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"Astrophysics of hot plasma in extended X-ray sources"
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Modelling and simulations of supernova remnants

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Modelling and simulations of supernova remnants
with a focus on morphological studies

Introduction to SNRs

Structure and evolution of a remnant
Multi-wavelength emission

1. SNRs as particle accelerators

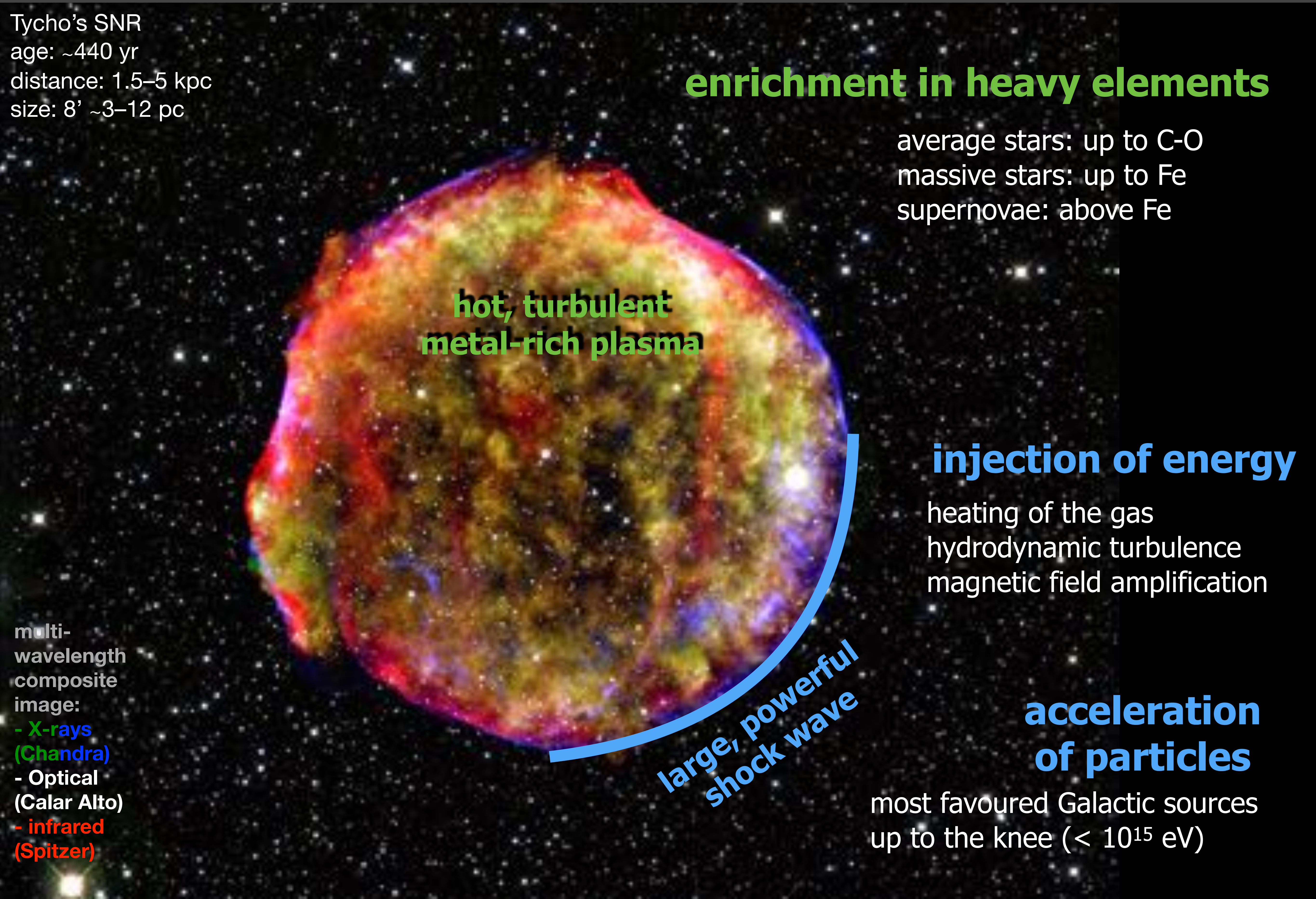
Hydro-kinetic coupling for diffusive shock acceleration (DSA)
Non-equilibrium ionization and thermal emission from the plasma
Magnetic field amplification and non-thermal emission from the particles

2. SNRs as probes of the explosion

From the supernova to the remnant: Cas A, Tycho
Example: the N100 supernova model
X-ray image analysis

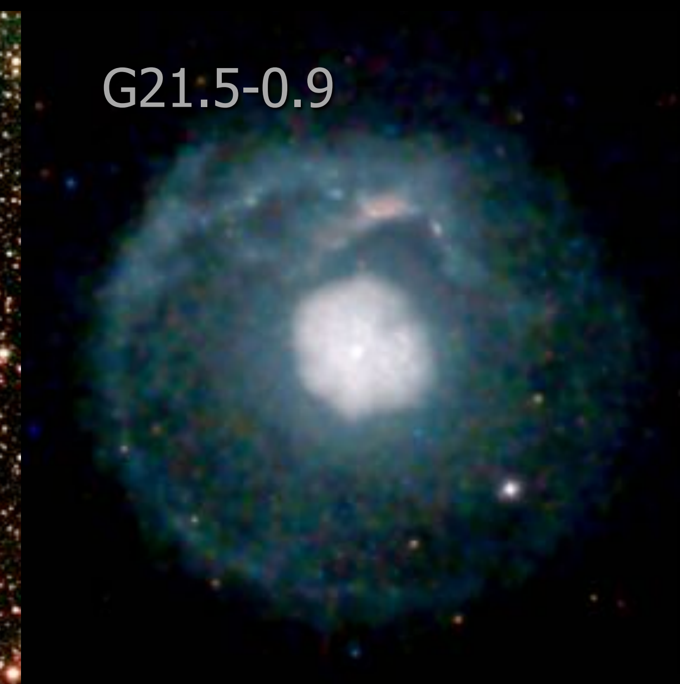
Supernova remnants

0.1 SNRs as a key link between stars and the ISM



Classification of SNRs

from radio + X-ray observations



shell

composites

"**mixed morphology**" = thermal composite: centrally peaked

plerionic composite (= non-thermal composite): PWN inside shell

(can be both)

filled-centre

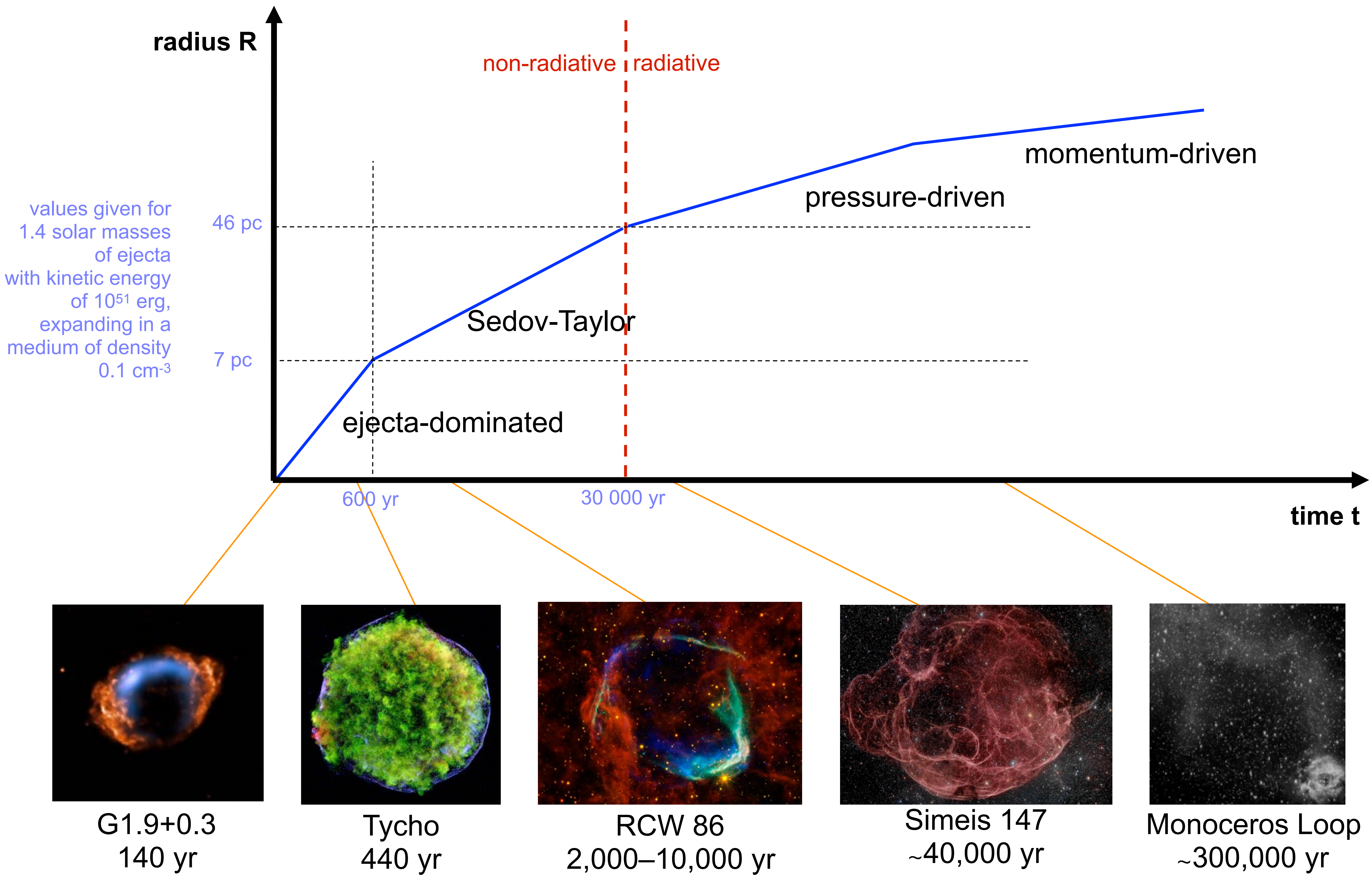
isolated/shell-less pulsar wind nebula = PWN (= plerion)

or

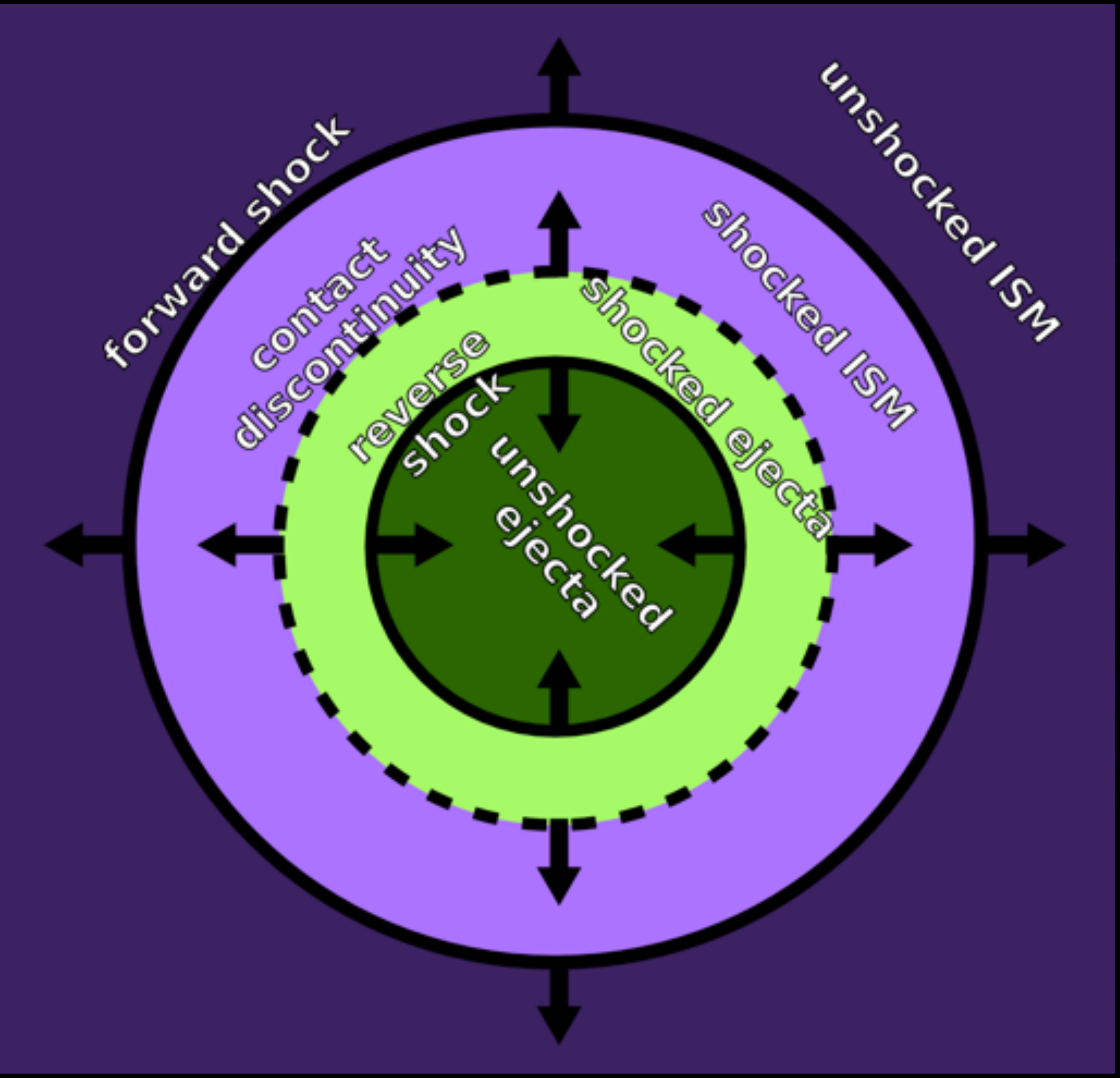
bow shock nebula

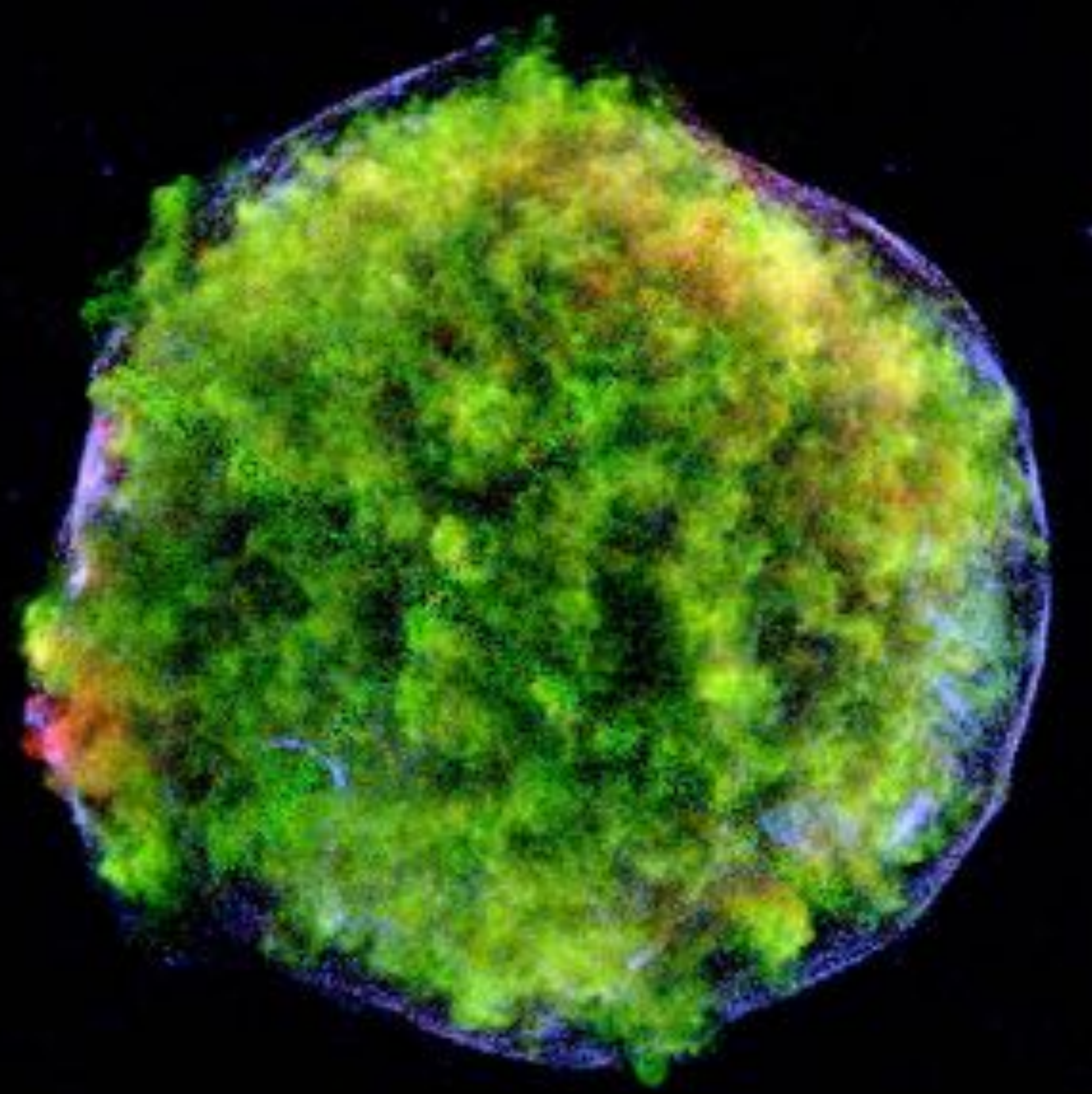
0.3

The evolution of a supernova remnant



The structure of a young shell SNR





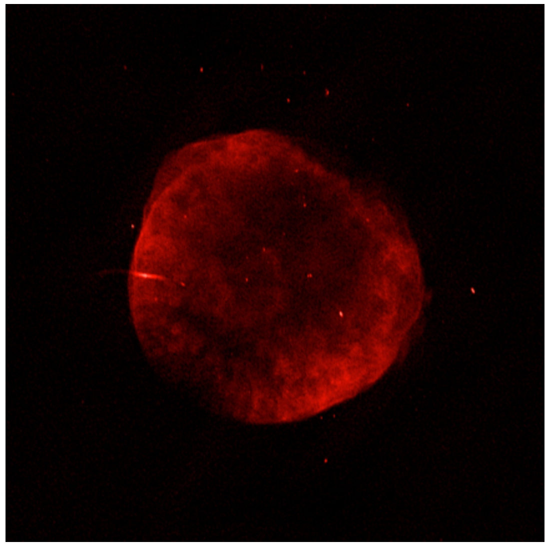
Tycho's SNR
as seen by Chandra
at age 433 yr

0.95 – 1.26 keV
1.63 – 2.26 keV
4.10 – 6.10 keV

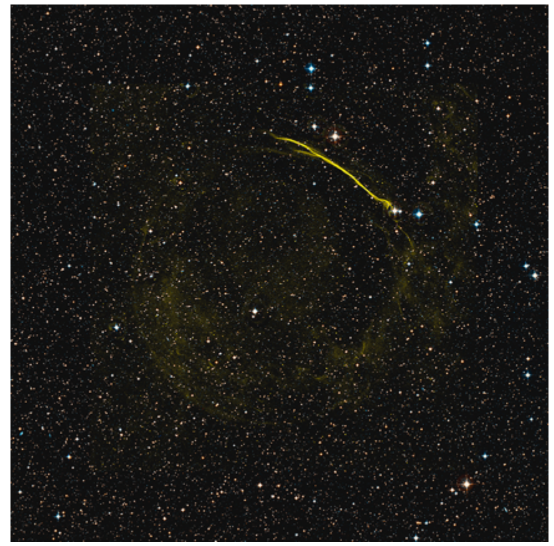
Warren et al 2005

SNR broad-band emission

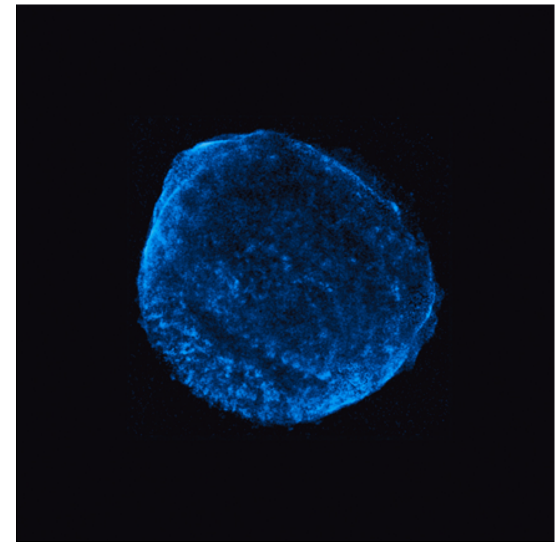
SN 1006



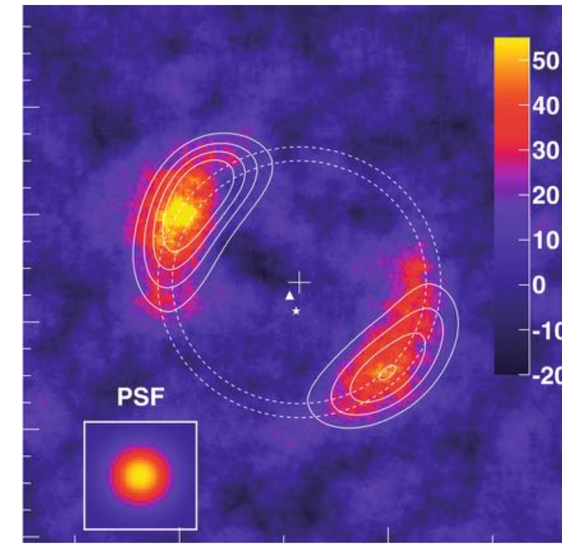
radio



optical



X



gamma

E →

keV — TeV

← λ

cm — µm

radio	optical	X	gamma
synchrotron in B field	Balmer lines forbidden lines	atomic lines of heavy elements + synchrotron	Inverse Compton ? pion decay ?
↑	↑	↑	↑
GeV e-	blast wave	hot ejecta + TeV e-	> TeV e- ? > TeV p ?

reviews (high energies perspective): Reynolds 2008, Vink 2012

SNRs as particle accelerators

Efficient particle acceleration

SNRs are widely believed to be the main producers of CRs in the Galaxy

- Available energy budget — but can we reach the knee?
- Known acceleration mechanism — but what spectrum?
- Observed energetic electrons — and protons?

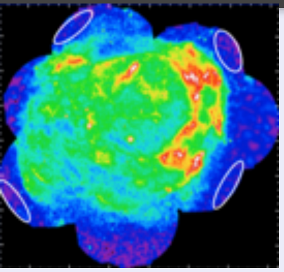
If CRs are efficiently accelerated by the blast wave, it must impact its dynamics

- fluid becomes more compressible
- energy leaks from the system

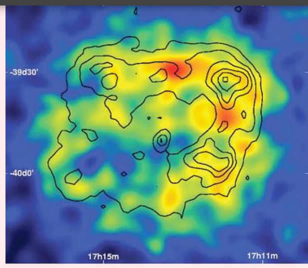
→ non-linearly coupled system

CRs are a key ingredient of SNRs

Diffusive shock acceleration: the coupled system



IR
Opt
UV
X



radio
X
γ

shock wave
(thermal magnetized plasma)

cosmic-rays
(non-thermal population)

magnetic waves
(collective movements of charges)

injection, acceleration
shock modification

damping
heating

generation (instabilities)
diffusion, injection,
stochastic acceleration

conservation laws

$$\frac{\partial \mathbf{X}}{\partial t} + \mathrm{div}\left(\mathbf{F}\left(\mathbf{X}\right)\right) = \mathbf{0}$$

$$\mathbf{X} = \begin{pmatrix} \rho \\ \rho\mathbf{u} \\ P \end{pmatrix} \quad \mathbf{F}\left(\mathbf{X}\right) = \begin{pmatrix} \rho\mathbf{u} \\ \rho\mathbf{u}\otimes\mathbf{u} + p\mathbf{I} \\ \left(e+P\right)\mathbf{u} \end{pmatrix}$$

particle distribution:

$$n\left(x,t\right) = \int_p f\left(x,p,t\right)\ 4\pi p^2\ \mathrm{dp}$$

transport equation:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}\left(uf\right) = \frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right) + \frac{1}{3p^2}\frac{\partial p^3 f}{\partial p}\frac{\partial u}{\partial x}$$

hydrodynamic treatment

kinetic treatment

reviews on DSA : Drury 1983, Jones and Ellison 1991, Malkov and Drury 2001
on numerical techniques for DSA: Marcowith et al (in prep)

Numerical simulations: hydro + kinetic

Chevalier 1982, 1983

SNR initialization: self-similar profiles from **Chevalier**

Teyssier 2002, Fraschetti et al 2010

SNR evolution: 3D hydro code **ramses**

parameters: Tycho (SN Ia)

$t_{\rm SN} = 440$ years
$E_{\rm SN} = 10^{51}$ erg
$n = 7\ ,\ M_{\rm ej} = 1.4\,{\rm M}_\odot$
$s = 0\ ,\ n_{\rm H,ISM} = 0.1\ {\rm cm}^{-3}$

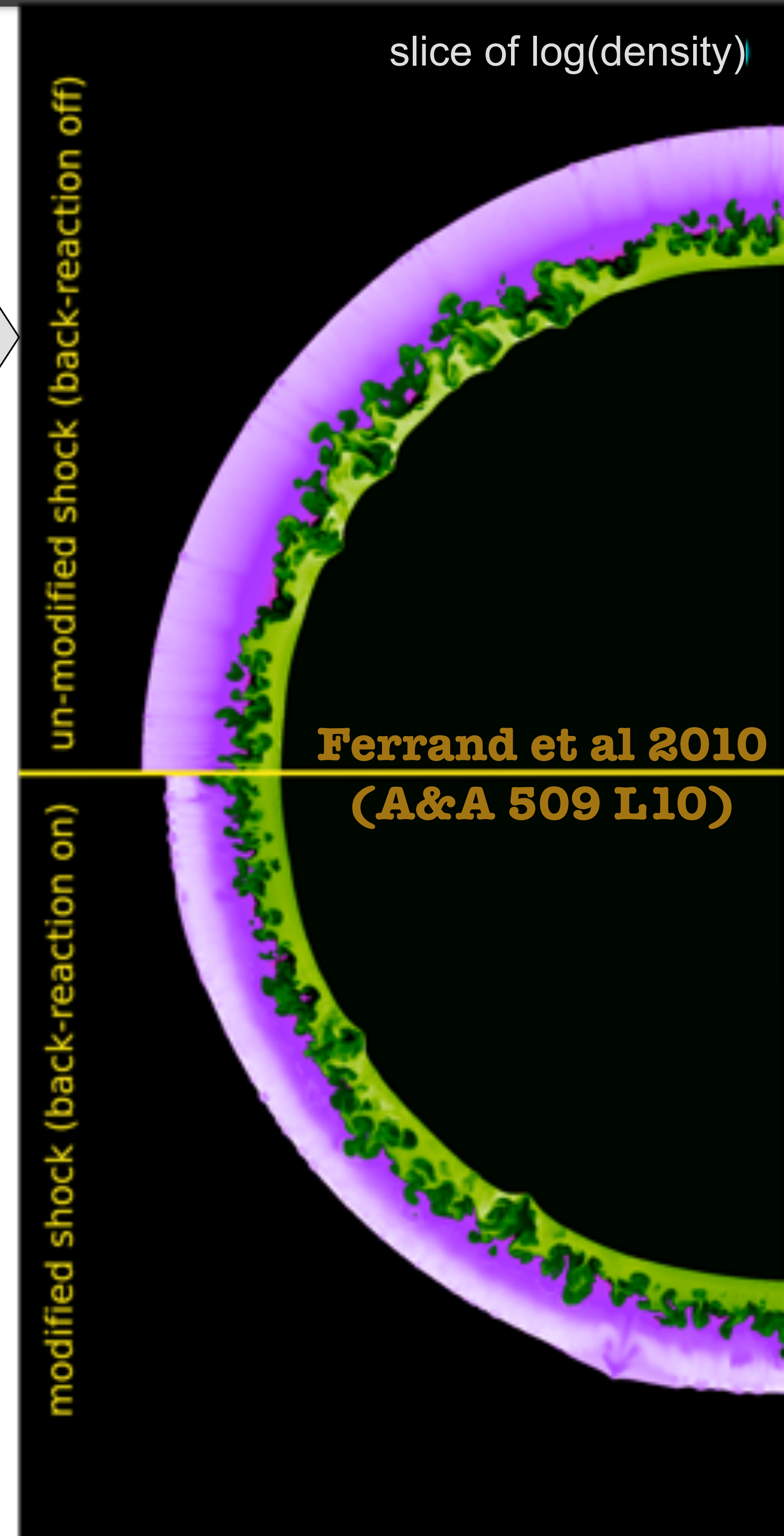
shock diagnostics

back-reaction: varying gamma

Ellison et al 2007

particle acceleration: non-linear model of **Blasi**

Blasi et al 2002, 2004, 2005 + Caprioli 2008, 2009



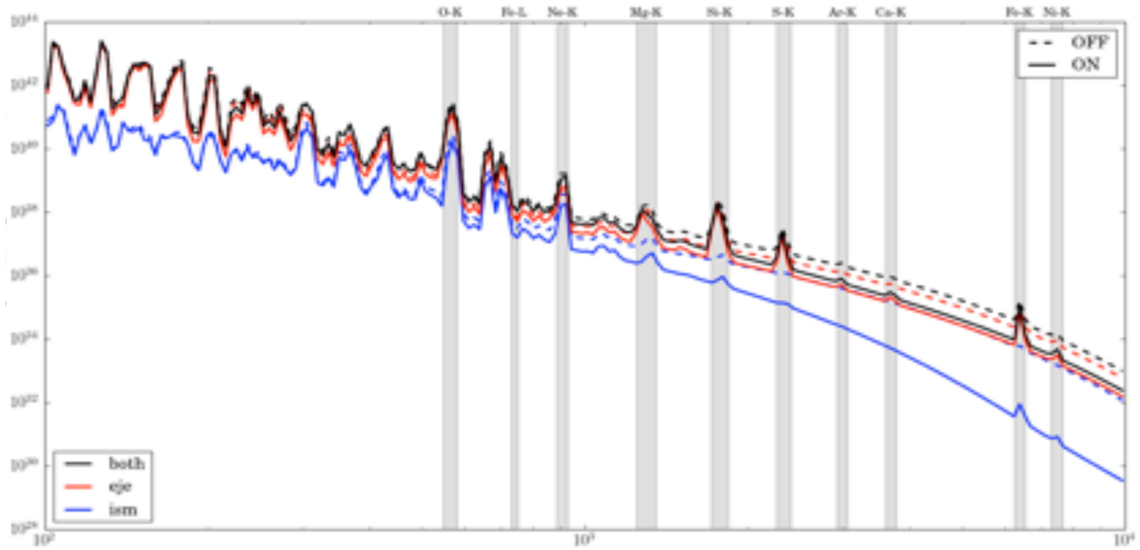
Anne Decourchelle
Head of Astrophysics Dpt. at CEA Saclay / Irfu

Using a comoving grid to factor out the expansion

Computing the emission from the SNR

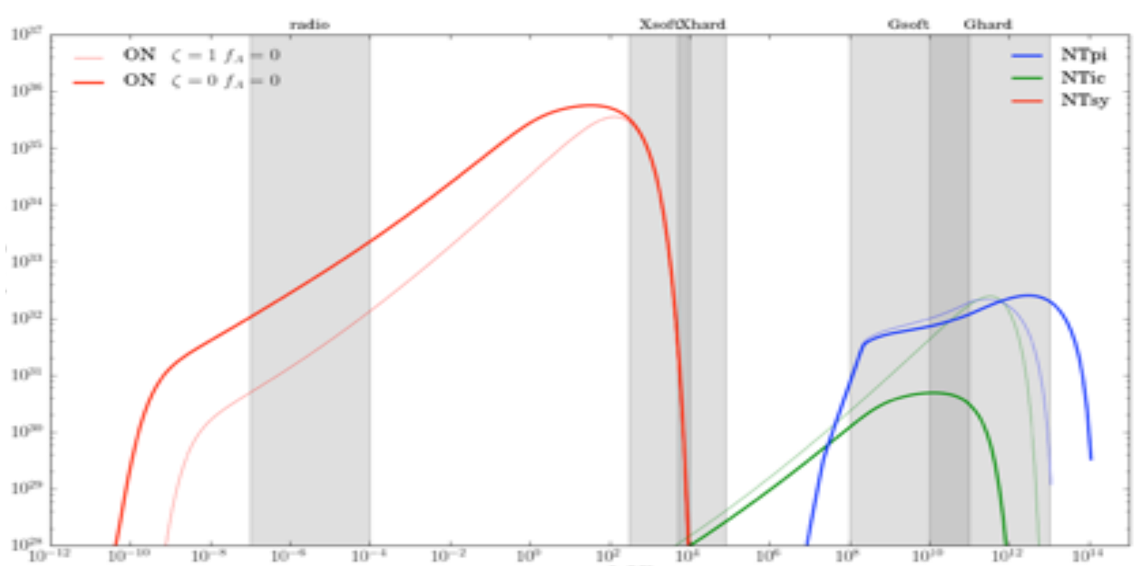
Samar Safi-Harb
Prof. at the University of Manitoba
Canadian Research Chair

Thermal emission
from the shocked plasma



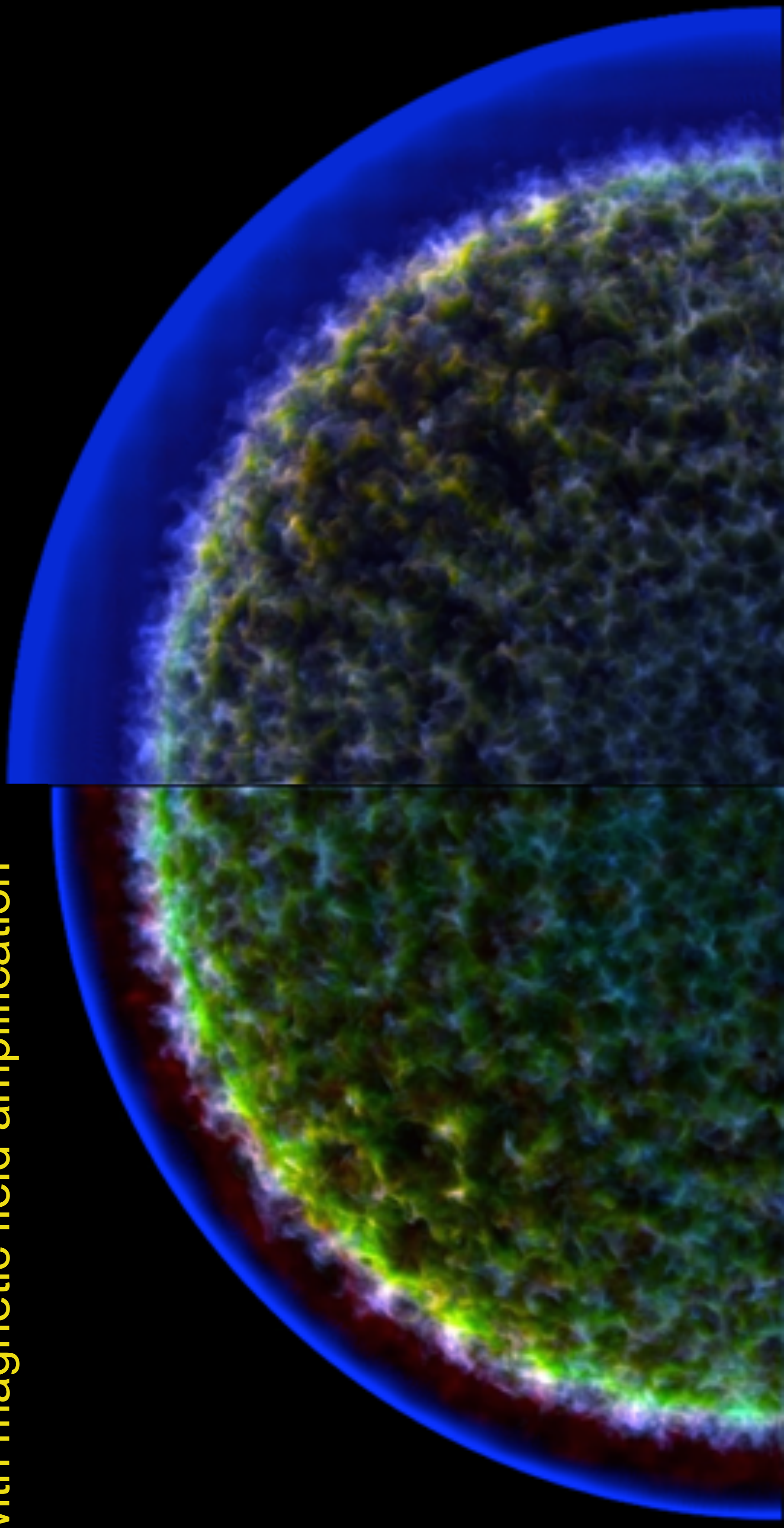
Ferrand, Decourchelle, Safi-Harb 2012

Non-thermal emission
from the accelerated particles



Ferrand, Decourchelle, Safi-Harb 2014

test-particle case



modified shock
with magnetic field amplification

Hydro- and thermodynamics of the plasma

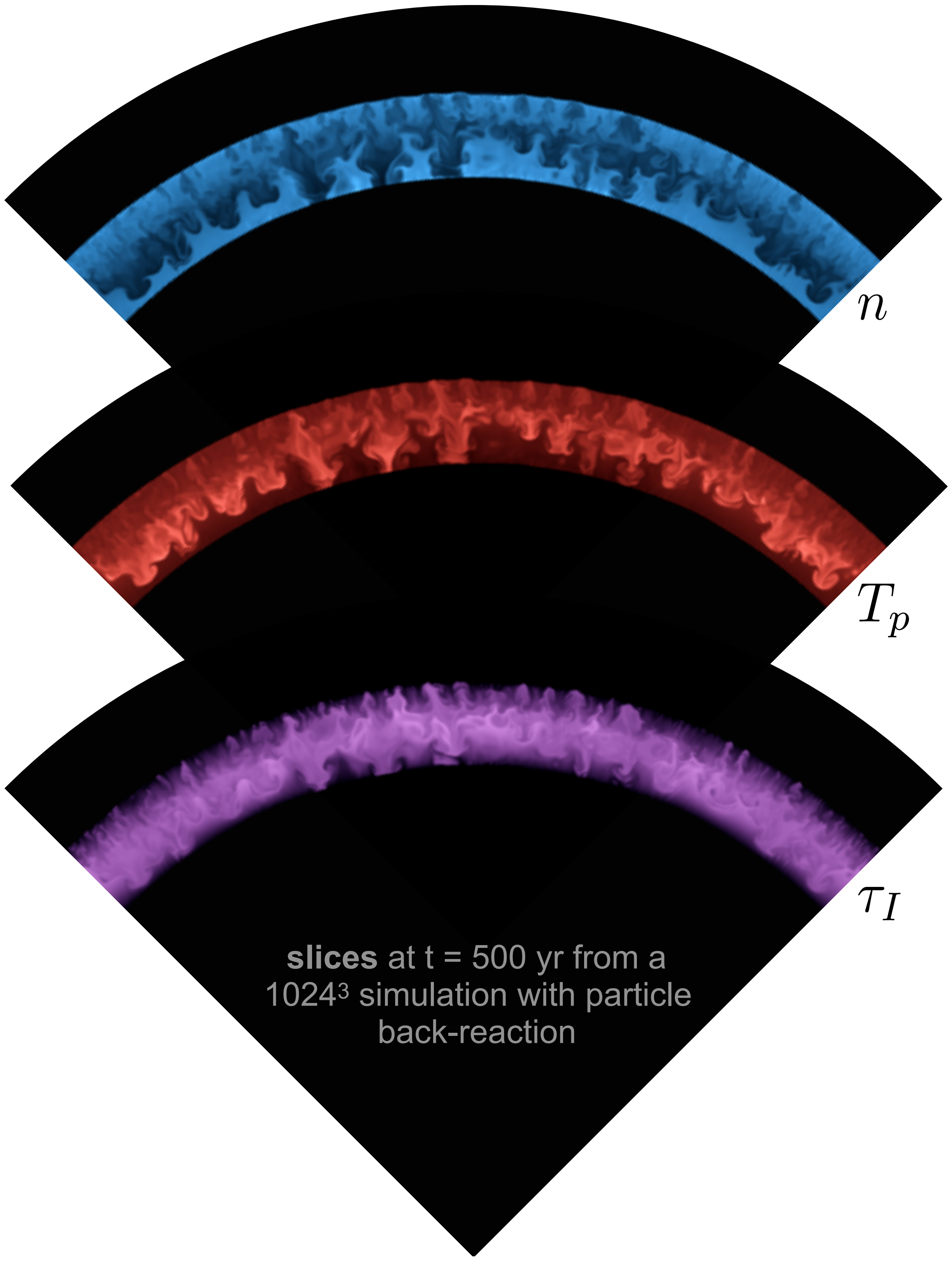
Thermal emission in each cell depends on:

- **plasma density** n^2
- **electron temperature** T_e
  progressive equilibration
  with protons temperature T_p
  via Coulomb interactions
- **ionization states** $f_i(Z)$
  computation of **non-equilibrium** ionization
  - solving the coupled time-dependent
    system of equations
    Patnaude et al 2009, 2010
  - using the exponentiation method
    in post-processing

$$\tau_I = \int_{t_S}^{t} n(t').\mathrm{d}t'$$

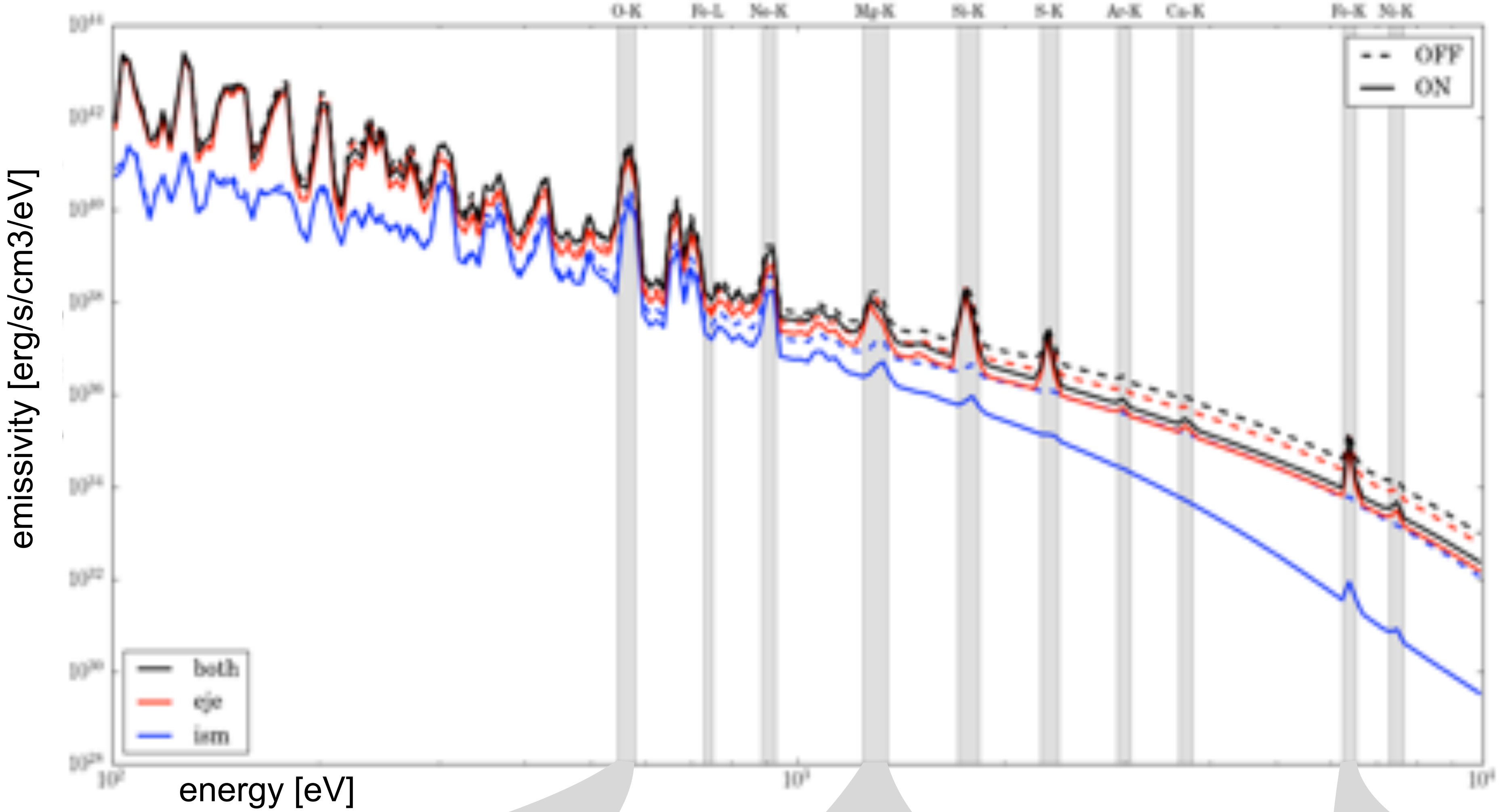
Smith & Hughes 2010

all these parameters depend on the **history** of the material after it was shocked.



Ferrand, Decourchelle, Safi-Harb 2012

Thermal emission

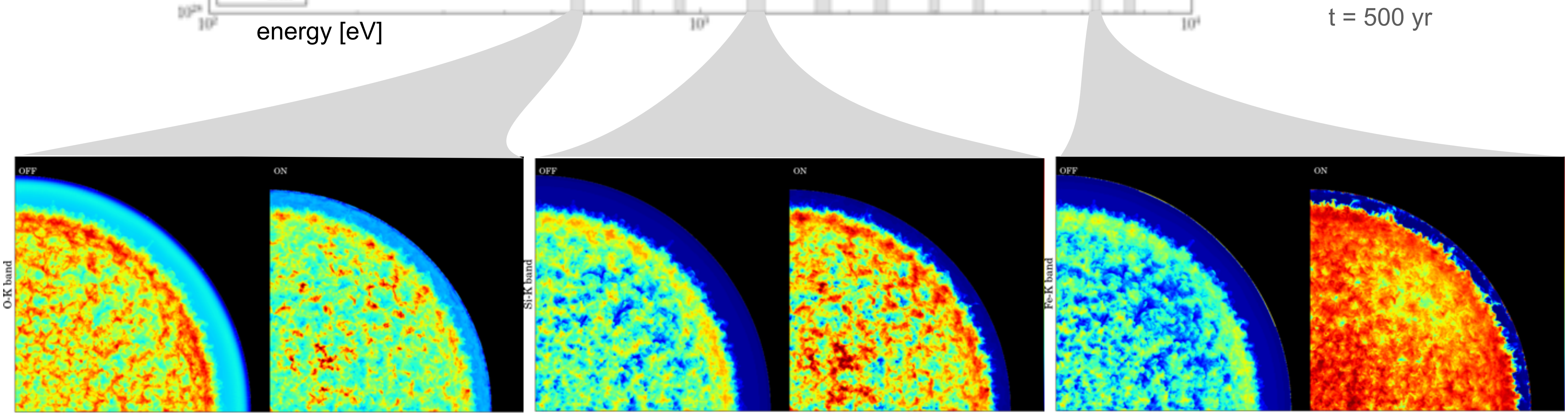


Ferrand, Decourchelle, Safi-Harb 2012

using an emission code adapted from Mewe, with rates from Arnaud

1024^3 cells

t = 500 yr



test particle vs. back-reaction

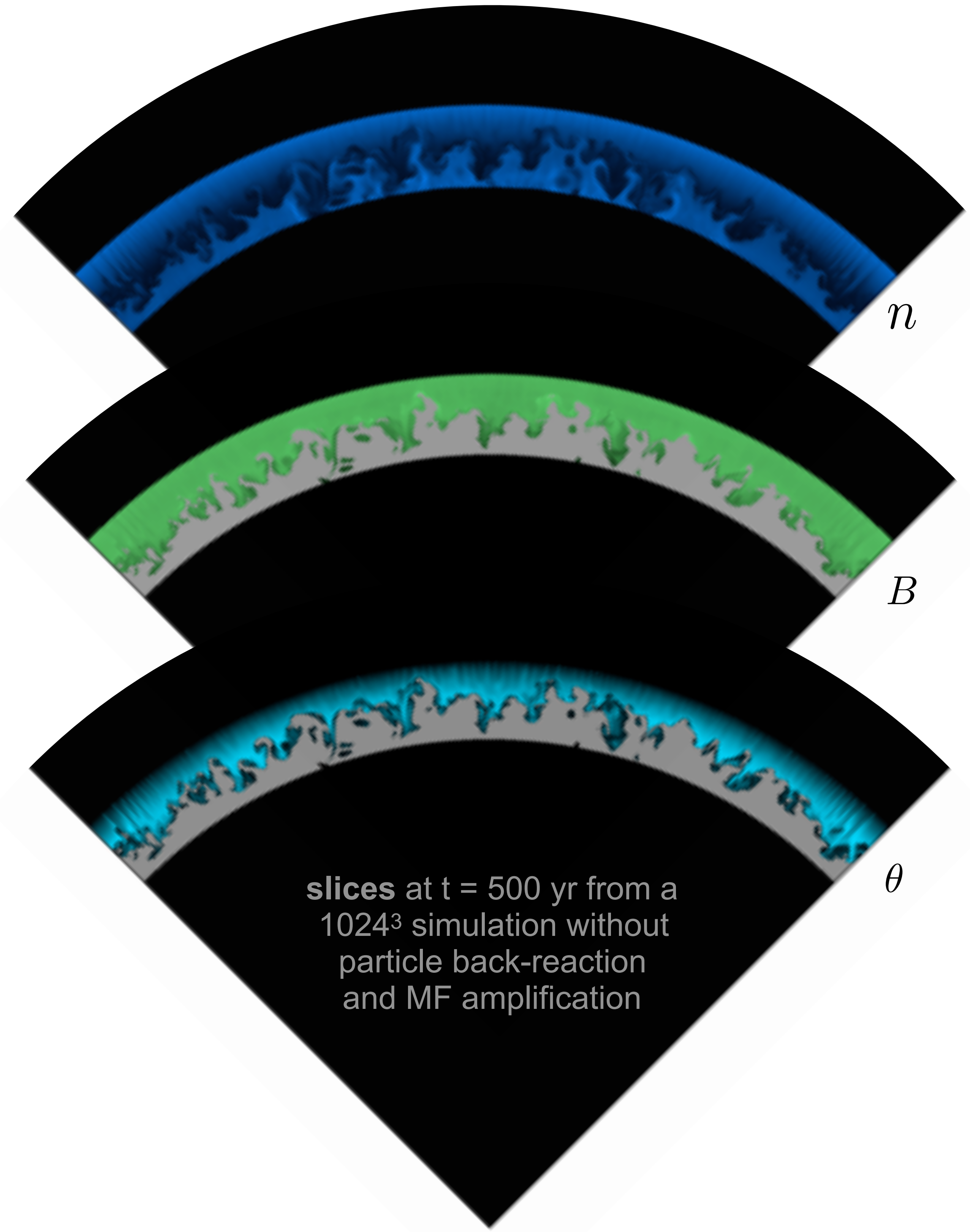
test particle vs. back-reaction

test particle vs. back-reaction

Magnetic field and radiative losses

Non-thermal emission in each cell depends on:

- pion decay: **plasma density** $n(x,t)$
- synchrotron: **magnetic field** $B(x,t)$
 (amplified at the shock, then frozen in the flow)
- Compton: ambient photon fields (CMB)

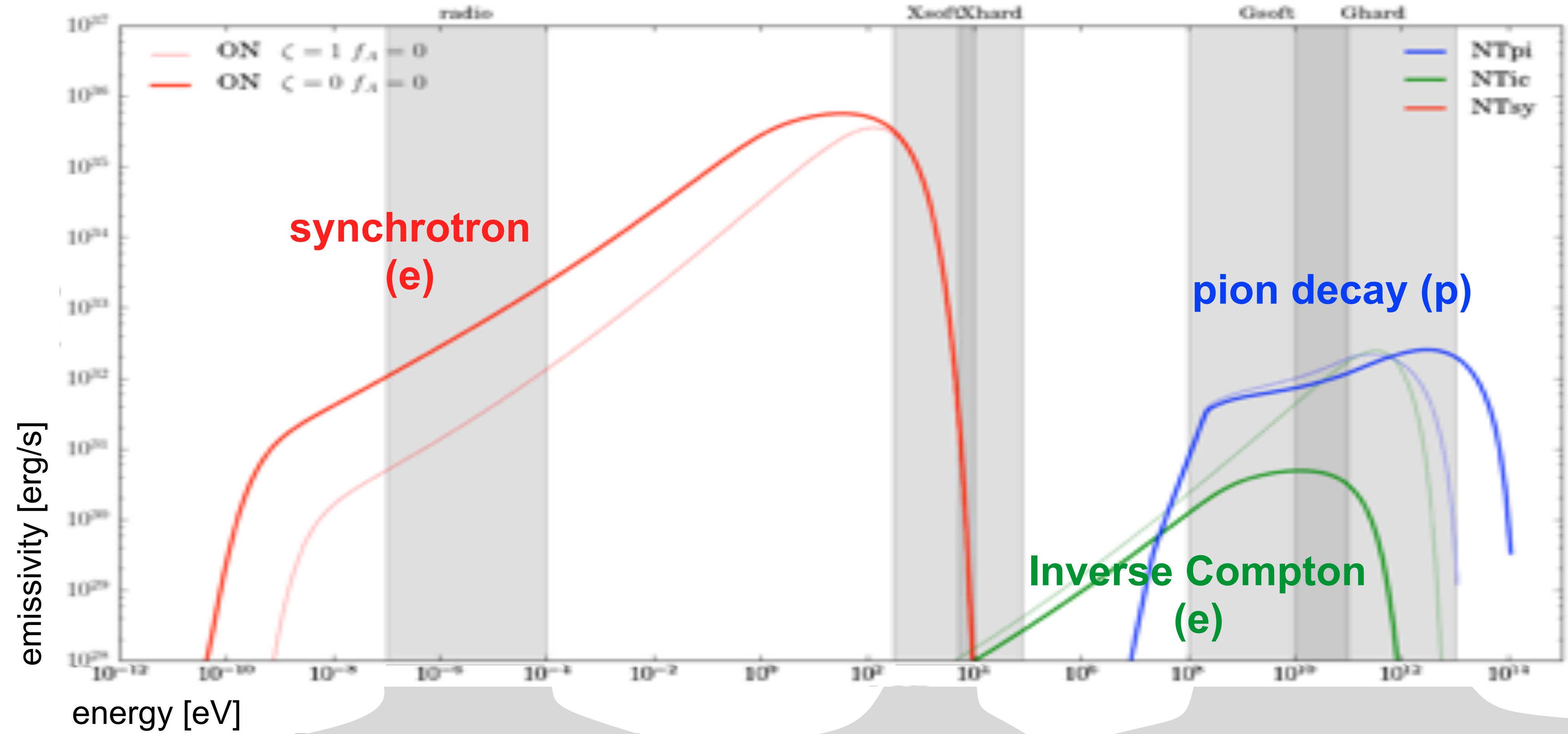


Note: the acceleration model gives the CR spectra just behind the shock $f_p(p,x,t)$, $f_e(p,x,t)$
they must be **transported** to account for losses:

- adiabatic decompression $\alpha = \dfrac{\rho(x,t)}{\rho(x_S,t_S)}$
- radiative losses $\Theta \propto \int_{t_S}^{t} B^2 \alpha^{\frac{1}{3}} \mathrm{d}t$

Ferrand, Decourchelle, Safi-Harb 2014

Non-thermal emission



Ferrand, Decourchelle, Safi-Harb 2014

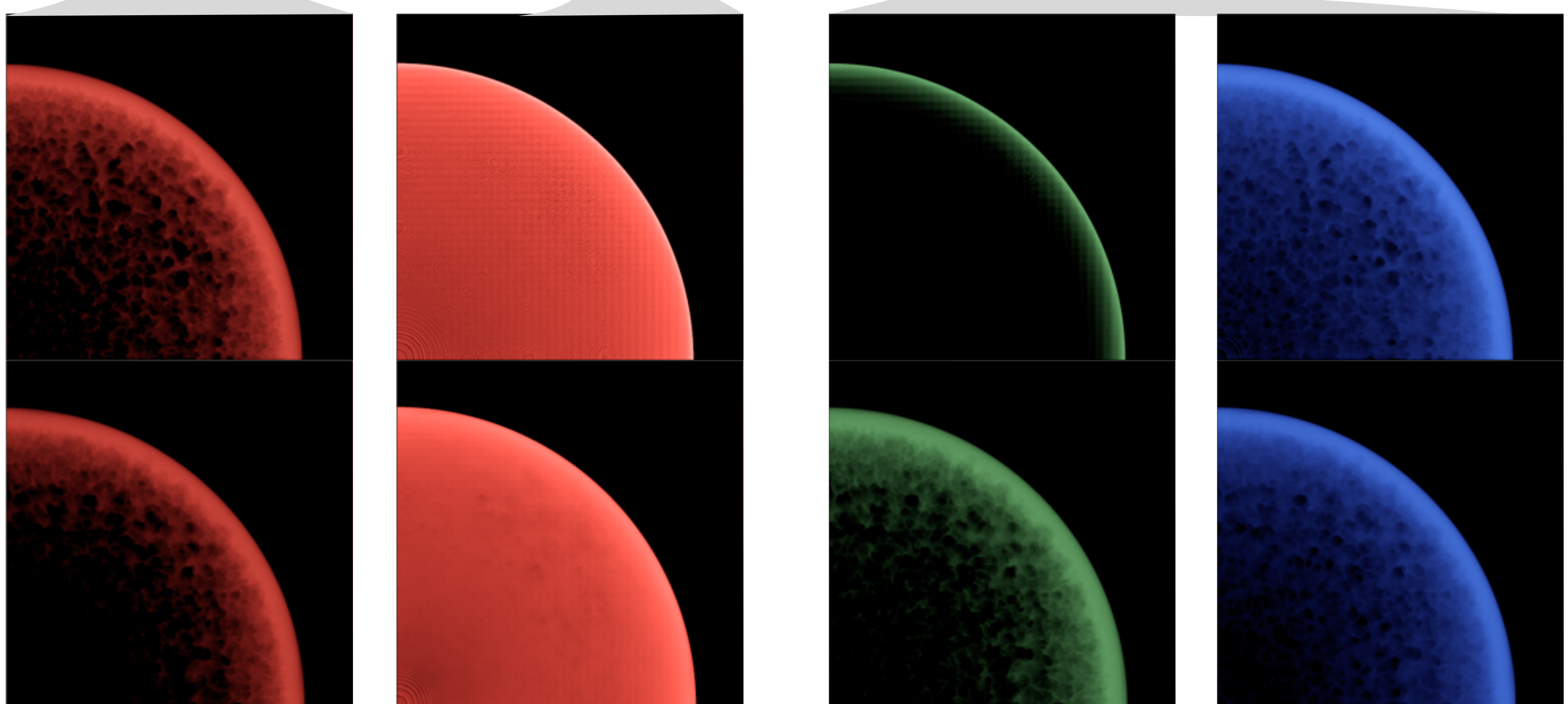
using the emission code from P. Edmon

1024^3 cells

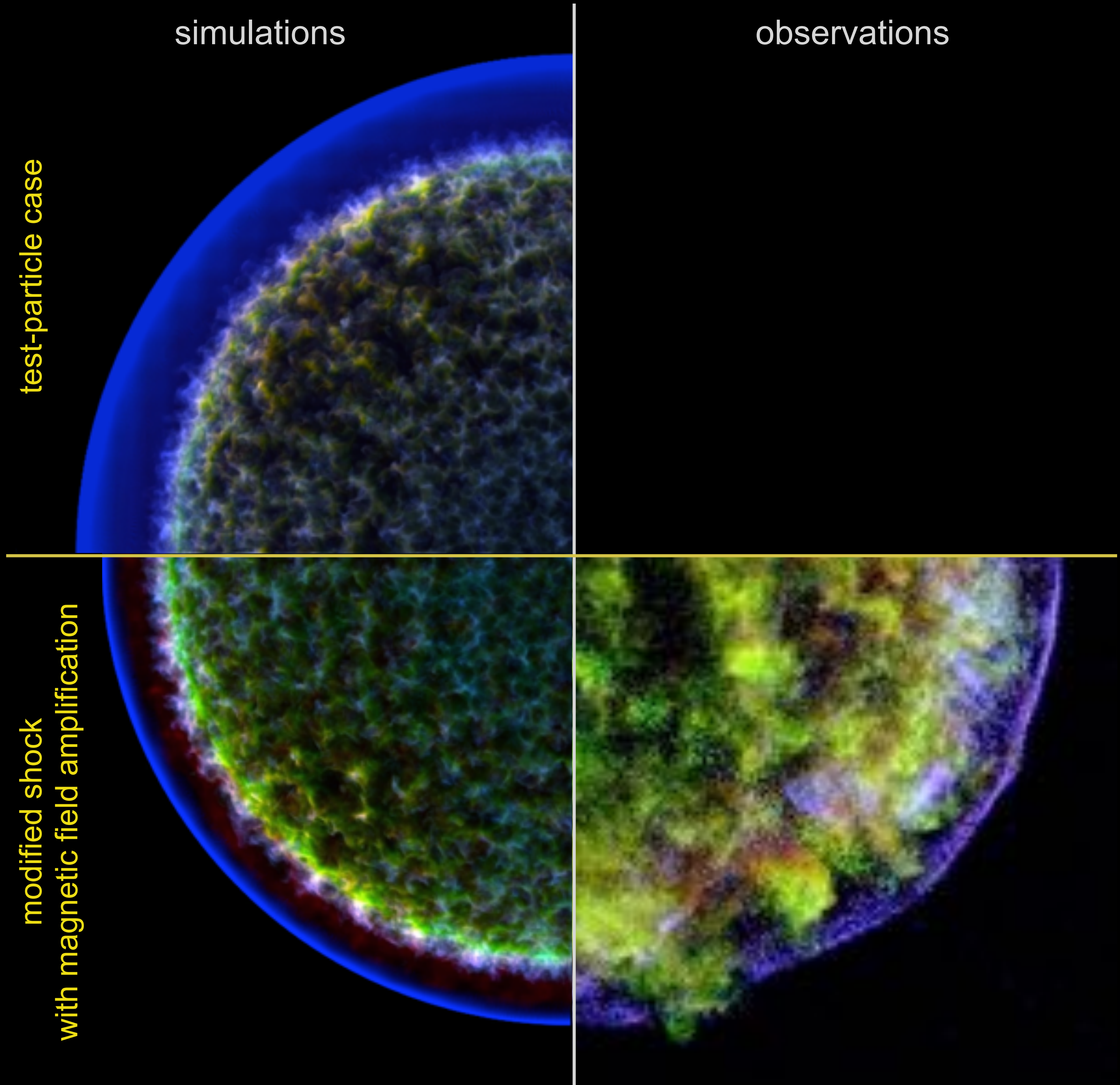
t = 500 yr

efficient MF amplification → high B

no net MF amplification → low B



Thermal + non-thermal emission



Energetic protons, accelerated at the shock front, don't radiate as efficiently as electrons, however:

1/ they impact the dynamics of the shock wave, and therefore the **thermal emission** from the shell (optical, X-rays)

2/ they impact the evolution of the magnetic field, and therefore the **non-thermal** emission from the electrons (radio – X-rays – γ-rays)

SNRs as probes of the explosion

From the supernova to the supernova remnant

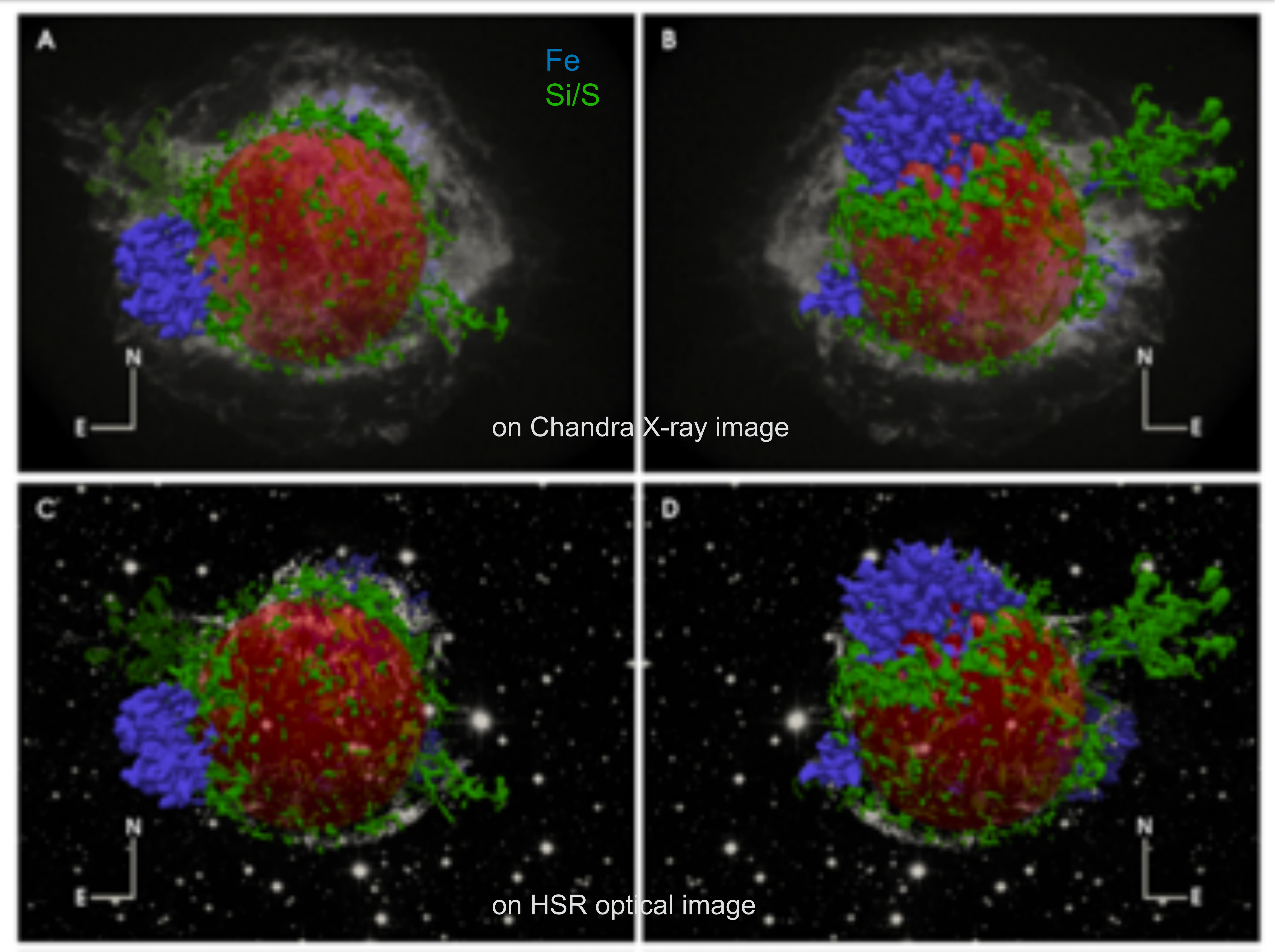
2 main types:
Type Ia : thermonuclear explosion of white dwarf
still many competing models
Type II, Ibc: core-collapse of massive star
need to revive the shock: probably neutrinos

Supernova simulations in 3D explode. Sometimes.
Successful explosions have a complex structure:
does it impact the morphology of the remnant?
What can the observed (morphology of the) SNR
tell us about the explosion?

It is time to bridge SN studies and SNR studies

Cas A (from the SN) to the SNR

asymmetries in the 3D SN ejecta imposed by hand ➔ can reproduce the overall morphology of the SNR after hundreds of years



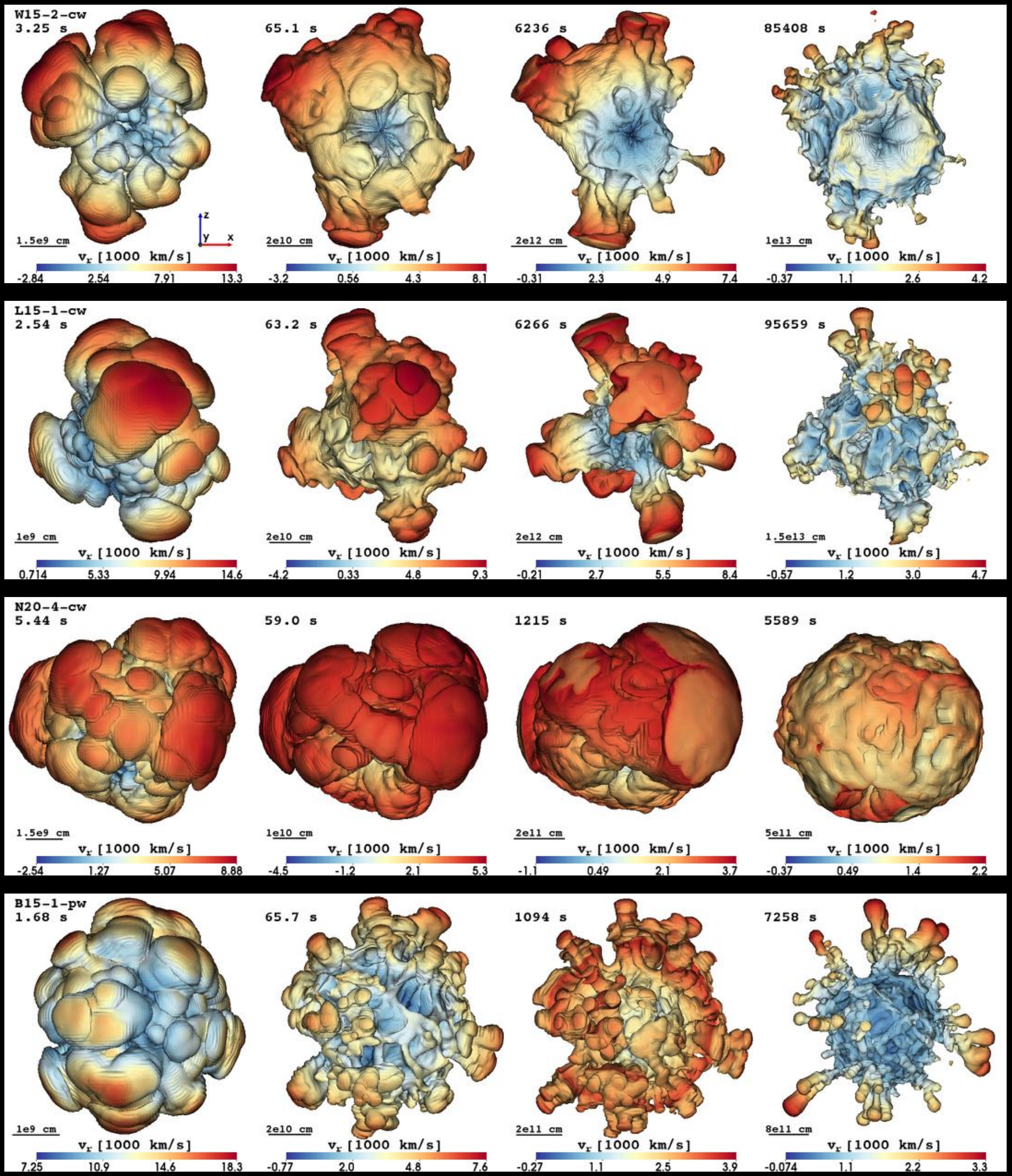
Orlando et al 2016

Conclusions: the bulk of asymmetries observed are intrinsic to the explosion

CC SNe: asymmetric explosions

a grid of parametrized core-collapse neutrino-driven explosions from different stellar evolution models from shock revival to shock breakout

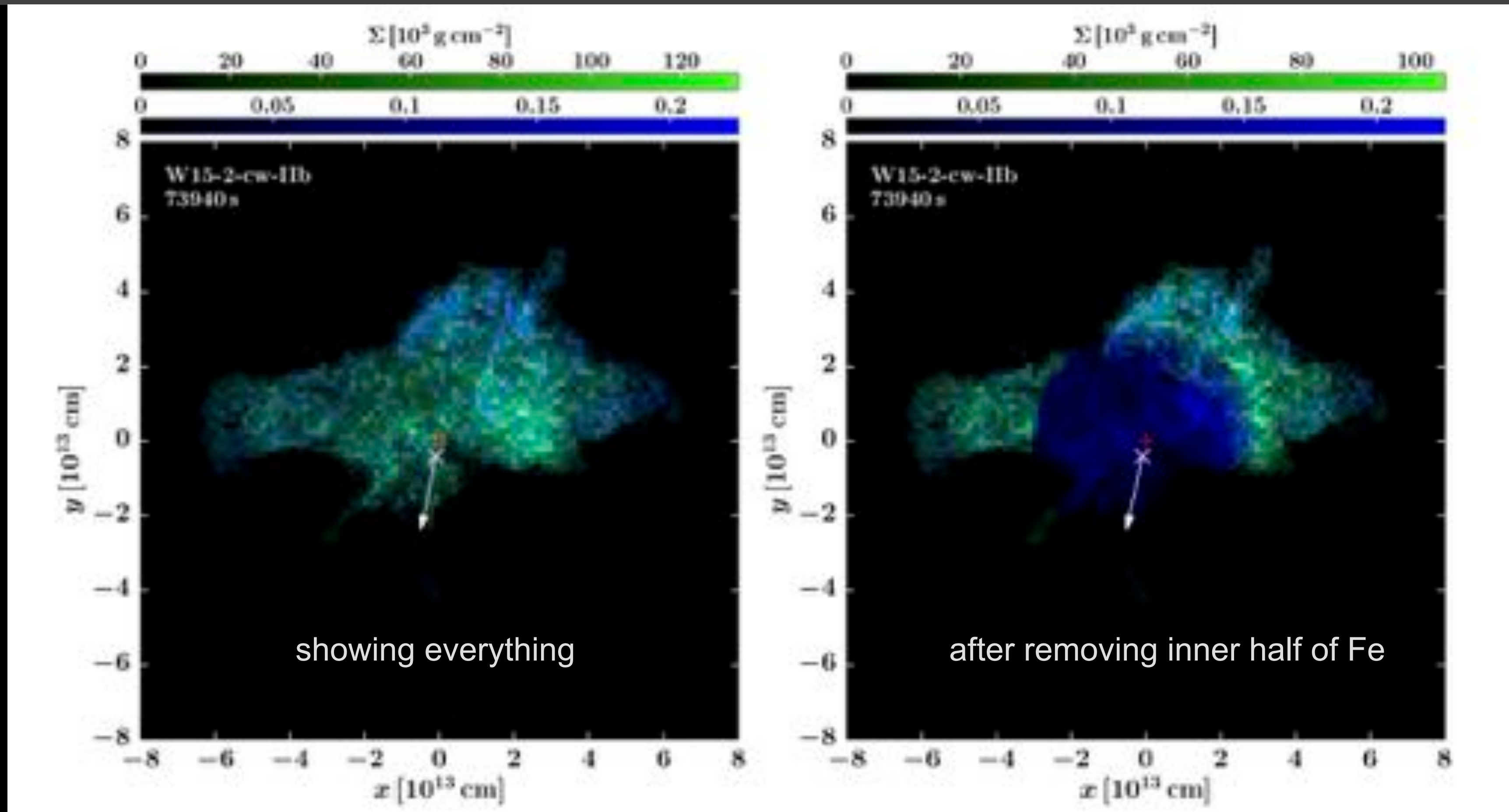
Wongwathanarat et al 2015



mass fraction of 56Ni,
color-coded by velocity

time

Cas A from the SN (to the SNR)



maps of
column density

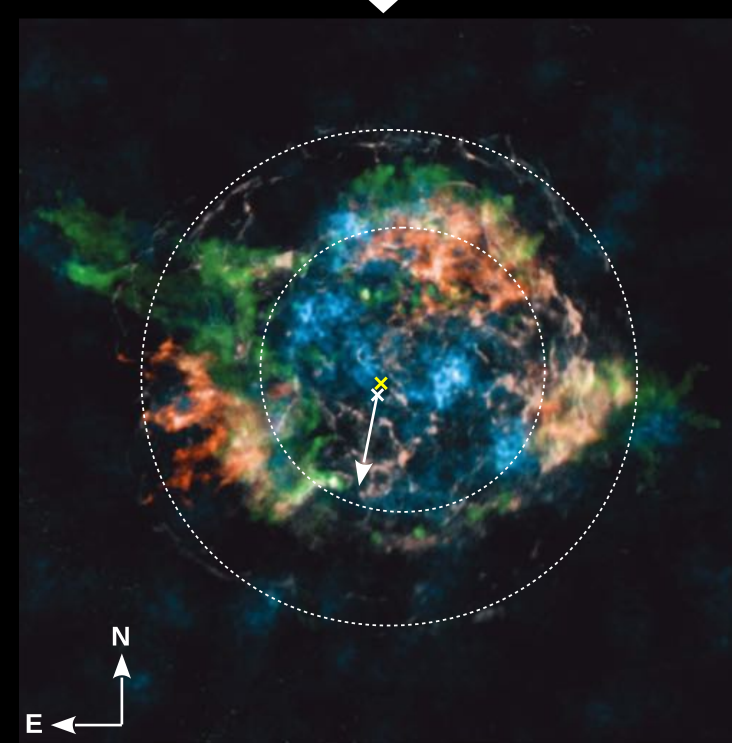
Fe (56Ni)
44Ti

Wongwathanarat
et al 2017

?

Gabler et al 2016

one of the CC
simulation models
happens to mimic
the morphology of
Cas A SNR



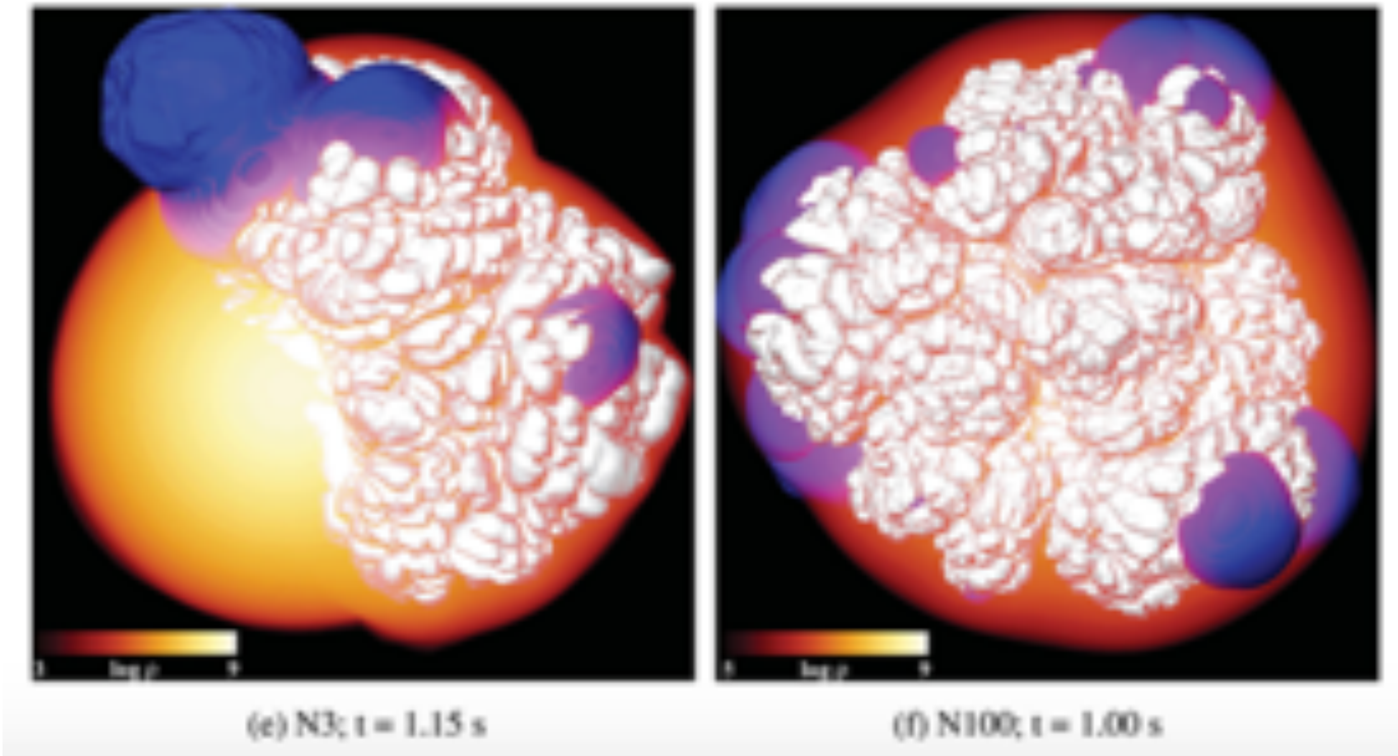
X-ray
observations

Fe
44Ti
Si

Grefenstette et al
2014

From the 3D thermonuclear SN to the 3D SNR

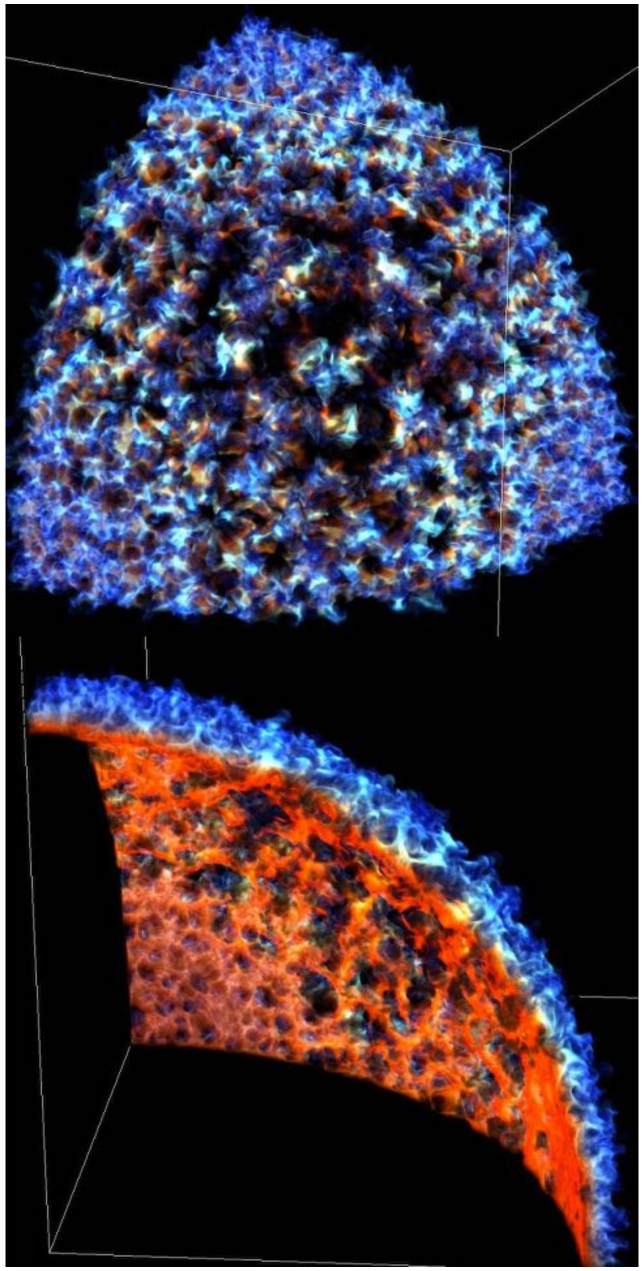
3D simulations of thermonuclear supernovae



Röpke 2007, Seitenzahl et al 2013

?

3D simulations of a TN supernova remnant



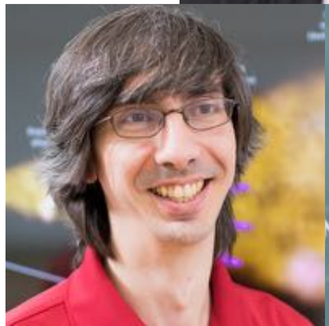
shocked ejecta at 500 yr

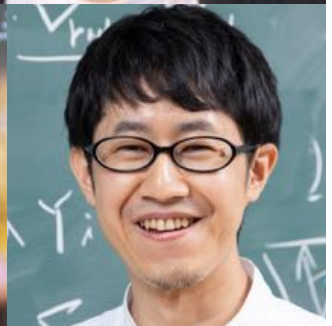
Ferrand et al 2010, 2012, 2014, 2016

Friedrich (Fritz) Röpke
Prof. at Ruprecht-Karls-Universität Heidelberg, Head of stellar group at Heidelberg Institute for Theoretical Studies

Ivo Seitenzahl
Research Fellow at School of Science, University of New South Wales (UNSW), Australia

Shigehiro (Hiro) Nagataki
Chief Scientist, Astrophysical Big Bang Laboratory





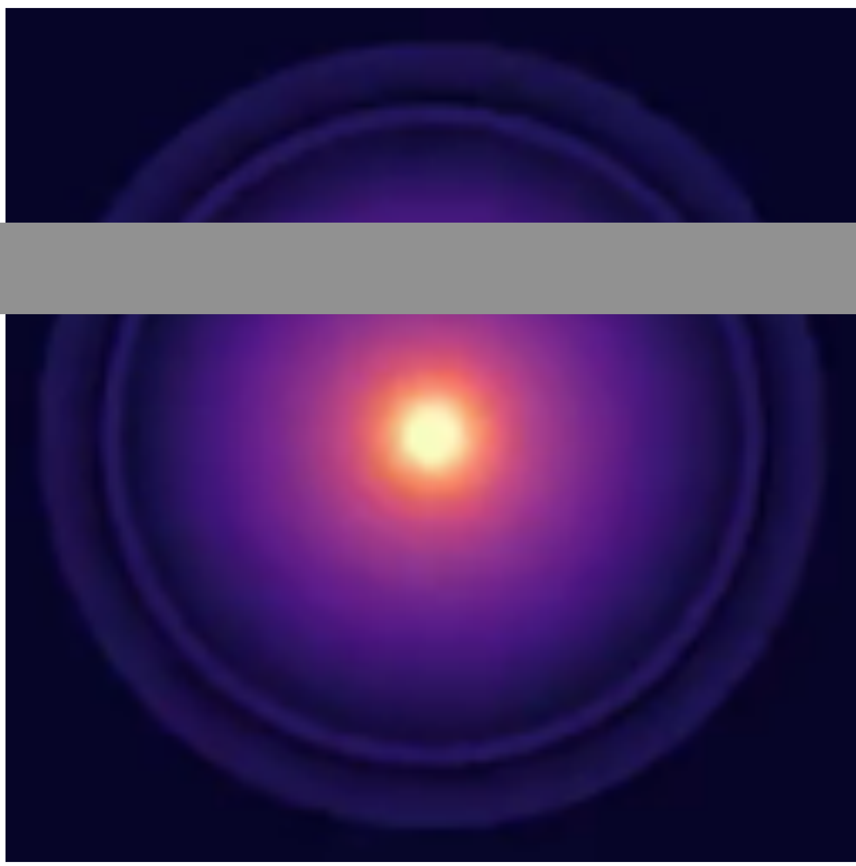
Don Warren
Masaomi Ono
Research Scientists

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)

see movies in online article



Chevalier
1D initial profile
(power-law)

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

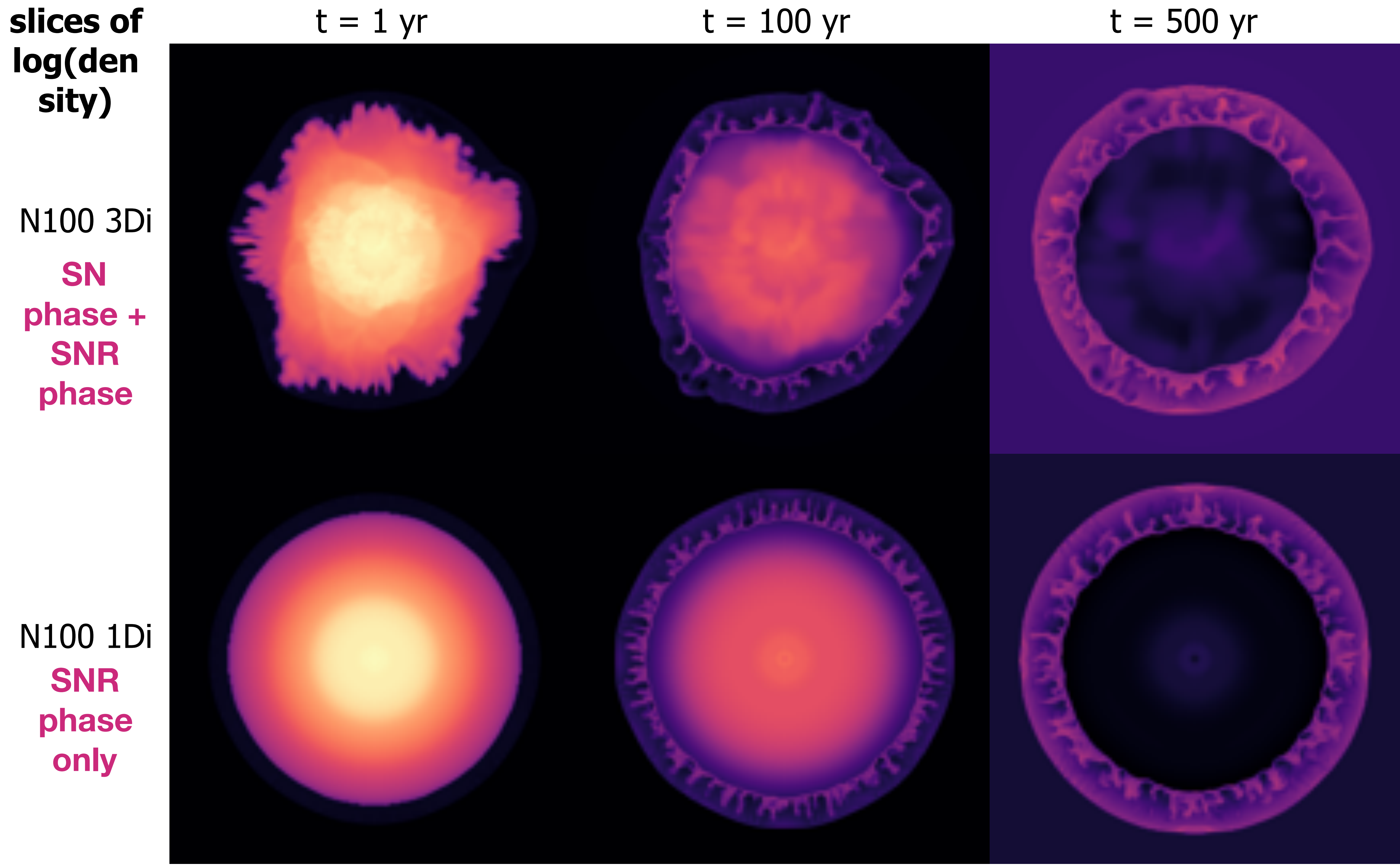
N100
full 3D initial profile

what SNR people used to do

what SN people are telling us

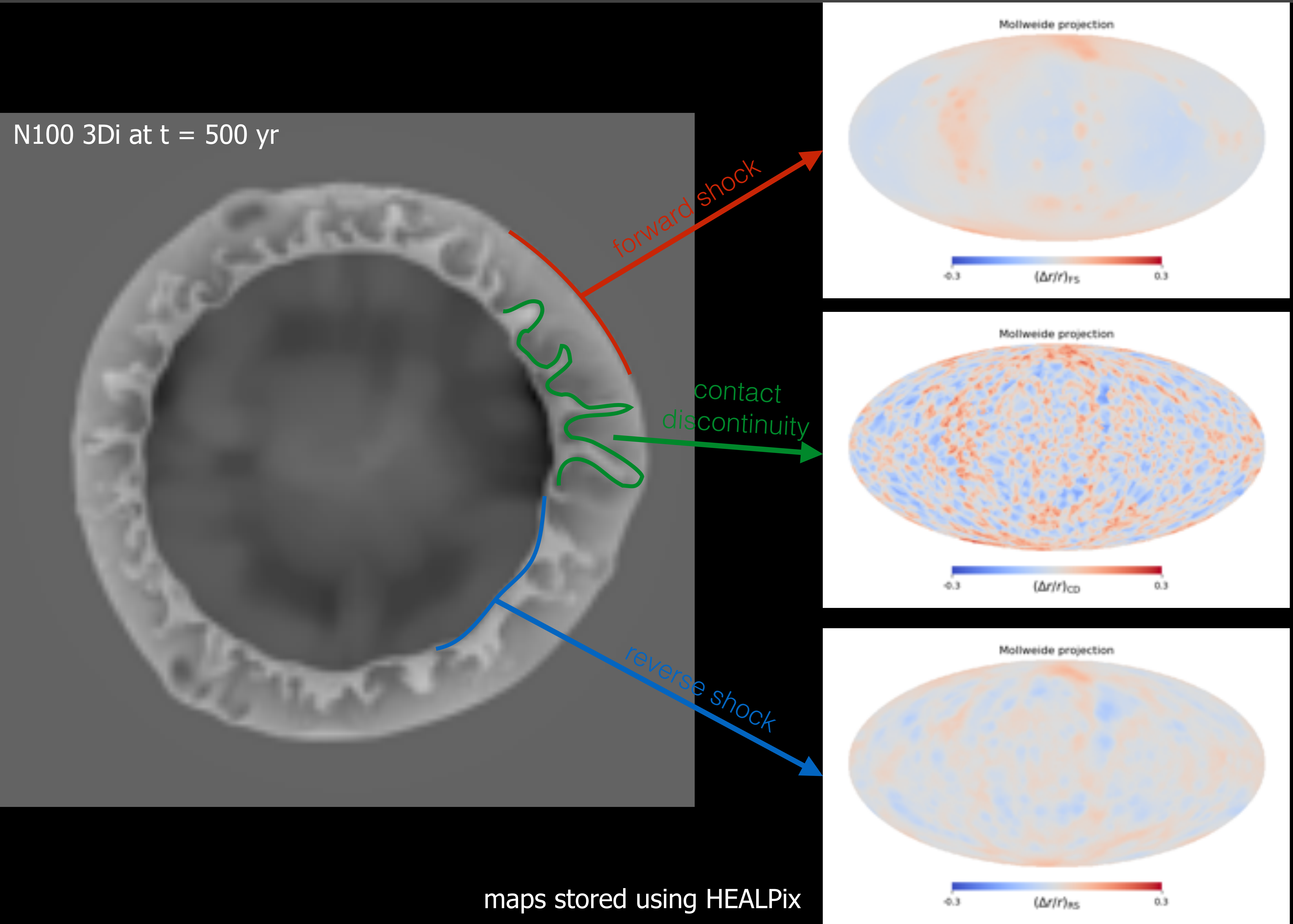
Ferrand et al 2019

Hydro evolution of the SNR



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.

Mapping the wavefronts (RS, CD, FS)

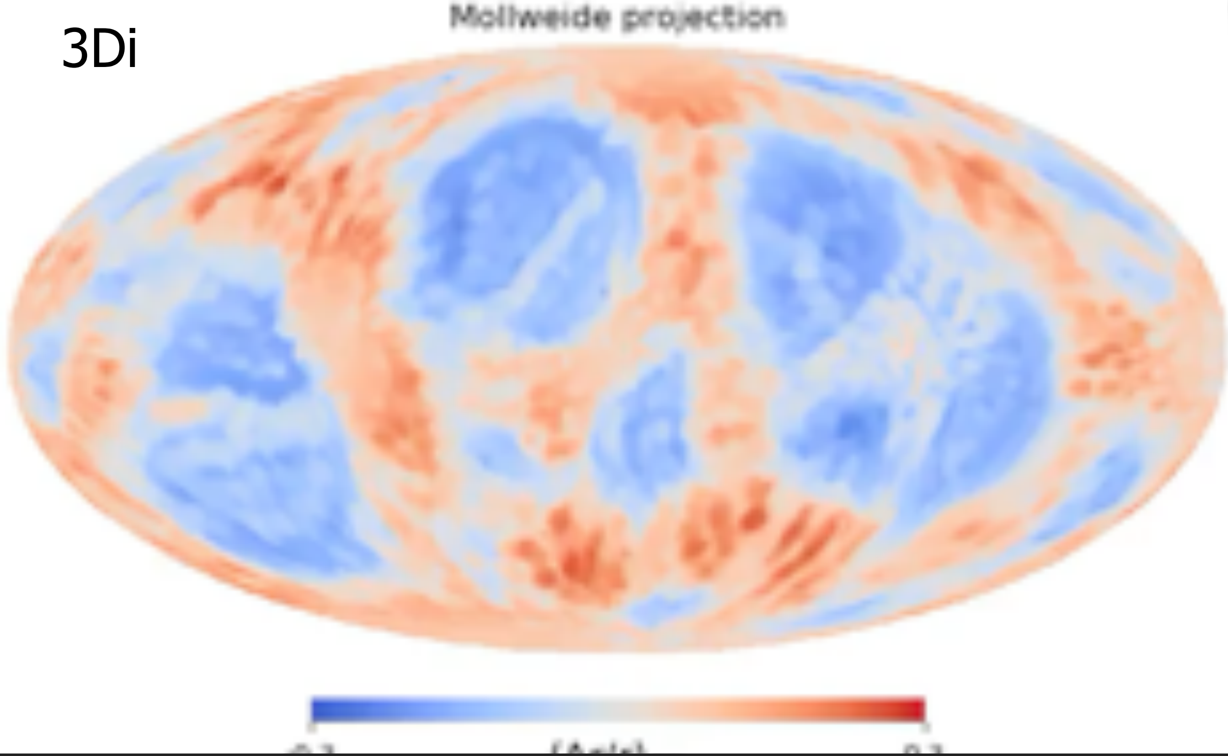


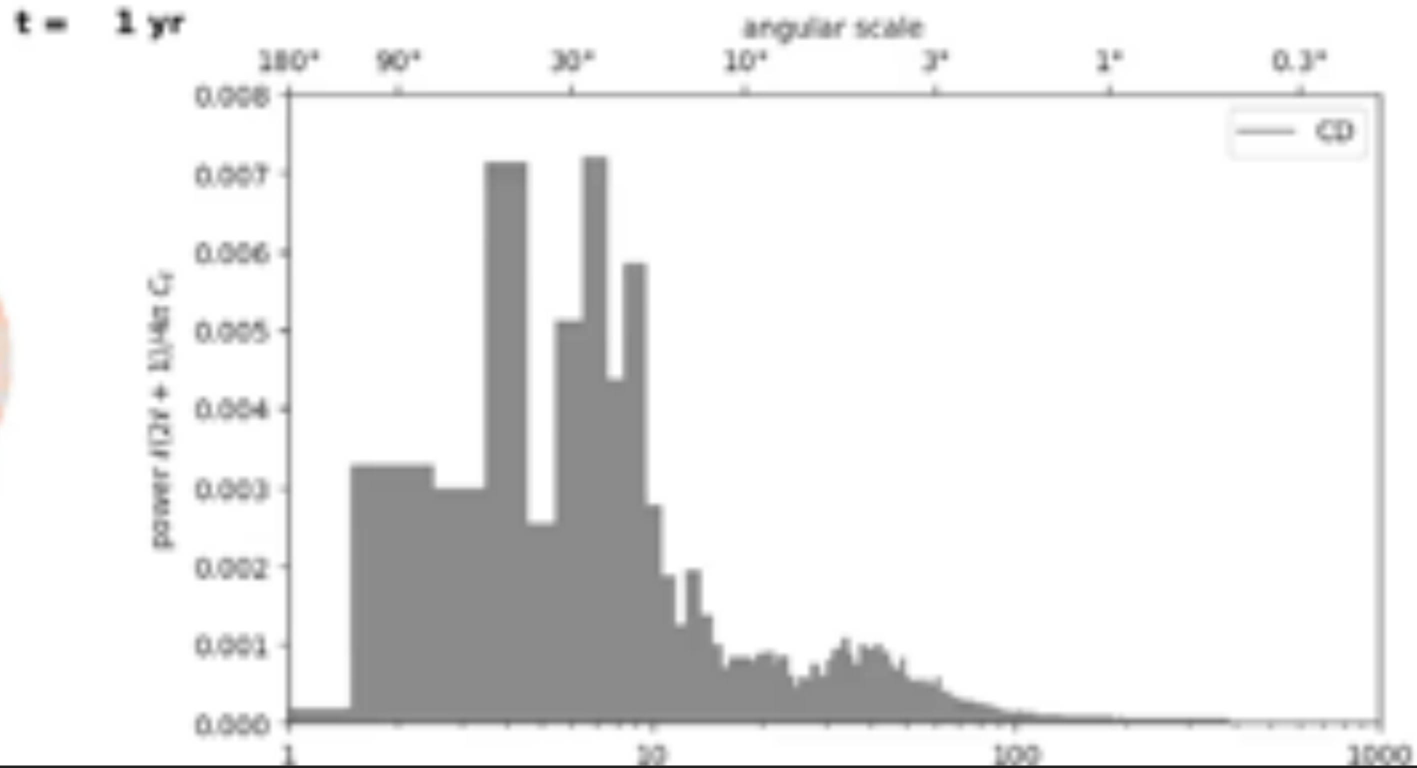
maps stored using HEALPix

Spherical harmonics expansion of the wavefronts

contact discontinuity (CD) from 1 yr to 500 yr

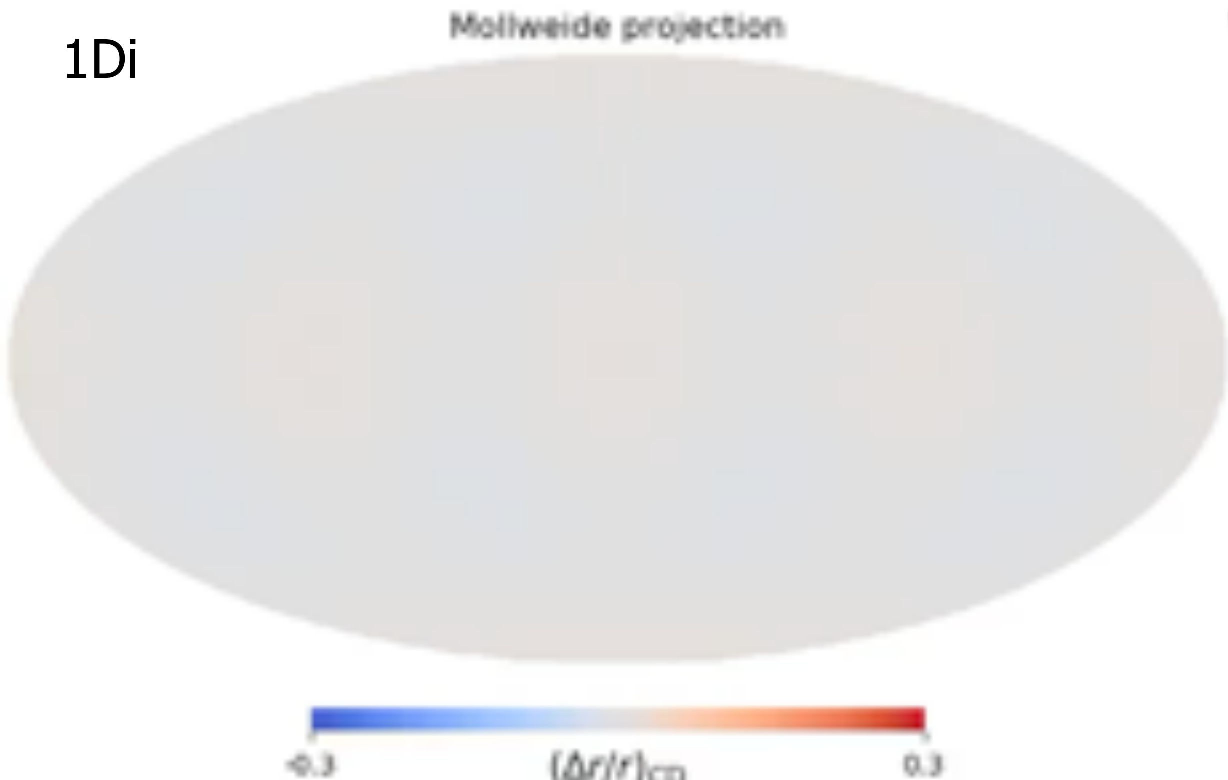
3Di

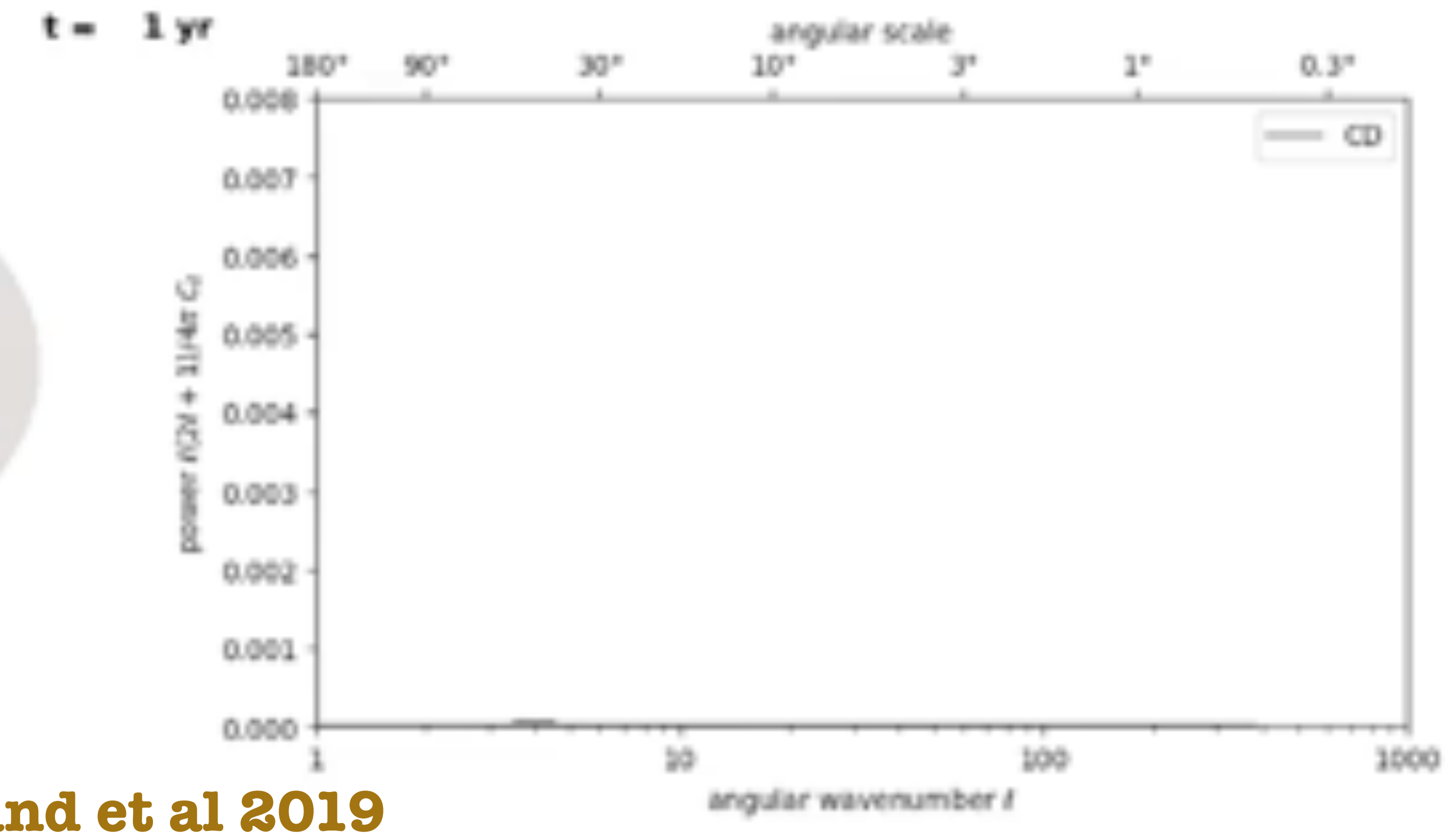




see movies in online article

1Di

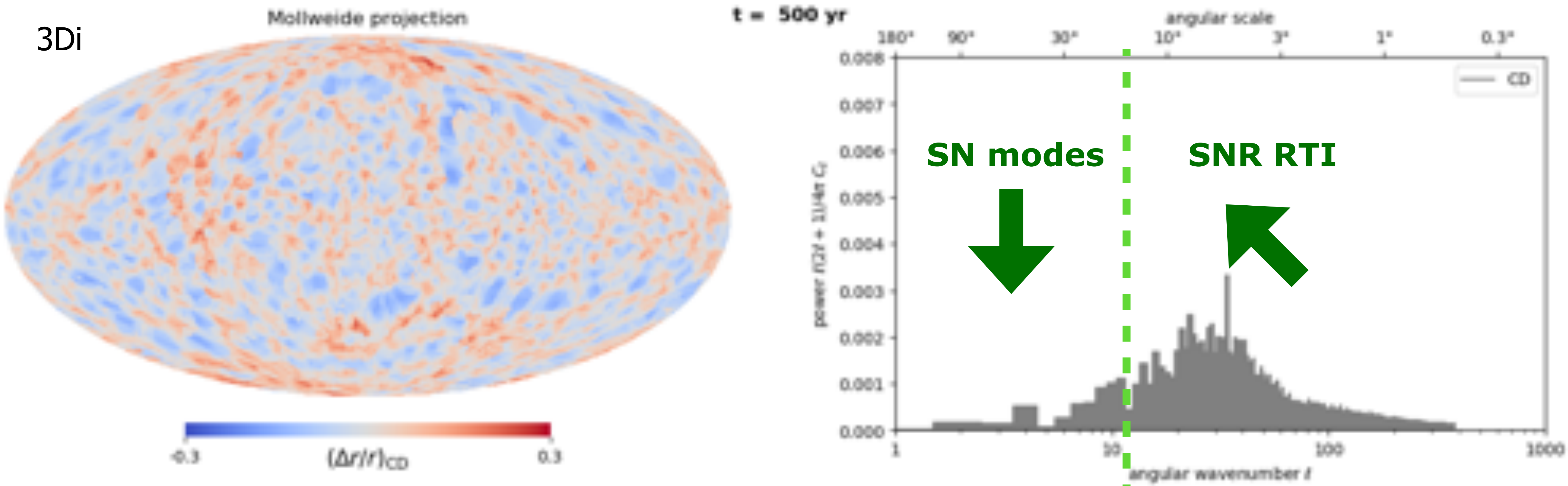


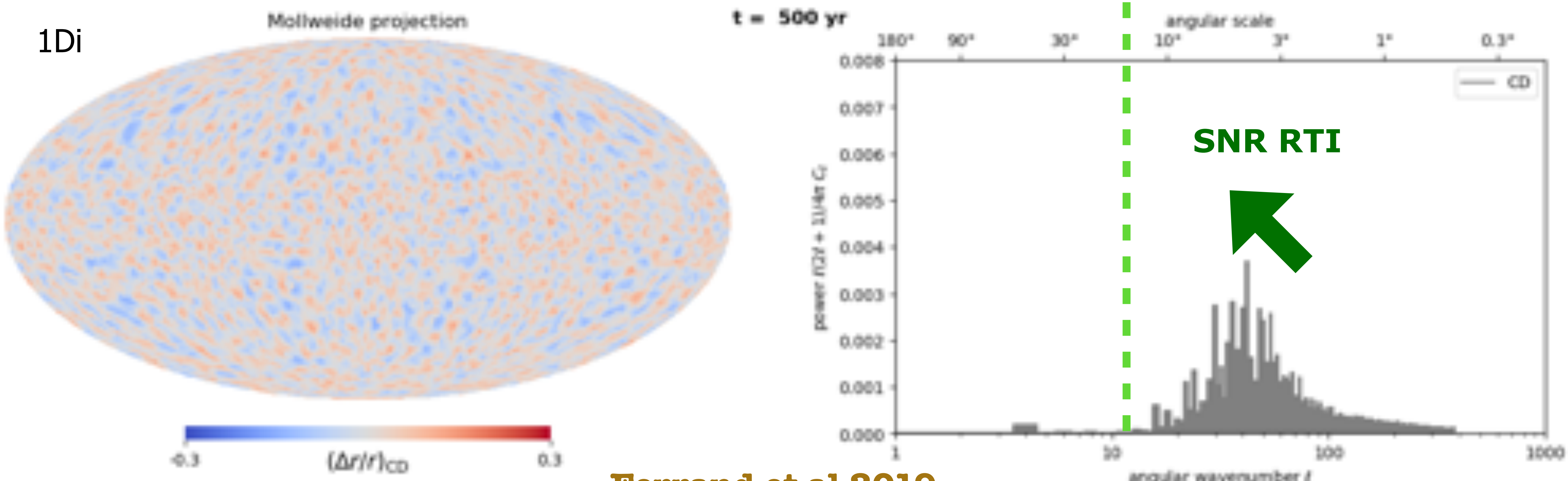


Ferrand et al 2019

Rayleigh-Taylor from the SN and SNR phases

contact discontinuity (CD) at 500 yr

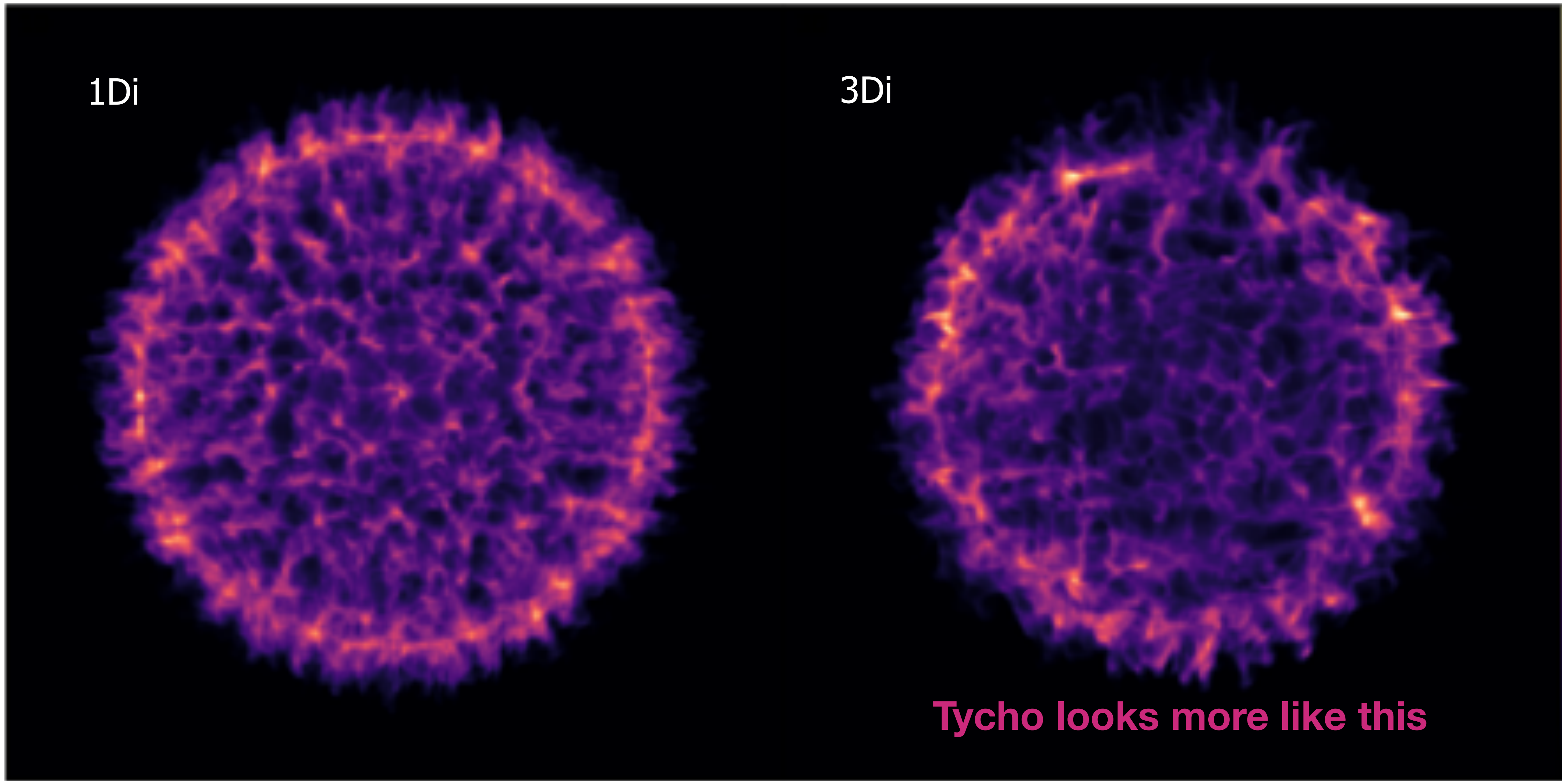




Ferrand et al 2019

First conclusions and application to Tycho

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

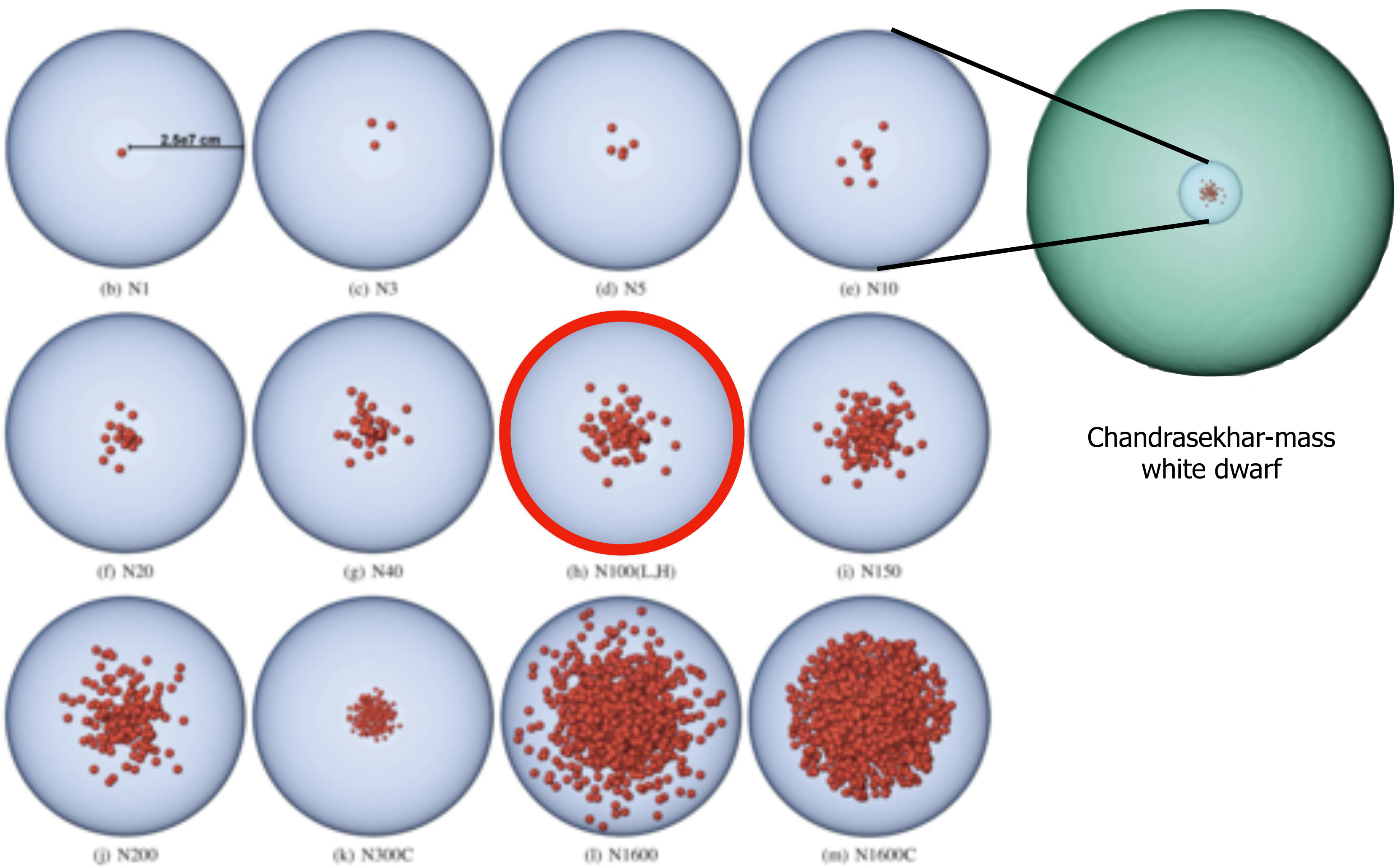
projection along l.o.s. of the density squared = proxy for the thermal emission
➔ next will compute the synthetic thermal (and non-thermal) emission

Perspectives for type Ia SNe

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

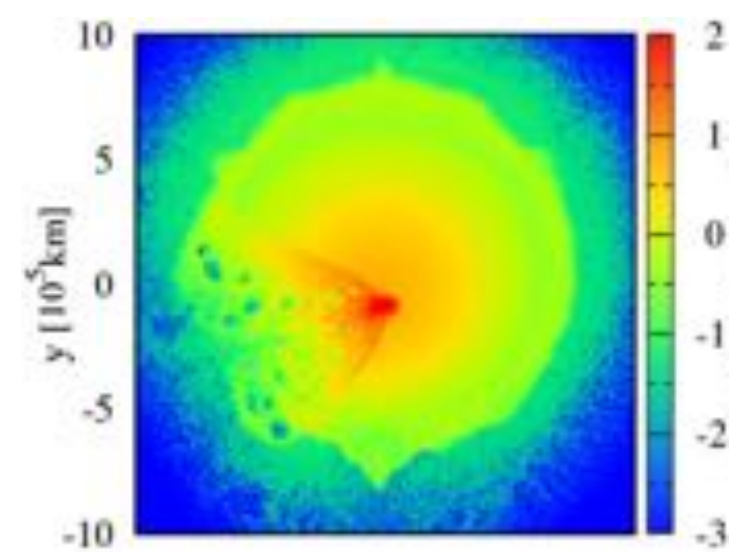
- between different ignition setups for the DDT model, that produce different initial asymmetries and yields
- between different SN explosion models: pure deflagration, pure detonation, other detonations, other channels…

(Role of the companion star?)



grid of DDT explosions: varying ignition patterns

Seitenzahl et al 2013

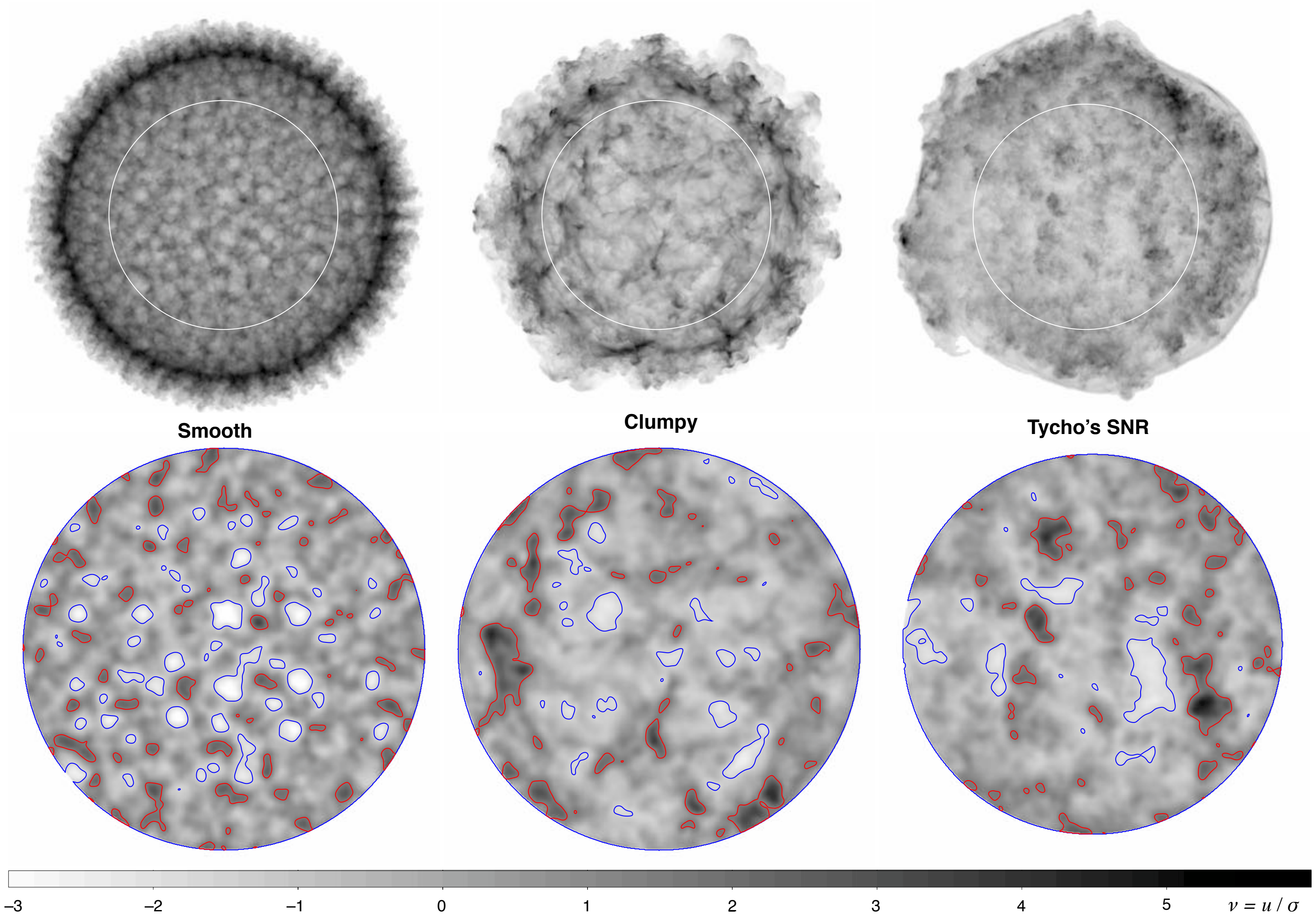


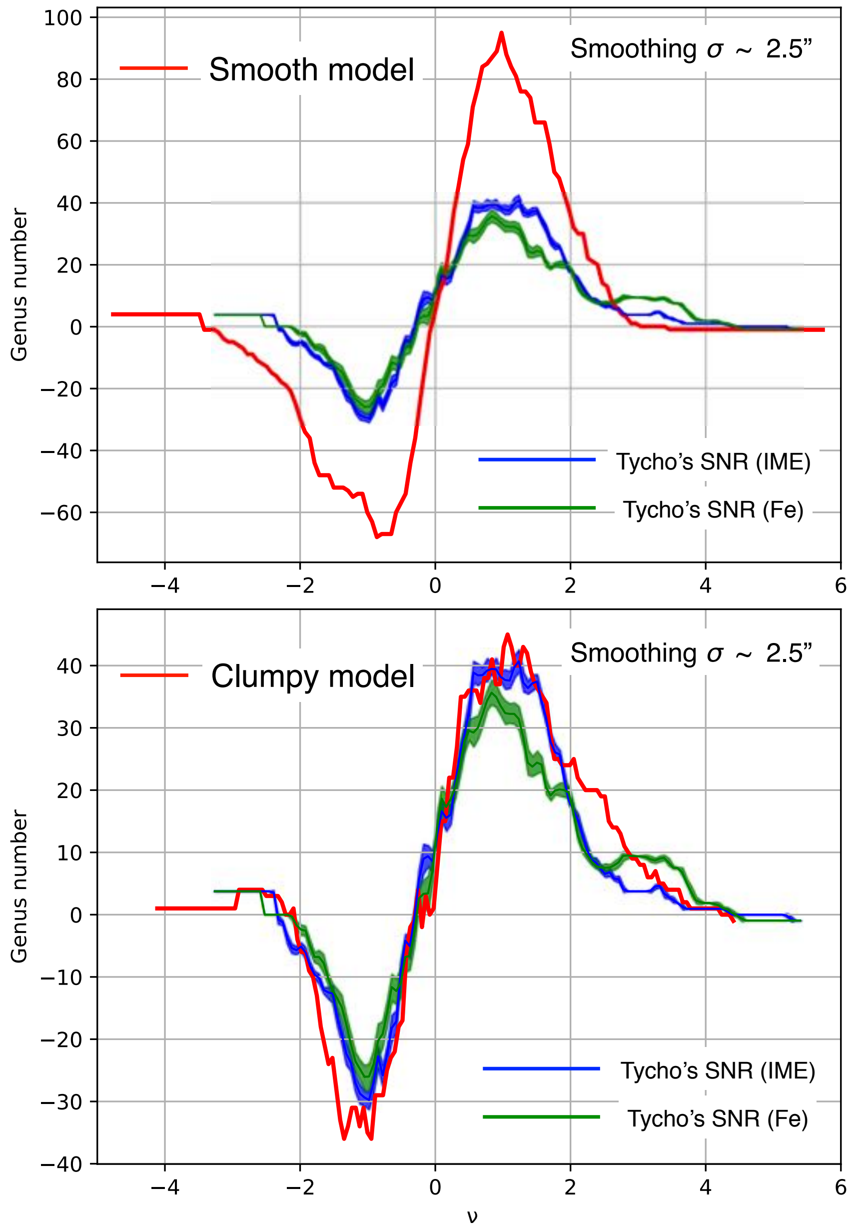
example of double-detonation double-degenerate explosion

Tanikawa et al 2018

X-ray image analysis with genus statistics

"genus number" = no. of "clumps" - no. of "holes"
for a black & white image, so for a given intensity threshold
(Euler-Poincaré characteristic on the excursion set)

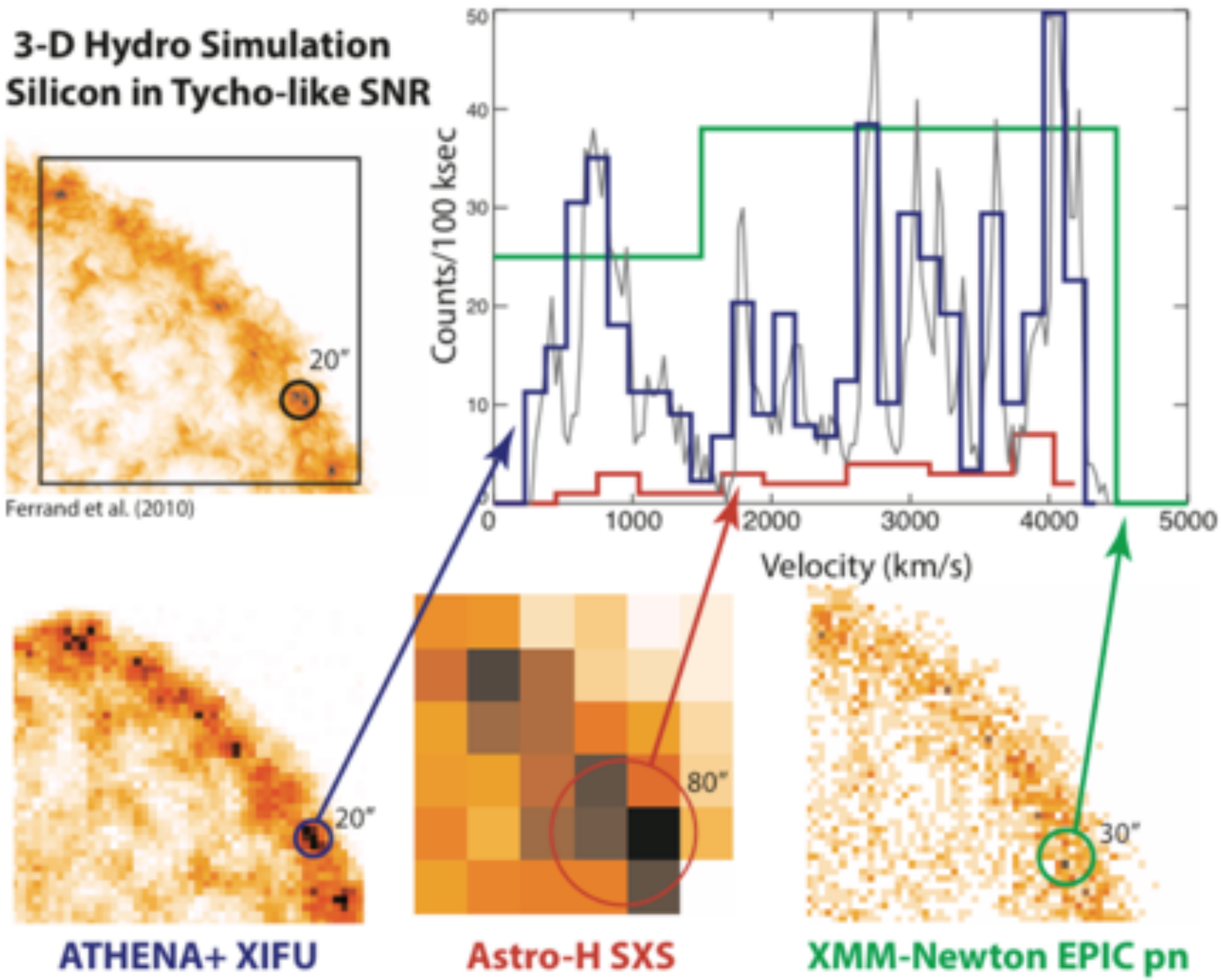




can distinguish smooth vs. clumpy ejecta profiles
→ can quantify (the obvious) that Tycho is not smooth

Williams et al 2017, Sato et al 2019

A new way of investigating SNR kinematics



"The Hot and Energetic Universe" **Athena+** supporting paper

Decourchelle, Costantini, et al 2013

Let’s explore the SNR in real 3D

Ferrand & Warren 2018 (CAPjournal)