# Making Normal Type Ia Supernovae with Double Detonations

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## Abstract

The double detonation scenario in which a white dwarf (WD) is incinerated by a sequence of detonations, first in the surface helium shell and successively in the carbon-rich interior, has emerged as a promising sub-Chandrasekhar mass scenario for Type Ia Supernovae (SNe Ia). Previous work on this scenario has shown that a helium shell that is too thick will produce spectral peculiarities that are not seen in SNe Ia. We discuss two dimensional simulations targeted at determining the characteristics of the He shell, such as mass and enrichment, that are required for an explosion to produce a spectroscopically normal SNe Ia. The results of this comparison will inform future work on dynamic ignition of helium detonations by determining the range of characteristics of the helium shell that must ignite. An example case is shown here, with a broader exploration of the parameter space ongoing.

## Simulation Software

Simulations of the explosion were computed using several pieces of software. The hydrodynamic evolution of the explosion was computed using *Flash* with nuclear reaction networks integrated from the Modules for Experiments in Stellar Astrophysics (*MESA*) project. 55 nuclides were used to model reactions during the hydrodynamic simulation. Lagrangian tracers were propagated in order to record the density and temperature histories of fluid elements, and these histories were post-processed using *MESA* with a larger, 205 nuclide, reaction network. Finally the nucleosynthetic results were binned for computation of the radiative transfer during the expansion of the ejecta using *Sedona*, to obtain light curves and spectra.

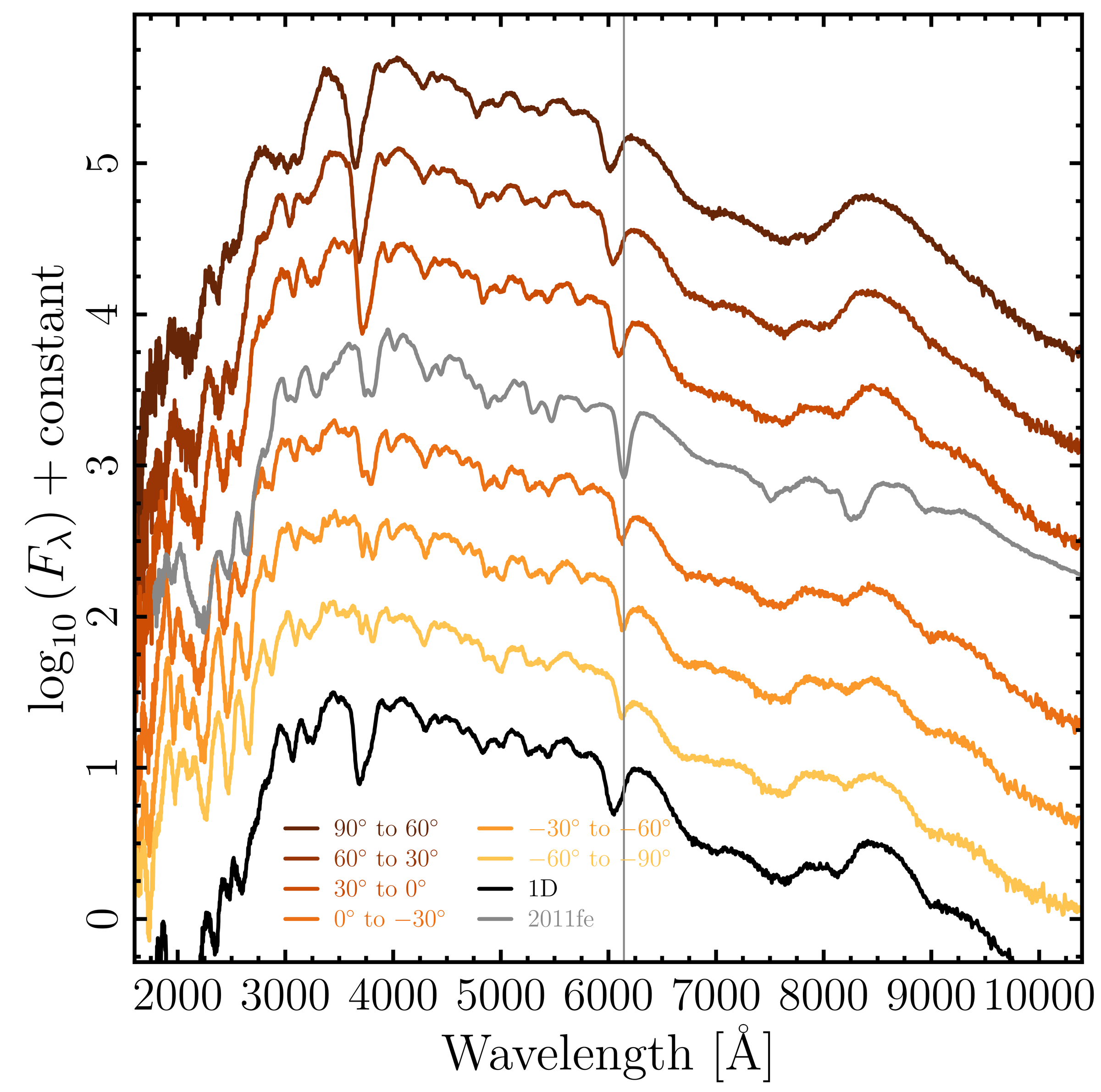


**Figure 1:** Maximum light spectra for ejecta representative of the six regions separated by angle from the equatorial plane. The near-maximum-light spectrum of SN 2011fe is shown for comparison (gray), as well as the maximum-light spectrum from a 1.0 $M_\odot$ detonation model with no He layer (black) from Shen et al. (2018a). The vertical line indicates the wavelength of the minimum of the Si II feature in SN 2011fe. Even with the helium layer ashes, the spectra compares well to observations.

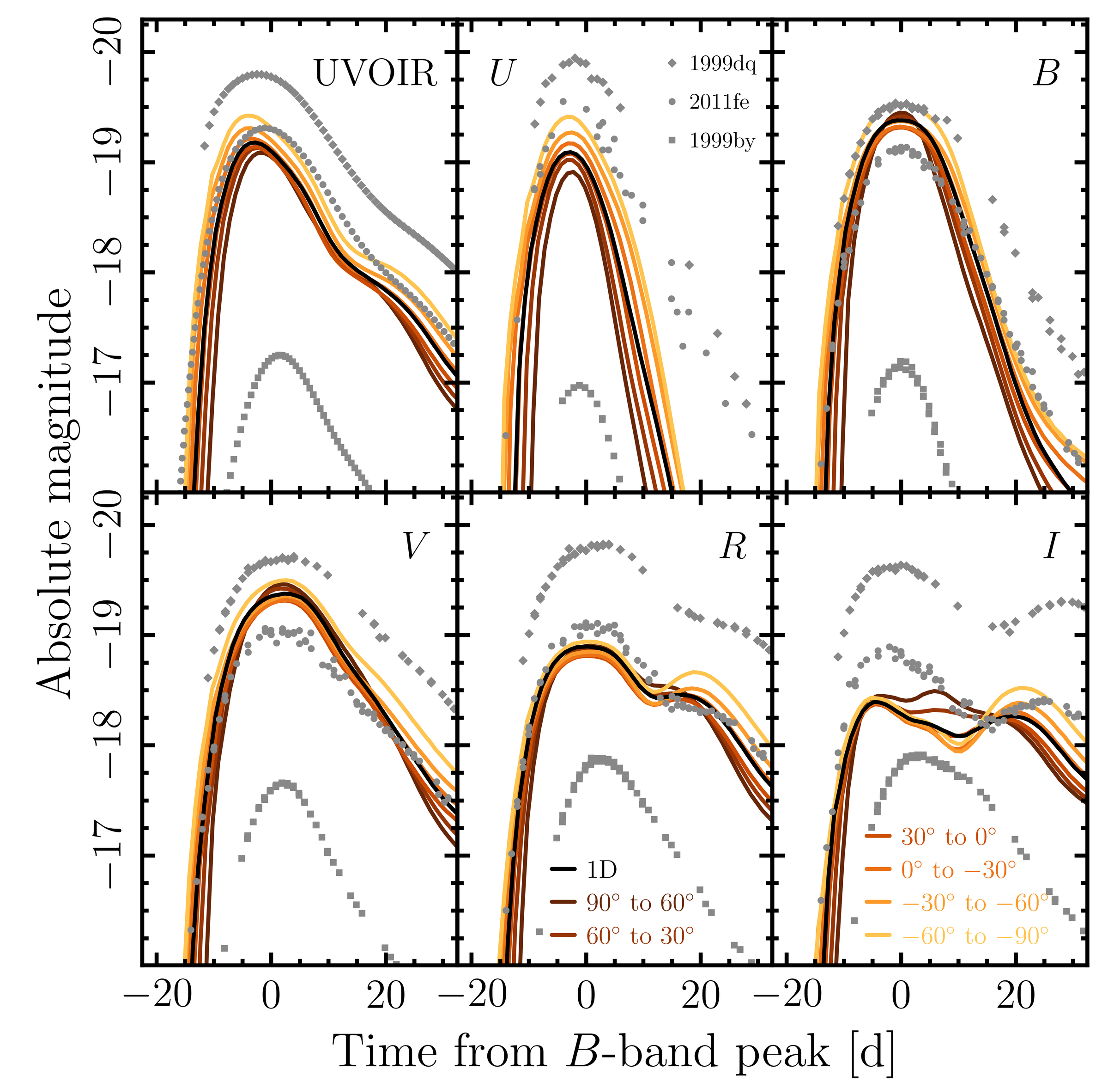


**Figure 2:** Time evolution of magnitude in various bands for different regions of ejecta. The 1.0 $M_\odot$ detonation model from Shen et al. (2018), which has no He layer , is shown as black lines. Gray points represent the sub-luminous SN 1999by, the normal SN 2011fe, and the over-luminous SN 1999dq.

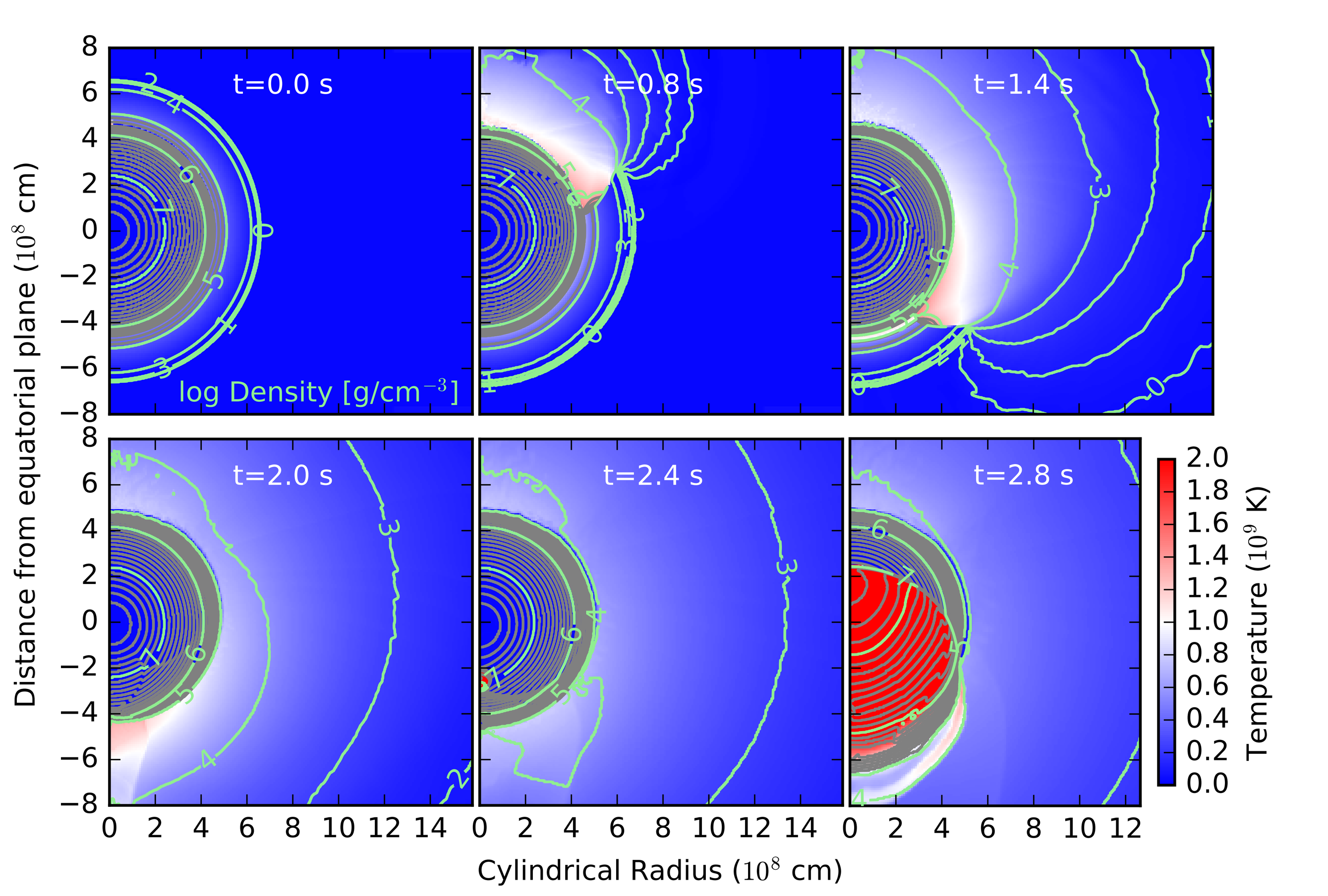


**Figure 3:** Time sequence of a helium shell double-detonation supernova. Intermediate density contours are only shown above $10^5$ g cm$^{-3}$, 10 per decade equally spaced logarithmically, in order to highlight the inward compression wave.

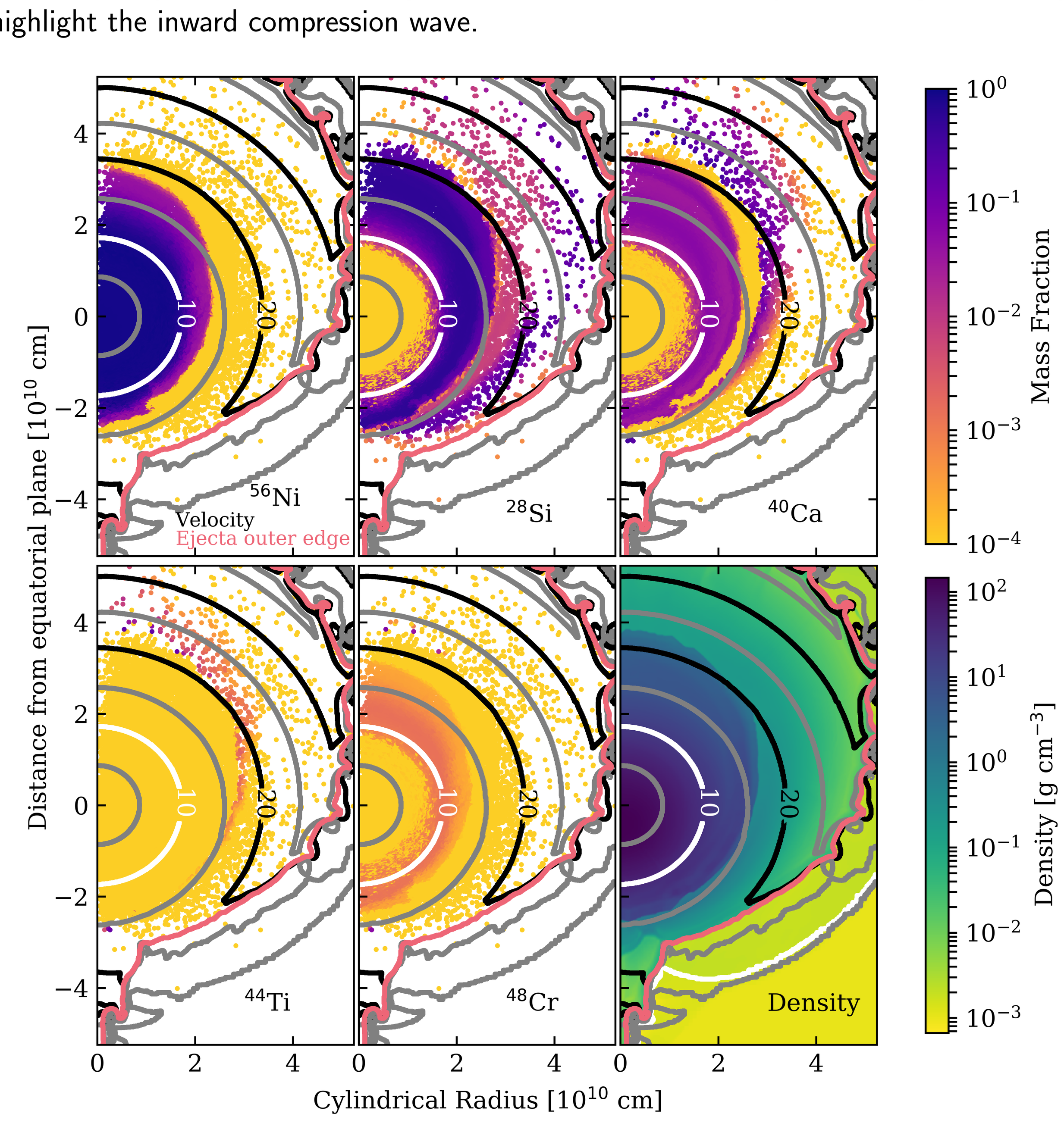


**Figure 4:** Ejecta 20 s after ignition, having entered the free expansion phase. The first five panels show the distribution of various species, indicated in the lower right corner of each panel. Overlaid are contours in total ejecta velocity, labeled in units of $10^8$ cm s$^{-1}$. The lower right panel shows the density distribution. The red contour indicates the edge of material that was part of the star at the beginning of the simulation (see text). Very little $^{44}$Ti, $^{48}$Cr, or heavier elements is made in the helium shell detonation.

## Conclusions

Following up on work showing that thin, highly C-O enriched He shells lead to double-detonations that nearly reproduce spectroscopically normal SNe Ia (Kromer et al. 2010) and that a layer containing N, the product of the CNO cycle, can detonate at even lower densities with less complete burning (Shen & Moore 2014), we have simulated, in 2D, the double detonation of a 1.0 $M_\odot$ WD with a 0.02 $M_\odot$ He layer enriched with 5, 5, and 0.9% $^{12}$C, $^{16}$O, and $^{14}$N, finding that the resulting explosion produces a spectroscopically normal SN Ia from a wide range of viewing angles. This success provides a proof-of-concept that the dynamically driven double-degenerate double-detonation (D$^6$, Shen et al. 2018b) scenario, in which a thin He shell detonates early on in a WD-WD merger, can be a significant progenitor channel for a large fraction of SNe Ia.

While our spectra compare well with normal SNe Ia, the decline rate of our $B$ band light-curve is too fast. This was also true for the centrally ignited detonations without helium layers computed by Shen et al. (2018a) using the same radiative transfer as the present work. We believe this is a remaining uncertainty in the radiative transfer that will be addressed in future work. This conclusion is based on the fact that the decline rate is a better match for observations for similar models computed by Sim et al. (2010) and Blondin et al. (2017). These works used methods intended to capture non-LTE effects to varying degrees in ways that should be more realistic. The case shown here also motivates work to determine the range of He shell sizes, enrichments, and thermal states that are allowed by observations, as well as further study of the dynamically driven ignition mechanism in mergers of WD-WD binaries.

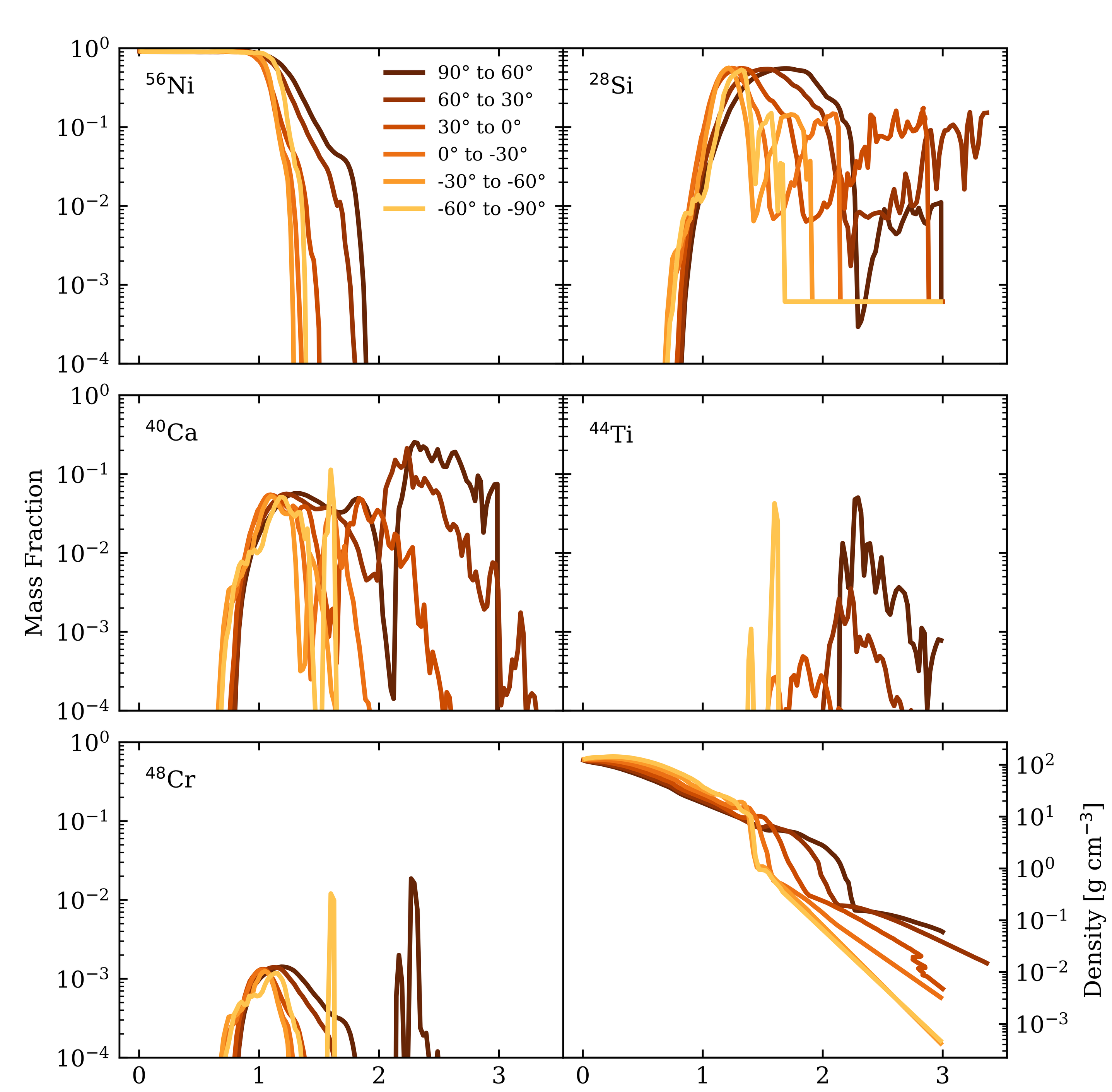


**Figure 5:** Post-processed ejecta abundances and density profiles 20 s after ignition, having entered the free expansion phase, as a function of ejection velocity. The first five panels show the same species as in Figure 4 and the lower right panel shows the density distribution. Each line shows a different wedge, with angular extent, in degrees latitude, indicated by shading and labeled in the first panel. Ti during the photospheric phase will come predominantly from $^{48}$Cr, which has very little contribution from the He shell ashes, except for some near the positive axis (90° to 60°).

## References

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Shen & Moore 2014, ApJ, 797, 46
Shen et al. 2018a, ApJ, 854, 52
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