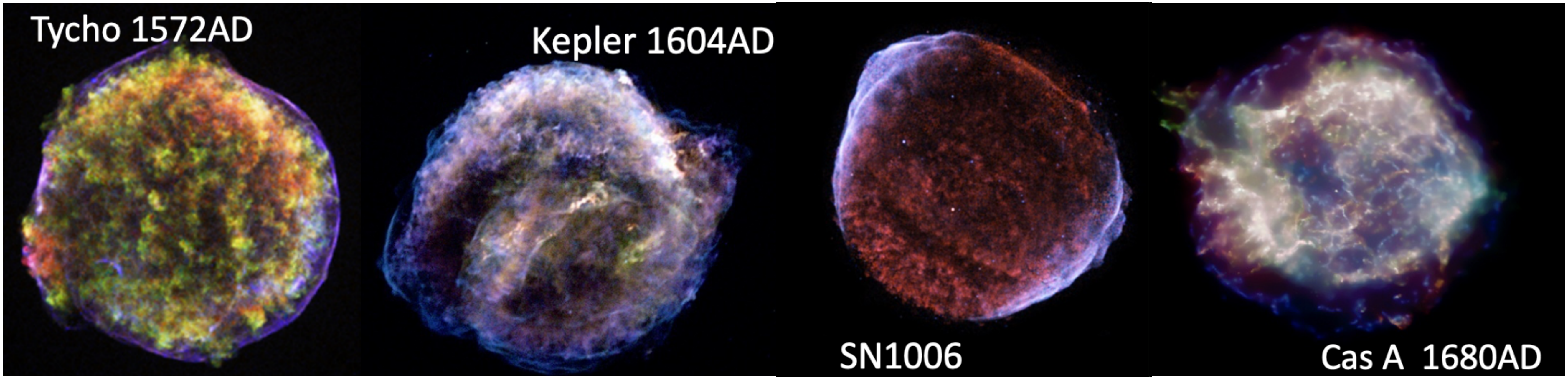

Middle-aged supernova remnants as test-bench for the PeVatron scenario

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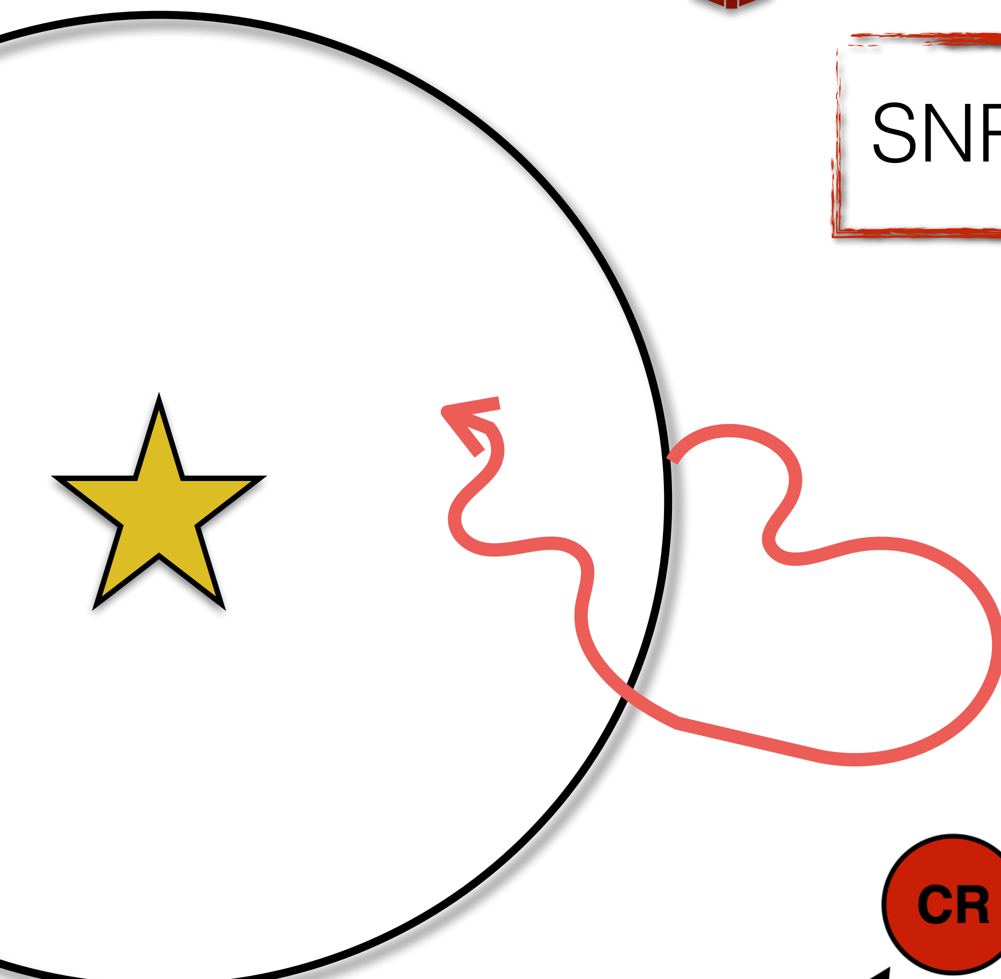
The SNR paradigm for the origin of Galactic CRs



Enough power in SN explosions to explain CRs

Baade & Zwicky, PNAS 20 (1934) 259

Ginzburg & Syrovatsky, PTPS 20 (1961) 1

SNR shocks ⟶ acceleration sites

Diffusive Shock Acceleration

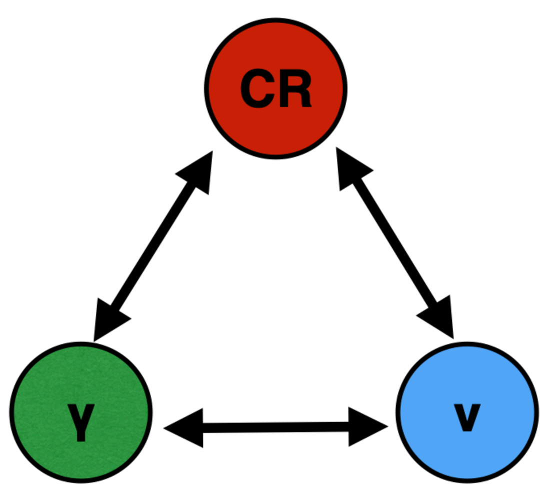
Axford et al., ICRC1977, 11 132

Krymskii, AKSSRD 234 (1977) 1306

Bell, MNRAS 182 (1978) 147

Blandford & Ostriker, ApJ 221 (1978)

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

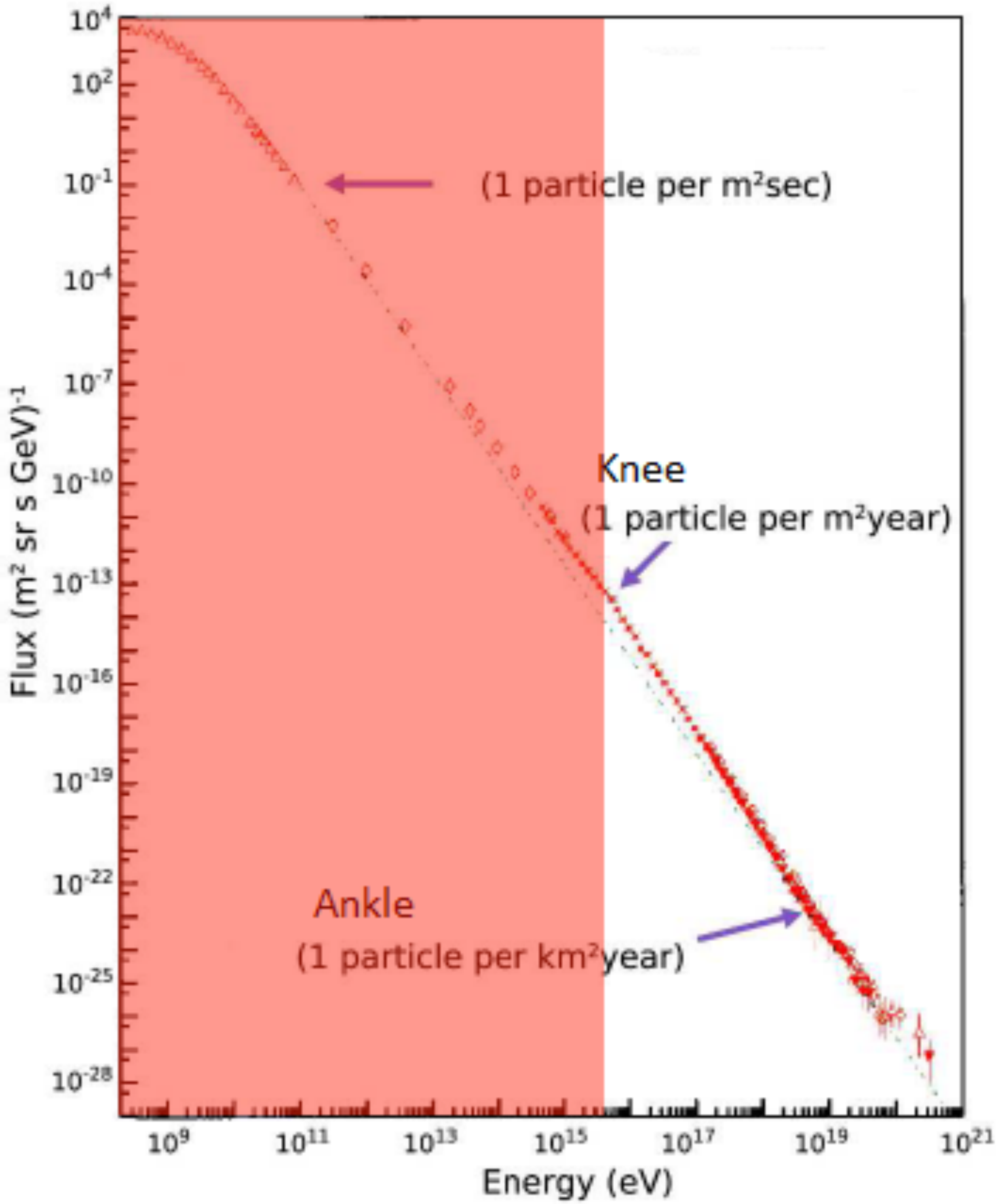


pp interaction ⟶ γ rays and ν

Aharonian et al., A&A 285 (1994) 645A

$$\longrightarrow \frac{dN}{dE} \propto E^{-2}$$

Are SNRs proton PeVatrons?



Hillas criterion

$$E_{max} \simeq v_s R B$$

shock speed — radius — magnetic field

$$E_{max} \simeq 1 \left(\frac{v_s}{10^3 Km/s} \right) \left(\frac{R}{pc} \right) \left(\frac{B}{\mu G} \right) TeV$$

3 **3** **10**

$$E_{max} \simeq 100\,\mathrm{TeV}$$

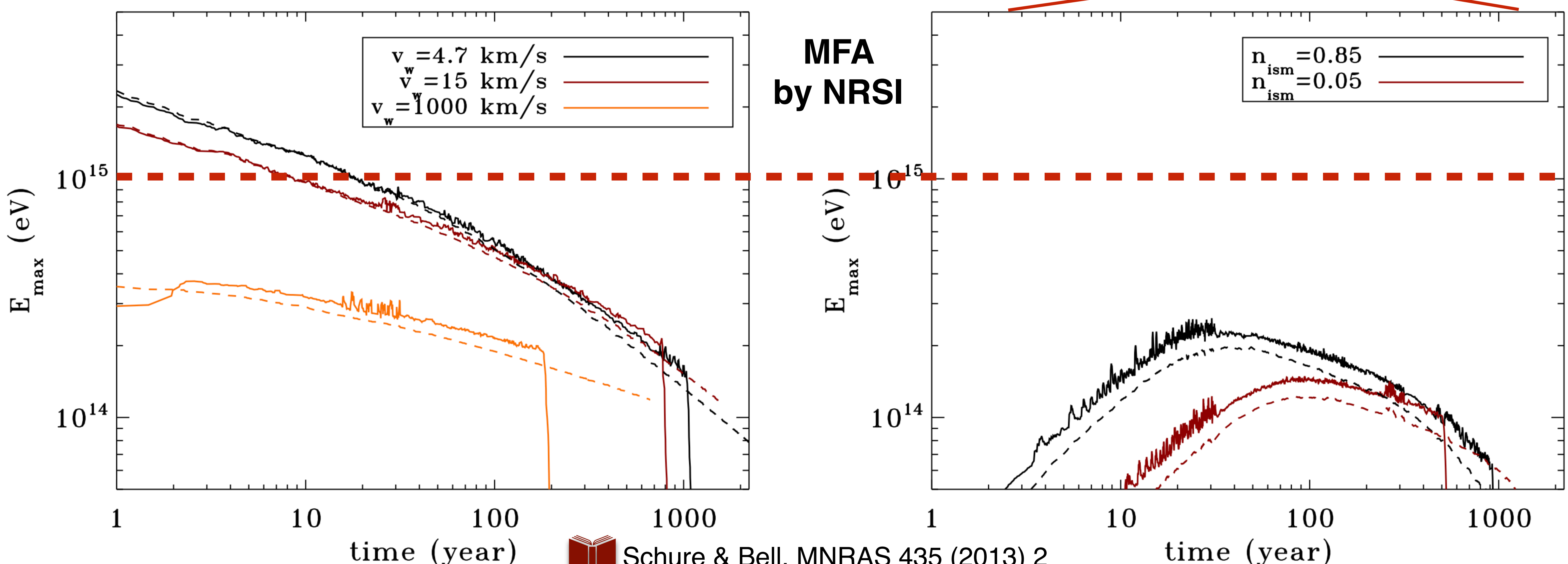
B-field amplification is required to achieve PeV energies

Cesarsky et al., SSRev 36 (1983) 173C

The problem of maximum energy in young SNRs

- Type Ia (e.g. Tycho) ⟶ expanding in constant density medium
- Core Collapse (e.g. CasA, RXJ1713.7-3946) ⟶ expanding in the dense slow wind of the progenitor star

Remnants of type II ~~**Remnants of type Ia**~~



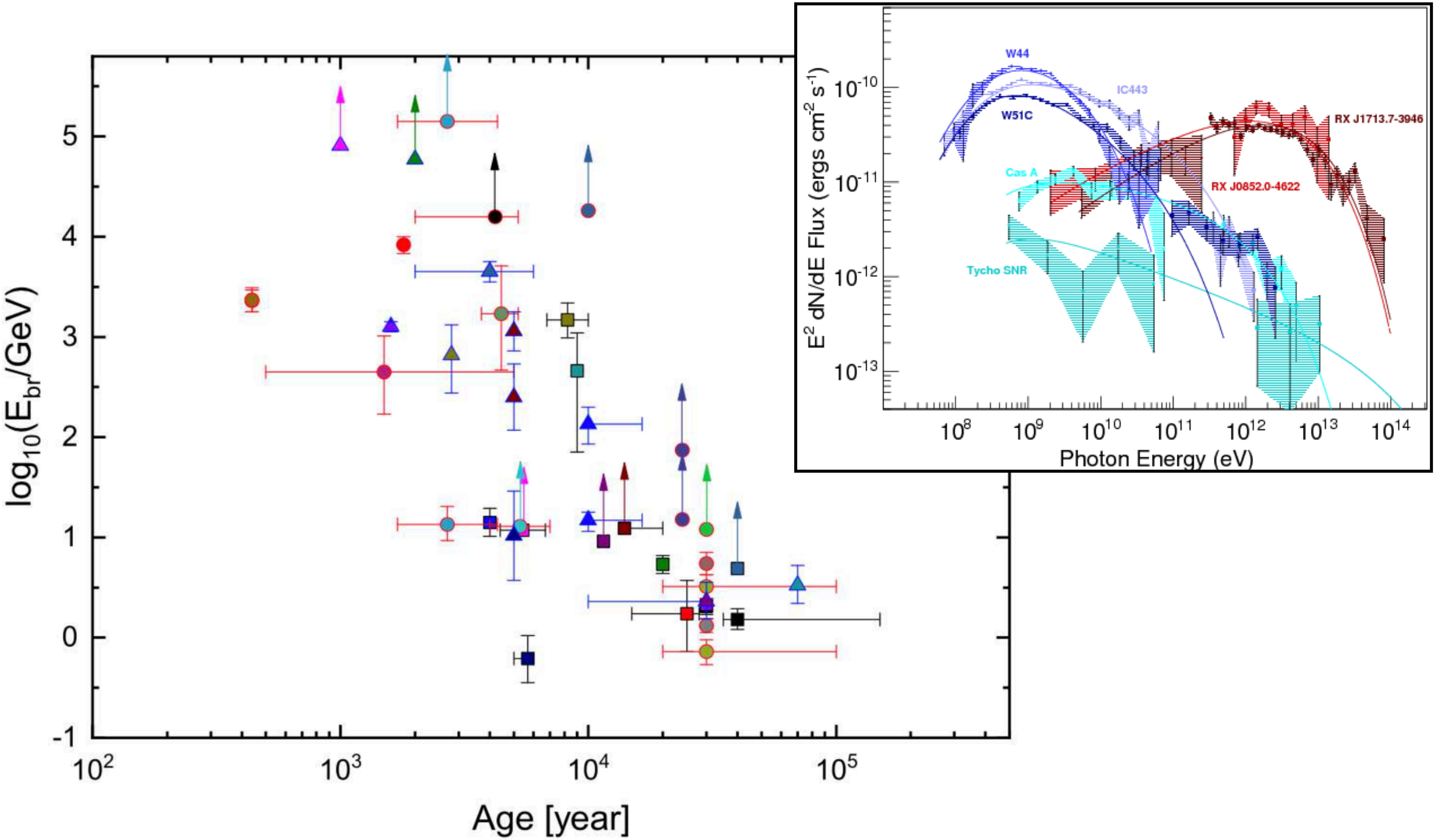
Schure & Bell, MNRAS 435 (2013) 2

Only special explosions might achieve the knee

Cardillo et al., Astropart. Phys. 69 (2015) 1

Cristofari et al., Astropart. Phys. 69 (2020) 102492

A population study of evolved SNRs



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

The role of particle escape or how do accelerated particles become CRs?

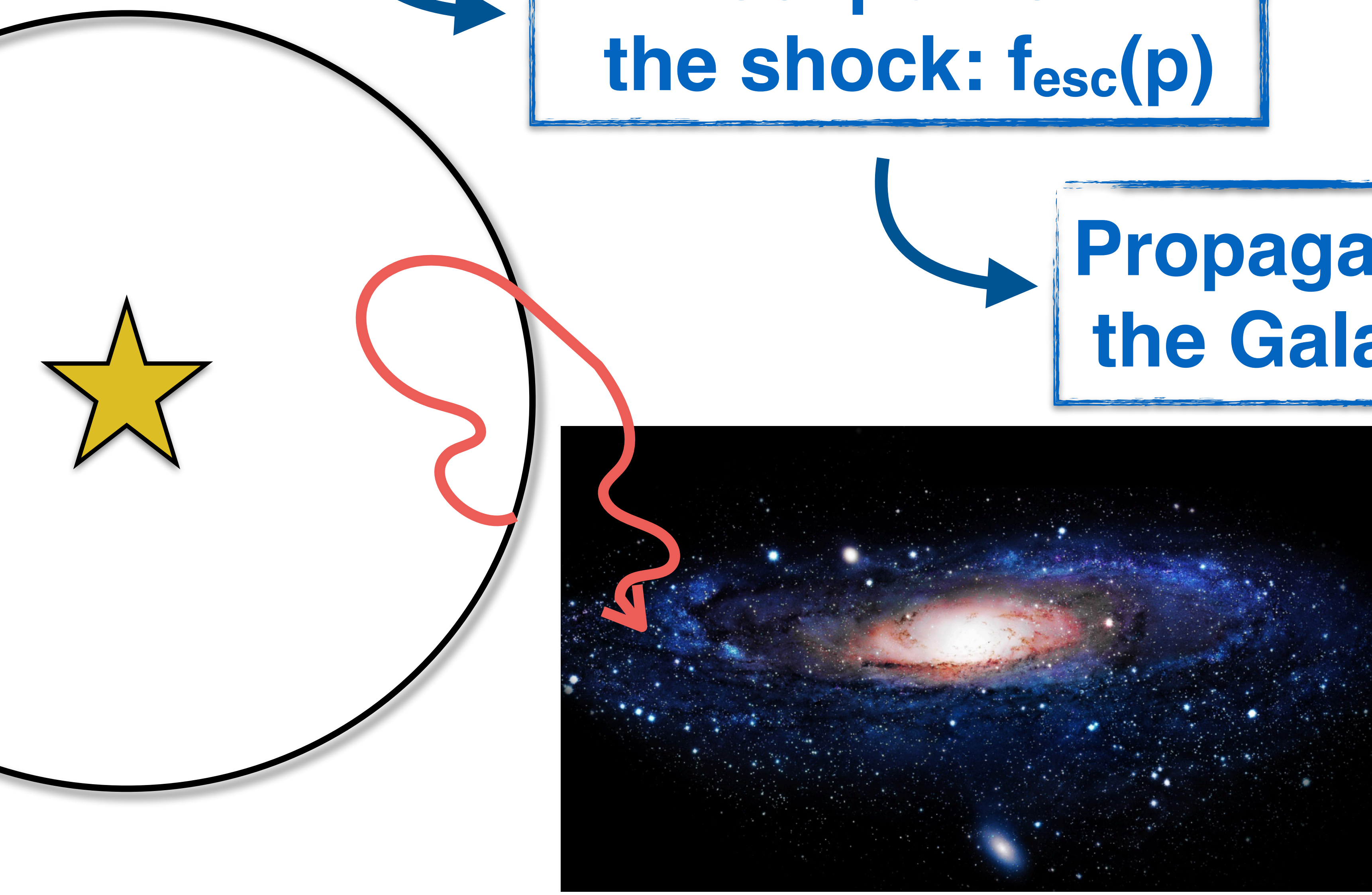
Acceleration at the shock: $f_0(p)$

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

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

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

Observation



The role of particle escape or how do accelerated particles become CRs?

Acceleration at the shock: $f_0(p)$

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

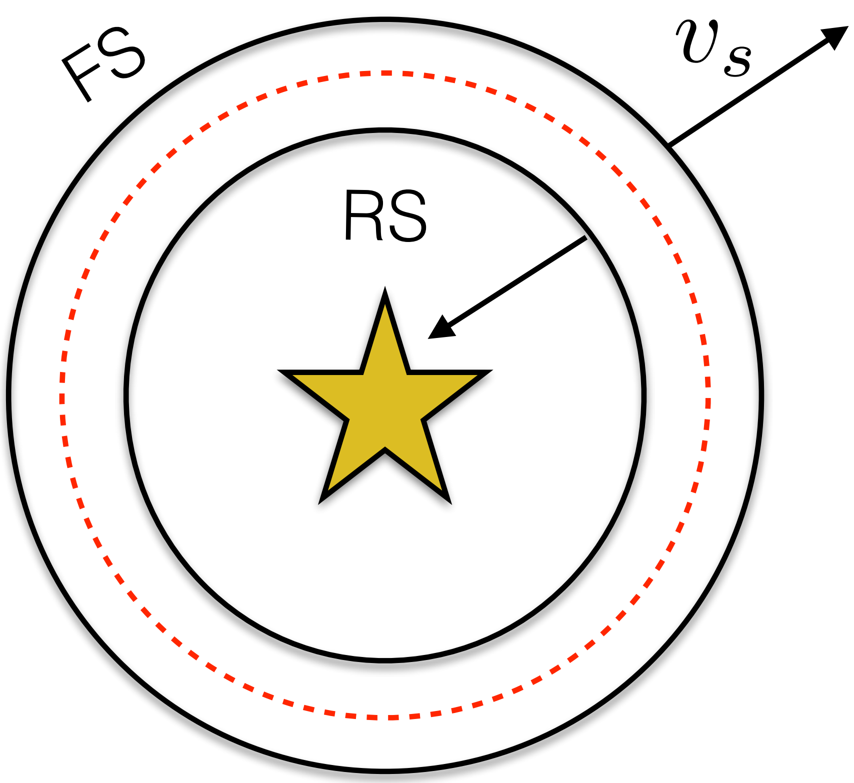
- Ptuskin & Zirakashvili, A&A 429 (2005) 755
- Gabici, Aharonian & Casanova, MNRAS (2009)
- Ohira, Murase & Yamakazi, A&A (2010) 513
- Bell & Shure, MNRAS 437 (2014) 2802
- Cardillo, Amato & Blasi, APh 69 (2015) 1

Defines $\mathbf{E_{max}}$ and **spectral slope** of both **particles** and **radiation**

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) 3

The hydrodynamical evolution of an SNR



Vink, A&A Rev 20 (2012) 1

I. Ejecta-dominated (ED) stage

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

⟶ free expansion

II. Sedov-Taylor (ST) stage

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

⟶ energy conservation

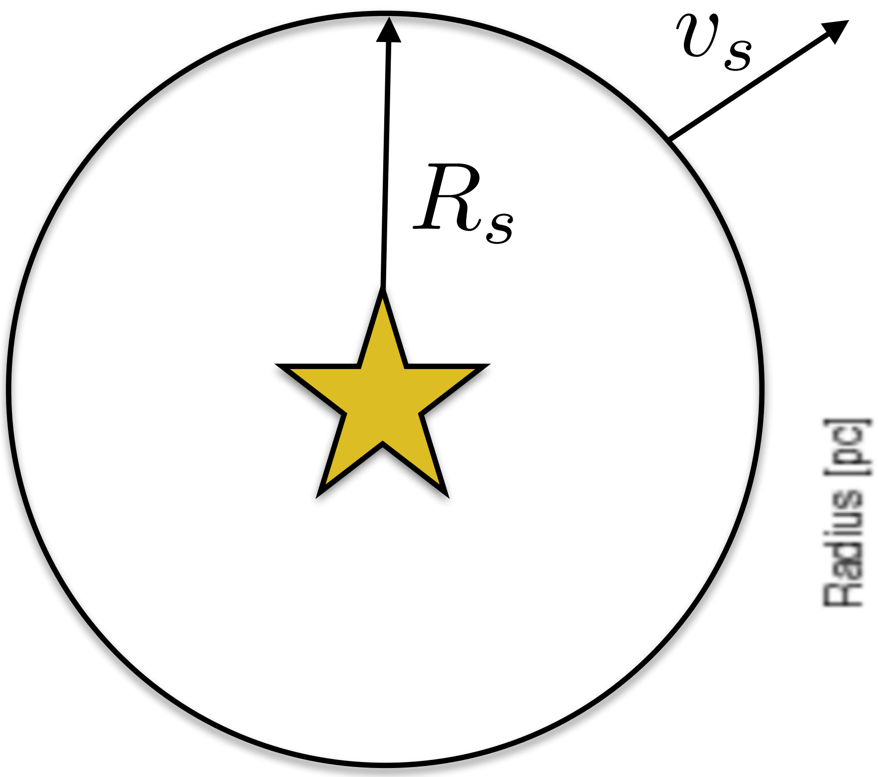
III. Radiative stage

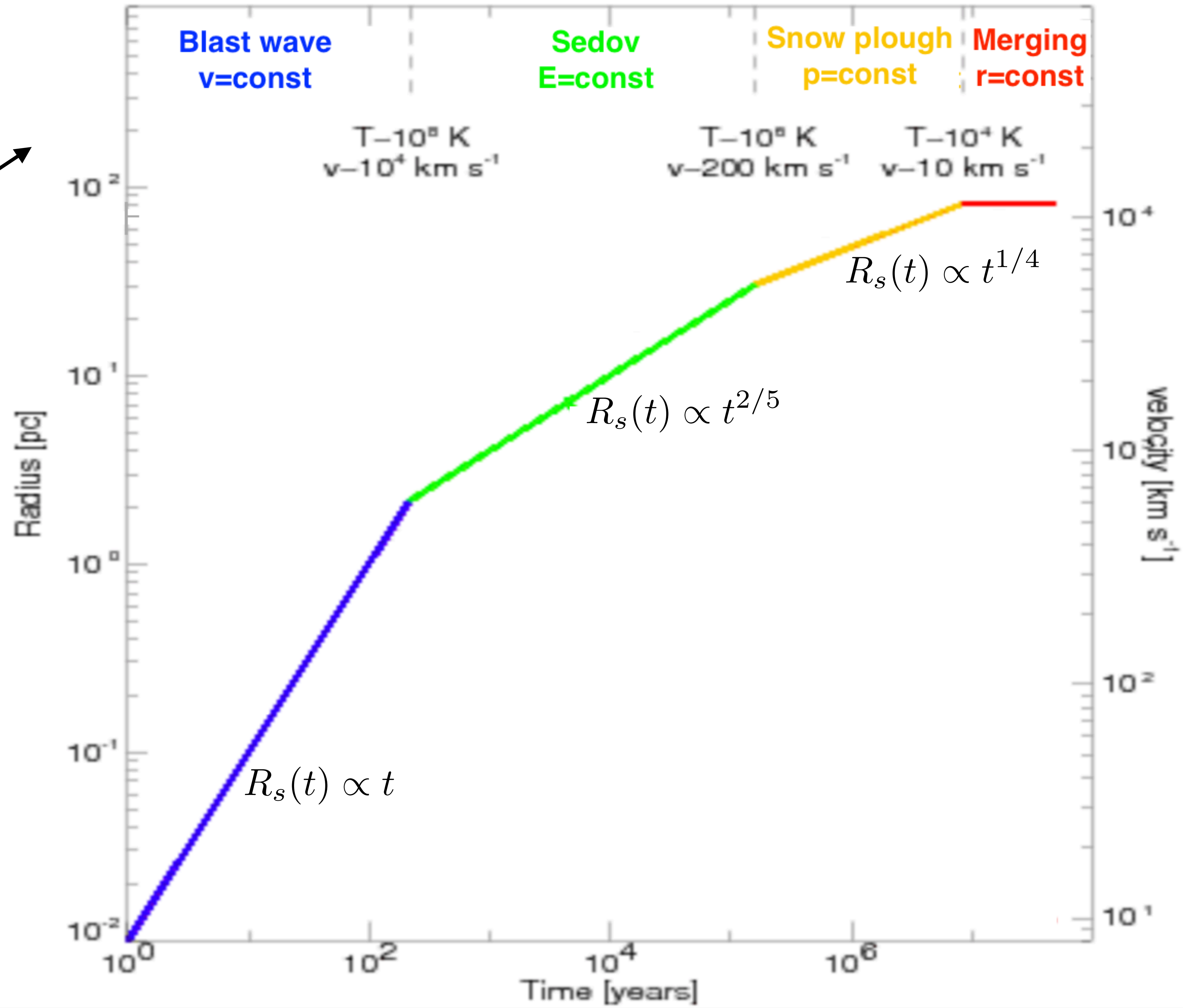
⟶ momentum conservation

IV. Merging phase

⟶ pressure comparable to ISM

The hydrodynamical evolution of an SNR

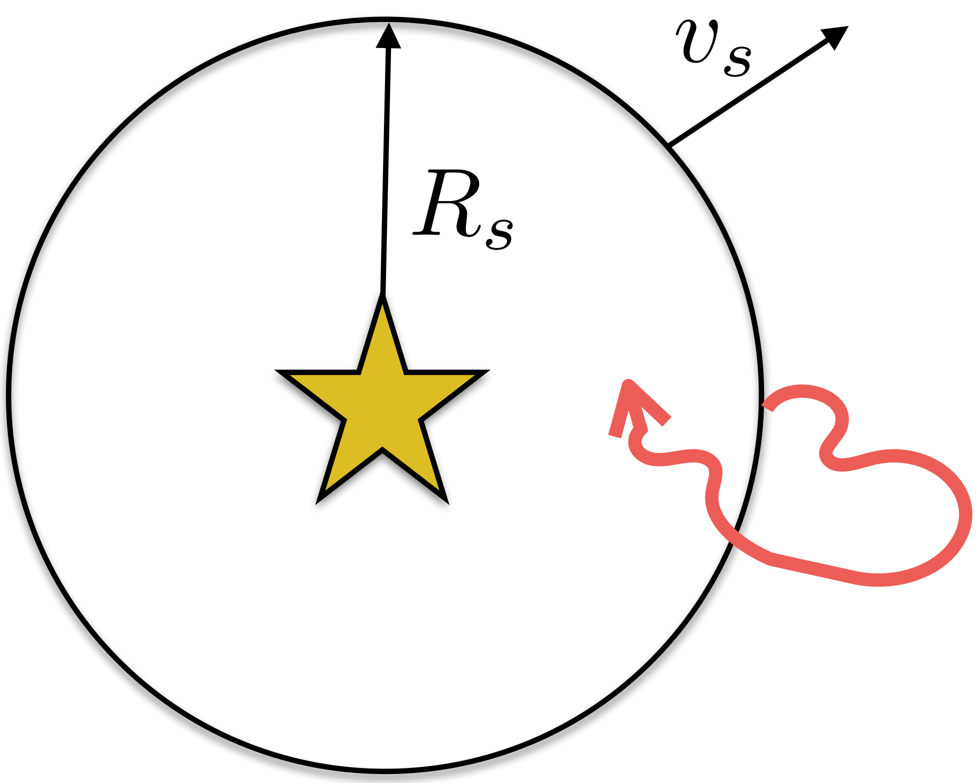




Vink, A&A Rev 20 (2012) 1

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

Maximum energy in SNRs



- At Sedov time, particles at maximum energy E_M are still confined:

$$\lambda_{\rm d}(E_{\rm M}, t_{\rm Sed}) \simeq R_{\rm s}(t_{\rm Sed})$$

- Later in the evolution, particles diffusion length increases faster than SNR shock size:

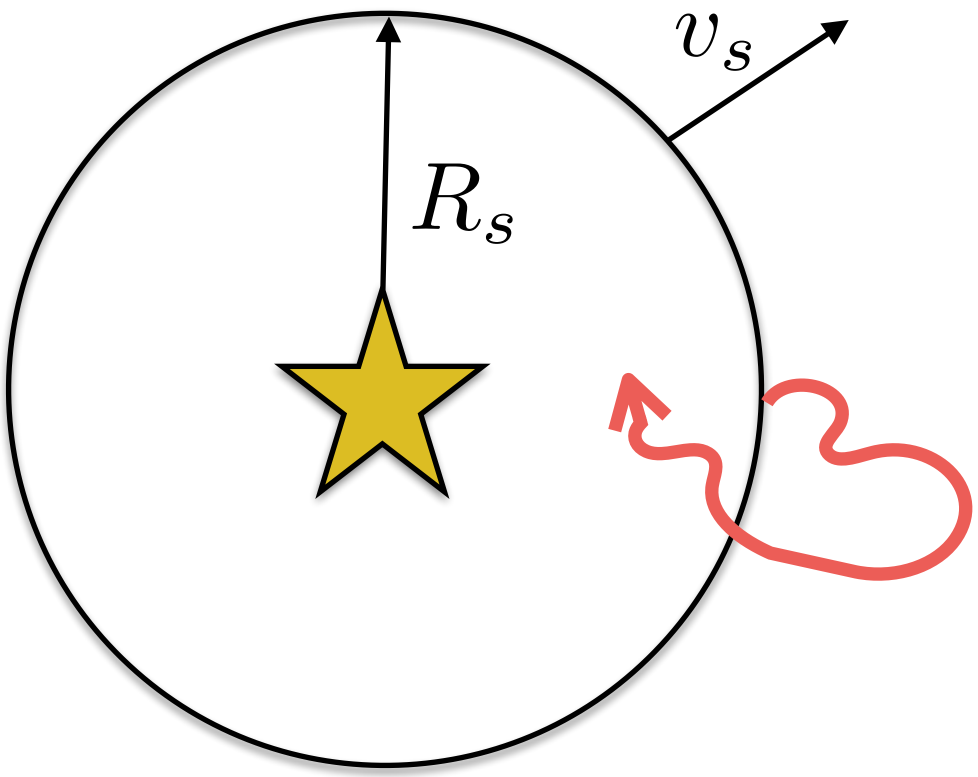
$$\lambda_{\rm d} \simeq D(E_{\rm M})/v_{\rm s} \propto t^{3/5}$$

$$R_s \propto t^{2/5}$$

Particles previously confined will now violate Hillas criterion

⟶ **escape is expected to occur on shorter timescales for the highest energy particles, but it is not an instantaneous process**

Maximum energy in SNRs



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

acceleration limited by remnant age

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

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

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

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

→ ED stage:

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

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

→ ST stage:

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

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

Maximum energy in SNRs

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

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

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

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

- 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

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

A model for particle propagation

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

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

Celli et al., MNRAS 490 (2019) 3

ANALYTICAL DESCRIPTION WITH A DOWNSTREAM VELOCITY PROFILE OF:

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

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

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

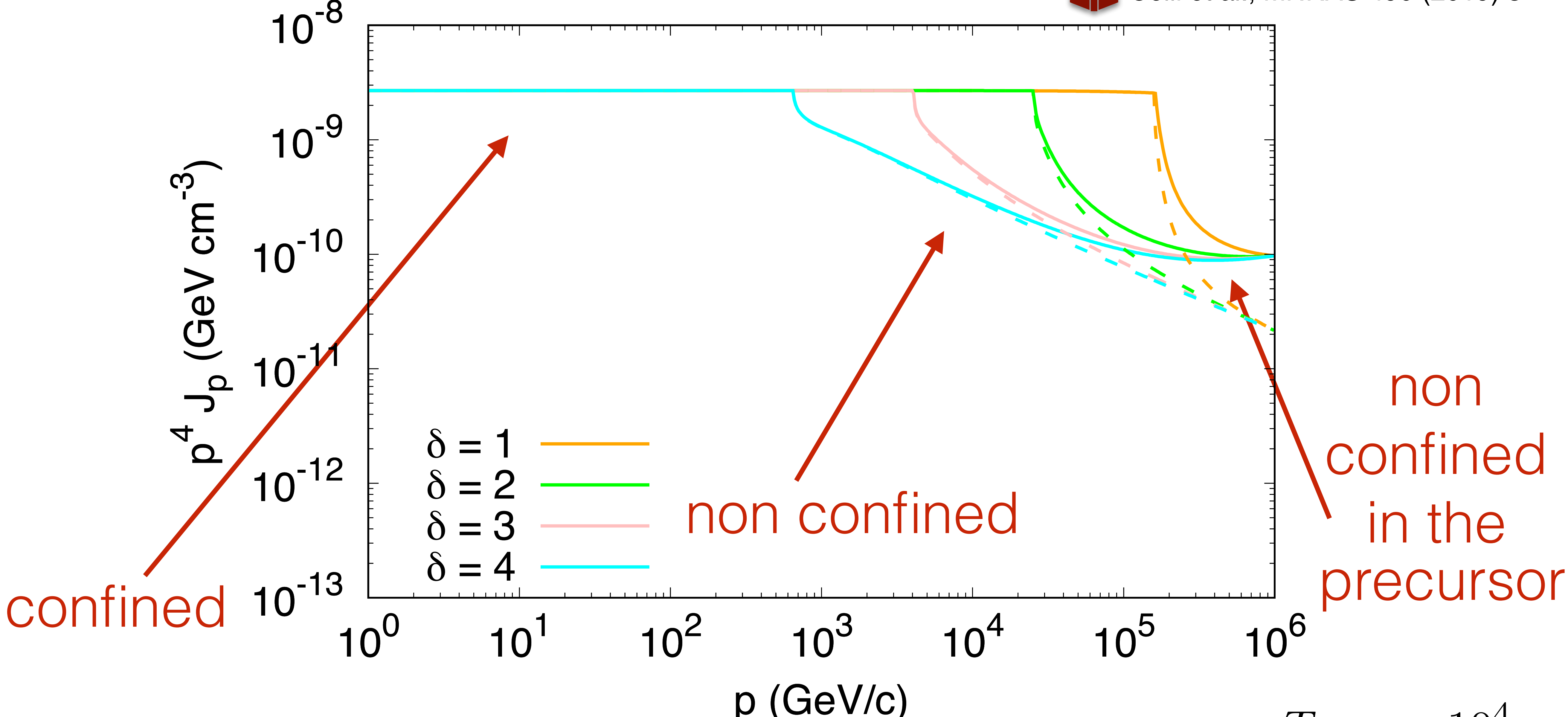
$$p > p_{\max,0}(t)$$

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

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) 3



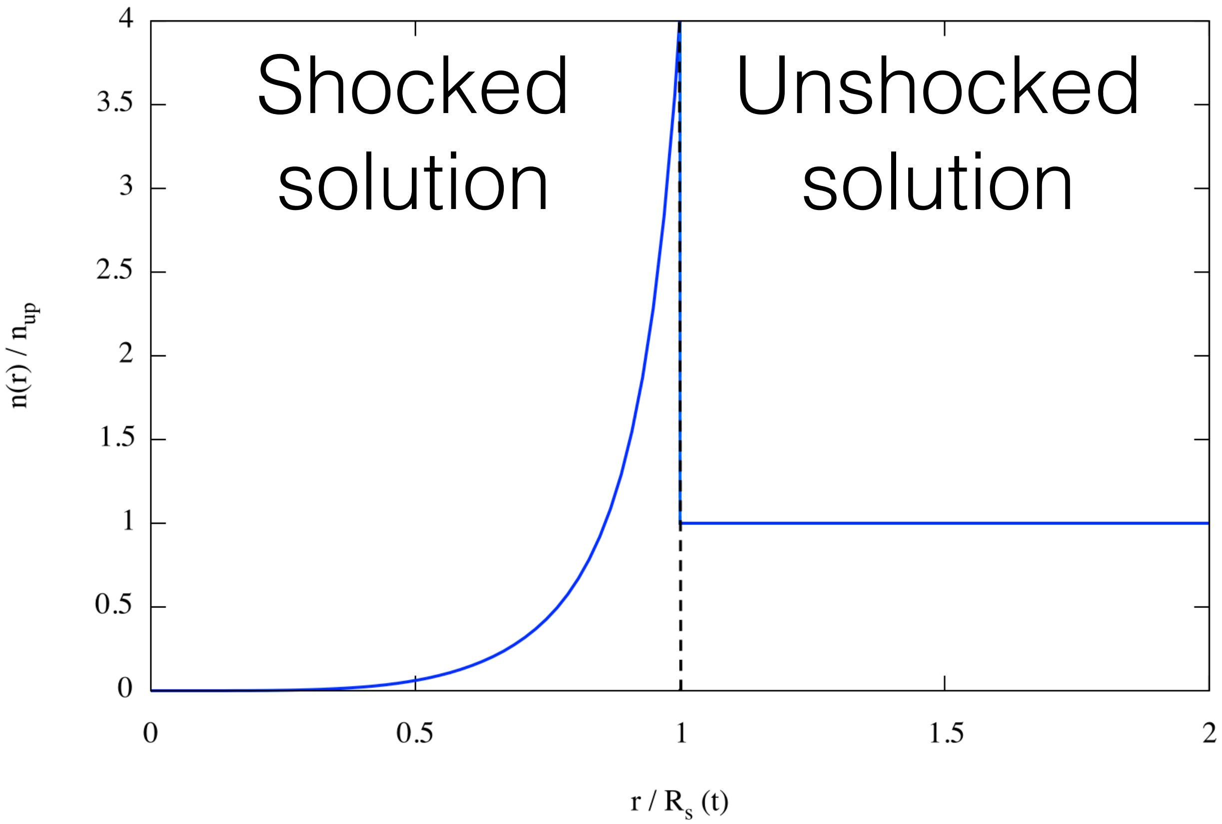
$$D(p) = 10^{27}\left(\frac{pc}{10\ \rm GeV}\right)^{1/3} \rm cm^2 s^{-1}$$

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

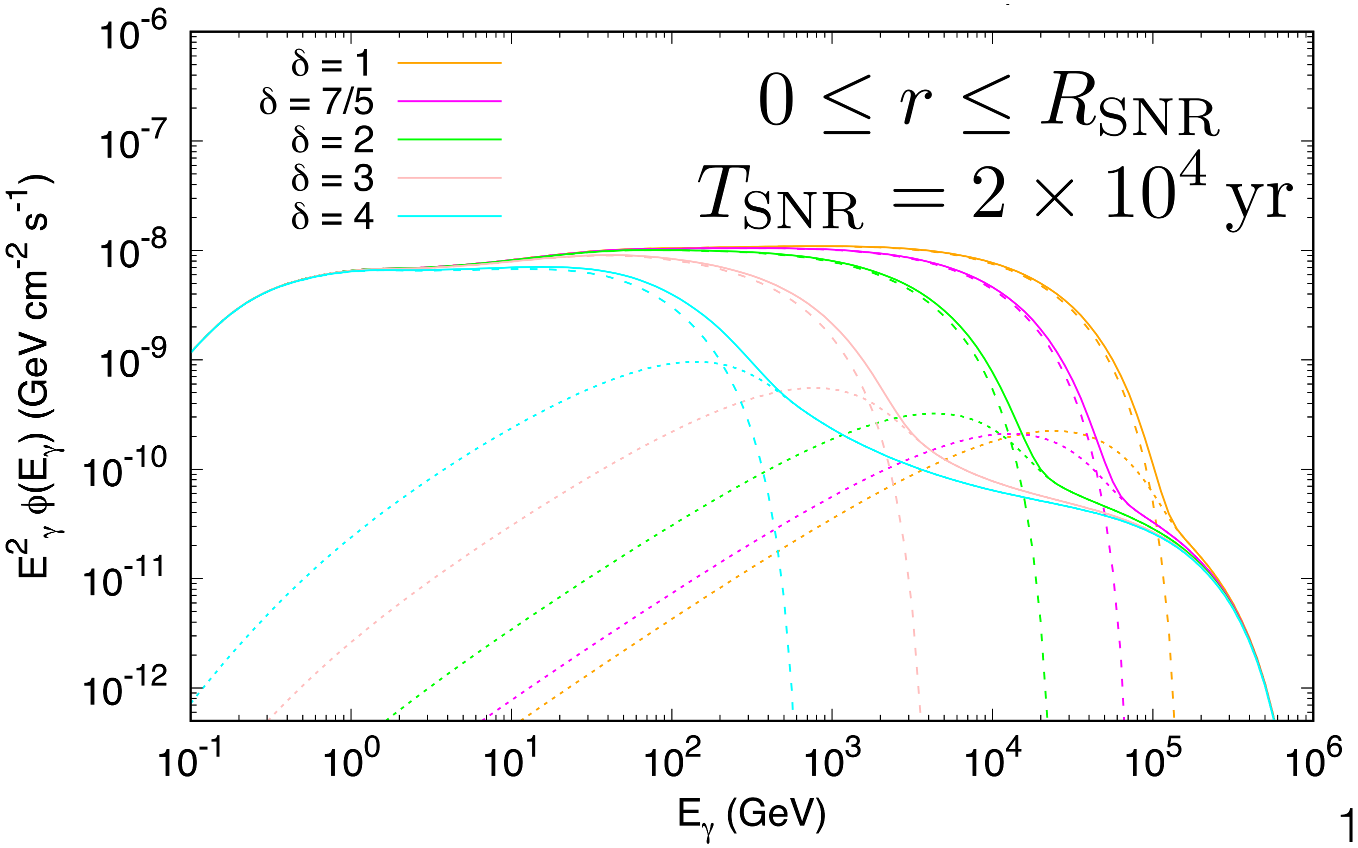
$\xi_{\rm CR} = 10\%$

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

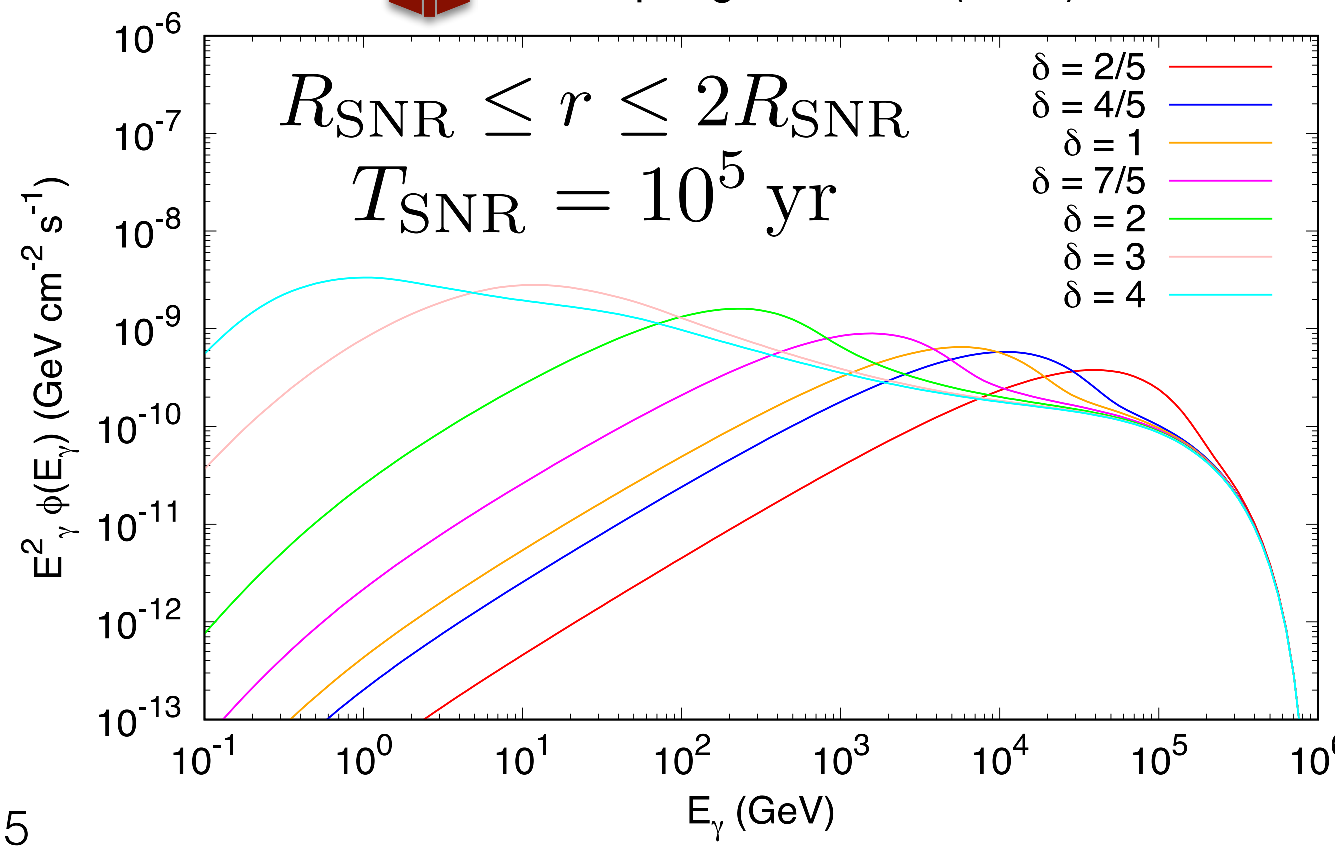
Volume integrated gamma-ray emission from hadronic collisions



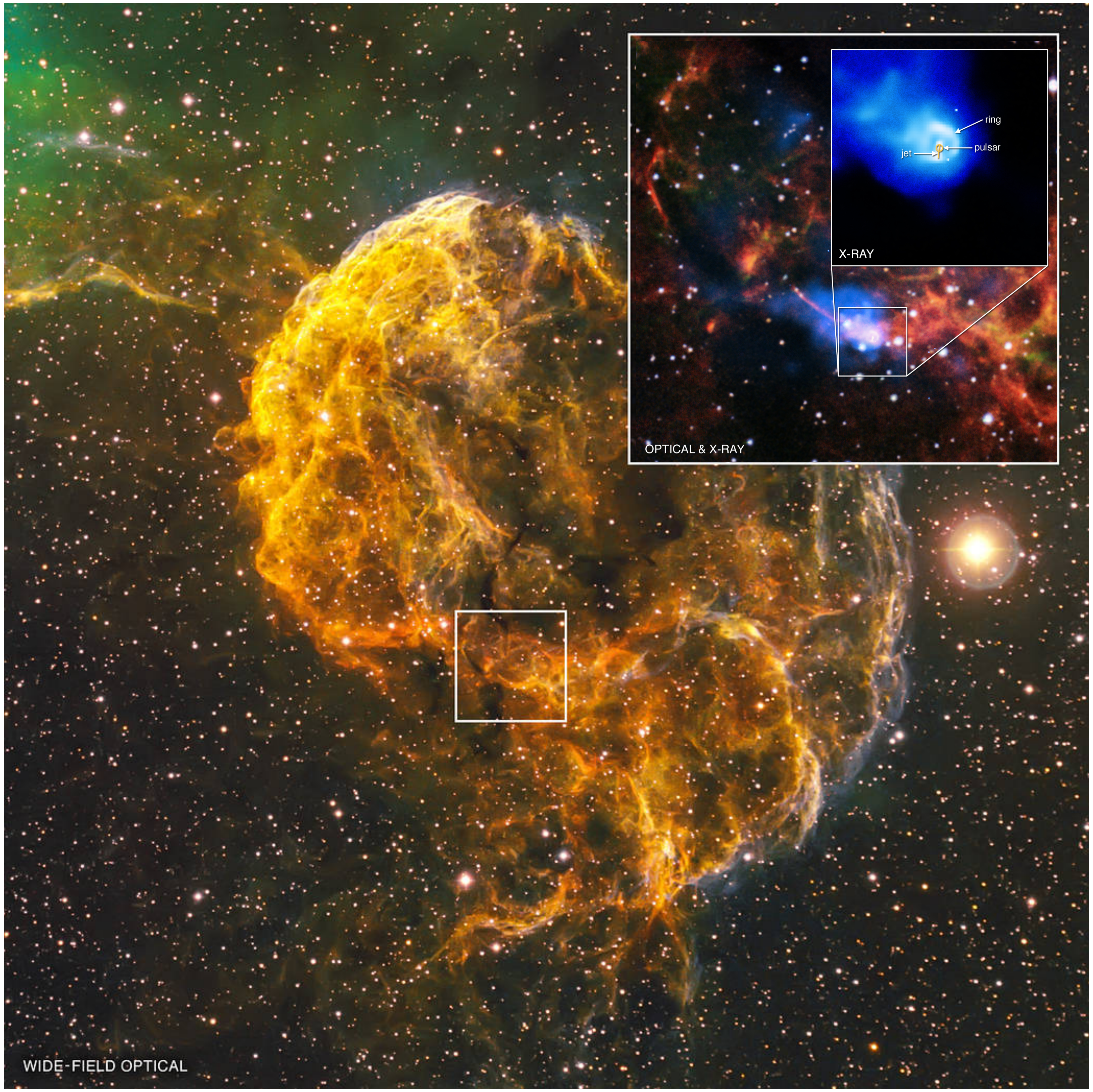
$$f_0(p) \propto p^{-4}$$
$$D(10\,\mathrm{GeV/c}) = 3 \times 10^{27}\,\mathrm{cm^2/s}$$
$$\xi_{\mathrm{CR}} = 1\,\%$$
$$n_{\mathrm{up}} = 1\,\mathrm{cm^{-3}}$$
$$d = 1\,\mathrm{kpc}$$

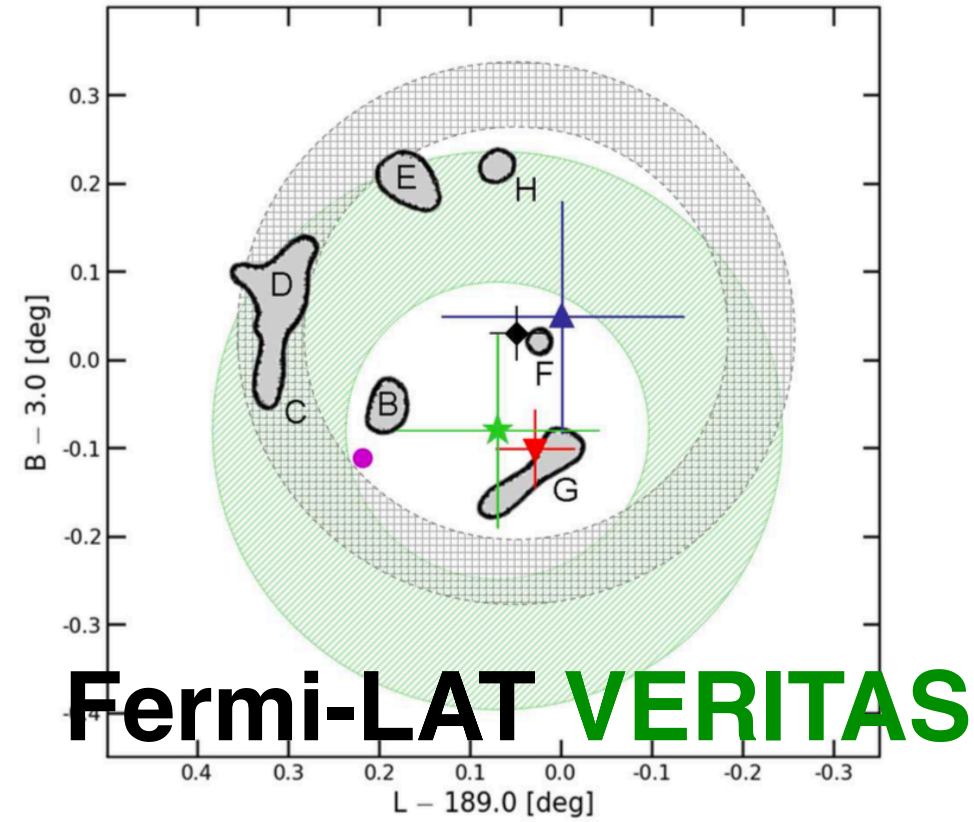


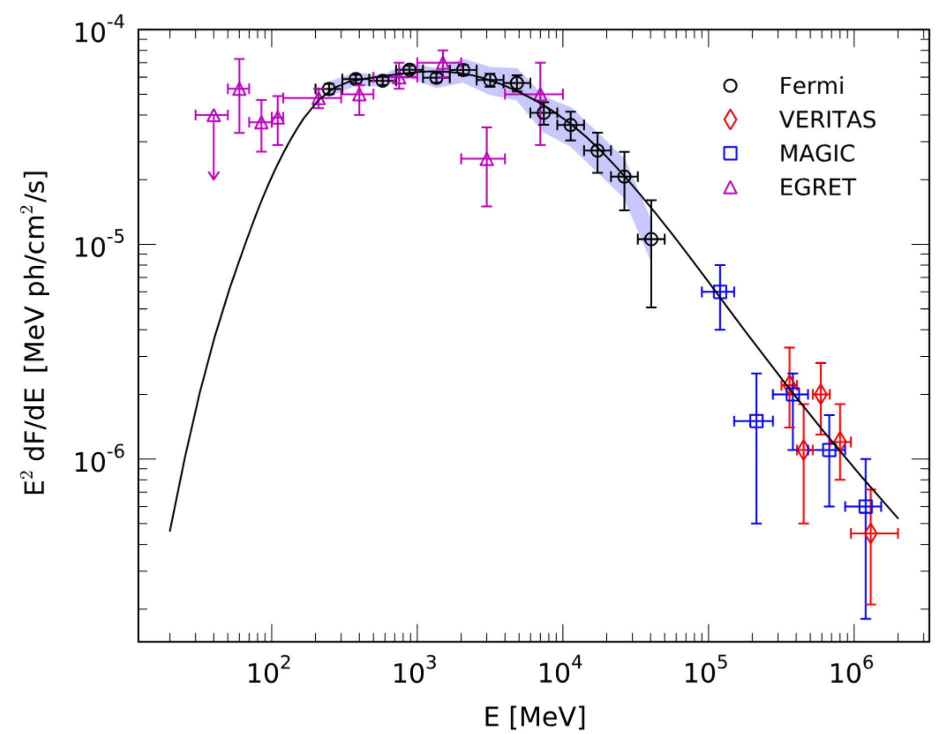
Celli, Springer Theses (2019)



IC 443 or the Jellyfish Nebula

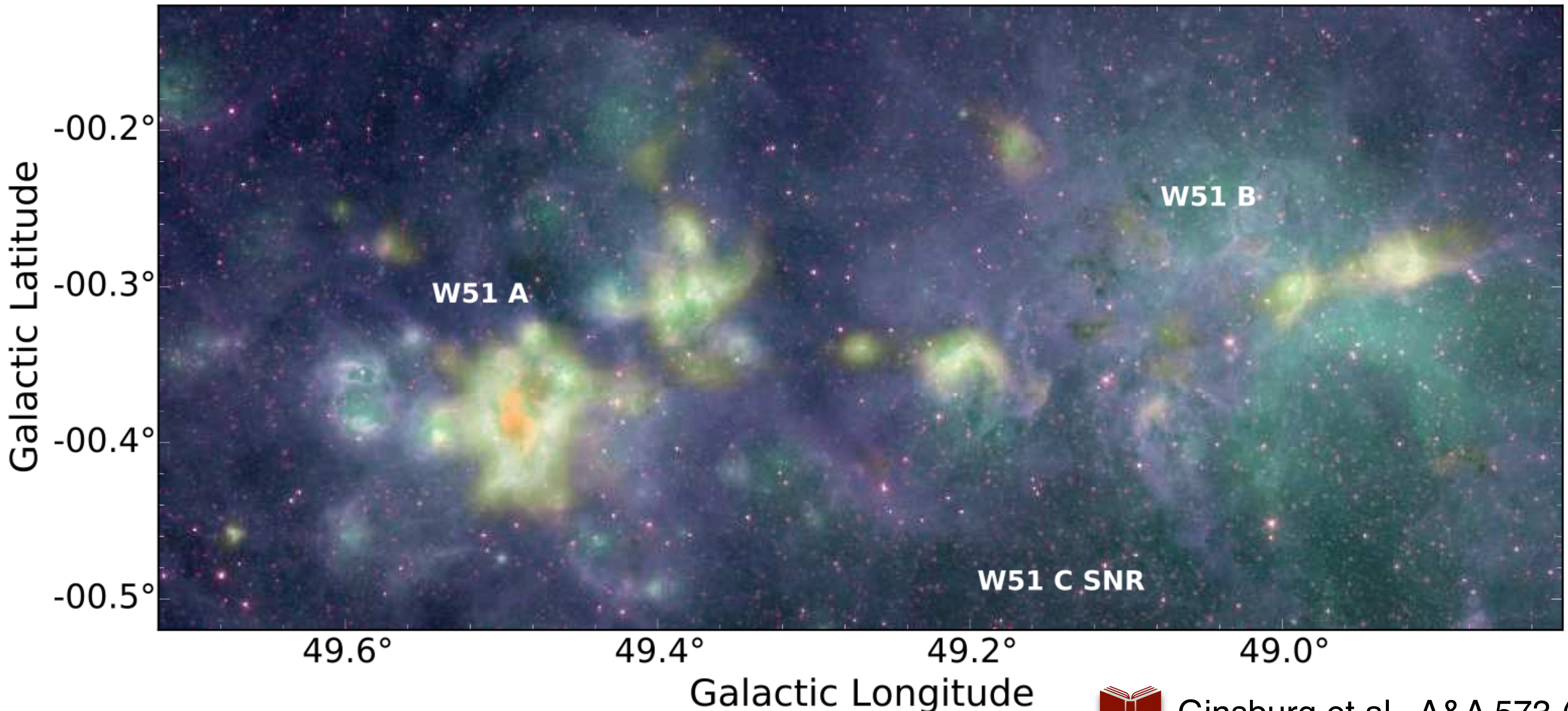




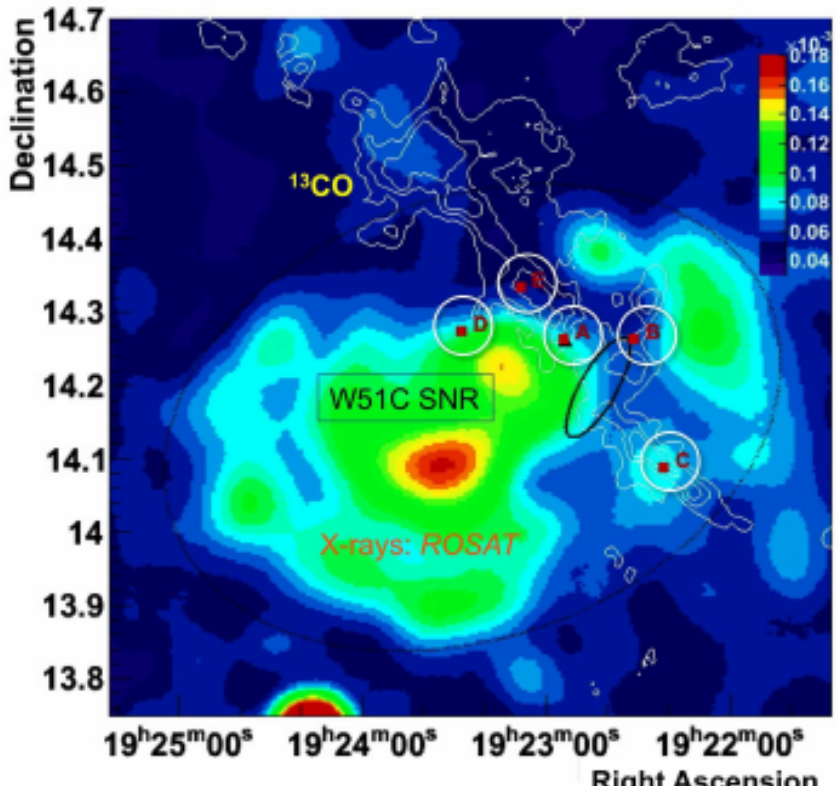


Abdo et al., ApJ 712 (2010) 459

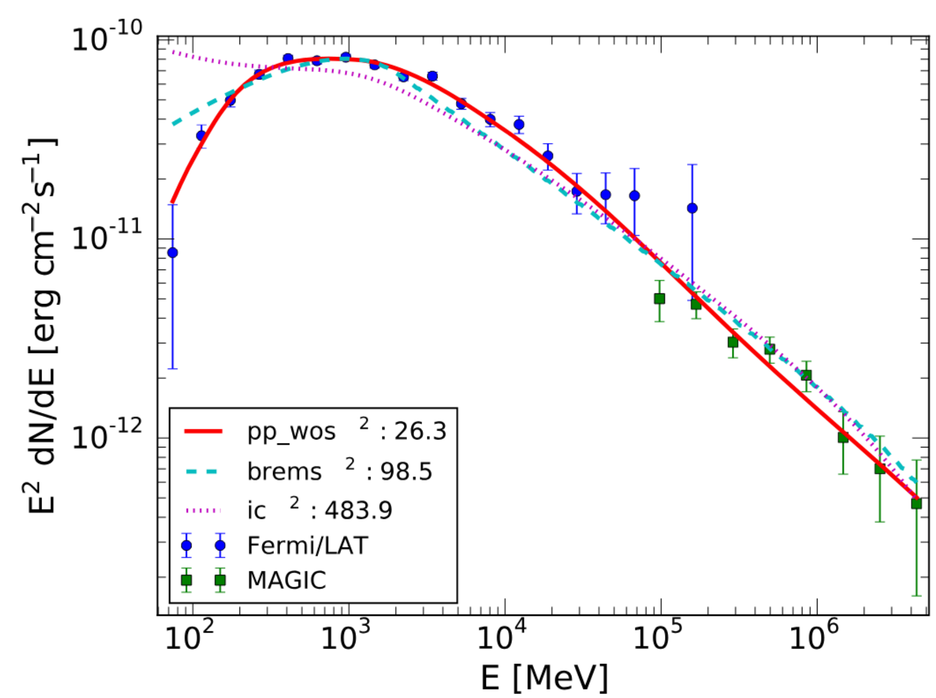
W51C (G49.1–0.1)



Ginsburg et al., A&A 573 (2015) A106



Montmerle, Mem. SAIT (2011)



Jogler & Funk, ApJ 816 (2016) 100

Take-home messages

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

→ **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)

$$p_{\rm M} < 1\,{\rm PeV/c}$$

→ **UHE observations** are setting **progressively more stringent constraints** about the role of SNRs as **PeVatron sources**

Thanks for your kind attention!