Remnants of Triple and Quadruple Detonations in Binary White Dwarfs

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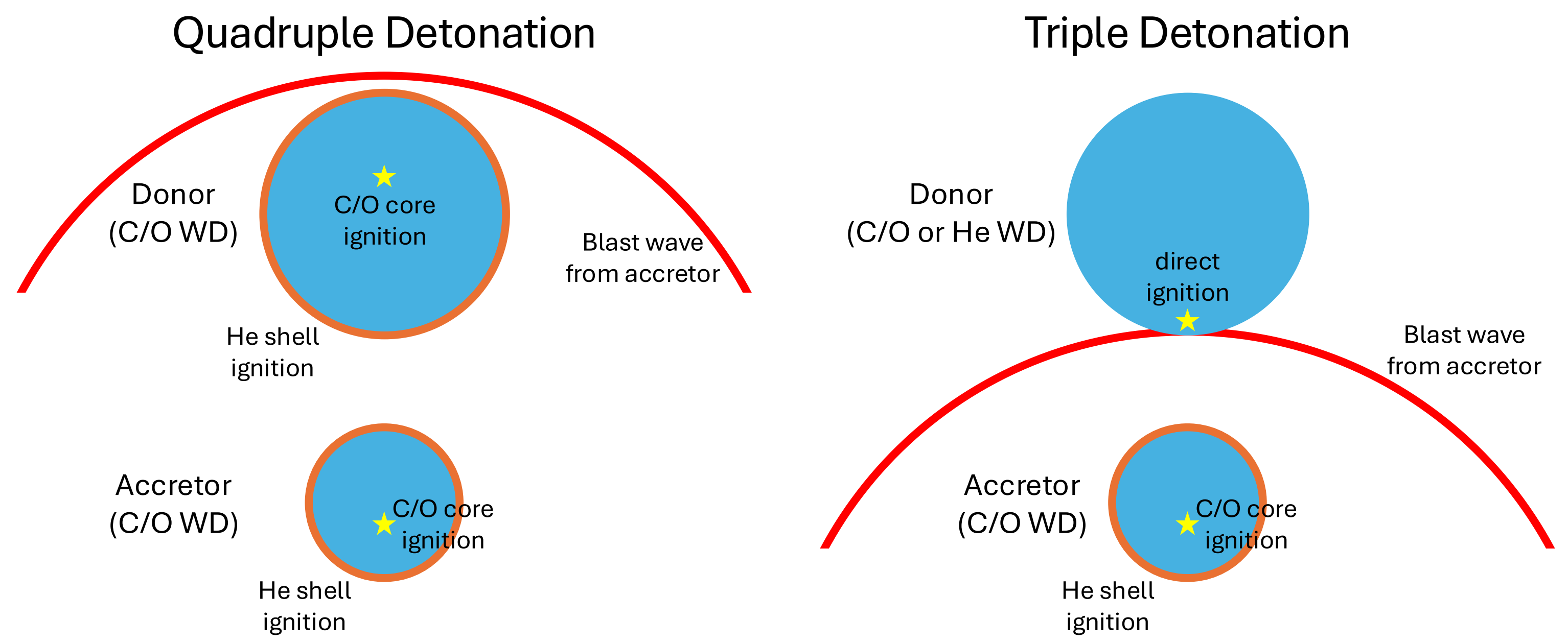
Background

The "double-detonation" mechanism is one method by which a white dwarf may explode as a type Ia supernova. Here a white dwarf accretes helium-rich material from a donor until its surface helium shell becomes hot enough to ignite nuclear burning. If the donor is also a white dwarf, the supernova blast wave may be sufficiently strong to ignite the donor, **resulting in the destruction of both objects.** If the donor undergoes its own double detonation, this is known as the "quadruple-detonation" mechanism, as it involves four consecutive detonations:

(1) The accretor's helium shell detonates, sending a converging shock wave into its C/O core.
(2) The core ignites, creating an expanding detonation wave which destroys the accretor.
(3) The blast wave from the accretor ignites the helium shell of the donor.
(4) The donor's core ignites, creating a second supernova.

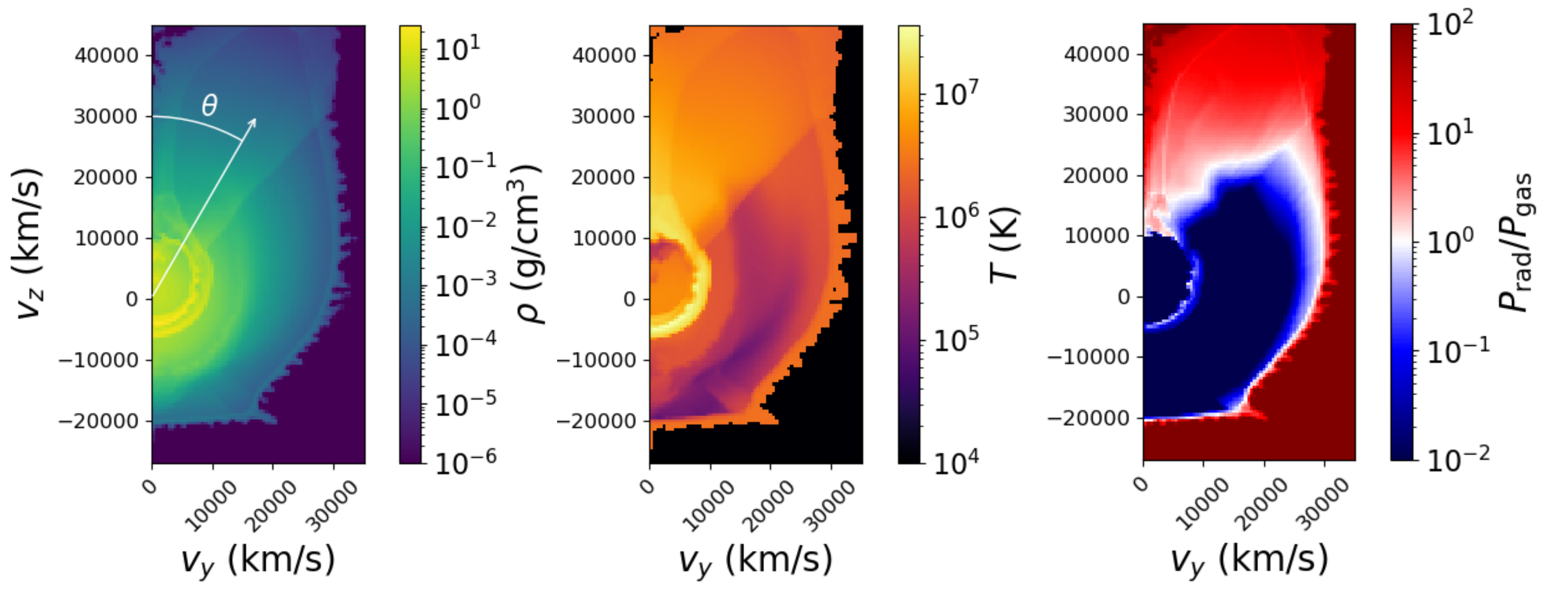
In cases where the blast wave is strong enough to directly ignite the donor core, step (3) is skipped; this is called a "triple detonation" and results in a shorter time delay between the two supernovae. These mechanisms are depicted qualitatively in the diagram below.



As the destruction of the donor substantially alters the ejecta structure, we here ask the question: **what is the nature of the supernova remnants resulting from the detonation of binary white dwarfs?**

Detonation Models

As our initial conditions, we use the detonation simulations of Boos et al. (2024), who used the FLASH code to detonate various progenitor binaries. A snapshot of a quadruple detonation ≈1 minute after the explosion is shown below, where the donor was initially along the $+z$-direction (north pole) from the accretor.



Here two important features can be identified:

- Hydrodynamical interactions between the ejecta and donor *before* the donor detonation carve out a **shock-heated, low-density wake** in the ejecta.
- The donor detonation injects an **inner shell of dense ejecta** at $v \approx 10{,}000$ km/s which differs chemically from the ejecta originating from the accretor.

M_1 ($M_\odot$)	M_2 ($M_\odot$)	Type of Detonation	Notes
1.00	—	Double	isolated WD
1.00	0.40	Triple	He WD donor
1.00	0.70	Quadruple	—
1.00	0.90	Quadruple	—
1.00	0.70	Double	surviving donor
0.85	0.80	Quadruple	—
1.10	1.00	Quadruple	—
1.10	1.00	Triple	—

Eight different binaries (tabulated above) were simulated, allowing for several useful comparisons:

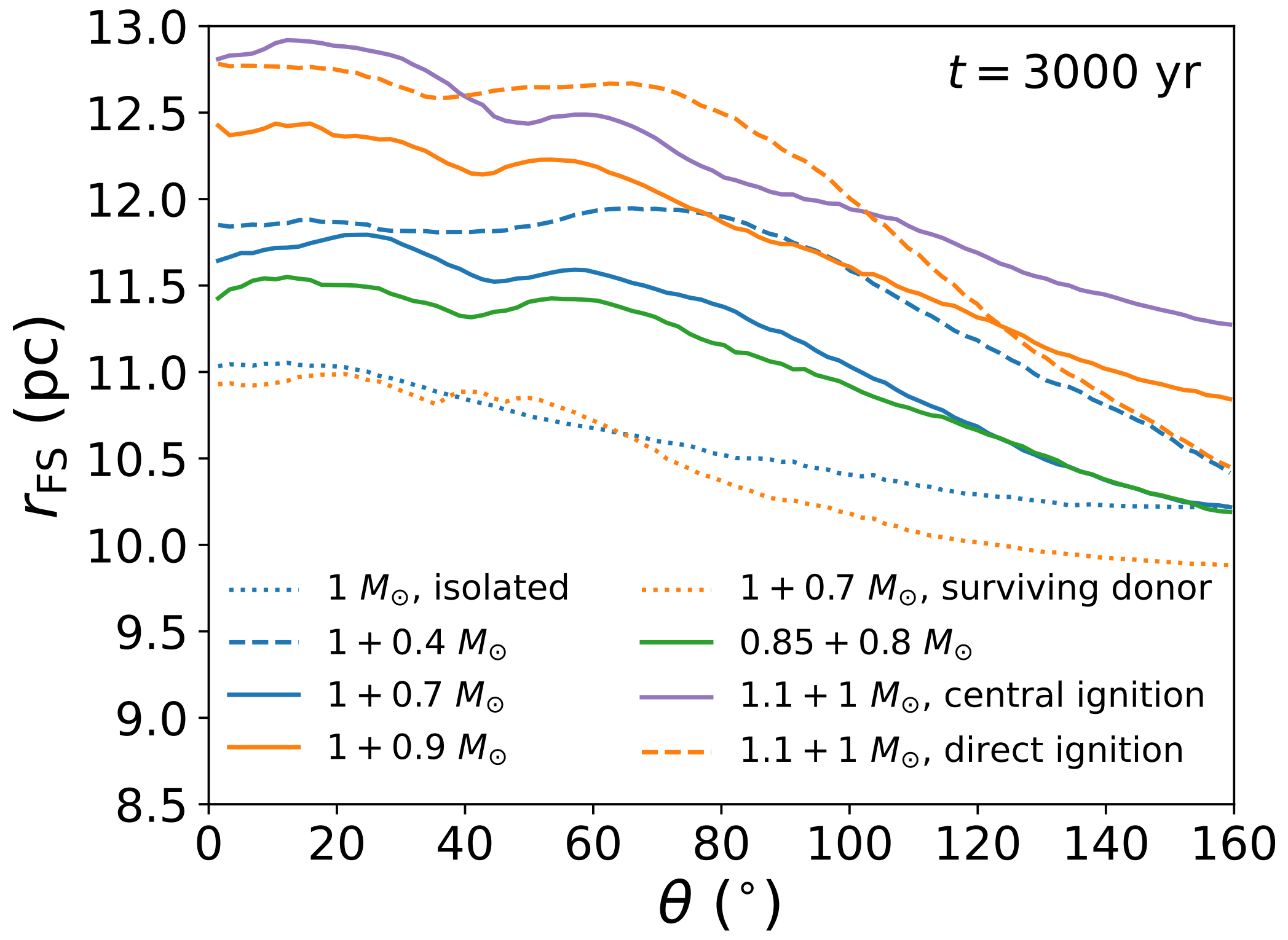
- The case of an isolated white dwarf is unphysical, but is included solely for the purpose of comparison.
- A binary in which the donor is present but does not detonate is also included.
- The $1 + 0.40 M_\odot$ case is unique in that the donor is a helium white dwarf (as opposed to a C/O white dwarf) which can only be ignited by the triple detonation mechanism.
- The two $1.1 + 1 M_\odot$ simulations allow for a direct comparison of different detonation mechanisms.

Remnant Phase Integration

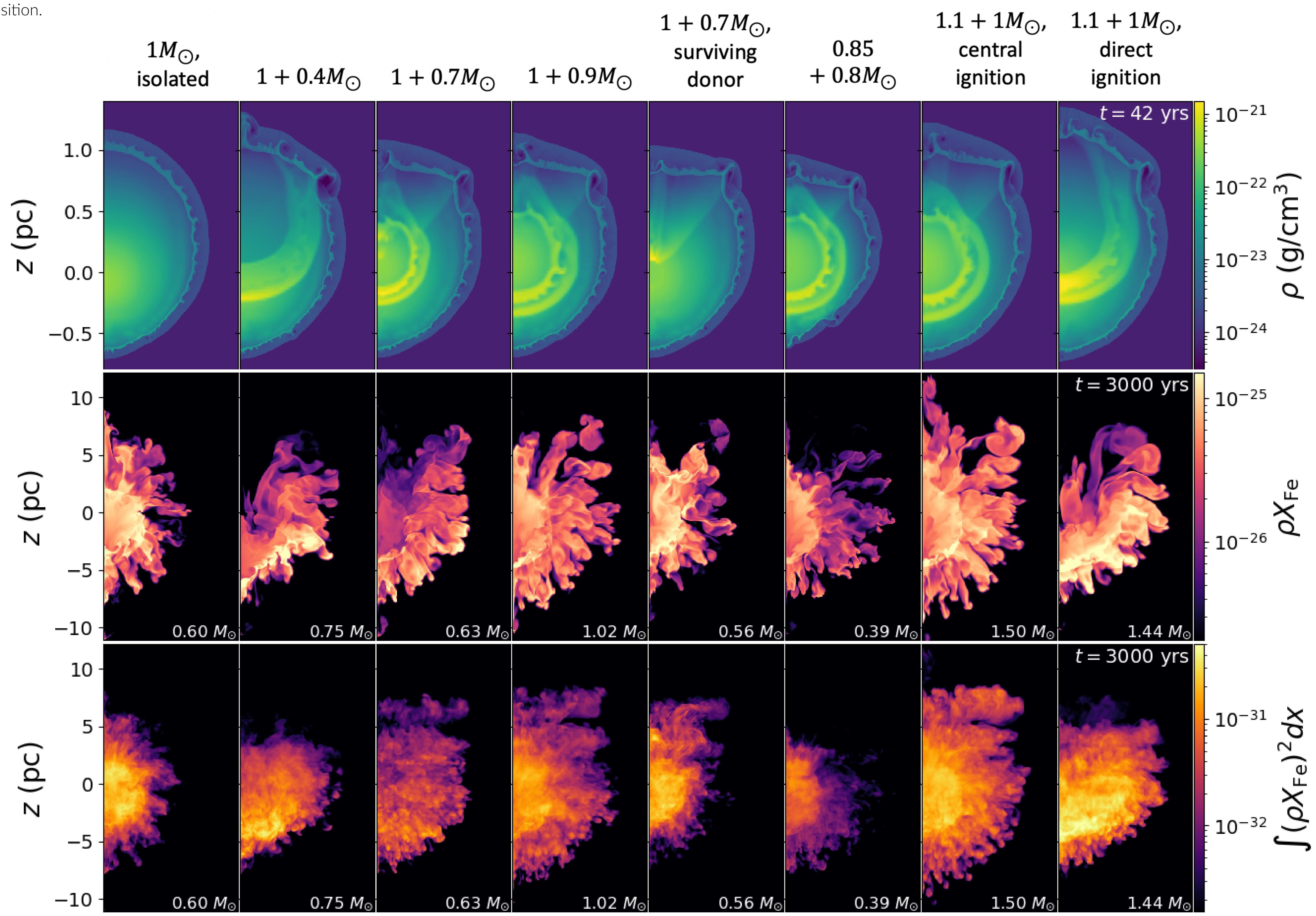
In this work, the evolution of the ejecta through the remnant phase (up to an age of 3000 years) is computed using the 3-D hydrodynamics code Sprout. **This code uses a uniformly-expanding Cartesian grid, allowing us to follow the expansion of the remnant over a large dynamic range.** This also minimizes advection errors and removes the need to remap the fluid onto larger grids, which would introduce spurious diffusion.

Remnant Dynamics

The differing ejecta structures between the detonation models have lasting consequences as the ejecta expands into the interstellar medium (ISM). For any binary in which the donor detonated, **the inner shell of ejecta bolsters the expansion** of the remnant as it sweeps up the ISM, leading to a larger remnant size.

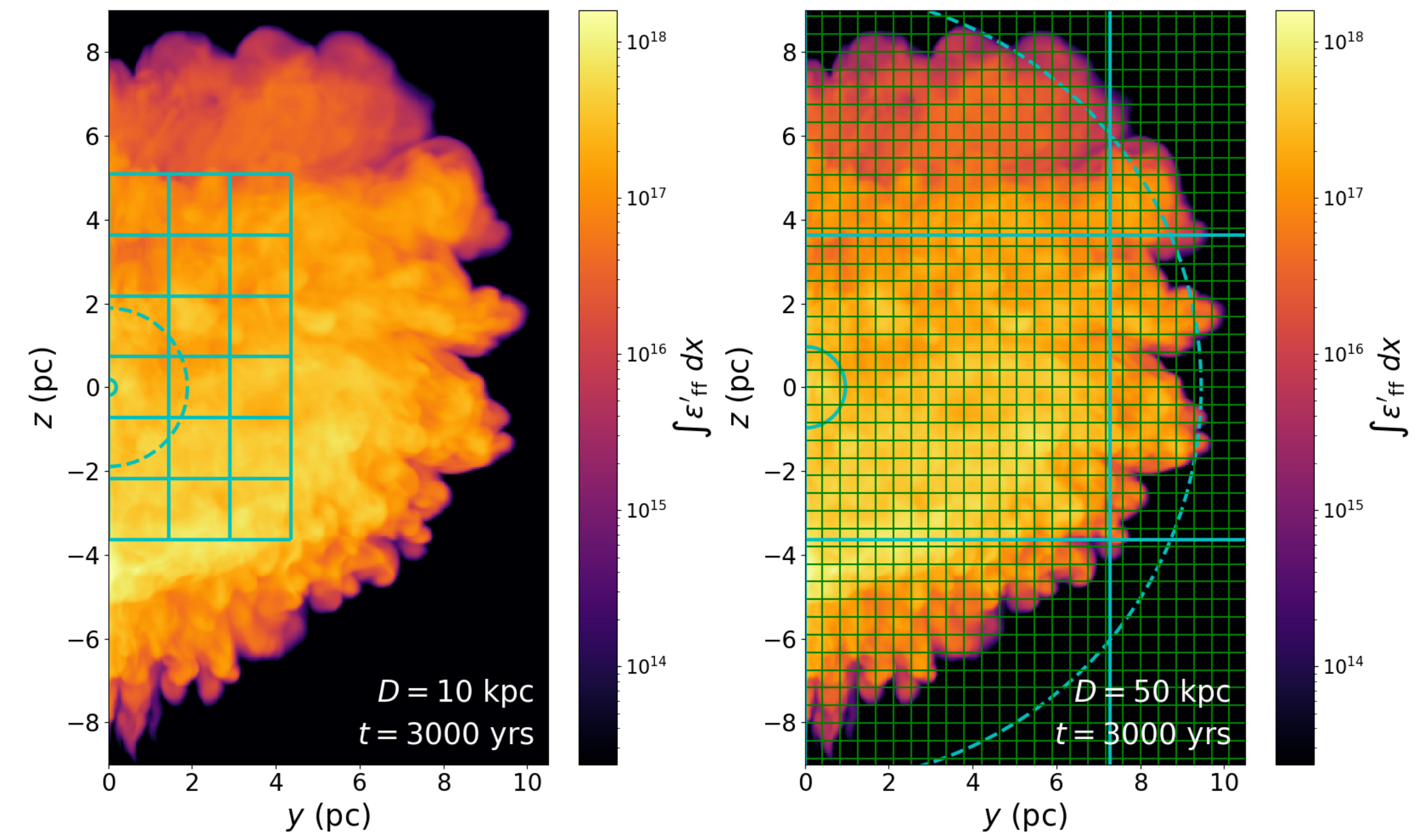


In the triple-detonation cases, the short time delay between WD detonations means that the explosion of the donor evacuates much of the material along the north pole. This subsequently allows a reverse shock to travel inward through the wake, **drawing material from the interstellar medium into the remnant** and altering its chemical composition.



X-Ray Tomography

As X-rays are produced by heavy elements in shocked ejecta and are able to exit remnants unimpeded, they provide an excellent probe of remnant morphology. Line emission from iron is particularly useful, as it is produced in large quantities in SNIa. We track the elemental abundances in our Sprout simulations, using the thermodynamic properties of the fluid to estimate the X-ray emission. We find that **the iron line emission is heavily concentrated in the southern hemisphere for triple detonations** due to their unique dynamics.



We can also compare our results to the capabilities of X-ray observatories; in particular, the XRISM telescope has a high-resolution X-ray imager as well as a spectrometer. Above, we show the continuum thermal X-ray emission (which is also dominated by iron) for the $1.1 + 1 M_\odot$ triple detonation case. On the left, we overlay the pixels for the spectrometer (blue) assuming a Galactic remnant at a distance of 10 kpc, finding that **XRISM can resolve the line emission within Galactic remnants.** On the right, we show the same remnant in the LMC (at a distance of 50 kpc) where the spectrometer pixels are much larger. We also overlay the pixels of the X-ray imager in green; even at this distance, the imager can easily resolve the thermal X-ray morphology.

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