CTA Linkages in Australia
28-29 November 2019, The University of Adelaide

Particle escape from middle-aged SNRs and related gamma-ray emission

Silvia Celli
silvia.celli@roma1.infn.it

Istituto Nazionale di Fisica Nucleare
Sapienza Università di Roma
Max-Planck-Institut für Kernphysik

In collaboration with G. Morlino, S. Gabici & F. Aharonian

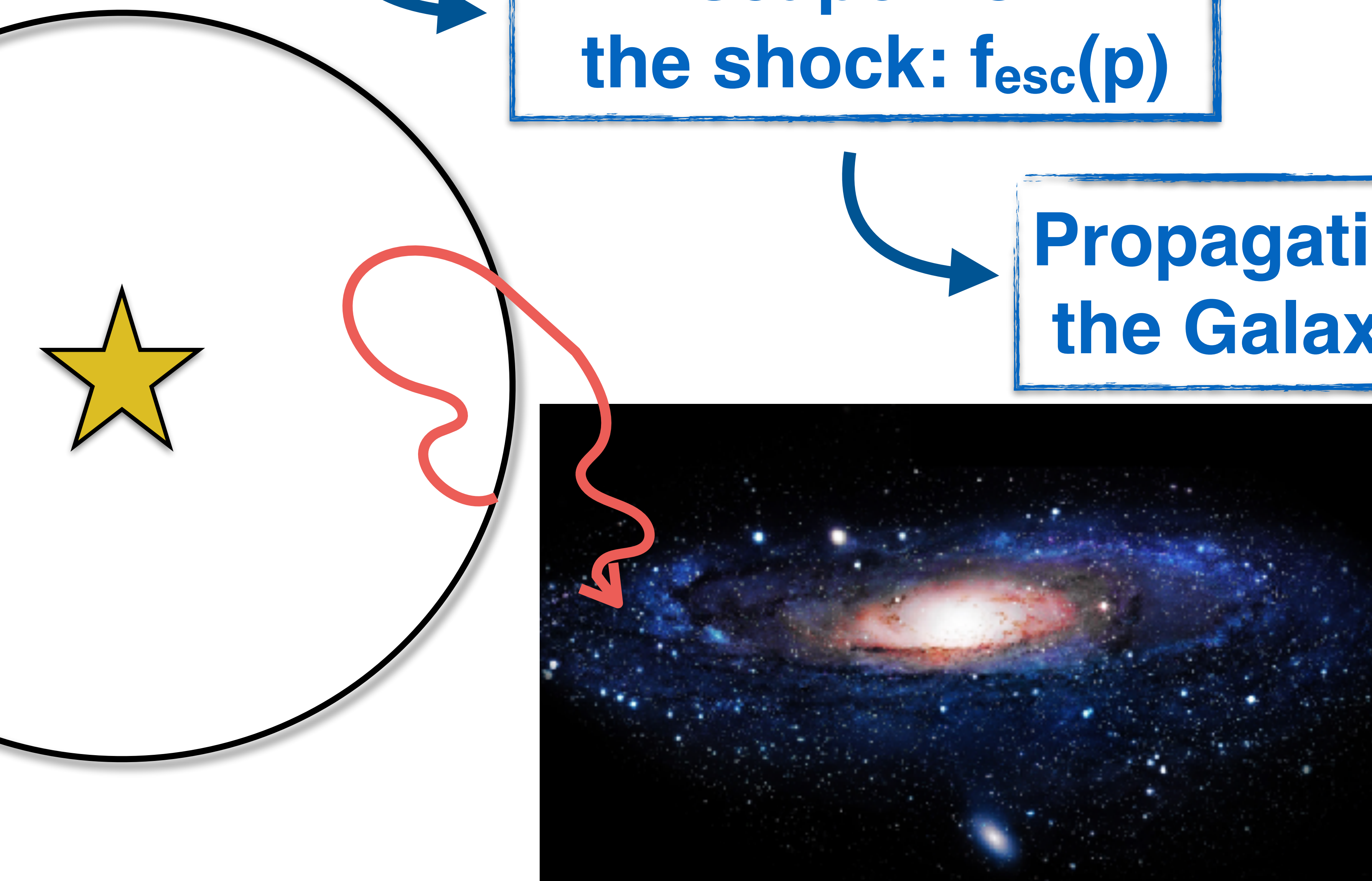
How do accelerated particles become CRs?

Acceleration at the shock: $f_0(p)$

$$f_0(p) \neq f_{\rm esc}(p) \neq f_{\rm prop}(p)$$

Escape from the shock: $f_{esc}(p)$

Propagation inside the Galaxy: $f_{prop}(p)$



How do accelerated particles become CRs?

Acceleration inside the shock: $f_0(p)$

Escape from the shock: $f_{esc}(p)$

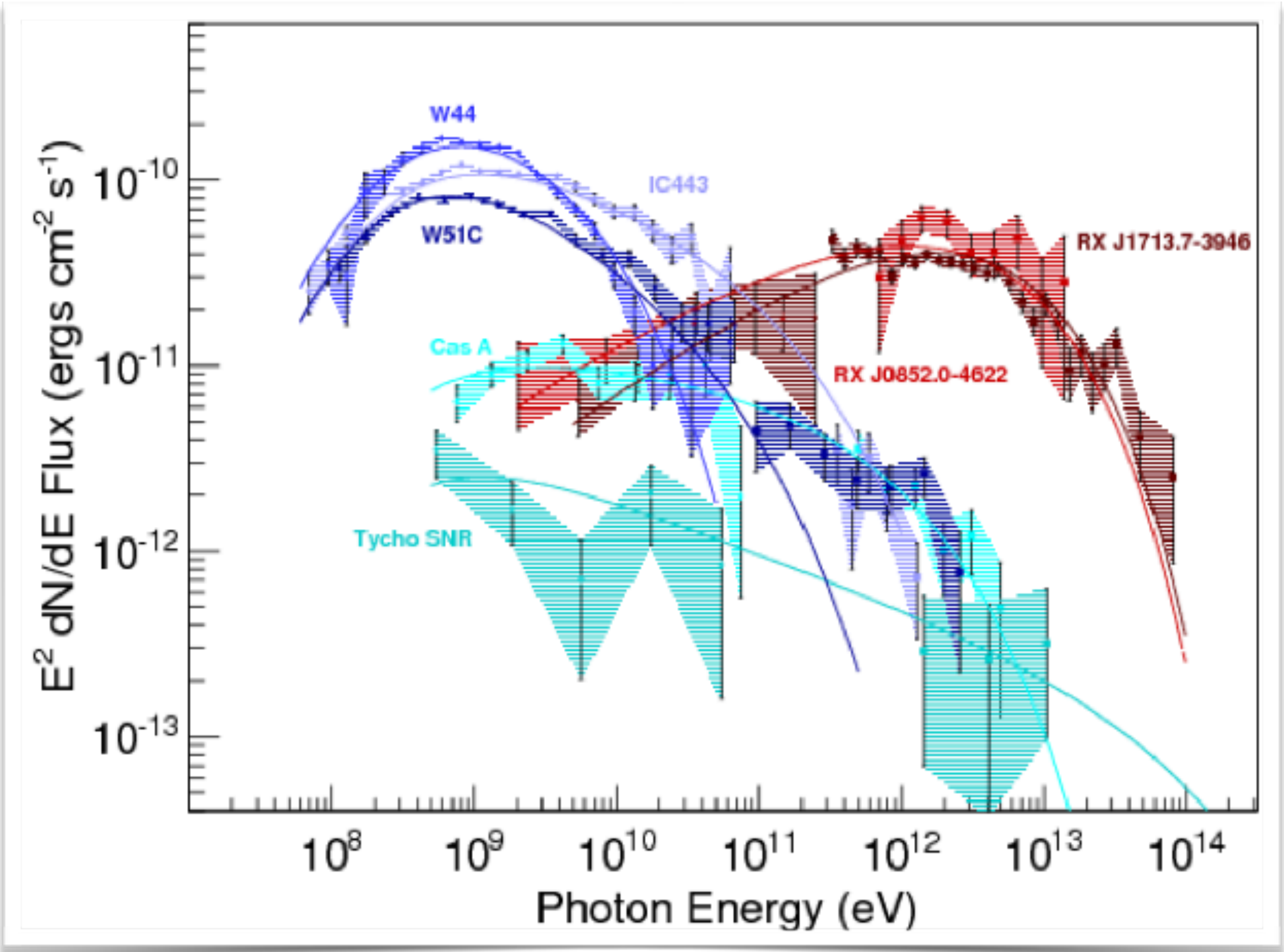
- Ptuskin & Zirakashvili, A&A 429 (2005) 755
- Gabici, Aharonian & Casanova, MNRAS (2009)
- Ohira, Murase & Yamakazi, A&A (2010) 513
- Bell & Shure, MNRAS 437 (2014) 2802
- Cardillo, Amato & Blasi, APh 69 (2015) 1

- Understand the current observations of **SNR spectra**;
- Unveil the presence of **PeV particle accelerators**;
- Connect the **CR spectrum** observed on Earth with the spectrum of particles released at the sources.

A **phenomenological** model to investigate the particle **escape** through spectral and morphological features of evolved SNRs in the HE and VHE domain.

Celli et al., MNRAS 490 (2019)

Are SNRs proton PeVatrons?



Drury et al., A&A 287 (1994) 959

Tsuguya & Fumio, J. Phys. G 20 (1994) 477

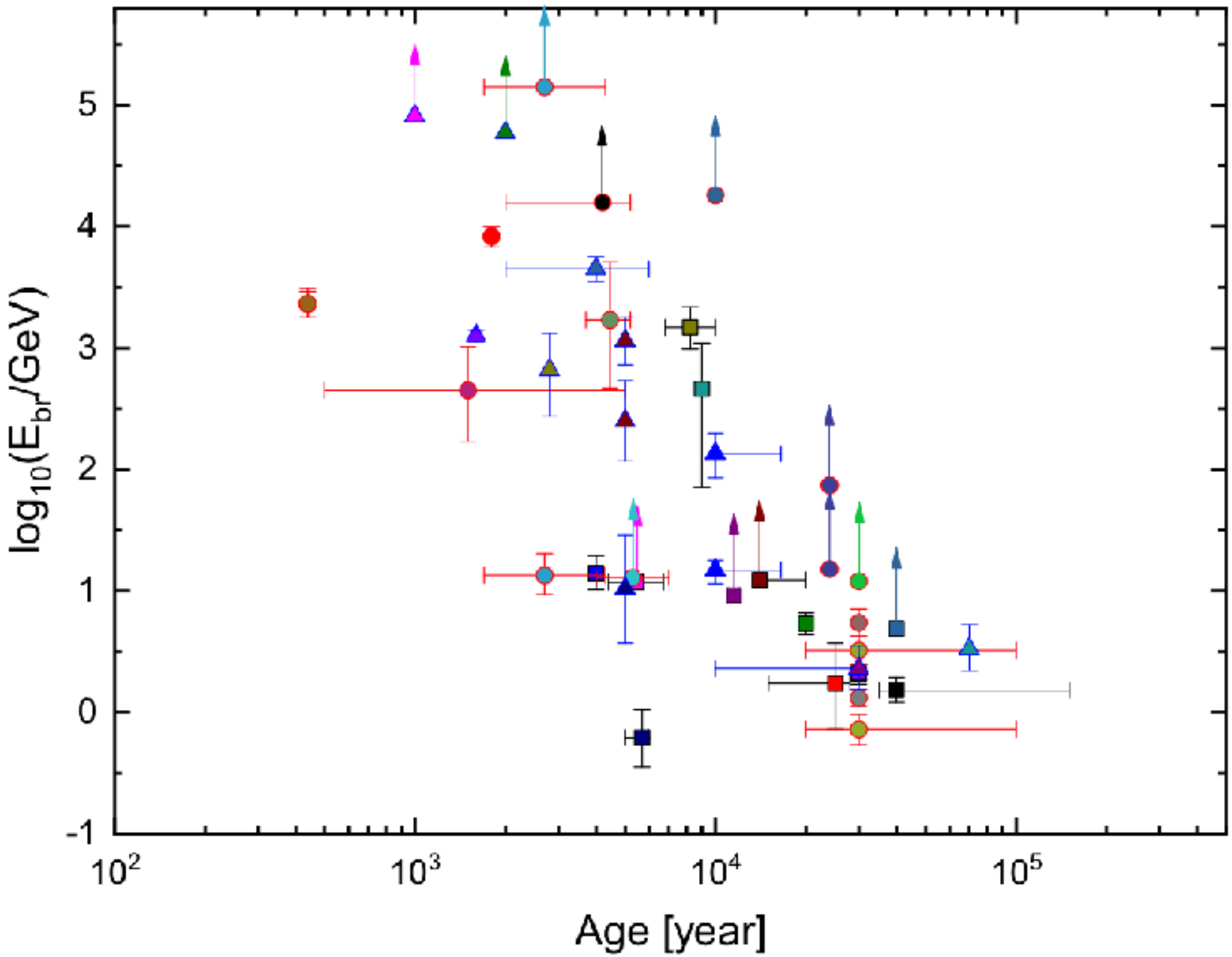
Funk et al., ARNPS 65 (2015) 245F

Middle-aged SNRs (20000 yrs)
- hadronic emission
- steep spectra
- E_{max} < 1 TeV

Young SNRs (2000 yrs)
- hadronic/leptonic ?
- hard spectra
- E_{max} = 10 - 100 TeV

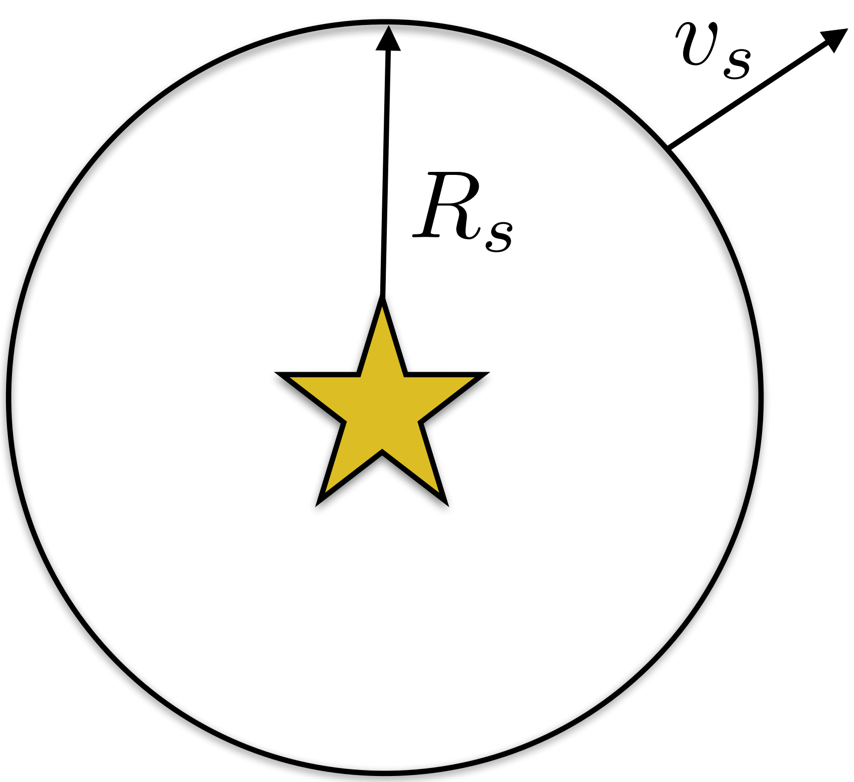
Very young SNRs (300 yrs)
- hadronic ?
- steep spectra $E^{-2.3}$
- E_{max} = 10 - 100 TeV

A population study of evolved SNRs



Zeng et al., ApJ 874 (2019) 50Z

The hydrodynamical evolution of an SNR



I. Ejecta-dominated stage

$$M_{\rm ej} \gg \frac{4}{3}\pi\rho R_s^3(t)$$

⟶ free expansion

II. Sedov-Taylor stage

$$M_{\rm ej} \sim \frac{4}{3}\pi\rho R_s^3(t)$$

⟶ energy conservation

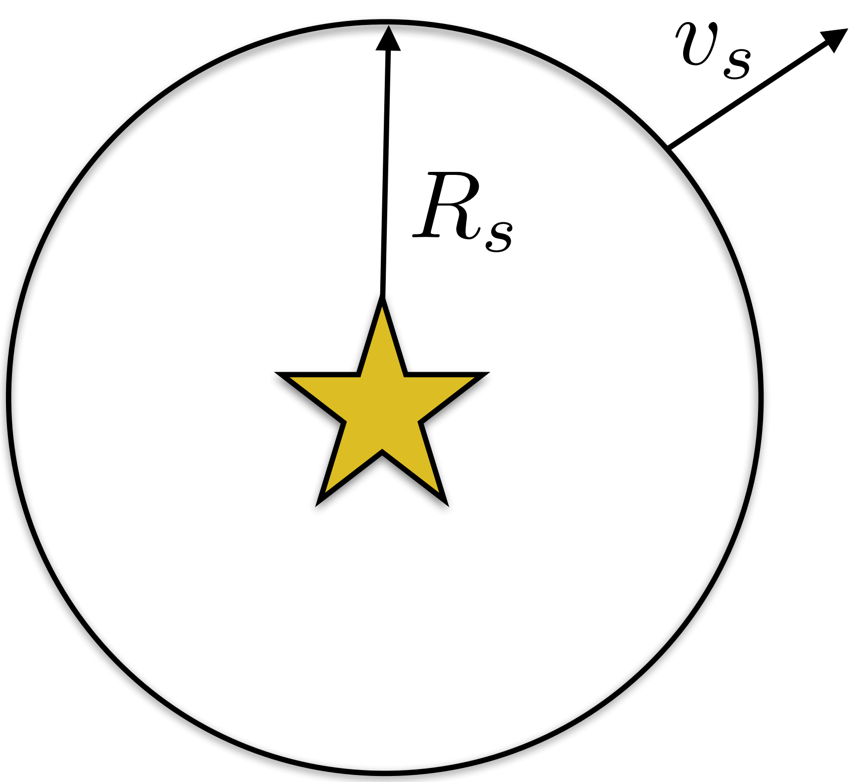
III. Radiative stage

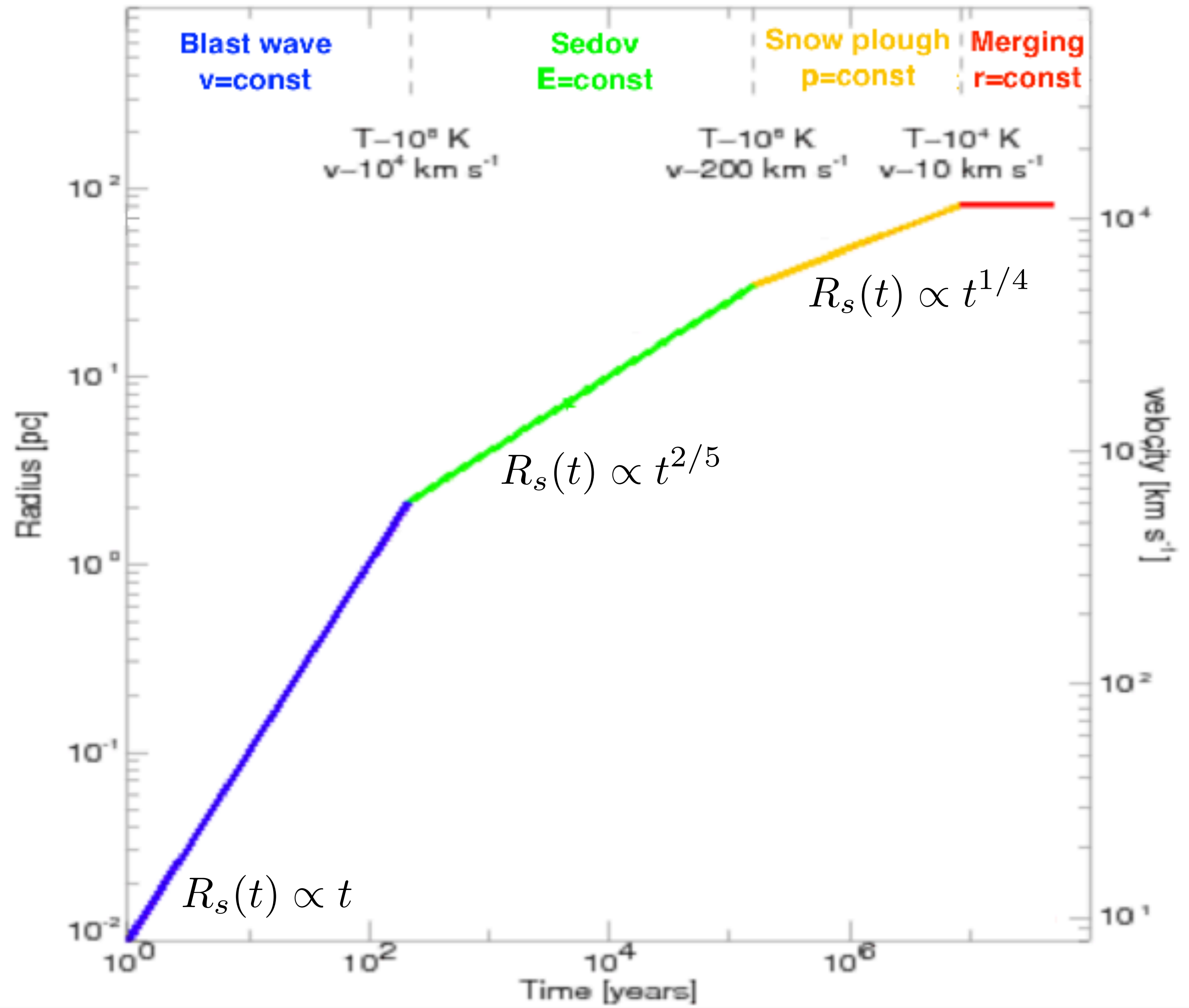
⟶ momentum conservation

IV. Merging phase

⟶ pressure comparable to ISM

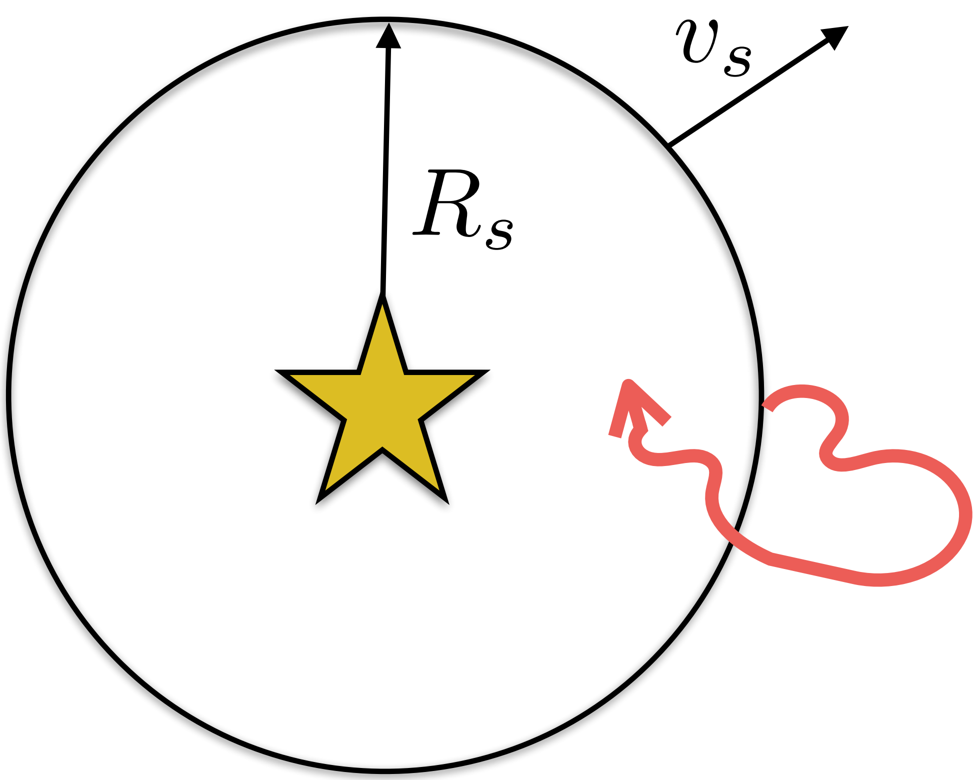
The hydrodynamical evolution of an SNR





$$t_{\rm Sed} \simeq 1.6 \times 10^3\,{\rm yr} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-1/2} \left(\frac{M_{\rm ej}}{10\,M\odot}\right)^{5/6} \left(\frac{\rho_0}{1\,m_{\rm p}/{\rm cm}^3}\right)^{-1/3}$$

Maximum energy in SNRs



$$t_{\rm acc} = t_{\rm age}$$

acceleration limited by remnant age

$$\frac{D(p_{\max})}{v_s^2(t)} = t$$

$$\frac{p_{\max}}{B_0\,\mathcal{F}(t)} = v_s^2(t)\,t$$

$$\left(\frac{\delta B(\mathbf{x},t)}{B_0}\right)^2 = \int \mathcal{F}(k,\mathbf{x},t)\,d\ln k$$

$$p_{\max,0} \propto \mathcal{F}(t)\,v_s^2(t)\,t$$

→ ED stage:

$$v_s(t) \simeq \text{const}$$

$$p_{\max,0}(t) \propto \mathcal{F}(t)\,t$$

→ ST stage:

$$v_s(t) \simeq t^{-3/5}$$

$$p_{\max,0}(t) \propto \mathcal{F}(t)\,t^{-1/5} \propto t^{-\delta}$$

A model for particle propagation

Solution of the transport equation for accelerated **protons**

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = \frac{p}{3}\frac{\partial f}{\partial p} \nabla \cdot \mathbf{v} + \nabla \cdot [D \nabla f]$$

ANALYTICAL DESCRIPTION

Particles confined inside the SNR

$$\frac{\partial f_{\rm conf}}{\partial t} + \mathbf{v} \cdot \nabla f_{\rm conf} = \frac{p}{3}\frac{\partial f_{\rm conf}}{\partial p} \nabla \cdot \mathbf{v}$$

Escaped particles

$$\frac{\partial f_{\rm esc}}{\partial t} = \nabla \cdot [D \nabla f_{\rm esc}]$$

Assumption 1: spherical symmetry **f=f(t,r,p)**;

Assumption 2: stationary homogeneous diffusion coefficient is assumed inside and outside the remnant

$$D_{\rm in}(p) = D_{\rm out}(p) \equiv \chi D_{\rm Gal}(p) = \chi 10^{28} \left(\frac{pc}{10\,{\rm GeV}}\right)^{1/3} {\rm cm}^2\,{\rm s}^{-1}$$

Matching condition: $f_{\rm esc}(r, t = t_{\rm esc}) = f_{\rm conf}(r, t_{\rm esc})$

A model for particle propagation

Assumption 3: at every time, a constant fraction $\xi_{\rm CR}$ of the shock ram pressure is converted into CR pressure, such that the acceleration spectrum reads as

$$f_0(t,p) = \frac{3\xi_{\rm CR}\rho_{\rm up} v_s^2(t)}{4\pi c (m_p c)^{4-\alpha} \Lambda(p_{\rm max}(t))} p^{-\alpha} \theta\left[p_{\rm max}(t) - p\right]$$

acceleration efficiency constant in time

normalization factor such that $P_{\rm CR} = \xi_{\rm CR}\rho_{\rm up} v_s^2(t)$

acceleration spectrum ($\alpha \sim 4$ from DSA)

Ptuskin & Zirakashvili, A&A 429 (2005) 755

Assumption 4: the shock is evolving through the ST phase

$$R_s(t) \propto t^{2/5} \qquad v_s(t) \propto t^{-3/5}$$

A model for particle propagation

Assumption 5: the maximum momentum at the shock is a decreasing function of time

$$p_{\max,0}(t) = p_{\mathrm{M}} \left(\frac{t}{t_{\mathrm{Sed}}} \right)^{-\delta}$$

Ptuskin & Zirakashvili, A&A 429 (2005) 755

$$\longrightarrow \quad t_{\mathrm{esc}}(p) = t_{\mathrm{Sed}} \left(\frac{p}{p_{\mathrm{M}}} \right)^{-1/\delta}$$

$\delta > 0$

high-energy particles escape earlier

A model for particle propagation

Assumption 5: the maximum momentum at the shock is a decreasing function of time

$$p_{\mathrm{max},0}(t) = p_{\mathrm{M}} \left(\frac{t}{t_{\mathrm{Sed}}} \right)^{-\delta}$$

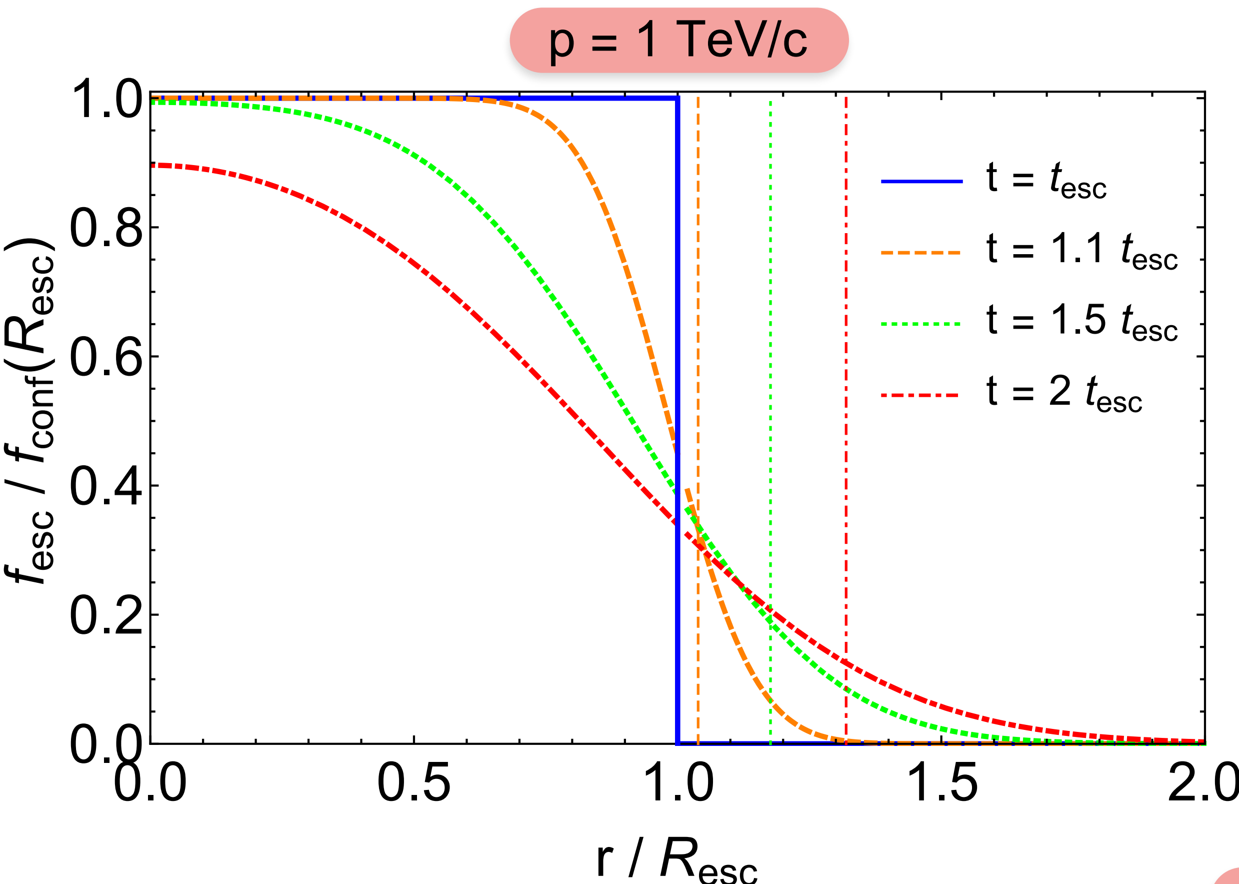
Ptuskin & Zirakashvili, A&A 429 (2005) 755

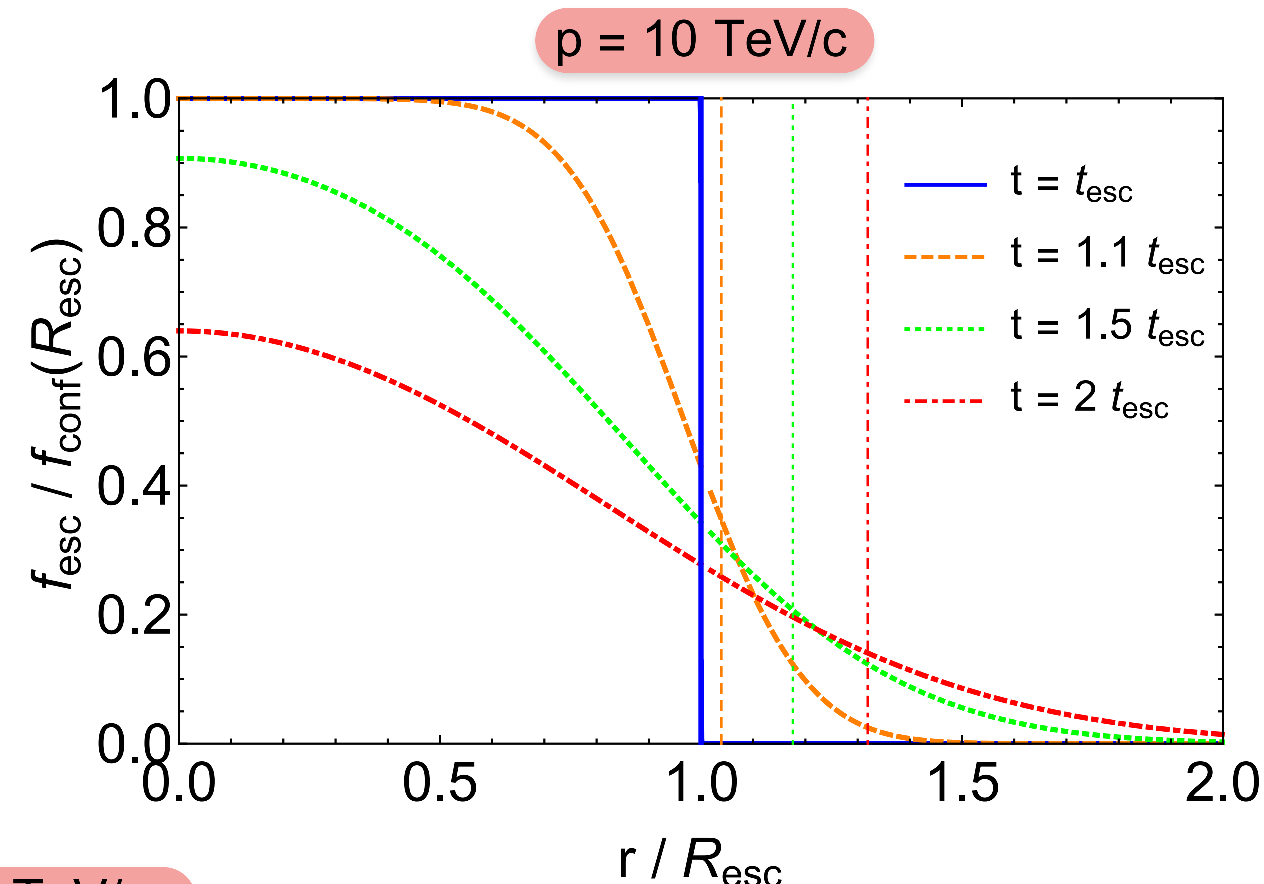
$$\longrightarrow t_{\mathrm{esc}}(p) = t_{\mathrm{Sed}} \left(\frac{p}{p_{\mathrm{M}}} \right)^{-1/\delta}$$

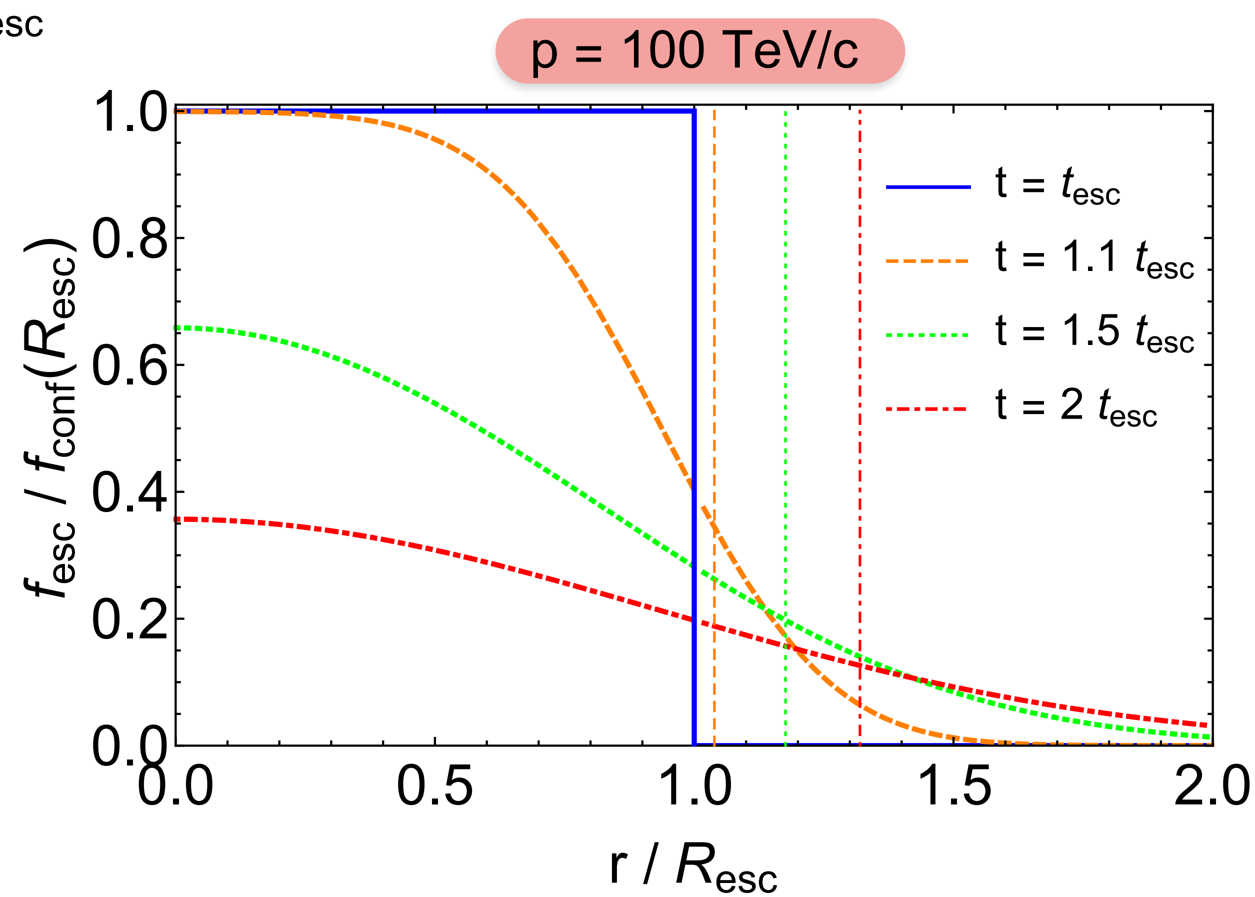
$\delta > 0$
high-energy particles escape earlier

- Magnetic field not amplified
  $p_{\mathrm{max},0}(t) \propto t^{-1/5}$
- Magnetic field amplification driven by resonant waves
  $p_{\mathrm{max},0}(t) \propto t^{-7/5}$
- Magnetic field amplification driven by non-resonant waves
  $p_{\mathrm{max},0}(t) \propto t^{-2}$

Density of non-confined particles





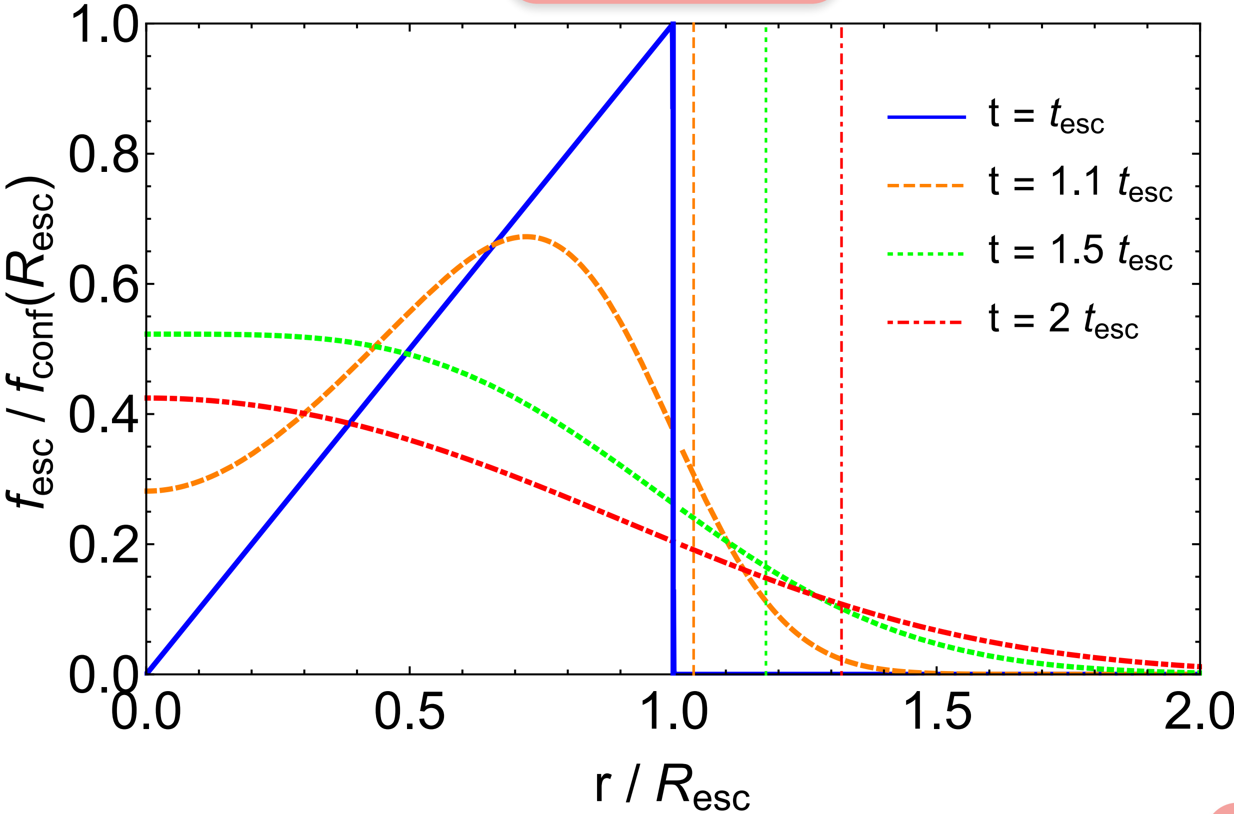


$\alpha = 4$

$\chi = 0.01$

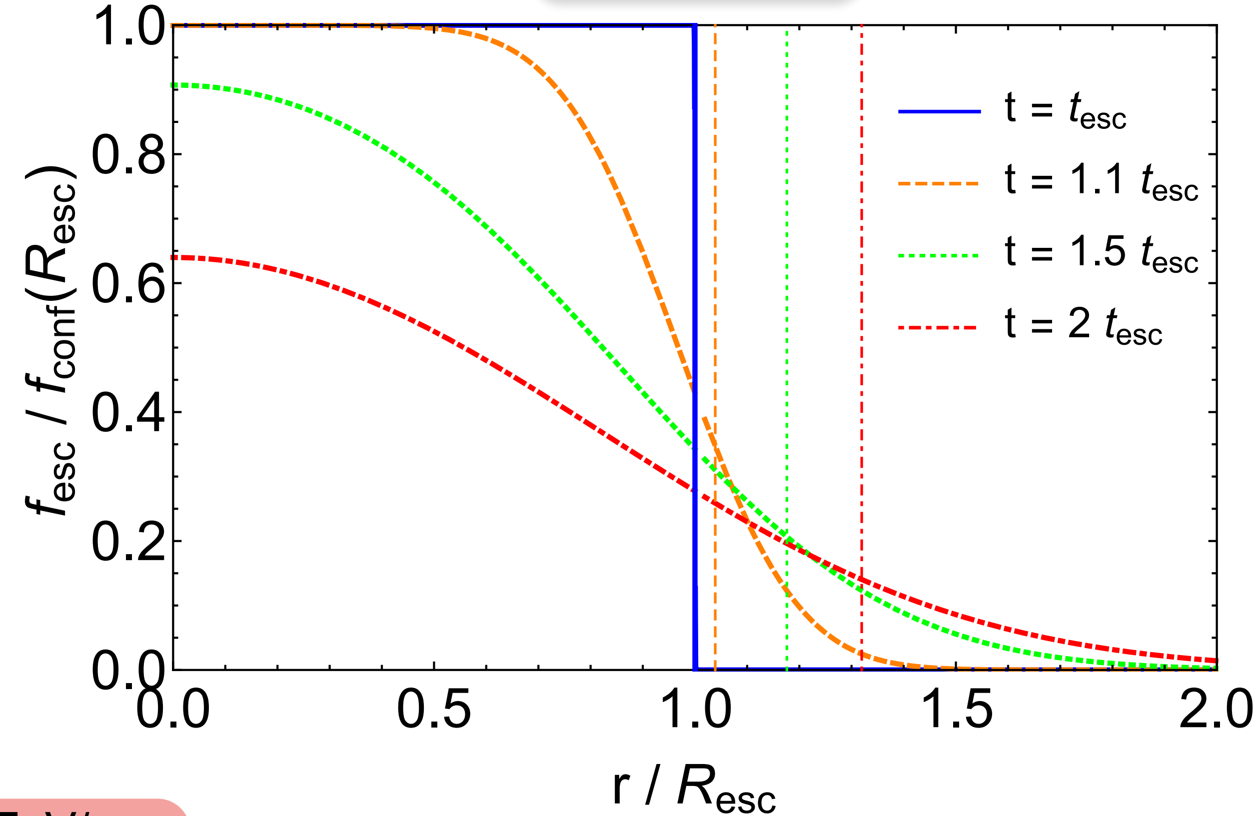
$\alpha = 4 + 1/3$

p = 10 TeV/c

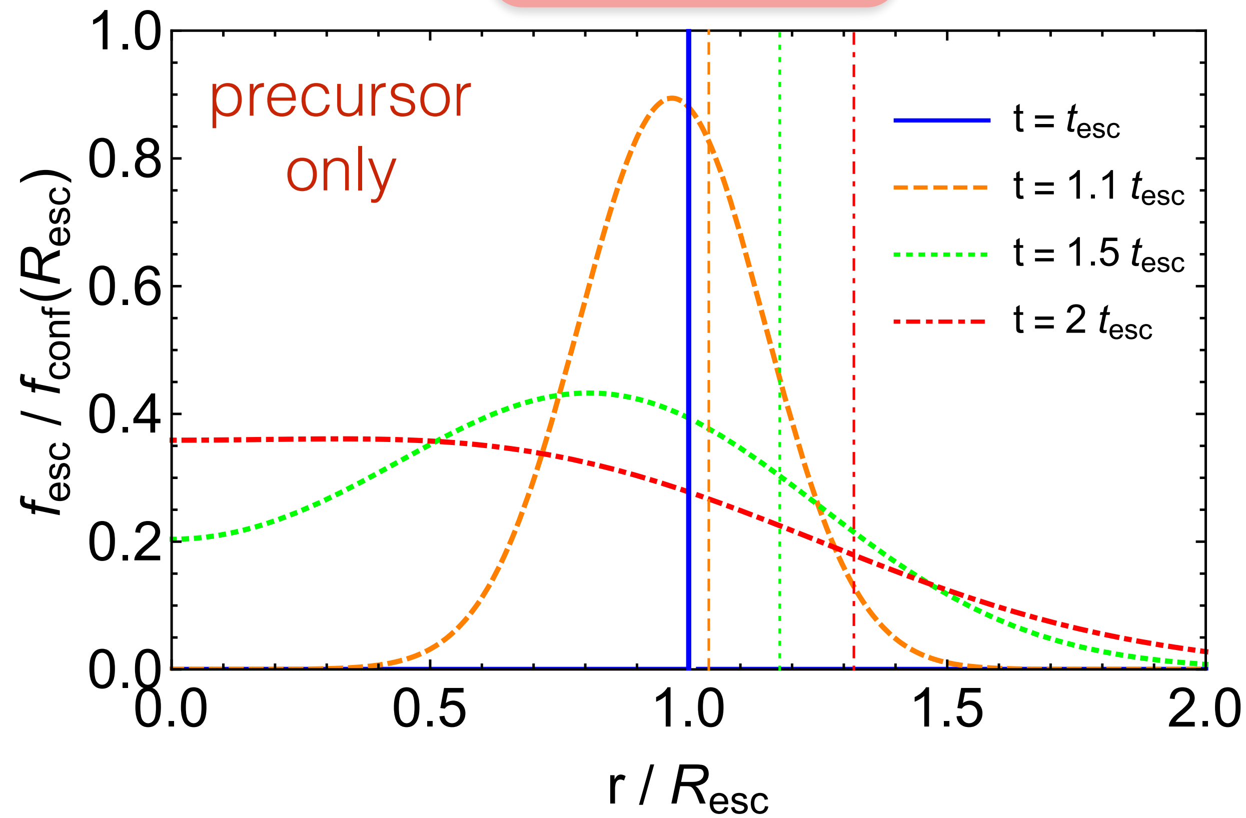


$\alpha = 4$

p = 10 TeV/c



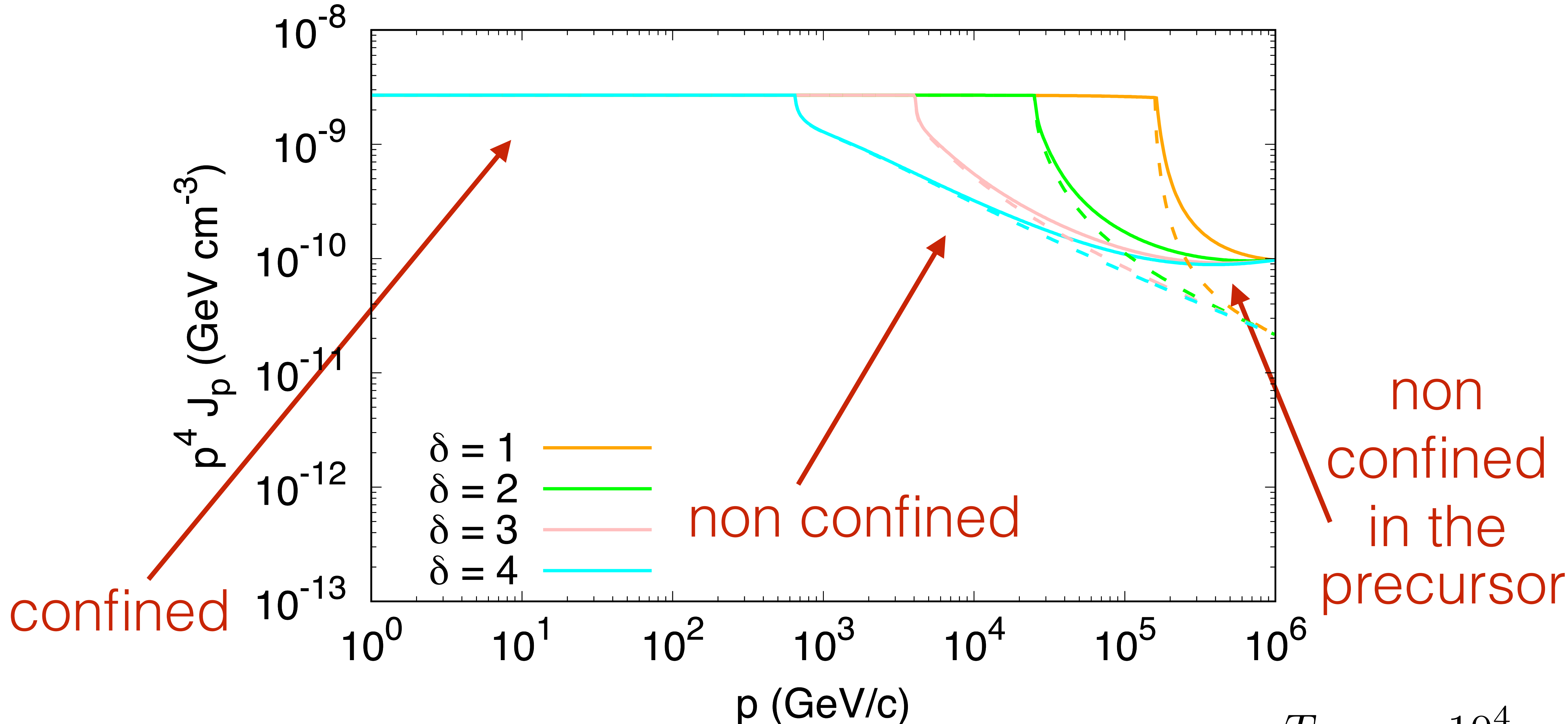
p = 10 TeV/c



$\chi = 0.01$

The spectrum of protons inside the SNR

$$J_p^{\rm in}(t,p) = \frac{4\pi}{V_{\rm SNR}} \int_0^{R_{\rm sh}(t)} \left[f_{\rm esc}(t,r,p) + f_{\rm p,esc}(t,r,p) + f_{\rm conf}(t,r,p)\right] r^2 dr$$



$$D(p) = 10^{27} \left(\frac{pc}{10\ \mathrm{GeV}}\right)^{1/3} \mathrm{cm}^2\mathrm{s}^{-1}$$

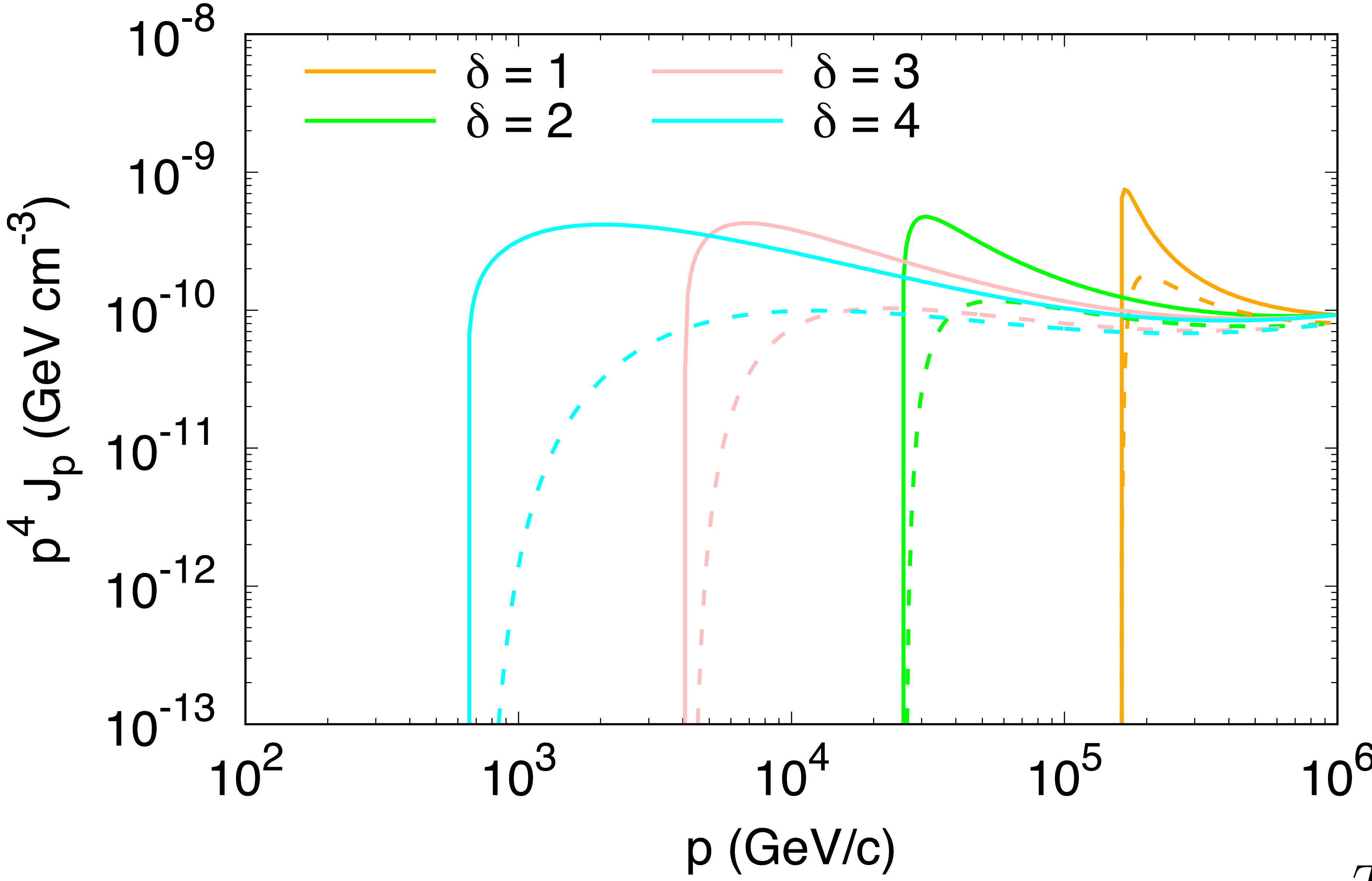
$T_{\rm SNR} = 10^4\,\mathrm{yr}$

$\xi_{\rm CR} = 10\%$

$n_{\rm up} = 1\,\mathrm{cm}^{-3}$

The spectrum of protons outside the SNR

$$J_p^{\rm out}(t,p) = \frac{3}{R_2^3 - R_1^3} \int_{R_1}^{R_2} \left[f_{\rm esc}(t,r,p) + f_{\rm p,esc}(t,r,p) \right] r^2 dr$$



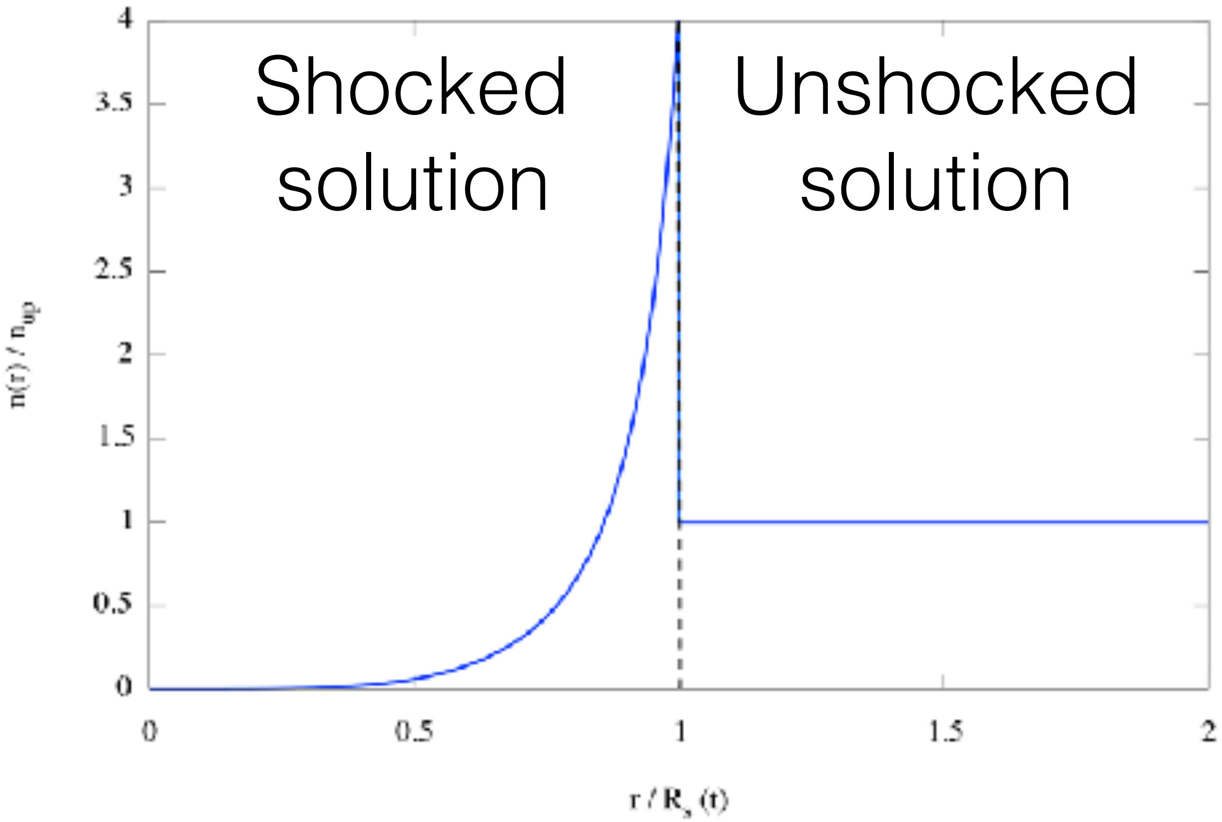
SOLID:
$R_1 = R_{SNR}$
$R_2 = 2R_{SNR}$

DASHED:
$R_1 = 2R_{SNR}$
$R_2 = 3R_{SNR}$

$$D(p) = 10^{27} \left(\frac{pc}{10\ \rm GeV} \right)^{1/3} \rm cm^2 s^{-1}$$

$T_{\rm SNR} = 10^4\,{\rm yr}$
$\xi_{\rm CR} = 10\%$
$n_{\rm up} = 1\,{\rm cm}^{-3}$

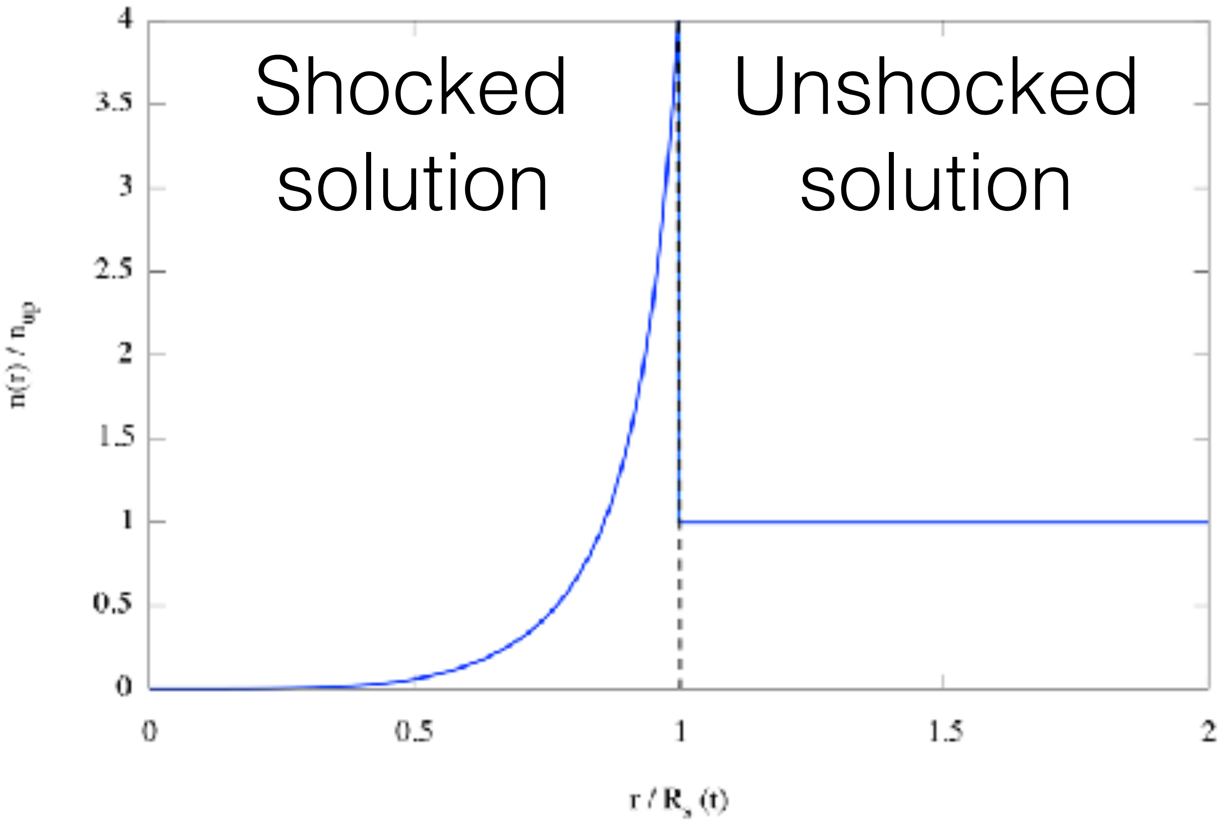
Volume integrated gamma-ray emission from hadronic interactions



Density profile of downstream medium

Sedov, New York Academic Press (1959)

Volume integrated gamma-ray emission from hadronic interactions



$$f_0(p) \propto p^{-4}$$

$$D(10\ \mathrm{GeV}/c) = 10^{27}\ \mathrm{cm^2 s^{-1}}$$

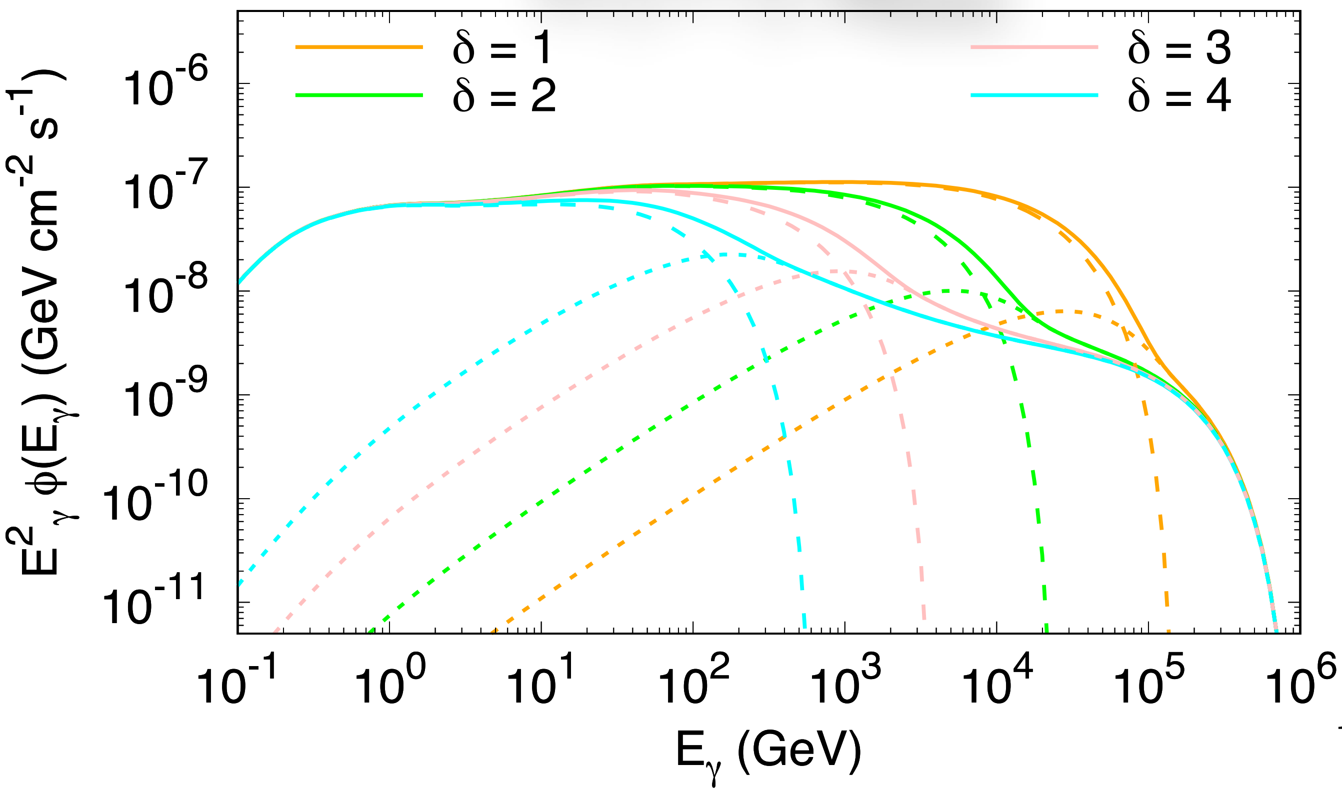
$$\xi_{\mathrm{CR}} = 10\%$$

$$n_{\mathrm{up}} = 1\ \mathrm{cm^{-3}}$$

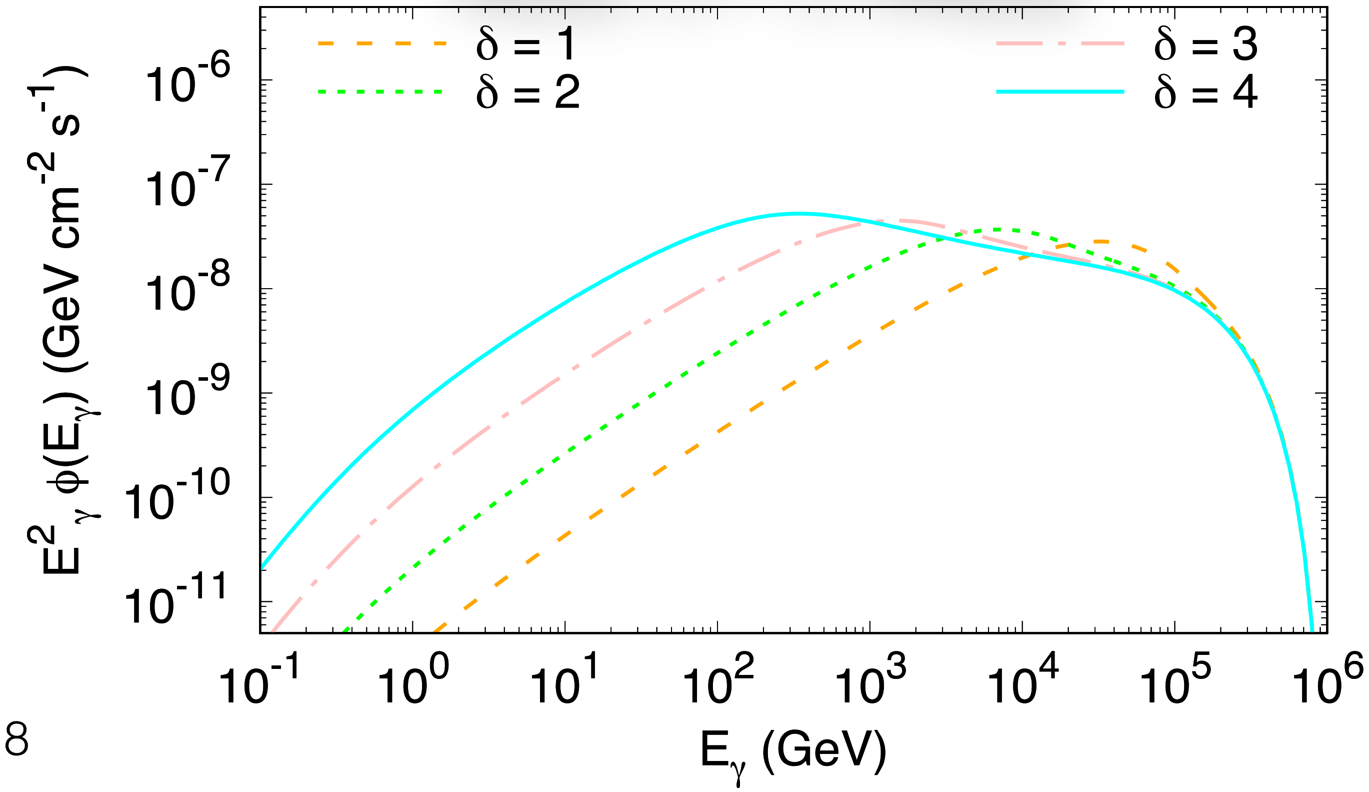
$$T_{\mathrm{SNR}} = 10^4\ \mathrm{yr}$$

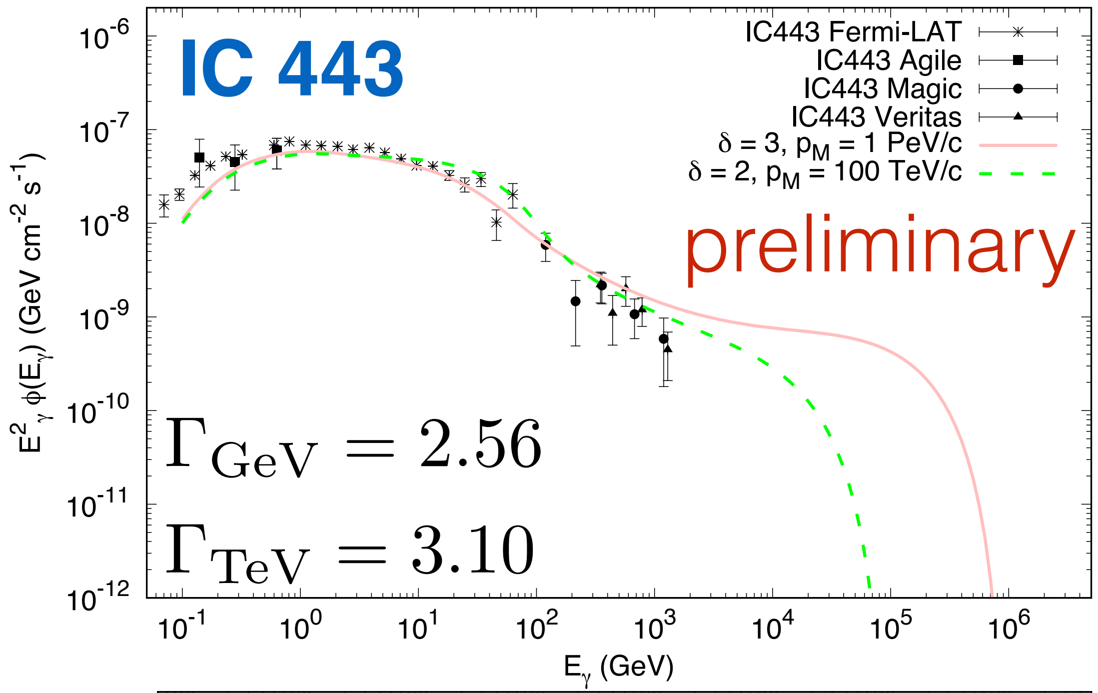
$$d = 1\ \mathrm{kpc}$$

$$0 \leq r \leq R_{\mathrm{SNR}}$$

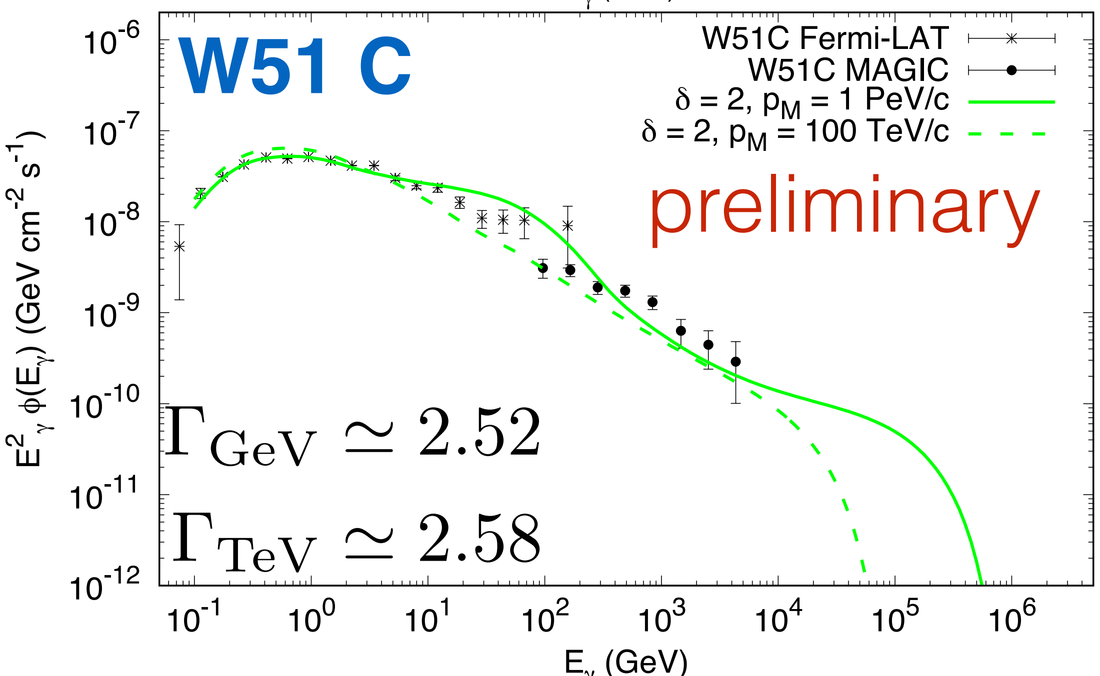


$$R_{\mathrm{SNR}} \leq r \leq 2R_{\mathrm{SNR}}$$

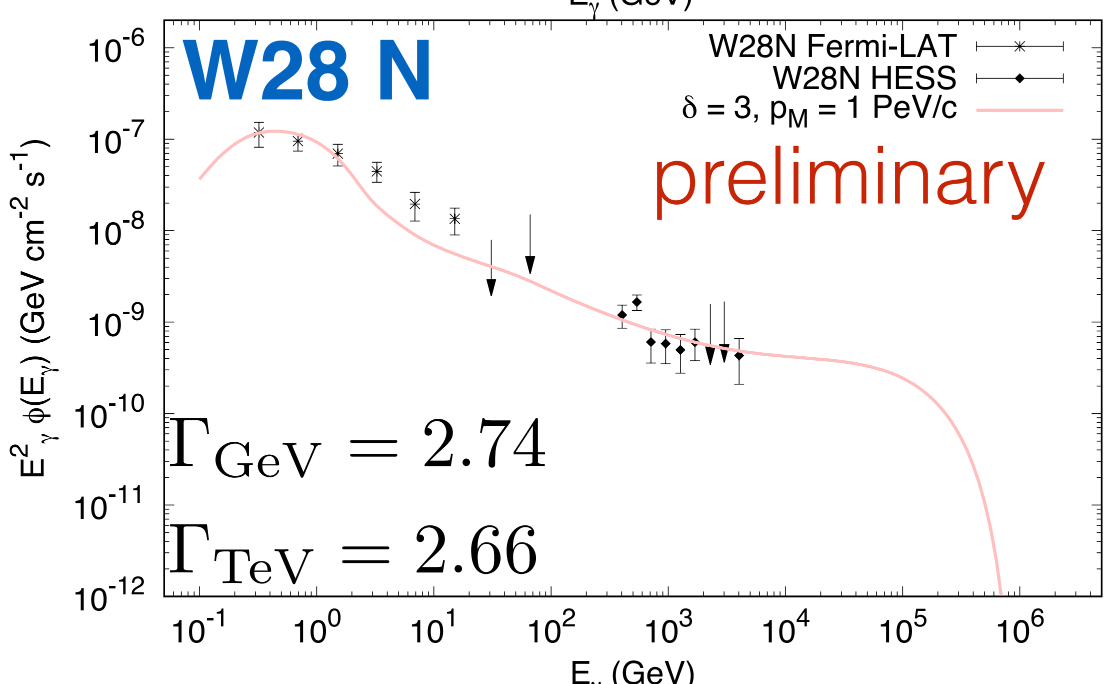




$$f_0(p) \propto p^{-4}$$
$$T_{\rm SNR} = 1.5 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$
$$d = 1.5\ {\rm kpc}, \xi_{\rm CR} = 2\%$$
$$D(10\ {\rm GeV}/c) = 10^{27}\ {\rm cm}^2{\rm s}^{-1}$$



$$f_0(p) \propto p^{-(4+1/3)}$$
$$T_{\rm SNR} = 3 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$
$$d = 5.4\ {\rm kpc}, \xi_{\rm CR} = 12\% - 15\%$$
$$D(10\ {\rm GeV}/c) = 3 \times 10^{26}\ {\rm cm}^2{\rm s}^{-1}$$



$$f_0(p) \propto p^{-4}$$
$$T_{\rm SNR} = 4 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$
$$d = 2.0\ {\rm kpc}, \xi_{\rm CR} = 15\%$$
$$D(10\ {\rm GeV}/c) = 3 \times 10^{27}\ {\rm cm}^2{\rm s}^{-1}$$

$$D/D_{\rm Gal} \leq 0.3$$

→ **Suppression of diffusion coefficient required:**

- local turbulence?
- CR-induced turbulence (streaming instability)?

Malkov et al., ApJ 768 (2013) 63

Nava et al., MNRAS 461 (2016) 3552N

D'Angelo et al., MNRAS 474 (2018) 1944D

$$\delta \geq 2$$

→ **How does turbulence evolve with time?**

Needs to include damping effects (MHD cascade, ion-neutral friction).

$$\xi_{\rm CR} \simeq 2 - 20\%$$

→ Standard assumption in the SNR paradigm for the origin of GCRs.

Conclusions

- The **escape process** is a key feature of the theory of particle acceleration, that requires specific treatment;

- Reasonable arrangement of parameters can explain the **steep spectra** observed in the **HE and VHE** emission of several middle-aged SNRs (IC 443, W 51C, W 28):
  ⟶ constraints on escape from SNR population studies?

- Results obtained can be used in the future as a strategy to search for **PeVatrons**: TeV halos around SNRs observable with CTA?