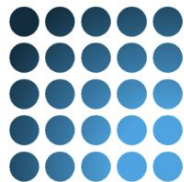




Department of Physics
UNIVERSITY OF WISCONSIN-MADISON



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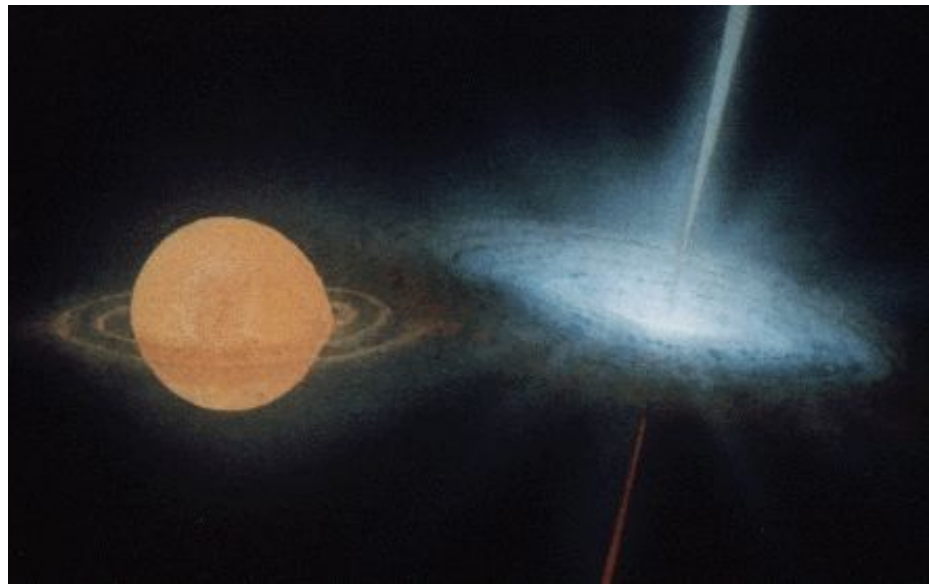


Leptonic Modeling of PeVatrons

Zach Curtis-Ginsberg,
Dan Hooper, Justin Vandenbroucke
IceCube Particle Astrophysics Symposium, 10/14/26

PeVatrons

- A cosmic-ray source which accelerates particles up to (at least) 1 PeV
- Either leptonic (accelerating electrons) or hadronic (accelerating protons)
- The “knee” (~ 4 PeV) in the cosmic-ray spectrum likely corresponds to the max energy Galactic sources can accelerate protons
- Observations of >100 TeV gamma rays has been used as evidence for a hadronic PeVatron
- We present a framework for modeling these gamma rays



Credit: NASA Artist's Visualization

Cosmic Ray Diffusion Equation

$$\frac{\partial}{\partial t} \frac{dn_e}{dE_e}(E_e, r, t) = \vec{\nabla} \cdot \left[D(E_e) \vec{\nabla} \frac{dn_e}{dE_e}(E_e, r, t) \right] + \frac{\partial}{\partial E_e} \left[\frac{dE_e}{dt}(r) \frac{dn_e}{dE_e}(E_e, r, t) \right] + \delta(r) Q(E_e, t)$$

Electron Density = Diffusion + Energy Loss + Injection

$$\frac{dn_e}{dE_e}(E_e, r, t) = \frac{Q_0 E_0^{2-\alpha}}{8\pi^{3/2} E_e^2 L_{\text{dif}}^3(E_e, t)} \exp \left[\frac{-E_0}{E_c} \right] \exp \left[\frac{-r^2}{4L_{\text{dif}}^2(E_e, t)} \right]$$

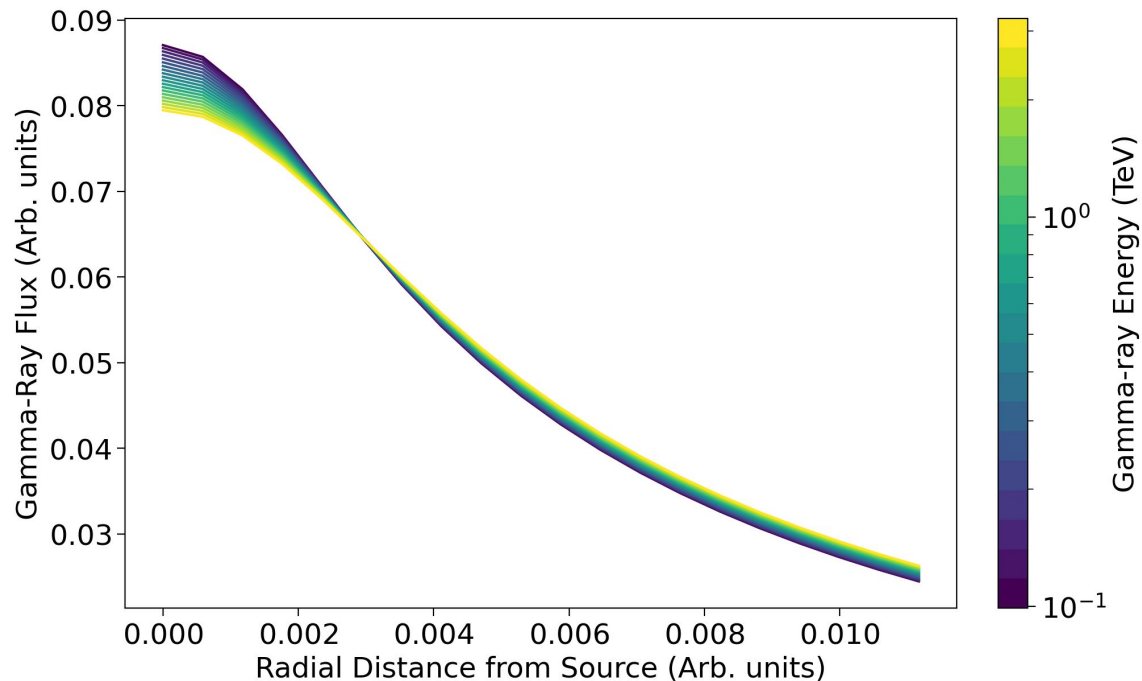
*with $Q(E_e, t) = \delta(t) Q_0 E^{-\alpha} \exp[-E_e/E_c]$, we model many injections

Spatial Output

Gamma-ray flux from a given electron spectrum is a function of gamma-ray energy and radial distance

Showing here one realization as a function of radial distance and energy

Integrating over the source to get the total flux as a function of energy



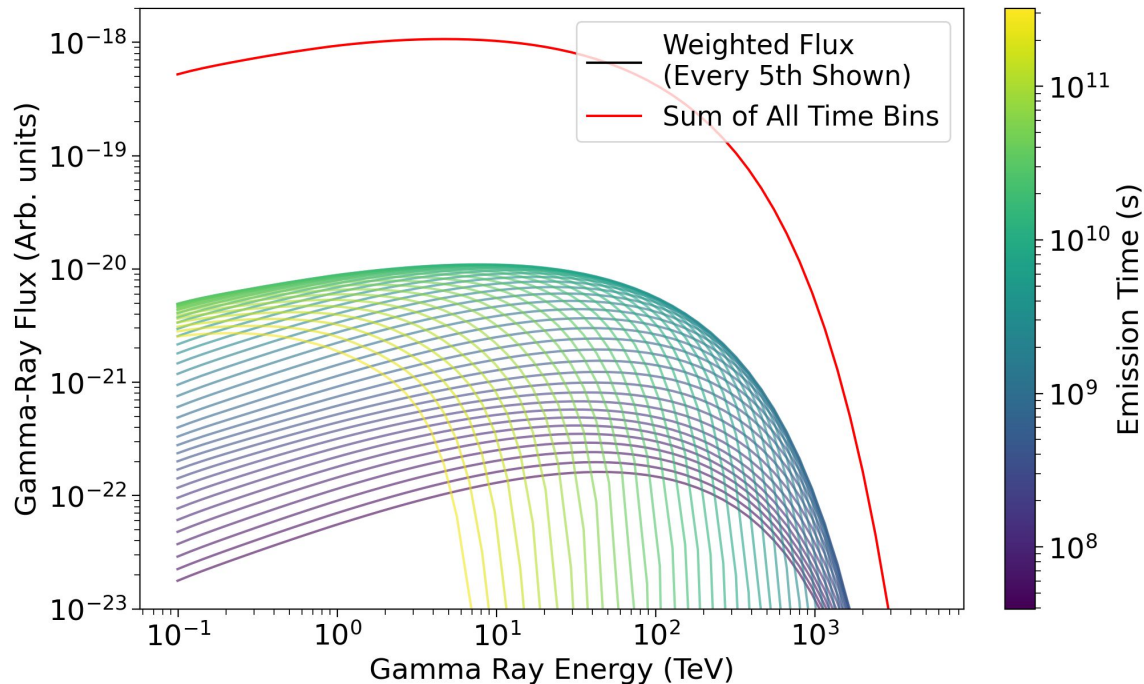
Spectral Output

Integrating over the line-of-sight and predicting the inverse Compton gamma-ray emission from the electrons

Time injections defined by synchrotron loss time for electrons

Weighting by the width of each time bin

Total flux given by the sum of the weighted times



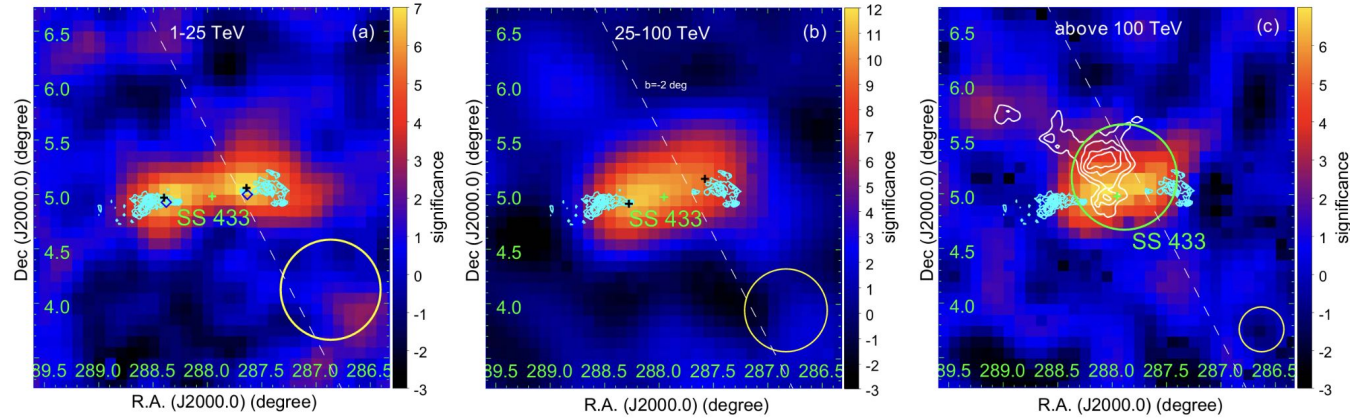
SS 433

First microquasar to
be discovered (1979)

Has been detected in
gamma rays by HAWC, H.E.S.S., LHAASO, and VERITAS

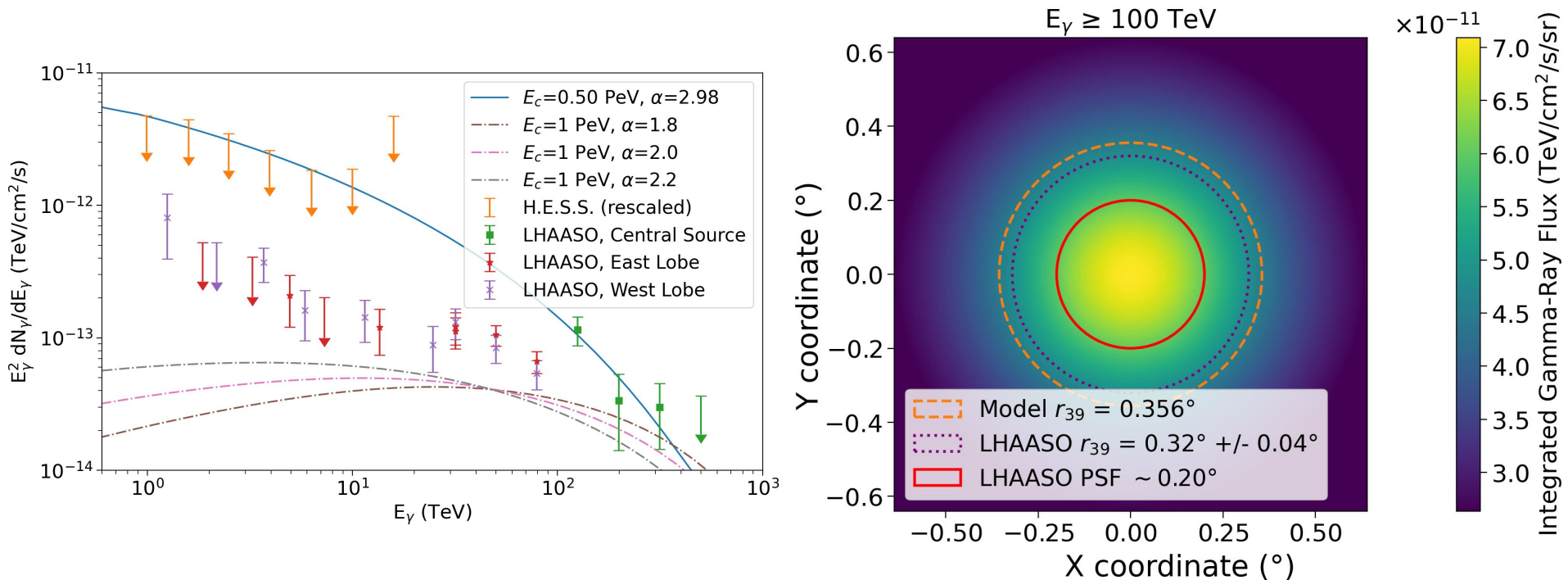
HAWC, H.E.S.S., and VERITAS observe the two jets

LHAASO sees the two jets below 100 TeV, above 100 TeV they prefer a symmetric
extended source



Credit: LHAASO, NSR 12, 12, nwaf496 (2025)

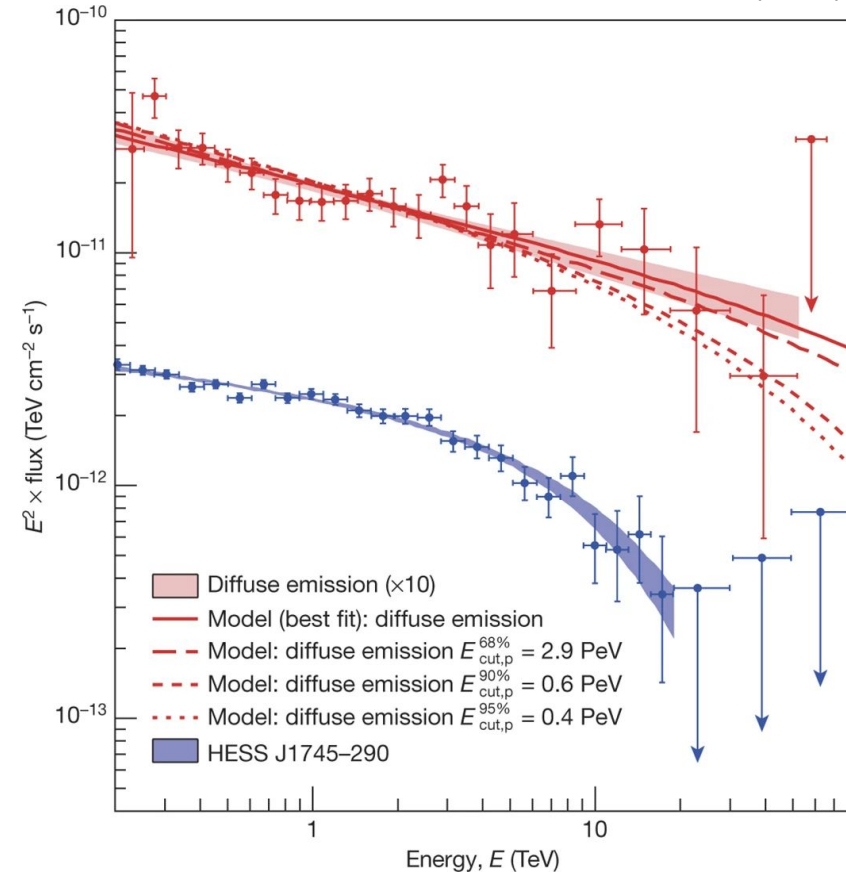
Fitting SS 433 with our Model



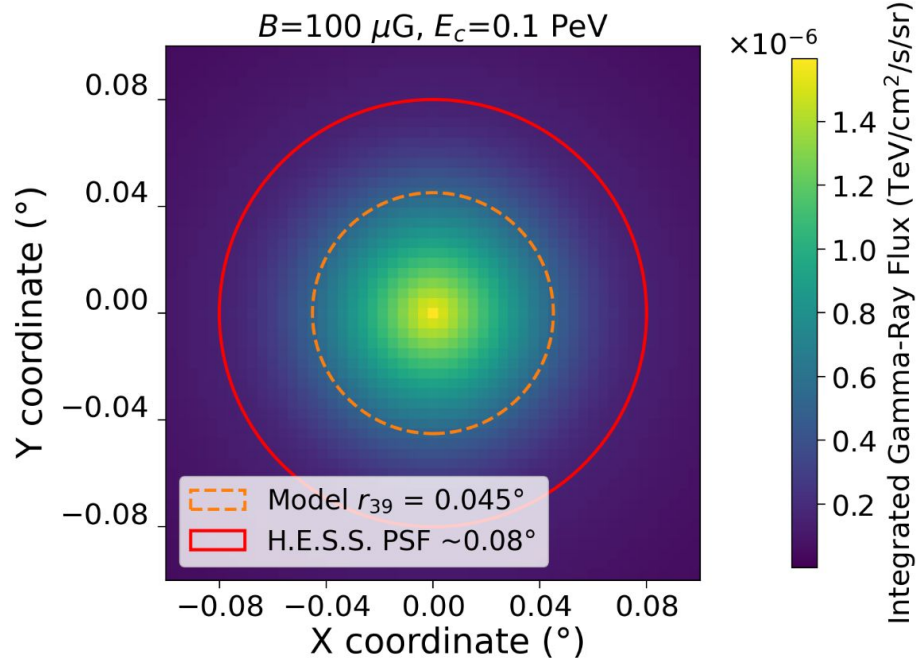
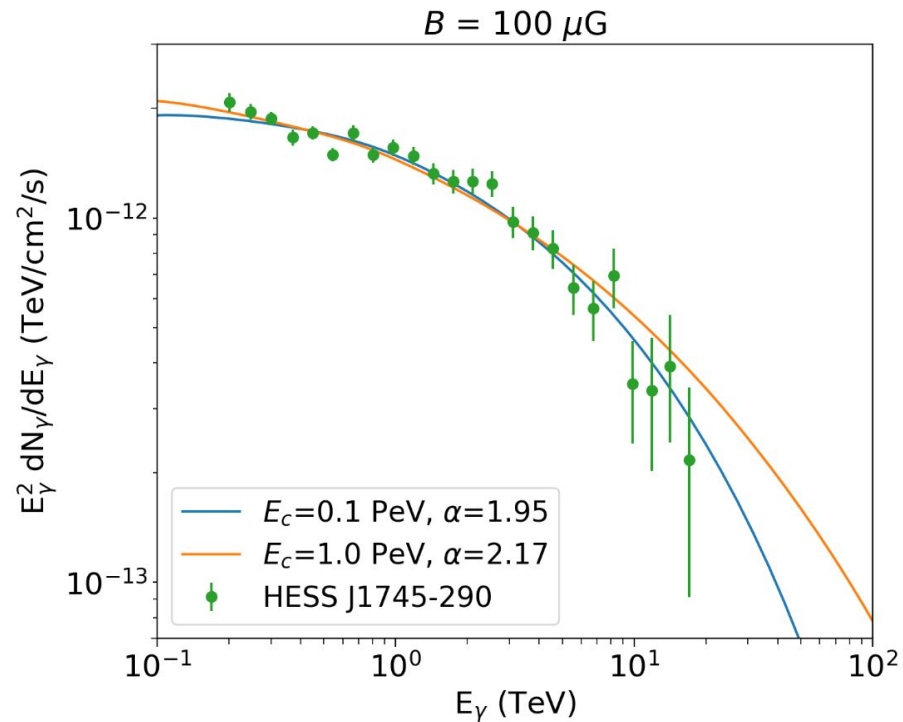
H.E.S.S. Galactic Center

H.E.S.S. detected gamma rays from two sources centered on the Galactic Center

A point source, HESS J1745-290, and diffuse emission across a ~ 200 pc region



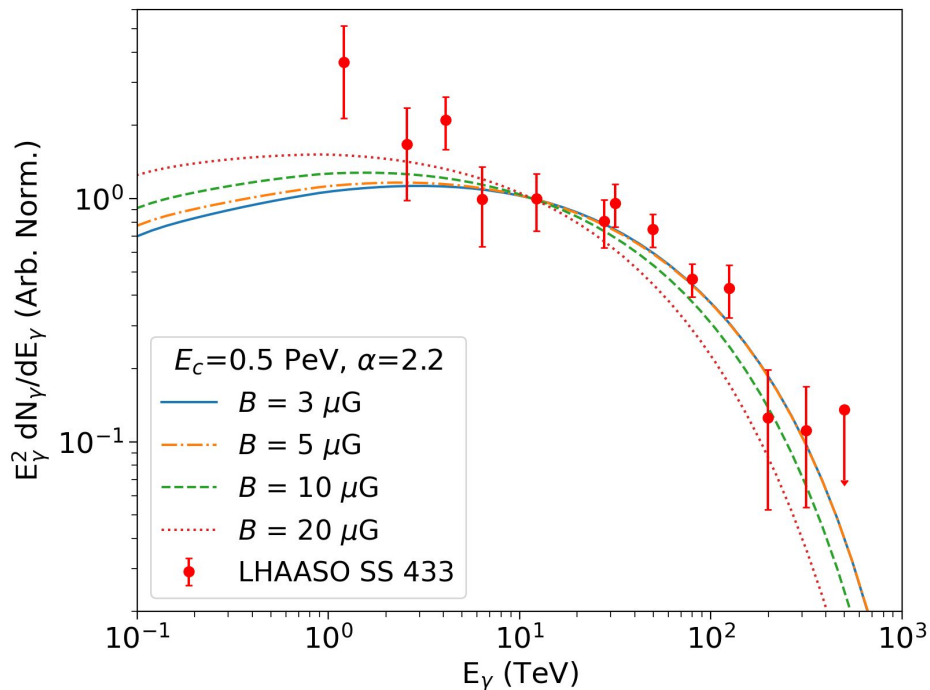
Fitting HESS J1745-290 with our Model



Comparing an Arbitrary Leptonic Spectrum

Any VHE spectrum can be compared to a leptonic model

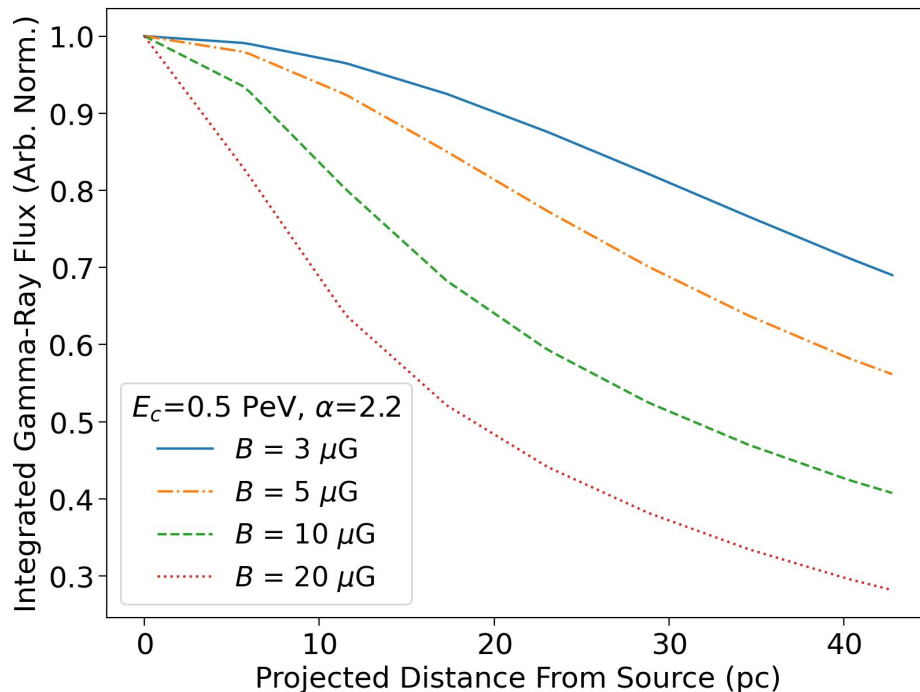
If the VHE spectrum cannot be explained by reasonable model parameters $\rightarrow$ hadronic?



Comparing an Arbitrary Leptonic Profile

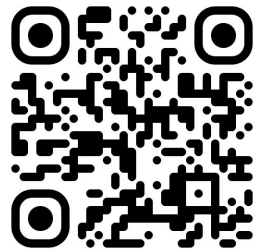
If the radial profile of a source and the distance is known a similar comparison can be done

If the radial profile cannot be explained by reasonable model parameters $\rightarrow$ non-ISM diffusion? hadronic?



Summary

arXiv:2603.17012



It seems easier to say VHE gamma rays cannot be created leptonically than to say they must be created hadronically

Here we put forward a framework for modeling of a leptonic PeVatron

We apply the model to LHAASO's observations of SS 433 and show that the highest energy gamma rays and the source extension can be explained by leptonic emission

We also show a generic leptonic reference for a VHE gamma ray source

Backup

Energy Losses

Inverse Compton scattering off of 4 radiation fields: CMB, IR, starlight & UV

Synchrotron radiation from a uniform magnetic field

$$\frac{dE_e}{dt} \approx - \sum_i \frac{4}{3} \sigma_t \rho_i S_i(E_e) \frac{E_e^2}{m_e^2} - \frac{4}{3} \sigma_t \rho_{\text{mag}} \frac{E_e^2}{m_e^2}$$
$$S_i(E_e) \approx \frac{45 m_e^2 / 64 \pi^2 T_i^2}{(45 m_e^2 / 64 \pi^2 T_i^2) + (E_e^2 / m_e^2)}$$

Diffusion Length Scale

$$L_{\text{dif}}(E_e, t) \equiv \left[\int_{E_0}^{E_e} \frac{D(E'_e)}{dE_e/dt(E'_e)} dE'_e \right]^{1/2}$$

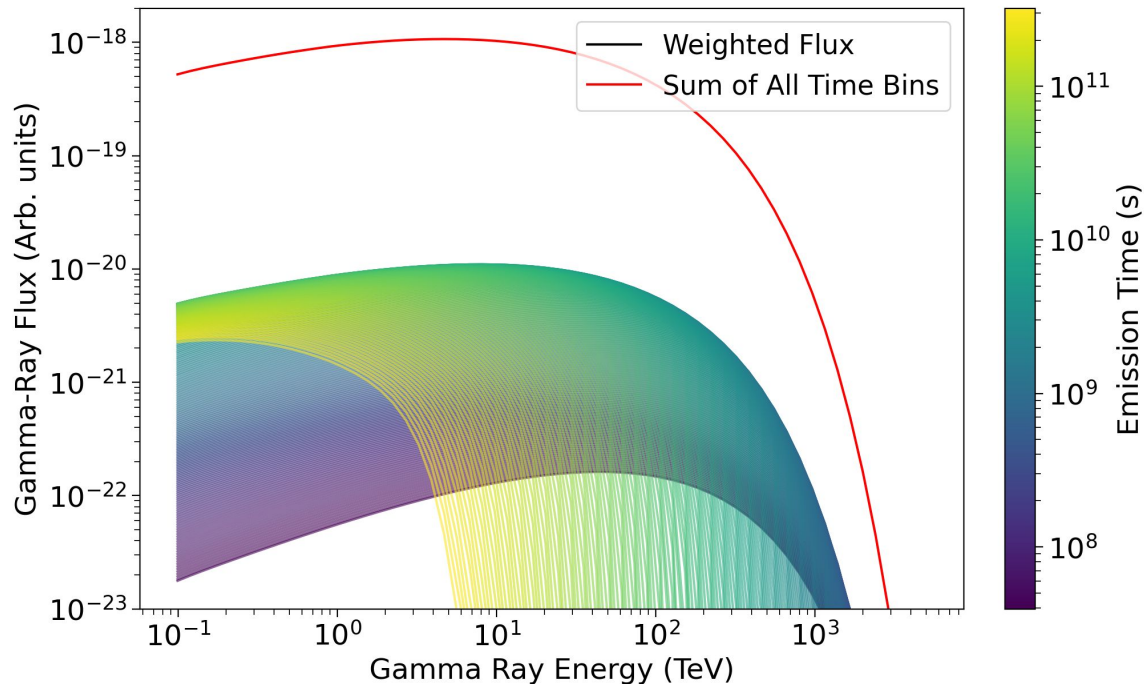
$$D(E_e) = D_0 E_e^\delta$$

Spectral Output

Injecting at many times defined by the synchrotron loss time for the electron energies used

Weighting by the width of each time bin

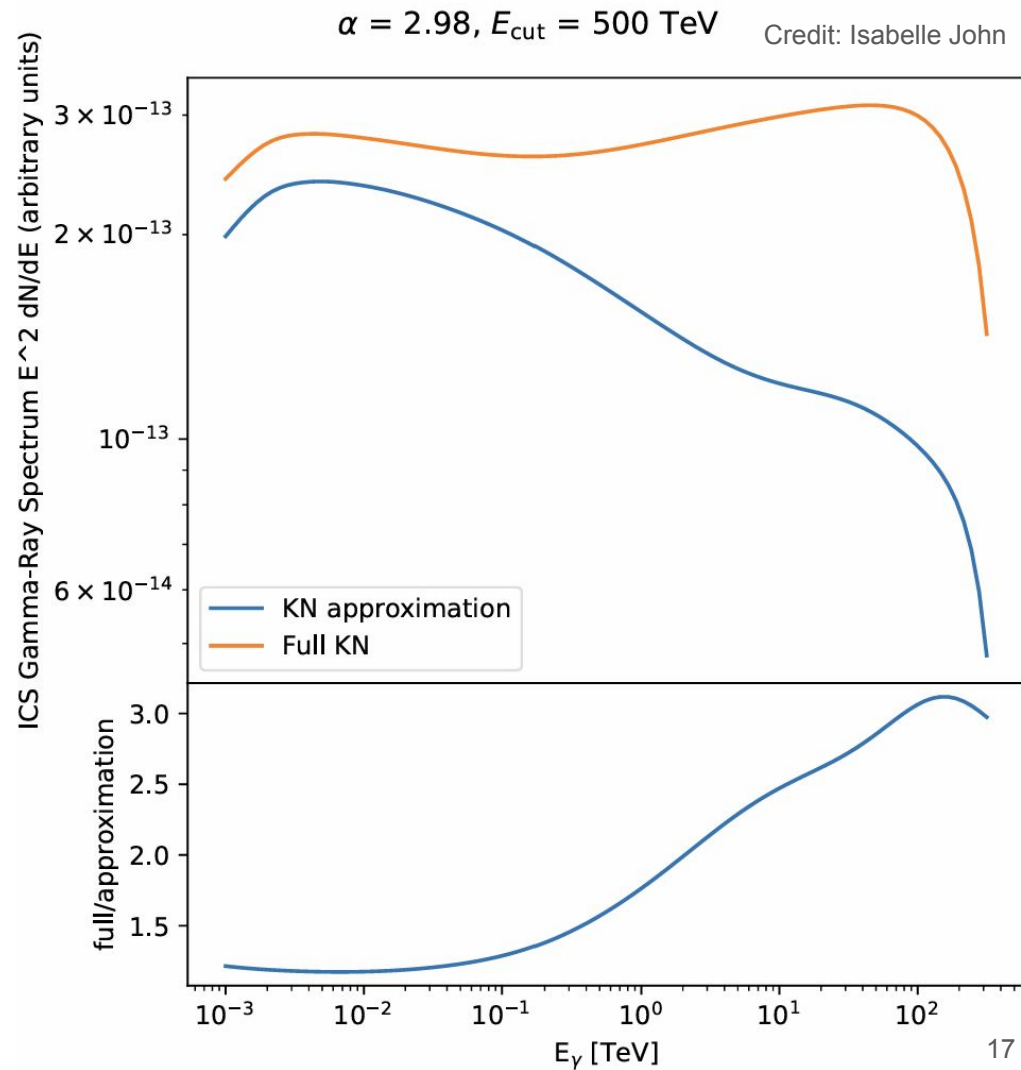
Total flux given by the sum of the weighted times



Klein-Nishina Suppression

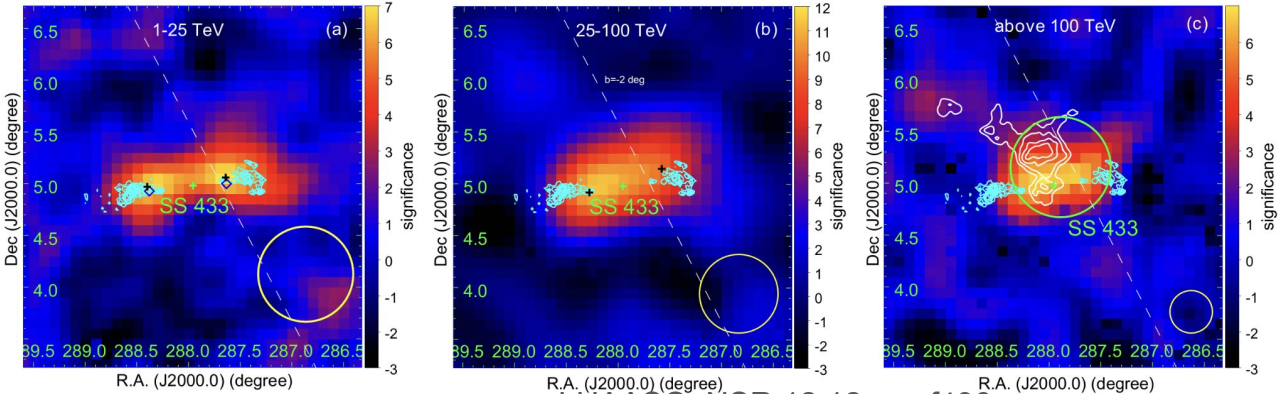
We use an approximation for Klein-Nishina suppression for computational

This approximation over-suppresses the gamma-ray spectrum compared to the full treatment

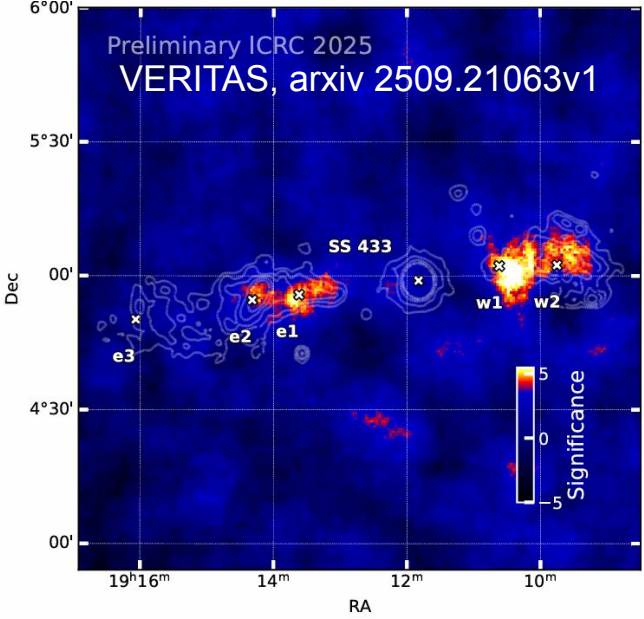
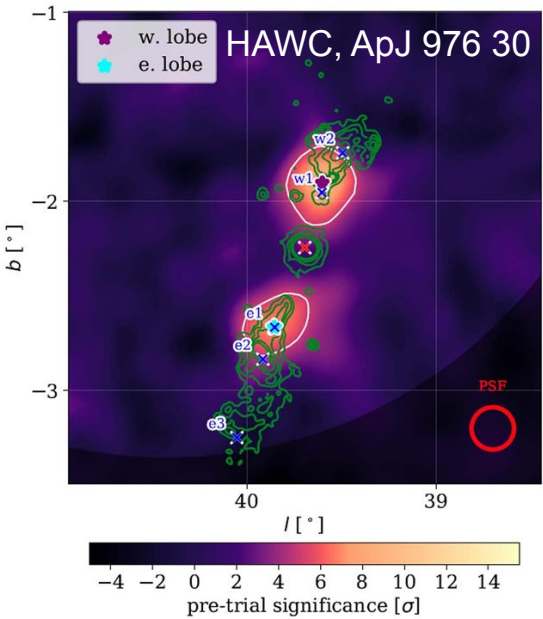
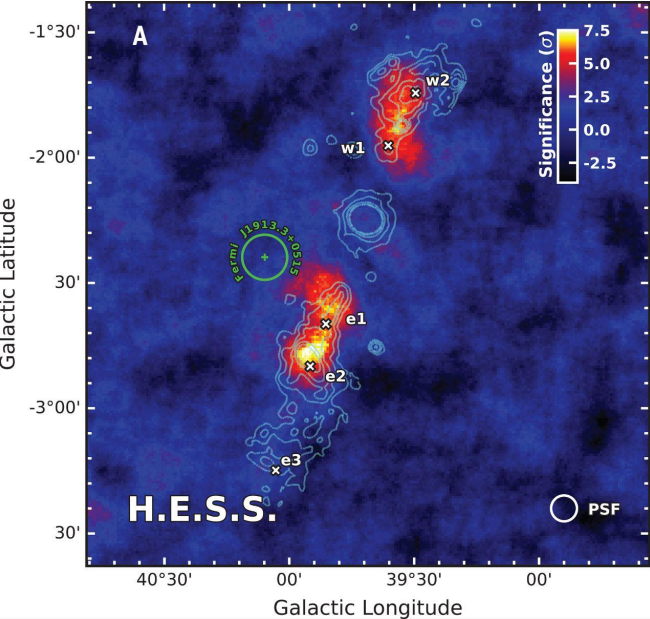


SS 433 Maps

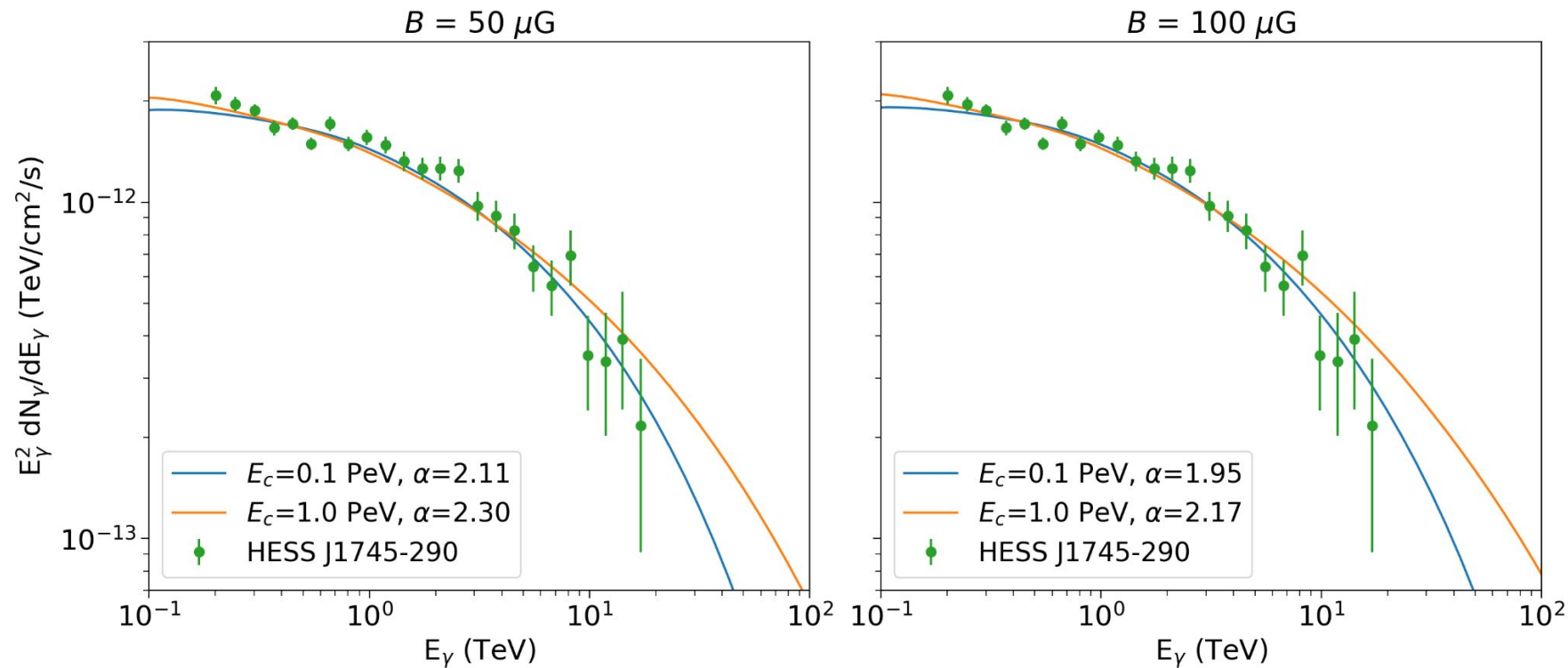
DOI 10.1126/science.adi2048



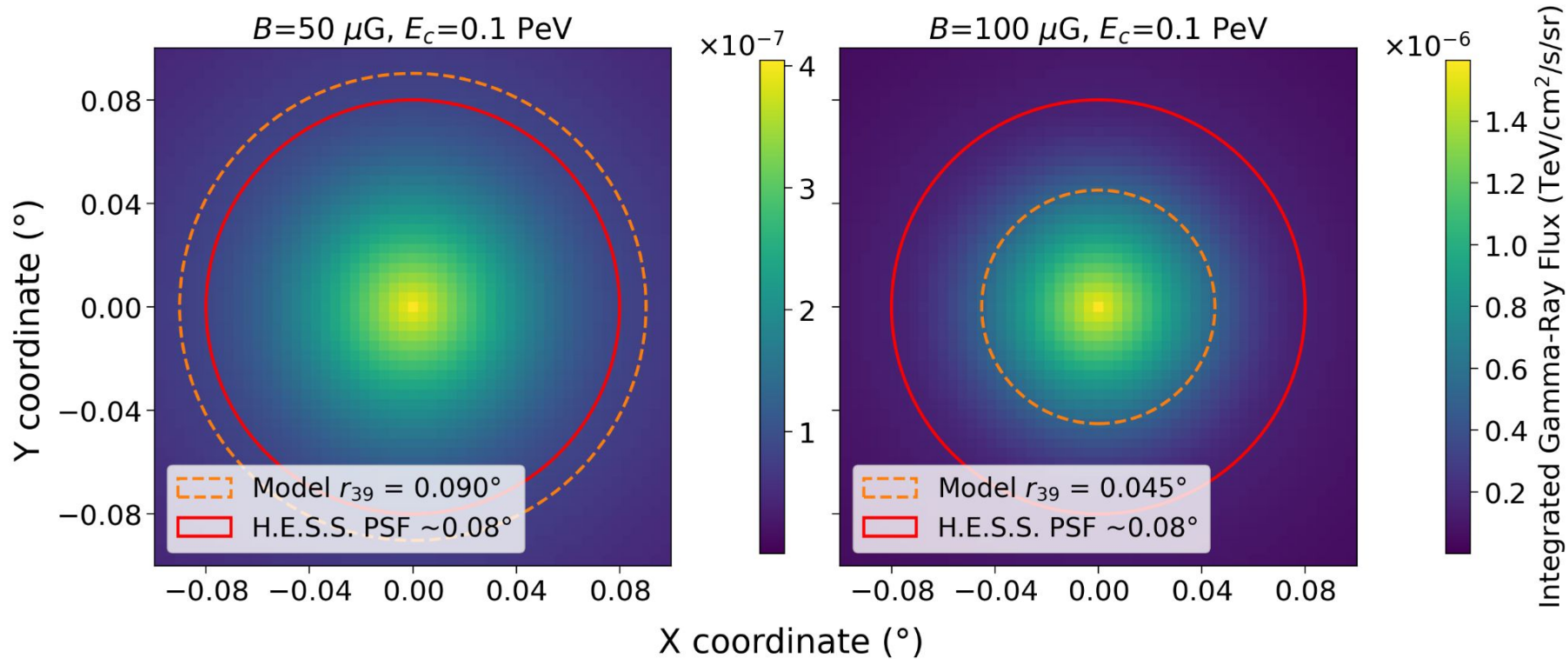
LHAASO, NSR 12 12 nwaf496



Fitting HESS J1745-290 with our Model



Fitting HESS J1745-290 with our Model



Fitting H.E.S.S. GC Diffuse with our Model

