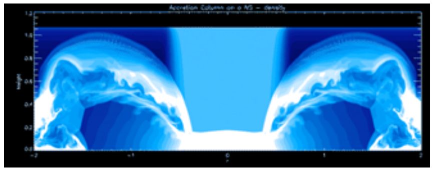
New Insights into Type Ia Supernova Explosions from Large-Scale Simulations

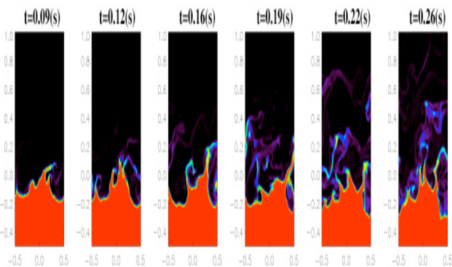
Don Q. Lamb
NNSA ASC ASAP Flash Center
University of Chicago

HPCC'08
Newport, RI, 25 March 2008

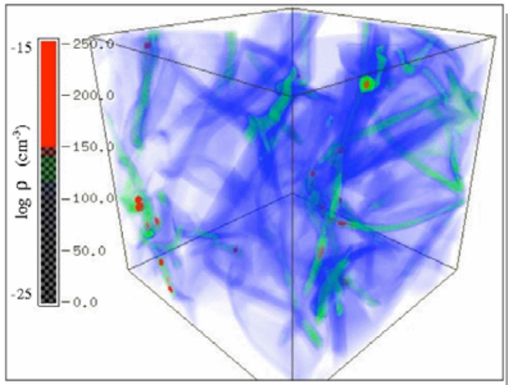
FLASH Capabilities Span a Broad Range…



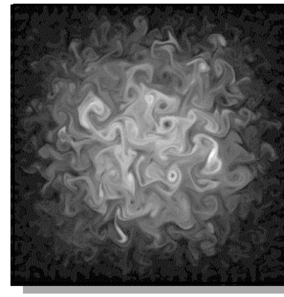
Relativistic accretion onto NS



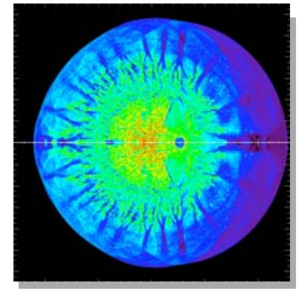
Wave breaking on white dwarfs



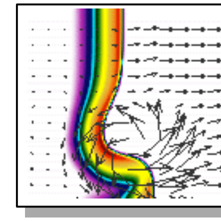
Gravitational collapse/Jeans instability



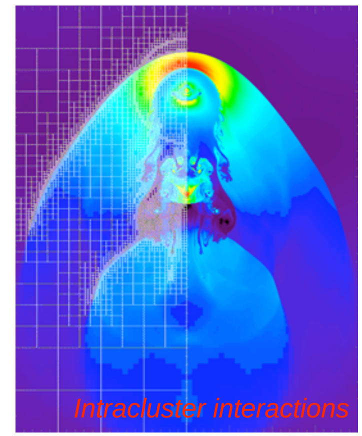
Compressed turbulence



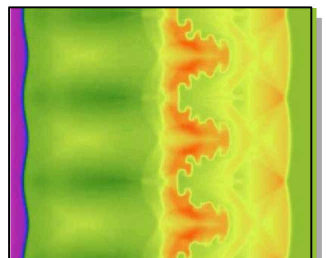
Type Ia Supernova



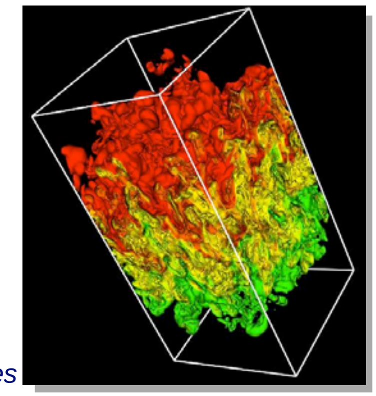
Flame-vortex interactions



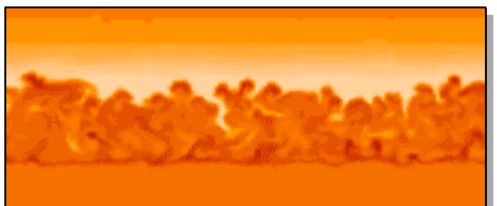
Intracluster interactions



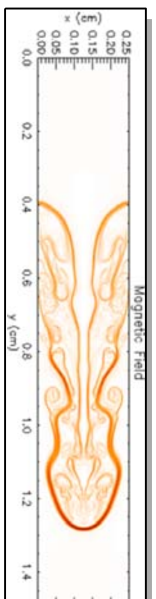
Laser-driven shock instabilities



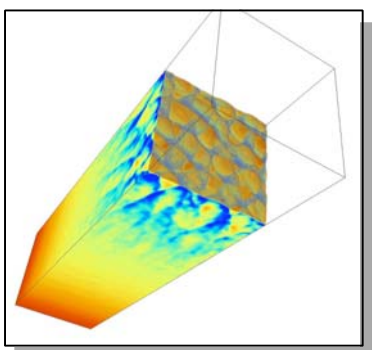
Rayleigh-Taylor instability



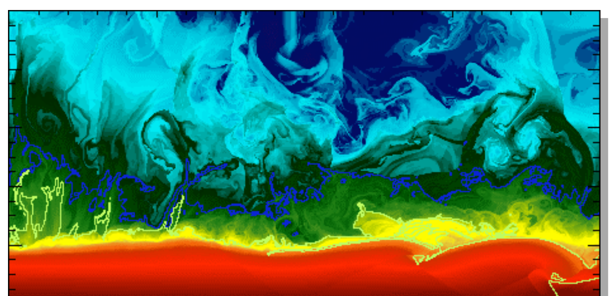
Nova outbursts on white dwarfs



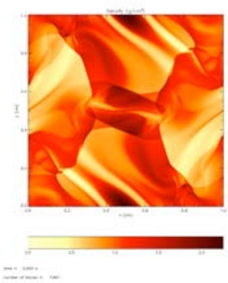
Magnetic Rayleigh-Taylor



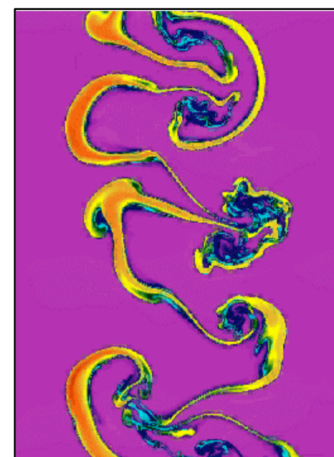
Cellular detonation



Helium burning on neutron stars



Orzag/Tang MHD vortex



Richtmyer-Meshkov instability

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

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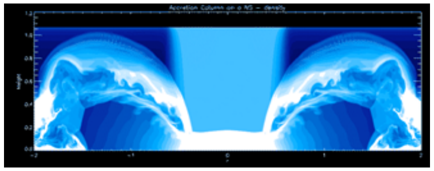

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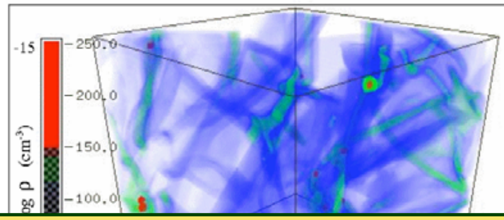
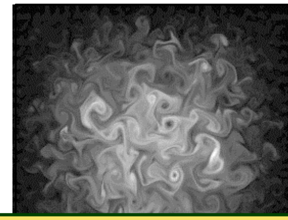
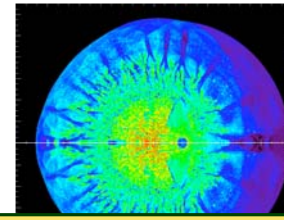
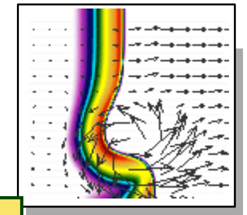
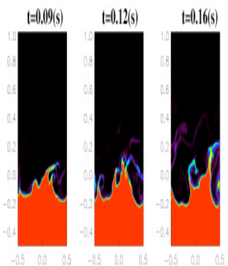








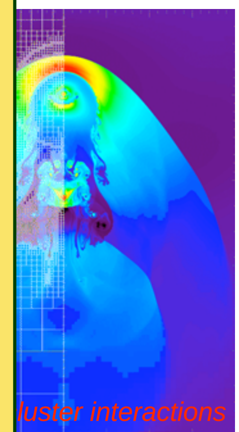
-vortex interactions



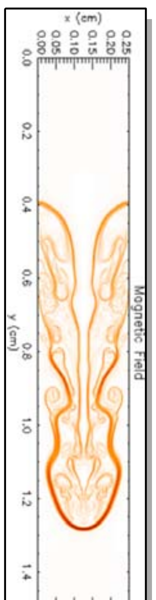
Wave breaking on

The FLASH code

1. Parallel, adaptive-mesh refinement (AMR) code
2. Block structured AMR; a block is the unit of computation
3. Designed for compressible reactive flows
4. Can solve a broad range of (astro)physical problems
5. Portable: runs on many massively-parallel systems
6. Scales and performs well
7. Fully modular and extensible: components can be combined to create many different applications



luster interactions



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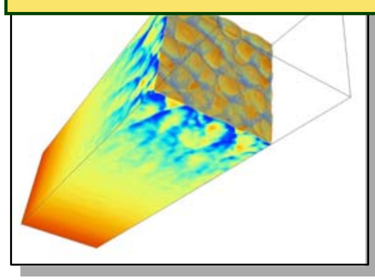

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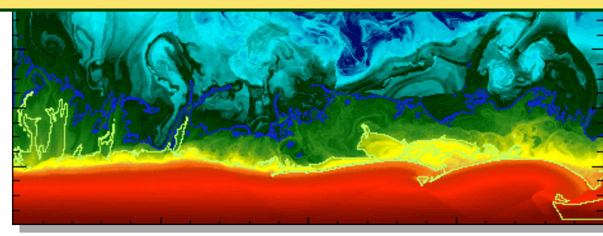

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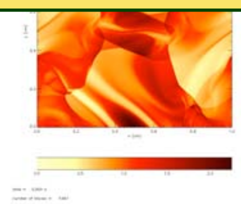

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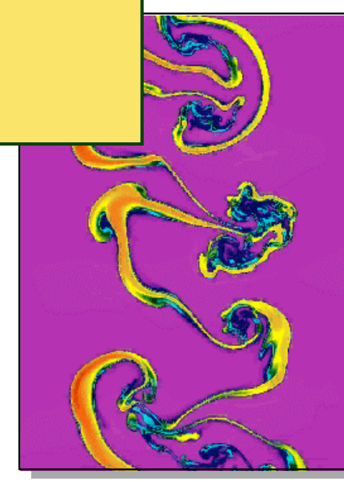

Richtmyer-Meshkov instability

FLASH Is Being Used by Groups Throughout the World

Munich University Observatory
CAST
Computational Astrophysics Group

Germany

http://www.usm.uni-muenchen.de/CAST/people.html
Pawel Ciecielag: Planets formation: planetesimals accretion, gas drag, disk-planet interaction; Cosmology: large scale velocity fields, density-velocity comparisons; Numerical methods: direct n-body (Nbody4++ code, special purpose hardware - GRAPE), hydro (PPM, AMR, FLASH code).
Steffi Walch: Star formation with emphasis on the formation of protostellar disks, evolution and fragmentation of protoplanetary disks and the evolution of their spectral energy distributions. Numerical Methods: hydrodynamics (FLASH code)

US

The Astrophysical Journal, 628:205–209, 2005 July 20

SUPERNOVA BLAST WAVES IN LOW-DENSITY HOT MEDIA: A MECHANISM FOR SPATIALLY DISTRIBUTED HEATING

Shikui Tang and Q. Daniel Wang
Department of Astronomy, University of Massachusetts, LGRT-B 619E, 710 North Pleasant Street, Amherst, MA 01003; tangsk@astro.umass.edu, wqd@astro.umass.edu
Received 2004 December 17; accepted 2005 April 11

ABSTRACT

Most supernovae are expected to explode in low-density hot media, particularly in galactic bulges and elliptical galaxies. The remnants of such supernovae, although difficult to detect individually, can be profoundly important in heating the media on large scales. We characterize the evolution of this kind of supernova remnant, based on analytical approximations and hydrodynamic simulations. We generalize the standard Sedov solution to account for both temperature and density effects of the ambient media. Although cooling can be neglected, the expansion of such a remnant deviates quickly from the standard Sedov solution and asymptotically approaches the ambient sound speed as the swept-up thermal energy becomes important. The relatively steady and fast expansion of the remnants over large volumes provides an ideal mechanism for spatially distributed heating, which may help to alleviate the overcooling problem of hot gas in groups and clusters of galaxies, as well as in galaxies themselves. The simulations were performed with the FLASH code.

Subject headings: cooling flows — galaxies: clusters: general — galaxies: ISM — ISM: structure — supernova remnants

Online material: color figures

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FLASH Workshop

Canada

Workshop
Wed, Mar 23, 2005, 9:00 AM
Location: MP1318A

Workshop on the FLASH code: a general-purpose, parallel, adaptive mesh, reactive astrophysical hydrodynamics code that is available to the research community

Tentative Schedule

Abstract:

On March 23 and 24th, CITA will host a mini-workshop on the FLASH code: a general-purpose, parallel, adaptive mesh, reactive astrophysical hydrodynamics code that is available to the research community. The FLASH code has been applied to problems from burning in or on compact objects, to the efficiency of cooling flows in galaxy clusters, to cosmological simulations.

Four people will be coming from the Chicago FLASH centre to give one day of talks on the capabilities of the code, and will be available to schedule meetings with on the second day for more focused, less formal discussions on applying the FLASH code to problems of interest to local projects.

Learning and Testing FLASH: Practical Notes

This page is intended for members of the Computational Astrophysics group at McMaster University who whish to learn and be involved with the testing of the FLASH code. The code was developed at the ASCI/Alliances Center for Astrophysical Thermonuclear Flashes at the University of Chicago.

Getting Started:

Canada

...step spoon-feed for ...s along the way.

FLASH Code Development

...m Members:

...n **Boss** (DTM)
...abeth **Myhill, Justin Domes** (Marymount University)
...ri **Vanhala** (Challenger Center)

US

...e FLASH Adaptive Mesh Refinement Hydrodynamics Code

...seek to study the dynamics of mixing and transport processes in the presolar cloud and in the solar ...ıla, in the context of isotopic heterogeneity introduced either by shock-triggered collapse of the presolar ...d or by infall from an x-wind outflow, the two leading explanations for the widespread evidence of ...t-lived radioactivities in chondritic refractory inclusions and, much more rarely, in chondrules. Myhill ... Domes are leading our effort to develop a new hydrodynamical code for studying these problems, the ...SH adaptive mesh refinement code. FLASH will allow the problem of shock-wave triggering and ...tion to be studied with an unprecedented degree of high spatial resolution, which is likely to be critical ...e question of simultaneous triggering and injection when nonisothermal shock front thermodynamics is ...loyed. We will work with Vanhala to define a nonisothermal shock test case to be calculated with both ...FLASH code and Vanhala's EVH-1 code. In addition, the FLASH code will permit extending these ...stigations down to the scale of the solar nebula, where nebular transport and mixing processes can be ...ied in general terms, applicable to isotopically heterogeneous grains falling onto the nebular surface as a ...lt of either shock-triggered collapse or x-wind outflows. We will seek in part to learn whether spatial ...temporal heterogeneity inherited from such sources can survive subsequent nebular mixing processes ...can help to explain certain isotopic abundance patterns seen in the inner Solar System and the asteroid ... The development of the FLASH code should also prove useful for Boss's studies of the formation of ...t planets by the disk instability mechanism.

OSSERVATORIO ASTRONOMICO DI PALERMO GIUSEPPE S. VAIANA

Italy

The FLASH code at OAPA

The Osservatorio Astronomico di Palermo is one of the test sites for the very accurate FLASH code, a 3-dimensional astrophysical hydrodynamic code for supercomputers mainly developed at the "Flash Center", the University of Chicago.

Palermo is the test site in which FLASH has been ported to Compaq architectures. The FLASH code solves the compressible Euler equations on a block-structured adaptive mesh, and its modular design permits the introduction of additional physics and of different solvers.

The Palermo team collaborates with the Flash Center to upgrade and to apply extensively FLASH to astrophysical systems.

The group in Palermo also develops new modules for FLASH which extend the field of applicability of the code to other problems in astrophysics, from solar and stellar coronae, to supernova remnants, and to galaxy clusters halos. In particular, the new modules so far developed and tested include:

1. the non-equilibrium ionization effects of the most abundant elements in astrophysical plasmas
2. the thermal conduction according to the formulation of Spitzer (1962)
3. the radiative losses from an optically thin plasma according to the Raymond spectral code and Peres et al. (1982) for the chromosphere.
4. the viscosity according to the formulation of Spitzer (1962)

In this project, the Palermo team takes advantage of its long experience in developing hydrodynamic codes for modeling astrophysical plasma and in optimizing the codes for efficient parallel execution on high performance computers. The group has recently acquired and uses, for 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).

3D AMR Simulations of Point-Symmetric Nebulae

Erik-Jan Rijkhorst, Vincent Icke, and Garrelt Mellema, Sterrewacht Leiden, The Netherlands
http://www.strw.LeidenUniv.nl/AstroHydro3D/

Numerical Implementation

We used the three-dimensional hydrocode *Flash* [6] to model the interaction between a spherical wind and a warped disk. This parallelized code implements block-structured adaptive mesh refinement (AMR) [7] (see images below) and a PPM type hydrosolver [8].

We added to the code the proper initial conditions for the wind-di... warped disk, Eq. (1) was combined with a constant 'wedge angle'... was given a constant density . The spherical wind was implemen... $1/r^2$ density profile and a constant velocity. The pressure was cal... constant Poisson index γ.

Netherlands

Monthly Notices of the Royal Astronomical Society
Volume 355 Issue 3 Page 995 - December 2004
doi:10.1111/j.1365-2966.2004.08381.x

UK

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 Astrophysical Journal, 630:740–749, 2005 September 10

Germany

ACTIVE GALACTIC NUCLEI HEATING AND DISSIPATIVE PROCESSES IN GALAXY CLUSTERS

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Joint Institute for Laboratory Astrophysics, Campus Box 440, University of Colorado, Boulder, CO 80309-0440; mr@quixote.colorado.edu
and
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Received 2005 January 10; accepted 2005 May 22

ABSTRACT

Recent X-ray observations reveal growing evidence for heating by active galactic nuclei (AGNs) in clusters and groups of galaxies. AGN outflows play a crucial role in explaining the riddle of cooling flows and the entropy problem in clusters. Here we study the effect of AGNs on the intracluster medium in a cosmological simulation using the adaptive mesh refinement FLASH code. We pay particular attention to the effects of conductivity and viscosity on the dissipation of weak shocks generated by the AGN activity in a realistic galaxy cluster. Our three-dimensional simulations demonstrate that both viscous and conductive dissipation play an important role in distributing the mechanical energy injected by the AGNs, offsetting radiative cooling and injecting entropy to the gas. These processes are important even when the transport coefficients are at a level of 10% of the Spitzer value. Provided that both conductivity and ...ty are suppressed by a comparable amount, conductive dissipation is likely to dominate over viscous dissipation. ...heless, viscous effects may still affect the dynamics of the gas and contribute a significant amount of dissipation ...red to radiative cooling. We also present synthetic *Chandra* observations. We show that the simulated buoyant ...s inflated by the AGN, and weak shocks associated with them, are detectable with the *Chandra* observatory.

...t headings: cooling flows — galaxies: active — galaxies: clusters: general — X-rays: galaxies

FLASH Is Being Used by Groups Throughout the World

FLASH is being used by over 300 scientists around the world to do simulations in computational fluid dynamics, astrophysics, cosmology, plasma physics, …; to do scaling studies, software development, etc. in CS; and is a key acceptance test for the IBM BG/P at ANL

Germany

US

Canada

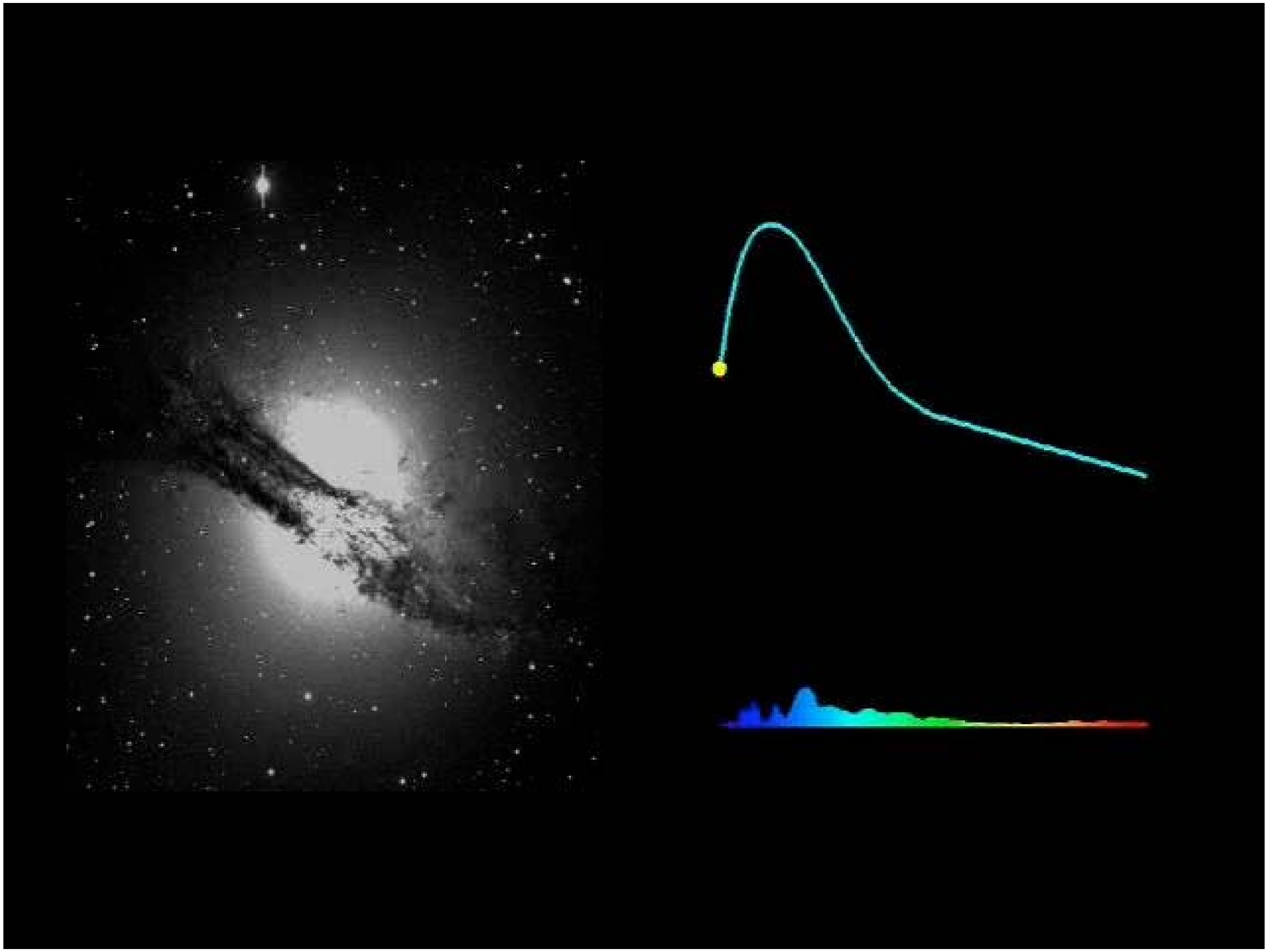
Italy

Germany

Netherlands

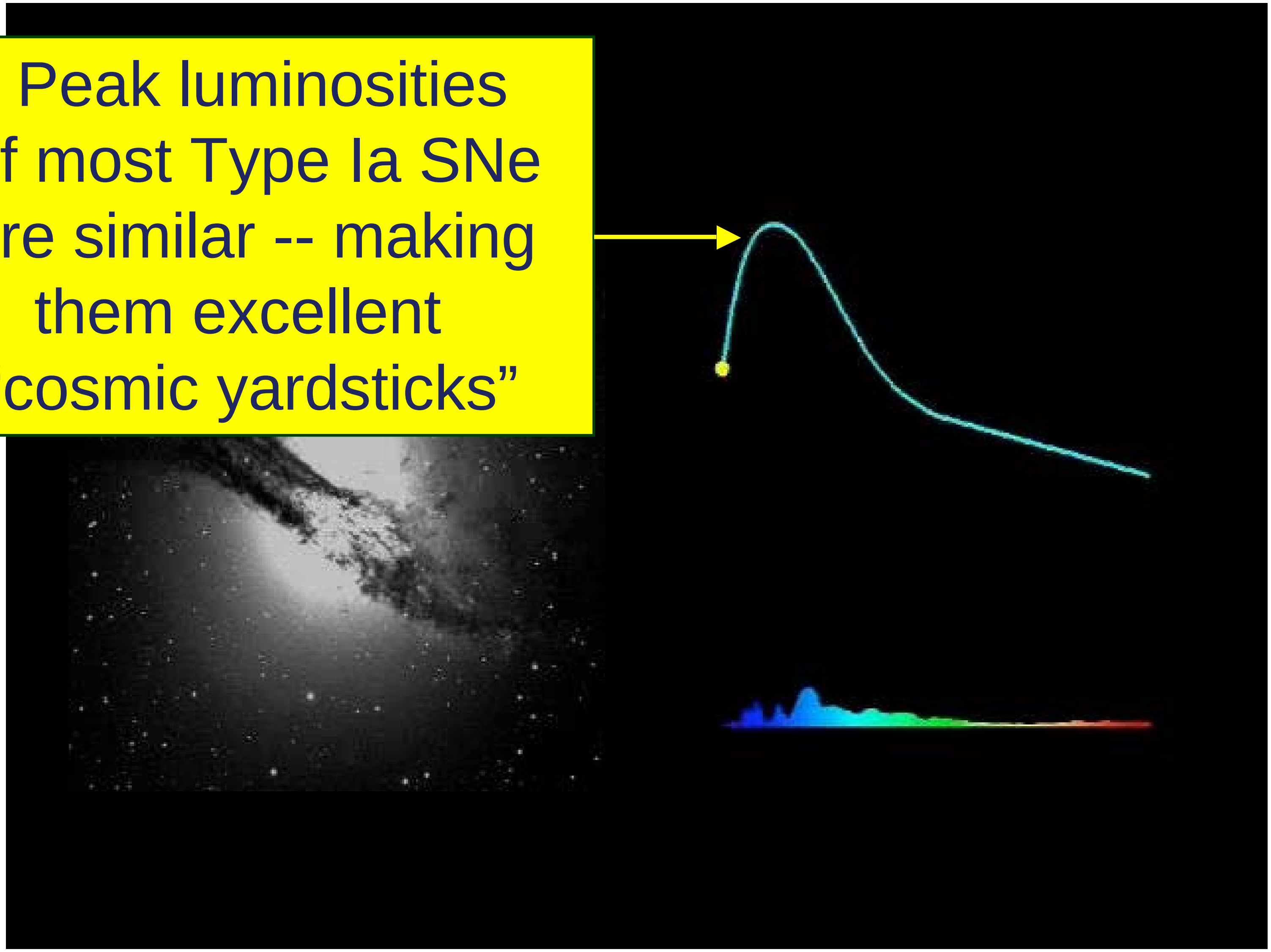
UK

What Are Type Ia Supernovae?

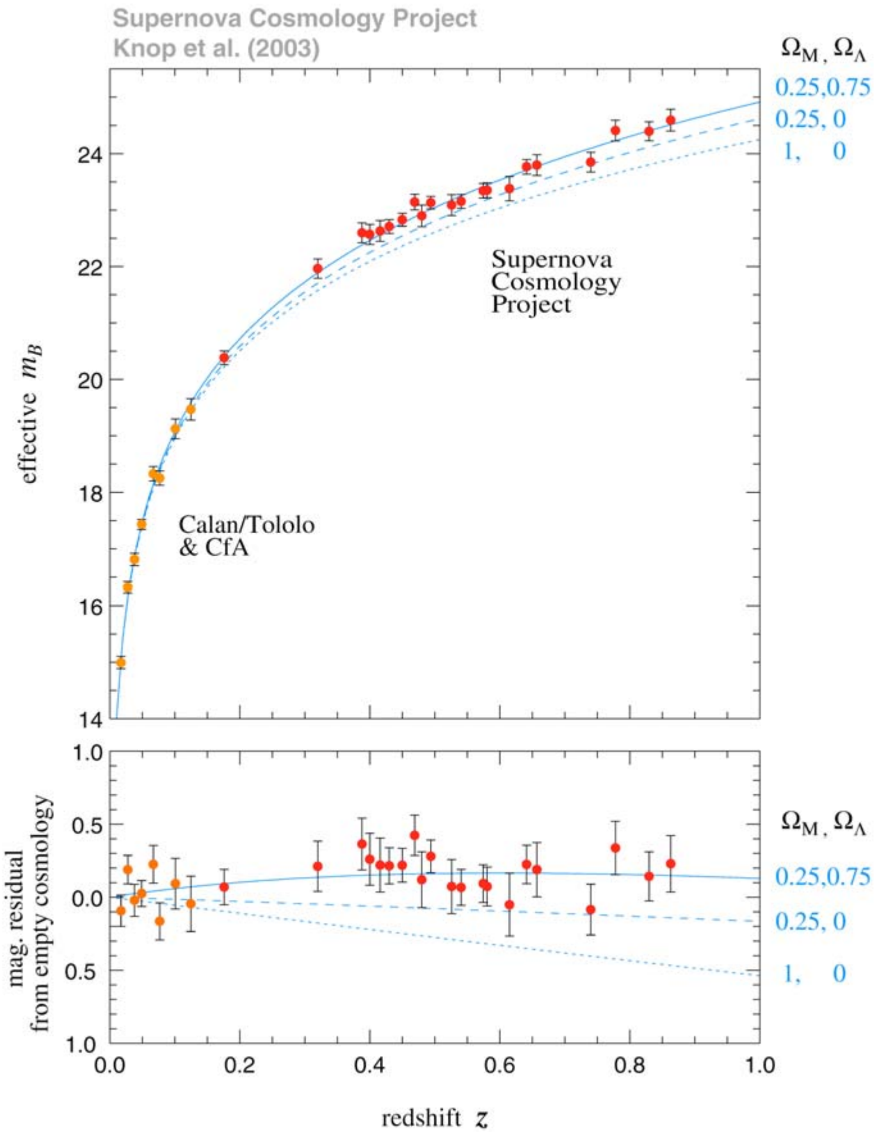


What Are Type Ia Supernovae?

Peak luminosities of most Type Ia SNe are similar -- making them excellent “cosmic yardsticks”



Use of Type Ia Supernovae as "Standard Candles" Led to Discovery of Dark Energy

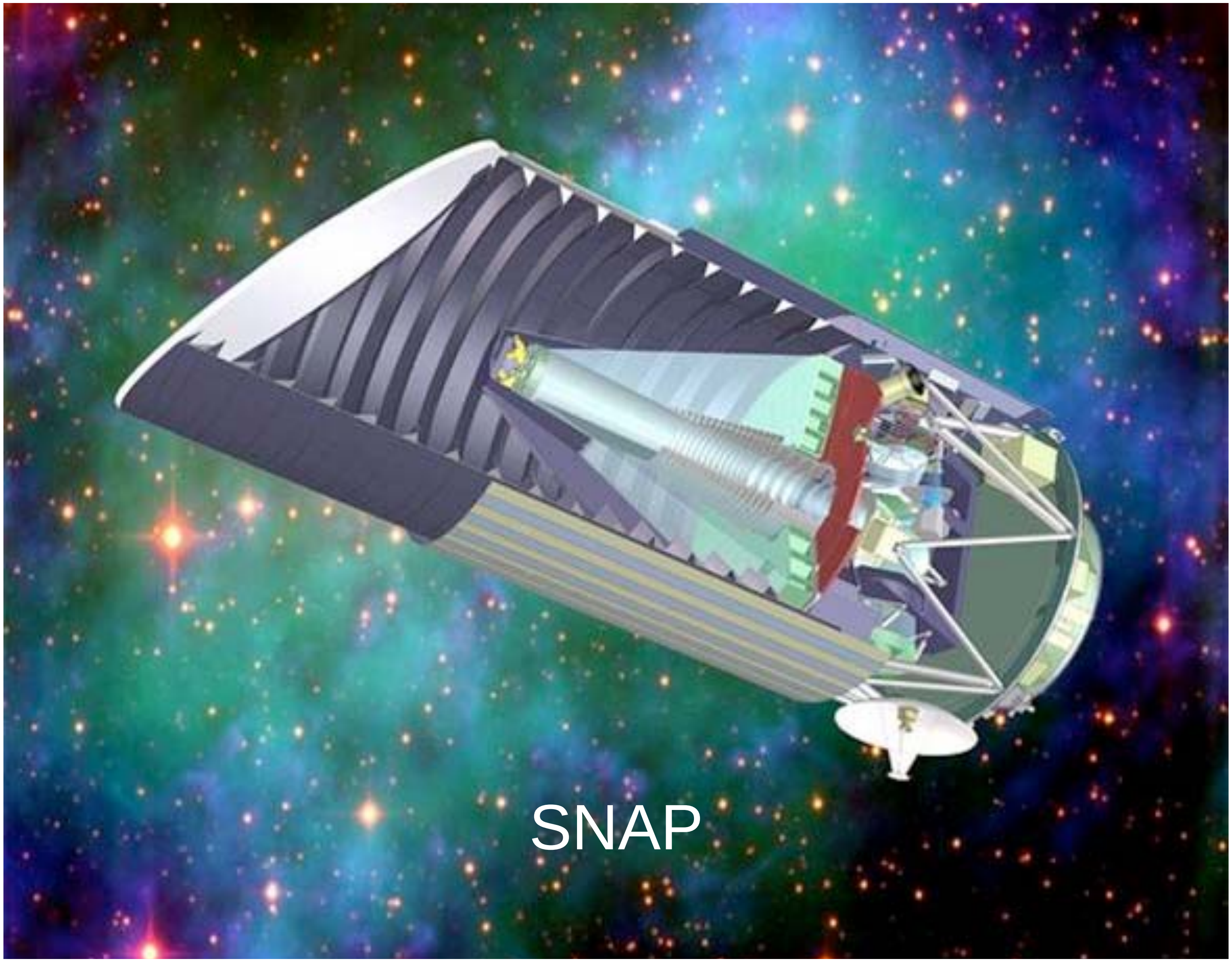


Type Ia supernovae appear *dimmer* in a universe with non-zero Ω_Λ

The apparent magnitude of Type Ia supernovae as a function of redshift are not even consistent with $\Omega_\Lambda = 0$

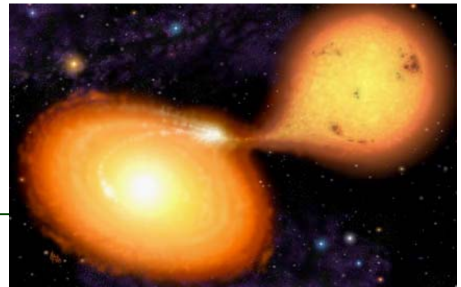
This means that the rate of expansion of the universe is accelerating, and implies the existence of Dark Energy

Joint Dark Energy Mission



Type Ia Supernovae

Image copyrighted by Mark A. Garlick



Accretion

- Stellar binary in which main sequence star transfers mass onto white dwarf

$>10^8$ yr

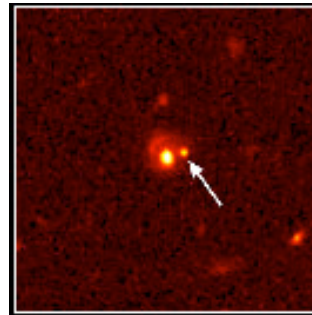
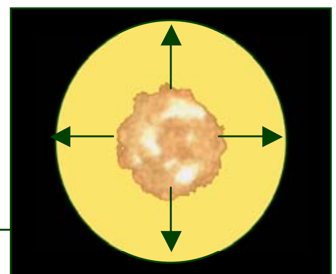


Image credit P. Garnavich/CfA

Lightcurve

- Free expansion of star
- Radioactive decay of nickel heats the ejecta
- This causes the ejecta to glow, which makes the supernova visible

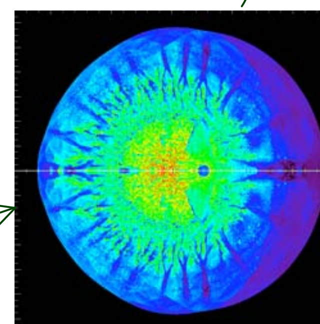


Smoldering

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

~1000 yr

Ignition



~seconds

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

Type Ia Supernovae

Image copyrighted by Mark A. Garlick

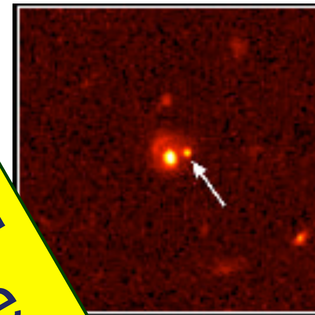


Image credit P. Garnavich/CfA

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

Accretion

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

Lightcurve

- F… xpansion of star … tive decay of … ts the ejecta … es the ejecta to … 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

Computational Demands of Type Ia Supernova Simulations

- Following turbulent nuclear burning requires ~ 1-10 km resolution, whereas radius of star is 10^9 km -- adaptive mesh refinement is therefore essential
- High-resolution, 3-D, whole star simulations require ~ 100K-300K cpu-hrs on current machines
- Each large simulation generates ~ 200 MB/cpu-hr; i.e., ~ 20-60 TB of data
- We used ~ 2M cpu-hrs on DOE ASC machines and ~ 5 M cpu-hrs on DOE Office of Science machines last year; we expect to use 80M cpu-hrs this year
- We generated ~ 1 PB of data last year; we expect to generate ~ 3-5 PB of data this year

The Center for Astrophysical Thermonuclear Flashes

Simulation of the Deflagration Phase of a Type Ia Supernovae

Ignition occurs 100 km from the center of the star.
Hot ash is shown in yellow and stellar surface in blue.

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.

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 Phase of a Type Ia Supernovae

Ignition occurs 100 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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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

Ignition occurs 40 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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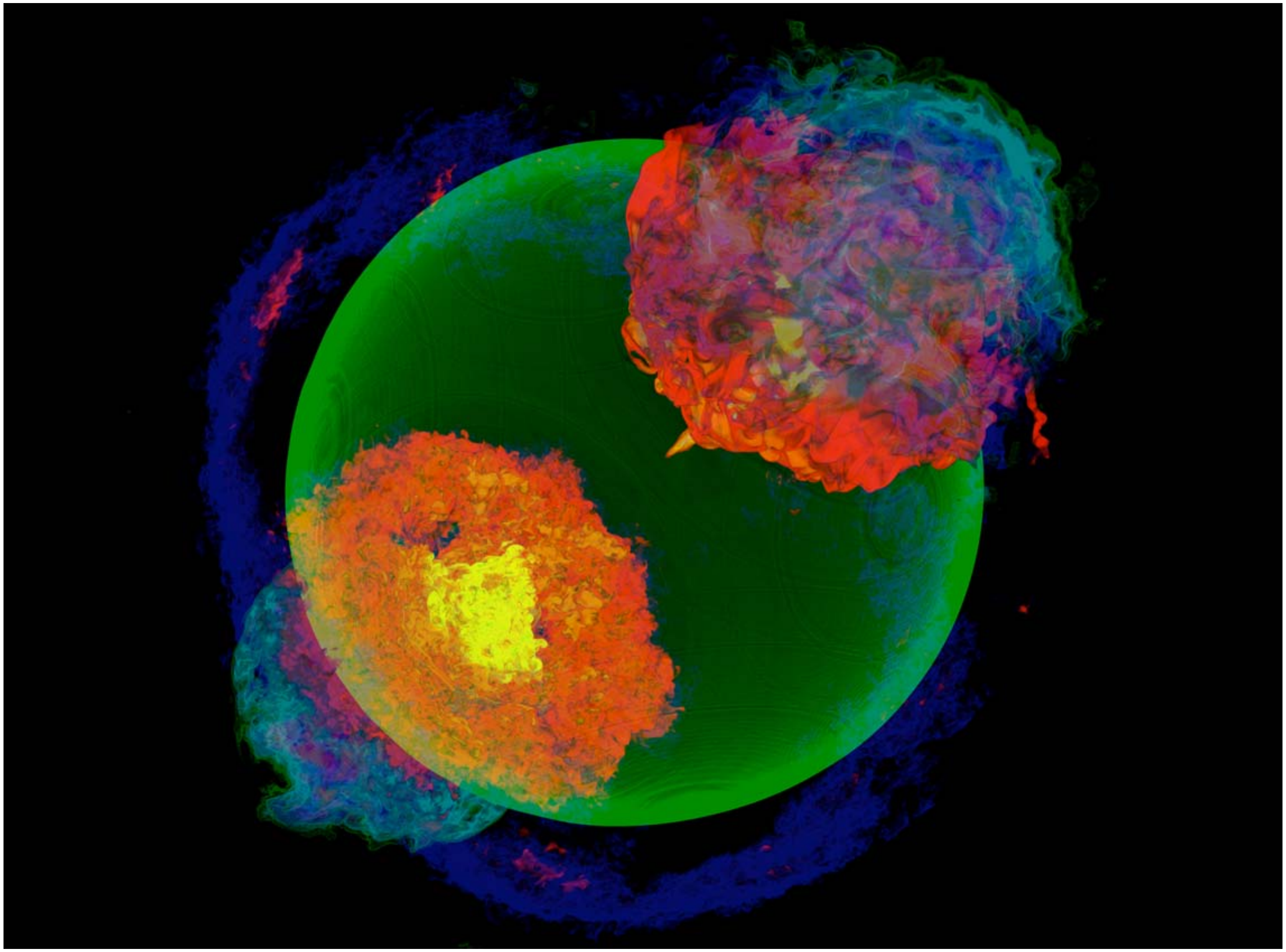
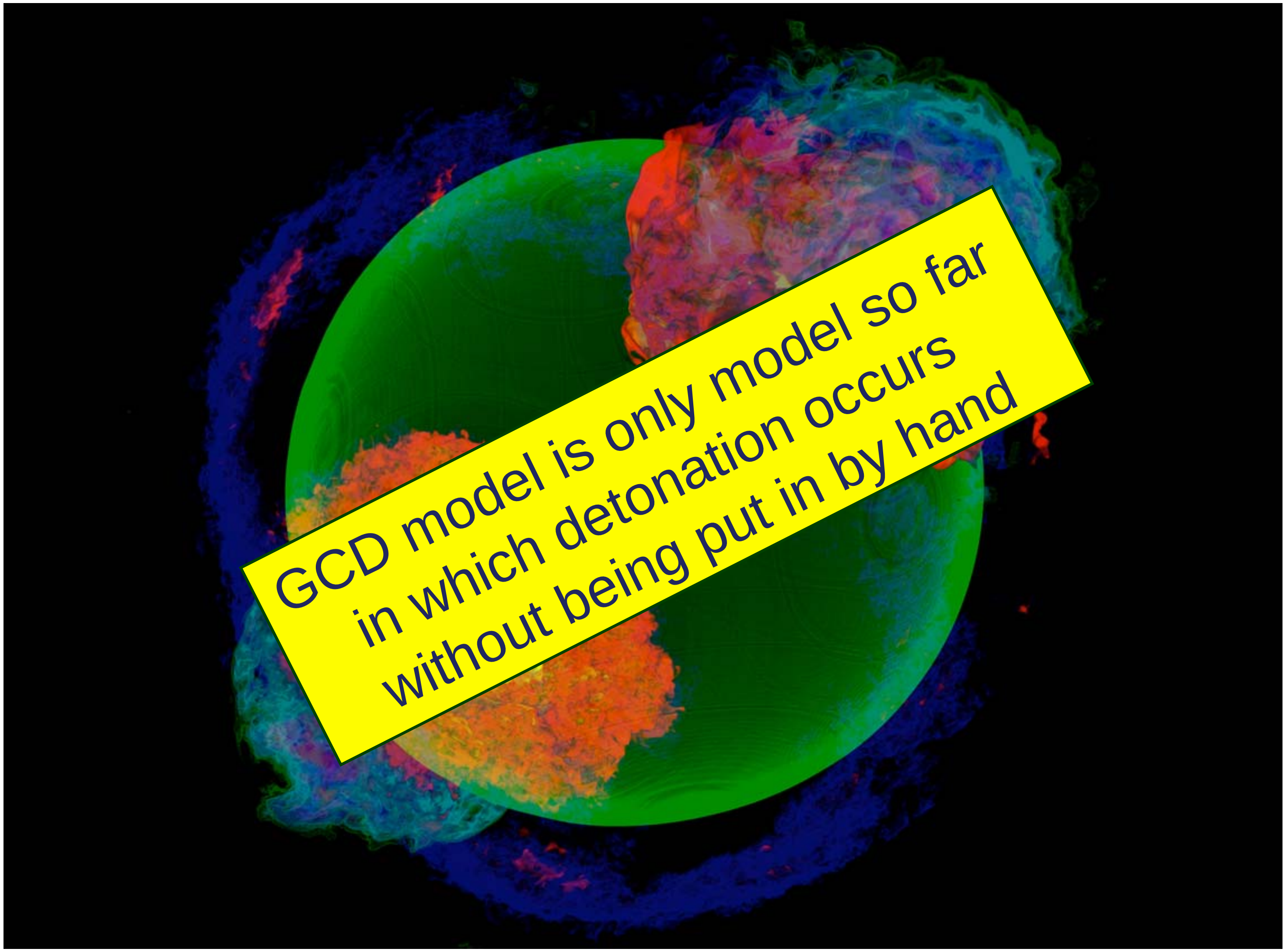
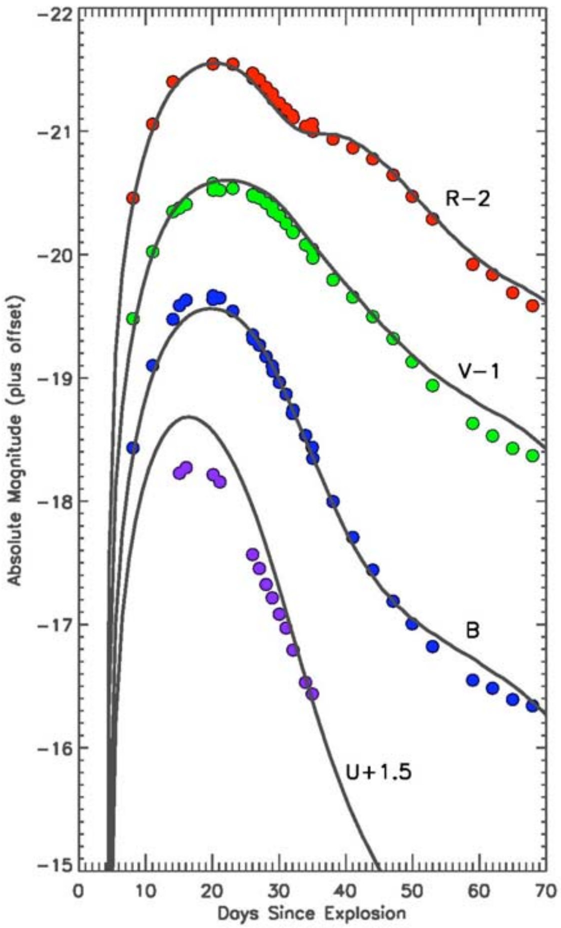
Detonation Conditions Are Robustly Produced by Inwardly Directed Jet



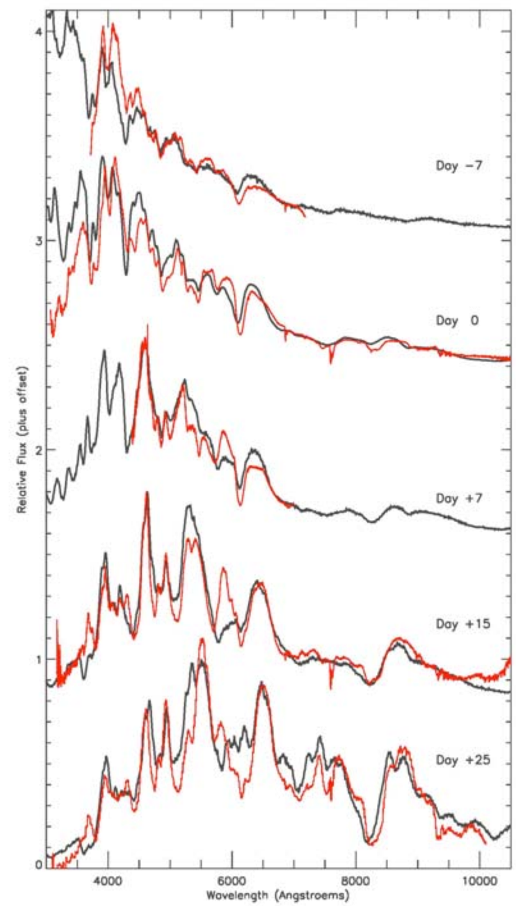
Detonation Conditions Are Robustly Produced by Inwardly Directed Jet



Global Validation of Light Curves and Spectra Predicted by GCD Model



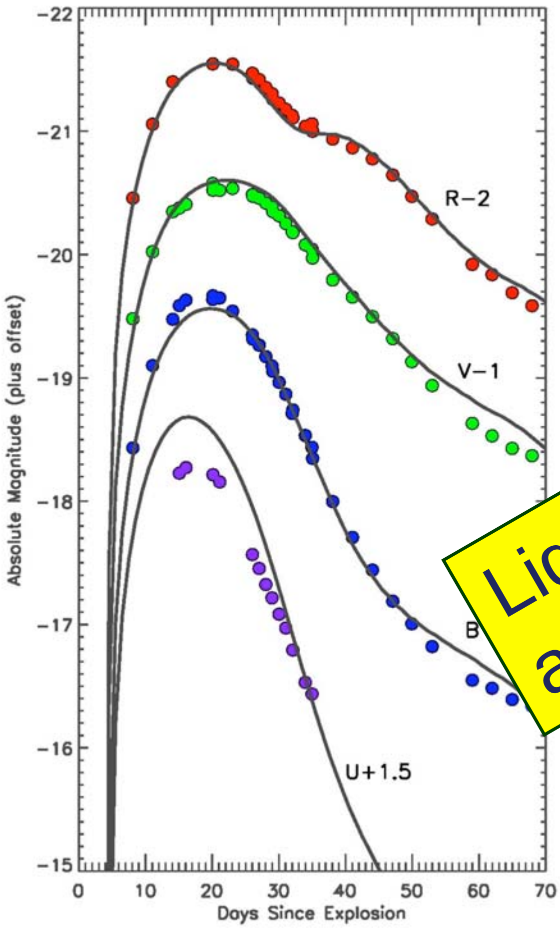
Comparison of U, V, B, R light curves predicted by GCD model and obs. of Type Ia Supernova SN 2001el



Comparison of spectra predicted by GCD model and obs. of Type Ia supernova SN 1994D

Kasen and Plewa (2006)

Global Validation of Light Curves and Spectra Predicted by GCD Model



Comparison of U, V, B, R light curves predicted by GCD m
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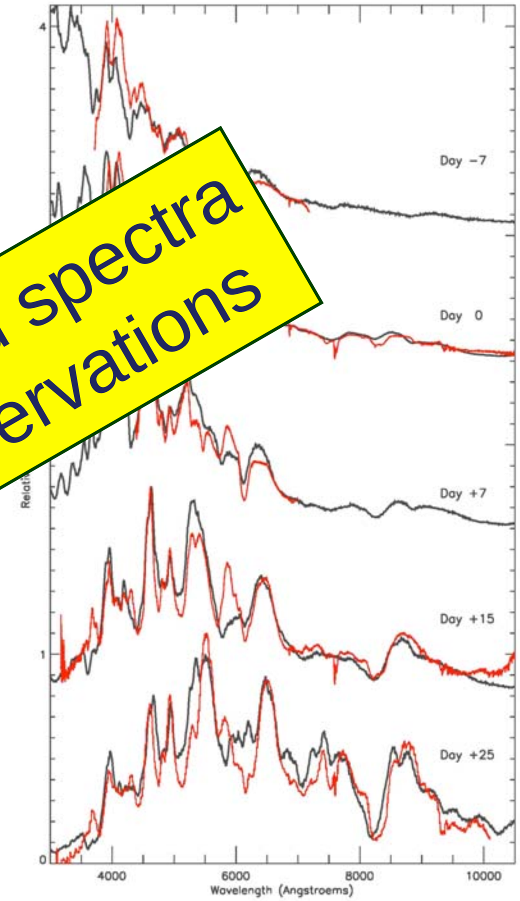
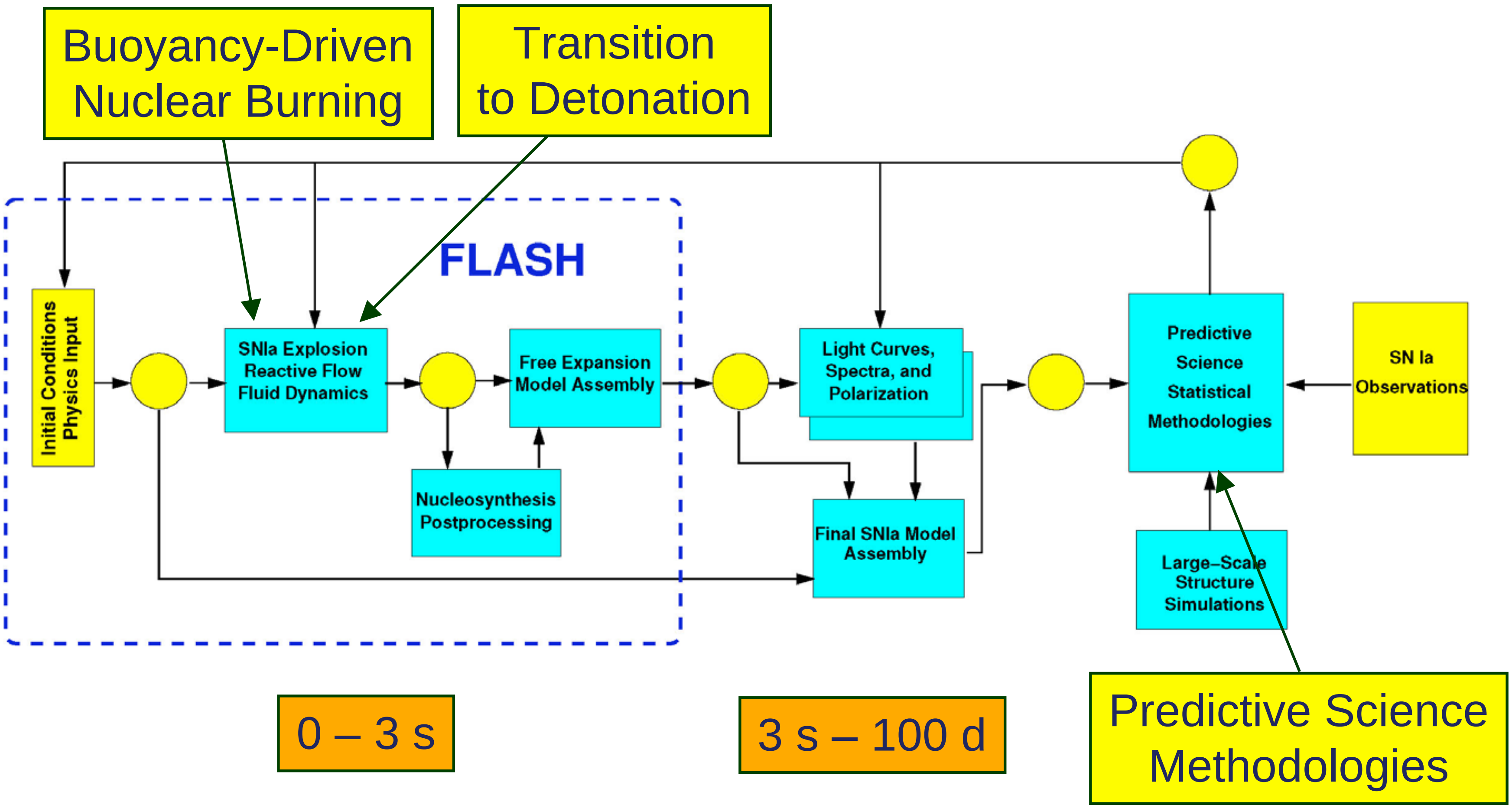
Light curves and spectra agree with observations



Comparison of spectra predicted by GCD model and obs. of Type Ia supernova SN 1994D

Kasen and Plewa (2006)

Type Ia Supernova Simulation Pipeline



Verification Study of Buoyancy--Driven Turbulent Nuclear Burning

- We will answer an important scientific question:
  - Does buoyancy-driven turbulent nuclear burning occur mostly at small or at large scales?
- Answering this question has the potential to produce a major paradigm shift in the Type Ia supernova field:
  - It will eliminate major uncertainties in the simulation of Type Ia supernovae, enabling more accurate simulations
  - It will increase the confidence in these simulations, motivating many more comparisons between simulations and observations
  - It will provide the foundation for a comprehensive, rigorous, and systematic validation of current Type Ia supernova models.
  - This has the potential to increase astronomers' ability to use these events as "standard candles" to determine the properties of dark energy

Argonne Leadership Computing Facility

- Existing Blue Gene/L Capabilities
  - BGL: 1024 nodes, 2048 cores, 5.7 TF speed, 512GB memory
  - Supports development + INCITE
- Readying for Spring'08 production
  - 111 TF Blue Gene/P system
  - Fast 0.8 PB file system
  - Initial 16 PB tape archive
  - Supports 20 INCITE projects
- Then for early 2009 production
  - 445 TF Blue Gene/P upgrade
  - 8 PB next generation file system
  - Supports even more challenging INCITE science projects

In 2004 DOE selected the ORNL, ANL and PNNL team based on a competitive peer review

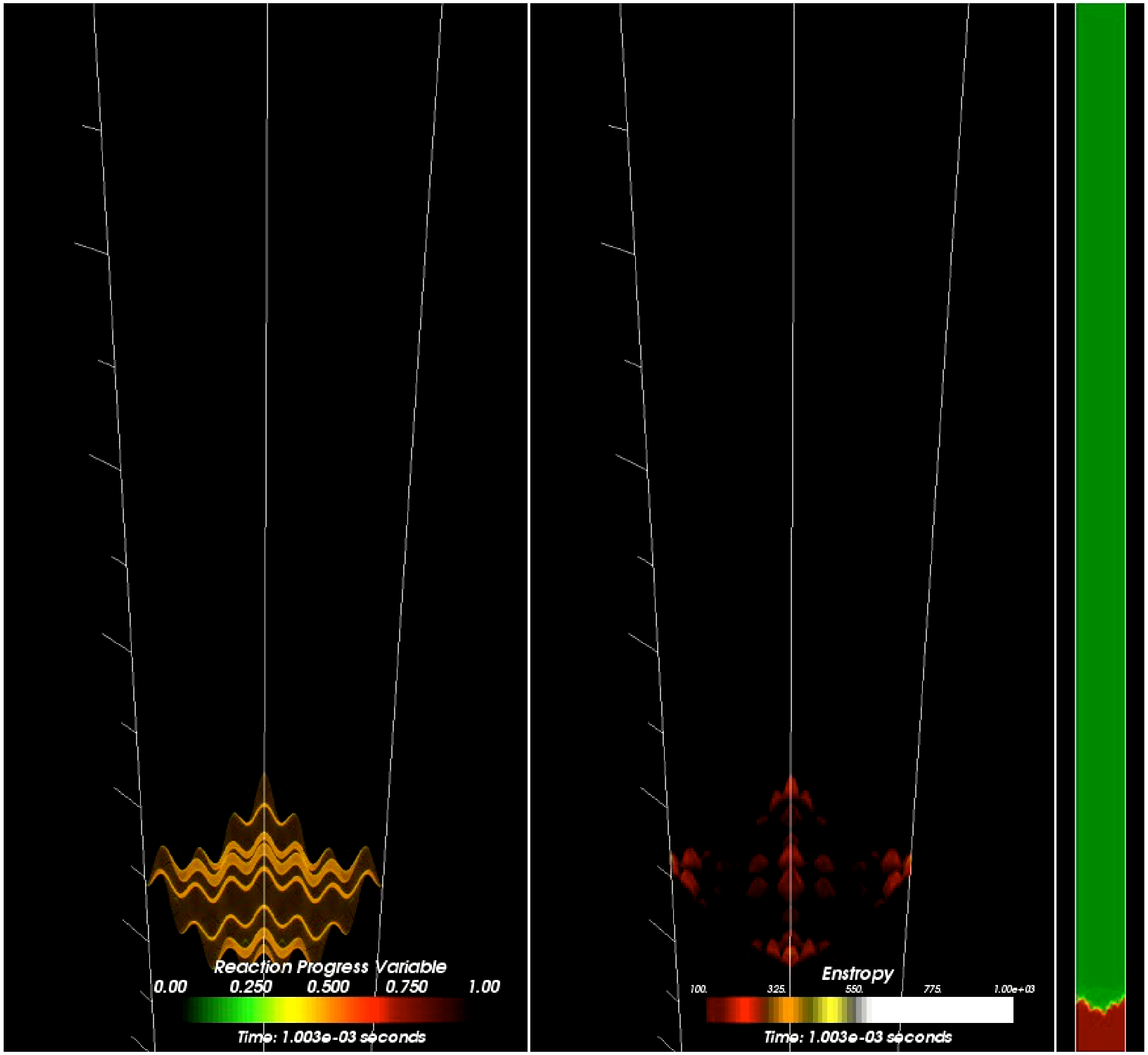
- ORNL to deploy a series of Cray X-series systems
- ANL to deploy a series of IBM Blue Gene systems
- PNNL to contribute software technology

556 TF Blue Gene/P System

FLASH Has Been Integral to Acceptance of ALCF BG/P

- FLASH properties
  - Is known to perform well and scale well on massively parallel machines
  - Exercises all aspects of the machine (hardware, system software, I/O)
  - As such, it helped shake out hardware and software issues
- FLASH is a core component of ALCF BG/P regression and validation tests
- FLASH simulations
  - **Science Tests** -- Type Ia supernova, turbulent nuclear flame
  - **AMR Test** -- Cellular
  - **Uniform Grid Test** -- Shock Cylinder
  - **Primary application-driven I/O test**

Simulation of Buoyancy-Driven Turbulent Nuclear Burning on IBM BG/P at ANL



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

Global Validation of Type Ia Supernovae

- Flash Center is collaborating with statistics group at LANL to develop statistical methodologies needed to validate large-scale simulations
- Flash Center is partnering with three world-class SN Ia observing teams:
  - Harvard-Smithsonian Center for Astrophysics supernova group led by Bob Kirshner
  - Carnegie Supernova Project led by Mark Phillips
  - SDSS Supernova Survey Project led by Josh Frieman
- These groups are focused on obtaining high-quality light curves and spectra of a large number of nearby SN Ia to explore the full range of SN Ia properties and to help to determine the explosion mechanism

Challenges in Getting to Petascale Type Ia Supernova Simulations

- Efficiency on multi-core chips -- FLASH achieves 1.9 x speed-up on BG/L at LLNL and 3.8 x speed-up on BG/P at ANL
- Scaling to 128K-1M cores -- FLASH scales well to 65K cores (BG/L at LLNL) and 128K cores (BG/P at ANL), but 1M cores?
- Memory -- astro memory needs are large but time to solution dominates
- I/O -- high bandwidth parallel I/O crucial
- Data transfer -- 200 Mbytes/cpu-hr generated
- Data storage -- many Petabytes, must be remote
- Scientific analysis pipeline -- must be remote
- Data archive -- Petabytes, must intelligently "compress" and "triage" data

Challenges in Getting to Petascale Type Ia Supernova Simulations

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- Data transfe...
- Data... be remote
- Scie... must be remote
- Data ...ytes, must intelligently "comp... triage" data

Astrophysical simulations are often "discovery science:" the phenomena are very complicated and highly non-linear; we therefore don't know all of the questions we want to ask before we see the data, so we must be able to explore it

Conclusions

- The Flash Center has conducted and is conducting extensive verification studies of physical processes in Type Ia supernovae
- The Center has carried out a series of high-resolution, 3-D, whole star simulations of Type Ia supernovae
- These simulations were made possible by a decade of support for development of the FLASH code and of computational resources provided by the NNSA ASC Academic Strategic Alliance Program
- Significant computational resources were also provided by the Office of Science INCITE program
- They led to the discovery of the “gravitationally confined detonation” (GCD) model of Type Ia supernovae -- the only model so far that detonates without the detonation being put in by hand
- While almost surely not the final story, the GCD model reproduces many key observed properties of Type Ia supernovae and is therefore promising
- Petascale simulations will enable us to understand key physical processes and conduct rigorous, systematic global validation of Type Ia supernova models, but getting there will be challenging!