Surface Detonations in Type Ia Supernova Explosions?

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Astrophysical Scenario

Type Ia supernova explosions are one of the brightest astrophysical events and have been applied in cosmology to geometrically survey the universe. Despite their importance, a consistent picture of the explosion mechanism is still lacking. Commonly, these supernovae are associated with the thermonuclear explosion of earth-sized white dwarf (WD) stars – the final stages of the evolution of small and intermediate-mass stars. These very dense objects consist of carbon and oxygen and their properties are governed by a degenerate electron gas. In a binary system, the WD can gain mass from its companion by accretion. However, there exists a fundamental limit, the Chandrasekhar mass, beyond which it gets unstable against gravitational collapse. Before reaching this stage, the density at the center of the WD increases to values at which nuclear reactions from carbon to heavier elements ignite. This gives rise to a stage of convective carbon burning at the end of which a thermonuclear runaway forms a flame. The exact way of flame ignition is not well determined yet, but numerical studies (supported by SciDAC) suggest that the ignition process may proceed on only one side of the star's center in a few patches. The effects of this scenario on the explosion process are investigated in the present study.
After ignition, the flame burns subsonically as a deflagration. It is subject to buoyancy and shear instabilities and generates strong turbulence. The interaction of the flame with turbulence is a key feature in the model and accelerates the flame. It has been speculated that the flame propagation undergoes a transition to a supersonic detonation in late stages. This possibility is studied in the scenario under consideration.

Numerical Model

- Hydrodynamics: *Piecewise Parabolic Method* (PPM) in Prometheus implementation
- Equation of state: degenerate White Dwarf matter
- Flame description: *level set approach*
- Turbulent flame propagation speed: determined from *sub-grid scale model*
- Nuclear burning: simplified description including only 5 species

→ *Self-consistent model of flame propagation*

Computation

The code is efficiently parallelized on the basis of domain decomposition in an MPI implementation. It has been run on several supercomputers and proved good scaling behavior.
Numerical simulations were performed both in two- and three-dimensional setups. The 3D runs on a 512^3 cells computational grid require about 20,000 CPU hours on the NCCS Jaguar Cray XT3 supercomputer. Simulations of this size were performed on 256 processors. All 3D runs were carried out at NCCS at Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

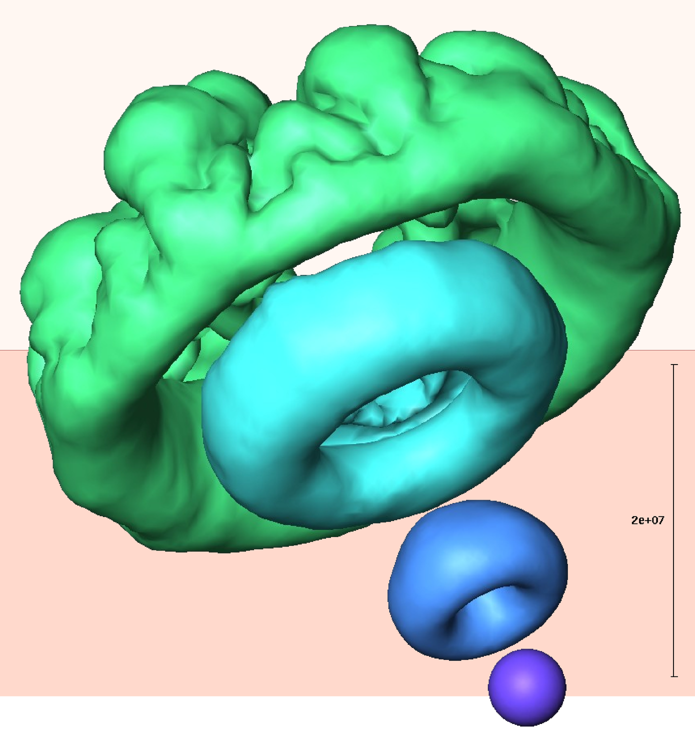
Numerical simulations

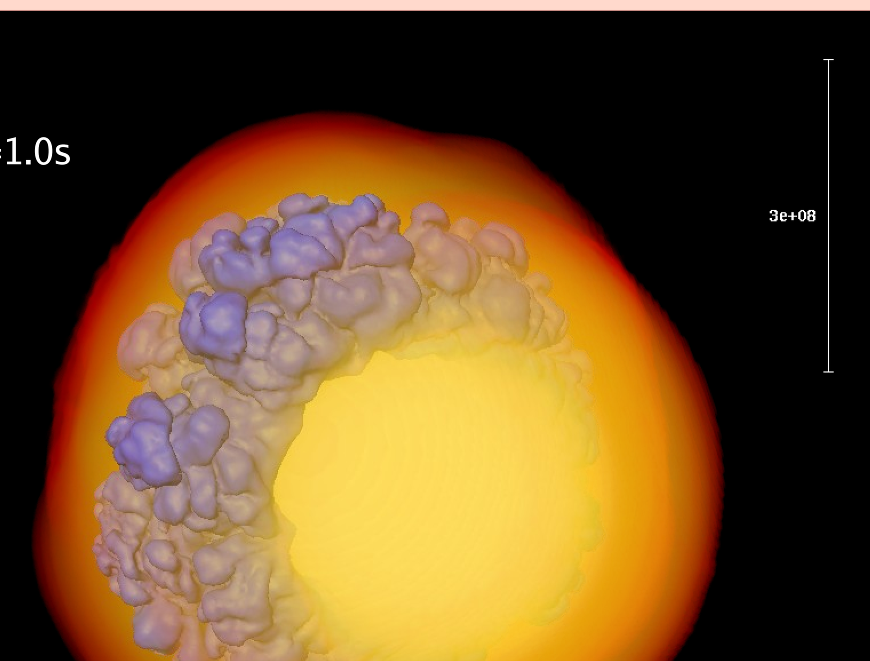
Exploring the parameter space

In our model, the flame is artificially ignited. Several numerical experiments with asymmetric ignitions have been performed.
Considered initial flame configurations:

- Single spherical bubble at different radii off-center
- Bubble-substructure/perturbations from perfect sphericity
- Teardrop shape – one and two-sided

In the example below, the deflagration started in a single spherical initial flame bubble ignited at 200 km off-center. This bubble is filled with hot ashes of lower density than the fuel and therefore is subject to buoyancy. Due to burning (subsonic turbulent flame propagation) and buoyant rise, the flame shape evolves from a sphere to a torus in the first tenths of a second. While ascending towards the surface, the torus becomes distorted by growing features that eventually connect.

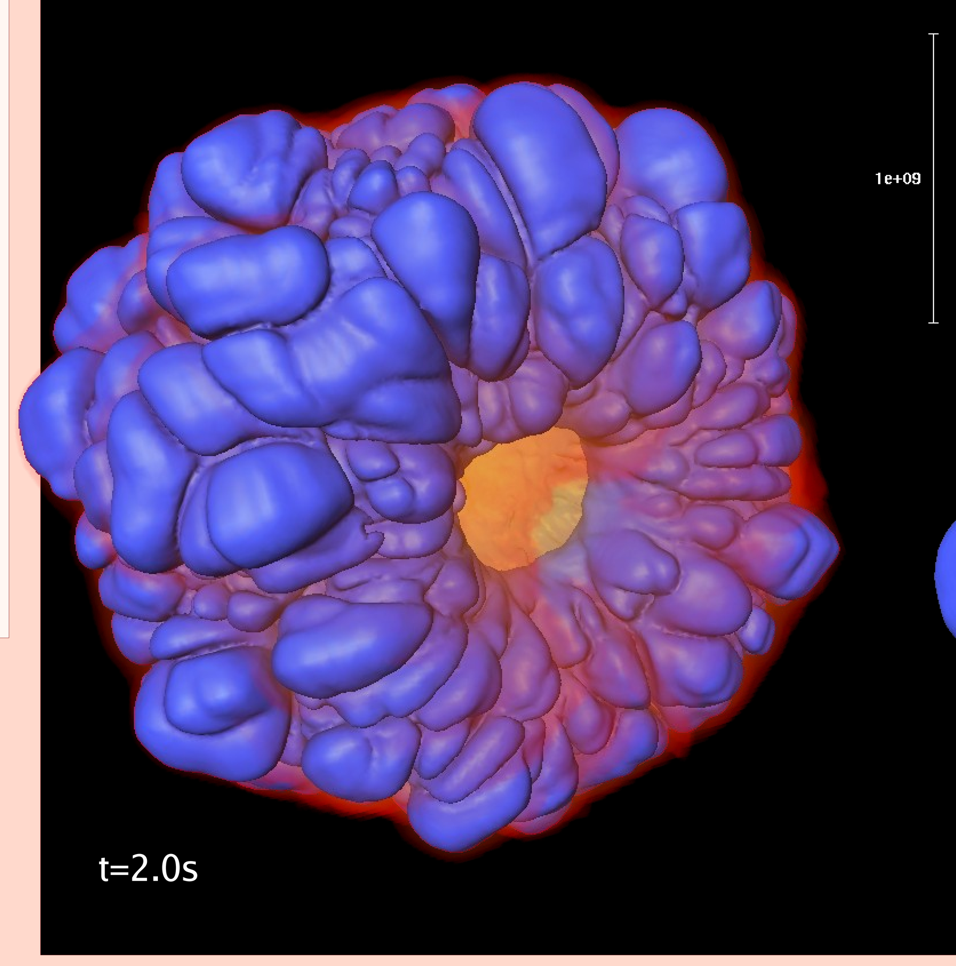


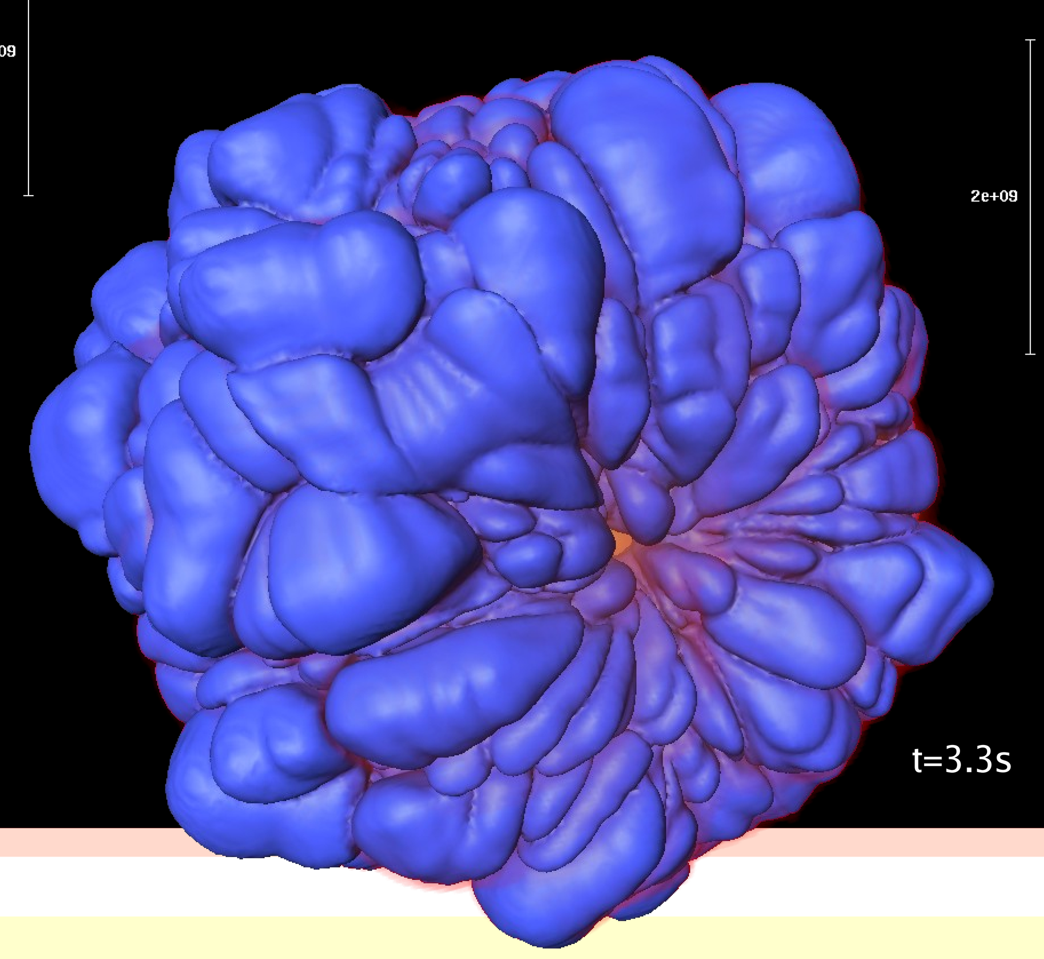


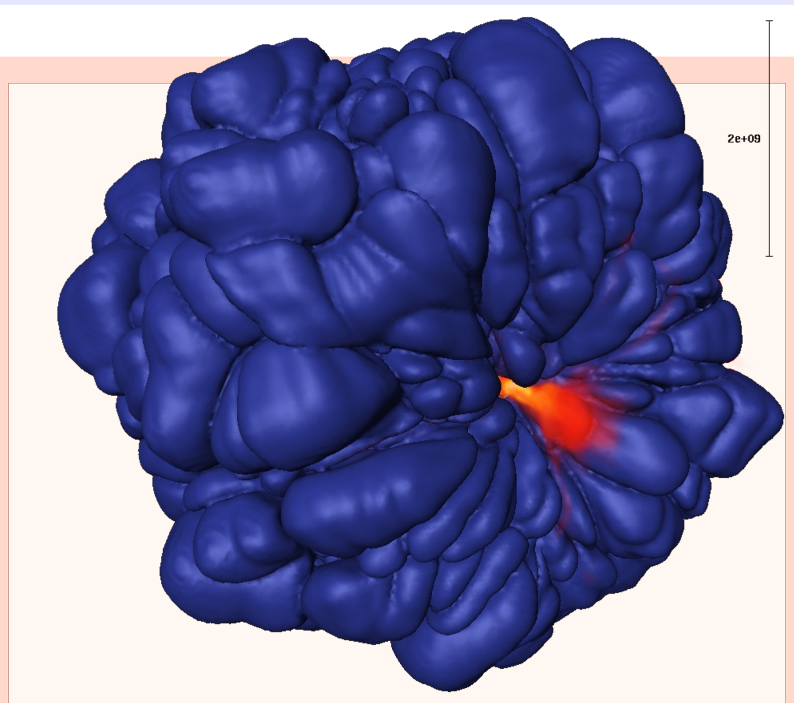
Model evolution

Once the bubble of ash has reached the outer layers of the star, it starts to sweep around the core. Since the energy release in this first stage is too small to explode the star, the material is still gravitationally bound. Finally, it collides on the diametrally opposed side of the star.

The isosurfaces in the images correspond to the zero-level set of a scalar filed G and are associated with the flame in early stages and with the approximate boundary between fuel and ash later on. Volume-rendered is the logarithm of the density indicating the extend of the white dwarf star.







Collision of the surface material

In the collision region, the temperature and the density of unburnt material increase due to compression. In the Figure above, the volume rendering indicates the temperature. It has been suggested, that the increase in density and temperature in the collision region initiate a detonation wave that would then supersonically propagate inwards burning the core of the star and leading to an explosion ("Gravitationally Confined Detonation", Plewa et al., 2004). For this, certain conditions must be met in the collision region.

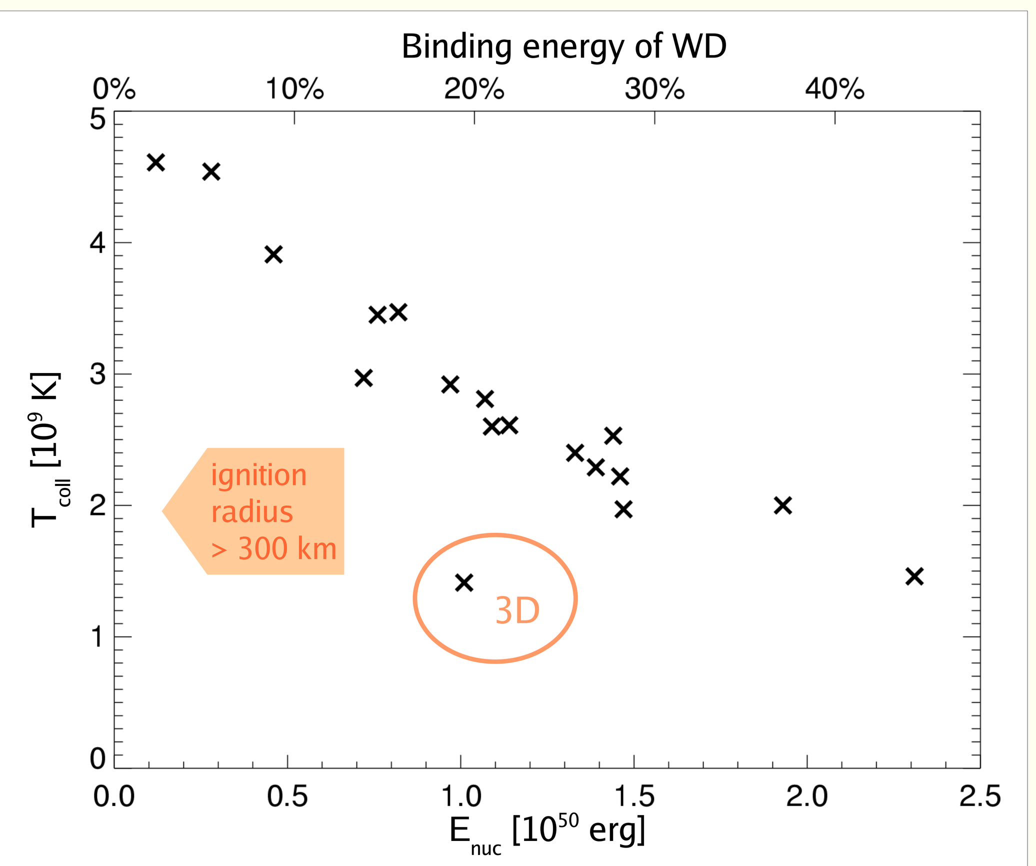
The survey comprises **about 20 2D simulations and 5 3D simulations**

In these, the initial flame shape, the displacement of the ignition region form the WD's center, and the numerical resolution were varied.

Collimation of the collision

An initiation of a detonation wave in the collision region depends on the *temperature reached*, the *density*, and the *spatial extend* of the collision region.

For 2D simulations a clear inverse correlation between nuclear energy release prior to collision and the maximum temperature reached is found. This correlation arises naturally from the expansion of the star due to the energy release. The more material is burnt in the flame on its way to the surface, the more the star expands and the weaker is the collision. The energy release depends on the displacement of the initial flame from the center. Initiating the flame at larger radii leads to less burning and thus to stronger collisions of the surface material.



The collision strength is very sensitive to perturbations of the initial flame from perfect sphericity, either directly by imposing more complex initial configurations (teardrop-like shapes,multiple initial flame kernels) or by different numerical resolution and resulting discretization errors.

3D simulations generally released more energy in burning and therefore the collisions here were significantly weaker. In some cases, the star got unbound. For the only 3D simulation, that falls into the energy region plotted, the maximum temperature reached in the collision was substantially lower than for 2D models with similar energy release.

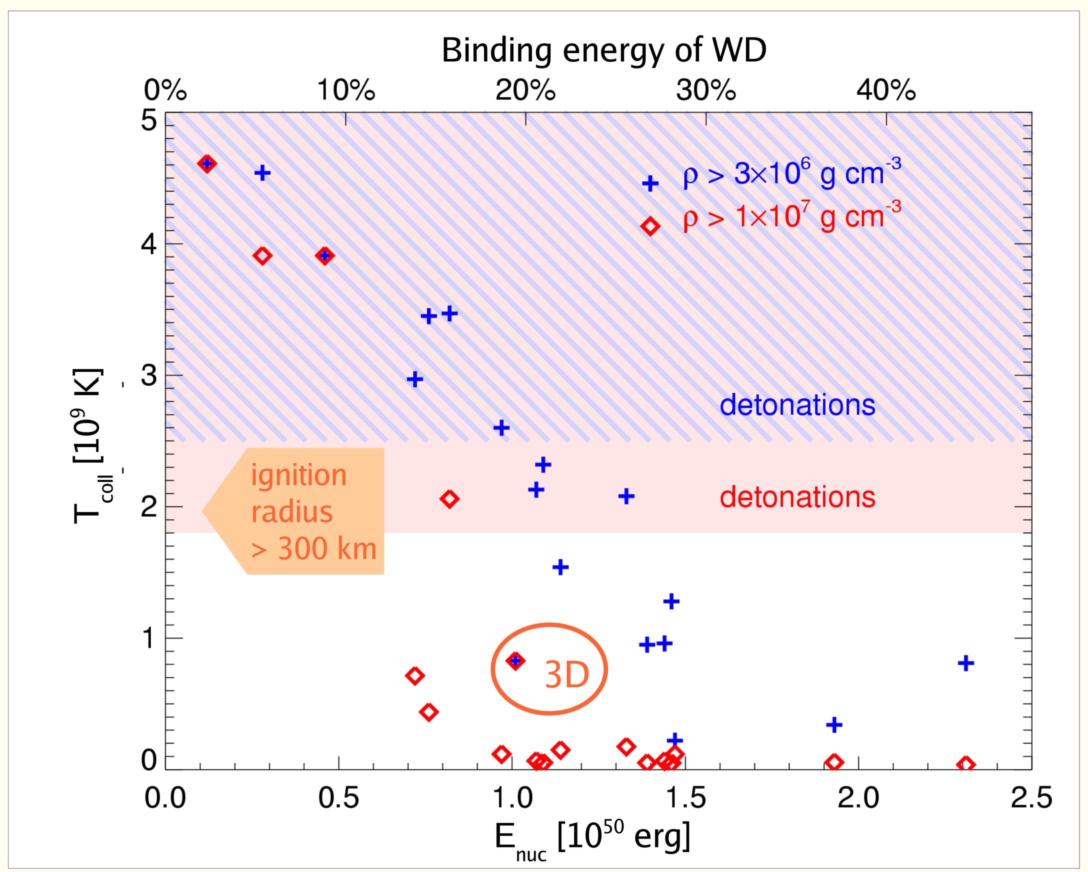
Surface Detonations?

For triggering a detonation a collimation temperature larger than 2×10^9 K is necessary. However, this threshold temperature needs to be reached for densities higher than ~$3...10\times10^6$ g/cm^3. Therefore, the maximum temperature in the collision region at a density exceeding these values was measured.

From this measurement, we find that a detonation initiation is only possible in 2D models starting with a spherical initial flame placed at unrealistically large radii (≥ 200 km) off-center of the WD star.

Due to the weaker collisions, a detonation is less likely when considering full 3D models.

For models that remain gravitationally bound, failures to initiate a detonation will lead to pulsations of the WD star. This may be a second chance for triggering a detonation ("pulsational delayed detonation scenario") and will be addressed in a follow-up study.



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