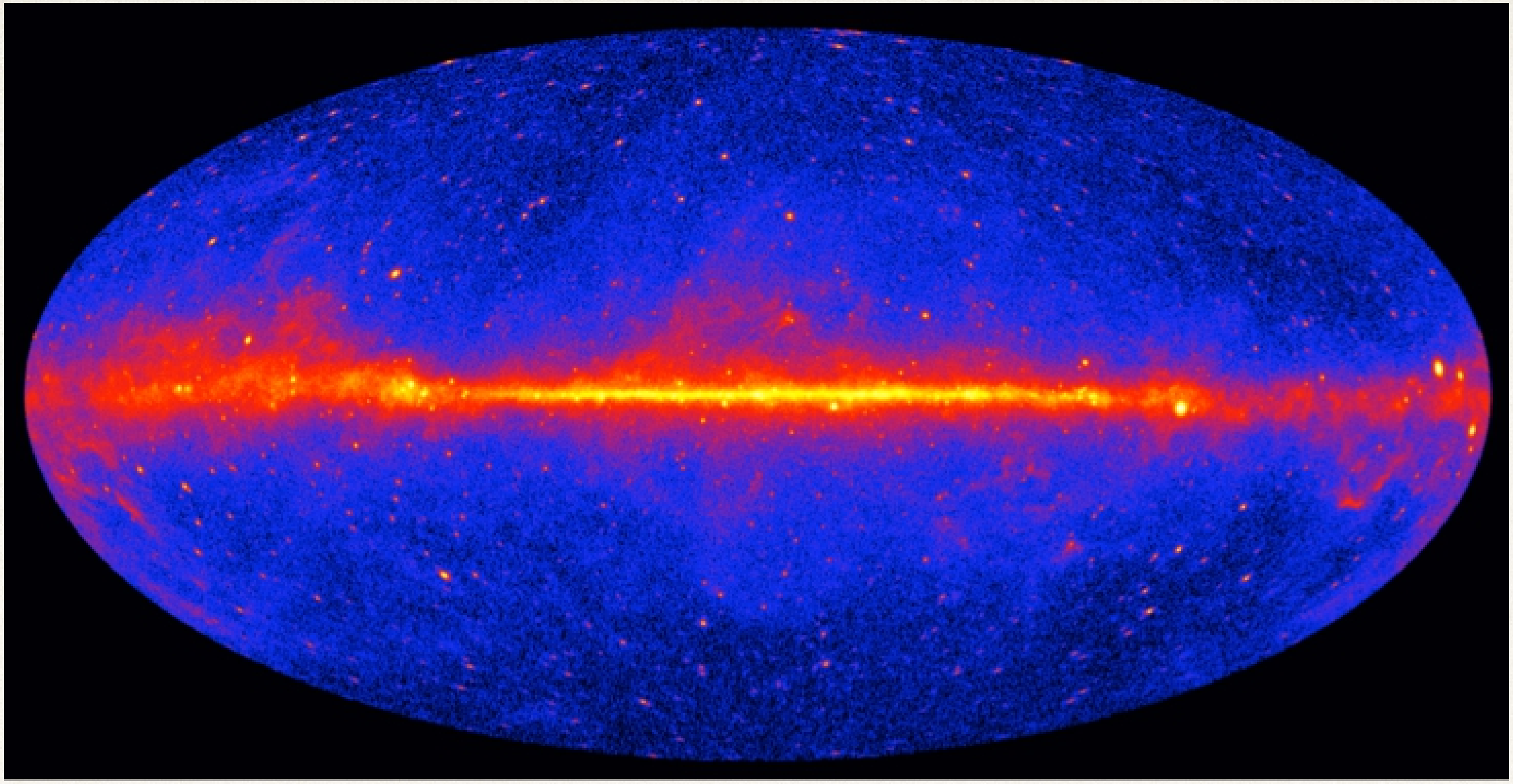

Cosmic Ray production and propagation: a (*not so*) short tutorial

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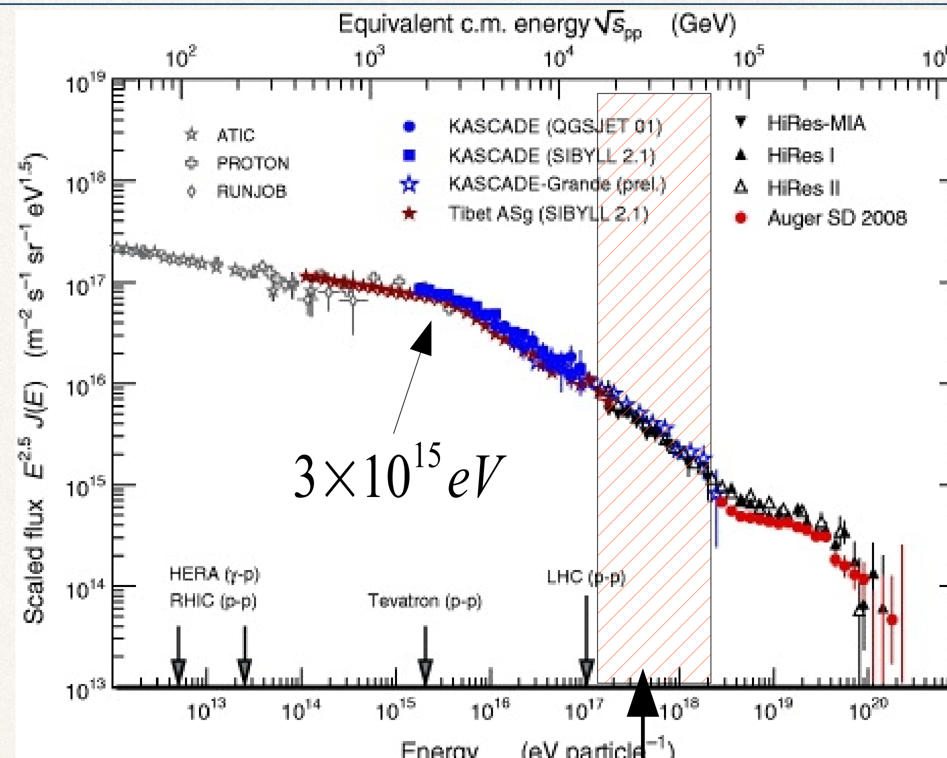
Astroplasma19 – Aug. 20, 2019 - KAVLI

The path to become a cosmic ray

Acceleration inside sources

Escape from sources

Propagation accross the Galaxy



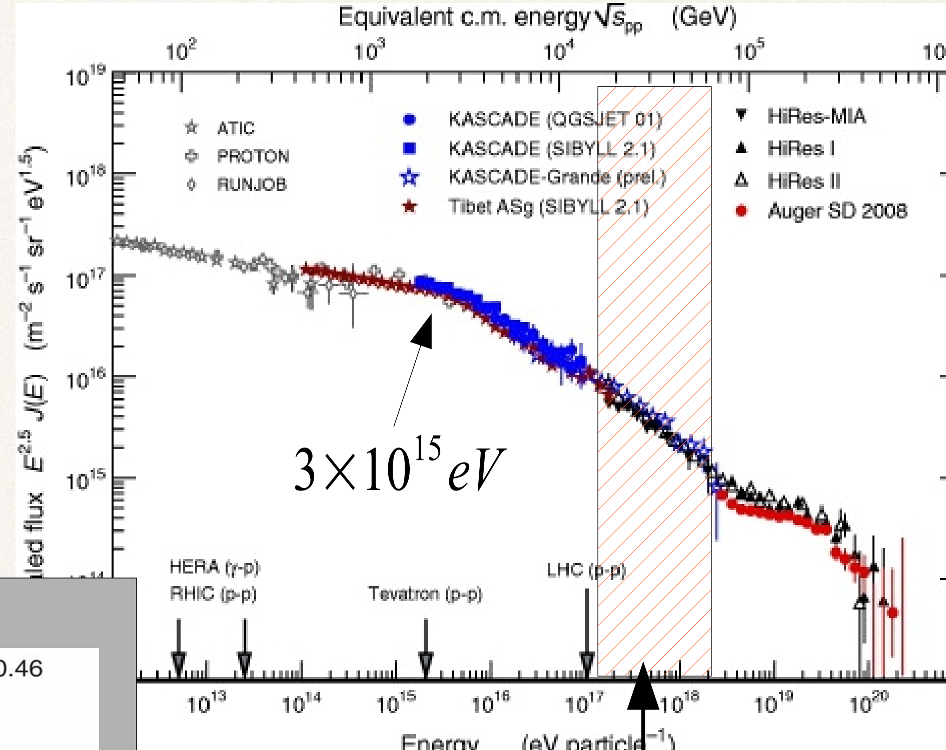
Transition from Galactic to extragalactic components

$$r_L(10^{18}, 3\mu G) = 300\ pc$$

The path to became a cosmic ray

Acceleration inside sources

Escape

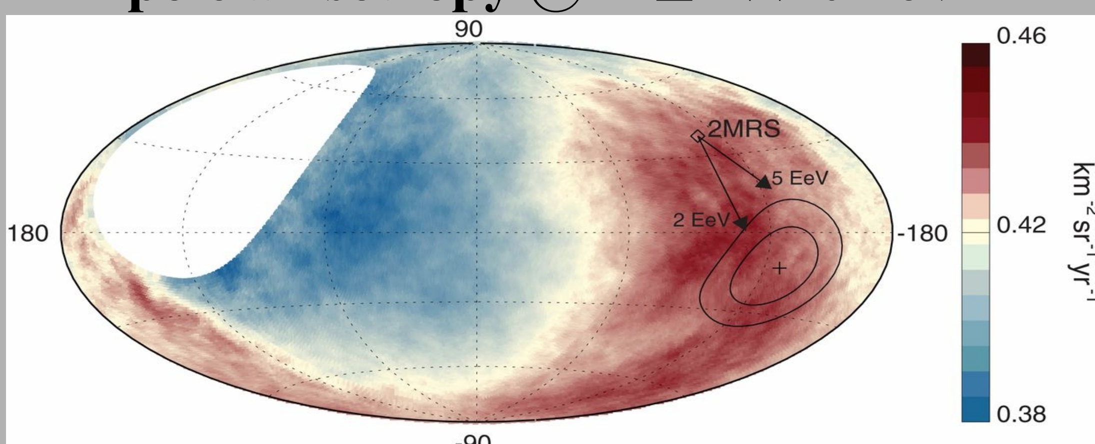


Transition from Galactic to extragalactic components

$$r_L(10^{18}, 3\,\mu G) = 300\ pc$$

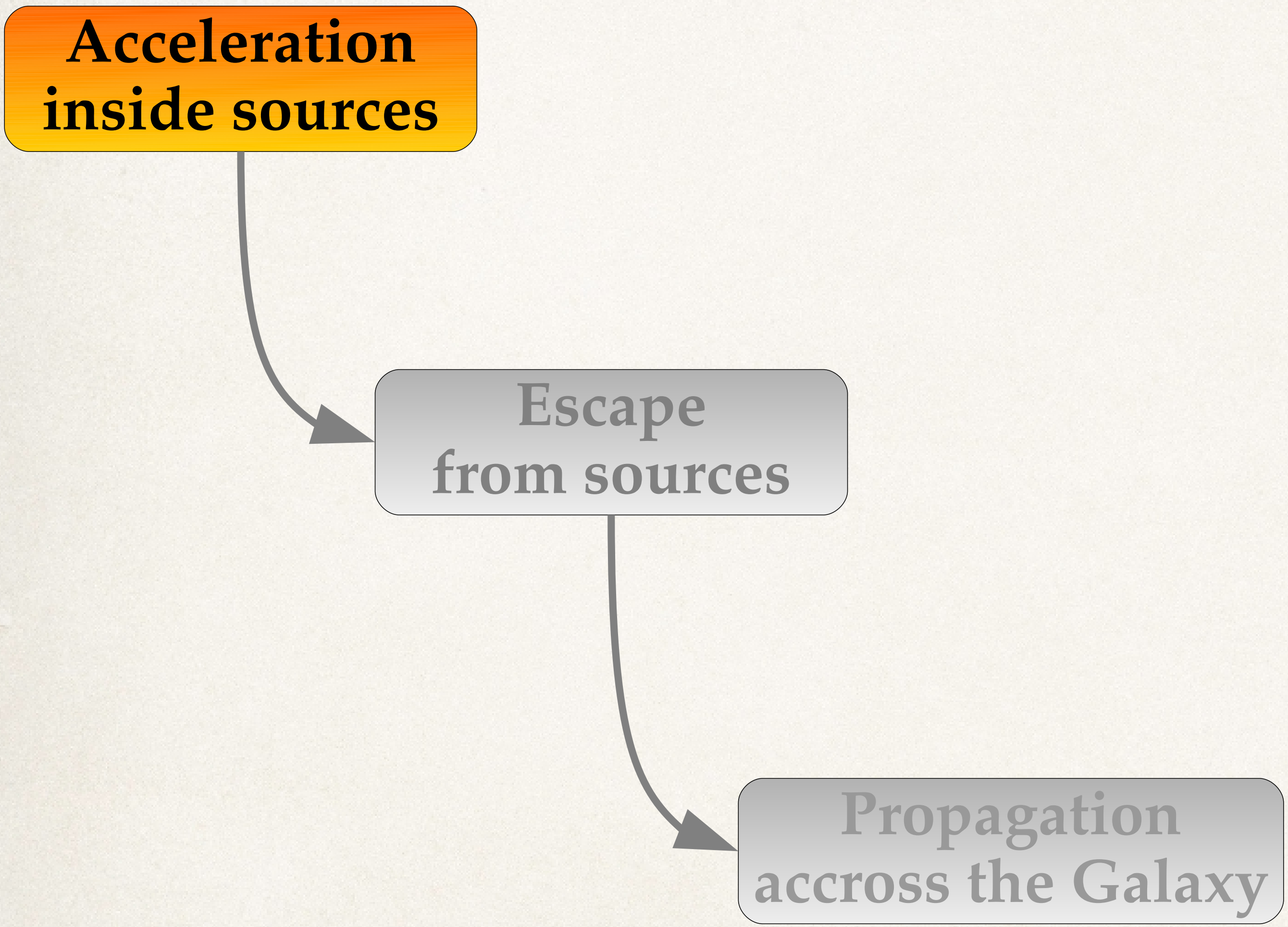
...on
...alaxy

Dipole anisotropy @ E ≥ 4×10^{18} eV



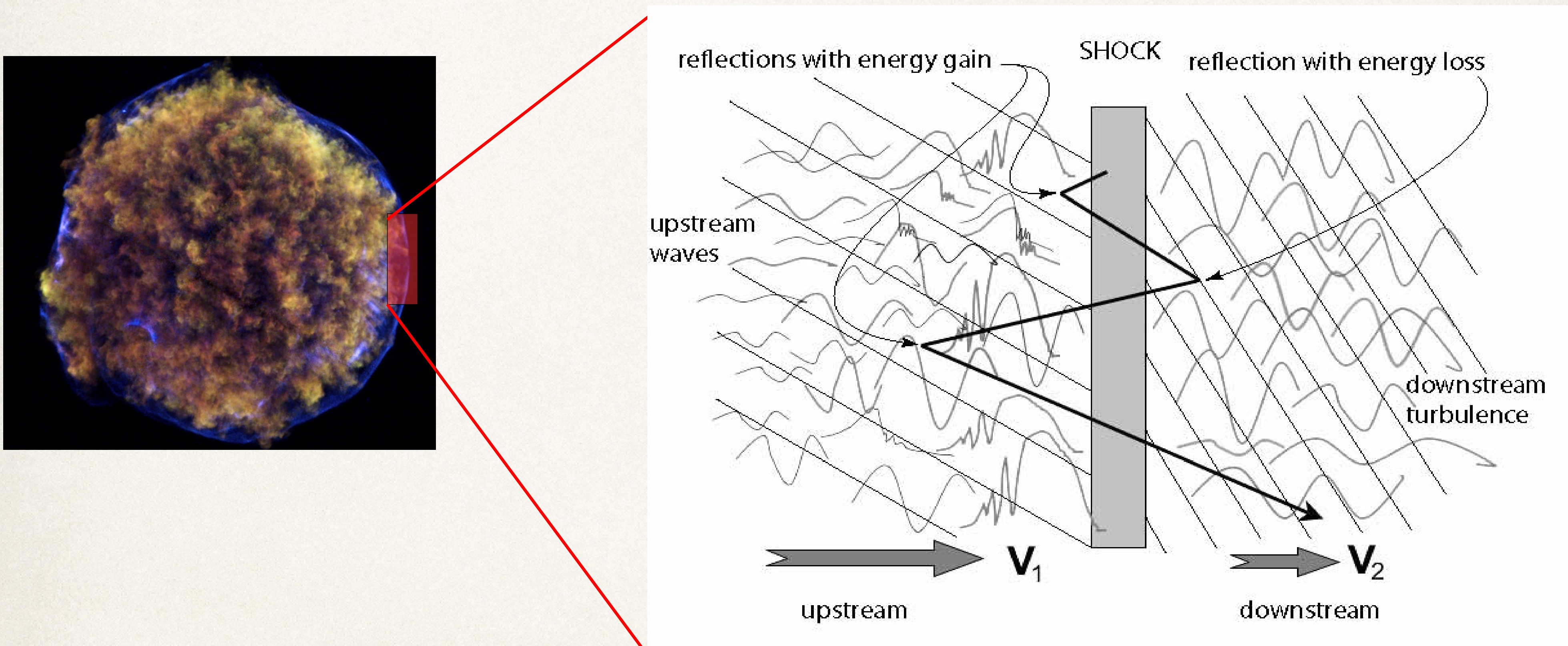
Discovered in 2017 by the *Pierre Auger Observatory* [Science 357, 1266]

Acceleration



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) predicts:

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

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

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

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

Strong dependence on magnetic field

Weak dependence on the ejecta mass and ISM density

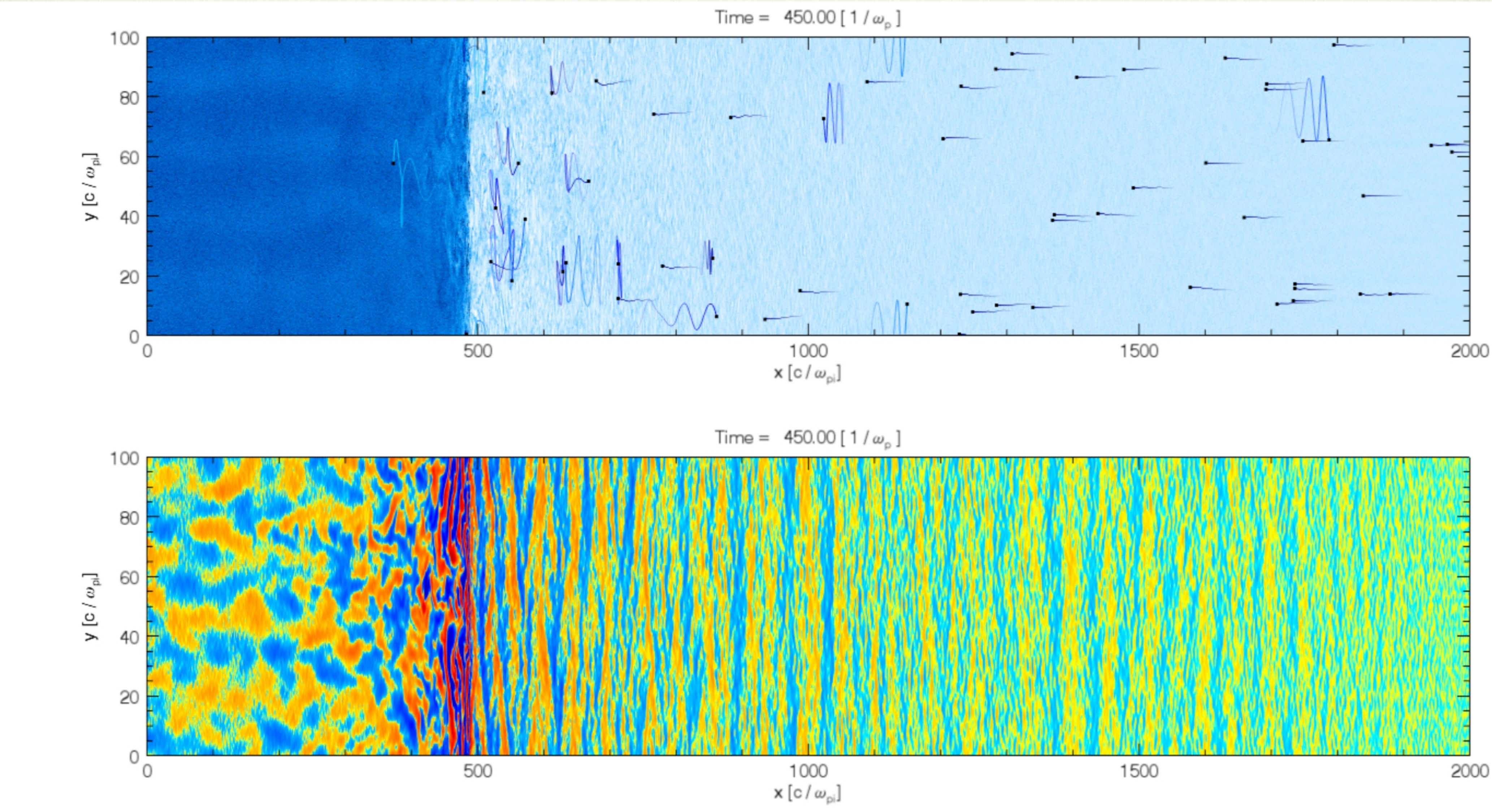
High energies, up to PeV, can be achieved only if

$$\mathcal{F}(\boldsymbol{k}) >> 1$$

This condition requires amplification of the magnetic field

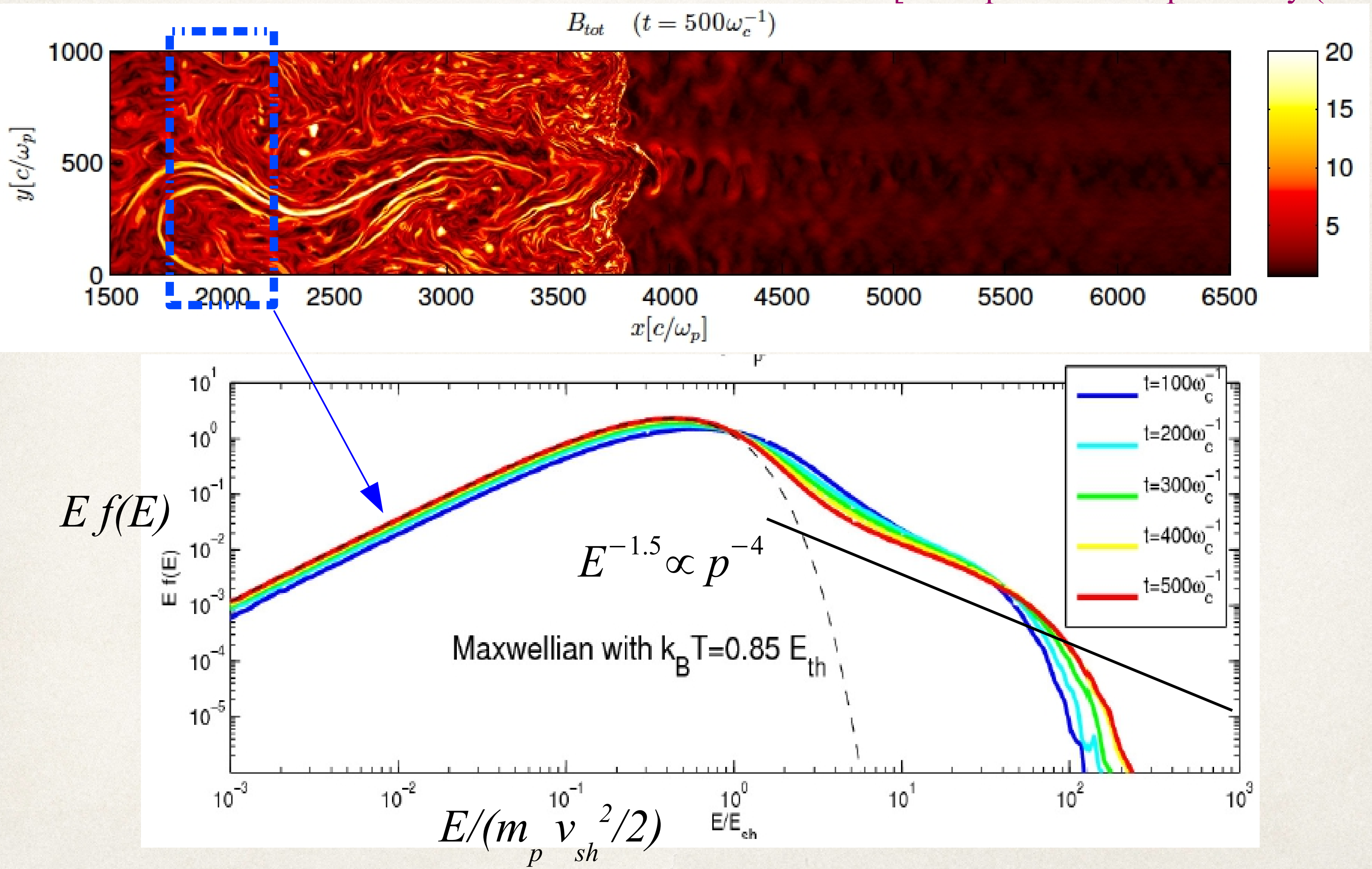
Fermi acceleration at work: PIC simulations

[From Gargaté & Spitkovsky (2013)]



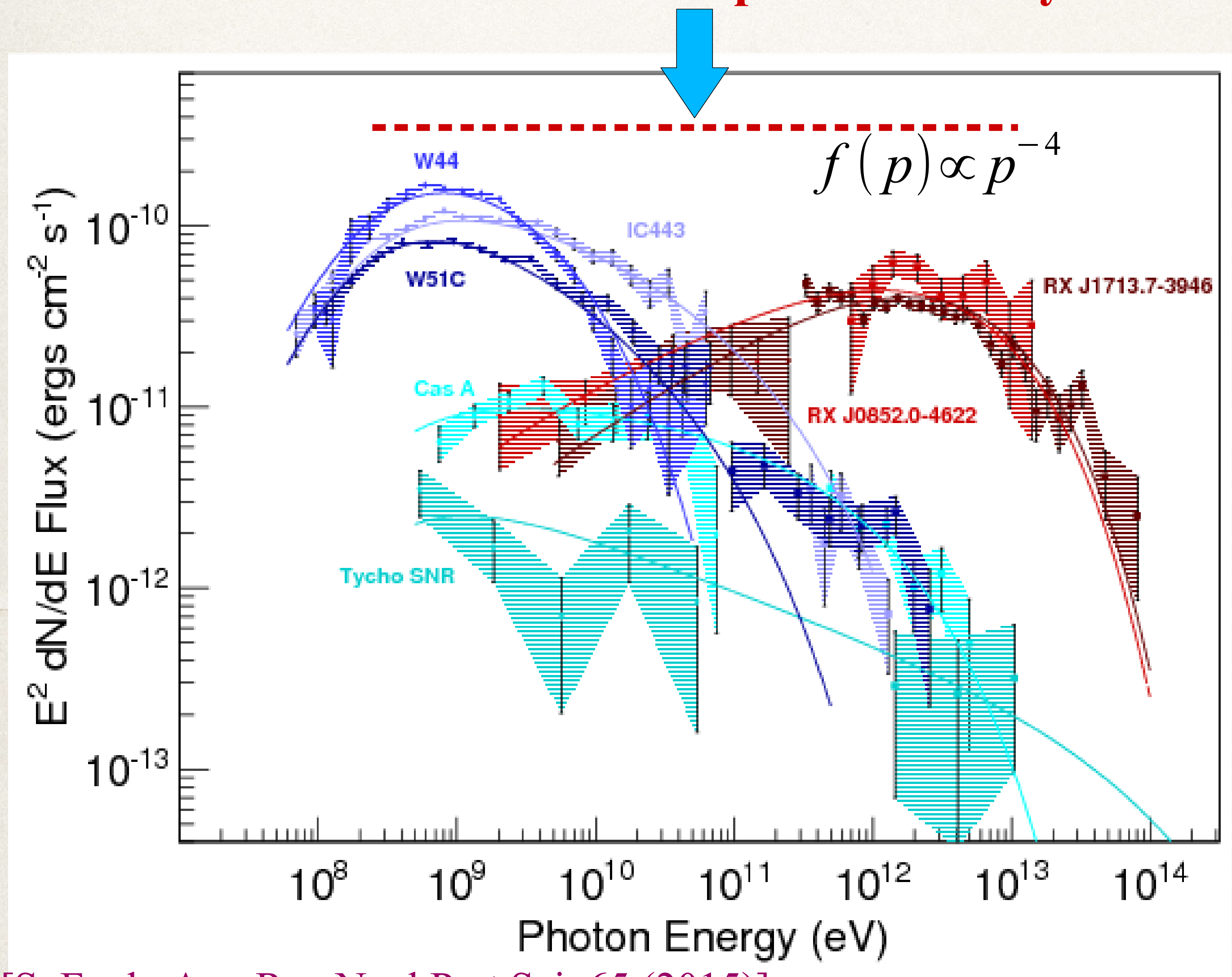
PIC simulation of particle acceleration

[D. Caprioli & A. Spitkovsky (2013)]



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

Prediction of test particle theory



[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

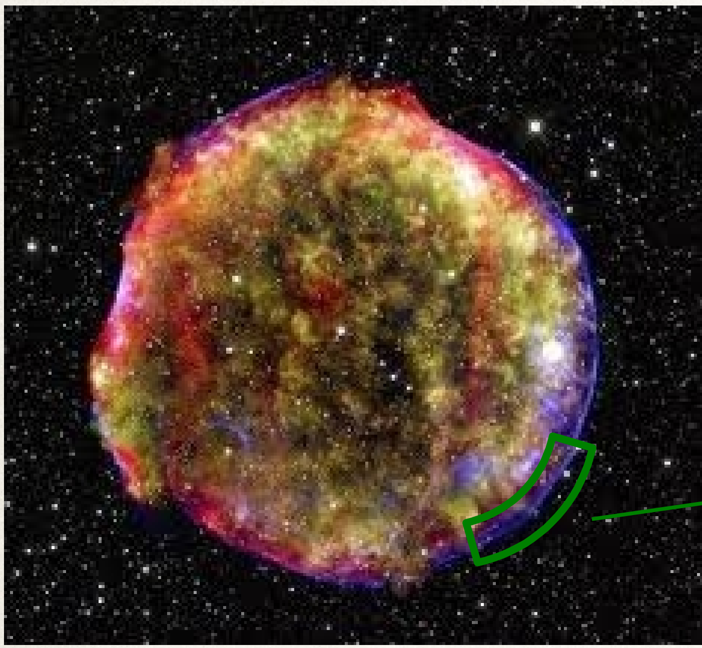
Very young SNRs (~300 yr)

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

Not enough to explain the Knee at ~ PeV

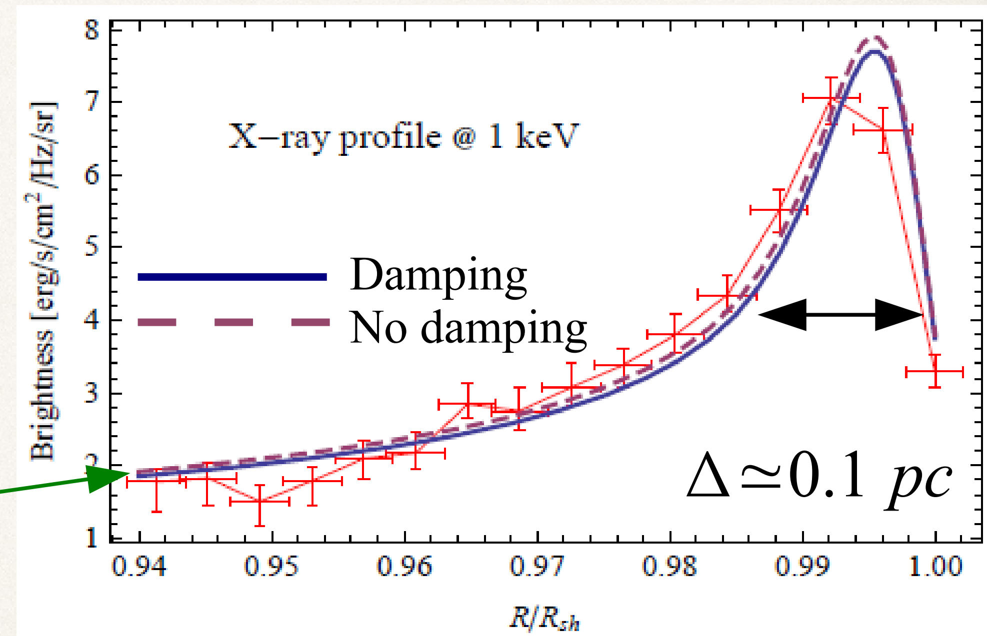
Magnetic field amplification: observations

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

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

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

B~200-300 μG >> B_{ISM}

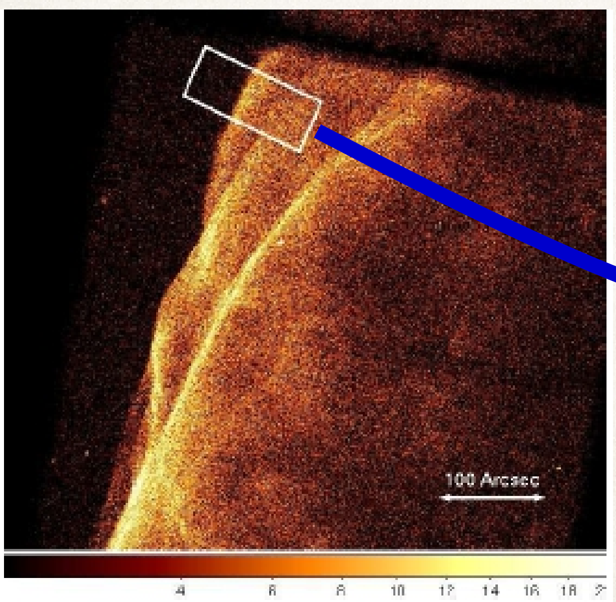
Where is the magnetic field amplified?

DOWNSTREAM: MHD instabilities (shear-like)

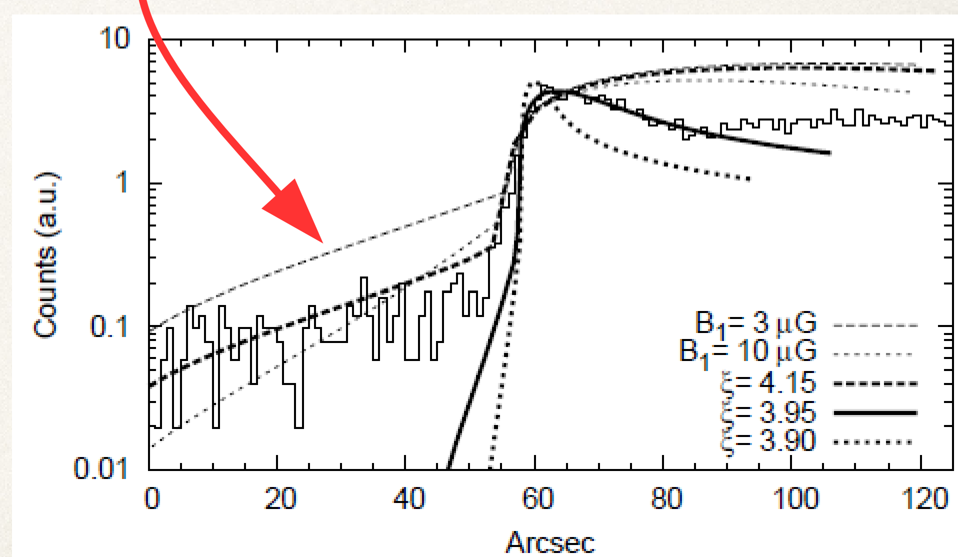
UPSTREAM: only through instabilities driven by CRs (Streaming, Bell)

BUT we need amplification upstream
of the shock to reach high energies

Low magnetic field upstream produces a more extended emission NOT OBSERVED!



SN1006 in X-rays (*Chandra*)



[from G.M., Amato, Blasi, 2009, MNRAS]

Magnetic field amplification: Theory

How is the magnetic field amplified?

Resonant Straming instability

[e.g. Skilling (1975), Bell & Lucek (2001), Amato & Blasi (2006), Blasi (2014)]

Particles amplify Alfvèn waves with wave-number $k_{res} = 1/r_L(p)$

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

Growth rate

Fast growth rate but

$$(\delta B/B_0)^2 \leq 1$$

→

$$E_{max} \approx 10-100\, TeV$$

A factor >10 below the knee

Magnetic field amplification: Theory

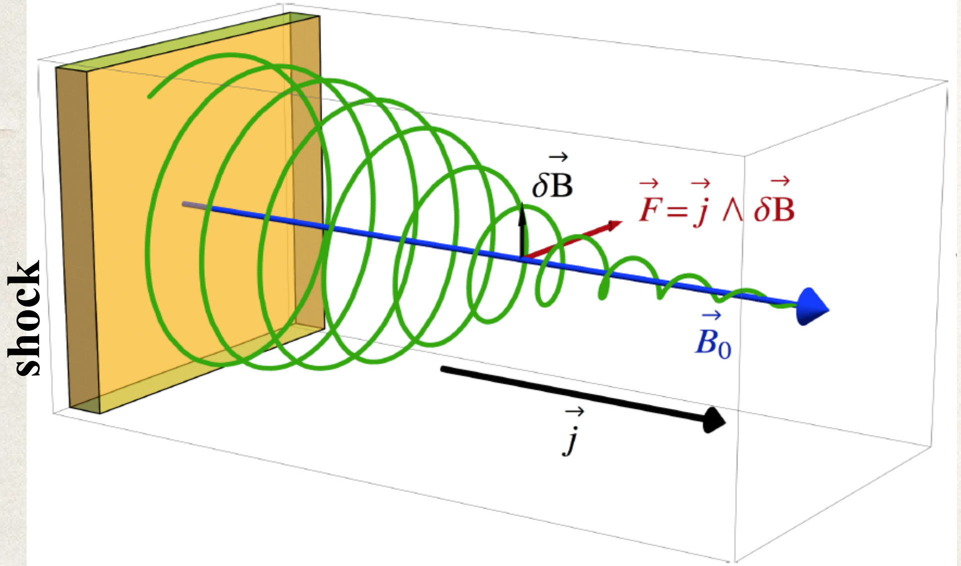
How is the magnetic field amplified?

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

From simulations the saturation is reacher after ~5 *e*-folding times



$$\left.\begin{aligned} &\gamma\tau = 5 \\ &\tau = R/u_{sh} \\ &\gamma \propto J_{CR} \\ &J_{CR} \propto 1/E_{max} \end{aligned}\right\} \text{Determine } E_{max}$$

Magnetic field amplification: Theory

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

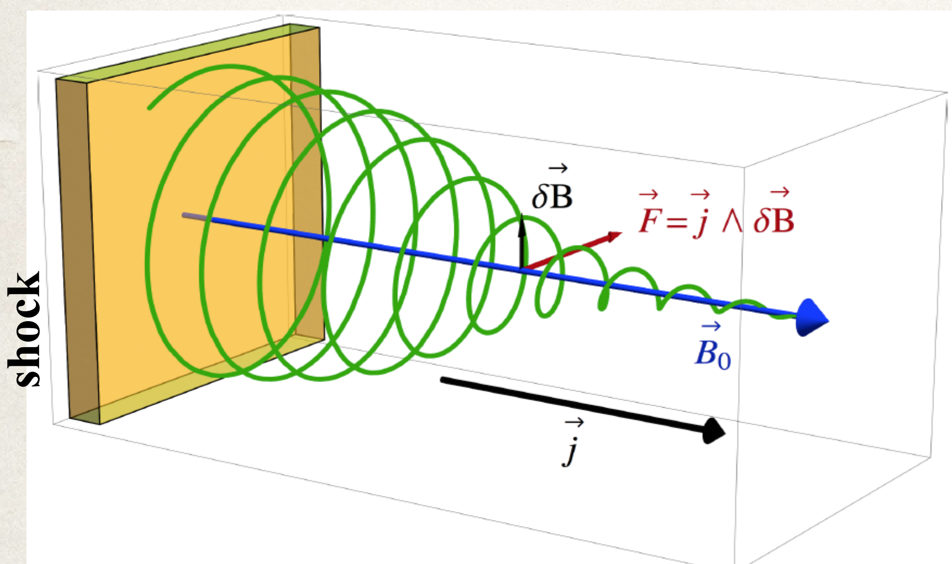
$$\Rightarrow \quad E_{max} \propto \sqrt{\rho_{CSM}}$$

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

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

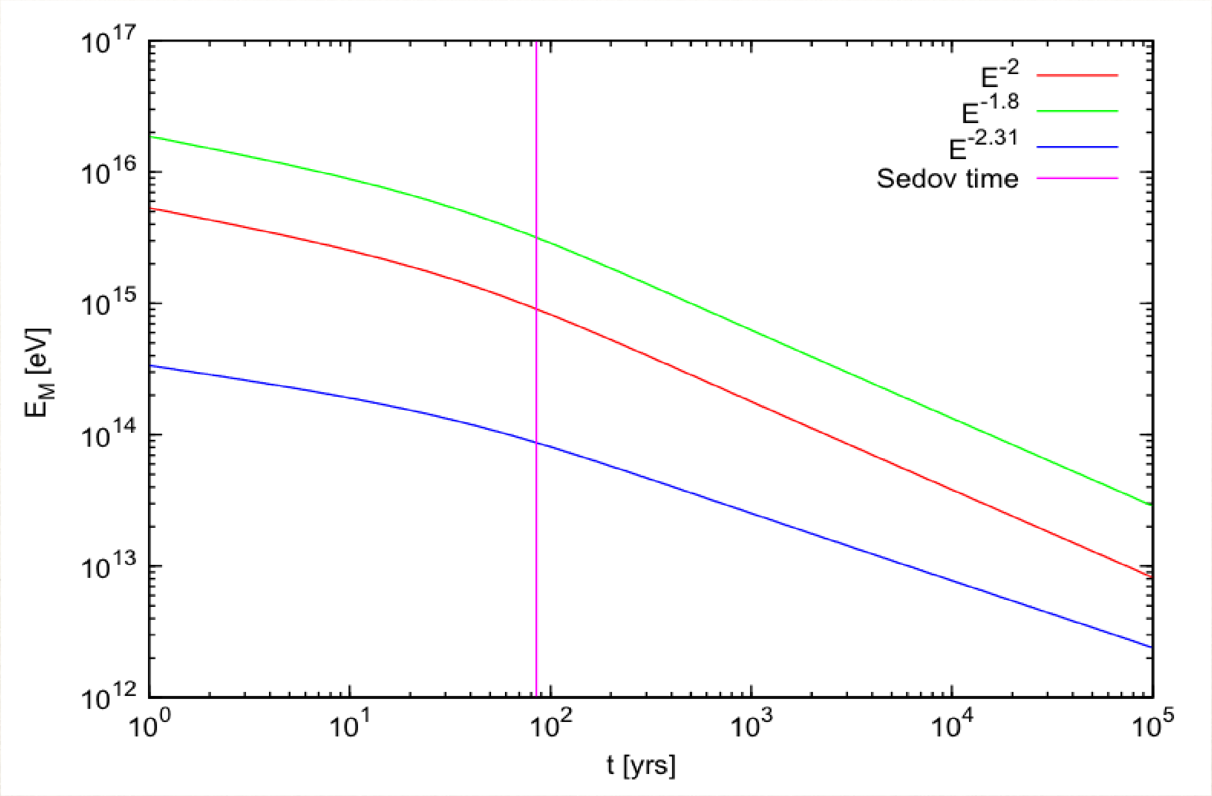


Magnetic field amplification: Theory

(Cardillo, Amato, Blasi, 2015)

If the spectrum is steeper than p^{-4} there are less particles at larger energies
^ the current is smaller ^ the maximum energy is reduced

Maximum enrgy of a core-collapse SNR expanding into a red supergiant wind



Conclusions: *acceleration*

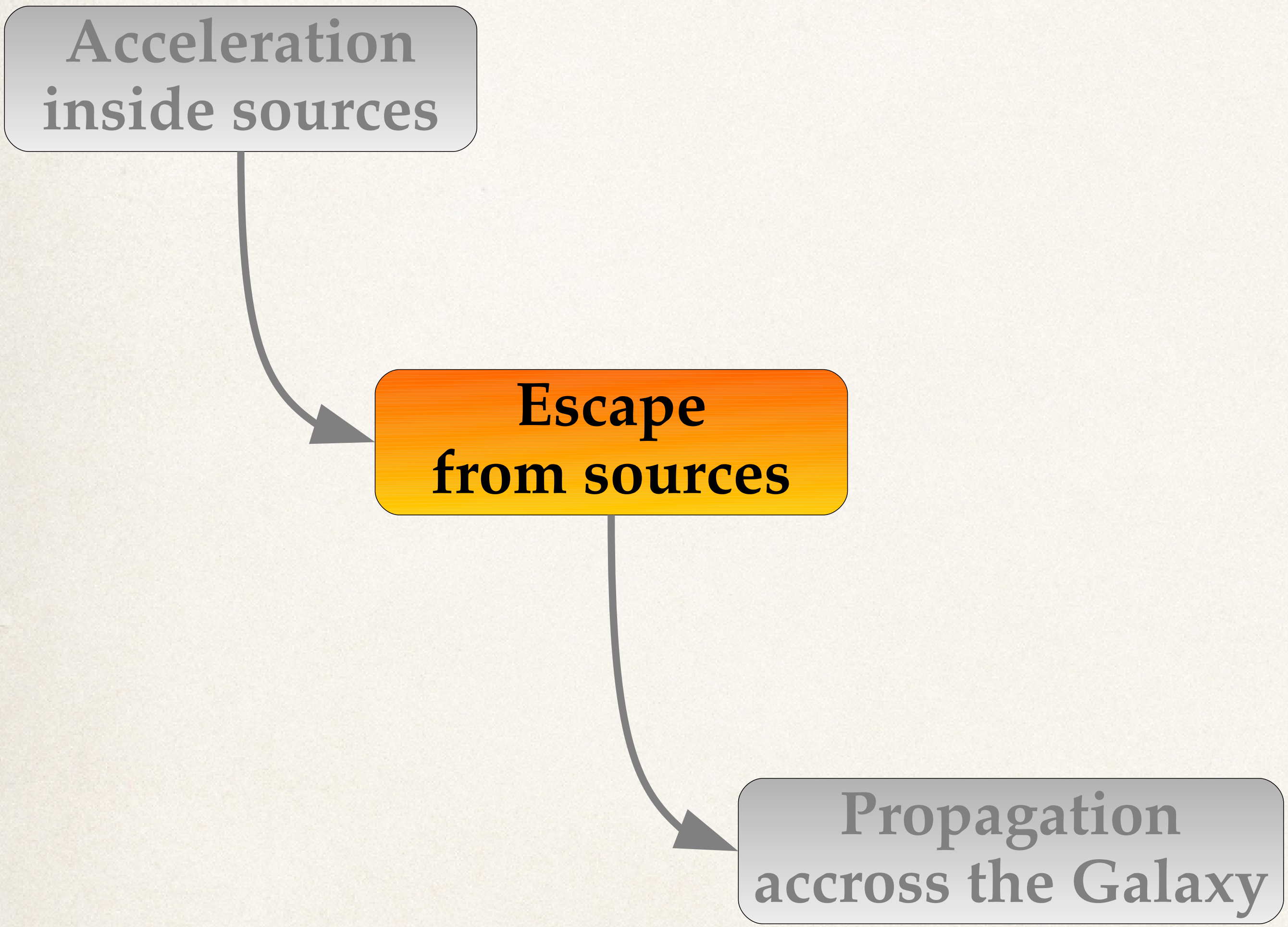
- From observations the $f(p) \propto p^{-4}$ s almost never realized:
  - Do we lack some foundamental element in the theory?
    - Role of scattering centers?
  - Important environmental effects?
    - Presence of neutrals?
    - Clumpy media?

- Amplification of turbulence up to $\delta B \sim B_0$ (and isotropization of the distribution function) are required 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})

- **If the spectrum is steeper than p^{-4} reaching PeV is even more problematic**

The path to became a cosmic ray



Particle escape from SNRs

If particles are not released all at the same time, in general:

Spectrum injected into the Galaxy $f_{esc}(p) \neq f_{SNR}(p)$ Spectrum inside SNRs

Assume that at time t only particles at maximum momentum $p_{max}(t)$ can escape

$$4\pi f_{esc}(p)\, c\, p\, p^2\, dp = \xi_{esc}(t) \frac{1}{2}\rho V_{sh}^3\, 4\pi R_{sh}^2\, dt$$

Released energy — Converted fraction — Incoming energy flux

$$f_{esc}(p) \propto p^{-4} V_{sh}(t)^{5\alpha-2} \xi_{esc}(t)$$

$$f_{esc}(p) \propto p^{-4}$$

- Expansion in omogeneous medium with $R_{sh}(t) \propto t^{\alpha}$
- Escaping during the Sedov-Tayor phase (^ $\alpha=2/5$)
- $\xi_{esc}(t) \approx$ const

Spectrum NOT related to Fermi acceleration process!

Particle escape from SNRs

More in general, using a more correct traitement for the maximum energy (see Cardillo, Amato & Blasi, 2015)

$$f_{esc}(p) = \begin{cases} p^{-s} & if\ s \geq 4 \\ p^{-4} & if\ s < 4 \end{cases}$$

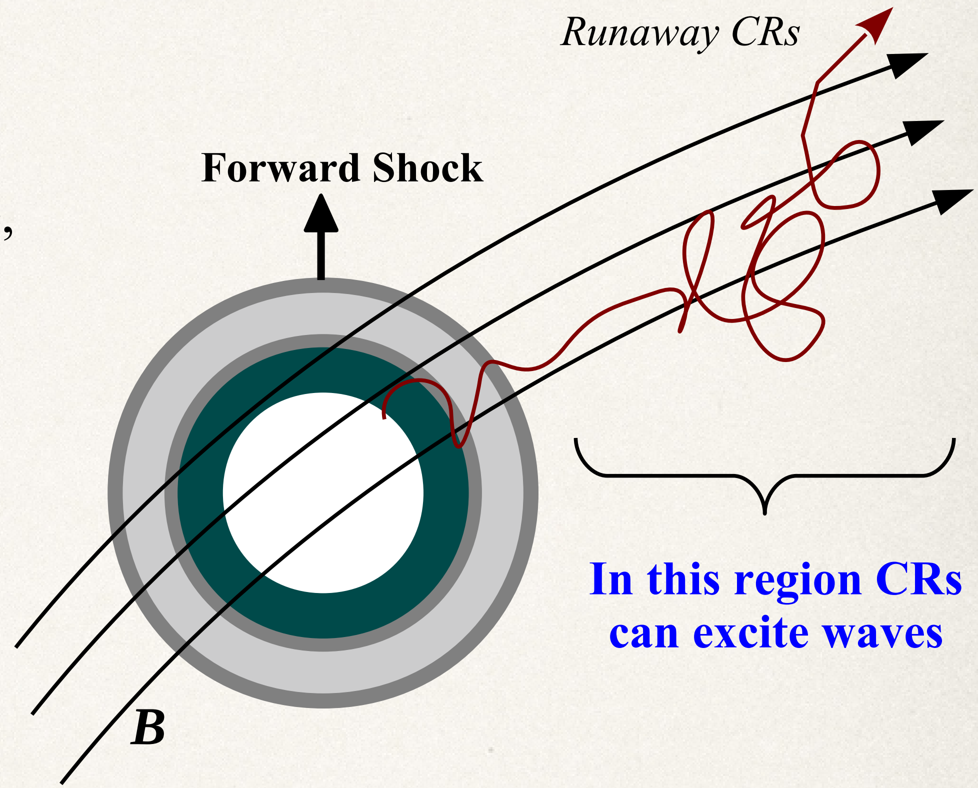
If :

1) ξ_{cr} (t)= const

2) the SNR is in Sedov-Taylor phase

Effect of self-amplification near the CR sources

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)]



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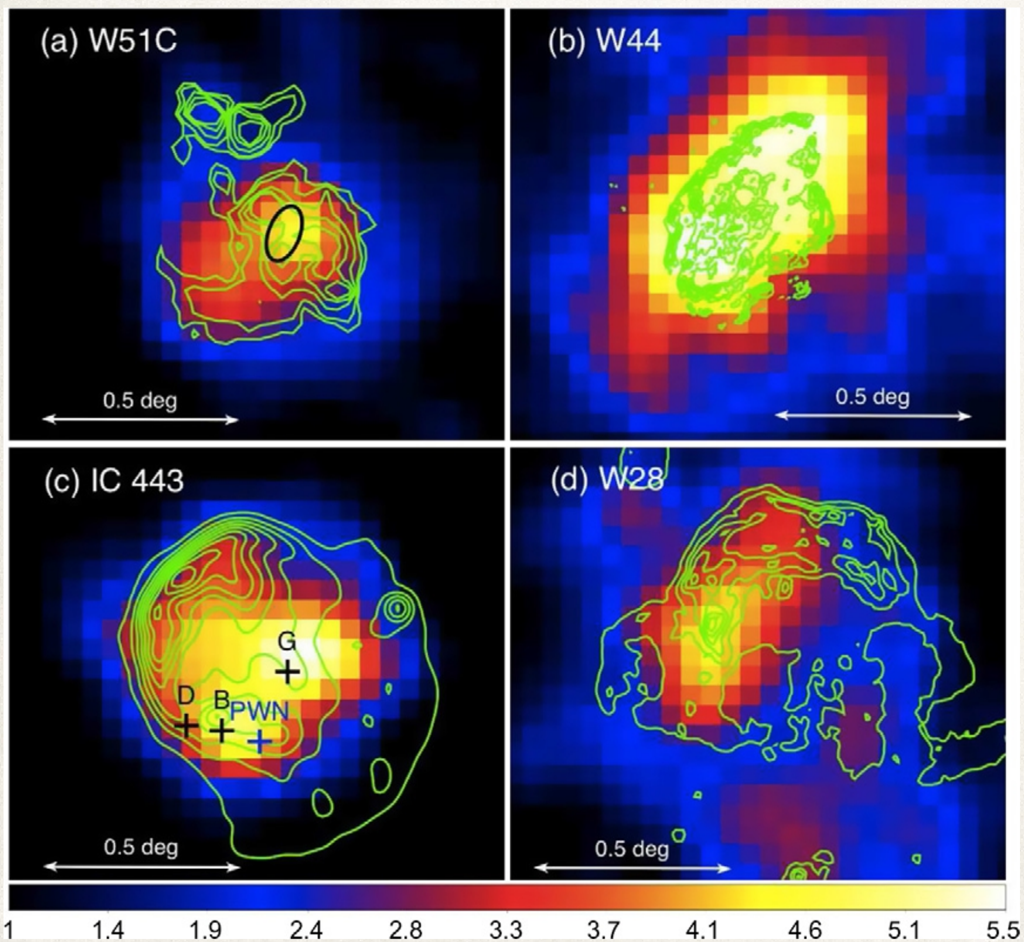

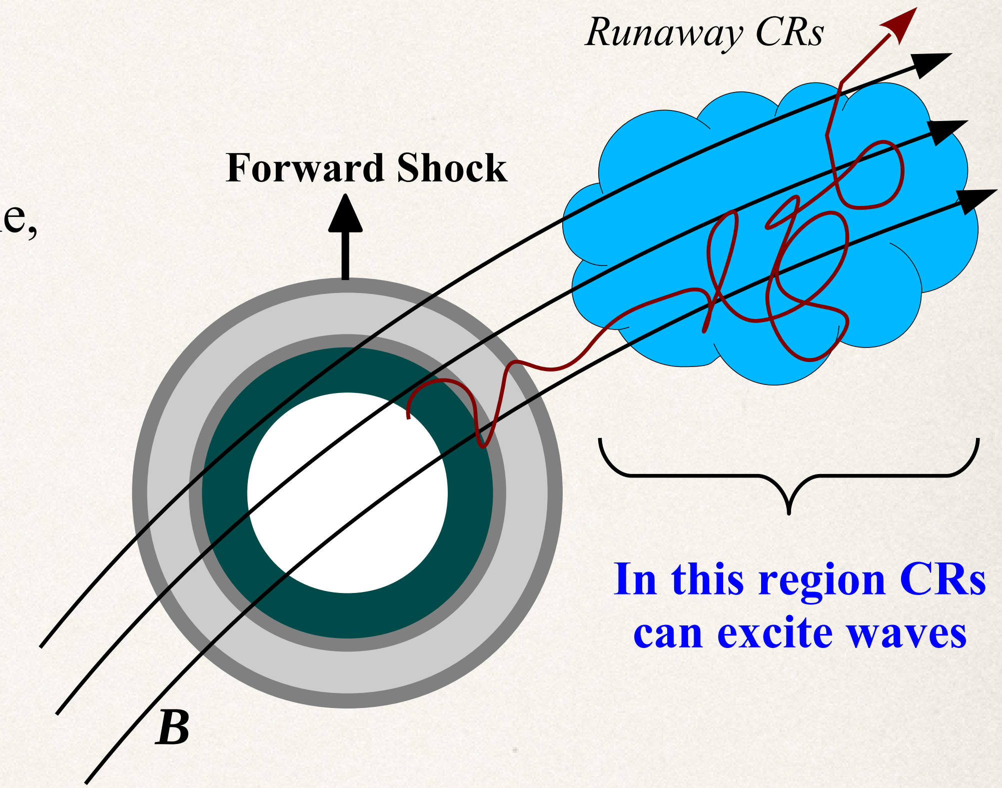

Examples of γ-ray emission from clouds close or interacting with SNRs - [*Fermi*-LAT]

A simplified analitical model: shock acceleration

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

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

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

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

A simplified analitical model: particle escape

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

Approximation largely used in the literature $p_{MAX} \simeq$ PeV/c

If $p > p_{max}(t)$ ➡ particles start escaping

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

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

A simplified analitical model: particle escape

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

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

Simple estimate of δ:

$$\begin{cases} t_{acc}(p_{max})=t_{SNR} \\ t_{acc}\simeq D/u_{sh}^2 \\ D(p)=D_{Bohm}(p)/F(k) \end{cases}$$

➡ $p_{max}\propto F(k,t)\,u_{sh}^2(t)\,t$

If there is no magnetic field amplification: $F(k)=const\,; \quad u_{sh}\propto t^{-3/5} \rightarrow \delta=1/5$

If the amplification is due to streming instability: $F(k,t)\propto P_{CR}\propto u_{sh}(t)^2 \rightarrow \delta=7/5$

If the amplification is due to Bell instability: $F(k,t)\propto P_{CR}\propto u_{sh}(t)^3 \rightarrow \delta=2$

A simplified analitical model: propagation

Full transport equation for accelerated particles in spherical simmetry:

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial f}{\partial r}\right] + \frac{1}{r^2}\frac{\partial (r^2 u)}{\partial r}\frac{p}{3}\frac{\partial f}{\partial p}$$

Particles confined inside the SNR

$$\frac{\partial f_c}{\partial t} + u\frac{\partial f_c}{\partial r} = \frac{1}{r^2}\frac{\partial (r^2 u)}{\partial r}\frac{p}{3}\frac{\partial f_c}{\partial p}$$

(particles attached to the plasma inside the SNR)

Escaping particles

$$\frac{\partial f_{esc}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D_{out}\frac{\partial f_{esc}}{\partial r}\right]$$

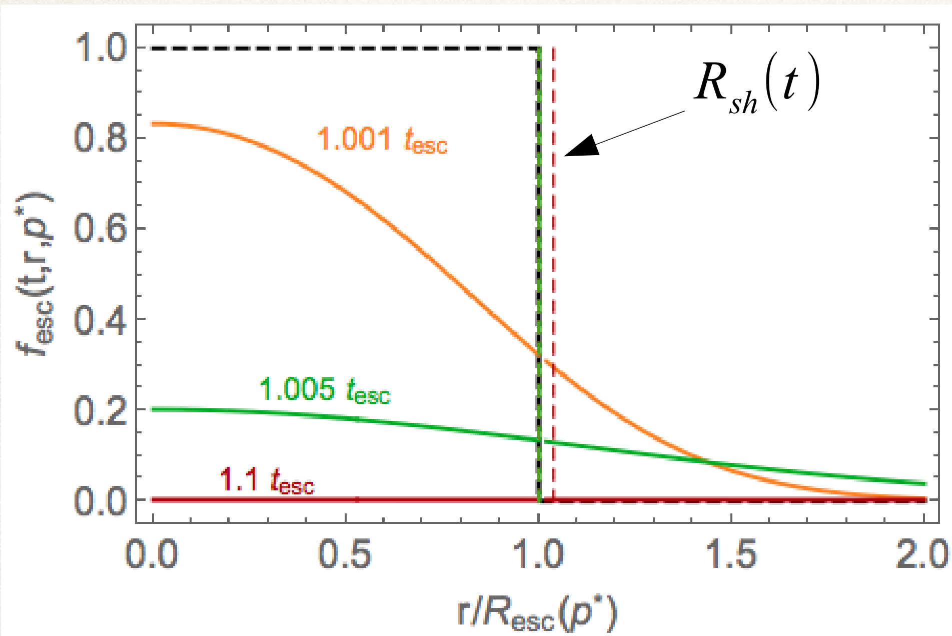
D_{out} const in space and time
(no more connection with the shocked plasma inside the SNR)

Bondary condition at the shock: $f_c(r=R_{sh}(t), t \le t_{esc}(p), p) = f_{sh}(p,t)$

Particle escape: an example

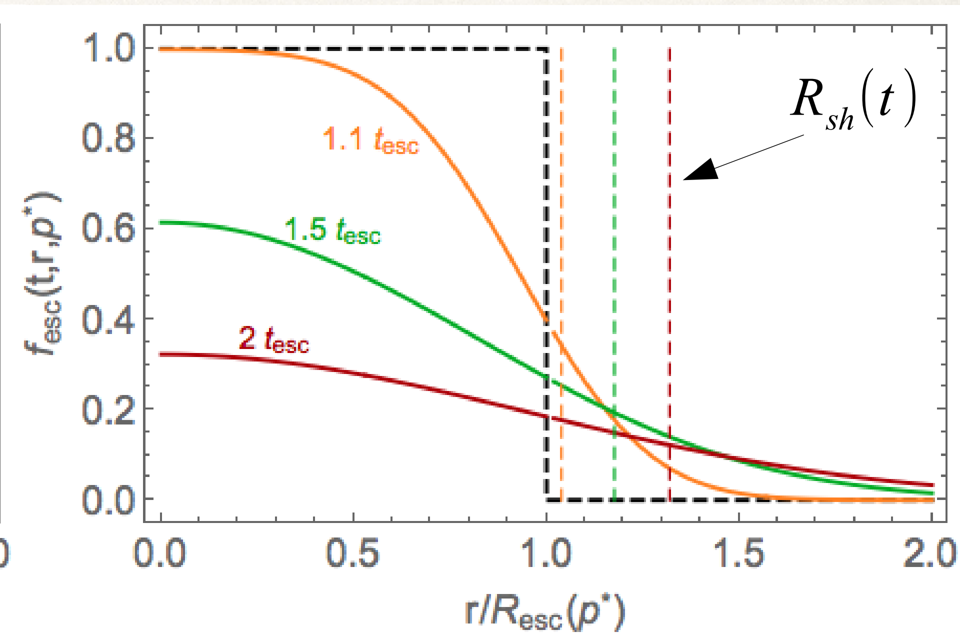
Instantaneous escape

$D_{ext} = D_{Gal}$



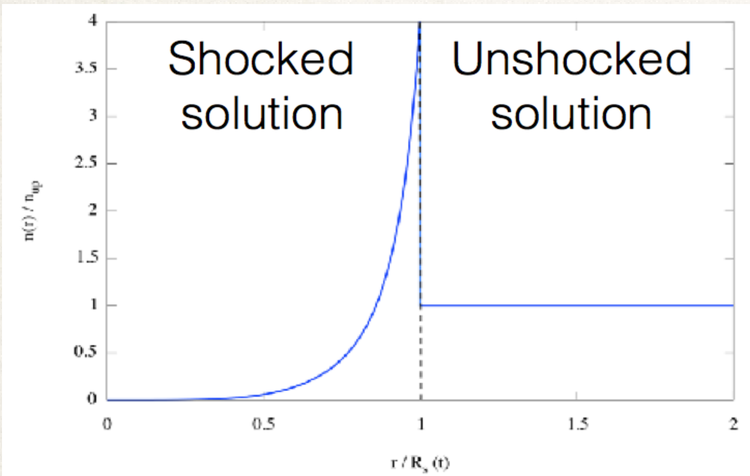
Delayed escape

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

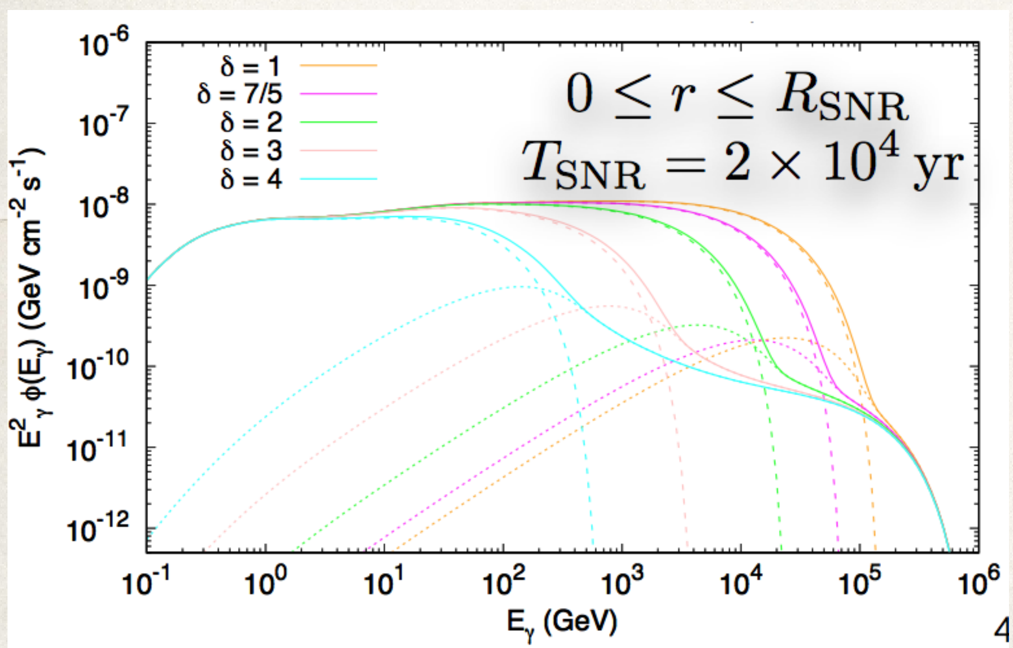


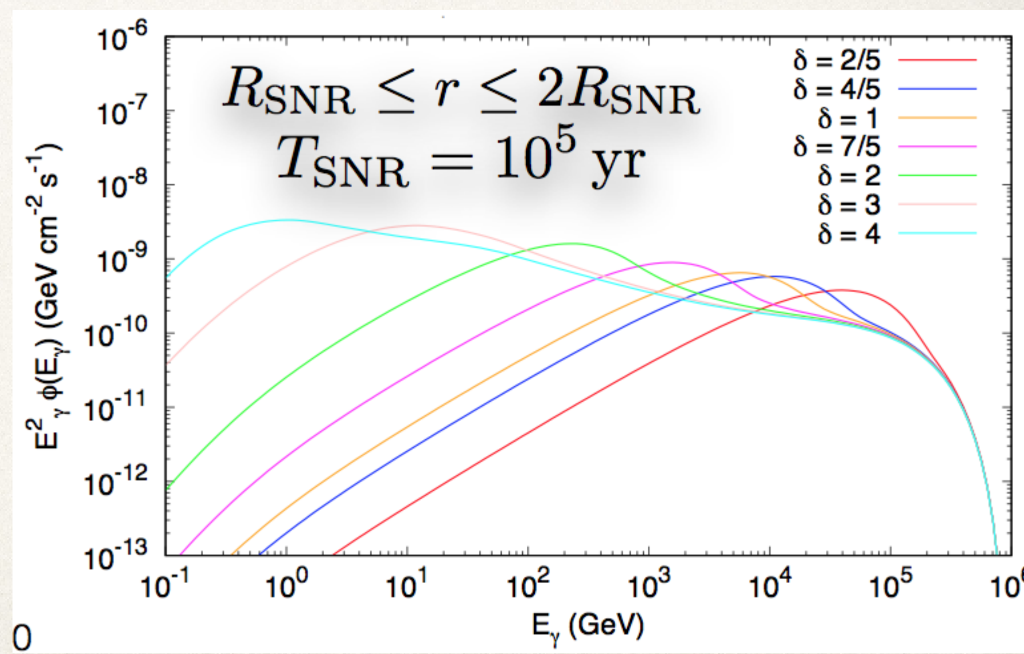
From Boron/Carbon: $$D_{Gal} \simeq 3\times 10^{28} \left(\frac{p}{m_p c}\right)^{1/3} cm^2 s^{-1}$$

Volume integrated gamma-ray flux from the SNR interior

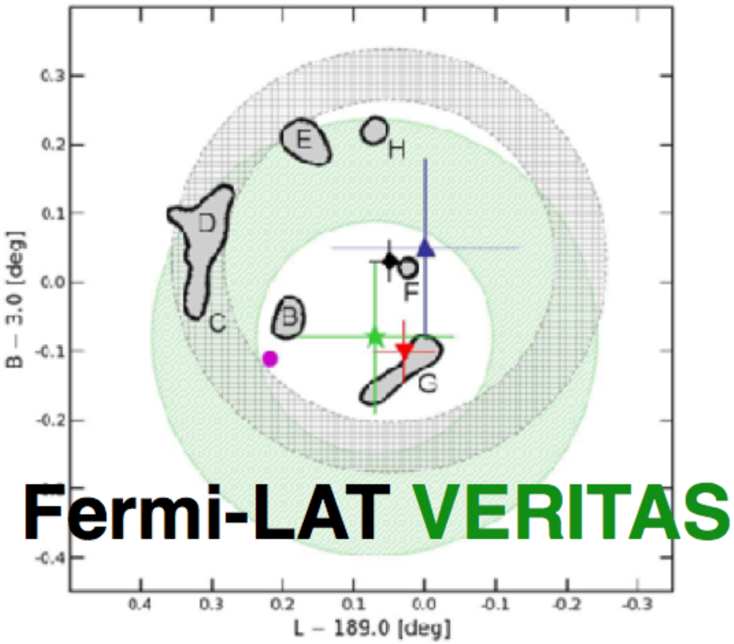


$$f_0(p) \propto p^{-4}$$
$$D(10\,\mathrm{GeV/c}) = 3 \times 10^{27}\,\mathrm{cm^2/s}$$
$$\xi_{\mathrm{CR}} = 1\,\%$$
$$n_{\mathrm{up}} = 1\,\mathrm{cm^{-3}}$$
$$d = 1\,\mathrm{kpc}$$

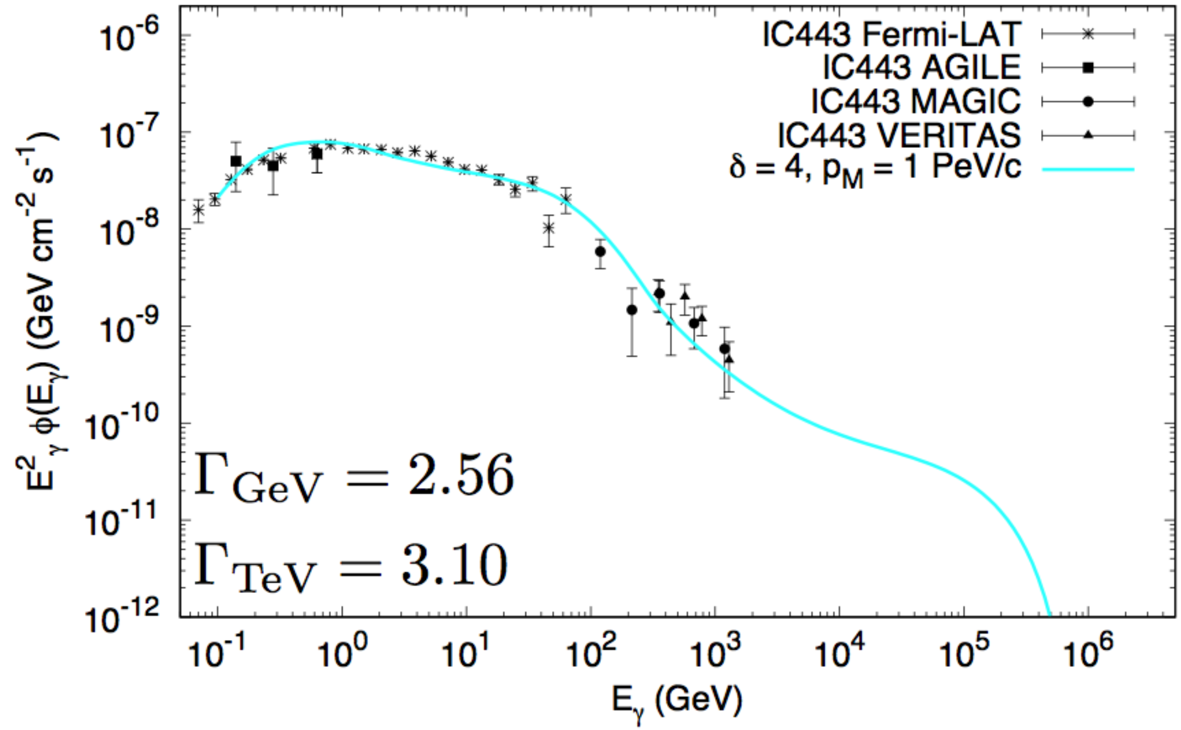


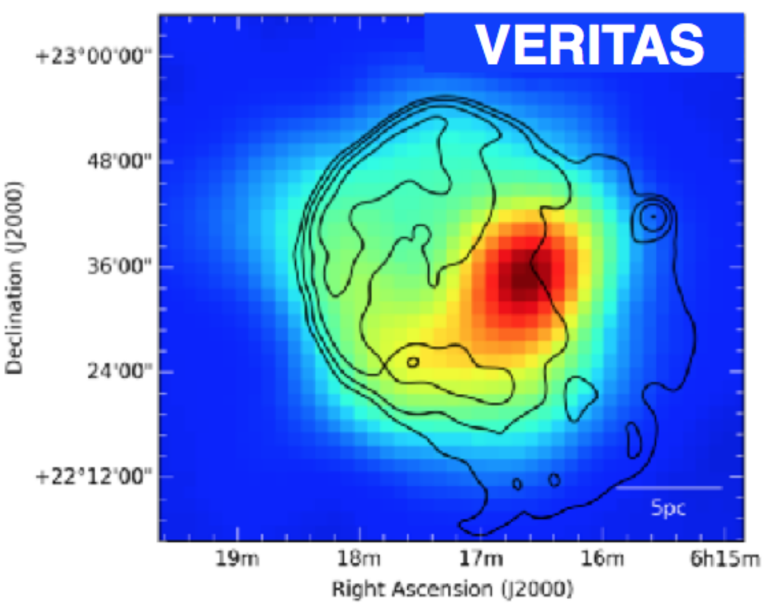


Middle-aged SNRs: IC 443



$\alpha_R = 0.36 \rightarrow s = 1.72$





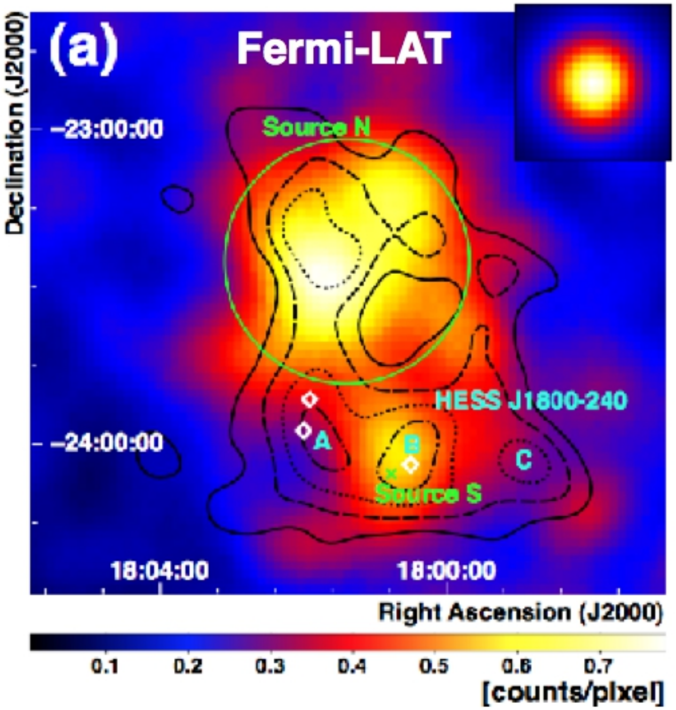
$$f_0(p) \propto p^{-(4+1/3)}$$

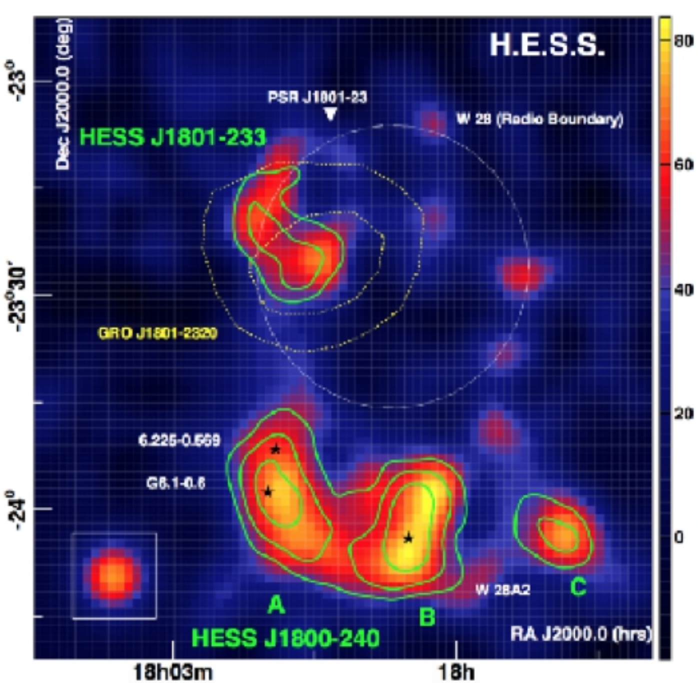
$$T_{\rm SNR} = 10^4\,{\rm yr},\ n_{\rm up} = 10\,{\rm cm}^{-3}$$

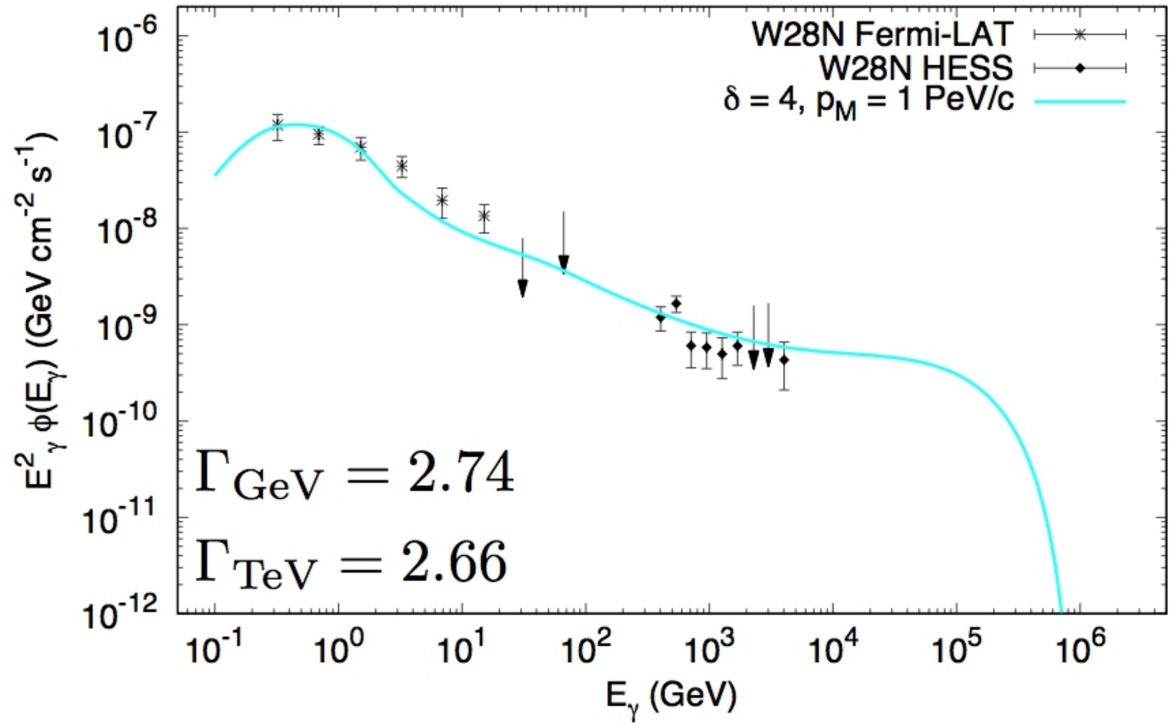
$$D(10\,{\rm GeV/c}) = 10^{27}\,{\rm cm}^2/{\rm s}$$

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

Middle-aged SNRs: W 28N







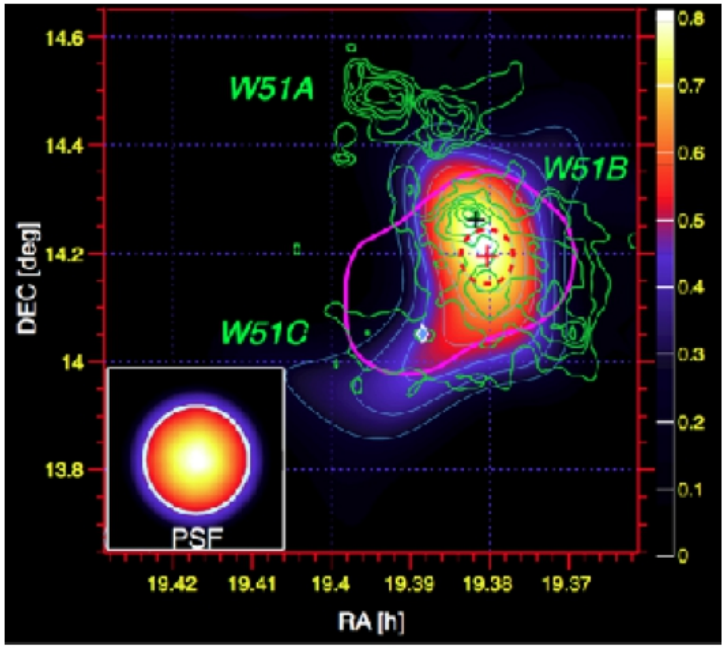
$$f_0(p) \propto p^{-4}$$

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

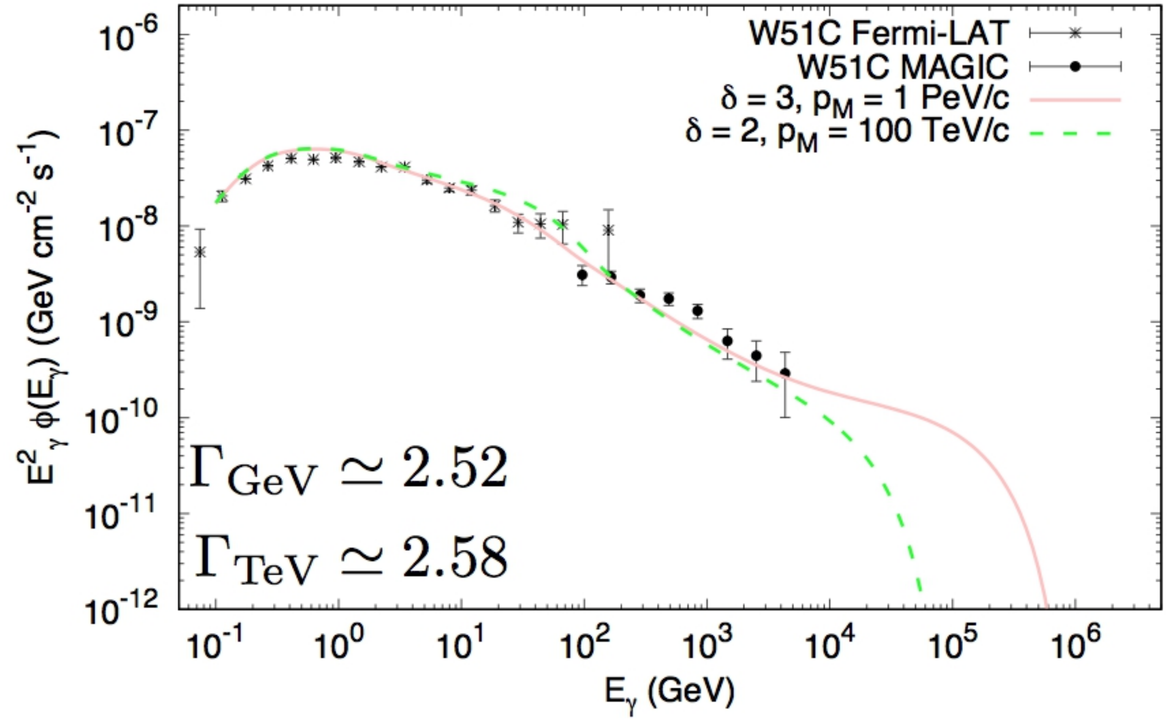
$$D(10\,{\rm GeV/c}) = 3 \times 10^{27}\,{\rm cm}^2/{\rm s}$$

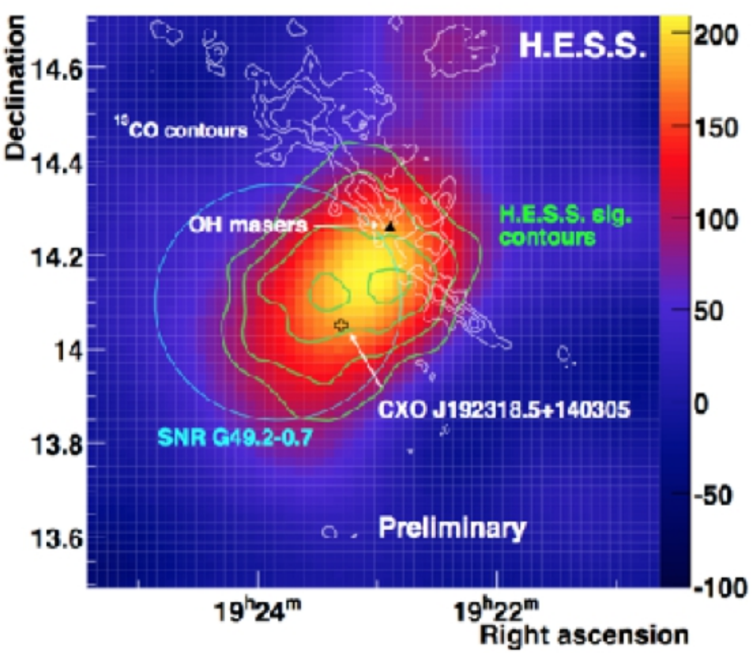
$$\xi_{\rm CR} \simeq 15\%$$

Middle-aged SNRs: W 51C



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





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

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

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

Conclusion on *escape*

- Escape determines the final spectrum released inside the Galaxy

How acceleration efficiency varies in time?

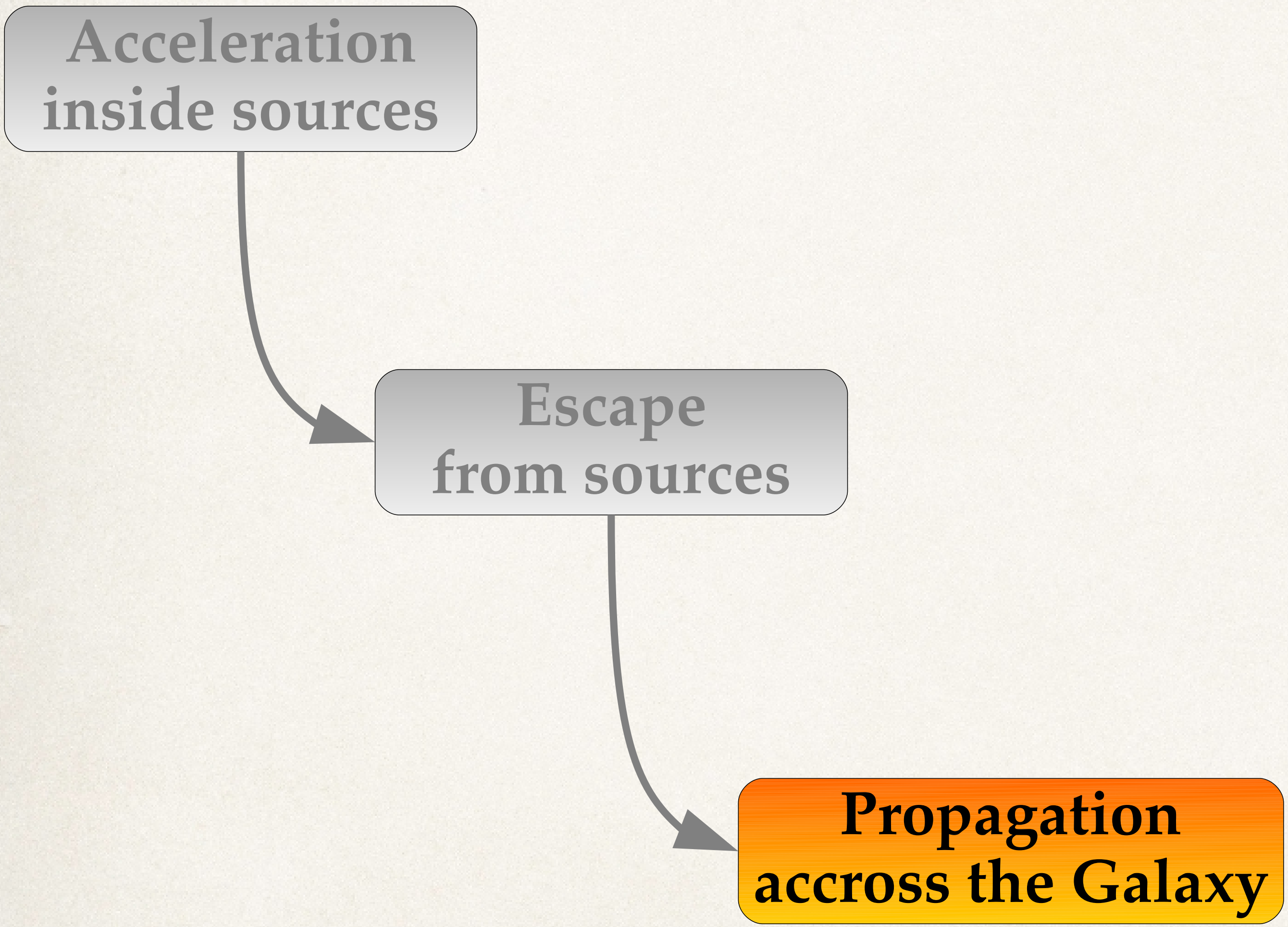
- Escape can determine the gamma-ray spectrum observed in SNR:
  - Under the assumption $D_{out} << D_{gal}$, γ-ray spectra favors $\delta < 2$ which requires:

    - magnetic field amplification
    - possibly magnetic damping

Which is the diffusion coefficient immediately outside the source?

- Spectrum detected at Earth favours f_{inj} steeper than p^{-4} (see next section)

Diffusion in the Galactic Halo



The Secondary/Primary ratio

Cross time for ballistic motion in the Galaxy

$$\tau_{cross} = \frac{h}{c} \simeq \frac{300\ pc}{c} \simeq 10^3\ yr$$

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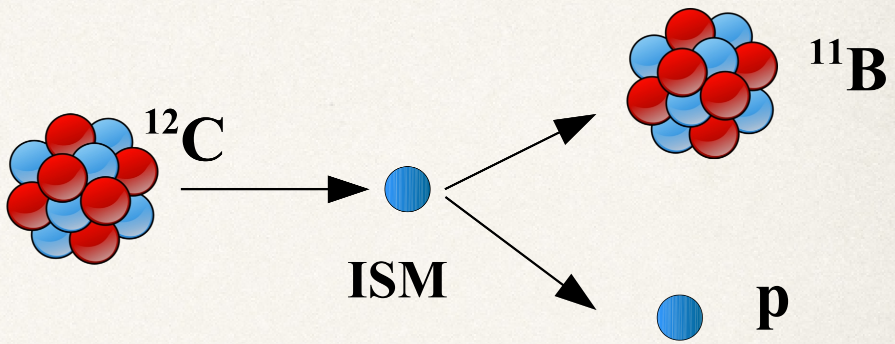
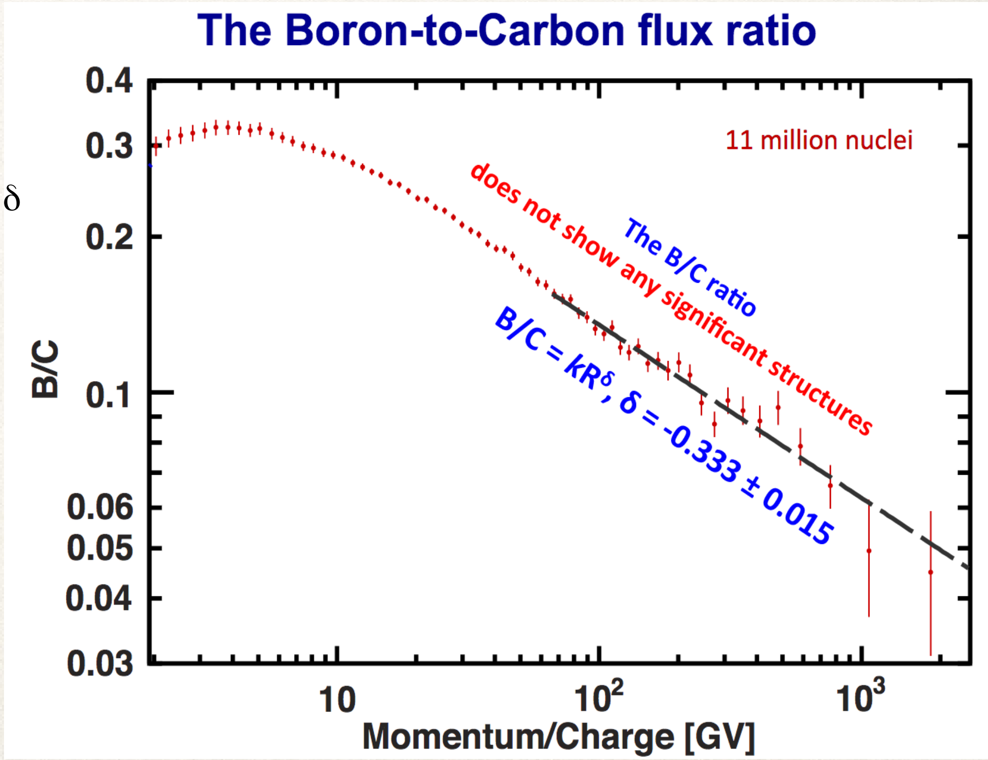
Cross time for ballistic motion in the Galaxy

$$\tau_{cross} = \frac{h}{c} \simeq \frac{300\ pc}{c} \simeq 10^3\ yr$$



Secondary/primary ratio:

$$\begin{cases} N_p(E) = Q_{inj}(E)\,\tau_{esc}(E) \propto E^{-\gamma-\delta} \\ N_s(E) = N_p(E)\,(n_H \sigma_{sp} c)\,\tau_{esc}(E) \propto E^{-\gamma-2\delta} \end{cases}$$



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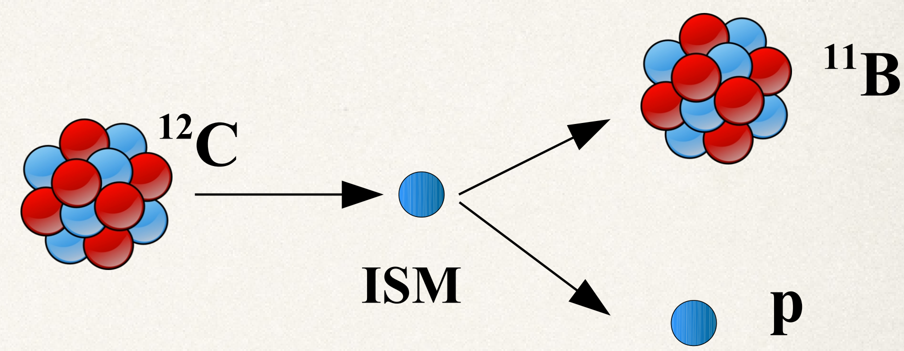

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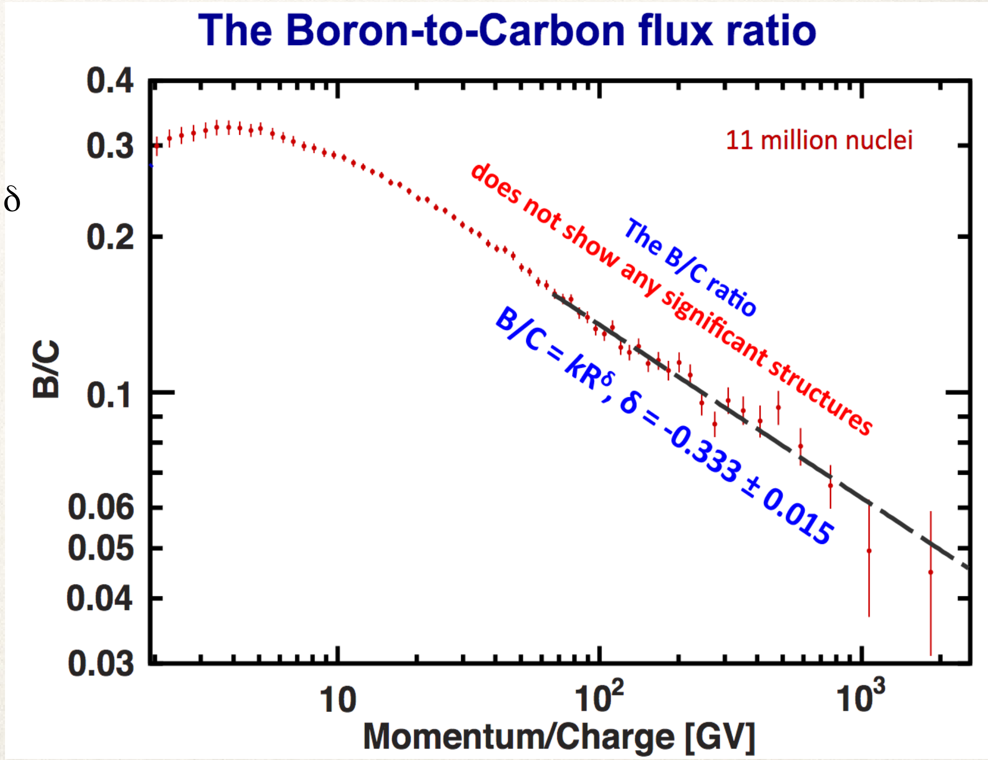
$$\frac{N_s}{N_p} \propto \tau_{esc}(E) \sim E^{-\delta}$$

$$\tau_{esc}(E \sim GeV) \sim 10^8\ yr$$



^ **The propagation is diffusive**

Basic Halo model

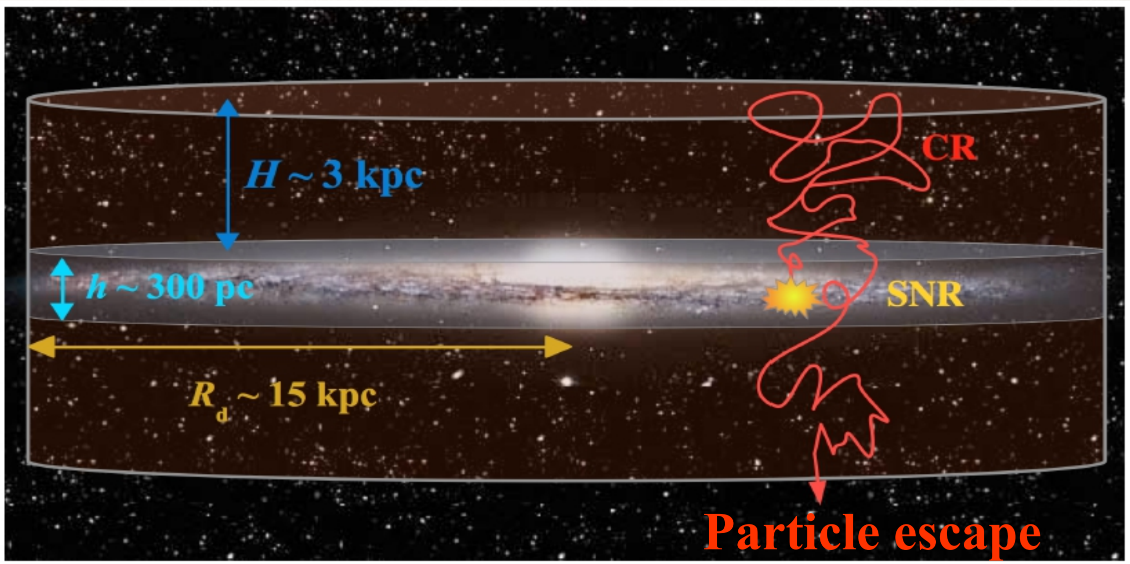
In the basic picture of CR propagation model:

- CRs diffuse in a magnetic halo larger than the Galactic disc
- The CR distribution vanish at $z = H$ (H~3-4 kpc from diffuse synchrotron emission)
- The diffusion coefficient $D(E)$ is assumed constant everywhere in the halo

$$\tau_{esc}(E) = \frac{H^2}{2D(E)}$$

$$D(E) \propto E^{1/3}$$

Suggesting Kolmogorov turbulence



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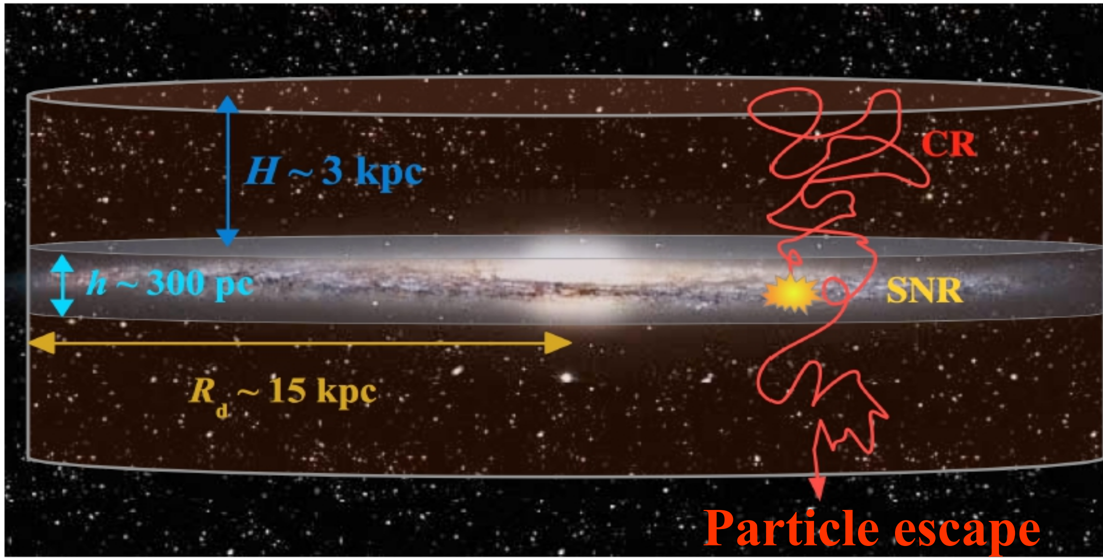


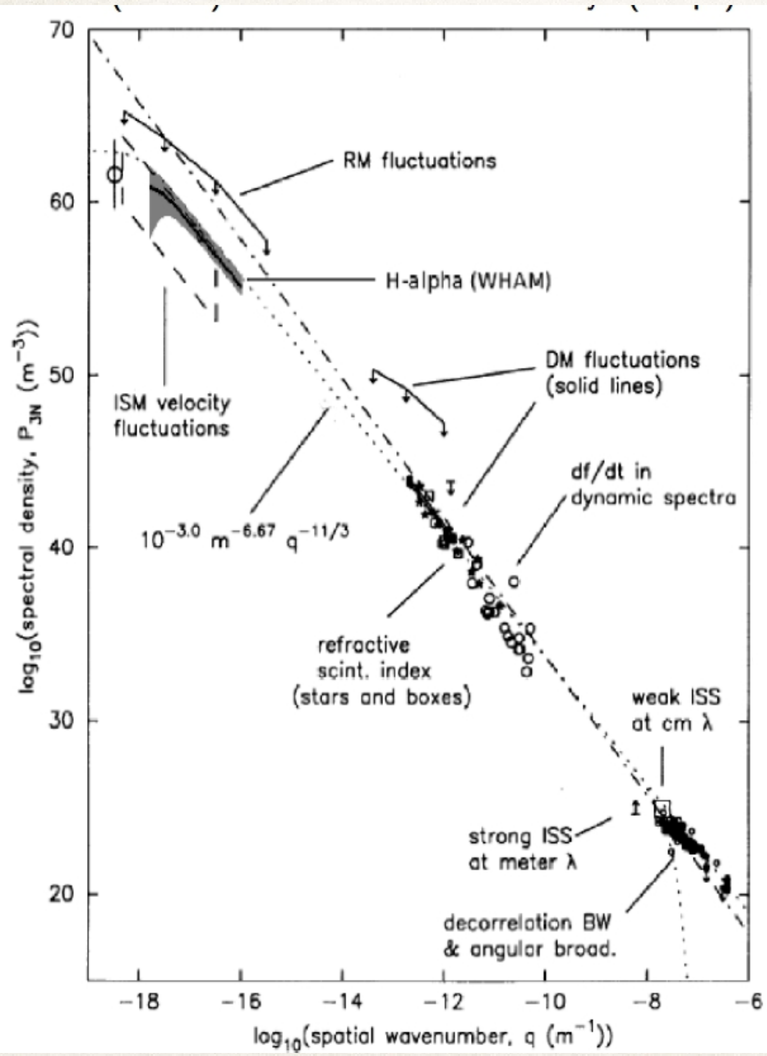
This picture is unsatisfactory for at least two reasons:

- Which is the physical meaning of H ?
- What generates the diffusion?

The interstellar turbulence

Electron density flucuation in the ISM

[Armstrong et al. 1995, Lazarian 1995]



BASIC ASSUMPTIONS:

- Turbulence is stirred by SNe at a typical scale L~ 10-100 pc

- The spectrum is Kolmogorov like $\sim k^{-5/3}$ (density is a passive tracer so it has the same spectrum: $\delta n \propto \delta B^2$):

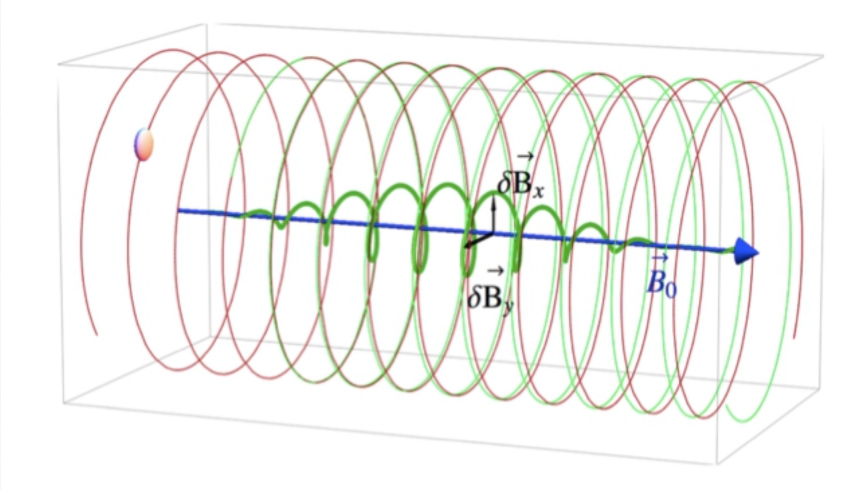
$$W(k)\,dk = \frac{\langle \delta B(k) \rangle^2}{B_0^2} = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}$$

where $k_0 = L^{-1}$ and the level of turbulence is

$$\eta_B = \int_{k_0}^{\infty} W(k)\,dk \sim 0.01 - 0.1$$

- **Magnetic field turbulence is Alfvénic**

Charged particles in a turbulent field: quasi-linear theory



- The turbulent field is a small perturbation with respect to the regular component

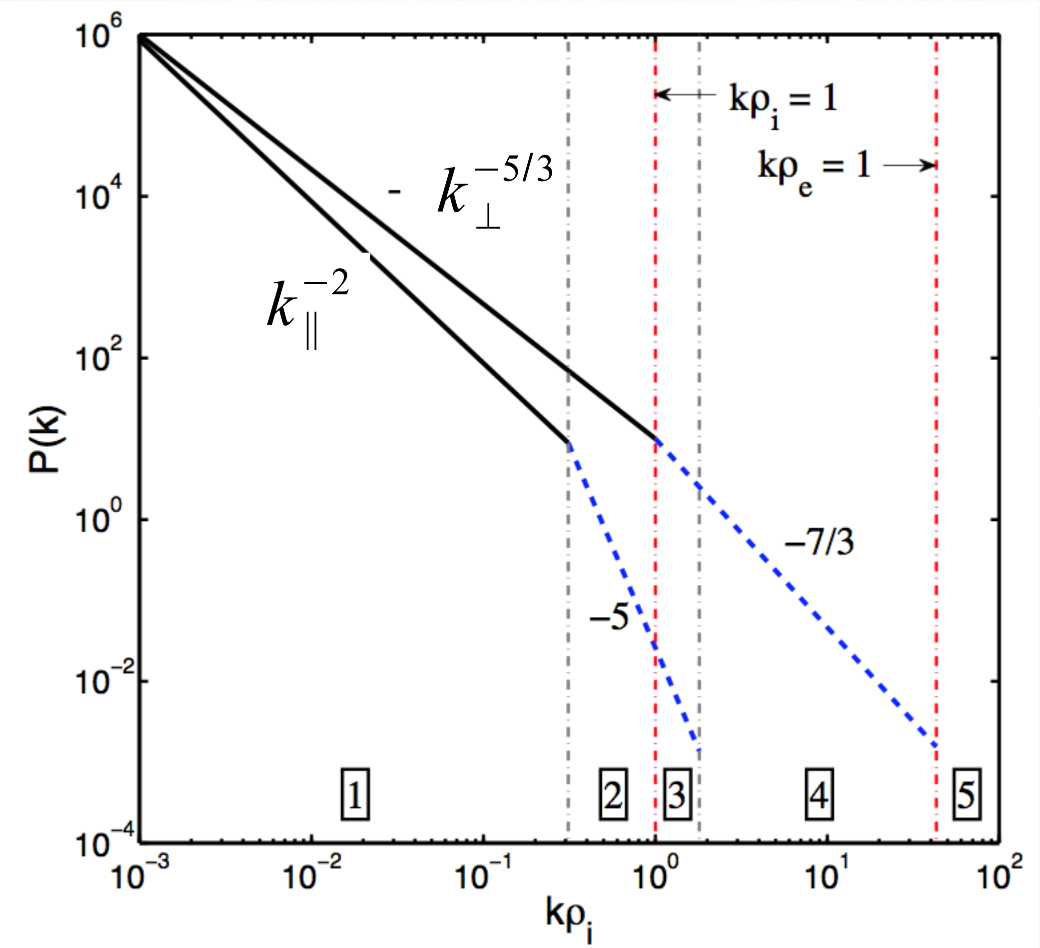
- Particles interact with parallel waves resonantly: $k_{res} = 1/r_L(p)$ $\quad k \| B_0$

- A diffusion behavior follows with typical diffusion coefficient

$$D_{zz}(p) = \frac{v\, r_L}{3} \frac{1}{k_{res} W(k_{res})} \sim 3\times 10^{28} \left(\frac{p}{GeV/c}\right)^{1/3} cm^2\, s^{-1}$$

1^{st} problem: anisotropic turbulent cascade

Energy spectra of Alfvénic turbulence from critical balance



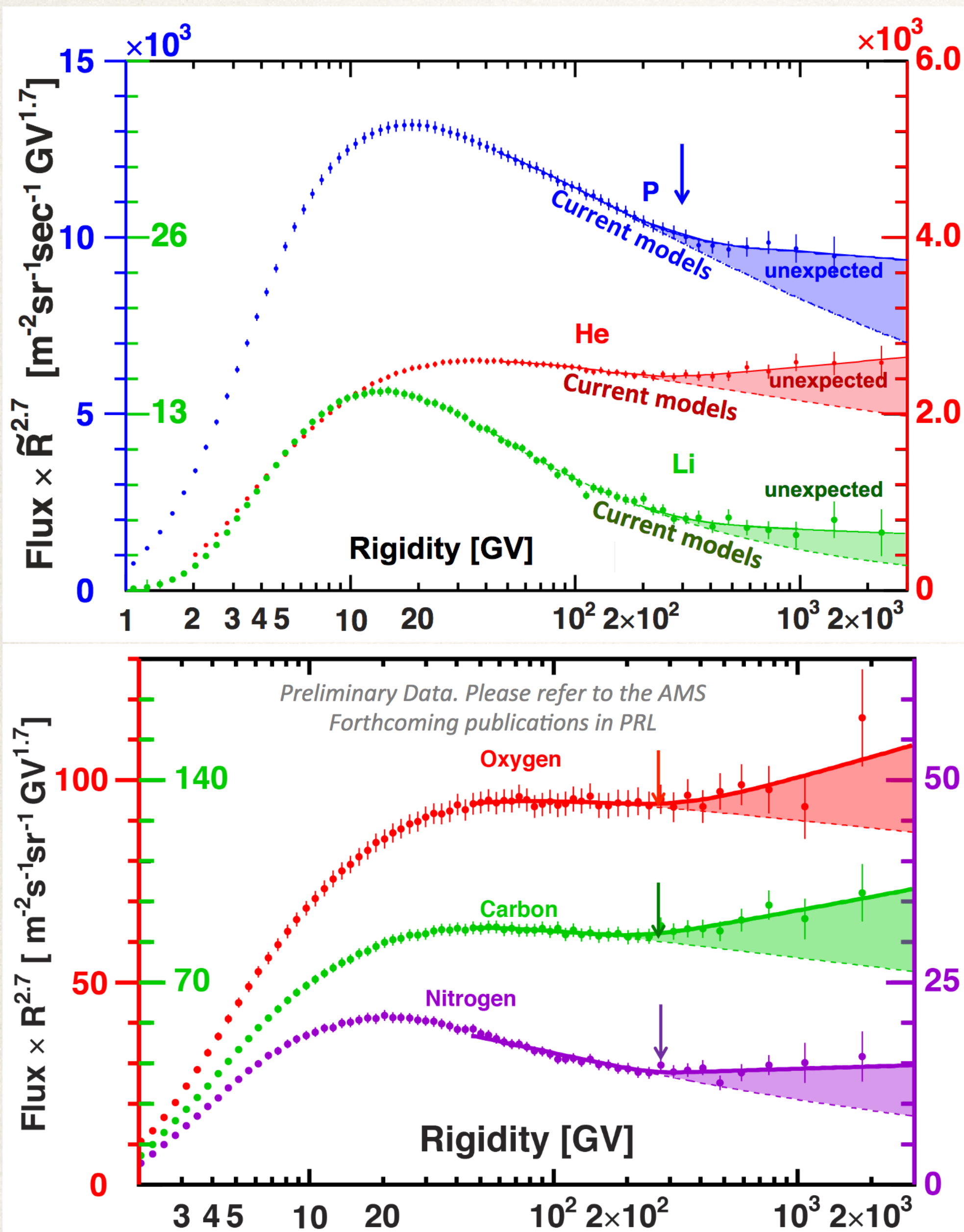
(Chen et al., (2010)

- The cascade of Alfvénic turbulence becomes anisotropic (Goldreich& Sridhar 1994, 1995)

$$P(k_{\parallel}) \propto k_{\parallel}^{-2}; \qquad P(k_{\perp}) \propto k_{\perp}^{-5/3}$$

- The power is mainly in modes perpendicular to the local magnetic field, which are inefficient to scatter particles
- At small scale there is not enough power to scatter particles

2^{nd} problem: spectral hardening



Recent measurements by PAMELA and AMS-02 revealed the existance of a fine structure:

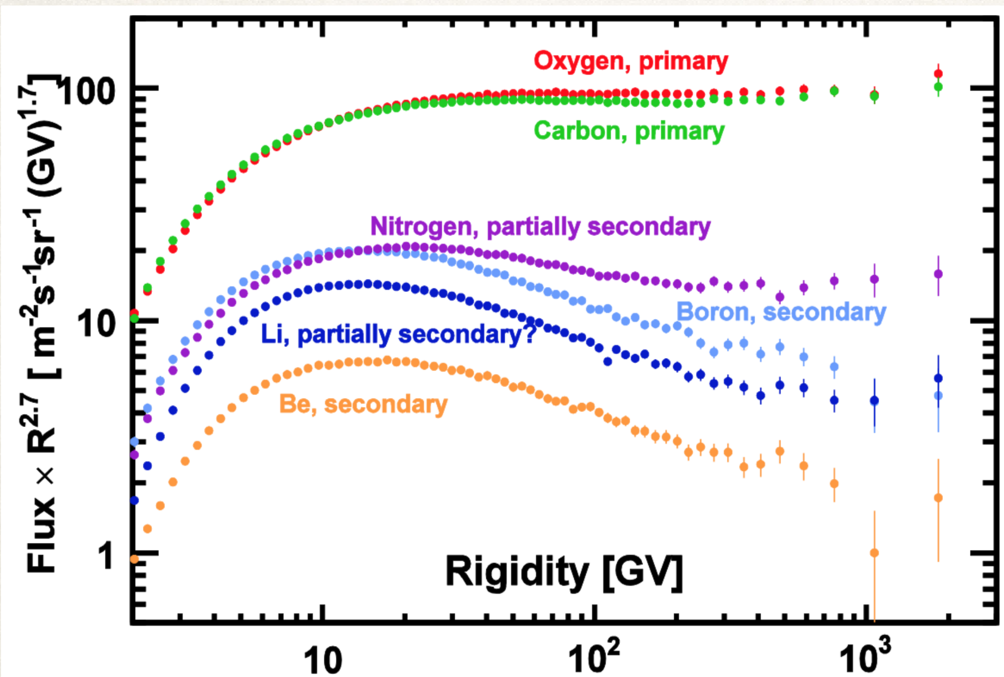
At rigidity of ~300 GV all spectra show a spectral hardening

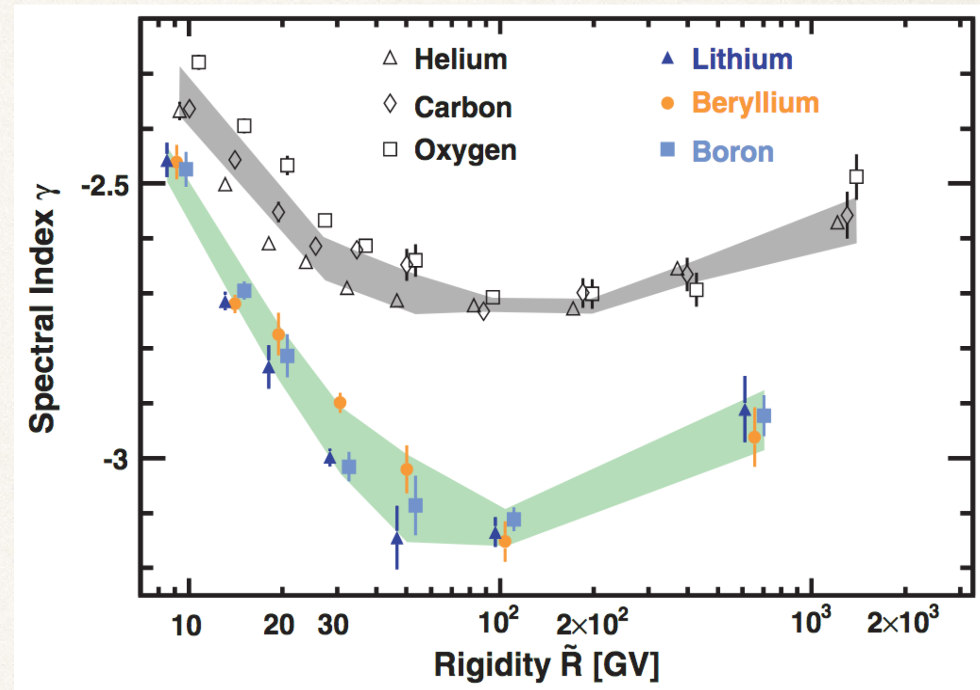
NO MORE A SIMPLE POWER-LAW

$$f_0(E) = \frac{Q_{SN}(E)}{2\pi R^2_{disc}} \frac{H}{D(E)} \propto E^{-\gamma-\delta}$$

Either the injected spectrum or the diffusion present a break at ~300 GV

Spectral hardening for secondary CRs





[AMS collaboration, PRL 120, 021101, 2019]

$$f_{sec}(E) = f_{pri} \times \tau_{esc} \propto E^{-\gamma-2\delta}$$

The spectral hardening of secondary species is larger than primaries

^ supports the origin of break due to propagation rather than primary acceleration

Waves from resonant streaming instability: a simple exercise

- Apply the resonant streaming instability to CR escaping from the halo

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

- The magnetic turbulence is damped by non-linear processes:

$$\Gamma_{NLD} = v_s k F(k)$$

- Equating the rate of amplification and damping we get $F(k)$ and the diffusion coefficient

$$\Gamma_{CR} = \Gamma_{NLD}$$

$$D(E) \simeq \frac{r_L v}{3F(k_{res})} = 6 \times 10^{27} \left(\frac{E}{10\,GeV} \right)^{0.85} \left(\frac{H}{4\,kpc} \right)^{1/2} \quad cm^2/s$$

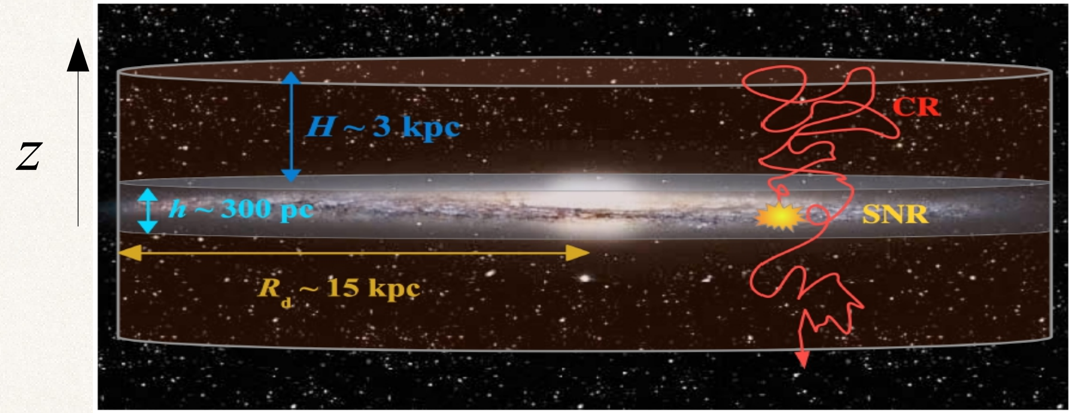
Normalization close to the value inferred from B/C

Different energy dependence from the Kolmogorov turbulence

Coupling CR transport with magnetic turbulence evolution

CR transport equation in 1-D

$$\frac{\partial f}{\partial t} + v_A \frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D \frac{\partial f}{\partial z}\right]$$



Self-generated diffusion coefficient

$$D(p,z,t) = \frac{r_L v}{3} \left.\frac{1}{\mathcal{F}(k,z,t)}\right|_{k=1/r_L}$$

$$\frac{\delta B^2}{B_0^2} = \int \mathcal{F}(k) \frac{dk}{k}$$

Turbulence spectrum

Transport equation for magnetic turbulence

$$\frac{\partial \mathcal{F}}{\partial t} + v_A \frac{\partial \mathcal{F}}{\partial z} = (\Gamma_{CR} - \Gamma_D)\,\mathcal{F} + Q_w$$

Damping **Injection**

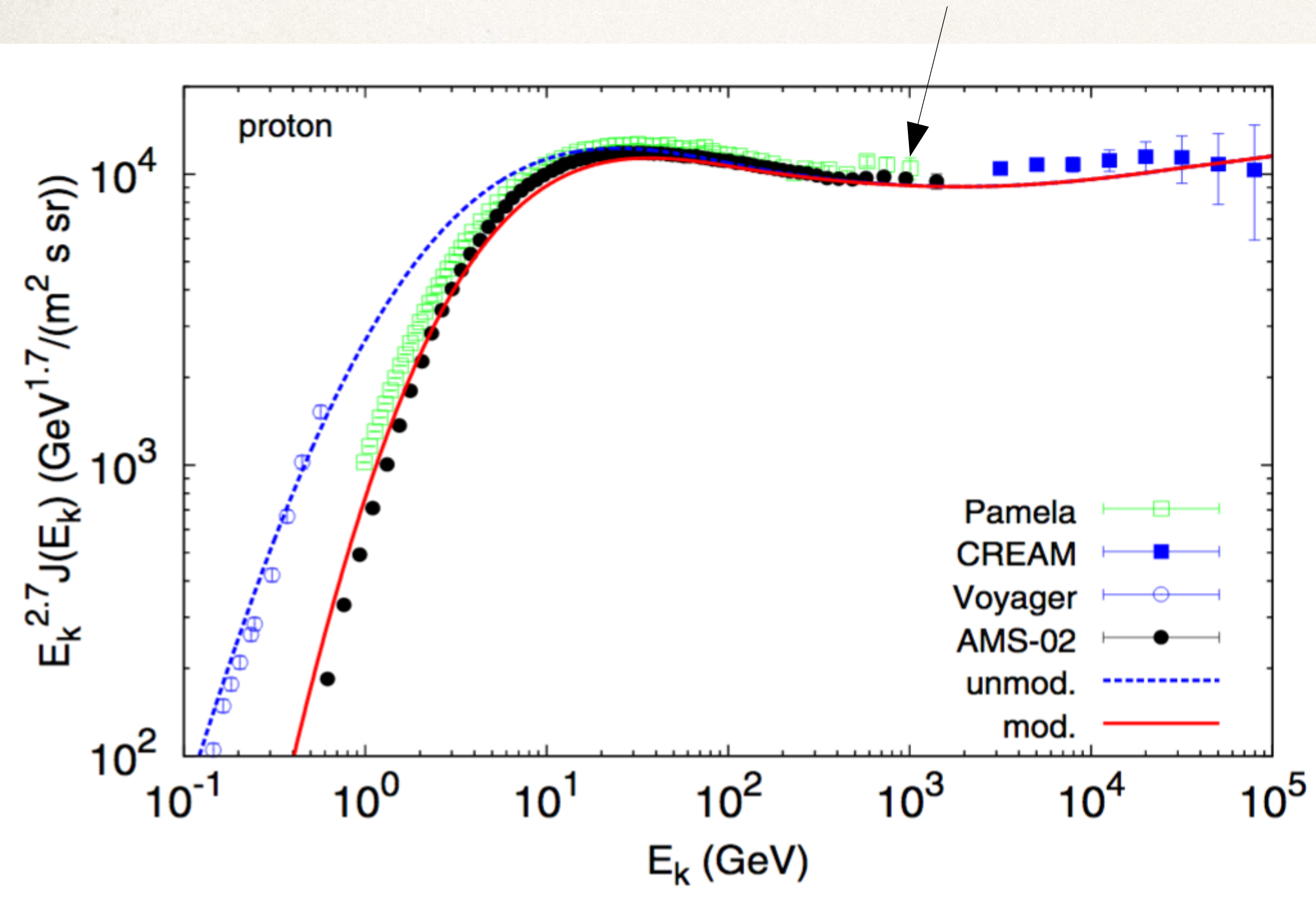
Resonant amplification:

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

Position of the break

(Blasi, Amato & Serpico, 2016)

$$E_{\rm tr} = 228\ {\rm GeV} \left(\frac{R_{d,10}^2 H_3^{-1/3}}{\xi_{0.1} E_{51} \mathcal{R}_{30}} \right)^{\frac{3}{2(\gamma_p - 4)}} B_{0,\mu}^{\frac{2\gamma_p - 5}{2(\gamma_p - 4)}}$$

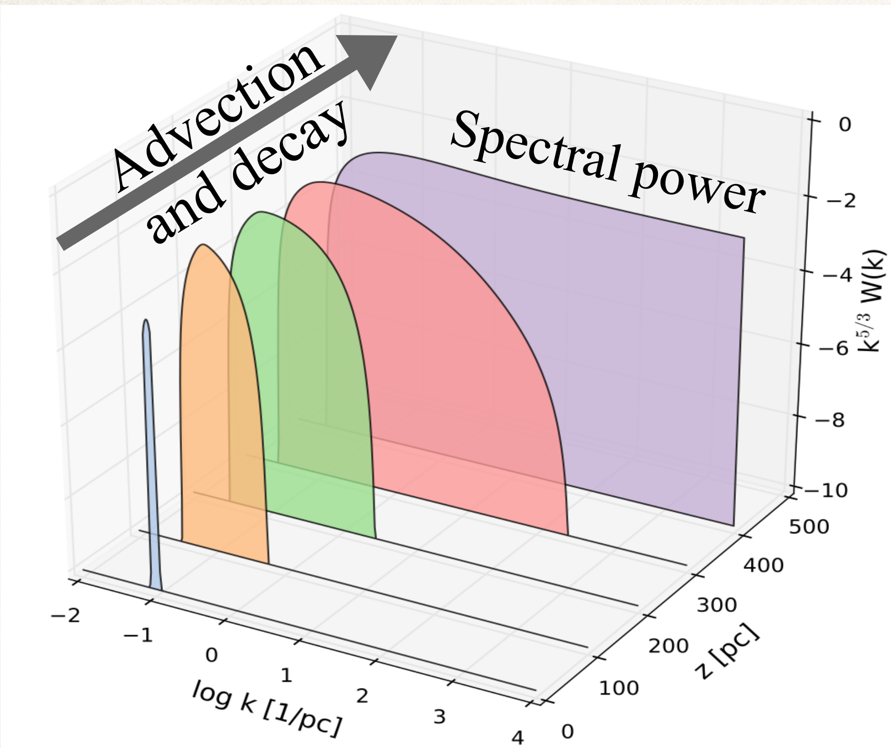


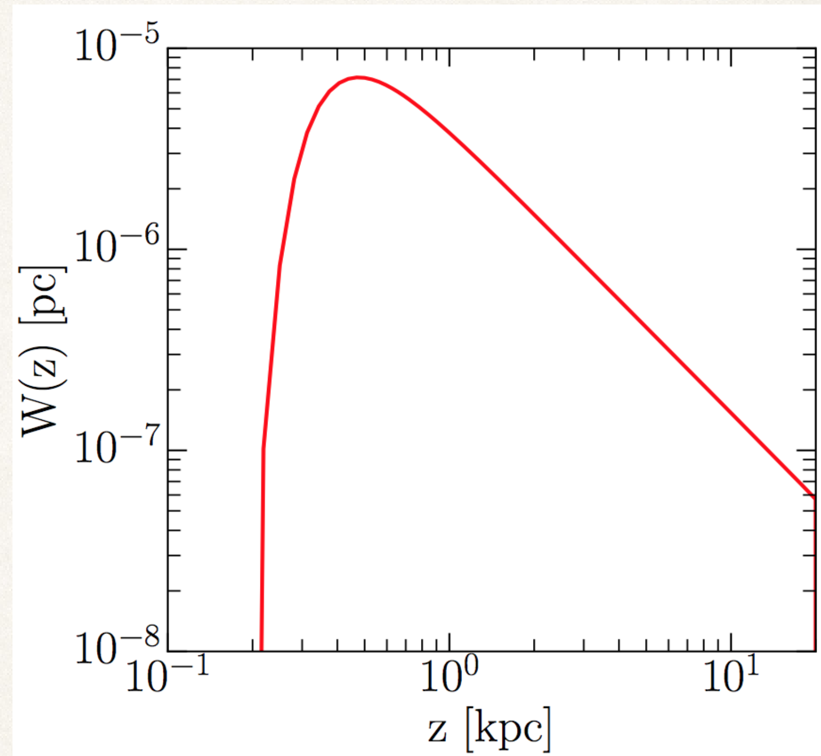
- Pre-existing waves (Kolmogorov) dominates above the break
- Self-generated turbulence dominates below ~100 GeV

Developing the turbulent halo

[Evoli, Blasi, GM, Aloisio, 2018, PRL]

Large scale turbulence generated inside the Galaxctic disc by SN explosion advected and decaying through Kolmogorov cascade.



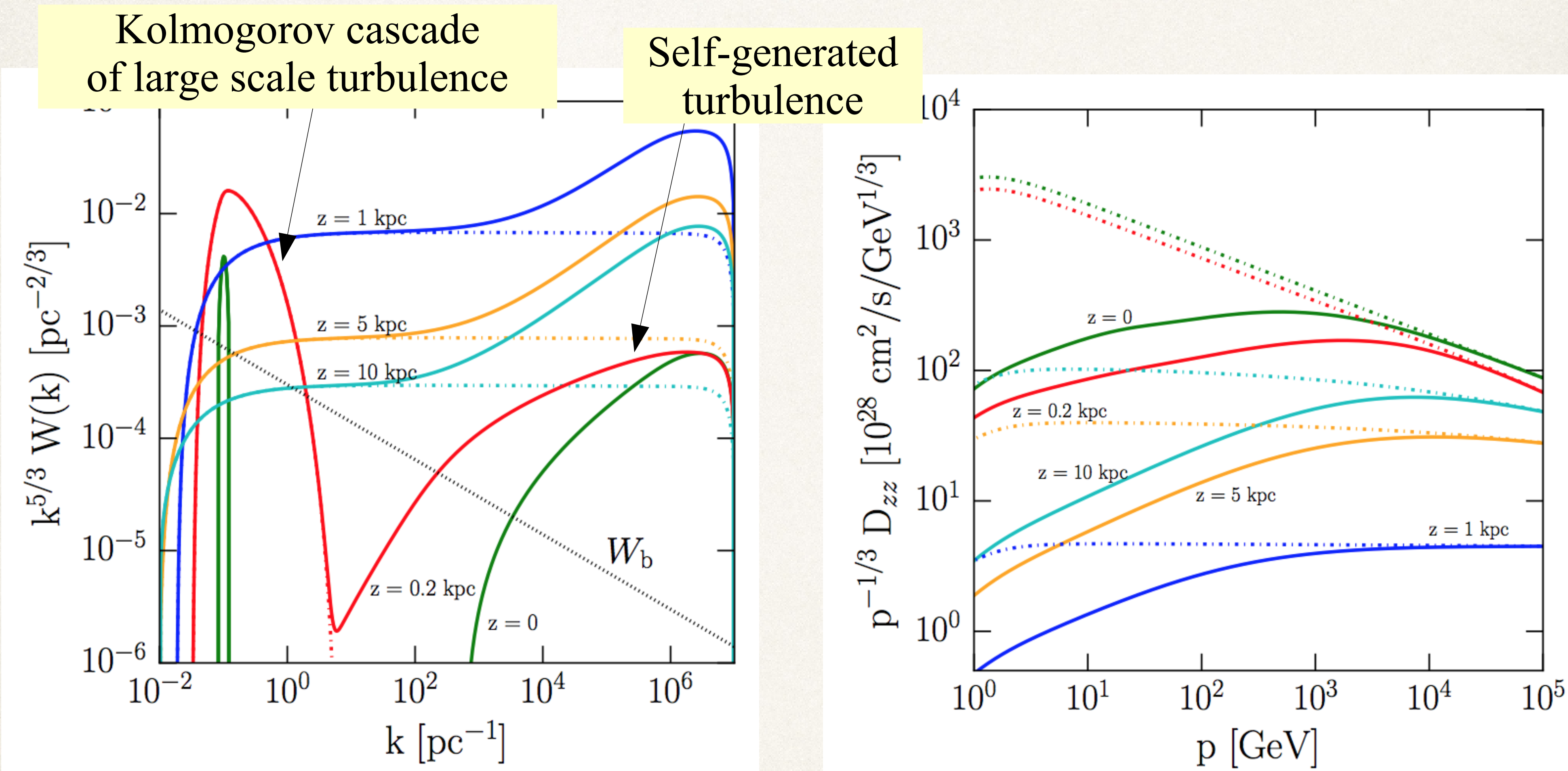


$$\tau_{cascade} = \tau_{adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_c}{v_A} \rightarrow z_c \sim kpc$$

- z_c sets the scale where the turbulent cascade develops
- The boundary H does not have any physical meaning

Non-linear cosmic ray transport: a global picture

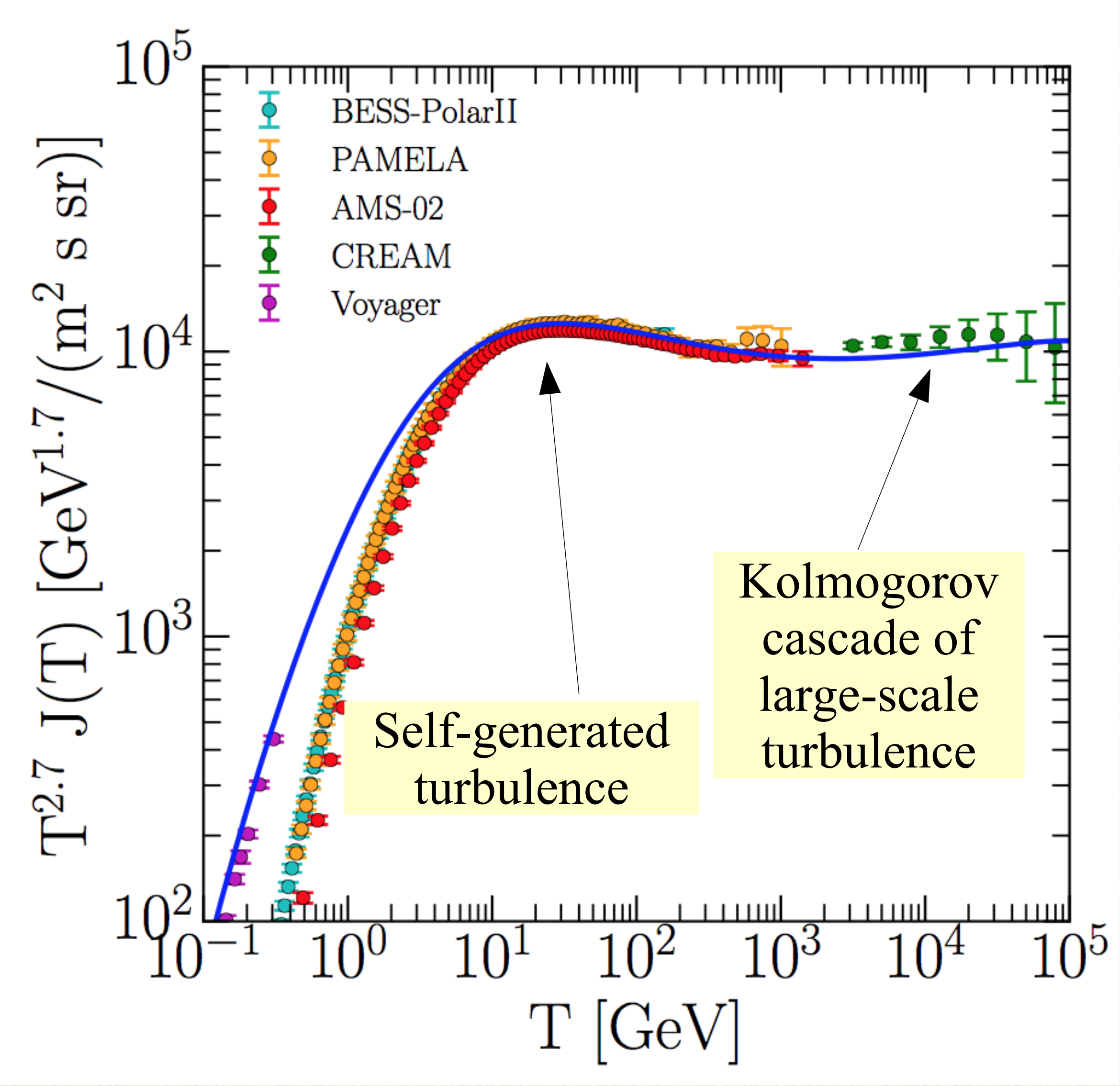
(Evoli, Blasi, GM, Aloisio, 2018, PRL)



Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

Non-linear cosmic ray transport: a global picture

(Evoli, Blasi, GM, Aloisio, 2018, PRL)

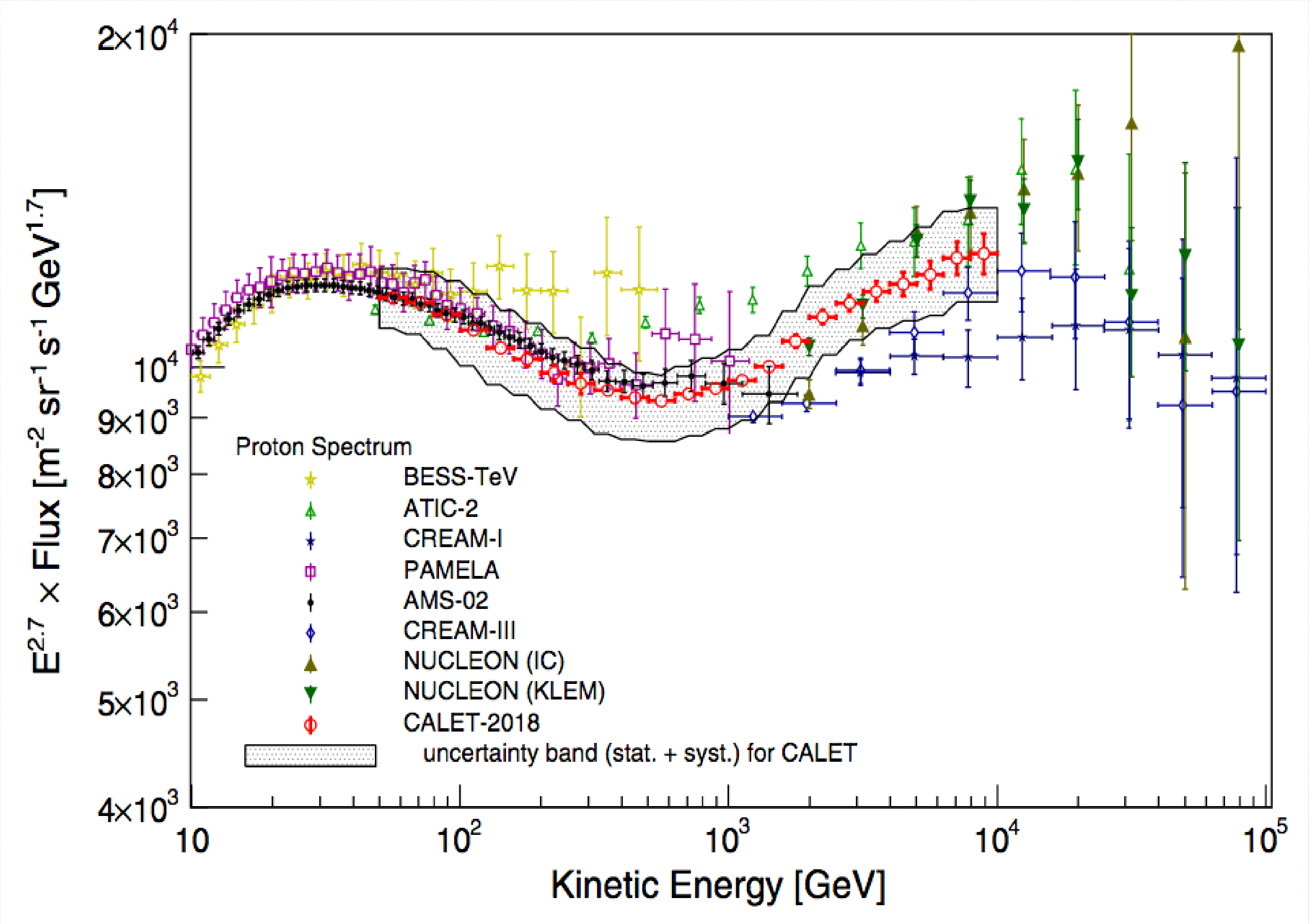


- Pre-existing waves (Kolmogorov) dominates above the break
- Self-generated turbulence dominates below ~100 GeV
- Voyager data are reproduced with no additional breaks, but due to advection with self-generated waves
- The boundary ($H = 100$ kpc) has no impact on the result
- Low energy spectrum is well accounted by advection without introducing *ad hoc* breaks in the primary spectra.

Comparison with CALET data

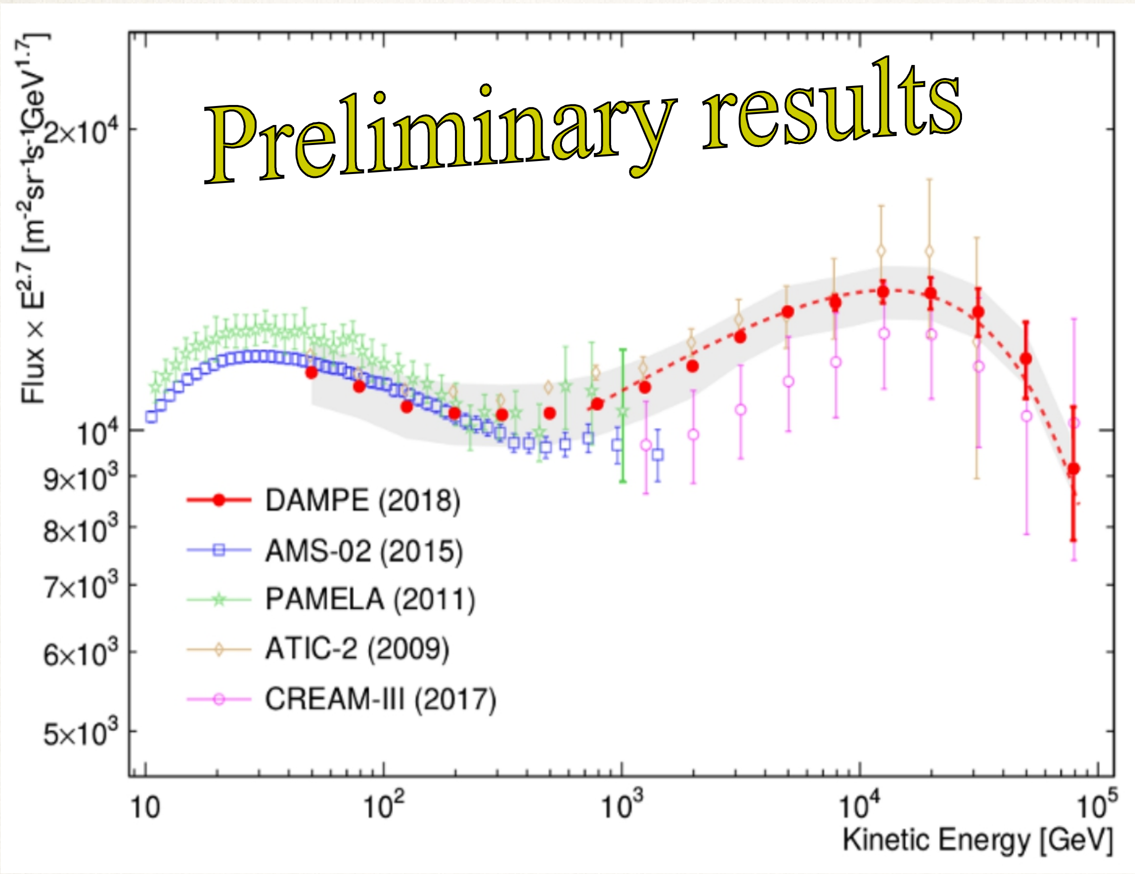
[Adriani et al., CALET colaboration, PRL 122,18, 2019]

- CALET also shows a breack but at $E \sim 500$ GeV
- The transition is sharper but still compatible with a smooth transition when systematic uncertainties are accounted for



Not the end of the story: more transport regimes?

Proton spectrum

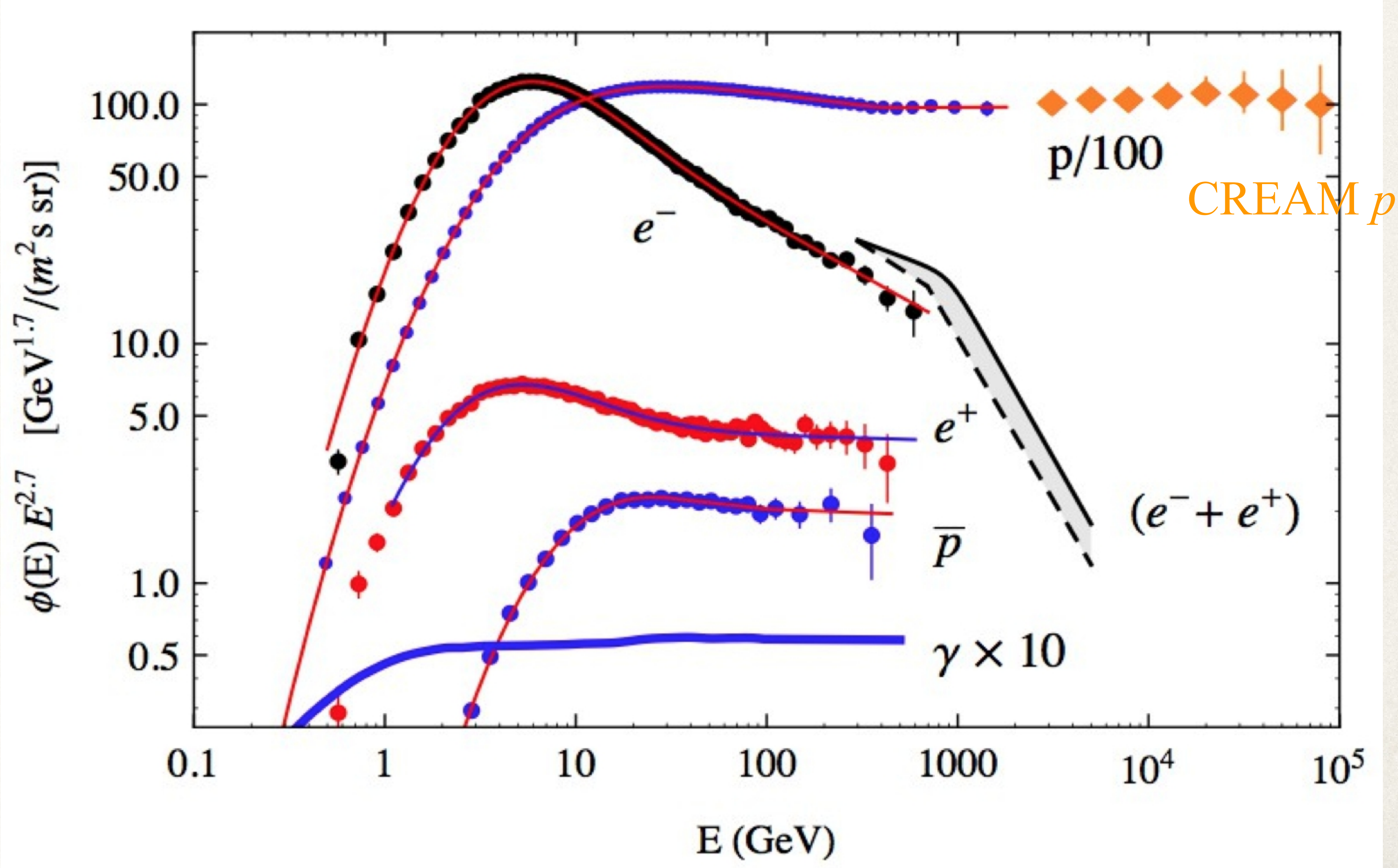


- Above ~10 TeV the proton specrum seems to steepen again
- Possible indication of a further change in transport regime?

[De Benedettis, DAMPE colaboration RICAP 2018]

What about positrons and anti-protons?

AM-02 data: above ~100 GeV p, e^+ and anti-p share the same slope, why?



Anti-protons

Three effects to take into account

- Production cross section increases with energy: $\sigma(E) \propto E^{\epsilon}$
- Inelasticity: $p(E) \rightarrow \bar{p}(E/20)$

→ harder parent protons beyond the break $N_p(E) \propto E^{-\gamma_1 + \Delta}$

- Flat diffusion coefficient $\delta < 0.5$

$$\frac{N_{\bar{p}}}{N_p} \propto \frac{E^{-\gamma_1 + \Delta + \epsilon - 2\delta}}{E^{-\gamma_1 - \delta}} \propto E^{\epsilon + \Delta - \delta}$$

In conclusion we have $\epsilon + \Delta - \delta \simeq 0$

More subtle effects

Data are increasing in quality: we are digging in more subtle secondary physical effects:

Two of these are:

Particles encountering a shock are reaccelerated
[Blasi (2017)]

No effects on primary spectra but flattening of secondaries

$$f_0(p) = s \frac{\eta n_1}{4\pi p_{\rm inj}^3} \left(\frac{p}{p_{\rm inj}}\right)^{-s} + s \int_{p_0}^{p} \frac{dp'}{p'} \left(\frac{p'}{p}\right)^{s} g(p'),$$

More important for steep secondaries (e.g. B)

Grammage accumulated within the source
[Aloisio, Blasi & Serpico (2015)]

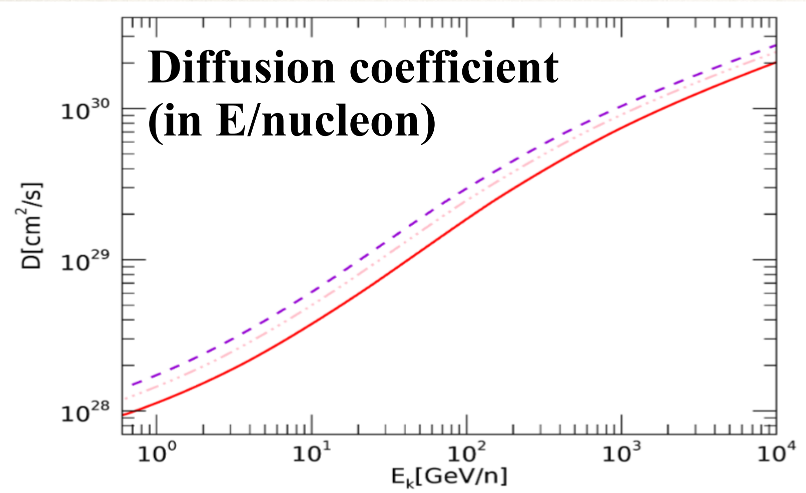
Flattening of secondaries at high energies

$$X_{\rm SNR} \approx 1.4 r_s m_p n_{\rm ISM} c T_{\rm SNR} \approx 0.17\,{\rm g\,cm^{-2}} \frac{n_{\rm ISM}}{\rm cm^{-3}} \frac{T_{\rm SNR}}{2\times 10^4\,{\rm yr}},$$

More sensible for small grammage

Effects of reacceleration and source grammage

[Bresci, Amato, Blasi, Morlino, 2019]

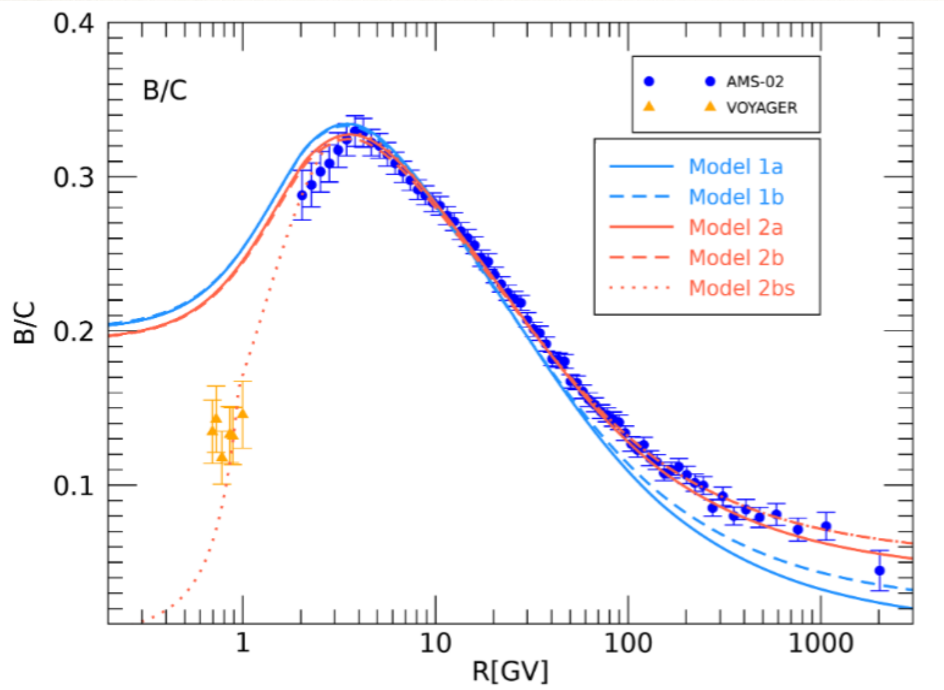


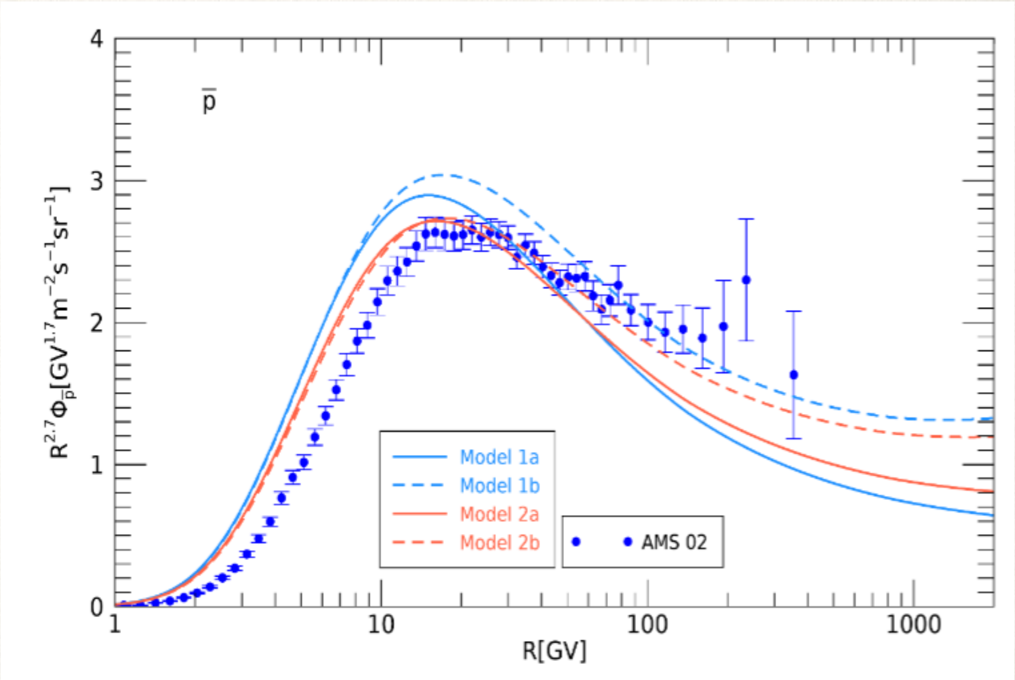
Basic model

+ source grammage

+ reacceleration

+ reacceleration+source grammage

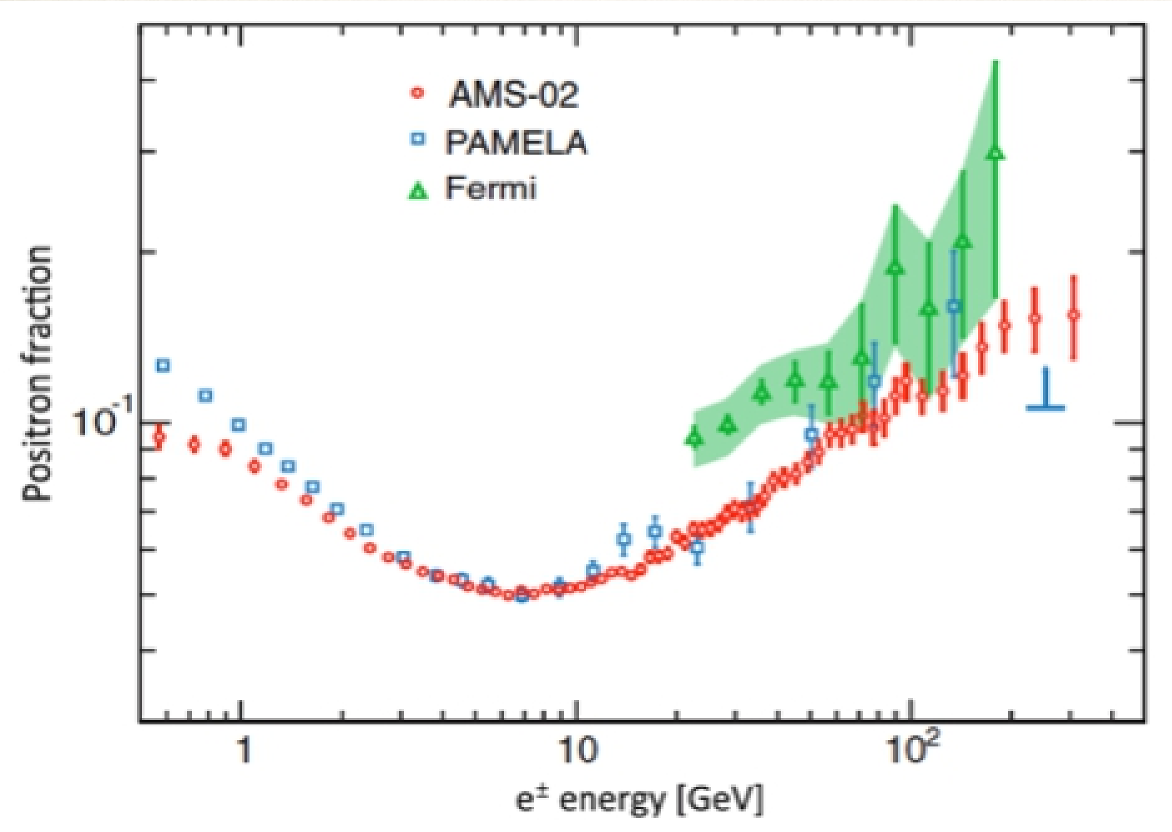




The positron excess

IF e^+ only secondaries
e^- have the same spectrum as p

$$\frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \propto E^{-\delta}$$

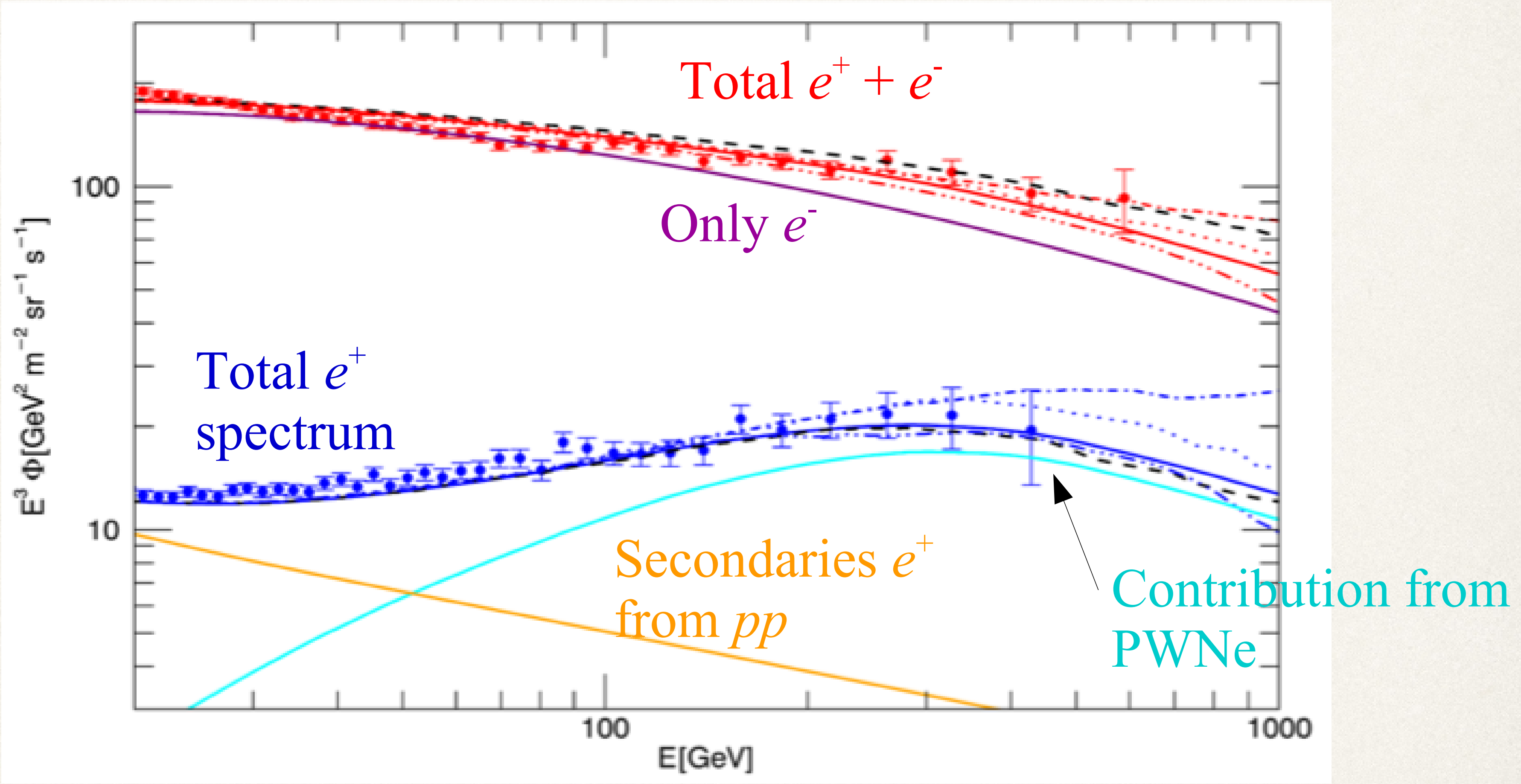


Pure secondary positions cannot explain the raising fraction.

Many many ideas (& papers):
- Dark matter
- New CR propagation scenarions
- Atrophysical sources

(e.g. Serpico 2012,
Di Mauro+ 2017,
Amaoto & Blasi 2017)

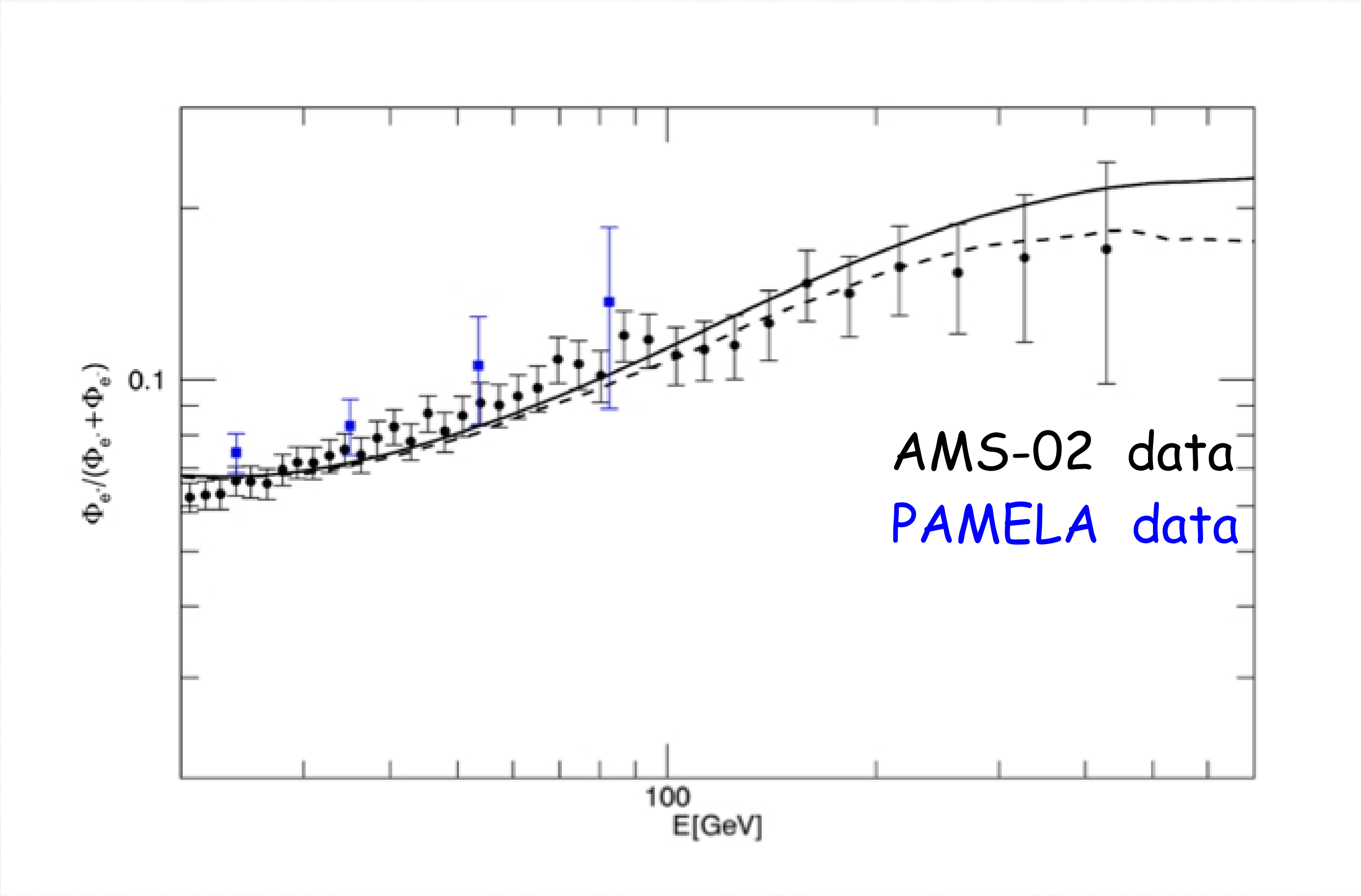
Positrons from PWNe



PWN ACCELERATION EFFICIENCY 12%

INJECTED SPECTRUM E-1.5 E<500 GEV

Positrons fraction



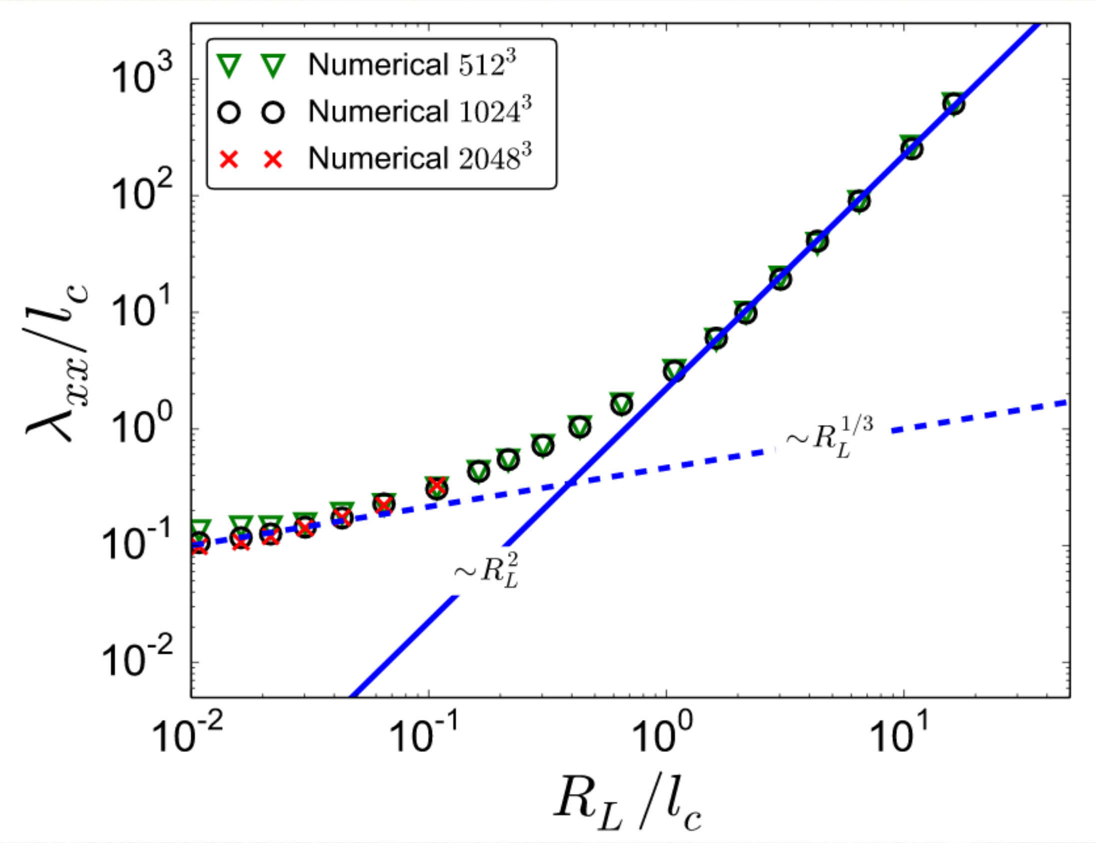
Amato & Blasi (2017)

What happens above the coherence scale?

Is there a signature in the CR spectrum associated with the injection scale of turbulence?

$$R_L(E, B_0) = 1\, E_{PeV}\, B_{\mu G}^{-1} \quad pc$$

Which is this injection scale? (usually assumed 50-100 pc but could be smaller)



Mean-free path of protons

$$D_{xx} = \frac{1}{3} \lambda_{xx} c$$

Diffusion of charged particles in fully three-dimensional isotropic turbulent magnetic fields with no mean field.

(Subedi et al., 2017 ApJ 837:140)

Conclusions: *propagation*

- Recent findings by PAMELA and AMS-02 (and CALET) show a break in the CR spectrum for all species
- Self generation of waves by CR can regulate the transport at low energies and can explain the spectral breaks
- Scattering at larger energies (~PeV) should be regulated by the large scale turbulence
  - The turbulence cascading from large scale may be unable to efficiently scatter CRs at lower energies (<0.1-1 TeV)(anisotropic cascade)
  - What abut meso scale (~10 TeV)?
- Expalining the spectrum of secondaries (B, e^+, anti-p) seems to require the inclusion of several second order effects.