RIKEN - RESCEU Joint Seminar
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The University of Tokyo, Hongo campus, Japan

From the (thermonuclear) supernova to the supernova remnant

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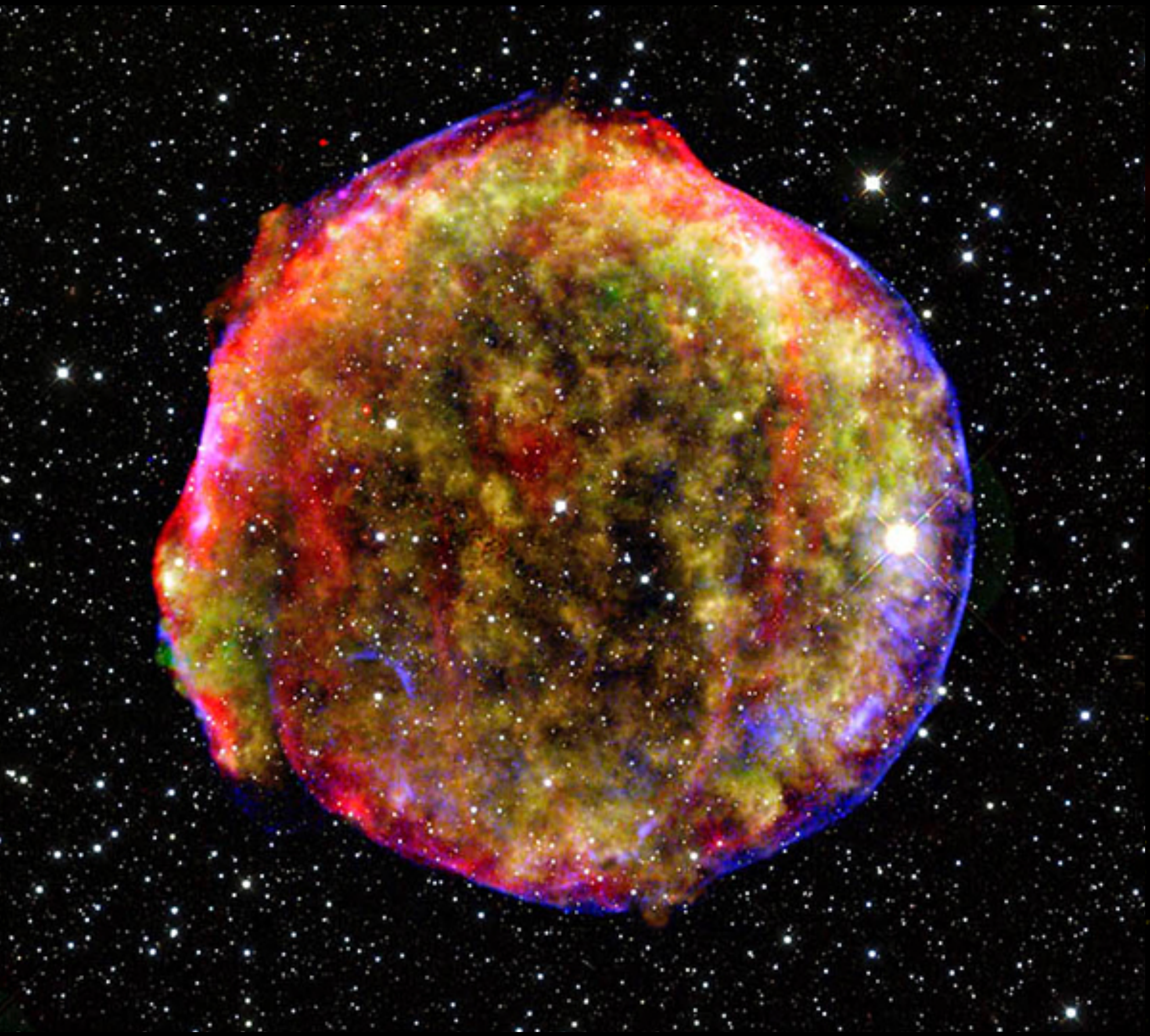
Two historical remnants

age: 446 yr
distance: 1.5-5 kpc
size: 8' ~5-12 pc

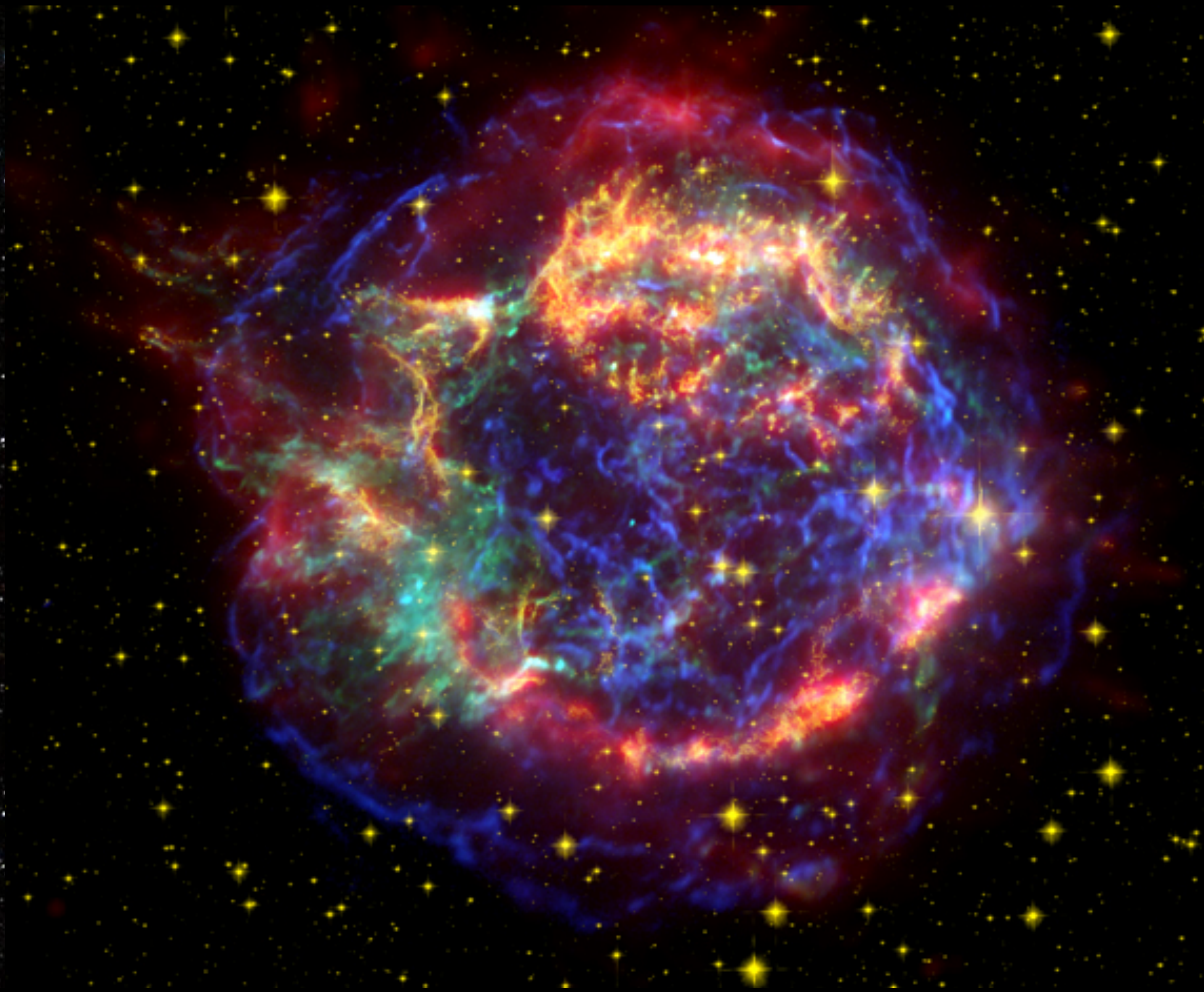
Tycho's SNR
SN 1572
thermonuclear

Cas A SNR
(missed SN)
core-collapse

age: ~330 yr
distance: 3.3-3.7 kpc
size: 5' ~5-7 pc



multi-wavelength composite:
X-rays (Chandra 1-2 keV and 4-6 keV)
optical (Calar Alto)
infrared (Spitzer)

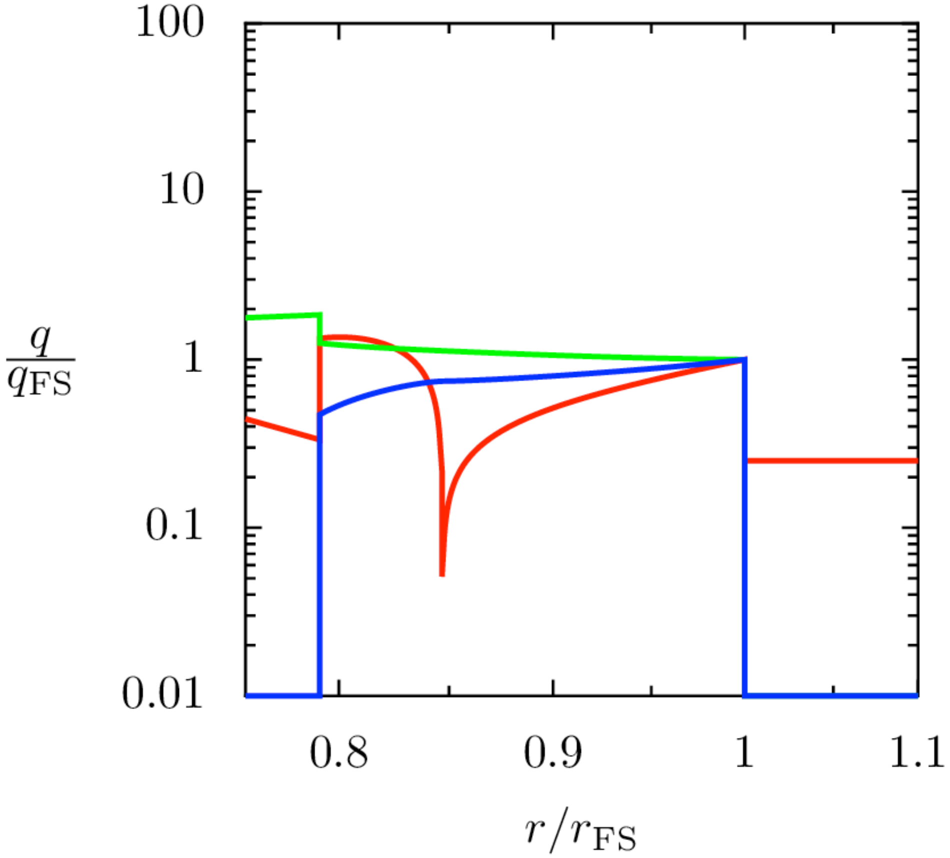


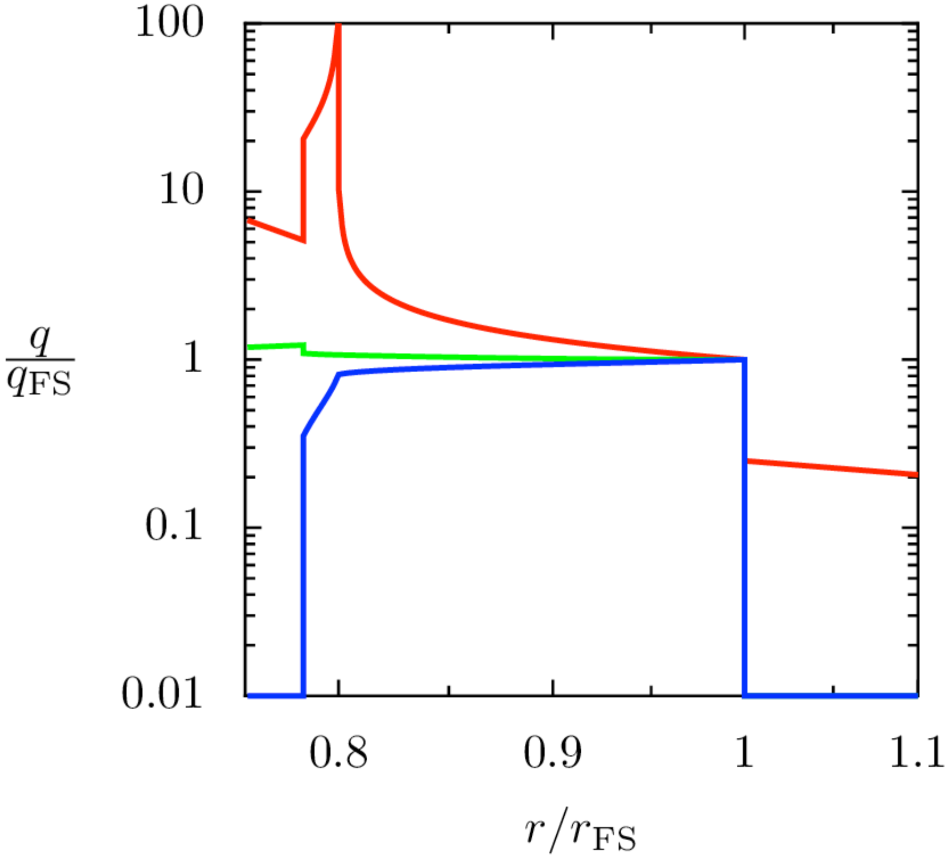
multi-wavelength composite:
X-rays (Chandra 0.5-2.5 keV and 4-6 keV)
near IR (Hubble)
infrared (Spitzer)

The two types of supernovae and their remnants

explosion SN type	**thermonuclear** **Ia**	**core-collapse** **II, Ib/c**
energy	10^{51} erg = 10^{44} J	10^{51} erg = 10^{44} J
ejected mass	1.4 solar masses	a few solar masses
ejecta profile	steep power-law $\propto r^{-7}$	steeper power-law $\propto r^{-9}$
ambient density profile	uniform ISM $\propto r^{0}$	stellar wind $\propto r^{-2}$
3D morphology	usually simple	often complex
ambient magnetic field	uniform ≈ few μG	(uncertain)

q = density, velocity, pressure





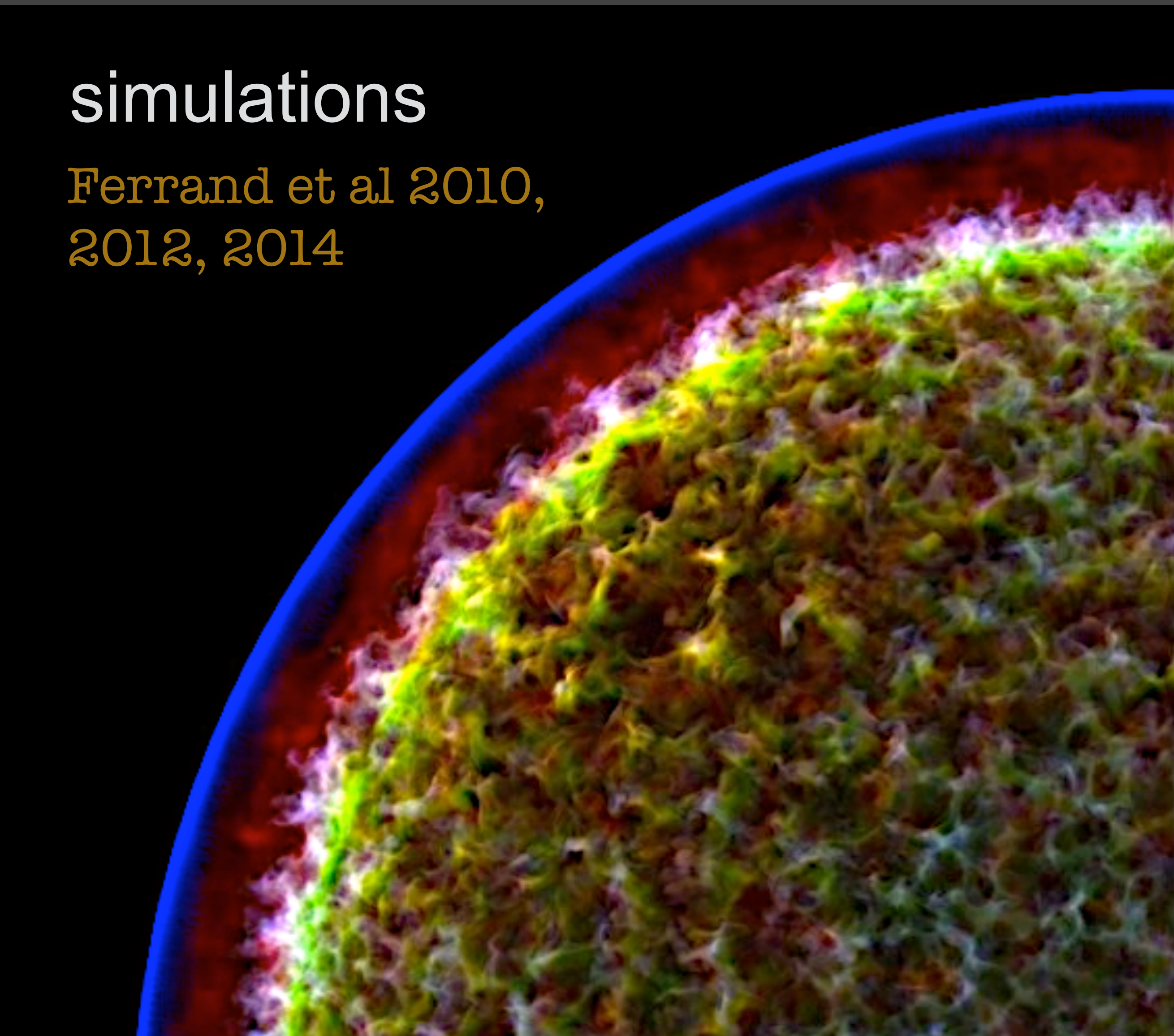
self-similar profiles

Chevalier 1982

Simulating a supernova remnant in X-rays

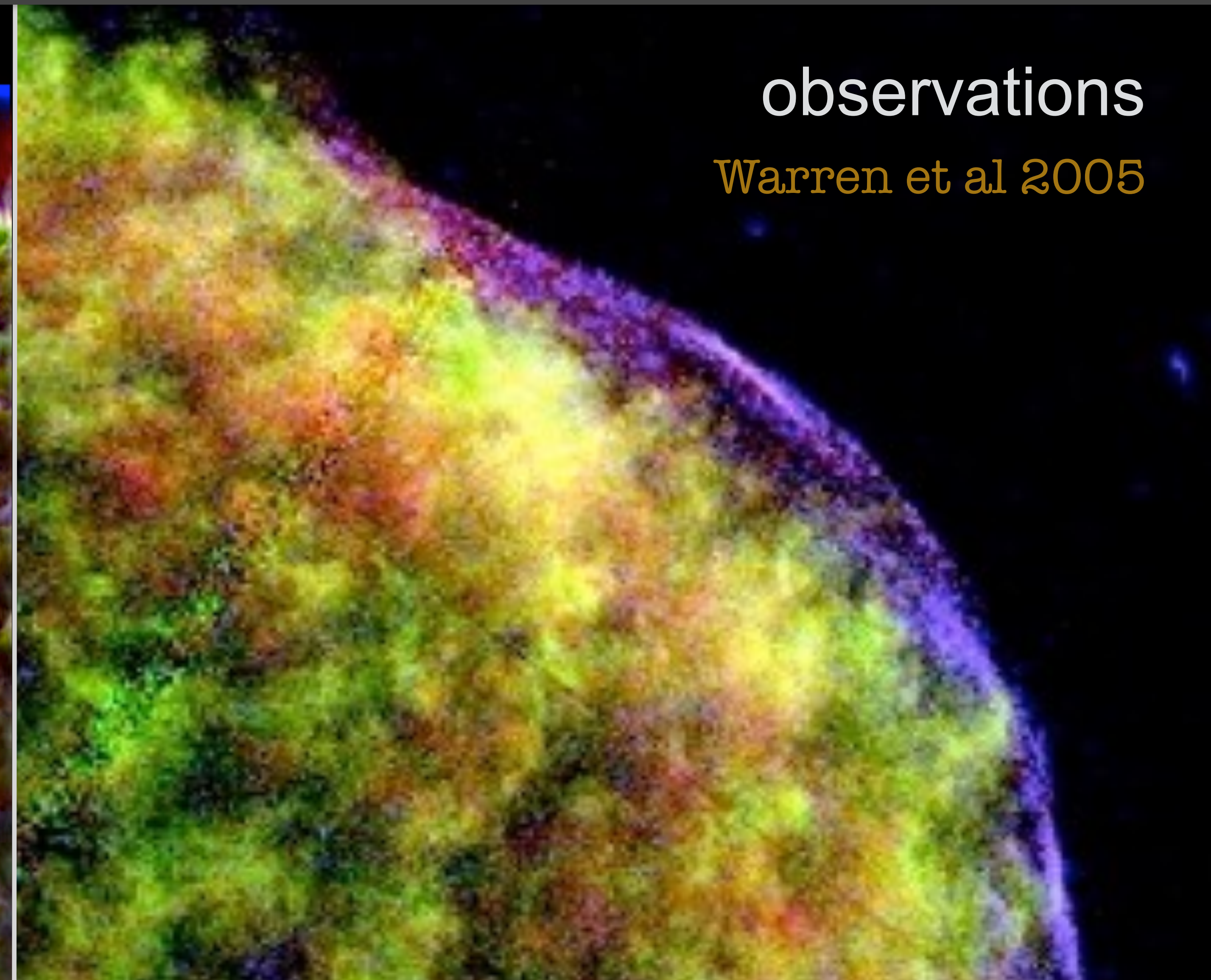
simulations

Ferrand et al 2010, 2012, 2014



observations

Warren et al 2005

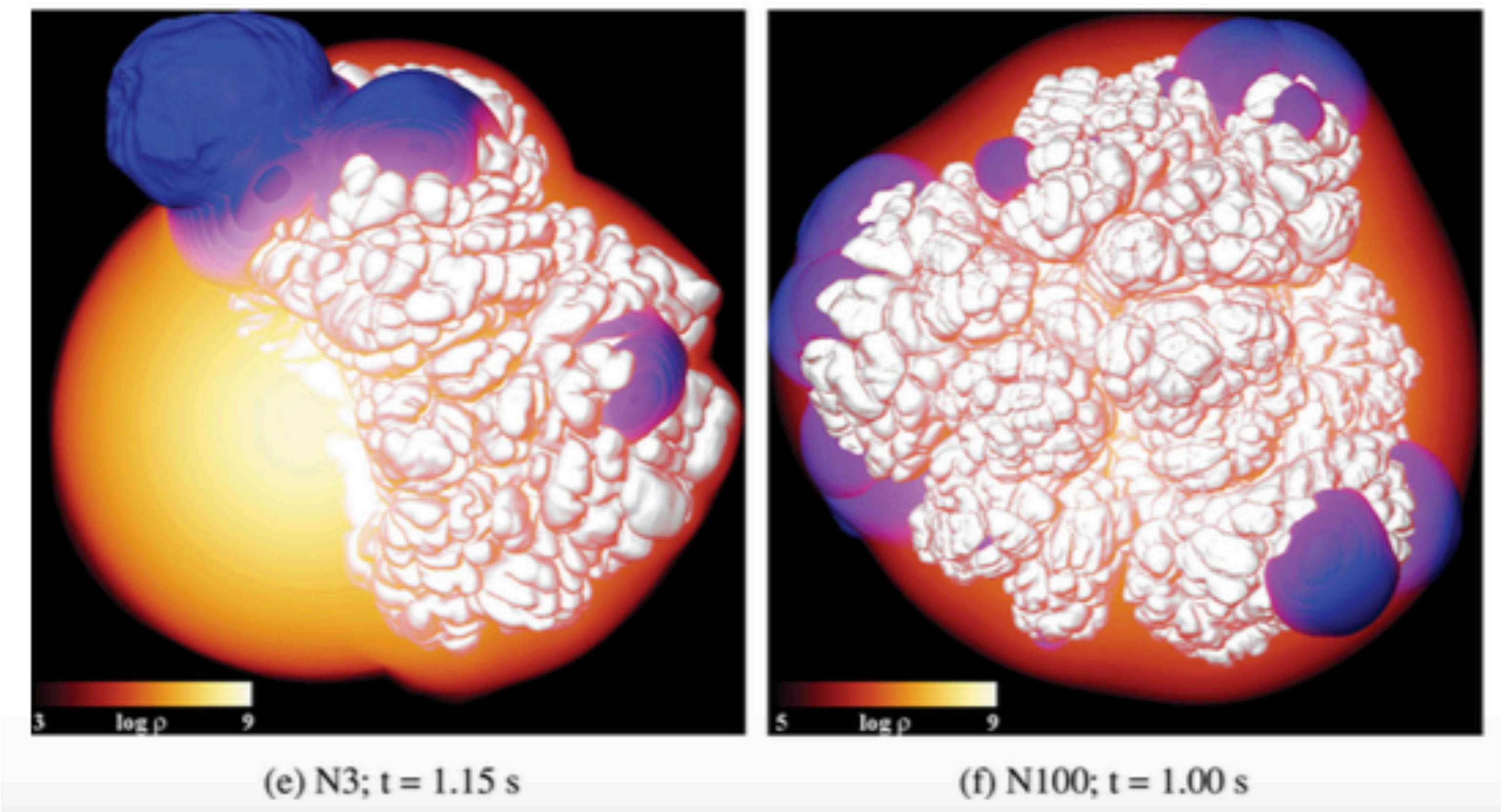


Grex supercomputer, UofM, 2011

Chandra observatory, NASA, 199

From the 3D supernova to the 3D remnant

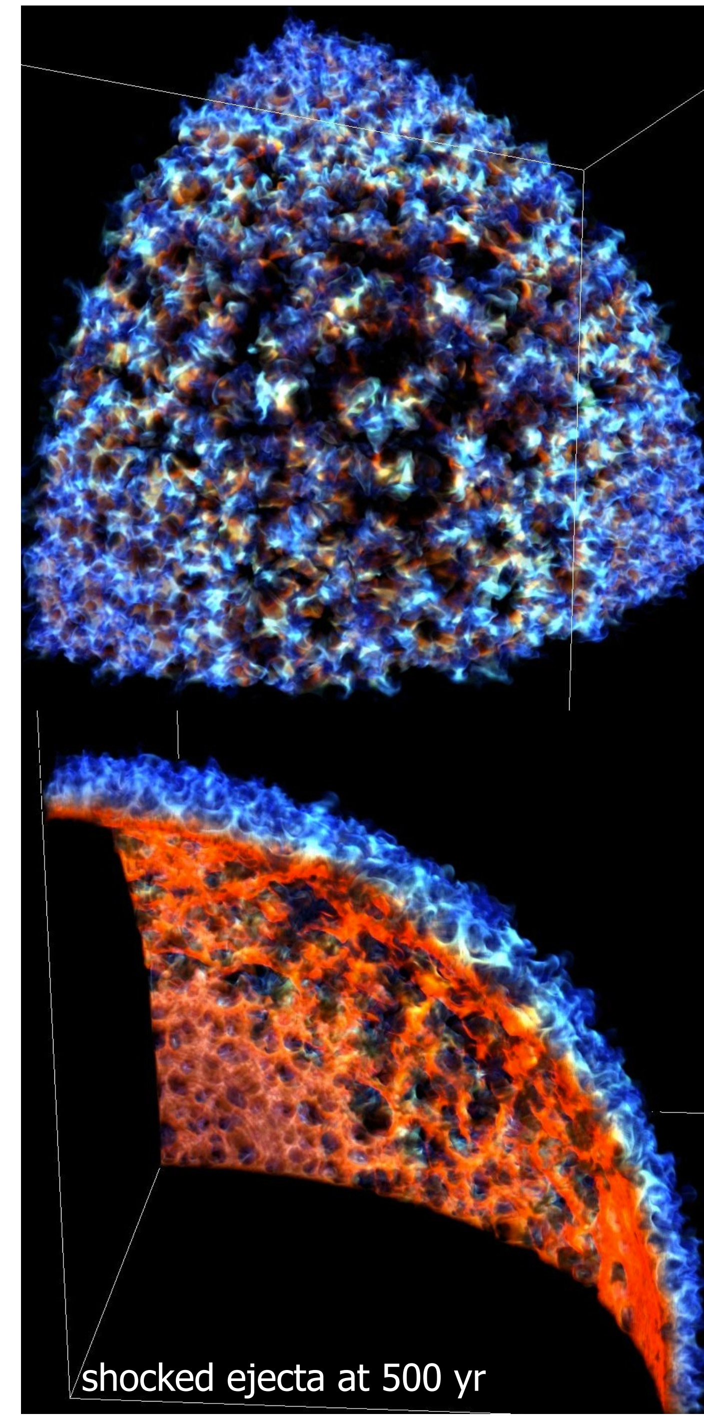
3D simulations of thermonuclear supernovae (TN SN)



Röpke 2007, Seitenzahl et al 2013

?

3D simulations of a supernova remnant (SNR)

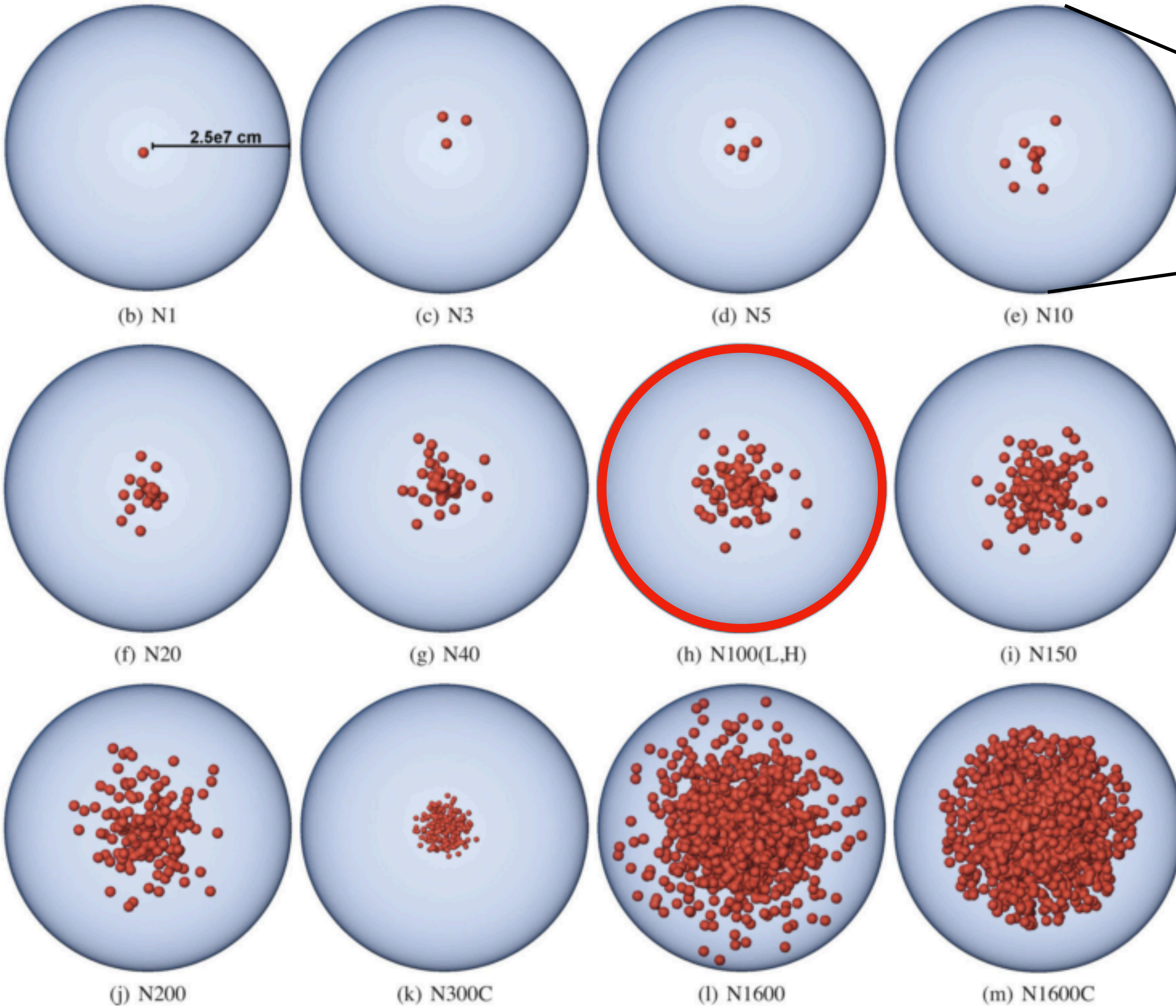


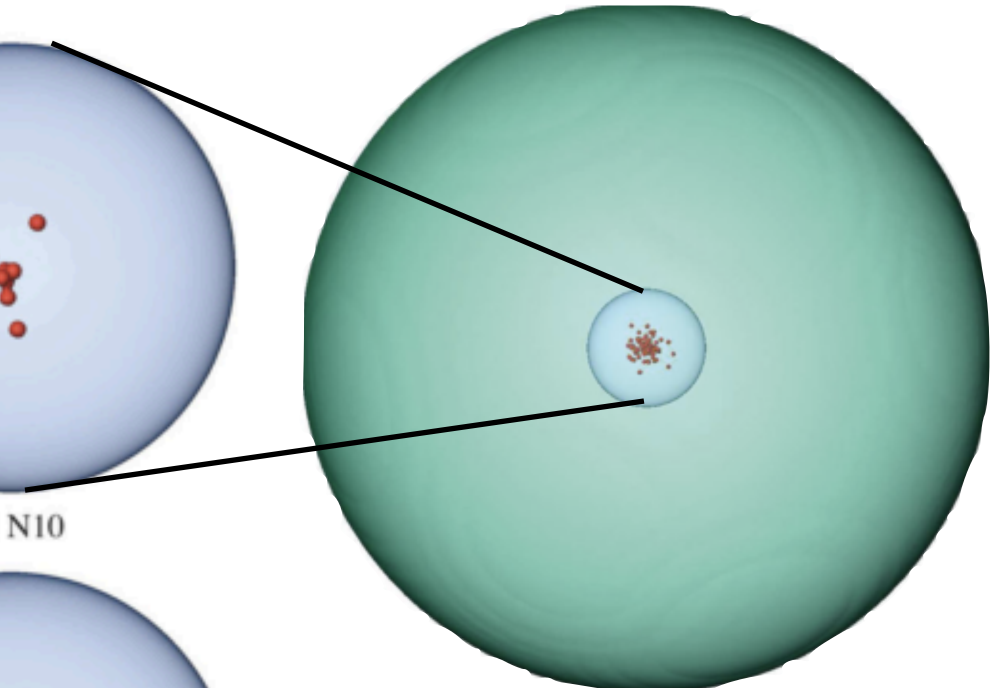
Ferrand et al 2010, 2012, 2014, 2016

What can the (morphology of the) SNR tell us about the explosion?

the supernova model: N100

Simulating a thermonuclear SN: initial conditions



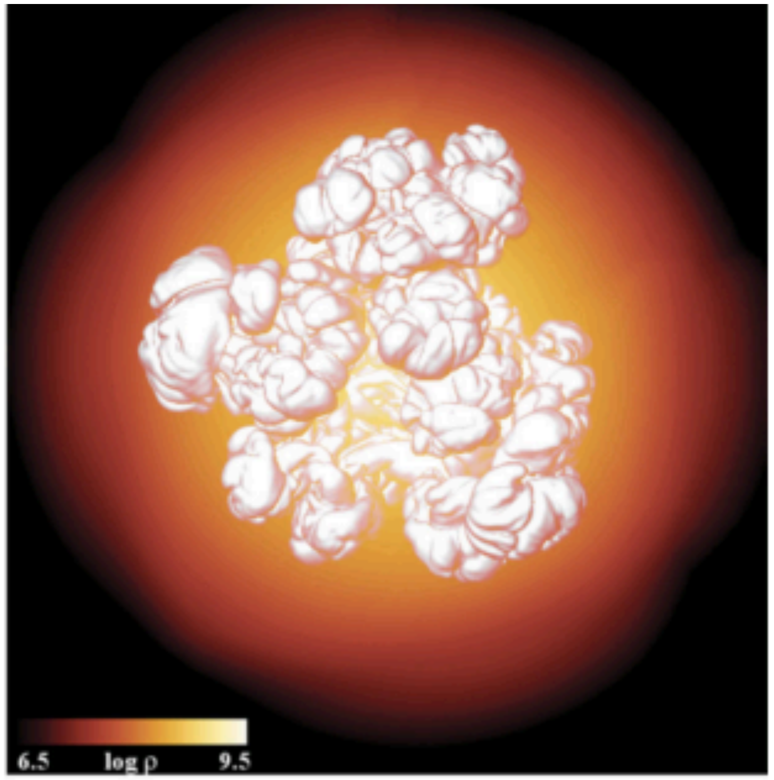


Chandrasekhar-mass white dwarf

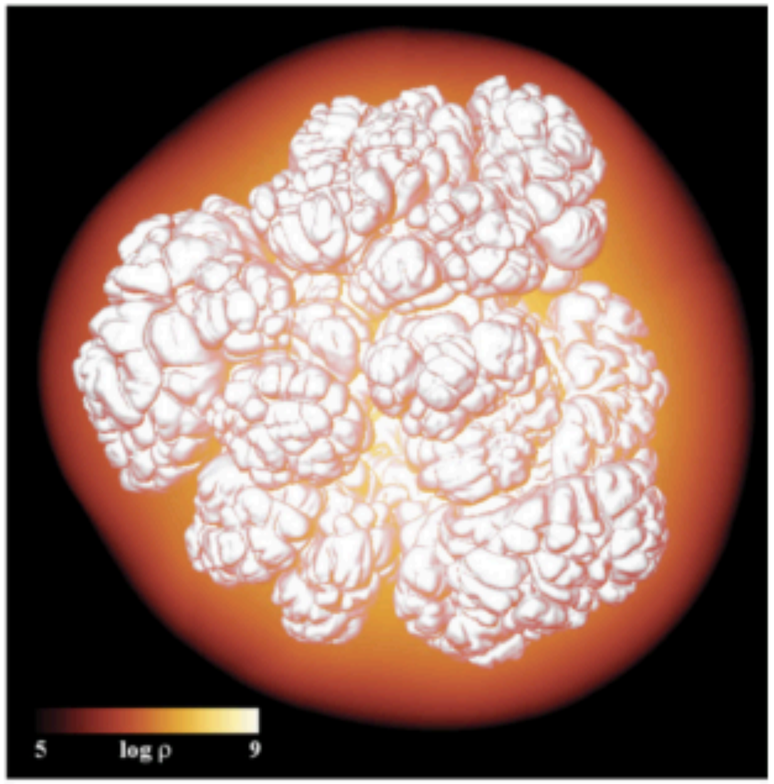
initial flame configuration? grid of ignition patterns

Seitenzahl et al 2013

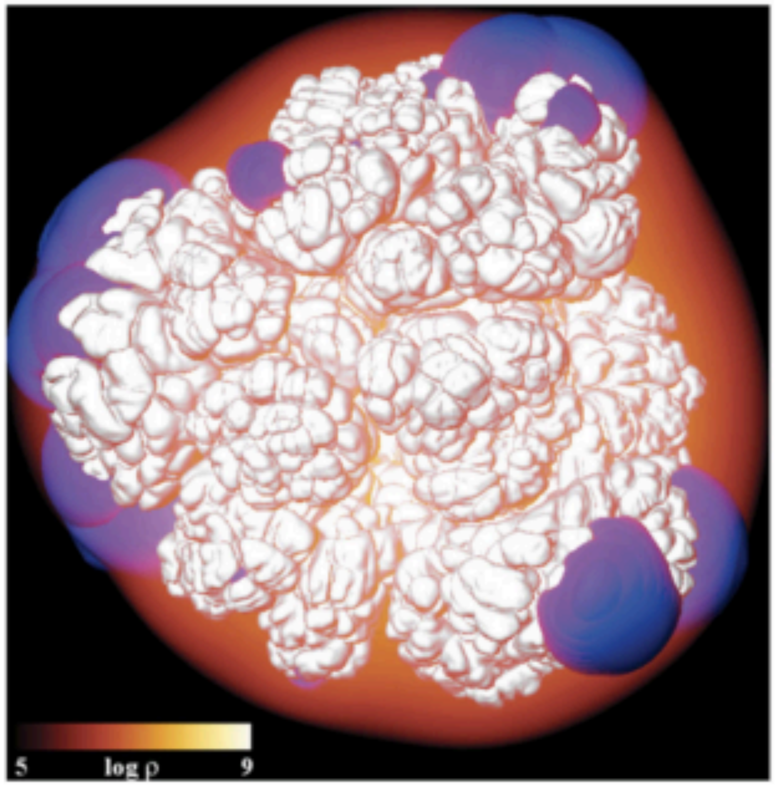
Simulating a thermonuclear SN: hydro 3D evolution



(b) N100; t = 0.70 s



(d) N100; t = 0.93 s



(f) N100; t = 1.00 s

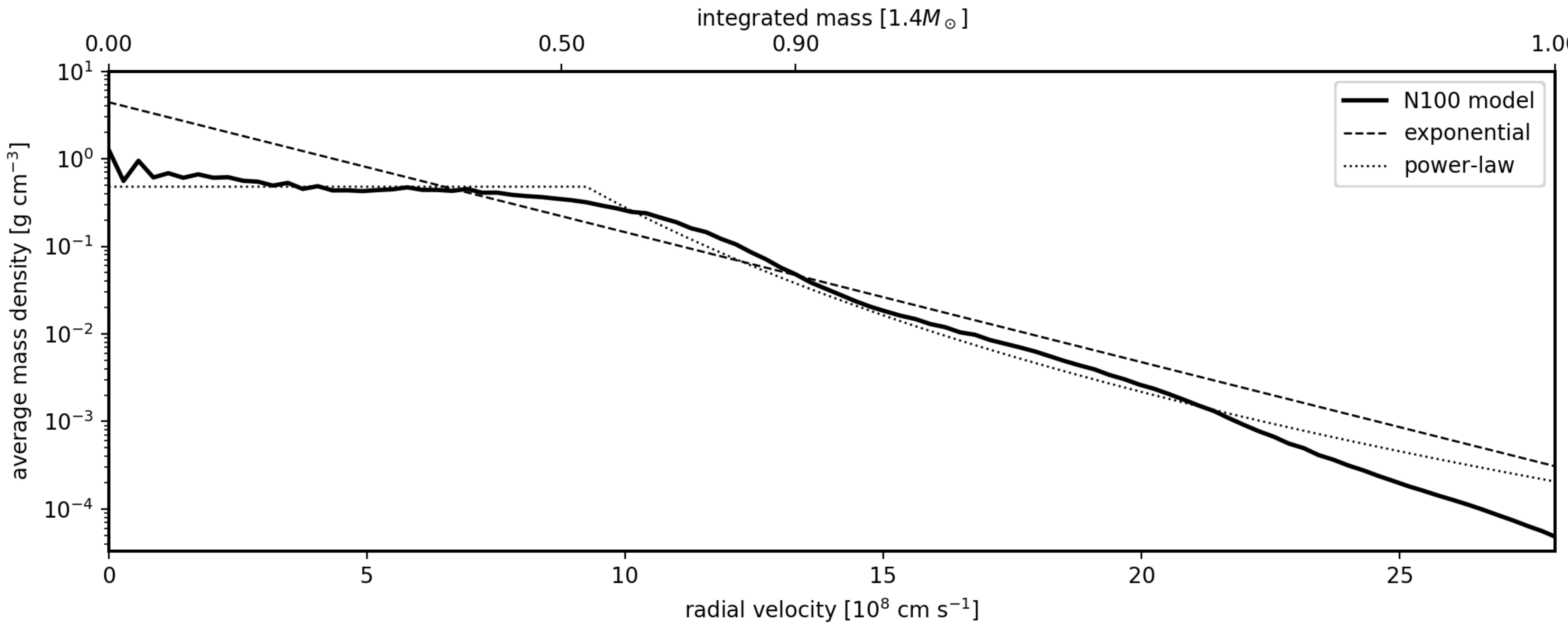
propagation of the flame?
interaction with turbulence
(sub-grid modeling)

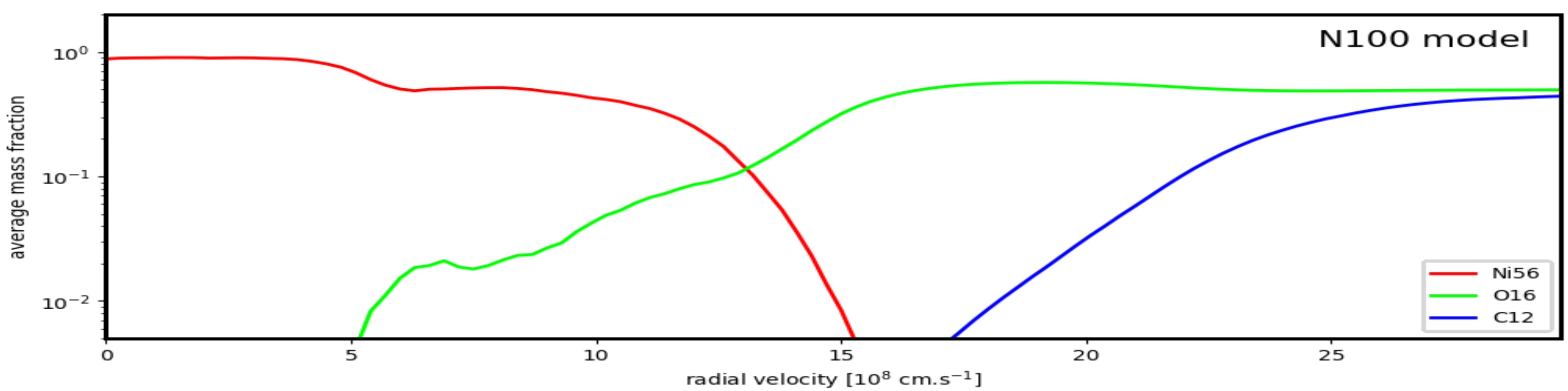
deflagration or detonation?
popular model = deflagration
to detonation transition (DDT)

Seitenzahl et al 2013

SN Ia explosion model: radial profiles

N100 model – delayed detonation of a Chandrasekhar mass white dwarf





data from Seitenzahl et al 2013 courtesy Fritz Röpke

SN Ia explosion model: 3D view

N100 model – delayed detonation of a Chandrasekhar mass white dwarf

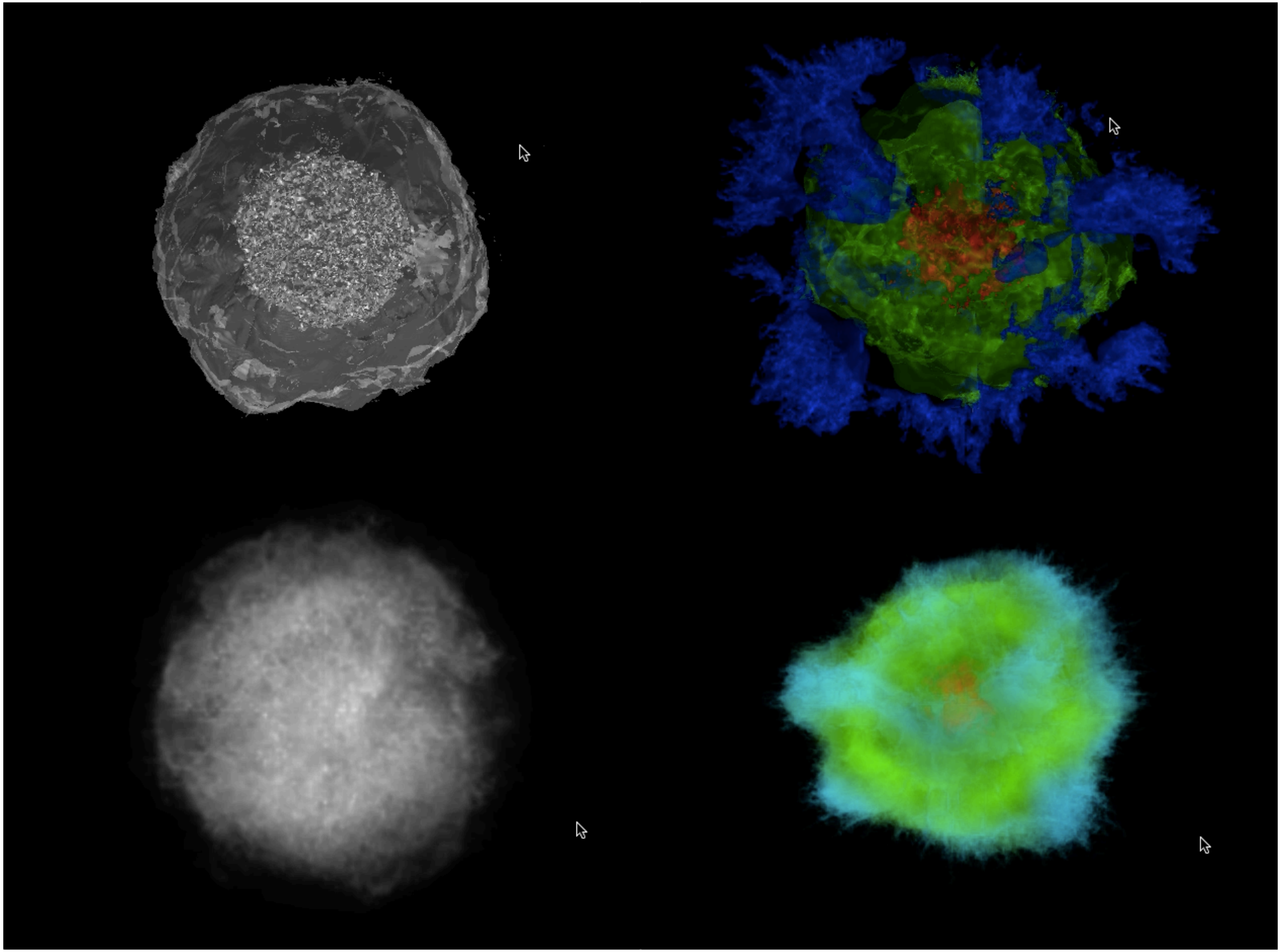
total mass density

composition: 56Ni 16O 12C

3D iso-contours

on Sketchfab https://skfb.ly/6pKYW

3D volume rendering



data from Seitenzahl et al 2013 courtesy Fritz Röpke

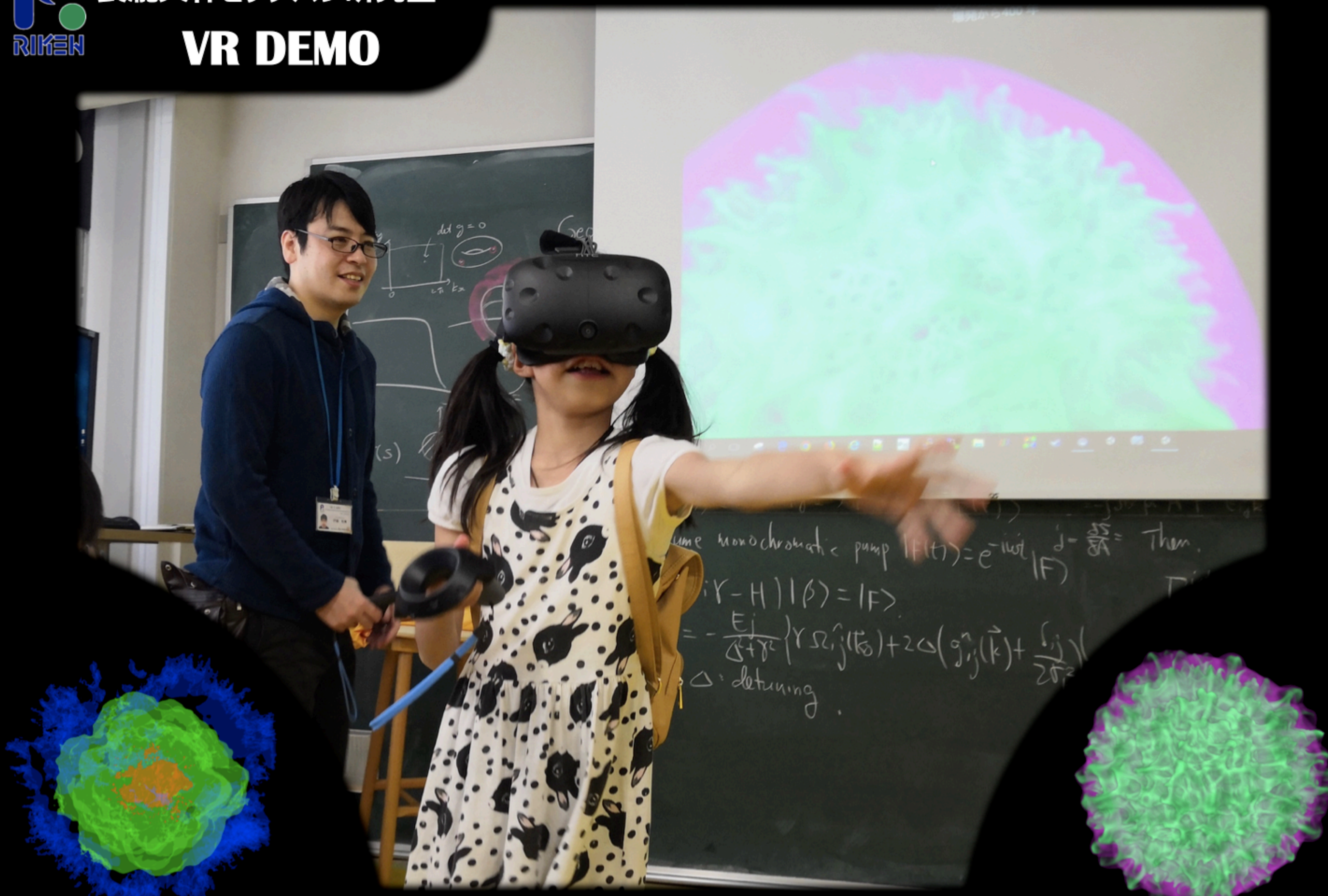
3D visualization with Virtual Reality

Ferrand & Warren 2018

Astrophysical Big Bang Laboratory
長瀧天体ビッグバン研究室

VR DEMO

理研和光一般公開 21.4.2018



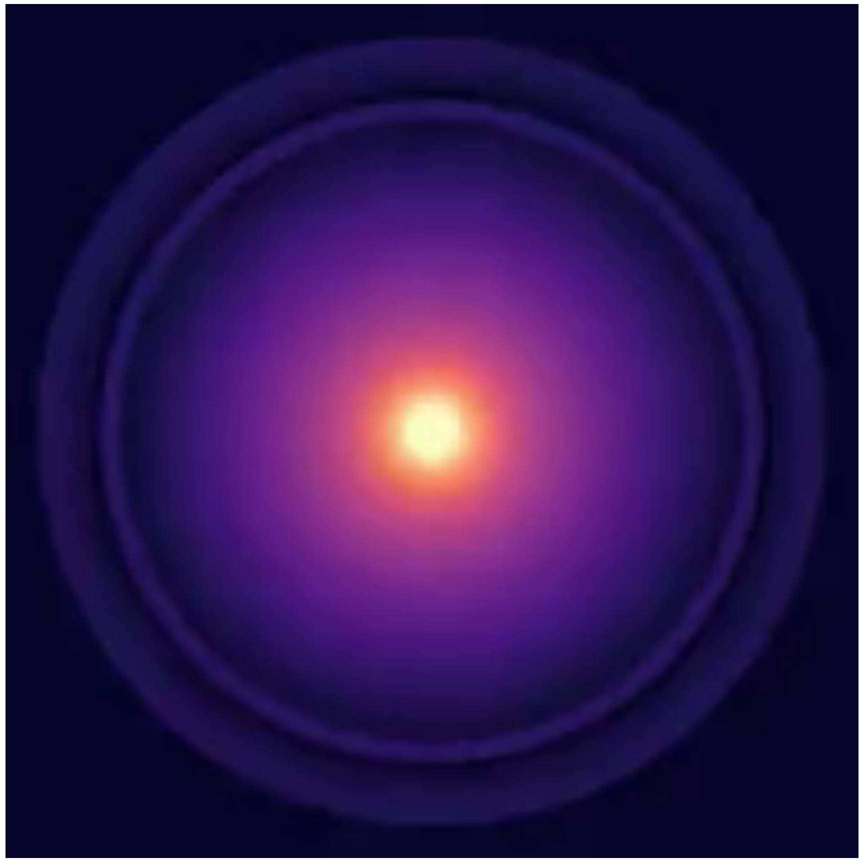
~160 people enjoyed the VR demo at ABBL booth during RIKEN Open Day

the supernova remnant

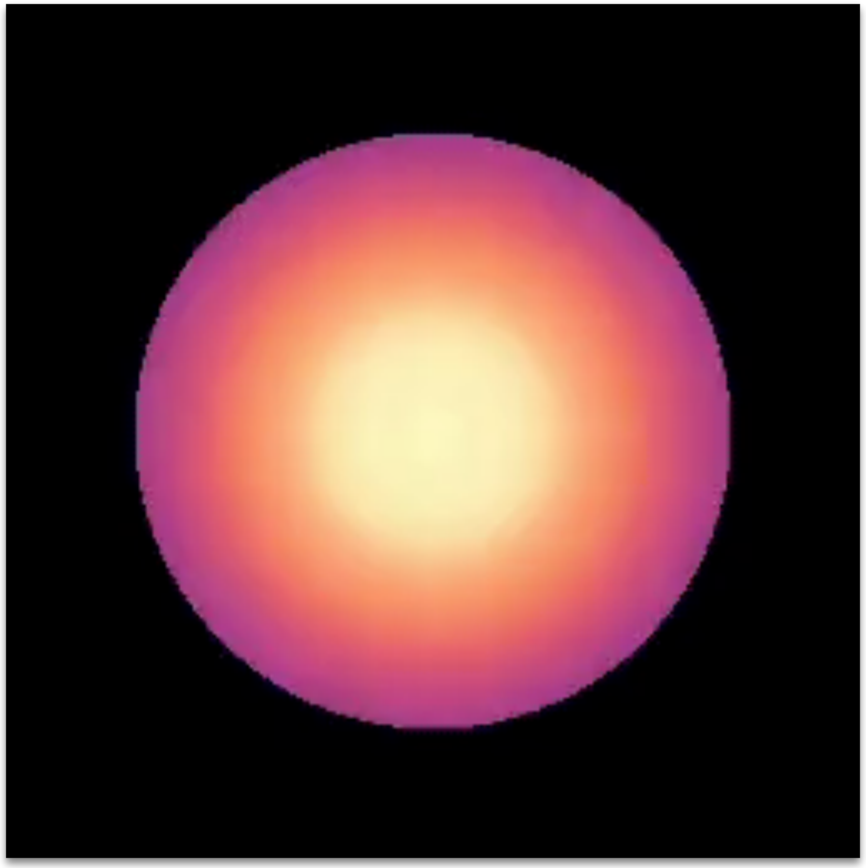
Hydro evolution of the SNR

slices of log(density)

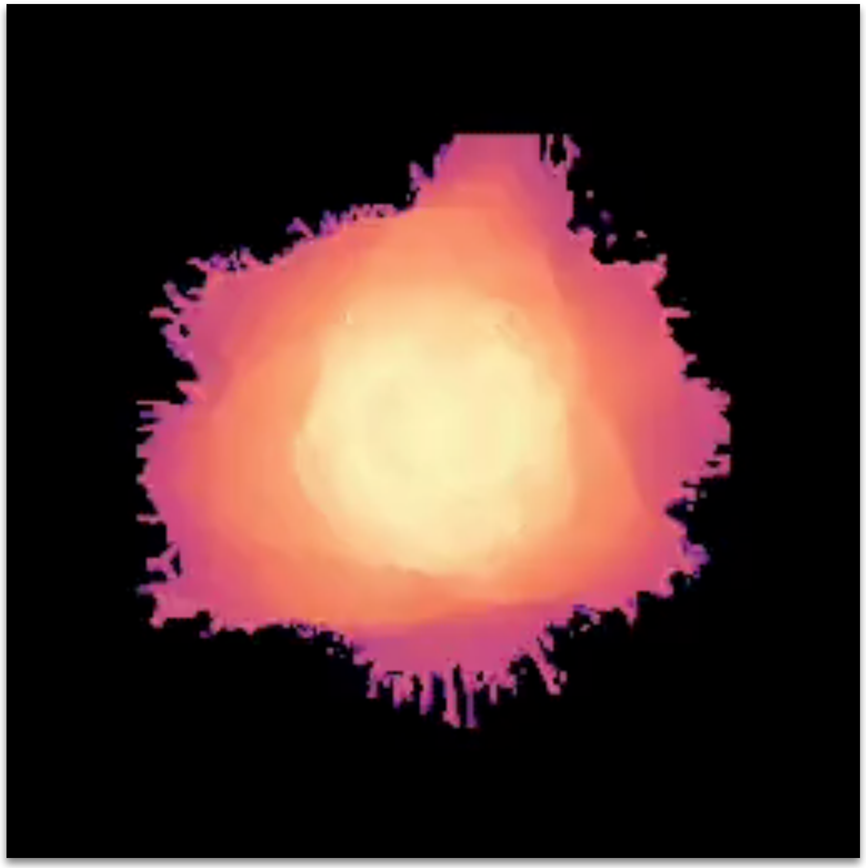
from 1 yr to 500 yr
on a 256^3 Cartesian grid
(simulation made in co-expanding grid, box size increases by factor ~150)



Chevalier
1D initial profile
(power-law)



N100 angle-averaged
effectively 1D initial
profile (~exponential)



N100
full 3D initial profile

what SNR people used to do

what SN people are telling us

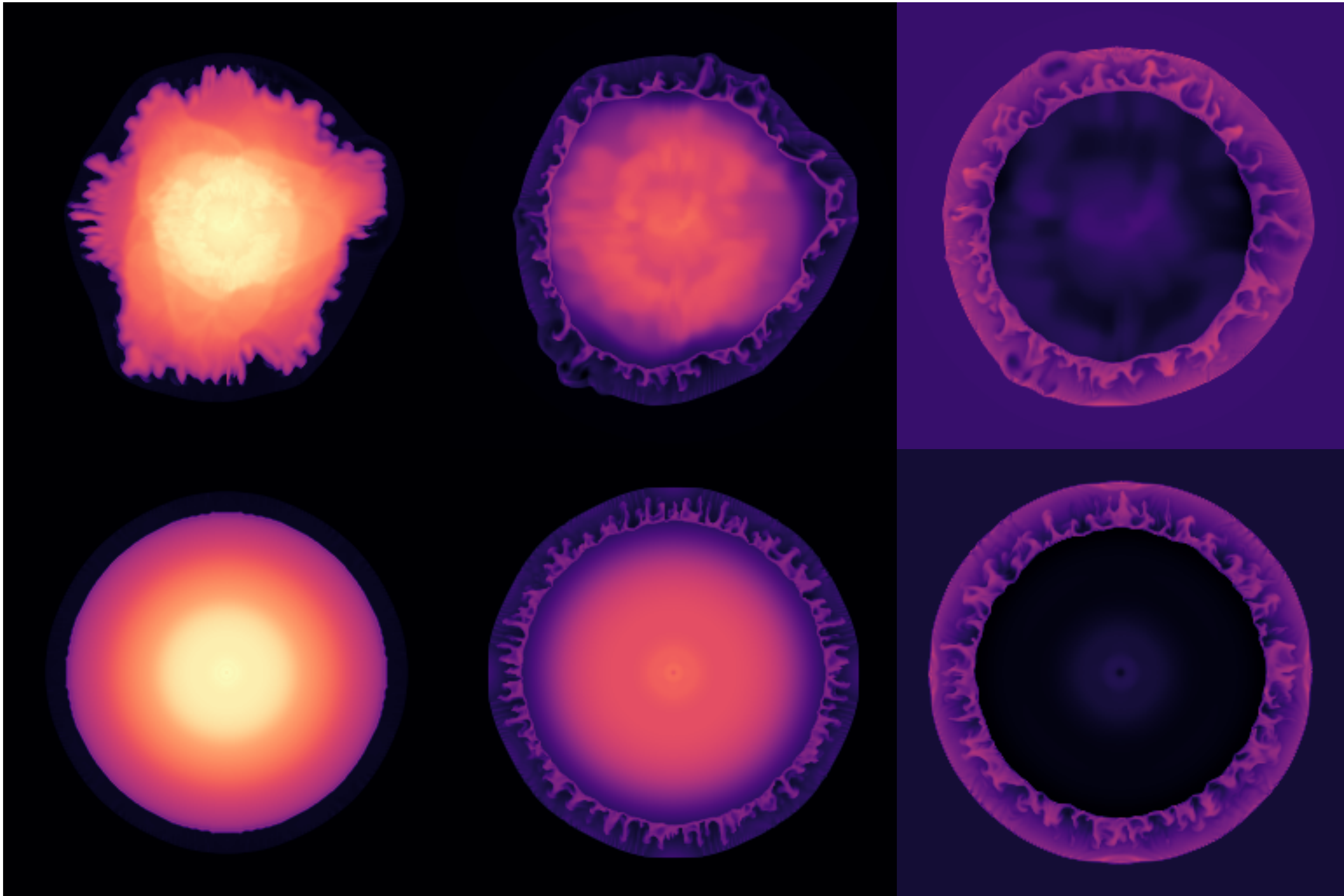
Hydro evolution of the SNR

slices of log(density)

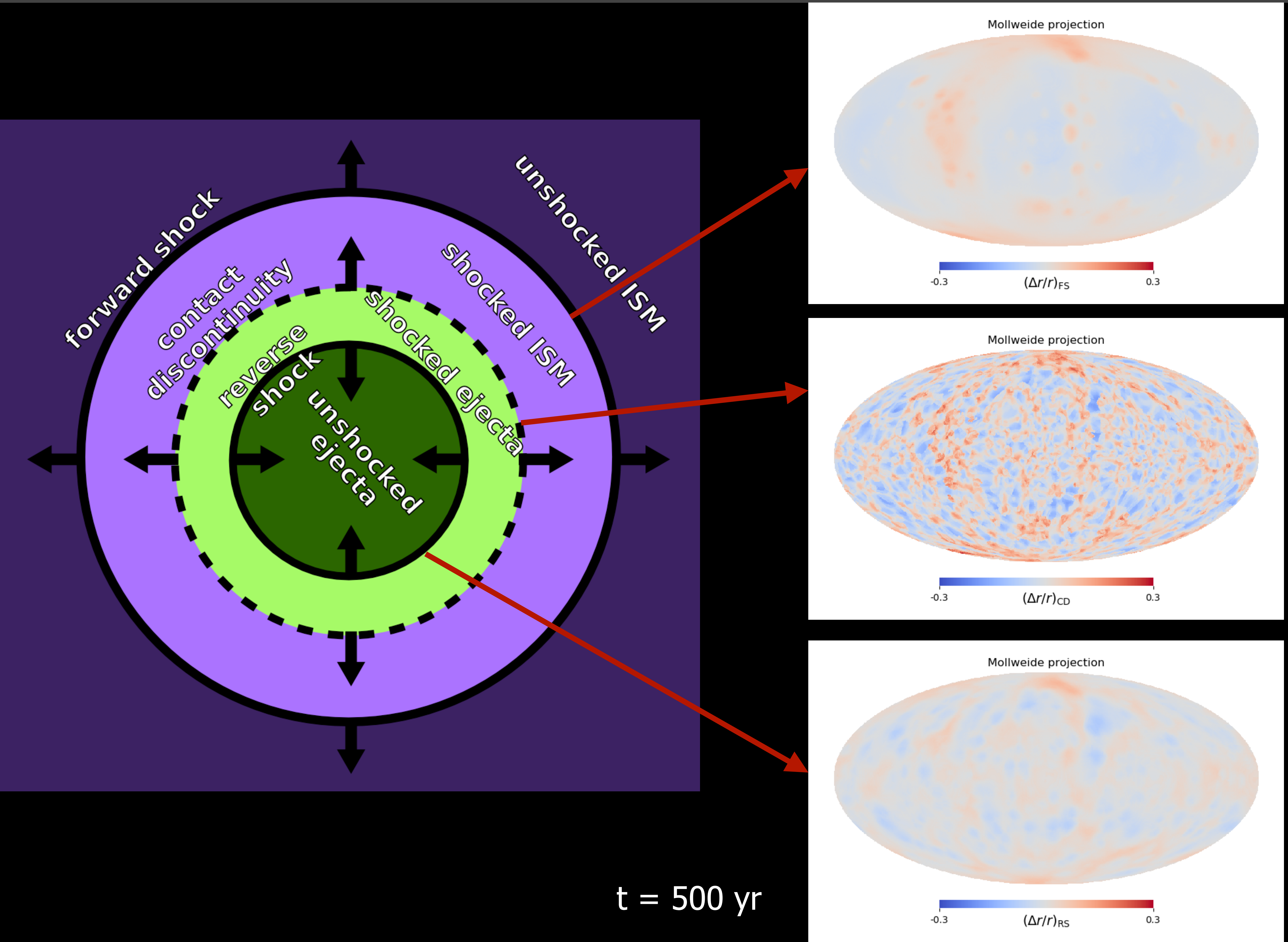
t = 1 yr | t = 100 yr | t = 500 yr

N100 3Di
SN phase + SNR phase

N100 1Di
SNR phase only



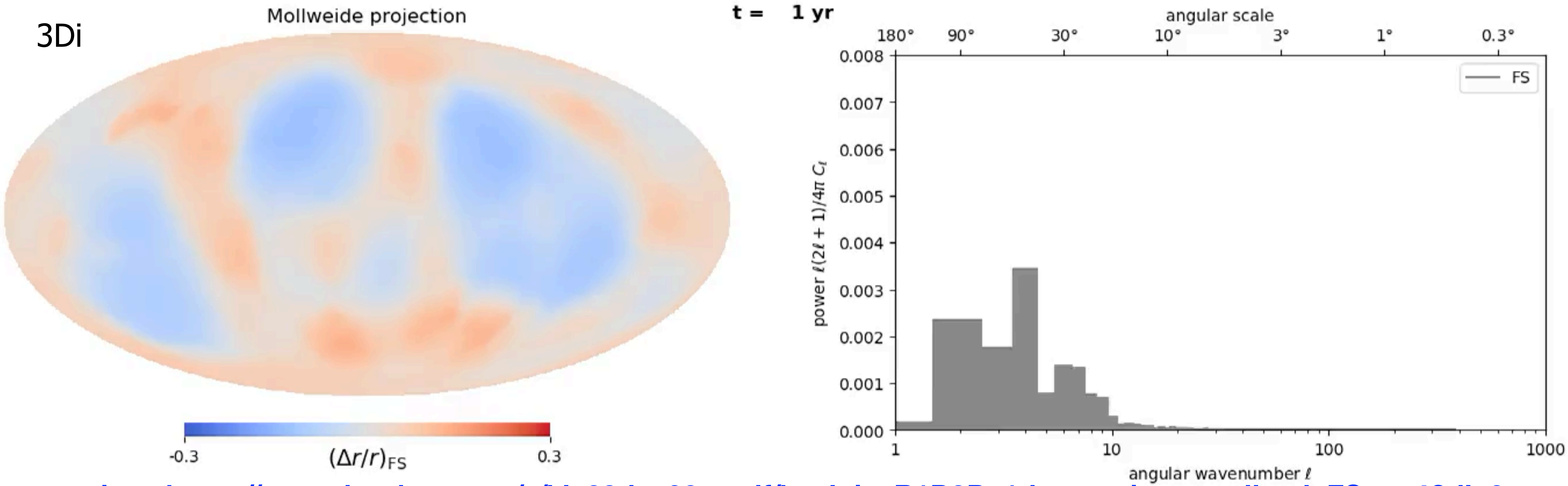
The structure of a young supernova remnant



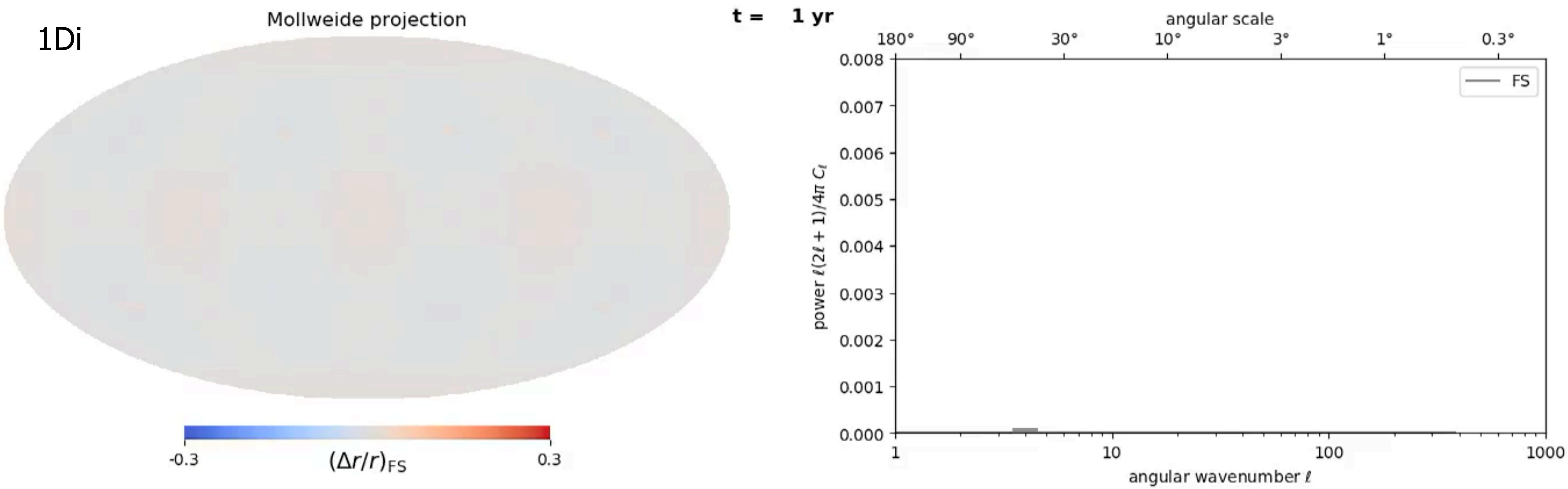
t = 500 yr

Spherical harmonics expansion of the SNR waves

forward shock (FS) from 1 yr to 500 yr



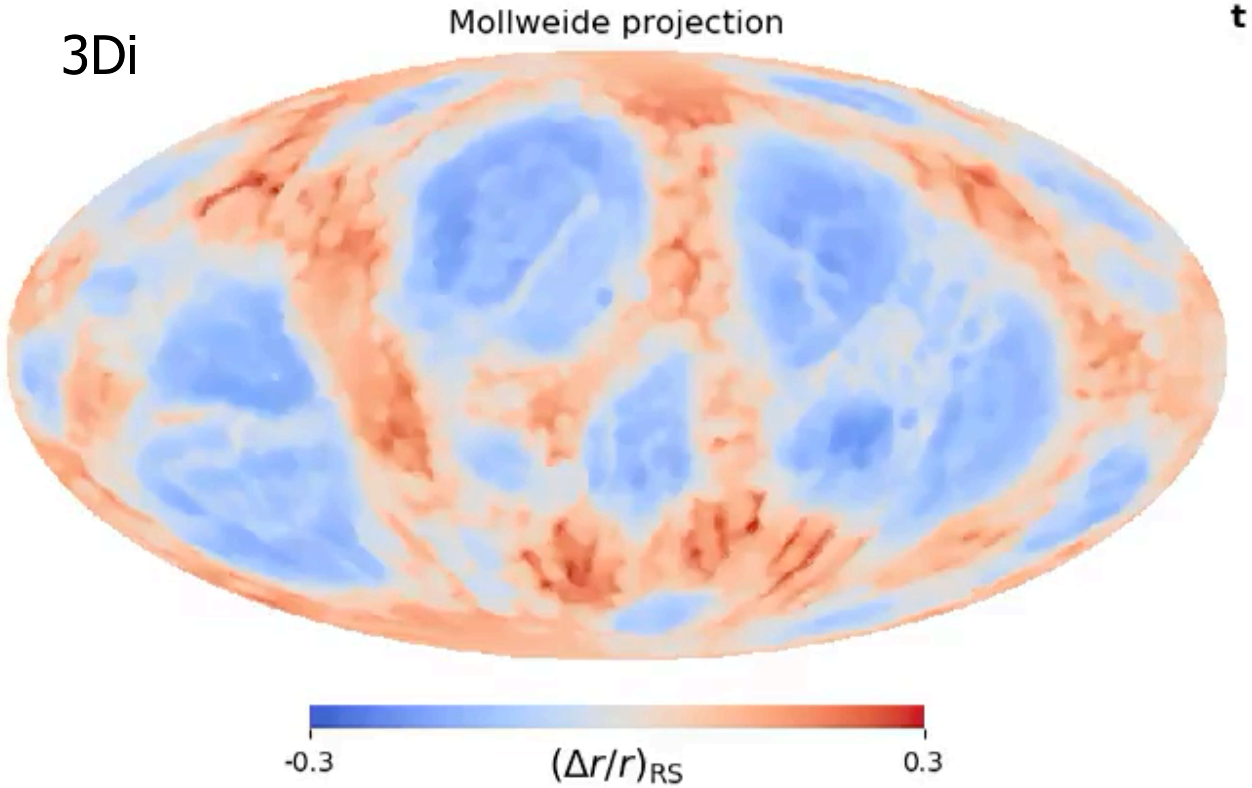
movie at https://www.dropbox.com/s/kla83dya92ezadf/healpix_R1D3D_1day_proj-spec_all_rel_FS.mp4?dl=0

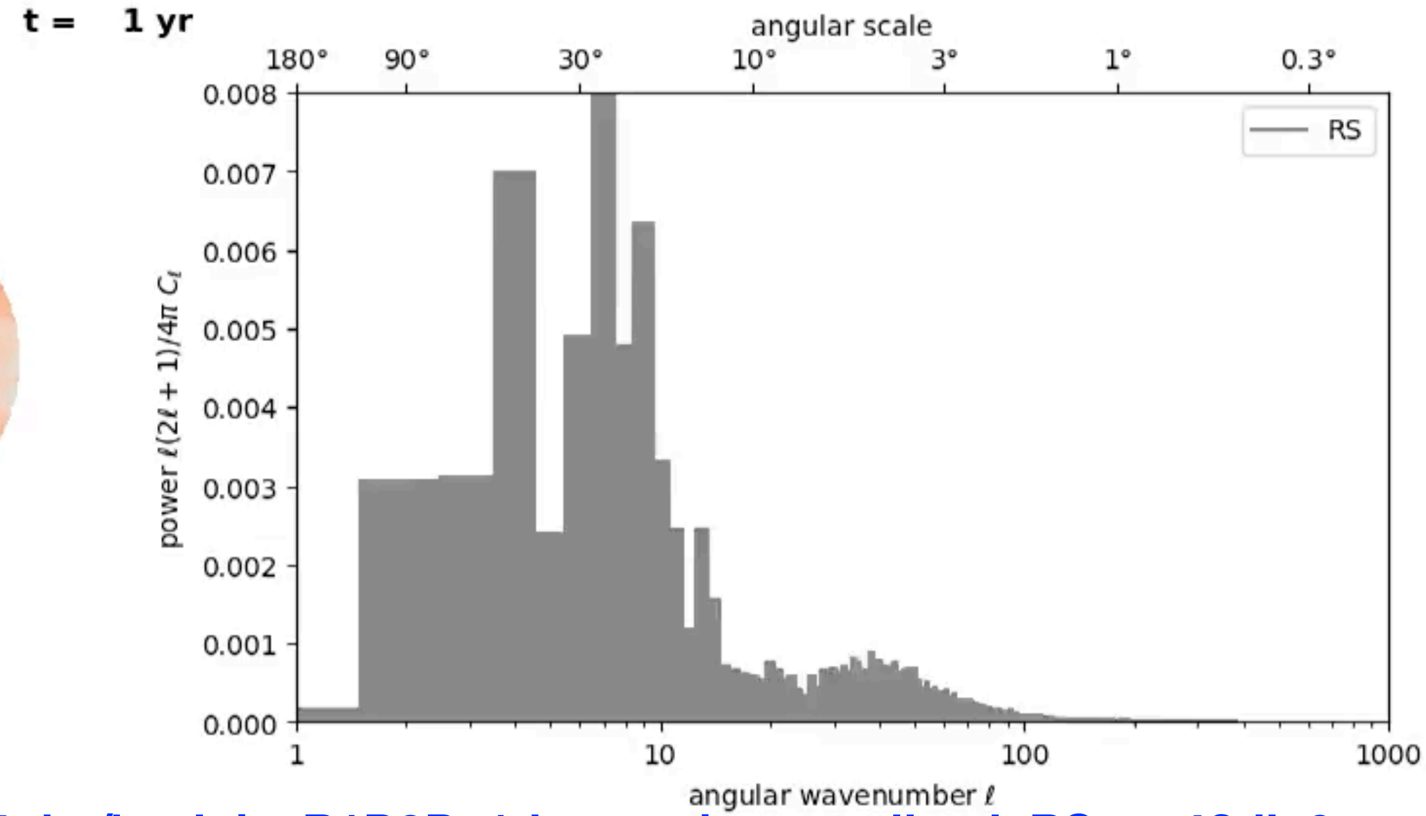


Spherical harmonics expansion of the SNR waves

reverse shock (RS) from 1 yr to 500 yr

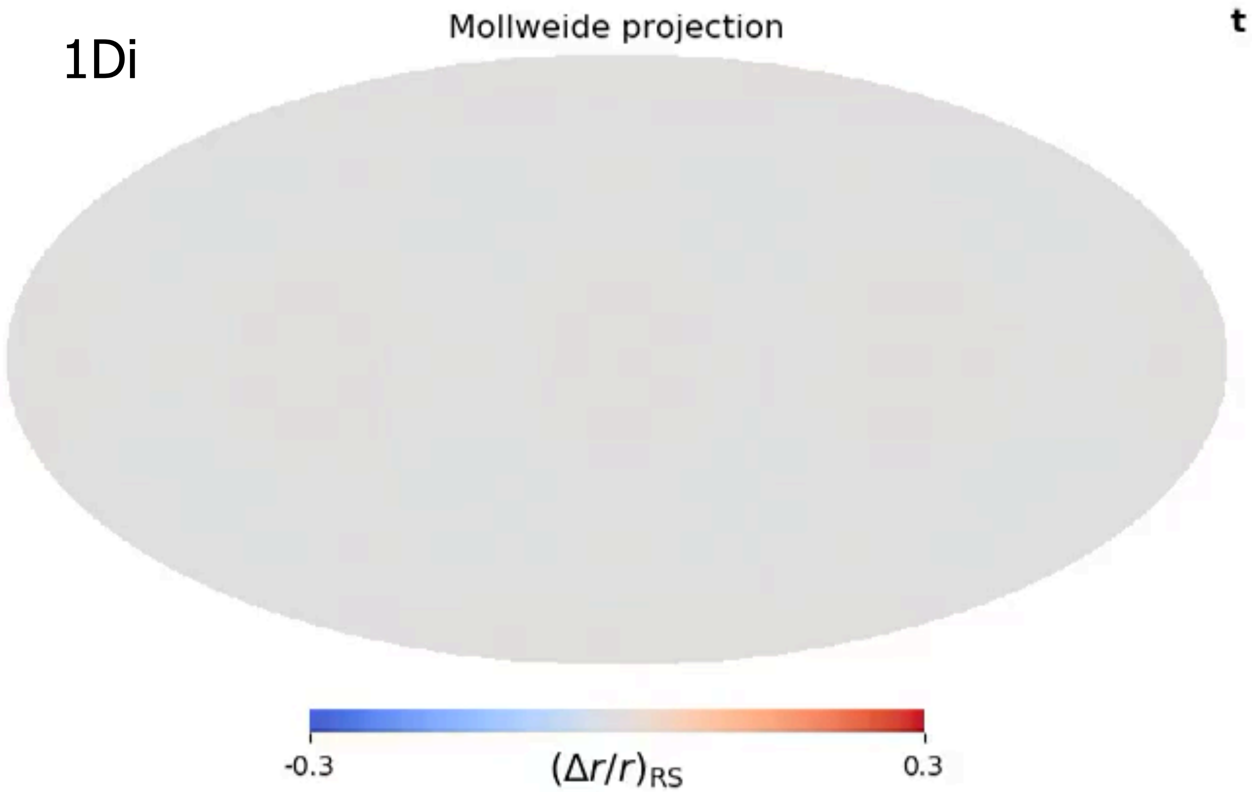
3Di

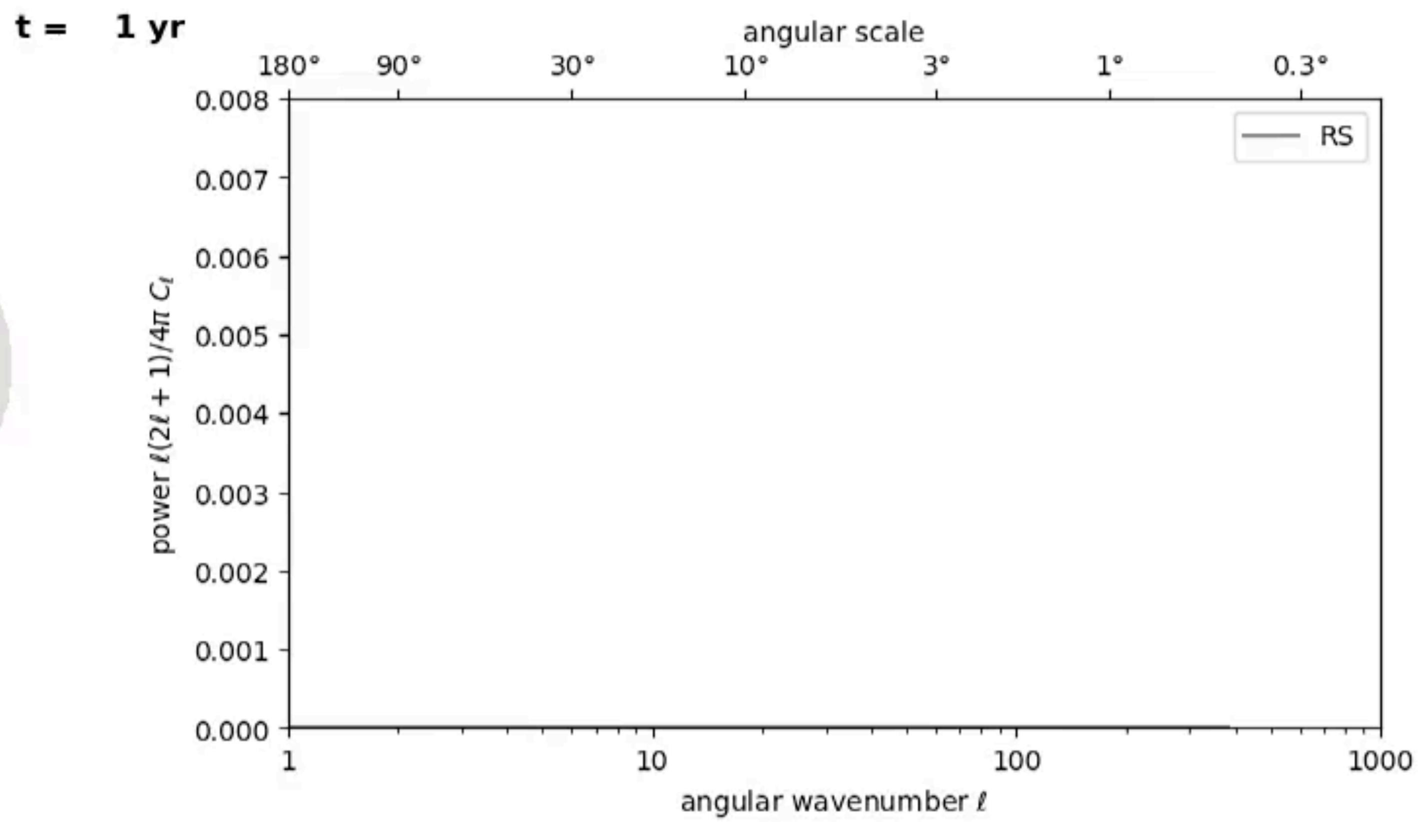




movie at https://www.dropbox.com/s/nradn026ffm4oby/healpix_R1D3D_1day_proj-spec_all_rel_RS.mp4?dl=0

1Di

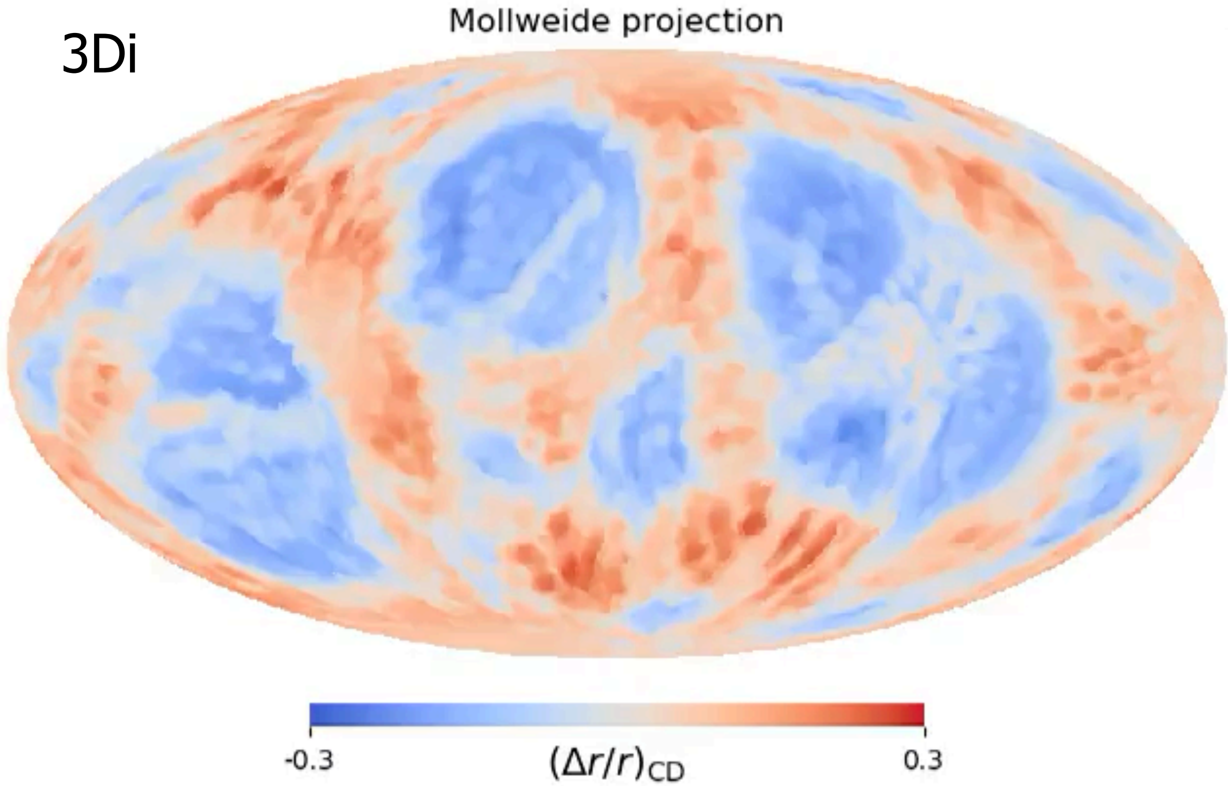


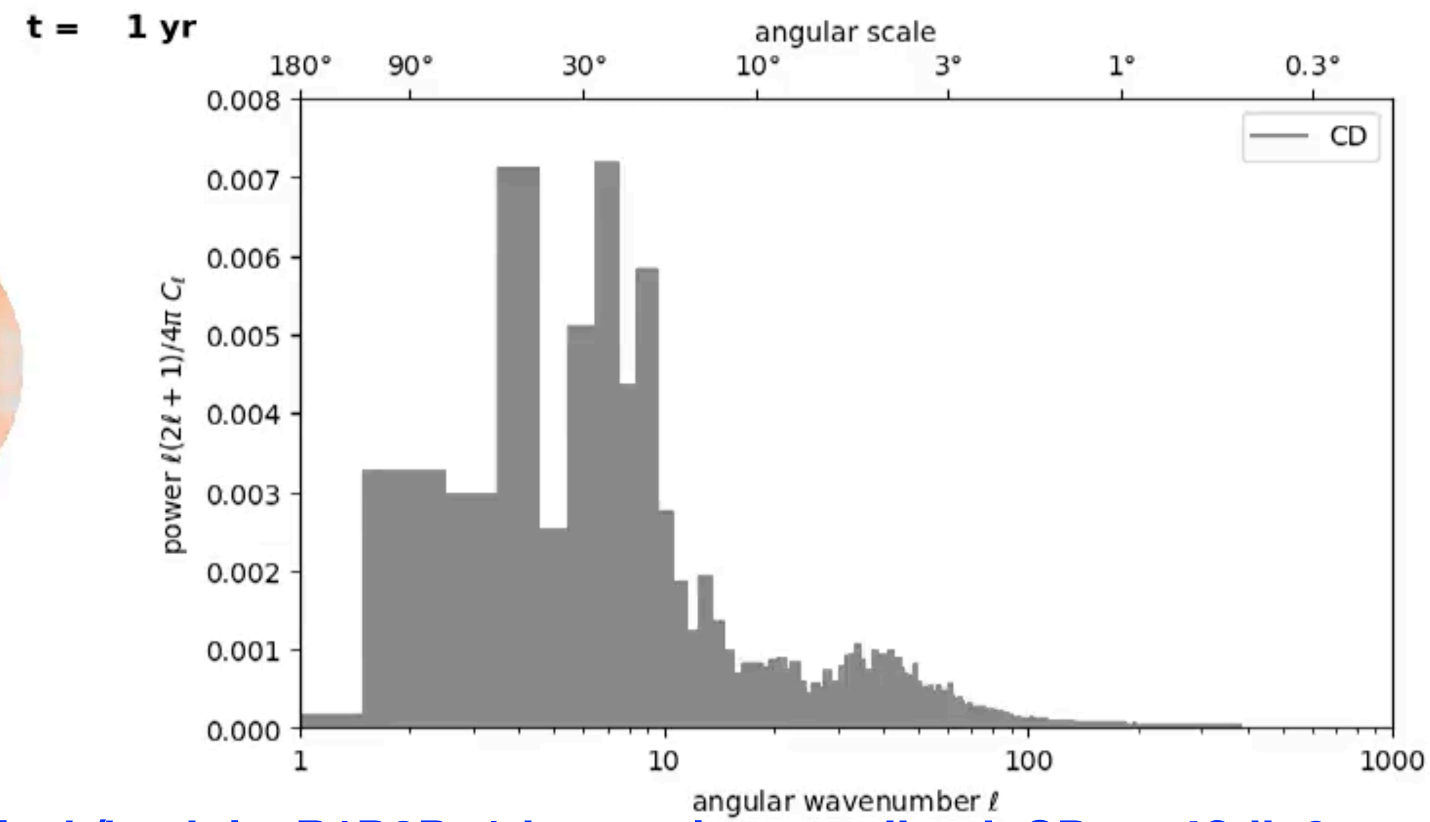


Spherical harmonics expansion of the SNR waves

contact discontinuity (CD) from 1 yr to 500 yr

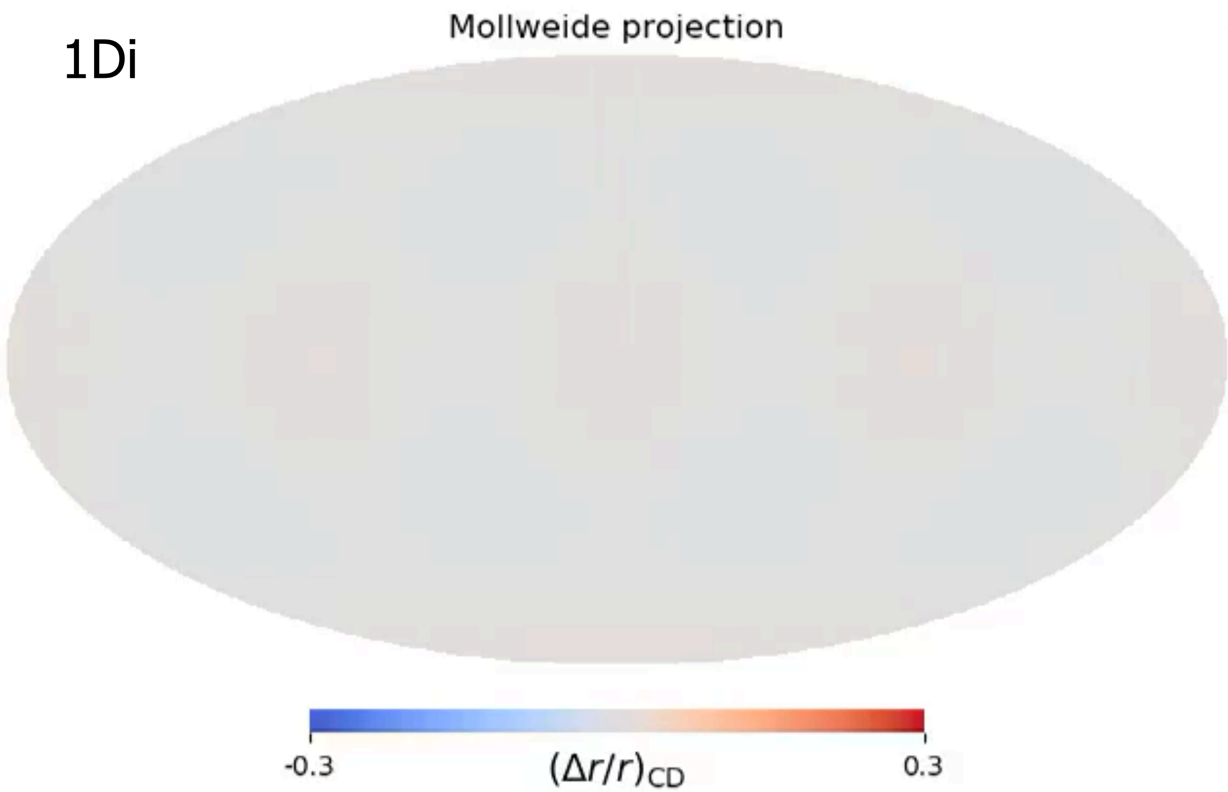
3Di

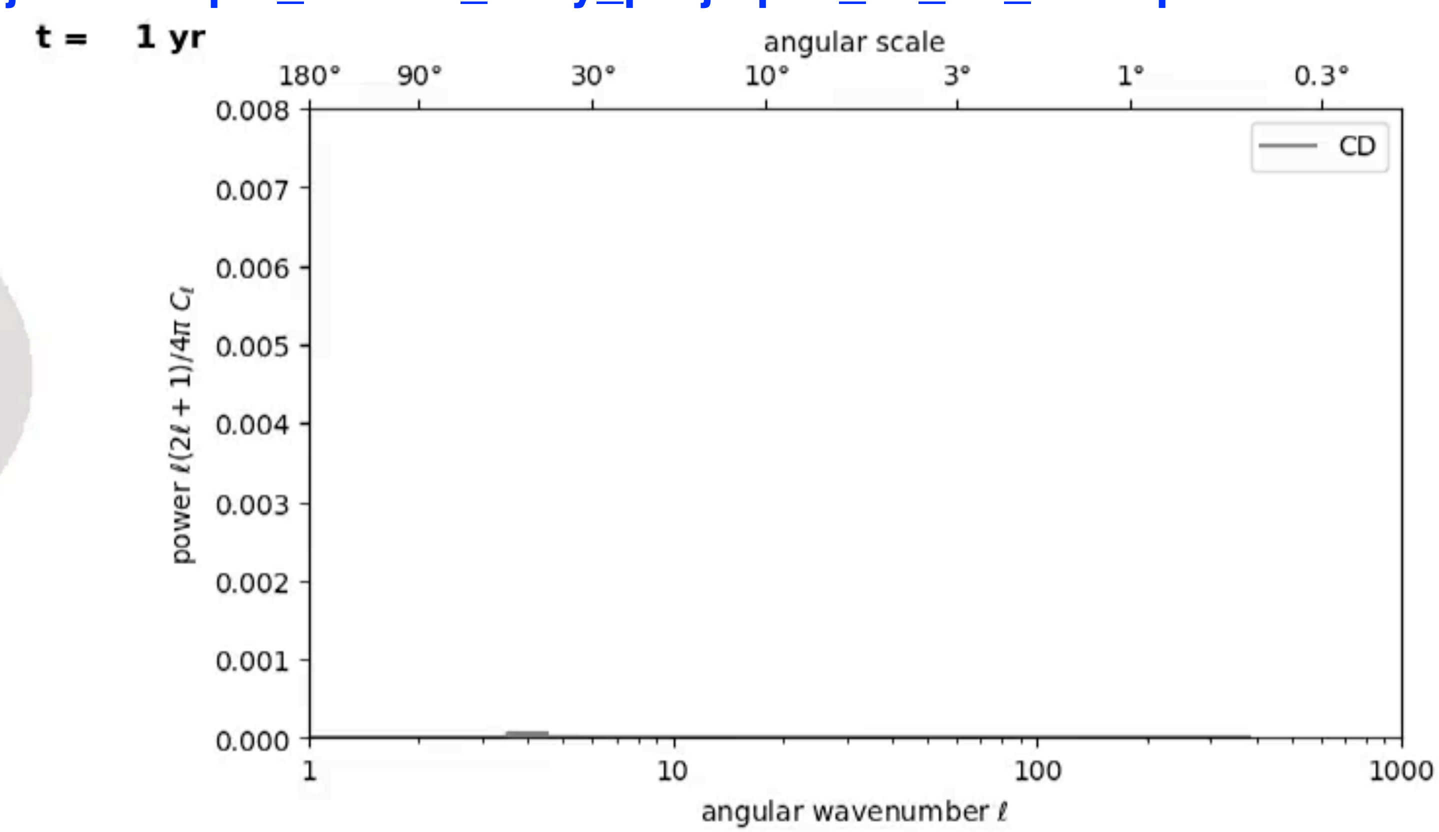




movie at https://www.dropbox.com/s/nnwrvlk8190jack/healpix_R1D3D_1day_proj-spec_all_rel_CD.mp4?dl=0

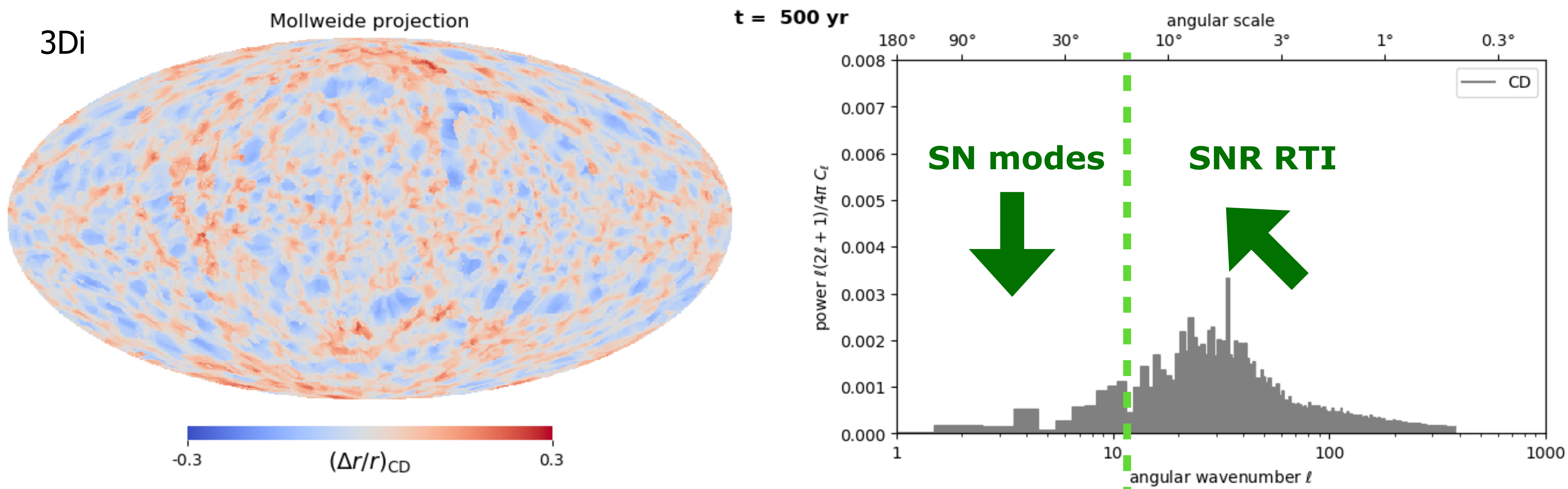
1Di

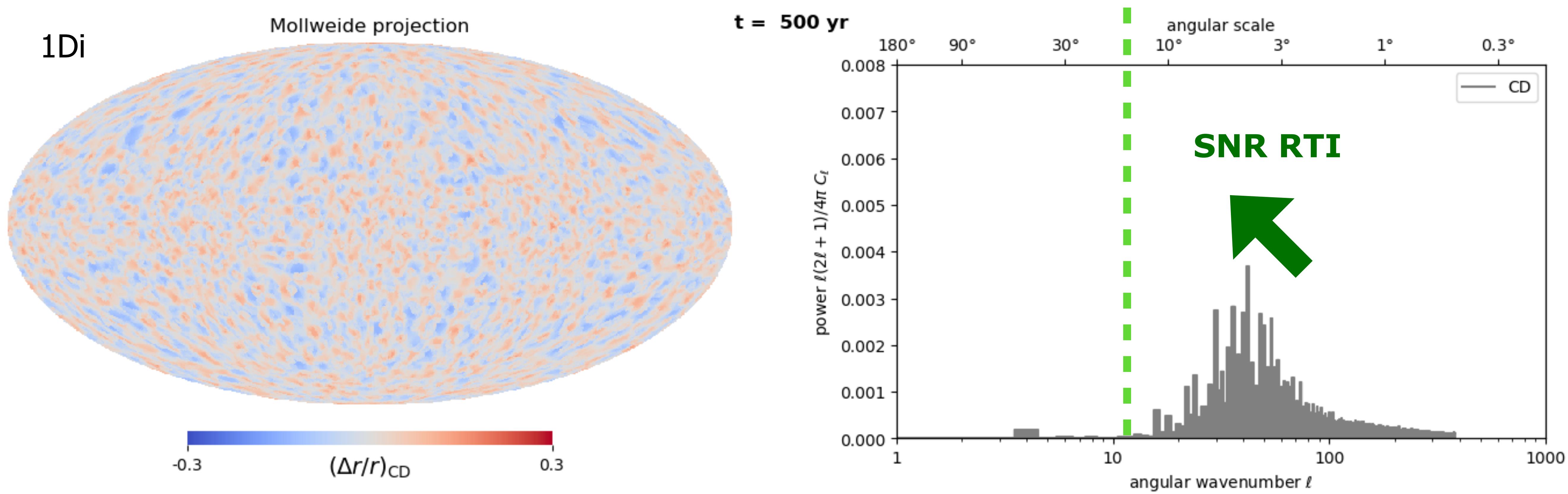




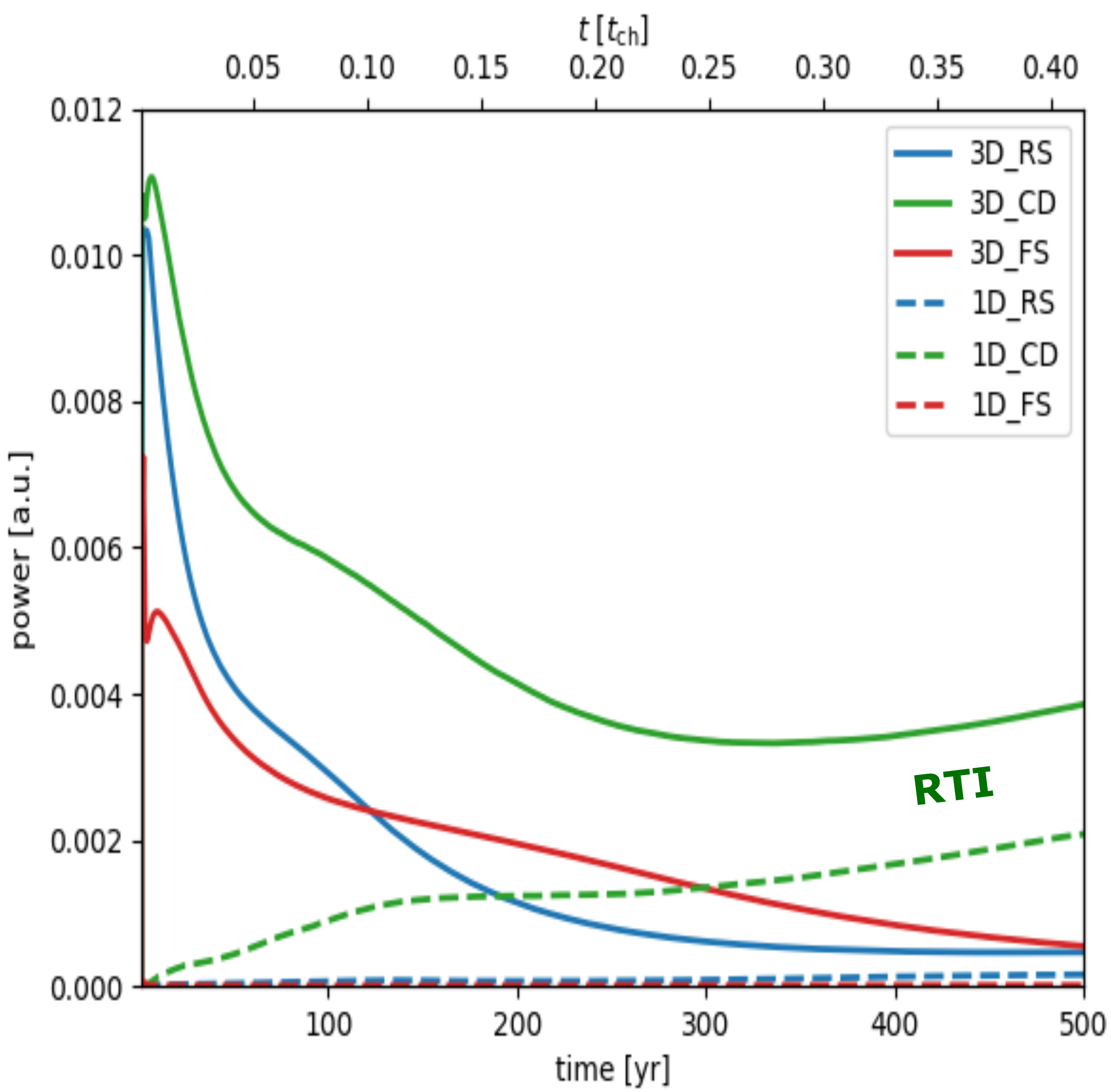
Rayleigh-Taylor from the SN and SNR phases

contact discontinuity (CD) at 500 yr

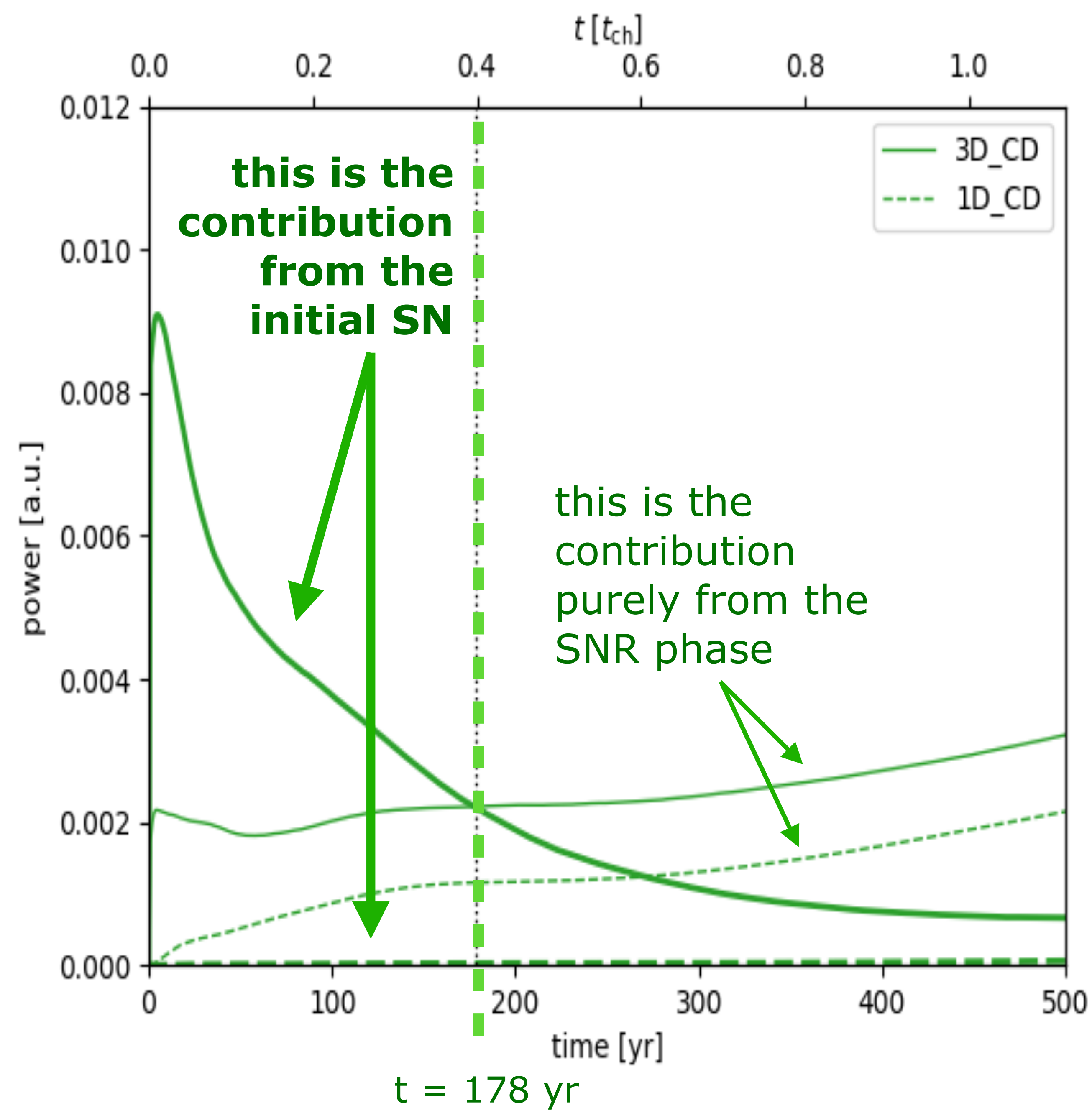




Global time evolution of the angular power



total power



total power for ℓ<10 (large scales)
vs. total power for ℓ>10 (small scales)
➔ separation of the contributions

Conclusions

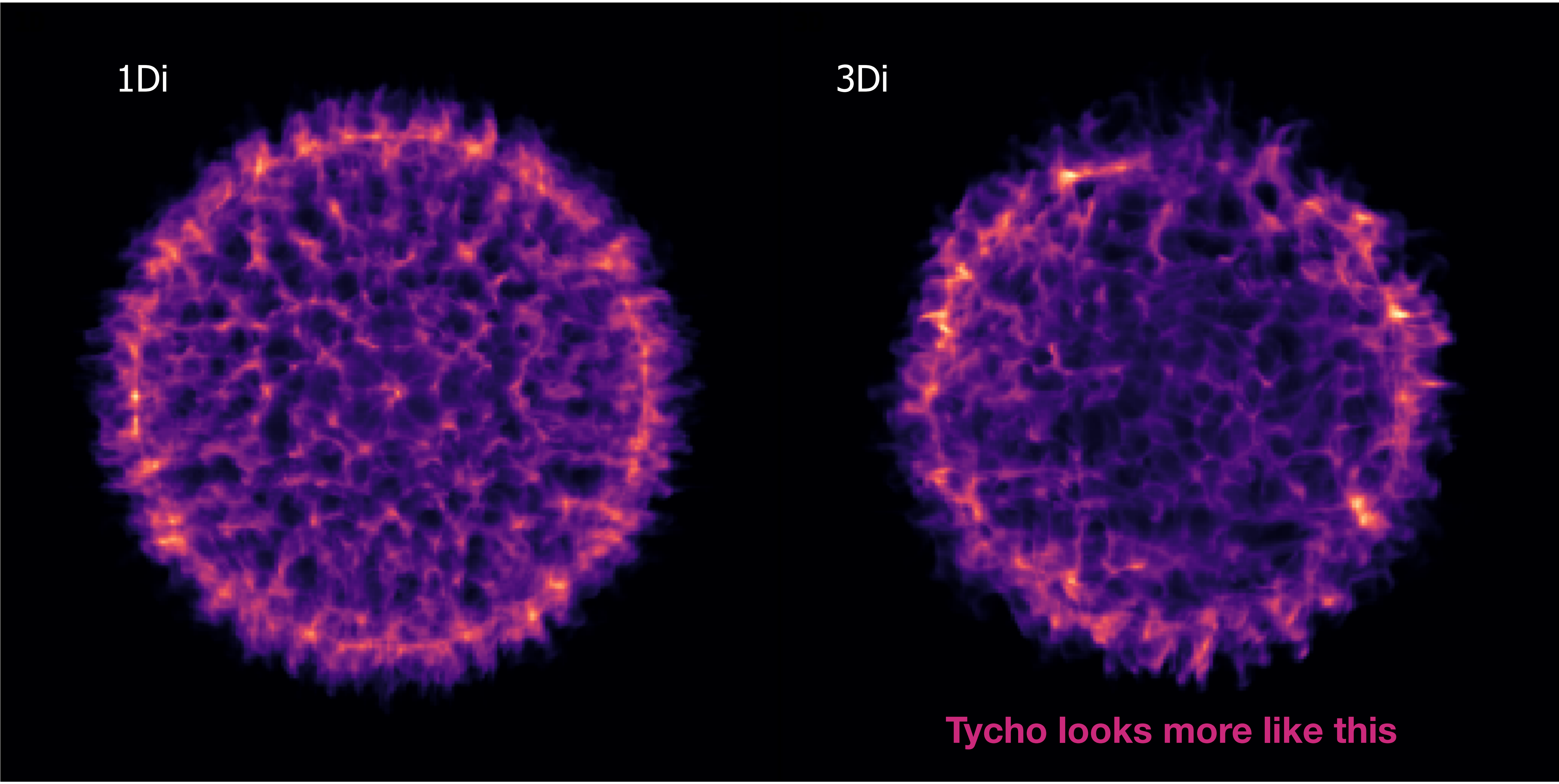
Morphological signatures of the (thermonuclear) explosion can be seen clearly in the first hundred years, and may still be detected after a few hundred years. The spherical harmonics analysis reveals that (for the N100 model) the RTI from the SNR is dominant only after ~200 yr.

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**.

Ferrand et al 2019, submitted

X-ray emission from the SNR

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



TO BE CONTINUED...

Perspectives

➔ Will compute the synthetic thermal (and non-thermal) emission as observed in projection.
This requires computation of time-dependent (non-equilibrium) ionization state of the plasma.

Future simulations will enable us to **make comparisons between different SN explosion models**:

- between different ignition setups for the DDT model, that produce different initial asymmetries and yields
- between different SN explosion models: pure deflagration, pure detonation, other detonations, other channels…

(Role of the companion star?)