Ringberg Workshop on the
Progenitor-Supernova-Remnant Connection
2017-07-28

3D simulations of young supernova remnants

- Particle acceleration and high-energy observations
- From the supernova to the supernova remnant

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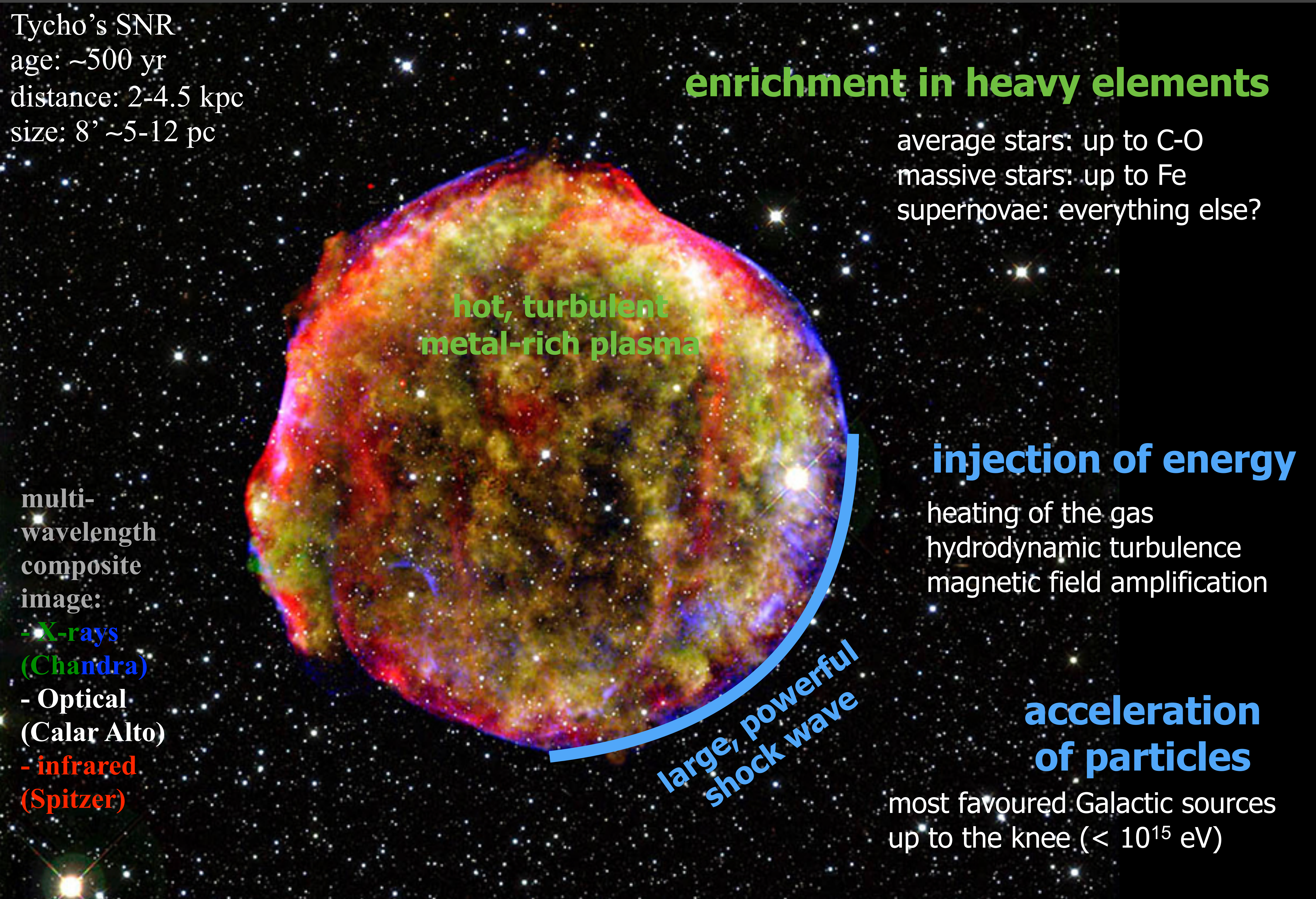
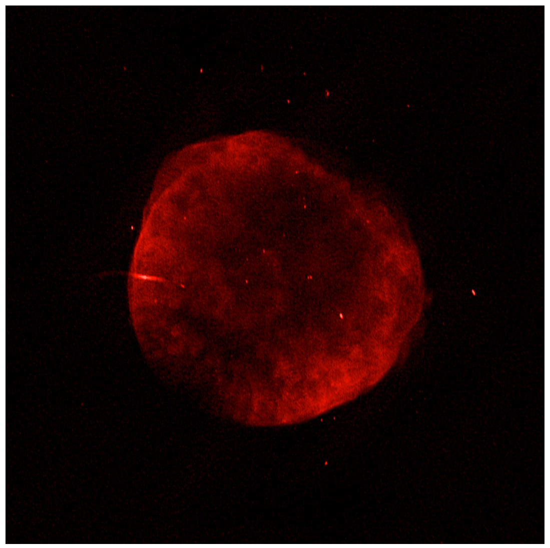
0.1 SNRs as a key link between stars and the ISM

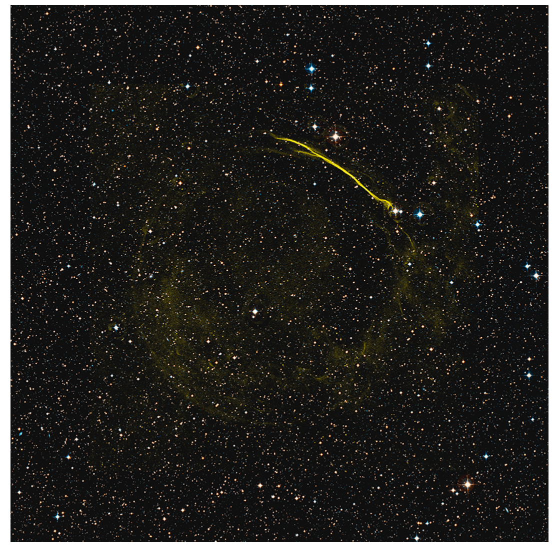


SNR broad-band emission

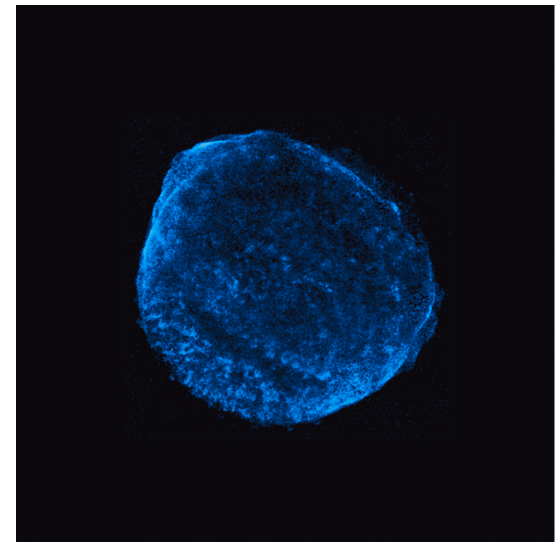
SN 1006



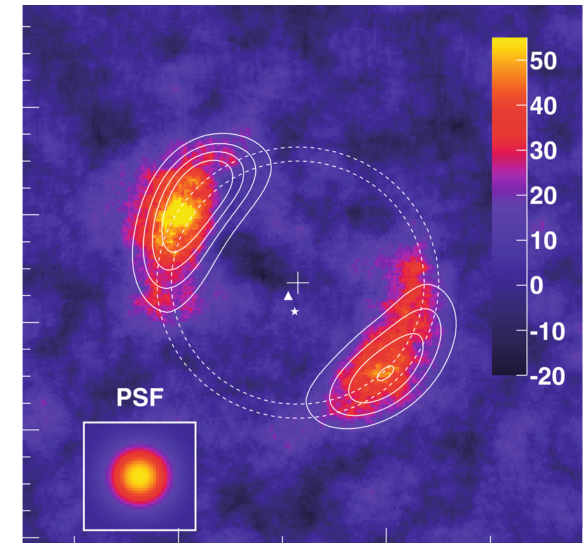
radio



optical



X



gamma

E

cm | μm | keV | TeV

λ

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 (at high energies): Reynolds 2008, Vink 2012

3D simulations of young SNRs with particle acceleration

Anne Decourchelle
Head of astrophysics division at CEA Saclay

Samar Safi-Harb
Prof. at the University of Manitoba

Numerical simulations: hydro + kinetic

Chevalier 1982, 1983

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

parameters: Tycho (SN Ia)

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

Teyssier 2002, Fraschetti et al 2010

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

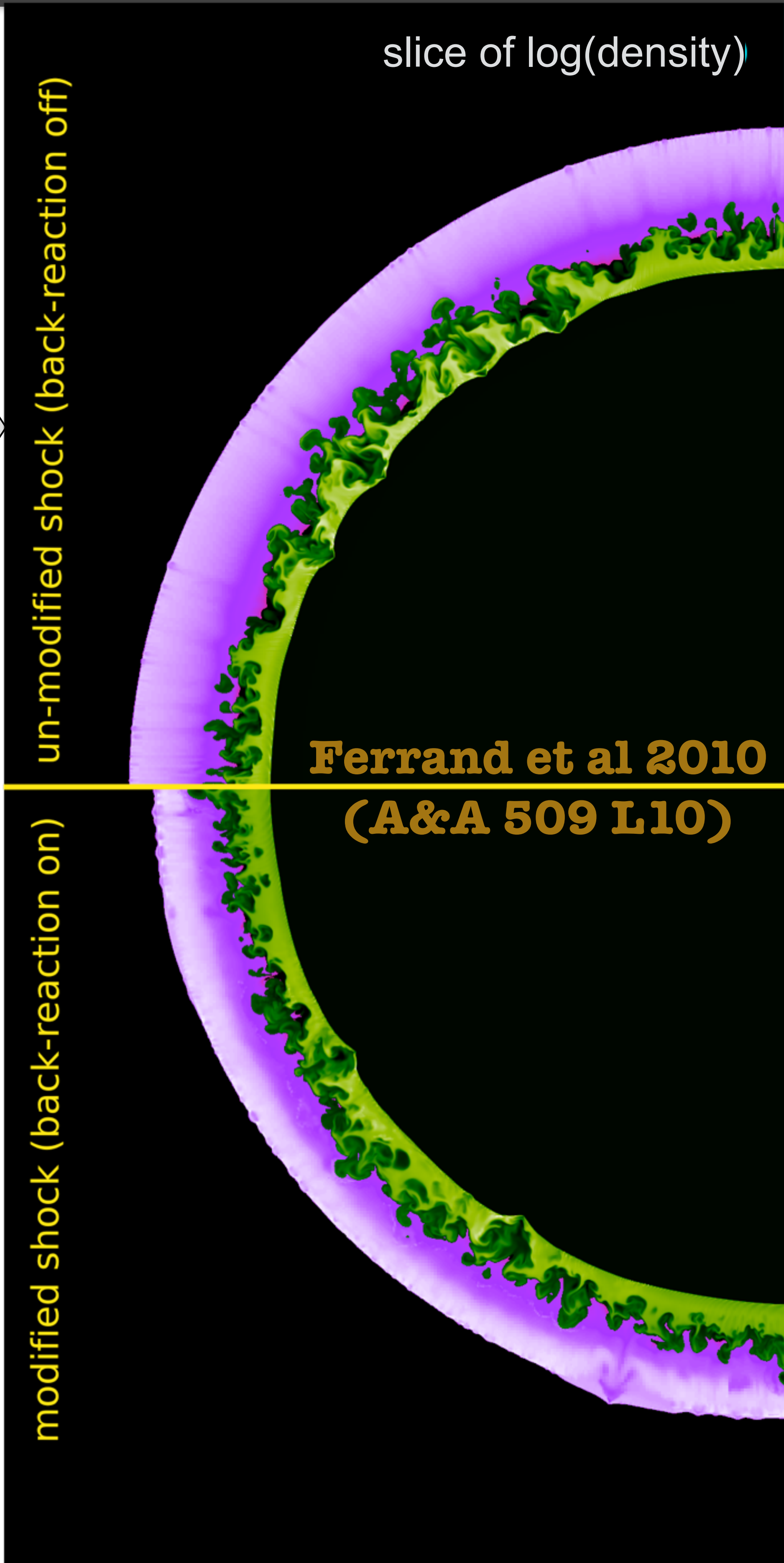
shock diagnostics

back-reaction: varying gamma

Ellison et al 2007

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

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

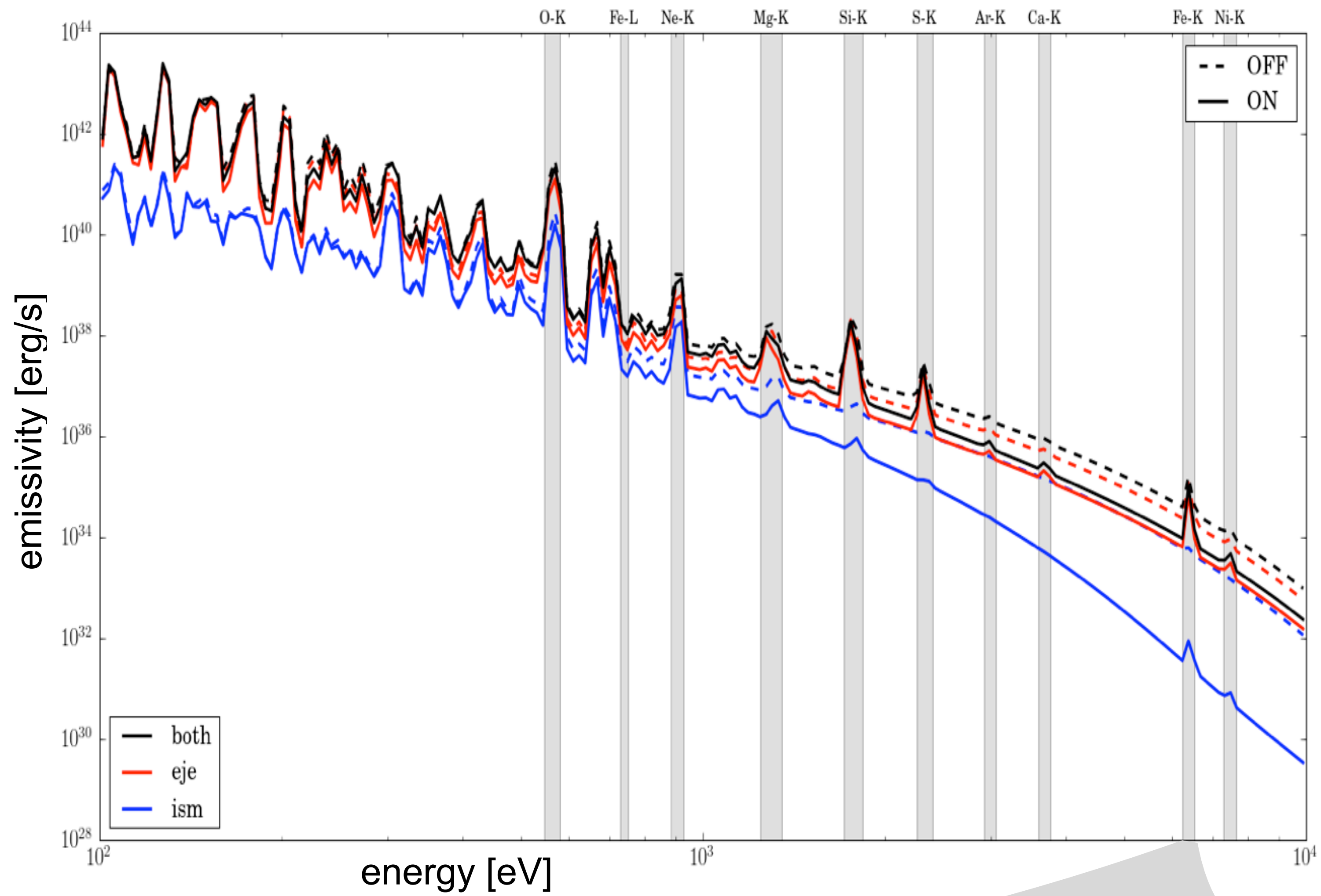


Thermal emission

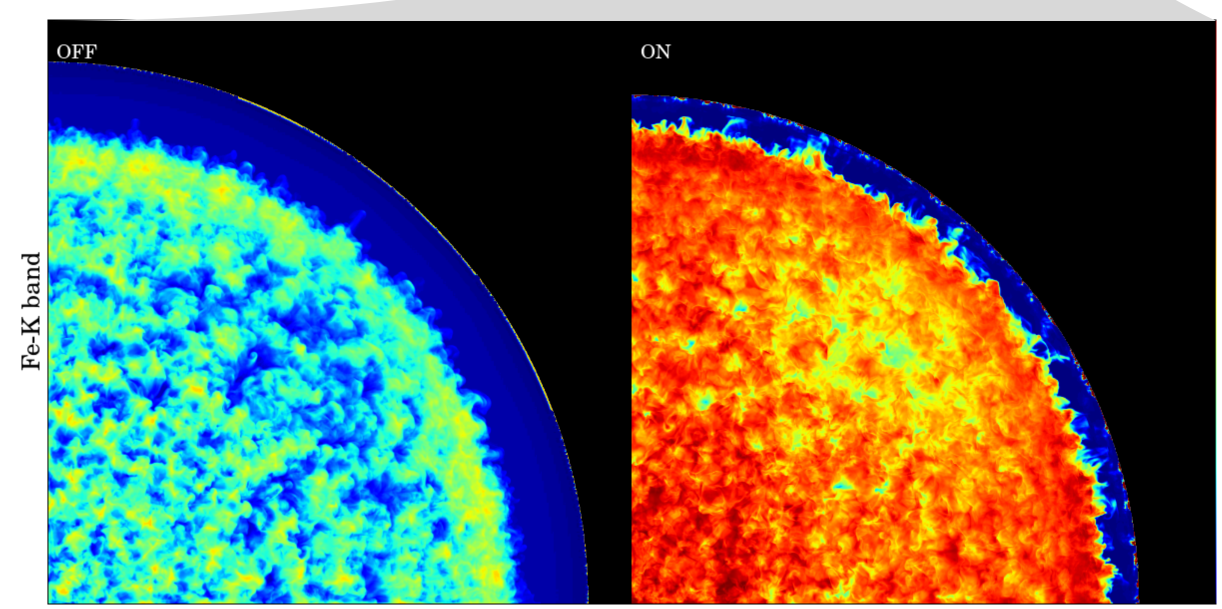
Thermal emission in each cell depends on:

- **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
  with the exponentiation method

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



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



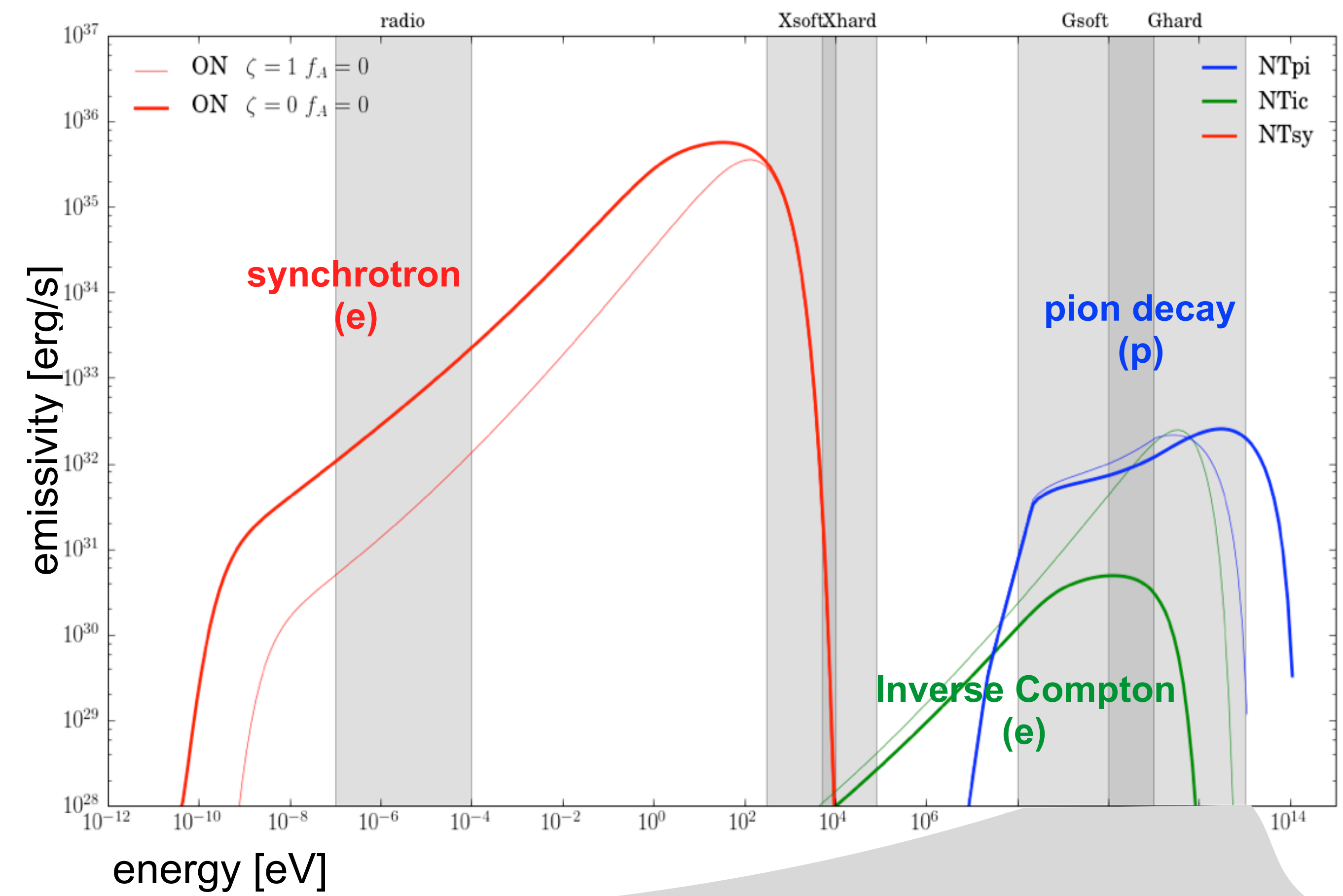
test particle vs. back-reaction

Ferrand, Decourchelle, Safi-Harb 2012

Non-thermal emission

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)

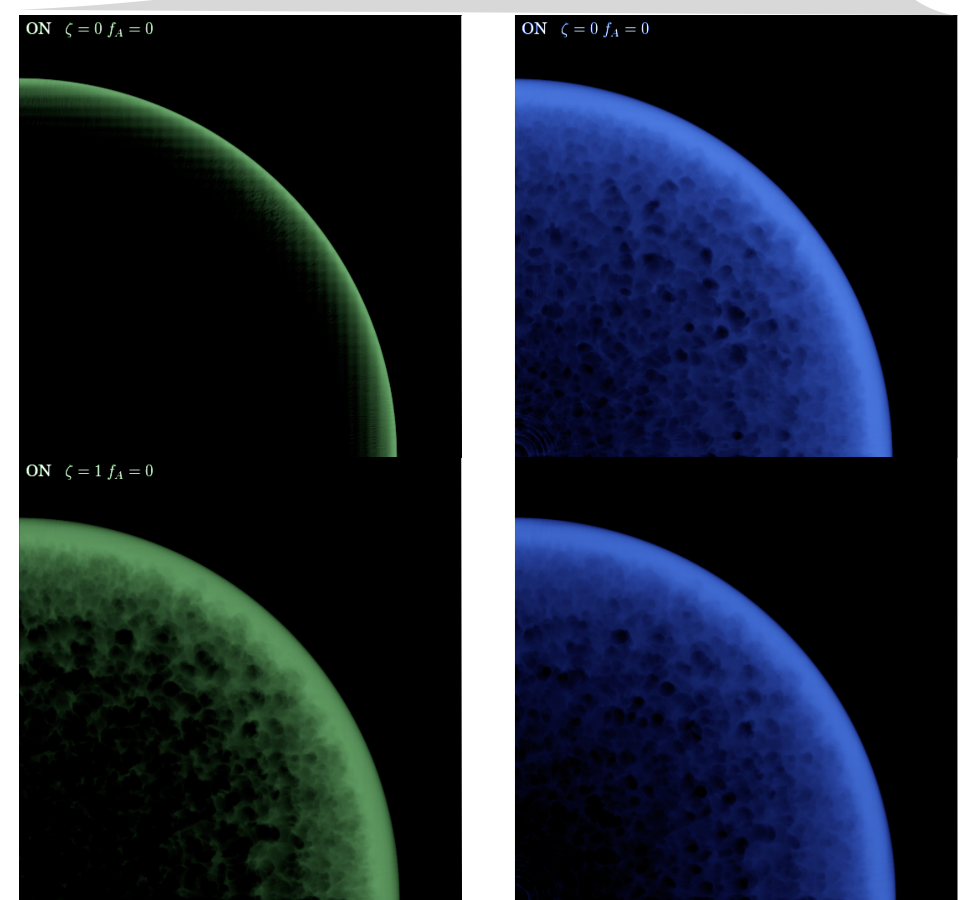


Note: the acceleration model gives the CR spectra just behind the shock $f_p(p,x,t)$, $f_e(p,x,t)$
they must be **transported** to account for losses:

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

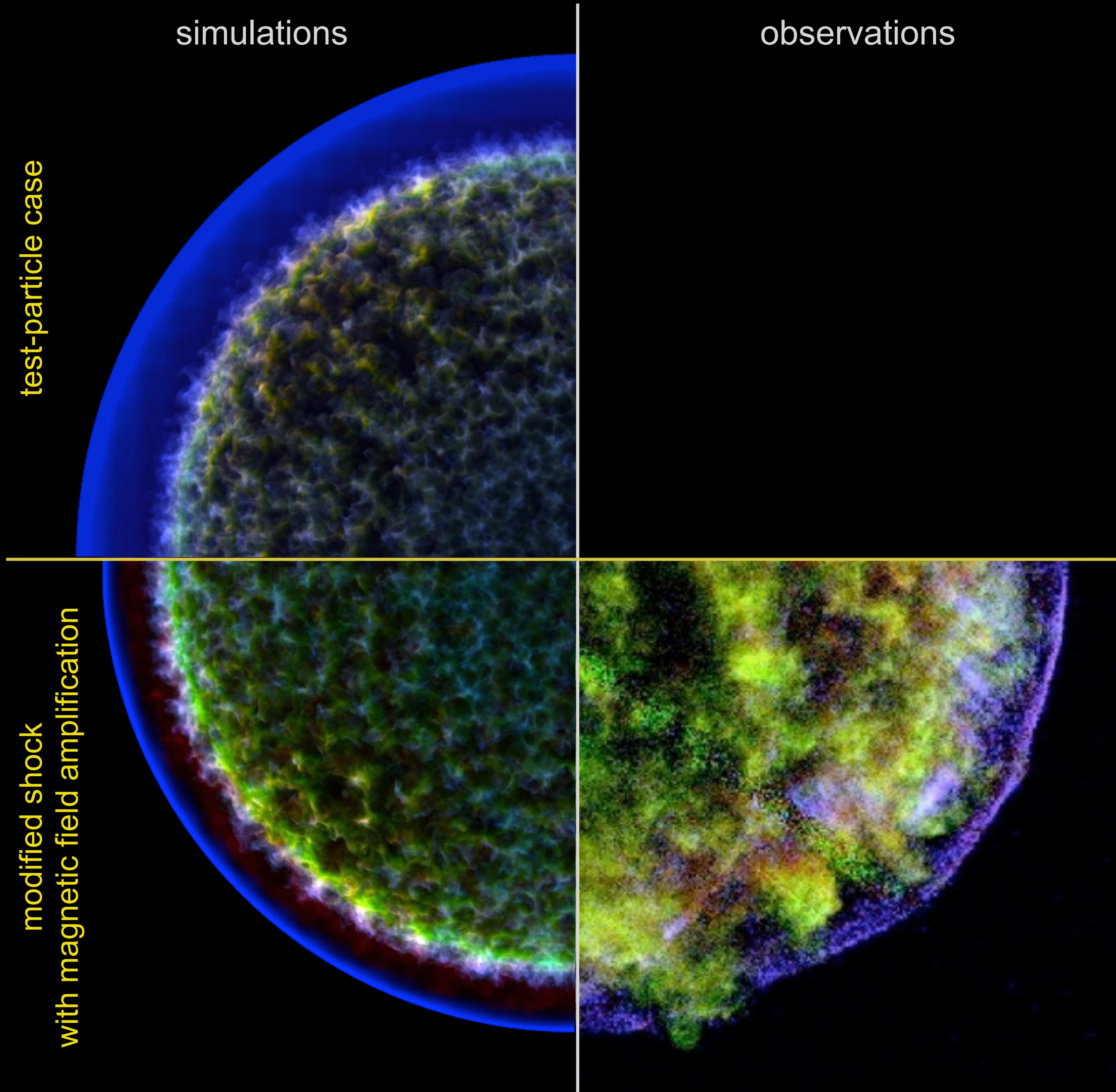
efficient MF amplification → high B

no net MF amplification → low B



Ferrand, Decourchelle, Safi-Harb 2014

Thermal + non-thermal emission in X-rays



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)

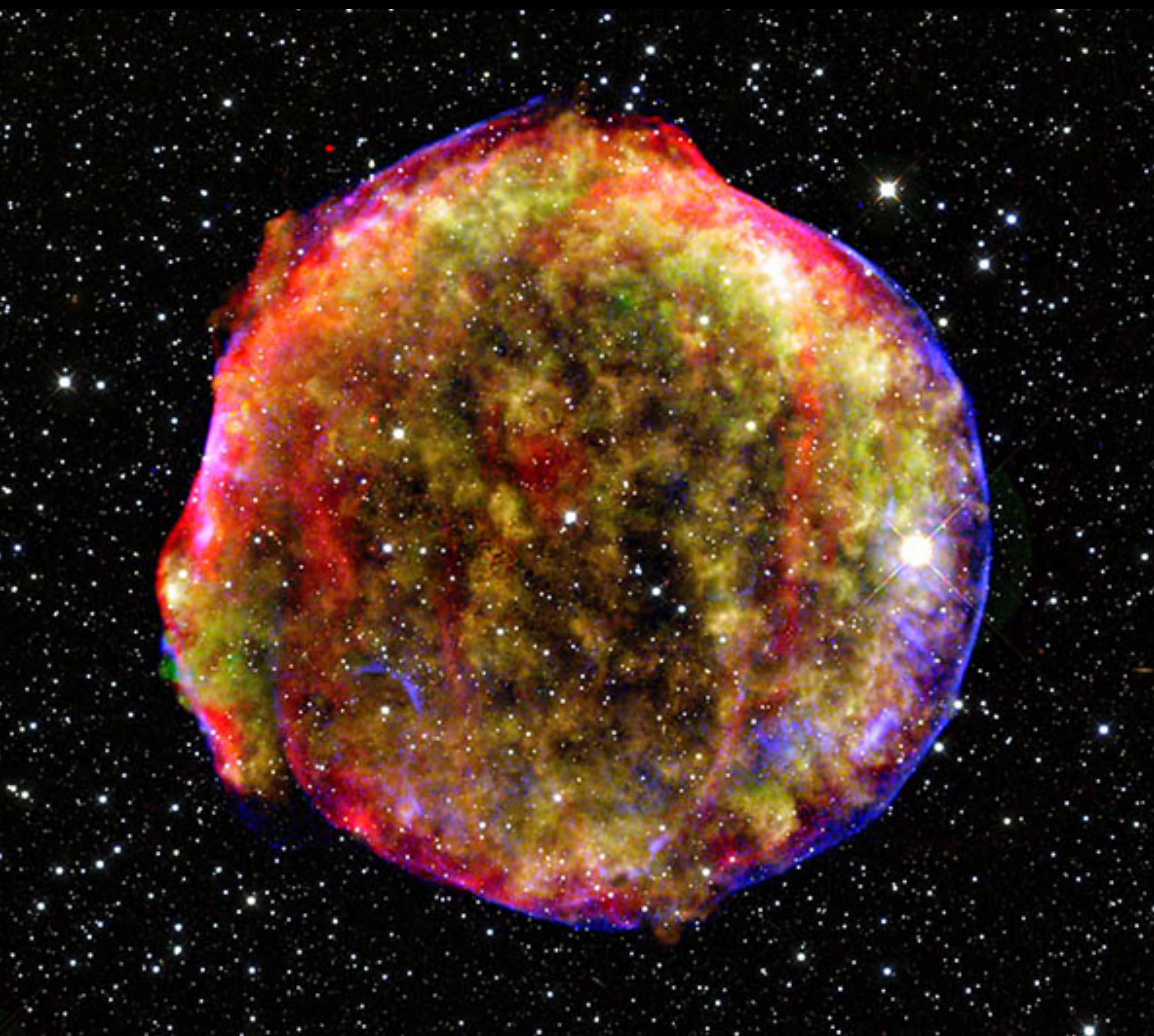
Two historical remnants

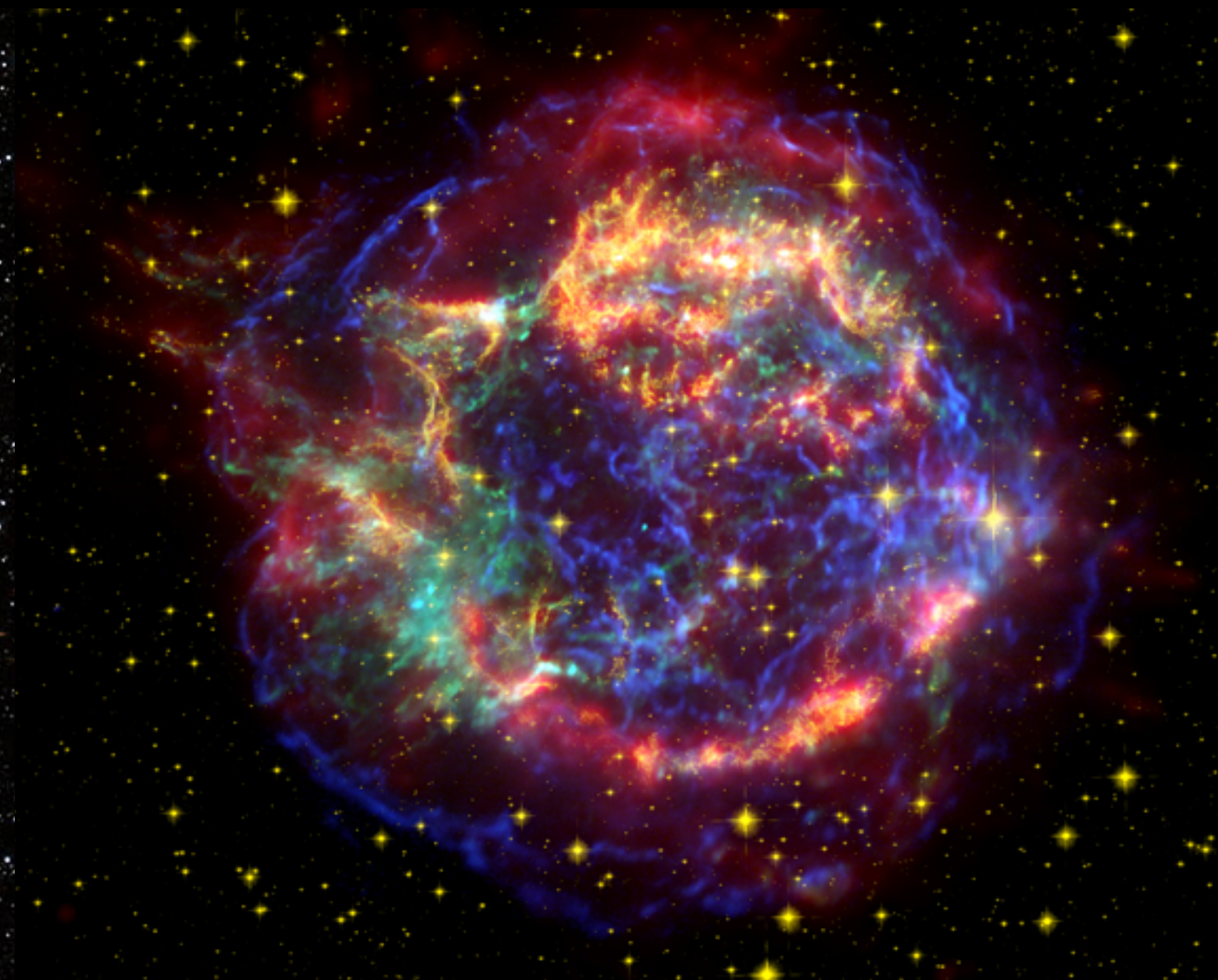
age: ~440 yr
distance: 1.7-5 kpc
size: 8' ~5-12 pc

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





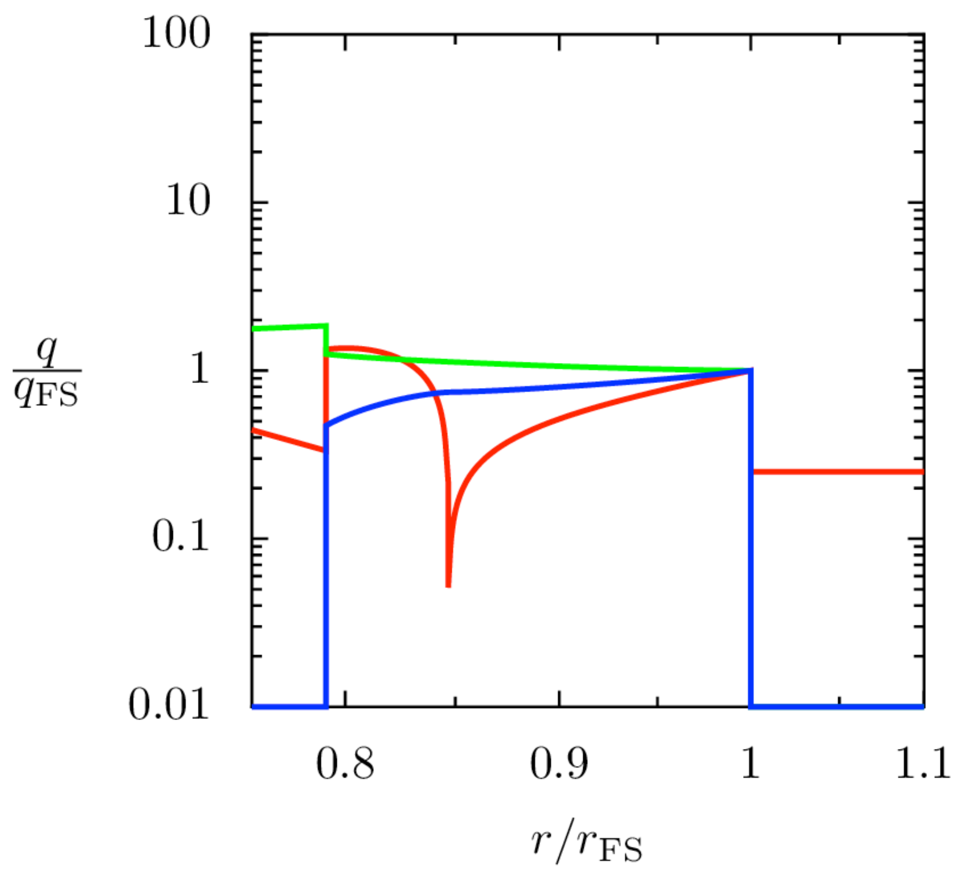
multi-wavelength composite:
X-rays (Chandra 1-2 keV and 4-6 keV)
optical (Calar Alto)
infrared (Spitzer)

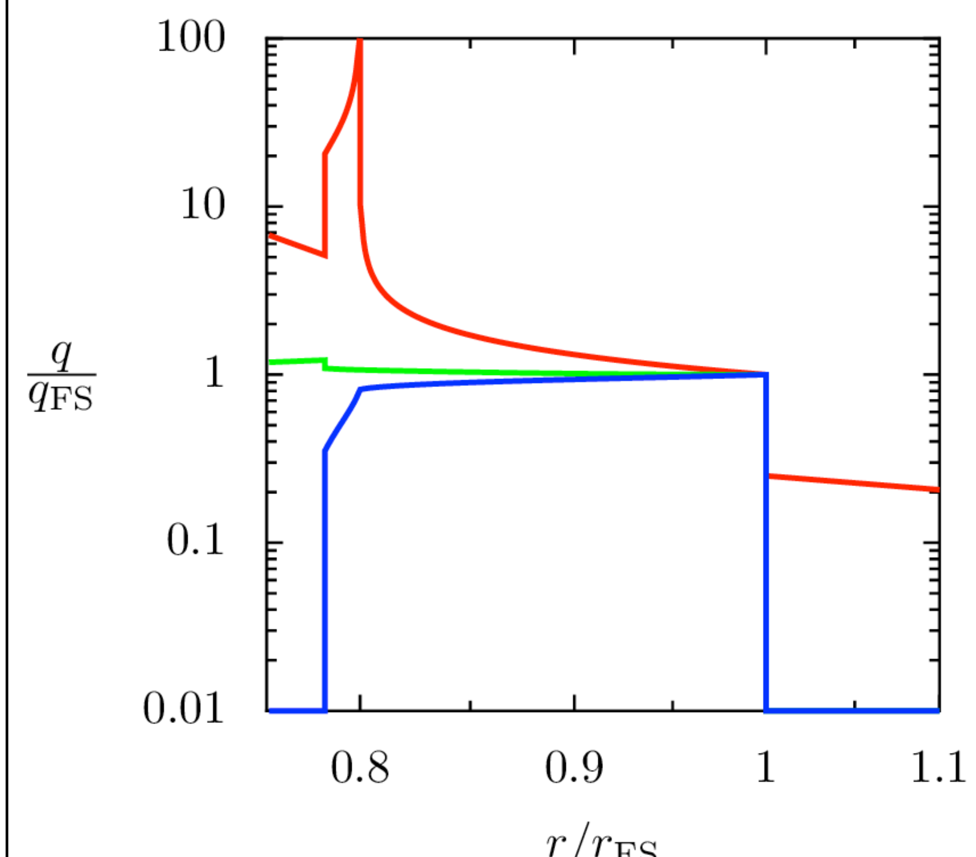
multi-wavelength composite:
X-rays (Chandra 0.5-2.5 keV and 4-6 keV)
near IR (Hubble)
infrared (Spitzer)

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

CC SNR vs TN SNR: density

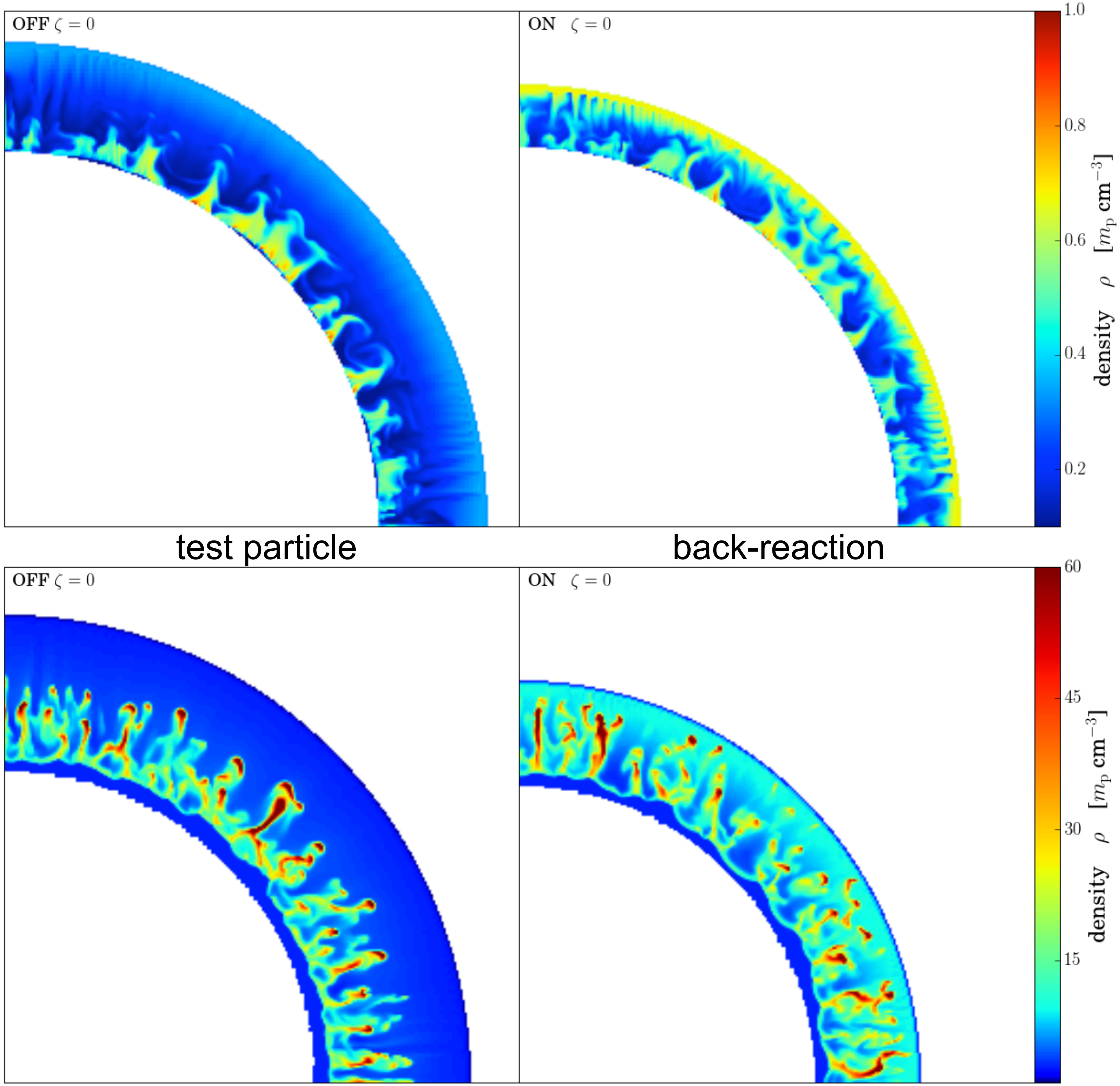
thermo-nuclear supernova

type Ia in a uniform ISM
n=7, s=0
(t = 500 yr)

Ferrand and Safi-Harb 2016

core-collapse supernova

type II in the progenitor's wind
n=9, s=2
(t = 300 yr)



CC SNR vs TN SNR: thermal X-rays

thermo-nuclear supernova

type Ia in a uniform ISM
n=7, s=0
(t = 500 yr)

Ferrand and Safi-Harb 2016

core-collapse supernova

type II in the progenitor's wind
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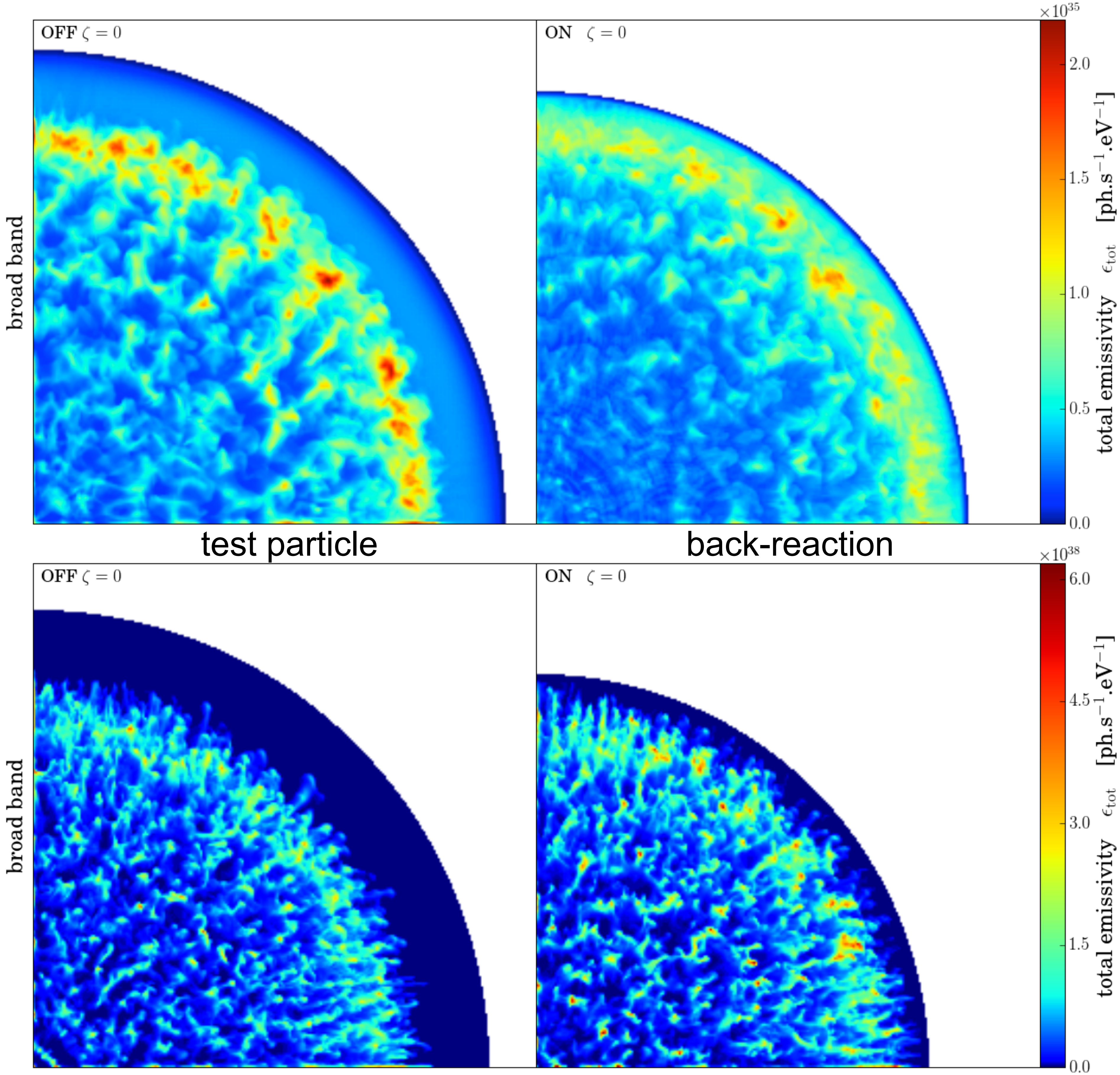


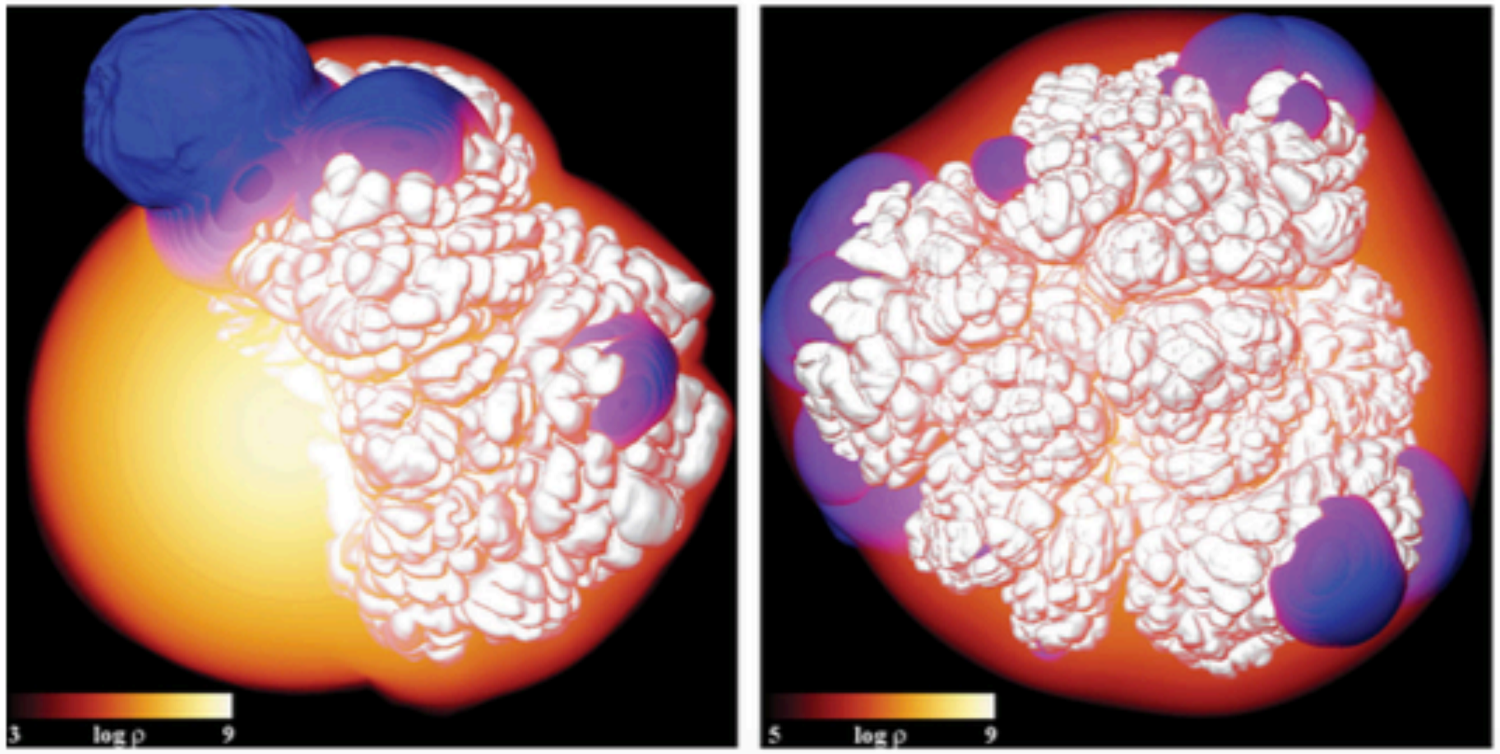
From the supernova to the remnant

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

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

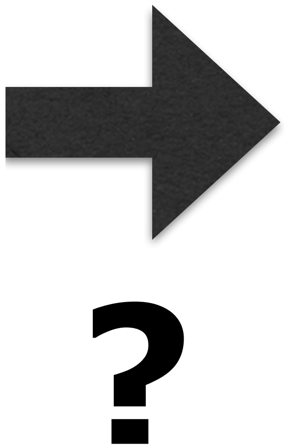
From the 3D supernova to the 3D remnant

3D simulations of thermonuclear supernovae

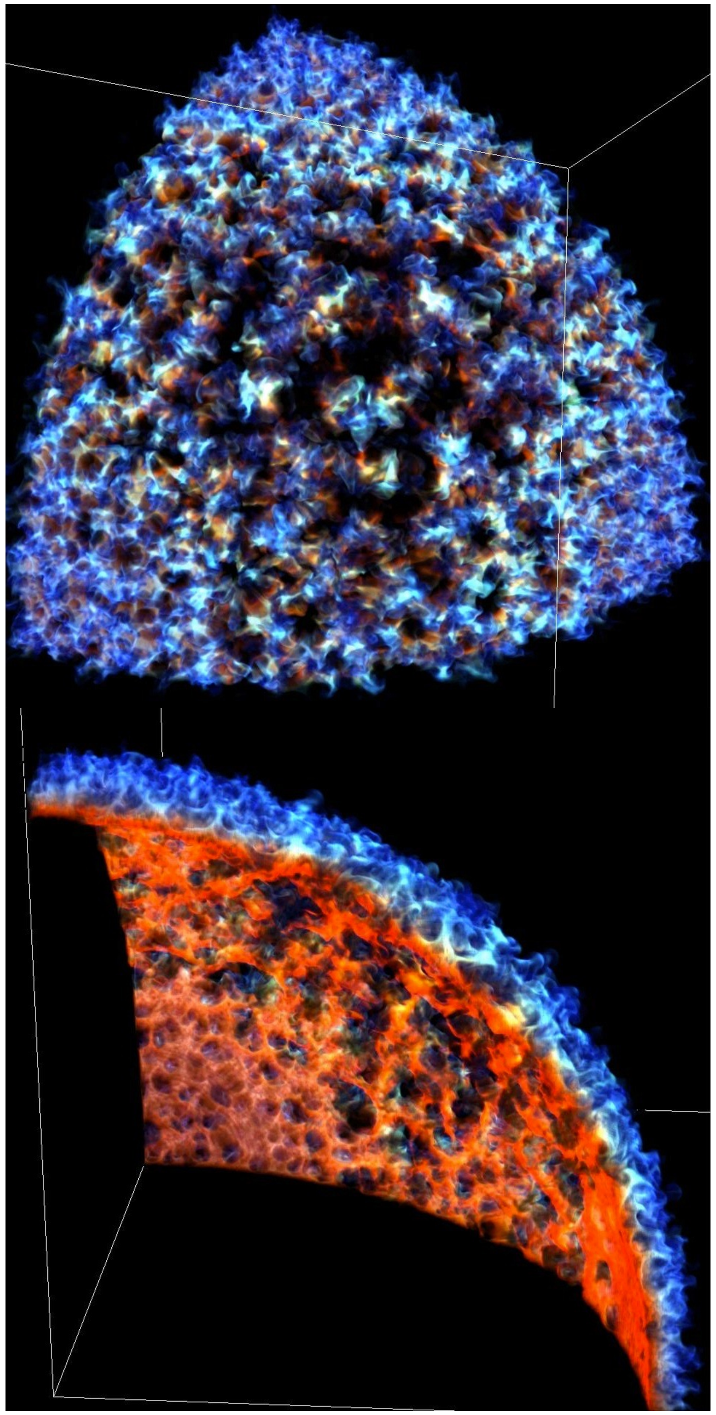


(e) N3; t = 1.15 s (f) N100; t = 1.00 s

Röpke 2007, Seitenzahl et al 2013

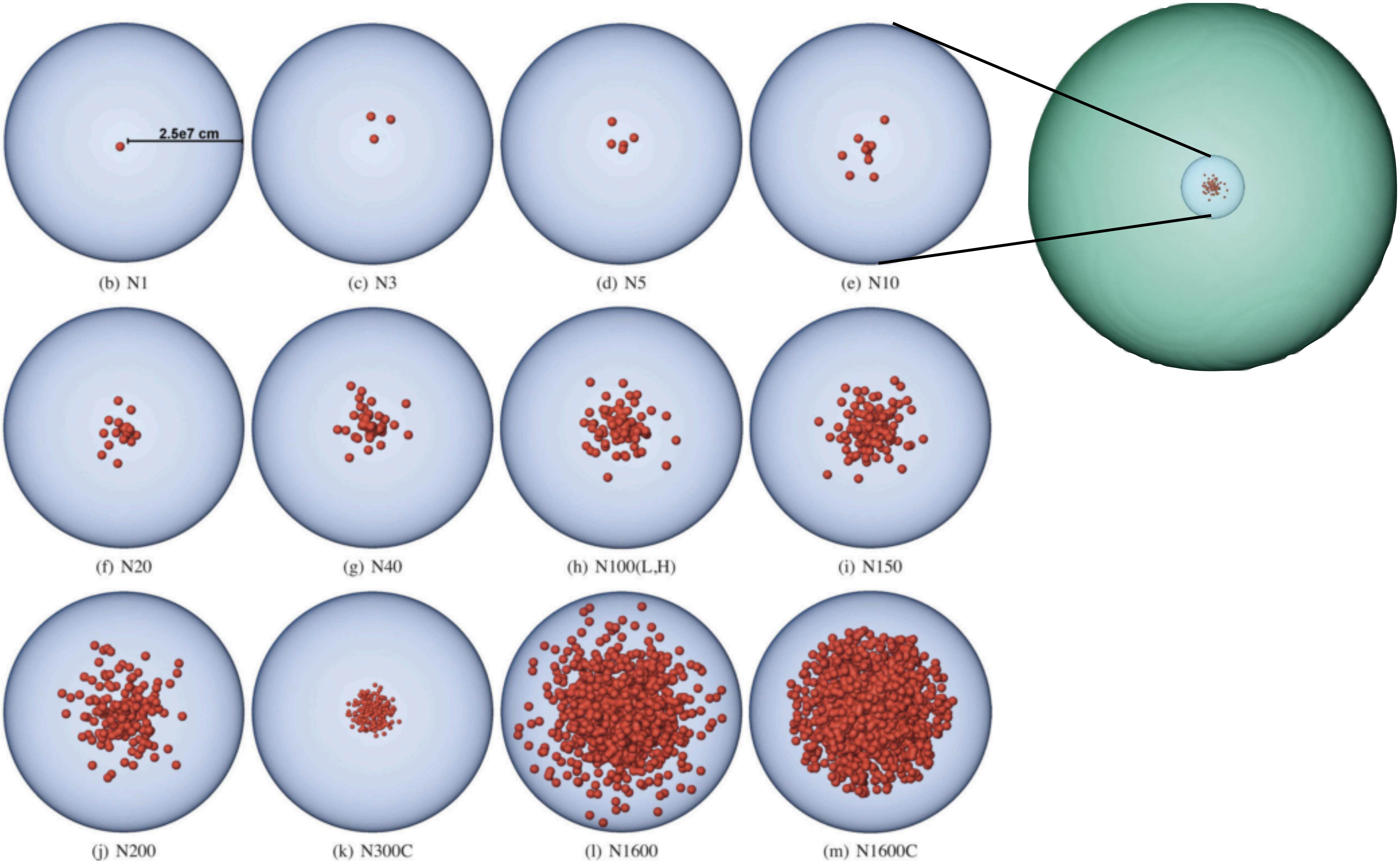


3D SNR simulations



What can the SNR tell us about the explosion?

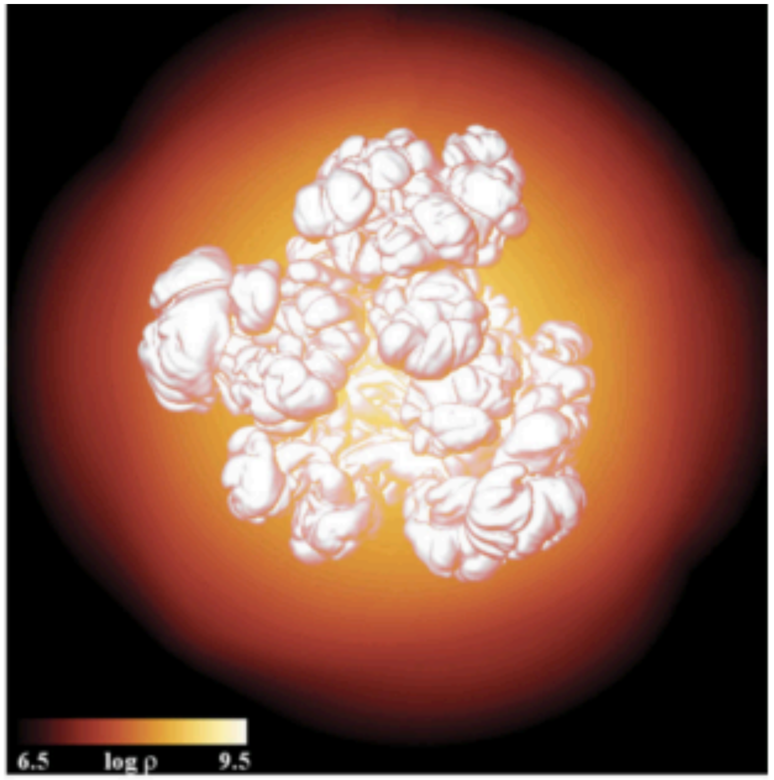
Simulating a TN SN: initial conditions



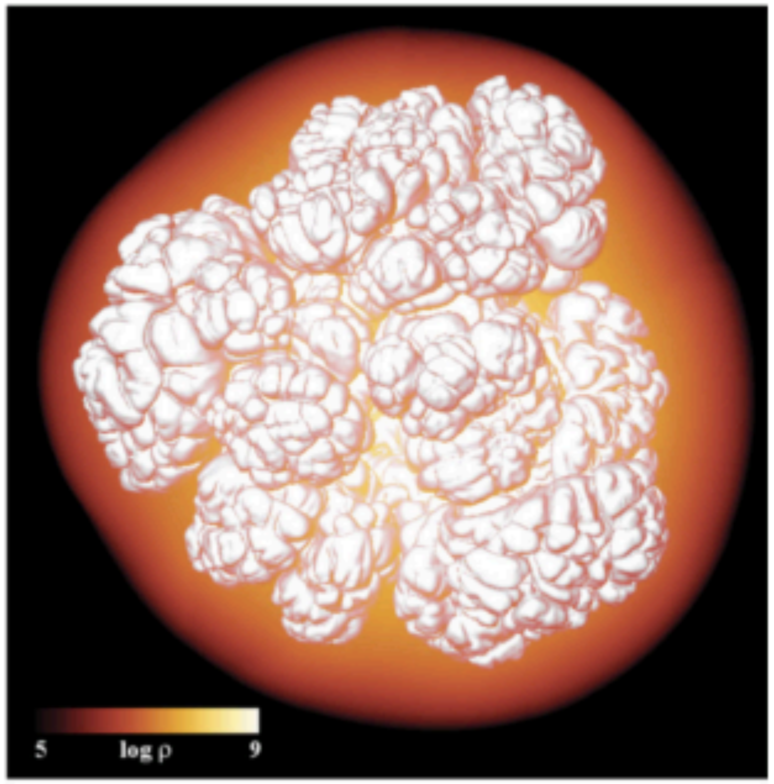
initial flame configuration? grid of ignition patterns

Seitenzahl et al 2013

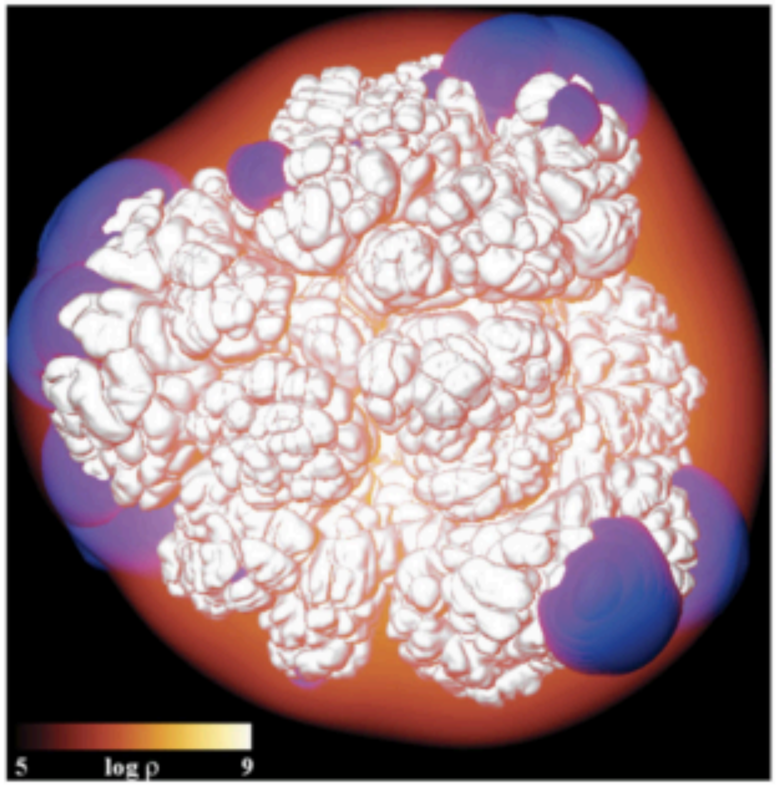
Simulating a TN SN: hydro 3D evolution



(b) N100; t = 0.70 s



(d) N100; t = 0.93 s



(f) N100; t = 1.00 s

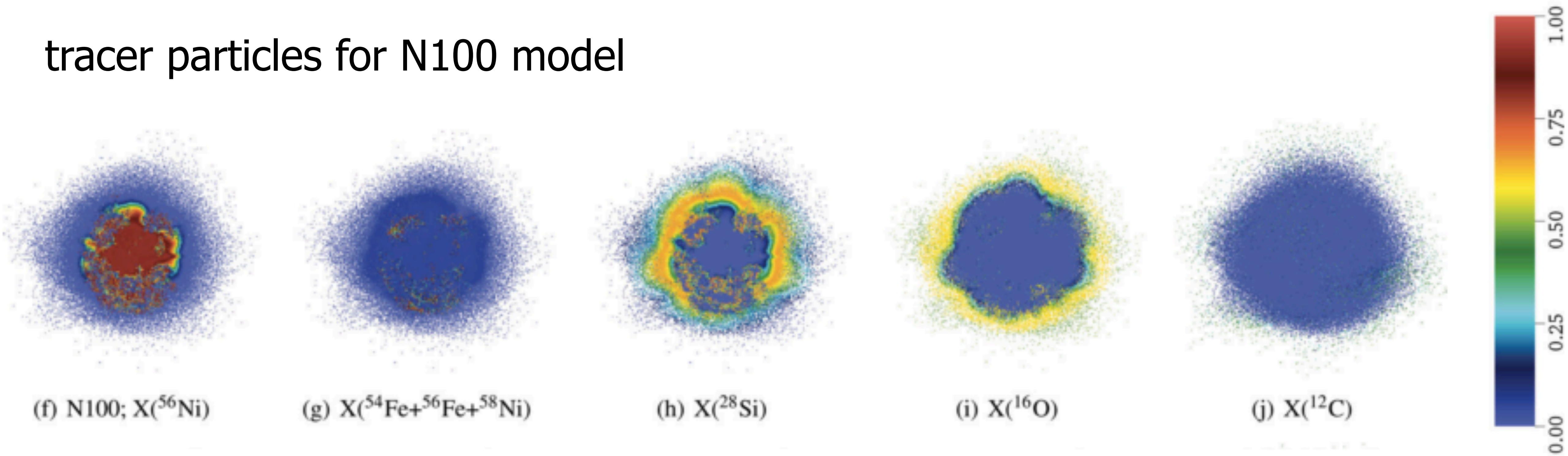
propagation of the flame?
interaction with turbulence
(sub-grid modeling)

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

Seitenzahl et al 2013

Simulating a TN SN: nucleosynthesis

tracer particles for N100 model



(f) N100; $X(^{56}Ni)$ (g) $X(^{54}Fe+^{56}Fe+^{58}Ni)$ (h) $X(^{28}Si)$ (i) $X(^{16}O)$ (j) $X(^{12}C)$

Element	Atomic mass A	Element	Atomic mass A
n	1	Sc	40 . . . 50
p	1	Ti	42 . . . 52
He	4, 6	V	44 . . . 54
Li	6, 7, 8	Cr	46 . . . 56
Be	7, 9, 10, 11	Mn	48 . . . 58
B	8, 9 . . . 12	Fe	50 . . . 62
C	10 . . . 15	Co	52 . . . 63
N	12 . . . 17	Ni	54 . . . 67
O	14 . . . 20	Cu	56 . . . 69
F	17 . . . 21	Zn	59 . . . 72
Ne	18 . . . 25	Ga	61 . . . 76
Na	20 . . . 26	Ge	63 . . . 78
Mg	21 . . . 28	As	71 . . . 80
Al	23 . . . 30	Se	74 . . . 83
Si	25 . . . 33	Br	75 . . . 83
P	27 . . . 35	Kr	78 . . . 87
S	29 . . . 38	Rb	79 . . . 87
Cl	31 . . . 40	Sr	84 . . . 91
Ar	33 . . . 44	Y	85 . . . 91
K	35 . . . 46	Nb	91 . . . 97
Ca	37 . . . 49	Mo	92 . . . 98

nuclear reaction network in
post-processing
with 384 nuclides
→ distribution of elements

many still unstable:
radioactive decay

Seitenzahl et al 2013

SN Ia explosion model

N100 model – delayed detonation of a Chandrasekhar mass white dwarf

total mass density

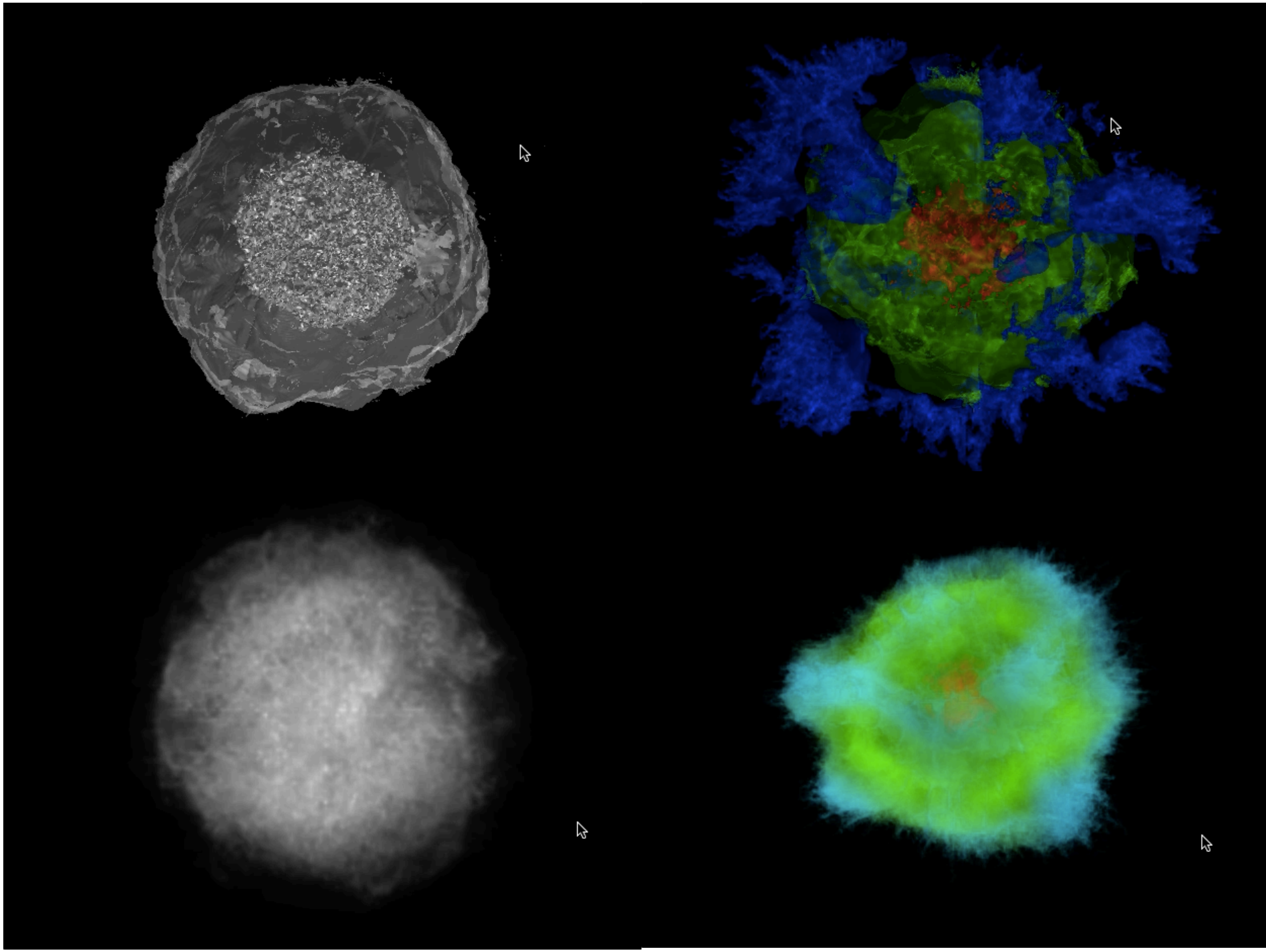
composition: 56Ni 16O 12C

iso-contours

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

volume rendering

(custom-made, live demo)



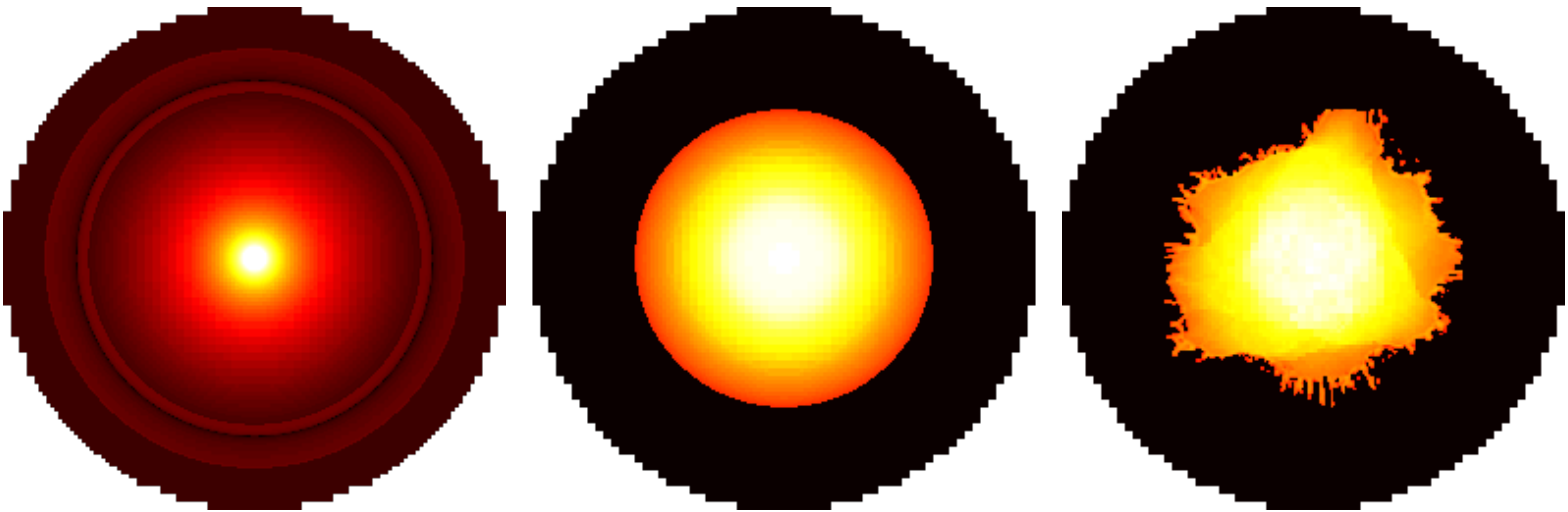
data from Seitenzahl et al 2013 courtesy Fritz Röpke

3D immersive visualization (Virtual Reality)

First results for the SNR (hydro)

PRELIMINARY

Chevalier 1D (power-law) | Röpke 1D (~exponential) | Röpke 3D

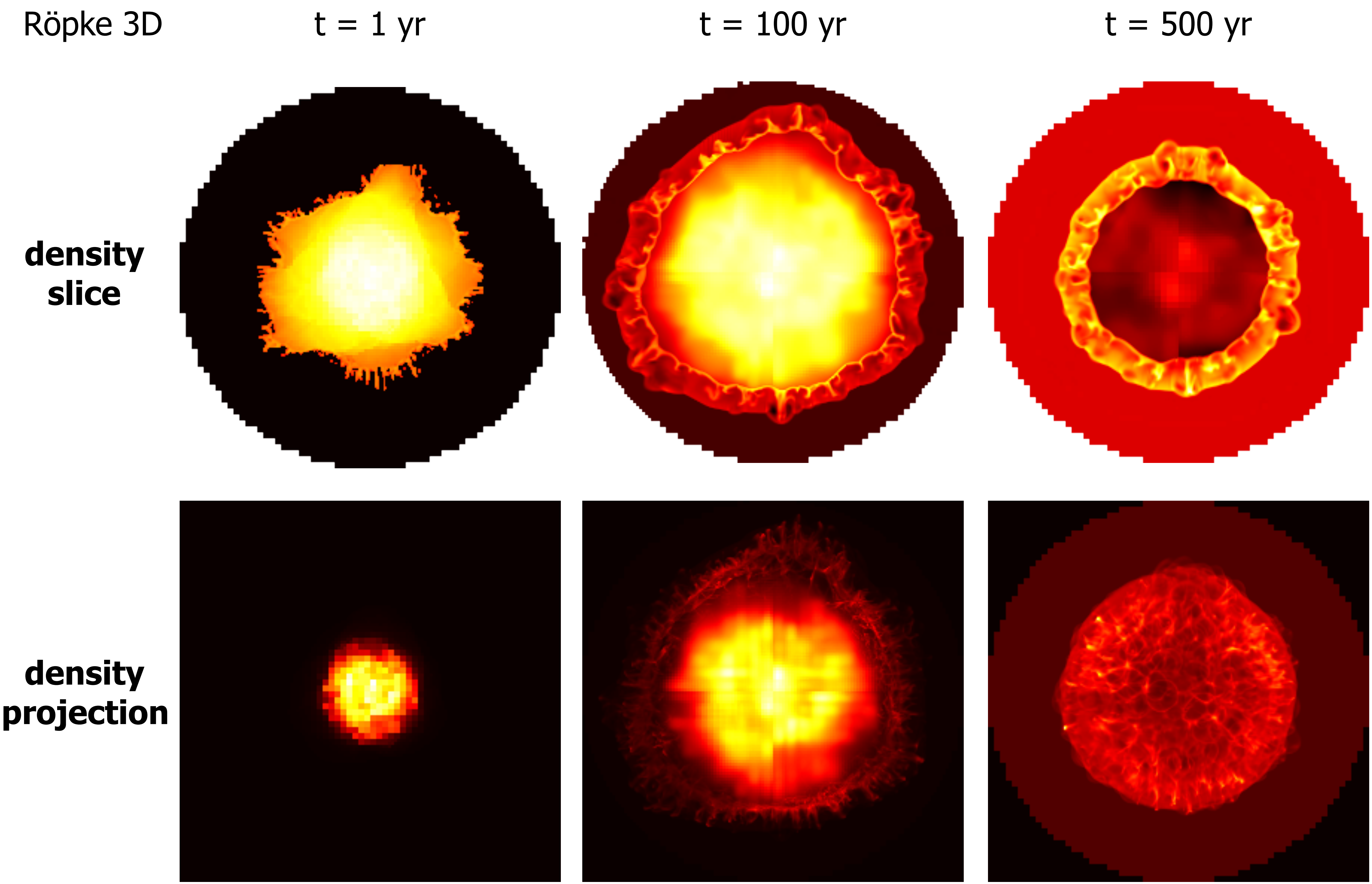


density slices

t = 1 yr, 2 yr, 5 yr, 10 yr, 20 yr, 50 yr, 100 yr, 200 yr, 300 yr, 400 yr, 500 yr

First results for the SNR (hydro)

PRELIMINARY



To be continued…