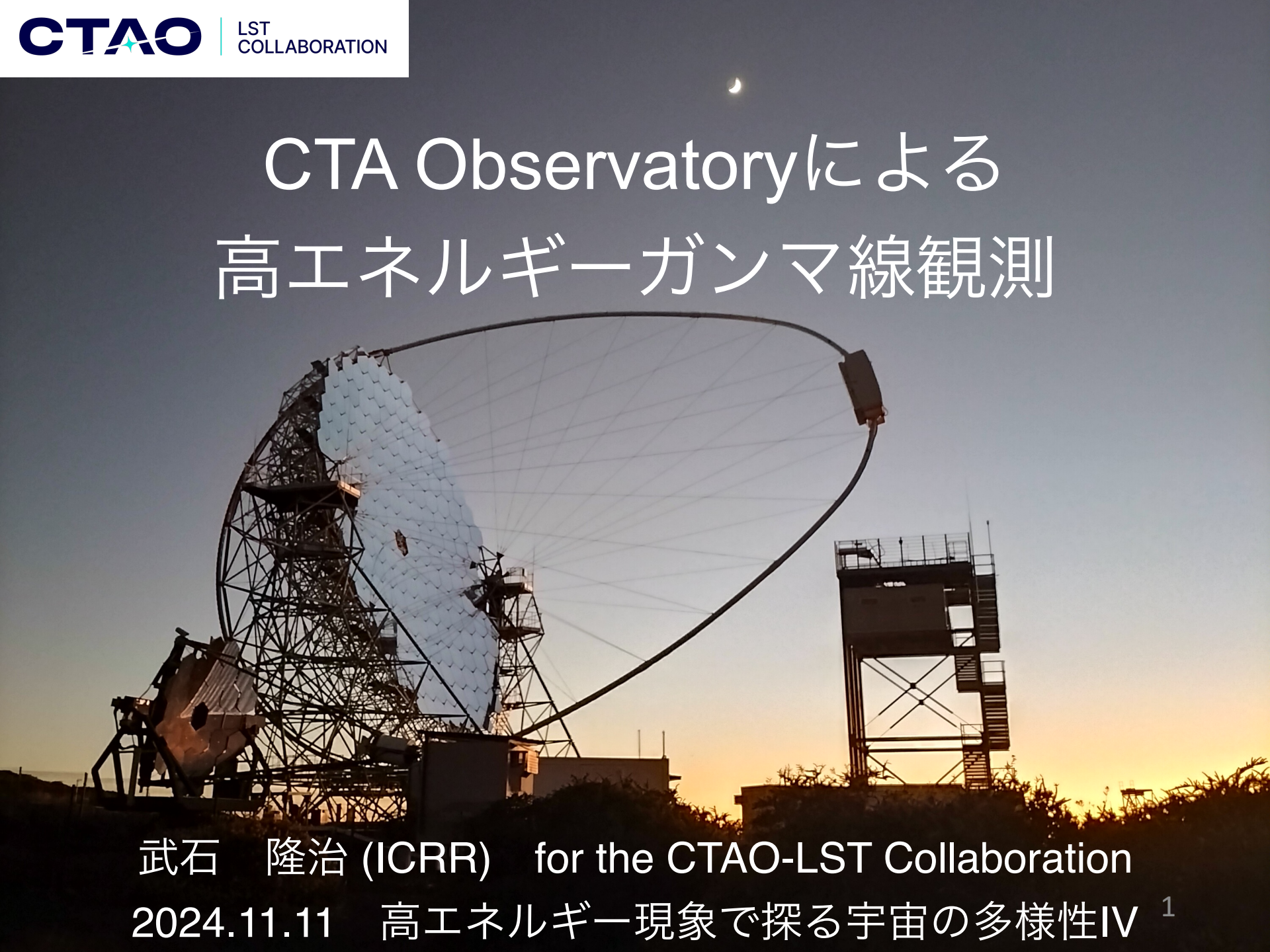
CTAO | LST COLLABORATION

CTA Observatoryによる高エネルギーガンマ線観測



武石　隆治 (ICRR)　for the CTAO-LST Collaboration

2024.11.11　高エネルギー現象で探る宇宙の多様性IV

The Cherenkov Telescope Array Observatory (CTAO) Consortium

- More than 1500 members
- > 150 institutes
- 25 countries

CTAO-JAPAN
~120 members
35 institutes

青山大	大林花織, 佐藤優理, 田中周太, 山崎了, 吉田篤正
茨城大	片桐秀明, 佐藤寛太, 柳田昭平, 吉田龍生
宇宙研	林克洋
大阪大	井上芳幸, 松本浩典, E. Owen,
神奈川大	辻直美
北里大	村石浩
岐阜大	佐野栄俊
京大基研	井岡邦仁, 石崎渉
京大理	鶴剛, 寺内健太, 李兆衡
熊本大	高橋慶太郎
KEK	田中真伸
甲南大	井上剛志, 鈴木寛大, 田中孝明, 千川道幸, 溝手雅也,山本常夏
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仙台高専	加賀谷美佳, 林航平
千葉大	井上進, 小林志鳳, 野田浩司
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東大宇宙線研	浅野勝晃, 阿部正太郎, 粟井恭輔, 糸川拓海, 猪目祐介 ,大石理子 大岡秀行, 大谷恵生, 窪秀利, 齋藤隆之,武石隆治, 手嶋政廣, バクスター ジョシュア 稜, 橋山和明,吉越貴紀, Y. Chai, D. Hadasch, D. Mazin, M. Strzys, I. Vovk, P. K. H. Yeung
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東大理	大平豊, 戸谷友則, 馬場彩
東北大	當真賢二
徳島大	折戸玲子
名大理	立原研悟, 早川貴敬, 福井康雄, 山本宏昭
名大ISEE	奥村曉, 高橋光成, 田島宏康, バン・ソンヒョン
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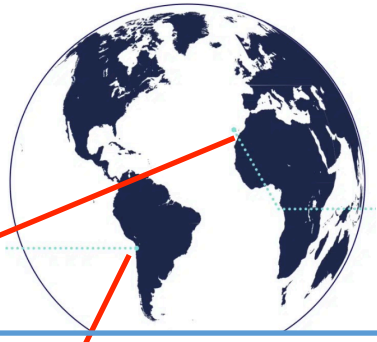
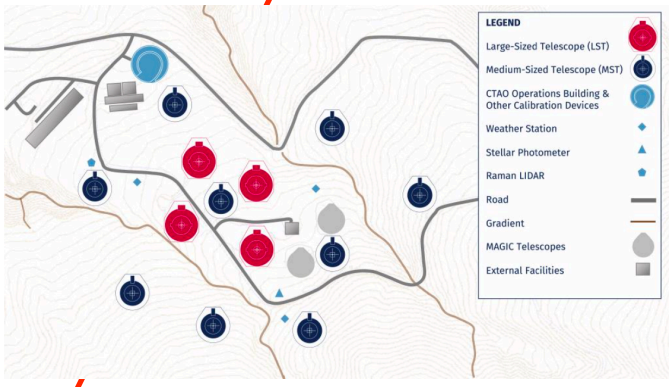
山形大	郡司修一, 坂本貫太, 門叶冬樹, 中森健之
理研	D. Warren, 榊直人, 澤田真理, M. Barkov, G. Ferrand, H. He, 長瀧重博
立教大	内山泰伸, 林田将明
早稲田大	片岡淳

CTAO array configuration

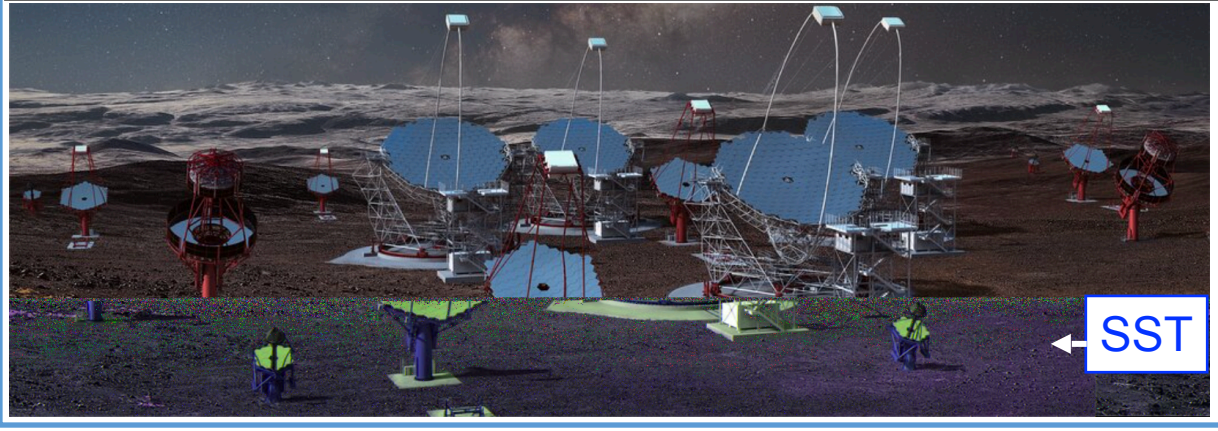
- Construct “alpha configuration” at first
- Expand the array next



Northern site: La Palma, Spain (4 LSTs, 9 MSTs)



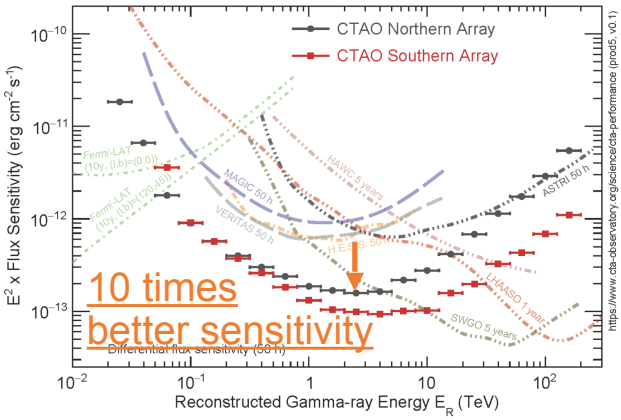
Southern site: Paranal, Chile (2 LSTs, 14 MSTs, 42 SSTs)



CTAO telescope

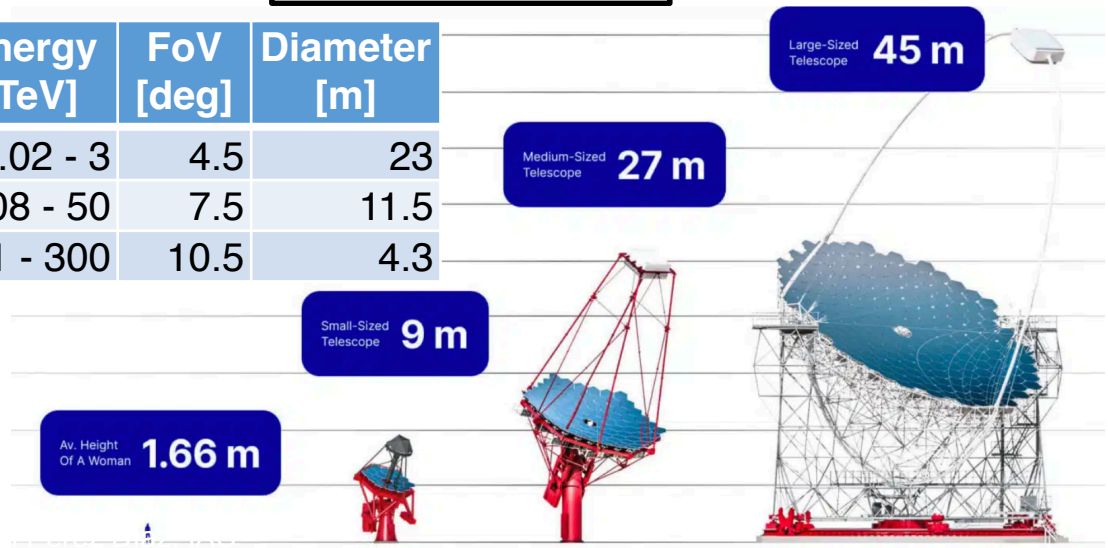
- New gamma-ray observatory under construction
- Compared to current telescopes,
  - 10 times better sensitivity
  - 10 times wider energy range: 20 GeV – 300 TeV
- We started LST-1 operation from 2018.

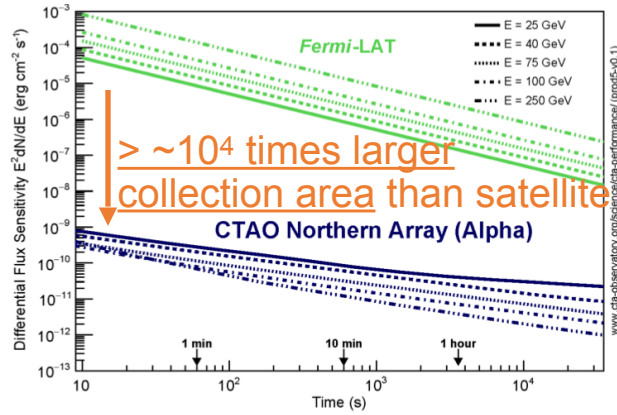
Sensitivity



Telescope design

	Energy [TeV]	FoV [deg]	Diameter [m]
LST	0.02 - 3	4.5	23
MST	0.08 - 50	7.5	11.5
SST	1 - 300	10.5	4.3

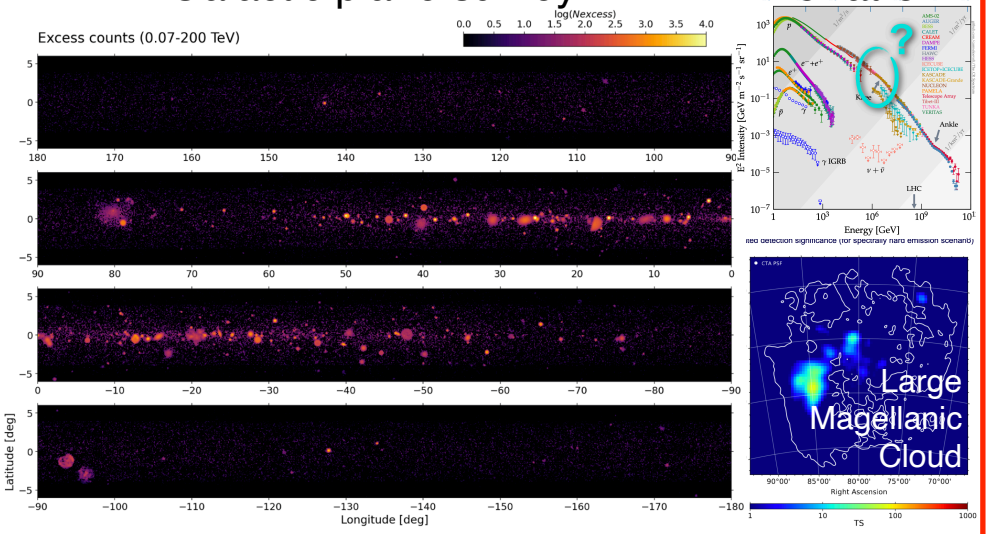




CTAO science

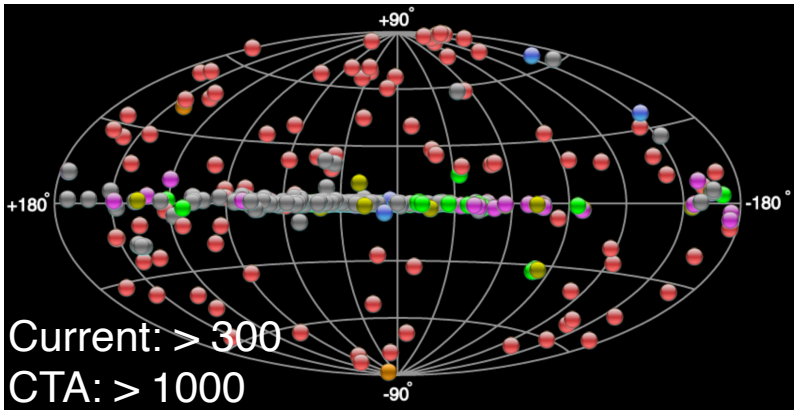
- Origin of cosmic rays
- Black hole and neutron star
- Dark matter search and fundamental physics

Galactic plane survey

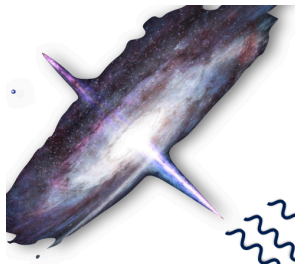


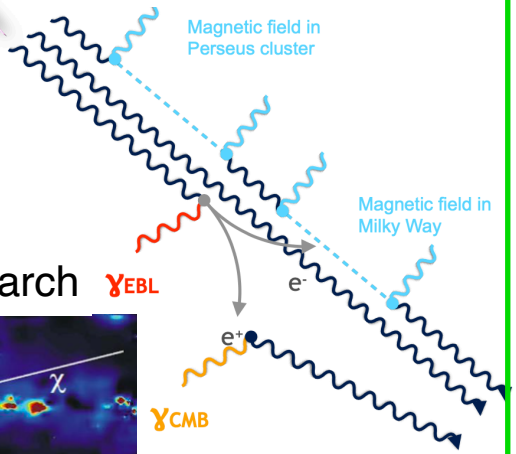
PeVatron

High energy source population study

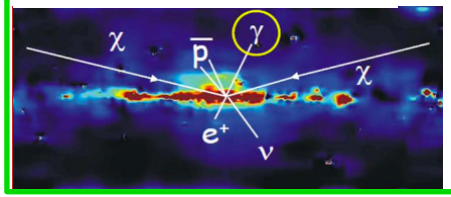


EBL, IGMF, ALP search



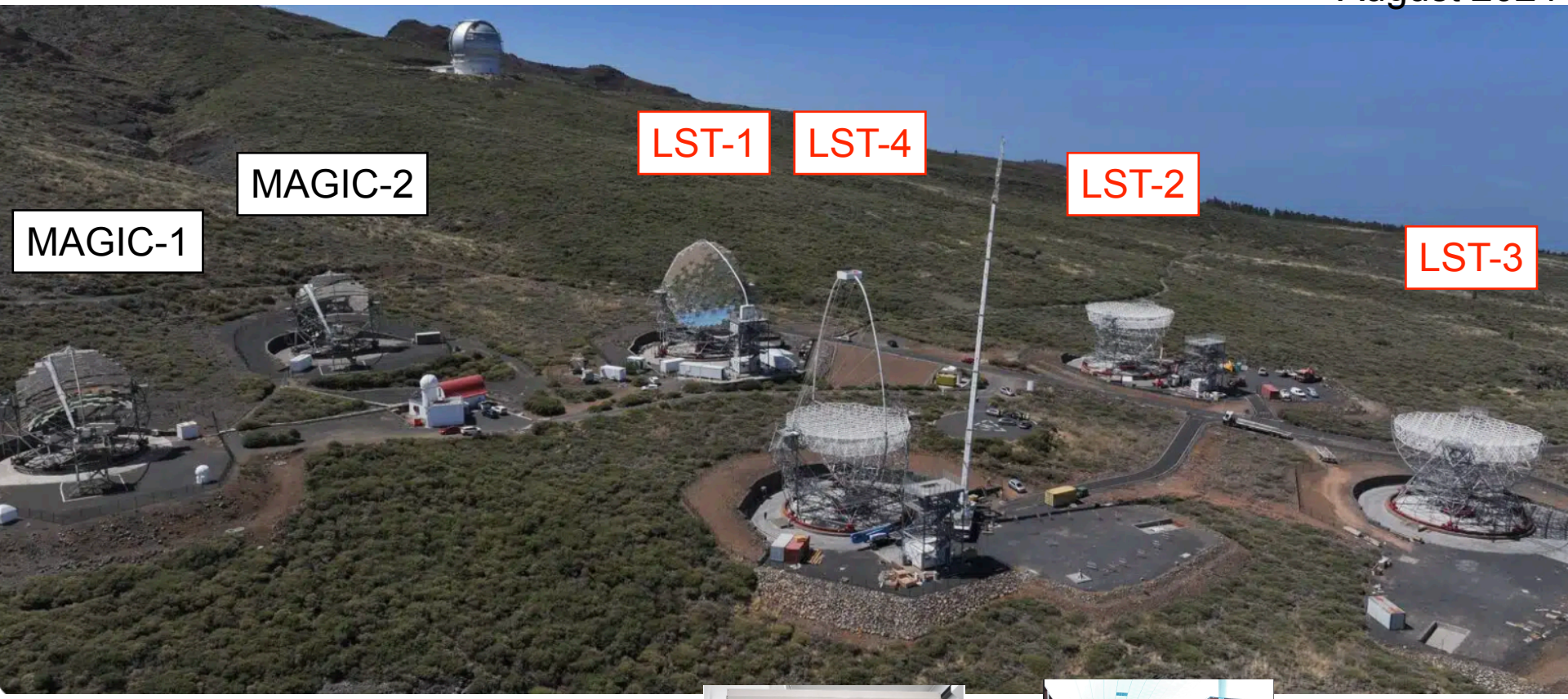


Dark matter search

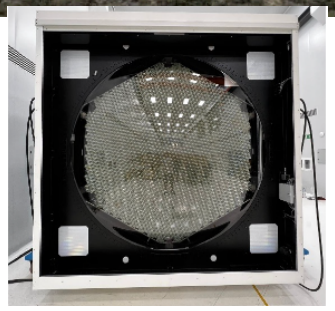


CTAO-north construction

August 2024



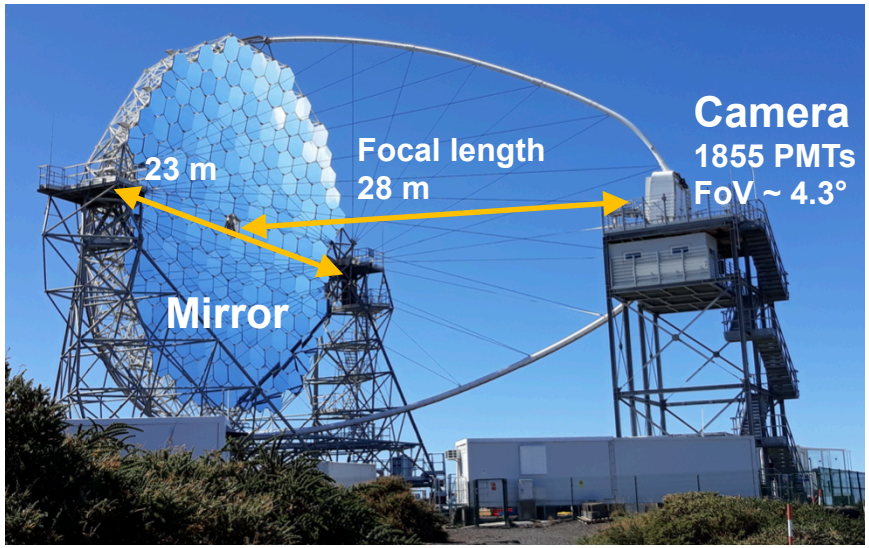
LST2-4 camera and mirror installation: 2024.12 - 2025.11

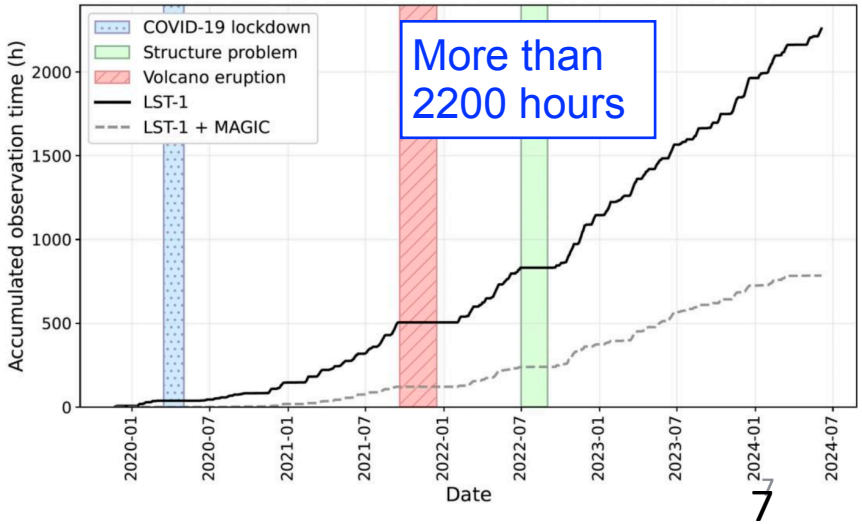


CTA large-sized telescope (LST)

- 23 m diameter: over 400 m² mirror area
- Targeting an energy threshold ~20 GeV
- Stereo observations at **lowest energy ever observed from ground**
- Ability to reposition to any point in the sky within 20 seconds
- Ideal for fast transients and soft sources

AGN flare, GRB, pulsars, …

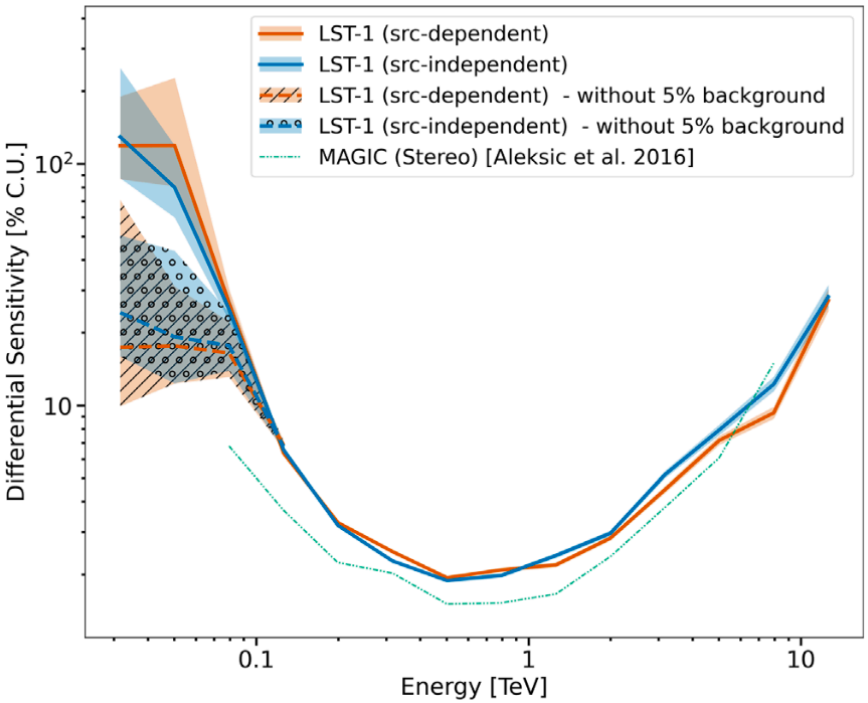




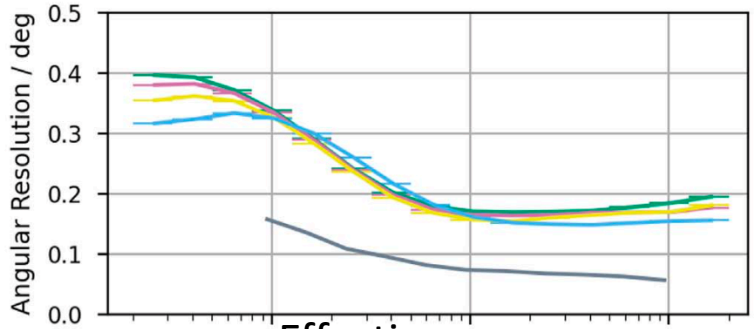
LST-1 performance

Flux Sensitivity
(zenith angle < 35 deg, 50 hours)

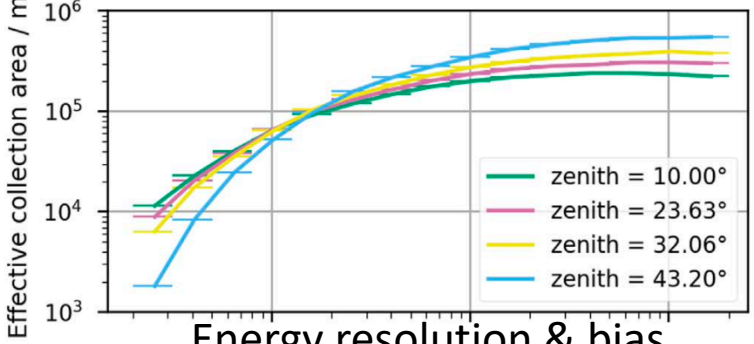
- Energy range widened to lower energy compared to MAGIC



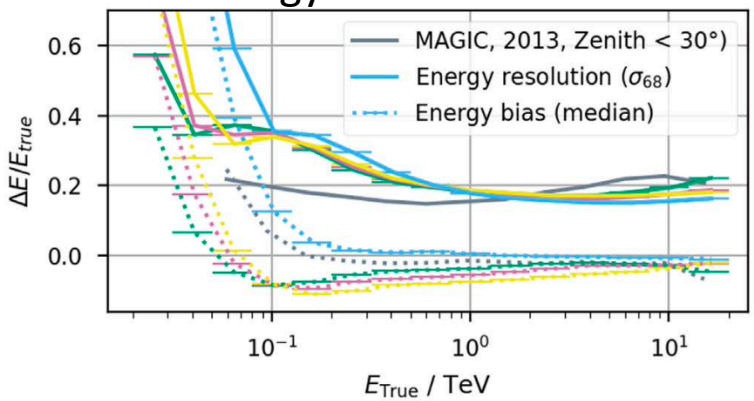
Angular resolution



Effective area



Energy resolution & bias

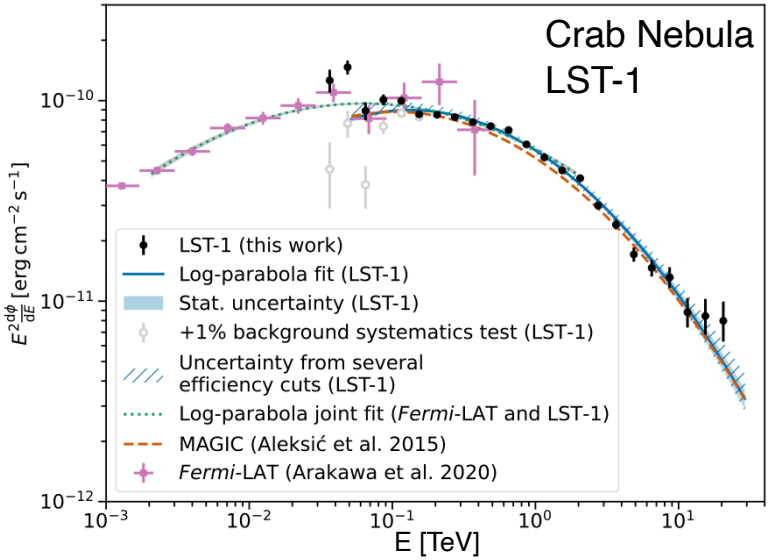


Astrophysical Journal 956, 80 (2023)

LST-1 performance

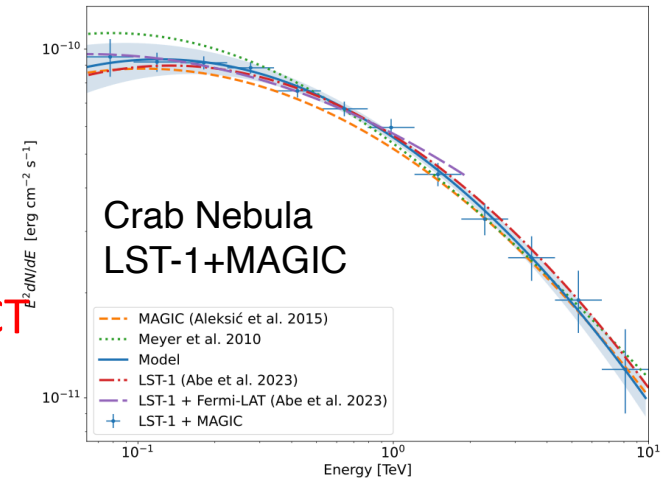
Crab Nebula spectrum

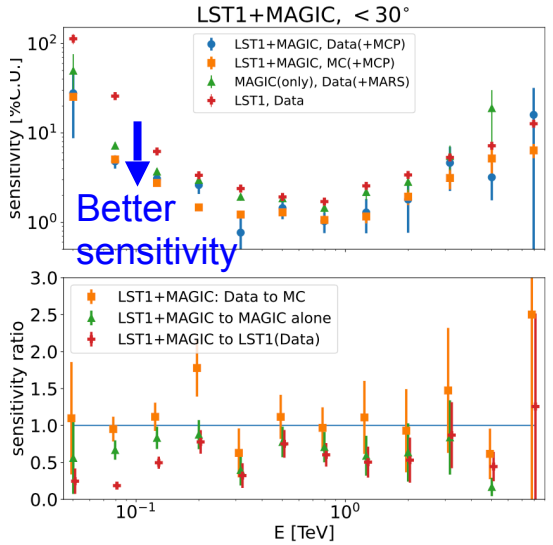
- 34.2 hours of data with zenith < 35°
- Systematic errors: gray points correspond to the effect of +1% background
- Compatible with MAGIC and *Fermi*-LAT



LST + MAGIC joint observation

- Allow detection of 30% (40%) lower fluxes than MAGIC alone (LST-1 alone)
- Current best sensitivity at tens of GeV in northern IACT





A&A 680, A66 (2023)

Crab pulsar

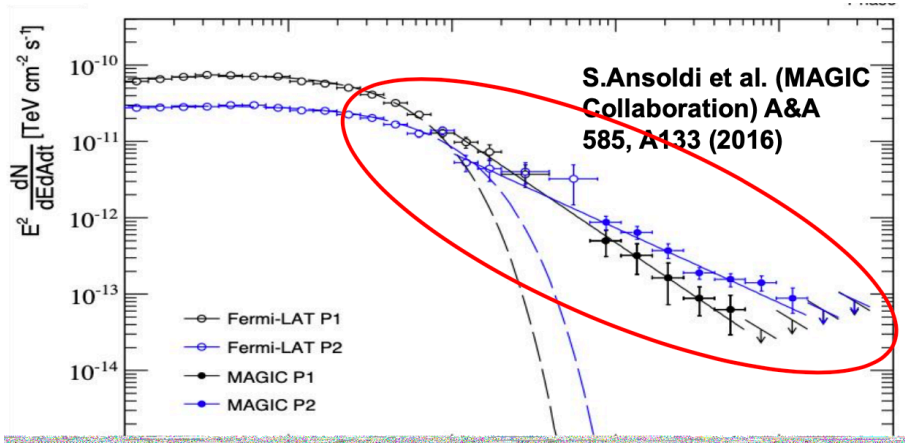
Pulsars: highly magnetized neutron stars in rapid rotation

- Gamma-ray classical models: MeV-GeV emission is due to synchro-curvature radiation (cutoff at a few GeV)
- There is a possibility of Inverse Compton at higher energies

TeV gamma-ray pulsars observed so far

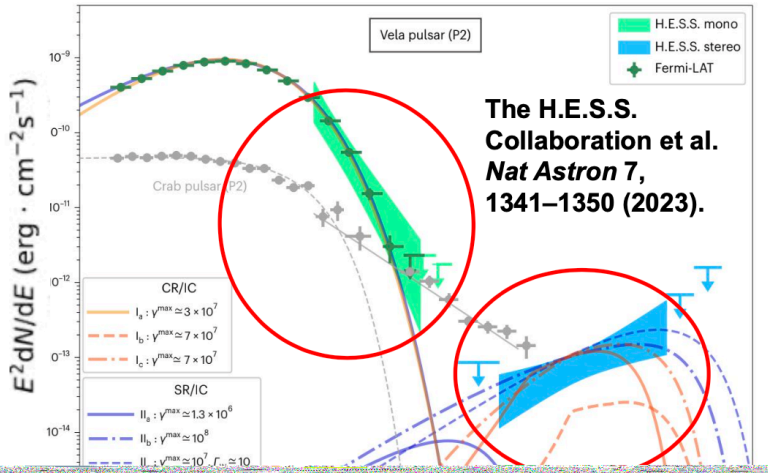
Crab Pulsar P2 detected up to 1.5 TeV

1 single continuous component



Vela Pulsar TeV emission up to 20 TeV.

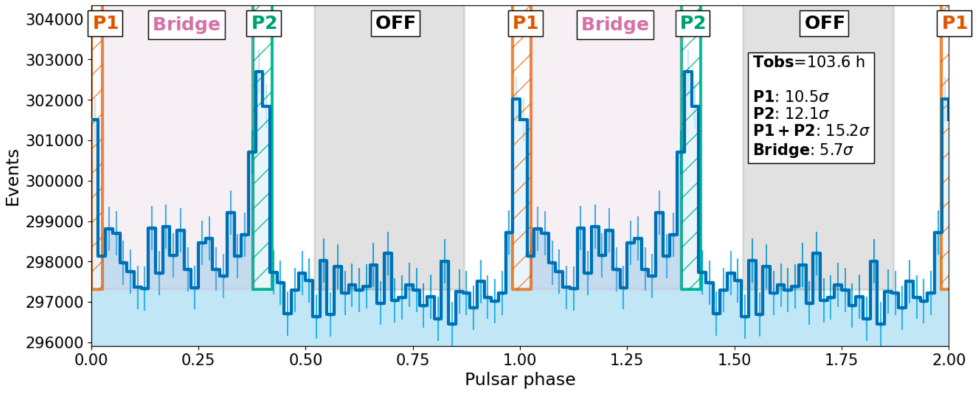
2 components: 1) E < 100 GeV 2) E > TeV

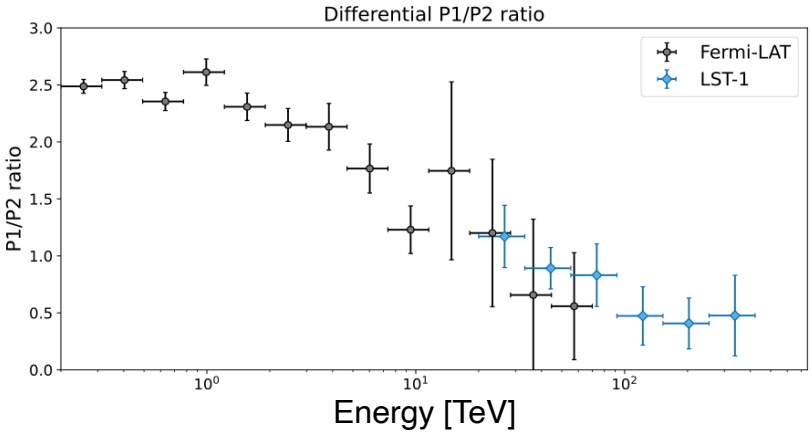


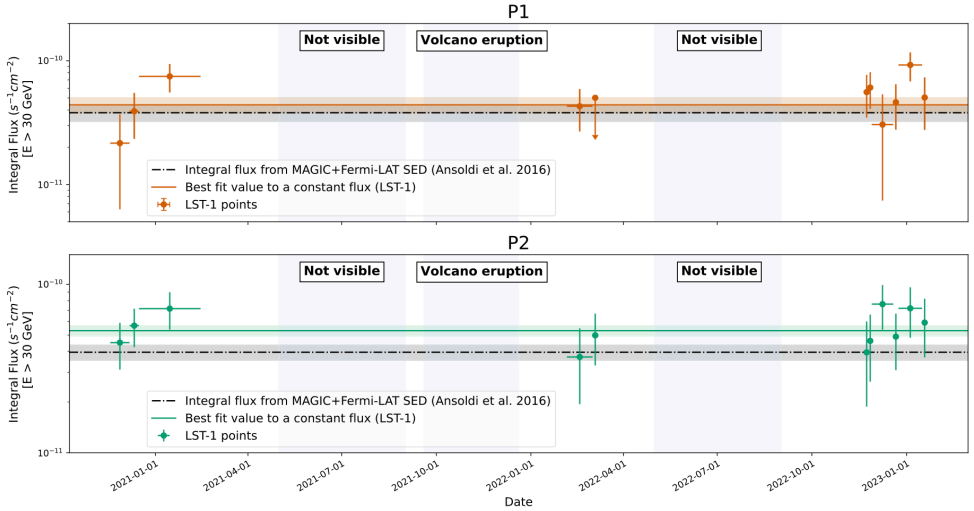
Crab pulsar

LST-1 observation (103 hours, Zd < 50 deg)

- Clear detection down to ~20 GeV







Peak morphology

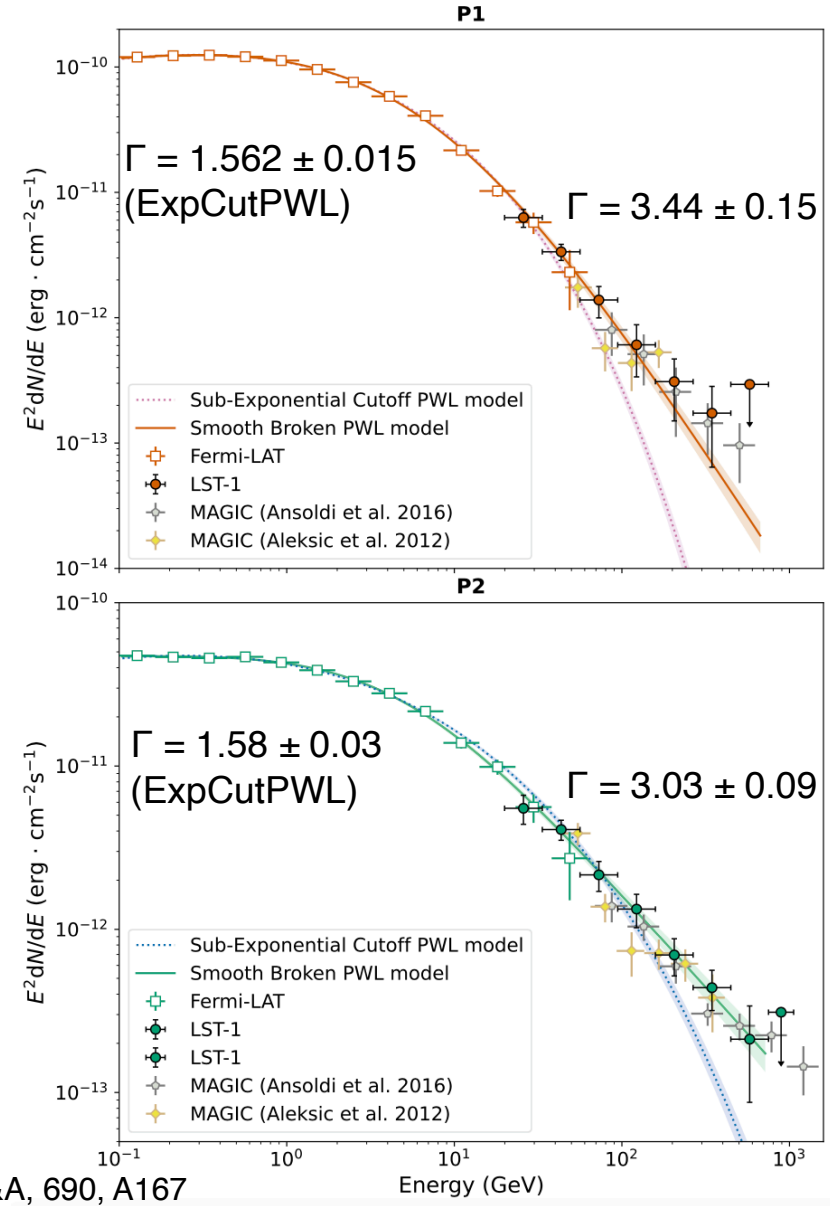
- P1/P2 ratio declines up to 100 GeV
- Constant (~ 0.5) at > 100 GeV

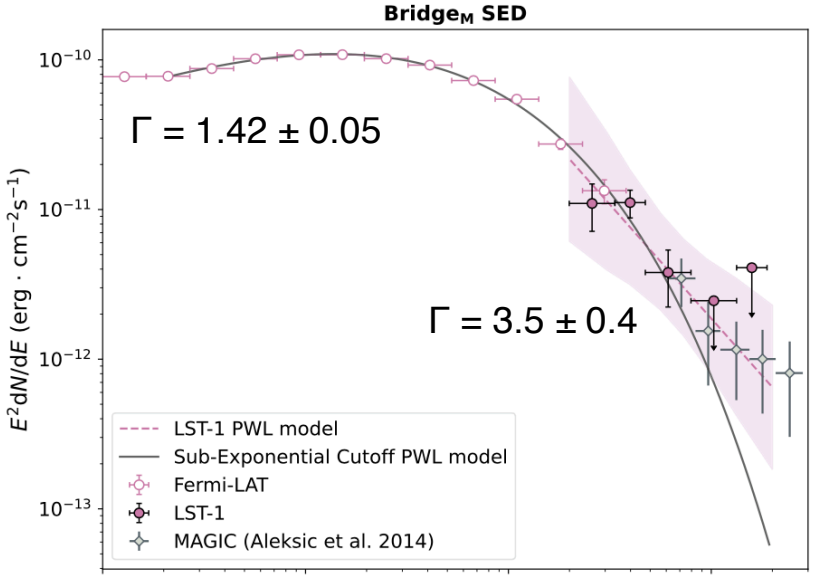
Light curve

- No hint of variability

A&A, 690, A167

Crab pulsar



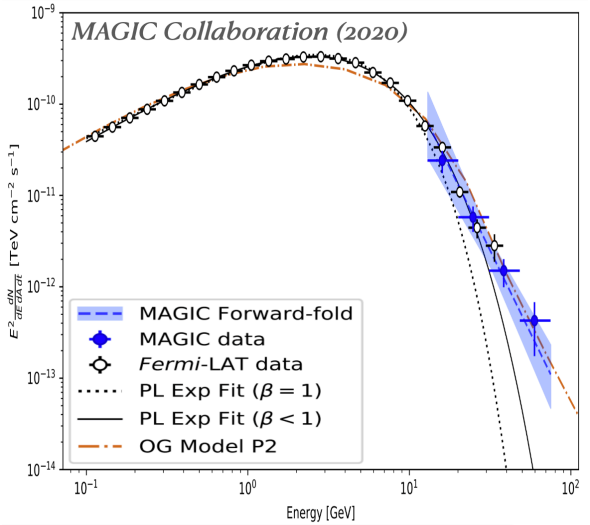


- Smooth transition between Fermi-LAT and LST-1 -> single e^- population
- SED follows Power Laws until 450 GeV in P1 and 700 GeV in P2 -> IC scattering?
- P1 SED steeper than P2 -> anisotropy of pulsar wind?
- Lack of statistics to identify cutoff for bridge emission

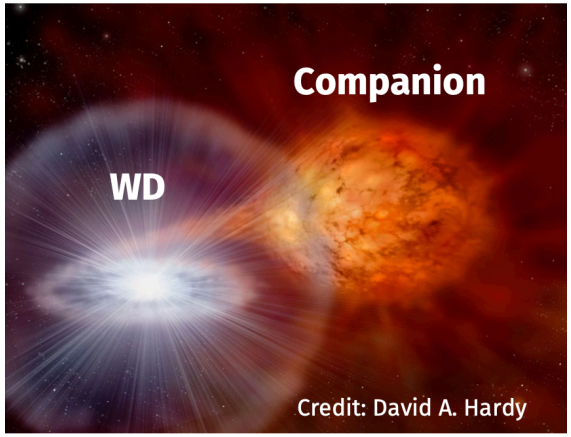
A&A, 690, A167

Geminga Pulsar

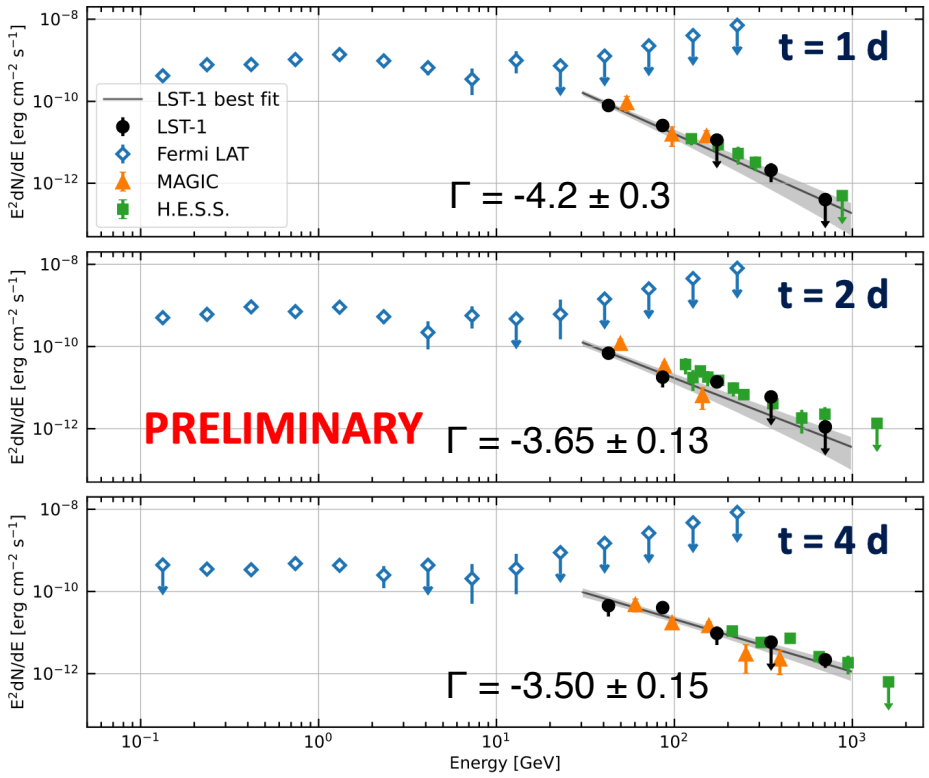
- Pulsar with steep VHE spectrum detected by LST-1
- Peak morphology and spectrum study is ongoing.



Detection of Nova RS Ophiuchi



- recurrent symbiotic nova, d~2.69 kpc
- First detected recurrent nova in VHE gamma rays by 2021 outburst (H.E.S.S. and MAGIC)



- LST-1 took part in the first VHE gamma-ray detection with >~6σ in each night

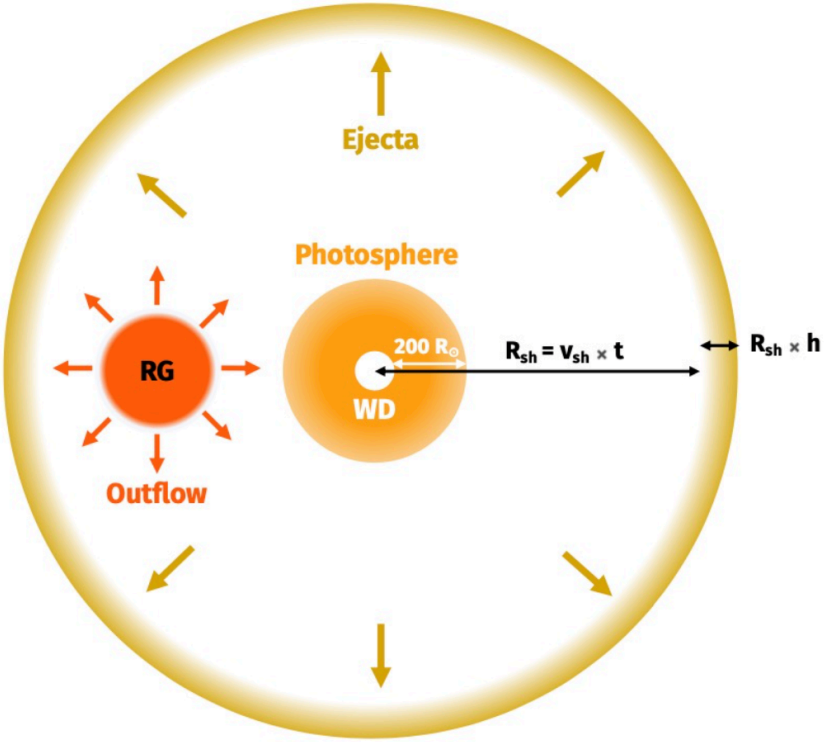
Novae established as new source class at VHE gamma rays

- Spectra in each day shows Power Law index -4.2 ± 0.3 ~ -3.5 ± 0.15
  LST-1 reaches lower energy than MAGIC.
- Consistent between LST-1, MAGIC, H.E.S.S., Fermi-LAT

Nova RS Ophiuchi modeling

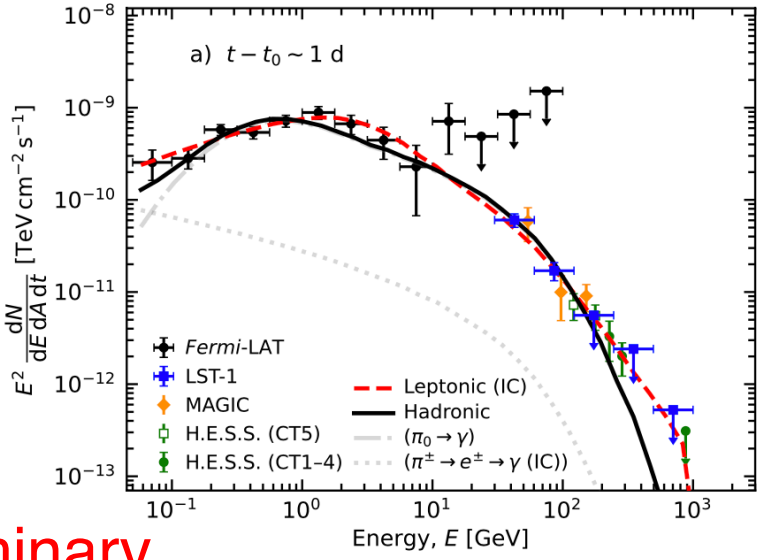
- Assuming a spherical shell structure
  - Expansion velocity: v_{sh} = 4500 km s^{-1}
- Hadronic model:
  - pp -> π^0 -> 2 γ
  - n_{ej} ~ 6 $\times 10^8$ cm^{-3} (t = 3 d)
- Leptonic model
  - IC of photons from the photosphere
  - u_{ph} ~ 0.14 erg cm^{-3} (t = 3 d)

- Software: a developing version of *JetSeT*
- Parameters are taken from MAGIC (2022)

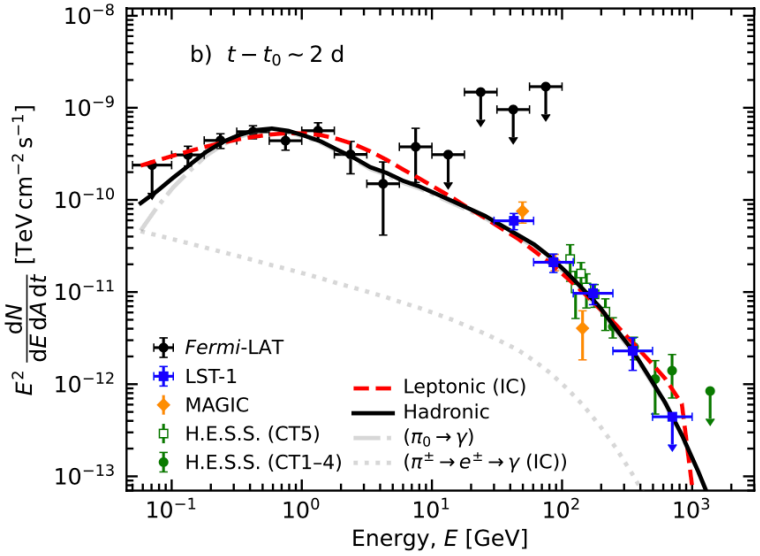


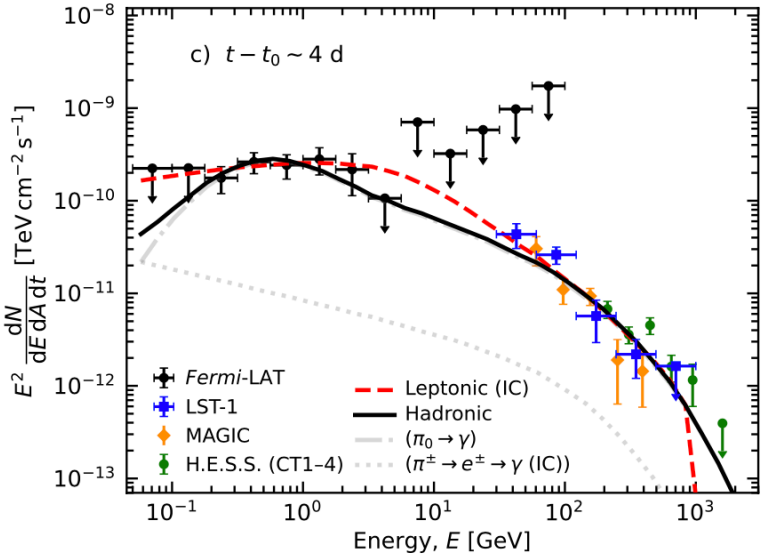
Nova RS Ophiuchi

- Hadronic scenario is favored.



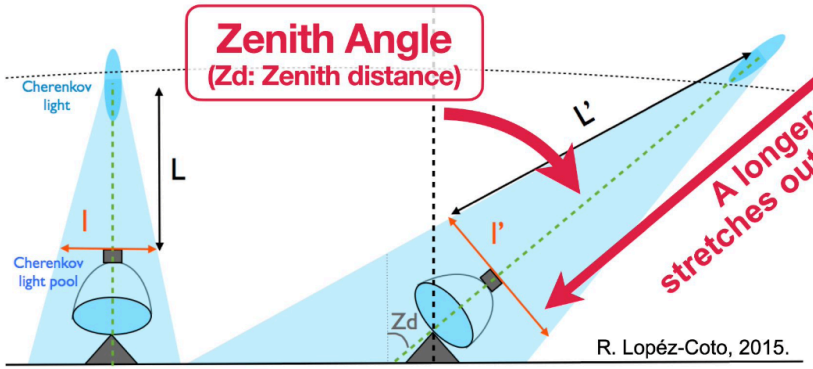
Preliminary

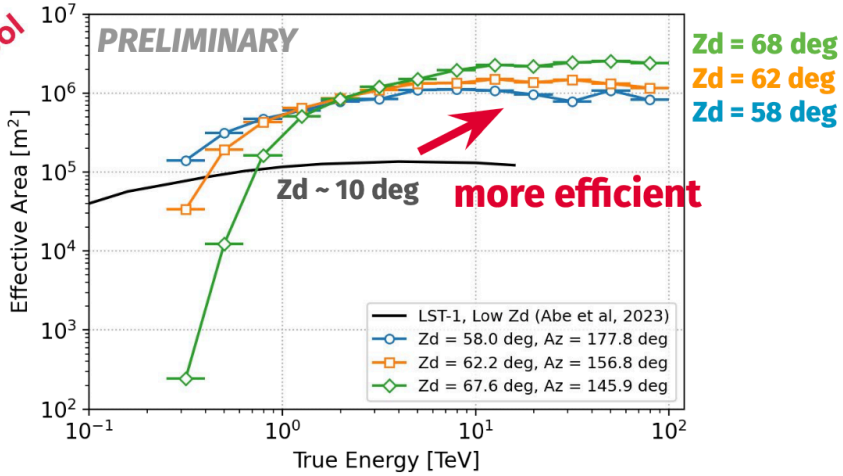


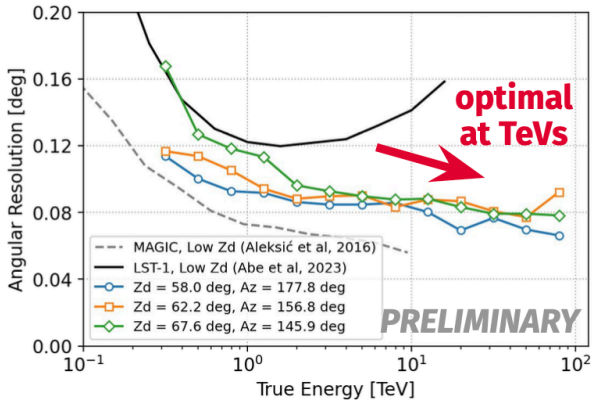


Large-zenith angle observation for Galactic Center

LST-1 requires the large-zenith-angle technique to observe the Galactic Center, leading to the enhanced collection area in the TeV regime.







+) **increased collection area** by an order of magnitude

+) **decreased image leakage** (better reconstruction) at higher energy

-) performance very sensitive to Zd even within the field of view

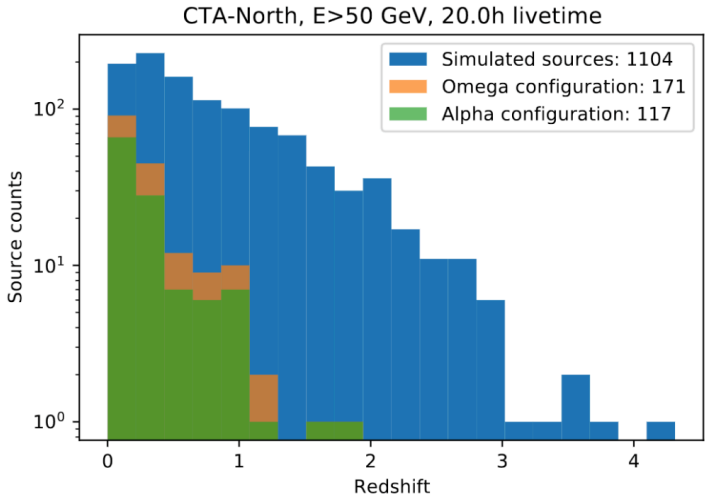
-) increased energy threshold from O(10) GeV to O(100) GeV or higher

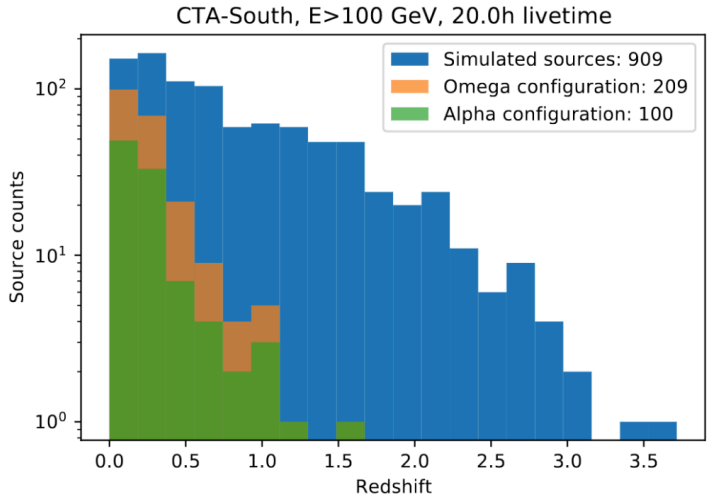
Galactic Center

- **39-hour data** in 2021/2022 after selection
- Analysis is carried out through a dedicated special background modeling.
- Successful extended-source observations
- Sgr A*, SNR G0.9+0.1, Ridge diffuse component spatial/spectral distributions are generally aligned with previous studies

AGN population study

- AGN constitute the most populous class of sources in the extragalactic very-high-energy (VHE; E > 100 GeV) sky.
- Detecting more VHE AGN at different energies and distances is crucial for a better understanding of their emission mechanisms.





Sources with known redshift from 4LAC catalog extrapolated with power law and EBL absorption

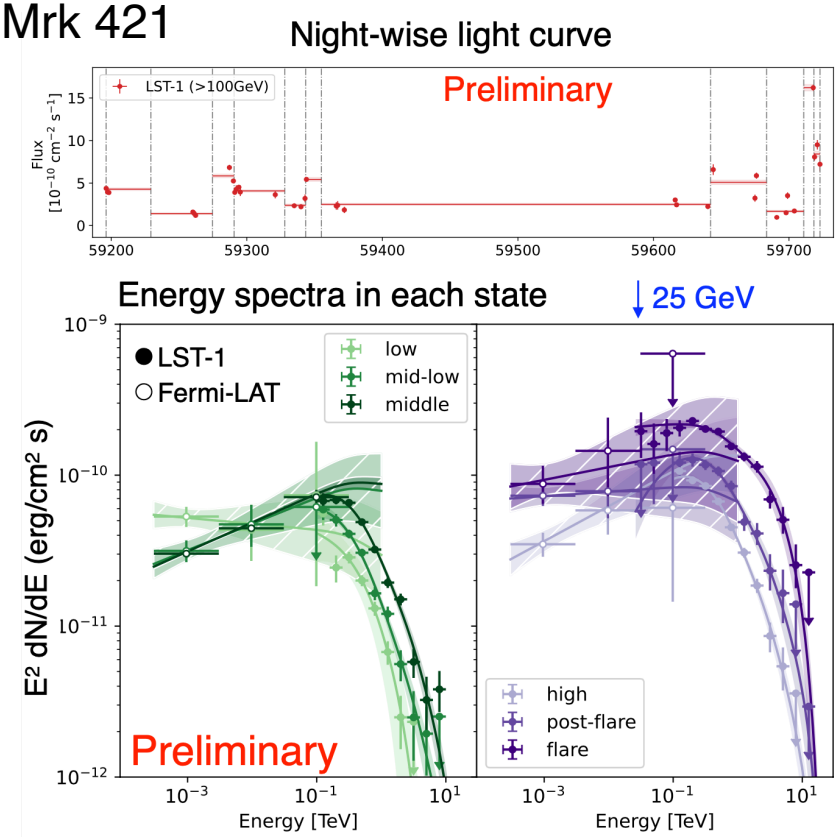
- CTAO will detect hundreds of AGN
  - Long term monitoring program
  - High quality spectra
  - Follow up of GeV and TeV flares
  - Extragalactic survey
- Will provide blazar luminosity function up to TeV energies

Brown et al., PoS (ICRC2021) 887

AGN zoo

- Using LST-1 commissioning data in 2020-2022, we analyzed spectral variability of bright AGN: Mrk 421, Mrk 501, 1ES 1959+650, etc.

Mrk 421



Measured gamma-ray peak without gaps

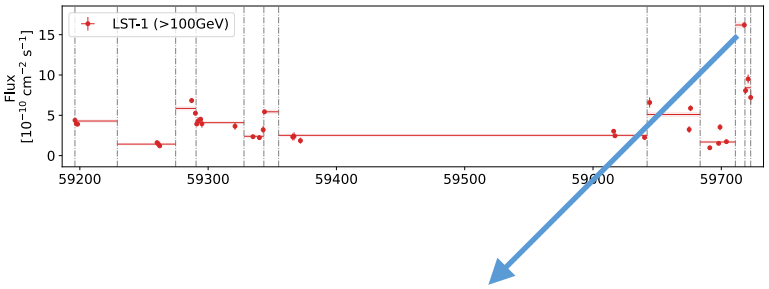
- Applied Bayesian block and the blocks were merged by checking spectrum parameters vary < 3σ
- Fermi-LAT spectra simultaneous to LST-1 observations show good agreement between both results
- LST-1 is highly sensitive to gamma-ray sources with time variation above 25 GeV for low-Zd observation

Exceptional performance of AGN detection with LST-1

AGN zoo

Mrk 421 flare light curve

- Flare on 2022-05-18 (0.91 hours data)
- ~3x brighter than Crab at > 100 GeV
- Doubling time scale: ~ 10 min.



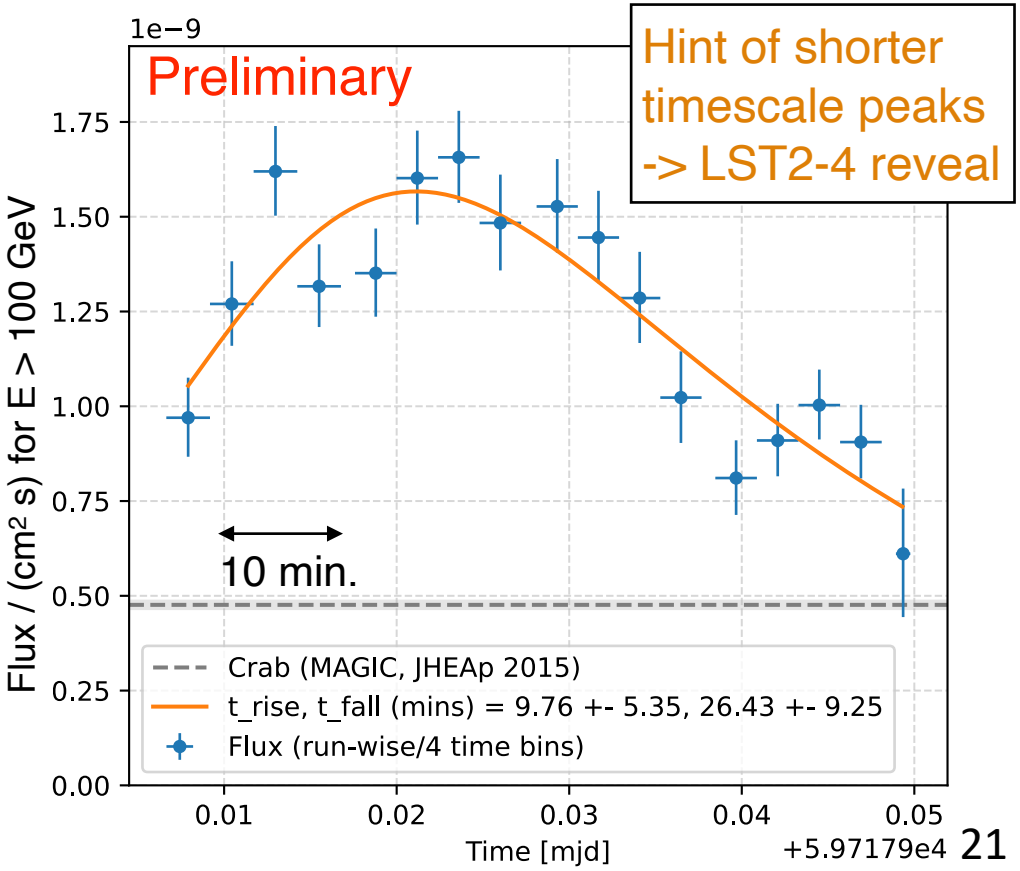
Emission region size

$$R \leq \frac{ct_{\mathrm{var}}\delta}{1+z}$$

δ: Doppler factor
z: redshift of the source

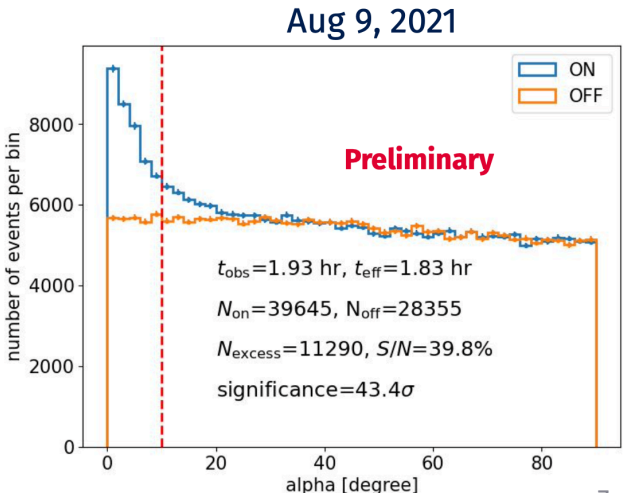
- Assuming δ = 10-50, using t_{var} ~ 10 min., z = 0.031,

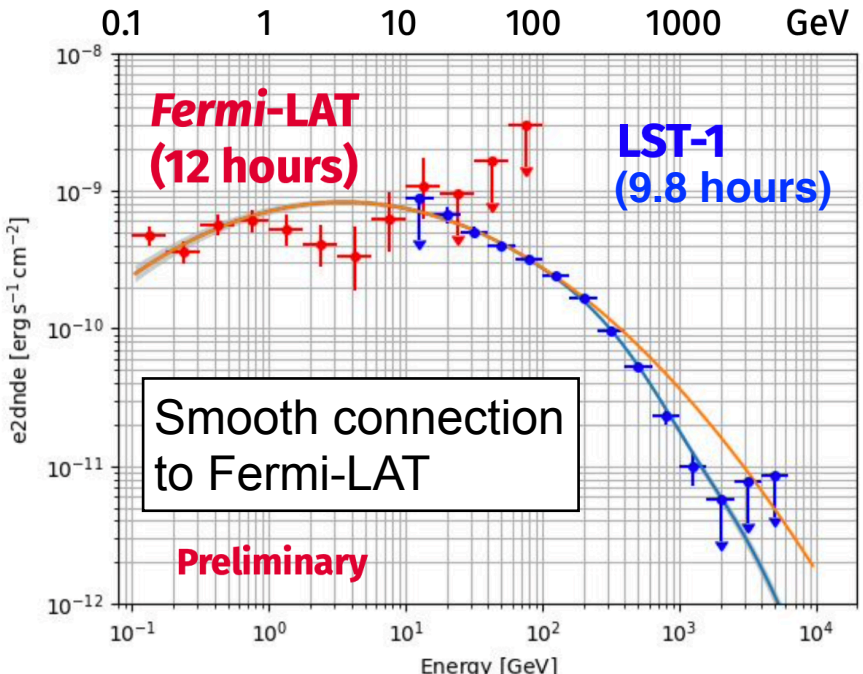
R < ~0.2-1 x 10^{15} cm

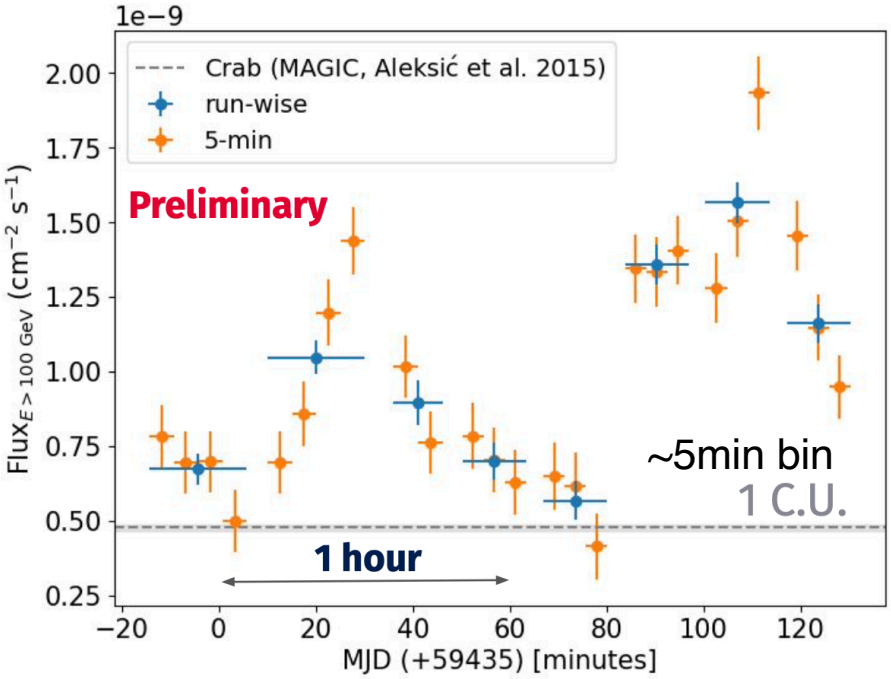


BL Lacertae

- Intermediate frequency peaked BL Lac at z = 0.069
- Flare in 2021 July and August was detected.
- Energy spectrum down to ~30 GeV
- Intra-night variability with sub-hour-scale was detected up to 3-4 Crab unit.
- MWL spectrum study is ongoing.
- QG and Relativity tests are ongoing.







Discovery of AGN OP 313 at VHE gamma-rays

- Flat Spectrum Radio Quasar (FSRQ), Redshift: z = 0.997
- Detected Dec. 2023 flare (ATel #16381)
- Most distant AGN with ground-based VHE observation
- This shows excellent performance of LST-1 for distant sources.
- Study of spectrum and EBL is ongoing.

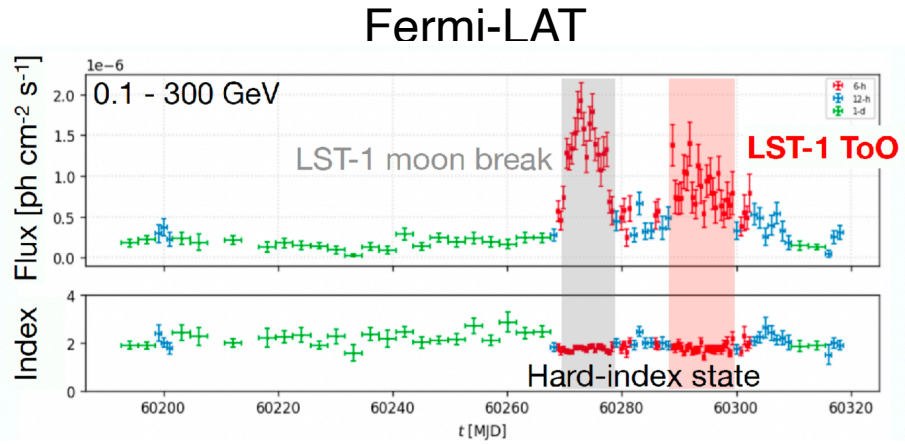
First detection of VHE gamma-ray emission from FSRQ OP 313 with LST-1

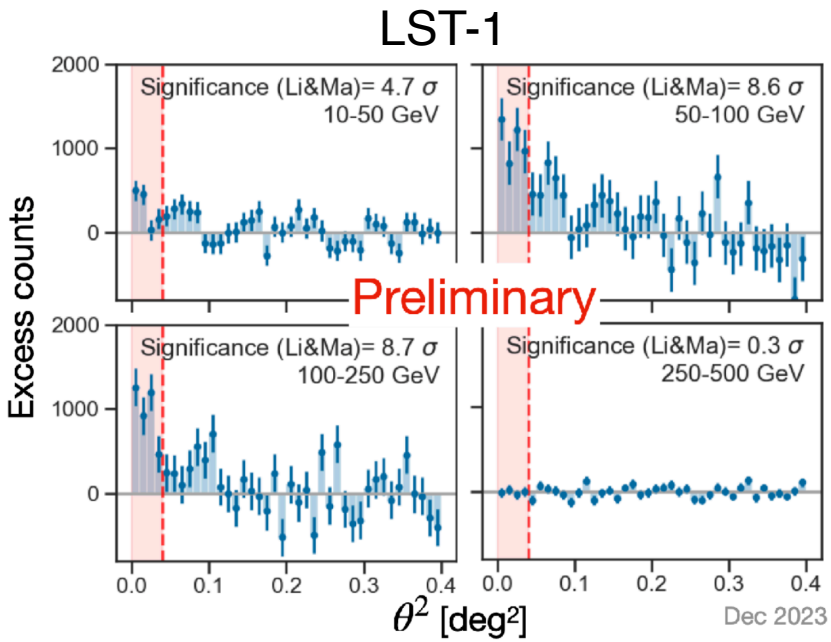
ATel #16381; *Juan Cortina (CIEMAT) for the CTAO LST collaboration*
*on **15 Dec 2023; 14:31 UT***
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, AGN, Blazar, Quasar

𝕏 Post

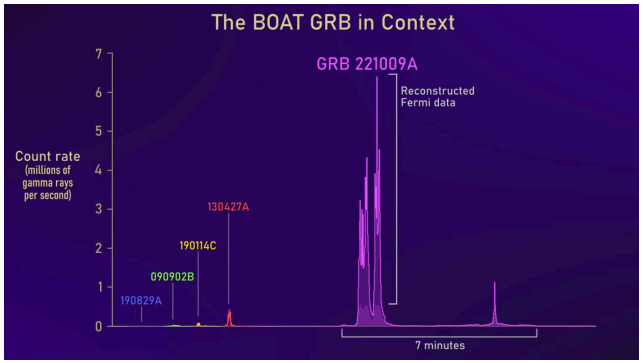
The Large-Sized Telescope (LST-1) on La Palma has been monitoring the very distant Flat





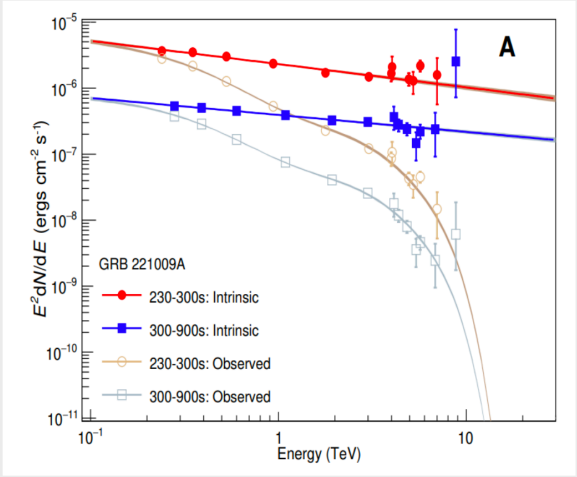
GRB221009A (BOAT)

- Extremely bright GRB (Brightest Of All Time)
- Redshift z = 0.151 (724 Mpc)
- $E_{\gamma, iso} \approx 1.0 \times 10^{55}$ erg
- Once-in-a-10,000-year event



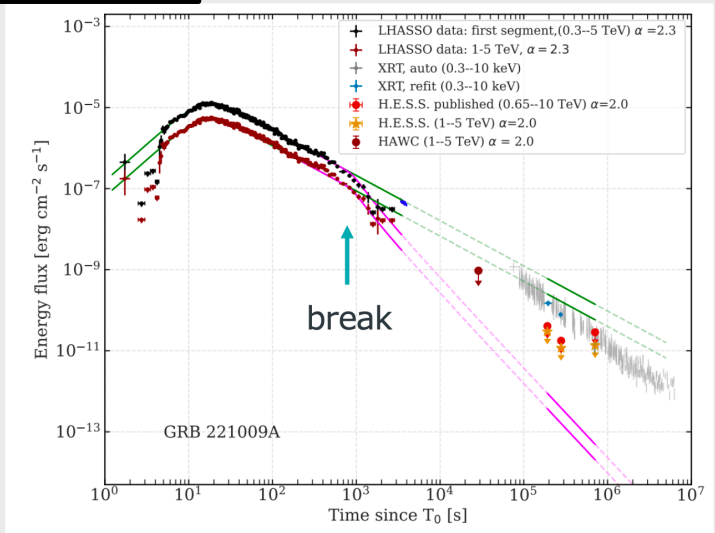
TeV observation

LHAASO Collaboration (2023)



Detection up to 13 TeV by LHAASO experiment

J.D. Mbarubucyeye et al. (ICRC2023)



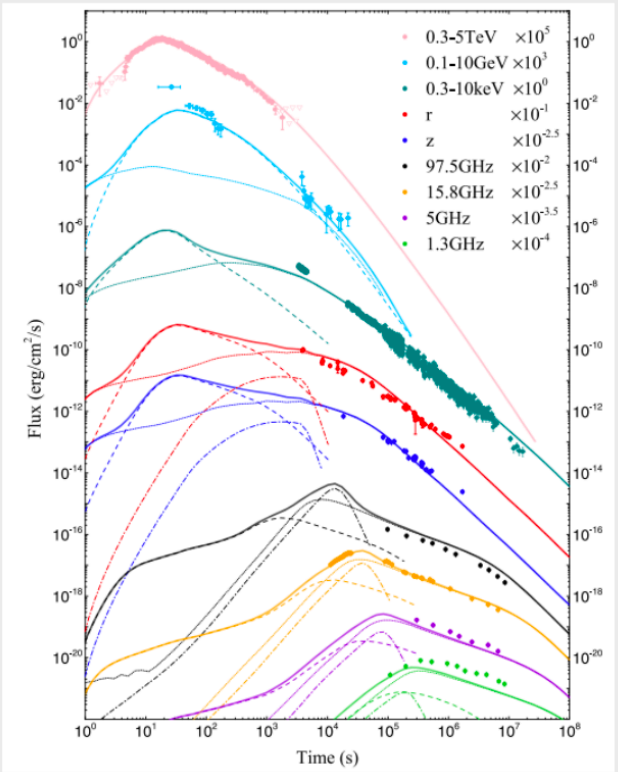
Break in LHAASO lightcurve suggests a jetbreak

➡ Emission at >10^5 s comes from outer component of the jet?

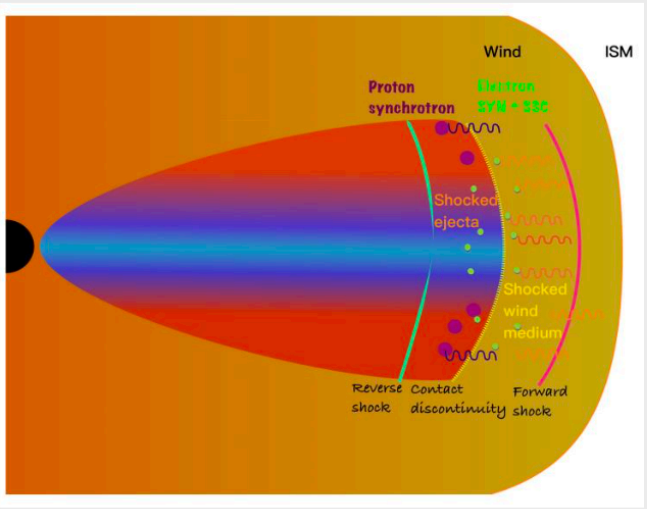
Structured Jet Model

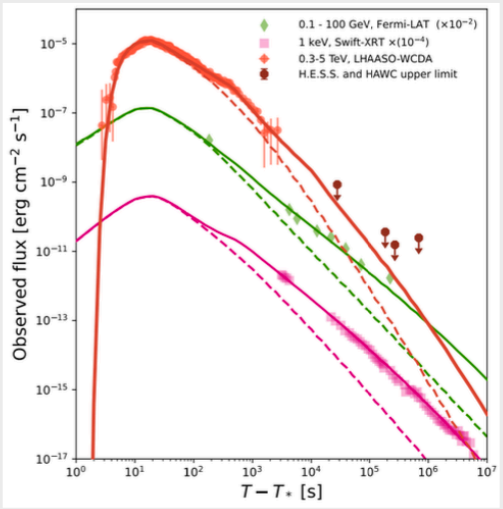
- Structured jet models are widely discussed to explain MWL data of GRB221009A
  - Narrow core + wide wing
  - Interesting comparison with GW/GRB 170817A (Explained by off-axis structured jet)

J. Ren et al. (2024)



B. T. Zhang et al. (2023; arXiv)





Latetime TeV observations provide clues to test different structured jet models

GRB221009A (BOAT)

- LST-1 observation:

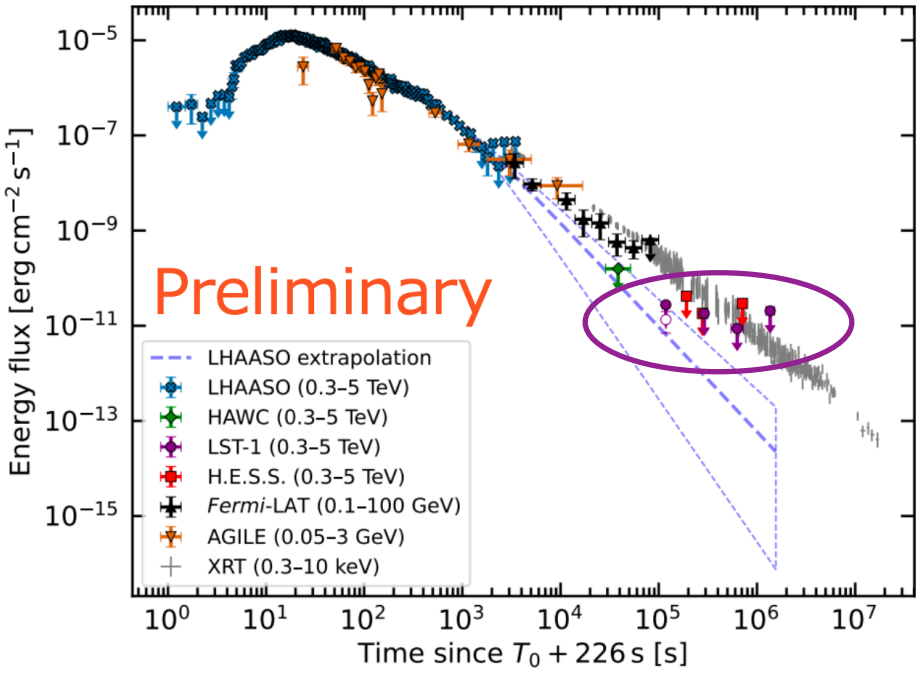
Start 1.3d after the burst

- Moon (T_0 + 1.3d and 3d, ~3 hours)

~4σ hint of signal

- Dark (T_0 + 6d - 19d, ~10 hours)

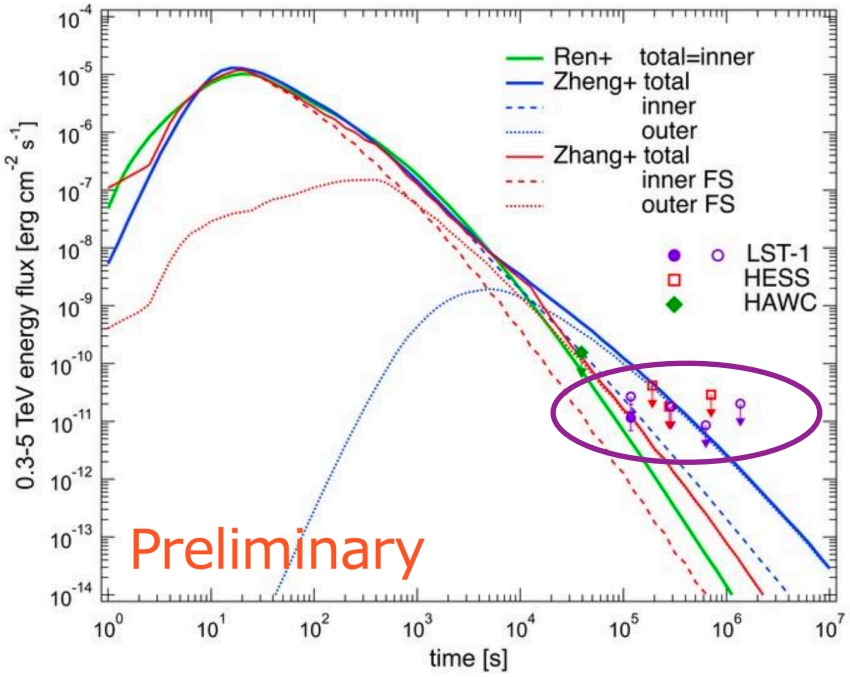
No detection



- Tested structured jet models
- Disfavor the model by Zheng+24
- Models by Zhang+23 and Ren+24 reproduce well LST-1 observation

• Ren+24: Latetime TeV emission from inner jet dominates

• Zhang+23: Latetime TeV emission from outer jet dominates



Summary

- CTAO is new gamma-ray observatory being constructed.
- LST-north construction is ongoing and LST-1 is operating, with a tens of GeV energy threshold and a fast follow-up capability of 20 sec.
- Geminga pulsar: significant detection of soft spectrum source
- Nova RS Ophiuchi: LST-1 took part in the first VHE gamma-ray detection with >~6σ in each night
- Galactic center: successful extended-source observation
- AGN zoo: highly sensitive to gamma-ray sources with time variation
- Blazar BL Lacertae: Flux variability with sub-hour-scale is observed.
- Observed FSRQ OP 313 (most distant AGN for ground VHE observation)
- Observing GRB following burst alerts