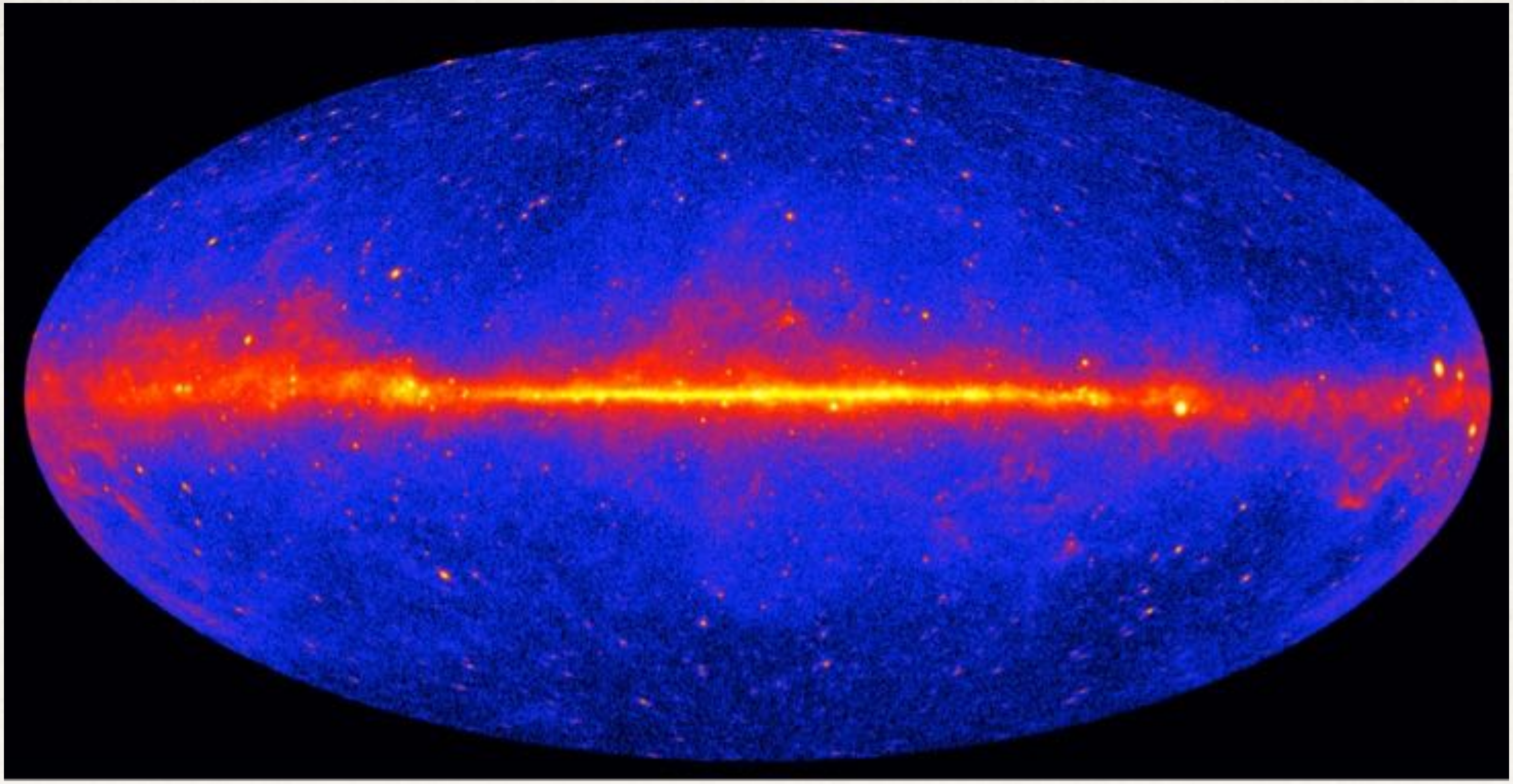


Cosmic Rays in the multi-messanger era

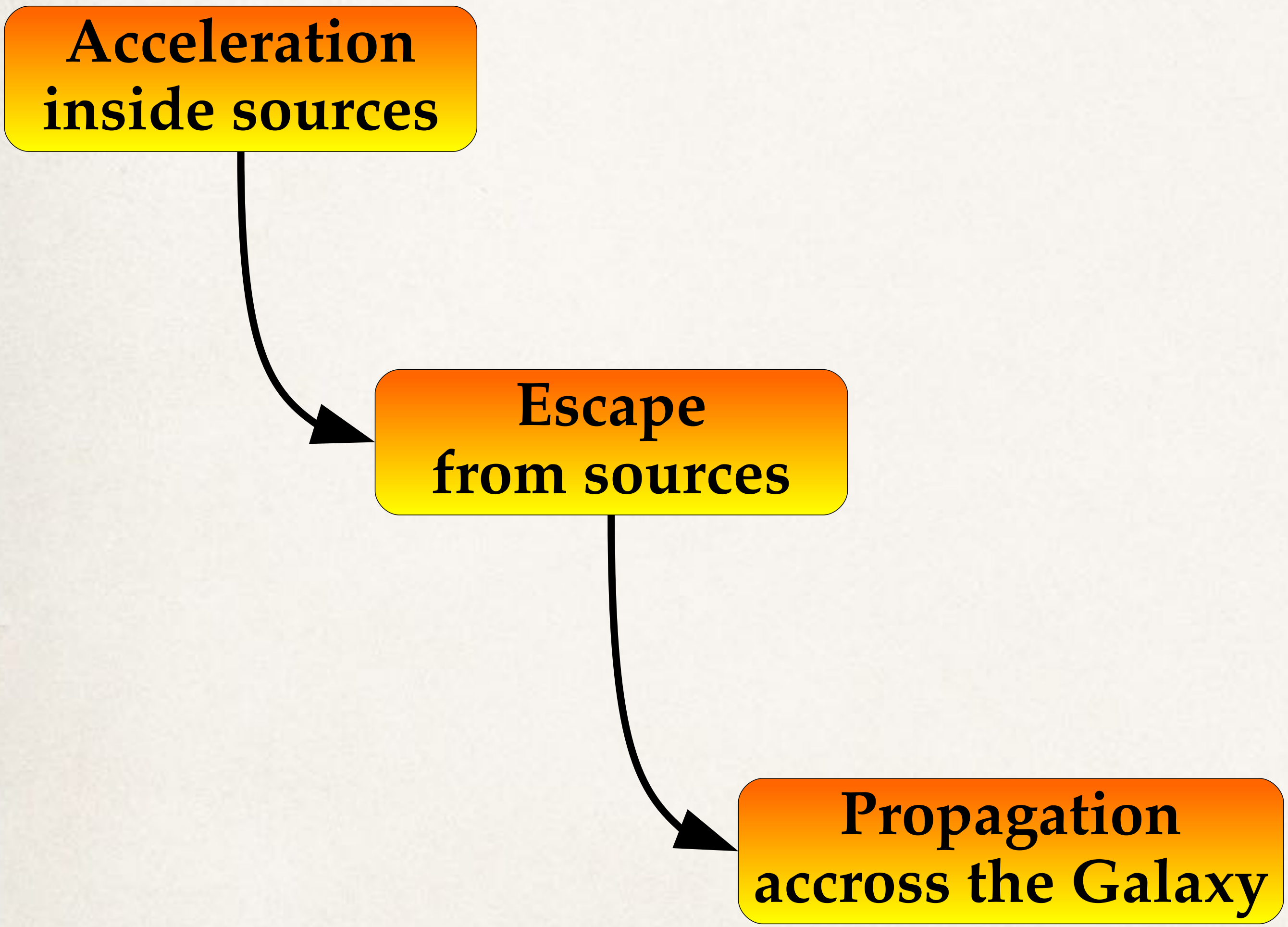
Giovanni Morlino,

Gran Sasso Science Institute, L'Aquila, ITALY

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Vulcano Workshop, 2018 – May 20-26, Vulcano, ITALY

The path to became a cosmic ray



The path to became a cosmic ray

Acceleration inside sources

- Gamma-ray emission from SNR
- Magnetic field amplification
- Maximum energy

Escape from sources

- Self confinement around the sources
- Interaction with molecular clouds

Propagation accross the Galaxy

- Standard halo model
- What produces the turbulence?
- CR-driven Galactic wind

Predictions of *diffusive shock acceleration*

(1) Spectrum: $f_{CR}(p) \propto p^{-4} \rightarrow f_{CR}(E) \propto E^{-2}$

(2) Acceleration efficiency: ~10%

(3) Maximum energy: $E_{max} \simeq 50 \left(\frac{\delta B}{B_0}\right)\left(\frac{B_0}{\mu G}\right) \; eV$

Strong dependence on magnetic field

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

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

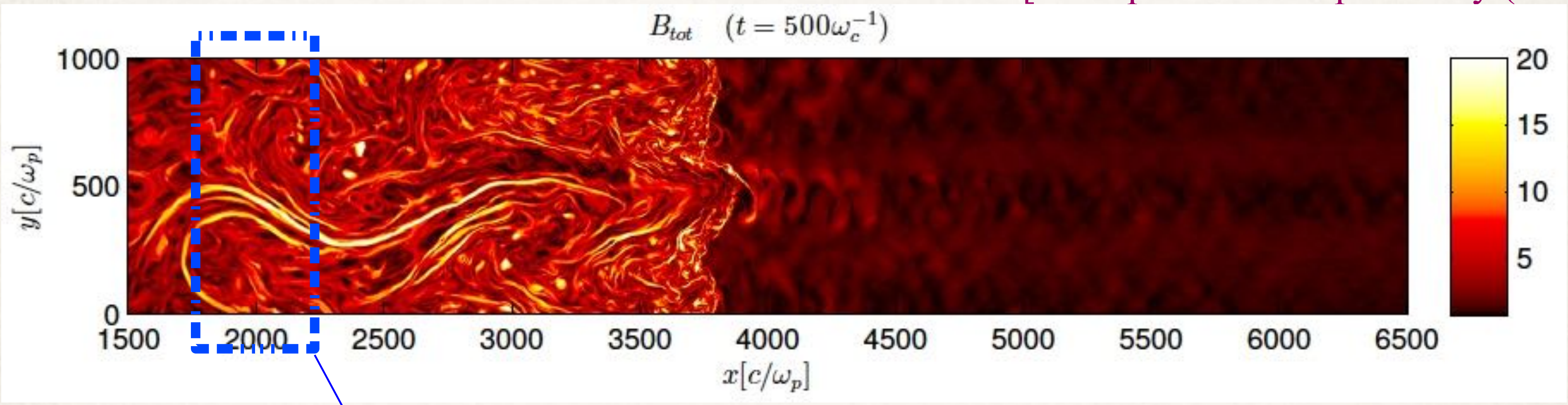
This condition requires amplification of the magnetic field

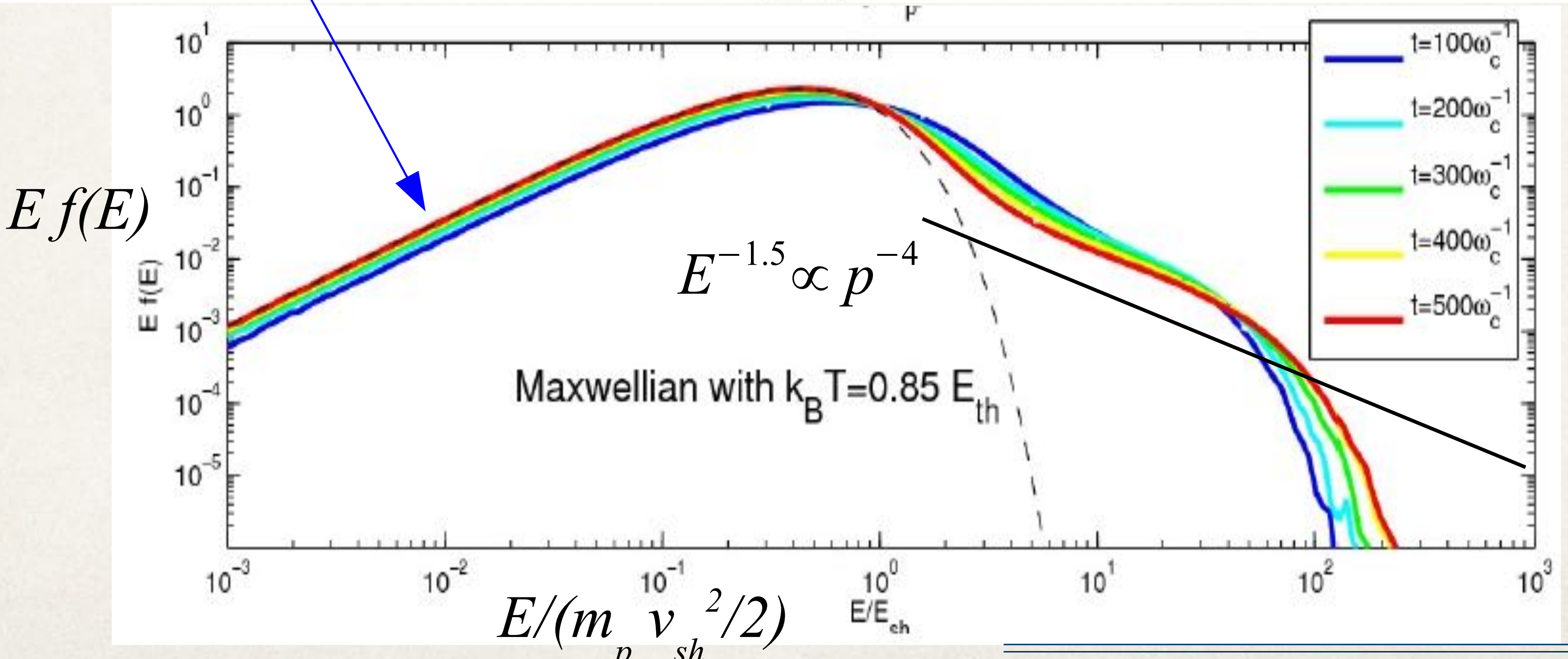
Fermi acceleration at work

[From Caprioli & Spitkovsky (2013)]

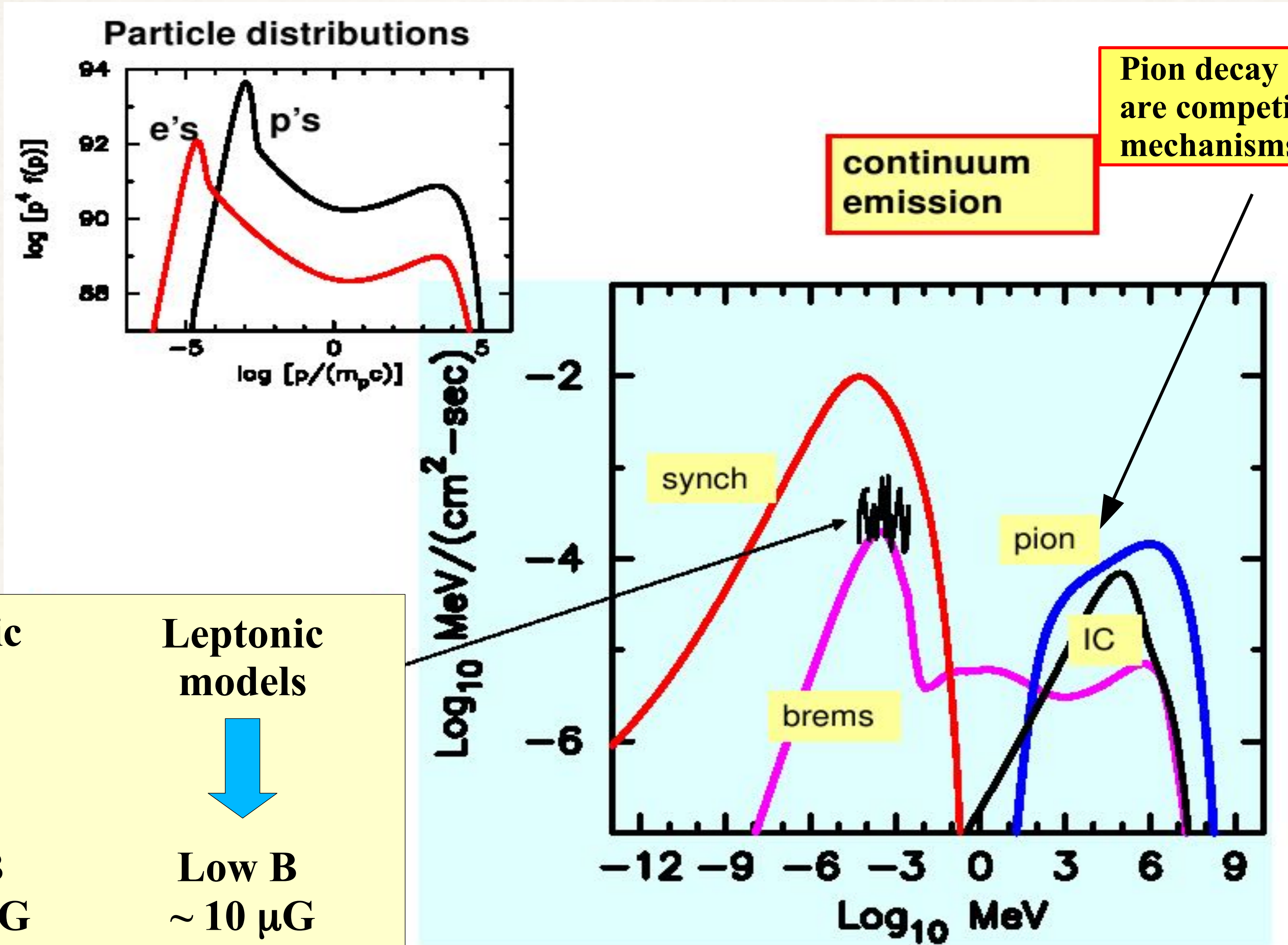
PIC simulation of particle acceleration

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



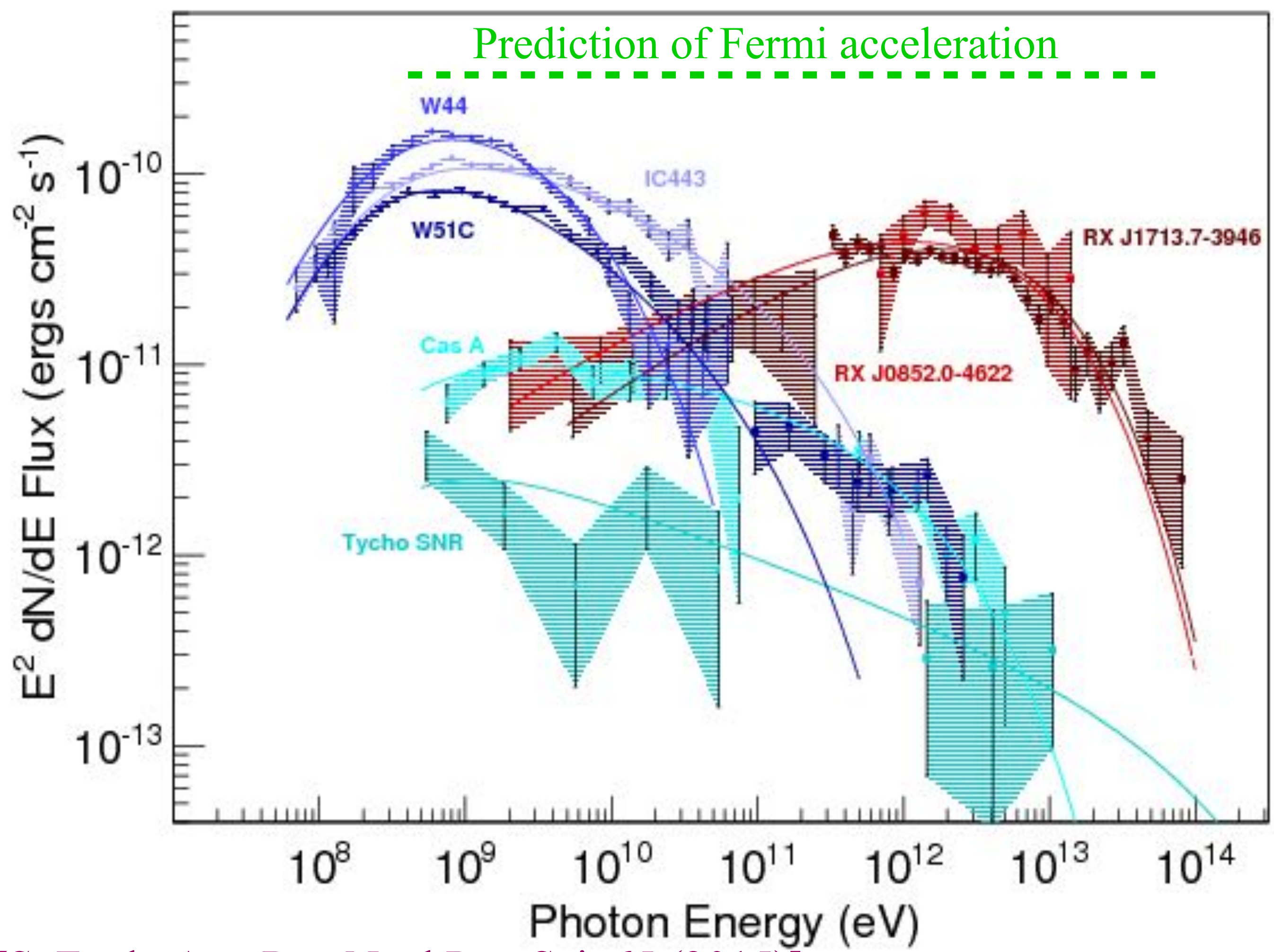


Non-thermal spectrum from SNRs



Hadronic models	Leptonic models
↓	↓
Large B	Low B
>~ 100 μG	~ 10 μG

Gamma-rays from SNRs



[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)

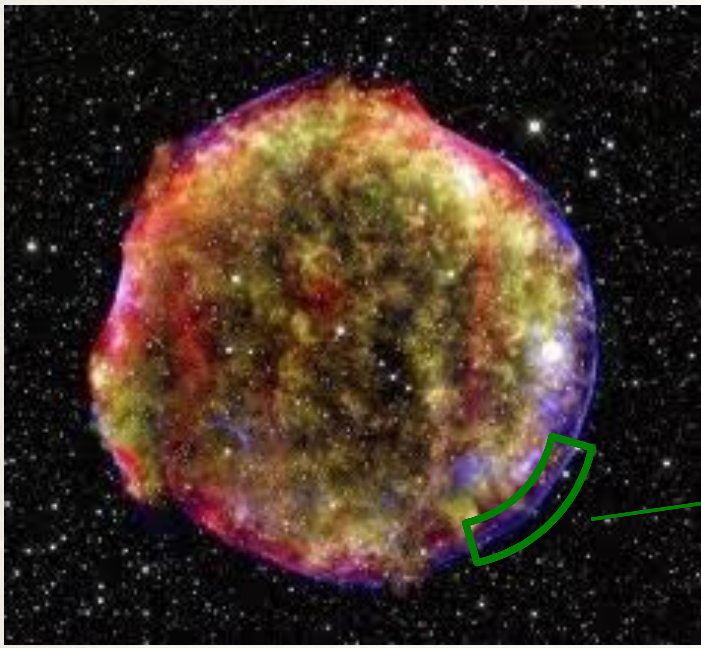
- hadronic
- steep spectra ~$E^{-2.3}$
- E_{max} ~ 10-100 TeV

Not enough to explain the Knee at ~ PeV

NOTE: this general trend could be an artifact of the enviromental conditions

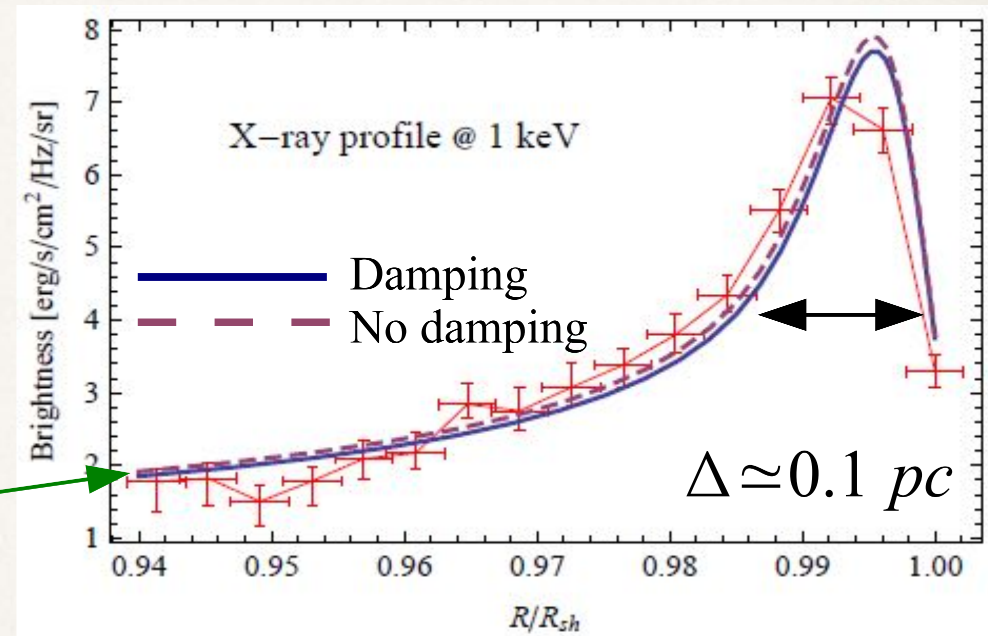
Magnetic field amplification: observations

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 loss-length

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

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

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

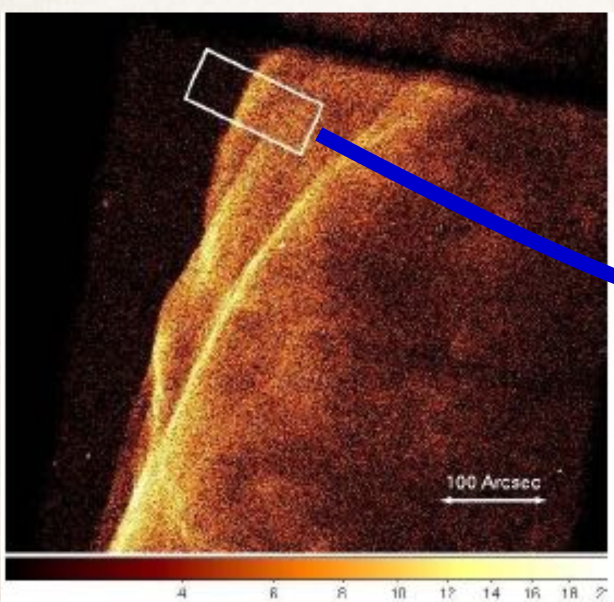
Where is the magnetic field amplified?

DOWNSTREAM: MHD instabilities (shear-like)

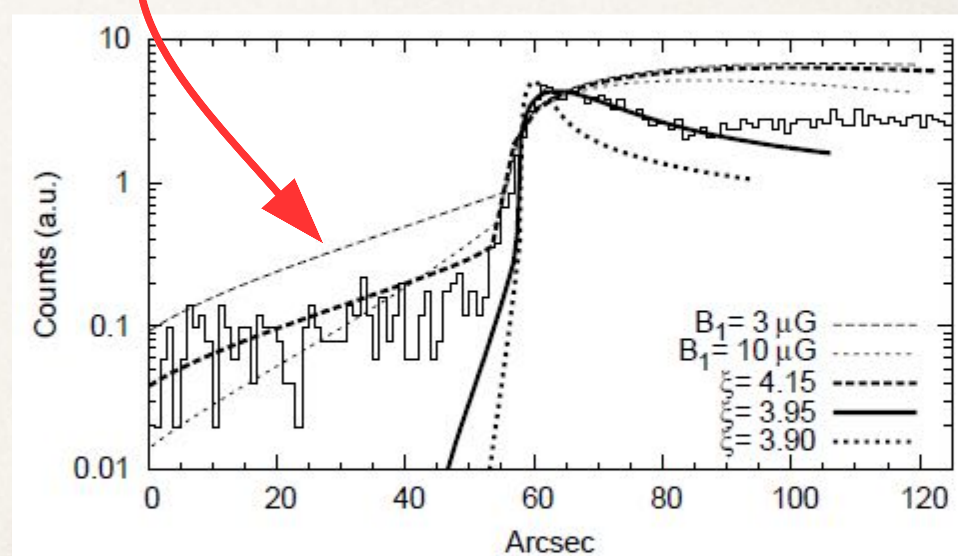
UPSTREAM: only through instabilities driven by CRs (Streaming, Bell)

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 $k = 1/r_L(p)$

Fast growth rate but

$$\left(\delta B / B_0\right)^2 \simeq few$$

$$E_{max} \approx 10^5\, GeV$$

A factor 10 below the knee

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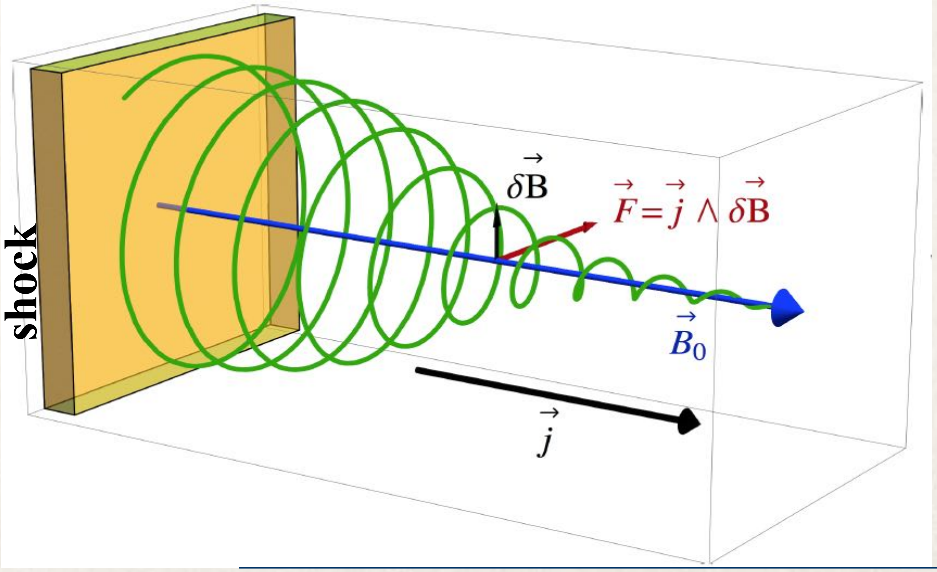
Non-resonant *Bell* instability

[Bell (2004)]

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

Amplification due to $\vec{j} \wedge \vec{B}$ force



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Non-resonant *Bell* instability

[Bell (2004)]

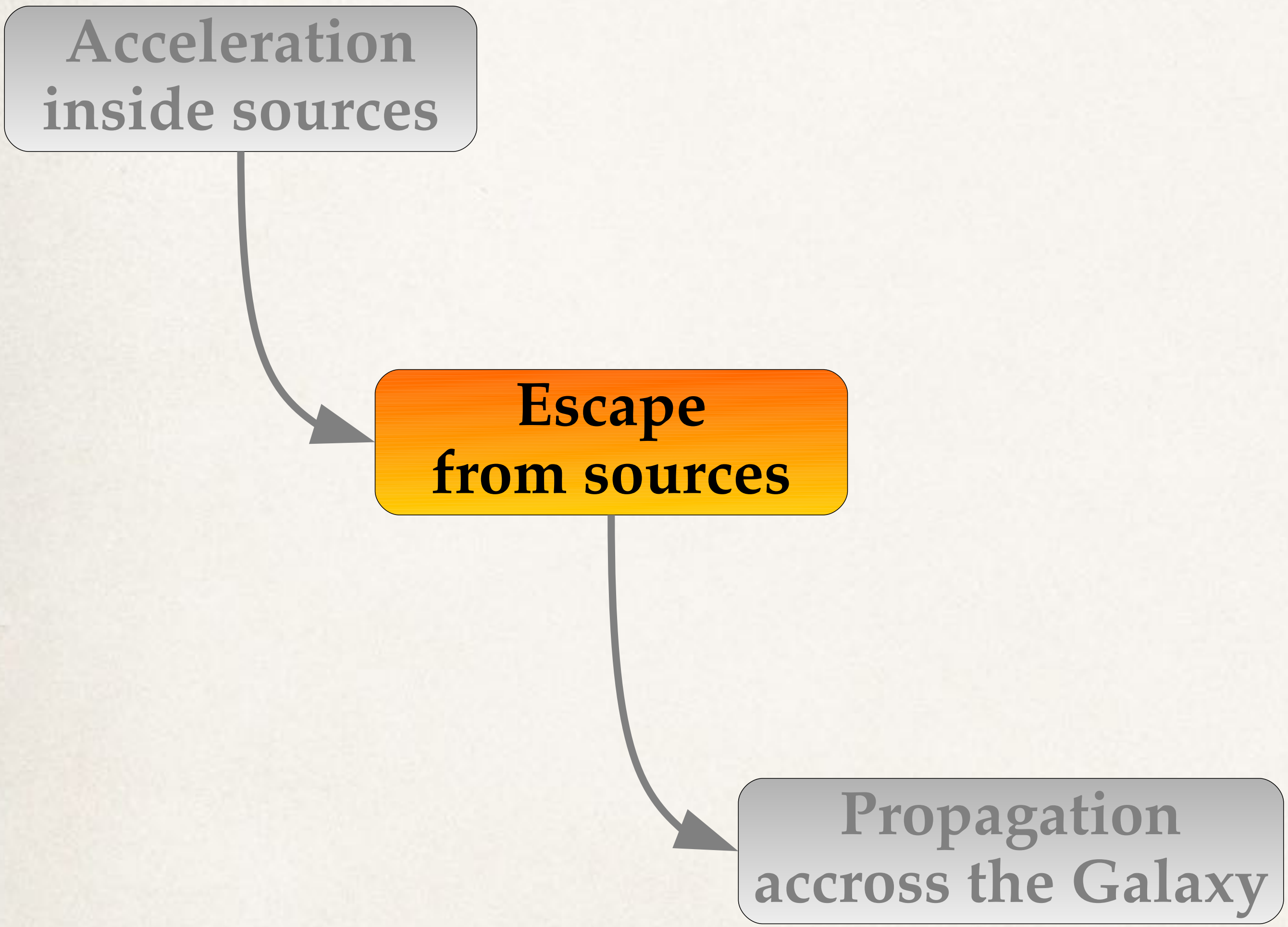
$E_{max} \propto \sqrt{\rho_{CSM}}$

Type Ia SNR expanding into a uniform medium → $E_{max} \approx 10^5\, GeV$

Core-Collapse SNR expanding into a red supergiant wind → $E_{max} \approx 2 \times 10^6\, GeV$

Right number, but this last only ~50 yr!

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

Particle escape from SNRs

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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

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

Released energy

Converted fraction

Incoming energy flux

Particle escape from SNRs

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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

$$\underbrace{4\pi f_{esc}(p)\, c\, p\, p^2\, dp}_{\text{Released energy}} = \underbrace{\xi_{esc}(t)}_{\text{Converted fraction}} \underbrace{\frac{1}{2}\rho V_{sh}^3\, 4\pi R_{sh}^2\, dt}_{\text{Incoming energy flux}}$$

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

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

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

Spectrum NOT related to Fermi acceleration process!

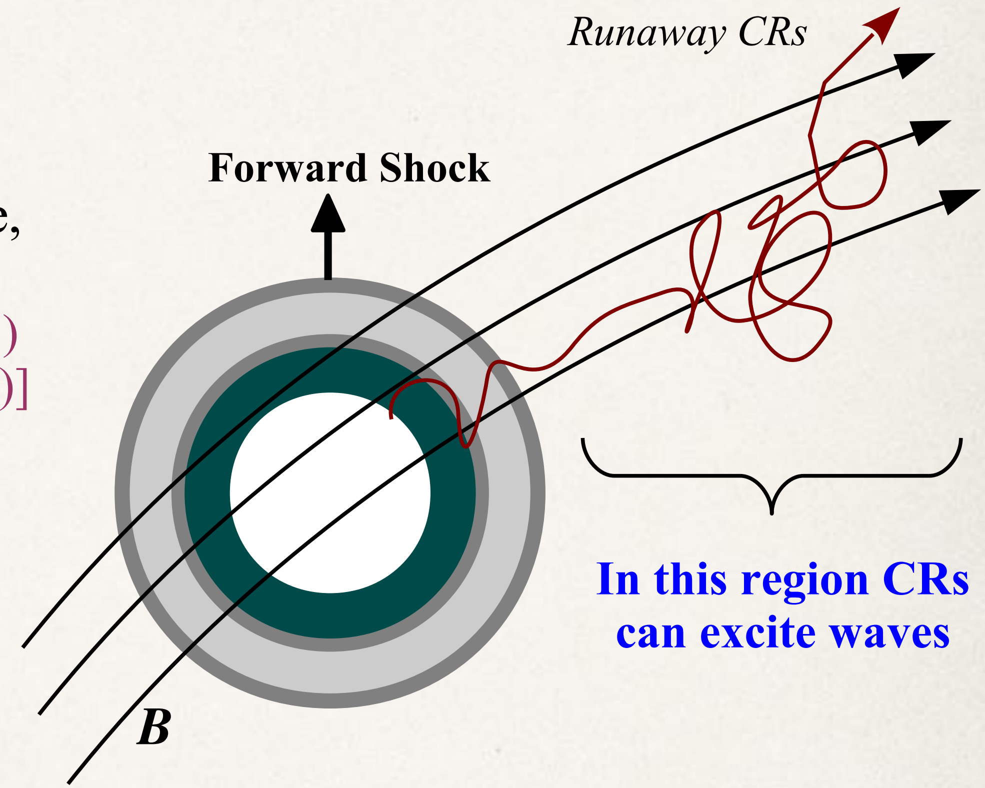
Effect of self-amplification near the CR sources

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

[Malkom et al. (2013)
Nava et al. (2015)]

During this time CR spend in the vicinity of sources they can produce diffuse emission via

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



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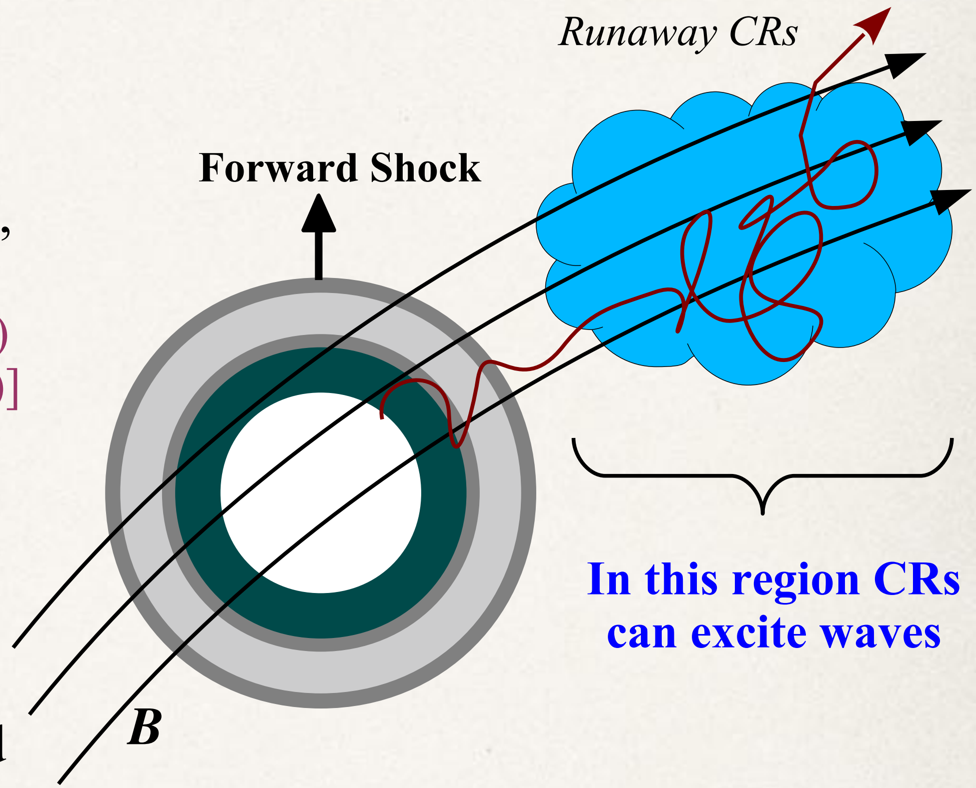
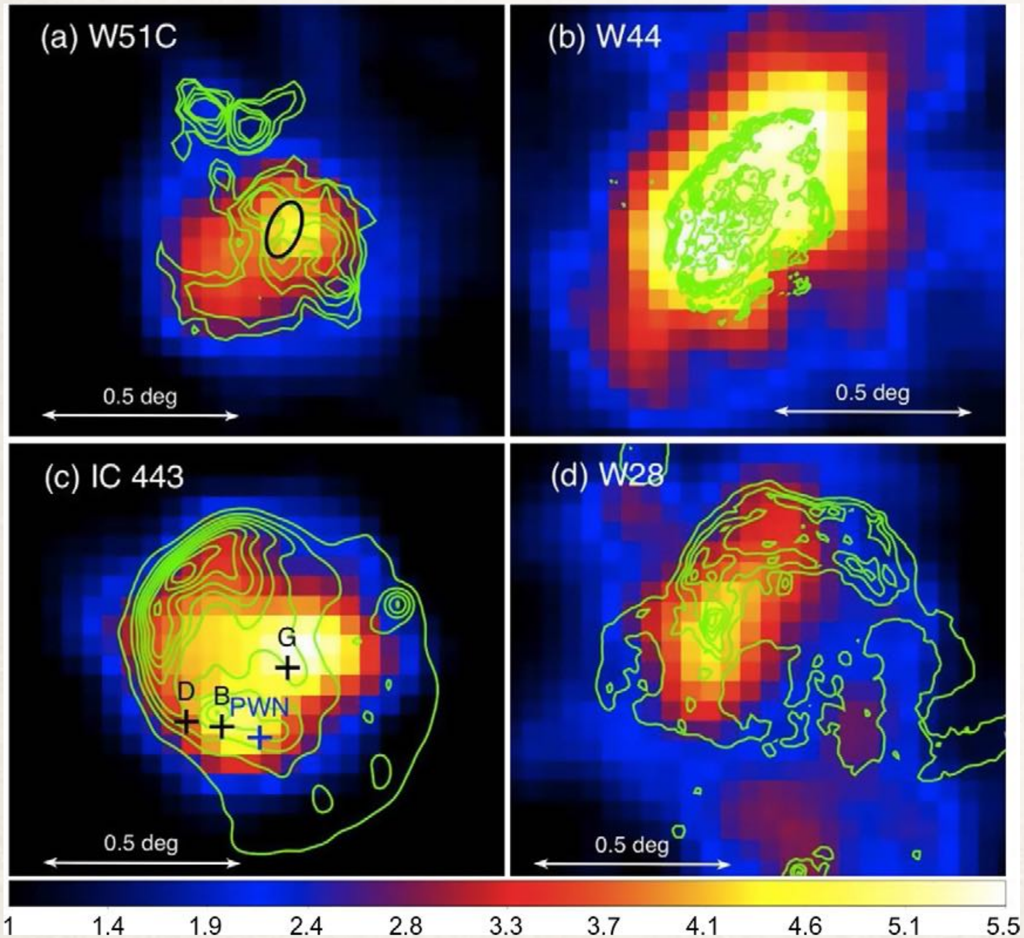
If a molecular cloud is close enough the enhanced γ-ray emission will be seen for long time



CTA will probably discover tens of SNR-MC associations

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

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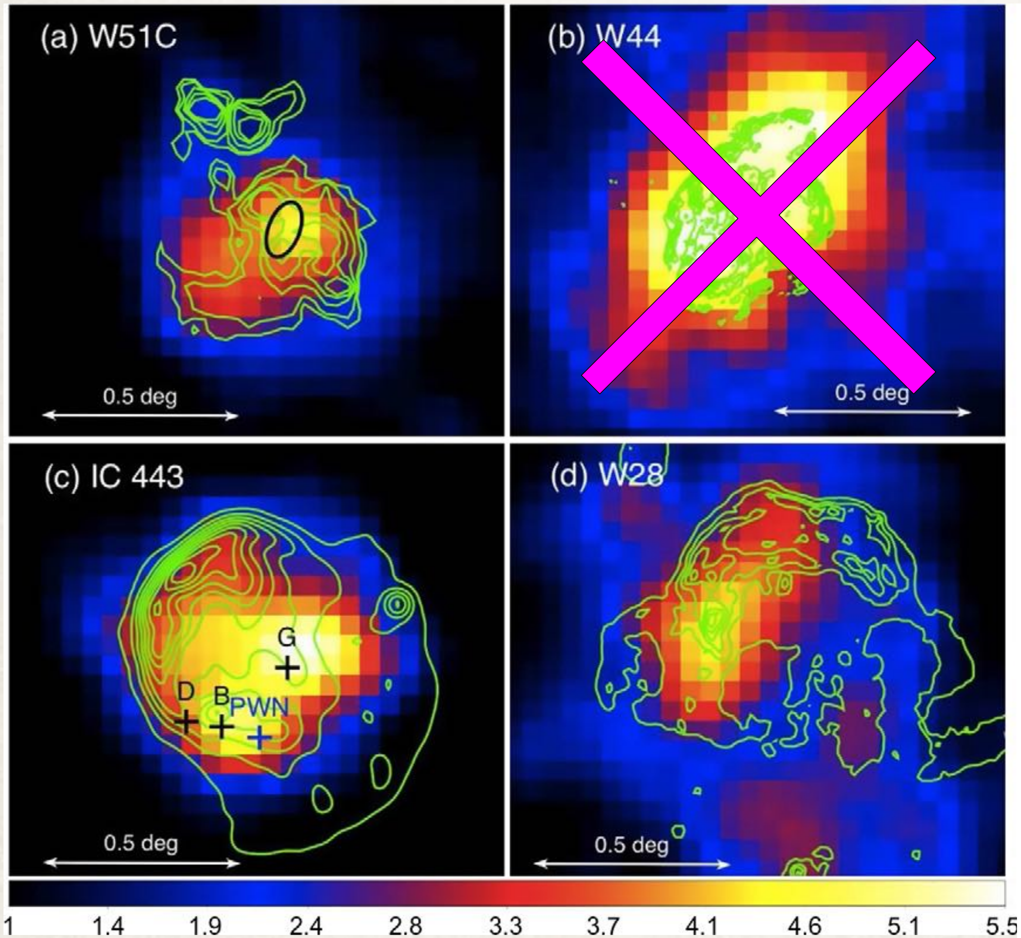
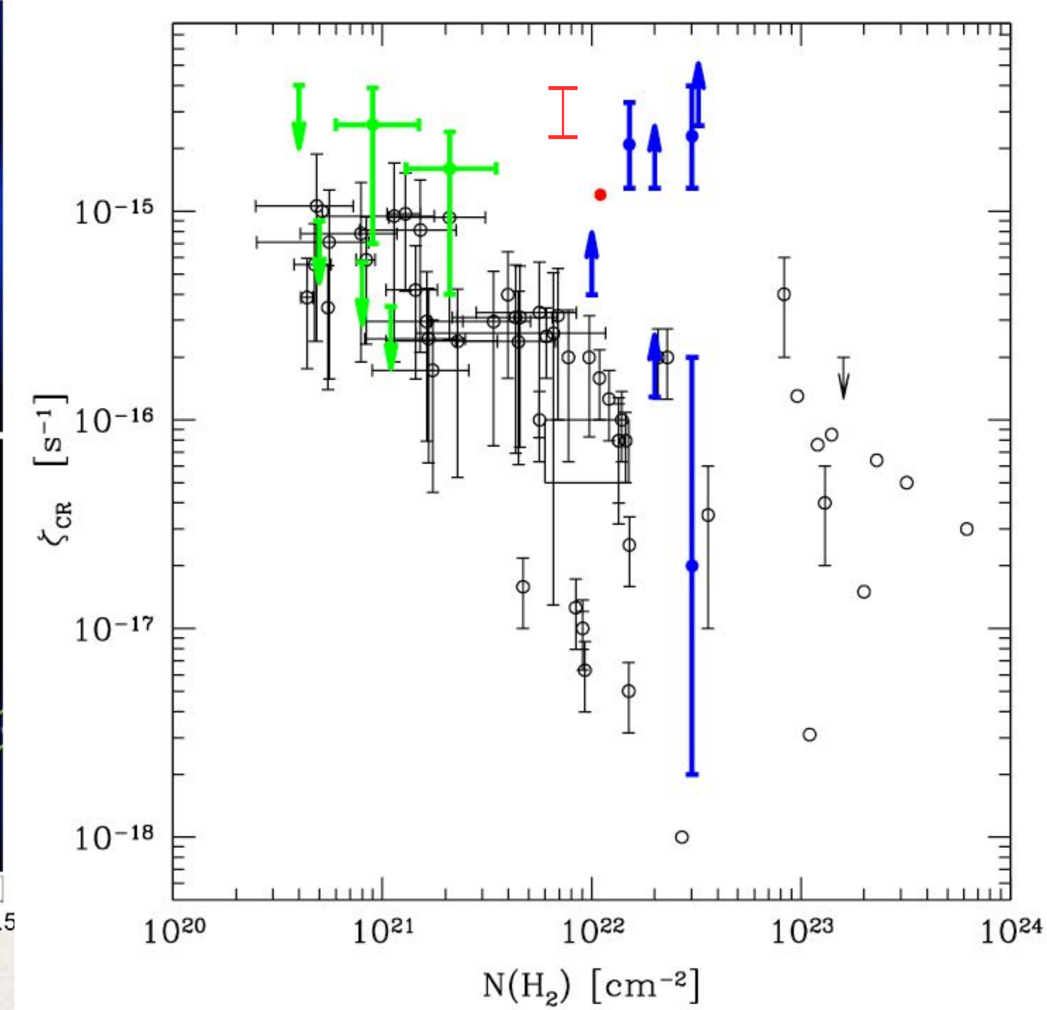
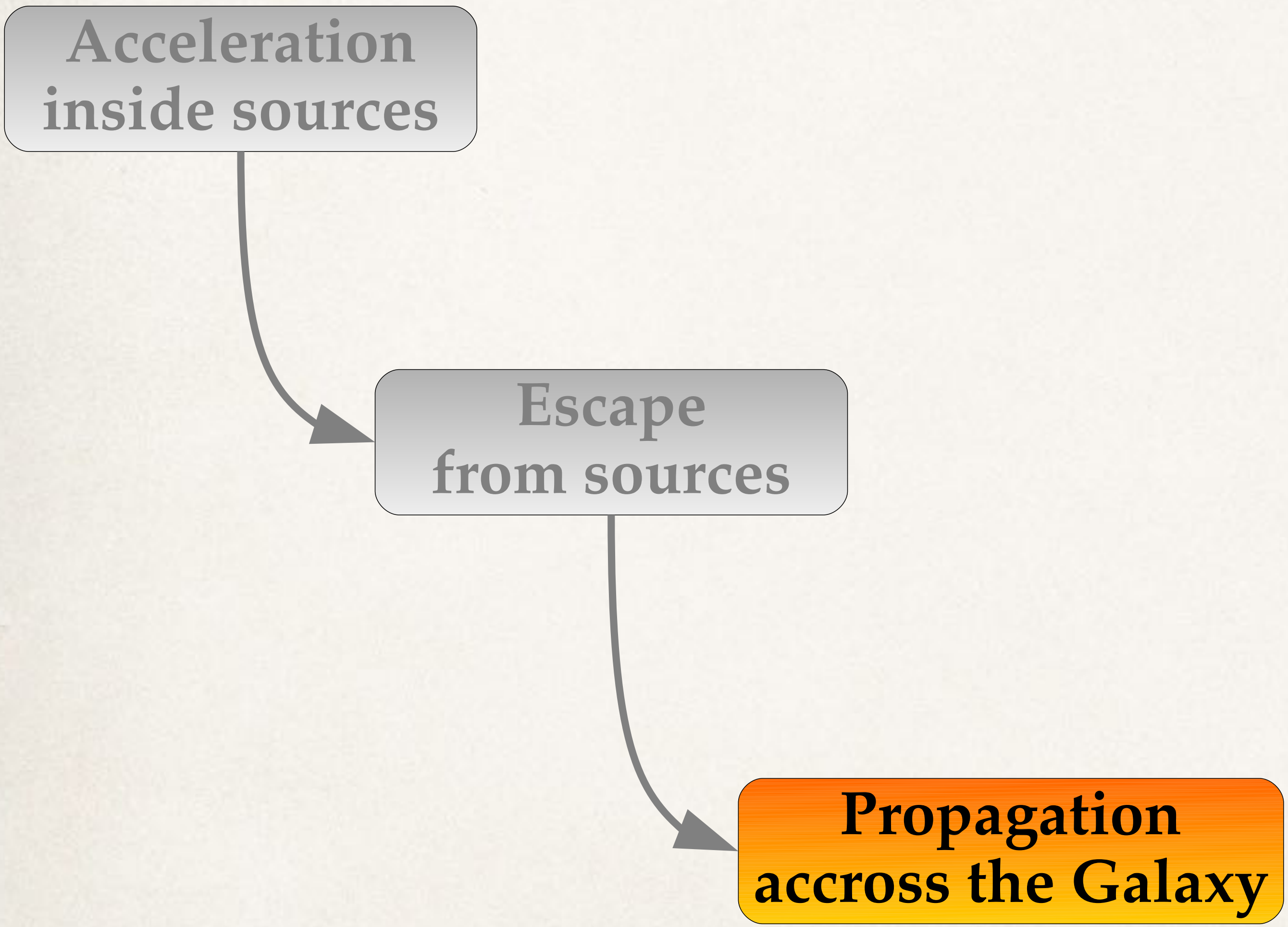


Average level of ionization is lager for MCs close to SNRs

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



Diffusion in the Galactic Halo



Basic Halo model

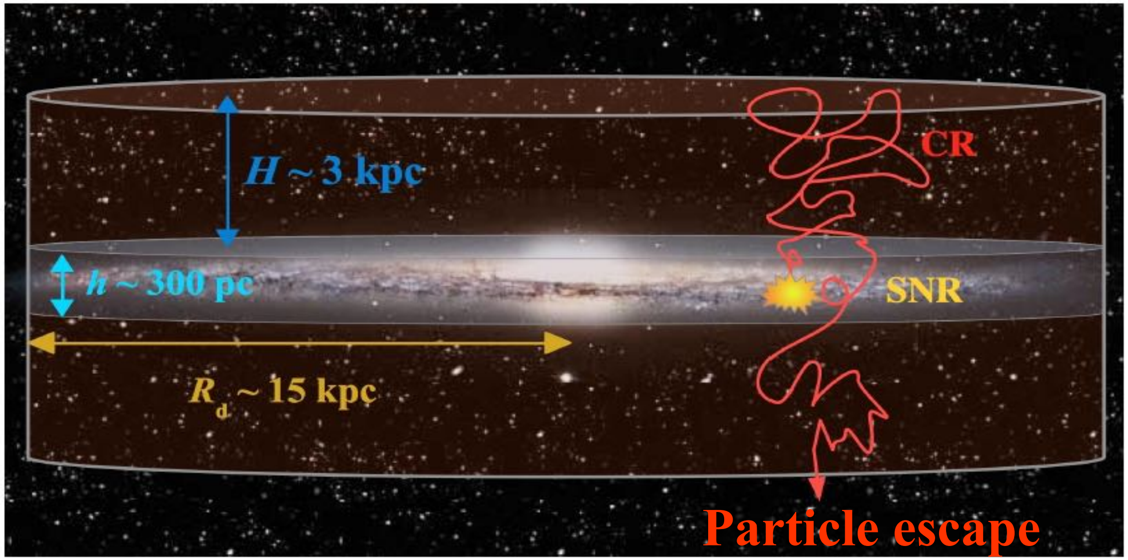
In the basic picture of CR propagation model:

- 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

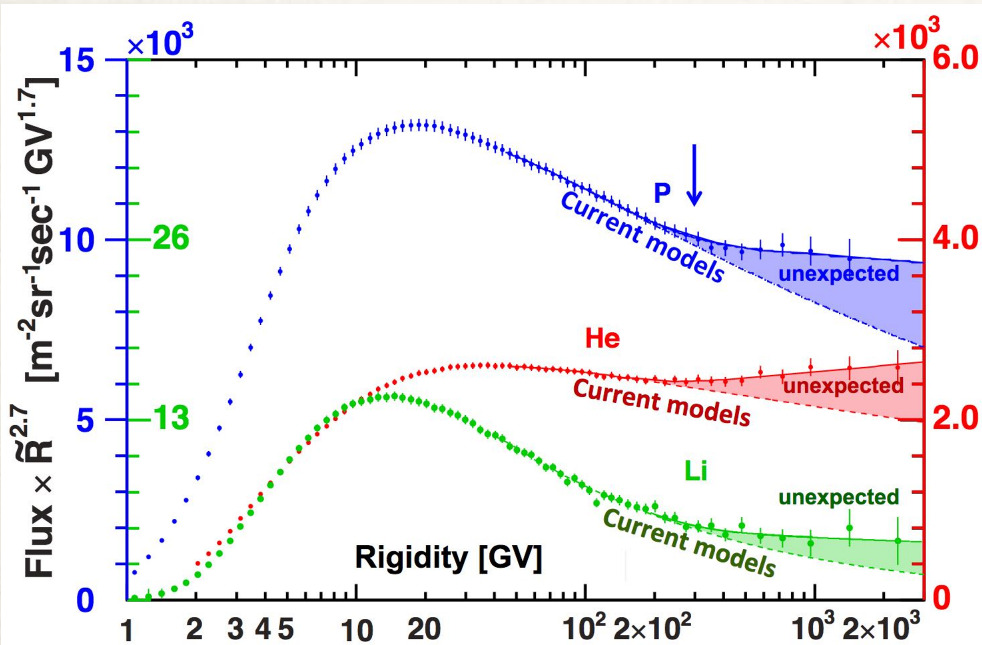


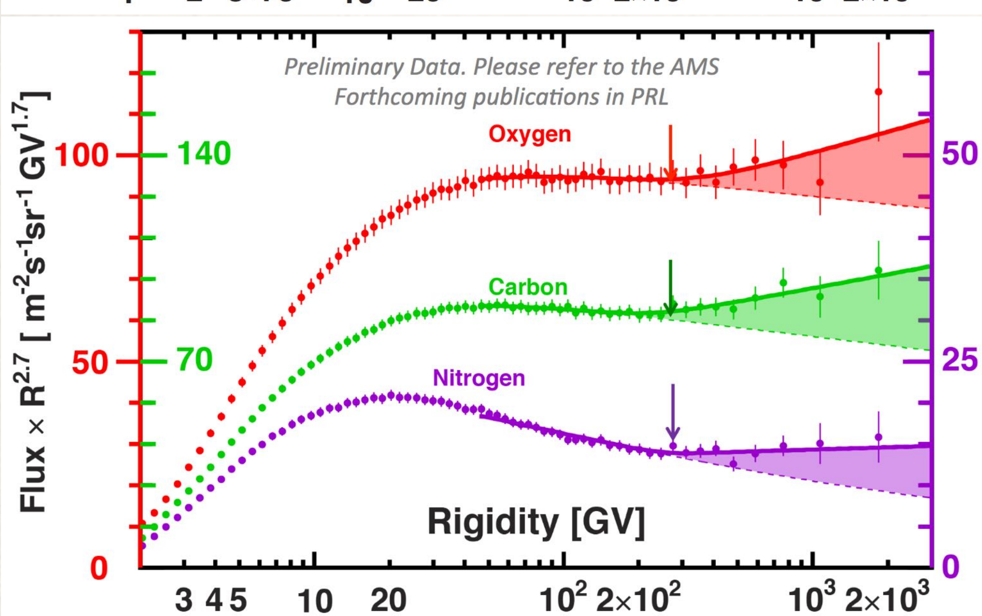
This picture is unsatisfactory for at least two reasons:

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

Some observed anomalies suggest a more complex propagation model

Anomaly: 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

$$N_p(E) = Q_{inj}(E)\frac{H^2}{2D(E)}$$

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

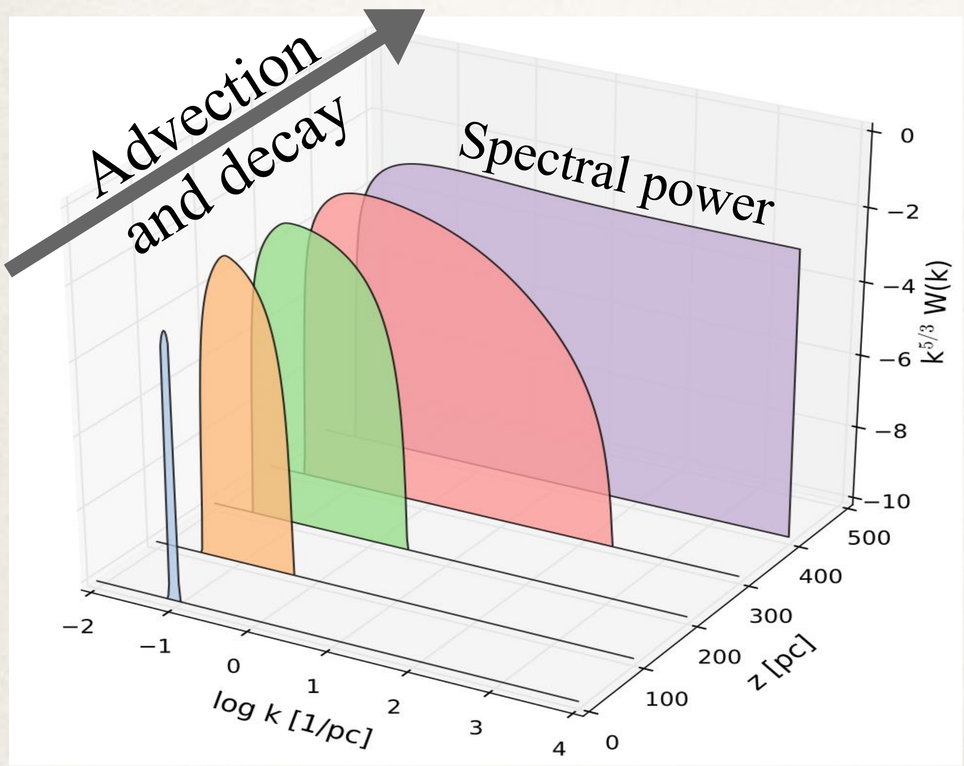
See talk by M. Vecchi

Self-generated magnetic Halo

(Evoli, Blasi, GM, Aloisio, 2018, submitted]

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

Dimention of the Halo determined by
Advection time = decaying time



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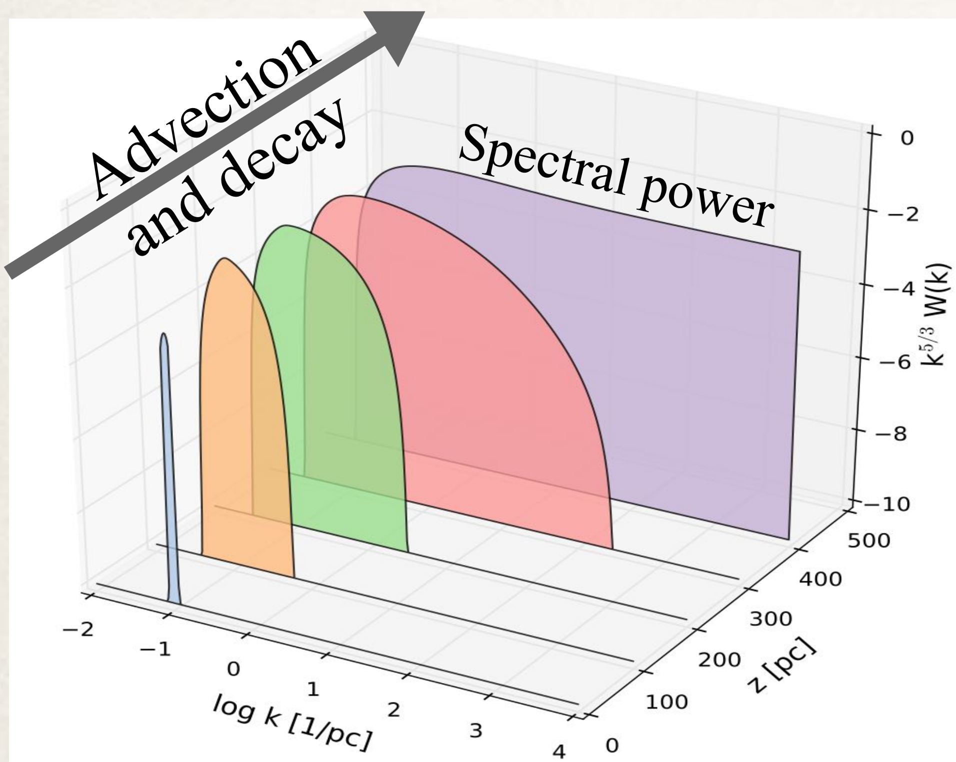

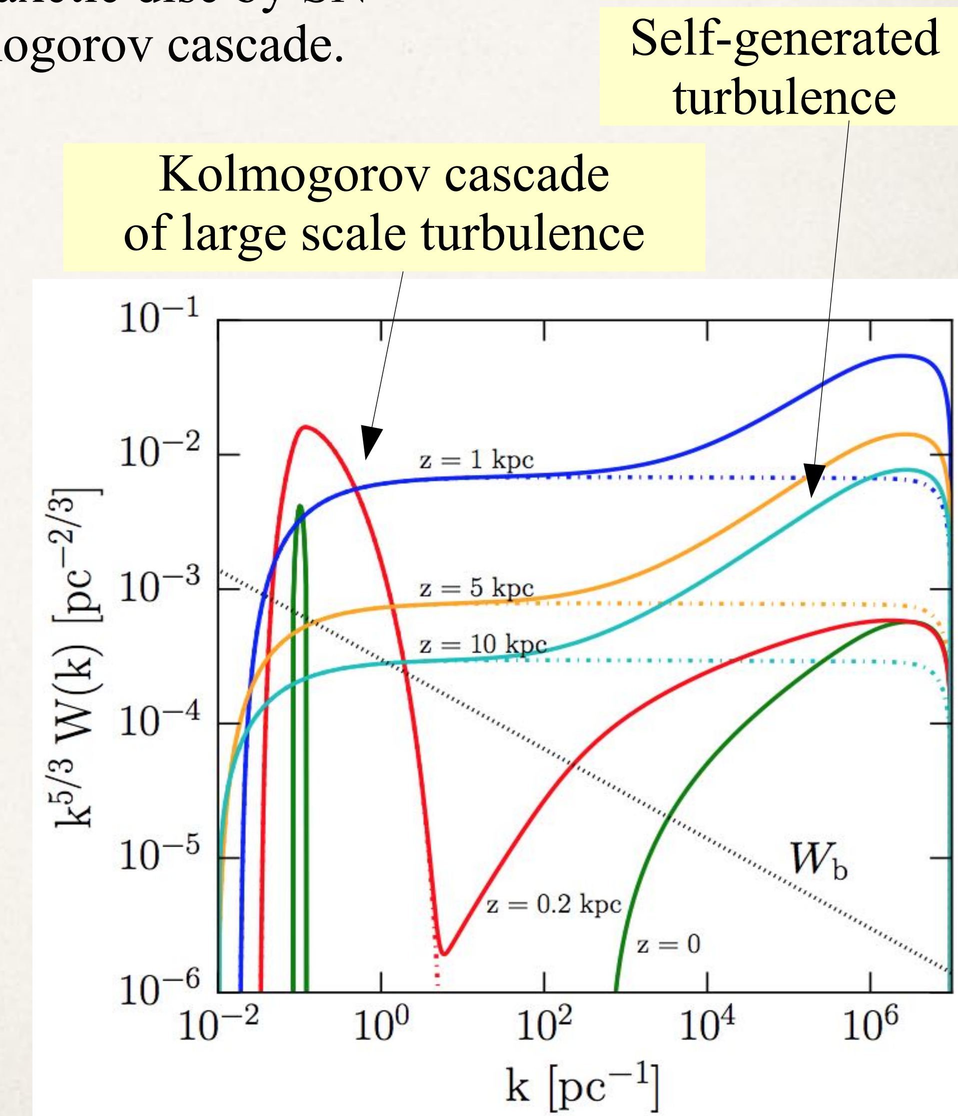

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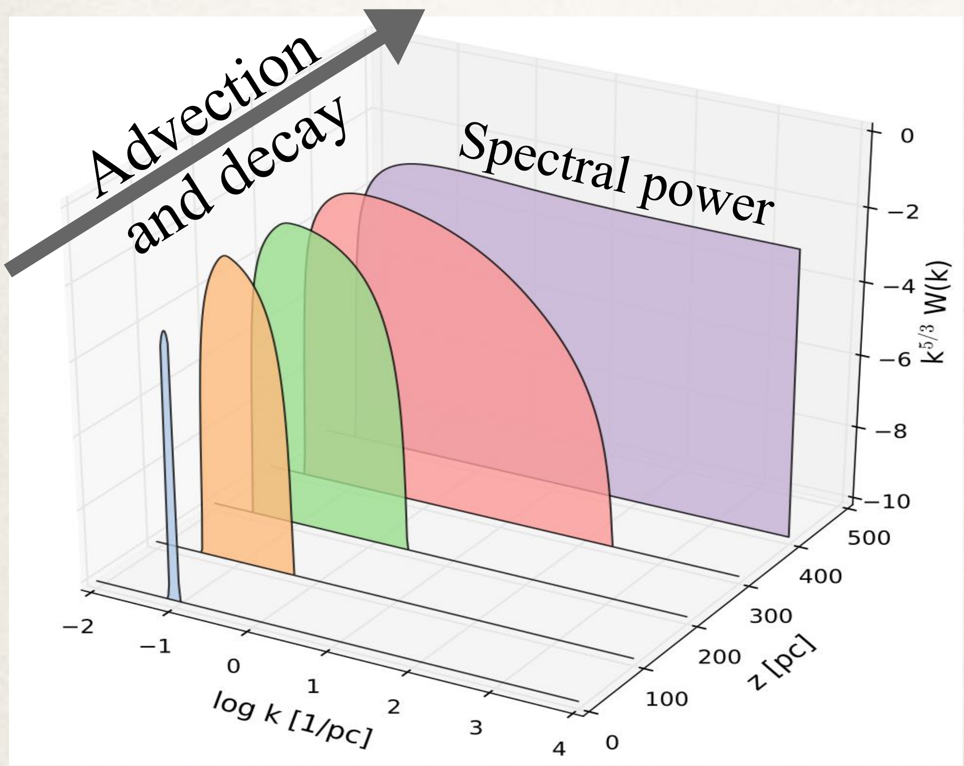
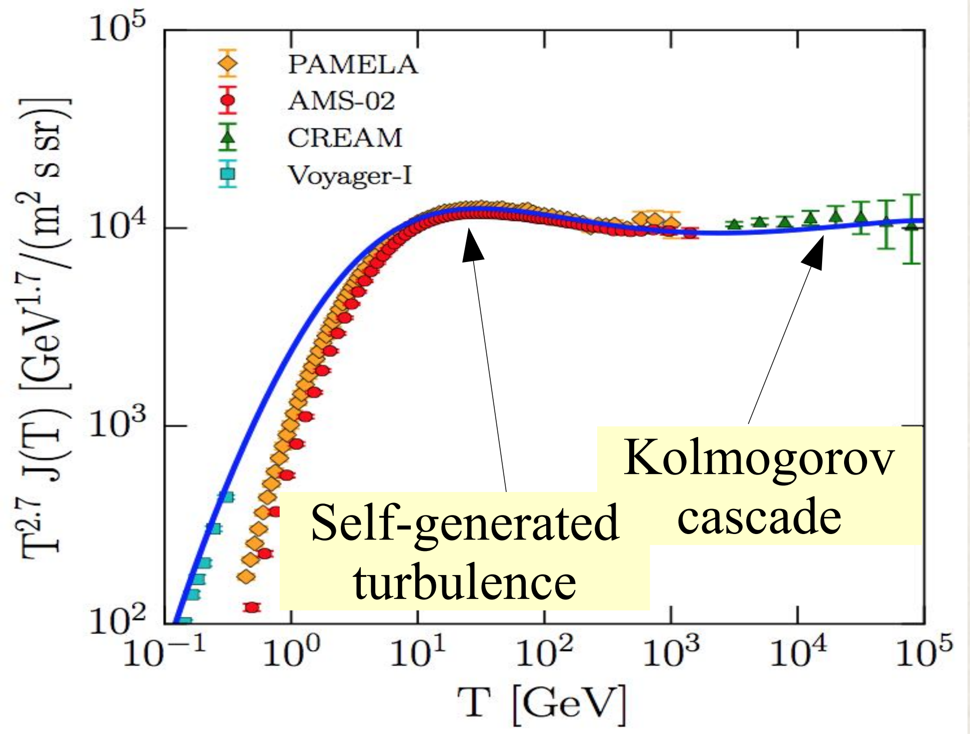
[see also: Blasi, Amato Serpico (2012)
Aloisio, Blasi, Serpico (2015)]

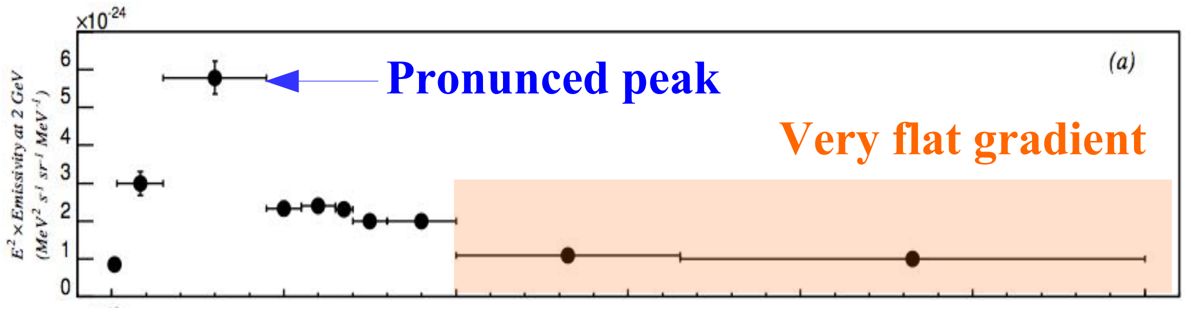
Dimention of the Halo determined by
Advection time = decaying time



Predicted proton spectrum



The problem of the cosmic ray gradient in the Galactic plane seen by Fermi-LAT



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

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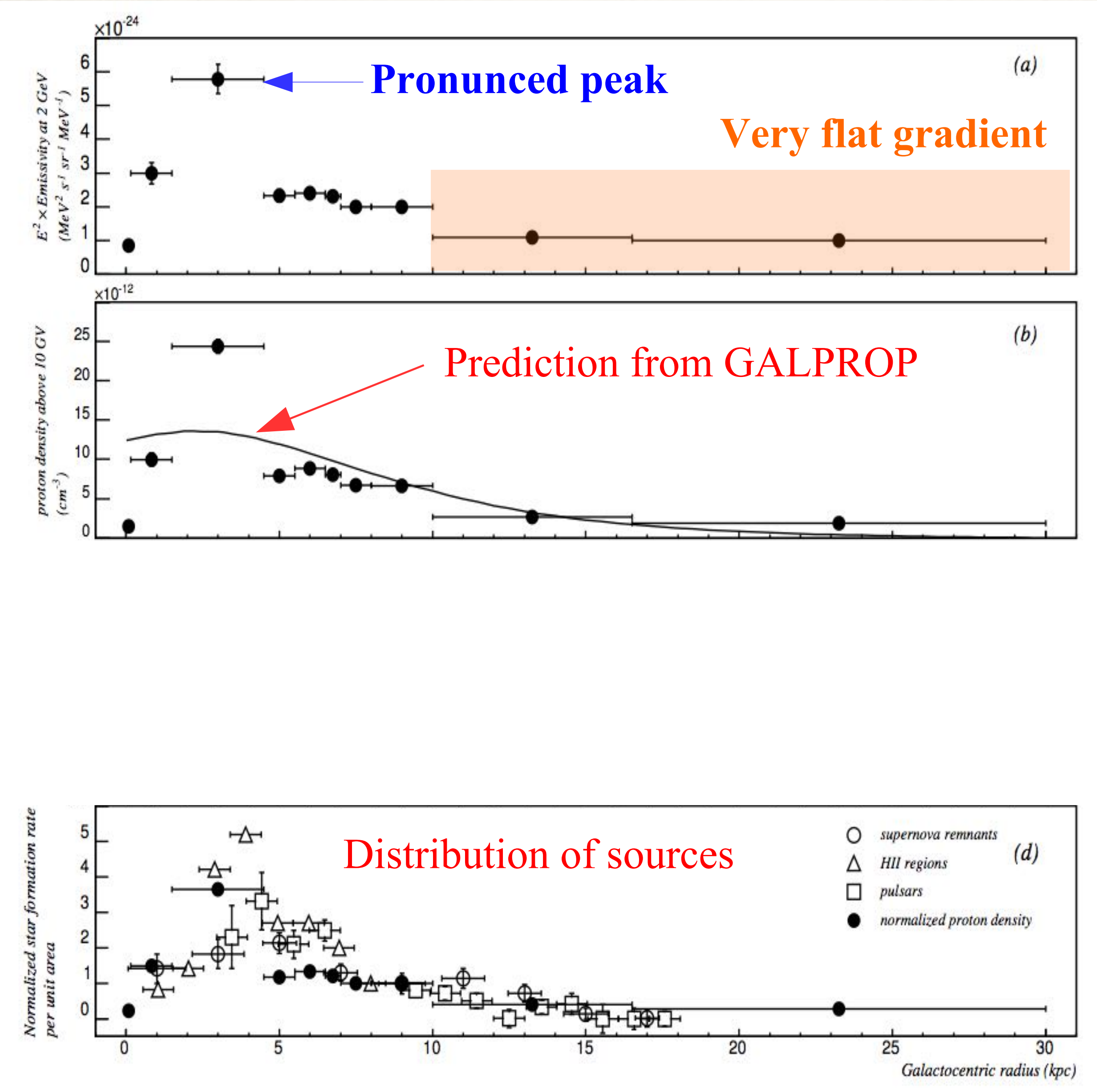

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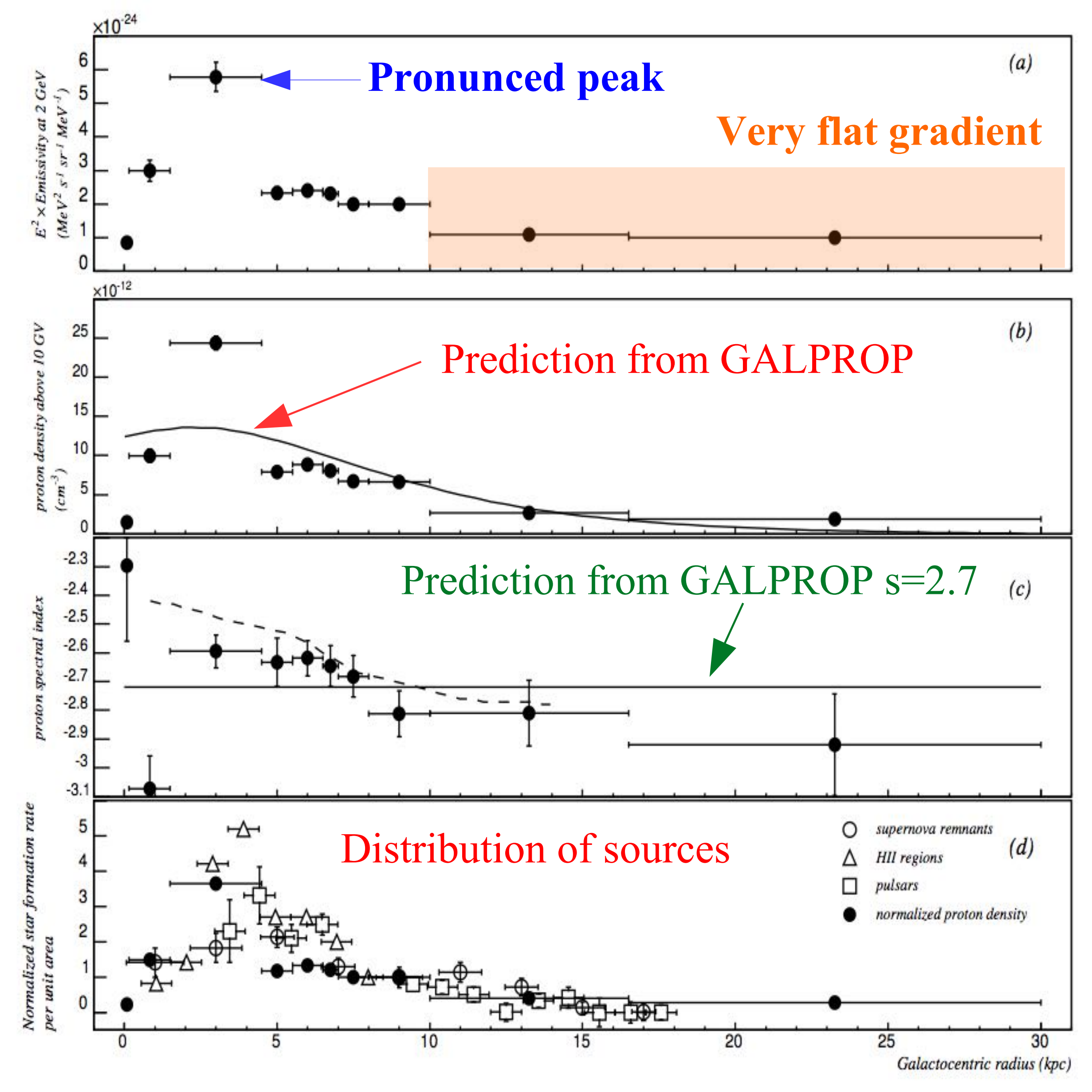

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- In the outer region ($R > 8$kpc) the CR density at ~20 GeV is flat (i.e. decreases much slower than the source distribution)

- 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 denity 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?

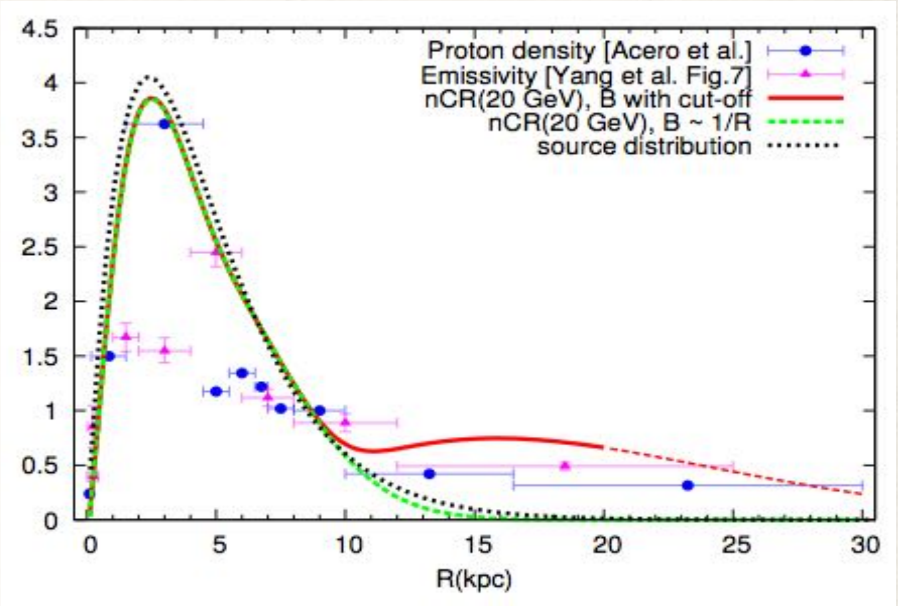
Self-generated turbulence and the gradient problem

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

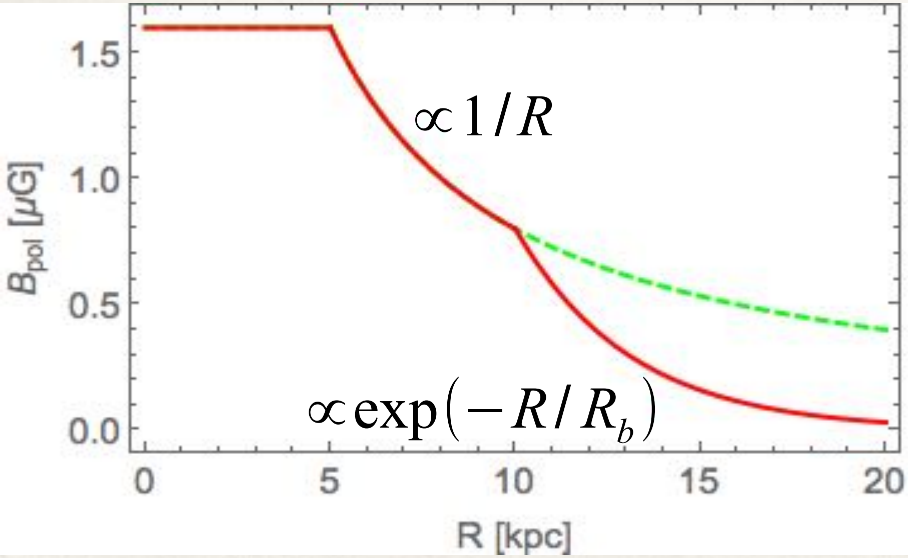
Self-generated turbulence could explain the gradient and the spectral index changes because it is more effective where *B* is smaller

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

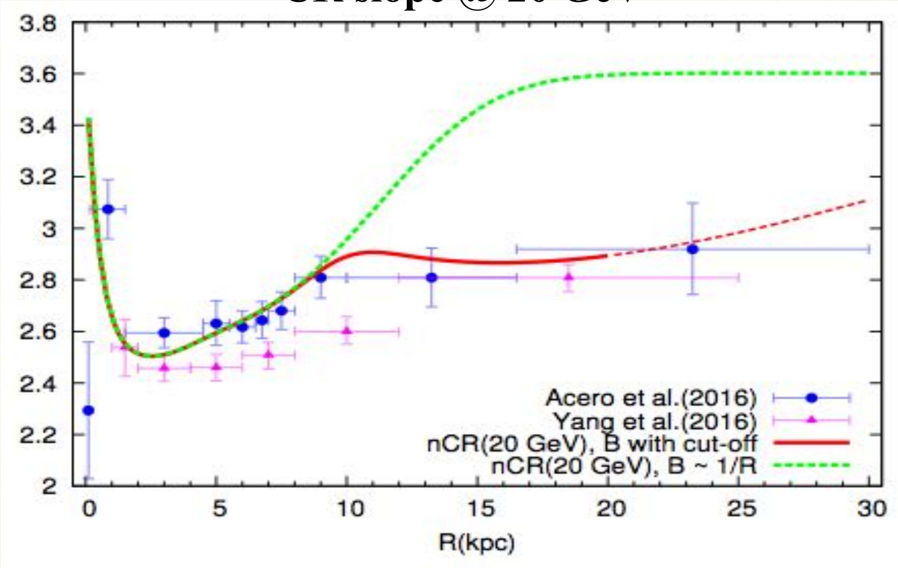
CR spectrum density @ 20 GeV



Strength of large scale magnetic field in the Galaxy



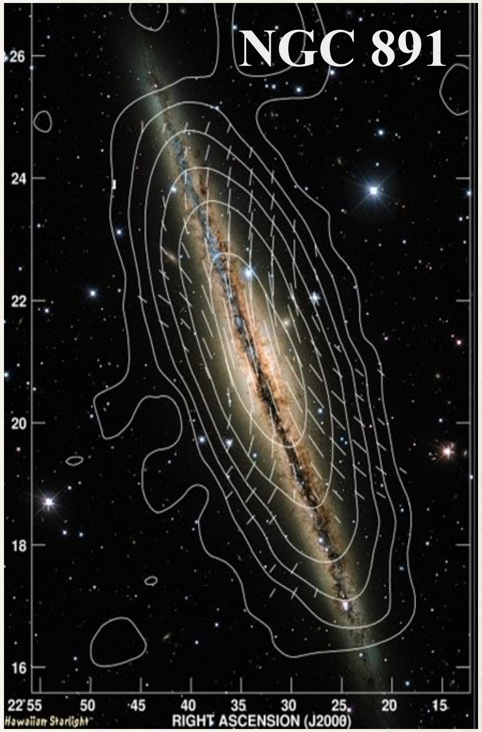
CR slope @ 20 GeV



Why a Galactic magnetic Halo?

Evidences for the Galactic magnetic halo:

1) Detection of magnetic field around other galaxies
2) Detection of synchrotron emission around the Milky Way
3) Evidence of hot plasma from X-ray emission and absorption lines

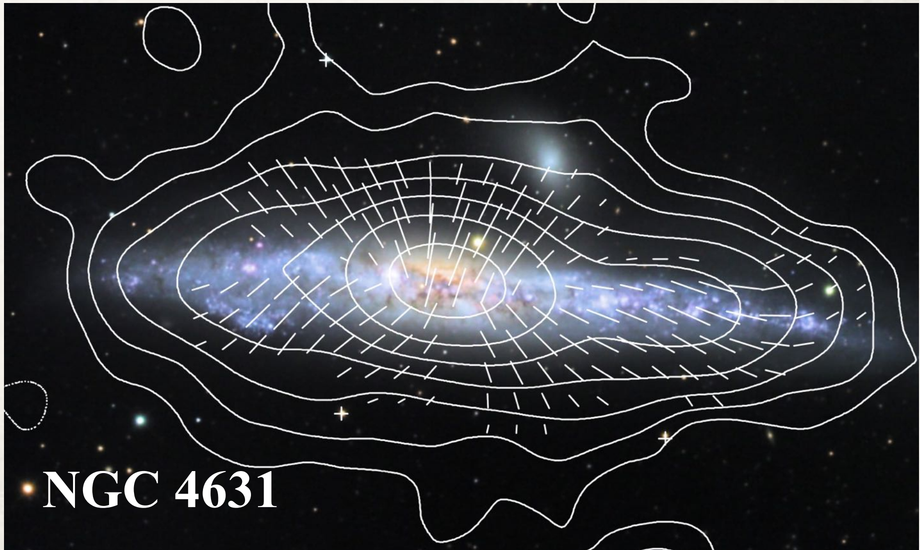


What is the origin of the magnetic Halo?

Sometimes the X-shaped magnetic field structure in the halo is accompanied by strong vertical fields above and below the central region of the disk.

These observations support the idea of a "**galactic wind**" which is driven by the energy of star formation processes in the disk and transports gas, magnetic fields and cosmic-ray particles into the halo.

The speed of the outflow can be measured from radio observations and it is of the order of 300 km/s.



Evidence from X-ray emission and absorption lines

Thermal X-ray emission has been observed from the region around sturbust galaxies.

- In some "normal" galaxies the presence of a hot temperature gax ($T \sim 10^6$ K) has been inferred from absorption lines in X-rays (especially lines OVI , OVII and OVIII)

- **Also the Milky Way presents the same absorption lines** [e.g. Kalberla & Dedes (2008), Miller & Bregman (2013)]

- From those lines the total mass of the halo can be estimated

$$M_{\mathrm{halo}} \sim 10^{10} M_{\mathrm{sol}}$$

(comparable with the total barionic mass in the disk!!)

- And also the matallicity: $Z \sim 0.2\text{-}0.3$

→ The halo has been probably polluted by a Galactic wind

BUT In the Milky Way thermal pressure alone is unable to drive a Galactic wind.

Galactic wind observed in X-rays from starburst galaxy M82

Can CRs drive a Galactic wind?

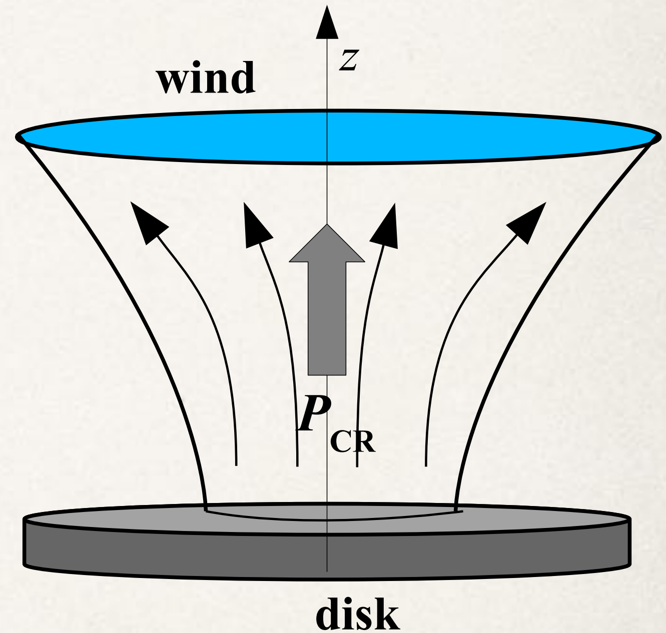
[Breitschwerdt, McKenzie & Vòlk (1993),
Everett & Zweibel (2011),
Recchia, Blasi, GM (2016)
Pakmor, Pfrommer et al. (2016)]

- CRs behave as a relativisic gas ⇒ pressure drops less than thermal pressure ⇒ **can drive a wind**

- Properties of the wind can explain the hot baryionic halo around Milky Way
  - Wind speed increases up to ~ few 100 km/s
  - The magnetic turbulence cascade can increase the wind temperature up to 10^6 K

- Wind can produce a mass loss rate ~0.5 $M_\odot$/yr
  - ⇒ in agreement with star formation models
  - ⇒ in agreement with the Halo metallicity > 0

- The CR halo ends where advection dominated over diffusion ⇒ **energy dependent halo size**



Conclusions

ACCELERATION

- DSA is a well developed theory but we need to account for different ambient media where SNRs expand
- Strong evidence for magnetic field amplification induced by CRs
- Lack of PeVatrons

ESCAPING

- Escaping process is a key issue and is not undestood yet.
- Possible way to study it
    - Emission from molecular cloud close to SNR
    - Contribution of escaping particles to diffuse γ-ray emission

PROPAGATION IN THE GALAXY

- We still lack of a realstic description of Galactic propagation
- Going beyond the simple view of the leaky-box model is required by data
    - Self-generated turblence produced via streaming instability could play a major role for the propagation of CRs with E <~ 100 GeV
    - CR pressure could drive a Galactic wind

Some anomalies in the CR composition

Low energy CR (~100 MeV/nucleon) give contradicting information

$$\left(\frac{^{22}Ne}{^{20}Ne}\right)_{CR} \simeq 5\left(\frac{^{22}Ne}{^{20}Ne}\right)_{Sol}$$

→ Preferential acceleration of wind material in massive stars

Prantzos, *A&A* 538 (2012)

Binns et al., ApJ 634, (2005)
ACE-CRIS collaboration

$$\left(^{60}Fe\right)_{CR} \simeq 500\left(^{60}Fe\right)_{ISM}$$

→ Requires acceleration of ejecta material in SNRs (possible role of reverse shock?)

Binns et al., Science 352, (2016)
ACE-CRIS collaboration

It is not clear how to combine these two constraints

1-D slab model with self-generated turbulence

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

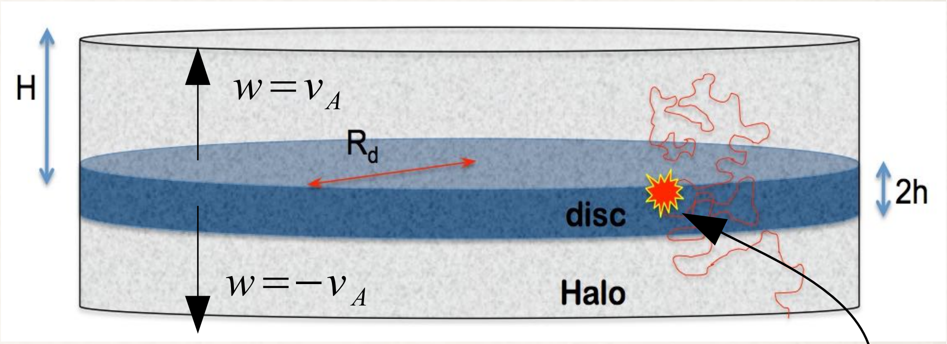
- CR escaping from the Galactic plane produce magnetic turbulence through resonant streaming instability

$$\Gamma_{cr} = \frac{16\pi^2}{3}\frac{v_A}{\mathcal{F}(k)B_0^2}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{p=eB_0/kc}$$

- Turbulence scatter CRs (mainly) along large scale mag. field lines with Bohm-like diffusion coefficent

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

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



Spectrum injected at the disk

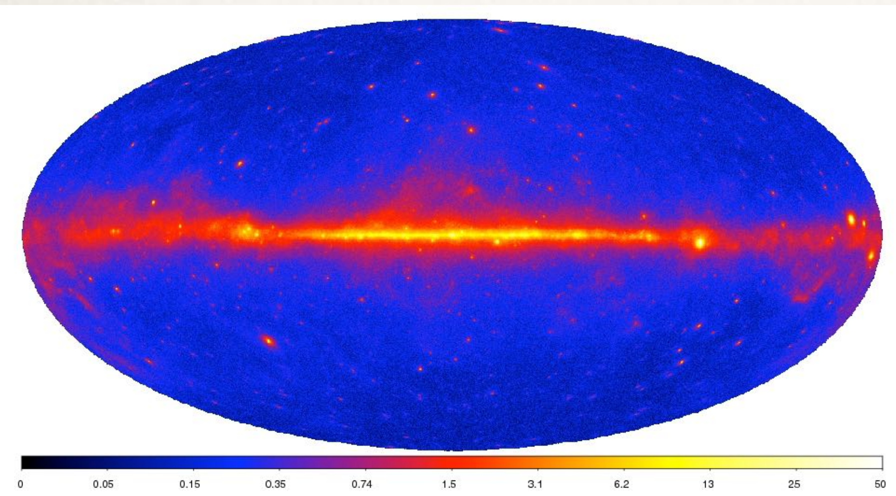
$$Q_0(p,R) \propto N_{SNR}(R)\, p^{-\gamma}$$

Propagated spectrum in the disk

$$f_{disk}(p) \propto p^7\left(\frac{Q_0(p,R)}{B_0(R)}\right)^s; \qquad s=1\div 3$$

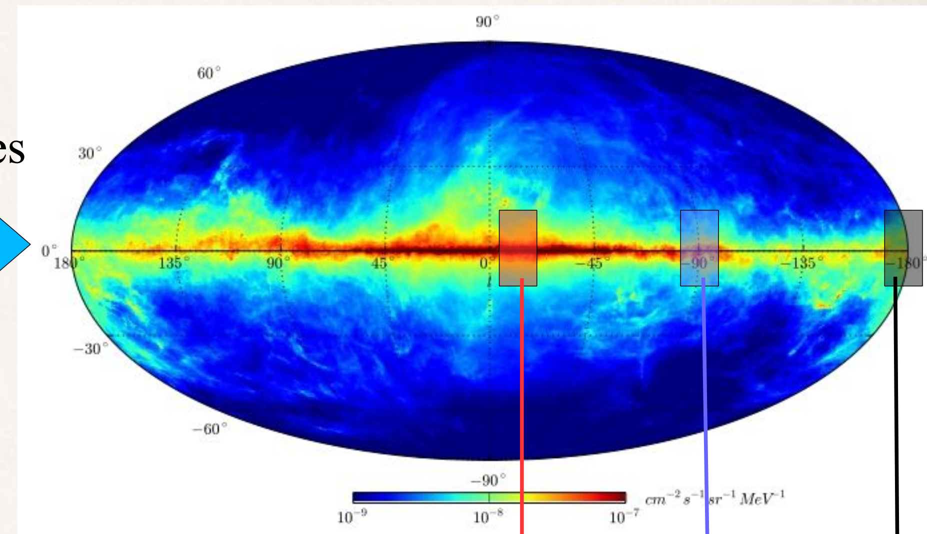
Using the diffuse Galactic γ-ray emission

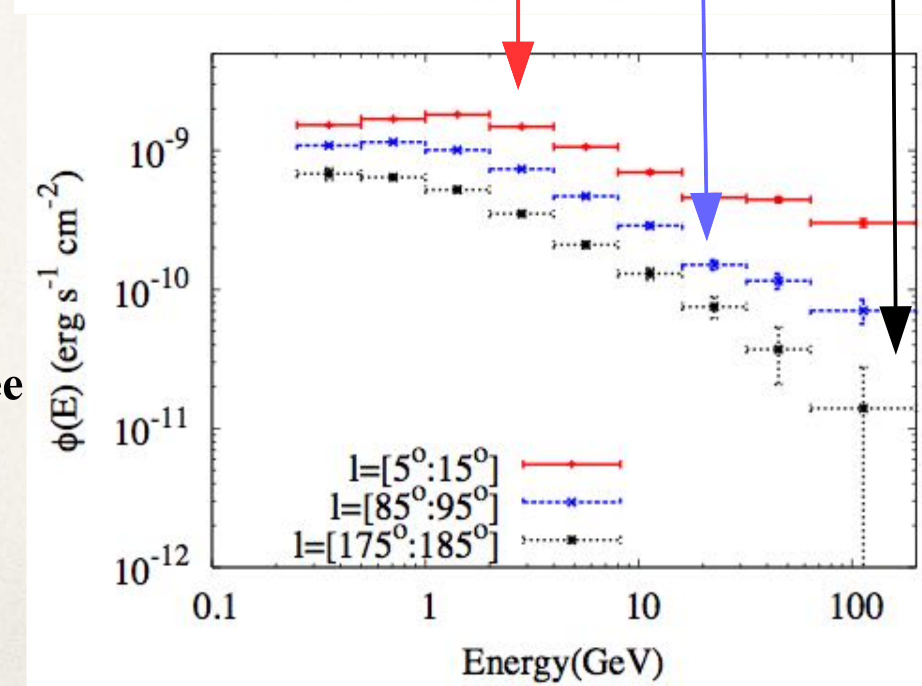
FermiLAT all sky map



Subtracting
known sources

FermiLAT diffuse emission





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

Comparison between Fermi-LAT data analized by Yang et al. (2016) and theoretical prediction [M. D'Angelo, GM, P. Blasi (2017)]

Distribution of SNR in the galactic plane during the last ~10^5 yrs using a rate of 1 SN/(30 yr)

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