PACIFIC conference
Gump Station, Moorea
Sept 14, 2015

Multi-D SNR Simulations with Particle Acceleration

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Outline of the Talk

Introduction: particle acceleration in supernova remnants

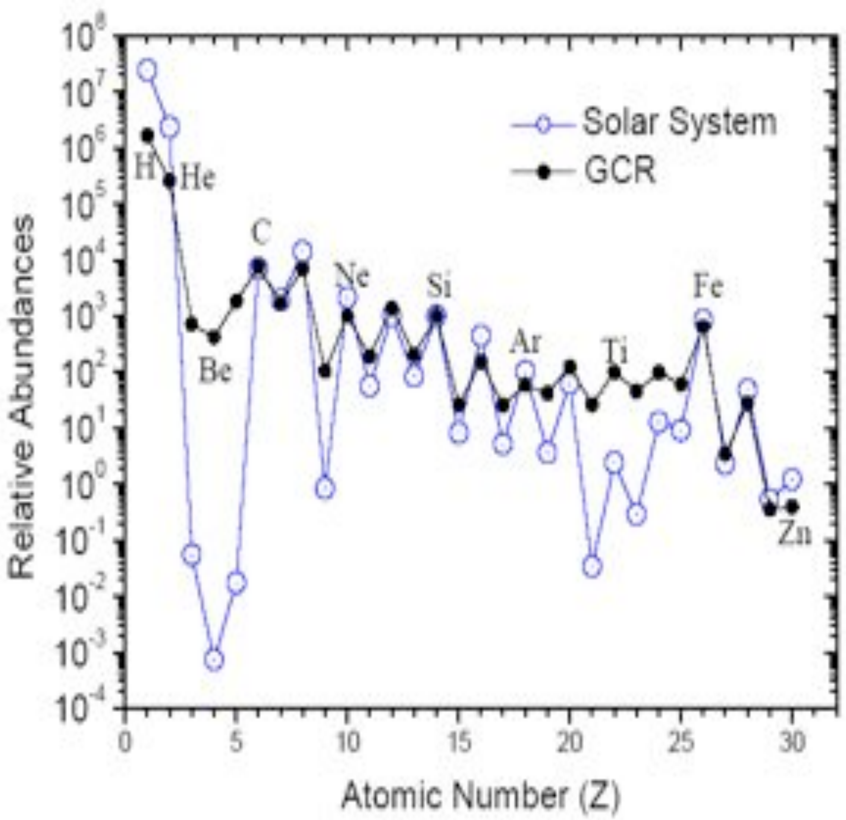
- SNRs as Cosmic Ray accelerators
- SNR structure and evolution

3D numerical simulations

- hydro+kinetic code (Ramses+Blasi)
- thermal emission
- non-thermal emission
- perspetives

The 3 dimensions of Cosmic Radiation

mass spectrum

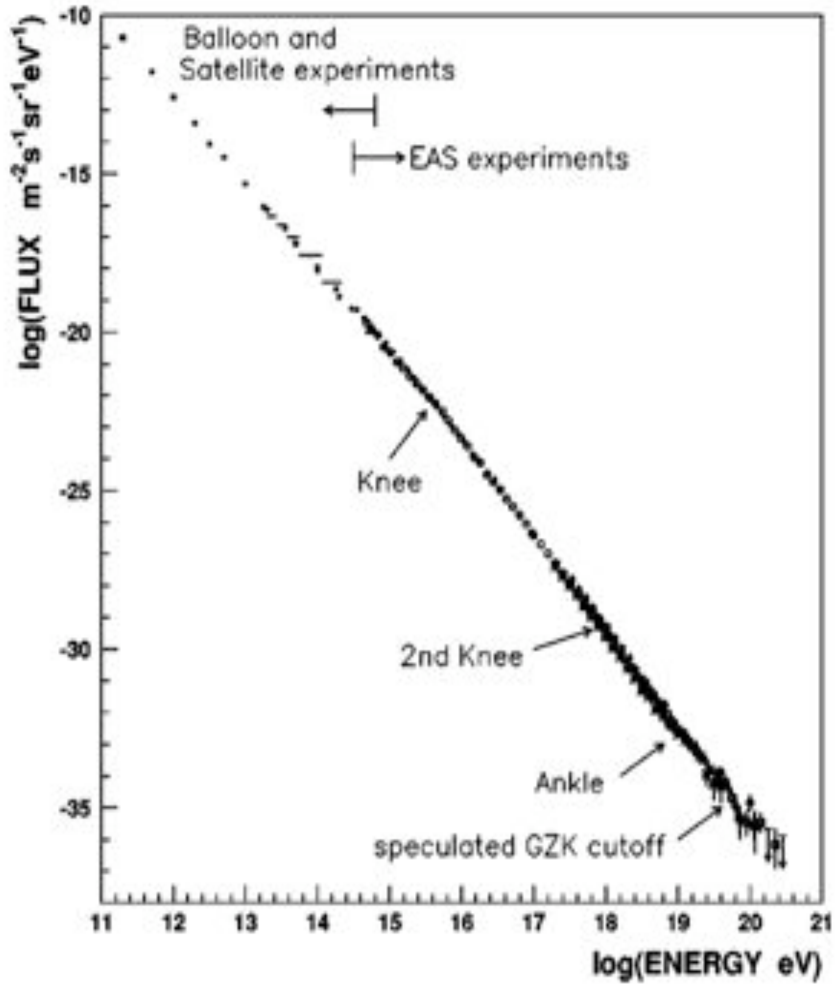


99% of nucleons
+ 1% e-

quasi-solar abundance,
with particularities

[Israel 2004]

energy spectrum

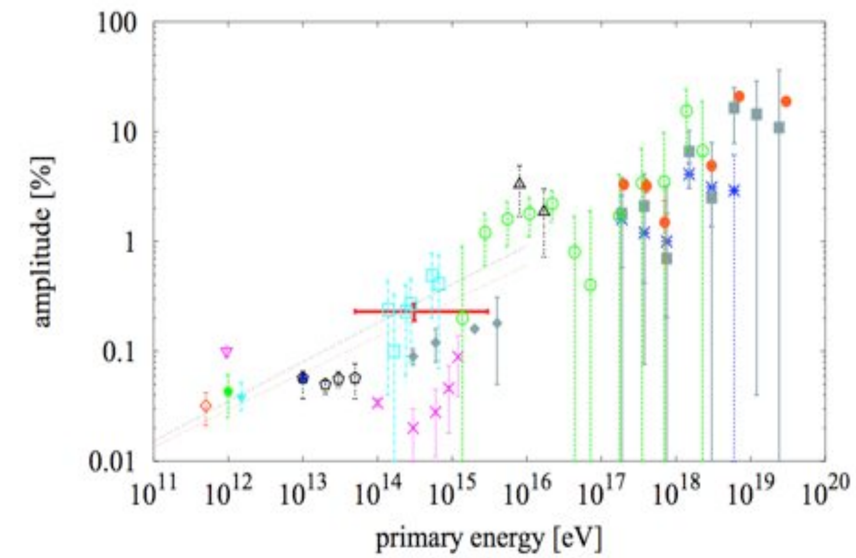


power-law, with breaks

> 10 orders of magnitude
in energy !

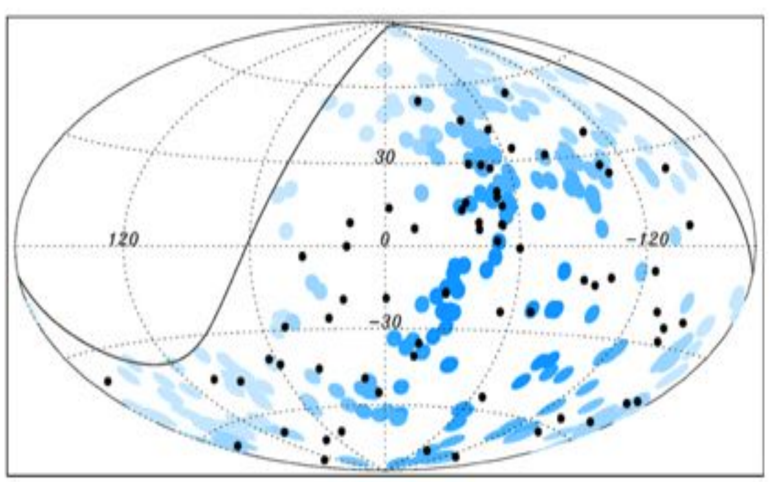
[Nagano & Watson 2000]

angular spectrum



isotropic radiation
(random walk in B)

[Iyono et al 2005]

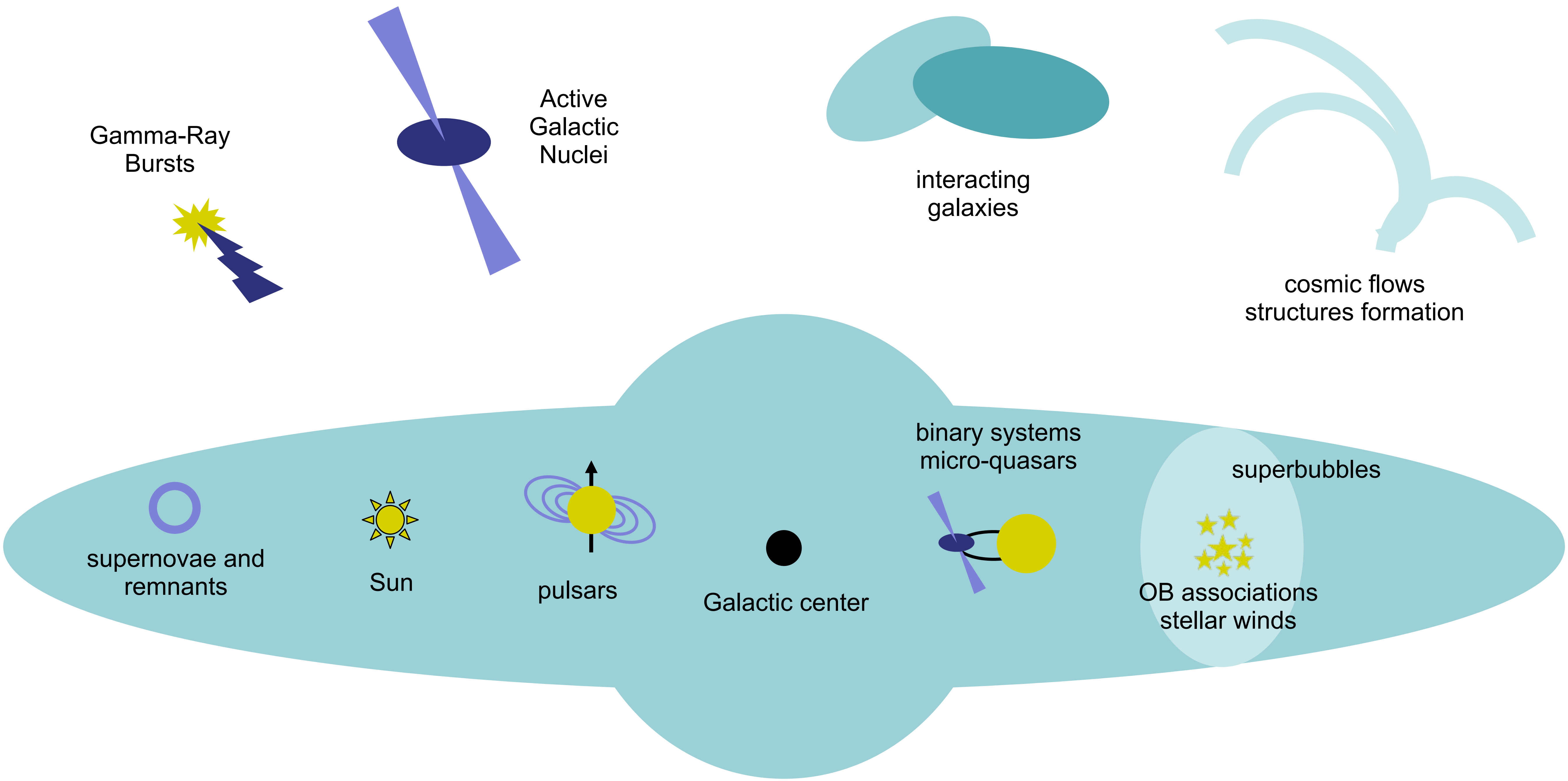


even at the highest energies?

[Pierre Auger Coll. 2010, 2012]

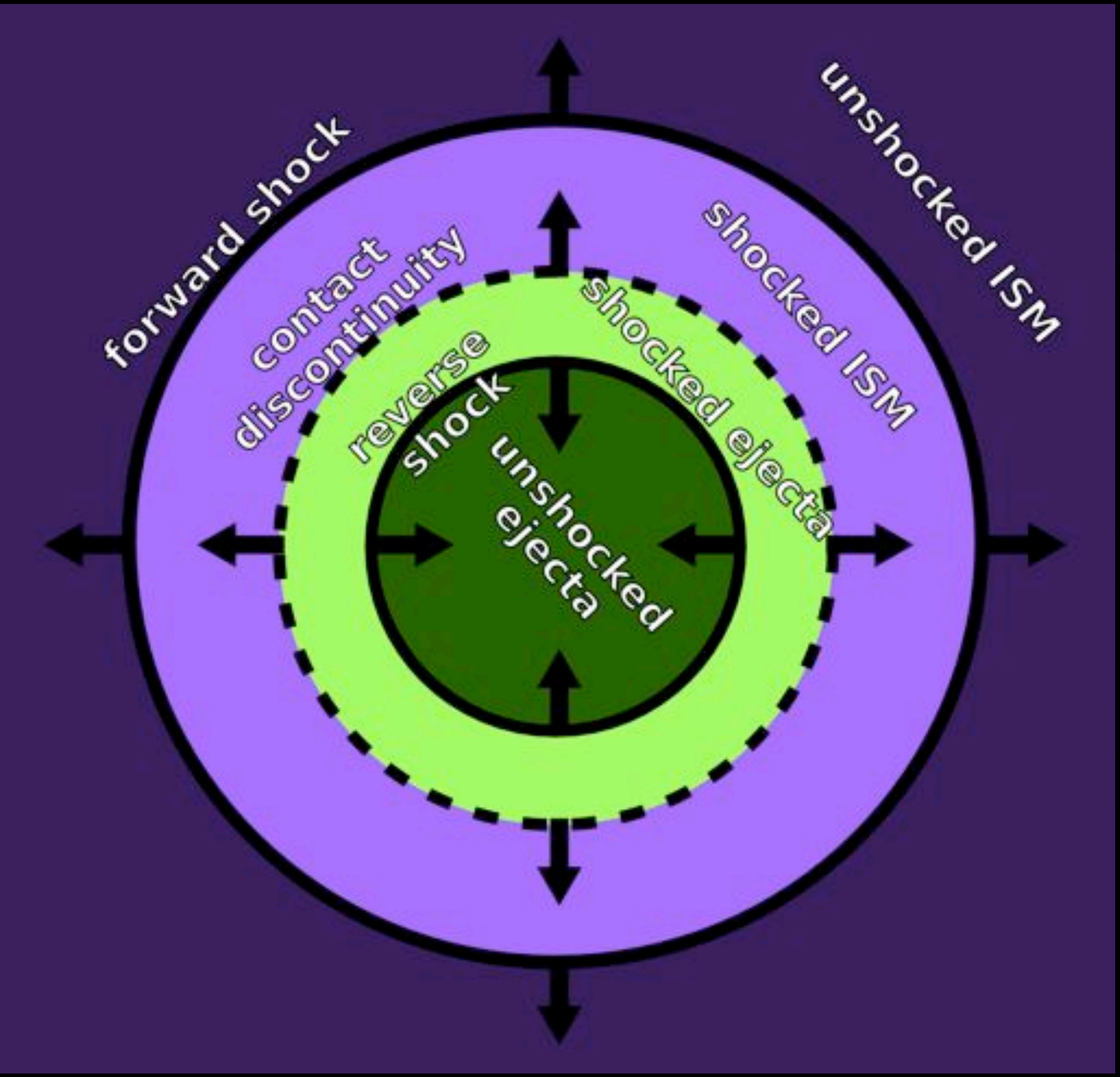
Particle acceleration in the Universe

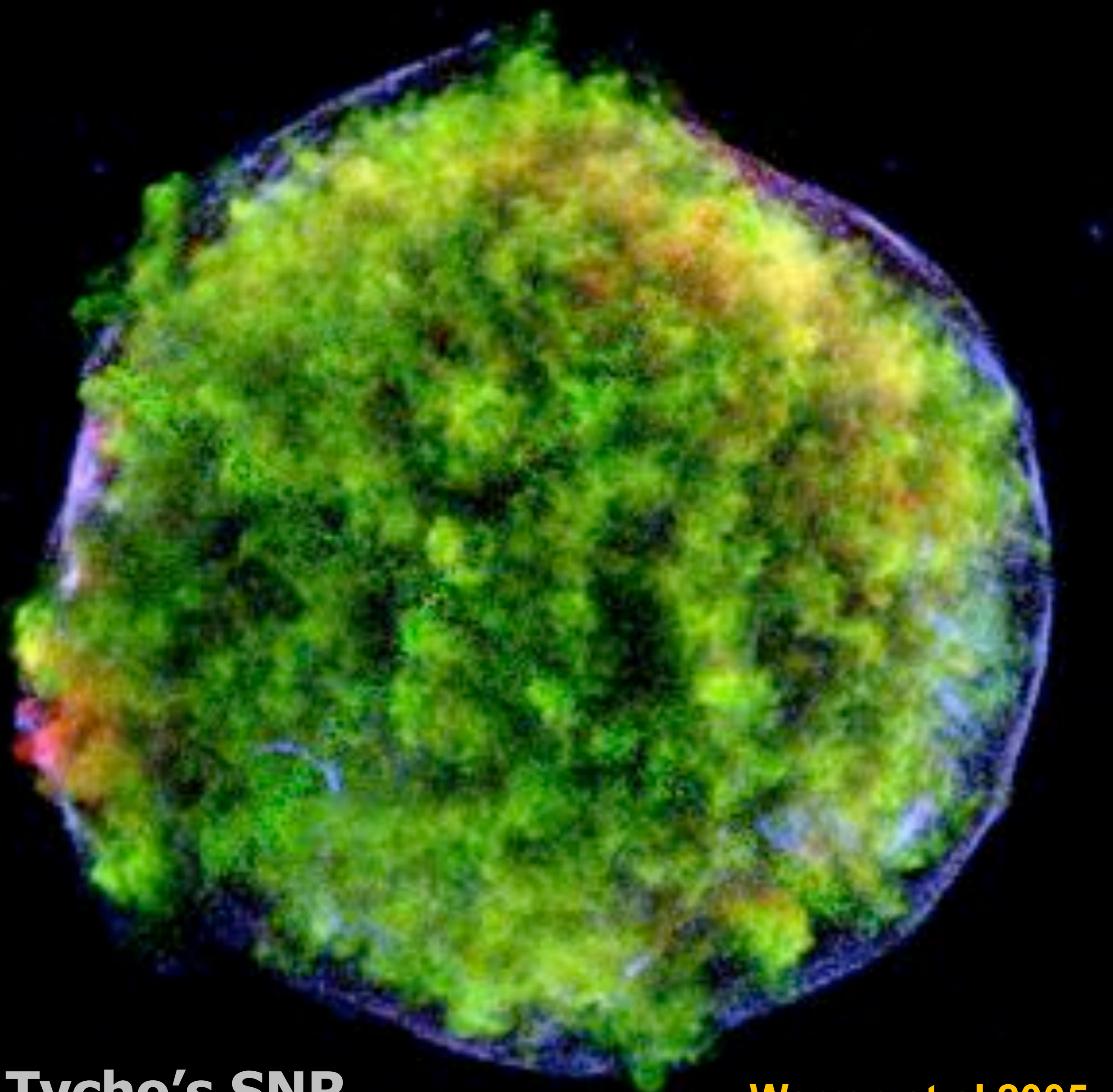
Engines of acceleration : **massive stars**, **compact objects**
Physics of **shocks**, of **accretion/ejection**, of **magnetic fields**



1.3

The structure of a young supernova remnant



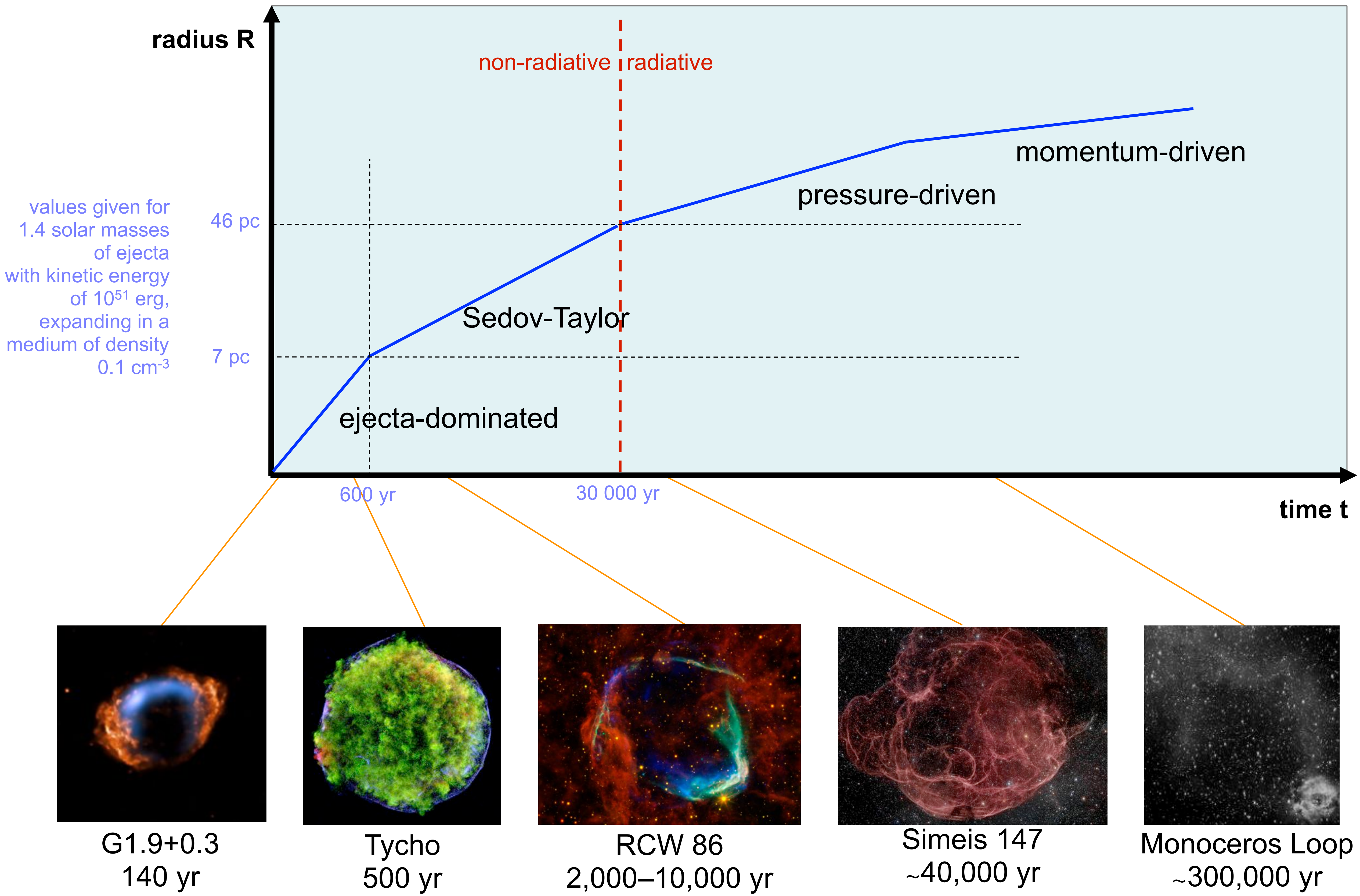


Tycho's SNR
seen by Chandra
(at age 433 yr)

Warren et al 2005

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

The evolution of a supernova remnant



SNRs as a key link between stars and the ISM

enrichment in heavy elements

Big Bang: H, He	Cosmic Rays: Li, Be, B	stars: all other elements from C to U

average stars: up to C-O
massive stars: up to Fe
supernovae: everything else

injection of energy

heating of the gas	hydrodynamic turbulence	magnetic field amplification

impact on subsequent star formation cycles?

acceleration of particles

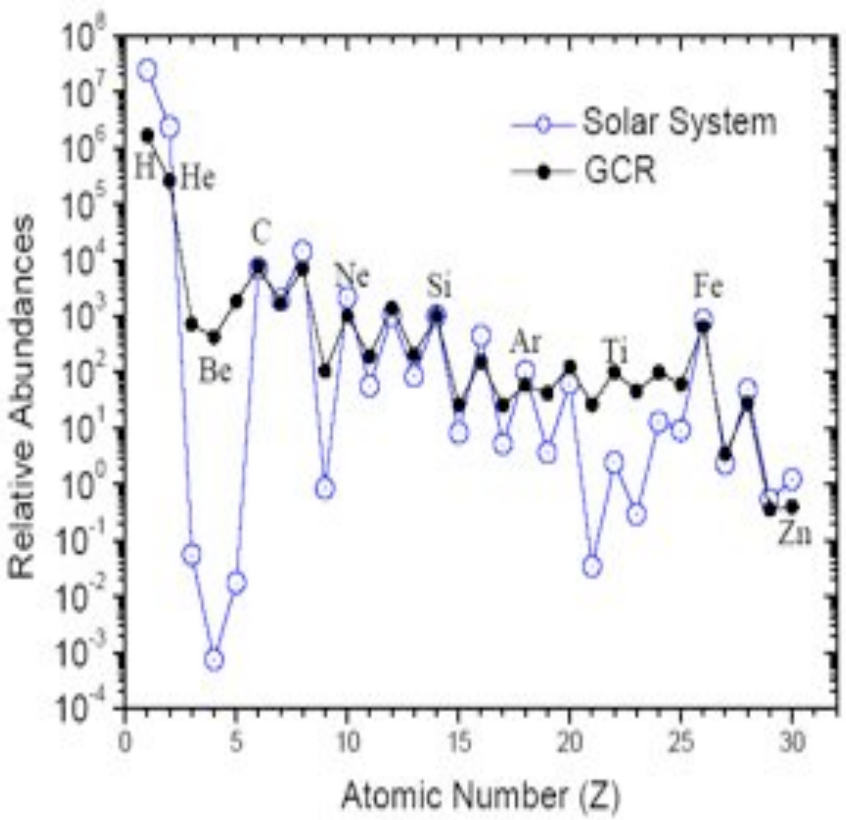
SNRs main sources?
Also PSRs and binaries

$< 10^{15}$ eV: Galactic	$> 10^{18}$ eV: extra-Galactic

the acceleration of charged particles is an important feature of magnetized shocks in collisionless plasma

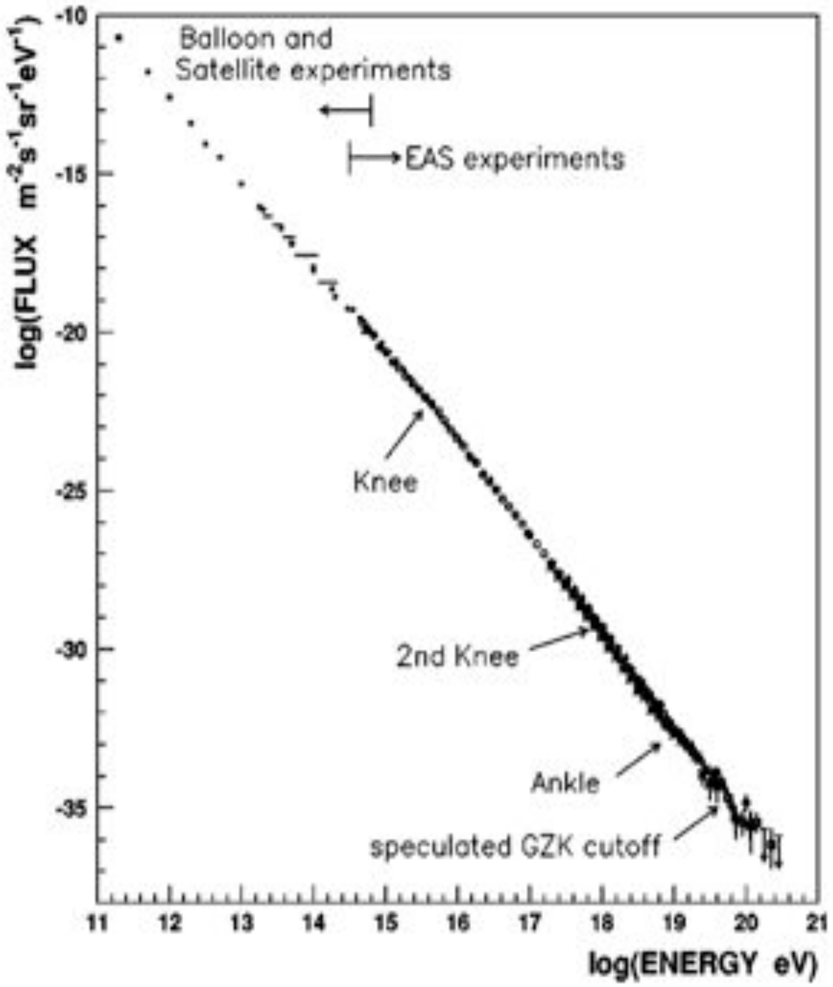
Supernova Remnants as Galactic CR sources

mass spectrum



☺ standard overall composition
☹ but what about all the "anomalies"?

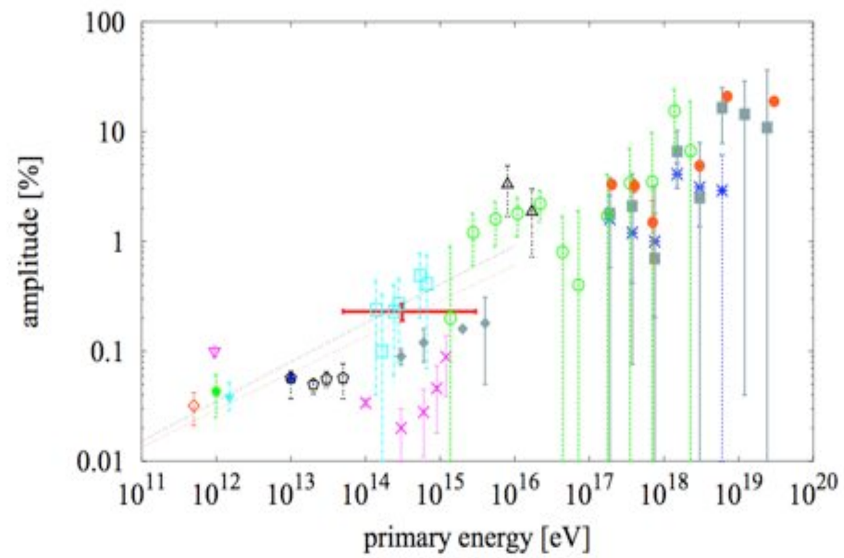
energy spectrum



☺ energetic budget
☹ but can we reach the knee / the ankle?

☺ mechanism producing power-law spectra
☹ but of which slope?

angular spectrum

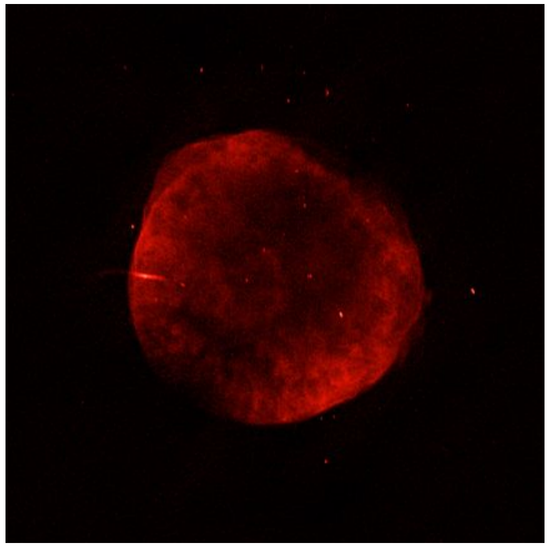


☺ observational proofs of acceleration of e-
☹ difficult to find energetic protons!

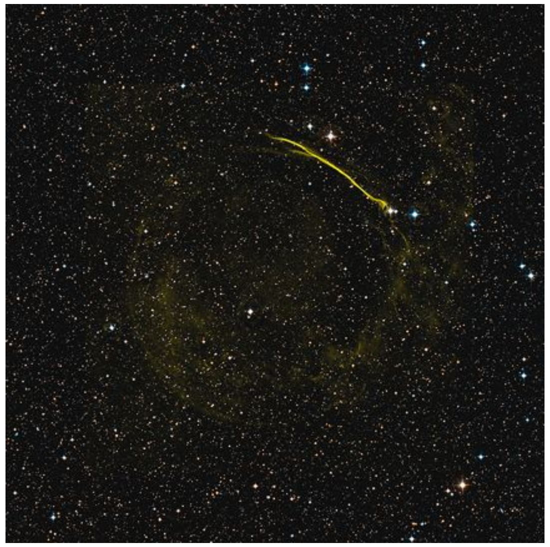
[recent reviews: Drury 2012, Blasi 2013, Bell 2013]

SNR broad-band emission

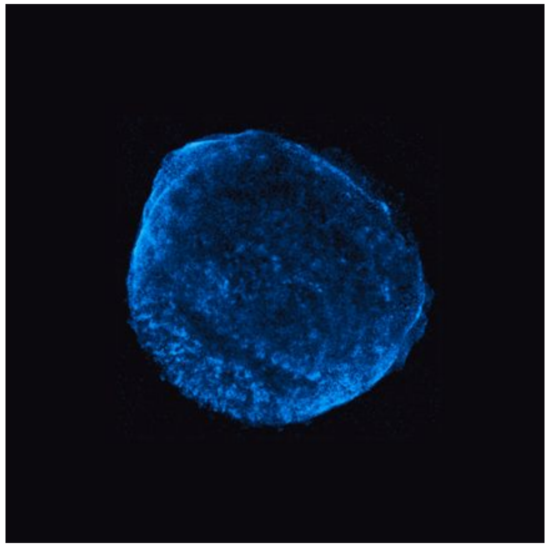
SN 1006



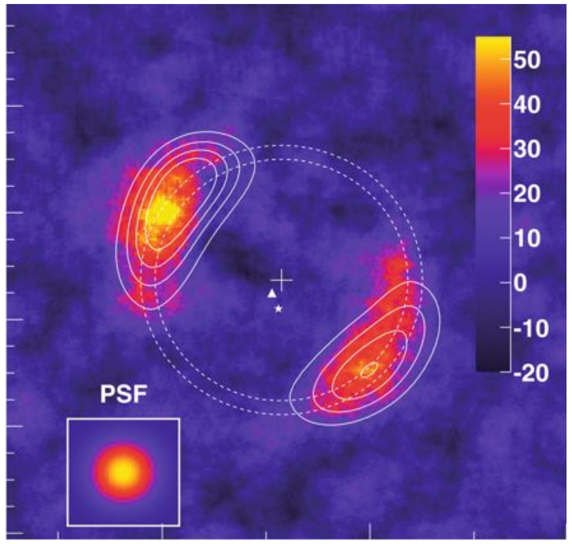
radio



optical



X



gamma

E

cm µm keV TeV

λ

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 ?

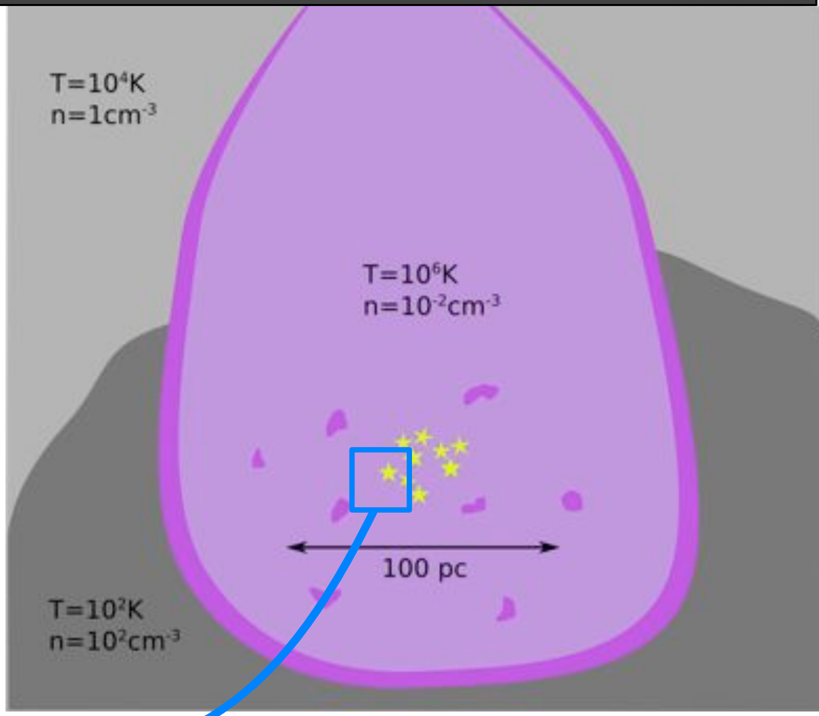
[review for CR evidence: Helder et al 2012]

Modelling DSA at different scales

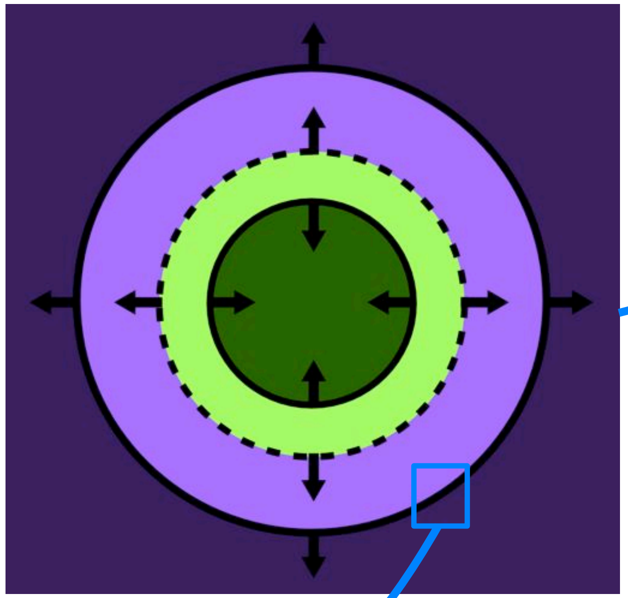
focus on → source description

↓ acceleration mechanism

superbubble



supernova remnant

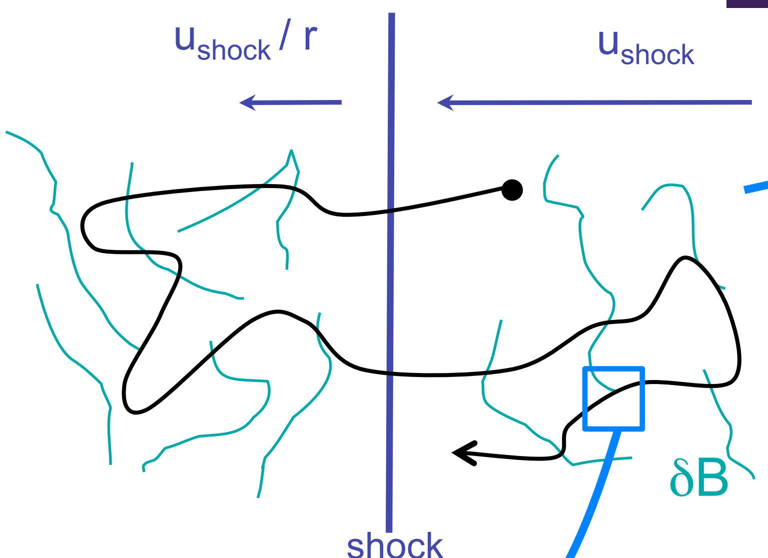


collective effects?

[Ferrand & Marcowith 2010]

SNOB

magnetized shock

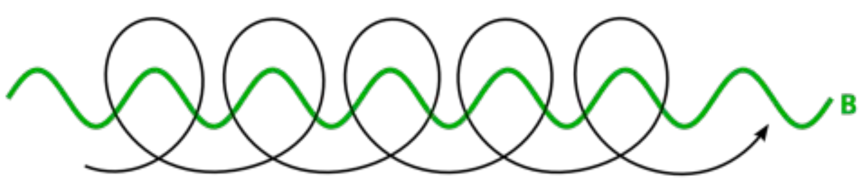


back-reaction on morphology?

[Ferrand, Decourchelle et al 2010]

accelRSN

wave - particle interaction

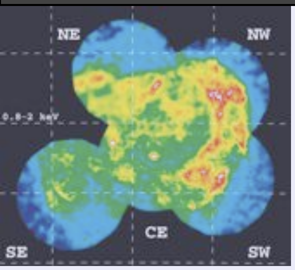


repeated modified shocks ?

[Ferrand, Downes, Marcowith 2008]

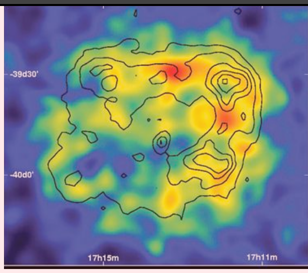
MARCOS

Diffusive shock acceleration: the coupled system



IR
Opt
UV
X

radio
X
γ



shock wave
(thermal magnetized plasma)

injection, acceleration
shock modification

cosmic-rays
(non-thermal population)

damping
heating

generation (instabilities)
diffusion, injection, stochastic acceleration

magnetic waves
(collective movements of charges)

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

2.3 Numerical simulations with Ramses

parameters: Tycho (SN Ia)

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

Chevalier 1982, 1983

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

Teyssier 2002, Fraschetti et al 2010

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

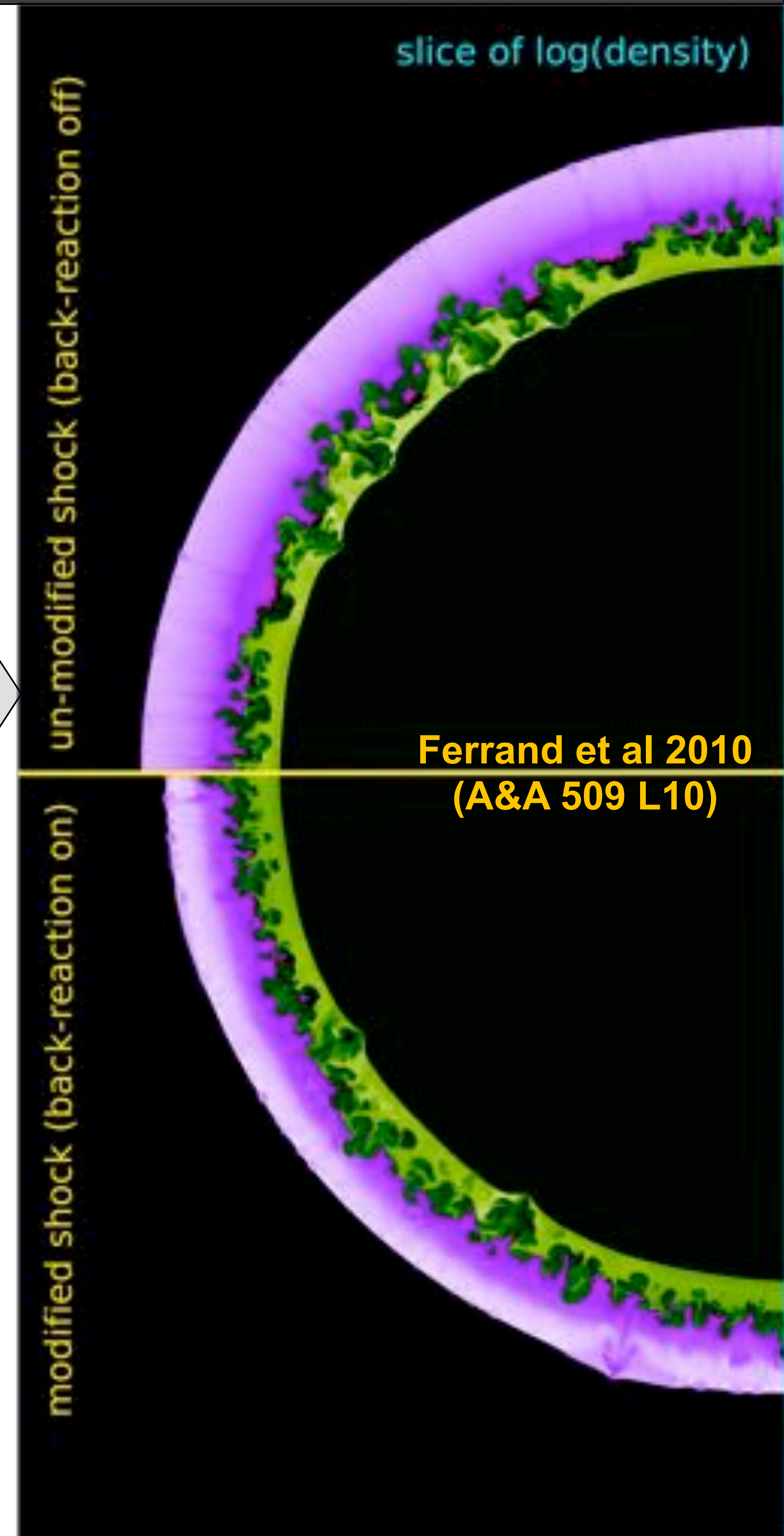
shock diagnostics

back-reaction: varying gamma

Ellison et al 2007

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

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



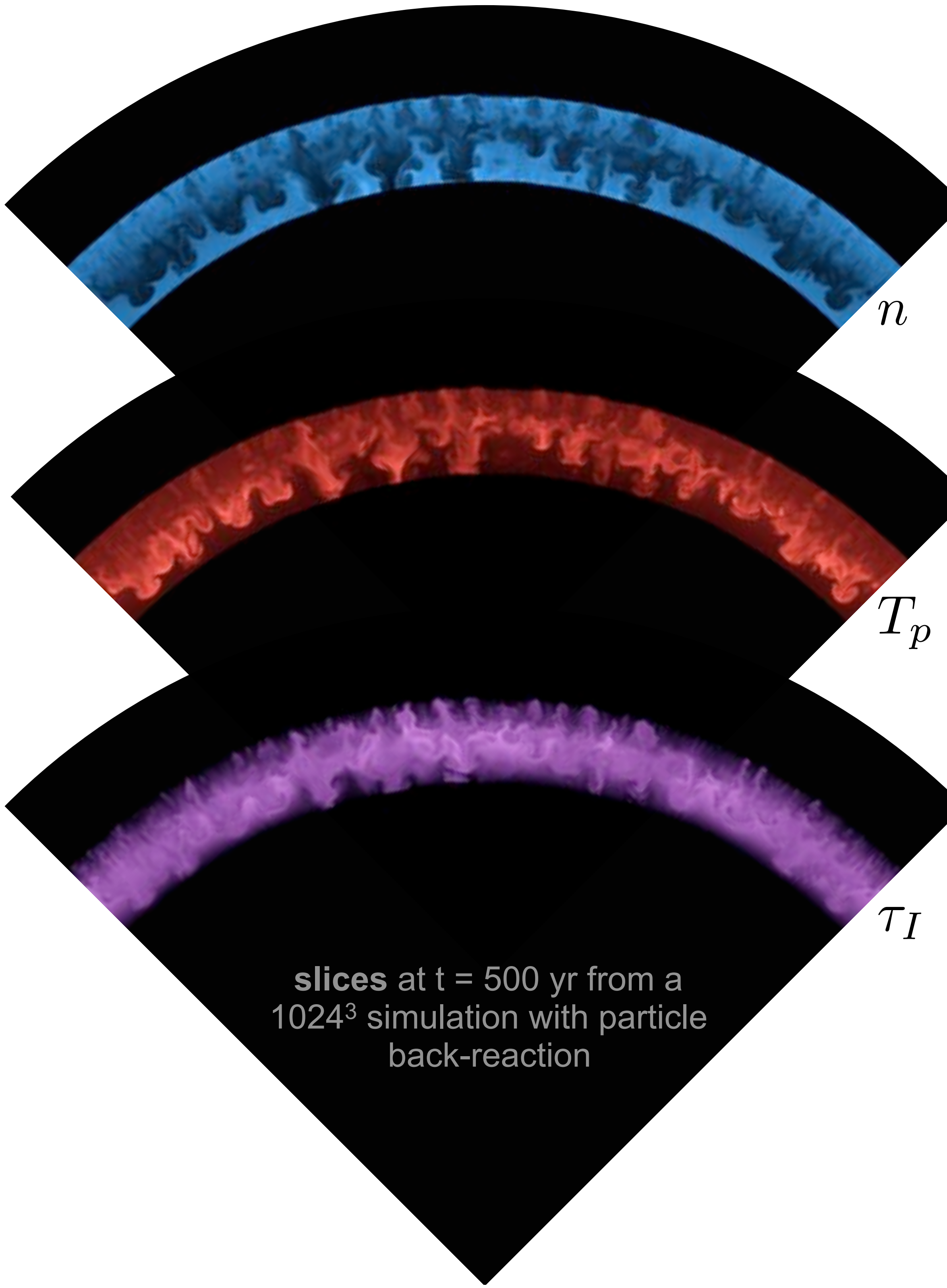
Hydro- and thermodynamics of the plasma

Thermal emission in each cell depends on:

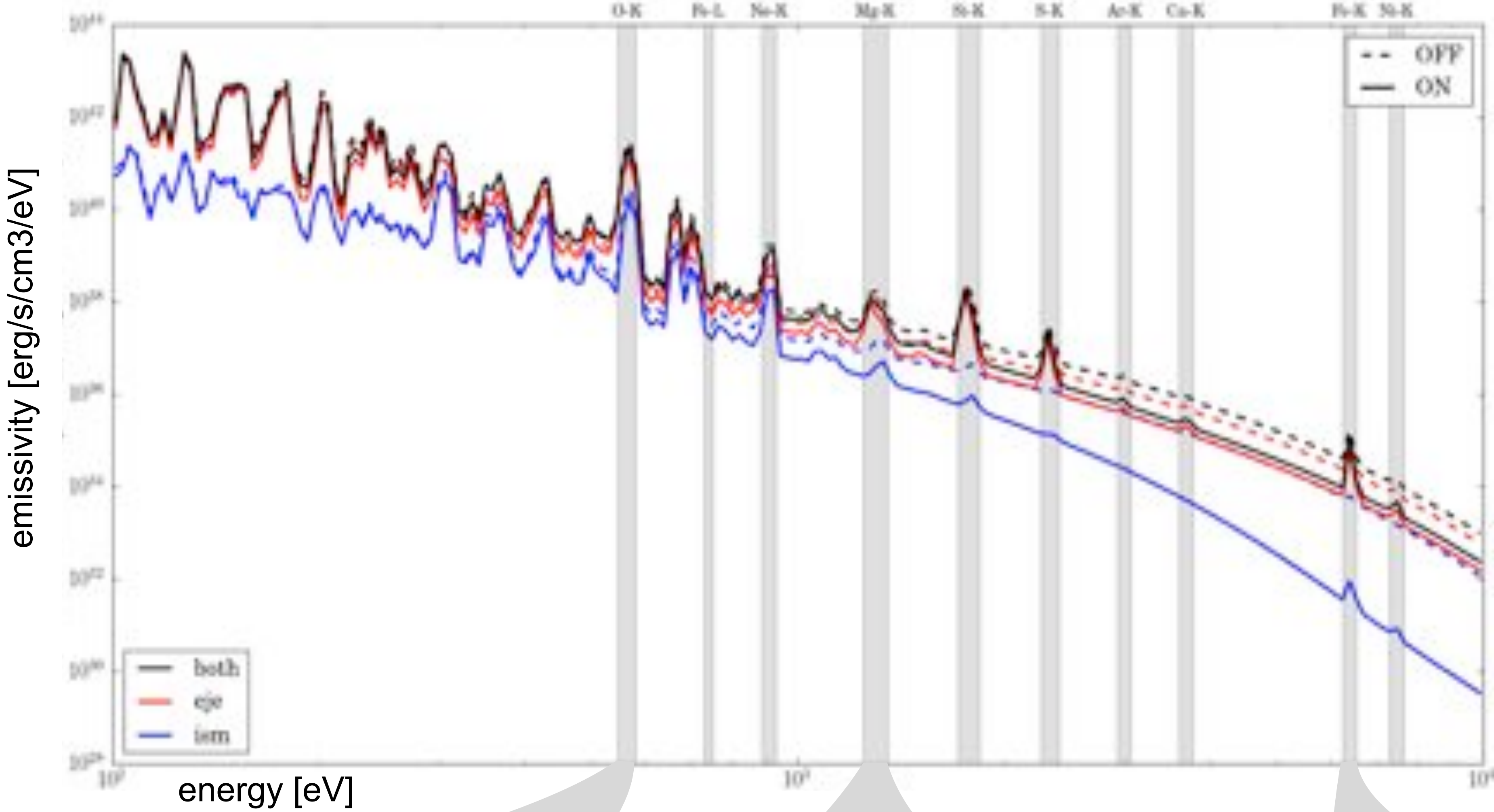
- **plasma density** n^2
- **electron temperature** T_e
  progressive equilibration
  with protons temperature T_p
  via Coulomb interactions
- **ionization states** $f_i(Z)$
  computation of non-equilibrium ionization
  with the exponentiation method

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

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



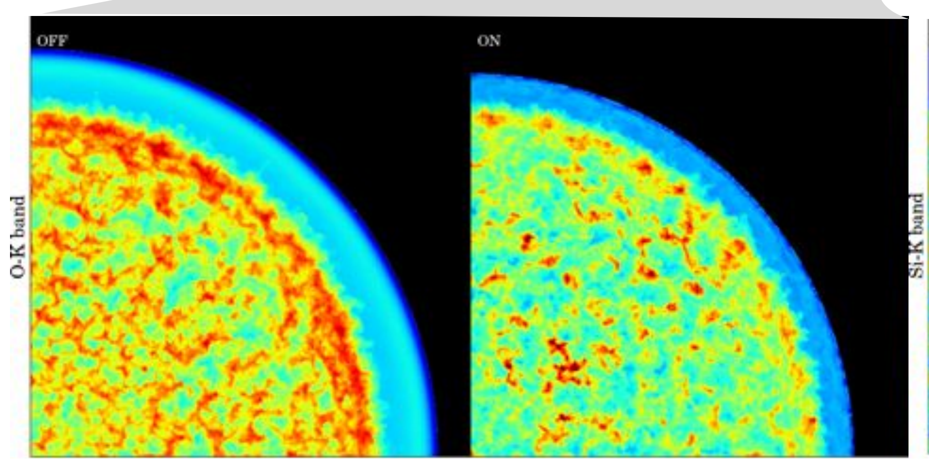
Thermal emission



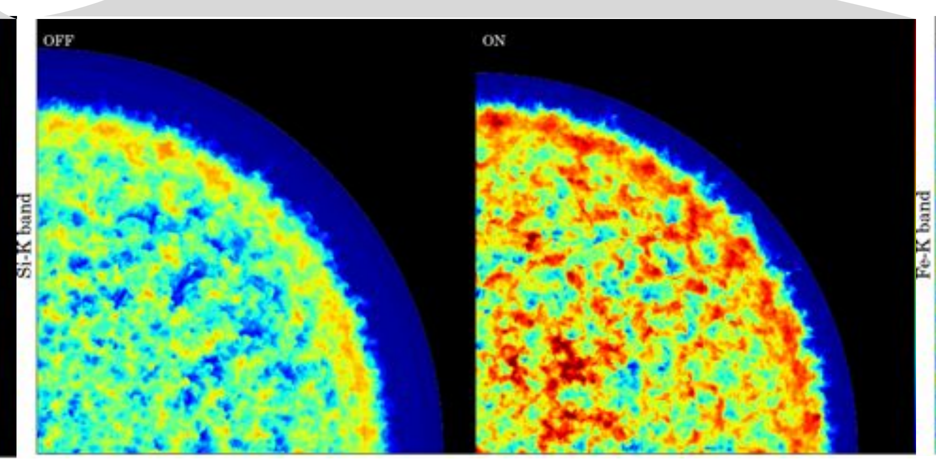
Ferrand, Decourchelle, Safi-Harb 2012 (ApJ 760 34) using the emission code from Mewe (depends on density, temperature and ionisation states)

1024^3 cells

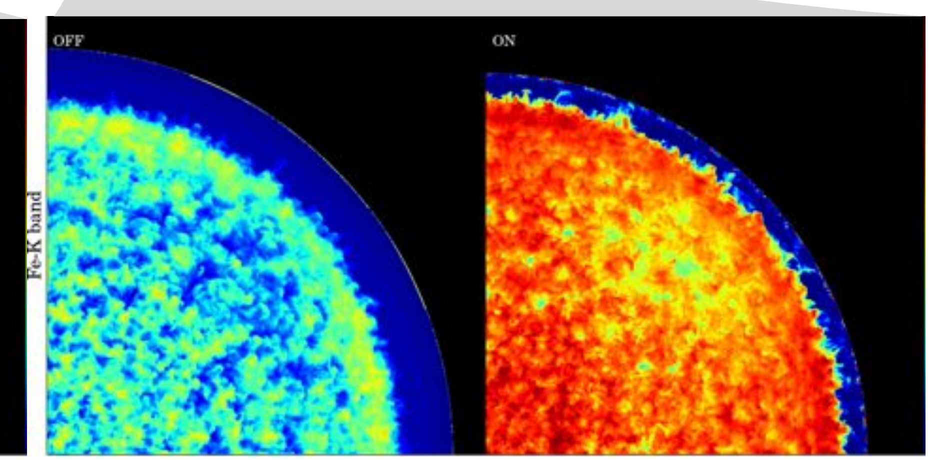
t = 500 yr



test particle vs. back-reaction



test particle vs. back-reaction

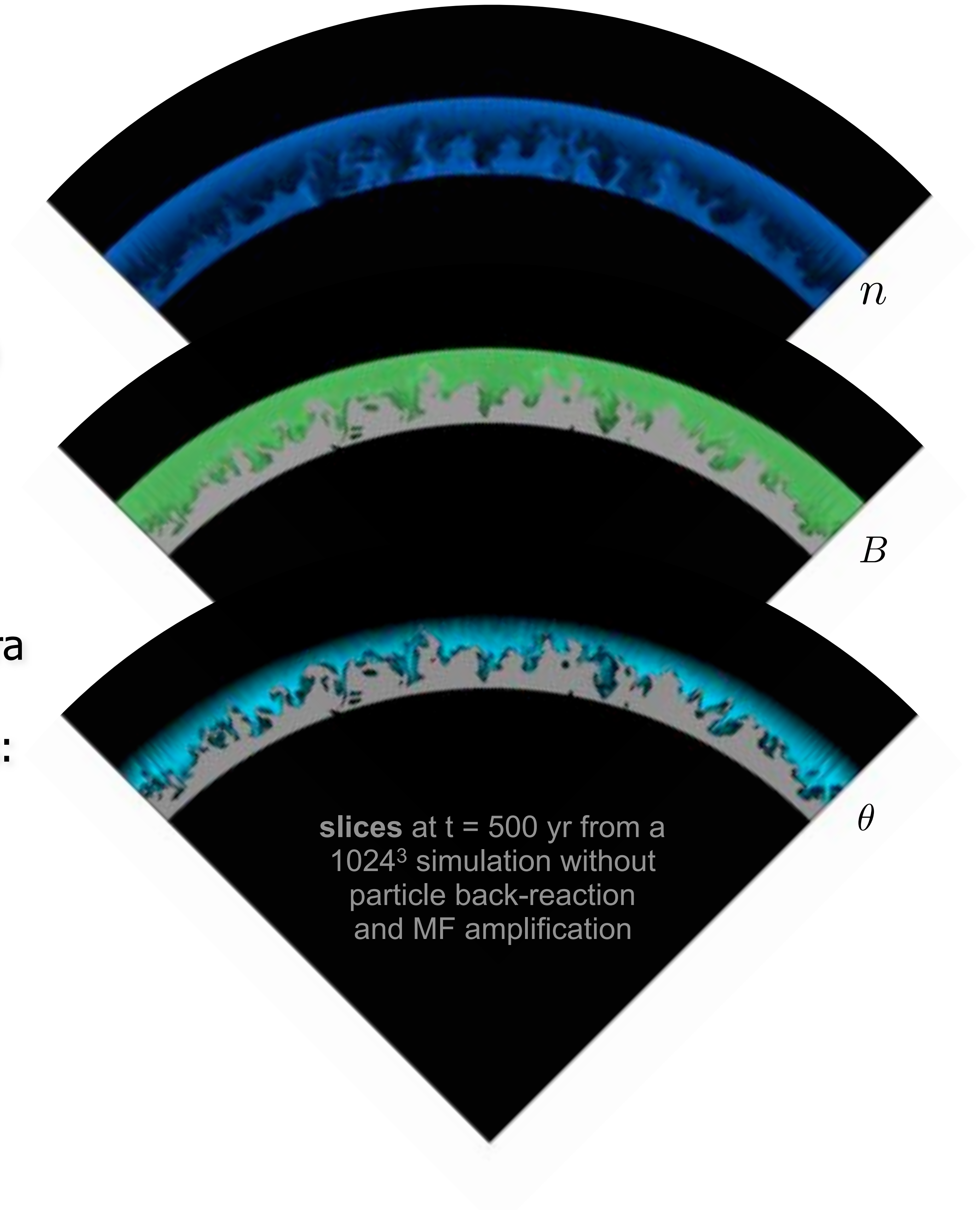


test particle vs. back-reaction

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: ambiant photon fields (CMB)

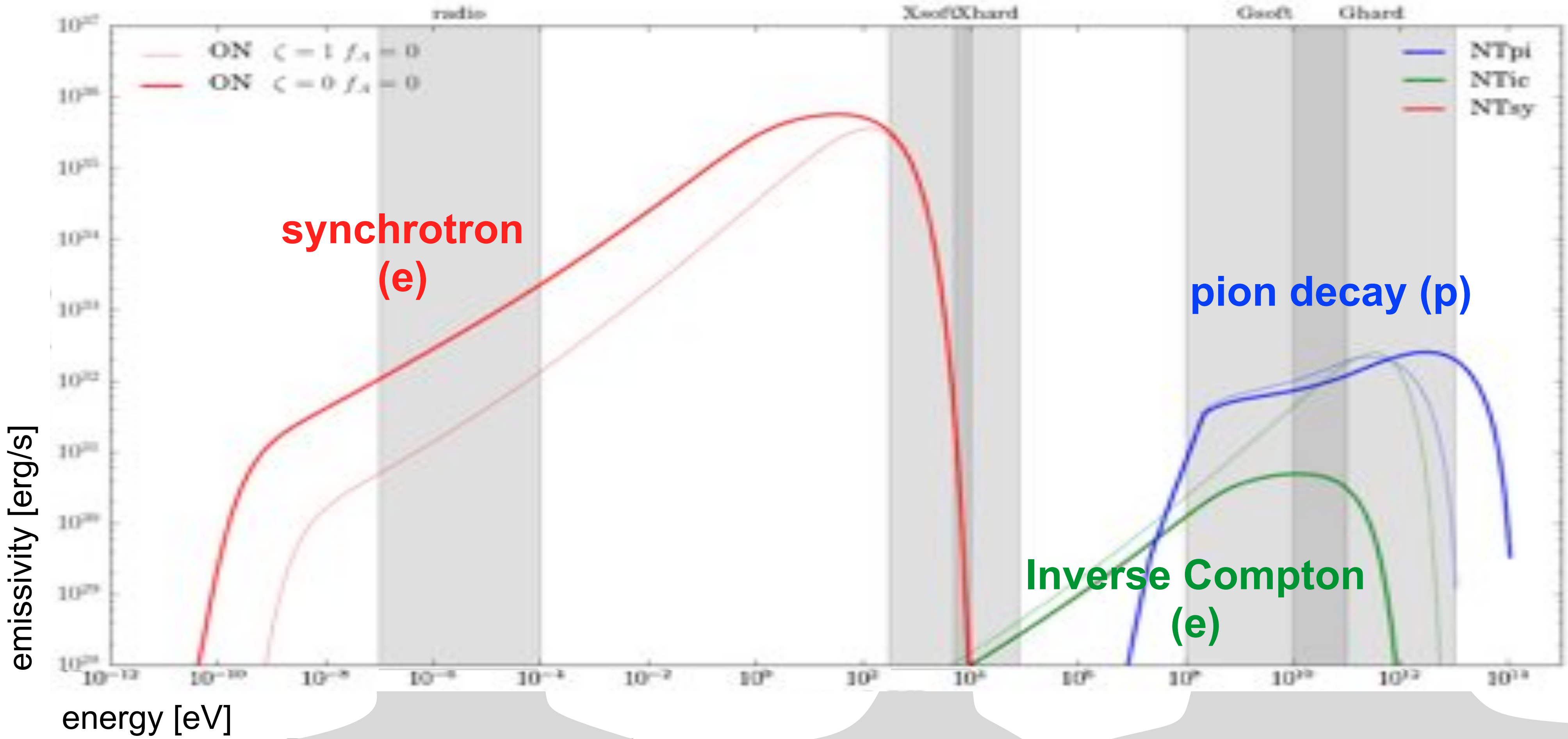


Note: the acceleration model gives the CR spectra just behind the shock $f_p(p,x,t)$, $f_e(p,x,t)$ they must be **transported** to account for losses:

- adiabatic decompression $\alpha = \dfrac{\rho(x,t)}{\rho(x_S,t_S)}$

- radiative losses $\Theta \propto \displaystyle\int_{t_S}^{t} B^2 \alpha^{\frac{1}{3}} \mathrm{d}t$

Non-thermal emission



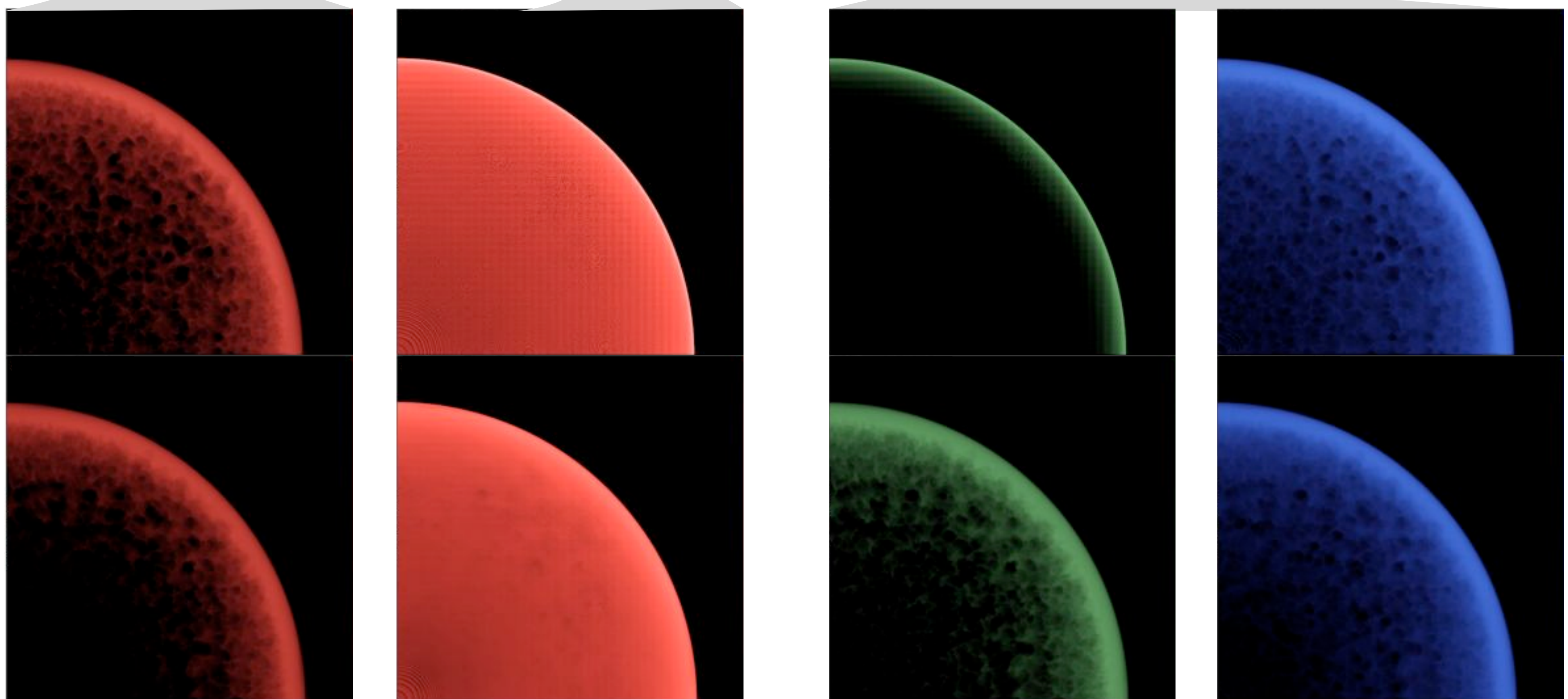
Ferrand, Decourchelle, Safi-Harb 2014 (ApJ 789 49) using the emission code from P. Edmon (depends on density and magnetic field)

1024^3 cells

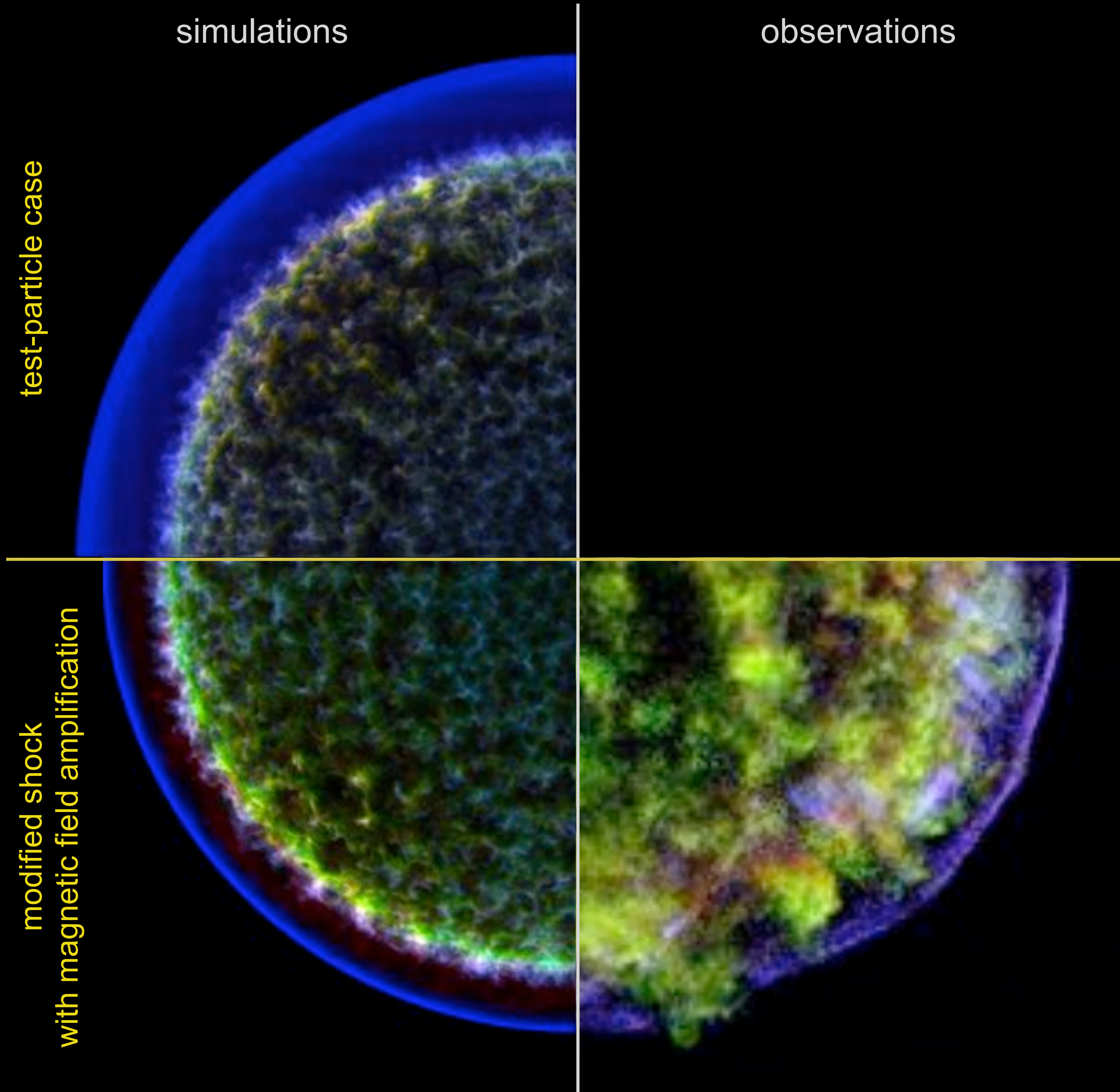
t = 500 yr

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)

Perspectives: the shock in context

- impact of the **progenitor** : | ejecta profiles (stratification, asymmetries)
  | stellar wind (for core-collapse)

- impact of the **environment** : | molecular clouds (radiative? ionized?)
  | ISM turbulence (hydro + mag)