Simulations of Detonating White Dwarfs

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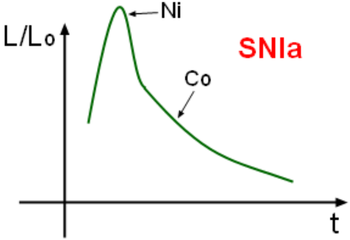
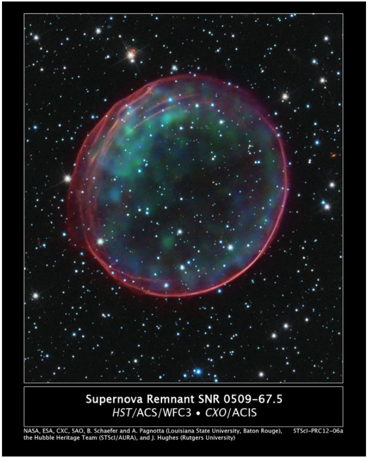
CScADS workshop on data-intensive science
July 30, 2012

Type 1a supernova

= nuclear reaction powered explosion of a white dwarf star
(which is the remnant of a star that has completed its normal life cycle, likely consisting of carbon and oxygen in a degenerate state)

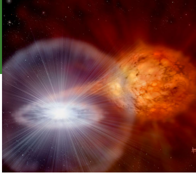


light from decay $^{56}\mathrm{Ni} \rightarrow ^{56}\mathrm{Co} \rightarrow ^{56}\mathrm{Fe}$



expanding blast wave

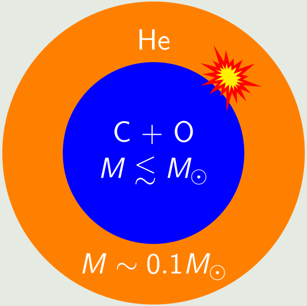
SN 1a formation channels



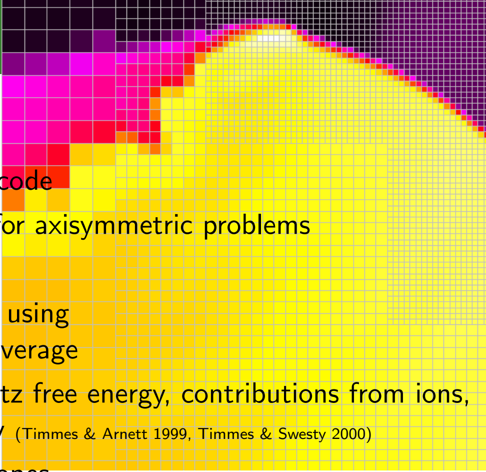
involving a binary companion and accretion:

- Traditional: companion spills material onto white dwarf until $M \approx M_{\text{Chandrasekhar}} = 1.4 M_{\odot}$, increase in central T and ρ $\Rightarrow$ convection $\Rightarrow$ thermonuclear runaway (deflagration $\rightsquigarrow$ detonation)
- Merger of two CO white dwarfs

- Sub-M_{Ch} models: helium shell accumulated through slow accretion ($\sim 10^{-8} M_{\odot}\,\text{yr}^{-1}$), $M_{\text{total}} < M_{\text{Ch}}$, detonation in He triggers detonation of the core
  - directly: detonation transcends the core/shell interface
  - indirectly: through focussing or collision of compressional waves



Numerical methods

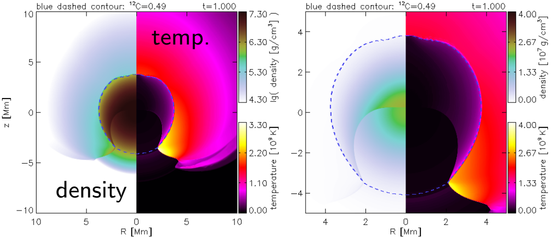


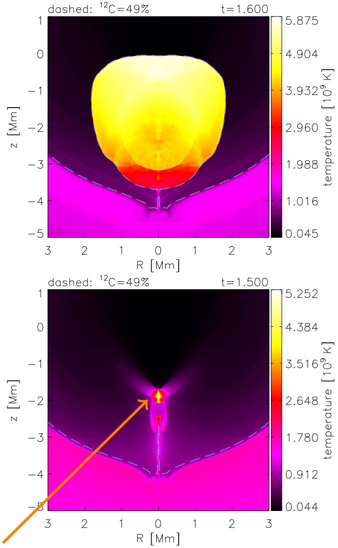
CASTRO

- multi-D Eulerian hydrodynamics code
- 3D Cartesian and 2D cylindrical for axisymmetric problems
- adaptive mesh refinement
- gravity: monopole approximation using (time-dependent) radial density average
- stellar EoS based on the Helmholtz free energy, contributions from ions, radiation and electron degeneracy (Timmes & Arnett 1999, Timmes & Swesty 2000)
- nuclear reaction network: 19 isotopes
- initial models from KEPLER
    - 1D implicit Lagrangian hydrodynamics code for stellar evolution
    - C+O white dwarf merging with a helium main sequence star, helium accretion rates $\sim 10^{-8} M_\odot\ \mathrm{yr}^{-1}$ (Woosley & Weaver 1994, Woosley & Kasen 2011)
    - convection: mixing length model

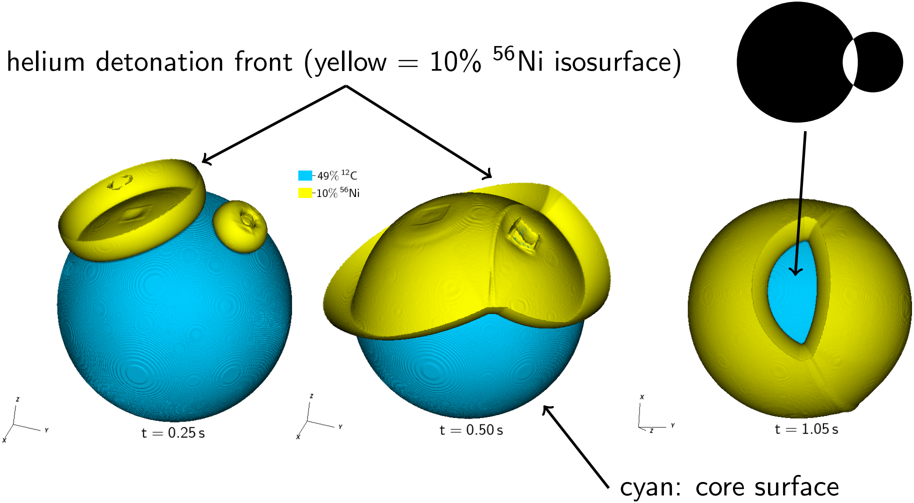
Sliding helium detonation with one detonator

^{4}He detonation is set off at the "north pole", wraps around the star and converges at the "south pole":





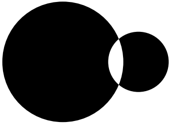
converging compressional wave: $T_9 = 5.25$, $\rho_7 = 6.21$ $\Longrightarrow$ core detonation

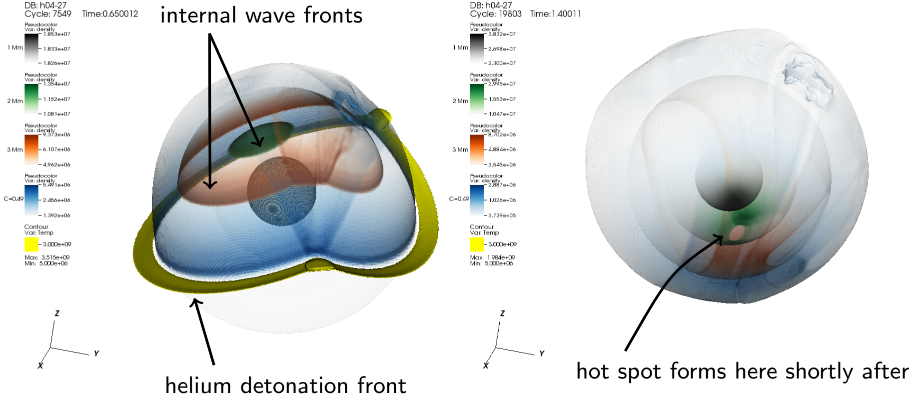


Shape of converging front depends on size: smaller ⇒ more elongated; i.e., it converges along a line rather than a point

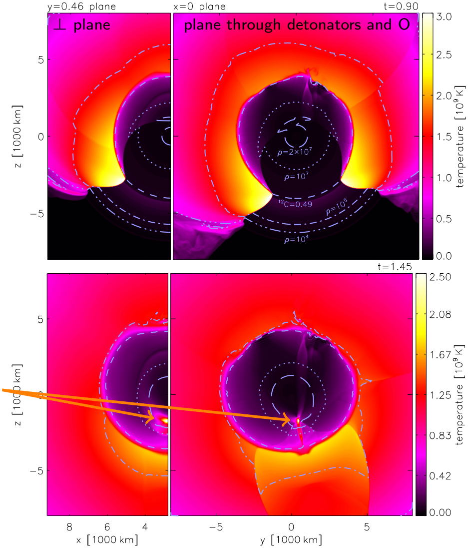
Two detonators (separation 54°, delay 0.15 s)

The same shape is present when
the wave fronts in the core converge:

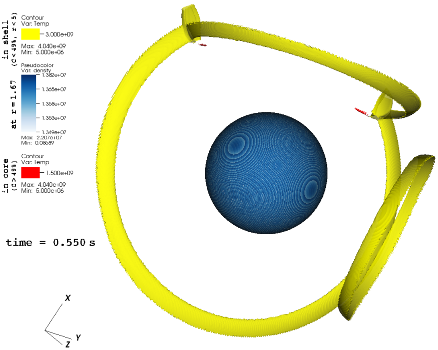




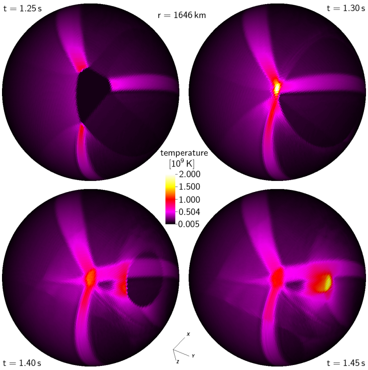
Two detonators (separation 54°, delay 0.15 s)



hot spot:
$T_9 = 3.67$, $\rho_7 = 9.51$
⇒ easily sufficient for detonation



detonation front (yellow) and density on a sphere through the hot spot

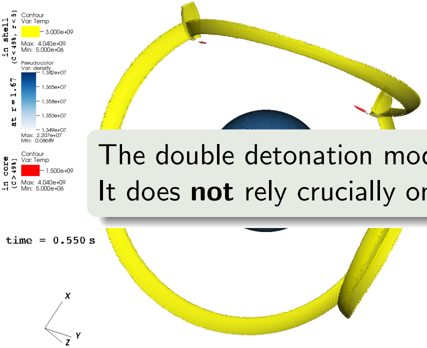


temperature on a sphere through the hot spot

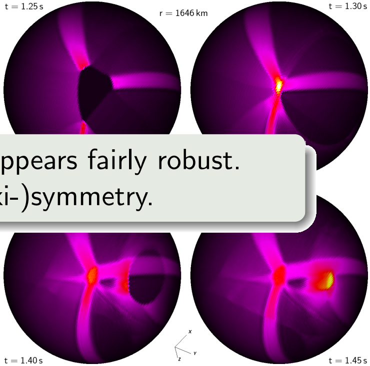
primary hot spot: $T_9 = 5.27$, $\rho_7 = 2.19$

wave induced by first detonator converging with itself 0.15 s later: $T_9 = 1.71$, $\rho_7 = 3.82$

Three asynchronous detonators (90°, 100° and 120°)



detonation front (yellow) and density on a sphere through the hot spot



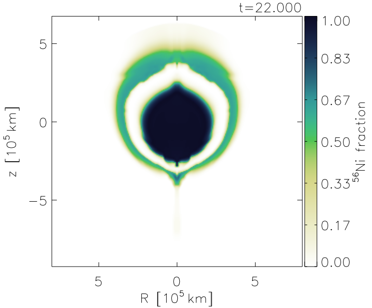
temperature on a sphere through the hot spot

The double detonation model appears fairly robust.
It does **not** rely crucially on (axi-)symmetry.

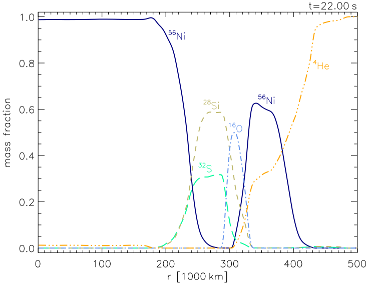
primary hot spot: $T_9 = 5.27$, $\rho_7 = 2.19$

wave induced by first detonator converging with itself 0.15 s later:
$T_9 = 1.71$, $\rho_7 = 3.82$

Complete detonations and yields



^{56}Ni mass fraction after complete core detonation



elements with mass fractions > 10% along the equatorial plane

- $(1.001 + 0.078)M_\odot$ dwarf: $0.52 M_\odot$ of ^{56}Ni, 90% produced in core
- $(0.801 + 0.143)M_\odot$ dwarf: $0.38 M_\odot$ of ^{56}Ni, 80% produced in core

Computational cost and data

- Largest 3D run: $640 \times 640 \times 640$ zones, full snapshot: 64 GB, appr. 59 hours on 8000 MPI cores = 472 000 core hours
- Other hi-res 3D runs produced 16 GB or 32 GB per full snapshot (depending on symmetries), 2000 or 4000 cores for ∼1–2 days
- Many 2D runs, producing data on the order of hundreds of MB per snapshot, running on ∼128 cores

Big jobs at NERSC (Oakland, CA) and ORNL (Oak Ridge, TN).
Small jobs at local (UC Santa Cruz) Linux cluster (total 828 cores).

Challenges:

- Data analysis (IDL): limited memory requires careful handling of data
- Visualization (VisIt): tedious, sluggish, difficult – lots of tinkering necessary to find good settings, fighting with the visualization eats a lot of time!