"Supernova Remnants and Pulsar Wind Nebulae in the Chandra Era"
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3D simulations of supernova remnants evolution with particle acceleration

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and Anne Decourchelle
in collaboration with Romain Teyssier

Contents

1) Motivation: the shocked region

- is modified by instabilities
- is modified by acceleration

2) Method: 3D numerical simulations

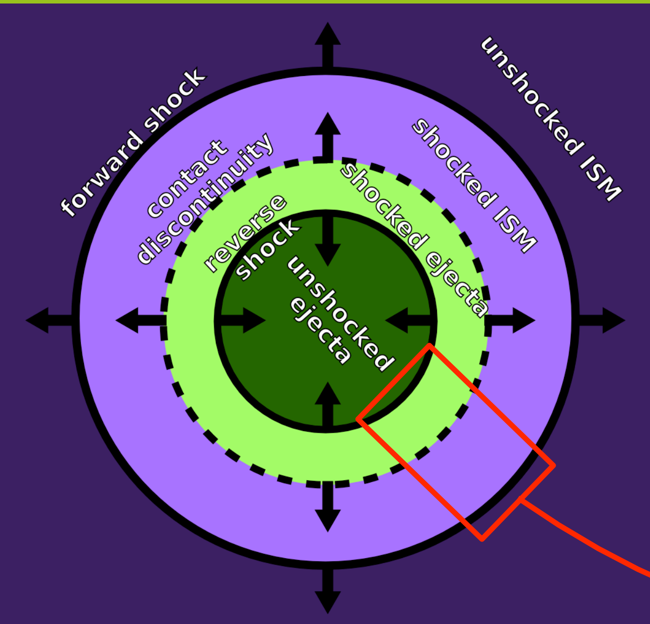
with the code `ramses`

- SNR initialization
- particle acceleration

3) First results and perspectives

- effective adiabatic index
- multi-fluid approach

1.1 Shock structure: Rayleigh-Taylor instabilities

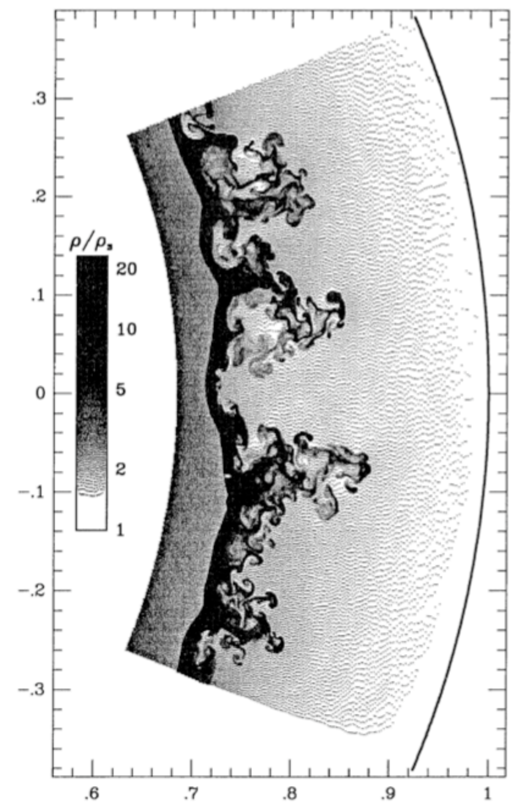


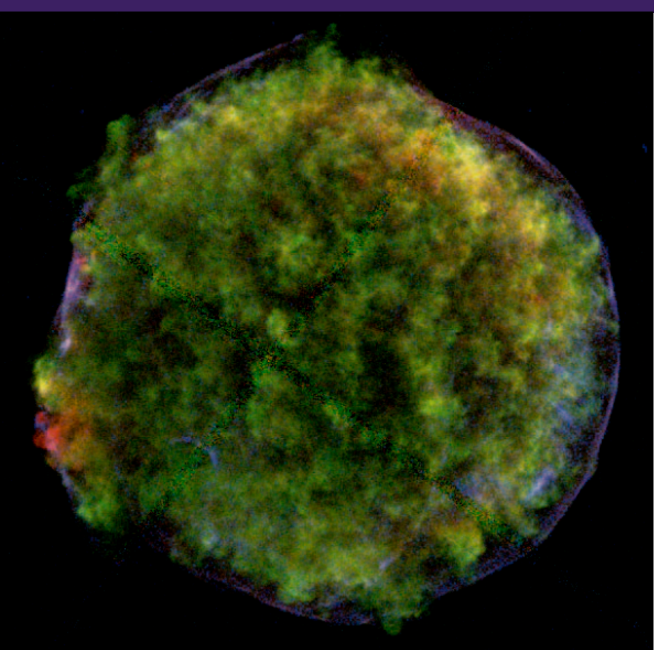
one SNR consists of **3 waves**:

- forward shock
- contact discontinuity
- reverse shock

the contact discontinuity is subject to the **Rayleigh-Taylor** instability
→ need for ≥ 2D modeling

Chevalier, Blondin, Emmering 1992





Tycho seen by **Chandra**

Warren et al 2005

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

Rayleigh-Taylor analysis in radio:

Velazquez et al 1998

Dwarkadas 2000

Wang and Chevalier 2001

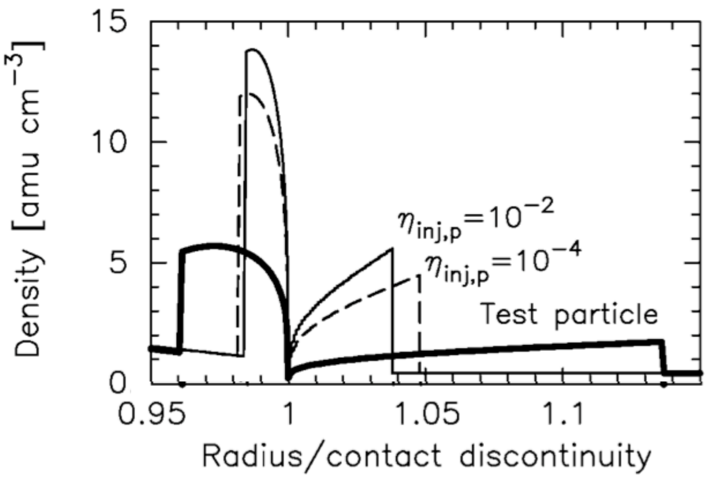
Shock structure: efficient acceleration

observed positions of the waves do not match pure hydrodynamical models in **Tycho** and SN 1006 **Warren et al 2005, Cassam-Chenaï et al. 2008, Miceli et al 2009**

→ evidence for **back-reaction** of accelerated particles on the shock

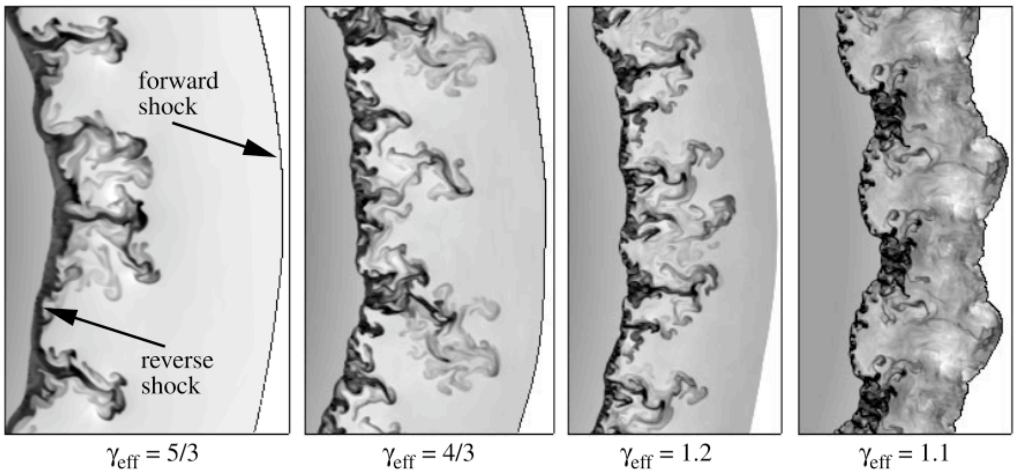
(investigation of the back-reaction in Cas A: **Patnaude et al. 2009**)

1D self-similar simulations with acceleration model (of **Berezhko and Ellison 1999**)



Decourchelle, Ellison, Ballet 2000

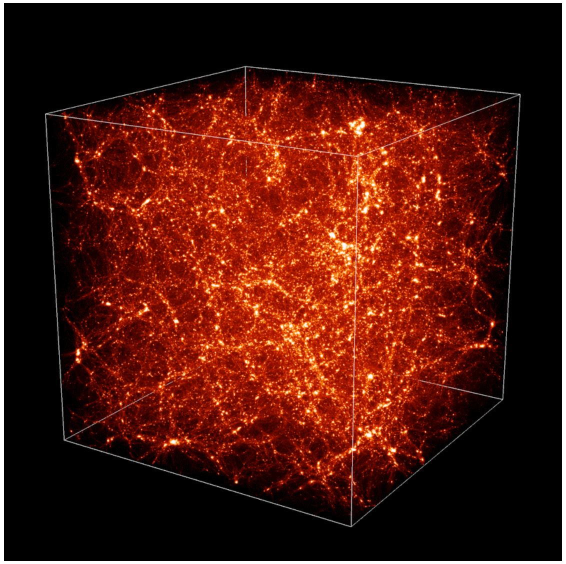
2D/3D hydro simulations (of a slice) mimicking acceleration (by varying gamma of the fluid)



Blondin and Ellison 2001

our aim = make full 3D simulations (1/8 of a sphere) of SNR evolution with space- and time- dependent acceleration and back-reaction

2.1 Numerical simulations: the code `ramses`



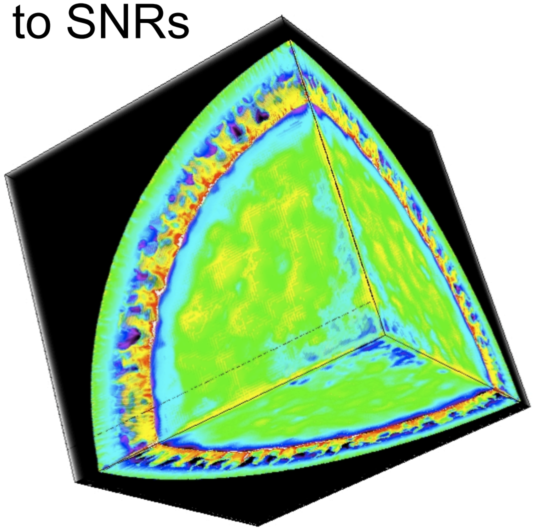
from large scale structures…

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 2009 (submitted)

Numerical simulations: SNR initialization

if power-law density profiles

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

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

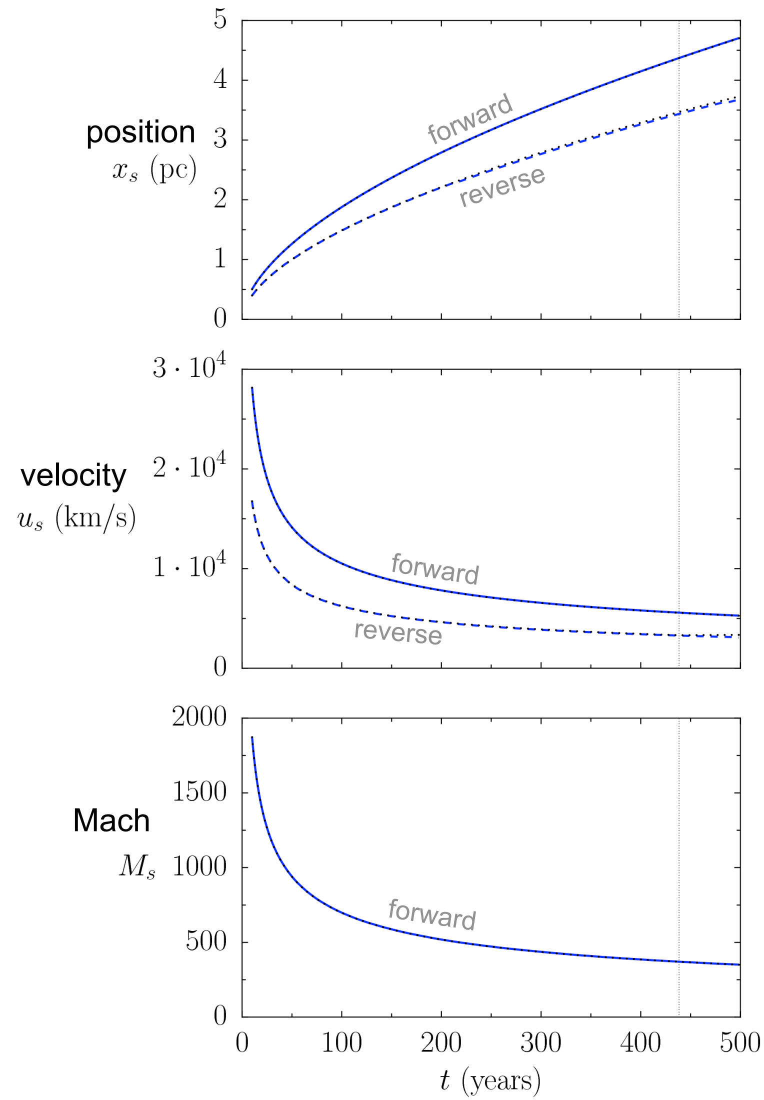
$$r_{\rm CD} \propto t^{\lambda} \quad \text{with} \quad \lambda = \frac{n-3}{n-s}$$

Chevalier 1982

parameters: **Tycho**-like (SN Ia)	$t_{\rm SN} = 437$ years $E_{\rm SN} = 10^{51}$ erg $n = 7\,,\ M_{\rm ej} = 1.4\,{\rm M}_\odot$ $s = 0\,,\ n_{\rm H,ISM} = 0.1\,{\rm cm}^{-3}$

+ seed energetic particles pressure

Chevalier 1983



shocks diagnostics on average profiles

theory: Truelove and McKee 1999

Numerical simulations: particle acceleration

shock speed, ambient density and pressure

magnetic field, diffusion coefficient

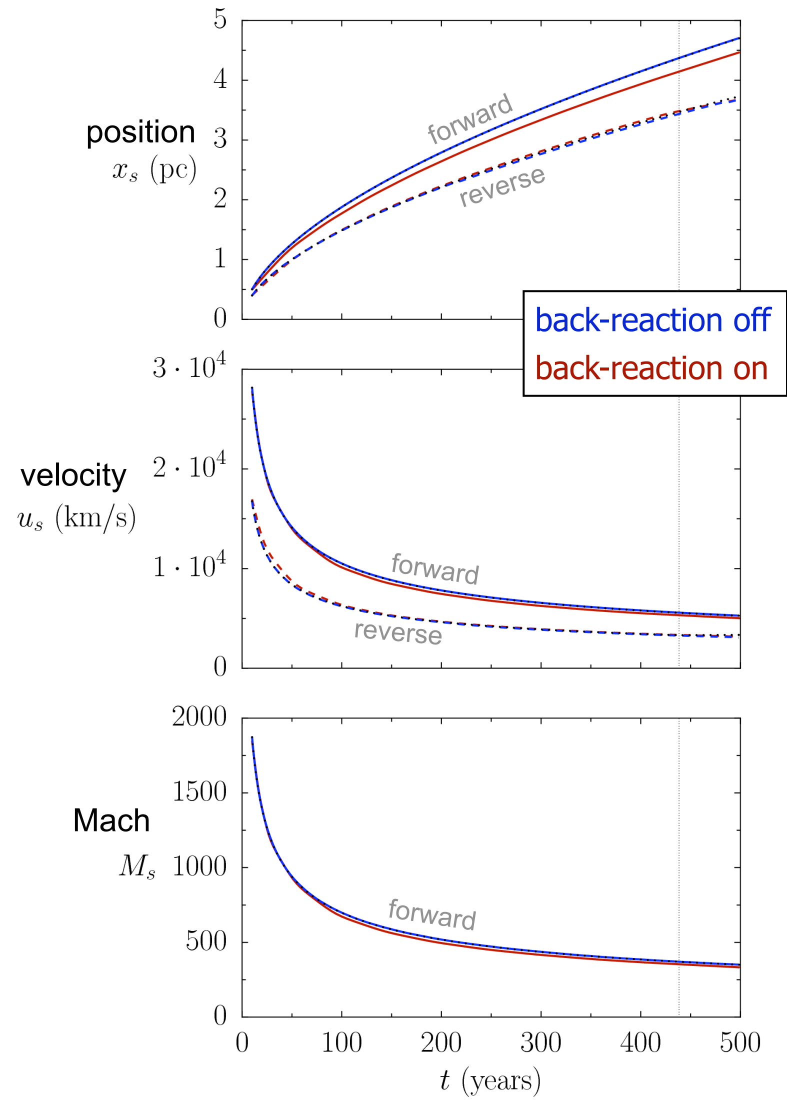
injection recipe:
- $p_{\rm inj} = \xi \; p_{\rm th,2}$
- fraction η

cutoff recipe:
$p_{\max}$ 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

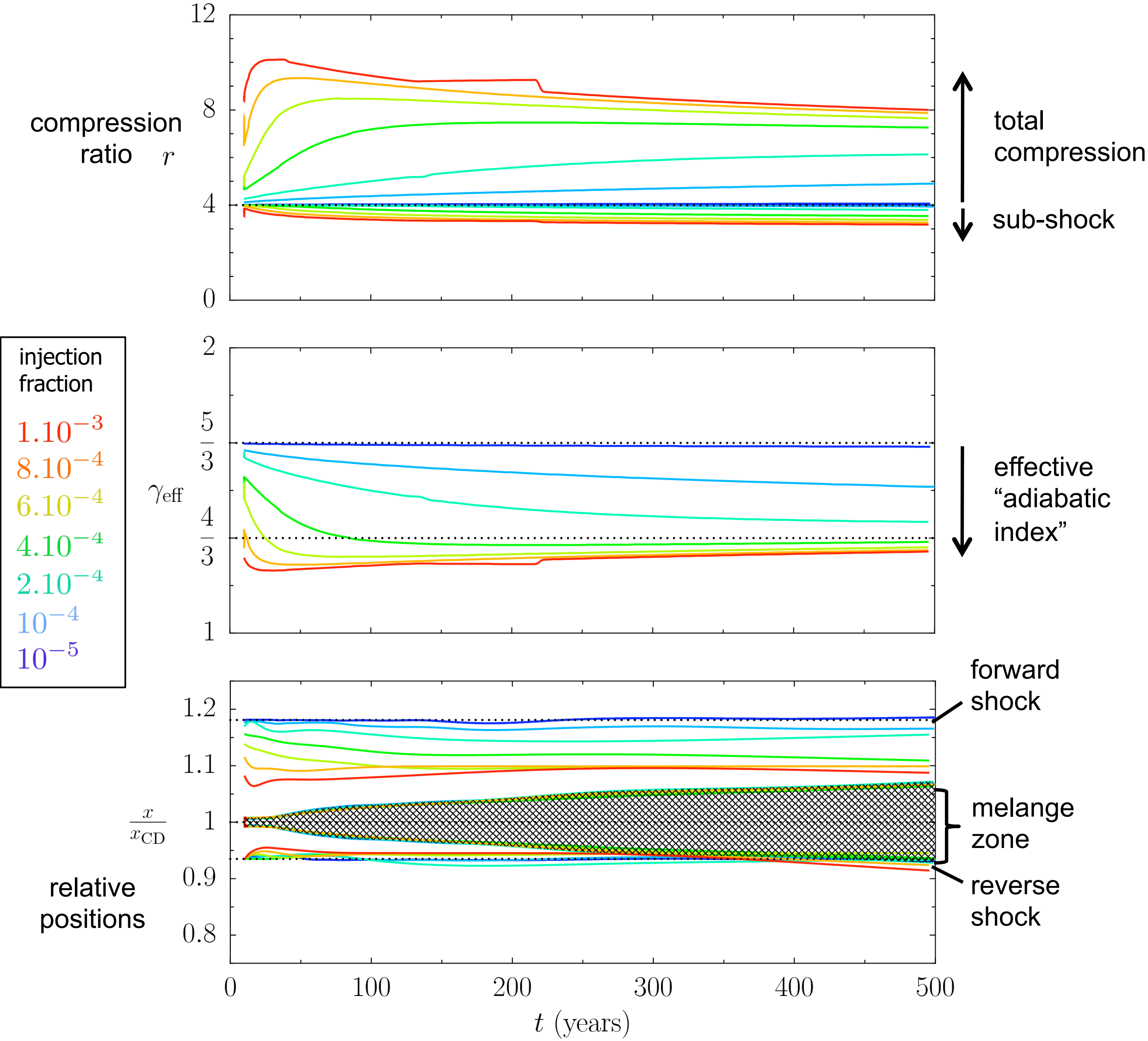
back-reaction parameters:
- compression ratios (total, sub, precursor)
- pressure in gaz and in energetic particles
- escaping energy flux



shocks diagnostics on average profiles

theory: **Truelove and McKee 1999**

First results with effective gamma



acceleration model

simple coupling method:

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

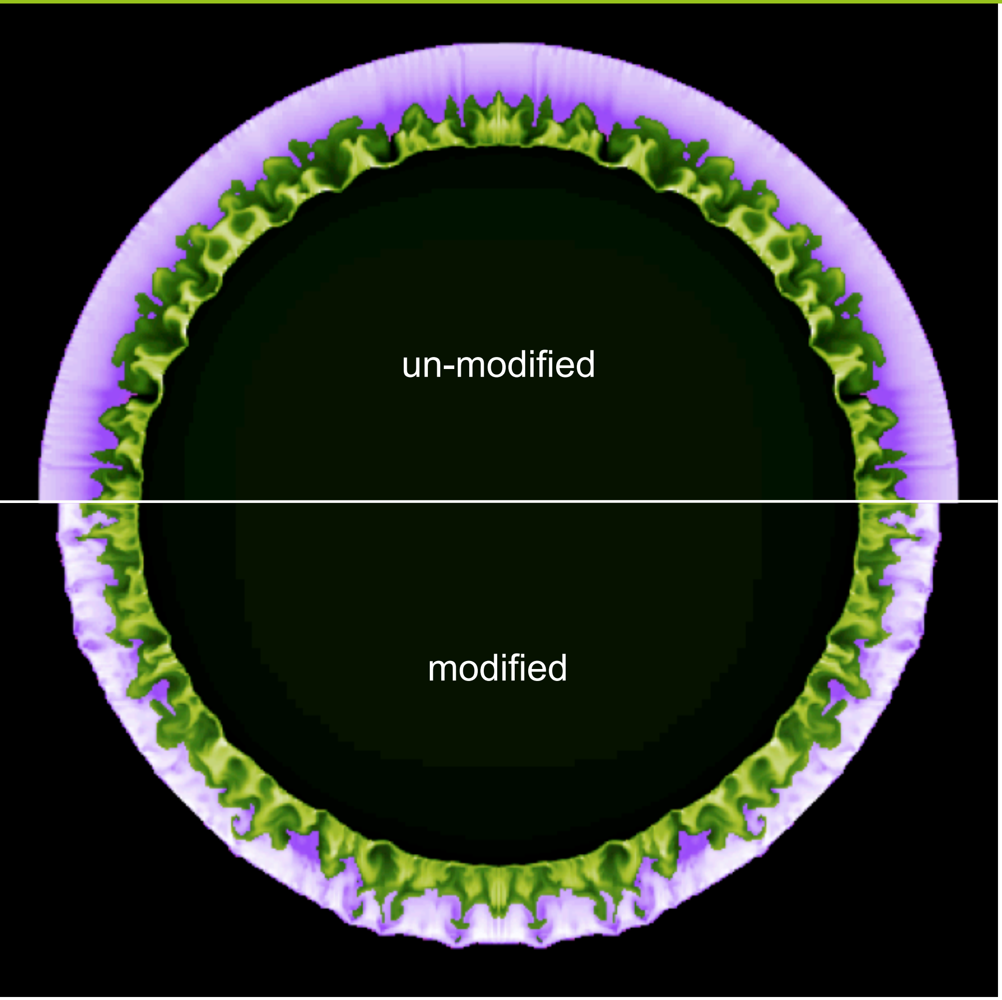
(at the shock front only, time-dependent)

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

Ferrand et al 2009 (in prep)

3.2

Perspectives: multi-fluid approach



2D slice of the density profile from a 256^3 simulation at t = 500 years

luminosity proportional to log(density)
color codes phases: ejecta / ambient

Summary:

- SNR initialization: `Chevalier` self-similar profiles
- SNR evolution: `ramses` 3D hydro code
- particle acceleration: `Blasi` non-linear model
- particle back-reaction: varying gamma

Next step:

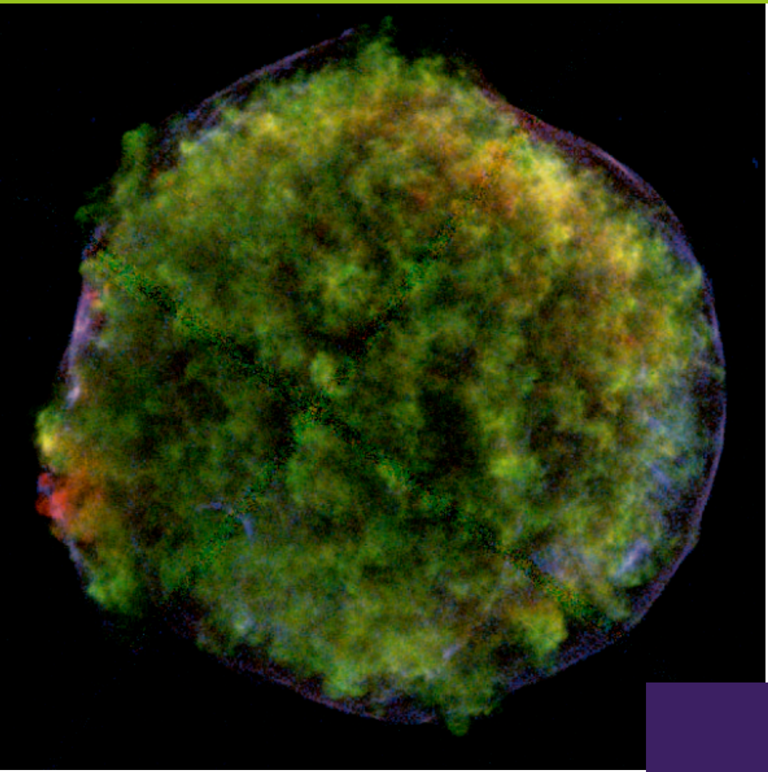
- multi-fluid: thermal fluid and non-thermal p+ / e-
- multi-lambda (projected) emission

  → realistic SNR maps

to compare with observations of eg. Chandra

The remnant structure

A1



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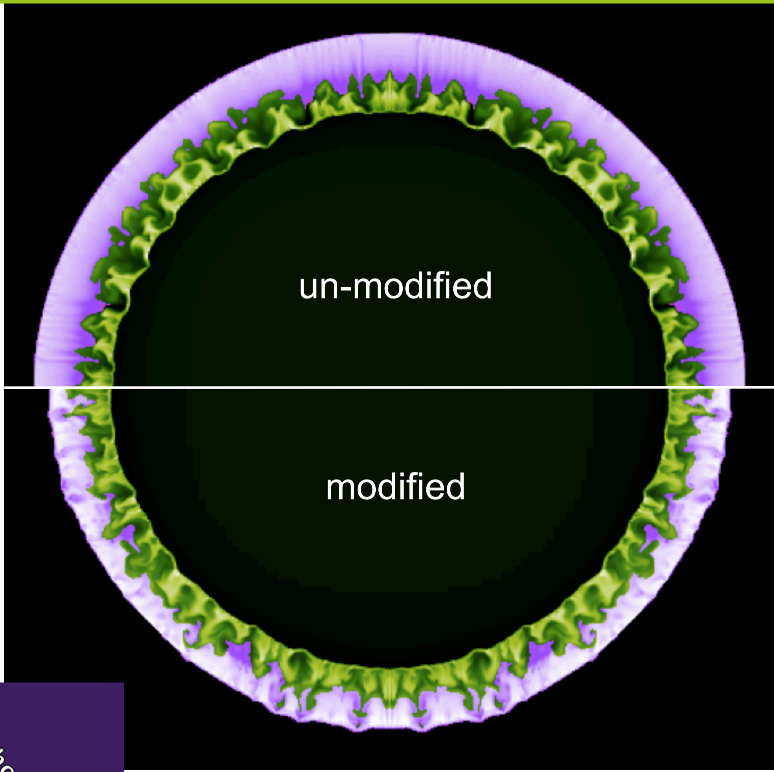

Tycho
seen by
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Warren et al 2005

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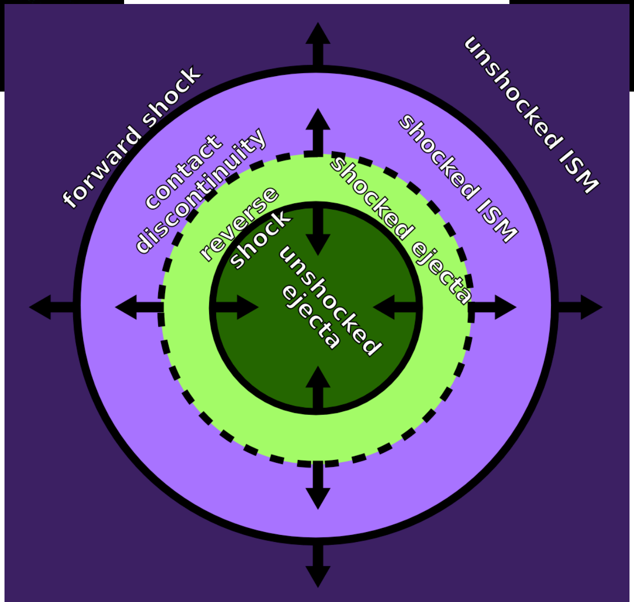
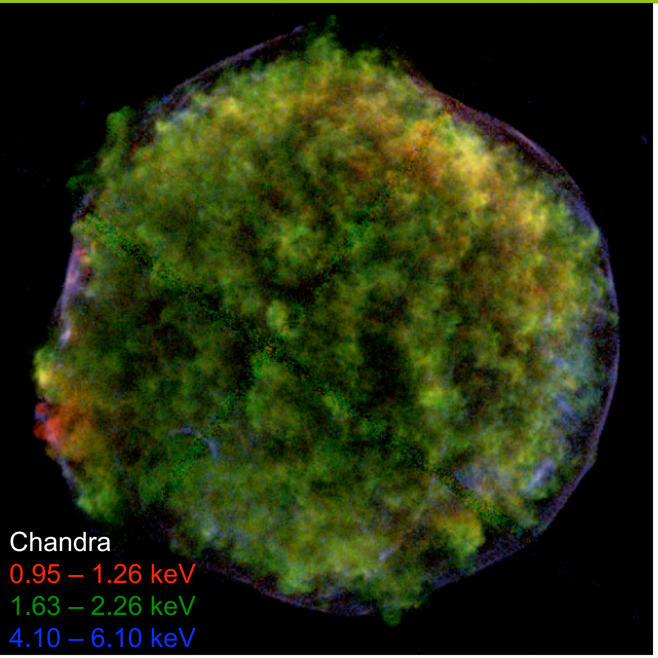
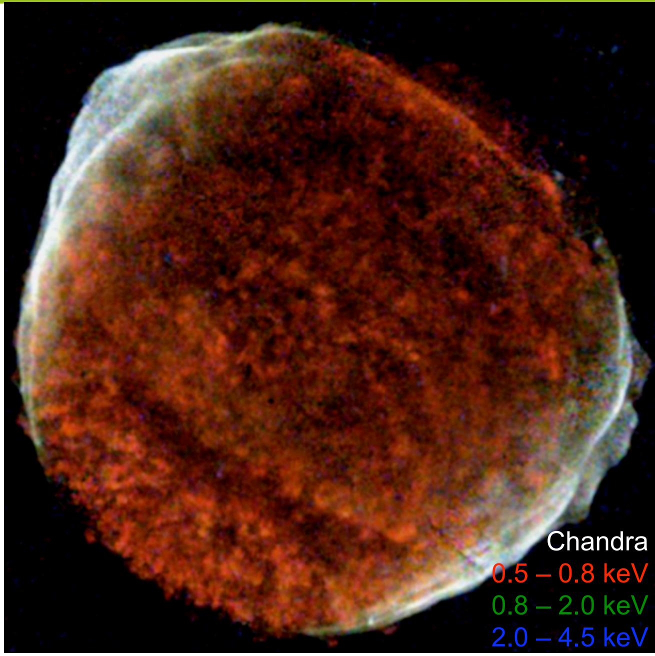


results from
numerical simulations
2D slice of the density profile
at t = 500 years
luminosity proportional to log(density)
color codes phases: ejecta / ambient

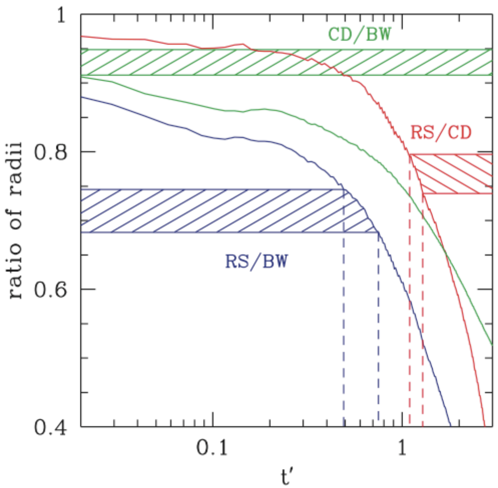
A2 Diagnostics of the waves positions



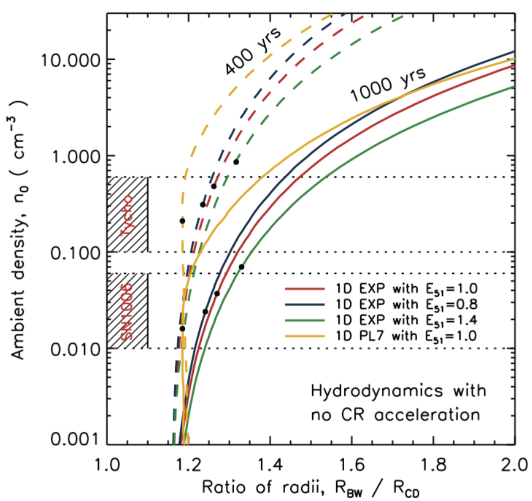
observed positions of the waves do not match hydrodynamical models
→ evidence for **back-reaction** of accelerated particles on the shock



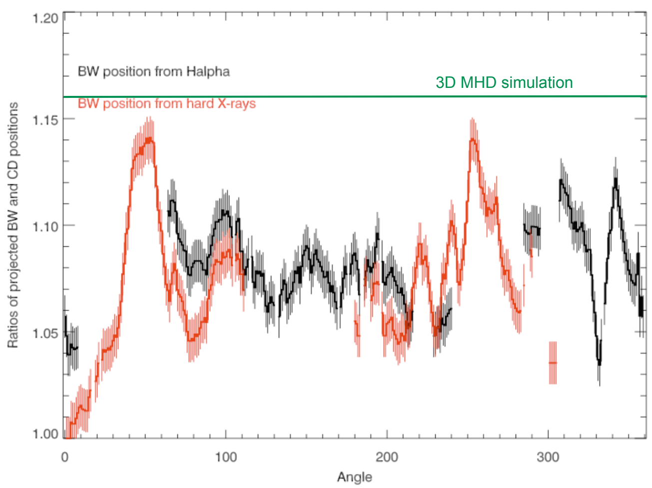
Tycho & SN 1006



Warren et al 2005



Cassam-Chenaï et al. 2008

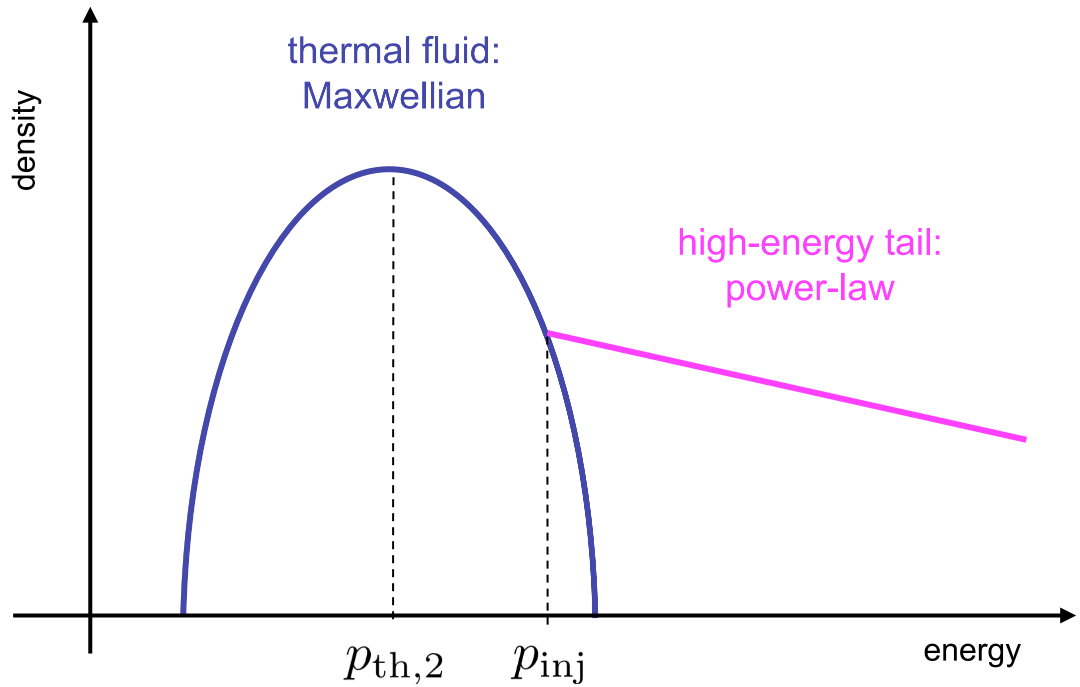


Miceli et al 2009

A3

Particle acceleration: injection recipe

simple prescription:
a fraction η of particles crossing the shock becomes "cosmic-rays" of momentum $p_{\rm inj}$



self-adjusted injection:
$$\begin{cases} p_{\rm inj} = \xi \, p_{\rm th,2} \\ \eta = \dfrac{4}{3\pi} \left(r_{\rm sub} - 1\right) \xi^3 \exp\left(-\xi^2\right) \end{cases}$$

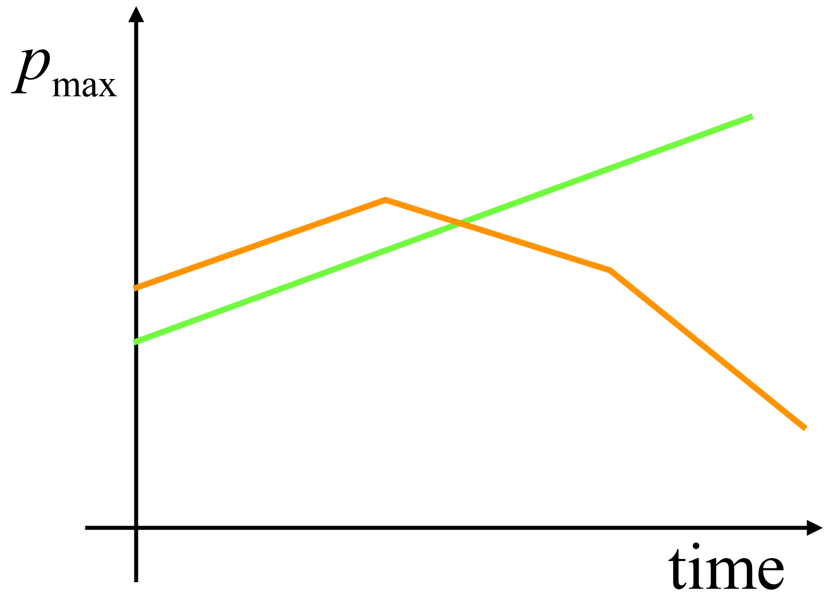
Malkov 1997, 1998; Blasi et al 2005

A4

Particle acceleration: maximum energy

size limitation:

$$x_{\rm diff}(p_{\rm max}) = \begin{cases} D_1(p_{\rm max})/u_S \\ \epsilon\, r_S \quad (\epsilon \ll 1) \end{cases}$$



age limitation:

$$t_{\rm acc}\,(p_{\rm inj} \to p) = \int_{p_{\rm inj}}^{p_{\rm max}} t_{\rm acc}(p')\,\frac{dp'}{p'}$$

$$t_{\rm acc}(p) = \frac{3}{u_1 - u_2}\left(\frac{D_1(p)}{u_1} + \frac{D_2(p)}{u_2}\right) = \begin{cases} \frac{6r}{r-1}\frac{D_1}{u_s^2} \underset{r=4}{=} 20\,\frac{D_1}{u_s^2} & D(x) = \text{cst} \\ \frac{3r(r+1)}{r-1}\frac{D_1}{u_s^2} \underset{r=4}{=} 8\,\frac{D_1}{u_s^2} & D(x) \propto \frac{\rho_1}{\rho(x)} \end{cases}$$

Drury 1983; Berezhko 1996