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Theories of Astrophysical Big Bangs 2025
RIKEN wakō

Typing thermonuclear explosions from observations of young supernova remnants

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+ S. Nagataki, D. Warren, M. Ono, A. Tanikawa, F. Röpke, I. Seitenzahl, R. Pakmor, S. Safi-harb, A. Decourchelle, and more

Outline of the talk

Introduction

Scenarios for thermonuclear explosions

Typing supernova remnants (SNRs)

From the 3D SN to the 3D SNR:

(single degenerate, Chandrasekhar mass)

- a “classic” model: N100
- a grid of models: N100 vs N5, detonation vs deflagration

(double degenerate, sub Chandrasekhar mass)

- a challenger model: D^6
- the fate of a secondary WD: OneExp/TwoExp

Perspectives

Scenarios for a thermonuclear explosion

Progenitor system?

• single degenerate scenario
1WD + 1 normal star
stable mass transfer

• double degenerate scenario
2WDs, dynamically unstable
stable mass transfer

• more scenarios, e.g. WD merges with companion
Kashi & Soker 2011

Explosion mechanism?

• close to Chandrasekhar mass WD
- pure deflagration — Nomoto et al 1984
- prompt detonation
- delayed detonation — Khokhlov 1991
and more

• sub-Chandrasekhar mass WD
- double detonation: He shell then C core — Nomoto et al 1982
- C-ignited merger — Pakmor et al 2012 — Pakmor et al 2013

(Too) many theoretical ways. Which ones are realized?

recent reviews: Liu, Röpke, Han 2023, Ruiter & Seitenzahl 2025

Typing and sub-typing the supernova remnant

- ➡ Ideally: observe **the SN** itself – or light echos! Krause et al 2008, Rest et al 2008

- ➡ Kind of **environment**: CC SNe correlate with massive star regions
  e.g. Badenes 2009, Jennings et al 2009, Maggi et al 2016

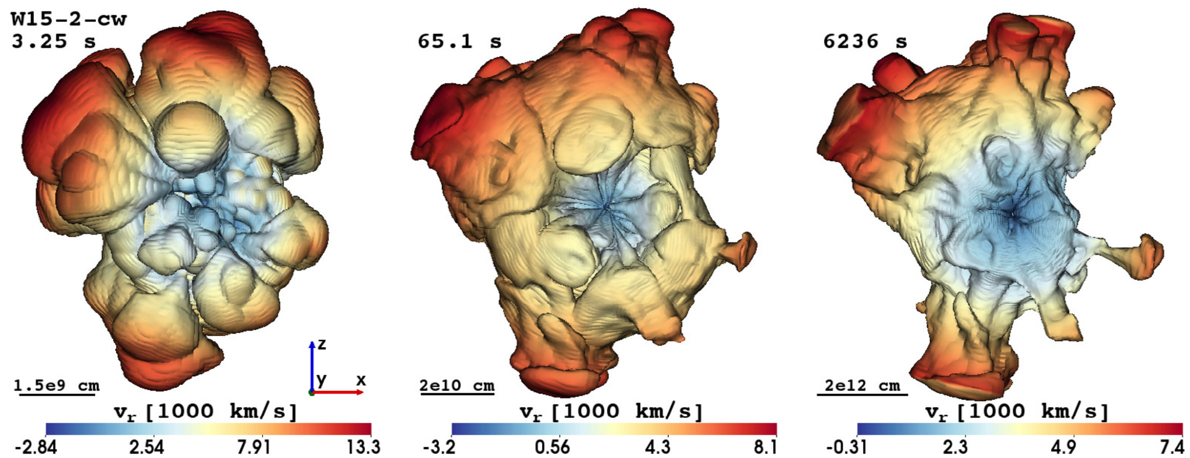
- ➡ Imprint of the progenitor systems on the ambient medium
- ➡ Presence of a **remaining compact object**: NS, unusual WD
- ➡ (Failed) searches for **surviving companions** review: Ruiz- Lapuente 2019

- ➡ From **X-ray spectroscopy**:
  metal abundances in the ejecta, e.g. Reynolds et al 2007
  position of the centroid of the Fe Kα line, Yamaguchi et al 2014
  line intensity ratios of IGE to IME Katsuda et al 2015
  characteristic nucleosynthesis effects Yamaguchi et al 2015, Ohshiro et al 2021
- ➡ Detection of coronal lines of shocked ejecta Seitenzahl et al. 2019

- ➡ **Morphological studies**: degree of asymmetry Lopez et al 2009
  Williams et al 2017, Yamaguchi et al 2017, Sato et al 2020

review: Lopez & Fesen 2018

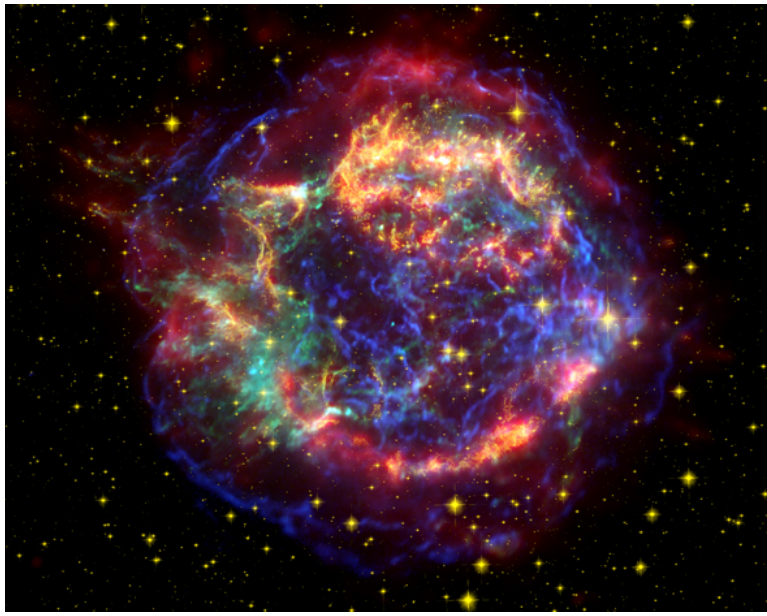
From the 3D supernova to the 3D remnant



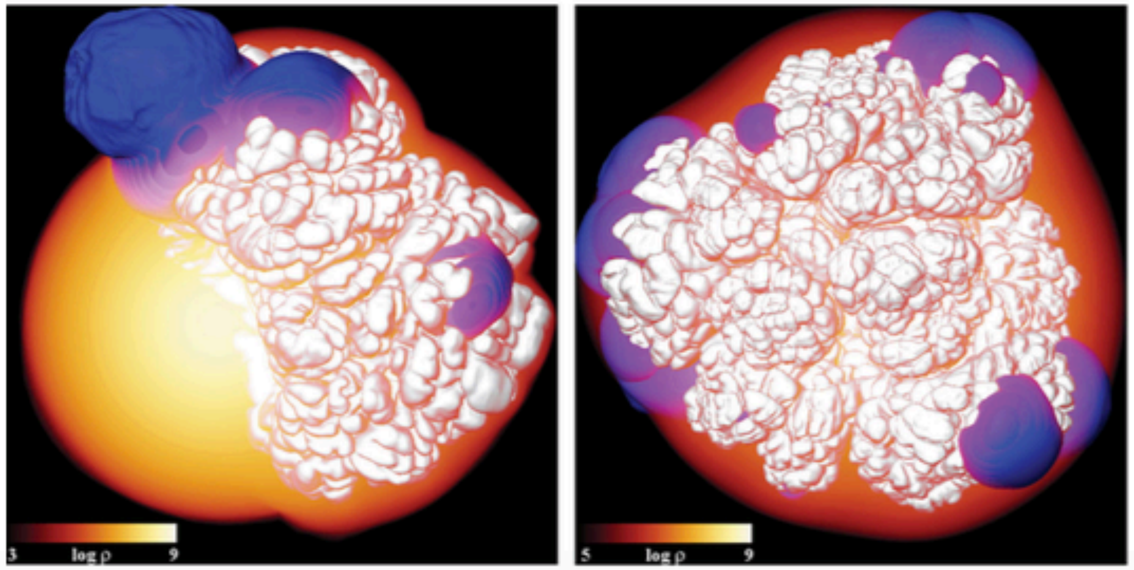
Wongwathanarat et al 2015, 2017

Cas A SNR
(missed SN)
core-collapse

age: ≈330 yr
distance: 3.3-3.7 kpc
size: 5’ ≈5 pc



?

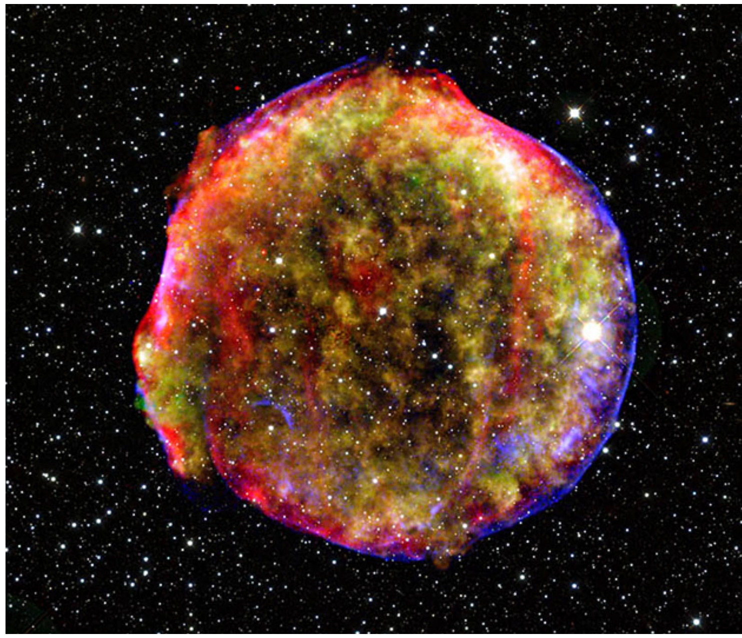


(e) N3; t = 1.15 s
(f) N100; t = 1.00 s

Röpke 2007, Seitenzahl et al 2013

Tycho’s SNR
SN 1572
thermonuclear

age: ≈430 yr
distance: 1.5-5 kpc
size: 8’ ≈3-12 pc



What can the SNR tell us about the explosion?

Hydro evolution of the SNR

slices of log(density)

t = 1 yr | t = 100 yr | t = 500 yr

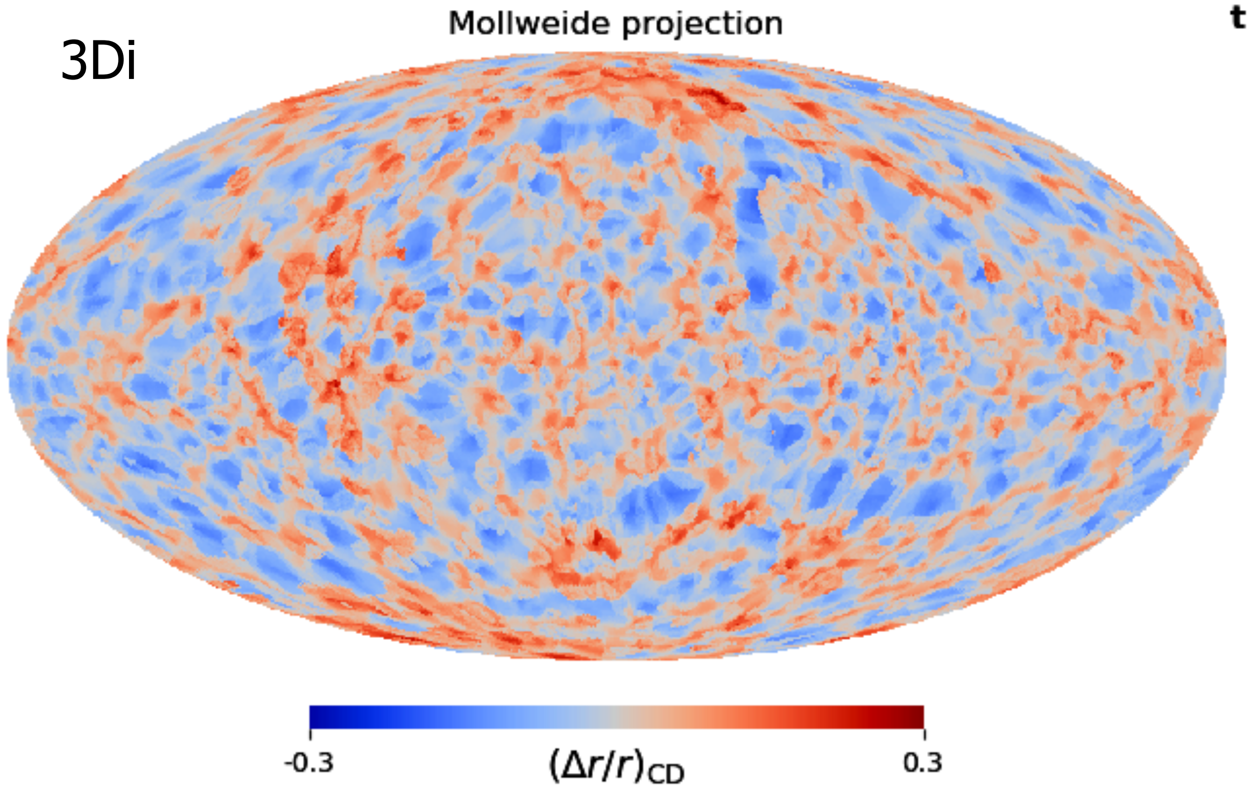
N100 3Di

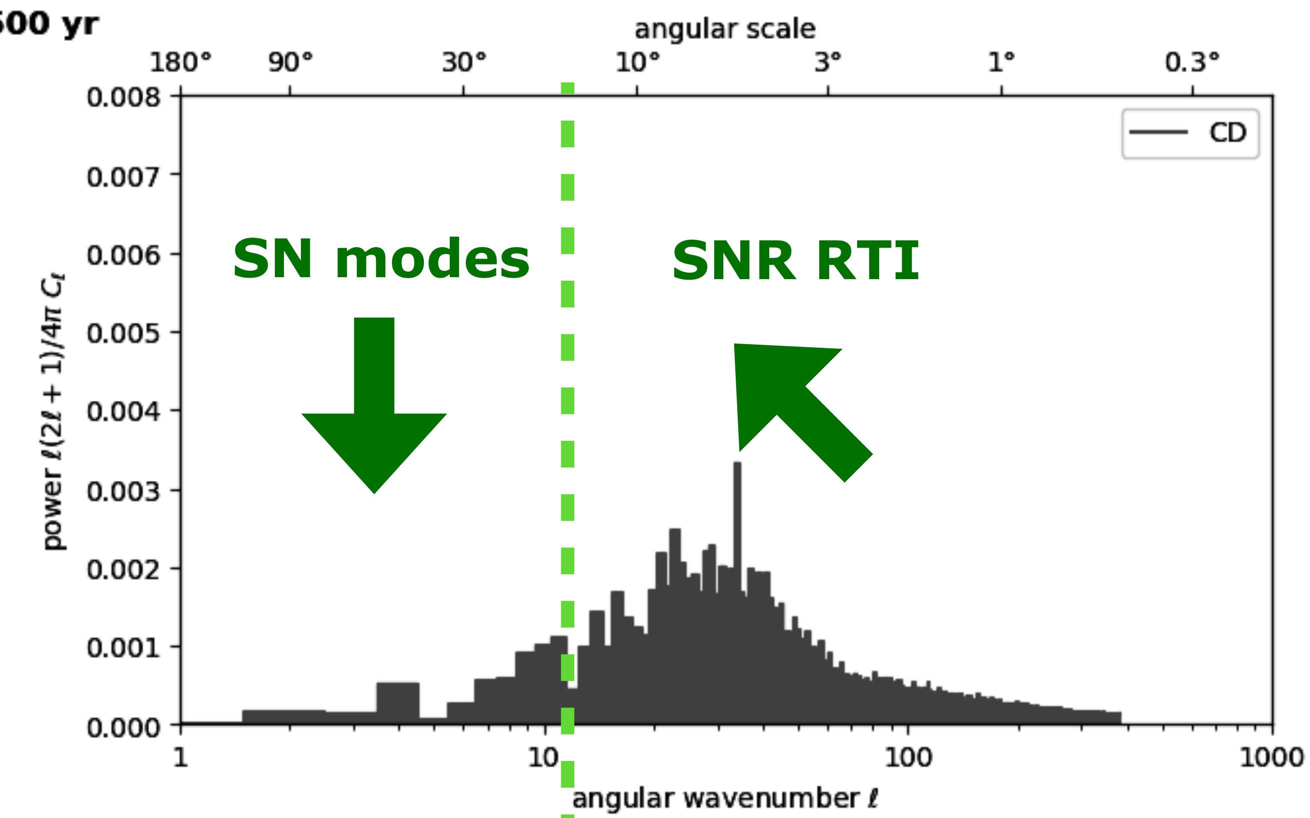
N100 1Di

Separating the SN and SNR modes

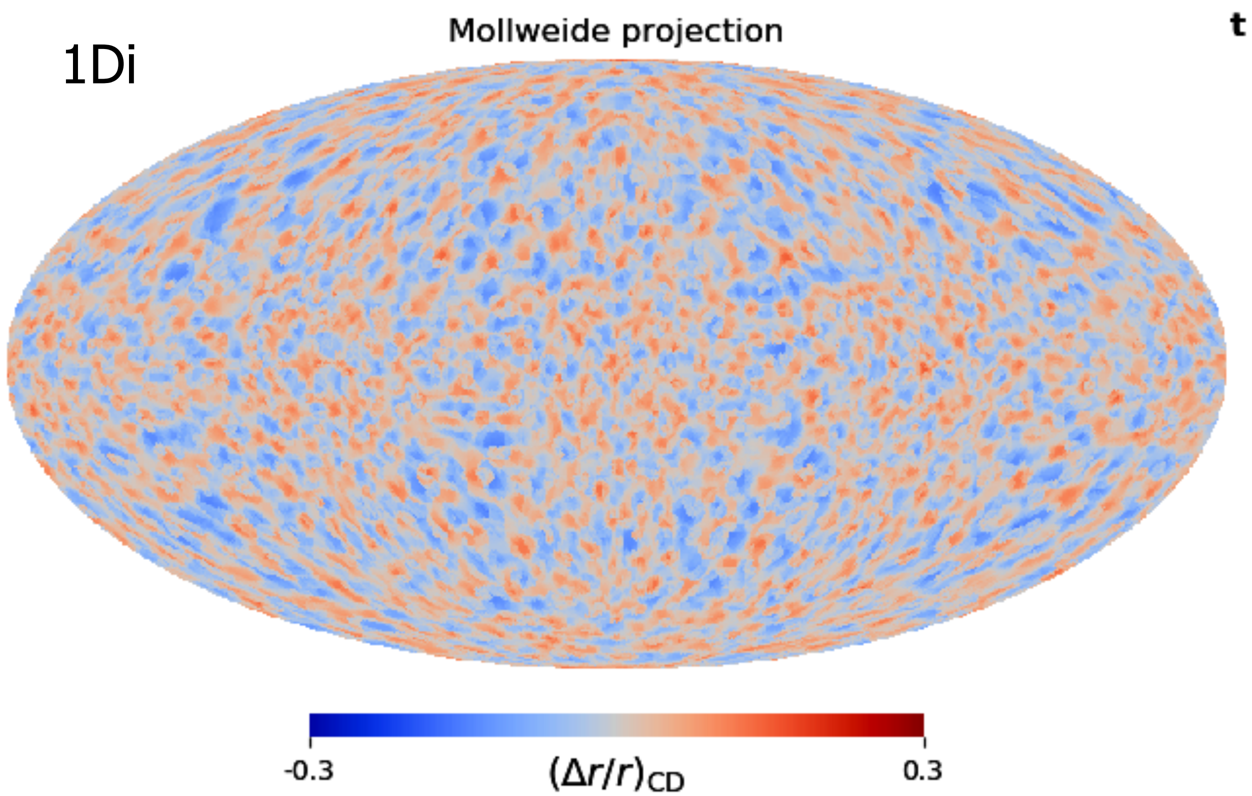
contact discontinuity (CD) at 500 yr

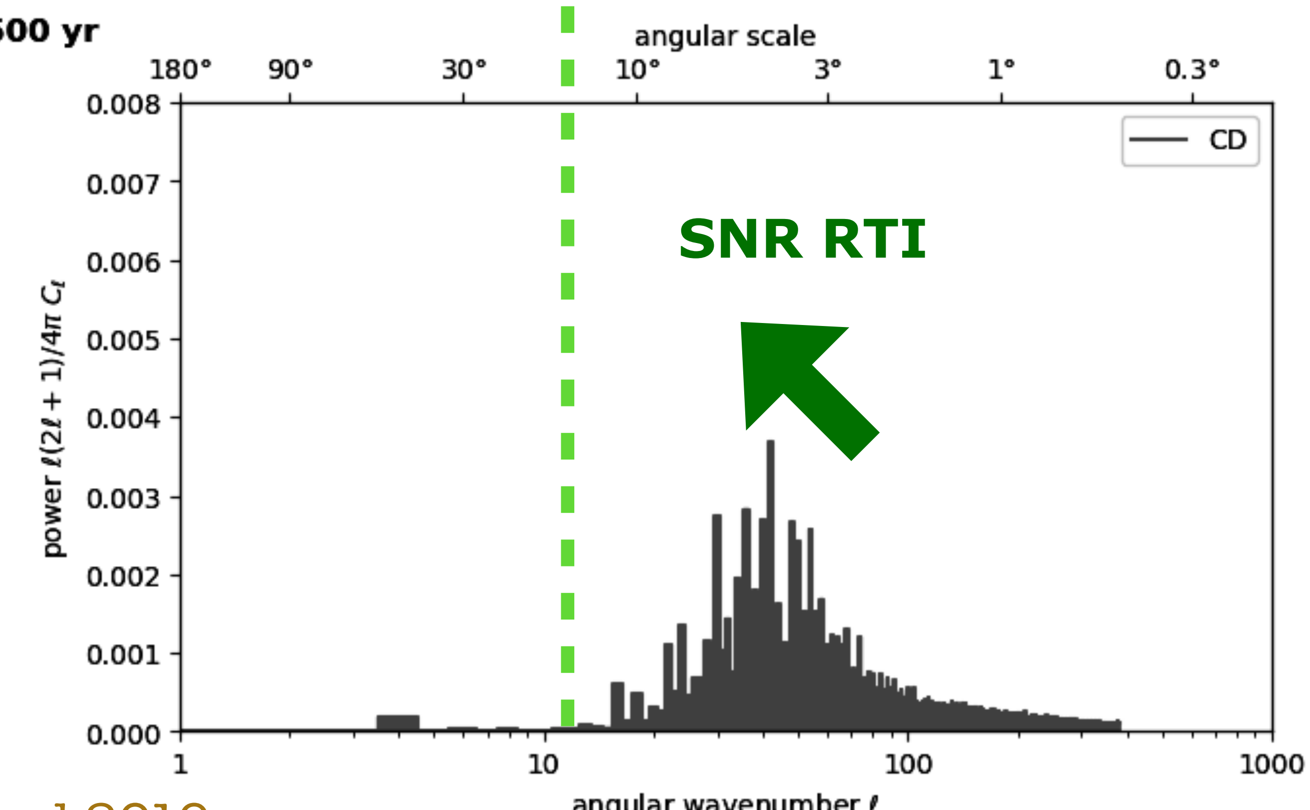
3Di





1Di

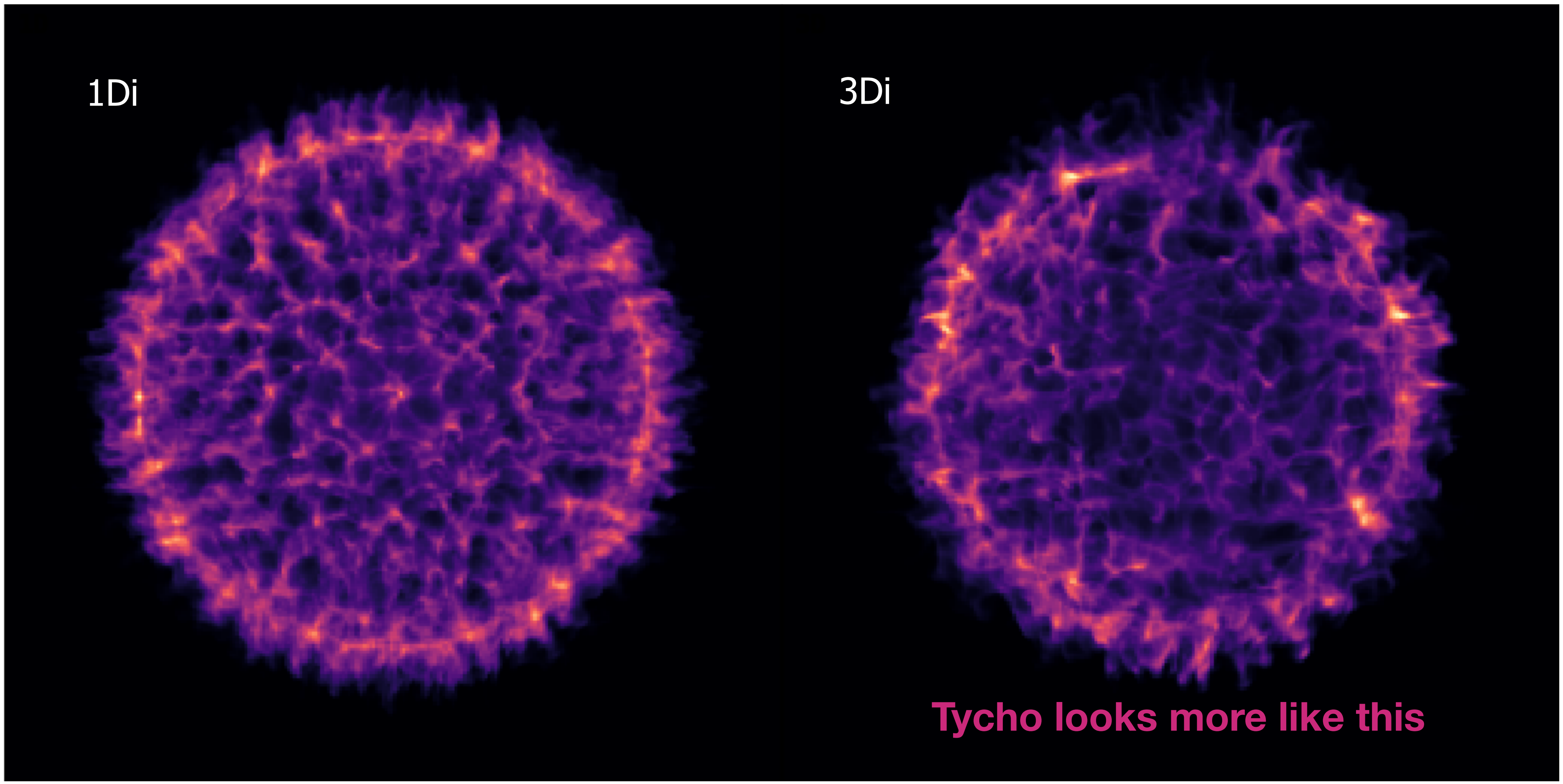




Ferrand et al 2019

The SNR morphology in projection

Interestingly, using a realistic 3D SN model leads to larger scale and more irregular structures, which were not seen in SNR simulations made from (semi-)analytical SN models, and which **better match X-ray observations of Tycho's SNR**.

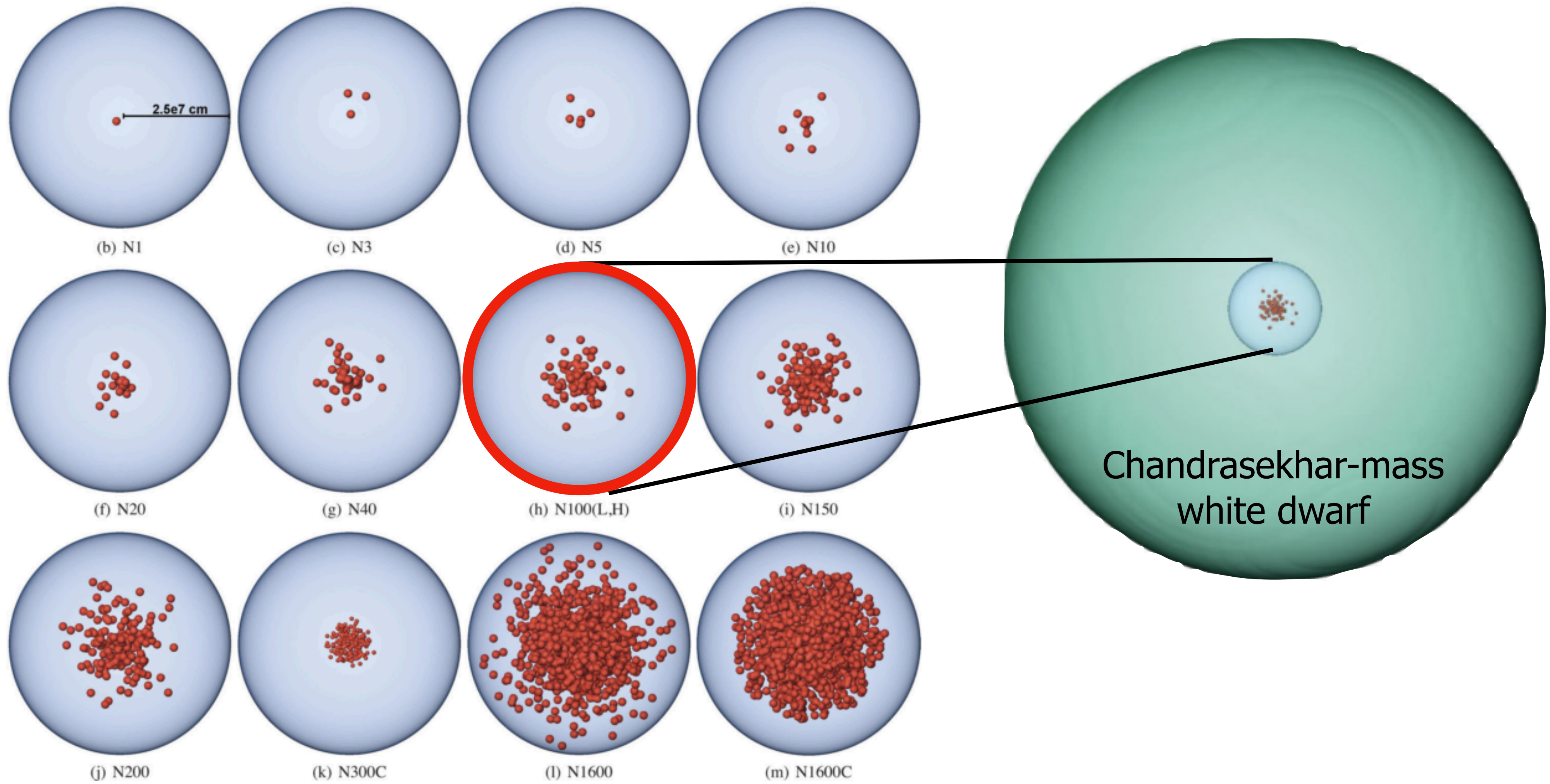


projection along l.o.s. of the density squared = proxy for the thermal emission

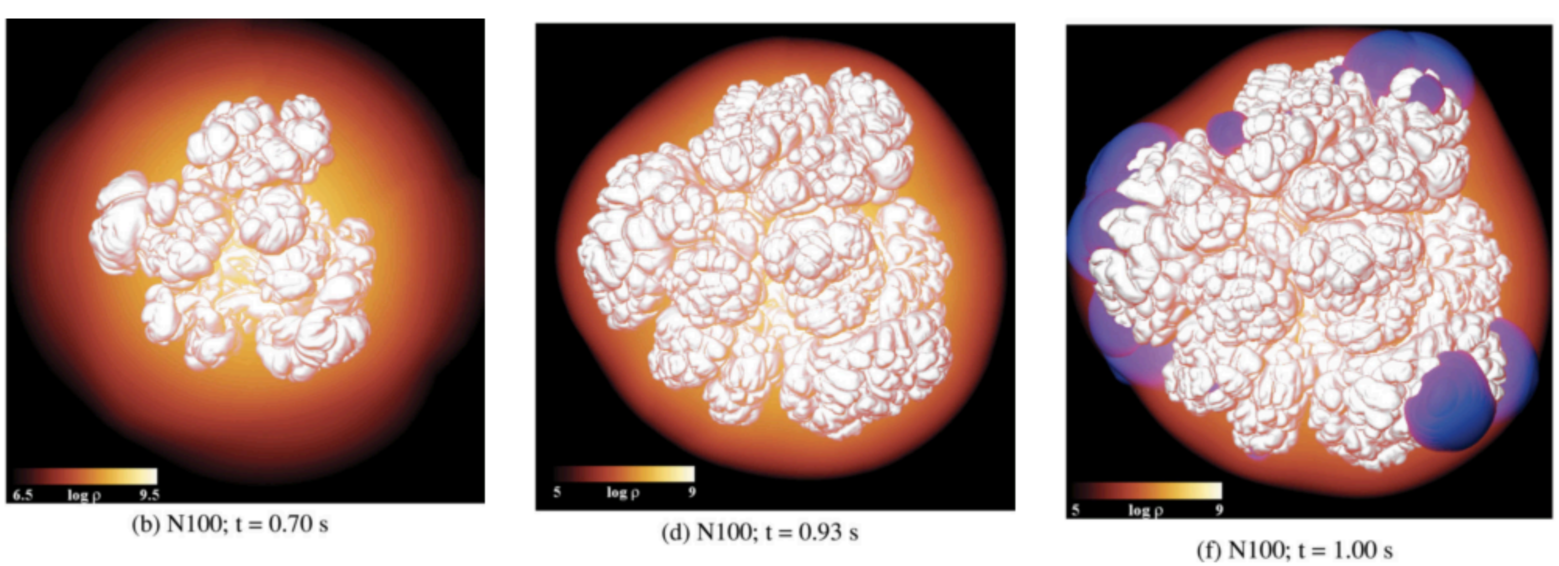
Ferrand et al 2019

Simulating a thermonuclear SN

Initial configuration of the flame? grid of ignition patterns



Propagation of the flame? deflagration and/or detonation



deflagration to detonation transition (DDT)

$M = 1.4\ M_\odot$

Seitenzahl et al 2013
Fink et al 2014

SNR morphology: N100 vs. N5 / DDT vs. def

N100ddt | N5ddt | N100def | N5def

x

y

z

movies in the online article

https://iopscience.iop.org/article/10.3847/1538-4357/abc951

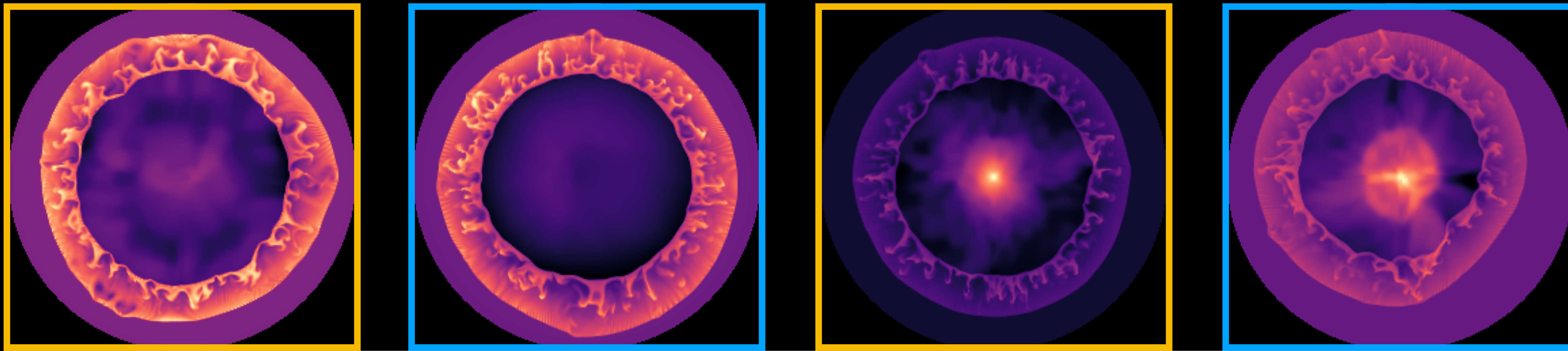
slices of log(density) t = 1 yr to 500 yr

Ferrand et al 2021

Signatures of the different N explosion models

N100ddt N5ddt N100def N5def

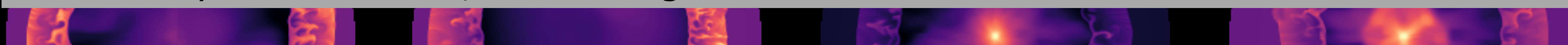
x



N100 models produce different remnants than N5 models

N5 models have a strong dipole component, and produce asymmetric remnants.
N5ddt: asymmetric shell, N5def: regular but off-set shell

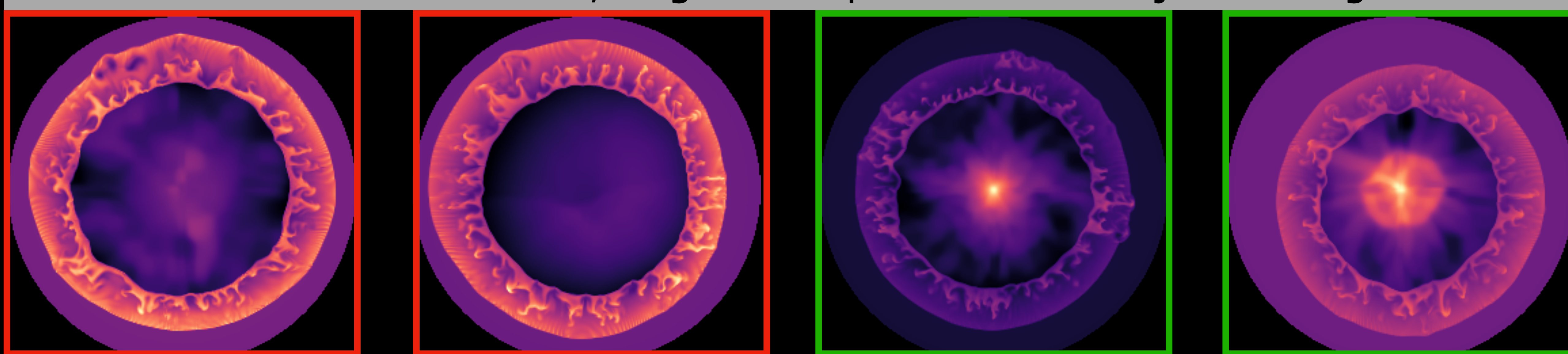
y



ddt models produce different remnants than def models

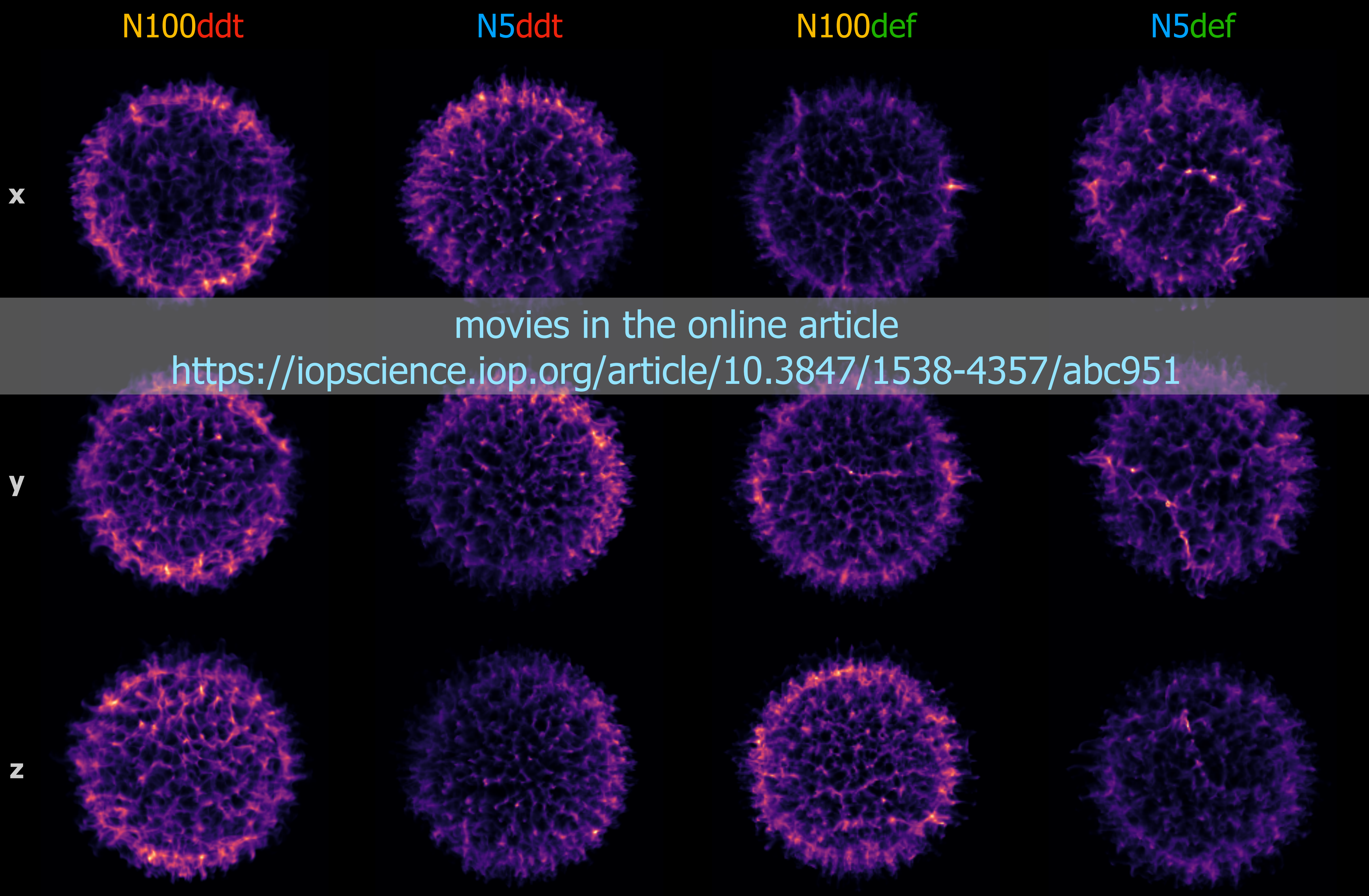
Pure deflagration models show the imprint of their specific mechanisms:
bound remnant at the centre, large-scale plumes at the ejecta's edge

z



Ferrand et al 2021

SNR emissivity: N100 vs. N5 / DDT vs. def



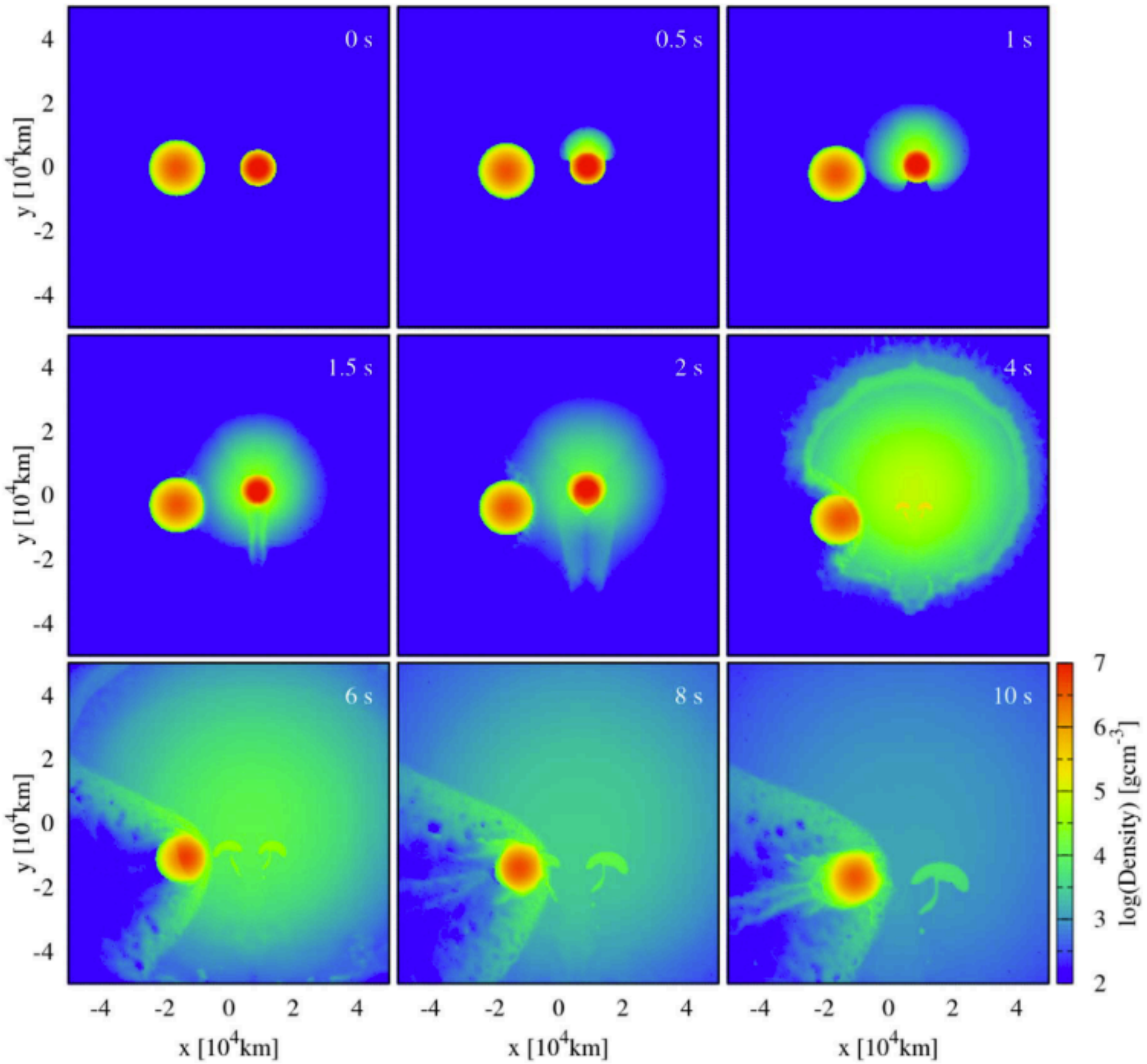
movies in the online article
https://iopscience.iop.org/article/10.3847/1538-4357/abc951

projection of (shocked) density squared at t = 500 yr

A different kind of model: D6

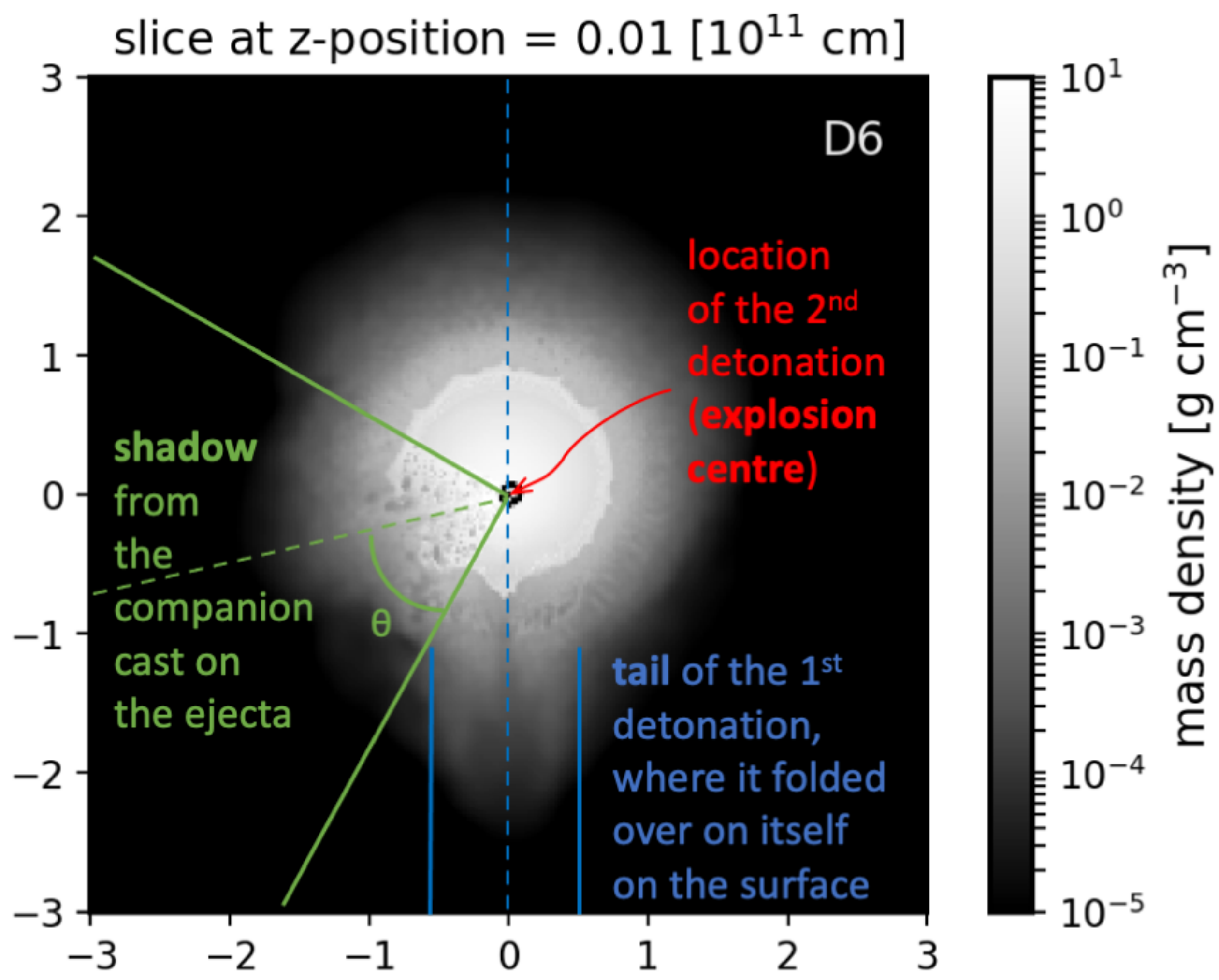
"helium-ignited violent merger" Guillochon et al. 2010; Pakmor et al. 2013

"dynamically-driven double degenerate double detonation" (D^6) Shen et al 2018



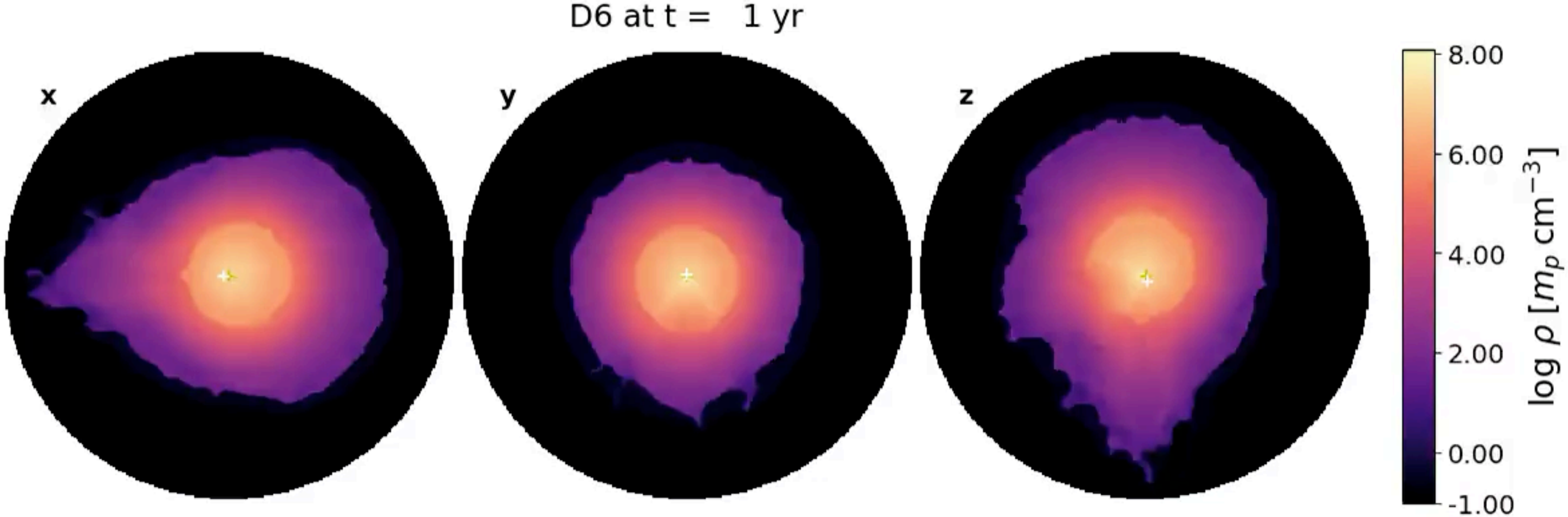
Tanikawa et al 2018

$M_1 = 1.0\ M_\odot$, $M_2 = 0.6\ M_\odot$



visible shadow from the surviving companion

D6 SNR morphology from 1 yr to 2500 yr



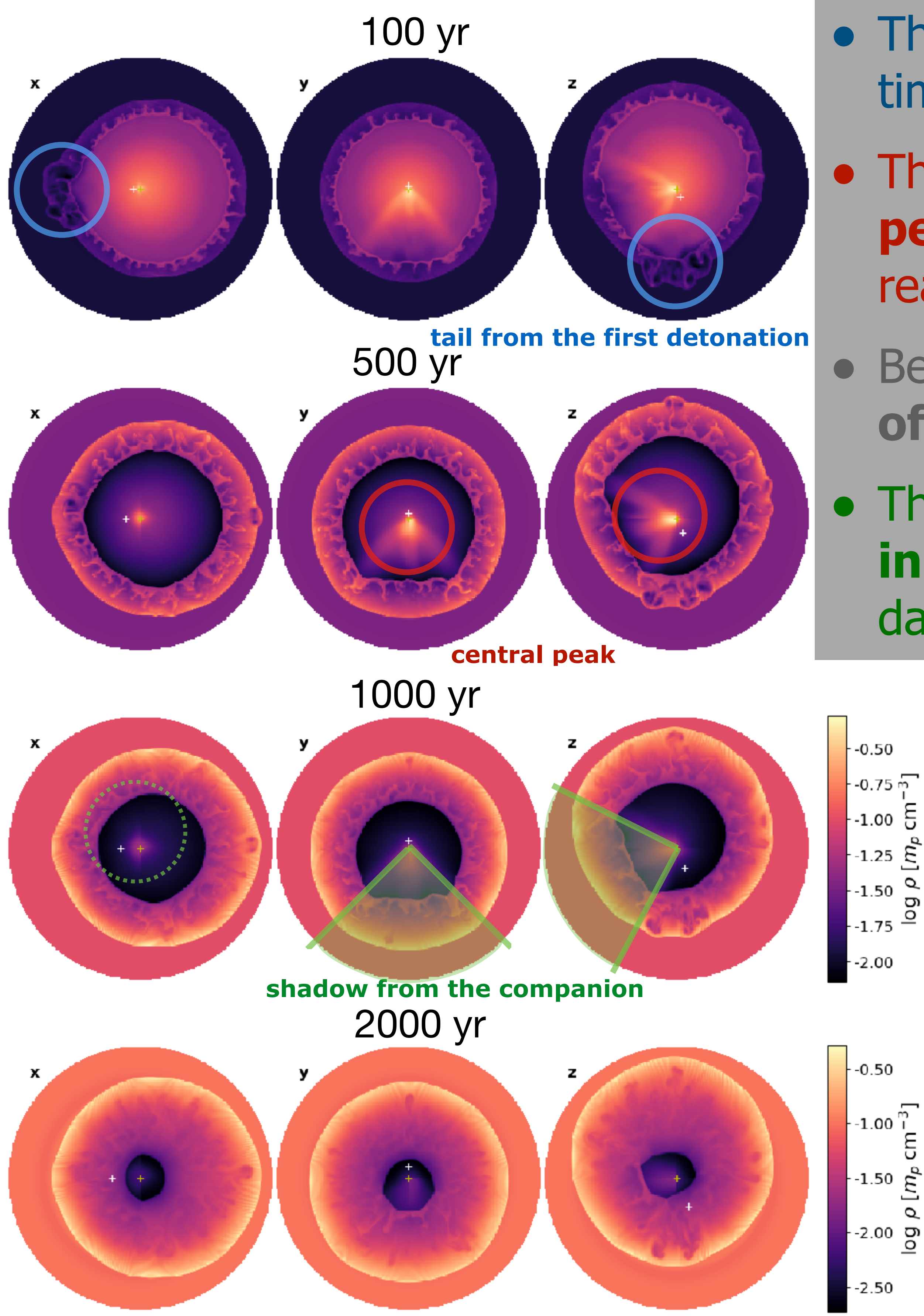
slices of log(density)

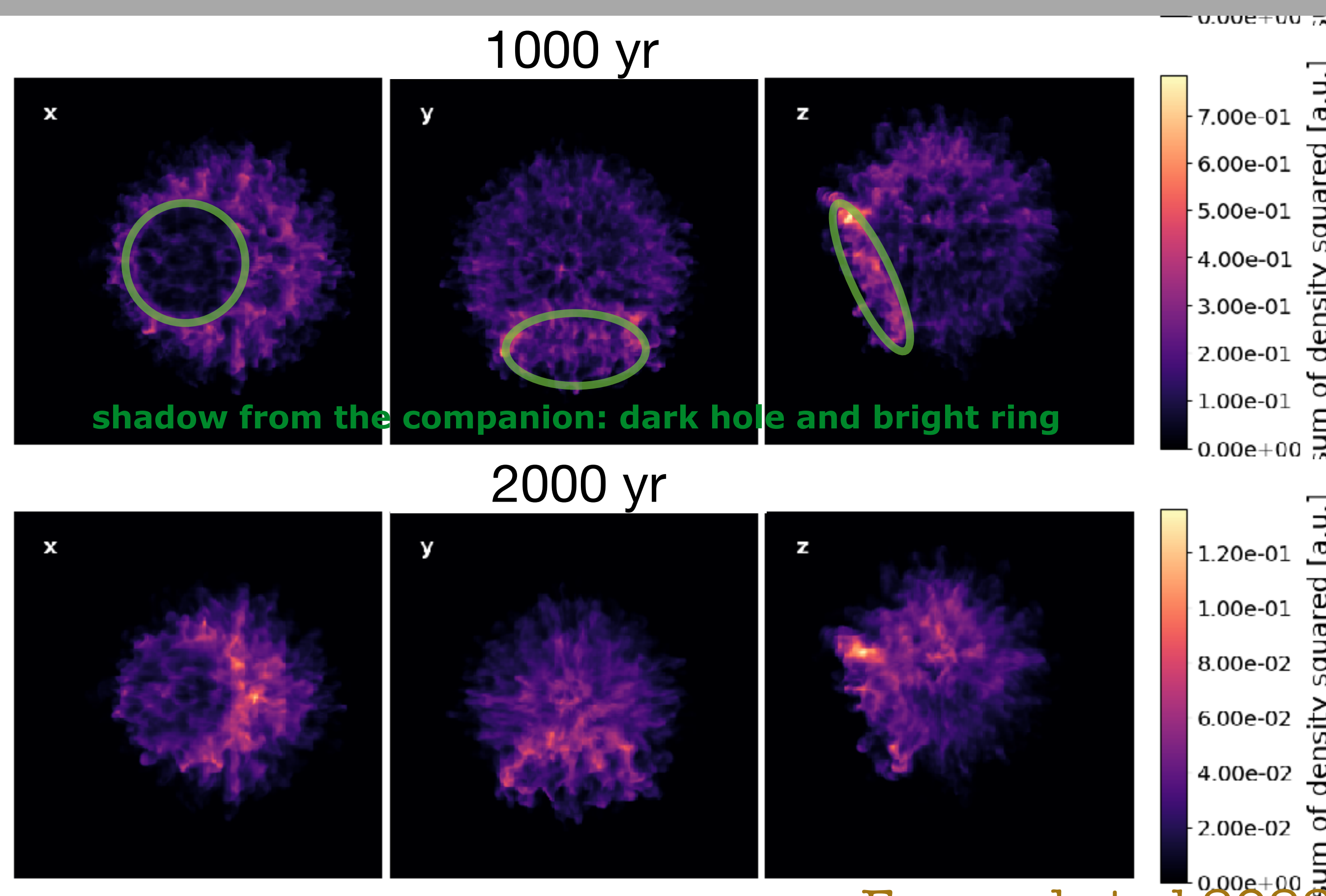
movies in the online article
https://iopscience.iop.org/article/10.3847/1538-4357/ac5c58

sum of density squared (shocked ejecta)

Signatures of a D6 SNR

- The first detonation produces a tail, which at early times looks like a **protrusion from the shell**
- The second detonation leaves a **central density peak**, which will be revealed in X-rays when the RS reaches the center
- Because of the initial velocity shift, the SNR **shell is off-center** at all times
- The companion star generates a **conical shadow in the ejecta**, which is visible in projection as a dark patch surrounded by a bright ring



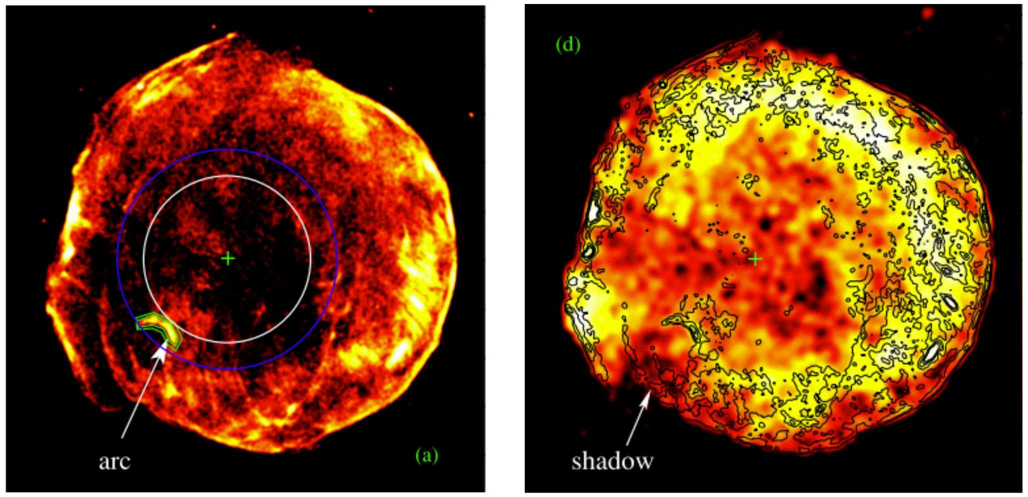


Ferrand et al 2022

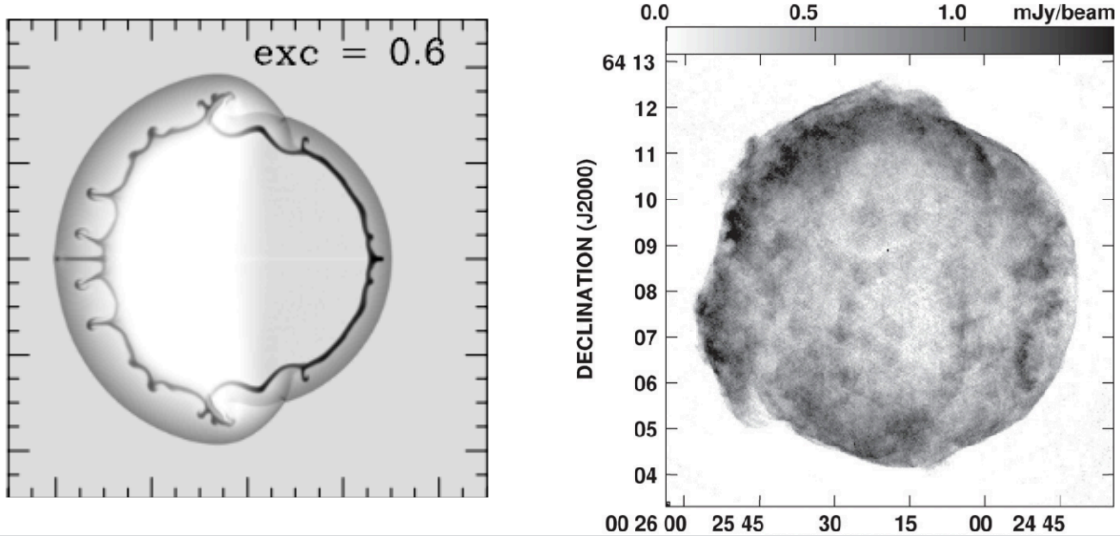
Previous studies of the companion-SNR interaction

interpretations of observations of Tycho SNR

an “arc” and “shadow” in the X-ray image of the SNR Lu et al 2011



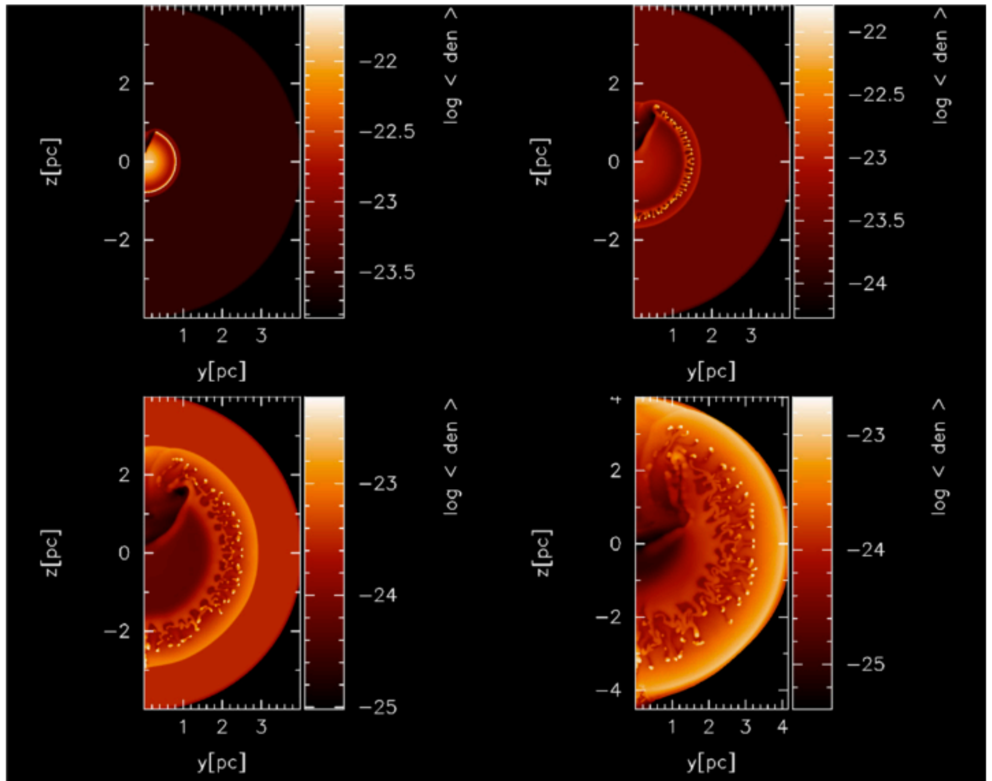
the SNR is two-sided because of mass loading Gray et al 2016



numerical simulations

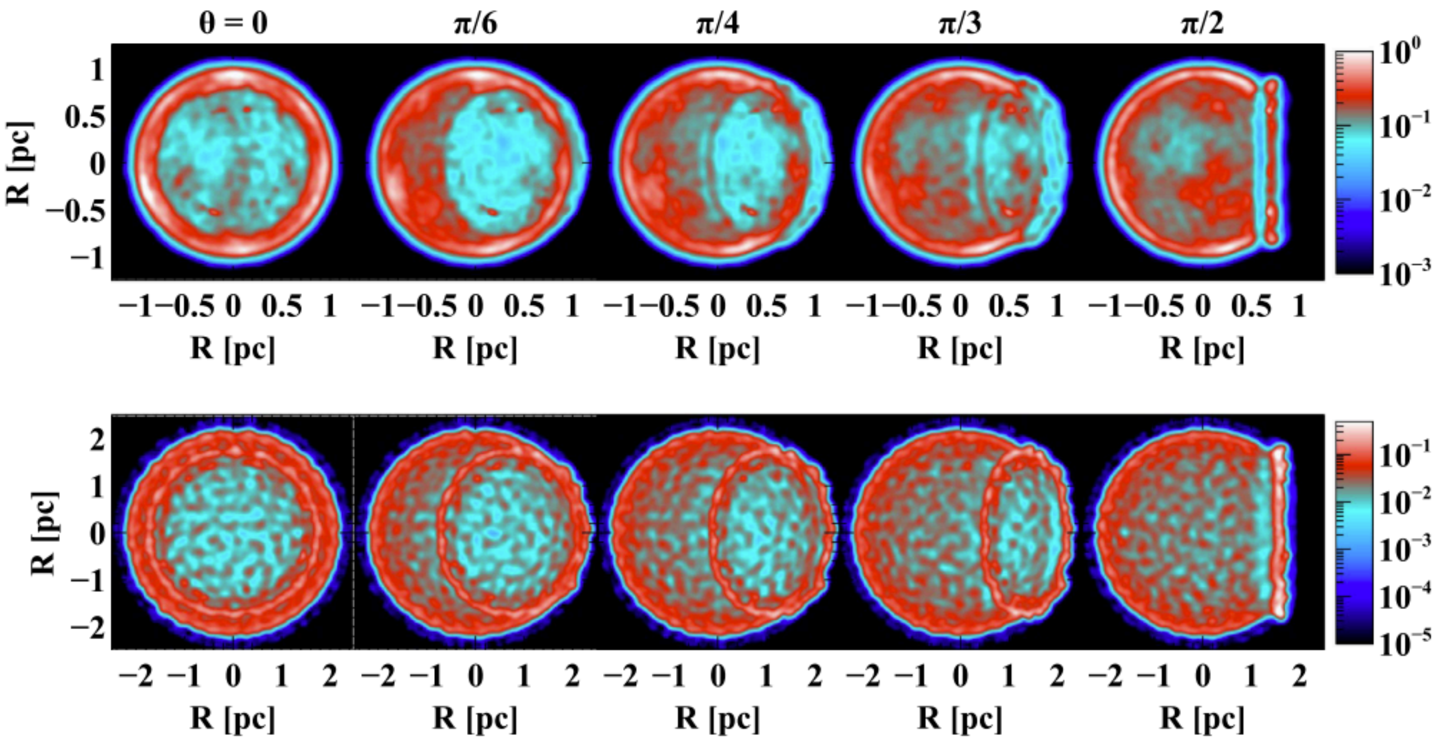
“Is there a hidden hole in Type Ia SNRs?”

Vigh et al 2011, Moranchel-Basurto et al 2020



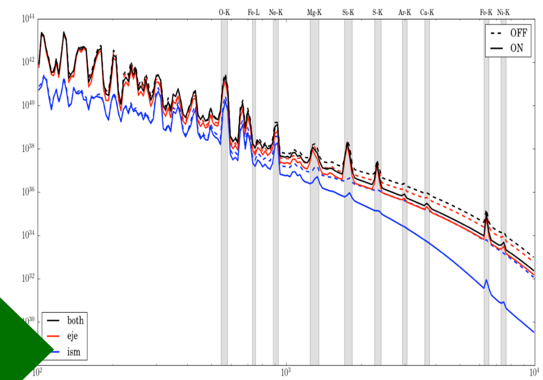
“Shadows of Our Former Companions”

García-Senz et al 2012, 2019



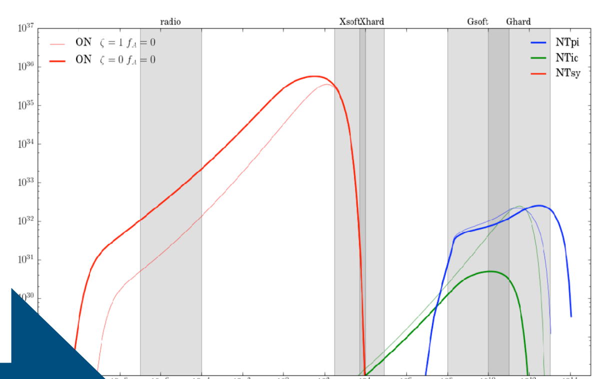
Computing the emission from the SNR

- **density** squared
- **electronic temperature** Te to be derived from Tp
- **ionization fractions** need to compute non-equilibrium ionization state

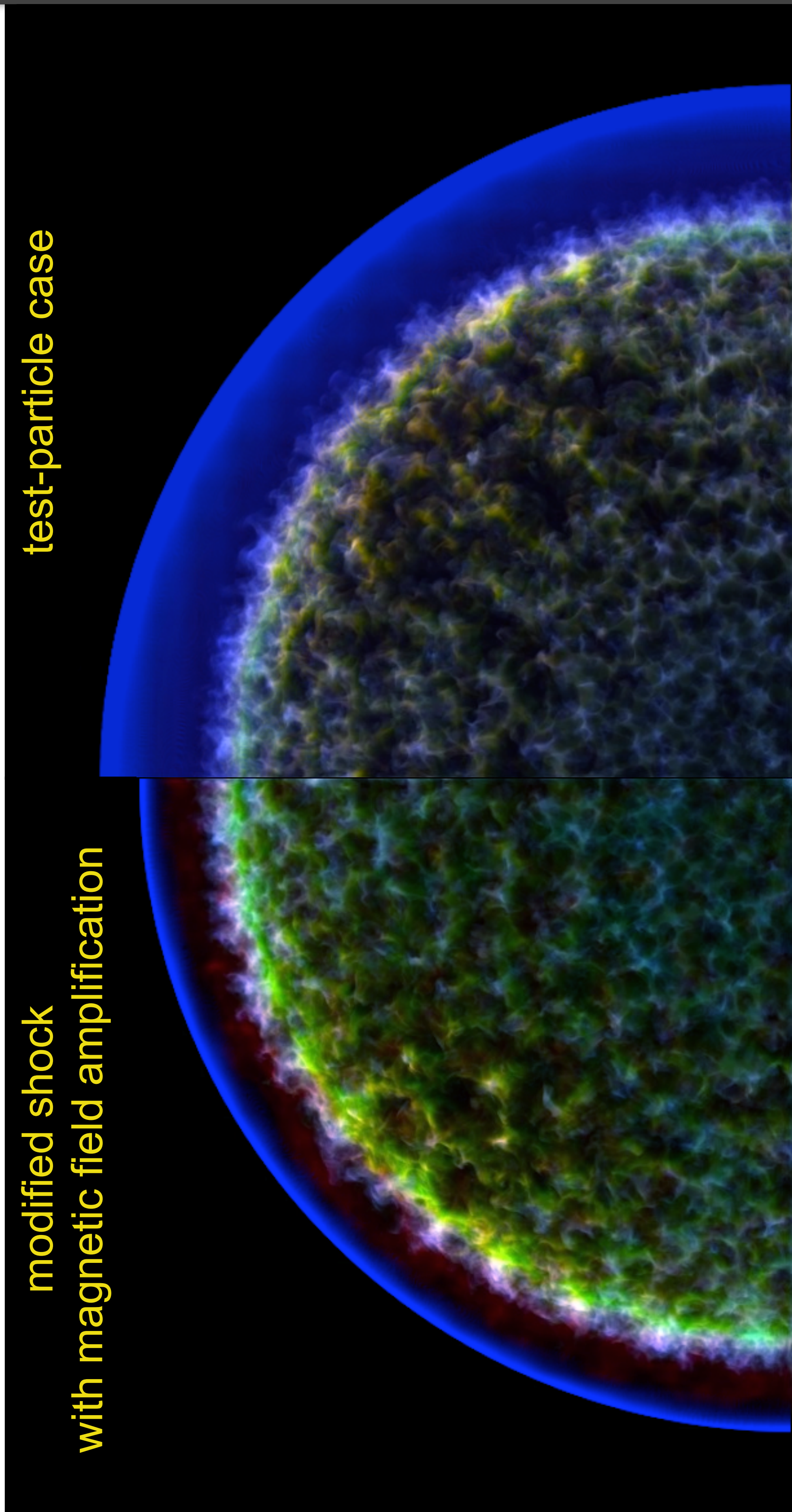


thermal emission from the shocked plasma

- target **density**
- **magnetic field** includes amplification at the shock
- ambient **photon fields**



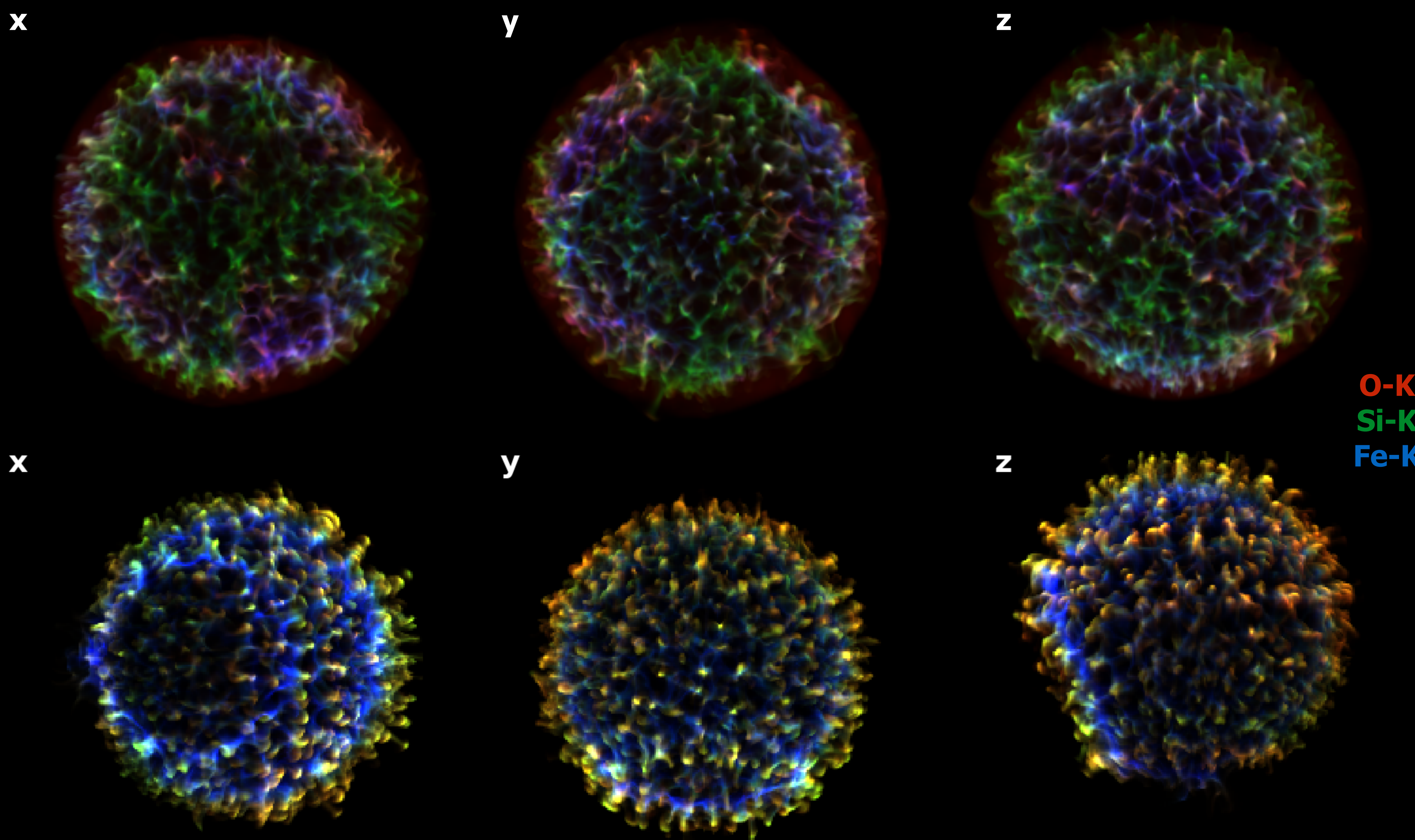
non-thermal emission from the accelerated particles



e.g. Ferrand et al 2012, 2014

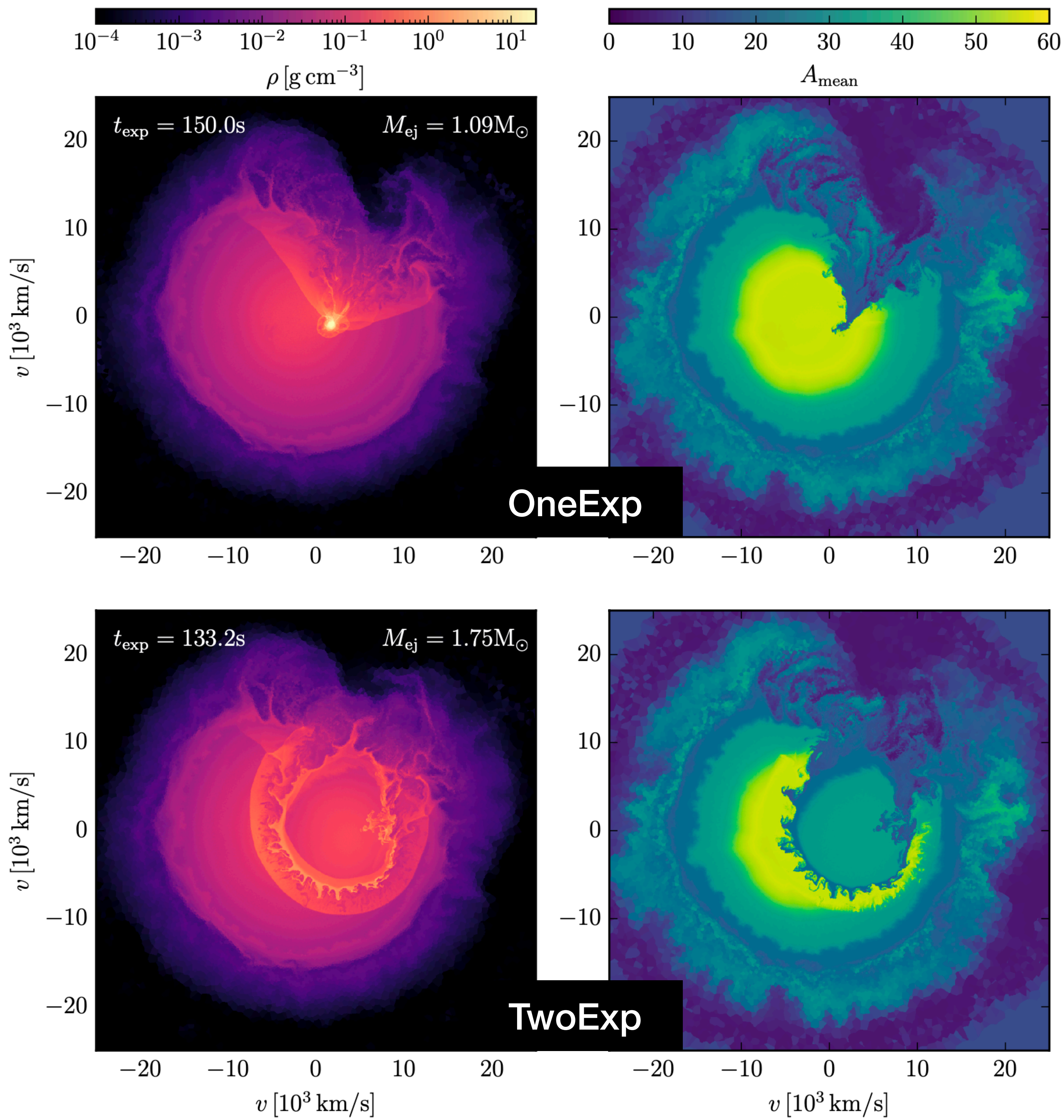
Thermal X-ray emission

N100 and D6 at 500 yr, 3 viewing directions



Being used to generate mock observations for existing and planned instruments

The fate of the secondary WD



shadow from the secondary

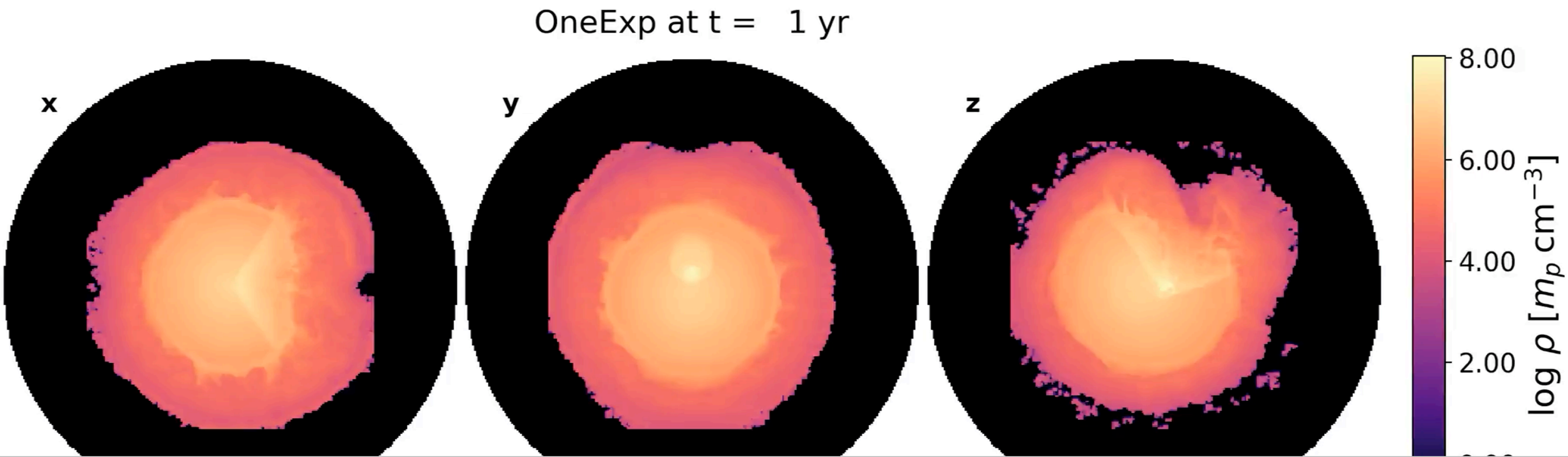
in a double degenerate system (with double detonation), **the secondary WD may or may not explode**

nested explosions: secondary within primary

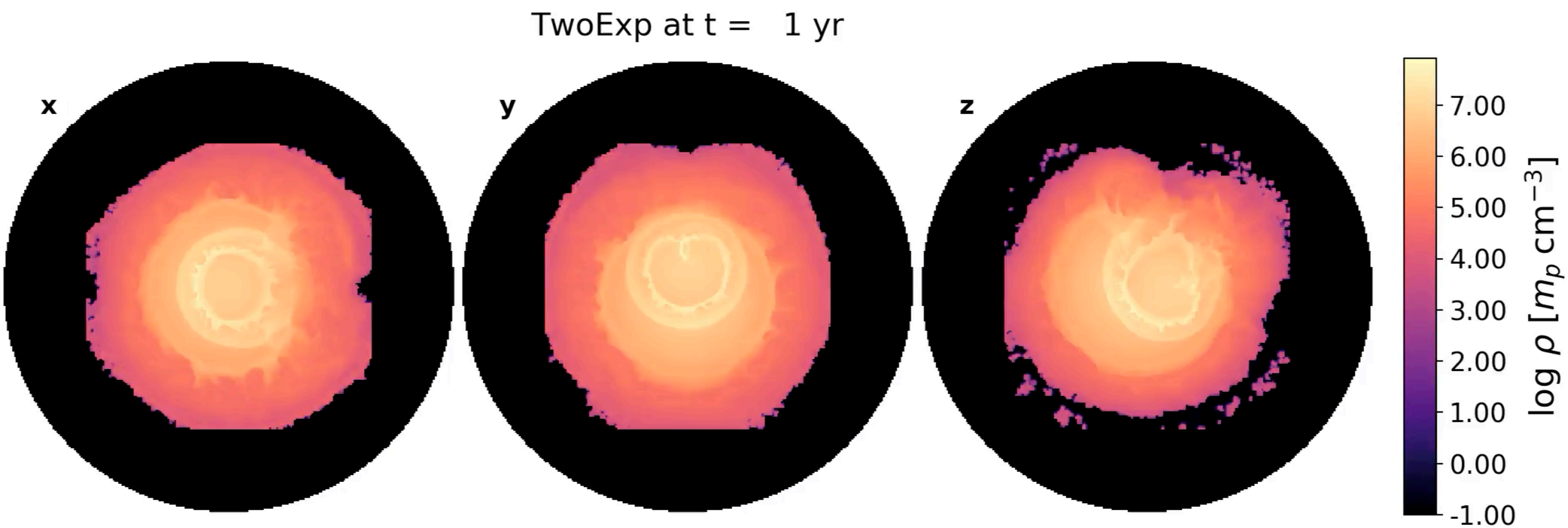
Pakmor et al. 2022

$M_1 = 1.05\ M_\odot$, $M_2 = 0.7\ M_\odot$

OneExp/TwoExp SNR morphology (1/2)

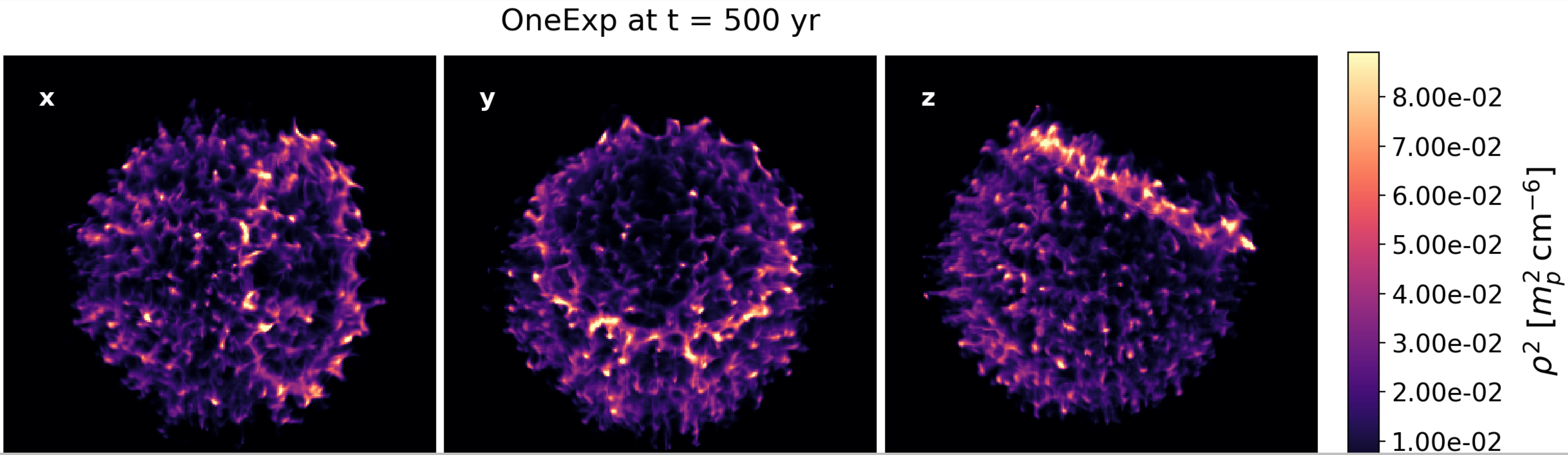


movies will be available in the online article

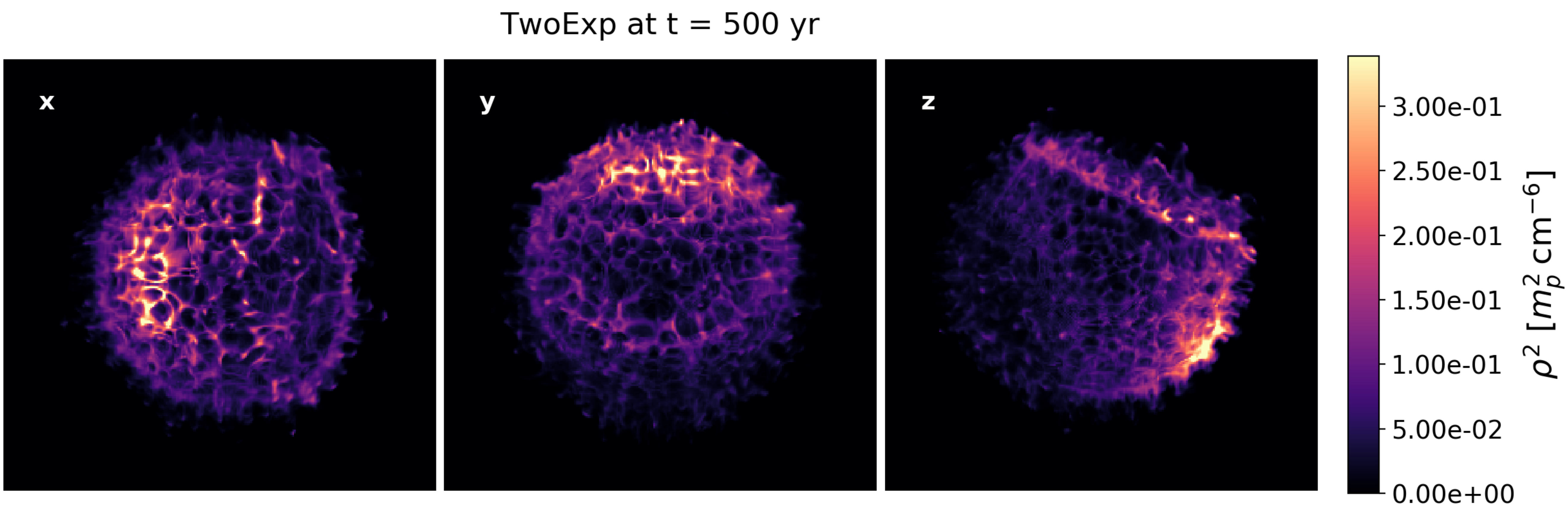


Ferrand et al. 2025 in prep

OneExp/TwoExp SNR morphology (2/2)

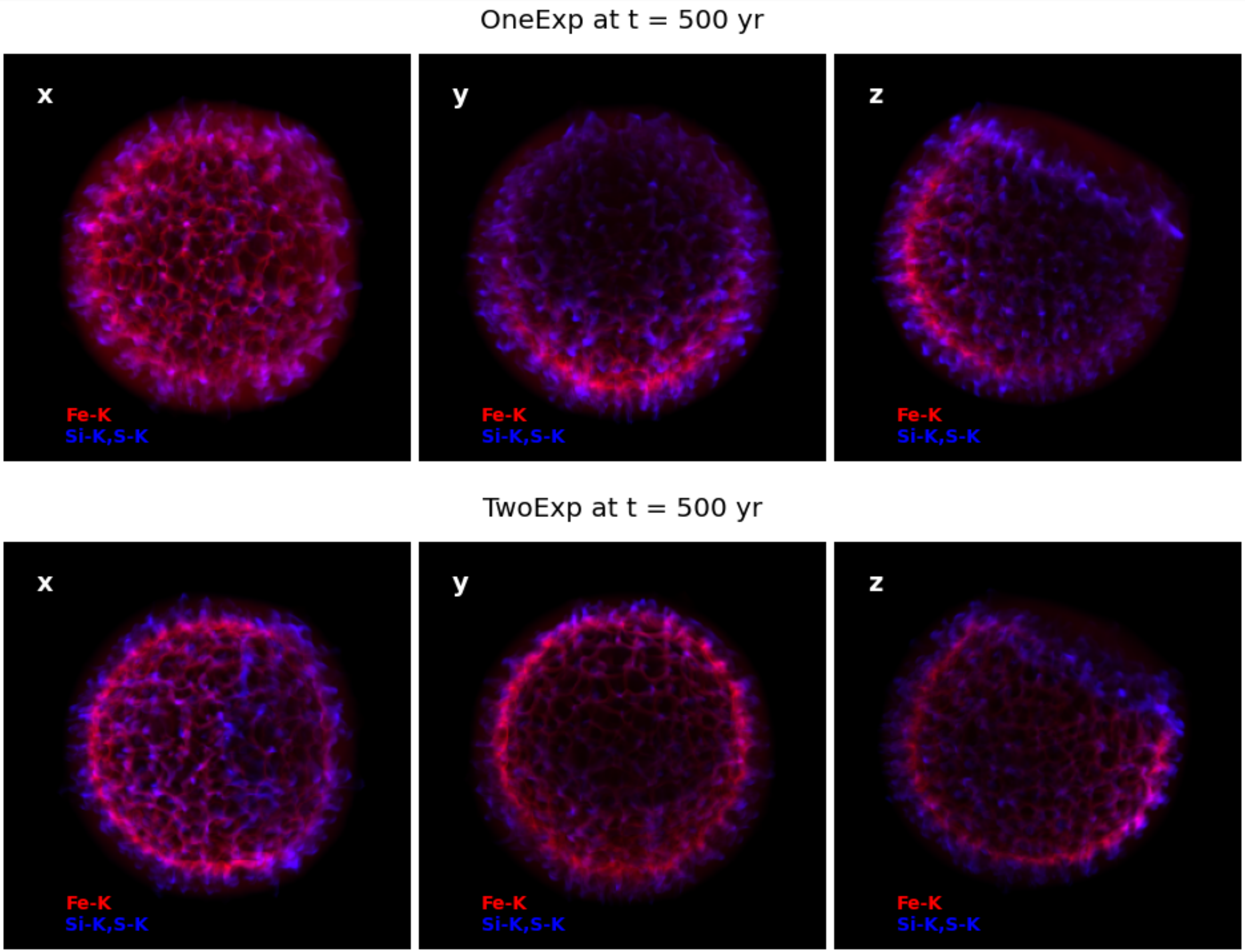


movies will be available in the online article



Ferrand et al. 2025 in prep

OneExp/TwoExp X-ray emission



Ferrand et al. 2025 in prep

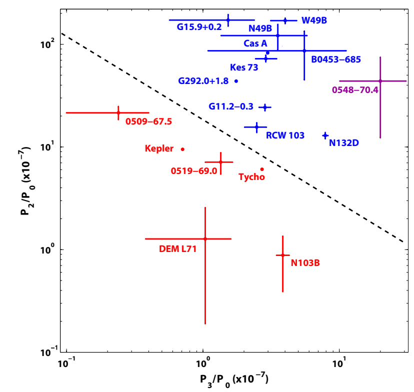
Tools for morphological analysis of images

Harmonic analysis: expand the brightness variations on some nice basis of functions

- **2D Fourier** transform: `exp(i(ux+vy))`
- **correlation-length** analysis

Lopez et al 2009

- **power-ratio method** = 2D multipole expansion: r^n `exp(inθ)` (related to solid harmonics)



Lopez et al 2009, 2011, Holland-Ashford et al 2019

- cylindrical **Fourier-Bessel**: `Jm(k_nm r)×exp(imθ)` (analogue to spherical harmonics)

- **wavelets**: localized in space and frequency

Lopez et al 2009, 2011

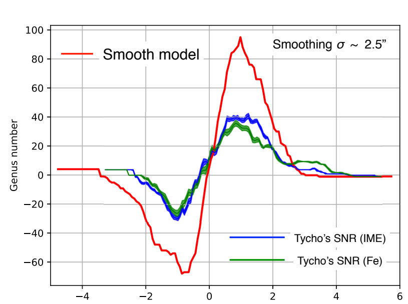
- **morphological component analysis** (MCA) dictionary of wavelet-like components

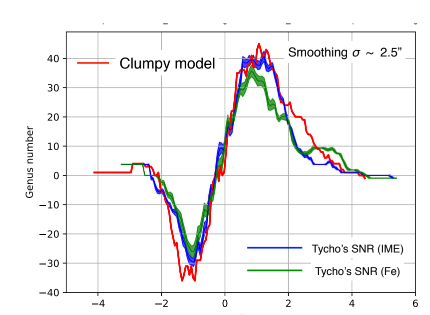
Picquenot et al 2019

Topological approach: compute Minkowski functionals on set of thresholded images

- **genus statistics** (Euler characteristic): counting number of clumps vs. holes

Sato et al 2019





Summary and perspectives

- **Making the link between the 3D modeling of SNe and the 3D modeling of SNRs.**
  Here investigating thermonuclear explosions (Type Ia), for the core-collapse case see Orlando, Ono, Gabler, et al

> some imprints of the SN in the SNR phase:
> N100: angular power at larger scales than RTI
> N5: large asymmetries (dipole, offset)
> def: remains in the centre, filaments at the edges
> DD: shadow from a companion (angle-dependent)
> nested explosions with peculiar ejecta structure

- The combination of 3D simulations and spatially resolved spectroscopic observations of young SNRs in X-rays will enable us to better constrain explosion mechanism(s). Ideally **we want to get more observational information on the 3D structure of the SNR**.

Interactive 3D models are available online https://skfb.ly/oTCrY (I also do Virtual Reality!)