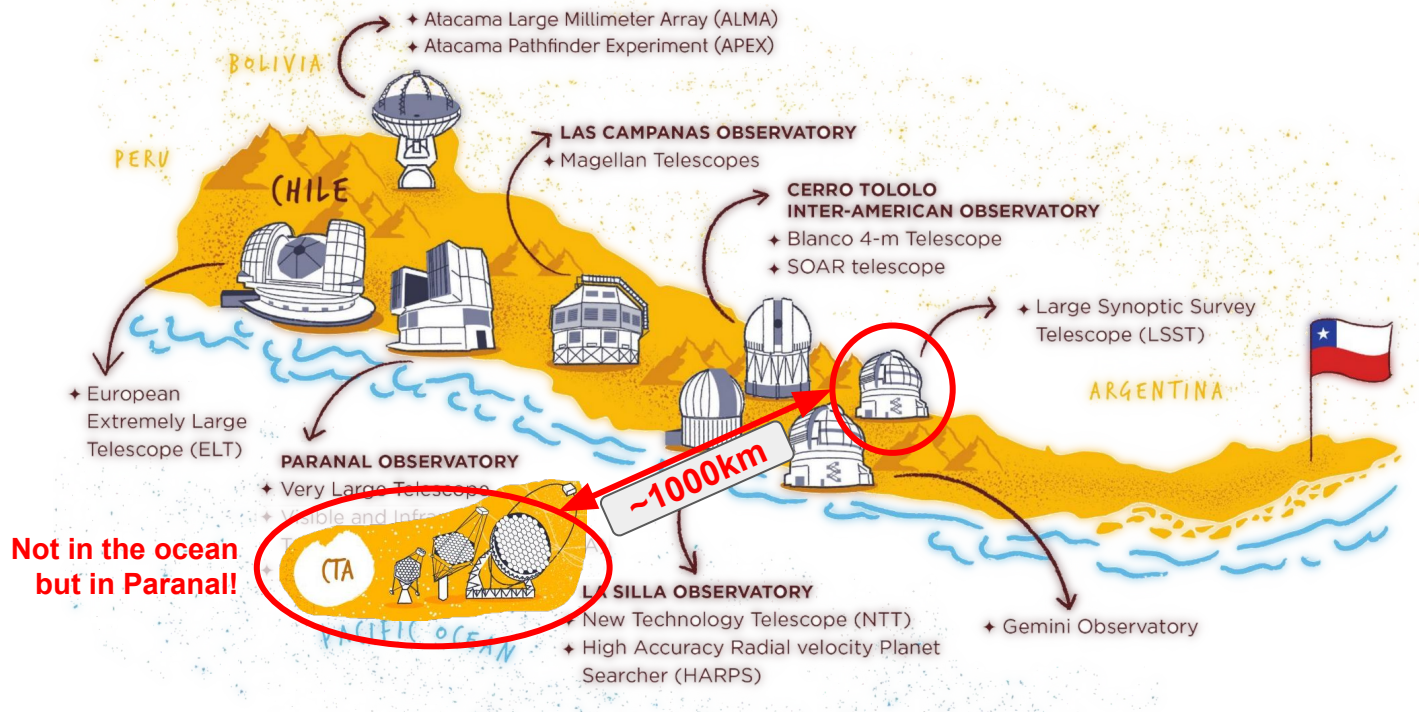


Optical- γ -ray Correlations in Blazars with Rubin and CTAO

From optical detection to gamma-ray triggers

Chile: A bustling hub of astrophysics



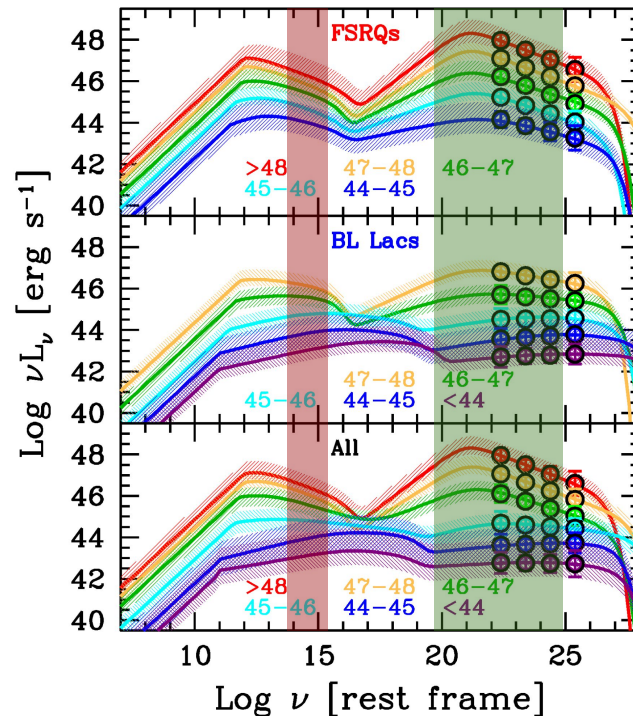
The peculiar SED of blazars

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 Vera C. Rubin Observatory and LSST

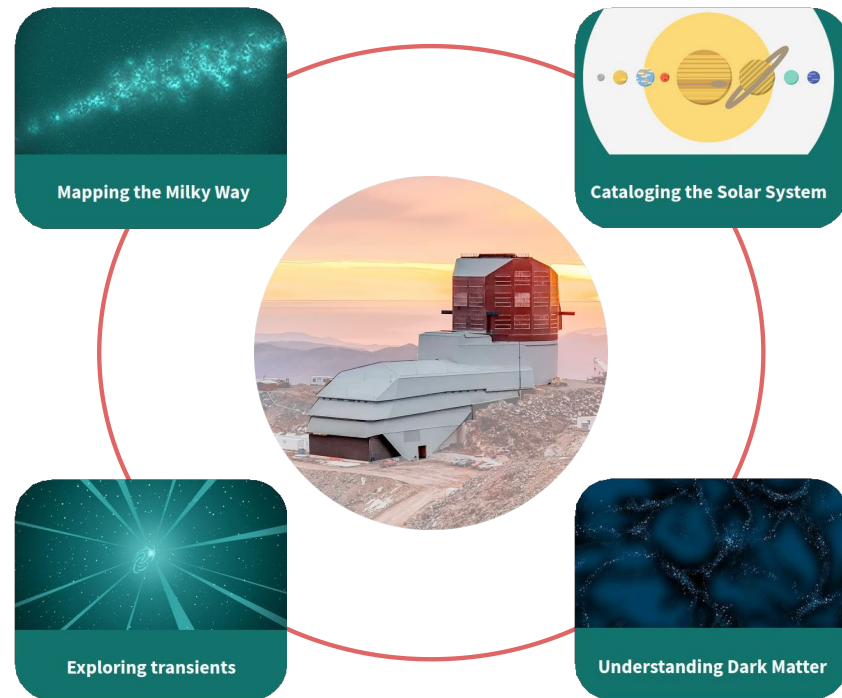
Large Scale optical Surveys:

Legacy Survey of Space and Time (LSST)

- 6 bands: *ugrizy*
- Sky coverage: up to $+30^\circ$ 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



Rubin's alerts: from millions to few per night

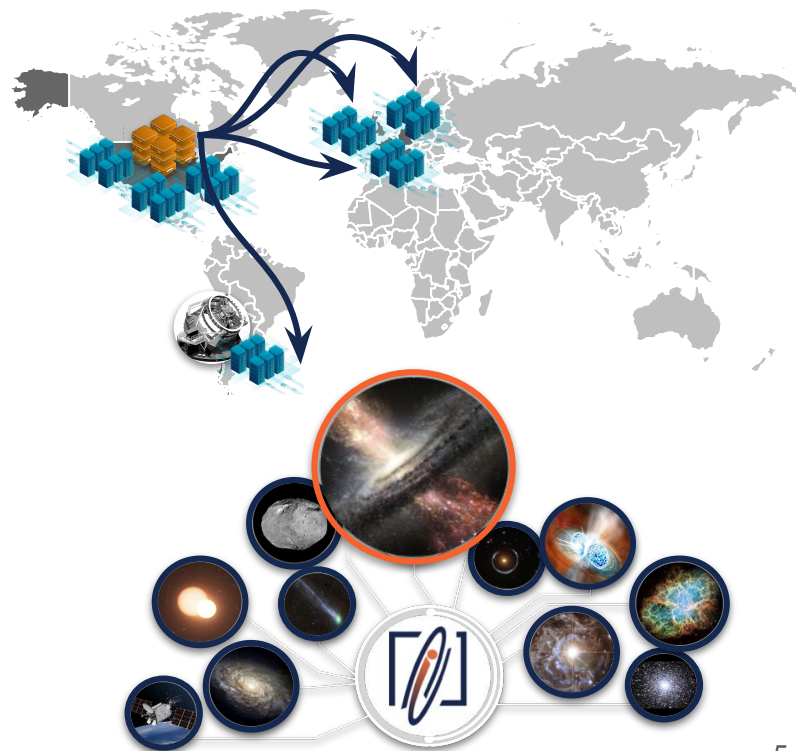
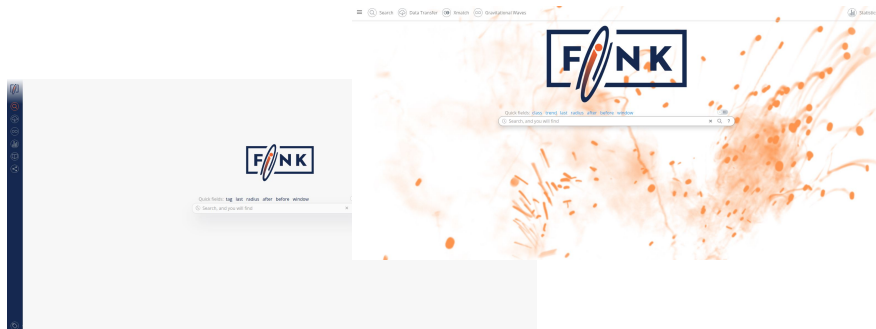
Estimated alert rate: **10M** / night

Available **60s** after data taking through brokers:

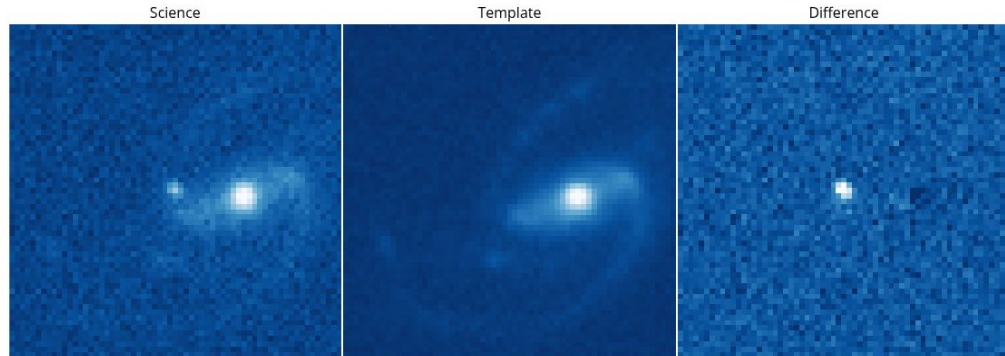
ALERCE, AMPEL, ANTARES, Babamul, Fink, Lasair, Pitt-Google

→ Classification and filtering of stream: stream reduced to your taste

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



Alert broker: Fink



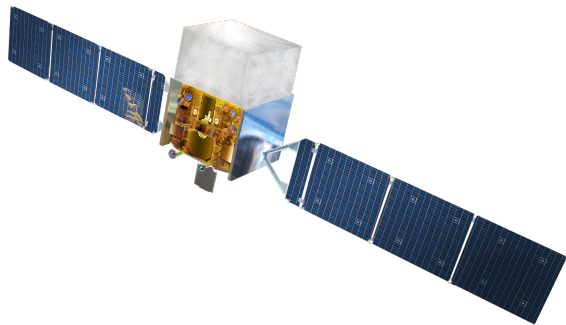
- ZTF/LSST stream real-time analysis
- Multi-messenger input (GW, neutrinos, MWL spectrum - through GCN)
- Community-based science modules with personalizable output - we do what you want!
- 10^7 alerts in a night, less than 60s seconds before the closing of the shutter and the data delivered at home

Gamma-ray data: the FLaapLUC pipeline

Gamma-ray surveys: Fermi-LAT

Light curves from FLaapLUC

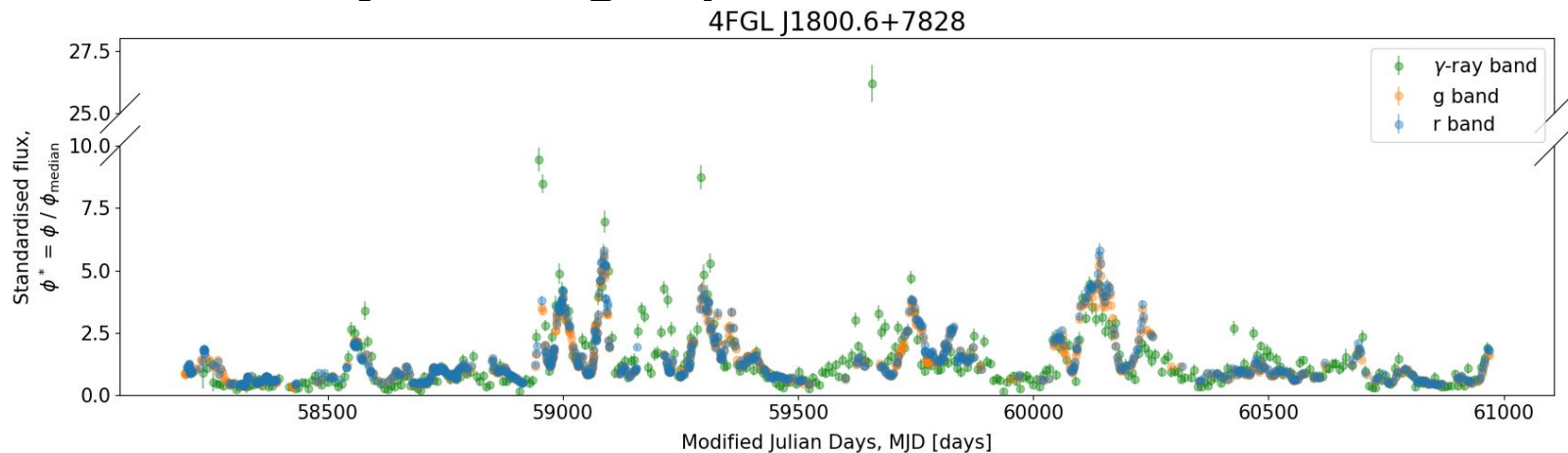
- Cadence: 3h - weekly-binned Fermi-LAT data (timescale of interest)
- Sky coverage: All-sky survey
- Field of view: ~ 8250 square degrees
- Energy range: 100 MeV to 500 GeV



FLaapLUC pipeline:

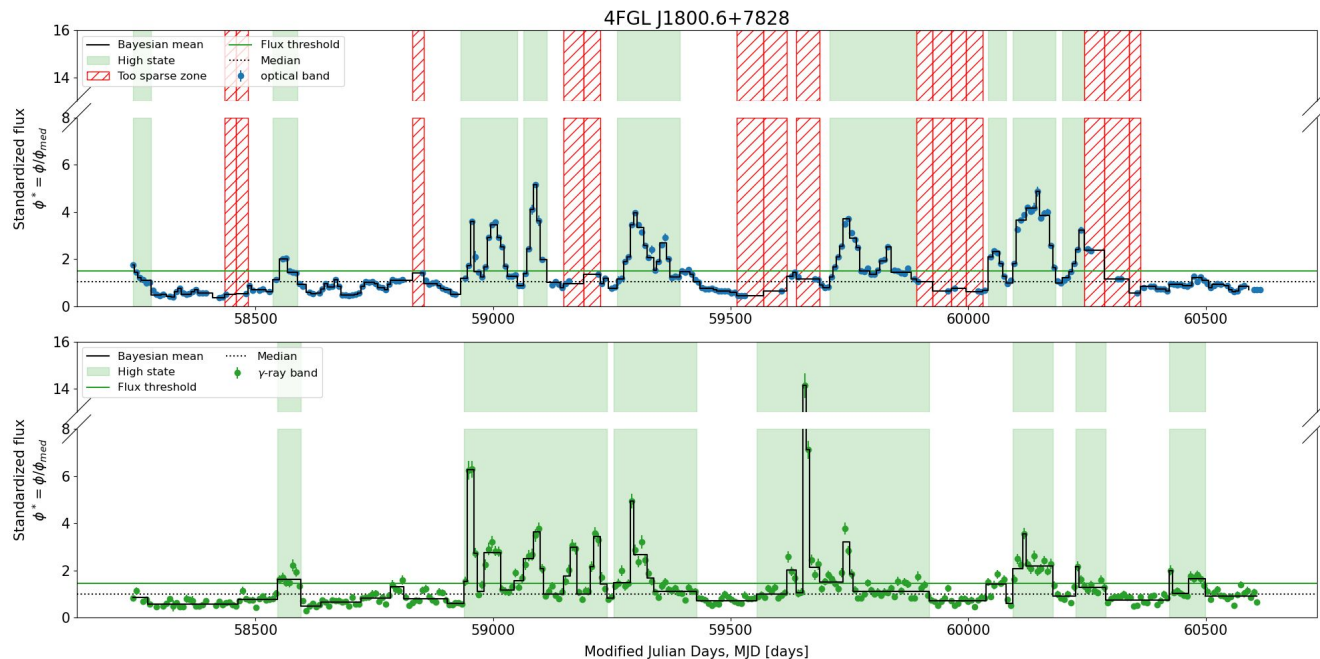
- Developed by J.P., Lenain (Lenain, J.-P. 2018, Astronomy and Computing) at LPNHE
- Gamma-ray photon counting (100 MeV - 500 GeV) without background subtraction
- Proven to follow trends but biased absolute flux reconstruction
- Already used to trigger potential observations of IACTs (H.E.S.S., LST, etc.)

Yes but why using optical data?



- Mean optical relative error: 5% vs mean gamma-ray relative error: 22%
- Design for large-scale surveys: LSST planned for the next 10 years
- Significant correlation between optical and gamma-ray light curve (Liodakis et al., 2018; Hamo et al., 2025)
- Disclaimer: 2/3-days cadence $\Rightarrow$ no intranight flare $\rightarrow$ sources of interest: exceptionally bright flares of high-z blazars

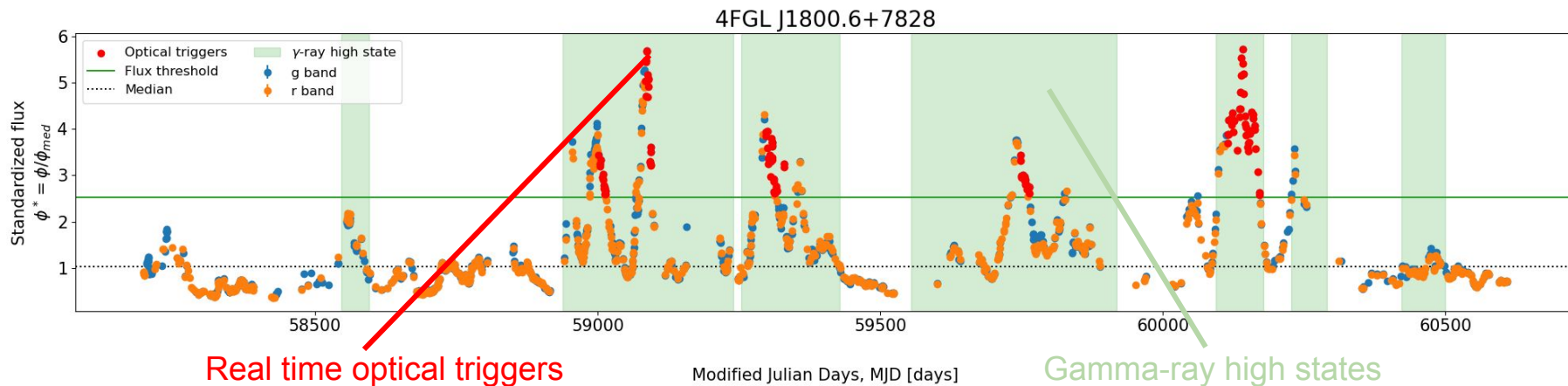
Extreme state detection



- **BL Lac & LSP (LBL)**
- Optical band accurate merging method
- Gamma-ray band from FLAapLUC (*Fermi*-LAT)
- Bayesian block construction $\rightarrow$ steady flux states
- Selection of greatest quartile
- Merge of concomitant high states + rise and fall parts $\Rightarrow$ 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



Trigger performances

Metrics on flare optical triggers

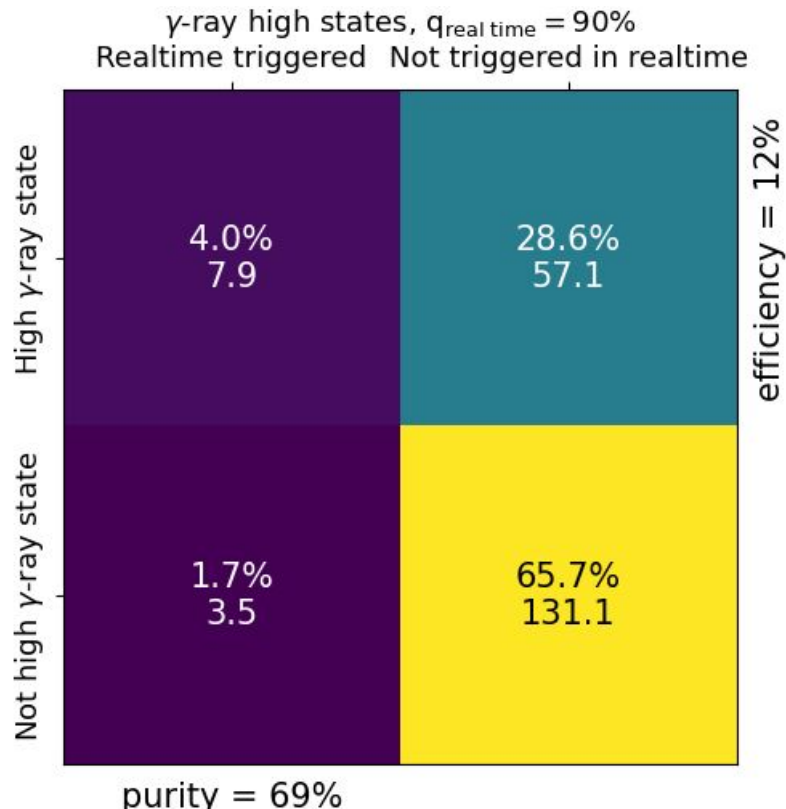
- Efficiency: $12 \pm 2 \%$
→ 0.2 detected new flares per source per year of 1.6 new flaring states per source per year
- Purity: $69 \pm 6 \%$

Real-time first optical trigger

- $\langle t_{\text{trigger}} \rangle \sim 10$ days before the highest γ -ray flux
- fraction of the flare left after the trigger: $\sim 76\%$

Flare duration

- Not correlated with class of blazar
- Poorly correlated with $v_{\text{syn}} \Rightarrow$ important spread



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 $\sim$ TeV observations from the CTAO
- Algorithm already implemented in Fink - both low states and flare detections
- FLAapLUC alert check when optical flare detection
- LST proposal program for blazar flare detection currently under discussion
- Current working step: setup of intermediate VM for likelihood reconstruction from Fermi-LAT when optical flare + fully informed trigger proposal sending

Backup slides

Time lag comparison with literature

Optical-gamma-ray correlation:

- Liodakis+ '19: $>3\sigma$ correlations for $\sim 6\%$ 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

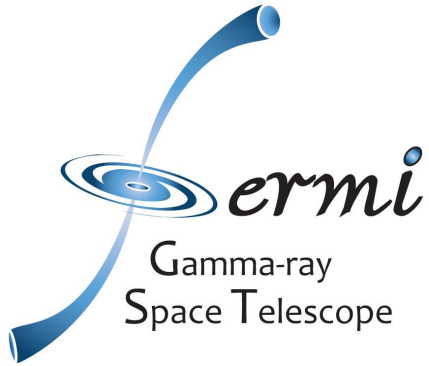


- 3 filters (g, r, i)
- Up to -30 declination
- 100k alerts/night
- ~20.5 max magnitude



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

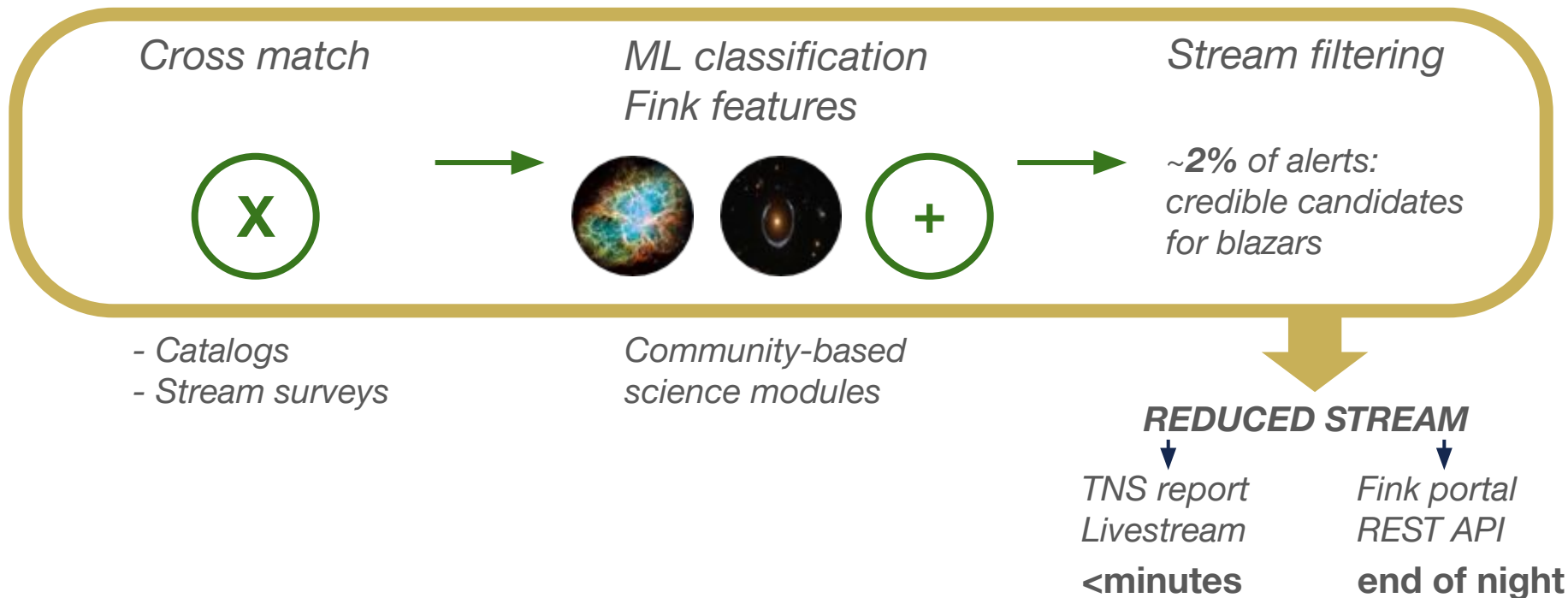


SDSS

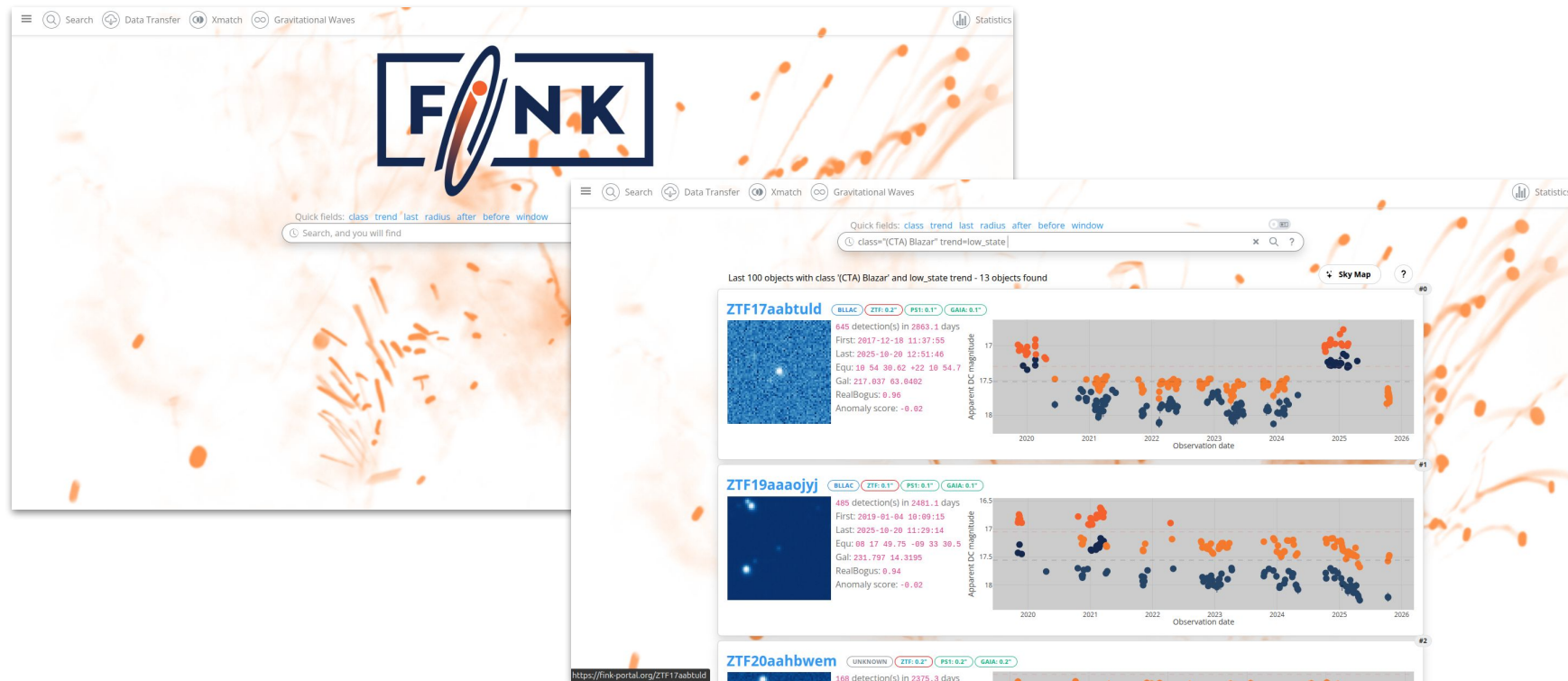
Pan-STARRS

Vera C. Rubin

What is Fink?

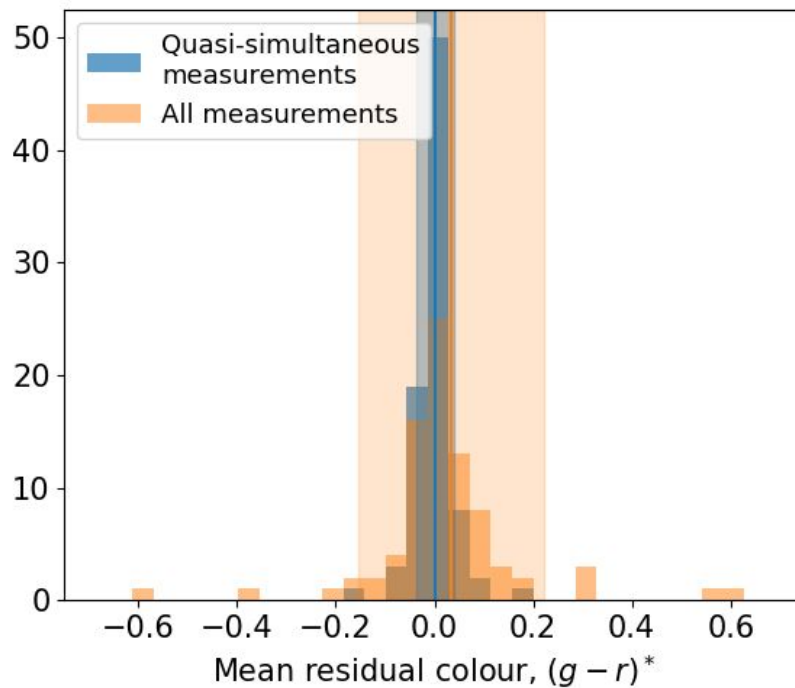


The Fink portal



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



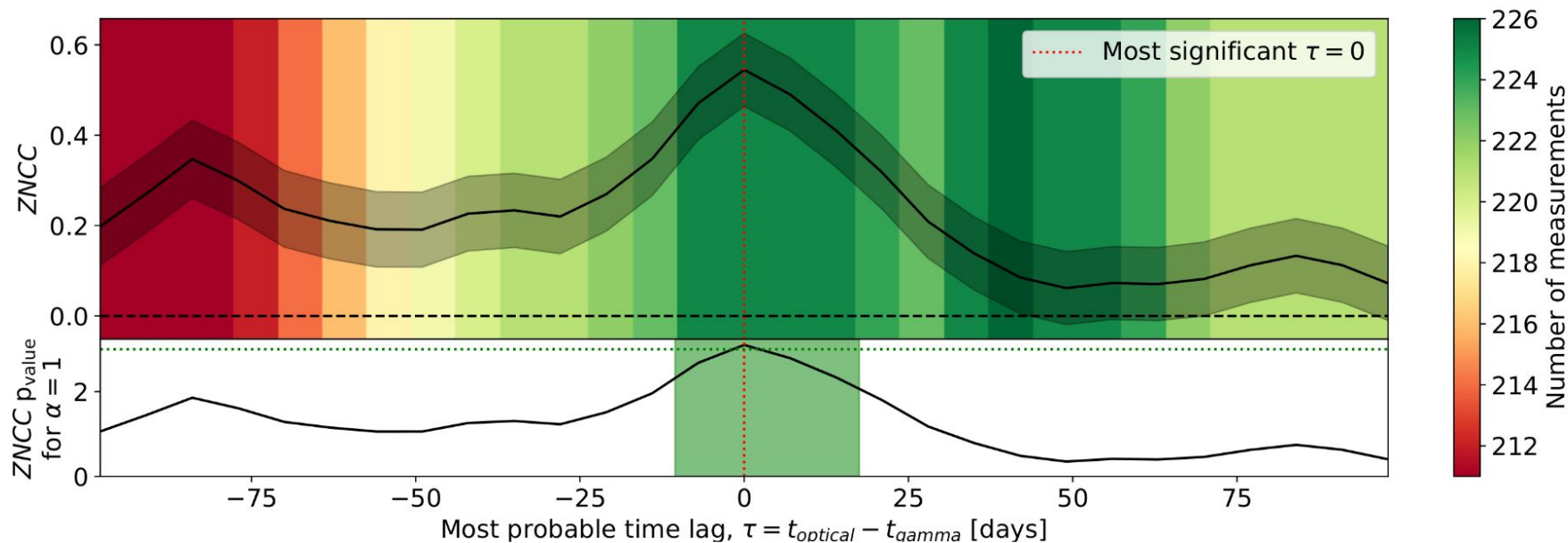
Normalized Cross-Correlation Function

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

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

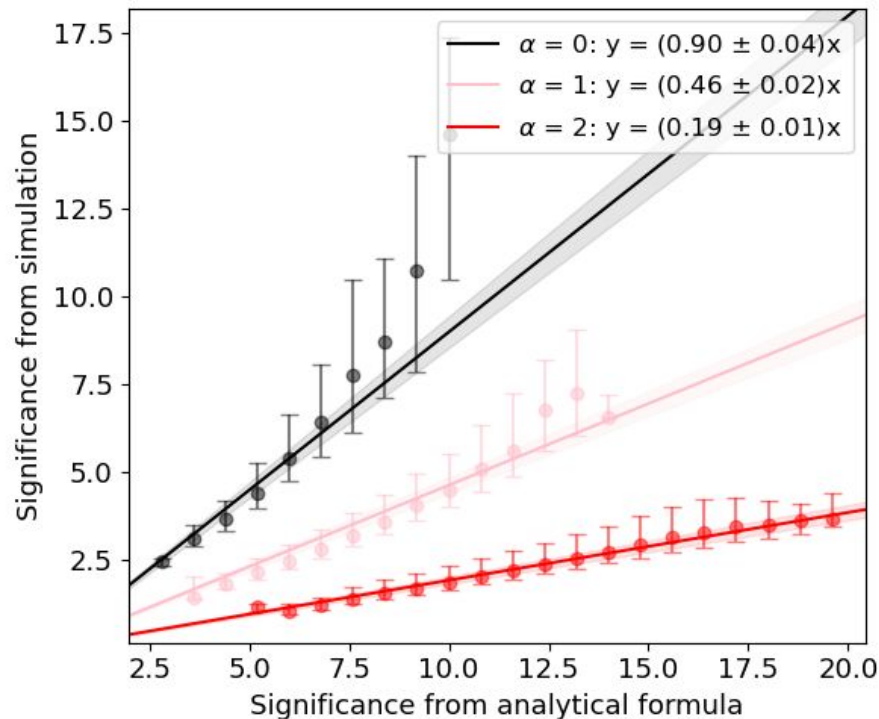
Caveat: Assume white noise for PSD → overestimation of the significance

Similarity metric

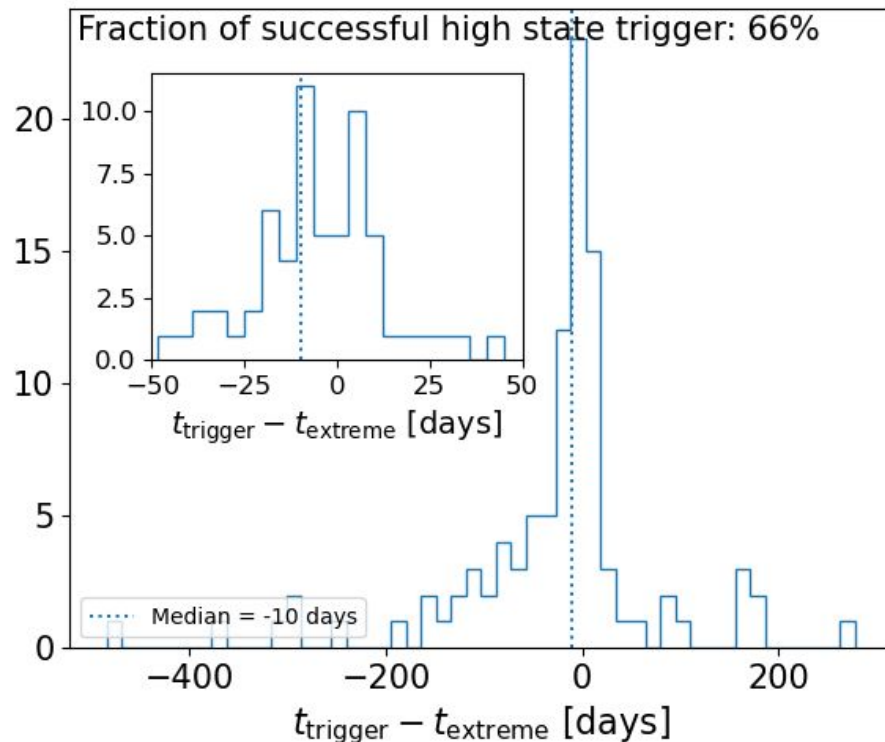


Penalization from noise colour

- 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

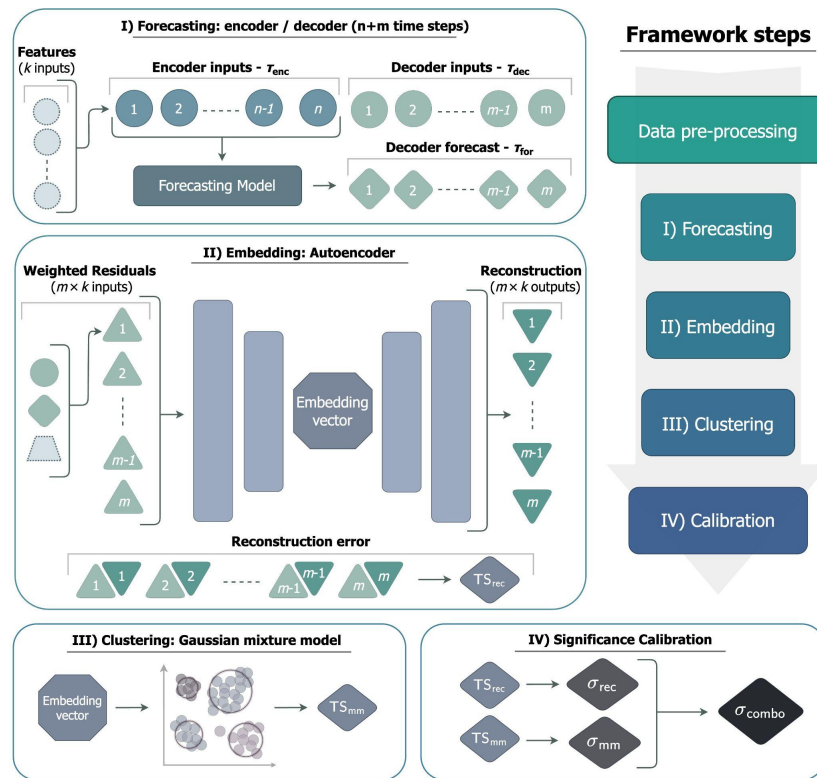


Time offset between trigger and peak

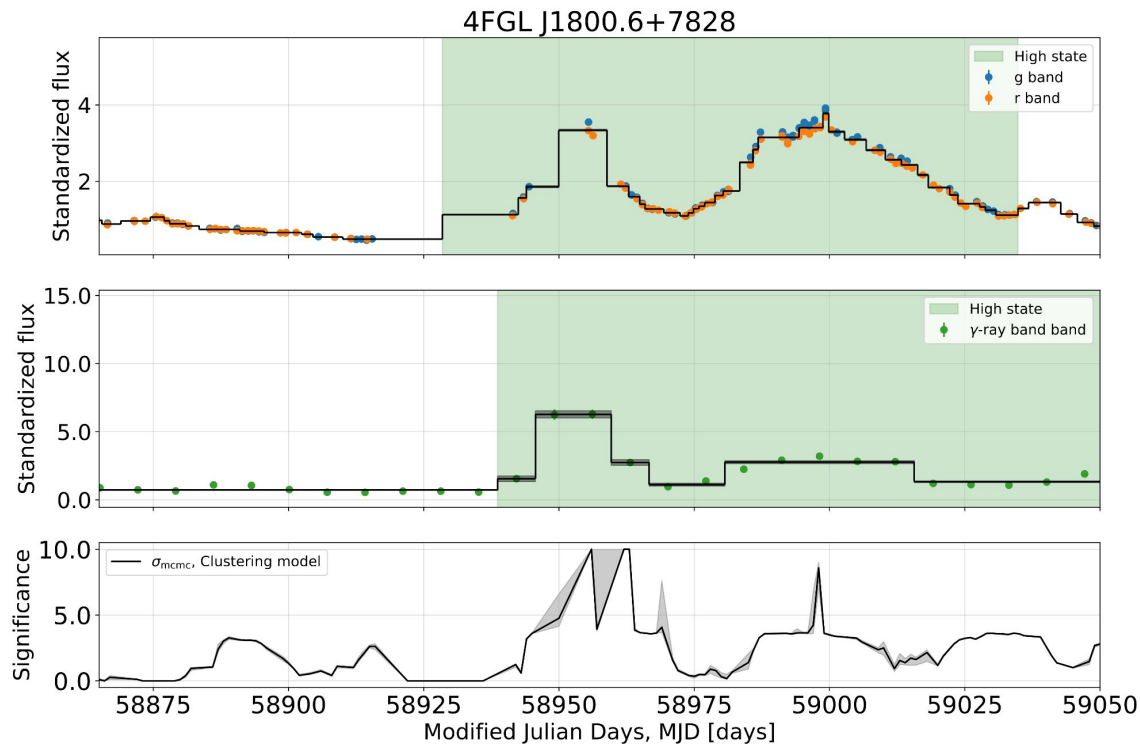


ML MWL flare detection

- 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



Significance of a ML detected flare



Detection of flares in 4C 27.50

