ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

UNIVERSITÀ DEGLI STUDI DI TORINO

Cosmic ray transport in the proximity of pulsars and the formation of gamma-ray halos

S. Recchia

S. Recchia, M. Di Mauro, F. A. Aharonian, F. Donato, S. Gabici and S.Manconi

Overview

- **HAWC detected extended gamma-ray halos around Geminga and Monogem** HAWC collaboration, Science 358(2017)
  - few degrees across the sky
  - Inverse Compton scattering halos
  - 20-200 TeV electrons and positrons

- **the extension of such halos has been interpreted in the assumption of pure isotropic diffusion, by the HAWC collaboration and other works**
  - the inferred diffusion coefficient is at least 100 times smaller than typical one
  - established consensus on suppressed diffusion around pulsars
  - such suppression is difficult to explain theoretically, plus poses problems for the location of the sources of multi-TeV electrons (observed up to ~ 20 TeV)

- **we revise this model, taking into account the transition between ballistic and diffusive regime in the CR propagation**
  - we show that, taking into account such effect, the gamma-ray halos of Geminga and Monogem can be explained with typical values of the diffusion coefficient

Ballistic-diffusive CR transport

- consider CR leptons released from a pulsar
- isotropic diffusion coefficient

$D_0 \sim 10^{28}\,\mathrm{cm}^2/\mathrm{s}$

$\delta \sim 0.5$

$$D(E_{\mathrm{GeV}}) = D_0 E_{\mathrm{GeV}}^{\delta}$$

$$\lambda_c(E_{\mathrm{GeV}}) = 0.3 D_{0,28} E_{\mathrm{GeV}}^{\delta}\ \mathrm{pc}$$

mean free path

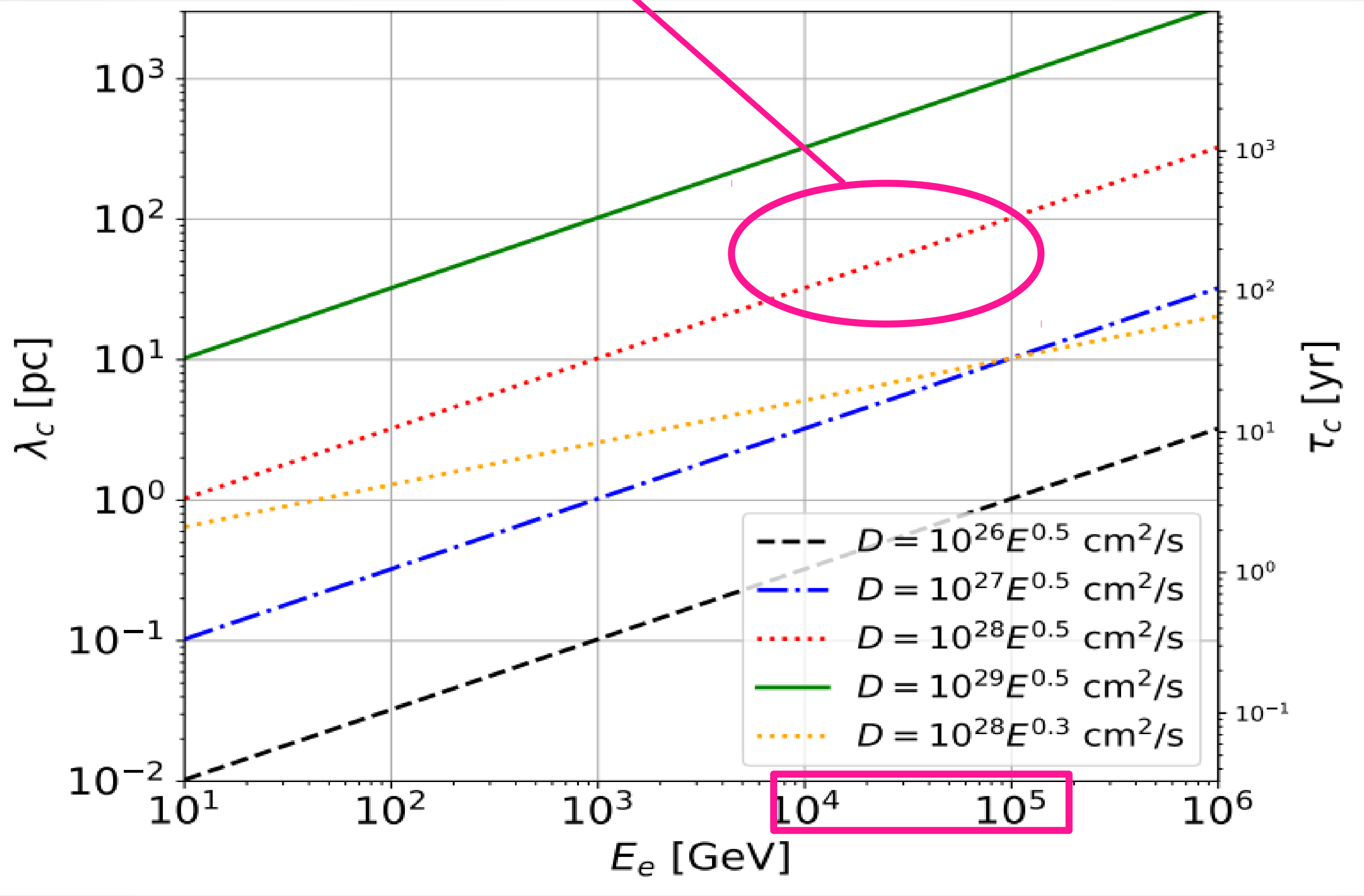
$$\tau_c(E_{\mathrm{GeV}}) = 1.0 D_{0,28} E_{\mathrm{GeV}}^{\delta}\ \mathrm{yr}$$

scattering time

- the mean free path and the scattering time are the spatial and time-scale for isotropization of the particle direction
- $\lambda_c(10\,\mathrm{TeV}) \approx 10\mathrm{pc}$

Ballistic-diffusive CR transport

few tens pc, comparable to pulsars halo extension



Ballistic-diffusive CR transport

Prosekin et al.(2015), Aloisio et al. (2005)

- the CR transport after injection from the source is characterized by three regimes
  - ballistic for $t < \tau_c$
  - diffusive for $t > \tau_c$
  - a transition between the two (quasi-ballistic)
- if applied at times below τ_c the diffusion equations is plagued by the superluminal propagation problem
- in a continuous source, at every moment there are recently injected particles (ballistic) and particles already isotropized (diffusive)

Application to pulsars

- pulsar of age t_a turns on at t=0 and inject leptons with

$$L(t) = \eta L_0 \left(1 + \frac{t}{\tau_0}\right)^{-2}$$

$$\tau_0 = \mathrm{spin-down\ timescale}$$
$$\eta = \mathrm{efficiency}$$

- particles injected within the last τ_c are treated in the ballistic regime f_{ball}
- particles injected earlier are treated in the diffusive regime f_{diff}

- $f_e = f_{ball} + f_{diff}$ total lepton density
- f_{ball} is found to dominate over f_{diff} below a distance $\sim \lambda_c$

Angular distribution

- Due to the relativistic nature of the ICS process, gamma-rays are emitted preferentially along the direction of the parent CR
- in the strictly ballistic regime the gamma-ray halo would appear as point like no matter the extension of the parent electron-positron halo
- in the diffusive regime the extension of the gamma-ray halo reflects that of the CR halo

Prosekin et al.(2015)

- function $M(\mu)$ takes into account the angular distribution in the transition between ballistic and diffusion regime

$$f_e = f_{ball} + f_{diff}$$

$$F_e = f_e M(\mu)$$

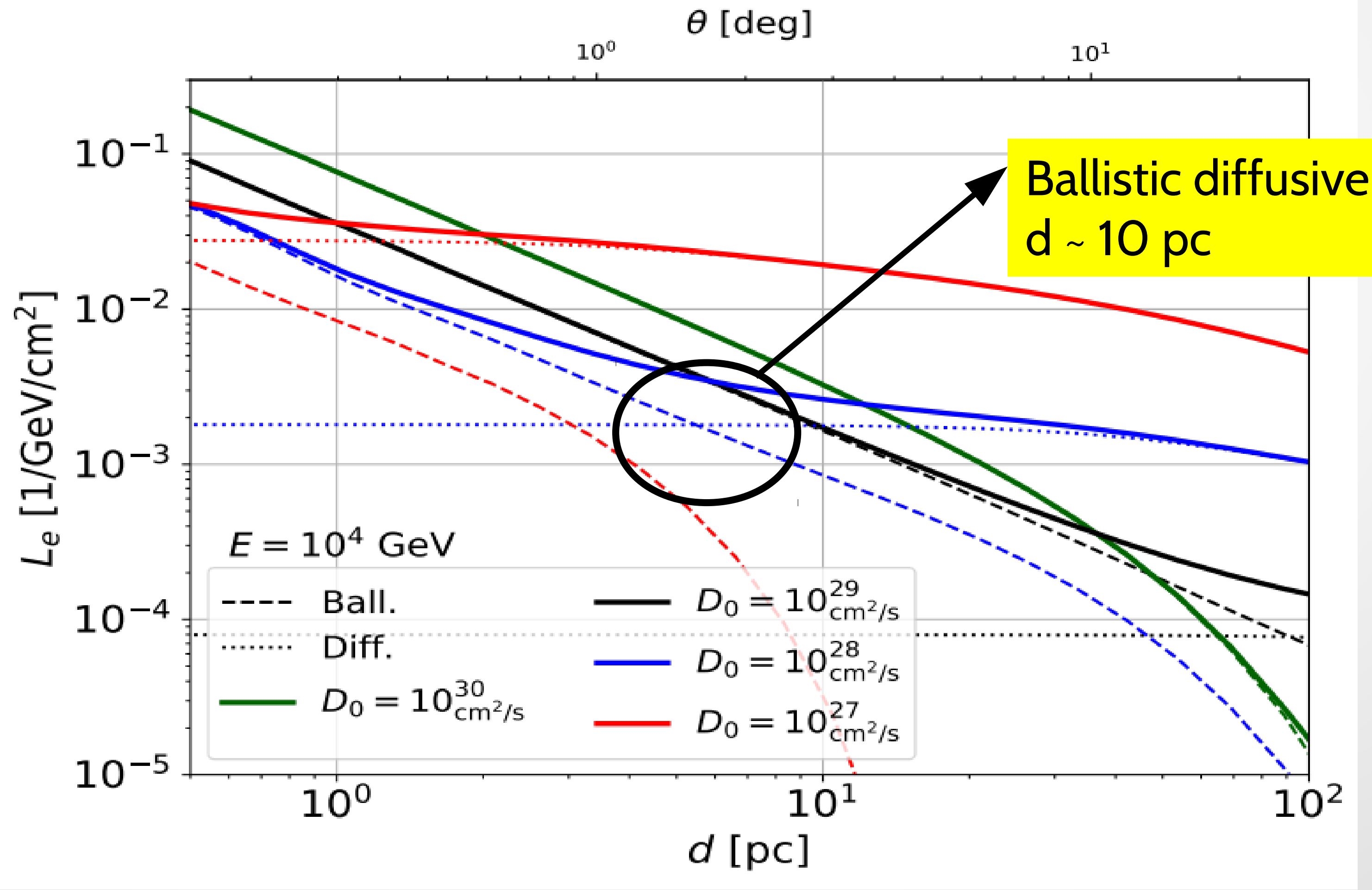
$$L_e(E,\theta) = \int_0^\infty ds F_e(E,s,\theta)$$

- integral along the line of sight
- gamma-ray morphology

Gamma-ray morphology

Lepton distribution integrated along the line of sight

10 TeV



Ballistic diffusive-transition
d ~ 10 pc

Gamma-ray morphology

- up to distances from the source $\sim \lambda_c(E)$ the electron distribution around the pulsar is dominated by the most recently injected particles, that move quasi-ballistically
  - $L_e \propto 1/d$ (... a bit steeper)

- beyond $\sim \lambda_c(E)$ the CR density is dominated by particles that have been isotropized and propagate diffusively
  - L_e is rather flat
  - up to the diffusion-loss length $d \approx \sqrt{4\, D(E)\, t_{\rm loss}(E)}$

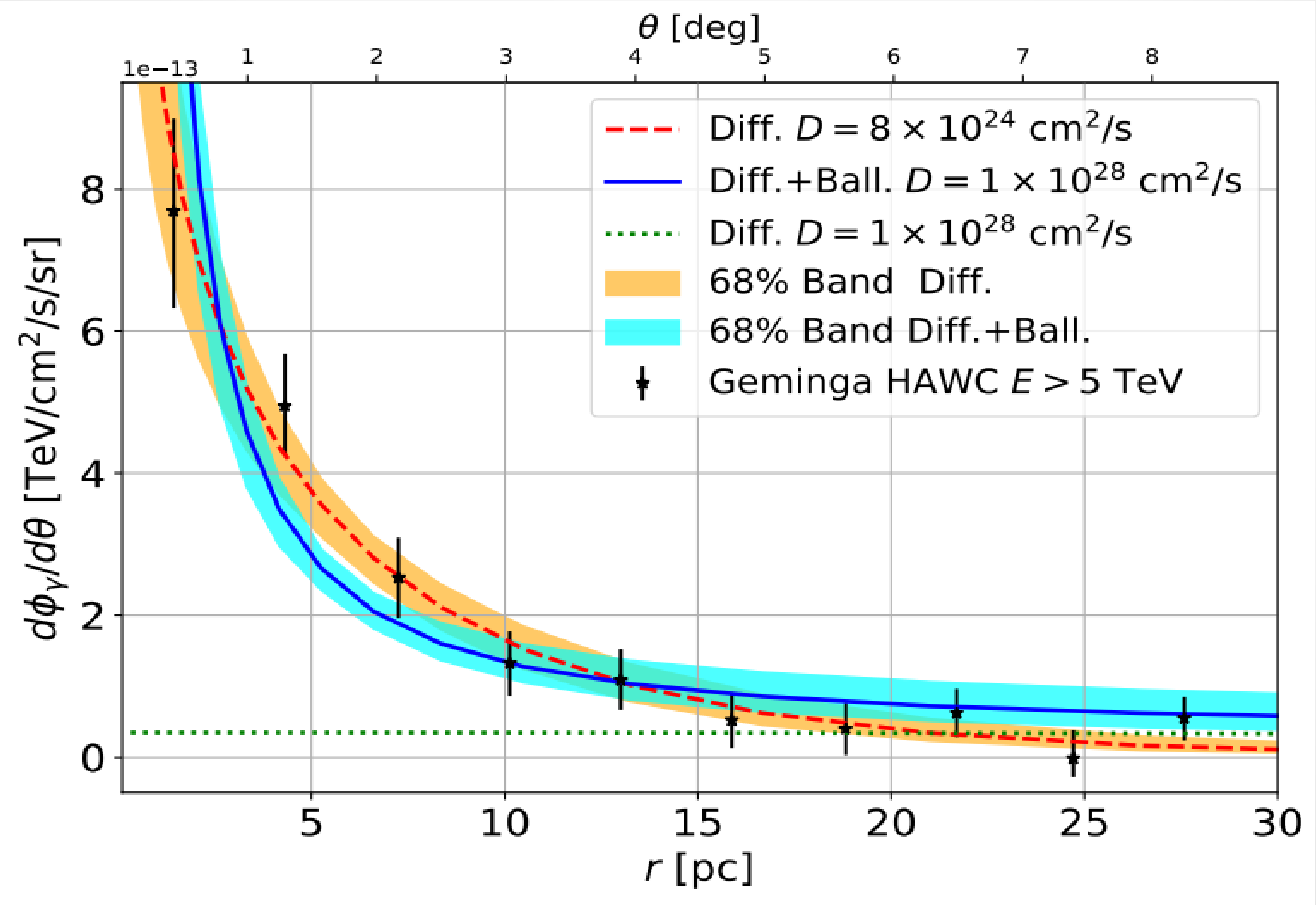
- the transition occurs at larger distances from the source at increasing particle and for larger values of the diffusion coefficient

Gamma-ray morphology

- in the **low diffusion scenario** $D(1\,\mathrm{GeV}) \sim 10^{25}\,\mathrm{cm}^2/\mathrm{s}$
  - the extension of Geminga and Monogem halos is connected to the diffusion-loss length
    $d \approx \sqrt{4\,D(E)\,t_{\mathrm{loss}}(E)}$
  - the transition takes place very close to the pulsar and the gamma ray morphology is not affected by such effect

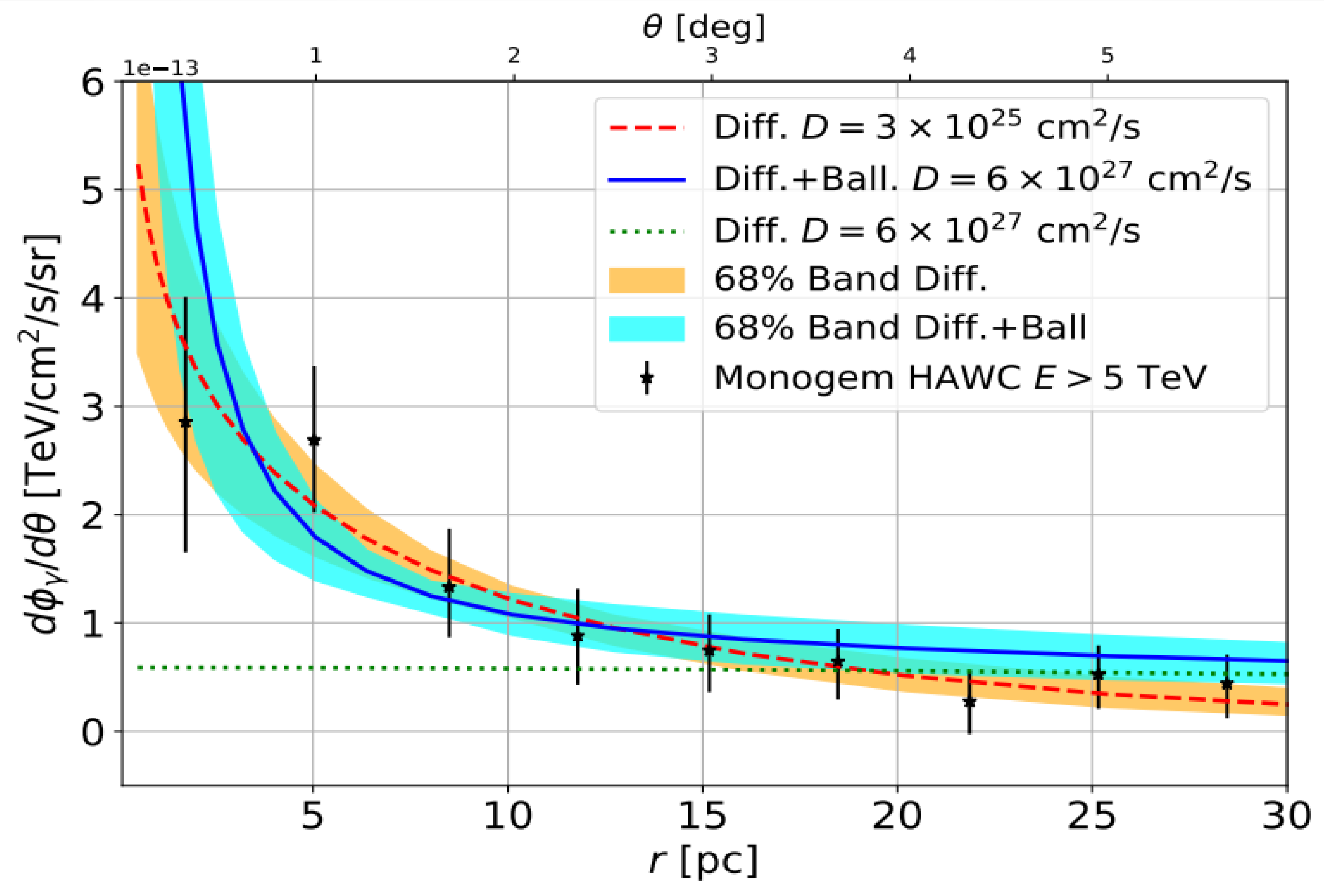
- with a **typical diffusion coefficient** $D(1\,\mathrm{GeV}) \sim 10^{28}\,\mathrm{cm}^2/\mathrm{s}$
  - the source extension is connected to the transition between ballistic and diffusive propagation

Fit to data



θ [deg]
1e−13
1
2
3
4
5
6
7
8
Diff. $D = 8 \times 10^{24}$ cm^2/s
Diff.+Ball. $D = 1 \times 10^{28}$ cm^2/s
Diff. $D = 1 \times 10^{28}$ cm^2/s
68% Band Diff.
68% Band Diff.+Ball.
Geminga HAWC $E > 5$ TeV
$d\phi_\gamma/d\theta$ [TeV/cm^2/s/sr]
0
2
4
6
8
5
10
15
20
25
30
r [pc]

Fit to data



θ [deg]
1e−13
1
2
3
4
5
6
5
4
3
2
1
0
dϕγ/dθ [TeV/cm²/s/sr]
Diff. D = 3 × 10²⁵ cm²/s
Diff.+Ball. D = 6 × 10²⁷ cm²/s
Diff. D = 6 × 10²⁷ cm²/s
68% Band Diff.
68% Band Diff.+Ball
Monogem HAWC E > 5 TeV
5
10
15
20
25
30
r [pc]

CR conversion efficiency

- the conversion efficiency of the spin-down luminosity to CR leptons is different in the low diffusion and typical diffusion scenario
  - **Geminga**: 0.3-3% (low diffusion), ~55-65%
  - **Monogem**: 1% (low diffusion), ~30%
- a high conversion efficiency is in agreement with the with the PWN paradigm, in which a major fraction of the spin-down luminosity is transferred to high energy electrons

Conclusions

- we investigate the CR propagation released from pulsars taking into account the ballistic-diffusion transition

- when such effect is taken into account, a satisfactory fit of the HAWC data for Geminga and Monogem is obtained without invoking a suppression of the diffusion coefficient with respect to the typical interstellar value

- contrary to the established consensus, a compact gamma-ray pulsar halo does not necessarily imply a small diffusion coefficient