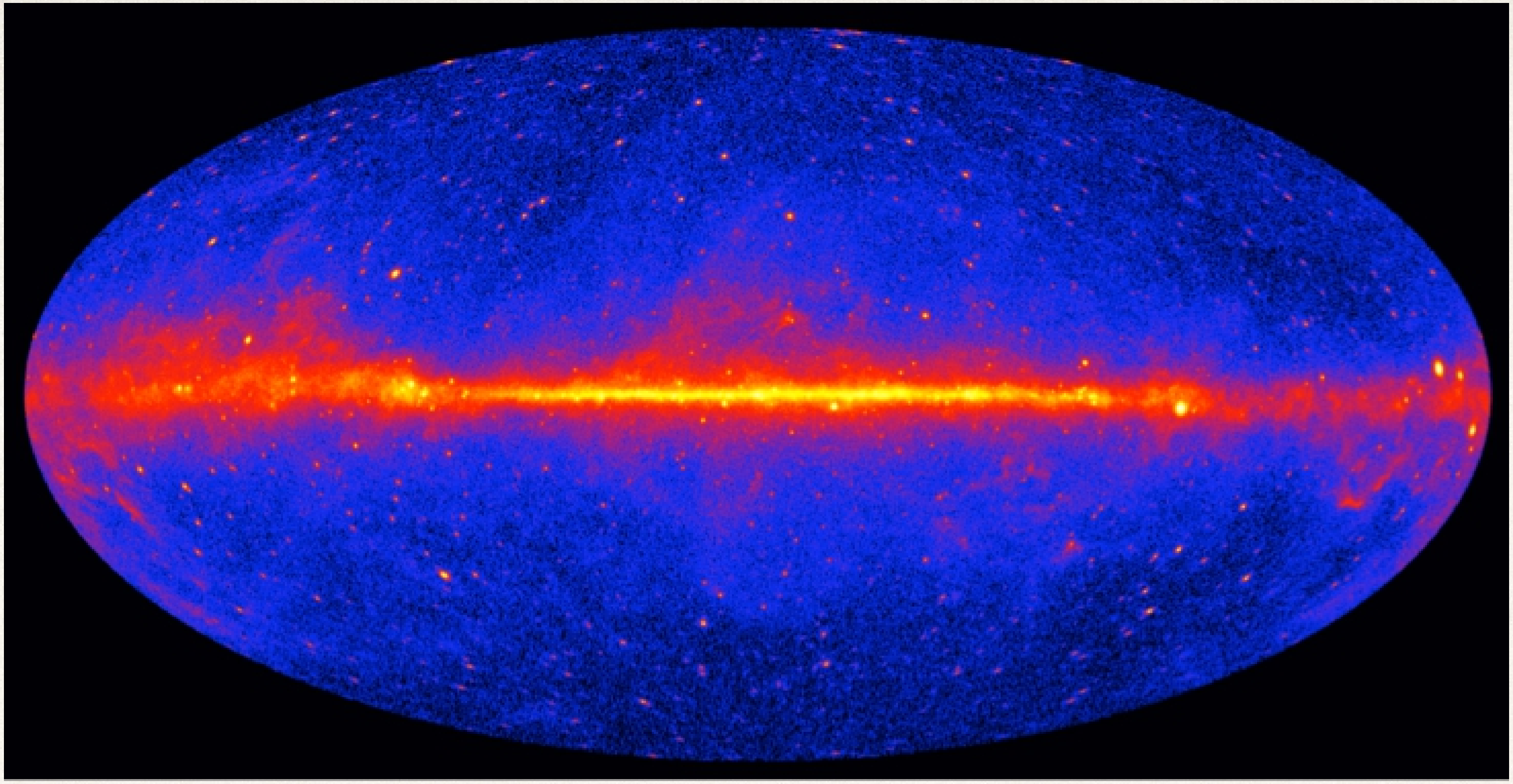


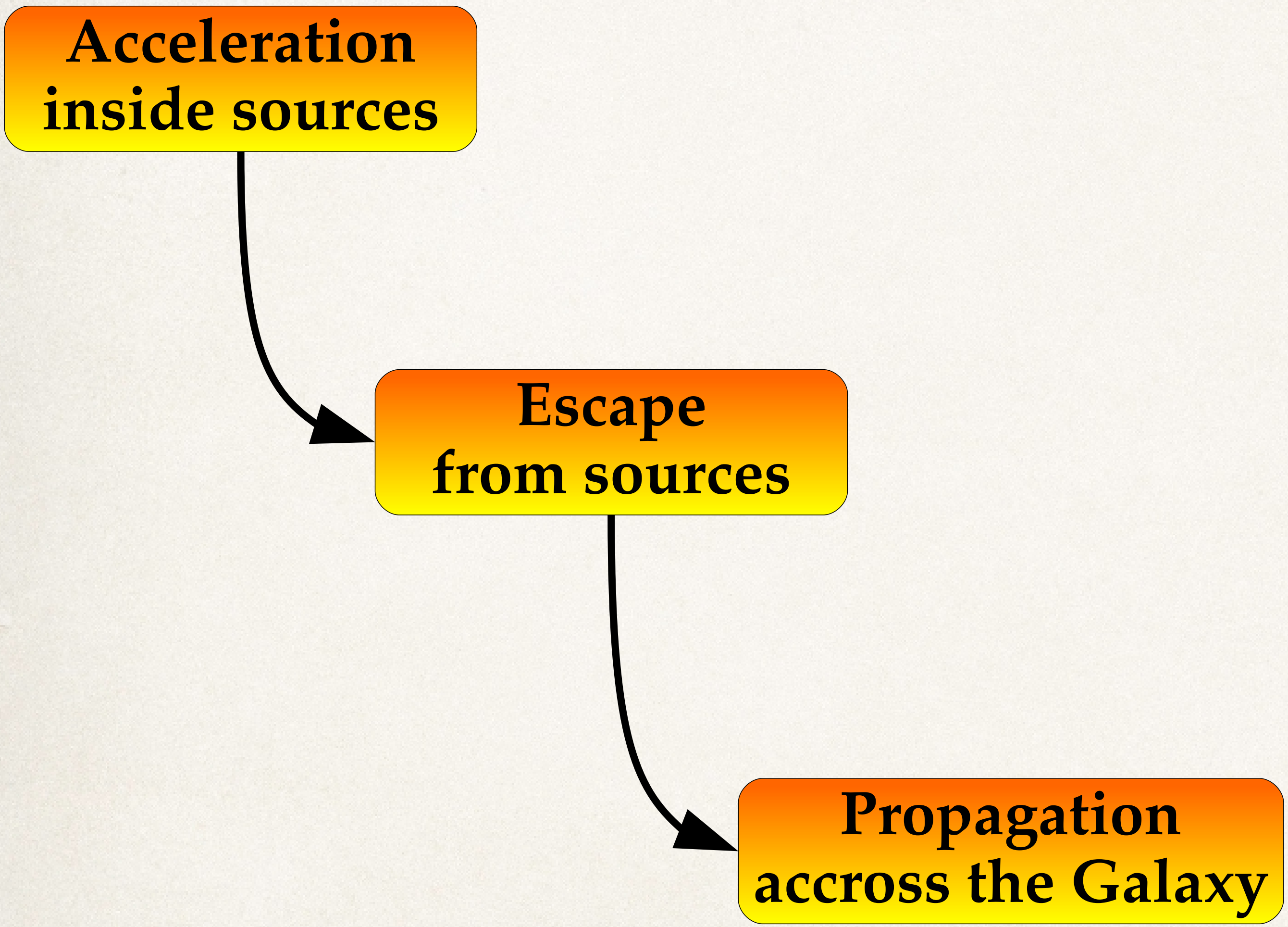
CR origin and propagation in the Milky Way

Giovanni Morlino,

Gran Sasso Science Institute, L'Aquila, ITALY

"4th Cosmic Ray Anisotropy Workshop" — October 11, 2017 — Guadalajara,Jalisco, MEXICO

The path to became a cosmic ray



The path to became a cosmic ray

Acceleration inside sources

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

Escape from sources

- Self confinement around the sources
- Interaction with molecular clouds
- Anisotropy from local sources

Propagation accross the Galaxy

Diffusive shock acceleration

Diffusive Shock Acceleration (DSA) predicts:

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

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

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

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

Strong dependence on magnetic field

Weak dependence on the ejecta mass and ISM density

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

$\mathcal{F}(\boldsymbol{k}) = (\delta B/B_0)^2 >> 1$.

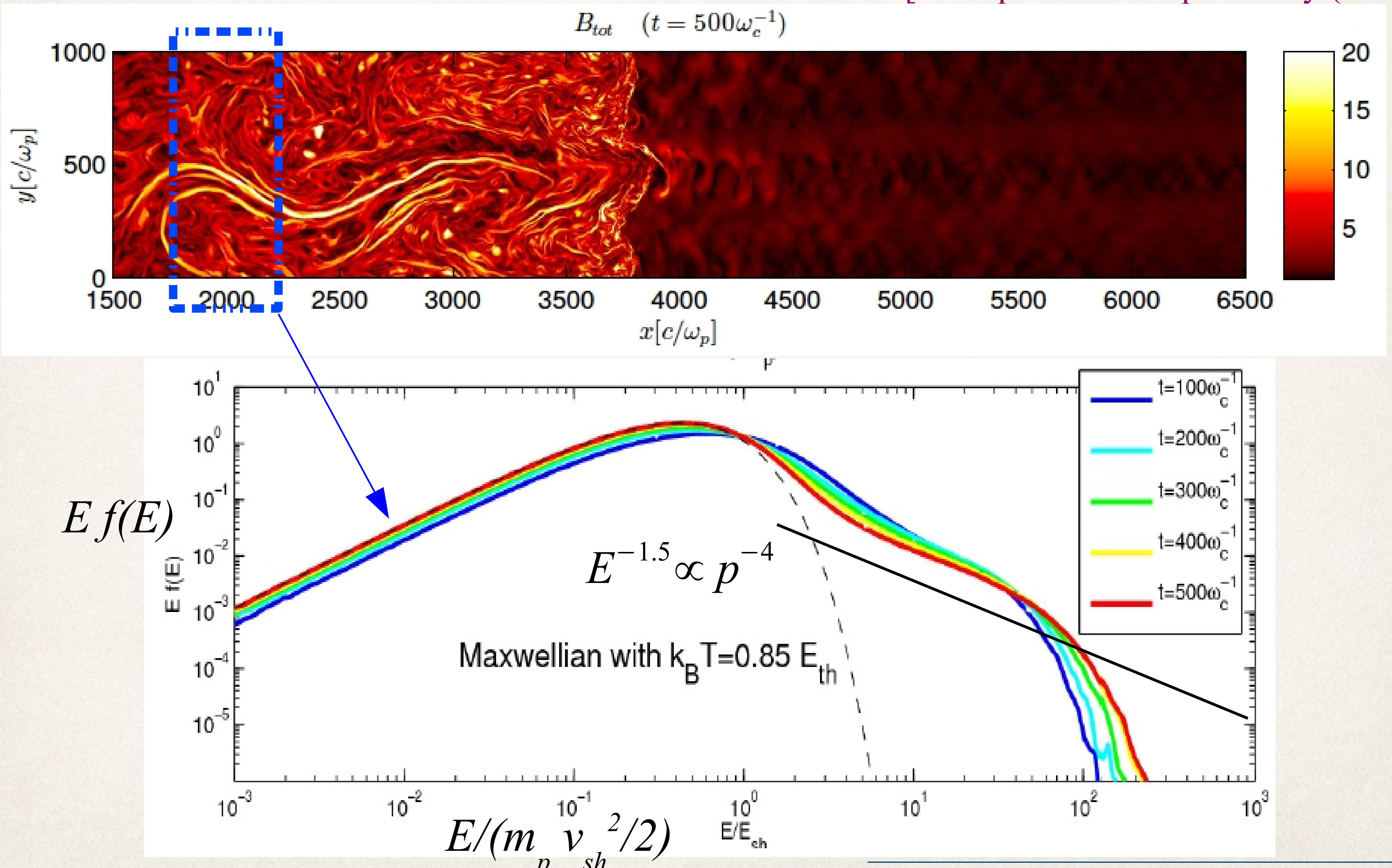
This condition requires amplification of the magnetic field

Fermi acceleration at work

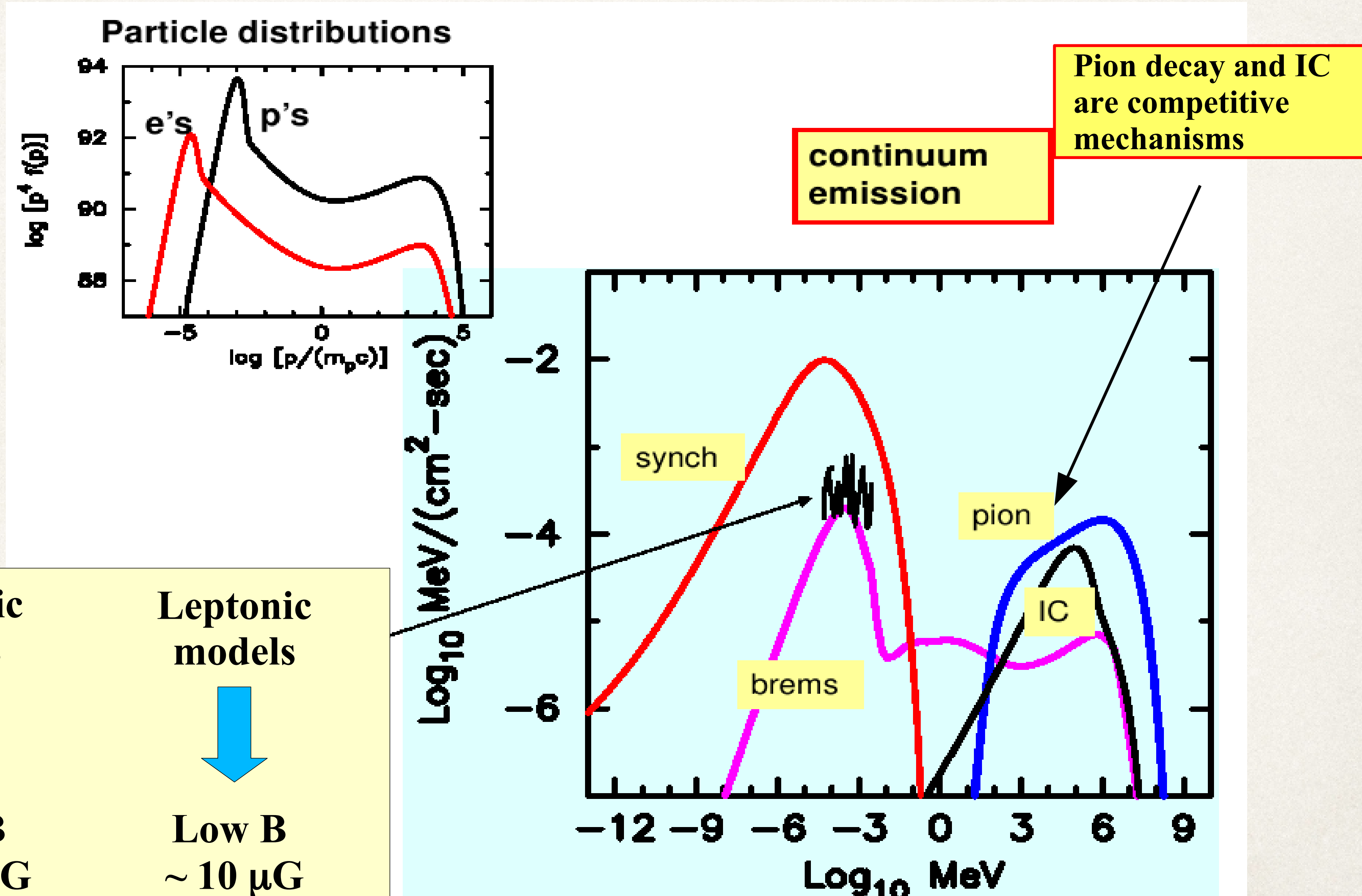
[From Gargaté & Spitkovsky (2013)]

PIC simulation of particle acceleration

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

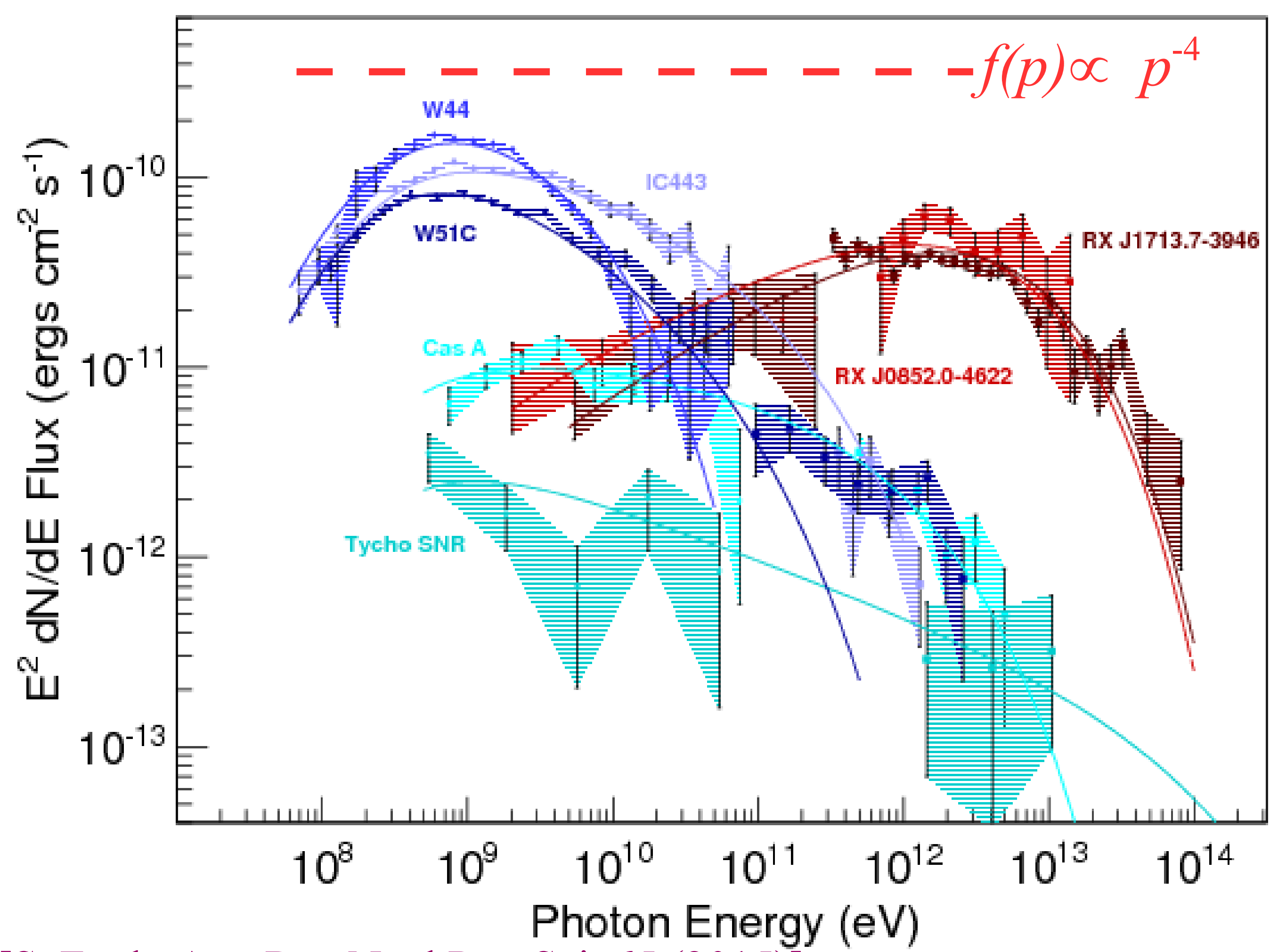


Non-thermal spectrum from SNRs



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

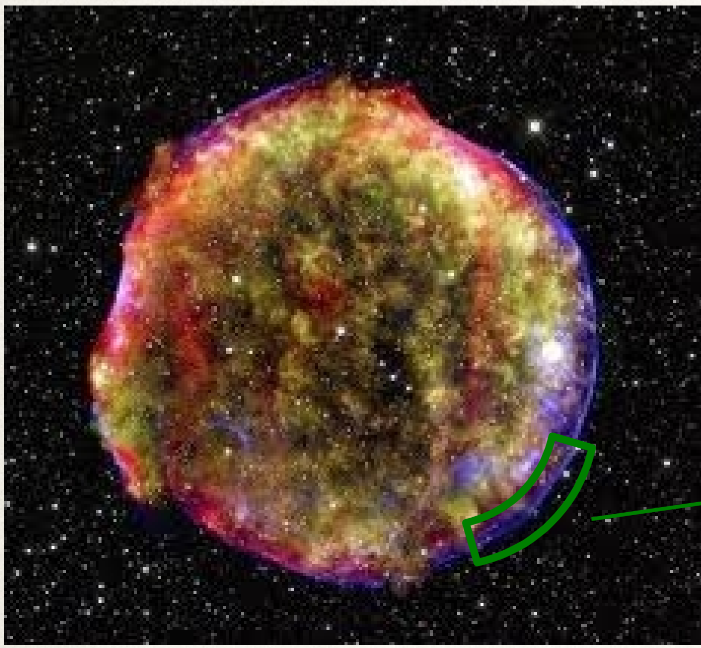
Very young SNRs (~300 yr)

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

Not enough to explain the Knee at ~ PeV

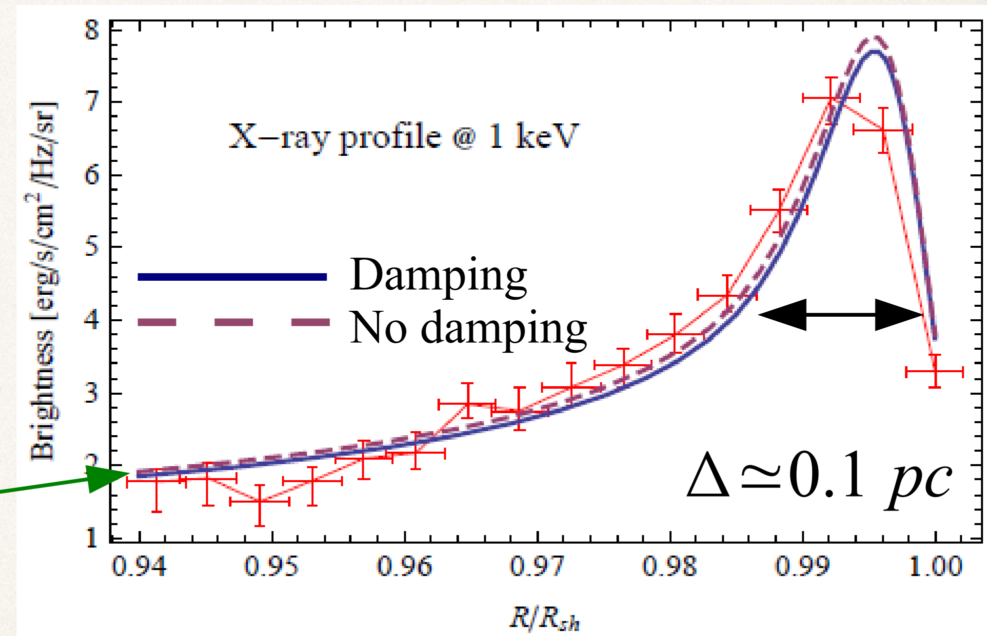
Magnetic field amplification: observations

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)]



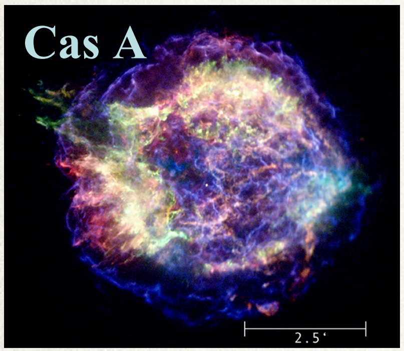
$$\begin{cases} D = r_L c/3 \propto E\,B^{-1} \\ \tau_{syn} = \dfrac{3\,m_e c^2}{4\,\sigma_T c\,\gamma\beta^2 U_B} \propto E\,B^{-2} \end{cases}$$

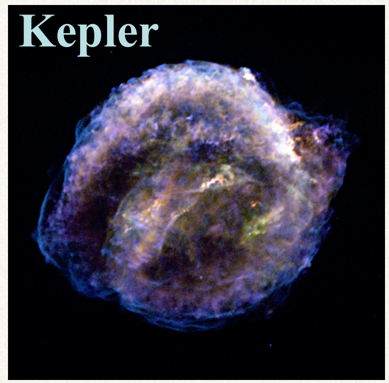
$$\Delta \simeq \sqrt{D\,\tau_{syn}} \propto B^{-3/2}$$

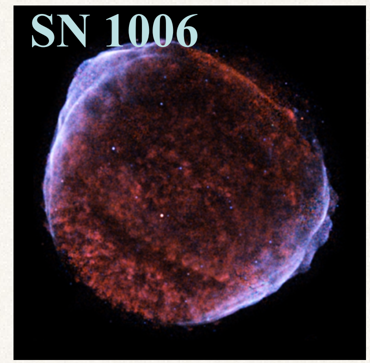
***B*~200-300 μG >> *B*$_{\text{ISM}}$**

Magnetic field amplification: observations

Thin X-ray rims (~0.1 pc) are observed in almost all young SNRs







Magnetic pressure downstream can reach ~few% of total pressure

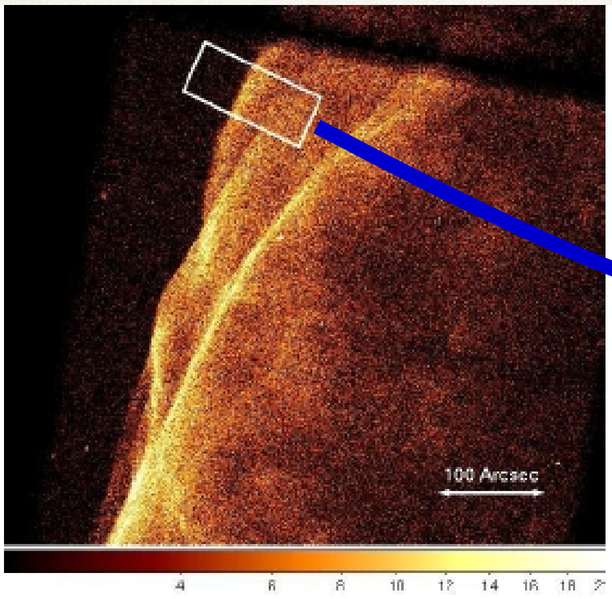
SNR	B_{down} (μG)	$B^2_{down}/(8\pi p)$ [%]
Cas A	250-390	3.2-3.6
Kepler	210-340	2.3-2.5
Tycho	240-530	1.8-3.1
SN1006	90-110	4.0-4.2
RCW 86	75-145	1.5-3.8

Where is the magnetic field amplified?

DOWNSTREAM: MHD instabilities (shear-like)

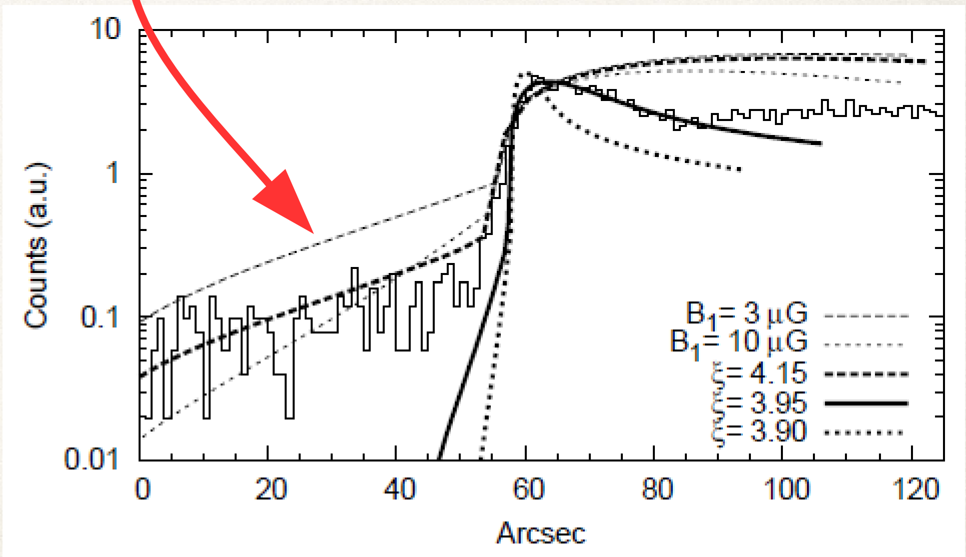
UPSTREAM: only through instabilities driven by CRs (Streaming, Bell)

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



SN1006 in X-rays (*Chandra*)

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



[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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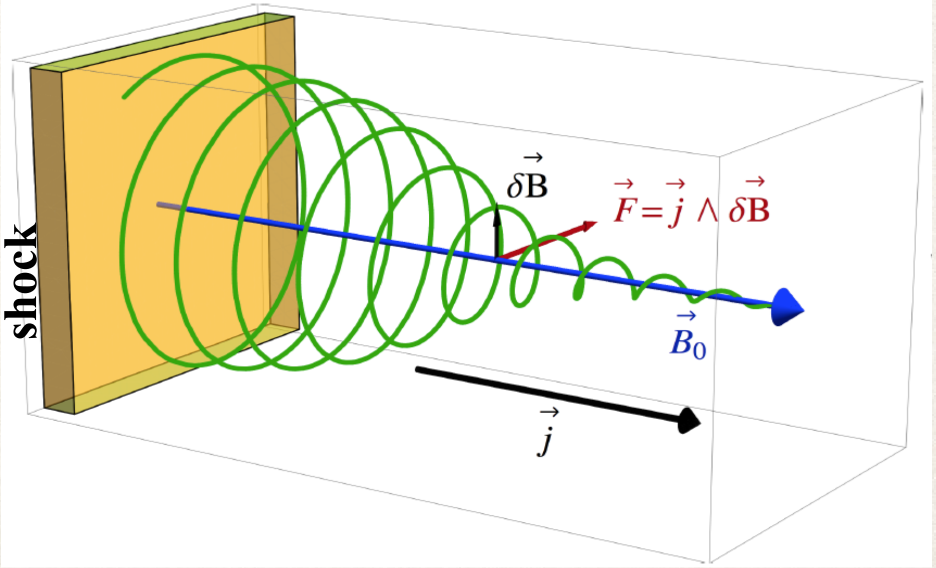
Non-resonant *Bell* instability

[Bell (2004)]

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

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



Magnetic field amplification: Theory

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

A factor 10 below the knee

Non-resonant
***Bell* instability**

[Bell (2004)]

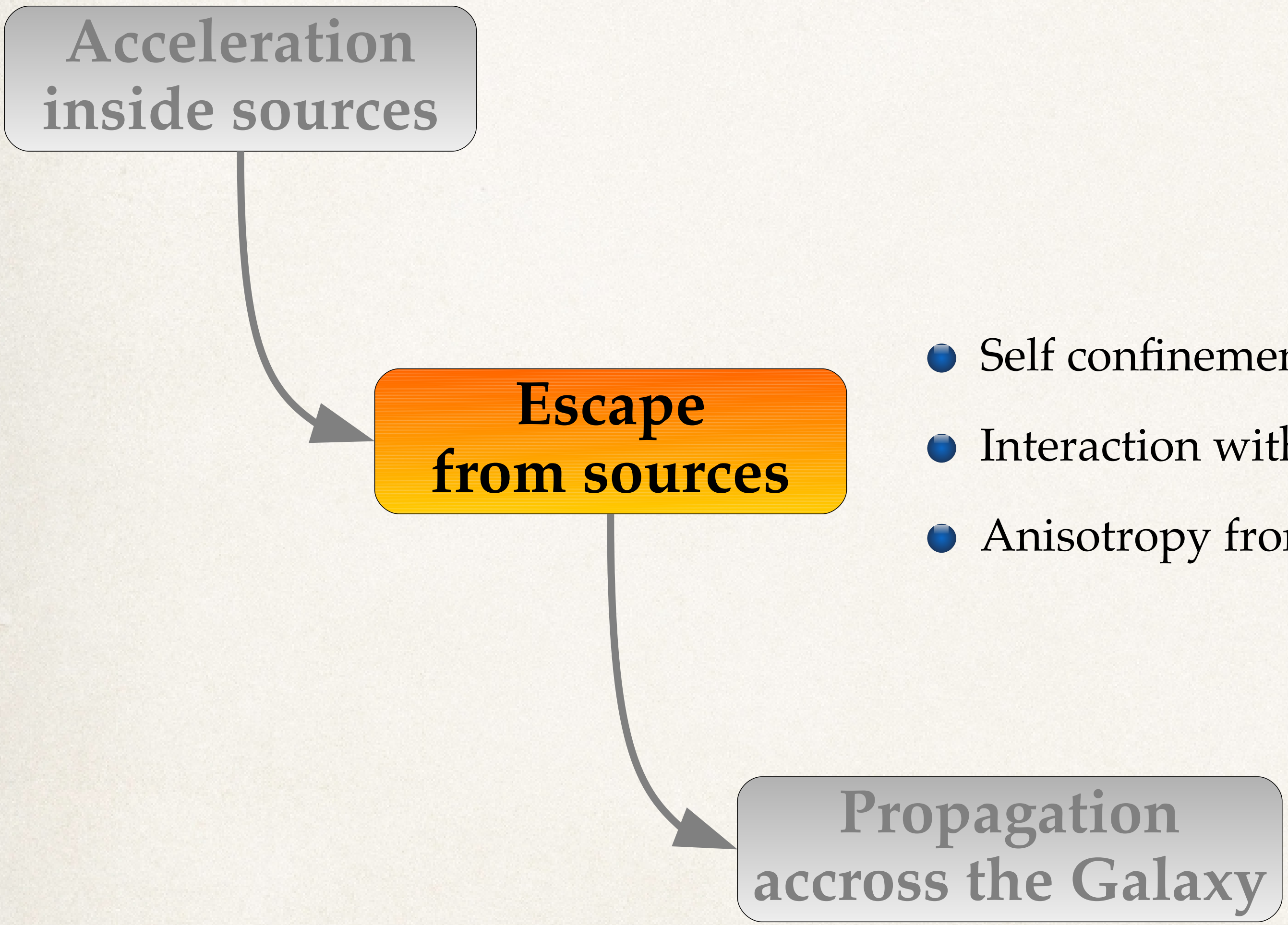
$E_{max} \propto \sqrt{\rho_{CSM}}$

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



- Self confinement around the sources
- Interaction with molecular clouds
- Anisotropy from local sources

Particle escape from SNRs

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

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

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

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

- Expantion 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!

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 $\sim 10^5$ yr

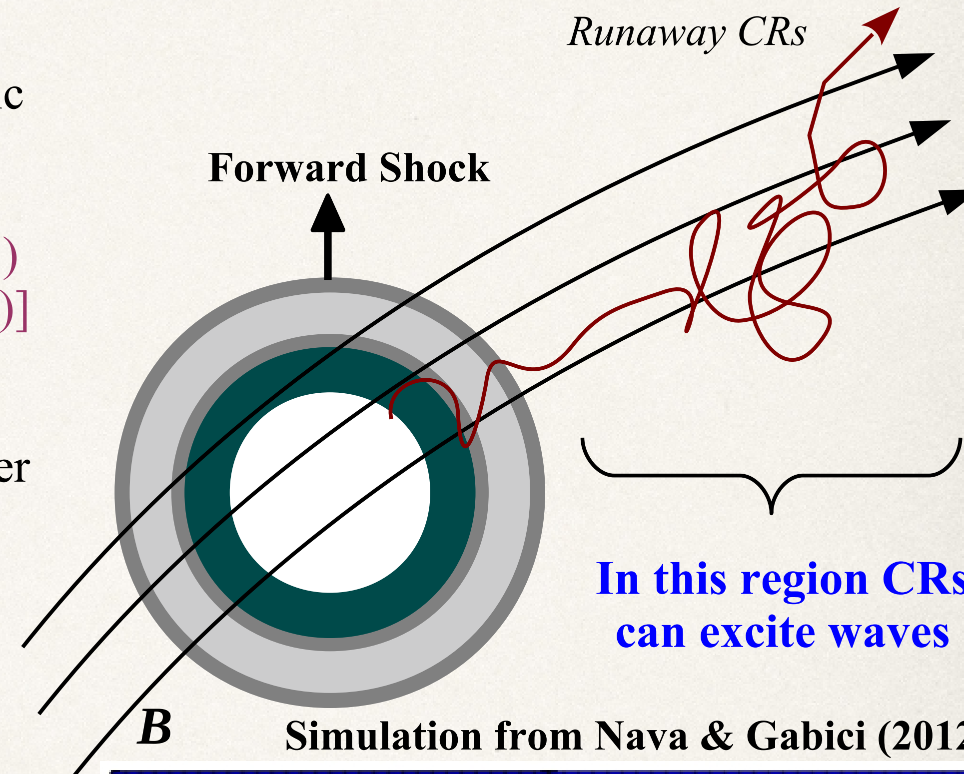
[Malkom et al. (2013)
Nava et al. (2015)]

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)

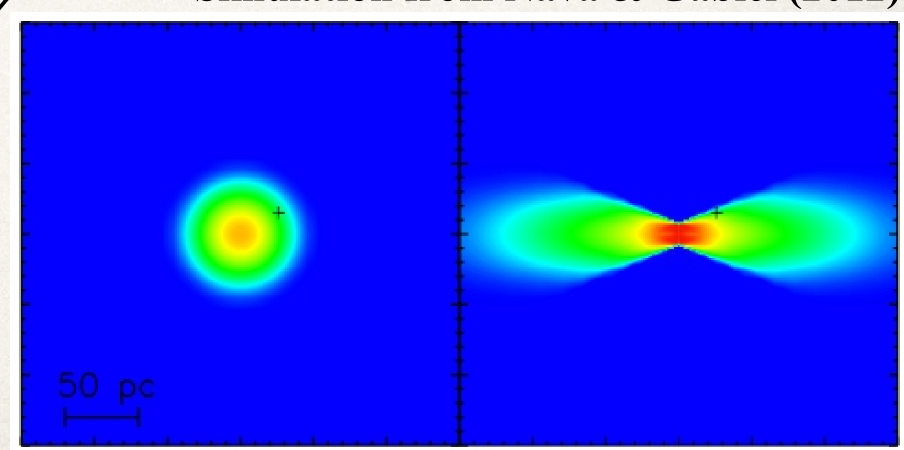
During the time CR spend in the vicinity of sources they can:

1) accumalate grammage

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



Simulation from Nava & Gabici (2012)



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

[D'Angelo, GM, Amato, Blasi, 2017, *submitted*]

CR transport equation in 1-D

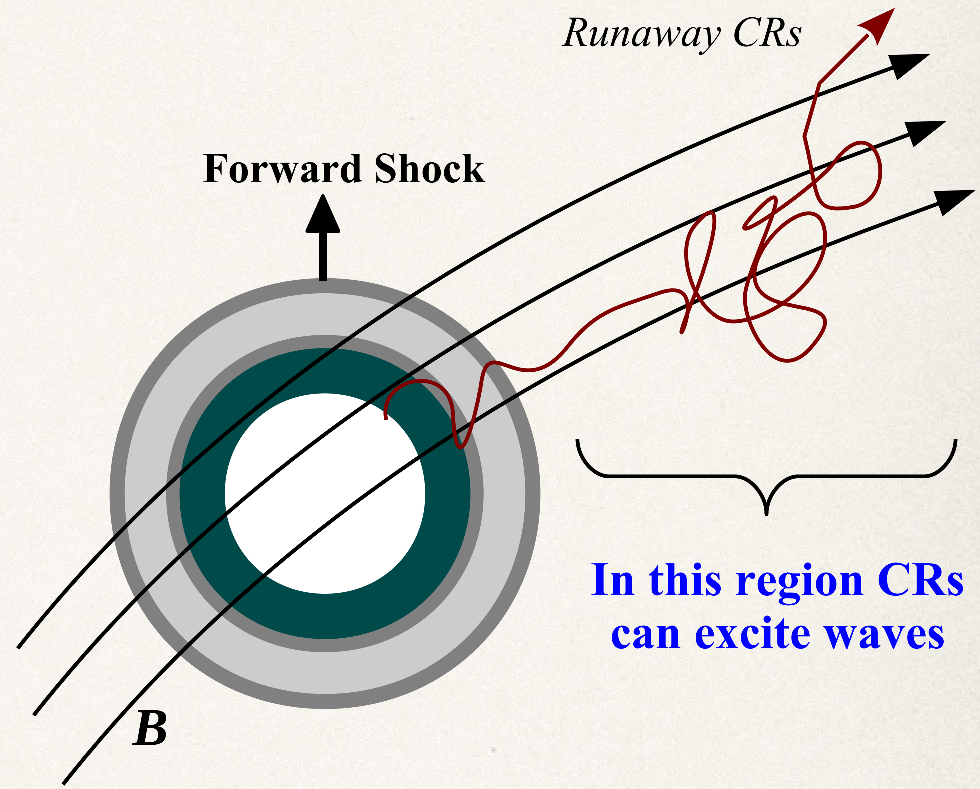
$$\frac{\partial f}{\partial t} + v_A \frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D \frac{\partial f}{\partial z}\right]$$

Self-generated diffusion coefficient

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

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

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:

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

Evolution of CR density close to the source

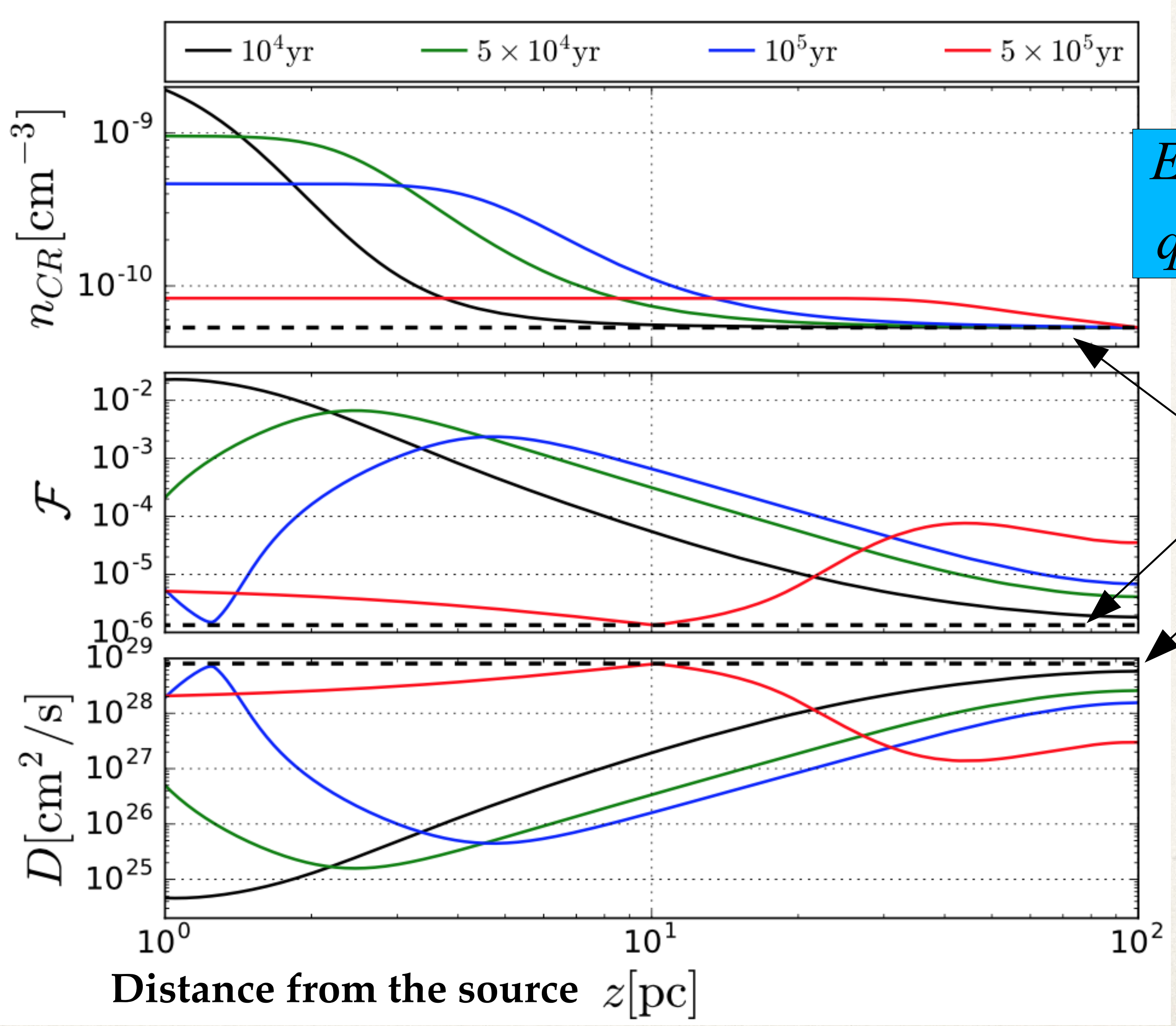
[D'Angelo, GM, Amato, Blasi, 2017, *submitted*]

CR distribution function @ 10 GeV for several ages

Distribution function of turbulence

Diffusion coefficient

$$E_{CR} = 0.2\, E_{SN}$$
$$q_{inj}(p) \propto p^{-4}$$

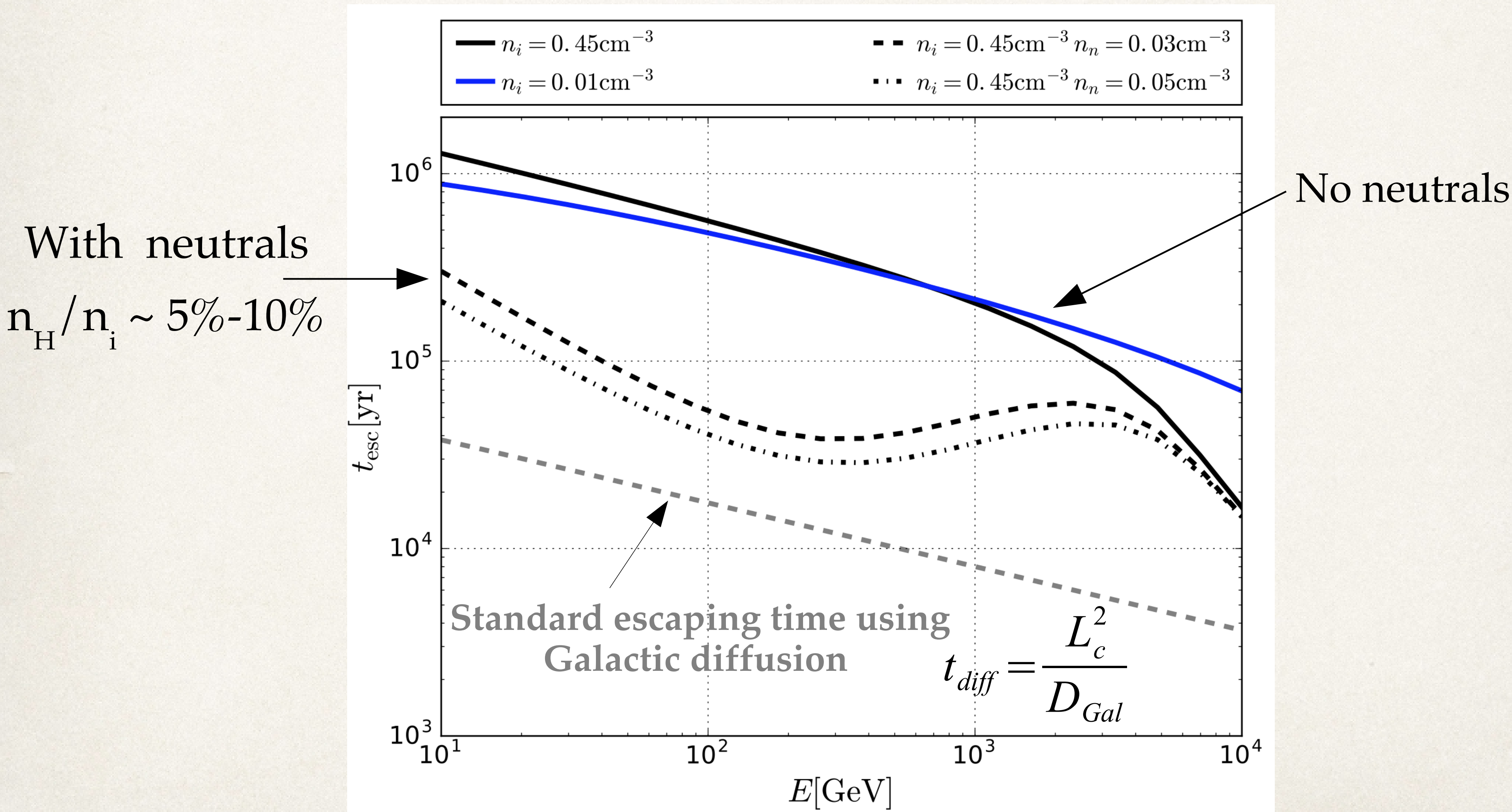


Average Galactic level

Escaping time from the near-source region

[D'Angelo, GM, Amato, Blasi, 2017, *submitted*]

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

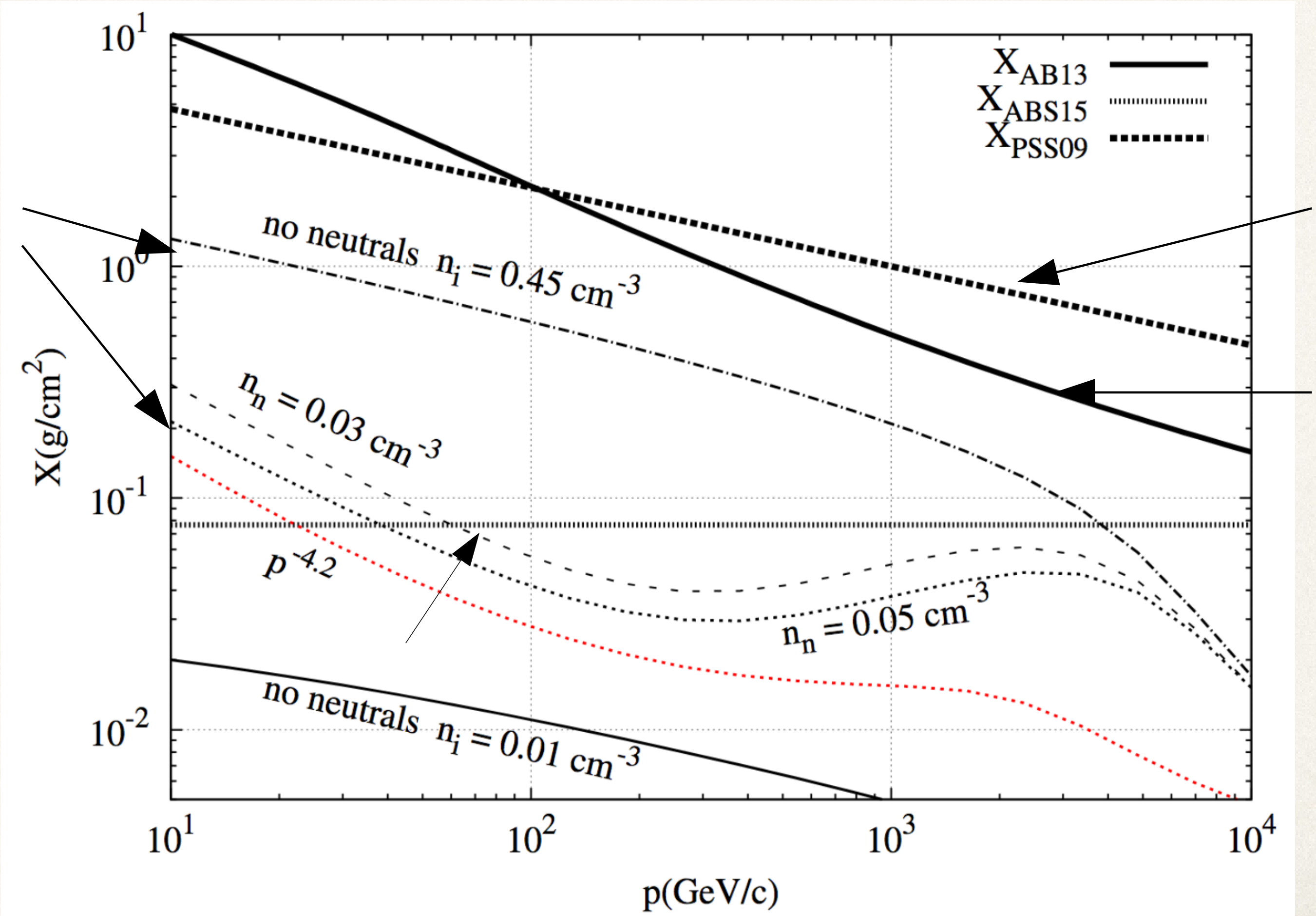


Grammage in the near-source region

[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:

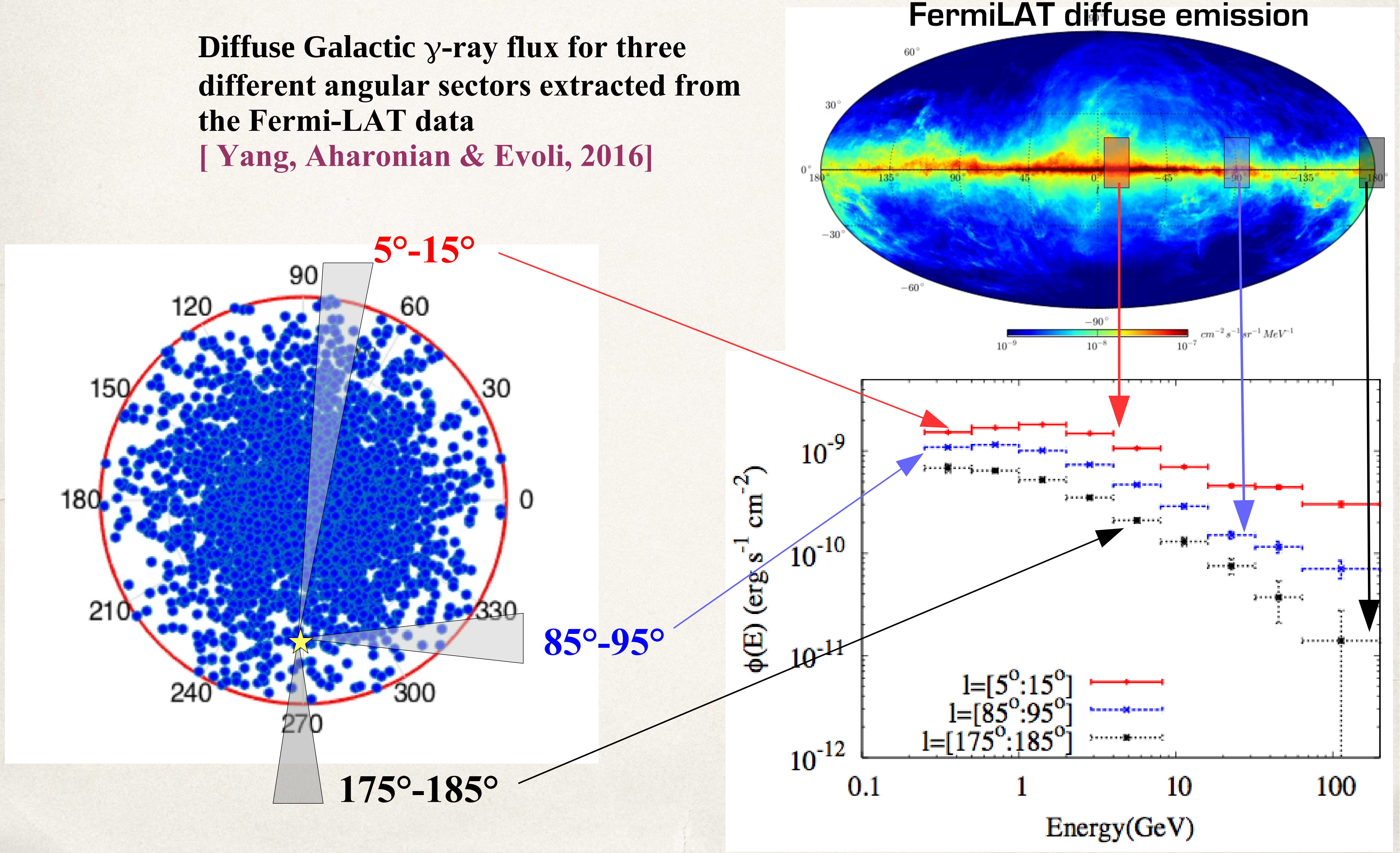
1) Standard halo model

2) Non-linear propagation

Diffuse Galactic emission from *Fermi*-LAT

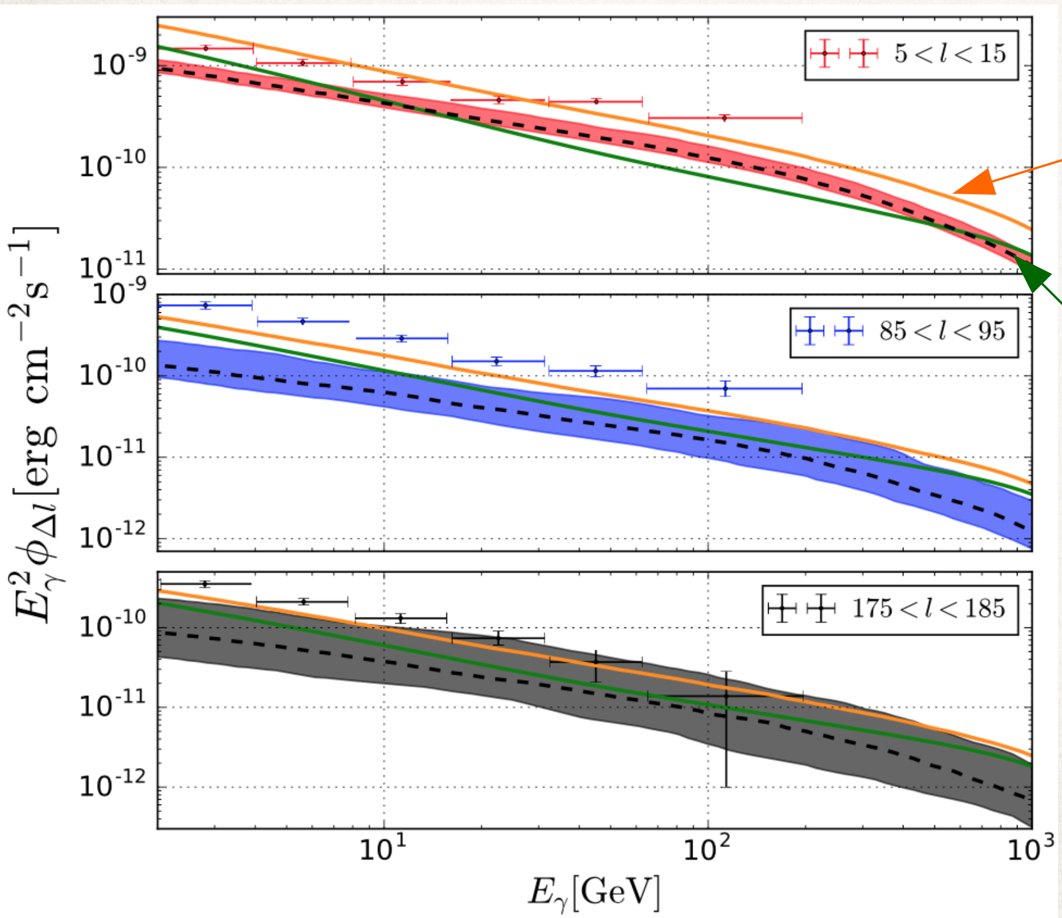
[D'Angelo, GM, Amato, Blasi, 2017, *submitted*]

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, 2017, *submitted*]

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



Sum of diffuse emission plus contribution from all the source cocoons

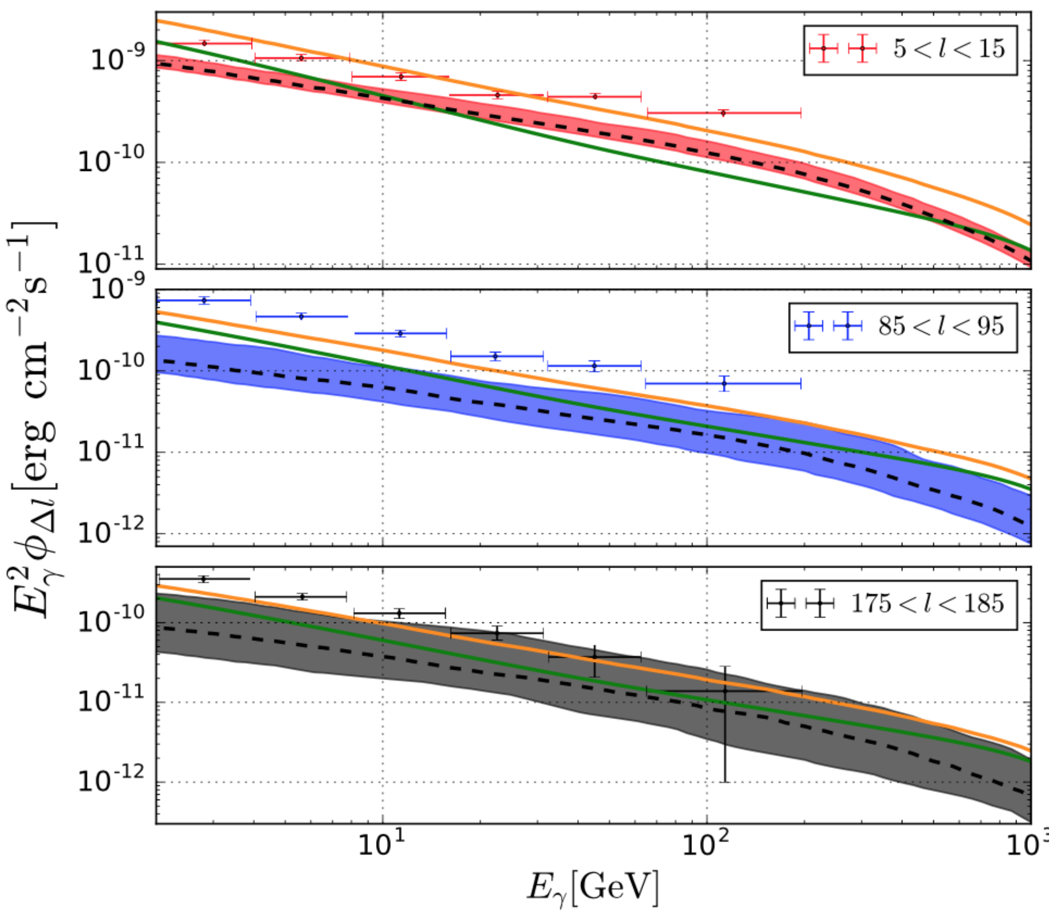
"Real" diffuse contribution assuming AMS spectrum in the whole Galaxy

Contribution of the escaping CRs to the diffuse Galactic emission [D'Angelo, GM, Amato, Blasi, 2017, *submitted*]

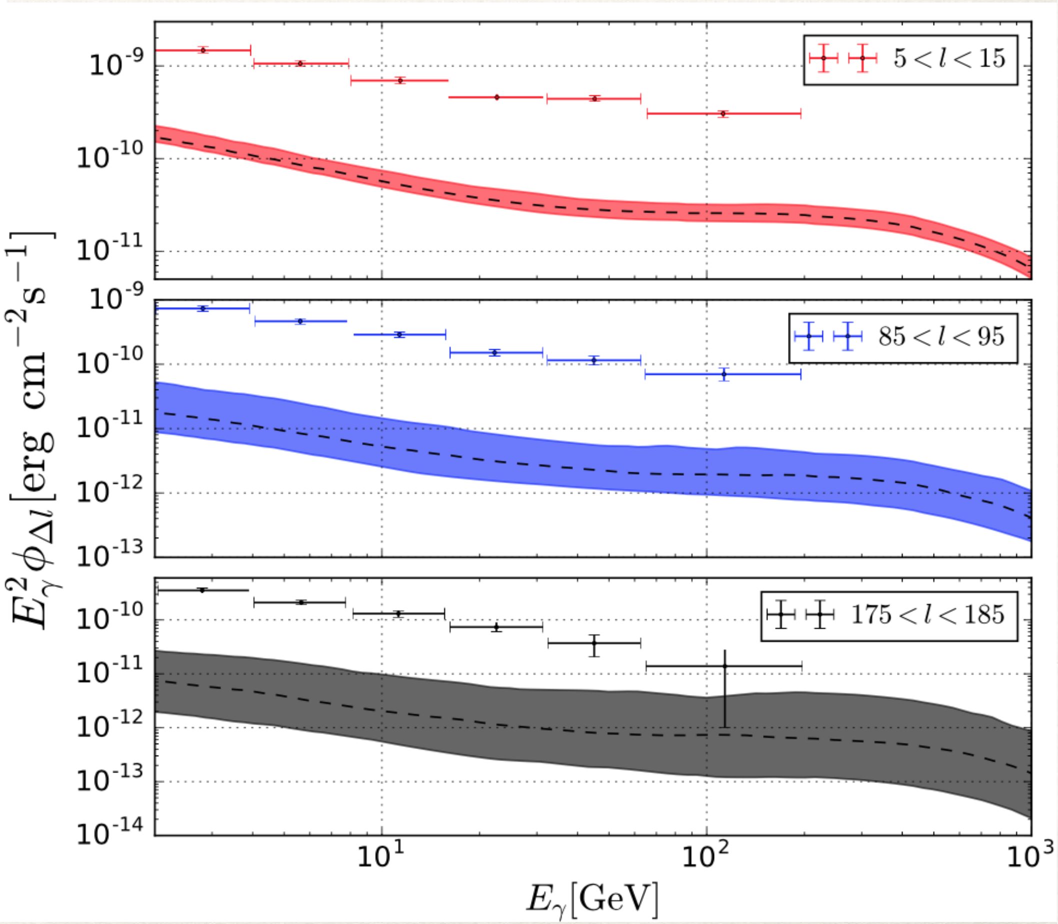
Number of sources contributing to the emission

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

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



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

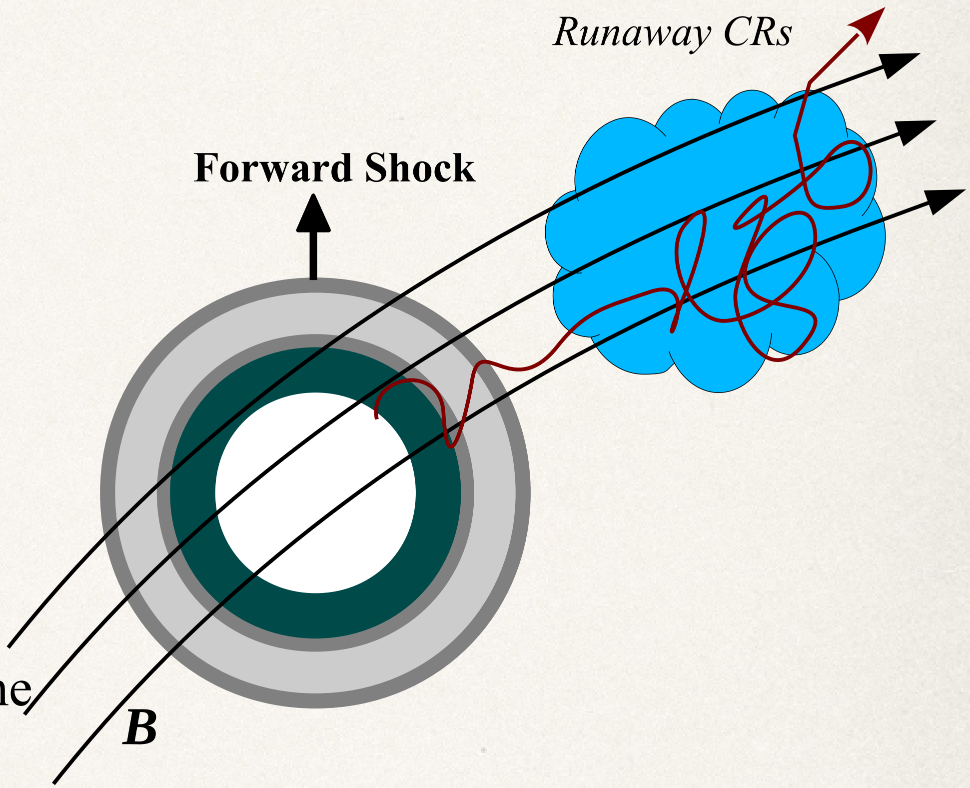


Presence of Molecular Clouds near the source

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

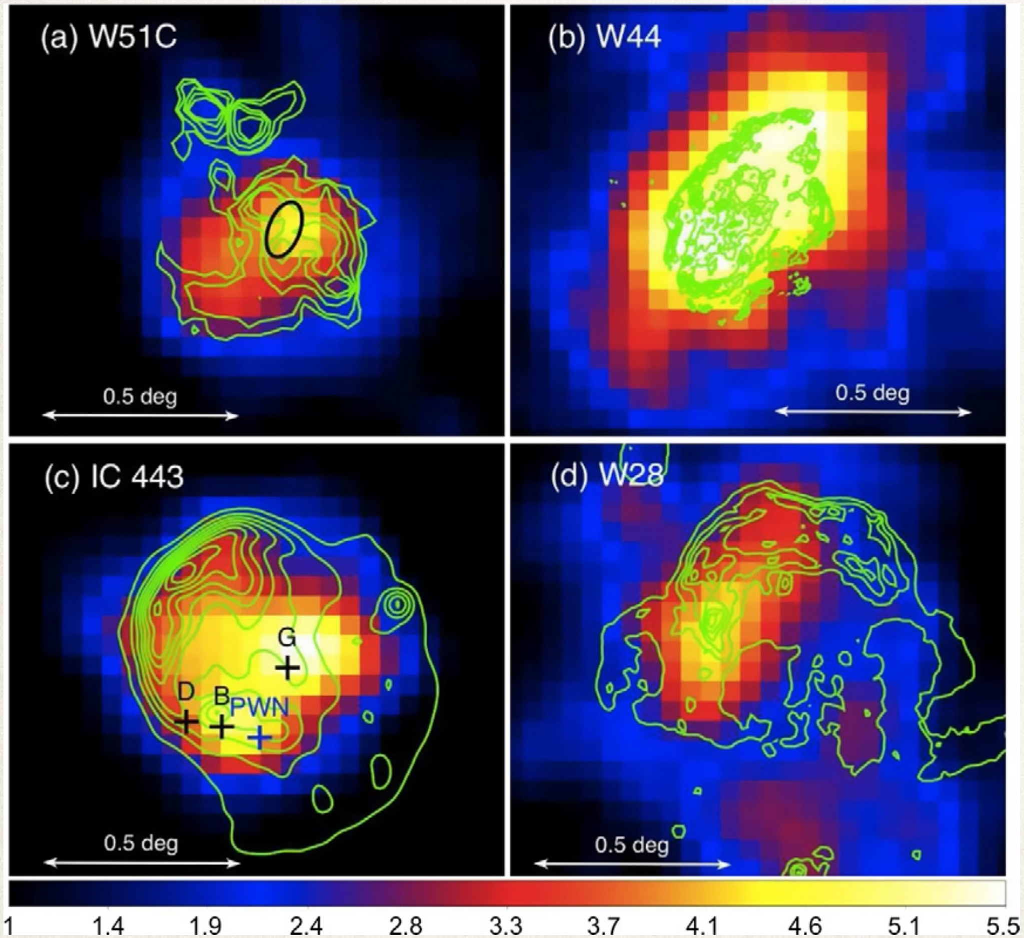


Is it possible to accumulate all the grammage in the near source region?
This possibility would support unorthodox models for the CR propagation

- **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]



OBSERVATIONS of MCs in γ-RAYS:

- 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

DETECTION OF IONIZATION

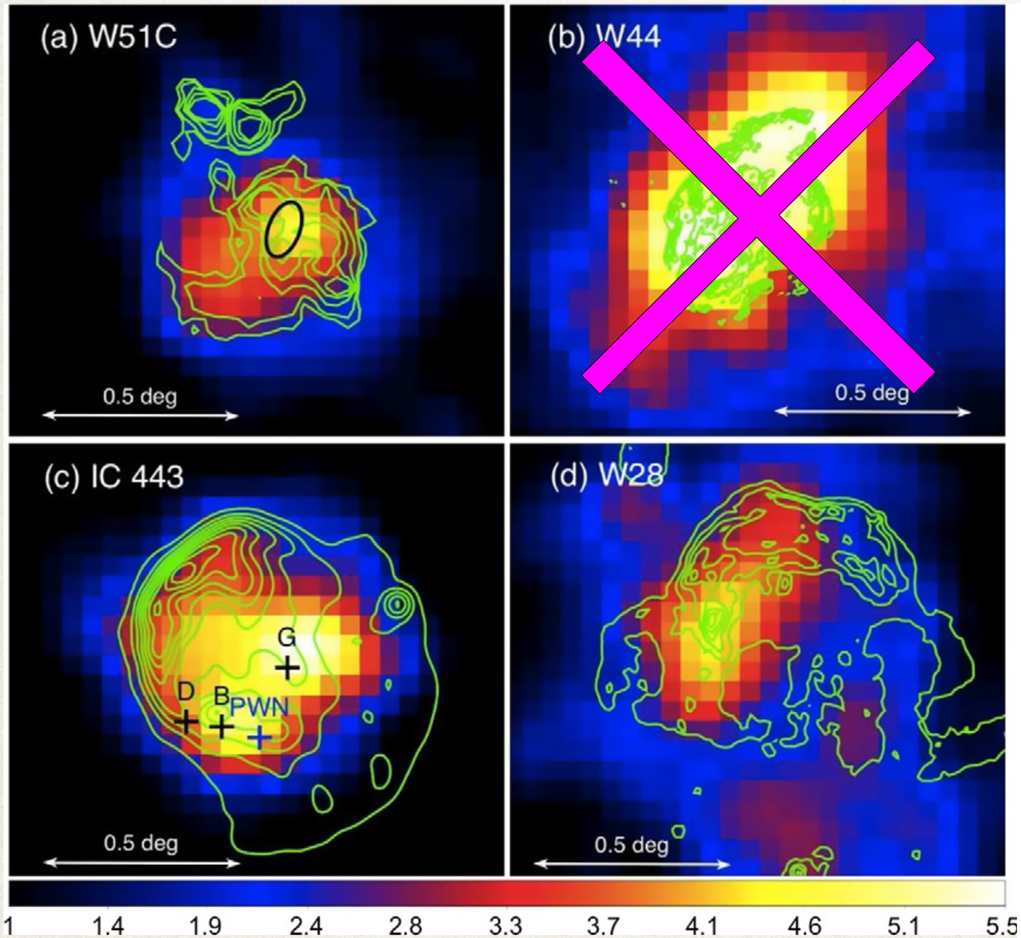
- The ionization rate of several molecules depends on the CR flux (H_2, H_3^+, CH, OH, C_2, DCO^+, HCO^+,......)

- 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

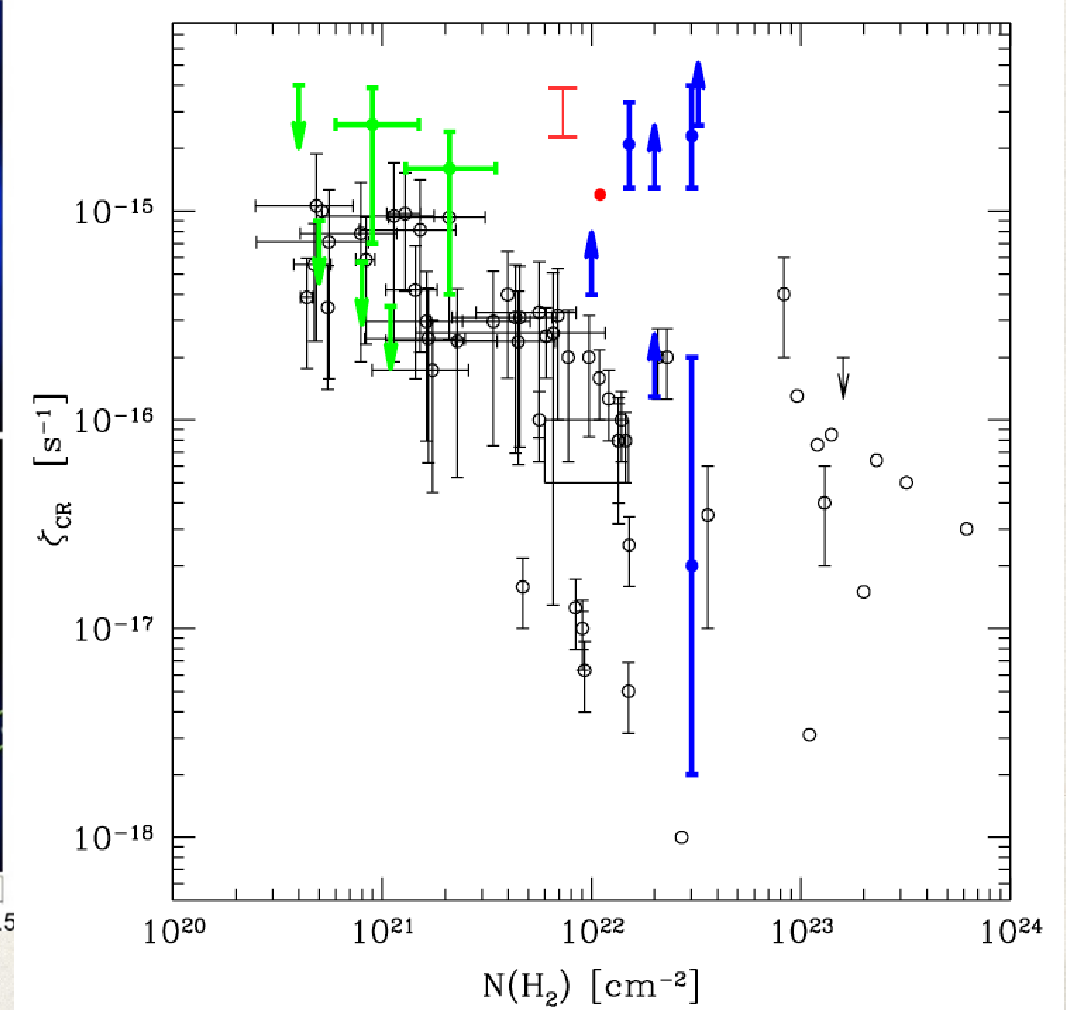
Using molecular clouds as CR barometer

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



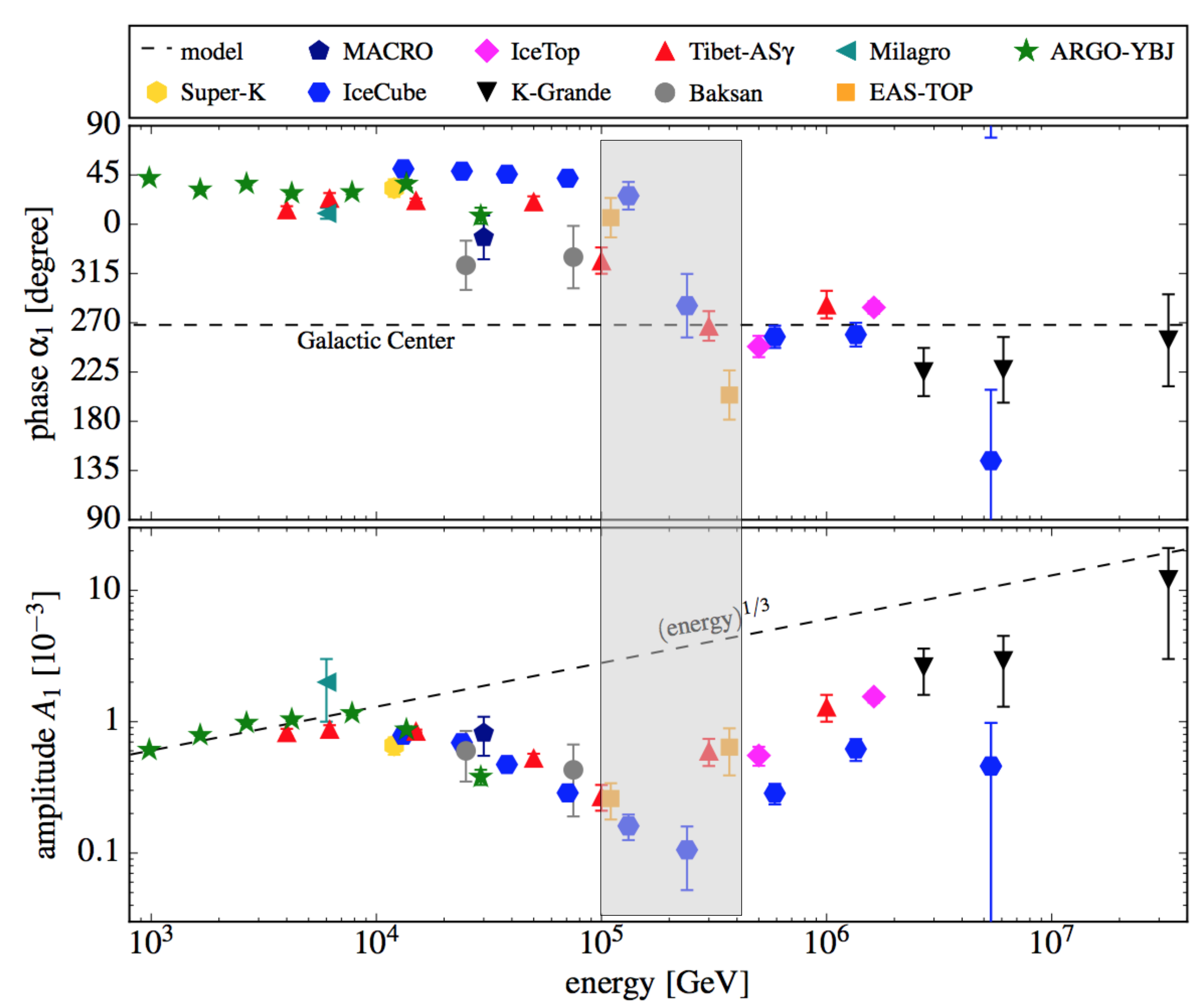
Average level of ionization is lager for MCs close to SNRs

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



Possible effect on anisotropy

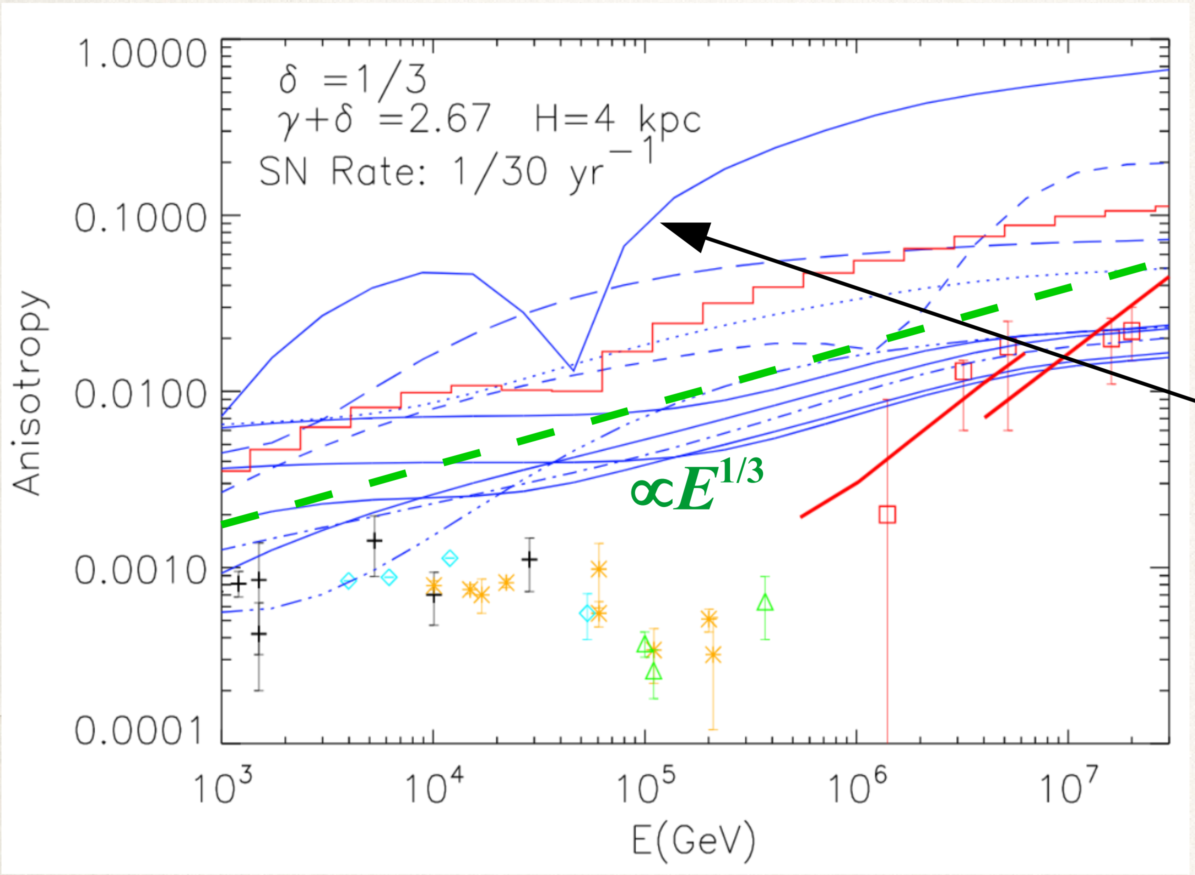
From Ahlers & Mertsch (2016)



The phase transition occurs where the amplitude changes behaviour

Can this be explained with the dominance of a local source?

Anisotropy from randomly distributed sources



[Amato & Blasi, 2012]

Anisotropy produced by different realization of randomly distributed sources in the Galaxy

- Single local sources can produce bumps in the anisotropy but gives higher ampilitude

$$\delta = \frac{3D}{c}\frac{\nabla n}{n}$$

$$D(E) = 3\times 10^{28}\left(\frac{E}{GeV}\right)^{1/3}$$

Local *D* assumed to be equal to the average Galactic *D* obtained fromm B/C

Anisotropy from a single local source

- Local SNe 2-3 Myr ago required by ^{60}Fe sediments in Earth crust

- Estimated distance ~50-100 pc

[Savchenko, Kachelriess, Semikoz ’15]

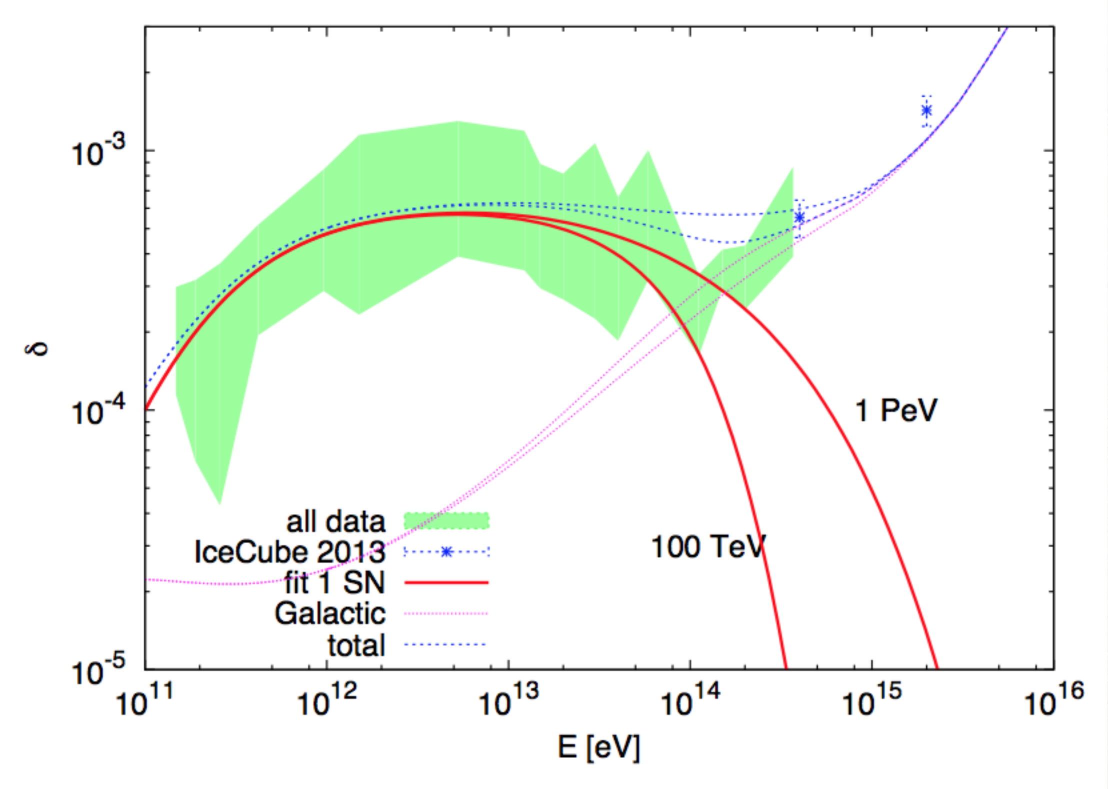
Anisotropy produced by a single Gaussian distribution:

$$n(R) = \frac{1}{(4\pi D t)^{3/2}} \exp\left[-\frac{R^2}{4Dt}\right]$$

Independent of D

$$\delta = \frac{3D}{c}\frac{\nabla n}{n} = \frac{3R}{2ct}$$

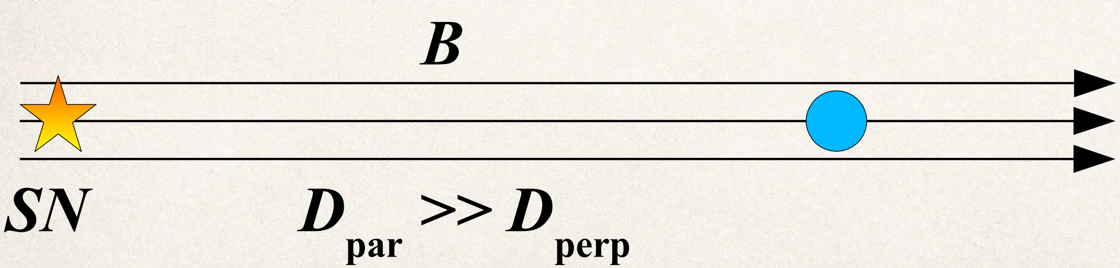
$$\simeq 5\times 10^{-4}\left(\frac{R}{100\,pc}\right)\left(\frac{t}{Myr}\right)^{-1}$$



Anisotropy from a single local source

Local SNR could explain the anisotropy if:

- Particles remain close to the source for time >~ Myr
    - Local diffusion has to be strongly enhanced with respect to the average Galactic level (self generated turbulence could provide this amplification)
    - Propgation has to be almost 1D within the flux tube ($D_{par} >> D_{perp}$)
- Earth is located within the flux tube of the local SNR



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

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

ANISOTROPY: local source(s) could explain the observed anisotropy if

- Particles remain close to the source for time >~ Myr
  - Local diffusion has to be strongly enhanced with respect to the average Galactic level (self generated turbulence could provide this amplification)
  - Propagation has to be almost 1D within the flux tube ($D_{par} >> D_{perp}$)
  - Earth is located within the flux tube of the local SNR