DOES THE GEMINGA, MONOGEM AND PSR J0622+3749 γ-RAY HALOS IMPLY SLOW DIFFUSION AROUND PULSARS?

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Solar Modulation and Dark Matter Workshop 2021

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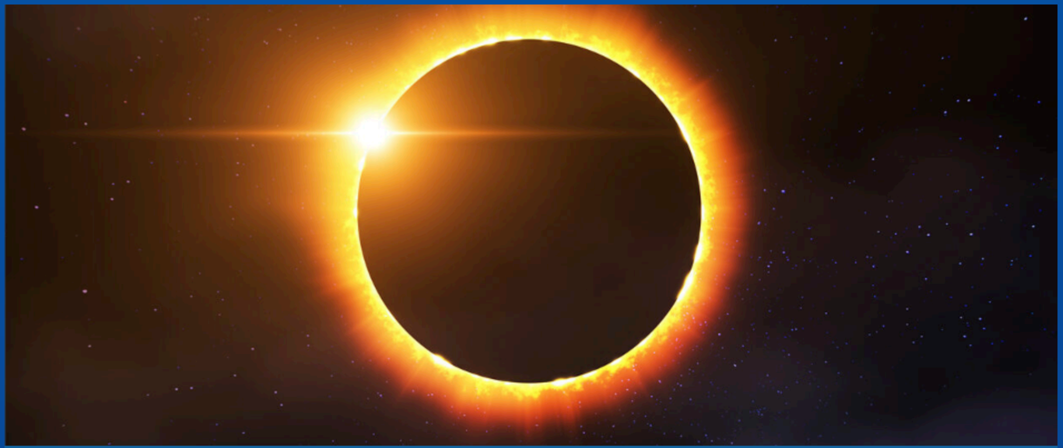

Solar Modulation and Dark Matter Workshop

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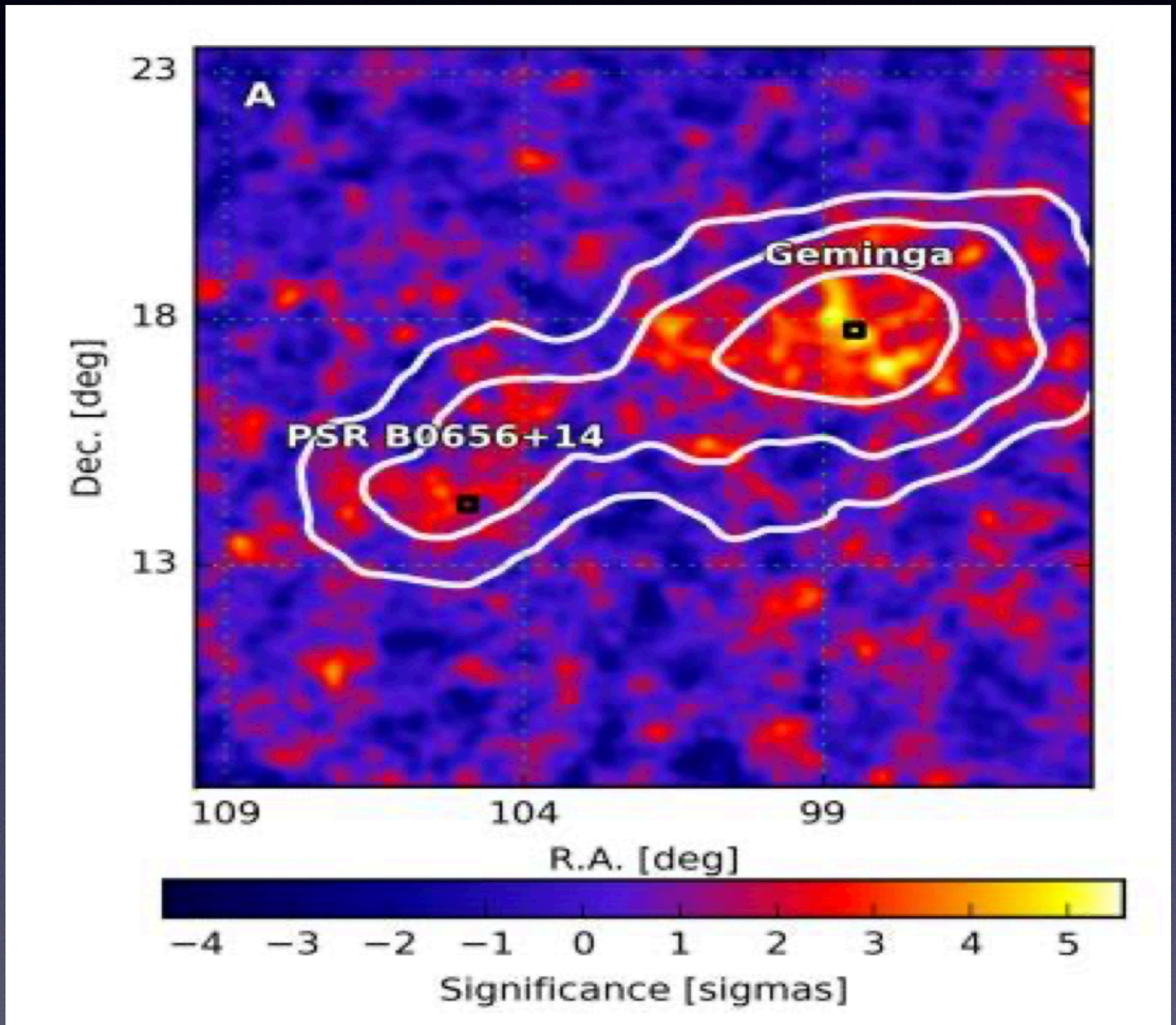
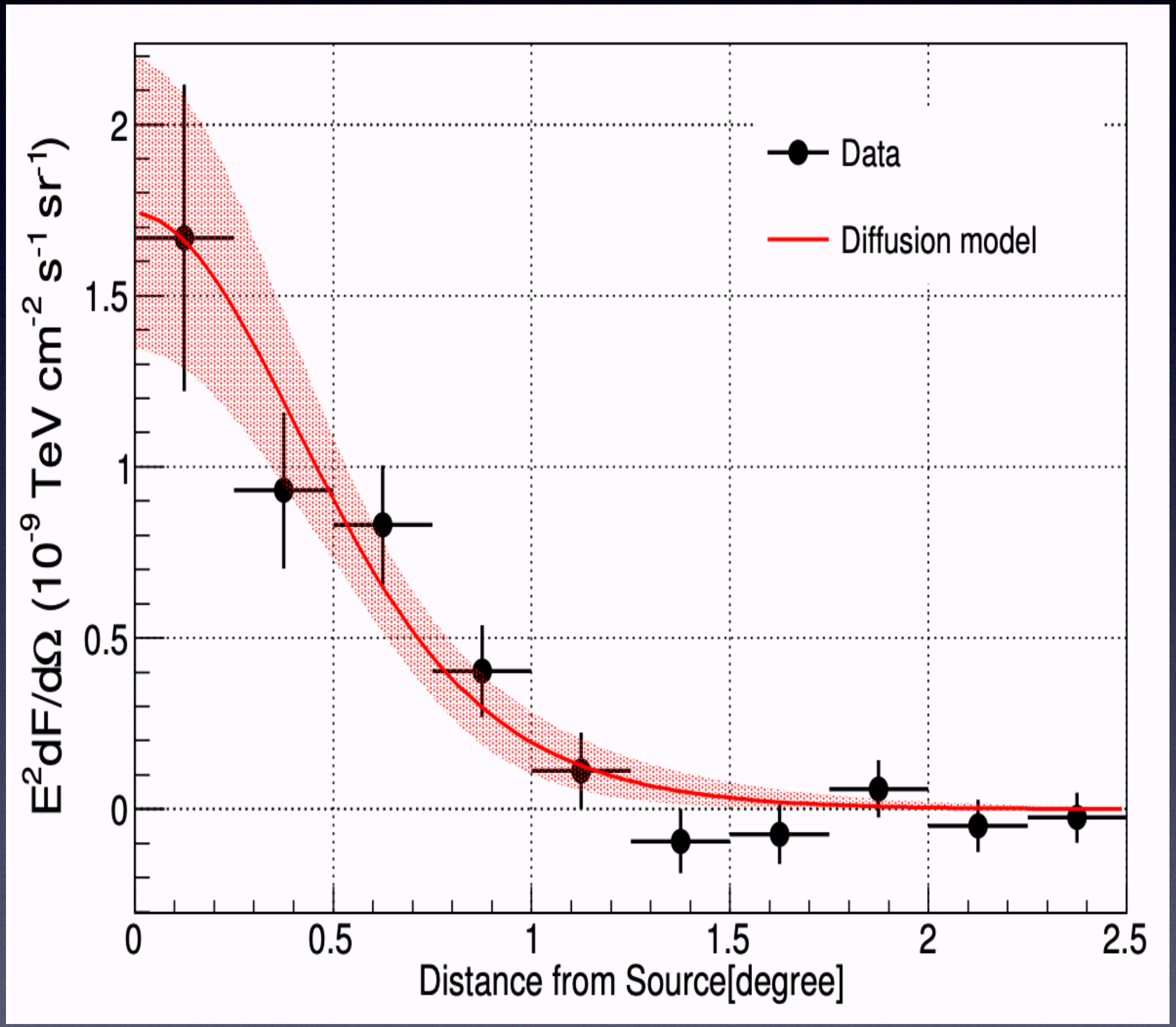
1. Pulsar as sources of inverse Compton halos

Detection of extended gamma-ray halos around Geminga and Monogem (HAWC collaboration, Science 358(2017)) and around PSR J0622+3749 (LHAASO collaboration,Physical Review Letters, 126(2021)).



HAWC collaboration, Science 358(2017)



LHAASO collaboration,Physical Review Letters, 126(2021)

Few degrees across the sky

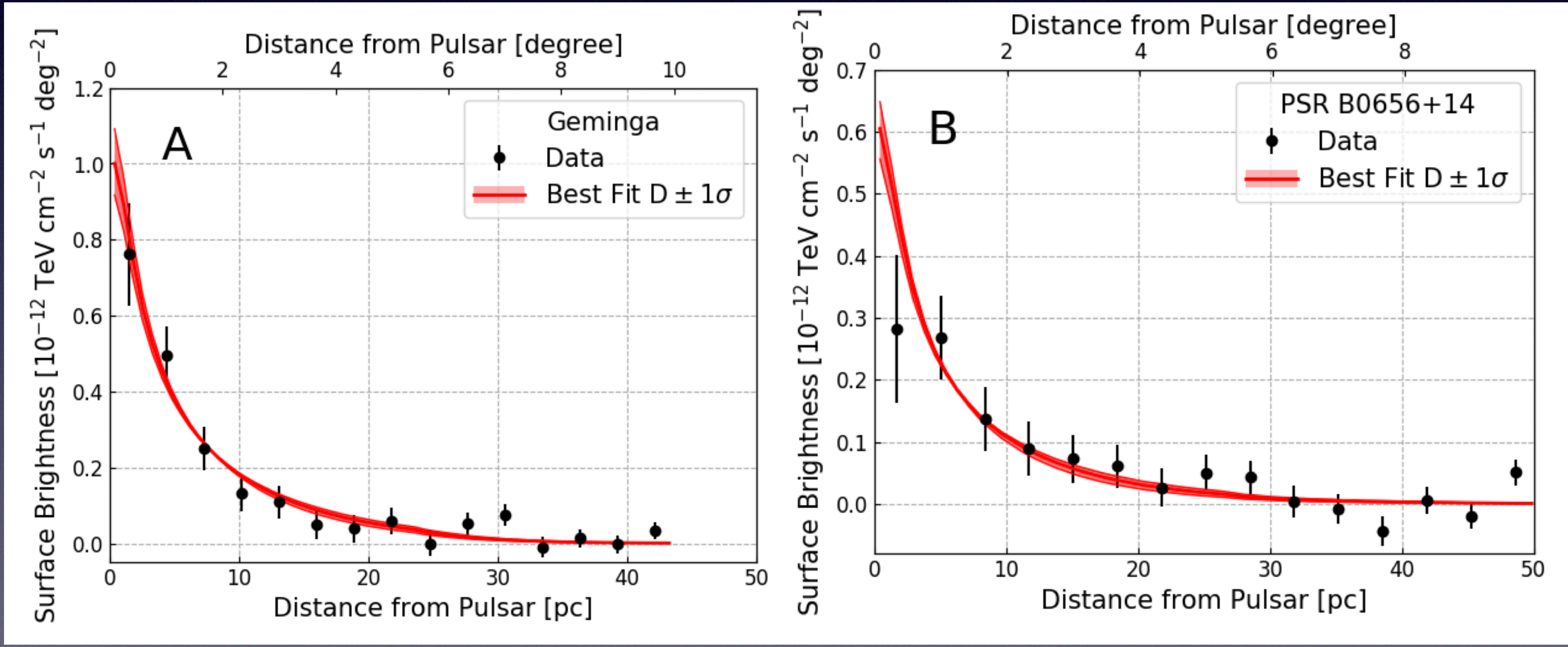
Inverse Compton scattering halos

Electrons and positrons energy > 20 TeV

1. Pulsar as sources of inverse Compton halos

The HAWC collaboration and other works interpreted the extension of such halos assuming a pure isotropic diffusion $D(E_{GeV}) = D_0 E_{GeV}^{\delta}$:

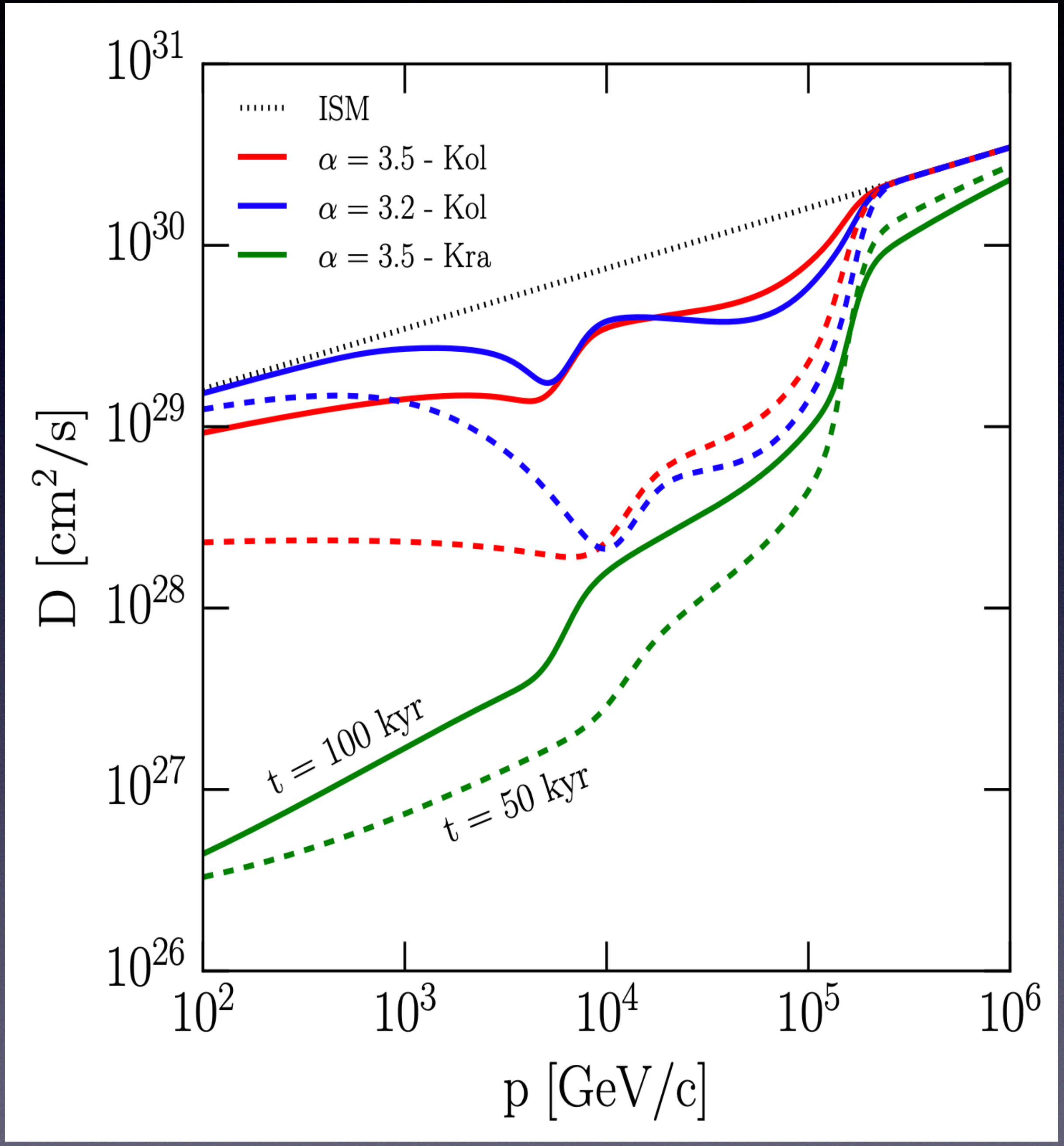
- the inferred diffusion coefficient is at least 100 times smaller than the typical one.
- established consensus on suppressed diffusion around pulsars.



HAWC collaboration, Science 358(2017)

2. Problematics of suppressed diffusion

- The explanation of the suppression.
- A proposal: cosmic-ray density produced by pulsars excites turbulence, which significantly inhibits the propagation of these same cosmic rays (Evoli et al. (2018)).
- If such strong suppression is a common feature of CR sources? Multi-TeV electrons could not actually leak-out of the small-diffusion region.
- Low diffusion zones may pose a serious concern on the location of the sources of 20 TeV electrons.



Evoli et al. Phys. Rev. D 98, 063017 (2018)

3. Ballistic-diffusive cosmic ray transport

We revise this model, taking into account the transition between ballistic and diffusive regime in the CR propagation:

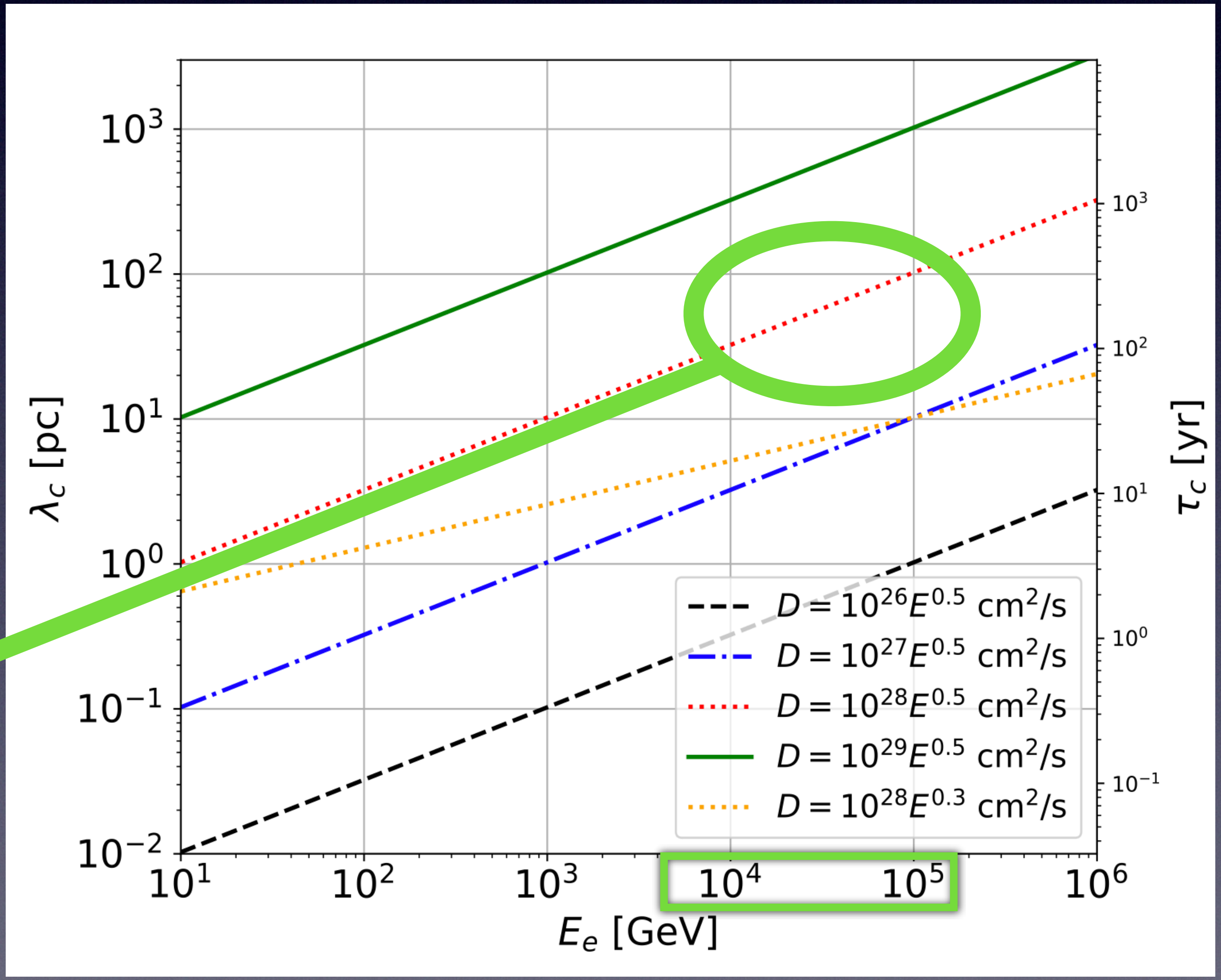
- consider CR leptons released from a pulsar
- isotropic diffusion coefficient $D_0 \sim 10^{28} cm^2/s \quad \delta \sim 0.5 \quad D(E_{GeV}) = D_0 E_{GeV}^{\delta}$ pc

The spatial and time-scale for isotropization of the particle direction are the mean free path and the scattering time defined as:

- Mean free path: $\lambda_c \approx 0.3 D_{0,28} E_{GeV}^{\delta}$ pc
- Scattering time: $\tau_c \approx 1.0 D_{0,28} E_{GeV}^{\delta}$ yr

$\lambda_c(10$ TeV$) \sim 30$ pc

few tens pc, comparable to pulsars halo extension



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)

In a continuous source, at every moment there are recently injected particles (ballistic) and particles already isotropized (diffusive).

	$\dot{E}$ [erg/s]	T [kyr]	l [kpc]
Geminga	3.25×10^{34}	342	0.19
Monogem	3.8×10^{34}	111	0.288
PSR J0622+3749	2.7×10^{34}	208	1.6

5. Application to pulsars

- The injection spectrum of $e^{\pm}$ is adopted as in LHAASO collaboration,Physical Review Letters, 126(2021): $Q(E) \propto E^{-\gamma} \exp\left(-E/E_c\right)$ with γ=1.5 and a cutoff at an energy of E_c = 150 TeV, that is compatible with multiwavelength observations of PSR J0622+3749.

- Pulsar of age t_a turns on at $t = 0$ and inject leptons with:

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

τ_0: spin-down timescale

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

6. Angular distribution

- γ-rays are emitted preferentially along the direction of the parent CR, due to the relativistic nature of the ICS process.
- In the strictly ballistic regime the gamma-ray halo would appear as point-like, no matter the extension of the parent $e^{\pm}$ halo.
- In the diffusive regime the extension of the gamma-ray halo reflects that of the CR halo.

Function $M(\mu)$ takes into account the angular distribution in the transition between ballistic and diffusive regime in the small-angle diffusion approximation:

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

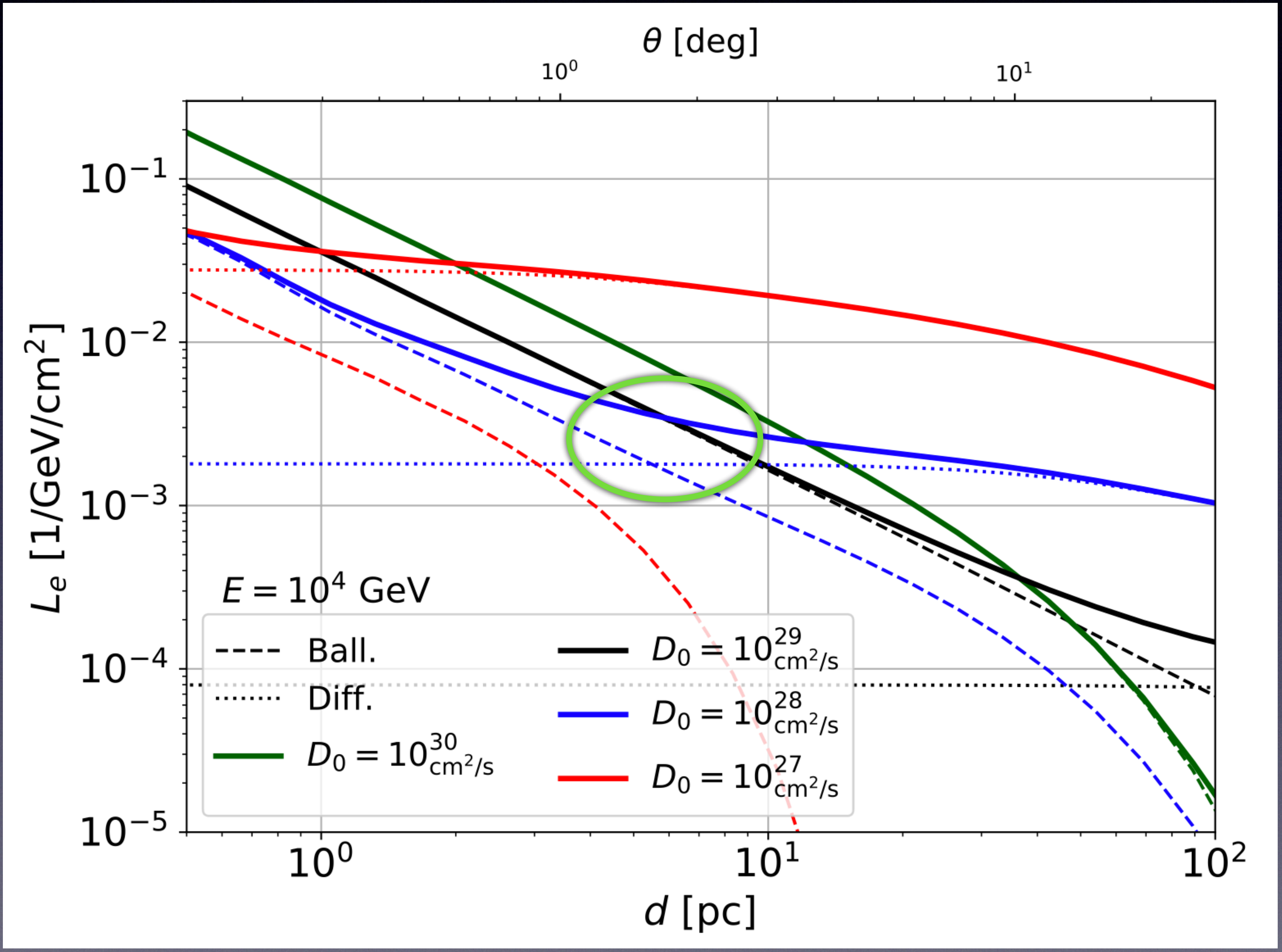
$F_e = f_e\, M(\mu)$

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

- integral along the line of sight

- gamma-ray morphology

Lepton distribution integrated along the line of sight at 10 TeV

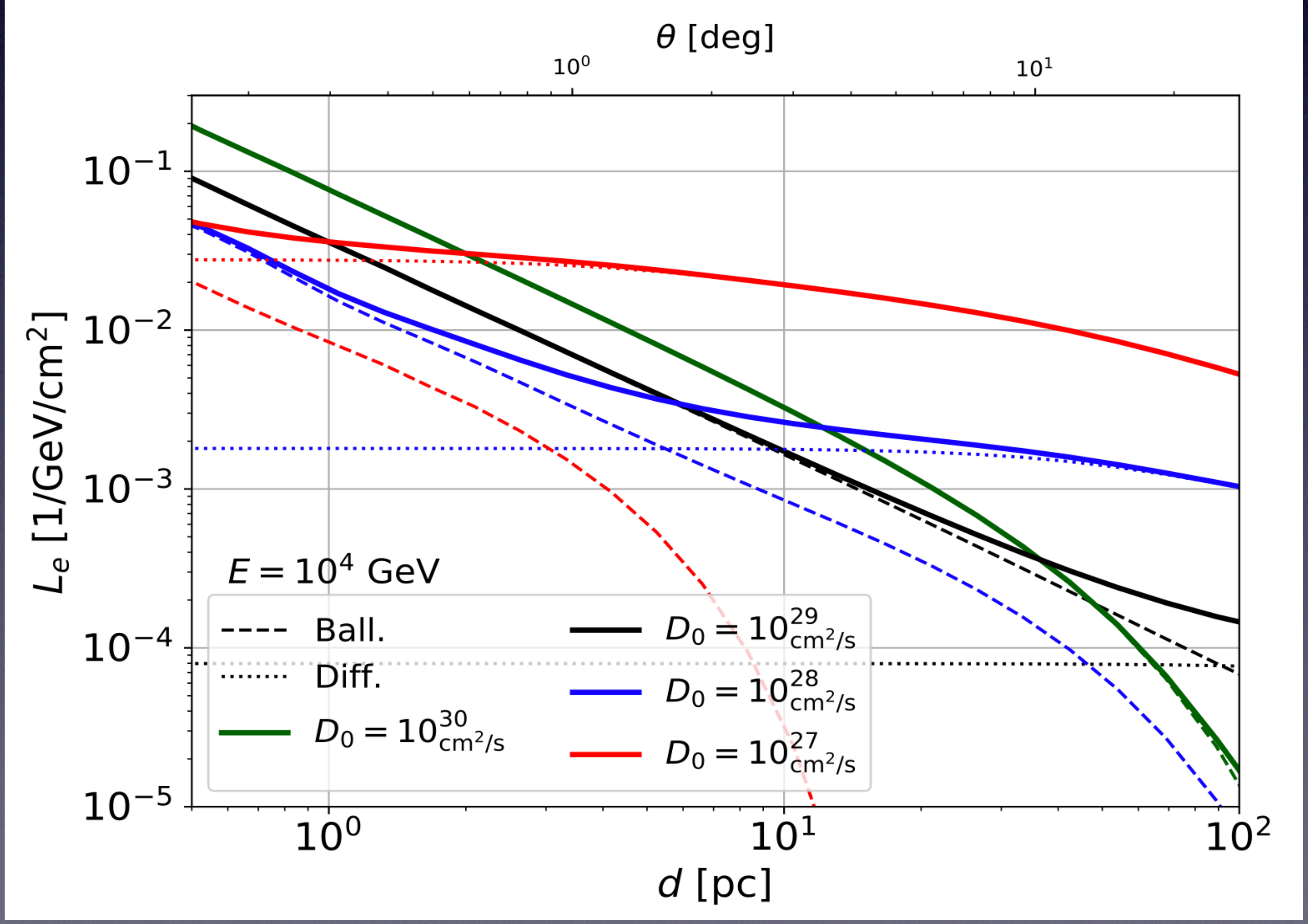


- Up to distances from the source $\sim \lambda_c$ the electron distribution around the pulsar is dominated by the most recently injected particles, that move quasi-ballistically:
$L_e \propto 1/d$

- Above $\sim \lambda_c$ 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 $d \approx \sqrt{4D(E)\tau_{loss}(E)}$

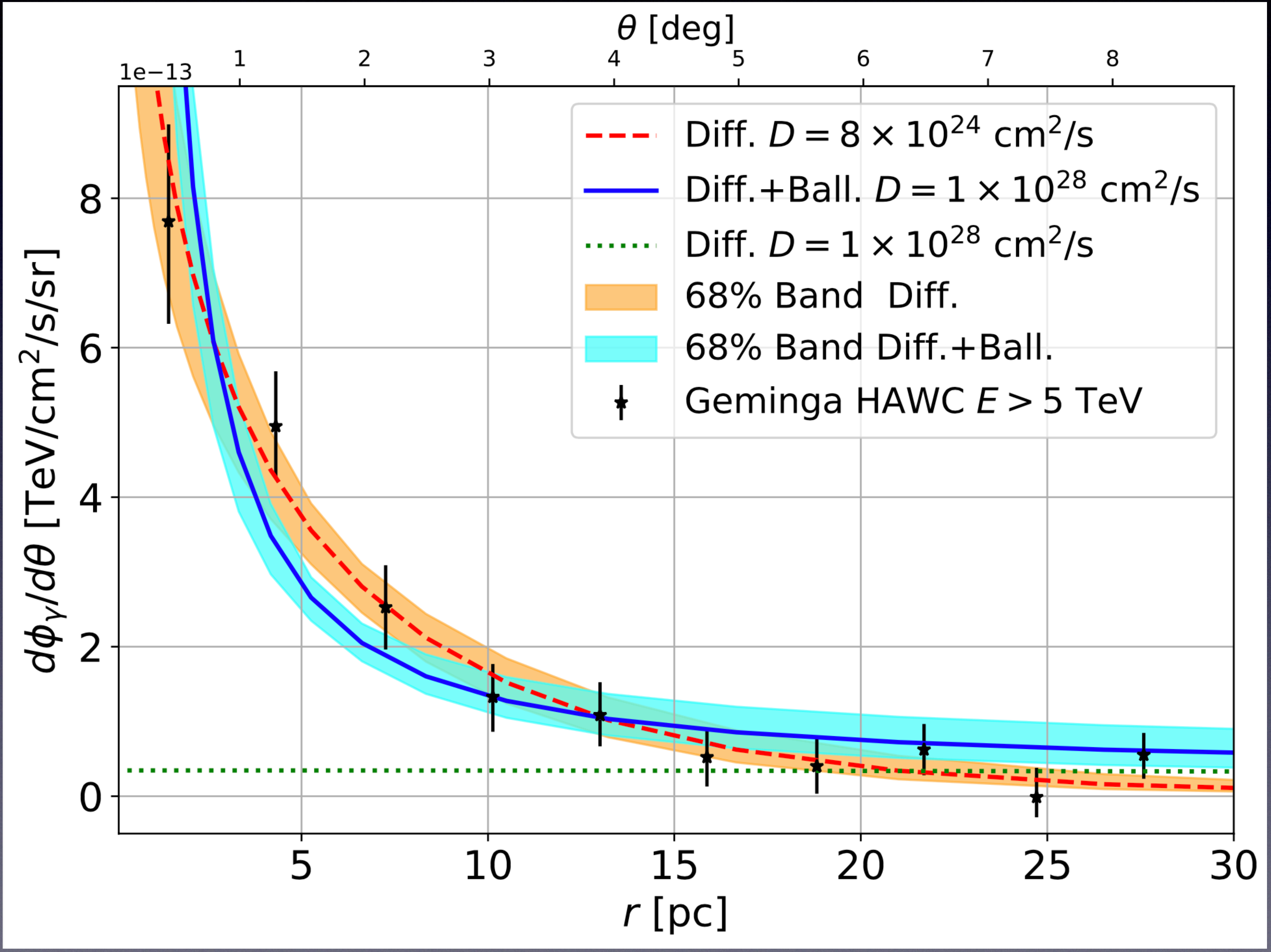
- The transition occurs at larger distances from the source for larger values of the diffusion coefficient.

- With a typical diffusion coefficient $D(1\ \text{GeV}) \sim 10^{28}$ cm²/s the source extension is connected to the transition between ballistic and diffusive propagation.
- In the low diffusion scenario $D(1\ \text{GeV}) \sim 10^{25}$ cm²/s the extension of pulsar halos is connected to the diffusion-loss length $d \approx \sqrt{4D(E)\tau_{loss}(E)}$.

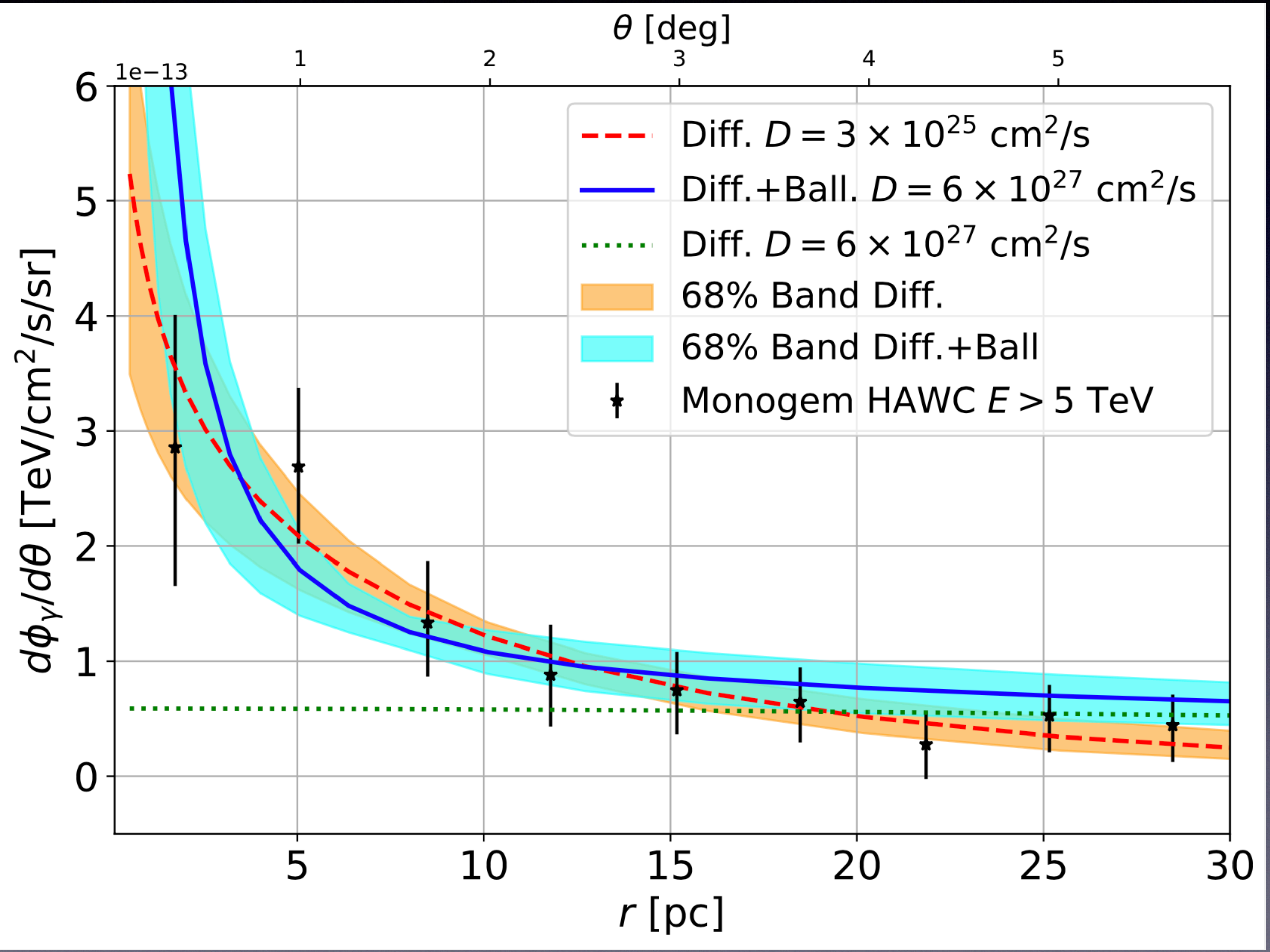


- The transition takes place very close to the pulsar and the gamma ray morphology is not affected by such effect.

Geminga, $T = 342$ kyr, $d = 0.19$ kpc

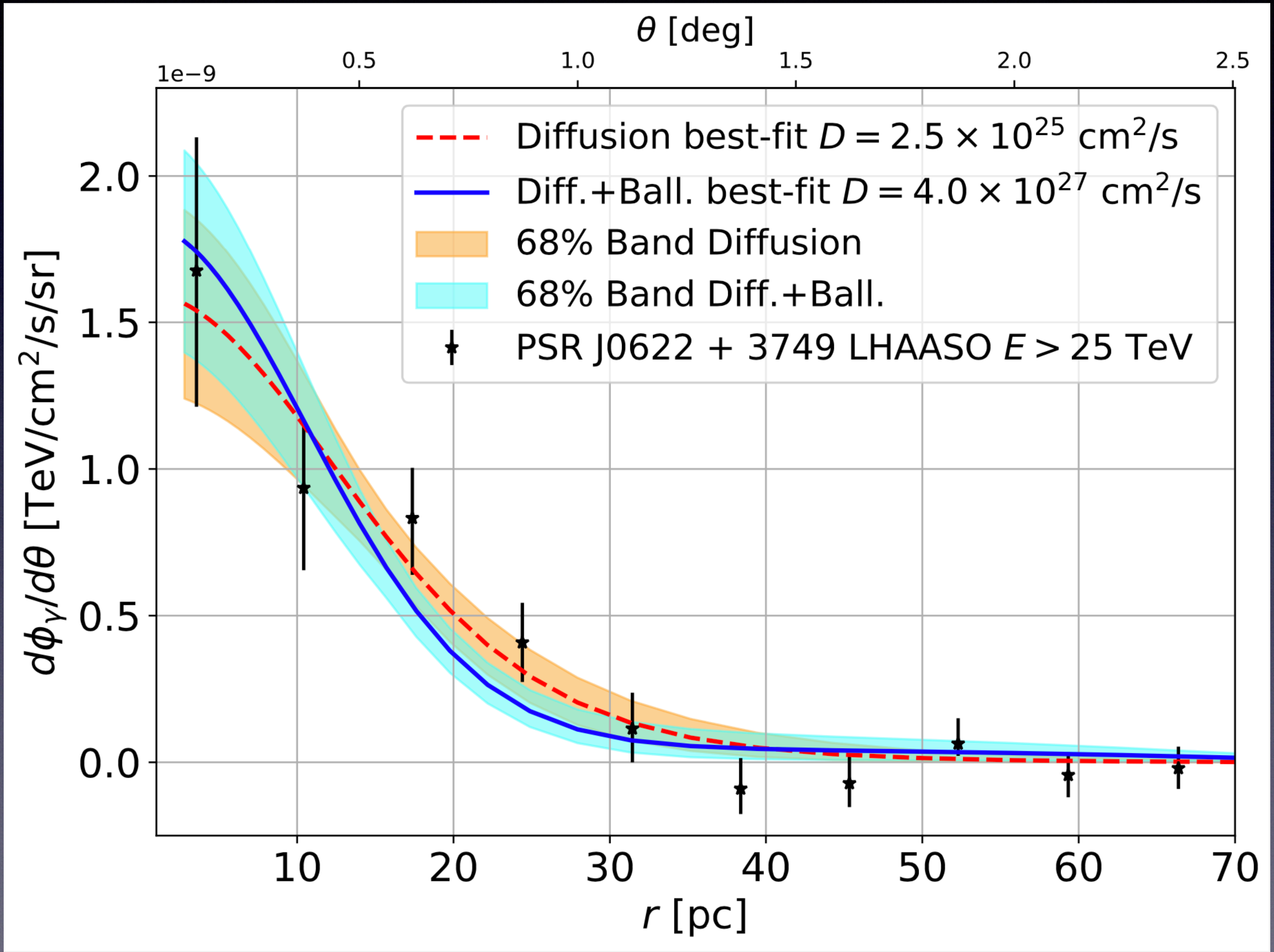


Monogem, $T = 111$ kyr, $d = 0.28$ kpc

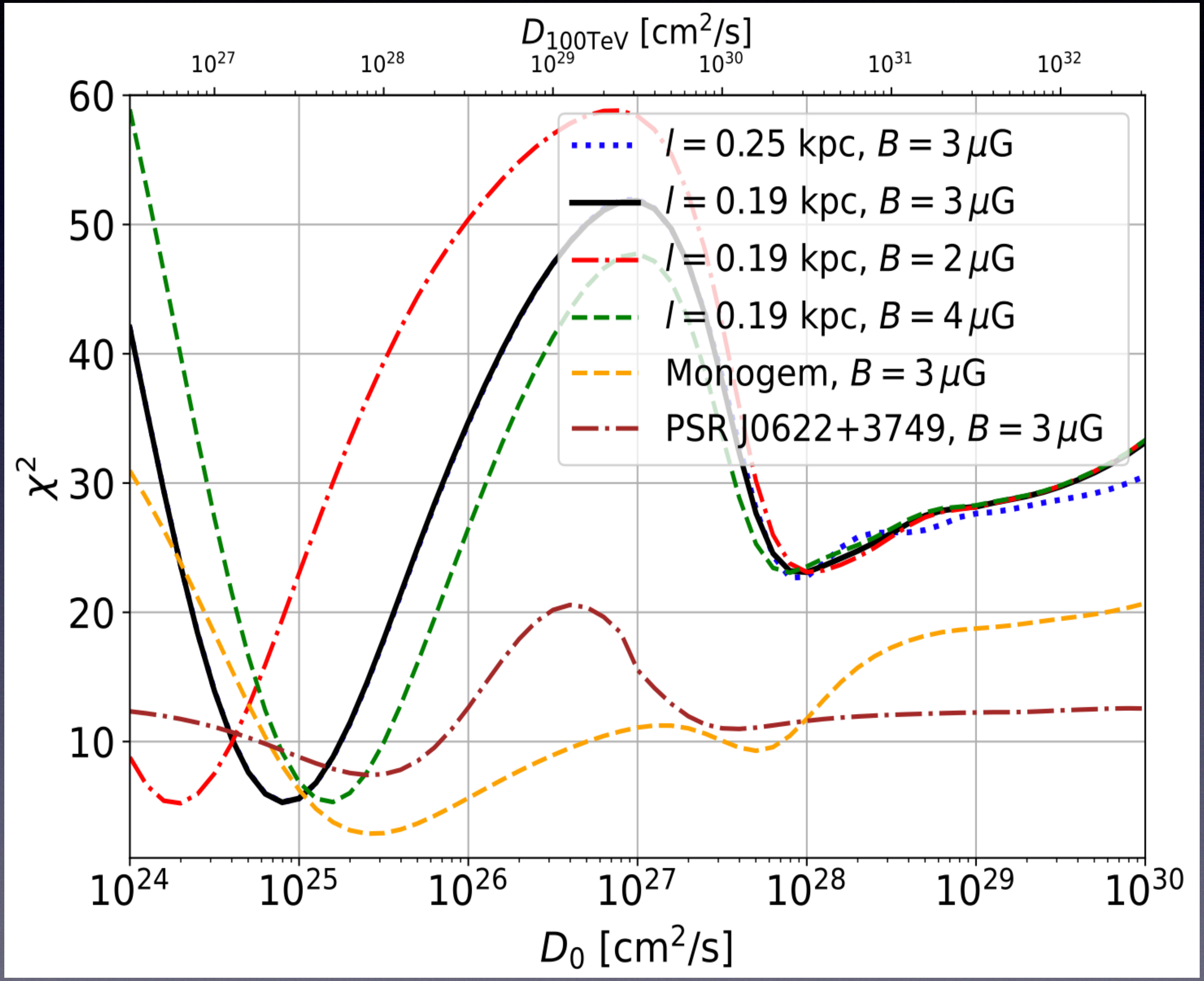


7. Fit to the data

PSR J0622+3749, $T = 208$ kyr, $d = 1.60$ kpc



7. Fit to the data



In the low diffusion scenario:

$\eta \sim 2 - 10\,\%$

In the typical diffusion scenario:

- Geminga:

  $\eta \sim 180 - 200\,\%$

- Monogem:

  $\eta \sim 60 - 100\,\%$

- PSR J0622+3749:

  $\eta \sim 40 - 100\,\%$

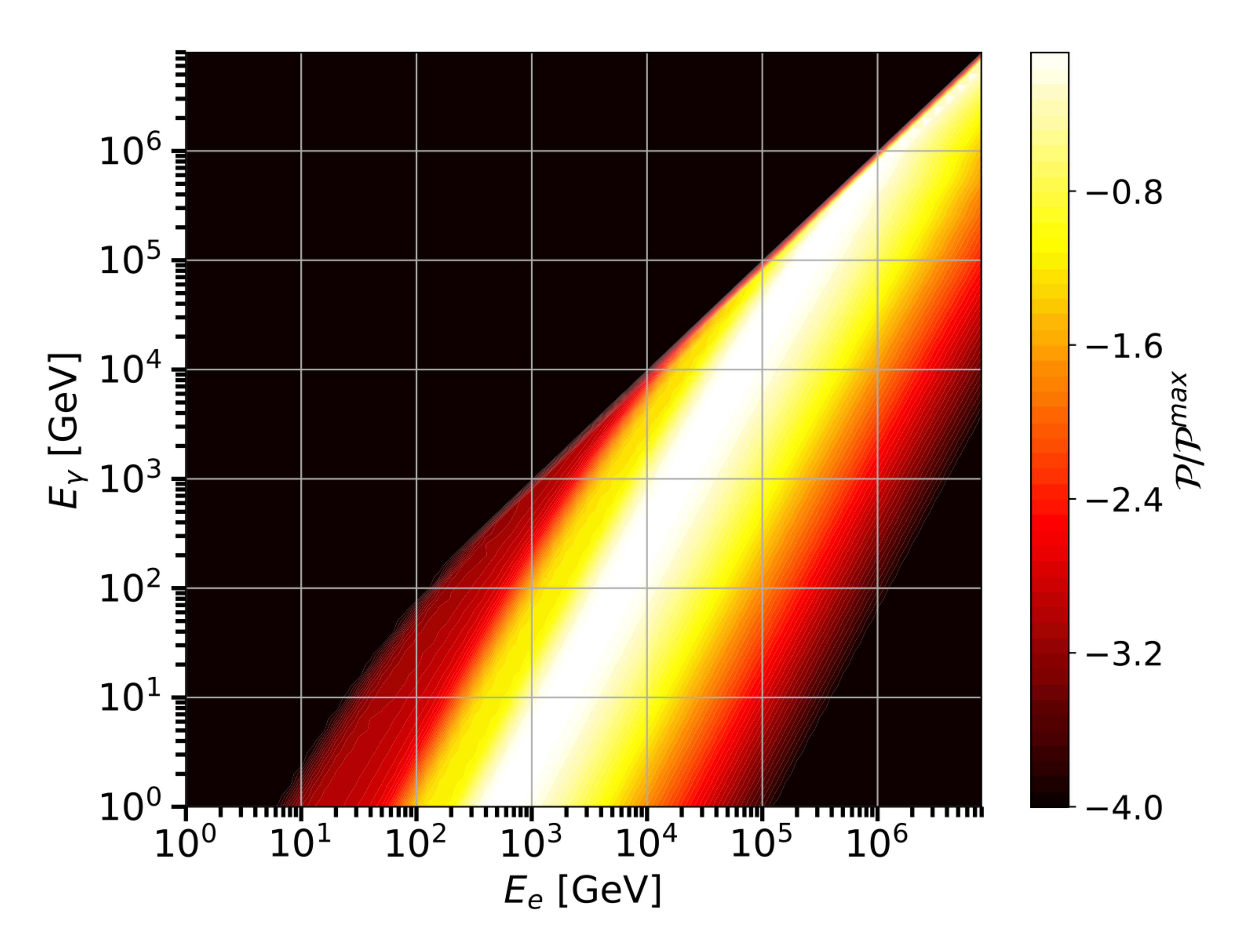
8. Efficiency

- Purely diffusive produces a flatter L_e at small distances from the source, while in the quasi-ballistic regime L_e is steeper at the same distances.
- The energy range of $e^{\pm}$ injected by pulsars is not precisely known.
- The spectral shape of the $e^{\pm}$ injected from PWNe is not well known, and the best-fit value of the efficiency can change for different spectral parameters.
- The way of treating mathematically the transition between ballistic and diffusive regimes and the form of the function $M(\mu)$ can lead to slightly different best-fit values for the diffusion coefficient and efficiency.
- In this model particles escape isotropically from the source and undergo isotropic diffusion. This description may break down within a few pc from the source, where the magnetic flux tube encompasses the source and the propagation change from 1-dimensional anisotropic to a 3-dimensional isotropic propagation.

9. Conclusions

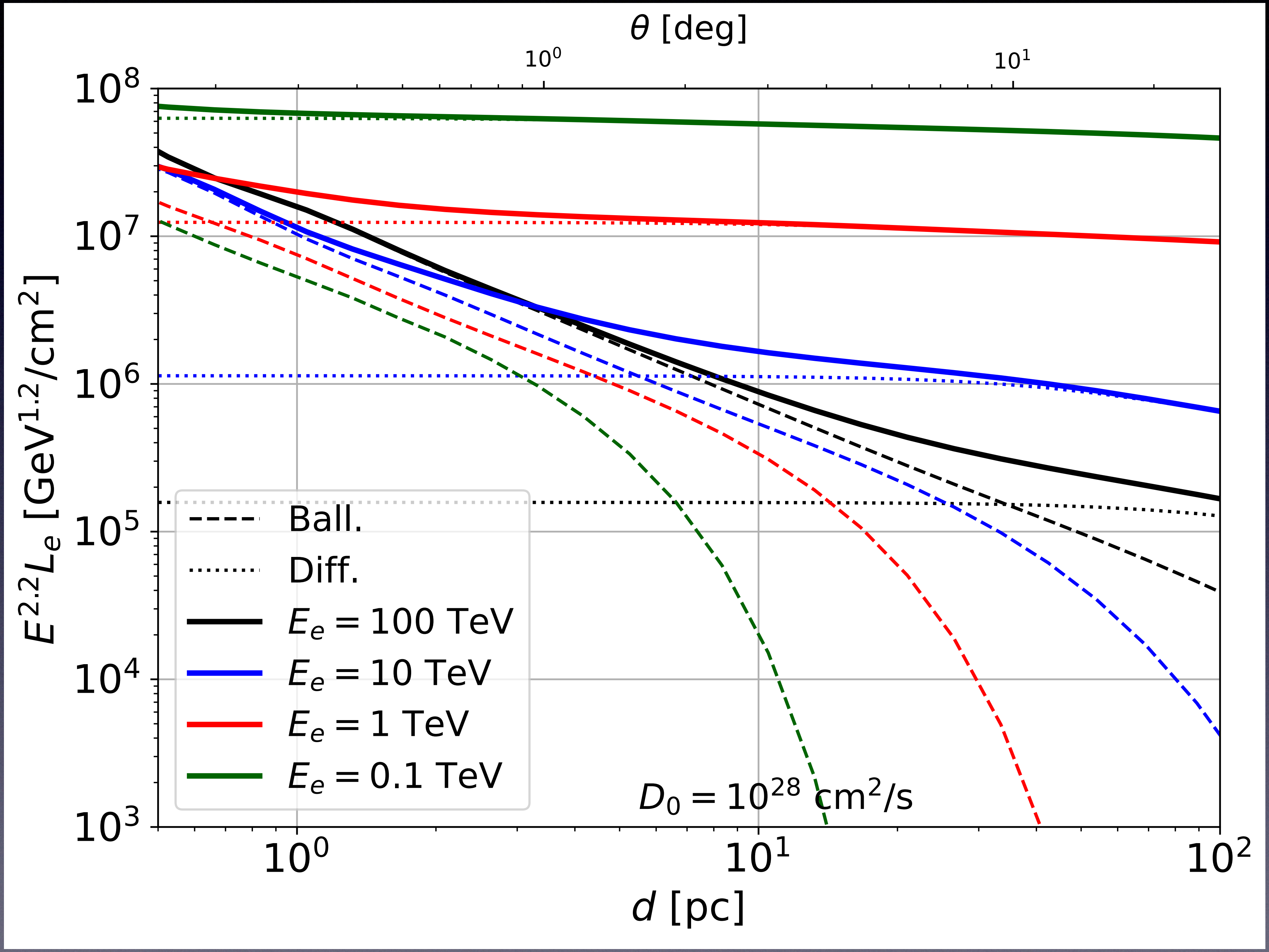
- We investigated the propagation of CR released from pulsars taking into account the ballistic-diffusion transition.
- When such effect is taken into account, a satisfactory fit of the HAWC data for Geminga and Monogem and LHAASO data for PSR J0622+3749 is obtained without invoking a suppression of the diffusion coefficient with respect to the typical interstellar value.
- Besides the final results, the correct way to analyze the ICS halos include also the ballistic regime. The exclusion of this aspect forbid a good fit to the data with standard diffusion coefficient.
- Partial issue: high efficiencies.

10. Backup



Di Mauro et al. 2020

10. Backup



θ [deg]
10^0
10^1
10^8
10^7
10^6
10^5
10^4
10^3
$E^{2.2}L_e$ [GeV$^{1.2}$/cm^2]
Ball.
Diff.
$E_e = 100$ TeV
$E_e = 10$ TeV
$E_e = 1$ TeV
$E_e = 0.1$ TeV
$D_0 = 10^{28}$ cm^2/s
10^0
10^1
10^2
d [pc]

Lepton ballistic density:

$$f_{ball}(r,E) = \int_{T-\tau_c}^{T} \frac{Q(E)L(T)}{4\pi c^3 (T-t_0)^2} \delta\left((T-t_0) - \frac{r}{c}\right) dt_0 = = \frac{Q(E)L(T)}{4\pi c r^2} H(\tau_c\, c - r)$$

Lepton diffusive density:

$$f_{\rm diff}(r,E) = \int_0^{T-\tau_c} dt_0 \frac{Q(E_0)L(t_0)}{\pi^{3/2} r_d^3(E,E_0)} \frac{b(E_0)}{b(E)} e^{-\frac{r^2}{r_d^2(E,E_0)}}$$

Normalization:

$$\int_0^T dt \int_{0.1\rm GeV}^{\infty} EQ(E,t)dE = \eta W_0$$

$M(\mu)$ and components:

$$M(\mu) = \frac{1}{Z(x)} \exp\left(-\frac{3(1-\mu)}{x}\right)$$

$$Z(x) = \frac{x}{3}\left(1 - \exp(-6/x)\right)$$

$$x(E) = rc/D(E) = 3\, r/\lambda_c$$

$$\mu = (l\cos(\theta) - s)/r$$

$$r(s,\theta) = \sqrt{l^2 + s^2 - 2\, l\, s\, \cos\theta}$$