Modeling supernova remnants: effects of diffusive cosmic-ray acceleration on the evolution, application to observations

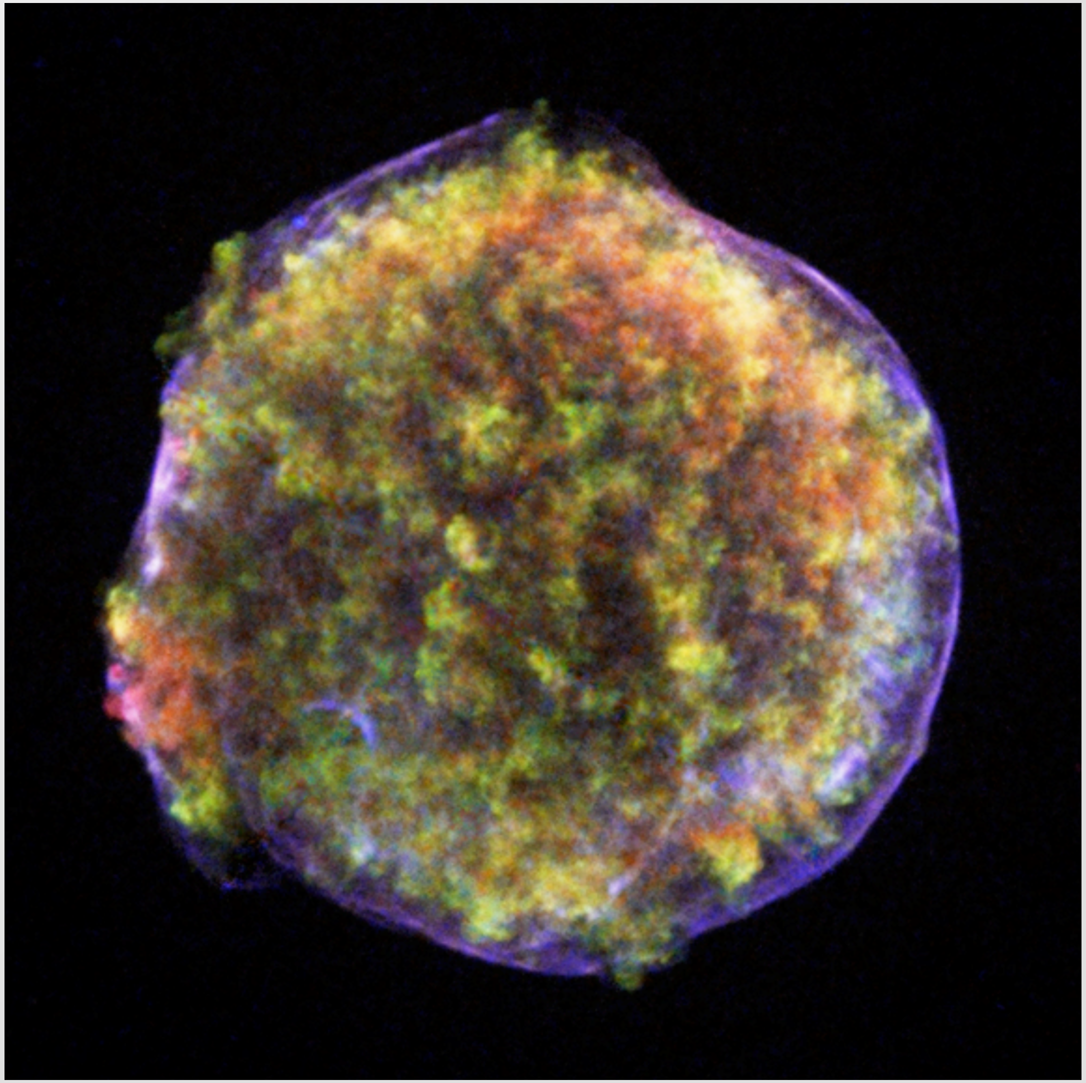
D. Kosenko, S. I. Blinnikov, J. Vink

Astronomical Institute Utrecht

Motivation: Geometry of Galactic SNRs

SN1572 (Tycho) SNR

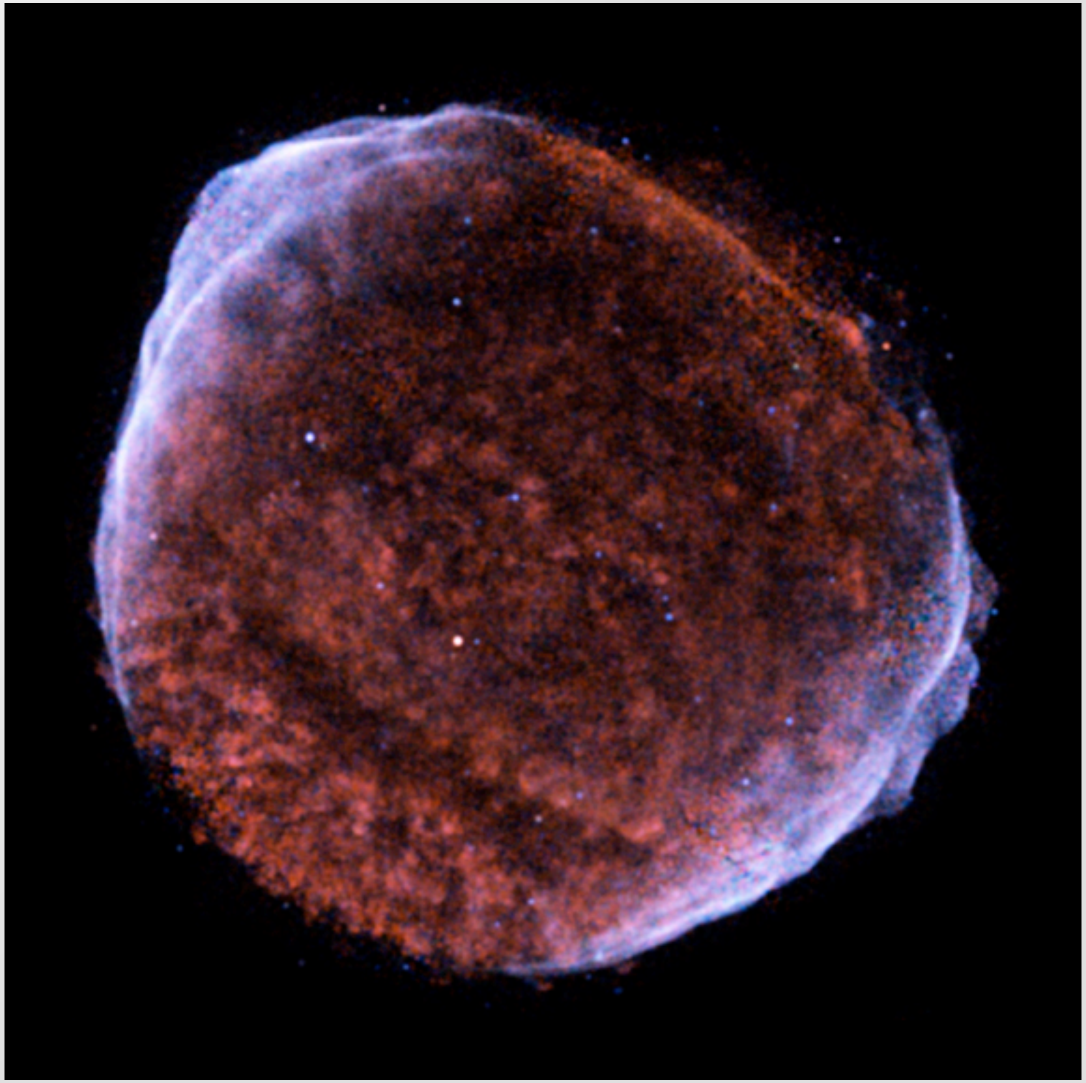
- J. Warren et al 05
  - Measurements of BW:CD:RS = 1:0.96:0.73
  - Non-modified HD modeling could not explain the observed BW:CD:RS



Motivation: Geometry of Galactic SNRs

SN 1006 SNR

- M. Miceli et al 09
  - measured BW:CD ~ 1.1 (1.05 -1.12)
  - Non-modified 3D MHD models yield BW:CD> 1.16



Objective

- Using only the the RS:CD:BW measurements, estimate the possible efficiency of CR acceleration in the SNR.
  - Assuming homogeneous ISM
  - Ignoring X-ray emission

Method: SUPREMNA

- Spherical-symmetrical HD code for SNR evolution calculations (E. Sorokina et al 04)
- Physical processes:
  - T_e/T_i equilibration
  - e^- thermal conduction
  - self-consistent NEI
  - X-ray emission

Basic Equations

$$
\begin{aligned}
\frac{\partial r}{\partial t} &= u\,, \\
\frac{\partial r}{\partial m} &= \frac{1}{4\pi r^2 \rho}\,, \\
\frac{\partial u}{\partial t} &= -4\pi r^2 \frac{\partial (P_e + P_i)}{\partial m} - \frac{Gm}{r^2}\,, \\
\left(\frac{\partial E_e}{\partial T_e}\right)_\rho \frac{\partial T_e}{\partial t} &= -4\pi P_e \frac{\partial}{\partial m}\left(r^2 u\right) - 4\pi \frac{\partial}{\partial m}\left(r^2 F_{\mathrm{cond}}\right) \\
&\quad -\varepsilon_r - \frac{\partial \varepsilon_{ion}}{\partial t} - \left(\frac{\partial E_e}{\partial X_e}\right)\frac{\partial X_e}{\partial t} + \frac{1}{\rho}\nu_{ie} k_b (T_i - T_e)\,, \\
\left(\frac{\partial E_i}{\partial T_i}\right)_\rho \frac{\partial T_i}{\partial t} &= -4\pi P_i \frac{\partial}{\partial m}\left(r^2 u\right) \\
&\quad - \frac{1}{\rho}\nu_{ie} k_b (T_i - T_e)\,, \\
\frac{\partial \mathbf{X}}{\partial t} &= f(T_e, \rho, \mathbf{X}).
\end{aligned}
$$

Diffusive cosmic-ray acceleration

- Two-fluid approximation
  - No CR spectra, no microphysics
- CR (γ =4/3) diffusion equation

$$\frac{\partial E_{\mathrm{CR}}}{\partial t} + \frac{\partial (u E_{\mathrm{CR}})}{\partial r} - \frac{\partial}{\partial r}\left(\kappa_{\mathrm{CR}} \frac{\partial E_{\mathrm{CR}}}{\partial r}\right) + P_{\mathrm{CR}} \frac{\partial u}{\partial r} = \Theta,$$

Particle generation via the source term:
$\Theta \sim q_{CR} Q$, Q - artificial viscosity

Source term: artificial viscosity

- $Q \sim \rho(\Delta u)^2$, where $\Delta u < 0$ (at the shock), otherwise - $Q = 0$
- Kinetic energy sharing:

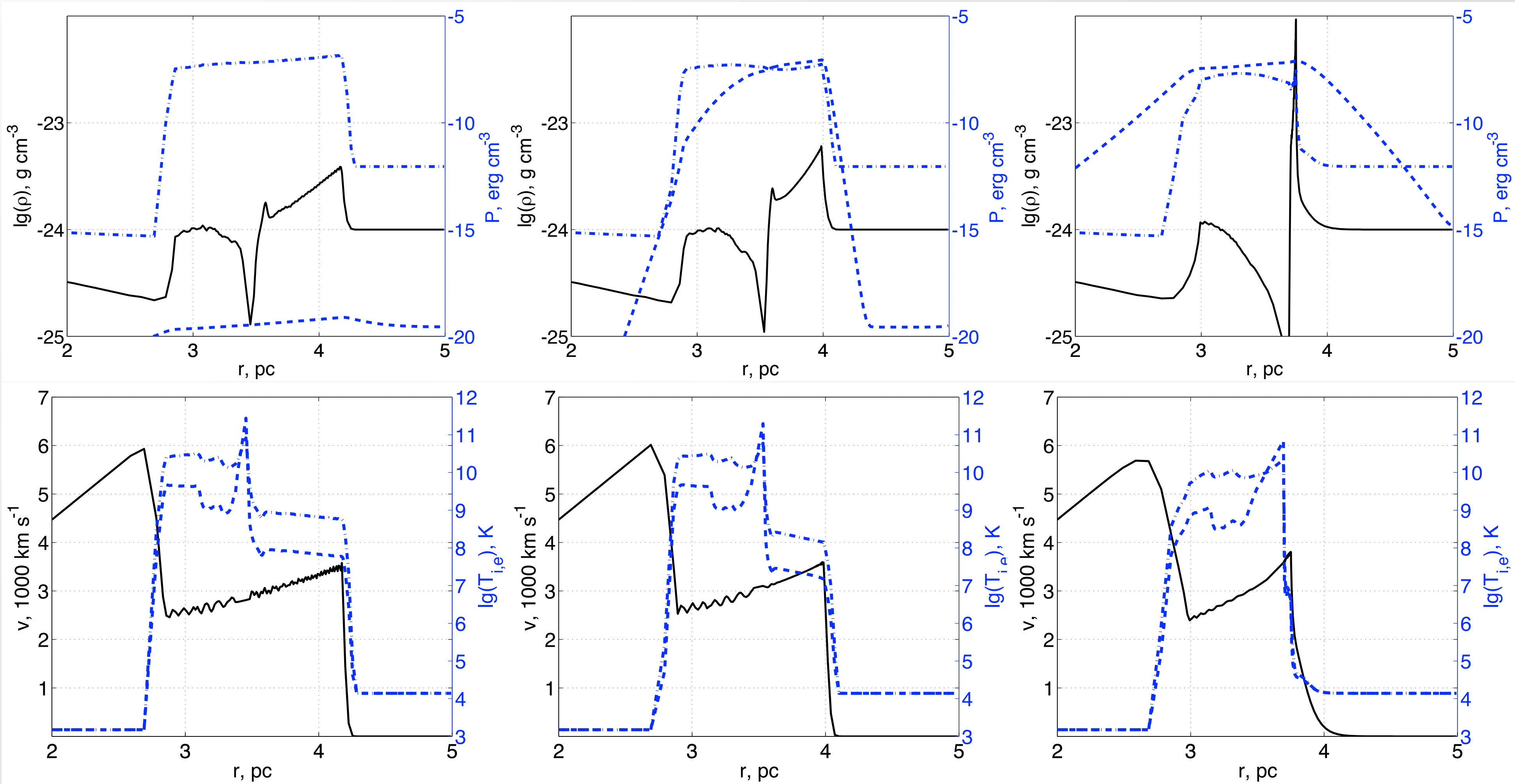
Before: q_i	Now: q_i, $\mathbf{q_{CR}}$
$P_i \leftarrow q_i \; Q$	$P_i \leftarrow \mathbf{(1-q_{CR})} \; q_i Q$
$P_e \leftarrow (1-q_i)Q$	$P_e \leftarrow \mathbf{(1-q_{CR})} \; (1-q_i)Q$
	$P_{CR} \leftarrow \mathbf{q_{CR}} \; Q$

Numerical models

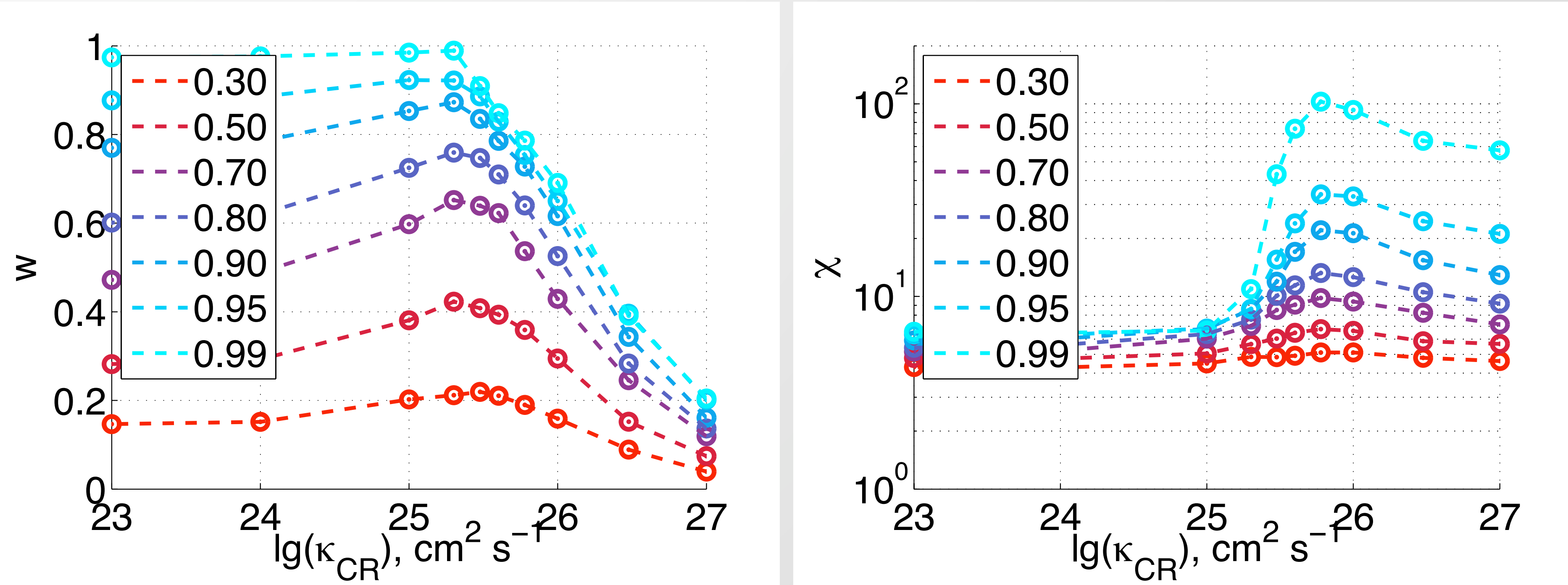
- A two-dimensional set of HD models for different values of CR generation parameter q_{CR} and different values of the diffusion coefficient κ_{CR} for the each q_{CR}
  - Tycho SNR set up:
    - $E = 1.4 \times 10^{51}$ erg
    - $\rho_0 = 10^{24}$ g cm^{-3} (0.6 cm^{-3})
    - t = 430 years

Numerical models. Tycho SNR case

$q_{CR} = 0.00$ | $q_{CR} = 0.70$, $\kappa_{CR} = 10^{25}$ cm^2 s^{-1} | $q_{CR} = 0.99$, $\kappa_{CR} = 10^{26}$ cm^2 s^{-1}

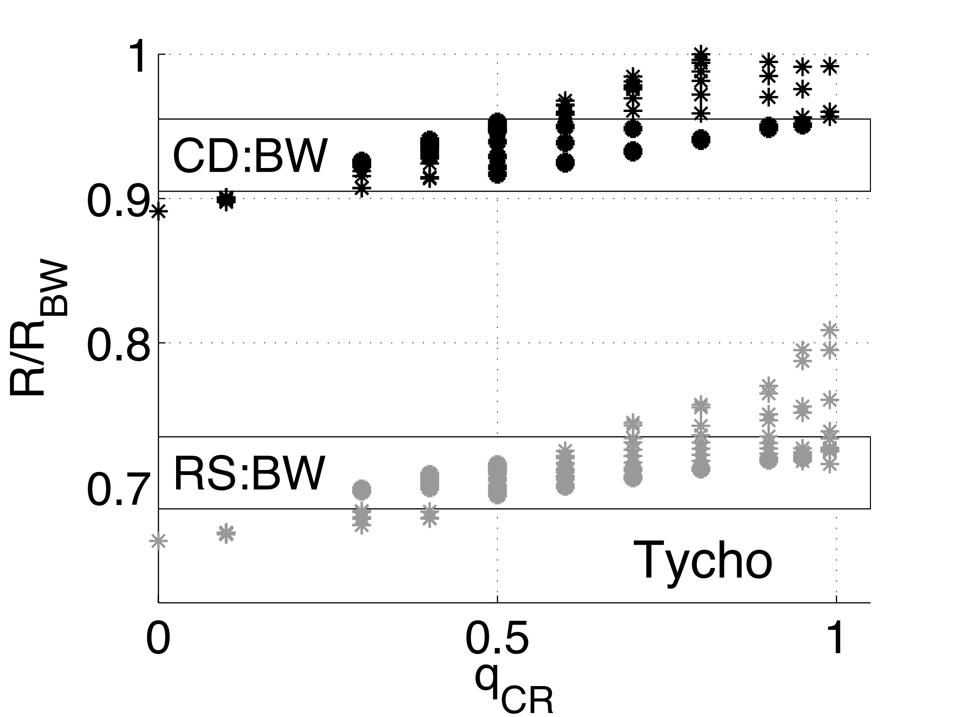


Implications of the diffusion coefficient for the CR escape rate

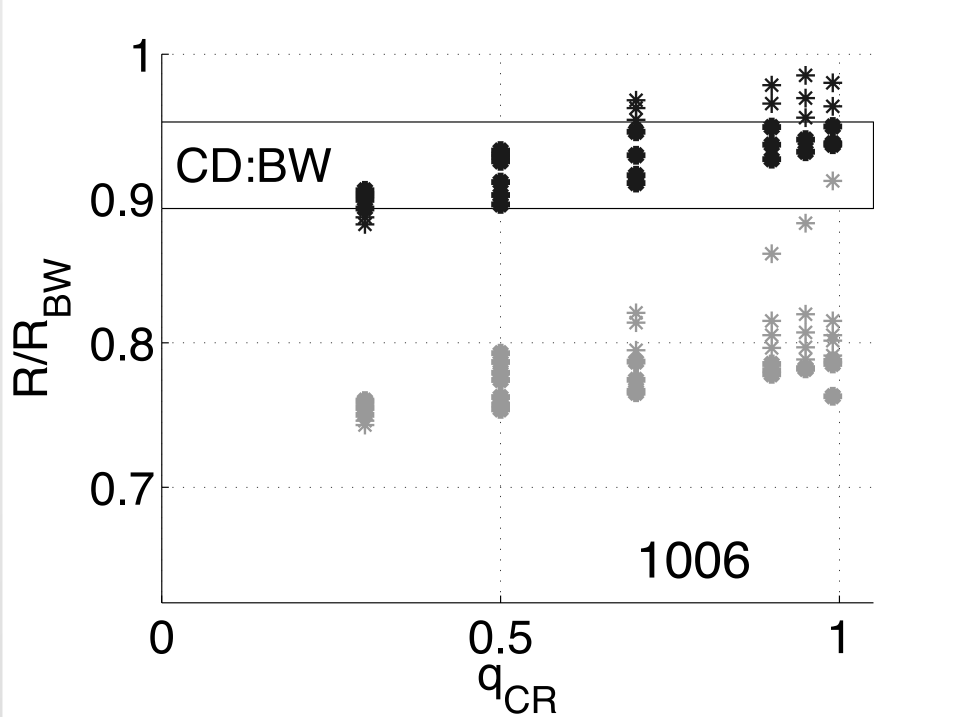


Models vs measurements

Tycho SNR: $\rho_0 = 10^{-24}$ g cm^{-3}, 430 yr
RS:CD:BW from Warren+ 05 // RT = 1.07
BW acceleration only



SN 1006 SNR: $\rho_0 = 4\times10^{-26}$ g cm^{-3}, 1000 yr
CD:BW from Miceli+ 09 // RT = 1.07
BW acceleration only



Results

Tycho SNR

In:

$q_{CR} = 0.4 - 0.7$

$\kappa_{CR} = (10^{24}\text{-}10^{25})\ \mathrm{cm}^2\ \mathrm{s}^{-1}$

Out:

$\chi = 4.3 - 6.8$

$\varepsilon_{CR} = (0.1\text{-}0.2)\ \rho_0 v^3/2$

SN1006 SNR

In:

$q_{CR} = 0.3 - 0.9$

$\kappa_{CR} = (10^{24}\text{-}10^{25})\ \mathrm{cm}^2\ \mathrm{s}^{-1}$

Out:

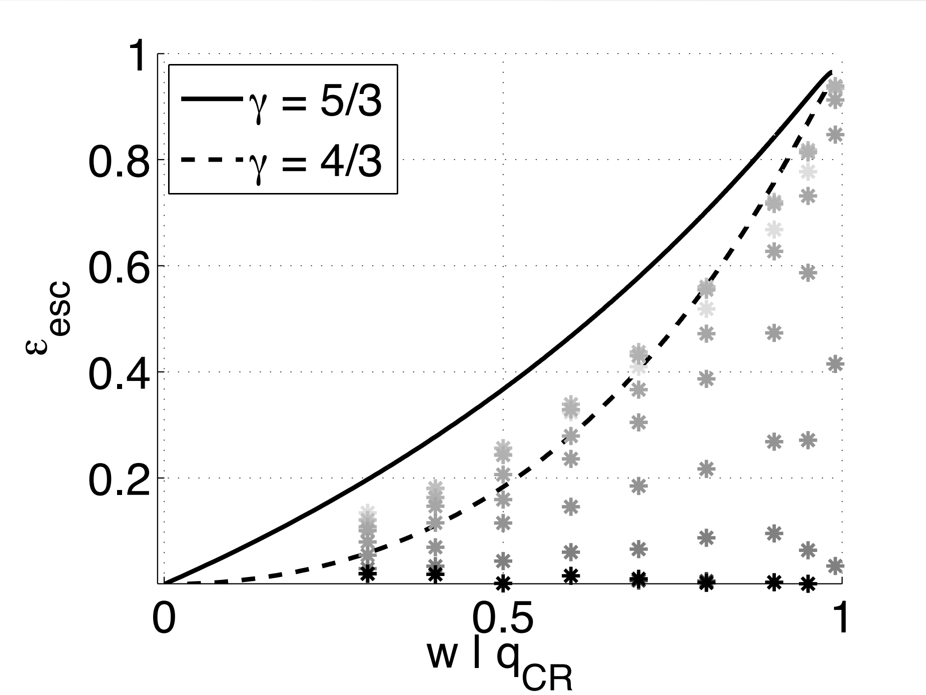
$\chi = 4.7 - 8.3$

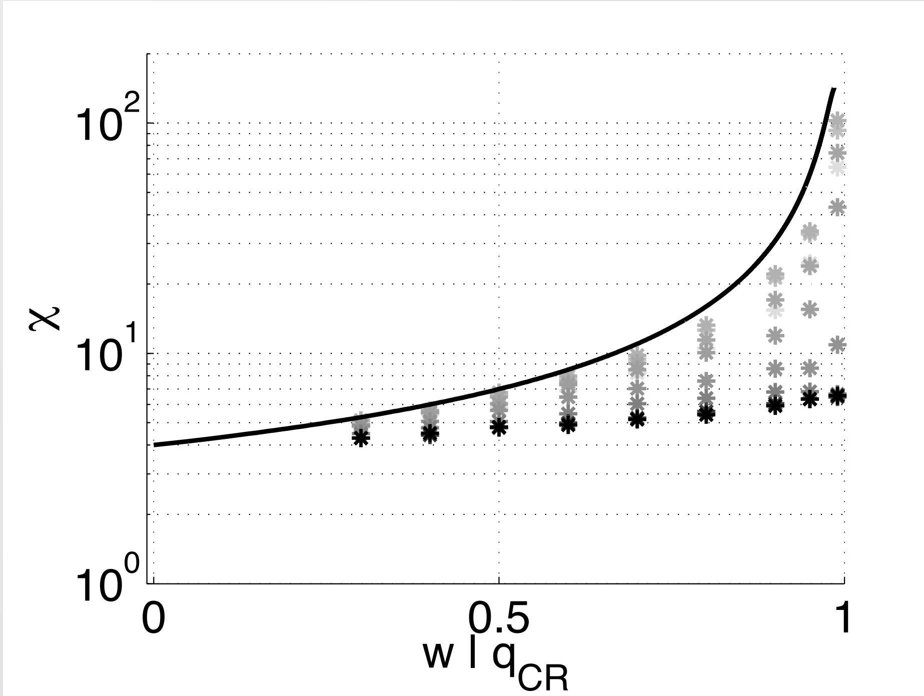
$\varepsilon_{CR} = (0.2\text{-}0.5)\ \rho_0 v^3/2$

Conclusions

- Other factors, that influence RS:CD:BW
  - The analysis is performed in a CR framework, nevertheless CSM features, such as presupernova wind, may have stronger effects on the SNR dynamics and should be taken into account.
- X-ray emission
  - It is important to study variations of X-ray spectra from such remnants for different CR acceleration efficiency. Our code is capable of performing X-ray emission calculation, but a number of unknown parameters such as explosion models and CSM profiles make such a study extremely difficult.
- The impact of these parameter on the observational properties of the SNR are under investigations.

Escape energy and compression ratio





Diffusive cosmic-ray acceleration

- Two-fluid approximation
  - No CR spectra, no microphysics

$$\frac{\partial E_{\rm CR}}{\partial t} + \frac{\partial (u E_{\rm CR})}{\partial r} - \frac{\partial}{\partial r}\left(\kappa_{\rm CR}\frac{\partial E_{\rm CR}}{\partial r}\right) + P_{\rm CR}\frac{\partial u}{\partial r} = \Theta,$$

$$\frac{DE_{\rm CR}}{Dt} = -\,(E_{\rm CR} + P_{\rm CR})\,4\pi\rho\frac{\partial (r^2 u)}{\partial m} + 4\pi\rho\frac{\partial}{\partial m}\left(r^2 F_{\rm CR}\right) - 4\pi\rho\frac{\partial (r^2 u)}{\partial m} q_{\rm CR} Q,$$

where $DE_{\rm CR}/Dt = \partial E_{\rm CR}/\partial t + 4\pi r^2 u\rho(\partial E_{\rm CR}/\partial m)$.