TeV Particle Astrophysics

TeVPA

Valencia 2025

3-7 November 2025

The Most Distant VHE Quasar: Probing OP 313's power with LST-1 and MAGIC

Mireia Nievas, David Sanchez, Jorge Otero, Axel Arbet-Engels, Lea Heckmann, Daniel Morcuende, Joshua Baxter, Ryuji Takeishi, Chitranshi Bakshi
+ *many others*

– CTAO-LST collab. + MAGIC collab. –

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The Flat Spectrum Radio Quasars

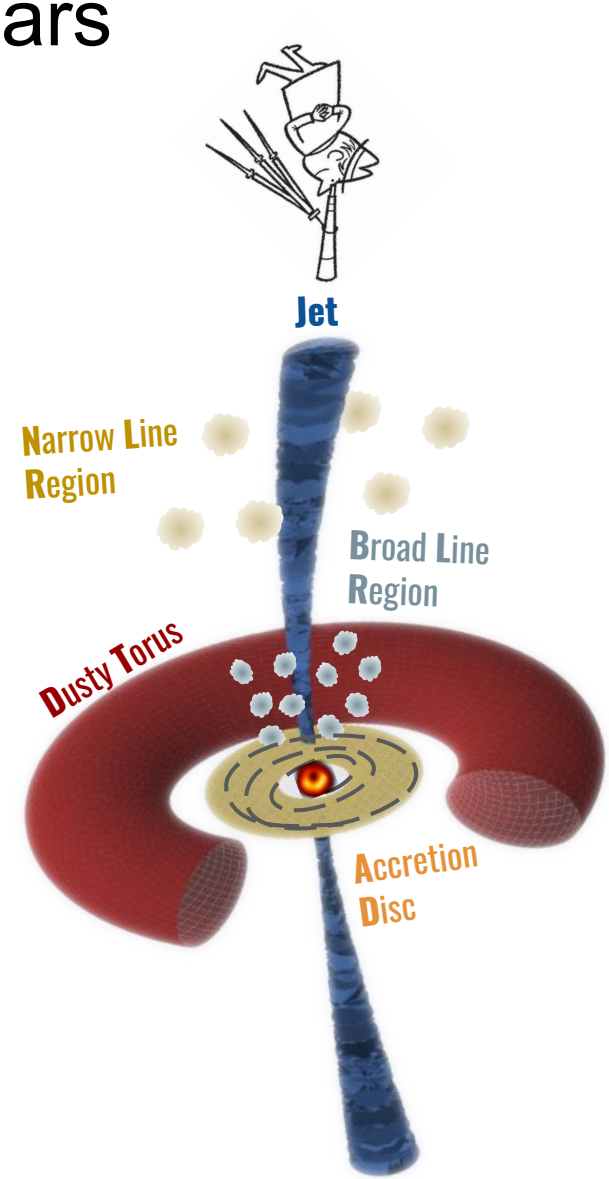
Blazars are a class of radio-loud AGNs with jets aligned with the line of sight

Two types:

- **BL Lacs:** weak/absent optical emission lines, inefficient accretion.
- **FSRQs:** luminous, efficient accretion, optical components (BLR, accretion disc, dusty torus)

At TeV energies: ~ 85 blazars detected, the majority (~90%) BL Lacs, just ~12 FSRQs.

FSRQs usually far away → strong extragalactic background light absorption



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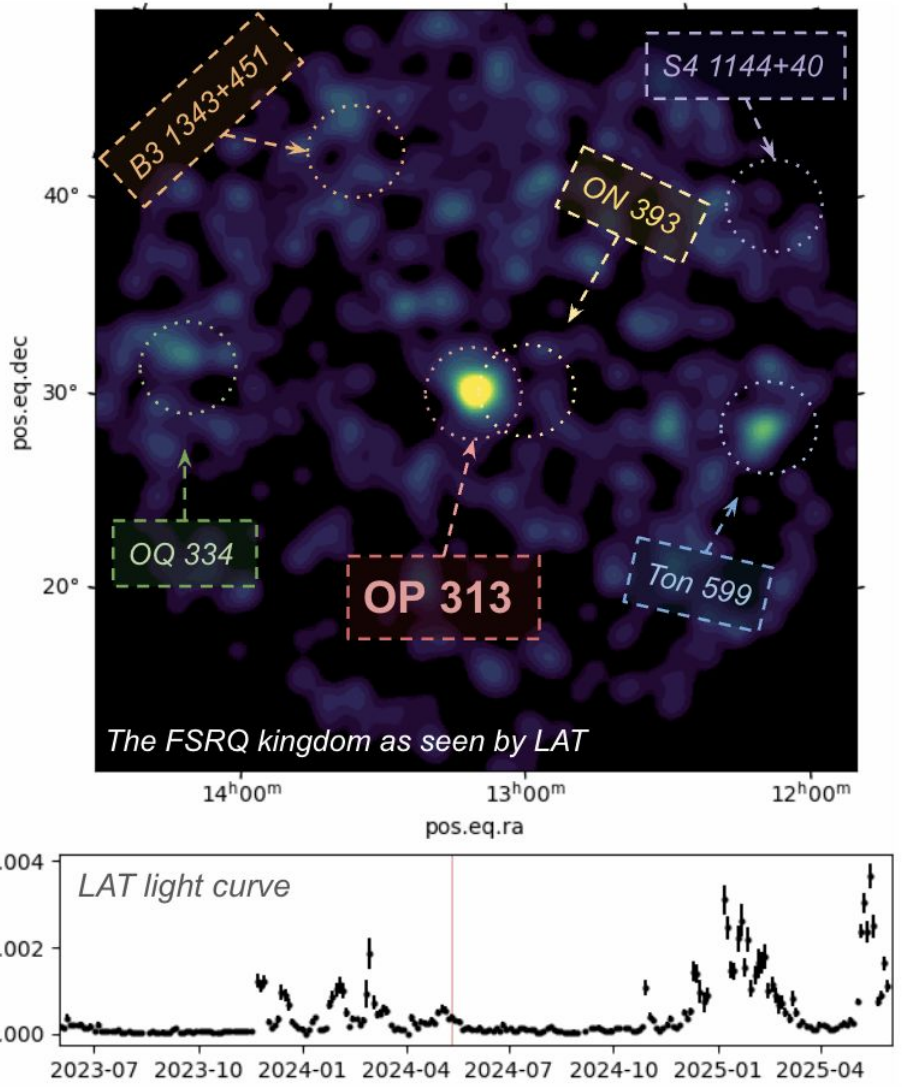
The Flat Spectrum Radio Quasar **OP313**

- Most distant quasar detected in VHE (**z=0.9973**), and second most distant source after GRB 201216C.
- 12 FSRQs discovered in VHE.
- Among the brightest and most luminous sources recorded by LAT.

Previous attempts:

- MAGIC 2014, 2019 → Upper limits: MAGIC coll. MNRAS 535 1484A (2024)

Very strong activity since 2023.



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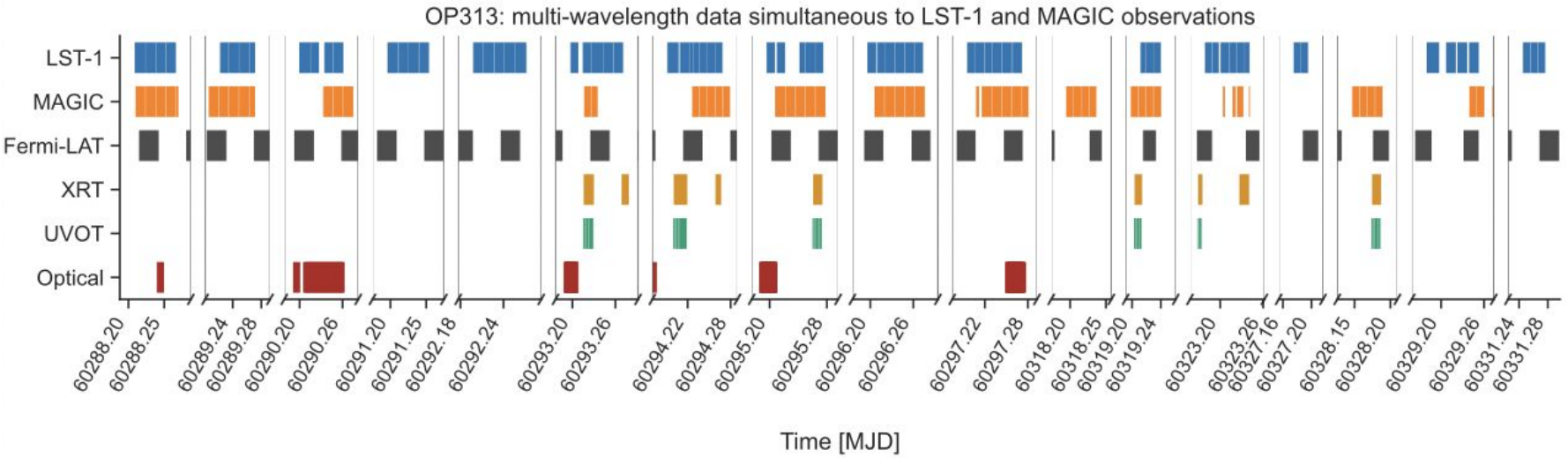
Data acquisition



- **LST-1:** 15h between Dec 10th and Dec 19th (2023) + 5h in January 2024
- **MAGIC:** 10h between Dec 10th and Dec 19th (2023) + 10h in January 2024.
- ***Fermi*-LAT:** Nightly-binned dataset, centred at 00h UTC.
- ***Swift*: XRT** (0.3-10 keV) and **UVOT** (V, B, U, W1, M2 & W2 bands).
- **Optical** observations: SNO (T90 & T150 photometry & polarimetry), IAC80 (photometry), LCO (r-band phot), Tuorla/Turku (R-band), Siena, Seveso & Montarrenti, Kanata (R, J), ASAS-SN, ZTF and ATLAS.
- **Radio/mm**: SMA, Effelsberg.

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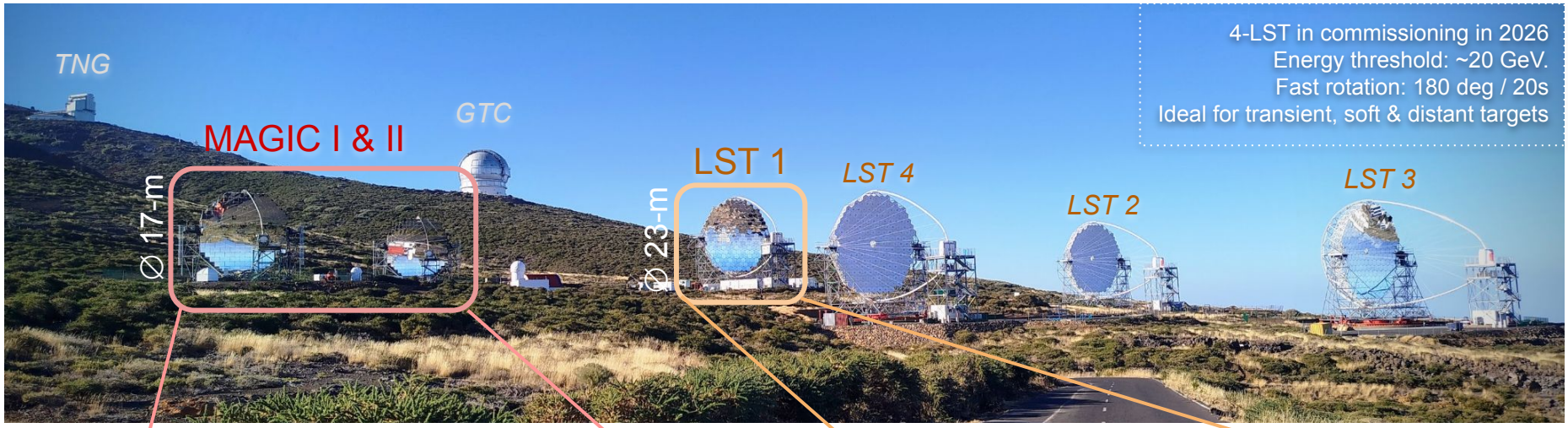
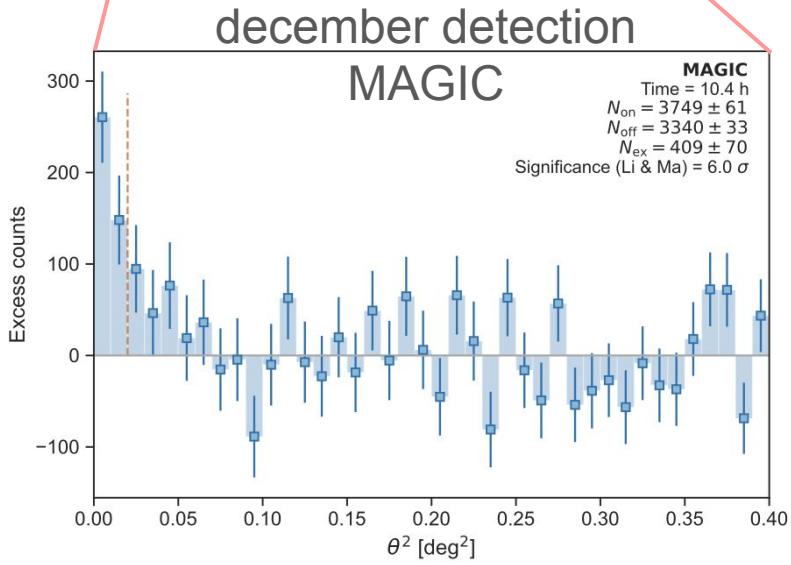
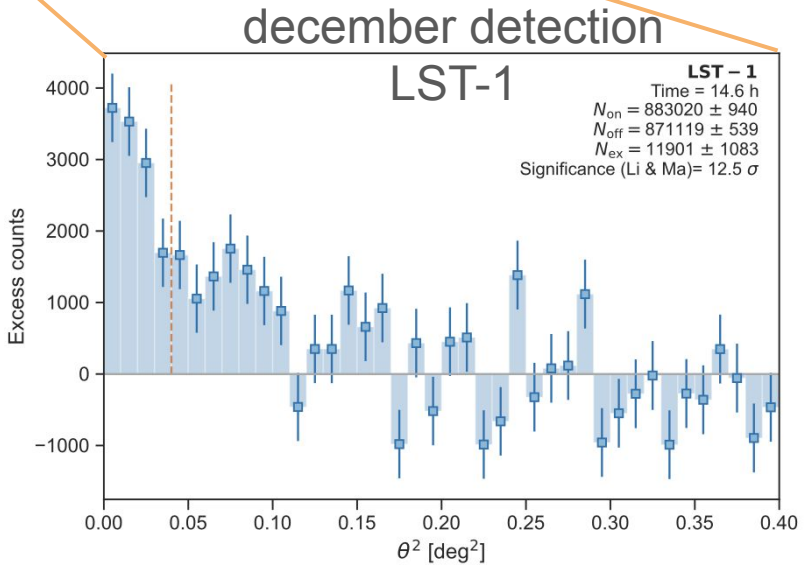
Detection by LST-1 and MAGIC

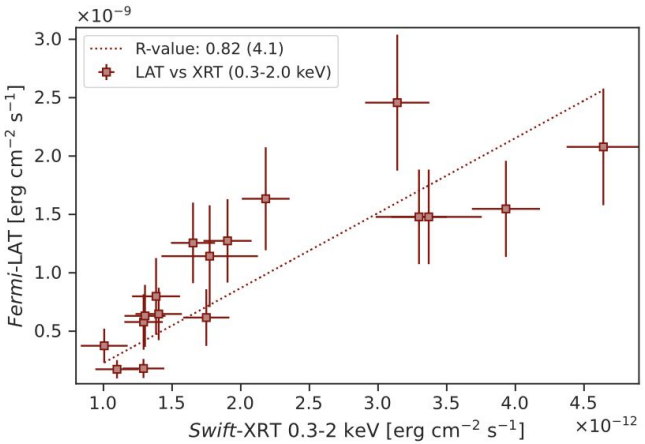




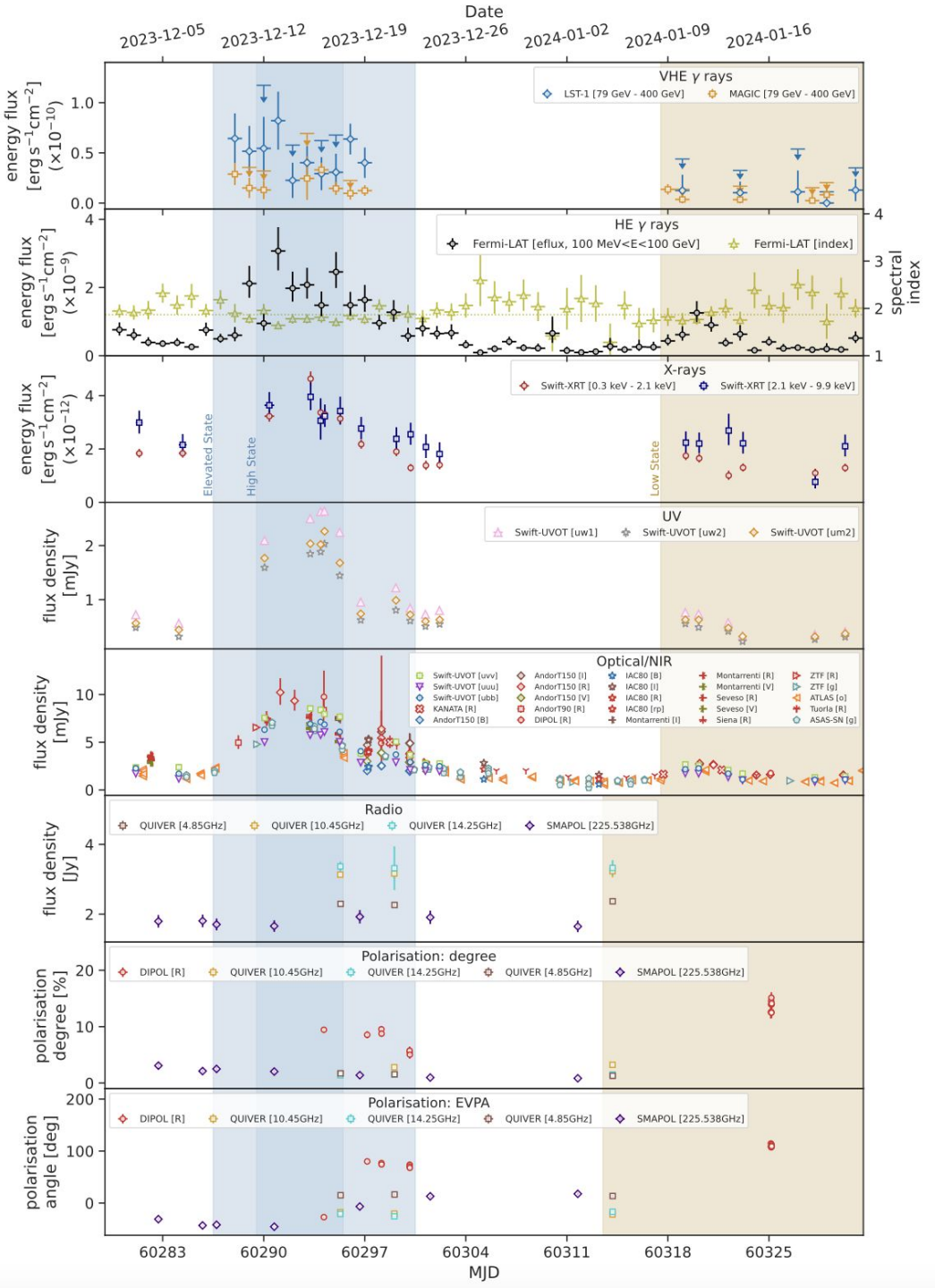


MWL LC

- Variability correlated from optical/NIR to HE gamma-rays. Harder to judge in VHE



- 3 activity periods defined:
  - ***Light blue band***: extended elevated state (December 2023) used for EBL estimation.
  - ***Dark blue band***: multi-wavelength stable high state used for broadband SED modeling.
  - ***Light brown band*** low state (January 2024).
- Radio: close to typical state - no strong hints of variability (in this timeframe)



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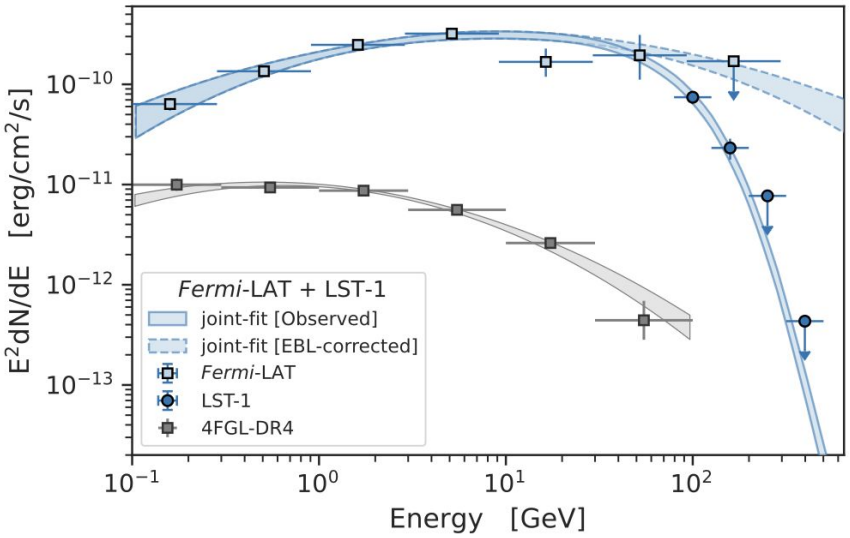
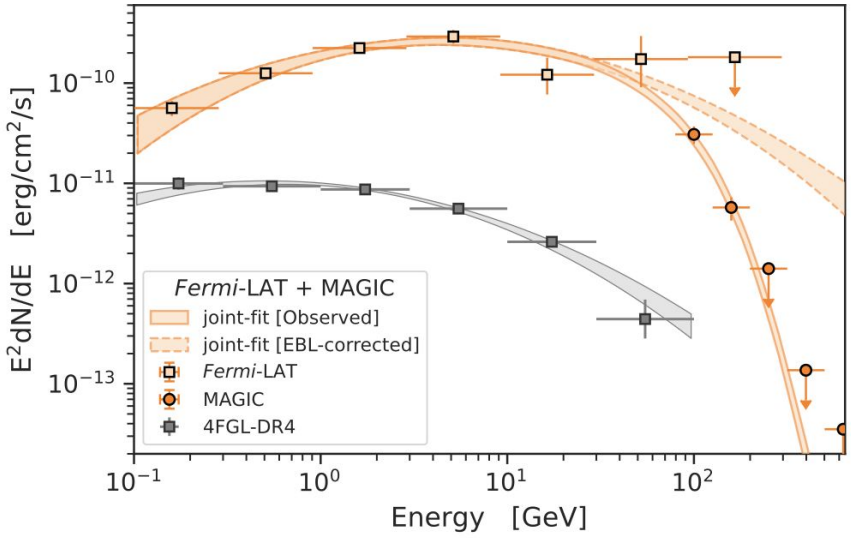
Results: joint gamma SED & EBL





(Stacking of nightly data during the extended high-state)

- Intrinsic emission: log-parabola spectrum preferred with marked curvature.
- Different best-fit for LST-1 and MAGIC due to slightly different integration times + systematics.
- Fermi-LAT analysis matching the observing nights of LST or MAGIC.

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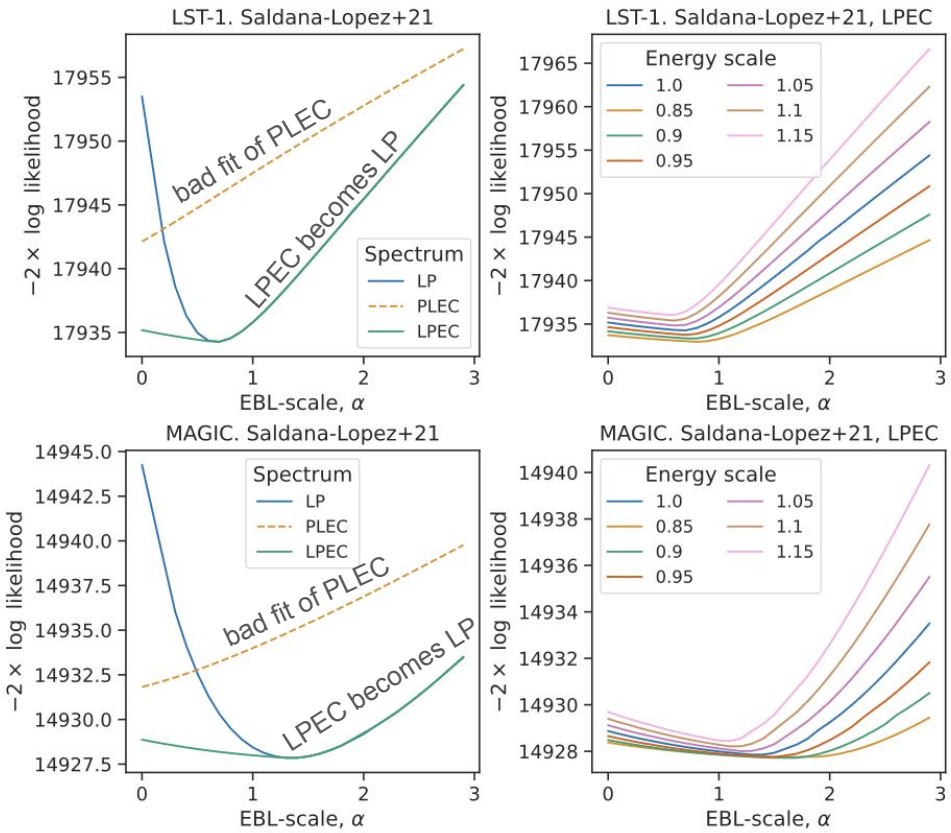
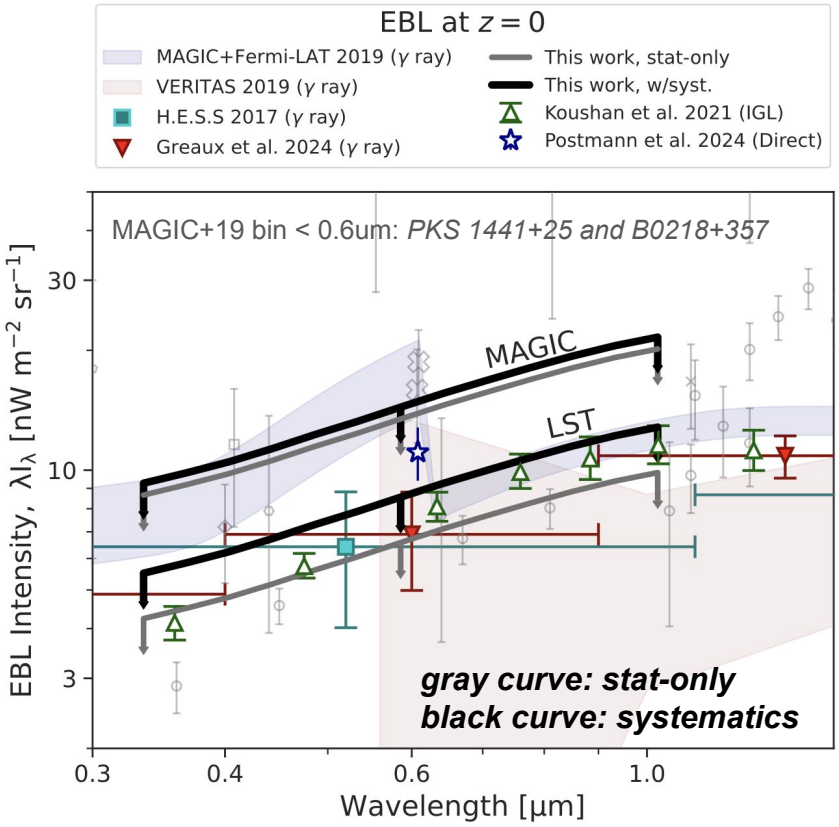
Results: joint gamma SED & EBL

- **Method**: Joint LST + *Fermi*-LAT and MAGIC + *Fermi*-LAT constraint of EBL in `gammapy`. Both separately.
- **EBL models**: Saldana-Lopez +21 & Dominguez+11 (showing only Saldana-Lopez +21)
- **Spectral shapes**: LP, LPEC, PLEC, PWL. The latter two very low fit probabilities
- **Systematics**: light scale, in steps of +/- 5% up to +/- 15%.
- **Wavelength range**: we split the Saldana-Lopez model in wavelength bins and test their individual impact.





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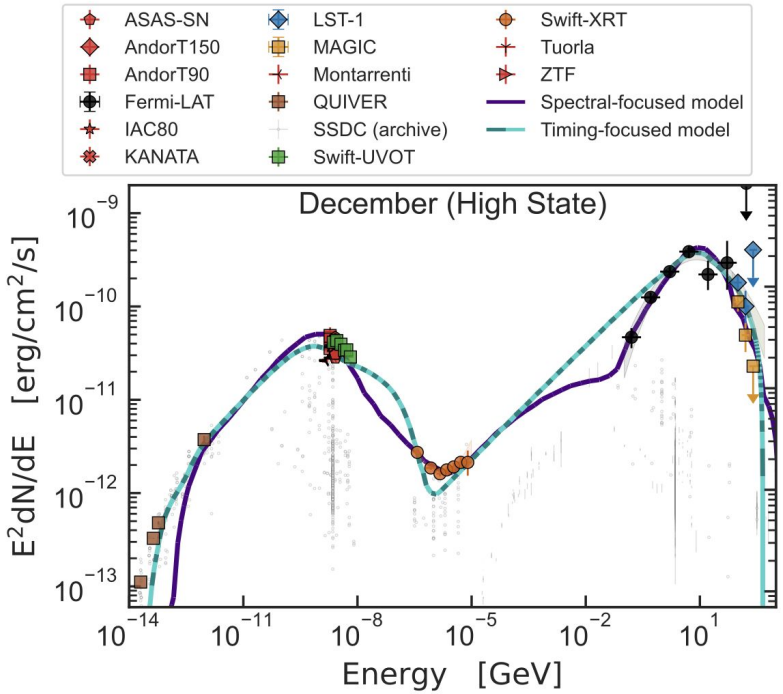
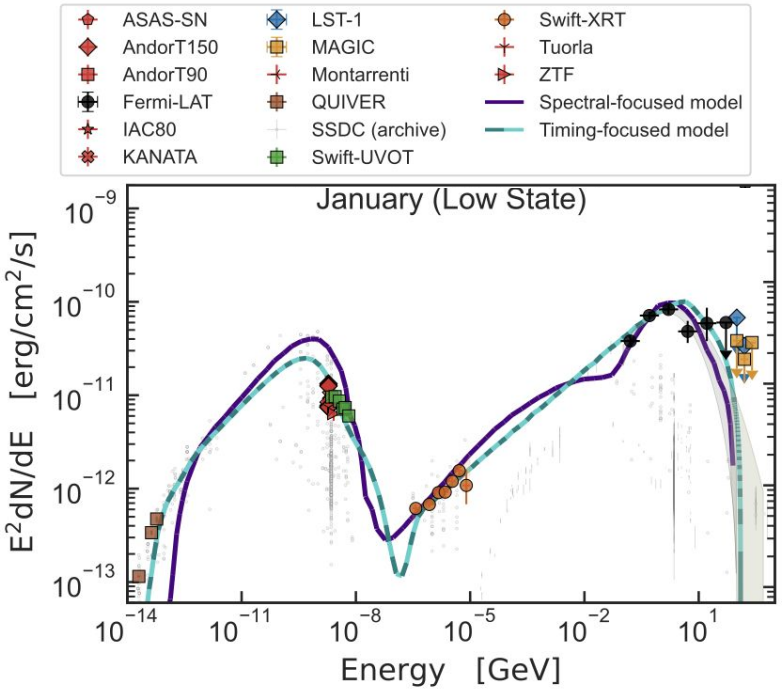
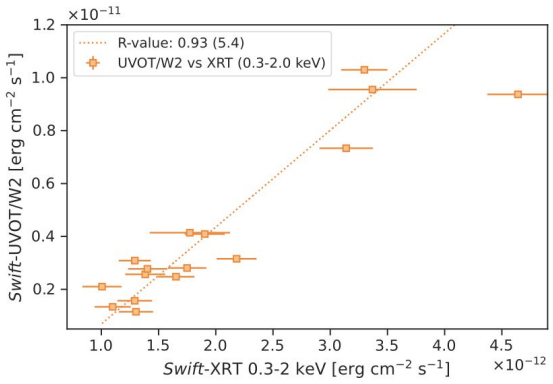
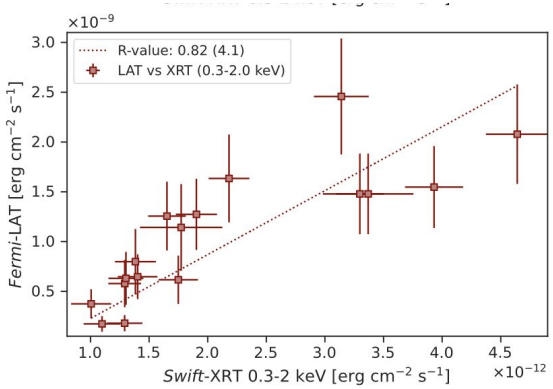
Results: SED modeling









Very challenging

- MWL correlations.
- FSRQ: BLR and DT relevant.
- Consistently variable from optical to gamma-rays.
- Very hard *Fermi*-LAT SED.
- LE and HE peaks “very separated”.

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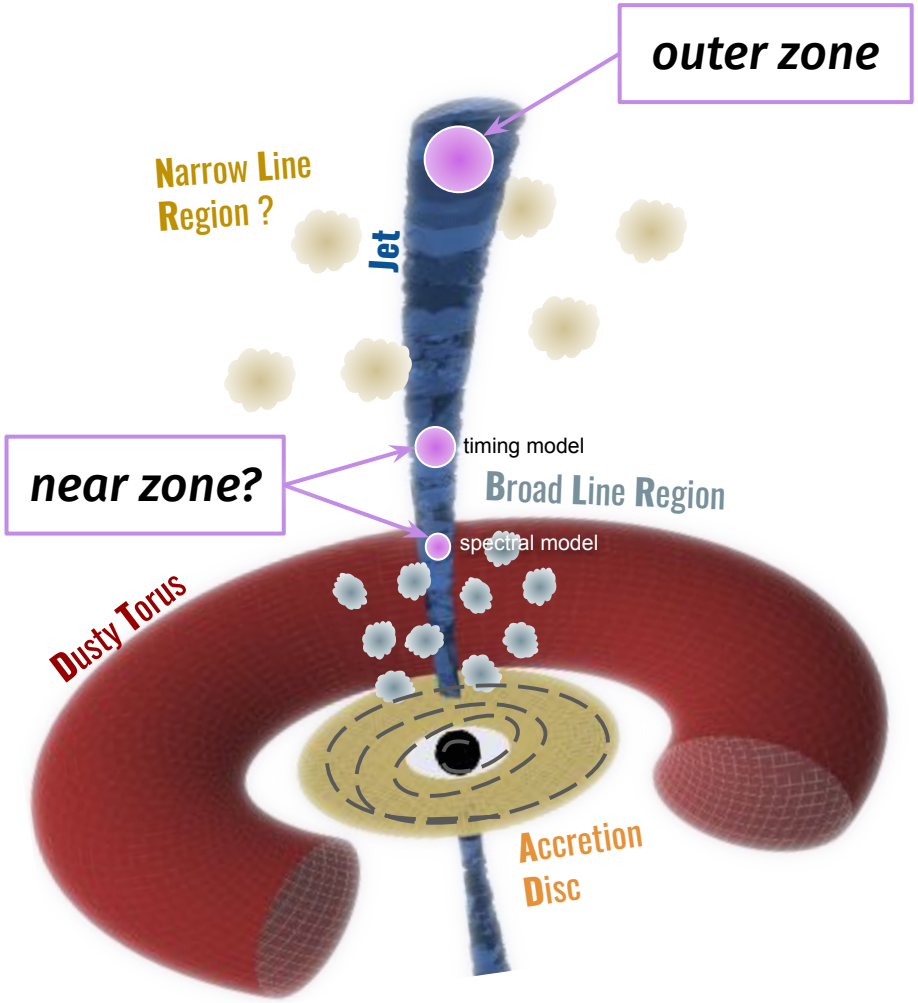
Results: SED modeling



Base model: Two-zone leptonic non-interacting model + external compton on BLR and DT fields.
Two suggested solutions: "spectral-focused" and "timing-focused"

Outer zone:

- Outside the BLR and DT photon fields. Negligible EC contribution.
- Stable over the observation periods.
- Synchrotron dominates in radio to IR.
- Contribution in X-rays
  - "spectral-focused" model: SSC dominates in hard X-rays.
  - "timing-focused" model: SSC negligible.

Inner zone:

- Inside DT field (both models), close to BLR field in spectral-focused model.
- Only electron densities and spectra change.
- Dominates UV (high-state), soft X-rays (also optical and hard X-rays in timing model) and gamma-rays.
- "timing-model": X-rays and gamma-rays due to EC-DT. SSC negligible.

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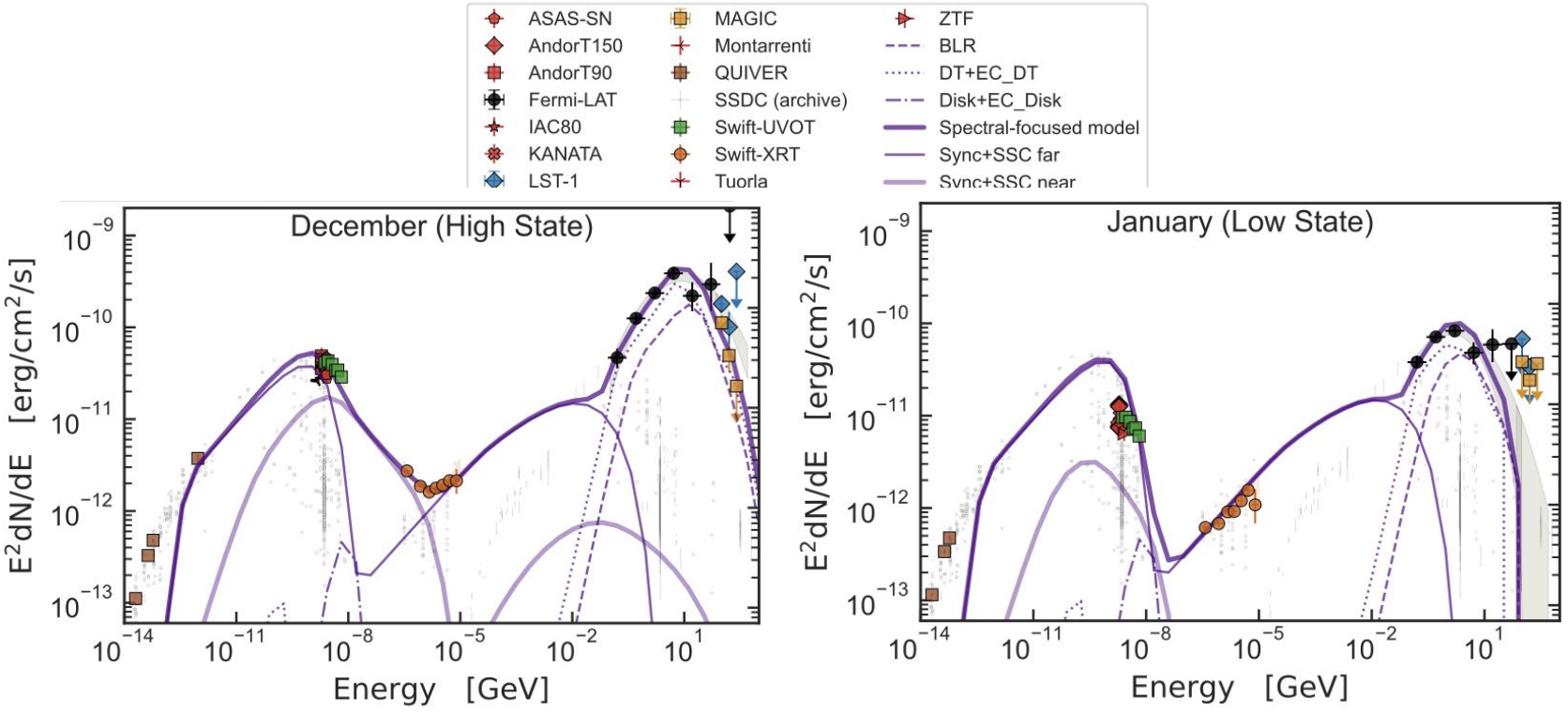
Results: SED modeling - *spectral-focused model*



- Captures nicely the "*X-ray-to-gamma-ray*" spectrum (allowed by balancing the different target photon fields).

- Near zone has a large Doppler factor (~100) → stationary shock in the jet? (otherwise over ~month scales a moving blob with Doppler ~100 would travel too long distances).

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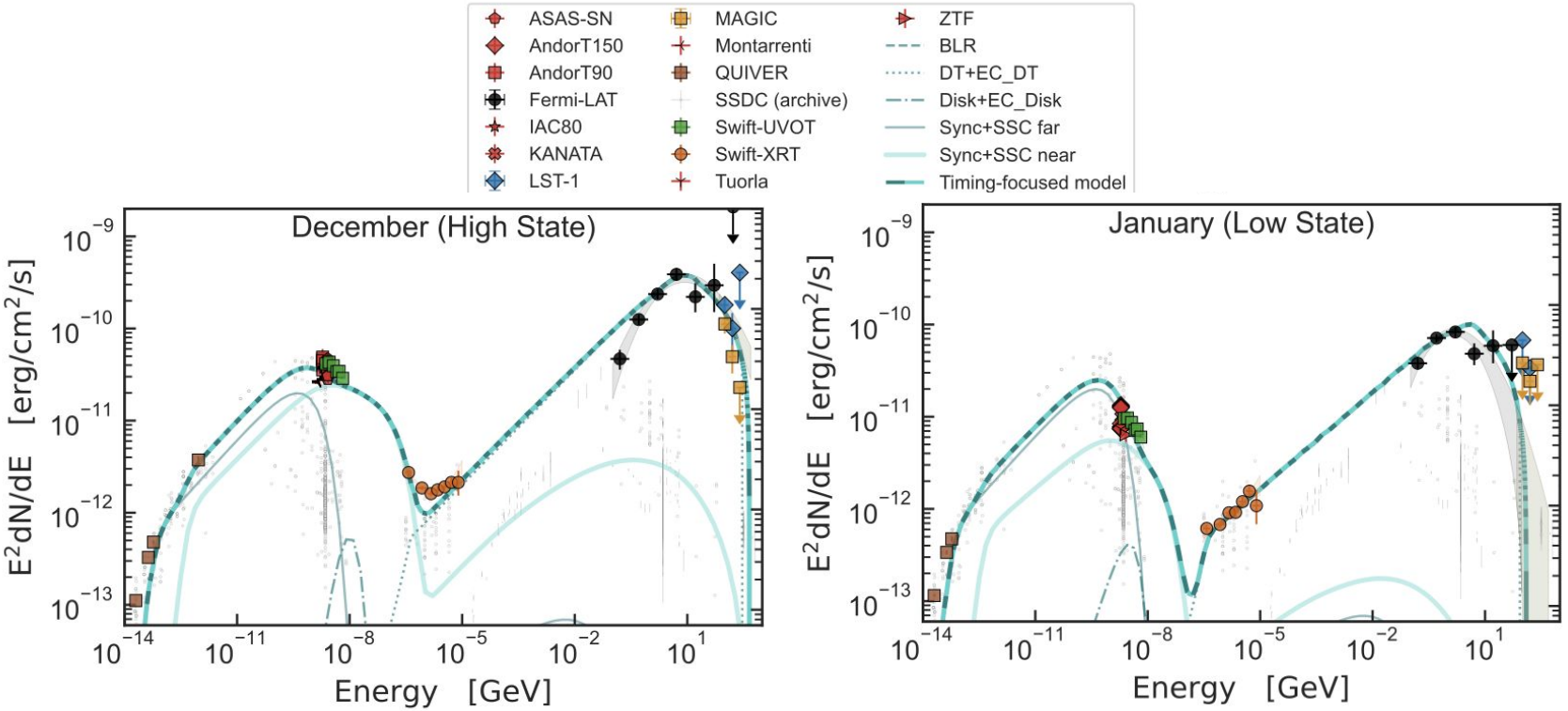
Results: SED modeling - *timing-focused model*



- Single zone dominates from optical to VHE band: reproduces correlations better
- "*X-ray-to-gamma-ray*" spectrum during high-state not so well reproduced.
- Optical/UV low-state better reproduced.
- Radio band better reproduced.
- More reasonable Doppler factor (~50).

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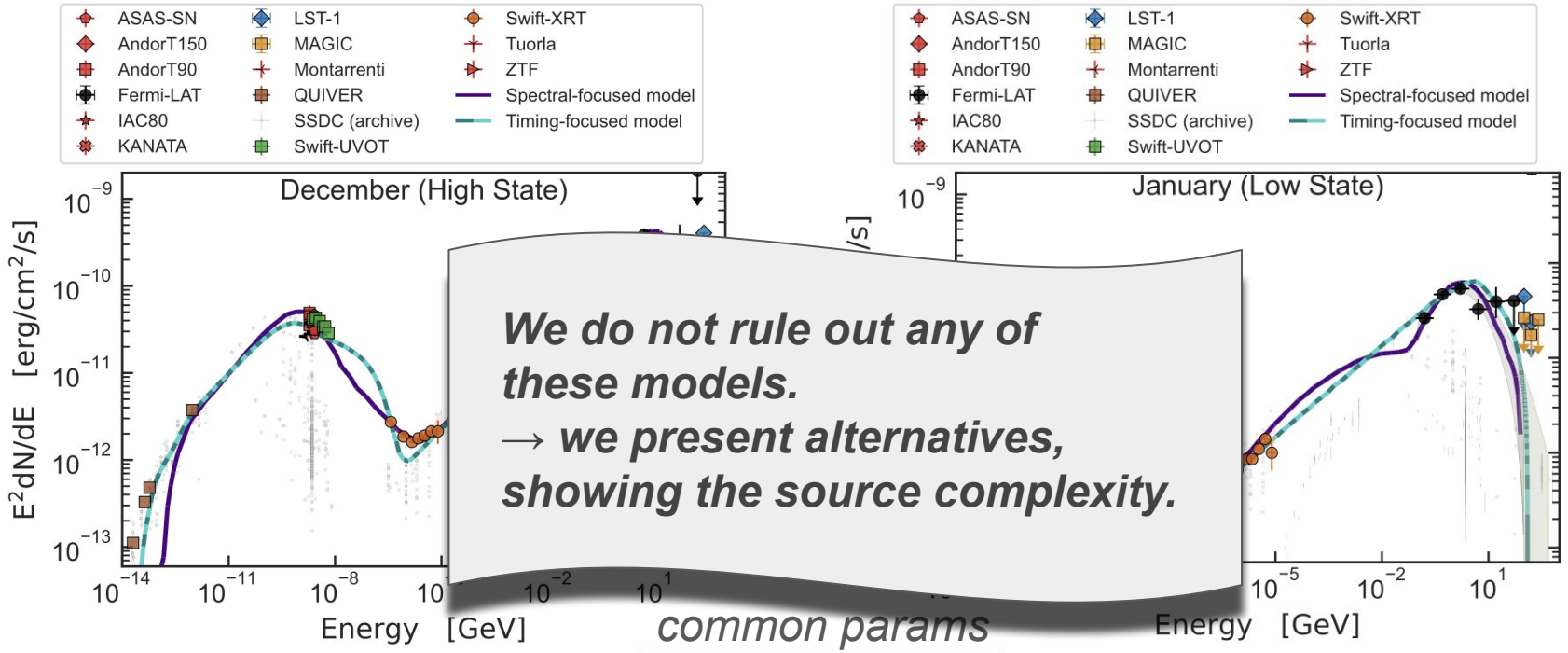
Results: SED modeling - *parameters*



We do not rule out any of these models.
→ we present alternatives, showing the source complexity.

common params

Parameters	Values
$M_{\rm BH}$ $[M_\odot]$	$10^{8.57}$
$L_{\rm AD}$ $[10^{45}$ erg s$^{-1}]$	9
η	1/12
R_{in} $[R_g]$	5
R_{out} $[R_g]$	50
$L_{\rm BLR}$ $[10^{44}$ erg s$^{-1}]$	9
$\xi_{Ly\alpha}$	0.023
$R_{Ly\alpha}$ $[10^{16}$cm]	9.5
$L_{\rm DT}$ $[10^{45}$ erg s$^{-1}]$	1.8
$T_{\rm DT}$ [K]	800
$\Xi_{\rm DT}$	0.2
$R_{\rm DT}{}^a$ $[10^{16}$cm]	1875

spectral-focused model

Parameters	"near zone"		"far zone"
	December 2023	January 2024	
B' $[10^{-2}$G]	35	35	23
R' $[10^{16}$cm]	1	1	20
δ	99	99	19
Γ	50	50	10
N_e $[10^{-5}$ cm$^{-3}]$	20	1.0	2.5
n_1	1.8	1.8	2.1
n_2	4.0	4.0	––
γ'_{min}	3×10^2	3×10^2	1.0
γ'_{br}	3×10^3	1×10^3	––
γ'_{max}	5×10^4	1×10^4	8×10^3
R_H $[10^{17}$cm]	2.9	2.9	200

timing-focused model

Parameters	"near zone"		"far zone"
	December 2023	January 2024	
B' $[10^{-2}$G]	15	15	15
R' $[10^{16}$cm]	6.5	6.5	200
δ	50	50	20
Γ	25.3	25.3	10
N_e [cm^{-3}]	1.15×10^3	1.04×10^3	1.13
n_1	2.2	2.3	2.1
n_2	3.3	3.6	–
γ'_{min}	1	1	1
γ'_{br}	6×10^3	4×10^3	–
γ'_{max}	5×10^4	2×10^4	7×10^3
R_H $[10^{17}$cm]	31.3	31.3	200

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Conclusions

the paper of the many *firsts*.

- First paper of the OP 313 series, more to come.
- First estimation (upper constraint) of EBL < 1 μm in the CTAO era. First with a real forward-folding of *Fermi*-LAT and LST & MAGIC data (!).
- First study of the systematics between IACTs at the lowest energies and new spotted challenges. More refinements on this to come in follow-up studies.
- First attempt to pack all data (including VHE, DL4 stage) and analysis code for fully reproducible results. Preparing a github + zenodo.
- Beautiful flare, with excellent temporal coverage from near IR to gamma-rays and high correlation for all bands except radio.
- Challenging SED modelling: two leptonic 2-zone scenarios proposed.
  No unique solution. Long-term dataset integration should give a clearer picture.
- Possible (lepto)-hadronic modeling to come in further studies.


← To Garafia
Residencia / dorms
LST-3
LST-4
LST-2
LST-1
MAGIC II
MAGIC I
To Santa Cruz →
To summit, GTC, TNG, NOT
STOP

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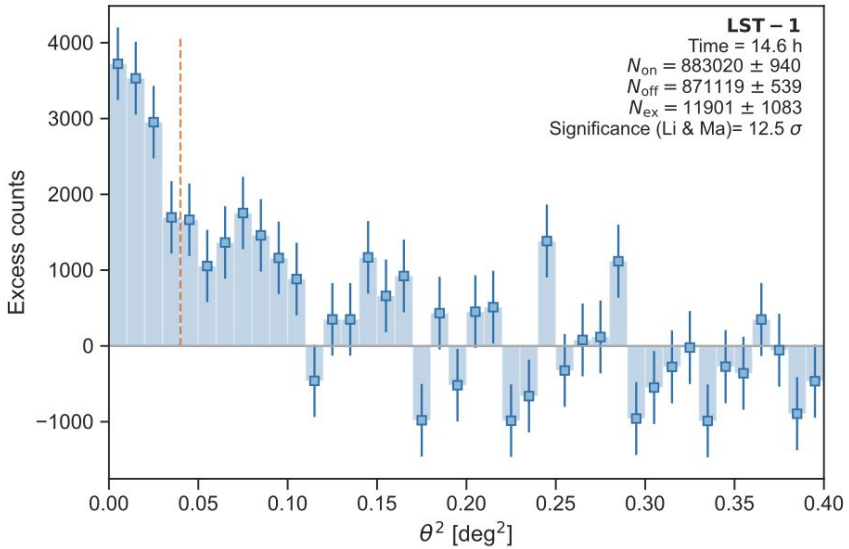
Backup

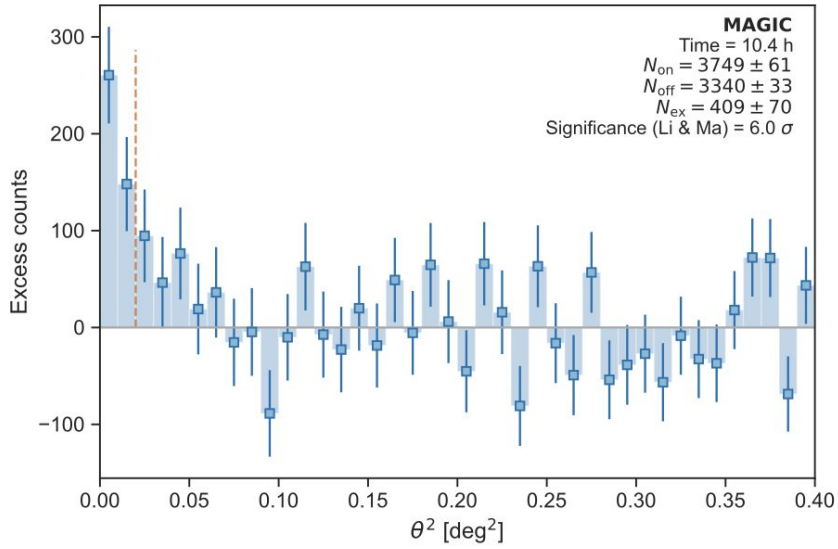
VHE analysis & detection

LST-1



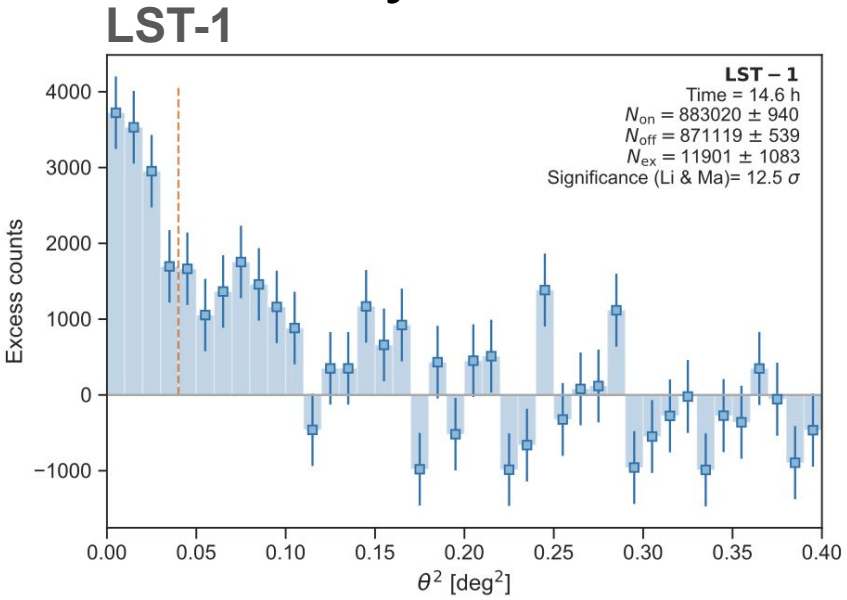
- Software: cta-lstchain
- RFs: trained with MCs (protons + gammas) along dec. 34.76 deg.
- IRF interpolation.
- Cuts: energy-dependent, 70% gammas in gammanness & theta2.
- Threshold: 60 GeV.
- Significance: 12.9 sigma, but only 1.4% SBR (syst. unc. 0.5%).
- Post-analysis: gammapy 1.3. Safe mask: 5% aeff.
- Nightly runs pre-stacked to maximize statistics in LC.
- Energy-scale syst (LST + MAGIC Crab): +/- 5%, likely higher <100 GeV. Flux syst: +57%/-47%.

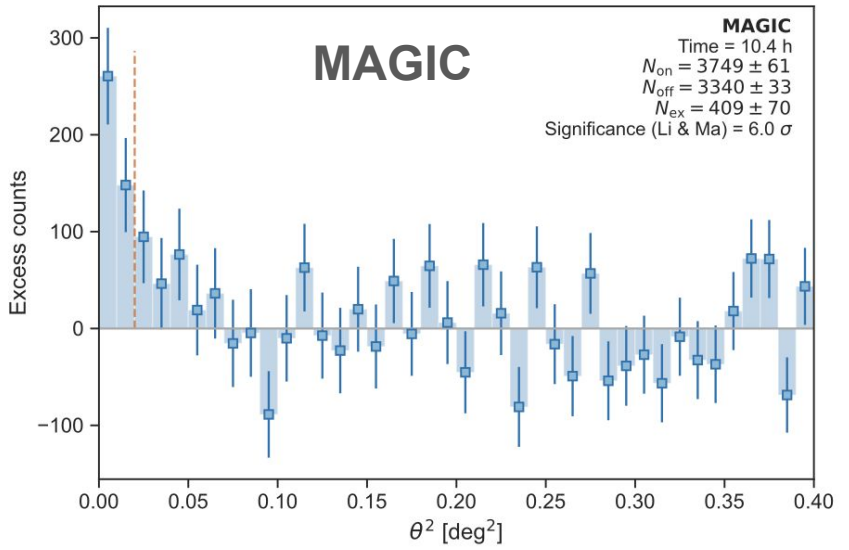
MAGIC



- Software: MARS + DL3 converter
- RFs: trained with MCs (gammas & real bkg).
- Cuts: energy-dependent for SED, fixed for theta2 plot. Optimized for low energies. 72% gammaness & theta2<0.2, size cut
- Threshold: 70 GeV.
- Significance: 6.0 sigma, SBR > 10%.
- Post-analysis: gammapy 1.3. Safe mask: 1% aeff.
- Nightly runs pre-stacked to maximize statistics in LC.
- Energy-scale syst (LST + MAGIC Crab): +/- 5%, likely higher <100 GeV. Flux syst. +74%/-52%.

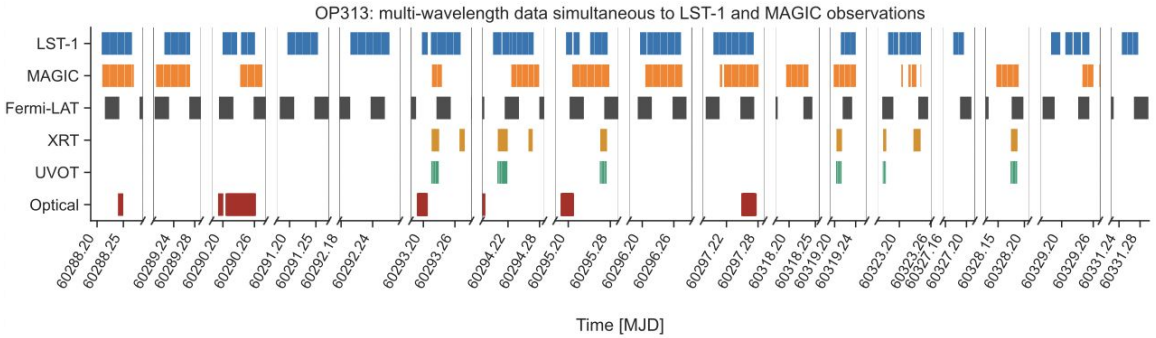
Why not LST-1+MAGIC joint analysis?





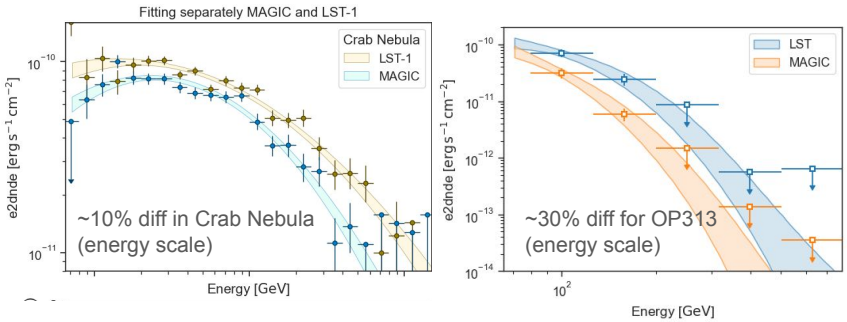
- **Observing times:** not everything is joint
  - Keeping only joint observations: excess statistics drops dramatically w.r.t to LST-1.
  - Doing a mix: complicated analysis (weight more events with better reconstruction?

- **Excess**: LST-1 has 11901 +/- 1083 events vs 409 +/- 70 events in MAGIC



Results: MWL LC

- Some discrepancies remaining for VHE. Understood as systematics



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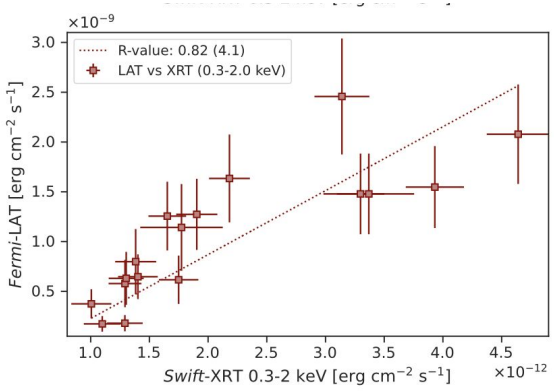

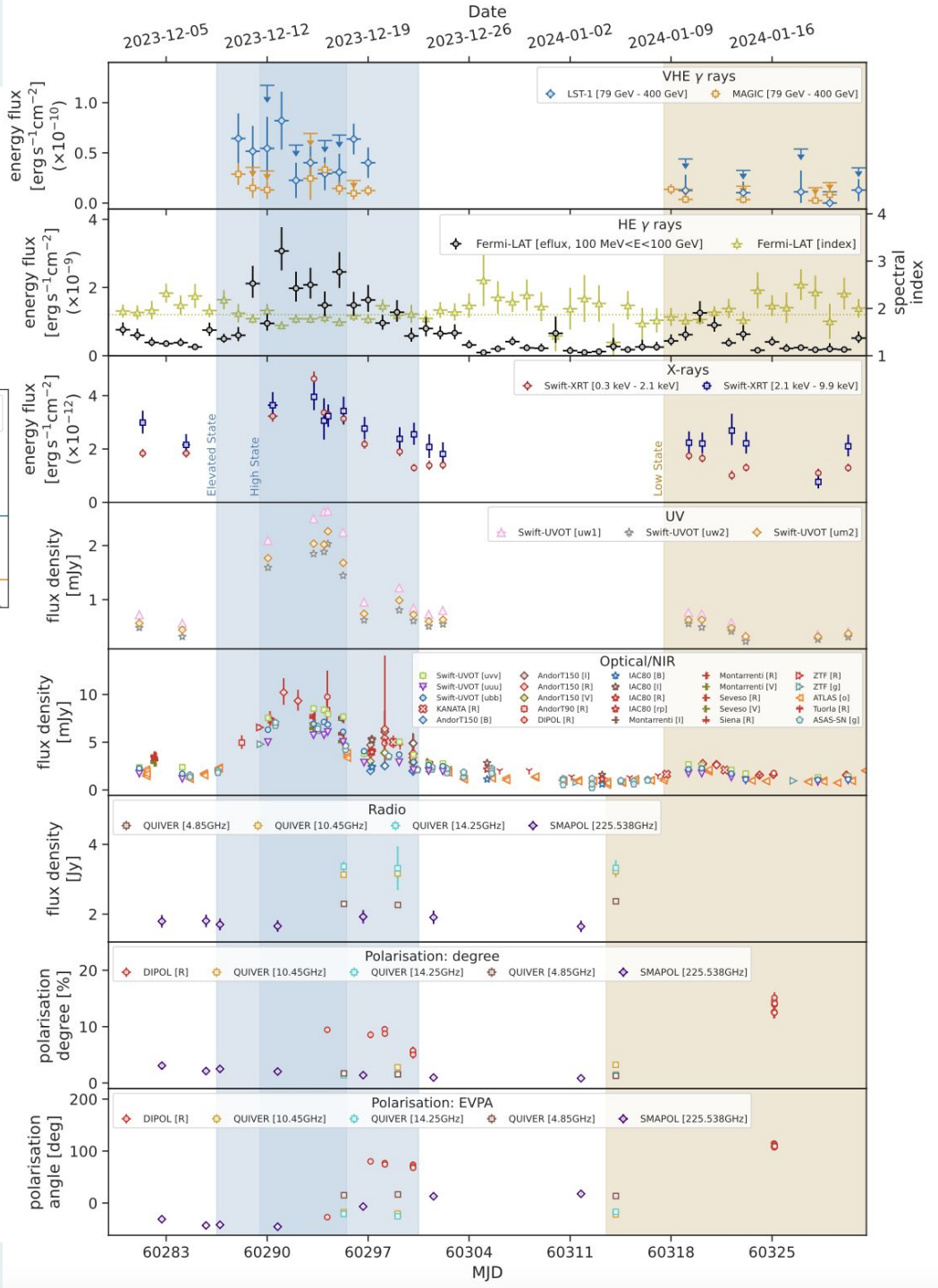

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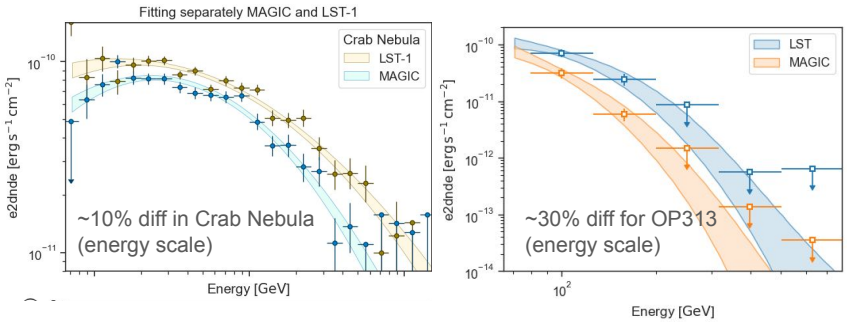

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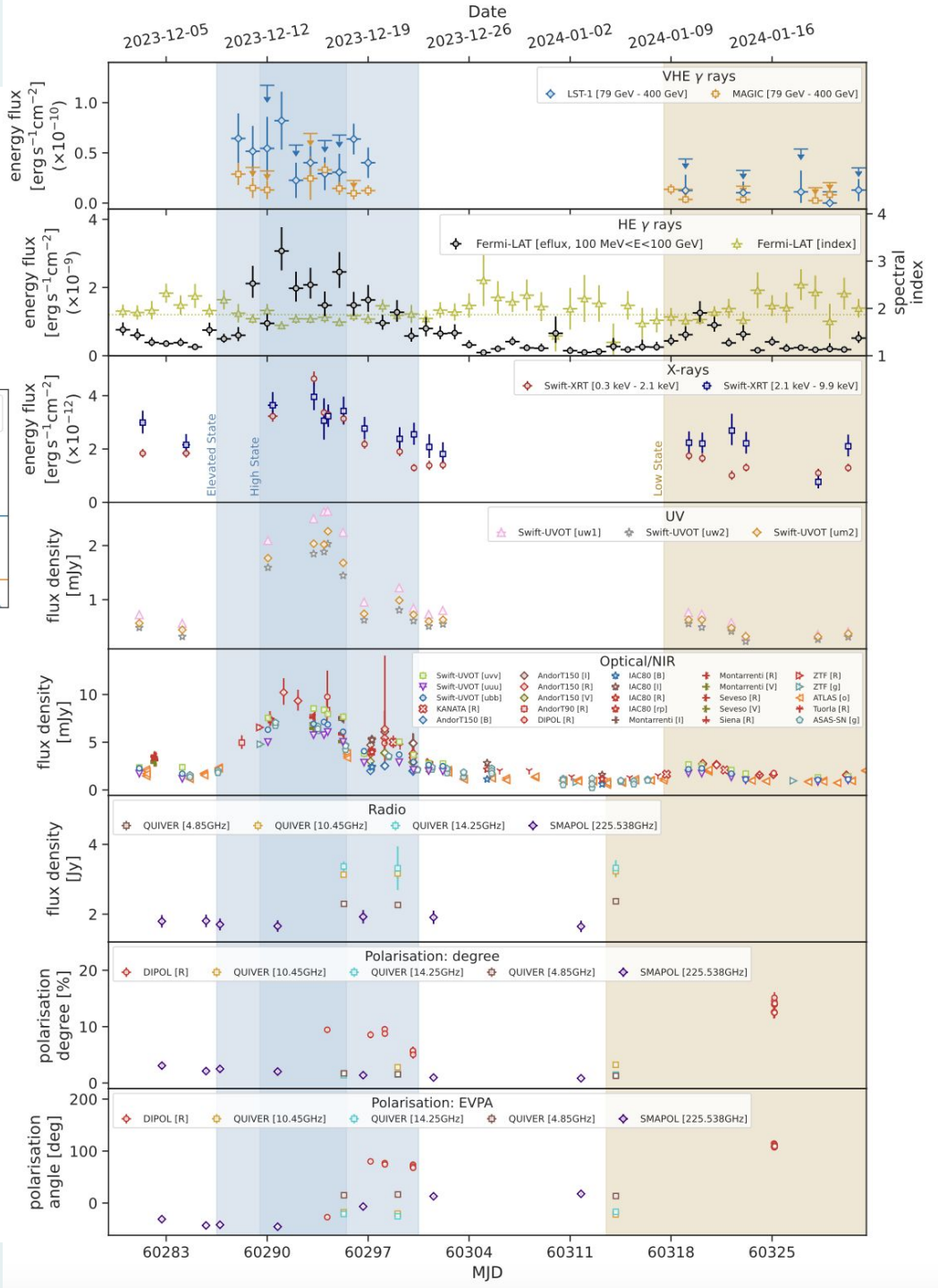
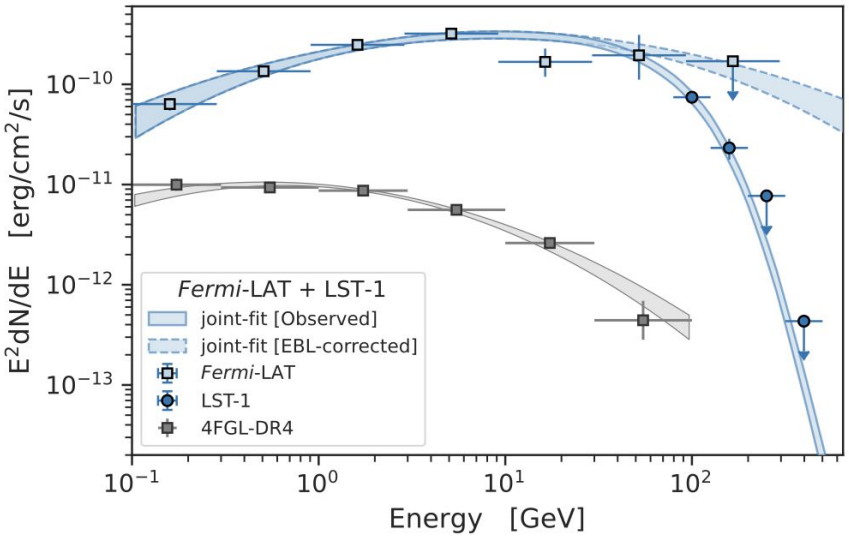
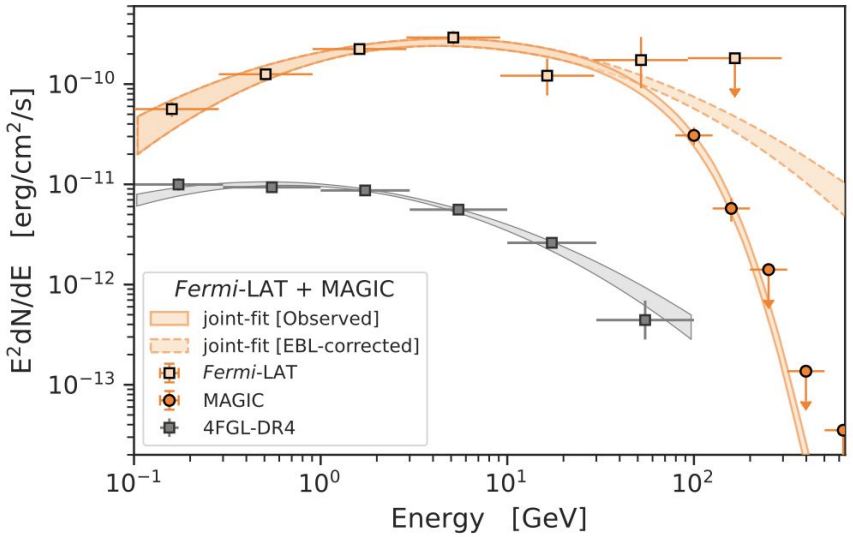


Results: joint gamma SED & EBL





(Stacking of nightly data during the extended high state)

- Intrinsic emission: clear curvature. LP fit is reasonable.
- Different best-fit parameters between LST-1 and MAGIC: different GTIs + systematics.
- Individual analysis provided for each set. Fermi-LAT extracted from individual night-bins matching the observing nights of LST or MAGIC.

Best-fit with IACT-only, LAT-only and LAT+IACT →

IACT

Period	Telescope	Observation time [h]	E_{th} [GeV]	Li & Ma significance	$\phi_0(E_0)$ [10^{-8} cm^{-2} s^{-1} TeV^{-1}]	Γ	F_γ (> 100 GeV) [10^{-10} cm^{-2} s^{-1}]
December	LST-1	14.6	~ 60	12.9	1.15 ± 0.14	1.99 ± 0.55	1.50 ± 0.21
	MAGIC	10.4	~ 60	6.0	0.39 ± 0.07	3.33 ± 0.64	0.41 ± 0.09

Fermi-LAT

Name	MJD	$\phi_0(E_0)$ [10^{-8} cm^{-2} s^{-1} GeV^{-1}]	α	β
LST-1 December	60287.5, 60288.5, 60289.5 60290.5, 60291.5, 60292.5 60293.5, 60294.5, 60295.5 60296.5	4.06 ± 0.31	1.70 ± 0.08	0.17 ± 0.05
MAGIC December	60287.5, 60288.5, 60289.5 60292.5, 60293.5, 60294.5 60295.5, 60296.5	3.70 ± 0.32	1.77 ± 0.09	0.14 ± 0.05
LST-1 January	60318.5, 60322.5, 60326.5, 60328.5, 60330.5	1.22 ± 0.20	2.07 ± 0.14	0.20 ± 0.02
MAGIC January	60317.5, 60318.5, 60322.5 60327.5, 60328.5	1.28 ± 0.20	2.14 ± 0.16	0.34 ± 0.09

LAT + IACT

Name	$\phi_0(E_0)$ [10^{-9} cm^{-2} s^{-1} TeV^{-1}]	α	β	E_{peak} [GeV]
LST-1 December	11.0 ± 1.4	2.47 ± 0.11	0.10 ± 0.02	8.90
MAGIC December	4.11 ± 0.56	2.89 ± 0.11	0.14 ± 0.02	4.53