Optical-γ-ray Correlations in Blazars

from Time-Domain Surveys

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

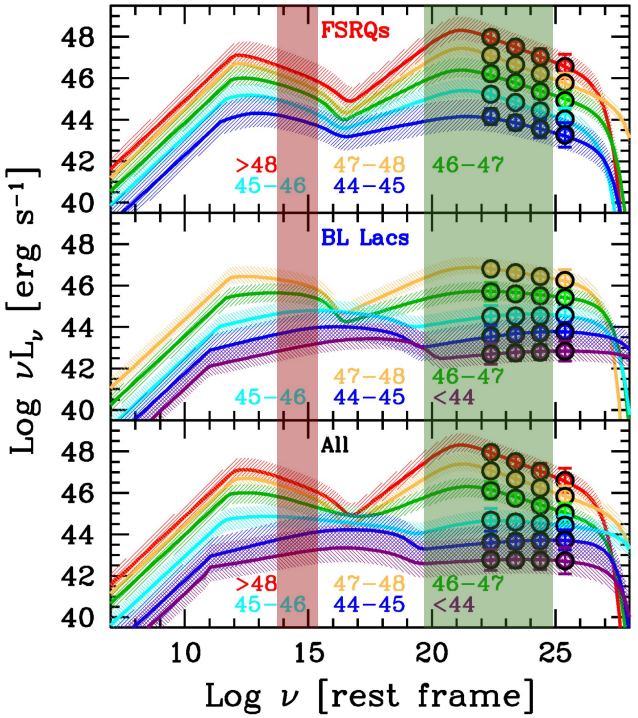
The peculiar SED of blazars

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

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

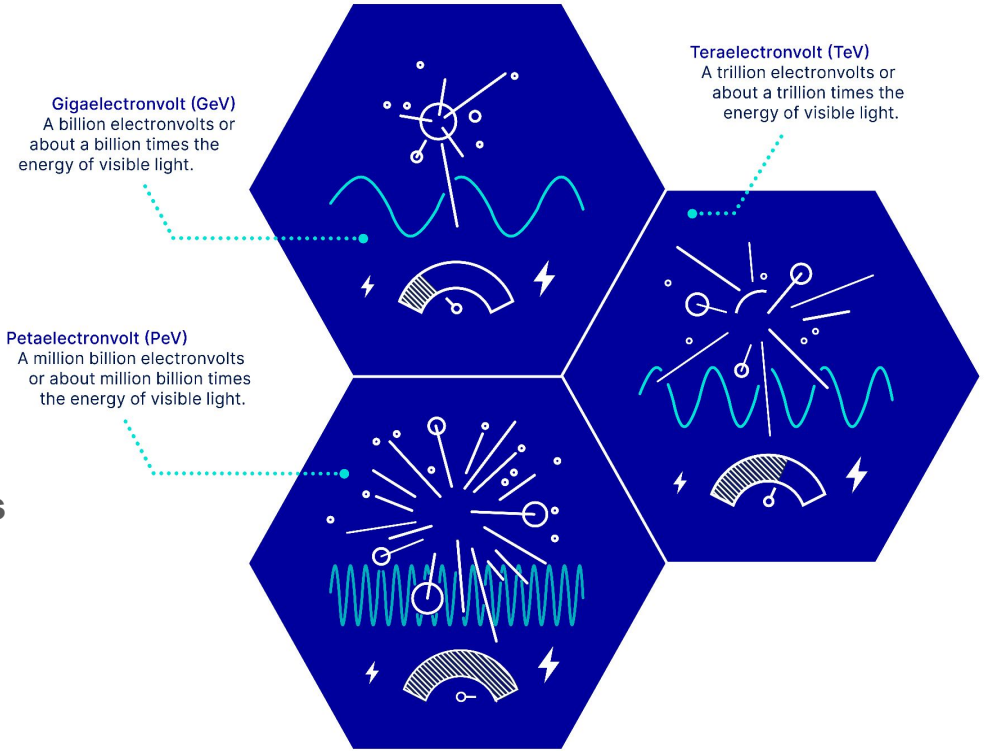
→ to be operated for 20+ years

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

→ sensitivity × 5-10

→ energy resolution × 1.5-2

→ angular resolution × 1.3-1.4



The Vera C. Rubin Observatory and LSST

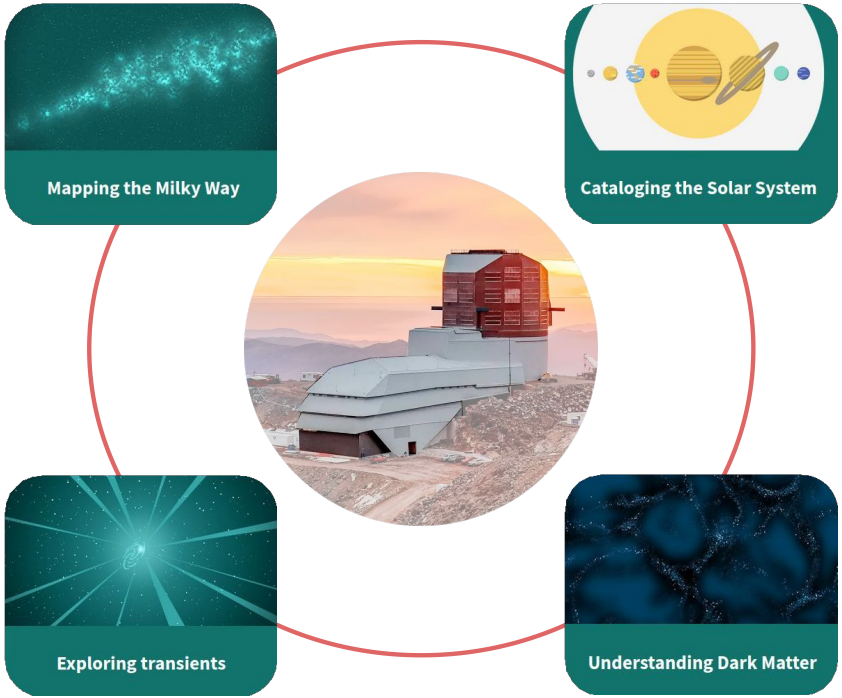
Large Scale optical Surveys:

Legacy Survey of Space and Time (LSST)

- 6 bands: *ugrizy*
- Sky coverage: up to +30^{o} of declination
- Cadence: 1 point / ~3 days (paired observation in 2 bands each time)
- Sensitivity down to 24th mag
- Saturation at 16th mag

Predecessor: **Zwicky Transient Factory (ZTF)**

- 3 bands: *gri*
- 1 measurement / ~2 days (usually paired observation in r- and g-band)
- Sensitivity: 20th mag
- Saturation: 11th mag



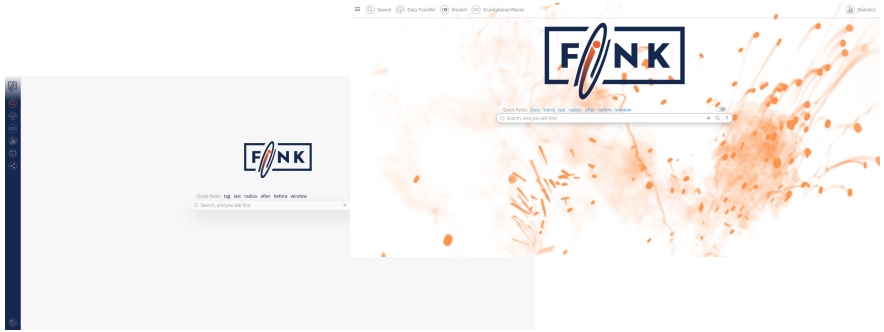
Adapted from D. Turpin

Rubin’s alerts: from millions to few per night

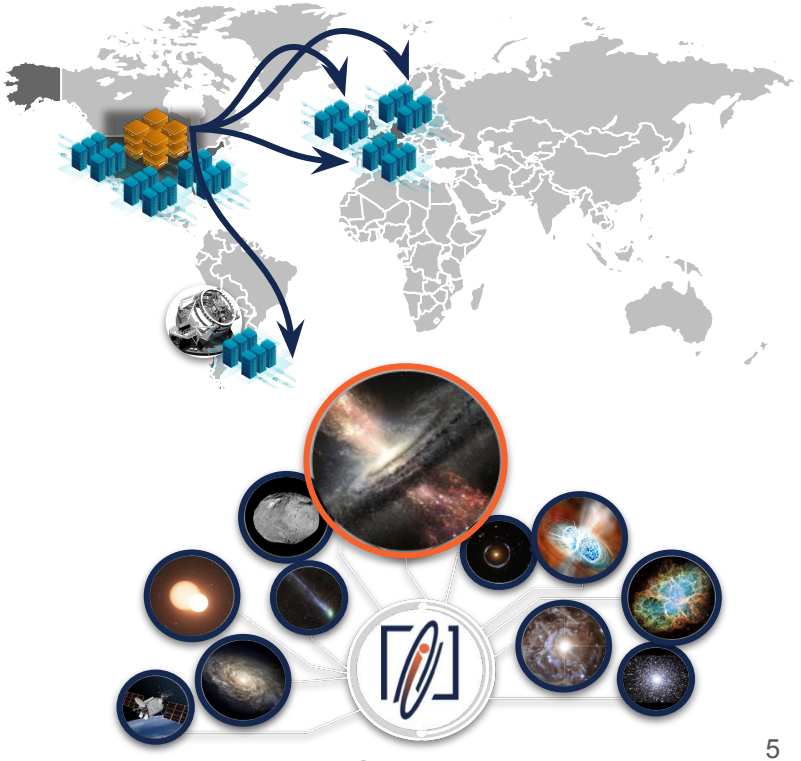
Estimated alert rate: **10M** / night

Available **60s** after data taking through brokers:
ALERCE, *AMPEL*, ANTARES, Babamul, *Fink*, *Lasair*, Pitt-Google
→ Classification and filtering of stream: stream reduced to your taste

Stream fraction for blazar in ZTF according to Fink: ~2%



Julian Hamo



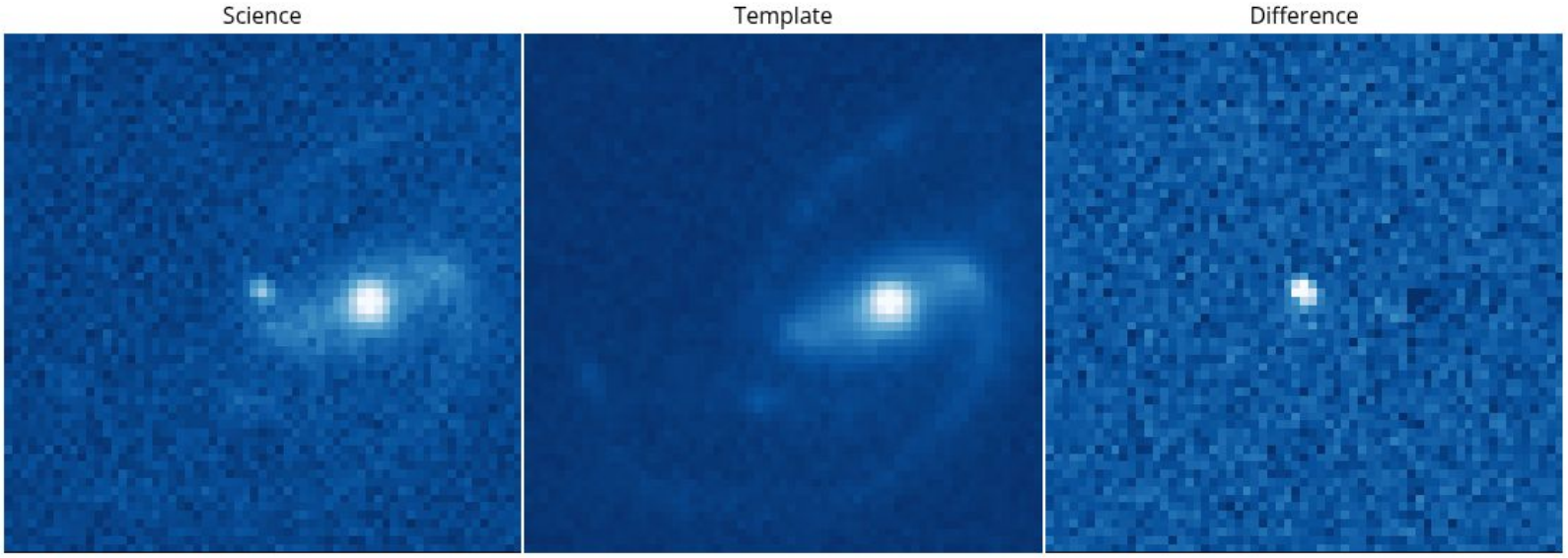
Adapted from J. Peloton

The Fink broker: a link between both

Estimated alert rate: **10M** / night

Avail
ALE
Pitt-
→ Cl
your

Strea

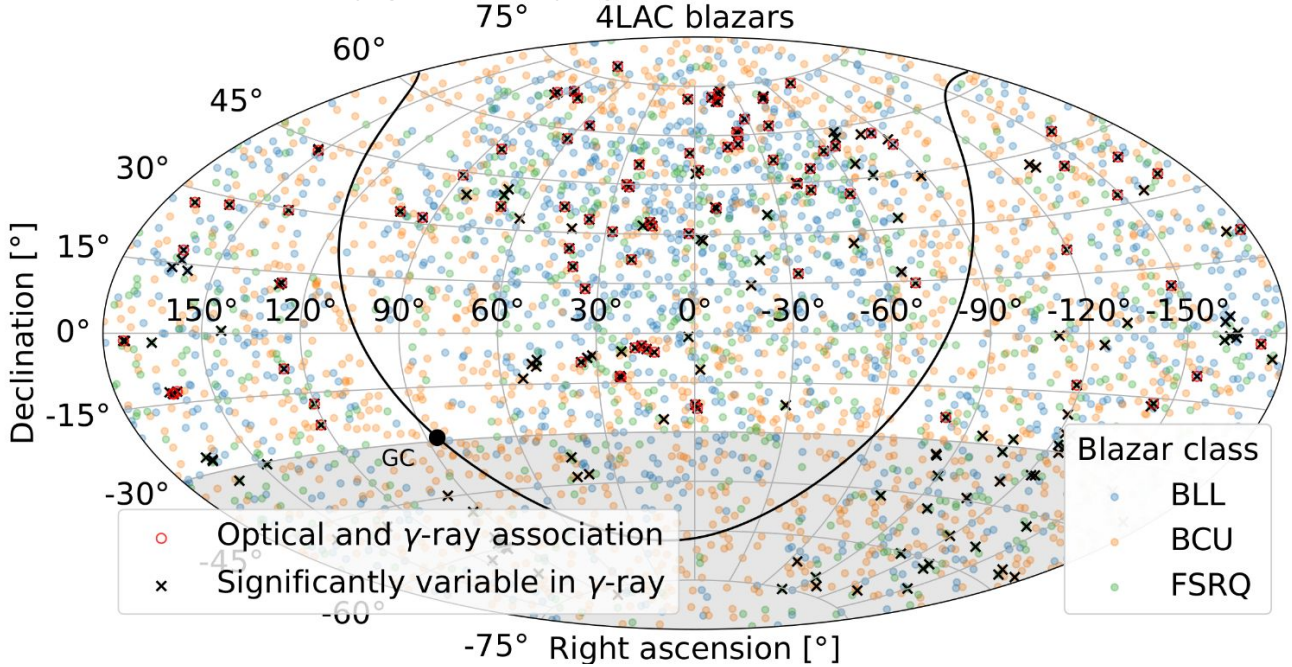


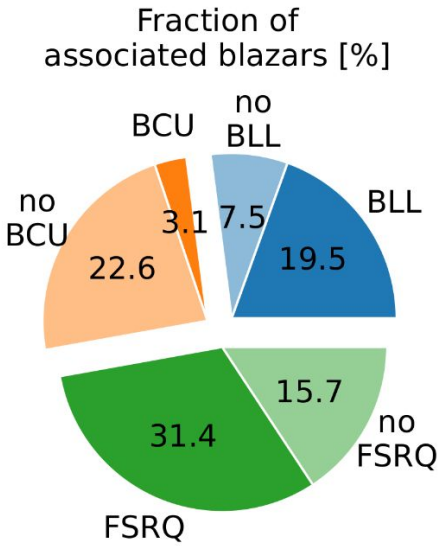
Sample of interest

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)



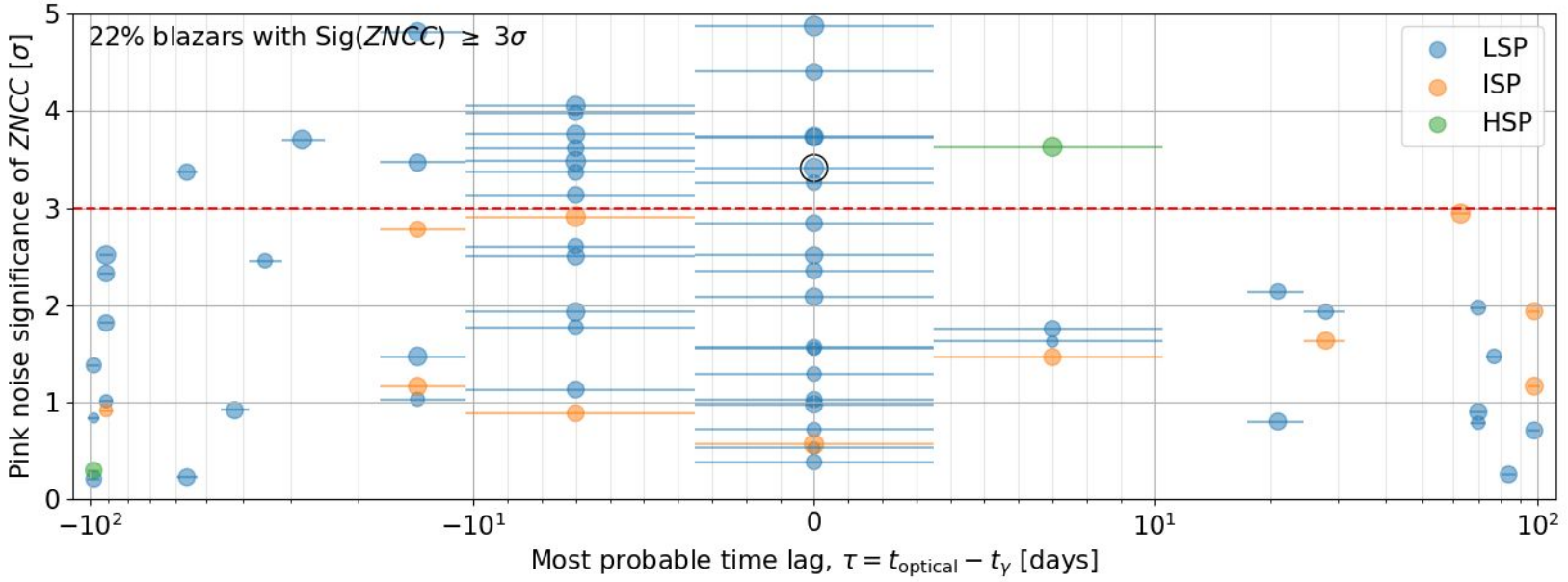


Correlation: optical and ɣ-ray emissions

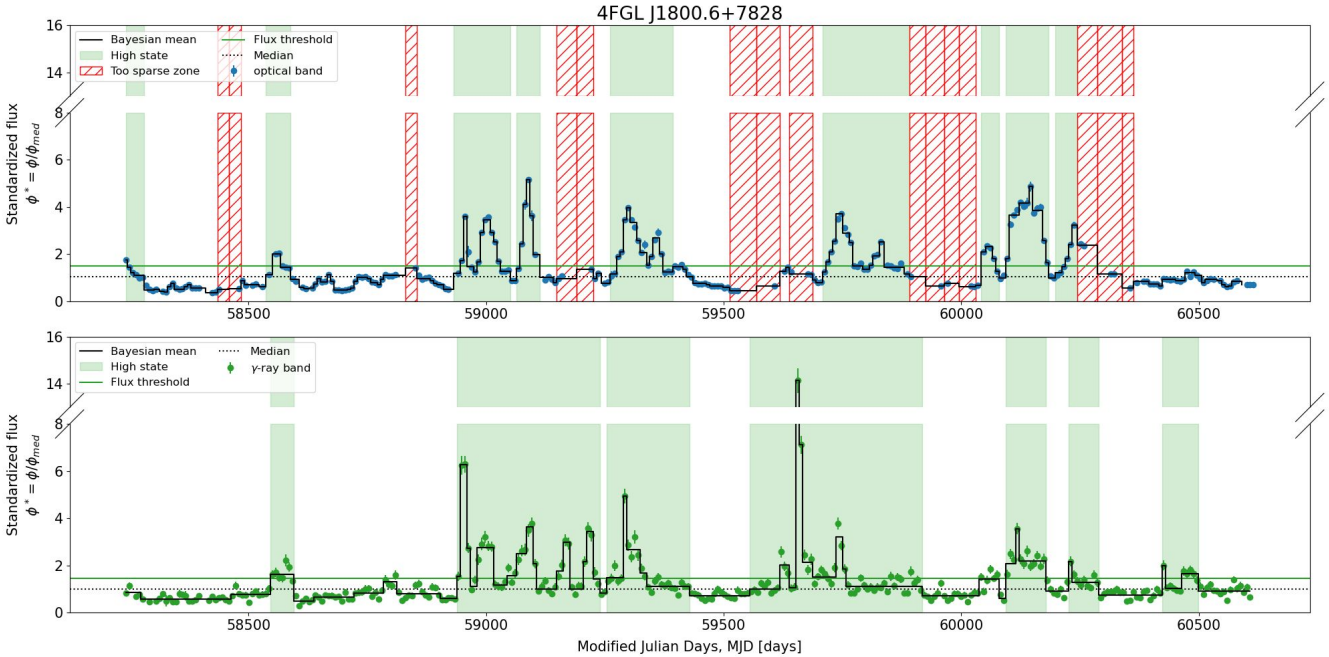
Similarity metric: cross-correlation over RMS of both light curves

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

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



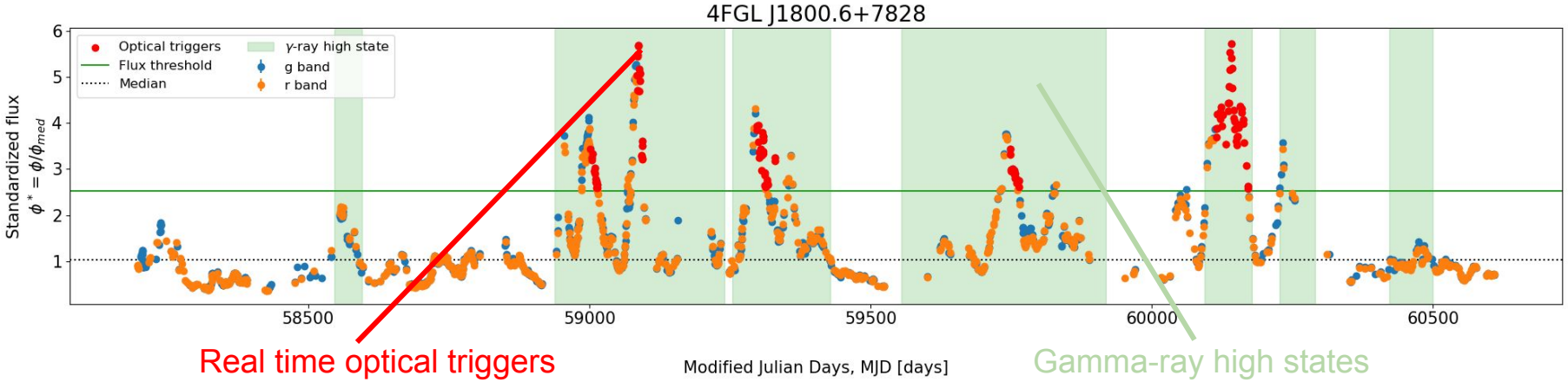
Extreme state detection



- **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 triggers

- 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)

Trigger performances

Metrics on flare optical triggers

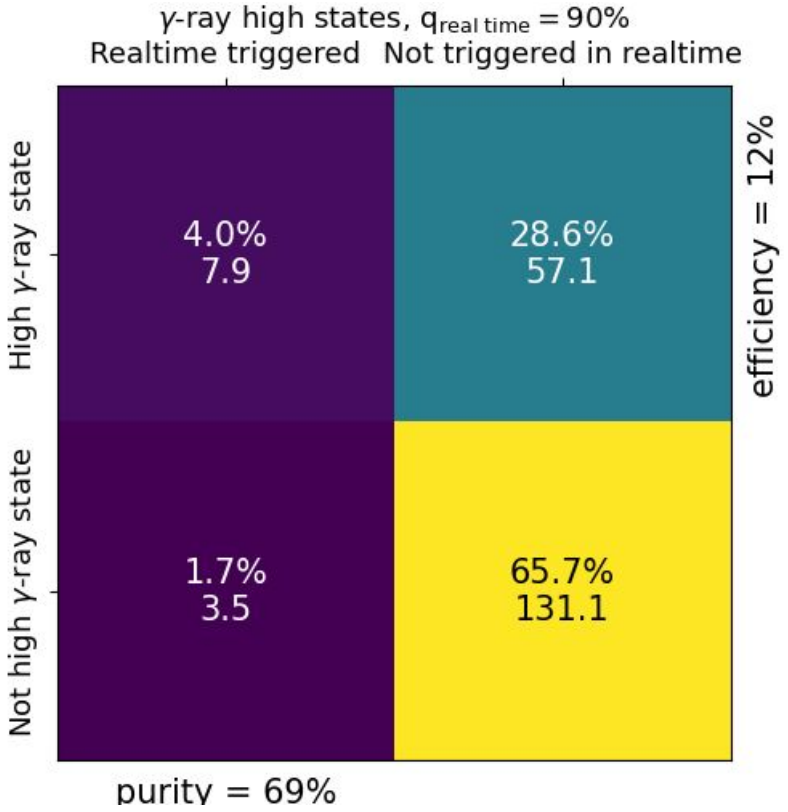
- Efficiency: 12 ± 2 %
  → 0.2 detected new flares per source per year ou
  of 1.6 new flaring states per source per year
- Purity: 69 ± 6 %

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

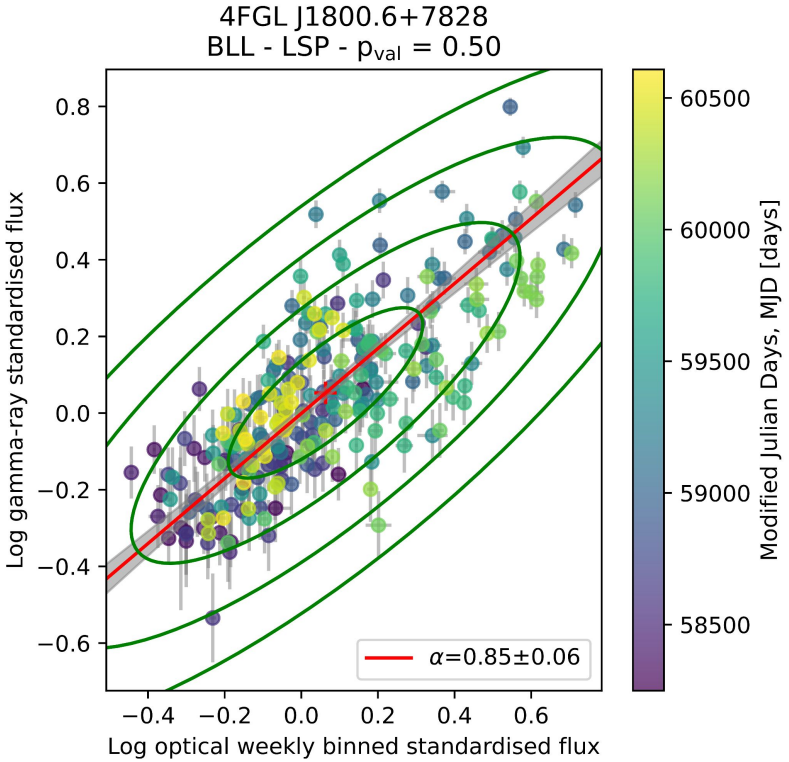
- Not correlated with class of blazar
- Poorly correlated with ν_{syn} ⇒ important spread



Linear vs. quadratic models

- Power law fit:
  - Distinction between quadratic and linear
  - Possible identification of orphan flares
- 2d Gaussian to retrieve PDF, power law index, intrinsic spread, and outliers at once

- Linear scenario favoured for 17 out of 19 >3σ-correlation blazars
- Possibility to predict flux at HE and VHE by SED extrapolation + EBL absorption (concept already used by the CTAO teams)

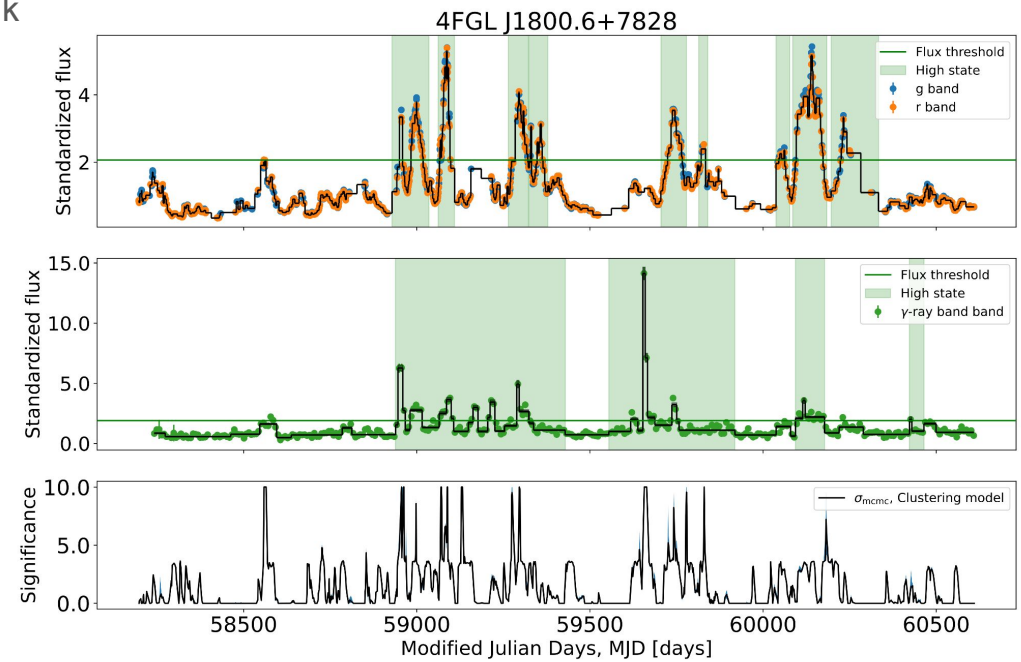


Towards a more refined method

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



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
- Linear correlation favoured: sampled biased towards FSRQs and LBLs
- Ongoing: Use of ML to detect features for MWL flares
- Alerts sent by Fink + possibility to estimate TeV flux → **Reach out if interested**

Note: low-state alerts already sent to AGN redshift task force of CTAO and used to ask for observation time

Backup slides

Time lag comparison with literature

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

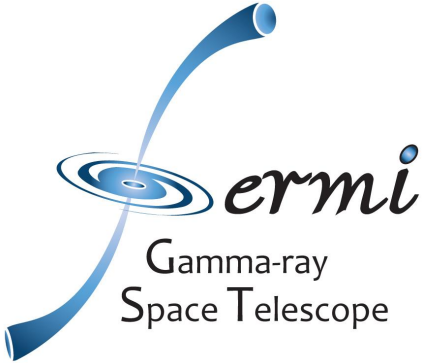
The Zwicky Transient Factory

ZTF with the Palomar Observatory

- 3 filters (g, r, i)
- Up to -30 declination
- 100k alerts/night
- ~20.5 max magnitude

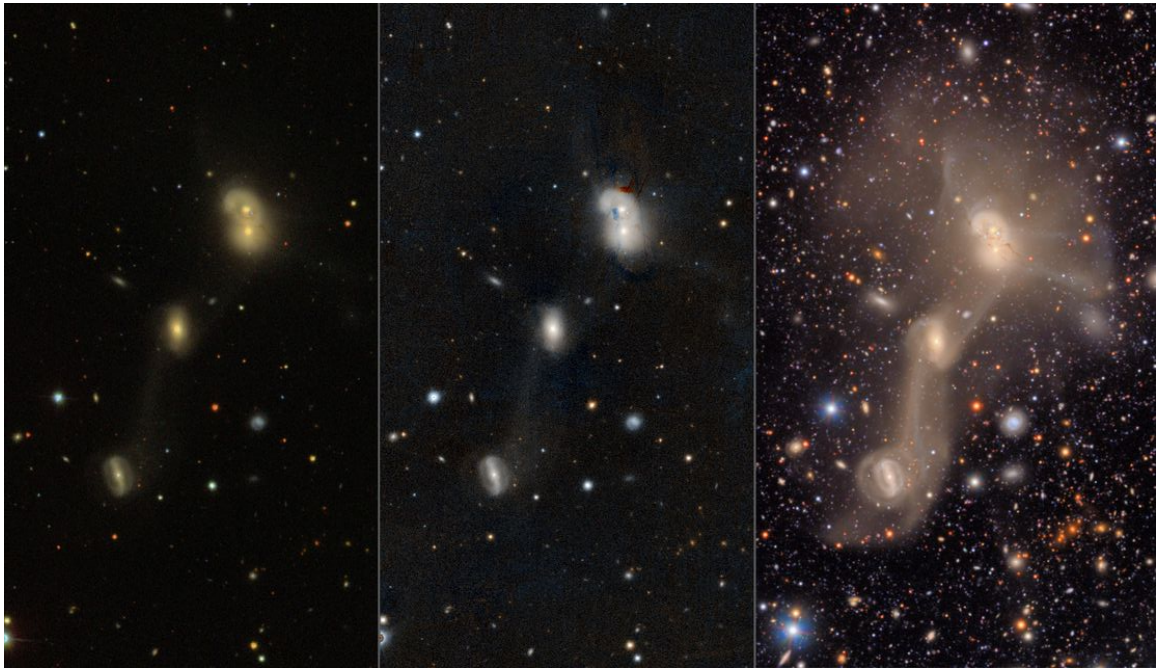
The *Fermi*-LAT instrument

***Fermi*-LAT satellite**



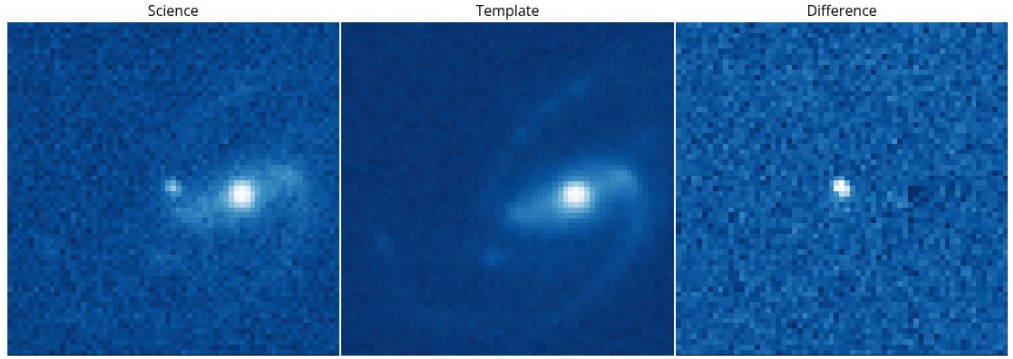
- Started in 2008
- Orbits in 3 hours
- Energy range: 100 MeV-1 TeV
- Weekly sampled light curve production

Vera C. Rubin performances



SDSS Pan-STARRS Vera C. Rubin

Alert broker: Fink



- ZTF/LSST stream real-time analysis
- Multi-messenger input (GW, neutrinos, MWL spectrum - through GCN)
- Community-based science modules with personalizable output - we do what you want!
- 10^7 alerts in a night, less than 60s seconds before the closing of the shutter and the data delivered at home

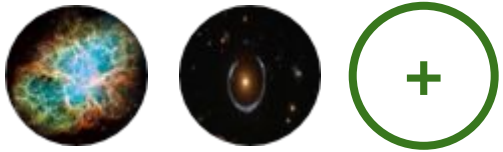
What is Fink?

Cross match

X

- *Catalogs*
- *Stream surveys*

ML classification
Fink features



Community-based science modules

Stream filtering

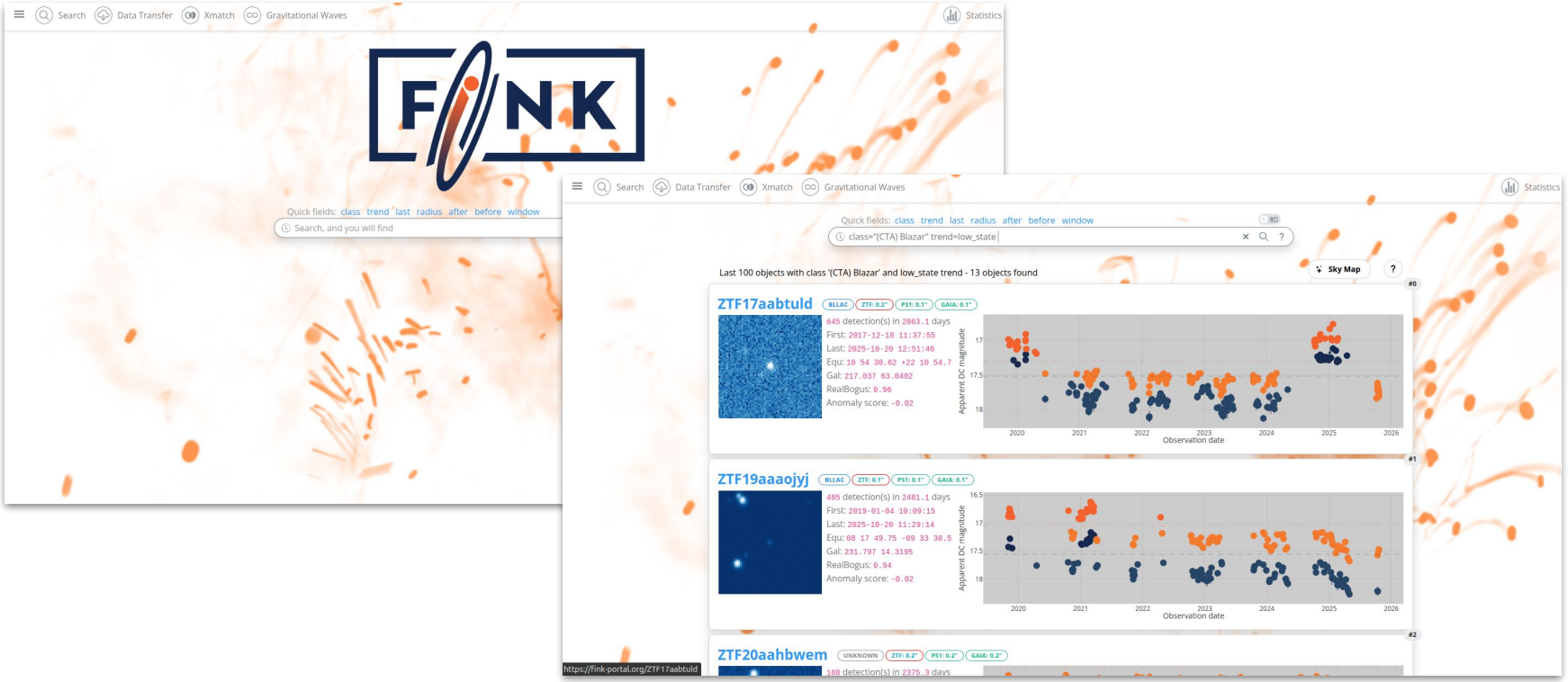
*~**2%** of alerts: credible candidates for blazars*

REDUCED STREAM

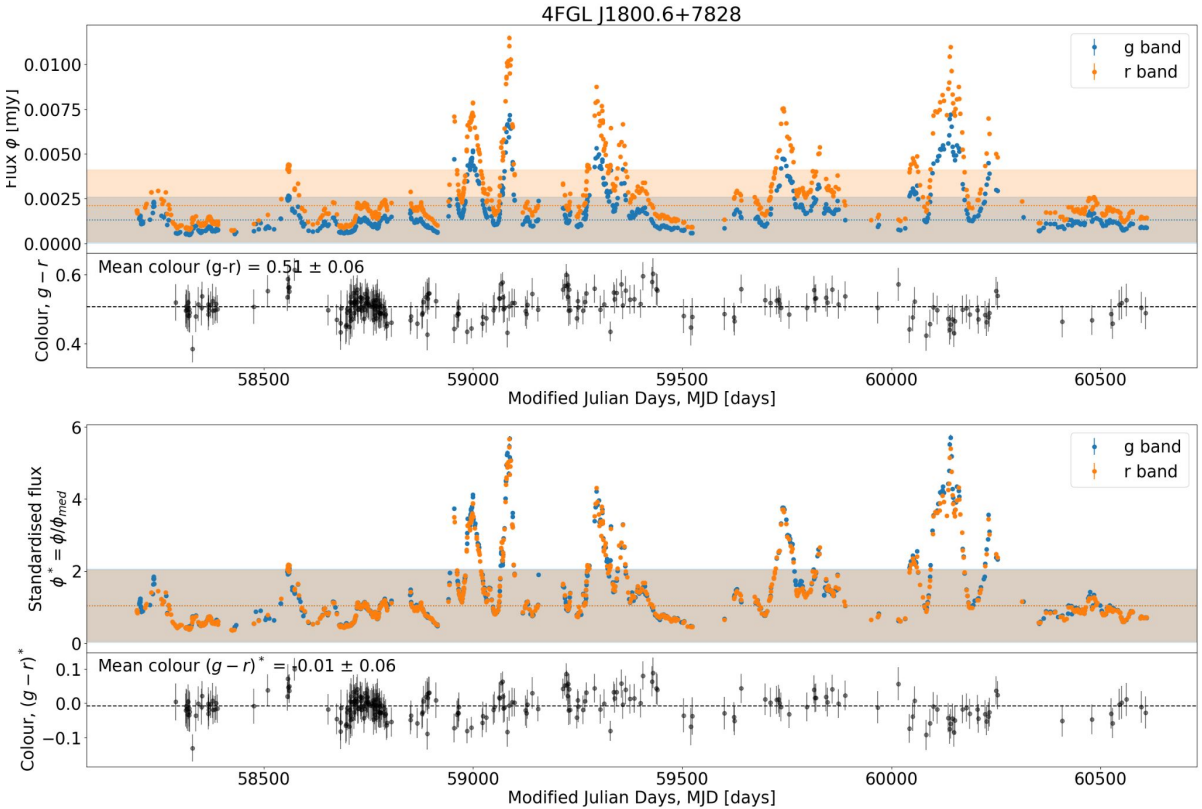
TNS report
Livestream
<minutes

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

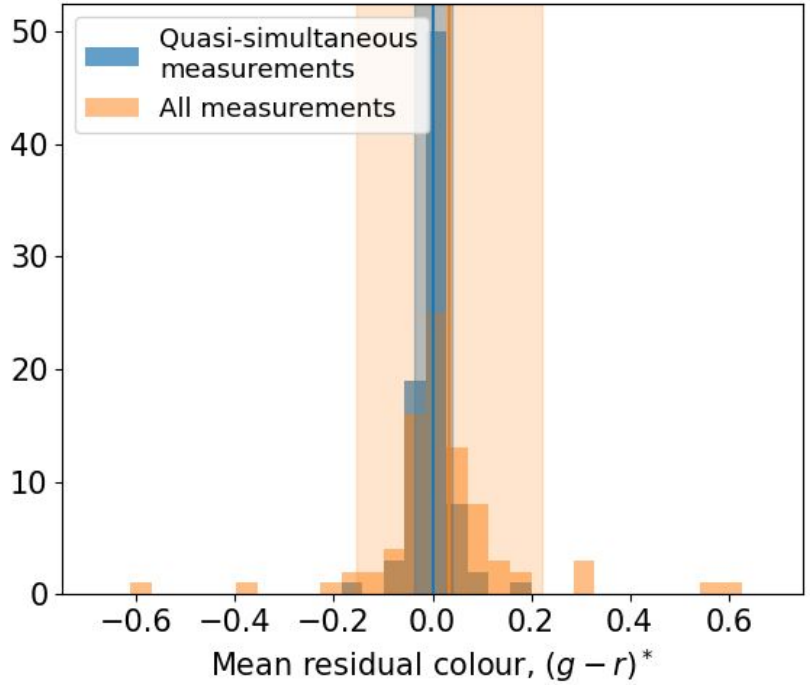
g- & r-bands can be merged into a single optical lightcurve

Method easily transposed to Rubin’s urgizy bands

Julian Hamo

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



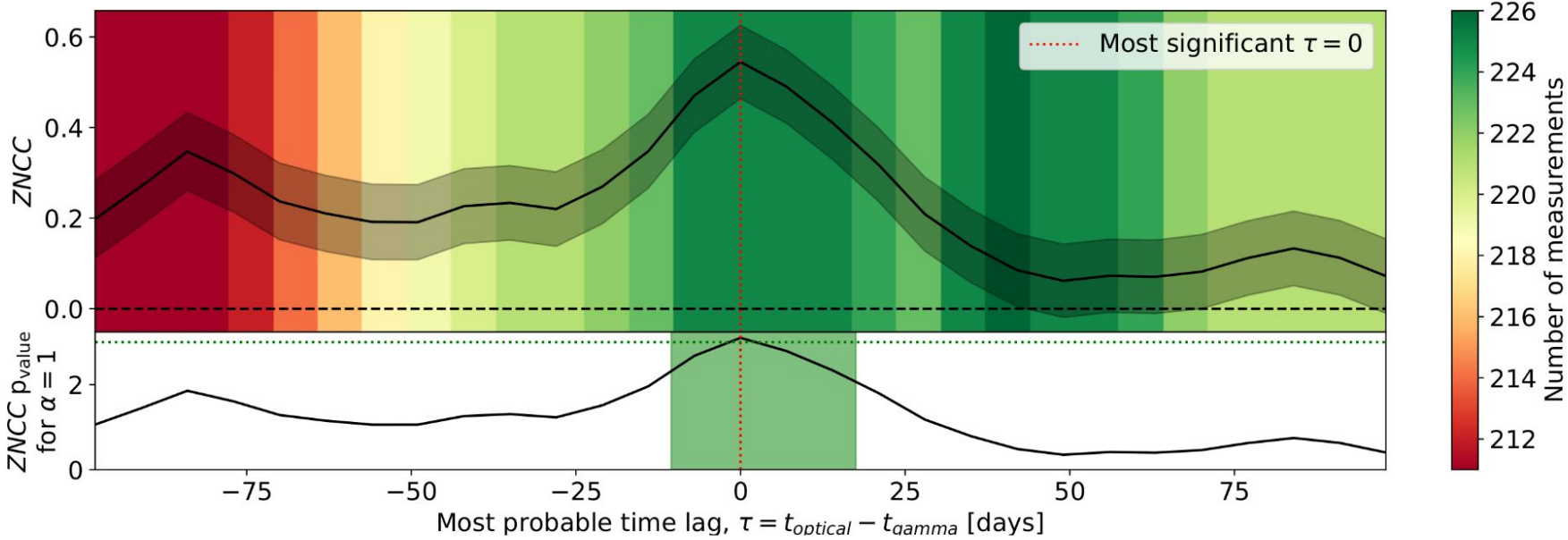
Normalized Cross-Correlation Function

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

$$\sigma_{\mathrm{NCCF}}(\tau) = \frac{1}{N - n_\tau + 1} \frac{1}{\sigma_x} \sqrt{\left(1 + \frac{1}{N}\right) \sum_{i=0}^{N} x_{i+n}^2 - \frac{1}{N} \left(\sum_{i=0}^{N} x_{i+n}\right)^2}$$

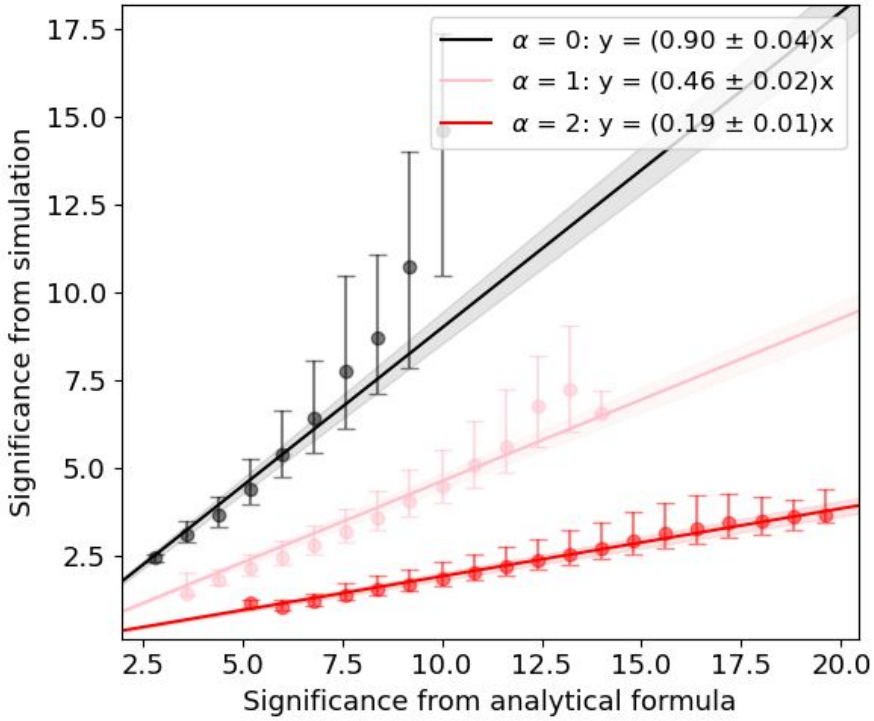
Caveat: Assume white noise for PSD → overestimation of the significance

Similarity metric

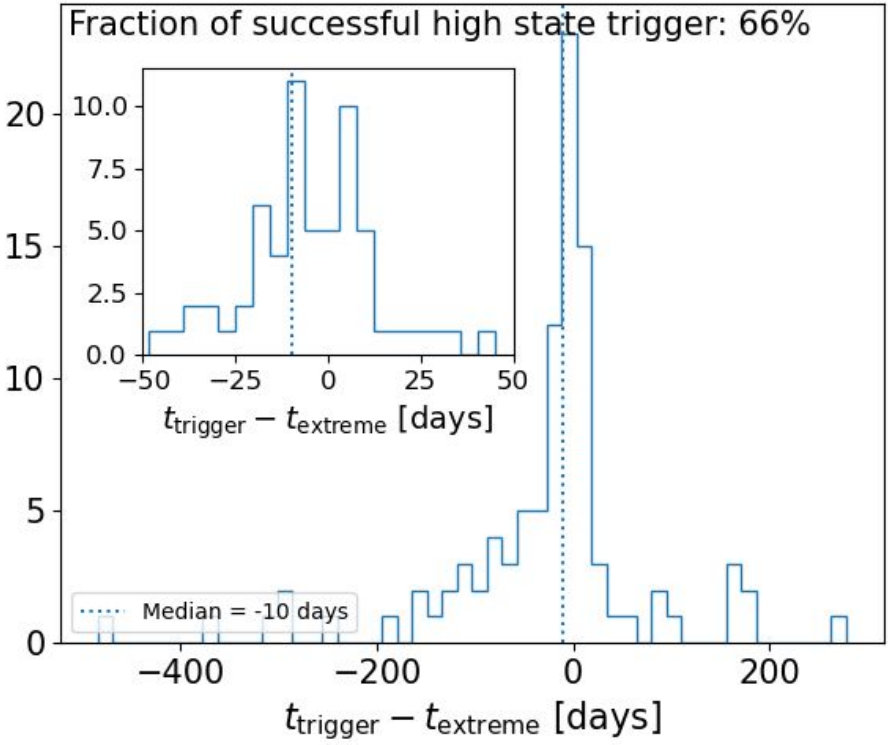


Penalization from noise colour

- ZNCC assumes uncorrelated data ⇒ 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

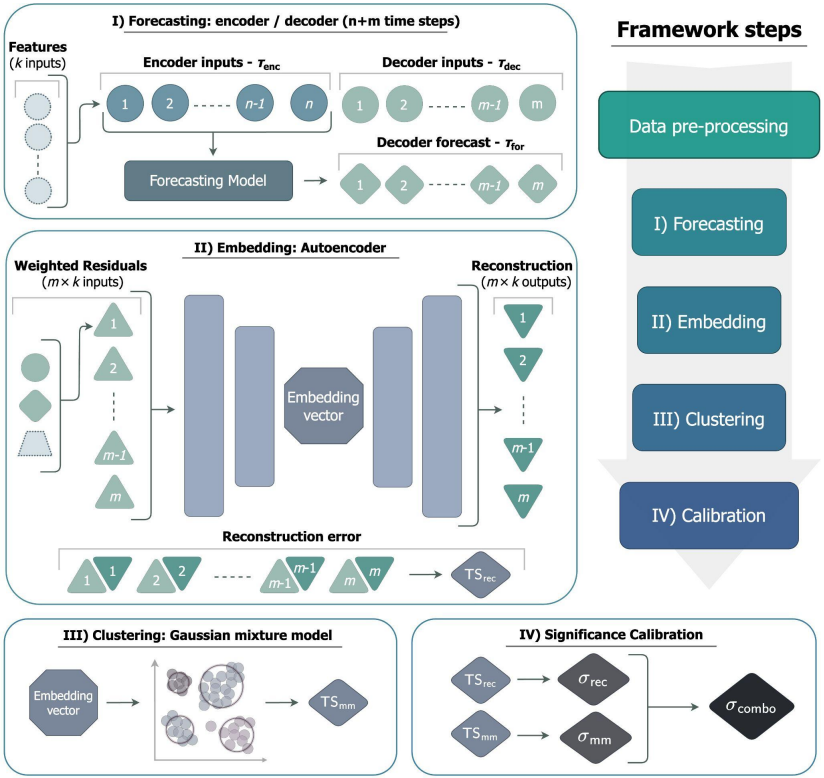


Time offset between trigger and peak



ML MWL flare detection

- 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



Adapted from Hermann, ‘25

Significance of a ML detected flare