Detecting and characterising pulsar halos with the Cherenkov Telescope Array

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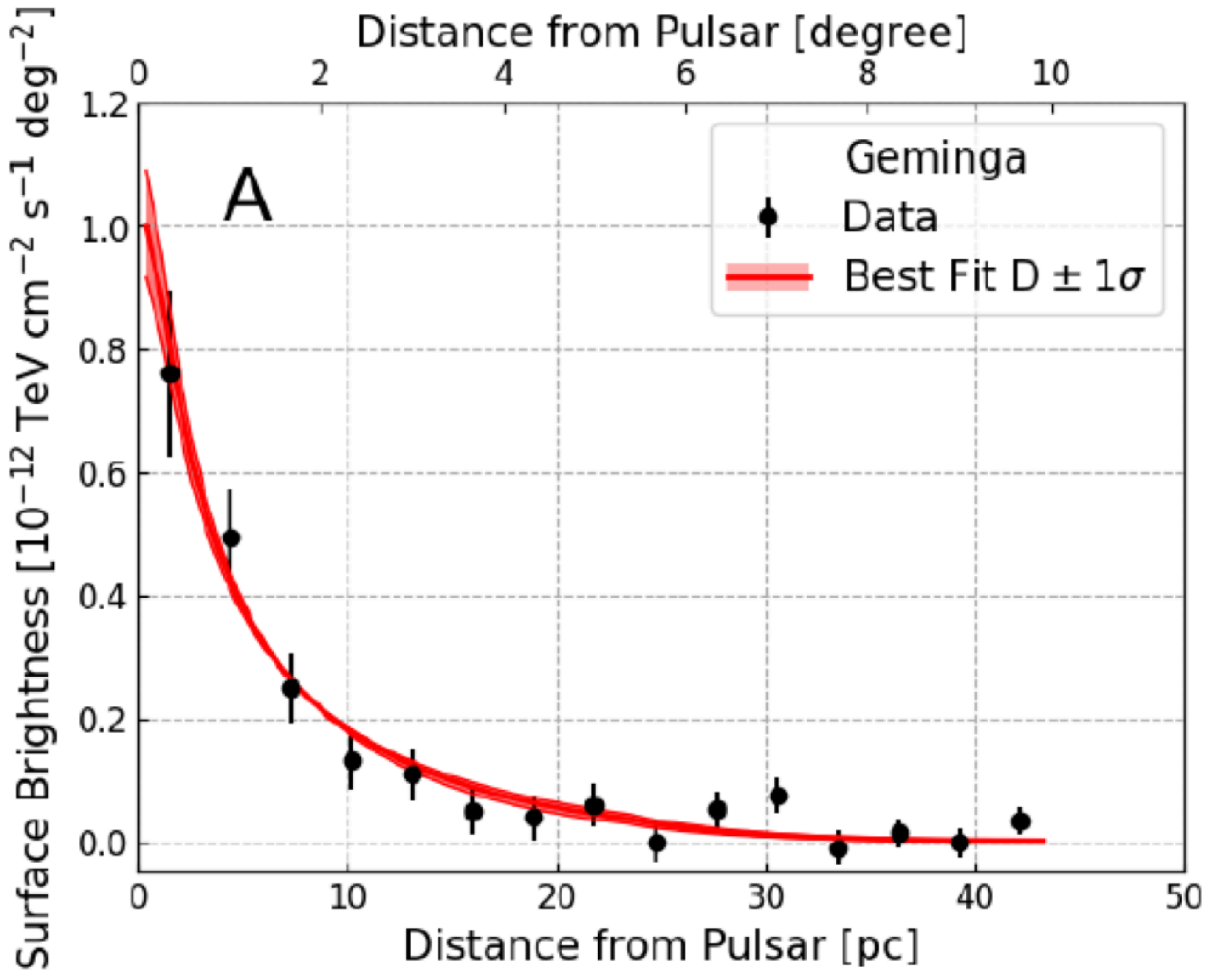
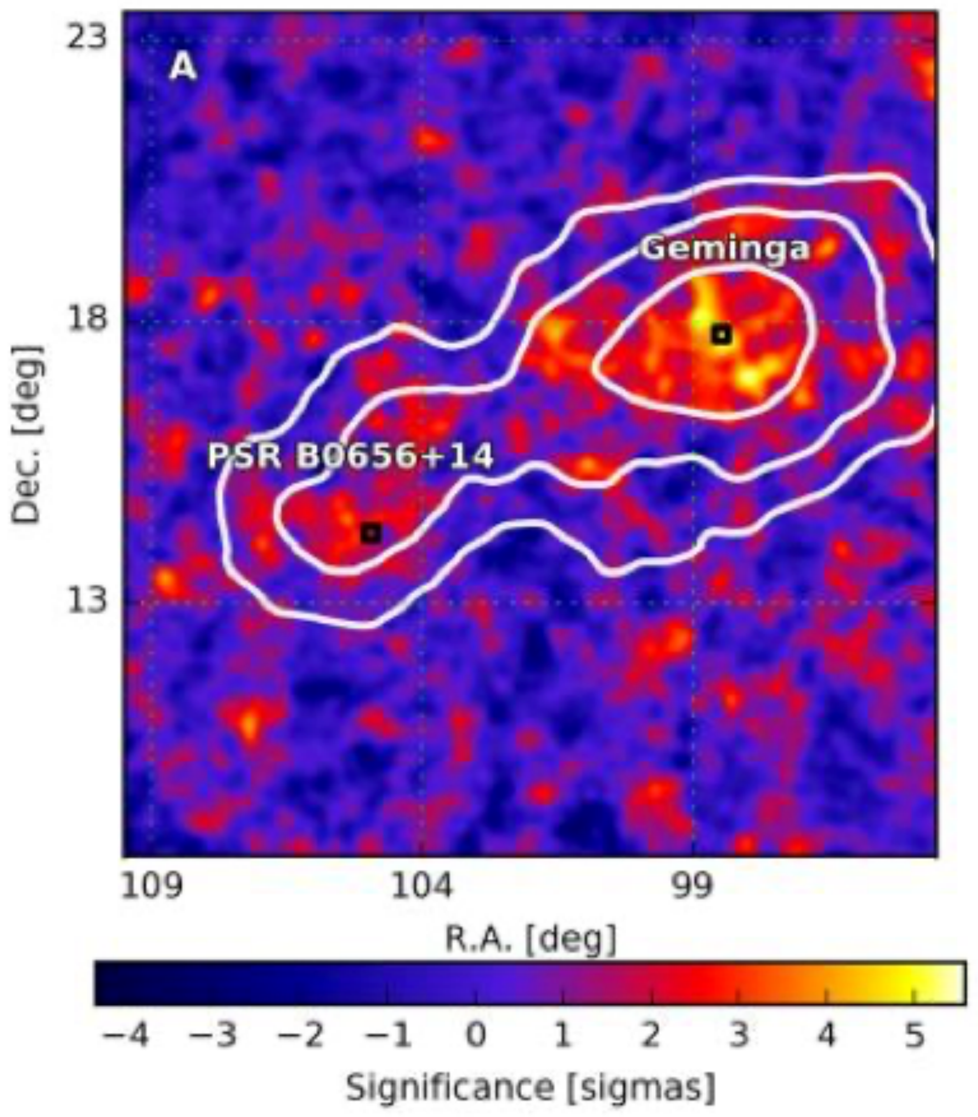
Introduction

Observations of nearby pulsars Geminga (J0633+1746) and B0656+14 with the HAWC observatory revealed that they are surrounded by multi-TeV gamma-ray emission spanning ~10°. [1] Gamma-ray emission around Geminga has also been detected with Fermi-LAT data. [2]

The properties of this extended emission can be accounted for from inverse-Compton scattering of ambient photons by electron-positron pairs efficiently confined over a physical extent of at least ~25 pc.



The HAWC Collaboration, *Science* 358, 911 (2017)



Pulsar halos might be a common feature of pulsars. This implies that many bright extended sources already detected may actually be halos, as well as that sub-threshold pulsar halos could possibly produce a significant fraction of TeV diffuse emission.

In this study, we examine the prospects offered by CTA for the detection and characterisation of pulsar halos.

[1] Abeysekara 2017, 1711.06223

[2] Di Mauro, Phys. Rev. D 100, 123015 (2019)

Cherenkov Telescope Array (CTA)

CTA is the next generation ground-based observatory for gamma-ray astronomy at very-high energies and will consist of an array of imaging atmospheric Cherenkov telescopes (IACTs) in the Southern and Northern Hemisphere. [3]

CTA will cover energies from 20 GeV to 300 TeV, bridging the ranges already probed with the Fermi Large Area Telescope and High Altitude Water Cherenkov Observatory. CTA will have an order of magnitude better angular resolution than the current IACTs at 1 TeV, thus providing a complementary look at pulsar halos.

Galactic Plane Survey (GPS)

The Galactic Plane Survey consists of a survey of the full Galactic Plane using both the Southern and Northern CTA observatories.

The GPS is expected to reach a typical sensitivity of ~6 mCrab. It has been proposed that more promising regions, such as for example the inner Galactic region (where -60° < l < 60°), will receive higher observation time, and with that deeper exposure than other regions.

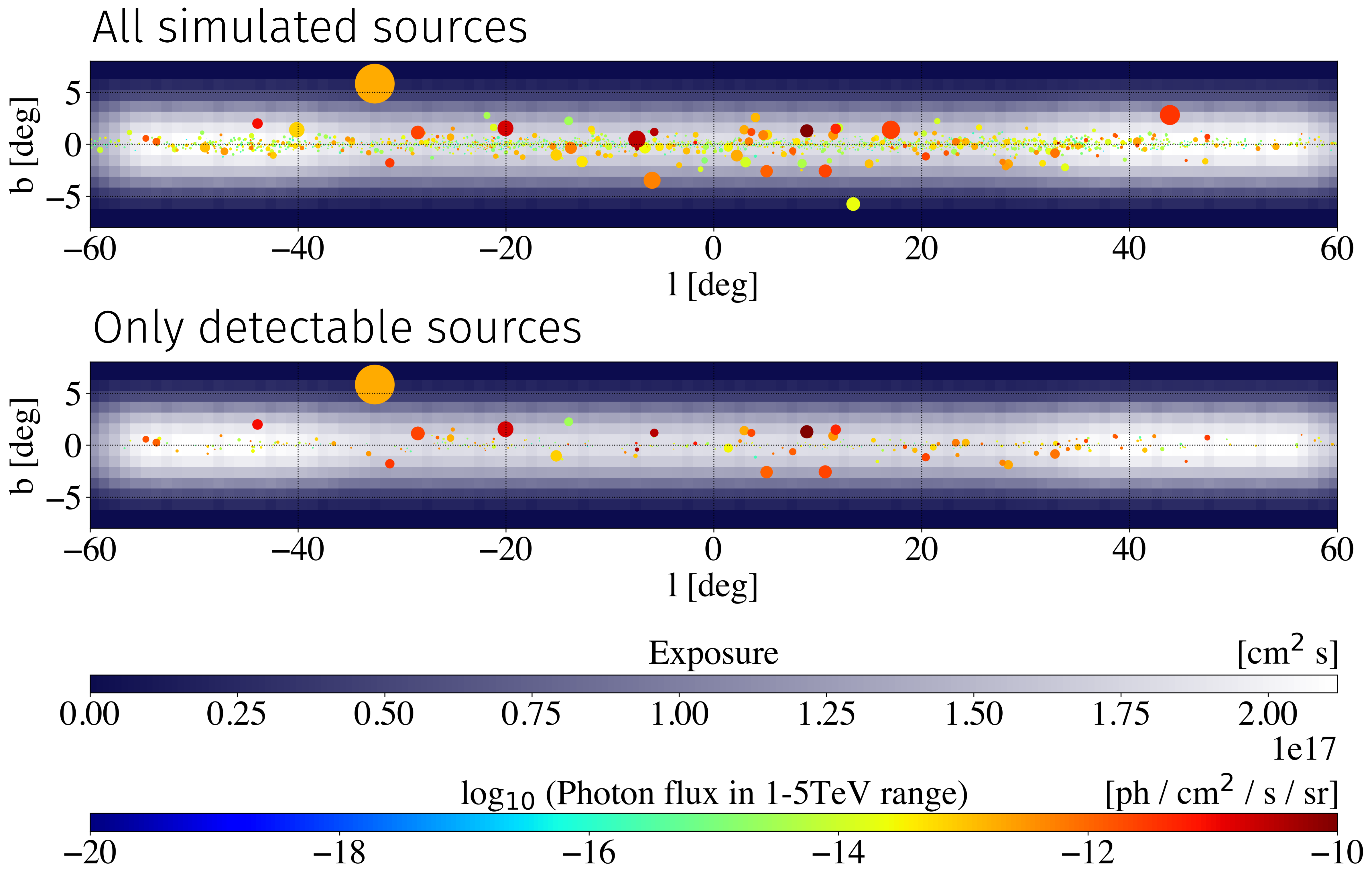


Figure 1: A synthetic pulsar halo population overlaid on an exposure map for the central regions surveyed in the GPS.

[3] The CTA consortium: Science with the Cherenkov telescope array, Feb 2018

GPS sensitivity to pulsar halos

cherenkov telescope array

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To derive the sensitivity, we use the planned GPS observations and the benchmark background model consisting of the cosmic-ray background (provided by *ctools*[1]) and an interstellar emission model (Base-Max [4]).

We simulated the pulsar halo emission following the physical model proposed in [2].

The properties of our baseline halo model:

- A pulsar with a current age of **200 kyr**, spin-down power of 10^{35} **erg s^{-1}**, and spin-down evolution with a braking index of **3**.
- Particle injection assumed to start **60 kyr** after pulsar birth and to last until the current pulsar age with a constant injection efficiency of **100%**.
- Injected particles have a constant broken power-law spectrum from **1 GeV** up to a cutoff at **1 PeV**, with indices **1.5** and **2.4** below and above a break at **100 GeV**.
- A suppressed diffusion region size r_{diff} = **50 pc** and a level of diffusion suppression in this region by a factor of **500**.
- The effects of proper motion on the halo morphology are neglected.

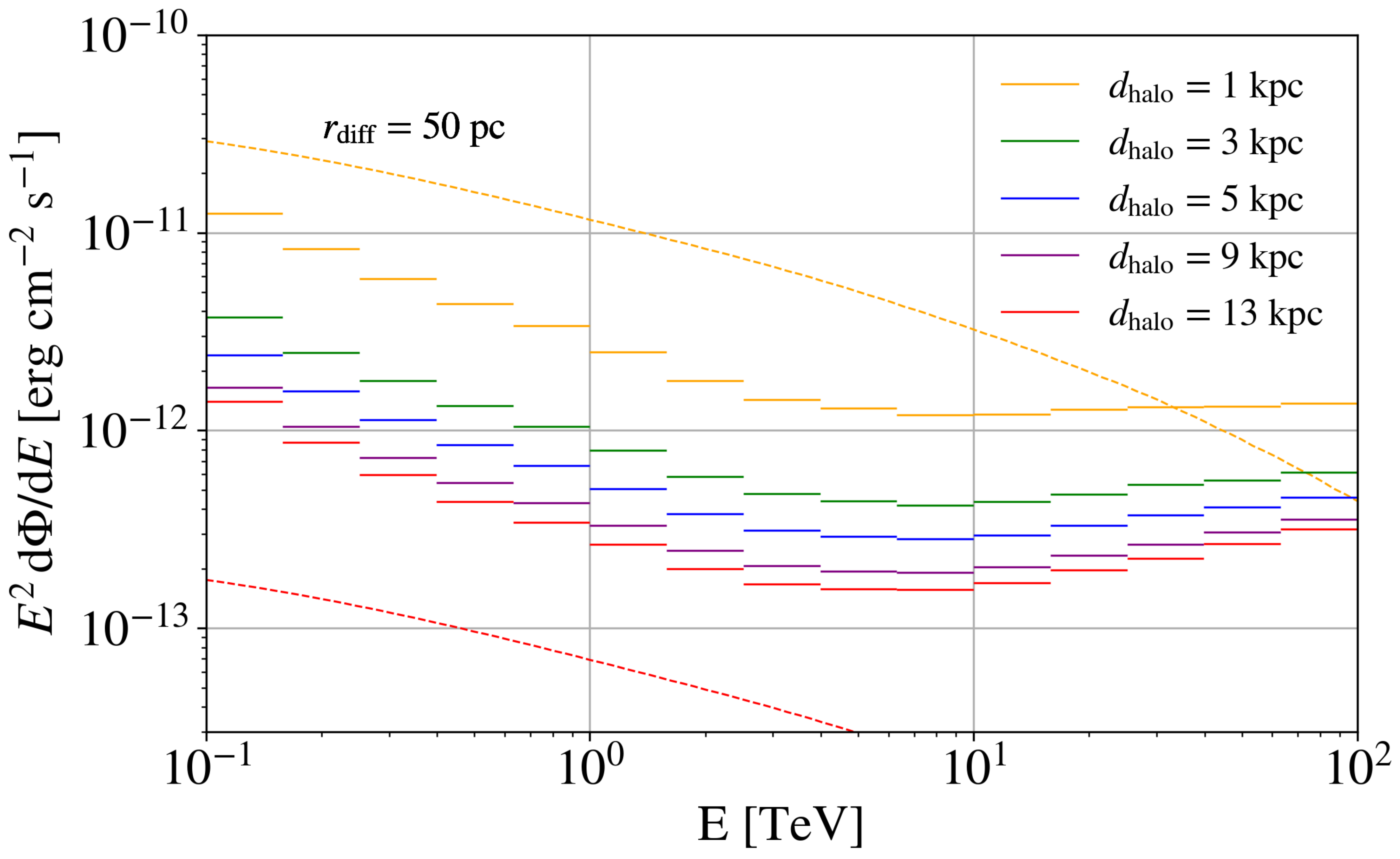

Figure 2: Differential spectral energy sensitivity to a baseline halo model, positioned at different distances from the observer. Results are shown for analysis focusing on a 6° region centred at (l, b) = (-10°, 0°), and are overlaid with the halo model intensities for halos at 1 and 13 kpc distance in orange and red dashed lines, respectively.

[1] We made use of the CTA instrument response functions provided by the CTA Consortium and Observatory, see https://www.cta-observatory.org/cta-performance-prod5/ and http://cta.irap.omp.eu/ctools/ for more detail.

[2] Di Mauro, 2019
[4] De La Torre Luque, 2022

The population study and angular sensitivity

We estimate the fraction of the halo population that should be detectable with CTA, assuming Geminga-like diffusion properties and supposing that all middle-aged pulsars develop a halo.

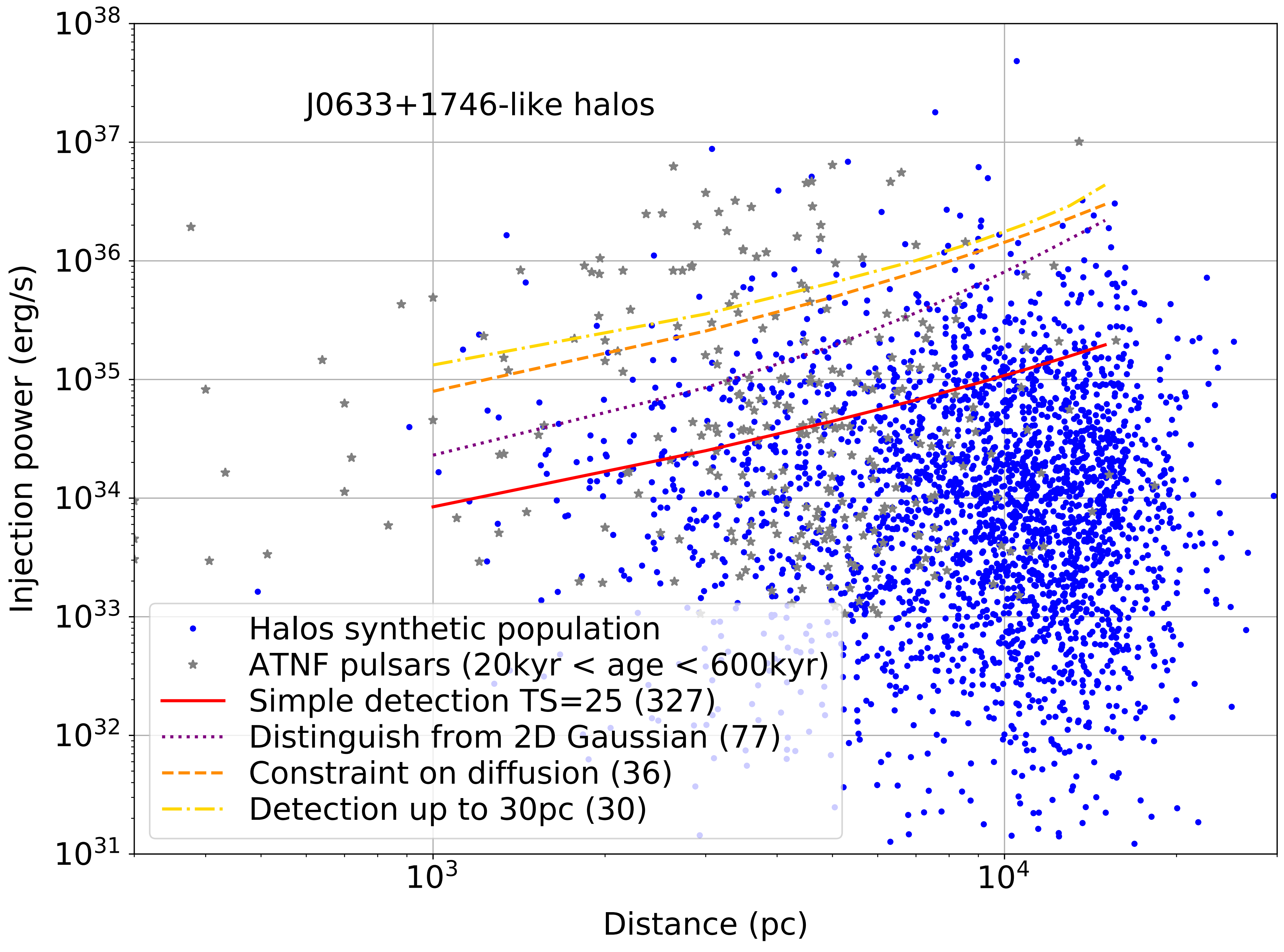

Figure 3: Sensitivity of the survey in terms of particle injection power as a function of distance. For each sensitivity curve, the numbers in parentheses indicate the number of mock halos lying above the curve.

We examine the following criteria:

1. Injection power such that the simulated halo signal is detected with a TS of 25 over the full energy range, using the true halo model in the fit process.
2. Injection power such that a fit of the simulated halo signal with the true halo model is significantly better than a fit with a simple energy-independent 2D Gaussian intensity distribution.
3. Injection power such that a fit of the simulated halo signal with the true halo model is significantly better than a fit with the true model clipped beyond a distance of 30 pc from the pulsar.
4. Injection power such that a fit of the simulated halo signal with the true halo model is significantly better than a fit with an alternative halo model having a 50% higher suppressed diffusion coefficient.

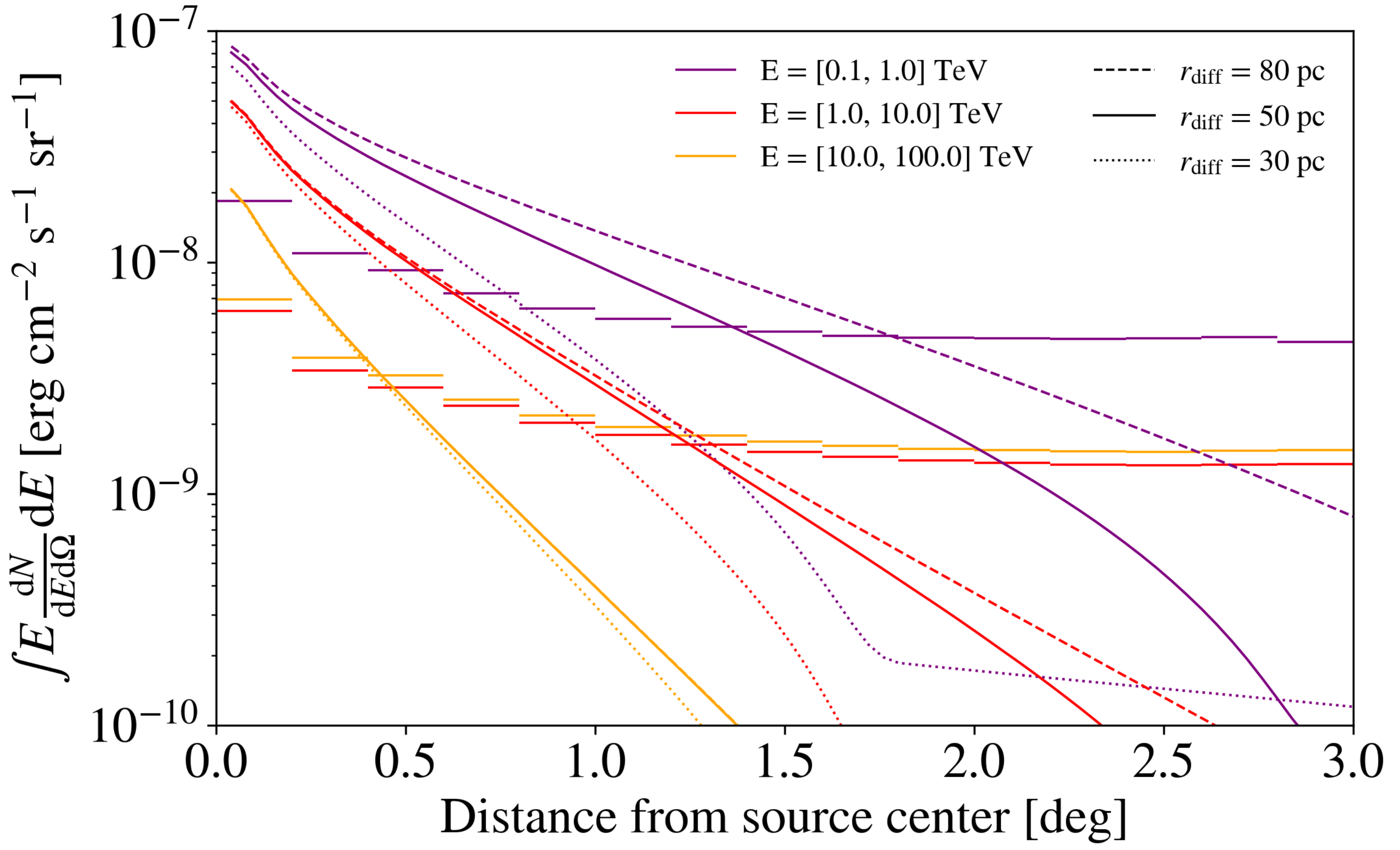

Figure 4: Model independent angular sensitivity studied under the conditions of the GPS, overlaid with the baseline halo model with a diffusion zones of 30/50/80 pc. The sensitivity analysis is decomposed into annuli with a width of 0.2°, and split into three energy bands.

Effects of systematics and interstellar emission models

We examine the effects of considering different interstellar emission models (IEMs) and levels of systematic uncertainty in our analysis.

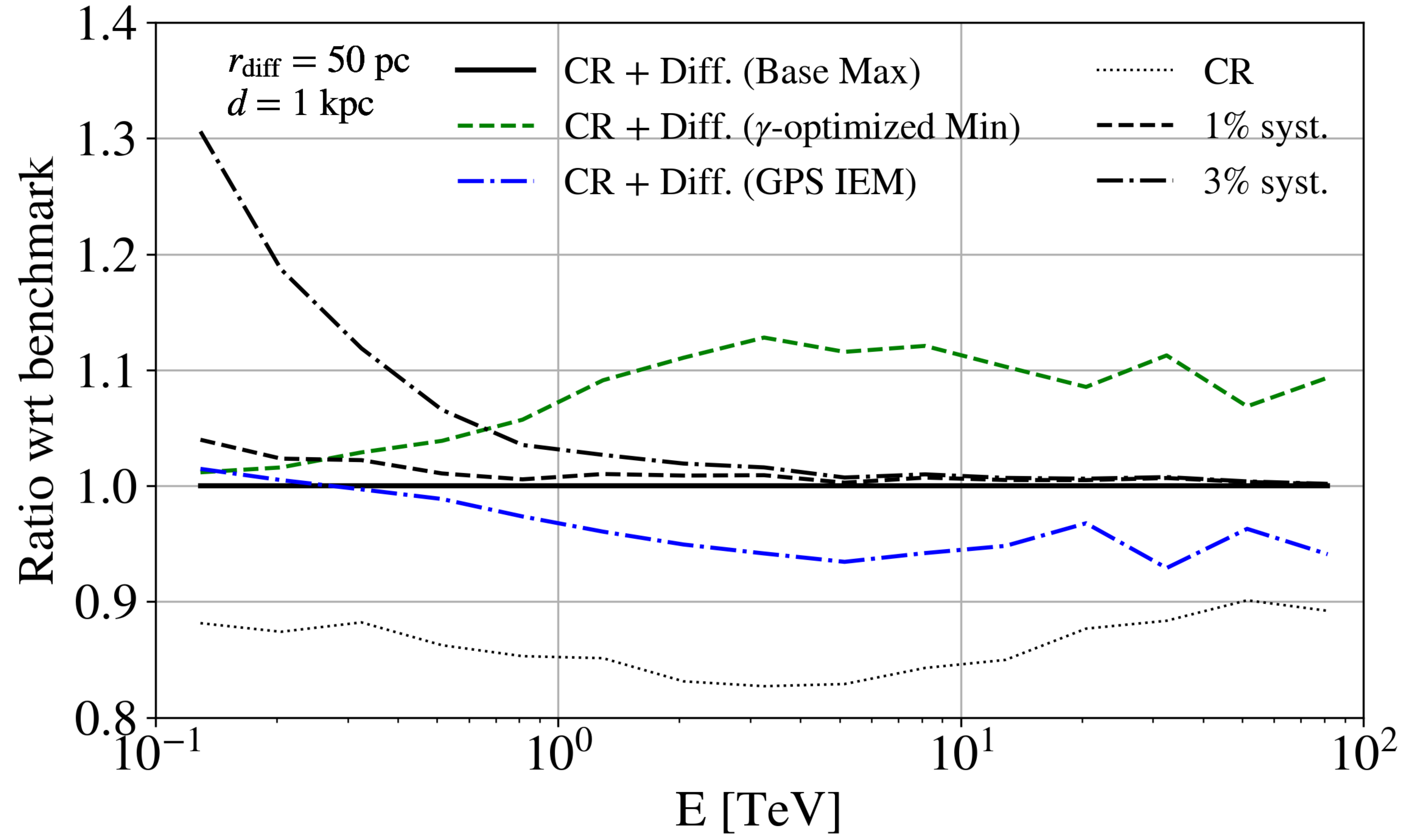

Figure 5: Differential sensitivity to our baseline halo model considering different diffuse emission models with respect to our benchmark background model (cosmic-rays + Base Max IEM). The dashed and dash-dotted black lines show the benchmark model sensitivity with added systematics of 1 and 3%, respectively.

Conclusions

- CTA promises good sensitivity to pulsar halo sources over whole CTA energy band, and represents a promising tool for answering open questions on the nature of pulsar halos.
- Preliminary population studies show that:
  - ☆ about **300** pulsar halos could be detectable,
  - ☆ ~**40** can be constrained in terms of diffusion coefficient,
  - ☆ ~**30** pulsar halos could be spatially resolved up to 30 pc.
- We also studied the impact of shallower halos that resemble the B0656+14 pulsar halo, of which ~70 could be detectable, and ~15 spatially resolved up to 30 pc.

Acknowledgements:
- This research was done with members of the CTA Consortium.
- This research made use of the CTA instrument response functions provided by the CTA Consortium and Observatory, see https://www.cta-observatory.org/cta-performance-prod3b-v2/ for more details.
- We made use of ctools (http://cta.irap.omp.eu/ctools/).
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