



Geminga

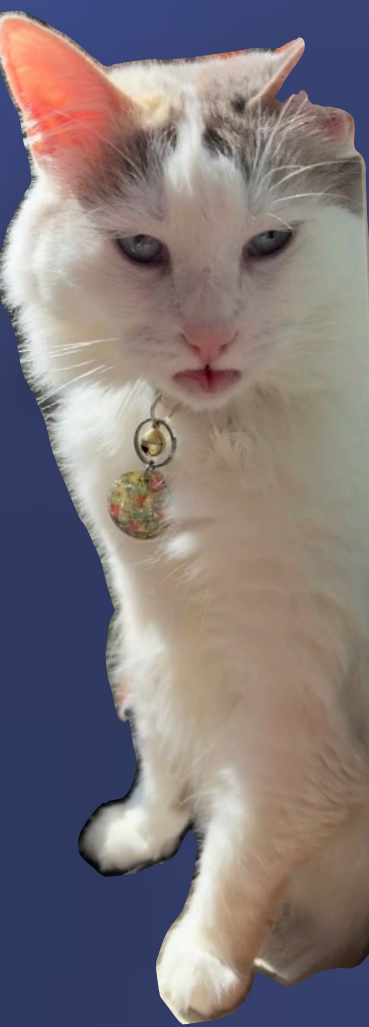


Modeling the TeV γ -ray emission of M31: cosmic ray diffuse emission and a TeV halo population

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PSR B0656+14



International School of Cosmic Ray Astrophysics, Maurice M. Shapiro, 24th course.

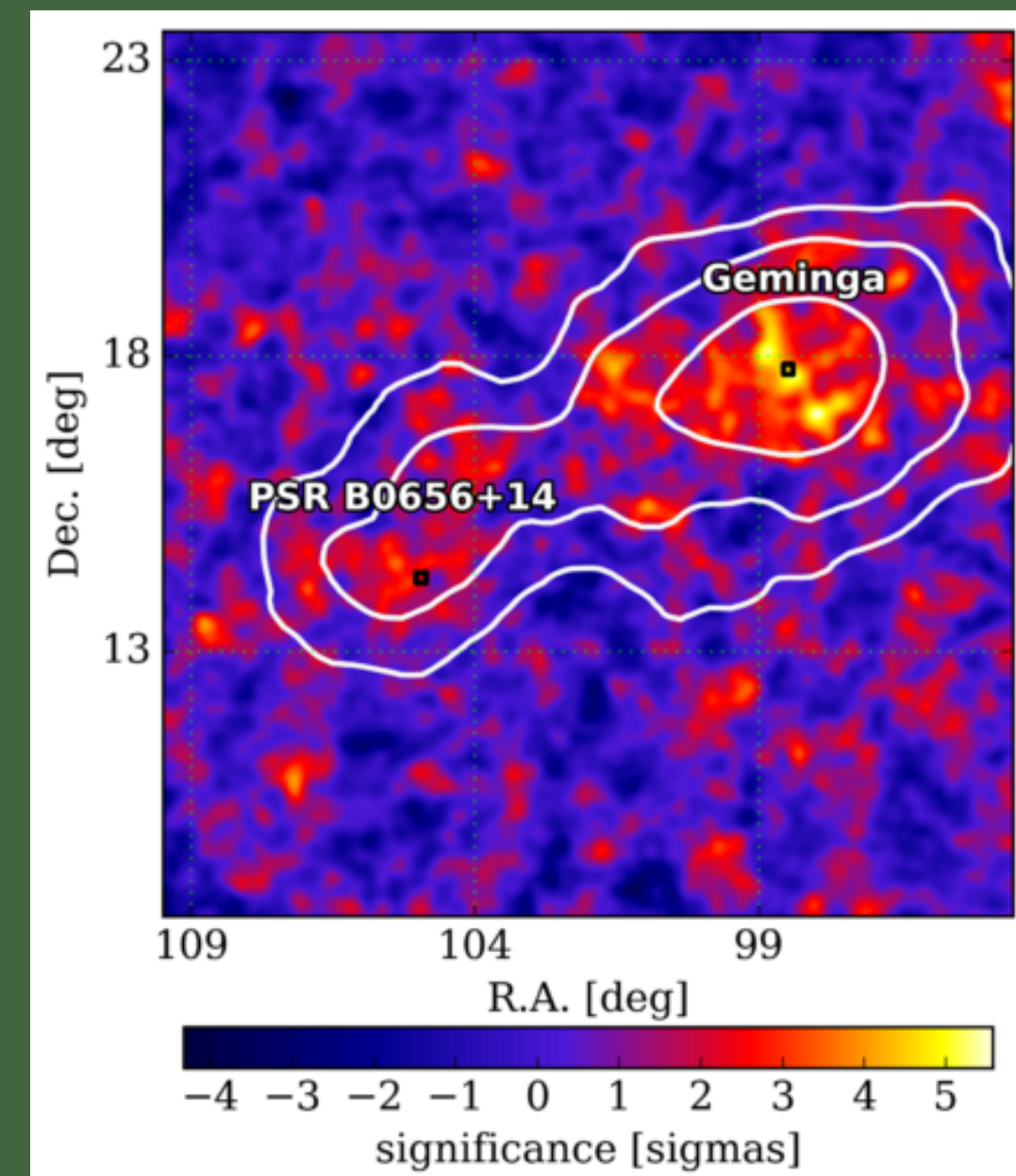
August 4th, 2026

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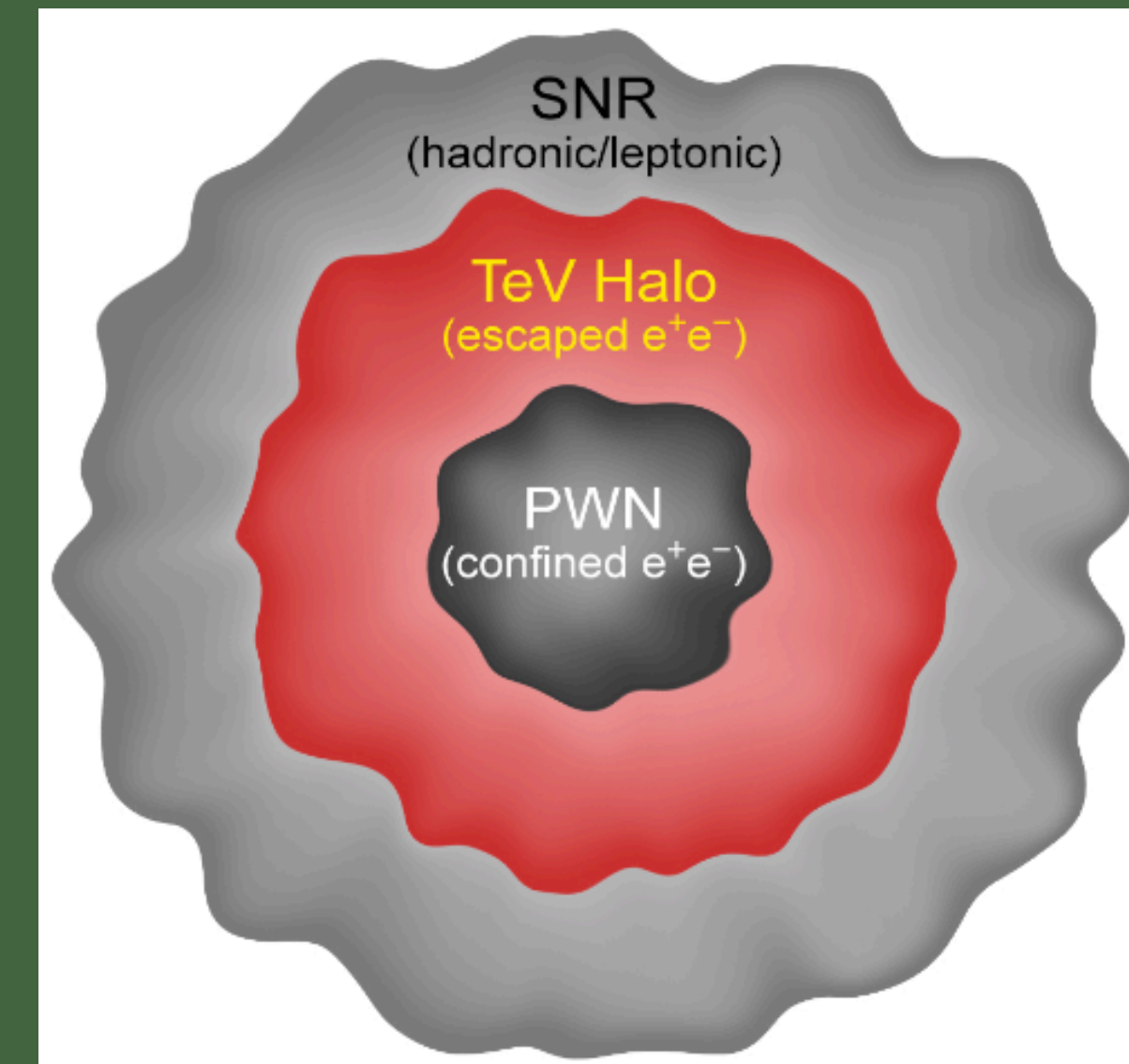
TeV Halos

- Officially detected in 2017
- Extended emission around middle-aged pulsars
- Emission produced via Inverse Compton
 - electrons accelerated by pulsar/PWN ($\sim 10\%$ of $\dot{E}$ (Abeysekara et al, 2017))
- low-energy photons from CMB



Significance maps of Monogem and Geminga's halos. HAWC, 2017.

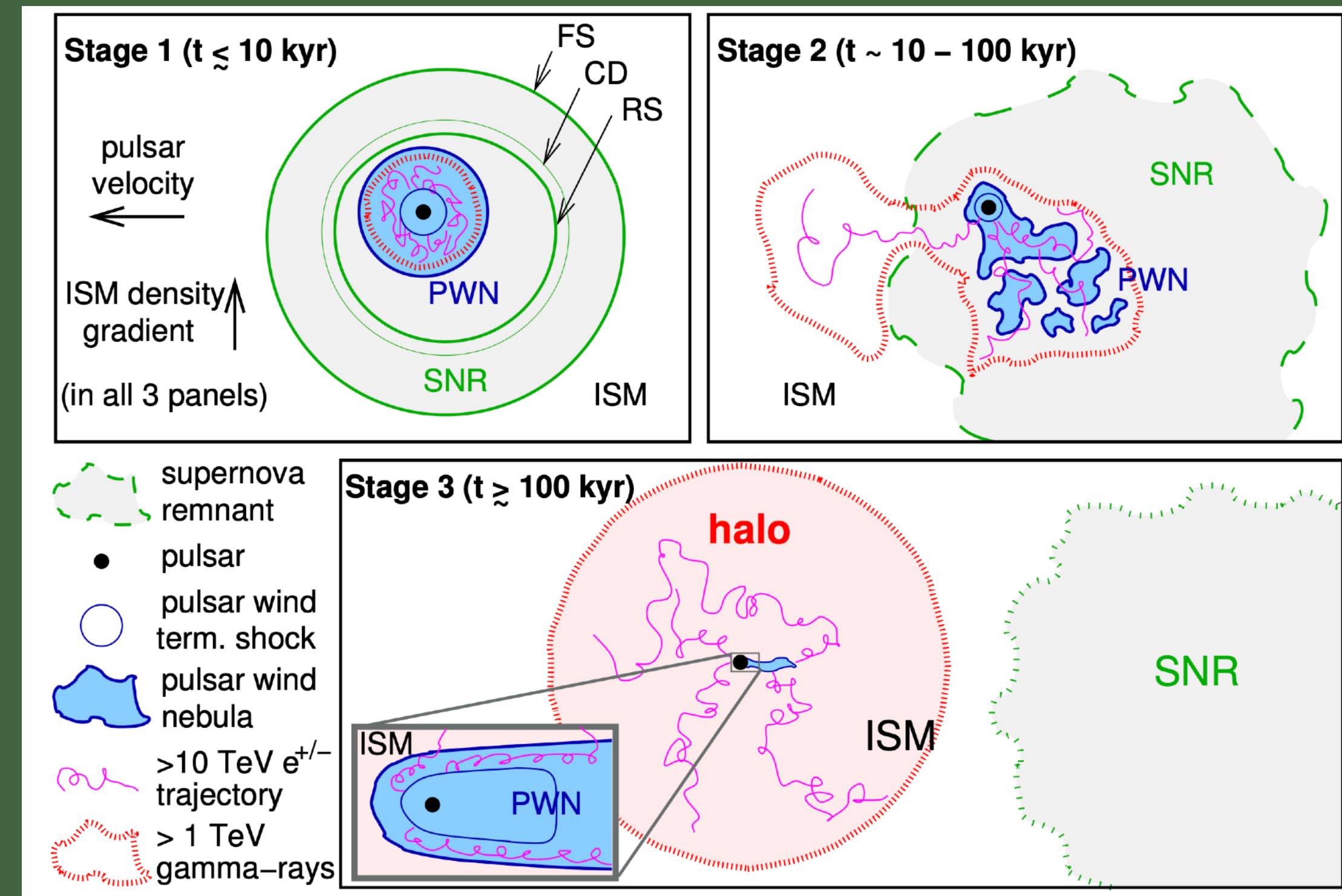
Illustrative schematic of the system SNR + Halo + PWN. Sudoh et al, 2019.



TeV Halos



- Stage 1
 - young pulsar (lepton accelerator → pulsar wind)
 - efficient confinement of leptons
- Stage 2
 - PWN disrupted by interaction with SNR (reverse shock)
 - some leptons start escaping



Evolutionary scheme of the formation of a tev halo.
Giacinti et al, 2020

- Stage 3
 - leptons diffuse freely (and slowly) in ISM

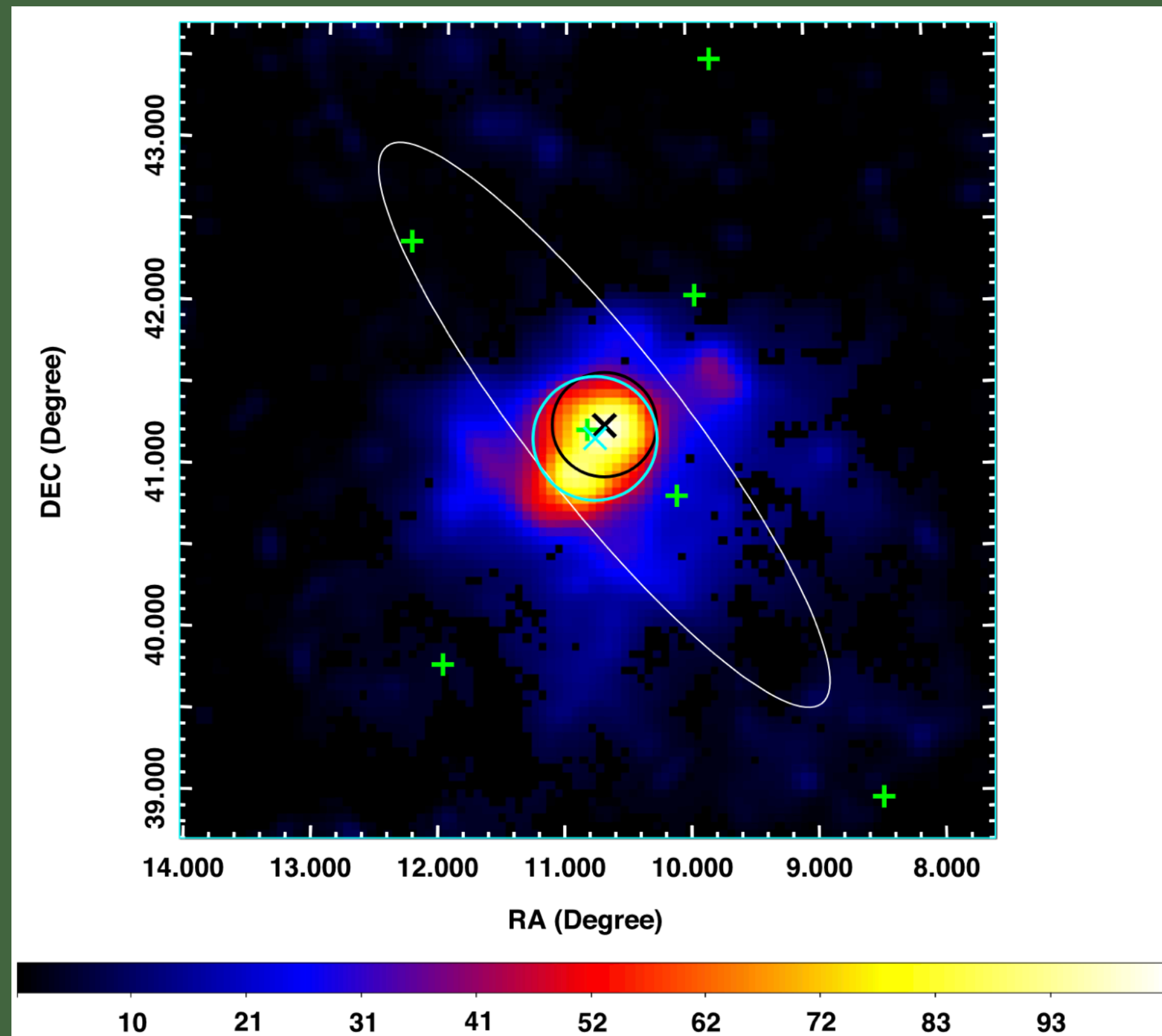
A common characteristic
of “old-enough” pulsars.

If TeV Halos are thought to be common in our Galaxy, should we expect them to be common in other galaxies with pulsar populations?



M31

Our neighbour, Andromeda



TS map of M31 in the energy range 0.1 — 500 GeV.
Xing et al, 2023.

- Spiral galaxy
- ~2 times stellar mass of the MW
- lower SRF vs the MW ($0.4 M_{\odot}/\text{yr}$ vs $1.65 M_{\odot}/\text{yr}$)
- close to us: ~780 kpc
- Evidence of a PSR population
 - galactic center gamma-ray excess (in GeV) most likely a MSP population
 - several x-ray binary systems have been detected

M31 at TeV energies

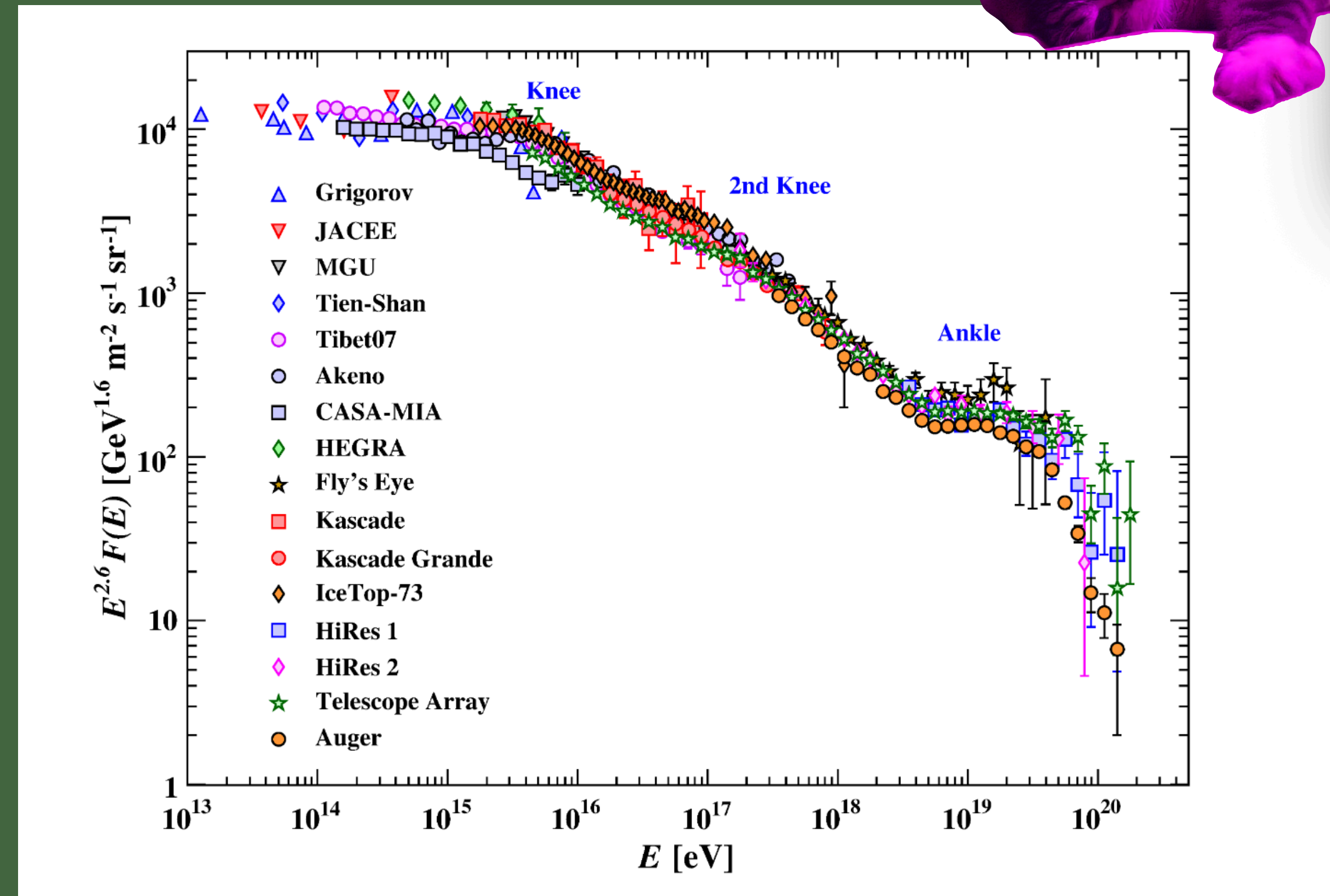
What are we expecting?

- Similar to the diffuse Galactic γ -ray emission (γ GDE)
 - unresolved sources
 - all sources, in M31's case
 - true gamma-ray diffuse emission
 - product of a cosmic ray spectrum



Cosmic Rays (CR)

- CR: relativistic charged particles permeating the ISM
 - mainly protons but also heavier nuclei and α -particles
- Particles are accelerated by astrophysical sources
 - SNR
 - PWN
 - PSRs
- They produce γ -ray via three processes
 - π^0 decay
 - Bremsstrahlung radiation
 - Inverse Compton scattering



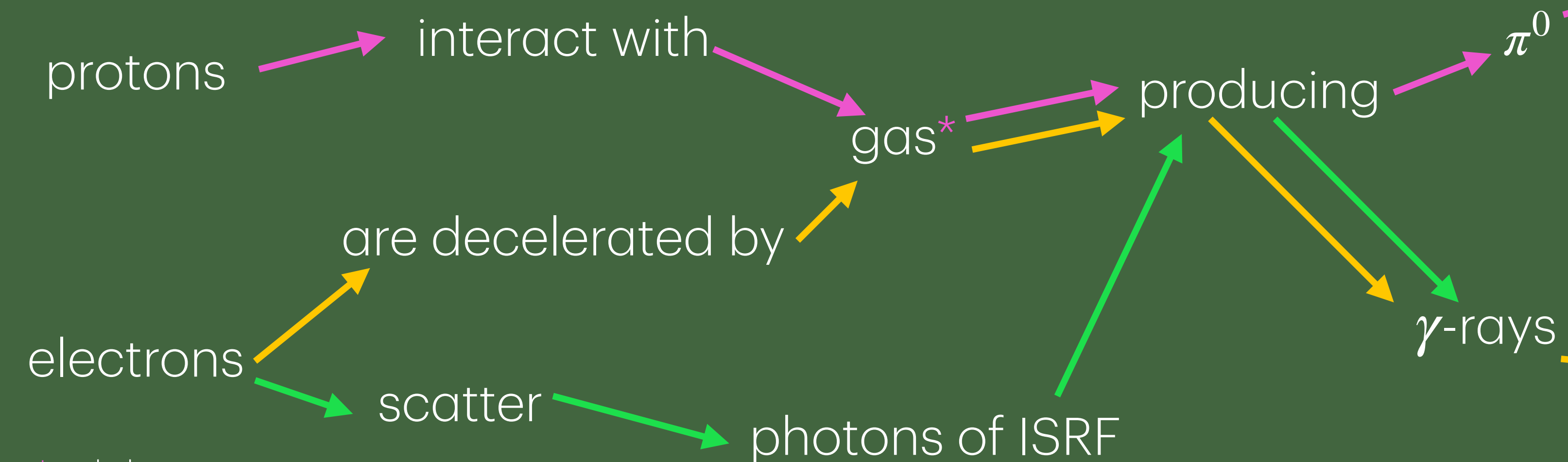
All-particle energy CR spectrum. Attallah, R. 2021.

Cosmic Ray and the γ -ray sky

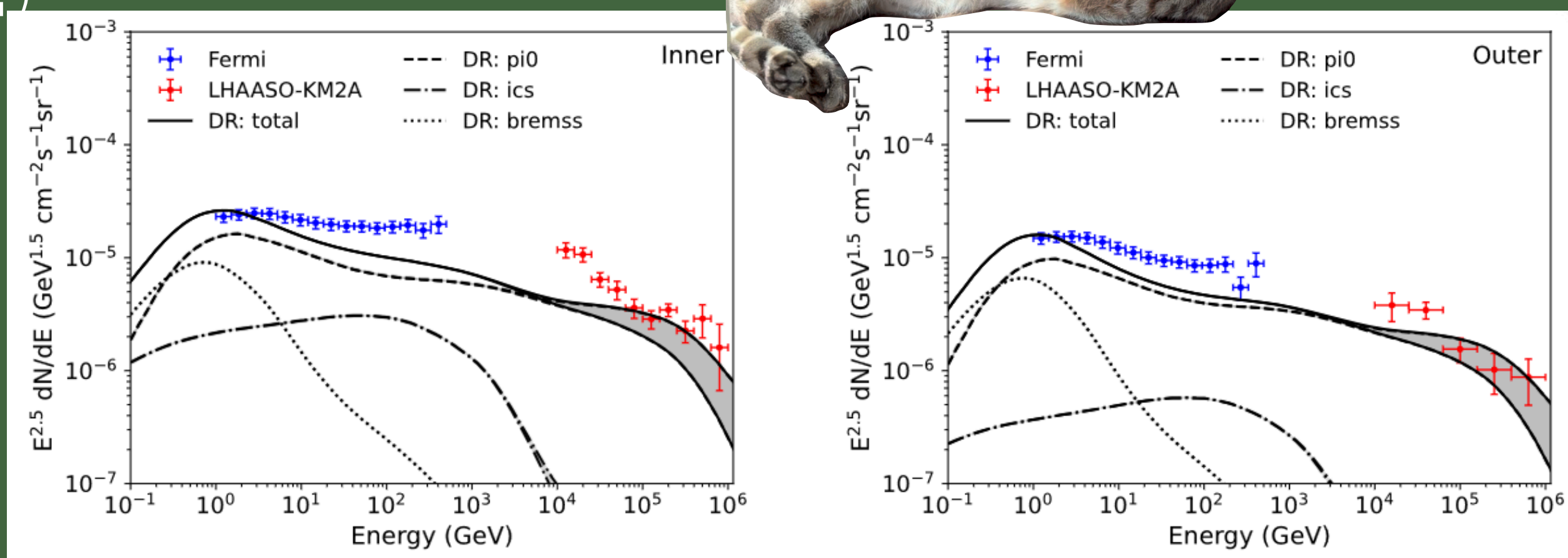
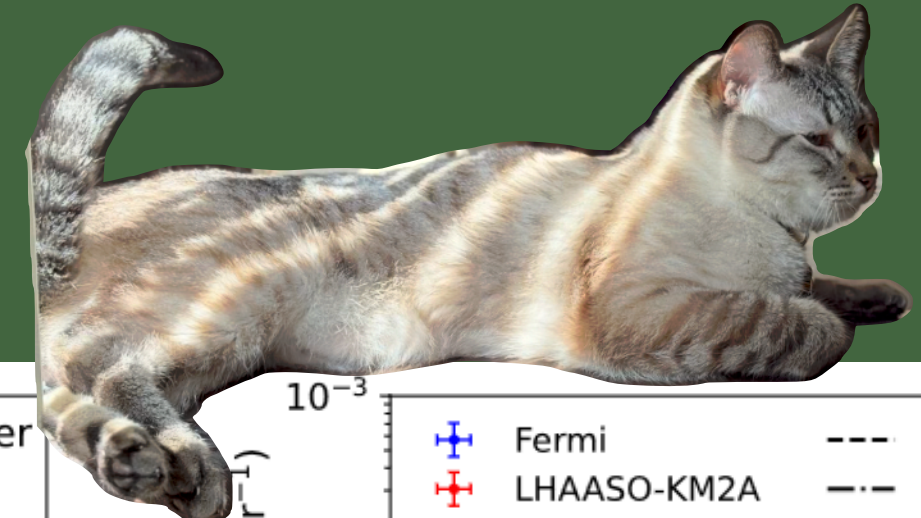
Galactic Diffuse γ -ray Emission (γ GDE)

- Wide distribution
- most emission is coming from the Galactic plane
- γ GDE intensity correlated to CR and gas density

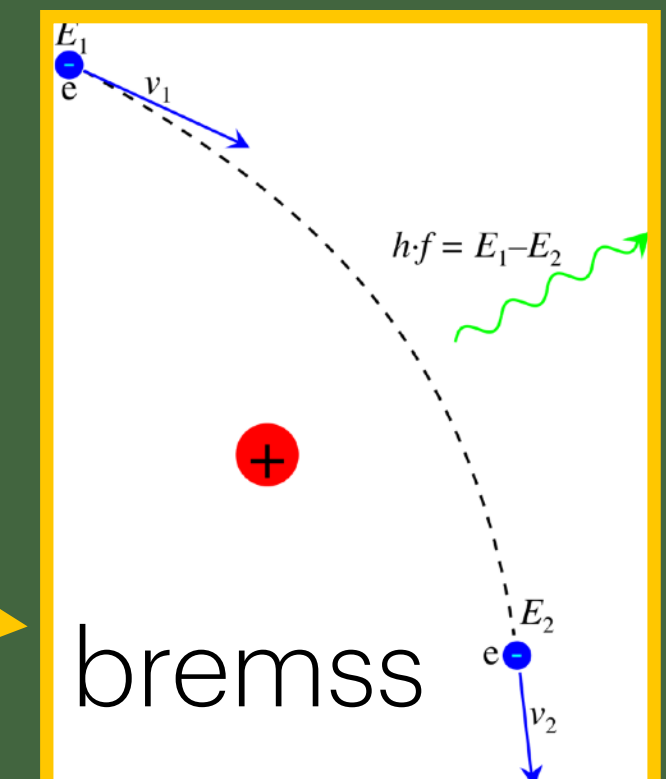
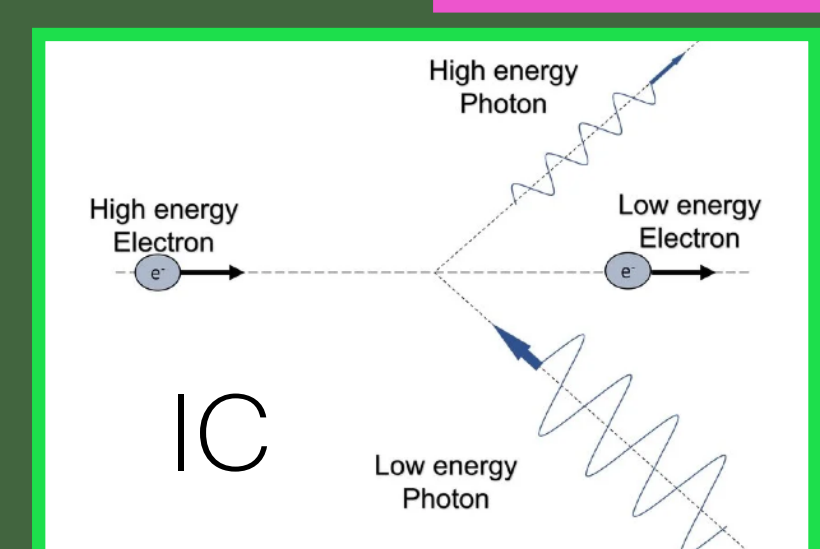
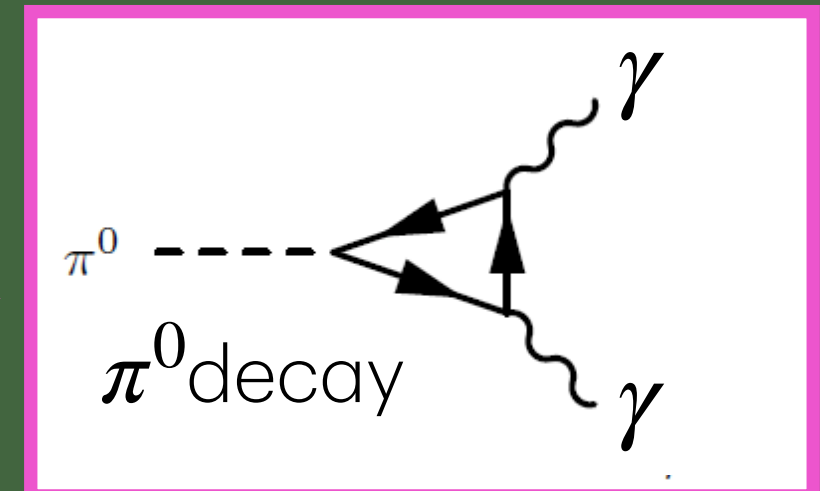
$$I_{\gamma} \propto N_{CR}(E) \times n_{gas}$$



*and photons



Wide-band spectra of the GDE. Zhang et al 2023.



We assume M31's TeV emission to be

True diffuse emission + a TeV halo population.

Our aim

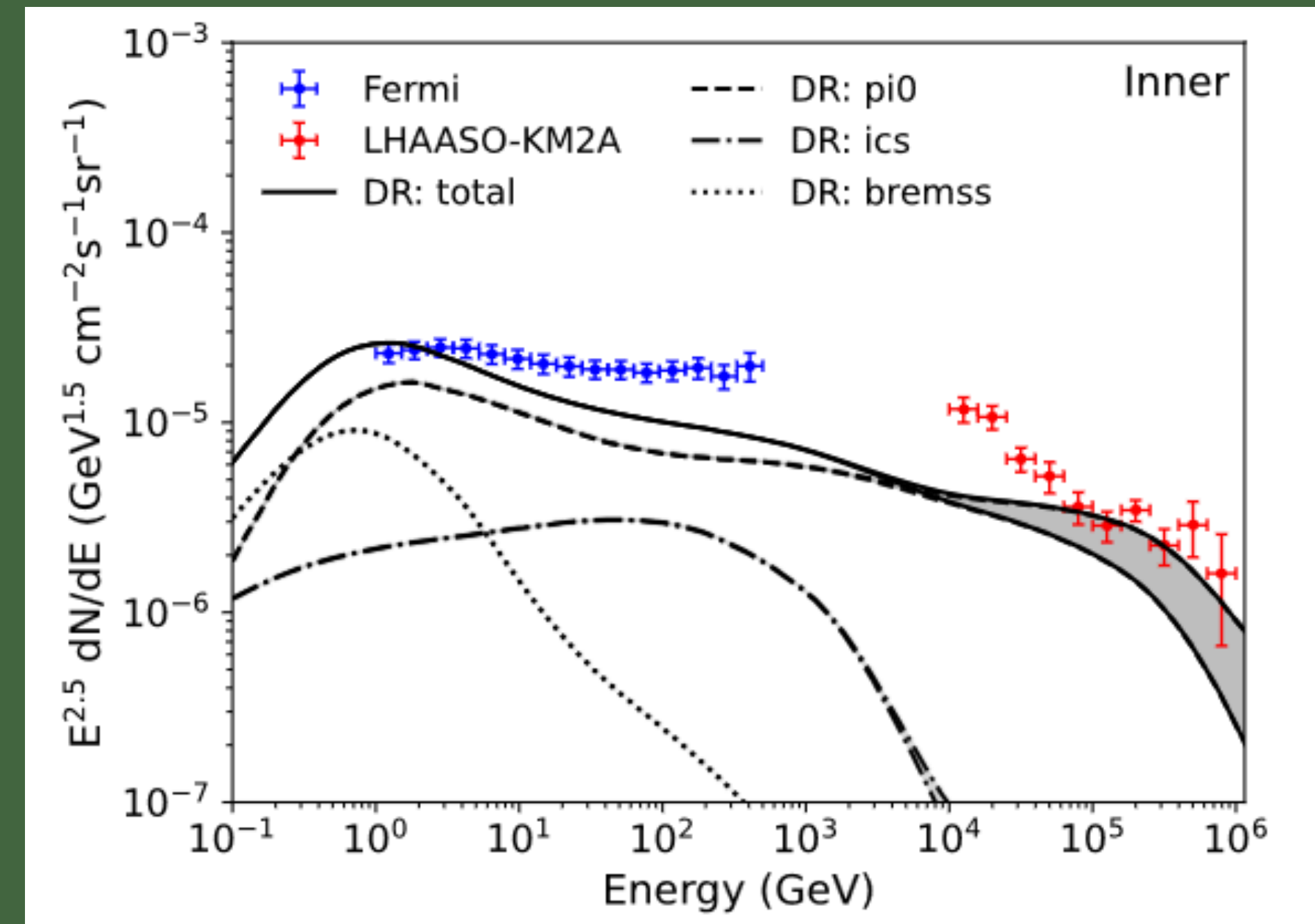
“We want to constraint the population of TeV halos in M31 using the flux upper limits obtained with all available HAWC data in the region of M31. There are several studies about the pulsar and TeV halo population in our Milky Way, which indicates TeV halos might dominate the emission at TeV energies. We want to extend these studies to the closest major spiral galaxy, M31.”



GALPROP

For the “real” diffuse emission

- Numerical CR propagation framework
- Physically self-consistent
 - solves a system of ~90 time dependant transport eq.
- Works “nicely” with MW, why not M31?



Zhang et al, 2023

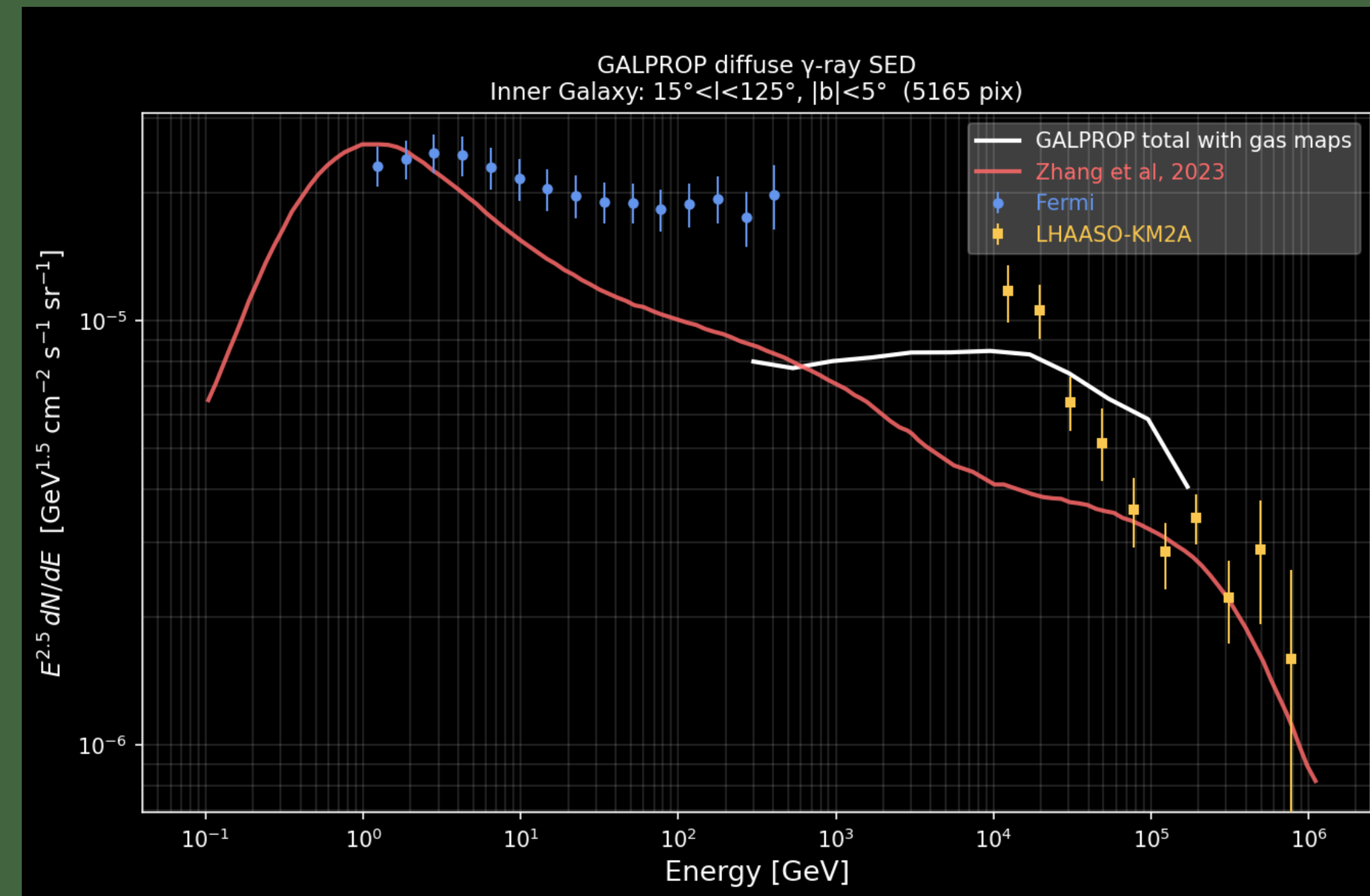
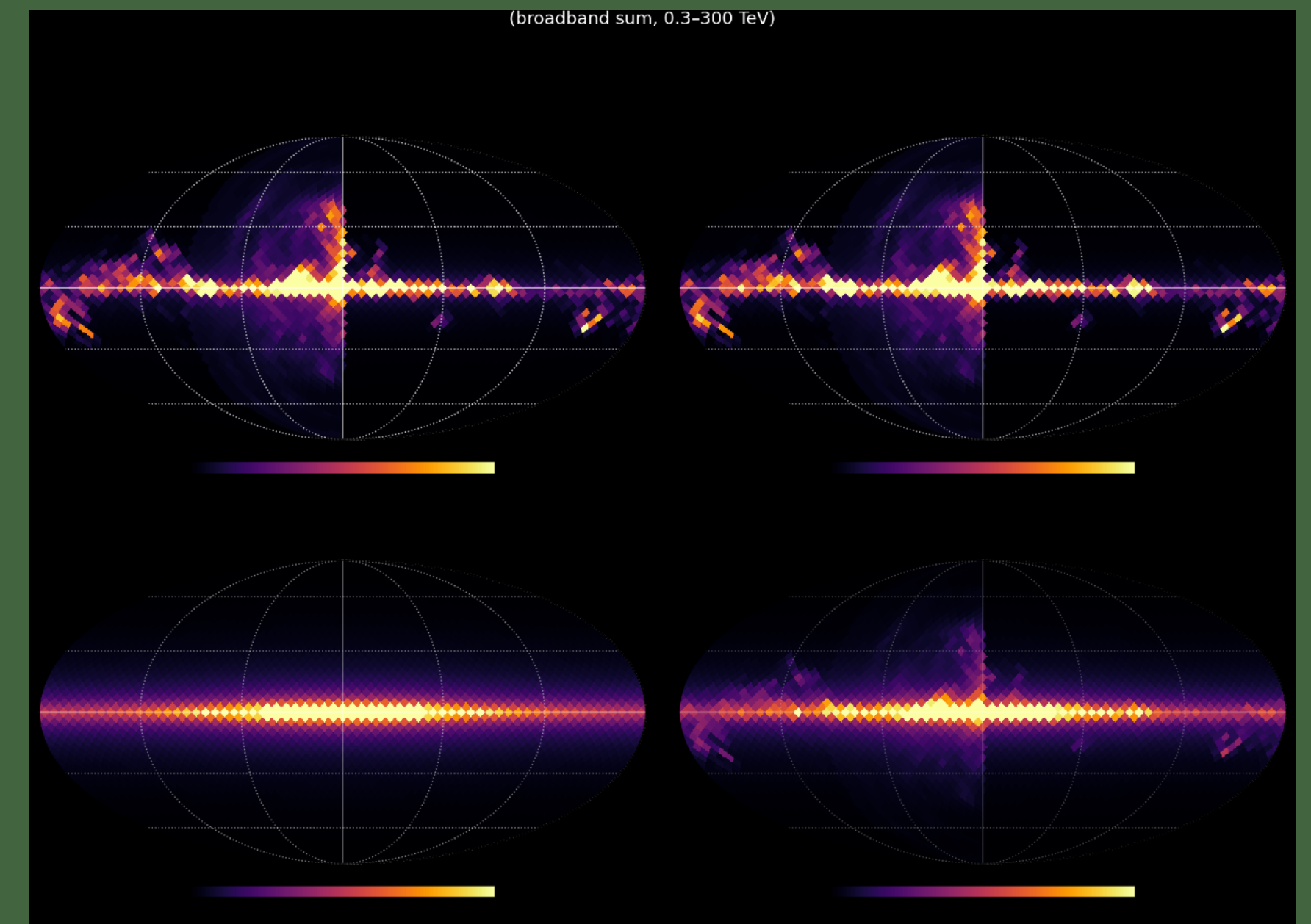
GALPROP

My preeliminary simulation

- Using gas maps
- HI (21 cm) — LAB Survey of Galactic HI (Kalberla et al, 2005)
- H2 (CO 2.6 mm) — 31 surveys in ~30 years (Dame, Hartmann & Taddeus, 2001)
- HII — analytical expression
- ISRF

$$j_{IC} \propto \int d\varepsilon \int d\Omega n(\varepsilon, \hat{k}) \frac{d\sigma_{KN}}{d\varepsilon_1}(\varepsilon, \theta)$$

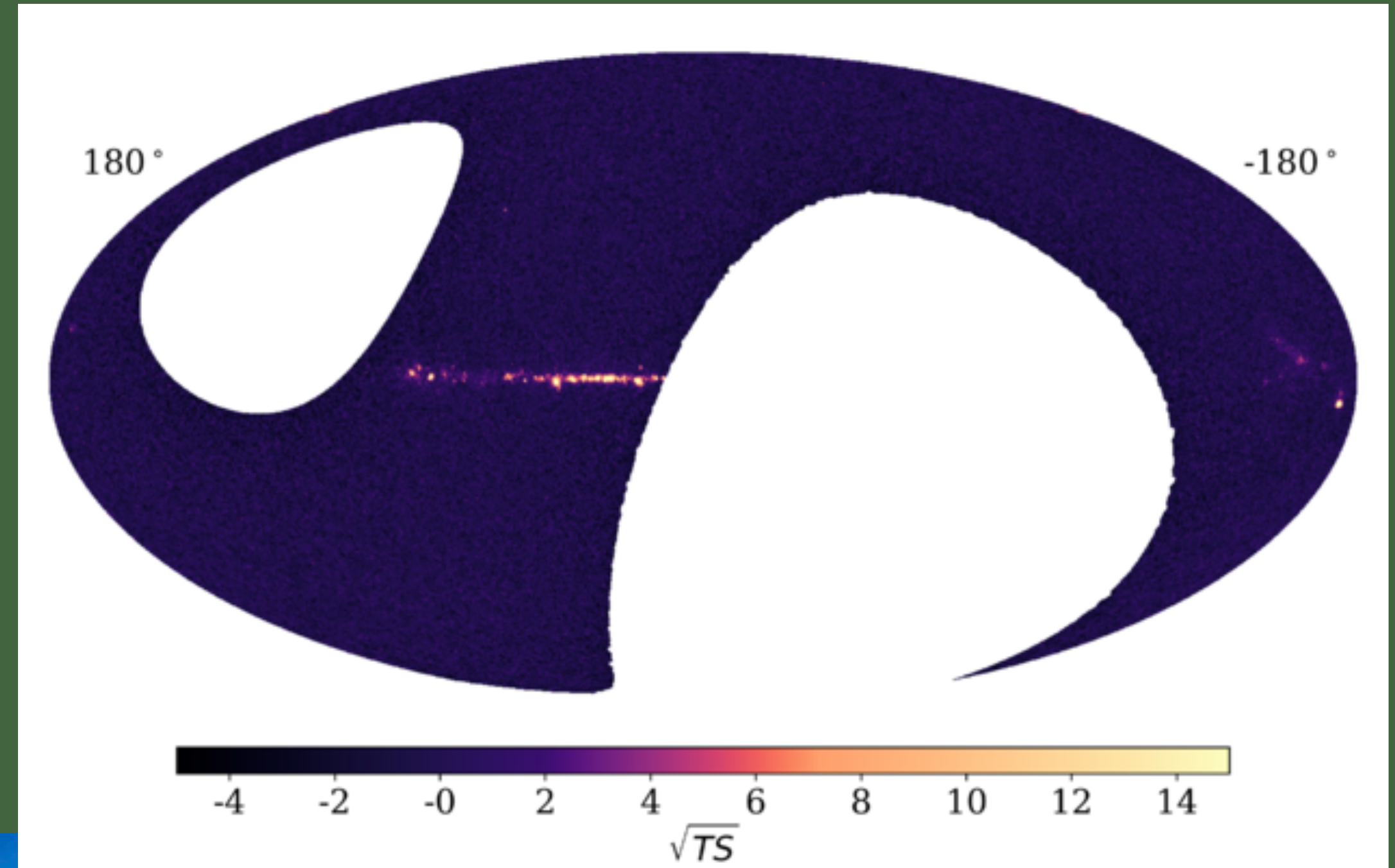
$$n(\varepsilon, \hat{k}) = \underbrace{n_{\text{opt}}(\varepsilon, \hat{k})}_{\text{UV/optic starlight}} + \underbrace{n_{\text{IR}}(\varepsilon, \hat{k})}_{\text{FIR}} + \underbrace{n_{\text{CMB}}(\varepsilon)}_{\text{isotropic BB}}$$



High Altitude Water Cherenkov

HAWC

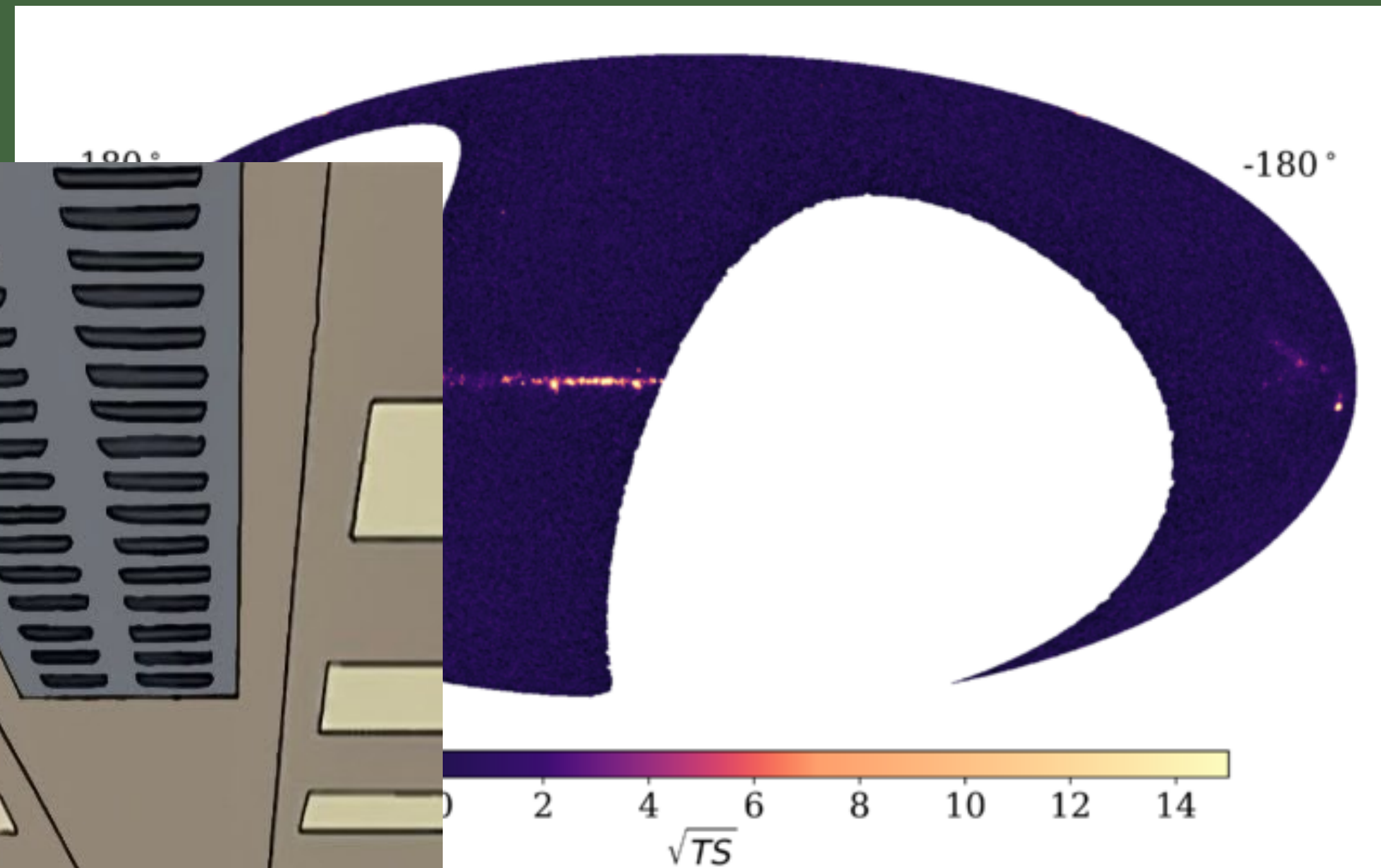
- Located at Volcán Sierra Negra, Puebla
- Duty cycle: >95%
- Instantaneous fov of 2 sr.
- Elevation: 4100 m
- 300 tanks (main array)
 - 200,000 L
- 345 outriggers
- 300 GeV— 100 TeV
- FOV: $[-26^\circ, +64^\circ]$ dec
- Angular resolution:
 $\geq 0.1^\circ$



High Altitude Water Cherenkov

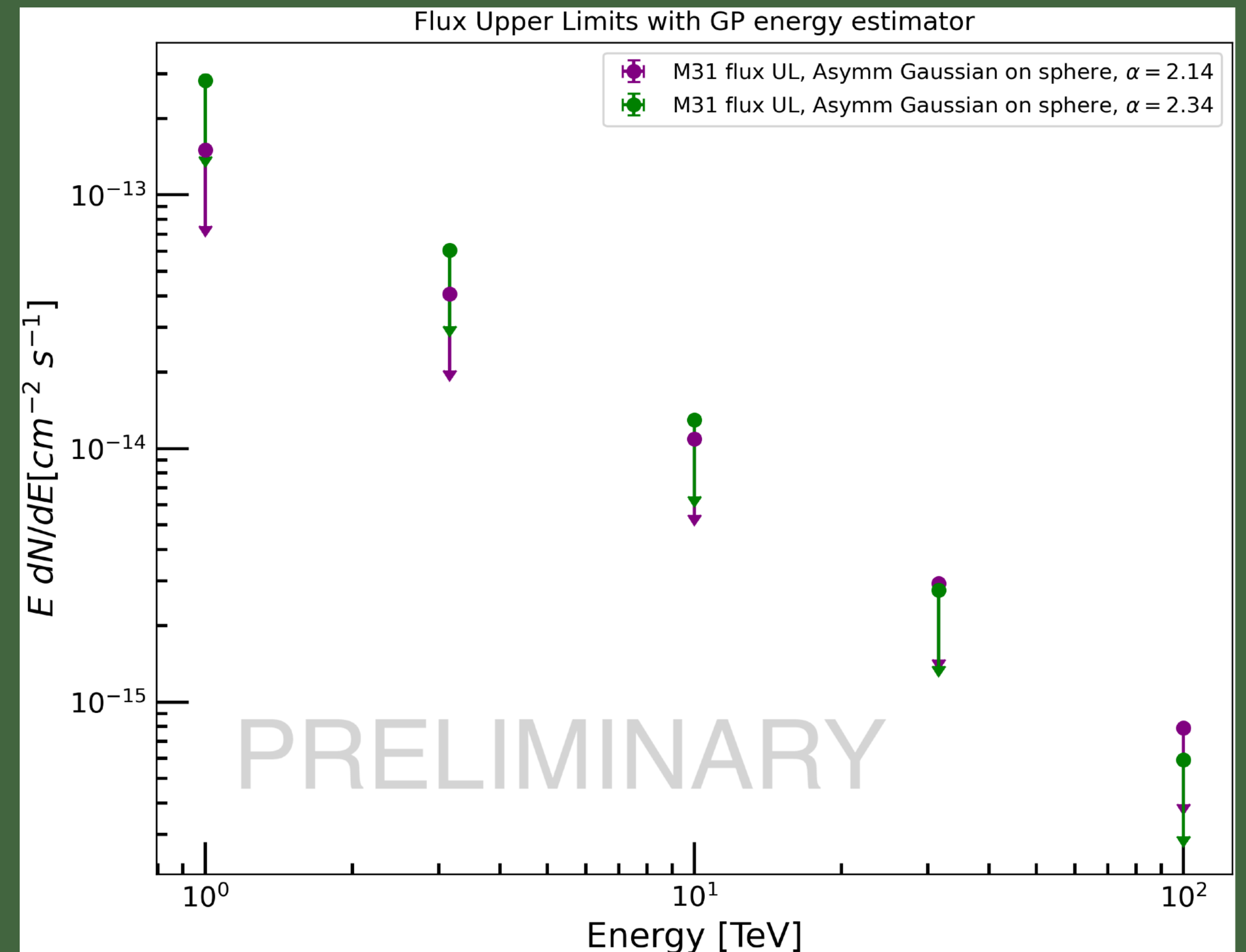
HAWC

- Located at Volcán Negro, Puebla
- Duty cycle: >
- Instantaneous
- Elevation: 41
- 300 tanks (m
- 200,000 L
- 345 outrigge



HAWC's Upper limits for M31

- No significant excess found
 - We obtain 95% confidence level upper limits for the TeV flux
- Asymmetric gaussian morphology
- Power law spectrum
 - $\alpha = (2.14, 2.34)$



GALPROP + M31's UL

How can we compare?

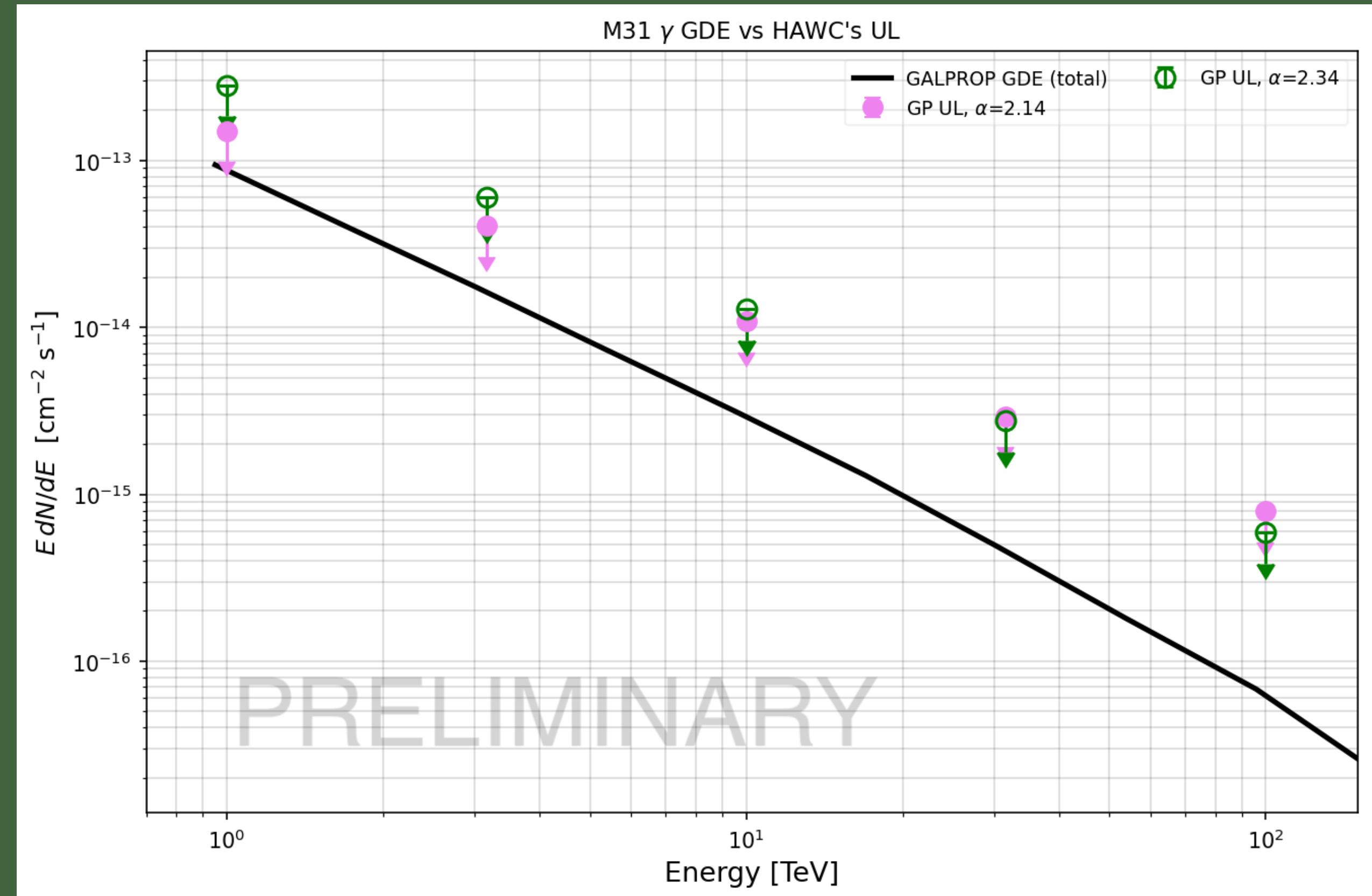
- Taking the inner Galaxy simulation
- scaling to M31 position

$$E \frac{dN}{dE} = E[MeV] \times I_{MW} \times \Omega$$

- flux can be approximated as

$$F = \int I d\Omega \approx I \times \Omega$$

- Our halo population lies between our simulation and the UL



Summary

& what's next for our project

- TeV halos are a common, age-driven feature of pulsars.
- M31 hosts a pulsar population (MSPs, X-ray binaries)
- GALPROP γ GDE (MW-validated) scaled to M31 + HAWC's new upper limits give the first joint constraint on M31's TeV emission
- Our model prediction sits below the ULs

- Next: GALPROP simulation needs to be more accurate to M31
 - gas content changes
 - size changes
 - ISRF changes
 - analytical diluted black bodies for the three* components
- A model for the halo population
 - Geminga-like



Back-up

10 years of HAWC

DOI: <https://doi.org/10.22201/ia.01851101p.2025.61.03.13>

HAWC Collaboration

The first 10 years of the HAWC Gamma-Ray Observatory: science results

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OPEN ACCESS <https://doi.org/10.22201/ia.01851101p.2025.61.03.13>



The first 10 years of the HAWC Gamma-Ray Observatory: science results

Abstract

The High-Altitude Water Cherenkov (HAWC) Observatory, located on the slopes of the Sierra Negra volcano in Mexico, began operations in March 2015. Over the past decade, HAWC has enabled the exploration of a broad range of topics in high-energy astrophysics and particle physics, resulting in more than 90 peer-reviewed publications. These studies have significantly advanced our understanding of several previously unexplored and poorly understood phenomena in the TeV energy regime. The present work provides an overview of the key scientific contributions of HAWC during its first ten years of operation.

Resumen

El Observatorio Cherenkov de Agua de Gran Altitud (HAWC), ubicado en las laderas del volcán Sierra Negra en México, inició operaciones en marzo de 2015. Durante la última década, HAWC ha permitido la exploración de una amplia gama de temas en astrofísica de altas energías y física de partículas, lo que ha dado lugar a más de 90 publicaciones arbitradas. Estos estudios han mejorado significativamente nuestra comprensión de varios fenómenos previamente inexplorados o poco comprendidos en el régimen de energía TeV. Este trabajo ofrece un resumen de las principales contribuciones científicas de HAWC durante sus primeros diez años de funcionamiento.

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TeV Halos

Diffusion model

- An indirect measurement of the diffusion coefficient

$$\frac{d^2N}{dEd\Omega} = N_0 \left(\frac{E}{20 \text{ TeV}} \right) \frac{1.22}{\pi^{3/2} \theta_d(E) (\theta + 0.6 \theta_d(E))} e^{-\frac{\theta^2}{\theta_d(E)^2}} \quad (\text{HAWC, 2017})$$

$$\theta_d = \frac{180^\circ}{\pi} \frac{r_d}{d_{psr}} \quad r_d = 2\sqrt{D(E)t}$$

$$D_{\text{Geminga}} = 4.5 \pm 1.2 \times 10^{26} \text{ cm}^2 \text{ s}^{-1}$$

$$D_{\text{Gal}} = 10^{28-29} \text{ cm}^2 \text{ s}^{-1}$$

Geminga-like model

for TeV Halos

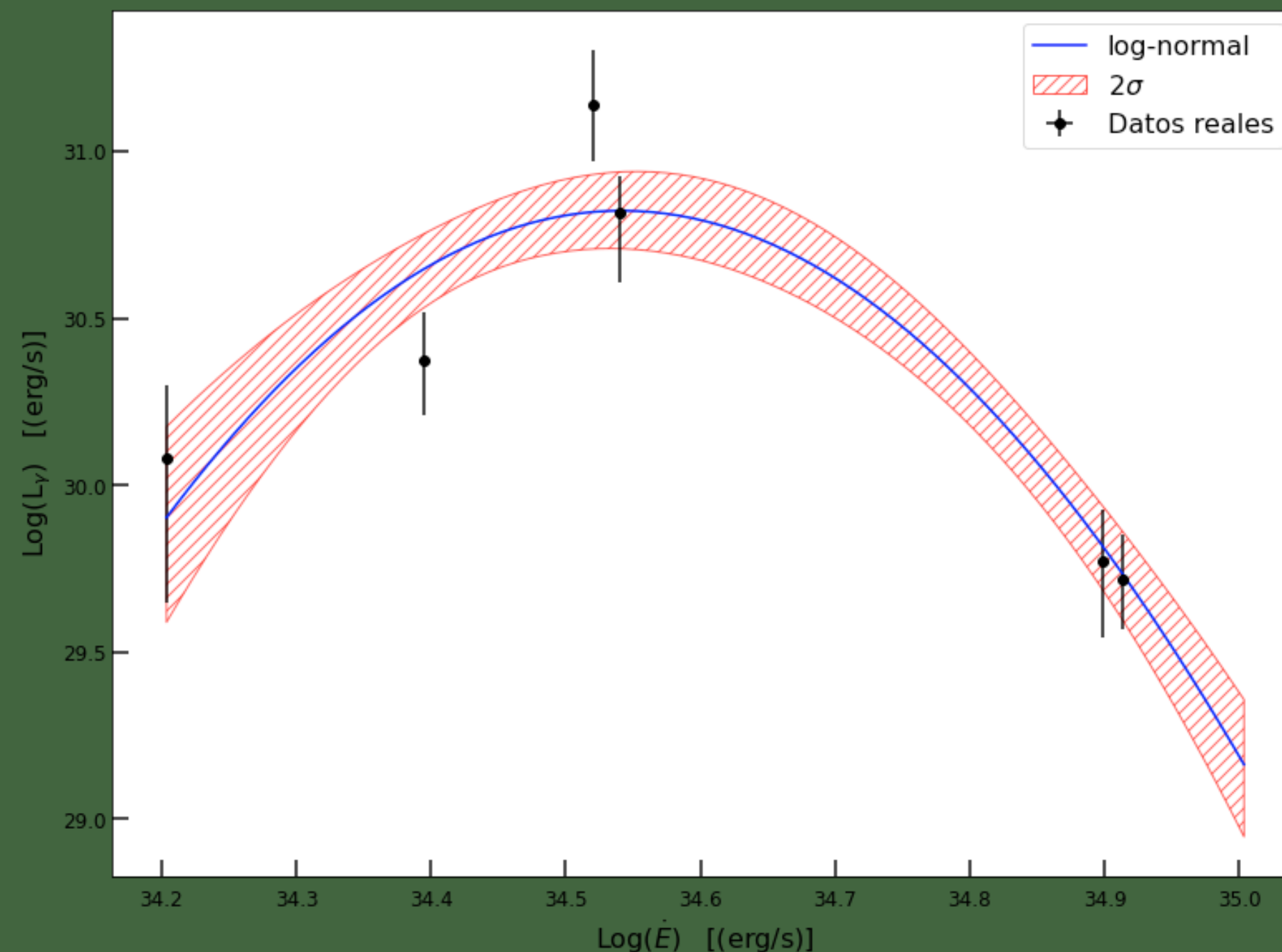
- Angular extension (if needed) is scaled from Geminga
- γ -ray luminosity at 7 TeV is parametrised as a function of only the age of the pulsar
- flux is a simple power-law

$$\frac{dN}{dE} = F_7 \left(\frac{E}{7 \text{ TeV}} \right)^{-2.34}$$

$$S = \frac{d_{\text{Geminga}}}{d_{\text{PSR}}} \times S_{\text{Geminga}}$$

$$\log(L) = \frac{107.46}{0.03\sqrt{2\pi}} \frac{e^{-(\ln(\log \dot{E}) - 3.54)^2 / 0.0018}}{\log \dot{E}}$$

$$\log(\dot{E}) = -1.45 \log(\text{Age}) + 42.23$$



Installation of Galprop v57

or how I almost lost my mind and decided to sell tacos instead (or smth)

- Galprop is a legacy code (respectfully, 'old')
 - base code written in 2005 (before modern standards of C++)
- Confusing (for me at least) installation
 - missing maps for examples in the galprop repository
- **Problem 1:** I'm using a computer with an apple silicon architecture (M3 chip)
 - Galprop is written for systems x86
 - My computer runs with ARM64
 - infinite loop in routines that calculate secondary positrons (not good)
- **Solution 1:** move to an ubuntu machine
- **Problem 2:** the machine runs with Ubuntu 24.04.2 (c++ compilers 'too new')
 - tbh, I don't remember well the details (🤔), but it didn't run
- **Solution 2:** running inside a Docker container with an older Ubuntu (20.04.6)
 - it worked!

Upper limit analysis pipeline

- I model M31 as a power law

$$\frac{dN}{dE} = K \left(\frac{E}{E_{\text{pivot}}} \right)^{-\alpha}$$

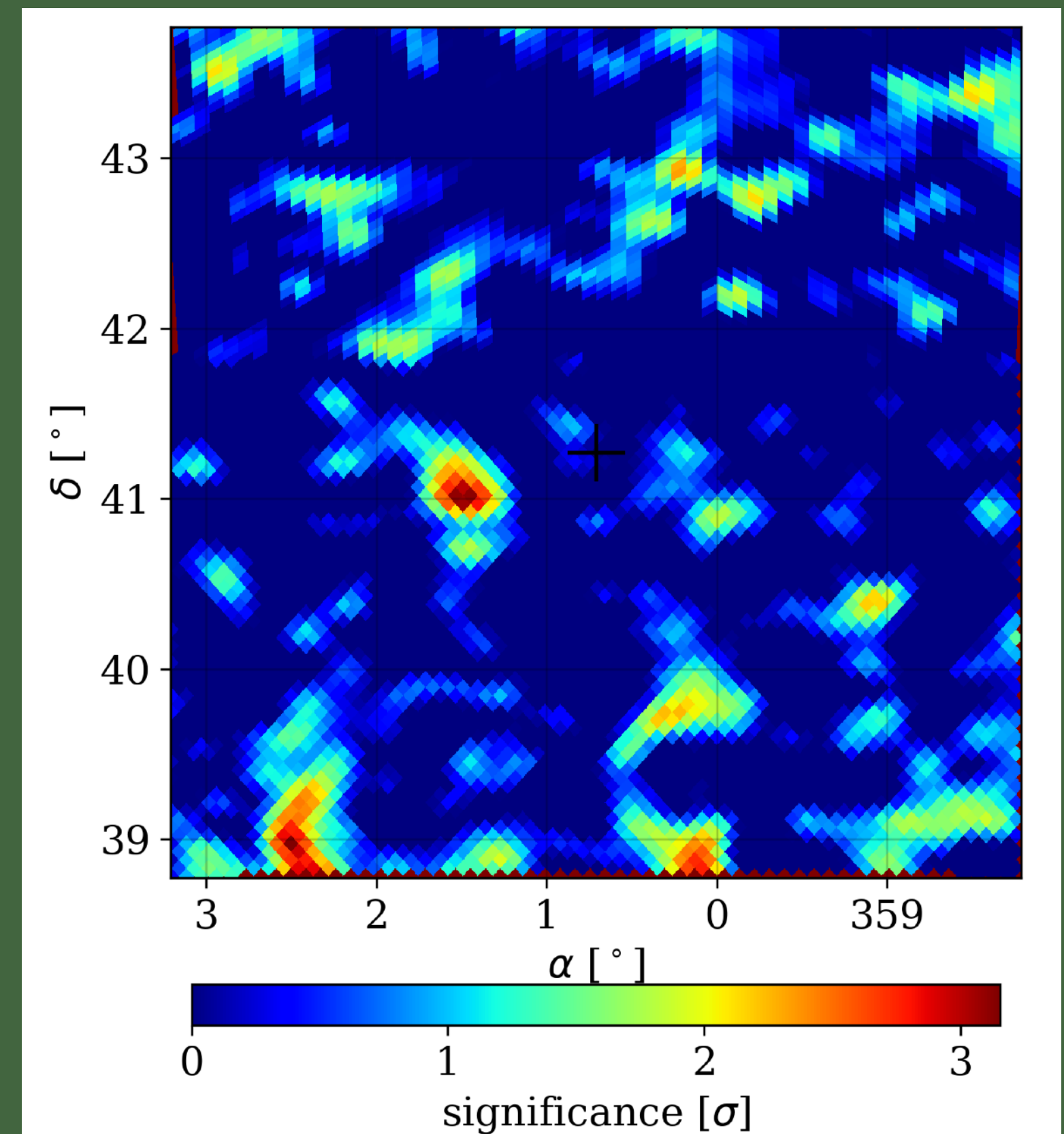
$$E_0 = 7 \text{ TeV}, \alpha = (2.14, 2.34)$$

Model: power law
Normalisation is our free parameter

Max likelihood
(HAL)

Bayesian MCMC

95th percentile of K



Milky Way vs Andromeda

MW vs M31

	Milky Way	M31
Distance	8.2 kpc (galactocentric)	785 ± 25 kpc
Angular size	full sky/interior view	$\sim 3.9^\circ \times 1.1^\circ$
Stellar disk scale length	~ 2.6 kpc	5.36 — 6.1 kpc
Gas quantities (HI, H2)	(HI) $\sim 8 \times 10^9 M_\odot$ (H2) $(1.0 \pm 0.3) \times 10^9 M_\odot$	(HI) $(7.3 \pm 2.2) \times 10^9 M_\odot$ (H2) $(3.6 \pm 1.8) \times 10^8 M_\odot$
Total gas quantities	$\sim 9 \times 10^9 M_\odot$	$\sim 7.7 \times 10^9 M_\odot$
SFR	$1.65 \pm 0.19 M_\odot/\text{yr}$	0.25 — 0.4 $M_\odot/\text{yr}$
Core-collapse SN rate	1.63 ± 0.46 per century	~ 0.17 per century

HII analytic expression

$$n_{\text{HII}}(R, z) = \underbrace{n_1 e^{-|z|/H_1}}_{\text{Gaensler wide}} + \underbrace{n_2 g_2(R) h_2(z)}_{\text{NE2001 narrow ring}}$$

$$n_{e1}(R, z) = 0.014 \cdot e^{-|z|/1.8} \quad [\text{cm}^{-3}]$$

$$n_{e2}(R, z) = 0.09 \cdot g_2(R) \cdot h_2(z) \quad [\text{cm}^{-3}]$$

$$g_2(R) = \exp \left[-\frac{(R - 3.7)^2}{1.8^2} \right]$$

$$h_2(z) = \text{sech}^2 \left(\frac{z}{0.14} \right)$$