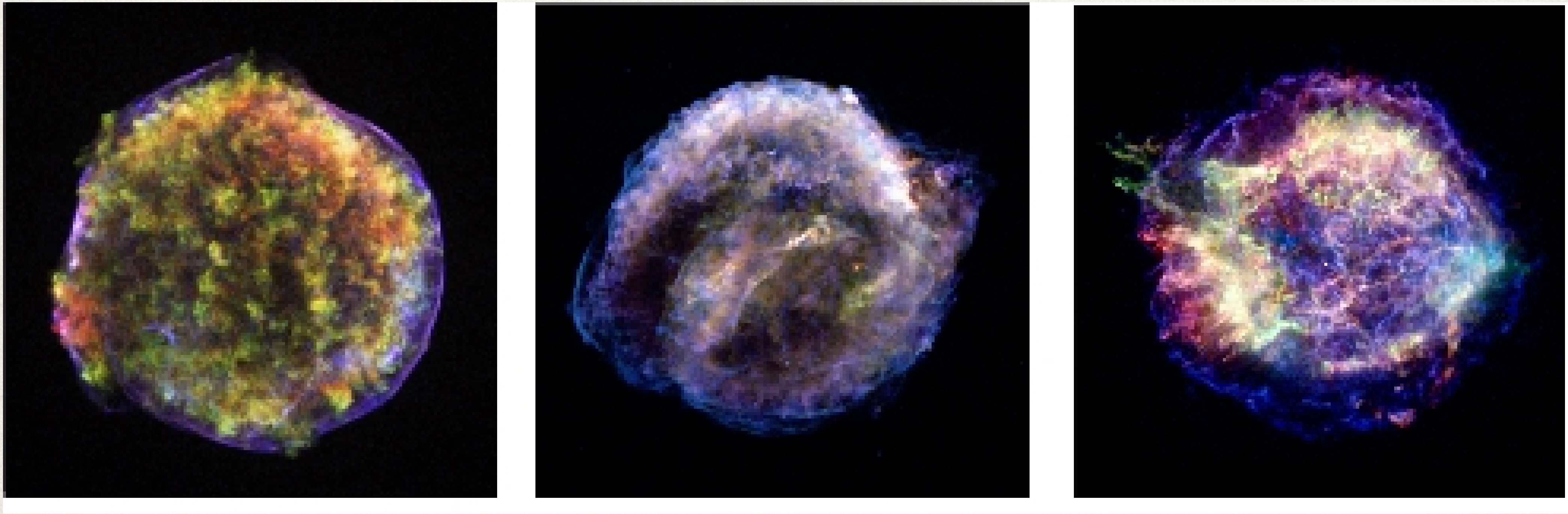
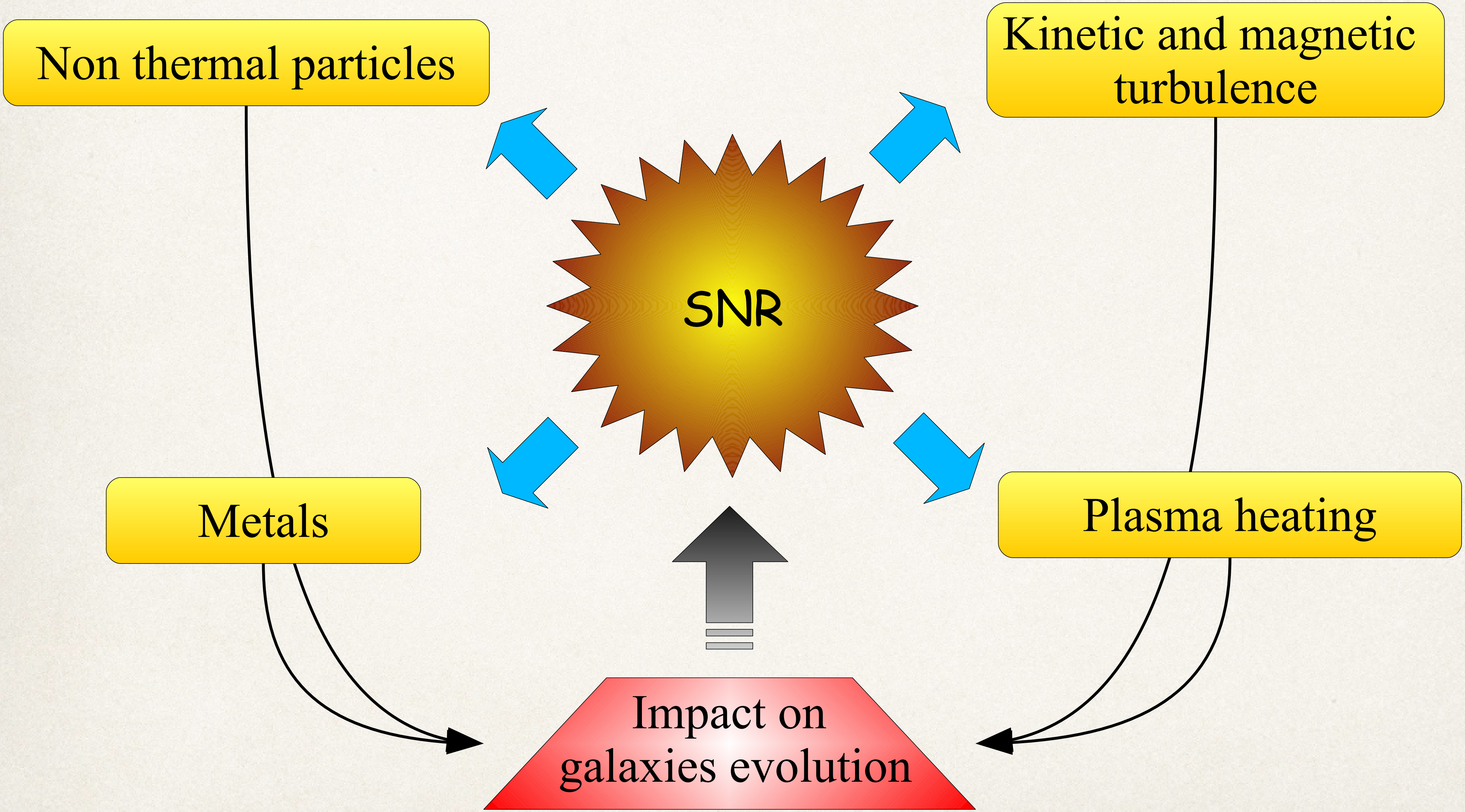


Supernova remnants in the era of LHAASO

Giovanni Morlino,

INAF/Osservatorio Astrofisico di Arcetri, Firenze, ITALY

Wide importance of SNRs



The SNR paradigm for the origin of CRs

Pros:

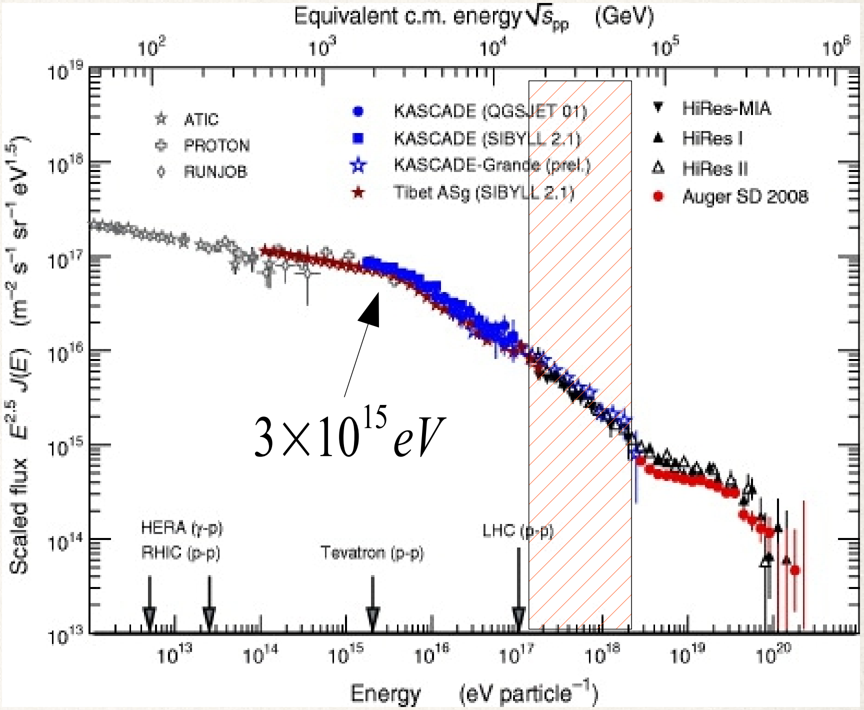
- Enough power to supply CRs energy density (~10% of explosion energy)
- Spatial distribution compatible with the CR distribution in the Galaxy
- Presence of non thermal emission
- Best acceleration theory (at the moment) applicable to SNR shocks

Unsolved problems:

- Which is the maximum energy?
- Injected spectrum into the Galaxy
  - Protons
  - Heavy nuclei
  - Electrons
- Chemical CR composition? (some anomalies: ^{22}Ne, ^{60}Fe, …)
- …

The path to become a cosmic ray

Understanding the CR spectrum
requires to link together
3 different steps:



Acceleration inside sources

Young SNRs

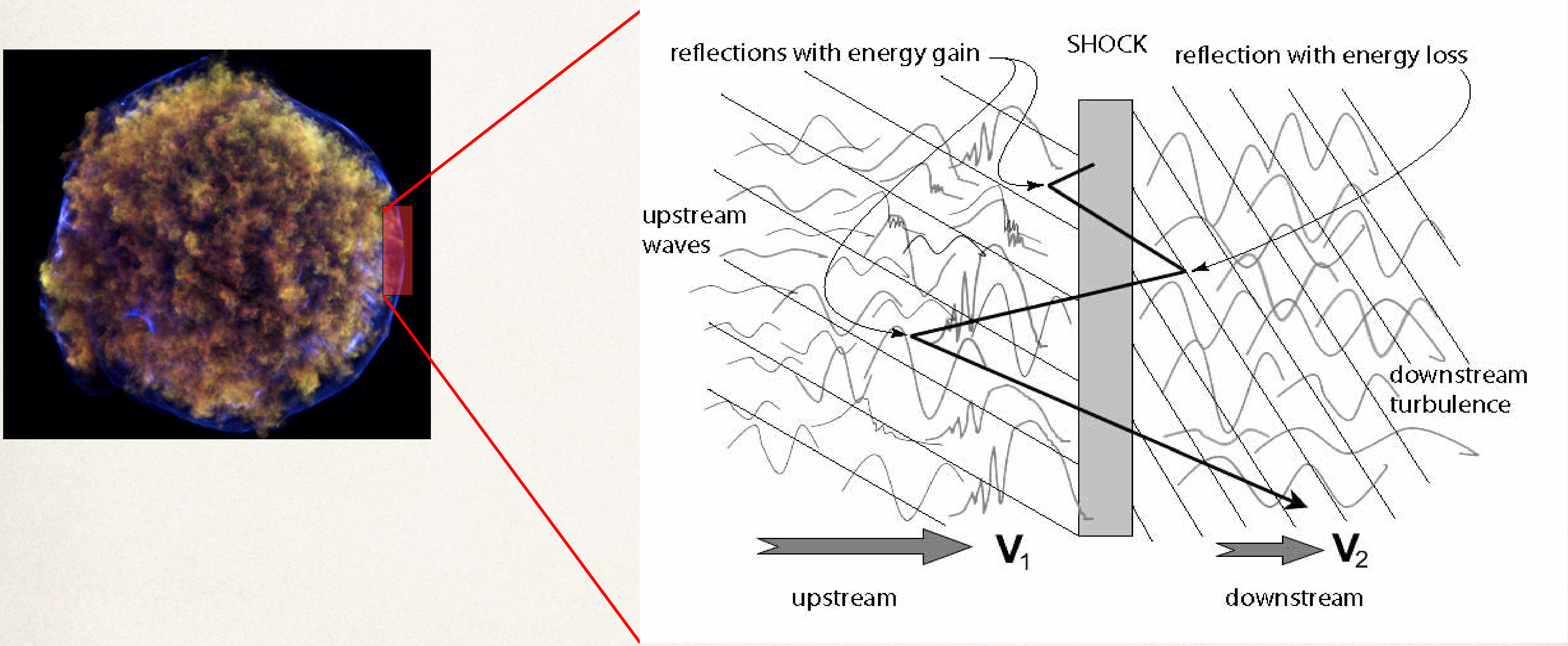
Escape from sources

Middle-aged SNRs

Propagation accross the Galaxy

Where does acceleration occur?

Diffusive Shock Acceleration



Repeated multiple scatterings with magnetic turbulence produce small energy gain at each shock crossing

Diffusive shock acceleration

Diffusive Shock Acceleration (DSA) predictions:

(1) ➡ **Spectrum:** $\boxed{f(p) \propto p^{-4} \rightarrow f(E) \propto E^{-2}}$

(2) ➡ **Acceleration efficiency ~10%**

(3) ➡ **Maximum energy**

Equating the acceleration time with the end of the ejecta dominated phase $t_{\mathrm{acc}} = t_{\mathrm{ST}}$:

$$\boxed{E_{\max} = 5 \times 10^{13}\, Z \mathscr{F}(k_{\min}) \left(\frac{B_0}{\mu\mathrm{G}}\right) \left(\frac{M_{\mathrm{ej}}}{M_{\odot}}\right)^{-\frac{1}{6}} \left(\frac{E_{\mathrm{SN}}}{10^{51}\,\mathrm{erg}}\right)^{\frac{1}{2}} \left(\frac{n_{\mathrm{ISM}}}{\mathrm{cm}^{-3}}\right)^{-\frac{1}{3}} \mathrm{eV}}$$

Strong dependence on magnetic field

Weak dependence on the ejecta mass and ISM density

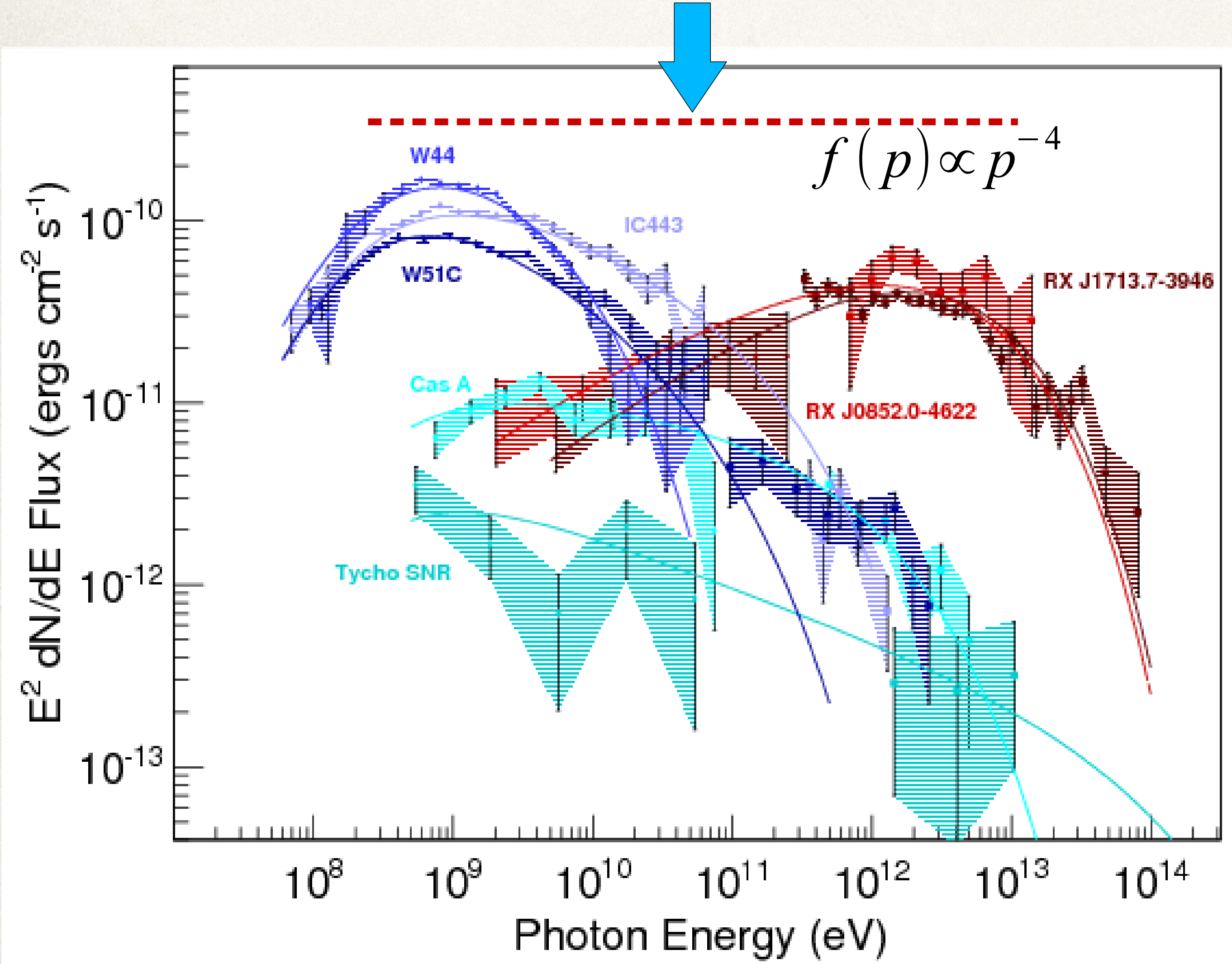
High energies, up to PeV, can be achieved only if

$$\mathcal{F}(\boldsymbol{k}) = (\delta \boldsymbol{B}/\boldsymbol{B}_0)^2 >> 1$$

This condition requires amplification of the magnetic field

Gamma-rays from SNRs:
what's wrong with DSA?

Prediction of test particle theory



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

[S. Funk, Ann.Rev.Nucl.Part.Sci. 65 (2015)]

Middle-aged SNRs
(~20.000 yrs)
- hadronic emission
- steep spectra ~E^{-3}
- $E_{\max}$ < 1 TeV

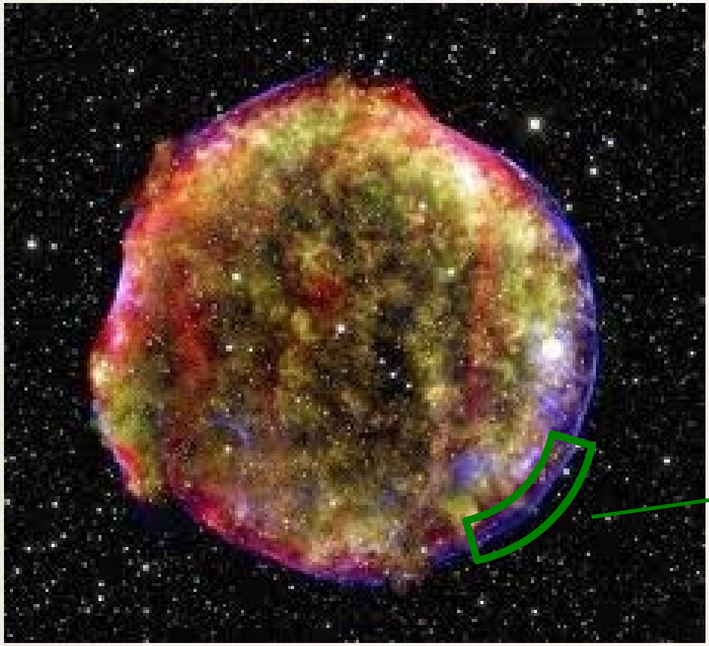
Young SNRs (~2000 yr)
- Hadronic/leptonic?
- Hard spectra
- $E_{\max}$ ~ 10-100 TeV

Very young SNRs (~300 yr)
- hadronic
- steep spectra ~$E^{-2.3}$
- $E_{\max}$ ~ 10-100 TeV

Not enough to explain the Knee at ~ PeV

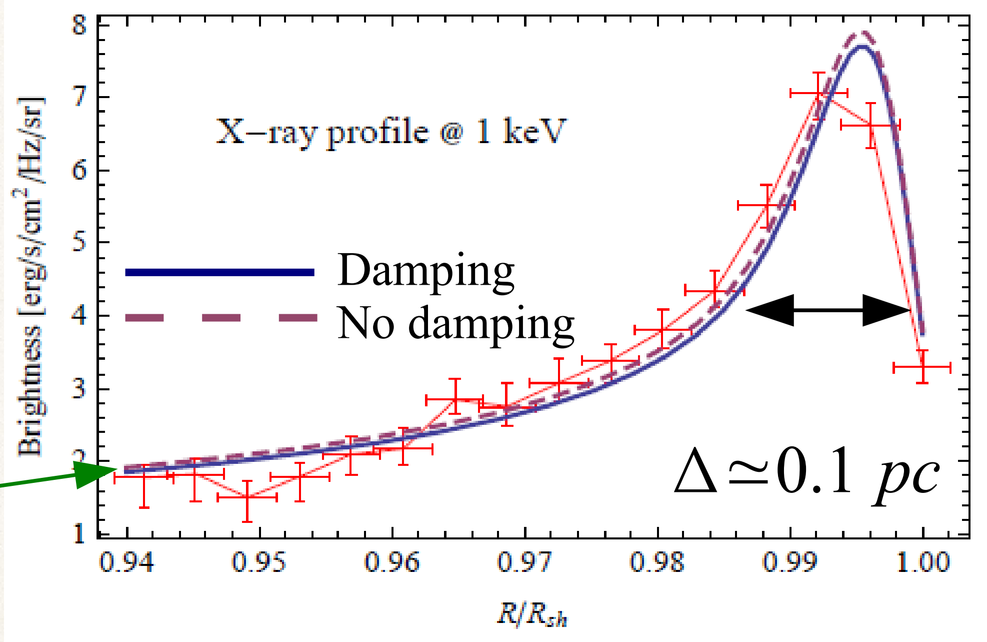
Magnetic field amplification: observations

Chandra X-ray map.
Data for the green sector are from
Cassam-Chenaï et al (2007)



Thin non-thermal X-ray filaments provide evidence for magnetic field amplification

[Hwang el al(2002); Bamba et al (2005)]



X-ray thickness = Synchrotron losslength

$$\Delta \simeq \sqrt{D\,\tau_{syn}} \propto B^{-3/2}$$

$$\begin{cases} D = r_L c/3 \propto E\,B^{-1} \\ \tau_{syn} = \dfrac{3\,m_e c^2}{4\,\sigma_T c\,\gamma \beta^2 U_B} \propto E\,B^{-2} \end{cases}$$

$\Rightarrow$ ***B*~200-300 μG >> *B*$_{\text{ISM}}$**

Magnetic field amplification: Theory 1

How is the magnetic field amplified?

Resonant straming instability

Skilling (1975),
Bell & Lucek (2001),
Amato & Blasi (2006),
Blasi (2014)

Particles amplify Alfvèn waves
with wave-number
$k_{\mathrm{res}}=1/r_{\mathrm{L}}(p)$

$$\Gamma_{CR}(k)=\frac{v_A}{B_0^2/8\pi}\frac{1}{F(k_{res})}\frac{\partial P_{CR}(>p)}{\partial z}$$

Growth rate

Fast growth rate but

$$\boxed{(\delta B/B_0)^2 \le 1}$$

→

$$E_{max}\approx 50\ TeV$$

A factor ~50 below the knee

Magnetic field amplification: Theory 2

How is the magnetic field amplified?

Non-resonant
***Bell* instability**

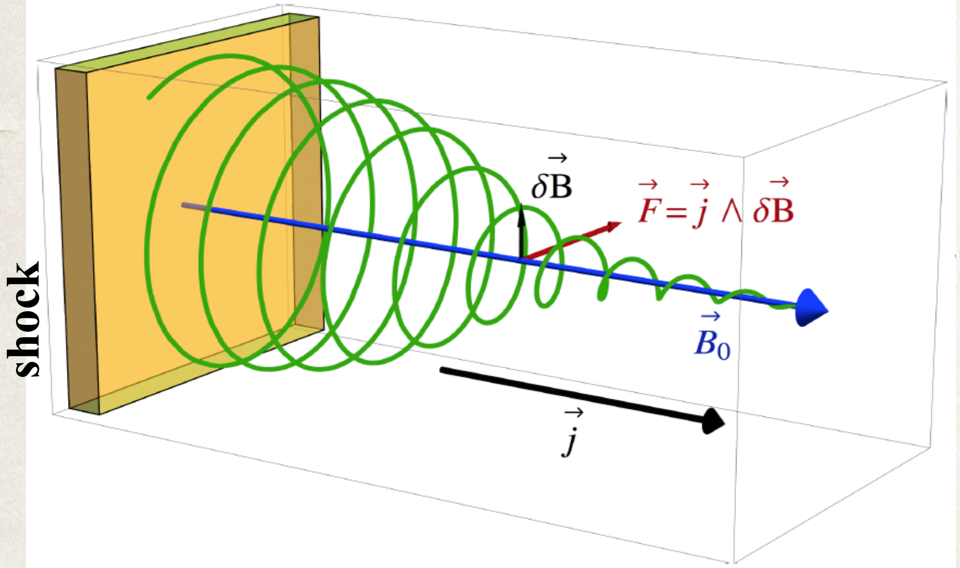
Bell (2004)
Amato & Blasi (2009)
Bell+ (2013, 2015)

Amplification due to $\vec{j} \wedge \vec{B}$ force of escaping CR current

➡ $E_{max} \propto \sqrt{\rho_{CSM}}$

Type Ia SNR expanding into a uniform medium

$$E_M \cong \frac{2e}{10c}\xi_{CR} v_0^2 \sqrt{4\pi\rho R_0^2}$$
$$= 130 \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-\frac{2}{3}}\left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)\left(\frac{n_{ISM}}{\mathrm{cm}^{-3}}\right)^{\frac{1}{6}}\mathrm{TeV}$$



Core-Collapse SNR expanding into a red supergiant wind

$$E_M \cong \frac{2e}{5c}\xi_{CR} v_0^2 \sqrt{4\pi\rho R_0^2}$$
$$\approx 1 \left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{M_{ej}}{M_\odot}\right)^{-1}\left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)\left(\frac{\dot{M}}{10^{-5} M_\odot\,\mathrm{yr}^{-1}}\right)^{\frac{1}{2}}\left(\frac{V_w}{10\,\mathrm{km\,s}^{-1}}\right)^{-\frac{1}{2}}\mathrm{PeV}.$$

Magnetic field amplification: Theory 3

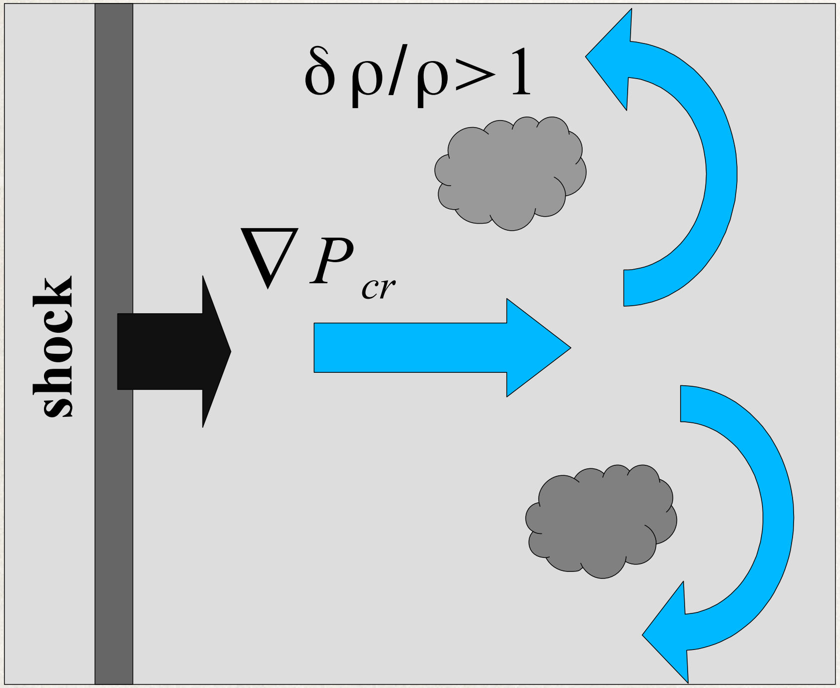
How is the magnetic field amplified?

Turbulent amplification

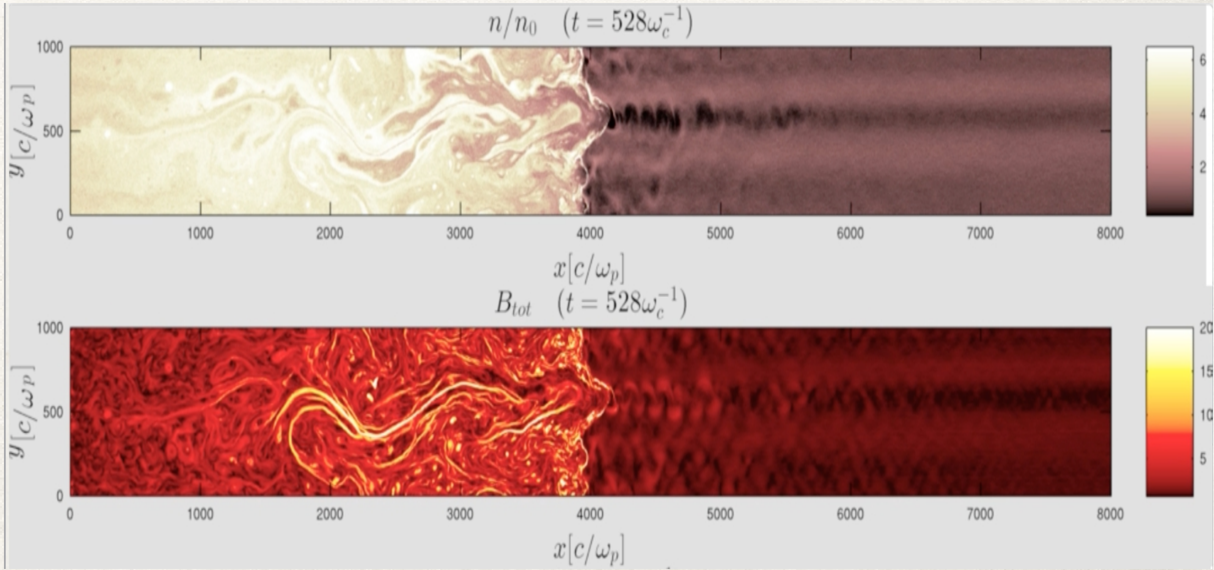
Drury & Downes (2012)
Xu & Lazarian (2017)

In presence of density discontinuities the different CR force acting onto the plasma may generate vorticity

The density discontinuity can be generated even through the non-resonant instability → filamentation



Confirmed by PIC simulations
[Caprioli & Spitkovsky (2013)]



Multiwavelength spectrum of Tycho

[G.M. & D. Caprioli, 2012]

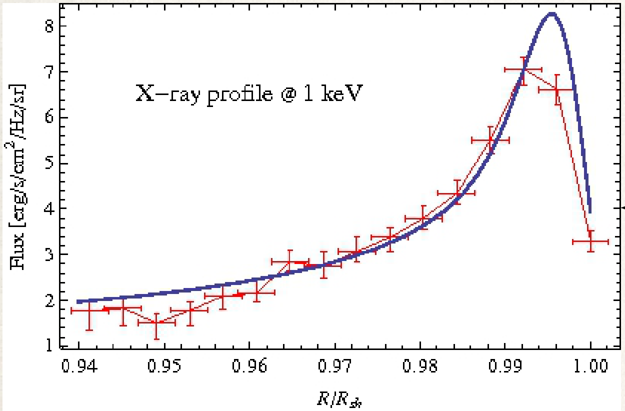
Simultaneous fit of multi-wavelength spectrum with non-linear DSA model

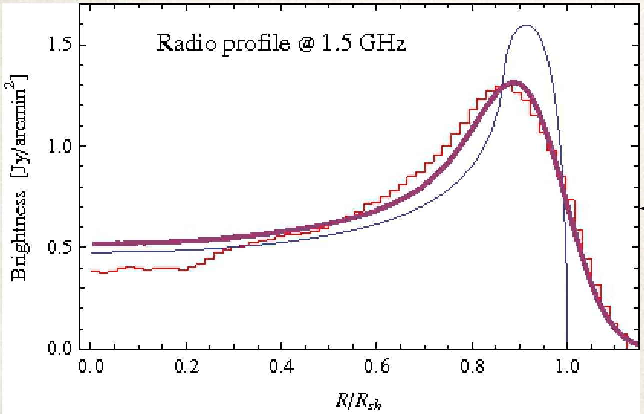
1) Maximum energy of ions $E_{max} = 470\,TeV$

2) Non-thermal spectrum $N(E) \propto E^{-2.3}$

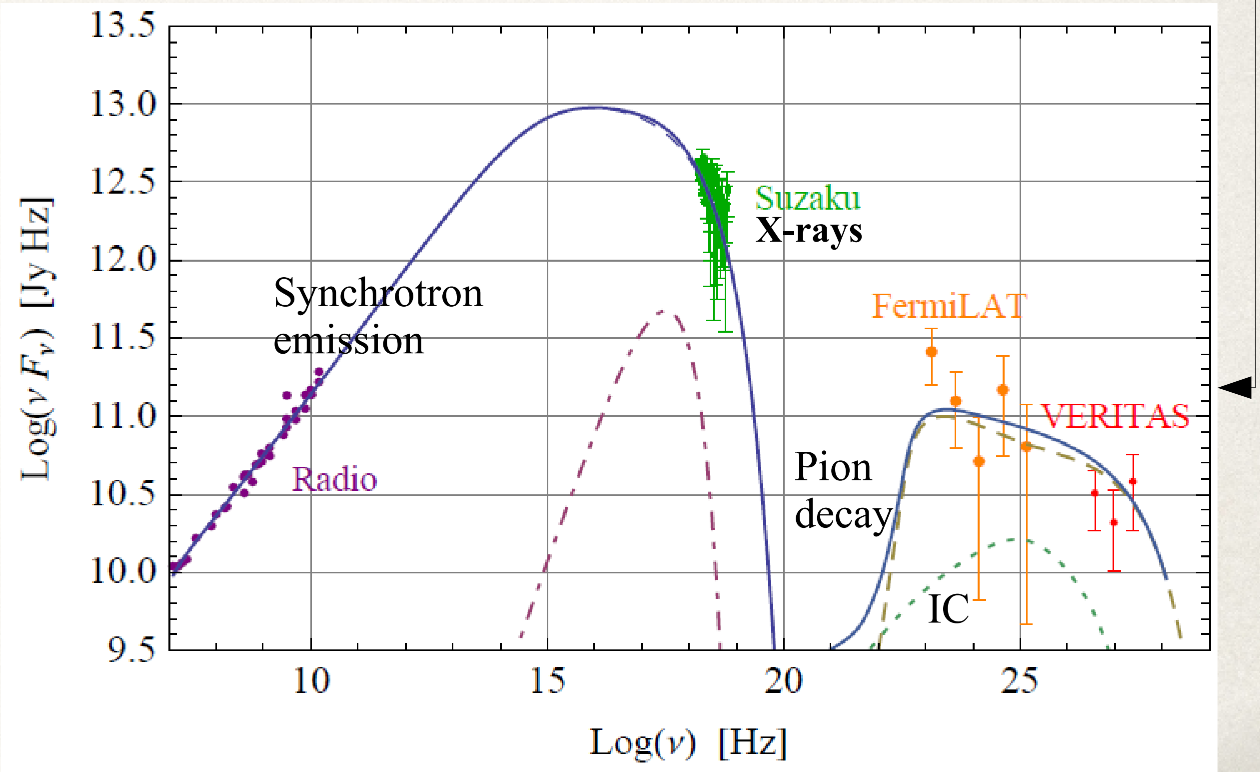
3) Amplified magnetic field $\delta B_2 \approx 300\,\mu G$

4) TOTAL CRs ENERGY ! CR = 12% ESN





Results for the Tycho's remnant



Multiwavelength spectrum of Tycho

[G.M. & D. Caprioli, 2012]

wavelength spectrum with non-linear

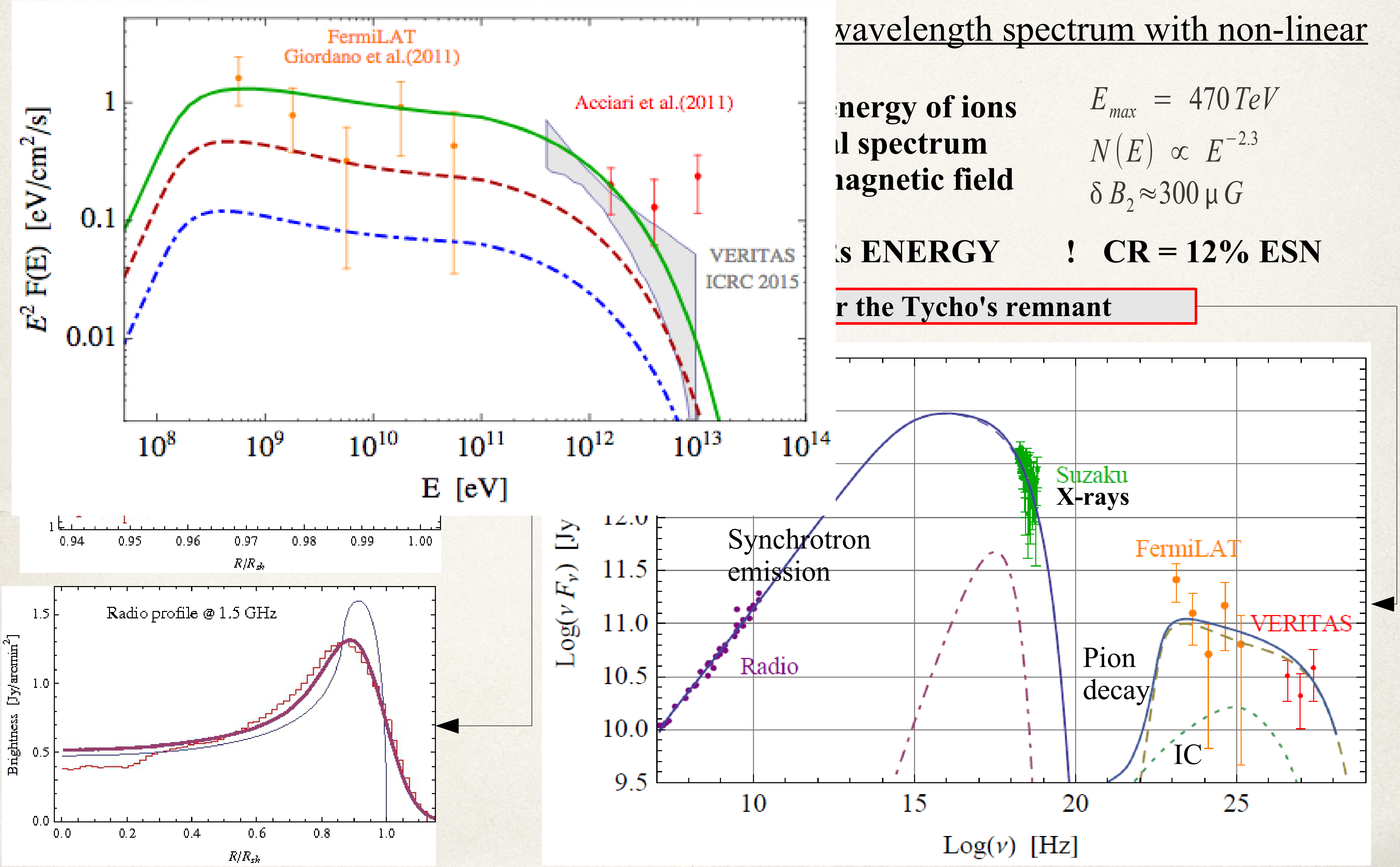
nergy of ions $E_{max} = 470\,TeV$

l spectrum $N(E) \propto E^{-2.3}$

nagnetic field $\delta B_2 \approx 300\,\mu G$

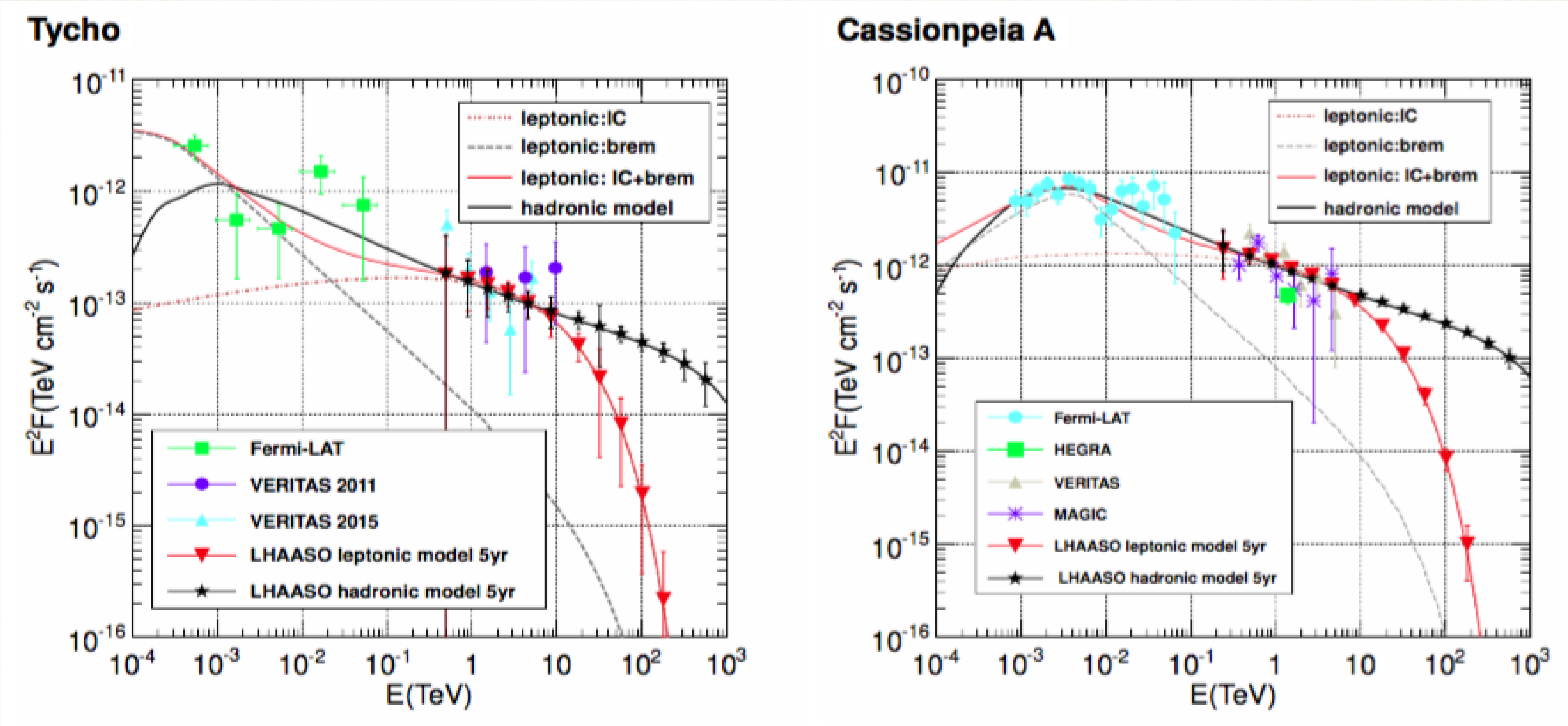
s ENERGY ! CR = 12% ESN

r the Tycho's remnant



Young SNRs with LHAASO

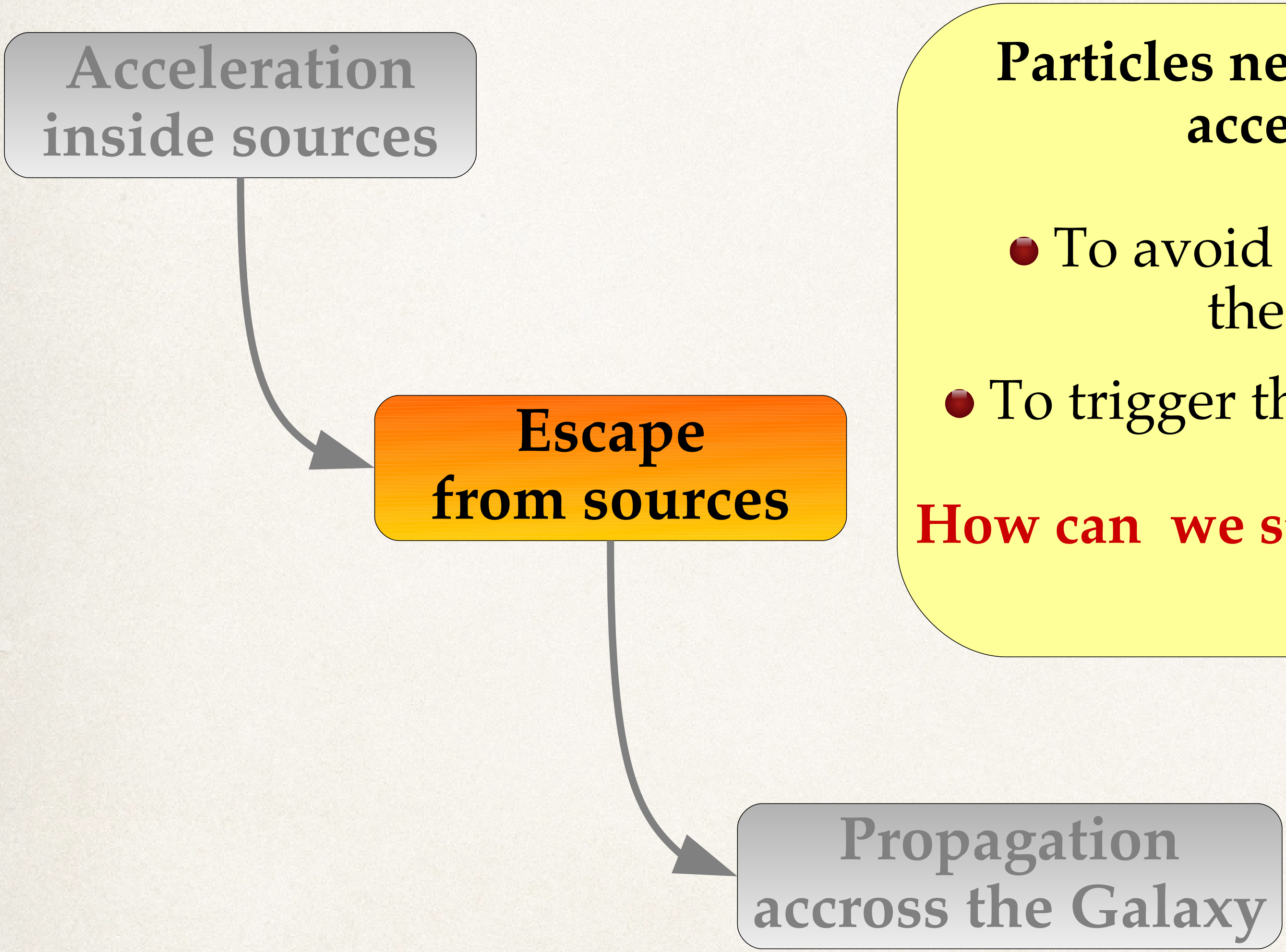
(LHAASO Science White Paper, arXiv:1905.02773v1)



Conclusions: *acceleration*

- From observations the $f(p) \propto p^{-4}$ is almost never realized:
  - Do we lack some foundamental element in the theory?
    - Role of scattering centers?
  - Important environmental effects?
    - Presence of neutrals?
    - Clumpy media?
- Amplification of turbulence up to $\delta B \sim B_0$ allow to reach E_{max} ~ 10-100 TeV
- Bell instability is required to reach E_{max} ~ 1 PeV (and possibly not sufficient… needs M_{ej} ~1 M_{sol}) **Maybe the turbulent amplication can help**
- **LHAASO will distinguish between leptonic and hadronic scenarios in young SNRs, allowing to determine the maximum energy**

Why escape?



Acceleration inside sources

Escape from sources

Propagation accross the Galaxy

Particles need to escape *during* the acceleration process

- To avoid adiabatic losses during the SNR expantion
- To trigger the non-resonant instability

How can we study the escaping process?

Diffusion near the CR sources

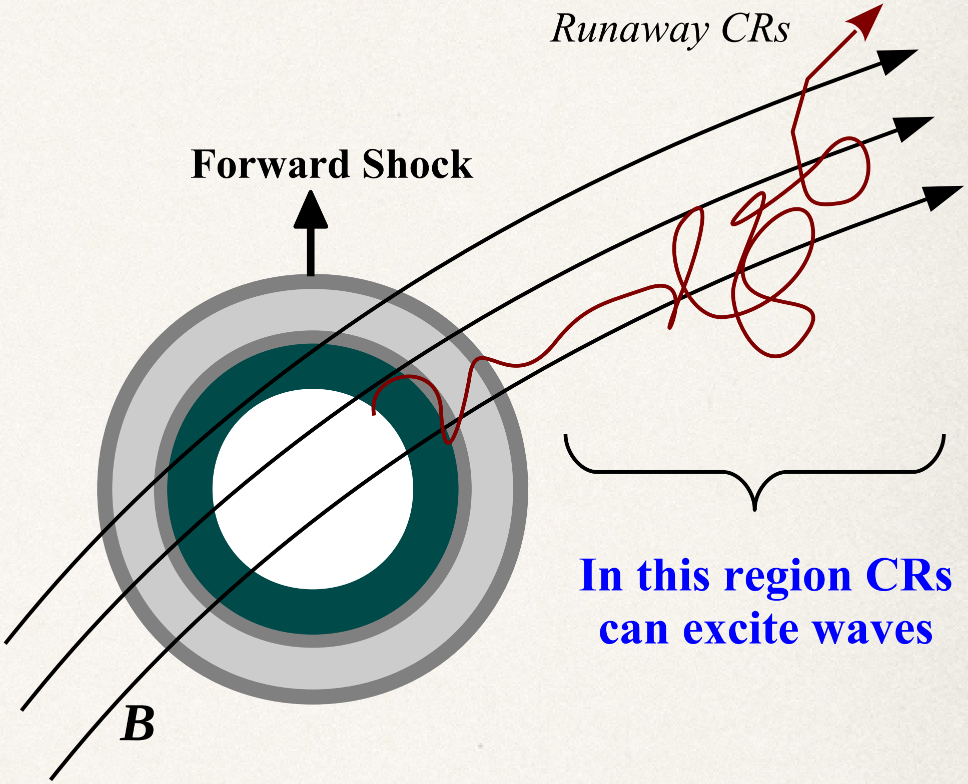
Diffusion outside the sources can be different from the average Galactic diffusion:

- Local turbulence may be stronger than the average Galactic turbulence
- During the process of escaping, CR can excite magnetic turbulence (via streaming instability) that keep the CR close to the SNR for a long time, up to ~10^5 yr [Malkov+(2013), Nava+(2015)]

⇓

The diffusion coefficient may be strongly reduced

Also supported by **TeV halos** detected around PWNe



A simplified analitical model: shock acceleration

Particle spectrum at the shock according to diffusive shock acceleration (see Ptuskin & Zirakashvili, 2005)

$$f_{sh}(p,t) = \frac{3\xi_{cr} u_{sh}(t)^2 \rho_0}{4\pi c (m_p c)^{4-\alpha} \Gamma(p_{max})} p^{-s} \theta(p - p_{max}(t))$$

acceleration efficiency
ξ_{cr} ~ *few* % (constant in time)

s free parameter (~ 4 from of DSA)

Normalization constant such that $P_{CR} = \xi_{cr} \rho_0 u_{sh}^2$

Further assumptions:
1. Spherical symmetry of the remnant;
2. Sedov-Taylor phase

$$\begin{cases} R_{sh}(t) = \left(\dfrac{\xi_0}{\rho_0} E_{SN}\right)^{1/5} t^{2/5} \\ u_{sh}(t) = \dfrac{2}{5} \left(\dfrac{\xi_0}{\rho_0} E_{SN}\right)^{1/5} t^{2/5} \end{cases}$$

A simplified model for particle escape

(Celli, GM, Gabici, Aharonian, 2019)

Maximum momentum

$$p_{max}(t) = p_{MAX}\left(\frac{t}{t_{Sed}}\right)^{-\delta};$$

Approximation largely used in the literature

p_{MAX} PeV/c

↓

If $p > p_{\mathrm{max}}(t)$ → particles start escaping

Escaping time

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

is unknown and depends on both the shock speed and the magnetic field amplification.

A simplified model for particle escape

(Celli, GM, Gabici, Aharonian, 2019)

Simple estimate of δ:

$$\left\{\begin{array}{l} t_{acc} \simeq D / u_{sh}^{2} \\ \\ D(p) = D_{Bohm}(p)\left(\dfrac{\delta B}{B_0}\right)^{-2} \end{array}\right. \xrightarrow{t_{acc}(p_{max}) = t_{SNR}} p_{max} \propto \left(\dfrac{\delta B}{B_0}\right)^{2} u_{sh}^{2}(t)\, t$$

No magnetic field amplification: $\left(\dfrac{\delta B}{B_0}\right)^{2} = const\,; \quad u_{sh} \propto t^{-3/5} \rightarrow \boxed{\delta = 1/5}$

Amplification is due to streming instability: $\left(\dfrac{\delta B}{B_0}\right)^{2} \propto P_{CR} \propto u_{sh}(t)^{2} \rightarrow \boxed{\delta = 7/5}$

Amplification is due to Bell instability: $\left(\dfrac{\delta B}{B_0}\right)^{2} \propto P_{CR} \propto u_{sh}(t)^{3} \rightarrow \boxed{\delta = 2}$

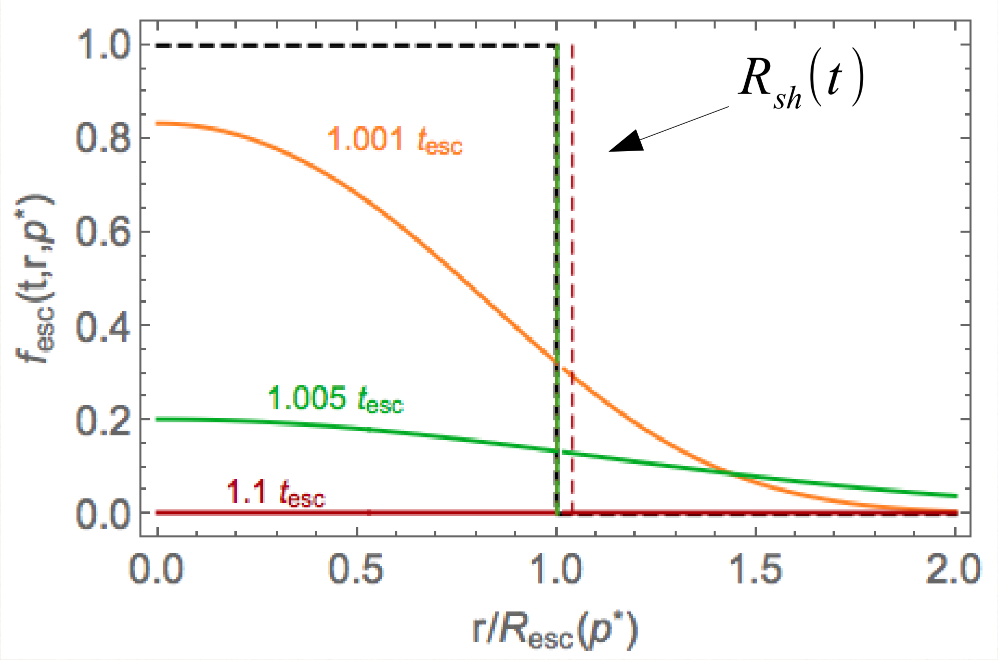
Particle escape: an example

(Celli, GM, Gabici, Aharonian, 2019)

From Boron/Carbon: $D_{Gal} \simeq 3\times 10^{28}\left(\frac{p}{m_p c}\right)^{1/3} cm^2 s^{-1}$

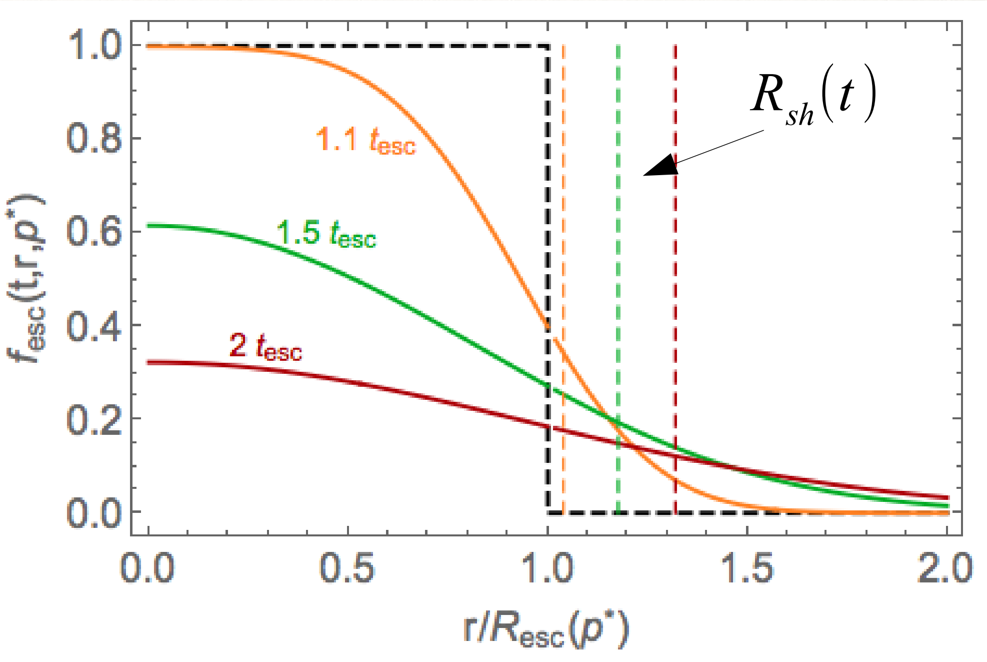
Instantaneous escape

$D_{ext} = D_{Gal}$



Delayed escape

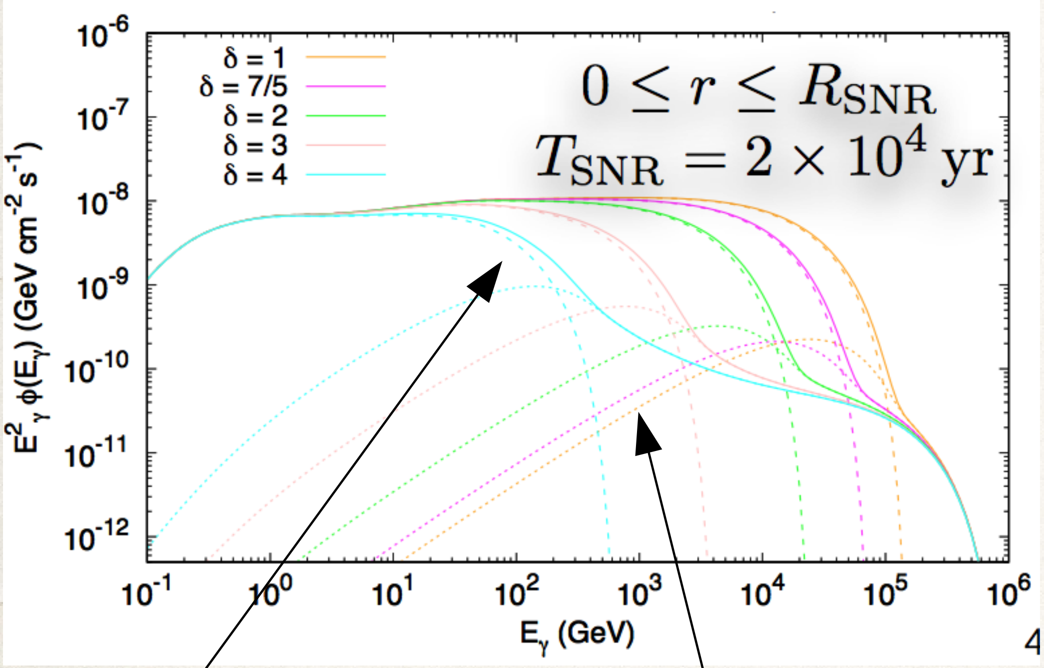
$D_{ext} = D_{Gal}/300$



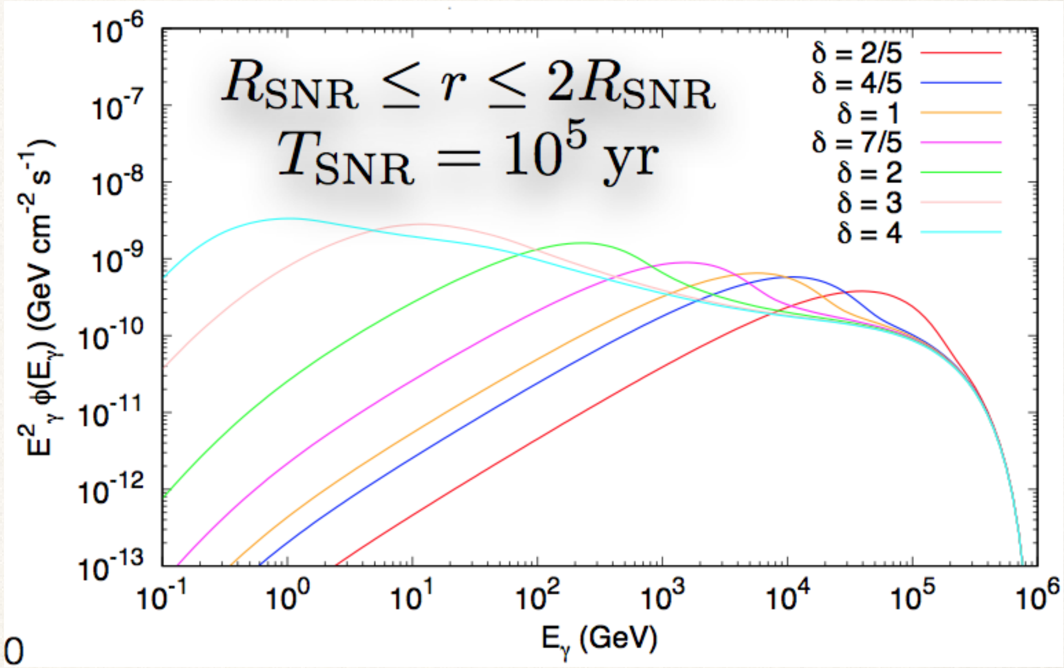
Volume integrated gamma-ray flux from the SNR interior

(Celli, GM, Gabici, Aharonian, 2019)

Emission from the SNR interior



Emission from the SNR exterior



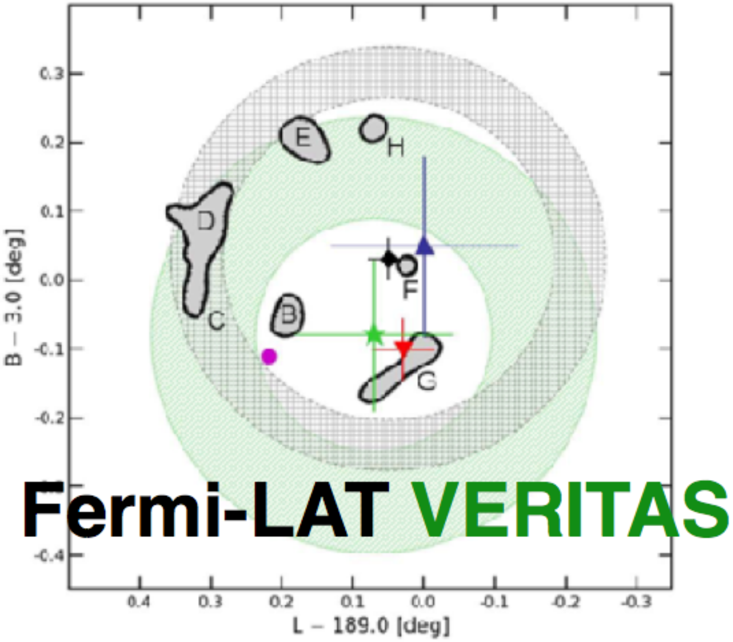
Confined particles

Non-confined particles

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

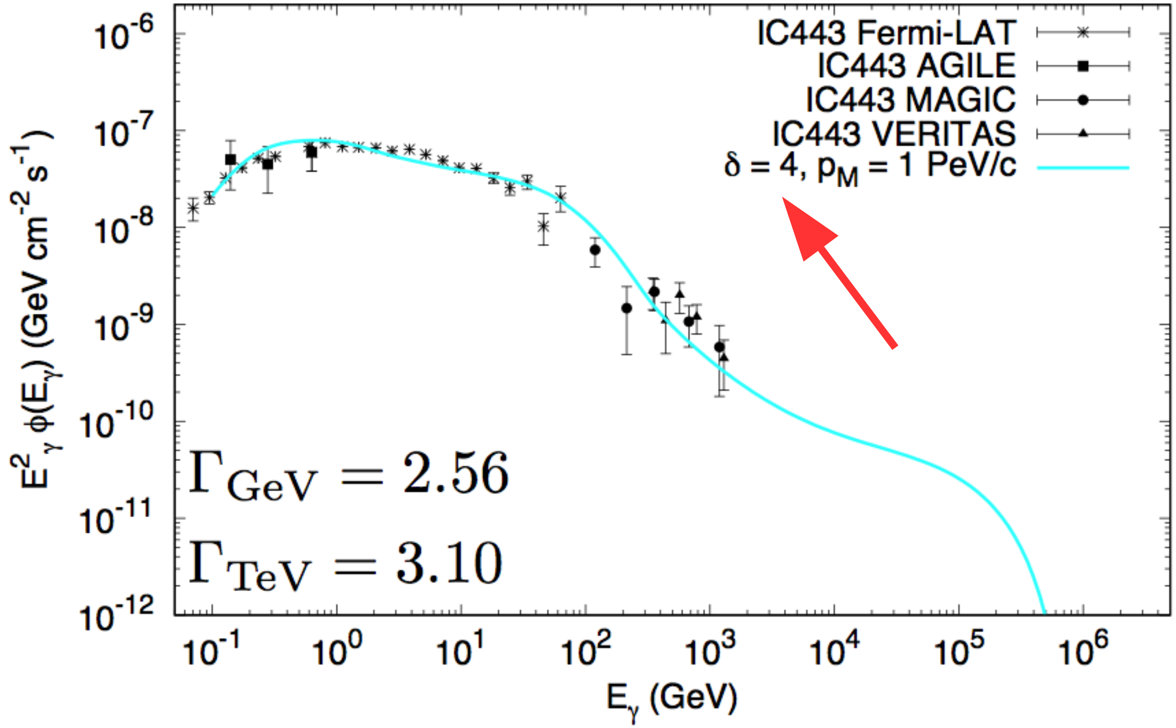
The presence of escaping particles close to the SNR mainly depends on δ and $D_{\rm ext}$

Middle-aged SNRs: IC 443



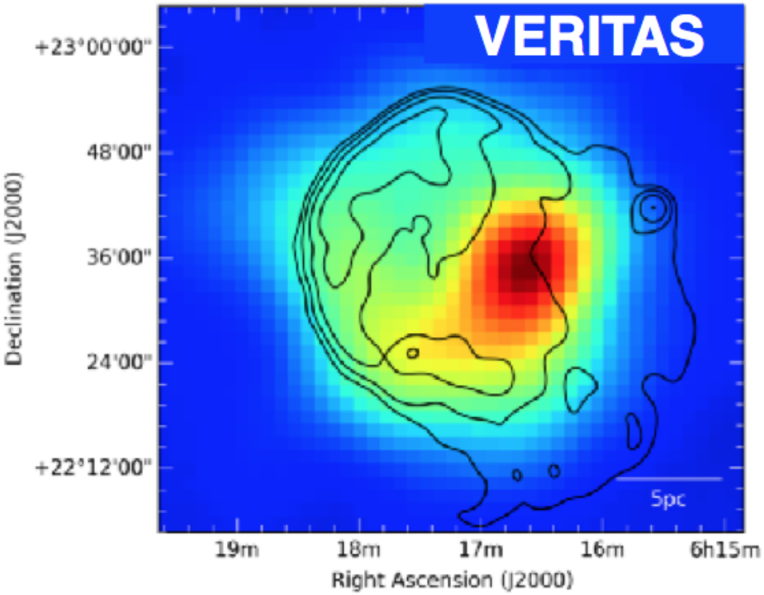
Fermi-LAT **VERITAS**

$\alpha_R = 0.36 \rightarrow s = 1.72$



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

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



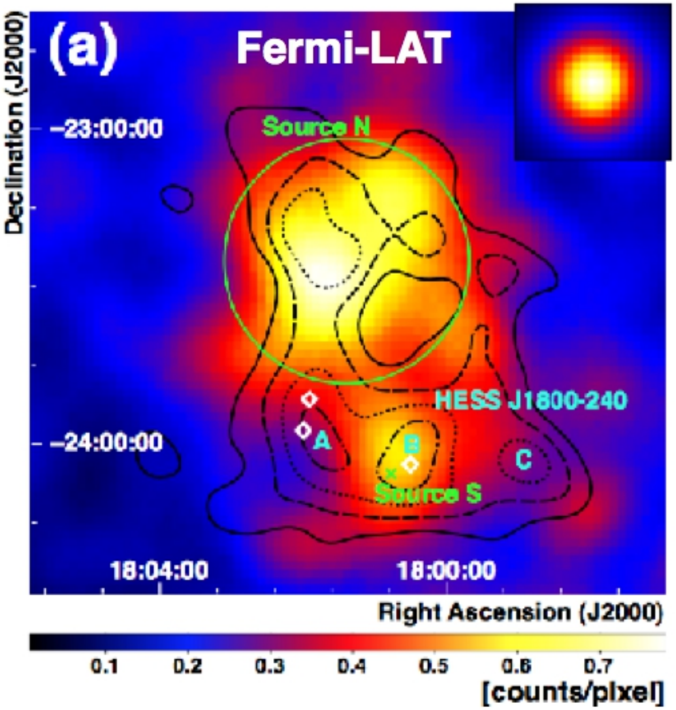
$$f_0(p) \propto p^{-(4+1/3)}$$

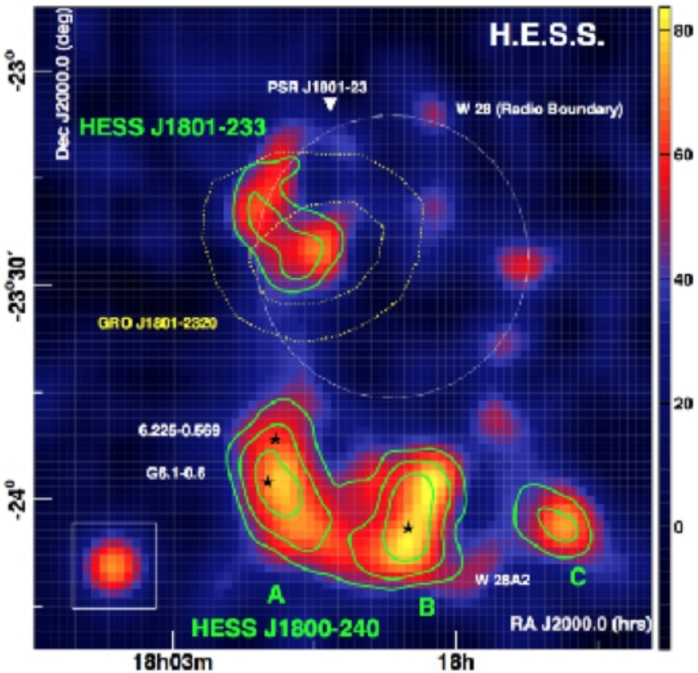
$$T_{\rm SNR} = 10^4\,{\rm yr},\ n_{\rm up} = 10\,{\rm cm}^{-3}$$

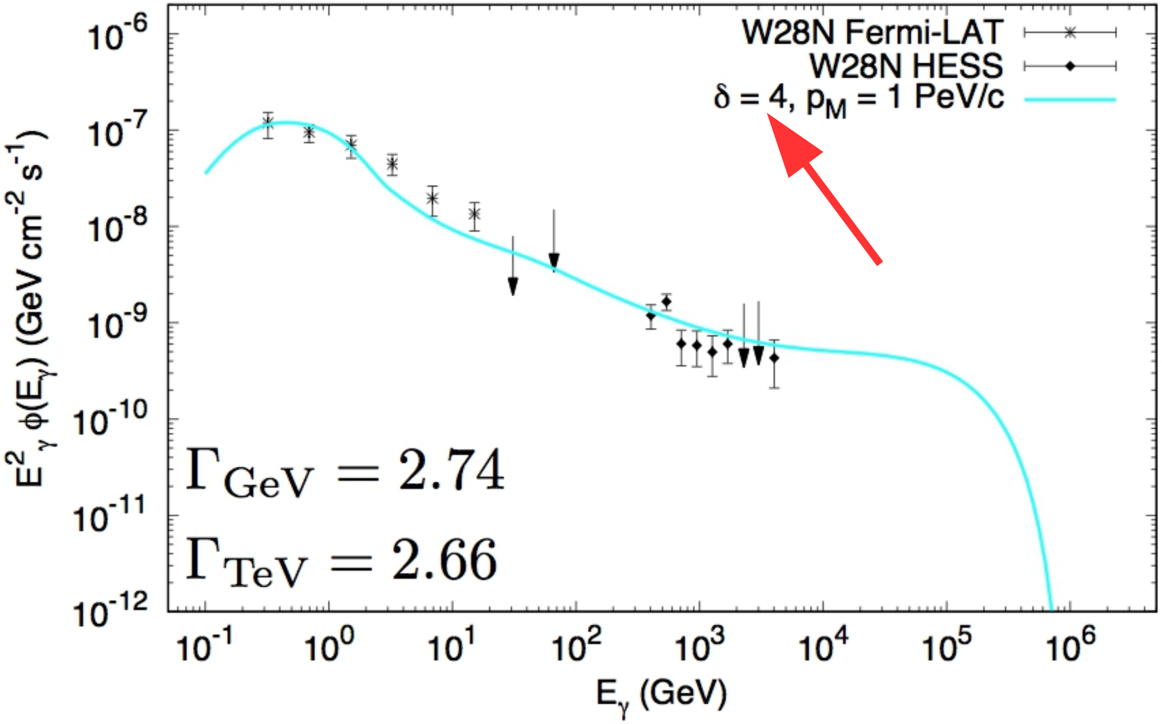
$$D(10\,{\rm GeV/c}) = 10^{27}\,{\rm cm}^2/{\rm s}$$

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

Middle-aged SNRs: W 28N







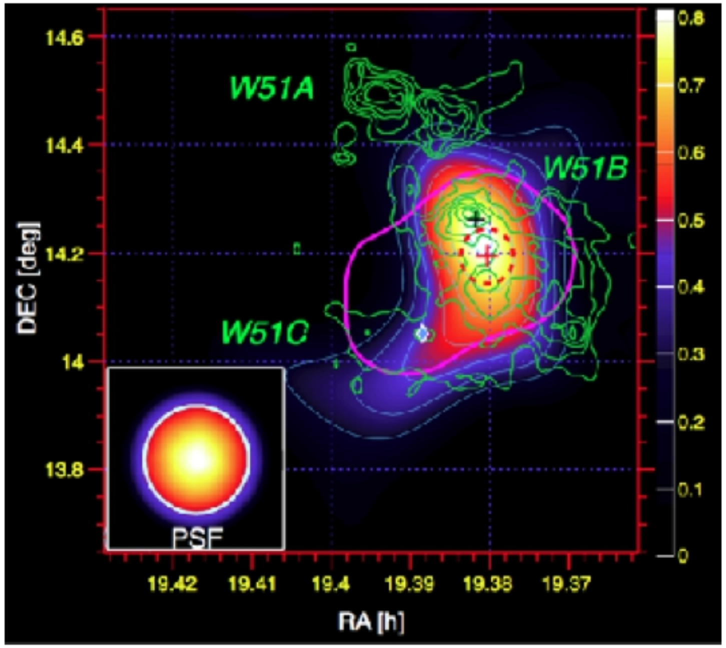
$$f_0(p) \propto p^{-4}$$

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

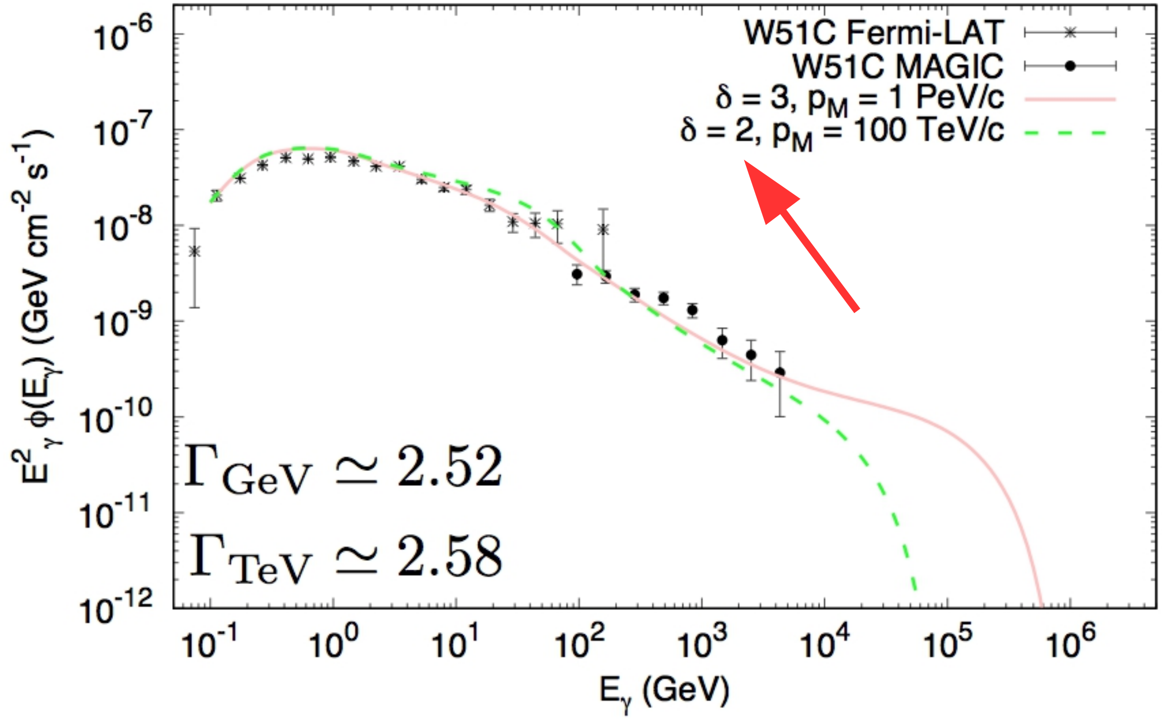
$$D(10\,{\rm GeV/c}) = 3 \times 10^{27}\,{\rm cm}^2/{\rm s}$$

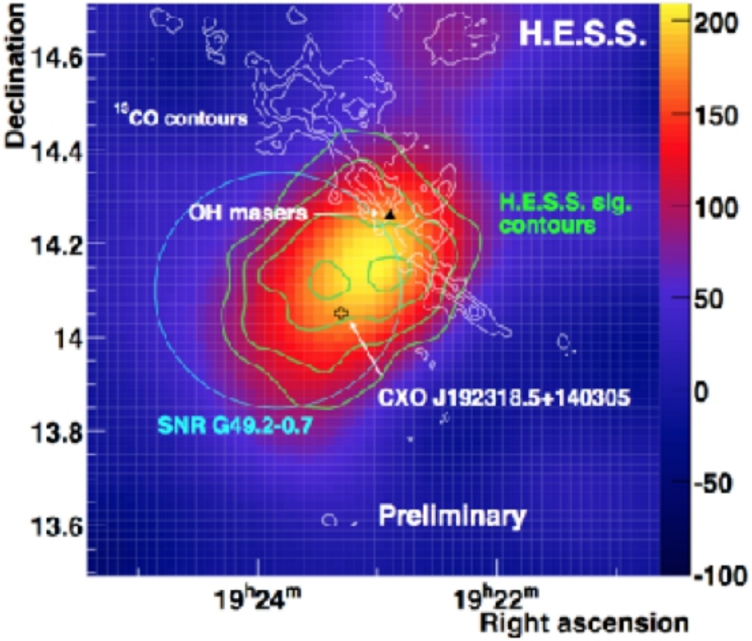
$$\xi_{\rm CR} \simeq 15\%$$

Middle-aged SNRs: W 51C



$\alpha_R = 0.26 \;\rightarrow\; s = 1.52$





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

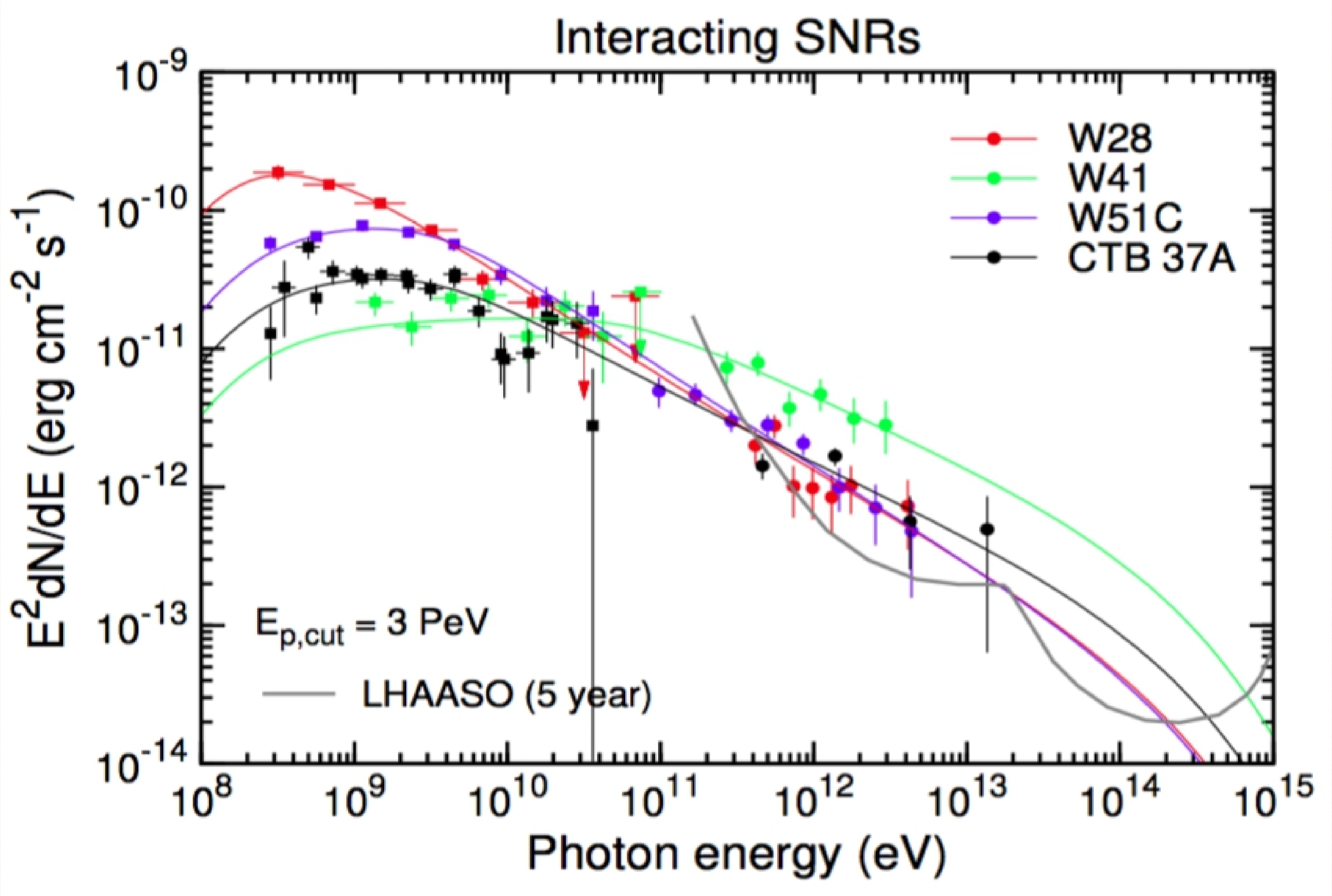
$$T_{\mathrm{SNR}} = 3 \times 10^4\,\mathrm{yr},\; n_{\mathrm{up}} = 10\,\mathrm{cm}^{-3}$$

$$D(10\,\mathrm{GeV/c}) = 3 \times 10^{26}\,\mathrm{cm}^2/\mathrm{s}$$

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

Interacting SNRs with LHAASO

(LHAASO Science White Paper, arXiv:1905.02773v1)



Escaping of electrons

It is often assumed that electrons are confined inside the SNR until the end of the acceleration phase

This depend on the magnetic field amplified by protons

$$\text{CR protons} \Rightarrow \delta \boldsymbol{B} \Rightarrow \text{Electrons} \begin{cases} \text{- Losses} \\ \text{- Confinement} \end{cases}$$

If amplification not strong enough → electrons start escaping like protons

Escaping electron can produce a diffuse gamma-ray halo independent of circumstellar density

Can we test the electrons escaping scenario?

If $\delta \boldsymbol{B}$ is amplified only by protons → electron spectrum is univocally determined

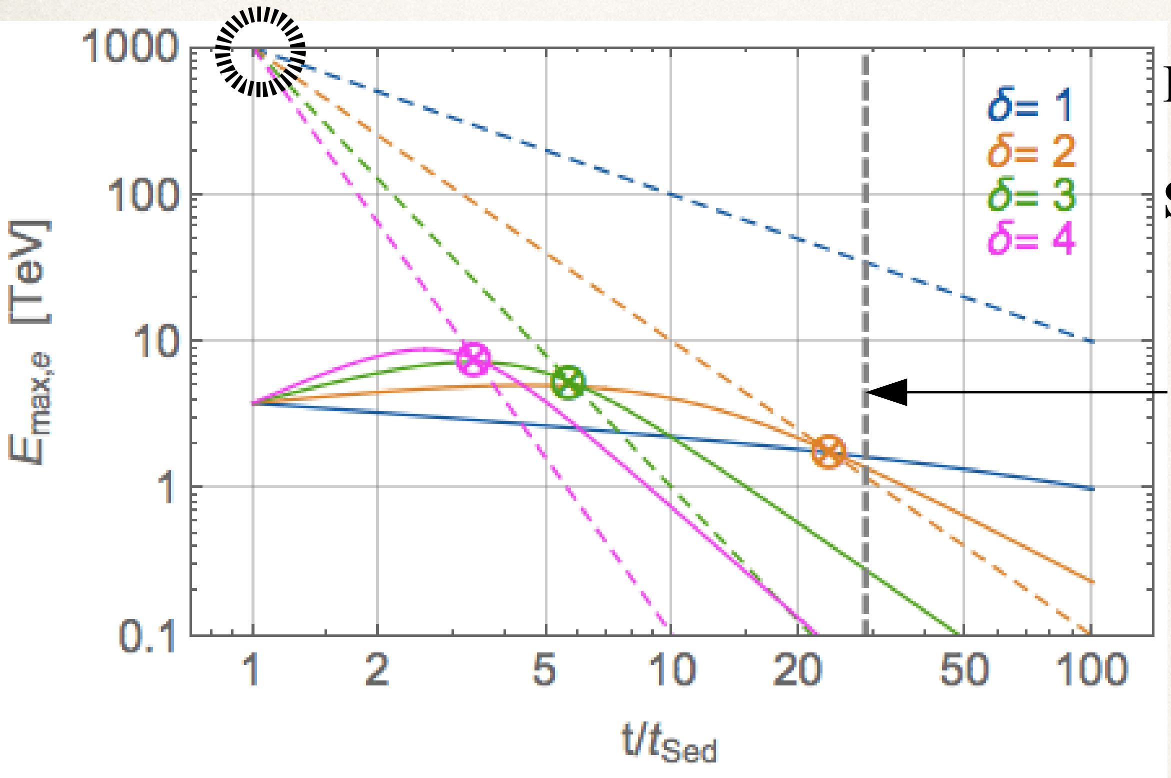
Escaping of electrons

(GM & S. Celli, 2020 - preliminary)

Maximum energy of electrons compared to protons

$$E_{max,el}=min[E_{max,p}, t_{acc}=t_{losses}]$$

1 PeV



Dashed – Proton's $E_{max} \sim t^{-\delta}$

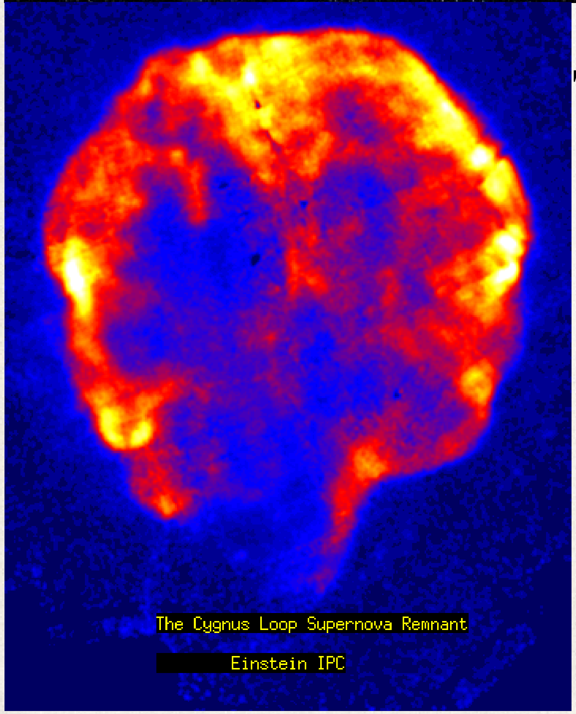
Solid – Electron's E_{max} determined by losses

Beginning of radiative phase (acceleration stops here)

- If δ < 2 ➔ electrons never escape during the ST phase
- $E_{max,el}$ <~ 10 TeV

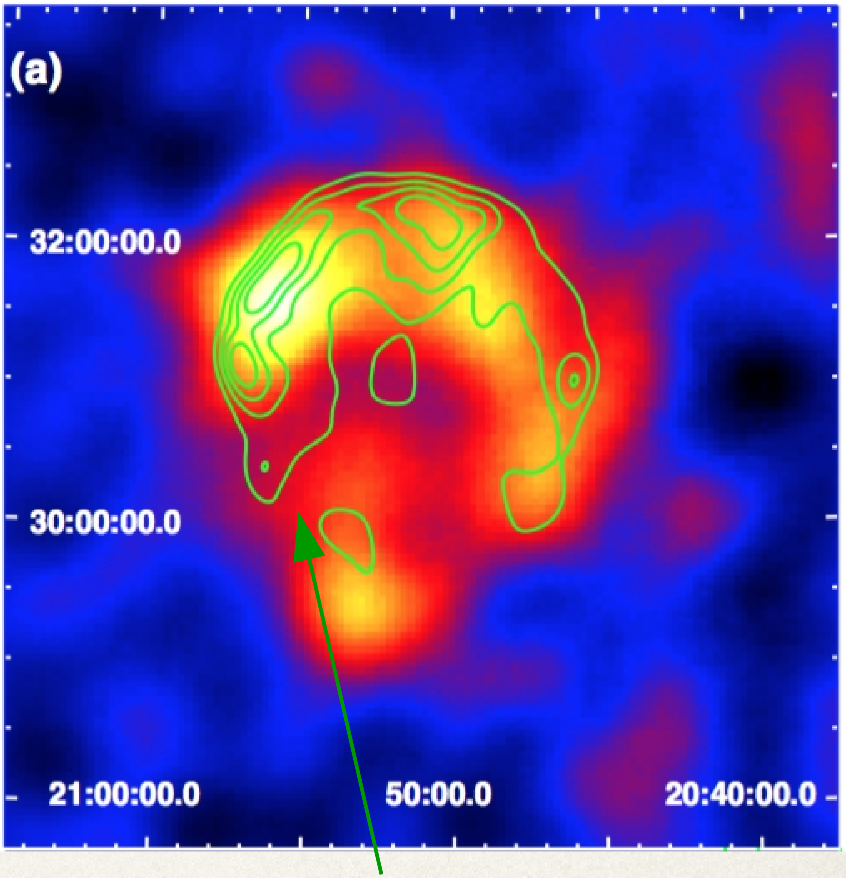
The Cygnus Loop SNR

Optical Hα



Thermal X-rays

Gamma-rays from Fermi-LAT [0.2-10 GeV]



Radio

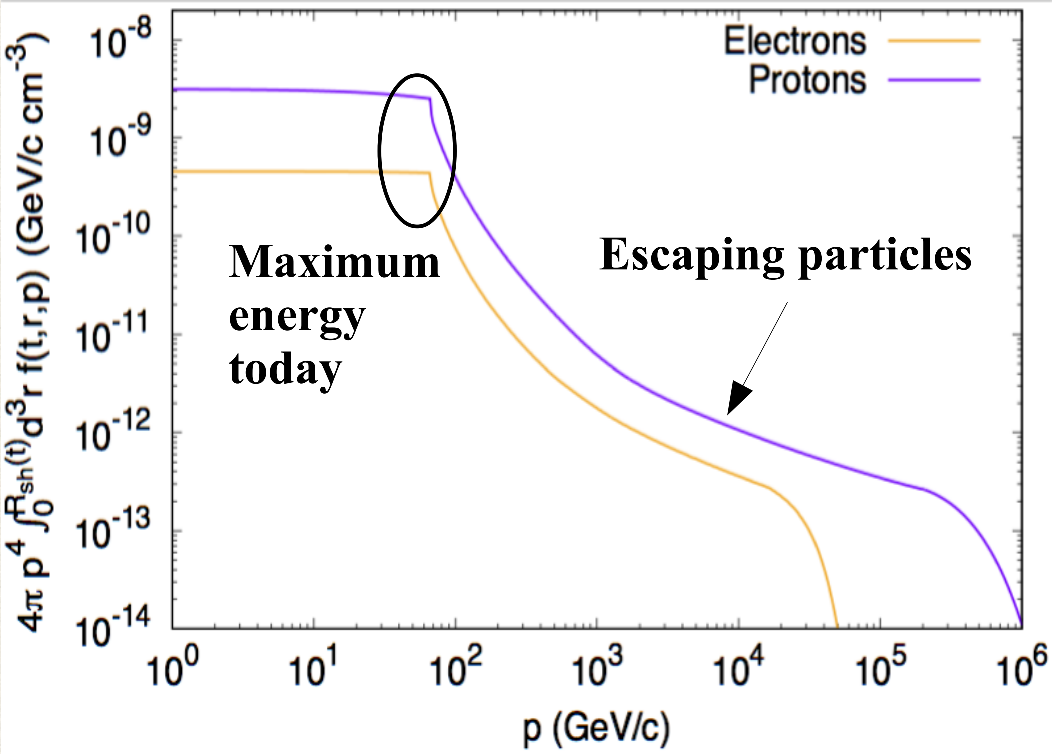
The Cygnus Loop: particle spectrum

(Loru, GM, S. Celli et al., 2020 submitted)

- Upstream density: $n_0 = 0.4\ \mathrm{cm^{-3}}$
- Ejecta mass: $M_{ej} = 5\ M_{sun}$
- Kinetic energy of blast wave: $E_{SN} = 0.7 \times 10^{51}$ erg
- $d = 735$ pc
- Remnant age: $T_{SNR} = 21$ kyr

Fesen et al (2018)

Fitting radio and gamma ray observations we get the Distribution of particles inside the SNR at $t = T_{SNR}$



Maximum energy today

Escaping particles

The magnetic field at the shock is small

$$\delta B \ll B_0$$

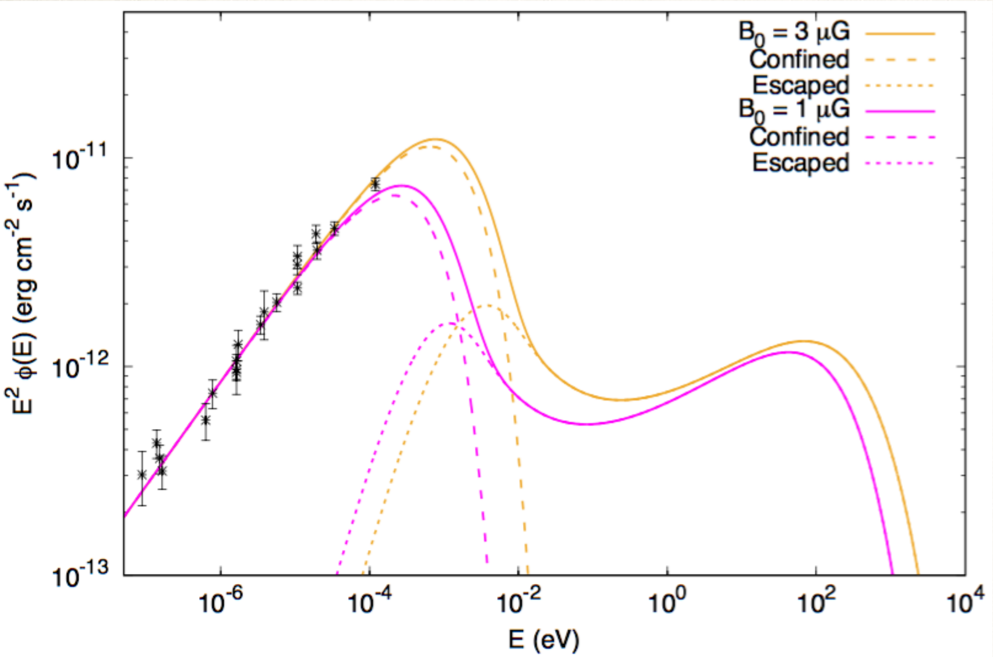
Maximum energy today is determined by escape

$$E_{max,el} = E_{max,p}$$

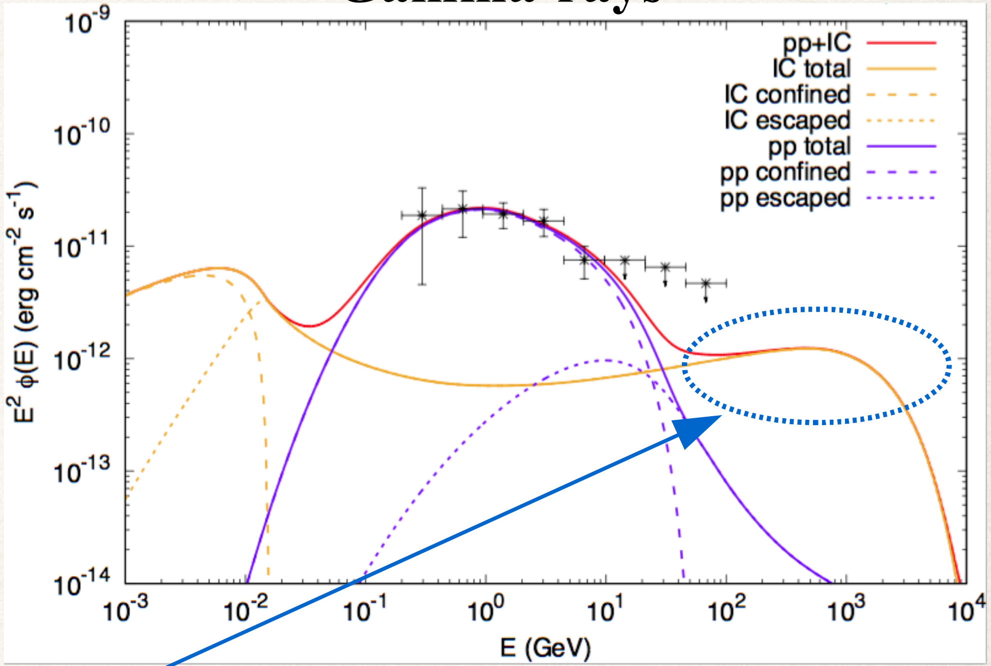
The Cygnus Loop: multiwavelength spectrum

(Loru, GM, S. Celli et al., 2020 submitted)

Radio



Gamma-rays



Escaping electrons can still produce a relevant TeV emission while protons don't. Current IACTs cannot easily detect such emission because the large size of the SNR ➡ **LHAASO can make the difference thanks to the large field of view**

Effect of self-amplification near the CR sources

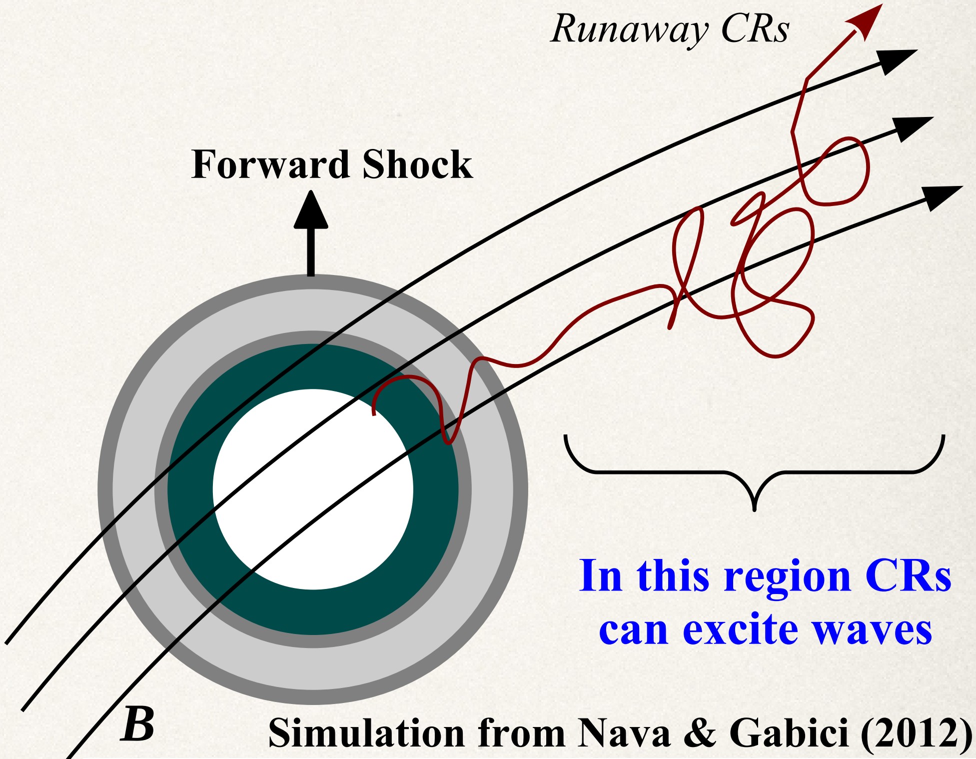
Escaping particles can produce large halos around SNRs (similar to the one observed from some PWNe)

- Confinement can be enhanced thanks to streaming instability of run away particles

- The Halo size is at most of the order of the coherence-length of the magnetic field (after this distance the diffusion becomes 3D and the CR density drops rapidly below the average Galactic value)

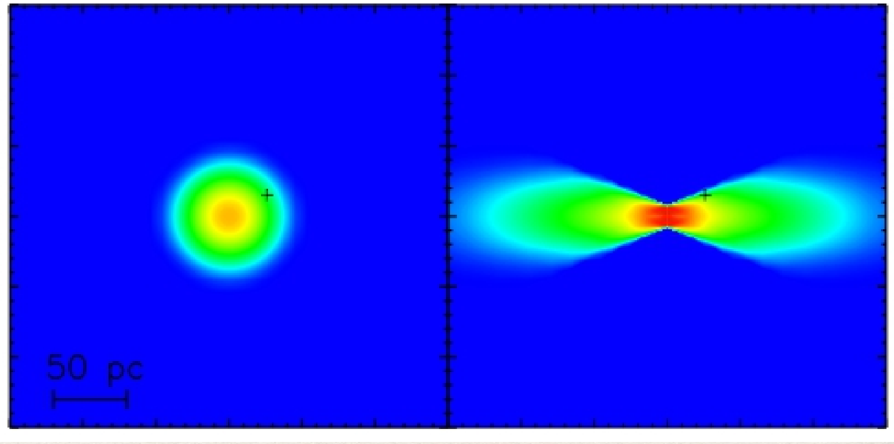
Understanding these halos is important to:

- interpret the diffuse gamma-ray emission
- estimate the CRs content in the Galaxy



In this region CRs can excite waves

Simulation from Nava & Gabici (2012)



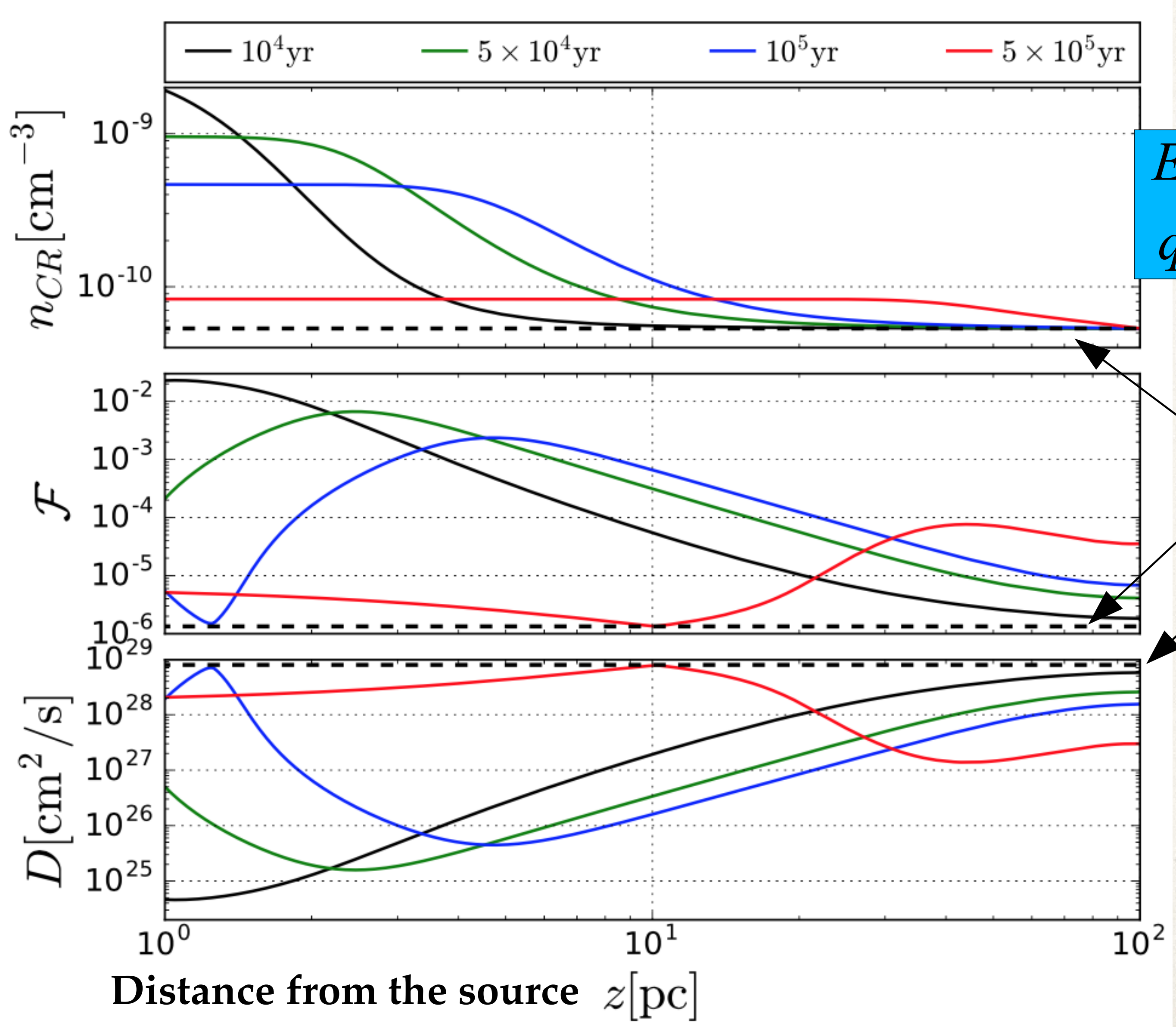
Evolution of CR density close to the source

[D'Angelo, GM, Amato, Blasi, 2018]

CR distribution function @ 10 GeV for several ages

Distribution function of turbulence

Diffusion coefficient



$E_{CR}=0.2\,E_{SN}$

$q_{inj}(p)\propto p^{-4}$

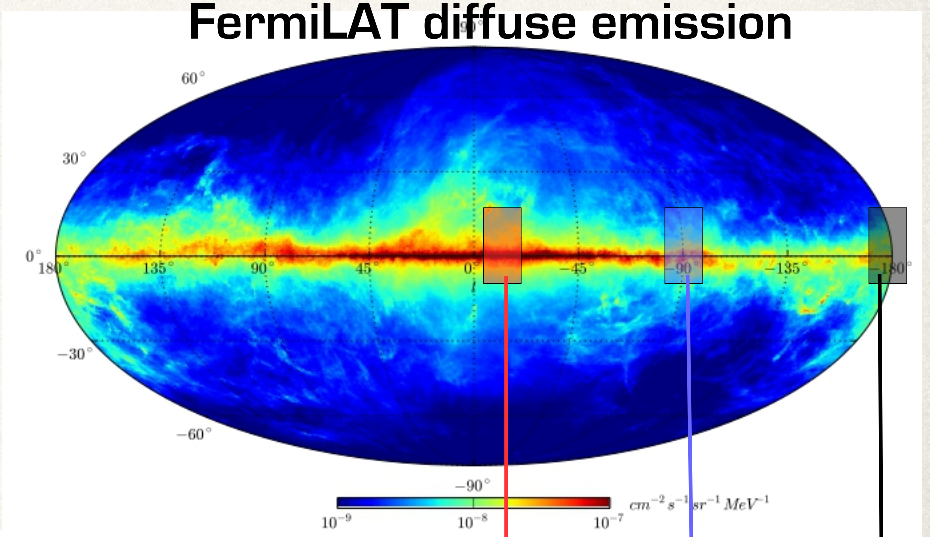
Average Galactic level

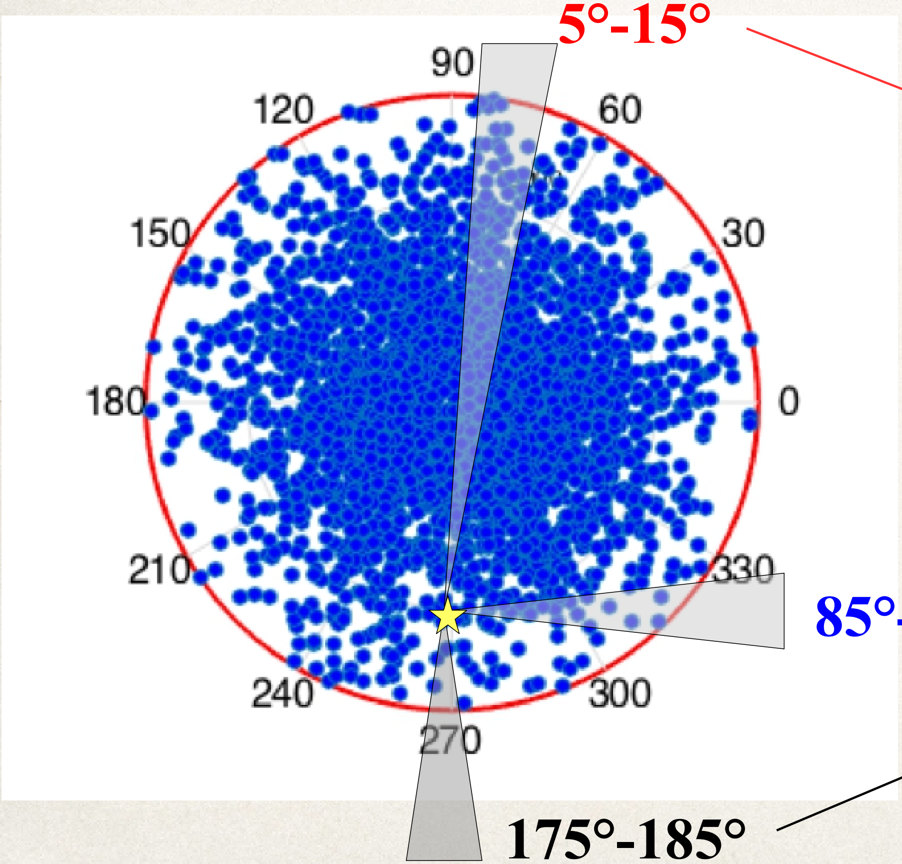
Importance of halos for diffuse Galactic emission

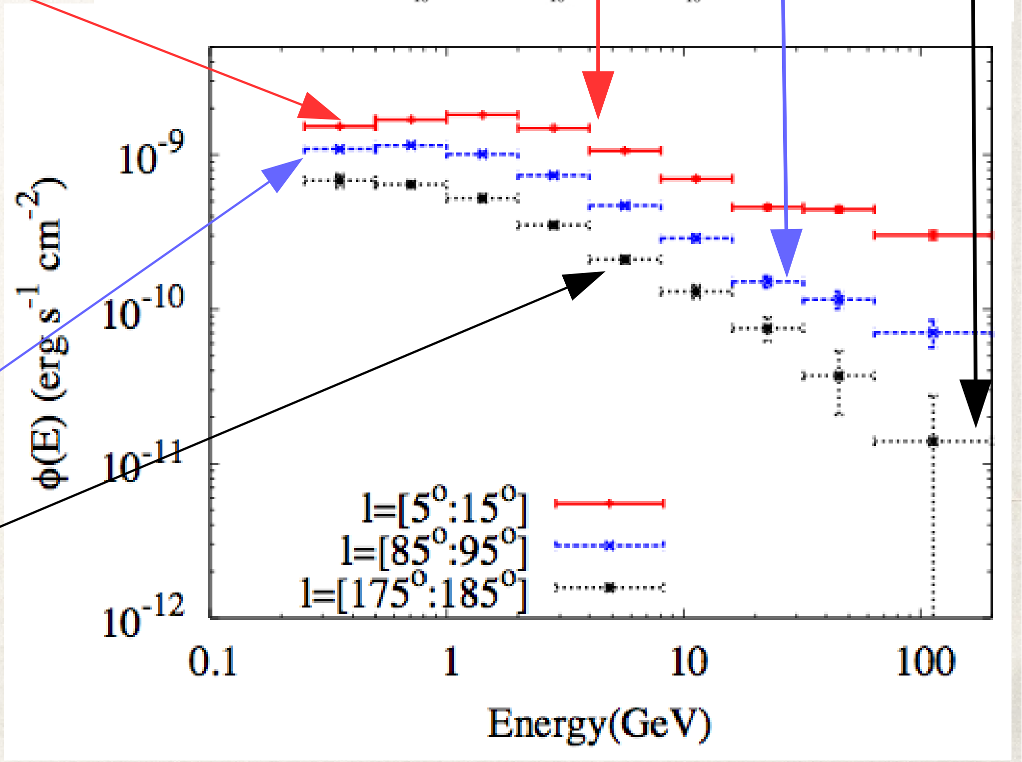
[D'Angelo, GM, Amato, Blasi, 2018]

Diffuse Galactic γ-ray flux for three different angular sectors extracted from the Fermi-LAT data
[Yang, Aharonian & Evoli, 2016]

FermiLAT diffuse emission



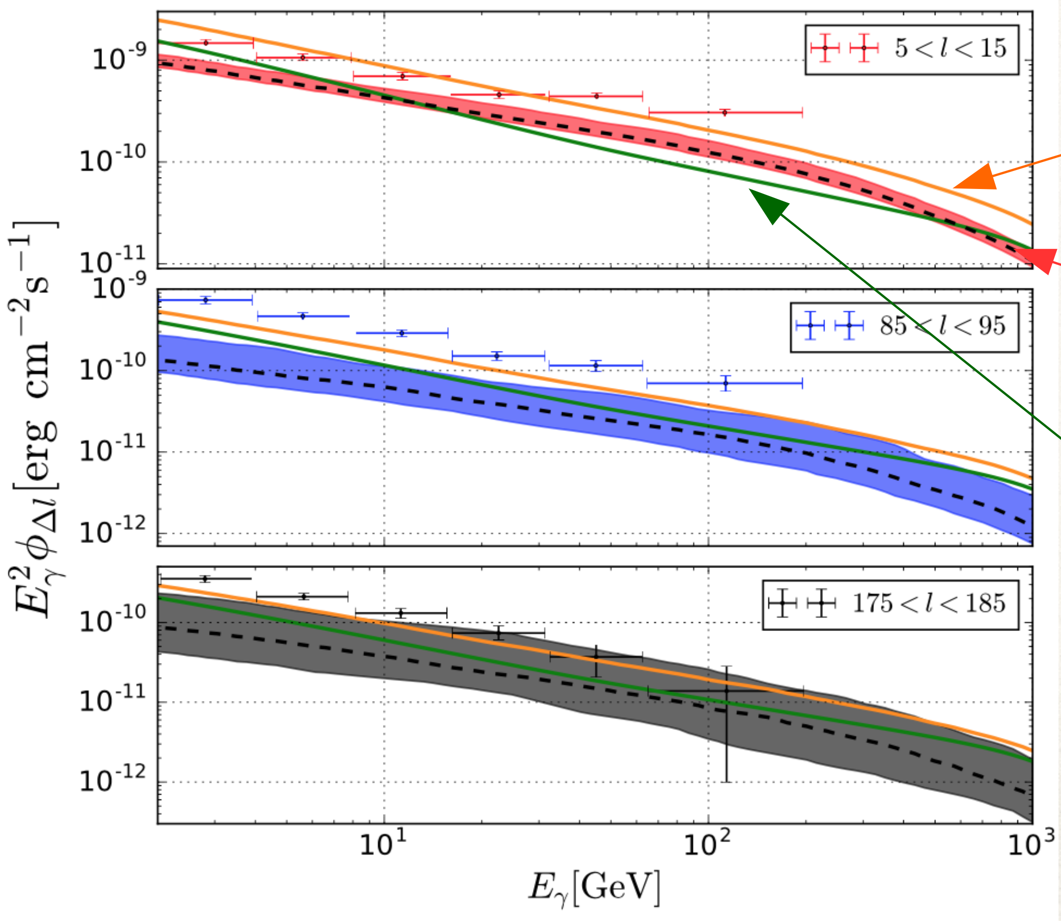




Contribution of the escaping CRs to the diffuse Galactic emission

[D'Angelo, GM, Amato, Blasi, 2018]

$n_i = 0.45\,cm^{-3}$; $\quad n_H = 0.0\,cm^{-3}$



Sum of diffuse emission plus contribution from all the source cocoons

Contribution from SNR halos

"Real" diffuse contribution assuming AMS spectrum in the whole Galaxy

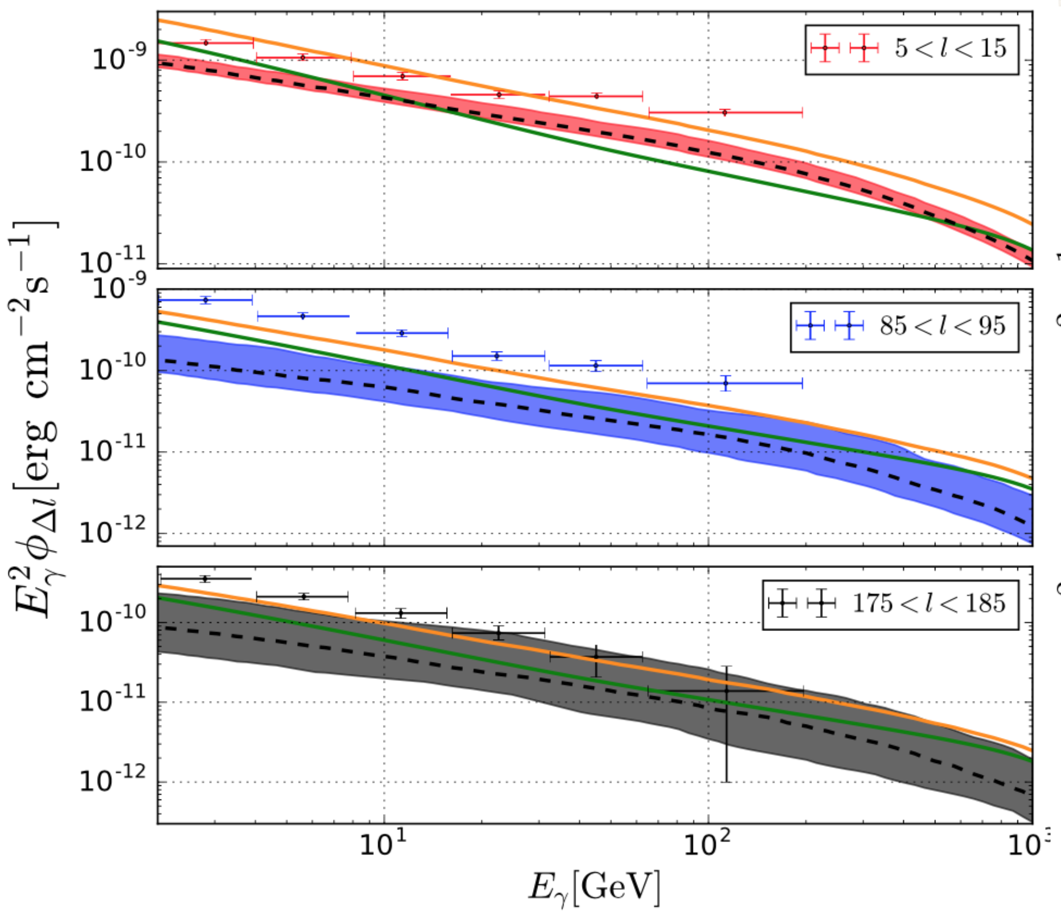
Contribution of the escaping CRs to the diffuse Galactic emission

[D'Angelo, GM, Amato, Blasi, 2018]

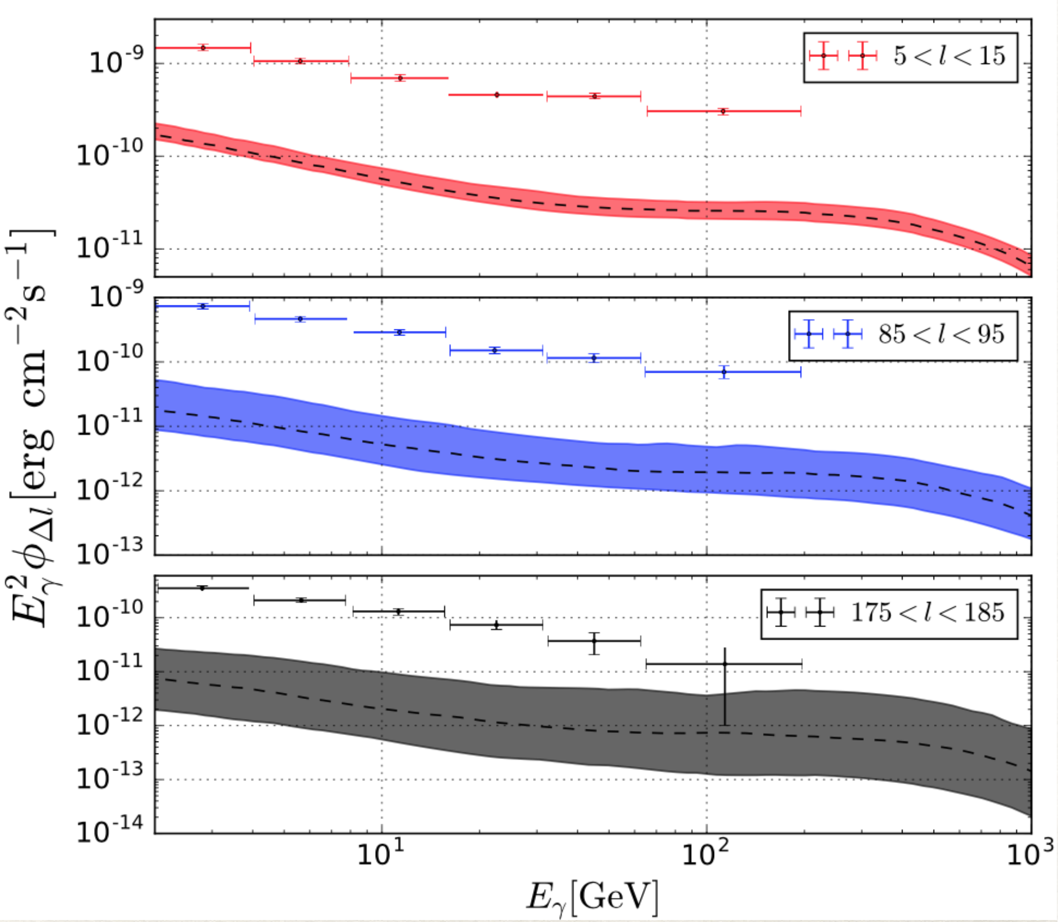
Number of sources contributing to the emission

Angular sector	Fully ionized	n_H=0.05
5°-15°	4500	740
85°-95°	350	57
175°-185°	77	13

$n_i = 0.45\,cm^{-3}\,; \quad n_H = 0.0\,cm^{-3}$



$n_i = 0.45\,cm^{-3}\,; \quad n_H = 0.05\,cm^{-3}$



Conclusion on *particle escape*

- Escape can determine the gamma-ray spectrum observed in SNR and explain the steep spectra observed in evolved SNR

- Under the assumption $D_{out} << D_{gal}$, γ-ray spectra favors $\delta > 2$ which requires:

  - magnetic field amplification
  - possibly magnetic damping

  - **A statistical study is needed to reach firm conclusions.**

- Escaping electrons can also produce *halos* similar to PWNe

- SNR halos can substantially contribute to diffuse Galactic gamma-ray background