cherenkov telescope array

LST-Galactic Science

1st VHEGAM meeting, Bologna, 15/01/2024

Pol Bordas

ICCUB

IEEC

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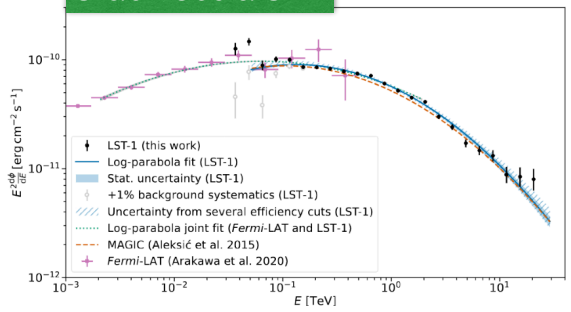
The LST-1 prototype

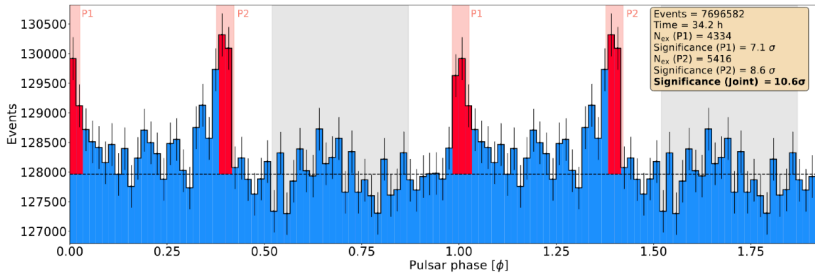
- LST is the Large-sized Telescope, a part of the Cherenkov Telescope Array Observatory (CTAO), the facility for Very High Energy gamma-ray astrophysics in the next decades
- LST-1 inaugurated in 2018, with >1400 h of observation taken from Jan. 2020 - June 2023 during its commissioning
- LST-1 performance paper already out (CTA-LST Project, Abe et al. 2023), demonstrating the unique capabilities of the instrument

Credits: Tomohiro Inada

Crab nebula SED



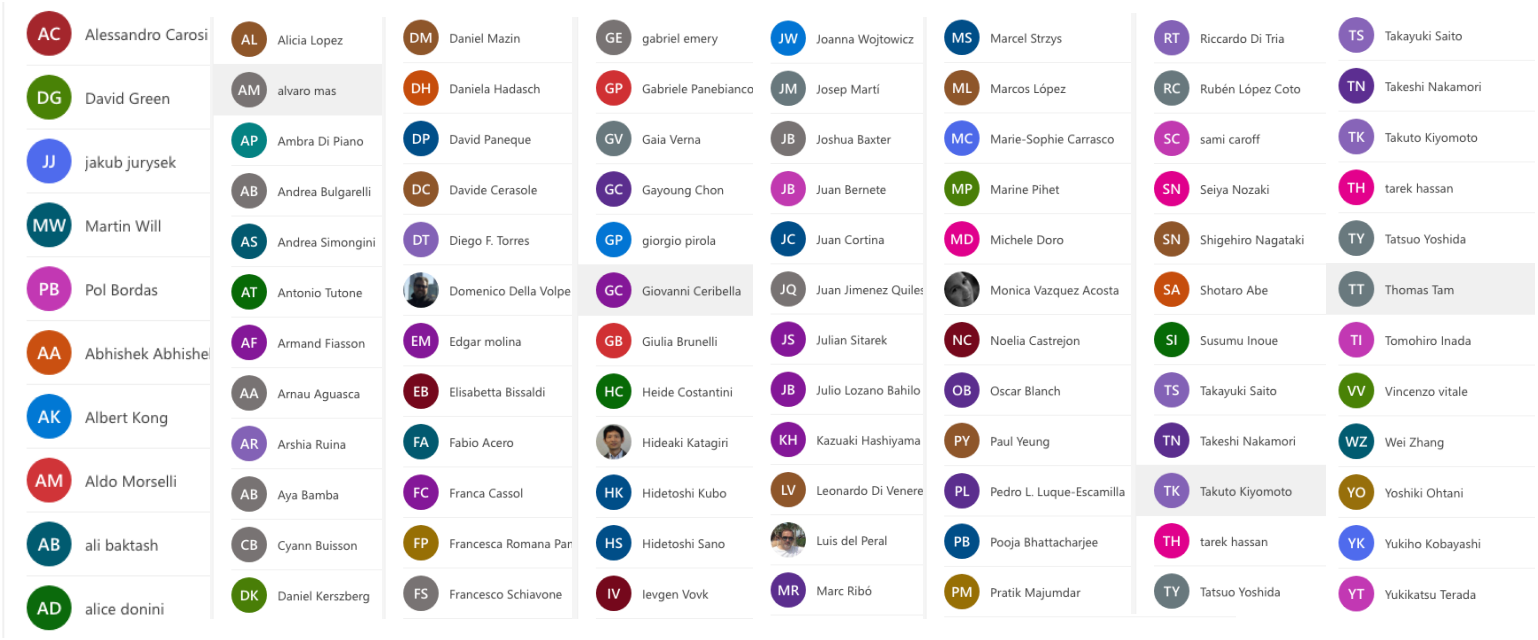
Crab pulsar phaseogram



CTA-LST Project, Abe et al. (2023). Adapted from Mazin+ (ICRC 2023)

LST Galactic Working Group

- Currently about 89 members in the group (caveat: taken from mailing list)
- Despite significant fraction is “involved" we need more humanpower !



LST Galactic WG projects

Contents [hide]

mailing lists & Slack channels
(including GAL transients)

LST-GAL meetings
regular telecons + links to
other/any GAL-related meetings

Ongoing Projects section
with summary & links to
dedicated TG wikis

LST-GAL Publications
both accepted papers
and conference contributions

New projects to come
data available for yet ~unexplored
novae, γBs, μQs, PSRs, XRBs, PWNe

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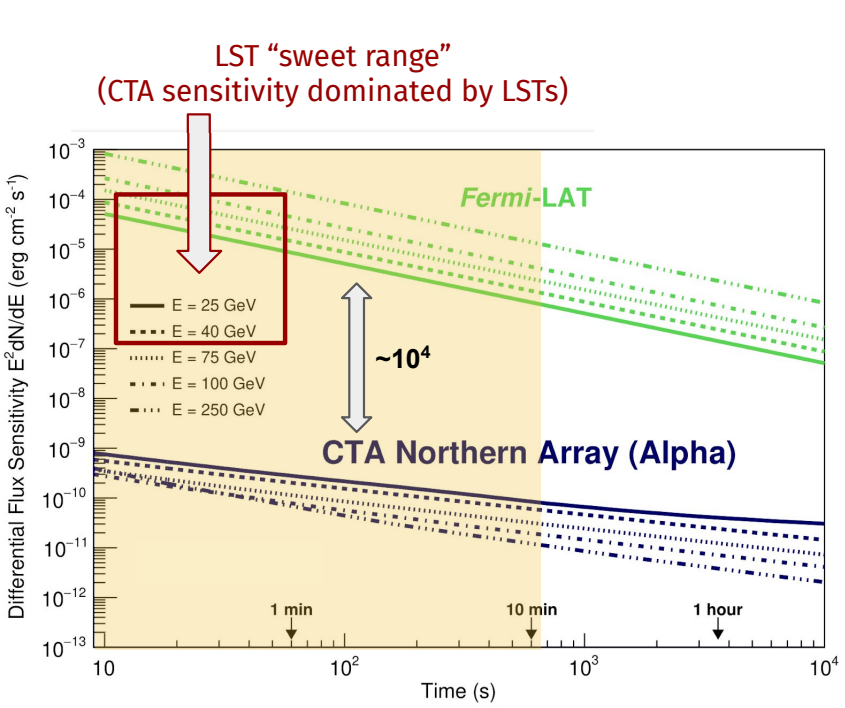
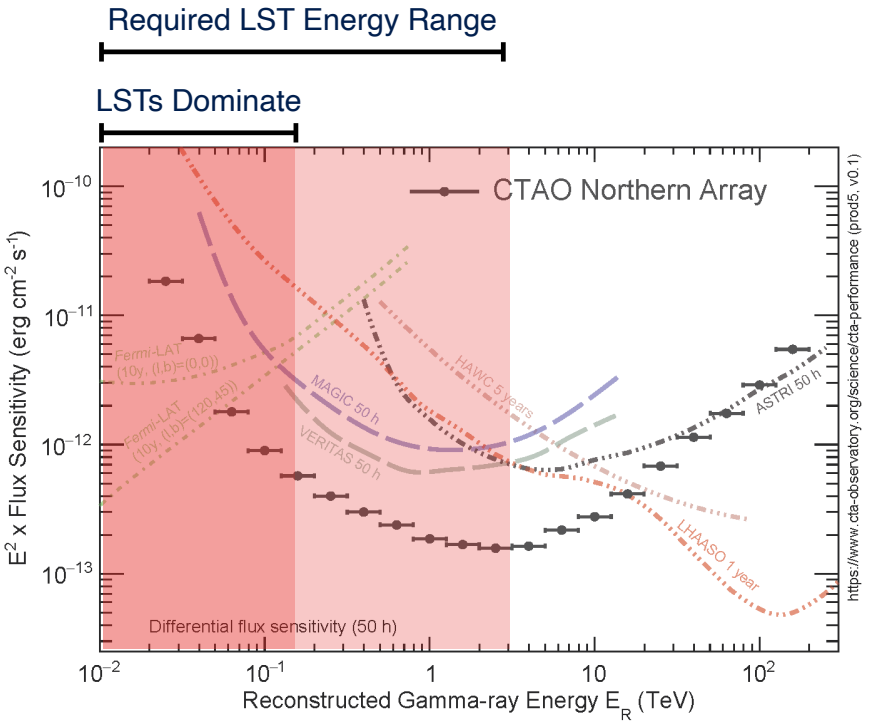
New projects to come

Cycle II coming soon

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



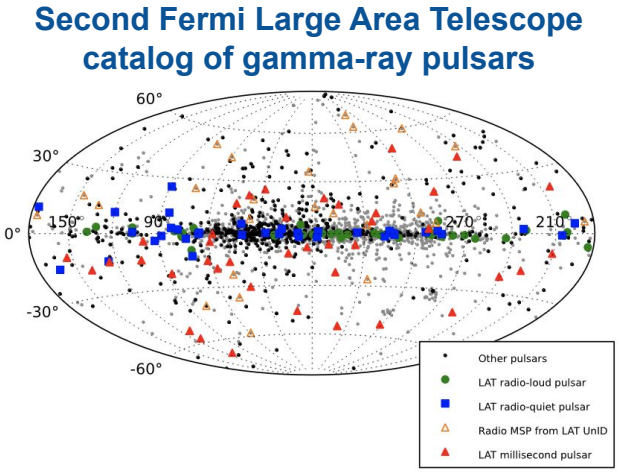


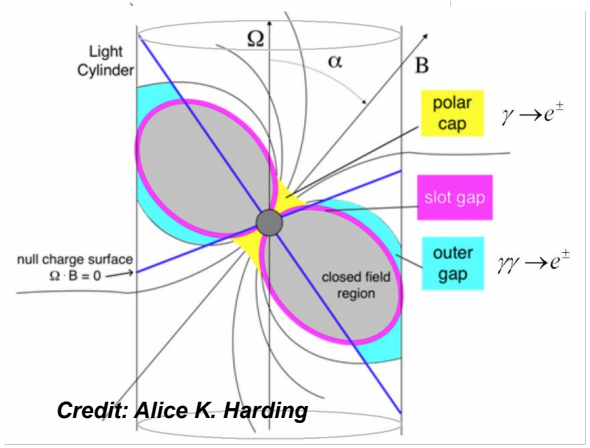
Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab and Geminga PSRs

See dedicated talk by G. Brunelli

- About 300 PSRs detected with *Fermi*-LAT, spectra displaying a characteristic PL + Exp. cutoff at a few GeV
- A few of them deviate from this Exp. cutoff and show a spectral tail extending up to 100 x GeV's and even to the TeV regime
- Three PSRs detected so far with IACTs: The Crab, Vela, Geminga, and PSR B1706
- The origin the gamma-ray emission at VHEs in PSRs is still not clear (e.g "polar cap", "slot gap"or "outer gap" models)
- Are these systems "unique", or there is a whole TeV PSR population to be detected?

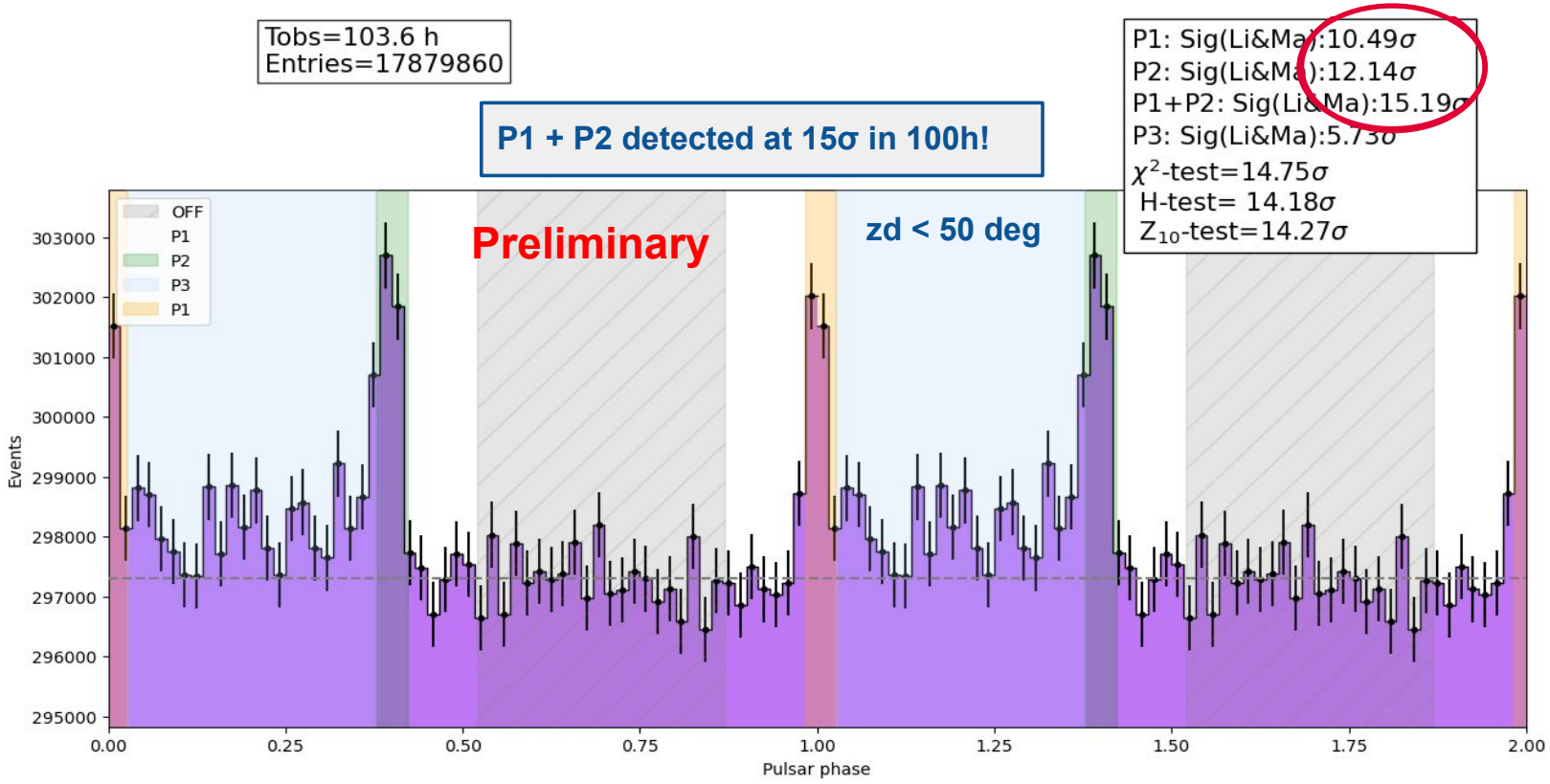




Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab

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



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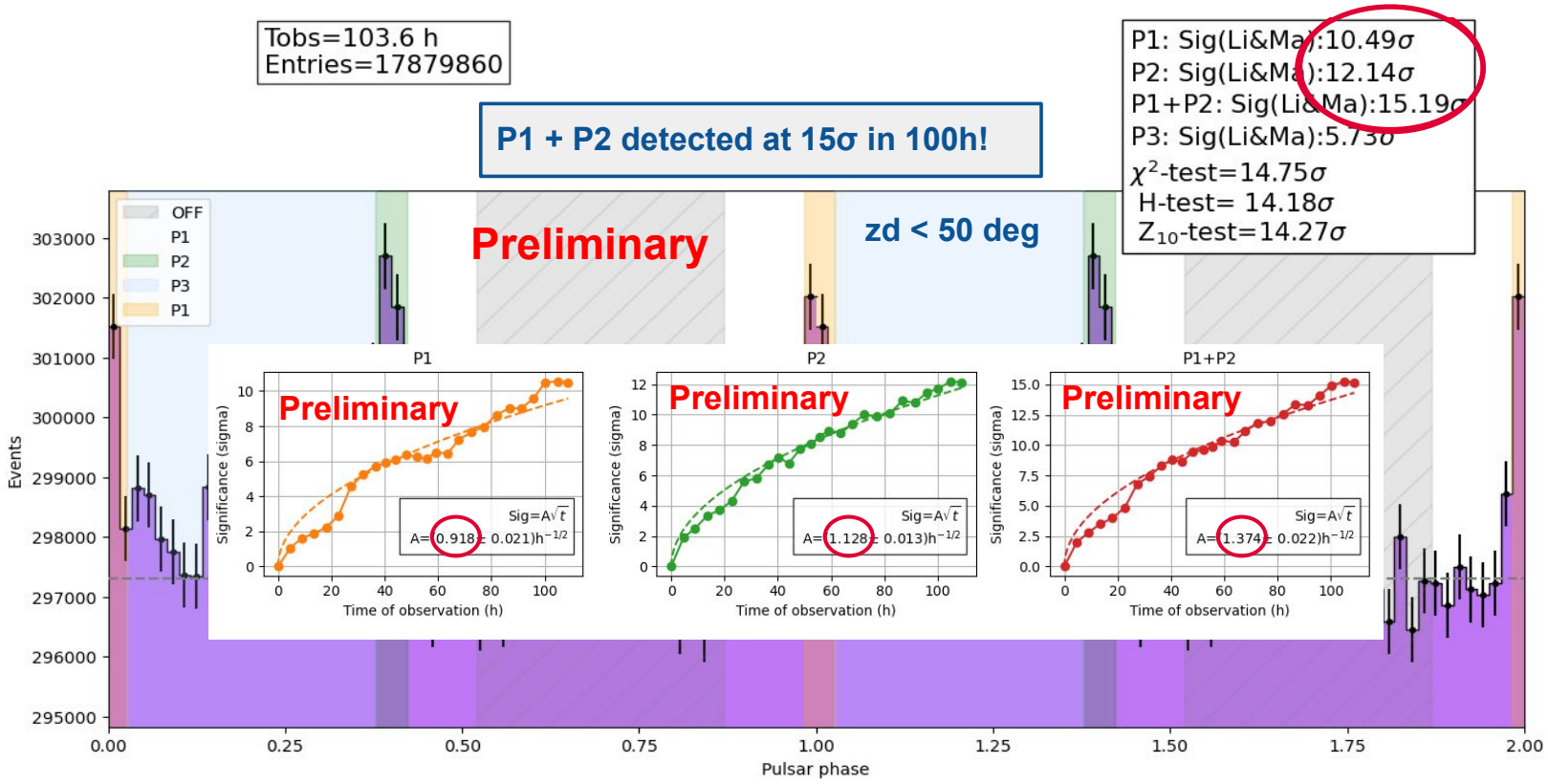
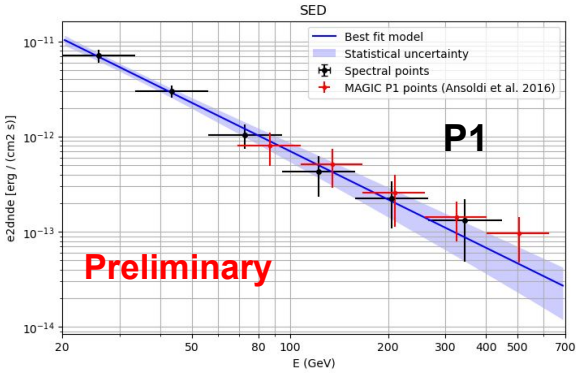
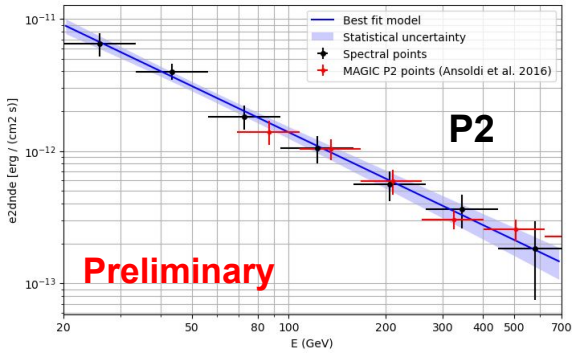


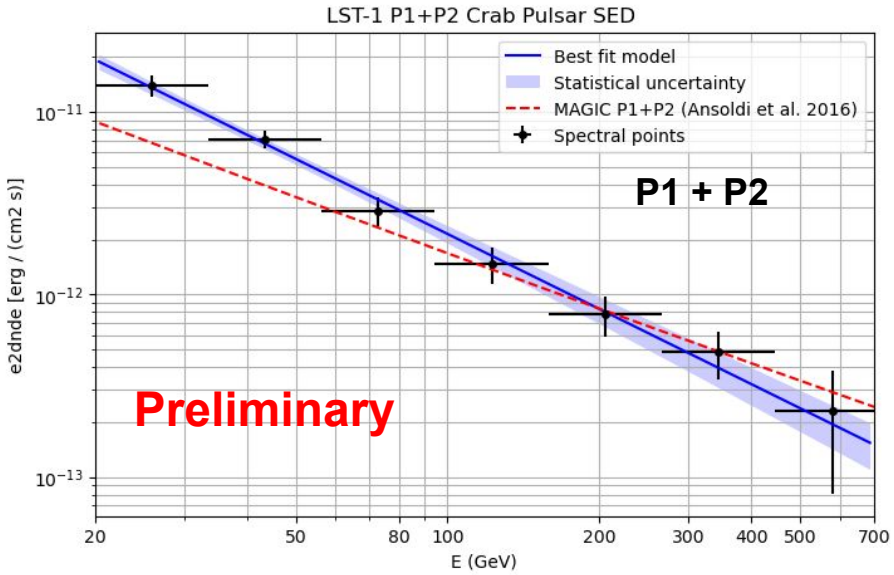
Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab

- SED displaying a PL shape up to 450 GeV for P1 and 700 GeV for P2 (Confirms MAGIC results > 500 GeV)
- Syst. uncertainties in spectral indices: ~10% and ~5% for P1 and P2.





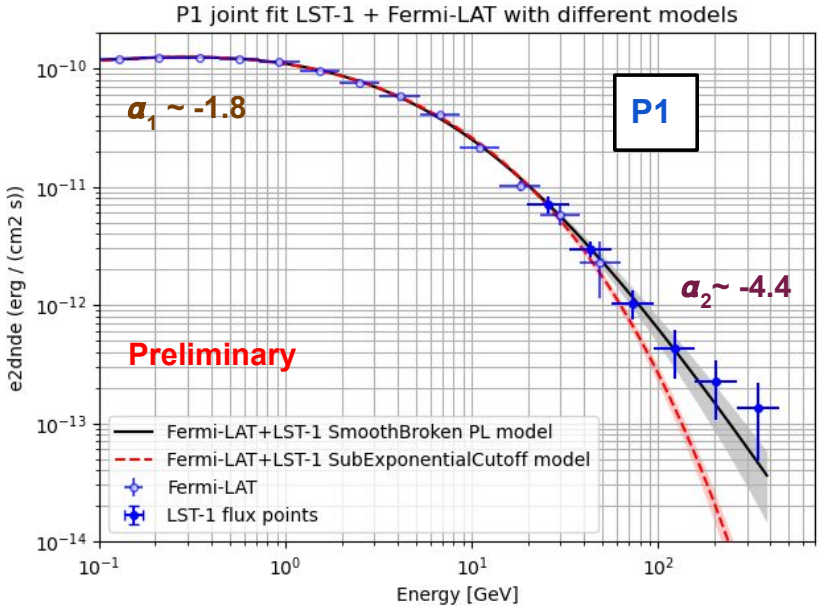


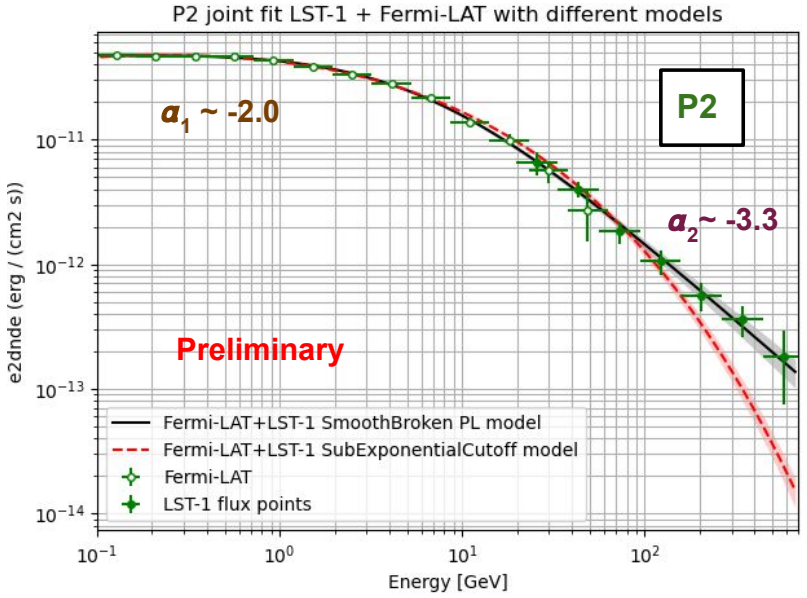
Pulsars at VHEs wit the LST-1

LST-1 observations of the Crab

- Dedicated LAT analysis (13 yrs) ⇒ smooth transition with LST-1
- Joint fit: preference for a smooth Broken PL model ⇒ PL extension at VHEs

$$\frac{dN}{dE} = f_0 \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-(\lambda E)^{\beta}\right) \quad < \quad \frac{dN}{dE} = f_0 \left(\frac{E}{E_0}\right)^{\alpha_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{\alpha_2-\alpha_1}{\gamma}}\right)^{-\gamma}$$

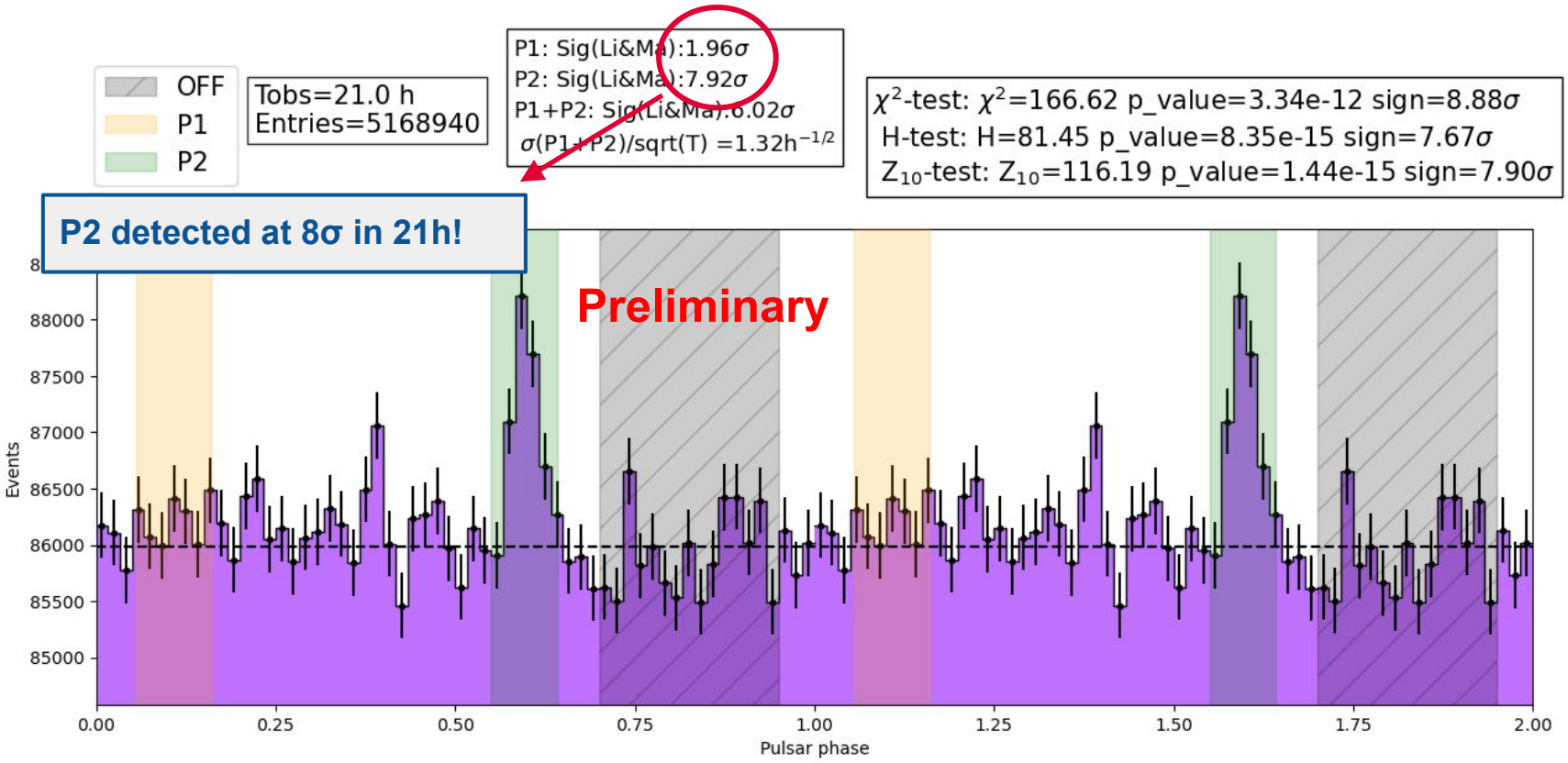




Pulsars at VHEs wit the LST-1

LST-1 observations of Geminga

- Second PSR observed with the LST-1 (Dec. 2022 - March 2023)
- Time after quality cuts: ~21h for Zd < 20deg



Pulsars at VHEs wit the LST-1

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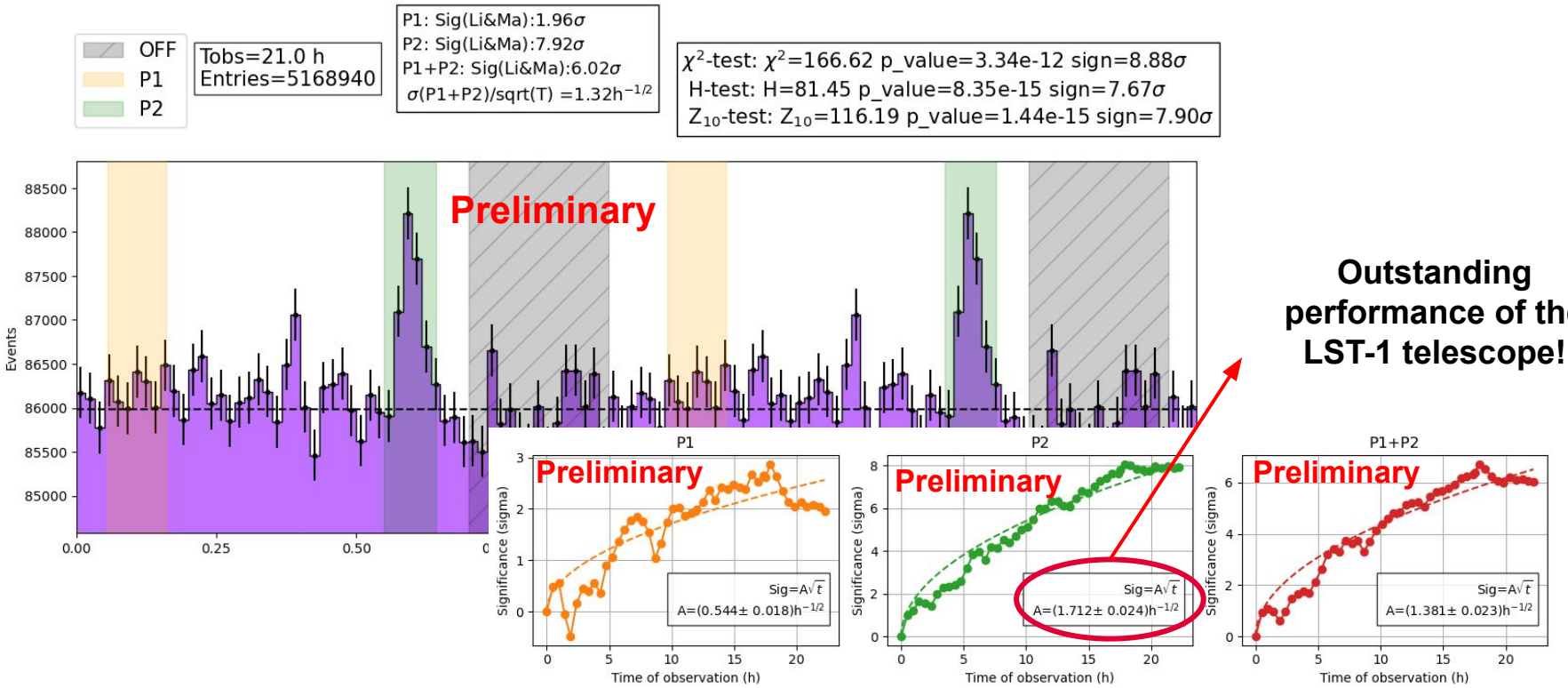


Outstanding performance of the LST-1 telescope!

LST-1 view on Galactic Transients

- LST-1 is designed for the discovery of new Galactic Transient sources @ VHEs
- 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: two MQs have detected at HE gamma-rays: Cygnus X-1 and Cygnus X-3. No emission from a MQ has been detected in the VHE (except interaction regions in SS433; see also HAWC claims on V4641) LST-1 will trigger on other MQs that show non-thermal transient emission, both based on Fermi-LAT or radio/X-ray alerts
  - gamma-ray binaries: gamma-ray binaries display periodic emission. However, they can show energetic outbursts, connected to clumps in the circumstellar disc of the star, e.g. in LS I +61 303 or HESS J0632+057. Some flaring could even be connected to magnetar-like events, as in LS I +61 303

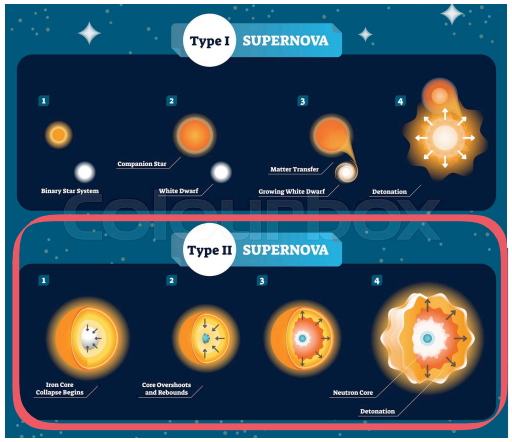
LST Galactic ToO Program

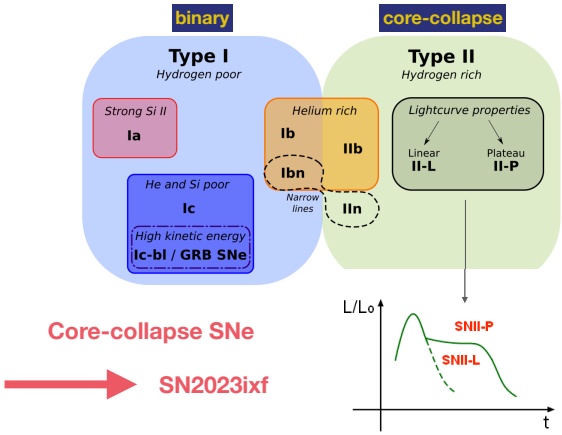
- Magnetars: in 2020 a FRB was associated with a known source,SGR 1935+2154. Magnetars can display different kinds of outburst, which might lead to VHE emission. *LST-1* aims at discovering for the first time VHE emission from a magnetar, triggering on external radio, X-ray or *Fermi*-LAT alerts.
- Supernovae: 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. The aim is to discover the VHE counterpart of SNe for the first time.
- 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 will perform observations of superflares of young and nearby M-dwarf stars, as reported by X-ray satellites
- Other unexpected Transients: LST-1 is open also to trigger on other serendipitous Galactic transients of unknown nature or with a different nature not included in the “classic" list of transients.

LST Galactic ToO Program

LST-1 observations of SN 2023 ixf

- Discovered on May 17th 2023 by K. Itagaki (TNS#178084)
- Type II SN: core-collapse of massive star + shock-driven shell expansion
- 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 !

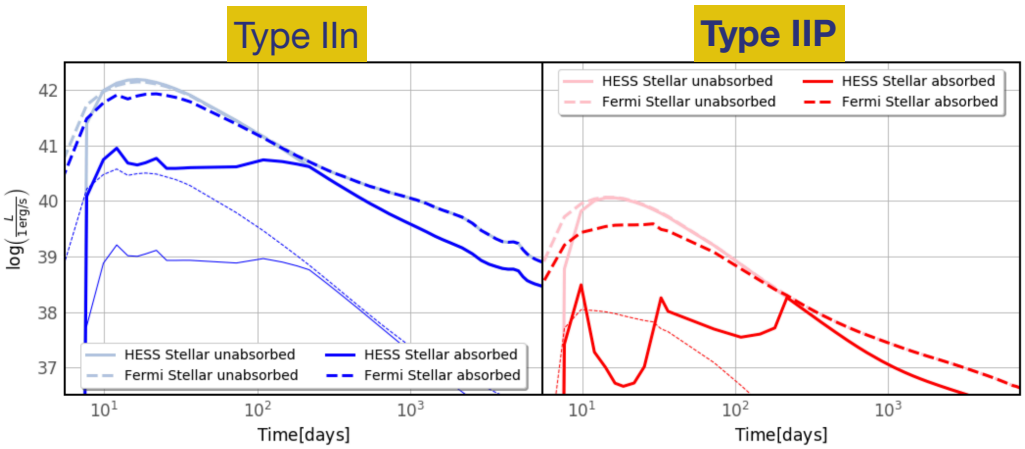




LST Galactic ToO Program

LST-1 observations of SN 2023 ixf

- Type II can be site of efficient particle acceleration (Murase et al. 2011, Bell et al. 2013, Cristofari et al. 2022, Brose et al. 2022).
- If hadrons are accelerated, they can interact with the CCSN surrounding medium to produce gamma-rays in the multi-TeV range



Adapted from Brose et al. 2022

Limiting factors:

- Distance
- opacity of the emitting region: (VHE gamma-ray can interact with the optical photons from SN photosphere)

gamma-opacity evaluation is complex and will depend on stellar progenitor radius, mass-loss rate, the explosion energy and mass of the ejected material.

LST Galactic ToO Program

LST-1 observations of SN 2023 ixf

- LST-1 observations joint with MAGIC starting on May 20th 2023, lasting for about 1 month
- MAGIC+LST performed an extensive coordinated follow-up campaign covering the rise, peak and plateau state of the optical LC
- Analysis of the data set still ongoing, report should be ready in the next weeks (but can take some time to become public...stay tuned!)

MAGIC and LST1 observations

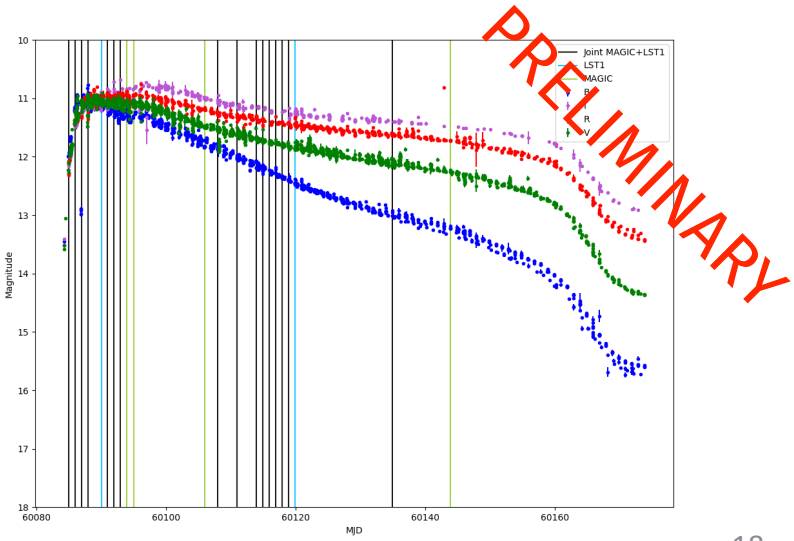
	joint	LST-1 only	MAGIC only
Time	41.6h	3.7h	15.3h

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



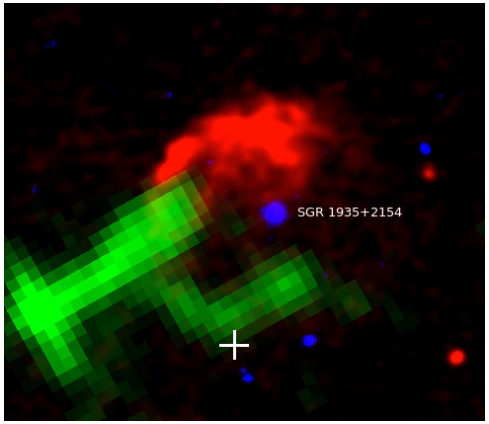
LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

See dedicated talk by G. Panebianco

- SGR 1935 is a Galactic Magnetar in the SNR G57.2+0.8 with Soft Gamma Repeater activity
- In April 28th 2020 a burst was reported in coincidence with a FRB from SGR 1935
  => FRBs can be produced magnetars !
- Can TeV emission be expected during known SGR activity, both persistent and/or transient?
- 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)
- Studies for short-term bursts @ VHEs still lacking (and being addressed with LST-1 + MAGIC)

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

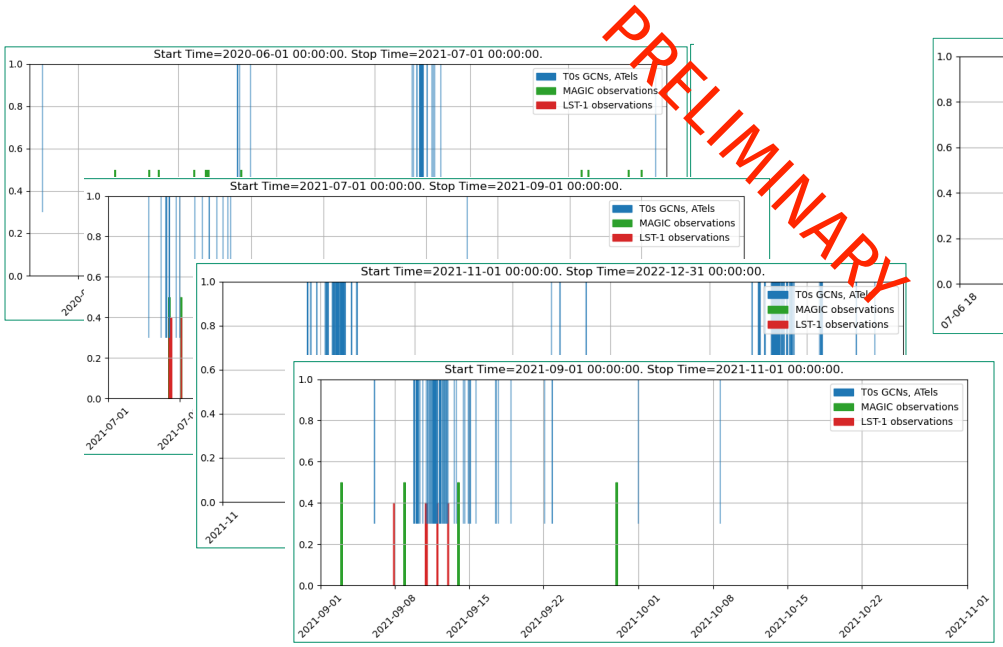


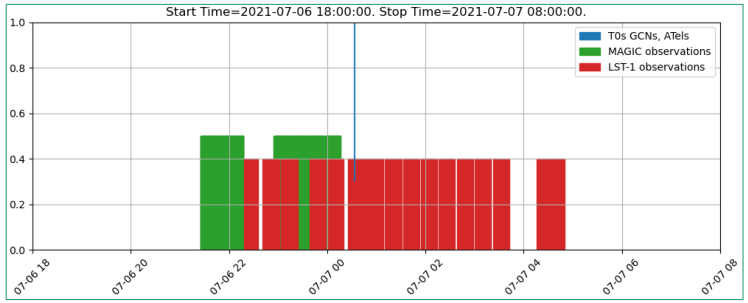
Composite image of SNR G57.2+0.8 (red, radio band), SGR 1935 (blue source in the center), and nearby molecular clouds (green), from Zhou et al. 2020)

LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

- 25h of good quality data 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



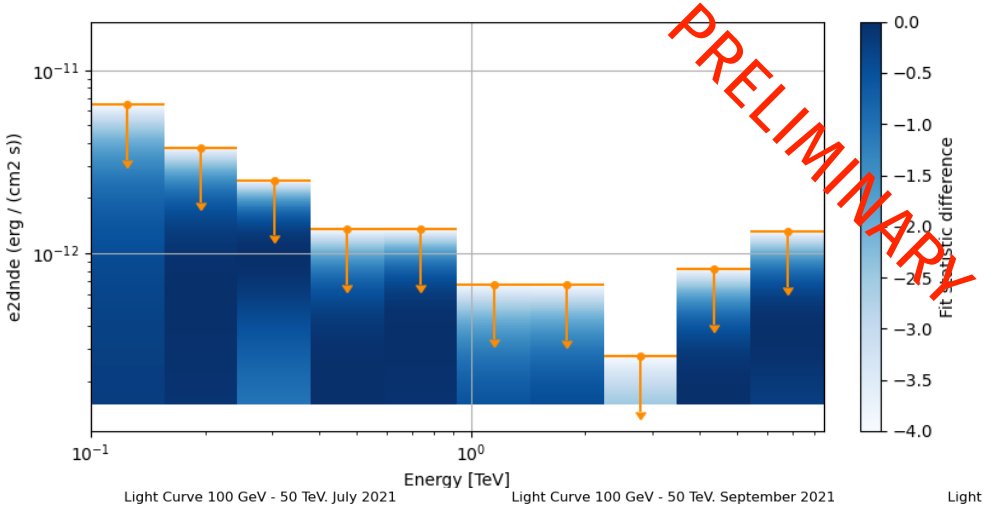


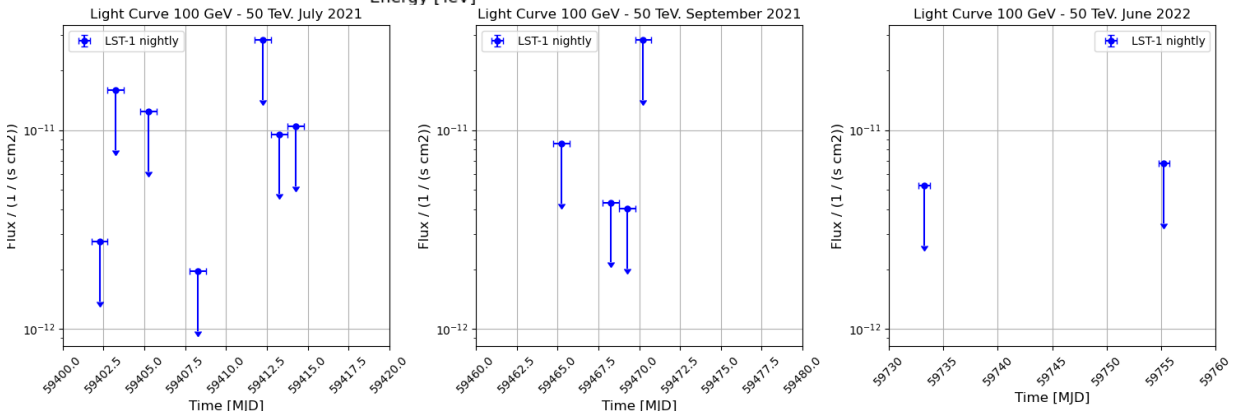
- 7 bursts coincident with LST-1 observations
- 1 burst for MAGIC

LST Galactic ToO Program

LST-1 observations of SGR 1935+2154

- Search for persistent emission





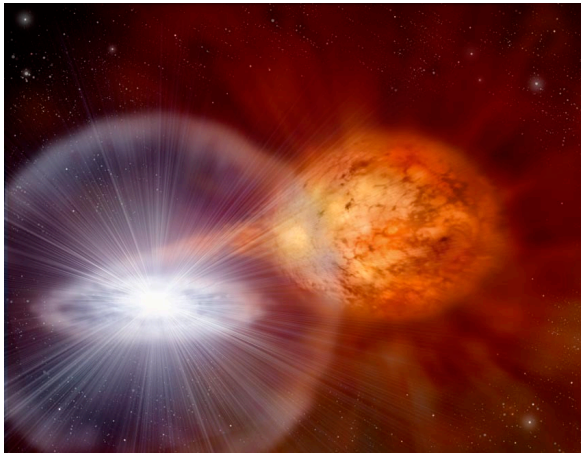
- First results do not show any significant signal for the steady emission from SGR 1935
- UULLs placed both using the whole (stacked) data set as well as on a nightly basis (13 nights)

See dedicated talk by G. Panebianco

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.

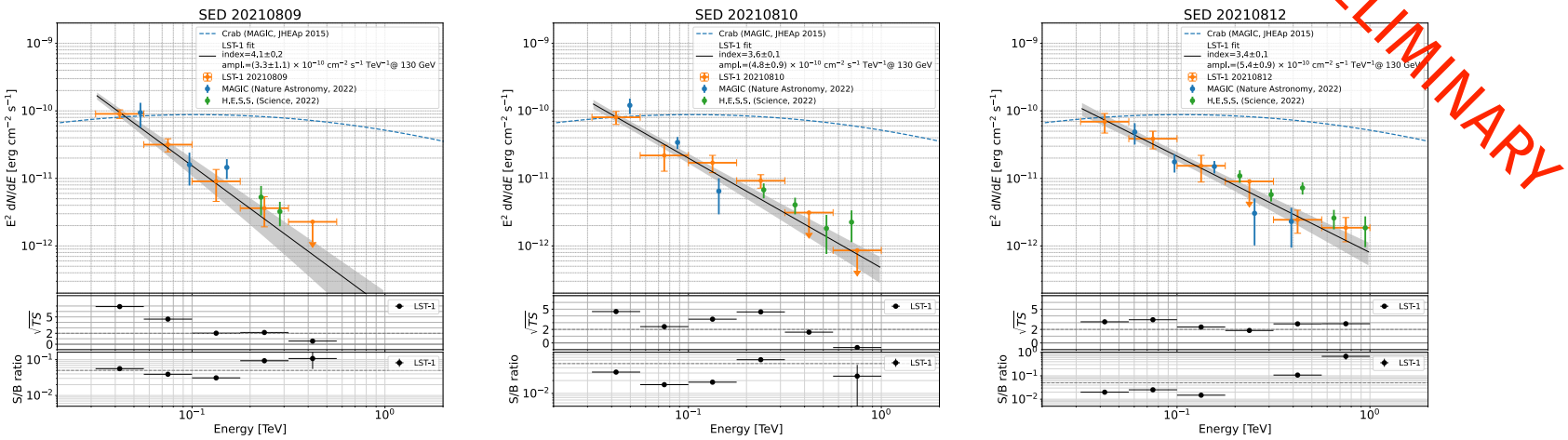
Date (YYYY-MM-DD)	T-T0 (days)	Zenith range (deg)	Transmission 9km (%)	Observation time (h)	
2021-08-09	0.97	36-43	> 90	1.43	Right after outburst
2021-08-10	1.97	36-60	> 90	2.68	
2021-08-12	3.97	36-56	> 90	2.24	
2021-08-13	4.99	37-55	15 - 90		Bad atmospheric transmission
2021-08-14	5.97	36-46	65		
2021-08-15	7.03	42-57	55		
2021-08-29	21.01	46-59	> 80	0.97	After moon break
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	

Novae at VHEs wit the LST-1

LST-1 observations of RS Ophiuchi

- t_obs = 6.5h accumulated in the first 3 nights of the outburst
- 12 σ detection for the 3 nights combined, 6 - 8 σ each night

PRELIMINARY



date	Φ [10^{-10} TeV^{-1} cm^{-2} s^{-1}] @ 130 GeV	PL index
20210809	3.3 ± 1.1	4.1 ± 0.2
20210810	4.8 ± 0.9	3.6 ± 0.1
20210812	5.4 ± 0.9	3.4± 0.1

SEDs consistent with MAGIC and H.E.S.S.

Novae at VHEs wit the LST-1

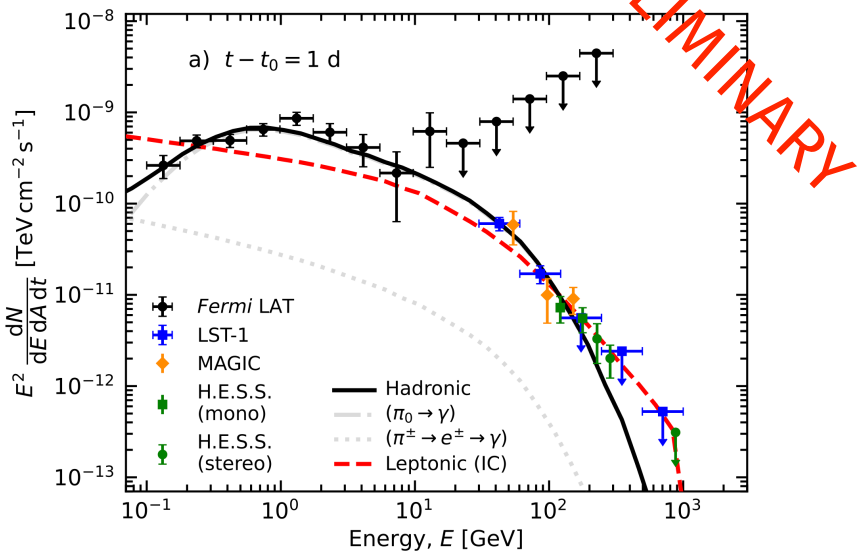
LST-1 observations of RS Ophiuchi

- 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)

PRELIMINARY

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

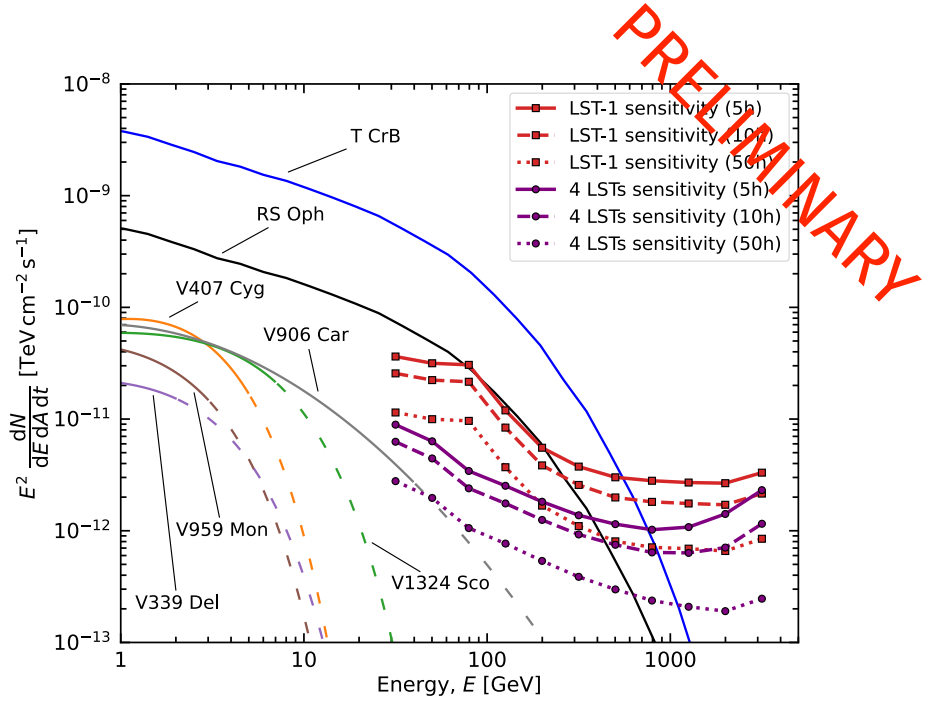
PRELIMINARY



Novae at VHEs wit the LST-1

Novae follow-up with LST

- Can LST-1 (or the full LST array) detect more novae (T CrB, classical novae)?
- very different γ-ray emission among different systems
- LST sensitivities computed using either classical (LAT) or RS Oph spectra



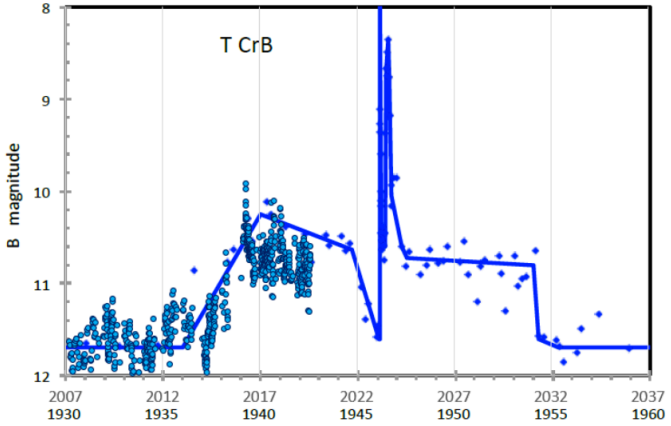
Novae at VHEs wit the LST-1

Next nova: T CrB

- ~3x closer => 9 times brighter than RS Oph; RG and WD about 2x closer
- showing same behaviour now as in previous eruption in 1946
- predictions by Schaefer et al.: estimate eruption by February - August 2024
- LST-1 + MAGIC + XMM + NuSTAR + CAHA + Liverpool + IXPE + ...

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

compiled by D. Green

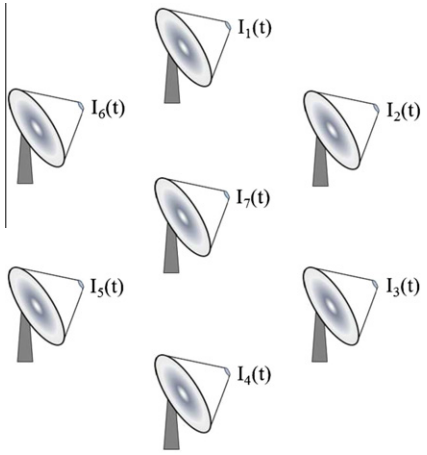


adapted from Schaefer (2019)

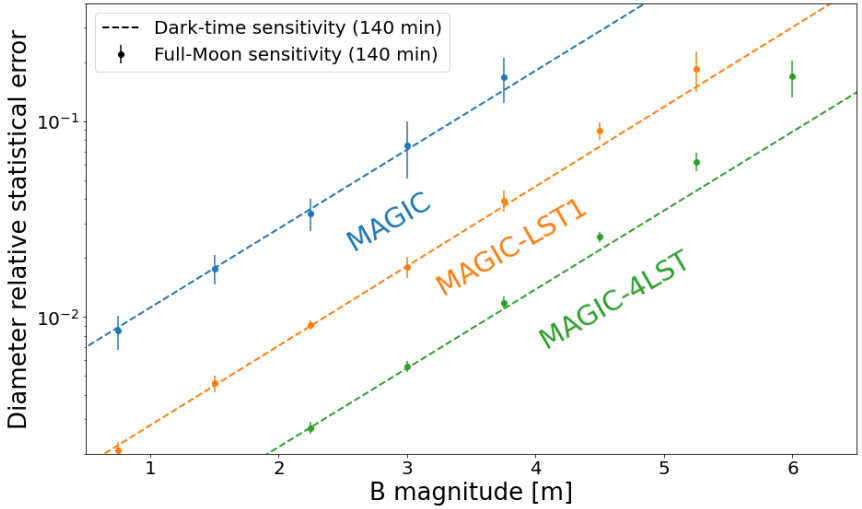
Novae at VHEs wit the LST-1

Next nova: T CrB

- Stellar interferometry with IACTs (Dravins et al. 2013) can provide critical information on the star photosphere: stellar sizes, asymmetries, time evolution...
- If MAGIC+LST SII system is ready for outburst (being worked on!), SII data will be taken on the first few days (only about ~20 min needed for SII)



from Dravins et al. (2013)



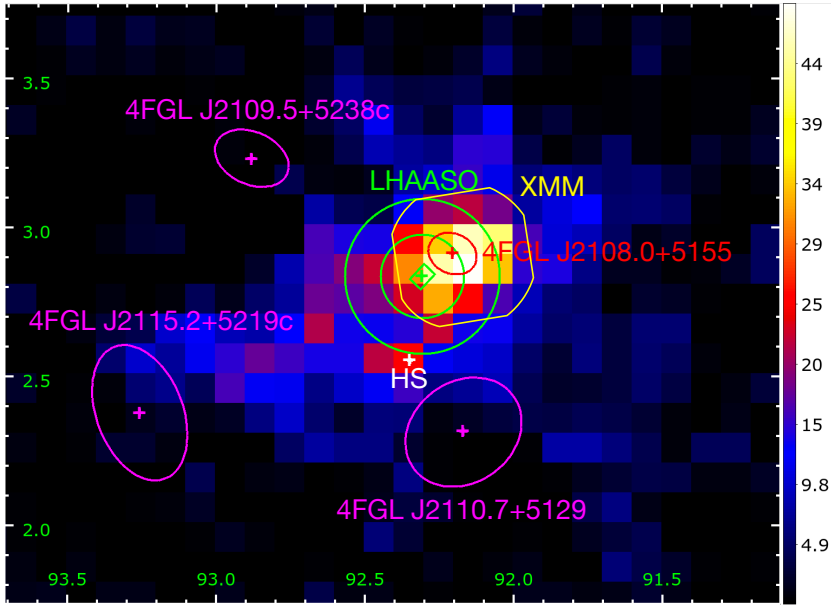
from Cortina et al. (2022)

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
-

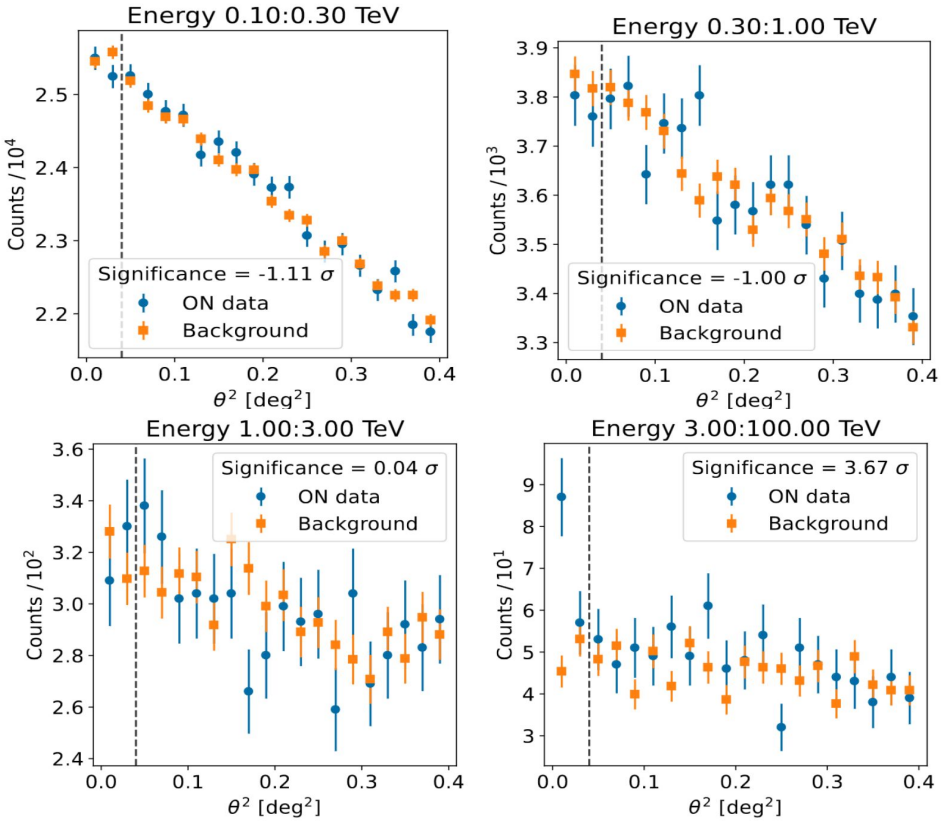


Abe et al. (CTA-LST collaboration) 2023

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

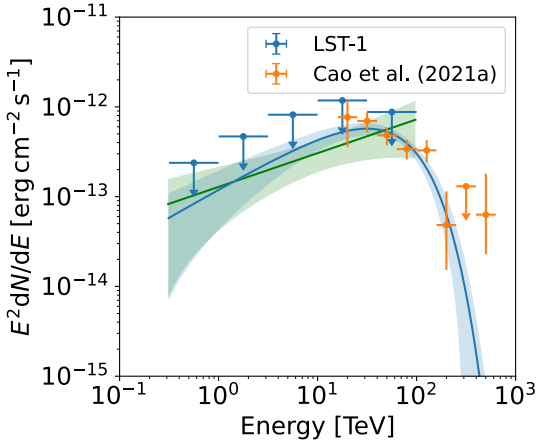


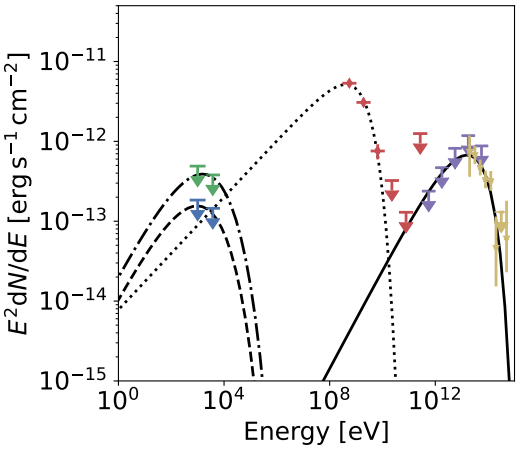
Abe et al. (CTA-LST collaboration) 2023

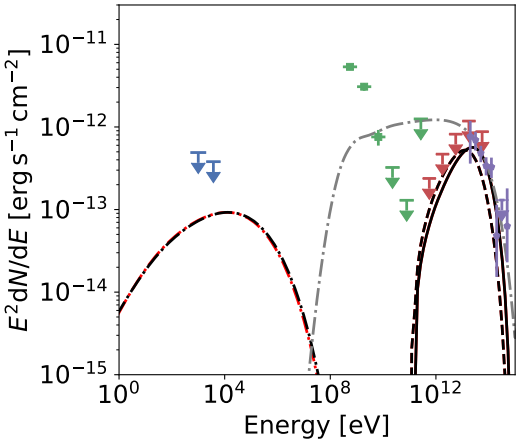
PeVatron candidates with LST-1

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?

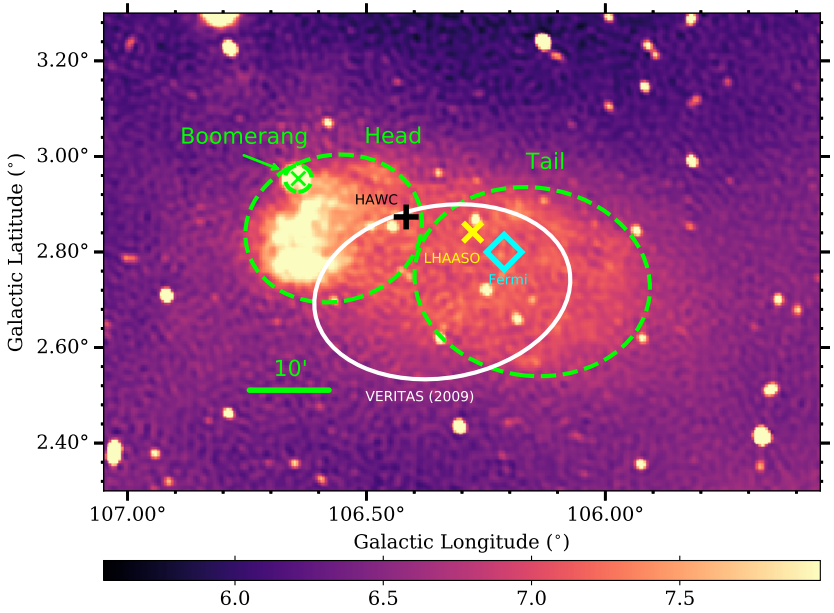
Abe et al. (CTA-LST collaboration) 2023

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).

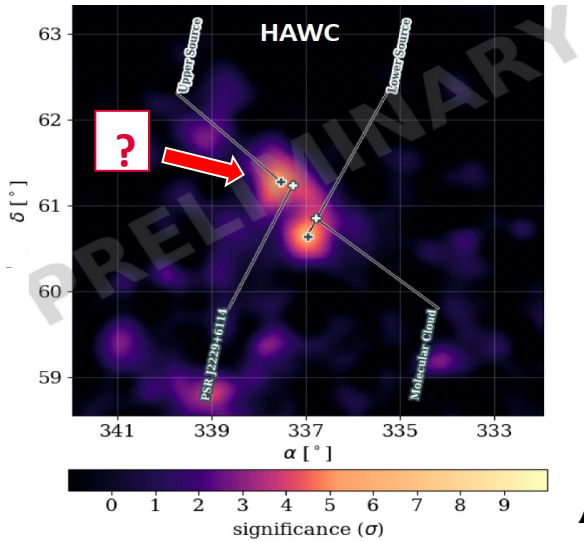


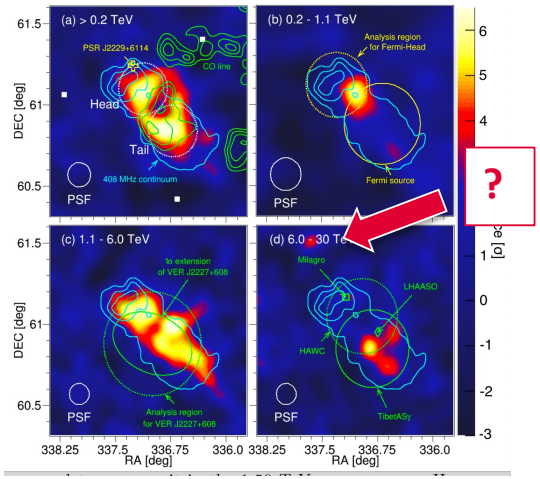
Pope et al. (NuSTAR & VERITAS coll.) 2023

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)?



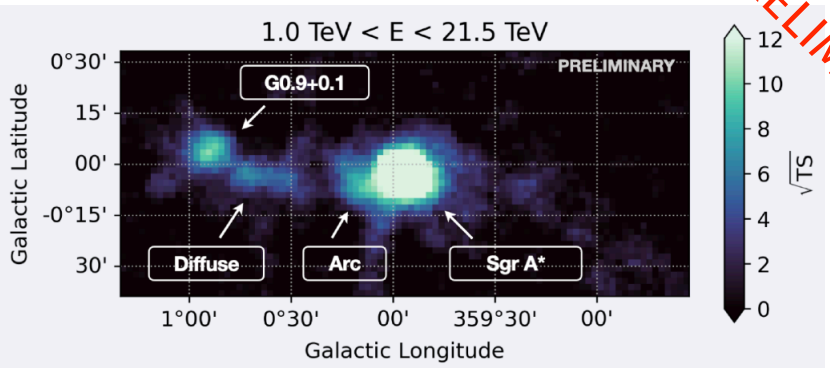


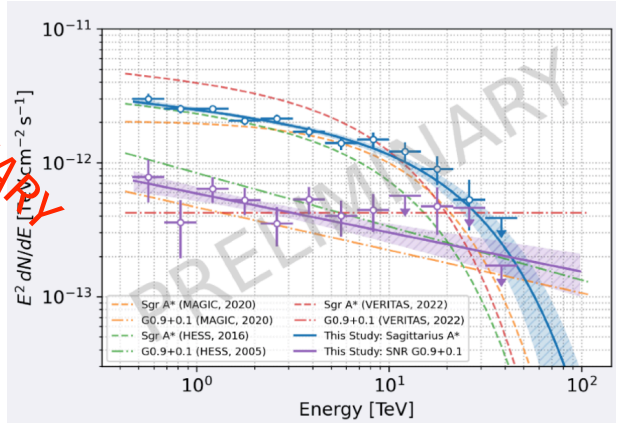
Adapted from Saito et al. (Gamma-Ray Symposium 2022); courtesy of F. Cassol

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





from Abe et al. (ICRC 2023)

Summary: LST & Galactic Science

- **LST capabilities for PSR studies**
  - Sensitivity and low-E threshold (~20 GeV) ideal for studying PSRs @ VHEs
  - Crab (100h, 15σ) and Geminga (20h, 8σ !) already detected with LST-1
- **LST observations of Novae outbursts**
  - RS Oph is the first galactic transient detected with LST-1
  - More novae to be detected with LST-1 (e.g. T CrB) and LST array (classical novae?
- **LST potential on Galactic Transients**
  - Fast repositioning, energy range, sensitivity: LST is a “Transients Machine”
  - Plenty of potential Gal Transients: from MQs to GBs, PWN flares, magnetars...
- **LST follow-up of PeVatron candidates**
  - Excellent sensitivity in the sub-TeV regime and relatively large FoV of LST-1 allow for spectral + morphological studies of recently discovered UHE sources
  - LHAASO J2108+5157 the first unidentified UHE source observed with LST-1.
  - Further LHAASO sources (from LHAASO catalog) will arrive in Cycle II