Supernova Remnants: An odyssey in space after stellar death
Chania, Crete, Greece
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3D simulations of young supernova remnants with efficient particle acceleration: thermo-nuclear vs. core-collapse

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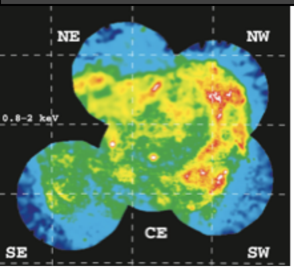
model

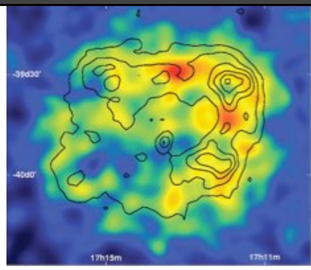
1.1 Diffusive shock acceleration: the coupled system



IR
Opt
UV
X

reviews : Drury 1983, Jones and Ellison 1991, Malkov and Drury 2001

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

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

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

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

recipes for magnetic field amplification

1.2

Numerical simulations: hydro + kinetic

From cosmology to supernova remnants
(in both cases: comoving grid to factor out expansion)

Chevalier 1982, 1983

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

Teyssier 2002, Fraschetti et al 2010

SNR evolution:
3D hydro code
ramses

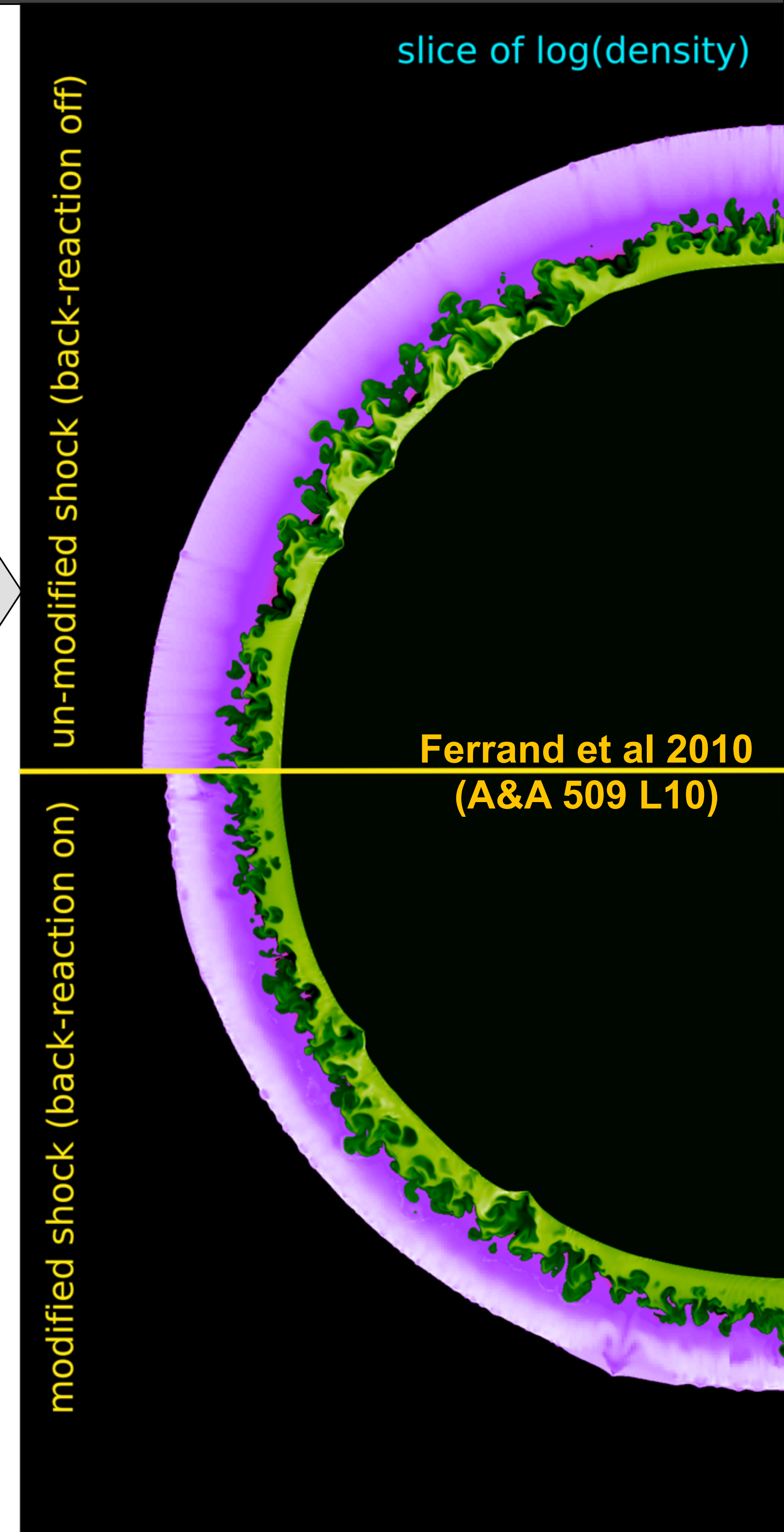
shock
diagnostics

back-reaction:
varying gamma

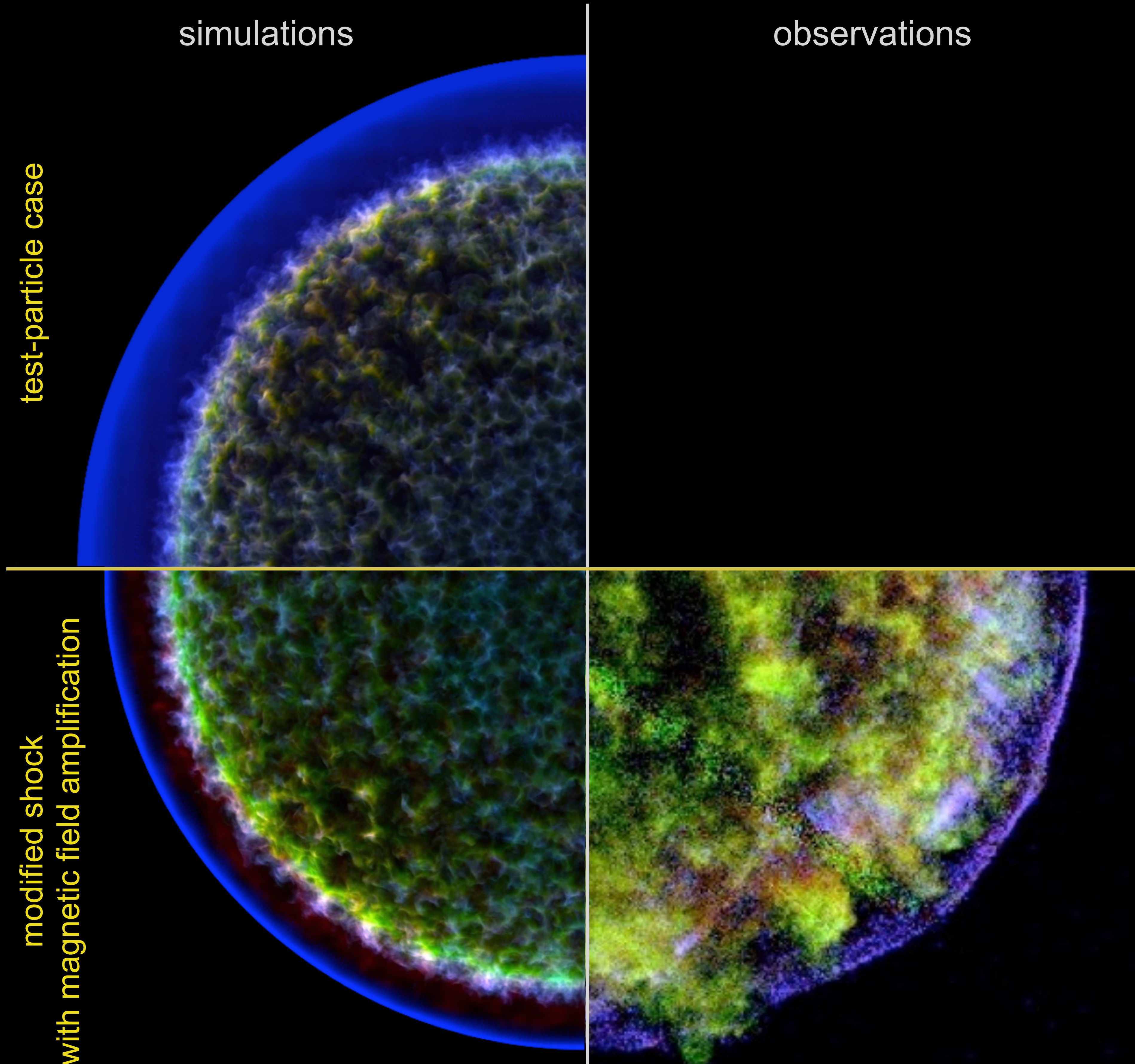
Ellison et al 2007

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

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



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)

Ferrand et al 2012 (ApJ 760 34)

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

Ferrand et al 2014 (ApJ 789 49)

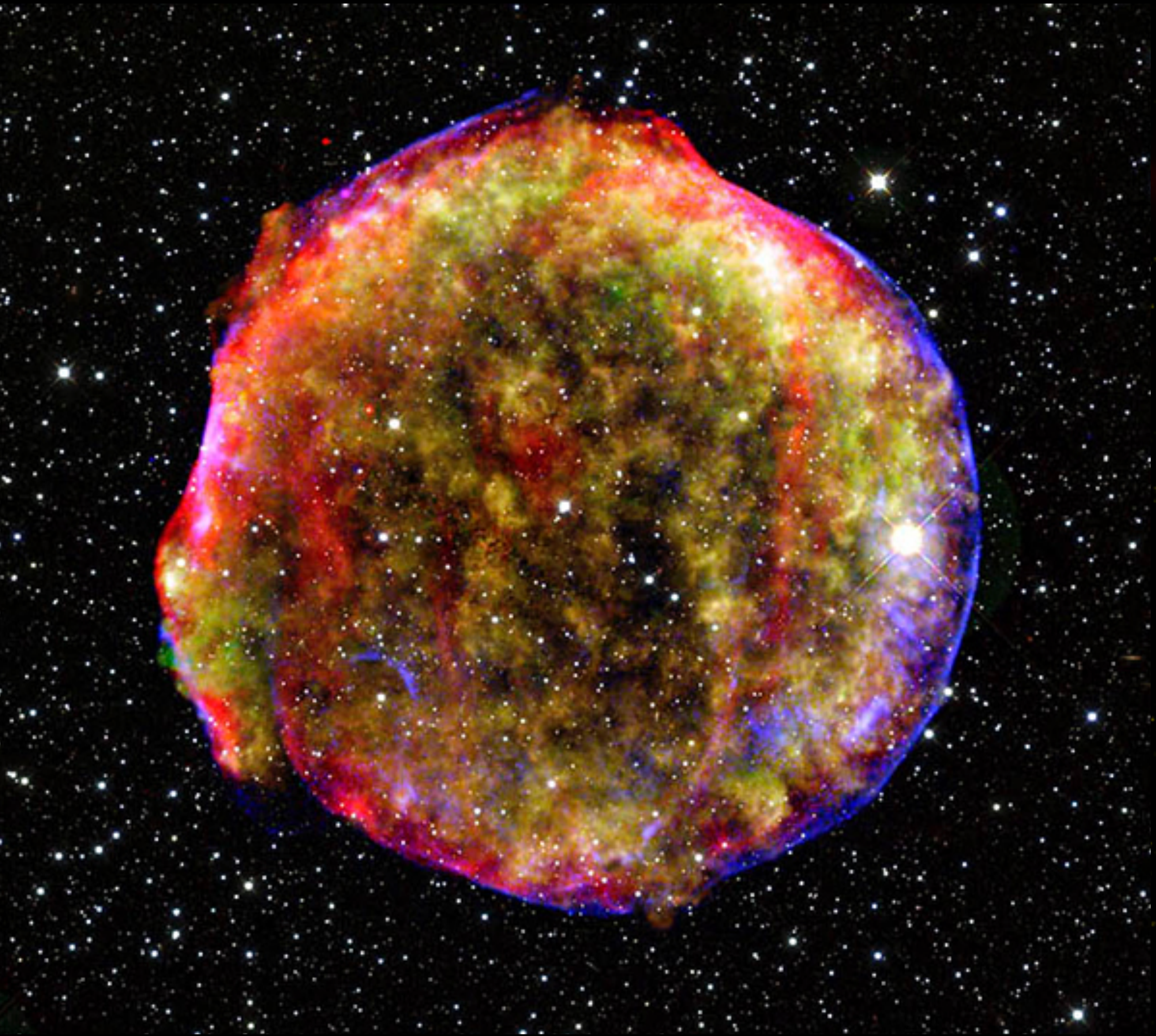
Two historical remnants

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

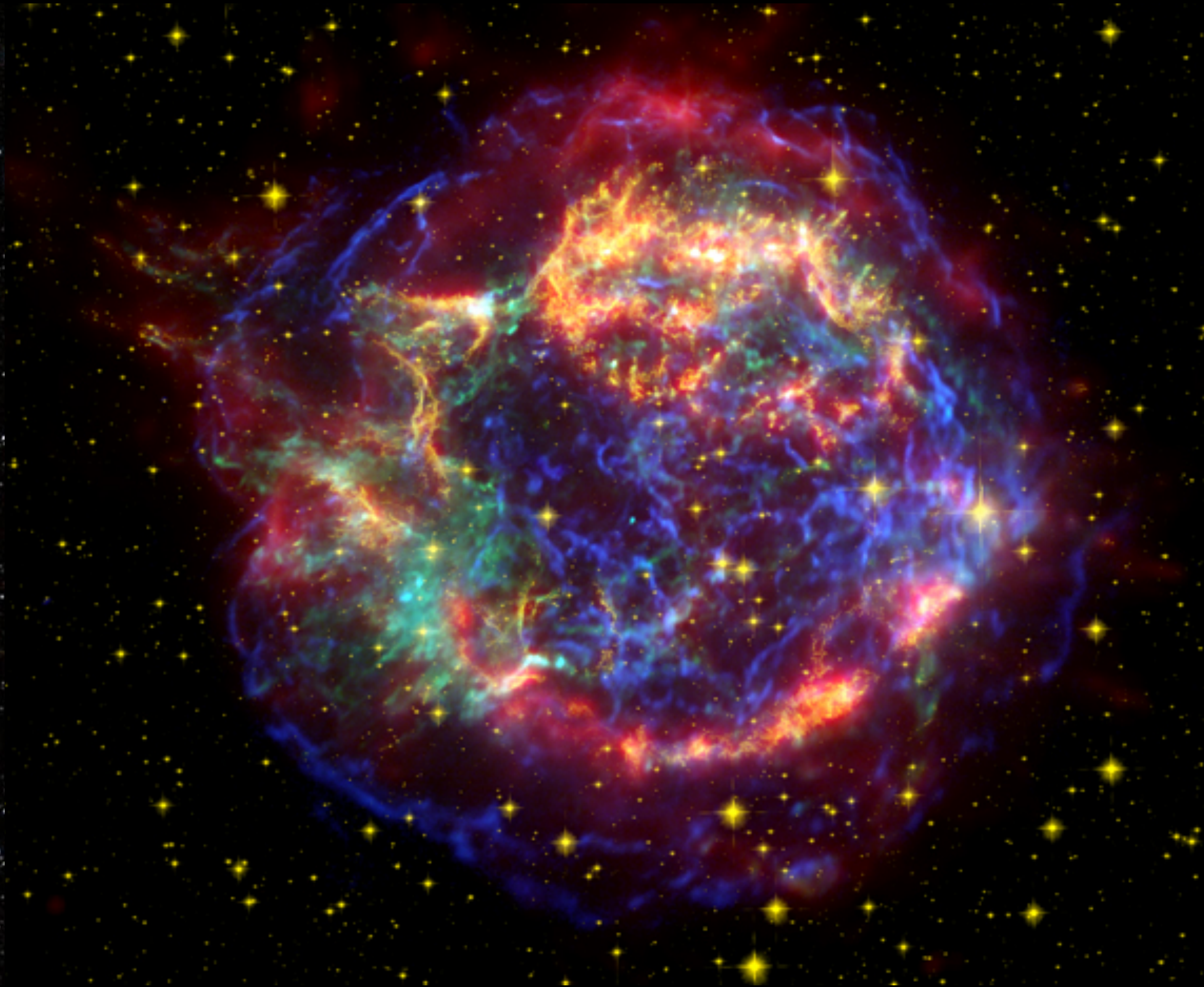
Tycho's SNR
SN 1572
thermonuclear

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)

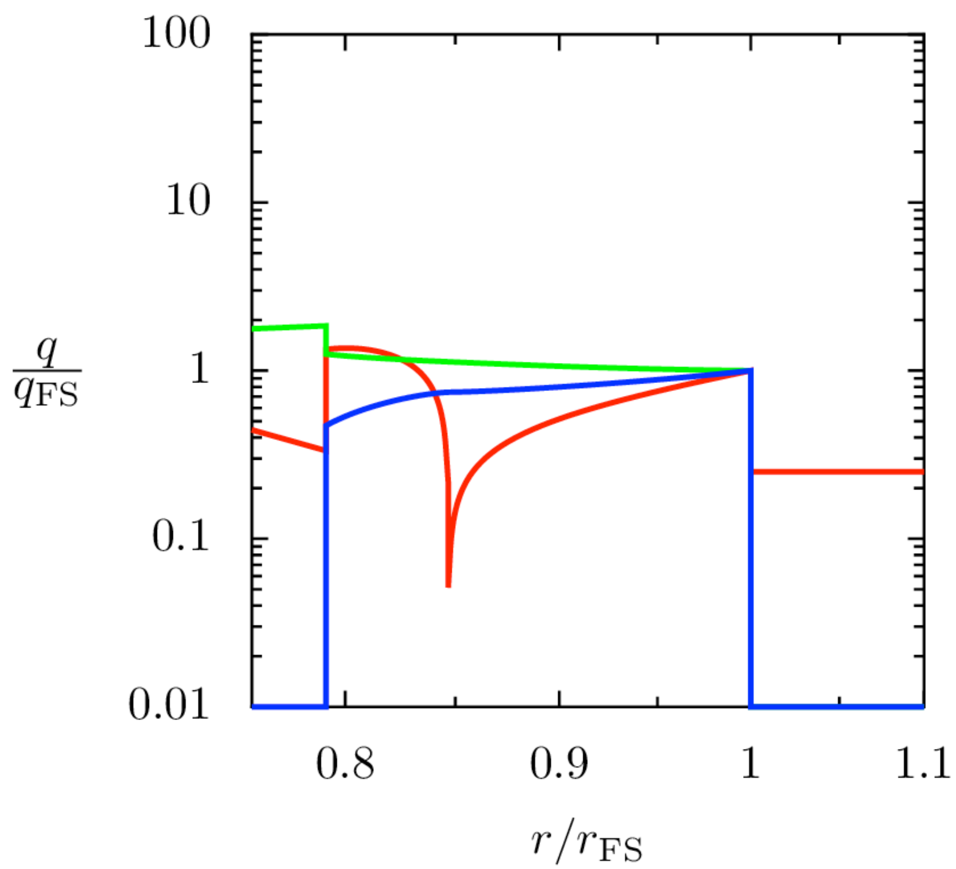


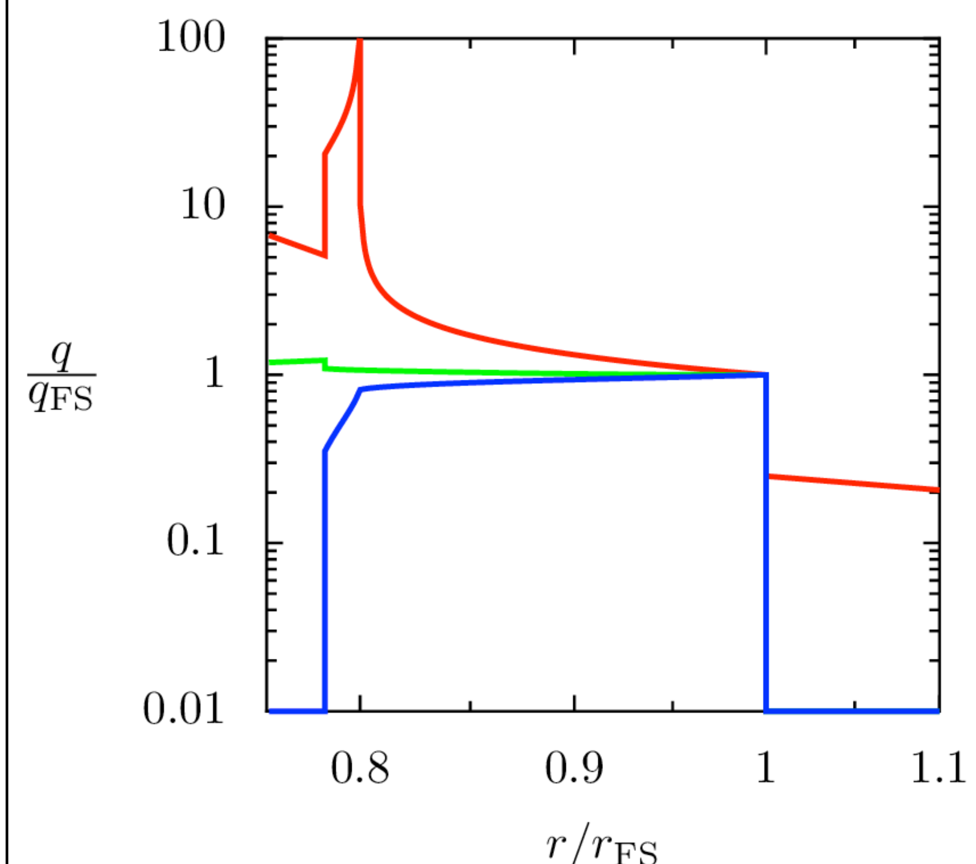
multi-wavelength composite:
X-rays (Chandra 0.5-2.5 keV and 4-6 keV)
near IR (Hubble)
infrared (Spitzer)

1.5 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





Wind properties: density profile

star type	**mass loss rate** $\dot{M}_w$	**speed** u_w
Sun	10^{-14} M⊙/yr	300 km/s
Red Supergiant (RSG)	**10^{-5}** – 10^{-4} M⊙/yr	**10** – 100 km/s
Wolf-Rayet (WR)	10^{-5} – 10^{-4} M⊙/yr	1000 – 3000 km/s

radial density profile (conservation of mass):

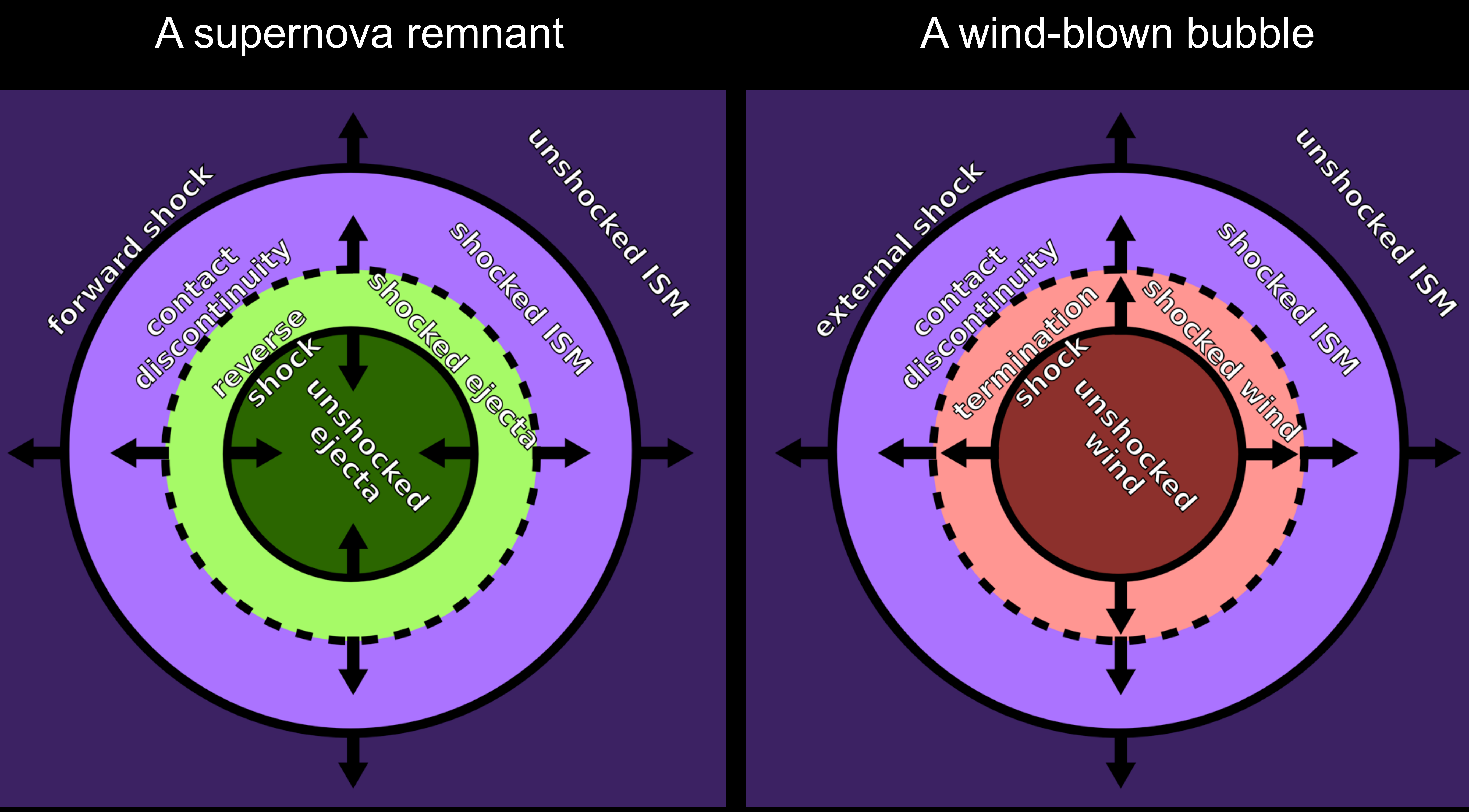
$$\rho(r) = \frac{\dot{M}_w}{4\pi r^2 v_w} \simeq 3\, m_p\, \mathrm{cm}^{-3} \left(\frac{\dot{\mathrm{M}}_\mathrm{w}}{10^{-5}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}}\right) \left(\frac{\mathrm{v_w}}{10\ \mathrm{km.s}^{-1}}\right)^{-1} \left(\frac{\mathrm{r}}{1\ \mathrm{pc}}\right)^{-2}$$

position of the termination shock:

$$r_\mathrm{term}(t) \simeq 2\mathrm{pc} \left(\frac{\dot{\mathrm{M}}_\mathrm{w}}{10^{-5}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}}\right)^{\frac{3}{10}} \left(\frac{\mathrm{v_w}}{10\ \mathrm{km.s}^{-1}}\right)^{\frac{1}{10}} \left(\frac{\mathrm{n_{ext}}}{1\ \mathrm{cm}^{-3}}\right)^{-\frac{3}{10}} \left(\frac{\mathrm{t}}{10^5\ \mathrm{yr}}\right)^{\frac{2}{5}}$$

We consider here a single wind phase, and a SNR young enough that it's propagating inside the un-shocked stellar wind within the bubble

The structure of an expanding bubble



How does the SNR evolve inside a wind?

(Dwarkadas 2005, 2007)

hydro/thermo-dynamics
&
thermal emission

Results: density

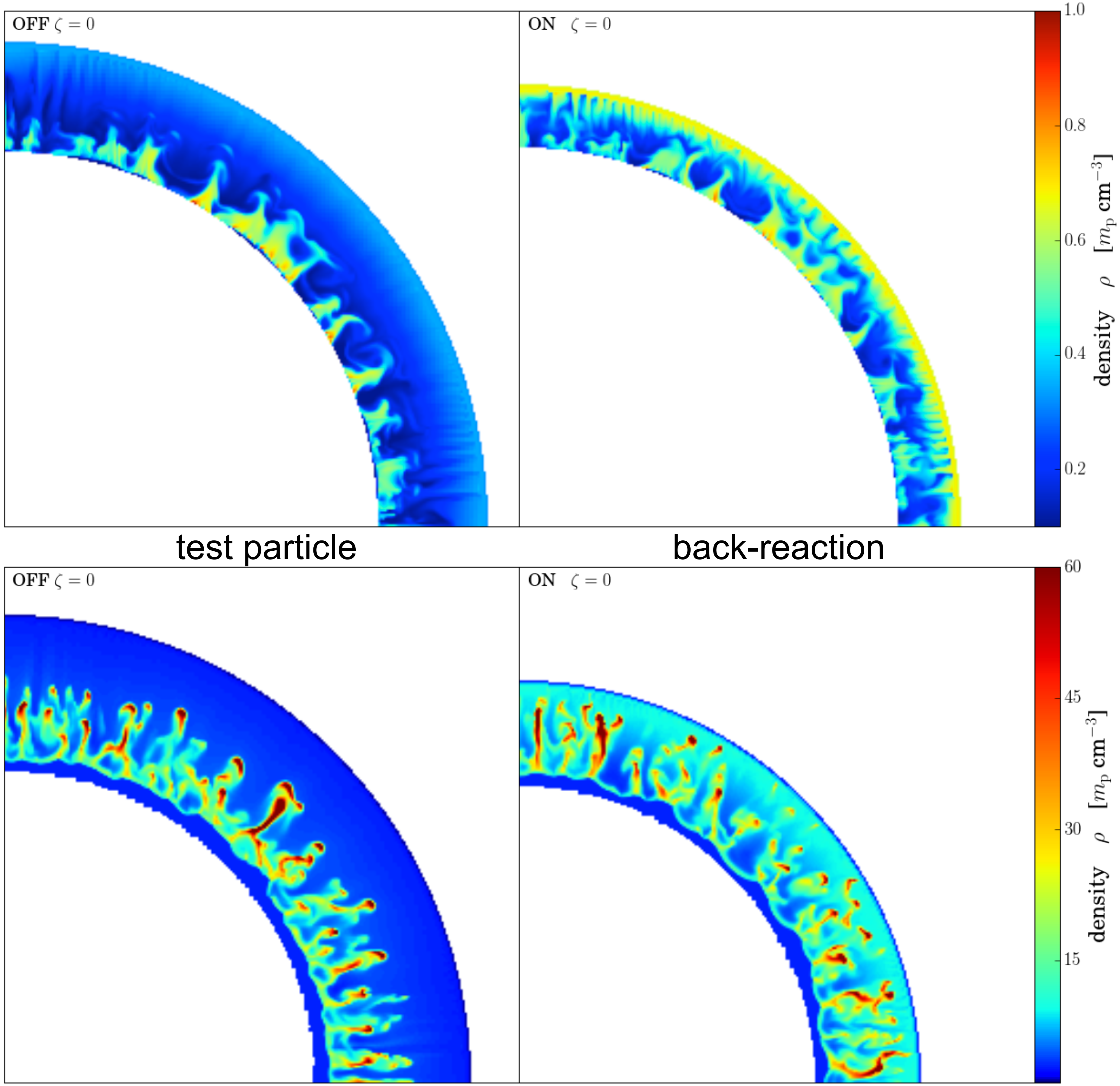
thermo-nuclear supernova

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

core-collapse supernova

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

PRELIMINARY



Results: temperature of electrons

thermo-nuclear supernova

type Ia in a uniform ISM
n=7, s=0
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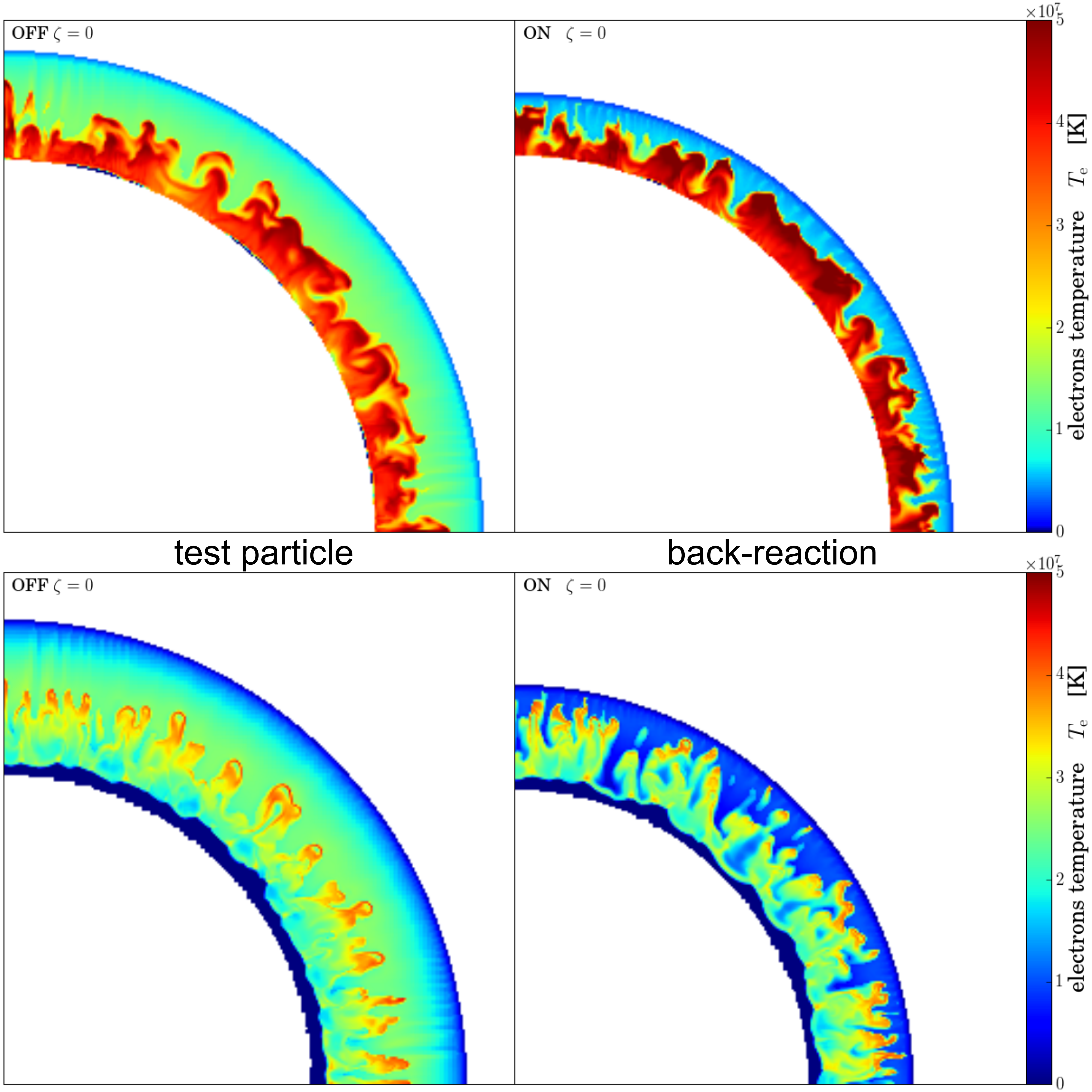

Results: thermal X-rays

thermo-nuclear supernova

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n=7, s=0
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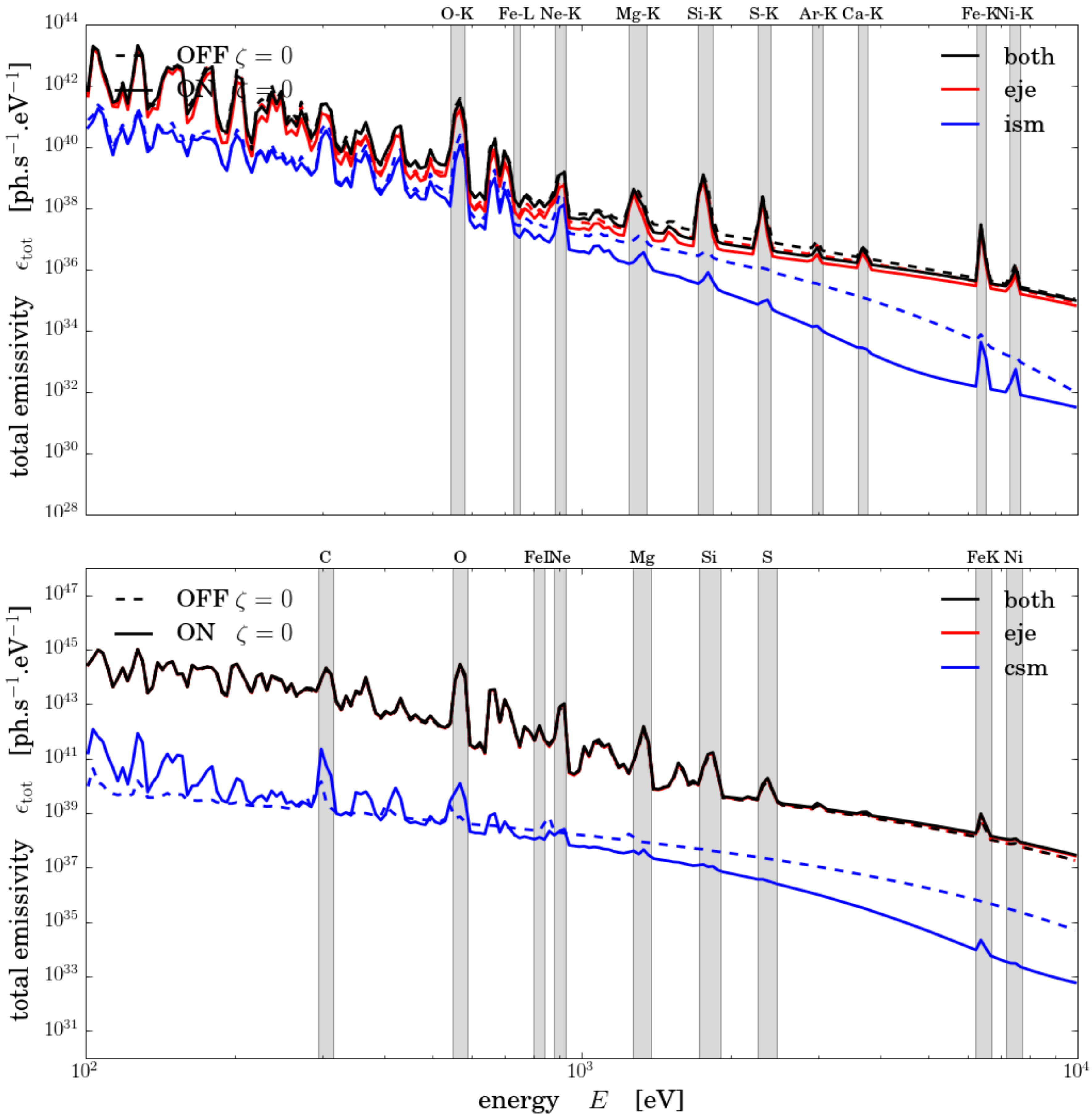
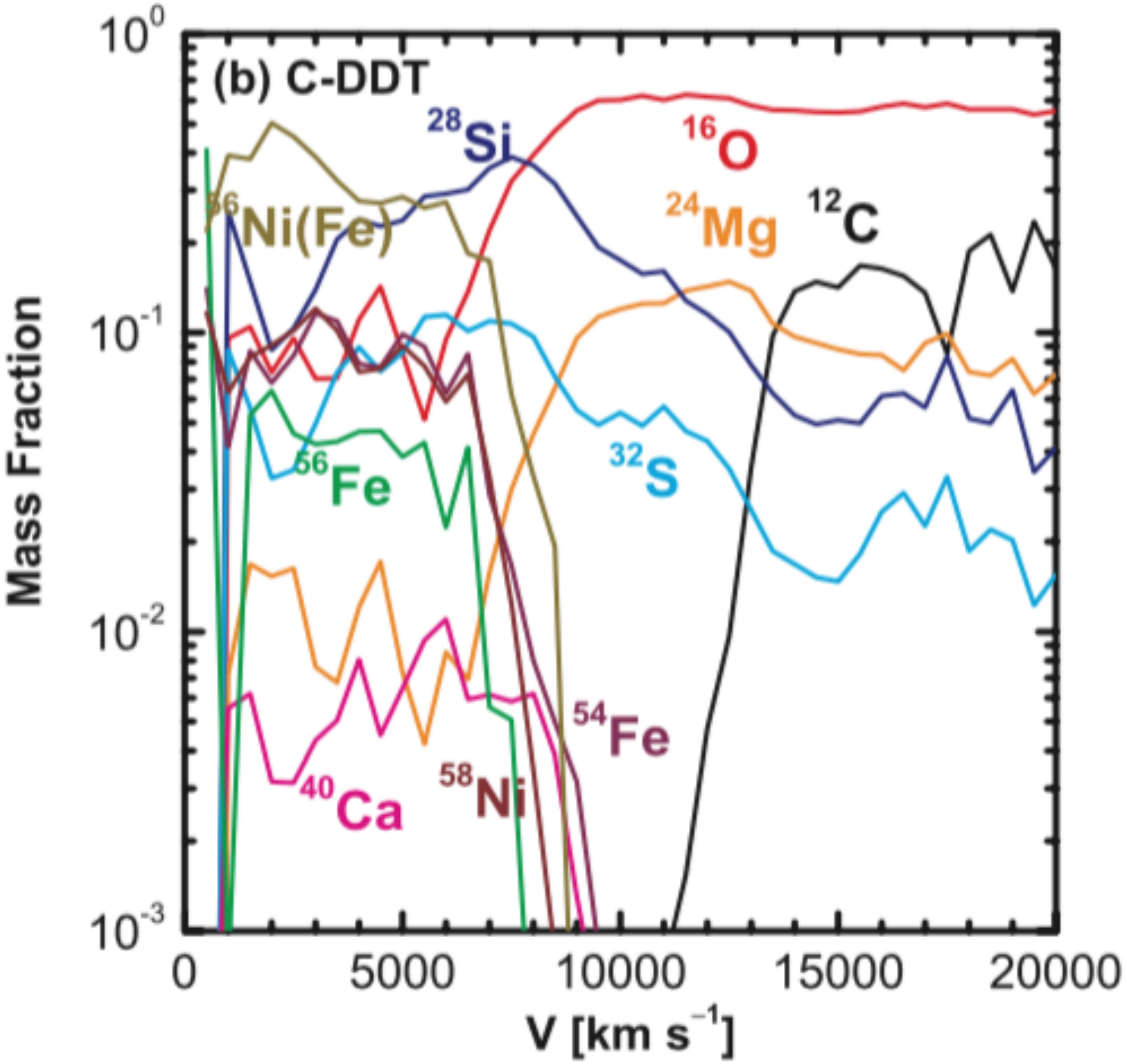


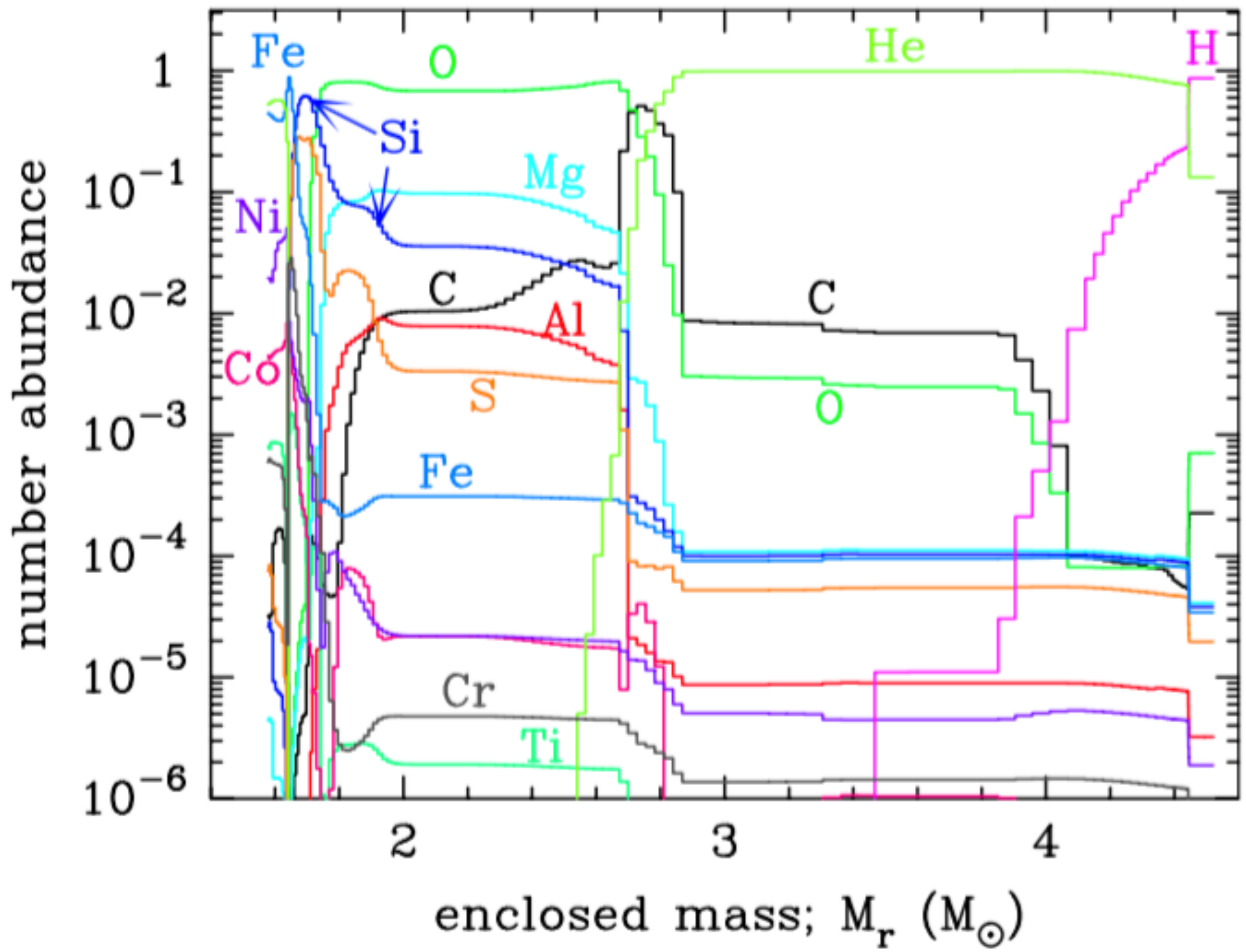
Abundances in the ejecta

for a Tycho-like thermonuclear SN



Maeda et al 2010

for a Cas A-like core-collapse SN



Nozawa et al 2010

Note: we use a spatially uniform distribution in our simulations, yet we obtain non-uniform thermal emission maps!

magnetic field
&
non-thermal emission

Wind properties: magnetization

Magnetic field needed to compute acceleration of particles at the shock, and to compute the synchrotron radiation from electrons

magnetization: $\sigma = \frac{\frac{B^2}{8\pi}}{0.5\rho v_w^2} = \frac{B^2 r^2}{\dot{M}_w v_w}$

Chevalier & Luo 1994
Lee et al 2014

constant in a steady wind from conservation of magnetic flux

then

$$B(r) = \frac{\sqrt{\sigma\, \dot{M}_w\, v_w}}{r} \simeq 0.8\mu\mathrm{G} \left(\frac{\sigma}{10^{-2}}\right)^{0.5} \left(\frac{\dot{\mathrm{M}}_\mathrm{w}}{10^{-5}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}\right)^{0.5} \left(\frac{\mathrm{v_w}}{10\,\mathrm{km.s}^{-1}}\right)^{0.5} \left(\frac{\mathrm{r}}{1\,\mathrm{pc}}\right)^{-1}$$

Here adopts $\sigma = 10^{-1}$

so that upstream of the SNR forward shock: $B_0 = 44\,\mu G \rightarrow 1\,\mu G$

2nd back-reaction loop: efficient amplification of the magnetic field **> ×100** by the energetic particles streaming in the shock precursor

Results: non-thermal (leptonic) X-rays

thermo-nuclear supernova

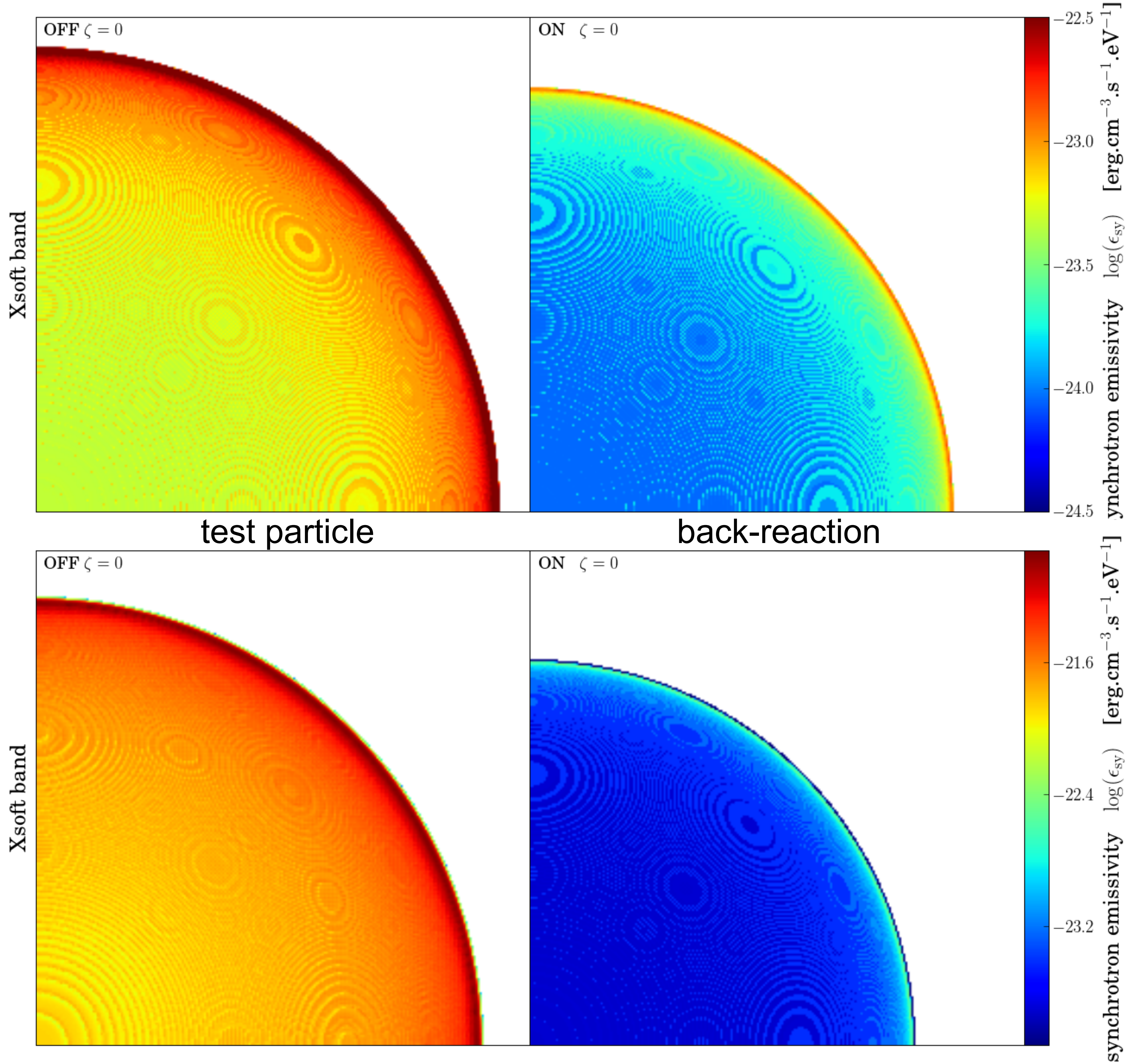
type Ia in a uniform ISM
n=7, s=0
(t = 500 yr)

synchrotron

core-collapse supernova

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

PRELIMINARY



Results: (non-thermal) leptonic γ-rays

thermo-nuclear supernova

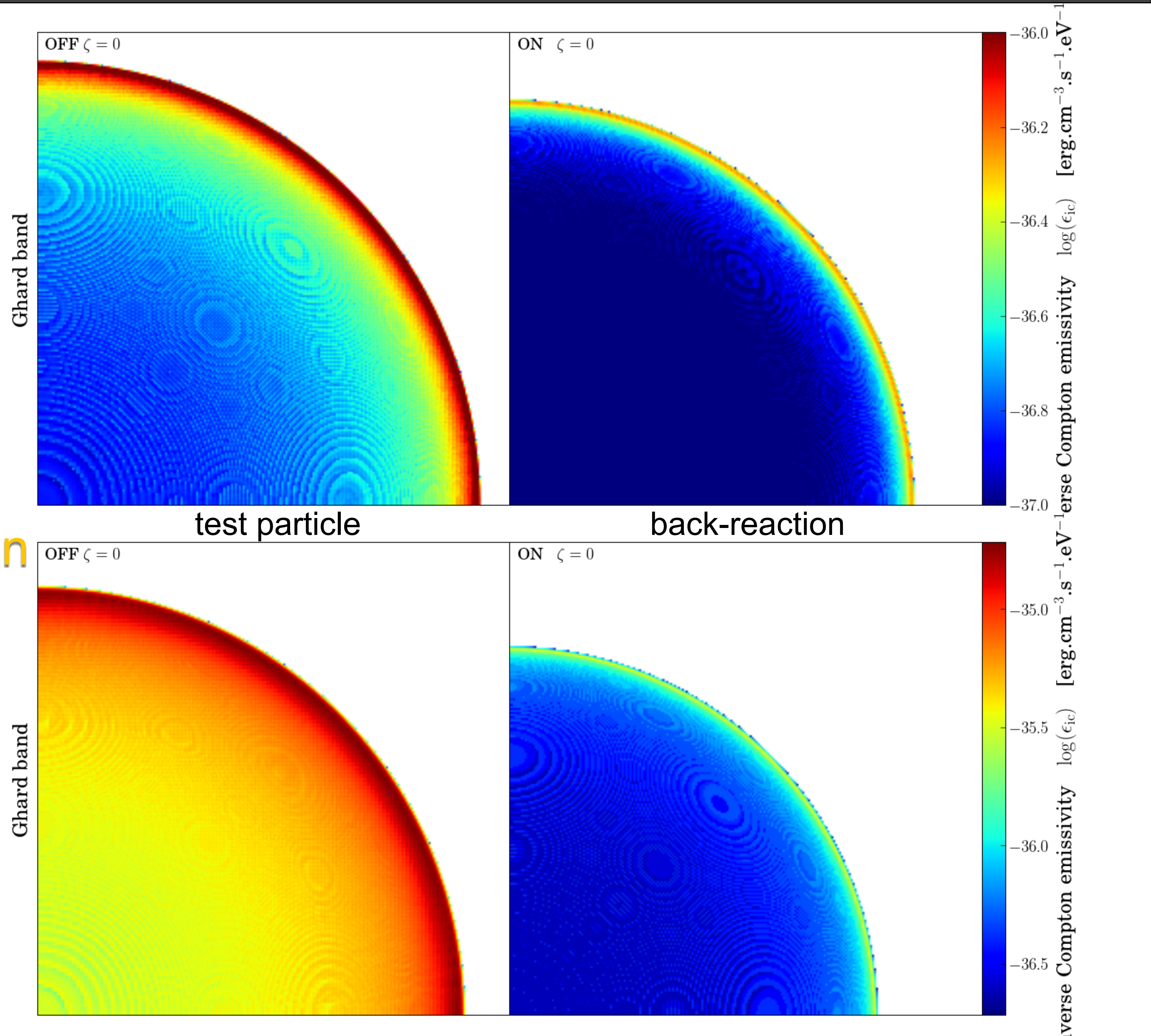
type Ia in a uniform ISM
n=7, s=0
(t = 500 yr)

inverse Compton

core-collapse supernova

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

PRELIMINARY



Results: (non-thermal) hadronic γ-rays

thermo-nuclear supernova

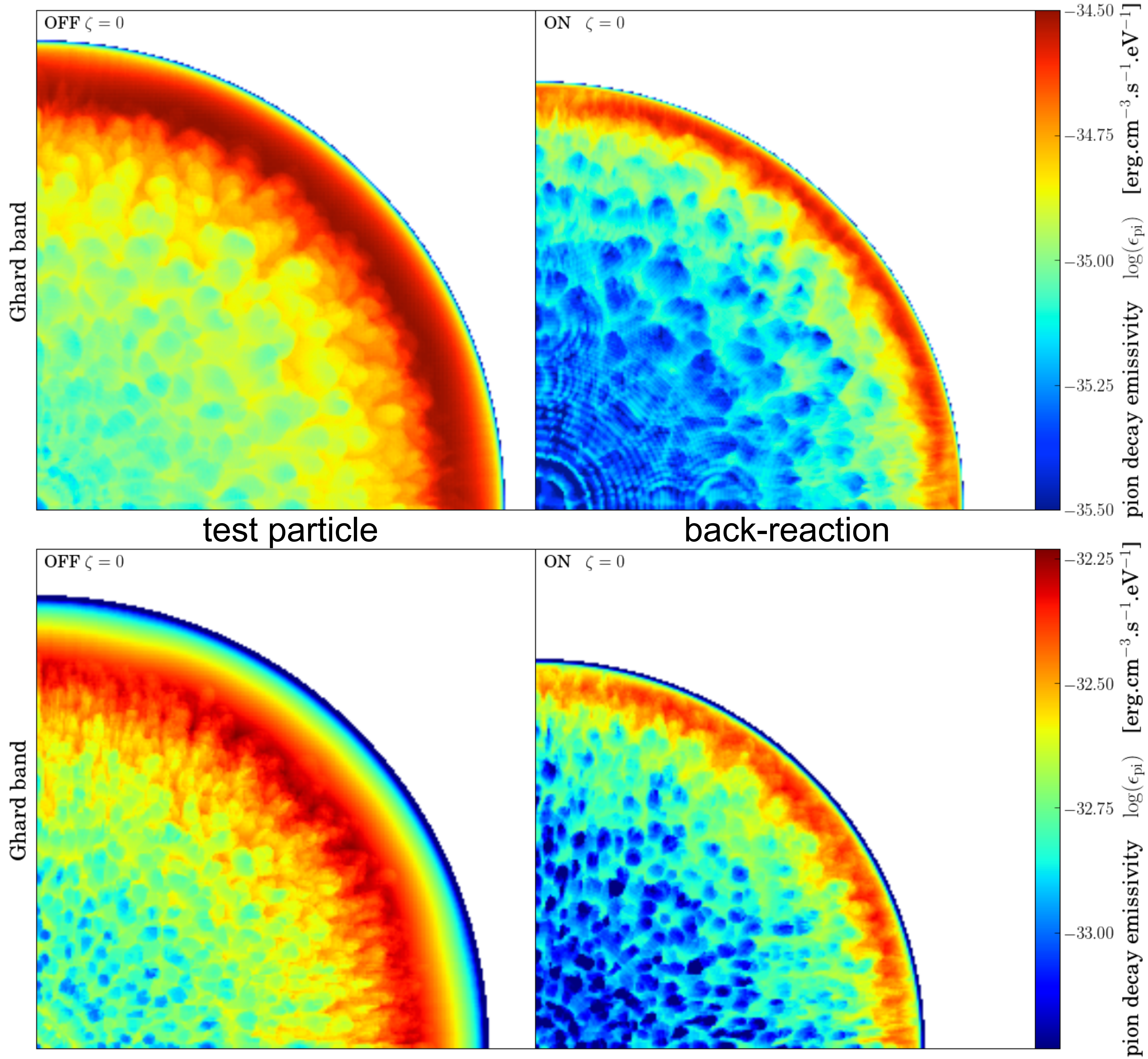
type Ia in a uniform ISM
n=7, s=0
(t = 500 yr)

pion decay

core-collapse supernova

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

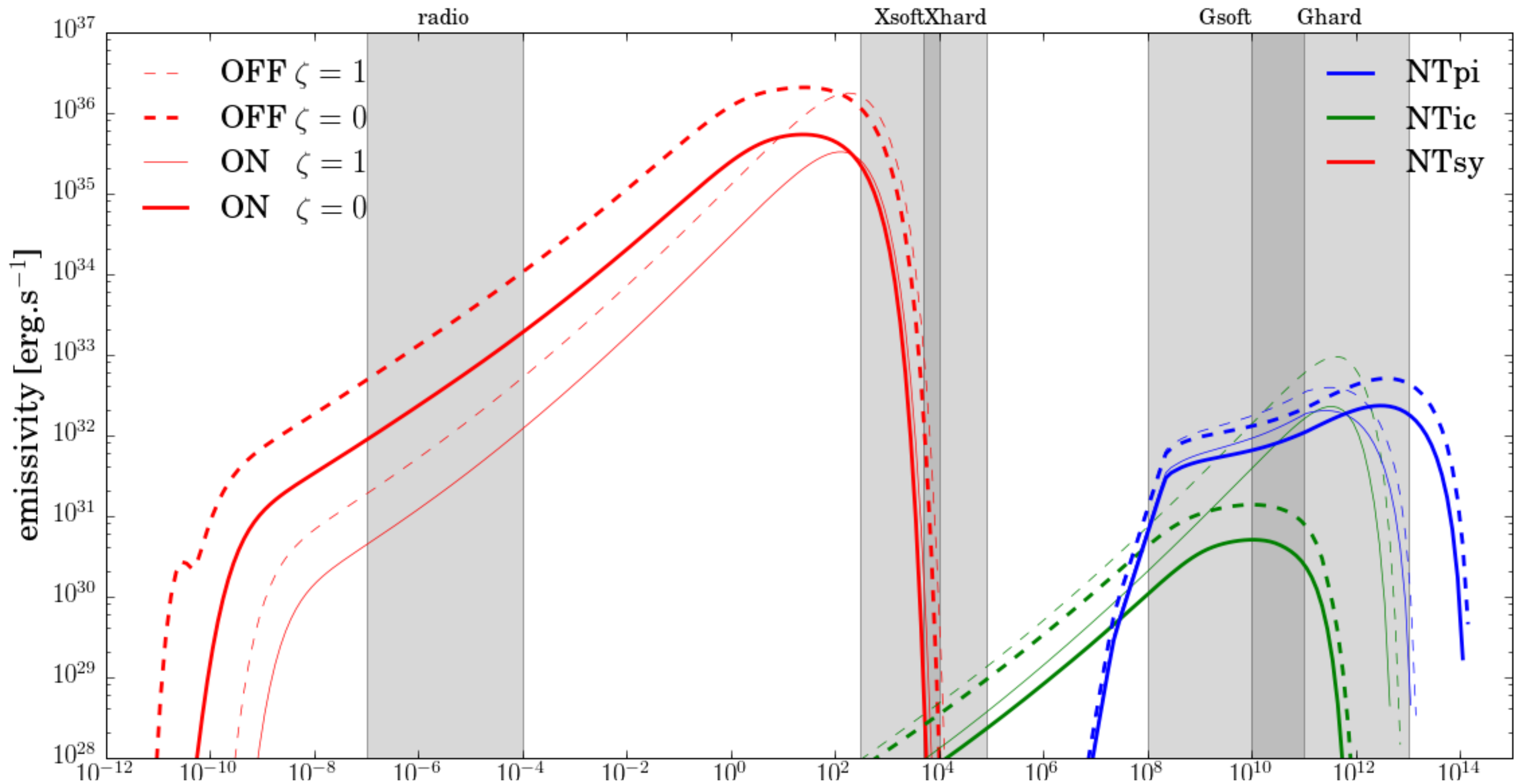
PRELIMINARY



Results: non-thermal broad-band emission

thermo-nuclear supernova

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

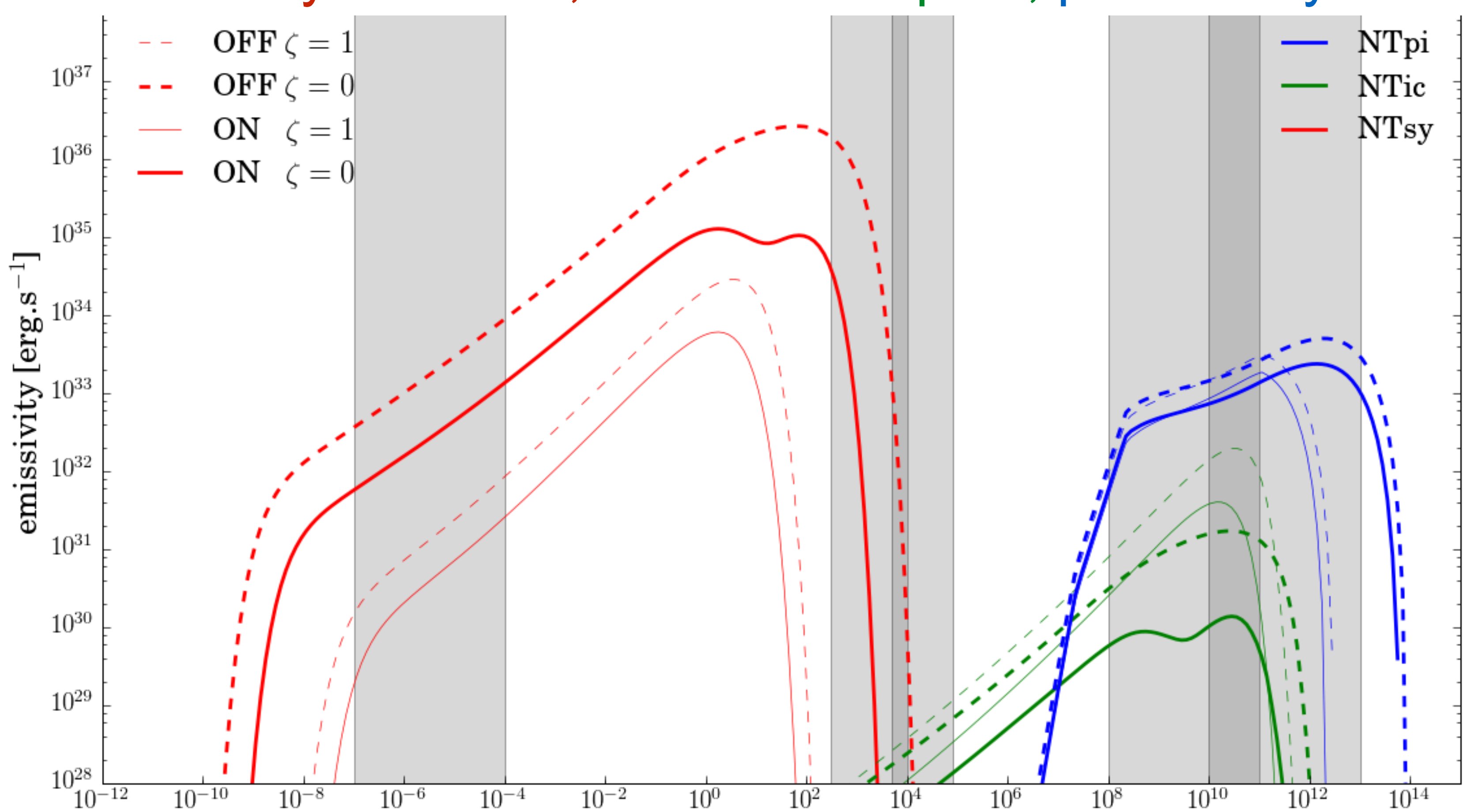


synchrotron, inverse Compton, pion decay

core-collapse supernova

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

PRELIMINARY



Conclusions

The impact of particle acceleration is dependent
- on the photon energy observed
- on the magnetic field evolution assumed

In our current model for a CC SNR it appears to be
- similar for the particles emission
- less visible for the plasma emission

(*but how about acceleration at the reverse shock?*)

The broad-band emission from a SNR (thermal emission from the plasma + non-thermal emission from the accelerated particles) is the result of an integration over both space (projection) and time:
- history of the shock strength
- history of particle acceleration
- history of magnetic field amplification

(*so how to match observations with a one-zone model??*)

Even more so when the SNR is evolving in a wind