Laboratoire d'Annecy de Physique des Particules

LST-1: Ensuring a correct pointing & Improving our GRB detection ability

JRJC – 27 November 2024

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

LST COLLABORATION

UNIVERSITÉ SAVOIE MONT BLANC

Summary

CTAO – Quick presentation

Bending Model
What is it?
Why do we need it?
How can we improve it?

Gamma Ray Burst Analysis
What are GRBs?
Why are they so important?
Can we improve the detection ability?

CTAO – Quick presentation

CTAO: array of imaging atmospheric Cherenkov telescopes

→ 2 sites in each hemisphere

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

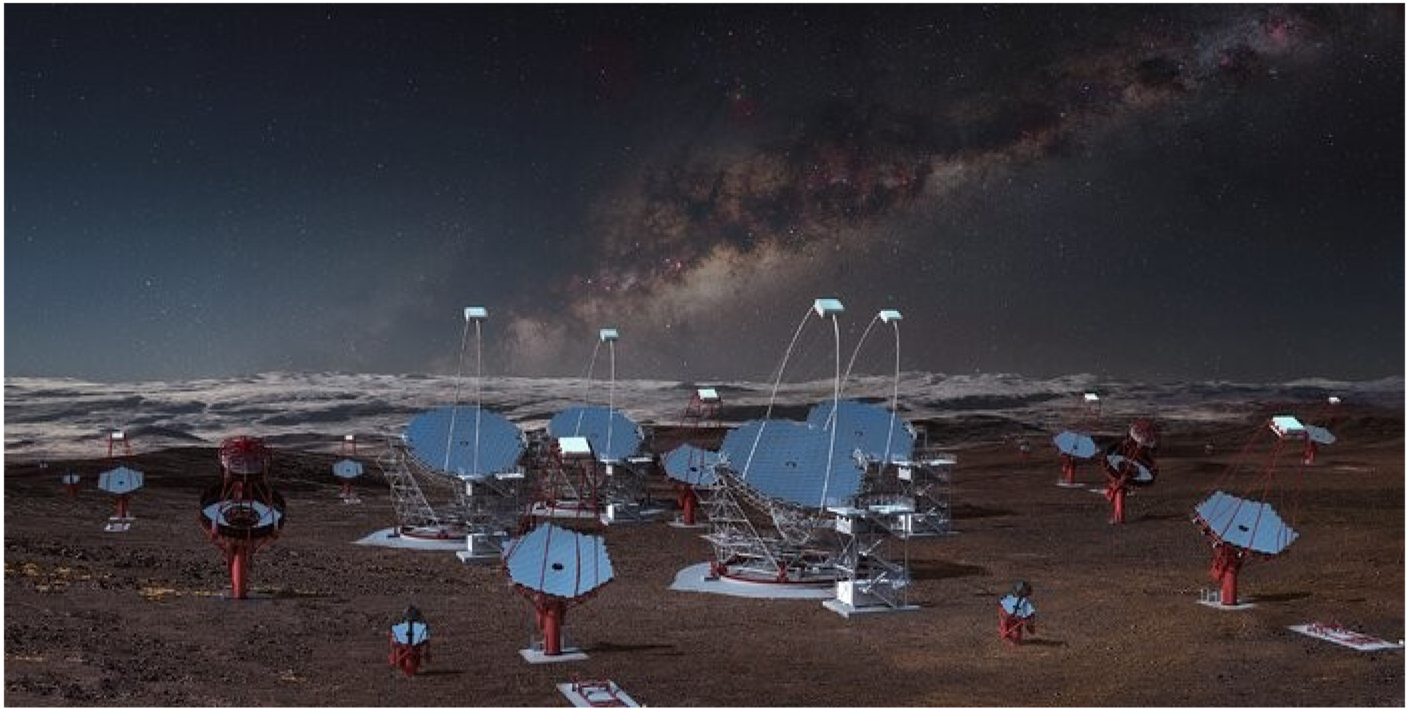


Illustration of the future CTAO South site,
Credit : Gabriel Pérez Diaz (IAC)/Marc-André Besel (CTAO)/ESO/ N. Risinger (skysurvey.org)

CTAO: array of imaging atmospheric Cherenkov telescopes

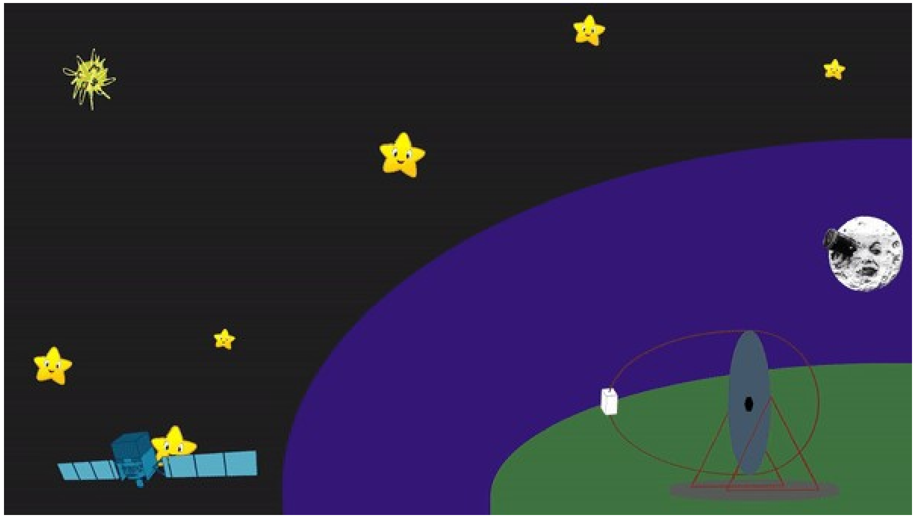
→ LST-1: first telescope of the array

LST-1 picture, at twilight

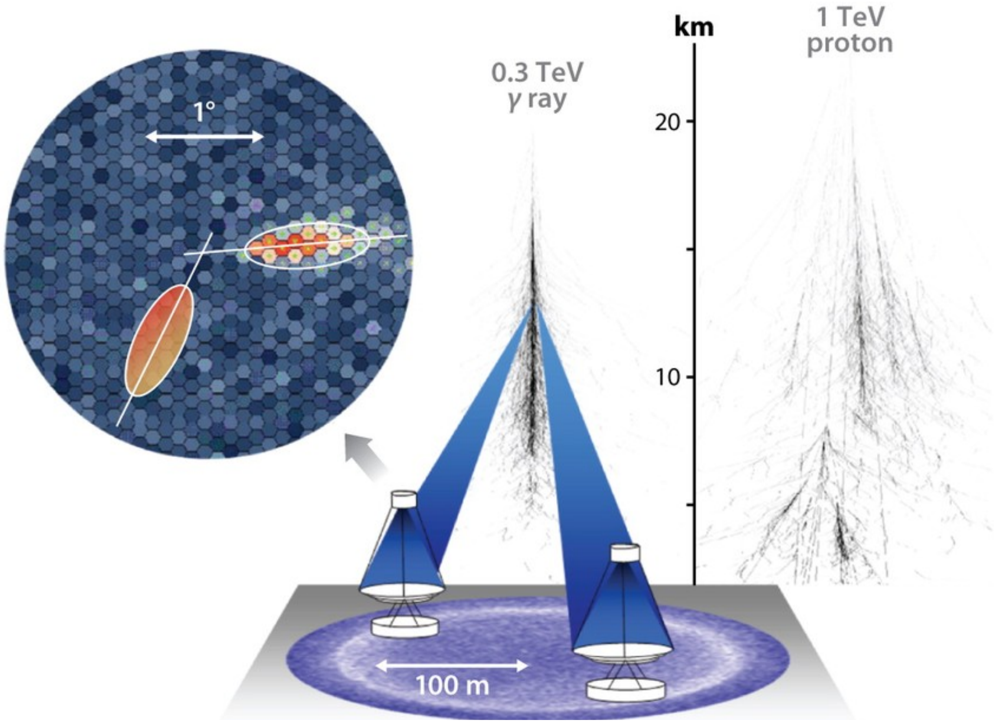
LST-1 moving

CTAO: array of imaging atmospheric Cherenkov telescopes

→ Detection principle



Working principle of LST-1 (don't judge please, I did this gif myself)



Scheme of the electromagnetic shower
Credit: J.A. Hinton and W. Hofmann

Laboratoire d'Annecy de Physique des Particules

Bending Model: Ensuring a correct pointing

Working principle, Optimization, Improvements

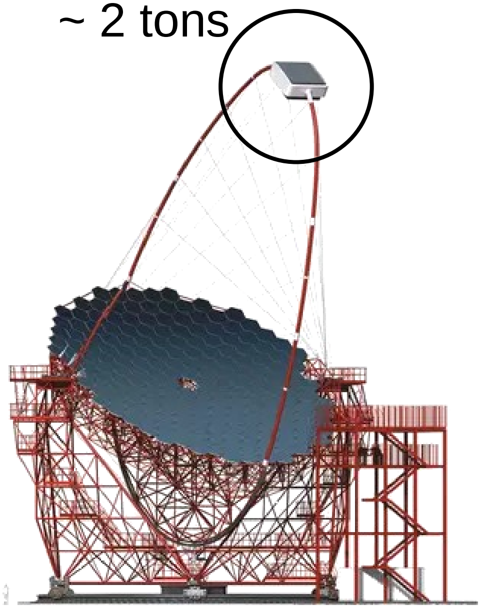
developed at LAPP by a former phd student, Mathieu de Bony

Goal

→ taking into account the deformation of the structure

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

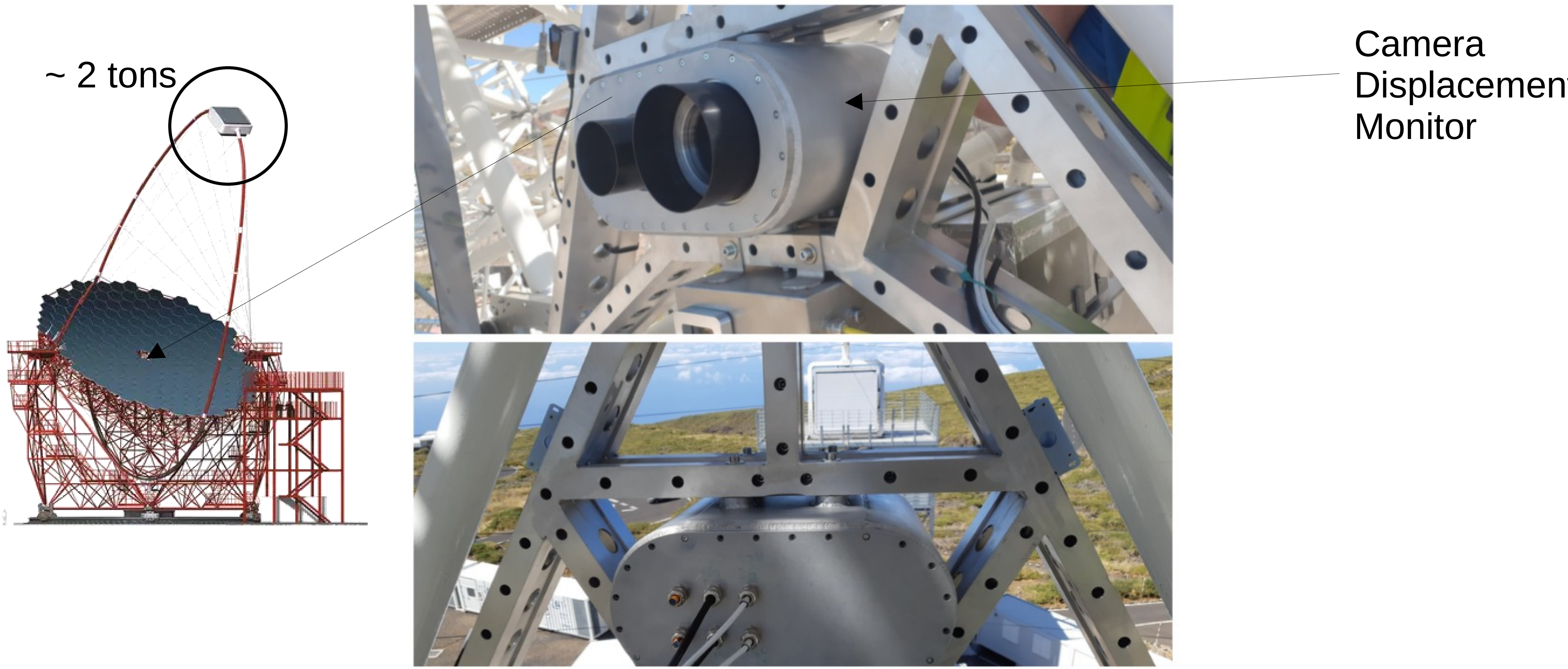
~ 2 tons



Goal

→ taking into account the deformation of the structure

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



Pictures of the CDM, at the center of the dish

Bending Model

Goal

→ taking into account the deformation of the structure

=> correcting the systematic errors of the pointing

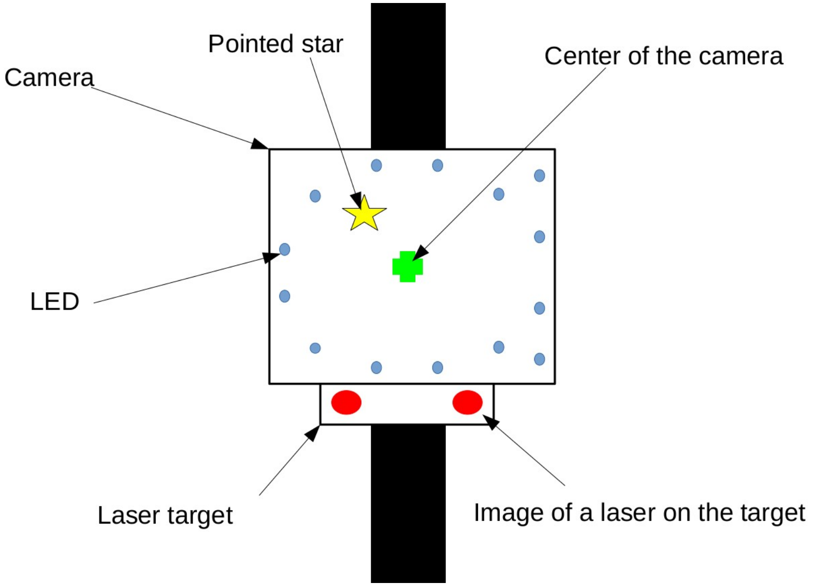
Basic procedure

→ 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

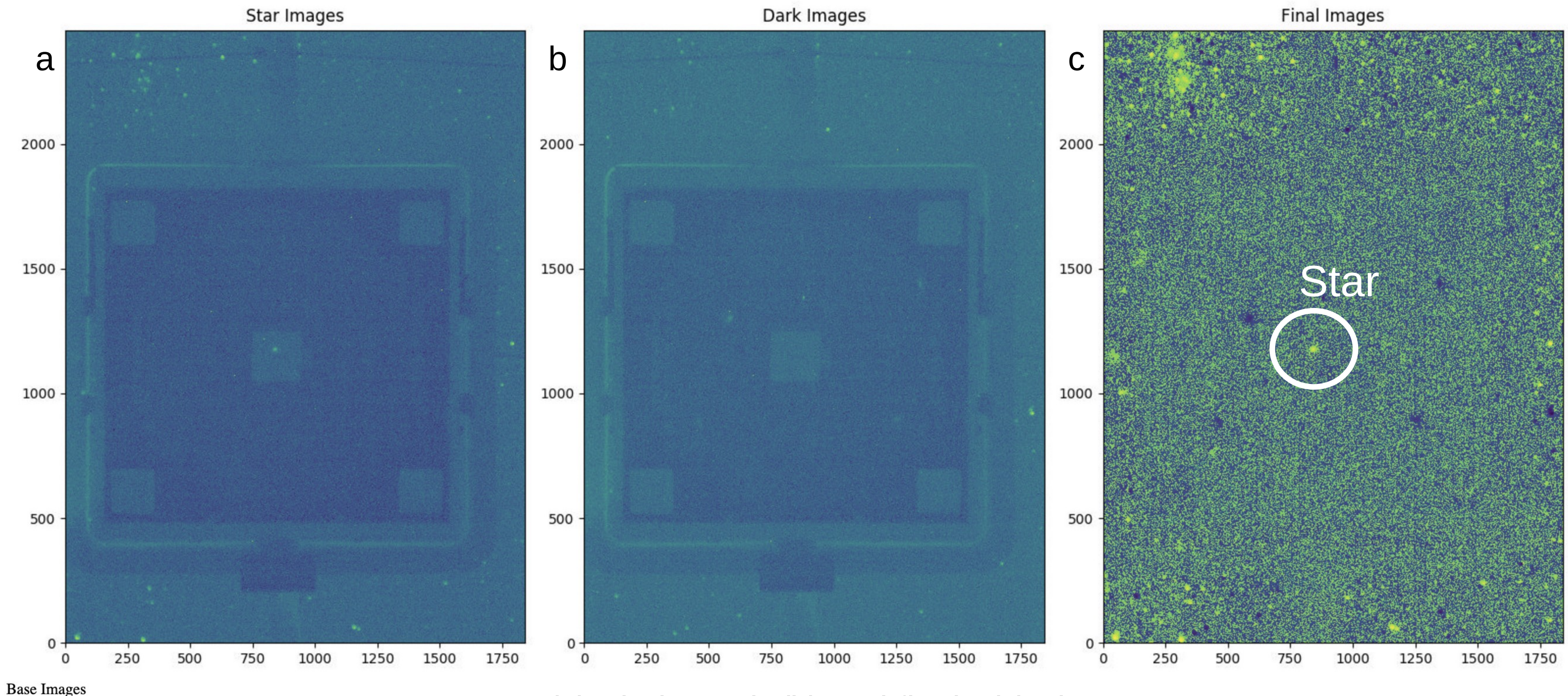


Sketch of the CDM field of view

Working principle

→ derive a mechanical model from star misspointing

Example of an observation



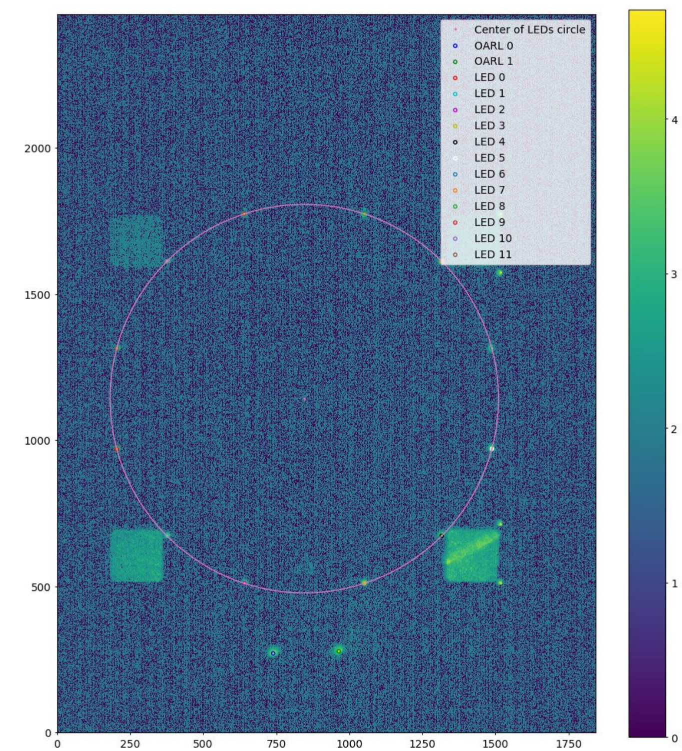
Star (a), dark patch (b) and finale (c) pictures

Working principle

→ derive a mechanical model from star misspointing

Example of an observation

LST-1 picture, with LEDs switched on



LEDs picture

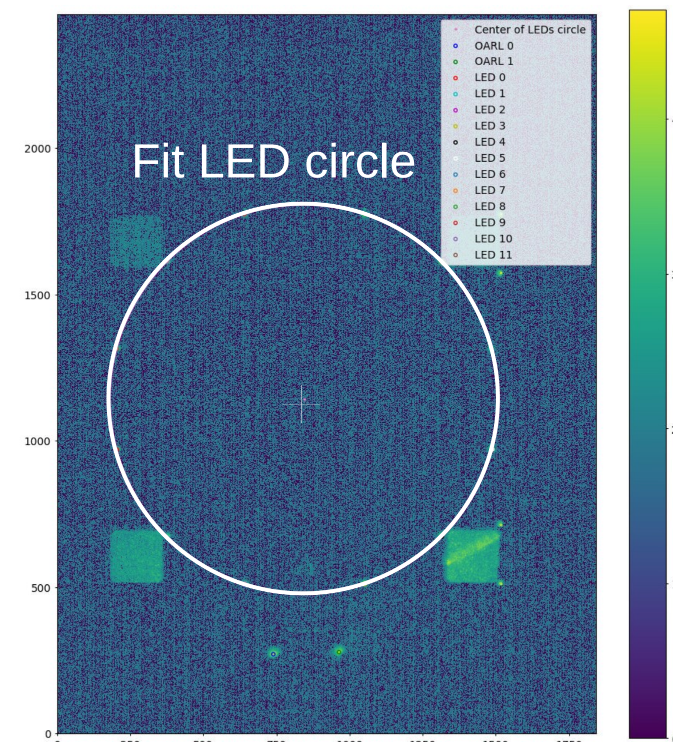
Bending Model

Working principle

→ derive a mechanical model from star misspointing

Example of an observation

LST-1 picture, with LEDs switched on

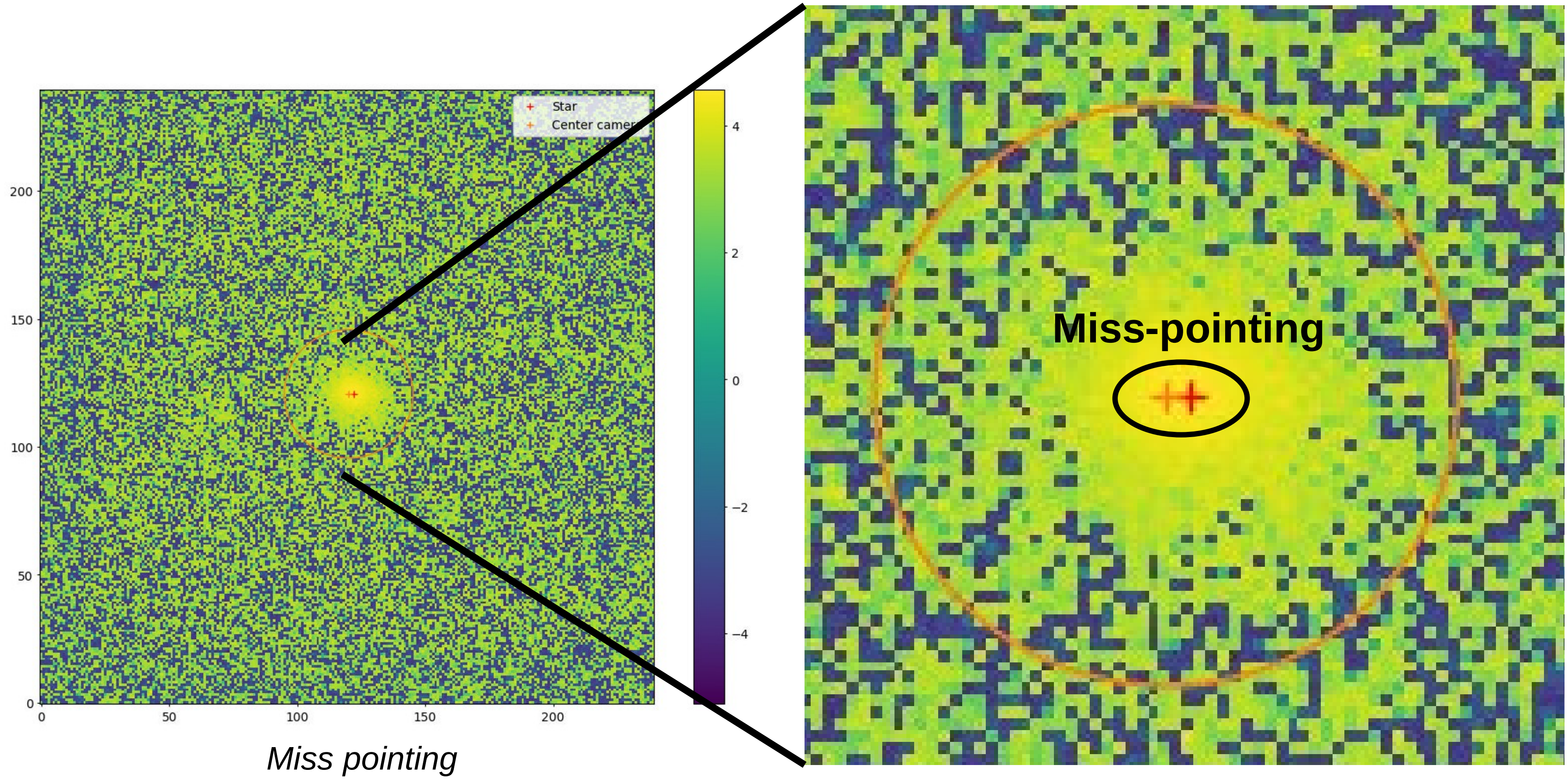


LEDs picture

Working principle

→ derive a mechanical model from star misspointing

Example of an observation

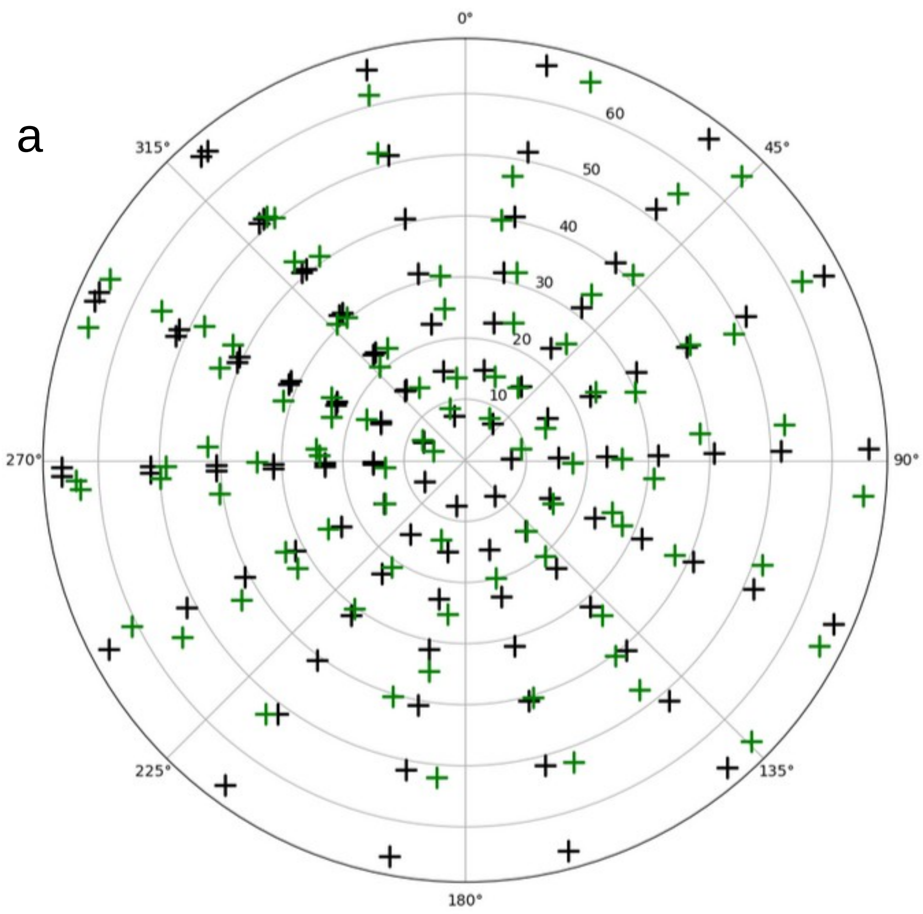


Miss pointing

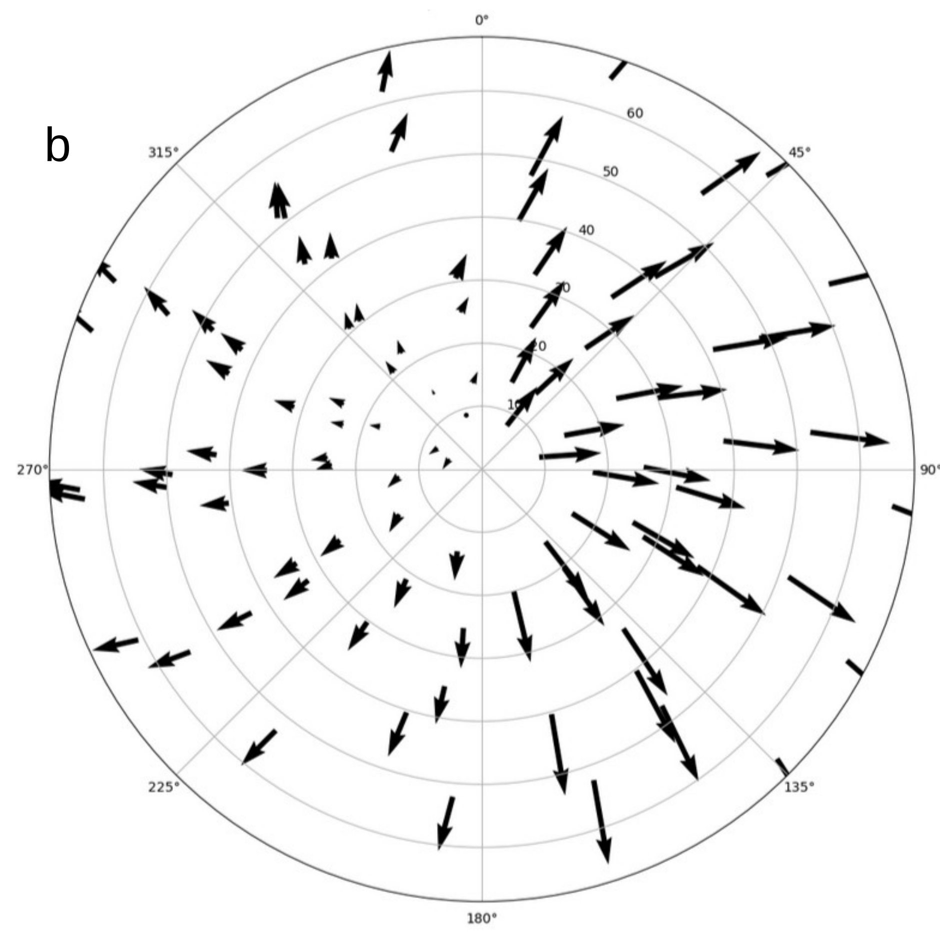
Working principle

→ derive a mechanical model from star misspointing

a



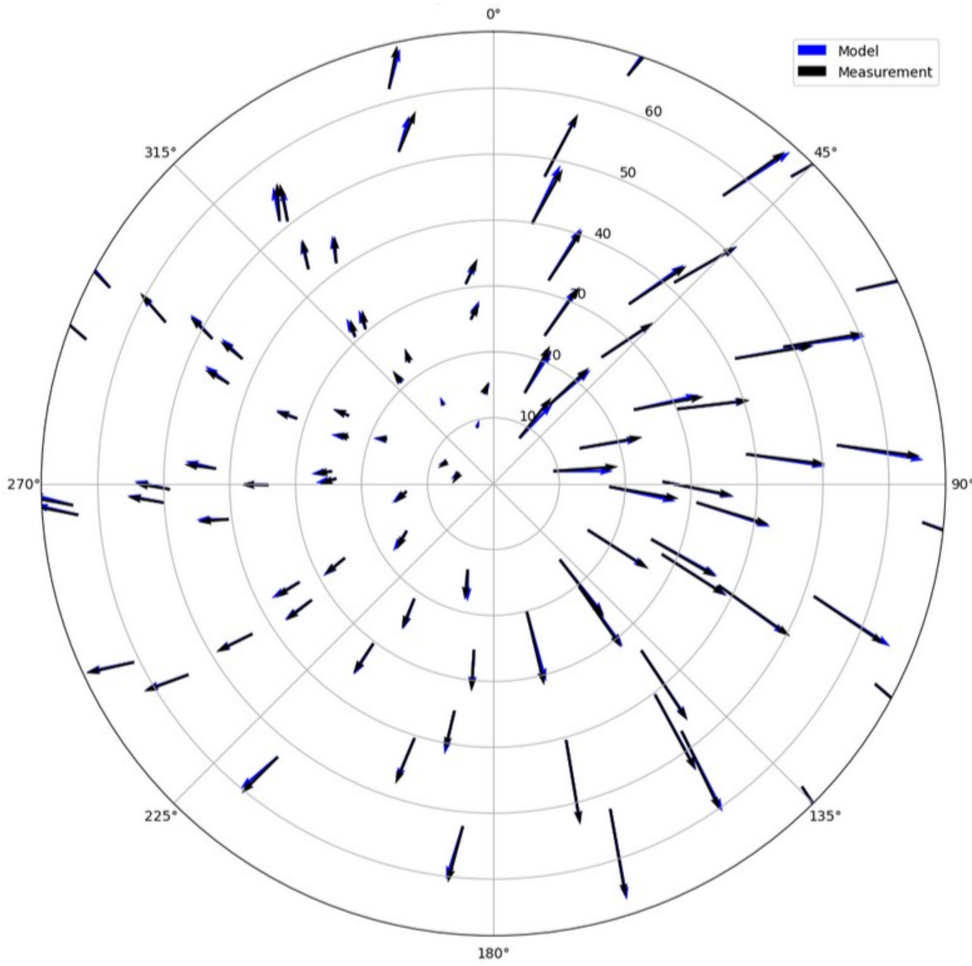
b



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

Working principle

→ derive a mechanical model from star misspointing



Compute the miss-pointing for each point, with mechanical model

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

One of the challenge of bending model: optimizing time

→ 9h/Moon cycle, *time is precious !*

Questions:

- how many stars do we need to ensure a robust mechanical model ?
- how can we gain time on data taking ?

One of the challenge of bending model: optimizing time

→ 9h/Moon cycle, *time is precious !*

Questions:

- how many stars do we need to ensure a robust mechanical model ?
- how can we gain time on data taking ?

100 points in the sky grid seems to be a good approximation

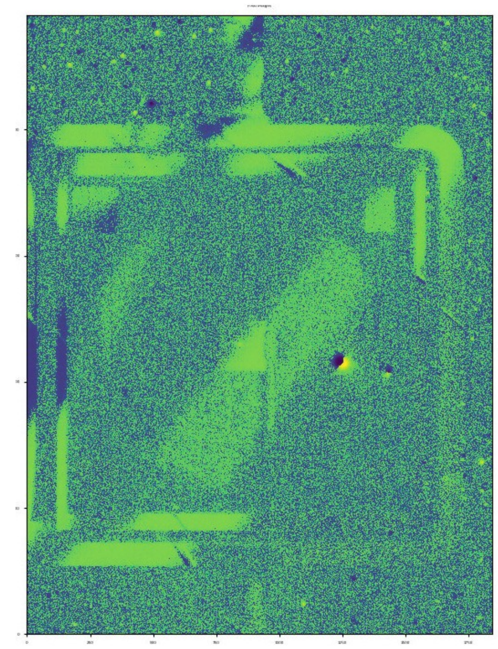
One of the challenge of bending model: optimizing time

→ 9h/Moon cycle, *time is precious !*

Questions:

- how many stars do we need to ensure a robust mechanical model ?
- how can we gain time on data taking ?

Bending model data taking can be done in **Moon condition** (not causing parasite light)



Bending Model

One of the challenge of bending model: optimizing time

→ 9h/Moon cycle, *time is precious !*

Questions:

- how many stars do we need to ensure a robust mechanical model ?
- how can we gain time on data taking ?

Bending model data taking can be done in **Moon condition** (not causing parasite light)

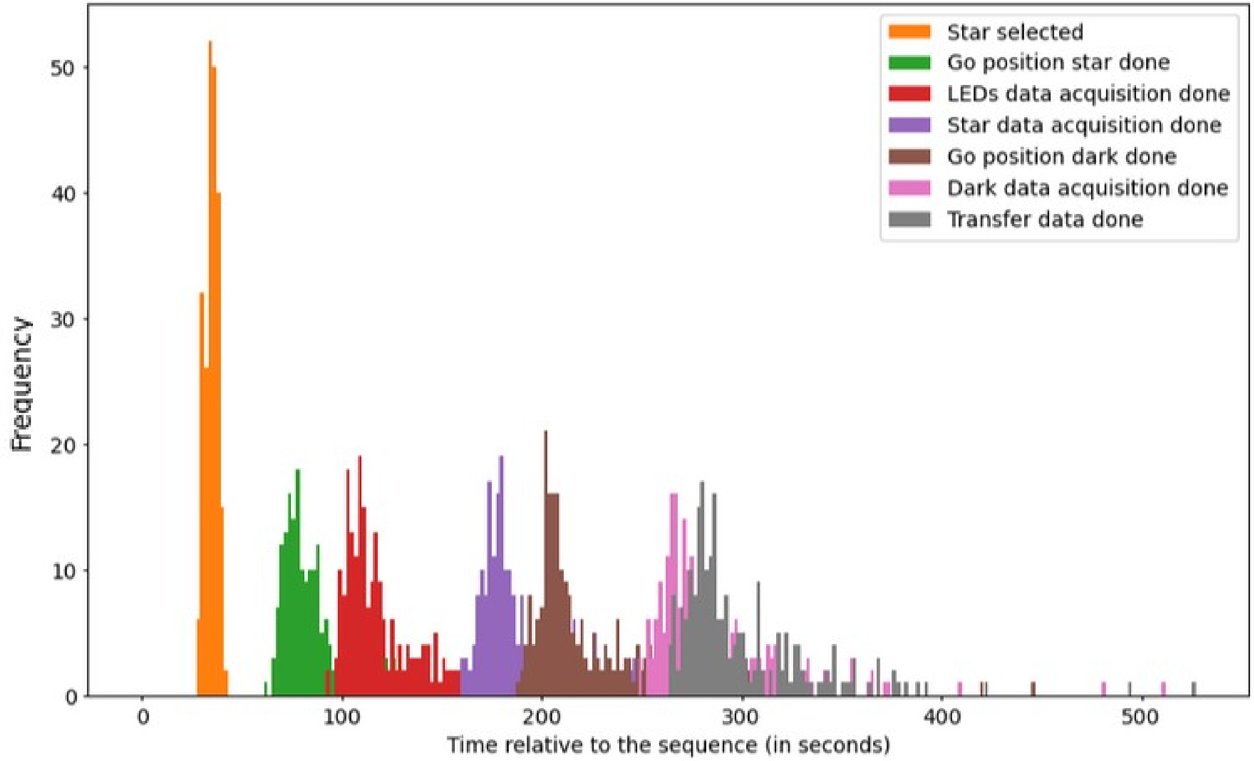
Optimize **observation sequence**

Improvement of the sequence

→ add scheduler process in the bending model code

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

Improvement of the sequence

→ add scheduler process in the bending model code

Sequence

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

(loop: transfer data → select a star)

→

New sequence

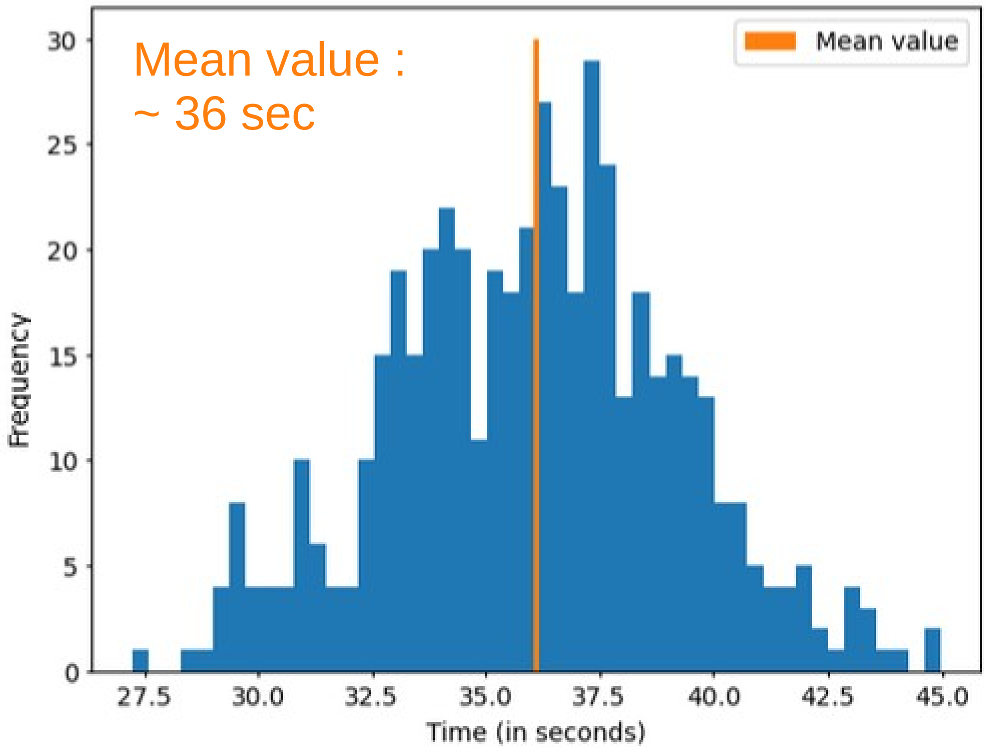
- select a star **(only first observation)**
- go to star position
- data acquisition LEDs
- data acquisition star
- go position dark
- data acquisition dark + **select next star**
- transfer data

(loop: transfer data → go to star position)

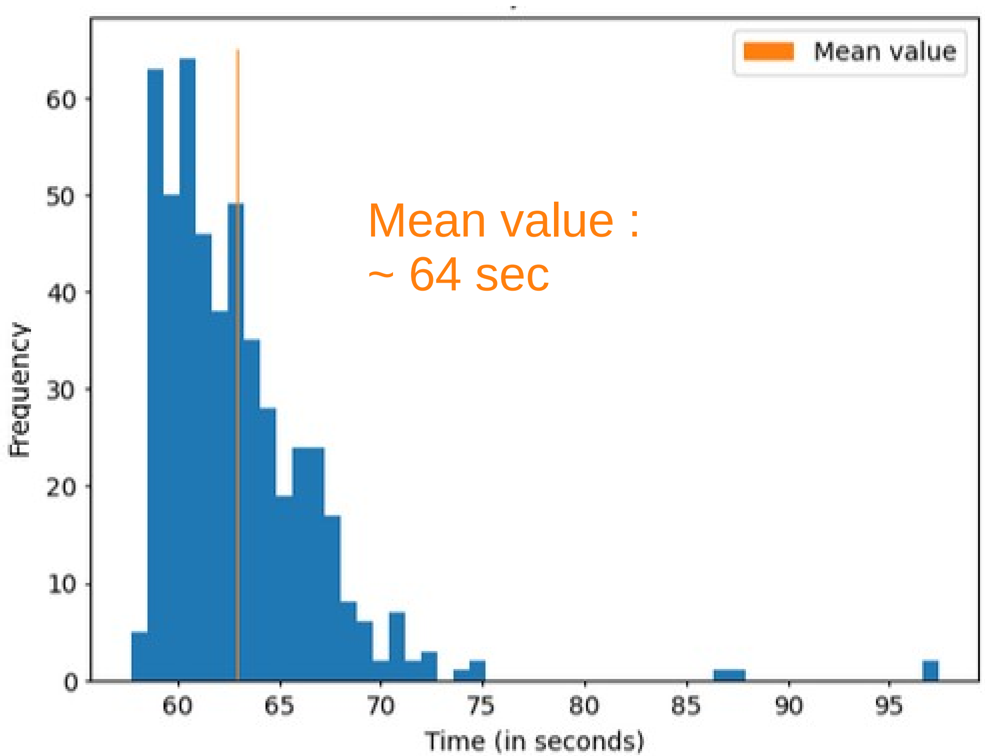
Improvement of the sequence

→ add scheduler process in the bending model code

How much time can be gained for each observation ?



Distribution of scheduler run method duration, since June 2023



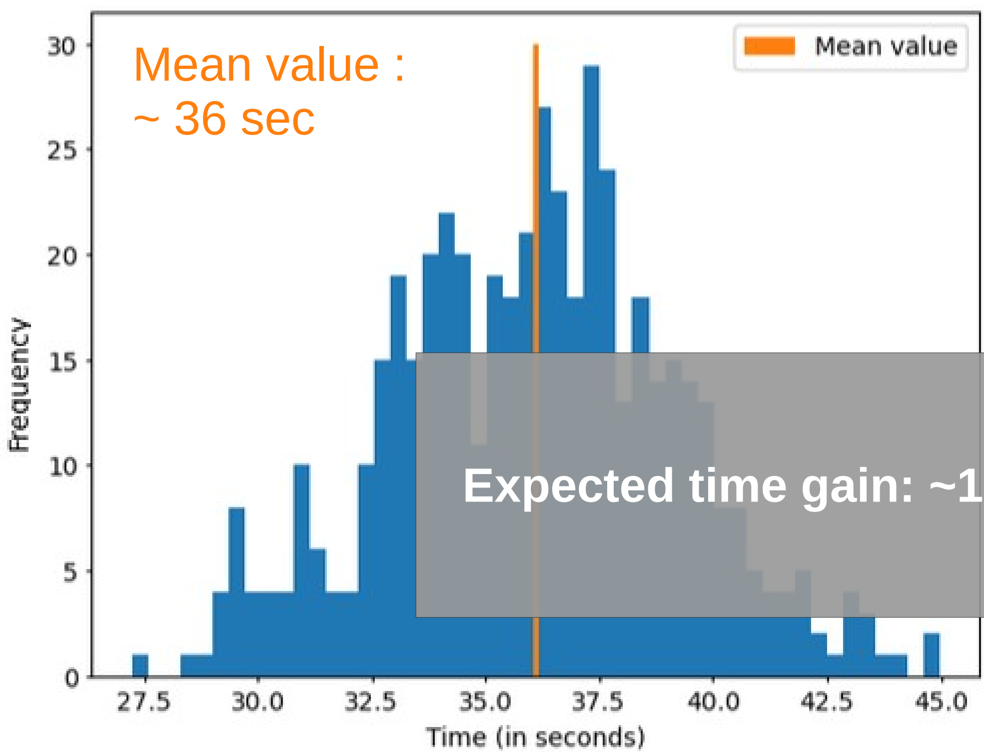
Distribution of dark patch data taking duration, since June 2023

Bending Model

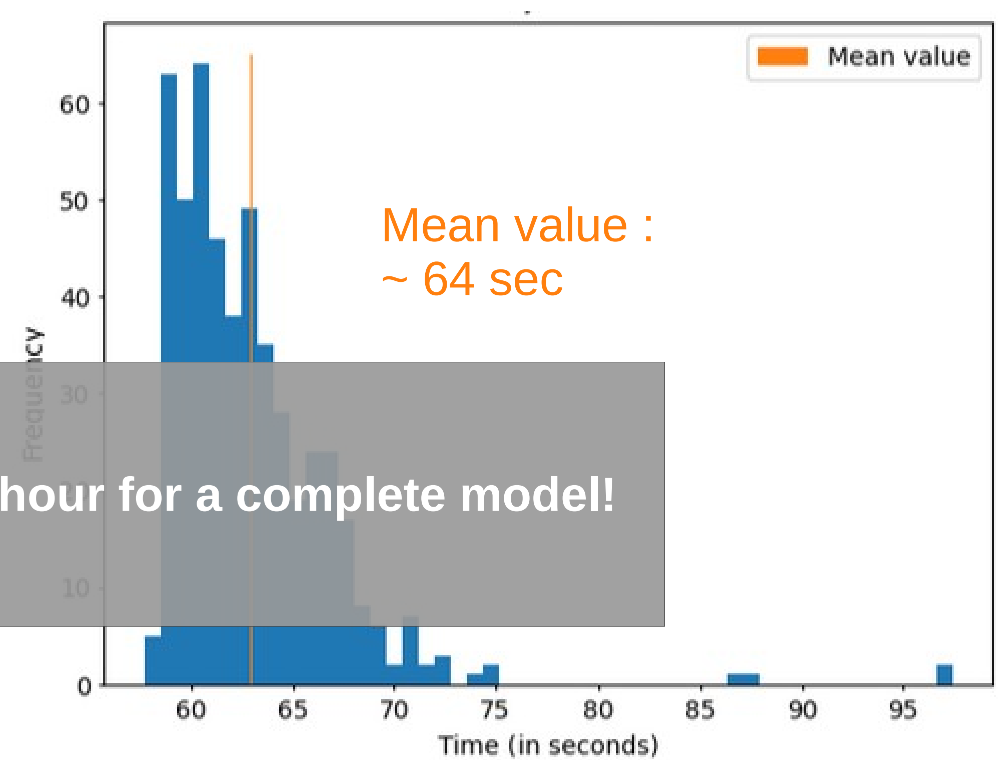
Improvement of the sequence

→ add scheduler process in the bending model code

How much time can be gained for each observation ?



Distribution of scheduler run method duration, since June 2023



Distribution of dark patch data taking duration, since June 2023

Expected time gain: ~1 hour for a complete model!

Improvement of the sequence

→ add scheduler process in the bending model code

First results

Tests have been done the 23rd and the 29th of October

→ over 2 observations, 36 seconds are gained

New mechanical model will be performed in December

→ wait & see...

Laboratoire d'Annecy de Physique des Particules

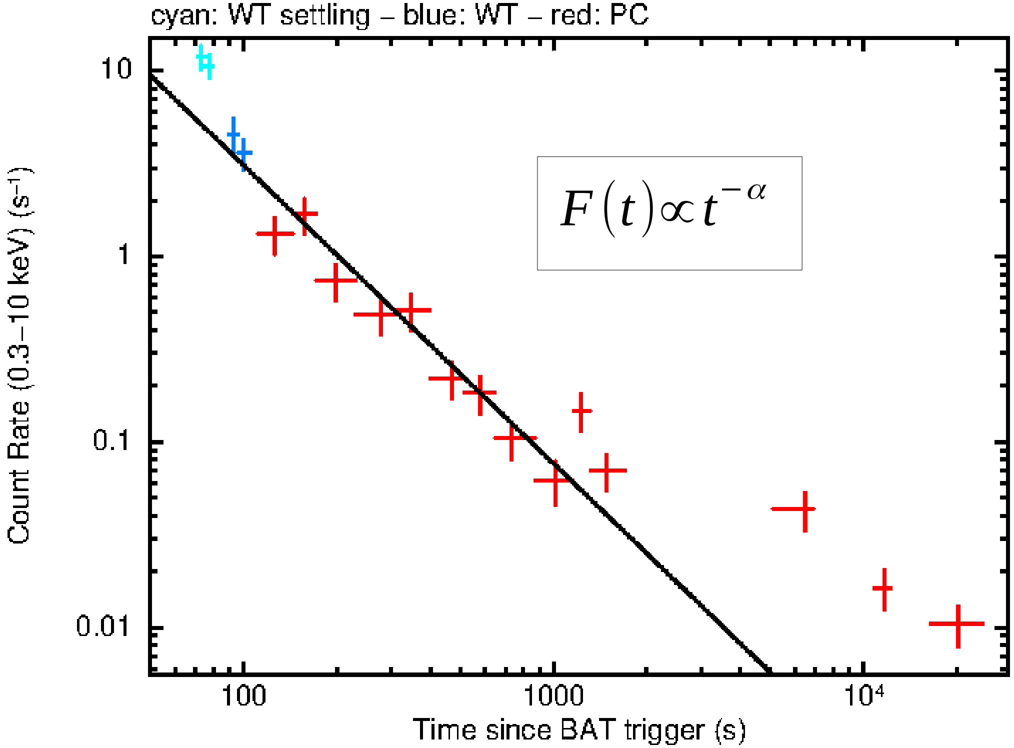
Gamma Ray Burst: Improving our detection ability

Analysis methods & first results

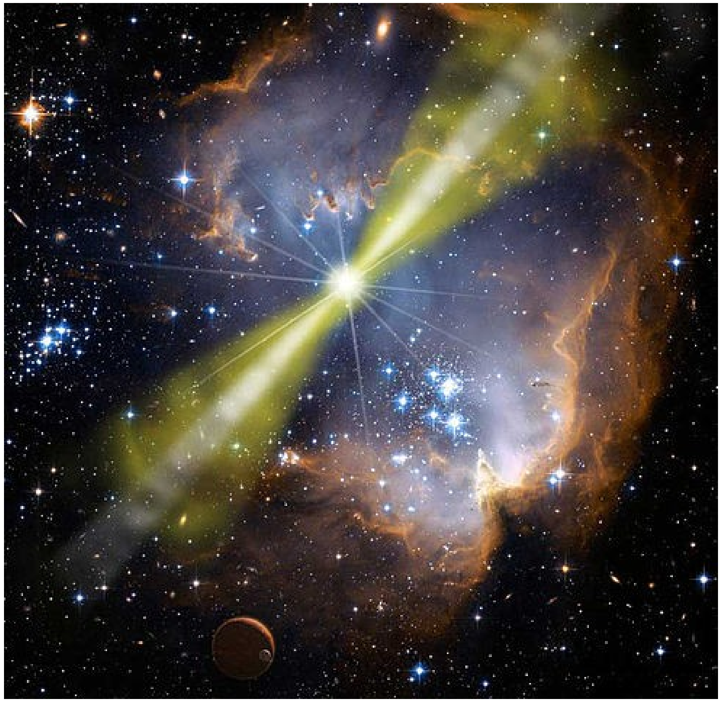
Context *with Mathieu de Bony and Edna Ruiz Velasco*

→ Gamma Ray Burst (GRB)

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



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

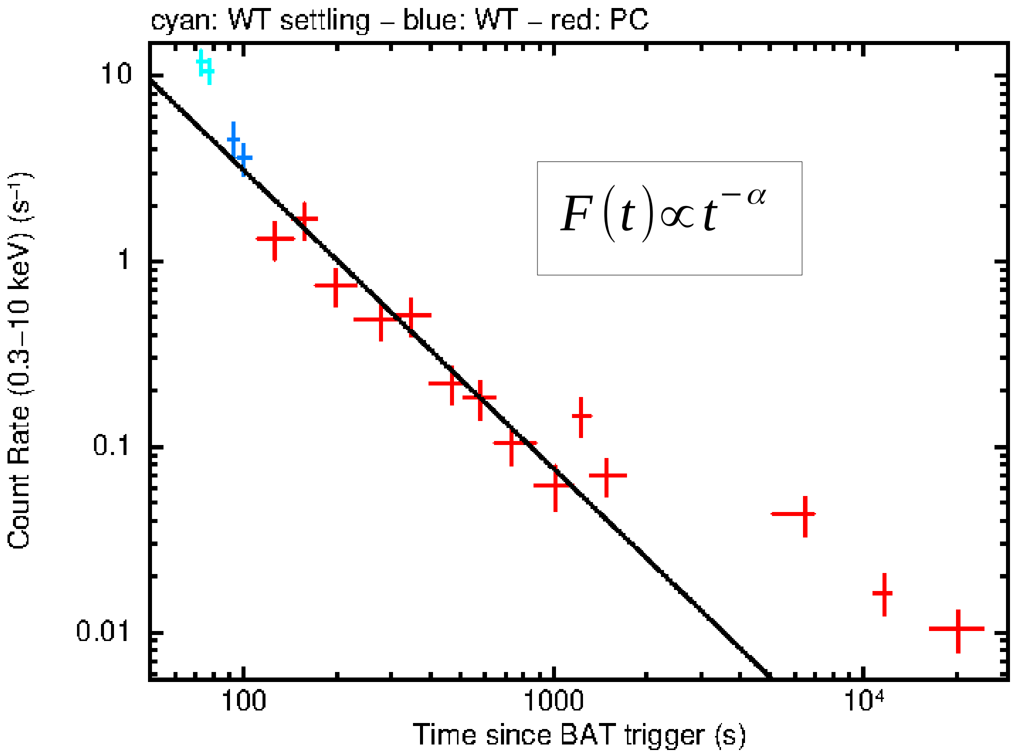


GRB artist impression

Context *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

→ observation of two regions

ON
signal ?
+
background

N_{ON} counts during T_{ON}

OFF

background

N_{OFF} counts during T_{OFF}

Methods

→ observation of two regions

ON
signal ?
+
background

N_{ON} counts during T_{ON}

OFF

background

N_{OFF} counts during T_{OFF}

Definition of background and signal

$$\bar{s}+\bar{b}=\frac{\langle N_{ON}\rangle}{T_{ON}}$$

$$\bar{b}=\frac{\langle N_{OFF}\rangle}{T_{OFF}}$$

Gamma Ray Burst analysis

Methods

→ Classic Li&Ma:

Poisson laws

$$L = P\left(N_{ON} \middle| \langle N_{ON} \rangle\right) P\left(N_{OFF} \middle| \langle N_{OFF} \rangle\right)$$

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

ON
s+bkg

OFF
bkg

Gamma Ray Burst analysis

Methods

Poisson laws

→ Classic Li&Ma:

$$L = P(N_{ON} | \langle N_{ON} \rangle) \, P(N_{OFF} | \langle N_{OFF} \rangle)$$

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

ON
s+bkg

OFF
bkg

→ Li&Ma time dependent:

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

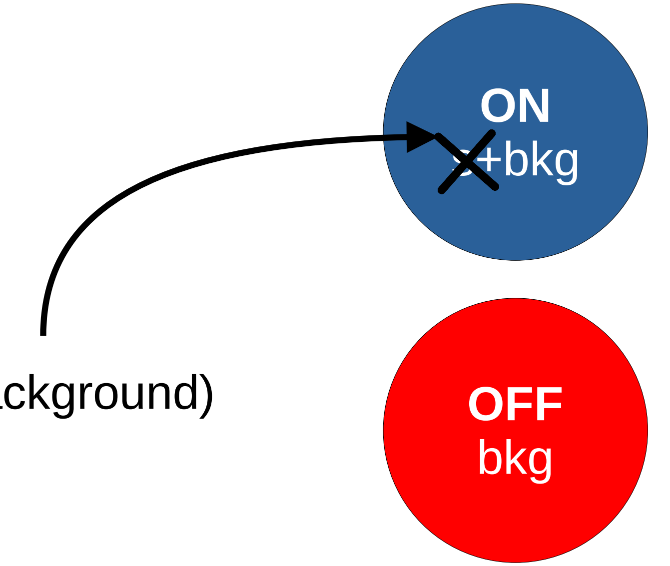
product of the probability mass function for each T_{ON} bin (0 or 1 event, for a large N)

probability mass function for OFF observations

with N.Δt = T_{ON}

Methods

→ Perform ratio test: $$TS = -2\log\left(\frac{L_0}{L}\right)$$



with L_0, the likelihood of the null hypothesis (only background)

→ Compute significance of the source: $$\sigma = \sqrt{TS}$$

=> σ > 5: detection !

First results

→ generate simulated bursts with parameters:

- delay
- **temporal index α**
- spectral index Γ
- normalization ϕ_0
- redshift z

Assuming:

- power law spectral model

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

- power law temporal model

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

First results

→ generate simulated bursts with parameters:

- delay
- **temporal index α**
- spectral index Γ
- normalization ϕ_0
- redshift z

→ compute:

- Significance
- Time dependent significance

Assuming:

- power law spectral model

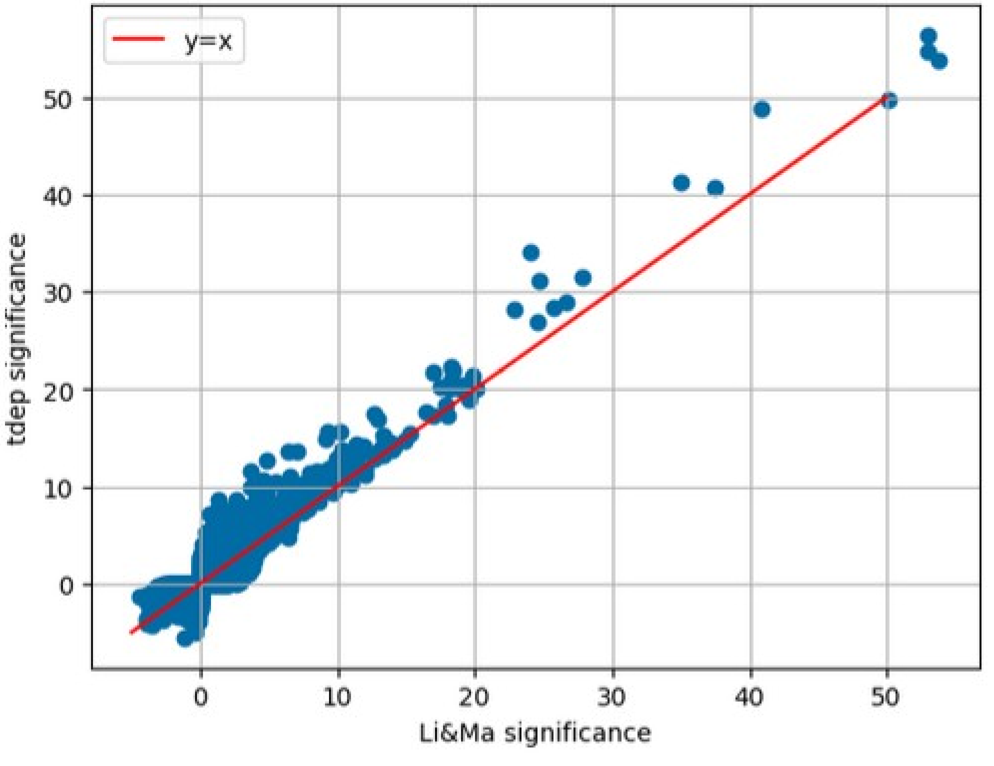
$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$$

- power law temporal model

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

First results

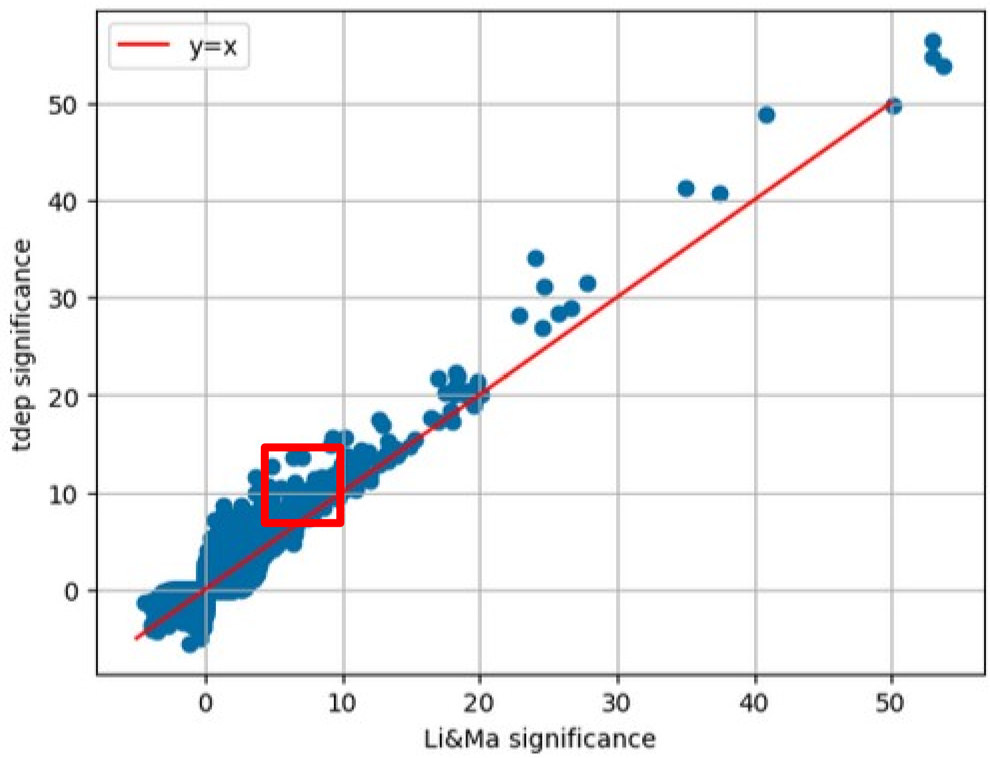
→ results with 50,000 simulations



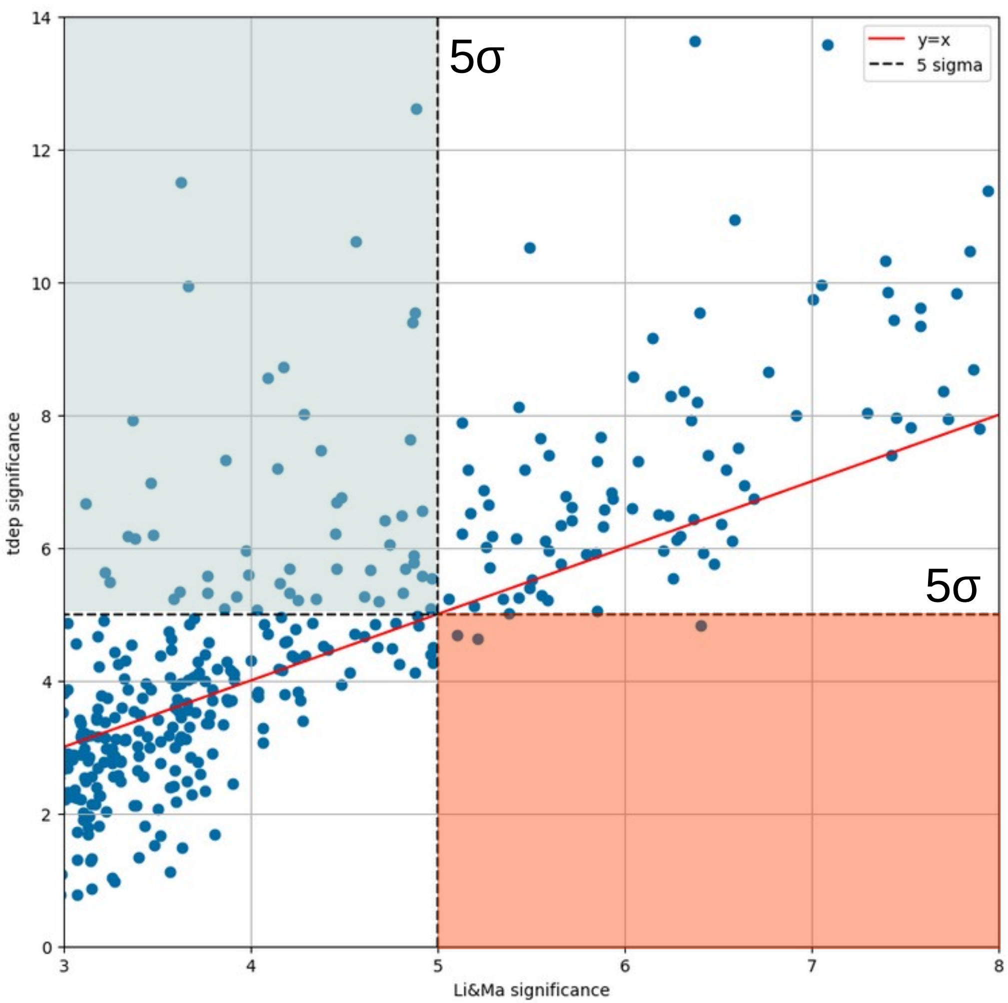
Plot of the significance computed with tdep depending on the classic Li&Ma significance

First results

→ results with 50,000 simulations



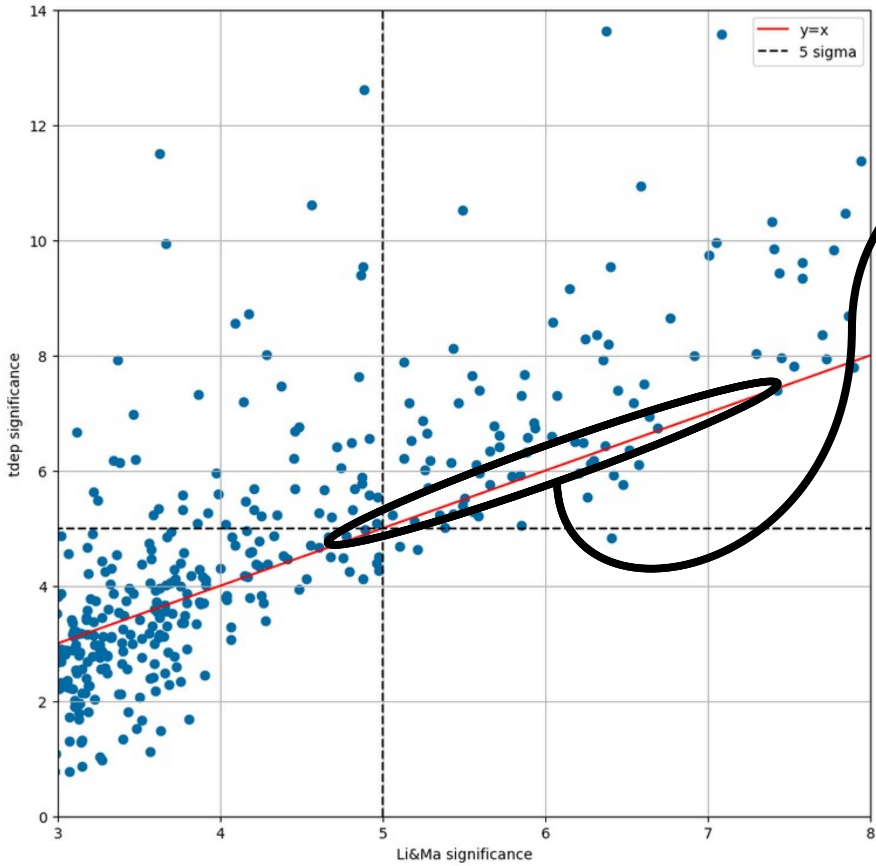
Plot of the significance computed with tdep depending on the classic Li&Ma significance



Plot of the significance computed with tdep depending on the classic Li&Ma significance (zoom around 5σ)

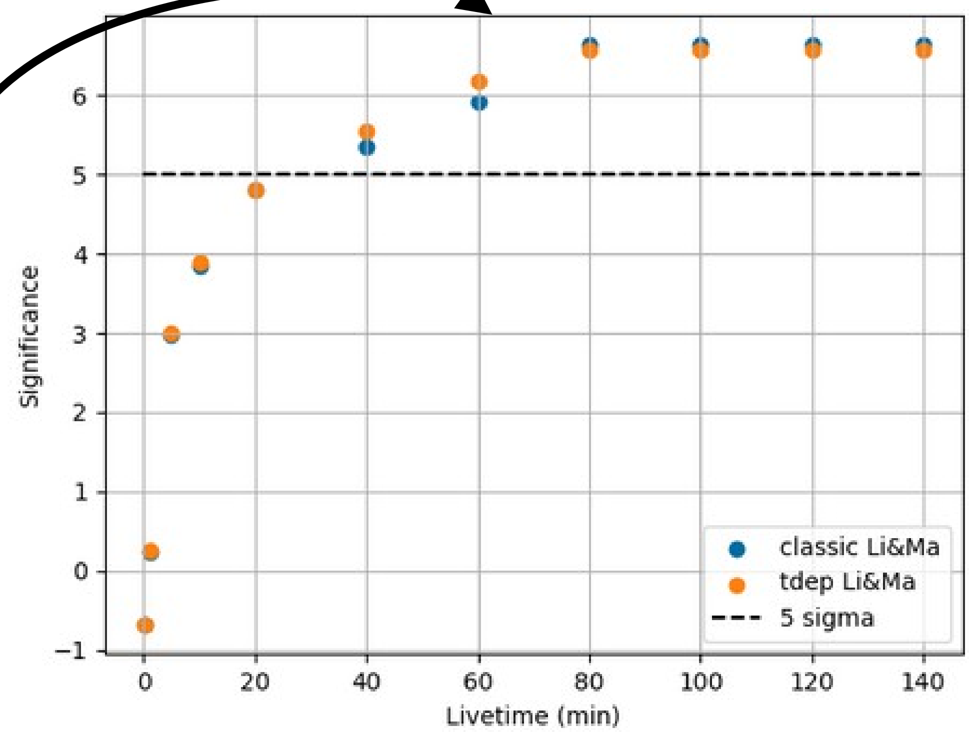
First results

→ results with 50,000 simulations



Plot of the significance computed with tdep depending on the classic Li&Ma significance

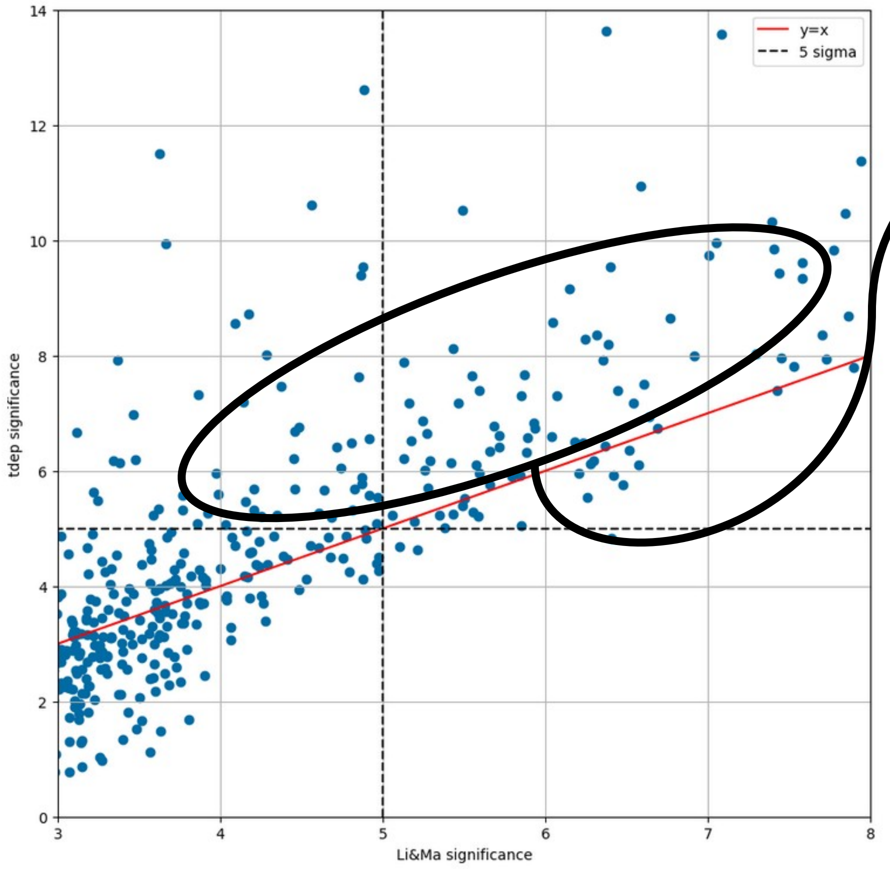
Similar behavior for both methods



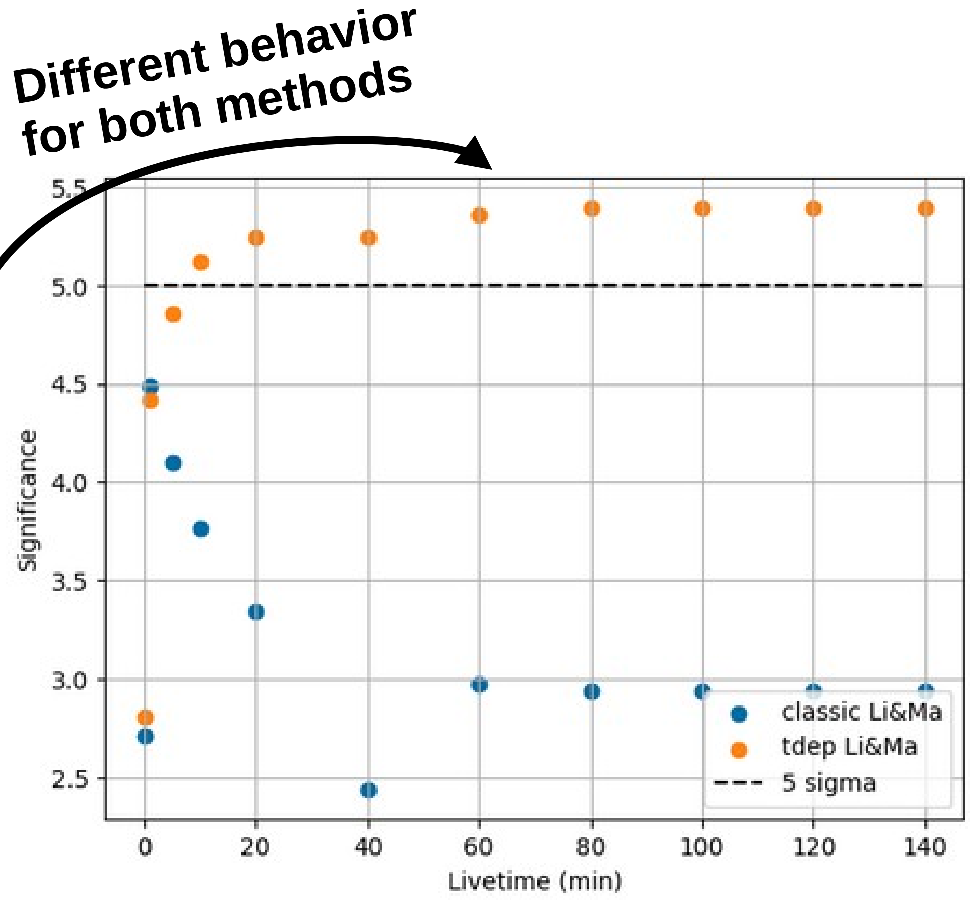
Evolution of the significance depending on time, with both methods

First results

→ results with 50,000 simulations



Plot of the significance computed with tdep depending on the classic Li&Ma significance

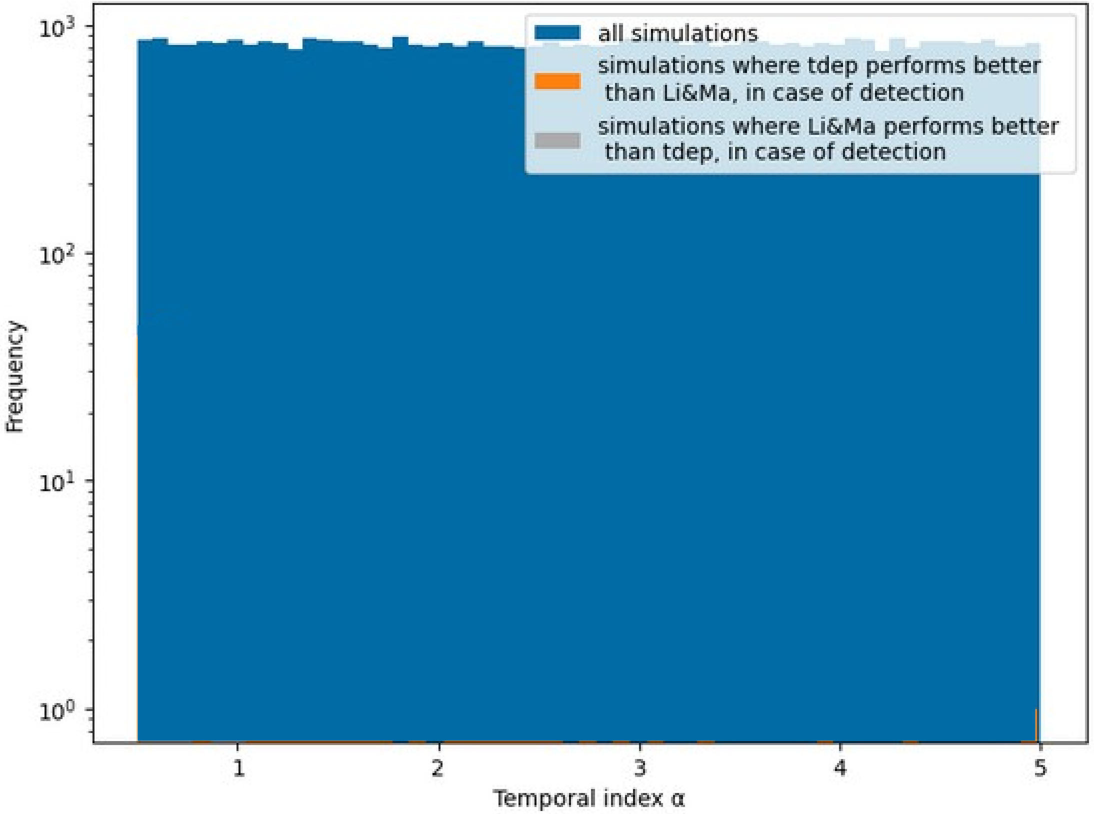


Evolution of the significance depending on time, with both methods

First results

→ results with 50,000 simulations

In which cases does time dependent Li&Ma performs better ?

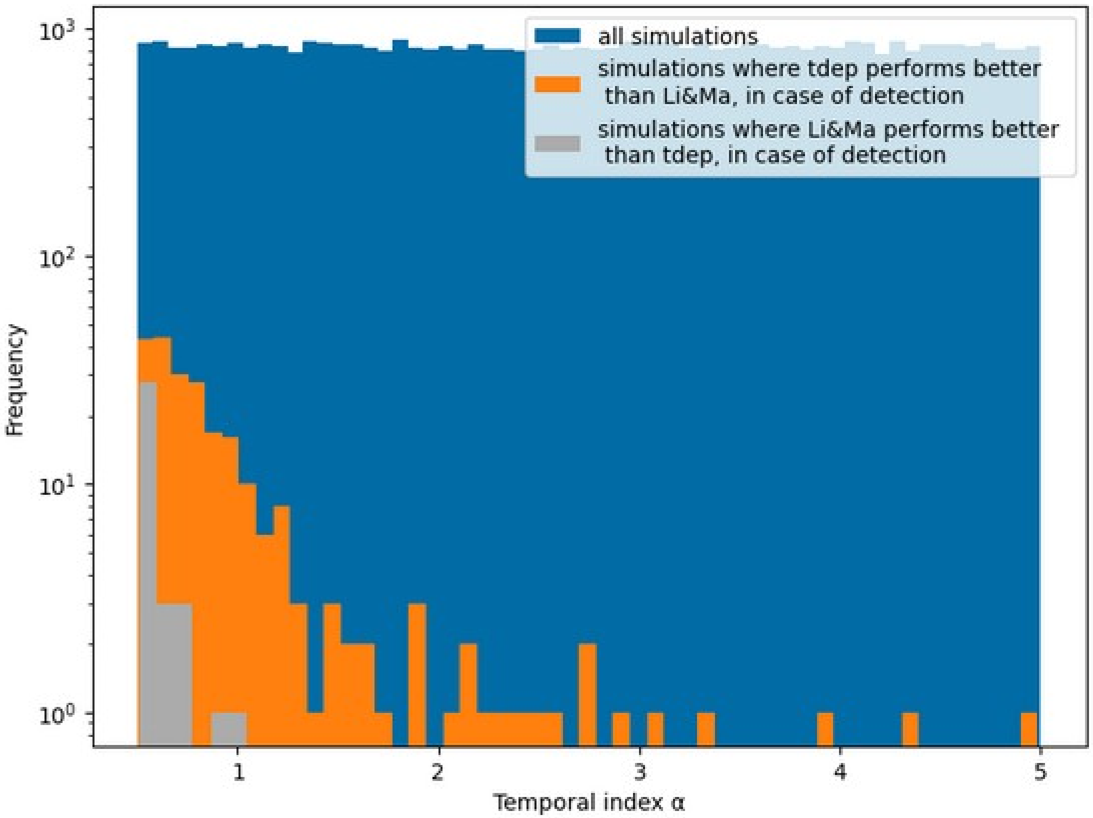


Distribution of the temporal index, for 50,000 simulations

First results

→ results with 50,000 simulations

In which cases does time dependent Li&Ma performs better ?



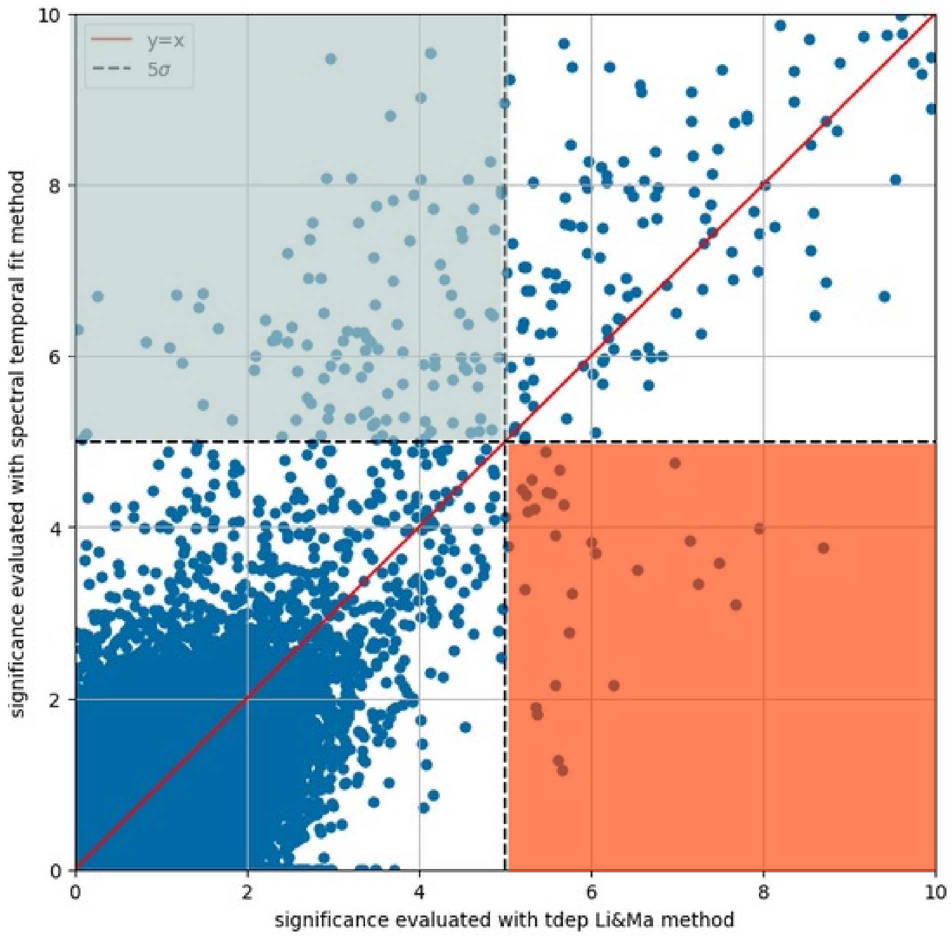
Distribution of the temporal index, for 50,000 simulations

Li&Ma time dependent performs better for GRBs with very **sharply temporal evolution** (i.e. high α)

Temporal evolution: $F(t) \propto t^{-\alpha}$

Coming soon...

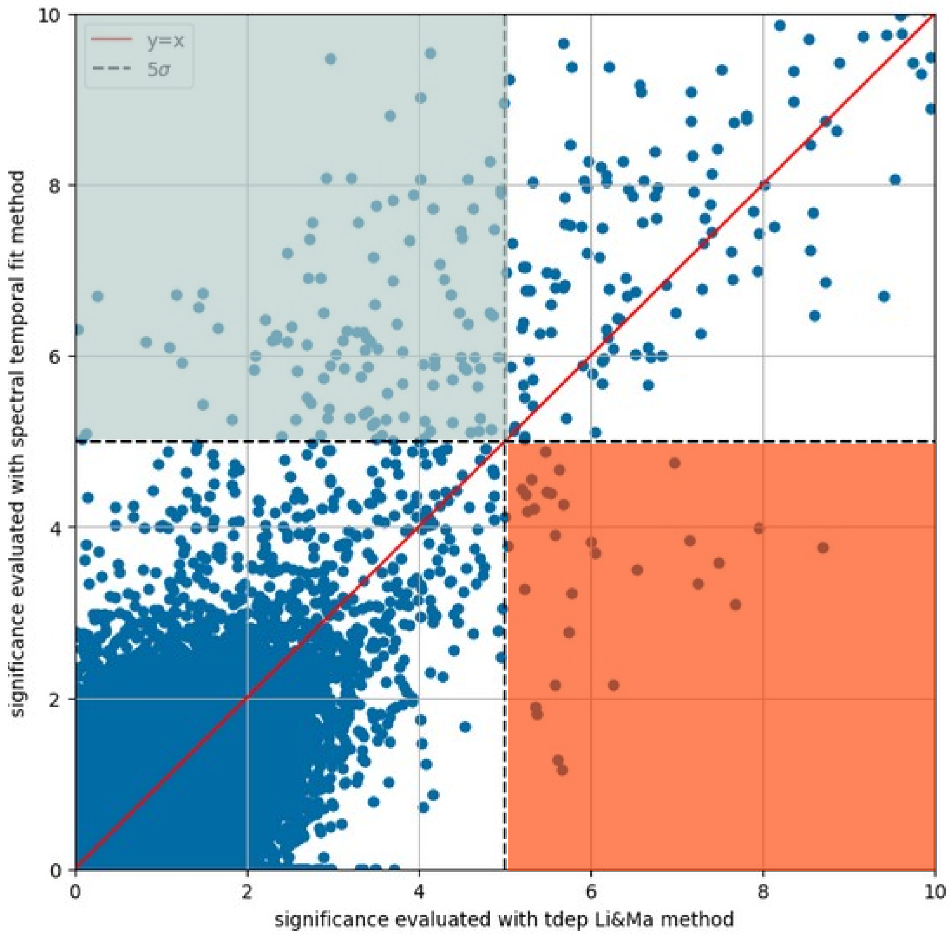
→ new method, developed by Mathieu de Bony



Plot of the significance computed with STF method depending on the classic tdep Li&Ma significance

Coming soon...

→ new method, developed by Mathieu de Bony



Plot of the significance computed with STF method depending on the classic tdep Li&Ma significance

Spectral temporal fit

→ appears to be performing better

→ still ~10% of the fit are failing

Laboratoire d'Annecy de Physique des Particules

Conclusion

Bending Model

- new bending model for the next LSTs
- calibration of new CDMs

Picture of the CTAO North site, with the 4 LSTs (September 2024)

Bending Model

- new bending model for the next LSTs
- calibration of new CDMs

Gamma Ray Burst

- article on analysis methods
- article on GRB catalog

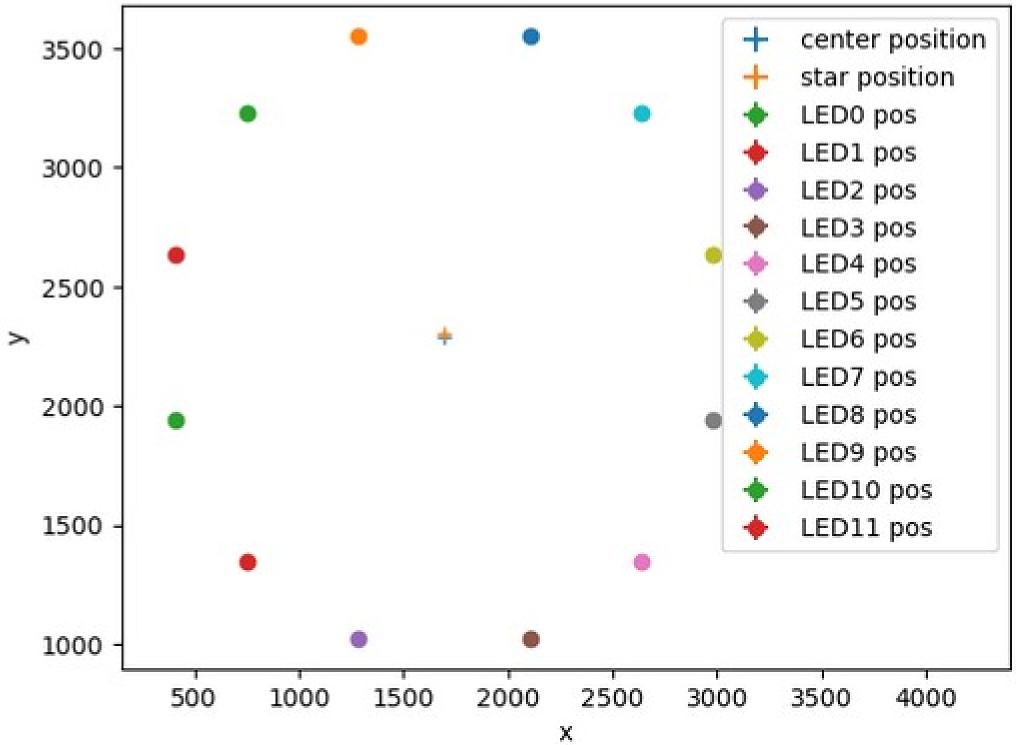

THANKS FOR YOUR ATTENTION

Laboratoire d'Annecy de Physique des Particules

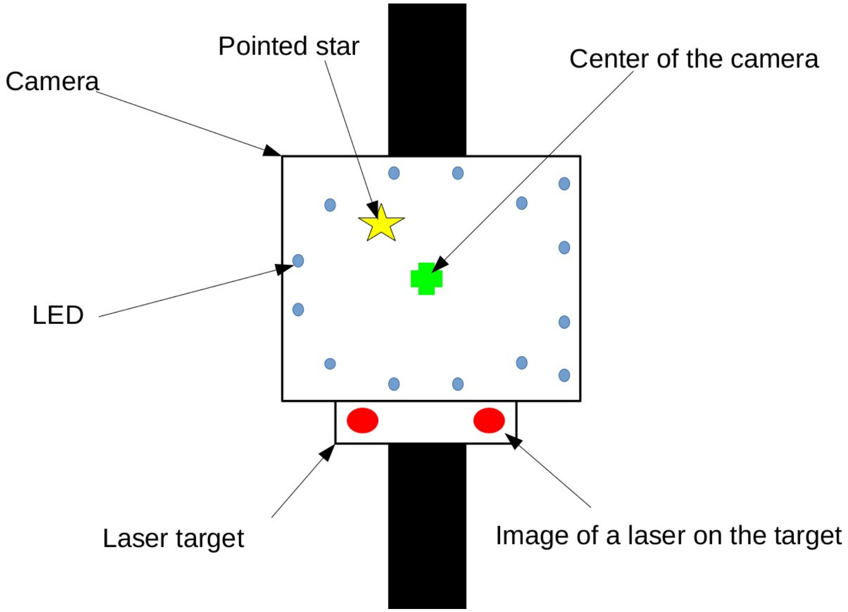
Back up - Part I

Bending Model

Working principle: fit the center of the camera with the LEDs



LEDs position in the camera plane



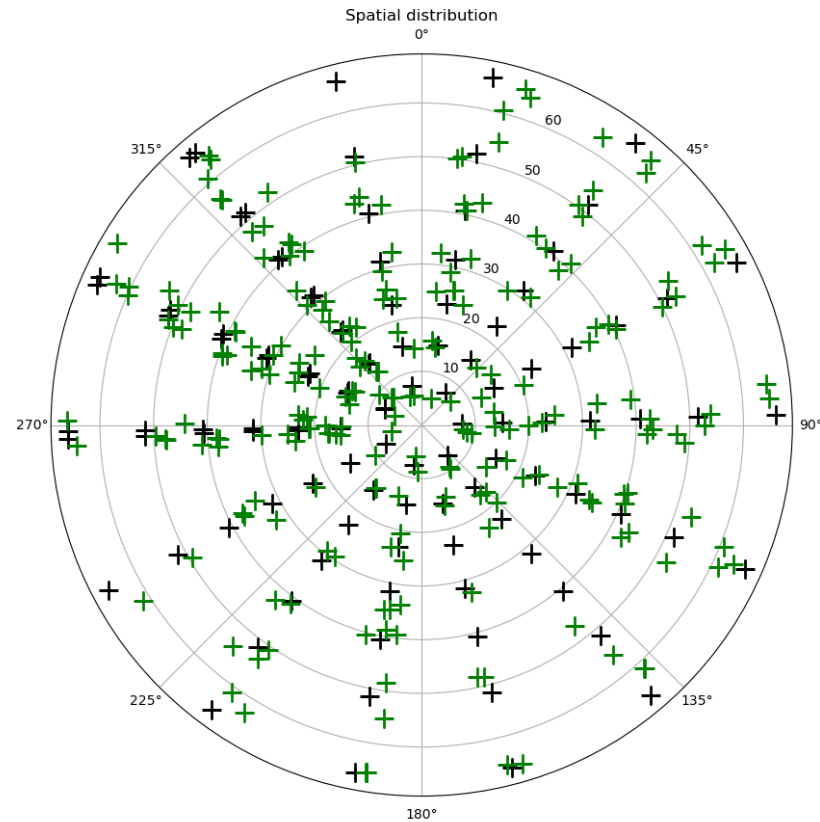
Sky grid: impact of a biased dataset

→ dataset used as a reference

Conditions : - correct repartition of the observations in the grid
- rather short period
- no OARL problems

Choice : from 1st of April to 1st of June

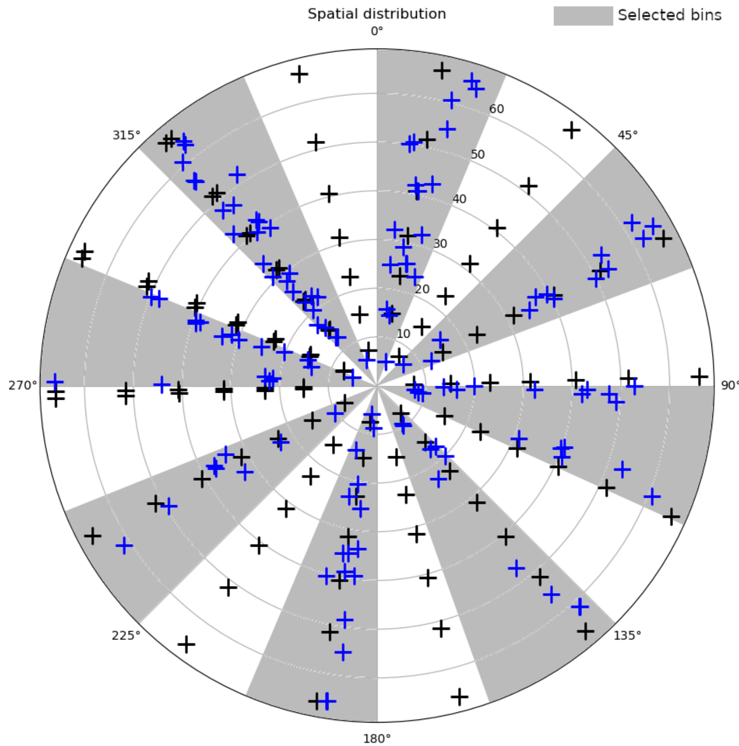
name	value	standard error	relative error	initial value	min	max	vary
AzEncoderShift	-89.2668883	12.4555810	(13.95%)	-49.45697415060795	-3600.00000	3600.00000	True
ZdEnodercShift	96.9081860	3.53827509	(3.65%)	113.39677416696668	-3600.00000	3600.00000	True
AltNonOrthogonality	35.1557247	3.32421149	(9.46%)	18.62210141639116	-3600.00000	3600.00000	True
AzNonVerticalityPhi	-191.257258	4.35101126	(2.27%)	-165.64267646108357	-360.000000	360.000000	True
AzNonVerticalityTheta	38.9776225	1.12350998	(2.88%)	37.4025104703328	-3600.00000	3600.00000	True
TelescopeBendingLin	-4.97996179	0.15222074	(3.06%)	-4.967946724361393	-10.0000000	10.0000000	True
TelescopeBendingQuad	0.03376945	0.00203067	(6.01%)	0.03405057373035647	-1.00000000	1.00000000	True
TelescopeToCameraAlpha	0.00000000	0.00000000		0.0	-1.00000000	1.00000000	False
CSSBendingLin	0.99999999	0.02417413	(2.42%)	0.8323424089095606	-1.00000000	1.00000000	True
OffsetOpticalAxisAzScan	0.30124737	5.2233e-04	(0.17%)	0.30106655416325845	-1.00000000	1.00000000	True
AmplitudeOpticalAxisAzScan	-0.00369529	6.7145e-04	(18.17%)	-0.003859152796957366	-1.00000000	1.00000000	True
OffsetElevationAxisAzScan	44.2902737	5.3198e-04	(0.00%)	44.30032352387971	0.00000000	90.0000000	True
AmplitudeElAxisAzScan	-0.00839285	8.4780e-04	(10.10%)	0.011053105594136081	-1.00000000	1.00000000	True
OARL1LEDShift	3.58920646	7.1223e-04	(0.02%)	3.58863984372369	2.00000000	5.00000000	True
OARL2LEDShift	3.56802705	7.1223e-04	(0.02%)	3.5629110624182836	2.00000000	5.00000000	True
ZdEncoderPlay	0.01350176	3.5098e-04	(2.60%)	0.013873682212690835	0.00000000	0.10000000	True
CSSBendingQuad	3.4205e-04	7.2016e-04	(210.54%)	0.0014596845761847277	-1.00000000	1.00000000	True
CSSAssymetricalEffectLin	2.51293567	0.29160683	(11.60%)	1.8283115937501861	-3600.00000	3600.00000	True
CSSAssymetricalEffectQuad	-0.01226263	0.00162158	(13.22%)	-0.008491107147619914	-3600.00000	3600.00000	True



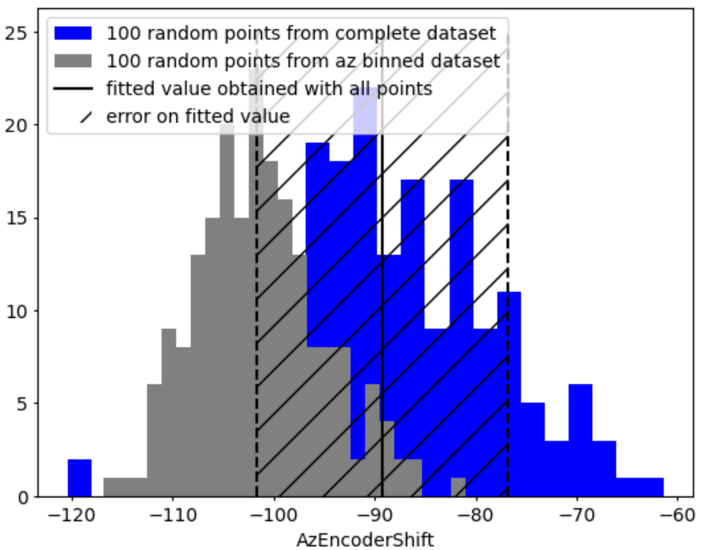
Observations grid for the selected period

Sky grid: impact of a biased dataset

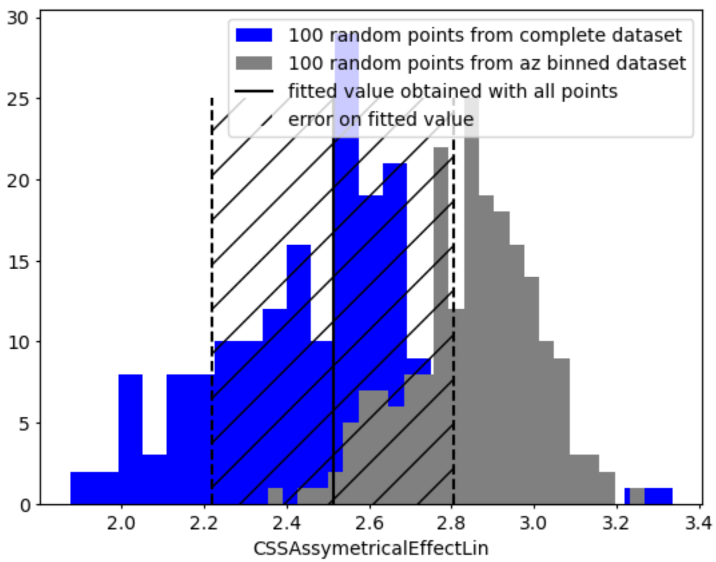
→ impact of a biased dataset on the mechanical model parameters



Grid for dataset with azimuth selection



Dispersion of the AzEncoderShift parameter values for both datasets

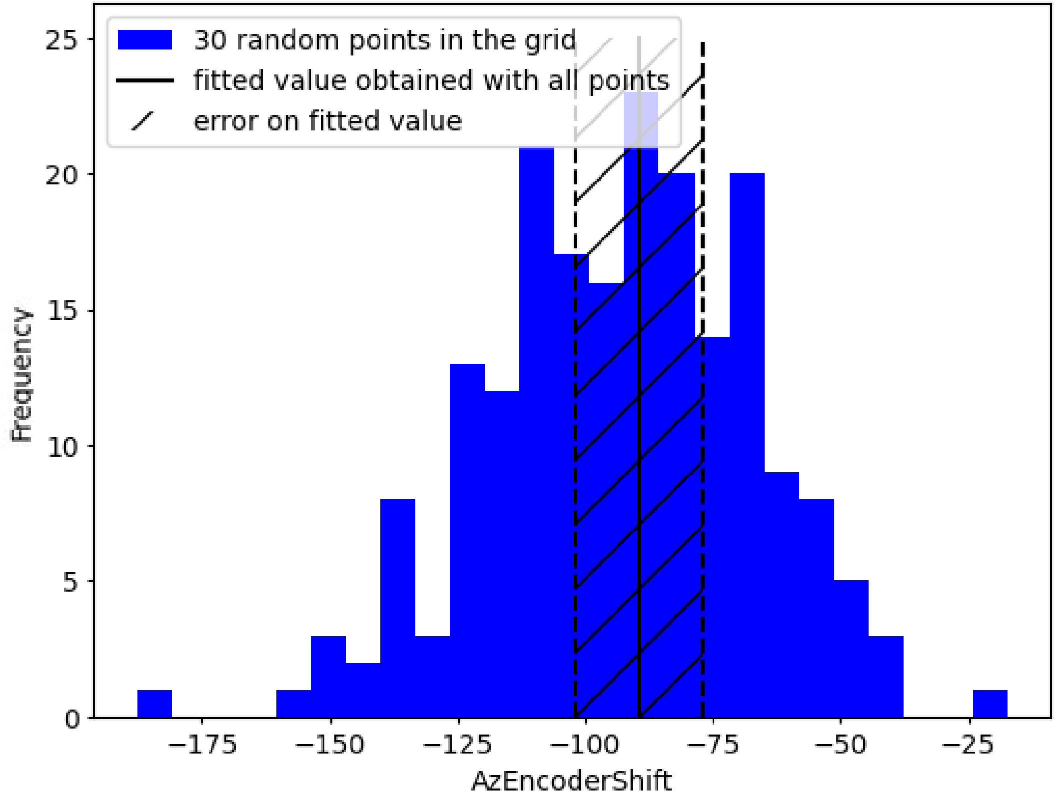


Dispersion of the CSSAssymetricalEffectLin parameter values for both datasets

Time optimization: impact of the number of observations

→ fit of the model parameters

→ how many observations are needed ?

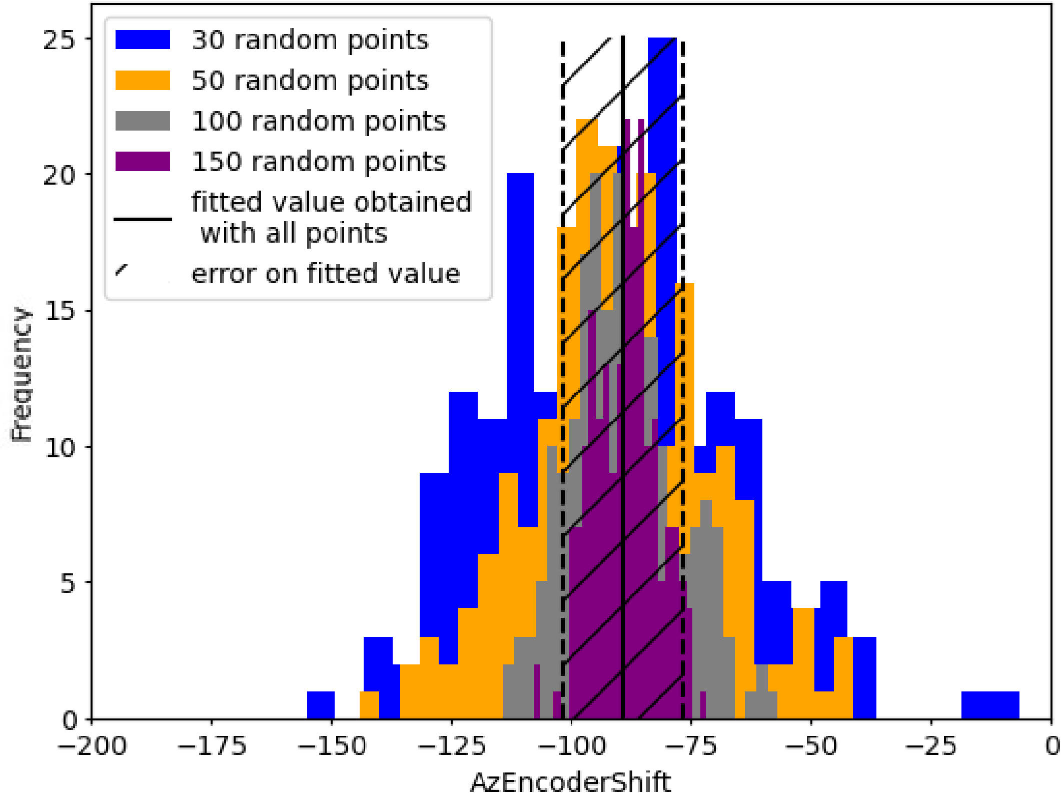


Distribution of the parameter values, fitted for different number of stars, for 200 random selection

Time optimization: impact of the number of observations

→ fit of the model parameters

→ how many observations are needed ?



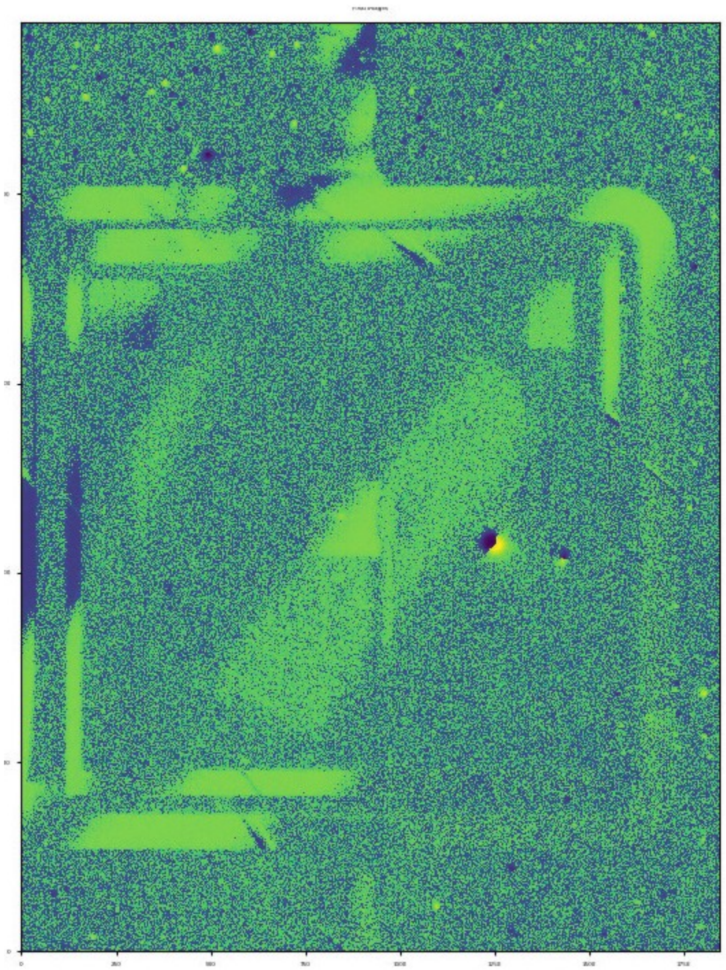
Distribution of the parameter values, fitted for different number of stars, for 200 random selection

100 points in the sky grid seems to be a good approximation, for the fit of the parameters

Time optimization: impact of the Moon

Some observations: failing

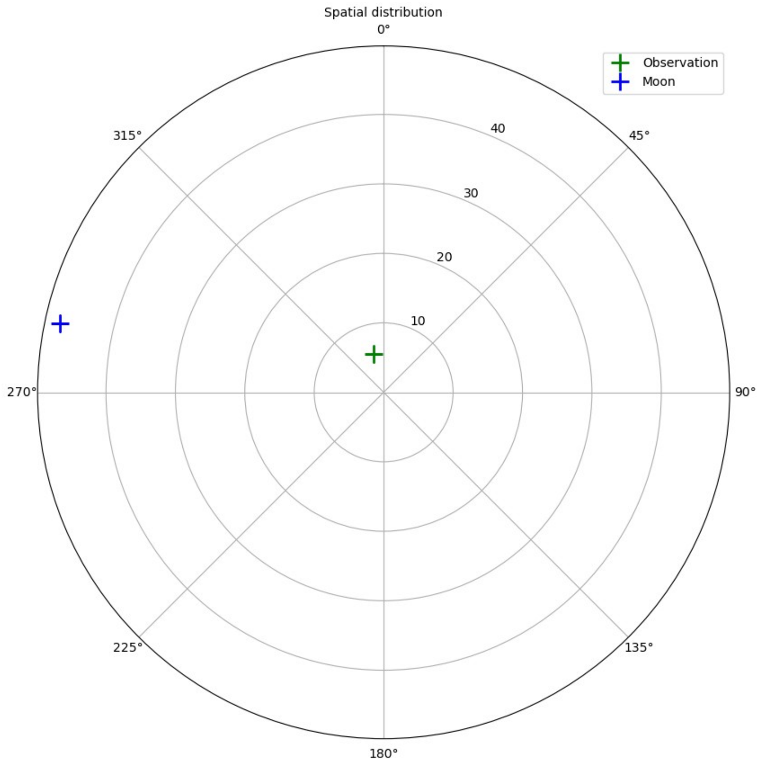
→ **does the Moon have an impact on the success of BM data taking ?**



Picture taken by the CDM, presenting strange effect due to parasite light

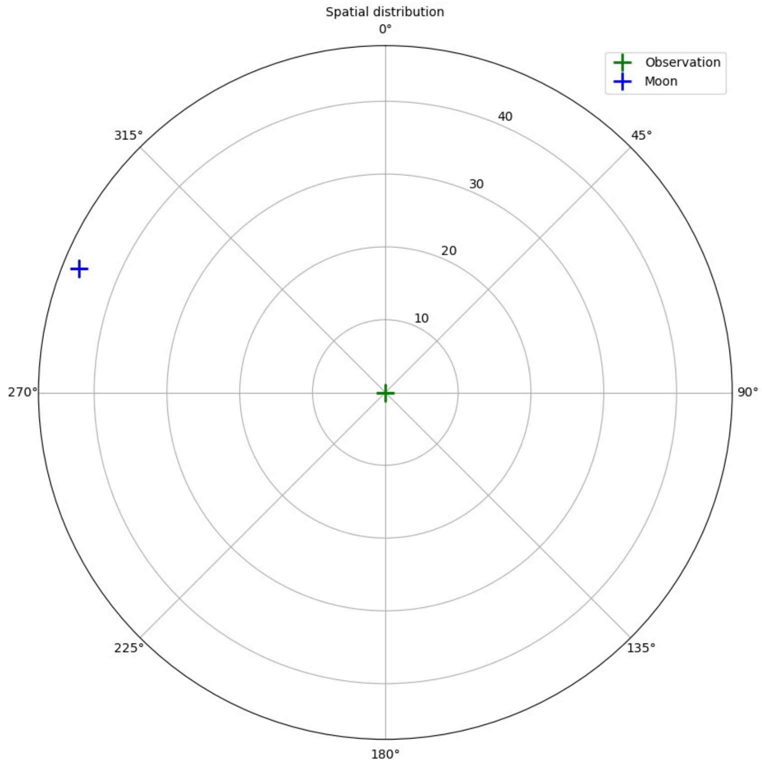
Time optimization: impact of the Moon

→ change of reference, with the example of BM observation 970



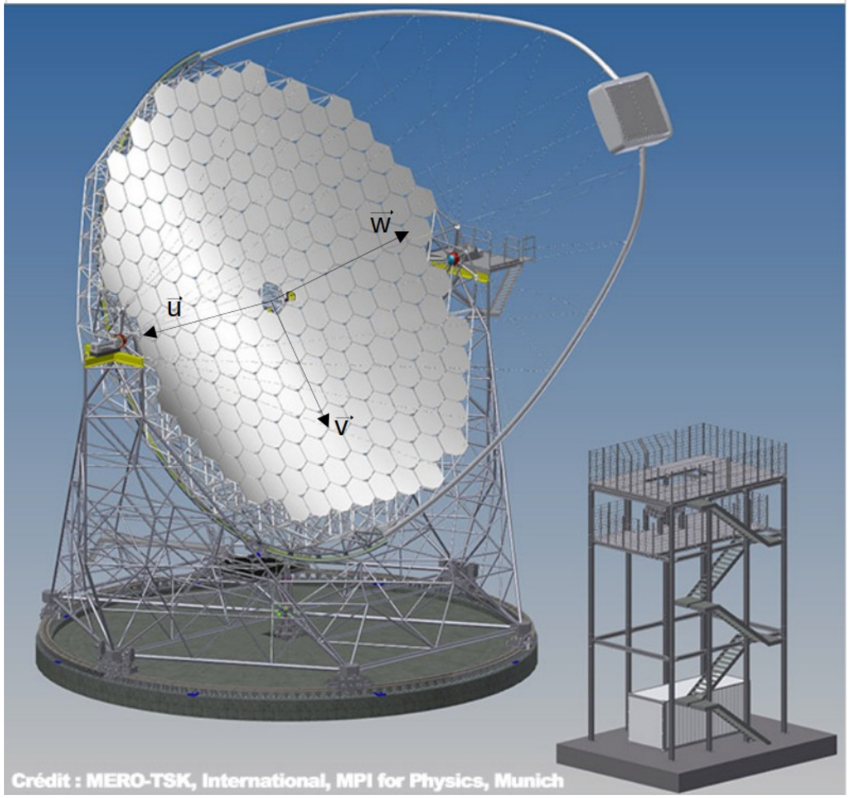
Pointing and Moon positions in the telescope reference for BM observation 970

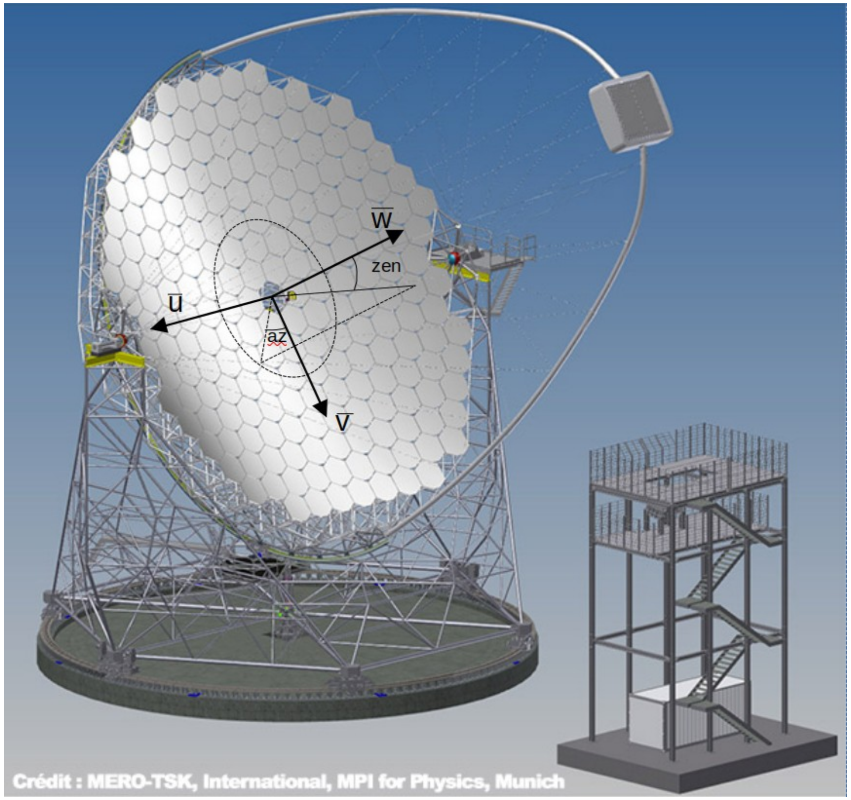
applying the basis change



Pointing and Moon positions in the dish reference for BM observation 970

Time optimization: impact of the Moon

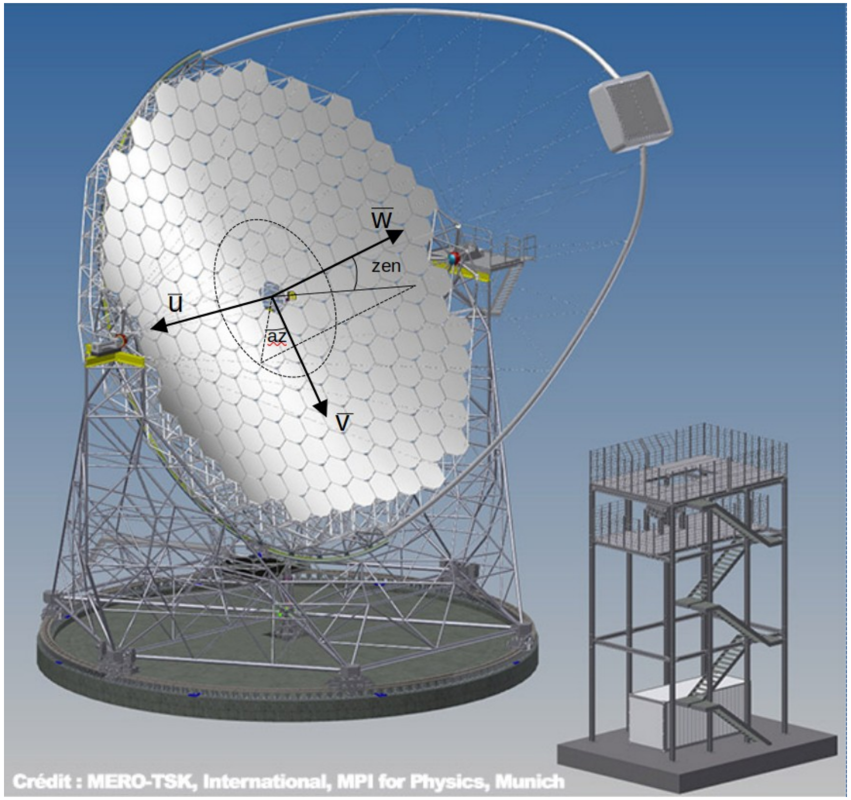




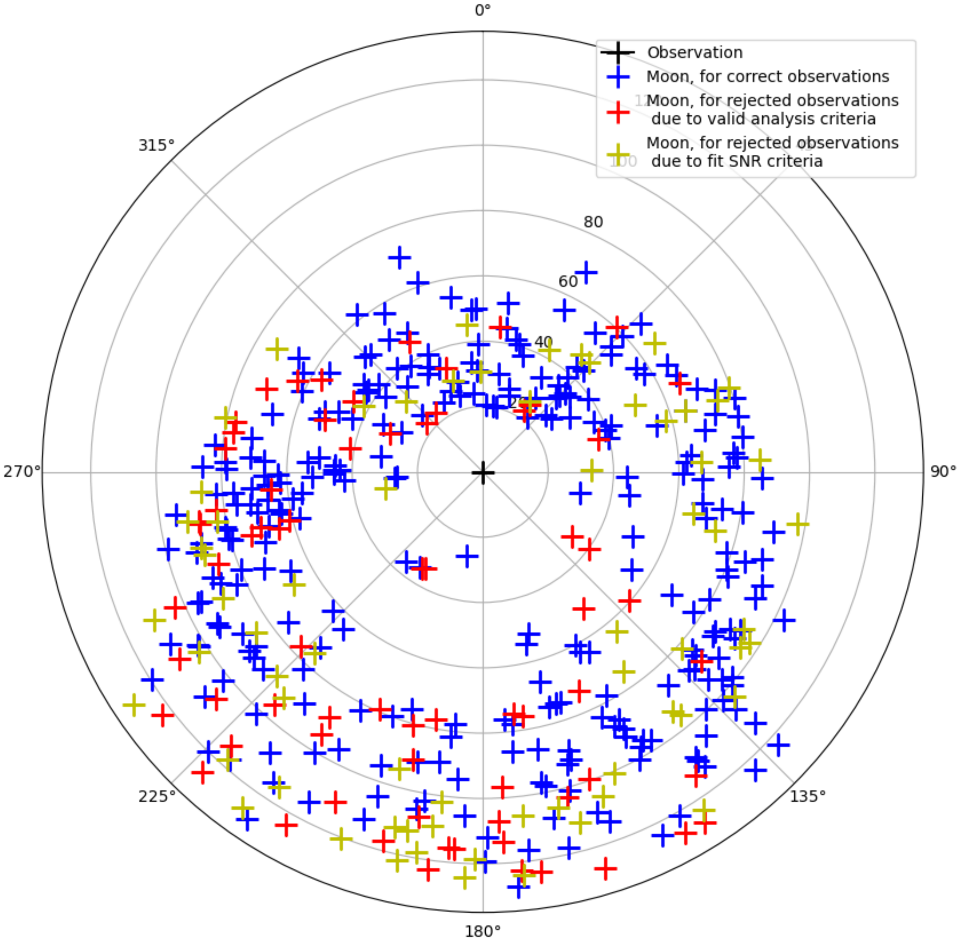
Change of reference for the study

Telescope reference → Dish reference

Time optimization: impact of the Moon



Pointing reference, useful for the stacking of relative Moon position



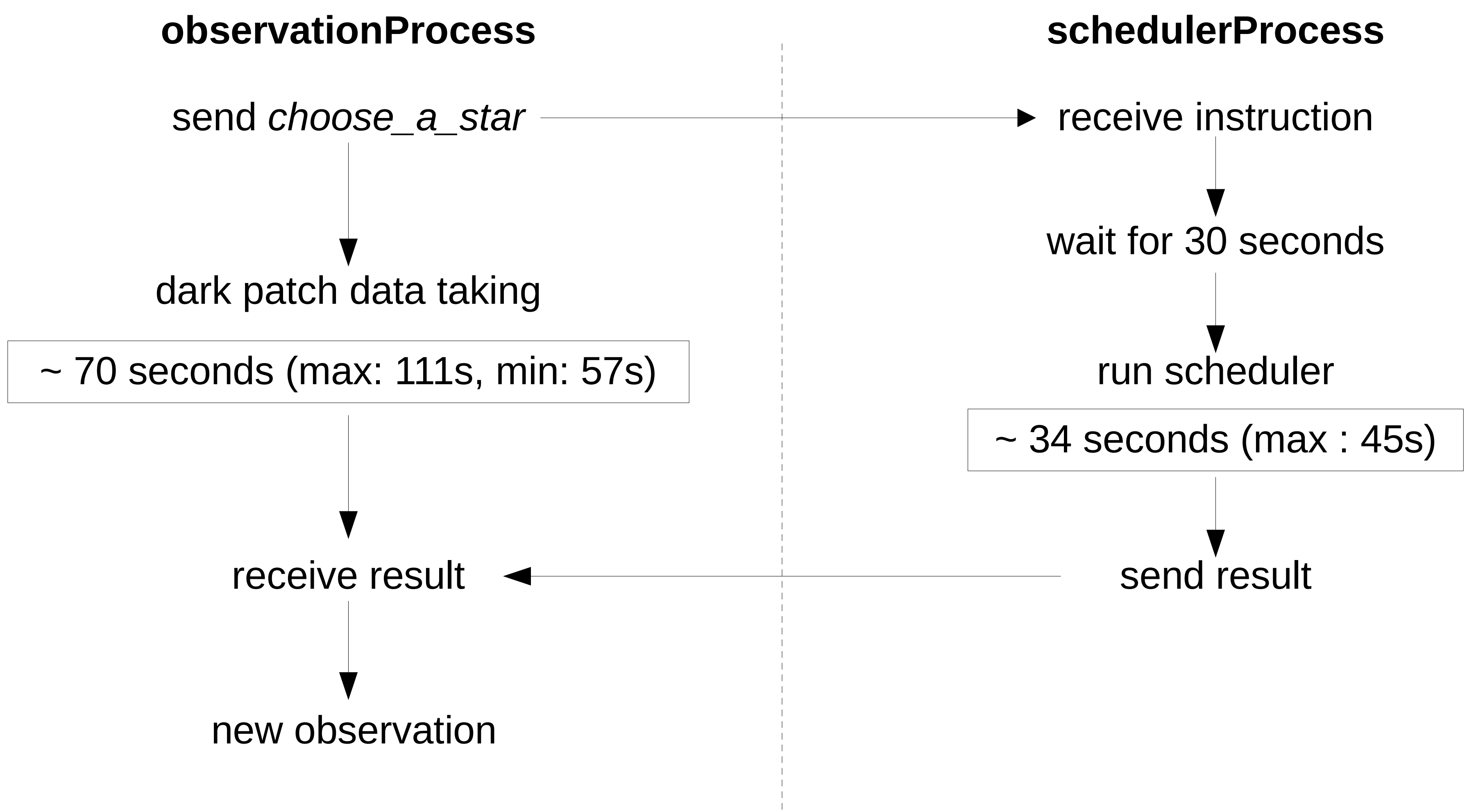
Spatial distribution of the Moon position (for correct and rejected observations), in the dish reference

Bending model data taking can be done in Moon condition

Back up - BM

Time optimization: scheduler process

→ 2 processes communicating via a pipe



Back up - BM

Time optimization: scheduler process

→ objective : recent full-sky view

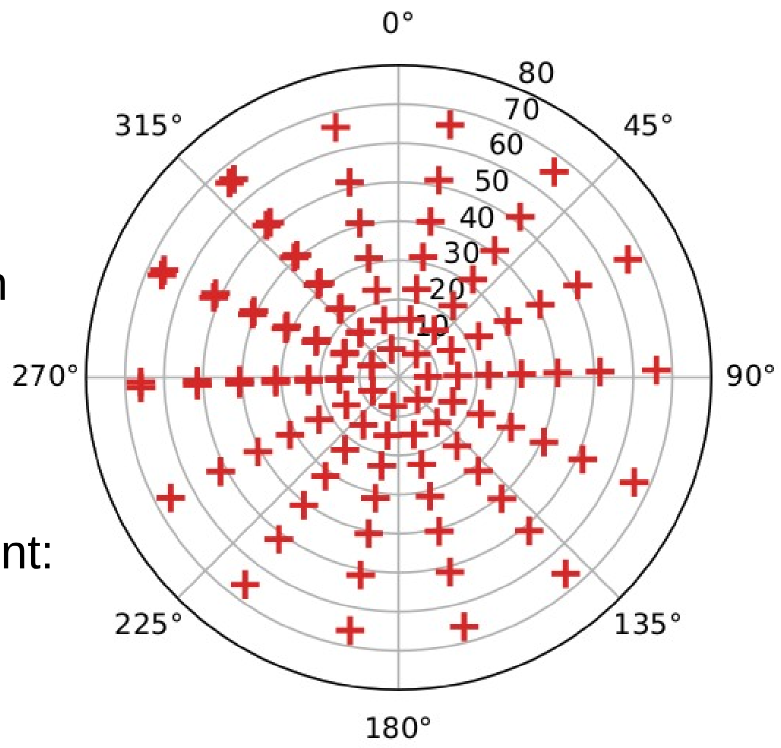
→ how does scheduler works ?

- associate each point with a priority (depending on the date of the last acquisition)

- determine if there is a valid star for each point

- select the star for each star region around the point:
  - → altitude in observable range
  - → distance with the Moon
  - → no other star that could be detected
  - → dark patch at 2°

- compute observation time for each star (depending on star magnitude and position)



Back up - Part II

GRB analysis

Time dependent Li&Ma: method

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

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

→ Only 1 free parameter: amplitude of the signal θ

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

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

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

Time dependent Li&Ma: method

→ Evaluating the likelihood:

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

→ Simplification of the likelihood:

$$\lim_{N\to+\infty} L=(\Delta t)^{N_{ON}} \prod_{t_i\in\{t_{ON}\}} (b+s(t_i))\,\frac{(b\,T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-b(T_{OFF}+T_{ON})-\int_0^{T_{ON}} dt\, s(t)}$$

→ With the identity:

$$\lim_{N\to+\infty} L=(\Delta t)^{N_{ON}} \prod_{t_i\in\{t_{ON}\}} (b+s(t_i))\,\frac{(b\,T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-(N_{OFF}+N_{ON})}$$

Time dependent Li&Ma: method

→ Evaluating the significance: $TS = -2\log\left(\frac{L_0}{L}\right)$ $\sigma = \sqrt{TS}$

with $$L_0 = \frac{e^{-\bar{b}_0 T_{ON}} (\bar{b}_0 T_{ON})^{N_{ON}}}{N_{ON}!} \frac{e^{-\bar{b}_0 T_{OFF}} (\bar{b}_0 T_{OFF})^{N_{OFF}}}{N_{OFF}!}$$

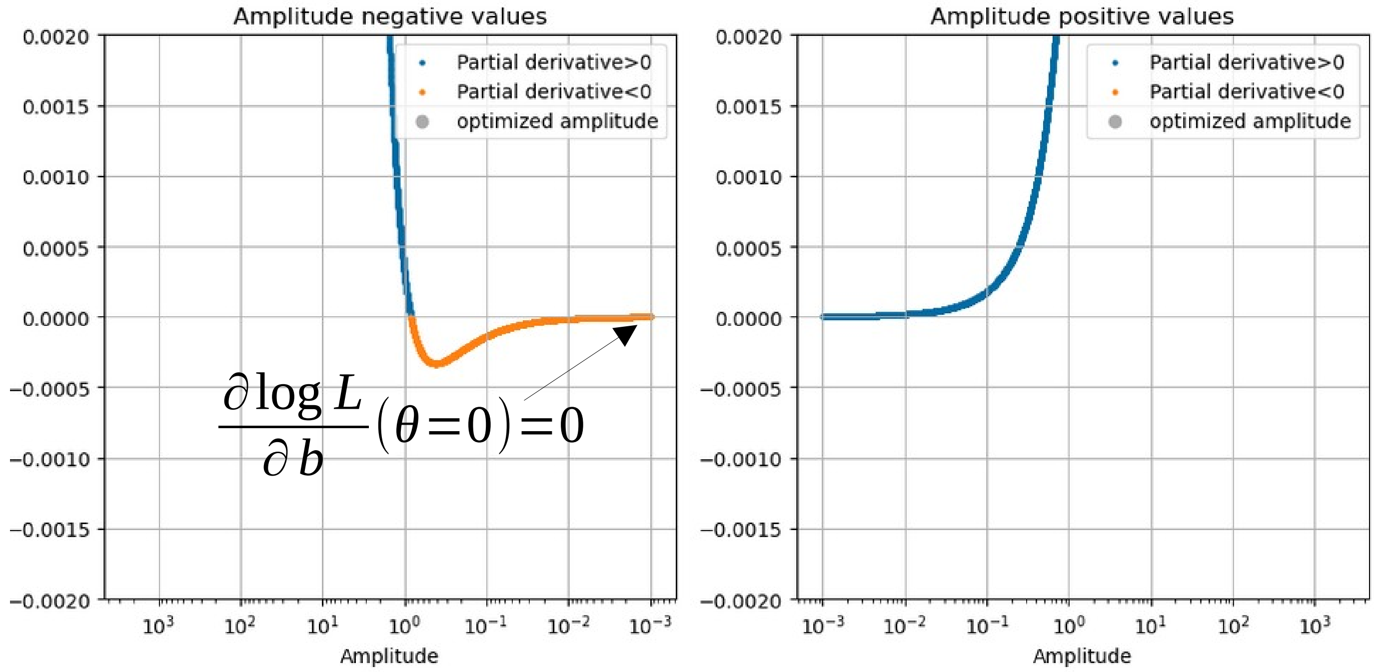
$$L = \left(\Delta t^{N_{ON}} \prod_{t_i \in \{t_{ON}\}} (b + s(t_i))\right) \frac{(b T_{OFF})^{N_{OFF}}}{N_{OFF}!} e^{-(N_{OFF} + N_{ON})}$$

and $$b_0 = \frac{N_{ON} + N_{OFF}}{T_{ON} + T_{OFF}} \qquad b = \frac{N_{ON} + N_{OFF} - \theta \int_0^{T_{ON}} dt\, f(t)}{T_{ON} + T_{OFF}} \qquad s(t) = \theta f(t) \qquad f(t) = t^{-1}$$

Time dependent Li&Ma: method

→ optimization issue

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

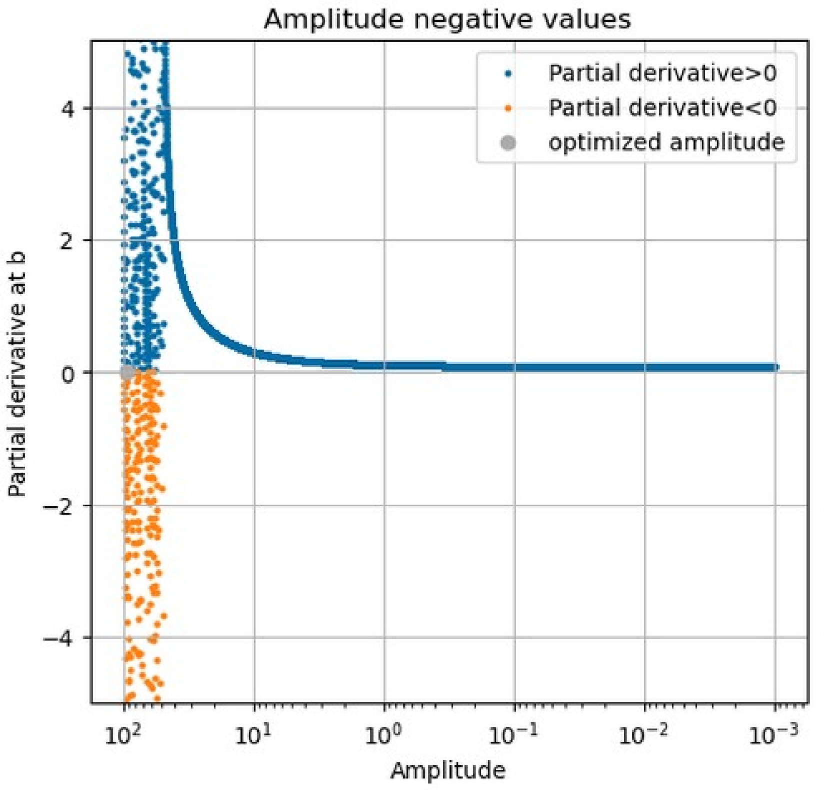


Plot of the partial derivative of the likelihood, depending on the amplitude of the signal

=> Need, in some cases, a negative amplitude

Time dependent Li&Ma: method

→ optimization issue



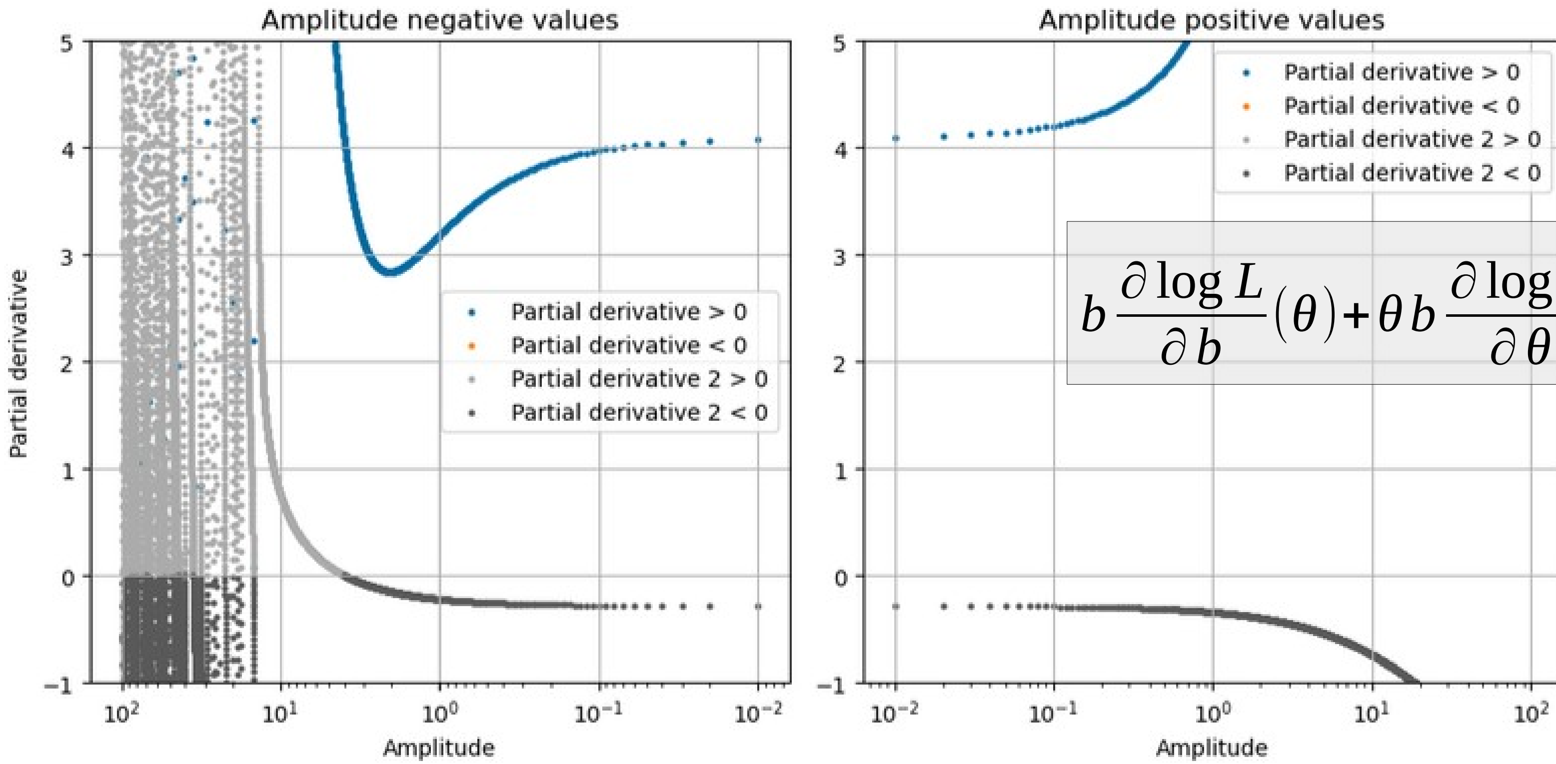
Plot of the partial derivative of the likelihood, depending on the amplitude of the signal, in the case of divergence with negative amplitude

In some cases, divergence for negative amplitude values

→ choose carefully the range

Time dependent Li&Ma: method

→ no root for ~0.7% of the analysis



$$b\,\frac{\partial \log L}{\partial b}(\theta)+\theta\, b\,\frac{\partial \log L}{\partial \theta}(\theta)\neq 0$$

Both partial derivative of log likelihood at b and θ, in the case where the identity is not respected

Spectral Temporal Fit: method (developed by Mathieu)

→ spectral temporal fit

- fit data with base model (no emission)
- fit data with spectral model
- fit data with temporal model
- fit data with complete model (spectral + temporal)
- evaluate significance of the complete model vs base model