GdR PCHE workshop
IAS, Orsay
08/06/10

3D simulations of supernova remnants evolution including non-linear particle acceleration

Irfu
cea
saclay

Gilles Ferrand (g.ferrand@cea.fr)
in collaboration with
Anne Decourchelle, Jean Ballet,
Romain Teyssier, Federico Frascetti

Contents

1) Motivation: indirect diagnostics of acceleration efficiency

- SNR radiation
- SNR structure and evolution
- observational and theoretical status

2) Method: 3D numerical simulations

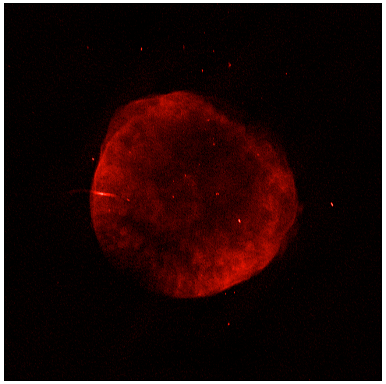
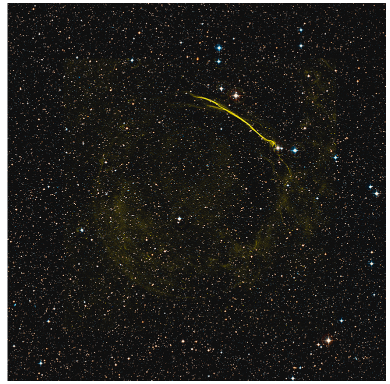
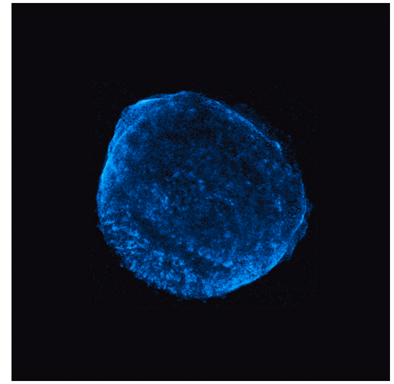
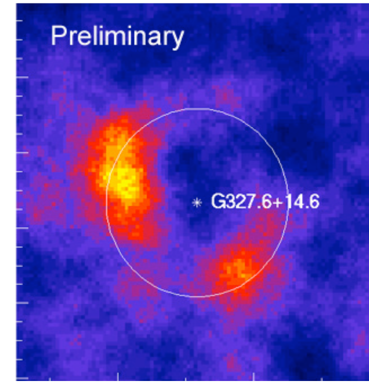
- hydro code (Ramses)
- SNR initialization (Chevalier)
- particle acceleration (Blasi)

3) First results and perspectives

- remnant evolution
- remnant morphology
- remnant environment

SNRs broad-band emission

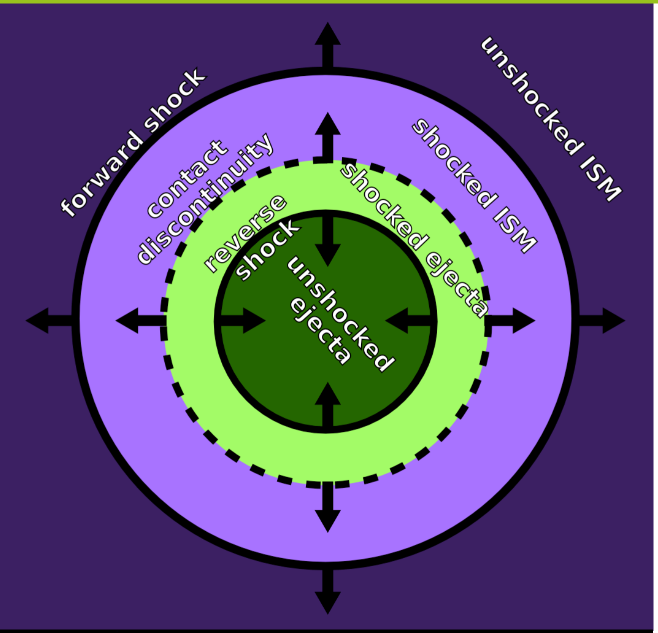
SN 1006

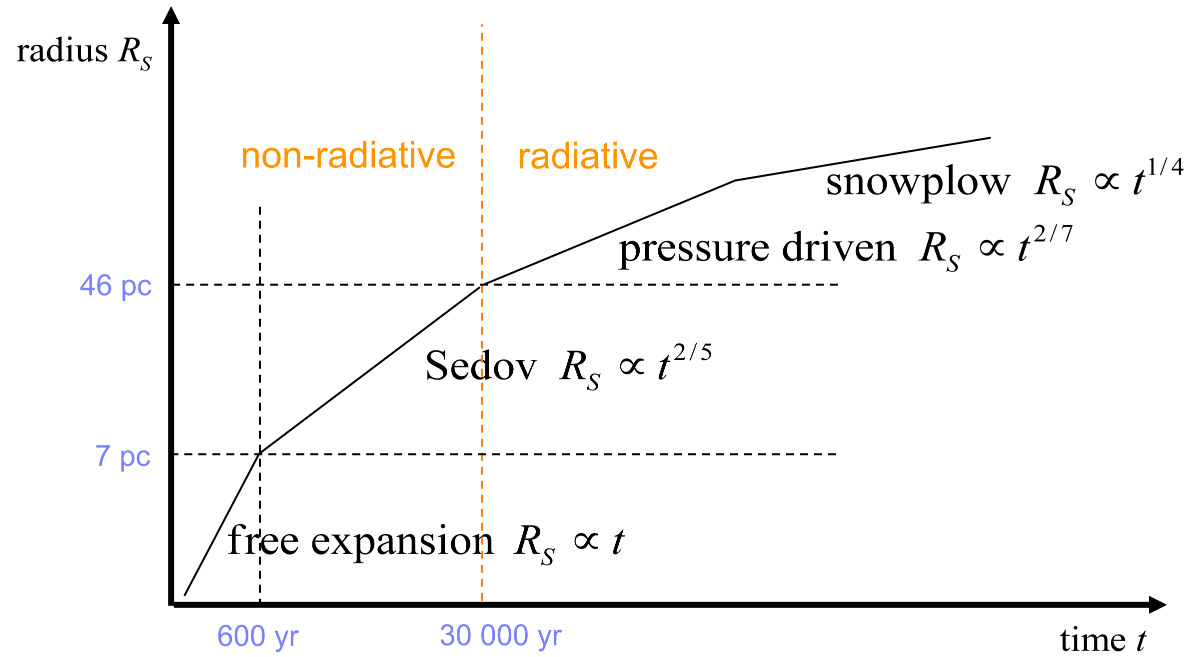
			
radio	optical	X	gamma
cm	μm	keV	TeV
synchrotron in B field	Balmer lines forbidden lines	atomic lines of heavy elements + synchrotron	Inverse Compton ? pion decay ?
↑	↑	↑	↑
GeV e-	blast wave	hot int. plasma + TeV e-	> TeV e- ? > TeV p+ ?
		[Casam-Chenaï et al 2008 (Chandra)]	[de Naurois et al 2008 (HESS)]

E →

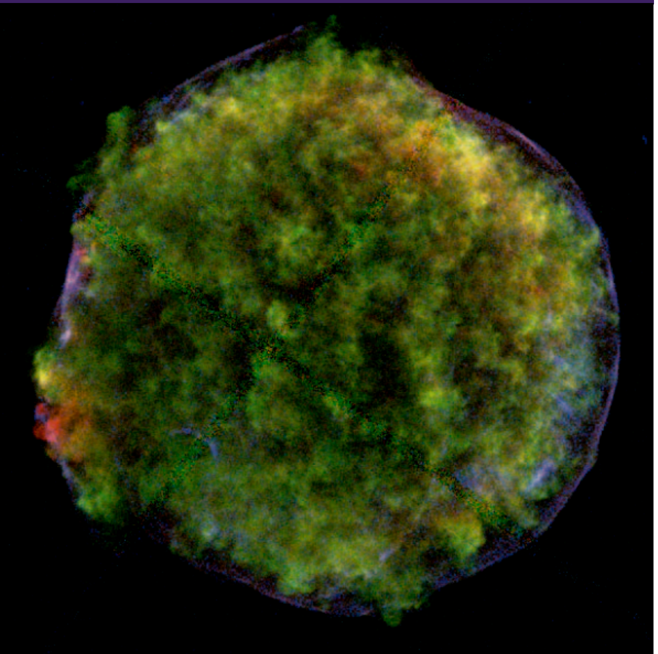
← λ

Remnant structure and evolution





values given for 1.4 solar masses of ejecta with kinetic energy of 10^{51} erg, expanding in a medium of density 0.1 cm^{-3}



Tycho seen by Chandra

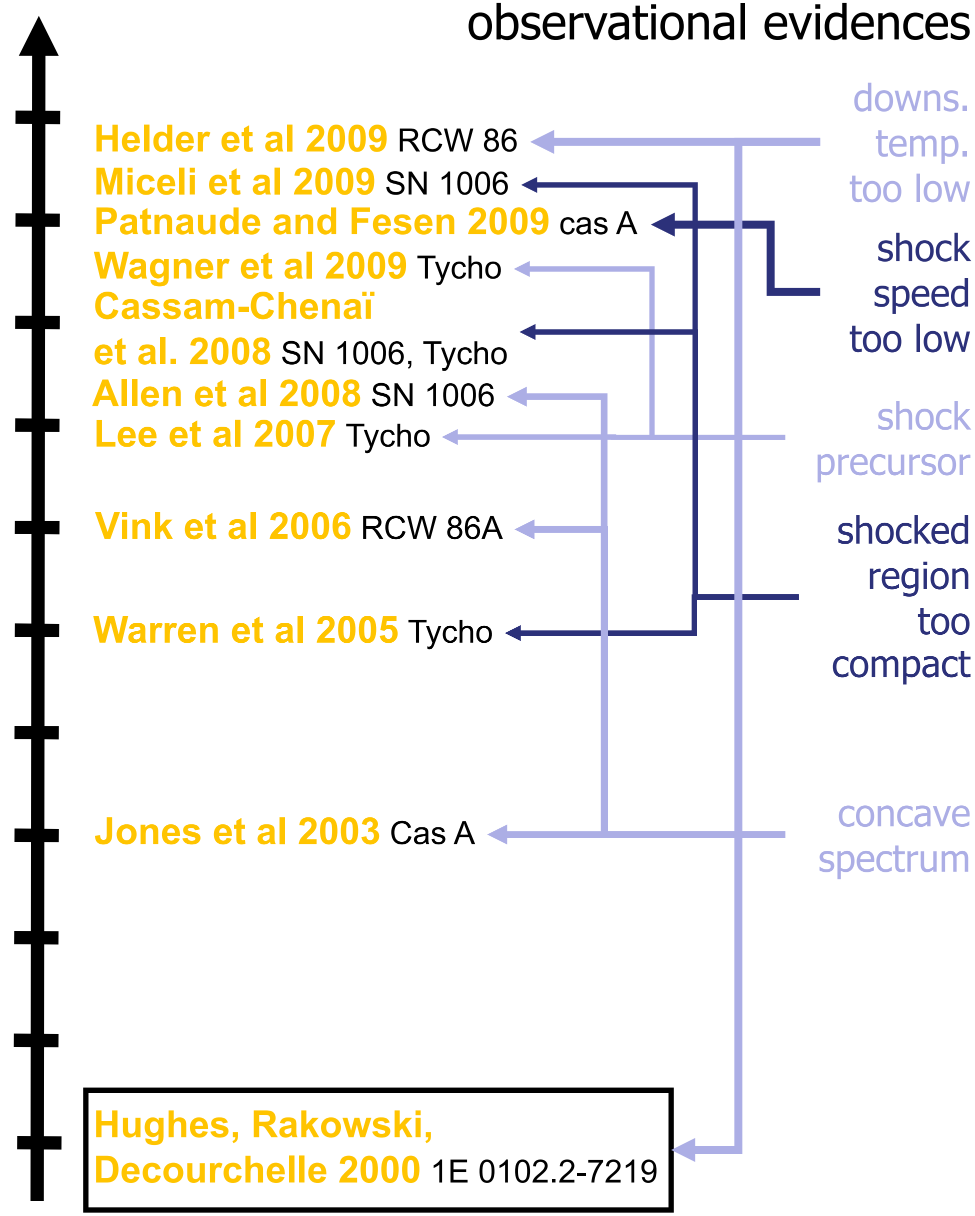
(age 438 yr)

Warren et al 2005

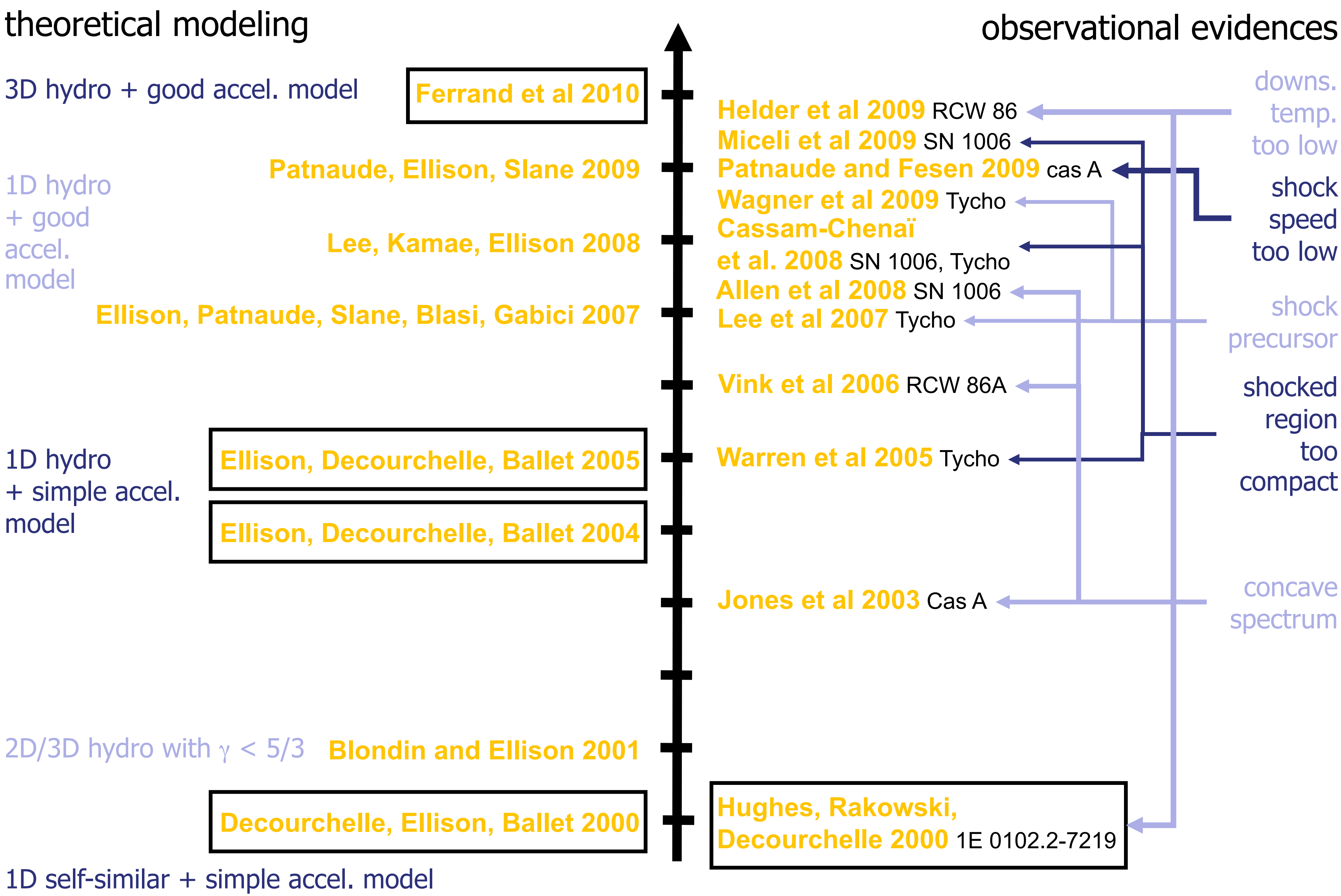
0.95 – 1.26 keV
1.63 – 2.26 keV
4.10 – 6.10 keV

1.3 Probing back-reaction of particles on the shock

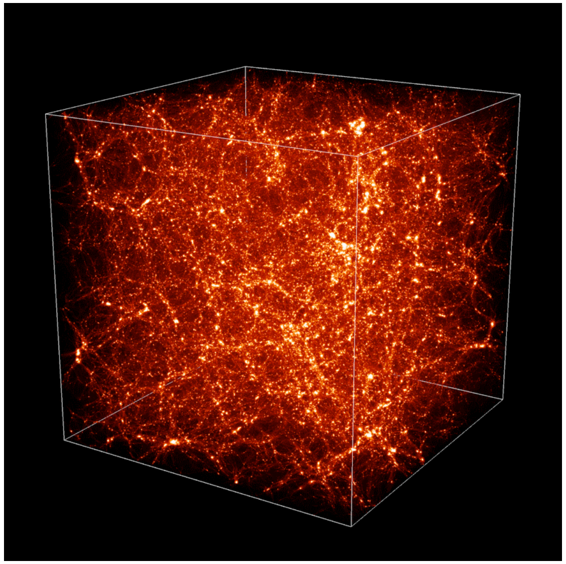
observational evidences



1.3 Probing back-reaction of particles on the shock



The hydrodynamical code RAMSES



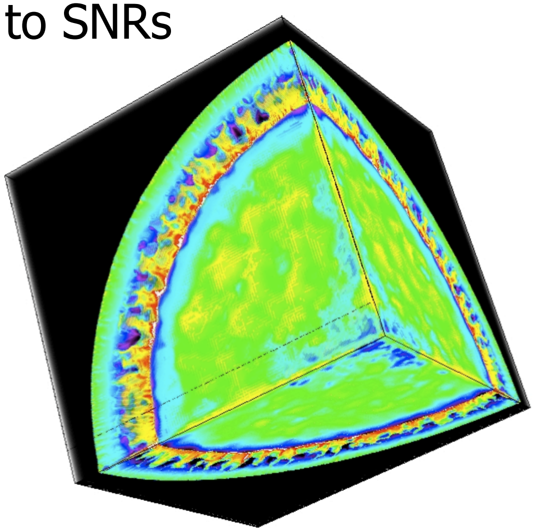
from large scale structures…

Existing code, developed for cosmological simulations
Includes hydrodynamics / MHD + particles

- **Godunov** scheme (MUSCL)
- **Adaptive Mesh Refinement** (tree-based)
- **parallelized** (MPI)

Teyssier 2002; Fromang, Hennebelle, Teyssier 2006

… to SNRs



Adapting to SNRs: **comoving grid**
= work in the expanding frame

BUT:
- non-inertial frame → additional force
- quasi-stationnary flow → numerical difficulties

Fraschetti et al 2010 (accepted)

SNR initialization

if power-law density profiles

$$\rho_{ej} \propto t^{-3} \left(\frac{r}{t}\right)^{-n} \qquad \rho_{ISM} \propto r^{-s}$$

then **self-similar** evolution (→ ODE)

$$r_{CD} \propto t^{\lambda} \quad \text{with} \quad \lambda = \frac{n-3}{n-s}$$

Chevalier 1982

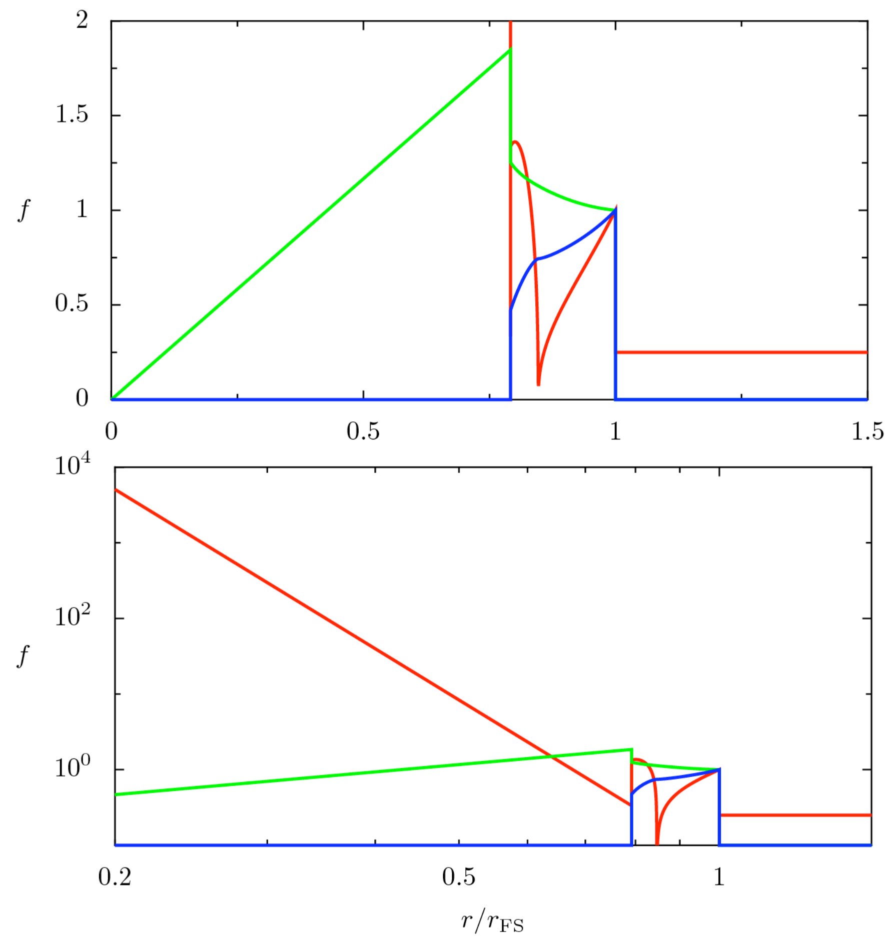
+ seed energetic particles pressure

Chevalier 1983

parameters: **Tycho**-like (SN Ia)

$t_{SN} = 437$ years
$E_{SN} = 10^{51}$ erg
$n = 7\,,\ M_{ej} = 1.4\,M_{\odot}$
$s = 0\,,\ n_{H,ISM} = 0.1\ cm^{-3}$

f = density, radial velocity, pressure



The acceleration model

shock speed, ambient density and pressure

magnetic field, diffusion coefficient

injection recipe:
- $p_{\rm inj} = \xi \, p_{\rm th,2}$
- fraction η

cutoff recipe:
$p_{\rm max}$ limited by age and size

semi-analytical **non-linear** model
solves the coupled system $f(p) - U(p)$

Blasi 2002; Blasi 2004; Blasi, Gabici, Vannoni 2005

+ recipes for B amplification and back-reaction

Amato & Blasi 2006; Caprioli et al 2008, 2009

back-reaction parameters:
- compression ratios (total, sub, precursor)
- pressure in gaz and in energetic particles
- magnetic turbulence
- escaping particles

The acceleration model

shock speed, ambient density and pressure

magnetic field, diffusion coefficient

injection recipe:
- $p_{\mathrm{inj}} = \xi\, p_{\mathrm{th},2}$
- fraction η

cutoff recipe:
$p_{\max}$ limited by age and size

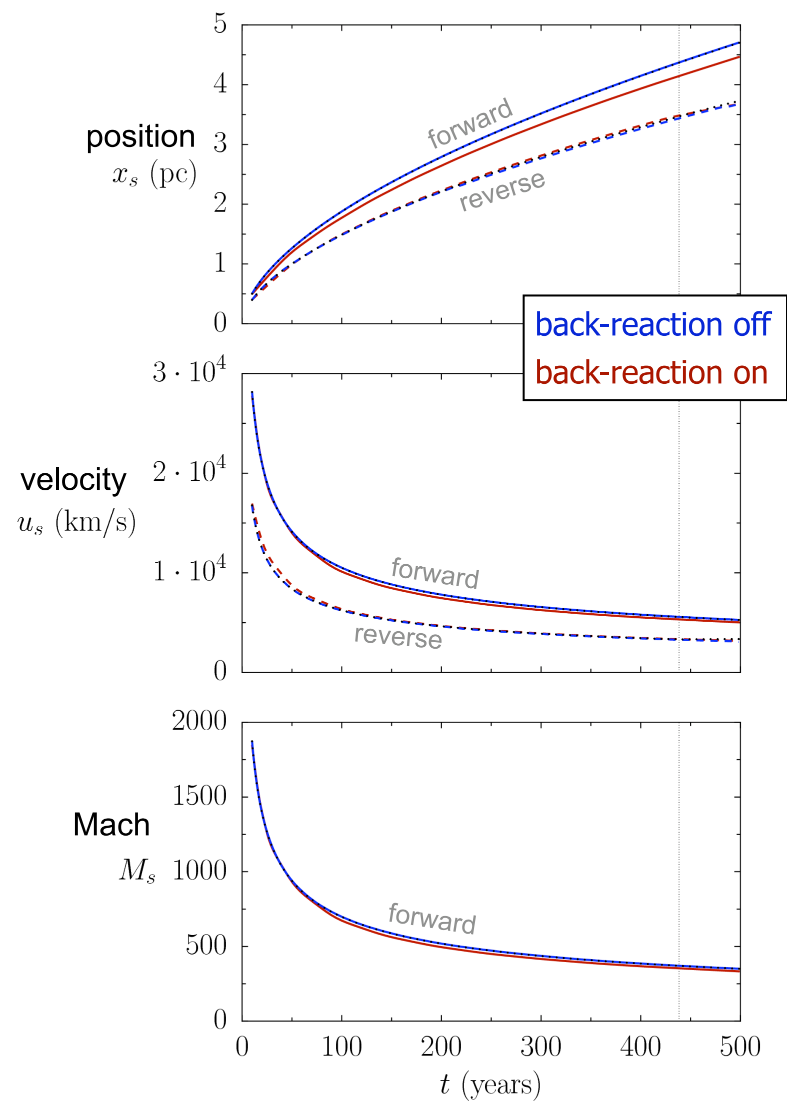
semi-analytical **non-linear** model
solves the coupled system $f(p)\ -\ U(p)$

Blasi 2002; Blasi 2004; Blasi, Gabici, Vannoni 2005

+ recipes for B amplification and back-reaction

Amato & Blasi 2006; Caprioli et al 2008, 2009

back-reaction parameters:
- compression ratios (total, sub, precursor)
- pressure in gaz and in energetic particles
- magnetic turbulence
- escaping particles

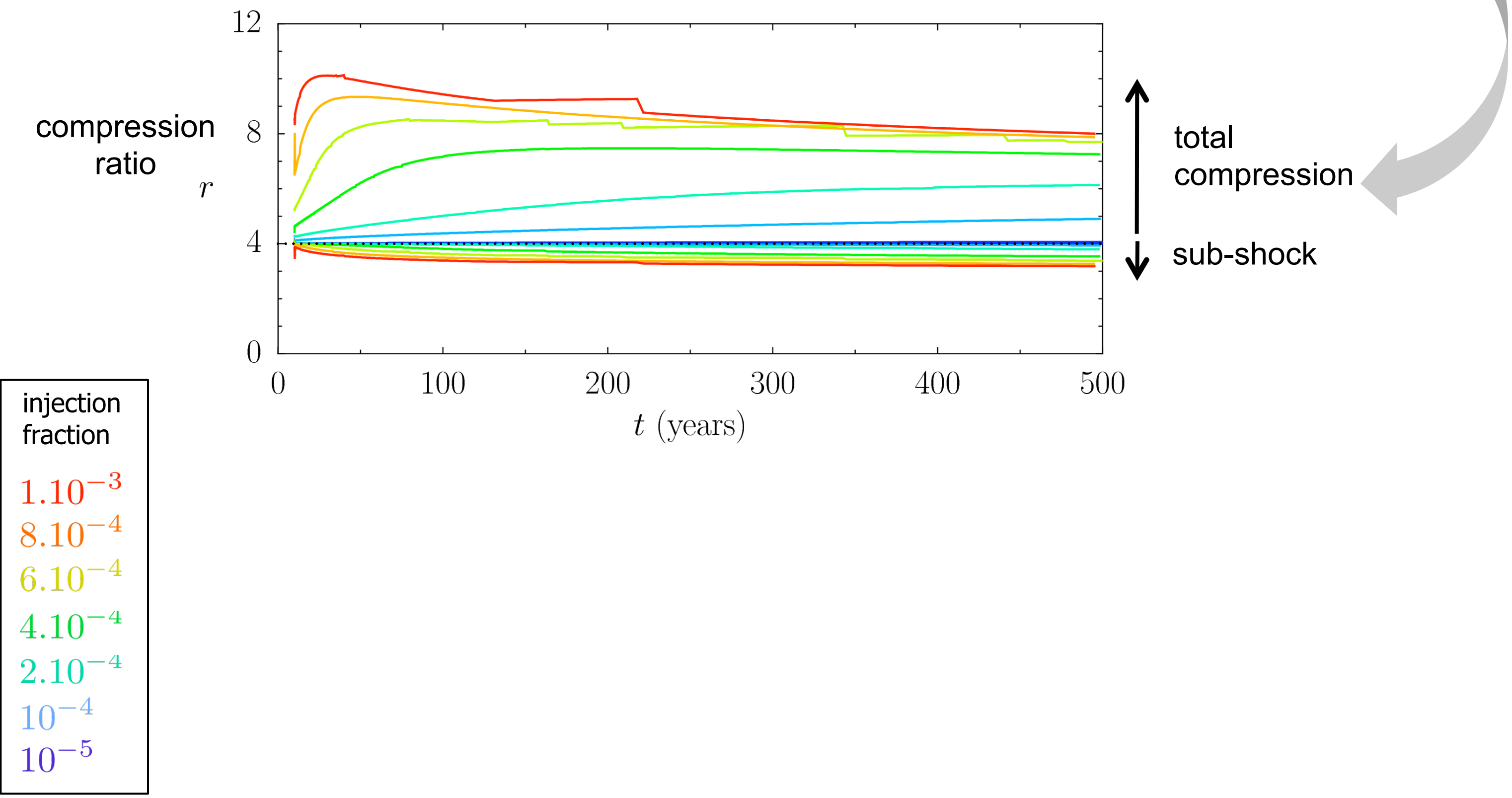


shocks diagnostics on average profiles

theory: Truelove and McKee 1999

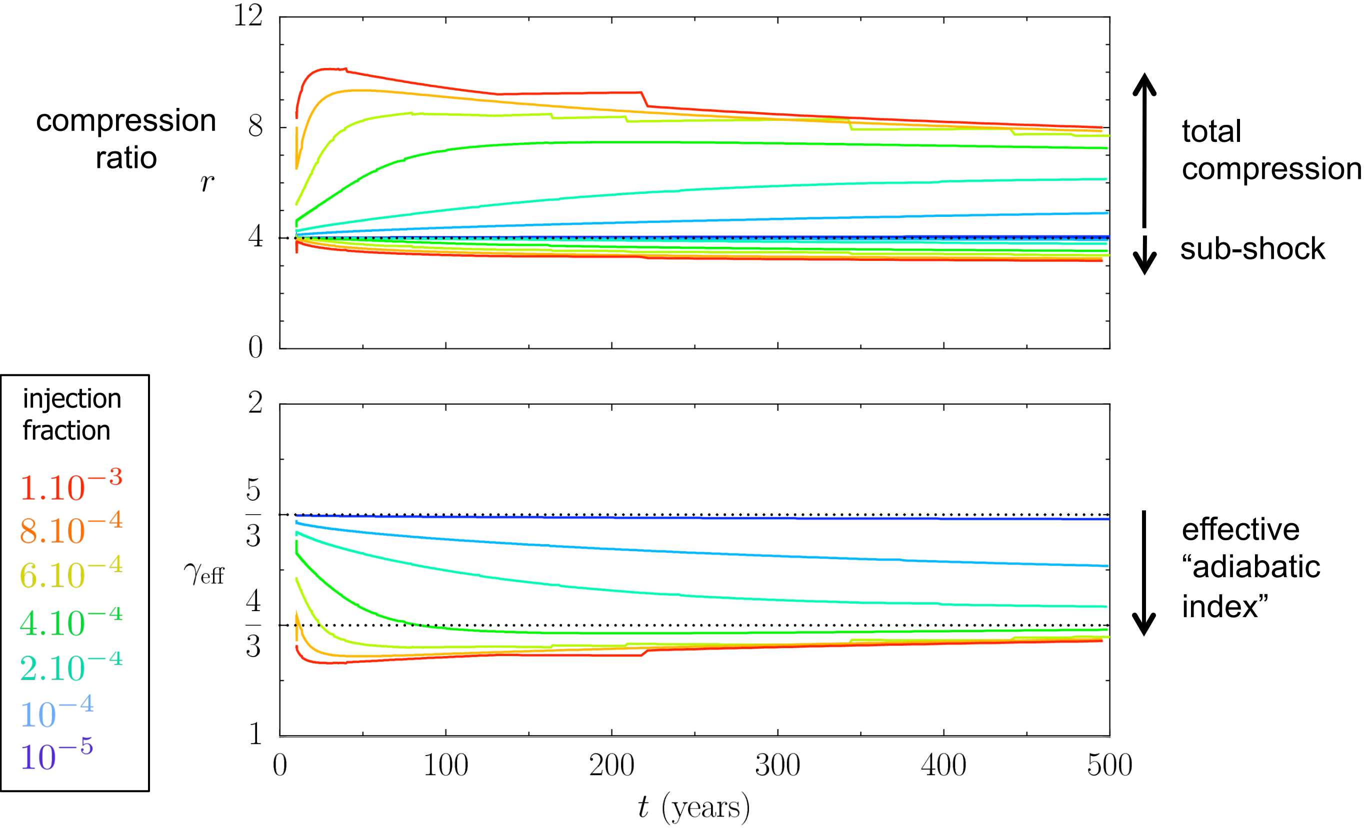
Results: remnant evolution

acceleration model



Ferrand et al 2010

Results: remnant evolution



acceleration model

simple coupling method:

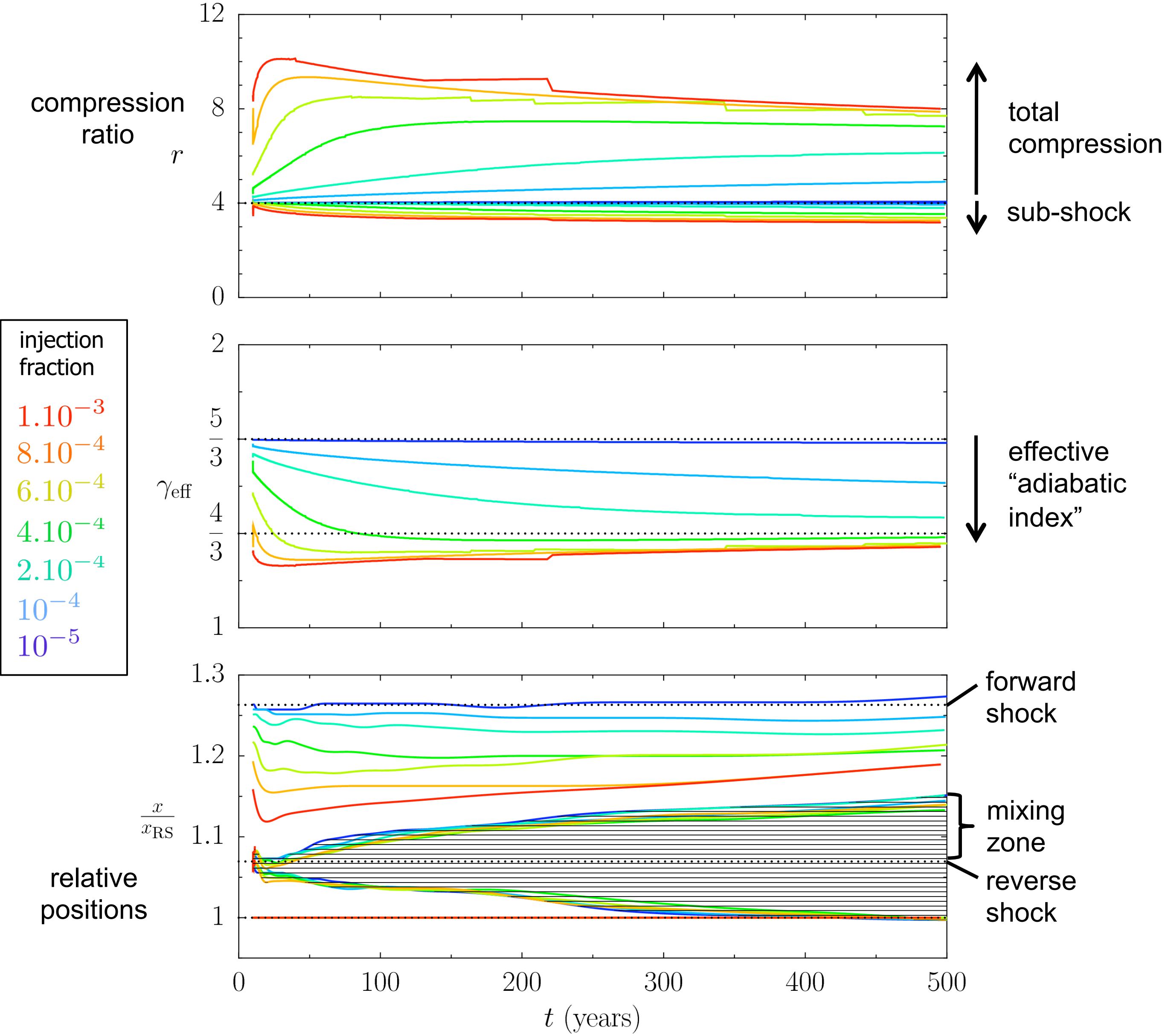
$$r_{\rm tot} \longrightarrow \gamma_{\rm eff}$$

(at the shock front only, time-dependent)

Ferrand et al 2010

3.1

Results: remnant evolution



acceleration model

simple coupling method:

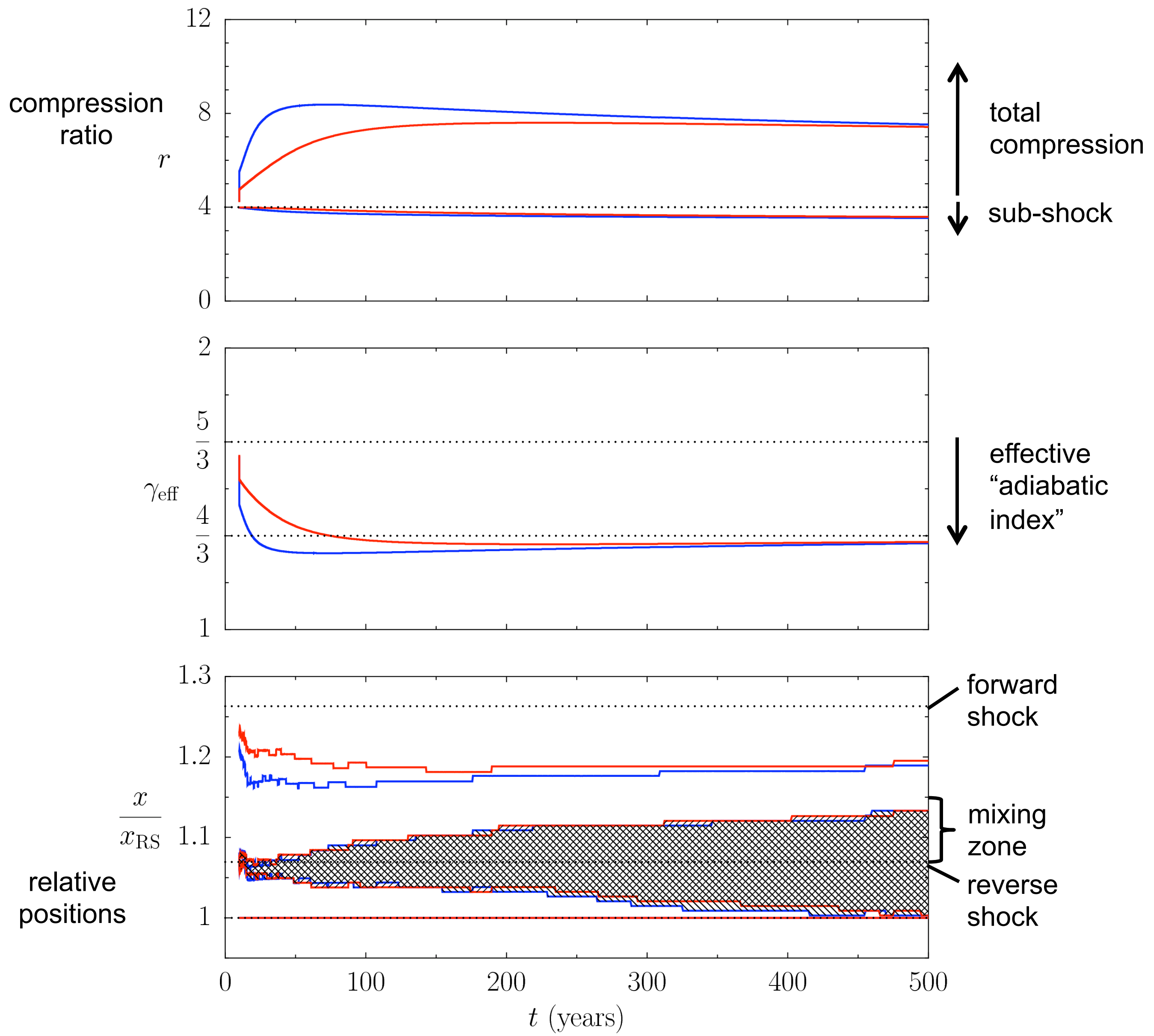
$r_{\text{tot}} \longrightarrow \gamma_{\text{eff}}$

(at the shock front only, time-dependent)

shocked region shrinks
→ possible diagnostic of acceleration efficiency, taking into account hydro instabilities

Ferrand et al 2010

Magnetic turbulence back-reaction

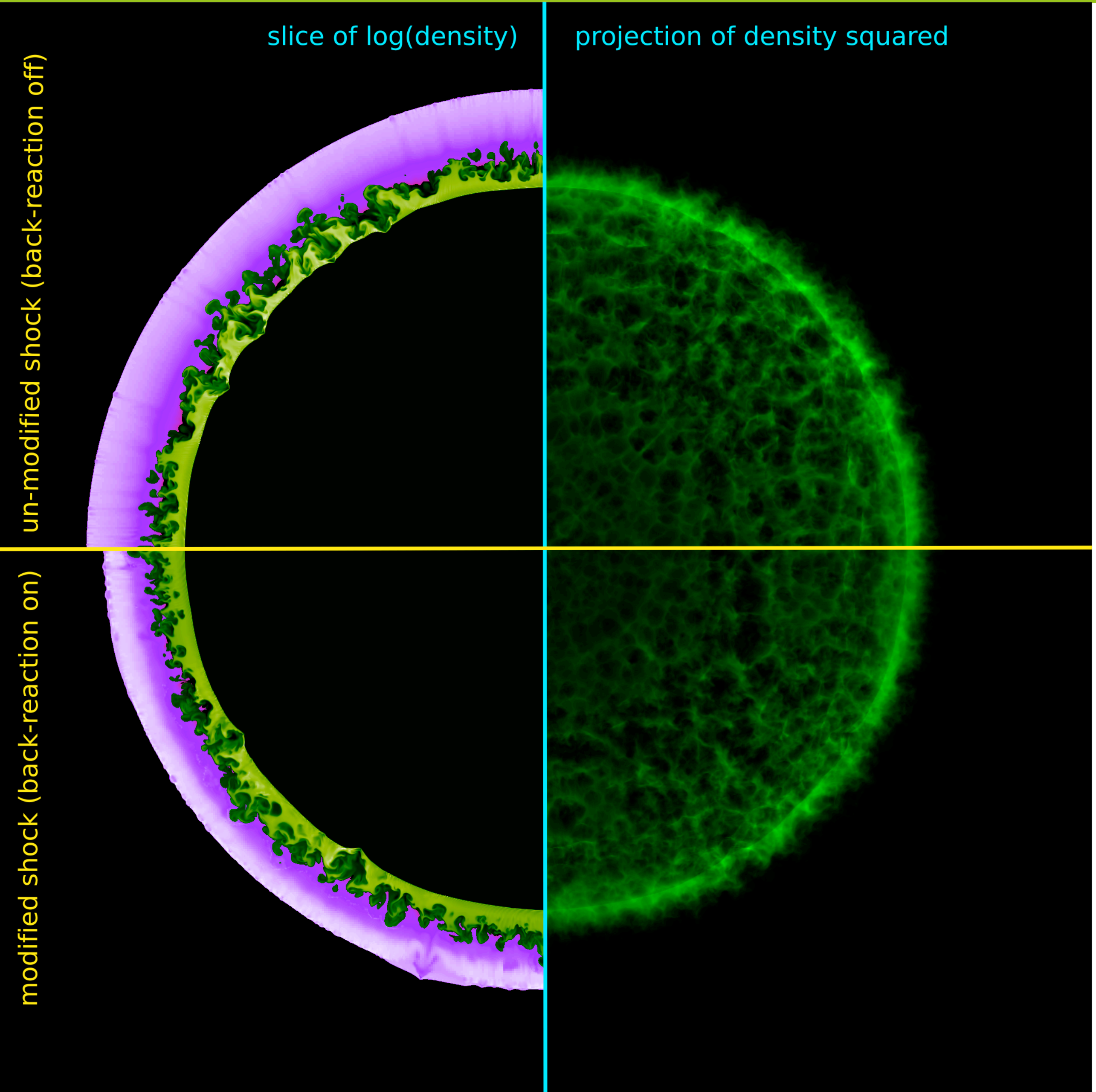


B limits the CR back-reaction, through either

- heating in the precursor (waves damping)
- magnetized subshock

PRELIMINARY

Results: remnant morphology



slices and projected maps from a 1024^3 simulation at t = 500 years
- color codes phases: ejecta vs. ambient
- injection of particles is here self-regulated

Regarding the case of Tycho's remnant, a first comparison of our simulations with X-ray observations (**Warren et al 2005**) strengthens the case for efficient acceleration of protons at the forward shock and unefficient acceleration at the reverse shock.

Ferrand et al 2010

Perspectives

short term

- thermal + non-thermal multi-lambda emission
- multi-fluid treatment

→ realistic SNR maps, to be compared with observations of Chandra / XMM / Suzaku, Fermi, HESS…

Anne Decourchelle, Jean Ballet, Gilles Maurin

- MHD version of ramses (instabilities)

- impact of the environment (winds, clouds, …)
- feedback on the environment (ISM turbulence…)

Edouard Audit, Patrick Hennebelle, Alexandre Marcowith

longer term