Anisotropic Cosmic Ray diffusion and γ-ray emission form Molecular Clouds

Nava & Gabici 2013

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Gamma-ray astronomy

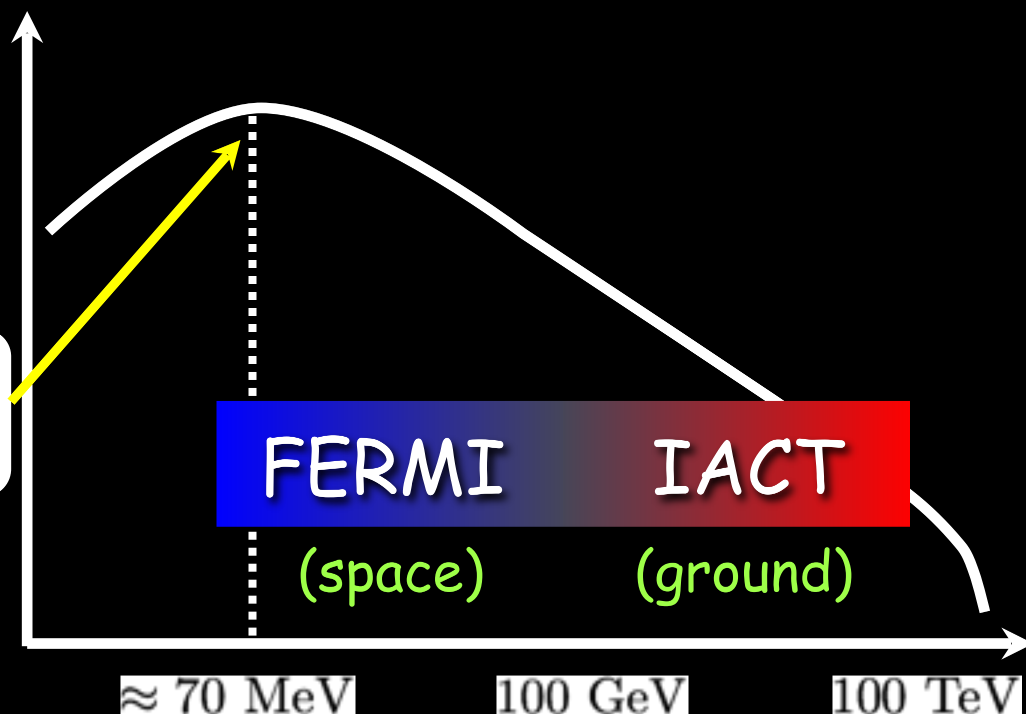
$$p + p \longrightarrow p + p + \pi^0$$

CR ISM

$$\pi^0 \longrightarrow \gamma + \gamma$$

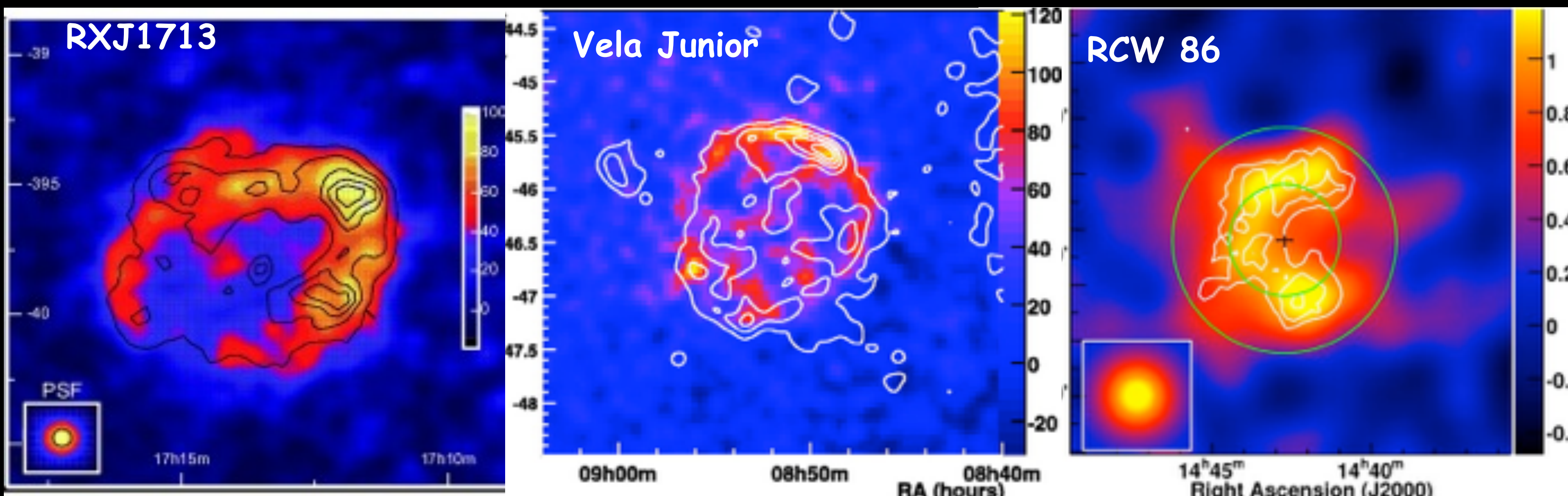
$$\langle E_\gamma \rangle \approx E_{CR}/10$$

$$E_{peak} = \frac{m_{\pi^0}}{2}$$



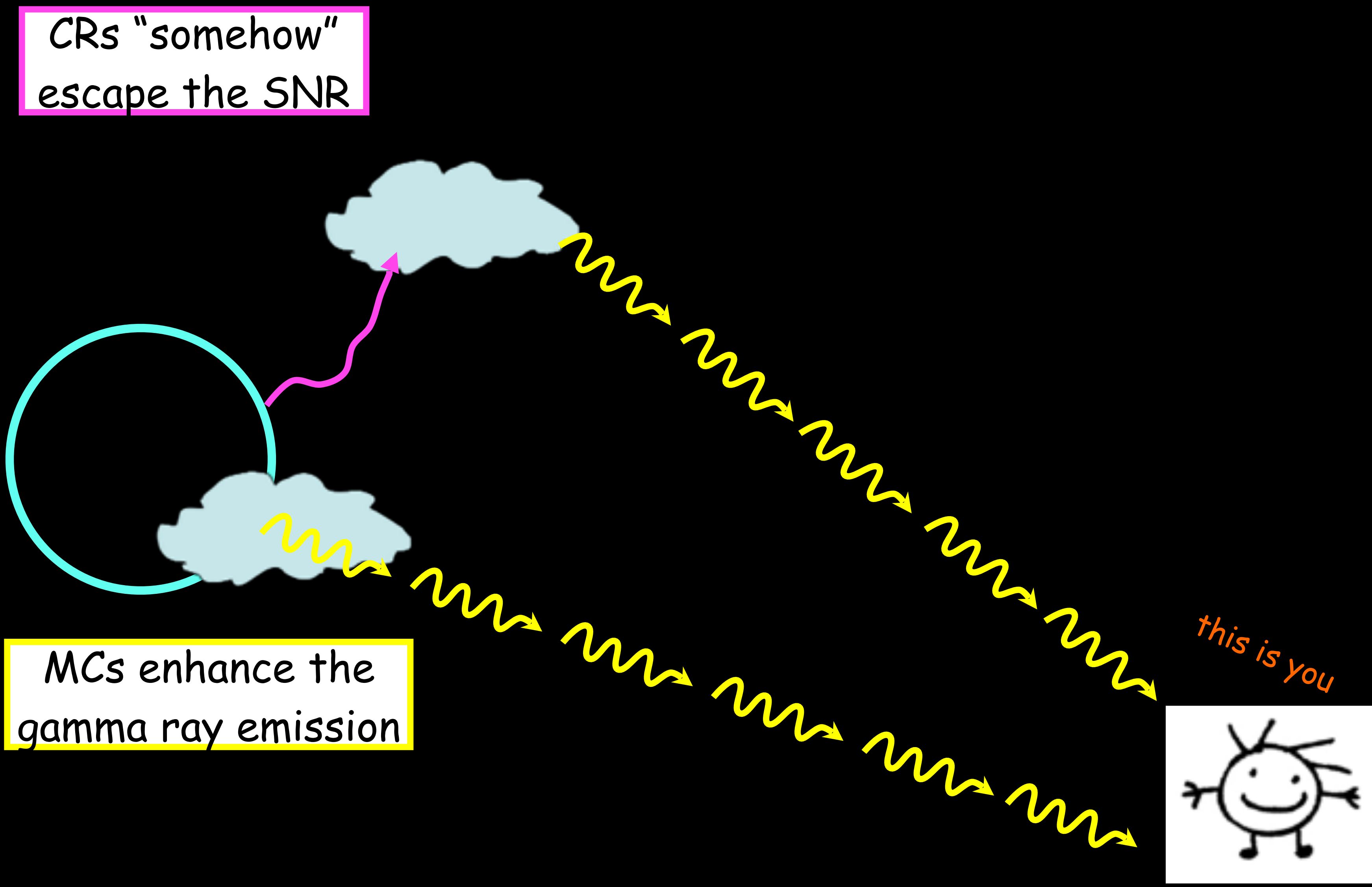
Gamma rays from SNRs: a test for CR origin

Drury, Aharonian & Volk, 1994



SNRs detected @TeVs ➜ TEST PASSED!

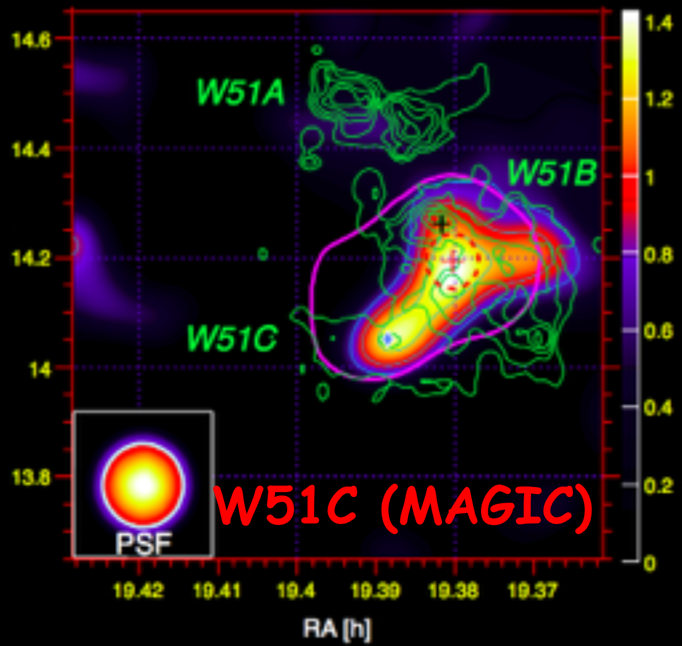
How to use Molecular Clouds to learn about the diffusion...



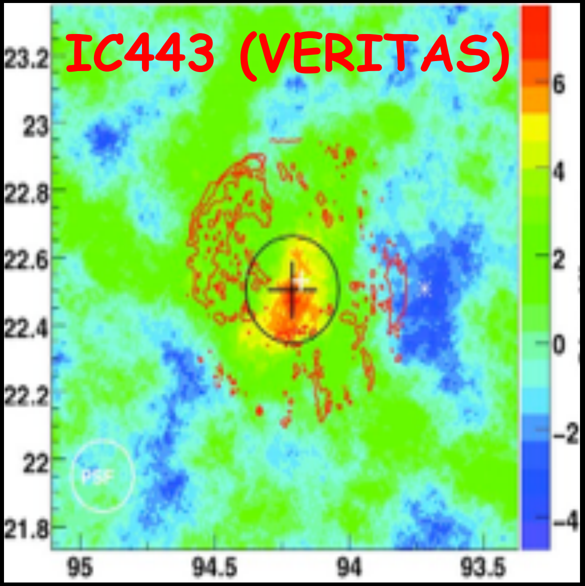
Aharonian & Atoyan, 1996; Gabici & Aharonian, 2007

Molecular clouds are gamma ray sources

Magic collab., 2012

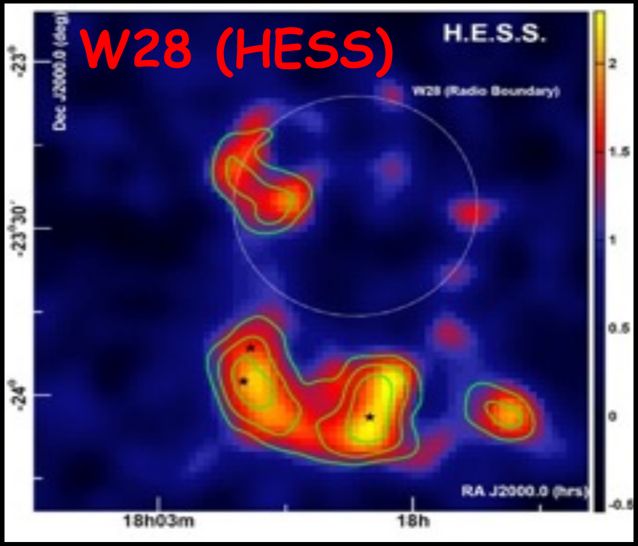


Acciari et a., 2009

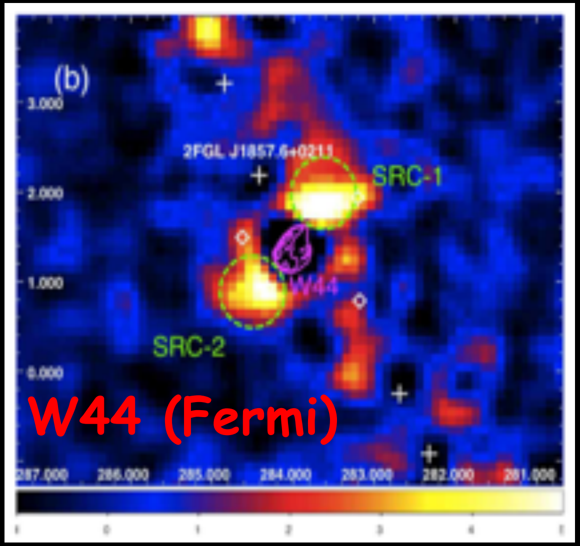


interaction at the shock?

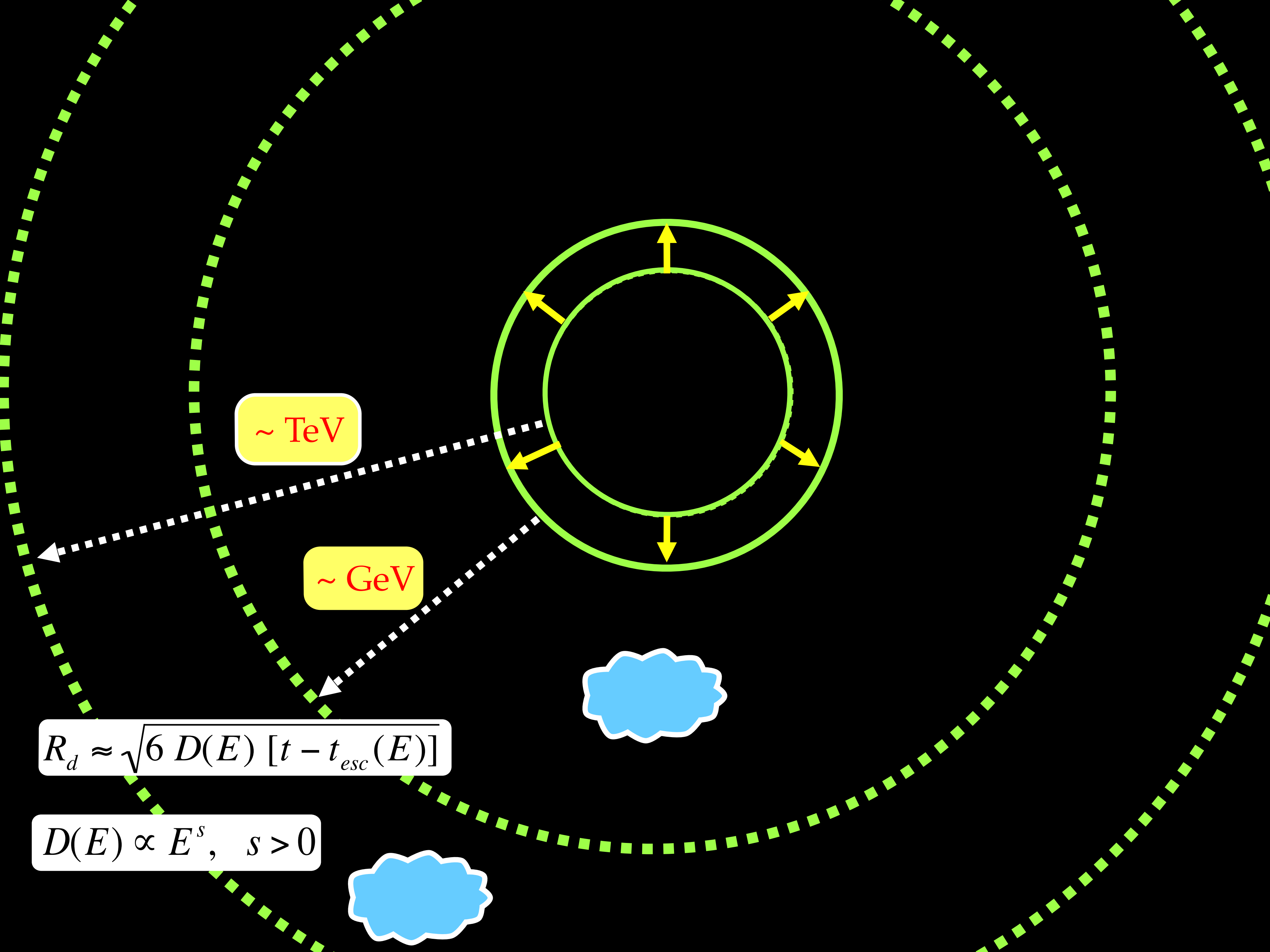
Aharonian et al, 2008



Uchiyama et al, 2012



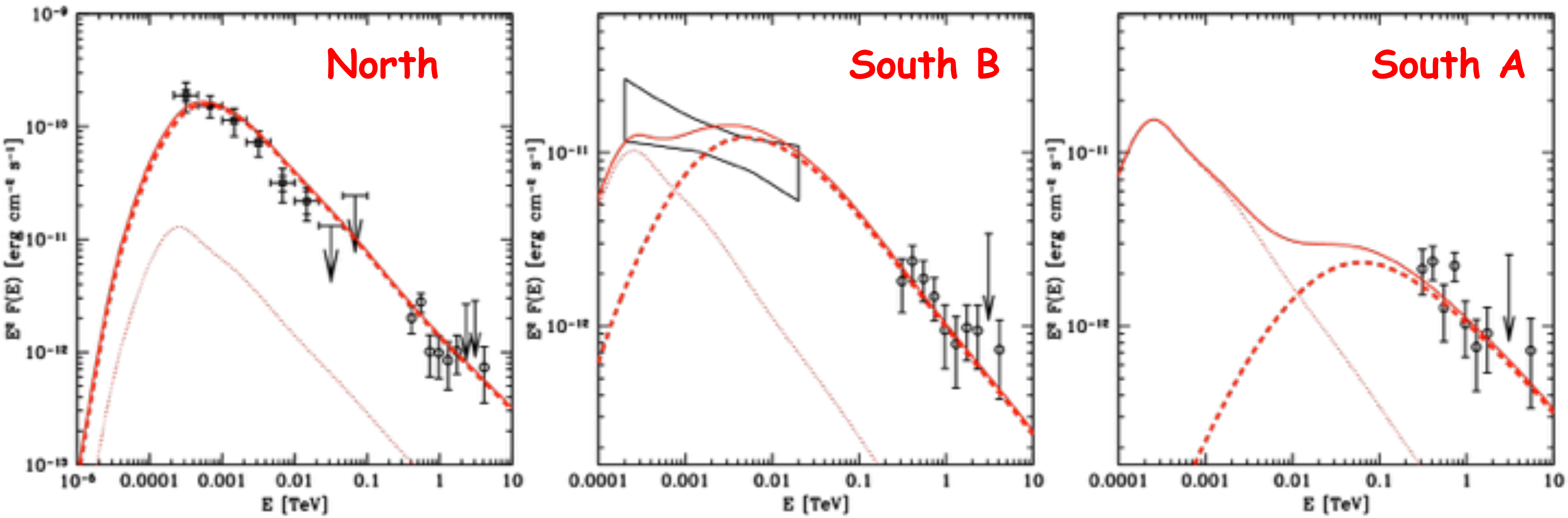
γ-rays outside the shell?



~ TeV
~ GeV
$R_d \approx \sqrt{6\, D(E)\, [t - t_{esc}(E)]}$
$D(E) \propto E^s, \quad s > 0$

W28: gamma-ray emission

Gabici et al., 2010



d = 12 pc

d = 32 pc

d = 65 pc

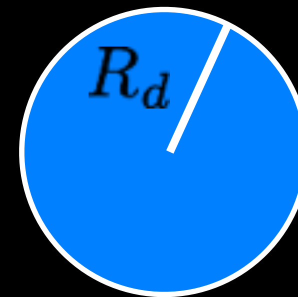
η = 30%
D= 0.06 D_{gal}

$D_{gal}=10^{28}(E/10GeV)^{0.5}cm^2s^{-1}$

Anisotropic diffusion: general considerations

reminder on isotropic D

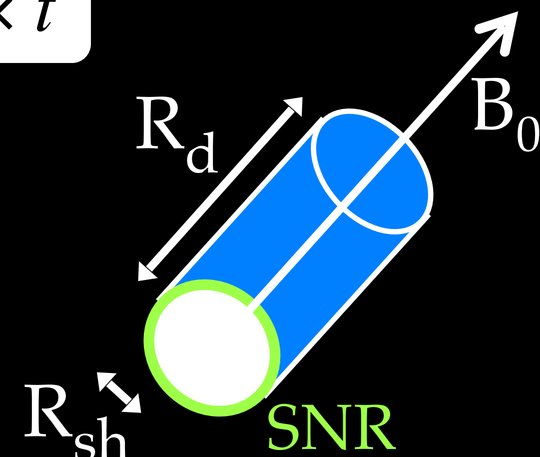
$$n_{CR} \approx \frac{N_{CR}}{R_d^3}$$



$$R_d \approx \sqrt{D \times t}$$

strictly anisotropic D

$$n_{CR} \approx \frac{N_{CR}}{R_d R_{sh}^2}$$



isotropic ~100 pc

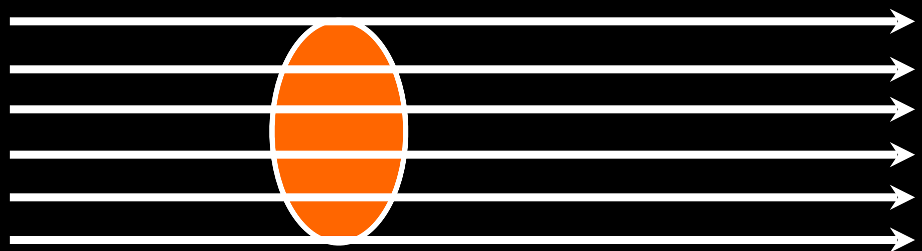
$$D = D_0 \left(\frac{R_d}{R_{sh}} \right)^{4/3}$$

~10 pc

much larger D for anisotropic diffusion

Anisotropic diffusion: field line wandering

Nava and Gabici, 2013, MNRAS, 429, 1643



$$\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}$$

Zero-order assumption:

CRs attached to field lines

⬇

perpendicular transport only due to B field lines wandering

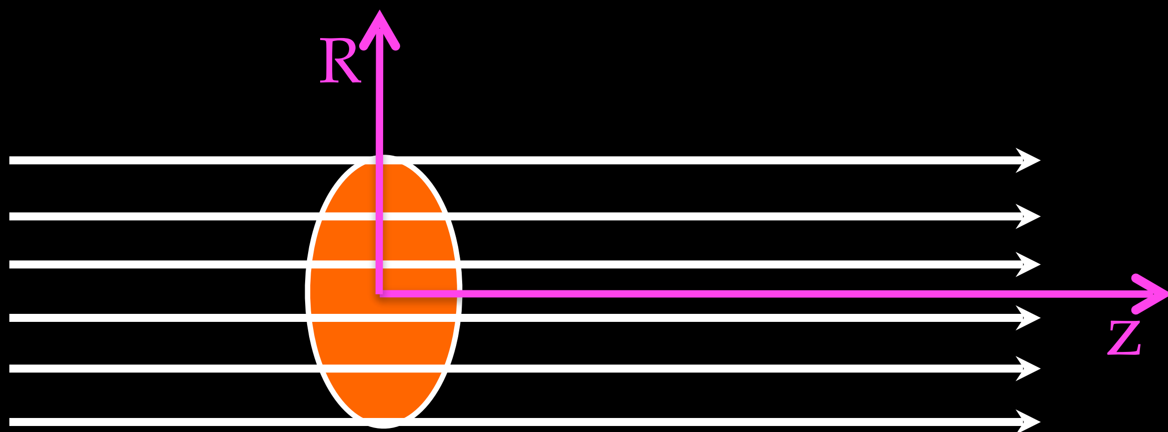
$$b = \frac{\delta B}{B_0} < 1$$

$$L \approx \frac{\lambda_B}{b^2}$$ size of the flux tube

λ_B coherence length

Anisotropic diffusion: field line wandering

Nava and Gabici, 2013, MNRAS, 429, 1643



diffusion coefficient of field lines

$$(\Delta z)^2 \approx 2\ D\ \Delta t$$

$$(\Delta R)^2 \approx 2 D_m \Delta z \propto (\Delta t)^{1/2}$$

$\delta B/B_0 < 1$

diffusion coefficient:

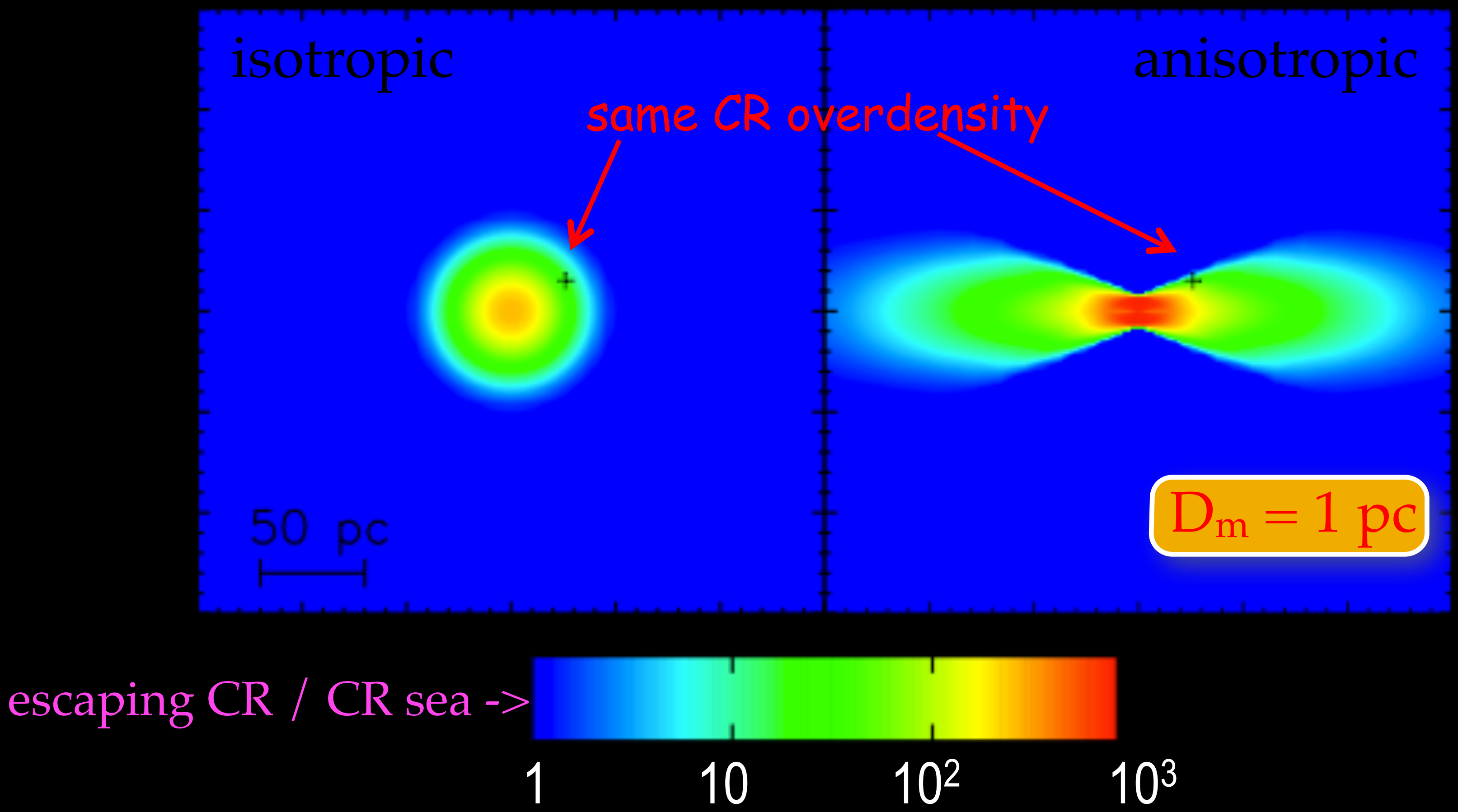
$$D_m = \frac{b^2 \lambda_B}{4}$$

coherence length

Kadomtsev & Pogutse 1979 Duffy et al 1995 Kirk et al 1996

Isotropic versus Anisotropic

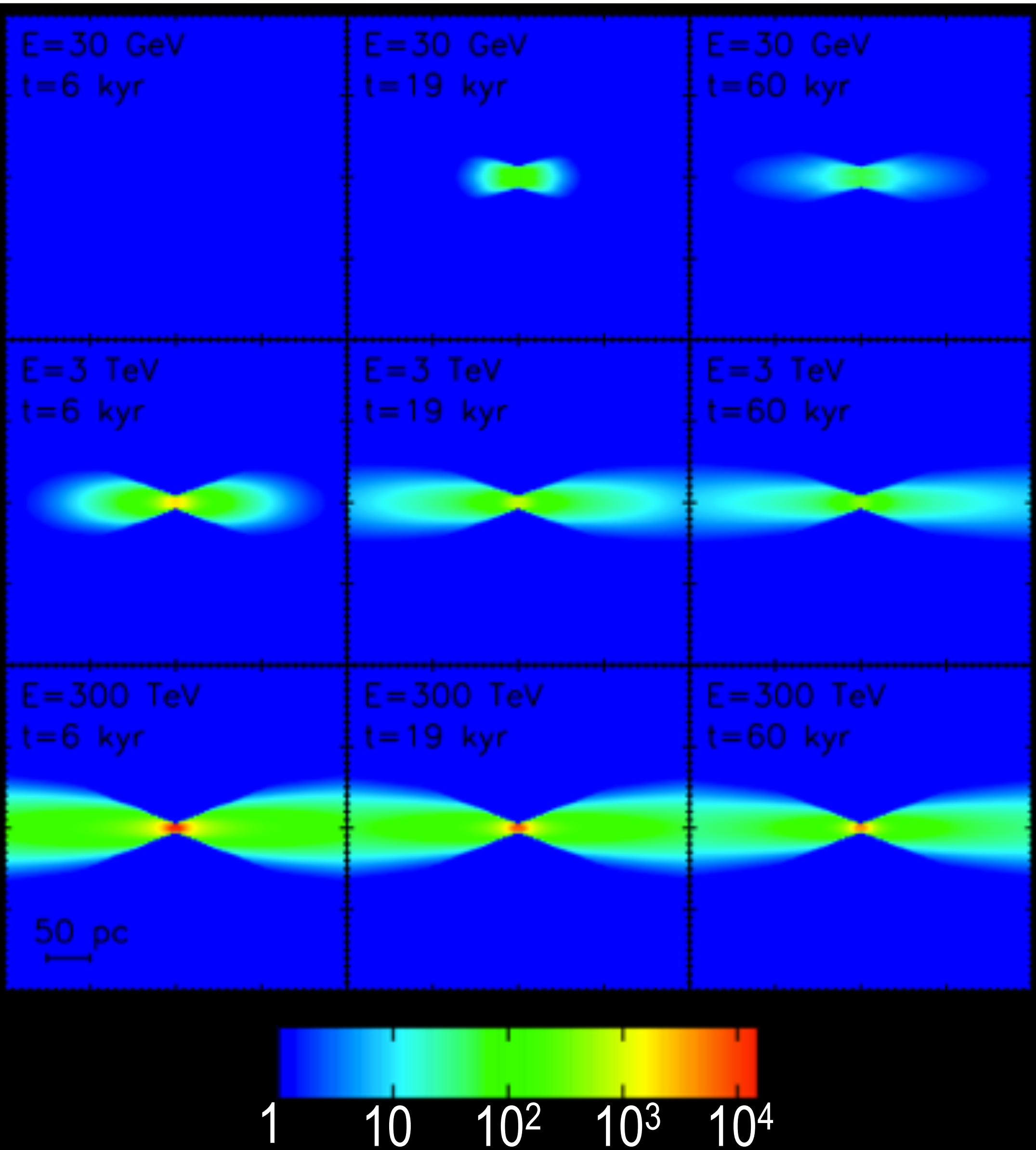
E = 1 TeV ; t = 10 kyr



$$D_{iso}(1\ \mathrm{TeV}) = 5 \times 10^{27}\ \mathrm{cm}^2/\mathrm{s}$$

$$D_{||}(1\ \mathrm{TeV}) = 10^{29}\ \mathrm{cm}^2/\mathrm{s}$$

Anisotropic diffusion: CR maps



overdensity above CR background

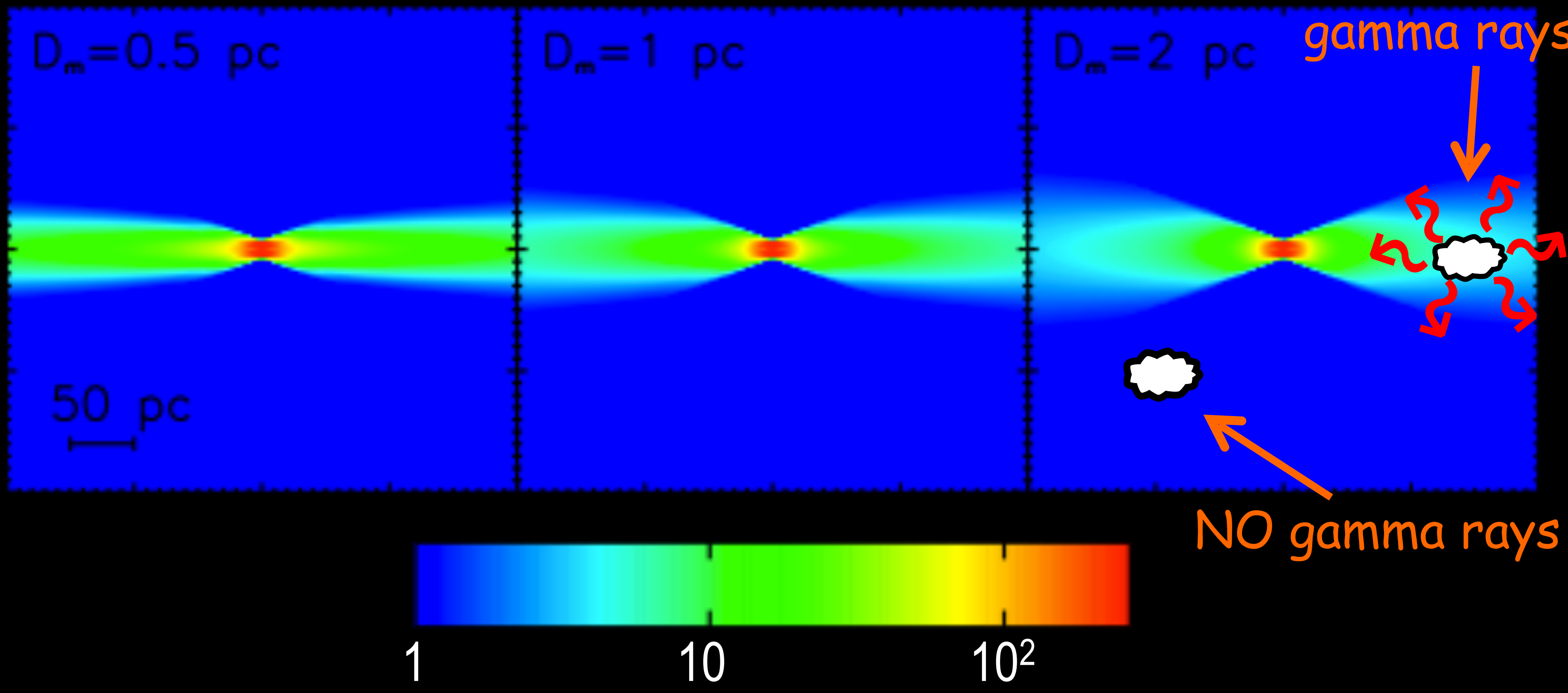
$E_{CR} = 10^{50}$ erg

$D \sim 10^{28}(E / 10GeV)^{0.5}$

$D_m = 1$ pc

CR slope = 2.2

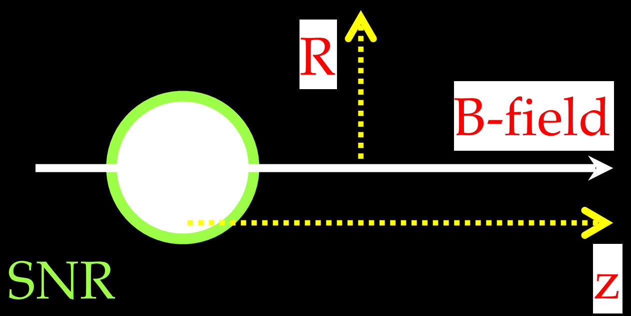
Anisotropic diffusion: CR maps



gamma rays? -> cloud and SNR must be magnetically connected

see also Ptuskin et al 2007 - Giacinti et al 2011, 2013 - Malkov et al 2012

Anisotropic diffusion: spectra



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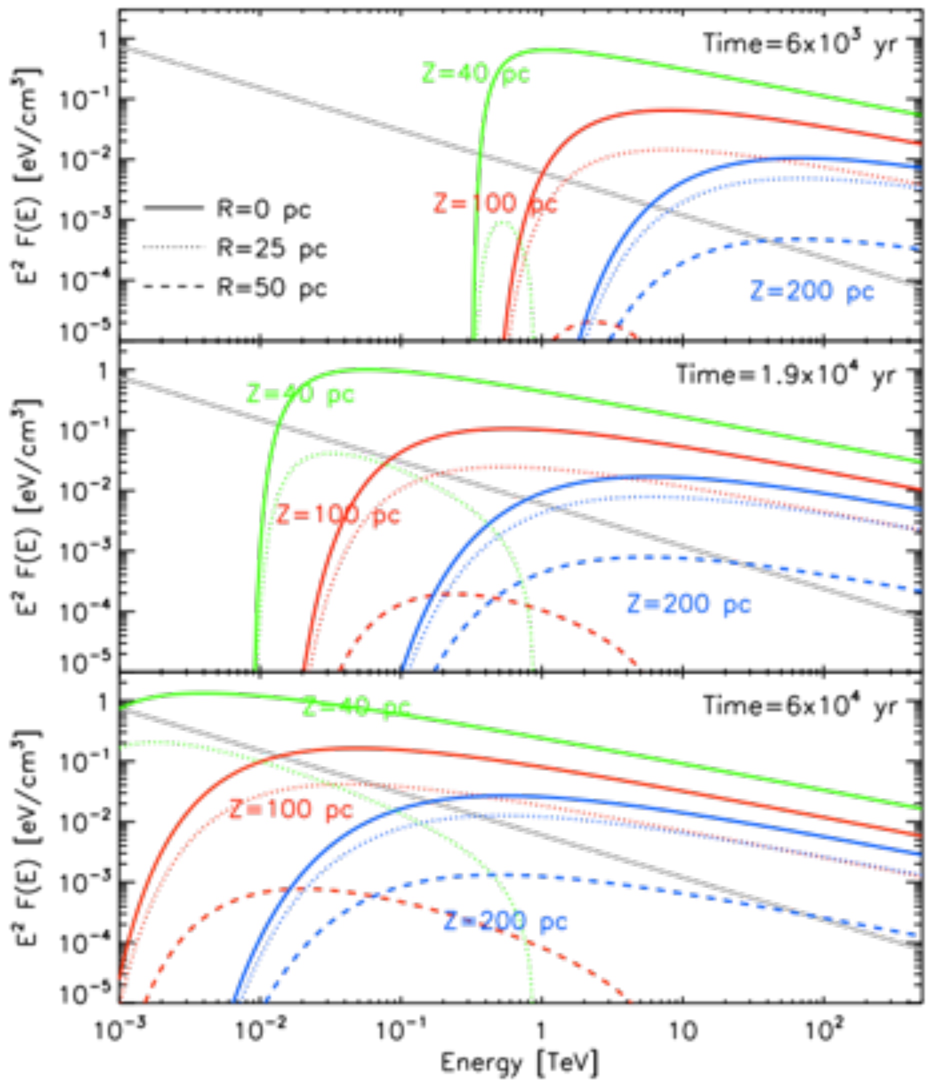
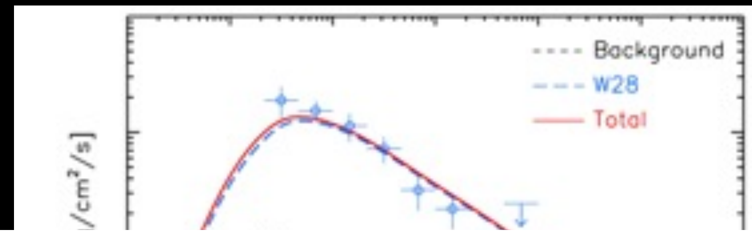
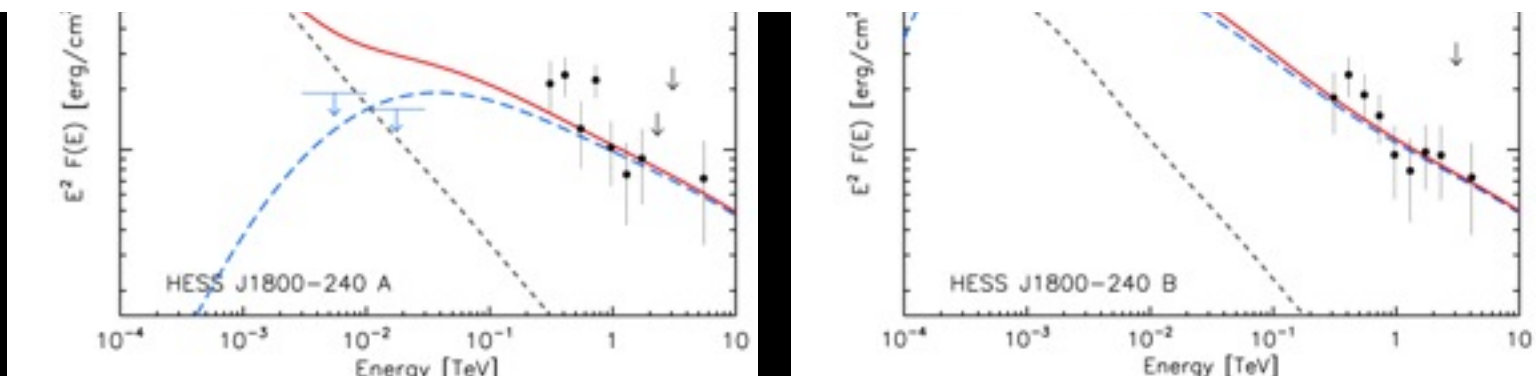


Constraints on propagation: anisotropic diffusion in the W28 region



if particles are "focused" towards the MCs a larger D can be used to explain data

$$D \approx 10^{28} \left(\frac{E}{10 \text{ GeV}} \right)^{0.5} \text{cm}^2/\text{s}$$



A comment about perpendicular diffusion

Quasi-Linear Theory

$$b = \frac{\delta B}{B_0} < 1$$

$$\frac{D_\perp}{D_\parallel} = \frac{1}{1+(\lambda_\parallel/r_g)^2} = \frac{1}{1+(D_\parallel/D_B)^2} = \frac{1}{1+1/b^4} \simeq b^4$$

perpendicular diffusion is negligible

Berezinskii et al. 1990; Casse et al., 2001; Duffy et al. 1995

Summary

- Constraints on the diffusion coefficient from γ-ray emission strongly depend on the model assumed to describe the diffusion around the sources
- Presently, the vast majority of studies of γ-rays from MC or from extended emissions around sources are based on the assumption of isotropic diffusion
- Local CR propagation within few 100 pc from the source is affected by the local geometry of the magnetic field
- In the future, γ-ray observations can be used to provide information on the local magnetic field, as well as on the geometry of field lines