New Insights into Thermonuclear-Powered Supernovae from Large-Scale Simulations

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FLASH capabilities span a broad range…

*Shortly:*

t=0.09(s)

Wave b

FLASH is a multi-physics finite-volume Eulerian code and framework whose capabilities include:

- Adaptive mesh refinement (AMR) on a block-structured mesh
- Multiple state-of-the-art hydrodynamic solvers
- State-of-the-art magnetohydrodynamics
- Implicit solvers for diffusion using the HYPRE library (currently being used to model thermal conduction, radiation diffusion, and viscosity)
- Many physics modules relevant to astrophysics and cosmology, including gravity and nuclear burning
- Generic, highly scalable parallel particles framework (currently used for PIC simulations, laser ray tracing, dark matter, tracer particles)
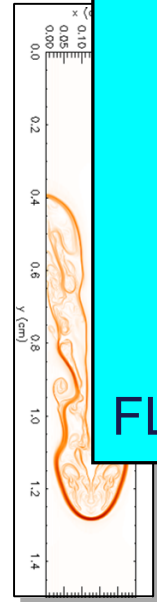
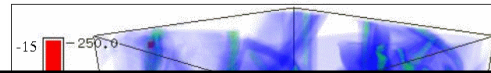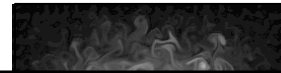FLASH contains 1.25 M lines of code of which > 1 M are executable

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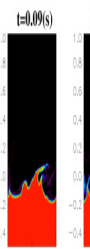
Magnetic Rayleigh-Taylor

Cellular detonation
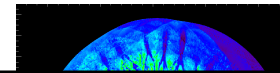
Helium burning on neutron stars

Orzag/Tang MHD vortex

Richtmyer-Meshkov instability

FLASH is being used
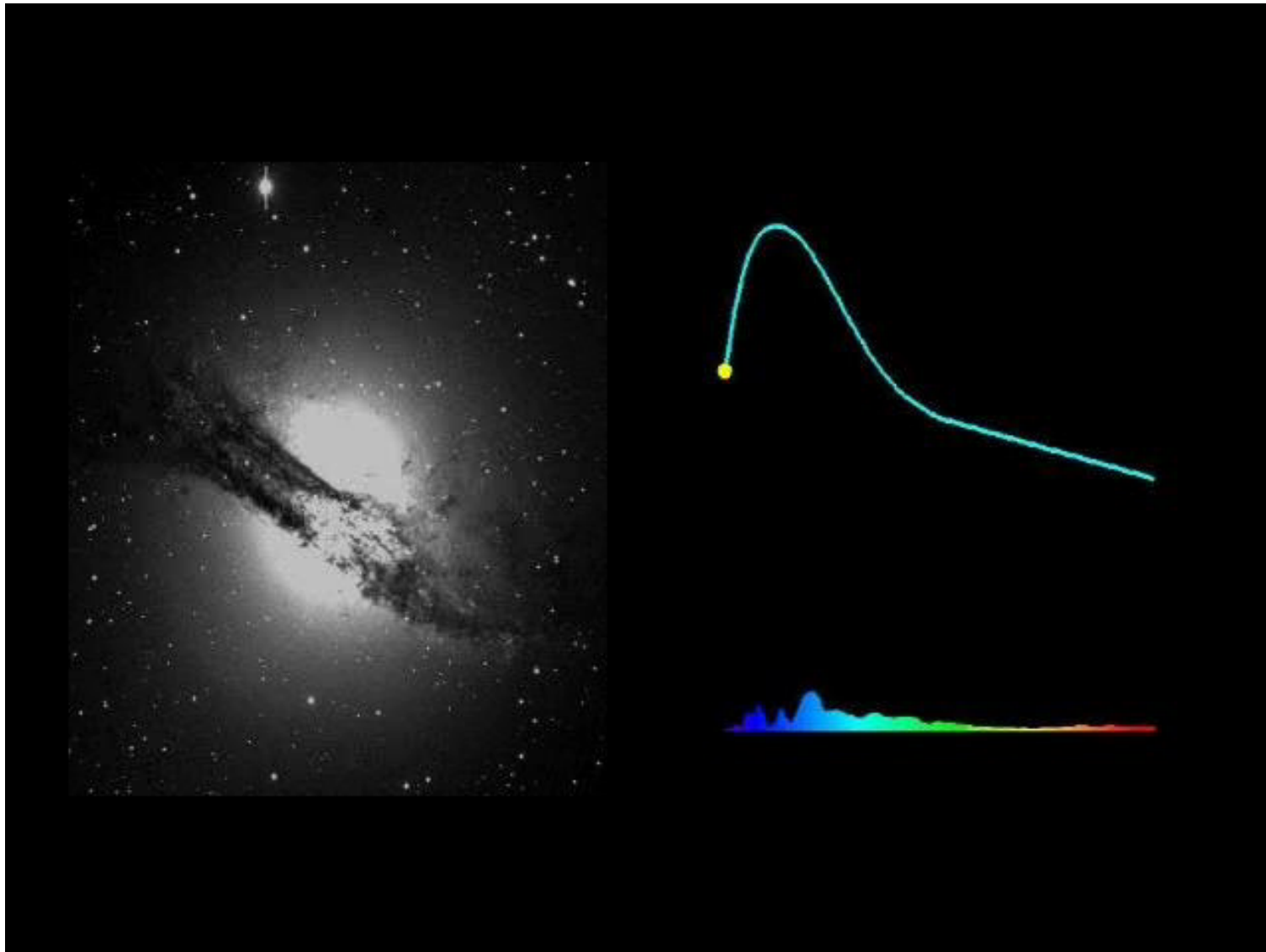# by groups throughout the world

- FLASH scales to well over a hundred thousand processors. FLASH uses a variety of parallelization techniques including domain decomposition, mesh replication, and threading to best utilize hardware resources.

- 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. Thus only the code relevant to a particular problem is included when FLASH is compiled. This also 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.

doi:10.1111/j.1365-2966.2004.08381.x

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]
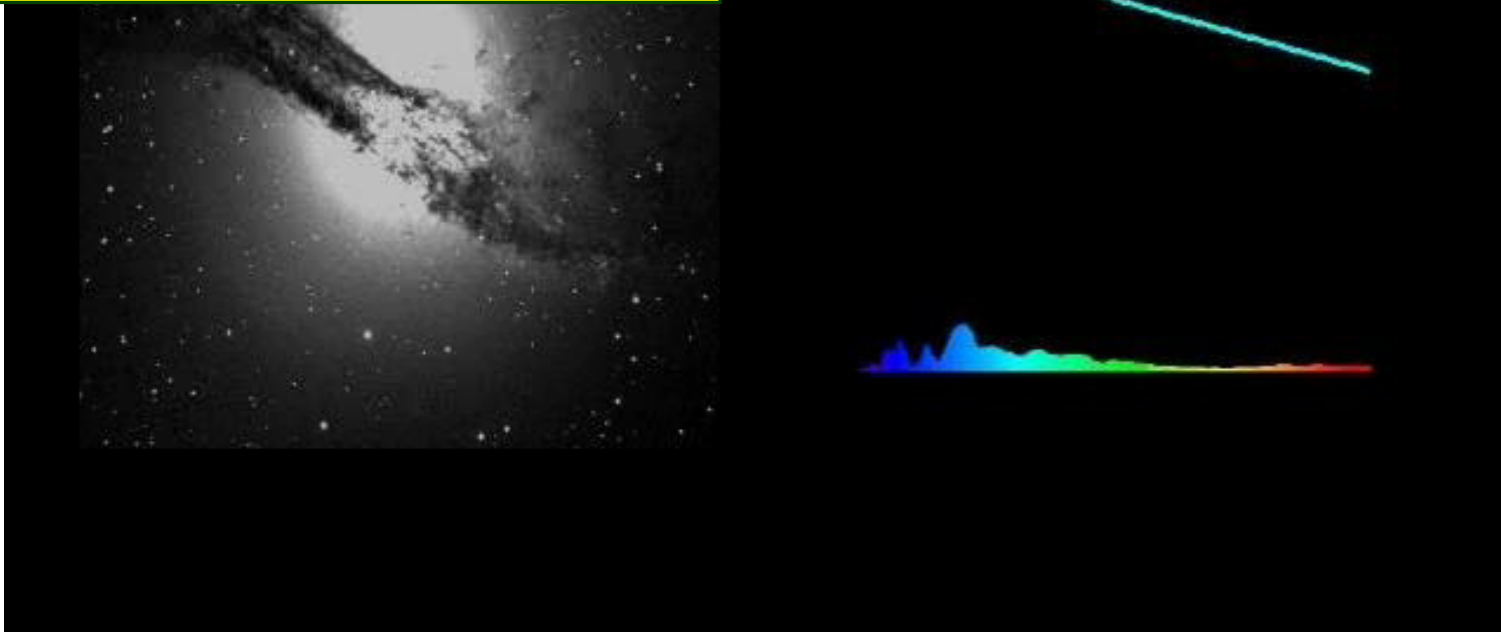
What are Type Ia supernovae?

Peak luminosities of most Type Ia SNe are similar – making them excellent "cosmic yardsticks"

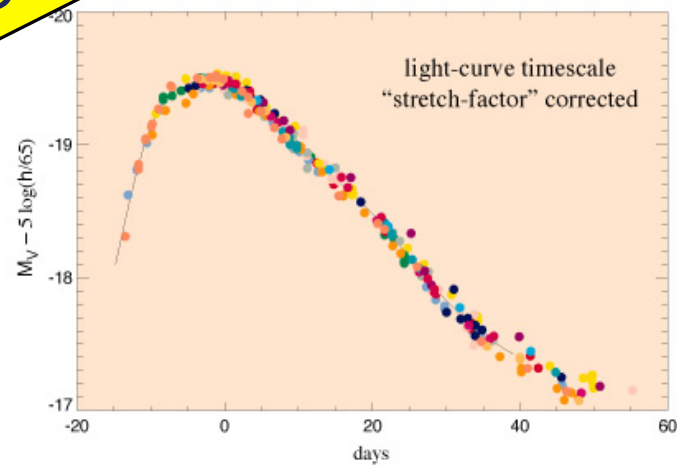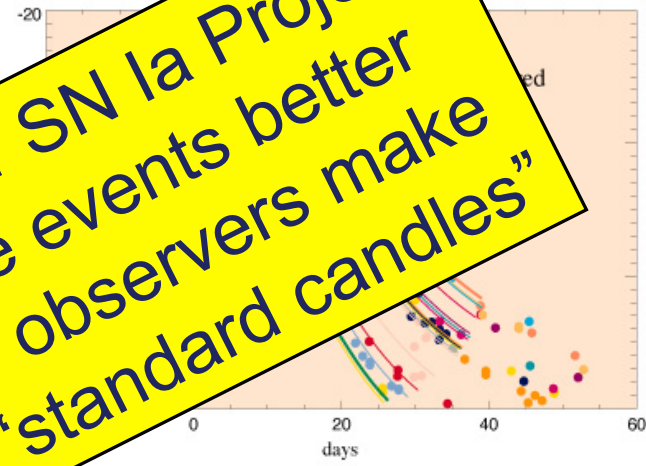# Calibration using empirical correlation between peak brightness and duration

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

be
and   ion can
be re   about 15%

Low Redshift Type Ia
Template Lightcurves

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"

$M_V - 5 \log(h/65)$

light-curve timescale
"stretch-factor" corrected

days

Type Ia supernovae are an important tool for determining the properties of dark energy
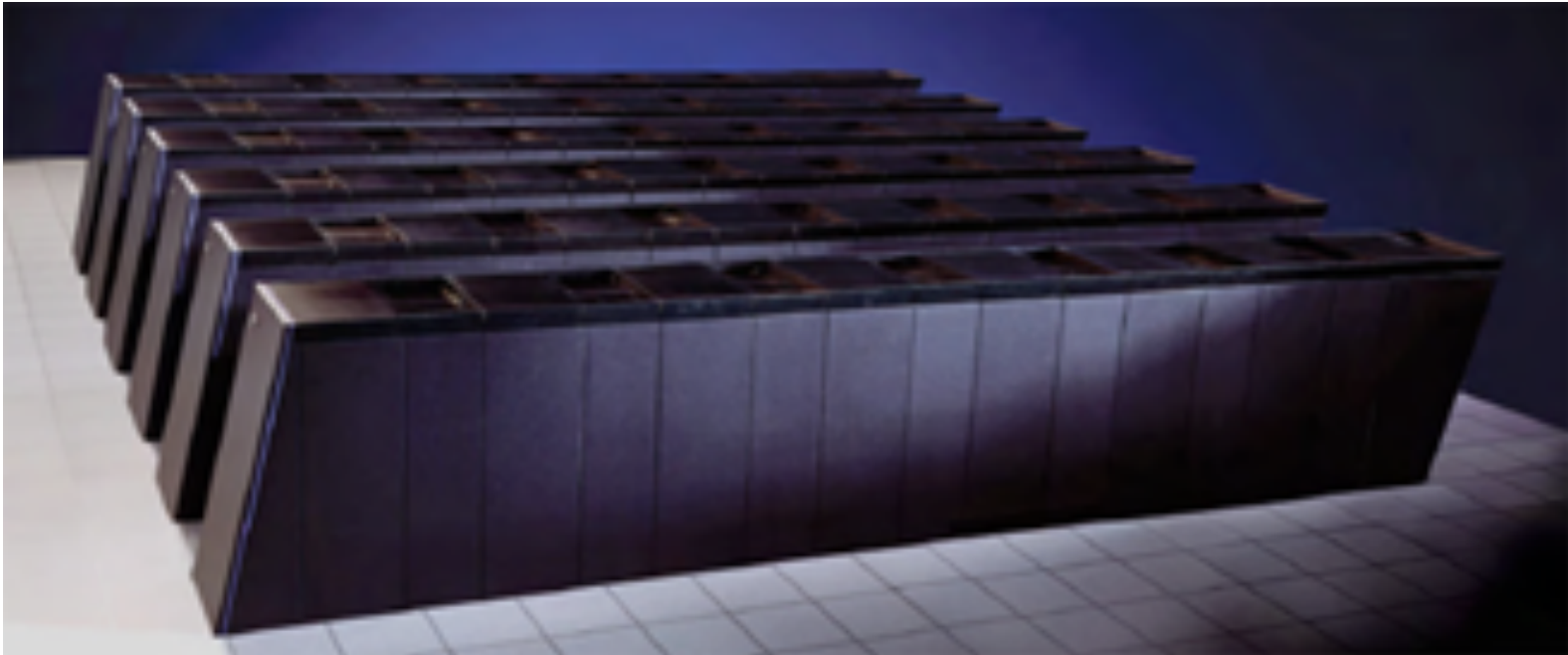
Flash Center uses the world's most powerful computers to do simulations with FLASH

❑ IBM Blue Gene/Q *Mira* supercomputer at Argonne Leadership Computing Facility has 768 K processors yielding 10 Petaflops

❑ FLASH capstone simulations of thermonuclear-powered (Type Ia) supernovae and of buoyancy-driven nuclear combustion – a key physical process in such supernovae – use a significant fraction of the machine

Computational demands of large-scale 3D Type Ia supernova simulations

❑ FLASH was an informal acceptance test for the IBM BG/L and was a formal acceptance test for BG/P and BG/Q

❑ FLASH has been fully threaded, which enables it to compute at scale on the BG/Q

❑ Capstone 3D simulations of the explosion phase of Type Ia supernovae require 300-800 K CPU-hrs; the radiation transfer phase requires more computational resources

❑ Each capstone simulation generates ~ 20-100 TB of data

❑ Each of the past three years we used ~ 80 M CPU-hrs on *Intrepid* at ANL under DOE Office of Science INCITE program; this year we will use 150 M CPU-hrs on *Mira* for Early Science plus 20 M CPU-hrs on *Intrepid* and 80 M CPU-hrs on *Mira* under INCITE

❑ We generated ~ 3 PB of data last year and we expect to generate more this year; in-line analysis and intelligent triaging of data is therefore essential
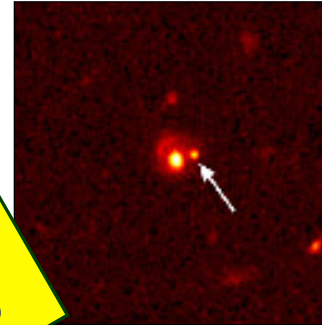
Physics of Type Ia supernovae

Image copyrighted by Mark A. Garlick

Image credit P. Garnavich/CfA

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

Nuclear energy powers the explosion

Accretion

- Stellar binary in which main sequence star transfer mass onto white

Lightcurve

- E expansion of star tive decay of ts the ejecta es the ejecta to w, which makes the supernova visible

~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
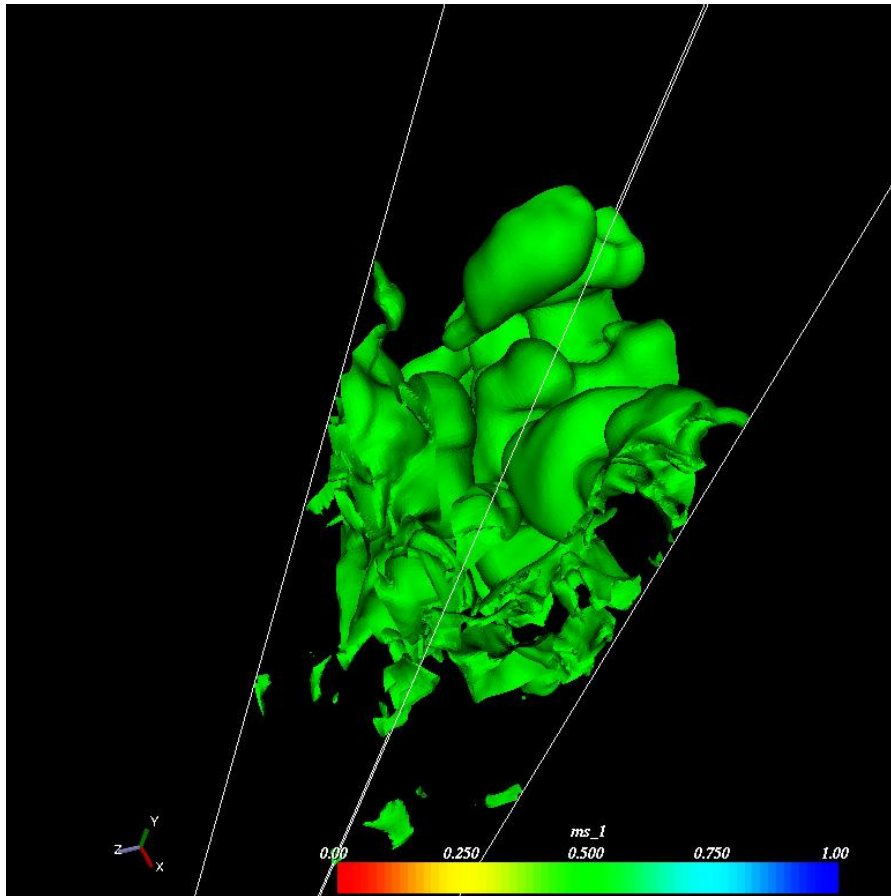
The ASC/Alliances Center for Astrophysical Thermonuclear Flashes
The University of Chicago
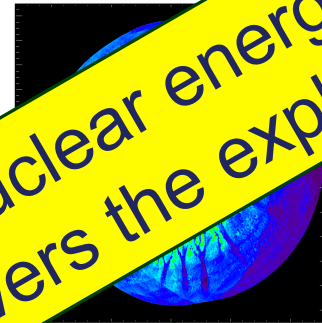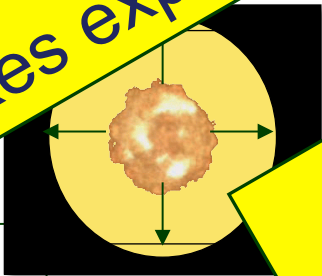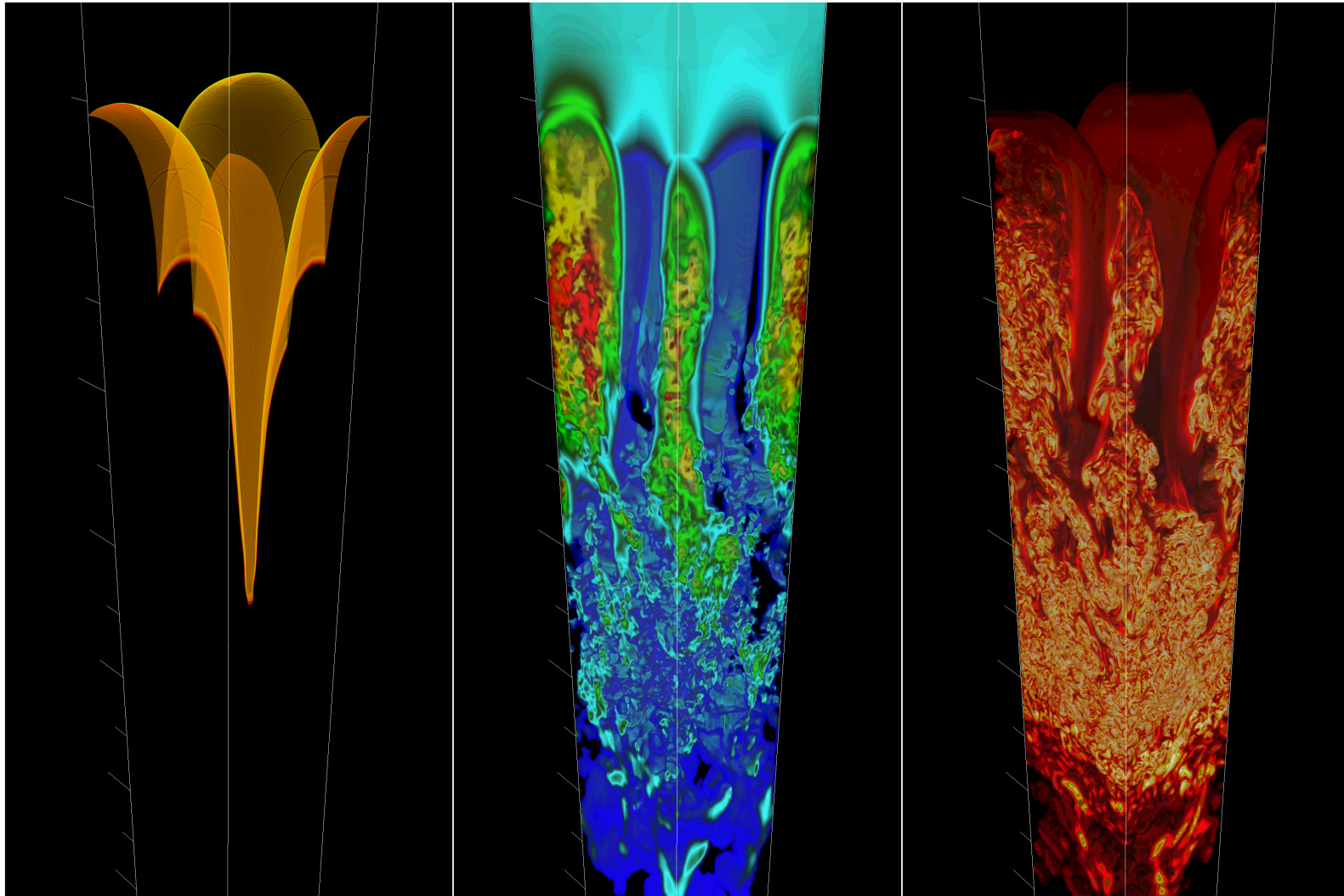
Buoyancy-driven turbulent nuclear burning

❑ 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 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 controversial

❑ We have done extensive simulations to better understand this key physical process

Zhang et al. (2007); Townsley et al. (2008, 2010) Jordan et al. (2011)

Large-scale simulations of buoyancy-driven turbulent nuclear combustion

The Center for Astrophysical Thermonuclear Flashes

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

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

ASC

Conclusions from extensive verification simulations of buoyancy-driven turbulent nuclear burning

❑ Buoyancy-driven turbulent nuclear combustion produces a much lower burning rate than nuclear combustion in the presence of fully developed turbulence

❑ One length scale determines the rate of burning: λ_c, the "flame polishing length"

❑ Variations in the rate of burning are due to variations in the area of the flame surface at large length scales

❑ We are using the results to develop a better model of such burning for use in our whole-star simulations of Type Ia supernovae

The Center for Astrophysical Thermonuclear Flashes

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

**Ignition occurs 40 km from the center of the star.
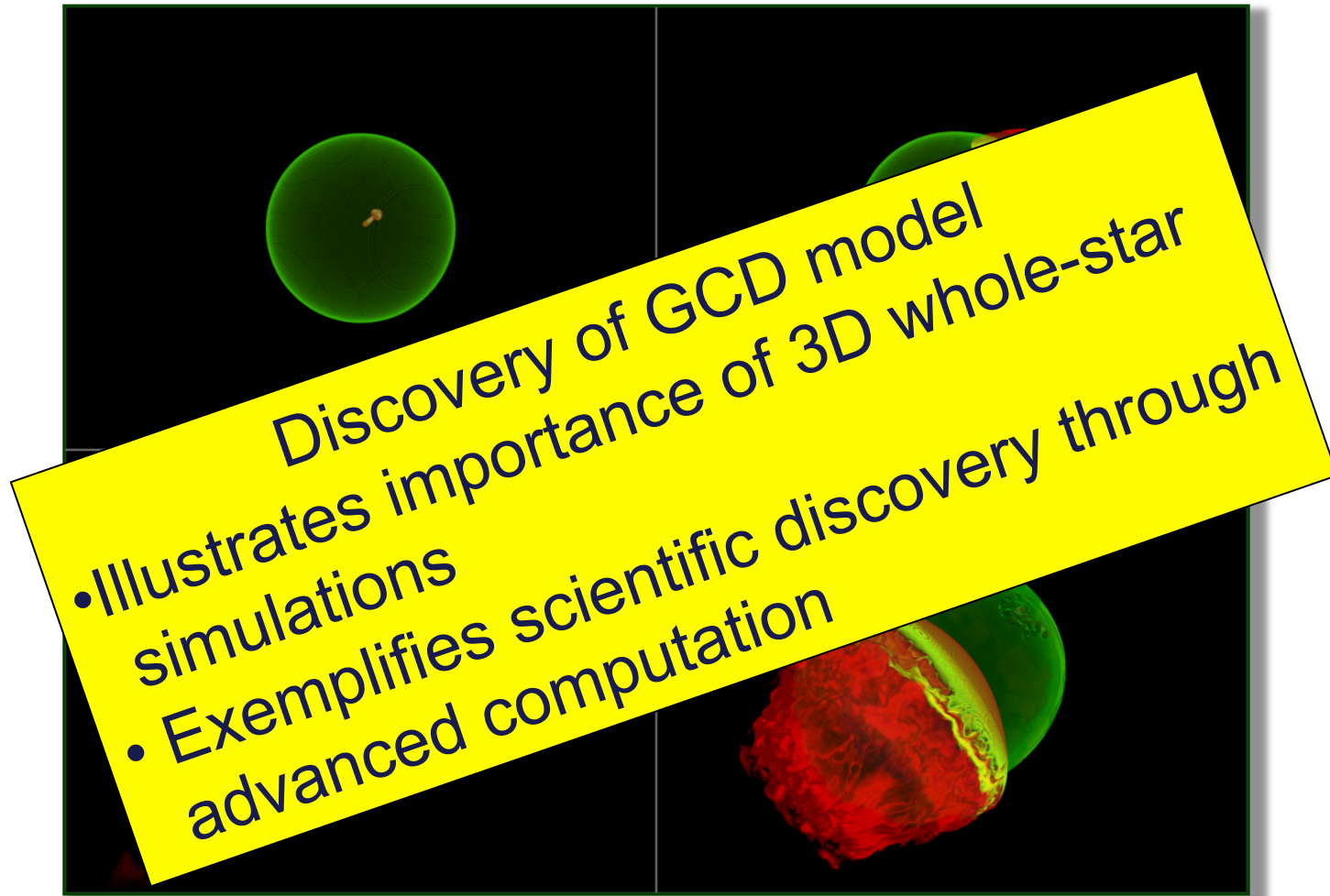Hot material is shown in color and stellar surface in green.**

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

ASC

Discovery of an entirely new explosion mechanism for Type Ia supernovae

Discovery of GCD model

- Illustrates importance of 3D whole-star simulations
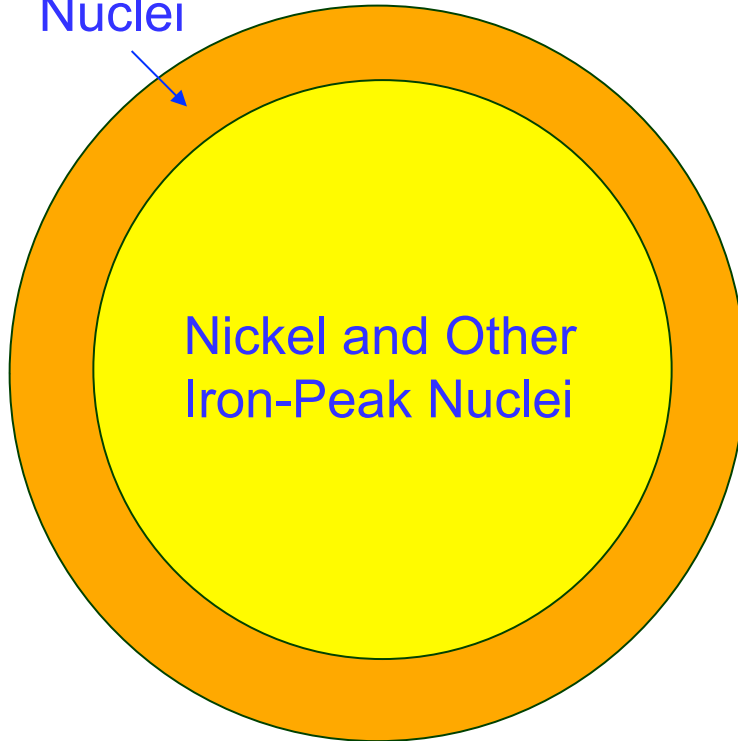- Exemplifies scientific discovery through advanced computation

Calder et al. (2003); Plewa, Calder and Lamb (2004); Townsley et al. (2007); Jordan et al. (2008); Meakin et al. (2009)

Impact of pre-expansion
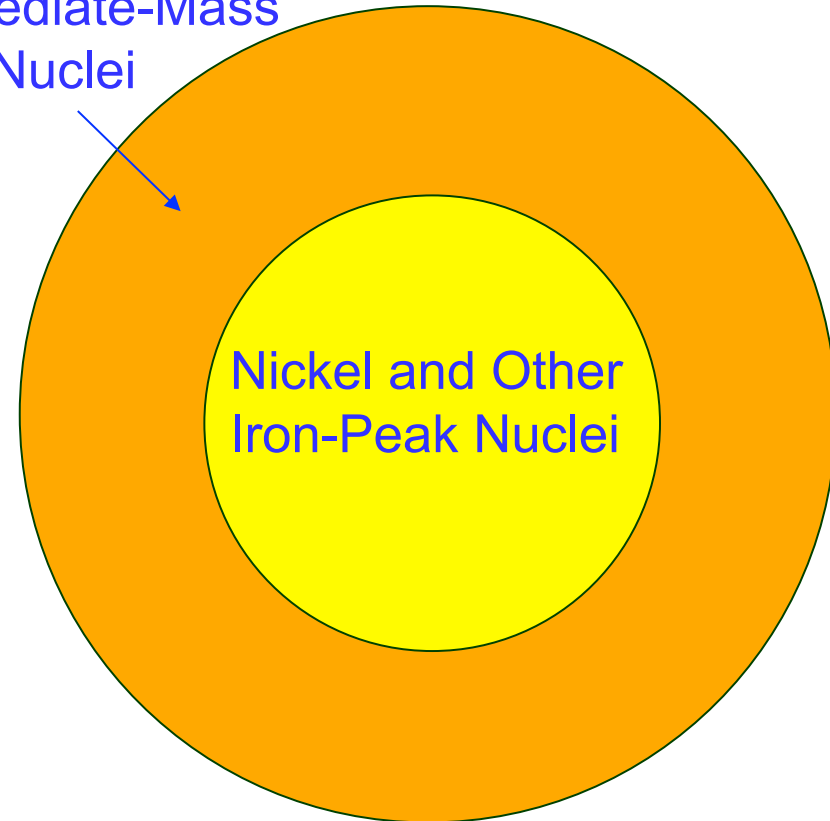# on nucleosynthetic products of supernova

Intermediate-Mass
Nuclei

Intermediate-Mass
Nuclei

Nickel and Other
Iron-Peak Nuclei

Nickel and Other
Iron-Peak Nuclei

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

Failed GCD model may explain peculiar underluminous Type Ia supernovae

Jordan et al. (2013)
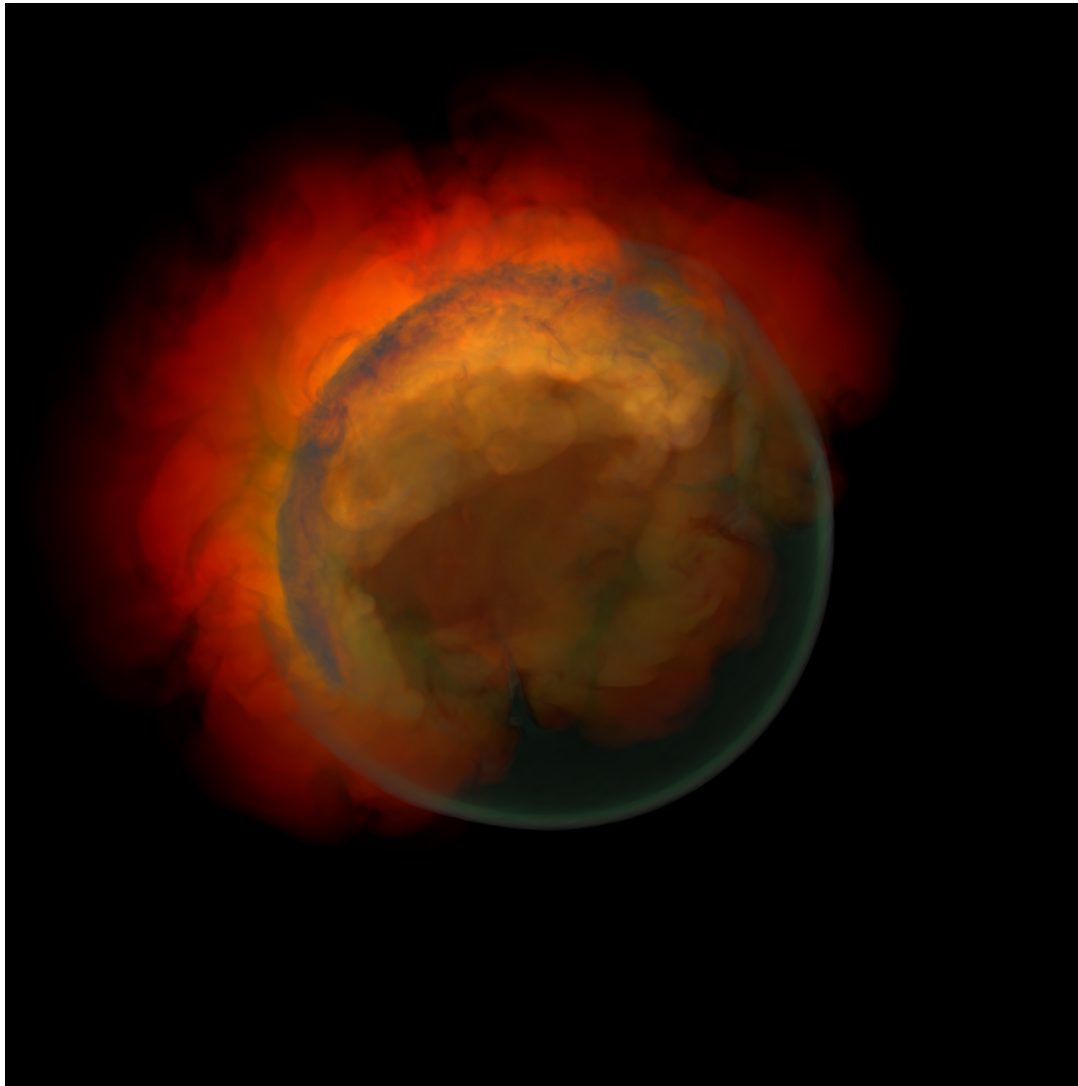
- ❑ Failed GCD model produces only ~ 0.05 -0.1 M_{sun} of Nickel compared to 0.5-0.7 M_{sun} for normal Type Ia supernovae.
- ❑ Consequently, these events are under-luminous by a factor ~ 10-100.
- ❑ The core of the white dwarf survives and gets a ~ 300 km s^{-1} kick which may allow it to escape from the binary in some cases

Partnership with SDSS-II Supernova Survey and Dark Energy Survey to validate Type Ia supernova models

SDSS Supernova Project has spectroscopically identified more than 500 Type Ia supernovae, and obtained high-quality light curves and spectra for many of them *(Holtzman et al. 2009, Kessler et al. 2009)*
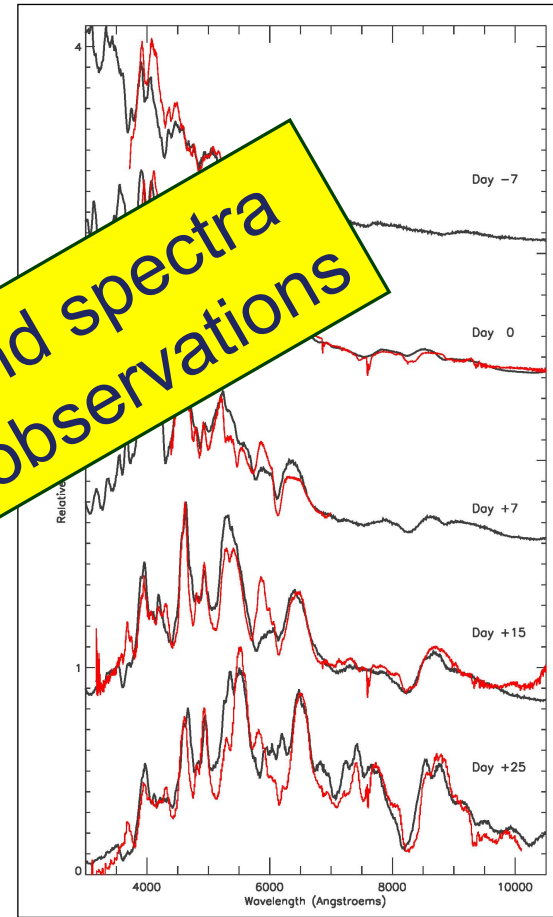
Validation of GCD model using light curves of individual Type Ia supernovae
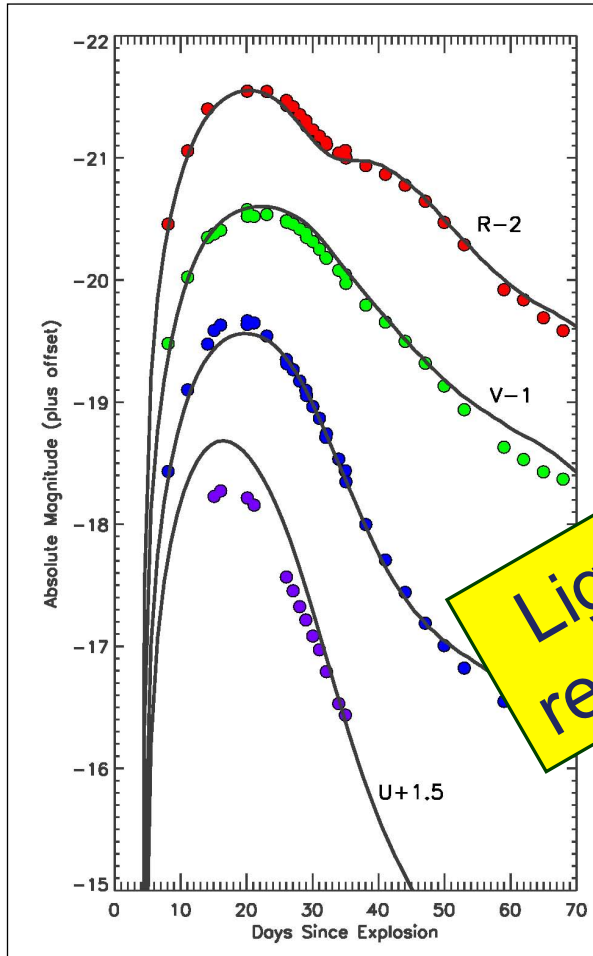
Comparison of U, V, B, R light curves predicted by GCD model and obs. of SN 2001el

Light curves and spectra resemble the observations

Comparison of spectra predicted by GCD model and obs. of Type Ia supernova SN 1994D
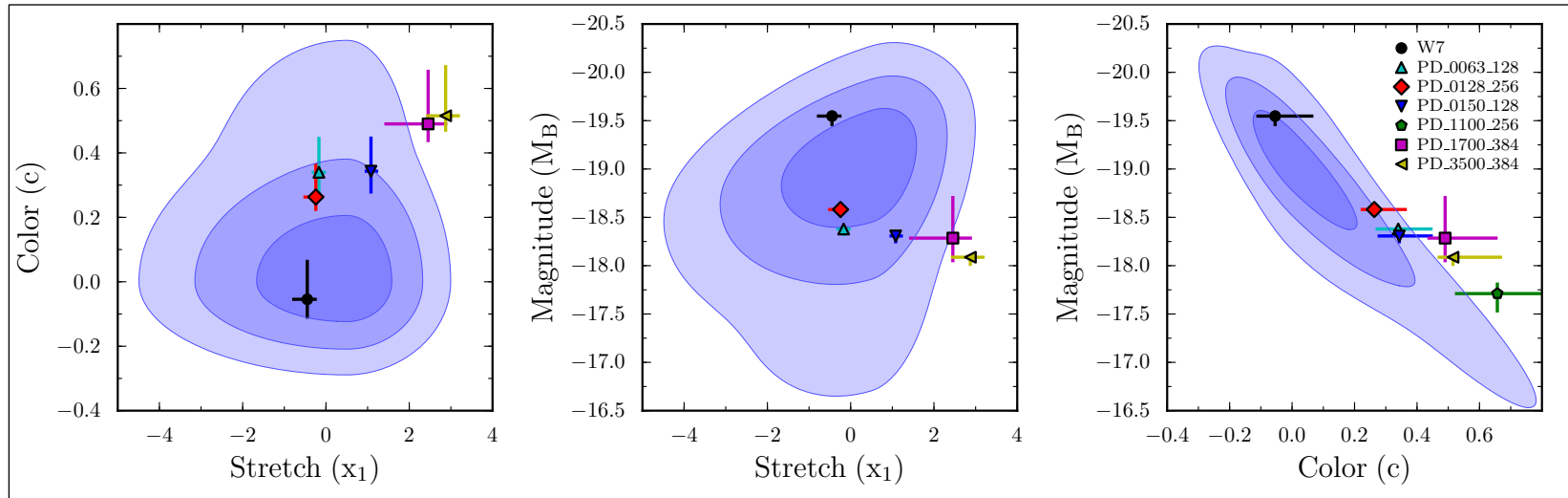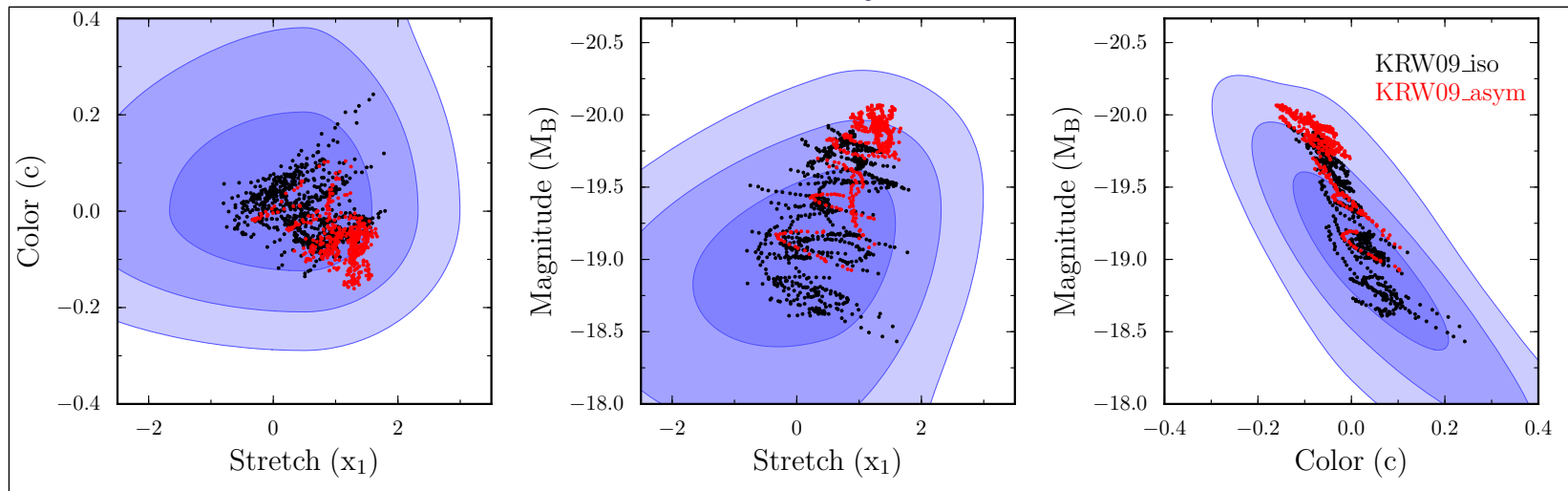
Kasen and Plewa (2006)

Validation of Type Ia supernova models using light curve properties of an ensemble of observed supernovae

Underluminous pure deflagration models

Normal luminosity DDT models

Diemer et al. (2013)

The ASC/Alliances Center for Astrophysical Thermonuclear Flashes
The University of Chicago

Conclusions

❑ The Flash Center has extensively simulated two key processes in Type Ia supernovae that are not fully understood:
- ❑ Buoyancy-driven turbulent nuclear combustion, and
- ❑ Transition to distributed nuclear combustion

❑ The Center is using the results of these simulations to develop a better model of buoyancy-driven turbulent nuclear combustion for use in its whole-star simulations of Type Ia supernovae

❑ While surely not the final story, the GCD model discovered by the Center reproduces several key observed properties of "Branch normal" Type Ia supernovae, and is therefore a promising model of these explosions

❑ The Center has done extensive large-scale, 3D simulations of all current Chandrasekhar-mass Type Ia supernovae models

❑ The Center has begun a rigorous, systematic validation of these models using high-quality data from the SDSS-II Supernova Survey and the Dark Energy Survey, and their collaborators