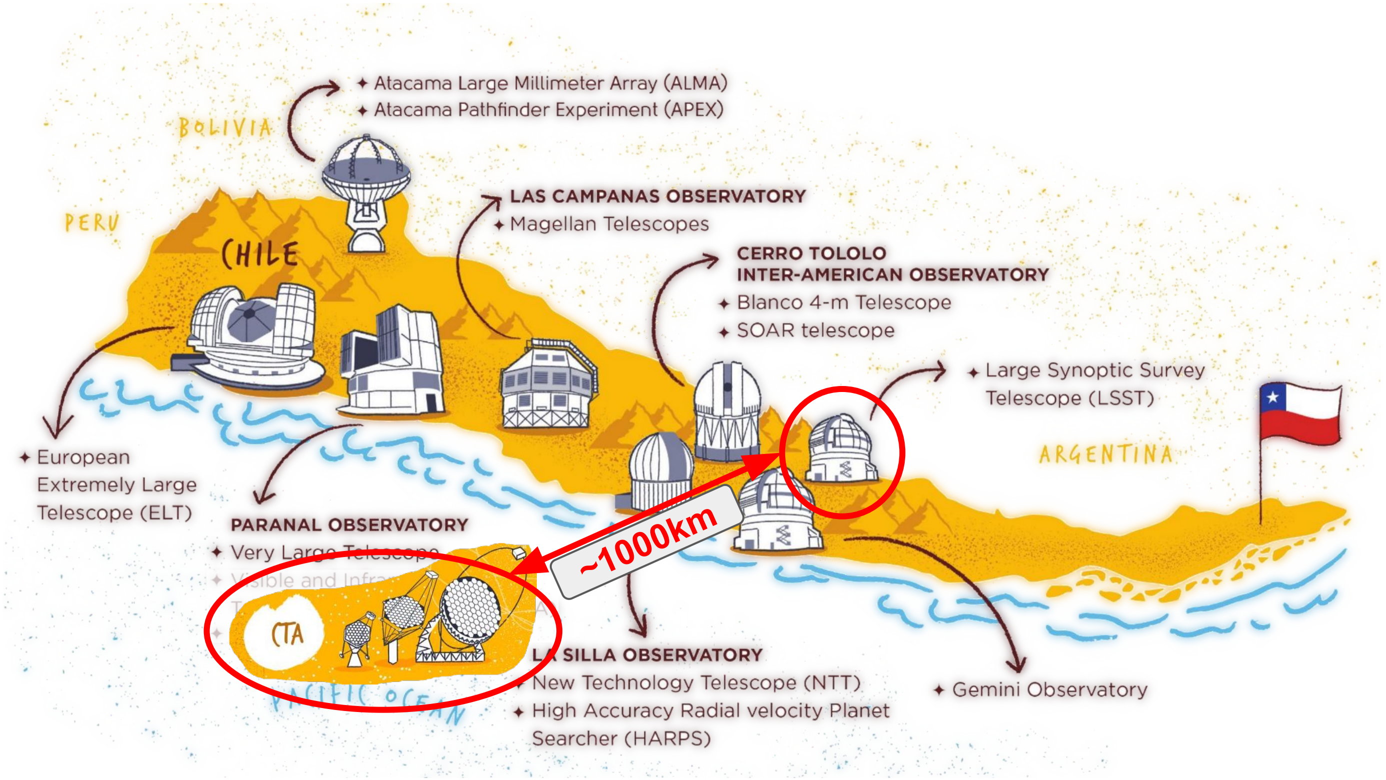
Blazar multi-wavelength studies with Rubin and the CTAO

Julian Hamo, with Maria Kherlakian, Iftach Sadeh, Jonathan Biteau, Elisa Pueschel and **Julien Peloton**

Chile: A bustling hub of astrophysics



The Cherenkov Telescope Array Observatory

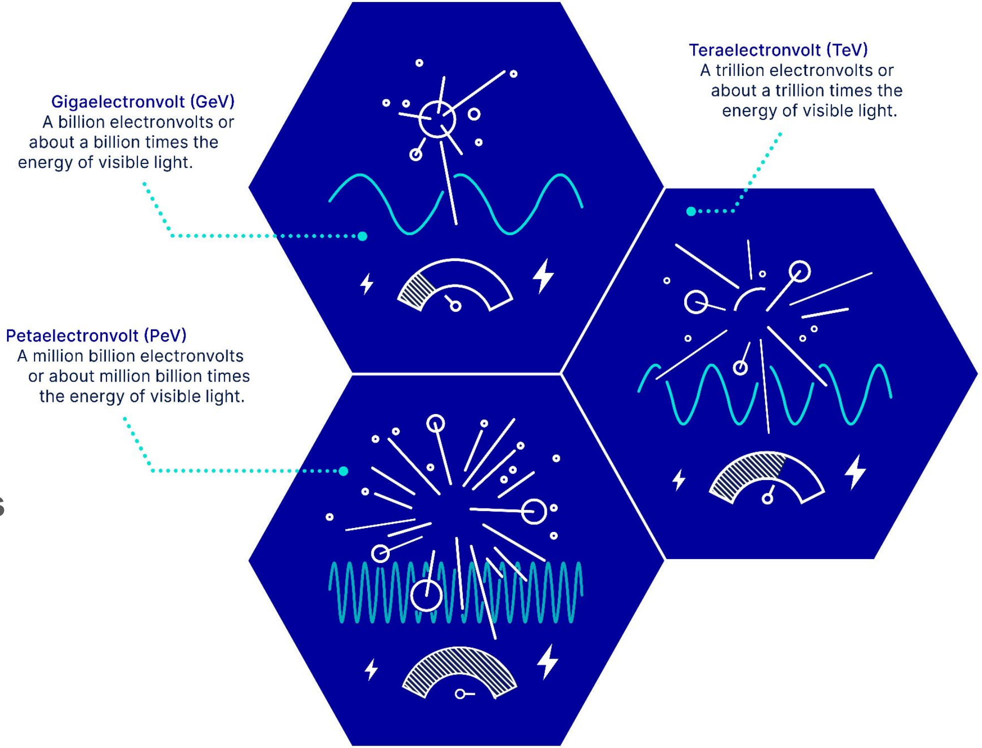
Exploring the GeV-TeV sky

Two observing sites to access any sky point
→ Paranal, Chile (in between the ELT and VLT)
→ La Palma, Canaries (close to MAGIC)

Open observatory
→ ~ ½ of the time on non-consortium proposals
→ to be operated for 20+ years

Enhancements with respect to its precursors (HESS, MAGIC, VERITAS)

→ sensitivity	× 5-10
→ energy resolution	× 1.5-2
→ angular resolution	× 1.3-1.4



Science case: extreme states of blazars

Blazars:

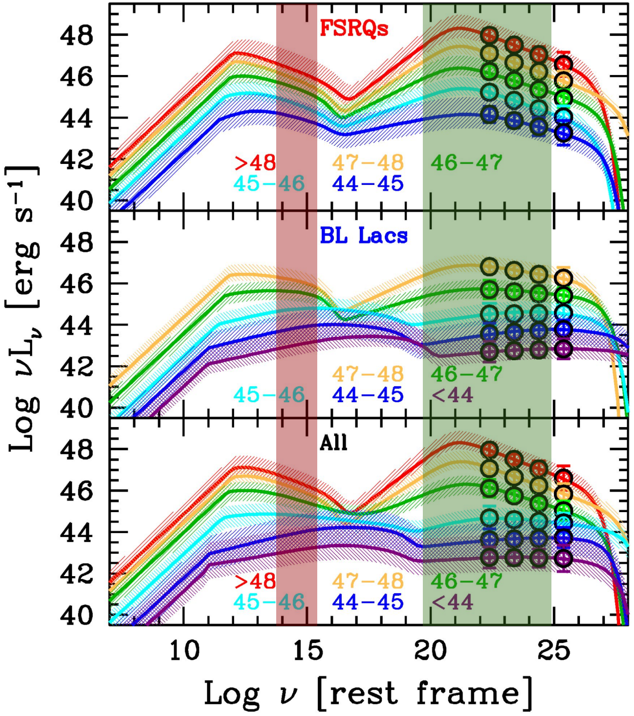
- jetted AGN with jet close to the line of sight
- Stochastic variability (no typical timescale)
- Non thermal emission processes

  → **optical** to X-ray emission: synchrotron radiation

  → X-ray to **gamma-ray** emission: Inverse Compton emission

Joint optical and gamma-ray observation → constraint on emission processes, interaction around extreme environments, etc.

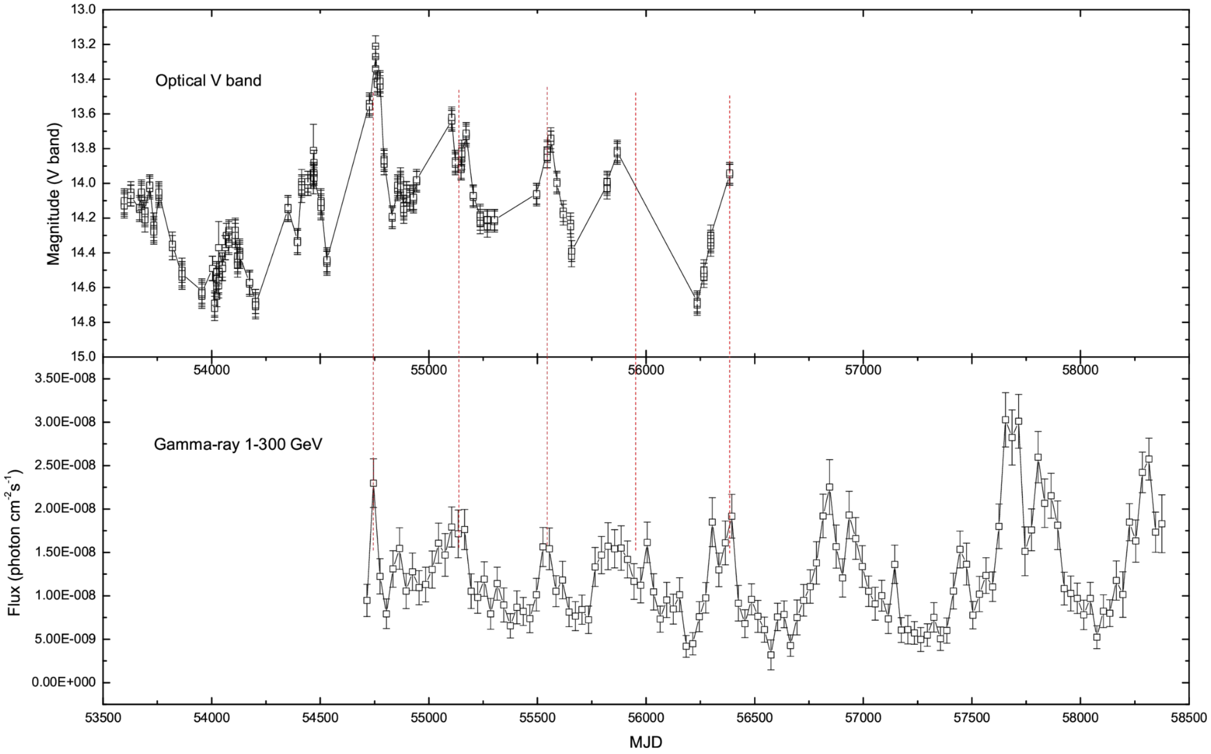
Already observed optical/gamma-ray correlations (cf. Hovatta+ '14, Liodakis+ '18, Liodakis+ '19)



Adapted from Ghisellini+ '17

Motivations on the extreme state detection

- Known flare correlations between **optical** and **gamma-ray** emissions
- Theoretical models to explain such correlations through EC or SSC emissions
- Recent studies on population of blazars showing correlations for a fraction of the sources
- Suggest to study the implementation of **trigger** from optical to gamma-ray observations



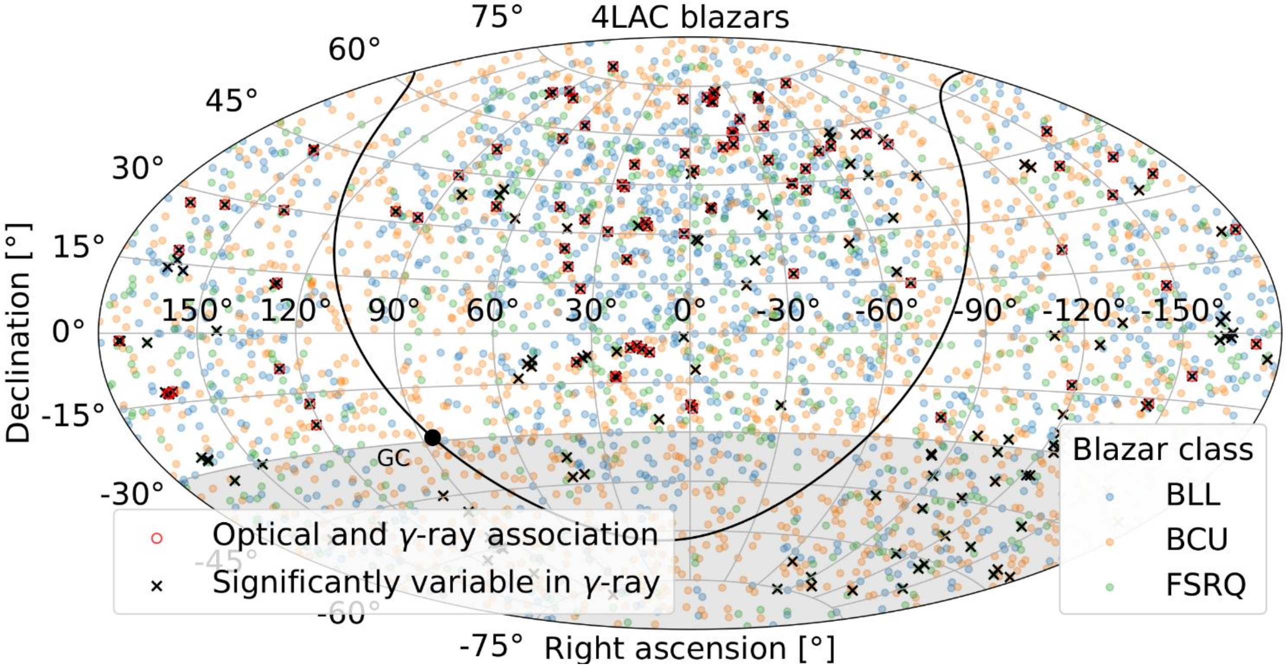
Adapted from Yang+ '20

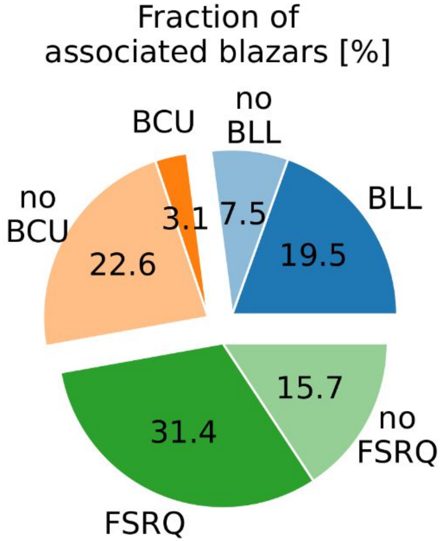
Selection of dataset

Gamma-ray blazars with significant optical variability:

→ 86 sources in common, with >150 ZTF measurements per source in g and r bands

→ aperture photometry gamma-ray light curves from *Fermi*-LAT (credit: J.P. Lenain)



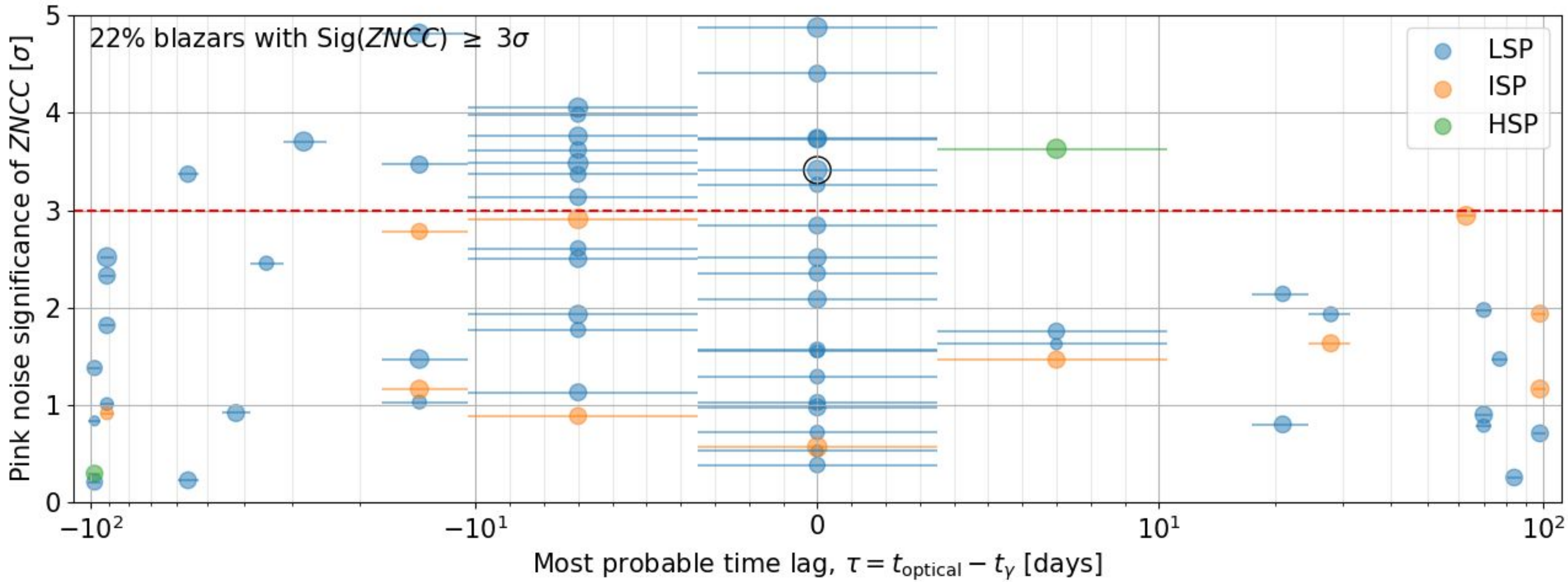


Optical to gamma-ray correlations

Similarity metric: cross-correlation over RMS of both light curves

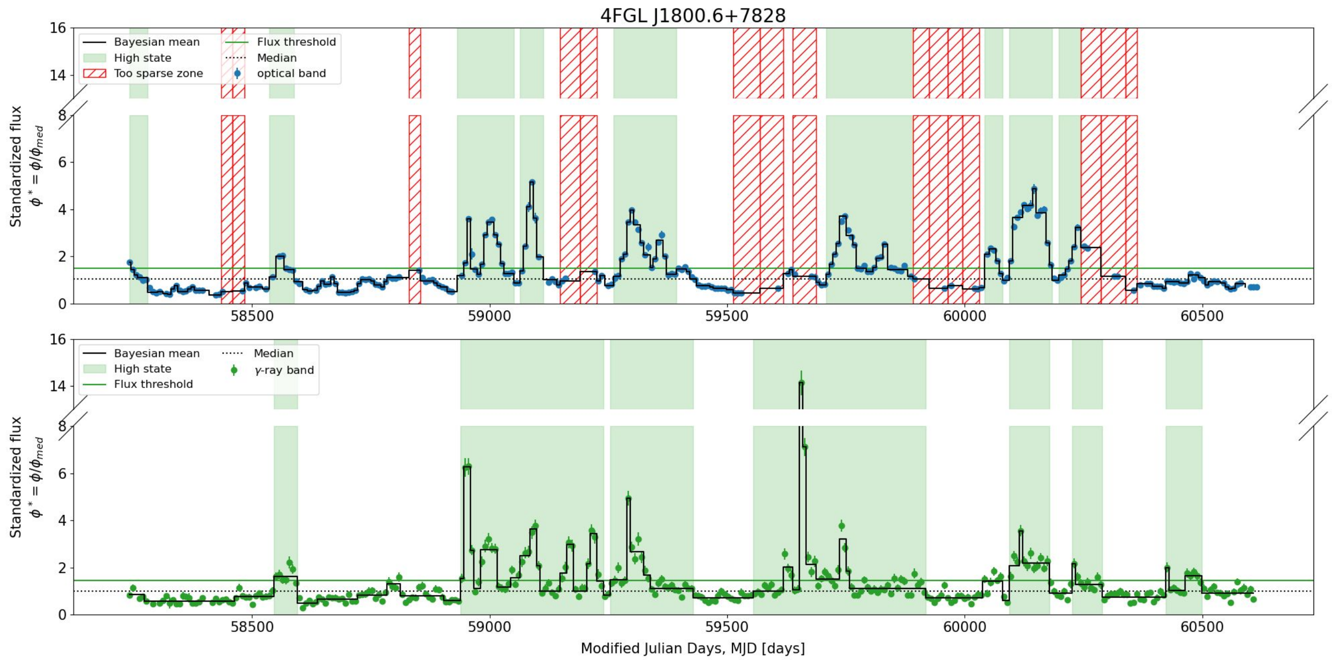
→ ~60% sources: no time lag between optical and gamma-ray

→ ~20% sources: >3σ correlation ⇒ co-spatial production



Julian Hamo

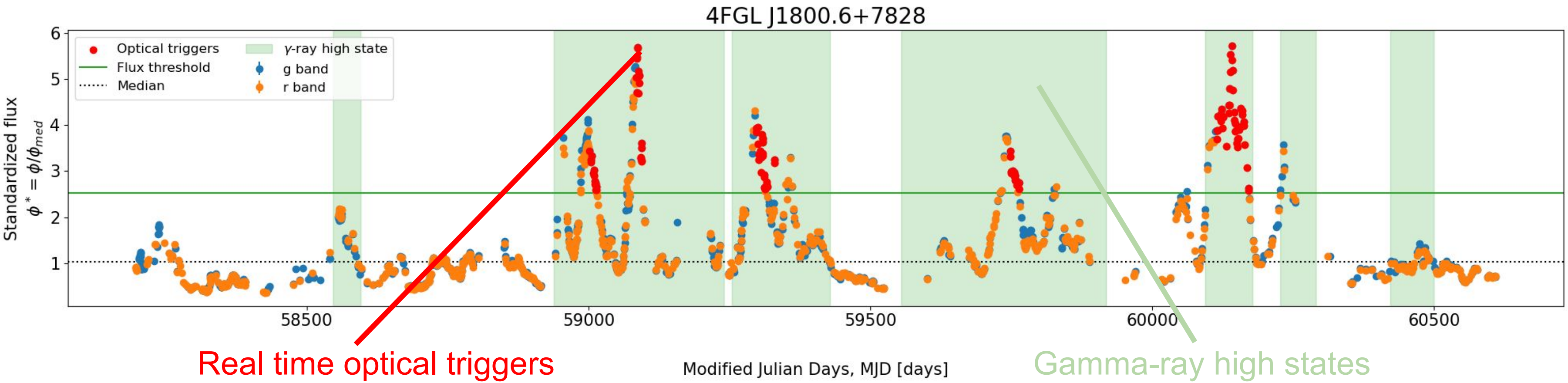
Extreme state detection: superblock method



- **BL Lac & LSP (LBL)**
- Optical band accurate merging method
- Gamma-ray band from FLaapLUC (*Fermi*-LAT)
- Bayesian block construction → steady flux states
- Selection of greatest quartile
- Merge of concomitant high states + rise and fall parts ⇒ superblock (= flare)

Real time extreme state detection

- Threshold computed from DR light curve greatest decile
- Flare optical trigger: both measurement and fluence over last 30 days above threshold
- Triggers as proxy of start of gamma-ray high states for IACT observations



+ Soon to come: ɣ-ray flare alerts from *Fermi*-LAT (FlaapLUC: Lenain, '18)

Methodology conclusion

Metrics on flare optical triggers

- Efficiency: 12 ± 2 %
  → 0.2 detected new flares per source per year out of 1.6 new flaring states per source per year
- Purity: 69 ± 6 %

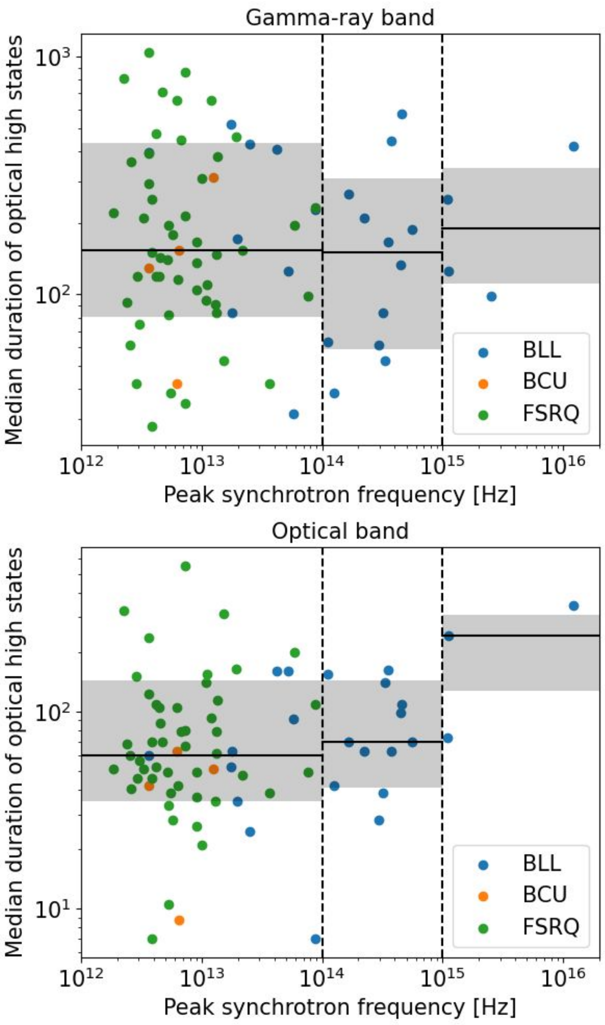
Real-time first optical trigger

→ $\langle t_{trigger} \rangle$ ~10 days before the highest γ-ray flux

→ fraction of the flare left after the trigger: ~76%

Flare duration

- Not correlated with class of blazar
- Poorly correlated with ν_{syn} ⇒ important spread

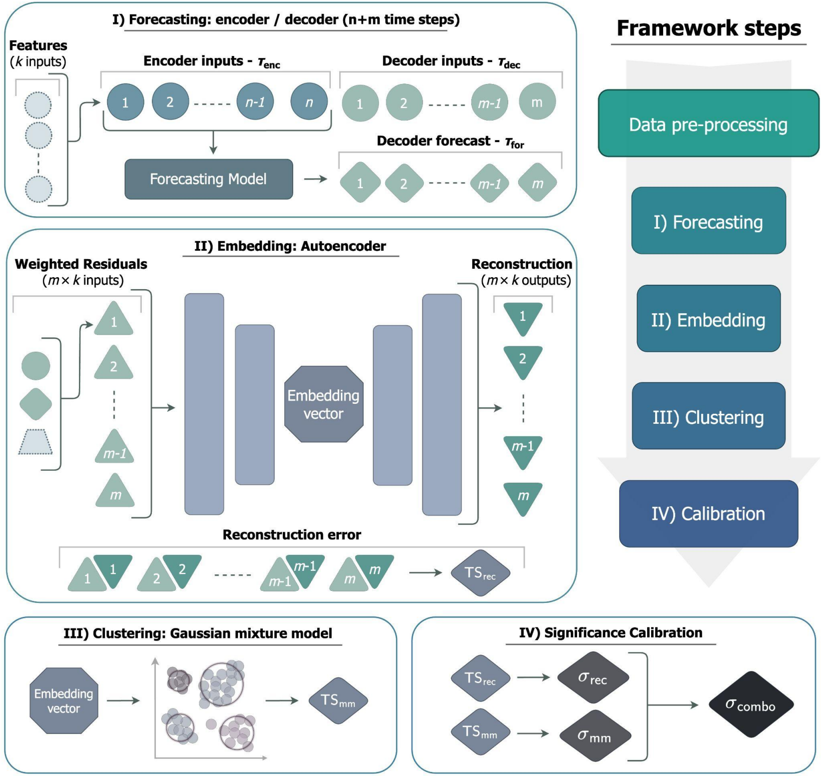


ML MWL flare detection

More advanced flare selection

Ongoing work with M. Kherlakian, E. Pueschel (Bochum) and I. Sadeh (DESY) to implement an unsupervised machine-learning anomaly detection algorithm in Fink

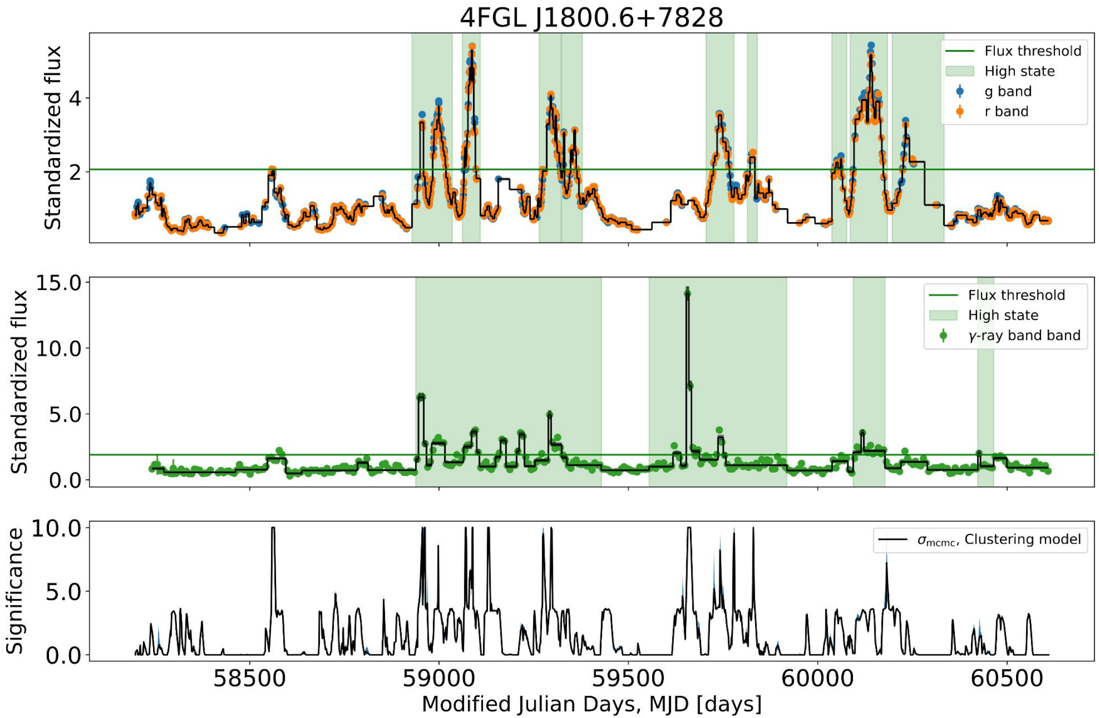
- Flares as anomalies over a trained background/passive state of a source
- Already tested on simulations of 1ES 1215+303
- Archival light curves of BL Lacertae test: 3 high significance detections (~6σ) coincident with VERITAS flares
- Detection of flares before community alerts
- Robust against cadence, gaps, and data quality inhomogeneity



Adapted from Hermann, '25

Example with ZTF and *Fermi*-LAT

- Optical (ZTF/LSST) bands ingested in pipeline
- Comparison with both method to statistical metrics + double weight of triggering
- Training on background only period
- Implementation to Fink broker automated detection for blazars →



Conclusion

Can LSST alerts trigger CTAO follow-ups on flares of blazars?

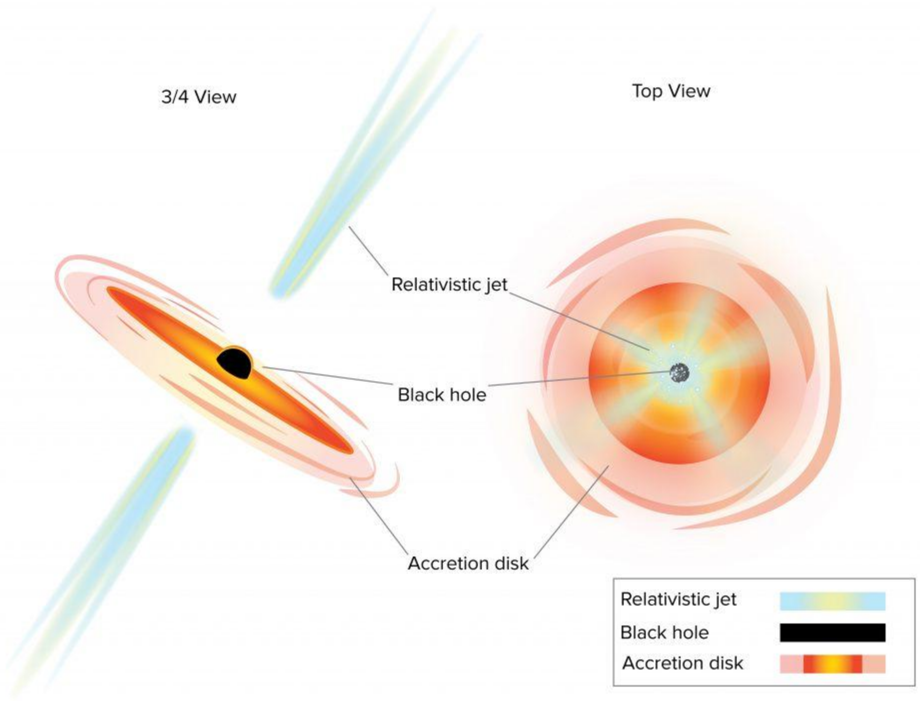
- Joint start of LSST reasonable alerts and CTAO network (2026/2027)
- Preliminary analysis using ZTF and *Fermi*-LAT GeV observations as proxy for ~TeV observations from the CTAO
- Conservative fine-tuning to trigger on a manageable rate of alerts: ~0.2 detected flare per source per year / ~1.6 flare per source per year
- Ongoing: Use of ML to detect features for MWL flares - comparison from ZTF and *Fermi*-LAT
- Alerts sent by Fink → **Reach out if interested**

Note: low-state alerts already sent to AGN redshift task force of CTAO

Backup slides

From AGNs to blazars

- Radio-loud jetted AGN
- Jet pointing the line of sight
- Extremely bright compared to the host galaxy (up to 10-100 times)
- Extremely variable (~min to years)

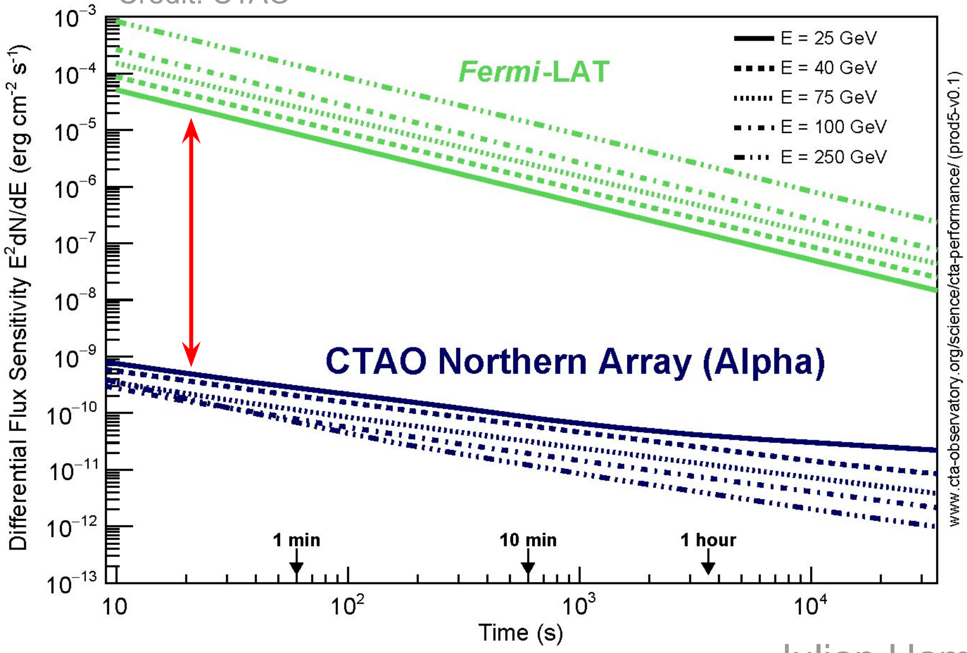


CTAO performance in the time domain

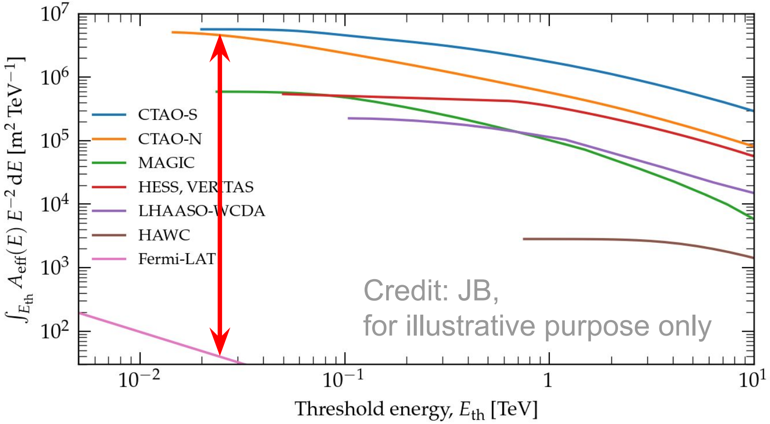
For short- and bright-enough events

→ signal dominated regime

Credit: CTAO



$$(Z[\sigma])^2 \approx N_\gamma(> E_{\rm th})$$
$$\approx T \times \int_{E_{\rm th}} \mathrm{d}E\, A_{\rm eff}(E) \frac{\mathrm{d}^3 N}{\mathrm{d}E \mathrm{d}A \mathrm{d}t}$$
$$\propto T \times \int_{E_{\rm th}} \mathrm{d}E\, A_{\rm eff}(E) \times E^{-2}$$



Current/new generation ɣ-ray observatories

Water Cherenkov Detectors (WCDs)
HAWC, LHAASO, next: SWGO

→ continuous, wide-field ɣ-ray observations.

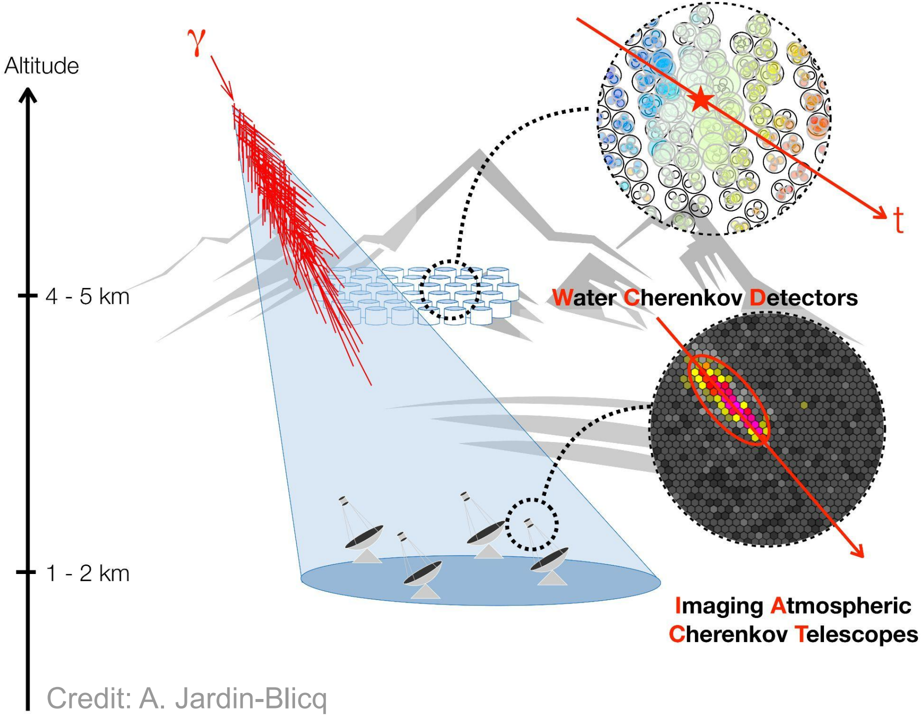
Imaging Air Cherenkov Telescopes (IACTs)
HESS, MAGIC, VERITAS, next: CTAO

→ deep, precision ɣ-ray observations.

Not in competition, need each other!

→ WCDs: operational 24/7, but higher *E*-threshold & smaller effective area

→ IACTs: better spectral and temporal resolution, but smaller field of view and 10% duty cycle



Credit: A. Jardin-Blicq

What is Fink?

Cross match

X

- *Catalogs*
- *Stream surveys*

ML classification
Fink features

+

Community-based science modules

Stream filtering

*~**2%** of alerts: credible candidates for blazars*

REDUCED STREAM

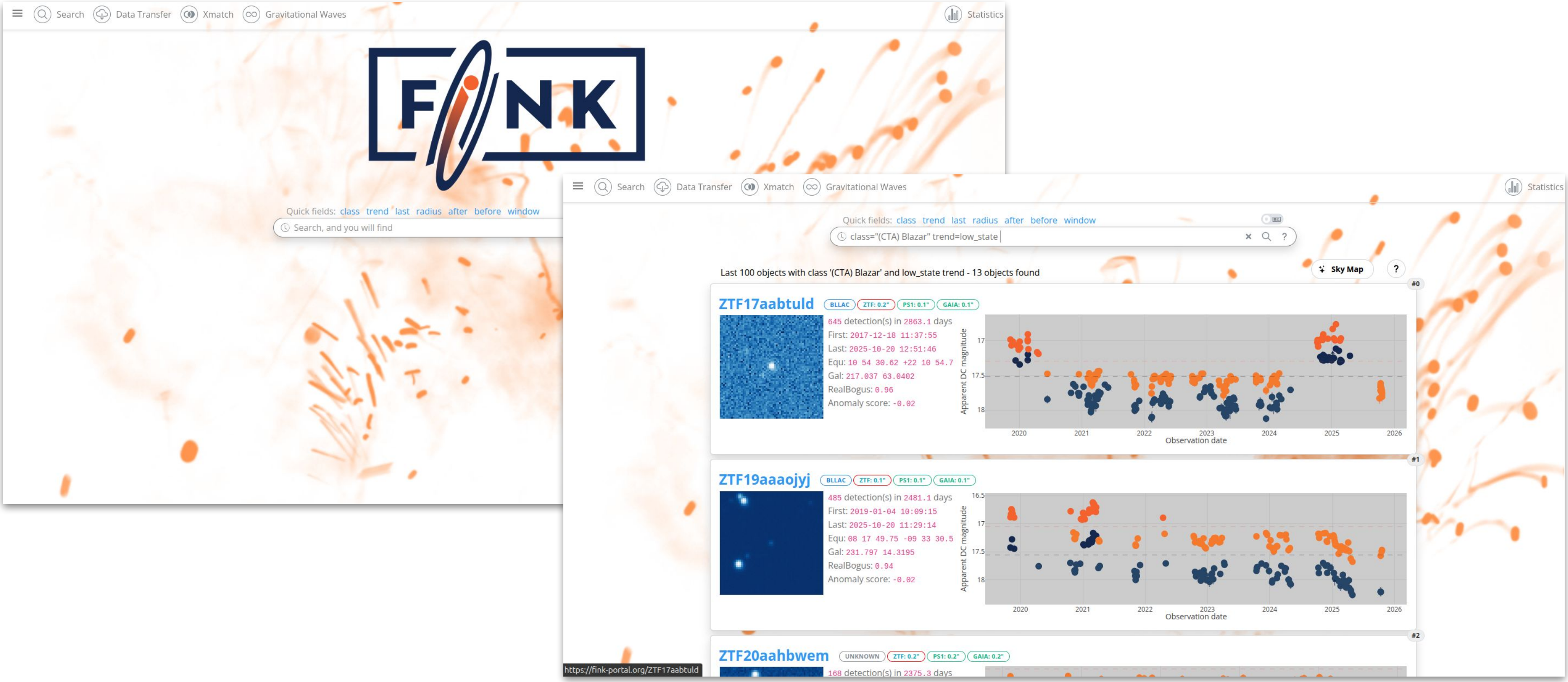
TNS report
Livestream

<minutes

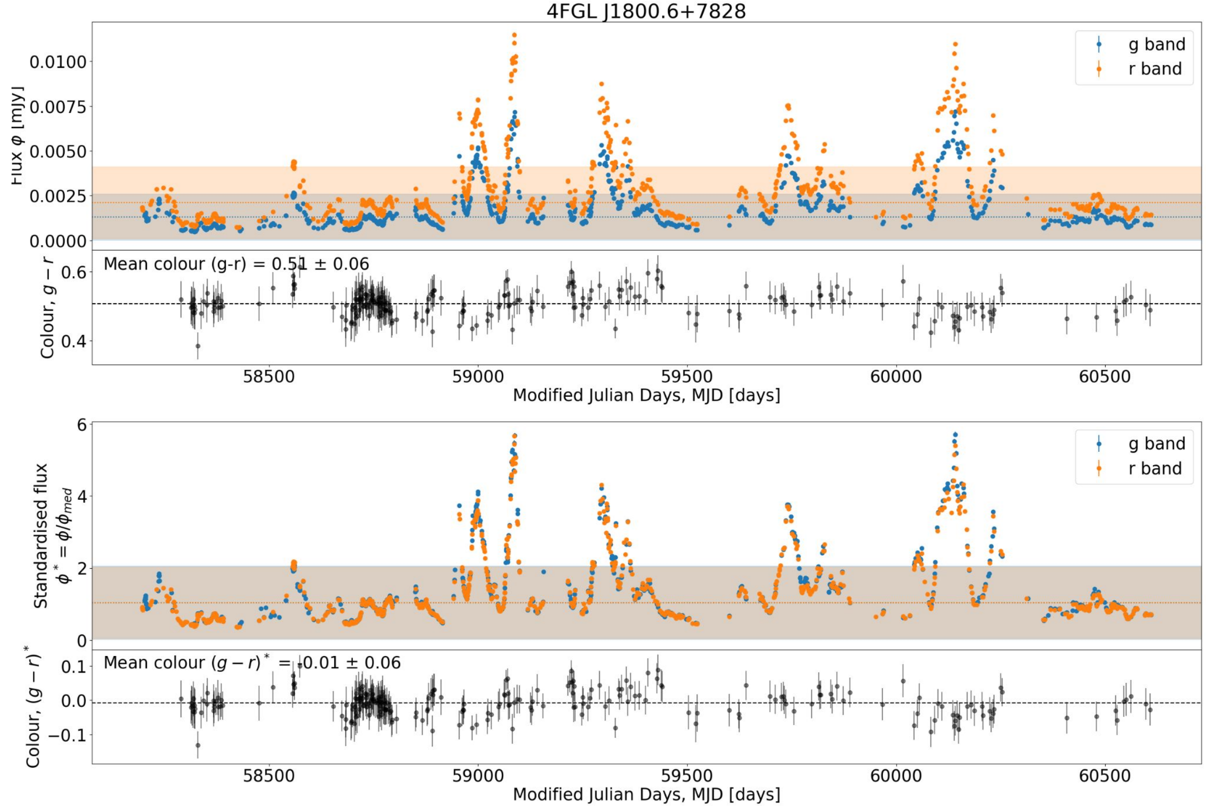
Fink portal
REST API

end of night

The Fink portal



Optical standardisation



Non-thermal emission in multiple optical bands

"Standardisation" of the g and r fluxes:

- Selection of quasi-simultaneous measurements (<1h) in each band
- Normalization in each band to the median over the preselected points.

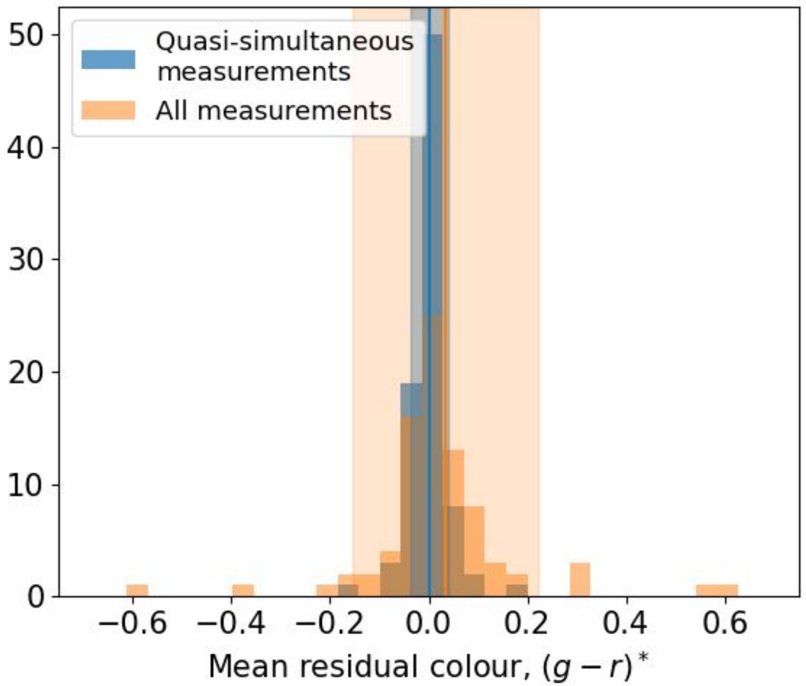
Little colour variation left

g- & r-bands can be merged into a single optical lightcurve

Method easily transposed to Rubin's urgizy bands

Standardisation precision

- Computation of the residual colour for quasi-simultaneous measurements
- Computation of mean of the residual colour per source
- Both agree with null mean
- Less spread of the residual colour mean for quasi-simultaneous measurements



Zero **N**ormalised **C**ross-**C**orrelation function

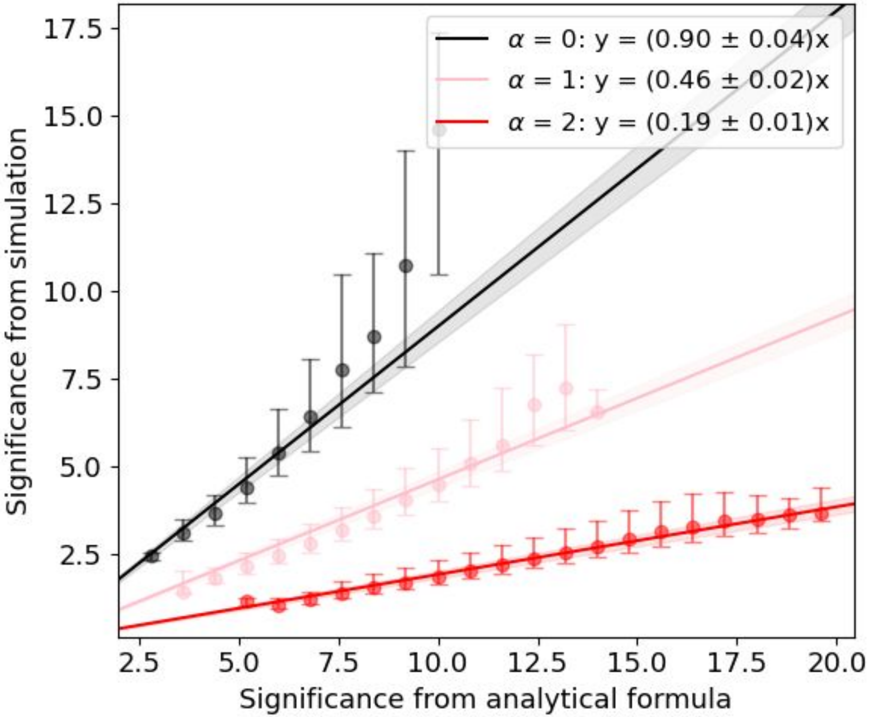
$$ZNCC_{\{x,y\}}(\tau) = \frac{1}{N-|n_\tau|} \sum_{i}^{N-|n_\tau|} \frac{(x_{i+n_\tau} - \overline{x})(y_i - \overline{y})}{\sqrt{(\sigma_x^2 - \overline{e}_x^2)(\sigma_y^2 - \overline{e}_y^2)}}$$

$$\mathrm{Var}_{ZNCC,\{x,y\}}(\tau) = \frac{1}{(N-|n_\tau|)^2} \frac{1}{(\sigma_x^2 - \overline{e}_x^2)(\sigma_y^2 - \overline{e}_y^2)} \left[\sum_{i}^{N-|n_\tau|} \left(e_{x_{i+n_\tau}}^2 y_i^2 + x_{i+n_\tau}^2 e_{y_i}^2 \right) + \sigma_y^2 \left((1 + \frac{1}{N}) \sum_{i}^{N-|n_\tau|} x_{i+n_\tau}^2 - \frac{1}{N} (\sum_{i}^{N-|n_\tau|} x_{i+n_\tau})^2 \right) \right]$$

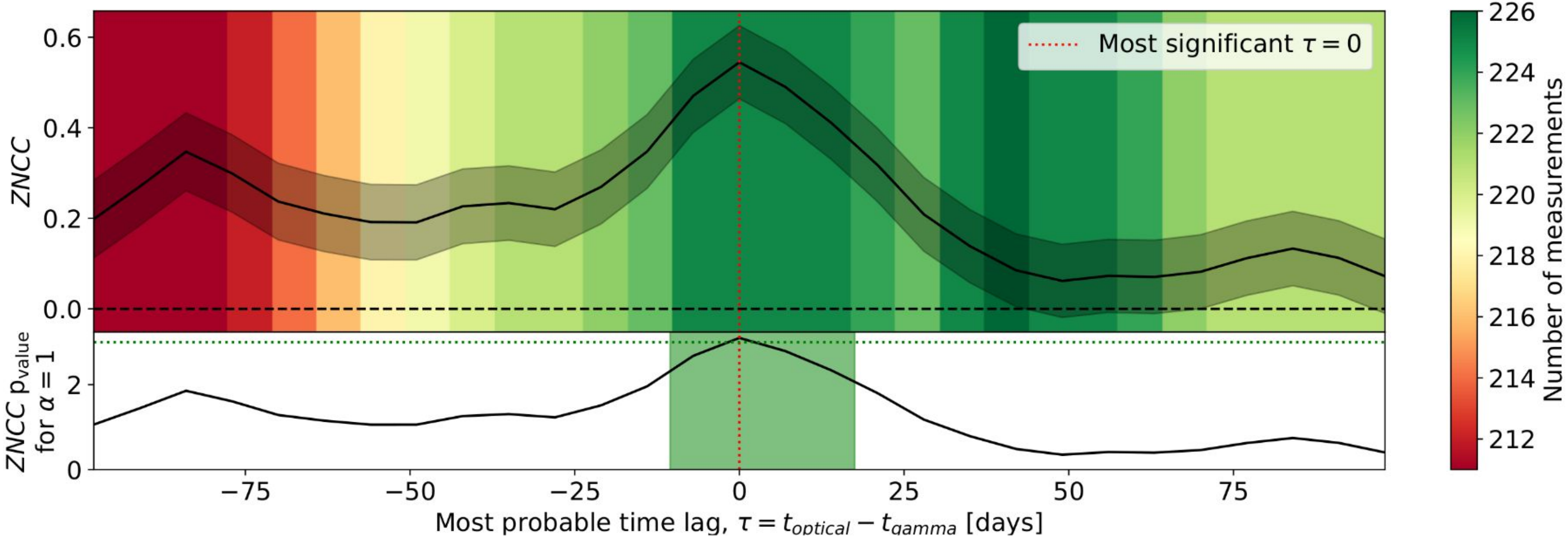
Caveat for variance: Assume white noise for PSD → overestimation of the significance

Penalization from noise colour

- ZNCC assumes uncorrelated data $\Rightarrow$ white noise PSD
- Penalization factor from the colour of the noise
- Computation of the factor from Monte Carlo simulations
- Assumed blazar to be modelled by a pink noise PSD



Similarity metric



Time lag comparison with litterature

Optical-gamma-ray correlation:

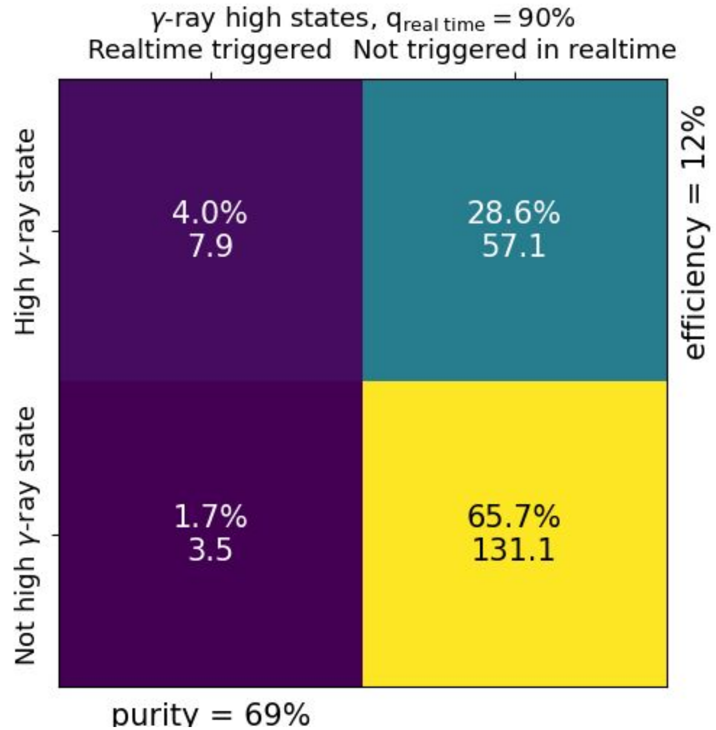
- Liodakis+ ‘19: >3σ correlations for ~6% of their (178 sources) dataset
- Liodakis+ ‘18: Higher correlations for FSRQs than BL Lacs

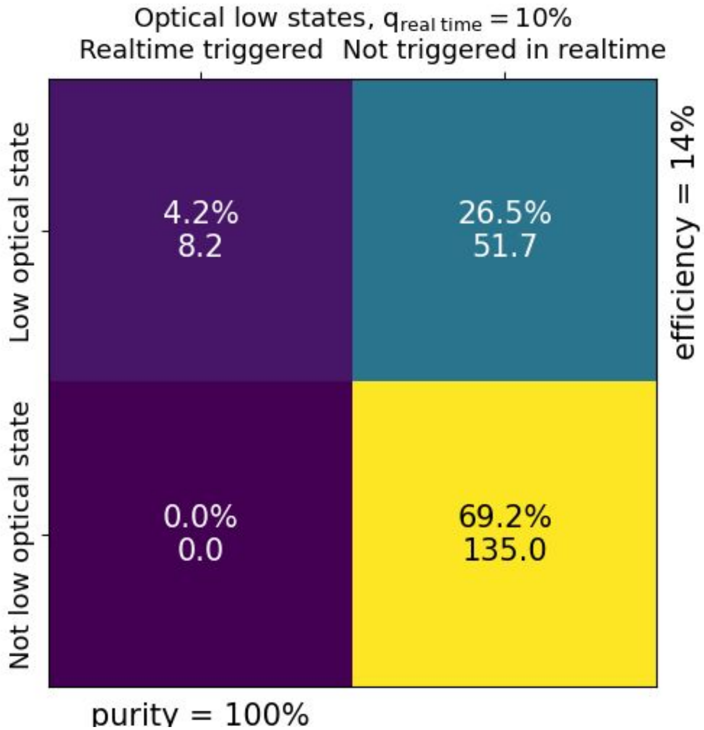
Time lag:

- Cohen+ ‘14: no significant time lag for a large proportion of blazars

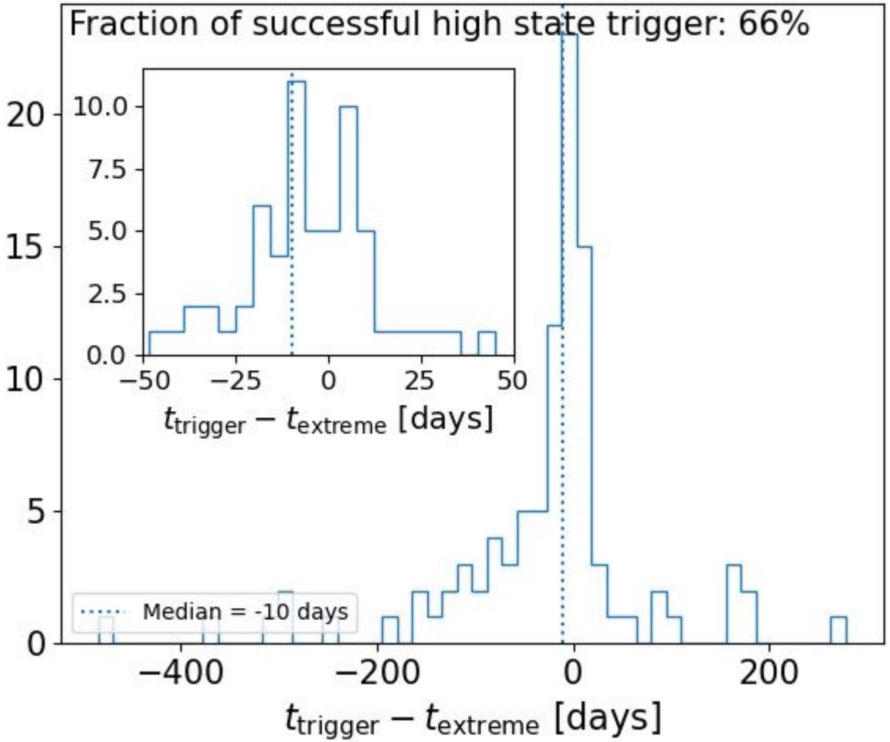
Overall message: Results in agreement with previous studies

Real time method comparison





Time offset between trigger and peak



Significance of a ML detected flare