LST-1: Bending Model & Gamma Ray Burst Analysis

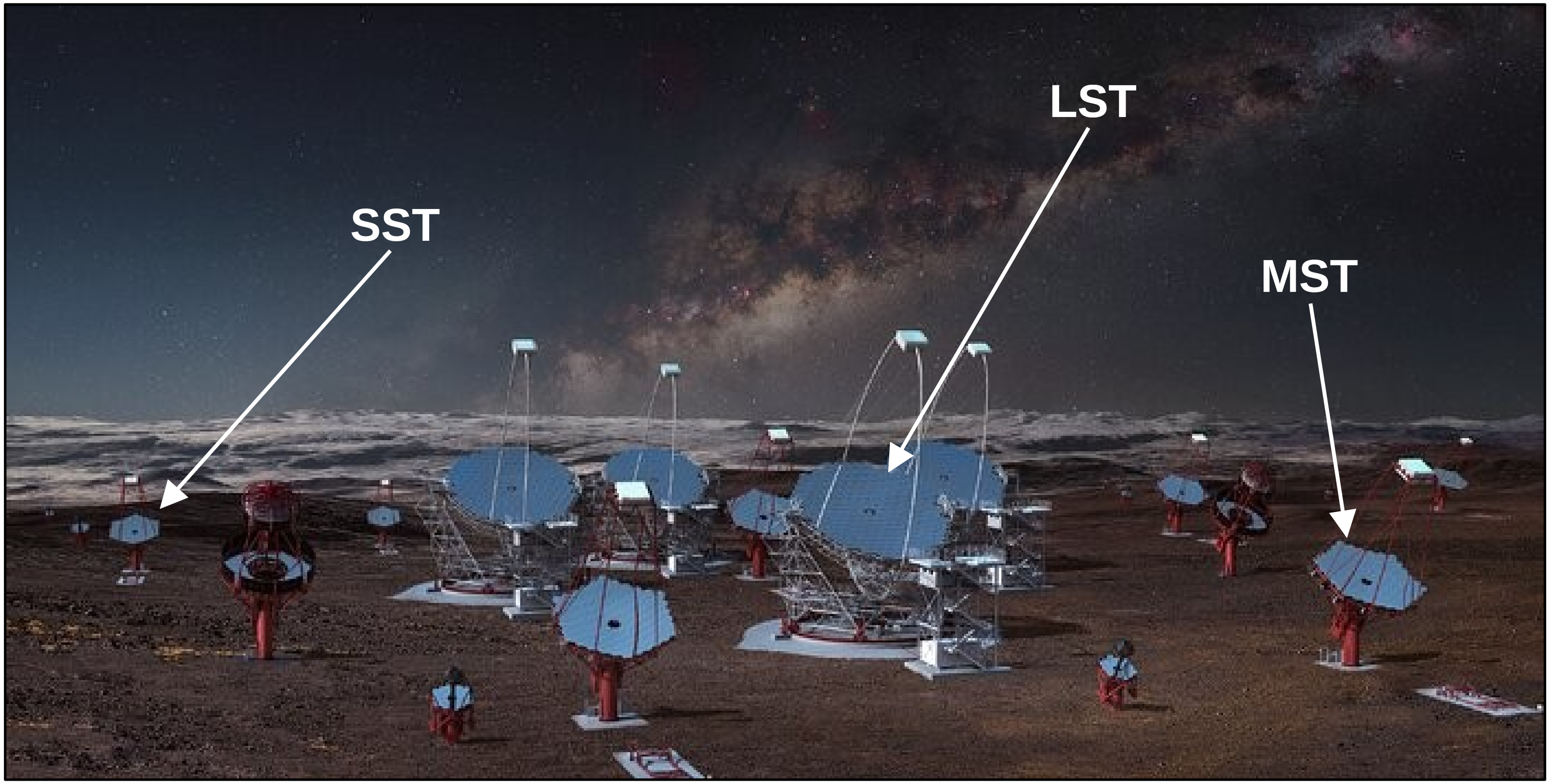
CSI – Second year PHD report – 12 September 2025

Léo Le Moigne – under the supervision of Armand Fiasson, David Sanchez and Edna Ruiz Velasco

CTAO: array of imaging atmospheric Cherenkov telescopes

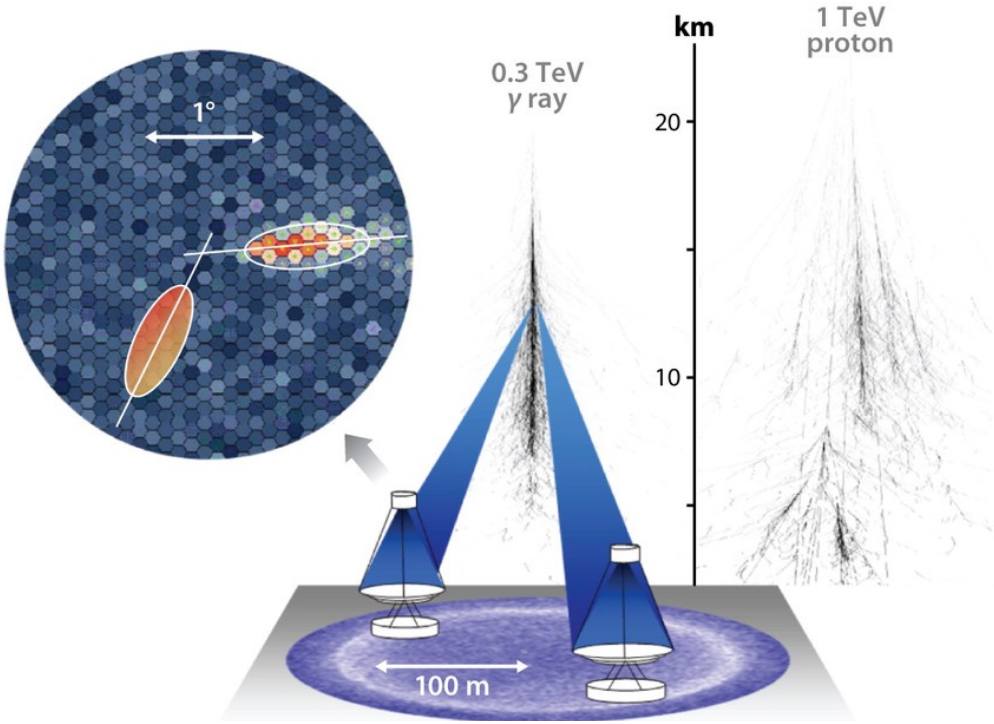
→ 2 sites in each hemisphere

→ 3 types of telescopes to cover from 20 GeV to 100 TeV



CTAO: array of imaging atmospheric Cherenkov telescopes

→ **LST-1**: first telescope of the array



Progress during PHD second year

Bending Model

Context

What is bending model ?

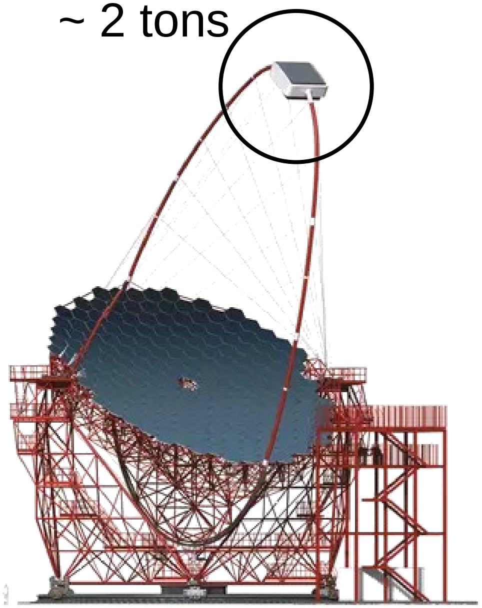
- software developed at LAPP by a former phd student, Mathieu de Bony
- written in python, using multiprocessing package
- should satisfy CTAO specifications

Goal

→ taking into account the deformation of the structure

=> correcting the systematic errors of the pointing (**< 1 arc-minute**)

~ 2 tons

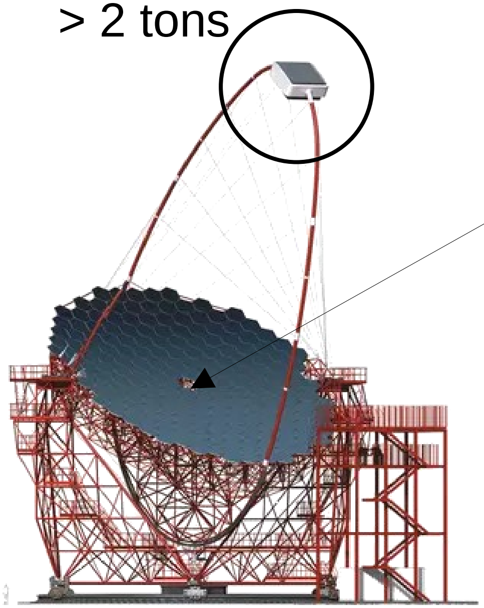


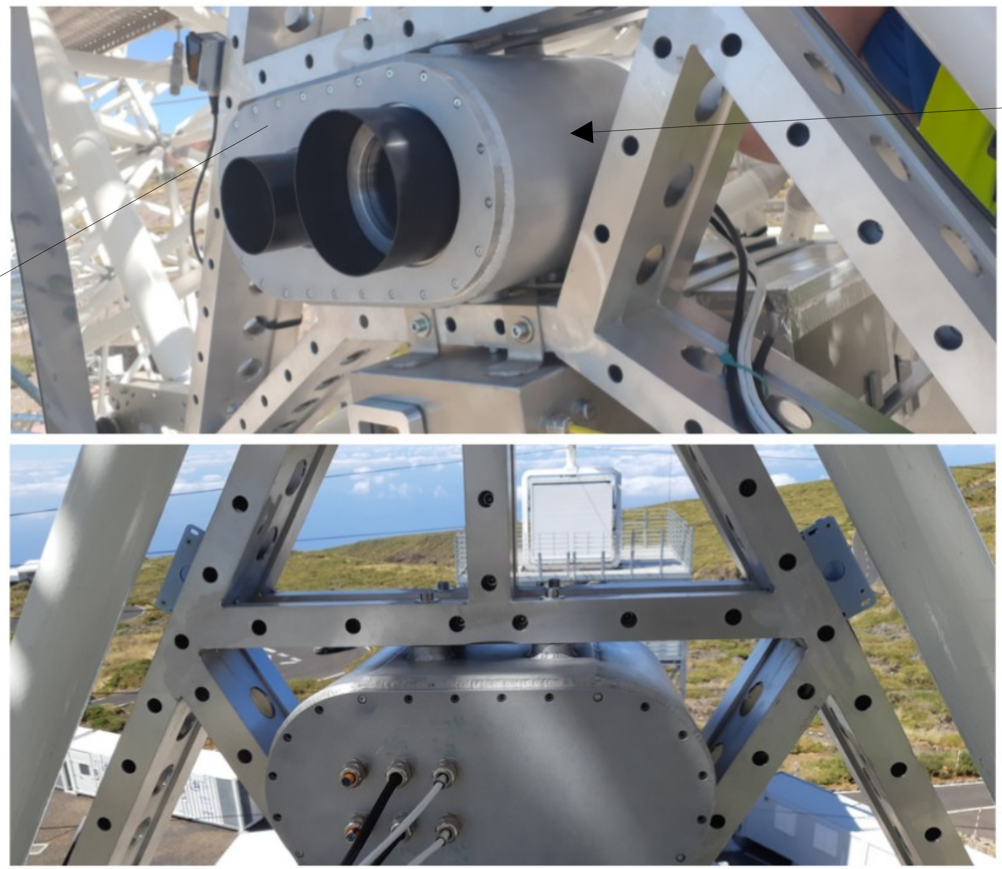
Goal

→ taking into account the deformation of the structure

=> correcting the <u>systematic errors</u> of the pointing (**< 1 arc-minute**)

> 2 tons





Camera Displacement Monitor

Progress : Bending Model

Goal

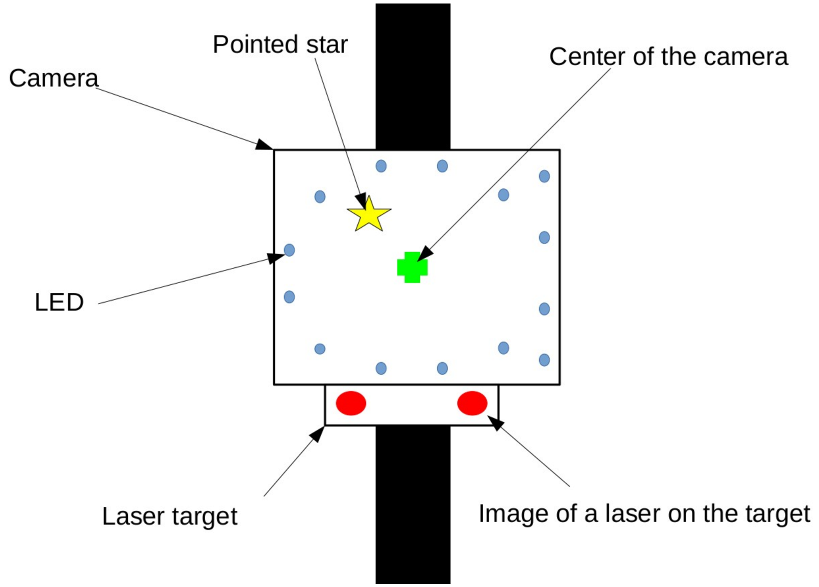
→ taking into account the deformation of the structure

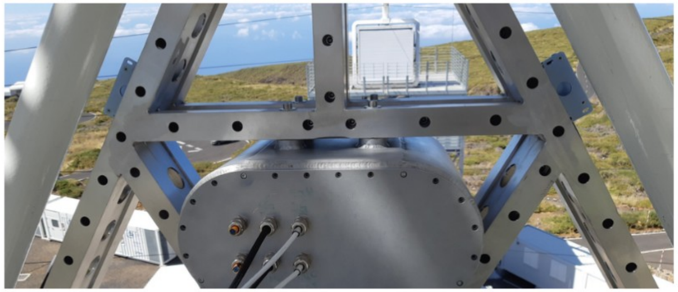
=> correcting the <u>systematic errors</u> of the pointing

Working principle

- → choose a star
- → point the star
- → measure the shift between the center of the camera and the image of the star

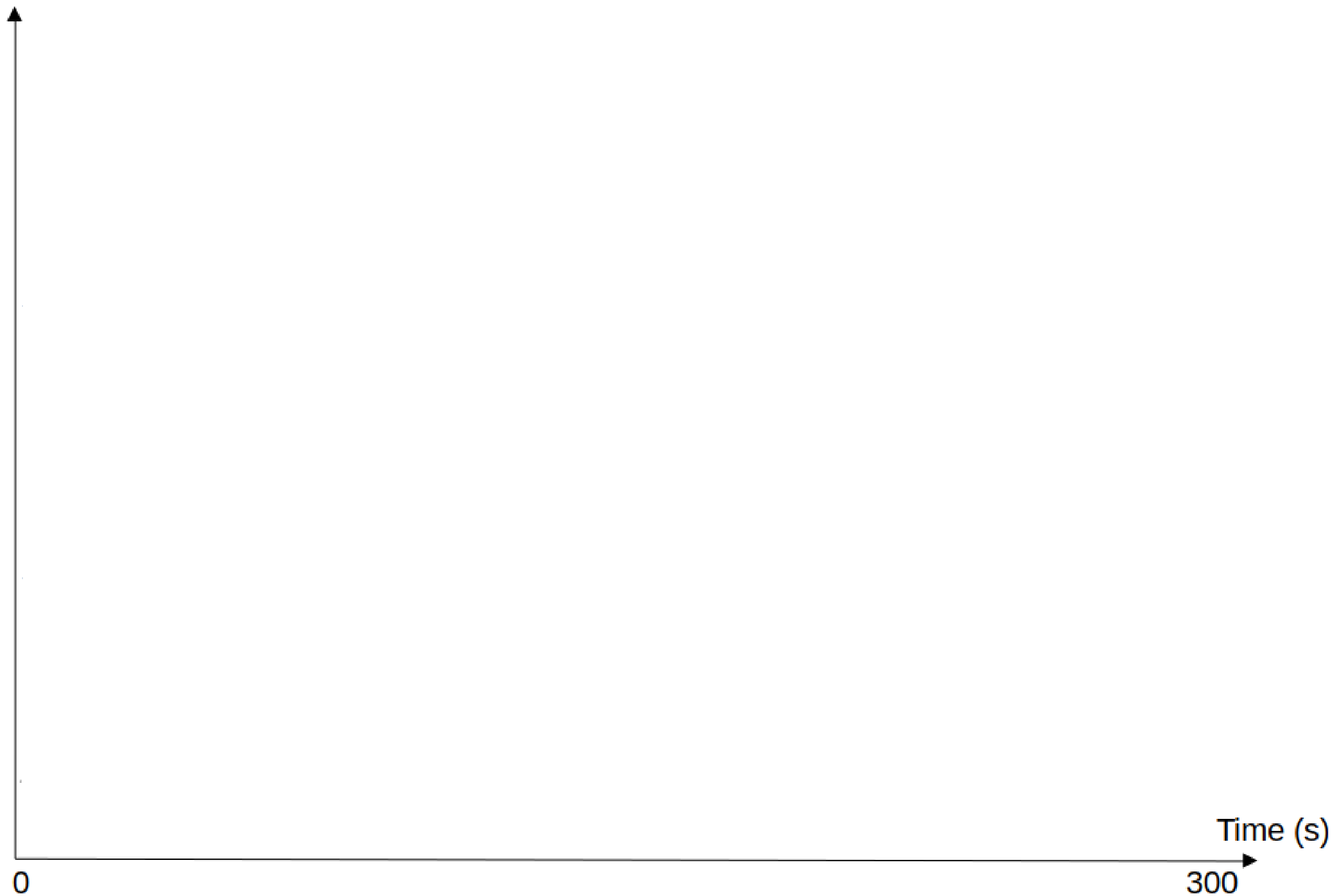
=> derive a mechanical model that predicts the shift





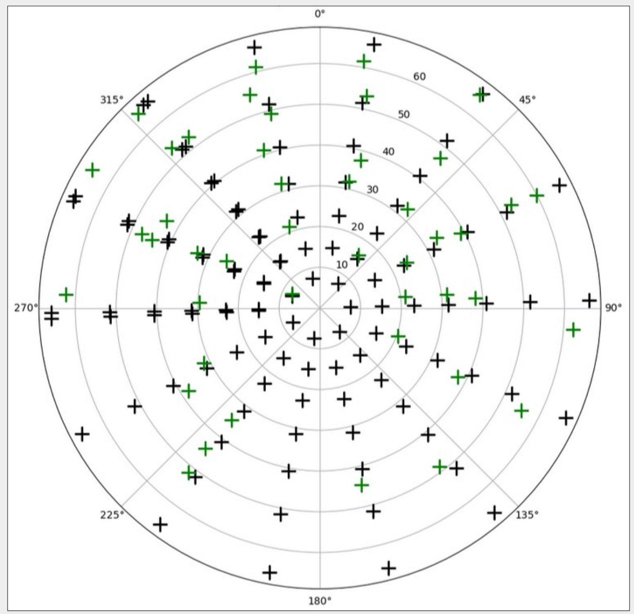
Progress : Bending Model

Description of the sequence



Relative mean time duration of a complete BM sequence

Description of the sequence



Hipparcos catalog
→ cut following different conditions (position, magnitude,...)

Example: cover all the sky grid

Star selection

35

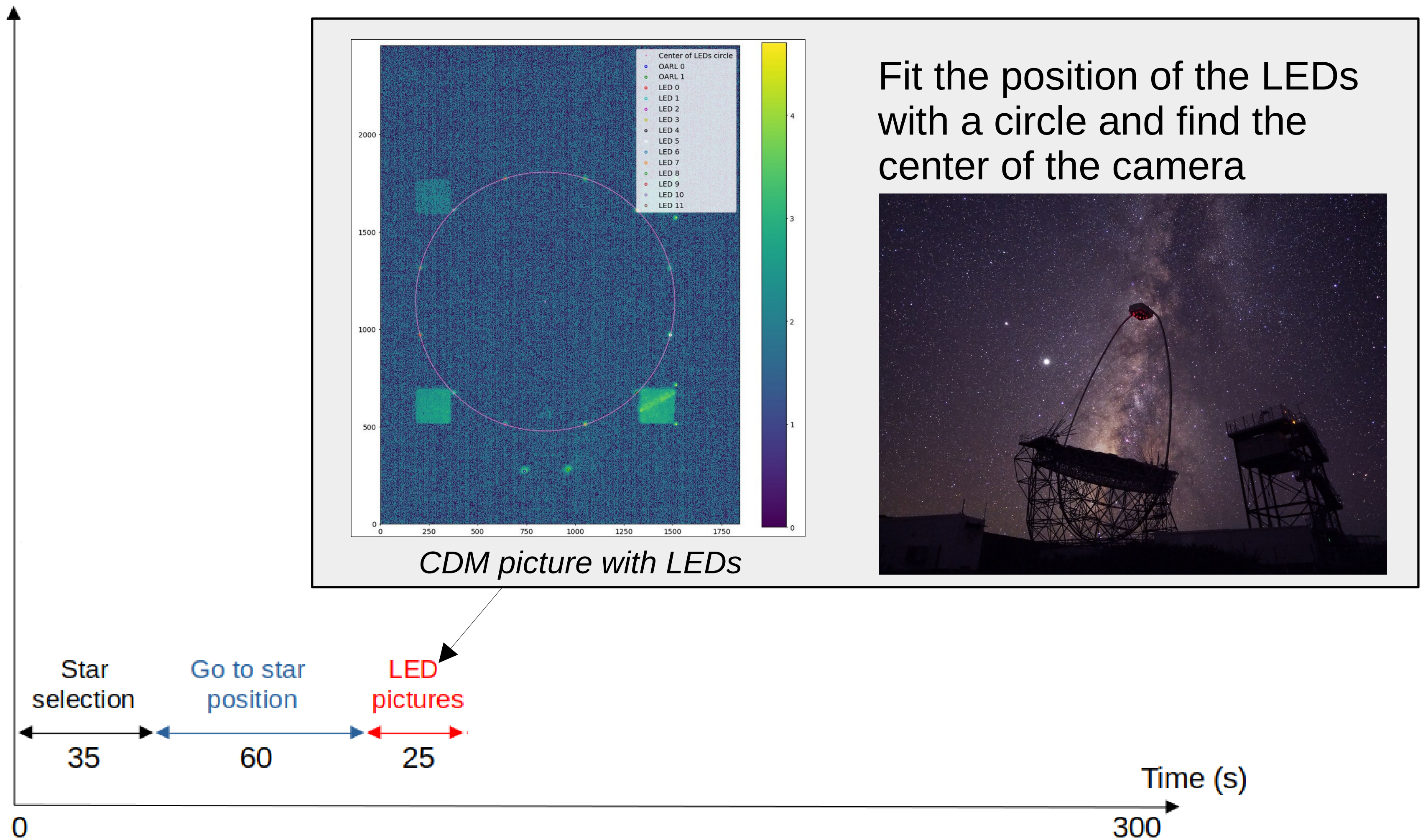
Time (s)

0

300

Relative mean time duration of a complete BM sequence

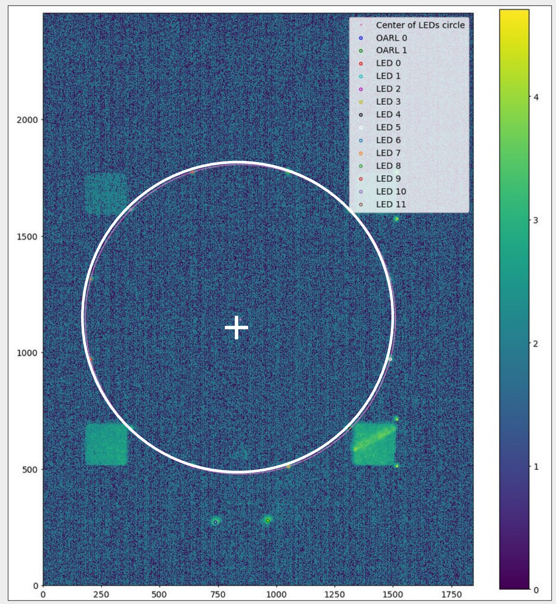
Description of the sequence



Relative mean time duration of a complete BM sequence

Description of the sequence

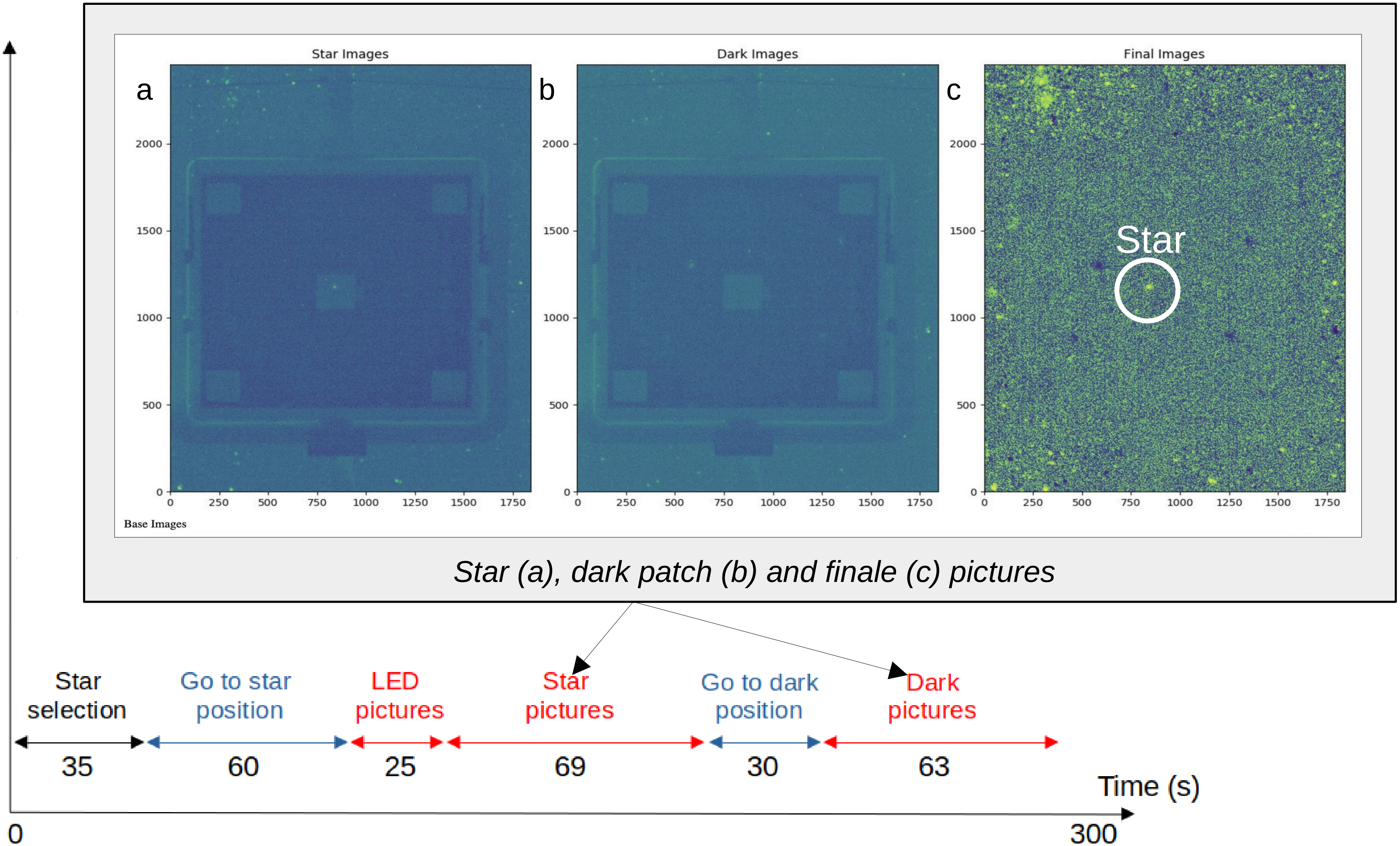
Fit the position of the LEDs with a circle and find the center of the camera



CDM picture with LEDs

Relative mean time duration of a complete BM sequence

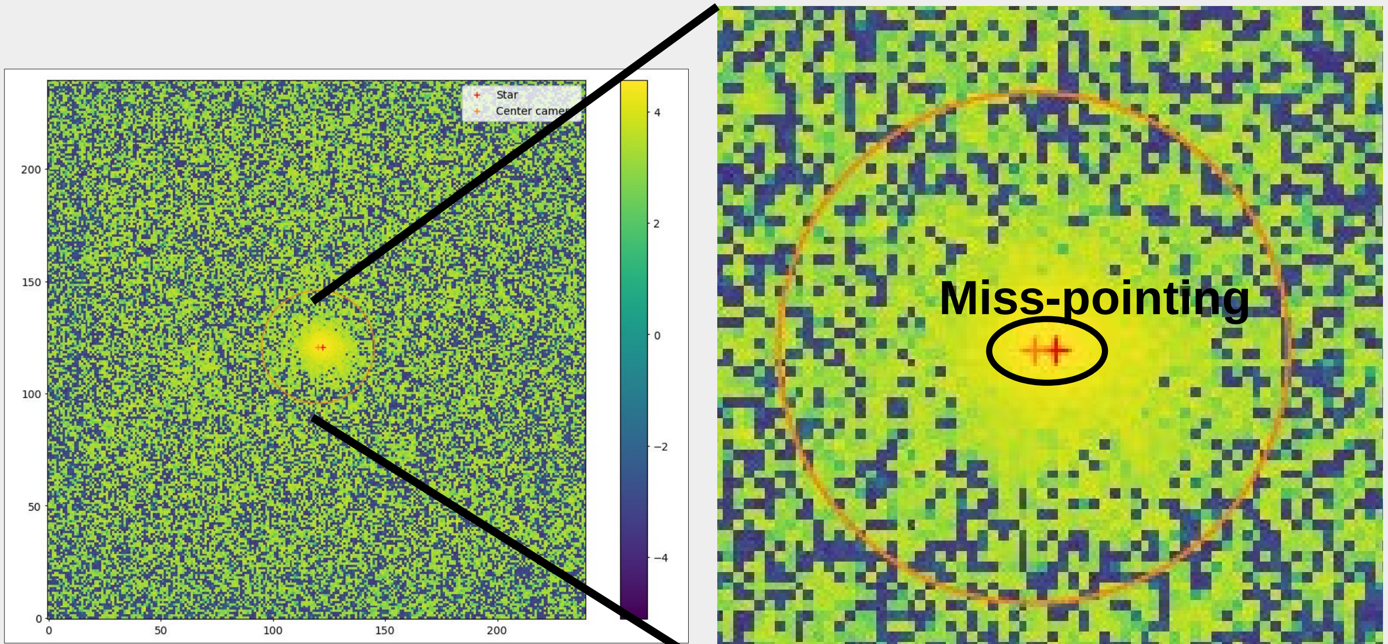
Description of the sequence



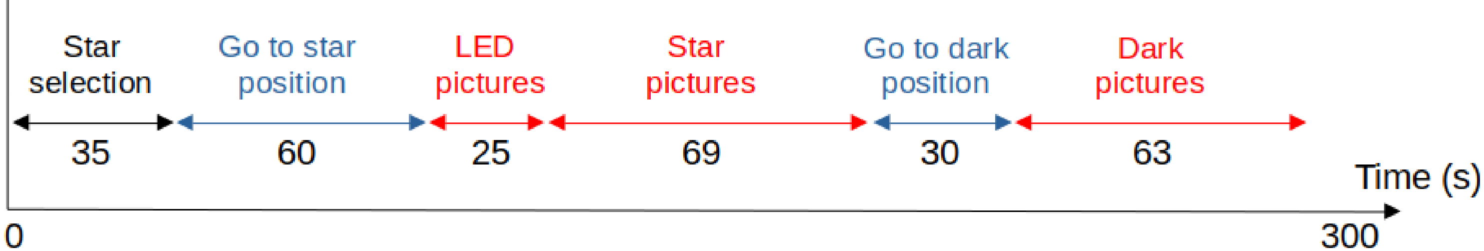
Star (a), dark patch (b) and finale (c) pictures

Relative mean time duration of a complete BM sequence

Description of the sequence



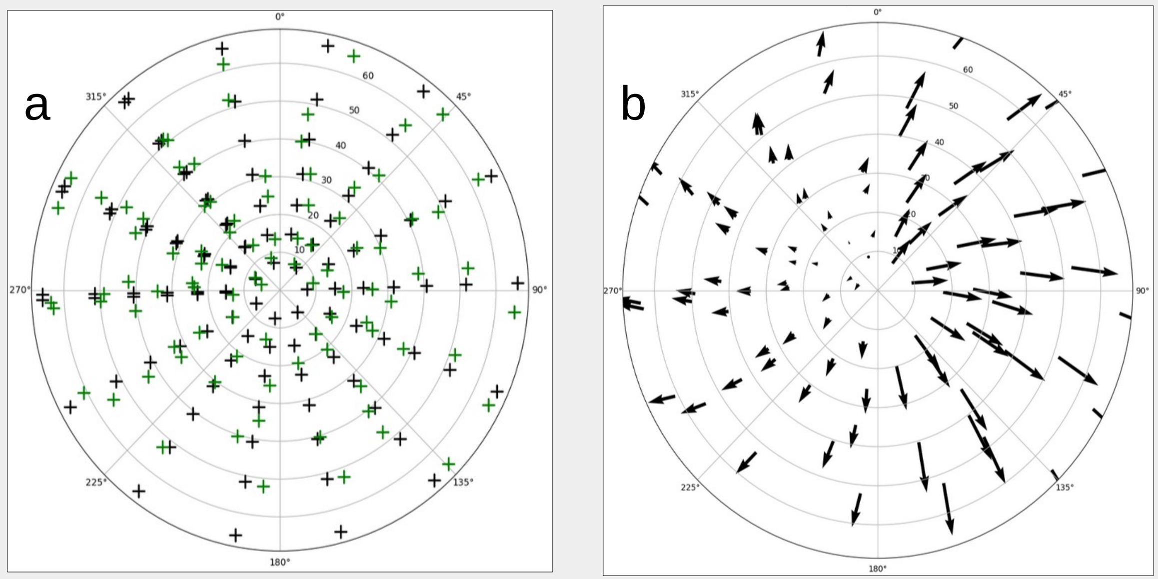
Miss pointing



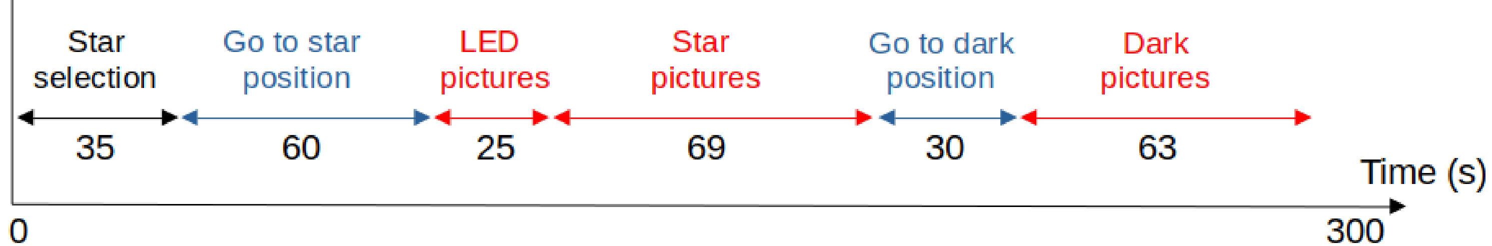
Relative mean time duration of a complete BM sequence

Progress : Bending Model

Description of the sequence



Distributions of (a) pointed stars between over a certain period and (b) corresponding miss-pointing, in polar representation



Relative mean time duration of a complete BM sequence

Progress : Bending Model

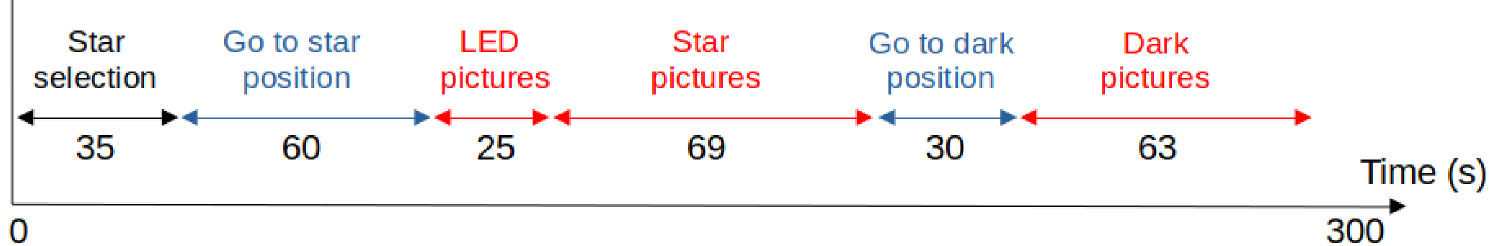
Improvement of the sequence

Why optimizing this sequence?

→ limited allocated time

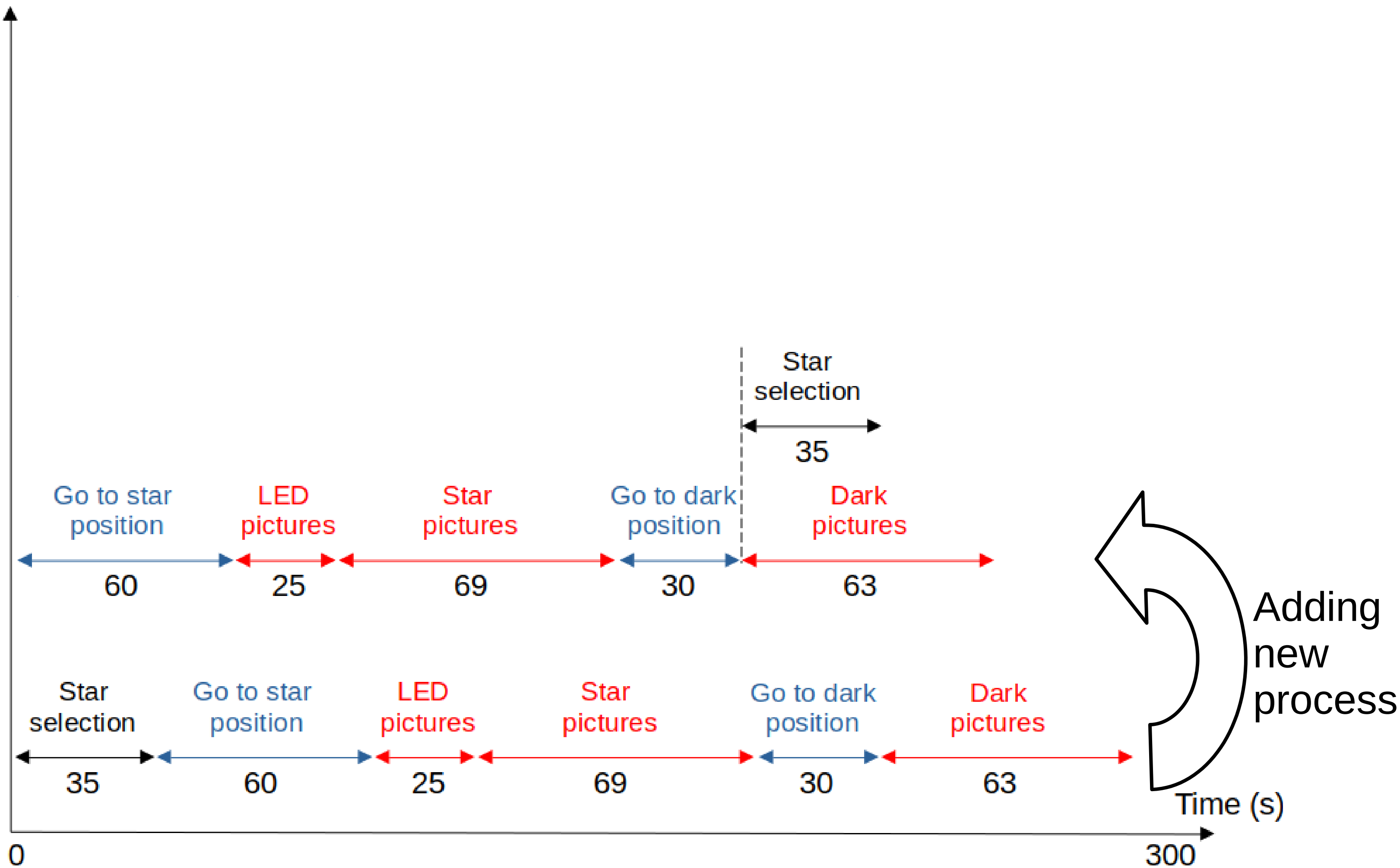
And how ?

→ tasks in concurrency
→ reduce the number of images taken



Relative mean time duration of a complete BM sequence

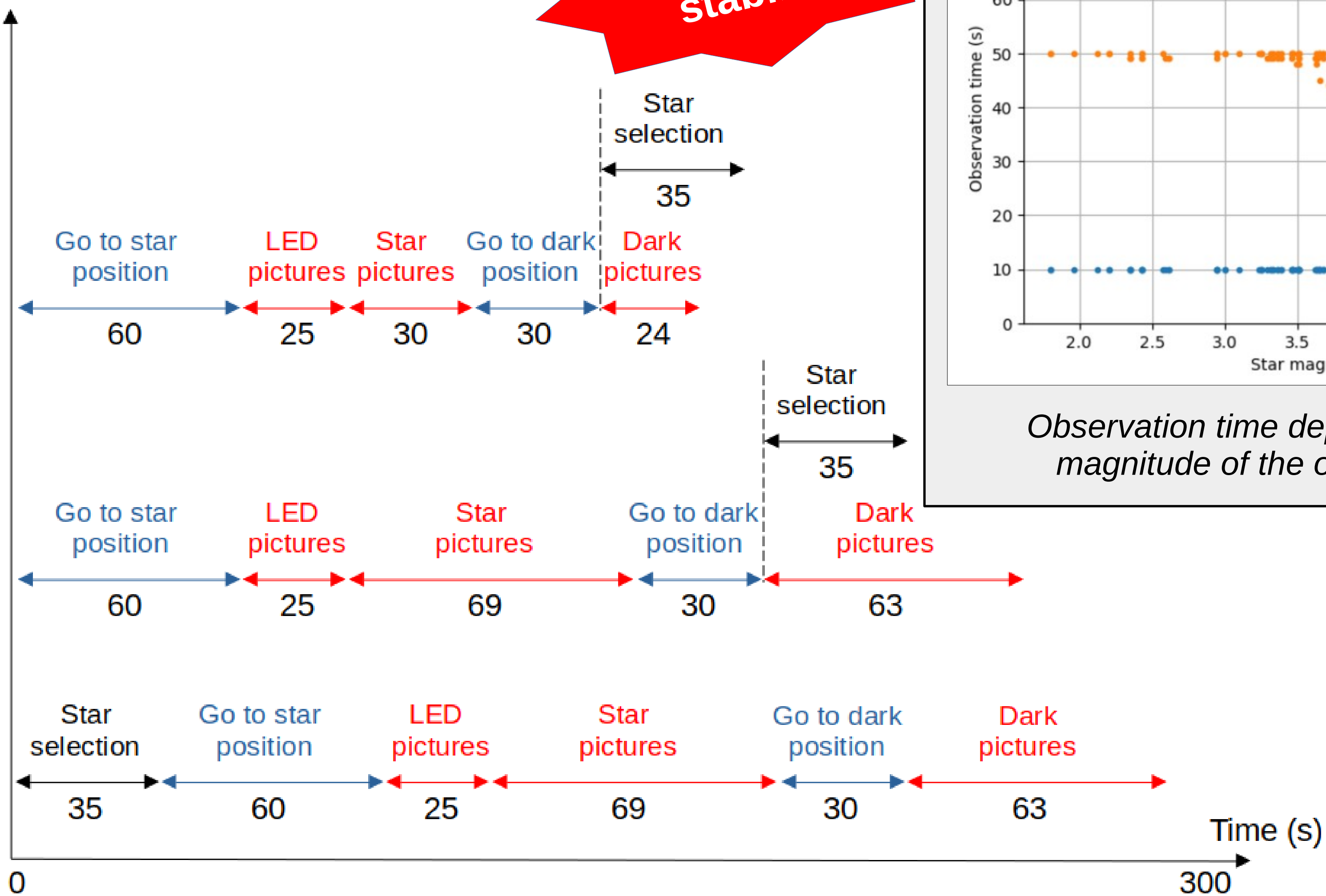
Improvement of the sequence



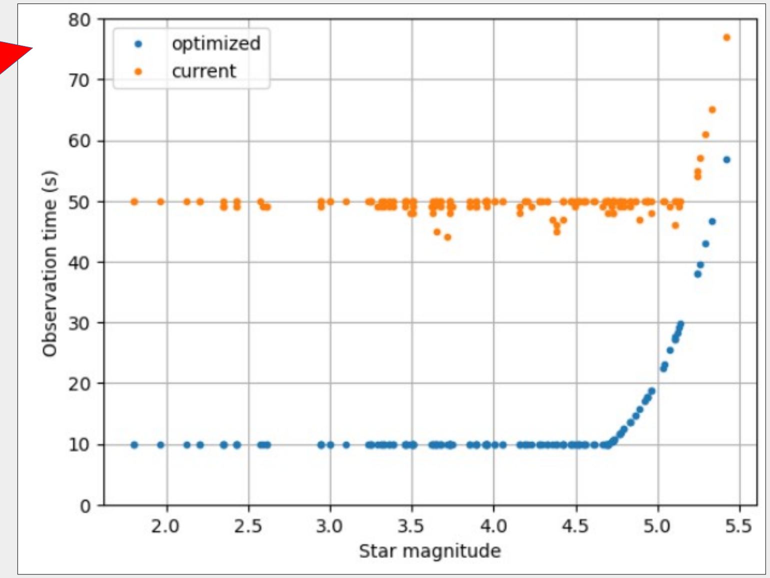
Relative mean time duration of a complete BM sequence

Improvement of the sequence

Ensure fit stability



Relative mean time duration of a complete BM sequence



Observation time depending on the magnitude of the observed star

Progress : Bending Model

Next…

→ Test on a large dataset the robustness of the optimized number of images

→ Perform tests with the scheduler in concurrency

→ Calibration script: involvement in **commissioning of LST-4**

- test different gain values for the CDM
- test for different star magnitude values

Useful for the calibration of the new LSTs

The four Large-Sized Telescopes from CTAO North, in July 2025 (credit: David Sanchez)

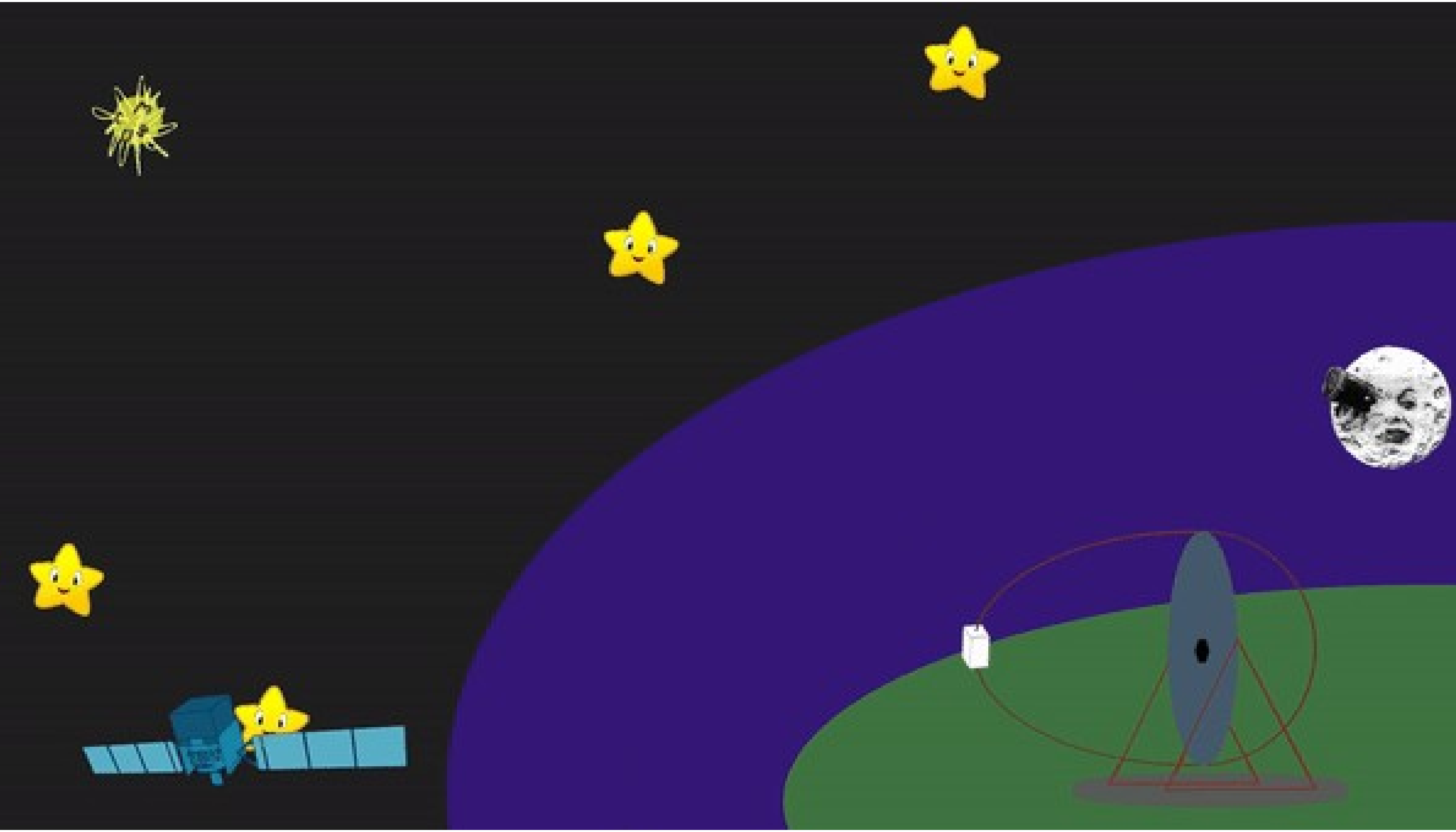
Laboratoire d'Annecy de Physique des Particules

Progress during PHD second year

Gamma Ray Burst analysis

UNIVERSITÉ
SAVOIE
MONT BLANC

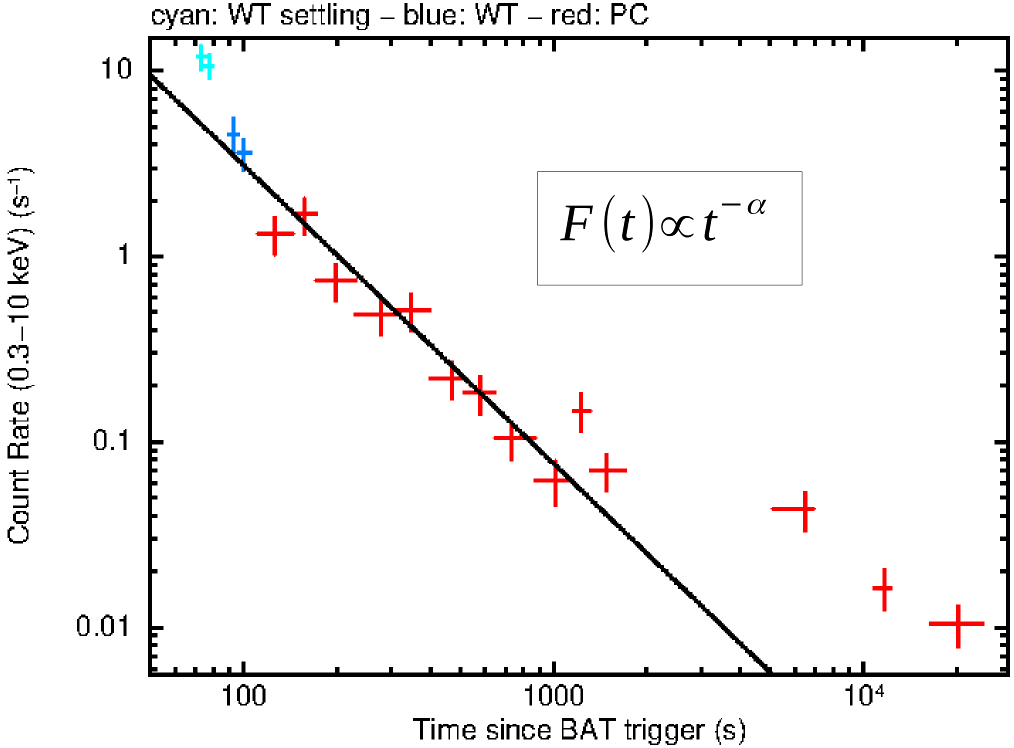
Progress : Gamma Ray Burst



Goals *with Mathieu de Bony and Edna Ruiz Velasco*

→ Gamma Ray Burst (GRB)

- transient events
- extragalactic sources (*isotropic distribution*)



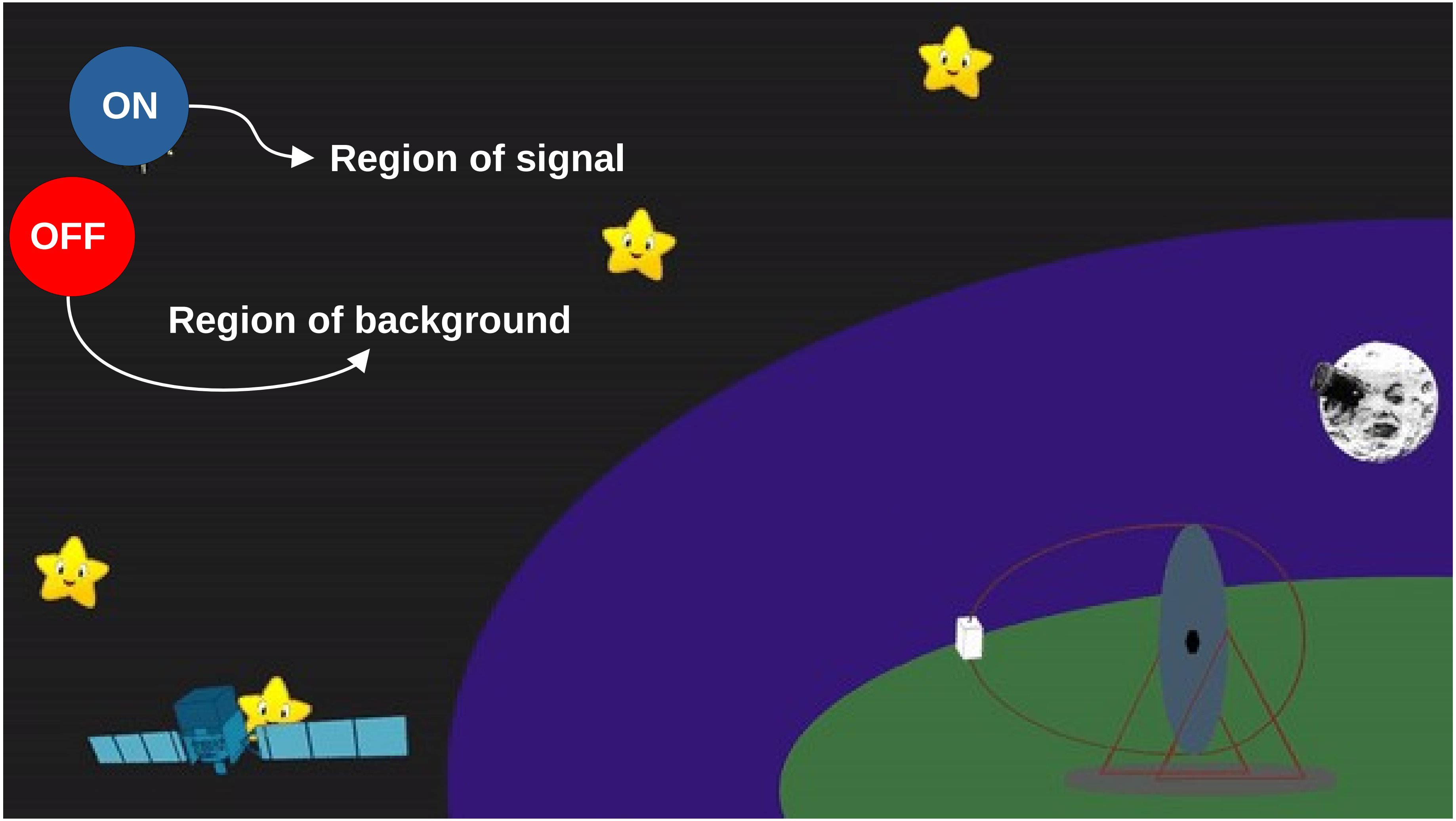
GRB220306B light curve, fitted with a power law (Swift/XRT data)

Detecting transient phenomenon : **one of the major objective for CTAO**

=> adapt current analysis methods

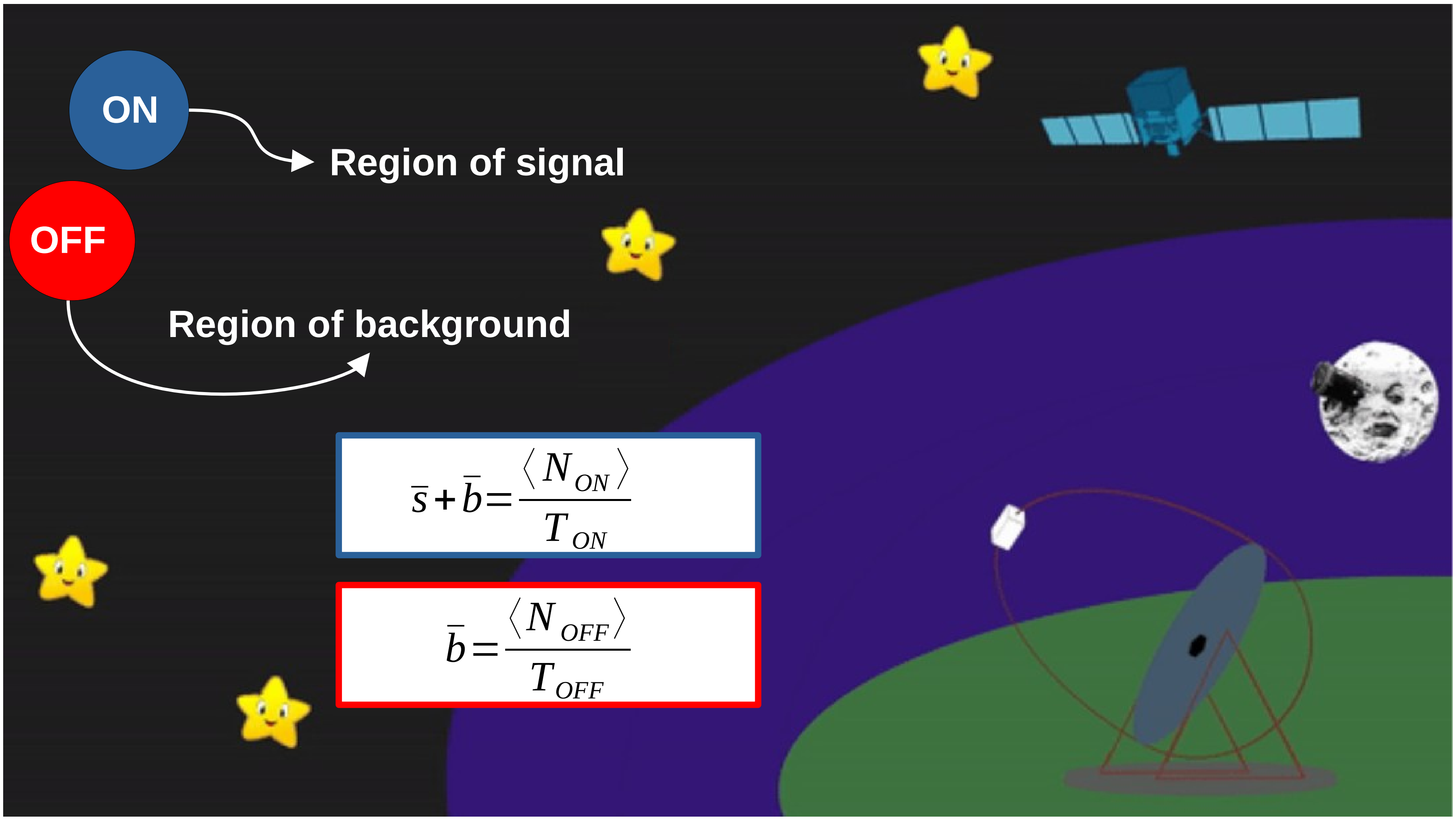
Methods

→ Classic Li&Ma



Methods

→ Classic Li&Ma



Methods

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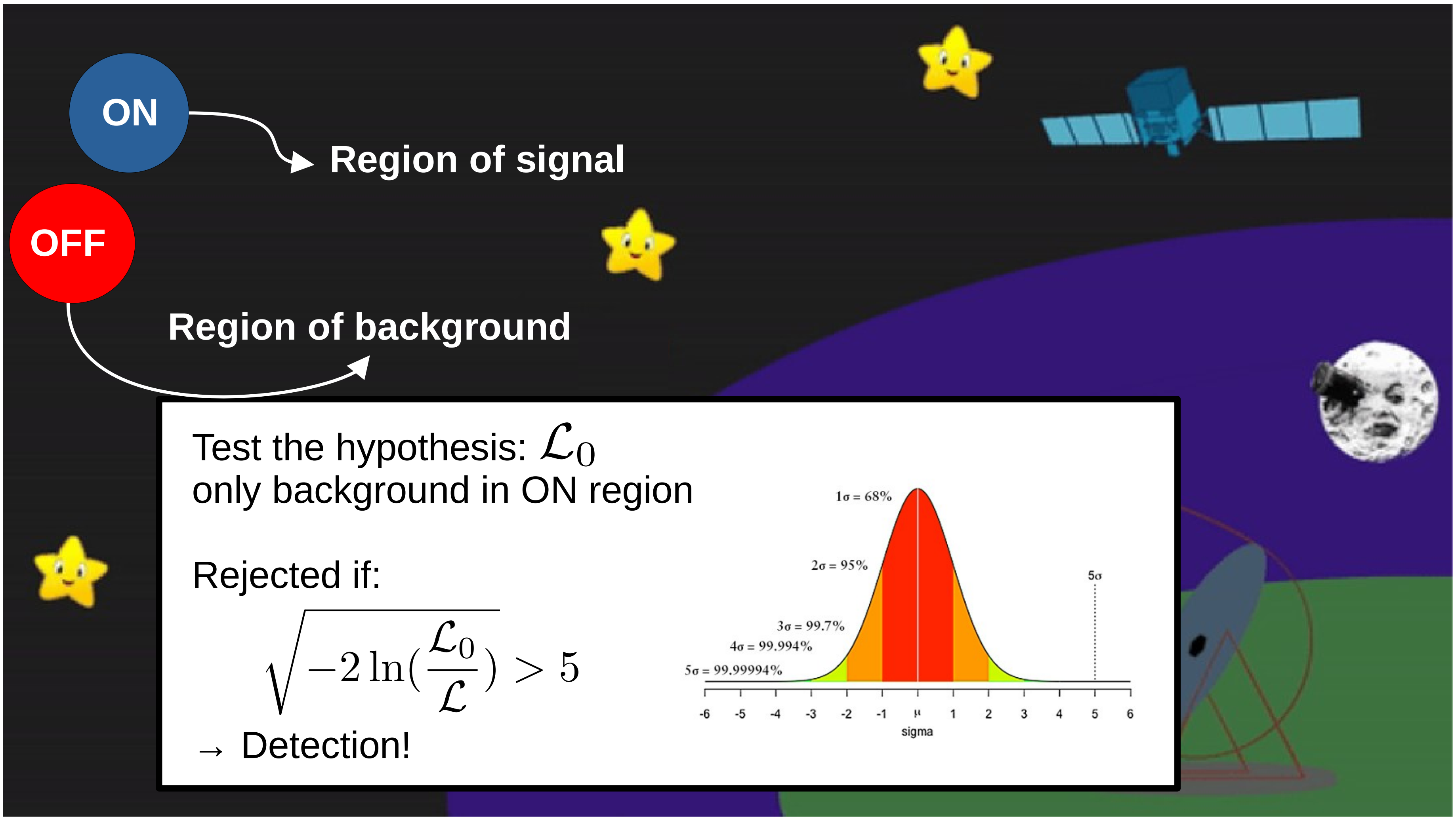


Test the hypothesis: $\mathcal{L}_0$
only background in ON region

Rejected if:

$$\sqrt{-2\ln\left(\frac{\mathcal{L}_0}{\mathcal{L}}\right)} > 5$$

→ Detection!

Methods

→ Classic Li&Ma:

ON
s+bkg

OFF
bkg

$$\mathcal{L}_0 = \underbrace{\frac{(\bar{b}\cdot T_{ON})^{N_{ON}}}{N_{ON}!}e^{-\bar{b}T_{ON}}} \cdot \frac{(\bar{b}\cdot T_{OFF})^{N_{OFF}}}{N_{OFF}!}e^{-\bar{b}T_{OFF}}$$

$$\mathcal{L} = \underbrace{\frac{((\bar{s}+\bar{b})\cdot T_{ON})^{N_{ON}}}{N_{ON}!}e^{-(\bar{s}+\bar{b})T_{ON}}} \cdot \underbrace{\frac{(\bar{b}\cdot T_{OFF})^{N_{OFF}}}{N_{OFF}!}e^{-\bar{b}T_{OFF}}}$$

Mean value!

Ref:
T.-p. Li et Y.-q. Ma. Analysis methods for results in gamma-ray astronomy.The Astrophysical Journal, 272 : 317-324, 1983

Methods

→ Classic Li&Ma:

$$\mathcal{L}_0 = \frac{(\bar{b} \cdot T_{ON})^{N_{ON}}}{N_{ON}!} e^{-\bar{b}T_{ON}} \cdot \frac{(\bar{b} \cdot T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-\bar{b}T_{OFF}}$$

$$\mathcal{L} = \frac{((\bar{s} + \bar{b}) \cdot T_{ON})^{N_{ON}}}{N_{ON}!} e^{-(\bar{s}+\bar{b})T_{ON}} \cdot \frac{(\bar{b} \cdot T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-\bar{b}T_{OFF}}$$

Mean value!

ON
s+bkg

OFF
bkg

Taking into account time variation of the burst!

Ref:
T.-p. Li et Y.-q. Ma. Analysis methods for results in gamma-ray astronomy.The Astrophysical Journal, 272 : 317-324, 1983

Methods

→ Alternative ones

Li&Ma modification

$$\bar{s} \longrightarrow s(t) \propto t^{-\Gamma}$$

$$L = \left(\prod_{t_i=(\Delta t, \ldots, N\Delta t)} \frac{(\Delta t(b+s(t_i)))^{\{0,1\}}}{\{0,1\}!} e^{-\Delta t(b+s(t_i))} \right) \left(\frac{(b T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-b T_{OFF}} \right)$$

with $N.\Delta t = T_{ON}$

ON
s+bkg

OFF
bkg

Ref:

Weiner, O. M., Humensky, T. B., Mukherjee, R., & Santander, M. (2017). *Estimating significance in observations of variable and transient gamma-ray sources. Astroparticle Physics*, 93, 1-7. https://doi.org/10.1016/j.astropartphys.2017.05.004

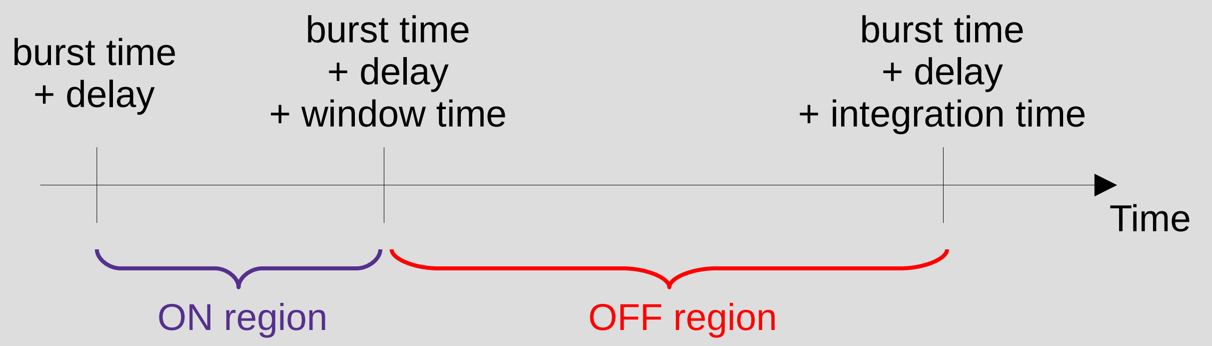
Progress : Gamma Ray Burst

Methods

→ Alternative ones

Temporal ON-OFF

→ consider temporal regions instead of spatial



Ref:
F. Brun, Q. Piel, M. de Naurois, S. Bernhard (2020) *Analysis methods to search for transient events in ground-based Very High Energy gamma-ray astronomy*, arXiv:2001.06084 [astro-ph.IM]

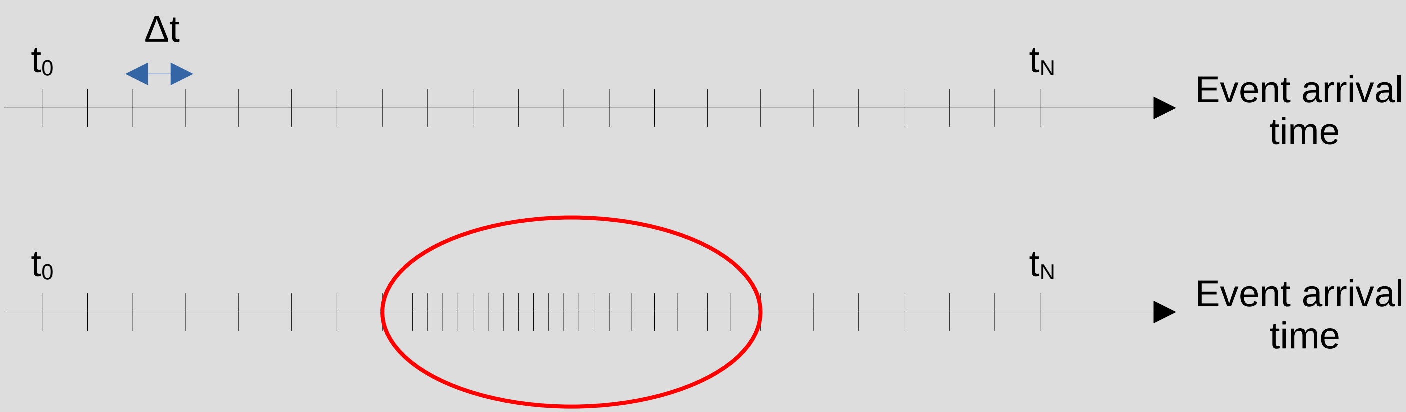
Progress : Gamma Ray Burst

Methods

→ Alternative ones

CuSum & ExpTest

→ determine the deviation from the delta arrival time distribution with 2 different estimators



Significant change in the delta arrival time

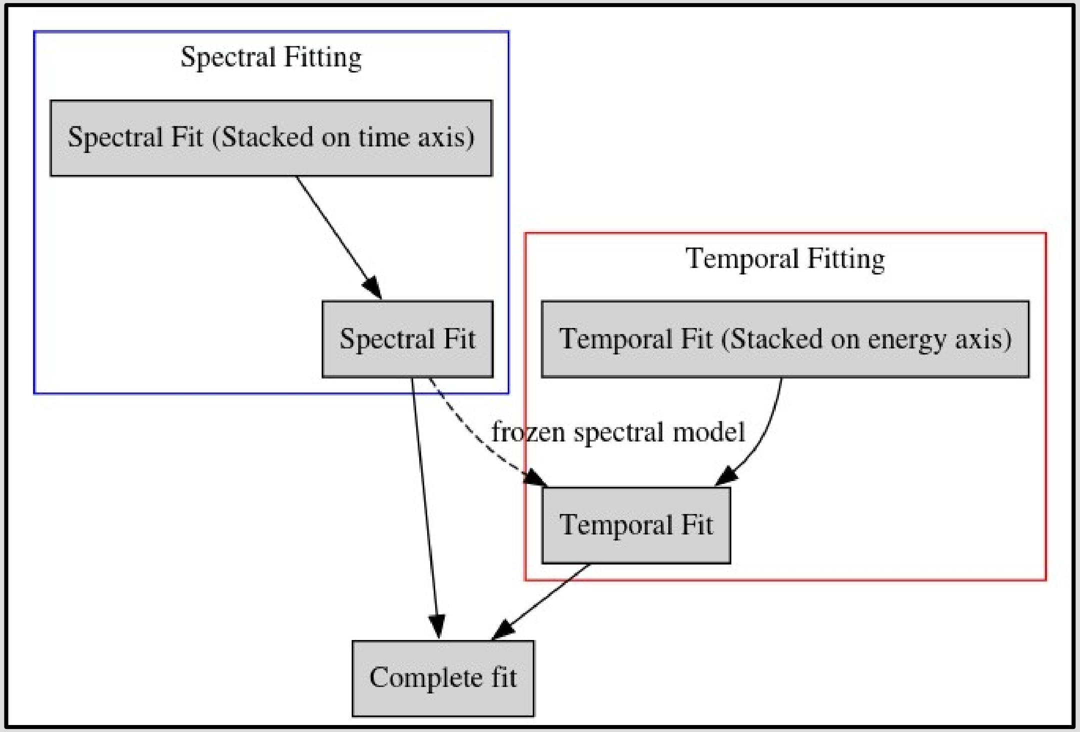
Ref:
F. Brun, Q. Piel, M. de Naurois, S. Bernhard (2020) *Analysis methods to search for transient events in ground-based Very High Energy gamma-ray astronomy*, arXiv:2001.06084 [astro-ph.IM]

Methods

→ Alternative ones

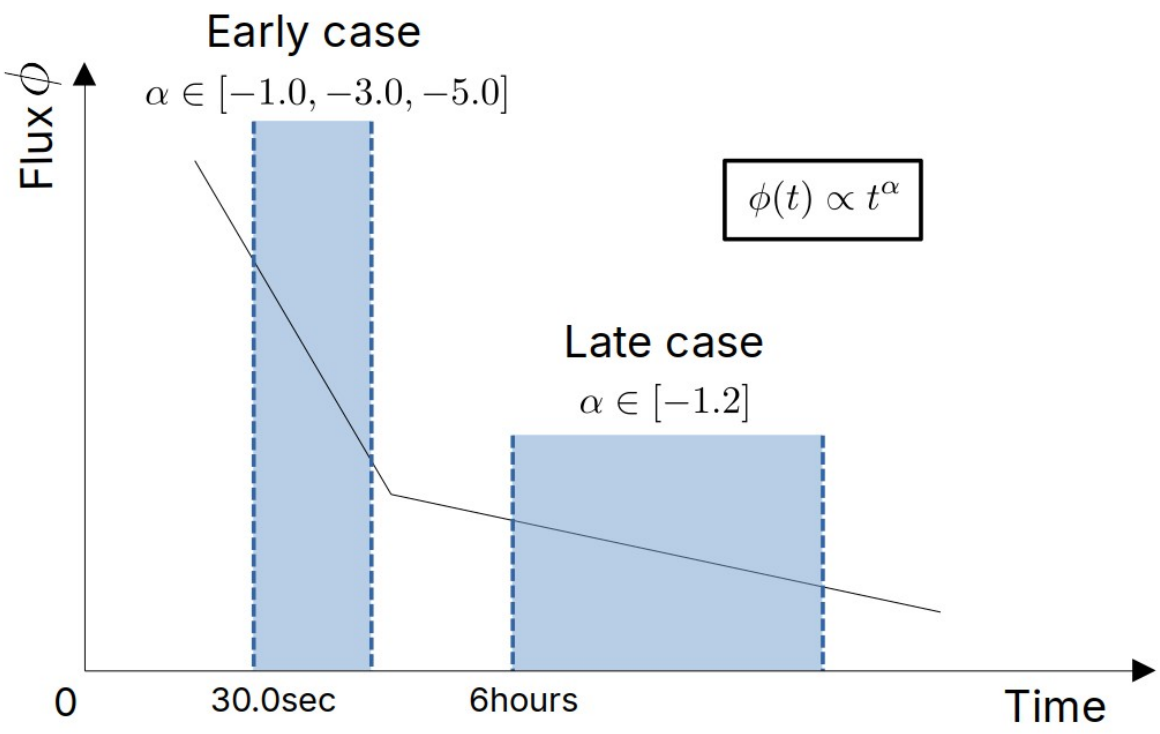
LiFT

→ based on fitting procedures



Simulations

→ random picking in realistic parameter spaces for each burst parameter



GRB temporal canonical behavior

Assuming:

- power law spectral model

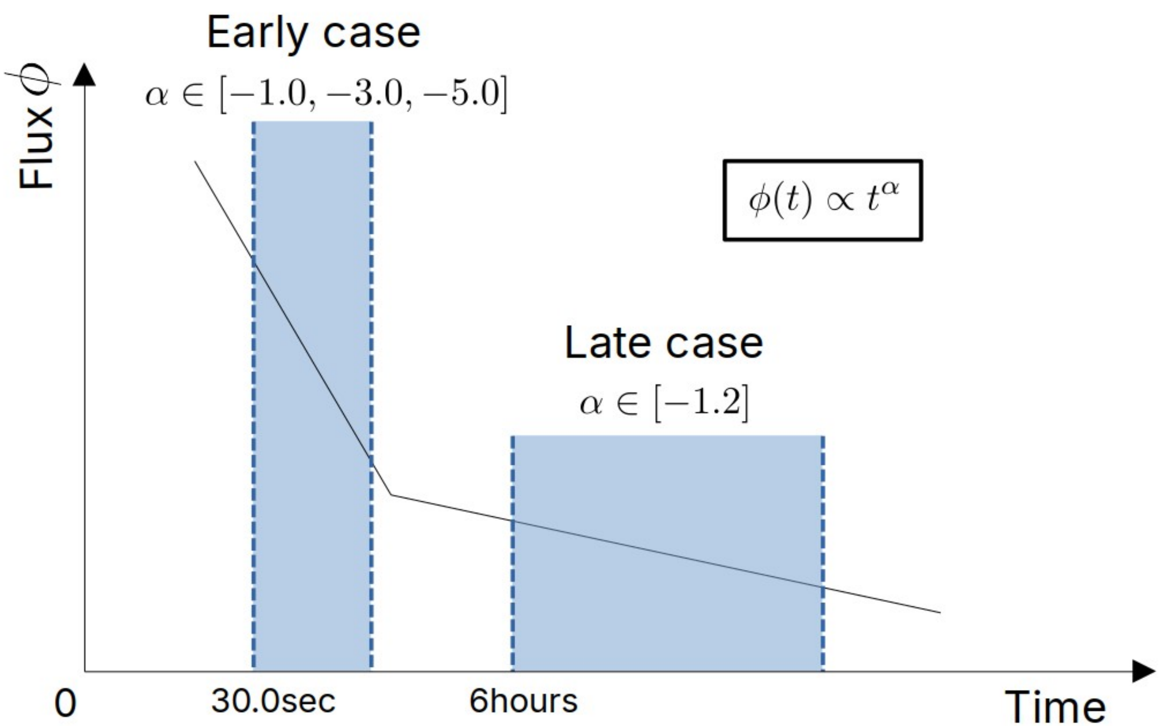
$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$$

- power law temporal model

$$F(t) = \left(\frac{t - t_{ref}}{t_0}\right)^{\alpha}$$

Simulations

→ random picking in realistic parameter spaces for each burst parameter



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- power law spectral model

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- power law temporal model

$$F(t) = \left(\frac{t - t_{ref}}{t_0}\right)^{-\alpha}$$

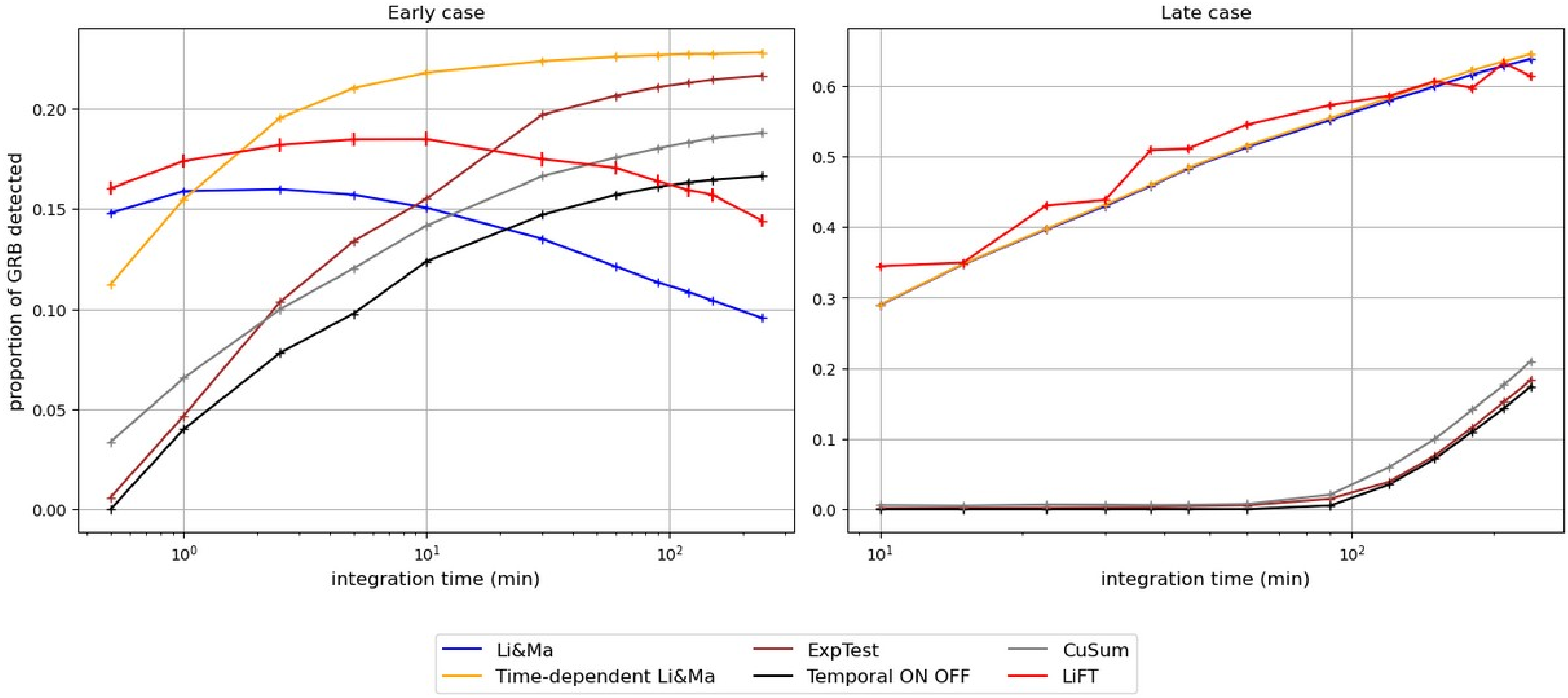
+ test optimizations of each method based on **TPR** – **FAR** criteria

→ True Positive Rate

→ False Alarm Rate

Results

Compare the fraction of detected GRBs for all the methods



Proportion of detected GRBs depending on the integration time, in both cases, for each method

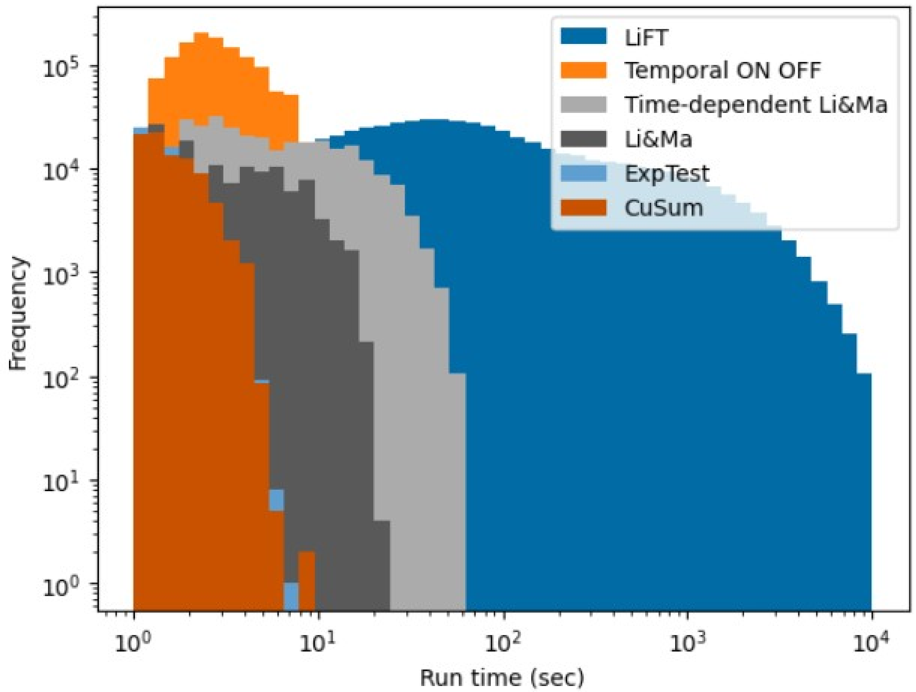
Progress : Gamma Ray Burst

Next…

→ finish the article

→ test the new methods with real GRB data

→ implement in LST Real Time Analysis



Distribution of the run time for each method

Laboratoire d'Annecy de Physique des Particules

Realizations / Trainings

Involvement in the collaboration

- remote presentation at the LST general meeting in November 2024
- presentation at the LST general meeting in May 2025, in Madrid
- presentation at CTA France in March 2025, in Paris

Conference

- poster at ICRC 2025, in July 2025, in Geneva

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

Trainings

Transversales : - Journée de rentrée des doctorants – 5 heures
- MOOC éthique de la recherche – 15 heures
- Formation vulgarisation scientifique – 8 heures
- Préparation au concours MT180 - 17 heures

Vulgarisation : - Pint of Science - 30 heures

Enseignement : - Vacations à l'USMB - 43,5 heures de TD + 17 heures de TP
- Formation *Enseigner les Sciences expérimentales* - 14 heures

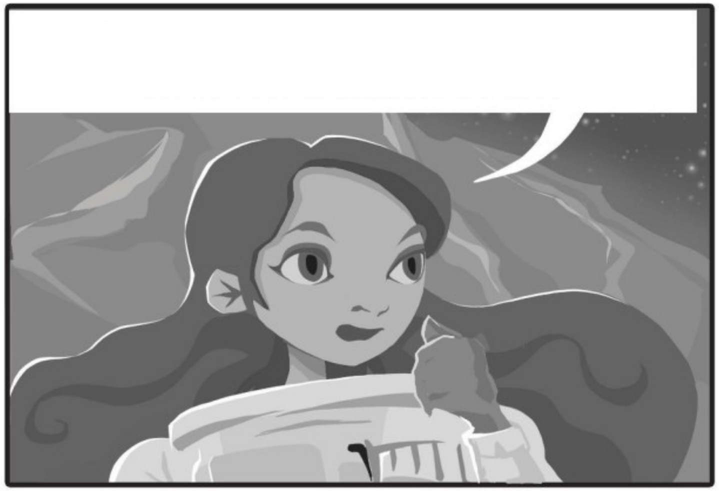
Disciplinaires : - Ecole de Gif 2024 - 24 heures

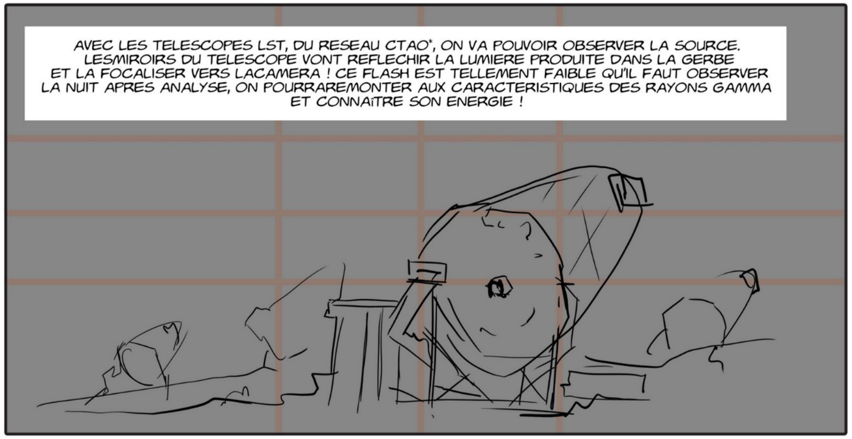
Poursuite de carrière : - MOOC Doctorat et poursuite de carrière/ PhD and career development - 24 heures

L'Odyssée Cosmique de Pénélope
with Cyann, Maël, Margaux, Nathan & Yann, drawn by Antoine Tassel

+ a wonderful comic book,

stay tuned :)



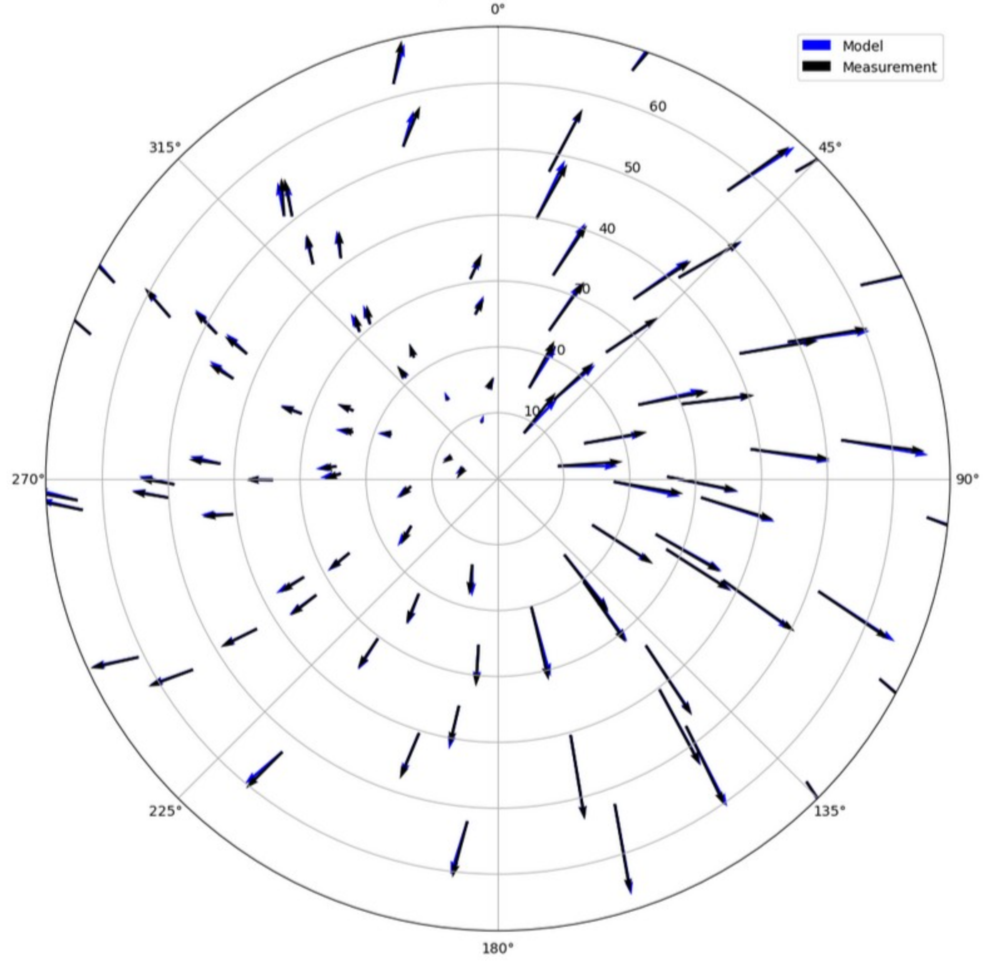



Thanks for your attention

BACK UP

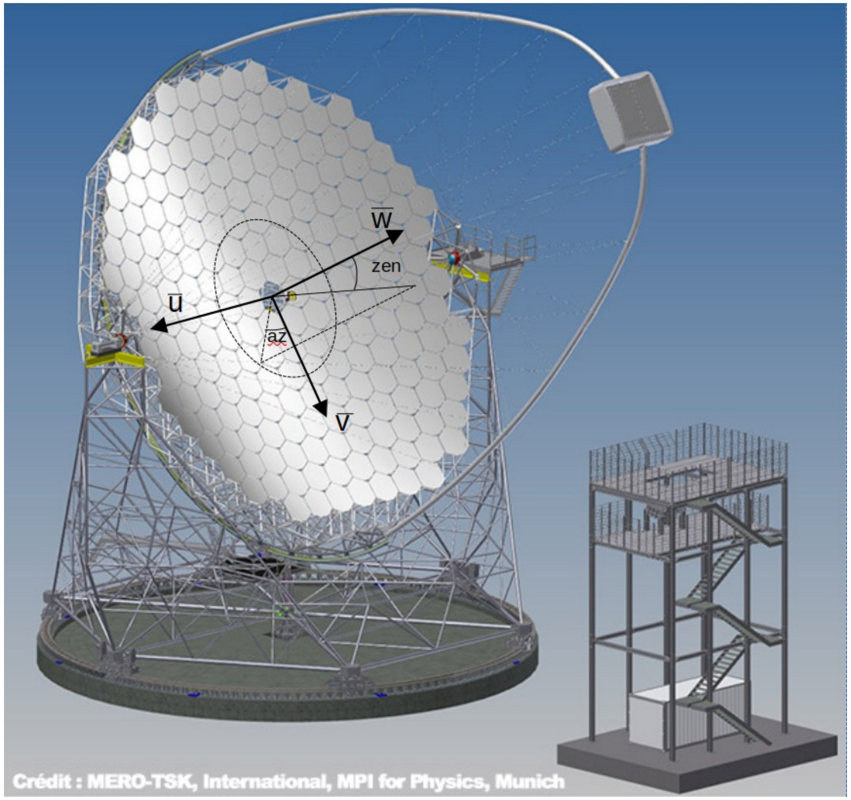
BM performances

→ compare the predicted miss-pointing with the actual one

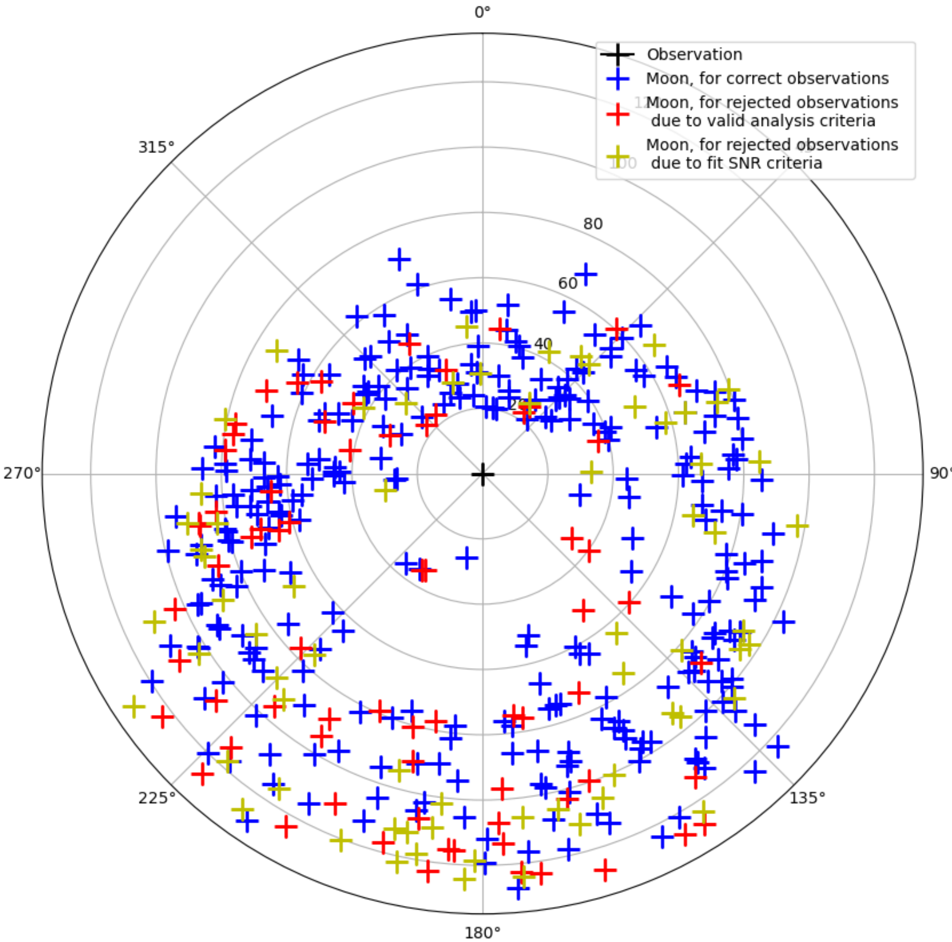


Distribution of miss-pointing compared with the predicted miss-pointing evaluated with mechanical model, in polar representation

Moon condition



Pointing reference, useful for the stacking of relative Moon position

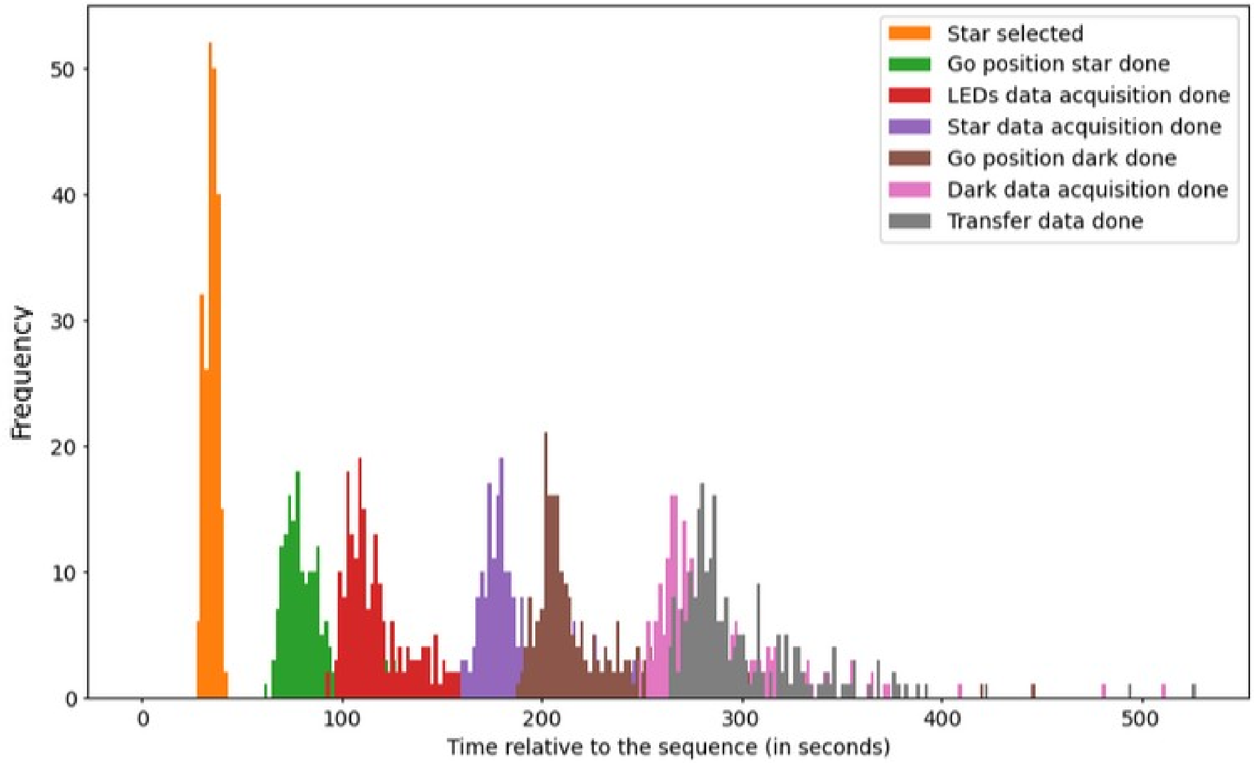


Spatial distribution of the Moon position (for correct and rejected observations), in the dish reference

Optimizing time

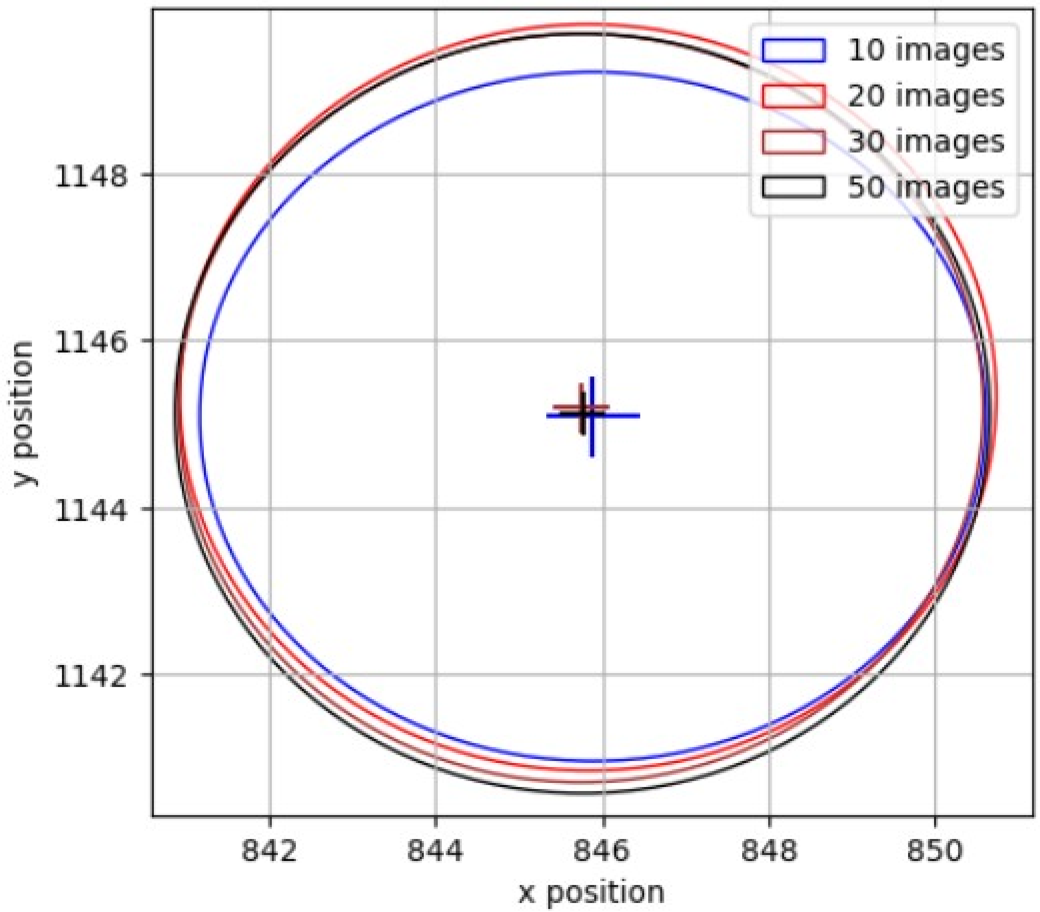
Sequence

- select a star
- go to star position
- data acquisition LEDs
- data acquisition star
- go position dark
- data acquisition dark
- transfer data



Distribution of the end event times, relatively to the start of the observation

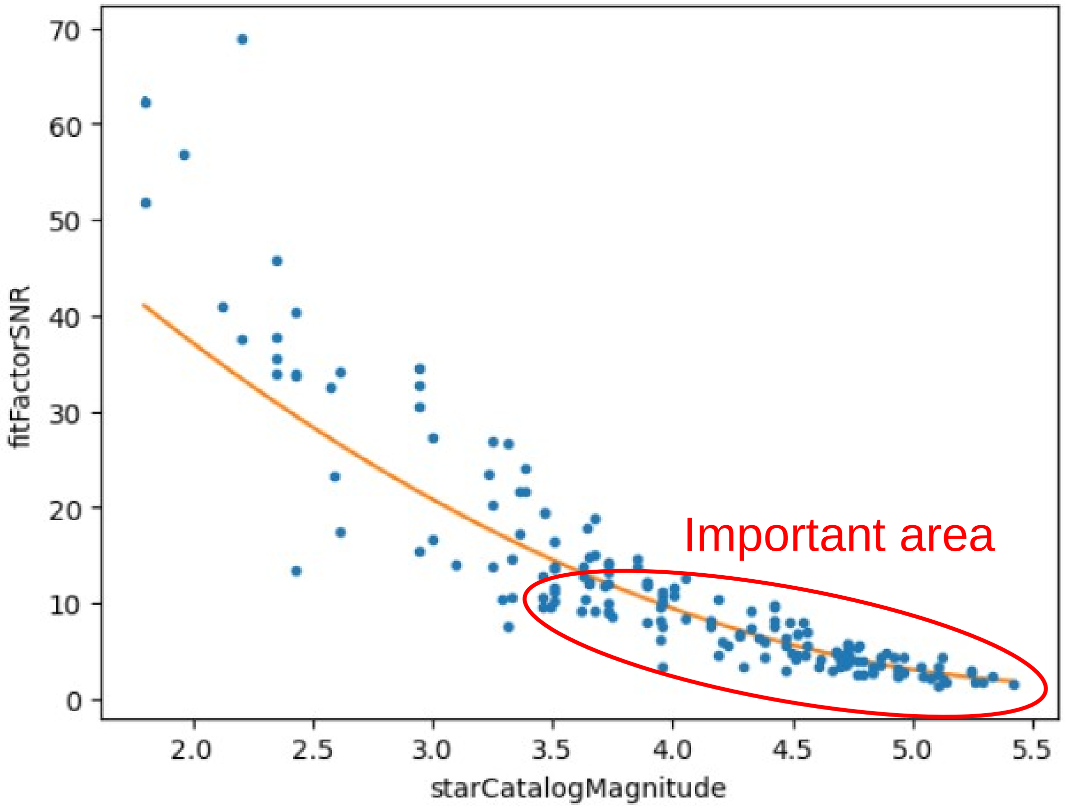
Number of images



Fit results of the star position, for different number of images

No significative difference between the current number of images (50) and the optimized one (10)

Computation of the optimized number of images depending on magnitude



Fit of the fit factor depending on the star magnitude

$$SNR_{goal} = 14$$

$$a = 2.50mag^2 - 28.80mag + 84.82$$

$$\boxed{obsTime = (\frac{SNR_{goal}}{a})^2}$$

Methods

→ Time-dependent Li&Ma

$$L=\Big(\prod_{t_i=(\Delta t,\dots,N\Delta t)} \frac{(\Delta t(b+s(t_i)))^{\{0,1\}}}{\{0,1\}!} e^{-\Delta t(b+s(t_i))}\Big)\Big(\frac{(b\,T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-b\,T_{OFF}}\Big)$$

→ Definition of the signal: $\boxed{s(t)=\theta f(t)}$

→ Only 1 free parameter: amplitude of the signal θ

because b is defined with the identity: $b\dfrac{\partial \log L}{\partial b}(\theta)+\theta\dfrac{\partial \log L}{\partial \theta}(\theta)=0$

→ Maximize the likelihood by finding the root of the partial derivative:

$$\frac{\partial \log L}{\partial b}(\theta)=\frac{N_{OFF}}{b}+\sum_{t_i\in t_{ON}} \frac{1}{b+\theta f(t_i)}-(T_{ON}+T_{OFF})$$

Methods

→ CuSum

Time intervals expected to follow Poisson distribution

Cumulative sum of all previous events:

C

$$\chi_i = \sum_{k=1}^{i} (\Delta T_k - \langle \Delta T \rangle)$$

Variance of the cumulative sum

$$Var(\chi_i) = \frac{iC^2}{N}(N - i)$$

Estimator

$$S = \frac{\chi_i}{Var(\chi_i)}$$

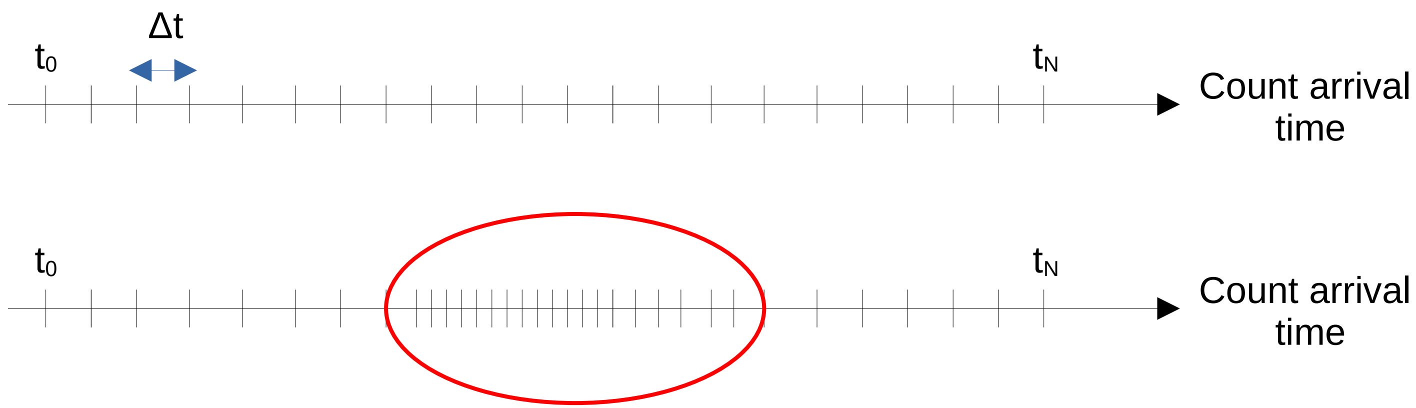
Methods

→ ExpTest

Time intervals expected to follow Poisson distribution

Deviation estimator: $$M = \frac{1}{N} \sum_{\Delta T_i < \bar{\Delta T}} (1 - \frac{\Delta T_i}{\bar{\Delta T}})$$

Gaussian estimator: $$M_r = \frac{M - (1/e - \alpha/N)}{\beta/\sqrt{N}}$$

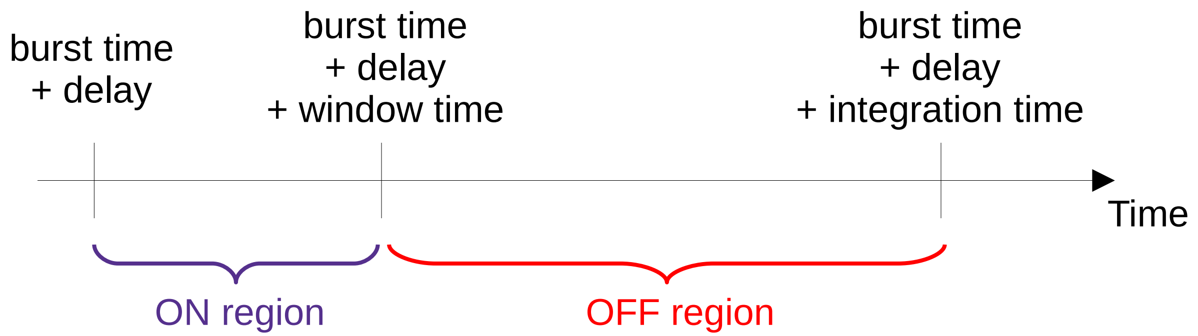


Methods

→ different version of the same method

ex: temporal ON OFF

→ choice of the size of the ON region (fixed size window, linear proportional window or log proportional window)



Methods

→ different version of the same method

→ choose by maximizing: $\boxed{FoM = TPR - FAR}$

method	falseAlertRate	trueAlertRate	FoM
lima	0.000000e+00	0.208793	0.208793
tdep	0.000000e+00	0.208281	0.208281
cumsumTest	2.025382e-04	0.000021	-0.000182
cumsumLinearProp	1.796502e-01	0.086801	-0.092849
cumsumLogProp	1.043193e-01	0.036862	-0.067457
cumsumFixed	1.212390e-01	0.054320	-0.066919
exptest_global	0.000000e+00	0.074058	0.074058
exptest_linearProp	3.301825e-04	0.203998	0.203668
exptest_logProp	5.843802e-04	0.243976	0.243392
tmpOnOff_fixed	1.963149e-07	0.130601	0.130601
tmpOnOff_logProp	3.161888e-07	0.177137	0.177137
tmpOnOff_linProp	4.742004e-07	0.152348	0.152347

Back Up - GRBs

Simulations

→ limitation: only Zenith 20deg

No big changes near transit (optimal case)