Particle escape from SNR shocks: gamma-ray and cosmic-ray signatures

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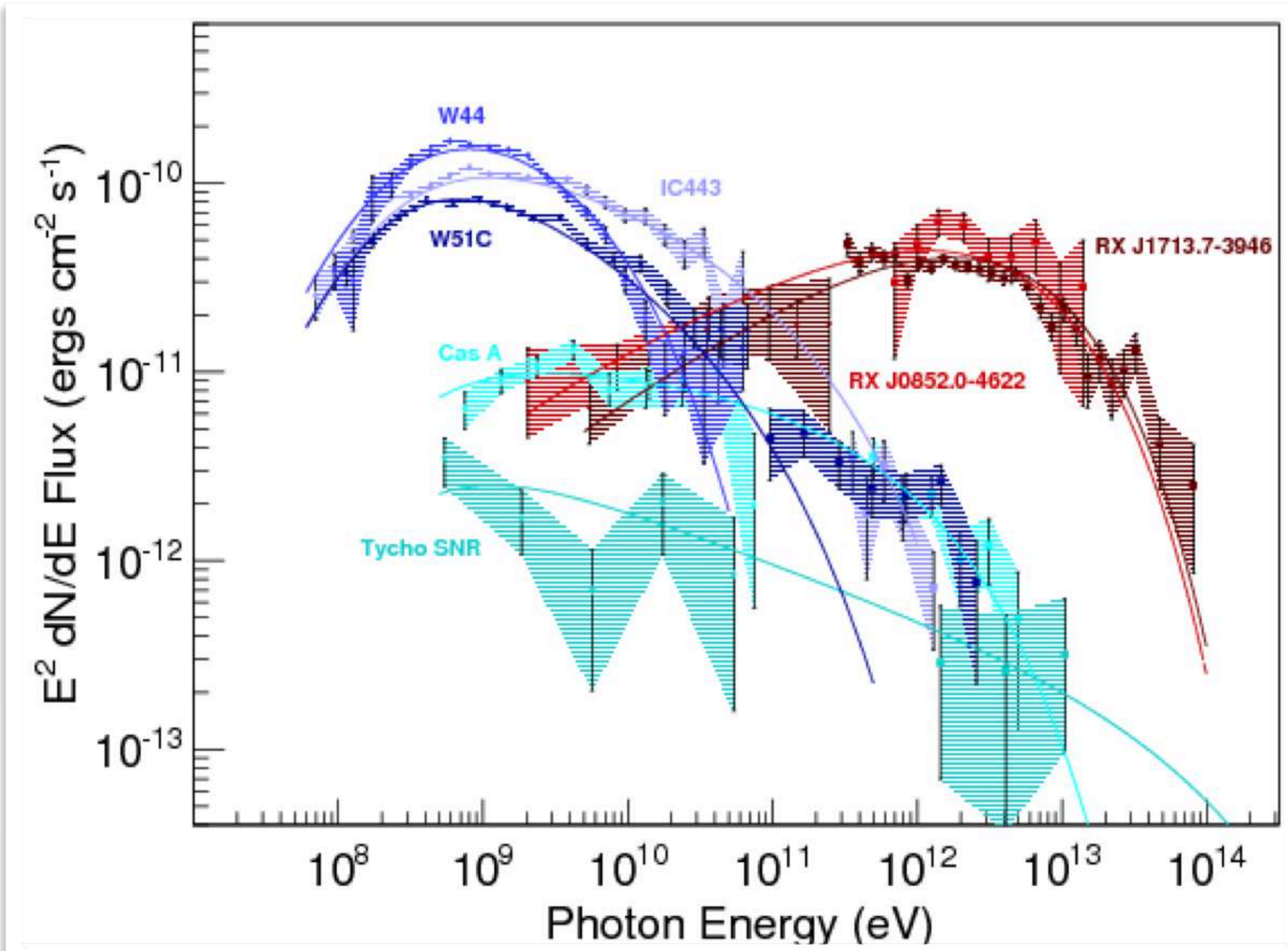
SNRs in the HE and VHE domain



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

How do accelerated particles become CRs?

Acceleration at the shock: $f_0(p)$

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

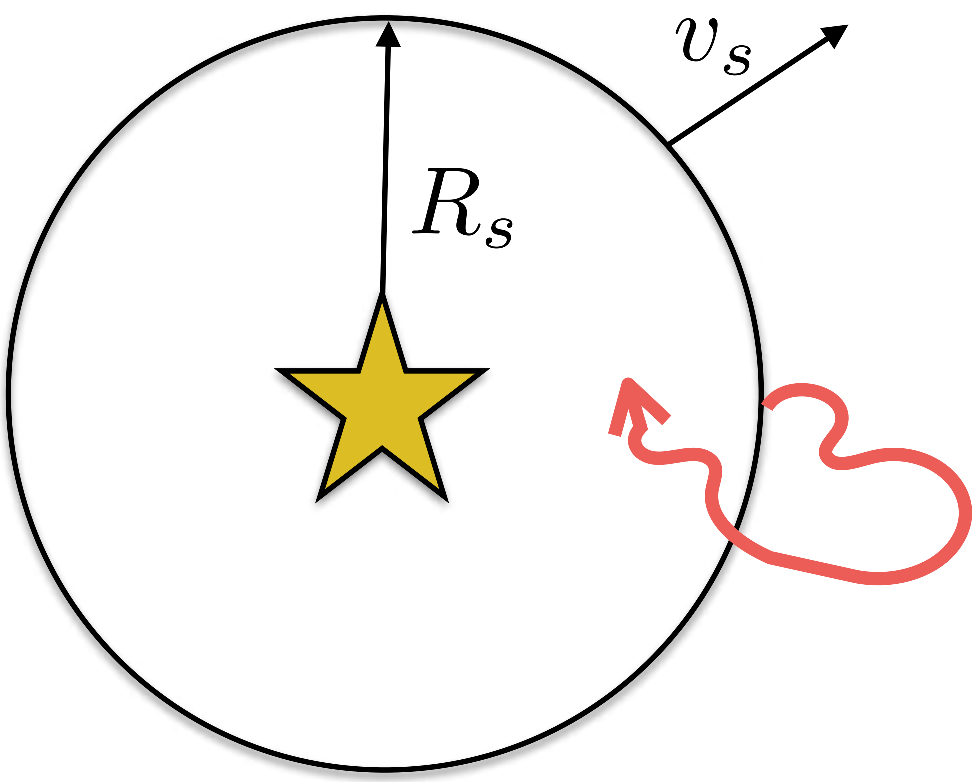
- Ptuskin & Zirakashvili, A&A 429 (2005) 755
- Gabici, Aharonian & Casanova, MNRAS (2009)
- Ohira, Murase & Yamakazi, A&A (2010) 513
- Bell & Shure, MNRAS 437 (2014) 2802
- Cardillo, Amato & Blasi, APh 69 (2015) 1
- Cristofari, Blasi & Caprioli, A&A 650A (2021) 62C

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

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

Celli et al., MNRAS 490 (2019) 4317C

Proton maximum energy in SNRs



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

acceleration limited by remnant age

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

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

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

ST stage: $v_{\rm s}(t) \propto t^{-3/5} \longrightarrow p_{\max,0} \propto \mathcal{F}(t) t^{-1/5}$

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

$\delta > 0$ →

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

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

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

A model for particle propagation

Analytical solution of the accelerated **proton** transport

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

$$v(t, r) = \left(1 - \frac{1}{\sigma}\right) \frac{v_{\rm sh}(t)}{R_{\rm sh}(t)} r$$

Particles confined inside the SNR

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

$$p \leq p_{\rm max,0}(t)$$

Escaped particles

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

$$p > p_{\rm max,0}(t)$$

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

Celli et al., MNRAS 490 (2019) 4317C

A model for particle propagation

Analytical solution of the accelerated **proton** transport

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

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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

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

Celli et al., MNRAS 490 (2019) 4317C

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

$$f_{0,\rm p}(t,p) = \frac{3\,\xi_{\rm CR}\rho_0 v_{\rm sh}^2(t)}{4\pi\,c(m_{\rm p}c)^4\Lambda(p_{\max,0}(t))}\left(\frac{p}{m_{\rm p}c}\right)^{-\alpha}\Theta\left[p_{\max,0}(t)-p\right]$$

acceleration efficiency constant in time

normalization factor such that $P_{\rm CR} = \xi_{\rm CR}\rho_0 v_{\rm sh}^2(t)$

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

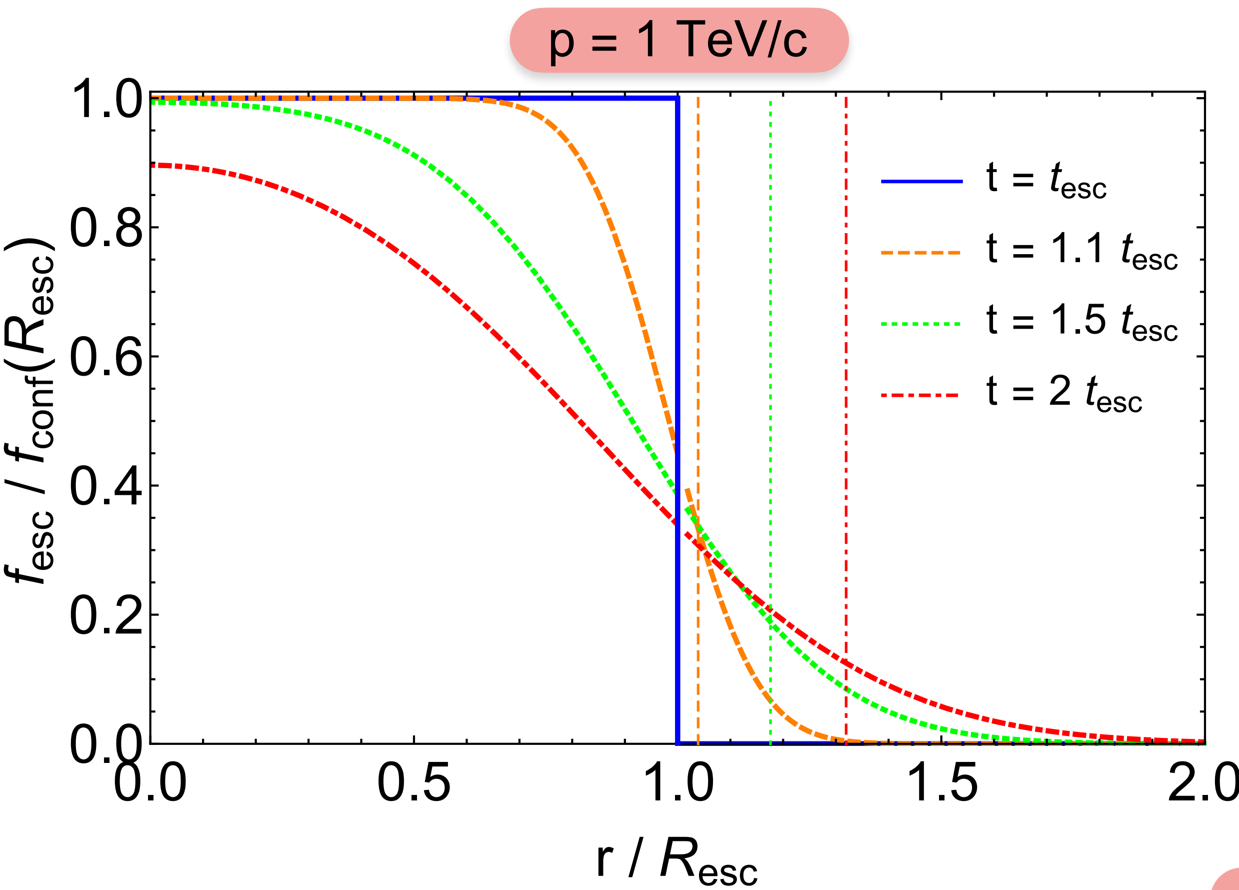
Ptuskin & Zirakashvili, A&A 429 (2005) 755

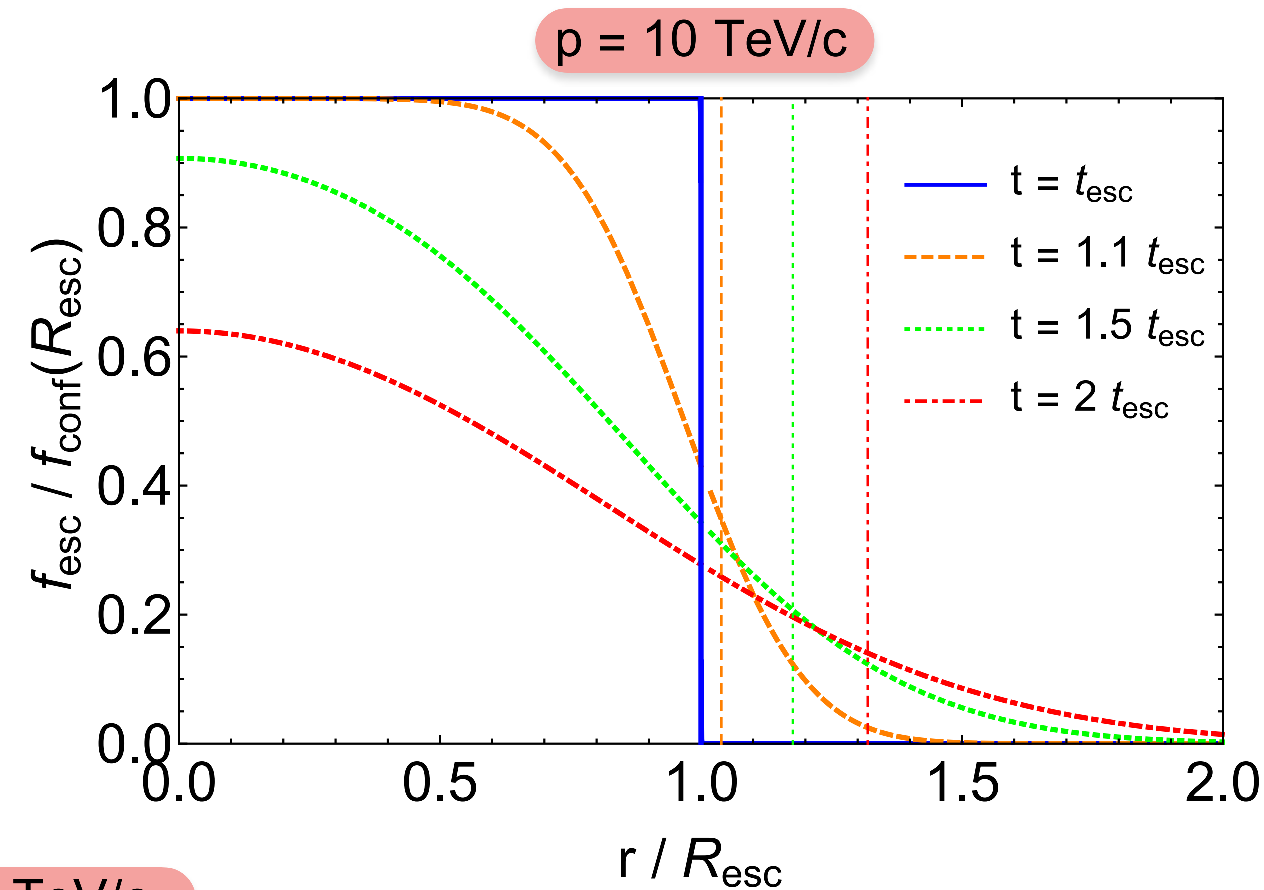
Assumption 4: the shock is evolving through the ST phase

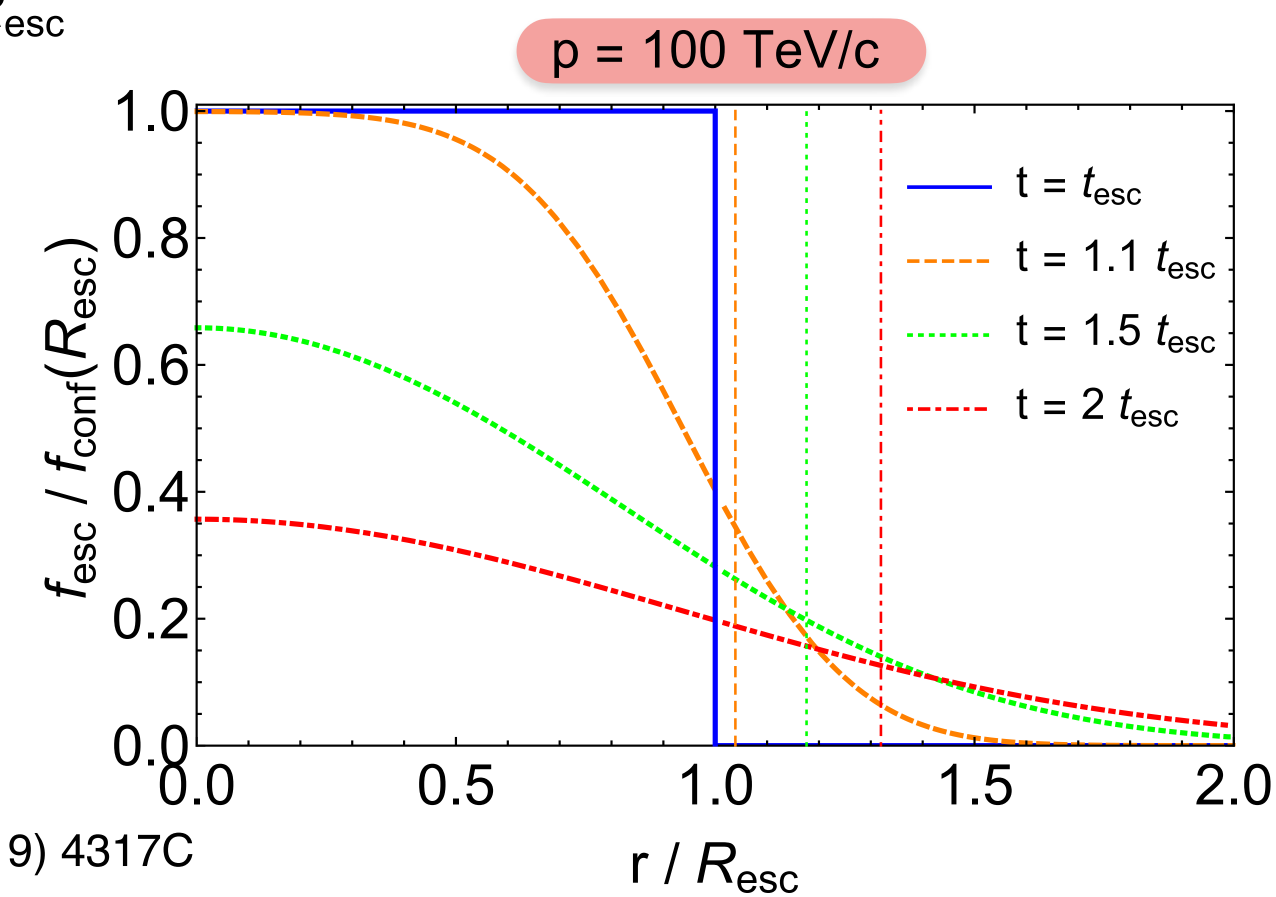
$$R_{\rm sh}(t) \propto t^{2/5} \qquad v_{\rm sh}(t) \propto t^{-3/5}$$

Celli et al., MNRAS 490 (2019) 4317C

Density of non-confined protons







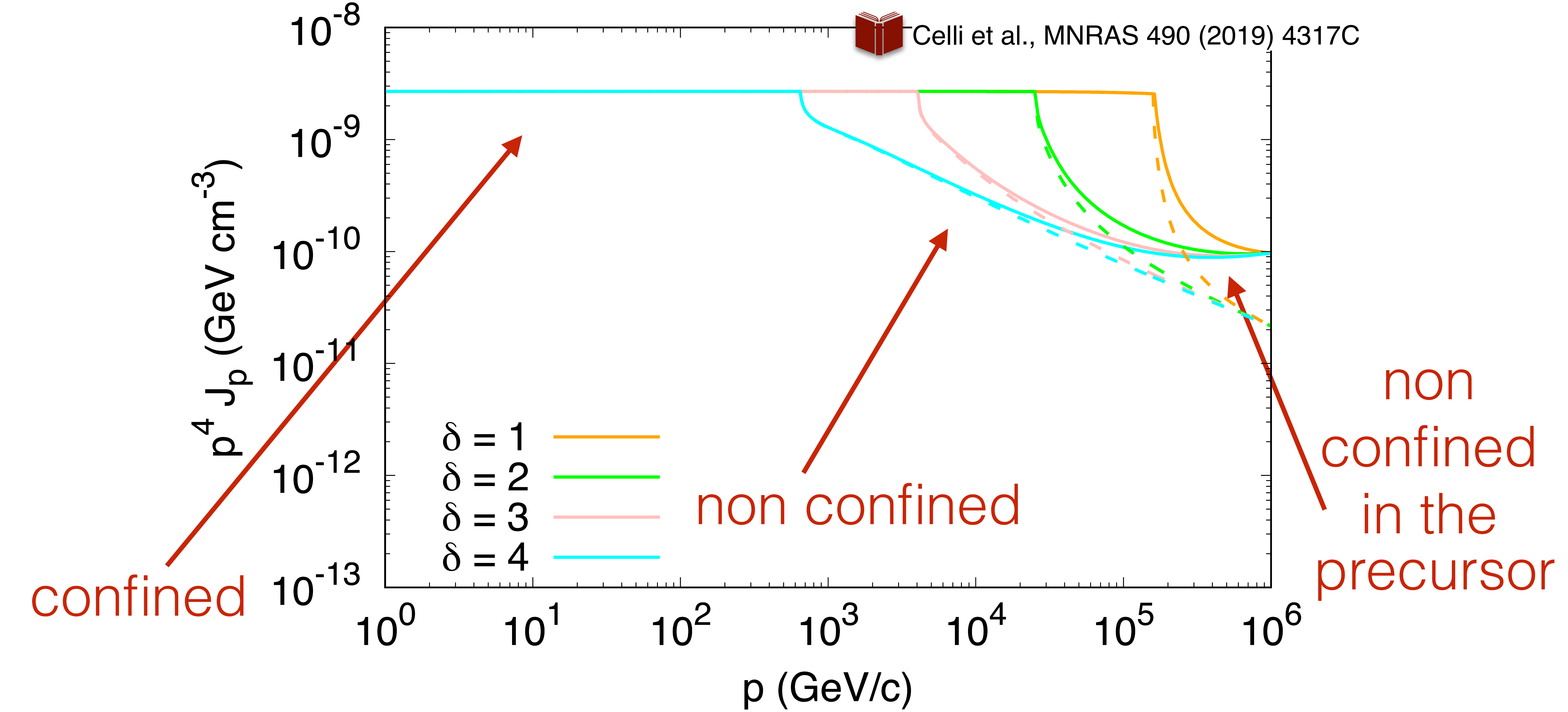
$\alpha = 4$

$\chi = 0.01$

Celli et al., MNRAS 490 (2019) 4317C

The spectrum of protons inside the SNR

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



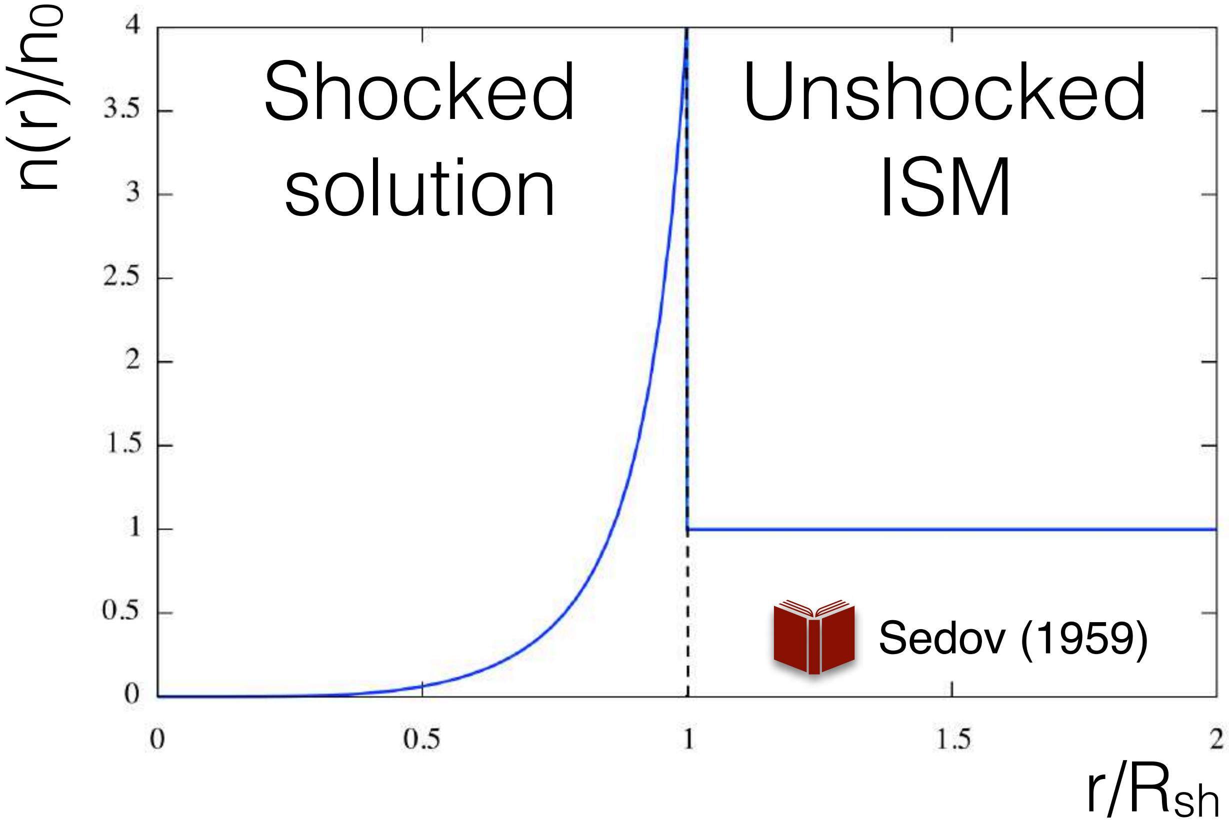
$$D(p) = 10^{27} \left(\frac{pc}{10\ \rm GeV} \right)^{1/3} \rm cm^2 s^{-1}$$

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

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

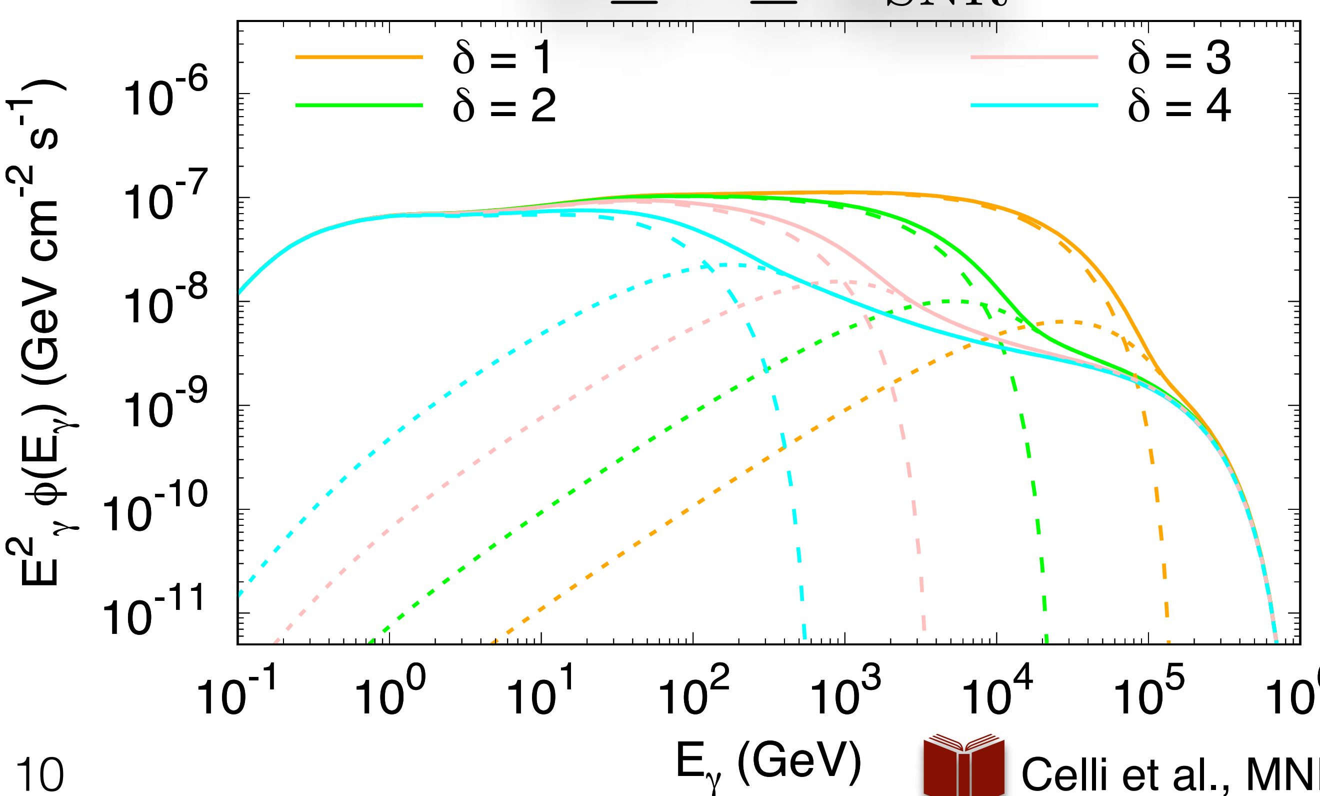
$n_0 = 1\,\rm cm^{-3}$

Volume integrated gamma-ray emission from hadronic (pp) interactions

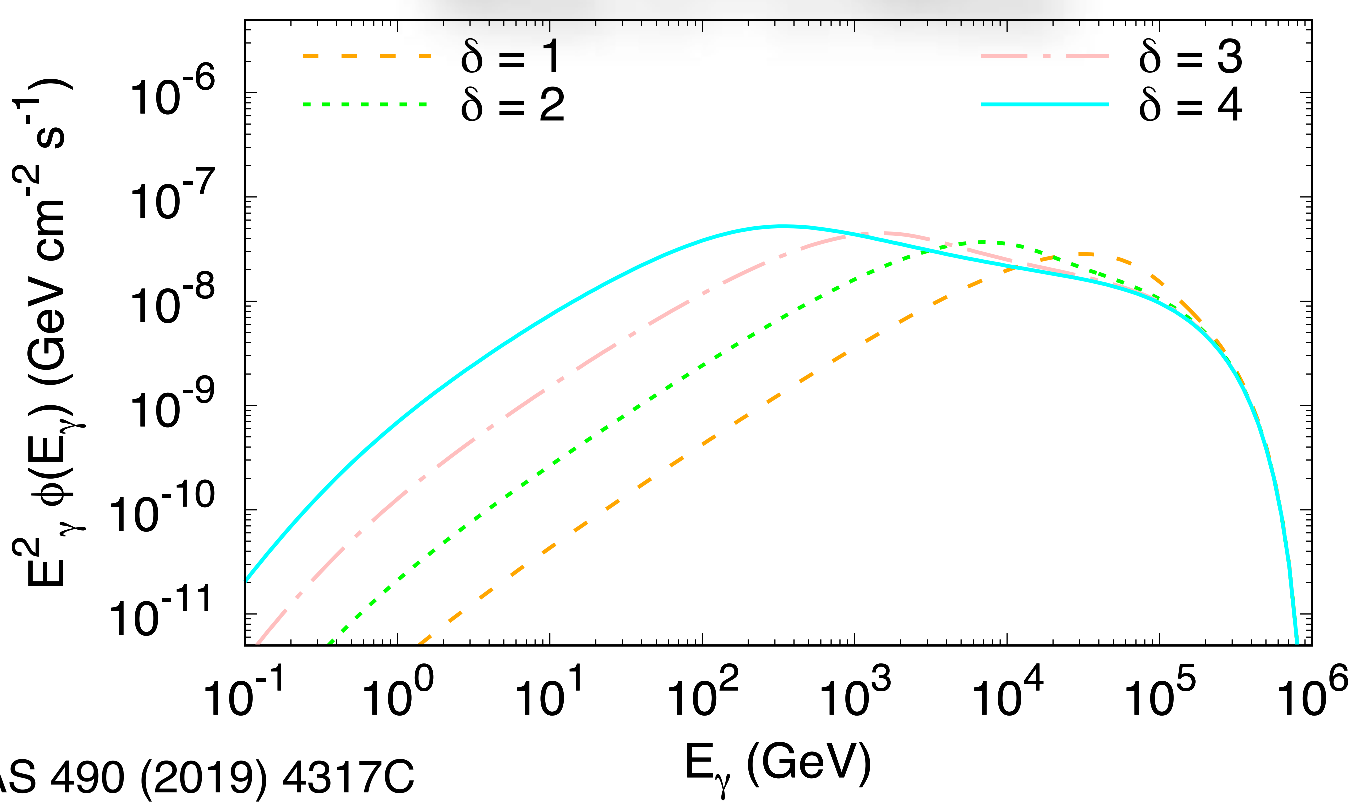


$$f_0(p) \propto p^{-4}$$
$$D(10\ \mathrm{GeV}/c) = 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$$
$$T_{\mathrm{SNR}} = 10^4\,\mathrm{yr}$$
$$n_0 = 1\,\mathrm{cm}^{-3}$$
$$\xi_{\mathrm{CR}} = 10\%$$
$$d = 1\,\mathrm{kpc}$$

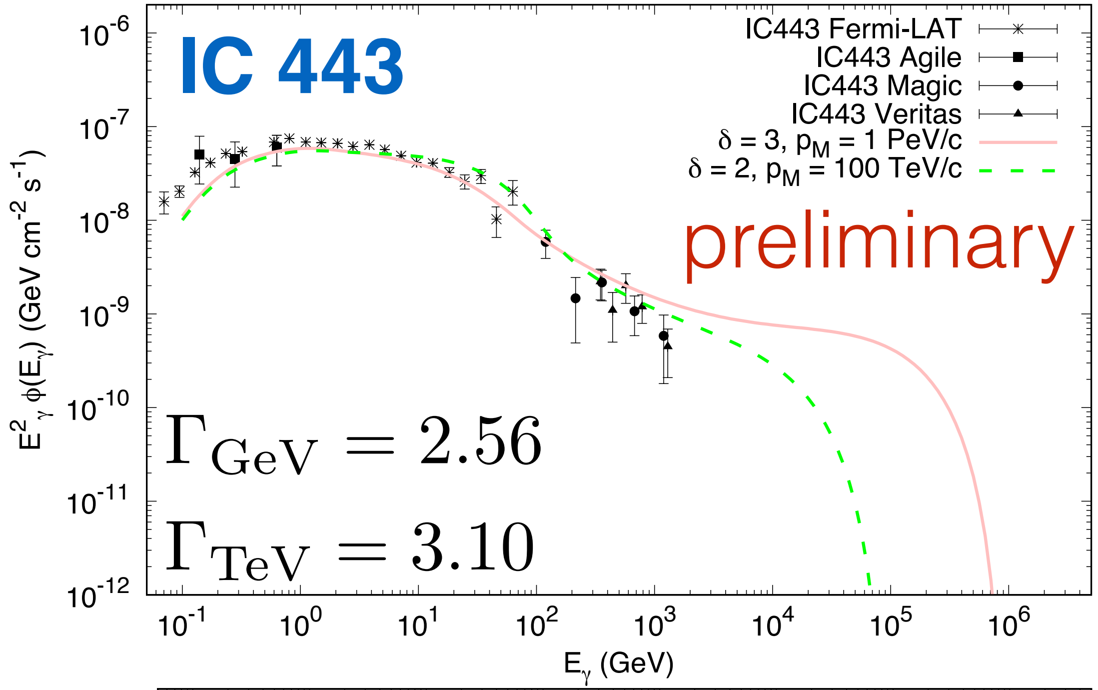
$0 \leq r \leq R_{\mathrm{SNR}}$



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



Celli et al., MNRAS 490 (2019) 4317C

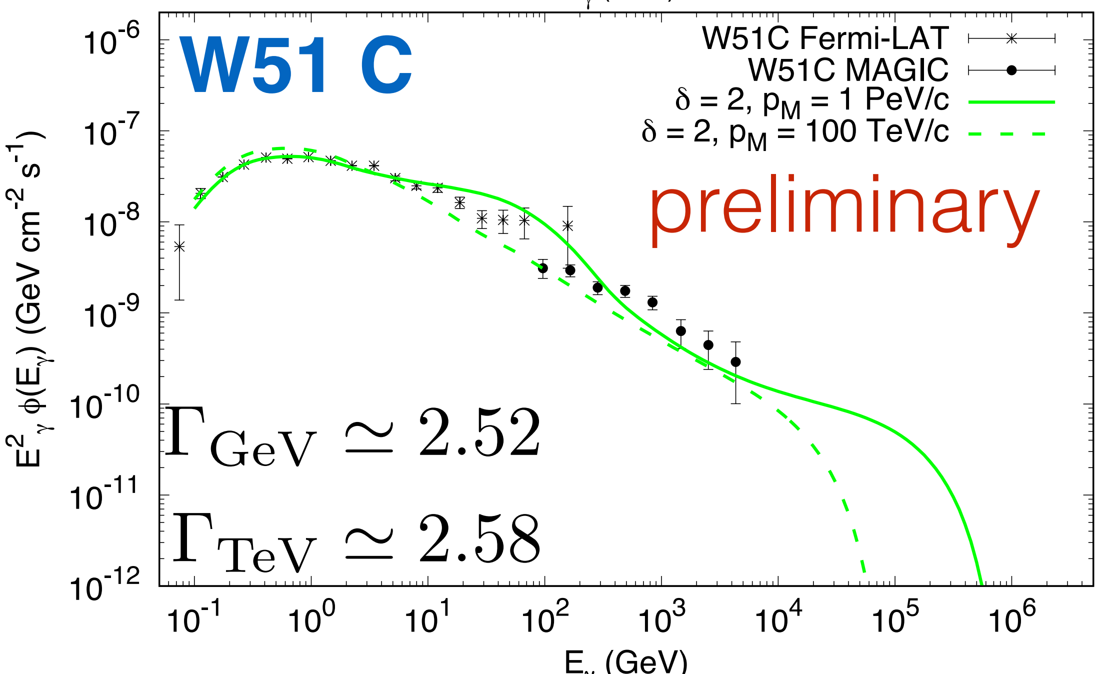


$$f_0(p) \propto p^{-4}$$

$$T_{\rm SNR} = 1.5 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$

$$d = 1.5\ {\rm kpc}, \xi_{\rm CR} = 2\%$$

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

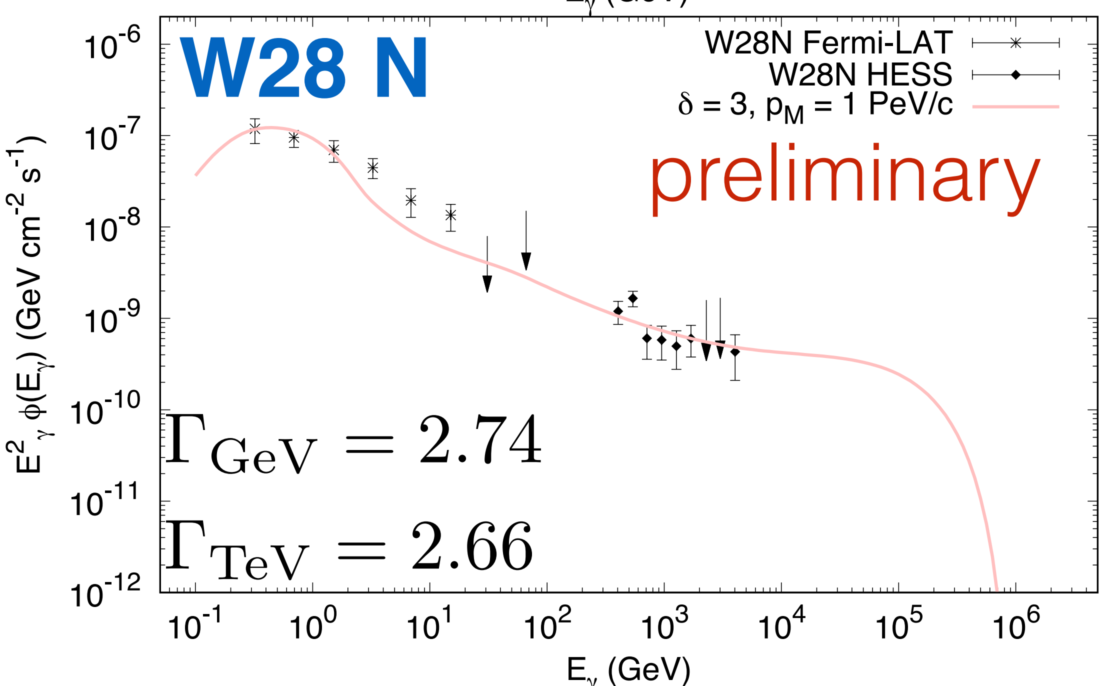


$$f_0(p) \propto p^{-(4+1/3)}$$

$$T_{\rm SNR} = 3 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$

$$d = 5.4\ {\rm kpc}, \xi_{\rm CR} = 12\% - 15\%$$

$$D(10\ {\rm GeV}/c) = 3 \times 10^{26}\ {\rm cm}^2{\rm s}^{-1}$$



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

$$T_{\rm SNR} = 4 \times 10^4\,{\rm yr}, n_{\rm up} = 10\ {\rm cm}^{-3}$$

$$d = 2.0\ {\rm kpc}, \xi_{\rm CR} = 15\%$$

$$D(10\ {\rm GeV}/c) = 3 \times 10^{27}\ {\rm cm}^2{\rm s}^{-1}$$

The CR-p spectrum injected into the Galaxy

$$f_{\rm inj}(p) = 4\pi \int_0^{R_{\rm esc}(p)} r^2 f_{\rm conf}\left(t_{\rm esc}(p), r, p\right) dr$$

$$\longrightarrow f_{\rm inj}(p) \propto v^2_{\rm esc}(p) R^3_{\rm esc}(p) \frac{p^{-\alpha}}{\Lambda(p)}$$

$$\longrightarrow f_{\rm inj}(p) \propto \frac{p^{-\alpha}}{\Lambda(p)}$$

Exact balance between v^2_{esc} and R^3_{esc} during the ST phase

- Ultra-relativistic limit ($p \gg m_p c$): $$f_{\rm inj}(p) \propto \begin{cases} p^{-\alpha} & \alpha > 4 \\ p^{-4} & \alpha < 4 \end{cases}$$

Bell & Shure, MNRAS 437 (2014) 2802

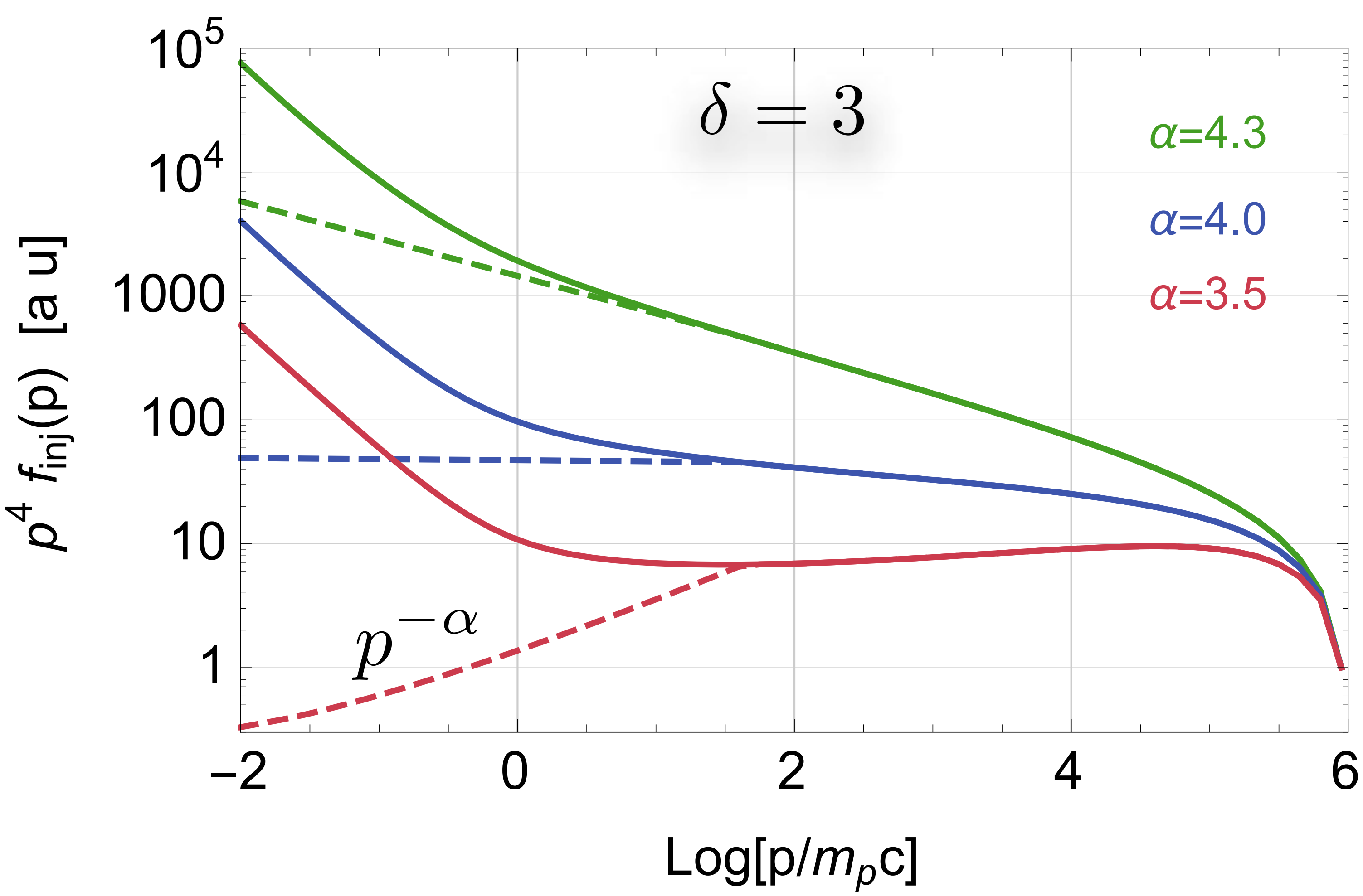
Cardillo, Amato & Blasi, APh 69 (2015) 1

Celli et al., MNRAS 490 (2019) 4317C

The CR-p spectrum injected into the Galaxy

The end of the acceleration phase produces visible signatures on the spectrum of the injected particles. Assuming this happens at t_{SP}

$$T \leq 10^6\,\mathrm{K},\ v_s \simeq 200\,\mathrm{Km/s} \longrightarrow p_{\max,0}(t_{SP}) \simeq 40\ \mathrm{GeV/c}$$



⟶ particles with $p < p_{\max,0}(t_{SP})$ do not suffer further adiabatic losses as they are instantaneously released into the ISM

Celli et al., MNRAS 490 (2019) 4317C

$^* t_{SP} \simeq 47\,\mathrm{kyr}$

Electron transport and E_{max} in SNRs

Radiative + adiabatic losses

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\text{syn+IC}} + \frac{E}{L}\frac{\mathrm{d}L}{\mathrm{d}t}$$

Reynolds, ApJ 493 (1998) 375

Morlino & Caprioli, A&A 538 (2012) 381

$$\longrightarrow f_{e,\text{conf}}(E,r,t) = f_{e,0}\left(\frac{E}{L(t',t)-IE}, t'\right)\frac{L^4}{(L-IE)^2}$$

TIME-LIMITED ACCELERATION: $f_{e,0}(p) = K_{\text{ep}}\, f_{p,0}(p)\, e^{-\left(\frac{p}{p_{\text{max,e,0}}}\right)}$

LOSS-LIMITED ACCELERATION: $f_{e,0}(p) = K_{\text{ep}}\, f_{p,0}(p)\left[1 + 0.523\,(p/p_{\text{max,e,0}})^{\frac{9}{4}}\right]^2 e^{-\left(\frac{p}{p_{\text{max,e,0}}}\right)^2}$

Aharonian et al., A&A 465 (2007) 695

Blasi, MNRAS 402 (2010) 2807

Radiative losses in the proton self-amplified magnetic field and radiation fields strongly affect the electron **maximum energy**:

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\text{syn+IC}} = -\frac{\sigma_{\text{T}} c}{6\pi}\left(\frac{E}{m_{\text{e}}c^2}\right)^2\left(B^2 + B_{\text{eq}}^2\right)$$

$$t_{\text{acc}} = t_{\text{loss}} \longrightarrow \frac{E_{\text{max,0,e}}(t)}{m_e c^2} = \sqrt{\frac{(\sigma-1)r_{\text{B}}}{\sigma\left[r_{\text{B}}(1+\sigma_{\text{eq}}^2) + \sigma(r_{\text{B}}^2 + \sigma_{\text{eq}}^2)\right]}\frac{6\pi e B_0 \mathscr{F}(t)}{\sigma_{\text{T}} B_{1,\text{tot}}^2(t)}\frac{v_{\text{sh}}(t)}{c}}$$

Electron transport and E_{max} in SNRs

The **CR self-amplified** magnetic field at the shock is given by:

$$t_{acc} = t_{SNR} \longrightarrow \mathcal{F}(t) = \frac{8\, p_M c}{3\, e B_0\, c\, t_{Sed}} \begin{cases} \left(\frac{v_{sh}}{c}\right)^{-2} & t < t_{Sed} \\ \left(\frac{v_{sh}}{c}\right)^{-2} \left(\frac{t}{t_{Sed}}\right)^{\delta-1} & t \geq t_{Sed} \end{cases}$$

$$\longrightarrow \delta B_1(t) = \frac{B_0}{2}\left(\mathcal{F}(t) + \sqrt{4\mathcal{F}(t) + \mathcal{F}^2(t)}\right)$$

In the shock **downstream**, magnetic field compression and adiabatic losses are included such that

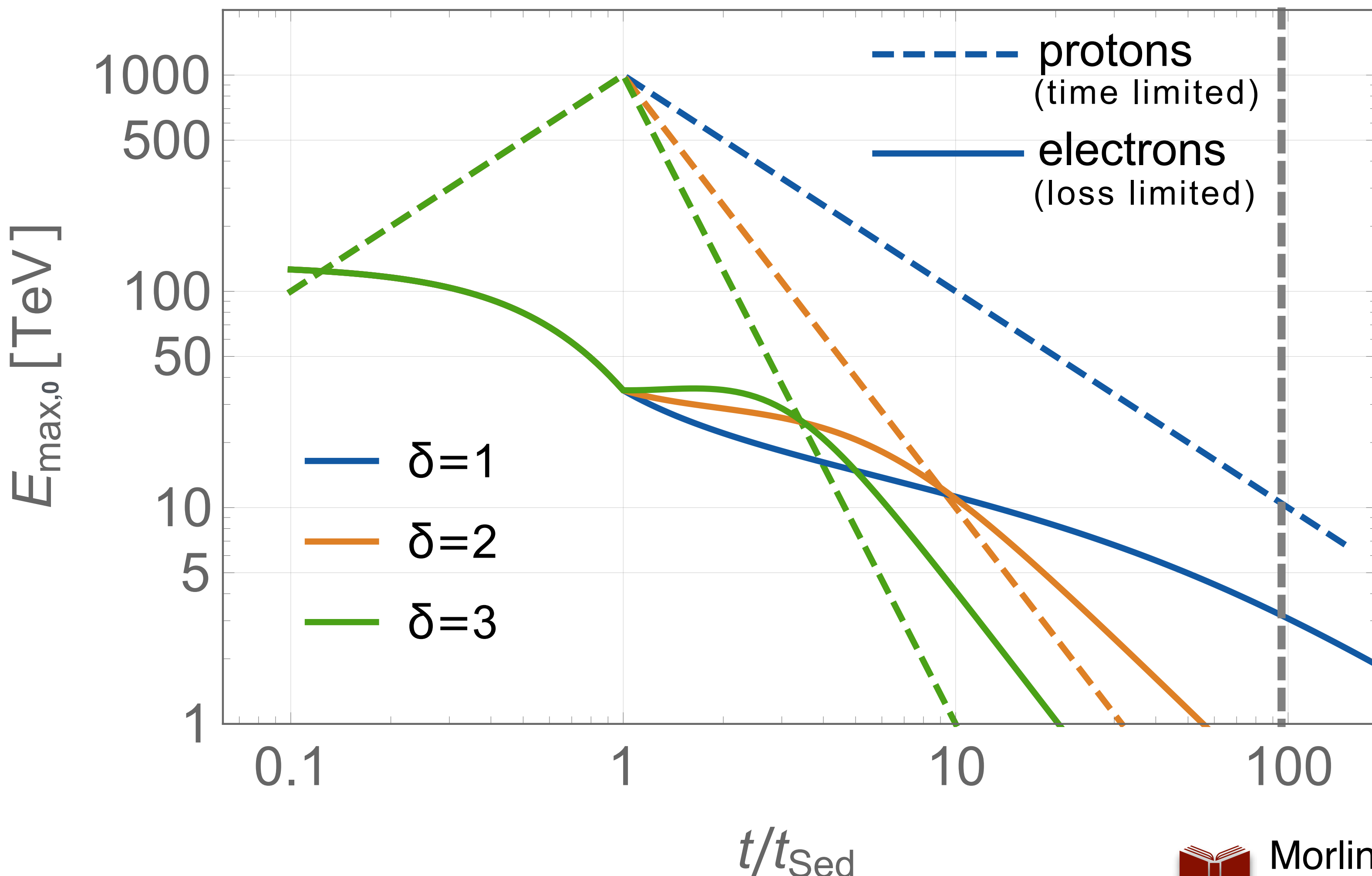
$$B_2^2(r,t) = \frac{B_0^2}{3}\left[\left(\frac{R_{sh}(t)}{r}\right)^4 + 2\sigma^2 L^6(t',t)\left(\frac{R_{sh}(t)}{r}\right)^2\right]$$

where $L(t',t) = \left[\frac{\rho_2(t,r)}{\rho_2(t'(t,r))}\right]^{1/3} \Longrightarrow L(t',t) = \left[\frac{R_{sh}(t')}{R_{sh}(t)}\right]^{3/4}$ accounts for continuous adiabatic energy losses between t' and t.

Morlino & Celli, MNRAS 508 (2021) 6142M

Solving electron propagation

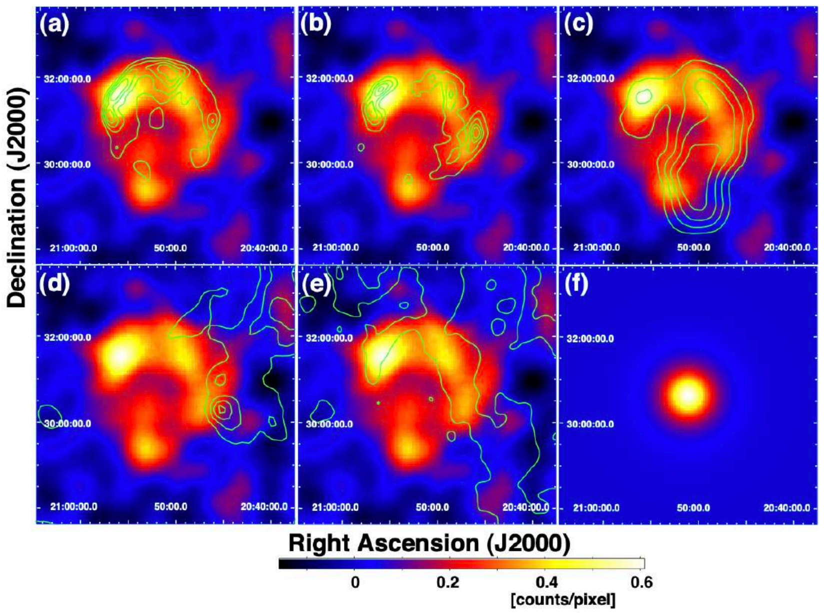
Numerical solution of the transport equation for accelerated **electrons**, including radiative and adiabatic losses

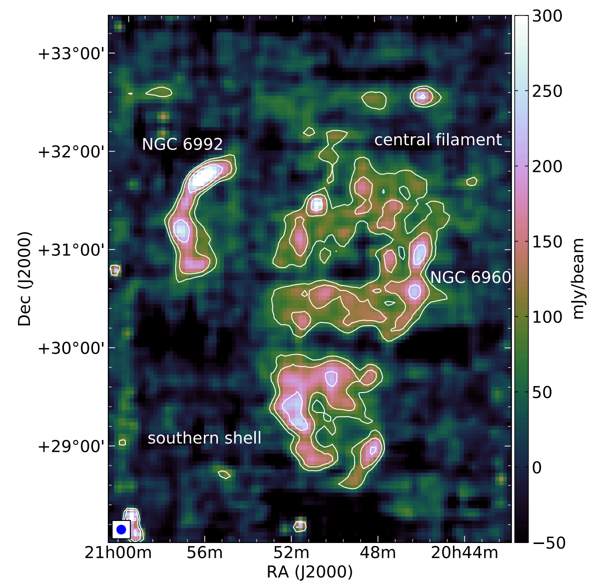


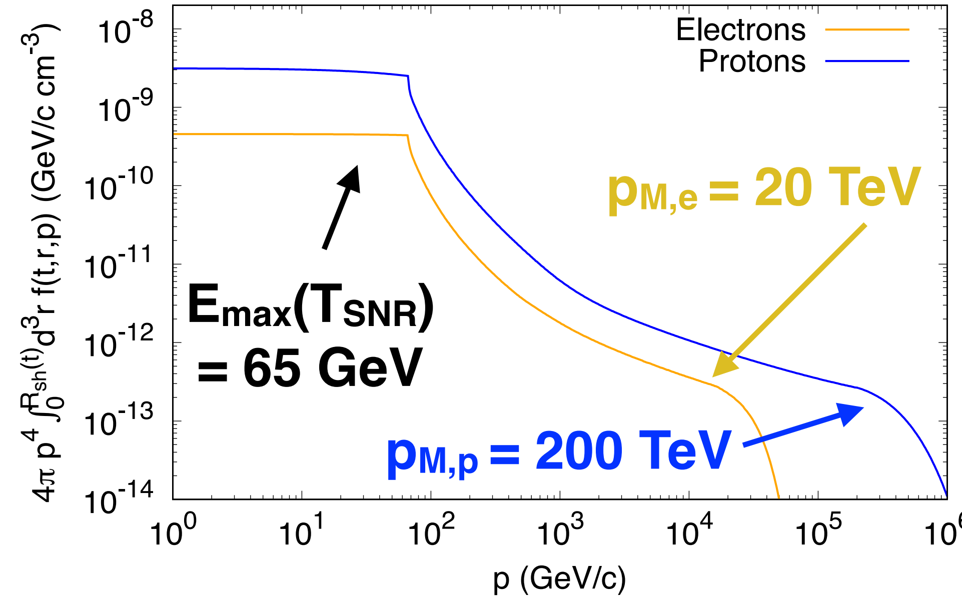
Morlino & Celli,
MNRAS 508 (2021) 6142M

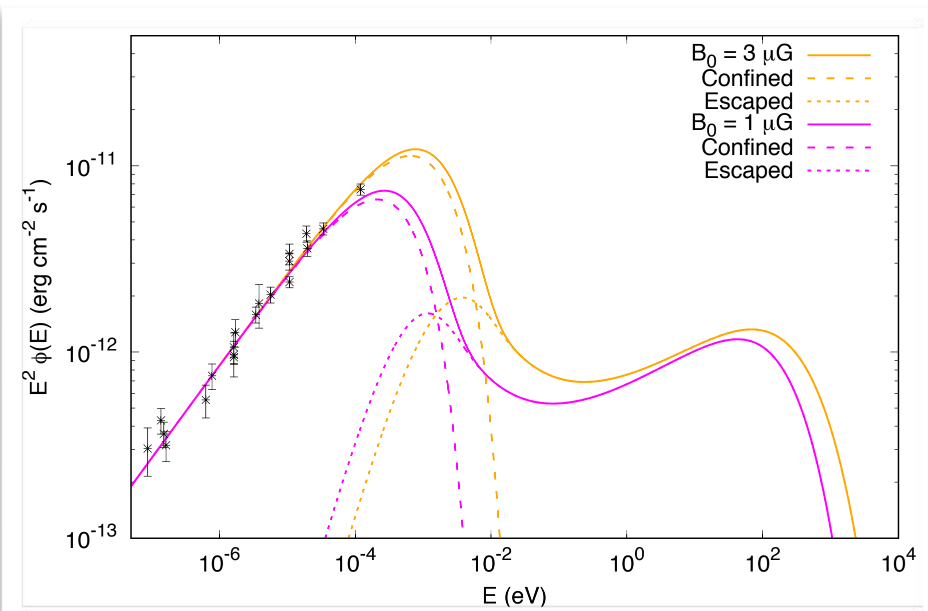
$$\frac{E_{\mathrm{max,0,e}}(t)}{m_e c^2} = \sqrt{\frac{(\sigma-1)r_{\mathrm{B}}}{\sigma\left[r_{\mathrm{B}}(1+\sigma_{\mathrm{eq}}^2)+\sigma(r_{\mathrm{B}}^2+\sigma_{\mathrm{eq}}^2)\right]}\,\frac{6\pi e B_0 \mathscr{F}(t)}{\sigma_{\mathrm{T}} B_{1,\mathrm{tot}}^2(t)}\,\frac{v_{\mathrm{sh}}(t)}{c}}$$

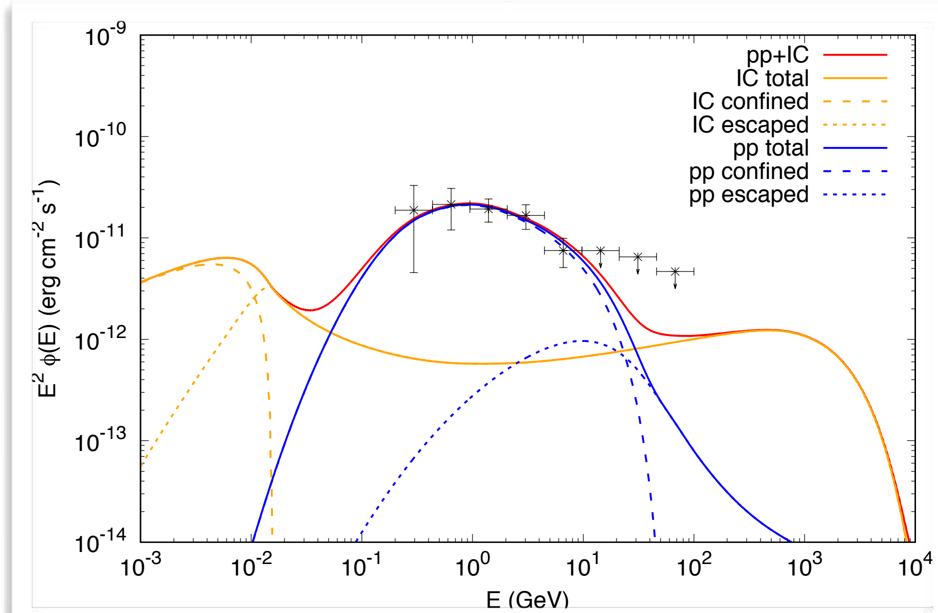
Cygnus Loop: particles and radiation







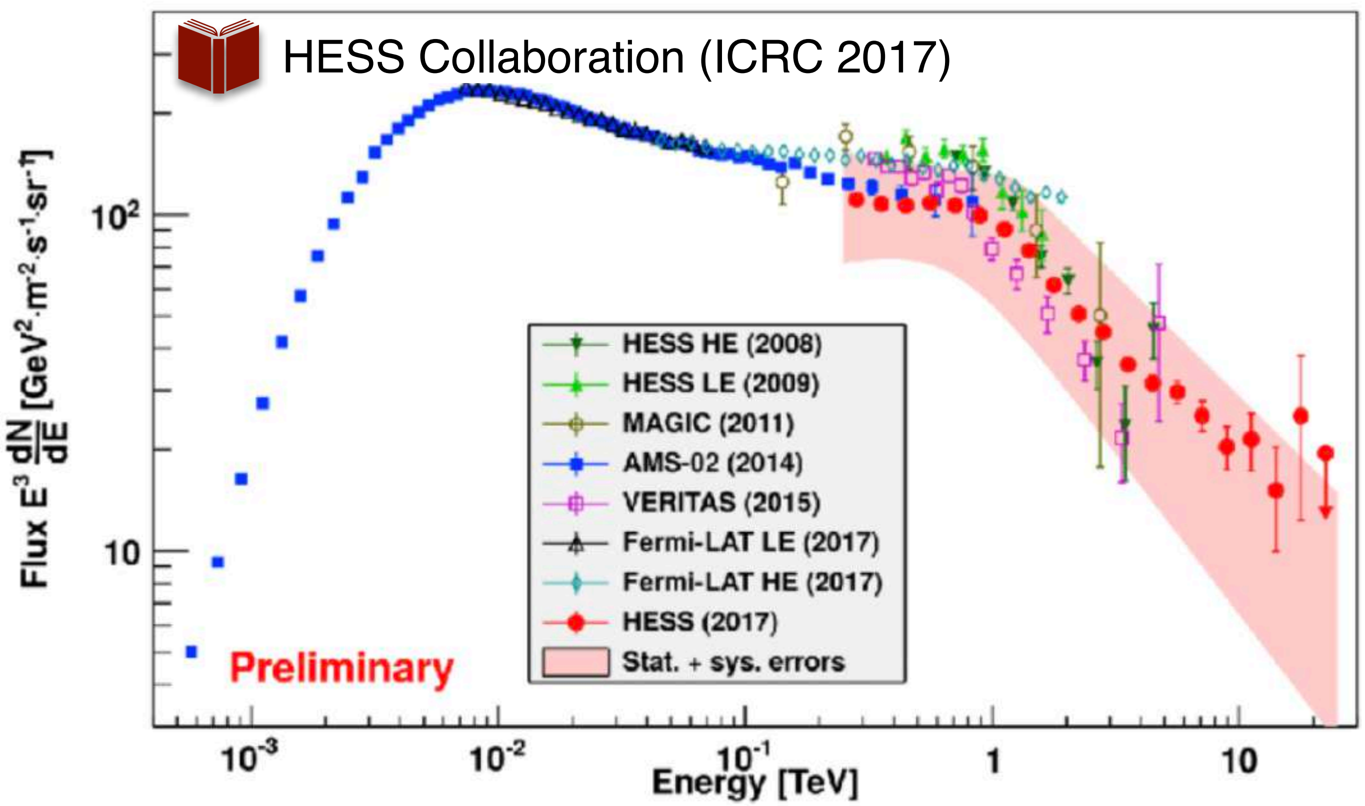




Loru et al., MNRAS 500 (2020) 5177

Cygnus Loop properties							Acceleration model parameters						
Assumed					Derived								
E_{SN}	M_{ej}	t_{age}	d	n_0	R_{sh}	u_{sh}	ξ_{CR}	s	E_M	δ	K_{ep}	B_0	χ
7×10^{50} erg	$5\,M_\odot$	2.1×10^4 yr	735 pc	0.4 cm^{-3}	20 pc	380 km s^{-1}	0.07	4.0	200 TeV	3	0.15	3 μG	1

The observed CR-e spectrum

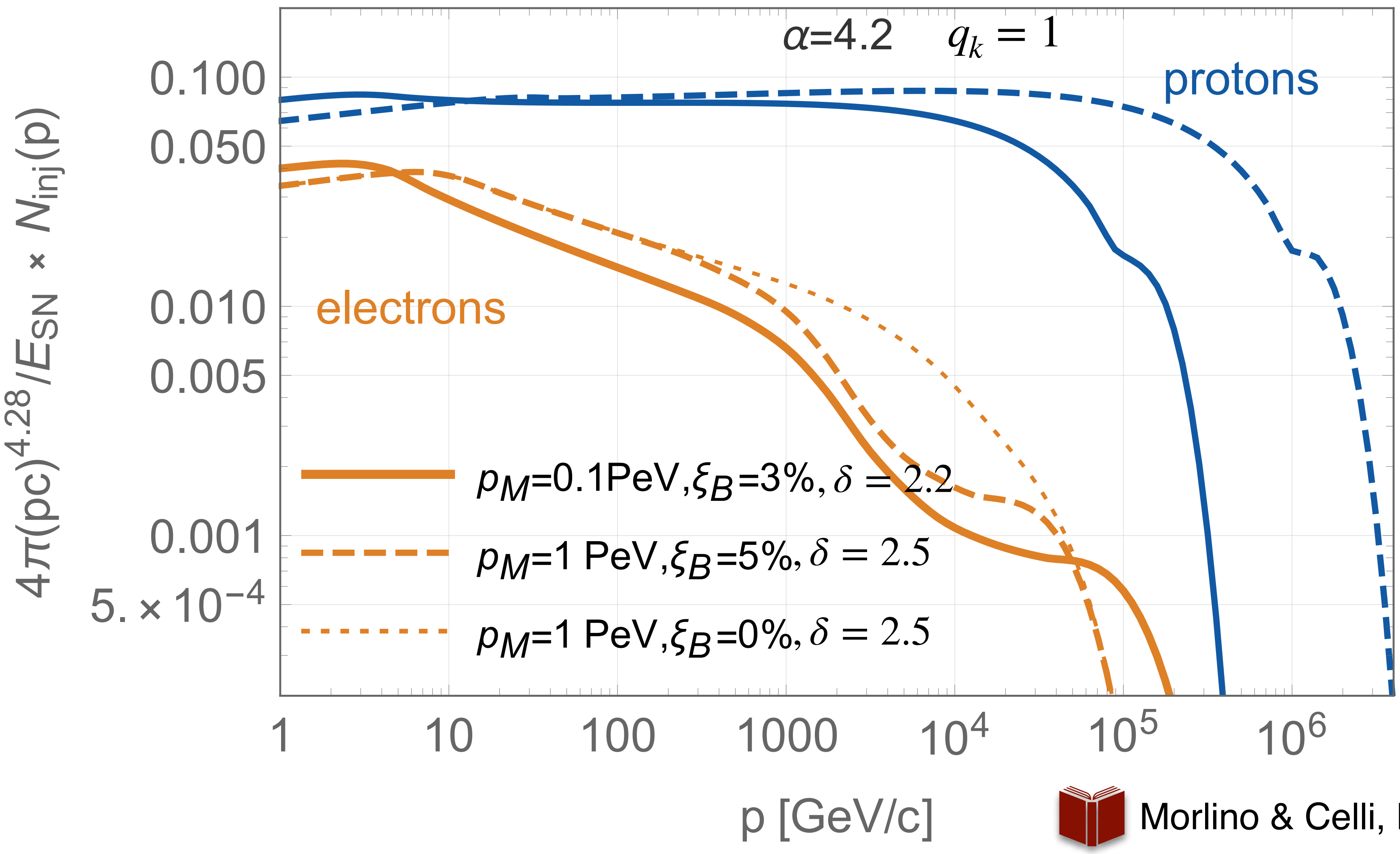


Many works on theoretical interpretation:

- Manconi et al., JCAP (2019) 024
- Diesing & Caprioli, PRL 123 (2019) 071101
- Recchia et al., PRD 99 (2019) 103022
- Brose et al., A&A 634 (2020) 359
- Di Mauro et al., PRD 8 (2020) 083012
- Fornieri et al., JCAP (2020) 009
- Cristofari, Blasi & Caprioli, A&A 650A (2021) 62C
- Evoli et al., PRD 103 (2021) 083010
- Morlino & Celli, MNRAS 508 (2021) 6142M

- Origin of the **spectral steepening** of the CR-electron spectrum above 10 GeV?
- Origin of the **TeV suppression** in the CR-electron spectrum?

The CR-e spectrum injected into the Galaxy



Morlino & Celli, MNRAS 508 (2021) 6142M

Turbulent MHD amplification:

$$\frac{\delta B^2_{2,\mathrm{tur}}}{8\pi} = \xi_B \frac{1}{2}\rho v_{\mathrm{sh}}^2$$

Time dependent e/p injection:

$$\frac{\xi_{\mathrm{CRe}}}{\xi_{\mathrm{CRp}}} = v_{\mathrm{esc}}(p)^{-q_k} \propto p^{-3q_k/(5\delta)} \equiv p^{-\Delta s_{\mathrm{ep}}}$$

Conclusions

- Particle **escape** is still nowadays a poorly understood mechanism, though strongly embedded in the process of particle acceleration, mainly because of its dependence on the temporal evolution of the magnetic turbulence.

- Modelling is needed for interpreting the **steep spectra** and low **maximum energy** observed in the **HE** and **VHE** emission of many middle-aged SNRs (e.g. IC443, W28, W51C, Cygnus Loop).

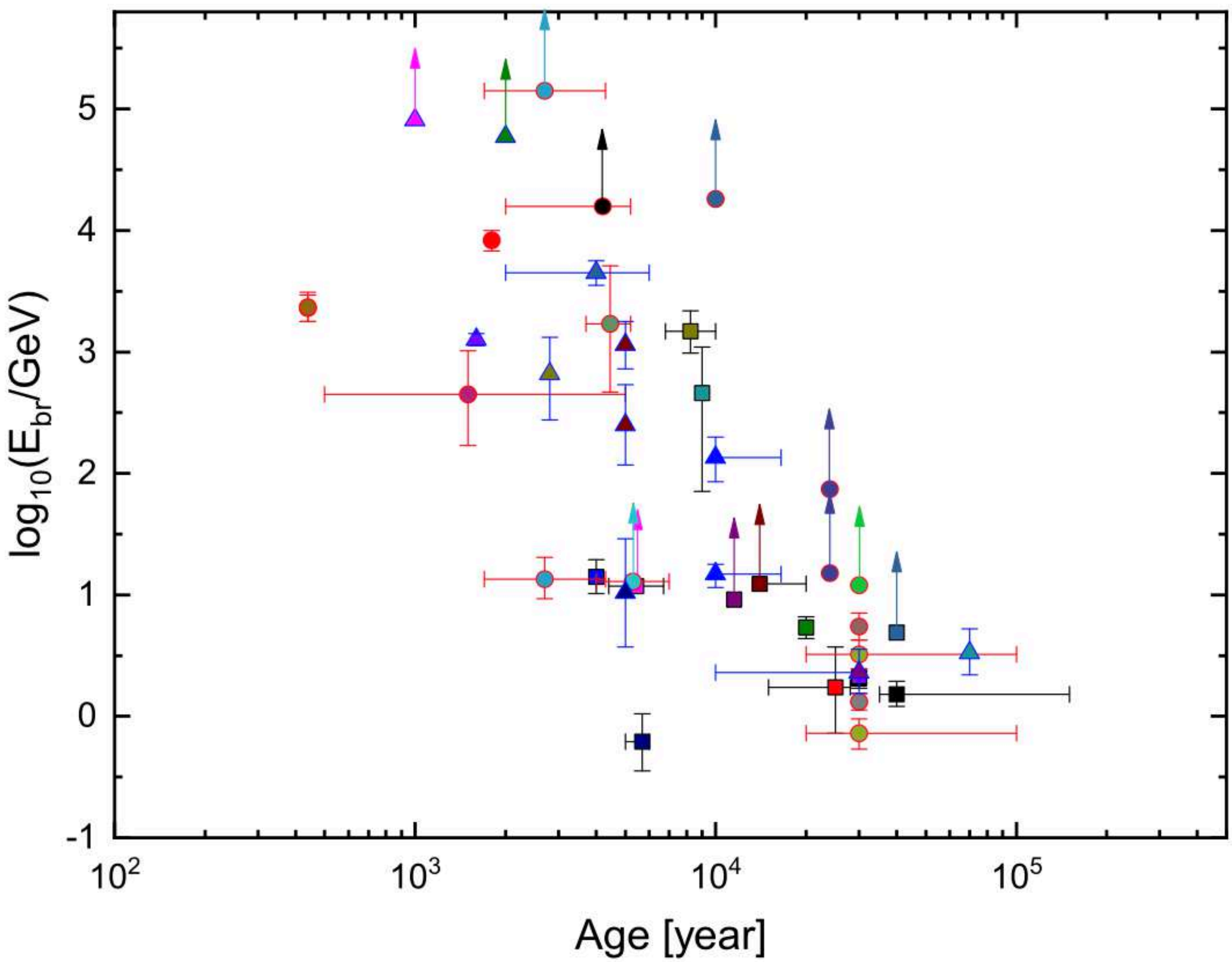
- Escape studies can also shed light on the nature of **magnetic field amplification** and **particle injection** in CR accelerators.

- Results obtained can be used as a strategy to search for **PeV CR-proton accelerators**:
  - TeV halos around young-middle aged SNRs (LHAASO, CTA);
  - Passive molecular clouds illuminated by PeVatrons.


Thank
You!

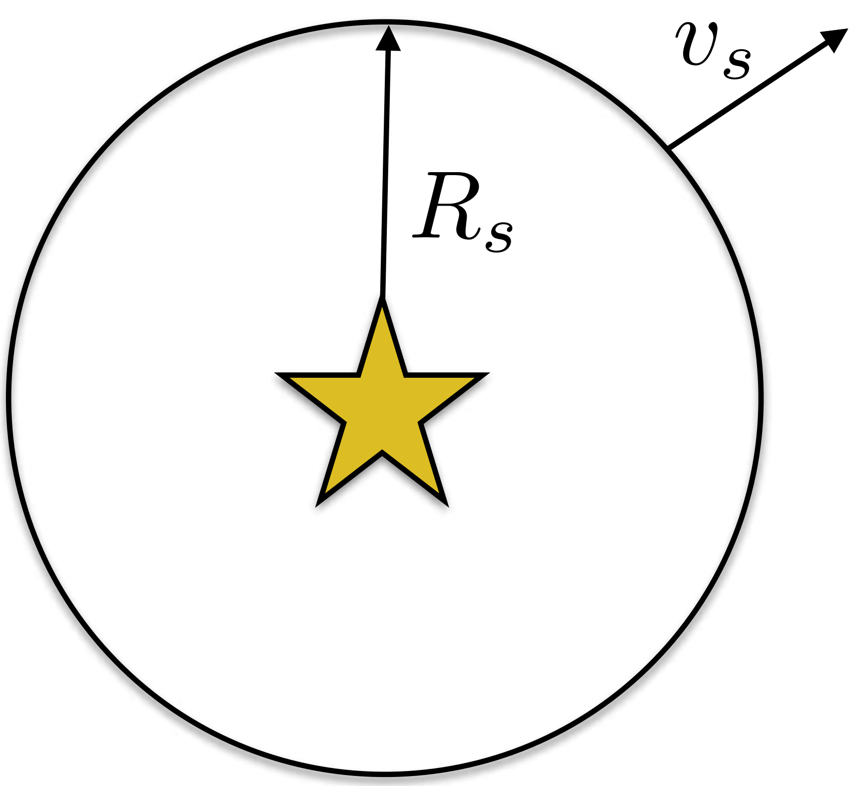
Backup slides

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

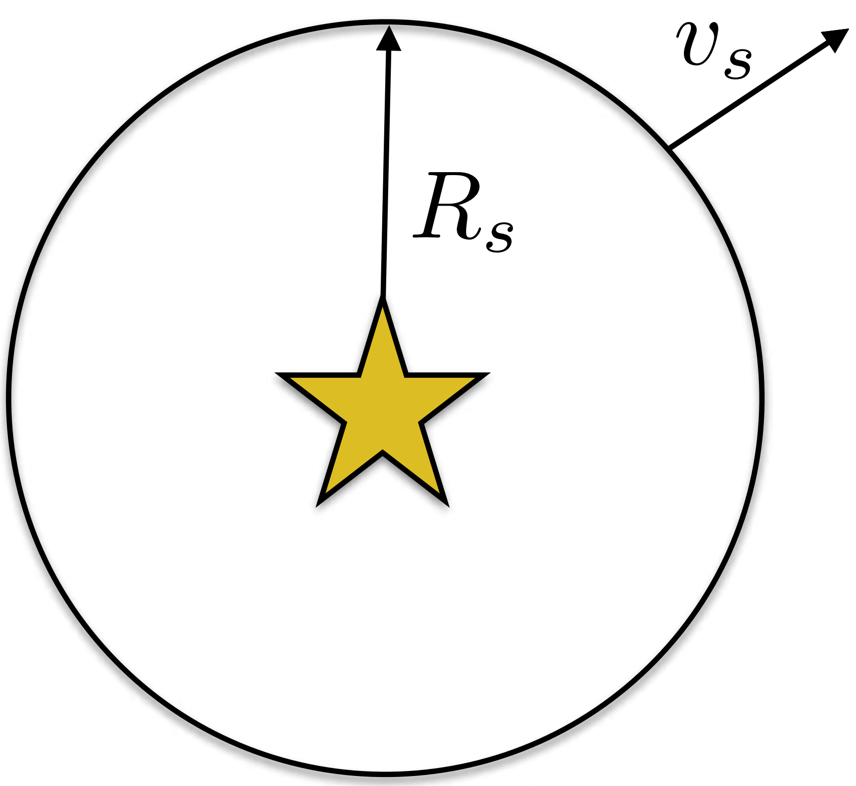
III. Radiative stage

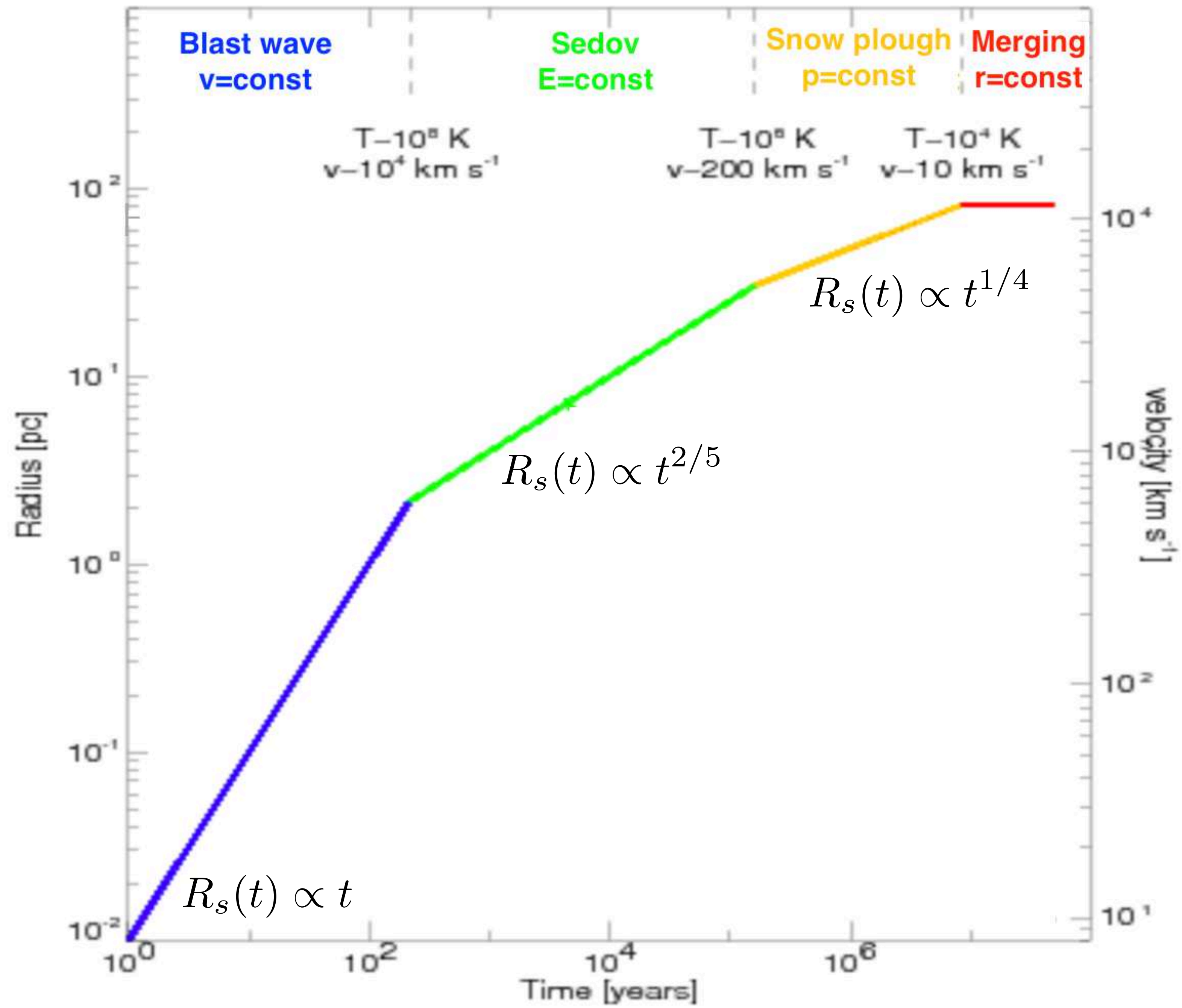
⟶ momentum conservation

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

In the scenario where the maximum momentum confined by the shock is a decreasing function of time, i.e.

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

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

- Magnetic field not amplified

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

- Magnetic field amplification driven by resonant waves

  $p_{\max,0}(t) \propto t^{-7/5}$

- Magnetic field amplification driven by non-resonant waves

  $p_{\max,0}(t) \propto t^{-2}$

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

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 magnetic turbulence evolve with time?

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

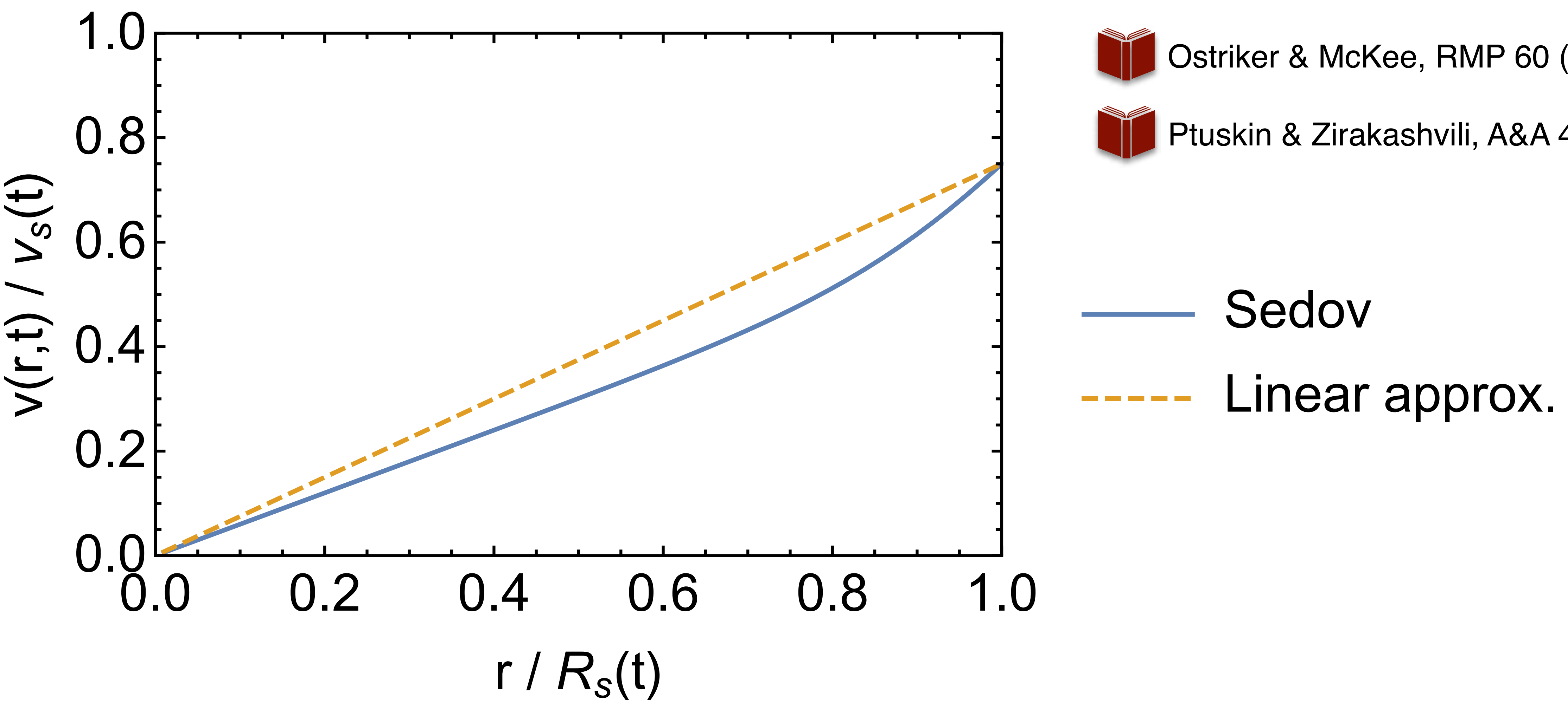
$$\xi_{\rm CR} \simeq 2 - 20\%$$

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

The velocity profile in the downstream

The **velocity field** in the downstream plasma, adopted for solution of the confined particle equation, follows from the ST solution in a homogeneous medium

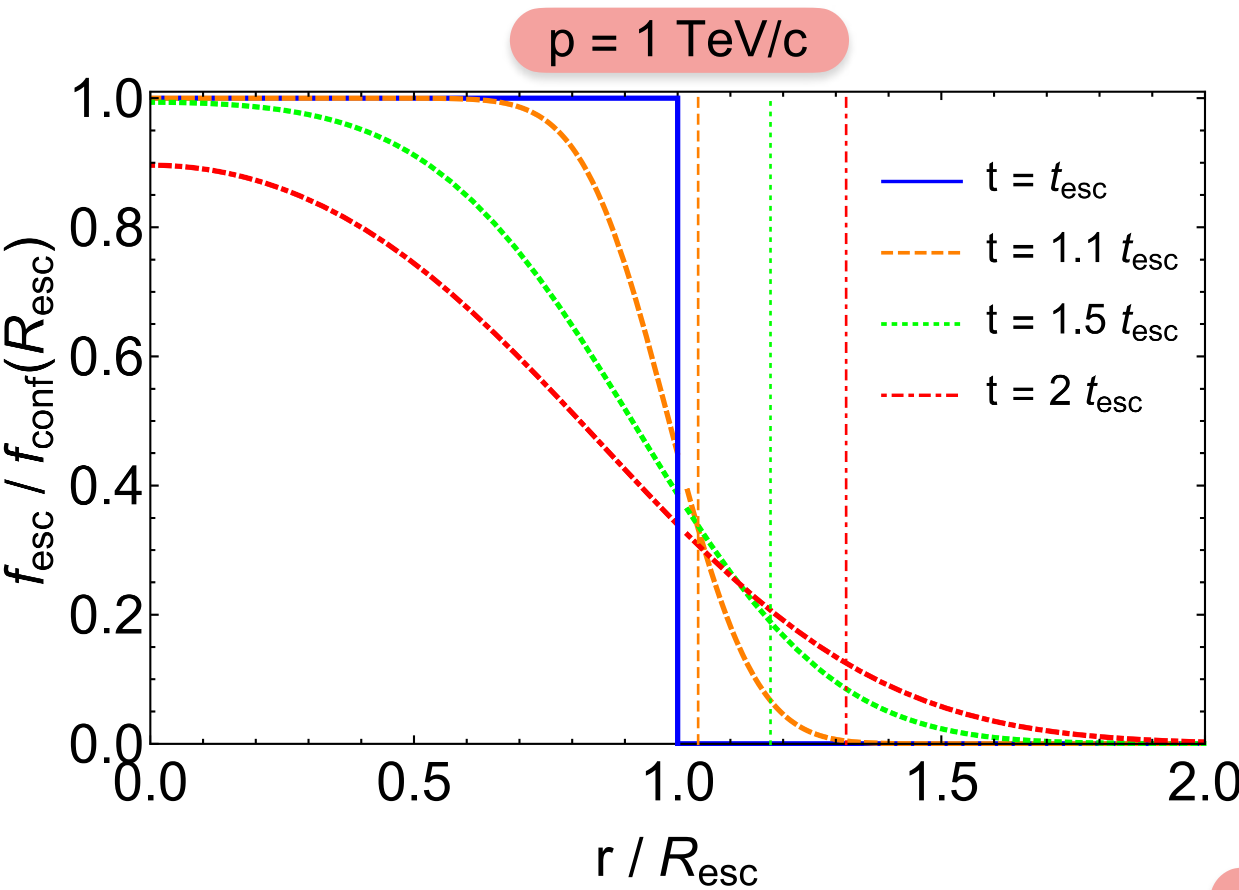
⟶ linear approximation: $$v(r,t) = \left(1 - \frac{1}{\sigma}\right) \frac{r}{R_s(t)} v_s(t)$$

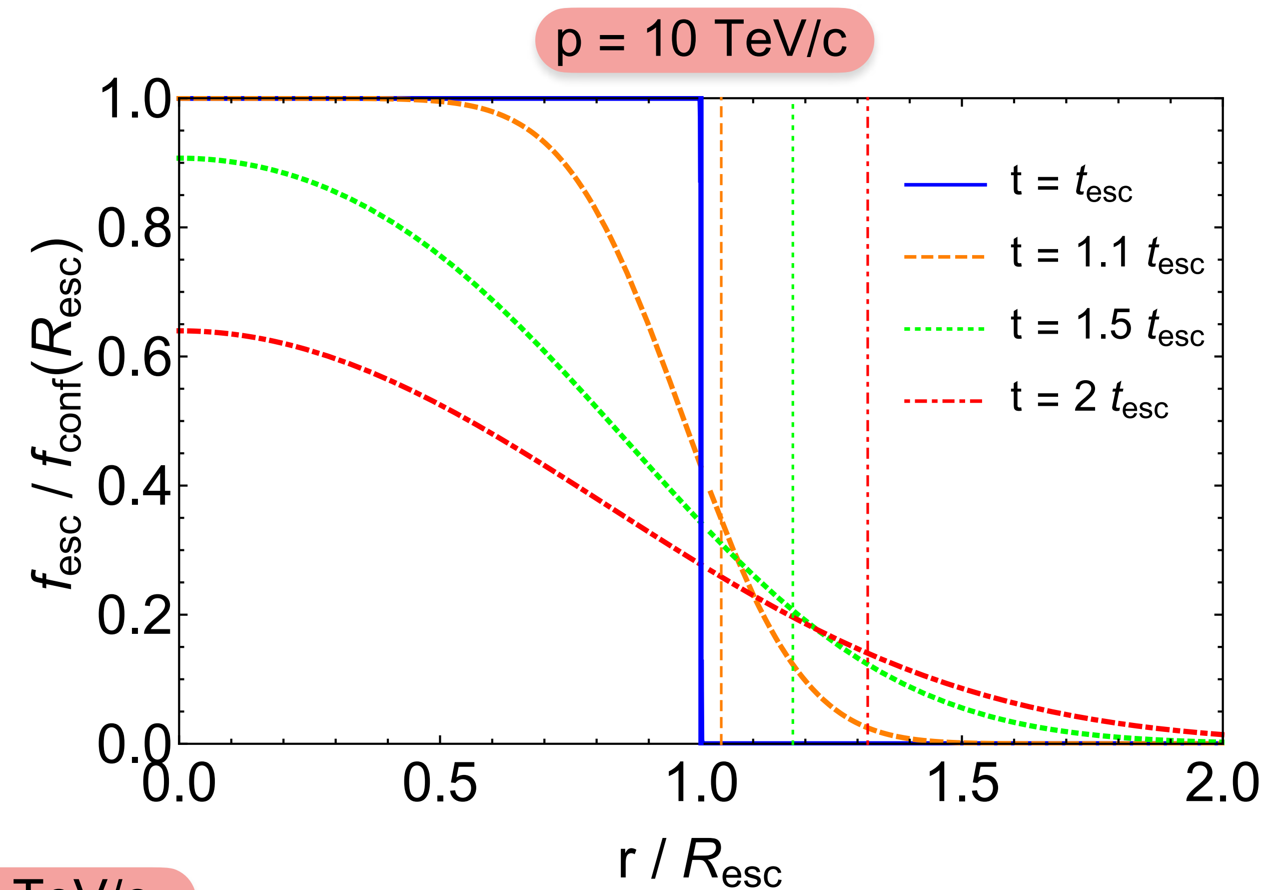


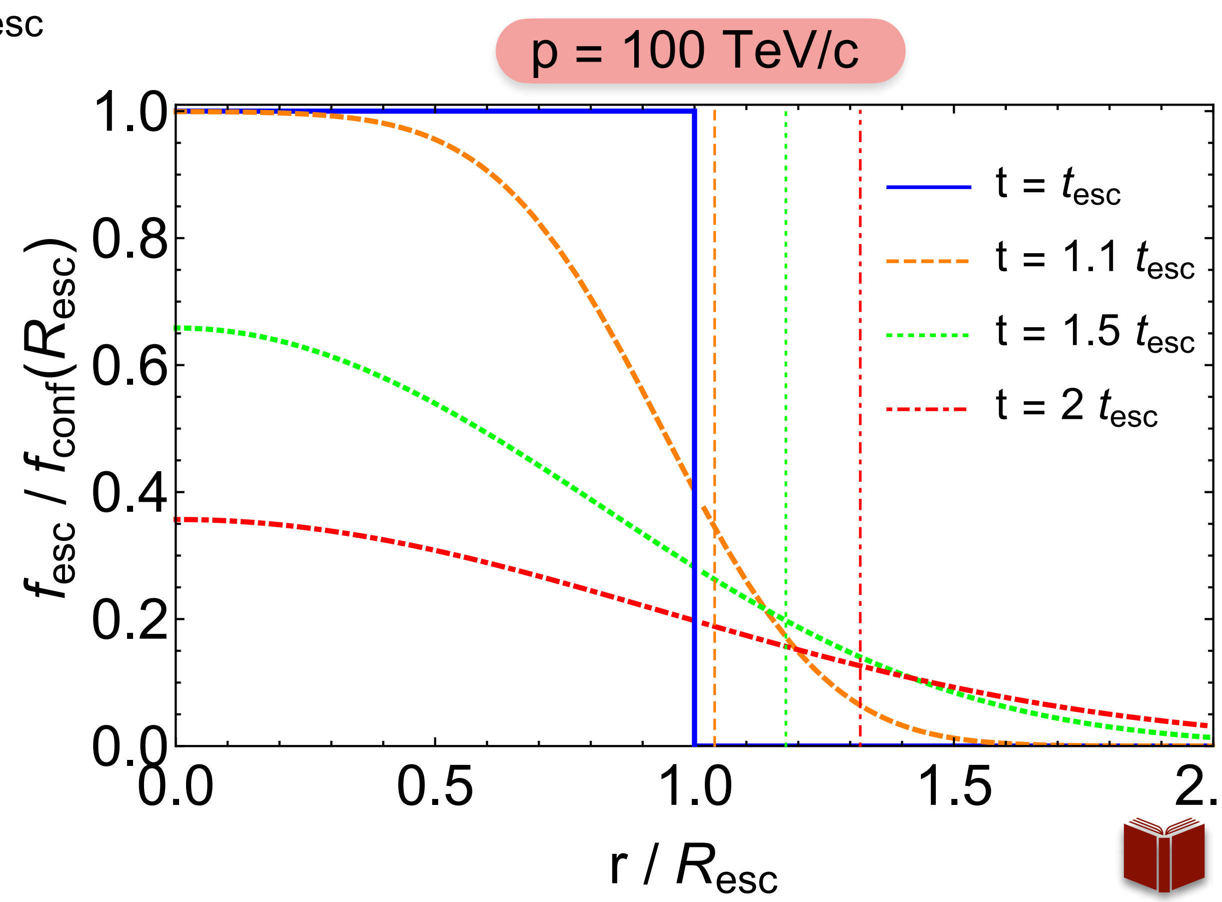
Ostriker & McKee, RMP 60 (1988) 1

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

Density of non-confined protons







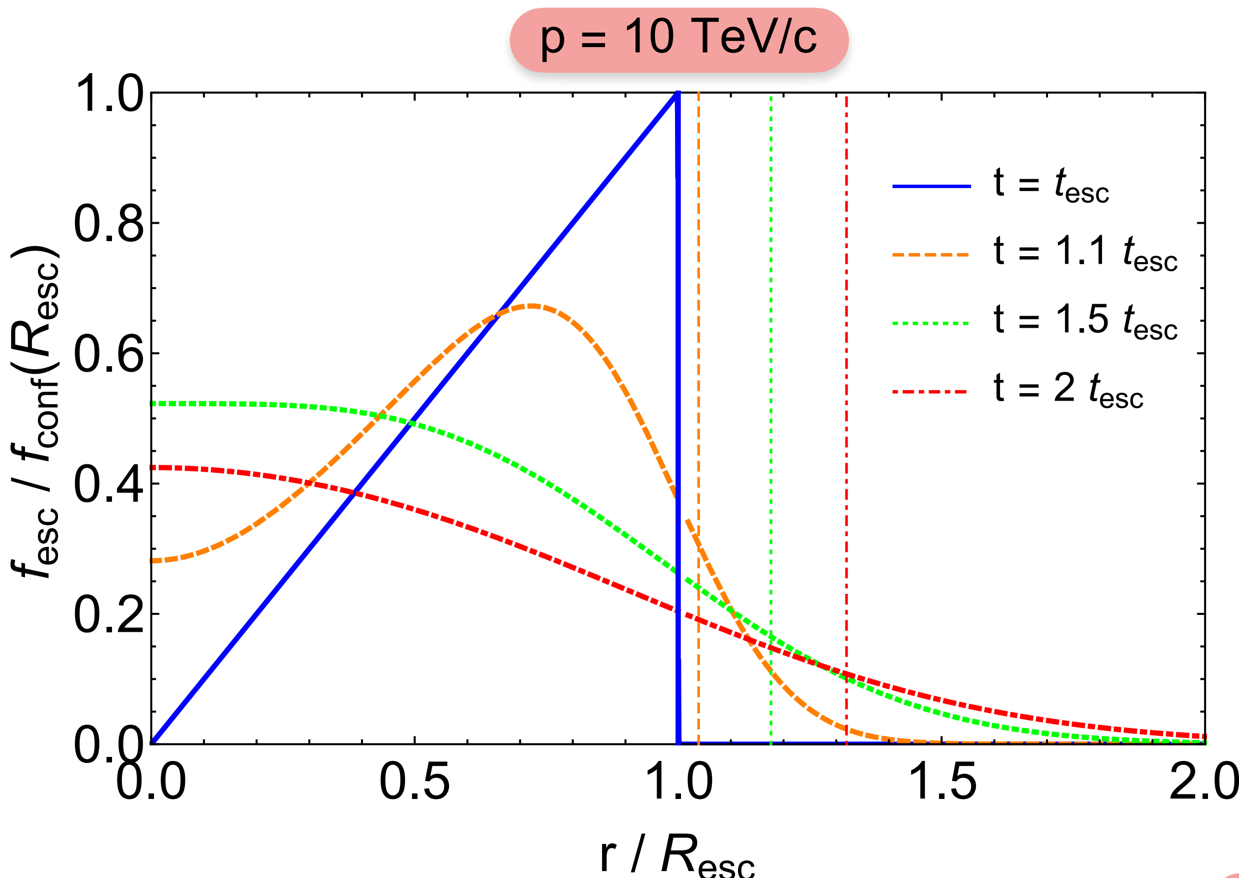
$\alpha = 4$

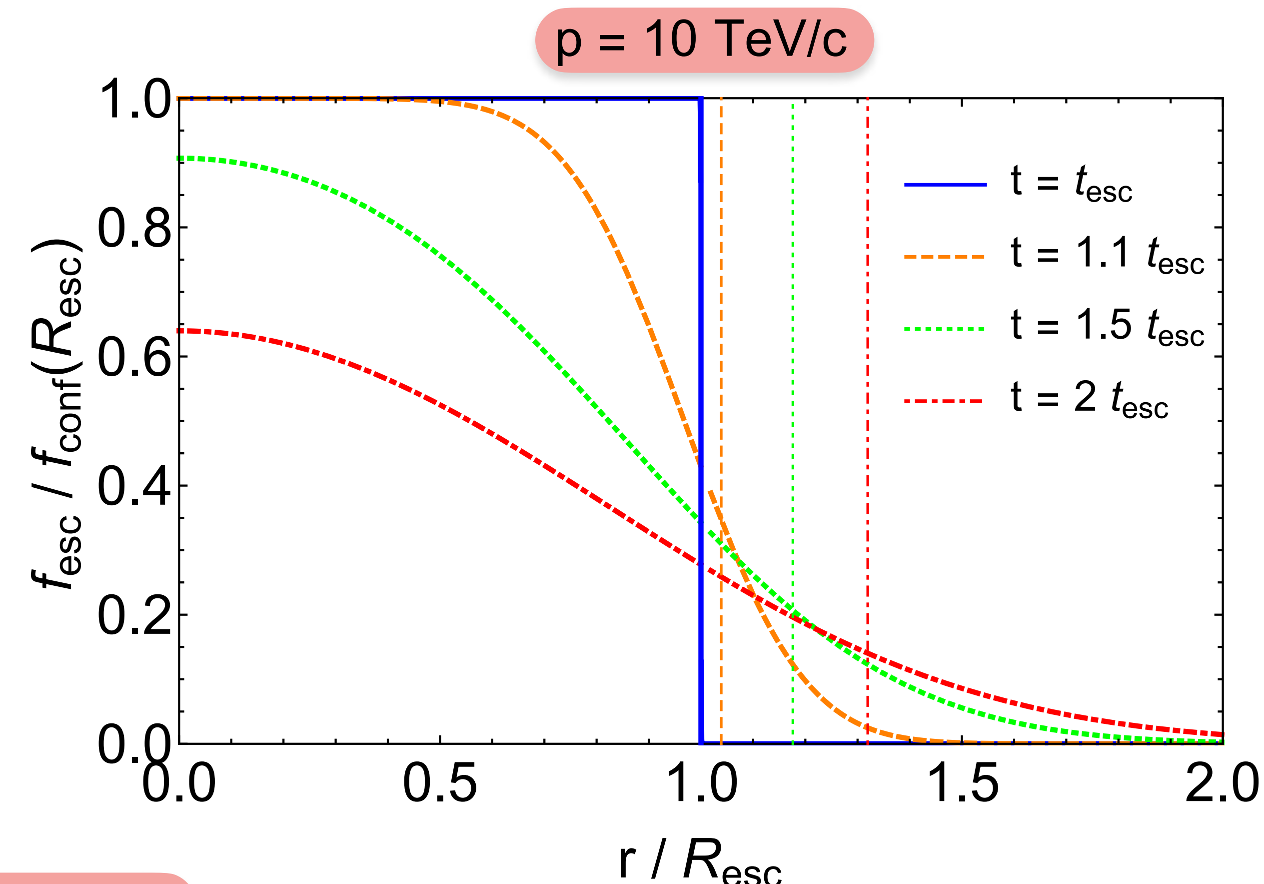
$\chi = 0.01$

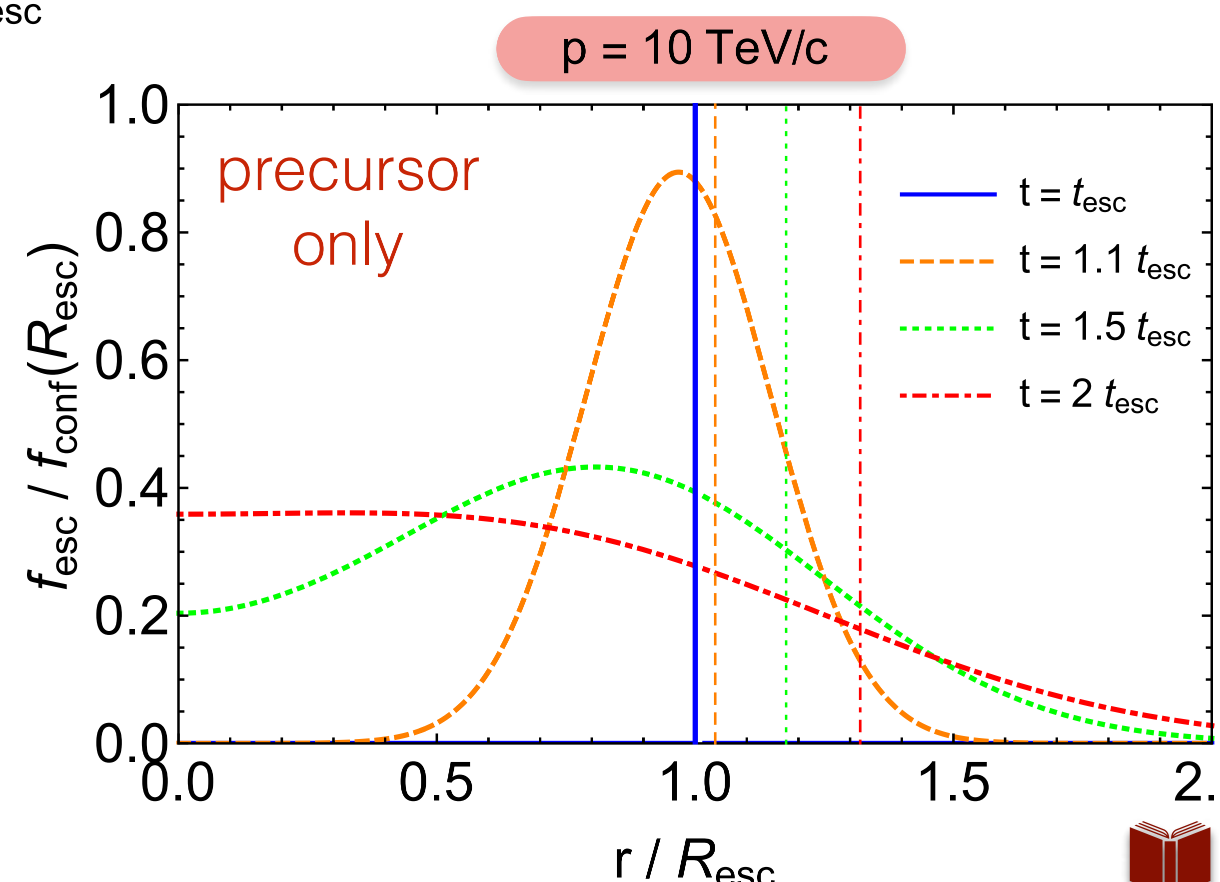
Celli et al., MNRAS 490 (2019) 4317C

$\alpha = 4 + 1/3$

$\alpha = 4$





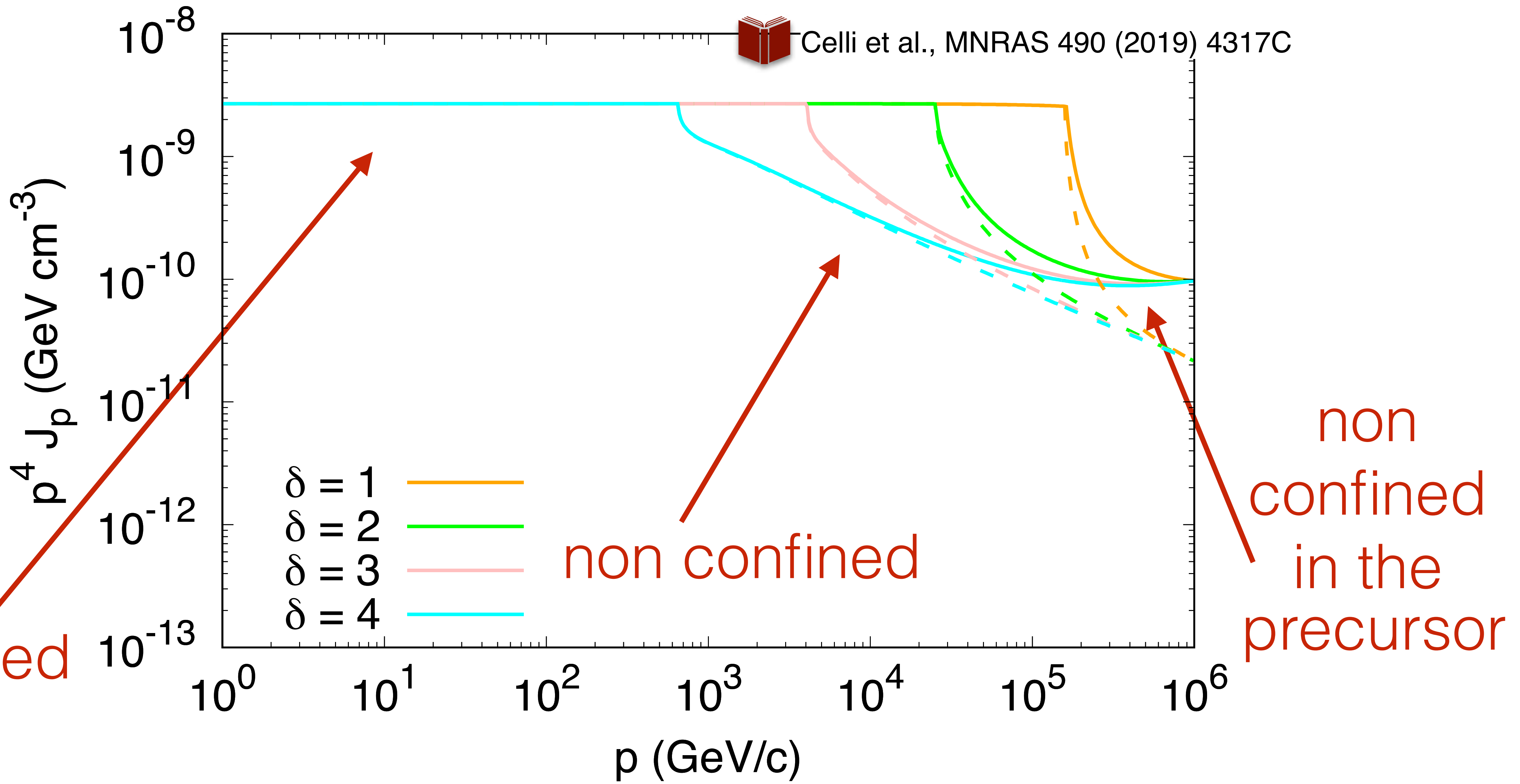


$\chi = 0.01$

Celli et al., MNRAS 490 (2019) 4317C

The spectrum of protons inside the SNR

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



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

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

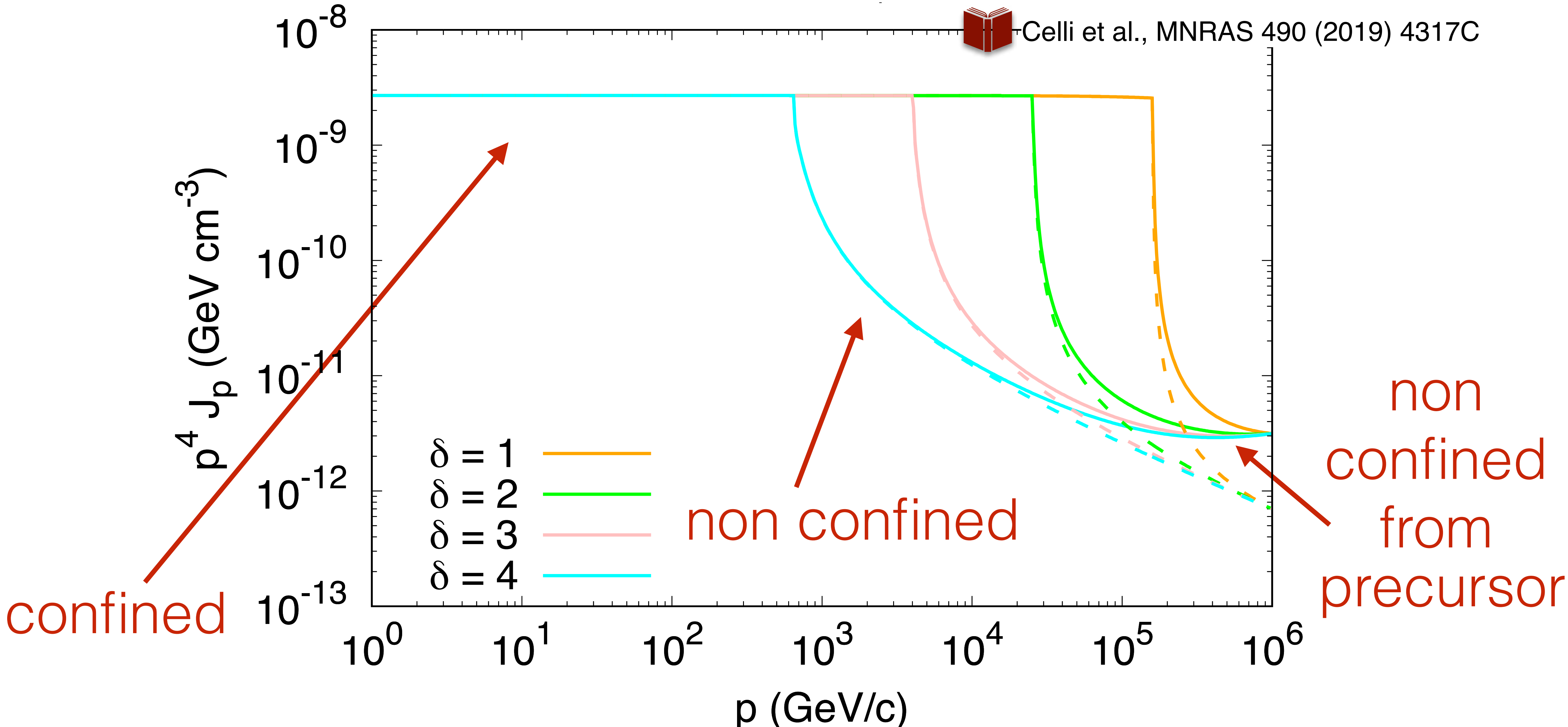
$\xi_{\rm CR} = 10\%$

$n_0 = 1 \, {\rm cm}^{-3}$

The spectrum of protons inside the SNR

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

Celli et al., MNRAS 490 (2019) 4317C



$$D(p) = 10^{28}\left(\frac{pc}{10\ \rm GeV}\right)^{1/3} \rm cm^2 s^{-1}$$

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

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

$n_0 = 1\,\rm cm^{-3}$

A model for particle propagation

1. Confined particle density ⟶ Method of characteristics

$$f_{\rm conf}(t,r,p) = f_0\left(t_0(t,r), p\left(\frac{R_s(t)}{R_s(t_0)}\right)^{3/4}\right)$$

adiabatic losses

2. Escaped particle density ⟶ Laplace transformation

$$\frac{f_{\rm esc}(r,t,p)}{f_{\rm conf}(t_{\rm esc},p)} = \frac{1}{2}\left[{\rm Erf}\left[\frac{R_+}{R_d}\right] + {\rm Erf}\left[\frac{R_-}{R_d}\right] + \frac{R_d}{\sqrt{\pi}r}\left(e^{-\left(\frac{R_+}{R_d}\right)^2} - e^{-\left(\frac{R_-}{R_d}\right)^2}\right)\right]\theta[t - t_{\rm esc}(p)]$$

$$R_+ = (R_{esc} + r) \qquad R_- = (R_{esc} - r) \qquad R_d(t,p) = 2D(p)\sqrt{t - t_{\rm esc}(p)}$$

$$\alpha = 4$$

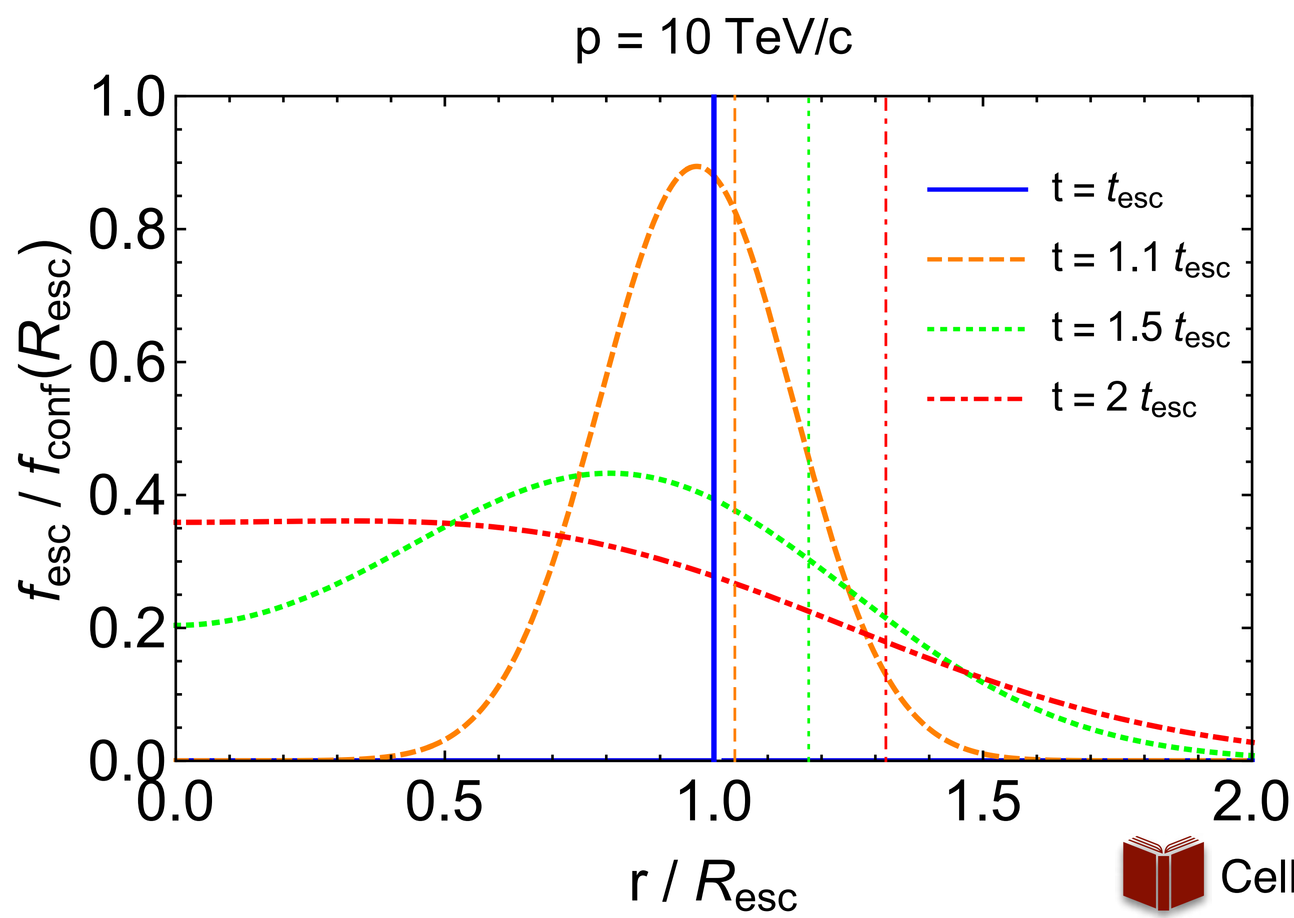
Celli et al., MNRAS 490 (2019) 4317C

The precursor contribution to the density of non-confined particles

$$f_{\rm p}(t,r,p) = f_0(t,p)\exp\left[-\frac{u_{\rm sh}(t)}{D_{\rm p}(p)}(r-R_{\rm sh})\right]$$

$$f_{\rm p,conf}(t,r,p) \simeq f_0(t,p)\frac{D_{\rm p}(p)}{u_{\rm sh}(t)}\delta(r-R_{\rm sh})$$

$$\longrightarrow \frac{f_{\rm p,esc}(r,t,p)}{f_0(p,t_{\rm esc})} = \frac{1}{\sqrt{\pi}}\frac{R_{\rm esc}}{R_d}\frac{D_p(p)}{v_s(t_{\rm esc})r}\left[e^{-(\frac{R_-}{R_d})^2} - e^{-(\frac{R_+}{R_d})^2}\right]\theta[t-t_{\rm esc}(p)]$$



Celli et al., MNRAS 490 (2019) 4317C

Self-generated turbulence

$$\Gamma_{\rm CR}(k) = \frac{16\pi^2}{3} \frac{v_A}{B_0^2 \mathcal{F}(k)} \left[p^4 v(p) \frac{\partial f}{\partial r} \right]_{p=p_{\rm res}}$$

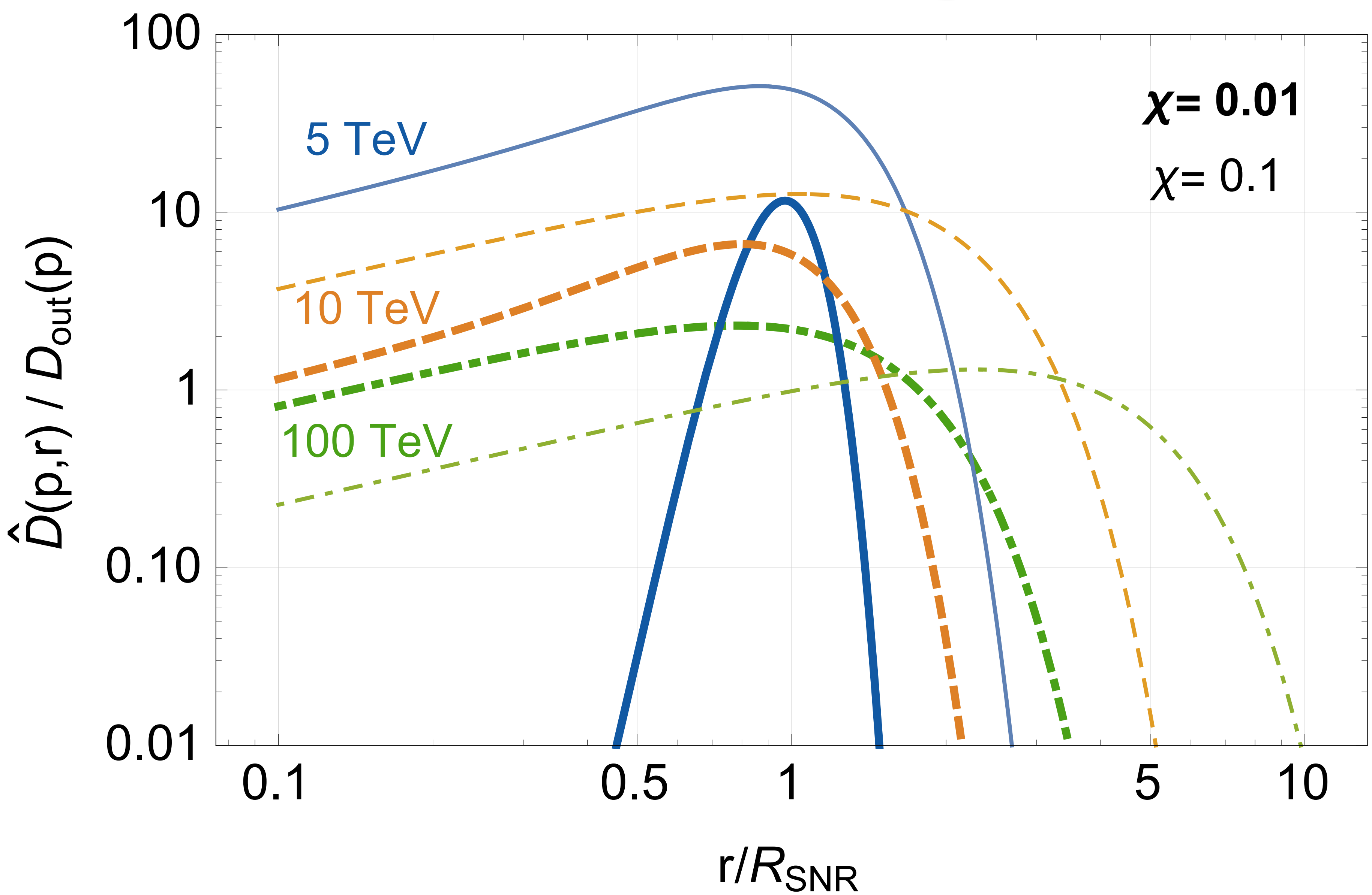
growth rate by resonant streaming instability

Skilling, ApJ 170 (1971) 265

$$\Gamma_{\rm NLD}(k) = (2c_k)^{-3/2} \, k v_A \sqrt{\mathcal{F}(k)}$$

non-linear damping rate

Ptuskin & Zirakashvini, A&A 403 (2003) 1



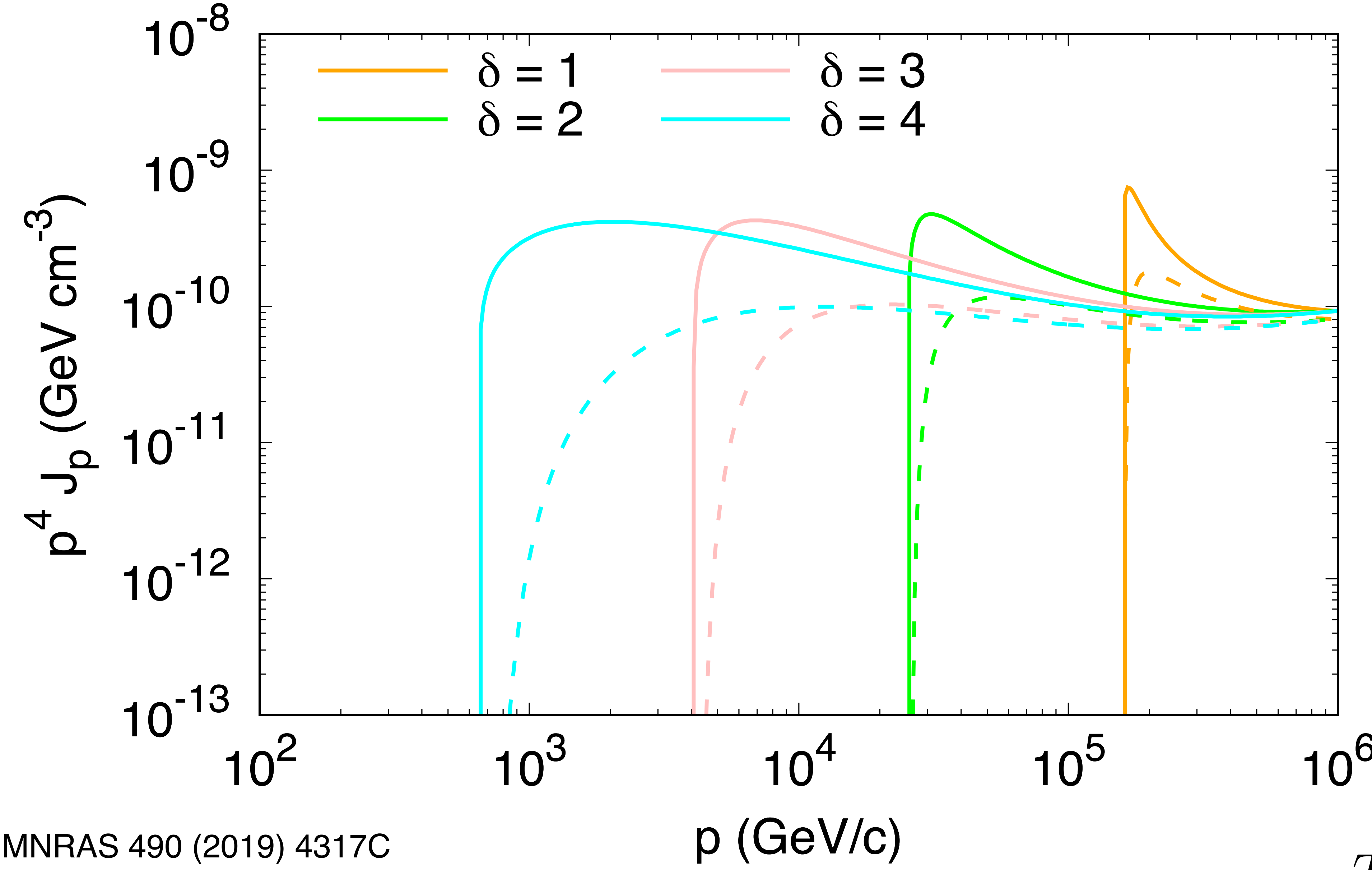
$$\xi_{\rm CR} = 10\%$$

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

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

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

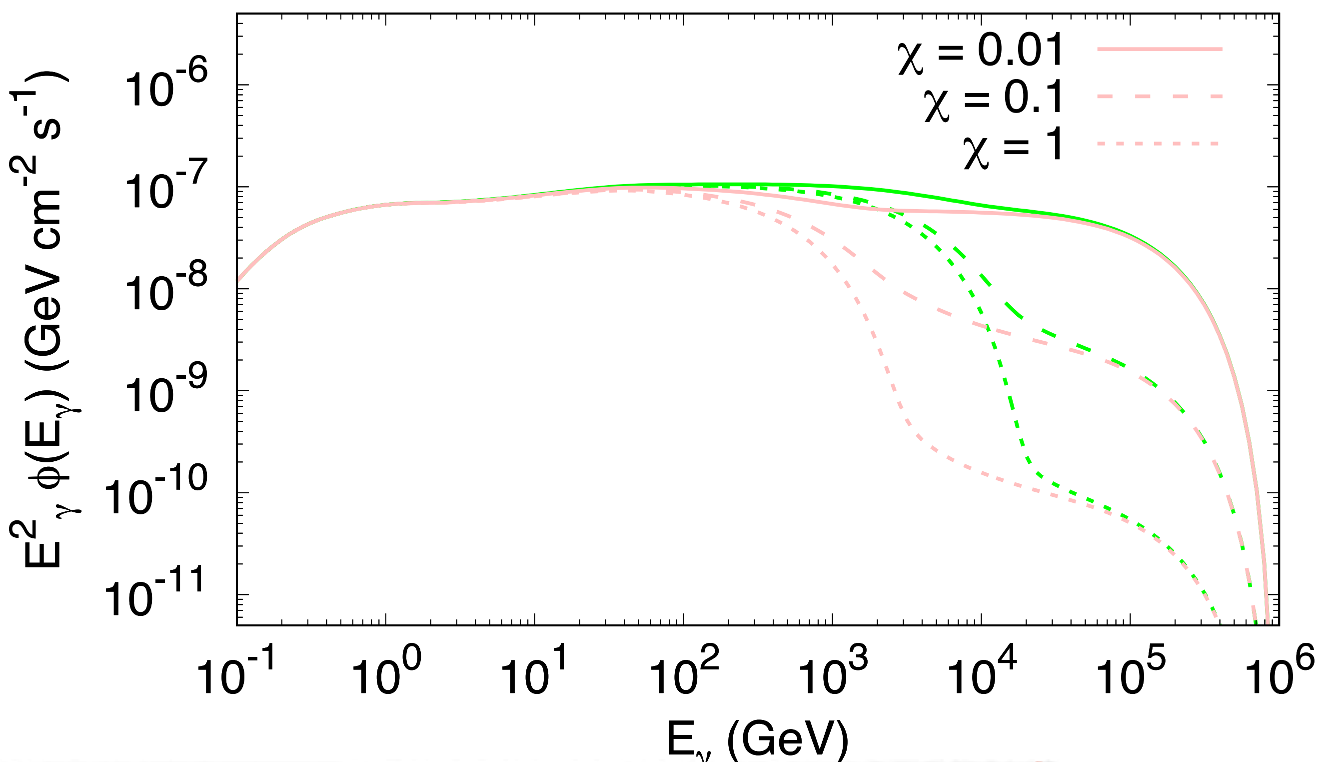
DASHED:
$R_1 = 2R_{SNR}$
$R_2 = 3R_{SNR}$

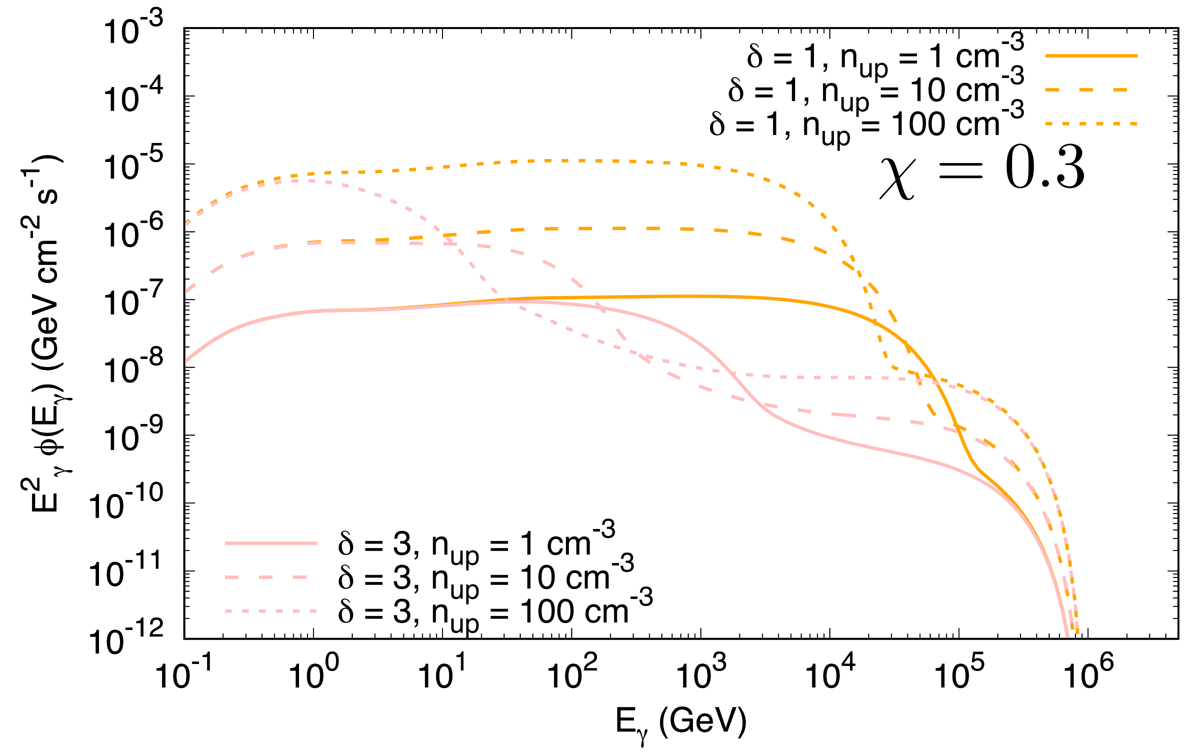
Celli et al., MNRAS 490 (2019) 4317C

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

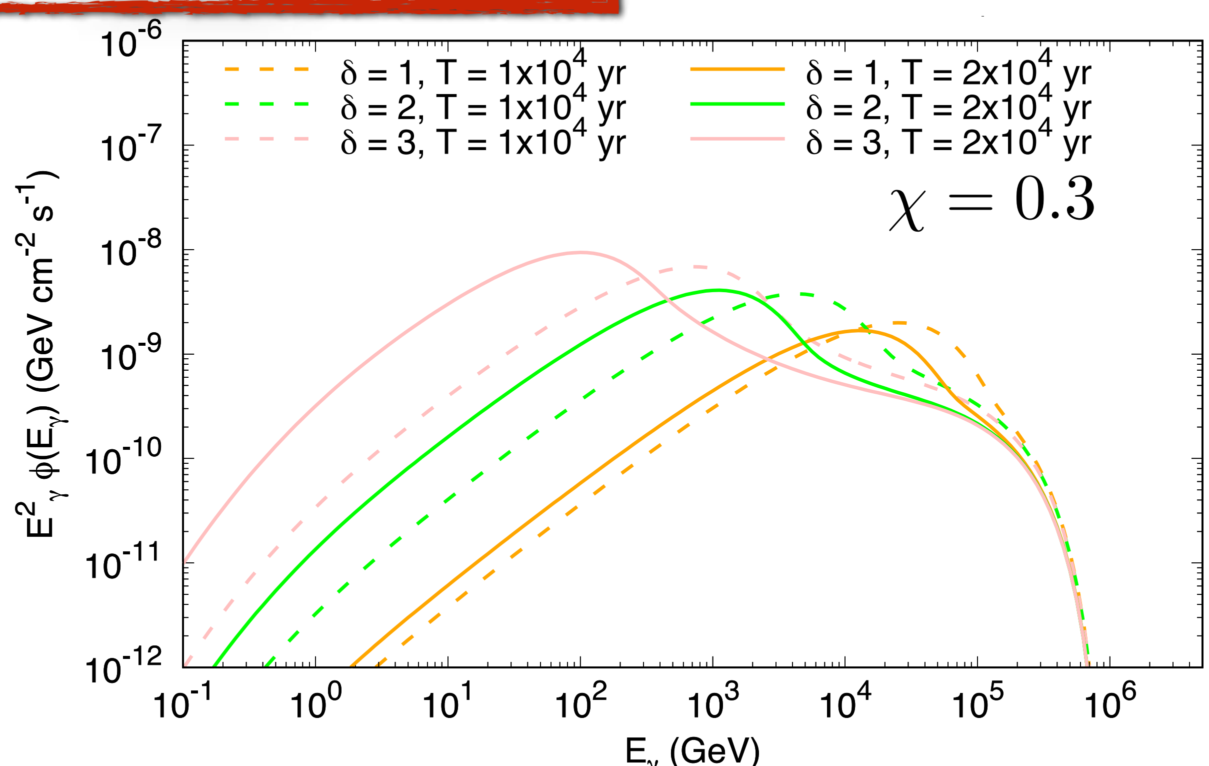
$T_{\rm SNR} = 10^4\,\rm yr$
$\xi_{\rm CR} = 10\%$
$n_{\rm up} = 1\,\rm cm^{-3}$

Volume integrated gamma-ray emission from hadronic interactions





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

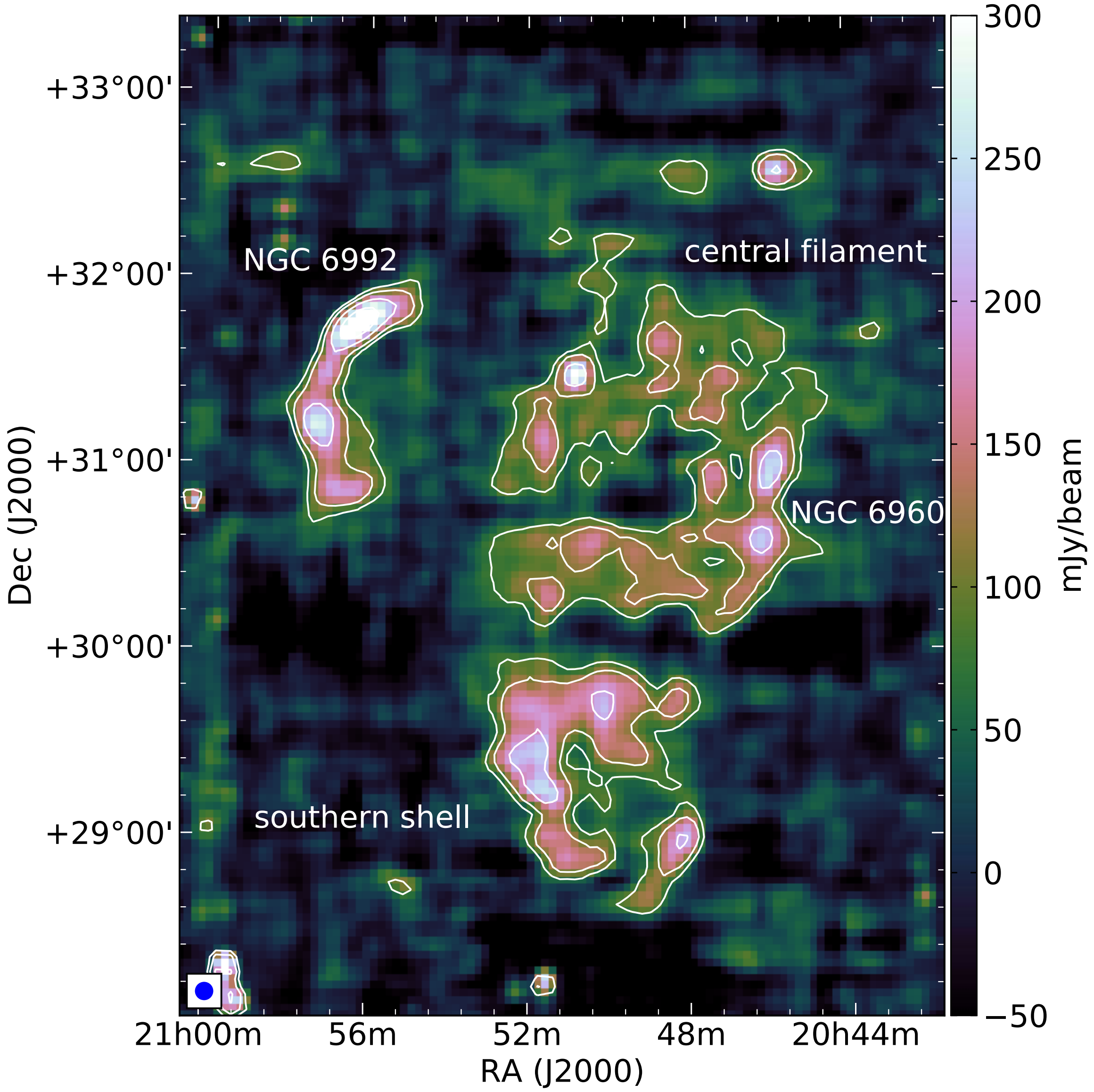


$$\xi_{\rm CR} = 10\%$$
$$n_{\rm up} = 1\ {\rm cm^{-3}}$$
$$T_{\rm SNR} = 10^4\ {\rm yr}$$
$$d = 1\,{\rm kpc}$$

Celli et al., MNRAS 490 (2019) 4317C

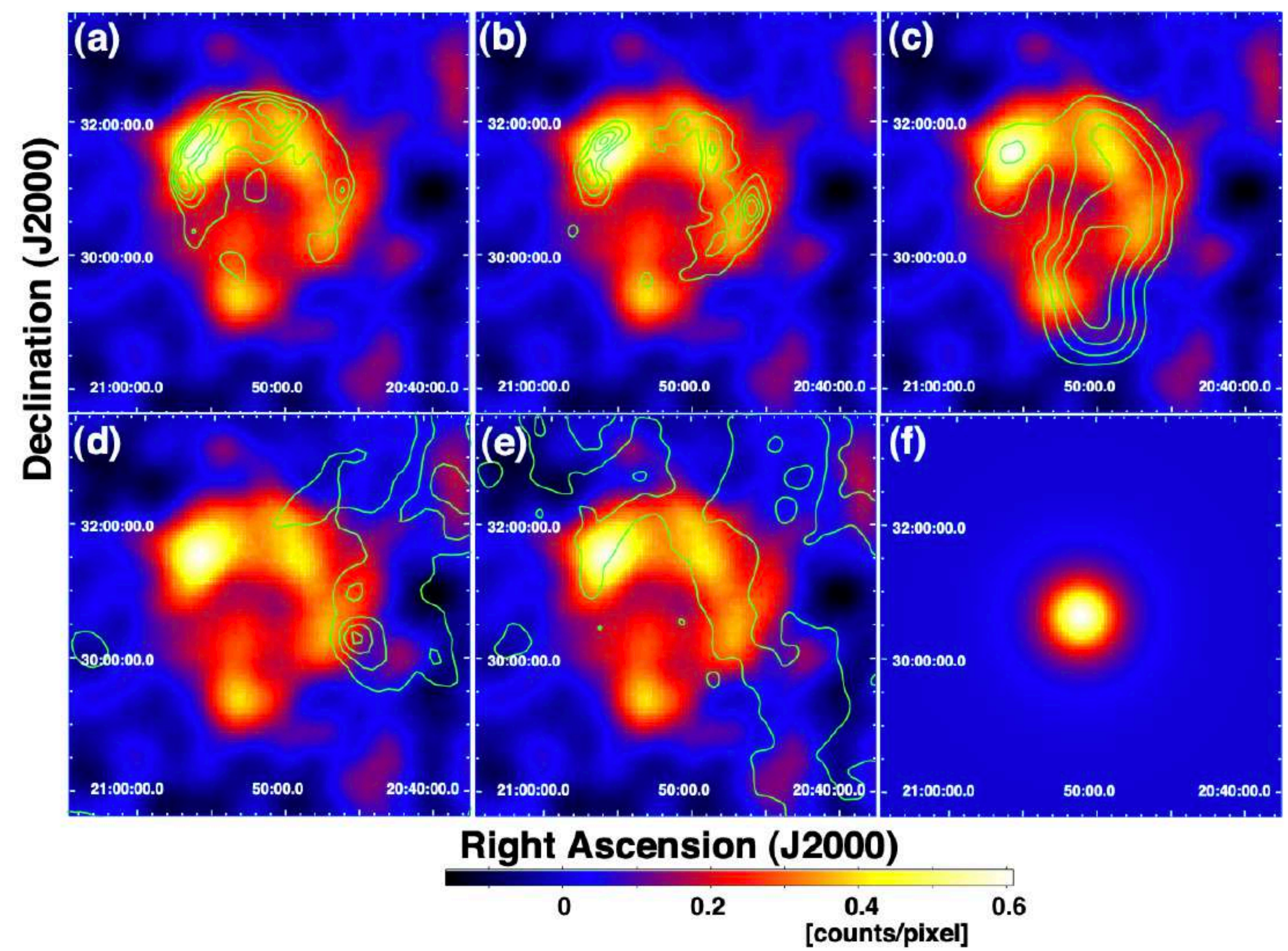
The Cygnus Loop SNR

Middle-aged SNR (~2x10^4 yr) located at high latitudes



Medicina radio telescope map @ 8.5 GHz

Loru et al., MNRAS 500 (2020) 5177

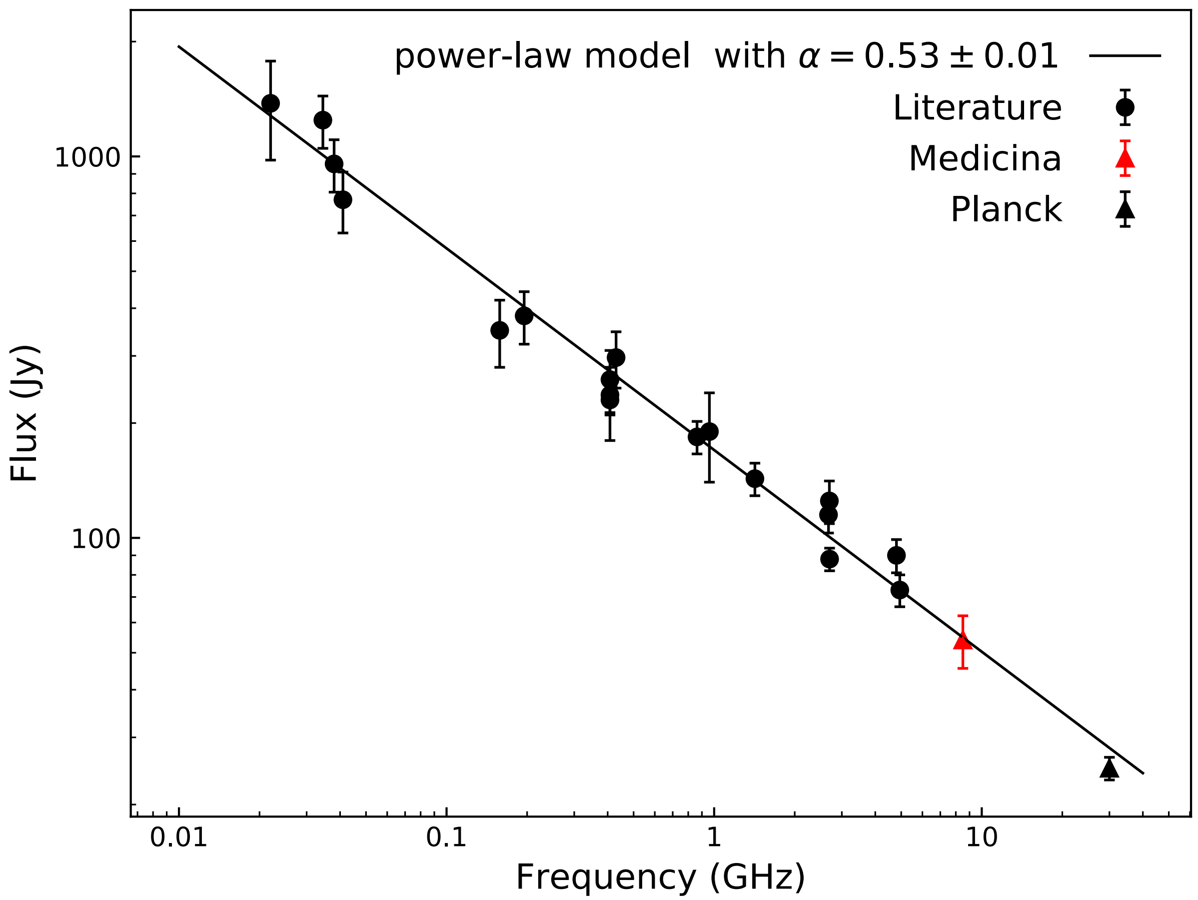


Fermi-LAT count map in [0.5 -10] GeV

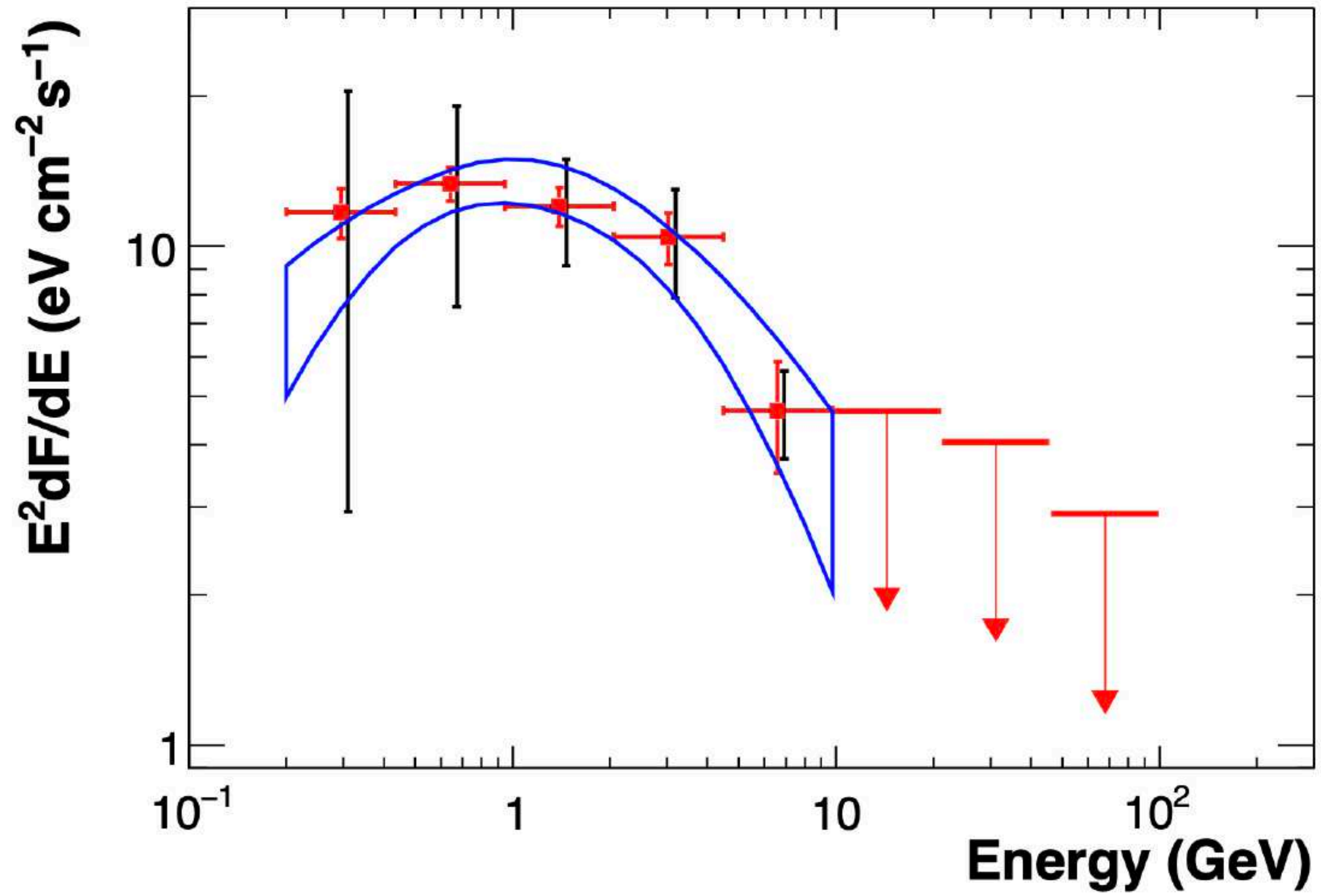
Katagiri et al., ApJ 741 (2011) 44

The Cygnus Loop SNR

Middle-aged SNR (~2x10^4 yr) located at high latitudes



Loru et al., MNRAS 500 (2020) 5177



Katagiri et al., ApJ 741 (2011) 44

$$s \simeq 0.5 \implies \alpha \simeq 4$$

$$n = 0.4\,\mathrm{cm}^{-3} \implies \xi_{\mathrm{CR}} \simeq 7\,\%$$

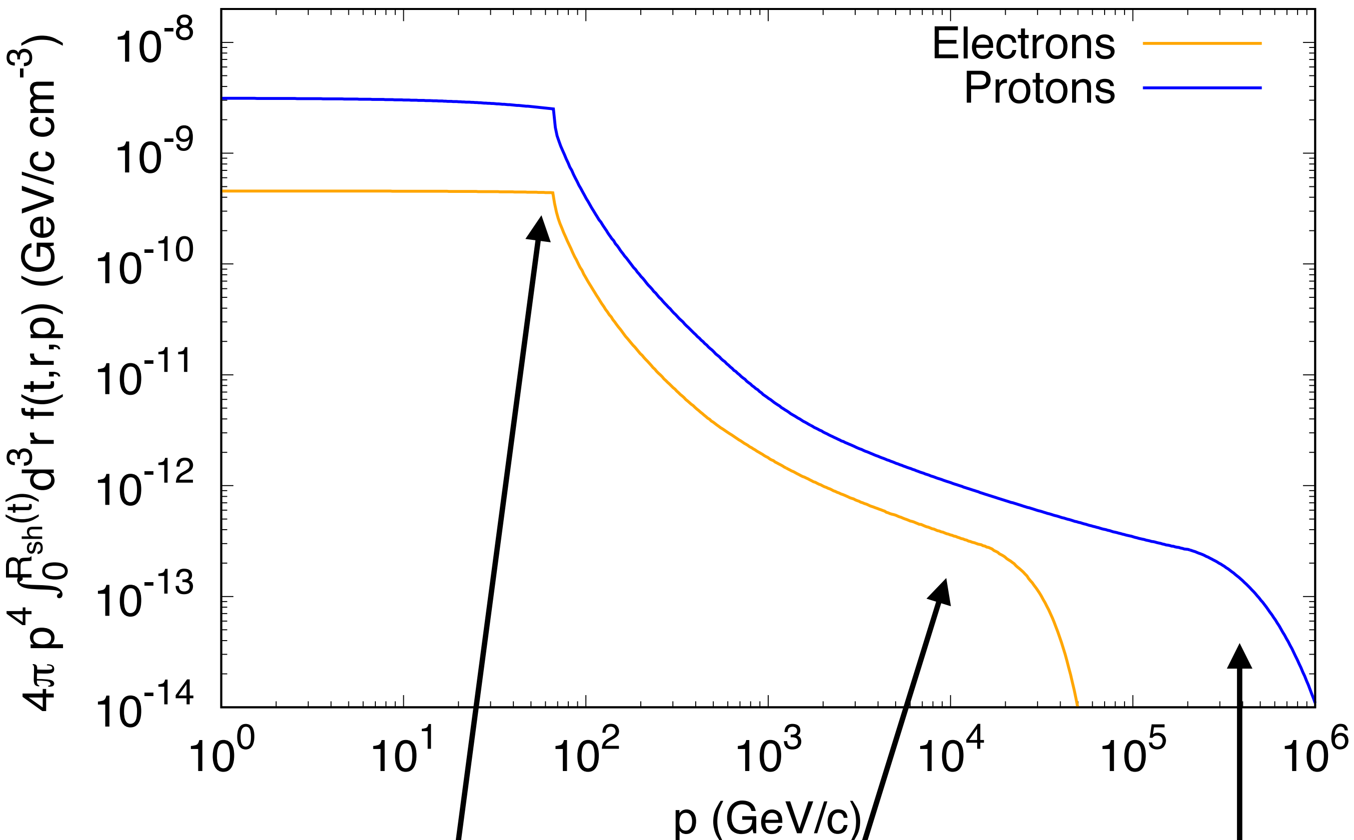
⟶ constraints over K_{ep} and B_0

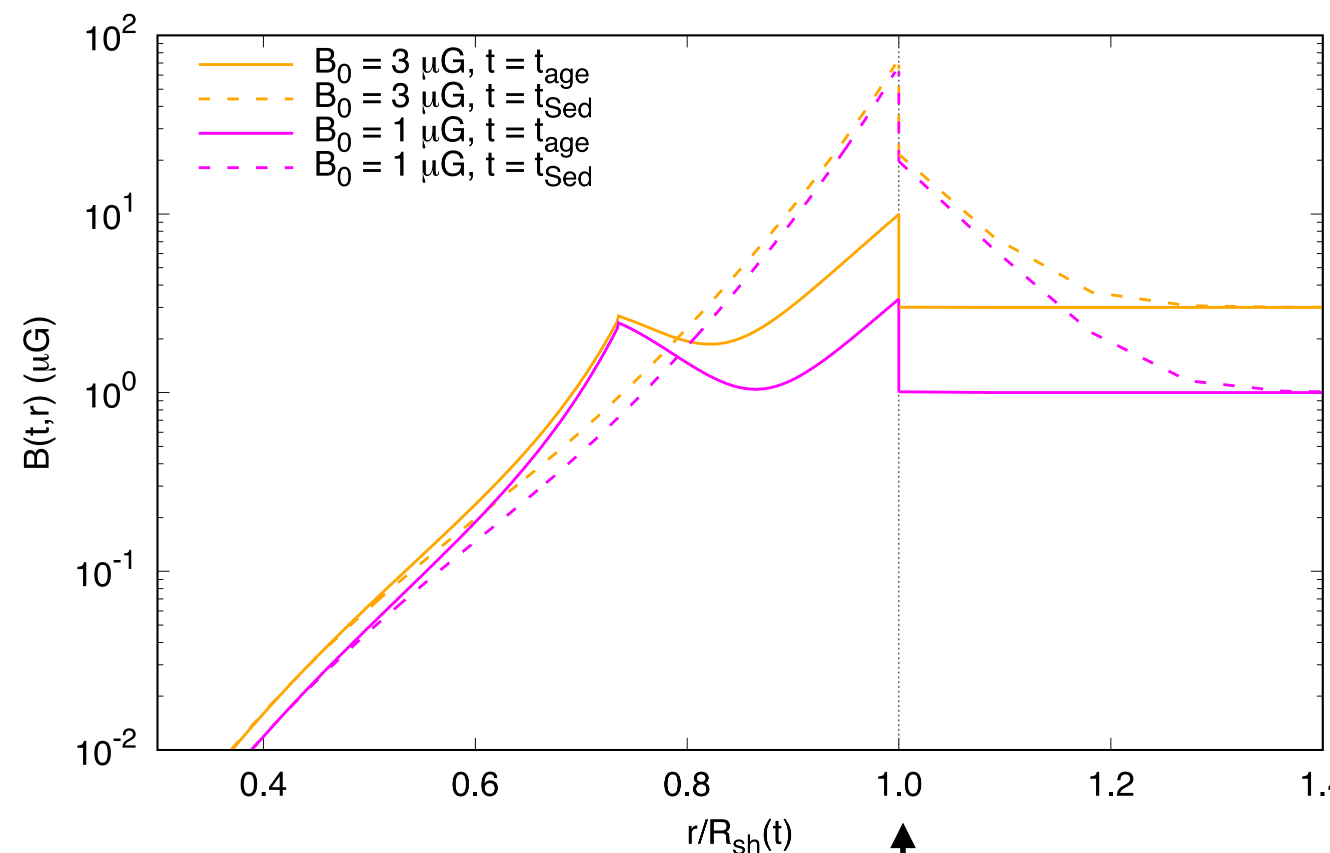
⟶ constraints over p_M, δ and χ

The Cygnus Loop SNR

Middle-aged SNR (~2x10^4 yr) located at high latitudes

Loru et al., MNRAS 500 (2020) 5177





$p_{M,e}$=20 TeV

$p_{M,p}$=200 TeV

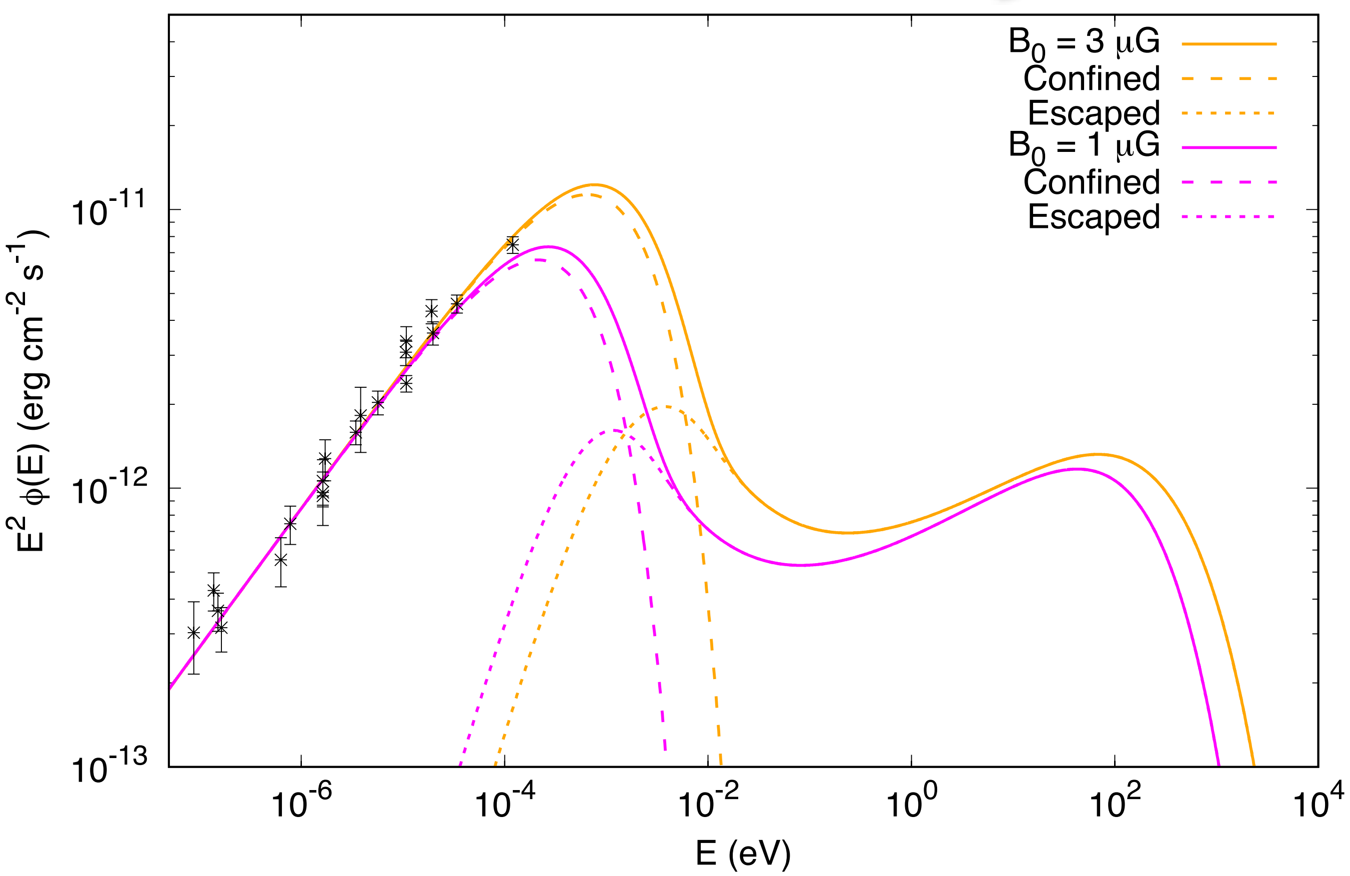
Magnetic field at the shock today at the level of 10 μG, compatible with compression

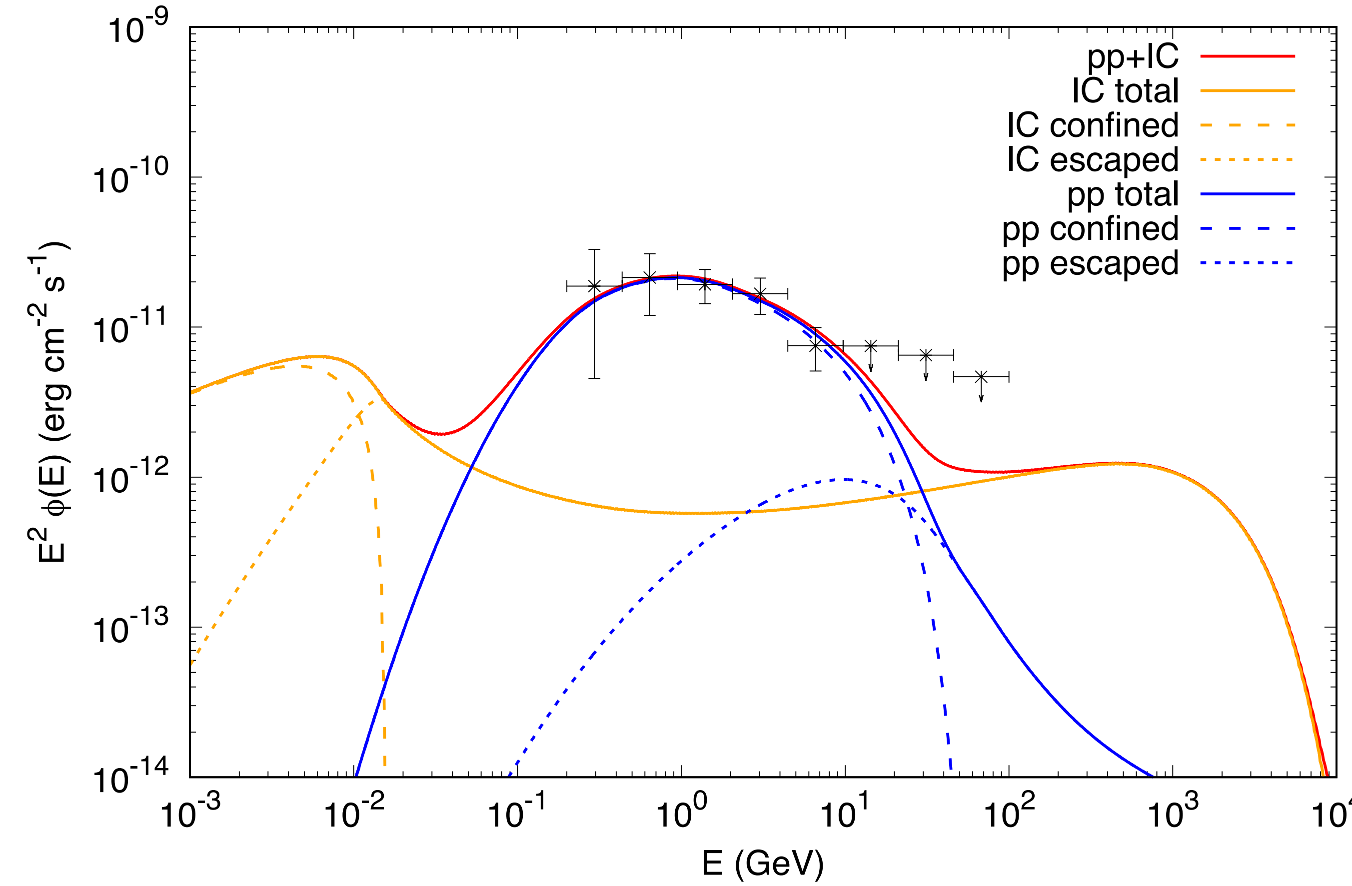
$E_{max}(T_{SNR})$=65 GeV

The Cygnus Loop SNR

Cygnus Loop properties							Acceleration model parameters						
Assumed					Derived								
E_{SN}	M_{ej}	t_{age}	d	n_0	R_{sh}	u_{sh}	ξ_{CR}	s	E_M	δ	K_{ep}	B_0	χ
7×10^{50} erg	$5\ M_\odot$	2.1×10^4 yr	735 pc	0.4 cm^{-3}	20 pc	380 km s^{-1}	0.07	4.0	200 TeV	3	0.15	3 μG	1

Loru et al., MNRAS 500 (2020) 5177





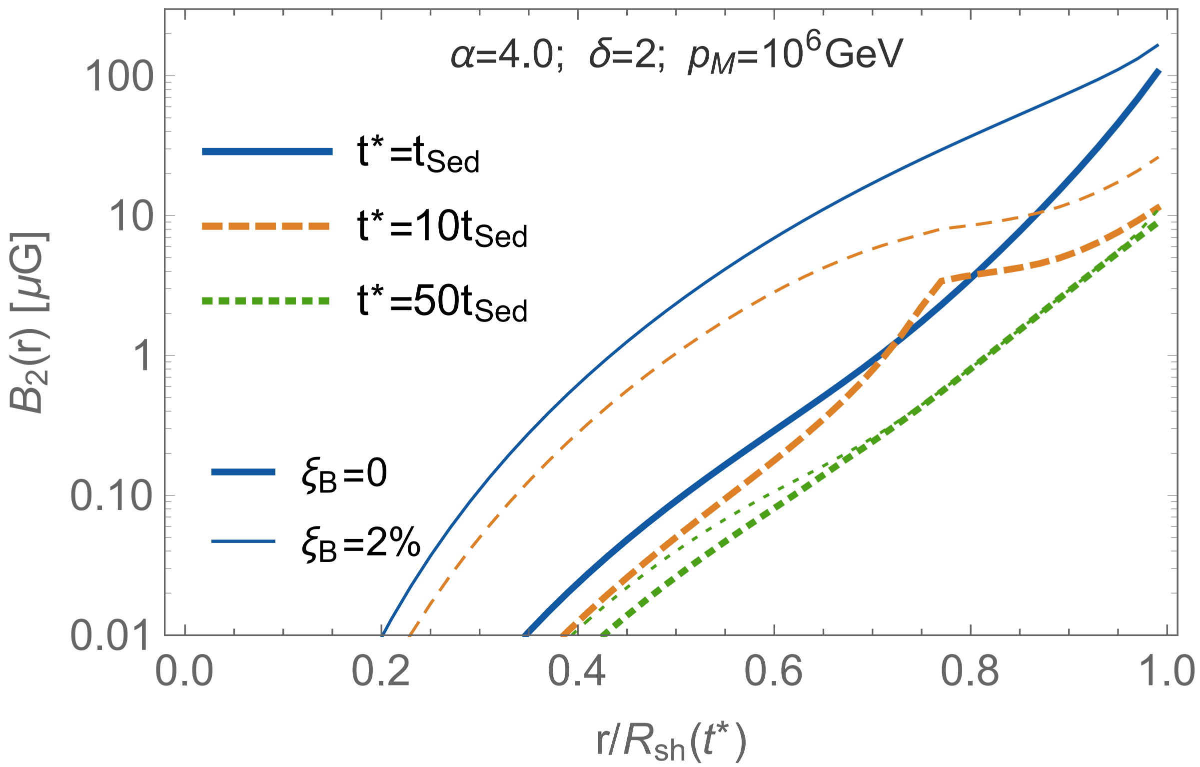
$\delta \geq 2$ → **Temporal evolution of magnetic turbulence:** MFA + damping effects?

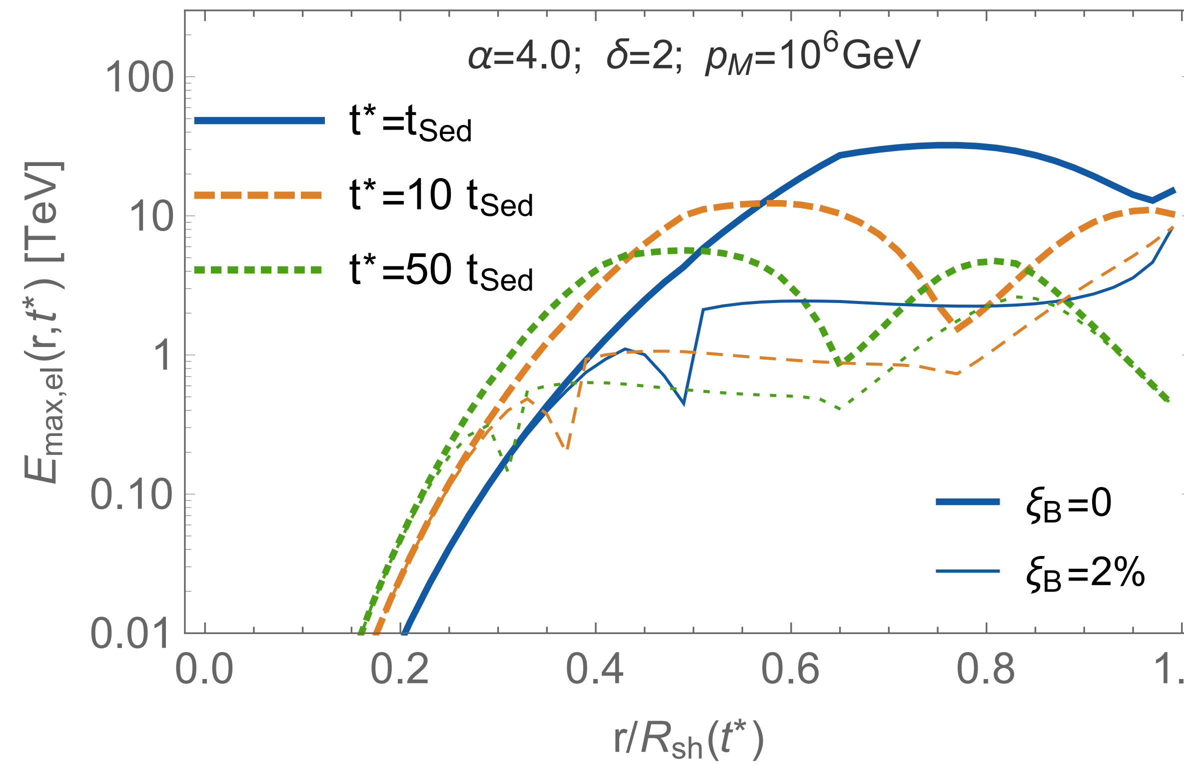
$K_{ep} \simeq 0.15$ → **Electron to proton injection ratio:** hints for Kep increasing with decreasing shock speed?

$\xi_{CR} \simeq 10\%$ → **CR acceleration efficiency:** Standard value in the SNR theory.

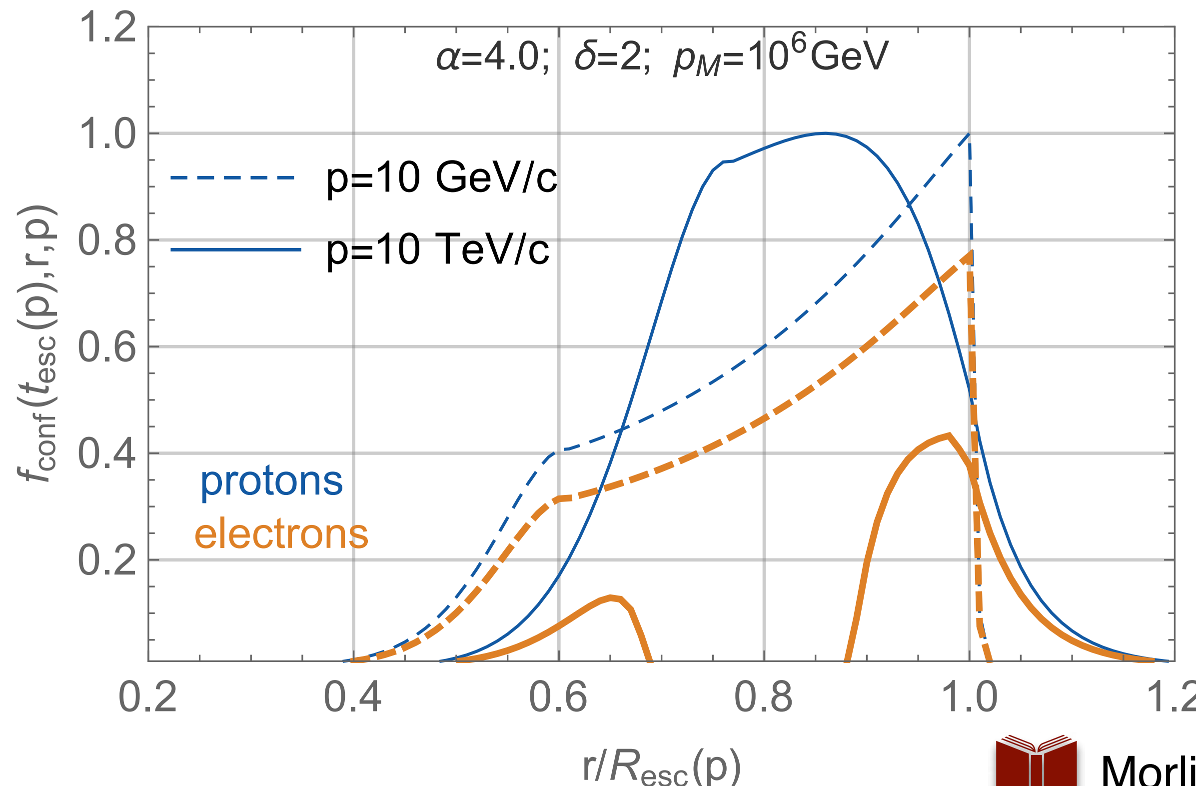
Solving electron propagation

Numerical solution of the transport equation for accelerated **electrons**, including radiative and adiabatic losses



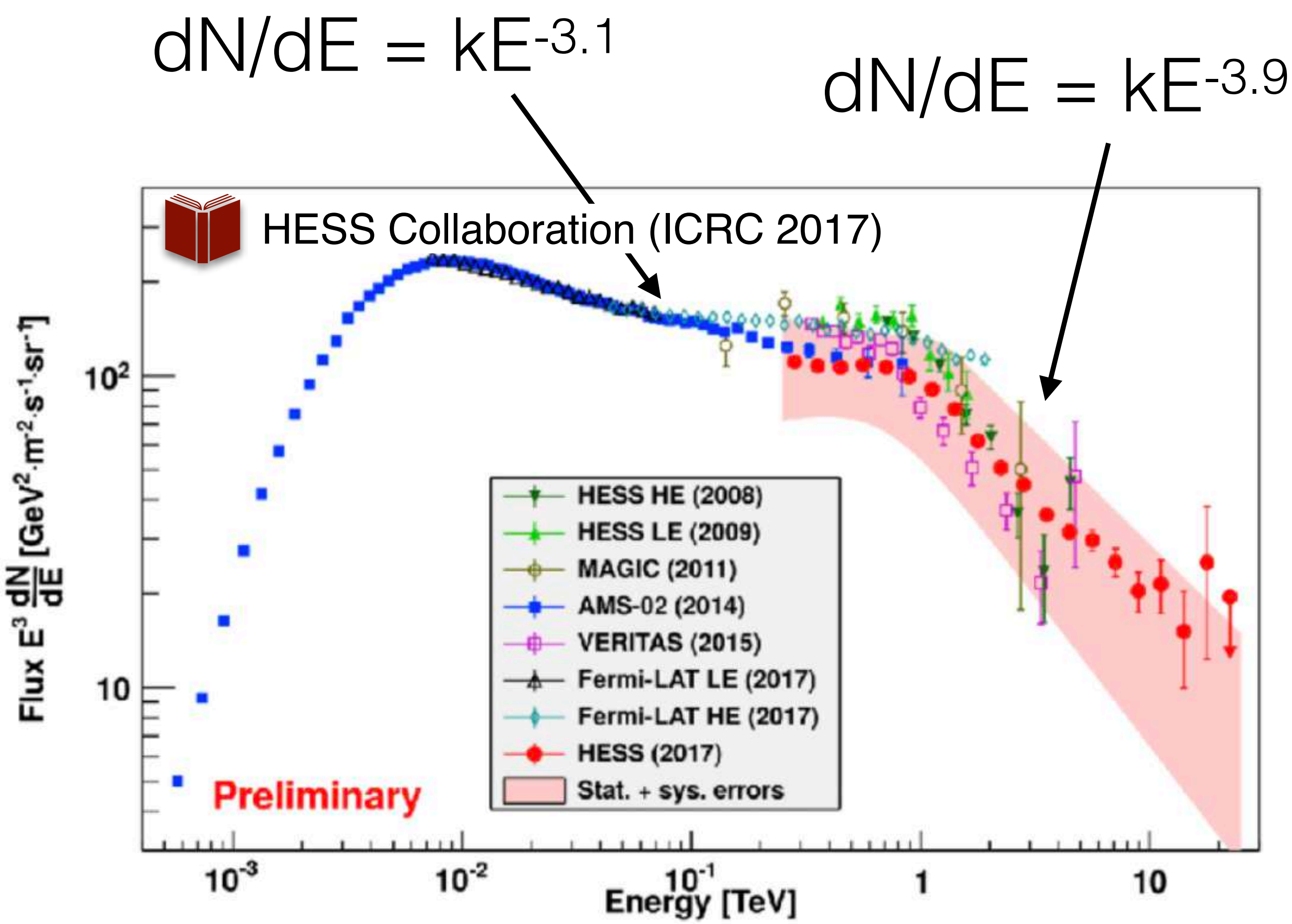


*t_{esc}(10 GeV)=t_{SP}
t_{esc}(10 TeV)=10t_{Sed}



Morlino & Celli (2021), arXiv:2106.06488

The observed CR-e spectrum



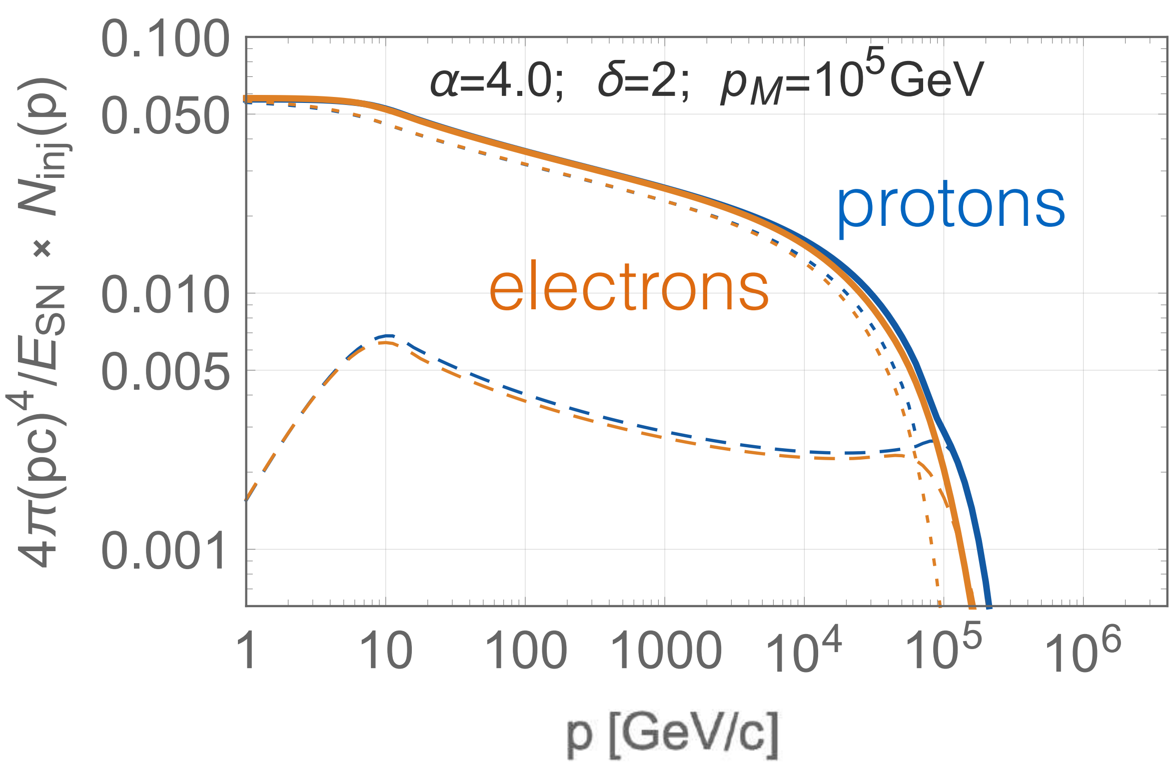
- Origin of the **spectral steepening** of the CR-electron spectrum below 1 TeV?
- Origin of the **TeV break** in the CR-electron spectrum?

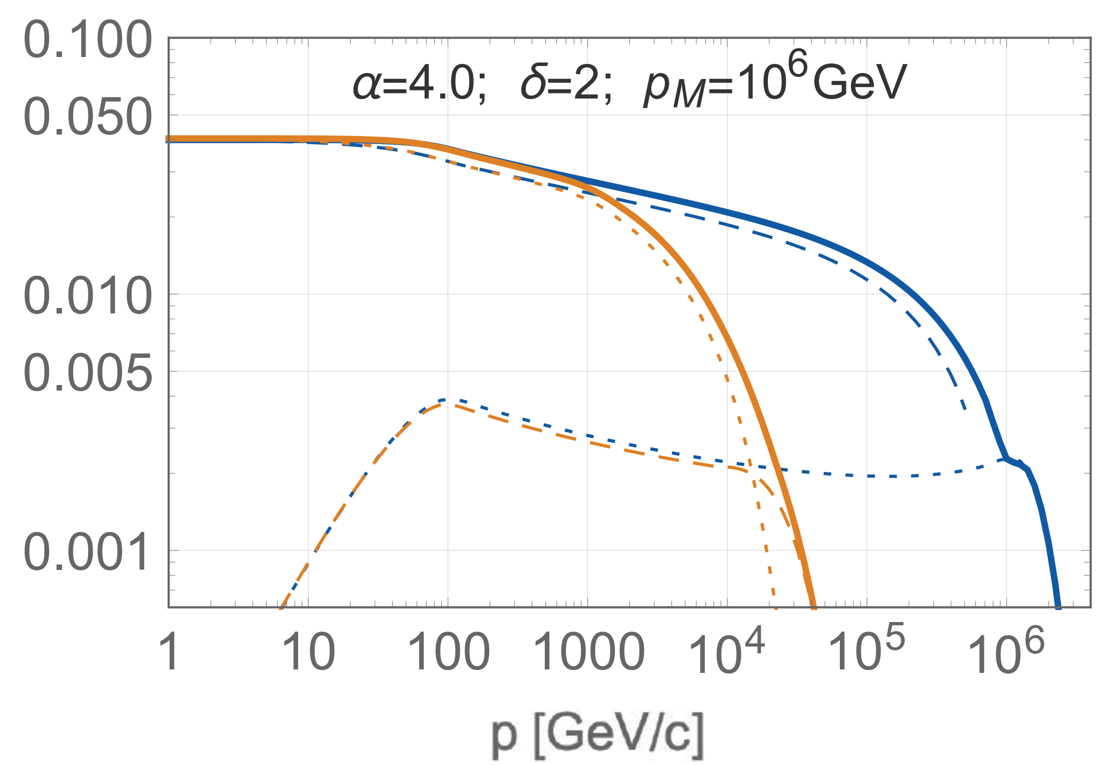
- In the sub-TeV domain, after accounting for energy losses during propagation to Earth, **proton and electron injection spectra** are characterized by **different slopes**: energy losses within the source? Other mechanism?

$$\frac{Q_e}{Q_p} \propto \frac{N_e}{N_p}\frac{1}{\sqrt{D\tau_{loss}}} \propto E^{-0.4}\frac{1}{\sqrt{E^{0.54}E^{-0.77}}} \propto E^{-0.28}$$

The CR-e spectrum injected into the Galaxy

1. Self generated turbulence



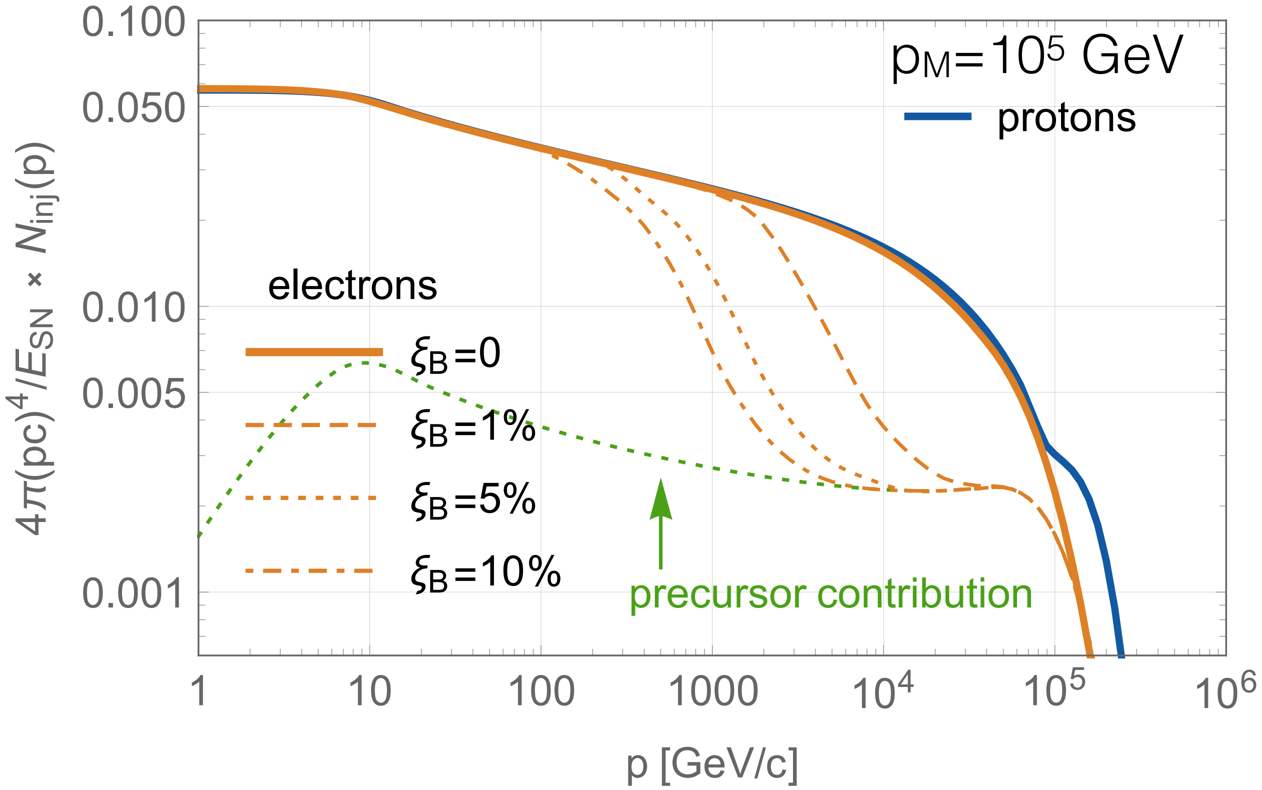


- Spectral steepening in both species of **~0.15 above $p_{max}(t_{SP})$**;
- Proton and electron spectra only differ if significant MFA is effective
  ⟶ large p_M (~PeV) or δ (>2);
- However, even in the **PeVatron** scenario, **self-amplified magnetic field can explain spectral differences only above ~1 TeV**.

Diesing & Caprioli, PRL 123 (2019) 071101
Brose et al., A&A 634 (2020) 359
Morlino & Celli, MNRAS 508 (2021) 6142M
Cristofari, Blasi & Caprioli, A&A 650A (2021) 62C

The CR-e spectrum injected into the Galaxy

2. Turbulent MHD amplification



$$\frac{\delta B^2_{2,\mathrm{tur}}}{8\pi} = \xi_B \frac{1}{2} \rho v^2_{\mathrm{sh}}$$

Morlino & Celli, MNRAS 508 (2021) 6142M

- It only affects electron losses **downstream**, not the maximum energy reached at the shock;
- **ξ_B=1%** : efficient losses above 1 TeV, produce a steepening in electron spectrum amounting to **0.8 up to 20 TeV**;
- ⟶ **ξ_B>>10% values required to get steepening down to ~10 GeV**.

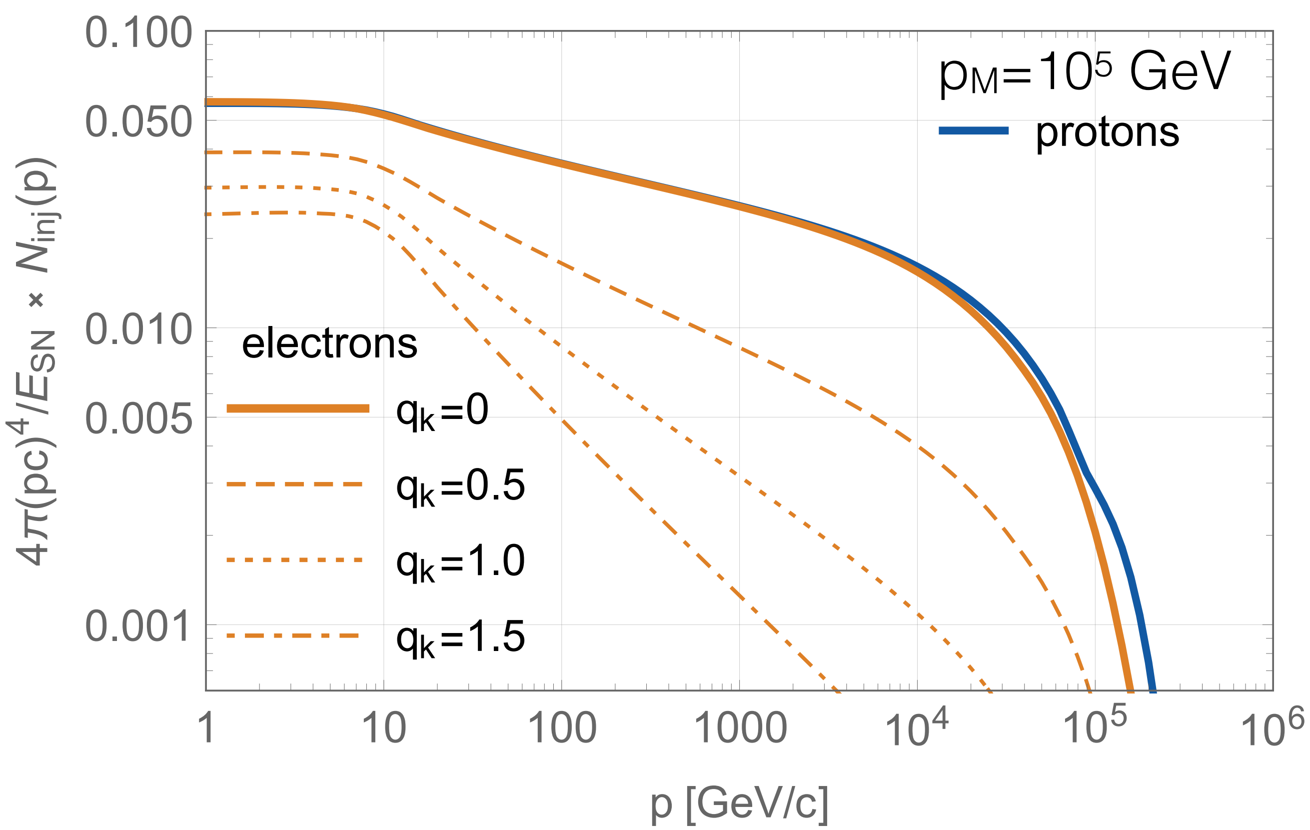
The CR-e spectrum injected into the Galaxy

3. Time-dependent electron-to-proton injection

$$N_{i,\rm inj}(p) \simeq \xi_{\rm CRi}\left(t_{\rm esc}(p)\right)\; v_{\rm esc}(p)^2\, R_{\rm esc}(p)^3\, p^{-\alpha}$$

$$\longrightarrow \frac{N_{\rm e,inj}}{N_{\rm p,inj}} = \frac{\xi_{\rm CRe}}{\xi_{\rm CRp}} = v_{\rm esc}(p)^{-q_k} \propto p^{-3q_k/(5\delta)} \equiv p^{-\Delta s_{\rm ep}}$$

Hp



$$q_k = 5\,\delta\,\Delta s_{\rm ep}/3$$

- **$\Delta s_{ep} \simeq 0.3 \longrightarrow q_k \simeq 1$**;
- Steepening down to 10 GeV consistent with observations only if **$p_{max}(t_{SP}) \lesssim 10$ GeV**.

Morlino & Celli, MNRAS 508 (2021) 6142M

On electron and proton injection

Time-dependent electron-to-proton injection might be connected to temperature ratio evolution:

- T_e / T_p estimated from Balmer lines in collisionless shocks propagating in neutral media

$$T_e/T_p \propto v_{sh}^{-2}$$

Van Adelberg et al., ApJ 689 (2008) 1089

also confirmed by PIC simulations up to Mach number ~20.

Tran & Sironi, ApJ 900 (2020) L26

- Protons are heated by pure randomization of their kinetic energy $\longrightarrow T_p \propto m_p v_{sh}^2$

- Electron temperature is almost constant with shock speed, **T_e ~ 0.3 keV**

Ghavamian et al., ApJ 654 (2007) L69

Rakowski et al., ApJ 686 (2009) 2195

On electron and proton injection

If electron injection into DSA is connected to their heating, then injection efficiency would scale inversely with v_{sh}.

In fact, electrons and protons develop a non-thermal tail at

$$p_{inj,i} = \xi_i p_{th,i}$$

From PIC simulations, it is found that $\xi_e = \xi_p$

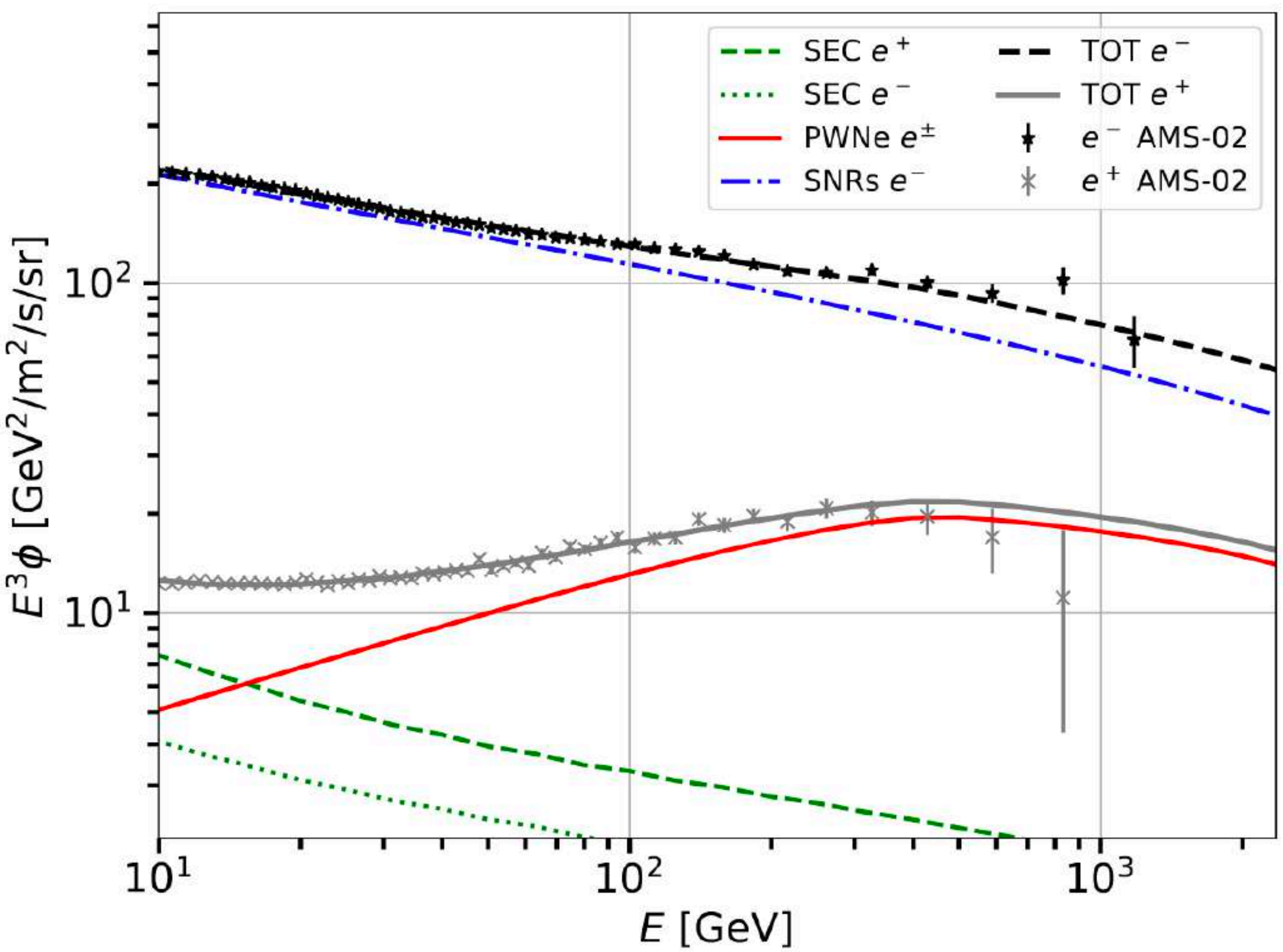
Arbutina & Zekovic, Astropart. Phys. 127 (2021) 102546

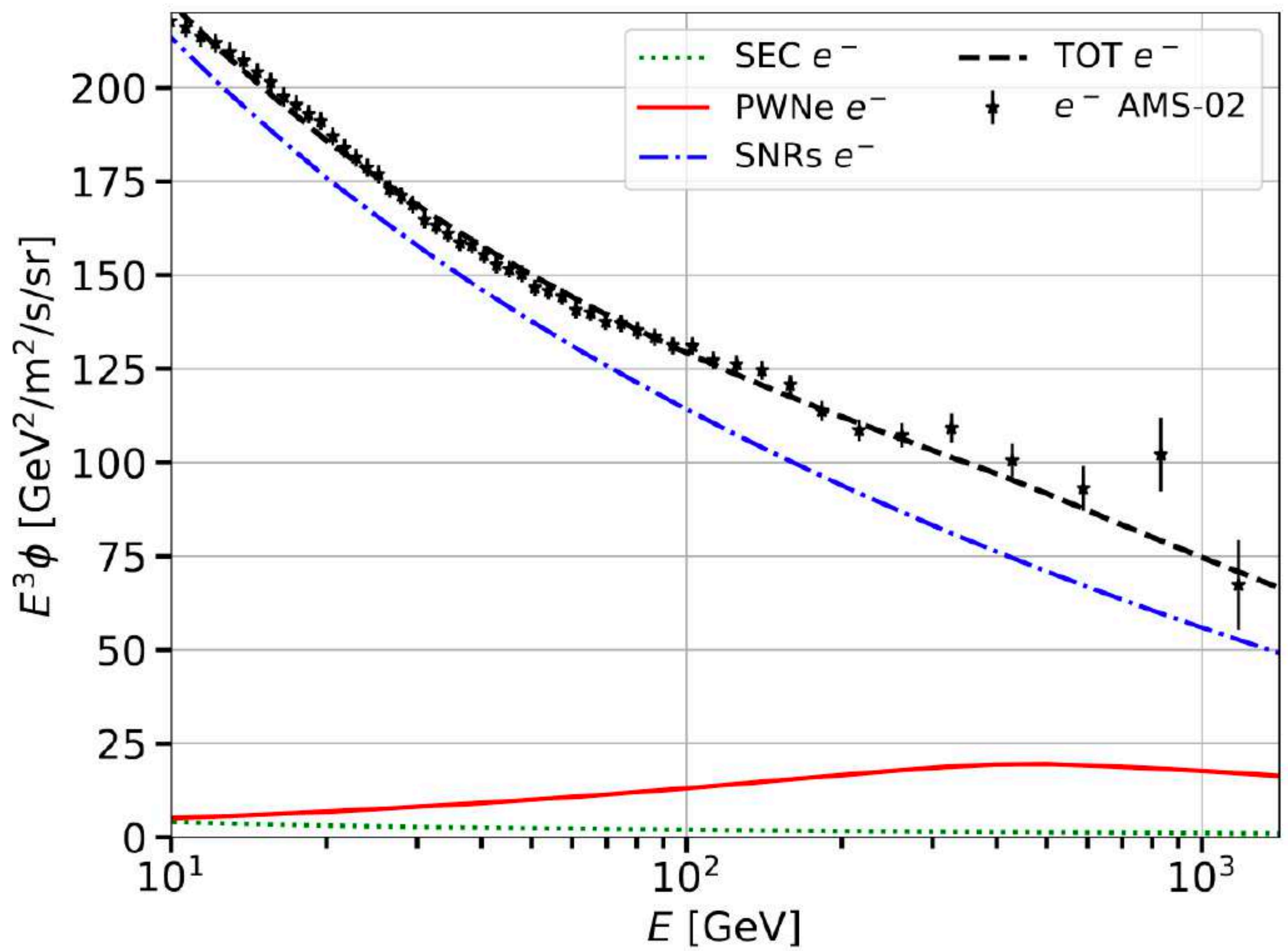
$$K_{ep} \simeq \left(\frac{m_e}{m_p} \frac{\Delta E}{\frac{3}{16} m_p v_{sh}^2} \right)^{\frac{3}{2(R_{sub}-1)}} \propto v_{sh}^{-\frac{3}{(R_{sub}-1)}}$$

Hence, for $R_{sub}<4$, $K_{ep} \sim v_{sh}^{-1}$ and $\Delta s_{ep} \sim 0.3$

The PWN contribution

Break at 40 GeV in electron spectrum also consistent with change in main source contributor, from SNRs to PWNe





Di Mauro et al., PRD 104 (2021) 083012

PWN contribution is maximal at 500 GeV, ~21%.