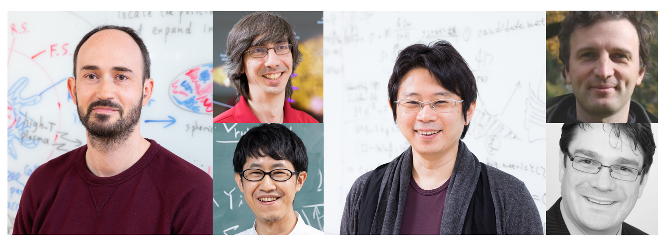

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From the thermonuclear supernova to the supernova remnant: the imprint of a 3D explosion

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ABSTRACT: Recent progress in the simulation of supernovae (SNe) has shown the importance of turbulence and asymmetries in successful explosions, which prompts us to revisit the subsequent phase, the supernova remnant (SNR). Can we use the SNR morphology as a probe of the explosion mechanism? Recent work by Orlando et al has shown the interest of this approach for a core-collapse SNR like Cas A. Here we argue for the case of a Type Ia SNR like Tycho. Our project is making the link between two communities, the one studying the explosion and the one studying the remnant. We have run 3D simulations of a SNR starting from the output of a 3D simulation of the thermonuclear explosion of a carbon-oxygen white dwarf. By analyzing the wavefronts we have quantified the imprint of the explosion on the remnant over time. Assuming a uniform ambient medium, we find that the impact of the SN on the SNR may still be visible after hundreds of years. And interestingly, the newly simulated maps look more realistic than in previous works based on spherically symmetric ejecta profiles.

CONTEXT. Despite substantial effort and recent progress, the very mechanism(s) by which stars explode have not been fully elucidated. For thermonuclear supernovae (type Ia SNe), it is still unknown whether they are produced by single-degenerate or double-generate progenitors – or a mixture of both. Yet, the (empirical) properties of their light curves have become a cornerstone of precision cosmology.

Our project brings together specialists of the supernova (SN) explosion itself, and of the subsequent supernova remnant (SNR) phase. Since multi-dimensional explosions that are successful are not symmetric, we want to know if and for how long the explosion can be imprinted on the supernova remnant. A common trait of previous works modeling SNRs is the use of idealized initial conditions. Ferrand et al. (2010) relied on semi-analytical solutions for the early self-similar phase valid for power-law profiles, while Warren & Blondin (2013) adopted an exponential ejecta profile. Such initial conditions were effectively one-dimensional (1D), being functions of radius only, even though the subsequent SNR evolution was three-dimensional (3D) [as in the plots on the left side of Fig. 1, 2, 4]. The main point of this new work is to use realistic initial conditions for the SNR phase [as in the plots on the right side of Fig. 1, 2, 4].

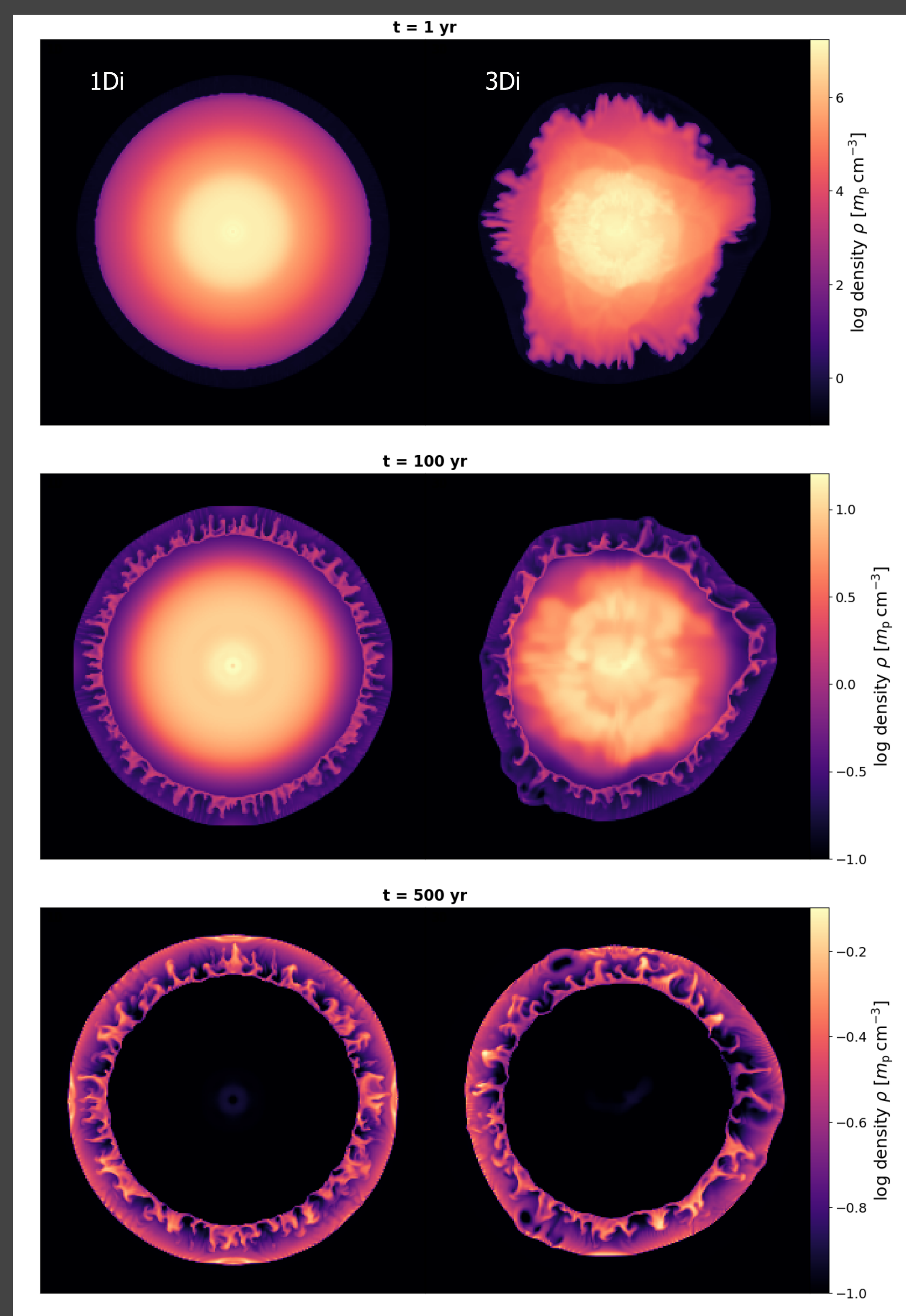

Figure 1. Slices of the mass density at three ages. An animation in time from 1 yr to 500 yr by steps of 1 yr is available in the online version of the published paper (a 3D movie was also developed for virtual reality headsets, Ferrand & Warren 2018). The colour scale is logarithmic, its upper value is adjusted over time so that all frames have similar contrast. The linear size of the physical box is of the order of 0.085 pc at 1 yr, 5 pc at 100 yr, and 13 pc at 500 yr.

METHOD.

For the supernova, in this work we treat the case of a thermonuclear explosion. We concentrate on the single degenerate scenario: an accreting CO white dwarf, and we consider a popular explosion model, a delayed detonation. Seitenzahl et al. (2013) presented a suite of 14 3D hydro simulations of a DDT explosion of a Chandrasekhar-mass white dwarf ($M = 1.4\ M_\odot$), with the ignition configuration parametrized. Such models reproduce the range of spectra of SN Ia, although they still fall short of recovering the width-luminosity relation. For a start we are using the N100 model ($E = 1.4\times10^{51}$ erg).

For the SNR evolution, we are performing hydro simulations as in Ferrand et al 2010, using a custom version of the RAMSES code (Teyssier 2002). The output of the SN simulation at 100 s is re-scaled to 1 day assuming self-similarity; it is then evolved until 500 yr (similar to Tycho's age). We assume a uniform ambient medium $n_H = 0.1$ cm^{-3}. We are not concerned here with radiative transfer or cooling, although we tested the negligible effect of heating from radioactive decay. Simulations are performed in an expanding Cartesian grid, with a fixed number of cells 256^3, but a physical box size that follows the global expansion.

Analysis of the SNR morphology. We focus on the shell of shocked material, bounded by the reverse shock (RS) and the forward shock (FS), and containing the ejecta boundary (contact discontinuity, CD). At each time step, we detect the position of each wavefront. The 3D surface is projected on the sphere using the HEALPix tessellation scheme (Gorski et al 2005) [see maps in Fig. 2 for the CD]. To quantify the asymmetries observed, the normalized radius of the wavefronts is expanded in spherical harmonics $Y_{\ell m}$, producing angular power spectra [see histograms in Fig. 2 for the CD, the total power for RS, CD, FS is shown in Fig. 3].

SNR simulations were performed on the iTHEMS clusters at RIKEN

RESULTS.
In all the plots we compare two initial conditions: effectively 1D ("1Di"), obtained by averaging out the SN profiles over angles so depending on radius only, versus fully 3D profiles ("3Di") as obtained from the SN simulation. The 1Di case, similar to previous studies, shows the Rayleigh-Taylor instability (RTi) developing at the CD, purely during the SNR phase. The 3Di case shows, for the first time, how the RTI grows on on top of existing SN asymmetries. It appears easier for the RT fingers to get into contact with the FS [Fig. 1]. Using angular spectra, we can separate the SN contribution (below $\ell = 10$) from the SNR contribution; curves for the power match at 187 yr [Fig. 3], which is our estimate of the SN-to-SNR transition timescale. Over time the overall shape of the RS, FS, and CD becomes more spherical. However, signatures of the explosion may still be detected after a few hundred years. At 500 yr, the CD power spectrum looks like a single distribution, just extending over a wider range of ℓ than would be expected from RTI alone [Fig. 2]. This could easily be confused with an enhanced RTI growth. This actually looks like what is being observed in Tycho's SNR.

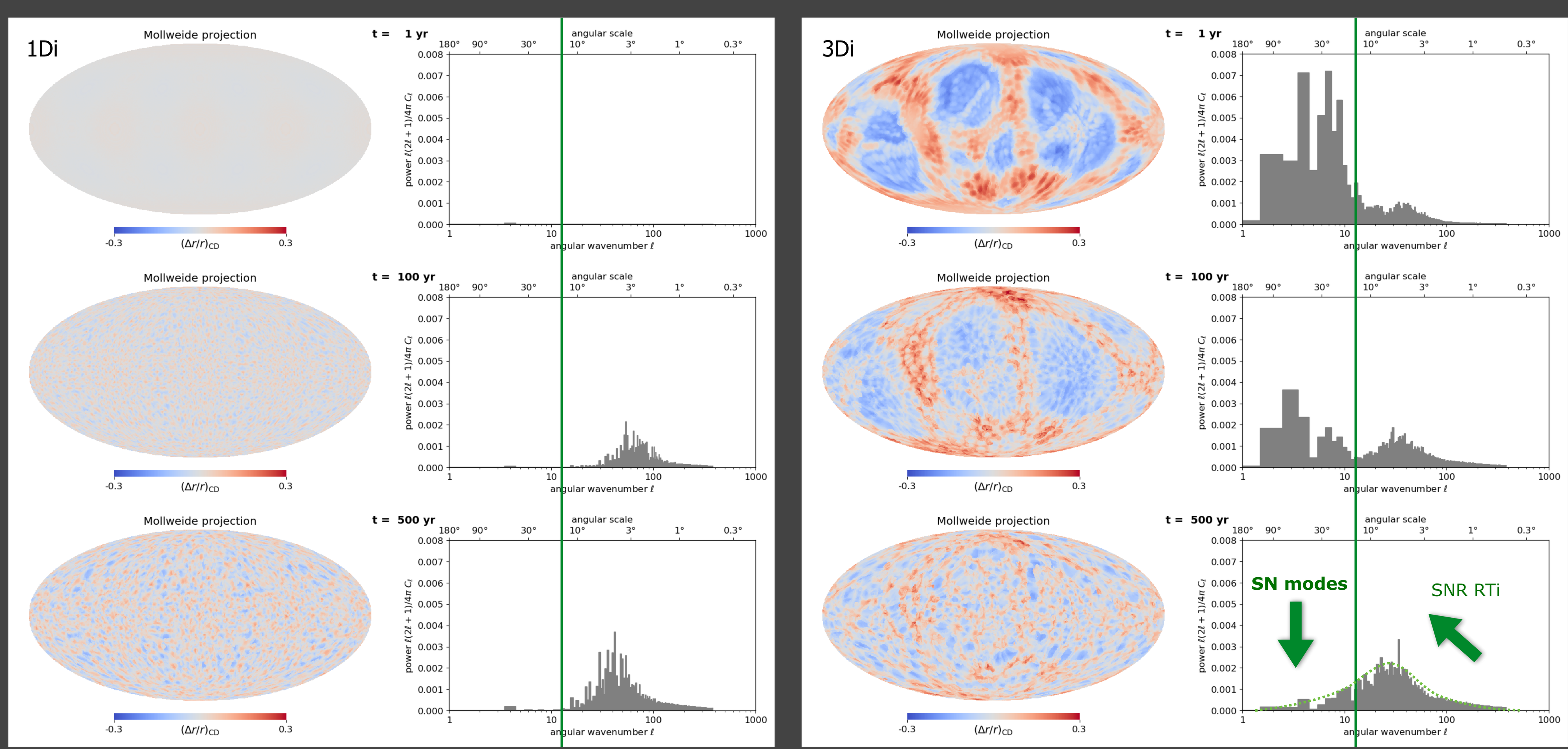

Figure 2. Morphology of the contact discontinuity. Maps on the left are spherical projections of the radial variations of the location of the wave. Spectra on the right result from an expansion in spherical harmonics of these variations. Three times are shown, an animation in time from 1 yr to 500 yr by steps of 1 yr is available in the online version of the published paper.

PERSPECTIVES.
Using a realistic 3D SN model leads to larger scale and more irregular structures, which better match **X-ray observations** of Tycho's SNR [Fig. 4]. Next we will compute the thermal X-ray emission, which depends on the electronic density and temperature, and the ionization state of all the species, which for young SNRs depends on the history of the material since it was shocked (Ferrand et al 2012). We are working on a dedicated analysis of the 2D projected images, and will do a comparison for Tycho's SNR.

The results presented here were obtained with a particular SN model. Next we will run the entire **grid of models** from Seitenzahl et al 2013 – the N100 model has a relatively mild asymmetry. We will also try other models, like pure-deflagration, or double-detonation in double-generate system. We will determine if and how we can discriminate between different thermonuclear SN theories, which is an important step to be able to use SNRs as probes of the explosion physics.

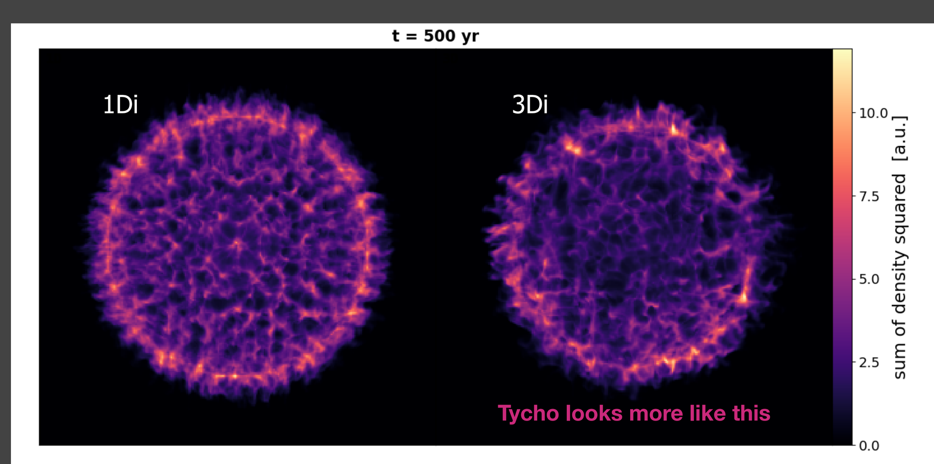

Figure 4. Maps of the sum along an axis of the simulation cube of the mass density squared for the shocked ejecta, which is a proxy for the thermal emission as can be observed in X-rays. Shown at an age of t = 500 yr, close to the age at which Tycho's SNR is observed.

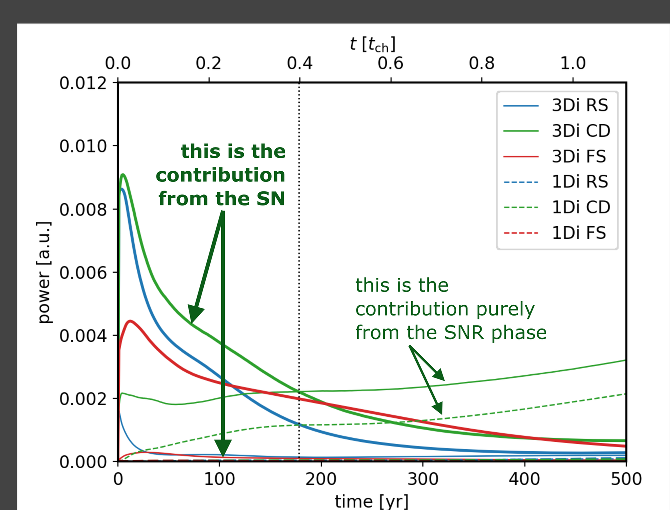

Figure 3. Evolution of the angular power as function of time, for the three waves: FS in red, CD in green, RS in blue. Time is indicated in years and in characteristic timescale. The power is plotted separately at large scales ($\ell < 10$, thick lines) and at small scales ($\ell > 10$, thin lines). The vertical dotted line indicates the time at which the two curves intersect for the CD for the 3Di case.

References: Ferrand et al 2010, A&A, 509, L10; Ferrand et al 2012, ApJ, 760, 34; Ferrand et al 2018, CAPJ, 24, 25; Gorski et al, ApJ, 622, 759; Orlando et al 2015, ApJ, 810, 168; Orlando et al 2016, ApJ, 822, 22; Seitenzahl et al 2013, 429, 1156; Teyssier 2002, A&A, 385, 337; Warren and Blondin 2013, MNRAS, 429, 3099.