Particle escape from SNRs and related gamma-ray signatures

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How do accelerated particles become CRs?

Acceleration at the shock: $f_0(p)$

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

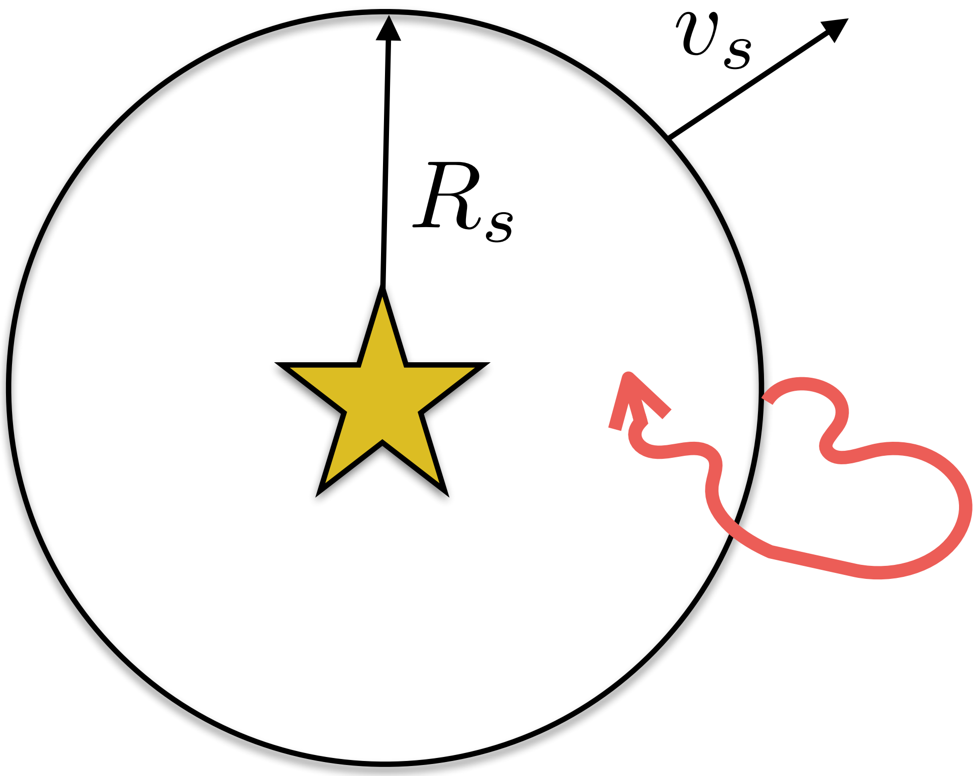
- Ptuskin & Zirakashvili, A&A 429 (2005) 755
- Gabici, Aharonian & Casanova, MNRAS (2009)
- Ohira, Murase & Yamakazi, A&A (2010) 513
- Bell & Shure, MNRAS 437 (2014) 2802
- Cardillo, Amato & Blasi, APh 69 (2015) 1
- Cristofari, Blasi & Caprioli, A&A 650A (2021) 62C

- Connect the **CR spectrum** observed on Earth with the spectrum of particles released at the sources;
- Understand the current 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



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

acceleration limited by remnant age

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

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

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

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

$$\boxed{p_{\rm max,0}(t) = p_{\rm M} \left(\frac{t}{t_{\rm Sed}}\right)^{-\delta}} \xrightarrow{\delta > 0} \boxed{t_{\rm esc}(p) = t_{\rm Sed} \left(\frac{p}{p_{\rm M}}\right)^{-1/\delta}}$$

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

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

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

Particles confined inside the SNR

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

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

Escaped particles

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

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

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

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A model for particle propagation

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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

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

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

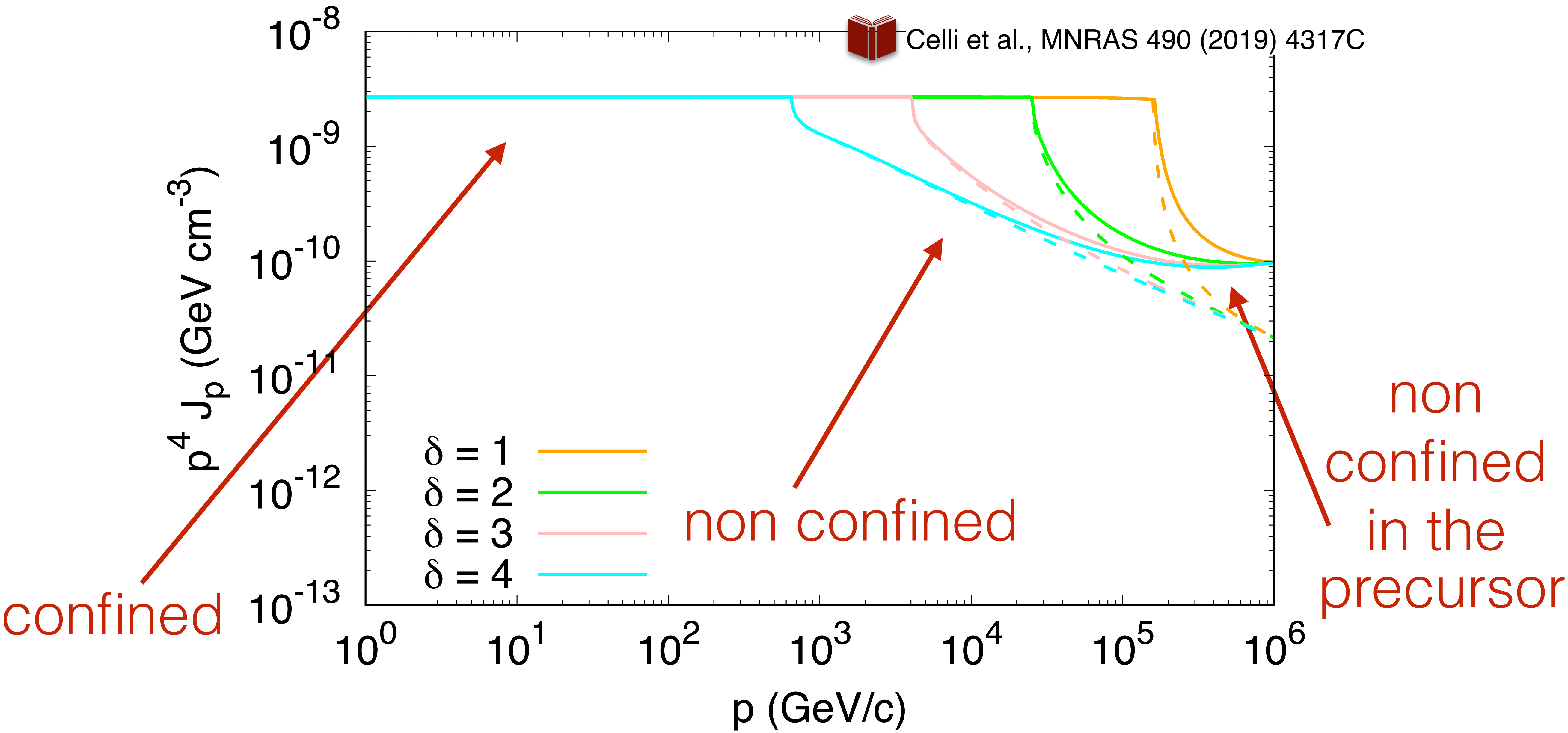
Assumption 4: the shock is evolving through the ST phase

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

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

The spectrum of protons inside the SNR

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



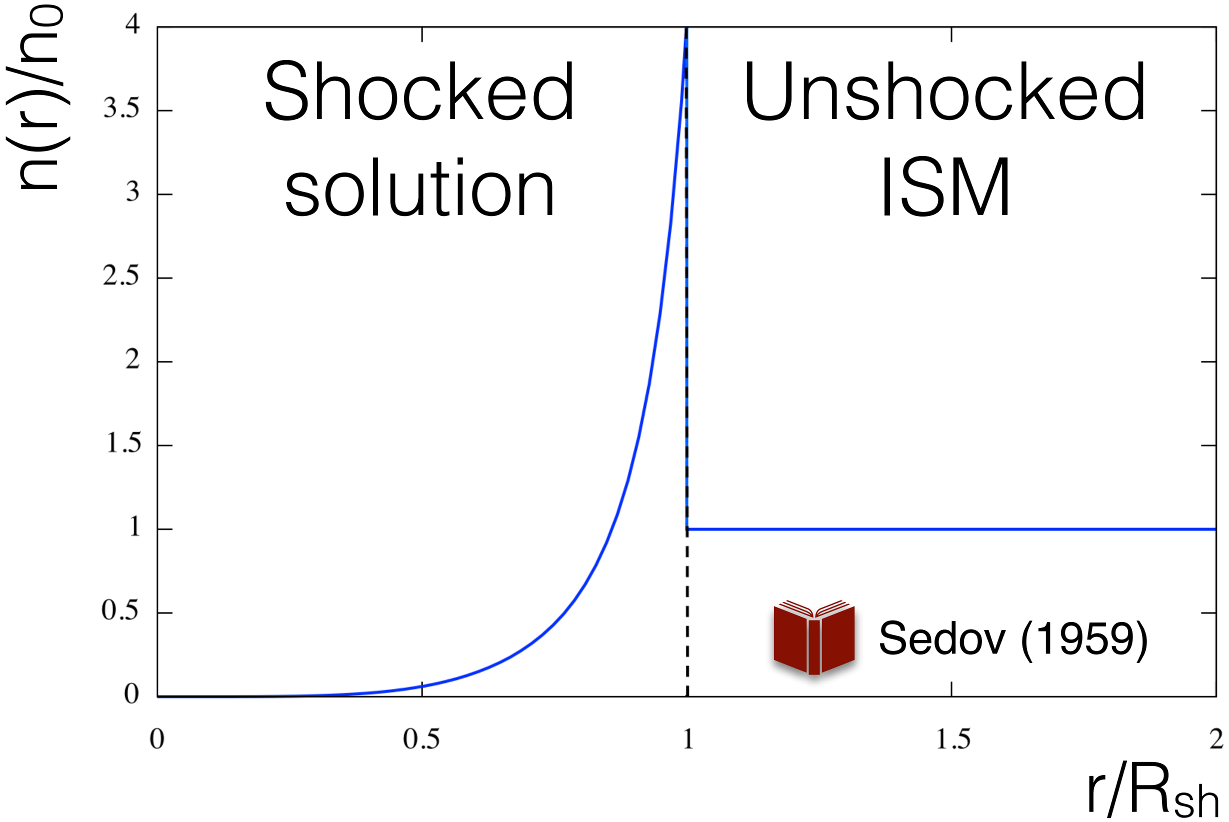
$$\boxed{D(p) = 10^{27}\left(\frac{pc}{10\ \rm GeV}\right)^{1/3} \rm cm^2 s^{-1}}$$

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

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

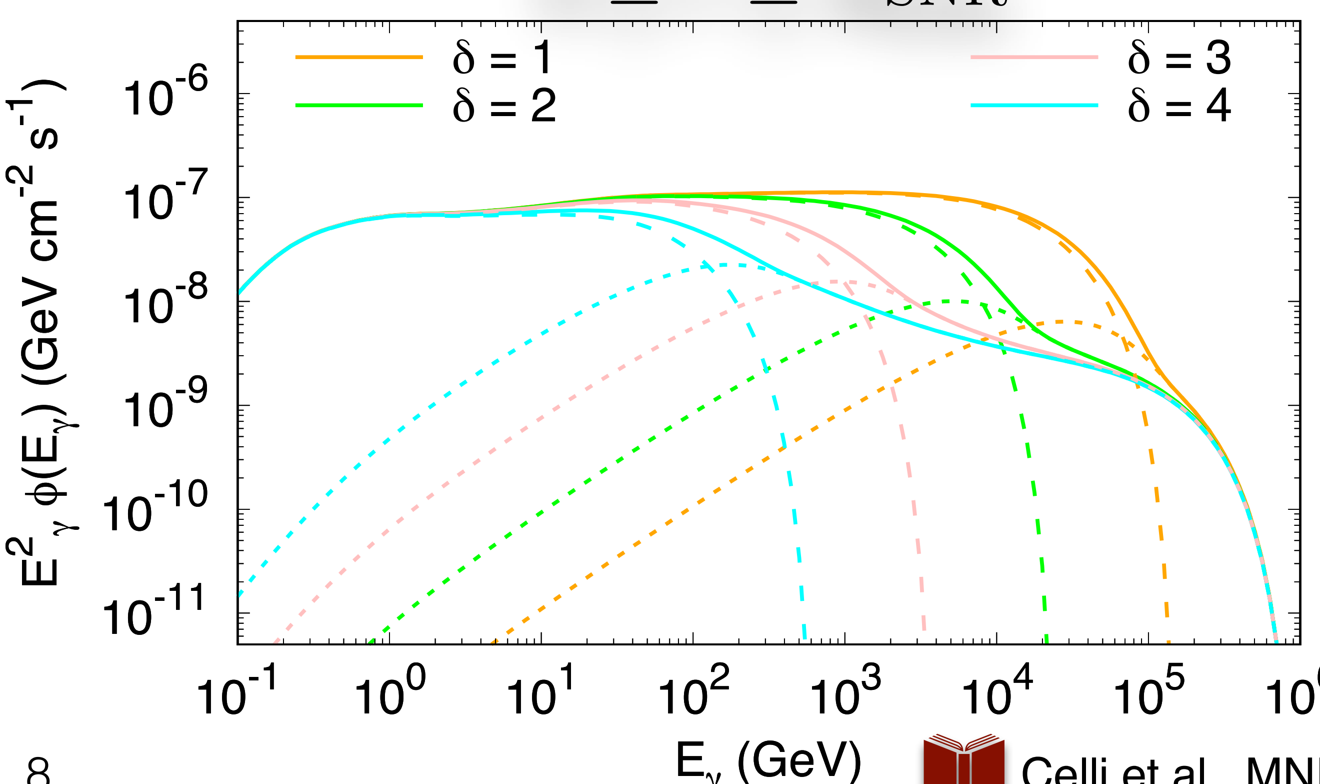
$n_0 = 1\,\rm cm^{-3}$

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

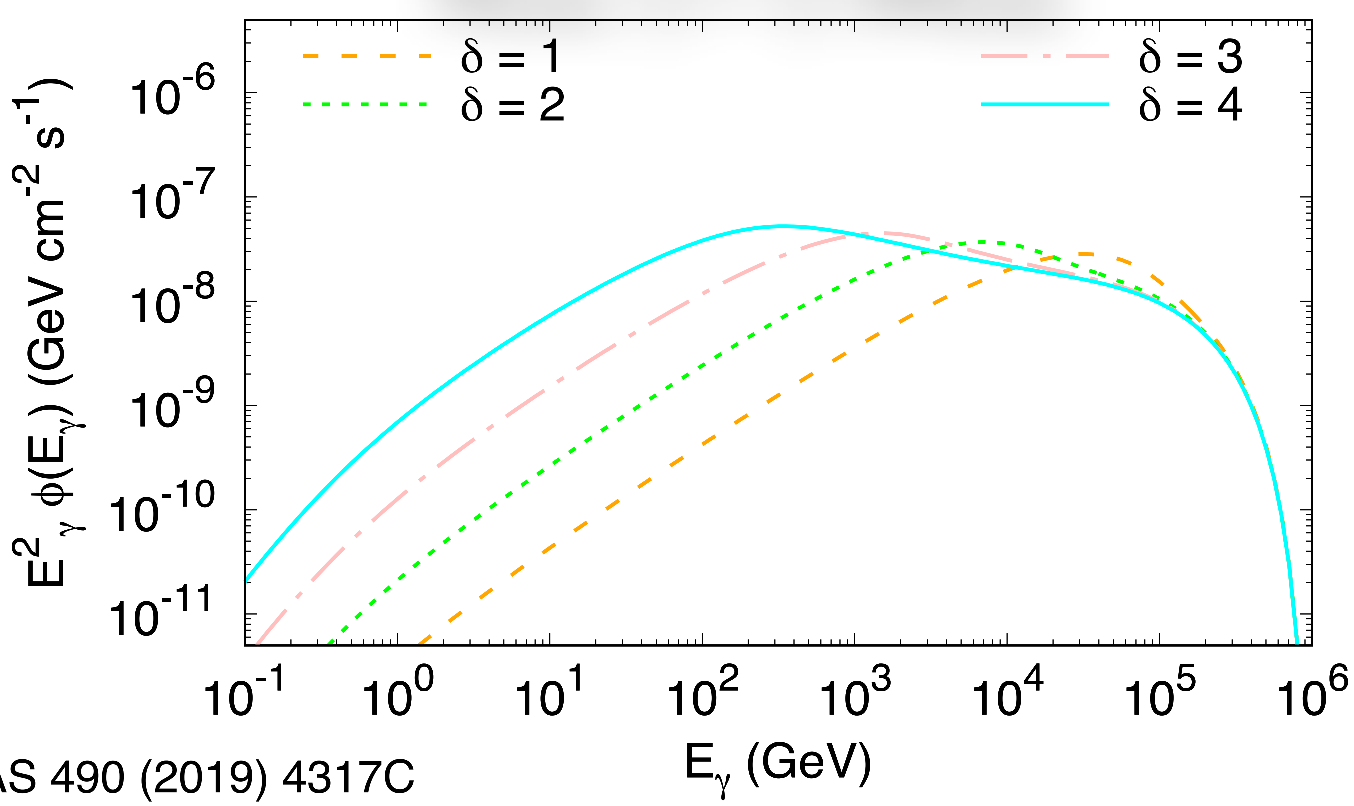


$$f_0(p) \propto p^{-4}$$
$$D(10\ \mathrm{GeV}/c) = 10^{27}\,\mathrm{cm^2\,s^{-1}}$$
$$T_{\rm SNR} = 10^4\,\mathrm{yr}$$
$$n_0 = 1\,\mathrm{cm^{-3}}$$
$$\xi_{\rm CR} = 10\%$$
$$d = 1\,\mathrm{kpc}$$

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



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



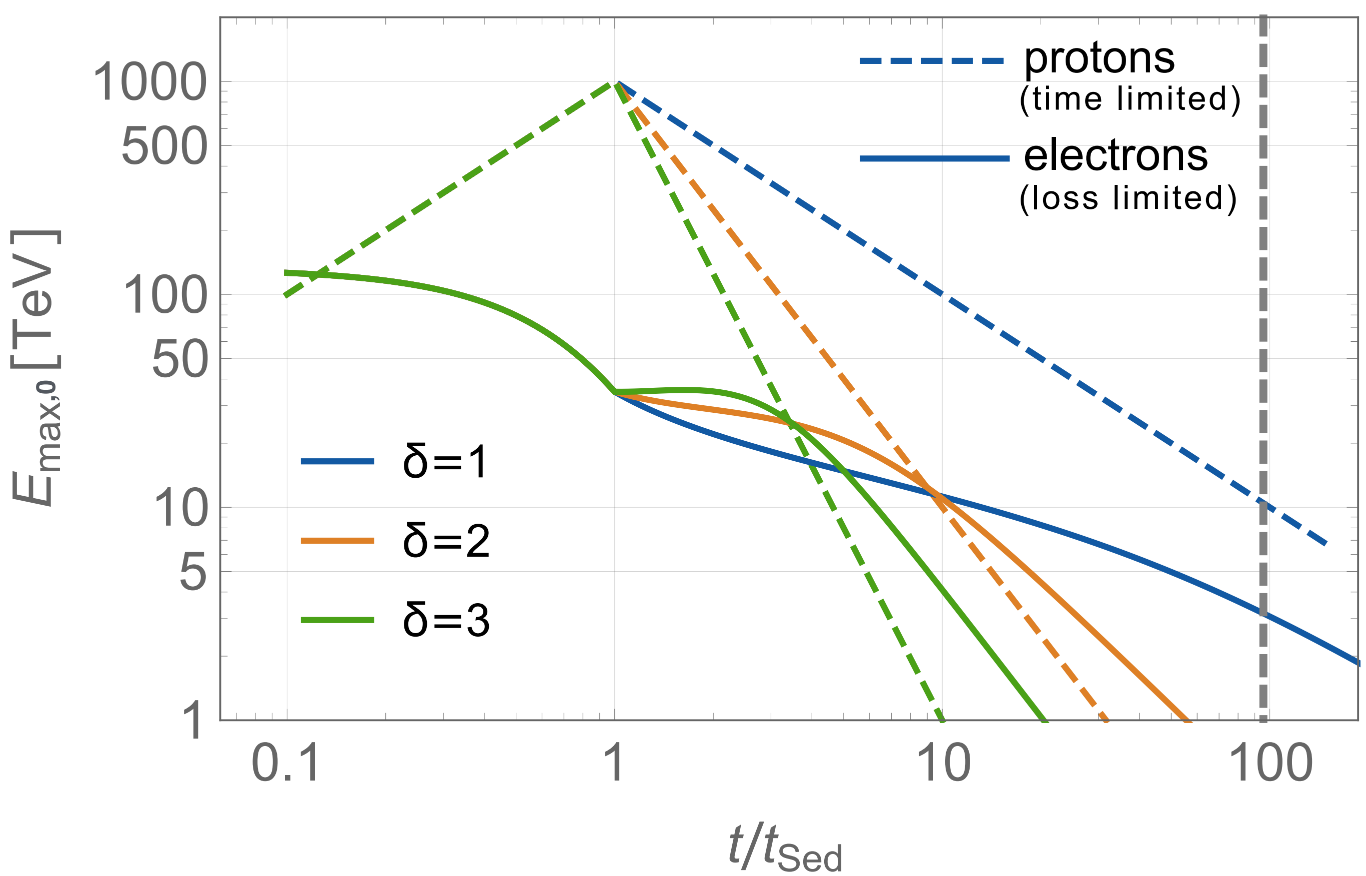
Celli et al., MNRAS 490 (2019) 4317C

Electron transport and E_{max} in SNRs

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

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{syn+IC}} = -\frac{\sigma_T c}{6\pi}\left(\frac{E}{m_e c^2}\right)^2 \left(B^2 + B_{\mathrm{eq}}^2\right)$$

$$t_{\mathrm{acc}} = t_{\mathrm{loss}} \longrightarrow \boxed{\frac{E_{\mathrm{max,e}}(t)}{m_e c^2} = \sqrt{\frac{(\sigma-1)r_B}{\sigma\left[r_B(1+\sigma_{\mathrm{eq}}^2)+\sigma(r_B^2+\sigma_{\mathrm{eq}}^2)\right]}\,\frac{6\pi e B_0 \mathcal{F}(t)}{\sigma_T B_{1,\mathrm{tot}}^2(t)}\,\frac{v_{\mathrm{sh}}(t)}{c}}}$$



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

Reynolds, ApJ 493 (1998) 375

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

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

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

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

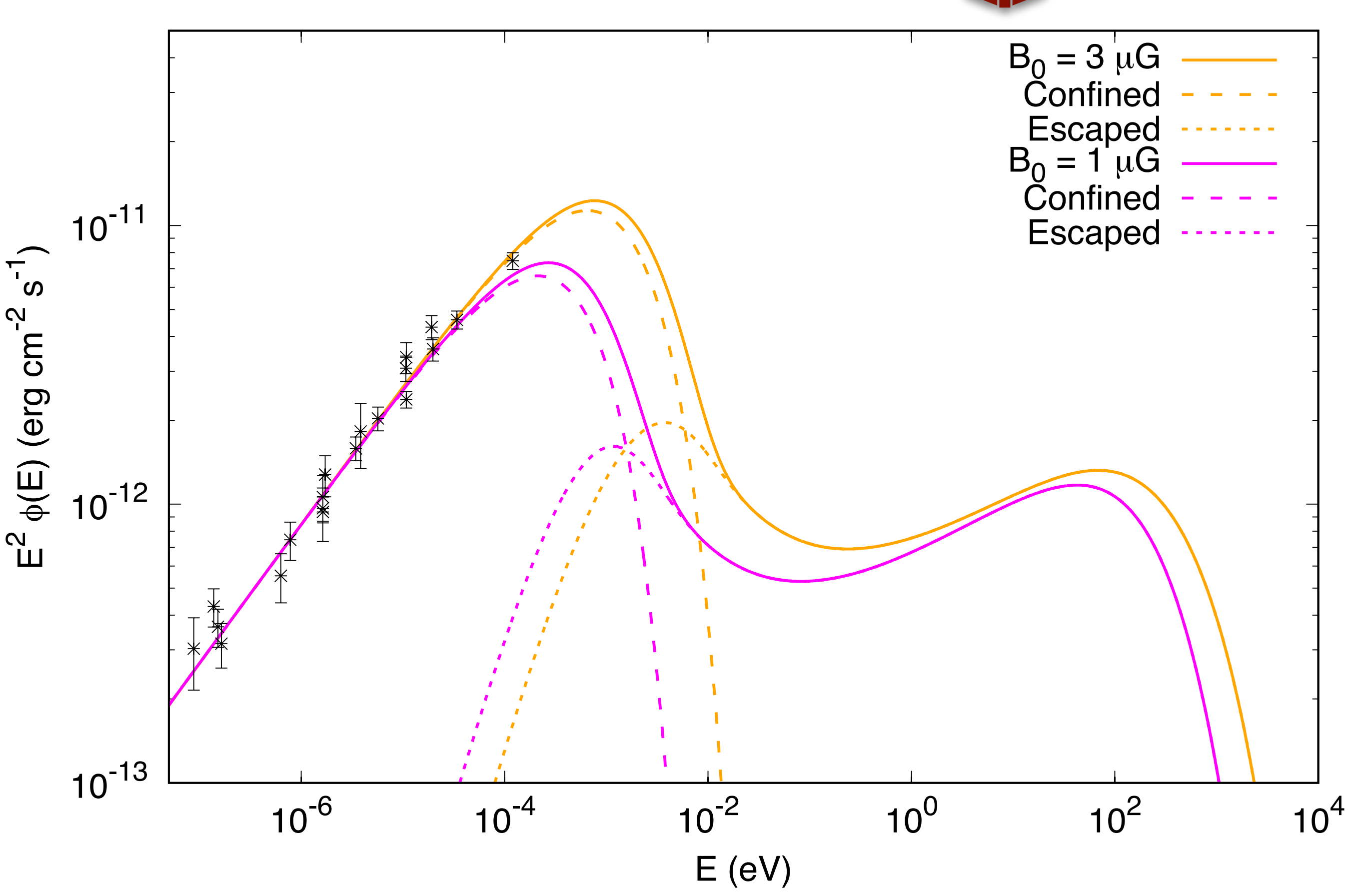
Blasi, MNRAS 402 (2010) 2807

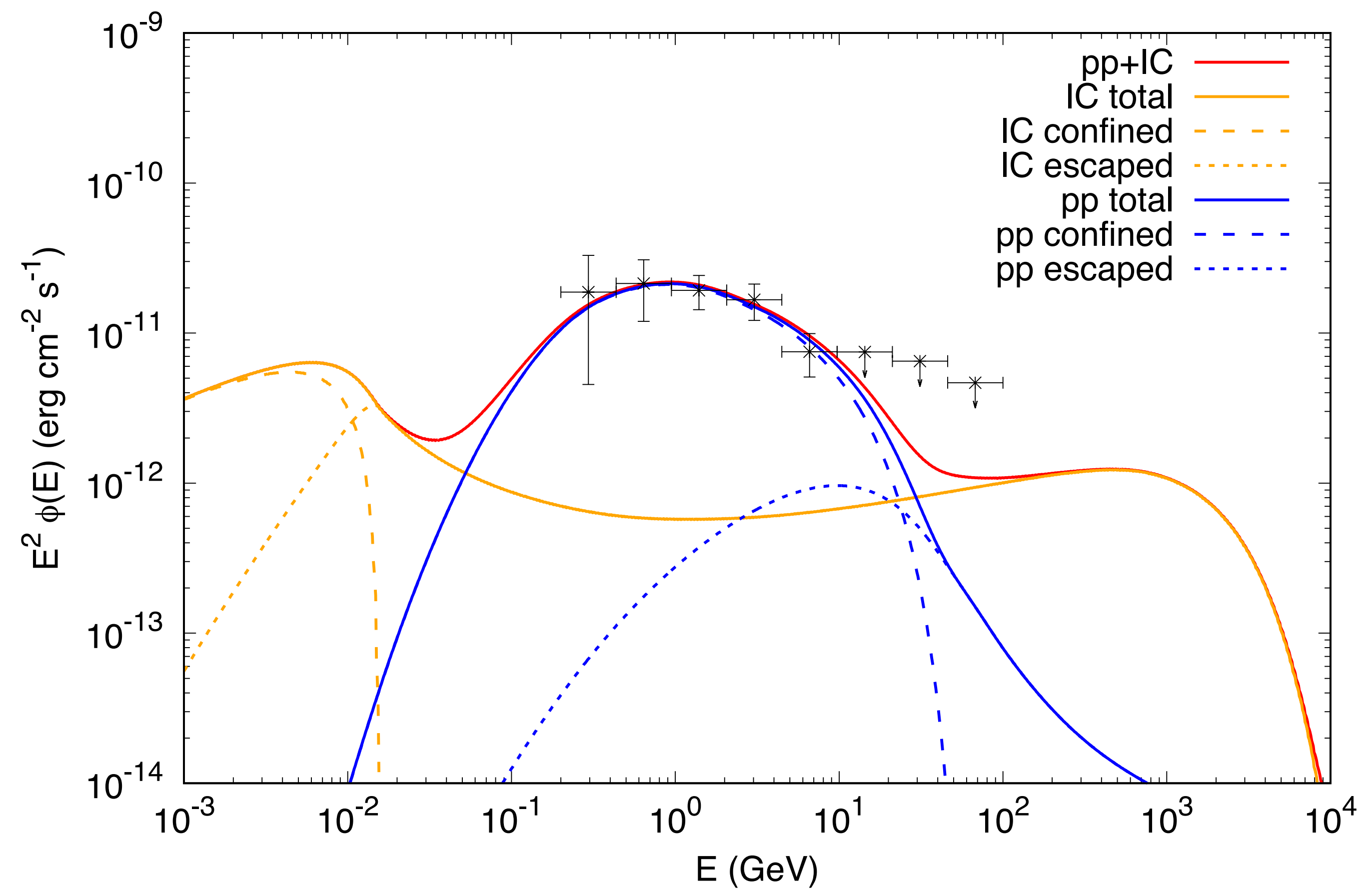
Morlino & Celli (2021), arXiv:2106.06488

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	$0.4\ \mathrm{cm}^{-3}$	20 pc	$380\ \mathrm{km\ s}^{-1}$	0.07	4.0	200 TeV	3	0.15	$3\ \mu$G	1

Loru et al., MNRAS 500 (2020) 5177





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

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

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

Conclusions

- Particle **escape** is a poorly understood mechanism, strongly embedded in the process of particle acceleration
  → it depends on the time evolution of magnetic turbulence.

- Modeling of the broadband emission of middle-aged SNRs (e.g. Cygnus Loop) can explain the **steep spectra** and low **maximum energy** observed in the **HE** and **VHE** emission
  → constraints on escape from SNR population studies.

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

Please have a look at A. Mitchell et al. contribution #756, poster session 55 GRI on 14 July 2021,12:00 CEST