Galactic Center Studies with CTA-LST-1

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Abstract

The **Galactic center** region is known to host a wide variety of very-high-energy gamma-ray sources. To observe the Galactic center in the southern sky, LST-1, located in the Northern hemisphere, requires a special observation mode at a low telescope elevation. In this study, **we assessed the efficacy of LST-1 at the large zenith angle**, based both on simulations and observational data for the standard candle Crab Nebula. We demonstrated that, in the TeV energy range, **the LST-1 sensitivity at the large zenith angle surpasses the standard low zenith angles**. Building upon this performance study, we analyzed LST-1 data from Galactic center observations. **We obtained the spectral energy distribution and the light curve of the central gamma-ray emission**, which were comparable with the results from the current imaging atmospheric Cherenkov telescopes, **with a broad energy coverage** owing to the large-zenith-angle observation and the low energy threshold of LST-1.

FEATURED ACHIEVEMENTS in This Study: Check Them Out!

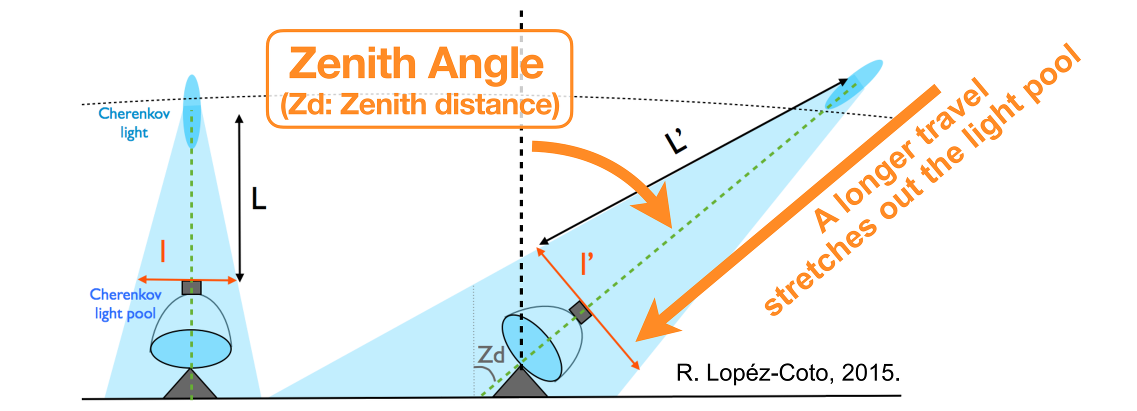
- **Successfully validated a non-standard observation mode: the large-zenith-angle observation, achieving significant enhancement in sensitivity at TeV as compared to the standard low-zenith-angle observations.**
- **Detected Sagittarius A* at 300 GeV. Only HESS has previously achieved detection at the energy [1].**
- **Pioneered the extended-source analysis in the collaboration: first astrophysical skymap from observation data.**

Galactic Center Region

- one of the prime targets for Cherenkov telescopes: housing supermassive black hole, dense molecular clouds, strong star-forming activity, and so forth.
- a location of paramount importance (and complexity) to search for dark matter thanks to high density
- a unique source for an extended gamma-ray source study: parent-cosmic-ray models can be derived *a priori*
- LST-1 is capable of observing the Galactic center only at the large zenith angle (Zd > 58 deg)

Large-Zenith-Angle Observation

- The large-zenith-angle observation (55-70 deg) geometrically expands the Cherenkov light pool
- one-order-of-magnitude larger effective area at TeVs

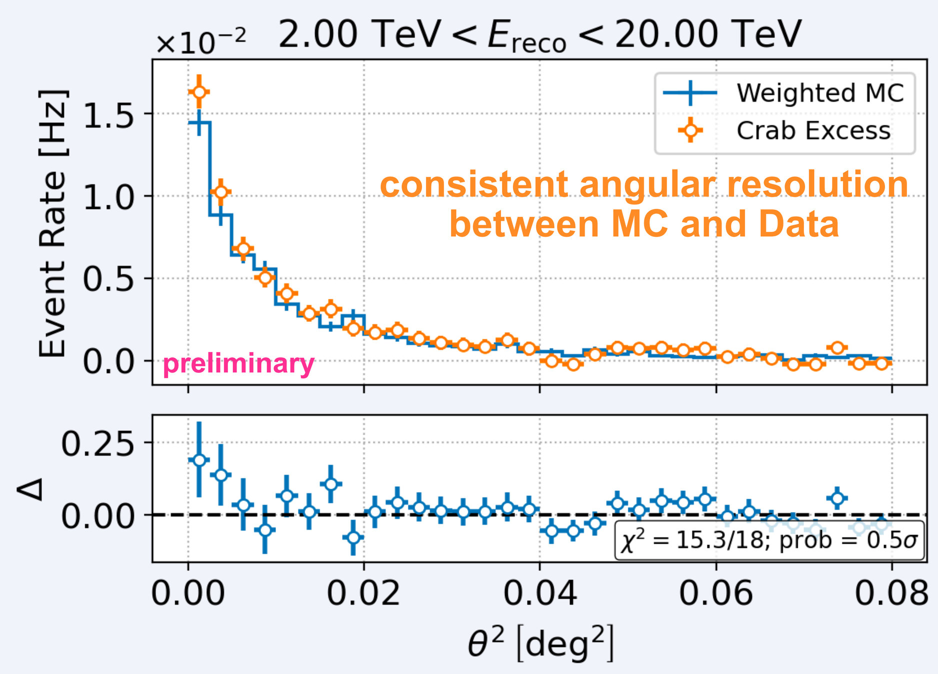


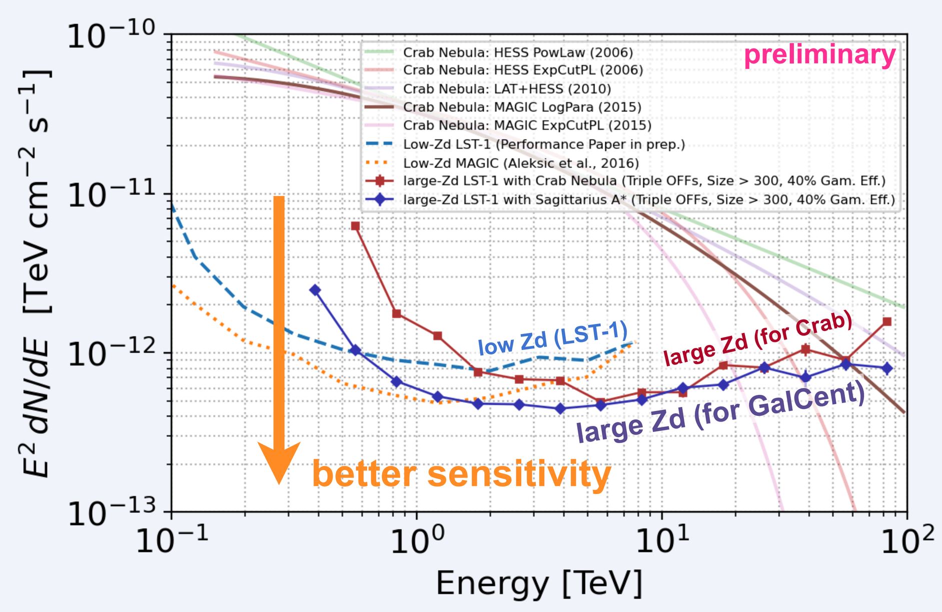
Data & Analysis Overview

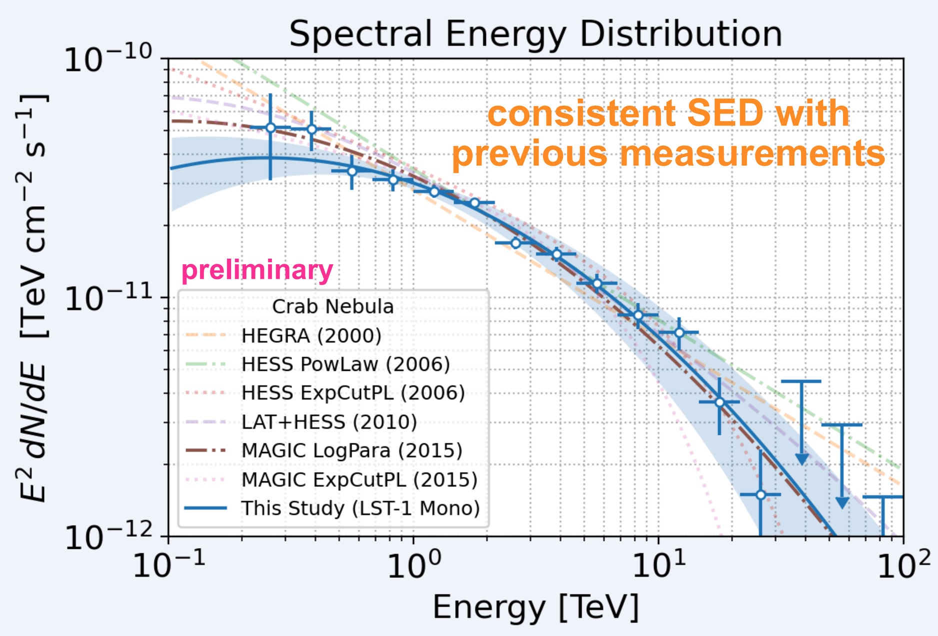
- [Data Collection] All data of Crab & GalCent were taken at the large zenith angles, in the so-called wobble-mode observation [2] with an offset angle of 0.4 deg for Crab, 0.5 deg (2021), and 0.7 deg (2022) for GalCent.
- [To Ensure Data Quality] we applied the standard data selection criteria both for Crab & GalCent data. The telescope transmission was for example checked using hadron-originated muon events.
- [Strict Monitoring of Trigger Stability] We additionally checked run-by-run photoelectron spectrum. After all the data selections, this study adopted **5.9 hours of Crab data** and **38 hours of GalCent data**.
- [Event Reconstruction] We applied the standard analysis up to the reconstruction of primary particles, including minor adjustments to use diffuse MC simulations. **The MC simulations used for this study were closely aligned with the trajectories of Crab & GalCent.**
- [Background Suppression] size > 100 phe, leakage < 0.2, 80%-efficiency gammaness (regressed by trained classifiers)
- [Point-Source Analysis for Flux Estimation] Events beyond 0.1 deg from the assumed source positions were removed. The background was estimated in OFF regions (4,5 for Crab, 6,7 for GalCent) placed with the same offset as the ON regions (= within 0.1 deg from the sources).
- **[New Implementation of Skymap]** We used a method for background estimation known as "the exclusion map", combining it with a template background model [3].

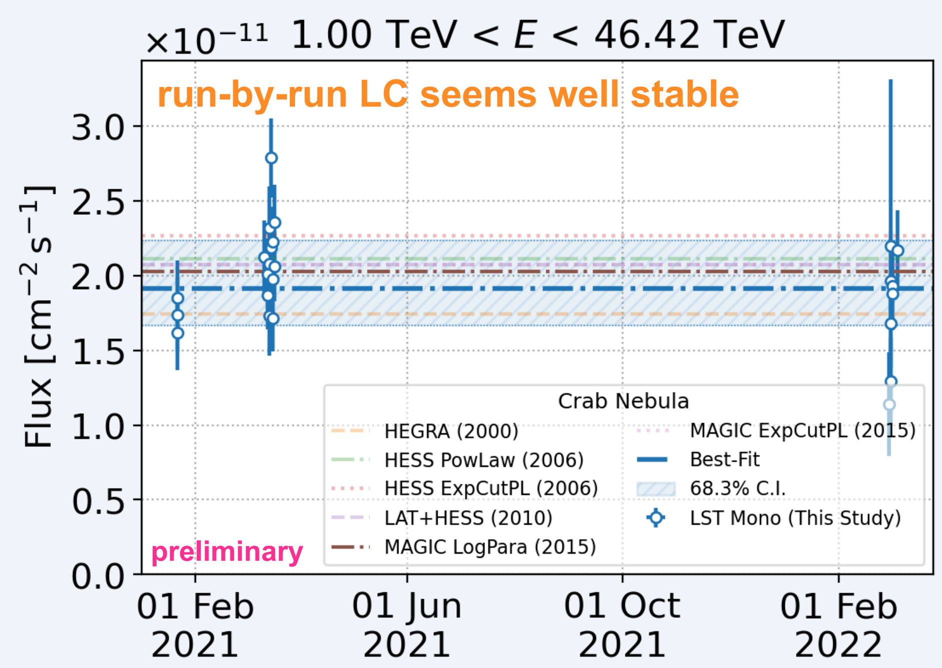
Telescope Performance Studies with Crab Nebula

- We validated the large-zenith-angle MC simulations using the Crab Nebula, the standard candle. The squared-theta plot shows **consistency in the angular resolution between the MC simulations and observational data**.
- The spectral energy distribution and the light curve of the Crab Nebula also demonstrate **stable data-taking and effectual analysis even at the large zenith angle**. Well calibrated!
- The sensitivity was estimated based on actual observation data, **outperforming the standard low-zenith-angle above TeV**.









Galactic Center SED/LC

- We performed the standard point-source analysis to estimate the flux of the central emission (Sagittarius A*).
- The spectral energy distribution, fitted by the log parabola with an exponential cutoff, is **comparable to results from MAGIC and HESS**, and connects smoothly with *Fermi*-LAT measurements below 100 GeV [1, 4, 5].

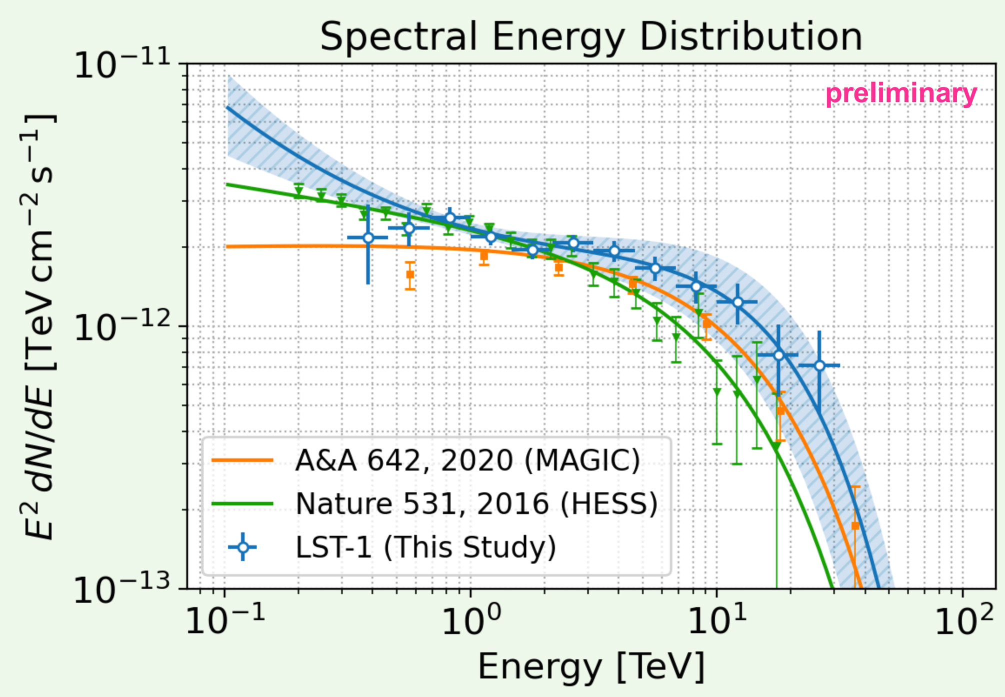
$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\alpha-\beta\ln(E/E_0)} \cdot \exp\left(-\frac{E}{E_{\rm cut}}\right)$$

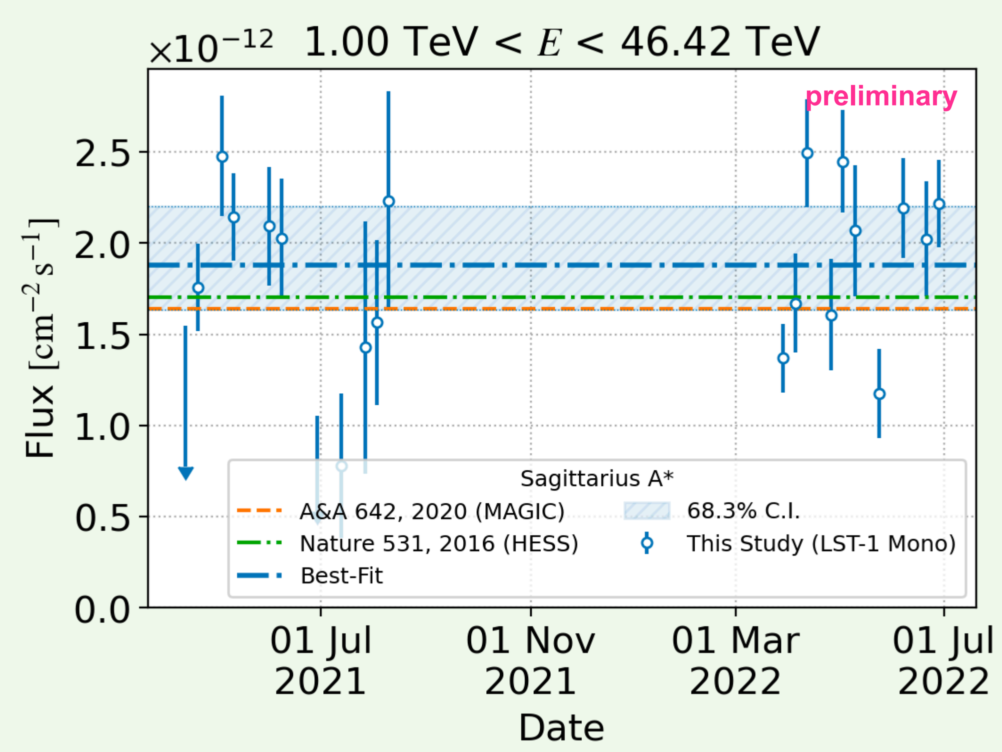
- In the light curve, we **tested the variability of the central gamma-ray emission**, assuming different systematic uncertainties before and after the 2022 La Palma volcanic eruption. We found **no variability or significant systematic difference** in both Crab & GalCent cases.

$$\mathcal{L}(x \mid \mu, s) = \prod_i \frac{1}{\sqrt{2\pi(\sigma_i^{\rm sys})^2}} \exp\left(-\frac{(s_i-1)^2}{2(\sigma_i^{\rm sys})^2}\right) \times \prod_j^{n_i} \frac{1}{\sqrt{2\pi\left(\sigma_j^{\rm stat}\right)^2}} \exp\left(-\frac{\left(x(t_j)-f(\mu,t_j)\right)^2}{2\left(\sigma_j^{\rm stat}\right)^2}\right)$$

Systematic Uncertainty

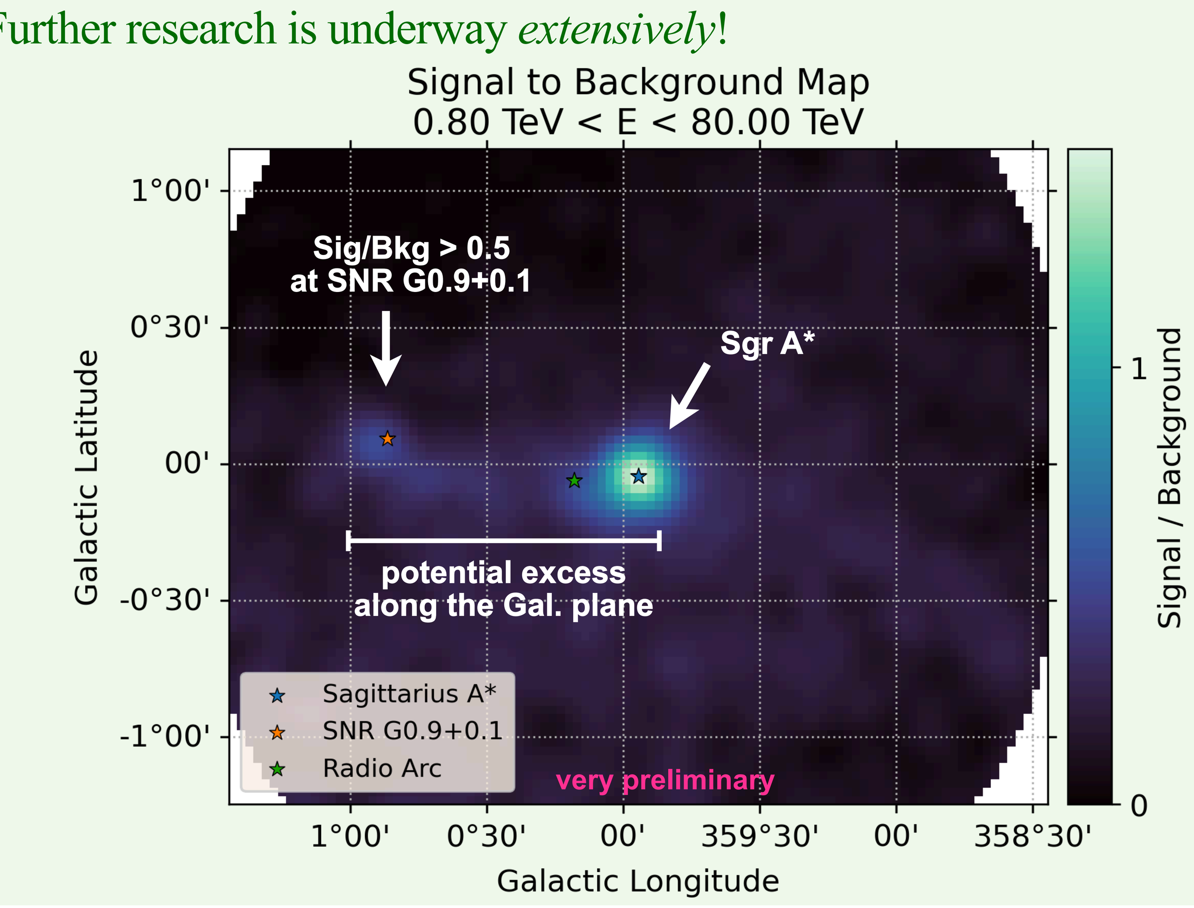
Point-By-Point Statistical Uncertainty





Galactic Center Skymap

- We estimated the background in the camera coordinates using the GalCent dataset. We excluded three regions where the gamma-ray signals are expected to be located: within 0.3 deg from Sgr A*, within 0.3 deg from G0.9+0.1, and 6.0 × 0.4 deg rectangle along the Gal plane.
- We fitted a deformed Gaussian, which can describe the MAGIC detection efficiency in the camera coordinates [3], to the background events above.
- The signal was estimated by excesses of counts of all the events against the estimated background. **The skymap suggests an excess at G0.9+0.1 and along the Galactic plane**.
- Further research is underway *extensively*!



1. HESS Collaboration, "Acceleration of petaelectronvolt protons in the Galactic Centre", *Nature* **531**, 476–479 (2016). https://doi.org/10.1038/nature17147
2. V. Fomin, A. Stepanian, R. Lamb, et al.,"New methods of atmospheric Cherenkov imaging for gamma-ray astronomy. I. The false source method", *Astroparticle Physics*, **2**, 137 (1994). https://doi.org/10.1016/0927-6505(94)90036-1
3. I. Vovk, M. Strzys, C. Fruck. "Spatial likelihood analysis for MAGIC telescope data From instrument response modelling to spectral extraction", *Astronomy & Astrophysics* **619**, A7 (2018). https://doi.org/10.1051/0004-6361/201833139
4. MAGIC Collaboration, "MAGIC observations of the diffuse γ-ray emission in the vicinity of the Galactic center", *Astronomy & Astrophysics* **642**, A190 (2020). https://doi.org/10.1051/0004-6361/201936896
5. D. Malyshev, M. Chernyakova, A. Neronov, & R. Walter, "Leptonic origin of the 100 MeV γ-ray emission from the Galactic centre", *Astronomy & Astrophysics* **582**, A11 (2015). https://doi.org/10.1051/0004-6361/201526120

cta cherenkov telescope array
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