Follow-up of LVK O4 Gravitational Wave events with MAGIC and LST-1

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and MAGIC & CTAO/LST collaborations.

TeV Particle Astrophysics
TeVPA
Valencia 2025

MAGIC

CTAO

IFAE
Institut de Física d'Altes Energies

Why Search for VHE emission from Binary Black Holes (BBHs)?

LIGO–Virgo–KAGRA (LVK) reported mergers; **most are BBHs**.

So far, no confirmed electromagnetic counterpart observed. But several models predict transient GeV–TeV emission if residual accretion or jet formation occurs.

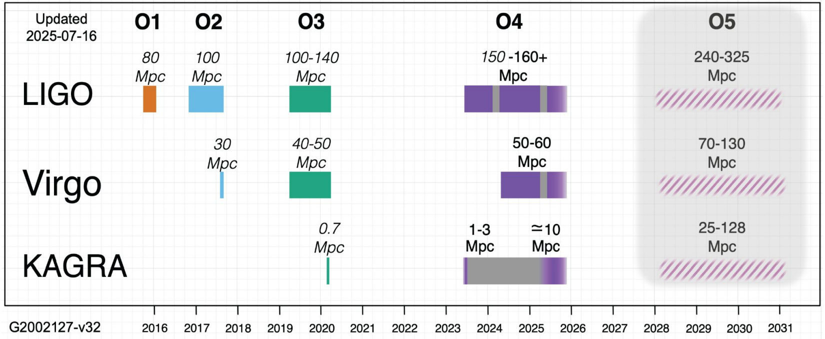
- We observed **two of the most interesting events** of O4.

MAGIC: Two Imaging Atmospheric Cherenkov Telescopes (IACTs). Energy threshold: ~50 GeV (FoV: 3.5 deg).

LST-1: The first Large-Sized Telescope (23m) of the CTAO. Energy threshold: ~20 GeV (FoV: 4.3 deg).

- **Joint setup**, both located at the Observatorio del Roque de los Muchachos, La Palma, Spain. With offline stereo event coincidence.

dcc.ligo.org



The Development of Ground-Based Gamma-Ray Astronomy (R. Mirzoyan)

The BBH Merger Candidates

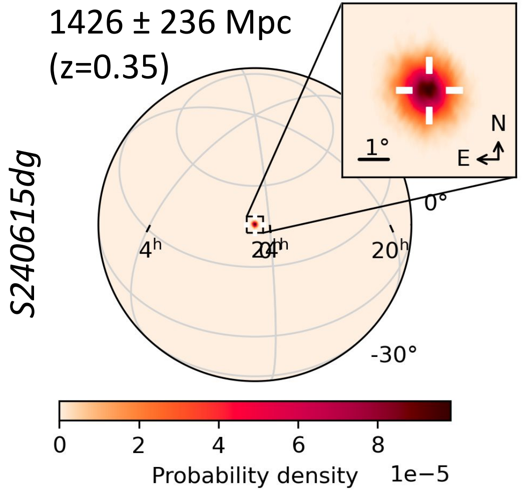
- Both classified as **Binary Black Holes** (BBHs)

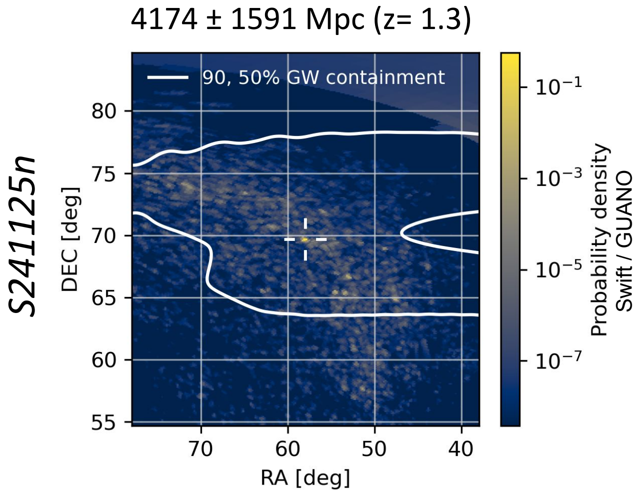
S240615dg [GCN, GraceDB]

- **Best localized GW up to now** (90% area is ~5 deg²).
    - Could be covered by one MAGIC / LST pointing (No tiling).
    - No detection in the EM by any other instrument.
- Estimated chirp mass of the events: M ~ 140 M⊙.

S241125n [GCN, GraceDB]

- **Swift/GUANO potential counterpart** ($T - T_0 = 11$ s).
    - Sub-threshold detection.
    - Spatial coincidence rate 1 / 12 yrs.
    - No known redshift.
- No other detection for other instruments. Many observed it.
- Estimated chirp mass: M ~ 115 M⊙.





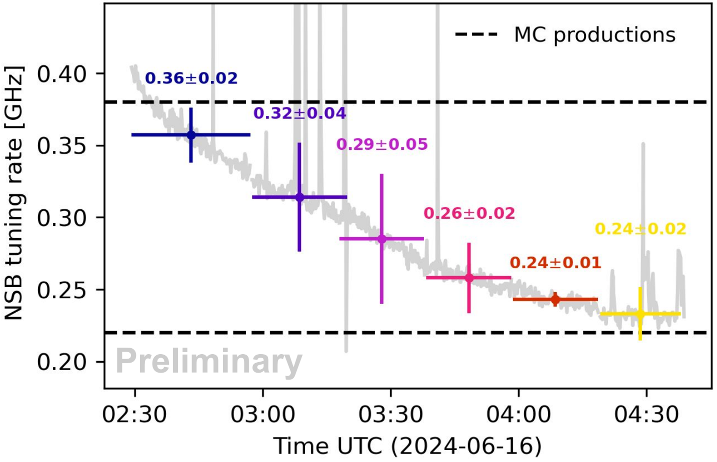
Observation conditions

S240615dg

- Observed at T - T0 = 15h (t_{obs} = 2h).
- **High Zenith** observations (45 deg < ZD < 65 deg).
- **High NSB**, moon just set before observations start.

Energy threshold, ~0.2 TeV (LST-1), ~0.4 TeV (LST+MAGIC).

S240615dg



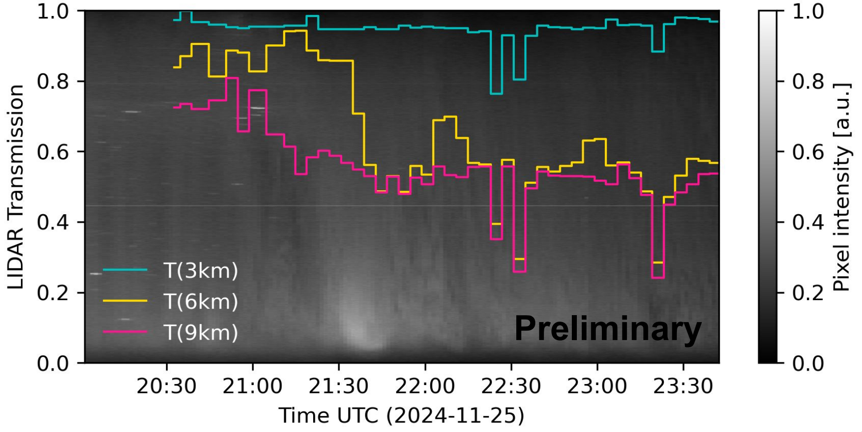
S241125n

- Observed at T - T0 = 19h (t_{obs} = 4h).
- **Bad weather**. LIDAR shows a cloud @ 6 km a.g.l.
- **High Zenith** observations (40 < ZD < 60)deg.

Energy threshold, ~0.5 TeV (LST+MAGIC).

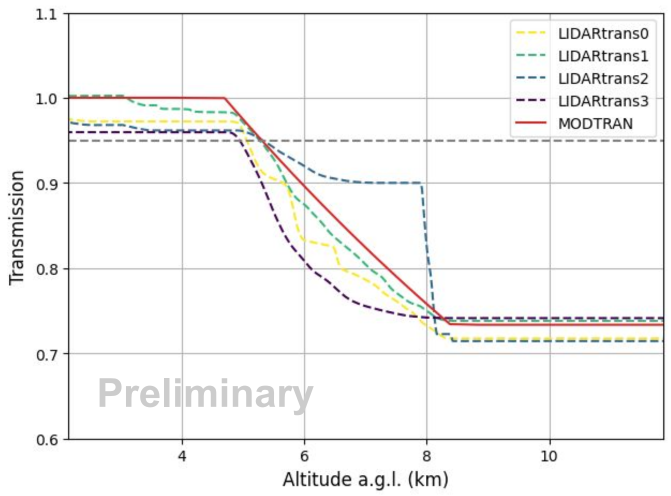
Only ~1h out of 4 can be saved (with mixed mono/stereo data)

S241125n



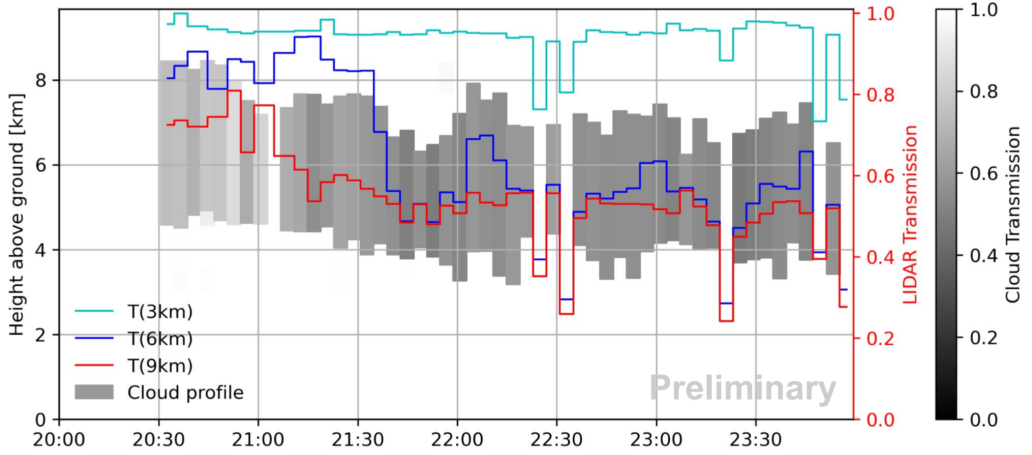
Correcting for adverse atmospheric conditions in IACT observations

- For **S241125n**
- Possible methods:
  - Height-dependent corrections [A&A, 685, A165 (2024)]
  - **Dedicated MCs**, specific MC simulations.



LIDAR atmospheric profile showing a cloud at 6km with ~0.75 transmission.

- We include this cloud in the MC files used to analyse the data.



Global Upper Limits from GW-Weighted analysis

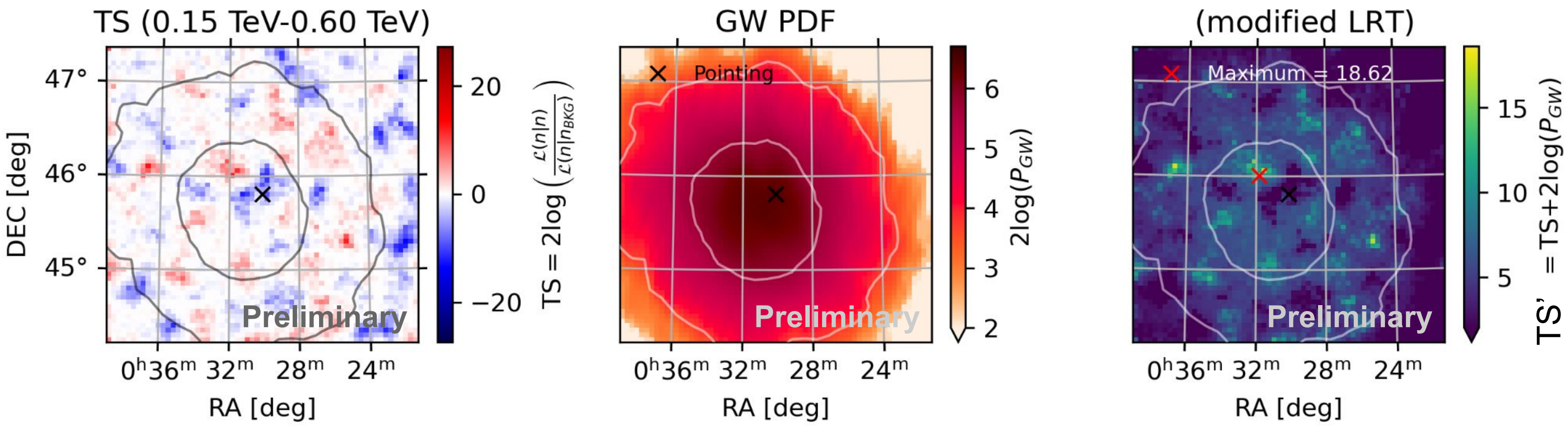
We compute **sky-maps** of statistical significance and flux Upper Limits (ULs) but also a **single global significance and UL** for gamma emission spatially coincident with the GW source.

- Inspired from neutrino analysis, frequentist approach (IceCube2019) to estimate unique **significance and flux ULs**.

We **modify the standard Test Statistics to add the GW information** using LVK Sky-Map.

$$\mathrm{TS}'_i = 2\log\left(\frac{\mathcal{L}_i^{\text{source+BKG}} \cdot P_i^{GW}}{\mathcal{L}_i^{\text{BKG}}}\right)$$

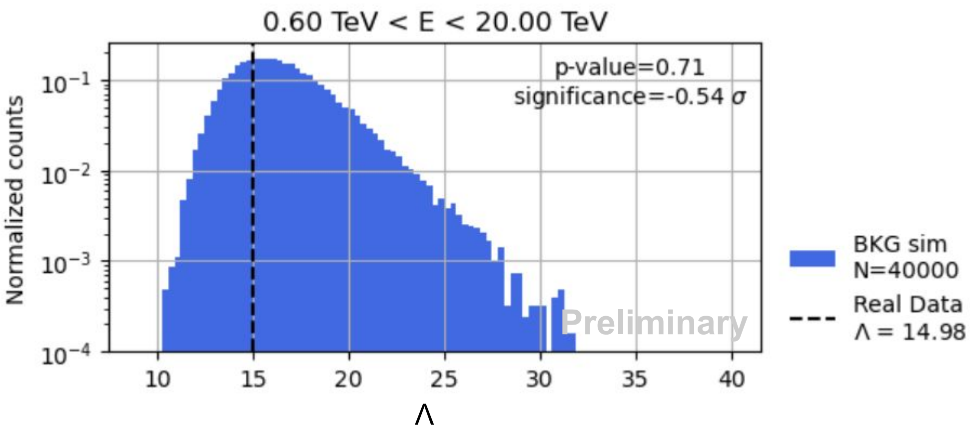
Then we define our **parameter Λ as the maximum TS' in the 95%** probability region.



We produce simulations for same observation conditions.

- First **under the null hypothesis** (No source).
- We compare Λ_{data} with the Λ_{BKG} distribution, and then we compute the significance based on the p-value.

We can repeat the simulations but **injecting a source with different amplitudes** in a position following the LVK Sky-Map PDF.

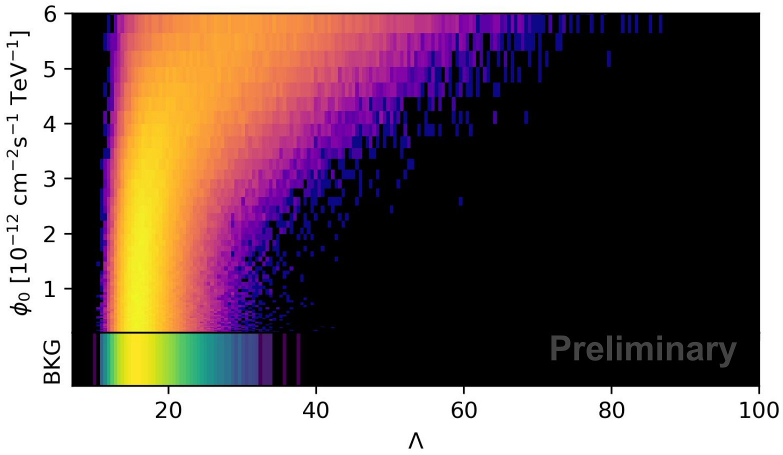


After some value, the distribution deviates from BKG distribution.

- **Flux UL**: flux required such that 95% of trials return $\Lambda f > \Lambda_{data}$.

Conservative approach. If data comes from negative fluctuations we compare Λ with the BKG simulation.

- **Sensitivity**: flux required such that 95% of trials return $\Lambda f > \Lambda_{BKG\text{-}median}$.



Results: S240615dg

Two different analysis are performed:

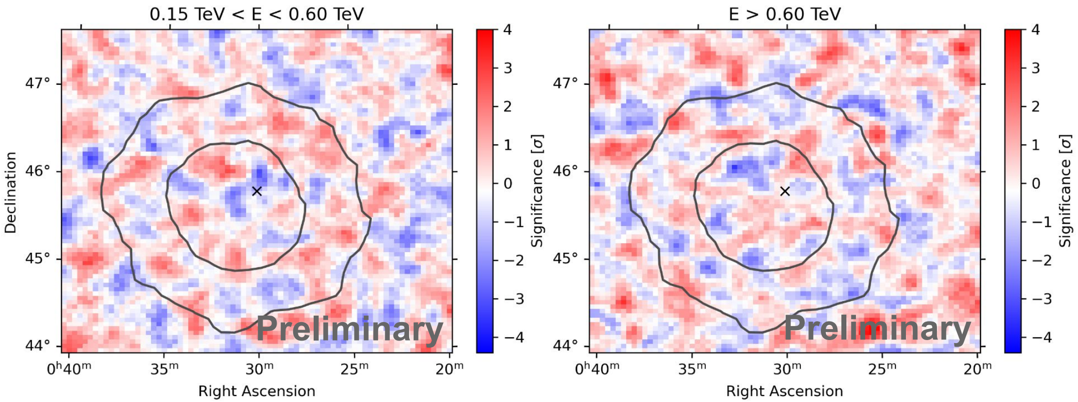
- **Low Energy**: Taking advantage of mono-LST lower energy threshold. **(0.15 TeV < E < 0.6 TeV)**.
- **High Energy**: using stereo LST+MAGIC. **(E > 0.6 TeV)**.

No significance hot spots are seen.

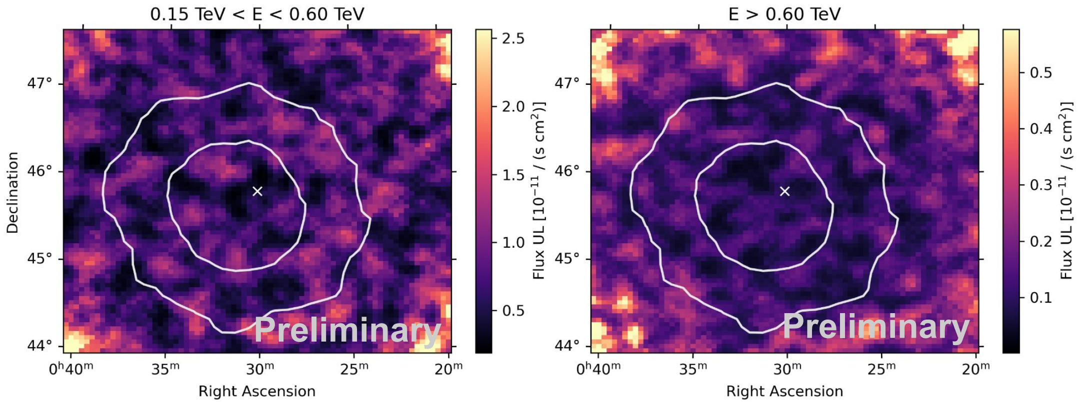
Flux Sky-Map for both analysis and estimation of **global ULs**.

	Significance	U.L. $(s^{-1}\,cm^{-2})$	U.L. (C.U.)
$0.15 < E < 0.6$ TeV (LST-1)	-0.73σ	4.41×10^{-11}	10.96 %
$E > 0.6$ TeV (LST+MAGIC)	-1.00σ	3.48×10^{-12}	5.93 %

Significance Sky-Maps



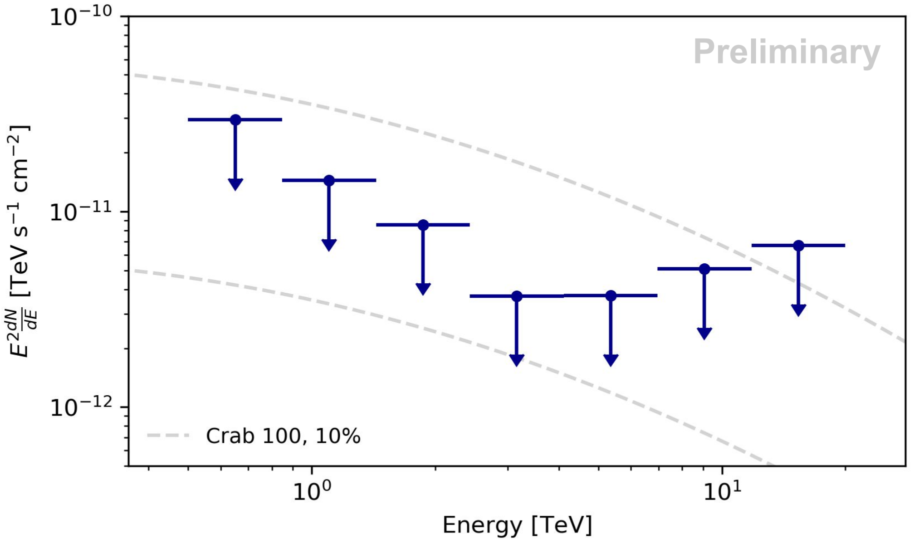
Flux Upper Limits Sky-Maps



Results: S241125n

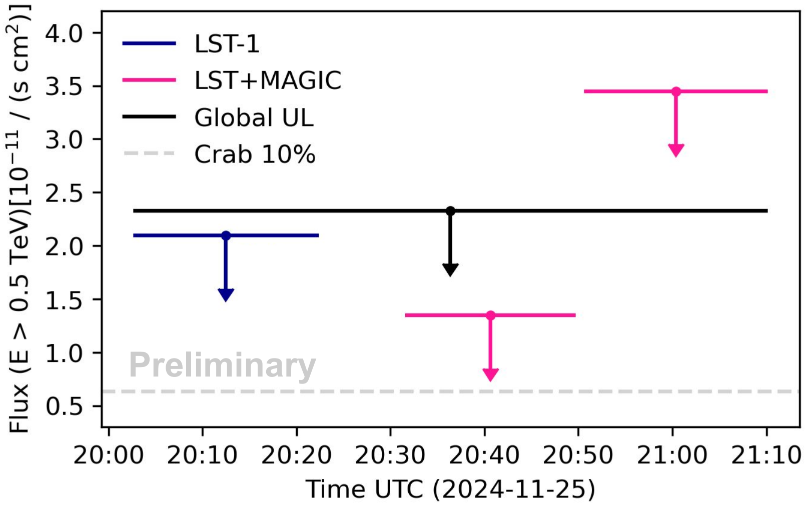
We are covering only the candidate counterpart region. We perform *point-like* analysis.

- Detection significance: -0.12σ
- Spectral Energy Distribution (SED).

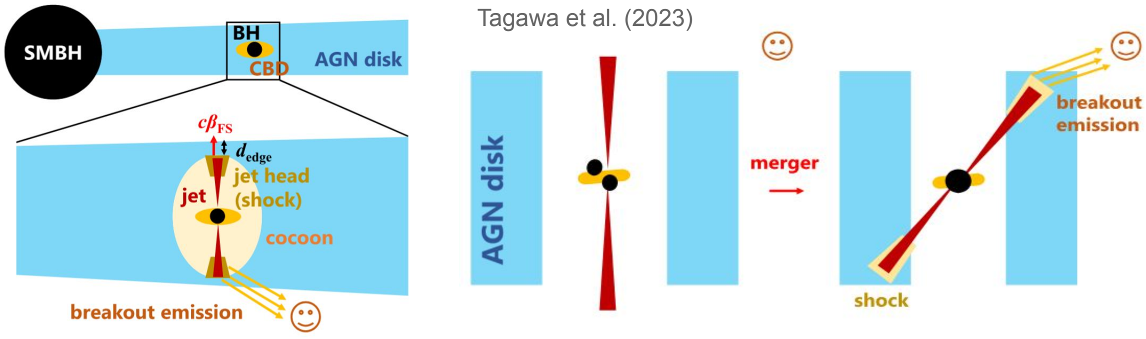


- Light Curve (LC).
  - Variation due to statistical fluctuations.

E > 0.5 TeV



Theoretical Interpretations



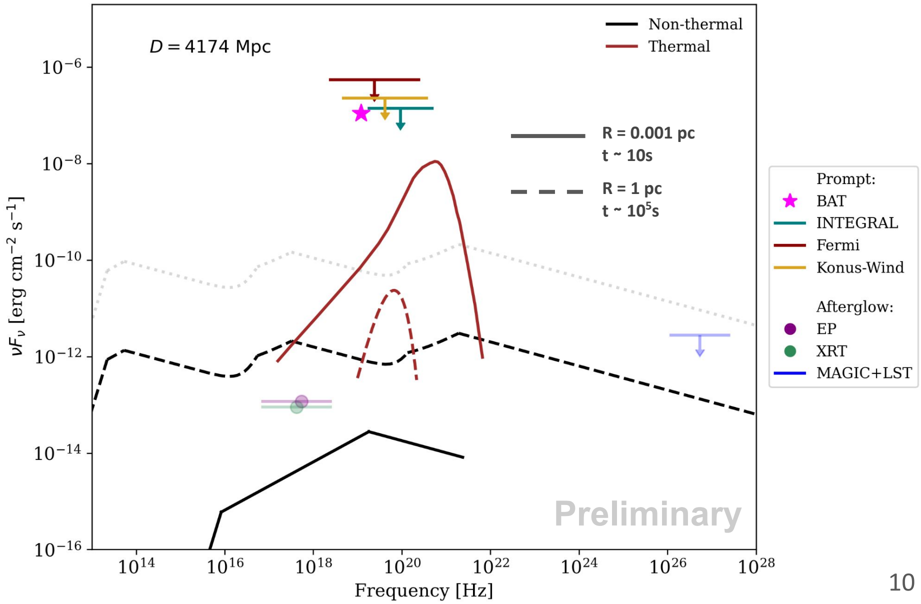
Inside an AGN disk, BBHs can accrete gas from the dense environment.

- **Super-Eddington accretion** mechanism for emission inside the disk.
- **Post-merger jet** scenario (Blandford–Znajek jet). Strong dependence on R, (radial distance from SMBH).

We can then, compute **upper limits on the Super-Eddington efficiency** parameter. Orders of magnitude above plausible values detectable by IACTs.

For S241125n, observed Swift-BAT delay (**≈ 6 s rest-frame**) and short duration imply a **merger deep inside the disk** (R ≲ 0.01 pc), then highly absorbed at TeV energies.

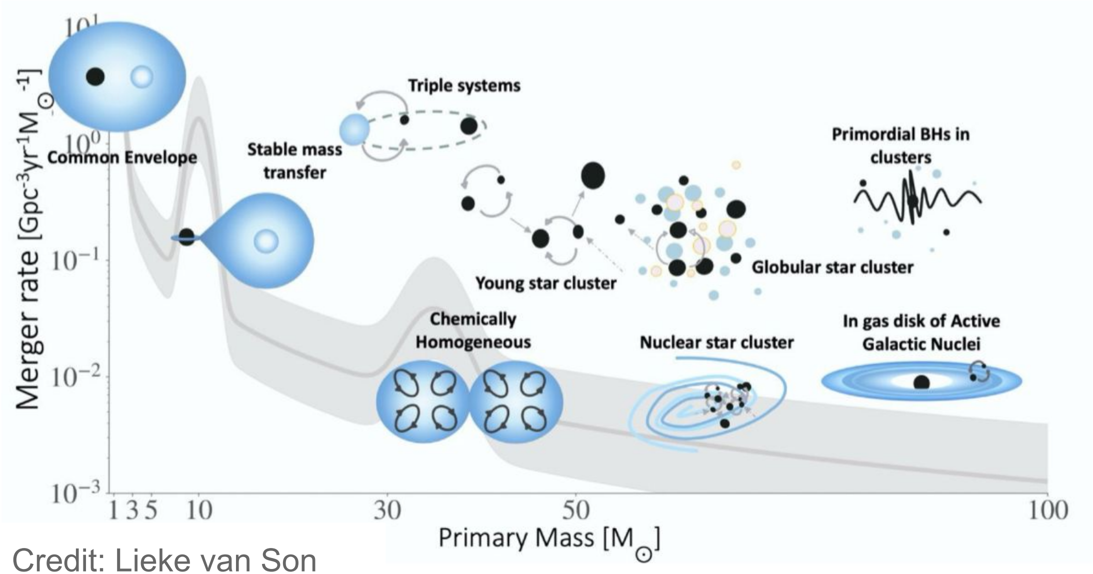
VHE fluxes are orders of magnitude below MAGIC + LST-1.



AGN Counterpart search for BBH merger events

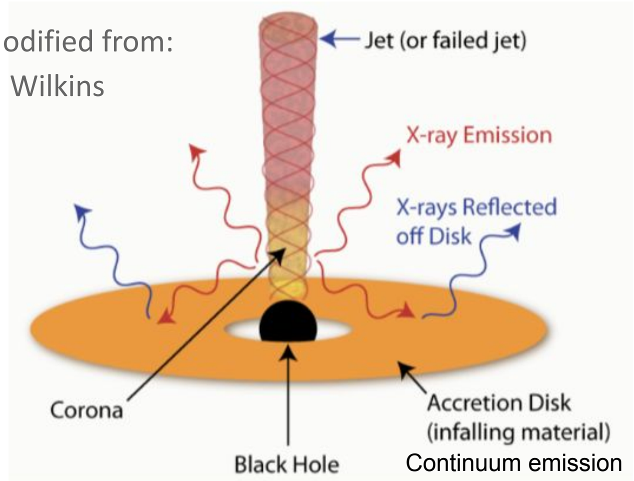
Both events are likely to have **large Primary Mass** > 100 M⊙.

- Then the scenario of the merger to be in an AGN disk becomes more relevant.
- Then we will try to find AGN candidates looking into different catalogs.
- Searching for continuum, UV and X-ray emission.



Credit: Lieke van Son

Modified from:
D. Wilkins



* redshift information included

Different catalogs to check

- Gaia DR3
- Glade+
- DESI-DR1 AGN
- GALLEX UV
- XXM-Newton 4XMM-DR10s
- Chandra CSC 2.1
- Swift XRT

Cross-matching different AGN catalogs with the LVK sky-map

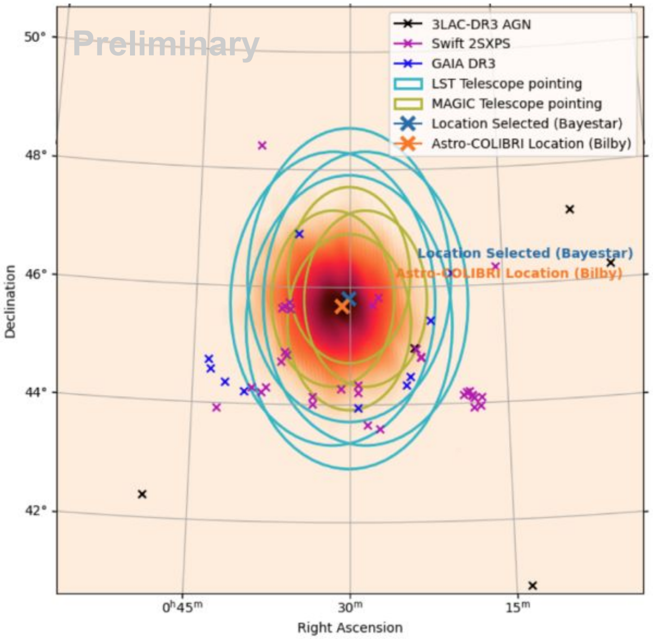
- First we look for the 2D coincidence.
- Then if the catalog contains redshift we use all 3D.

$$\frac{dP}{dV} = \rho_i \frac{N_{\mathrm{pix}}}{4\pi} \frac{\hat{N}_i}{\sqrt{2\pi}\hat{\sigma}_i} \exp\left[-\frac{(r-\hat{\mu}_i)^2}{2\hat{\sigma}_i^2}\right]$$

Going the Distance, Singer et al, 2016.

For ***S240615dg*** we found several AGNs in the volume. Still crosscheck between the different catalogs is being done.

For ***S241125n*** the search region is much smaller. Still the crossmatch is ongoing.



Conclusion and future prospects

- Analysis & Methodology:
  - **Global upper-limit** framework integrating GW skymap probability.
  - Implemented **tailored MC corrections** enabling analysis under suboptimal atmospheric conditions.
- Results:
  - **First joint MAGIC+LST-1** stereoscopic **follow-up of GW BBH events**.
  - No significant VHE gamma-ray emission detected from either BBH.
- Physical Interpretation:
  - Non-detections consistent with current *Super-Eddington accretion* and *BZ jet* models (Tagawa et al. 2023).
  - No compelling evidence of AGN association, but **compatible with merger occurring in AGN disk**.
- Outlook:
  - Analysis pipeline can be applied as well in poorly localised GRBs.
  - The global upper-limit methodology can be applied to observations in other wavelengths.

Backup

Instrumentation details

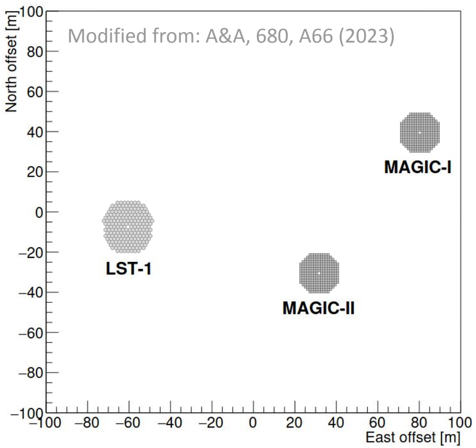
- **MAGIC**: Two 17 m Imaging Atmospheric Cherenkov Telescopes (IACTs) located at the Observatorio del Roque de los Muchachos, La Palma, Spain.

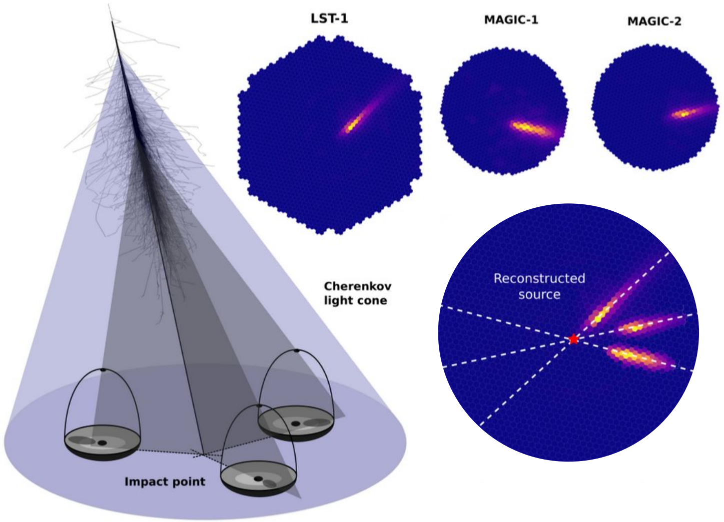
  Energy threshold: ~50 GeV. FoV: 3.5 deg.

- **LST-1**: The first Large-Sized Telescope (23m) of the CTAO.

  Energy threshold: ~20 GeV. FoV: 4.3 deg.

- **Joint setup** with offline stereo event coincidence
  - Larger collection area.
  - Better background rejection.
  - Sensitivity ~30% better than MAGIC.





About the False Alarm Rate of Swift-BAT detection

"The GRB candidate False Alarm Rate (FAR) is 3.74E-4 Hz. The joint GW-GRB FAR, combining the spatial and temporal information of both signals and correcting for trials, is 2.581E-9 Hz, or 1 every 12 years. "

- “Correcting for trials” refers to trials with different pipelines.
- No other trials are considered:
  - Taking into account the Swift time of observation.
  - Coincidence with LVK observation time.
  - Field of view of instrument and coverage over time.

Analysis parameters

`lstchain`: v0.10.20, `magic-cta-pipe`: v0.5.4, `gammapy`: 1.1

- FoV bins [0, 2.5] deg 5 bins.
- Energy bins: 4 bins per decade.
- Intensity cut (standard) intensity > 50 p.e.

- S240615dg:
  - Standard GammaDiffuse MCs.
  - Missing definitive stereo MCs (using before period).
  - Low Energy: gh-dyn cut 50% (background dominated).
  - High Energy: gh-dyn cut 70% (standard cut).
- S241125n:
  - Full enclosure MCs + point-like.
  - Dedicated MCs (50% splitting RF train + IRF).
  - Run-wise NSB settings.
  - Energy range: gh-dyn cut 90% (to gain more statistics)

Background modelisation

- FoV bins [0, 2.5] deg 5 bins
- Ring BKG [0.35 to 0.55] deg

Software used:

- Analysis: `pybkgmodel`
- Crosscheck: `BAccMod`

No exclusion masks (no HE sources nearby)

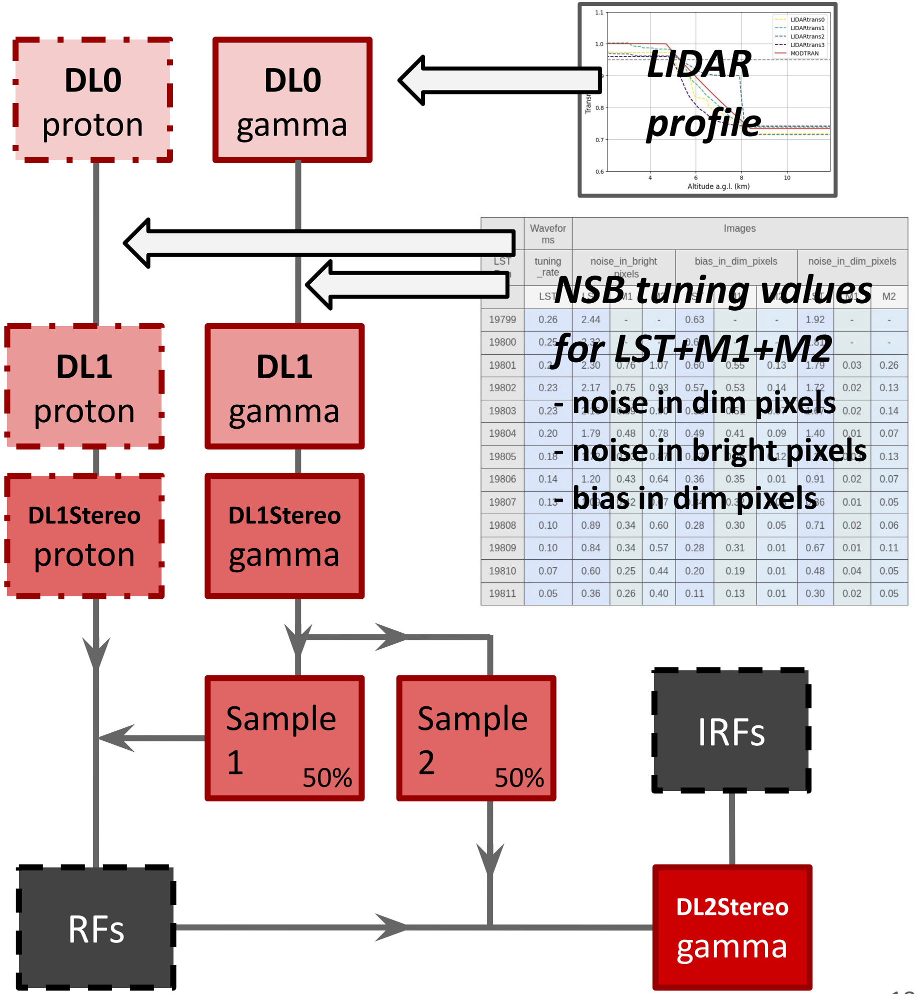
- 3D model
- FoV + Ring BKG

Dedicated MC simulations and fine tuning of RFs and IRFs

G. Voutsinas produced for us both the CORSIKA and SimTelArray simulations for the given atmospheric profile.

- Atmospheric profile provided by M. Pecimotika.
- NSB run-wise tuning.

All GammaDiffuse production is divided in 2 samples with proportion 1/2.



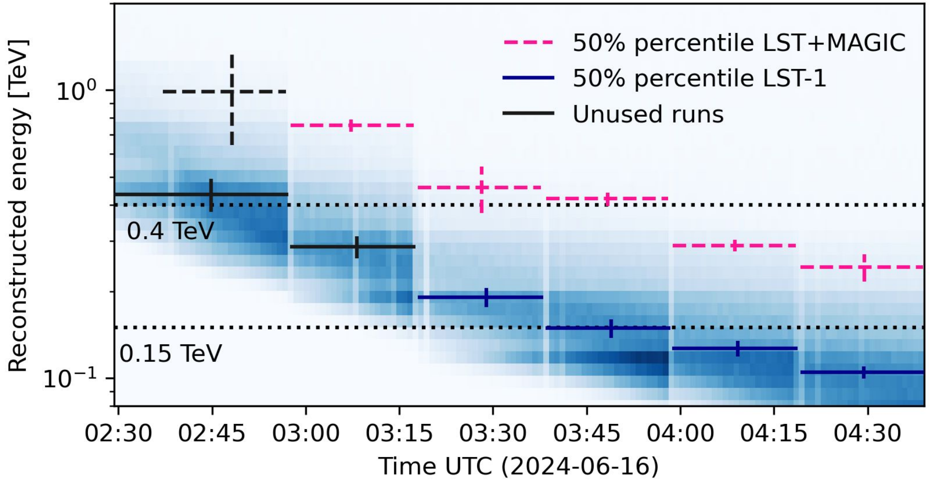
Observation conditions and energy threshold selection

Strong time evolution due to different factors:

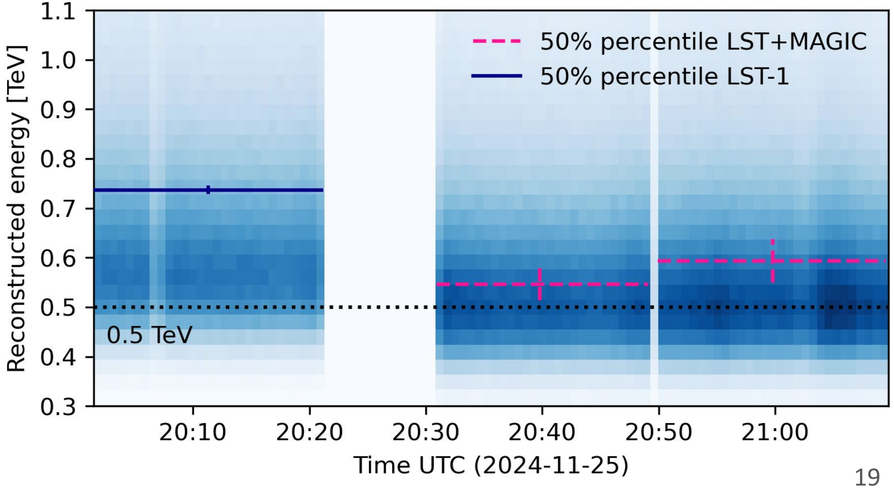
- Zenith going from ~60 deg to ~40 deg
- NSB decreasing over time

Using LST (mono) and LST+MAGIC (stereo) data together, so the selected threshold need to be common for both instruments.

S240615dg



S241125n

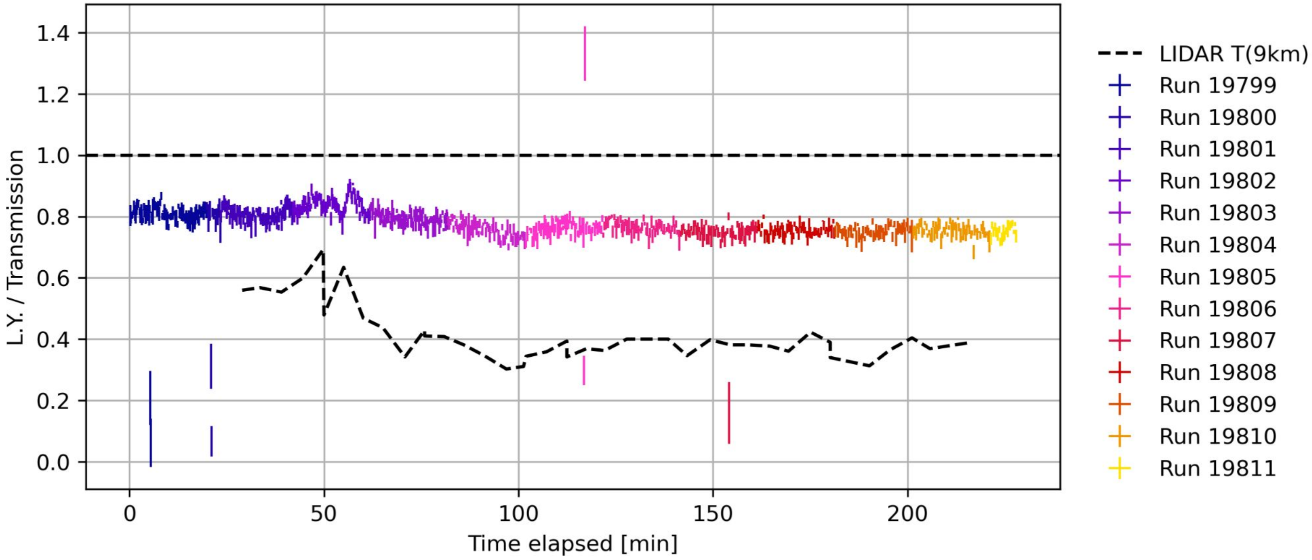


Correlation between LIDAR and Cherenkov Transparency

We can see a correlation of the LY and the LIDAR transmission @ 9km.

Following this correlation we can state:

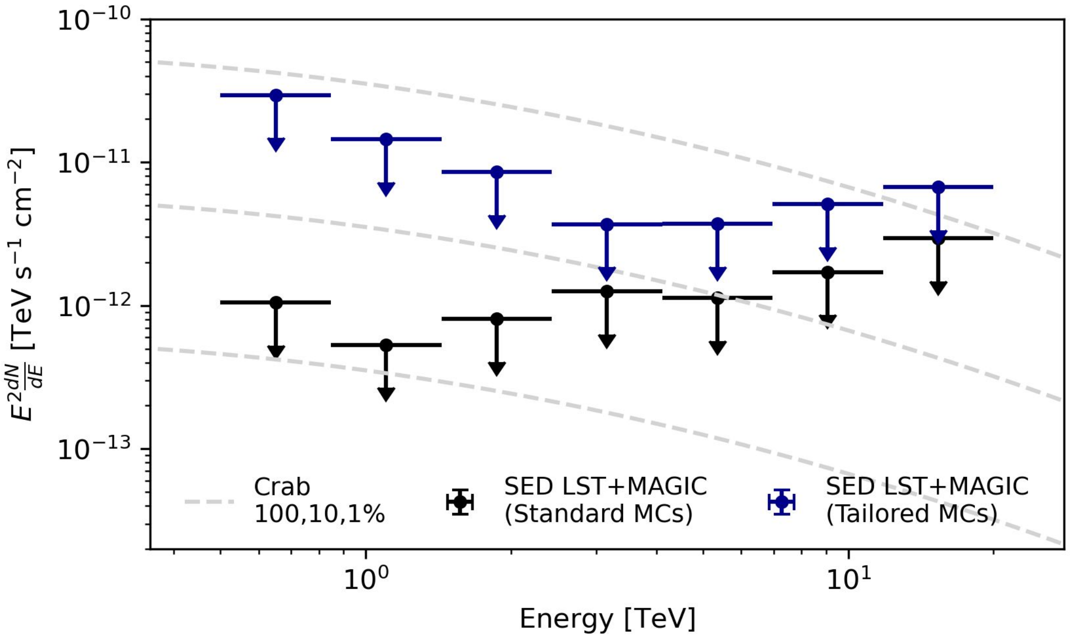
- In first 30 min of datataking (LST only) **LY is constant**. And stays the same for the next 20 min of joint datataking.



Comparison of standard MCs and atmospheric accurate simulations

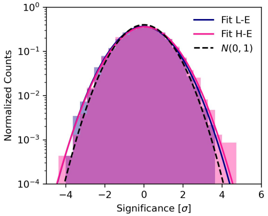
- Standard MCs will overestimate atmospheric conditions resulting on stronger upper limits.

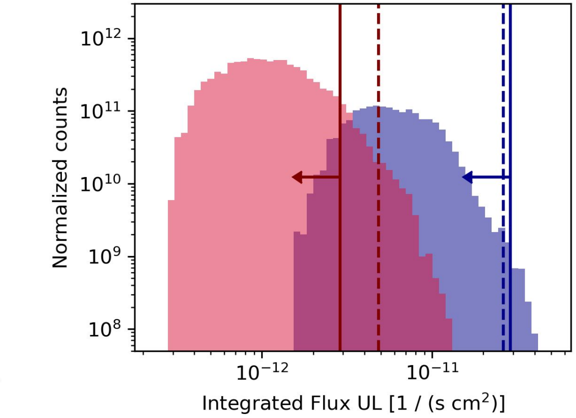
- Systematics not taken into account if data is analysed with standard MCs.



More details on the results

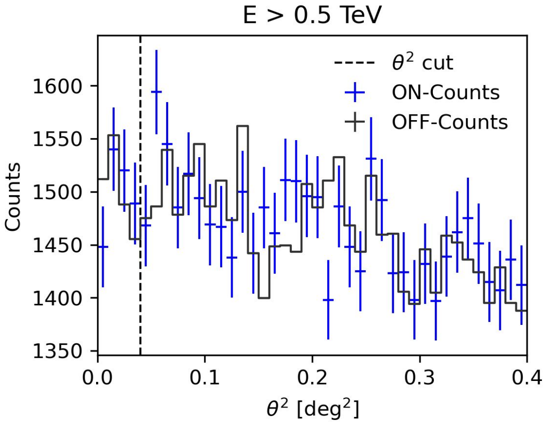
S240615dg





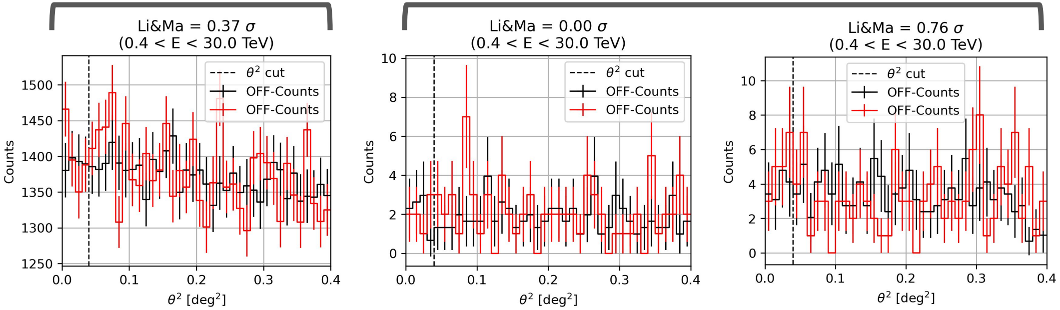
S241125n

Statistics **dominated by LST-only**, but any excess seen either in run-wise plots (-0.12 σ).

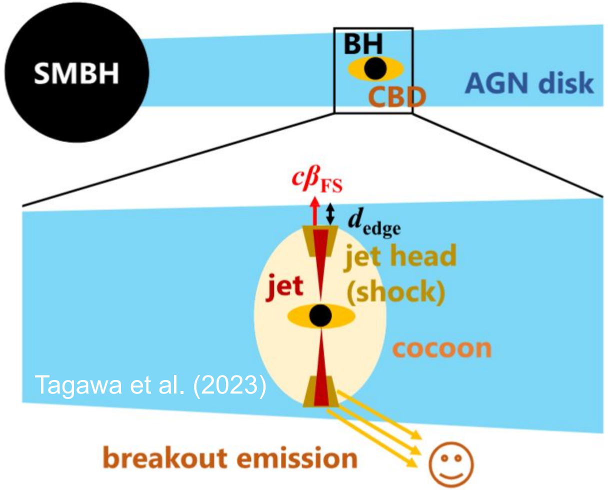


Statistics **dominated by LST-only**, but any excess seen.

LST-only ***LST + MAGIC***



Theoretical Interpretations: Super-Eddington accretion scenario



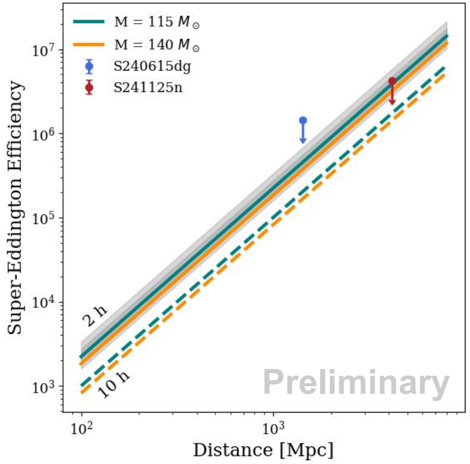
Inside an AGN disk, BBHs can accrete gas from the dense, viscous environment. (If the accretion rate exceeds the Eddington limit)

- The escaping radiation could, in principle, extend to high energies via **inverse Compton scattering**.

- Using MAGIC + LST-1 sensitivities, our flux upper limits are **orders of magnitude above physically plausible values.**

We can then, compute **upper limits on the Super-Eddington efficiency** parameter.

$\eta_\gamma = L_\gamma / L_{\mathrm{Edd}}$ > 10^6 (for IACTs)



Post merger Jet scenario

After merger, the **remnant BH spin can realign (Blandford–Znajek jet)** interacting with other dense regions creating strong forward/reverse shocks:

- **Thermal + non-thermal breakout emission.**
- This emission will have some delay.
- **Strong dependence on R**, (radial distance from the SMBH). And depending on the distance from us, we have different scenarios.

For S241125n, observed **Swift-BAT delay (≈ 6 s rest-frame)** and short duration imply a merger **deep inside the disk (R ≲ 0.01 pc)**, then highly absorbed at TeV energies.

Predicted **VHE fluxes are orders of magnitude below** MAGIC + LST-1.