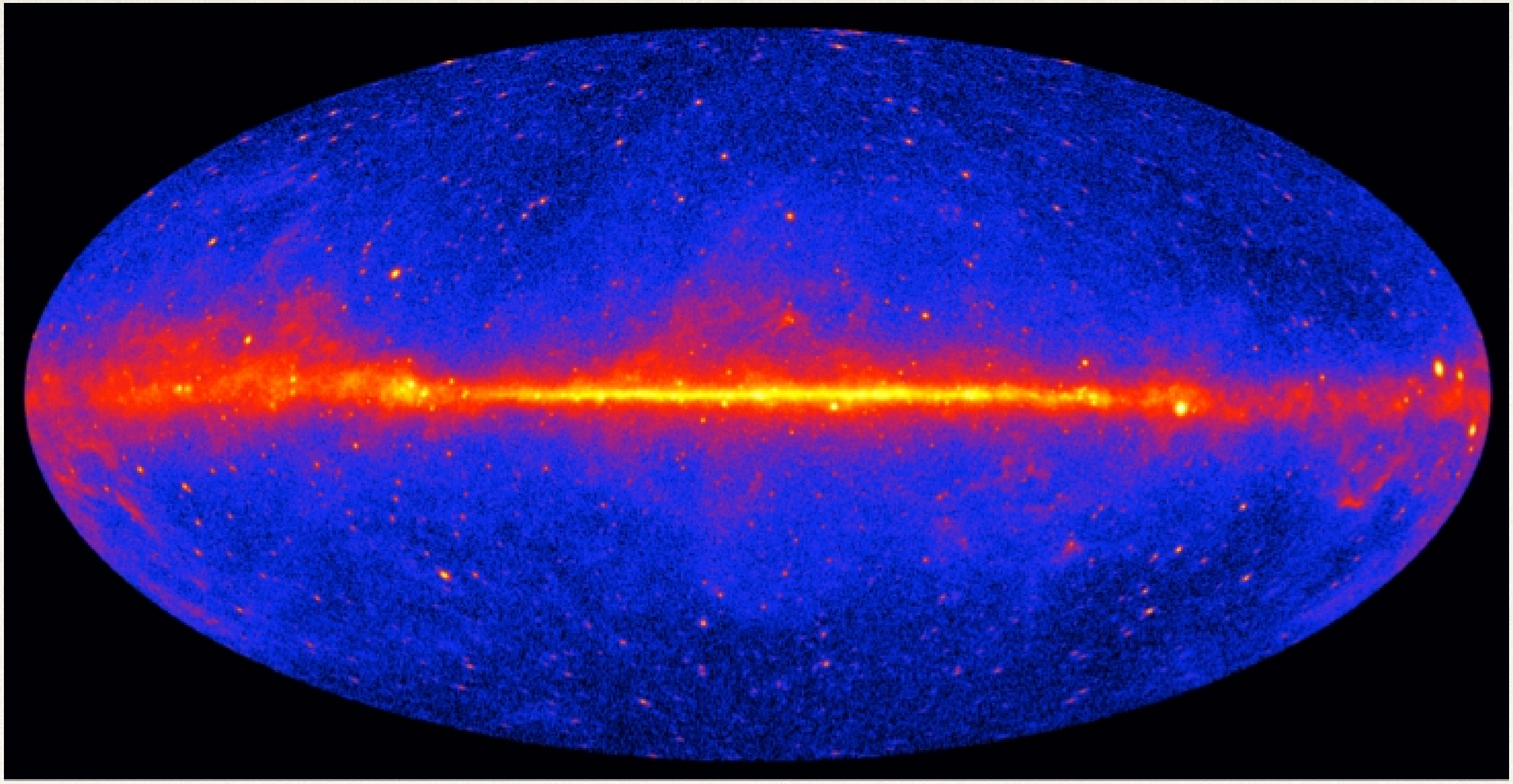


Cosmic Ray propagation in the Galaxy: the role of "*self-confinement*"

Giovanni Morlino,

INAF/Osservatorio Astrofisico di Arcetri, Firenze, ITALY

CRA 2019 – October 7-11, L'Aquila, ITALY

Role of self-generated turbulence

In the current picture of CR physics, the magnetic turbulence self-generated by the streaming of CRs plays a role in all basic steps of their life:

Acceleration inside sources → **Escape from sources** → **Propagation accross the Galaxy**

- This talk will cover only the turbulence generated through ***Resonant Streaming Instability***

- ***Non-Resonant (Bell) Instablity*** could also play a relevant role but has not been fully explored yet

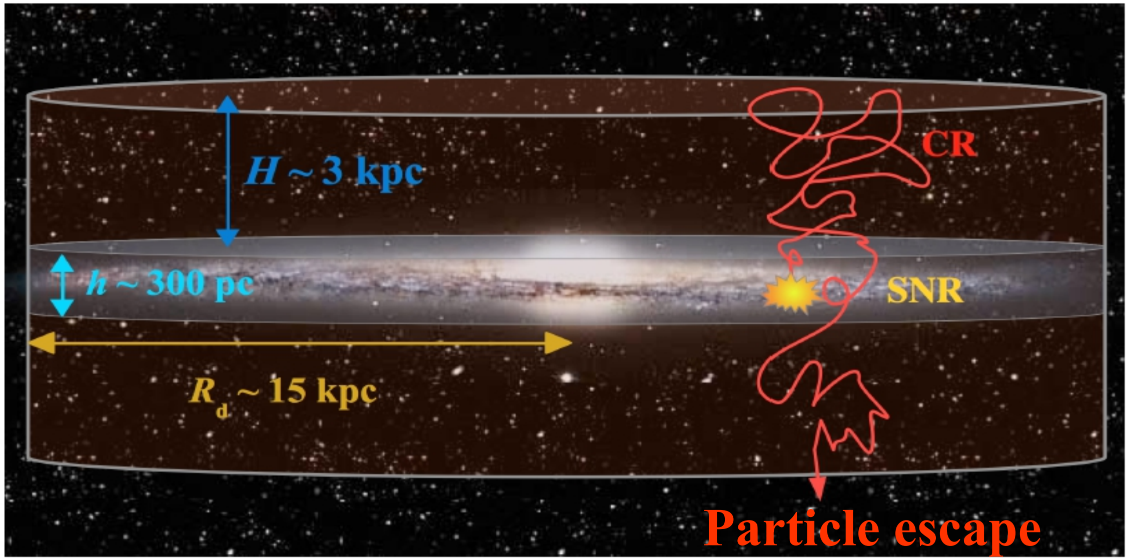
Basic *diffusive halo model*

In the basic picture of CR propagation model:

- CR sources are located inside the Galactic disc
- 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

  (Diffusion in the disc play a minor role)

Cylindrical simmetry



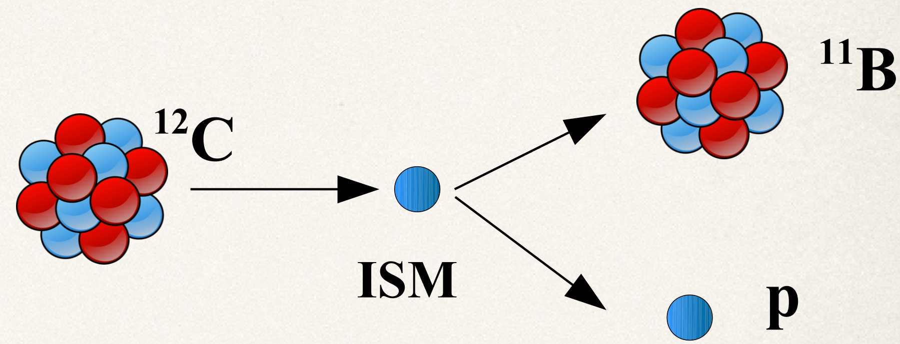
Escaping time from the halo

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

The Secondary/Primary ratio

Secondary / primary ratio:

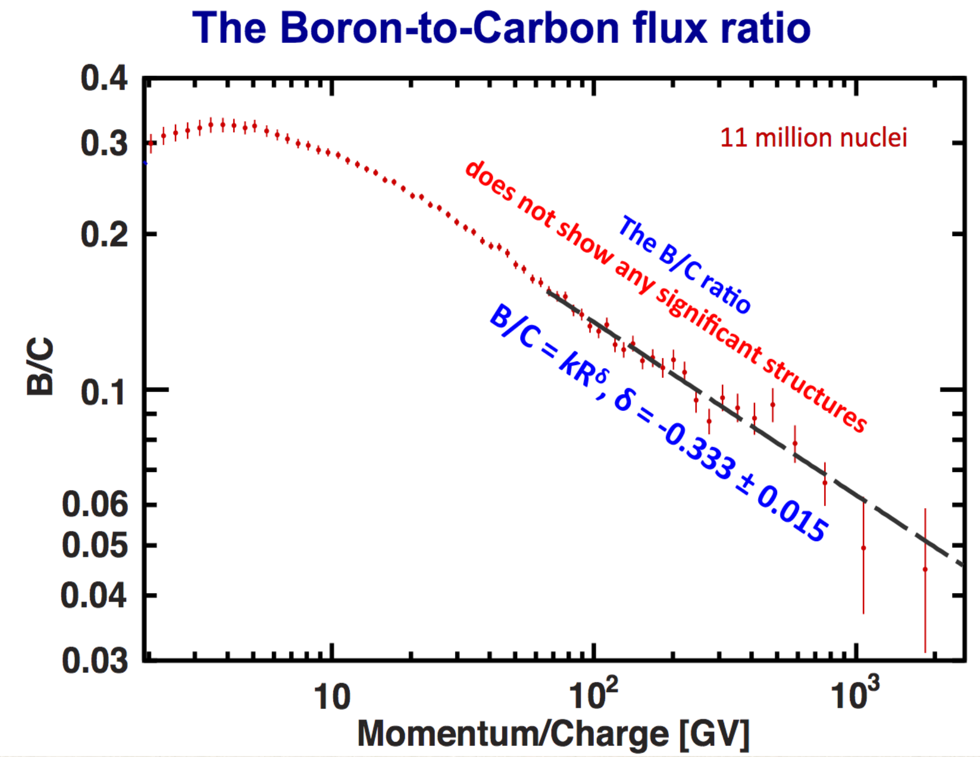
$$\begin{cases} N_p(E) = Q_{inj}(E)\,\tau_{esc}(E) \propto E^{-\gamma-\delta} \\ \\ N_s(E) = N_p(E)\,(n_H \sigma_{sp} c)\,\tau_{esc}(E) \propto E^{-\gamma-2\delta} \end{cases}$$



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

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

Suggesting Kolmogorov turbulence



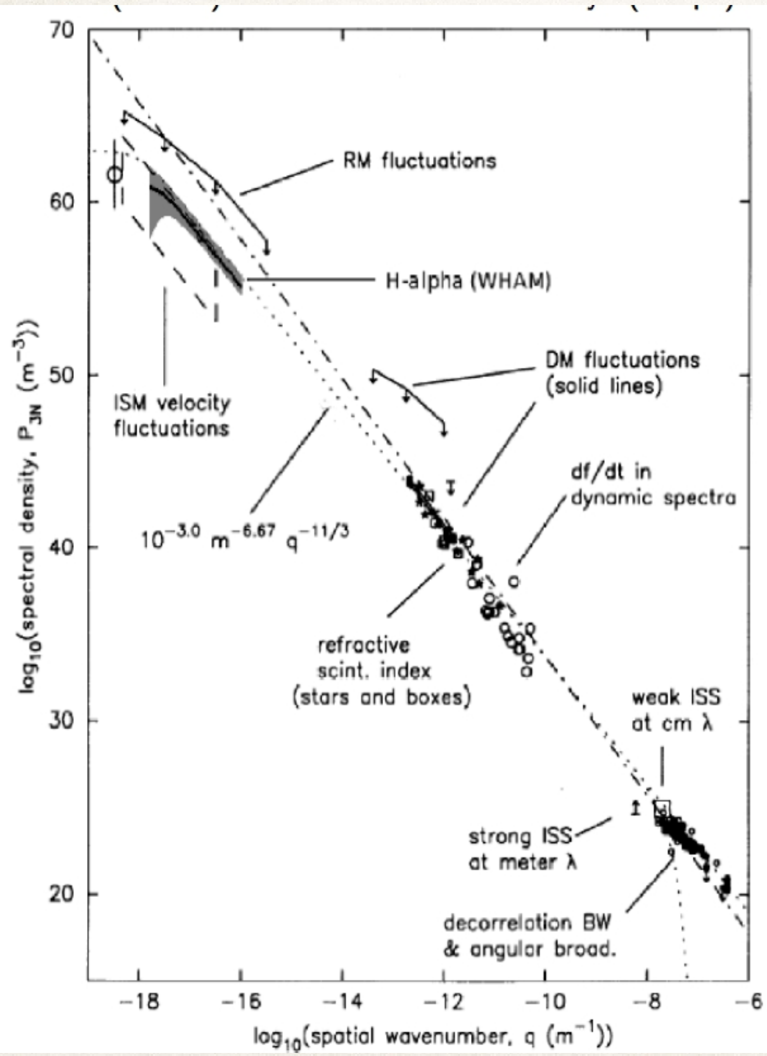
This picture is unsatisfactory for at least two reasons:

- 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: $\delta n \propto \delta B^2$):

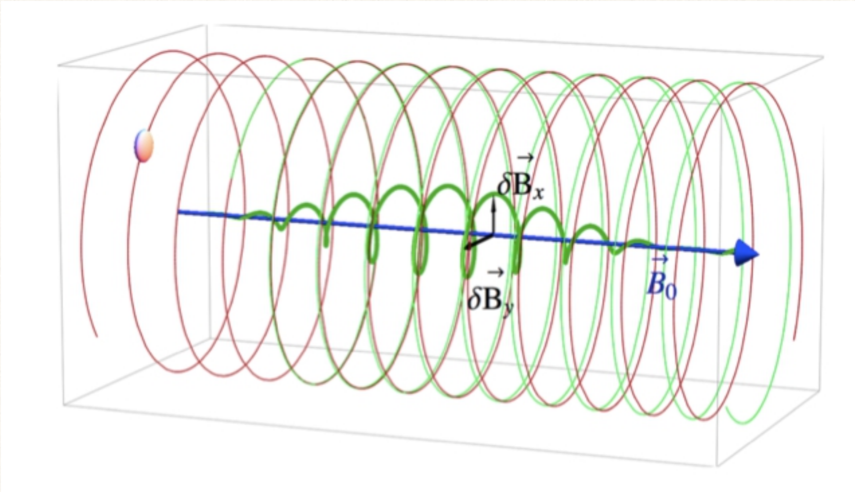
$$W(k)\,dk = \frac{\langle \delta B(k) \rangle^2}{B_0^2} = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}$$

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

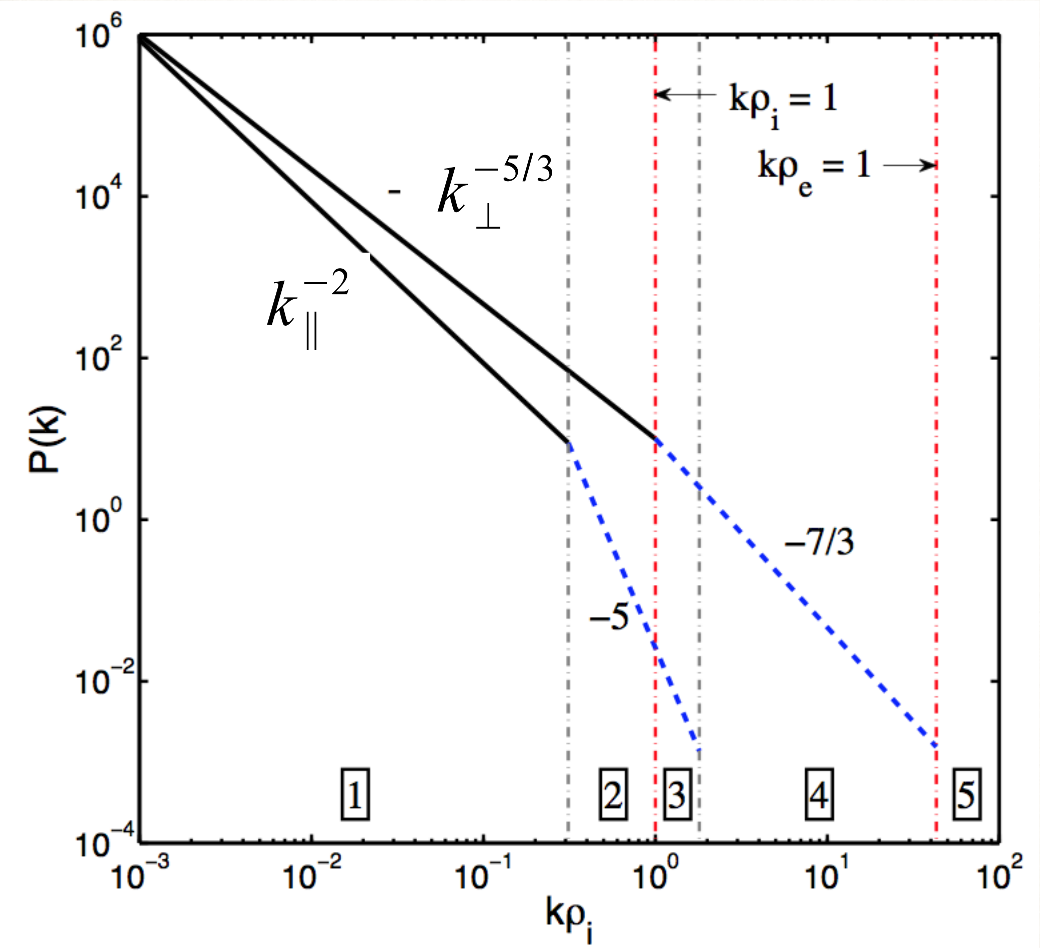


- The turbulent field is a small perturbation with respect to the regular component
- Particles interact with parallel waves resonantly: $k_{\rm res} = 1/r_{\rm L}({\rm p})$ $\quad k \| B_0$
- A diffusion behavior follows with typical diffusion coefficient

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

1st problem: anisotropic turbulent cascade

Energy spectra of Alfvénic turbulence from critical balance



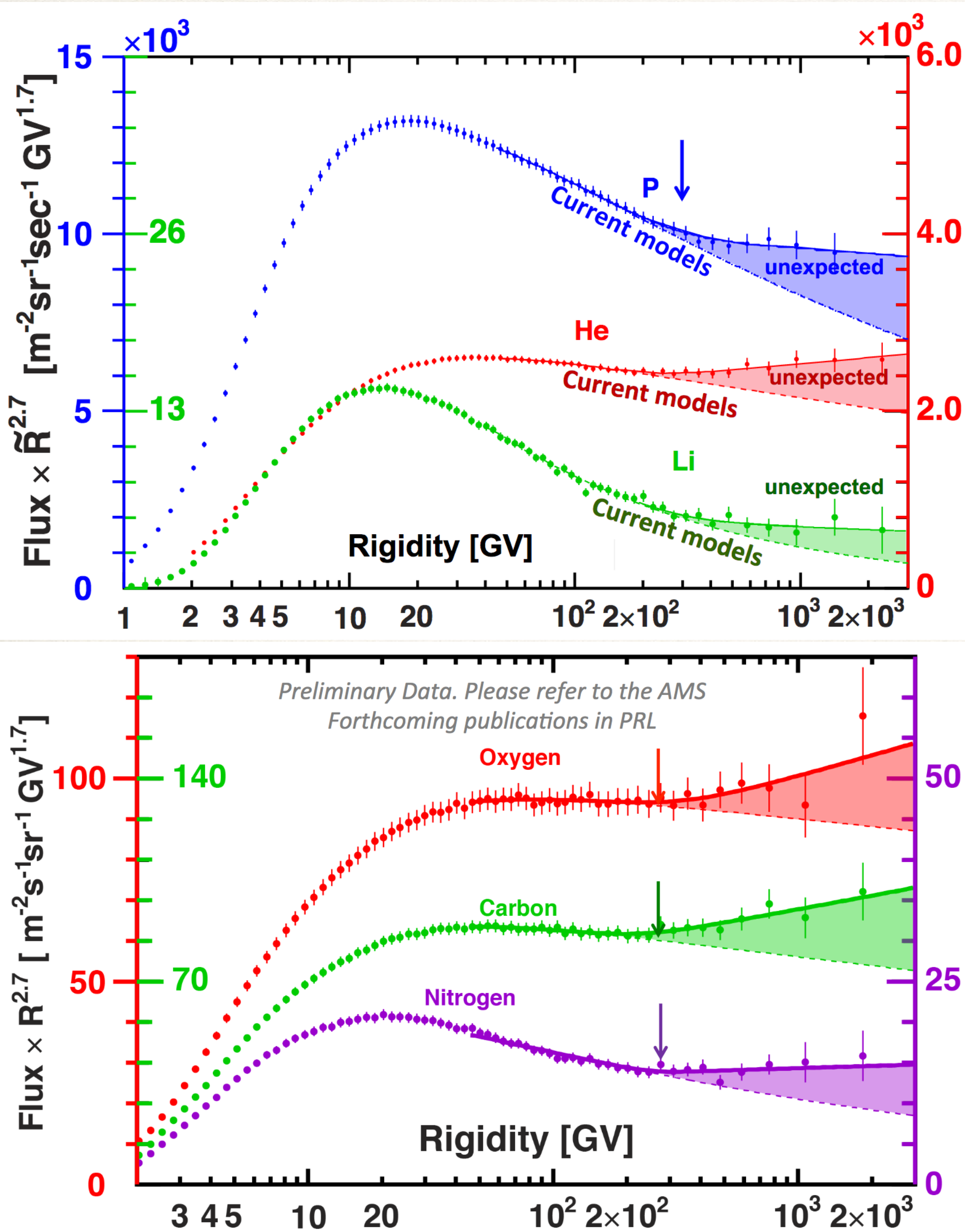
(Chen et al., 2010)

- 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:

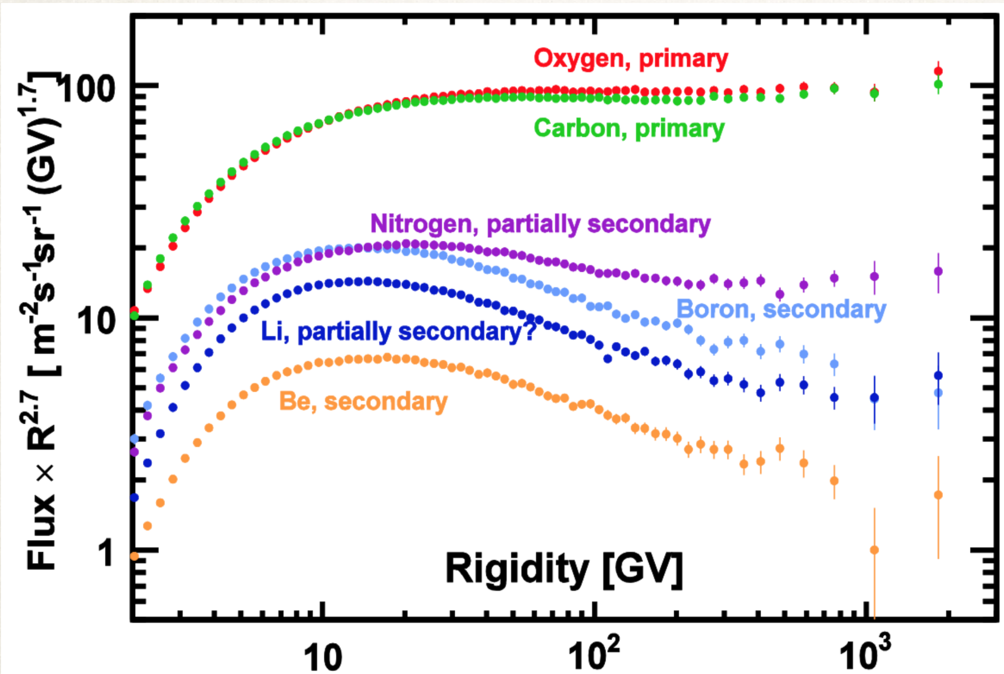
At rigidity of ~300 GV all spectra show a spectral hardening

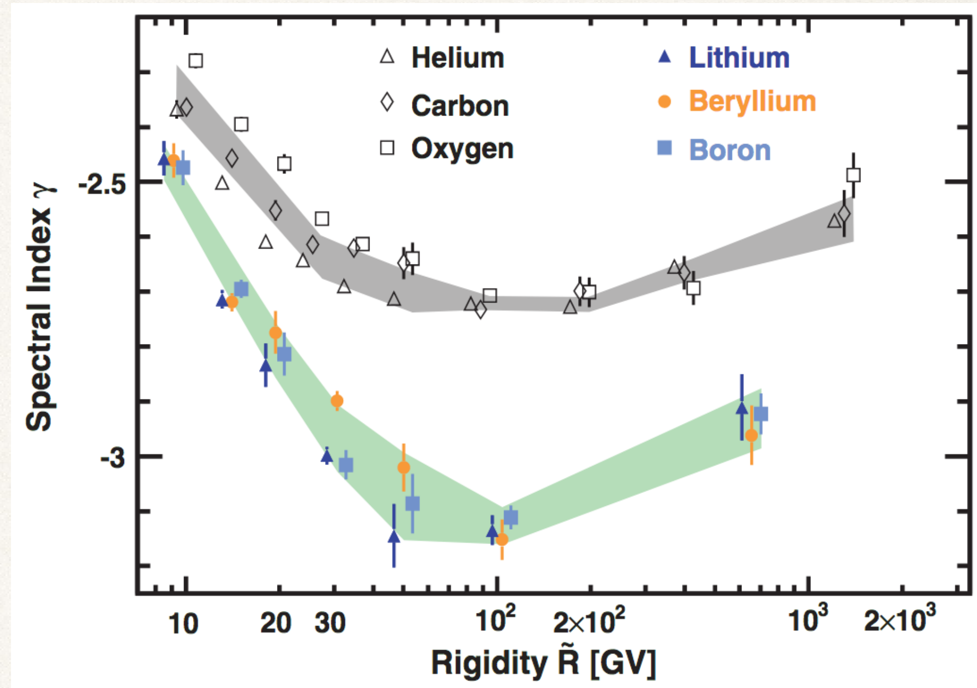
NO MORE A SIMPLE POWER-LAW

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

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

(Blasi, Amato & Serpico, 2016)

- 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

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

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

Normalization close to the value inferred from B/C

Different energy dependence from the Kolmogorov turbulence

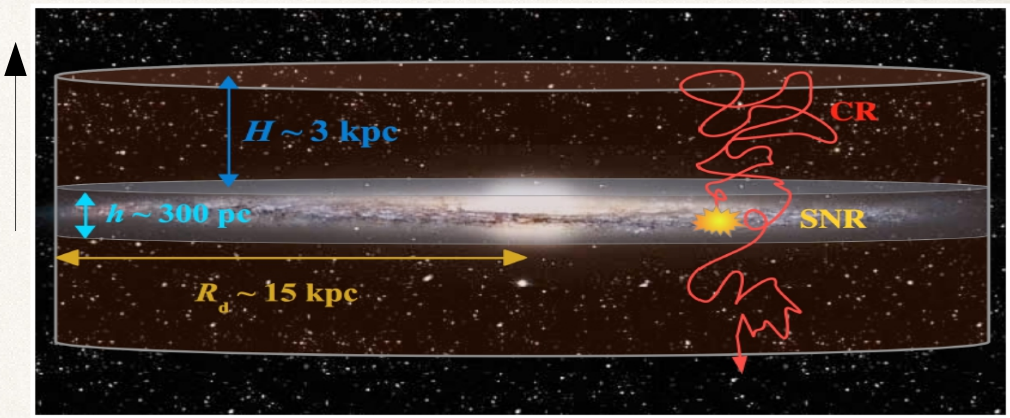
Coupling CR transport with magnetic turbulence evolution

(Blasi, Amato & Serpico, 2016)

CR transport equation in 1-D

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

z



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

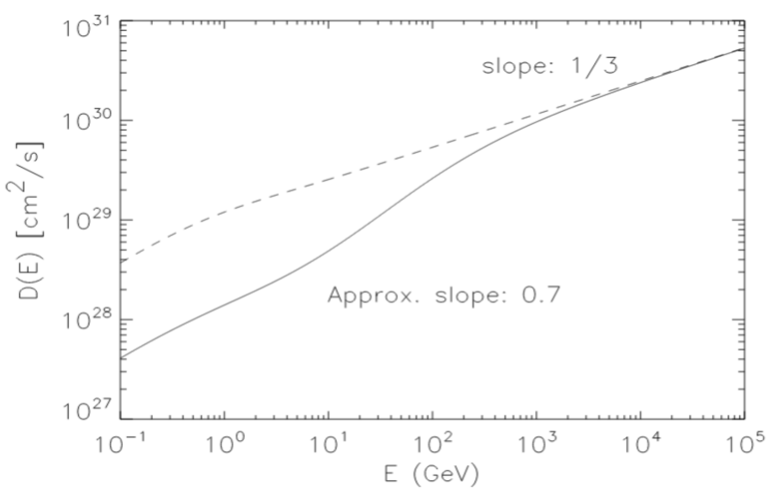
Resonant amplification:

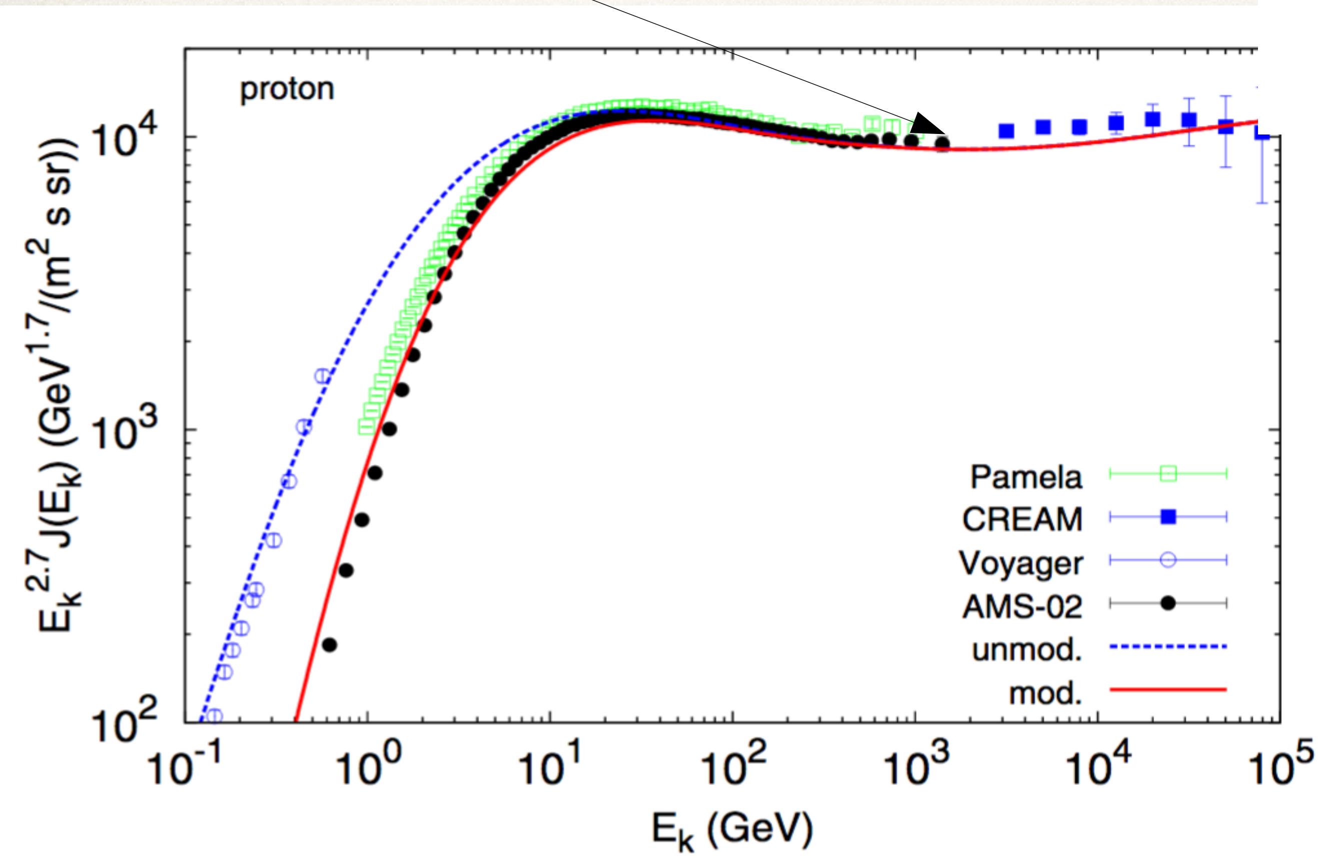
$$\Gamma_{CR} = \frac{16\pi}{3} \frac{v_A}{\mathcal{F} B_0^2} \left[p^4 v \nabla f\right]_{p=p_{\rm res}}$$

Position of the break

(Blasi, Amato & Serpico, 2012)

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





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

Equation for the turbulence evolution

(Jones 1993, ApJ 413, 619)

- CR transport equation is now coupled with evolution of turbulence

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}\left(v_A W\right) + \Gamma_{CR} W + Q_k$$

- Diffusion in *k*-space (non-linear): $D_{kk} = c_k \, | v_A | \, k^{7/2} \, W^{1/2}$
- Advection of waves at the Alfvén speed
- Waves growth due to CR streaming: $\Gamma_{CR} \propto \partial f / \partial z$

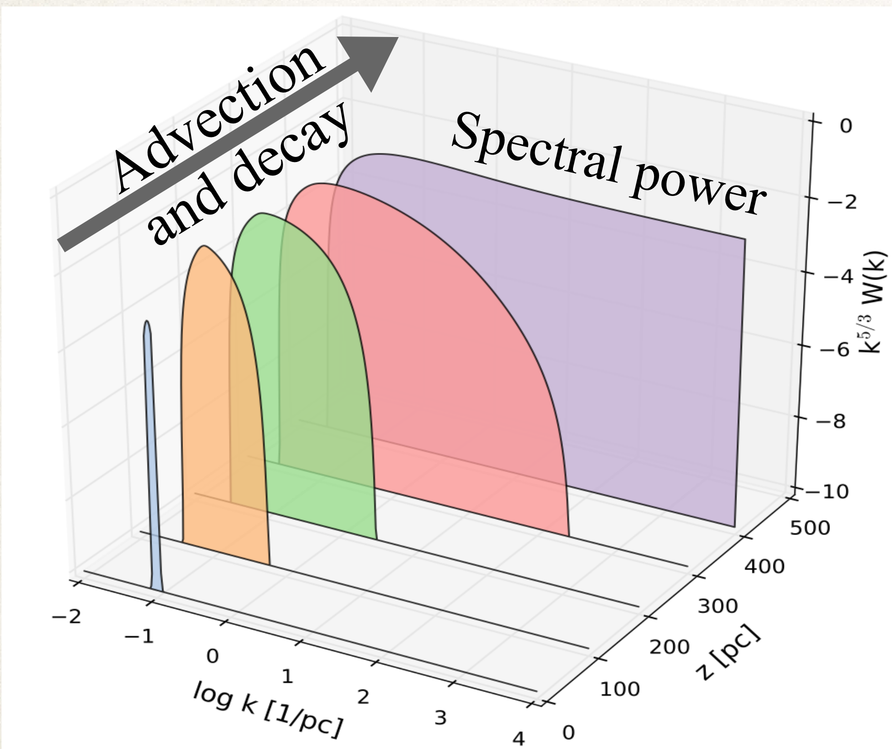
$$\Gamma_{CR} = \frac{16\pi}{3}\frac{v_A}{k\,W(k)\,B_0^2}\left[v\,p^4\frac{\partial f}{\partial z}\right]$$

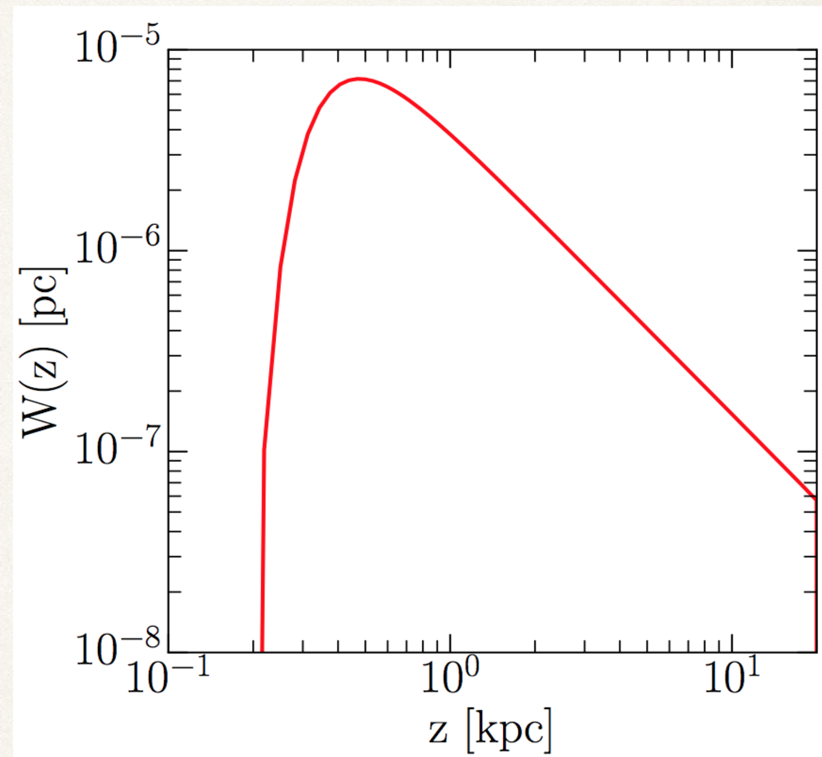
- External (e.g. SNe) source term in the disc: $Q \sim \delta(z)\,\delta(k - k_0)$
- In the absence of CR it returns the Kolmogorov spectrum: $W(k) \sim k^{-5/3}$

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.



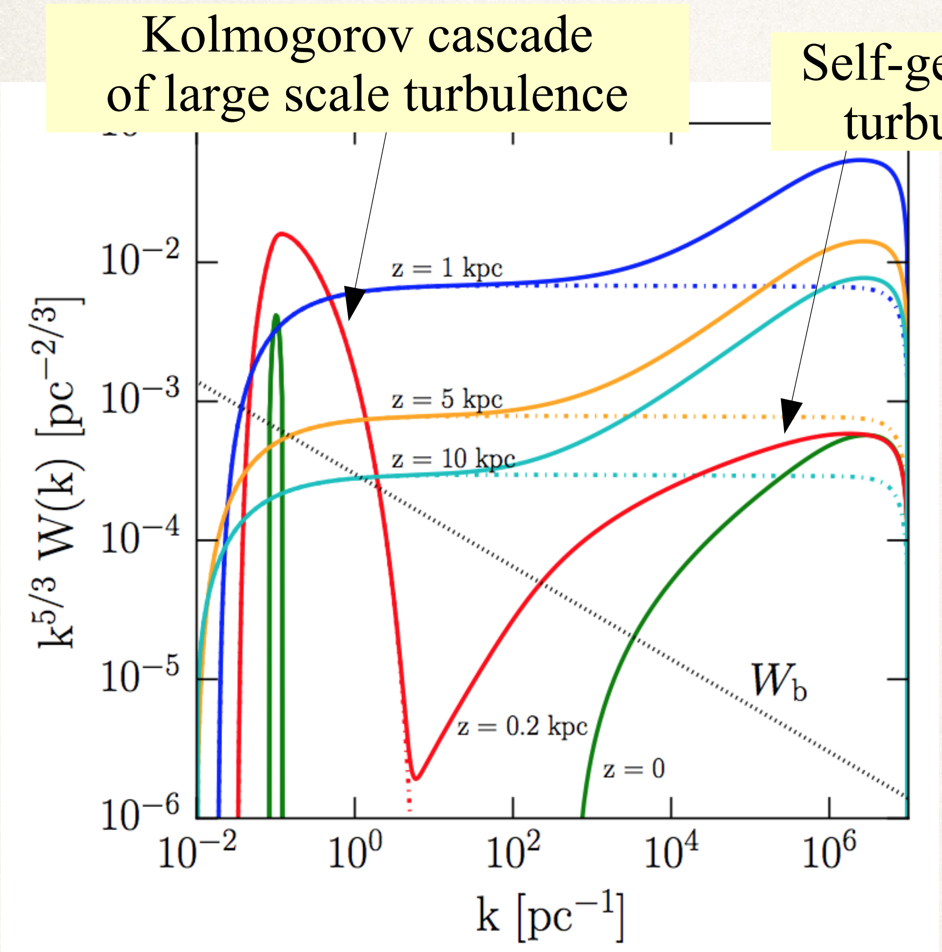


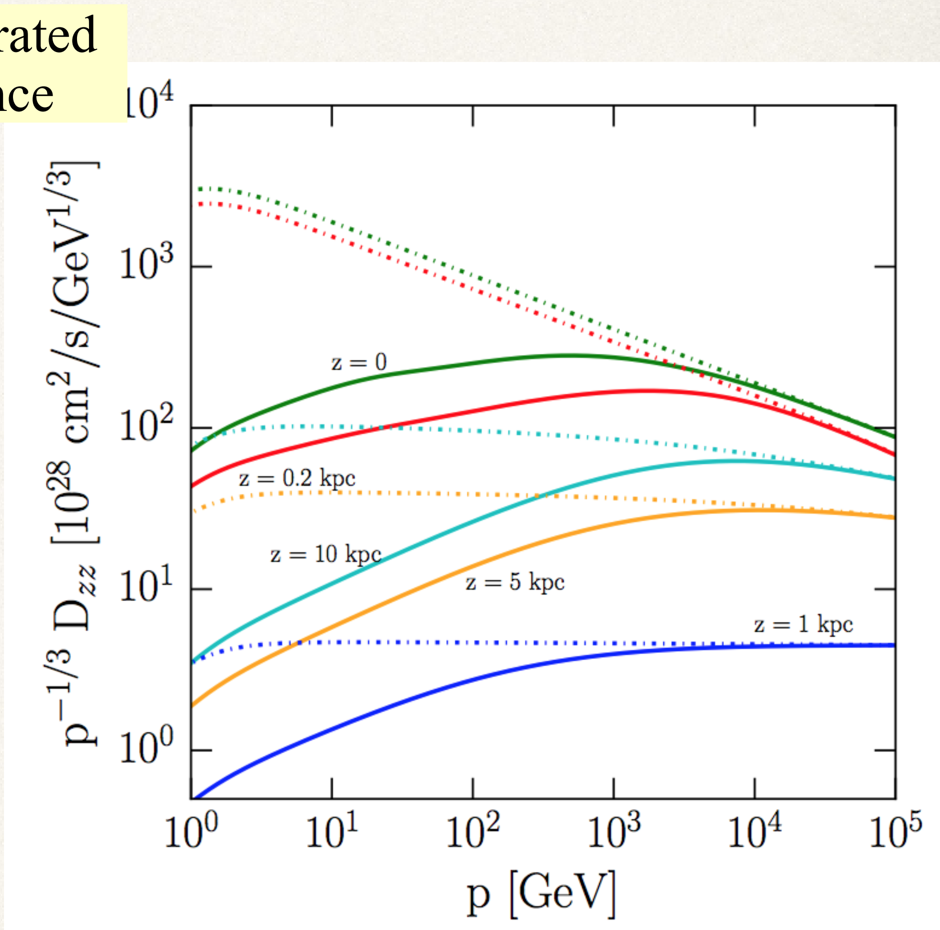
$$\tau_{cascade} = \tau_{adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_c}{v_A} \rightarrow \boxed{z_c \sim kpc}$$

- 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]

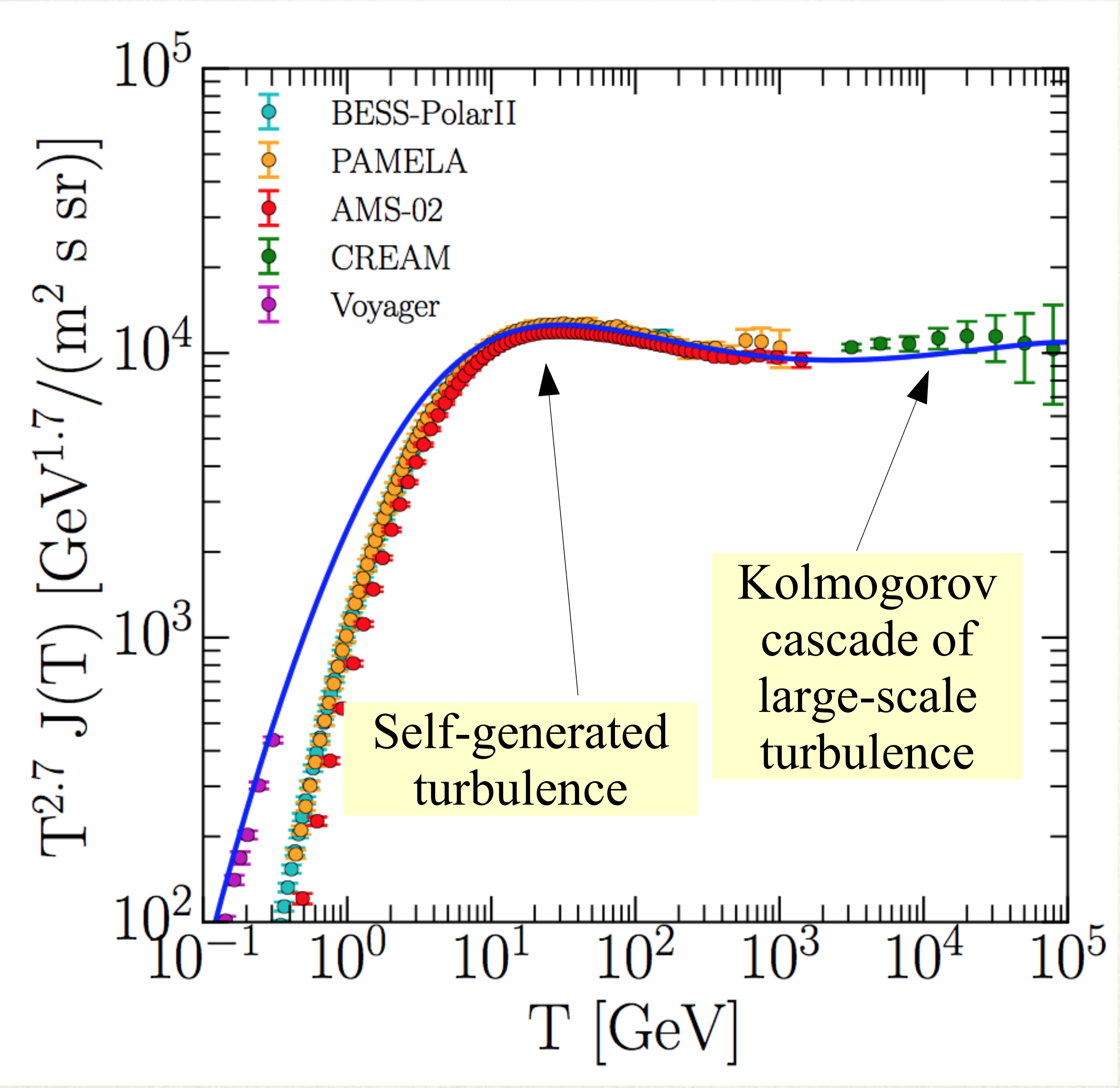




Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

Non-linear cosmic ray transport: a global picture

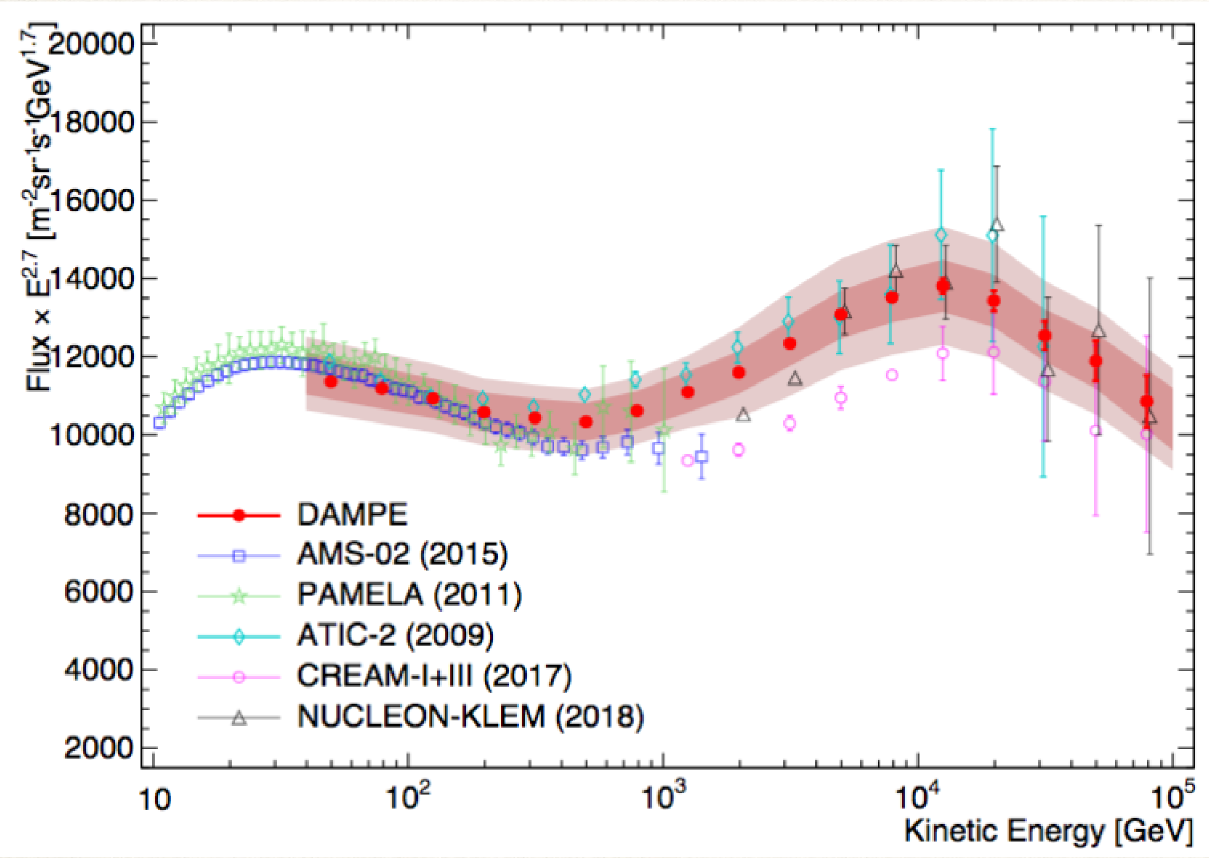
(Evoli, Blasi, GM, Aloisio, 2018, PRL)



- 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.

Not the end of the story: more transport regimes?

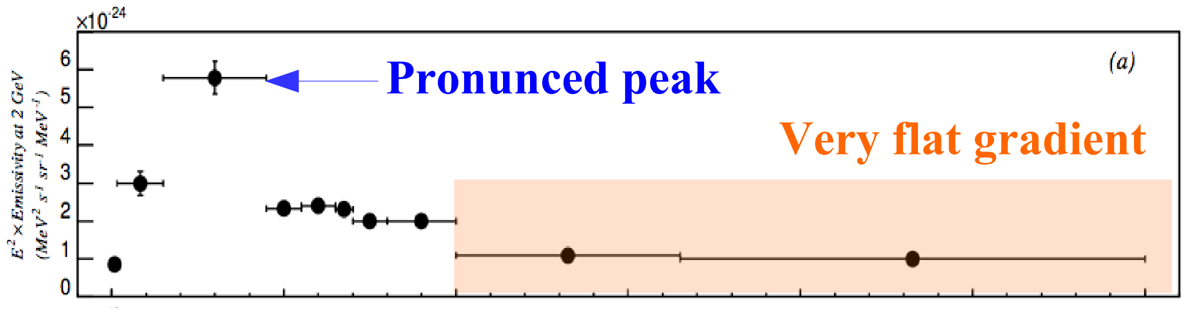
Proton spectrum above 1 TeV



- Above ~10 TeV the proton specrum seems to steepen again
- Possible indication of a further change in transport regime?
- The answer could come from the measurement of secondaries spectra

[An+, DAMPE colaboration 2019, Science]

3rd anomaly: the cosmic ray gradient in the Galactic plane

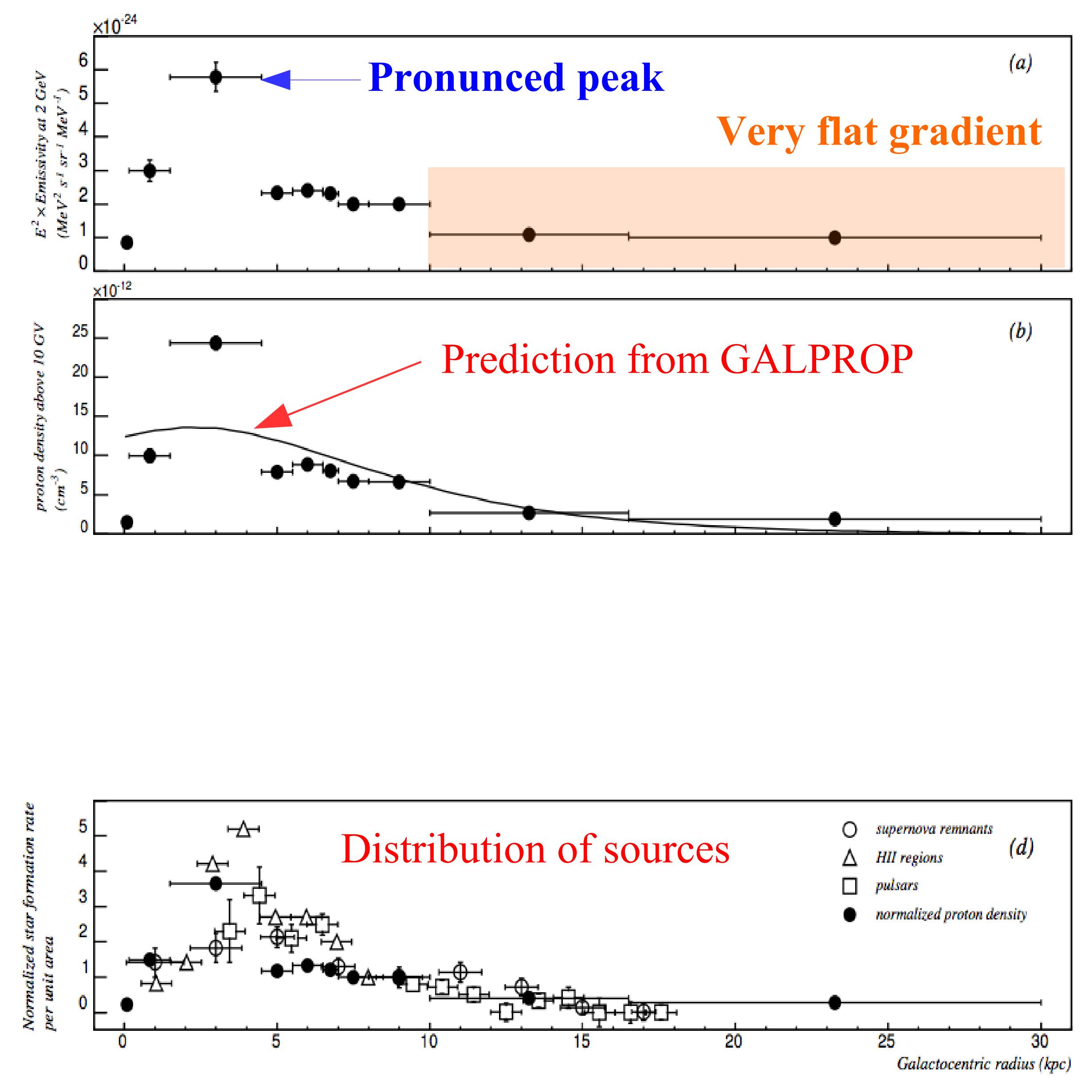


Recent results from FermiLAT collaboration on the CR distribution in the Galactic plane
[Acero et al. arXiv:1602.07246]

- In the outer region (R > 8kpc) the CR density at ~20 GeV is flat
(i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

3rd anomaly: the cosmic ray gradient in the Galactic plane



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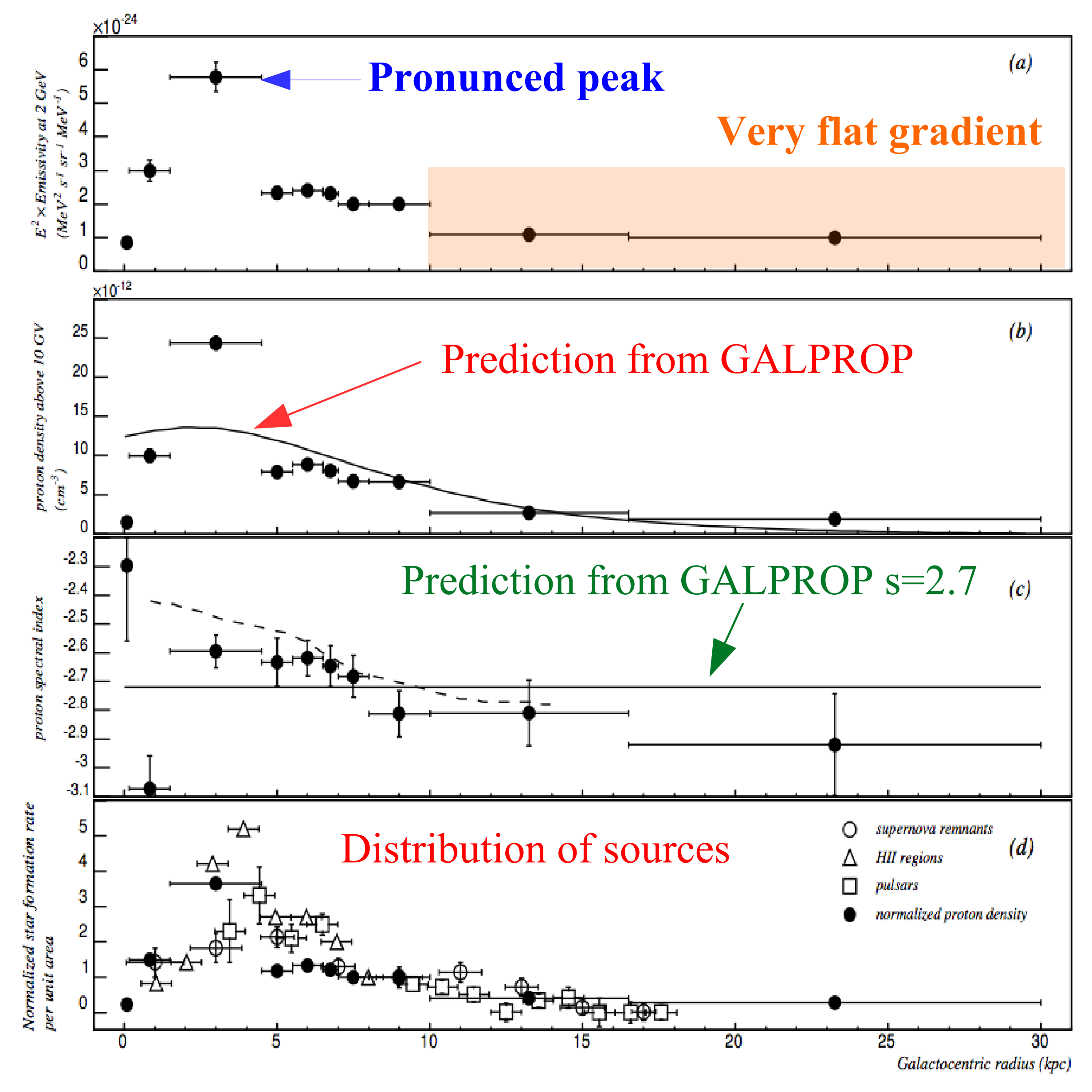


Recent results from FermiLAT collaboration on the CR distribution in the Galactic plane
[Acero et al. arXiv:1602.07246]

- In the outer region ($R > 8$kpc) the CR density at ~20 GeV is flat (i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

- The slope @ 20 GeV is not constant

This scenario is difficult to accommodate in a standard diffusion model

Possible solutions

In the context of leaky-box model several solution have been proposed:

- Extended halo, $H > 4$ kpc
  (Dogiel, Uryson, 1988; Strong et al.,1988; Bloemen, 1993, Ackerman et al., 2011)
  - ^ predices a flat spectrum (but not flat enough)
  - ^ cannot explain the density bump in the inner Galaxy
- Flatter distribution of SNR in the outer Galaxy
  (Ackerman et al., 2011)
- Enhancement of CO/H_2 density ratio (X_{CO}) in the outer Galaxy (Strong et al., 2004)
- Injection dependence on the ISM temperature
  (Erlykin et al., 2015)
- Advection effects due to the Galactic wind
  (Bloemen, 1993; Breitschwerdt, Dogiel, Voelk, 2002)

None of these ideas can simoultaneously account for all signatures

- flatness R > 8 kpc,
- peak at R~3-4 kpc,
- variation in the slope

CAN SELF-GENERATED DIFFUSION EXPLAIN THE OBSERVATIONS?

1-D slab model with self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

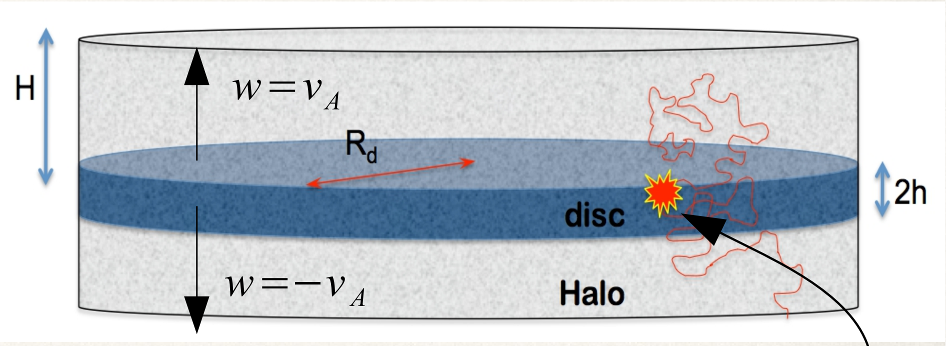
- CR escaping from the Galactic plane produce magnetic turbulence through resonant streaming instability

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

- Non-linear damping $\quad \Gamma_{NLD} = v_s k F(k)$

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

- CRs are also advected by the global motion of the waves at the Alfvén speed



Spectrum injected at the disk

$$Q_0(p,R) \propto N_{SNR}(R)\, p^{-\gamma}$$

Propagated spectrum in the disk

$$f_{disk}(p) \propto p^7 \left(\frac{Q_0(p,R)}{B_0(R)} \right)^{s(p)};$$

$$s = 1 \div 3$$

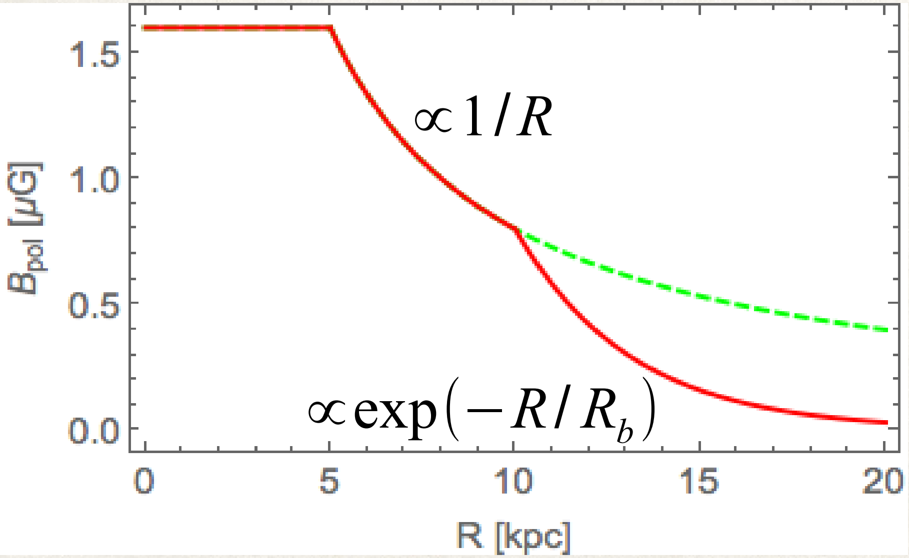
Self-generated turbulence and the gradient problem

(Recchia, Blasi, GM, MNRAS 462, 2016)

Self-generated turbulence could explain the gradient and the spectral index changes because it is more effective where B is smaller

- less effective in the inner Galaxy
- more effective in the outer Galaxy

Strength of large scale magnetic field in the Galaxy – popoidal component



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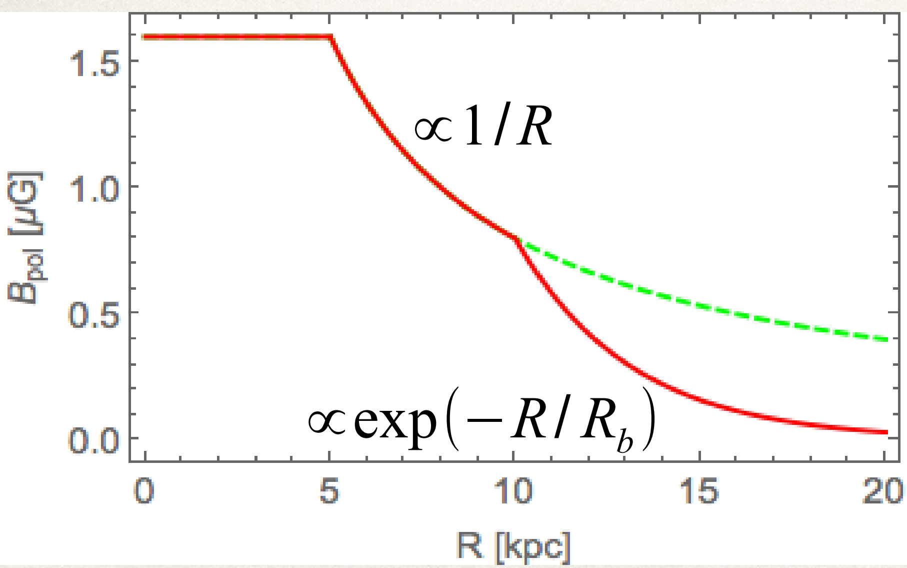
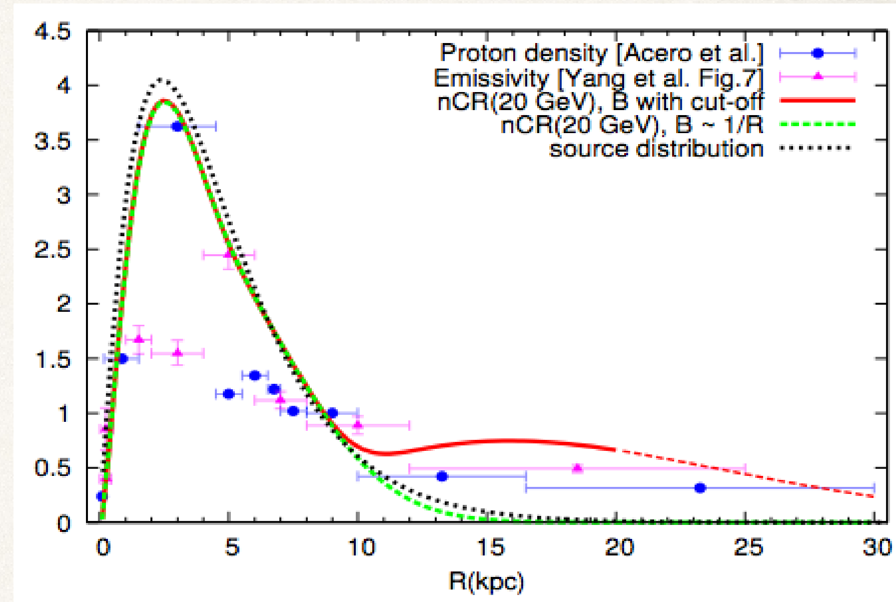
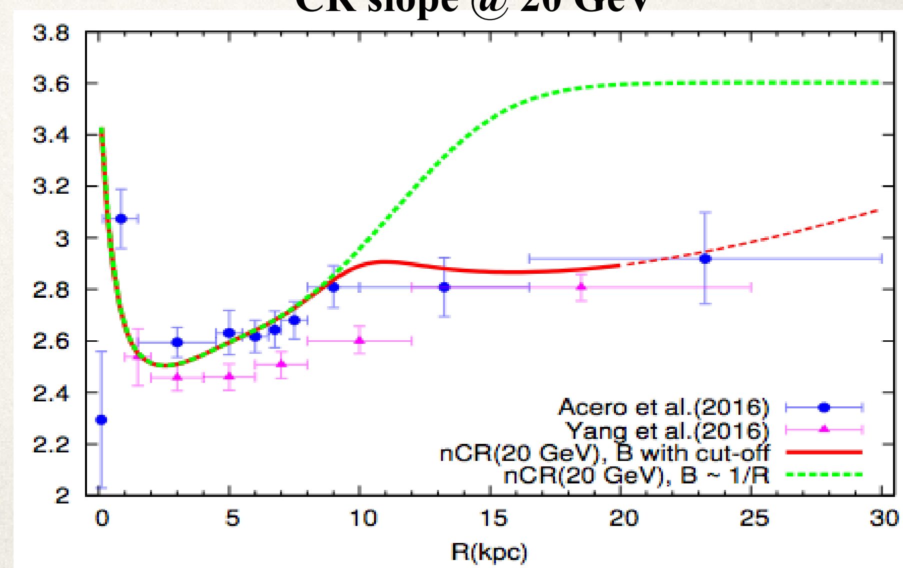


CR spectrum density @ 20 GeV



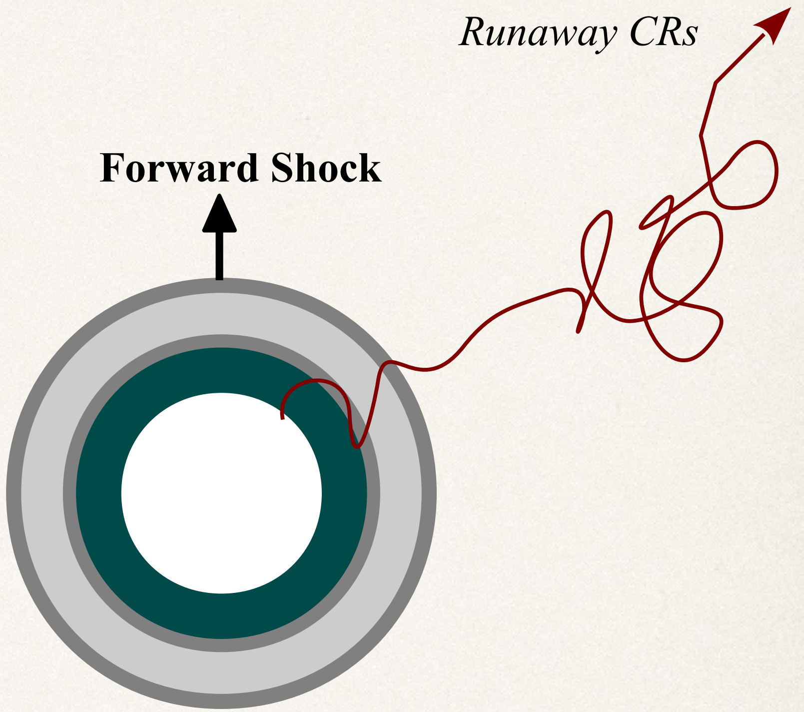
CR slope @ 20 GeV



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

[Malkom et al. (2013)
Nava et al. (2015)
D'Angelo et al.(2016)]



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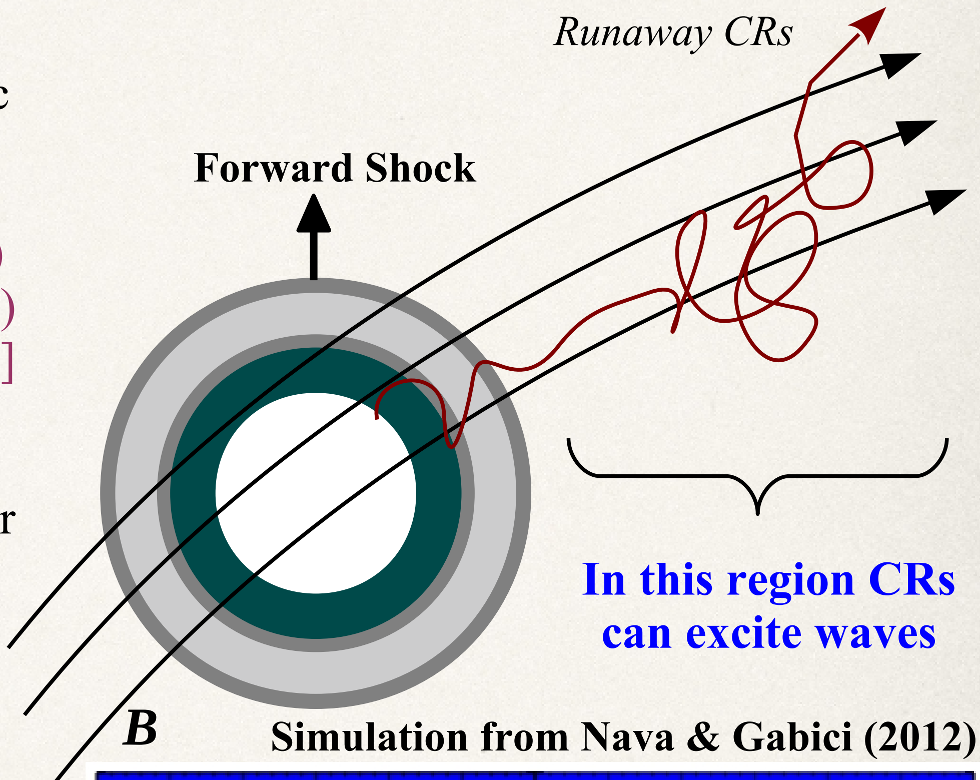
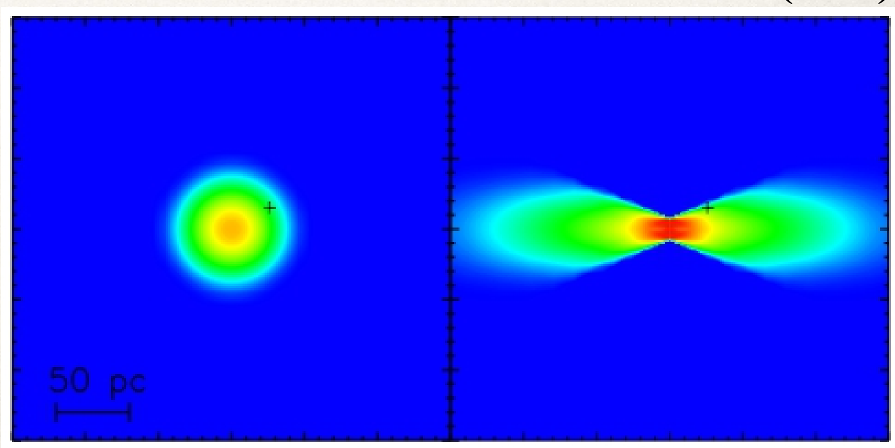


The region where this can happen is at most of the order of the coherence-length of the magnetic field (after this distance the diffusion becomes 3D and the CR density drops rapidly below the average Galactic value)

Simulation from Nava & Gabici (2012)



During the time CRs spend in the vicinity of sources they can:

1) accumalate grammage

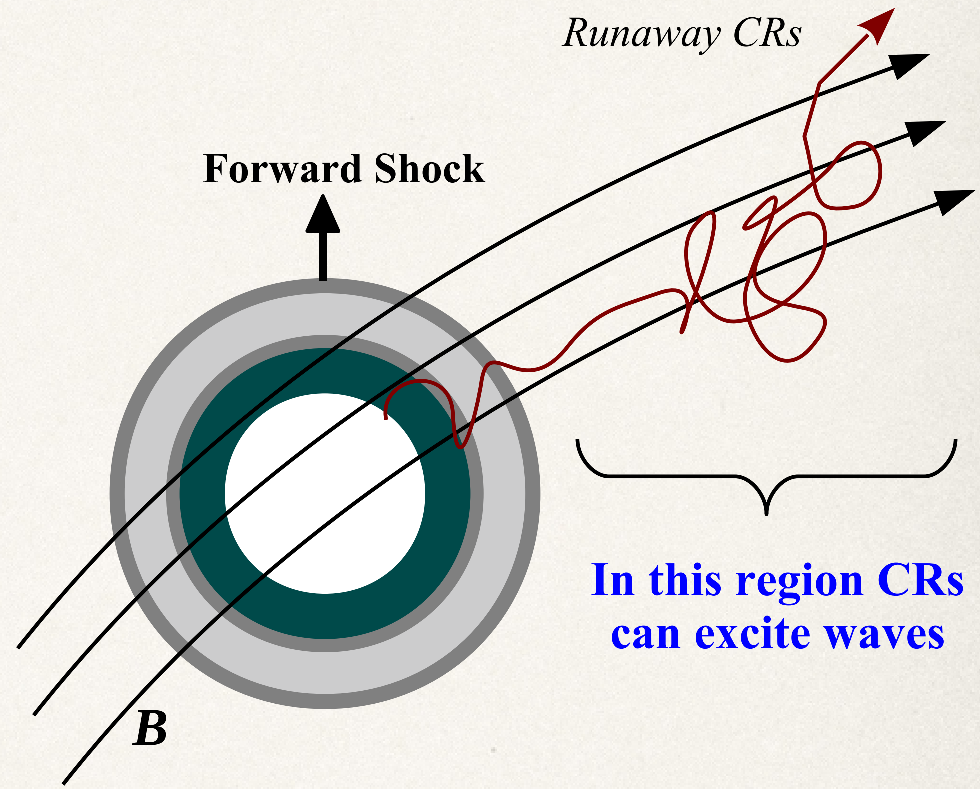
2) produce diffuse emission via $\pi^0 \rightarrow \gamma\ \gamma$

Effect of self-amplification near the CR sources: basic equations

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

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

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

Resonant straming

Injection

Damping mechanisms

- Non linear damping
- Ion-neutral damping

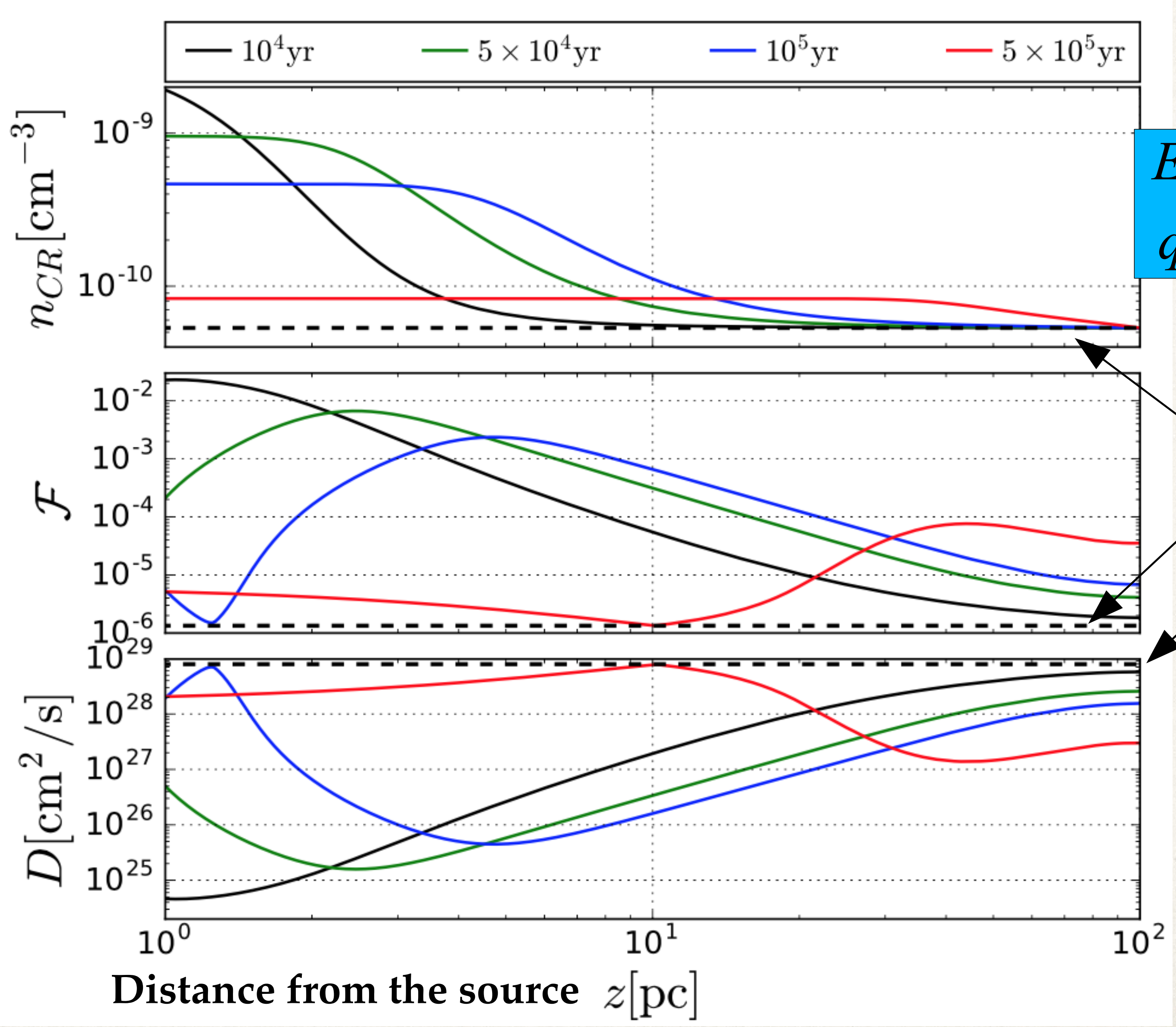
Evolution of CR density close to the source

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

CR distribution function @ 10 GeV for several ages

Distribution function of turbulence

Diffusion coefficient



Distance from the source

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

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

Average Galactic level

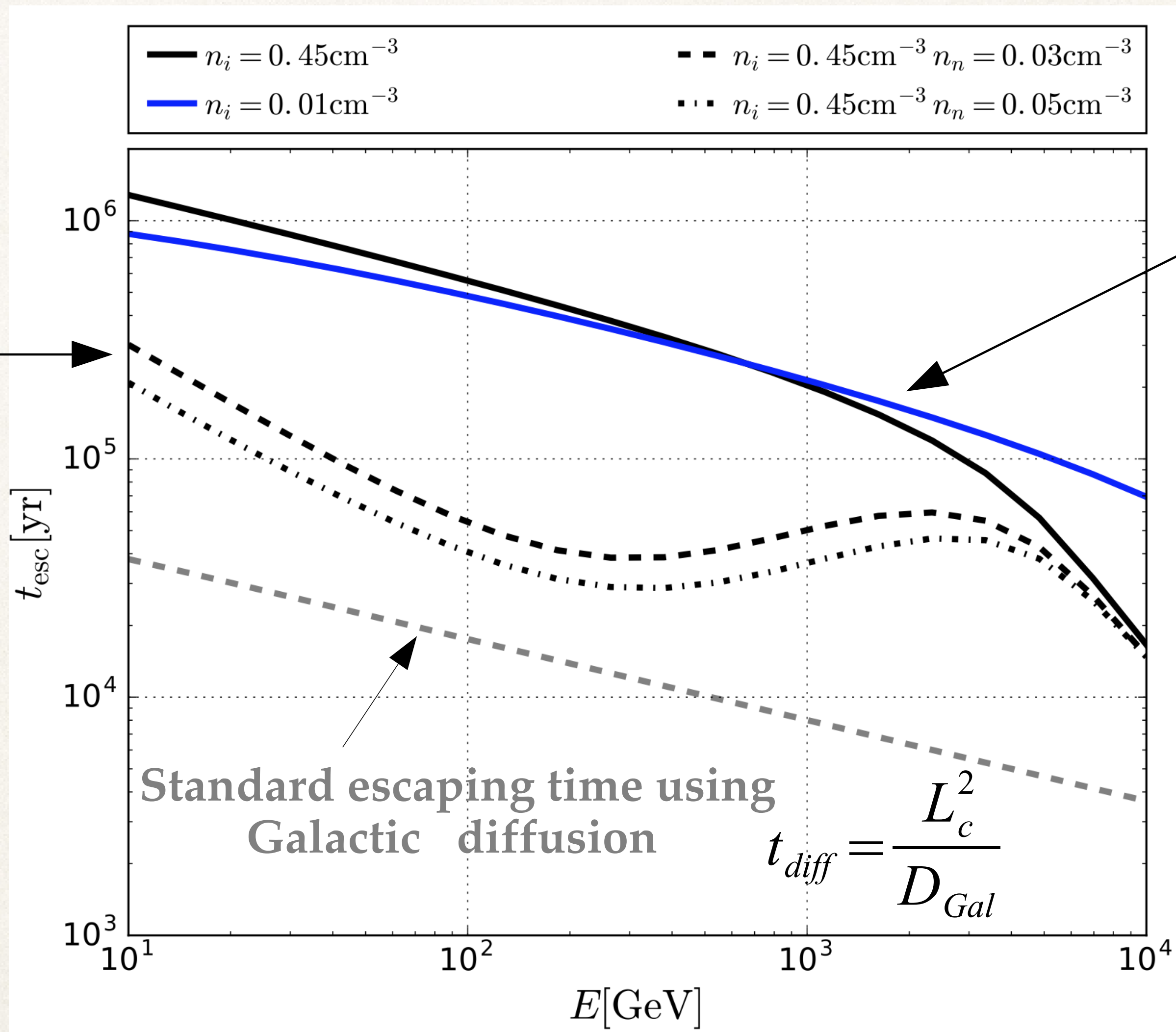
Escaping time from the near-source region

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

Assuming injected spectrum p^{-4}
CR energy ~ 20% E_{SN}

With neutrals

n_H/n_i ~ 5%-10%

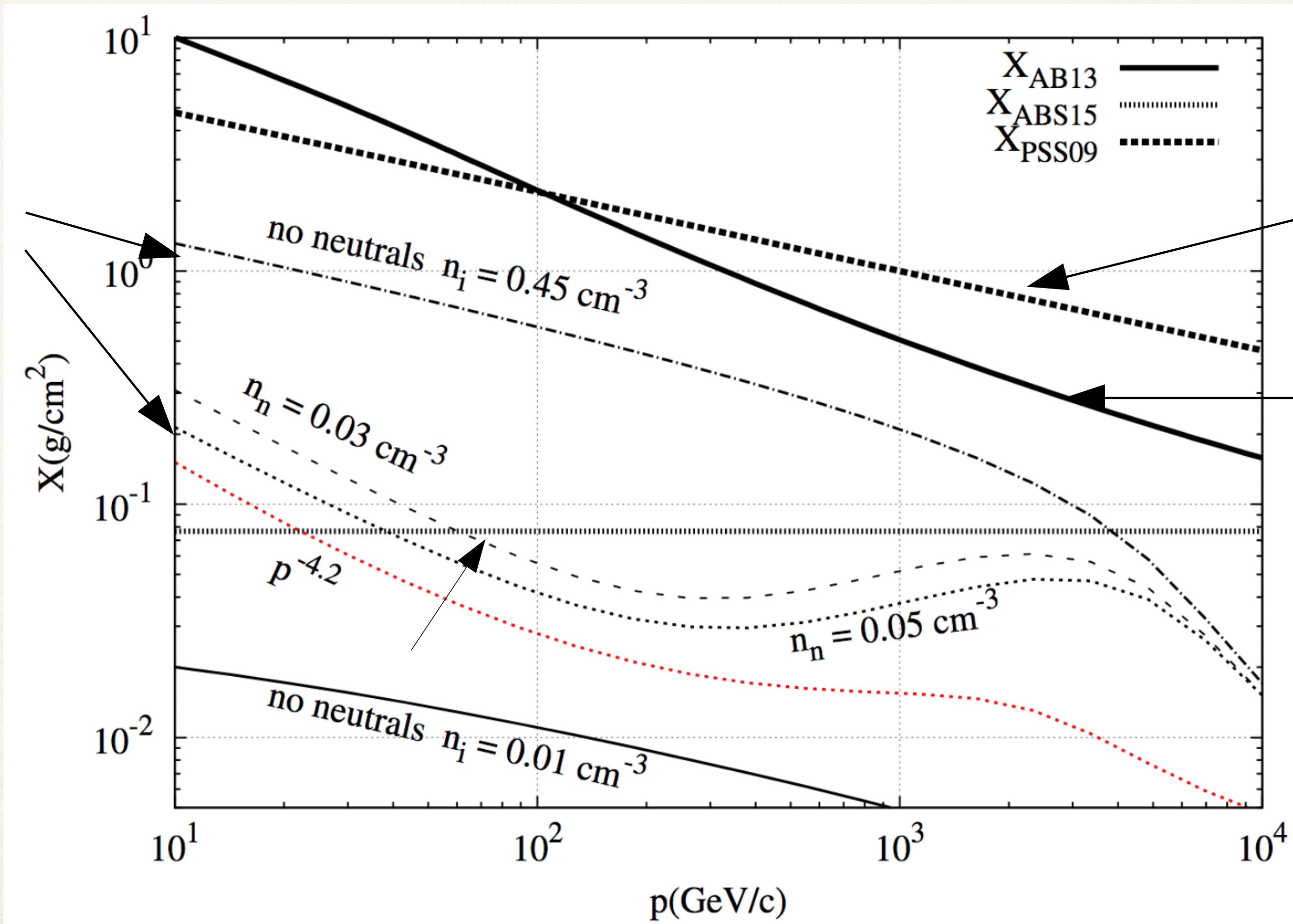


Grammage in the near-source region

[D'Angelo, Blasi, Amato 2016, *PRD*]

Assuming injected spectrum p^{-4}
CR energy ~ 20% E_{SN}

Grammage from the near source region



Grammage inferred from B/C:

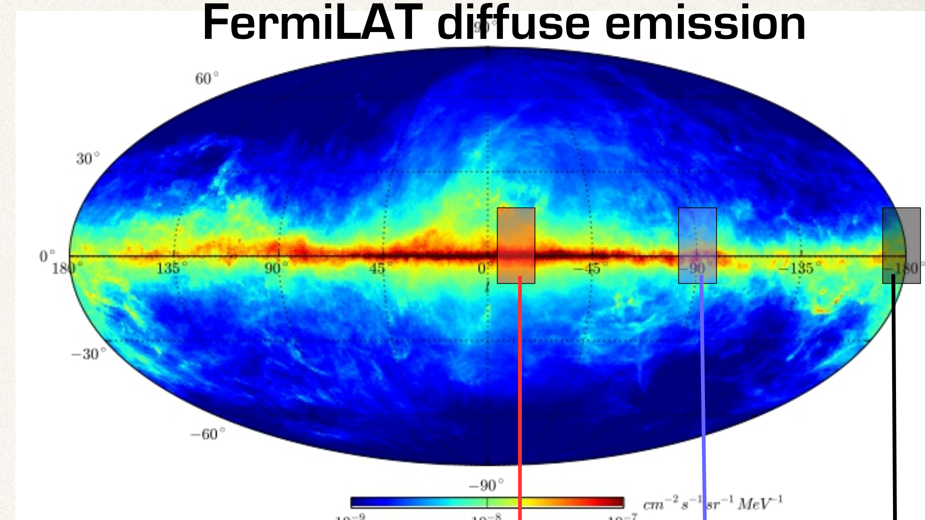
1) Standard halo model

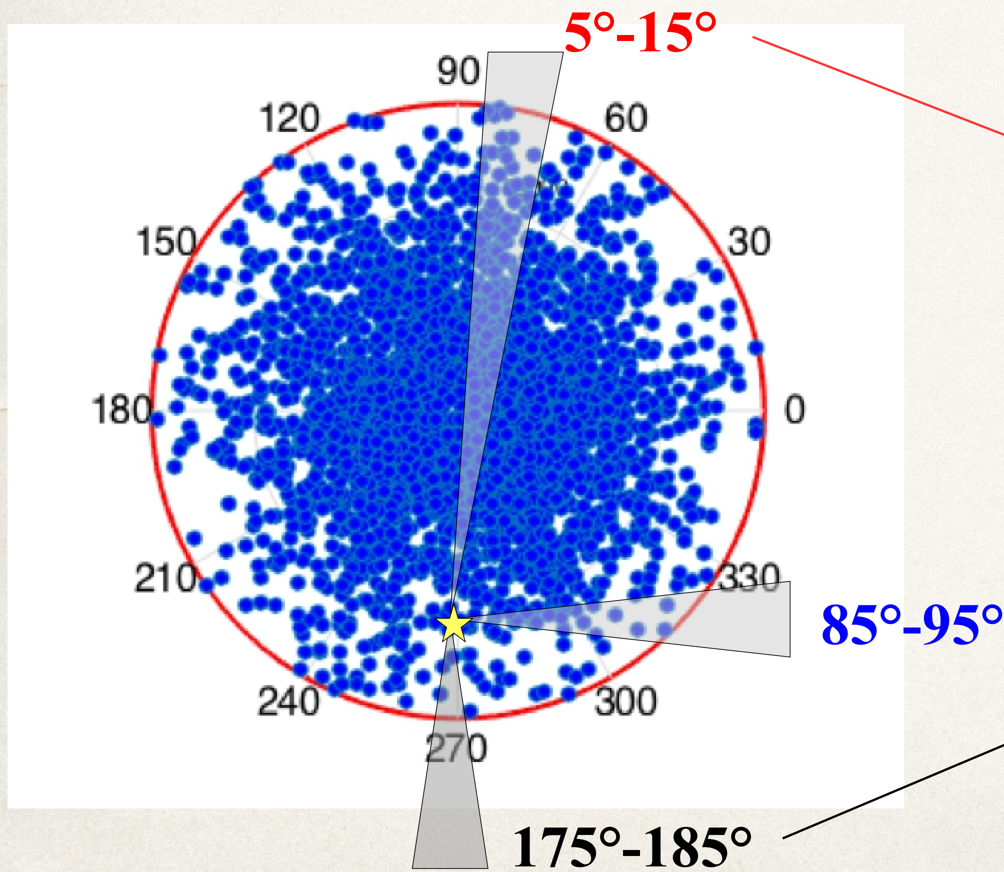
2) Non-linear propagation

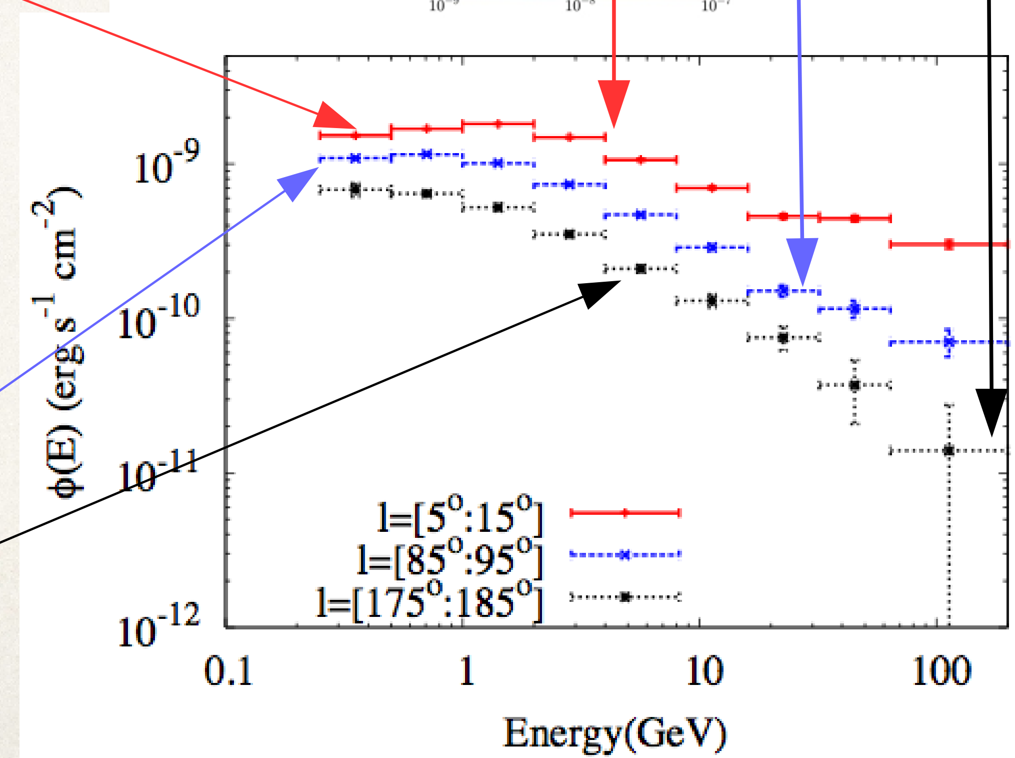
Diffuse Galactic emission from *Fermi*-LAT

[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]



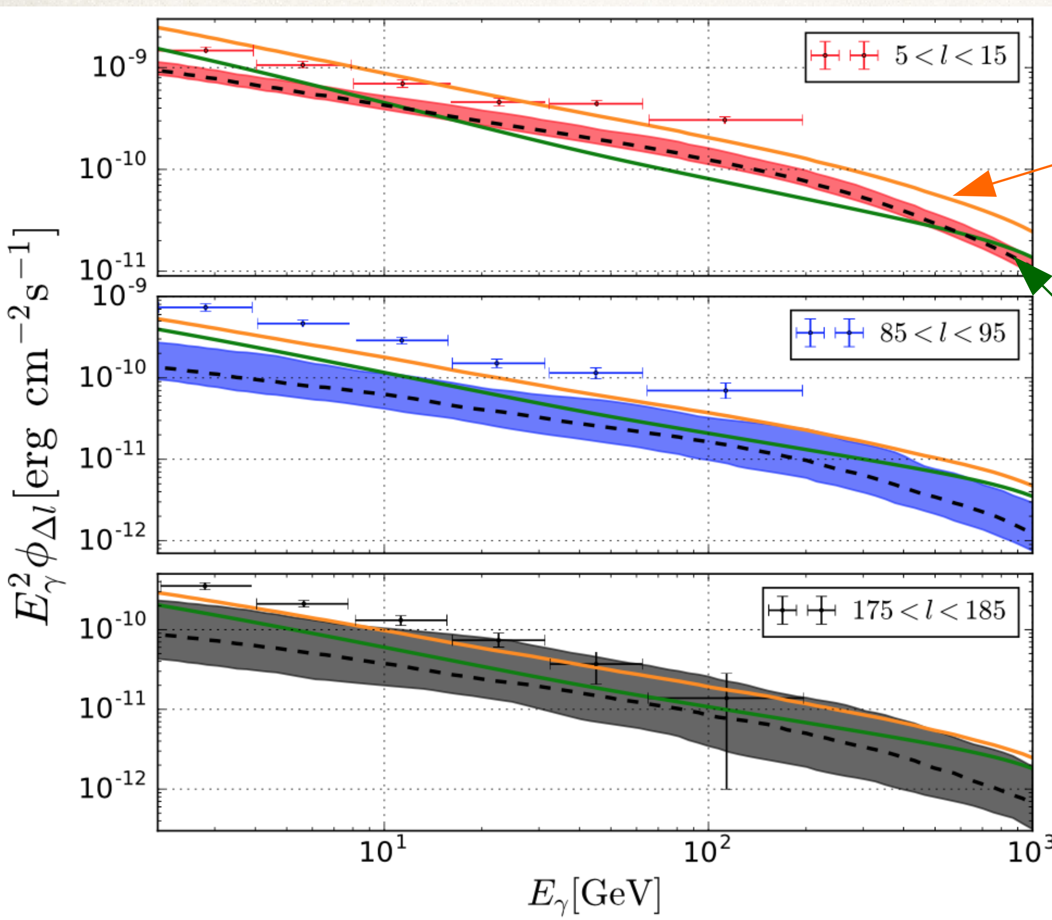




Contribution of the escaping CRs to the diffuse Galactic emission

[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

“Real” diffuse contribution assuming AMS spectrum in the whole Galaxy

Contribution of the escaping CRs to the diffuse Galactic emission

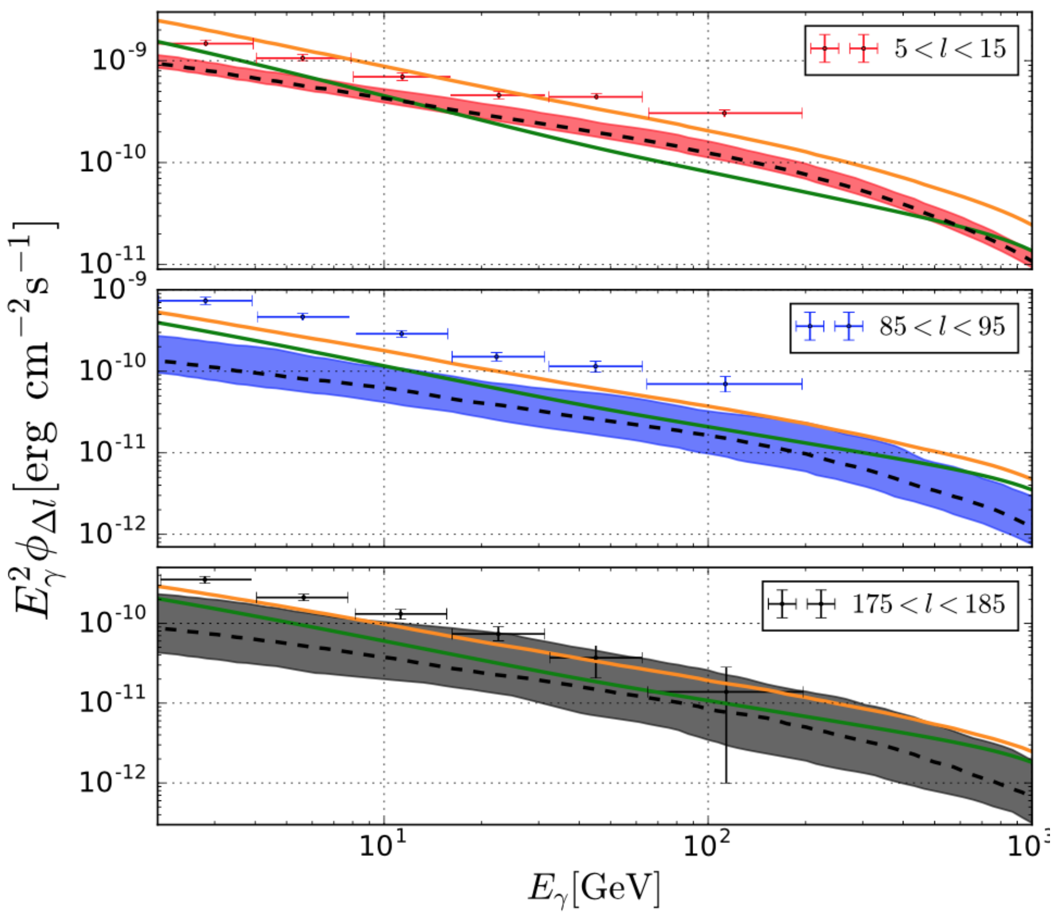
[D'Angelo, GM, Amato, Blasi, 2018]

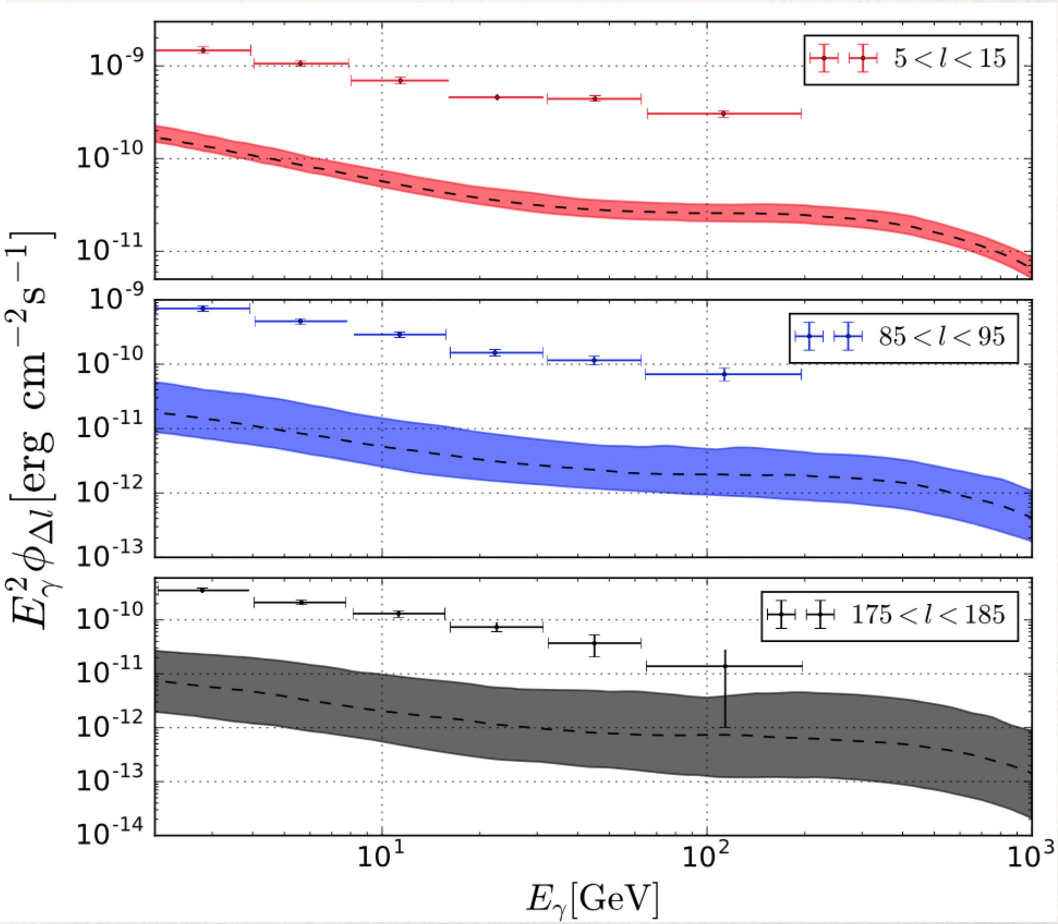
Number of sources contributing to the emission

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

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

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



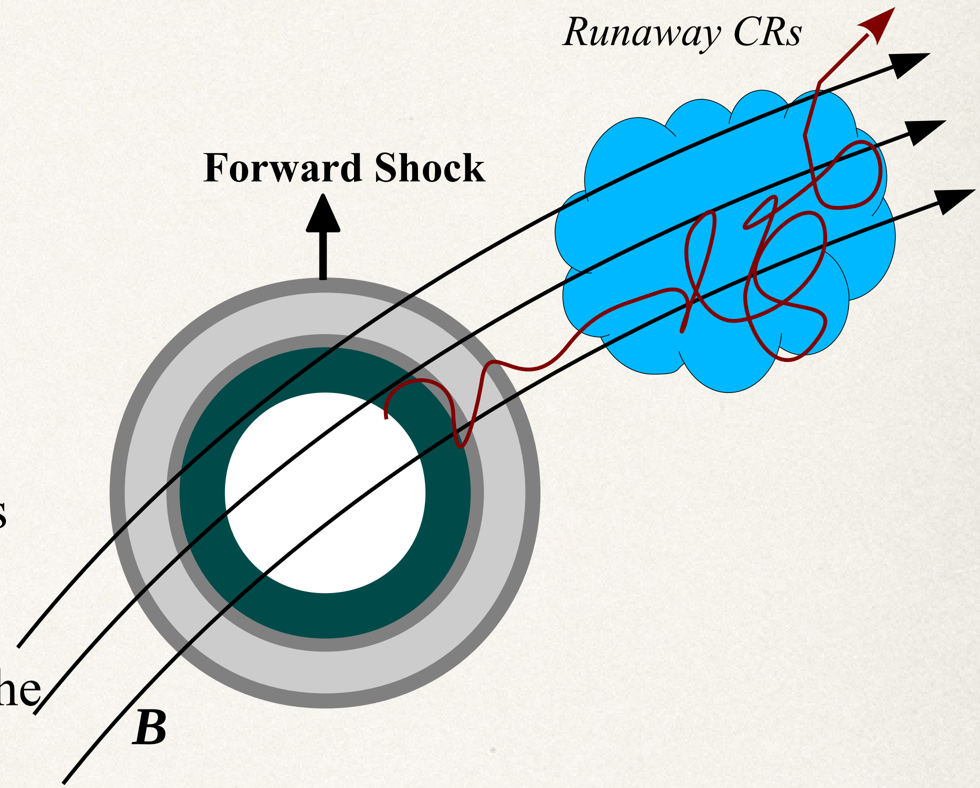


Presence of Molecular Clouds near the source

If a molecular cloud is close to the SNR both the **gamma-ray emission and the grammage accumulated can be enhanced**

- Several SNR-MC association are known from gamma-ray observation

- CTA will probably discover tens of such objects

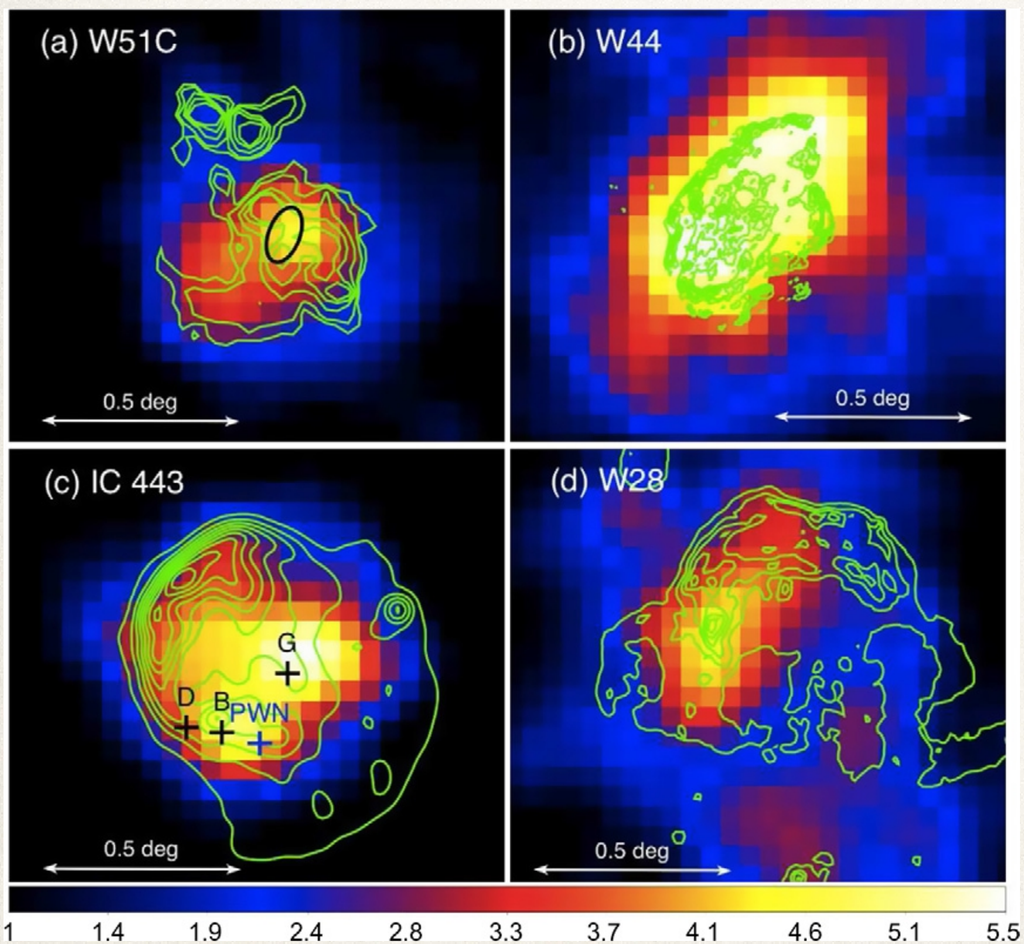


Is it possible to accumulate all the grammage in the near source region?
This possibility would support unorthodox models for the CR propagation which require fast escape from the Galaxy

- **Cowsik at al.(1975, 2016) "*Nested Leaky-box*"**
- **Lipari (2016)**

Using molecular clouds as CR barometer

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



<u>OBSERVATIONS of MCs in γ-RAYS:</u>

- CRs interact inside MCs

$$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$

- strong emission in GeV range
- γ-emission sensible to CR energy $E > 280$ MeV

<u>DETECTION OF IONIZATION</u>

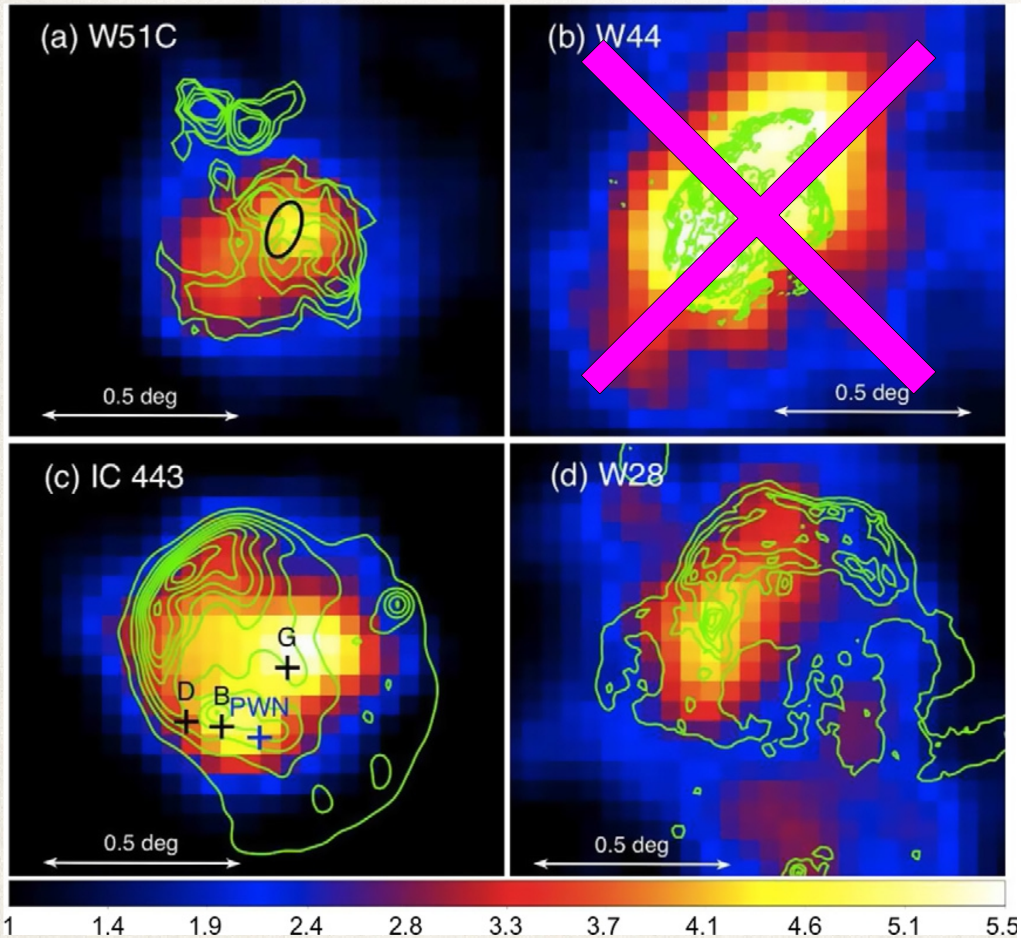
- The ionization rate of several molecules depends on the CR flux (H_2, H_3^+, CH, OH, C_2, DCO^+, HCO^+,......)

- Ionization sensible to CR energy $E > 0.1$ MeV

Is it possible to use combined information from ionization and γ-ray emission to infer the CR spectrum from ~MeV up to ~TeV

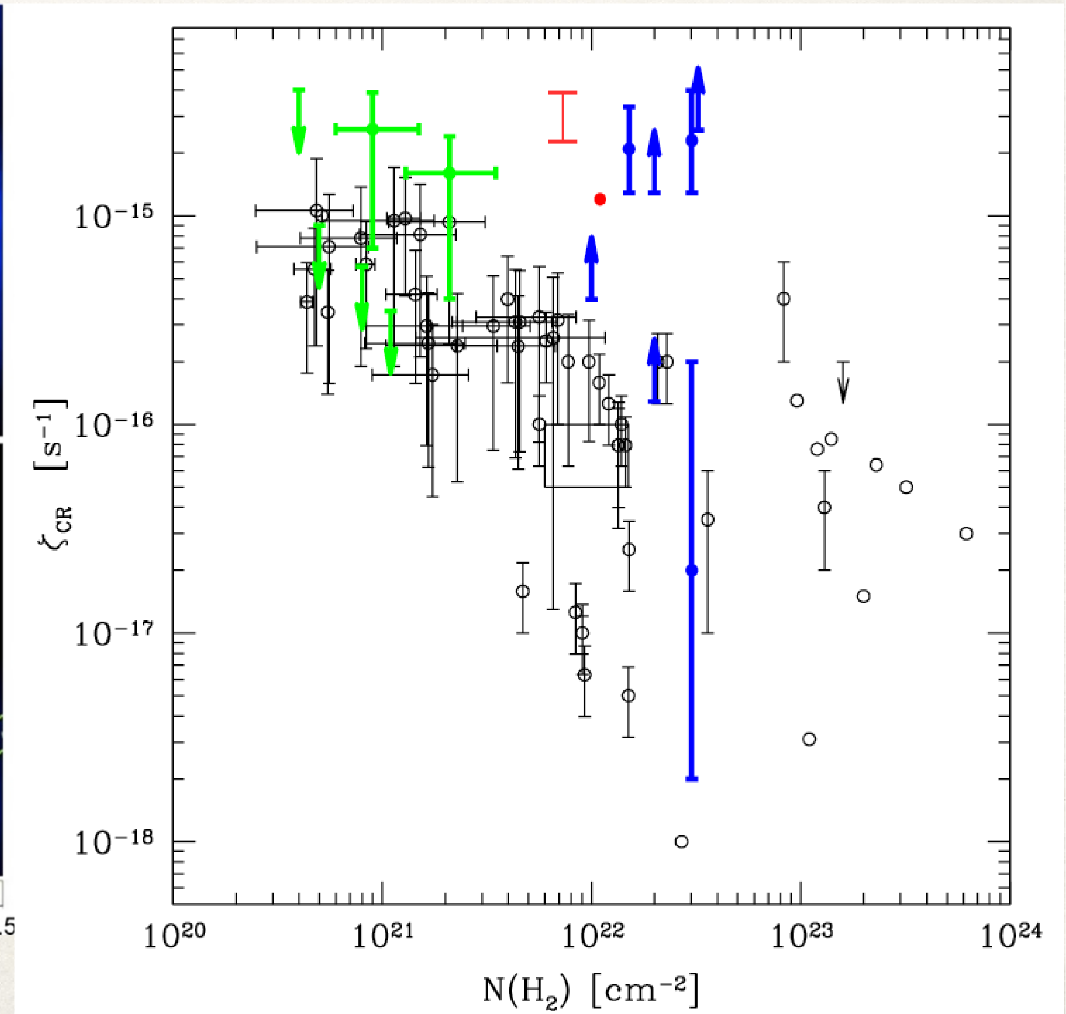
Using molecular clouds as CR barometer

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



Average level of ionization is lager for MCs close to SNRs

IC 443 **W 51C** **W28**



Conclusions

CR self-generated turbulence seems to be an ubiquitous fenomenon

- **Acceleration at shocks** (not covered here)
- **Propagation**:
  - Can explain the spectral breacks (@300 GeV)
  - Can account for the gradient problem in the galactic plane
- **Escaping from sources** $\longrightarrow$ SI increases the escaping time:
  - Increase the accumulated grammage (but not the dominant contribution)
  - Enhance the gamma-ray emission from the cocoon (possible contribution to the diffuse gamma-ray emission)
  - Effect on anisotropy? (see talk by Kachelriess on Friday)