CTAO | LST COLLABORATION

Doctoral Dissertation

東京大学 THE UNIVERSITY OF TOKYO

ICRR Institute for Cosmic Ray Research University of Tokyo

FoPM

TeV Gamma-Ray Emission across the Galactic Center Ridge with the First CTA Large-Sized Telescope

CTA大口径望遠鏡初号機で観測する
天の川銀河中心リッジに広がる TeVガンマ線放射

阿部 正太郎 / Shotaro Abe
ICRR, UTokyo, starting JSPS PD here next month
shotaro@icrr.u-tokyo.ac.jp

*public (some slides skipped)

General Introduction

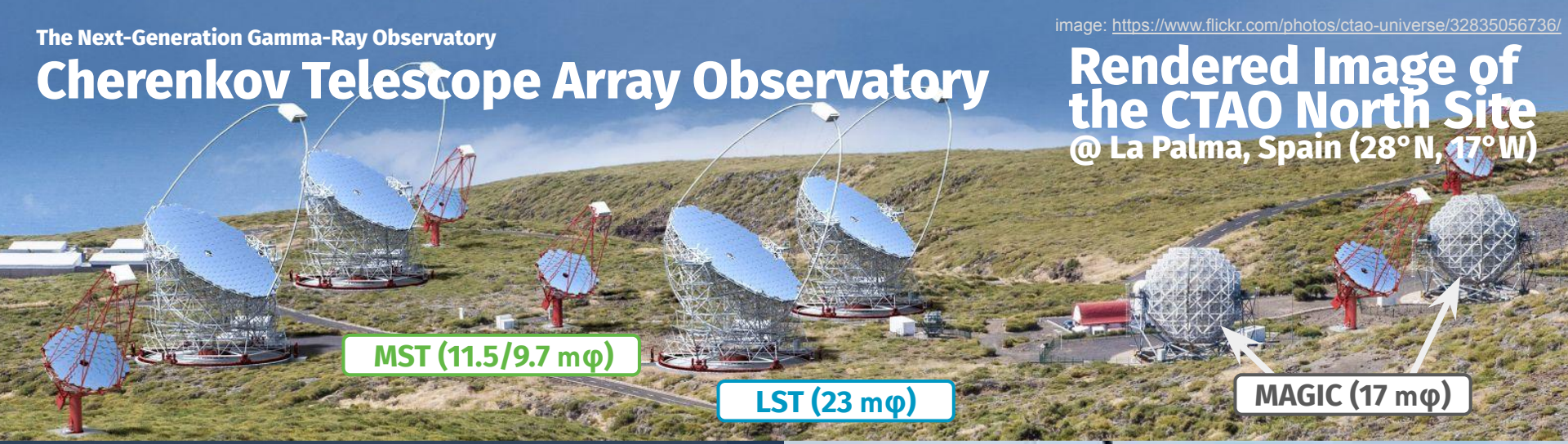
The Next-Generation Gamma-Ray Observatory

Cherenkov Telescope Array Observatory

image: https://www.flickr.com/photos/ctao-universe/32835056736/

Rendered Image of the CTAO North Site

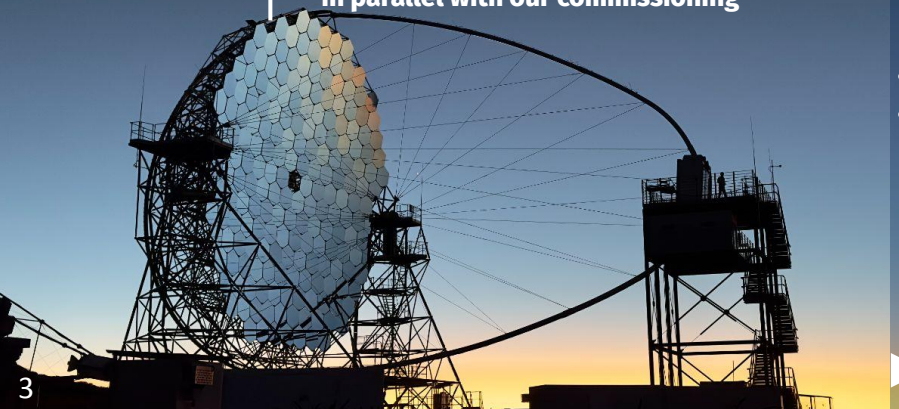
@ La Palma, Spain (28° N, 17° W)



The First Large-Sized Telescope

LST-1

- inaugurated in 2018
- taking scientific data in parallel with our commissioning

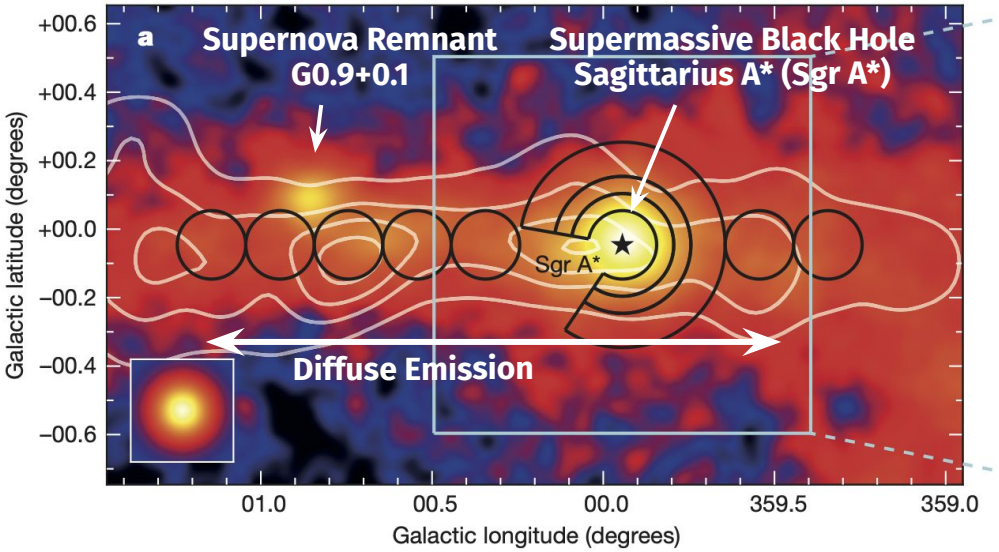


and we are building more!

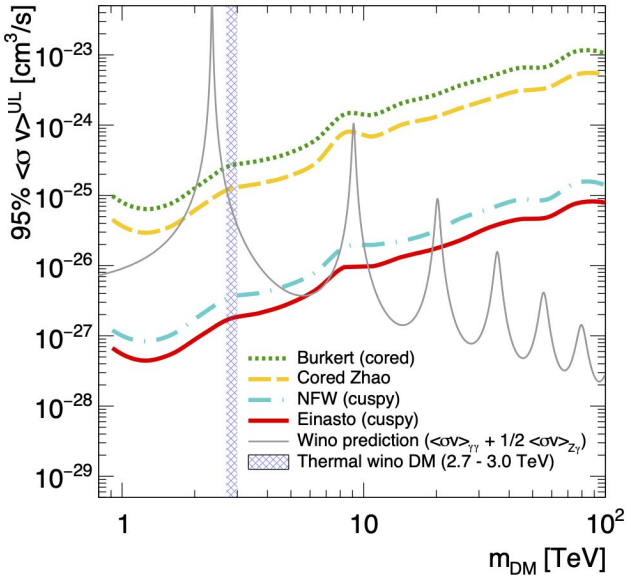
Video: LST-3 Dish Lifted (June 2024)

Morphological/spectral studies of the Galactic Center play an essential role in understanding cosmic-ray propagation and searching for WIMP dark matter.

Diffuse Emission: PeVatron scenario?
fig: HESS, Nature 531, 2016



Stringent Constraints on WIMP dark matter
fig: MAGIC, PRL 130:061002, 2023



My motivation lies in the TeV diffuse emissions in the Galactic Center region, which require to develop a new observation/analysis.

2018 LST-1 inaugurated in Oct.
the first light recorded in Dec.

2019 science data taking started.

2021 first observations of the Galactic Center.
Sgr A* detected with a point-source analysis.

2023 LST-1 performance paper published,
focusing on typical zenith/off-axis angles.

what was *technically missing*
at the beginning of this doctoral research:

- **Large Zenith Angle Observation**
  - performance understanding
  - MC/Obs consistency
- **Extended Source Analysis**
  - following the official analysis stages
  - applicable even up to 100 TeV.

Technical Themes

① Large Zenith Angle Observation

② Extended Source Analysis

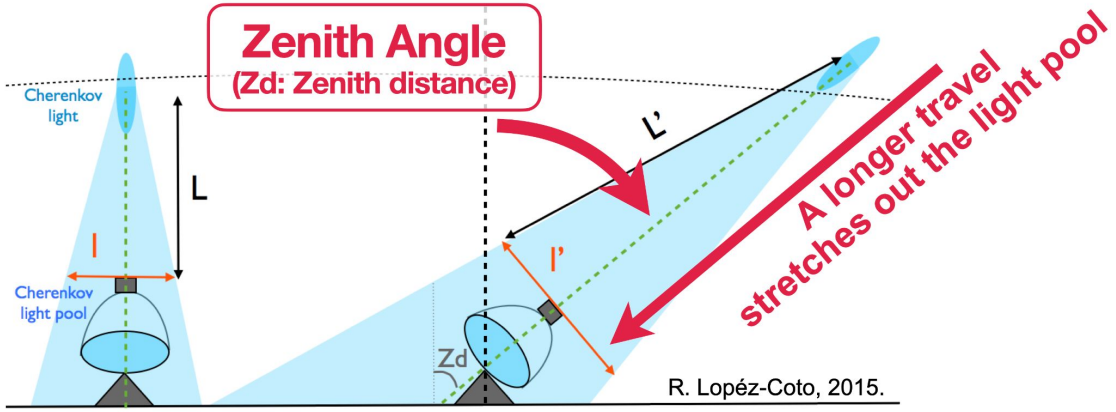
Scientific Themes

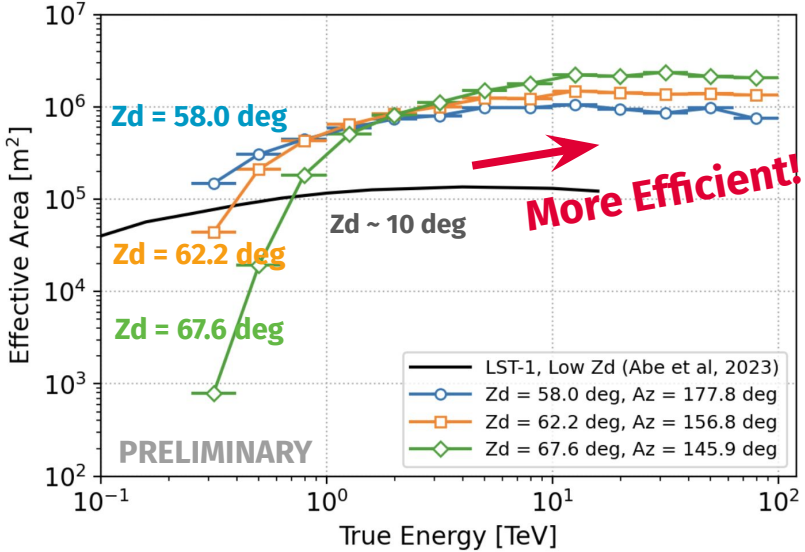
Galactic Center Diffuse Emission

▸ **③ PeVatron**, WIMP DM, ...

Large Zenith Angle Observation

When observing a source at low altitude, telescope performance is quite different from typical observations; need to quantify/test this operation mode.





At large zenith angles, in general

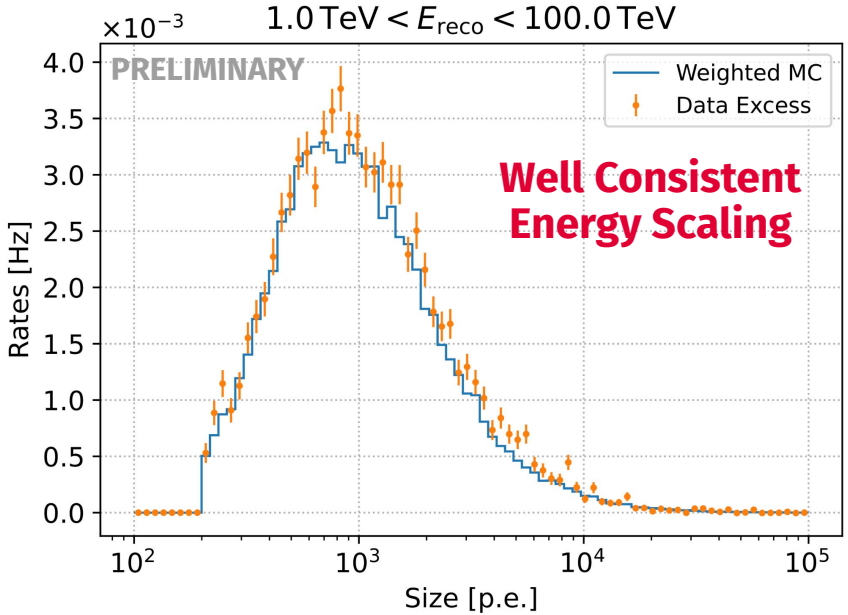
- \+ **increased collection area** by an order of magnitude
- \+ **decreased image leakage** at higher energy, leading to better reconstruction
- \- **performance very sensitive to Zd** even within the field of view
- \- **increased energy threshold** to a few hundreds of GeV or even higher

*Crab Nebula: point-like standard candle widely used at VHE

Parameter spectra were compared between γ-ray MC and Crab Nebula excess, ensuring the good MC/Obs consistency even at the large zenith angles.

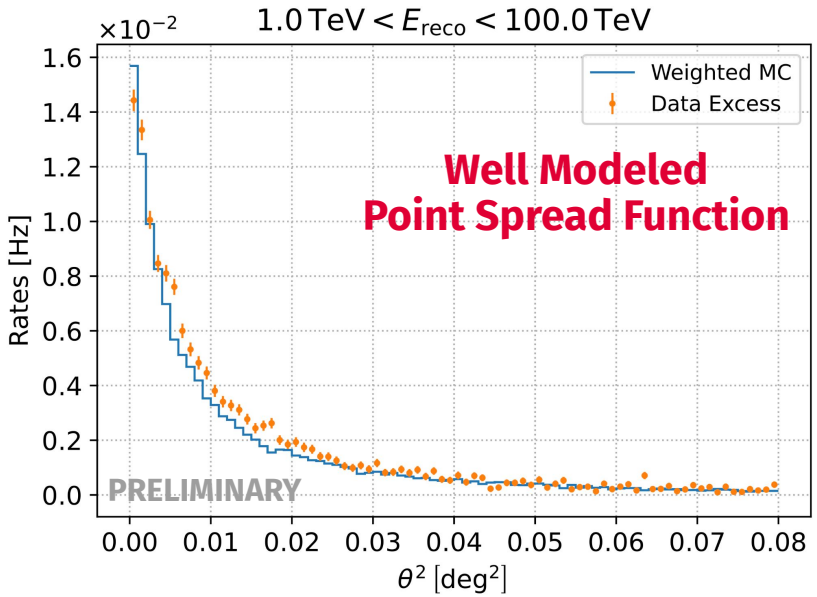
Size

= total number of photoelectrons after image cleaning showing the consistent energy scaling



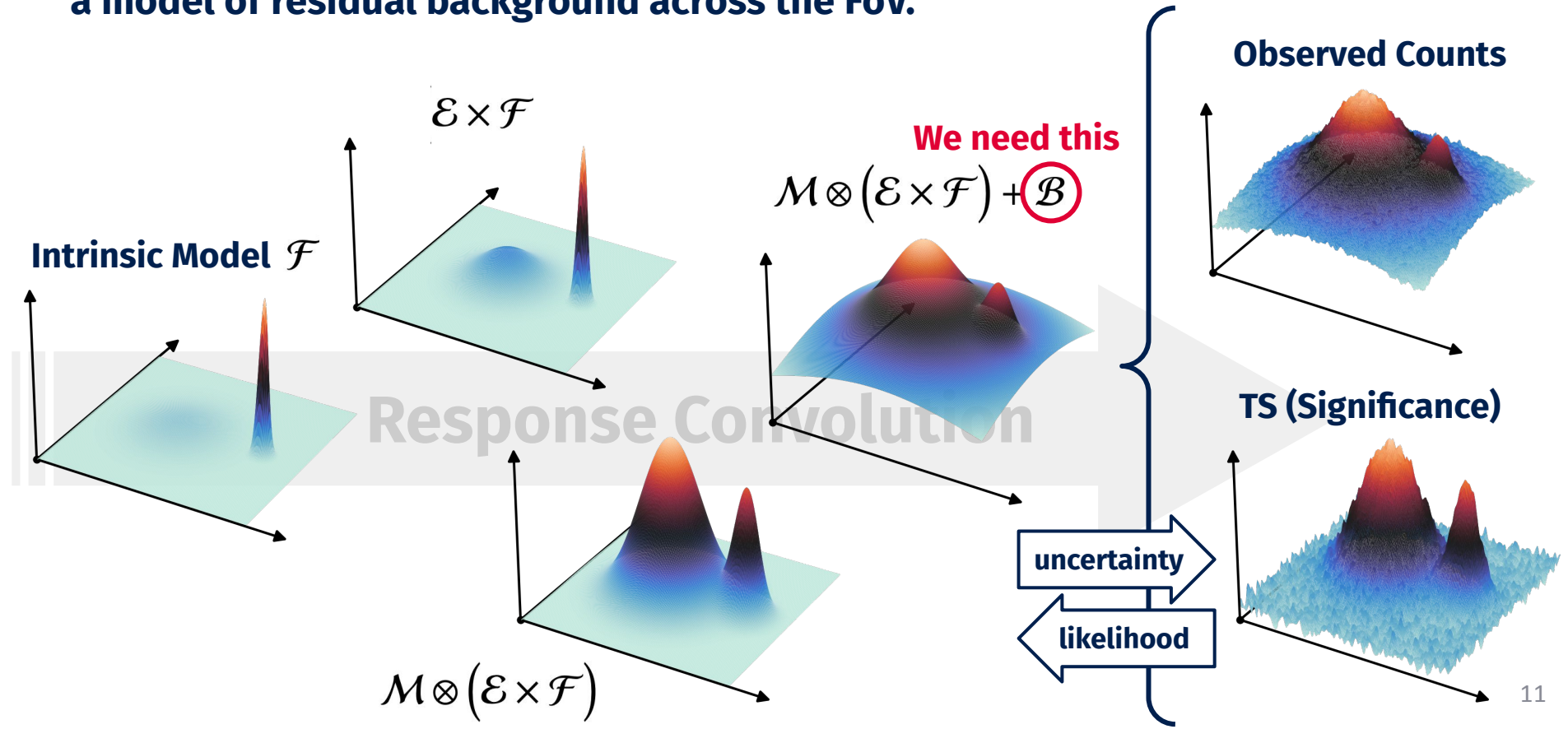
Theta Squared

= angular separation between true/estimated position a slight discrepancy: Δσ ~ 0.03 deg in the King function.

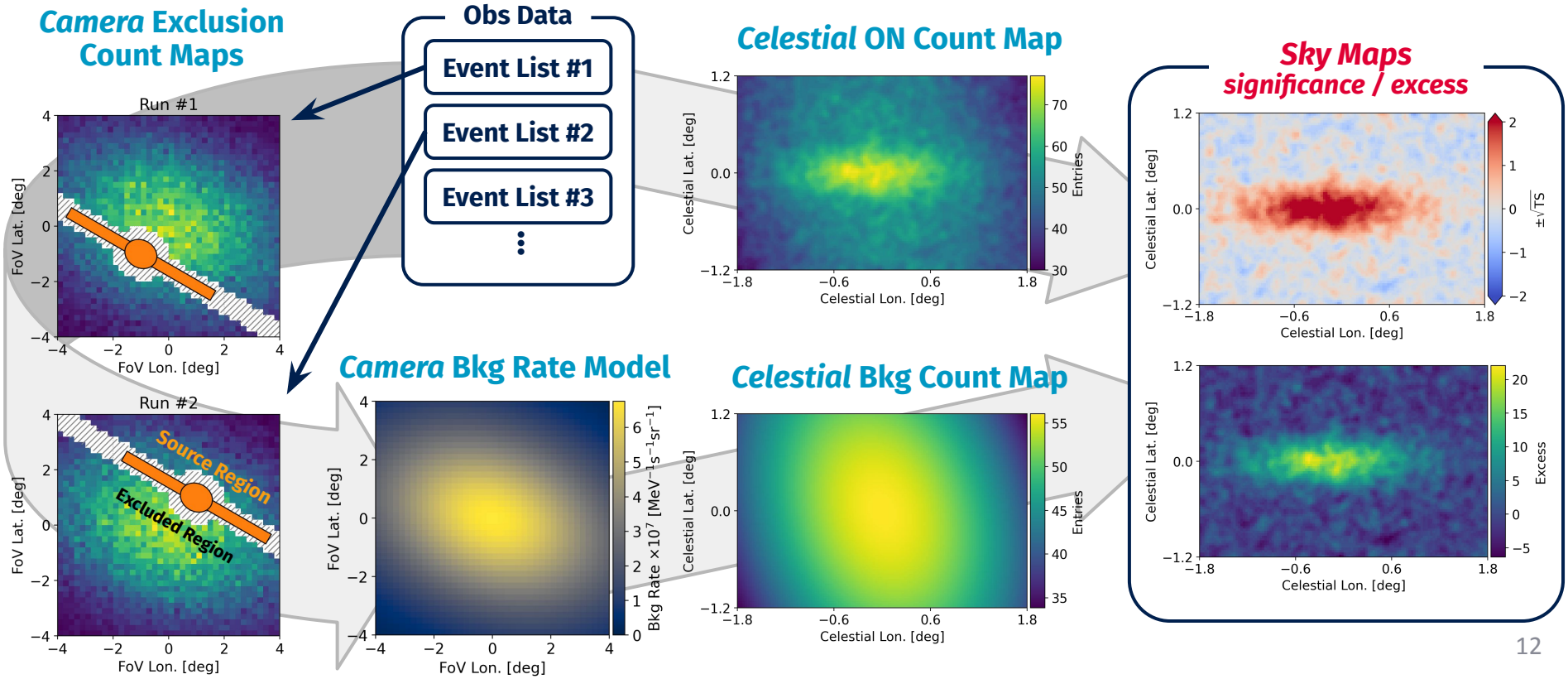


Extended Source Analysis

The 3D Analysis of extended sources needs a model of residual background across the FoV.



The residual background is characterized in the camera (and Alt/Az) frame. Masked signal regions are covered by different pointings (*wobble* partners).



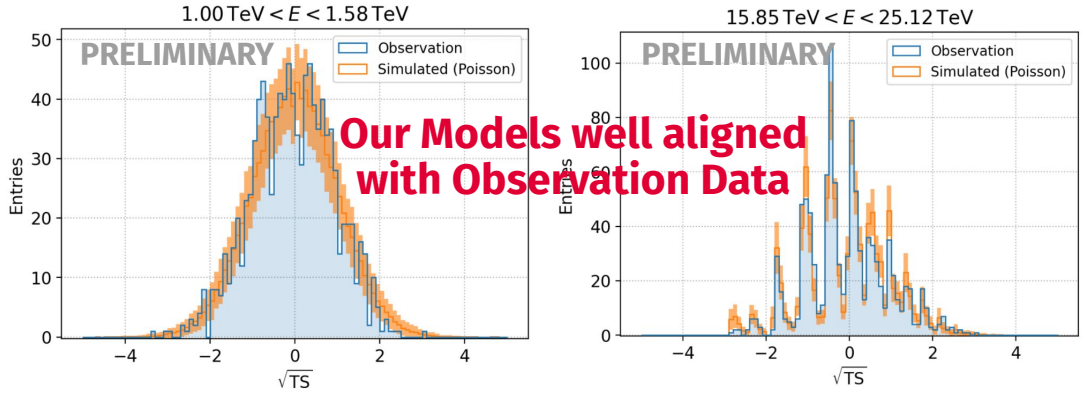
The background modeling and sky map technique were tested with Crab Nebula data; demonstrating that our approach works well.

Top: **pixel-wise signed significance,**

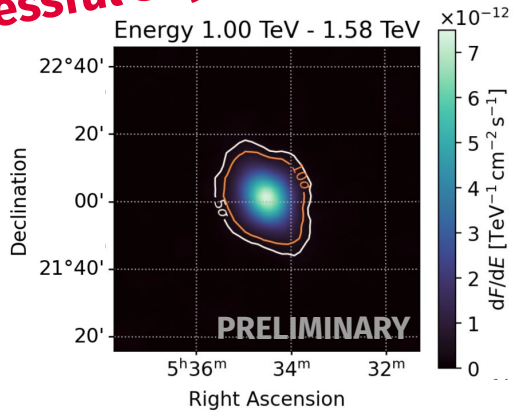
demonstrating the consistency between the actual and modeled background

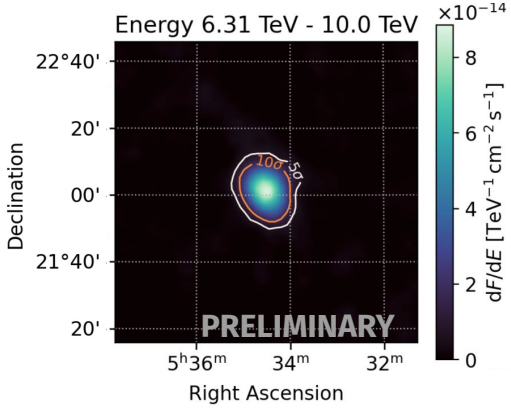
Bottom: **sky map in the unit of flux,**

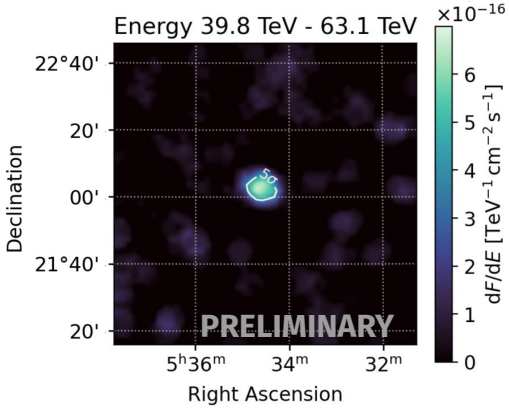
showcasing the clearly resolved signals of the Crab Nebula



Successful Sky Map!





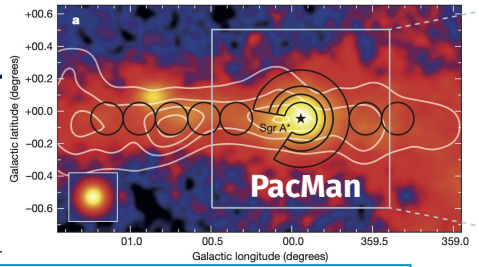


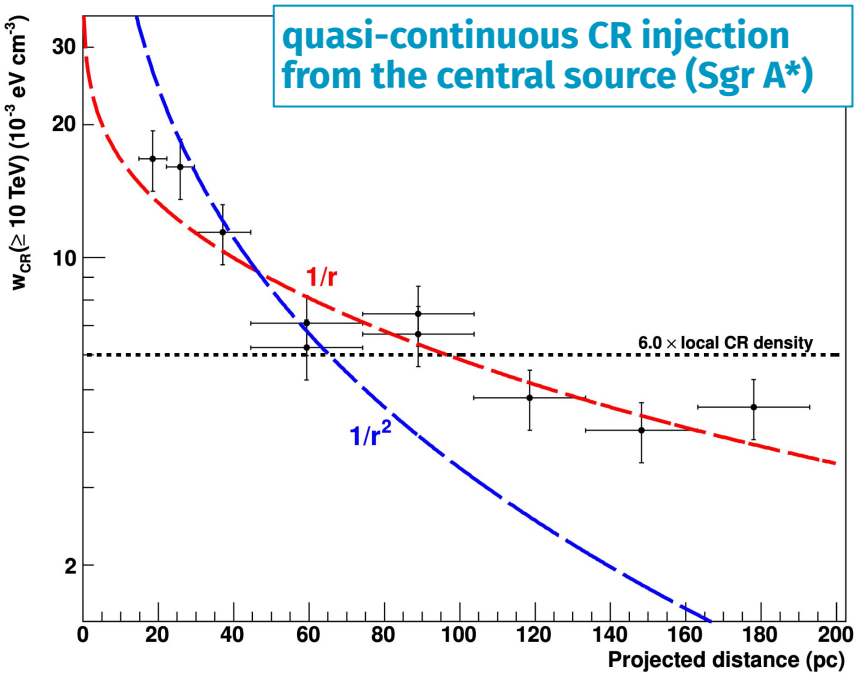
Using dedicated MC simulations & test observations of Crab Nebula, this study enabled the full use of the large zenith angles and the whole field of view.

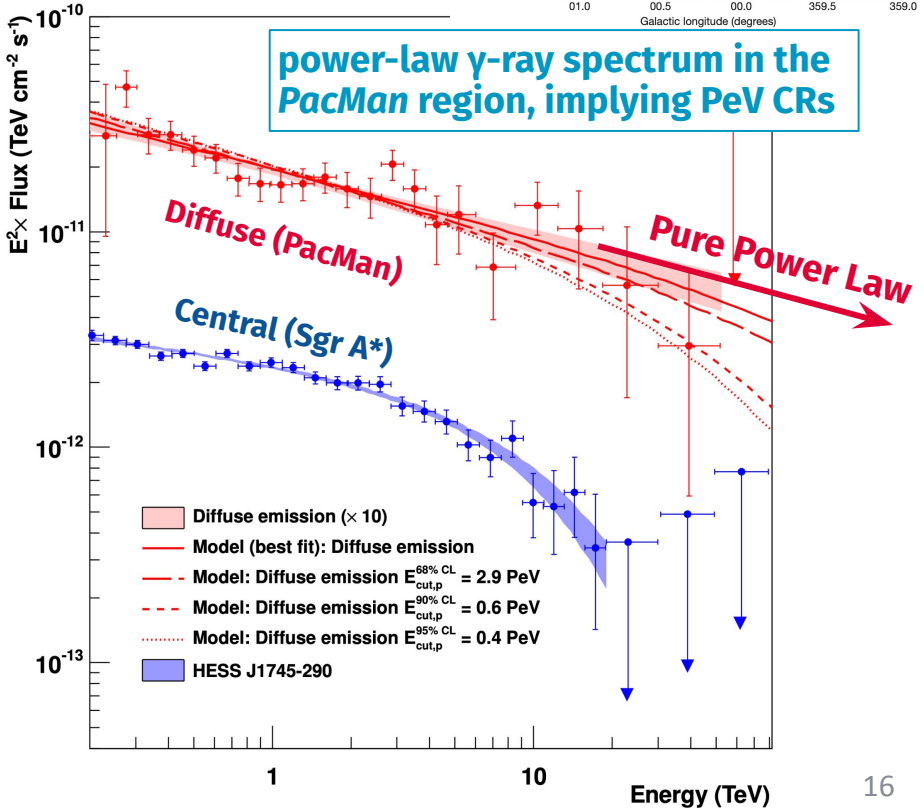
- **New Capabilities of LST-1 Uncovered: Large Zenith Angle Observations**
  - Effective Area: ~10^6 m^2 at E > 10 TeV
  - Angular Resolution: ~0.08 deg at best
  - Detection Sensitivity: enhanced at energies above 1 TeV / offset angles above 1 deg
- **Successful Background Modeling and Extended Source Analysis**
  - Sky Map: the residual uncertainty is as suppressed as the statistical deviation
- **Good Consistency throughout Tests with Crab Nebula**
  - MC/Obs: well consistent shower-image parameters; PSF widening of 0.03 deg
  - SED: well consistent with other measurements:
    systematic uncertainty: < 15% energy scaling, < 20% normalization.
  - LC: stable across the zenith, energy, and offset: residual run-wise flux uncertainty ~10%.

Previous VHE Views towards the Galactic Center

HESS 2016 (followed by HESS 2018 & VERITAS 2021) obtained suggested Sgr A* was the primary PeVatron for the Galaxy.

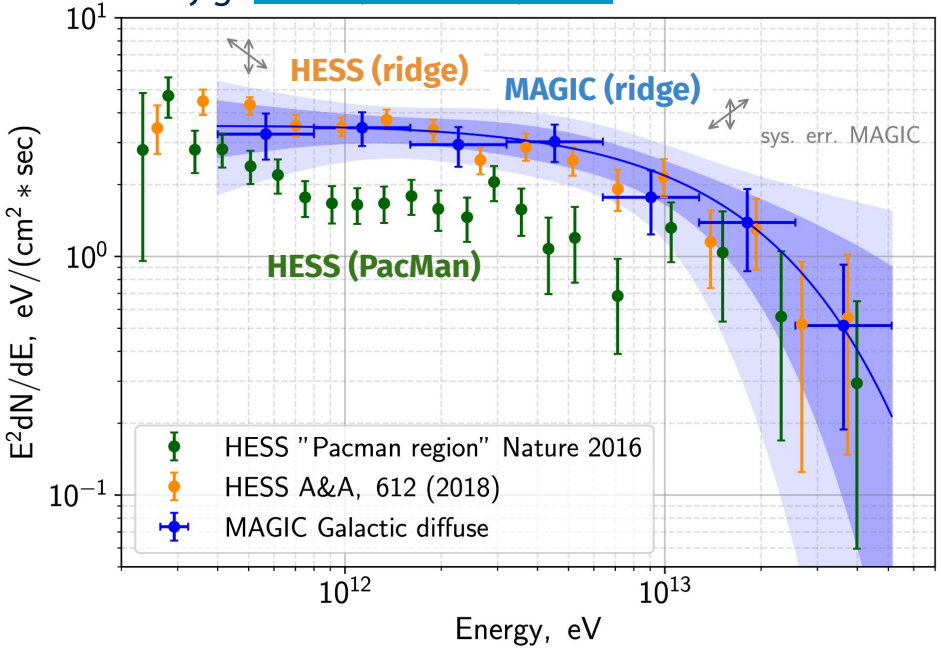




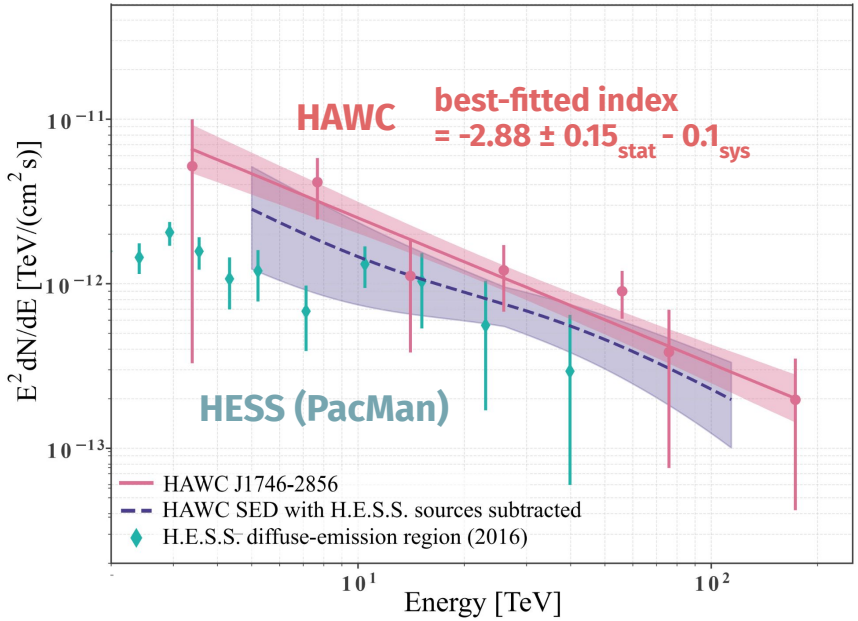


However, MAGIC 2020 suggested a 2σ-hist for a spectral cut-off in the diffuse component; and HAWC 2024 reported a much softer spectrum.

Exponential Cutoff around 20 TeV
fig: MAGIC, A&A 642, 2020



Softer Spectrum at higher energy
fig: HAWC, ApJL 973, 2024



Findings and interpretations that the current-generation telescopes reported are not well consistent with one another.

	HESS (2016, 2018)	MAGIC (2020)	VERITAS (2021)	LST-1 (This Study)
Pac Man	Power Law	Not Reported	Not Reported	
total ridge	Power Law	Cut-off at 20 TeV	Power Law	?
CR longitudinal profile: $r^{-\alpha}$	alpha = 1.10 ± 0.12	alpha = 1.2 ± 0.3	Not Reported	
Zenith Angle	Low Zd	Large Zd	Large Zd	Large Zd
Field of View	5.0 deg	3.5 deg	3.5 deg	4.5 deg

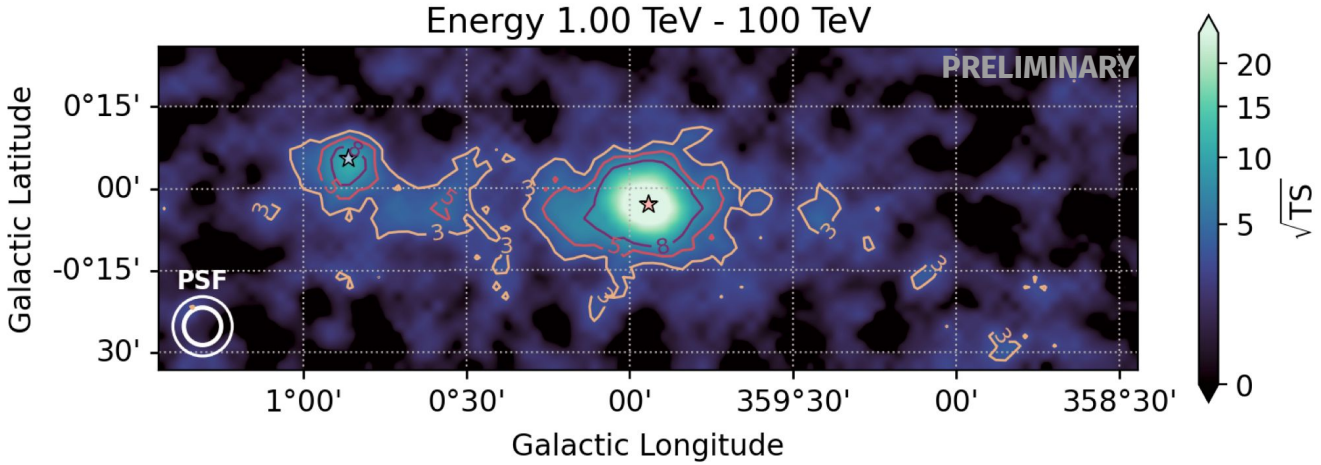
We provide the best observations of the TeV Diffuse Emissions!

Galactic Center Studies with LST-1

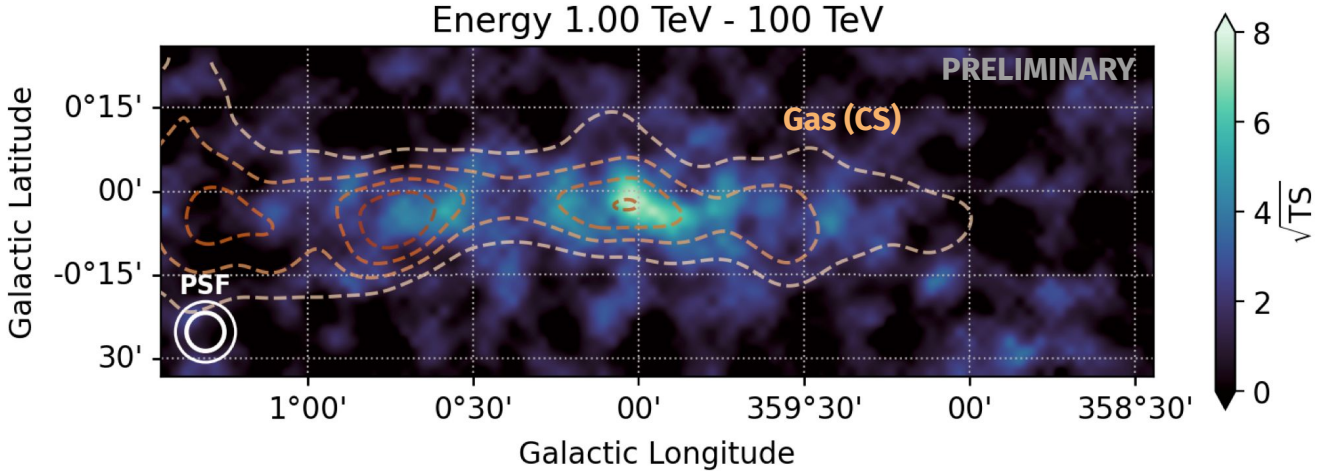
Result: Clear & Wide View of LST-1 (39 hr)

*Contours: the integrated/smeared radio emission from CS molecules (Tsuboi+, 1999)

TS Map



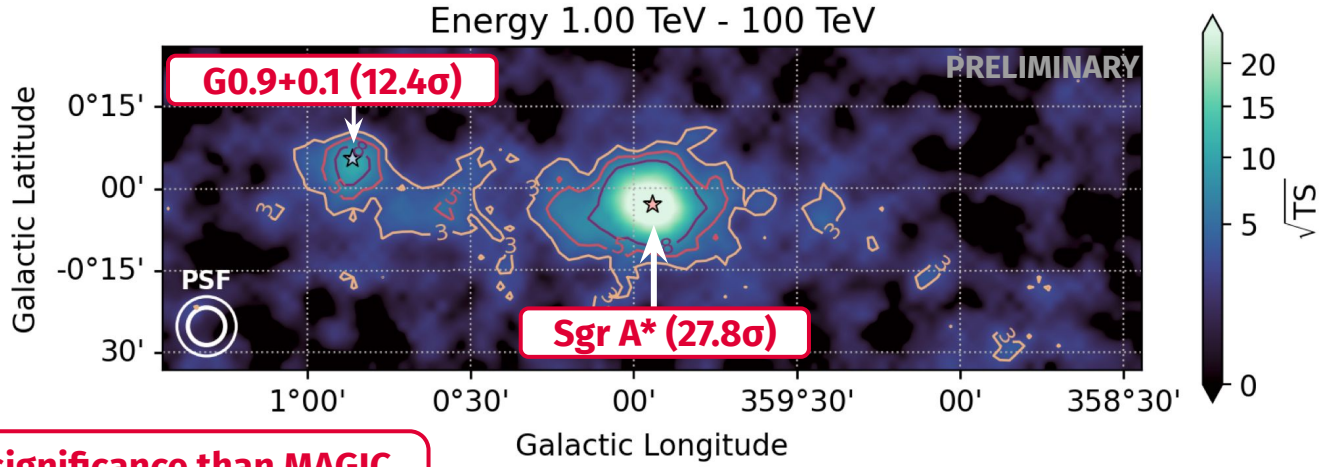
Sgr A* & G0.9+0.1 subtracted



Result: Clear & Wide View of LST-1 (39 hr)

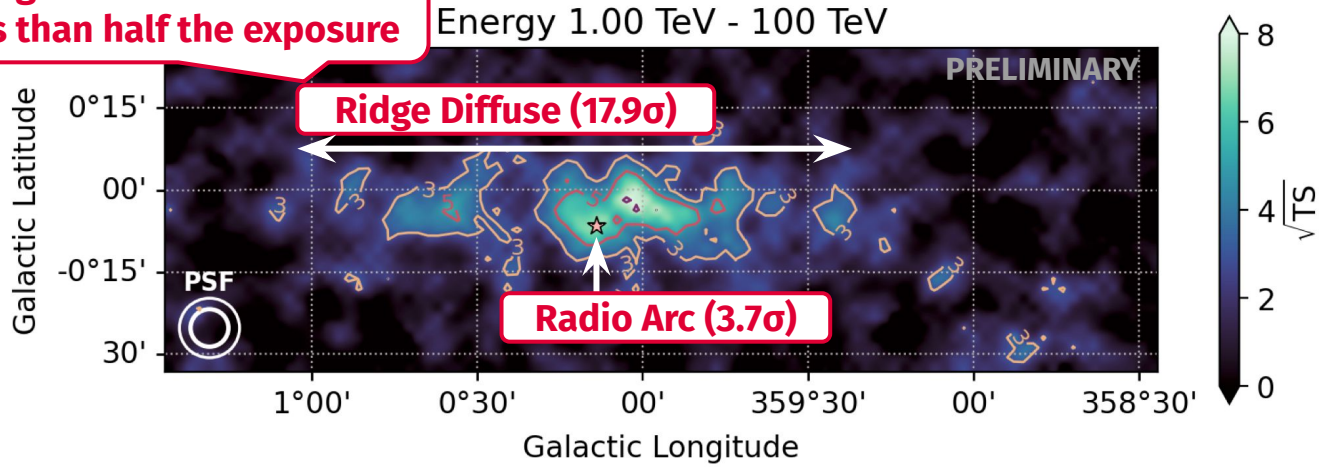
*Significance in this study: >398 GeV
**cf. MAGIC 2020 (100hr, >1 TeV): Sgr A*: 48σ, G0901: 11σ, Arc: 6.4σ, Diffuse: 17σ.

TS Map

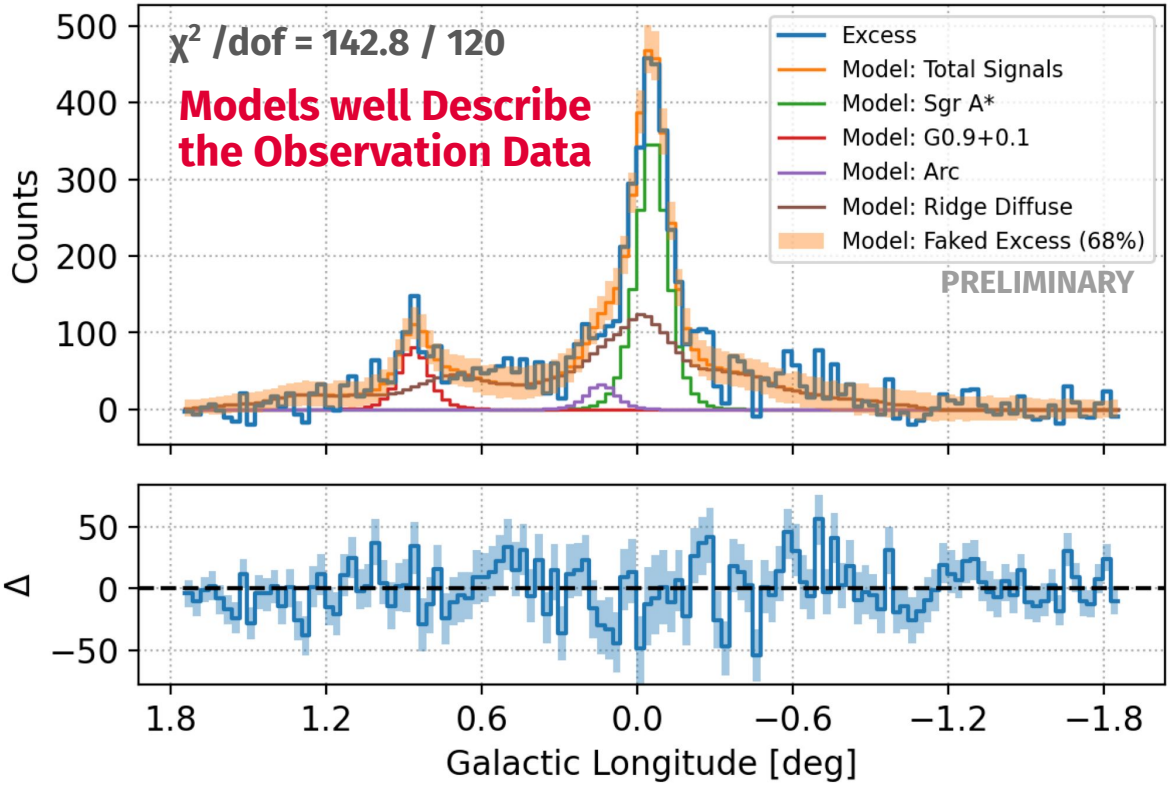


Higher significance than MAGIC with less than half the exposure

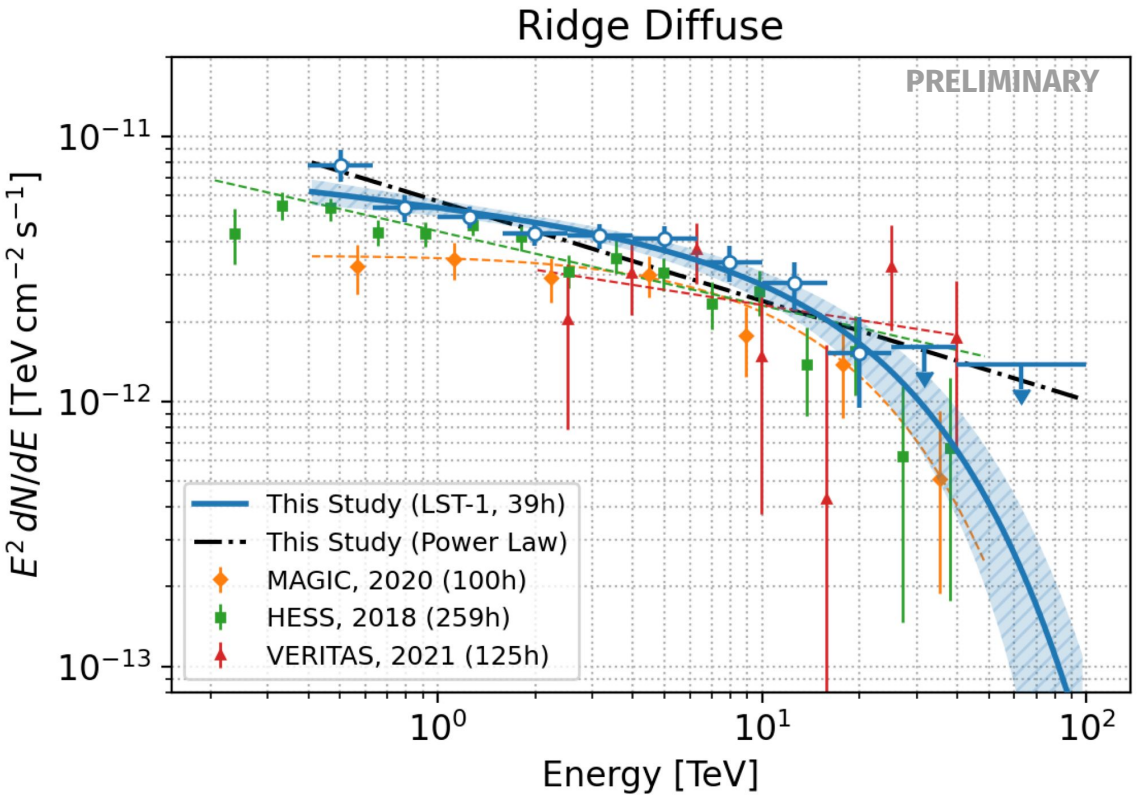
Sgr A* & G0.9+0.1 subtracted



The longitudinal profile obtained at -0.2° < b < 0.2° demonstrates that the current set of models generally describes data well.



Aligned with MAGIC 2020, the sectral cut-off at Ecut ~ 24 TeV is preferred with a significance of 2.8σ.



Attained the first spectral differentiation of the Gal. Center diffuse components, reasonably solving the discrepancy among the previous measurements.

- **New and Clear view with LST-1**
  - detection significances of G0.9+0.1 and the ridge diffuse higher than MAGIC 2020.
- **Quasi-constant CR diffusion from Sgr A* reconfirmed**
  - the two analysis approaches both favor the 1/r profile over the flat and $1/r^2$ profiles.
- **Spectral cutoff of the diffuse ridge emission**
  - estimated to be at 24 TeV with a significance of 2.8σ.
- **No sign of cutoff in the PacMan region, suggesting a presence of PeVatron**
  - yielding the lower bound of 46 TeV at a 90% confidence level.
- **Sgr A* might be a PeVatron in the more limited time window**
  - PeV CRs might be supplied from Sgr A* only 10^4 years ago?

Uncovering the new potential of LST-1 across the field of view, this study *resolves* the diffuse emissions across the Galactic Center ridge.

Technical Contributions

- New Capabilities of LST-1 Uncovered
- Successful Background Modeling and Extended Source Analysis
- Good Consistency throughout Tests with Crab Nebula

Future Prospects:

- technical developments are beneficial for many sources as well (e.g. TeV Halo)
- GalCent studies: doubling data will bring about a cutoff significance of 4σ.

Scientific Contributions

- New and Clear view with LST-1
- Quasi-constant CR diffusion from Sgr A* reconfirmed
- Spectral cutoff of the diffuse ridge emission
- No sign of cutoff in the PacMan region, suggesting a presence of PeVatron
- Sgr A* might be a PeVatron in the more limited time window

New Studies as a Postdoc

Higgsino search with CTAO-N is *the* impending effort. New paper under collaboration review now, stay tuned!

- Targeting WW & γγ/Zγ from thermal Higgsino annihilation (1.1 TeV).
- N. L. Rodd+ 2024 (right figures): with 500h CTAO-S observations, Potential detection >3σ, or even >5σ.
- CTAO-S full operation: 2030s. CTAO-N (4 LSTs) starts in 2026
  - **early accumulation of exposure at large zenith angles**
- **New paper under collaboration review** (and will present in ICRC). **Stay tuned!!**
  - **detectability study with CTAO-N/S considering their realistic timeline**