Supernova physics:

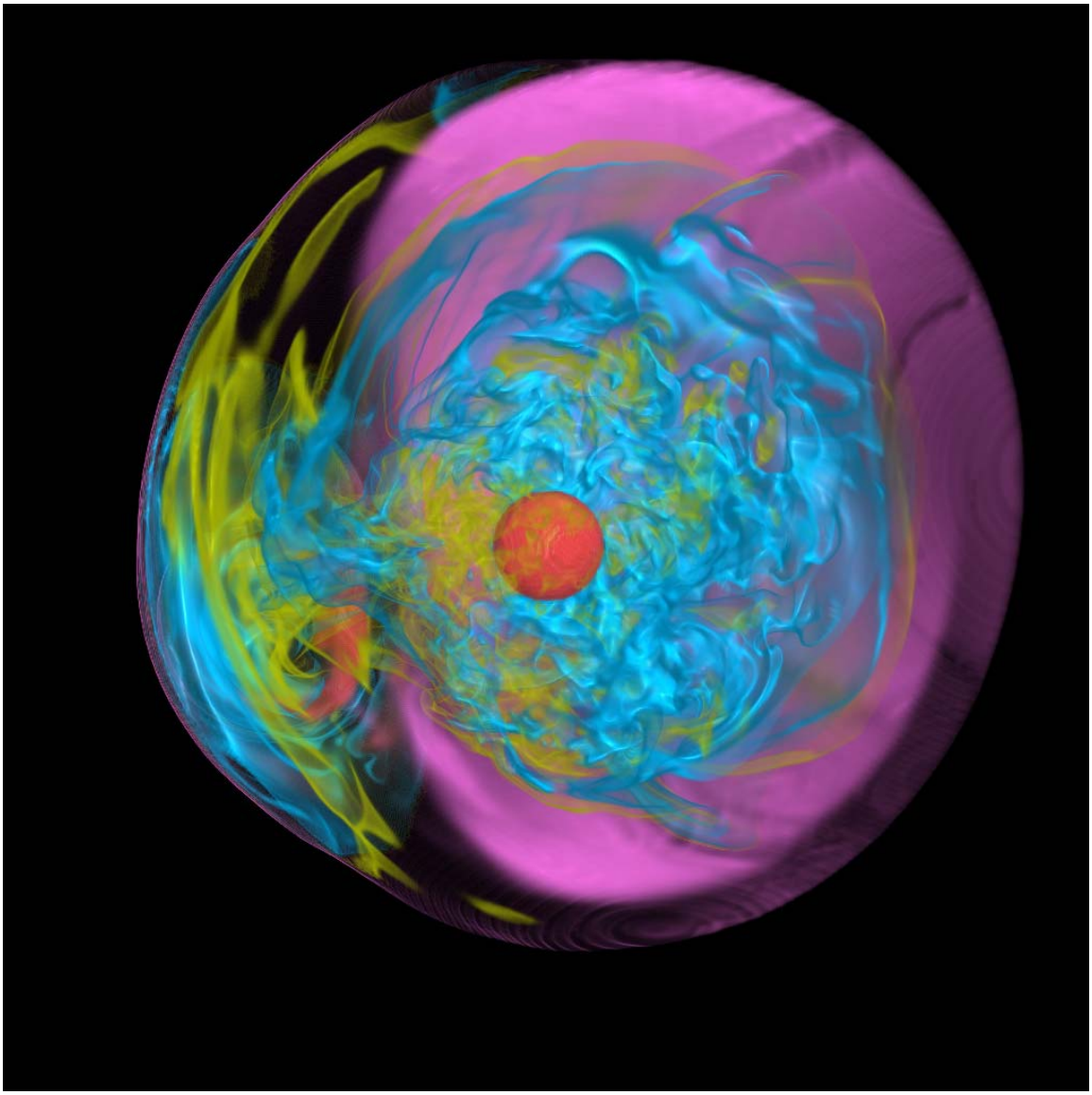
NERSC resources have been brought to bear on two of the most significant problems in computational astrophysics: (1) understanding core collapse supernova explosions and the production of many of the elements in the Universe and (2) understanding thermonuclear supernovae and their use as standard candles in illuminating the evolution of the Universe and its ultimate fate.

Core Collapse Supernovae:
Explosions of massive stars (stars more massive than ten of our suns), known as core collapse supernovae, are arguably the most important link in our chain of origins from the Big Bang to the formation and evolution of life on Earth. They are the dominant source of most elements in the Periodic Table between oxygen and iron, and are believed to be responsible for producing half of all elements heavier than iron. These explosions also serve as cosmic laboratories for nuclear and particle physics at extremes that may be inaccessible in terrestrial experiment. Observations of supernova neutrinos (nearly massless, radiation-like particles), gravitational waves (ripples in space predicted by Einstein's theory of gravity), and photons across the electromagnetic spectrum, in conjunction with realistic three-dimensional models, will make the latter possible.

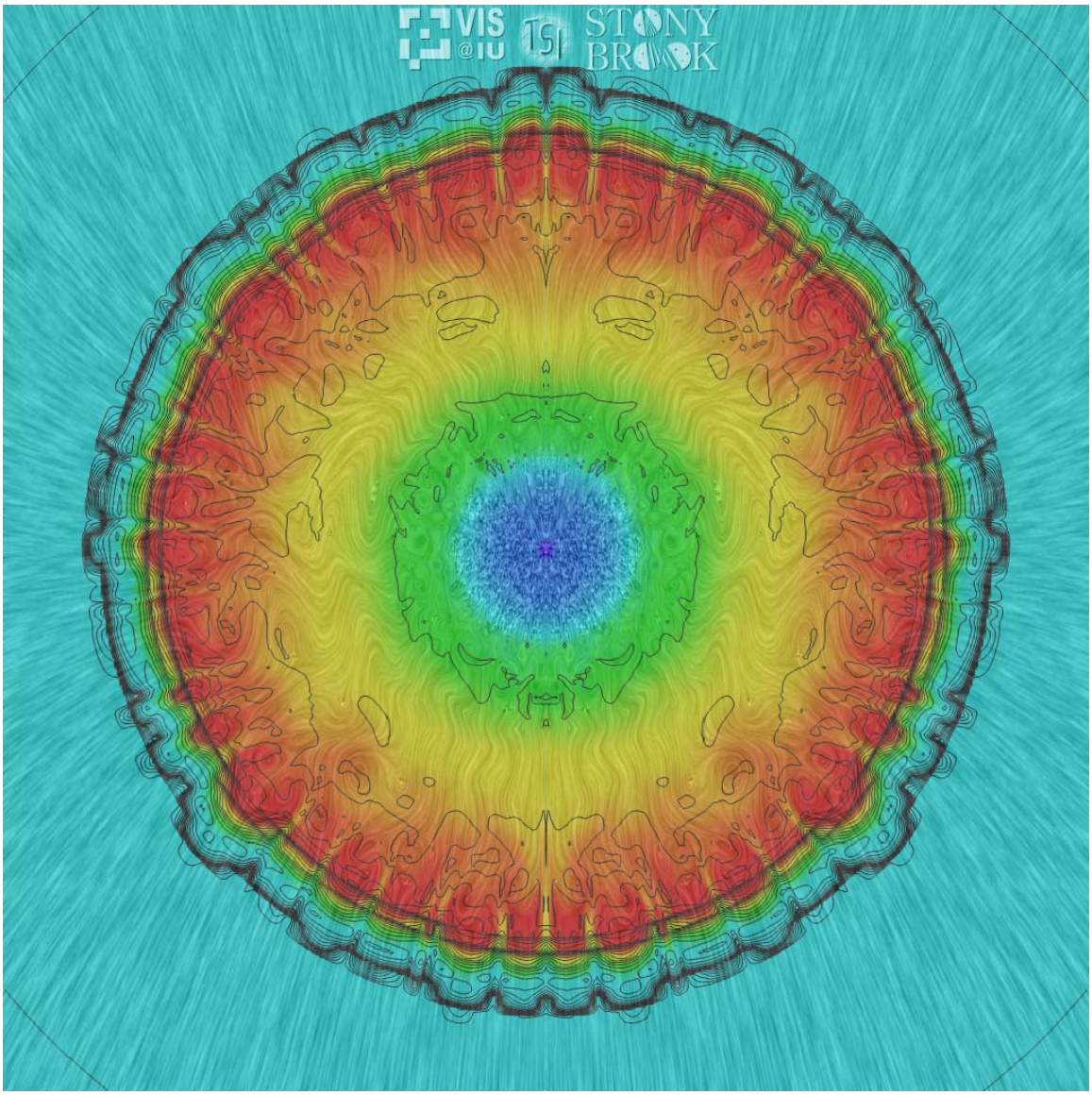
The principal goals of the core collapse supernova research are (a) to understand the mechanism(s) responsible for the explosions of massive stars, (b) to understand all of the phenomena associated with these stellar explosions, such as their contribution to the synthesis of the elements, their emission of neutrinos, gravitational waves, and, in some cases, intense bursts of gamma radiation, (c) to provide the theoretical foundations supporting the scientific mission of the Office of Science's existing and proposed premier experimental facilities, such as the Relativistic Heavy Ion Collider (RHIC), the Rare Isotope Accelerator (RIA), and the Deep Underground Science and Engineering Laboratory (DUSEL), whose scientific missions are in part defined by supernova science, (d) to develop the methods to simulate three-dimensional, multiangle, multifrequency, precision radiation transport on TeraScale to PetaScale computers, (e) to develop the theory and methods to predict using TeraScale computers the physical states of the complex nuclei found in stars that participate in supernova explosions, and (f) to serve as a testbed for the development of enabling technologies such as data management and analysis, networking, and visualization, of relevance to many applications.

As their name suggests, core collapse supernovae result from stellar core collapse and the formation of a shock wave that is ultimately responsible for the explosion. They are radiation- (neutrino-) driven, and perhaps also magnetically-driven, turbulent events. One-, two-, and three-dimensional simulations that include different physics components [neutrino transport, turbulent fluid flow, rotation, magnetic fields, gravity, weak (neutrino) interactions, equations of state (thermodynamic state of the stellar core)] must be performed systematically in order to understand the role of each physics component in the explosion. NERSC resources have therefore been used to perform a variety of simulations. These include three-dimensional simulations focusing on the hydrodynamics of the stellar core during the explosion and the development of a newly discovered shock

wave instability [by John Blondin (NCSU) and Tony Mezzacappa (ORNL)], and the first realistic two-dimensional supernova simulations, which include realistic two-dimensional multi-frequency flux-limited diffusion neutrino transport [by Doug Swesty (SUNYSB) and Eric Myra (SUNYSB)]. The latter are currently exploring the interaction of the neutrino radiation and stellar core fluid flow with an eye toward the development of fluid instabilities and turbulence and their impact on the explosion and will continue in order to explore whether or not a supernova explosion can be powered by neutrinos and turbulent fluid flow alone (i.e., *sans* rotation and magnetic fields). NERSC resources will also be used to perform the first contemporary simulations to include realistic neutrino transport, rotation, and magnetic fields, with an eye toward understanding the role of magnetic fields in the explosion mechanism [by John Hayes (UCSD), Steve Bruenn (FAU), and Tony Mezzacappa (ORNL)]. At the moment, the supernova community has very little guidance from detailed computational models on this issue.



Visualization of the supernova shock wave instability by K.-L. Ma (UCD) based on a three-dimensional simulation performed by J.M. Blondin (NCSU) under the SciDAC-sponsored TeraScale Supernova Initiative led by A. Mezzacappa (ORNL).



Visualization by E. Bachta (IU) and P. Baker (IU)
of the development of turbulence in the stellar core and
isocontours of neutrino "optical-depth" in a two-dimensional
supernova simulation performed by F.D. Swesty (SUNYSB) and E. Myra (SUNYSB)
as part of the SciDAC-sponsored TeraScale Supernova Initiative.

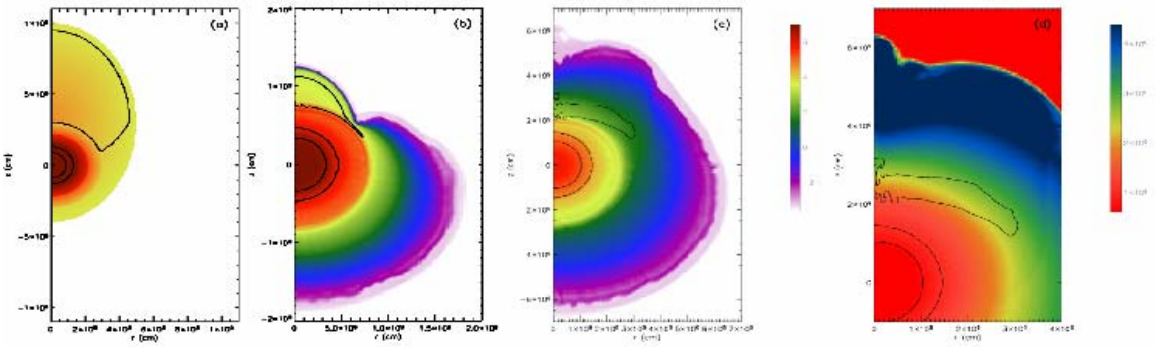
Thermonuclear Supernovae:
Unlike their core collapse cousins, thermonuclear supernovae signal the death of a star not much larger than our sun. The star, most likely a degenerate carbon-oxygen white dwarf, is in a binary system and has been accreting matter from a nearby companion and growing in mass for several million years. The star can entirely support itself by electron degeneracy pressure up to the Chandrasekhar mass (about 1.4 times the mass of our sun). Within one percent of this mass a unique conspiracy in nuclear physics occurs such that the density and temperature at the center reach the point where the carbon ignites in a

runaway thermonuclear explosion. The entire star is destroyed in this explosion with material reaching velocities greater than a tenth of the speed of light. Over one third of the star is burned to radioactive nickel, which then decays to cobalt and the cobalt to iron. The energy released from this chain of radioactive decay powers the optical light from the supernova for several months. At its peak the supernova can be as bright as the light from all the rest of the stars in galaxy where it was born.

Due to the fact that these supernovae, known as Type Ia supernovae, explode in a very similar manner every time it is not so surprising that their peak brightnesses are very similar. Over the past decade astronomers have been exploiting this fact and a correlation between the shape of the optical lightcurve and the peak brightness to measure distances to better than 10% to these objects. Since Type Ia supernovae are so bright they can be seen across most of the observable universe. Thus distances to them along with their redshifts can be used to measure the expansion history of the universe and constrain the cosmological parameters.

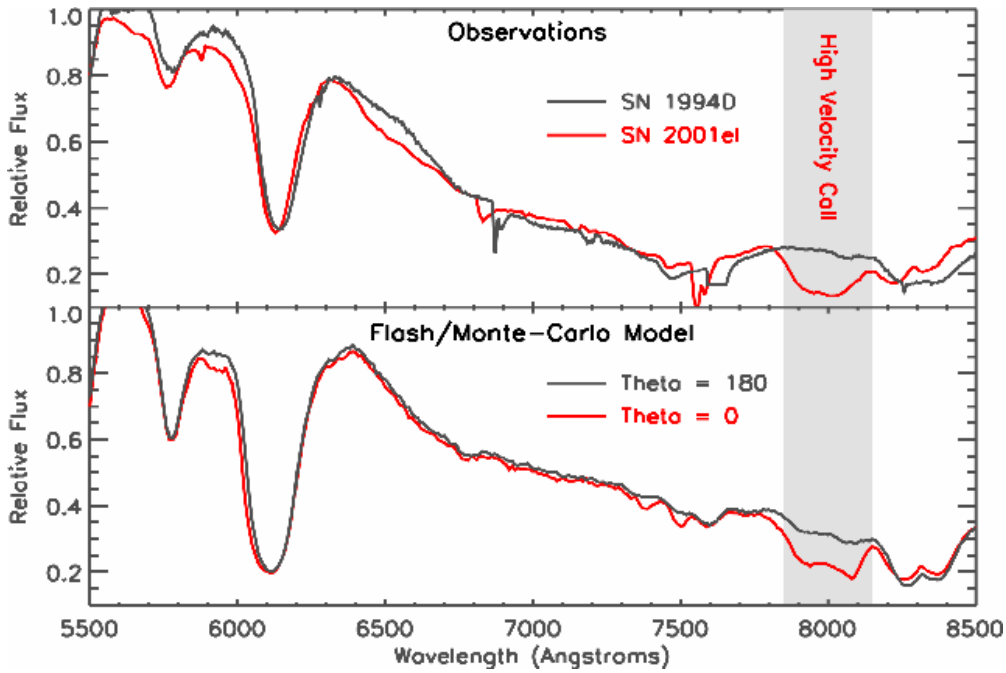
For the past several years at NERSC we have been modeling the spectra of supernovae of all types. The goal of this work is to better understand the physics of supernovae and, for the Type Ia's, to improve their utility as cosmological tools. Spectrum synthesis is one of the only ways to validate or falsify detailed hydrodynamic models of the explosion event. This past year we have concentrated on the 3-D spectrum synthesis of Type Ia supernovae in order to probe the explosion mechanism behind these objects. Unlike core collapse supernovae, the progenitors of these supernovae have never been observed. Thus this modeling may be the only way to gain insight on how Type Ia supernovae explode.

In Kasen & Plewa (2005) they have considered some of the spectral and polarimetric signatures of the gravitational confined detonation scenario for Type Ia supernova explosions. In that model, material produced by an off-center deflagration forms a metal-rich atmosphere above the white dwarf surface. Using hydrodynamical simulations, they show that this atmosphere is compressed and accelerated during the subsequent interaction with the supernova ejecta, eventually leading to the formation of a high-velocity pancake of metal-rich material that is geometrically detached from the bulk of the ejecta. When observed at the epochs near maximum light, this absorbing pancake produces a highly blueshifted and polarized calcium IR triplet absorption feature similar to that observed in several Type Ia supernovae (see Figure 1).



(1) Hydrodynamical simulation of the model supernova ejecta interacting with the extended atmosphere. Panels (a)-(c) show the density in log scale; panel (d) depicts the magnitude of the velocity. The density scale is shown by the colorbar in panel (c) while the velocity scale is shown by the colorbar in panel (d). The black contour line corresponds to a calcium number abundance of 0.01. (a) Density distribution at the beginning of the simulation (t=0 s). (b) Density distribution at t=0.3 s. Notice the remarkable deformation of the calcium-rich material in the upper part of the computational domain. (c) Density distribution at the final time (t=1.24 s). Notice that the calcium-rich region has been strongly compressed into a pancake-like structure. (d): Velocity magnitude at the final time. The calcium-rich absorber is seen moving at velocity ~21,000 km/s with a substantial velocity gradient across the structure.

The synthetic spectrum of the above model at a time when the supernova is near maximum light has been obtained after homologously expanding the ejecta to 20~days (see Figure 2). Given the enhanced abundance of intermediate mass elements and relatively low temperature, the pancake is opaque in the Ca II IR triplet lines. For a viewing angle in which the observer looks directly down upon the pancake (θ=0), the pancake obscures the supernova photosphere, creating a broad and highly blueshifted high-velocity (HV) calcium absorption feature near 8000 angstroms. The HV feature seen in the model compares well to that observed in SN~2001el. For larger viewing angles, the pancake obscures less (or none) of the photosphere, and the HV feature is weaker or absent in the model spectrum. This orientation effect may explain why in some supernovae, such as SN~1994D, a HV calcium feature at maximum light is seen only weakly or not at all. As this hydrodynamical model is the first one which naturally goes from a deflagration to a detonation, which many believe is a key aspect for a successful Type Ia explosion, observations which constrain the geometry of a Type Ia supernovae may be the critical for understanding why the explode and how far they can be pushed as cosmological probes.



(2) Comparison of the synthetic model spectra to Type Ia supernova observations. Top panel: Spectral observations of two Type Ia SNe near maximum light; SN 2001el (red line) shows a strong HV calcium absorption at 8000 Angstroms while SN 1994D (black line) does not. Bottom panel: Synthetic model spectra at 20 days. A HV calcium absorption is clearly seen when looking straight down on the calcium-rich pancake (θ=0, red line), whereas none is seen from the opposite side (θ=180, black line).

TeraScale supernova simulations require a TeraScale applied mathematics and computer science infrastructure, including (a) solvers for TeraScale algebraic equations at the heart of the solution of the neutrino transport equations, (b) parallel I/O scalable to thousands of processors, (c) workflow management and automation, (d) visualization of TeraBytes of data, and (e) networking at hundreds of Mbps to Gbps to enable the research of a nationally distributed scientific team. The demands will escalate rapidly over the next few years. Three-dimensional supernova simulations with realistic three-dimensional multifrequency, multiangle neutrino transport will require sustained computational speeds in excess of one hundred TeraFlops. Moreover, these simulations will require platforms with significant memory bandwidth, memory per processor, and speed in processing global communications. In addition, they will generate hundreds of TeraBytes of data per simulation, over a period of months, pushing the data management (e.g., parallel I/O) and analysis, networking, and visualization requirements yet another order of magnitude further.