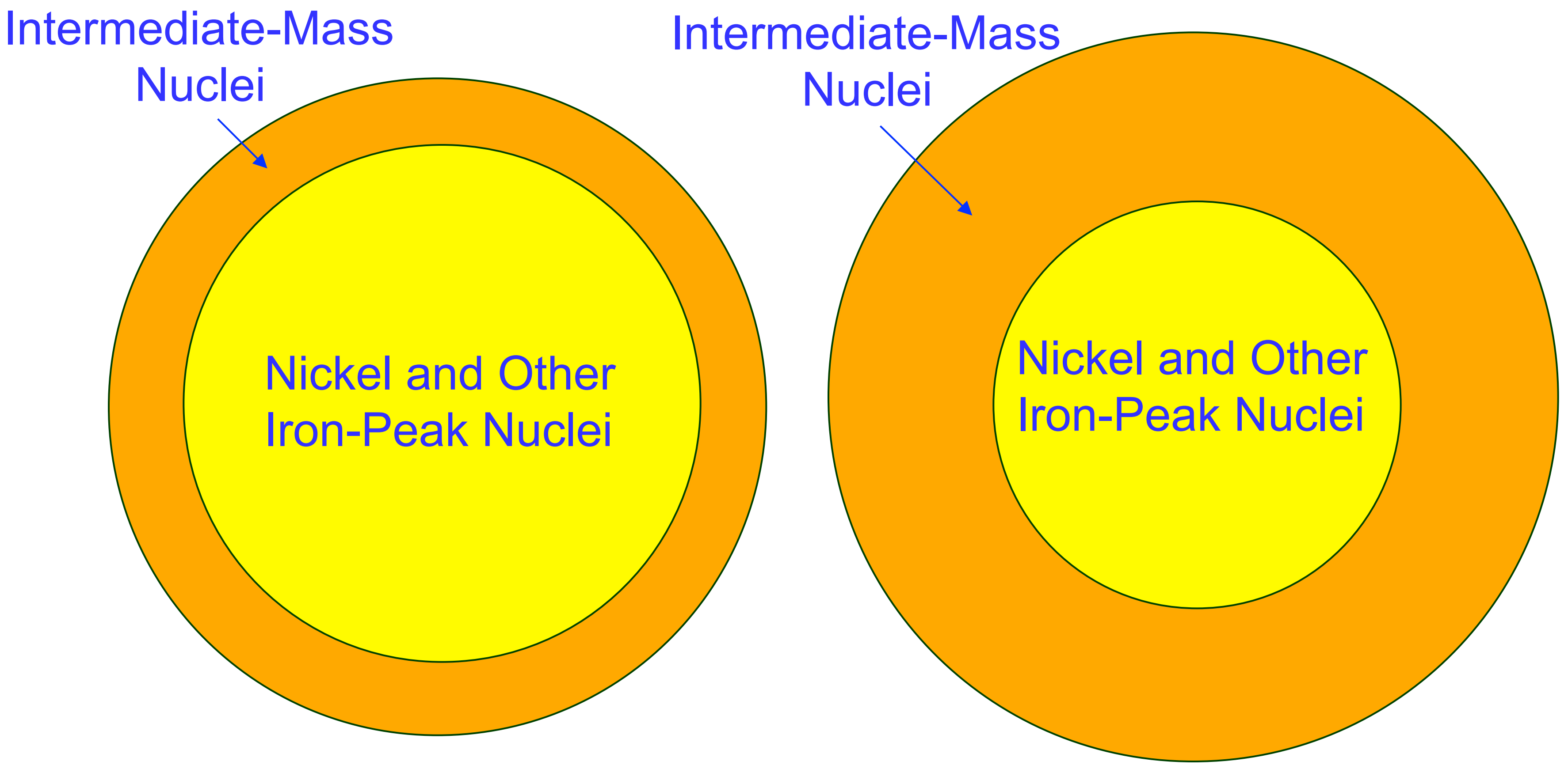
3D simulations of GCD model for single ignition point



3D simulations of pulsationally assisted GCD model for multiple ignition points

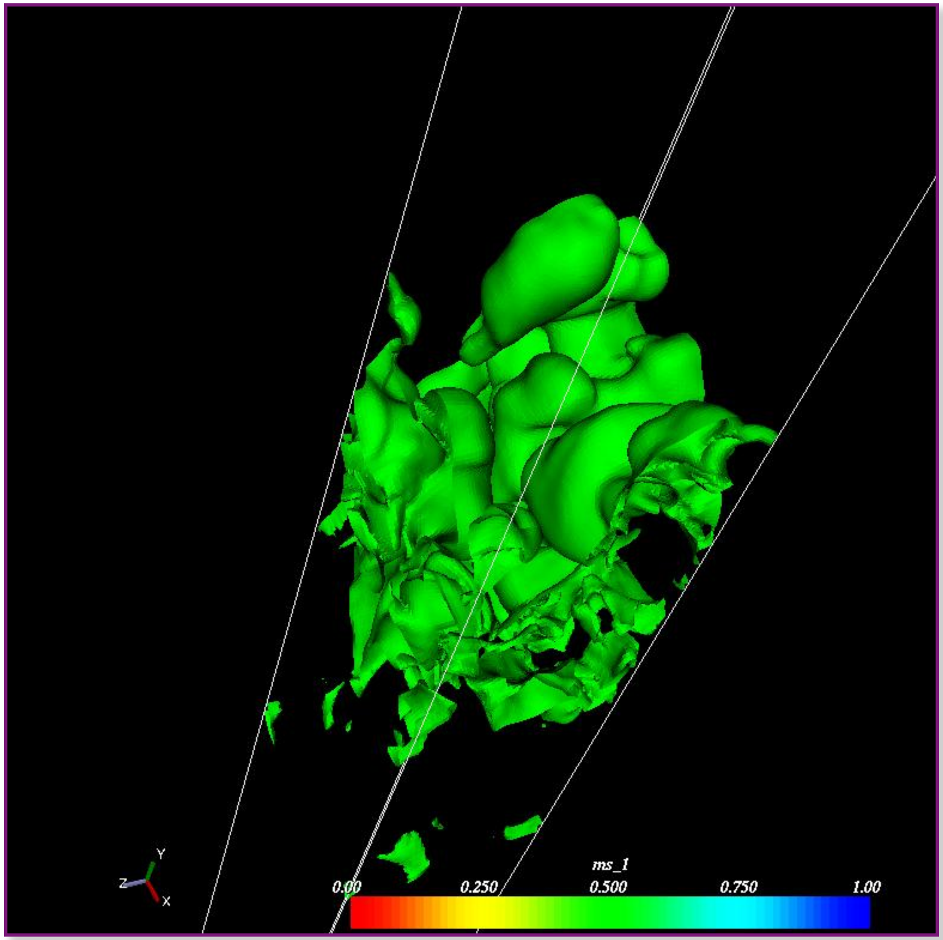


Impact of pre-expansion on nucleosynthetic yield of supernova



Products of nuclear burning essentially depend only on density at which burning occurs: iron-peak nuclei at high densities, intermediate mass nuclei at lower densities

Need for a subgrid model of buoyancy-driven turbulent nuclear combustion



Khokhlov (1995); Zhang et al. (2007); Townsley et al. (2010, 2013)

- The nuclear flame is initially ~ 1 mm thick while the resolution of our best simulations is 1 km – a factor of 10^8 larger!
- A subgrid model of the nuclear flame is therefore essential
- The burning rate during the deflagration phase and the physical conditions at which a DDT might occur depend on the model
- The correct model to use is uncertain
- We have done extensive simulations to better understand these key physical processes

The Center for Astrophysical Thermonuclear Flashes

Simulation of Buoyancy-Driven Turbulent Nuclear Burning for a Froude Number of 0.010

This work was supported in part at the University of Chicago by the DOE NNSA ASC ASAP and by the NSF. This work also used computational resources at LBNL NERSC awarded under the INCITE program, which is supported by the DOE Office of Science.

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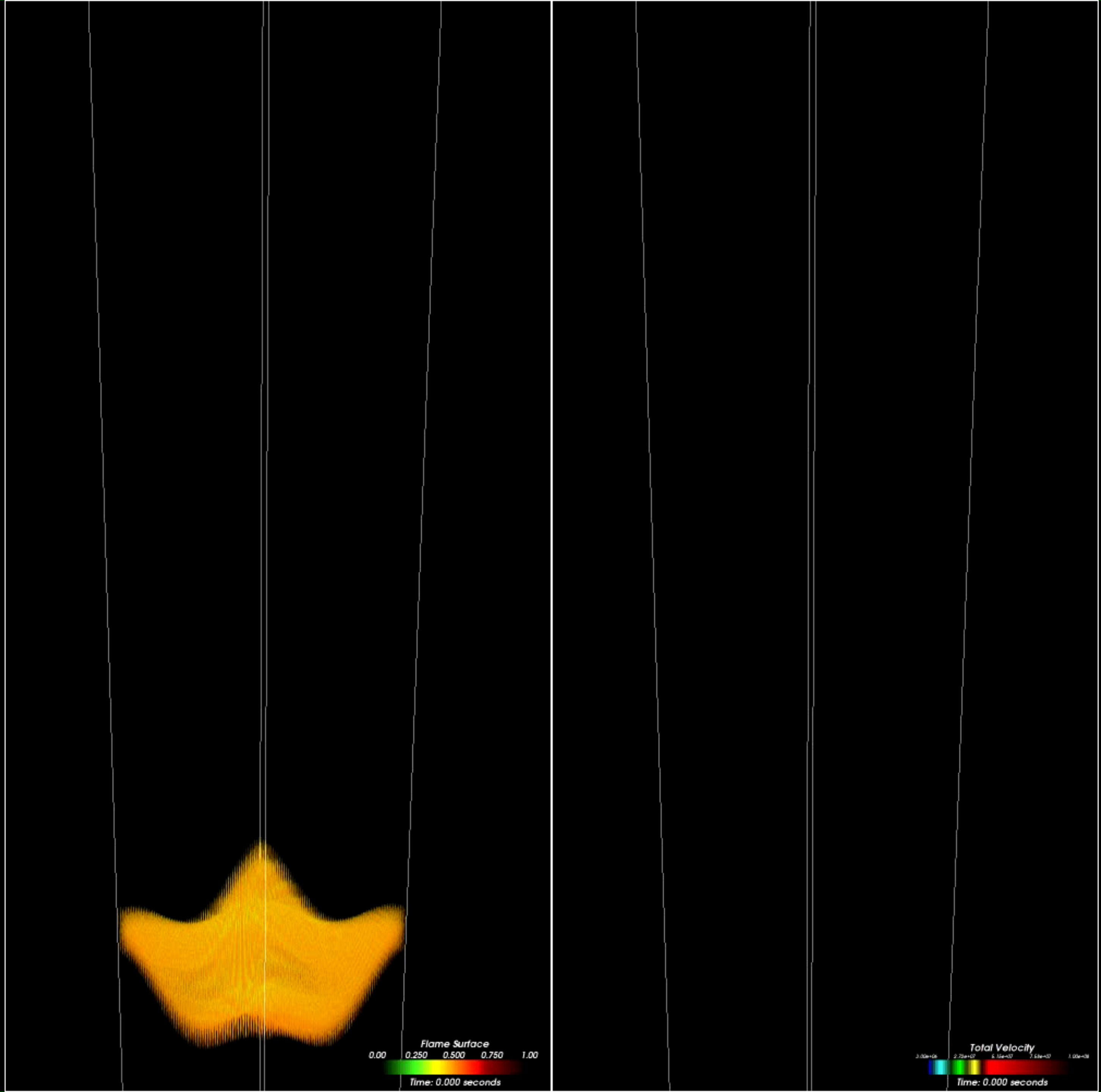
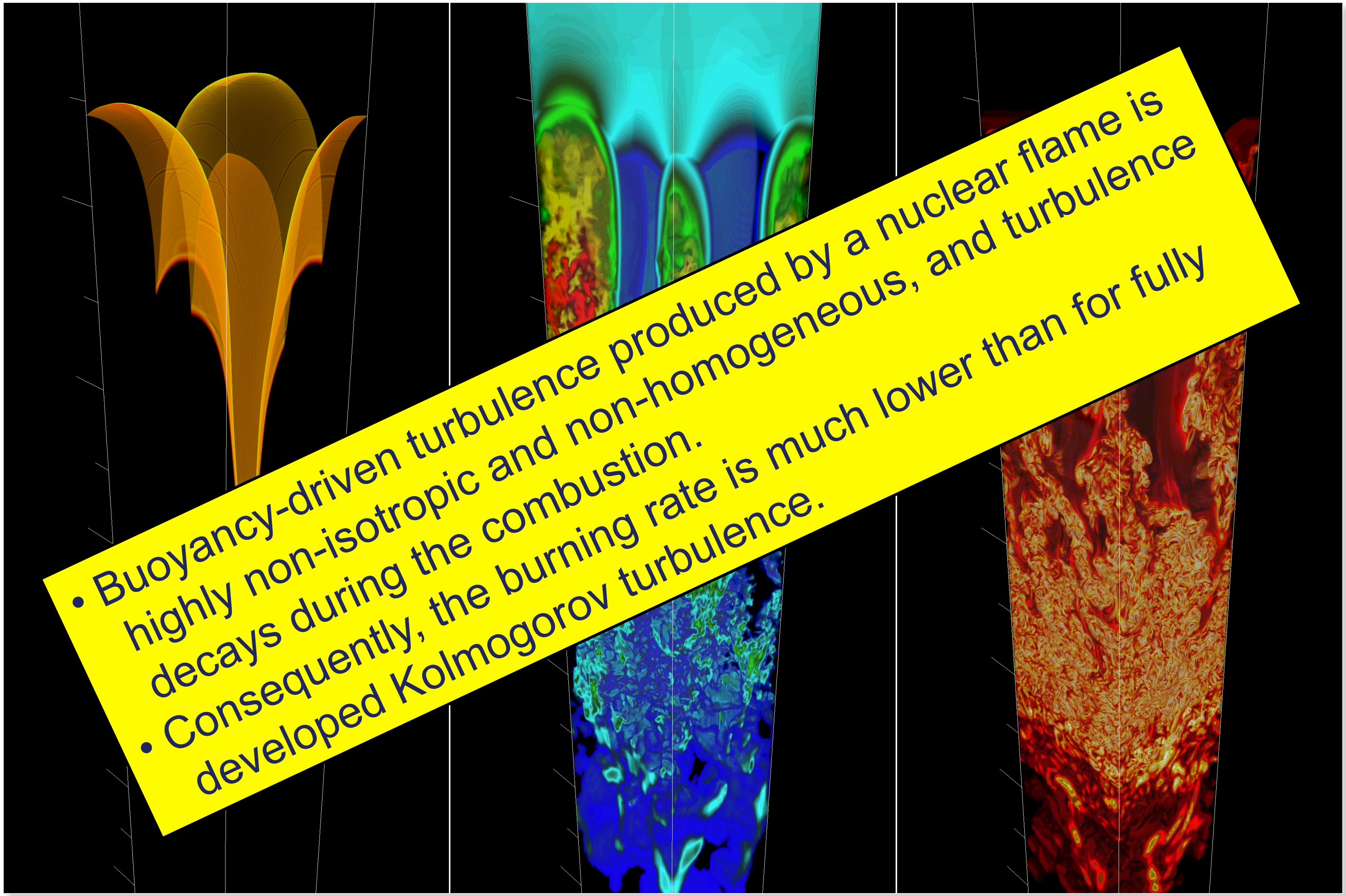
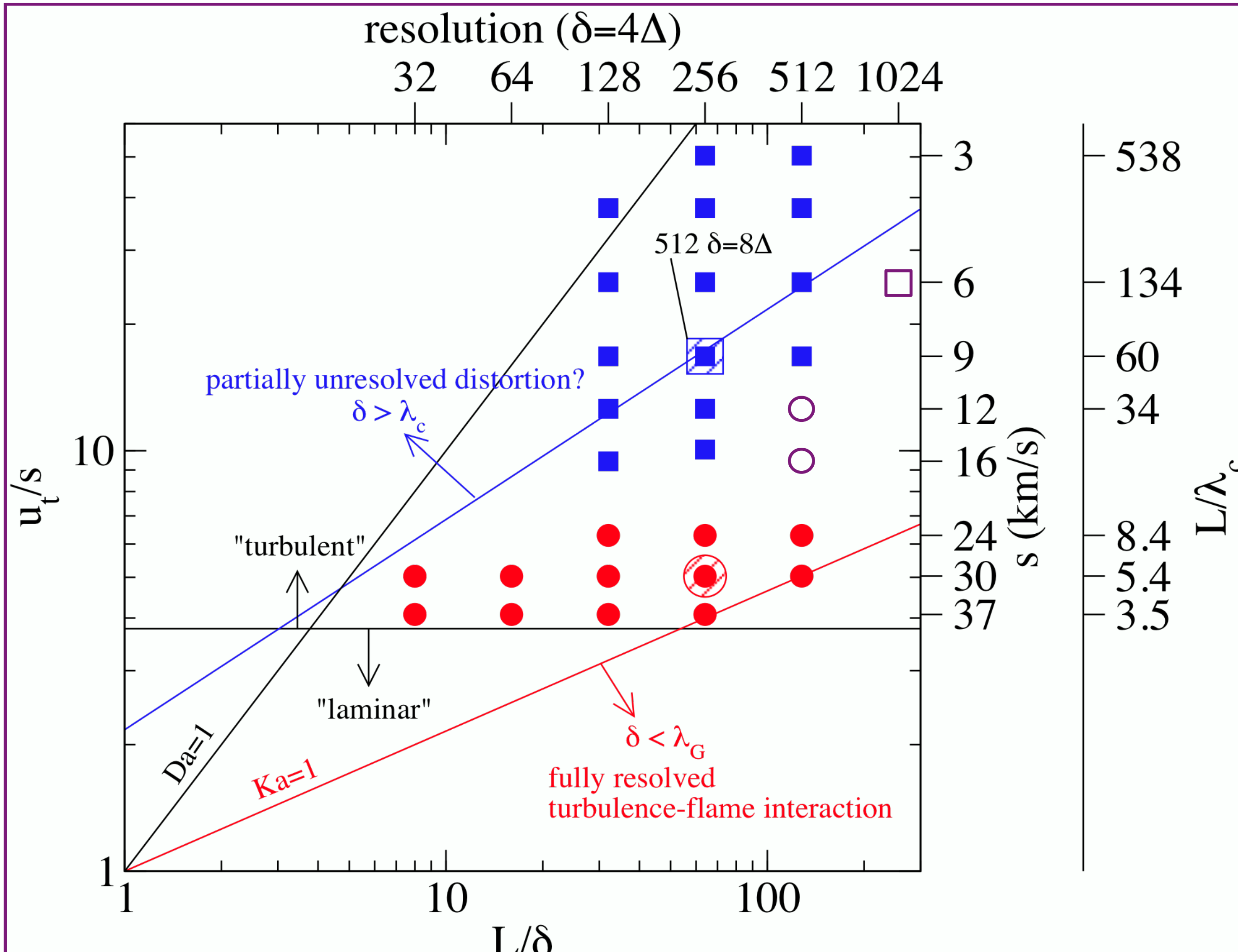

Flame Surface
0.00 0.250 0.500 0.750 1.00
Time: 0.000 seconds
Total Velocity
Time: 0.000 seconds

Large-scale simulations of buoyancy-driven turbulent nuclear combustion

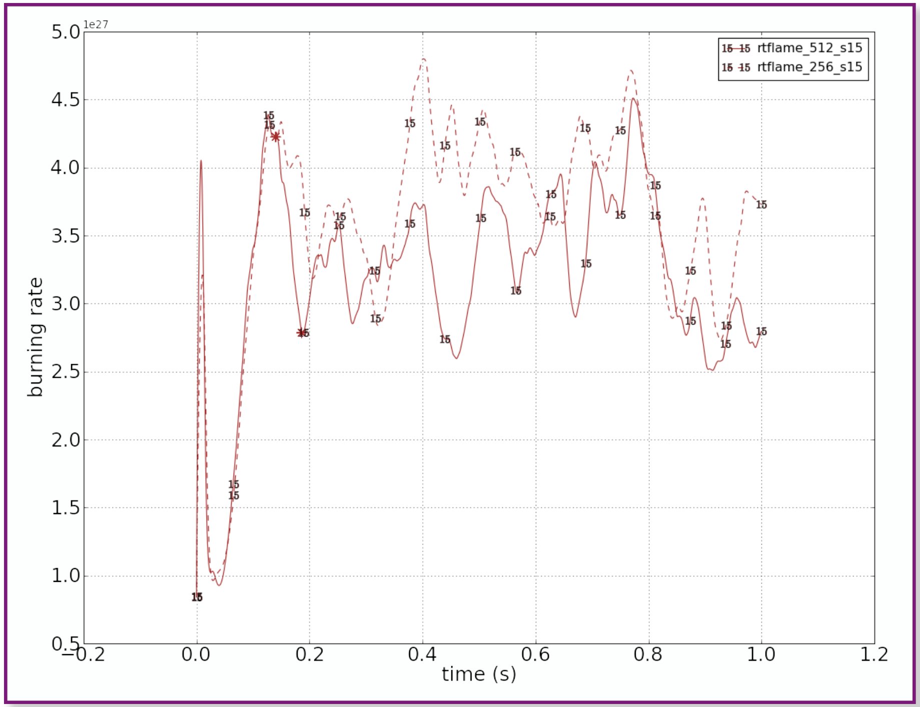


We have performed an extensive grid of simulations of buoyancy-driven turbulent nuclear combustion



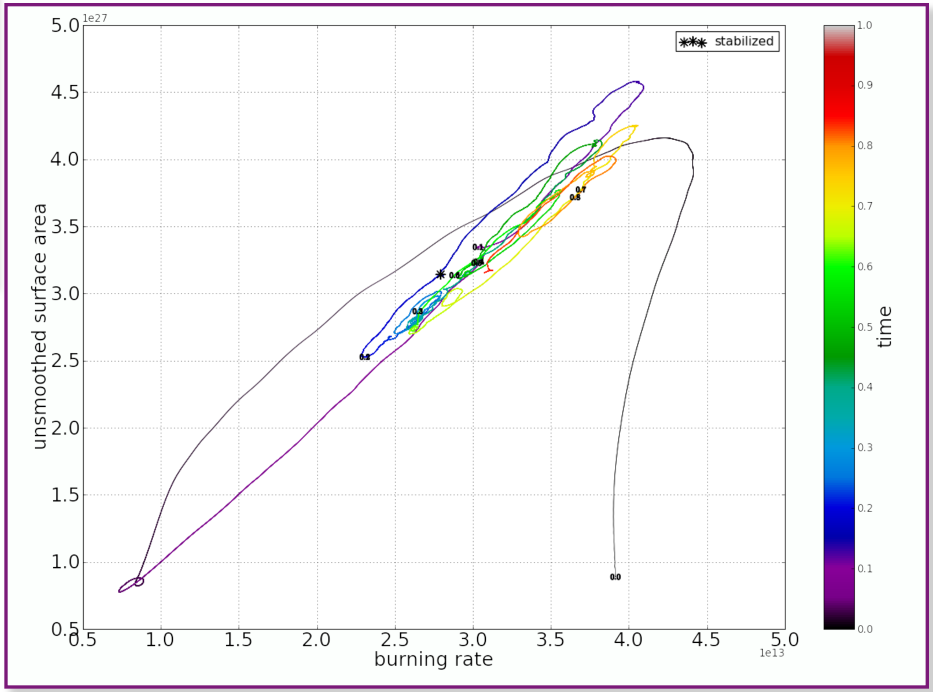
Townsley et al. (2010, 2013)

Temporal behavior of the nuclear burning rate and the surface area of the flame are stochastic

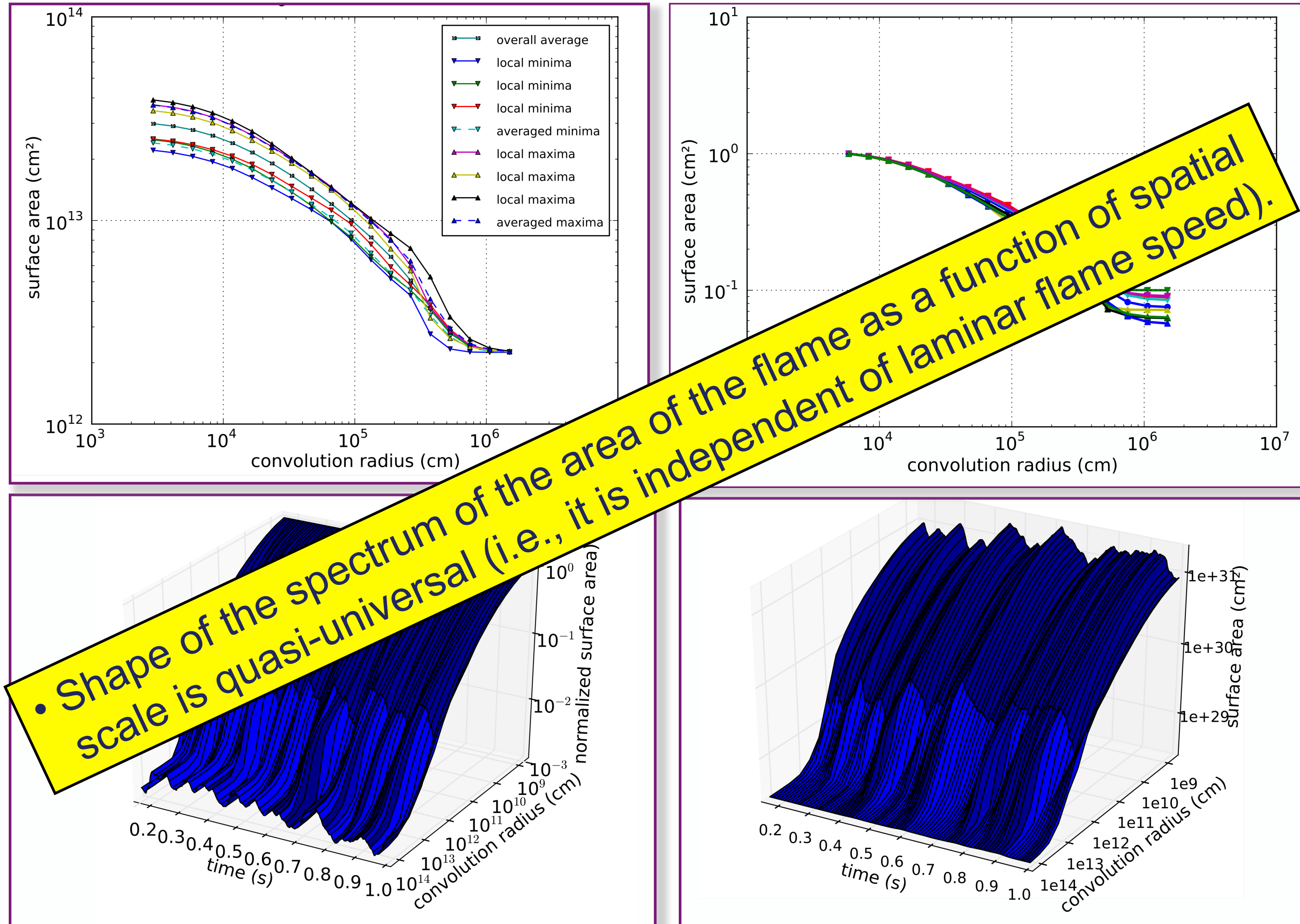


Nuclear burning rate

Surface area of flame versus nuclear burning rate

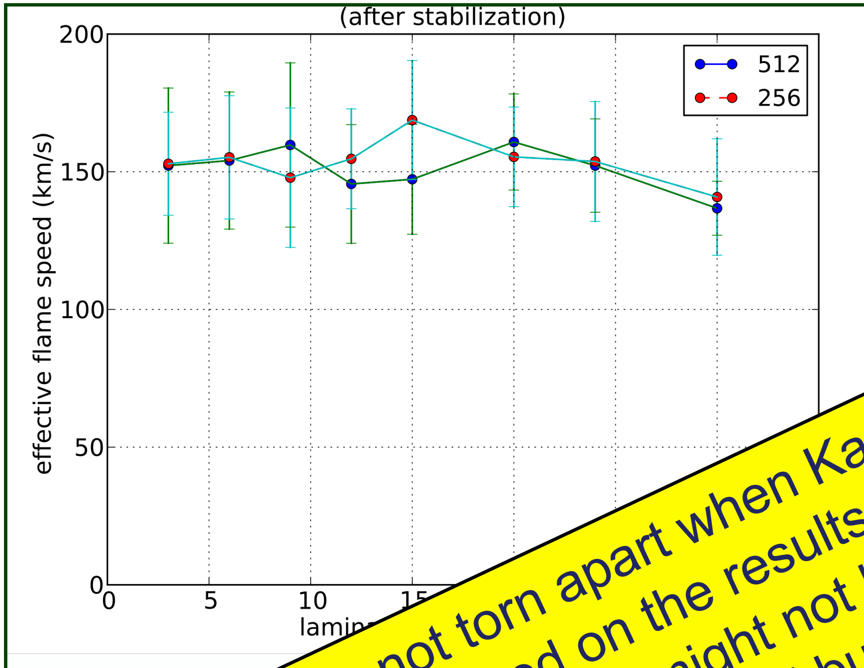


Changes in the overall burning rate are due to changes in the area of flame at large length scales



- Shape of the spectrum of the area of the flame as a function of spatial scale is quasi-universal (i.e., it is independent of laminar flame speed).

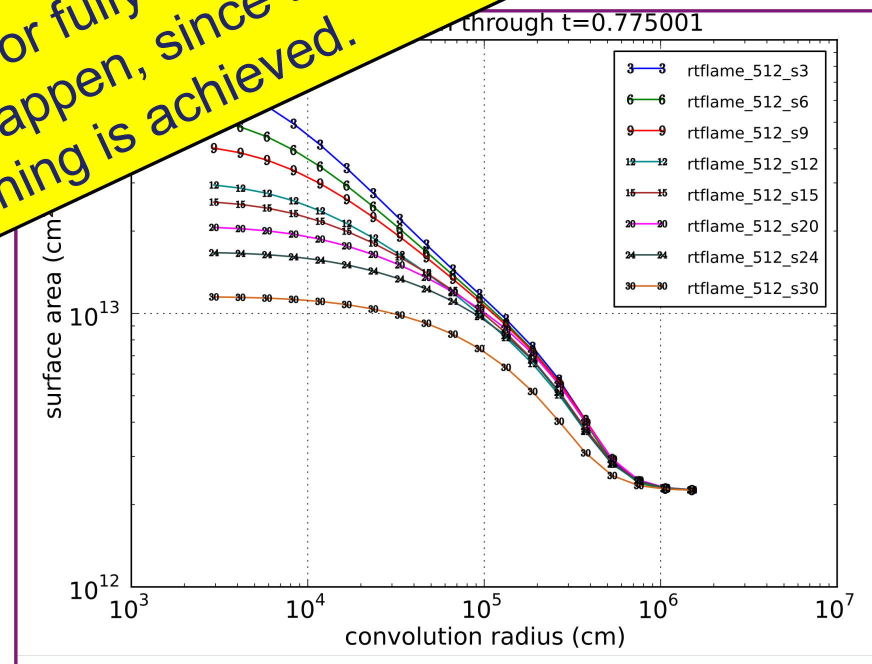
Self-regulation produces an effective flame speed that is independent of the laminar flame speed



Area of flame at s... h scales
is larger wh... speed
Is small... fective

Fl... t
of ... speed

- Flame is not torn apart when Ka = 1, as has sometimes been assumed (based on the results for fully developed turbulence).
- This means a DDT might not happen, since the flame might quench before distributed burning is achieved.



Conclusions

- Buoyancy-driven turbulent combustion is a key physical process in Type Ia supernovae: it governs how much the white dwarf star expands prior to detonation, and thus how much radioactive ^{56}Ni is produced in the explosion phase (and therefore the peak luminosity of the resulting supernova)
- Using *Mira*, we have done extensive direct numerical simulations of buoyancy-driven turbulent nuclear combustion using a model flame (KPP) to better understand
  - The properties of buoyancy-driven turbulent nuclear combustion;
  - The physical conditions under which the nuclear flame becomes "extended" in space
  - The physical conditions under which the nuclear flame transitions to distributed nuclear burning – a pre-requisite for initiation of a detonation, as posited in the deflagration-to-detonation transition model

Conclusions

- The simulations of buoyancy-driven turbulent nuclear combustion that we have done on *Mira* show that
  - Buoyancy-driven turbulence produced by a nuclear flame is highly non-isotropic and non-homogeneous, and turbulence decays during the combustion.
  - Consequently, the burning rate is much lower than for fully developed Kolmogorov turbulence.
  - Shape of the spectrum of flame area as a function of spatial scale is universal (i.e., independent of laminar flame speed).
  - Nuclear flame is not torn apart when Ka = 1, as has sometimes been assumed (based on results for fully developed turbulence); this means a DDT might not happen, since flame might quench before distributed burning is achieved.
- We are using what we have learned about the properties of buoyancy-driven turbulence to inform a better subgrid model of this key process for our whole-star simulations of Type Ia supernovae