Particle escape from supernova remnants: a multi-messenger view

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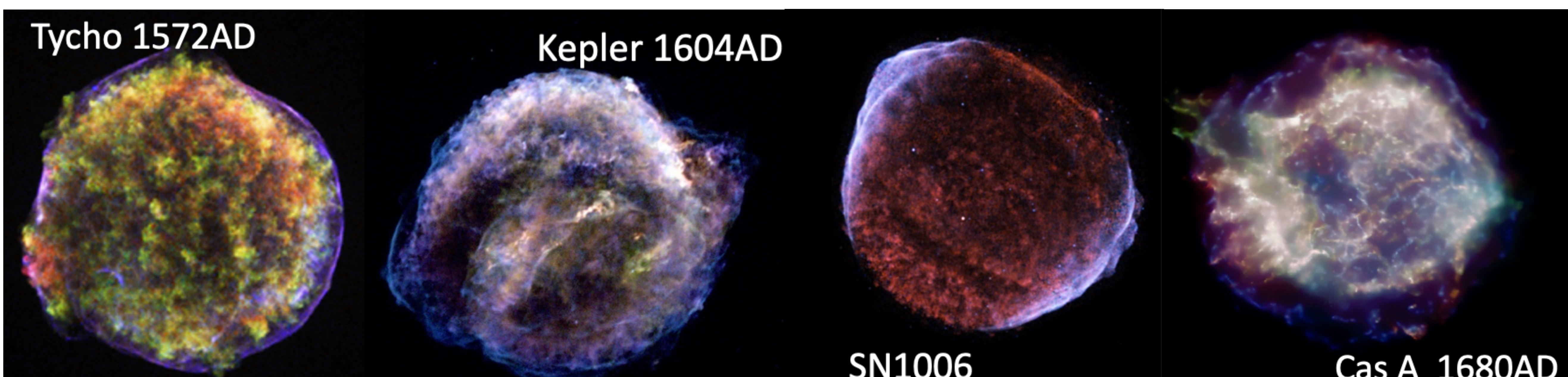
Outline of the talk

- The **Supernova Remnant (SNR)** paradigm for the **origin of Galactic cosmic rays**:
  - the issue with maximum energy;
  - the role of particle escape in SNRs;
  - radiative signatures of SNR PeV activity.

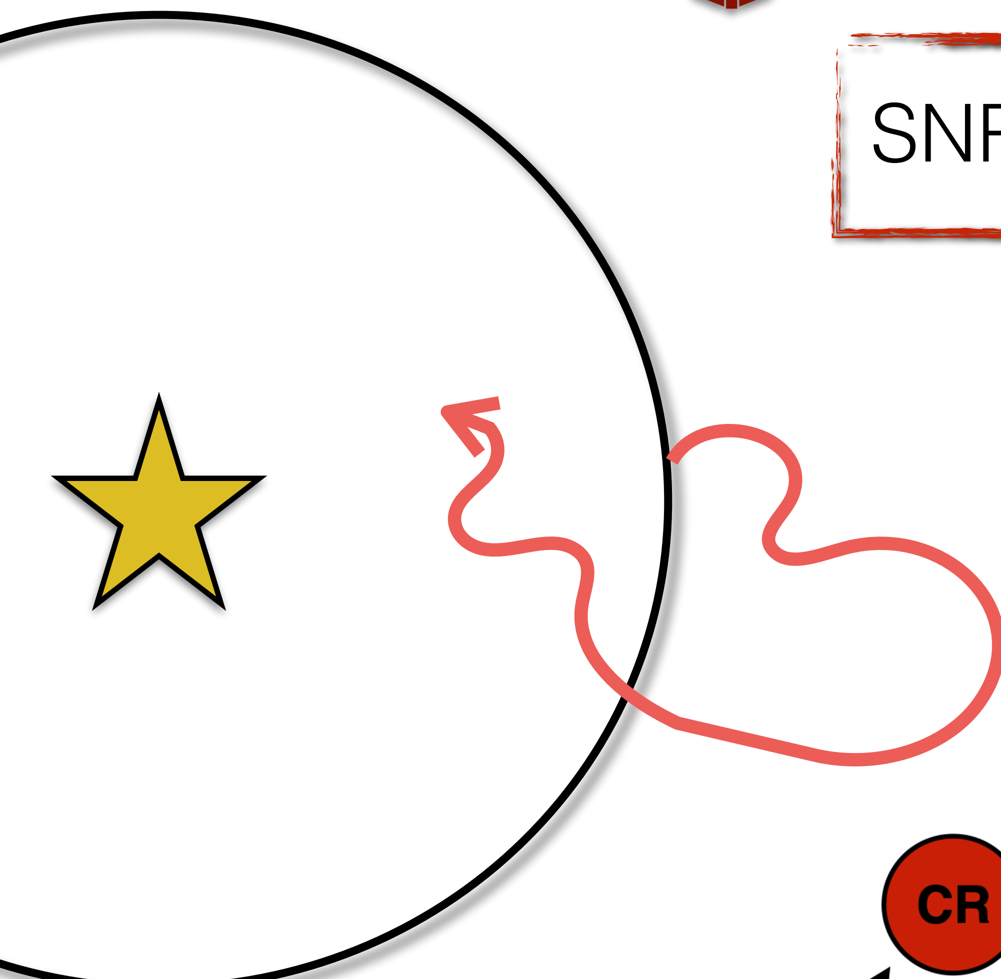
- SNR-escaping particles **illuminating nearby molecular clouds**:
  - a catalog-based analysis of Galactic SNR-cloud pairs;
  - comparison with **LHAASO unidentified sources**.



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



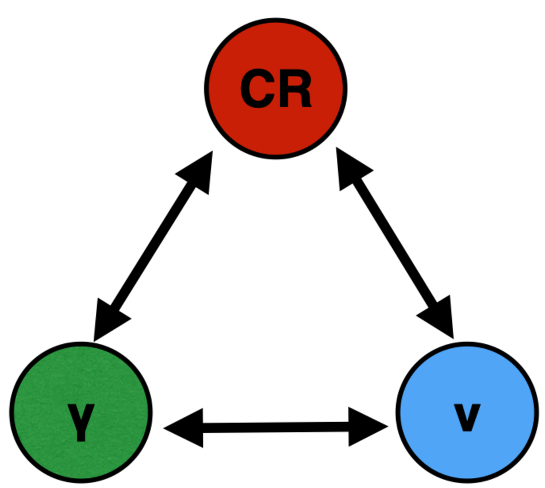
SNR shocks ⟶ acceleration sites

Diffusive Shock Acceleration

Axford et al., ICRC1977, 11 132 — Krymskii, AKSSRD 234 (1977) 1306

Bell, MNRAS 182 (1978) 147 — Blandford & Ostriker, ApJ 221 (1978)

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

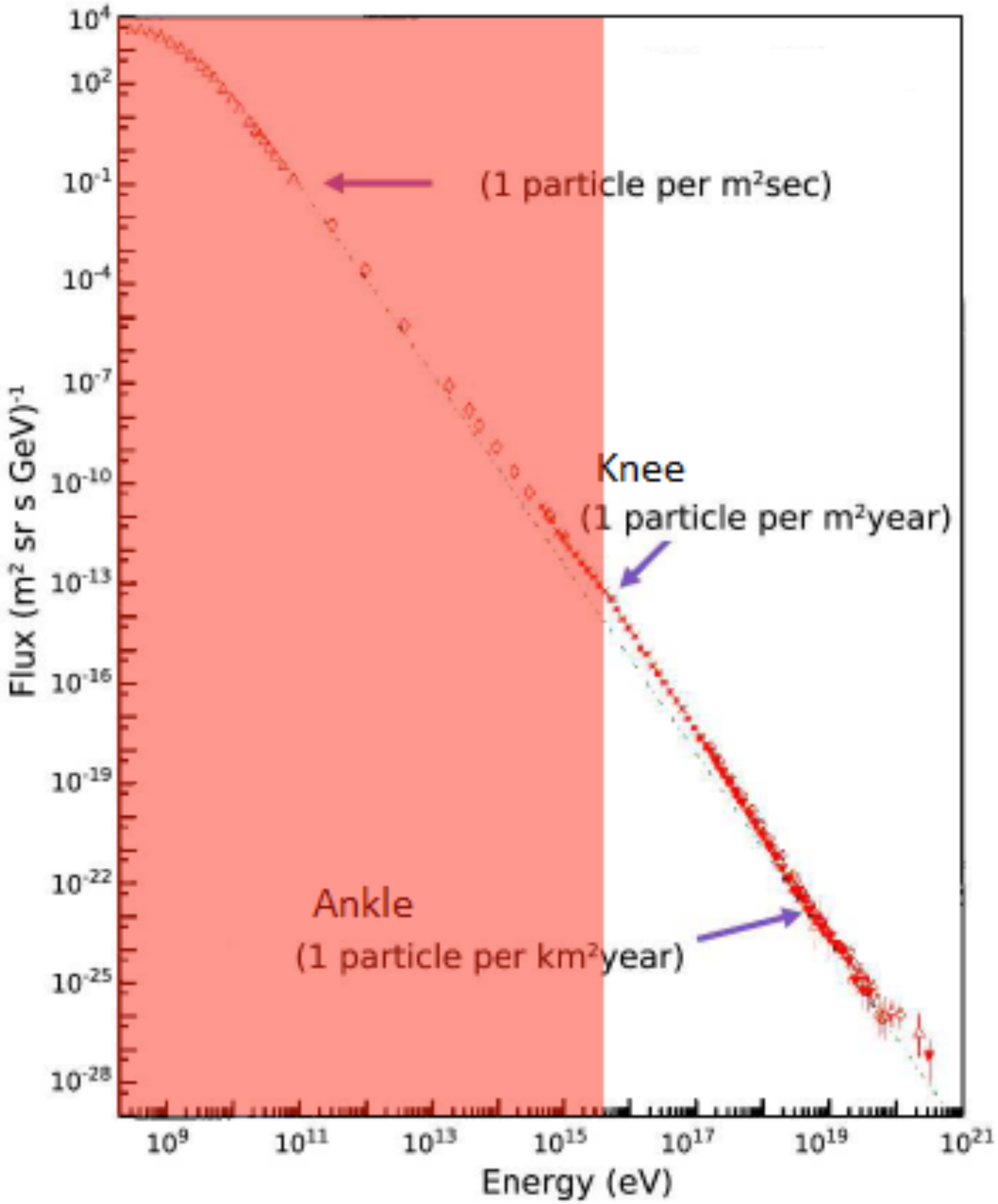


pp interaction ⟶ γ rays and ν

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

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

The SNR paradigm for the origin of Galactic CRs



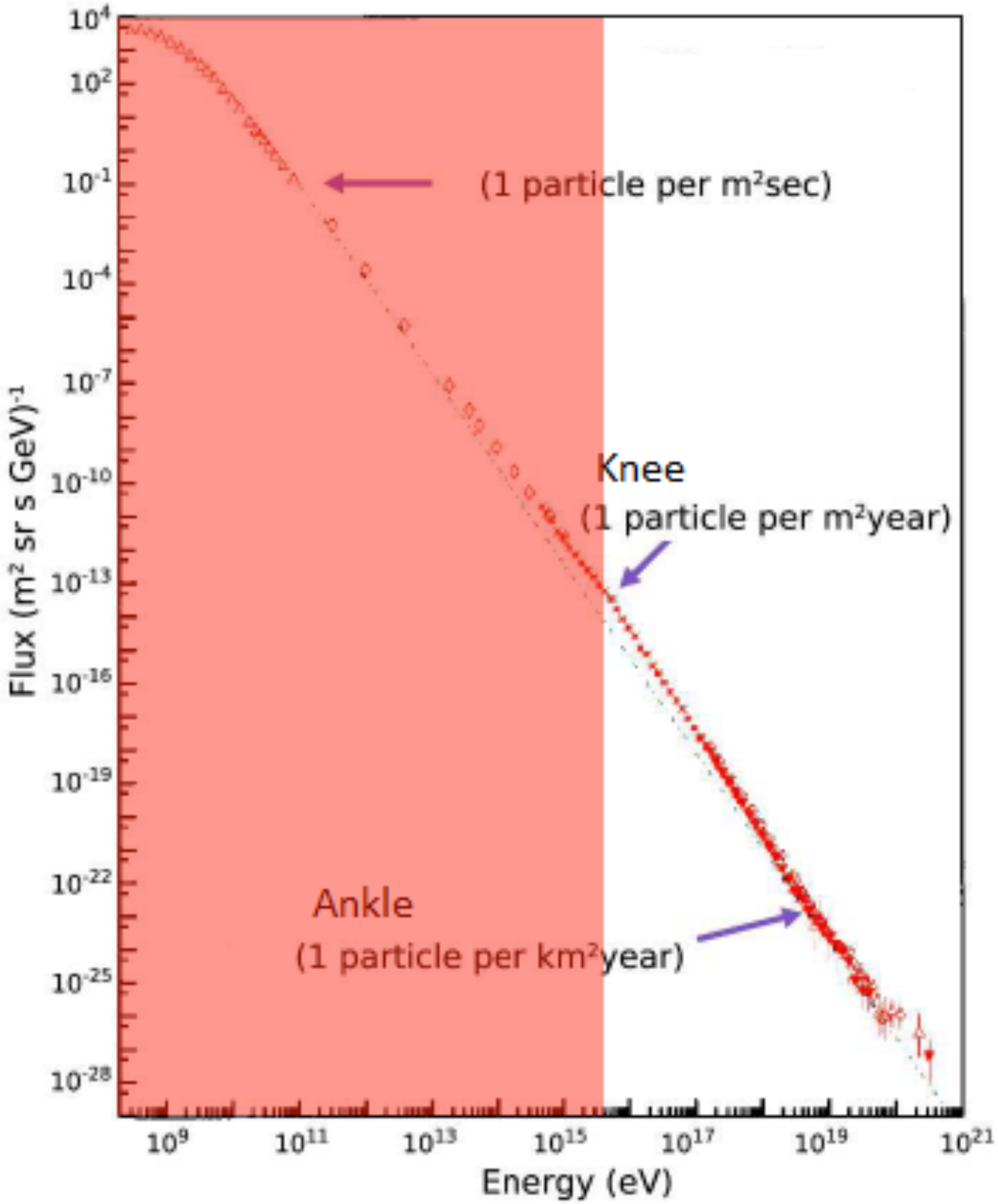
$$U_{\rm CR} = 0.5\,{\rm eV/cm^3}$$

$$V = 4000\,{\rm kpc^3}$$

$$\tau_{\rm res} = 15 \times 10^6\,{\rm yr}$$

$$P_{\rm CR} = \frac{U_{\rm CR} V}{\tau_{\rm res}} \sim 3 \times 10^{40}\,{\rm erg/s}$$

The SNR paradigm for the origin of Galactic CRs



$$U_{\rm CR} = 0.5\,{\rm eV/cm^3}$$
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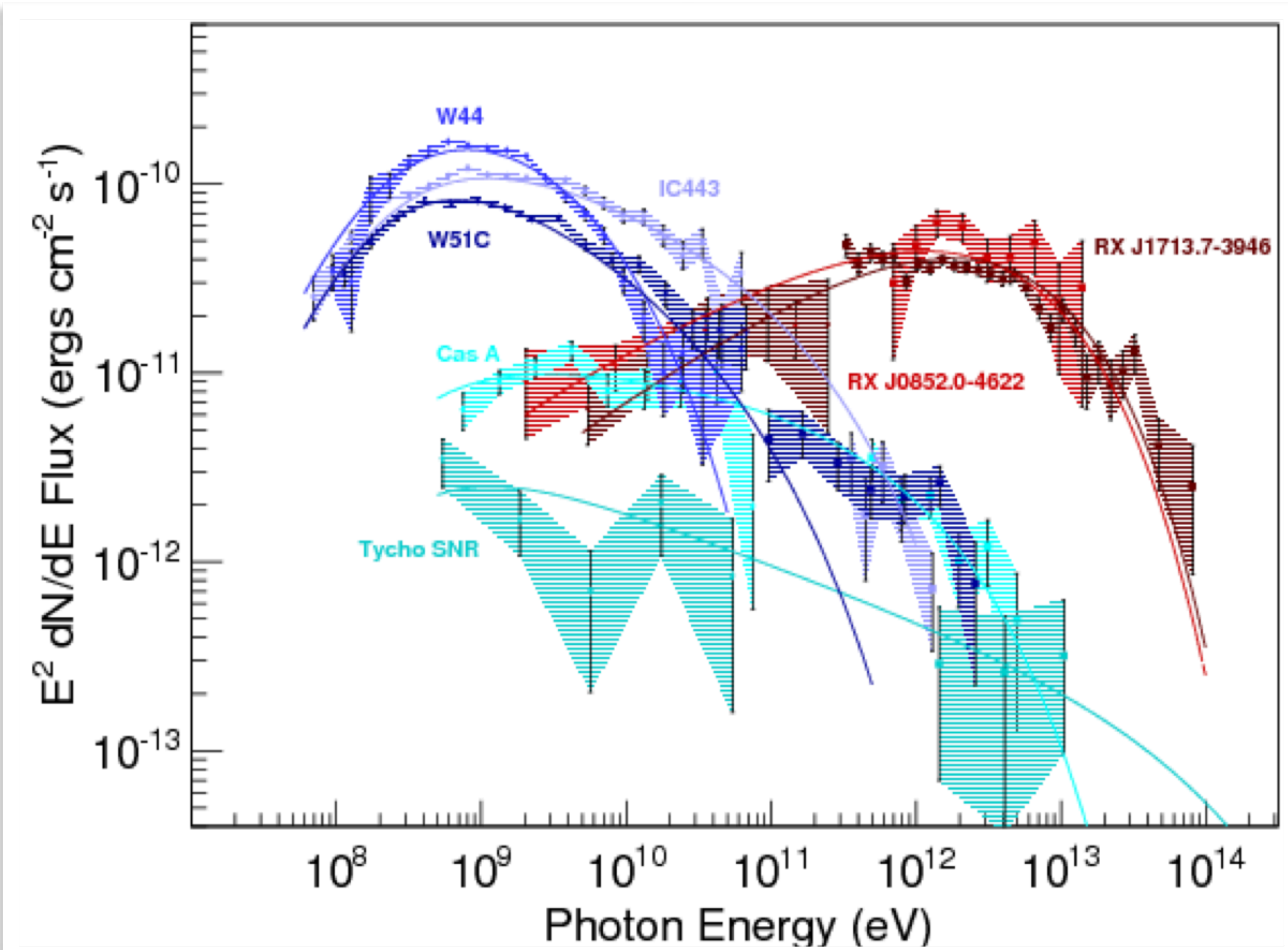
$$\tau_{\rm res} = 15\times10^6\,{\rm yr}$$
$$P_{\rm CR} = \frac{U_{\rm CR}V}{\tau_{\rm res}} \sim 3\times10^{40}\,{\rm erg/s}$$

$$E_{\rm SN} = 10^{51}\,{\rm erg}$$
$$R_{\rm SN} = 0.03\,{\rm yr^{-1}}$$
$$P_{\rm SN} = R_{\rm SN}E_{\rm SN} \simeq 3\times10^{41}\,{\rm erg/s}$$
$$\longrightarrow \xi_{\rm CR} \simeq 10\%$$

Gamma rays from SNRs



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)

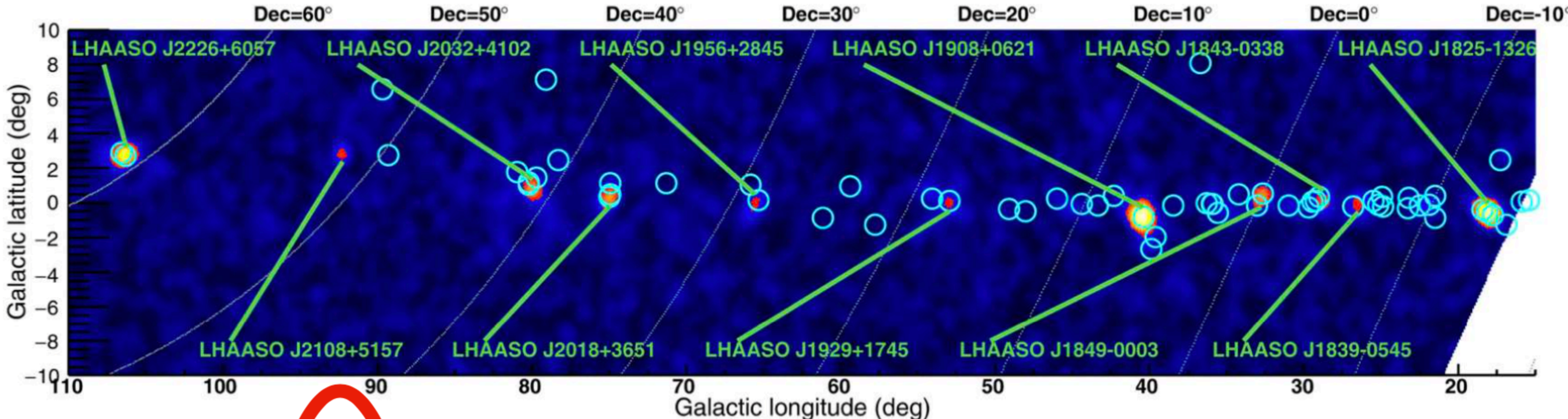
- hadronic/leptonic ?
- hard spectra
- E_{max} = 10 - 100 TeV

Very young SNRs (300 yrs)

- hadronic ?
- steep spectra $E^{-2.3}$
- E_{max} = 10 - 100 TeV

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

LHAASO Coll., Nature 594 (2021) 33



LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3[e]	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3[f]	< 2[f]	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7[g]	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5[h]	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10 - 20$[j]	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}$[d]	$1.8 - 3.3$[k]	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2[d]	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}$[l]	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$.3 \pm 0.3$[m]$/4.0 \pm 0.5$[n]	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08[o]	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08[o]	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	NR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8[p]	~ 10[p]	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}	

Uncertain nature of sources,
Not many SNRs

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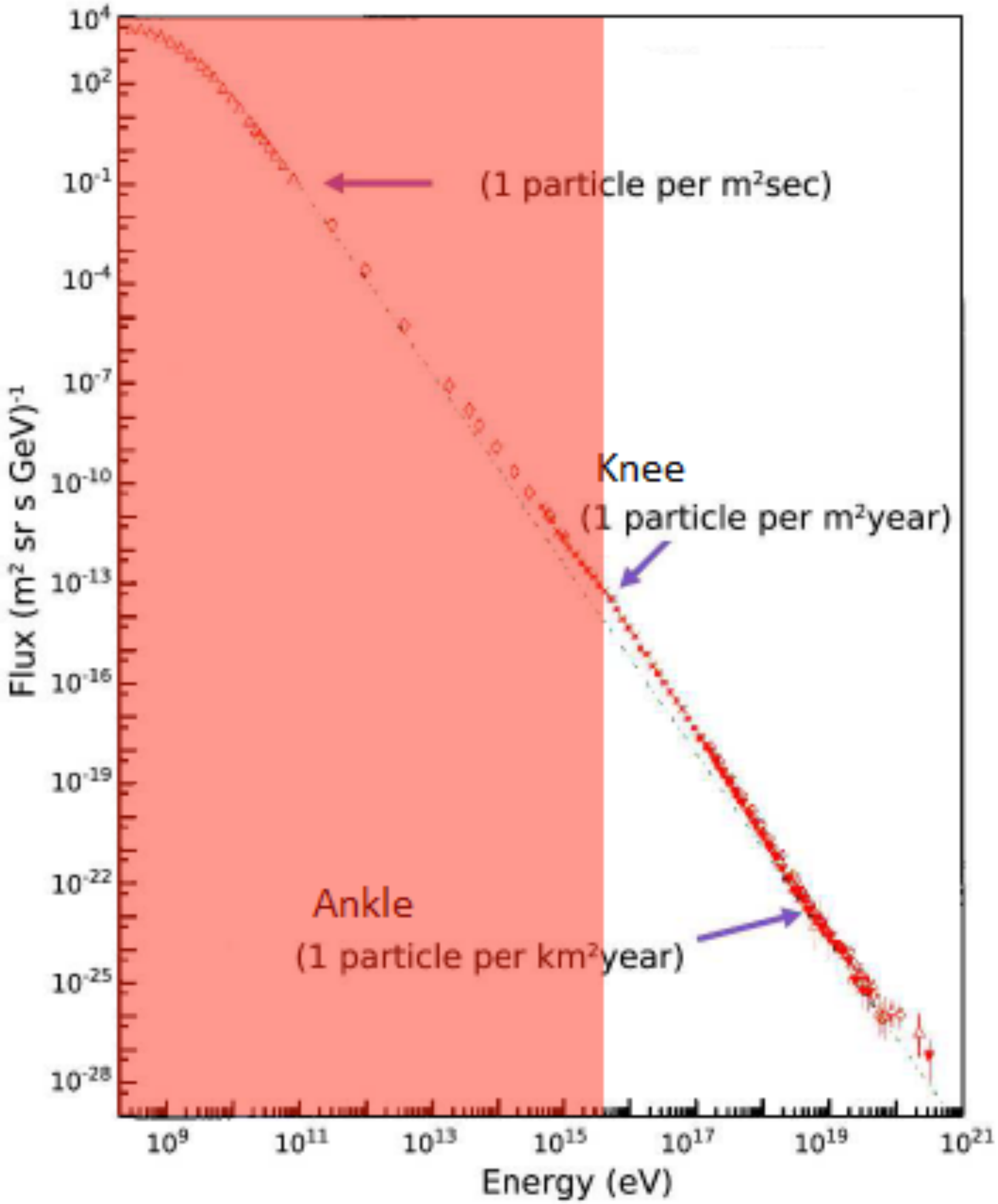
Are SNRs proton PeVatrons?



Hillas criterion

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

shock speed — radius — magnetic field

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

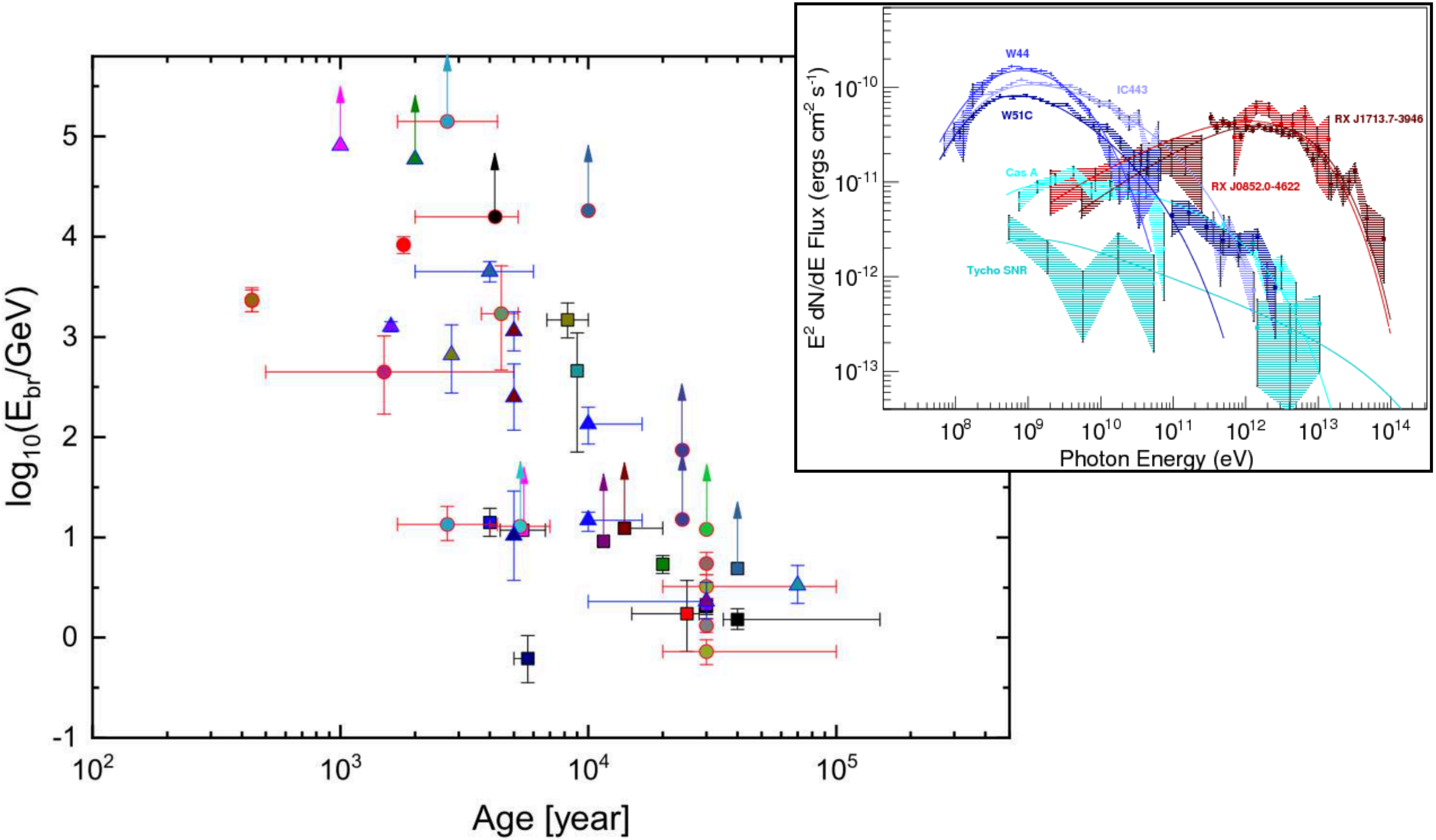
3 **3** **10**

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

B-field amplification is required to achieve PeV energies

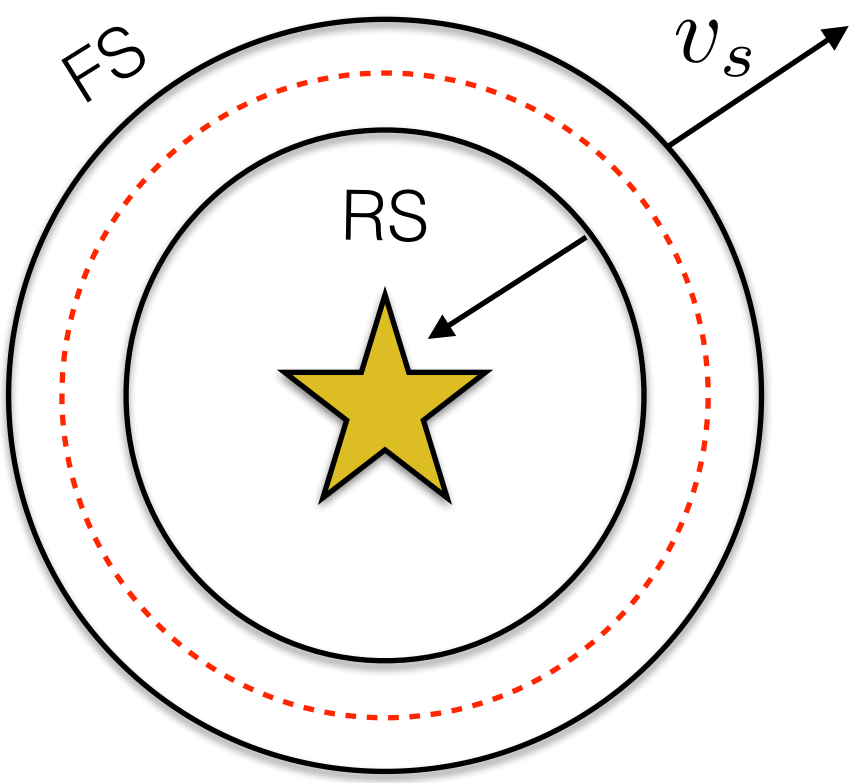
Cesarsky et al., SSRev 36 (1983) 173C

A population study of evolved SNRs



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

The hydrodinamical 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

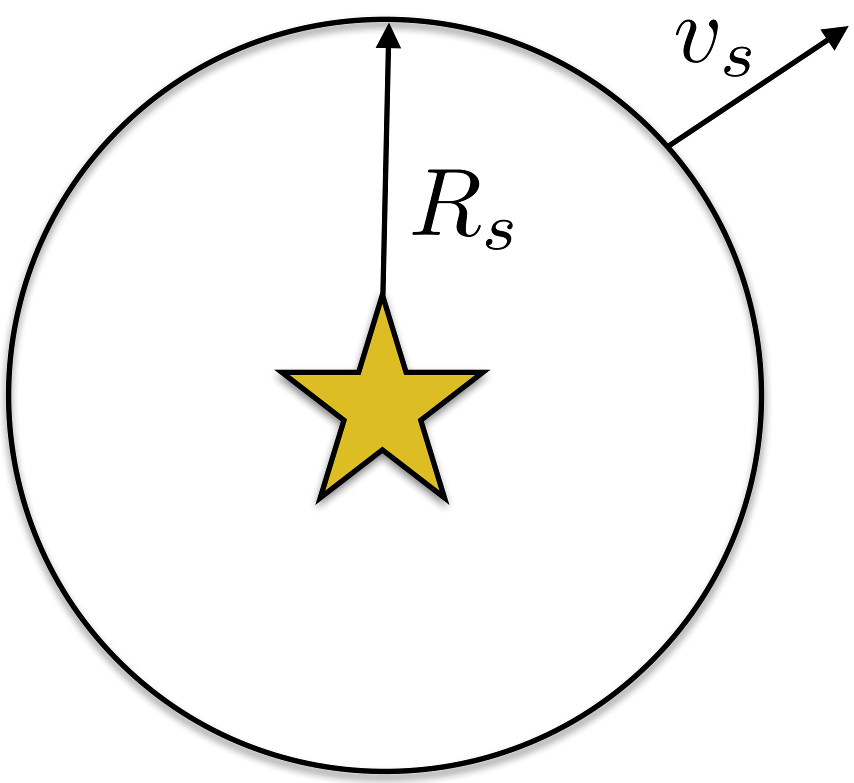
III. Radiative stage

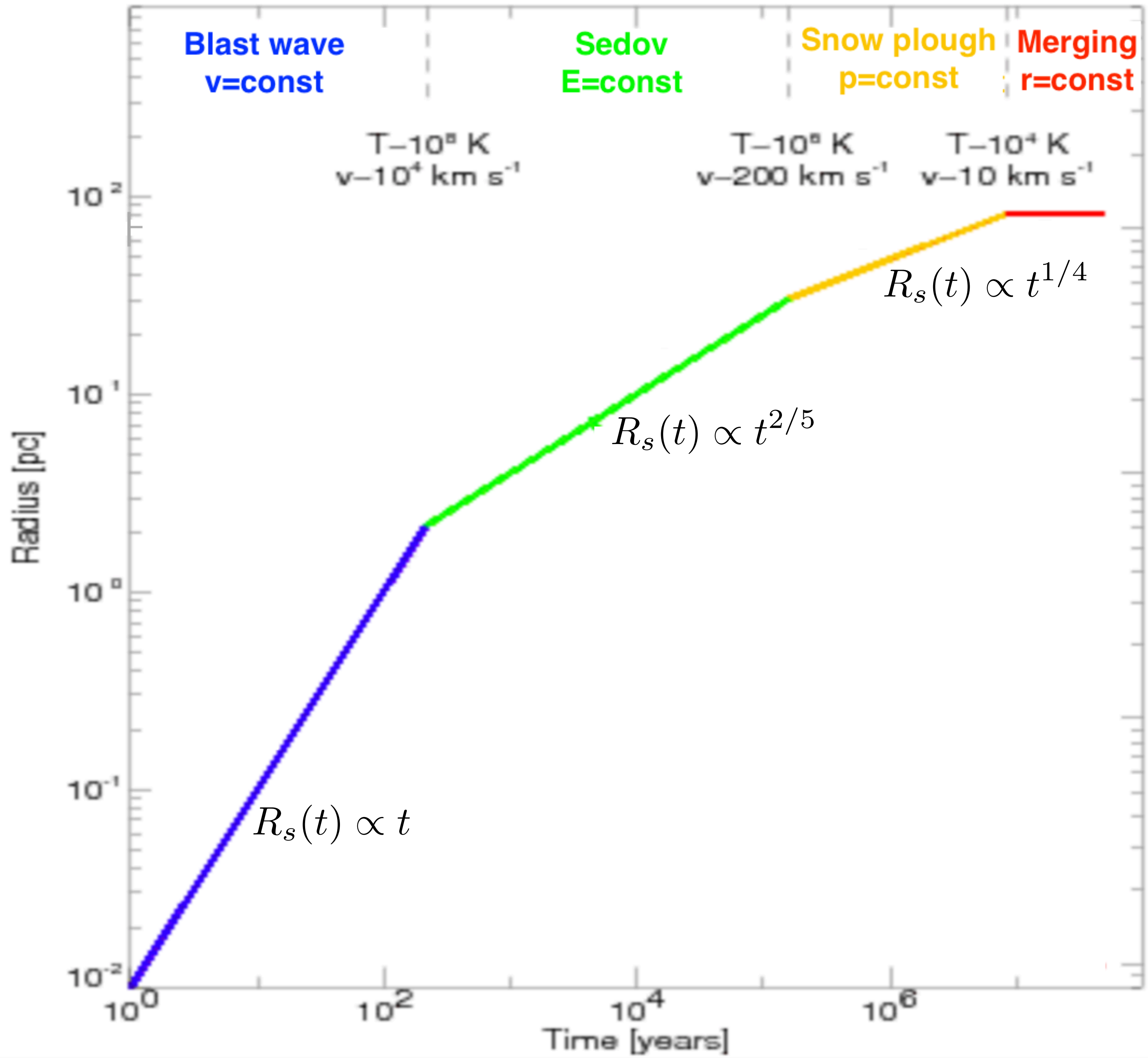
⟶ momentum conservation

IV. Merging phase

⟶ pressure comparable to ISM

The hydrodinamical evolution of an SNR

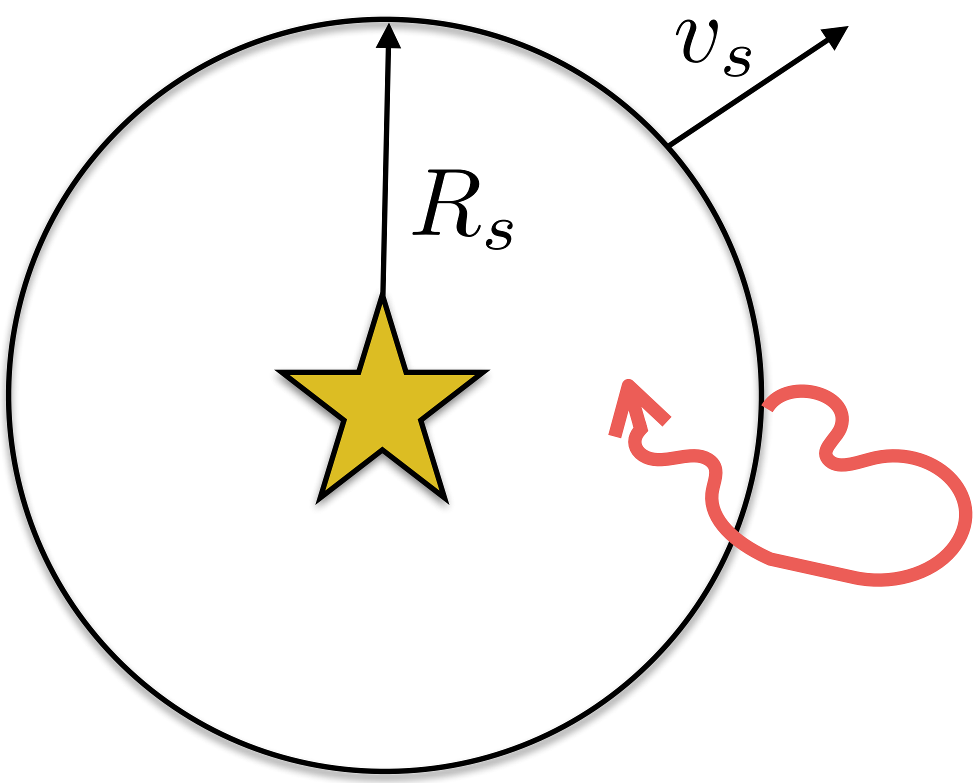




Vink, A&A Rev 20 (2012) 1

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

Maximum energy in SNRs



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

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

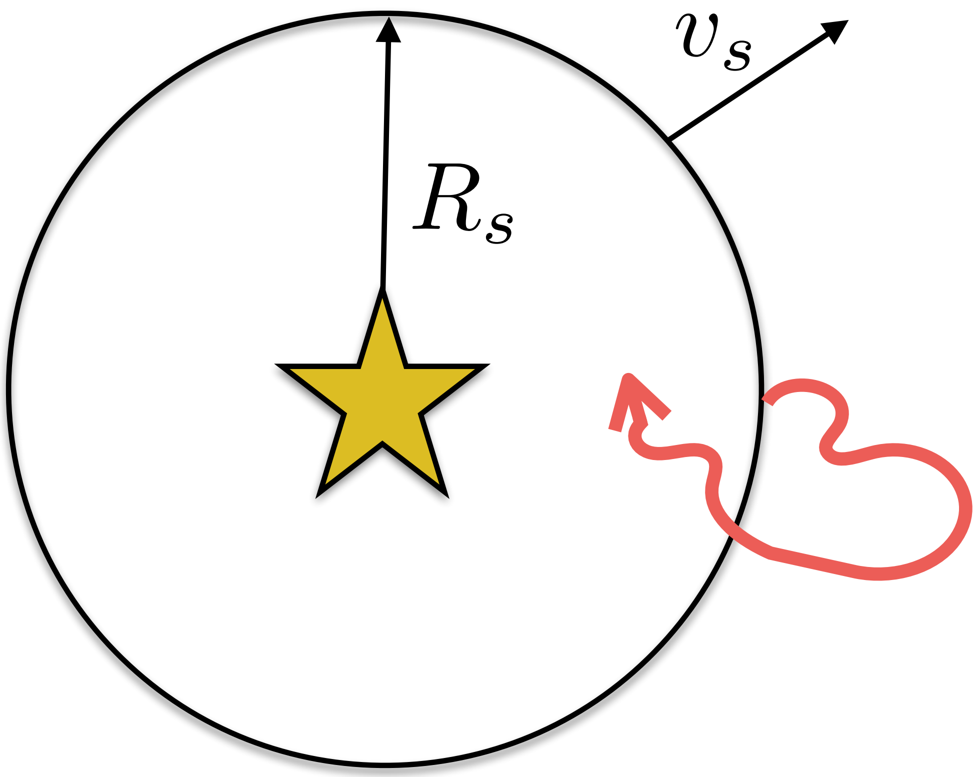
- Later in the evolution, particles diffusion length increases faster than SNR shock size:

$$\lambda_{\rm d} \simeq D(E_{\rm M})/v_{\rm s} \propto t^{3/5}$$
$$R_s \propto t^{2/5}$$

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

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

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

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

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

ED stage:

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

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

ST stage:

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

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

Celli et al., MNRAS 490 (2019) 3

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.

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

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

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

- Magnetic field not amplified

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

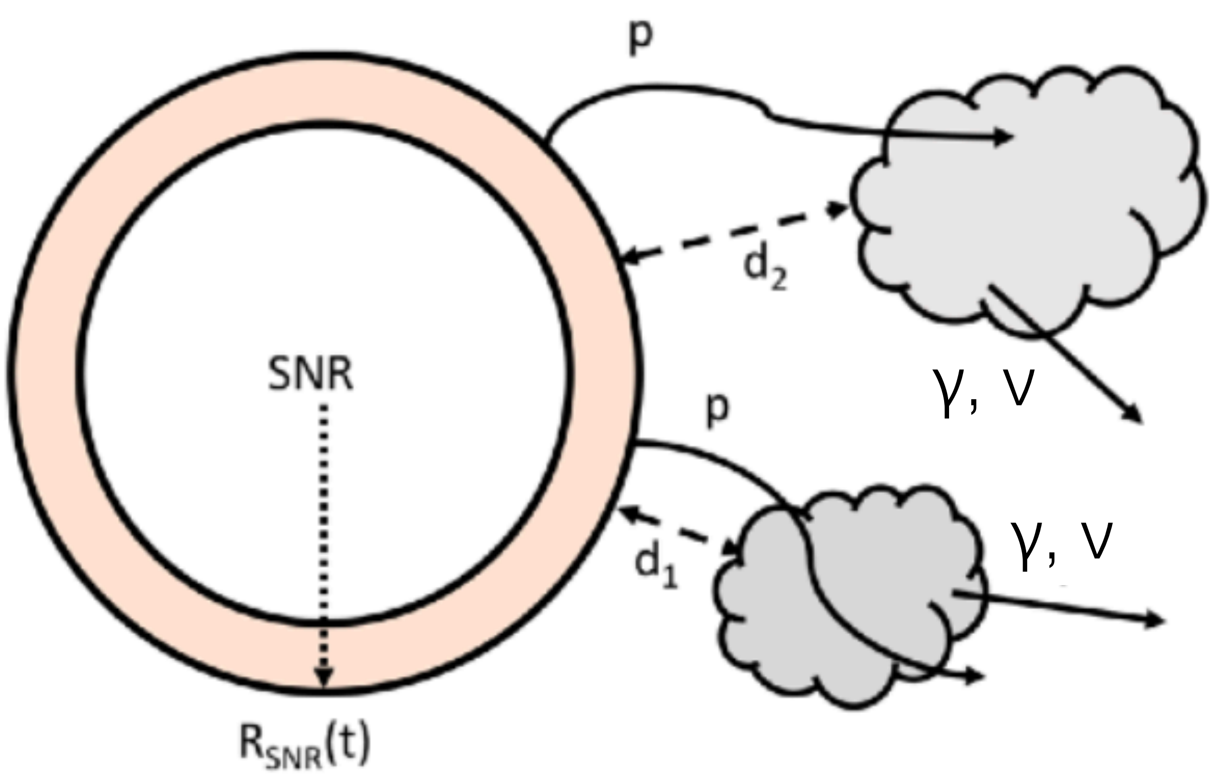
- Magnetic field amplification driven by resonant waves

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

- Magnetic field amplification driven by non-resonant waves

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

Escaping particles & molecular cloud illumination



- **Delayed emission** from **molecular clouds** could help us understanding whether nearby **SNRs** have ever behaved as **PeVatron**

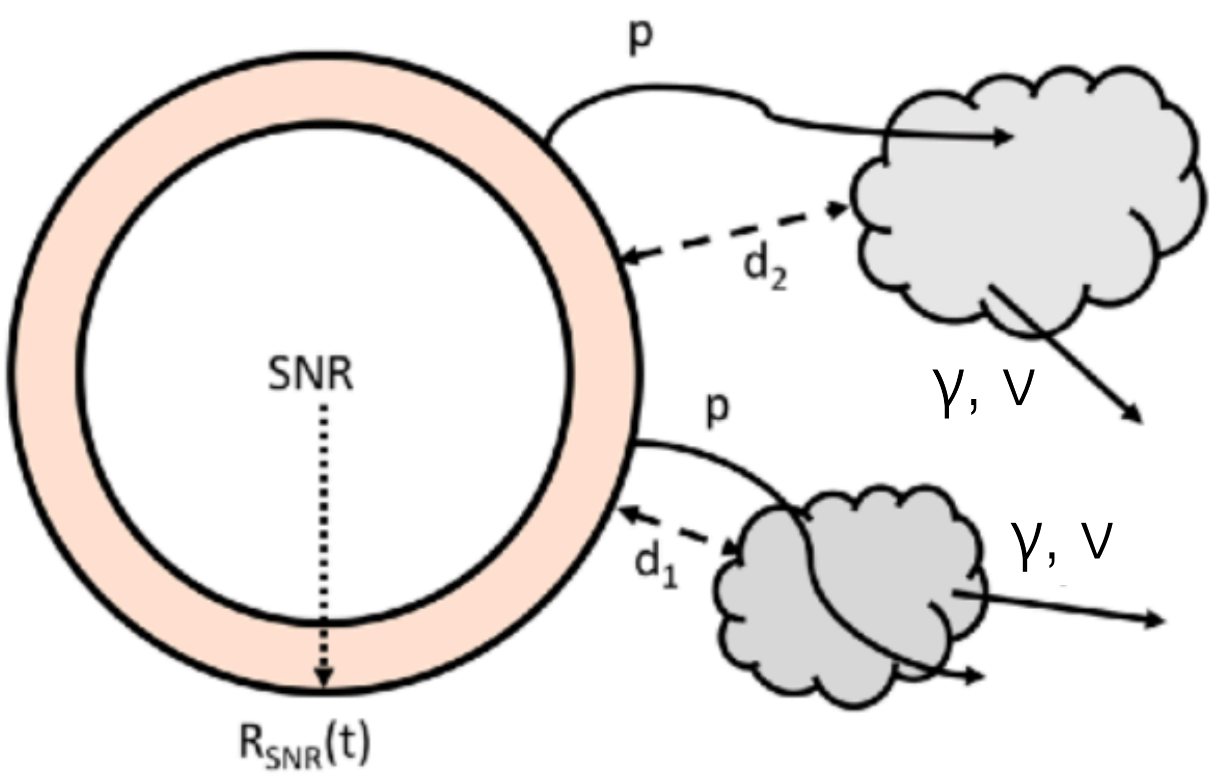
Gabici et al., MNRAS 396 (2009) 1629G

Methods

Mitchell & Celli, 2024 JHEA submitted

- SNRs from 2 catalogs: **GreenCat** & **SNRCat**;
- Molecular Clouds detected through ^{12}CO line from **Rice catalog**: distance, size and density known (with uncertainties);
- **SNR-MC pairing** requires angular separation and distance to imply a physical separation < 100 pc;
  - If SNR distance is unknown, it is considered at cloud distance and only angular separation is used as a selection criterion.

Escaping particles & molecular cloud illumination



Mitchell & Celli, 2024 JHEA submitted

CR injection model @ SNRs:

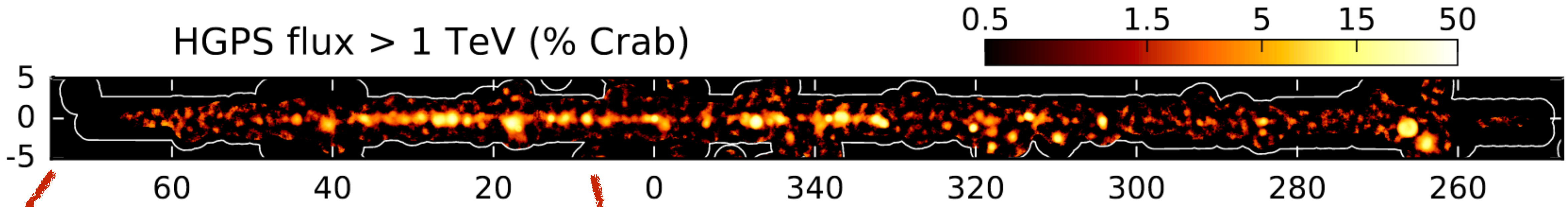
$$f(E,r,t) = \frac{f_0 E^{-\alpha}}{\pi^{3/2} R_d(E)^3} \exp\left[-\frac{r^2}{R_d^2(E)}\right]$$

- Acceleration slope **α=2**;
- Conversion efficiency **ξ_{CR}=0.1**;
- Both **type IA** and **type II** SN modelling, with different t_{Sed};
- Time-dependent escape with **δ=2.5** and **p_M=3 PeV/c**;
- Transport in **Kolmogorov**-like diffusion coefficient, locally suppressed @ D_0(1GeV)=3x10^{26} cm^2/s.

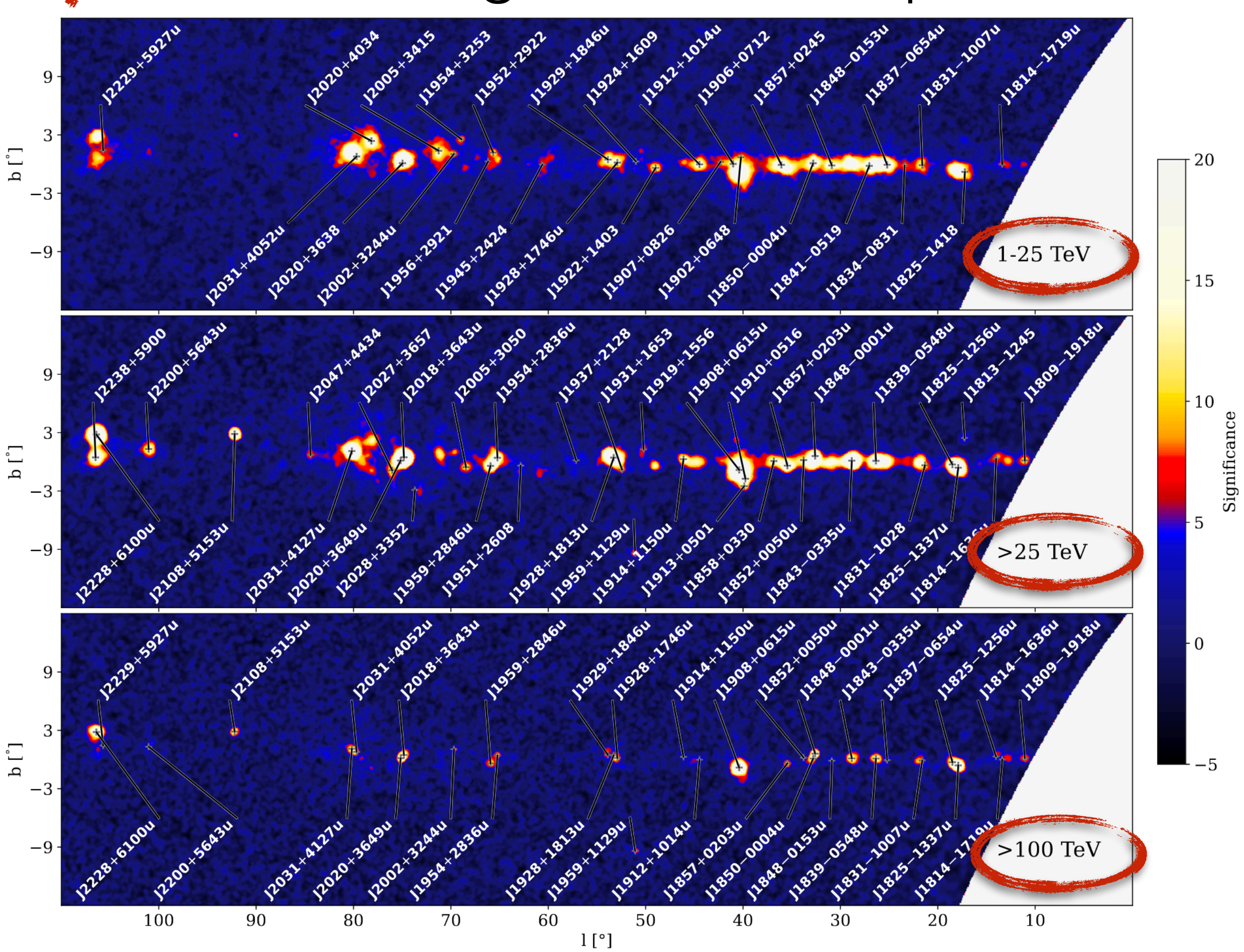
Hadronic (pp) collisions in clouds:

- Computation of emerging gamma rays and neutrinos (GeV-multi TeV);
- Additional contribution from CR sea
- Spectral analysis of spatially coincident **LHAASO unidentified sources**.

VHE & UHE gamma-ray sources in the Galaxy

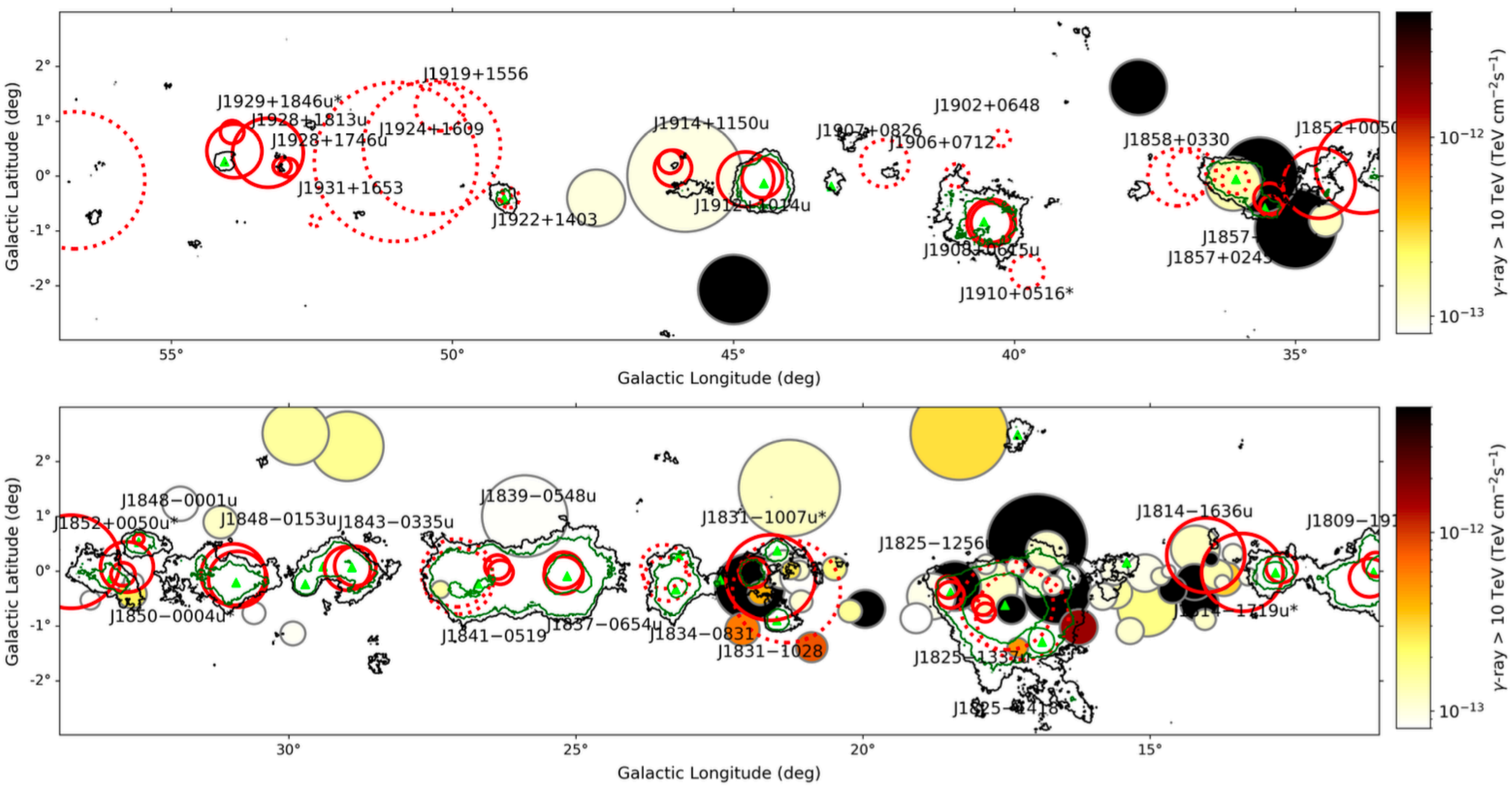


LHAASO significance maps

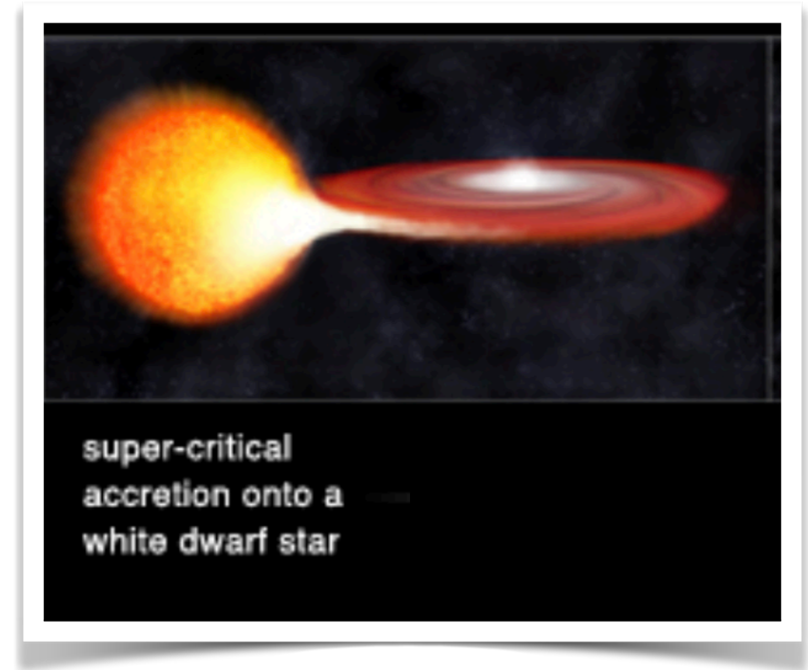


- Galactic Plane Survey by **H.E.S.S.**
  - 78 sources detected
  - **47 unidentified**
  - Abdalla et al., A&A 612 (2018) A1
- 1st **LHAASO** catalog:
  - 90 sources detected
  - 43 with UHE emission (σ>4 @ E>100 TeV)
  - **32 new TeV sources**
  - Cao et al., ApJSS 271 (2024) 25

Are UNID sources related to molecular clouds as illuminated by SNR-escaping CRs?

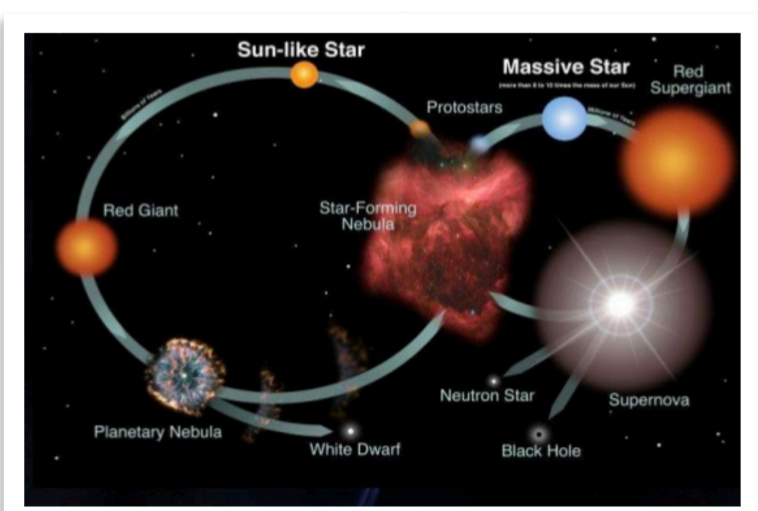


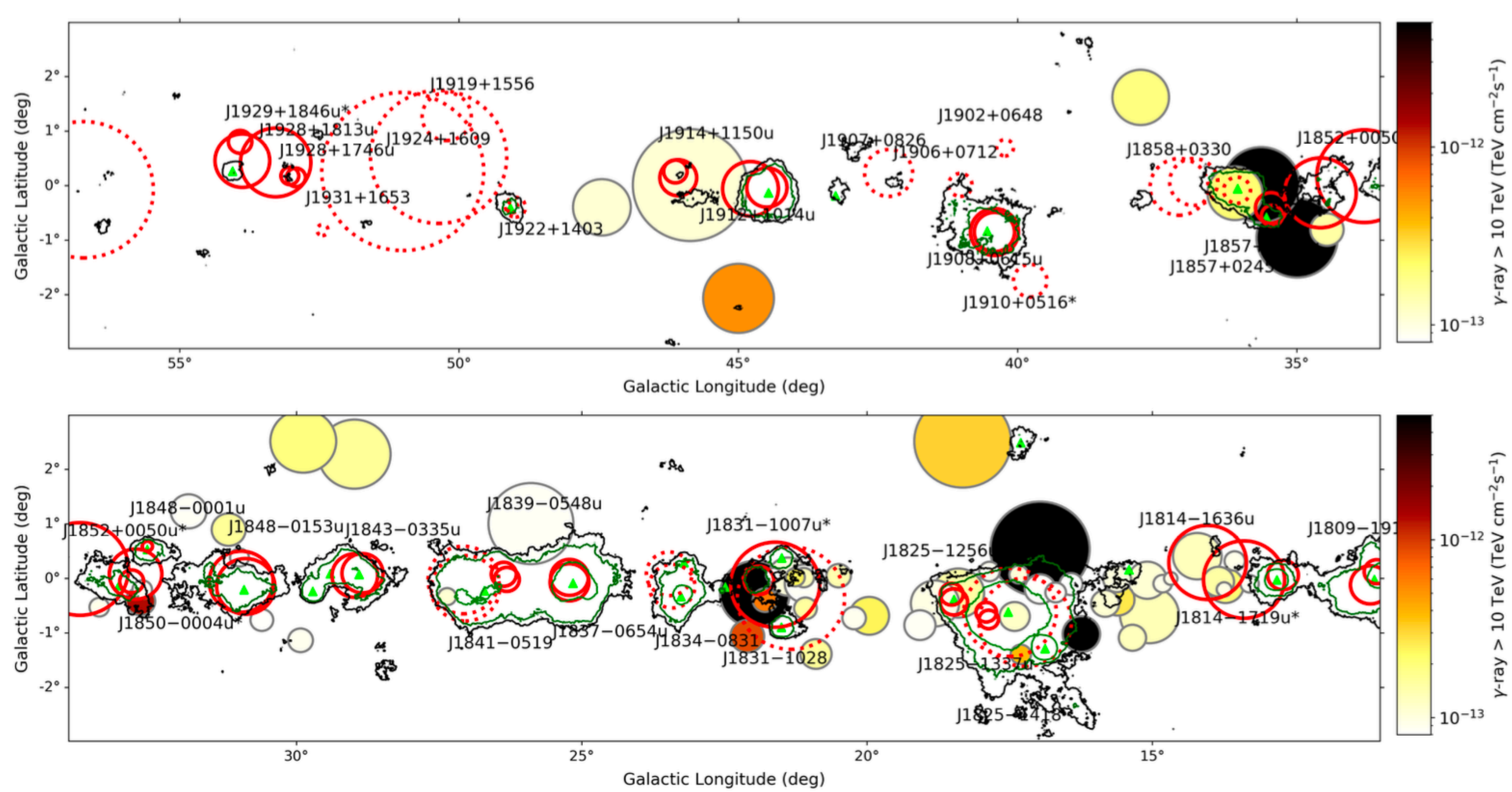
Type Ia SN scenario



Mitchell & Celli, 2024
JHEA submitted

Type II SN scenario

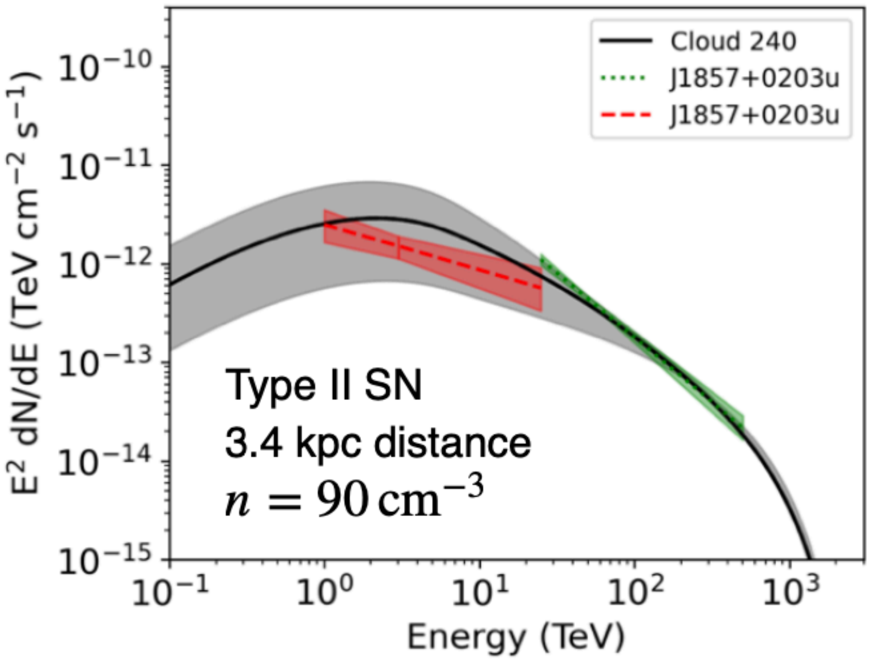


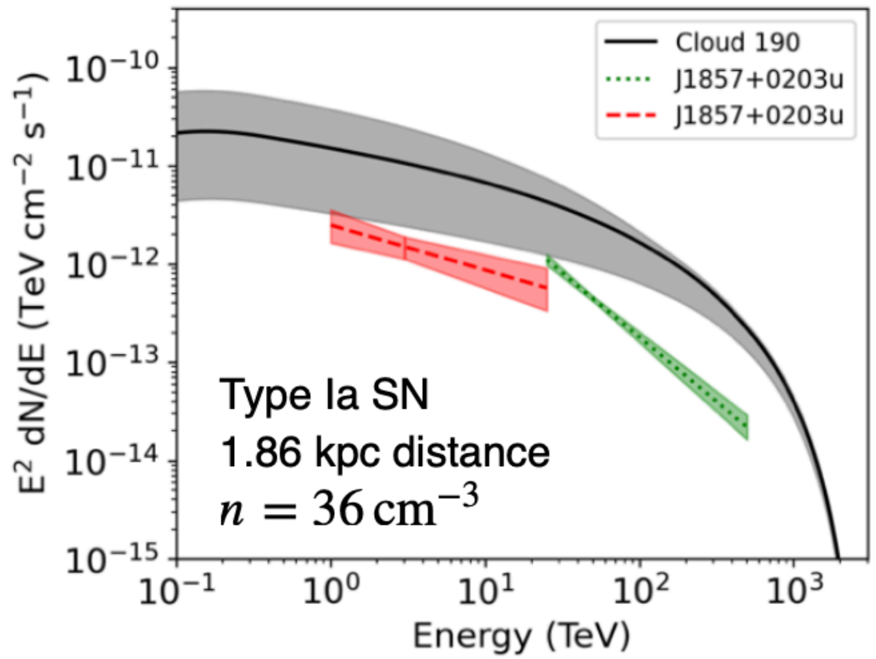


1LHAASO J1857+0203u

Mitchell & Celli, 2024 JHEA submitted

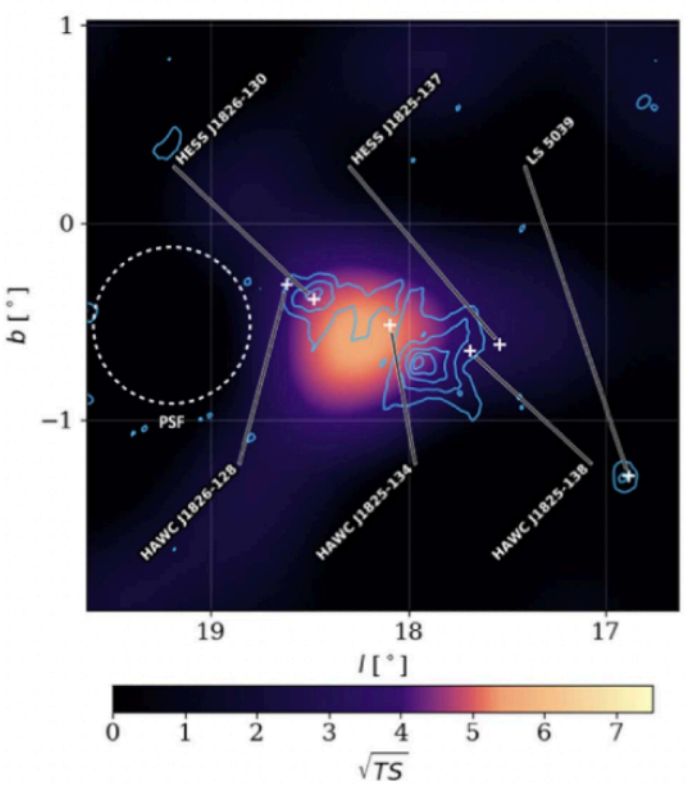
- **UNID source coincident with HESS J1858+020**
- **Spatially coincident with clouds 240 & 190, illuminated by SNR G036.6-0.7**

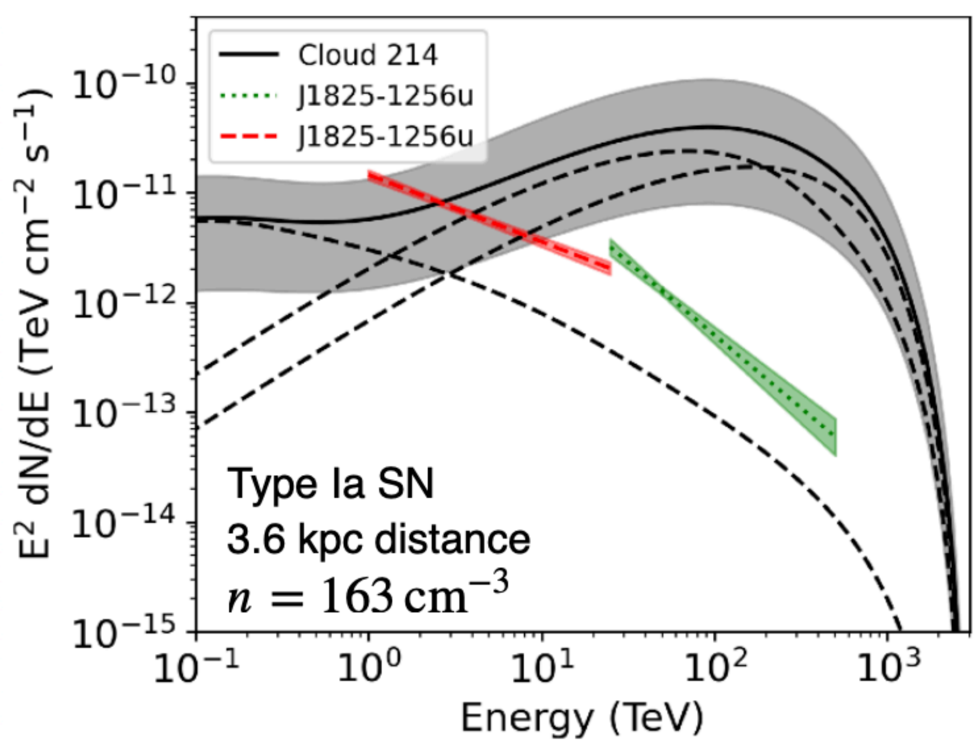




- These are not fits, but model prediction with benchmark parameters
- 10% CR efficiency here assumed, lower values would result more favorable!

1LHAASO J1825-1256u





- **A formally UNID source in a complex sky region**
- Here, **multiple SNRs** contribute to the total flux, namely G017.0-0.0, G017.4-0.1, **G019.1+0.2**
  - their contributions can also be considered individually.

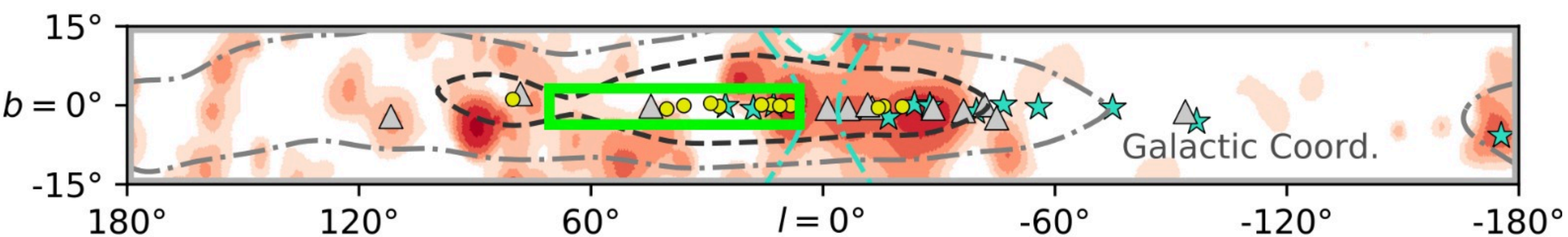
Conclusions

- The most energetic particles — approaching ~PeV — are expected to escape their source at early times

- Potentially illuminating nearby molecular clouds?
  - The spectrum of particles penetrating the molecular cloud is different from that injected by the accelerator
  - A **new population** of high energy sources may be emerging, coincident with **target** material rather than accelerators themselves

- The scenario of molecular clouds illuminated by nearby SNRs appears viable to explain several **unidentified UHE sources**

- Ongoing investigation with **neutrinos**!



Aartsen et al., Science 380 (2023) 1338

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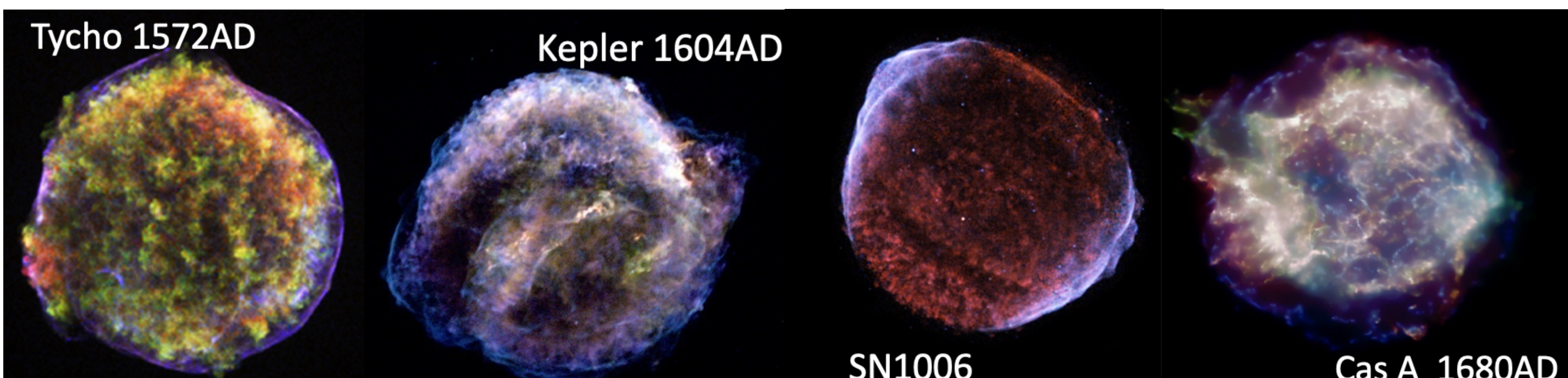
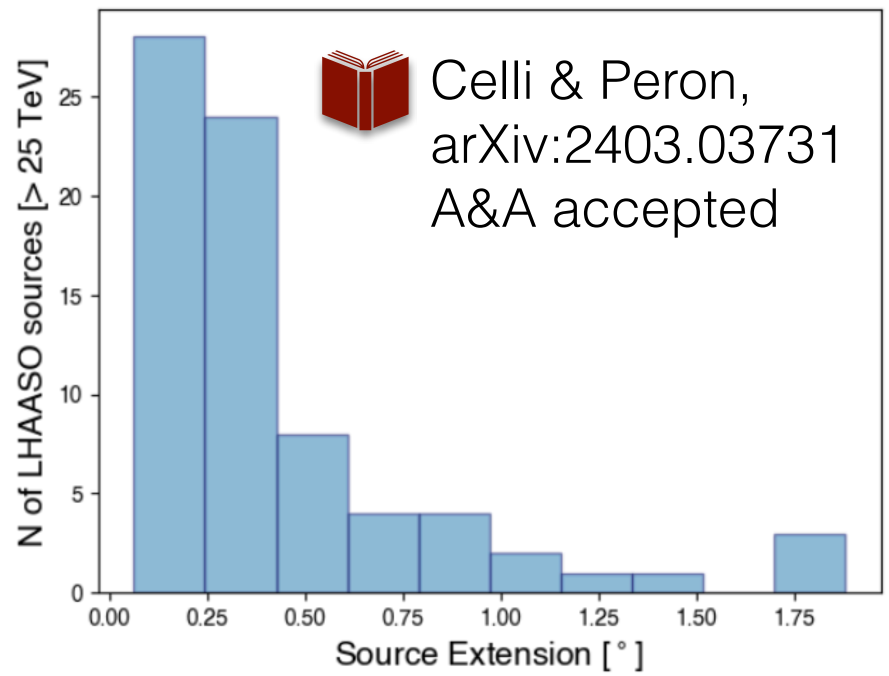
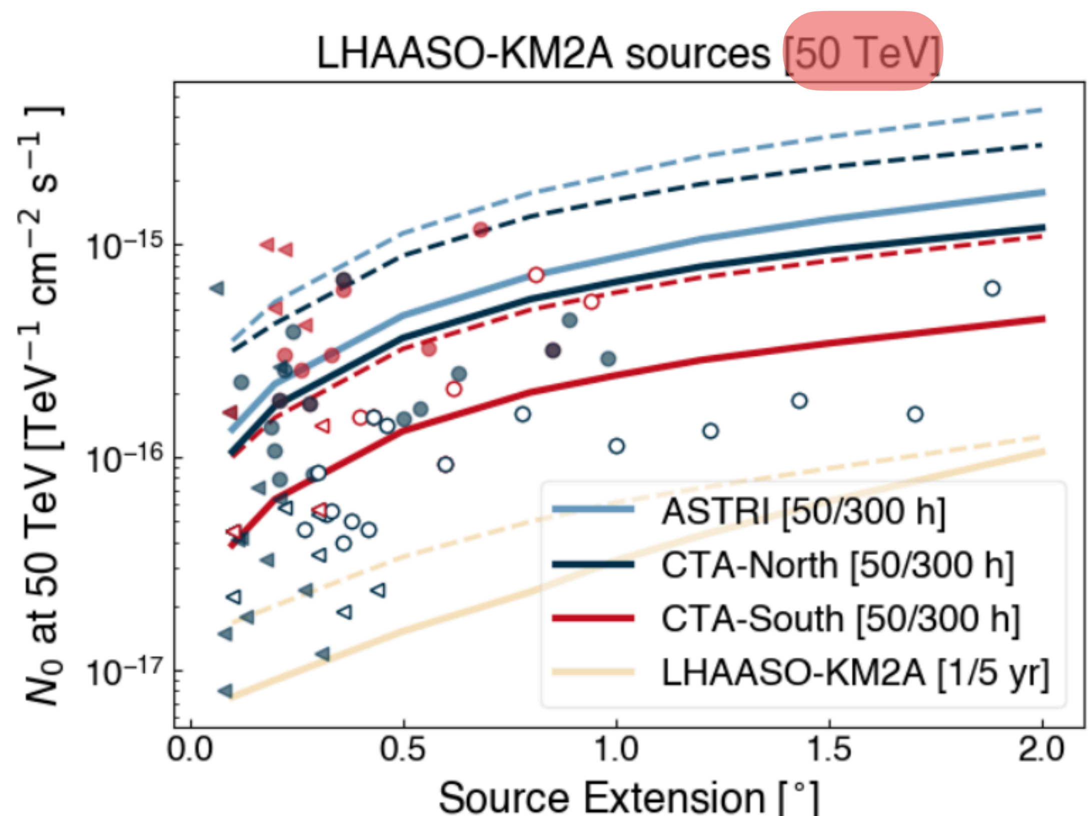
Neutrino Oscillation Workshop

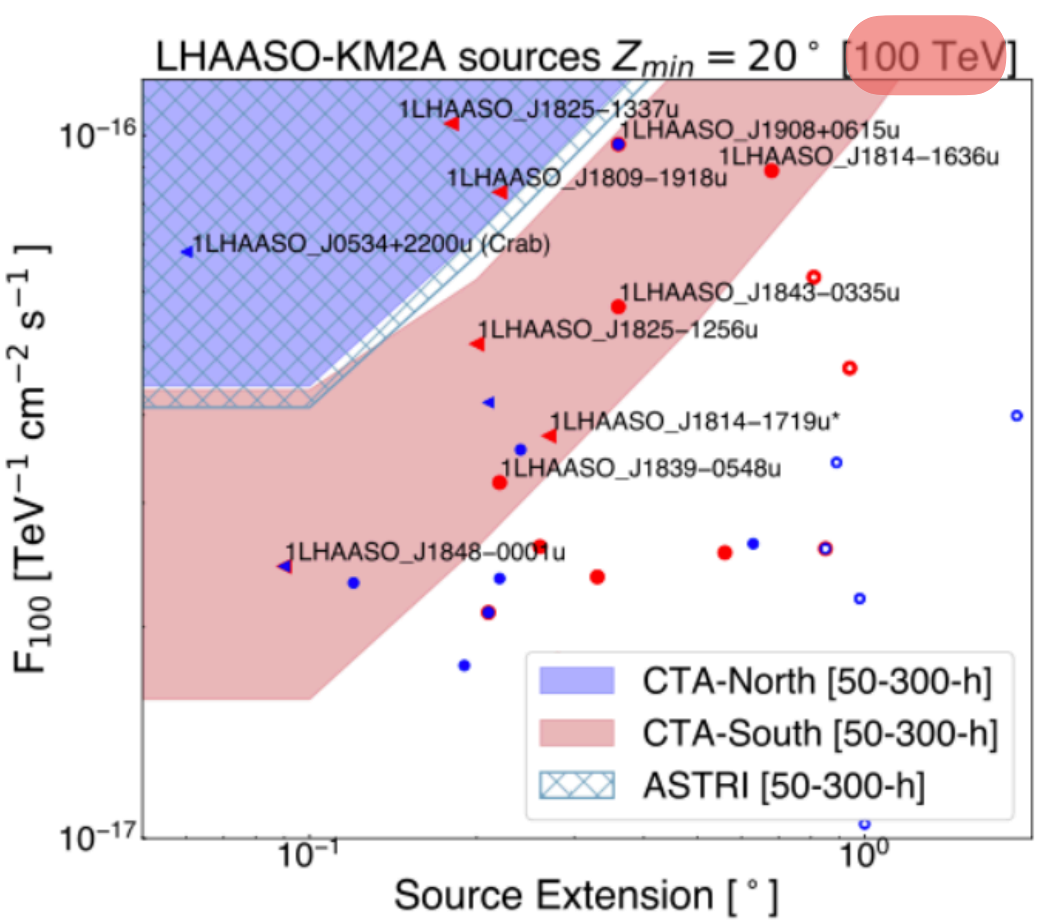
Thanks for your kind attention!

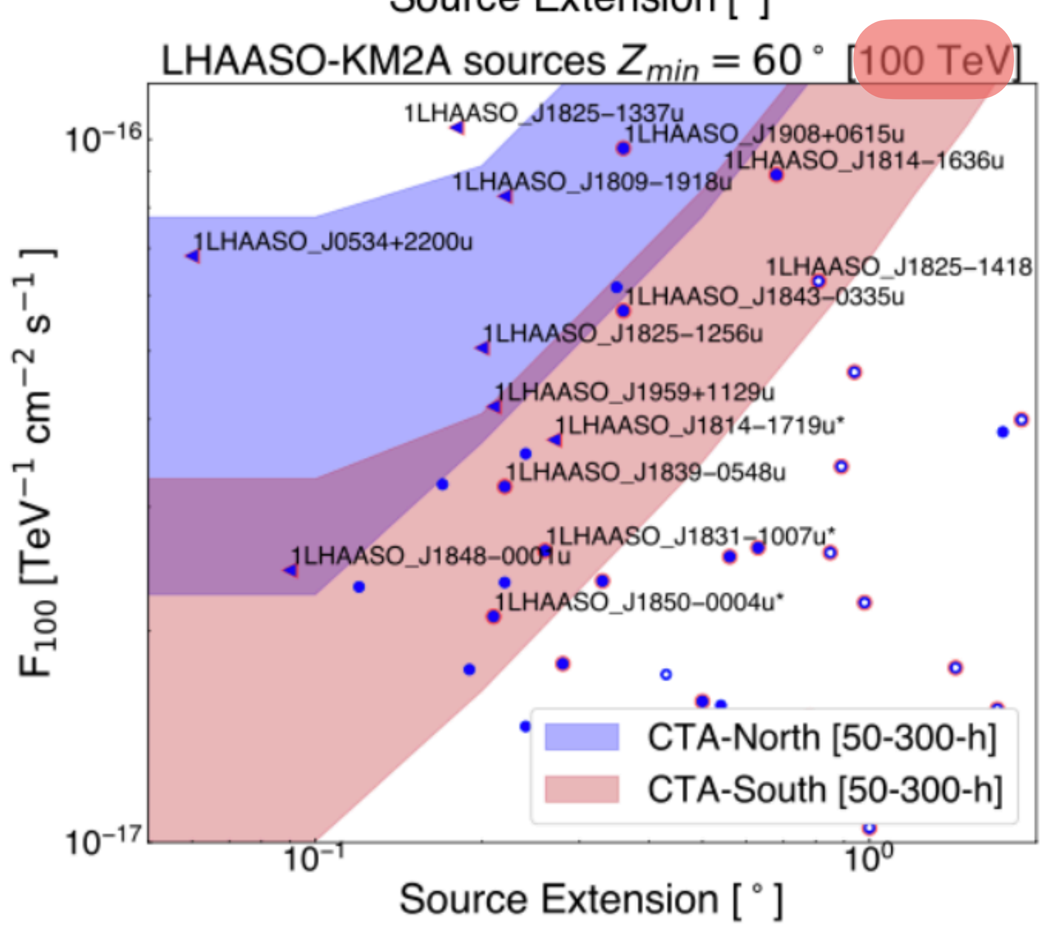


Future prospects with IACTs: a sensitivity study with ASTRI & CTA









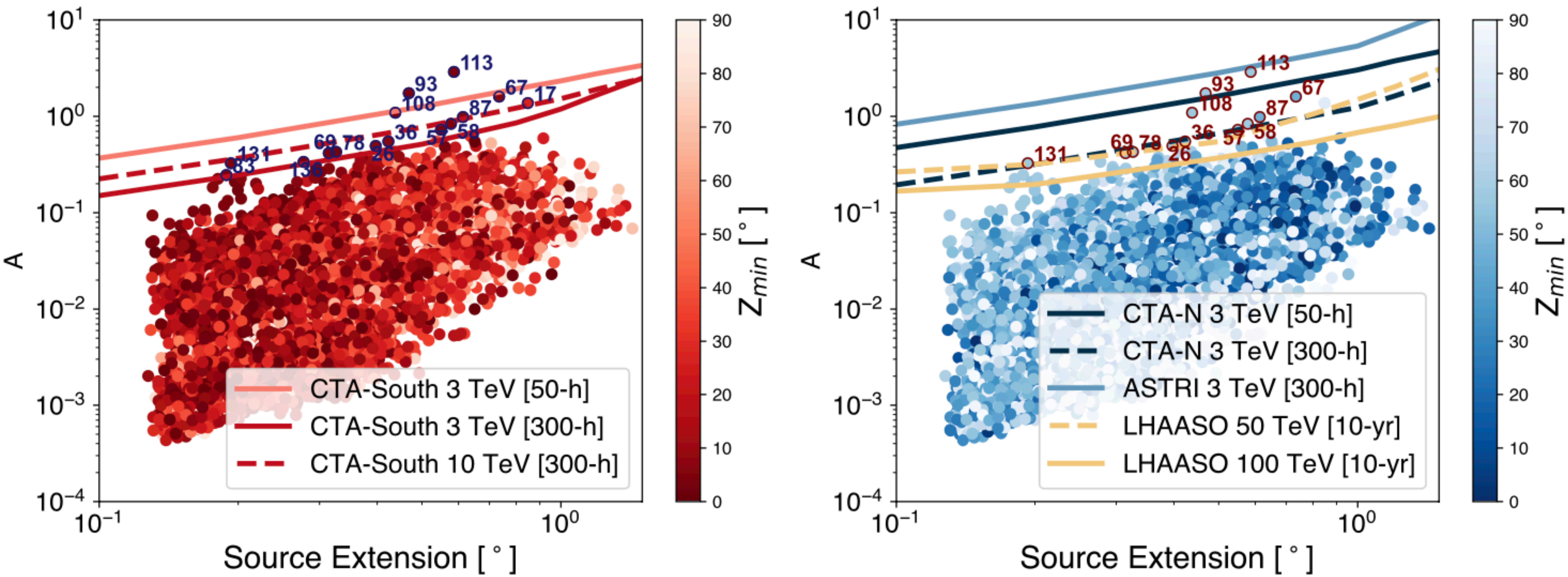
Molecular clouds illuminated by the CR sea

$$F_\gamma^{MC} = A \times \varphi_{gamma}$$

$\Longrightarrow$ The MC is visible if

$$A > \frac{Sensitivity(E_\gamma)}{\varphi(E_\gamma)}$$

$$A = M_5/d^2_{\rm kpc}$$



Celli & Peron, arXiv:2403.03731, A&A accepted

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 **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.

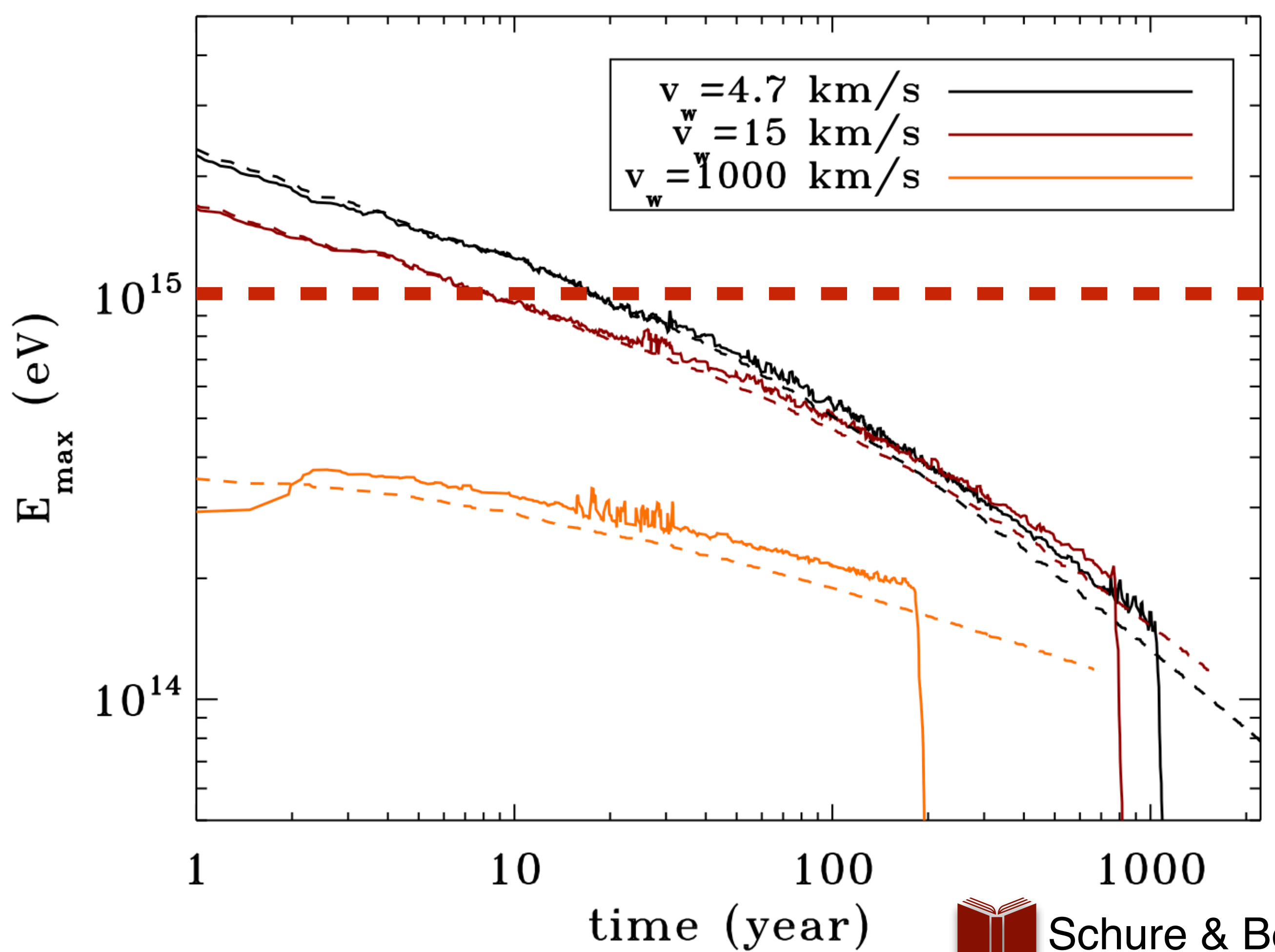
Celli et al., MNRAS 490 (2019) 3

The problem of maximum energy in young SNRs

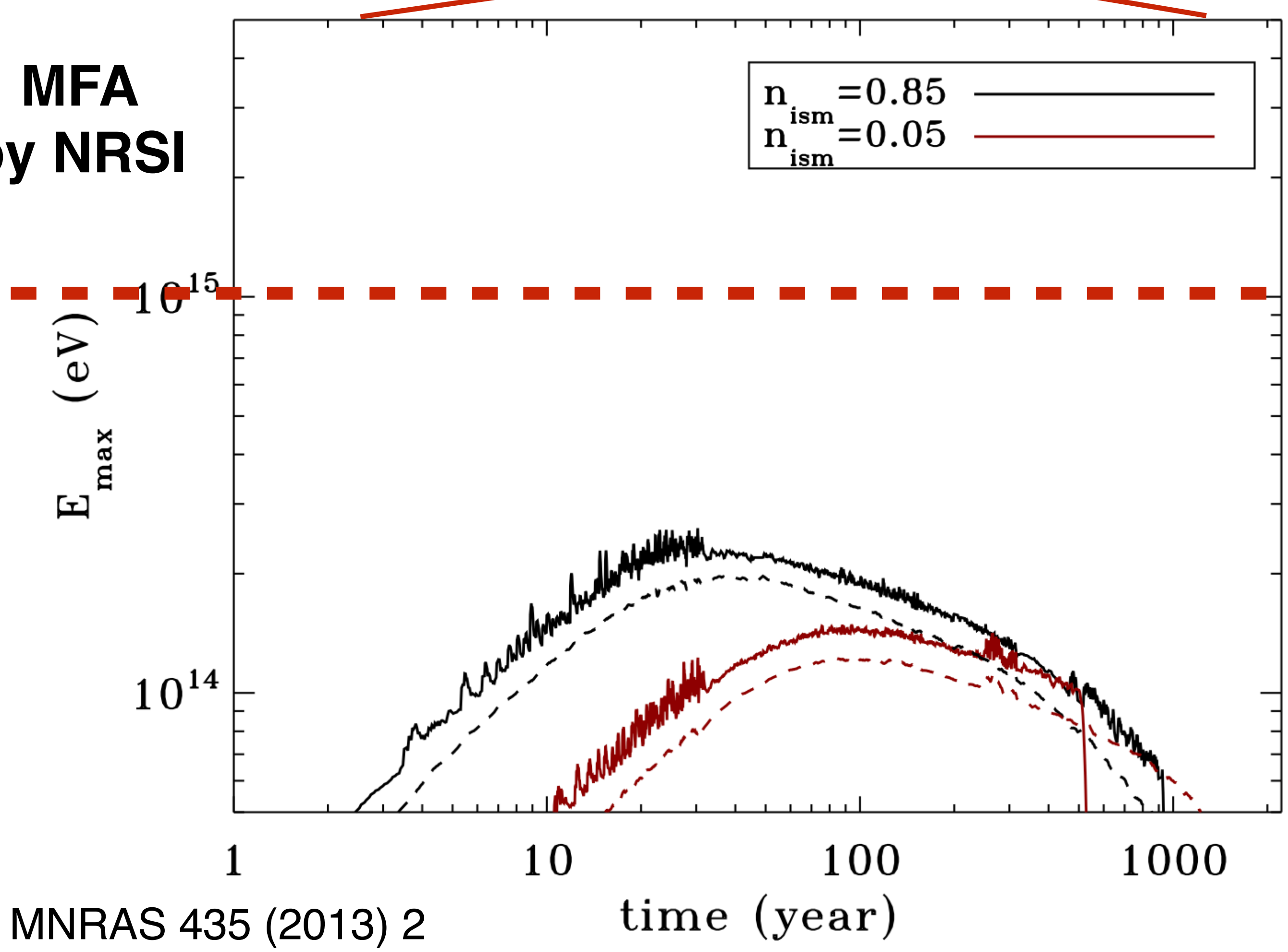
- Type Ia (e.g. Tycho) ⟶ expanding in constant density medium
- Core Collapse (e.g. CasA, RXJ1713.7-3946) ⟶ expanding in the dense slow wind of the progenitor star

Remnants of type II

~~Remnants of type Ia~~



MFA by NRSI



Schure & Bell, MNRAS 435 (2013) 2

With NRSI, only special explosions can achieve the knee

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

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

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

Celli et al., MNRAS 490 (2019) 3

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

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

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

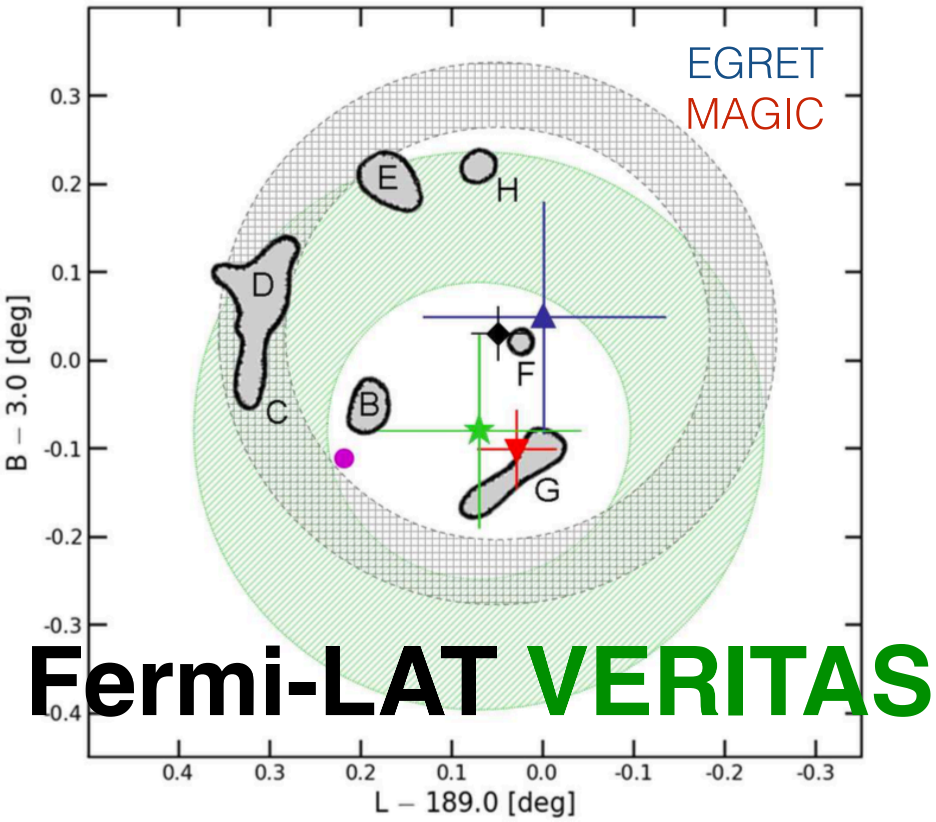
acceleration spectrum ($\alpha \sim 4$ from DSA)

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

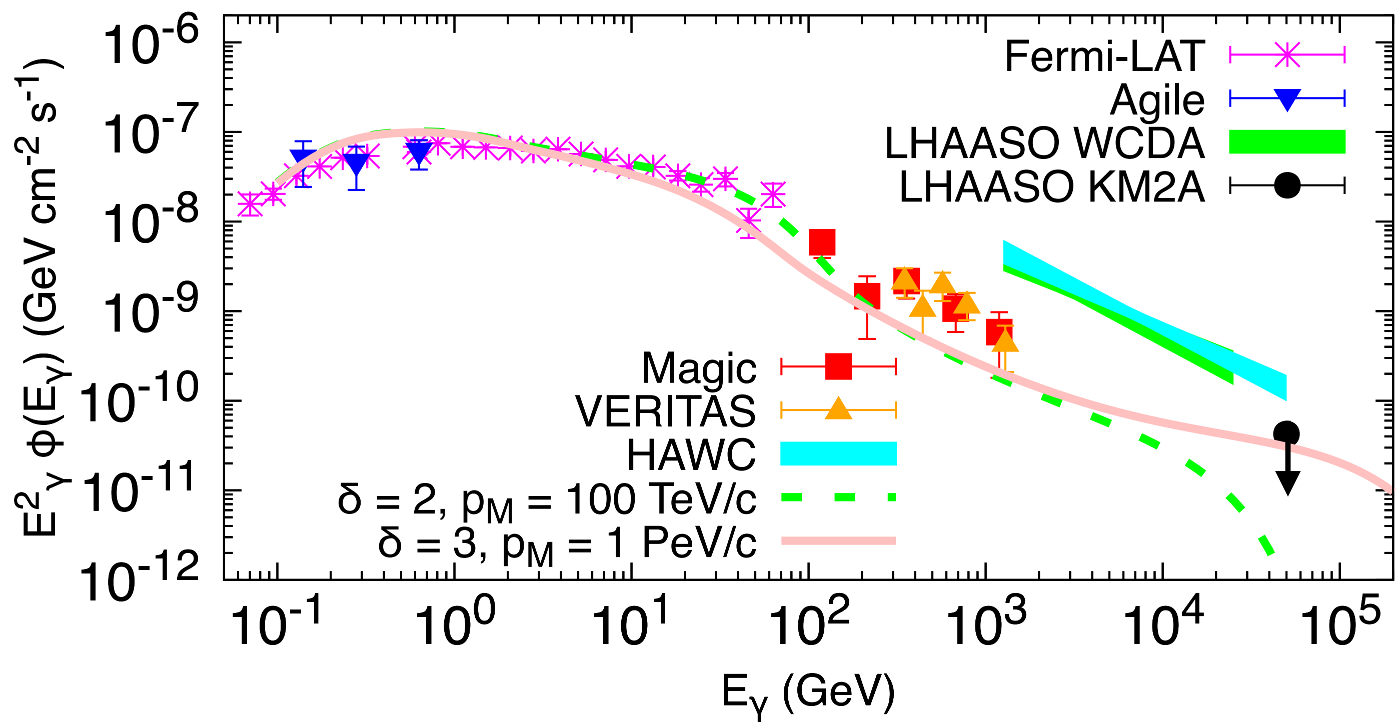
Assumption 4: the shock is evolving through the ST phase

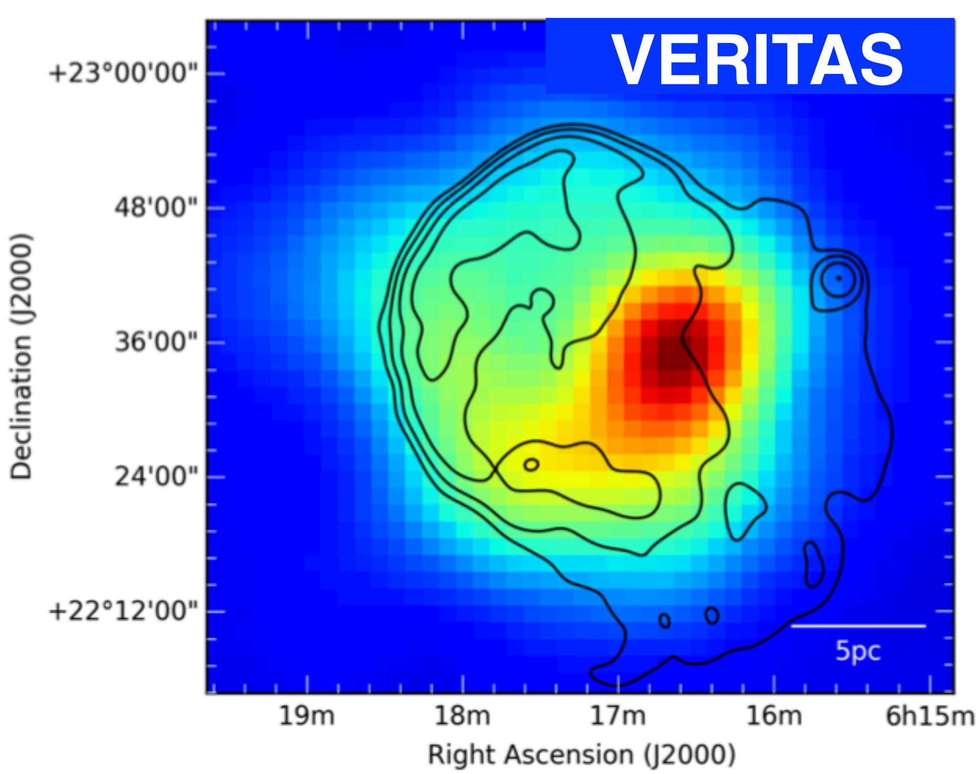
$$R_s(t) \propto t^{2/5} \qquad v_s(t) \propto t^{-3/5}$$

Middle-aged SNRs: IC 443



$$\Gamma_{\rm GeV} = 2.56$$
$$\Gamma_{\rm TeV} = 3.10$$





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

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

Kolm. $D(10\,{\rm GeV/c}) = 10^{27}\,{\rm cm}^2/{\rm s}$

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

$D/D_{\mathrm{Gal}} \leq 0.3$ → **Suppression of diffusion coefficient required:**

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

Malkov et al., ApJ 768 (2013) 63

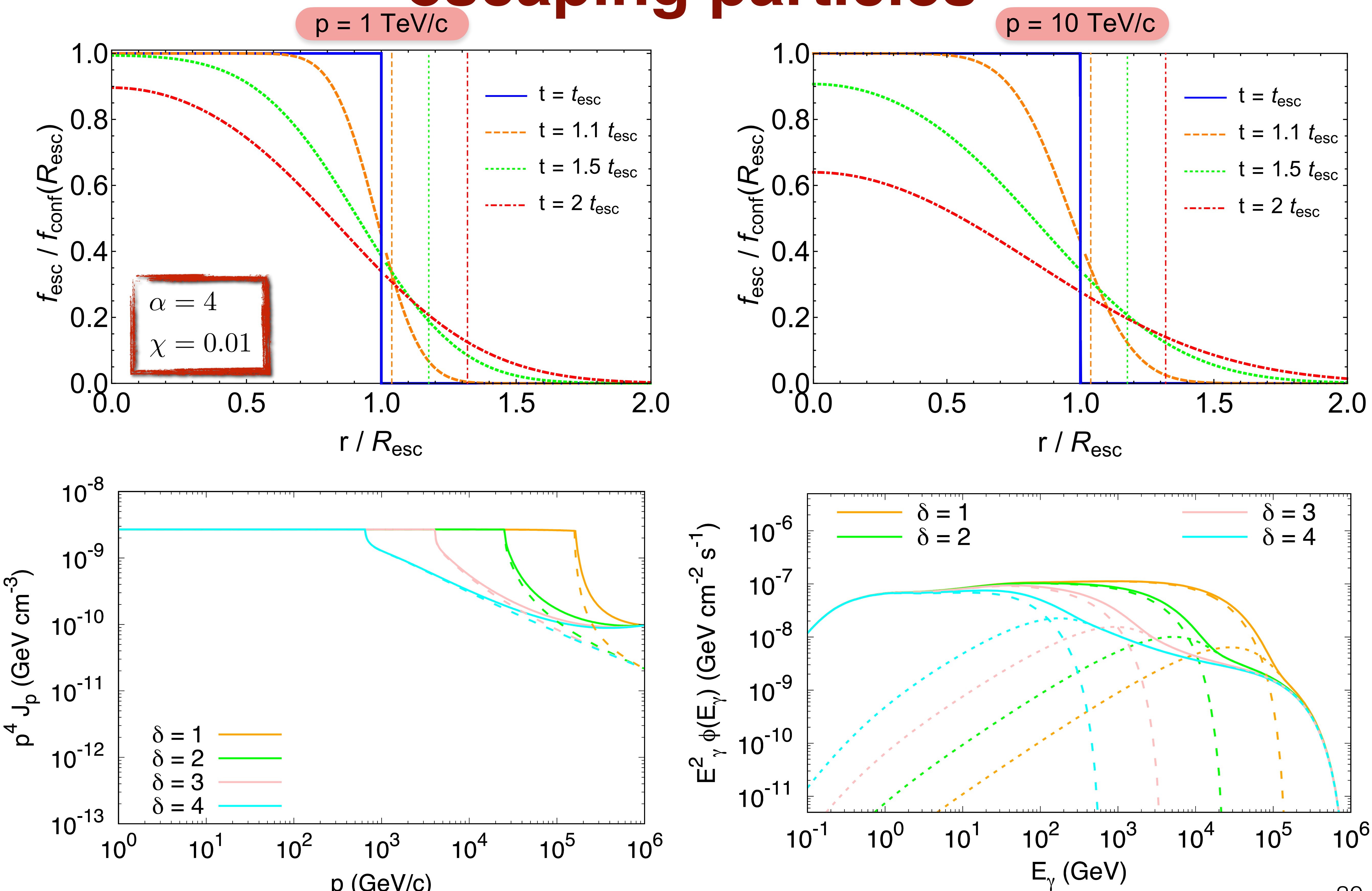
Nava et al., MNRAS 461 (2016) 3552N

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

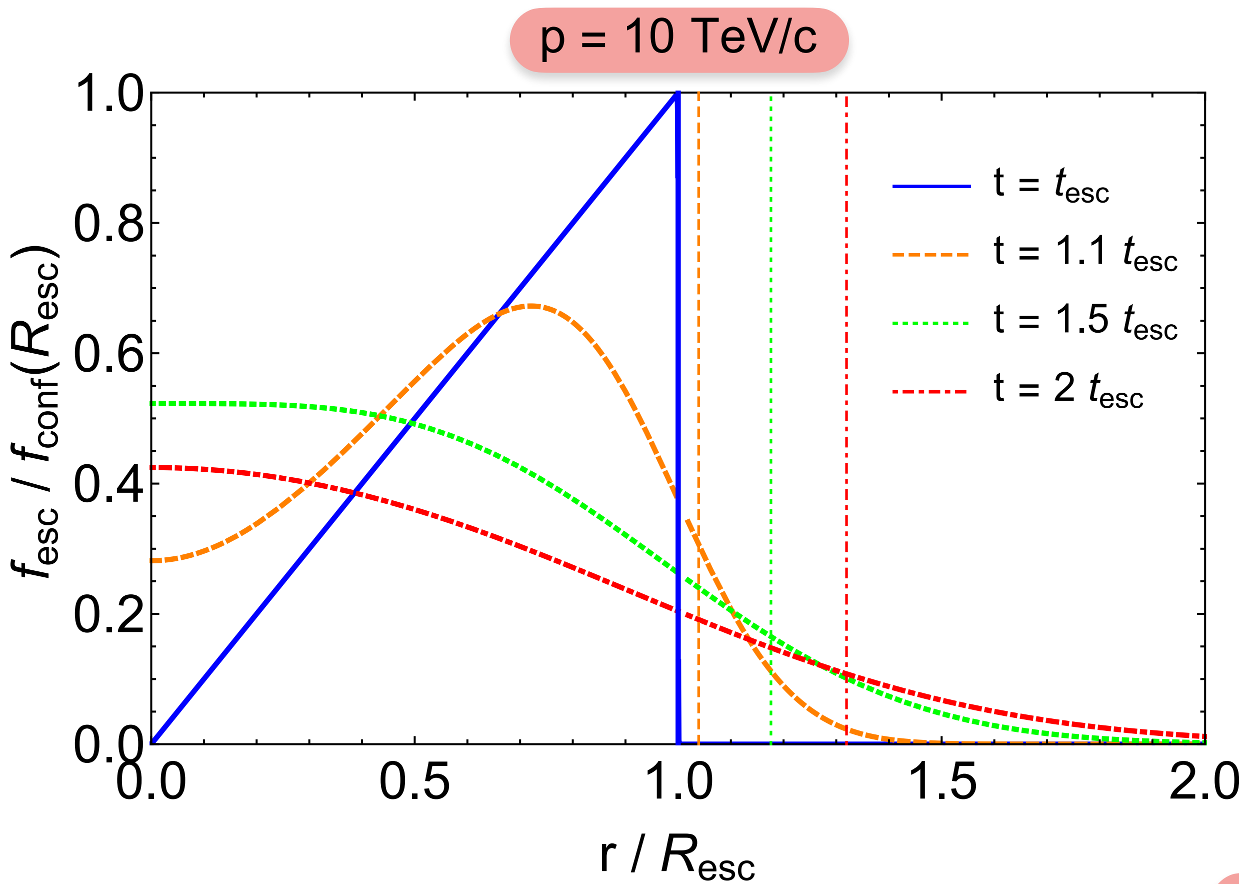
$\delta \geq 2$ → **How does magnetic turbulence evolve with time?**
Needs to include damping effects (MHD cascade, ion-neutral friction).

$\xi_{\mathrm{CR}} \simeq 2 - 20\%$ → Standard assumption in the SNR paradigm for the origin of GCRs.

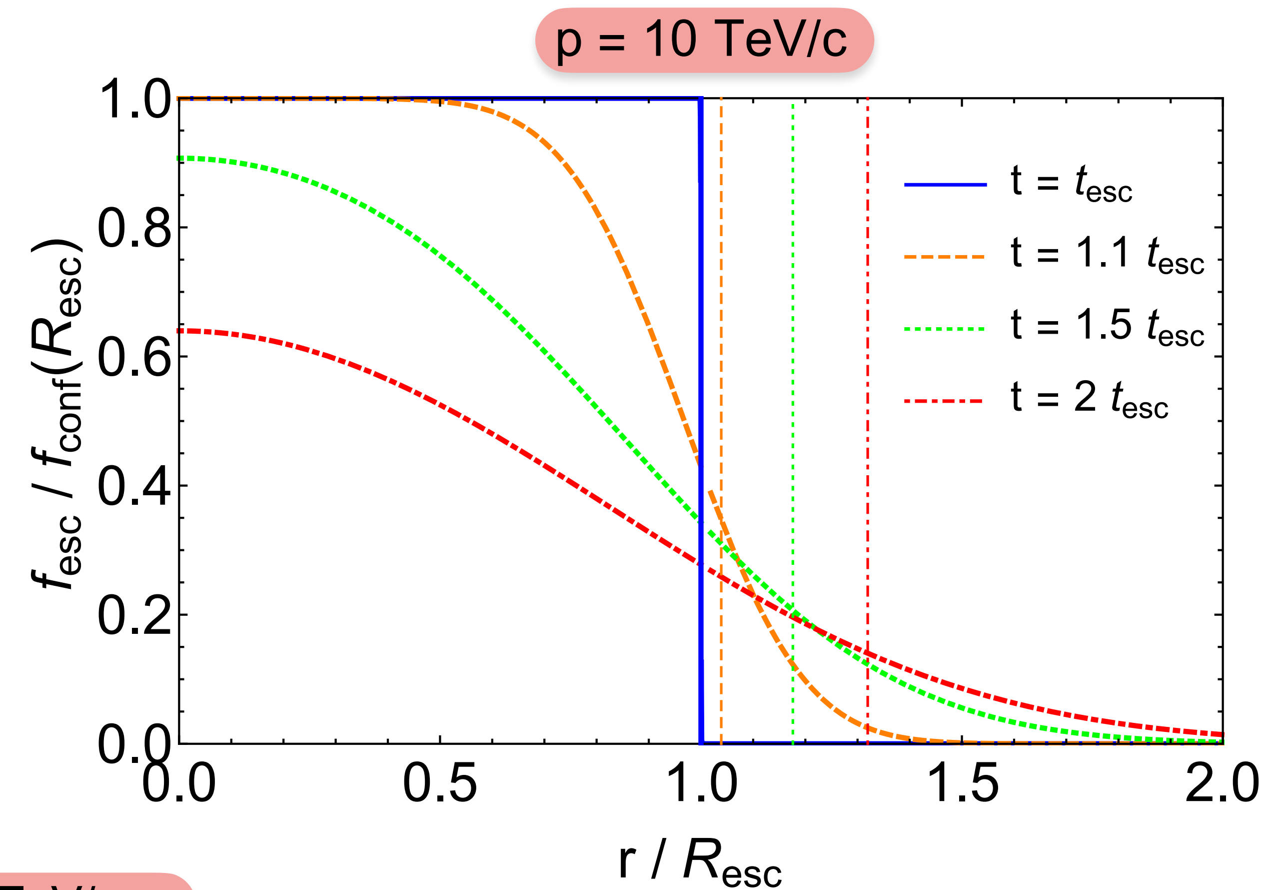
Morphological and spectral features of escaping particles

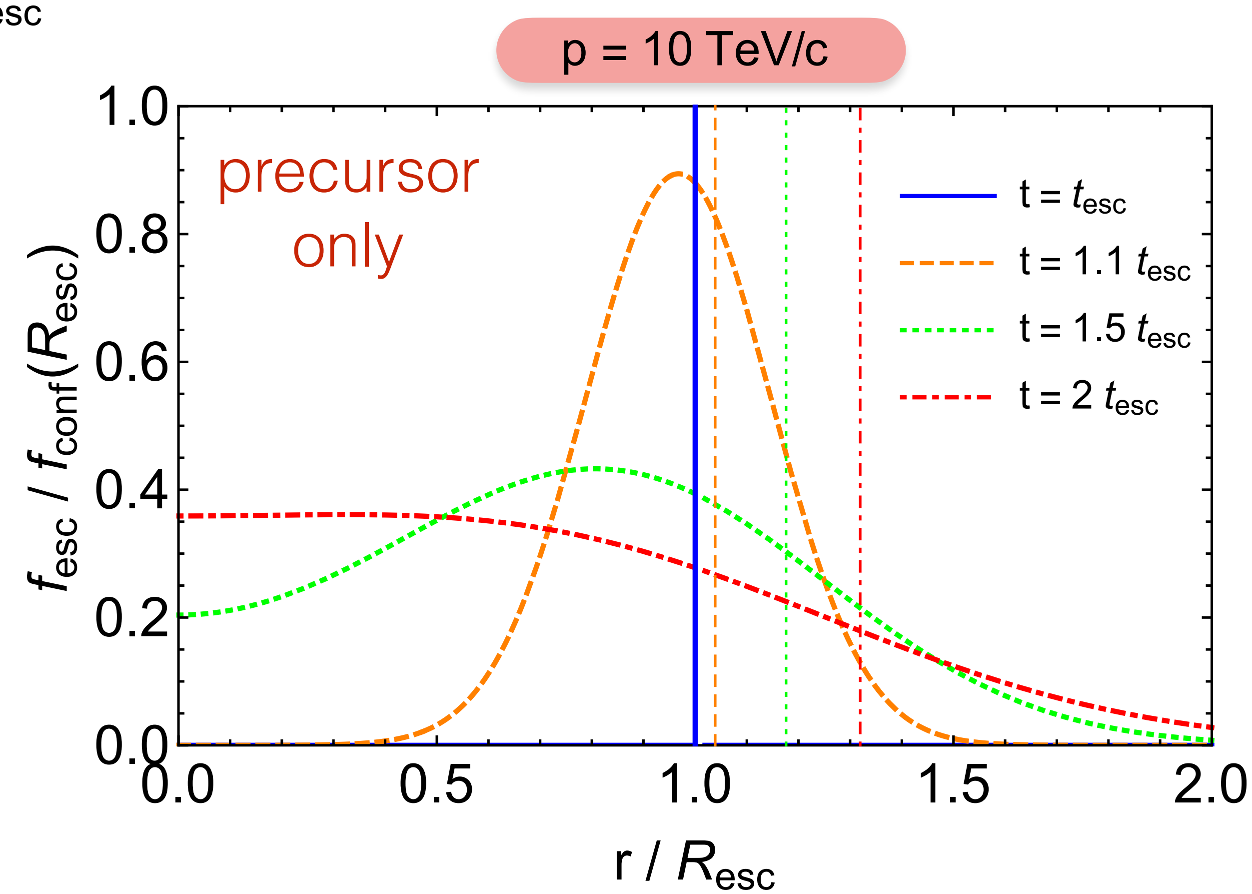


$\alpha = 4 + 1/3$



$\alpha = 4$

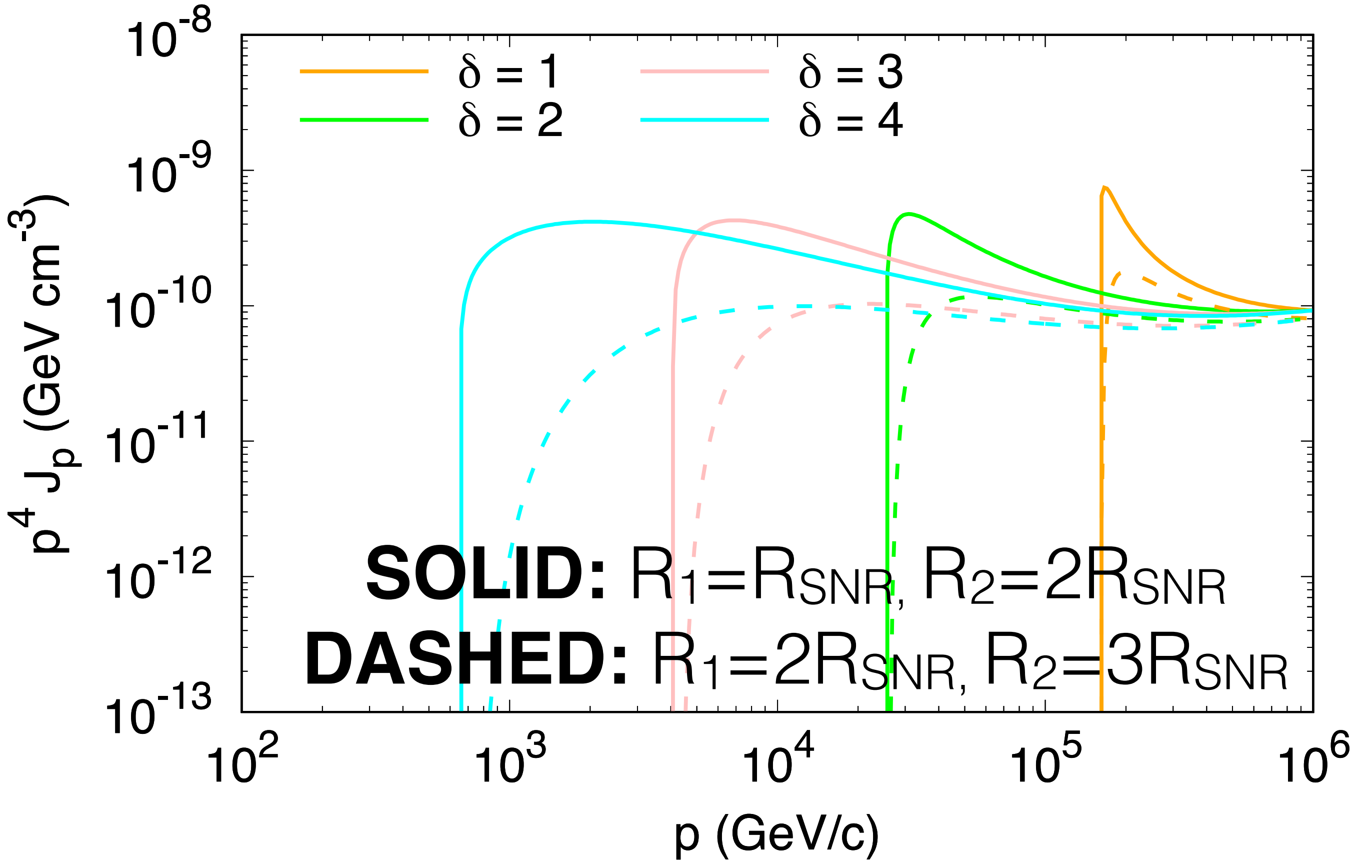


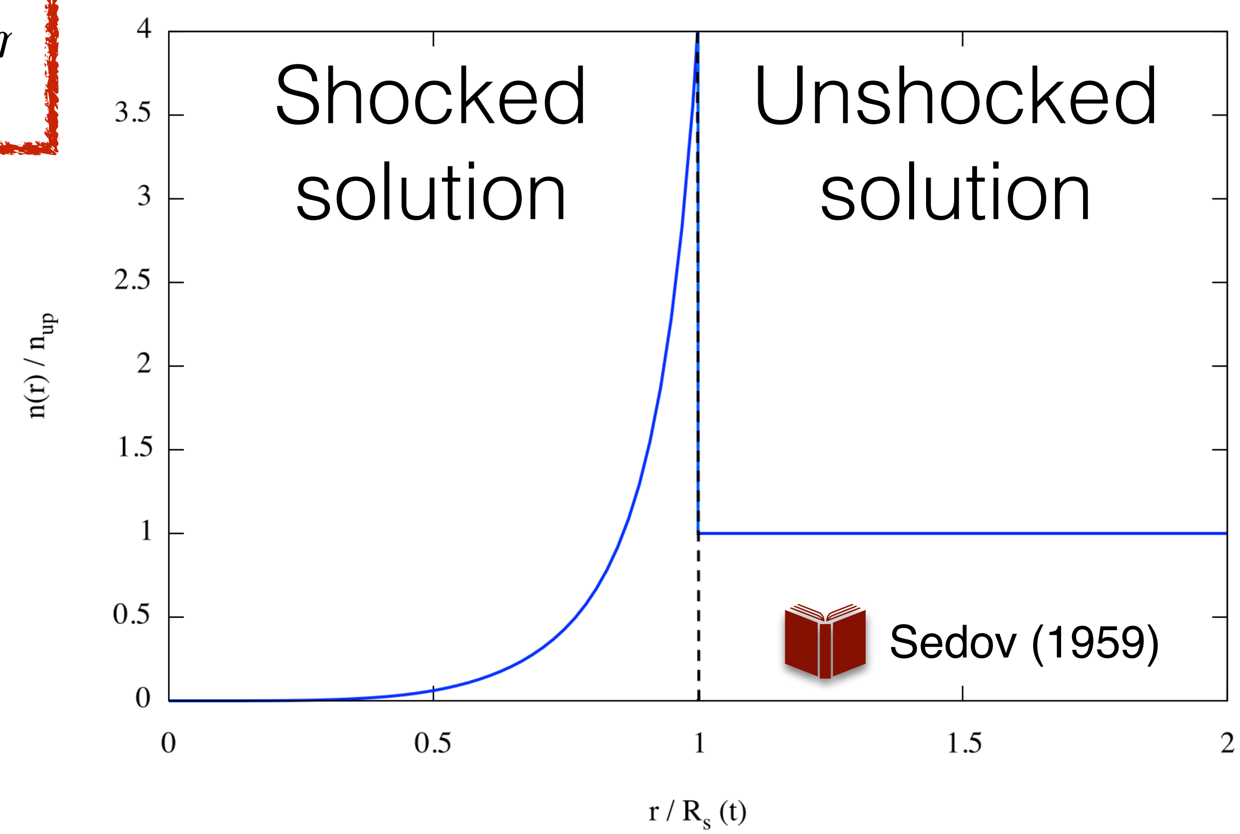


$\chi = 0.01$

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

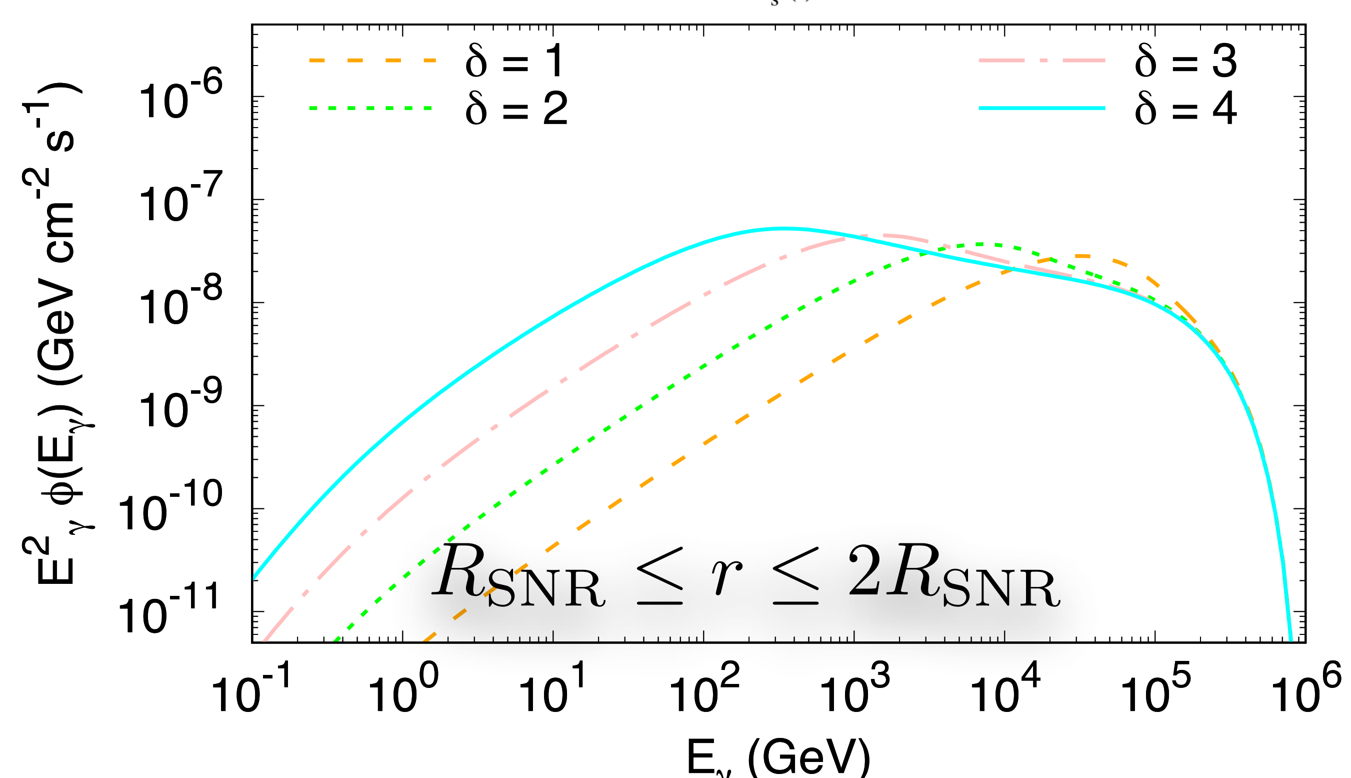
$$J_p^{\rm out}(t,p) = \frac{3}{R_2^3 - R_1^3}\int_{R_1}^{R_2}\left[f_{\rm esc}(t,r,p) + f_{\rm p,esc}(t,r,p)\right] r^2 dr$$



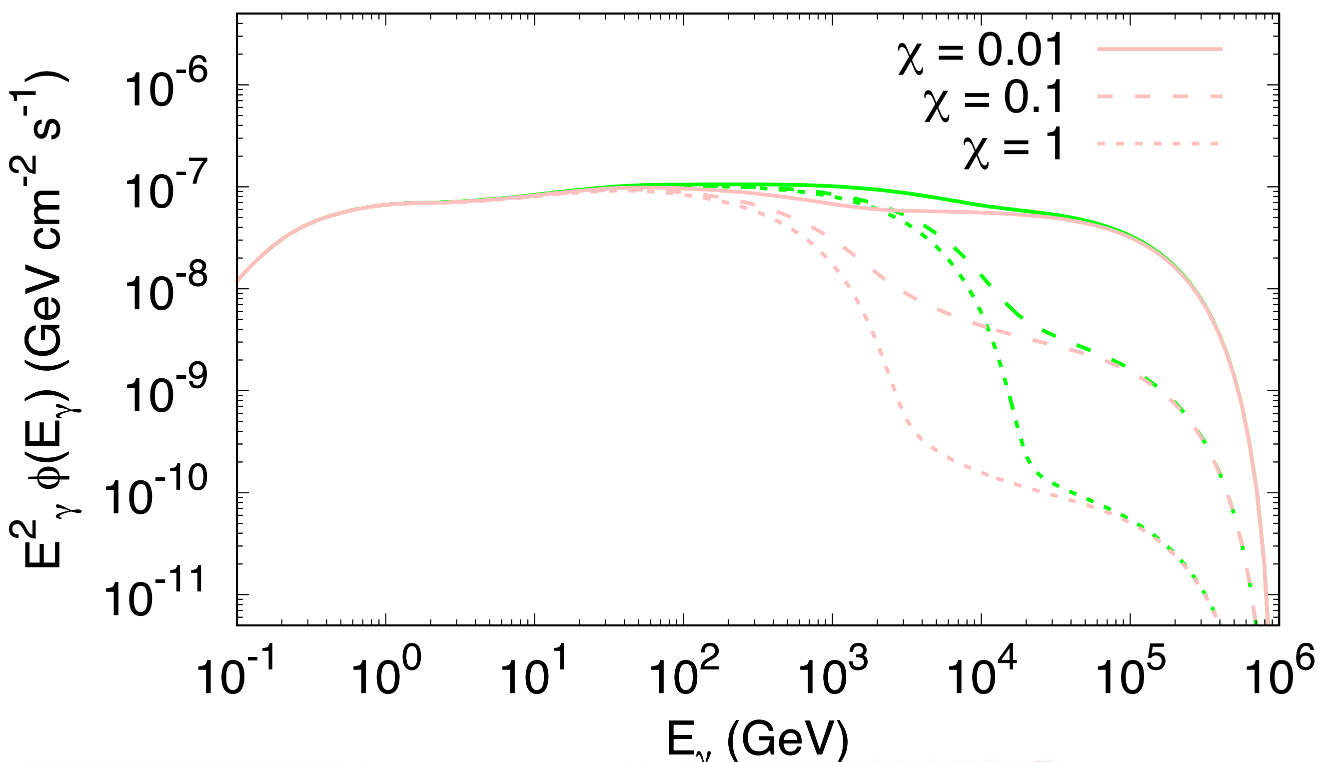


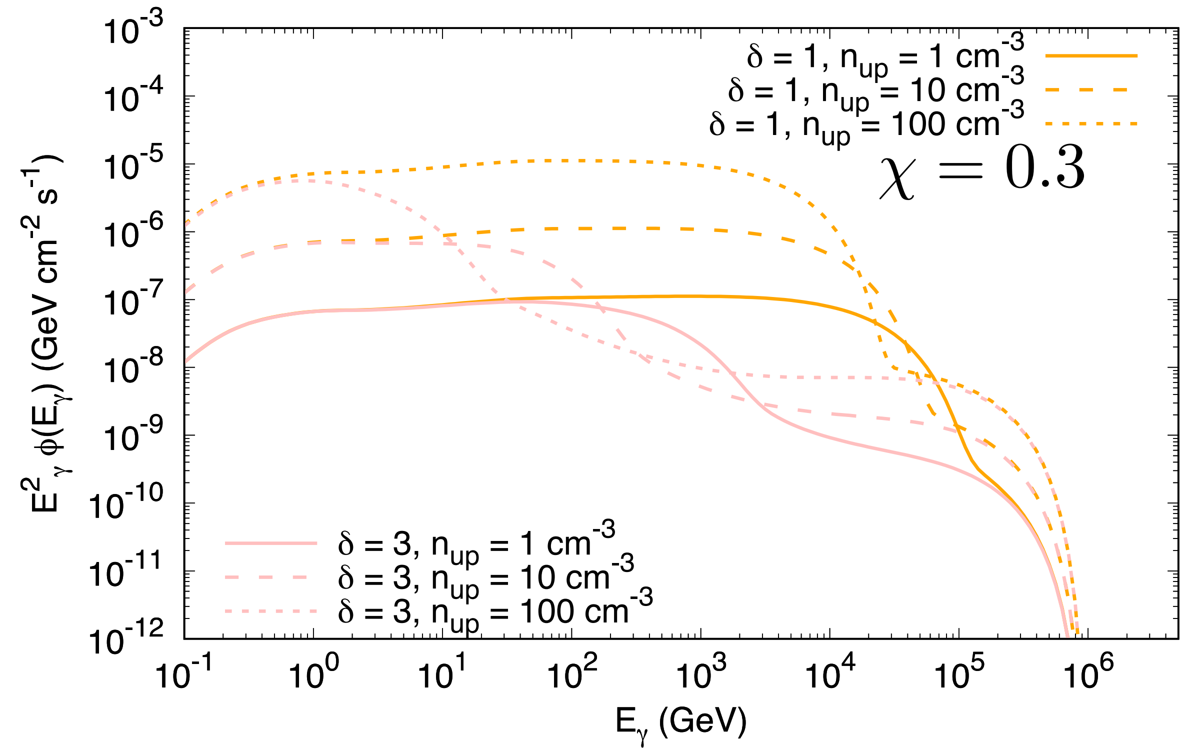
$$f_0(p) \propto p^{-4}$$
$$D(10\ {\rm GeV}/c) = 10^{27}\ {\rm cm^2 s^{-1}}$$
$$\xi_{\rm CR} = 10\%$$
$$n_{\rm up} = 1\ {\rm cm^{-3}}$$
$$T_{\rm SNR} = 10^4\ {\rm yr}$$
$$d = 1\ {\rm kpc}$$

Celli et al., MNRAS 490 (2019) 3

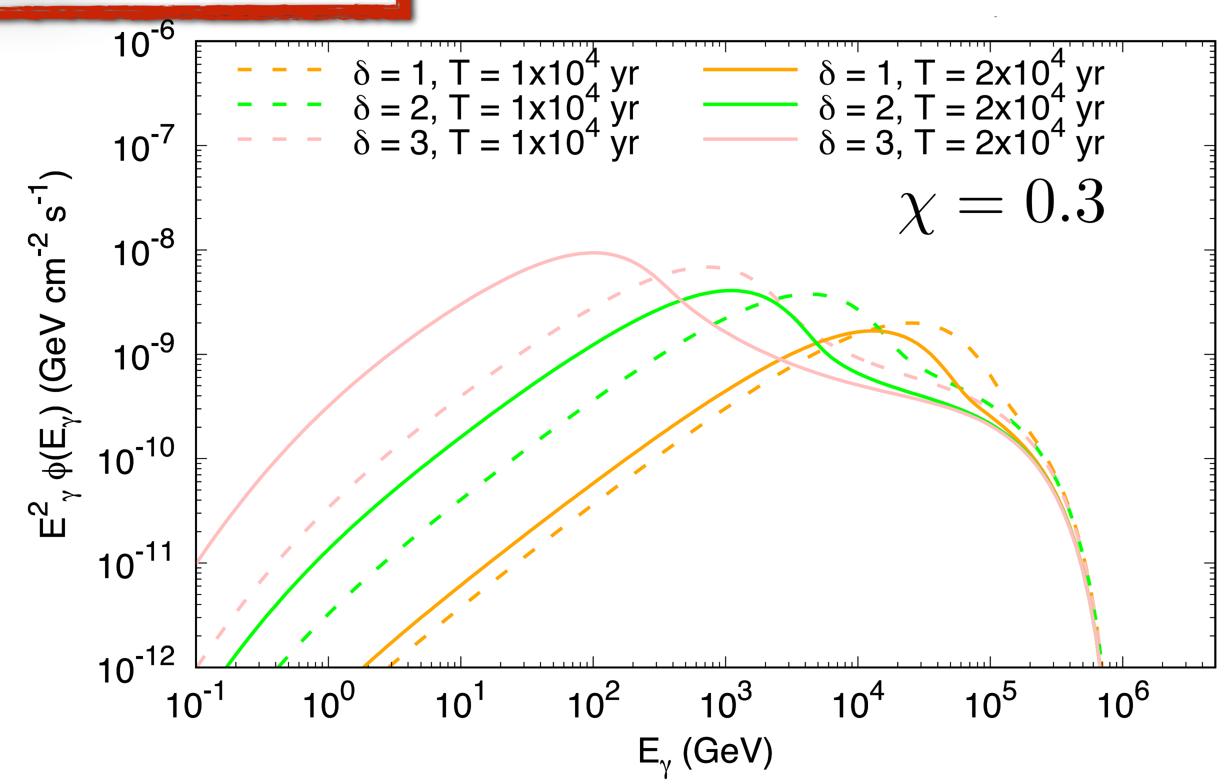


Volume integrated gamma-ray emission from hadronic interactions



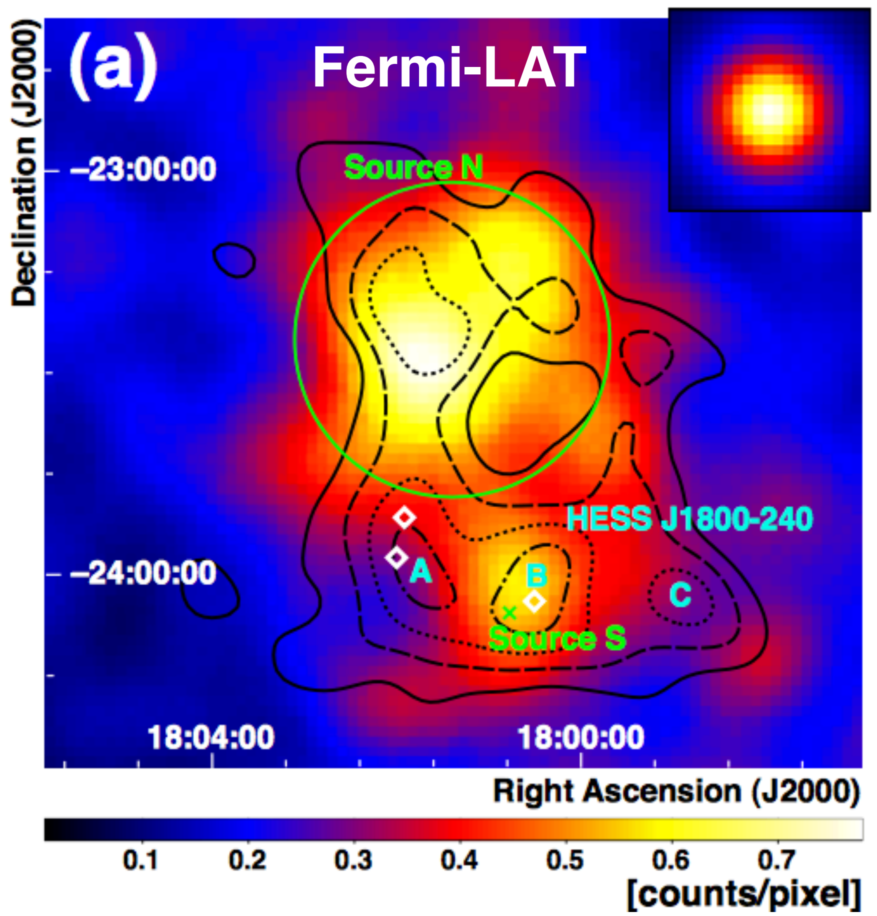


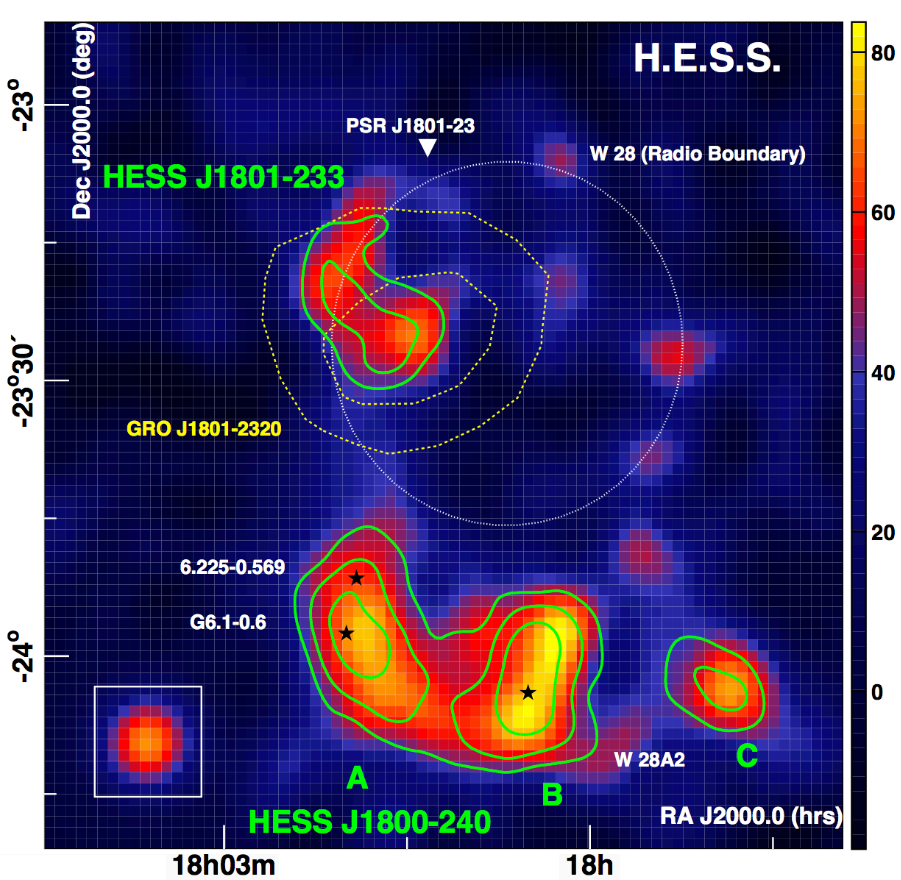
$$D(p) \equiv \chi D_{\rm Gal} = \chi 10^{28} \left(\frac{pc}{10\ \rm GeV}\right)^{1/3}\ \rm cm^2 s^{-1}$$

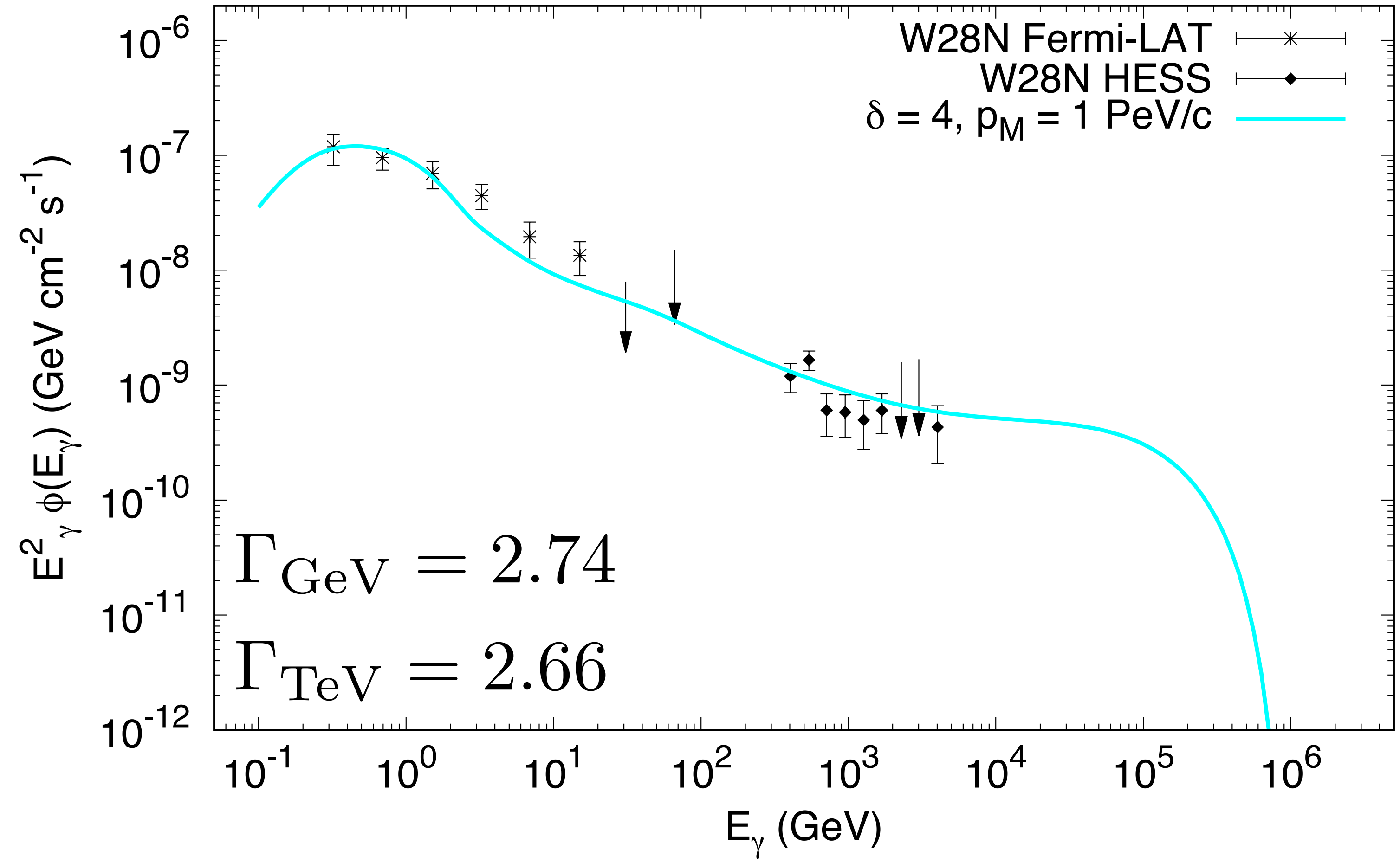


$$\xi_{\rm CR} = 10\%$$
$$n_{\rm up} = 1\ \rm cm^{-3}$$
$$T_{\rm SNR} = 10^4\ \rm yr$$
$$d = 1\,\rm kpc$$

Middle-aged SNRs: W 28N







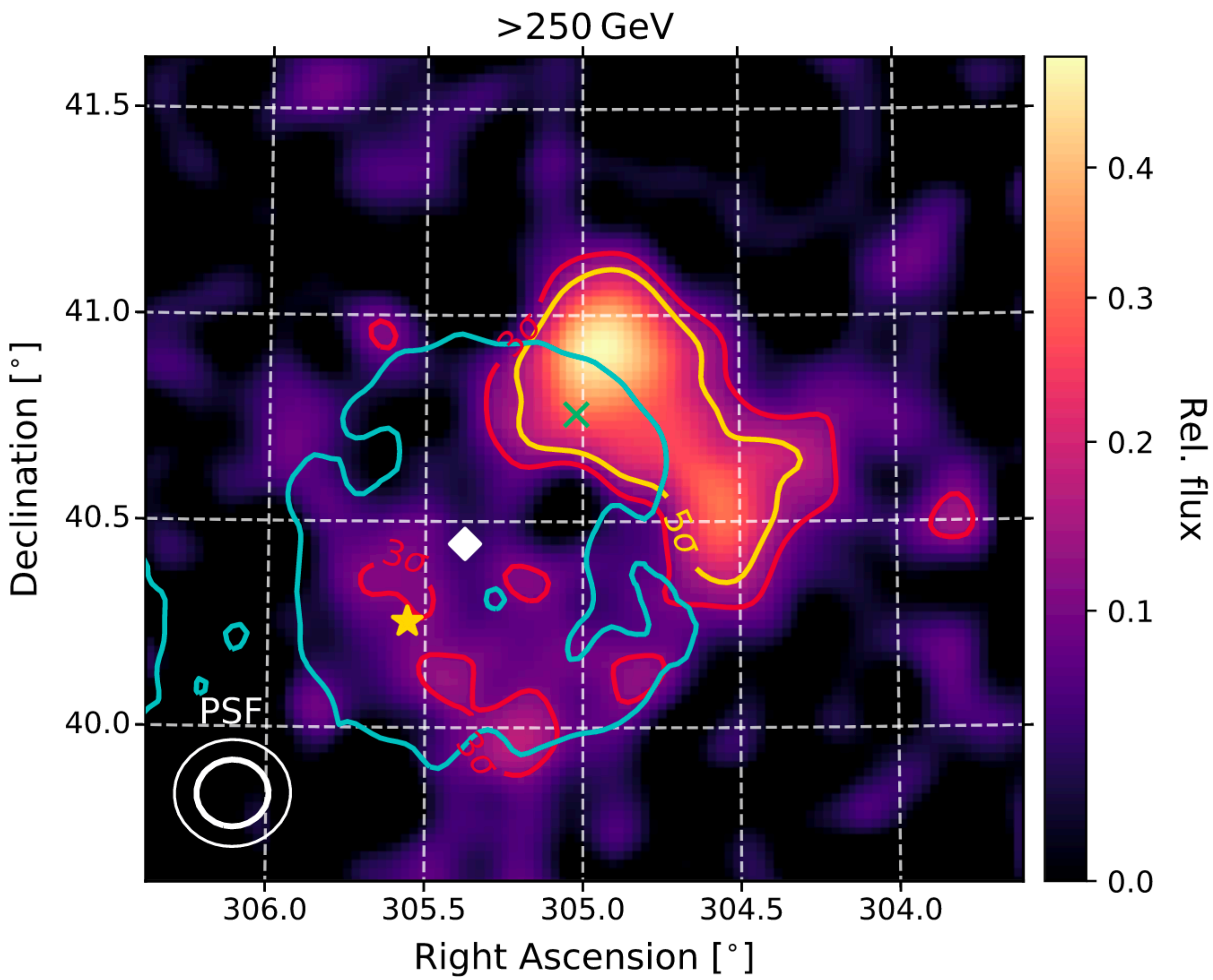
$$f_0(p) \propto p^{-4}$$

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

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

$\xi_{\rm CR} \simeq 15\%$

The Gamma Cygni SNR

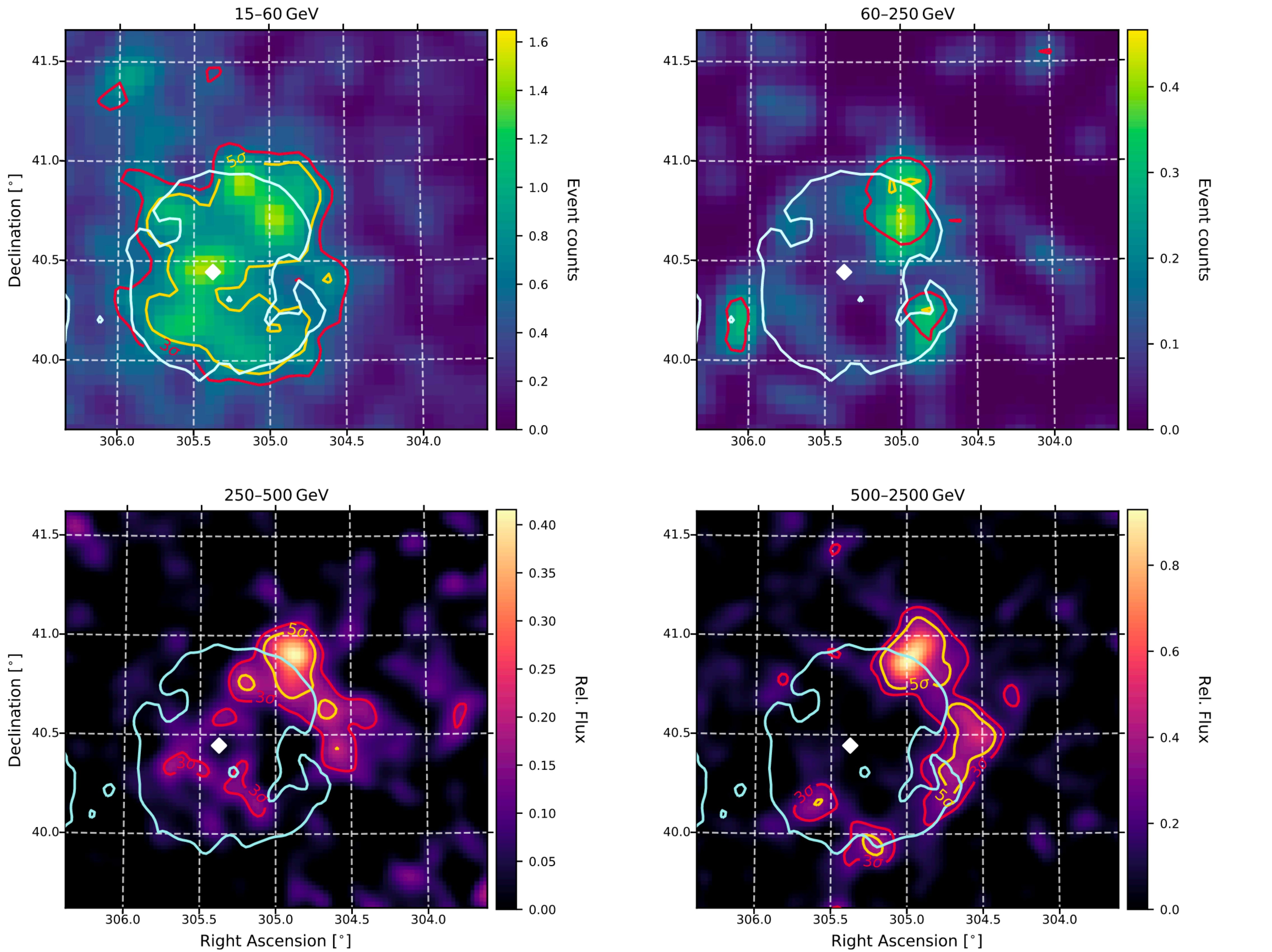


Characteristic	value used in this work	value range
Radius [°]	0.53	0.51 – 0.56
Distance [kpc]	1.7	1.5 – 2.6
Age [kyr]	7	4 – 13
shock speed [km/s]	1000	600 – 1500
gas density at γ-Cygni [1/cm^3]	0.2	0.14 – 0.32
explosion energy [10^{51} erg]	1	0.8 – 1.1

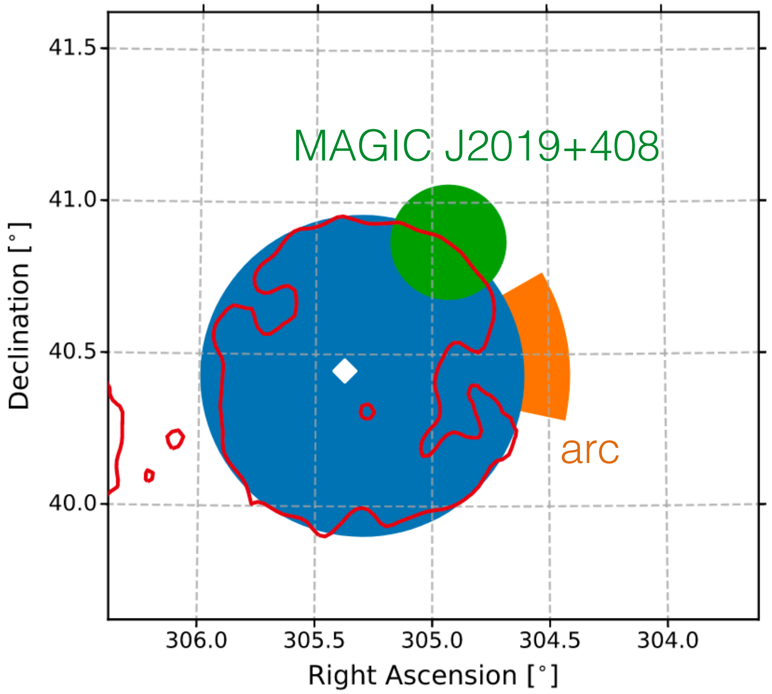
- MAGIC observes a patchy and extended emission in the NW of the radio shell: a joint analysis with Fermi resolves this emission into a point source, MAGIC J2019+408, and an arc-like structure;

- Energy dependent morphology hints for relevance of escape.

The Gamma Cygni SNR



The Gamma Cygni SNR

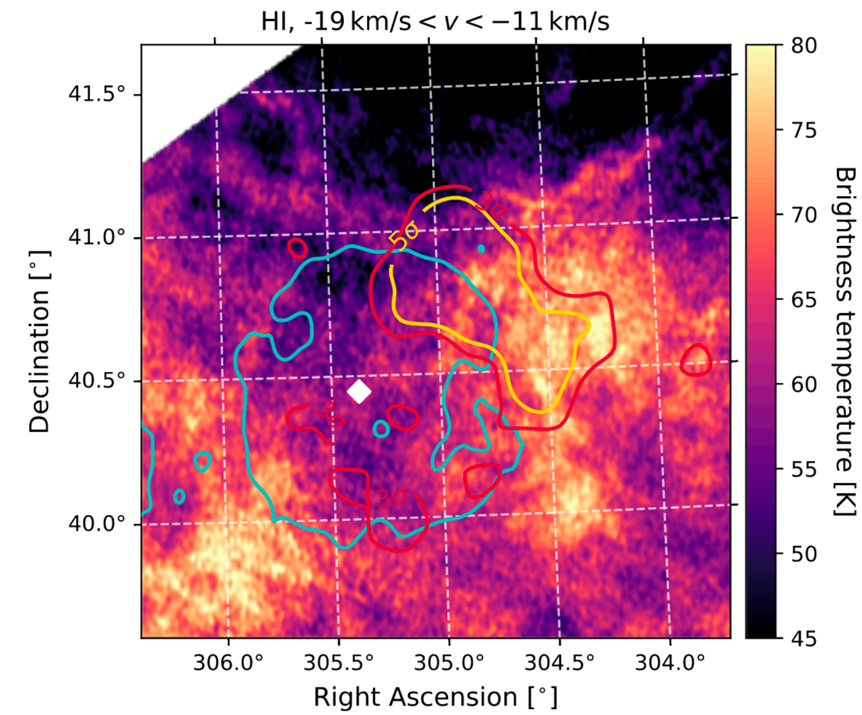


Spatial templates:

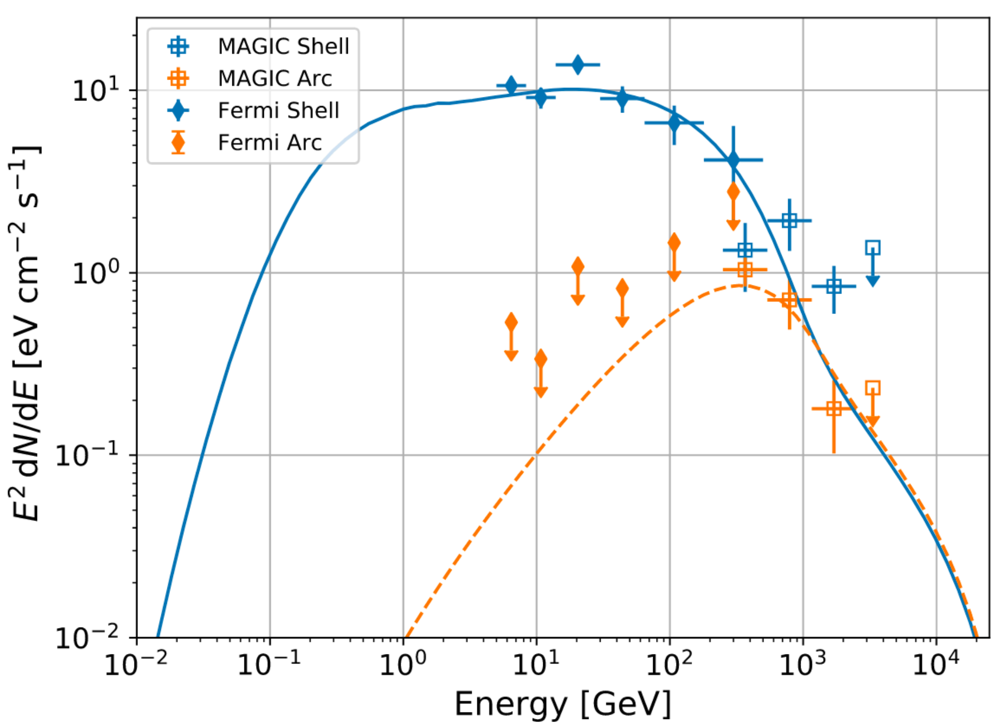
Source name	Spatial model	Centred at RA [deg]	Centred at Dec [deg]	Extension [deg]
SNR shell	disk	305.30	40.43	0.53 (radius)
MAGIC J2019+408	Gaussian	304.93	40.87	0.13 (σ)
Arc	annular sector	305.30	40.43	0.15 ($r_{out} - r_{shell}$)
Arc (alternative)	Gaussian	304.51	40.51	0.12 (σ)

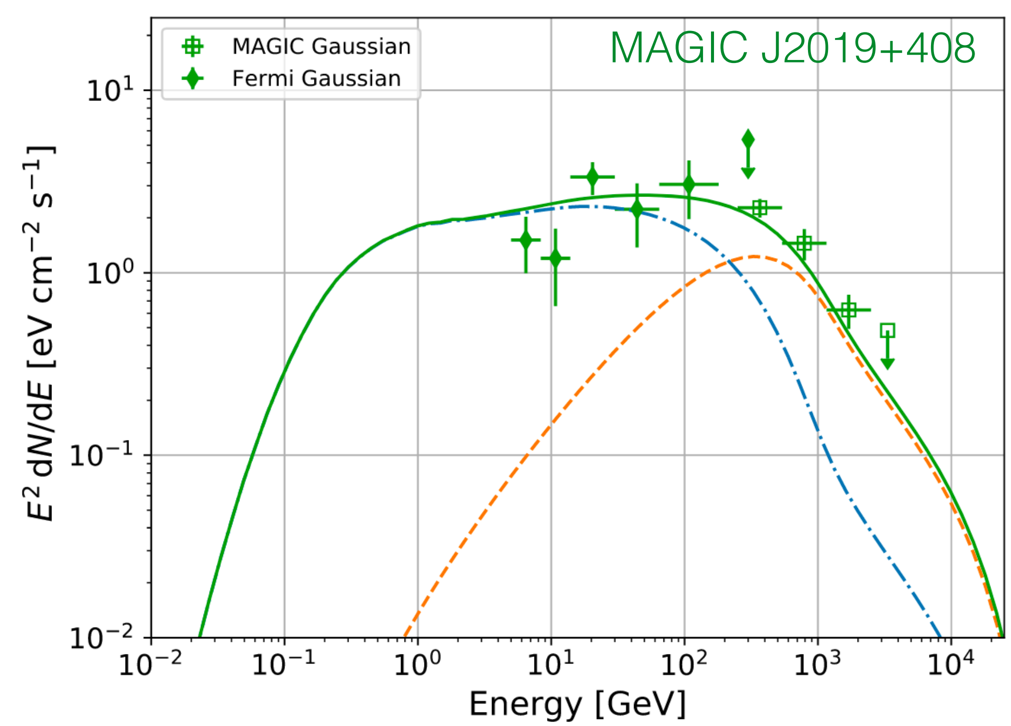
Spectral models:

Source name	N_0 [TeV^{-1} cm^{-2} s^{-1}]	Γ	E_0 [TeV]	Det. Sign. [σ]
MAGIC				
SNR Shell	$\left(10 \pm 2_{stat}{}^{+6.7}_{-3.5 sys}\right) \times 10^{-13}$	$-2.55 \pm 0.16_{stat}{}^{+0.30}_{-0.25 sys}$	1.0	6.1
MAGIC J2019+408	$\left(10.0 \pm 0.9_{stat}{}^{+6.0}_{-3.5 sys}\right) \times 10^{-13}$	$-2.81 \pm 0.10_{stat}{}^{+0.21}_{-0.19 sys}$	1.0	16.7
Arc (annular sector)	$\left(3.9 \pm 0.7_{stat}{}^{+2.6}_{-1.5 sys}\right) \times 10^{-13}$	$-3.02 \pm 0.18_{stat}{}^{+0.22}_{-0.20 sys}$	1.0	10.1
Arc (Gaussian model)	$\left(5.2 \pm 0.8_{stat}{}^{+3.6}_{-2.2 sys}\right) \times 10^{-13}$	$-2.99 \pm 0.16_{stat}{}^{+0.22}_{-0.22 sys}$	1.0	10.3
Fermi-LAT				
SNR Shell	$\left(37 \pm 2_{stat}{}^{+4.6}_{-4.0 sys}\right) \times 10^{-10}$	$-2.11 \pm 0.06_{stat} \pm 0.01_{sys}$	0.05	23.2
MAGIC J2019+408	$\left(9.8 \pm 1.8_{stat}{}^{+1.1}_{-1.0 sys}\right) \times 10^{-10}$	$-1.86 \pm 0.13_{stat} \pm 0.01_{sys}$	0.05	8.9



E_{SN}	M_{ej}	t_{SNR}	d	n_0	ξ_{CR}	α	E_{MAX}	δ	$\eta_{arc} n_{arc}$	D_{Gal}/D_{out}
10^{51} erg	5 $M_\odot$	7 kyr	1.7 kpc	0.2 cm^{-3}	3.8%	4.0	78 TeV	2.55	0.31 cm^{-3}	16
		[see Table 1]			[3% – 7%]	[3.9 – 4.2]	[20 – 250]	[2.2 – 3.8]	[0.25 – 0.45]	[10 – 35]

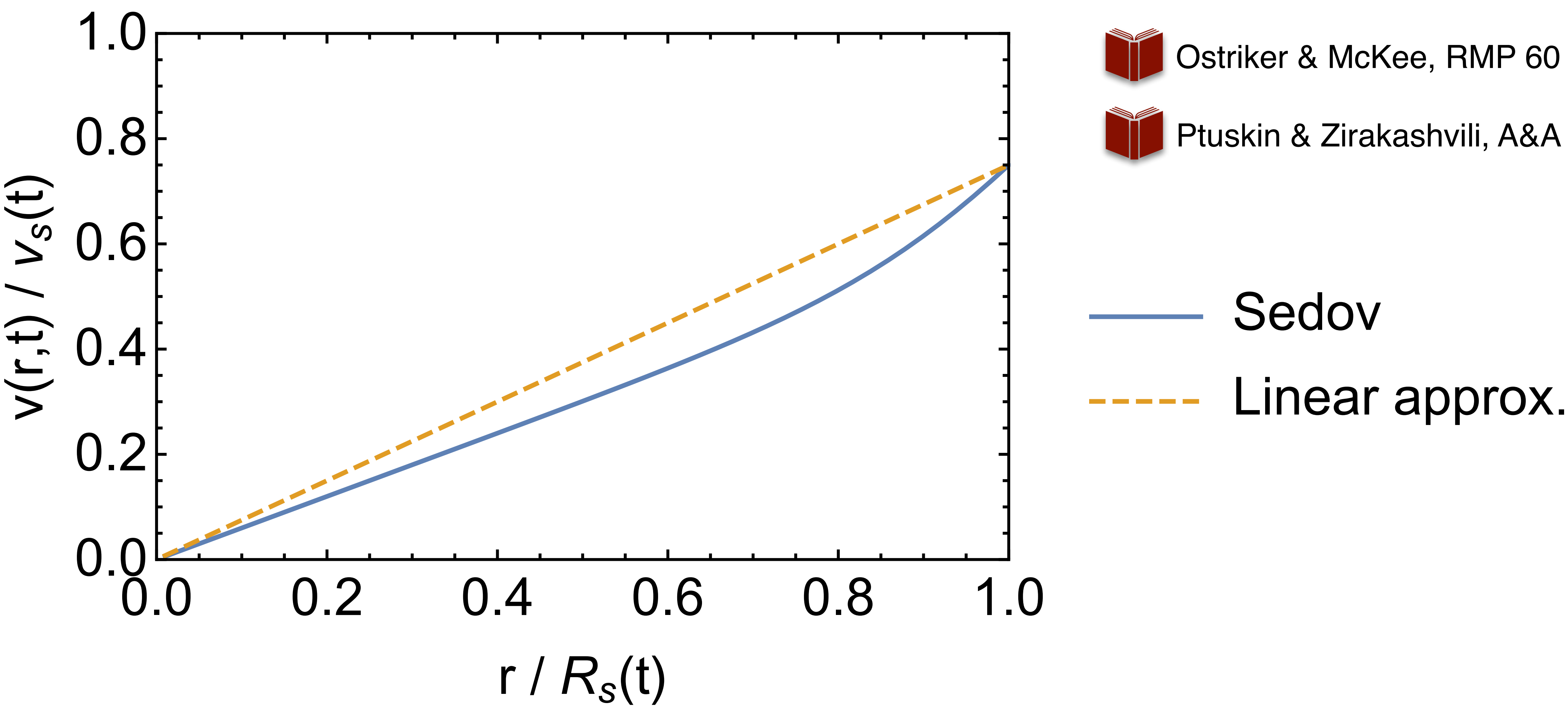




The velocity profile in the downstream

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

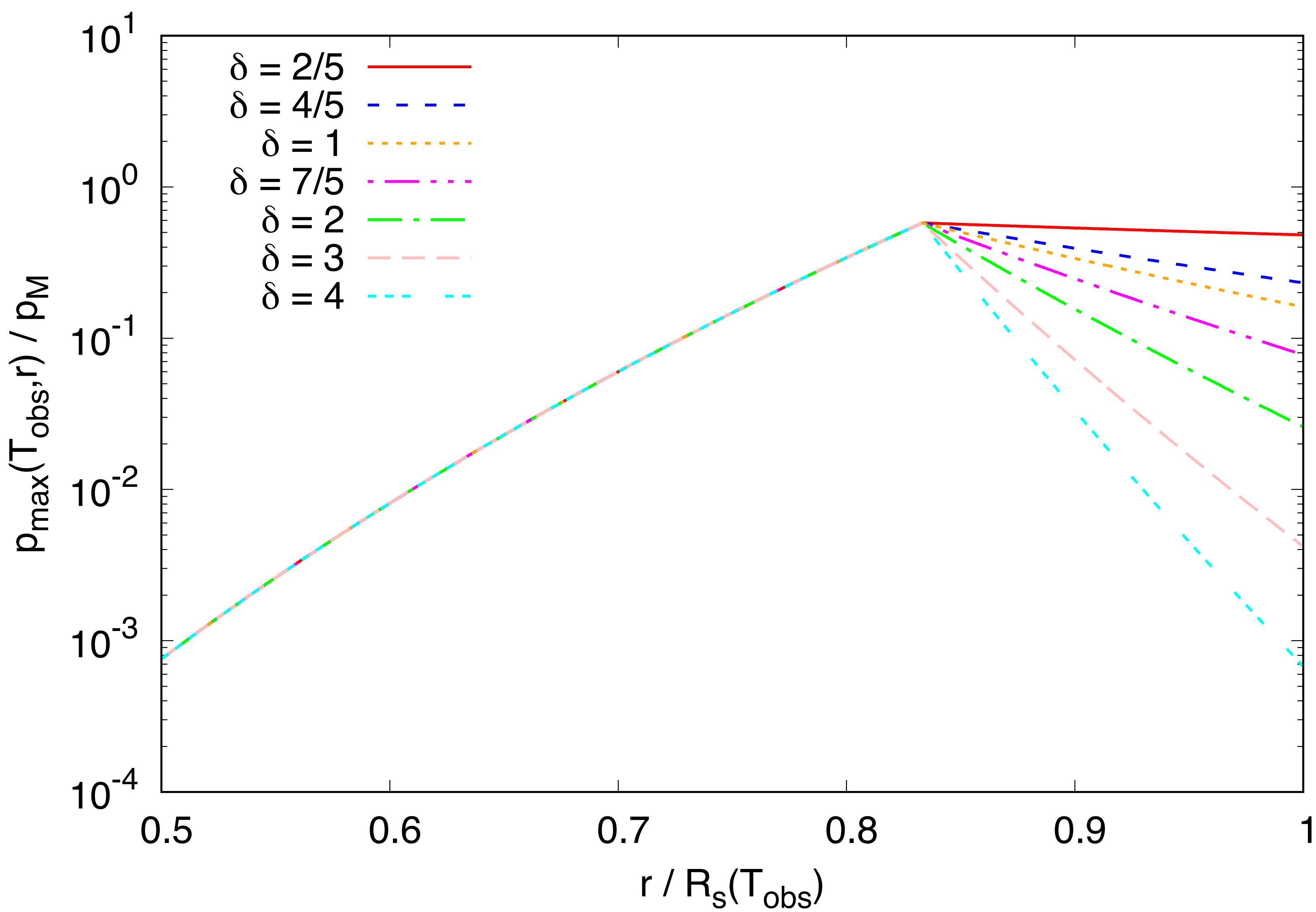
The confined density function

⟶ **Method of characteristics**

Spectrum of particles contained within the shock:

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

adiabatic losses



Self-generated turbulence

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

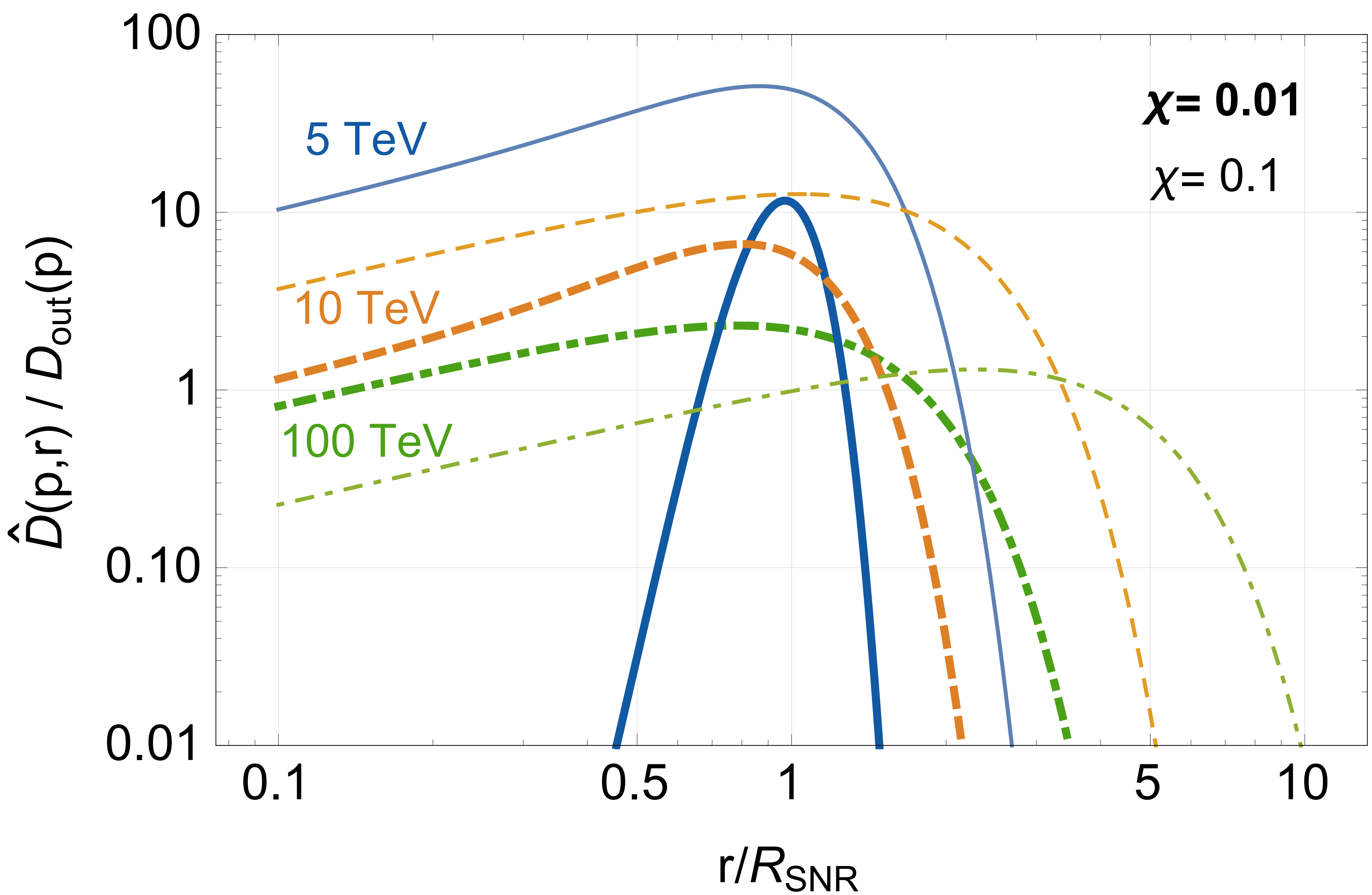
growth rate by resonant streaming instability

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



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

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

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

CR self-confinement around middle-aged SNRs and TeV halos

$$\alpha = 4$$

	$D_{\mathrm{self}}/D(r = 0.5R_{\mathrm{SNR}})$	$D_{\mathrm{self}}/D(r = 1.5R_{\mathrm{SNR}})$
$p = 10$ TeV/c	9.2×10^{-1}	1.1×10^{0}
$p = 50$ TeV/c	3.6×10^{-1}	4.0×10^{-1}
$p = 100$ TeV/c	2.9×10^{-1}	3.0×10^{-1}

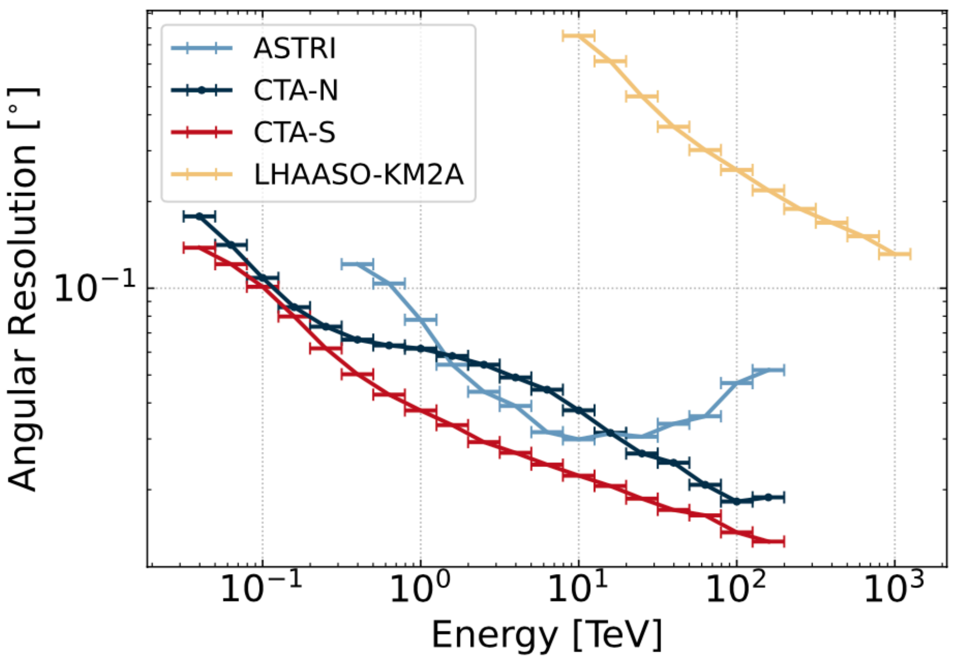
$$\alpha = 4 + 1/3$$

	$D_{\mathrm{self}}/D(r = 0.5R_{\mathrm{SNR}})$	$D_{\mathrm{self}}/D(r = 1.5R_{\mathrm{SNR}})$
$p = 10$ TeV/c	1.7×10^{-1}	2.0×10^{-1}
$p = 50$ TeV/c	1.7×10^{-2}	1.9×10^{-2}
$p = 100$ TeV/c	1.2×10^{-2}	1.3×10^{-2}

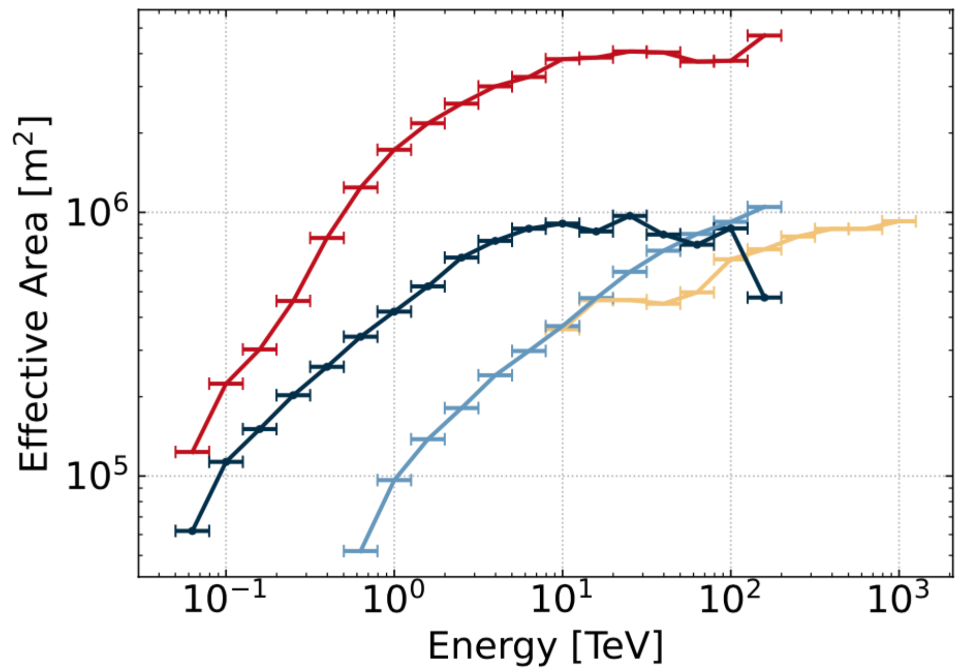
*No ion-neutral friction here included

Sensitivity to extended sources: synergies in neutrino and gamma-ray astronomy

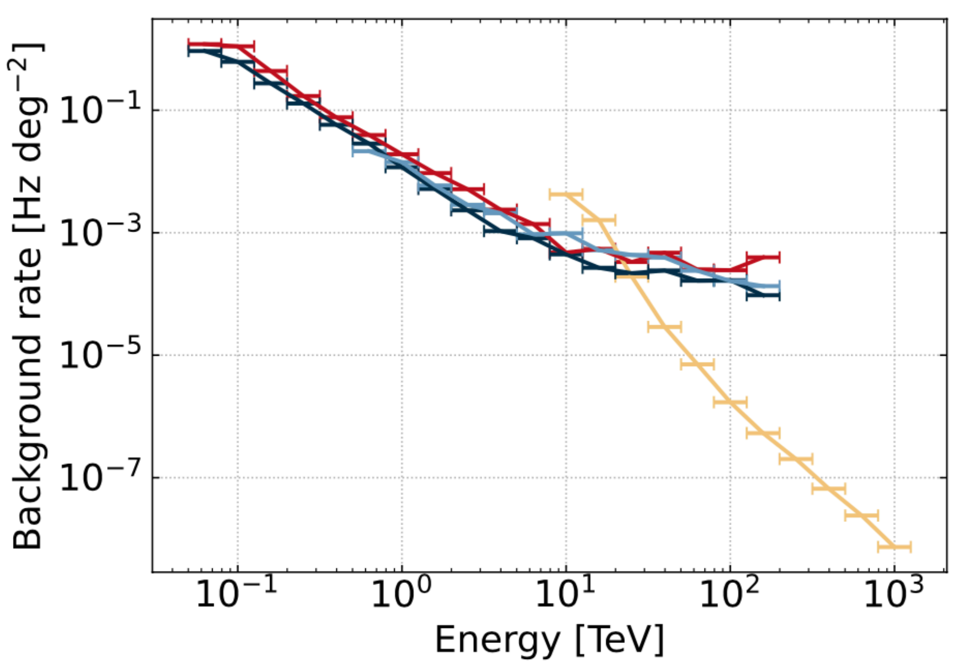
Next generation gamma-ray instrument performances

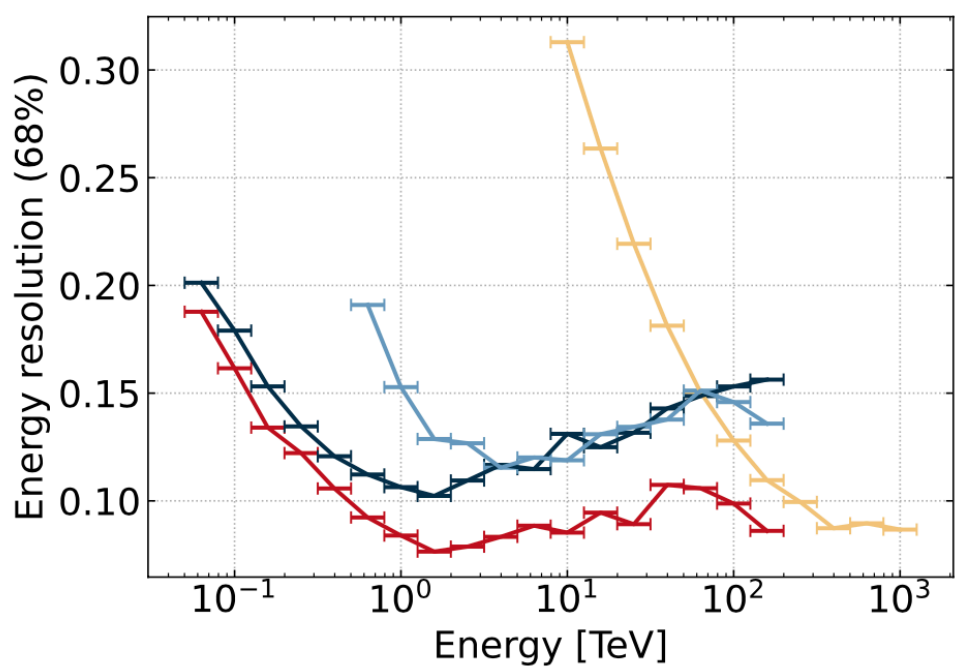


(a)



(b)





CTA Alpha Array

- **North:**

4 LSTs (23m, FoV=4.5°),
9 MSTs (12m, FoV=7°),

- **South**

14 MSTs (12m, FoV=7°),
37 SSTs (4m, FoV=9.5°)

ASTRI

9 SSTs (4.3 m, FoV=10°)

LHAASO KM2A

5195 EDs, 1188 MDs

Celli & Peron (2024), A&A

Sensitivity studies

In each energy bin, these conditions have to be satisfied:

- Minimum **number of signal events**, $N_s^{\min}$;
- Minimum **significance** in bkg rejection, $\sigma_{\min} = N_s/\sqrt{N_b}$;
- Minimum **signal excess** over background uncertainty level (data driven for CTA);

$$N_s^{\min} \geq 10$$
$$\sigma_{\min} \geq 5$$
$$N_s/N_b \geq 0.05$$

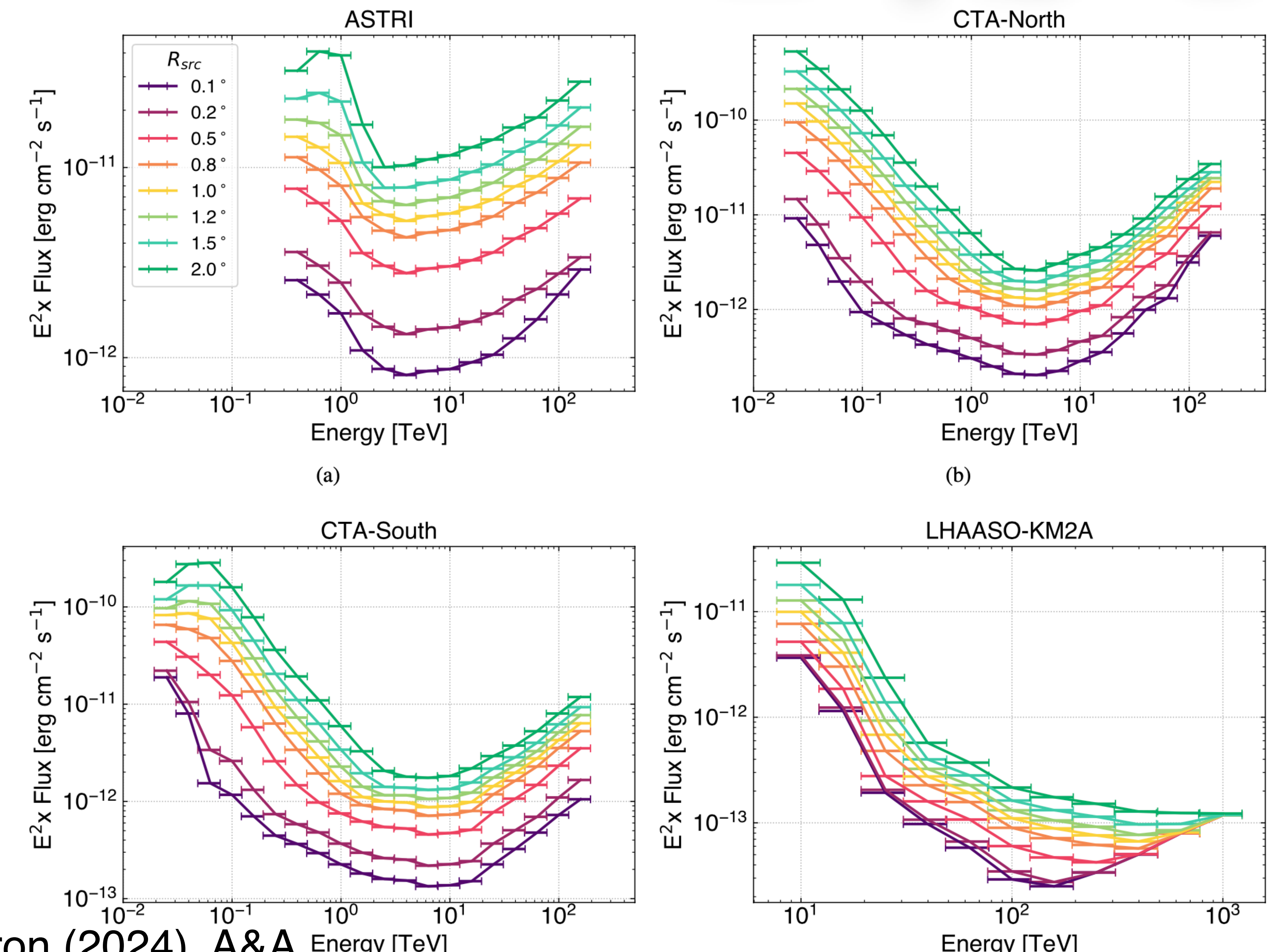
The energy bin is driven by the instrument energy resolution:

$$\sigma\,(\ln E) = 0.2$$

Extended sources

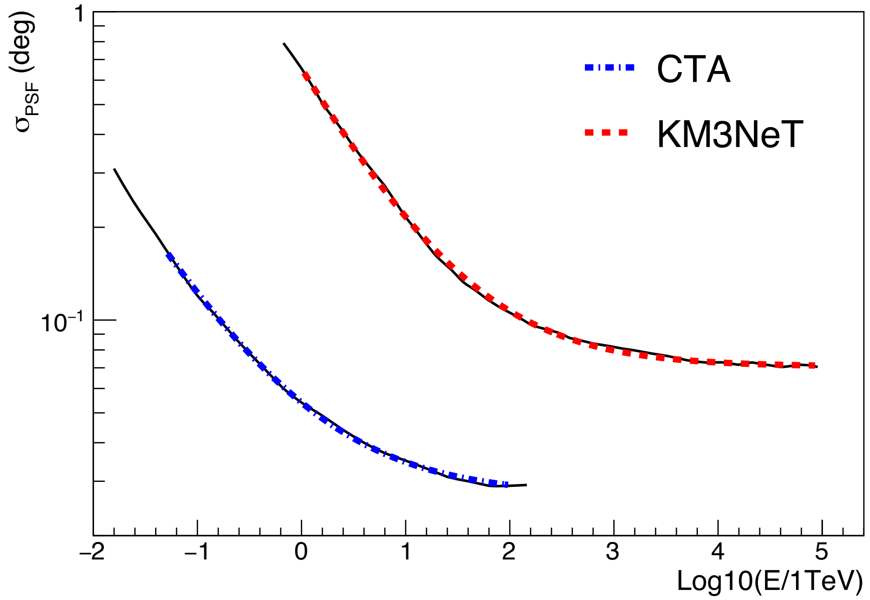
The bkg is very sensitive to the source extension, as

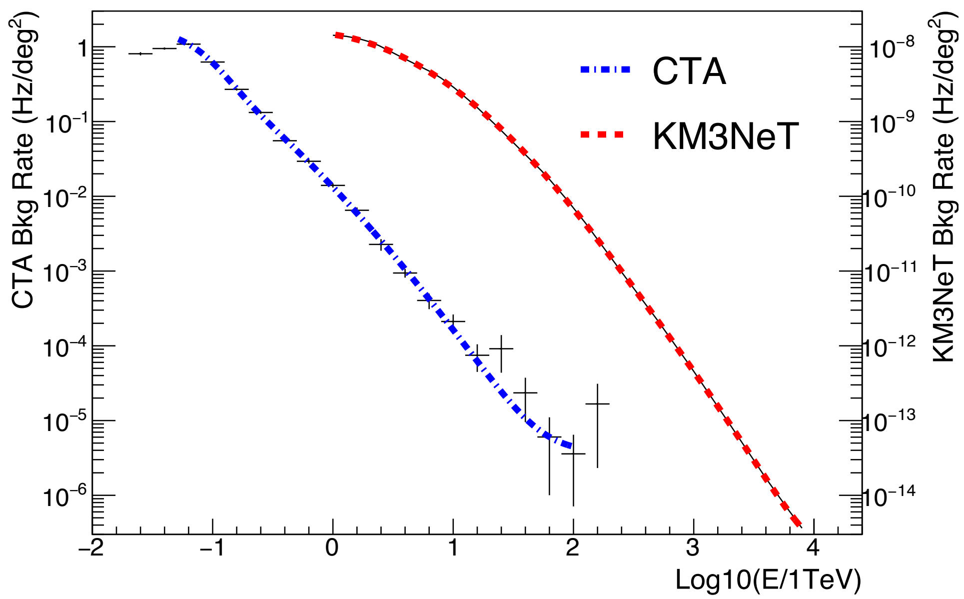
$$N_b \propto R^2_{\mathrm{ROI}} \qquad R_{\mathrm{ROI}} = \sqrt{\sigma^2_{\mathrm{PSF}} + R^2_{\mathrm{src}}}$$

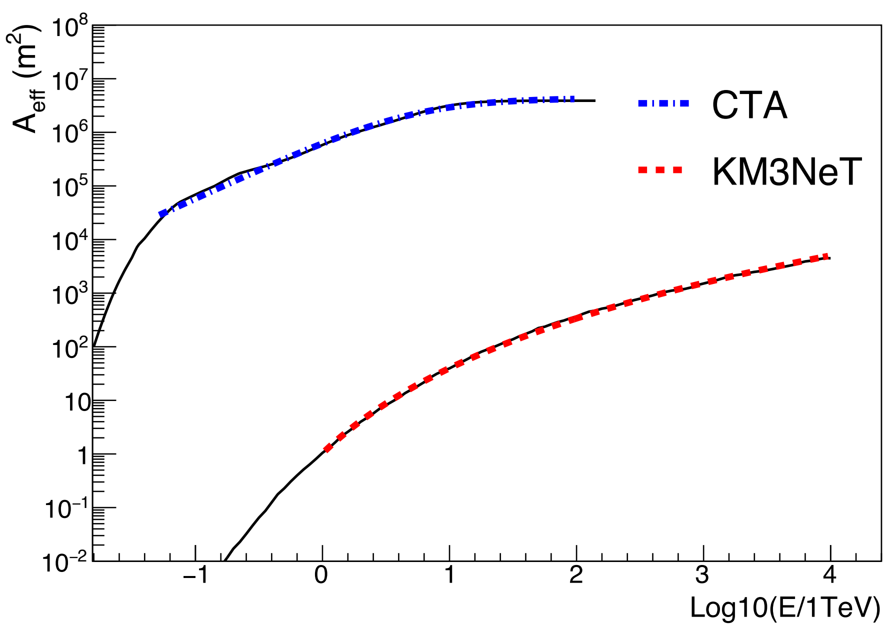


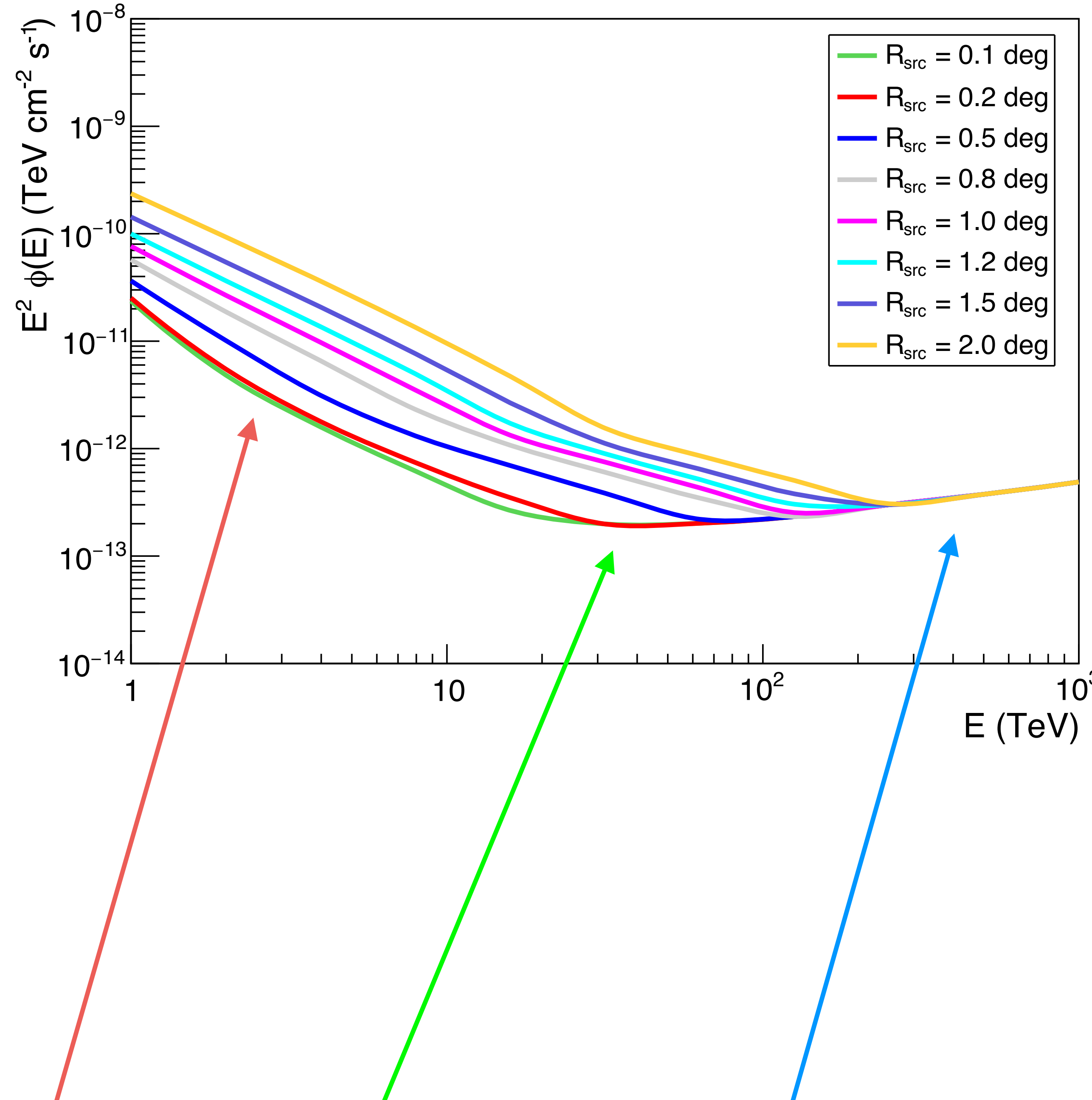
Celli & Peron (2024), A&A

KM3NeT





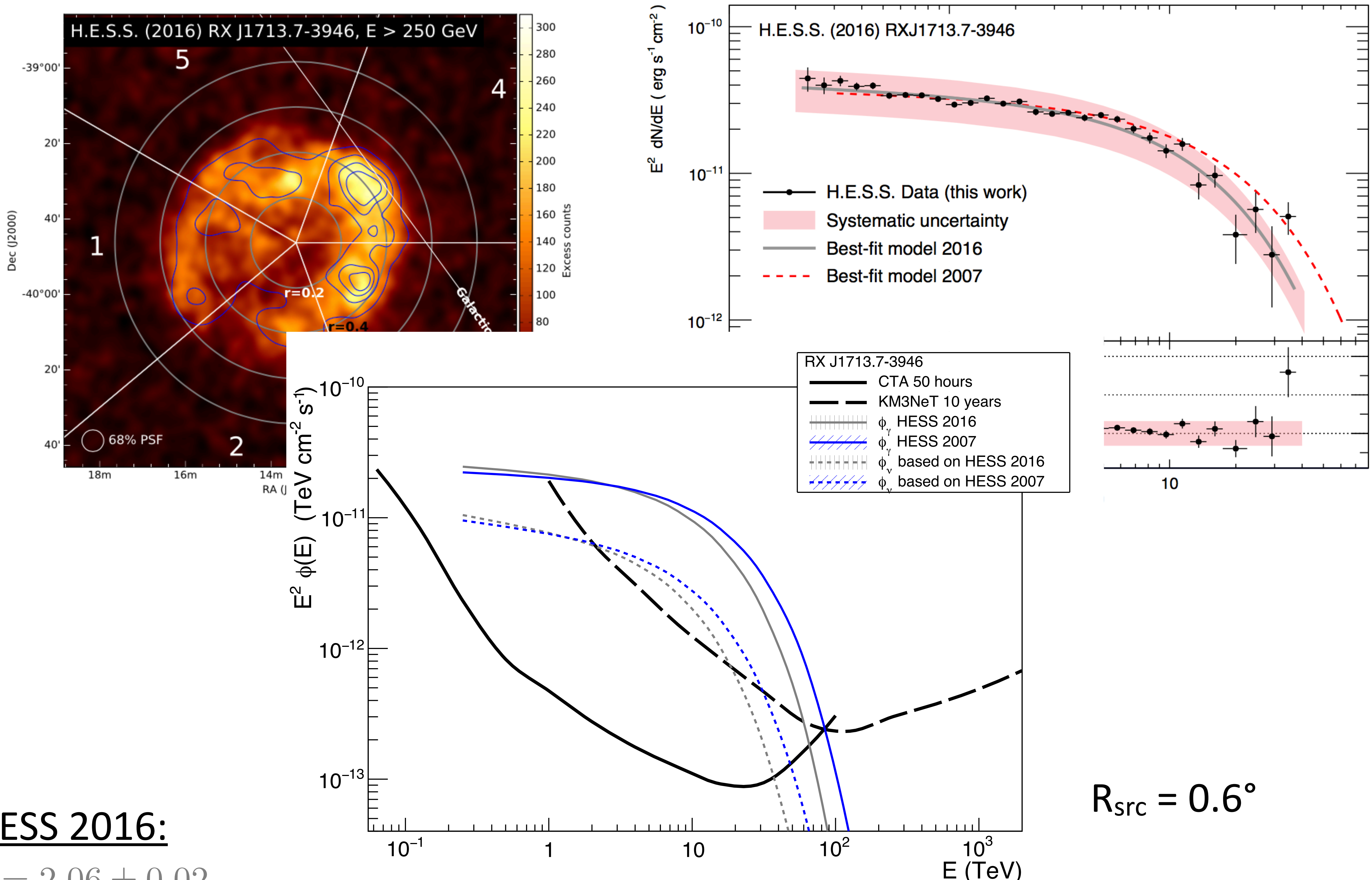




systematics **significance** **statistics**

Ambrogi, Celli & Aharonian, APh 100 (2018) 69

Galactic sources: RX J1713.7-3946



$R_{src} = 0.6°$

HESS 2016:

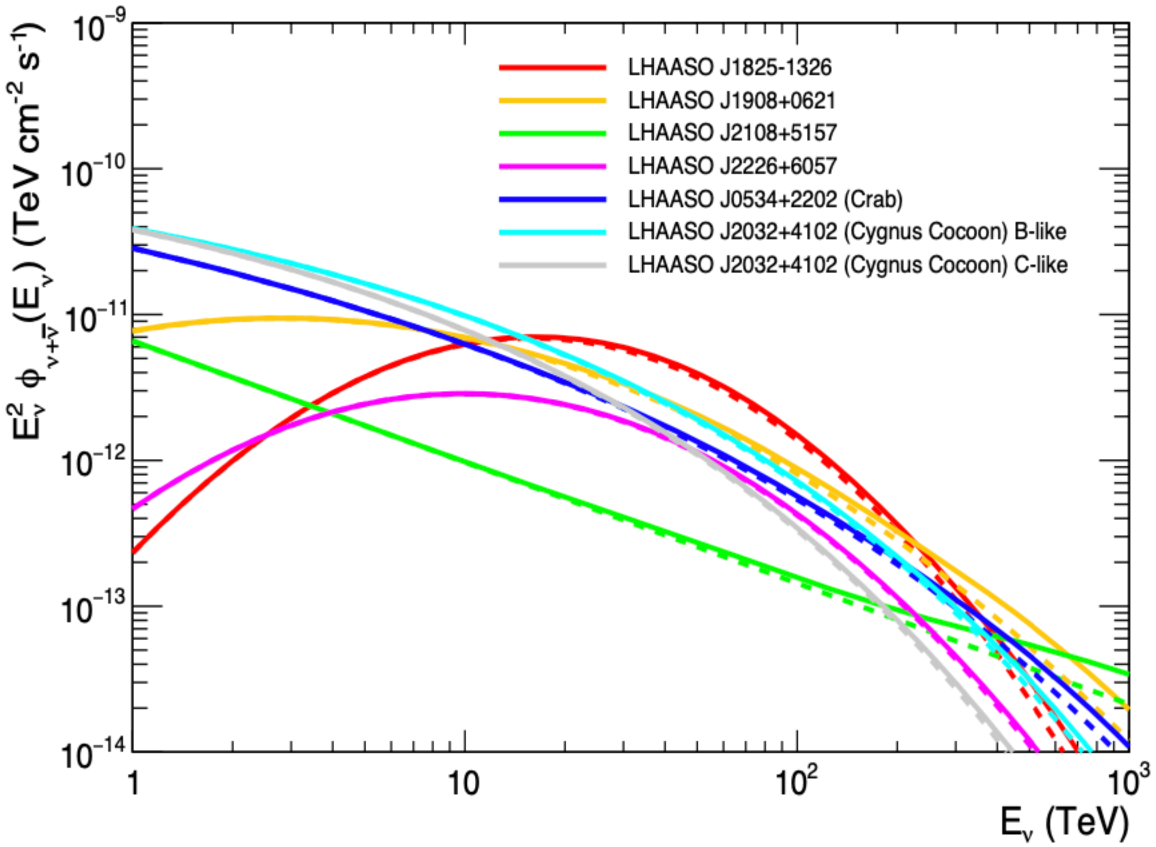
$\Gamma = 2.06 \pm 0.02$

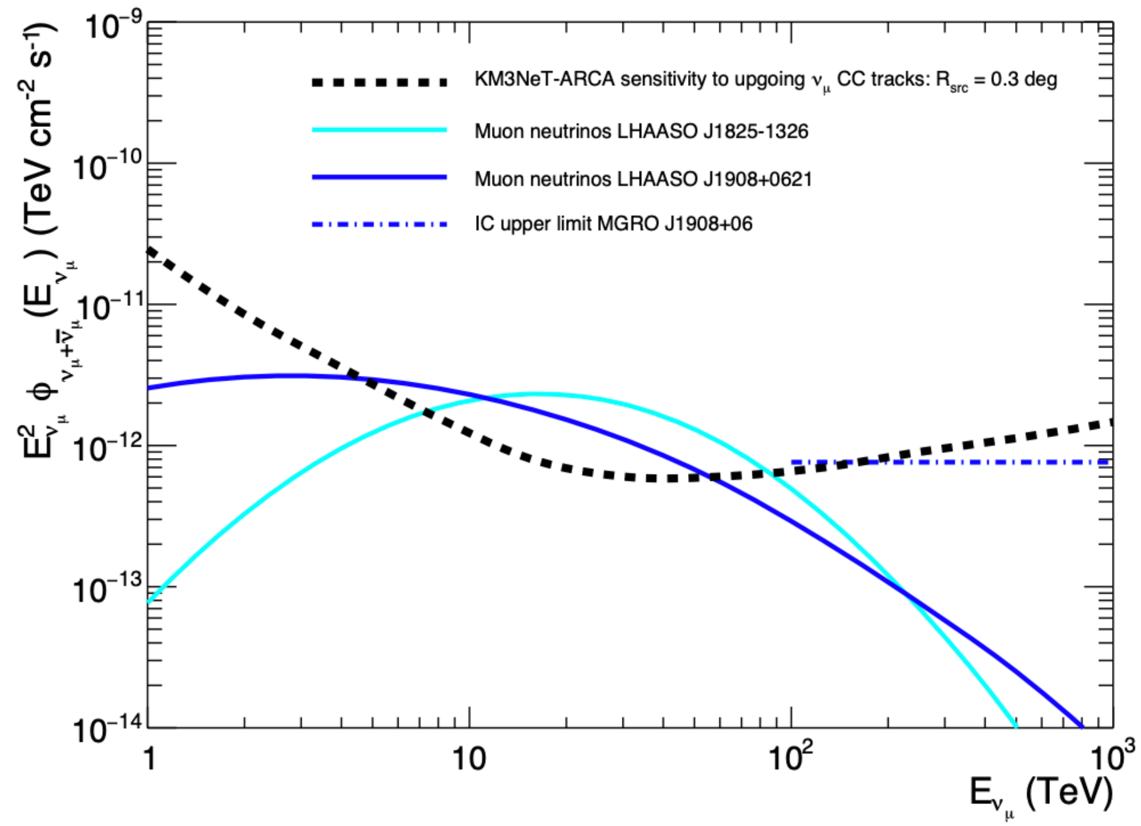
$\phi_0 = (2.3 \pm 0.1) \times 10^{-11}\ \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Ambrogi, Celli & Aharonian, APh 100 (2018) 69

Neutrinos from LHAASO PeVatrons

Unique probes of hadronic acceleration



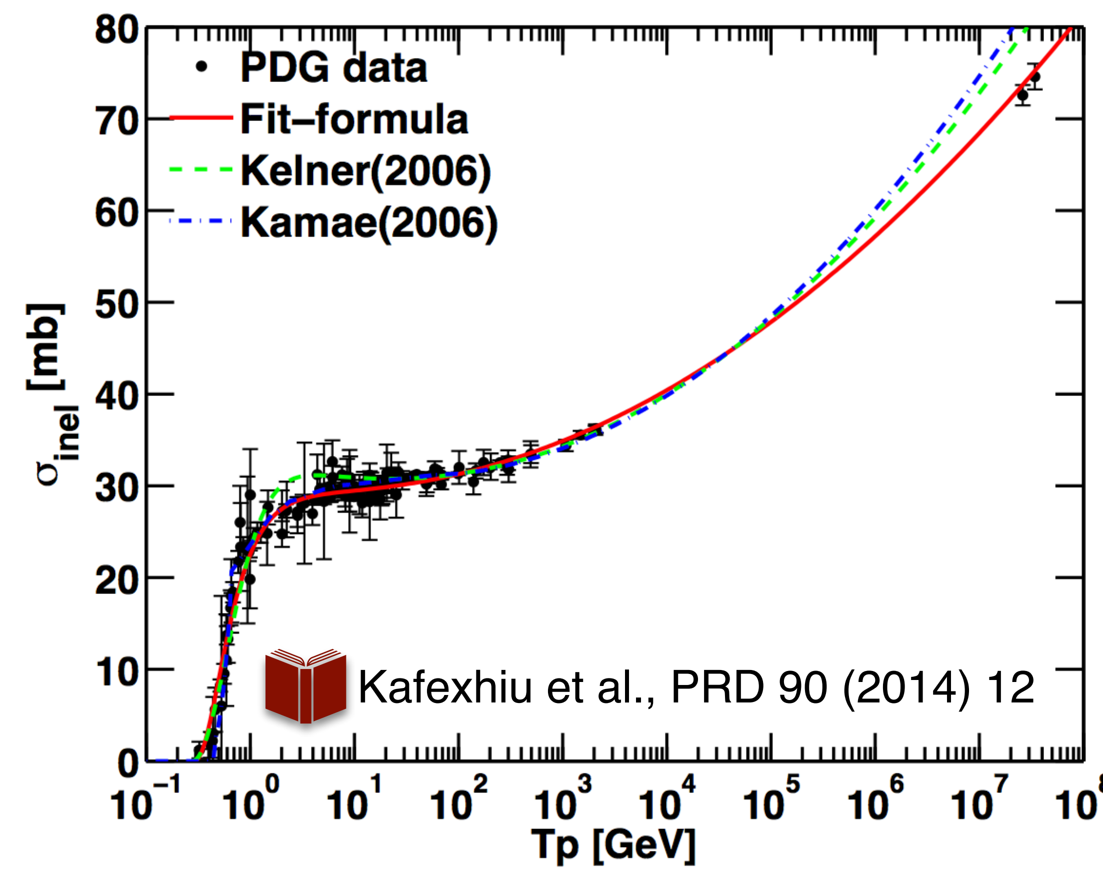


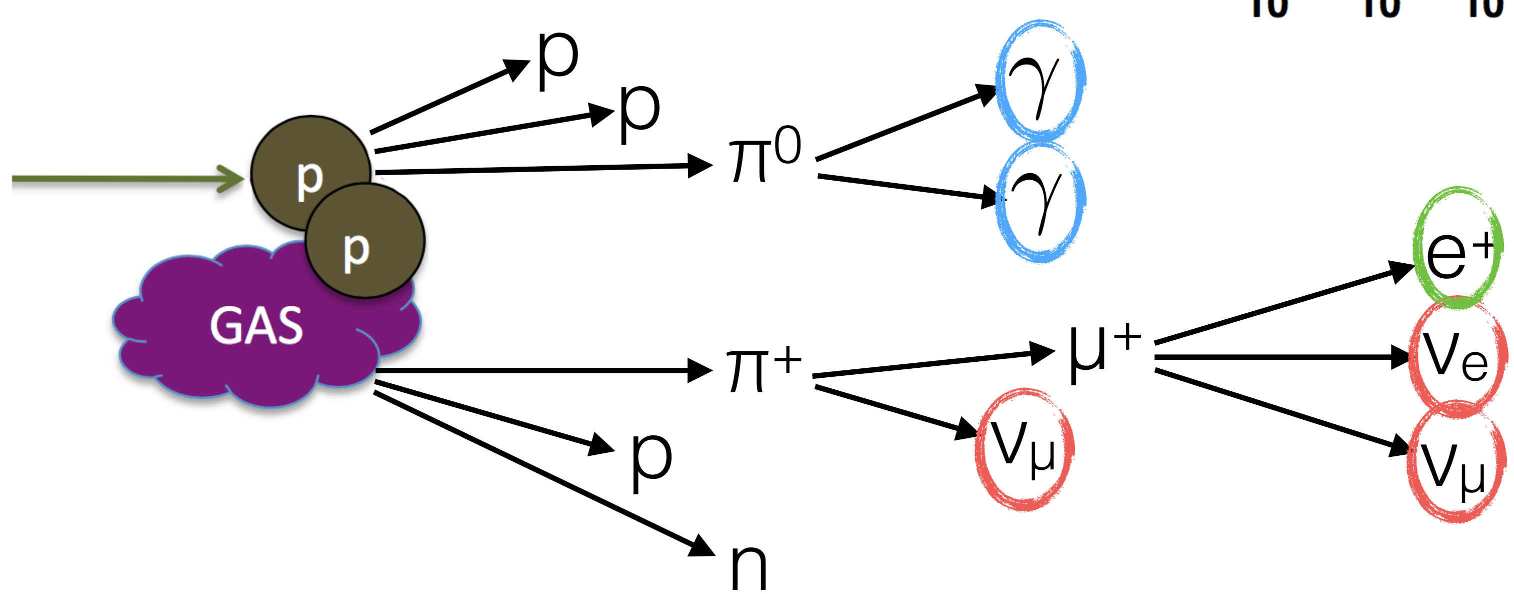
Celli & Aharonian [in prep.]

Proton-proton collisions

$$p + p \longrightarrow N\pi + X$$

accelerated proton — target gas





$$E_\gamma \simeq E_\mathrm{p}/10$$

$$E_\nu \simeq E_\mathrm{e} \simeq E_\mathrm{p}/20$$

1 PeV proton ⟶ ~100 TeV gamma rays, ~50 TeV neutrinos/electrons

…but cut-off region deserved detailed modeling

Celli, Aharonian & Gabici, ApJ 903 (2020) 61C

From protons to secondaries

Secondaries produced from spectrum of accelerated protons **$J_p(E_p)$** **uniformly propagating** within a target of **density n**:

$$\epsilon_{\rm i}(E_{\rm i}) = cn\int_{E_i}^{\infty} \sigma_{\rm inel}(E_{\rm p})J_{\rm p}(E_{\rm p})F_{\rm i}\left(\frac{E_{\rm i}}{E_{\rm p}}, E_{\rm p}\right)\frac{dE_{\rm p}}{E_{\rm p}}$$

Kelner, Aharonian & Bugayov, PRD 74 (2006) 3

- Hp 1: Proton spectrum is

$$J_{\rm p}(E_{\rm p}) = K_{\rm p}E_{\rm p}^{-\alpha_{\rm p}} \exp\left[-\left(\frac{E_{\rm p}}{E_{0,\rm p}}\right)^{\beta_{\rm p}}\right]$$

- Hp 2: Secondary electrons cooled in surrounding B field:

$$J_{\rm e}(E_{\rm e}) = \frac{\tau_{\rm sy}(E_{\rm e})}{E_{\rm e}}\int_{E_{\rm e}}^{\infty}\epsilon_{\rm e}(E)dE$$

Synchrotron radiation from secondary electrons

$$\tau_{\rm sy}(E_{\rm e}) = \frac{6\pi m_e^2 c^3}{\sigma_{\rm T} E_{\rm e} \beta_e^2 B_0^2} \simeq 1.3\times 10^4 \left(\frac{E_{\rm e}}{\rm GeV}\right)^{-1} \left(\frac{B_0}{1\ \rm mG}\right)^{-2}\ \rm yr$$

Warning: Cooling assumption is valid as long as $T_0 > \tau_{sy}(E_e)$

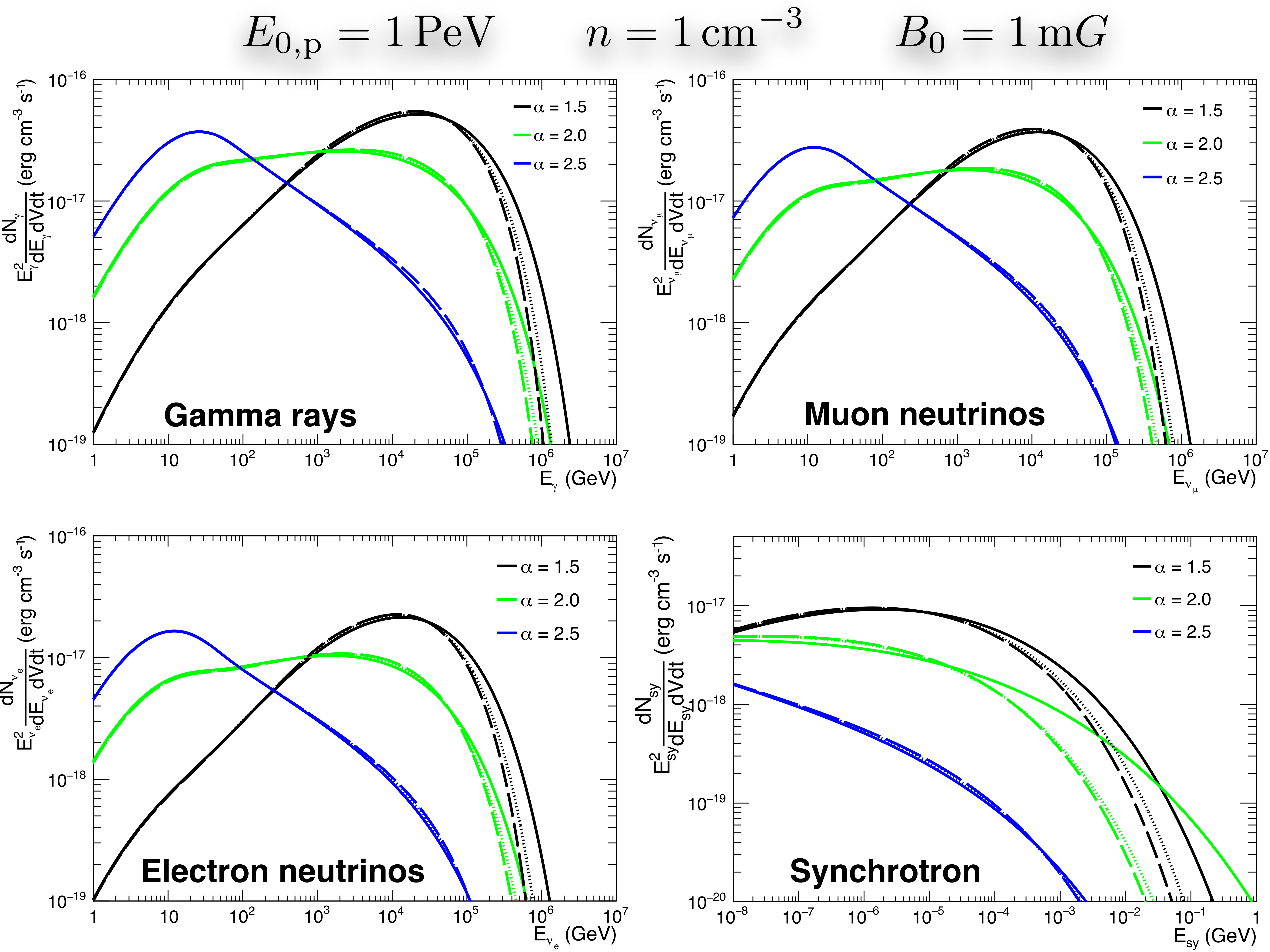
$$\epsilon_{\rm sy}(E) = \frac{\sqrt{3}}{2\pi}\frac{e^3 B_0}{m_{\rm e} c^2}\frac{1}{\hbar E}\int_0^\infty J_{\rm e}(E_{\rm e}) R\left(\frac{E}{E_{\rm c}(E_{\rm e})}\right) dE_{\rm e}$$

$$E_{\rm c} = 1.5\hbar e B_0 \frac{E_{\rm e}^2}{m_{\rm e}^3 c^5} \simeq 0.04 \left(\frac{B_0}{\rm mG}\right)\left(\frac{E_{\rm e}}{\rm TeV}\right)^2 \rm keV$$

$$R(x) = \frac{\alpha}{3\gamma_e^2}\left(1 + \frac{1}{x^{2/3}}\right) e^{-2x^{2/3}}$$

Derishev & Aharonian, ApJ 887 (2019) 181

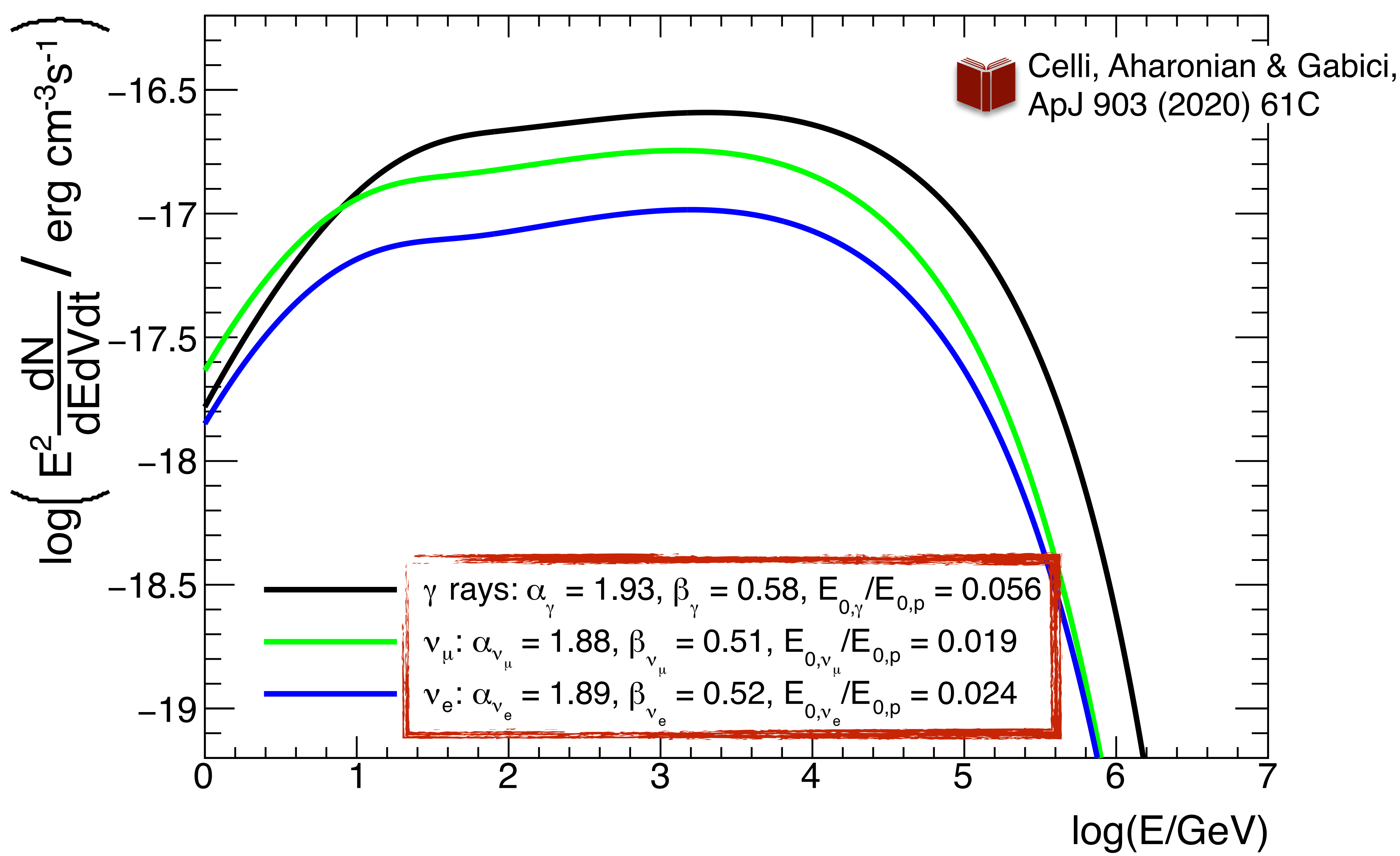
$$x = 9E/(8E_{\rm c})$$



$E_{0,\mathrm{p}} = 1\,\mathrm{PeV}$
$n = 1\,\mathrm{cm}^{-3}$
$B_0 = 1\,\mathrm{m}G$
Gamma rays
Muon neutrinos
Electron neutrinos
Synchrotron
α = 1.5
α = 2.0
α = 2.5
E_γ (GeV)
E_{ν_μ} (GeV)
E_{ν_e} (GeV)
E_{sy} (GeV)
$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma dV dt}$ (erg cm^{-3} s^{-1})
$E_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{dE_{\nu_\mu} dV dt}$ (erg cm^{-3} s^{-1})
$E_{\nu_e}^2 \frac{dN_{\nu_e}}{dE_{\nu_e} dV dt}$ (erg cm^{-3} s^{-1})
$E_{sy}^2 \frac{dN_{sy}}{dE_{sy} dV dt}$ (erg cm^{-3} s^{-1})

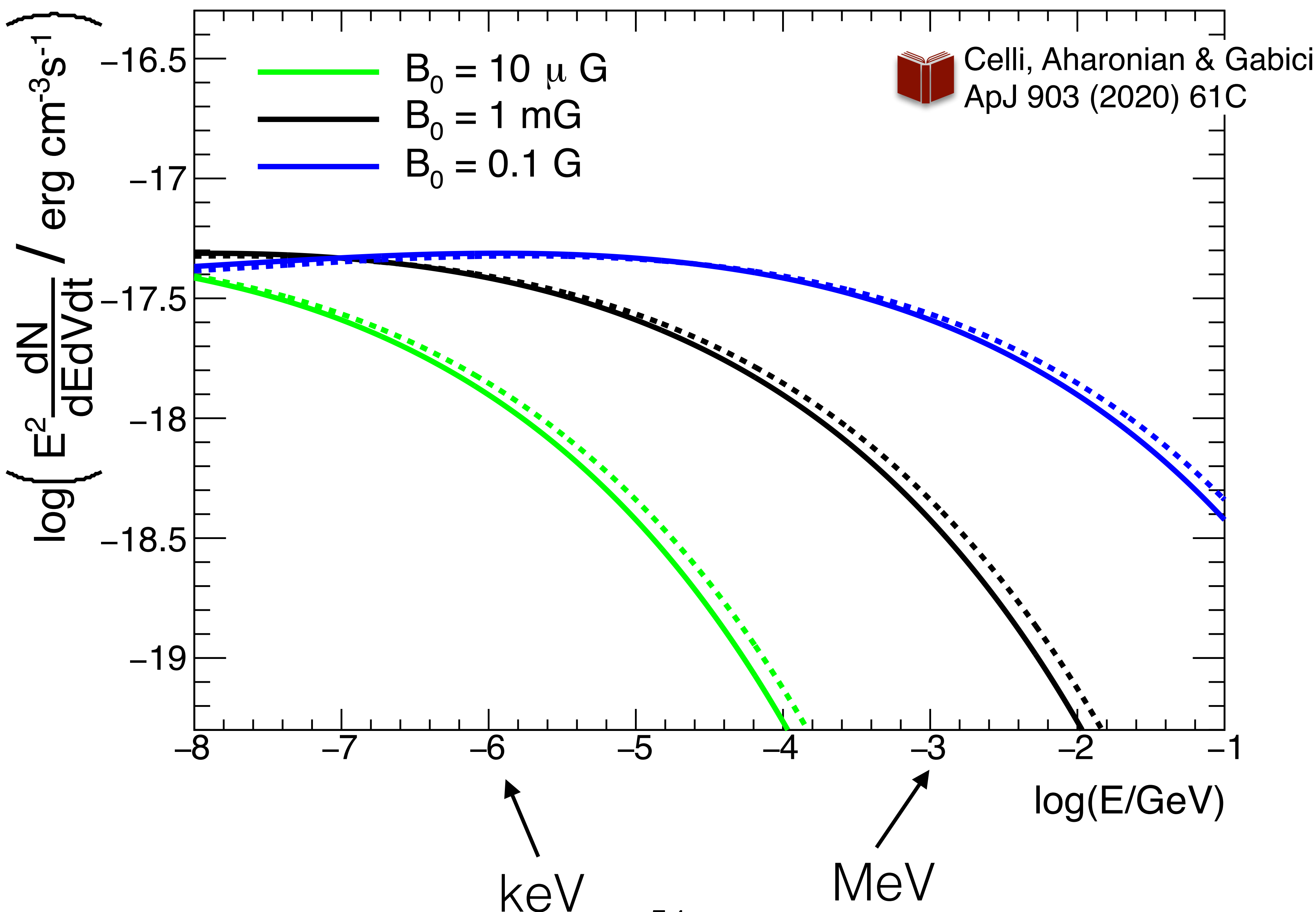
A closer look to gamma rays and neutrinos

$$\alpha_{\rm p} = 2,\ \beta_{\rm p} = 1,\ E_{0,\rm p} = 1\,\rm PeV$$

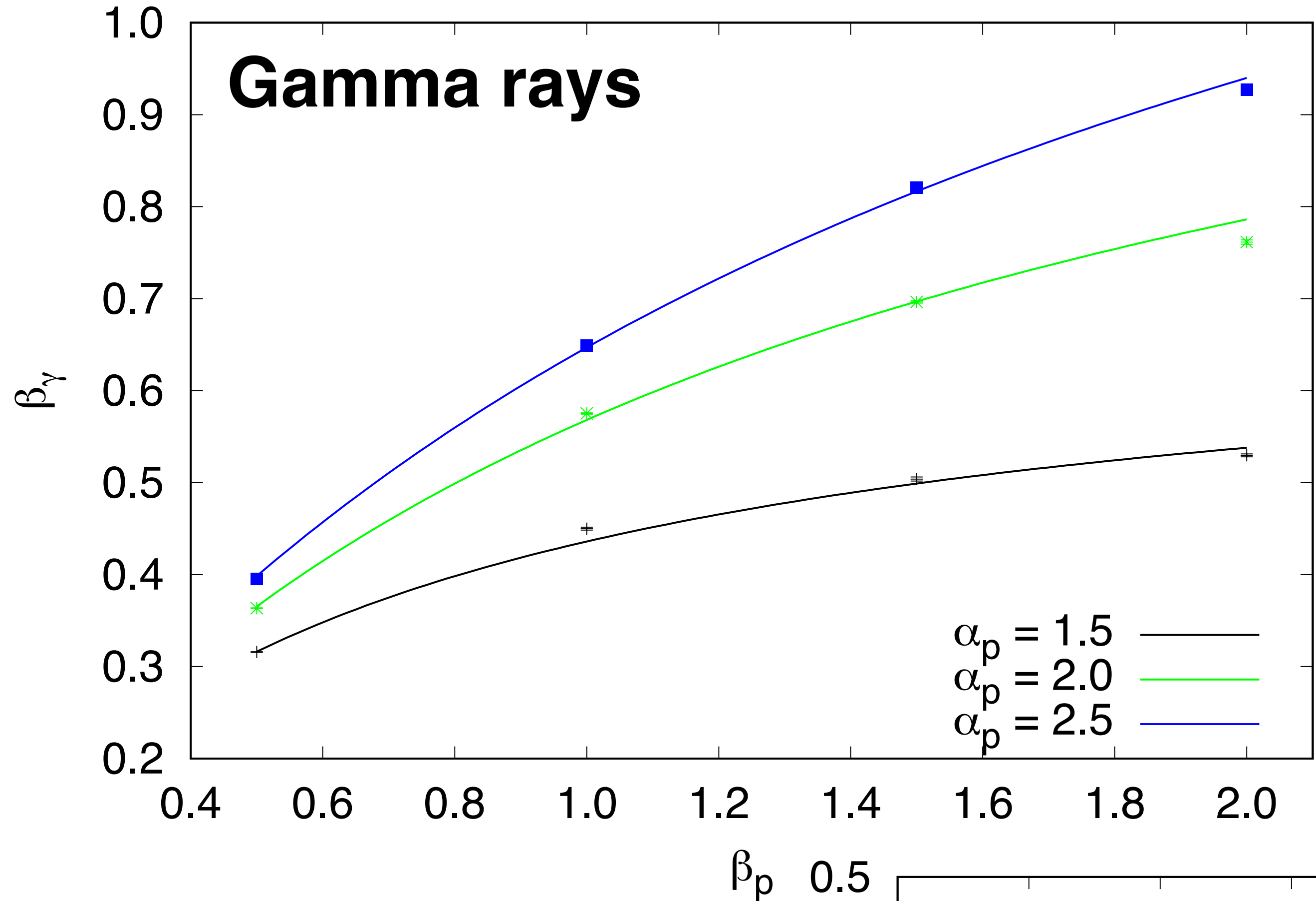


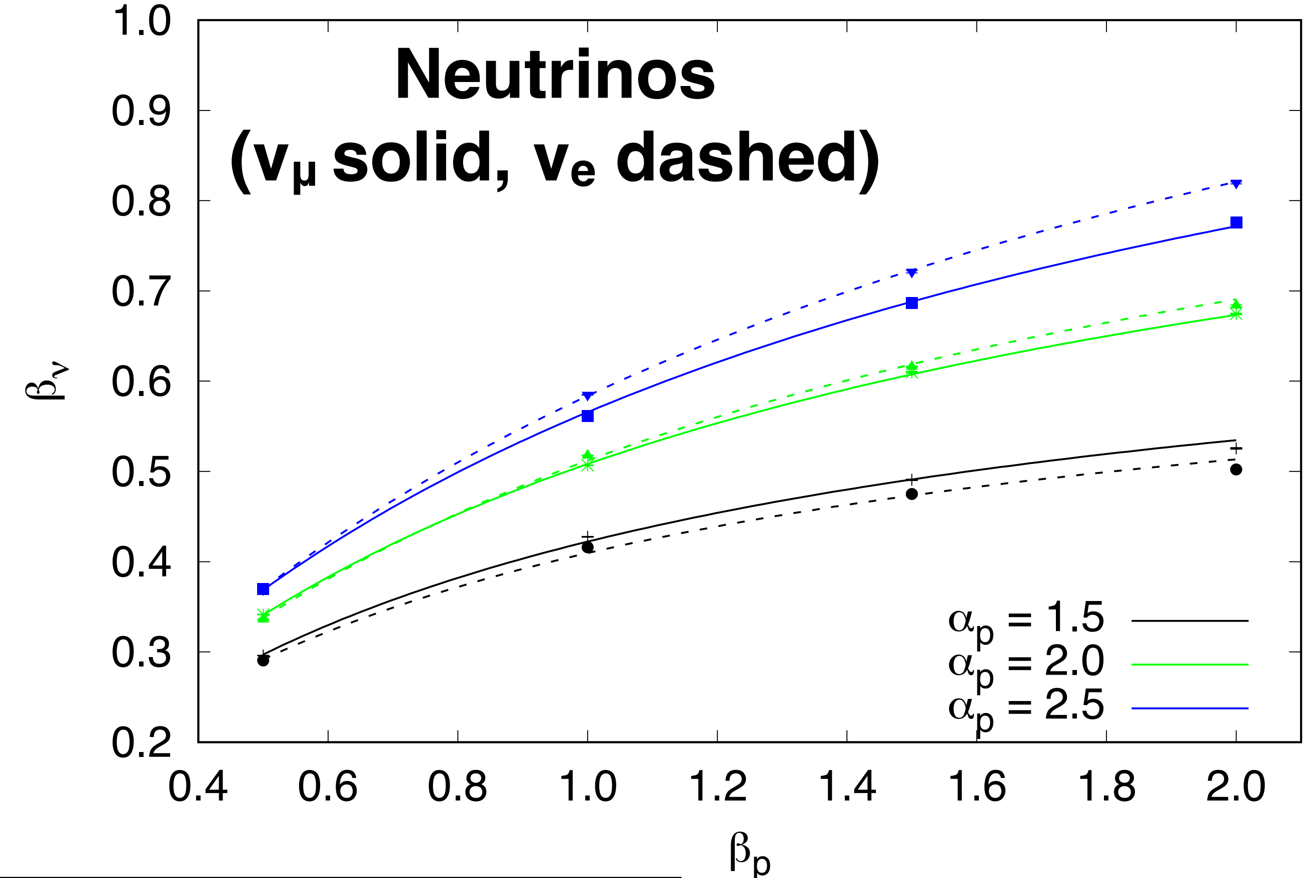
A closer look to synchrotron radiation

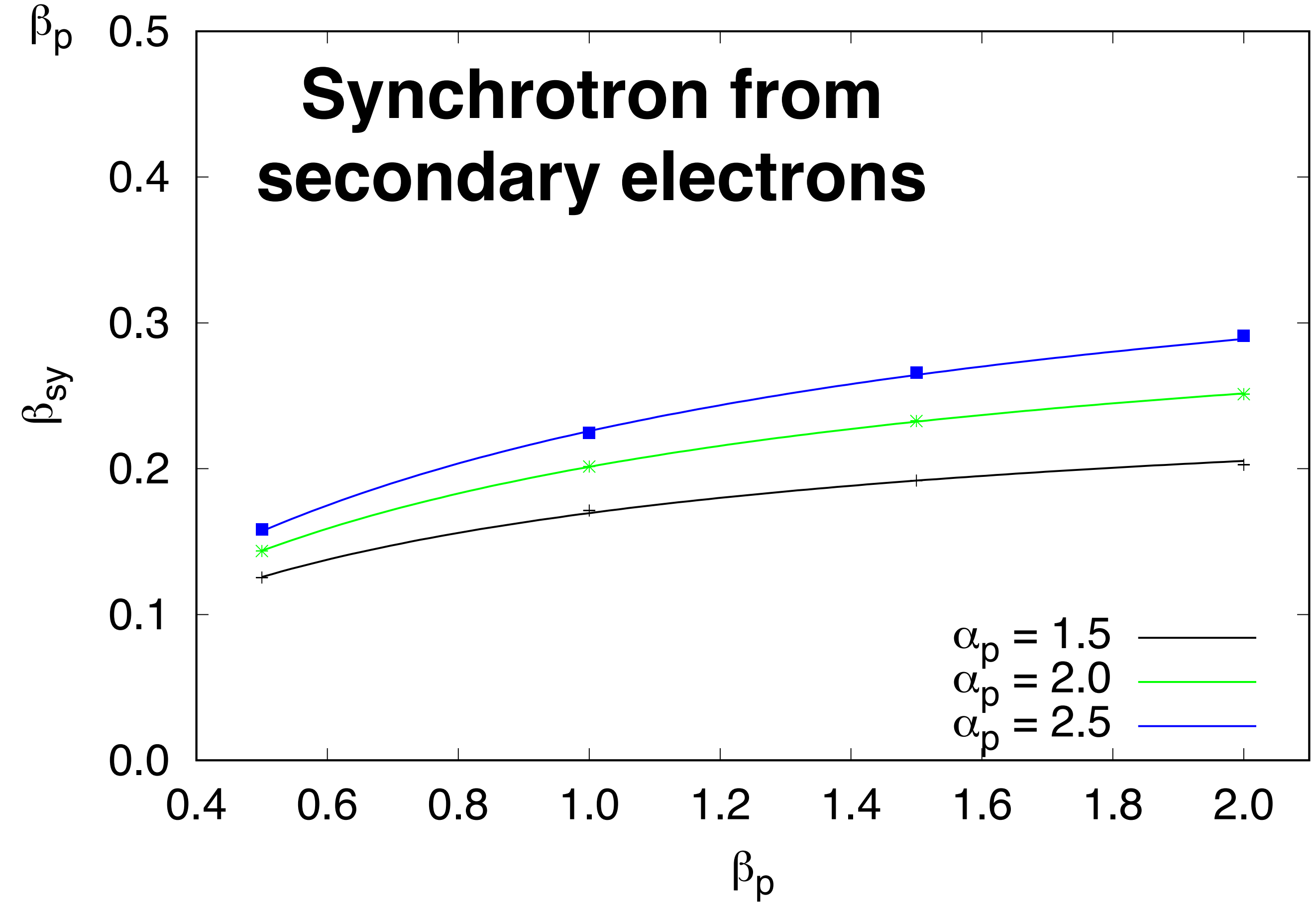
$$\alpha_{\rm p} = 2,\ \beta_{\rm p} = 1,\ E_{0,{\rm p}} = 1\,{\rm PeV},\ B_0 = 1\,{\rm m}G$$



$$J_{\rm p}(E_{\rm p}) = K_{\rm p} E_{\rm p}^{-\alpha_{\rm p}} \exp\left[-\left(\frac{E_{\rm p}}{E_{0,{\rm p}}}\right)^{\beta_{\rm p}}\right]$$

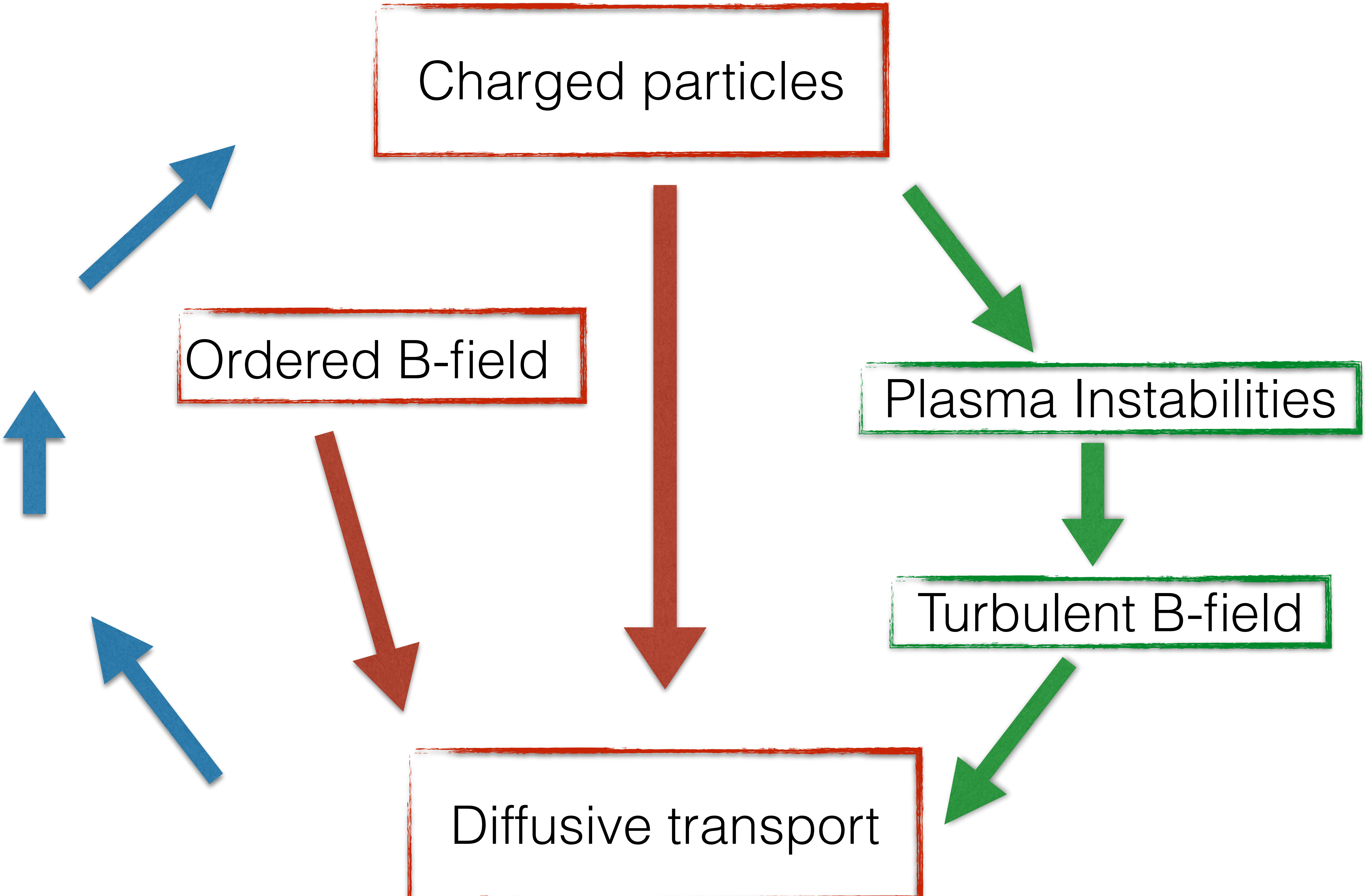




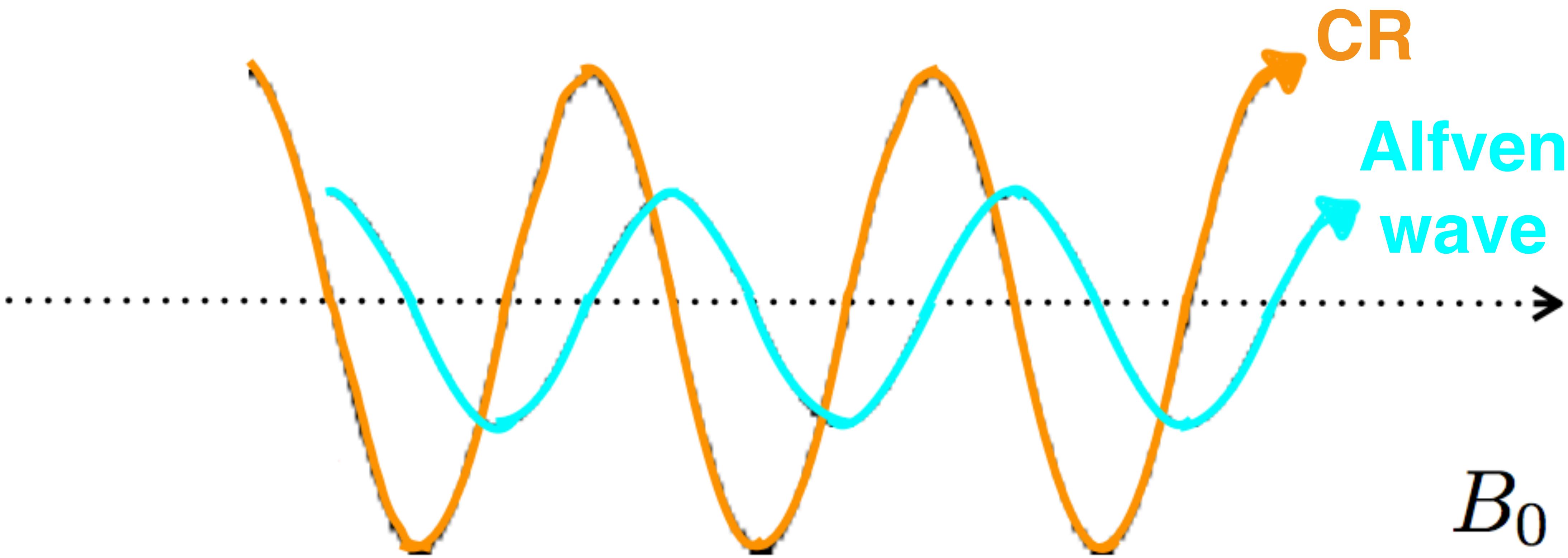


Celli, Aharonian & Gabici, ApJ 903 (2020) 61C

Escaping CRs and related instabilities


Charged particles
Ordered B-field
Plasma Instabilities
Turbulent B-field
Diffusive transport

Self-amplification of the magnetic field: the streaming instability

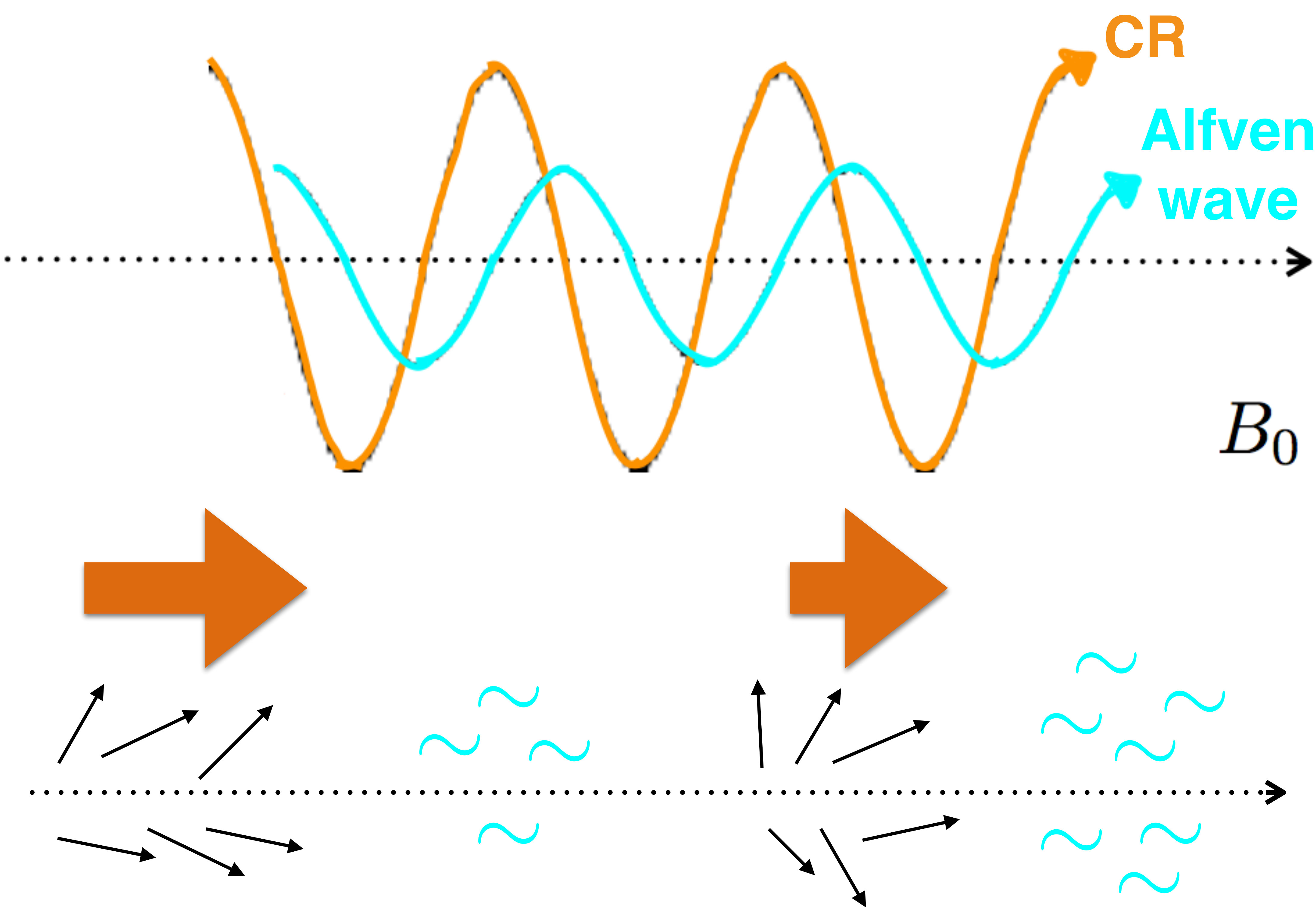


Kulsrud & Pearce, 156 (1969) 445

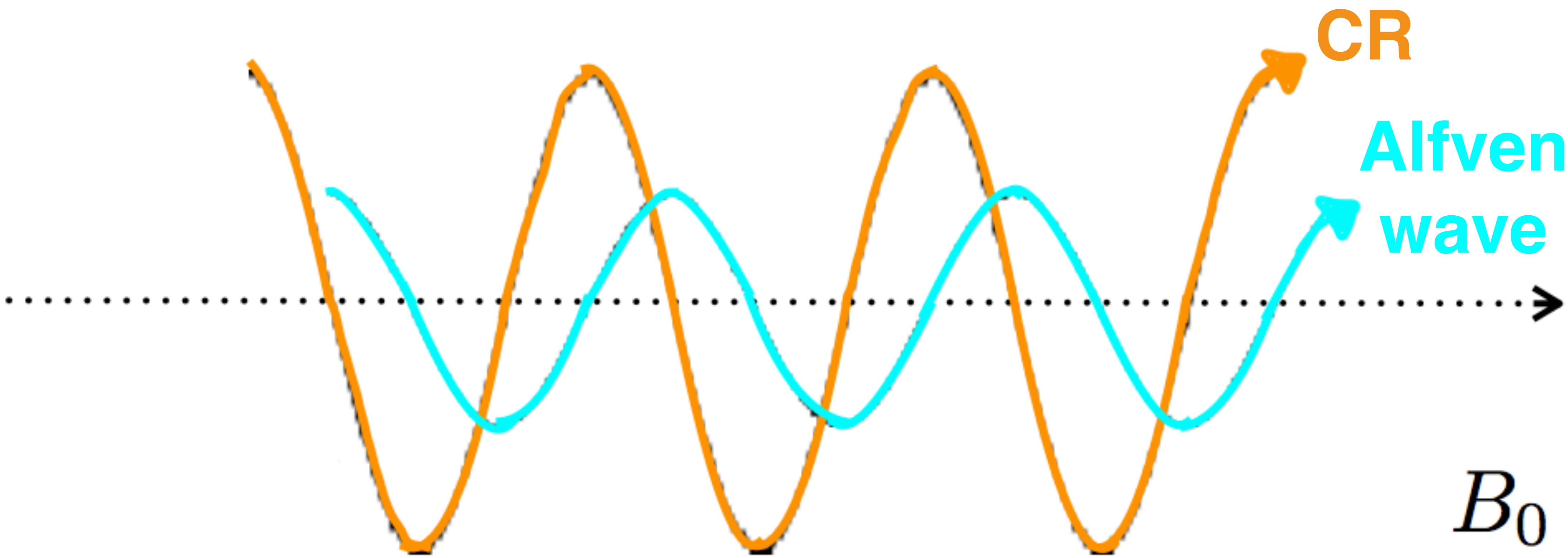
Skilling, ApJ 170 (1971) 265

$$r_L \sim \frac{1}{k}$$ → Power transfer from CRs to resonant magnetic waves

Self-amplification of the magnetic field: the streaming instability



Self-amplification of the magnetic field: the streaming instability



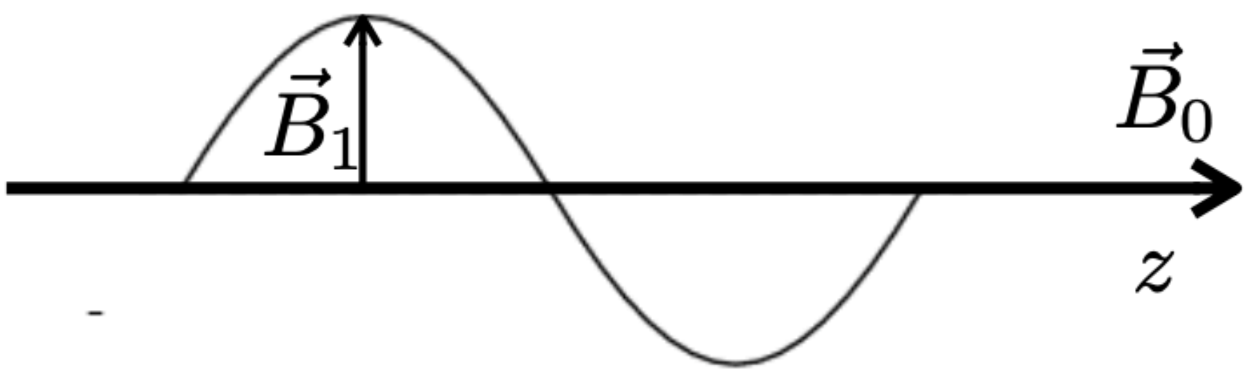
$$\left(\frac{\delta B(\mathbf{x},t)}{B_0}\right)^2 = \int \mathcal{F}(k,\mathbf{x},t)\, d\ln k$$

instability growth rate

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

Self-amplification of the magnetic field: non-resonant streaming instability

circularly polarised



wavelength << Larmor radius

escaping CRs barely deflected
—> CR current j along B_0
—> return current in the opposite direction

$-\vec{j} \times \vec{B}_1$ **force acting on the plasma —> expands the helical perturbation of B**

(until the size of the perturbation is of the order of the Larmor radius or magnetic tension balances it)

Bell, MNRAS 353 (2004) 550

Bell et al., MNRAS 341 (2013) 1

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

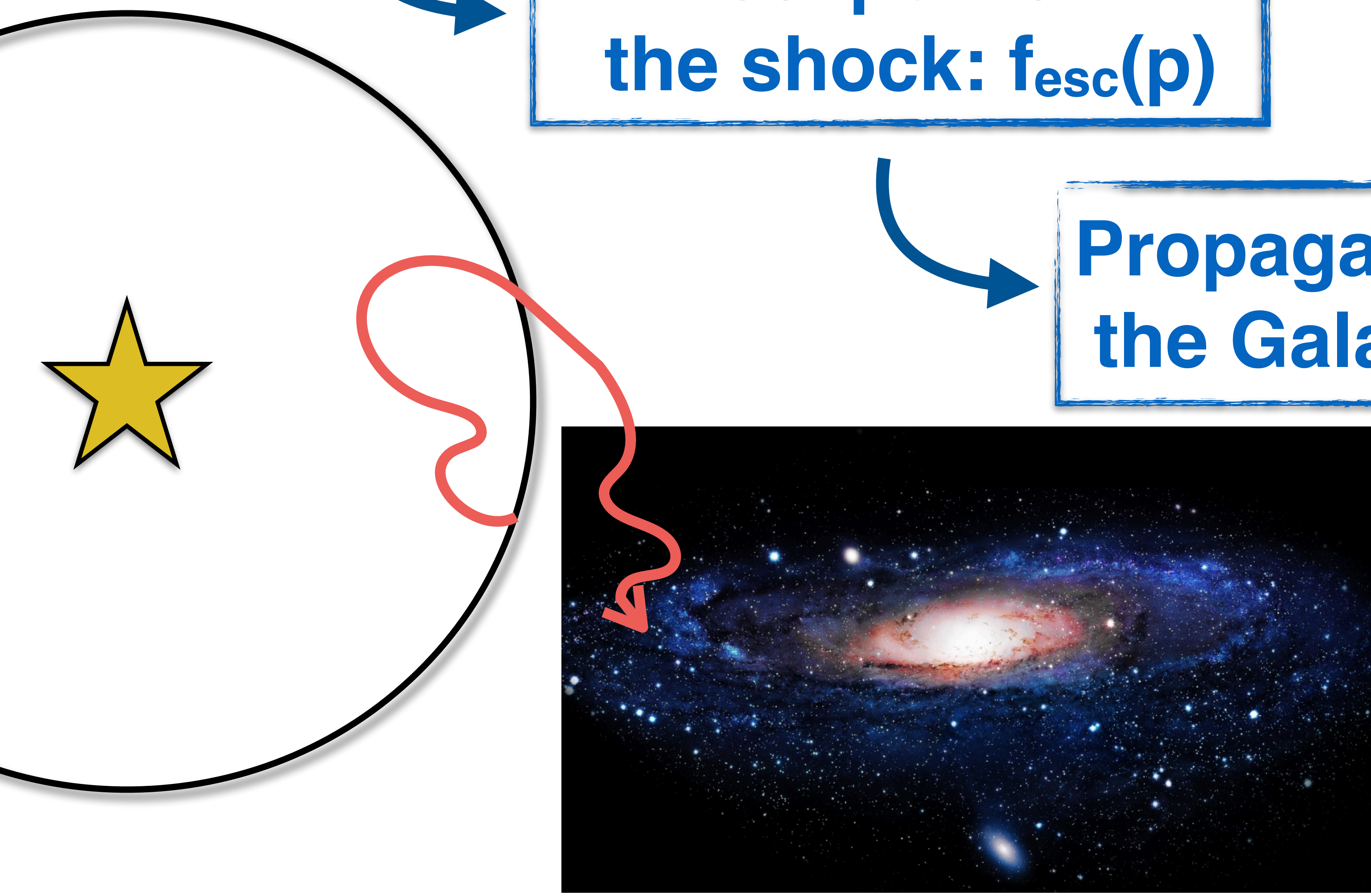
Acceleration at the shock: $f_0(p)$

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

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

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

Observation



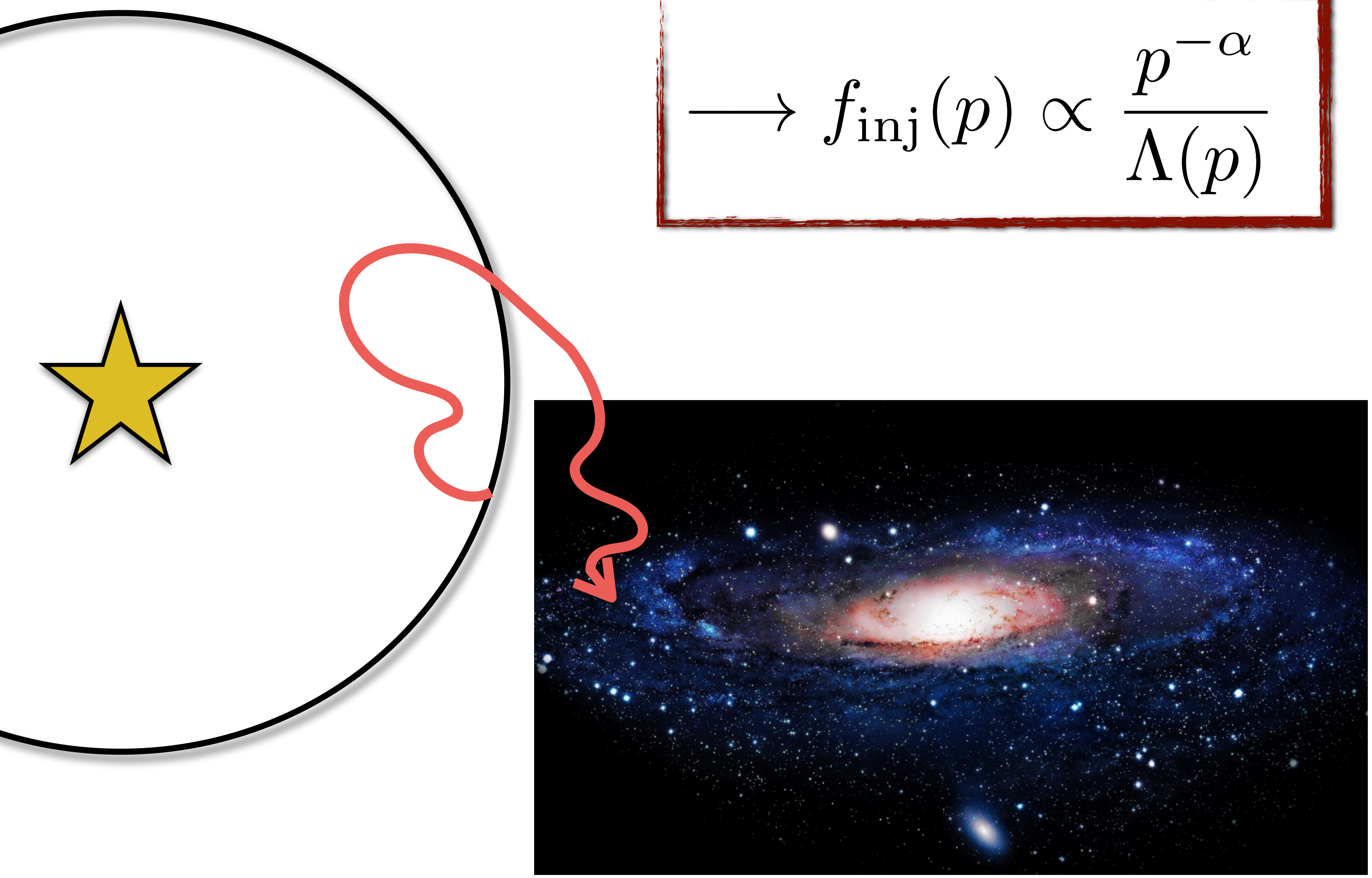
The CR spectrum injected into the Galaxy

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

$$\longrightarrow f_{\mathrm{inj}}(p) \propto v_{\mathrm{esc}}^2(p) R_{\mathrm{esc}}^3(p) \frac{p^{-\alpha}}{\Lambda(p)}$$

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

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



The CR spectrum injected into the Galaxy

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

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

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

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

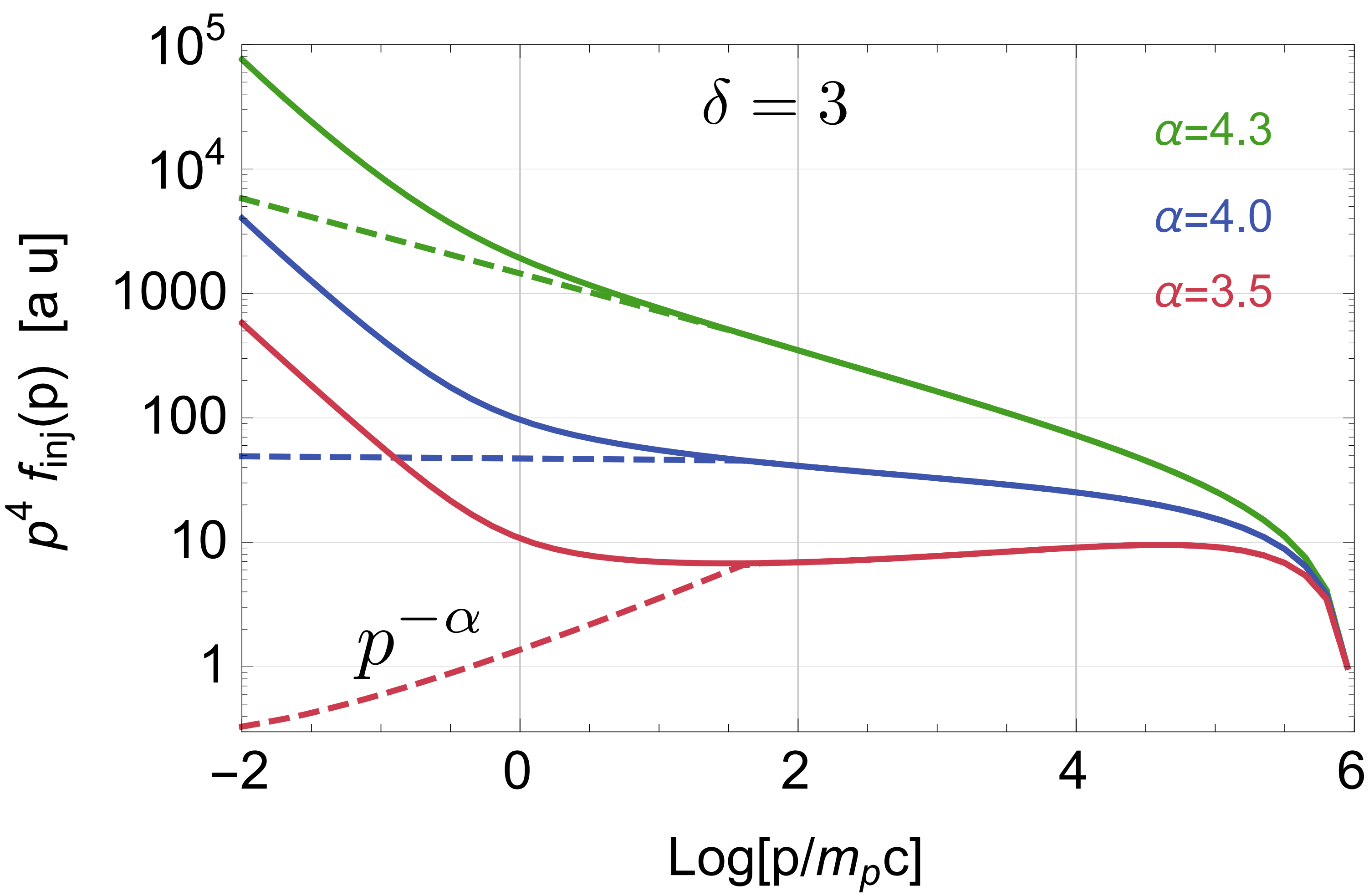
Celli et al., MNRAS 490 (2019) 4317C

The CR spectrum injected into the Galaxy

What if acceleration suddenly stops when the remnant enters the radiative phase of its evolution?

$$T \leq 10^6\,\mathrm{K},\ v_\mathrm{s} \simeq 200\,\mathrm{Km/s},\ t_\mathrm{rad} \simeq 47\,\mathrm{kyr}$$

$$p_{\mathrm{max},0}(t_\mathrm{rad}) \simeq 40\,\mathrm{GeV/c}$$



→ particles with $p < p_{\mathrm{max},0}(t_\mathrm{rad})$ do not suffer further adiabatic losses and are soon released in the ISM

Electron transport and E_{max} in SNRs

Radiative + adiabatic losses

$$\frac{dE}{dt} = \left(\frac{dE}{dt}\right)_{\rm syn+IC} + \frac{E}{L}\frac{dL}{dt}$$

Reynolds, ApJ 493 (1998) 375

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

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

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

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

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**:

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

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

Electron transport and E_{max} in SNRs

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

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

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

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

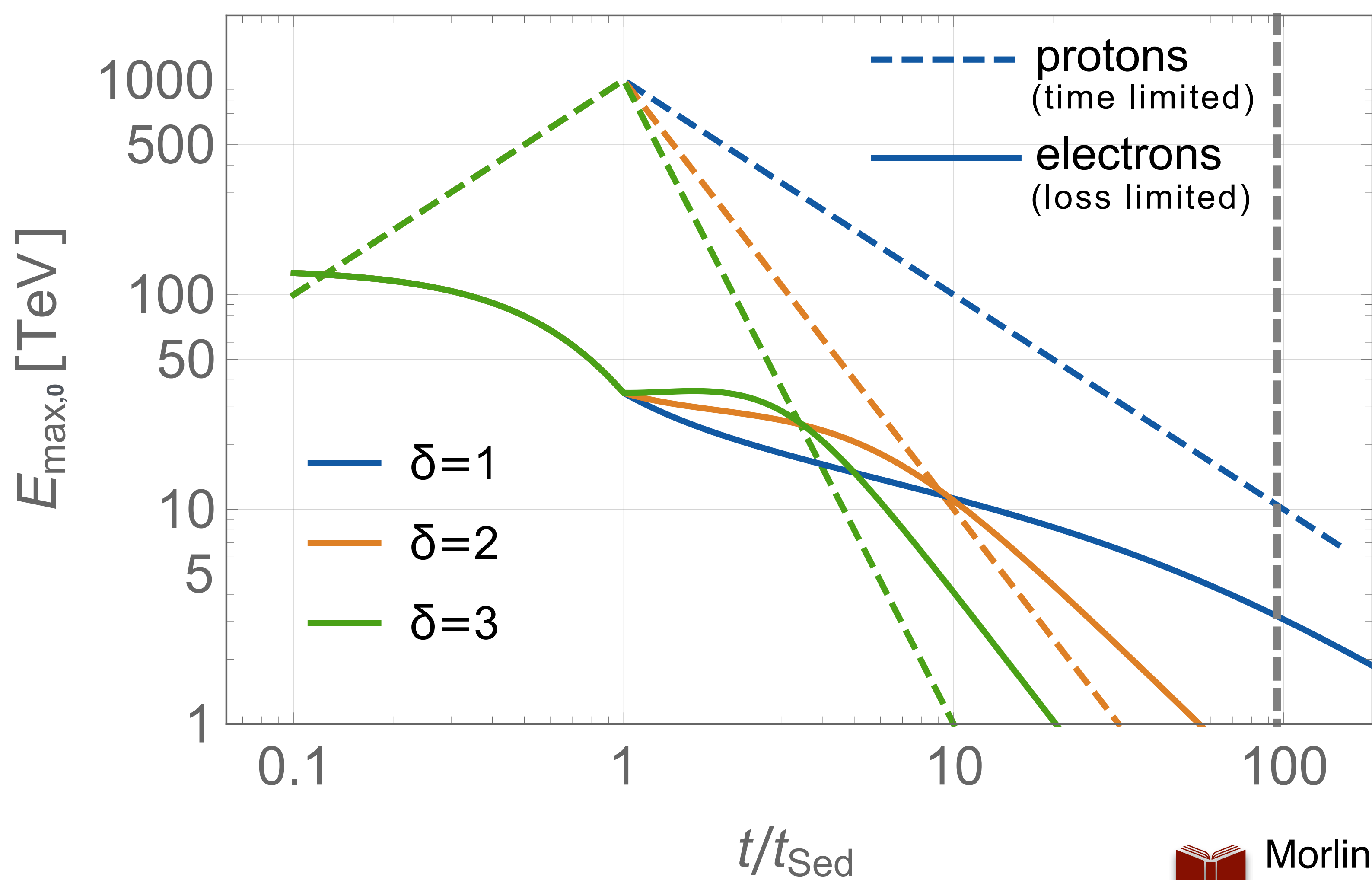
$$B_2^2(r,t) = \frac{B_0^2}{3}\left[\left(\frac{R_{sh}(t)}{r}\right)^4 + 2\sigma^2 L^6(t',t)\left(\frac{R_{sh}(t)}{r}\right)^2\right]$$

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

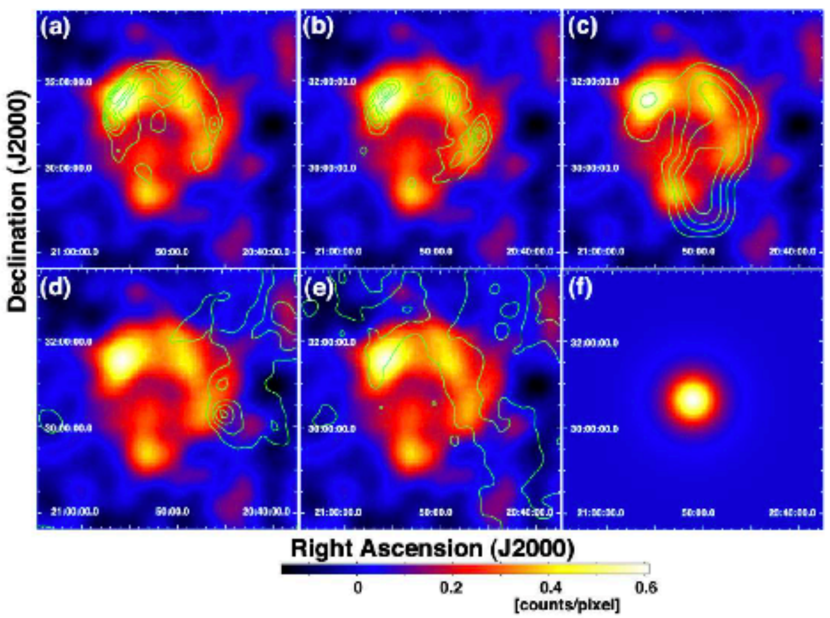
Numerical solution of the transport equation for accelerated **electrons**, including radiative and adiabatic losses

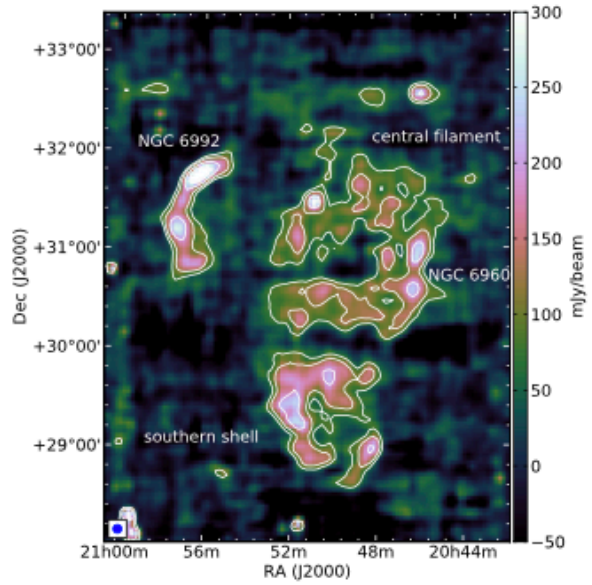


Morlino & Celli,
MNRAS 508 (2021) 6142M

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

The Cygnus Loop SNR: particles



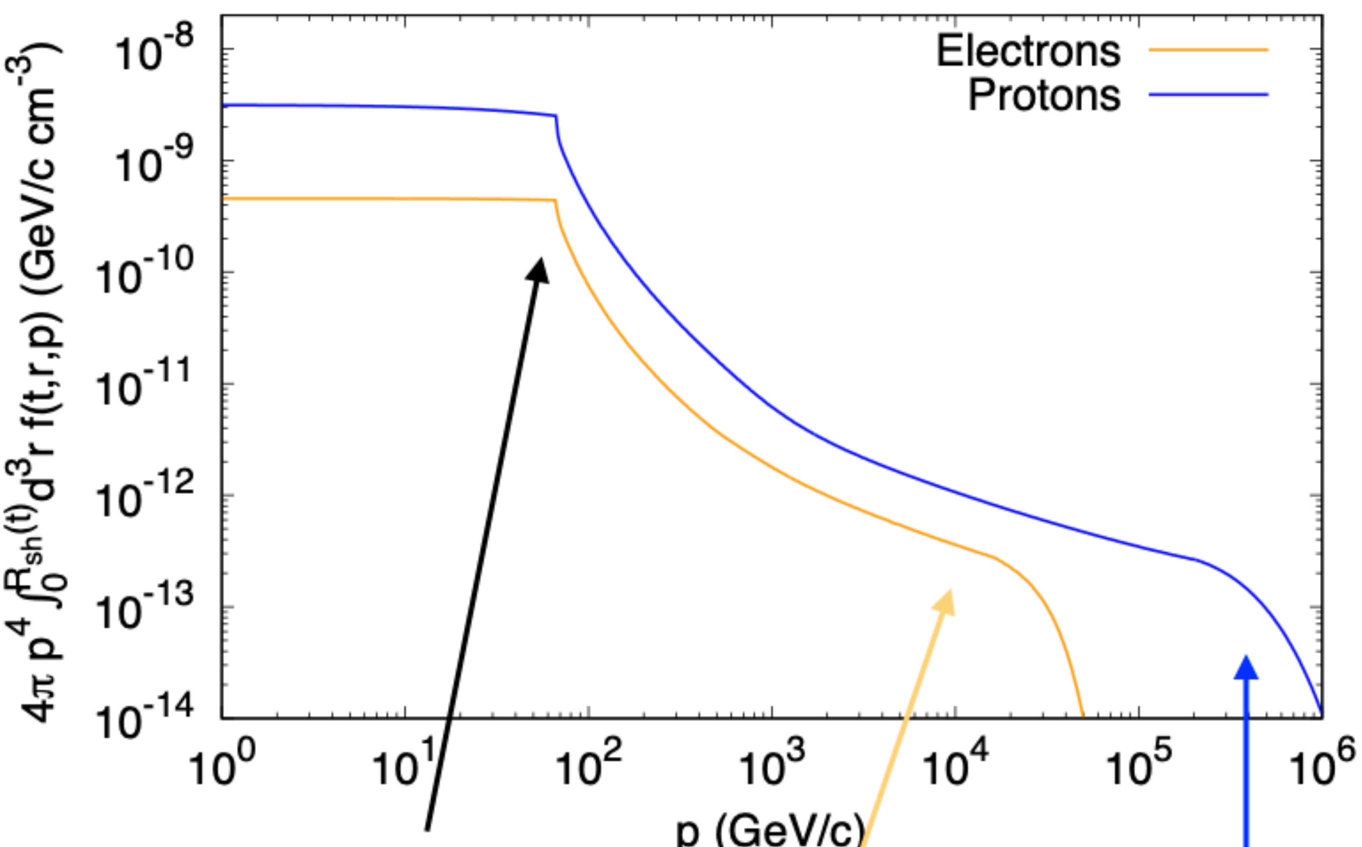


Middle-aged SNR

($\sim 2\times10^4$ yr)

located at high latitudes

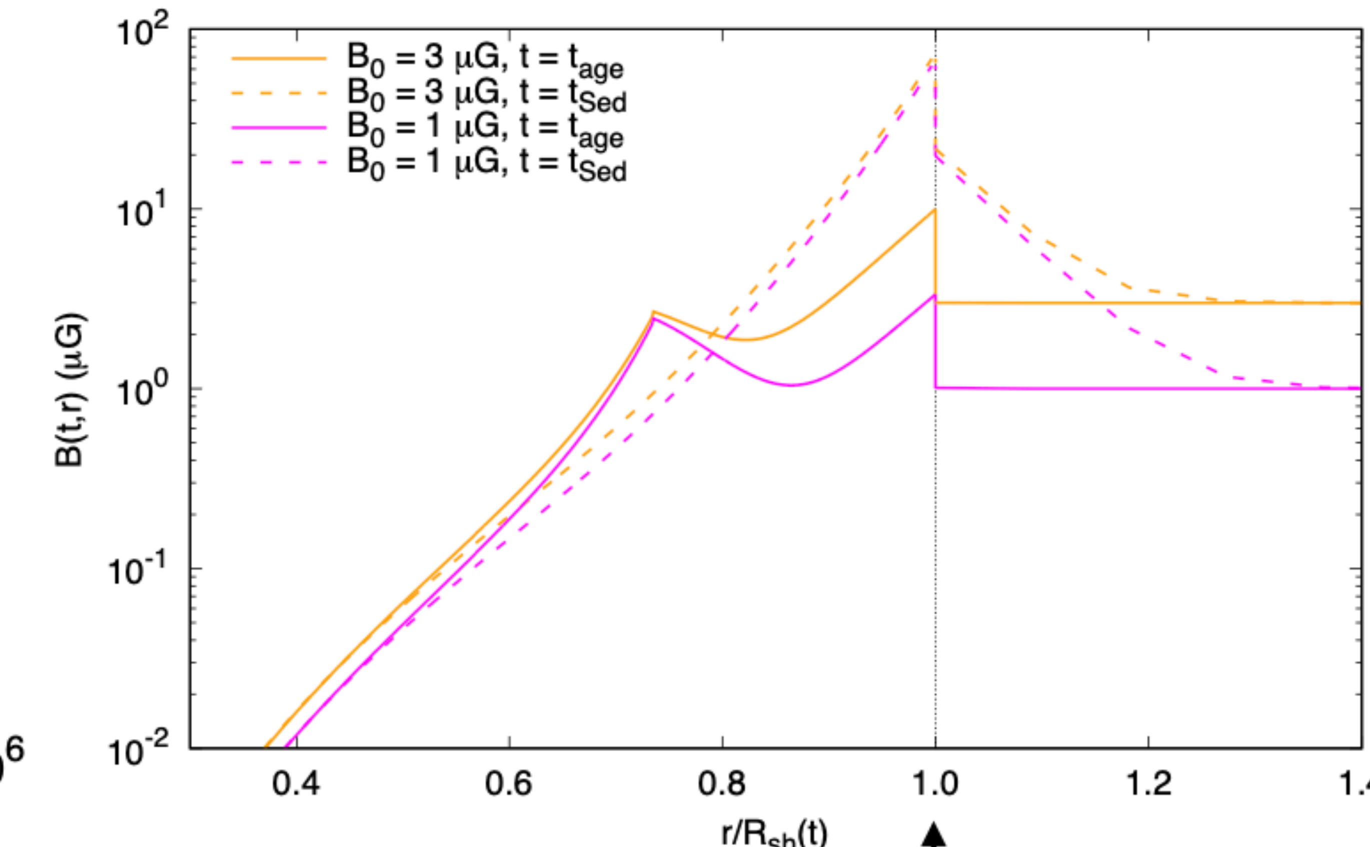
Loru et al., MNRAS 500 (2020) 5177



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

$p_{M,e}$=20 TeV

$p_{M,p}$=200 TeV

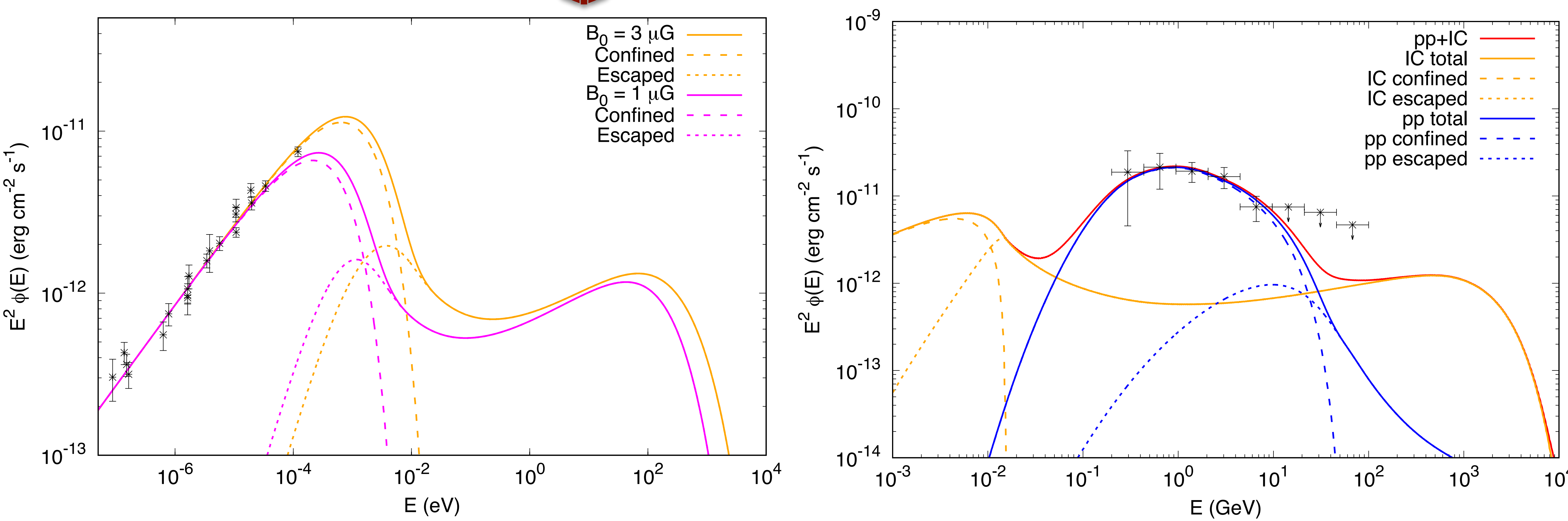


Magnetic field at the shock today at the level of 10 μG, compatible with compression

The Cygnus Loop SNR: radiation

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	$3\ \mu$G	1

Loru et al., MNRAS 500 (2020) 5177

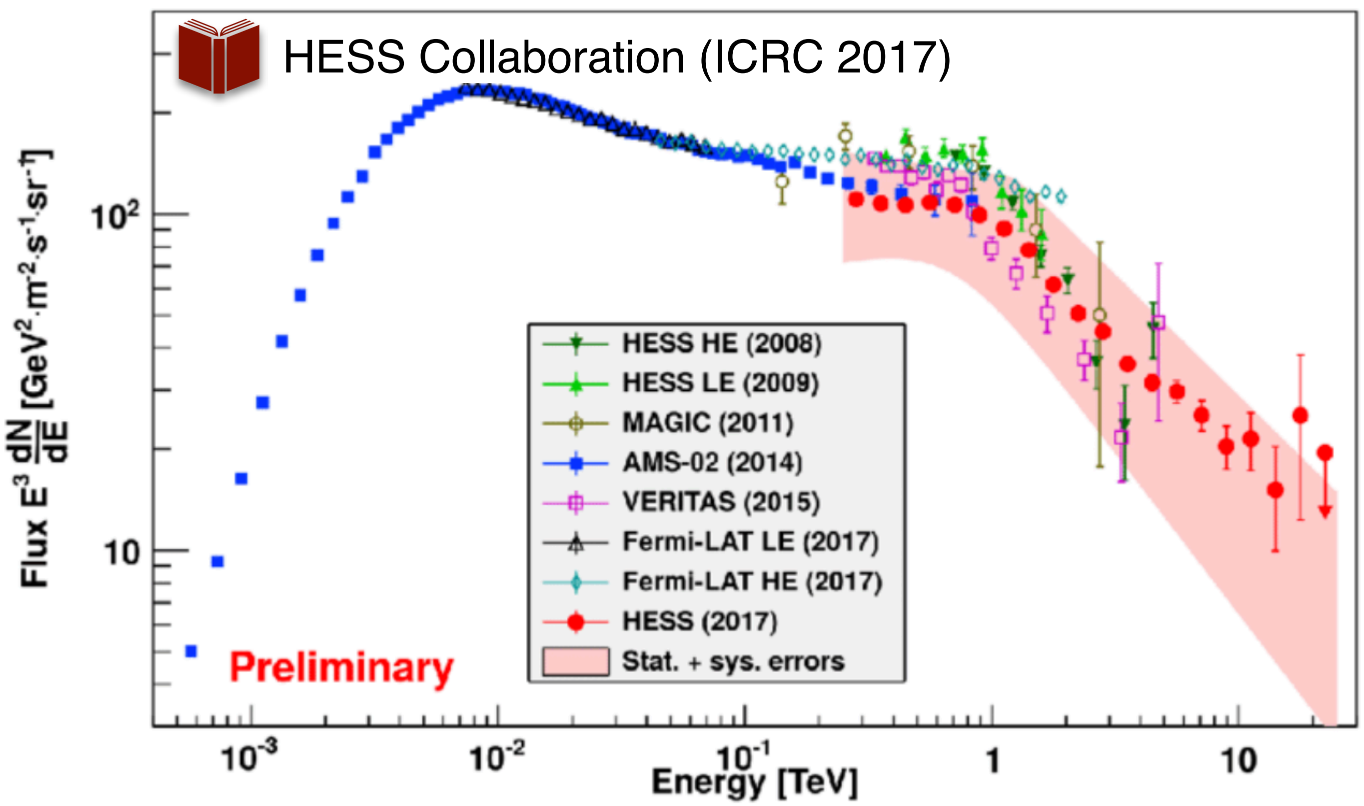


$\delta \geq 2$ → **Temporal evolution of magnetic turbulence:** MFA + damping effects?

$K_{ep} \simeq 0.15$ → **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.

The observed CR-e spectrum



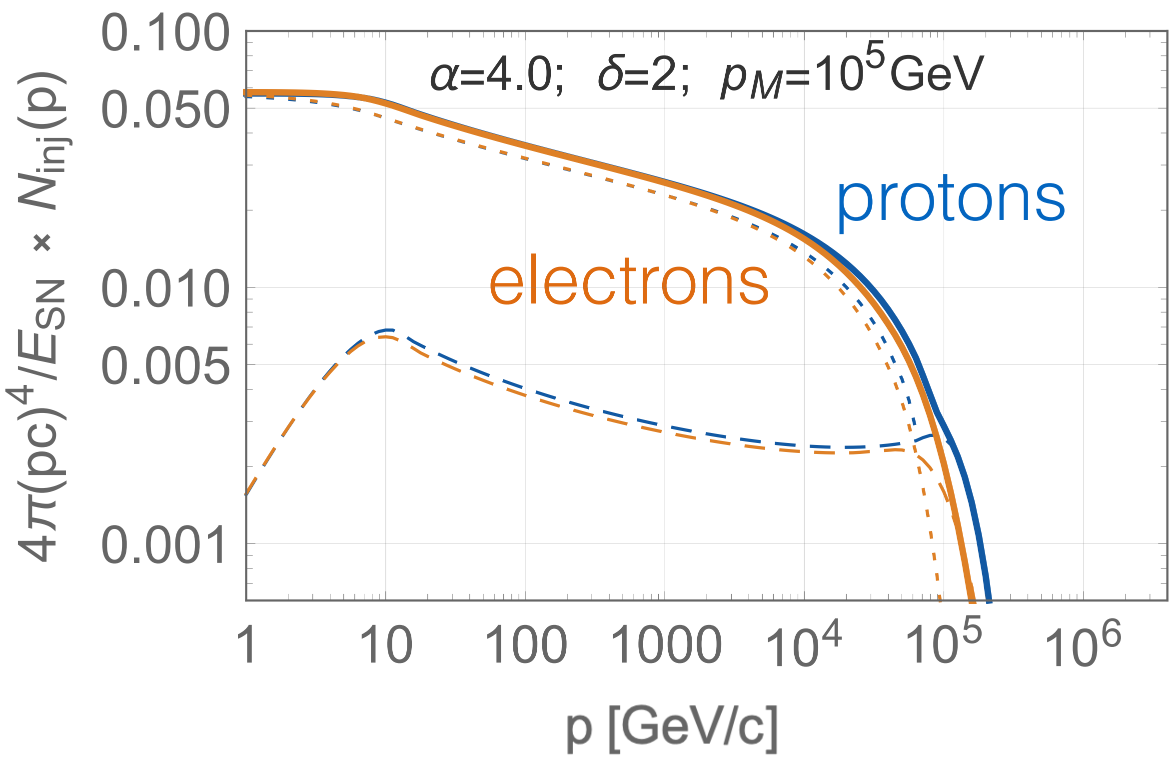
Many works on theoretical interpretation:

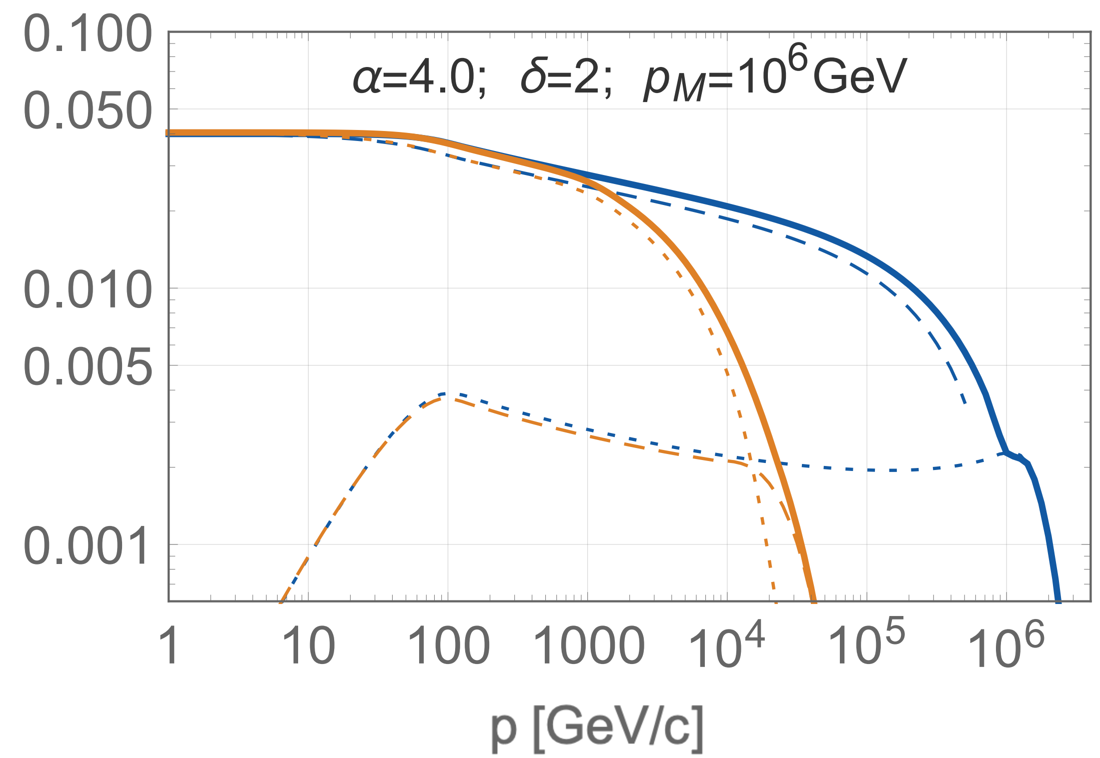
- Manconi et al., JCAP (2019) 024
- Diesing & Caprioli, PRL 123 (2019) 071101
- Recchia et al., PRD 99 (2019) 103022
- Brose et al., A&A 634 (2020) 359
- Di Mauro et al., PRD 8 (2020) 083012
- Fornieri et al., JCAP (2020) 009
- Cristofari, Blasi & Caprioli, A&A 650A (2021) 62C
- Evoli et al., PRD 103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

1. Self generated turbulence



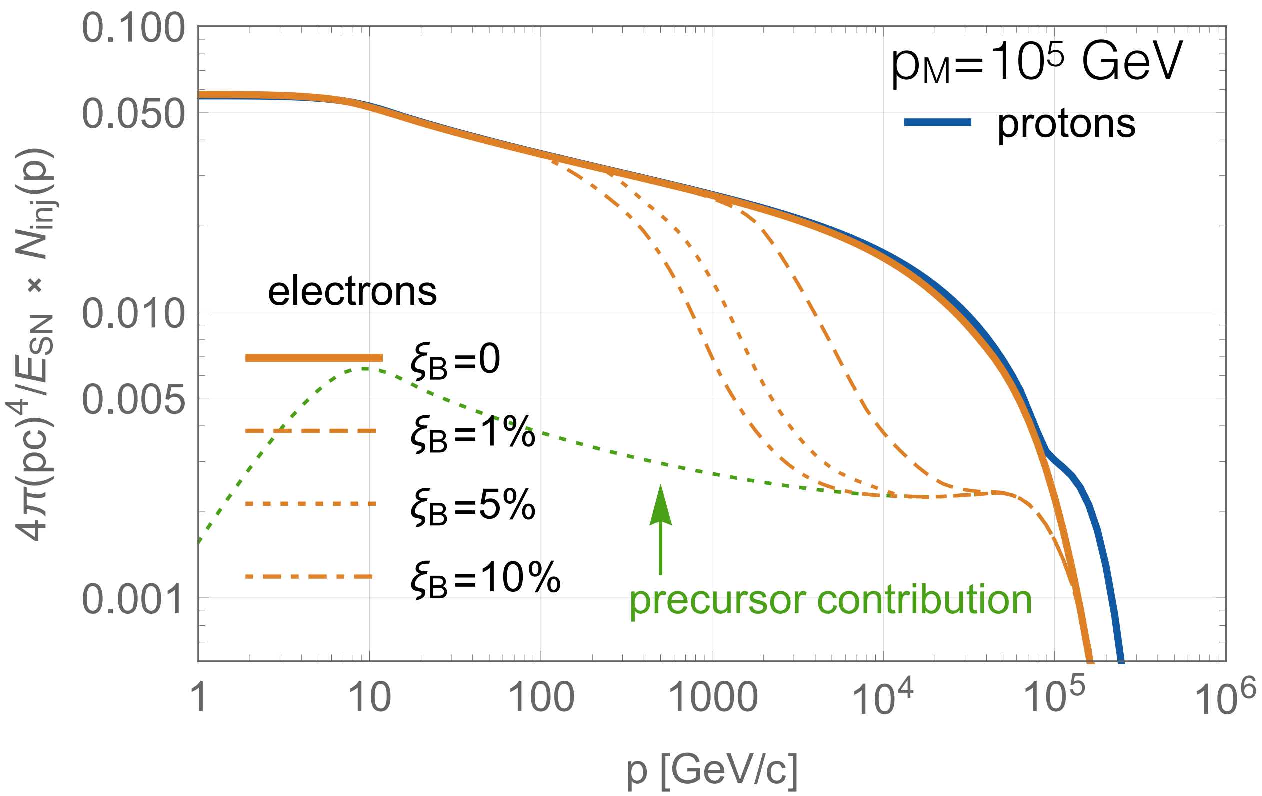


- Spectral steepening in both species of **~0.15 above $p_{max}(t_{SP})$**;
- Proton and electron spectra only differ if significant MFA is effective ⟶ large p_M (~PeV) or δ (>2);
- However, even in the **PeVatron** scenario, **self-amplified magnetic field can explain spectral differences only above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

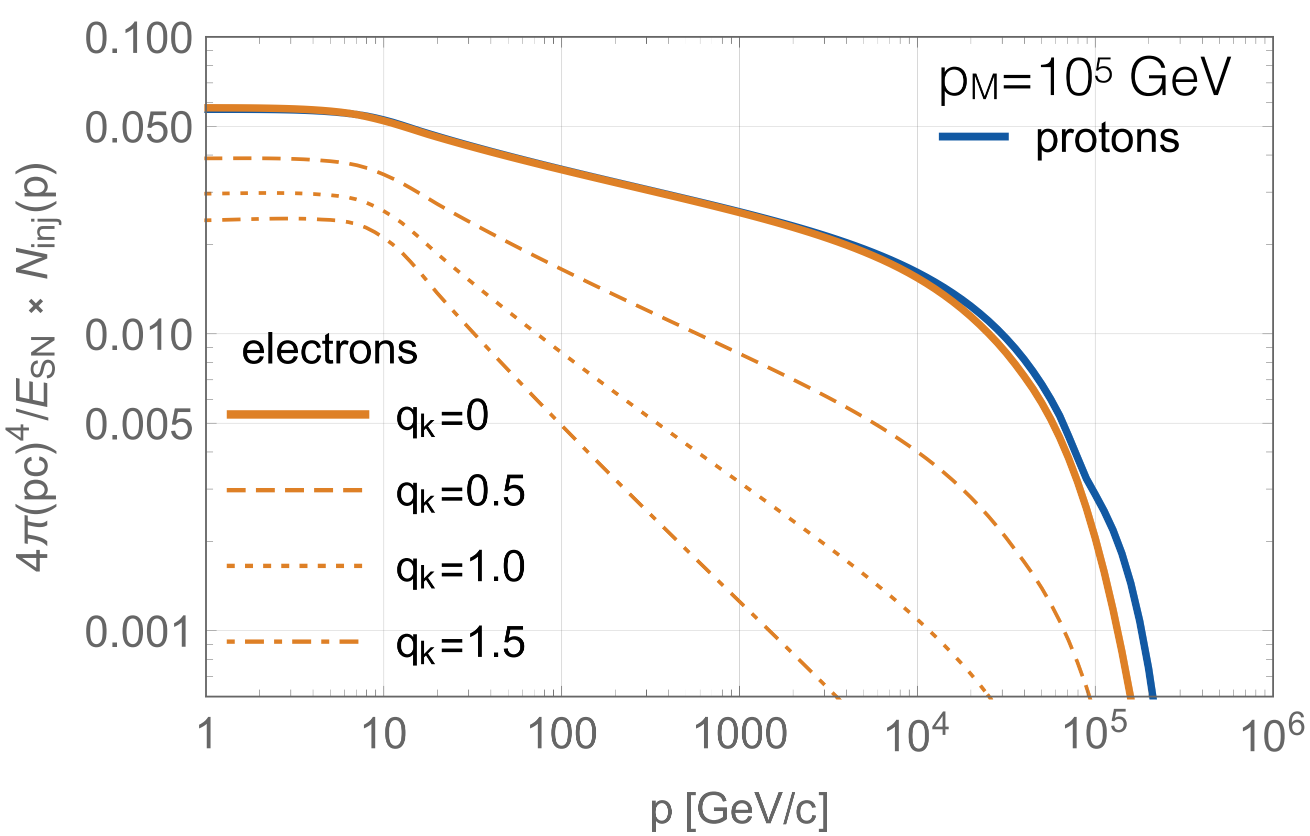
3. Time-dependent electron-to-proton injection

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

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

Hp

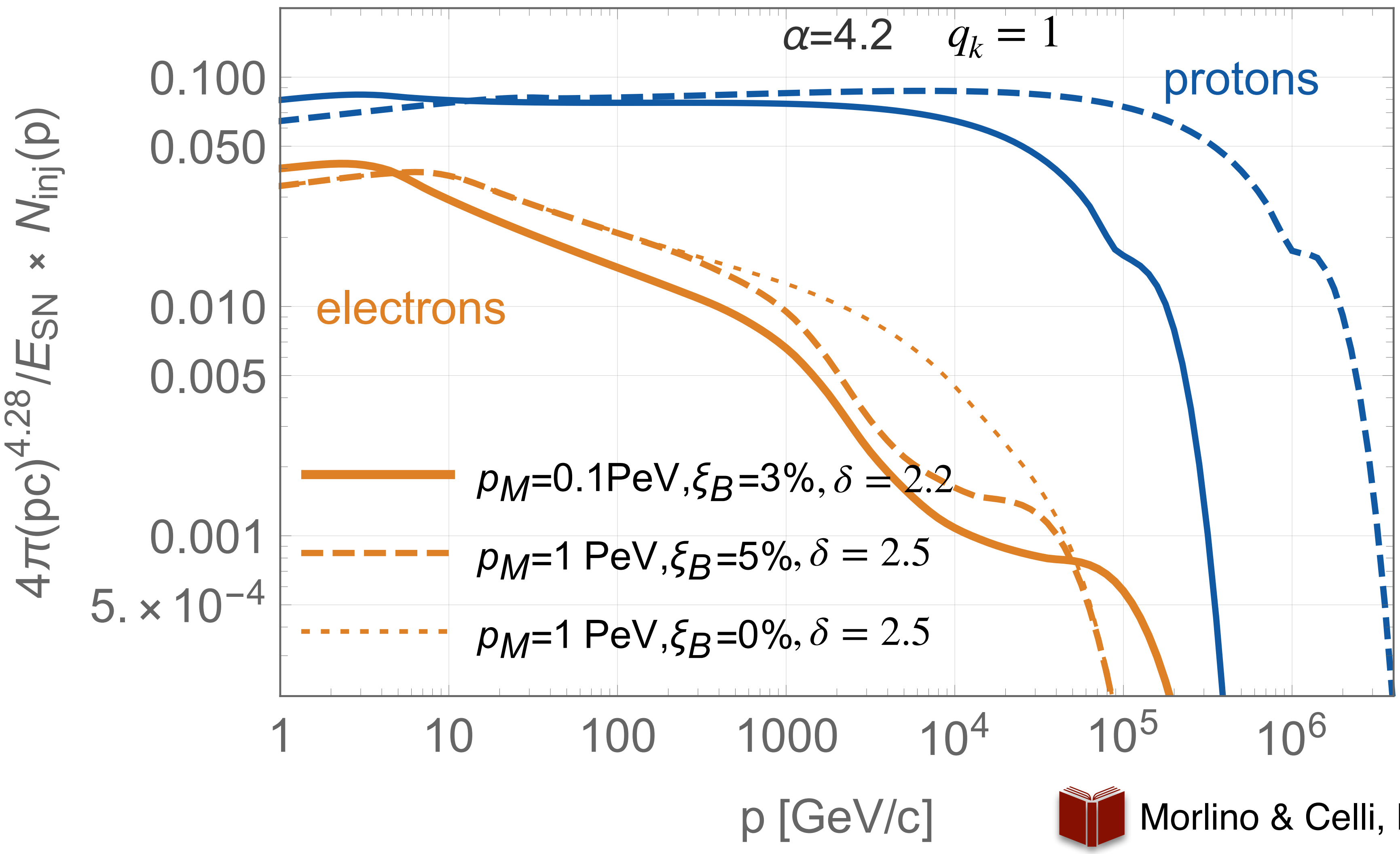
$$q_k = 5\,\delta\,\Delta s_{\mathrm{ep}}/3$$



- with $\delta \simeq 2$, $\mathbf{\Delta s_{ep} \simeq 0.3}$
  $\longrightarrow$ $\mathbf{q_k \simeq 1}$;
- Steepening down to 10 GeV consistent with observations only if $\mathbf{p_{max}(t_{SP}) \lesssim 10}$ **GeV**.

Morlino & Celli, MNRAS 508 (2021) 6142M

The CR-e spectrum injected into the Galaxy



Morlino & Celli, MNRAS 508 (2021) 6142M

Turbulent MHD amplification:

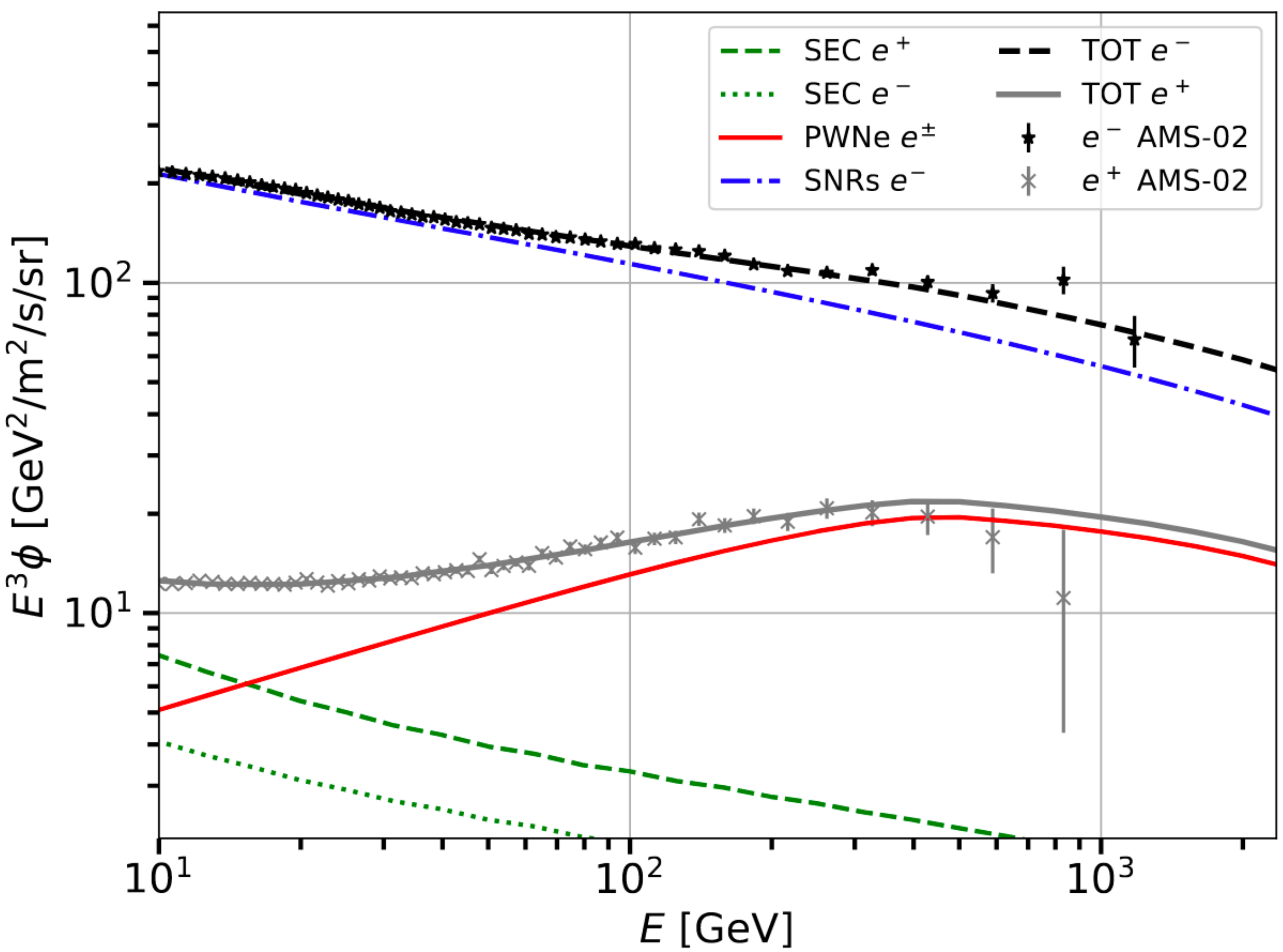
$$\frac{\delta B^2_{2,\rm tur}}{8\pi} = \xi_{\rm B}\frac{1}{2}\rho v^2_{\rm sh}$$

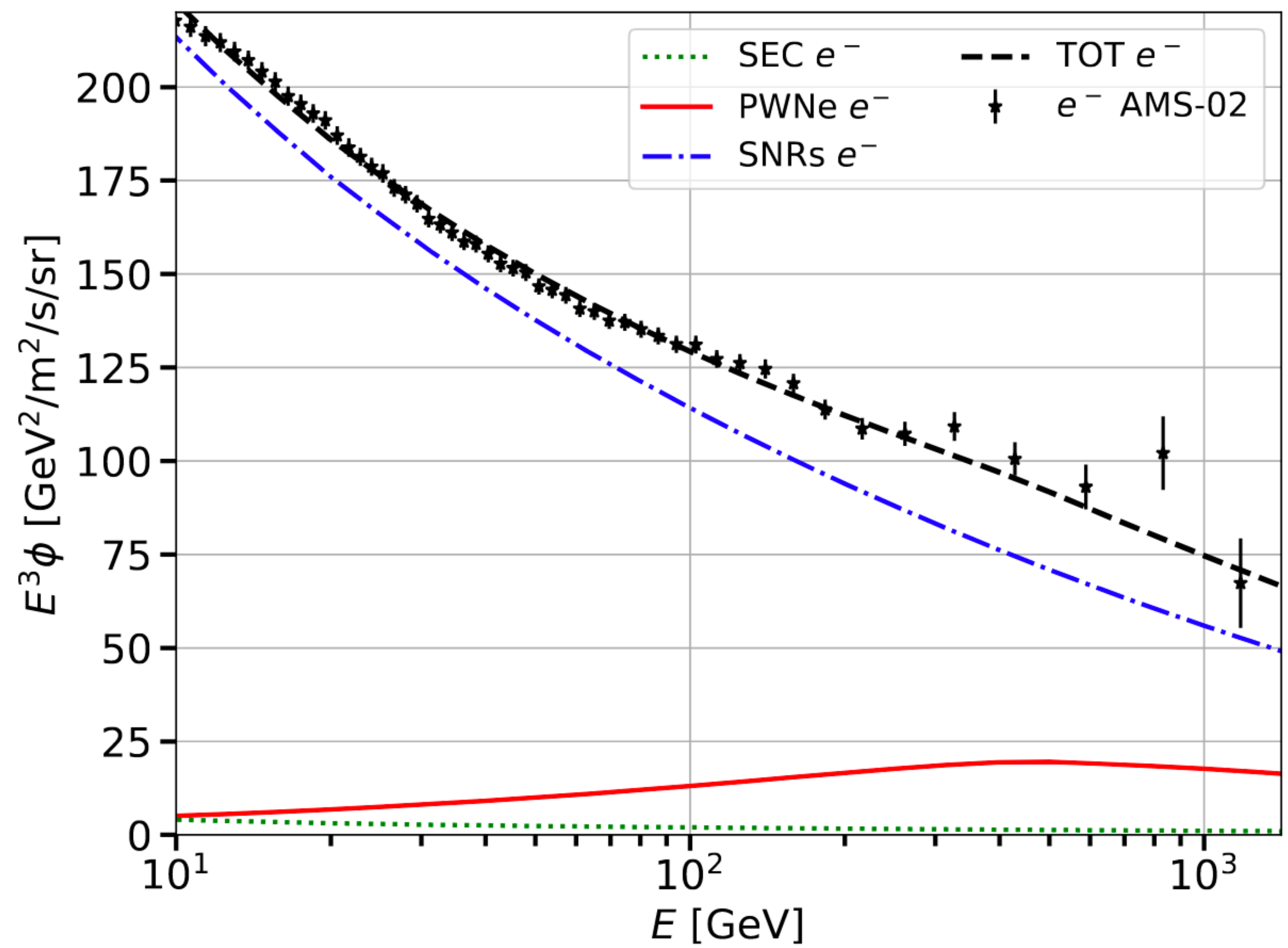
Time dependent e/p injection:

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

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%.