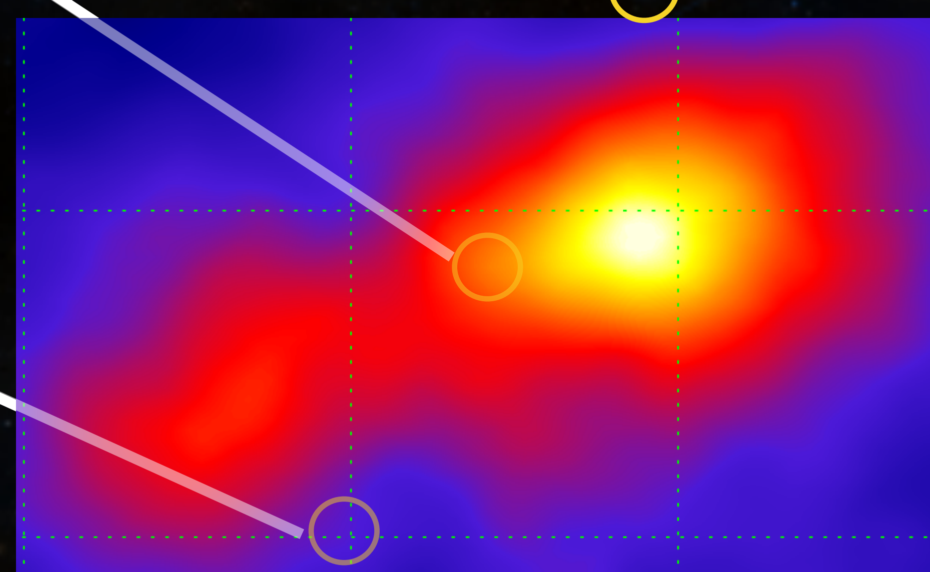
Constraints on cosmic ray propagation and magnetic fields using gamma-ray observations

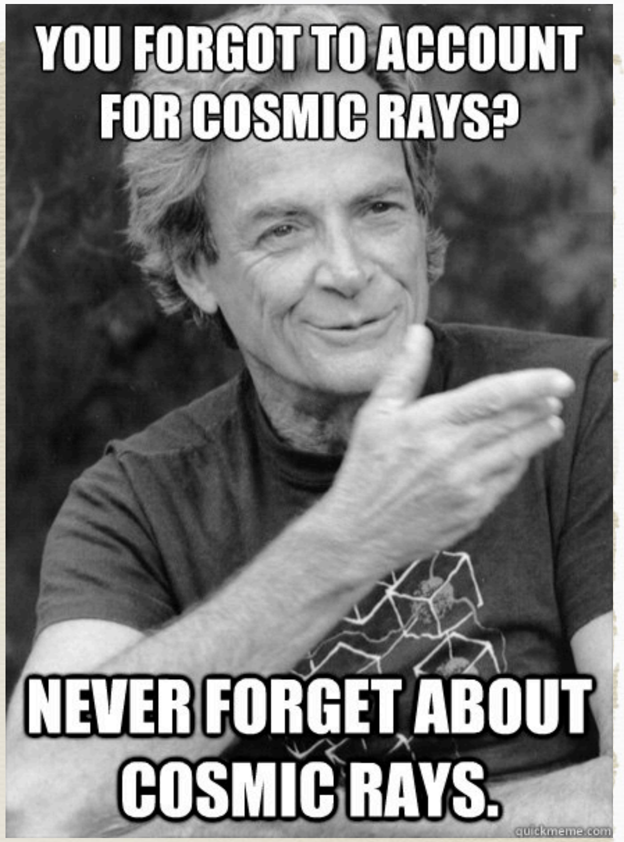


Rubén López-Coto - Istituto Nazionale di Fisica Nucleare, Sezione di Padova

Dark Mater Searches in the 2020s - Kashiwa, Japan - 13/11/19

Funded by H2020 Marie Sklodowska Curie FELLINI - Grant 754496

Outline



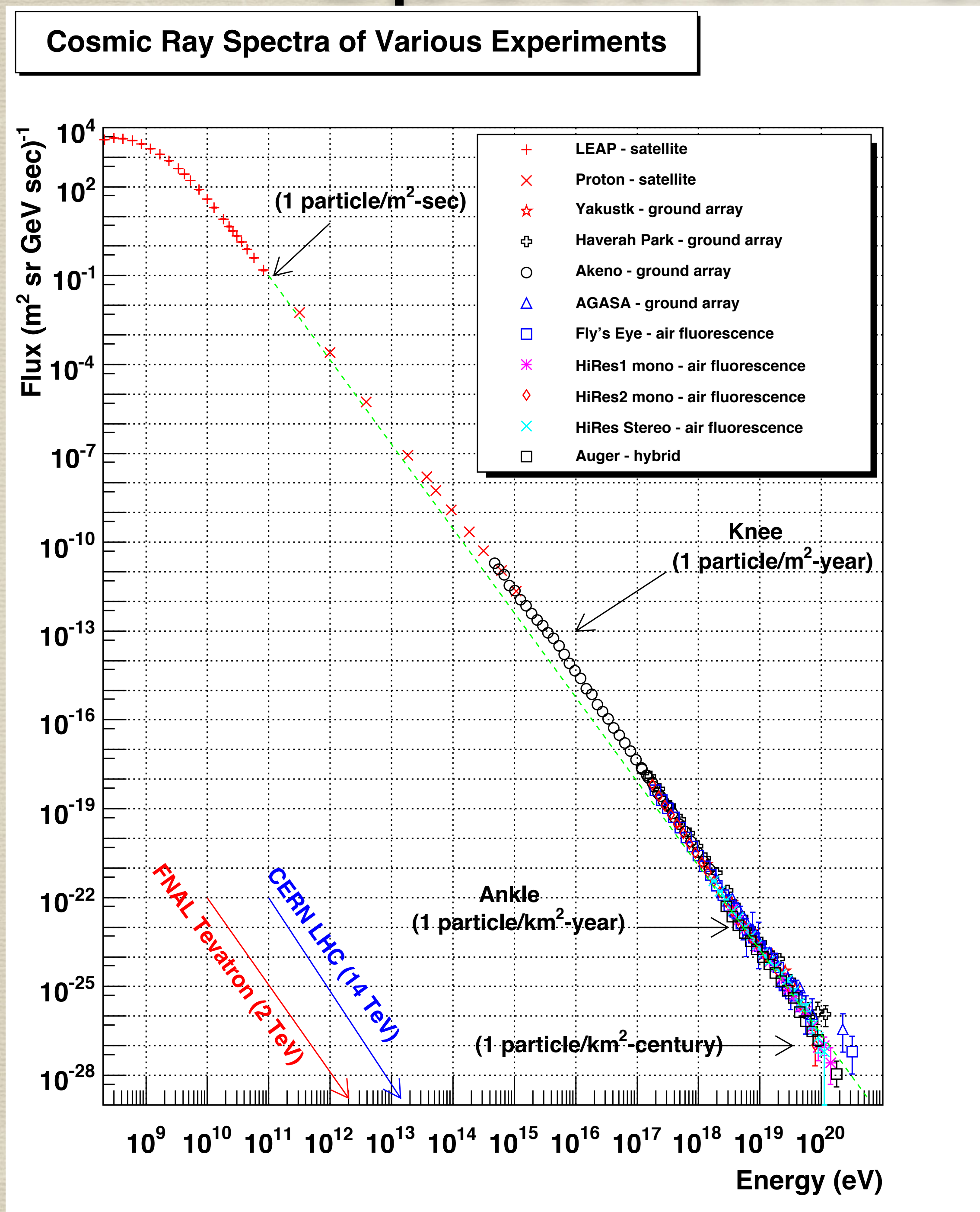
A few words about Cosmic Rays (CRs)

- Spectrum and composition
- CR propagation
- Hadronic CRs
- Electrons and positrons

Gamma-ray observations to study their propagation

- Satellites
  - Gamma-ray diffuse emission in the galaxy
- Imaging Atmospheric Cherenkov telescopes
  - Cosmic ray scape and acceleration in sources
- Water Cherenkov Detectors
  - Very extended gamma-ray sources

Cosmic rays
Spectrum and composition

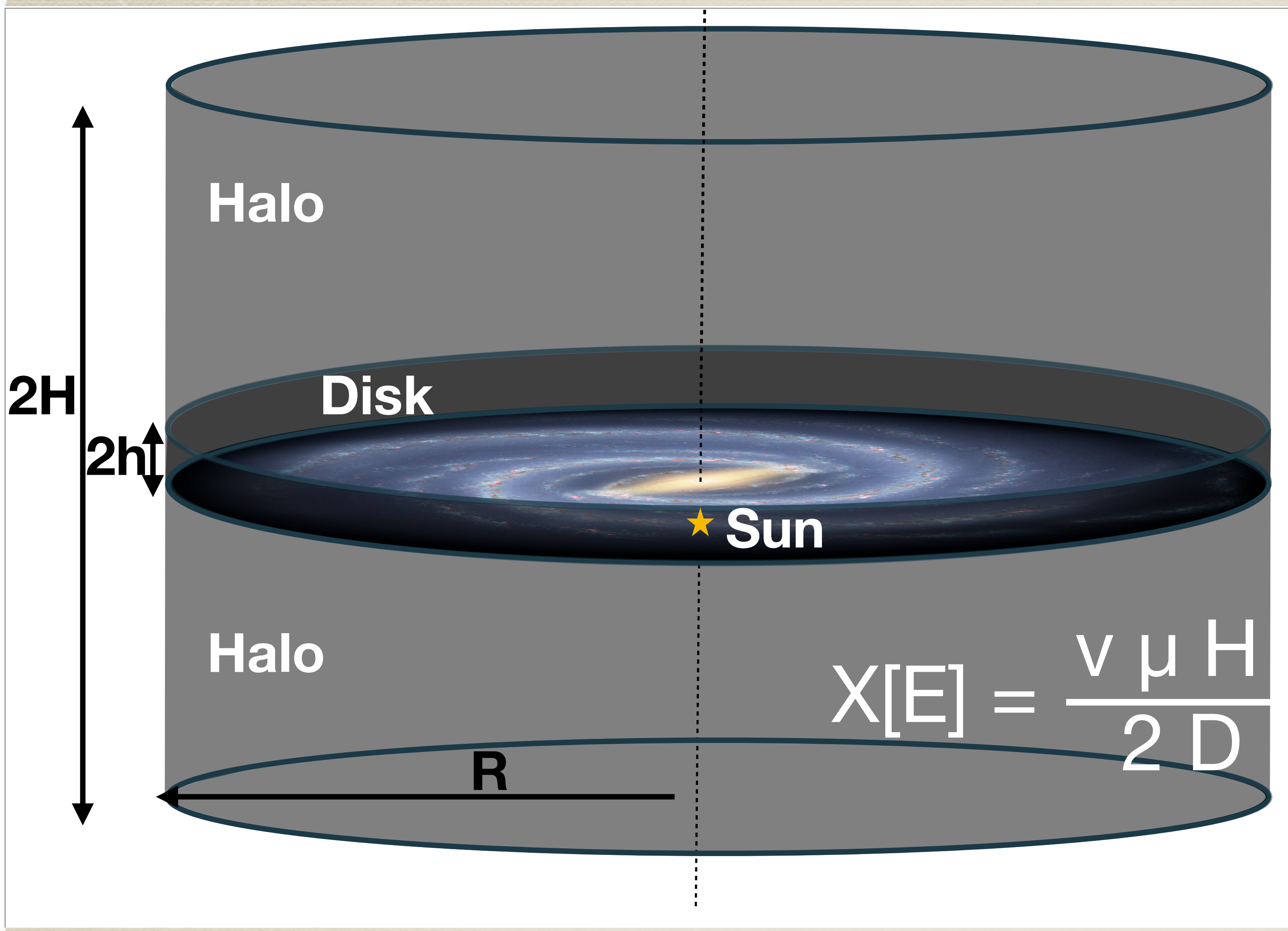


- Spectrum and composition measured by **satellites**, **balloons** and **extended air shower arrays.**

- Different origin:
  - Solar (E < 1 GeV)
  - Galactic (1 GeV < E < ~PeV)
  - Extragalactic (E > PeV)

- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, …

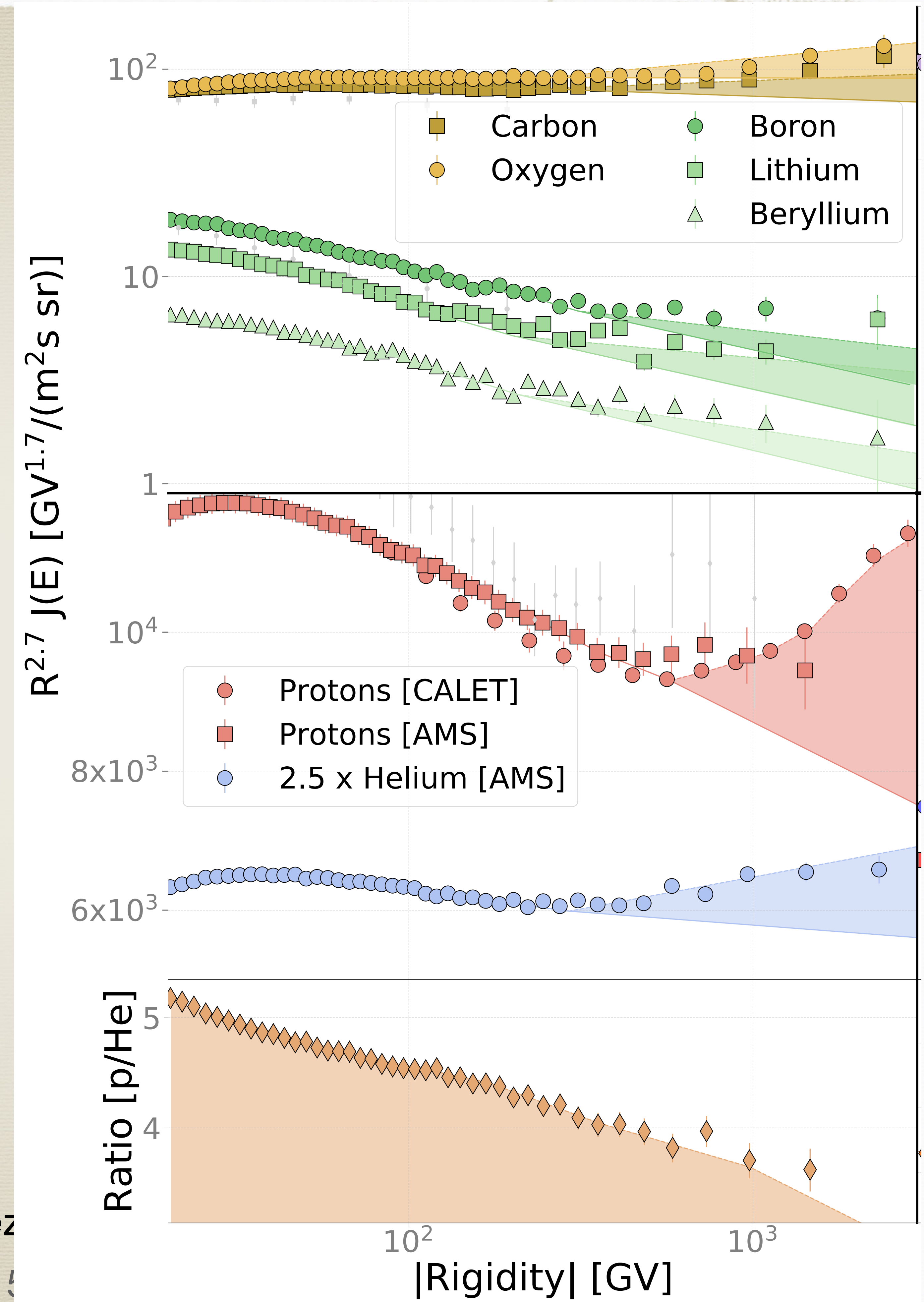
Cosmic Ray propagation



- CRs diffuse in the galactic *disk* (the region where the gas is contained) and *halo*
- Galactic winds and reacceleration are also suffered by CRs
- Grammage X ~ 10 g/cm^2 at 1 GeV/nucleon

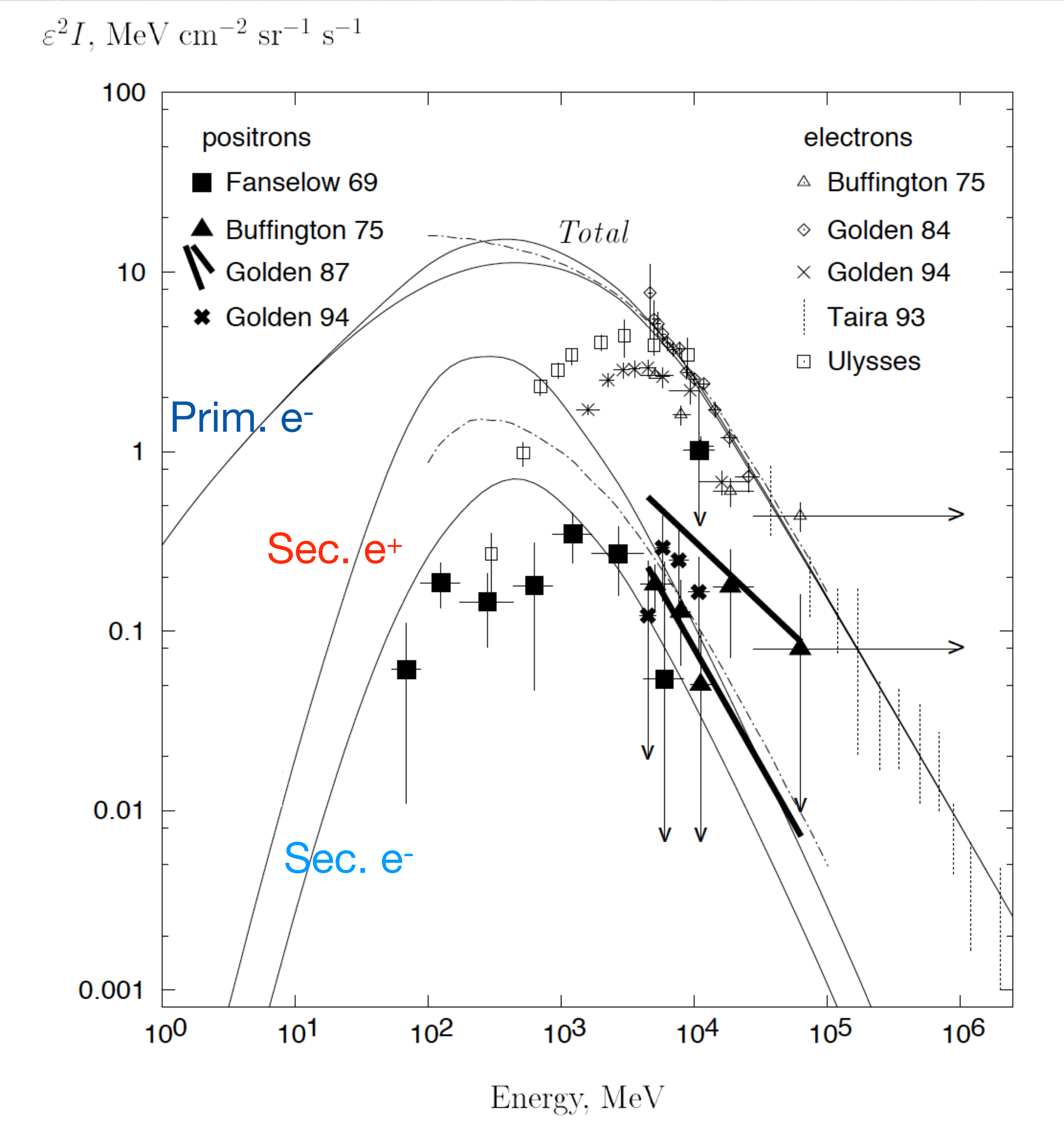
Hadronic fluxes

- Hardening of primary and secondary fluxes at ~200 GV fluxes
  - Propagation effect?
- Hardening of proton and Helium spectrum at different rigidities
- Decrease of the proton to Helium ratio
  - Against Diffusive Shock Acceleration theory



Rubén López

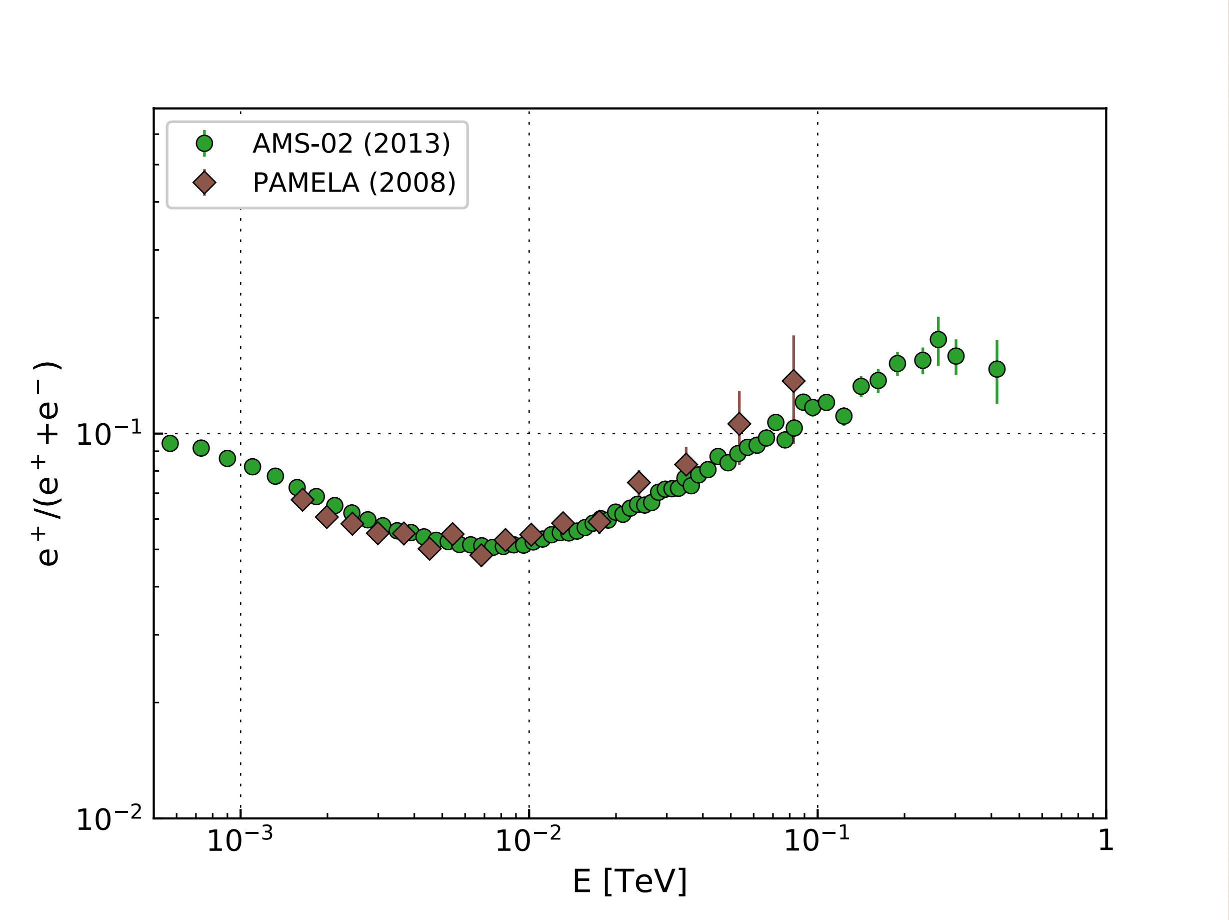
Positrons and Electrons



Primary electrons are produced in astronomical sources such as Supernova Remnants

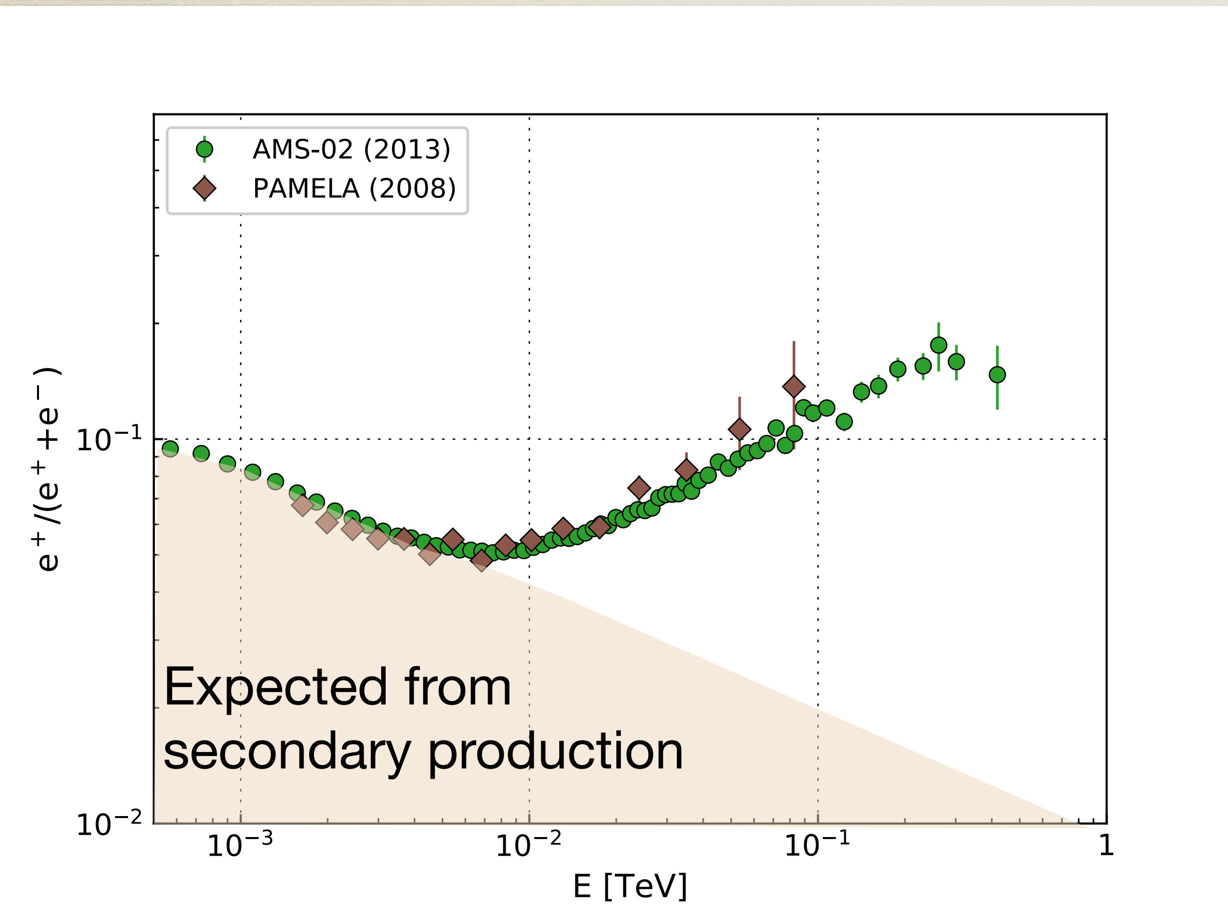
Secondary electrons and positrons are produced in cosmic ray collisions

Positron Fraction



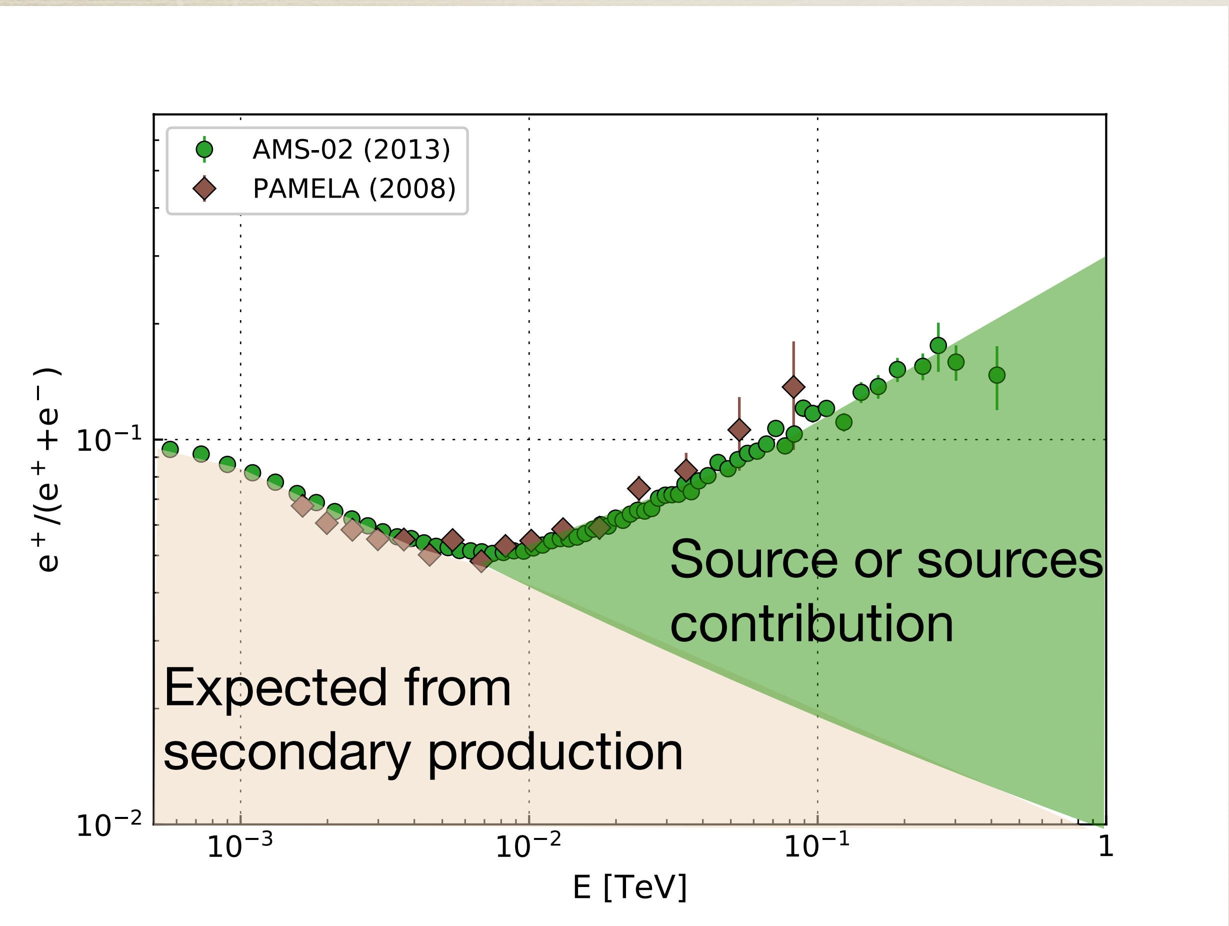
- The positron fraction is expected to decrease with Energy

Positron Fraction



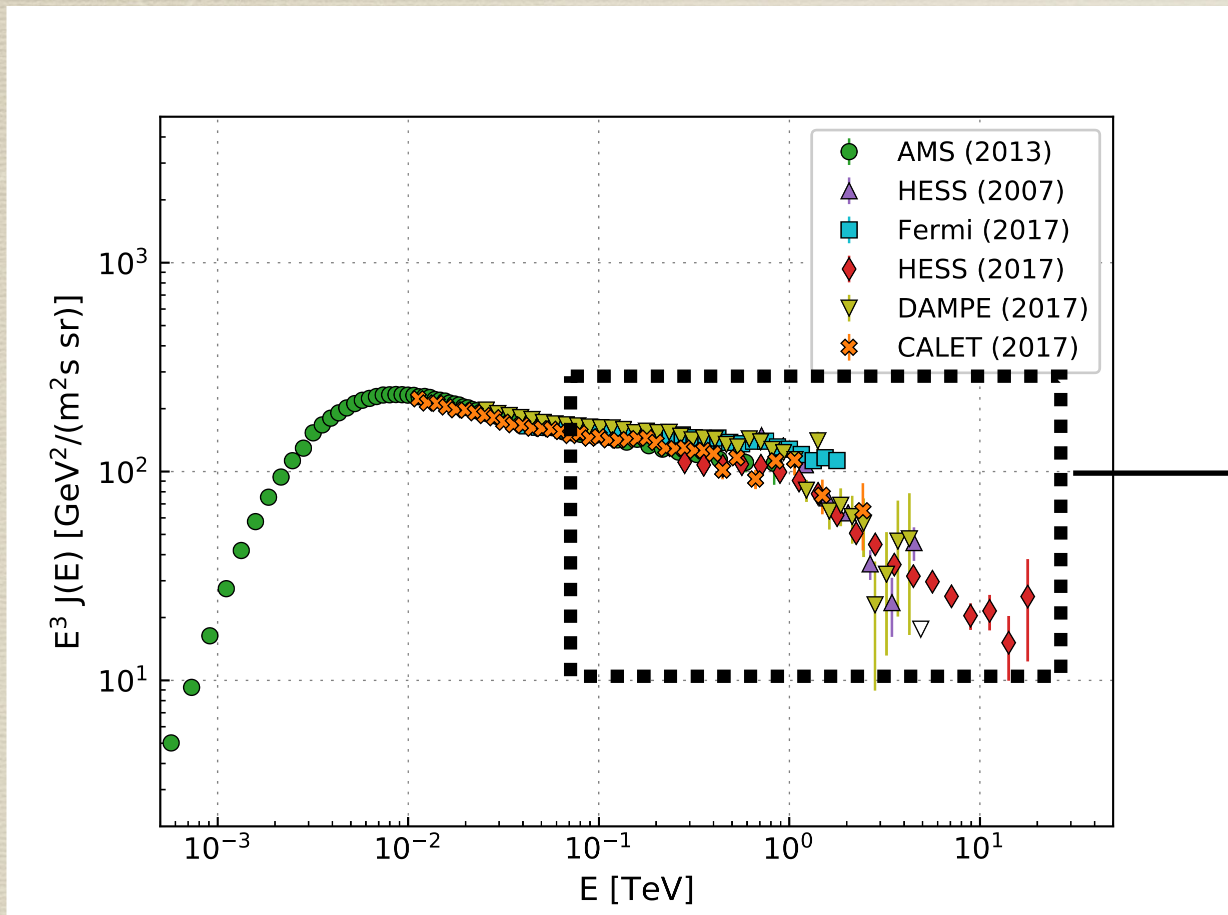
- The positron fraction is expected to decrease with Energy
  - This is the case for energies below a few GeV

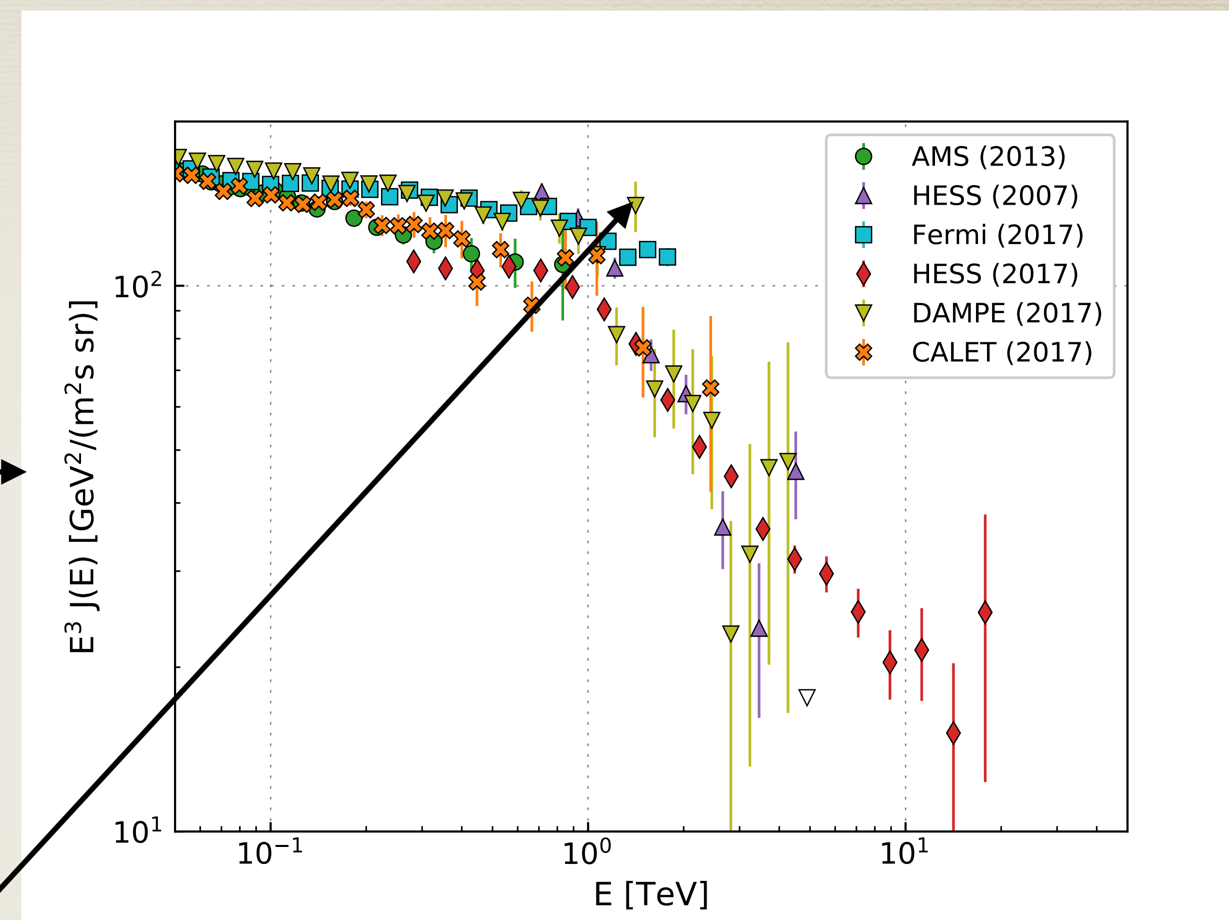
Positron Fraction



- The positron fraction is expected to decrease with Energy
  - This is the case for energies below a few GeV
- At higher energies the positron fraction increases -> There has to be a source injecting them
- If we take the diffusion coefficient derived from the ratio between secondary to primary cosmic ray species, the highest energy electrons and positrons should come from a nearby source

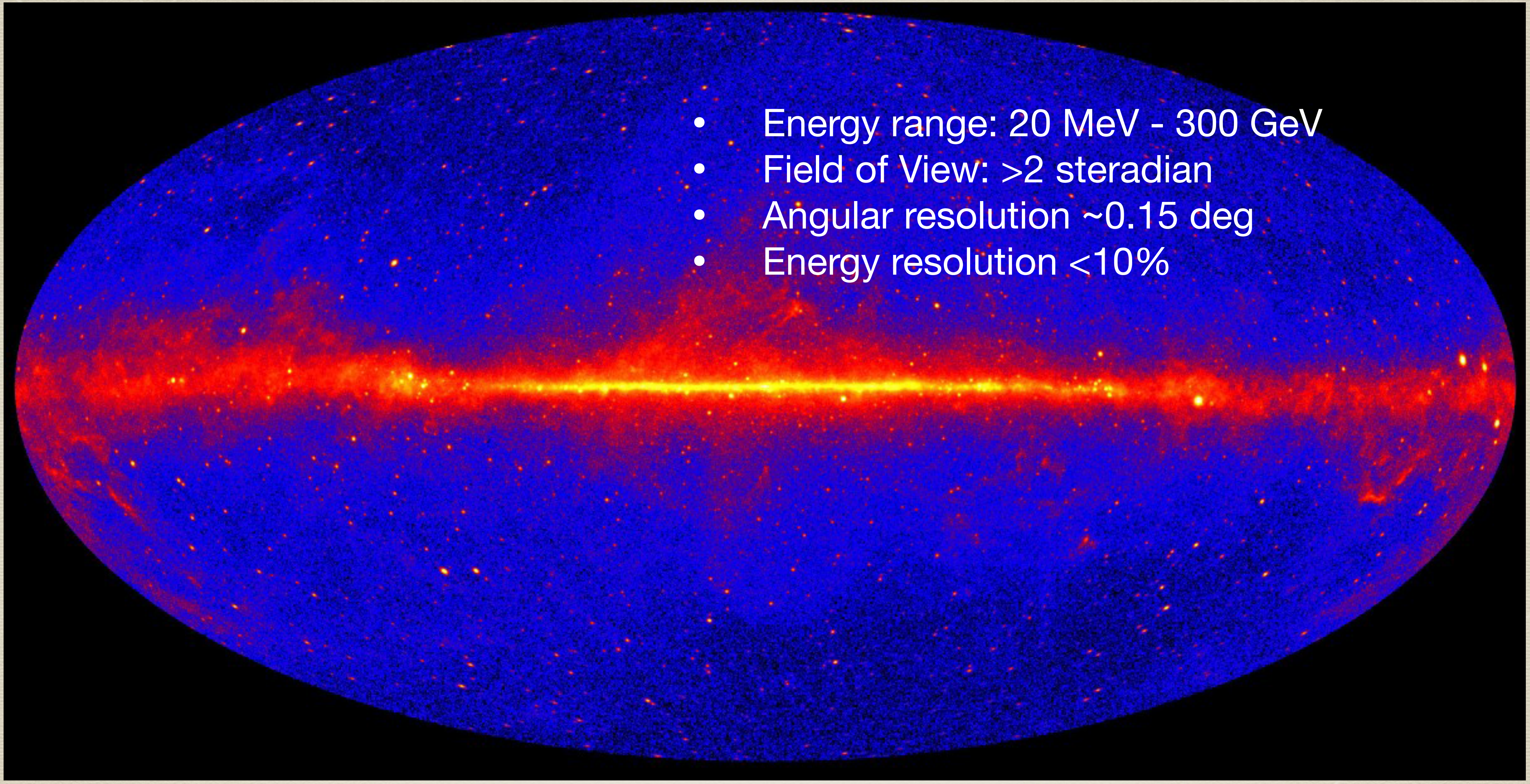
All-electron spectrum





- Extending up to 20 TeV
- Line-like feature (?) at 1.4 TeV in DAMPE data
  - Not seen by any other experiment operating in the same energy range.

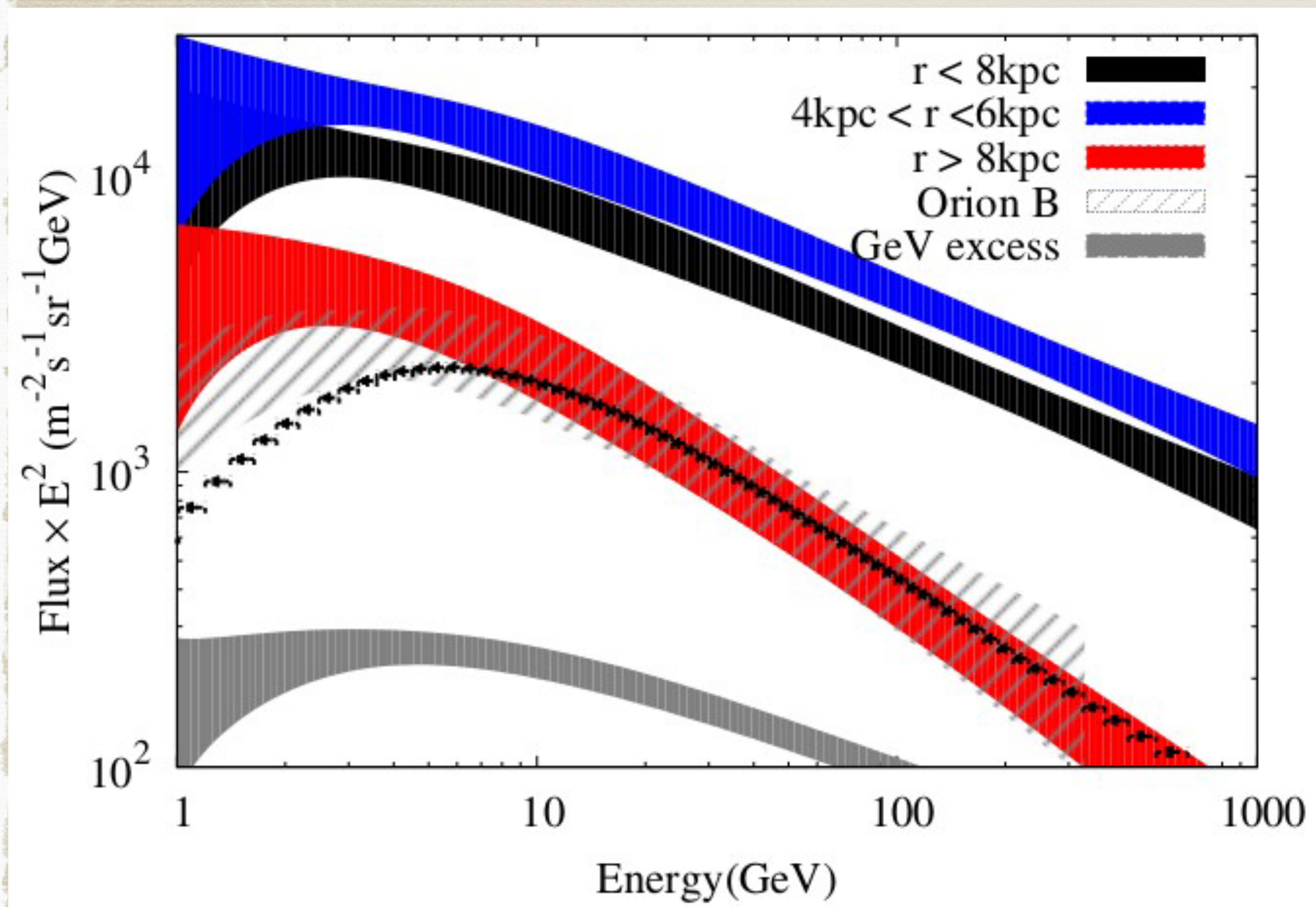
Fermi-LAT



- Measurement of CR densities in
  - **Disk:** Diffuse emission
  - **Halo:** Emission from CRs interacting with high latitude clouds.

Fermi-LAT

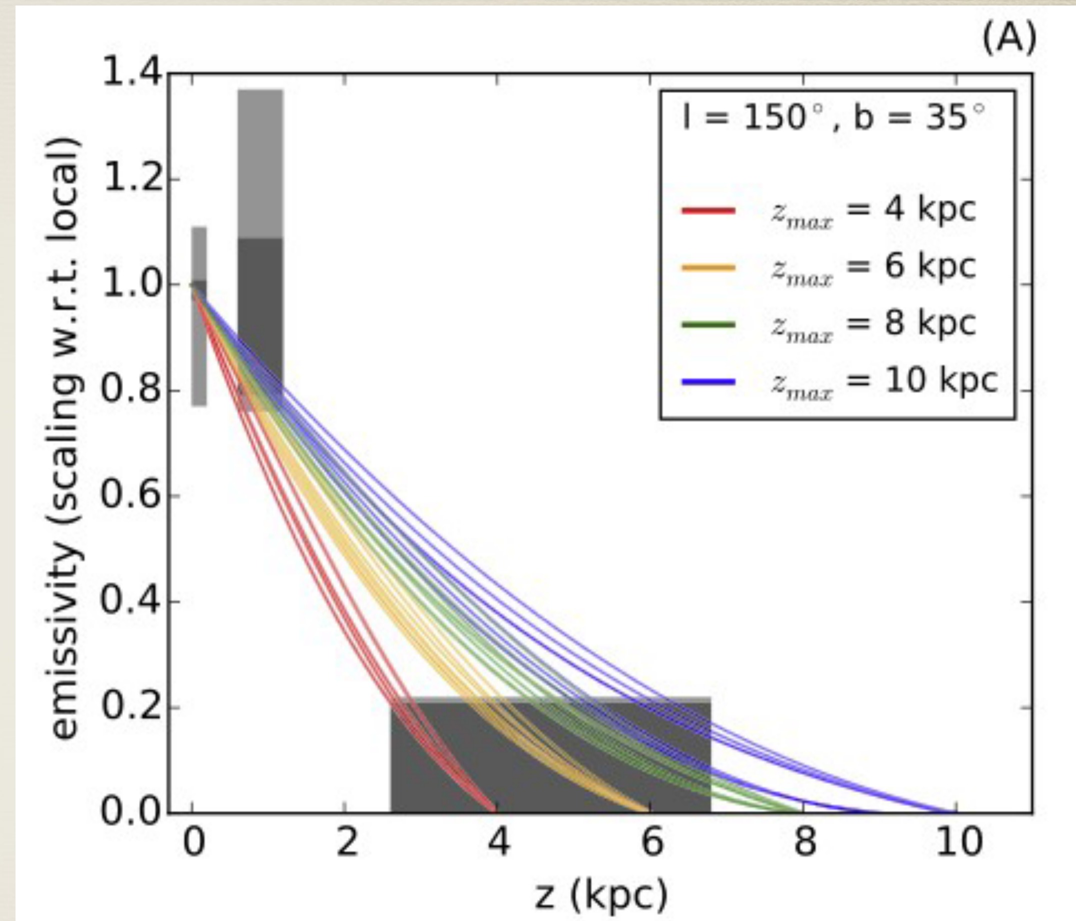
Disk



Yang et al., PRD, **93**, 123007 (2016)

- Larger CR density in the inner galaxy
  - -> Against models with uniform CR propagation in the galaxy

Halo

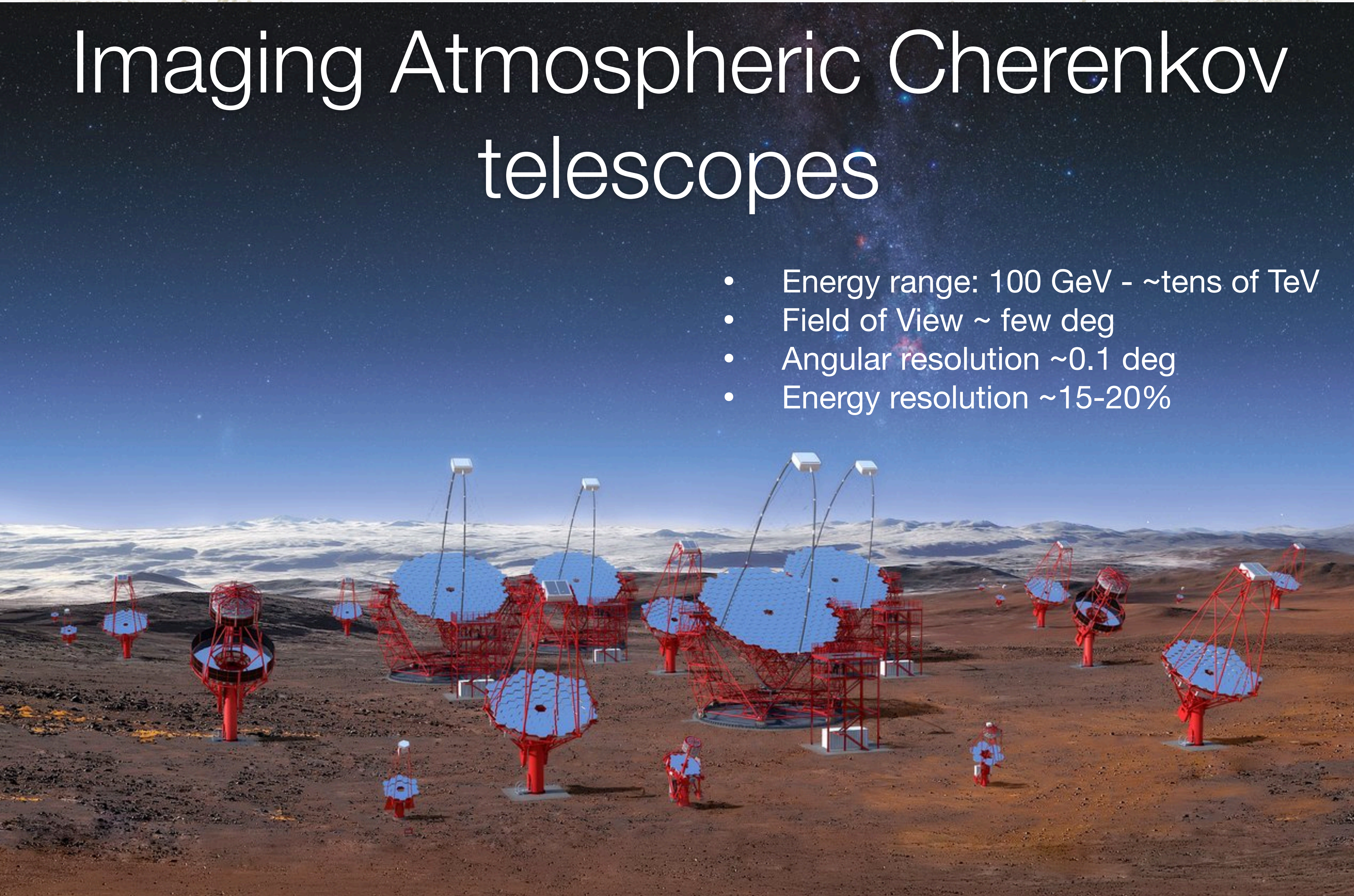


Tibaldo et al., ApJ, 807, 2 (2015)

- Compatible with different heights of the halo

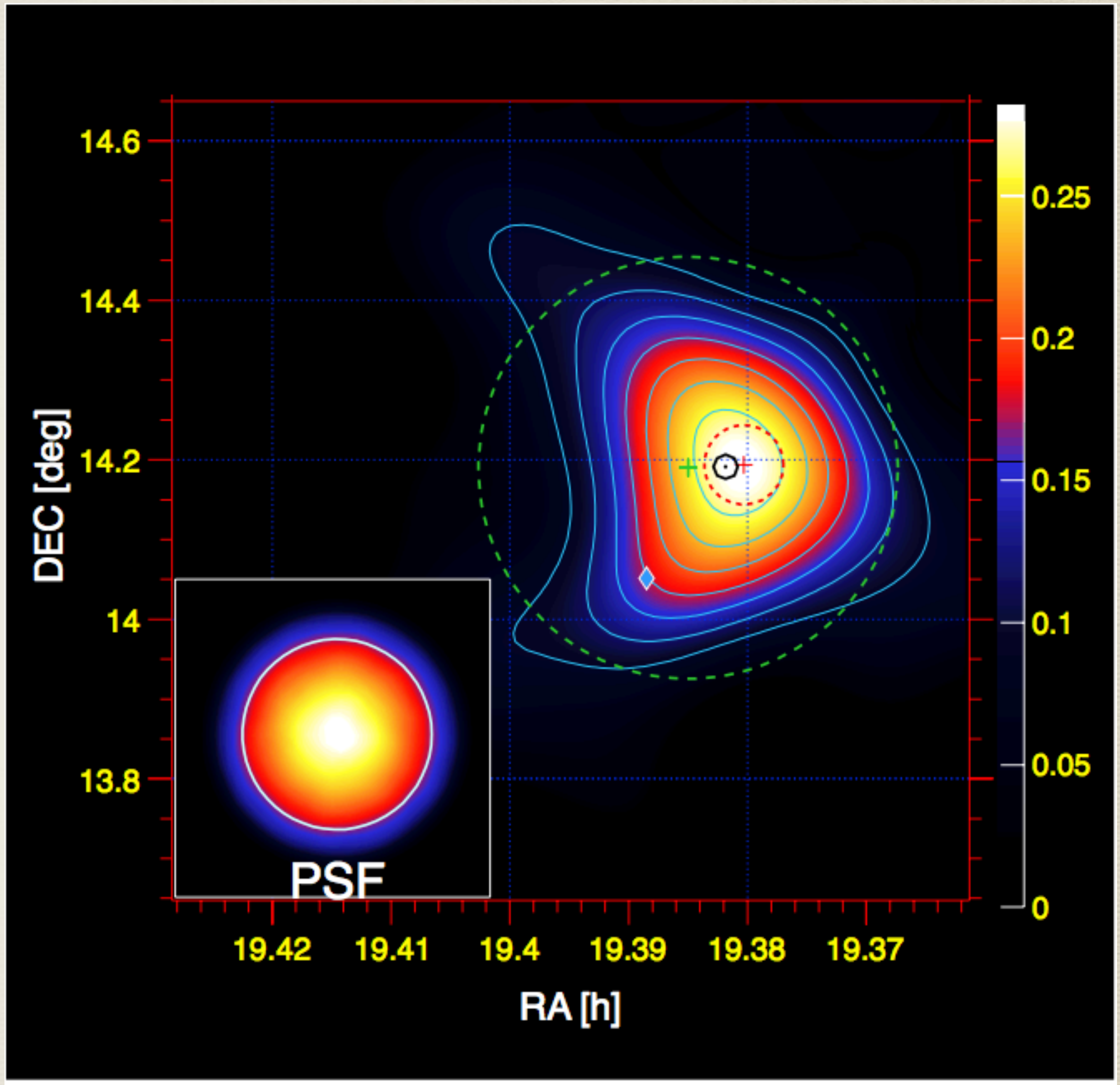
Imaging Atmospheric Cherenkov telescopes

- Energy range: 100 GeV - ~tens of TeV
- Field of View ~ few deg
- Angular resolution ~0.1 deg
- Energy resolution ~15-20%



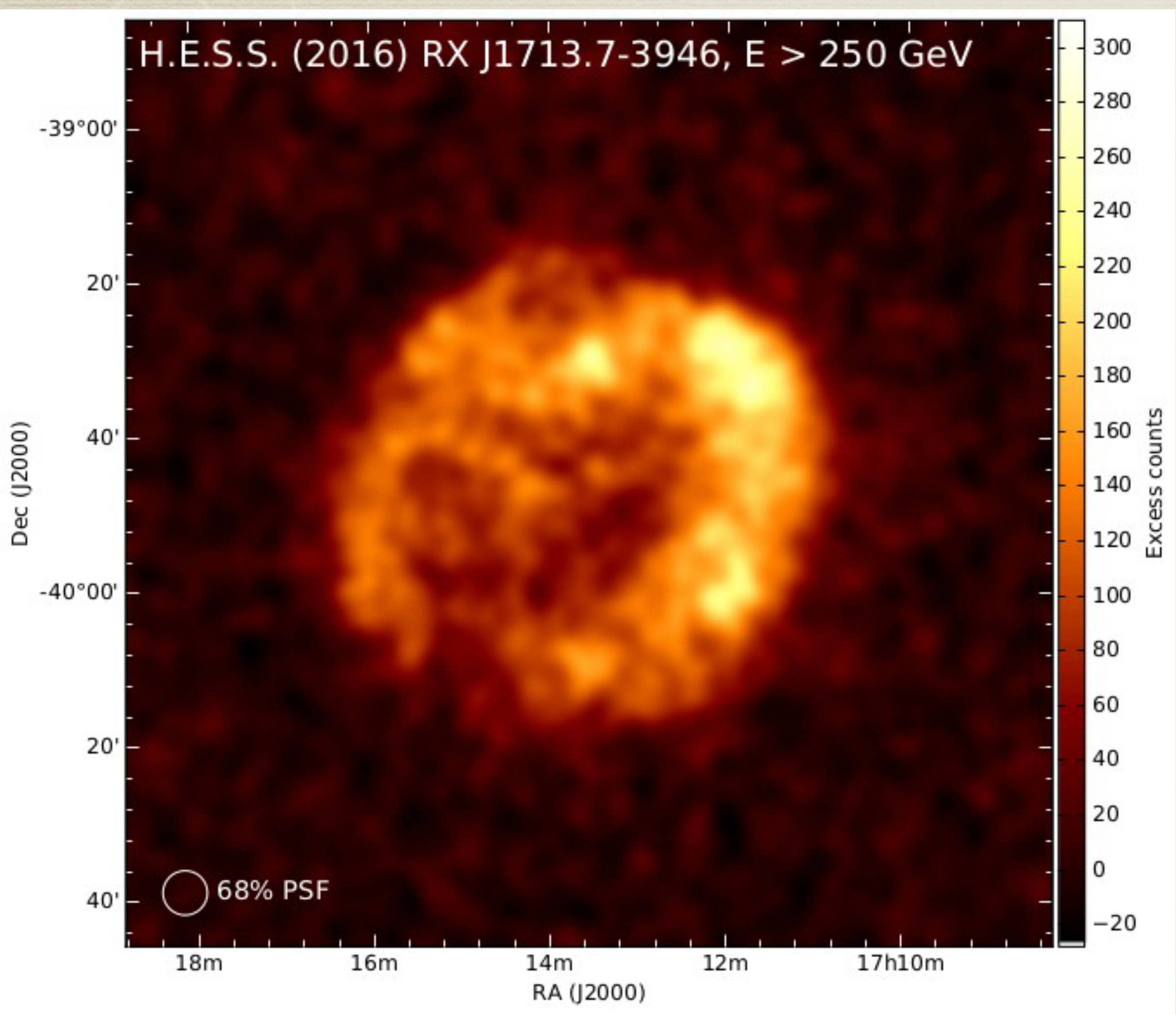
CRs illuminating molecular clouds

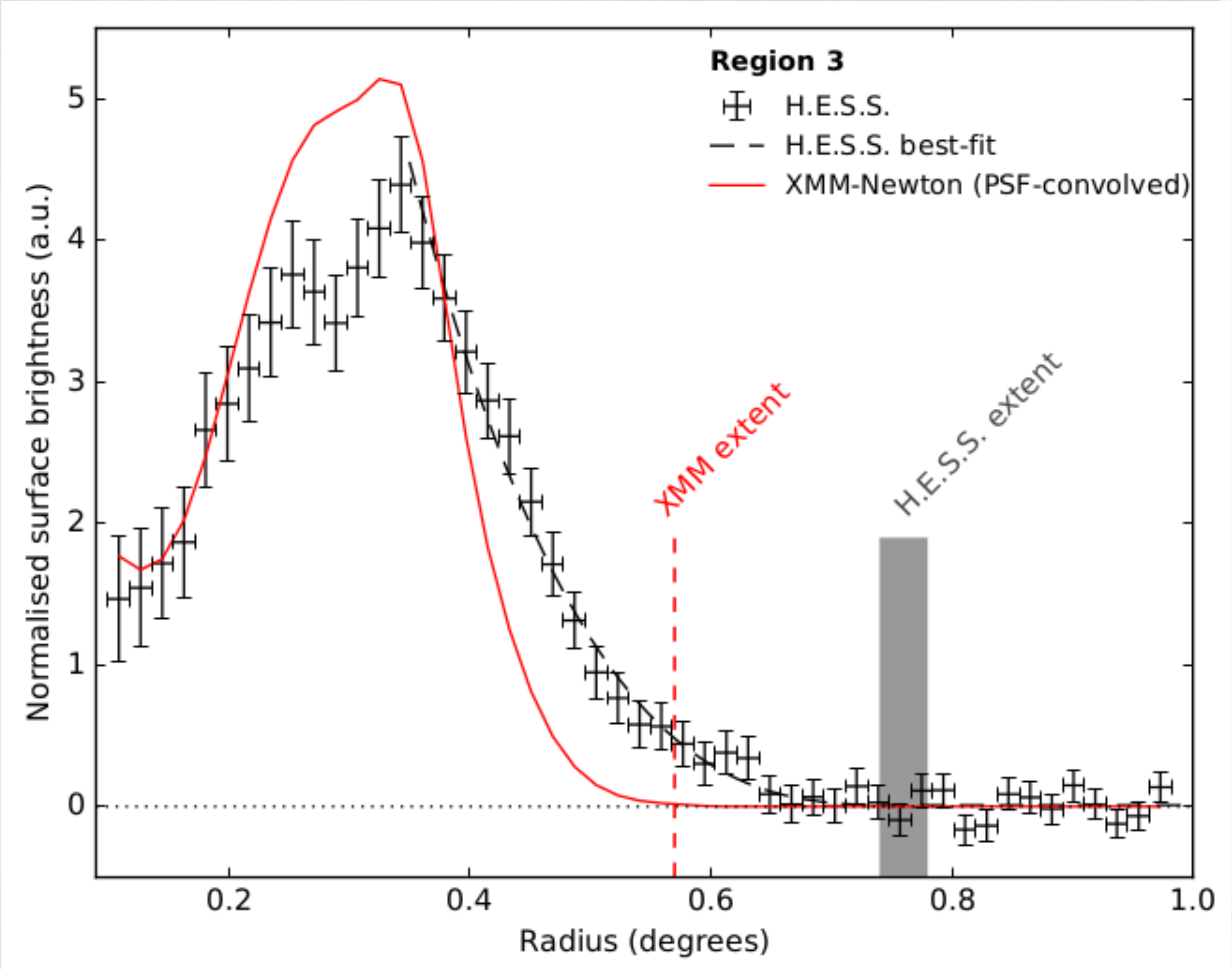
- Sources like W51C illuminate Molecular clouds with escaping CRs, glowing in gamma rays.
- Assuming isotropic diffusion gamma-ray, these observations can be explained only if the CR diffusion coefficient in the region surrounding the SNR is significantly suppressed with respect to the average in the Galaxy



MAGIC Coll., A&A, 541, A13 (2012)

CRs beyond SN shells





H.E.S.S. Coll., A&A, 612, A6 (2018)

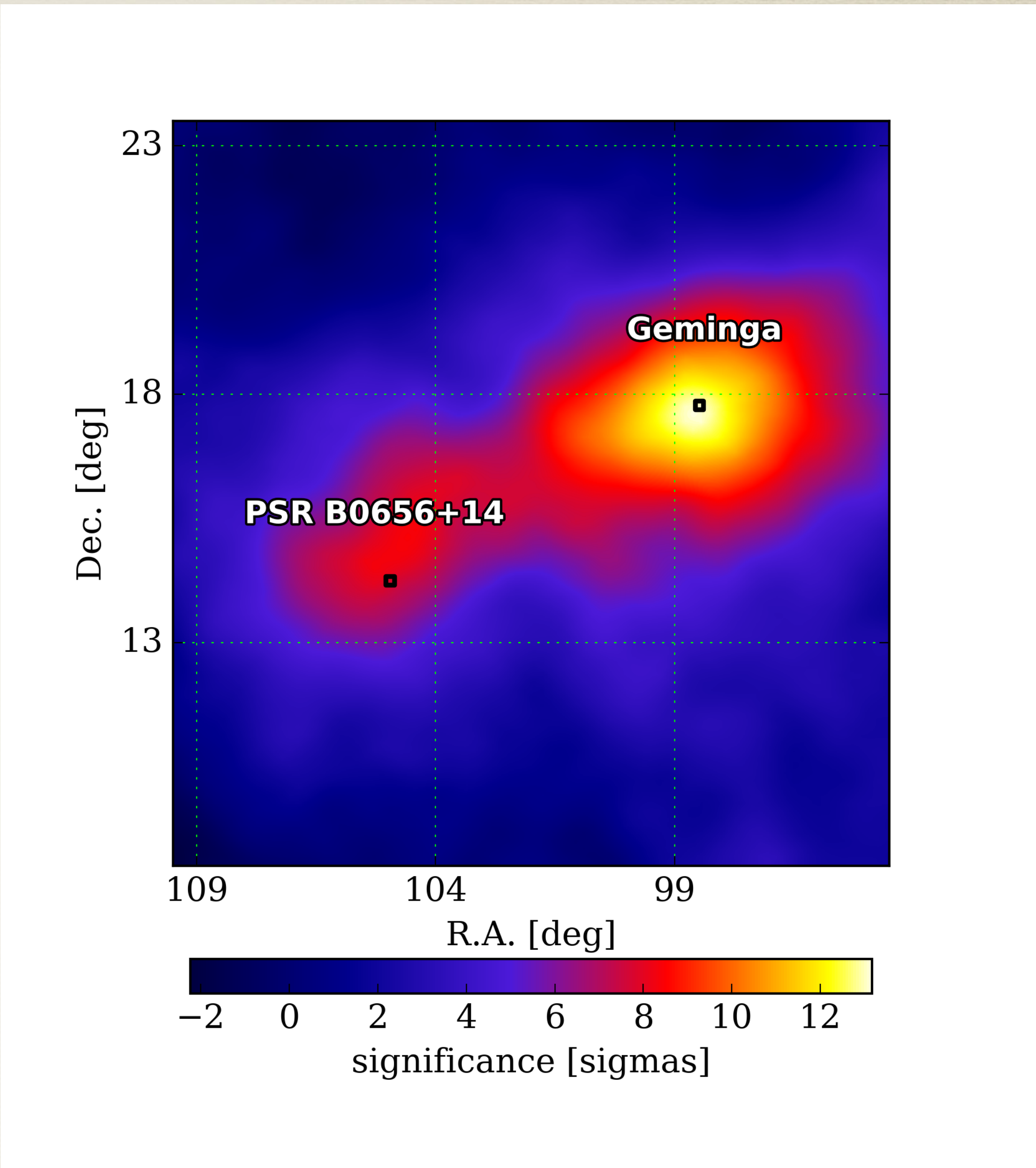
- TeV emission extending beyond the X-ray shell.
  - Very important measurement of CR escape.
  - Hadronic or leptonic origin is possible.

Water Cherenkov detectors

- Energy range: 1 TeV - ~hundreds of TeV
- Field of View: ~ steradian
- Angular resolution >0.2 deg
- Energy resolution >50%

Detection of very extended sources

- Detection of two very extended gamma-ray sources coincident with Geminga and PSR B0656+14
- We measured the gamma-ray spectrum as a single power-law between 8 and 40 TeV.
- Emission coming from very high energy electrons (~100 TeV) inverse Compton upscattering CMB

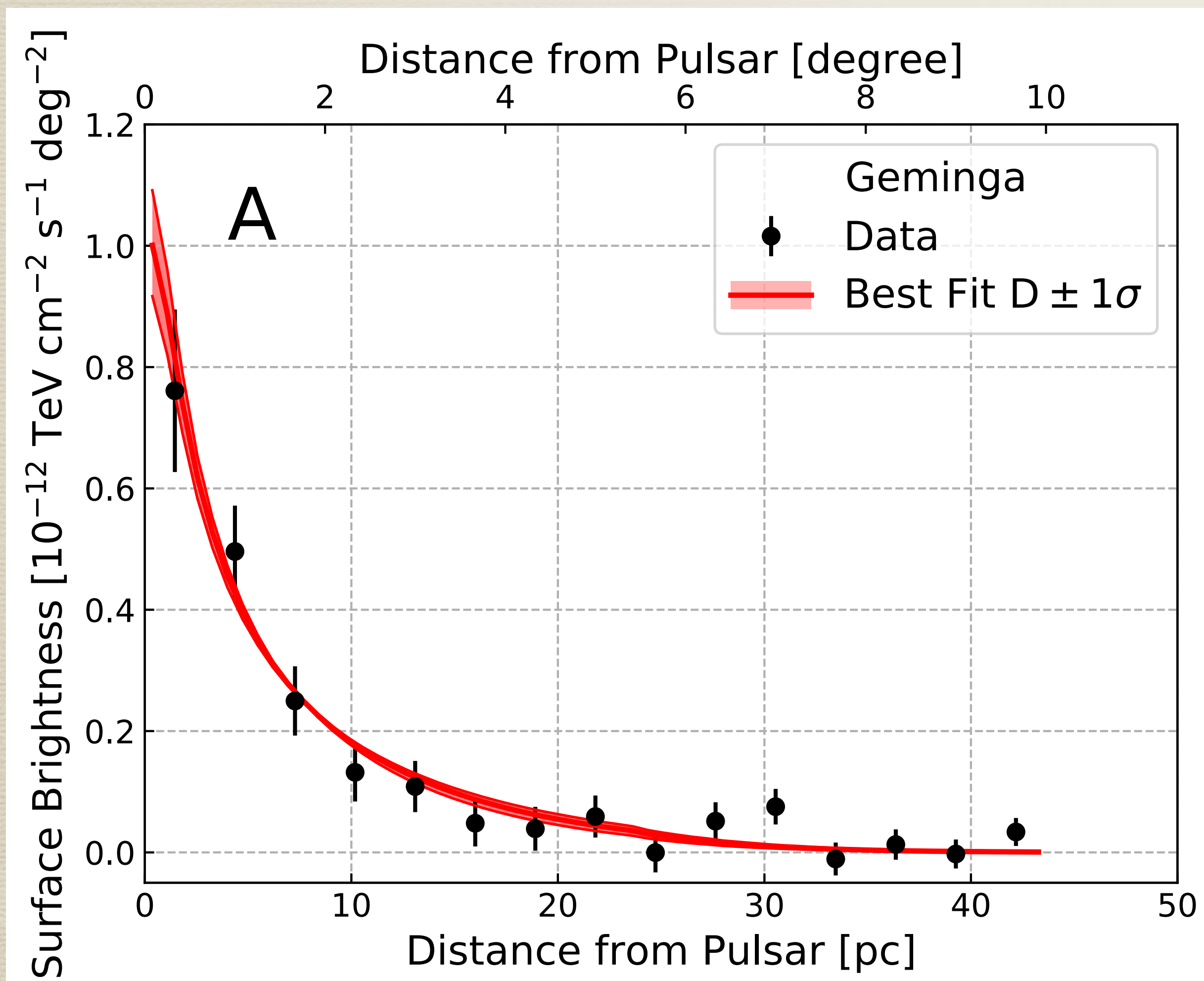


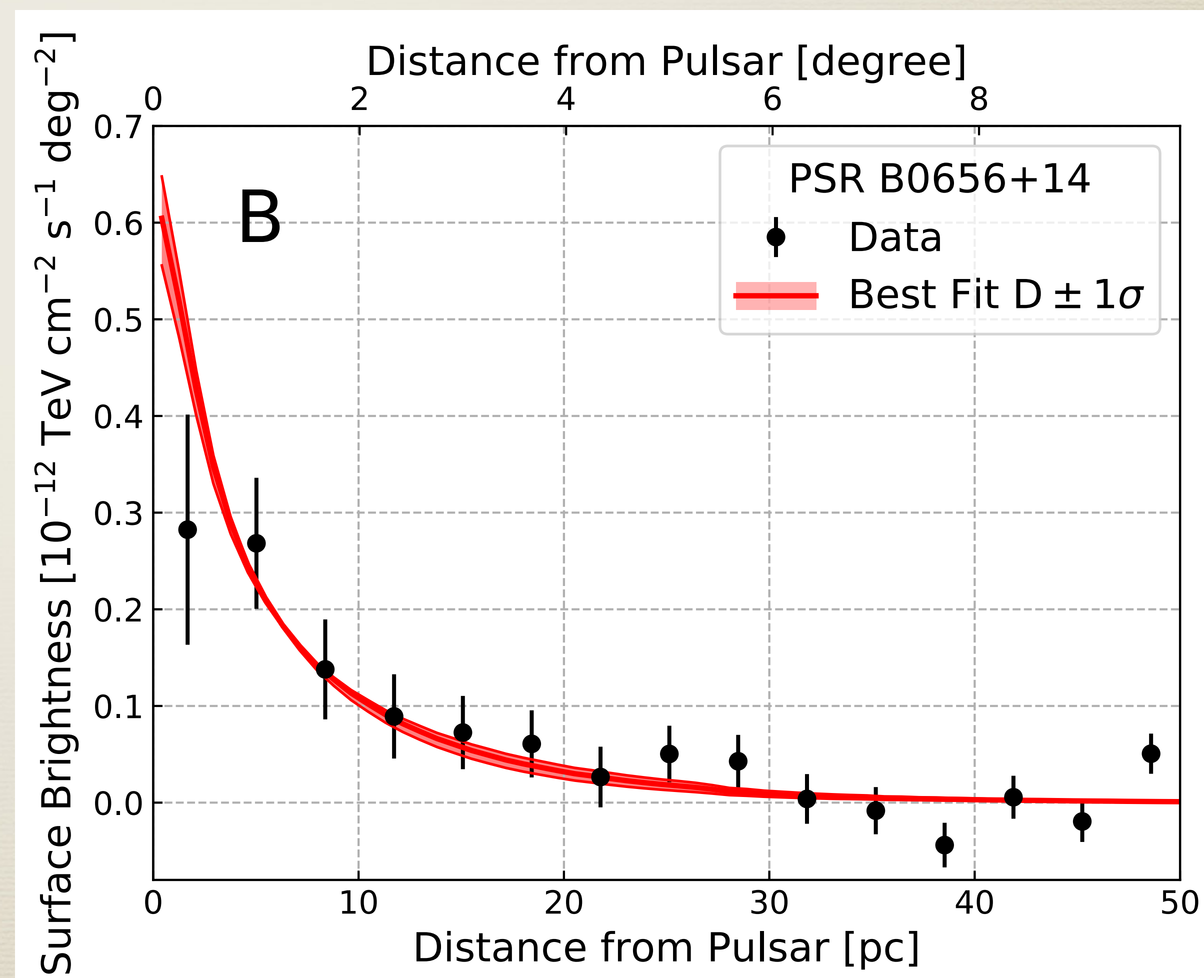
HAWC Coll., Science, 358, 911 (2017)

Diffusion coefficient

- The best fit is given by a diffusion morphology with a diffusion coefficient **D(100 TeV) = 4.5 x 10^{27} cm^2/s**

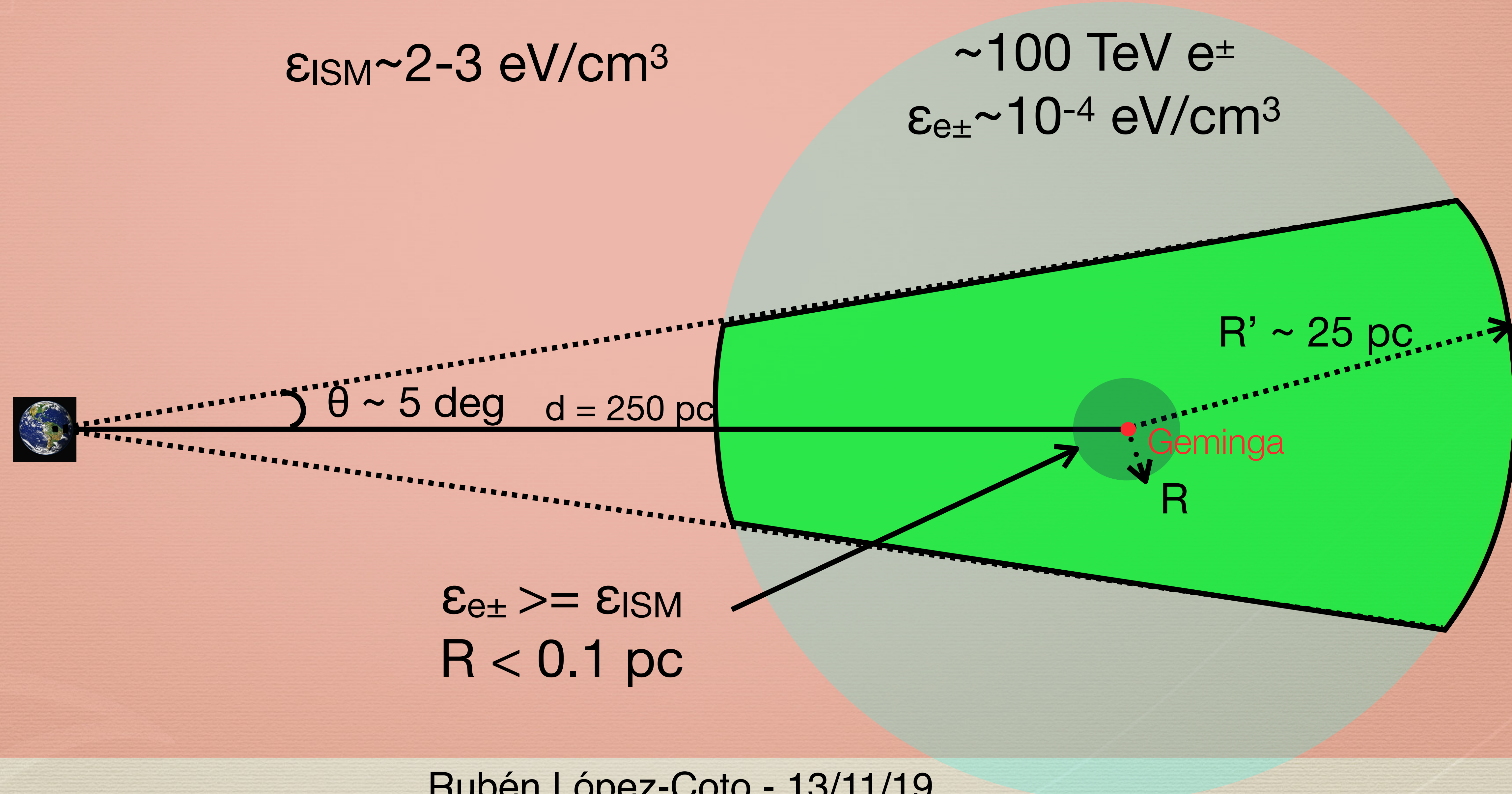
- This is ~2 orders of magnitude smaller than ISM averages



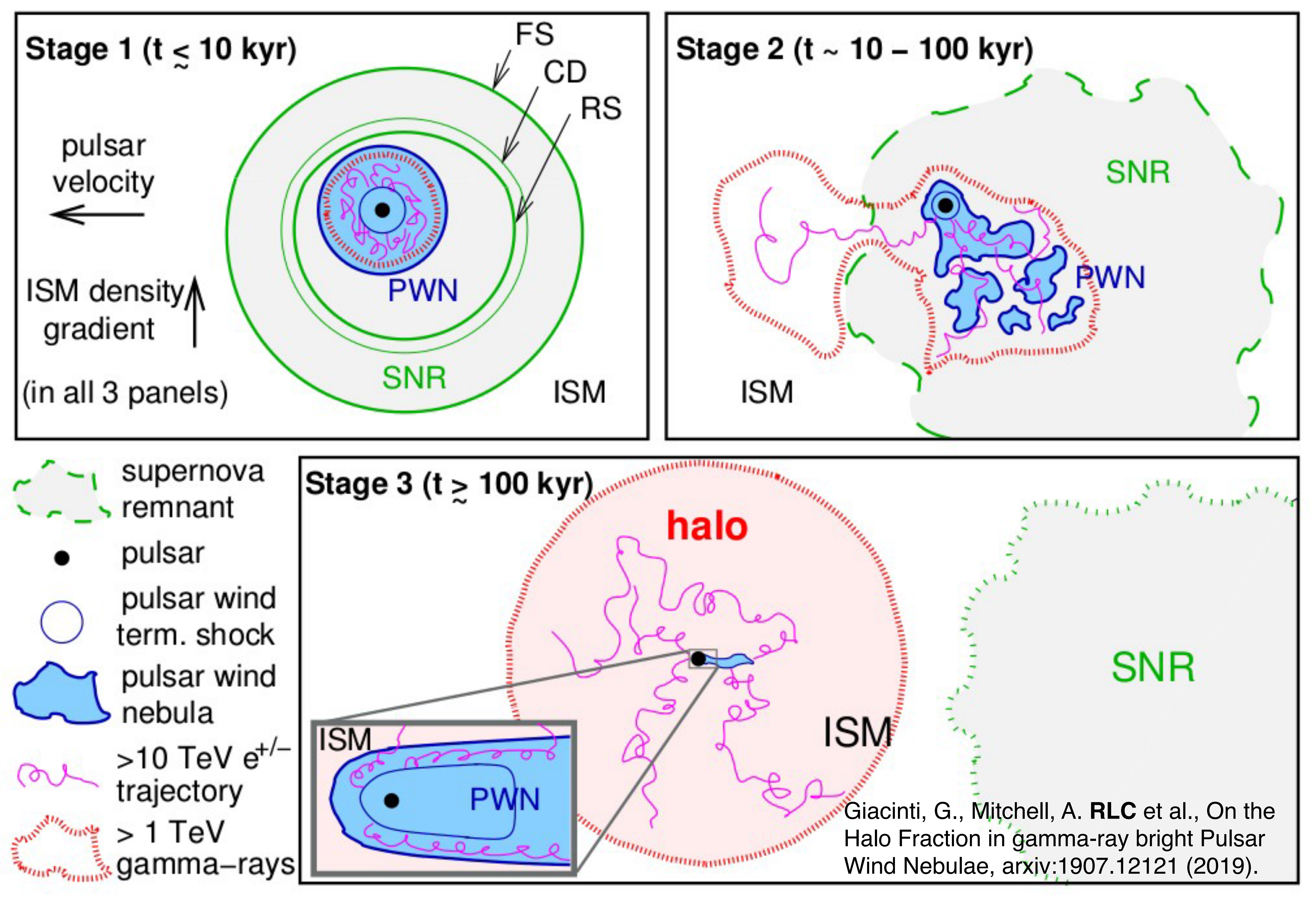


Energetics in the region

- We are not seeing in VHE gamma rays the emission of a “standard PWN”, but the **emission of electrons diffusing into the ISM** for the first time at these energies.

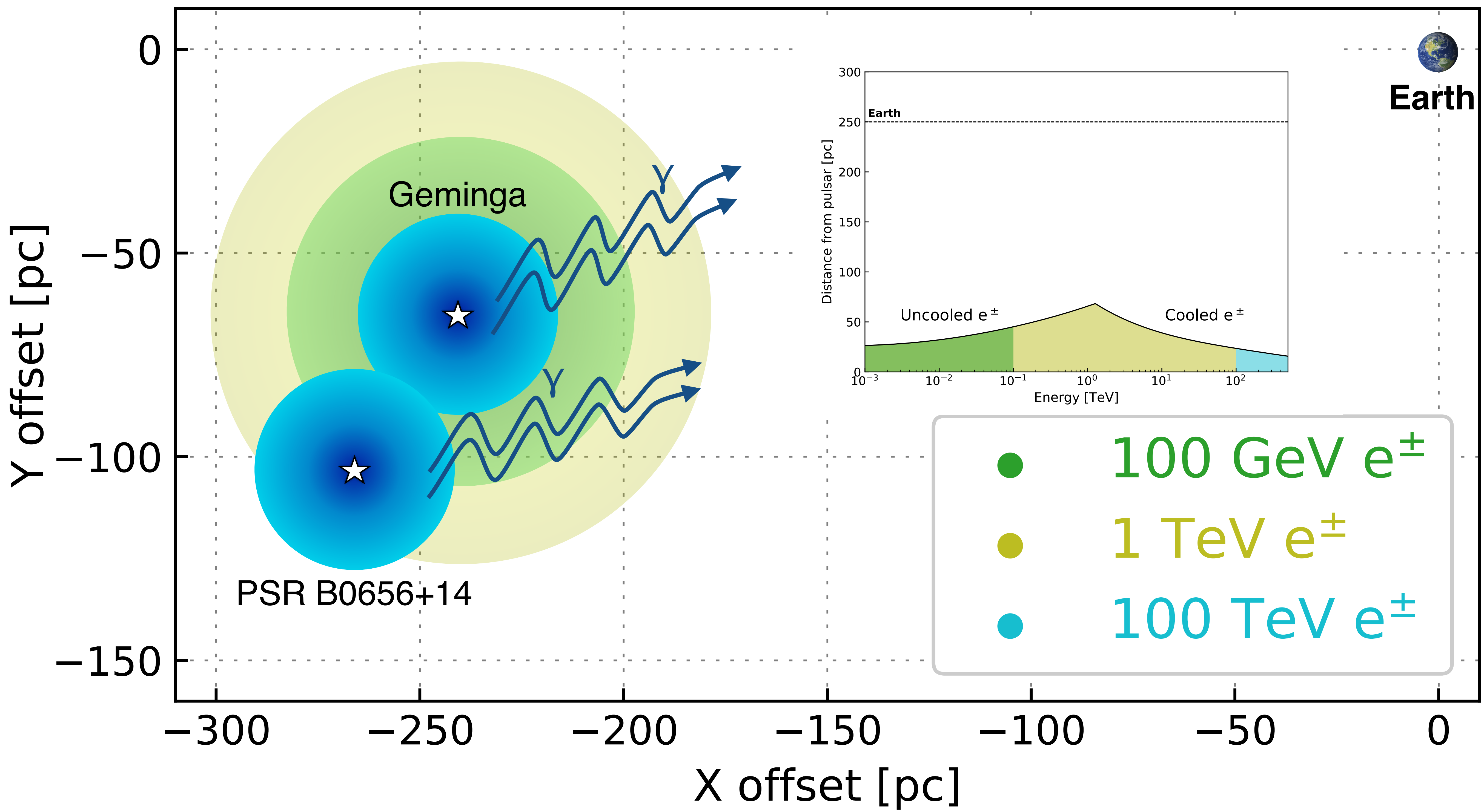


Definition of TeV halos



Giacinti, G., Mitchell, A. **RLC** et al., On the Halo Fraction in gamma-ray bright Pulsar Wind Nebulae, arxiv:1907.12121 (2019).

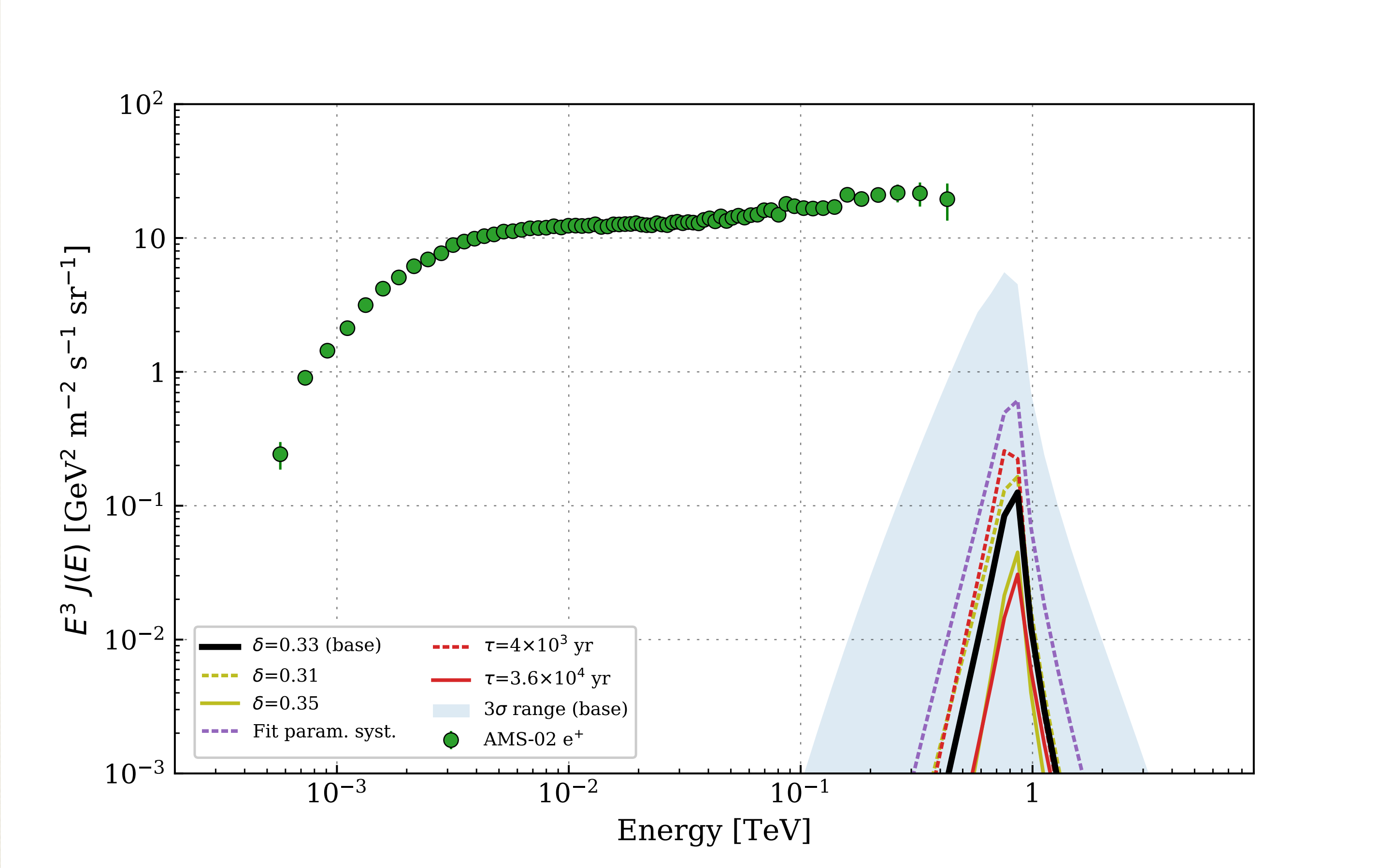
How far are e± traveling?



Positron flux

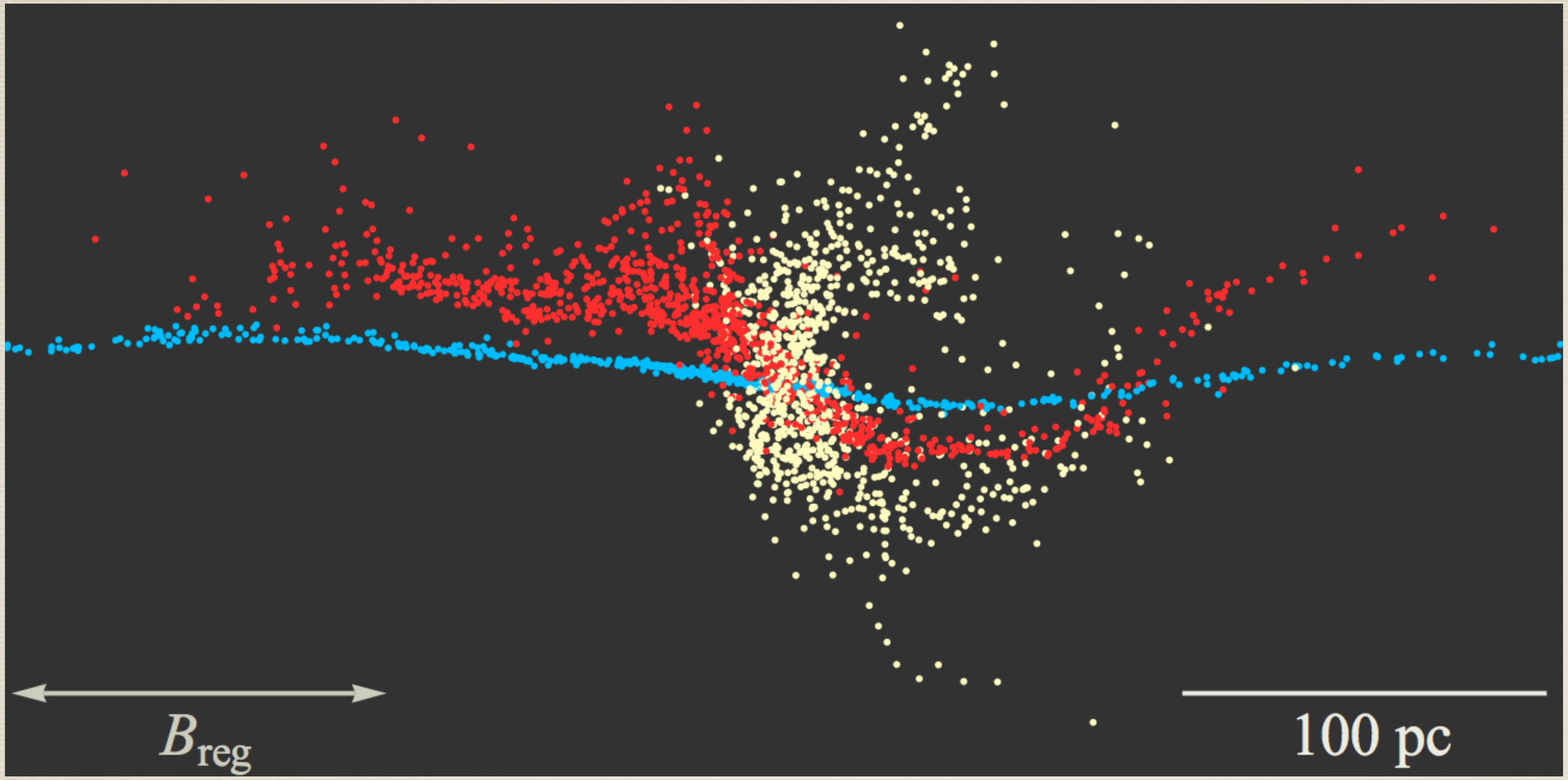
- Using the base parameters for the Geminga pulsar and measured ones for diffusion, under the assumption of a uniform diffusion coefficient from Geminga to the Earth, the contribution of Geminga to the local positron flux cannot explain any of it
  - Contribution of PSR B0656+14 is even lower (off-axis)

- Varying different parameters to their extreme values do not change these conclusions



HAWC Coll., Science, 358, 911 (2017)

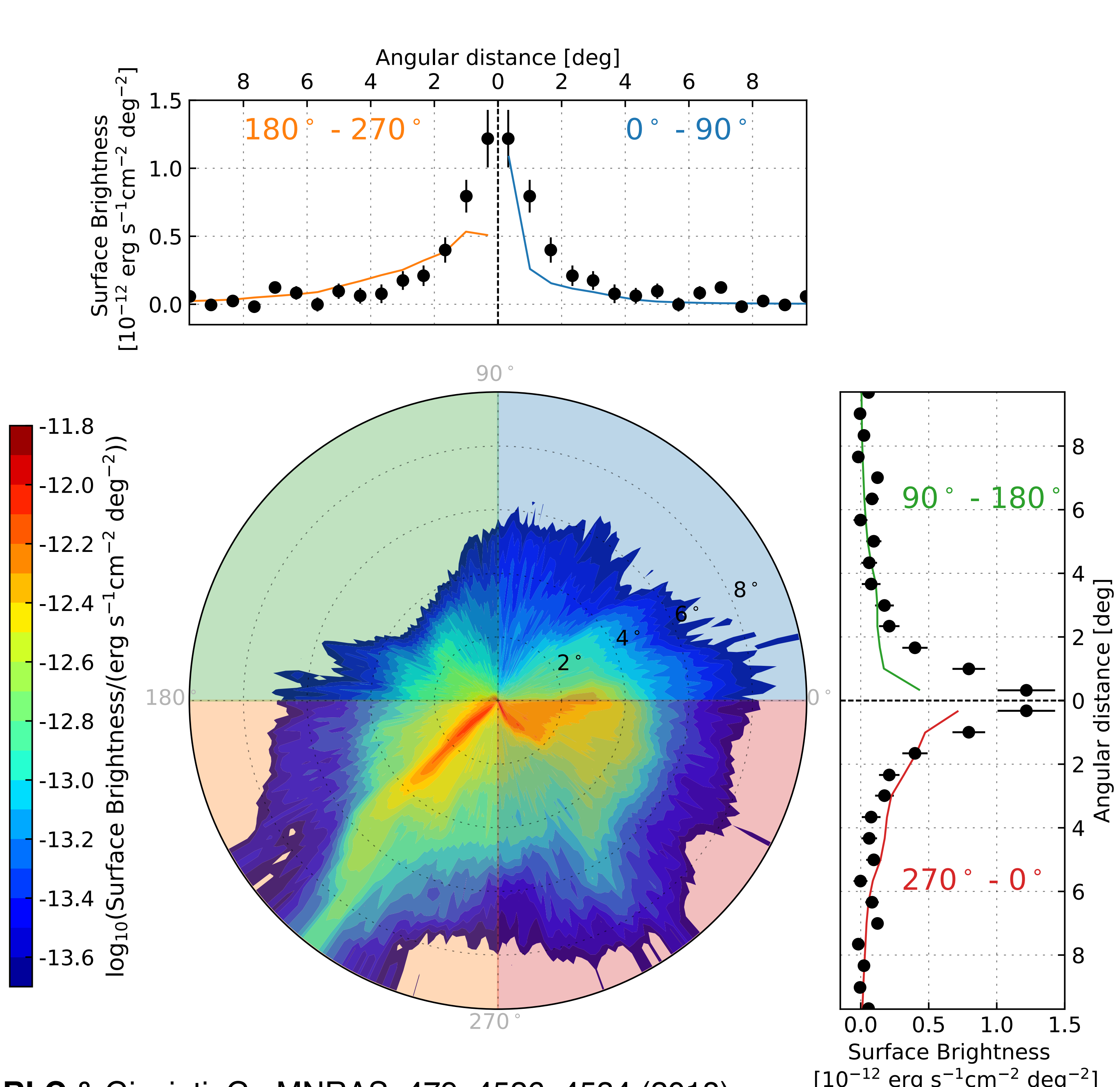
What about streams of cosmic rays?



Kistler, Yüksel and Friedland, arXiv: 1210.8180

- If one assumes a coherence length of the turbulent component of the magnetic field of ~100 pc, there could be streams of electrons efficiently propagating towards the Earth

Magnetic turbulence in Geminga



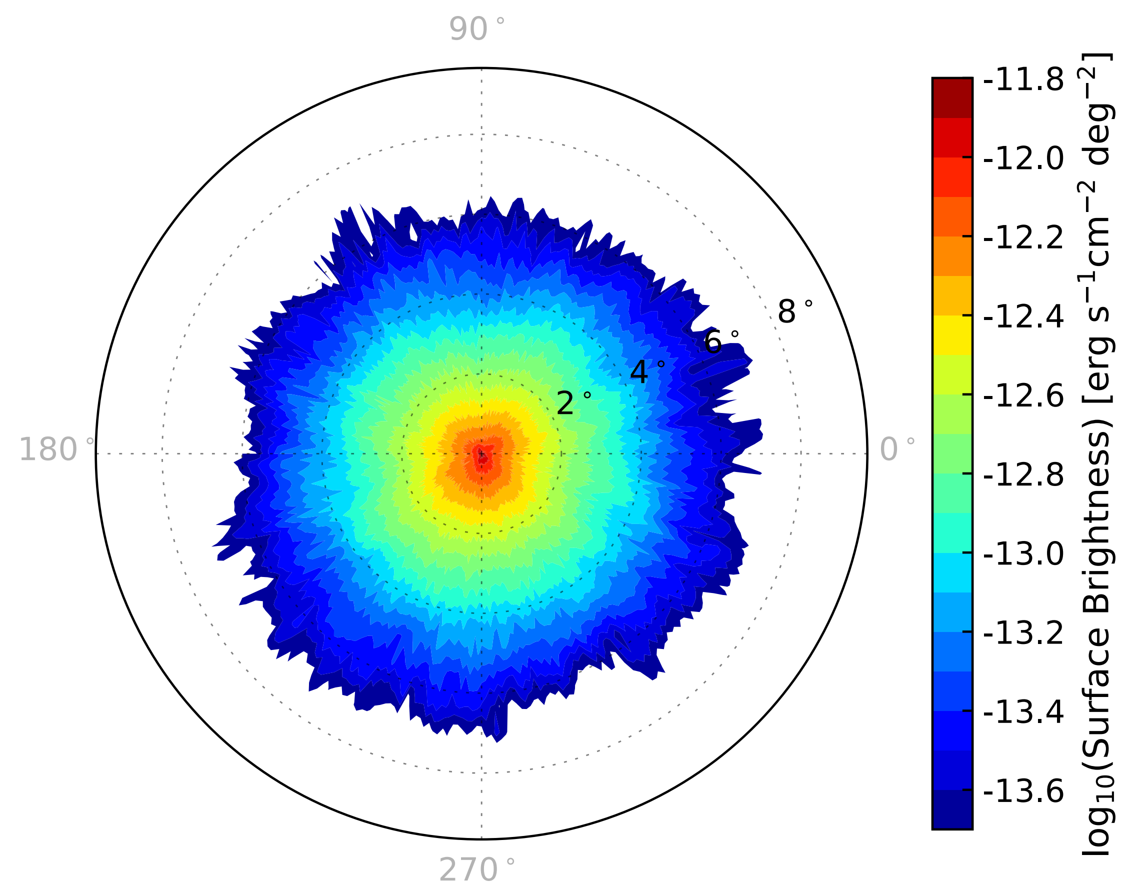
RLC & Giacinti, G., MNRAS, 479, 4526–4534 (2018).

Simulated Correlation length = 40 pc

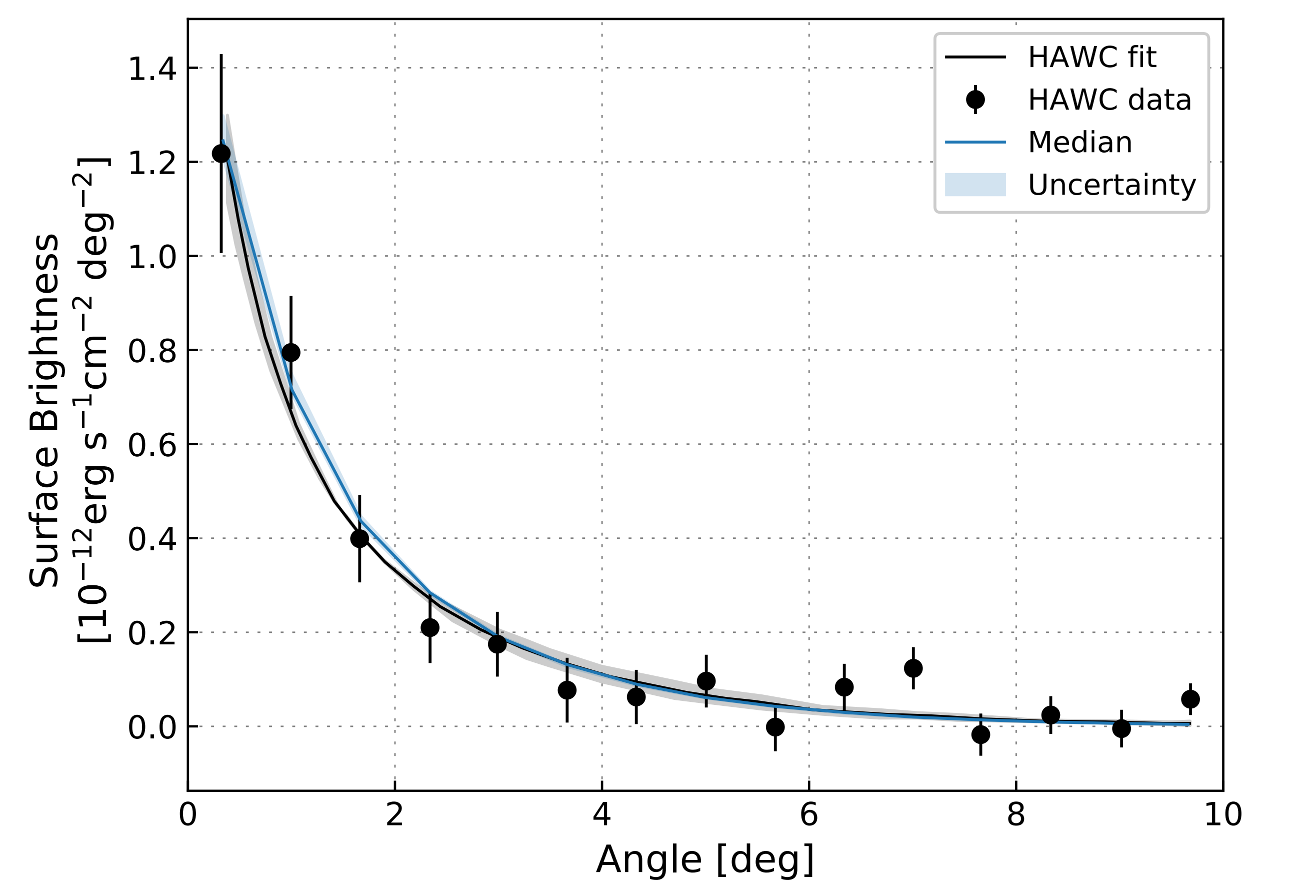
For correlation lengths of the magnetic field larger than a few parsec, the radial profile cannot be reproduced

Magnetic fields larger than 3-4 μG or smaller than 2 μG do not reproduce the data either

Magnetic turbulence in Geminga



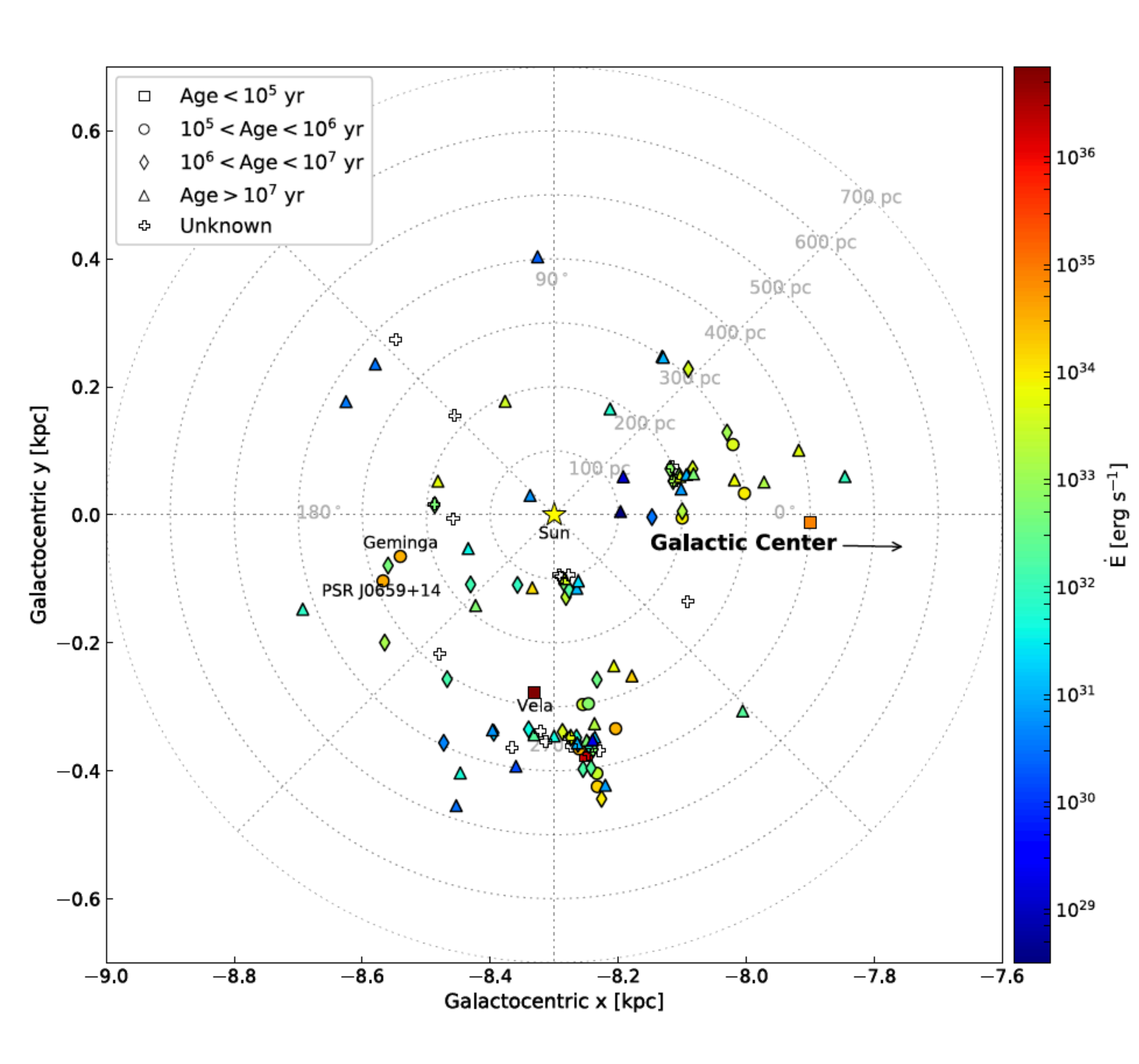
RLC & Giacinti, G., MNRAS, 479, 4526–4534 (2018).



Best fit: Correlation length = 1 pc

Can pulsars still explain the positron excess or do we need **dark matter**?

The diffusion radius, assuming HAWC's diffusion, should be ~25 pc ——————> more nearby than any known pulsar



An undiscovered pulsar as an explanation

A pulsar located at < 90 pc would make it.

- The general characteristics for this pulsar

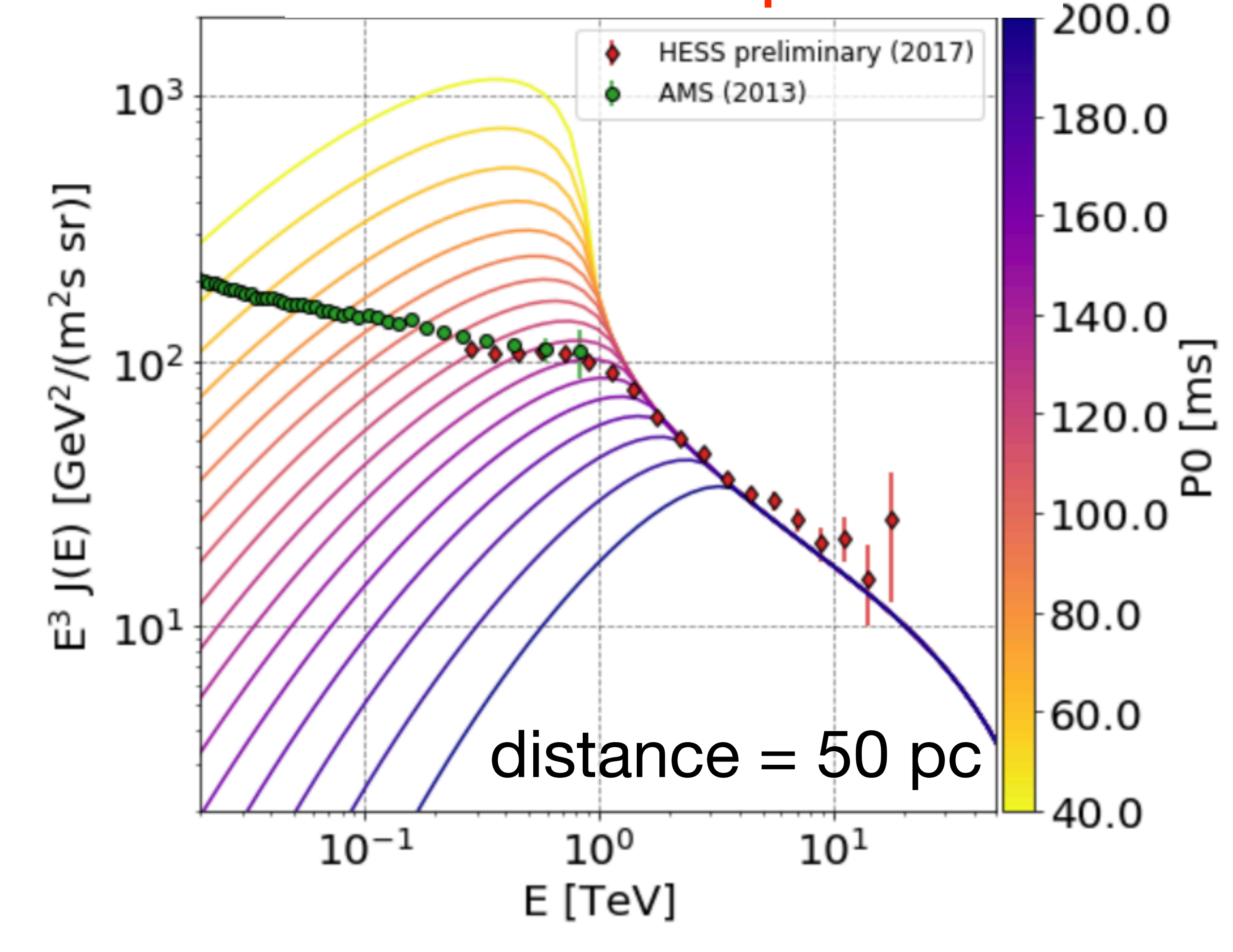
are:

- Age > 300 kyr
- Distance < 80-90 pc
- Spin-down power ~10^{33} -10^{34} erg/s

- Probability for this pulsar to exist if it is <1 Myr old is 5-10%

- Characteristics coincident with those of the latest SNe that carved the Local Bubble

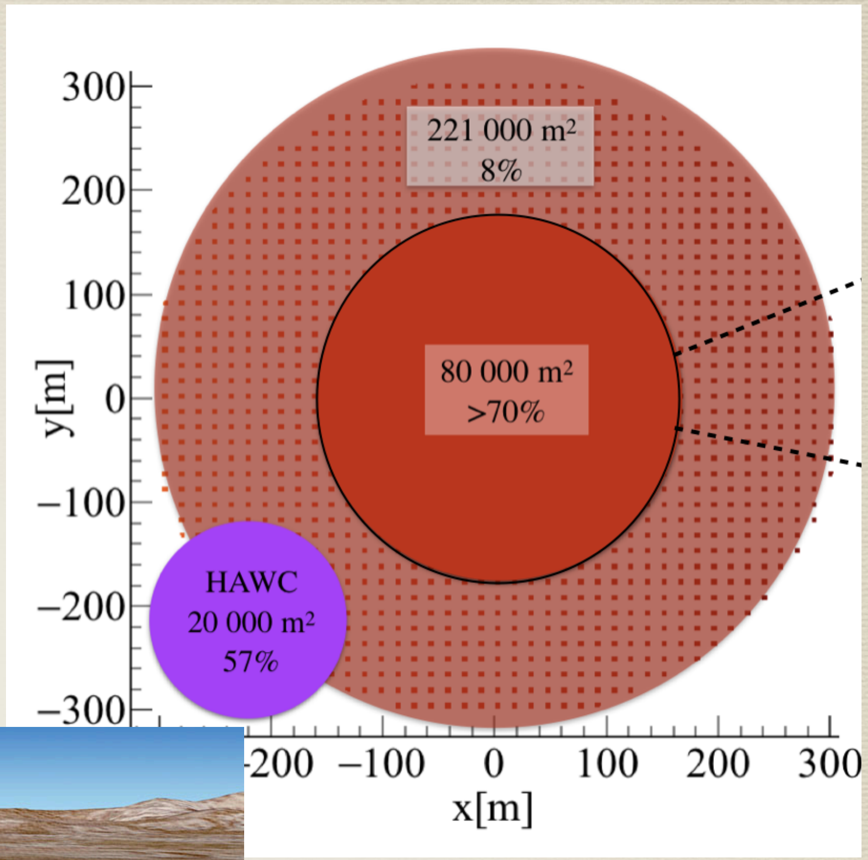
All-electron spectrum



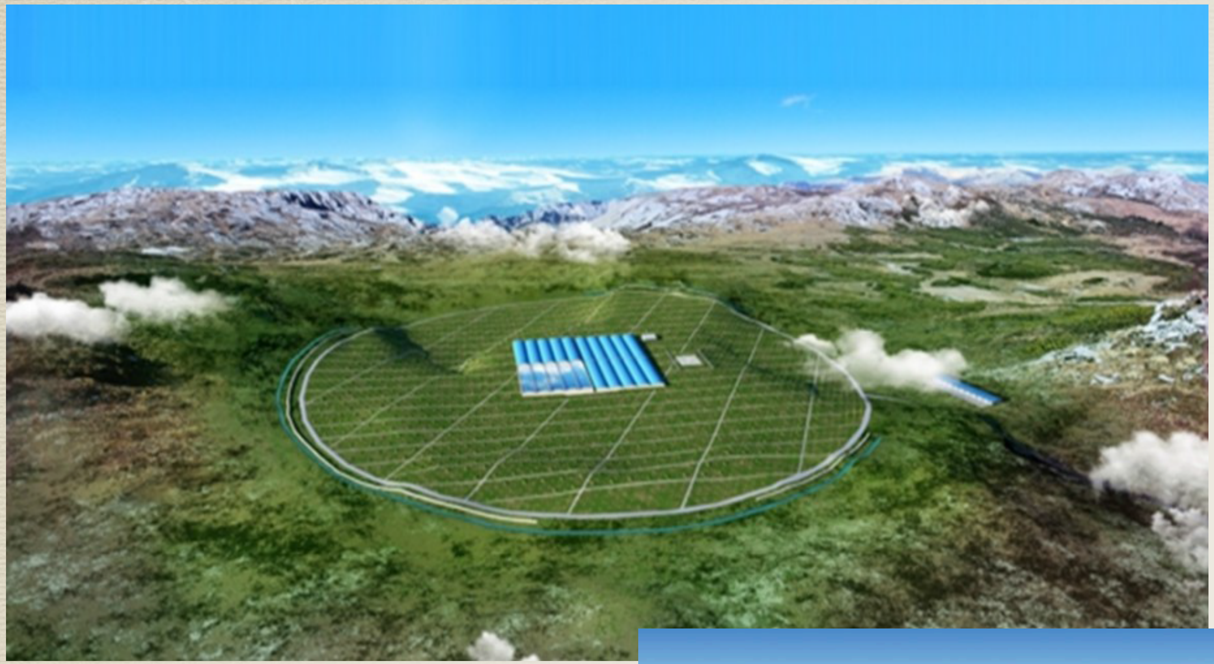
RLC, Parsons, Hinton & Giacinti, PRL, 121, 251106 (2018).

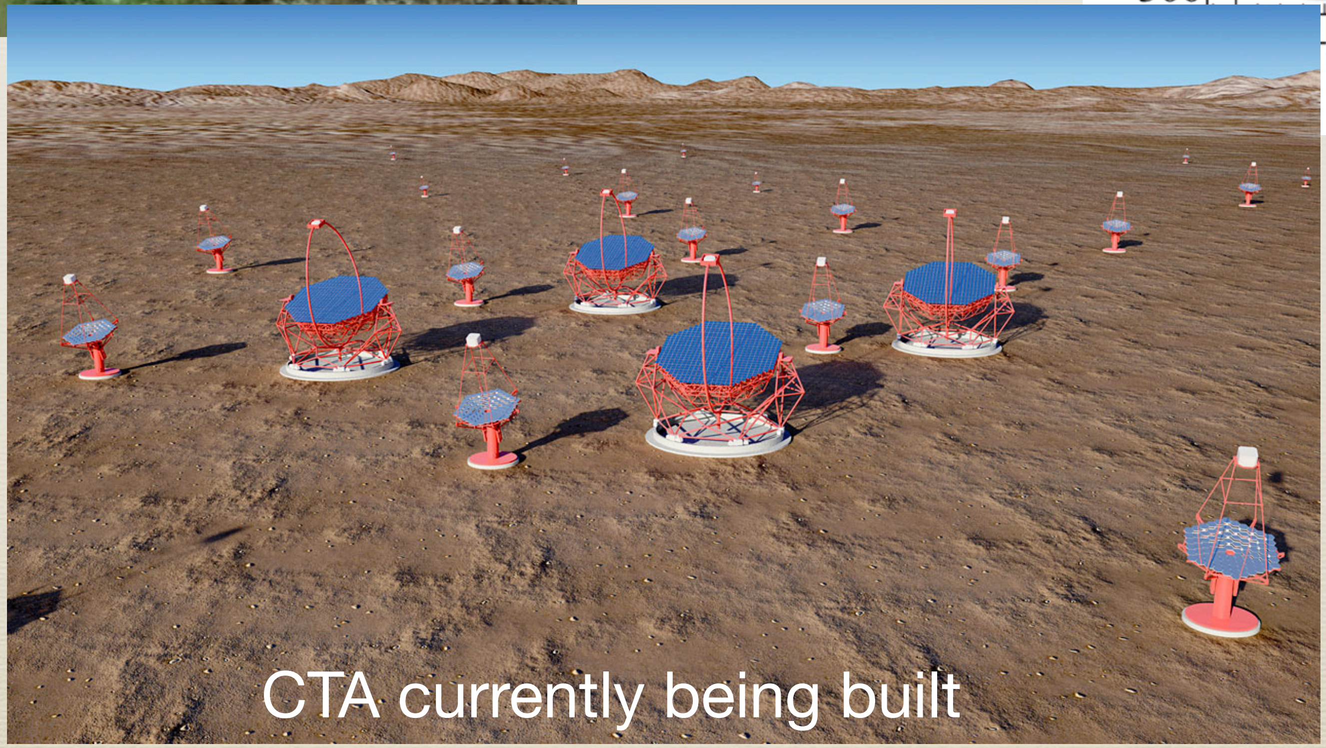
Gamma-ray future is very bright!

SWGO collaboration started



LHAASO just started operation





Summary

- Gamma ray observations are the only way to directly measure the propagation of cosmic rays

- Observations from different types of observatories are complementary:
  - Satellites with wide FoV and good performance in the GeV region can measure the **diffusion emission** produced by CRs.
  - Imaging Atmospheric Cherenkov telescopes with excellent sensitivity and angular resolution resolve **CR escape** from Supernova Remnants.
  - Water Cherenkov detectors with wide FoV and ~TeV coverage measure **electron escape** from TeV halos

- Gamma rays are already becoming a way of testing magnetic turbulence in the Interstellar Medium
  - **Slow diffusion** from regions surrounding SNRs and TeV halos
  - Direct measurement of the **correlation length** of the magnetic field thanks to the symmetry/asymmetry of these sources.

- Gamma rays as an indirect prove of the locally measured CRs.
  - The only way to perform Dark Matter searches using local CR measurements is by understanding the **background from local sources**.

THANK YOU!

BACKUP

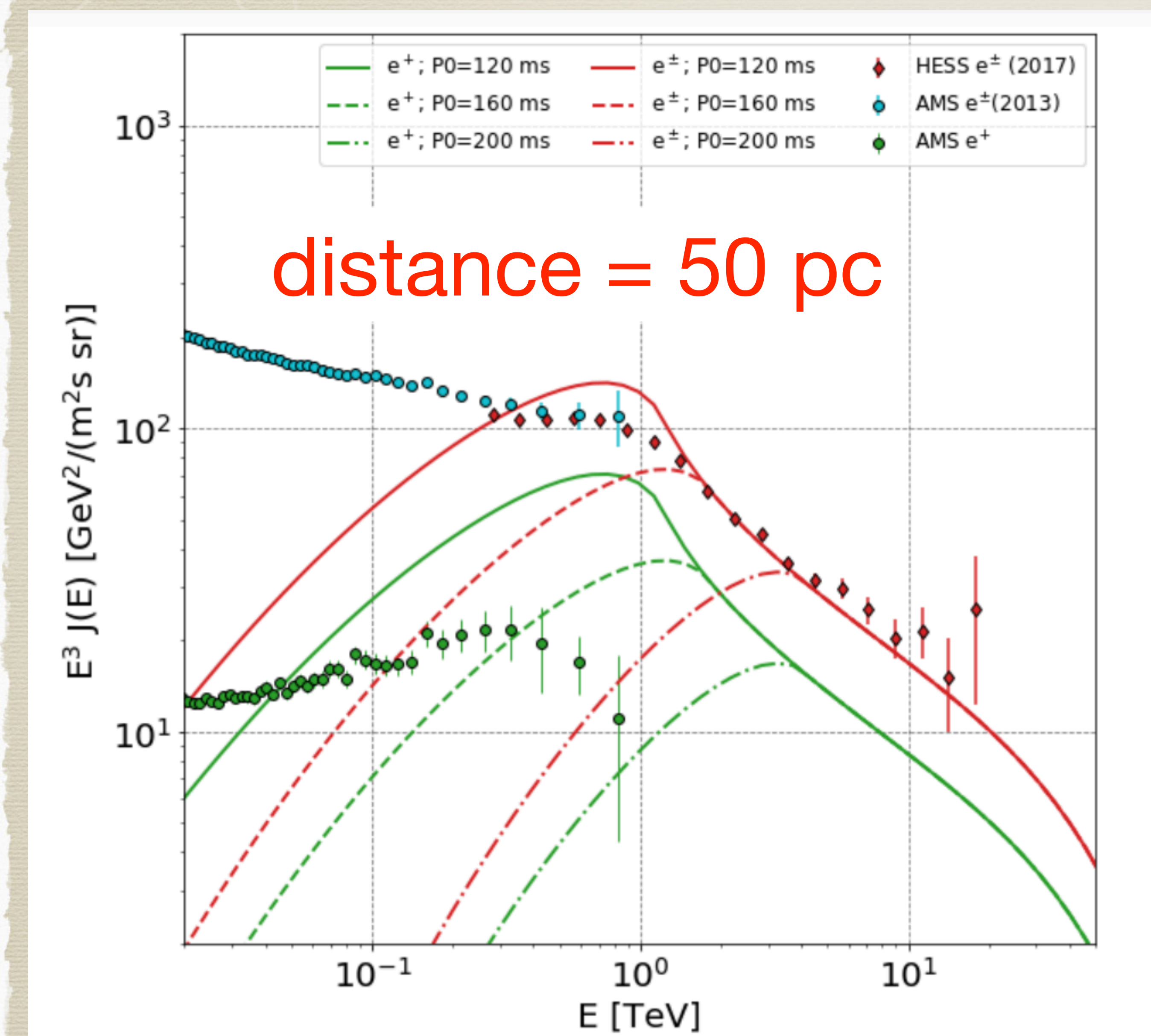
What if the D_{diff} is not constant?

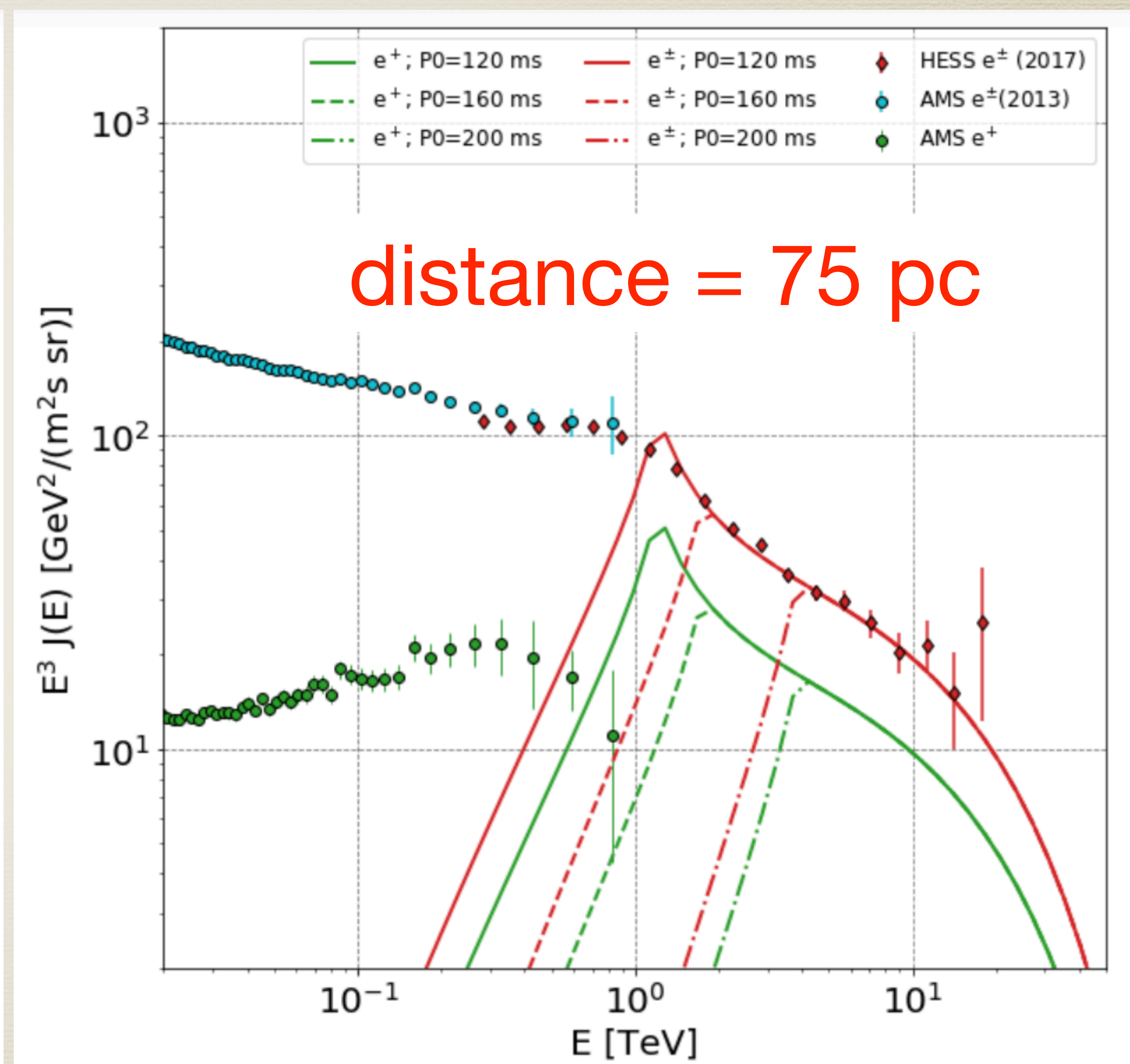
- Several reasons to think that Geminga is not in a specially different region from the rest of the local ISM
  - The pulsar proper movement is very high -> It has already escaped its SNR
  - The pulsar is not modifying the conditions of the ISM -> The energy density injected by the pulsar in the region is much lower than that of the ISM
  - Geminga might be inside the Local Bubble -> conditions do not need to be the same as the average in the ISM

- Papers using two zone models to fit the all-electron spectrum at the Earth:
  - Profumo et al. (2018)-> Burst-like emission + two-zone model
  - Hooper et al. (2017) -> Convection + Diffusion
  - Evoli, C. et al. (2018) -> Alfven waves are the physical mechanism generating a region of low diffusion.
  - Fang et al. (2019) -> H-alpha region creating the turbulence -> But no increase in the CR flux implies same density in both sides.

- Very recently: **Fermi confirms** HAWC measurement on D_{diff} (Di Mauro et al. 2019) -> even using a two-zone diffusion model these two pulsars do not significantly contribute to the local positron flux

An undiscovered pulsar as an explanation





PAMELA paper on the positron excess

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Affiliation: AA(University of Florence, Department of Physics, Via Sansone 1, I-50019 Sesto Fiorentino, Florence, Italy), AB(University of Naples "Federico II", Department of Physics, Via Cintia, I-80126 Naples, Italy), AC(Lebedev Physical Institute, Leninsky Prospekt 53, RU-119991 Moscow, Russia), AD(University of Bari, Department of Physics, Via Amendola 173, I-70126 Bari, Italy), AE(INFN, Sezione di

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dark matter 1 of 803

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