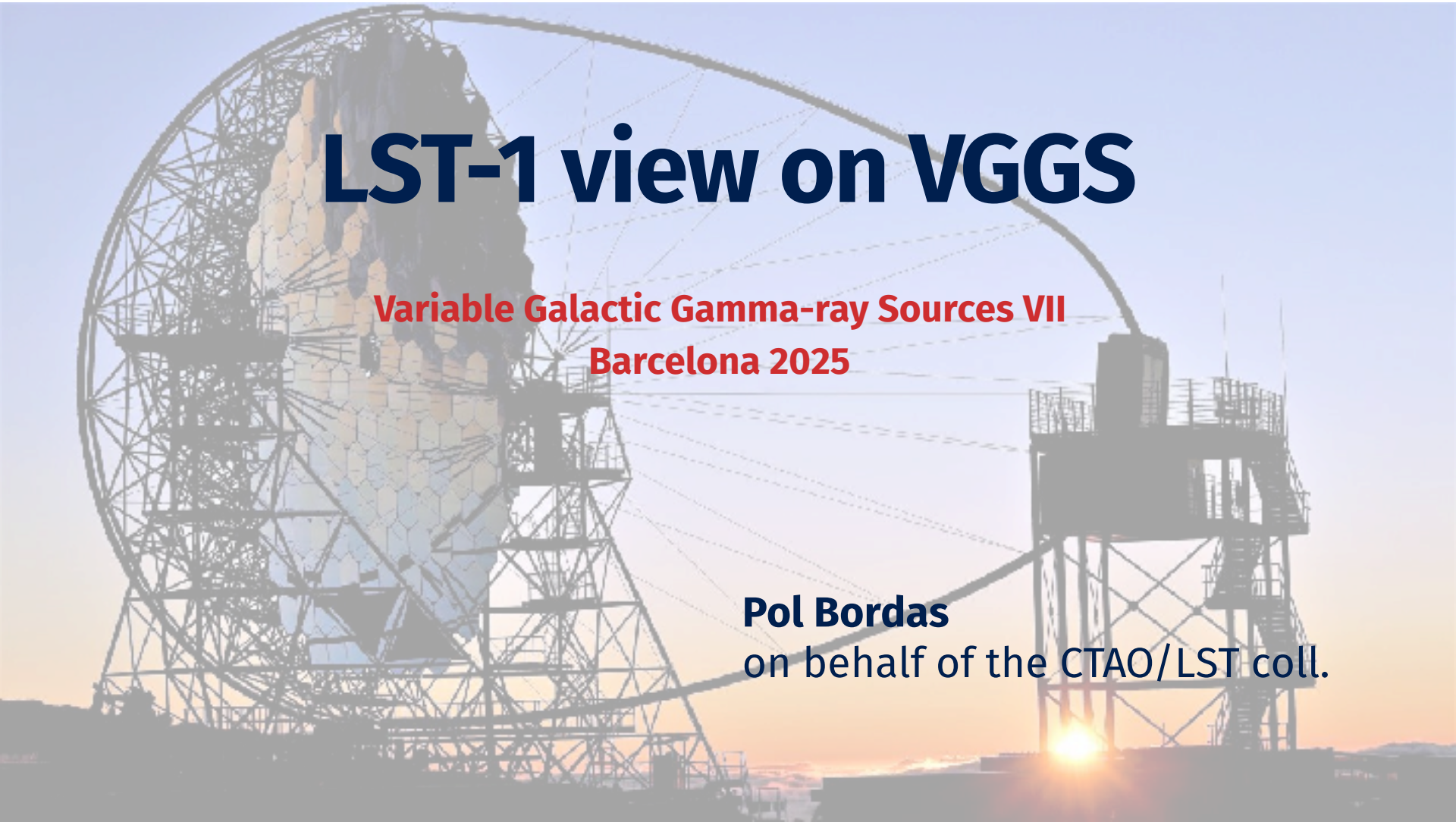


LST-1 view on VGGS

Variable Galactic Gamma-ray Sources VII
Barcelona 2025

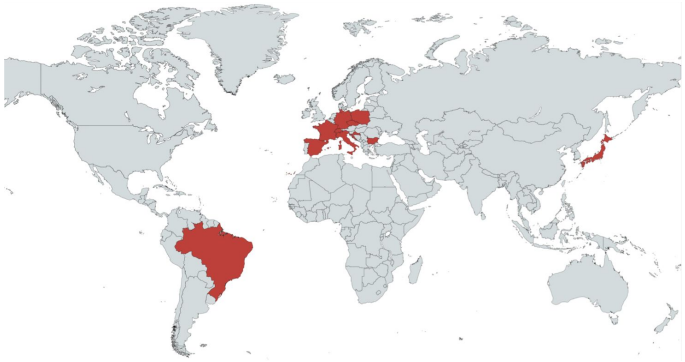
Pol Bordas
on behalf of the CTAO/LST coll.

ICCUB Institut de Ciències del Cosmos
EXCELENCIA MARÍA DE MAEZTU
UNIVERSITAT DE BARCELONA
IEEC Institut d'Estudis Espacials de Catalunya

OUTLINE

- LST-1: the first CTAO prototype
- LST-1 view on variable Galactic sources
  - Pulsars: Crab, Geminga
  - mangetars: SGR 1035
  - Novae: RS Oph, T CrB
  - SNe explosions
- Perspectives
  - MAGIC + LST-1
  - LST array

The Large-Sized Telescope Collaboration

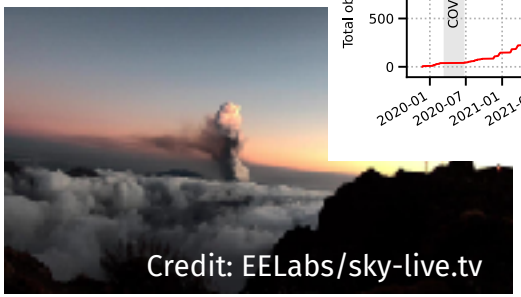


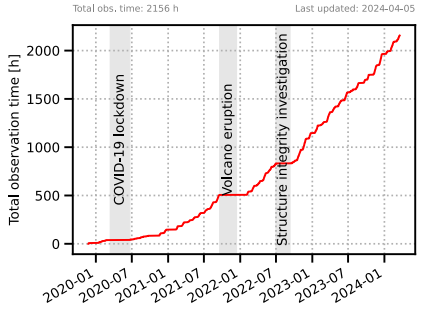
- **> 330 scientists** in 11 countries
- Development and building of
  - **4 LSTs on CTA North site**
  - **2+ LSTs on CTA South site**
- Learn more: https://www.cta-observatory.org/project/technology/lst/

3

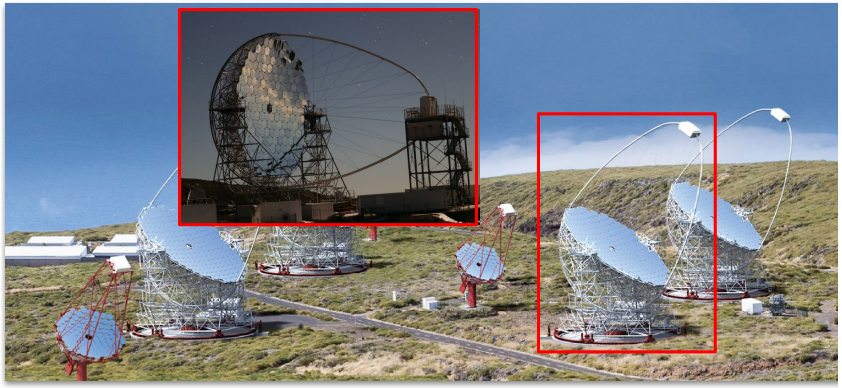
The LST-1 Prototype

- LST-1 inaugurated in October 2018
- Until ~mid 2022 mostly in commissioning phase, with some slowing down: COVID-19 (2020), Volcano eruption (2021)
- Regular Observations Cycles starting on 2023, Now in Cycle 3
- >2400 h of observations (commissioning/science) taken from Jan. 2020 - June 2024)



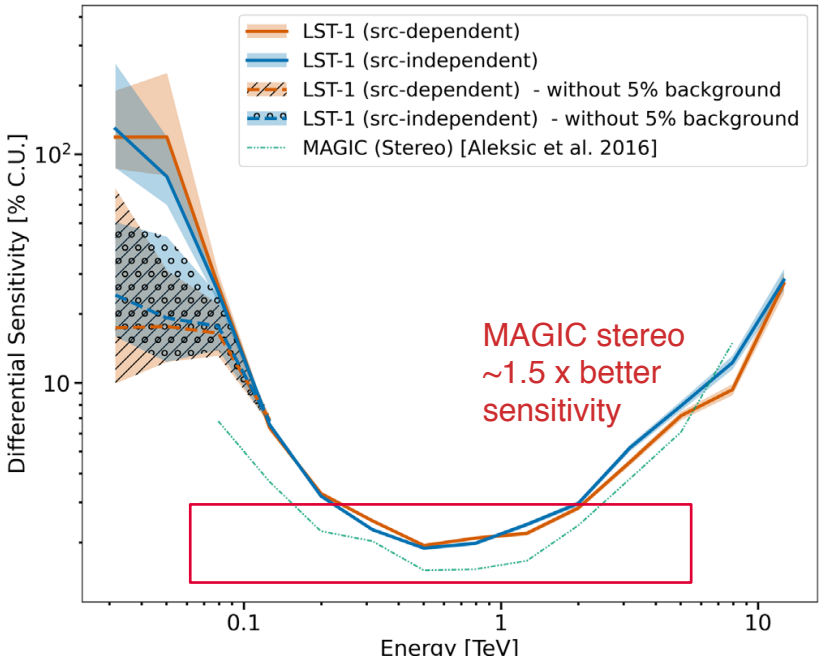


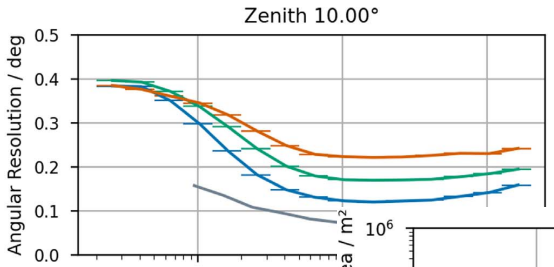
The LST-1 Prototype

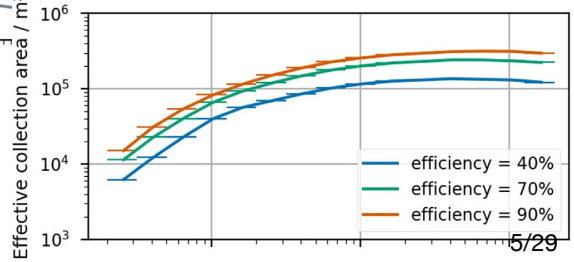


- Alt-Azimuth mount, with a **parabolic mirror** of **23m diameter**
- Camera:**1855 PMTs**, wide **FoV ~ 4.3°**
- Focal length: 28 m, **Eff. Area ~370 m2**

- **Low E_{th}** (down to **~20 GeV**)
- **Large eff. area** at multi-GeV range (**~ 10^4 x Fermi-LAT @ ~ minutes timescales**)
- **Fast slewing capabilities** (~20 s/ 180 in azimuth; weight ~100 tons)

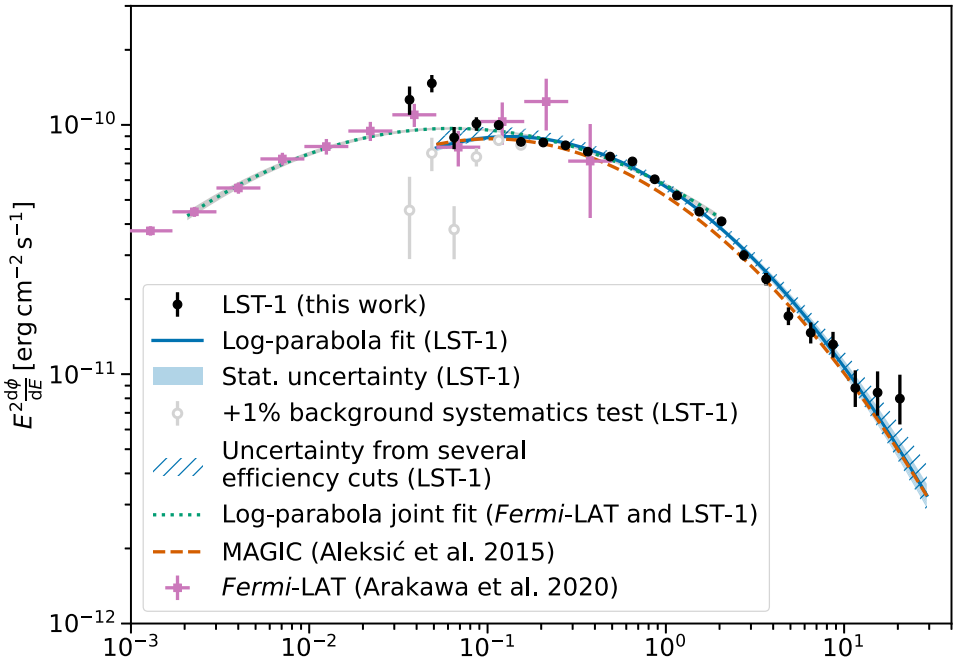


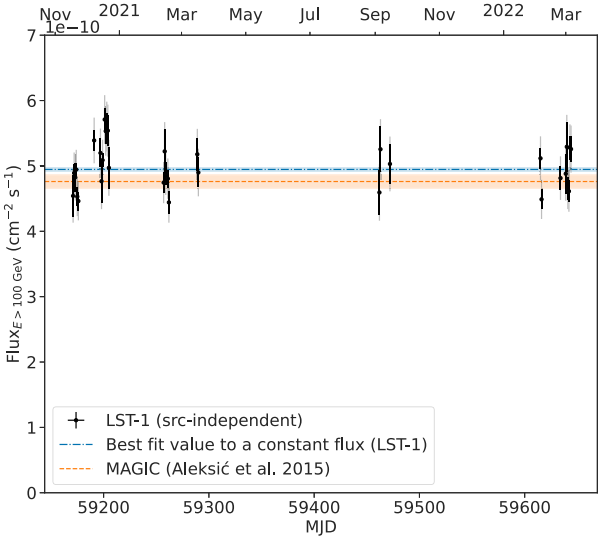




Abe et al. 2023a

The LST-1 Performance





Abe et al. 2023a

- "LST-1 performance paper" (Abe et al. 2023): **Crab Nebula** observations (~34h) taken during commissioning phase to evaluate LST-1 performance
- Angular resolution: 0°.12–0°.40, E-resolution: 15%–50%. Flux sensitivity around 1.1% of the Crab Nebula flux at E > 250 GeV (50h obs; 12% for 30min)
- Able to measure the nebula SED **down to 30 GeV.** Systematics from bkg begin to **dominate below 50 GeV**

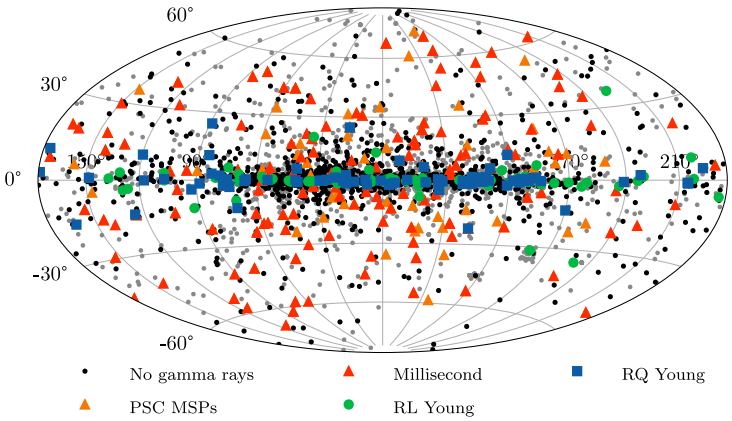
The LST-1 view on Variable Galactic sources

Credit: IAC

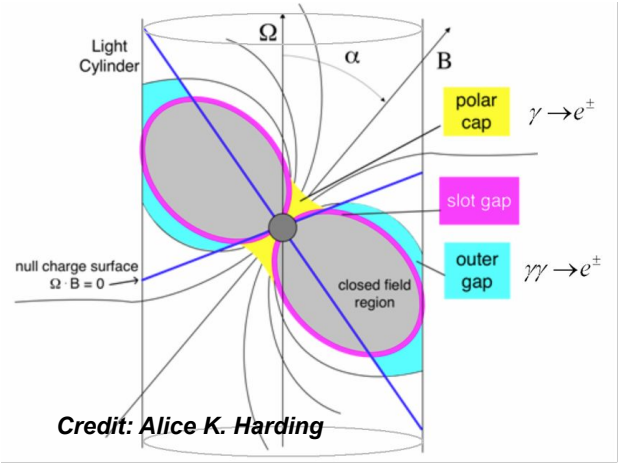
Pulsars at VHEs wit the LST-1

- About 330 PSRs detected with Fermi-LAT, spectra displaying a characteristic PL + Exp. cutoff at a few GeV
- **5 PSRs detected so far with IACTs**: The Crab (MAGIC, VERITAS), Vela (H.E.S.S.), Geminga (MAGIC), and PSR B1706 (4.7-sigma, H.E.S.S.). Also detection of PSR J1509-5850 recently claimed (H.E.S.S.)
- IACT's PSR spectra show a spectral tail extending up to 100 x GeV's and even to the TeV regime (Crab, Vela). Origin of VHEs in PSRs is still not clear (e.g "polar cap", "slot gap"or "outer gap" models)
- Are these 5 systems "unique", or there is a whole TeV PSR population to be detected?

3rd Fermi-LAT PSR catalogue



Smith et al. 2023



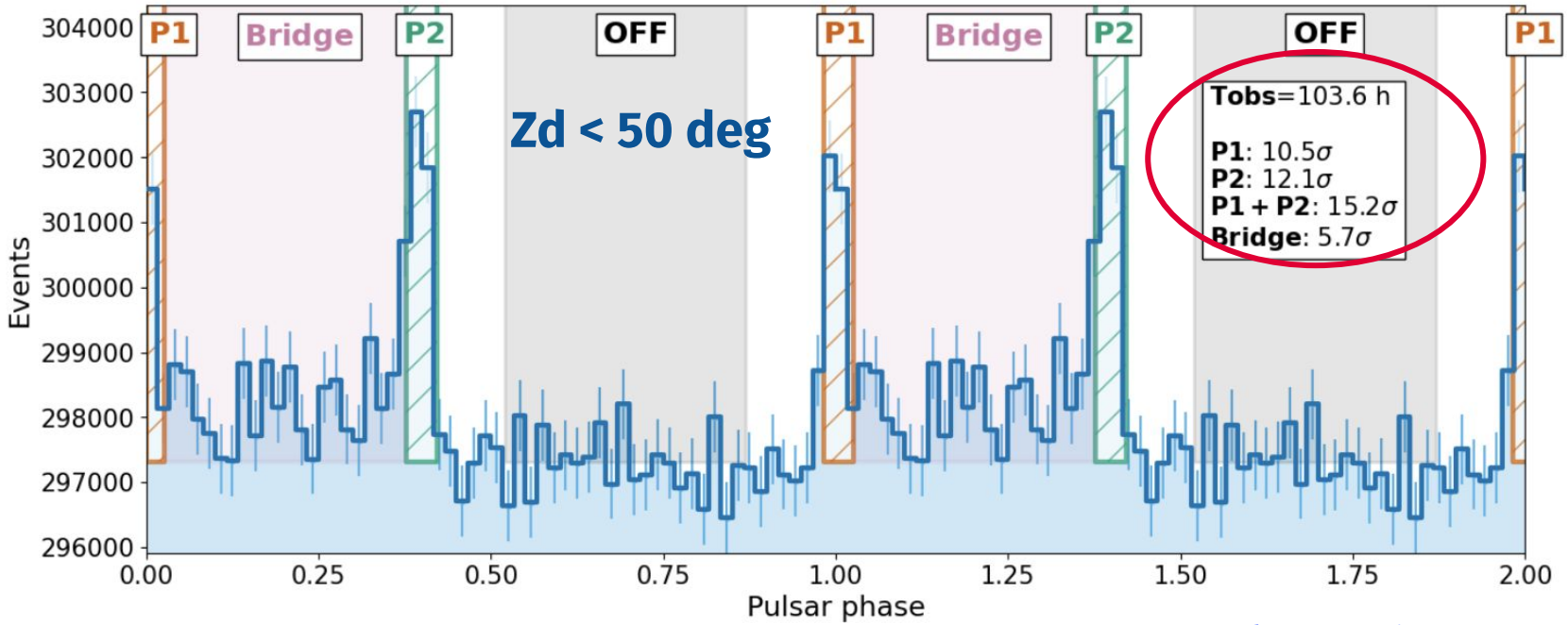
Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab

- Observed during LST-1 commissioning (Sep. 2020 - Jan. 2023)
- Time after quality cuts: ~103h for Zd < 50deg

P1 + P2 detected at >15σ in 100h

Similar to MAGIC Sumtrigger-II but with only one telescope!

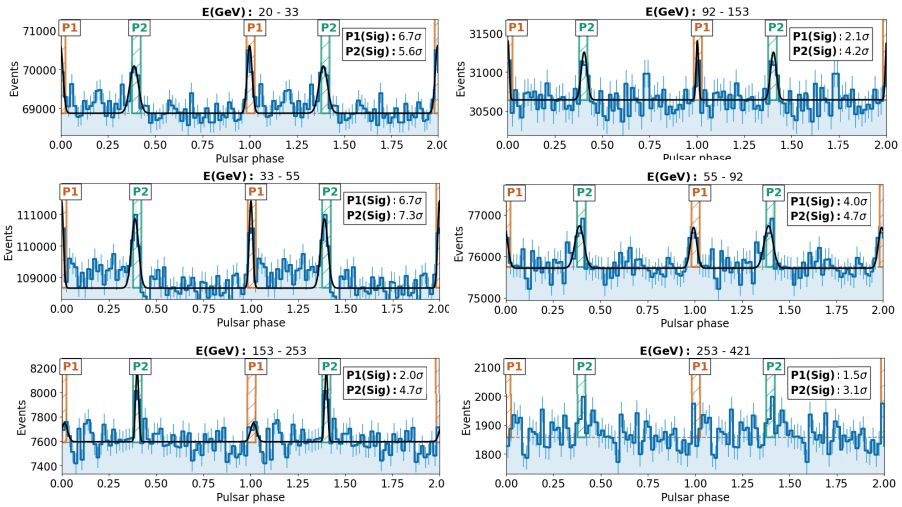


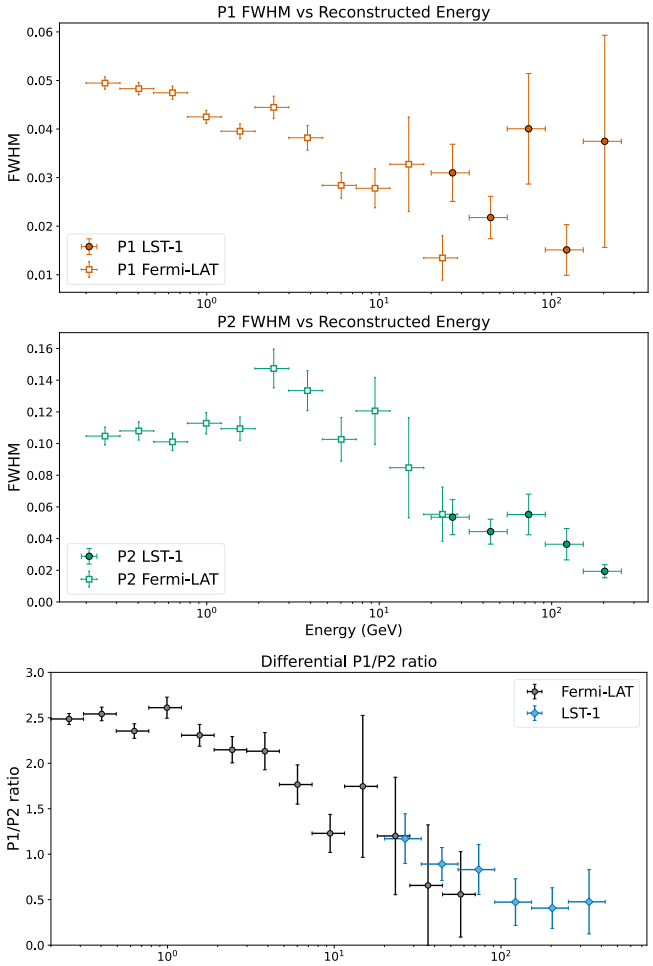
Abe et al. 2024

Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab + 14 yrs Fermi-LAT

- Peak location **does not change significantly** with increasing energy (20 - 700 GeVs)
- P1/P2 ratio declines up to 100 GeV, remains constant (P1/P2 ~0.5) at > 100 GeV



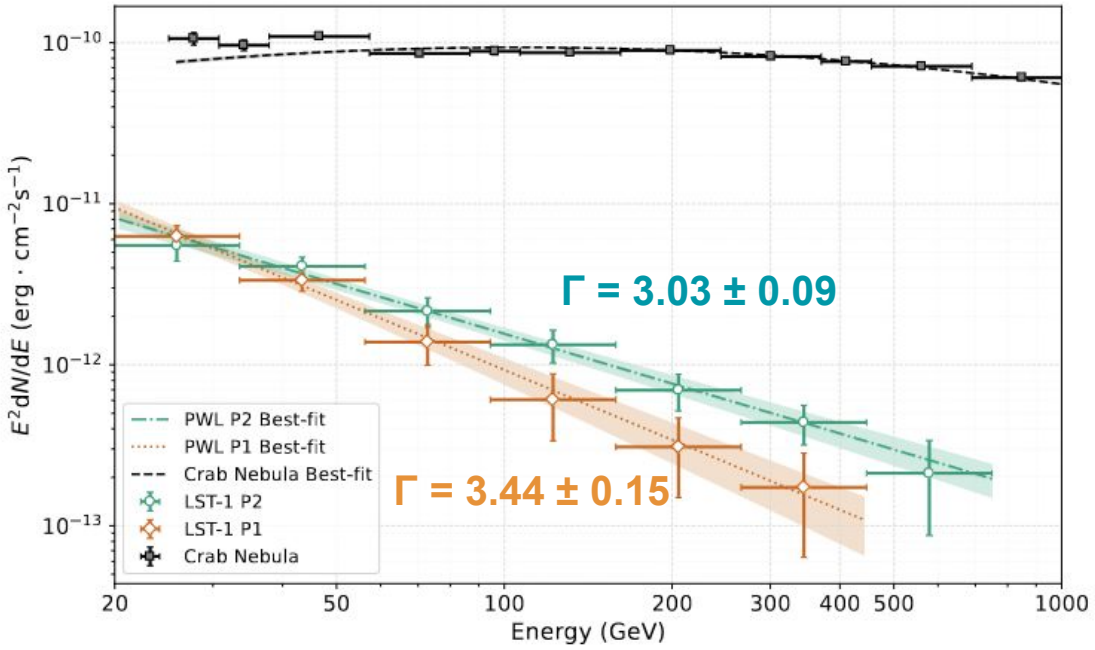


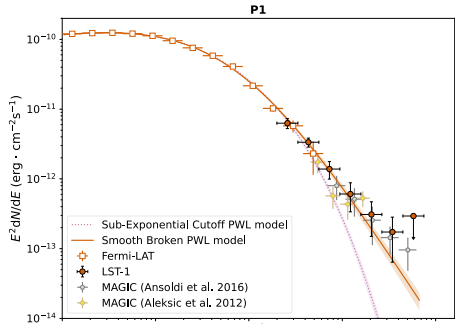
[Abe et al. 2024]

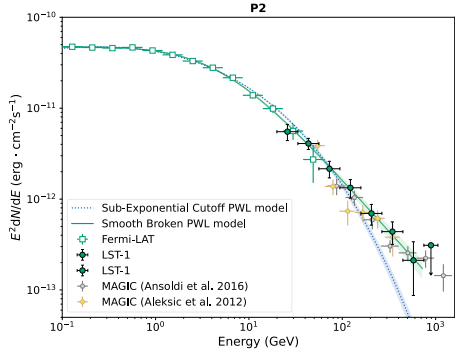
Pulsars at VHEs wit the LST-1

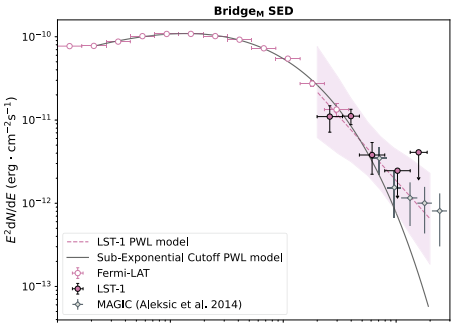
LST-1 observations of the Crab + 14 yrs Fermi-LAT

- LST-1 peaks' SED fit: PL models up to 450 GeV (P1) and 700 GeV (P2). P2 significantly harder (Γ= 3.03 ± 0.1) than P1 (Γ= 3.44 ± 0.15)
- LST-1 + Fermi-LAT SED: SmoothBrokenPL preferred over PL + SubExp cutoff (AIC and BIC tests)







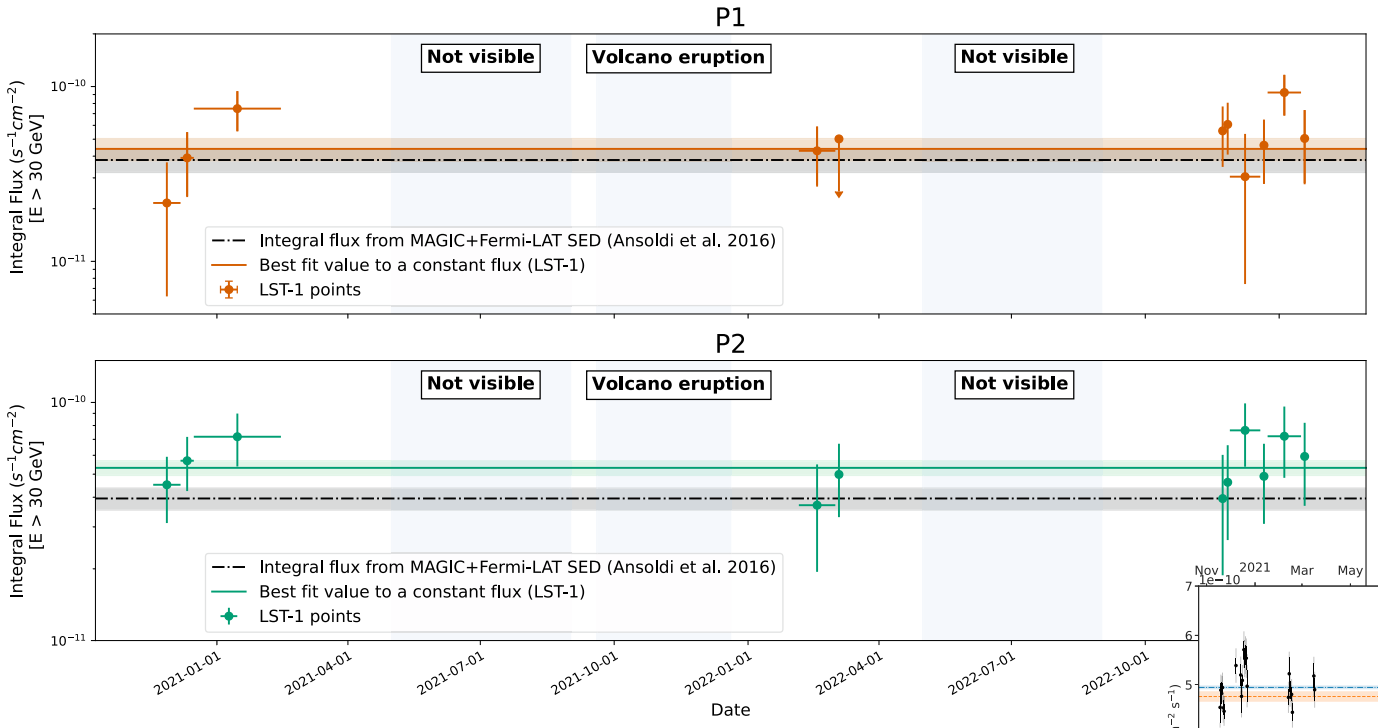


Abe et al. 2024

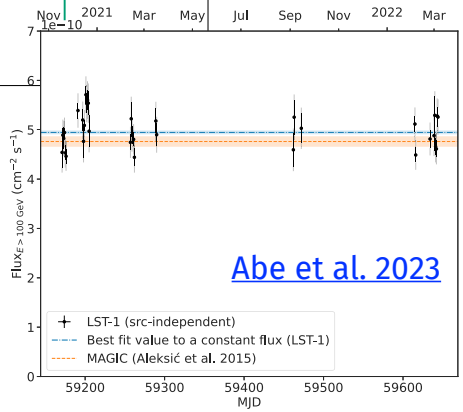
Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab: light-curve

- Search for variability in P1 and P2 peaks in the LST-1 data sample



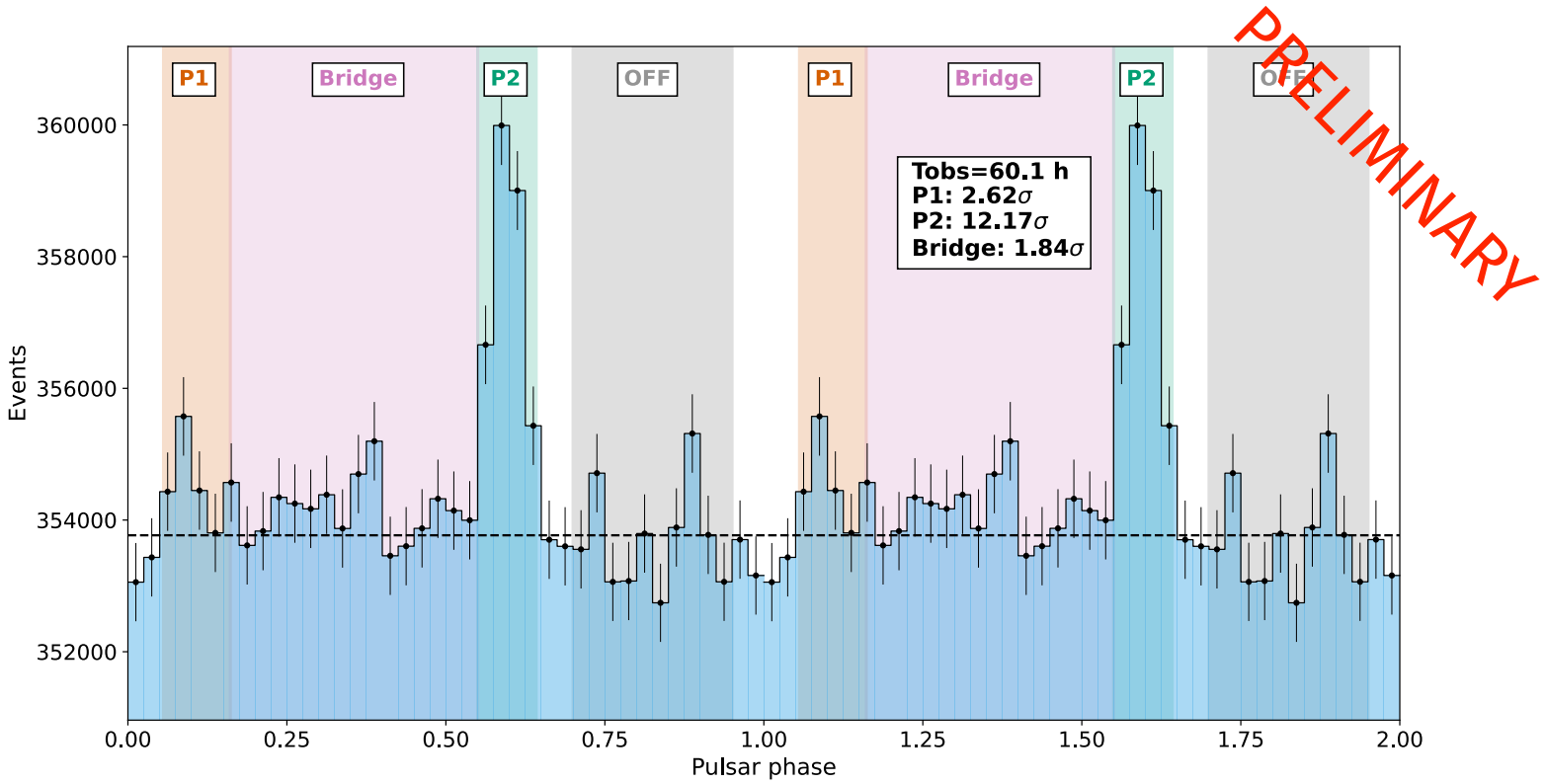
Abe et al. 2024



Pulsars at VHEs wit the LST-1

LST-1 observations of Geminga

- Second PSR observed with the LST-1 (Dec. 2022 - March 2023)
- Time after quality cuts: ~60h for Zd < 50deg

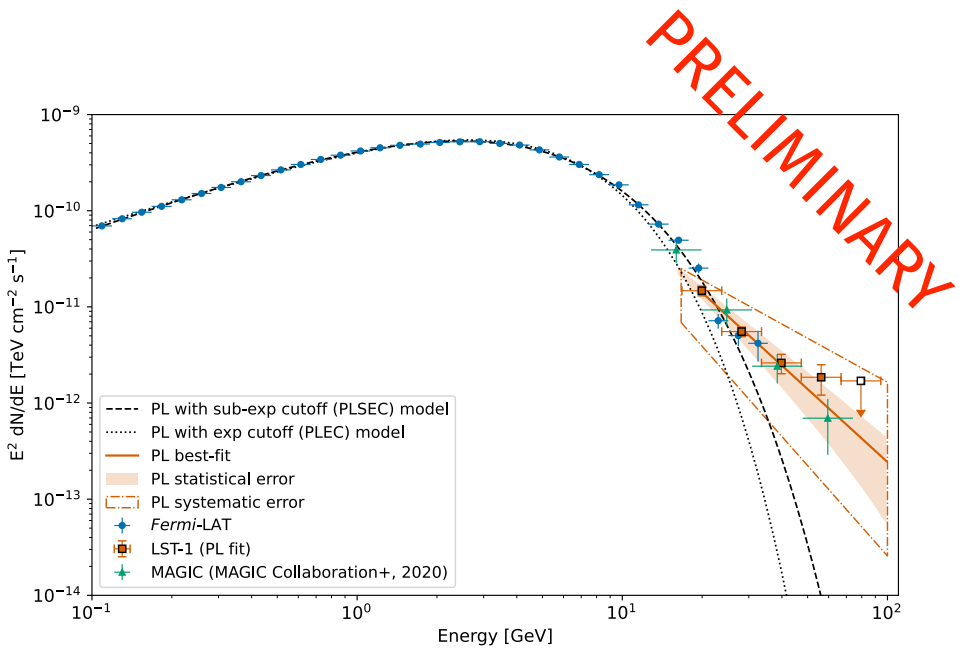


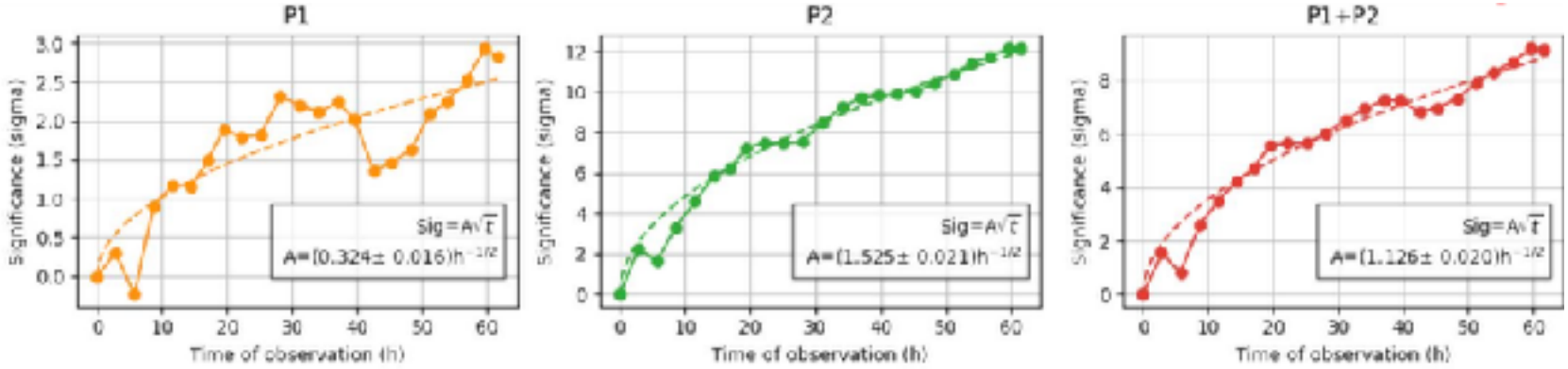
Abe et al. 2025a, submitted

Pulsars at VHEs wit the LST-1

LST-1 observations of Geminga

- Demonstrates LST-1 capabilities for PSR studies: LST-1 P2 detected at > 12σ in 60h *vs* MAGIC: 6.3σ in 80h
- P1 remains undetected, (2.6σ hint => 200h of LST-1 observations required for a 5σ signal, 30h with the full LST array)
- No E-dependent evolution within [15 - 31] and [31, 65] GeV bands





LST-1 view on Galactic Transients

- A dedicated Galactic ToO Program has been set since 2023, in which the trigger conditions to observe a number of Galactic Transients is defined:

  - Novae explosions: the first nova @ VHEs, RS Oph, detected with LST-1, prompting for the discovery of more recurrent symbiotic novae and to detect for the first time, classical novae. Trigger based on *Fermi*-LAT and/or bright optical novae (mag <7)

  - Microquasars: Variable gamma-ray emission detected in Cyg X-1, Cyg X-3 and SS 433 (surroundings) at HEs. Hint of Cyg X-1 flare detection at VHEs by MAGIC. LST-1 will trigger on other MQs that show non-thermal transient emission, based on Fermi-LAT or radio/X-ray alerts

  - gamma-ray binaries: gamma-ray binaries display periodic emission. However, they can show also energetic outbursts, connected to clumps, interactions with circumstellar disc of the star, e.g. in LS I +61 303, HESS J0632+057 or the flares seen periodically in PSR B1259-63

LST-1 view on Galactic Transients

- Magnetars: in 2020 a FRB was associated with a known source: SGR 1935+2154. Magnetars can display different kinds of outburst, which might lead to VHE emission. *LST-1* aims at discovering for the first time VHE emission from a magnetar, triggering on external radio, X-ray or *Fermi*-LAT alerts.

- Supernovae: SNe are among the most violent events in the Galaxy. LST-1 will trigger on Type II SNe (collapse of a massive star), in nearby SNe, ideally at <3 Mpc, and on those with neutrino alerts. No VHE counterparts to SNe to date

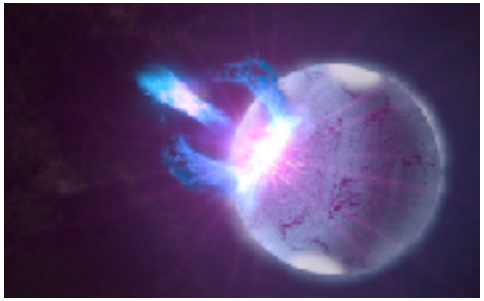
- Flares from PWNe: the Crab Nebula has been proven to emit flaring emission in the HE regime. However, no variability has been yet reported at VHEs. LST1 will closely follow these flares at low energies, aiming at catching the synchroton tail for these flares

- Stellar superlares: Some M-dwarf stars have been found to emit superflares in hard X-rays. LST-1 ToO program includes observations of superflares of young and nearby M-dwarf stars, as reported by X-ray satellites

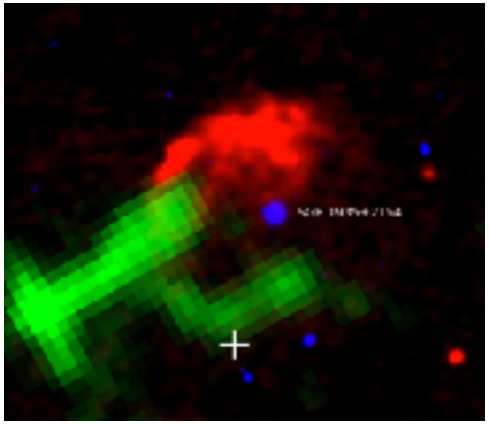
LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

- SGR 1935 is a Galactic Magnetar in the SNR G57.2+0.8 with Soft Gamma Repeater activity (typically observed at hard X-rays)
- In April 28th 2020 a burst was reported in coincidence with a FRB from SGR 1935: FRBs can be producedby magnetars !
- UULLs on persistent emission for SGR 1935 during high-activity periods: at GeVs with LAT (Li et al. 2017, and at VHEs with H.E.S.S. (Abdalla+ 2011)
- No reports yet for short-term bursts @ VHEs



Bursts from a magnetar, artist's conception; Credits: NASA's Goddard Space Flight Center



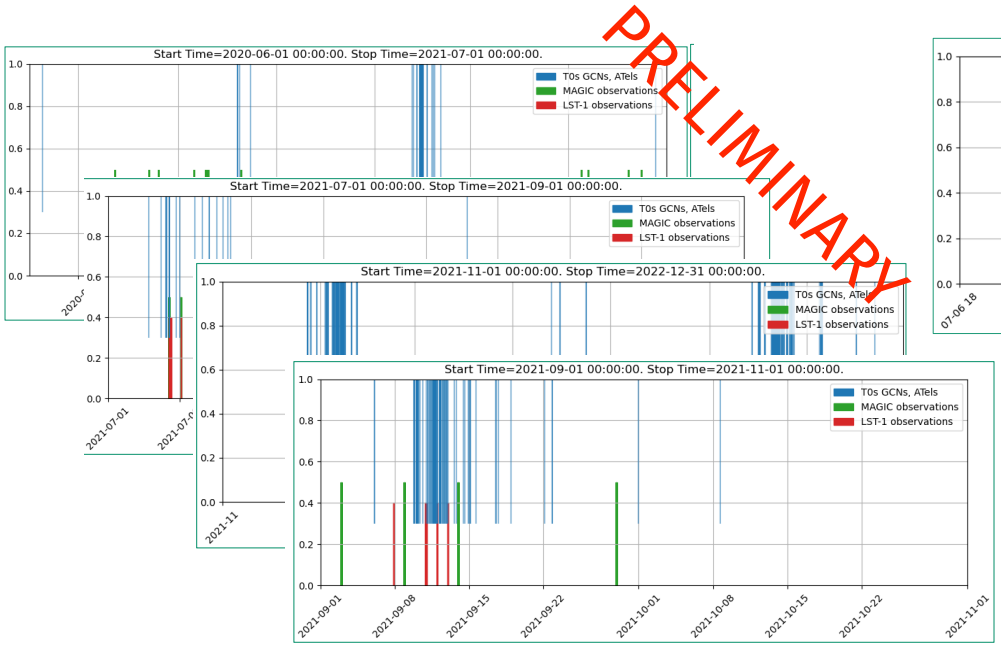
Composite image of SNR G57.2+0.8 (red, radio band), SGR 1935 (blue source in the center), and nearby molecular clouds (green), from Zhou et al. 2020)

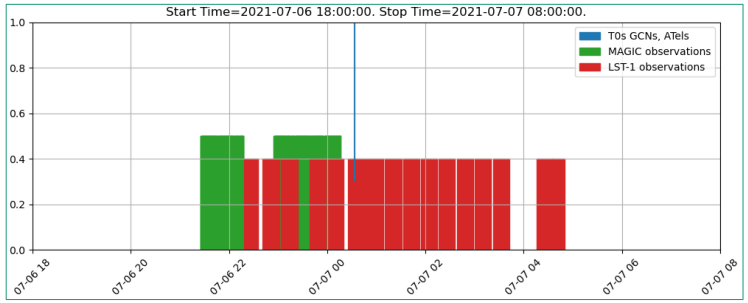
LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

- About 40h (25h after quality cuts) on SGR 1935 taken with the LST-1 in 2021 and 2022
- Joint campaign with MAGIC (which collected >100h from 2020 - 2022)
- MWL coverage:
  - Retrieved contemporaneous bursts listed in ATels, GCN's etc.
  - > 150 alerts from June 2020 to December 2022

Abe et al. 2025b, submitted



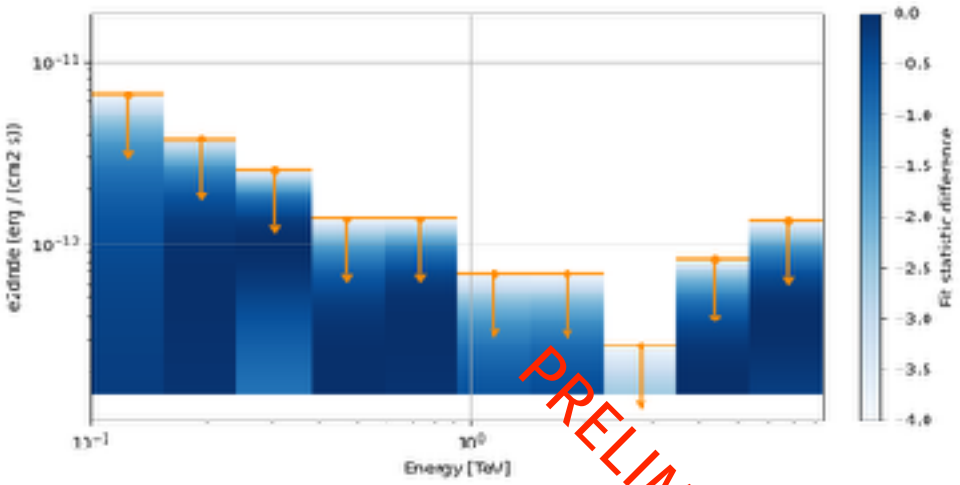


9 X-ray bursts coincident with LST-1 observations

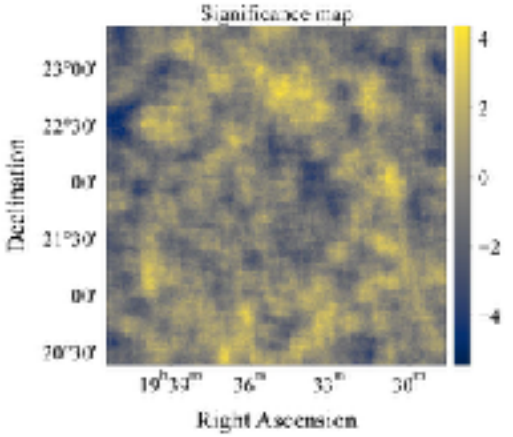
LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

Search for persistent emission

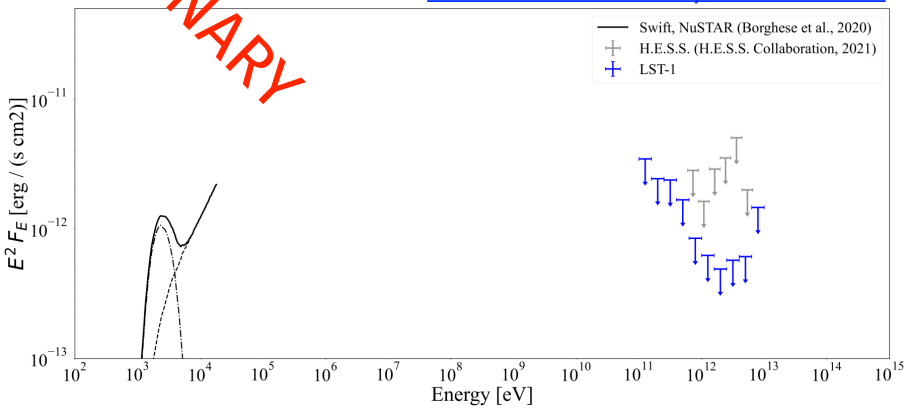


PRELIMINARY



- No significant signal for the steady emission from SGR 1935
- UULLs placed for the whole data and on a nightly basis (13 nights)
- LST-1 UULL: 2.4e-12 erg/cm2/s (at E> 0.1 TeV), or about 2 to 5 times lower than previous results (Abdalla+ 2011)

Abe et al. 2025b, submitted



LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

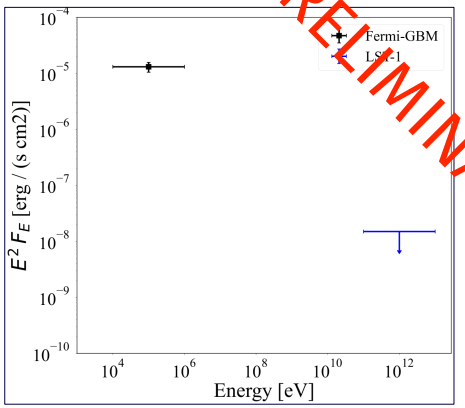
Search for Bursts at VHEs

- Analysis **optimised for the search of 0.1 s duration bursts** in a low-photon statistics regime, assuming Poisson BKG statistics
- **9 contemporaneous X-ray bursts** => LST-1 UULL: 1.6e-9 erg/cm2/s (at E> 0.1 TeV)
- Blind aearch for 0.1s bursts (no hard X-rays) in the whole (25h) LST data set (+ trials O(10^6)). No significant detection => UULL: 4.5e-9 erg/cm2/s (at E> 0.1 TeV)
-

PRELIMINARY

#	Time of Alert ISOT UTC	Instrument	LST-1 R_{BKG} s^{-1}	$N_{5\sigma}$	N_{ON}	Flux UL $10^{-8} s^{-1} cm^{-2}$	Fluence UL 10^{-9} $erg\ cm^{-2}$
1	2021-07-07 00:33:31.670	Fermi-GBM	0.81±0.02	4	0	2.01	1.50
2	2021-09-10 23:40:34.460	Fermi-GBM	1.05±0.03	4	0	1.95	1.45
3	2021-09-11 22:51:41.600	GECAM	0.95±0.03	4	0	2.03	1.51
4	2021-09-11 23:55:45.872	NICER	1.01±0.03	4	0	1.94	1.45
5	2021-09-12 00:34:37.450	GECAM	0.61±0.03	4	0	1.97	1.47
6	2021-09-12 00:45:49.400	GECAM	0.66±0.03	4	0	1.96	1.46
7	2021-09-12 22:16:36.200	GECAM	0.68±0.02	4	1	3.61	2.69
8	2021-09-12 23:19:32.080	Fermi-GBM	1.04±0.03	4	0	2.02	1.51
9	2021-09-13 00:27:25.200	GECAM	1.04±0.03	4	0	1.95	1.45
	STACKED $\delta t = 0.9s$		0.87±0.04	8	1	0.30	0.20

PRELIMINARY

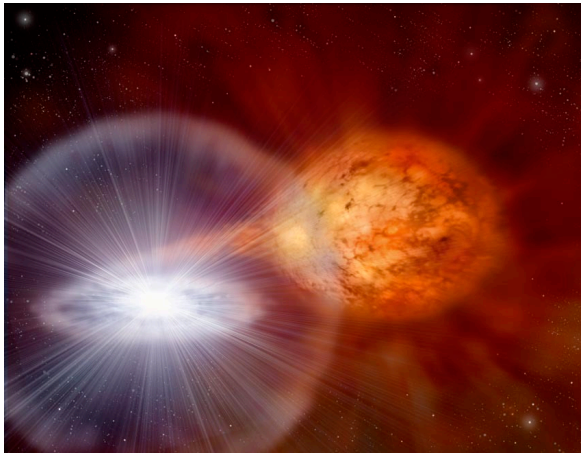


Abe et al. 2025b, submitted

Novae at VHEs wit the LST-1

LST-1 observations of RS Ophiuchi

- RS Oph: symbiotic binary composed of a white dwarf + red giant star. d~2.45 kpc
- Recurrent nova outbursts every ~15 yrs
- August 2021: first nova ever detected at VHE gamma-rays (MAGIC, H.E.S.S.)
- LST-1 also observed and detected RS Oph



Credit: David A.Hardy/ www.astroart.org & PPARC.

Date (YYYY-MM-DD)	T-T0 (days)	Zenith range (deg)	Transmission 9km (%)	Observation time (h)
2021-08-09	0.97	36-43	> 90	1.43
2021-08-10	1.97	36-60	> 90	2.68
2021-08-12	3.97	36-56	> 90	2.24
2021-08-13	4.99	37-55	15 - 90	
2021-08-14	5.97	36-46	65	
2021-08-15	7.03	42-57	55	
2021-08-29	21.01	46-59	> 80	0.97
2021-08-30	21.97	40-58	> 80	1.52
2021-09-01	24.05	57-65	> 90	0.32
2021-09-02	24.98	42-58	> 90	1.27

Right after outburst

Bad atmospheric transmission

After moon break

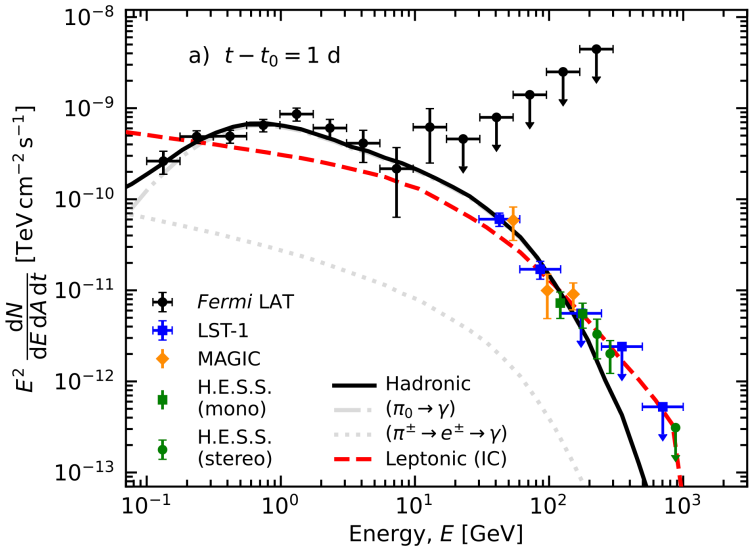
Abe et al. 2025

Novae at VHEs wit the LST-1

LST-1 observations of RS Ophiuchi

- Gamma-ray emission modelled in an hadronic and a leptonic scenario
- retrieve spectra of injected particles (using LST-1, MAGIC, H.E.S.S. and LAT)
- hadronic model preferred (AIC_{had} = 95.6, AIC_{lep} = 128.8)

Dataset	Obs. day 1	Obs. day 2	Obs. day 3
Hadronic modelling			
Slope, Γ_p	-2.2 ± 0.02	-2.24 ± 0.03	-2.49 ± 0.05
$E_{c,p}$ (GeV)	246 ± 51	404 ± 89	1709 ± 571
χ^2/d.o.f	18.3/15	32.7/20	26.6/15
Hadronic modelling with systematics			
Slope, Γ_p	-2.16 ± 0.05	-2.32 ± 0.11	-2.4 ± 0.03
$E_{c,p}$ (GeV)	228 ± 39	480 ± 151	1032 ± 257
LST-1 syst.	4.5	-2.3	-2.7
MAGIC syst.	3.1	7.8	12.3
H.E.S.S. syst.	-2.9	-3.9	-10.7
χ^2/d.o.f	17.3/12	20.4/17	19.3/12
Leptonic modelling			
Slope 1, $\Gamma_{e,1}$	-2.41 ± 0.08	-2.01 ± 0.07	-1.27 ± 0.28
Slope 2, $\Gamma_{e,2}$	-3.48 ± 0.01	-3.95 ± 0.03	-3.51 ± 0.12
$E_{b,e}$ (GeV)	30 ± 1	39 ± 1	21 ± 4
χ^2/d.o.f	56.2/14	24.2/19	24.4/14



Abe et al. 2025

Novae at VHEs wit the LST-1

LST-1 observations of RS Ophiuchi

- Gamma-ray emission modelled in an hadronic and a leptonic scenario
- retrieve spectra of injected particles (using LST-1, MAGIC, H.E.S.S. and LAT)

"VHE gamma-ray novae: RS Oph modelling & CTAO perspectives"

Arnau Aguasca-Cabot talk later today

χ^2/d.o.f	18.3/15	32.7/20	26.6/15
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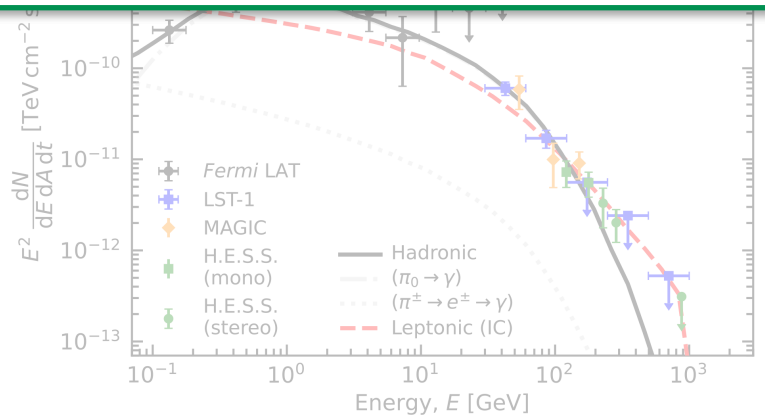


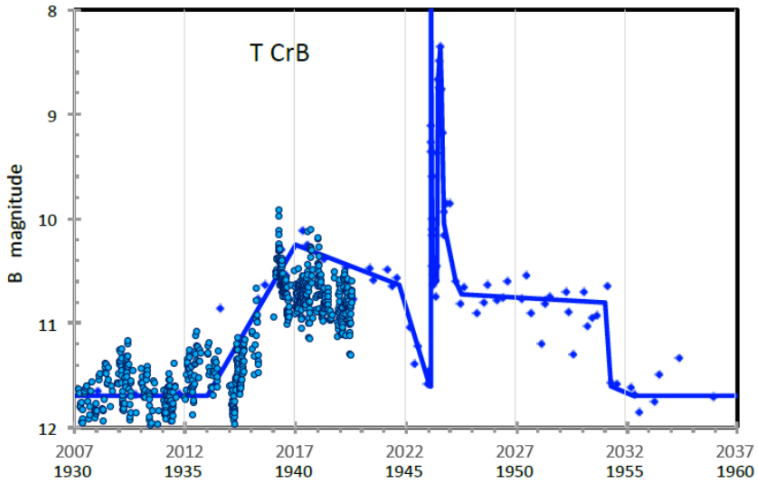
Abe et al. 2025

Novae at VHEs wit the LST-1

Next nova: T CrB

- Recurrent nova located ~3x closer => 9 times brighter than RS Oph;
- RG and WD about 2x closer, enhancing particle interactions
- showing same behaviour now as in previous eruption in 1946
- LST-1 + MAGIC + XMM + NuSTAR + CAHA + Liverpool + IXPE + ...
- predictions by Schaefer et al. already passed (2024.4 ± 0.3)
- Recent enhancement of accretion activity (ATel #17030, ATel #17052)

Parameter	RS Oph	T CrB
Shock Speed	~4000 km/s	~4500 km/s
Distance	2.69 kpc	0.91 kpc
Peak Magnitude (V band)	~5	~2
Binary Seperation	2 au	1 au
Time between bursts	~15 years	~80 years

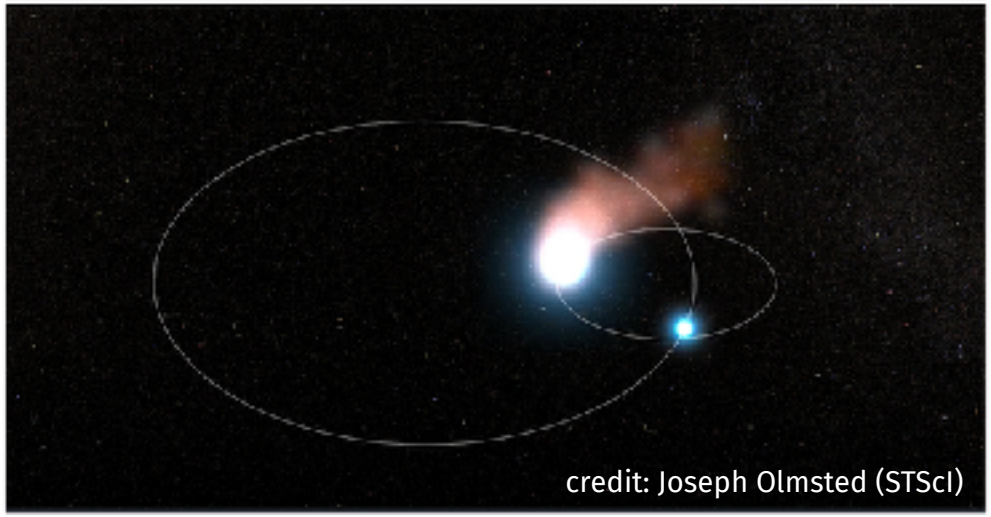


adapted from Schaefer (2019)

CWB at VHEs wit the LST-1

Observations of WR 140

- Colliding Wind binary system (CWB) composed by a O4–5 $30M_{sun}$ star + bright Wolf-Rayet $10M_{sun}$ sta located at 1.67 kpc, with an **orbital period of ~8 yrs**
- Radio detection of several systems, but strong X-ray emission reported in WR 140 and eta Carinae, the latter displayint TeV emission (H.E.S.S. coll 2020)
- Periastron passage of 2024 covered intensively with MAGIC+LST
- Data analysis in progress...



LST Galactic ToO Program

LST-1 observations of SN 2023 ixf

- Type II Core-collapse SN discovered on May 17th 2023.
- Mag 14.9 => SN 2023ixf the second brightest SN after SN 1987A
- Located in M101, with redshift = 0.000804 => distance ~6.4 Mpc => closest core-collapse SN (type II) in the last decades
- LST-1 observations joint with MAGIC starting on May 20th 2023, lasting for about 1 month, ~**20h of LST data** after quality cuts. Follow-up campaign covering the **rise**, **peak** and **plateau state** of the optical LC

MAGIC and LST1 observations

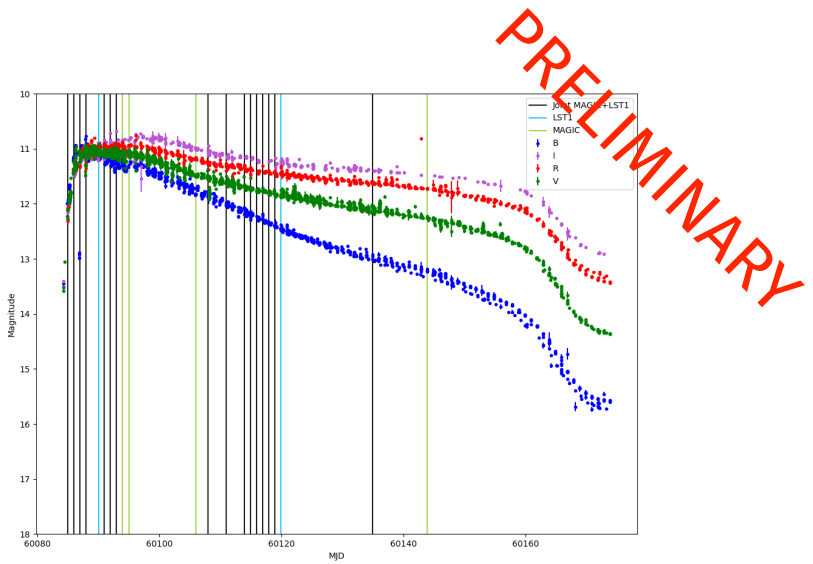
	joint	LST-1 only	MAGIC only
Time	41.6h	3.7h	15.3h

dark NSB (extra_dim_in_noise_pixel <3.5)

	joint	LST-1 only	MAGIC only
Time	33.7h	3.1h	5.5h

moon NSB (extra_dim_in_noise_pixel >3.5)

	joint	LST-1 only	MAGIC only
Time	7.9h	0.6	9.8h



Summary

LST potential on Variable Galactic Gamma-ray Sources

- **LST capabilities for PSR studies**
  - Sensitivity and low-E threshold (~20 GeV) ideal for studying PSRs @ VHEs. Crab and Geminga already detected with LST-1
- **LST observations of Galactic Transients**
  - Nova RS Oph: first galactic transient detected with LST-1
  - LST-1 limits on short-term bursts from magnetar SGR 1935+2154
  - ToO program including SNe explosions, flares from MQs, Gamma-ray Binaries, PWN flares, stellar flares...

Summary

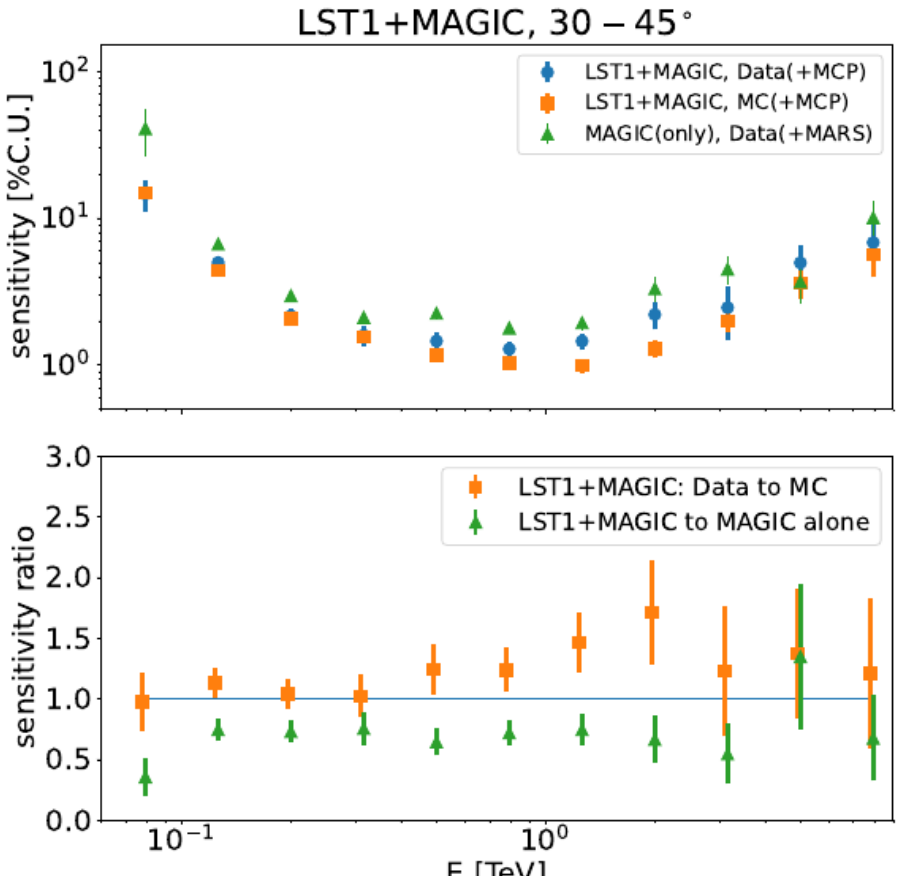
LST potential on Variable Galactic Gamma-ray Sources

- LST capabilities for PSR studies: low-E threshold (~20 GeV) ideal for studying PSRs @ VHEs. Crab and Geminga already detected with LST-1
- Nova RS Oph: first galactic transient detected with LST-1. MWL campaign on T CrB, including LST-1. Perspectives for detection of classical novae at VHEs
- LST-1 limits on short-term bursts from transients magnetar-like emission, e.g. in SGR 1935+2154
- ToO program including follow-up observations of SNe explosions, flares from MQs, Gamma-ray Binaries, PWN flares, stellar flares...

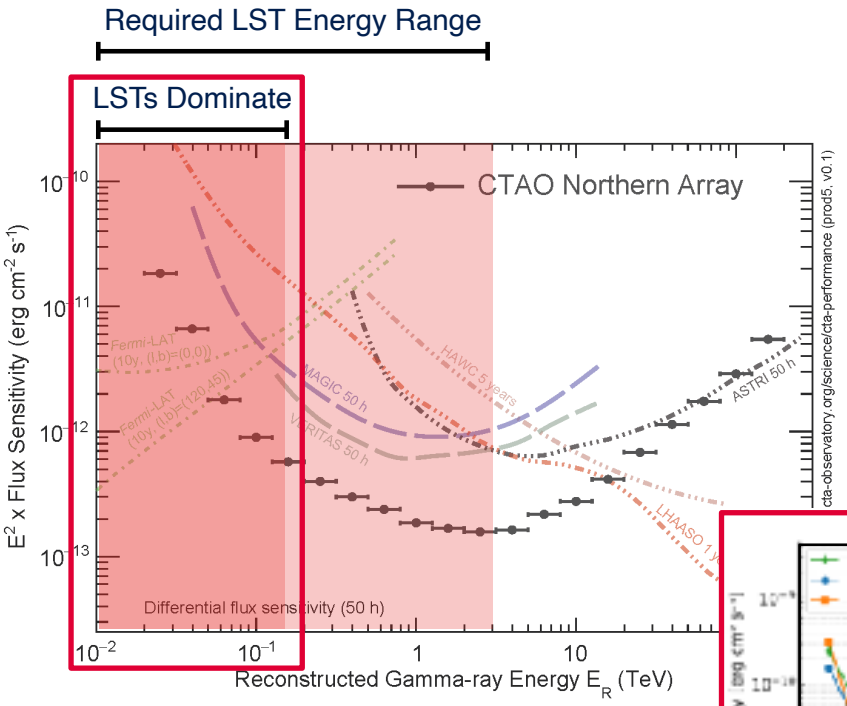
Perspectives I: LST+MAGIC

Joint LST-1 and MAGIC observations

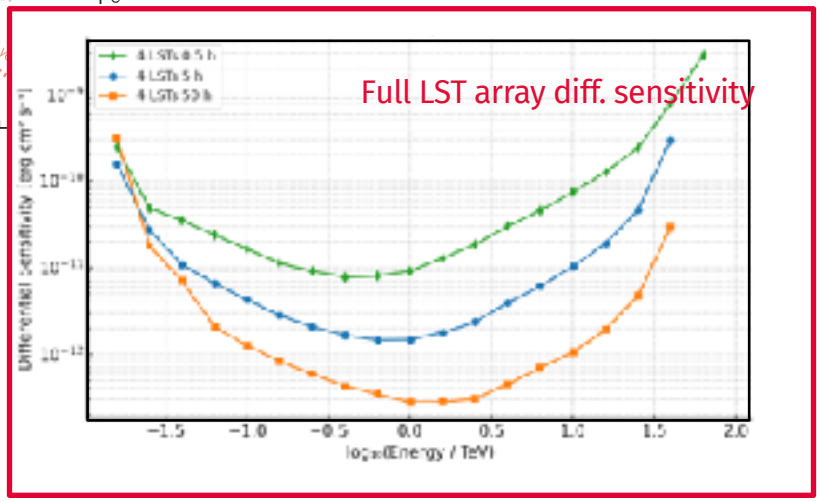
- MAGIC + LST-1 feagure a better performance than working separately
  - **detection of 30% (40%) lower flux** than MAGIC- alone (LST-1-alone).
- **Dedicated analysis tools**: processing of MAGIC and LST-1 as a single instrument
- **Joint Scientific Program** with a joint TAC scheme, scheduling, ToOs.. since current LST Cycle 3 and MAGIC Cycle
- Dedicated F2F Science and A&R meetings and collaboration between different Physics Working Groups being settled



Perspectives II: 4 LSTs



- **LST 2-4 construction progressing rather rapidly!**
  - LST2-4 commissioning in short succession in 2025-2026
- **Transition to CTAO** in the short-term future (> 2027?...)



Thanks

credit: CTA Consortium, Akihiro Ikeshita

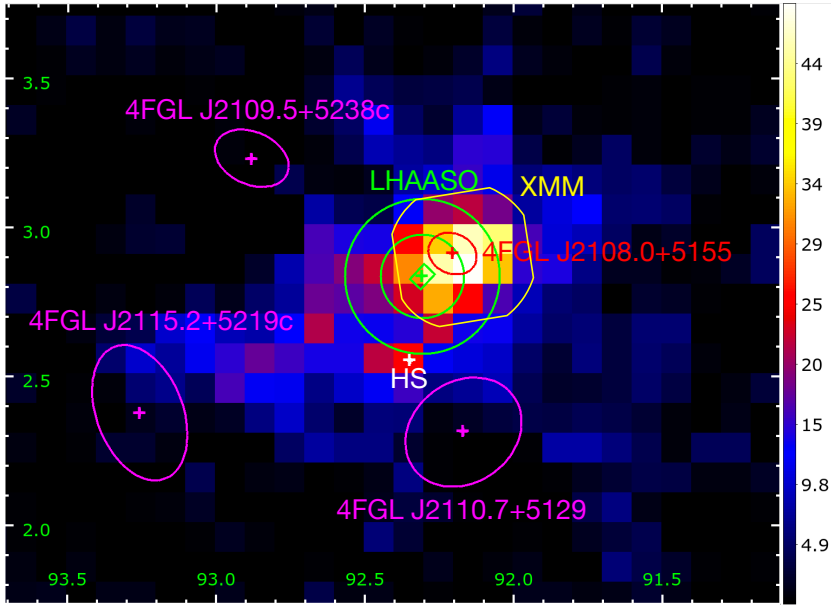
Backup

PeVatron candidates with LST-1

LST-1 observations of LHAASO J2108+5157

- First scientific publication by the LST-1 Collaboration (Abe et al. 2023)

- LHAASO J2108 is one of the first 12 UHE (E > 100 TeV) sources detected by LHAASO, and the only one without any associated counterpart at TeVs
- LST-1 data set: 91h taken from June to Sept. 2022 => 50h after quality cuts selection
- Dedicated *Fermi*-LAT analysis using ~12 yrs of data and the 12-year 4FGL-DR3 catalog
- Obtained XMM-*Newton* dedicated observations on the source for about 14 ksec
-

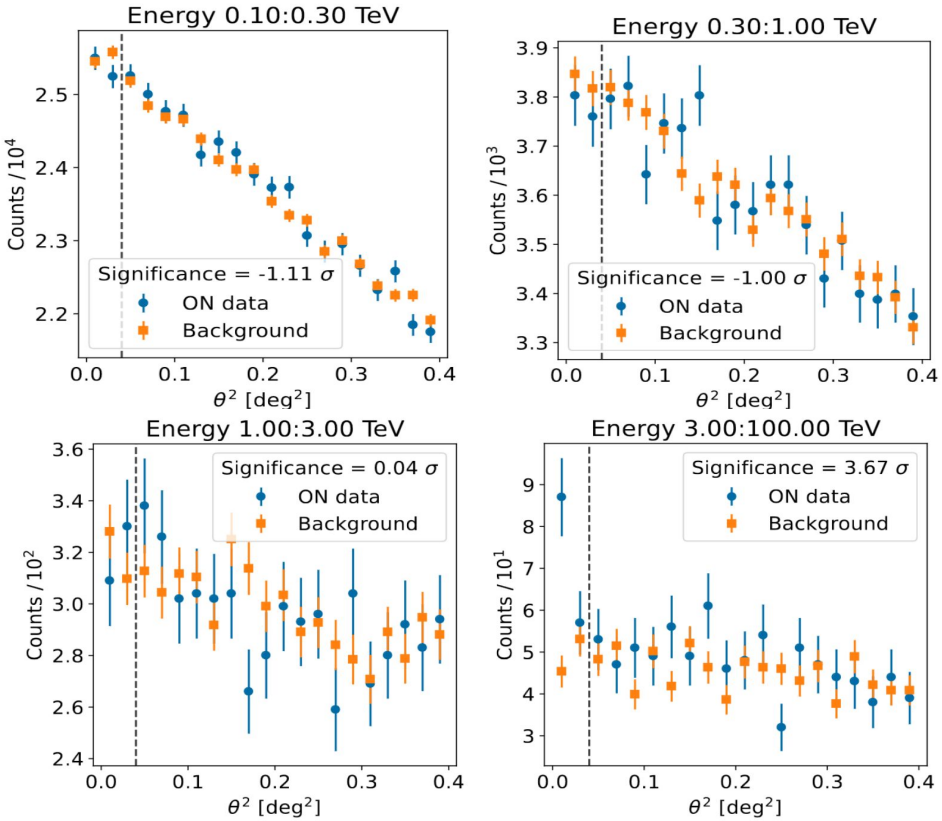


Abe et al. (CTA-LST collaboration) 2023

PeVatron candidates with LST-1

LST-1 observations of LHAASO J2108+5157

- LST-1 analysis yields a hint for an excess (3.7σ) in at E > 3 TeV.
- When the whole E-range is considered, a signal at 2.2σ is found (assuming point-like source morphology)
- Analysis of XMM data does not yield to any significant detection either, assuming extended emission around the SNR or associated PWN
- Fermi-LAT: soft emission from 4FGL J2108.0+5155, displaying a typical cutoff spectrum of GeV PSRs, no hints for extended emission

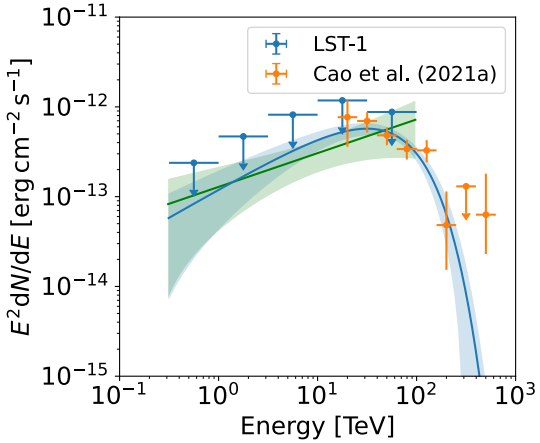


Abe et al. (CTA-LST collaboration) 2023

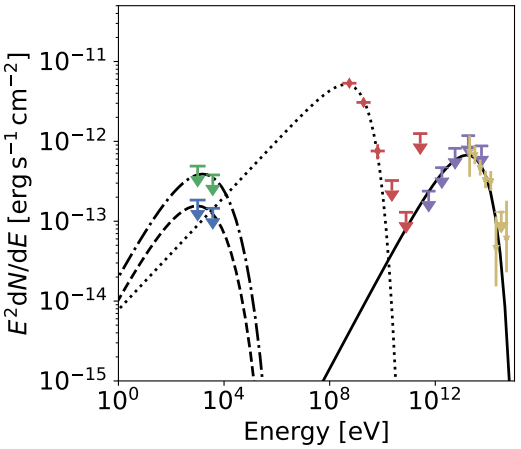
PeVatron candidates with LST-1

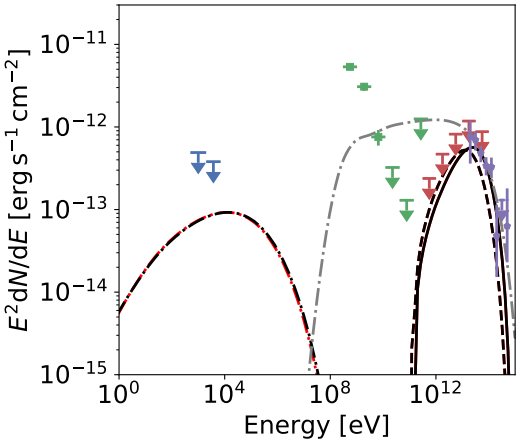
LST-1 observations of LHAASO J2108+5157

- Both leptonic (IC) and hadronic (pp interactions in nearby MCs) considered



- The LST-1 and LHAASO observations can be explained as IC emission by relativistic electrons with a cutoff energy of 100+70 TeV.
- The low magnetic field in the source imposed by the X-ray upper limits on synchrotron emission is compatible with PWN / TeV halo, but no PSR detected





- UHE emission and LST hint of hard spectrum could work in a hadronic scenario (protons from middle-aged SNR + MC interaction), but then the HE counterpart may not be related?

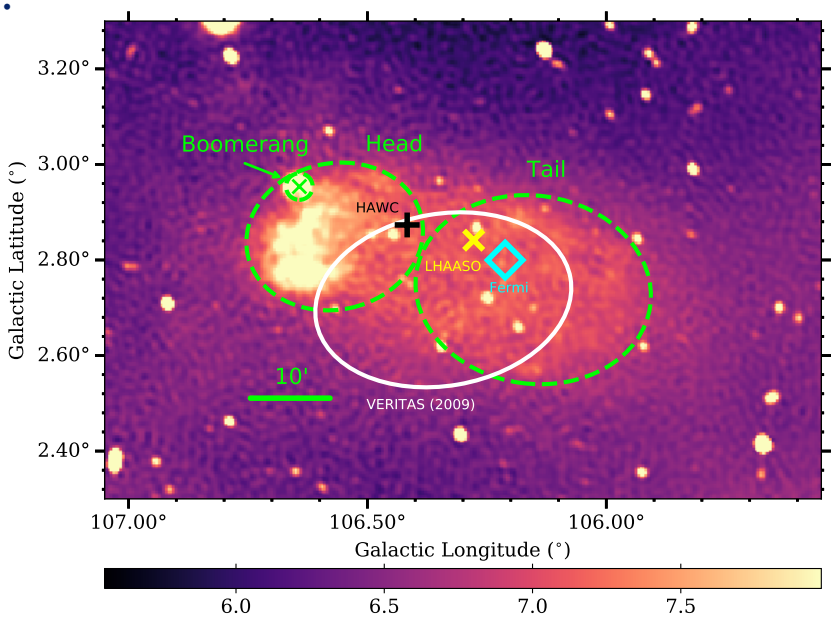
Abe et al. (CTA-LST collaboration) 2023

PeVatron candidates with LST-1

LST-1 observations of G106.3 + 2.0 (Boomerang SNR)

See dedicated talk F. Cassol

- Gamma-ray emission has been observed in the SNR G106.3+2.7 region from GeV up to few hundreds of TeV energy range.
- GeV emission coincident with PSR J2229+6114 (also pulsations; Abdo+ 2019), which was also associated with EGRET source 3EG J2227+6122 (Hartman et al. 1999)
- VHE emission from the tail region (VER J2227+608; Acciari et al. 2009), as well as from the head region (MAGIC, Oka et al. 2021).

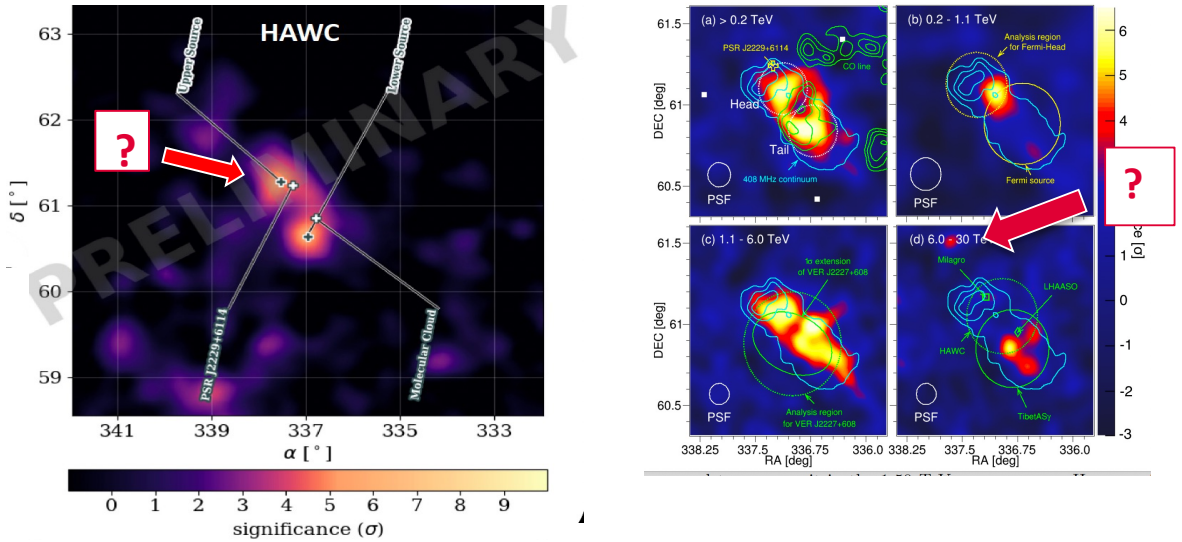


Pope et al. (NuSTAR & VERITAS coll.) 2023

PeVatron candidates with LST-1

LST-1 observations of G106.3 + 2.0 (Boomerang SNR)

- Emission at E > 100 TeV detected by HAWC, Tibet ASγ, and LHAASO, coincident with the VERITAS and Fermi-LAT tail region source
- LST-1 large zenith angle observations on G106.3+2.7 to better constrain its morphology and spectral properties
- VHE and UHE emission origin: leptonic (PWN?) or hadronic (SNR + MC interaction)?

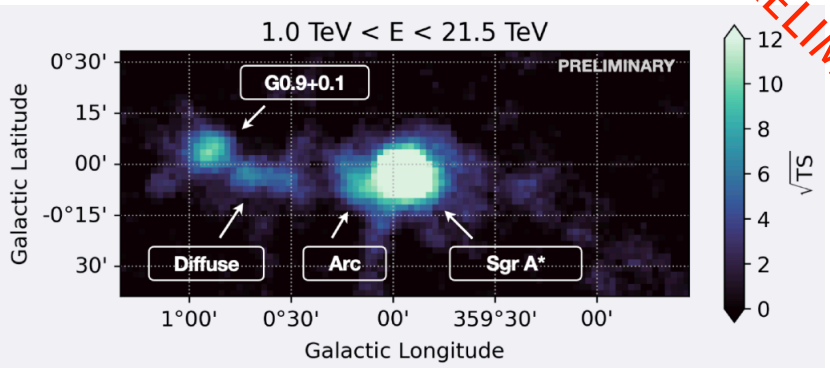


Adapted from Saito et al. (Gamma-Ray Symposium 2022); courtesy of F. Cassol

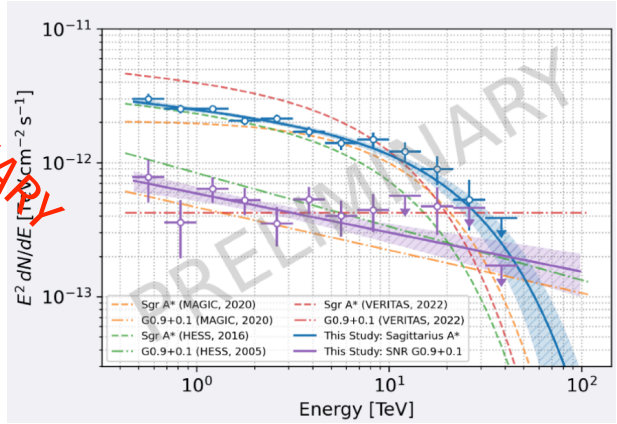
PeVatron candidates with LST-1

Galactic Center

- LST-1 has observed the Galactic Center, the first proposed Galactic PeVatron (H.E.S.S. Collaboration 2016)
- LST-1 obserations taken at LZA in 2021 - 2023, for a total of about 40h, using wobble observations at 0.5 and 0.7 deg offset.
- Analysis is being carried on using the standard analysis software lstchain, as well as dedicated (in development) background modelling
- Joint campaign with MAGIC



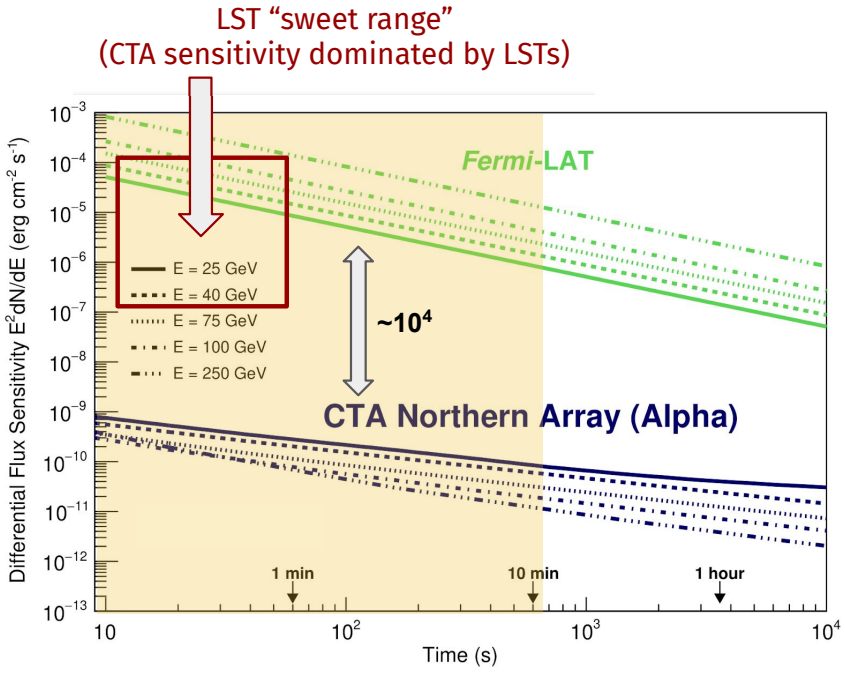
PRELIMINARY



from Abe et al. (ICRC 2023)

LST as a PSRs and Transients Machine

- LST will dominate CTAO sensitivity below ~150 GeV
- Low E-threshold (~20 GeV), large Aeff, fast repositioning…
- Ideal instrument for fast transients and spectrally soft sources



- LST-1: the first CTAO prototype
- LST-1 view on variable Galactic sources
    - Pulsars: Crab, Geminga
    - mangetars: SGR 1035
    - Novae: RS Oph, others/T CrB
    - SNe explosions
- Perspectives
    - MAGIC + LST-1
    - LST array