Friedrich-Alexander-Universität
Erlangen-Nürnberg

How many hours do I need for my proposal?

A hands-on tutorial in planning observations

Alison Mitchell
DFG Emmy Noether group leader
ECAP, FAU Erlangen-Nürnberg

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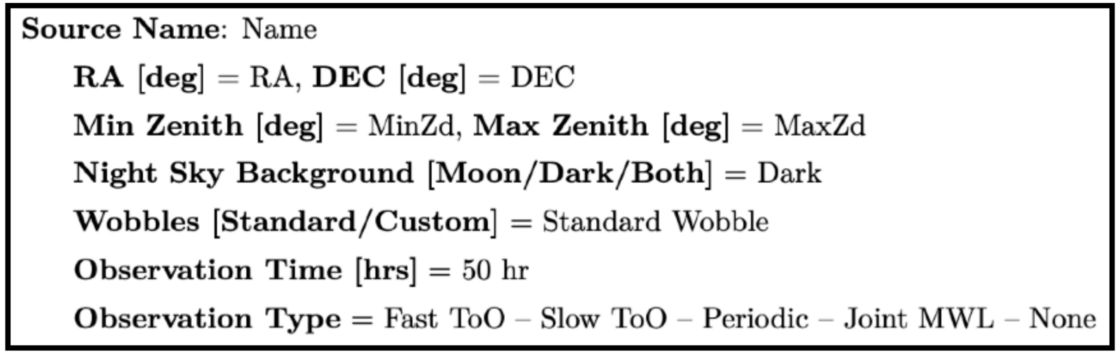
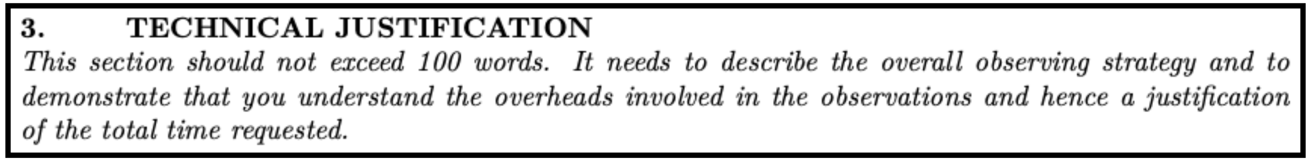
What aspects need to be considered?

- Observability — when is the target source observable?
- Visibility — under which conditions can or should the target be observed?
- Instrument performance —> how to estimate the required observing time
- Observing strategy —> determining the telescope pointing positions
- Putting it all together

We will focus on two sections of the proposal:



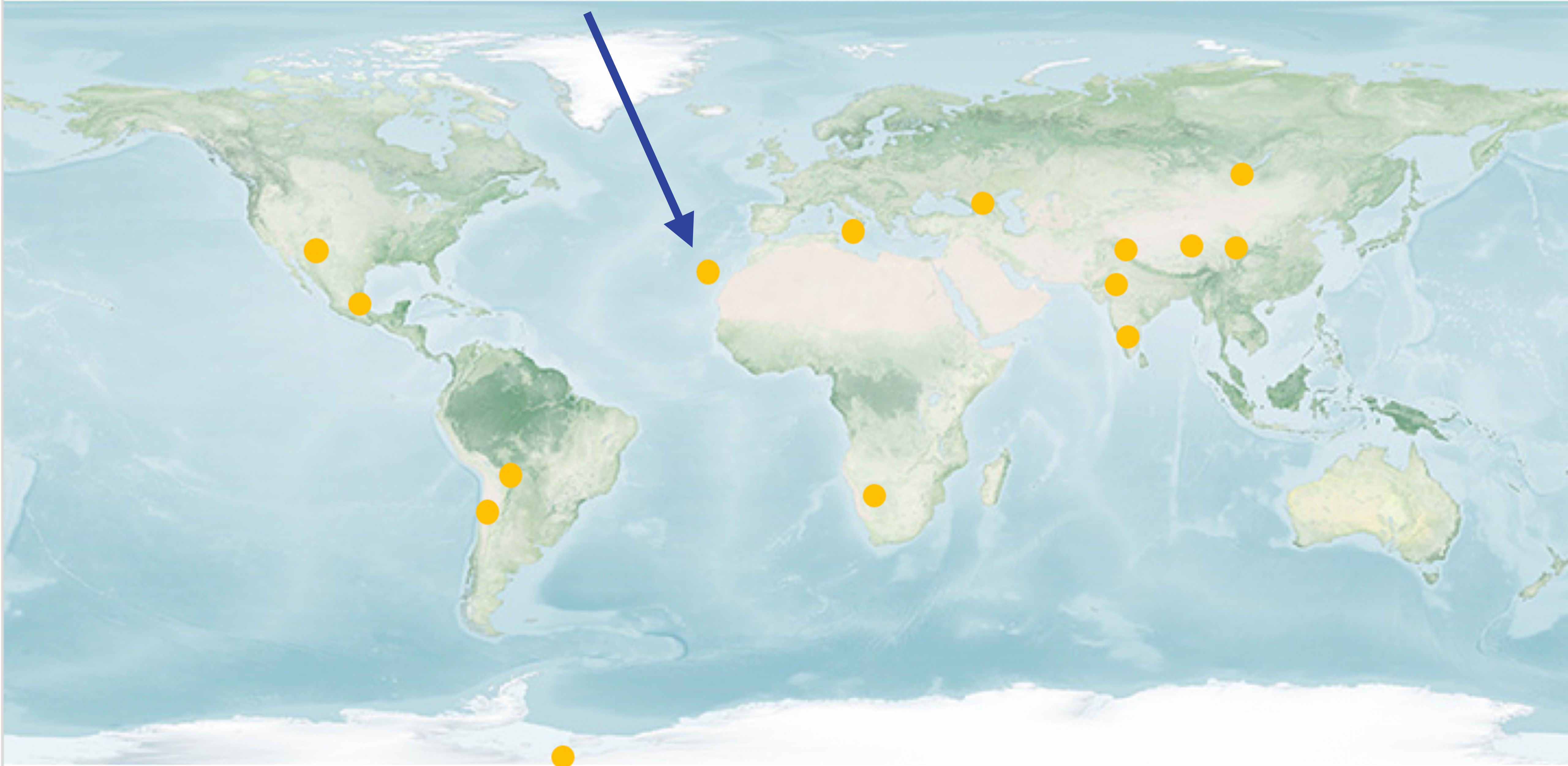
Source Name: Name
RA **[deg]** = RA, **DEC** **[deg]** = DEC
Min Zenith **[deg]** = MinZd, **Max Zenith** **[deg]** = MaxZd
Night Sky Background **[Moon/Dark/Both]** = Dark
Wobbles **[Standard/Custom]** = Standard Wobble
Observation Time **[hrs]** = 50 hr
Observation Type = Fast ToO – Slow ToO – Periodic – Joint MWL – None



3. TECHNICAL JUSTIFICATION
This section should not exceed 100 words. It needs to describe the overall observing strategy and to demonstrate that you understand the overheads involved in the observations and hence a justification of the total time requested.

LST-1 — Large Sized Telescope

CTA-North site, La Palma



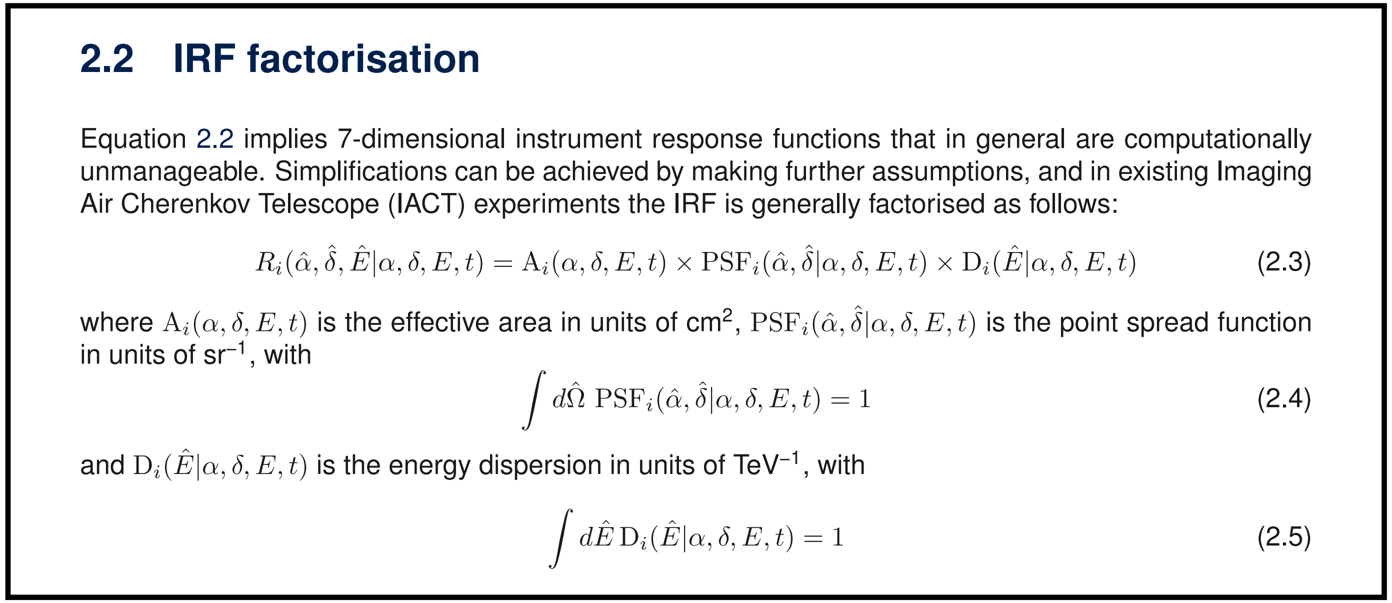
Onto the hands-on part…

For this session you will need:

- Gammapy version 1.2 or 1.0 https://docs.gammapy.org/1.2/index.html
- Material (notebooks & files) stored in the shared folder “Proposal_Hands-On_Material”
- CTA prod5 IRFs https://doi.org/10.5281/zenodo.5499840 (fits files for the LST sub-array)
- Your favourite source & an idea for a proposal

IRFs = Instrument Response Functions
—> describe how the reconstructed event distribution corresponds to the incoming true photon distribution

—> Response is (in general) a function of
direction, energy and time.



2.2 IRF factorisation

Equation 2.2 implies 7-dimensional instrument response functions that in general are computationally unmanageable. Simplifications can be achieved by making further assumptions, and in existing Imaging Air Cherenkov Telescope (IACT) experiments the IRF is generally factorised as follows:

$$R_i(\hat{\alpha},\hat{\delta},\hat{E}|\alpha,\delta,E,t) = \mathrm{A}_i(\alpha,\delta,E,t) \times \mathrm{PSF}_i(\hat{\alpha},\hat{\delta}|\alpha,\delta,E,t) \times \mathrm{D}_i(\hat{E}|\alpha,\delta,E,t) \tag{2.3}$$

where $\mathrm{A}_i(\alpha,\delta,E,t)$ is the effective area in units of cm^2, $\mathrm{PSF}_i(\hat{\alpha},\hat{\delta}|\alpha,\delta,E,t)$ is the point spread function in units of sr^{-1}, with

$$\int d\hat{\Omega}\ \mathrm{PSF}_i(\hat{\alpha},\hat{\delta}|\alpha,\delta,E,t) = 1 \tag{2.4}$$

and $\mathrm{D}_i(\hat{E}|\alpha,\delta,E,t)$ is the energy dispersion in units of TeV^{-1}, with

$$\int d\hat{E}\,\mathrm{D}_i(\hat{E}|\alpha,\delta,E,t) = 1 \tag{2.5}$$

Observability

Notebook 1 - visibility

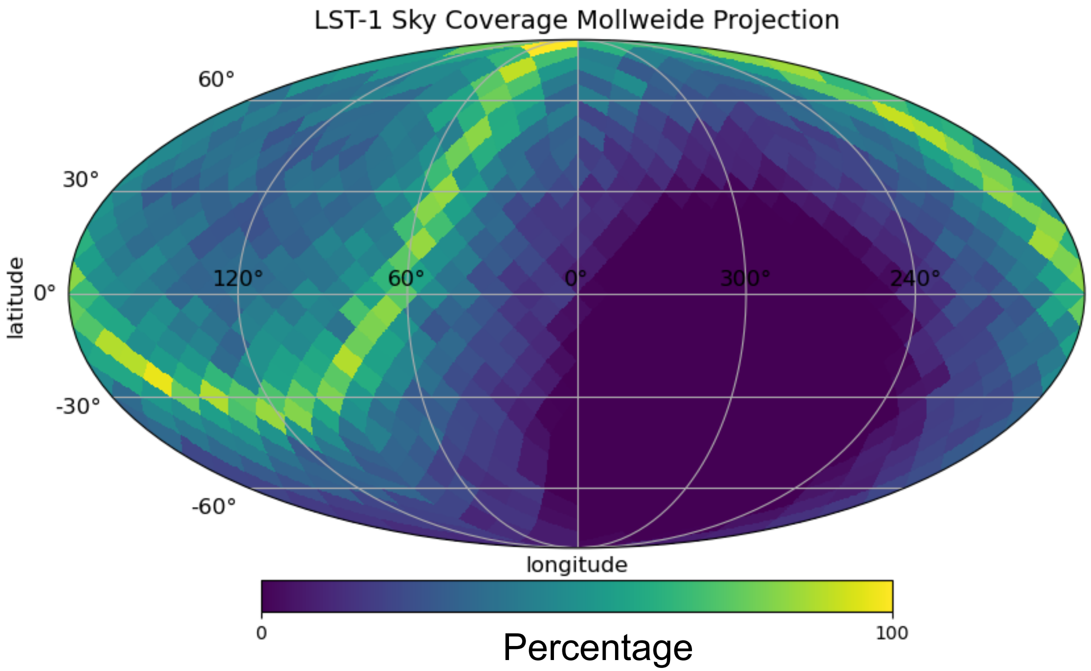
Not all of the sky is accessible to the LST-1

Different parts of the sky can be observed at different times during a year, or throughout

The first check for any target source is whether it can be observed at all by the telescope

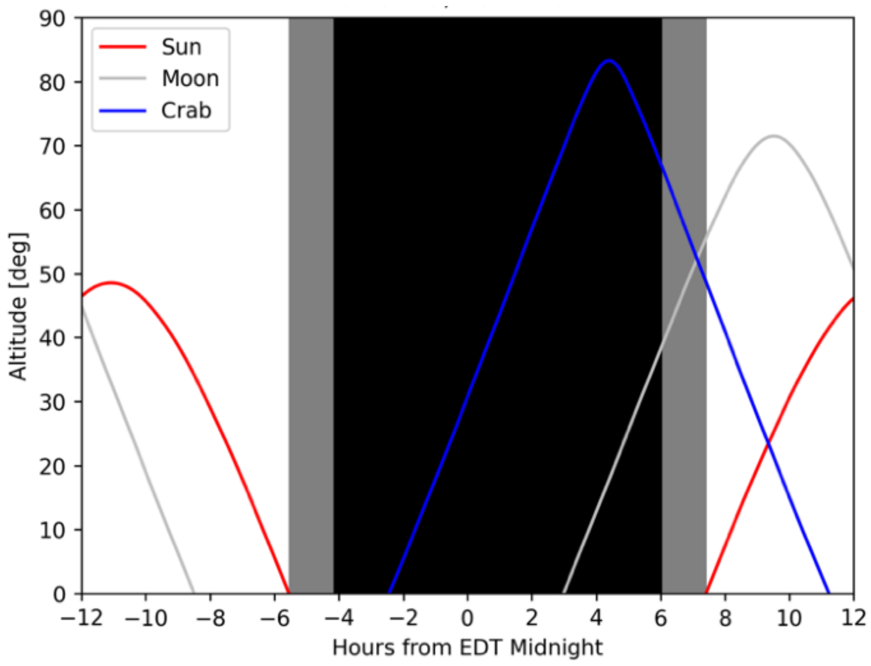
Sources are considered observable if the elevation exceeds 30°

We can check this by comparing the coordinates to this map, and see if the coverage is > 0.



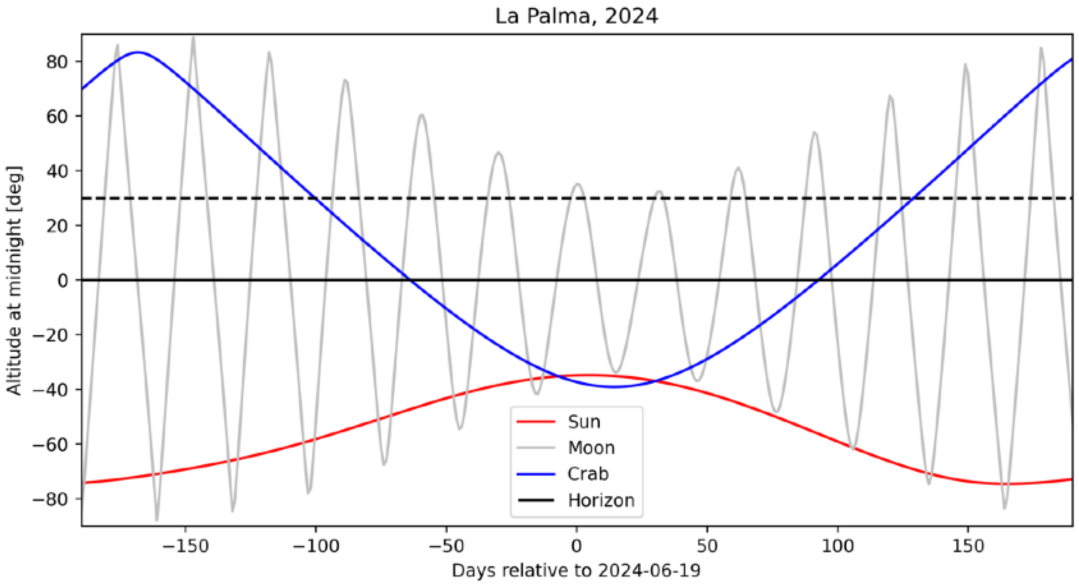
Visibility

Notebook 1 - visibility



Consider a single night:

- Altitude above horizon for objects of interest
- White = daylight, sun above horizon; grey = twilight, sun below horizon; dark = astronomical darkness, sun < -18°



Consider a year:

- Altitudes at midnight plotted
- Can identify moon cycles and seasons (sun elevation)
- Sky region observability depends on time of year

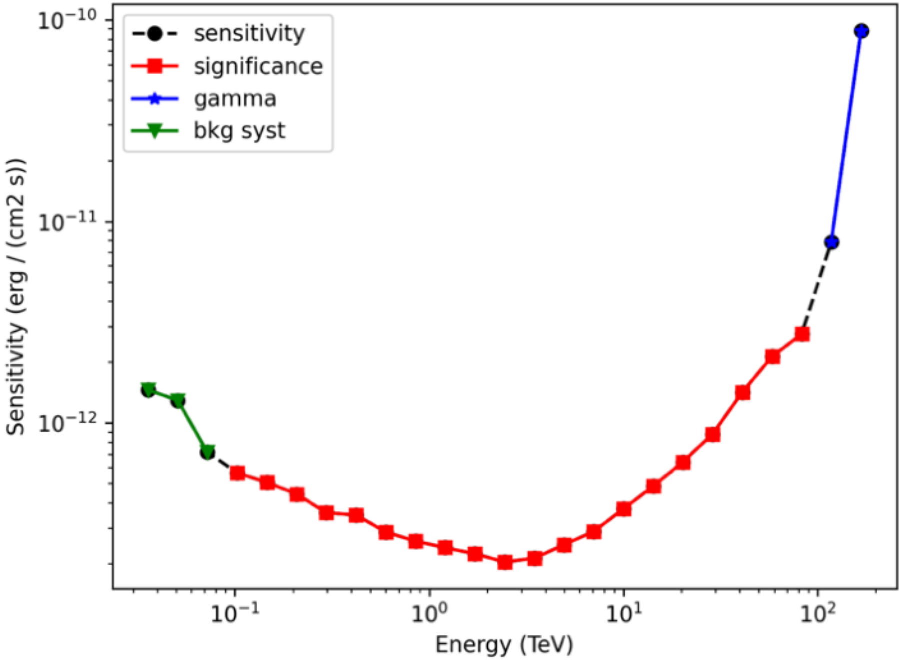
Sensitivity

Notebook 2 - time

CTA-N full array prod5 IRFs 50 hour

Criteria per energy bin include:
— a minimum of 10 gamma-ray events
— a minimum significance of 5 sigma
— a maximum background systematic of 10%

Which criterion dominates at which energy is indicated on the curve



Background systematics tend to dominate at lower energies

Gamma-ray counts tend to dominate at high energies

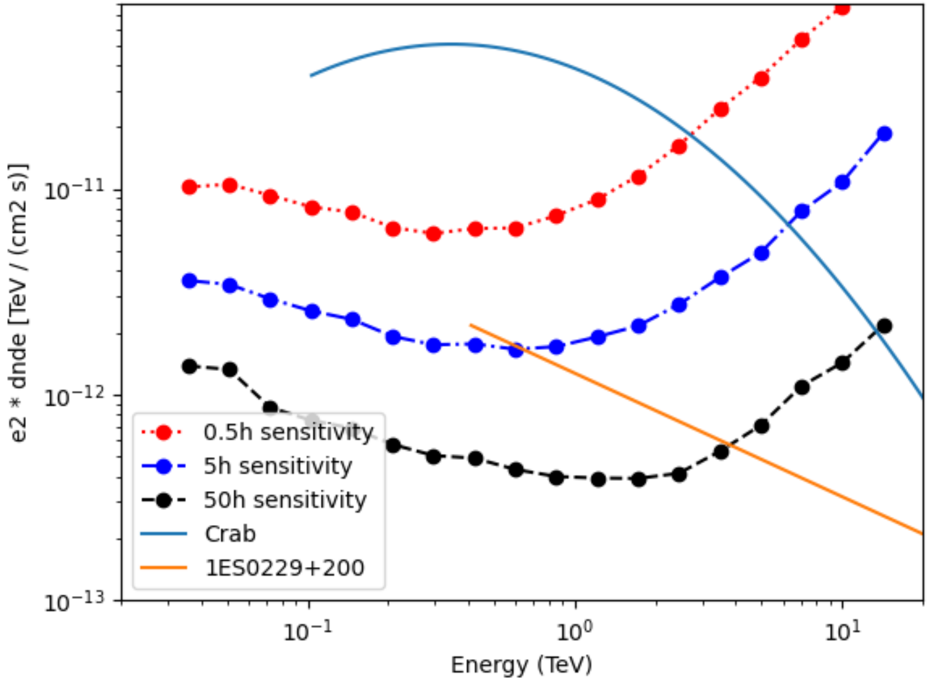
Sensitivity with time

Notebook 2 - time

Sensitivity improves over time, but not linearly.
Two approaches will be shown:

1) the *rough* approach guesstimating based on different sensitivity curves generated from Monte Carlo

2) using a python tool developed to do the full calculation



— interpolate between curves of different times at a given energy

— find where the **predicted source spectrum** intersects with the fitted function linking the sensitivity curves for different times

— This provides the time required for a 5 sigma detection of a point source.

Scaling arguments can be used to go further:
sensitivity improves with time as $\propto \sqrt{t}$
sensitivity degrades with increasing source size as $\propto \sqrt{\sigma_{\mathrm{psf}}^2 + \sigma_r^2}$

Calculate expected significance

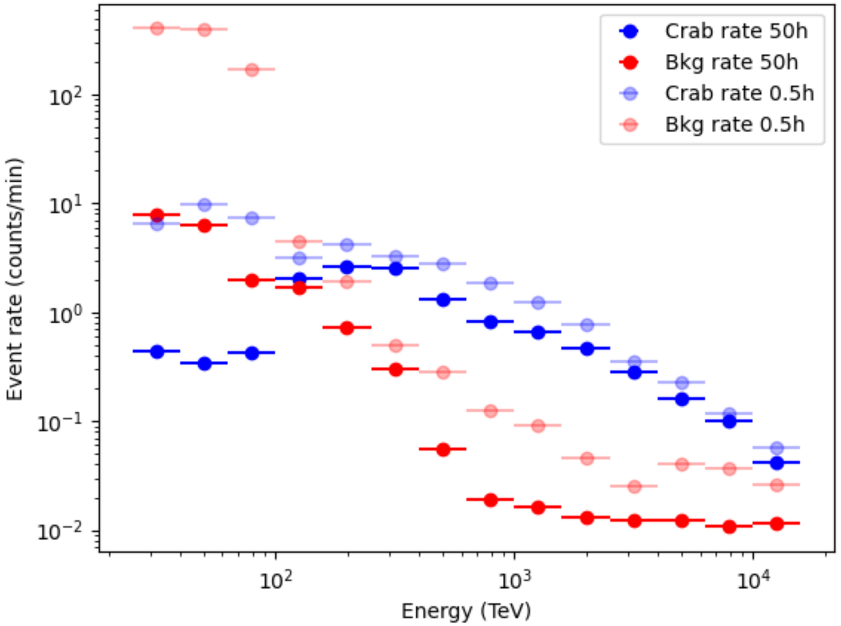
Colab notebook — Estimate_Time_tool

https://colab.research.google.com/drive/1VVDjOVhvrx78IgXWtgJq2y4Pc5EO6V0X?usp=sharing

Expected rate values provided based on selection cuts optimised for short (30 minutes) and long (50 hours) observations.

Again, need a **predicted source spectrum**.
Then calculate the expected significance per energy bin as follows:

1. Evaluate the expected source flux (integrate spectrum)
2. Expected off counts: $N^i_{\text{off}} = (R^i_{\text{bkg}} \times t_{\text{obs}}) \times \left(\dfrac{\sigma^2_{\text{psf}} + \sigma^2_{\text{ext}}}{\sigma^2_{\text{psf}}} \right)$
3. Expected excess counts: $N^i_{\text{excess}} = (R^i_{\text{Crab}} \times t_{\text{obs}}) \times \left(\dfrac{\phi^i_{\text{source}}}{\phi^i_{\text{Crab}}} \right)$
4. Expected on counts $N^i_{\text{on}} = N^i_{\text{excess}} + N^i_{\text{off}}$



See parameters in *config.yml*

Calculate expected significance

Colab notebook — Estimate_Time_tool

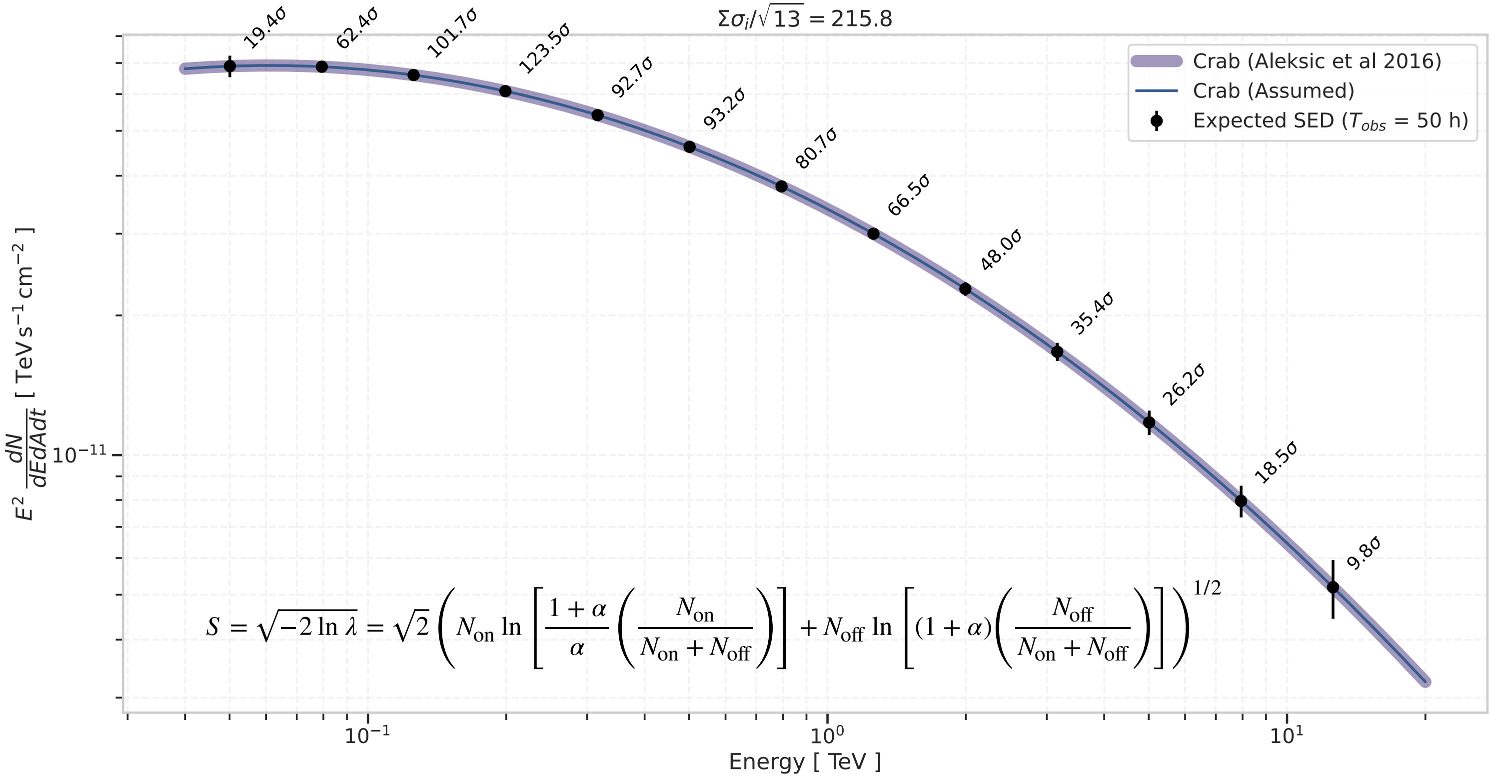
https://colab.research.google.com/drive/1VVDjOVhvrx78IgXWtgJq2y4Pc5EO6V0X?usp=sharing

5. Alpha parameter accounts for relative acceptance between ON and OFF regions. $\alpha = 1.0/n_{\text{off}}$ where n_{off} is the number of off regions = 3 as default.

6. The total N_{off} is therefore $N_{\text{off}} \times n_{\text{off}}$

6. Calculate the significance using the Li & Ma formula: Li & Ma, ApJ **272**, 317, (1983)

If the significance is above the threshold (default = 5 sigma) and the N^i_{excess} is above threshold (default = 10 counts) then the source can be detected in that energy bin i



$$S = \sqrt{-2\ln\lambda} = \sqrt{2}\left(N_{\text{on}}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right)\right] + N_{\text{off}}\ln\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]\right)^{1/2}$$

Remember! This is a **simulator** only.

A real data analysis will need to take e.g. alpha into account more carefully (depends on both position and energy)

Influence of zenith angle

Notebook 3 - zenith

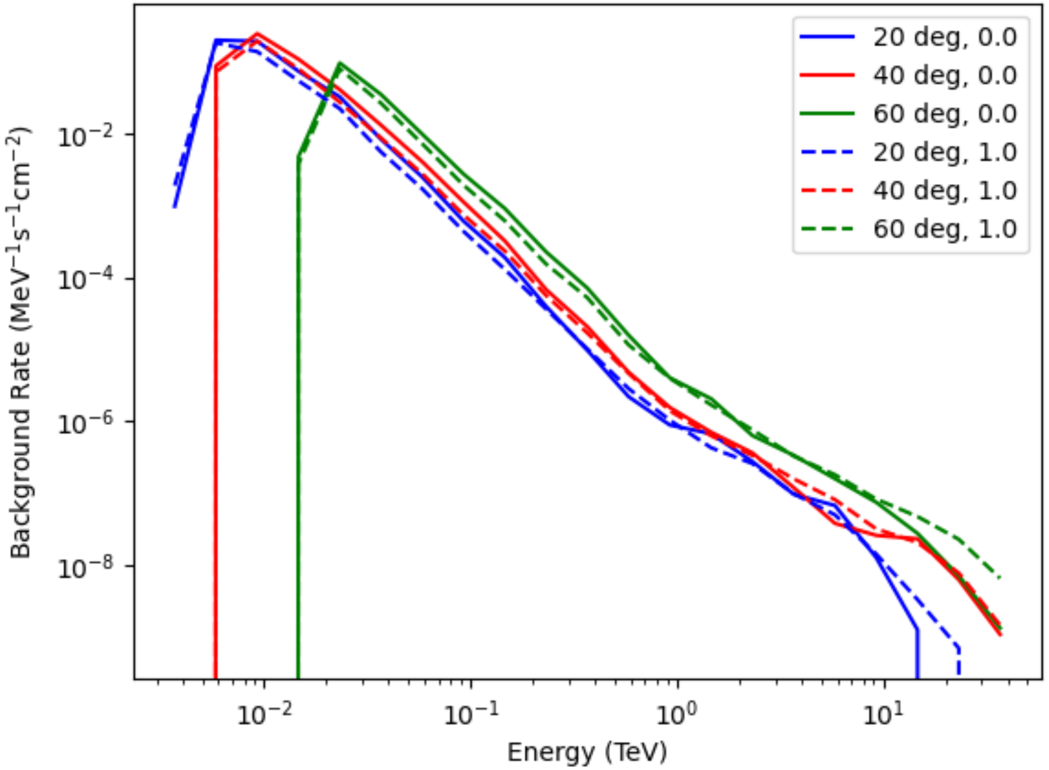
Not all sources can be observed at the same zenith angle.
(Try varying the zenith angle cuts in notebook 1)

With increasing zenith angle of observations (decreasing altitude / elevation) the air showers must pass through more atmosphere prior to reaching the telescope

Therefore, low energy events are more absorbed, and the energy threshold increases.

The overall rate of events at higher energies, however, also increases, as the effective area increases with zenith angle.

The offset angle starts to have an influence at ≥1°



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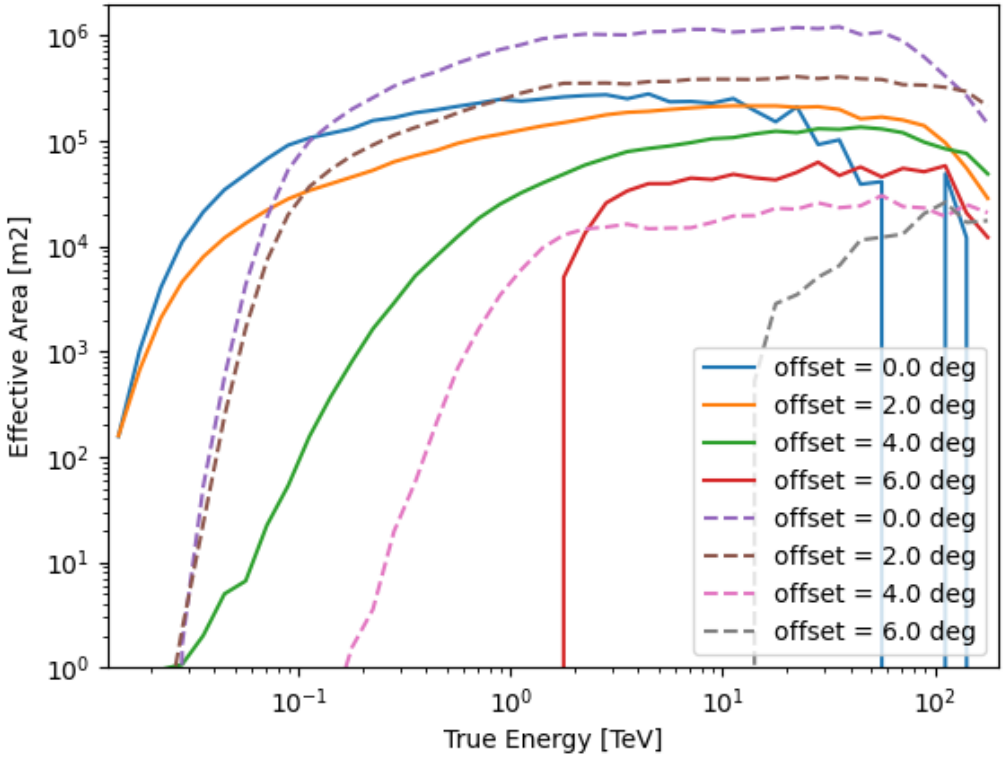


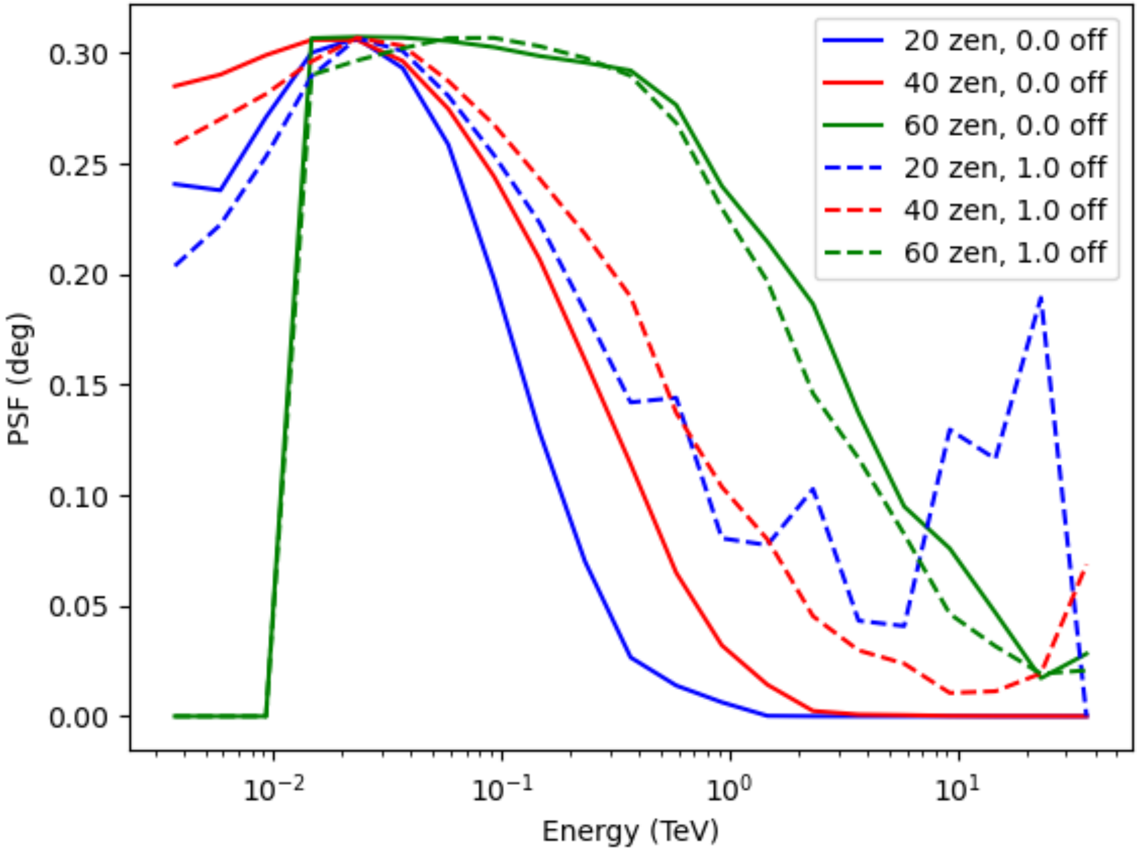
Influence of zenith angle

Notebook 3 - zenith

The point spread function (PSF) of the telescope also degrades with increasing zenith angle and with offset angle.

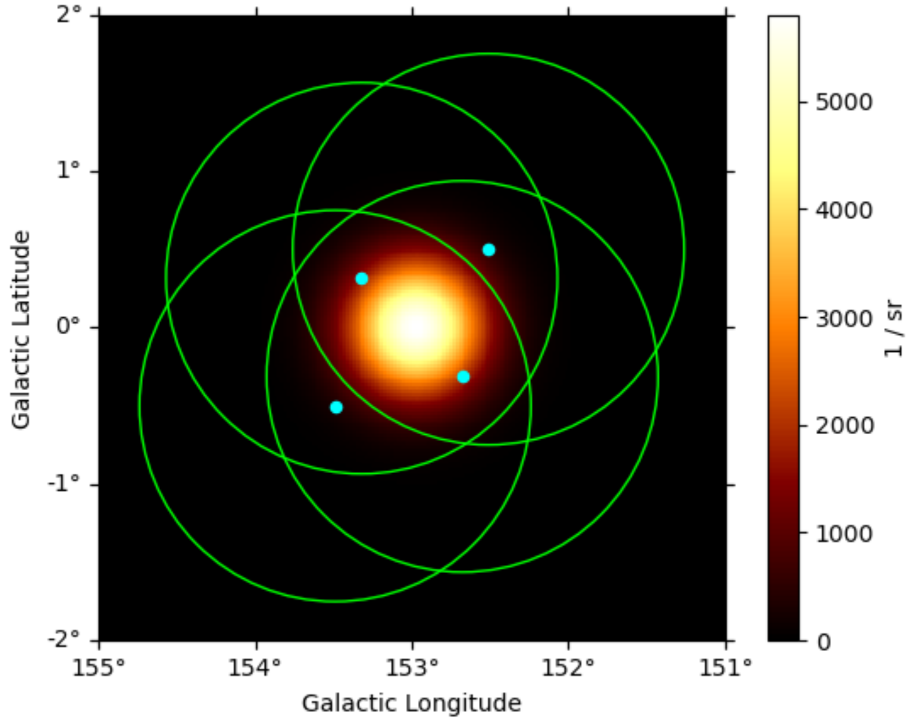
We can also compare the 68% containment (typically used as default) and the 95% containment.

Note that in general we assume a symmetric PSF, but it may be asymmetric.



Pointing Strategy

Notebook 4 - pointing



How should the observations be conducted?

Depends on the nature of the source being observed **and** the intended strategy for background estimation.

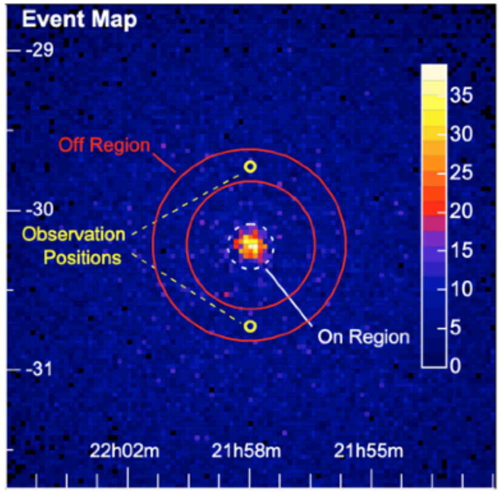
Most common case: point source or mildly extended source.

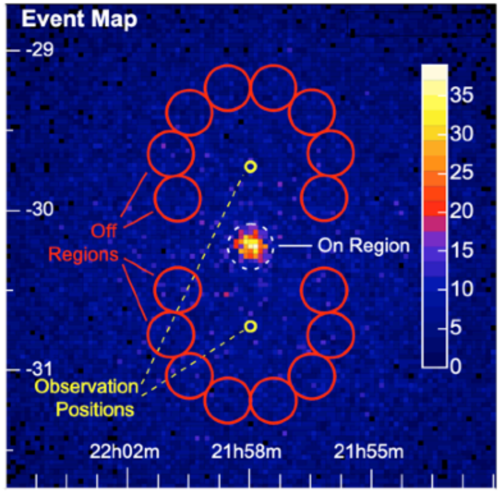
(Here we simulate a source in order to check the pointing positions.)

Most common strategy: “wobble” pointings.
The telescopes point alternately at ~four positions at equal offsets from the source, typically $\pm\theta$ in declination and $\pm\theta/\cos(\mathrm{dec})$ in Right Ascension.

The optimum value of θ depends on both the source *and* the field-of-view of the telescopes being used (and radial acceptance).
e.g. LST / MAGIC typically values ~0.4° whereas HESS uses ~0.7°

Wobble strategy is ideal for e.g. Ring and Reflected background methods



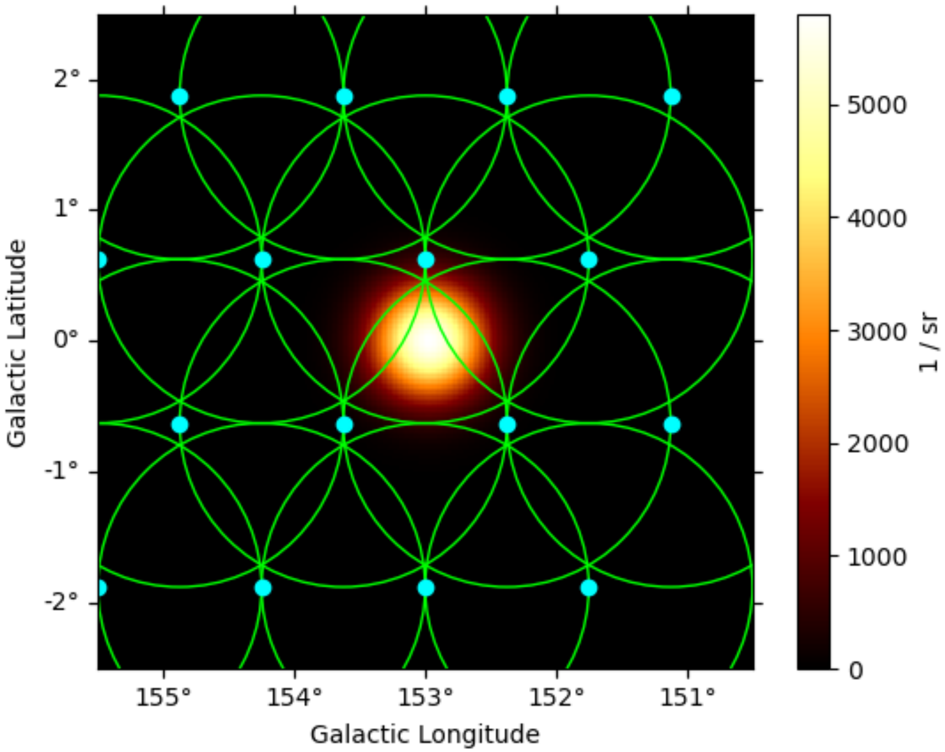


Pointing Strategy

Notebook 4 - pointing

If, however, we want to cover a larger region of the sky, a grid strategy might be more appropriate.

Here, the grid spacings should be chosen similarly to the wobble offsets: based (primarily) on the acceptance of the telescopes and their FoV.



Suitable background methods could be Field-of-View or template background approaches.

Another (less common) strategy is “drift-scan”: whereby the telescopes are at fixed elevation & azimuth with respect to the Earth and the sky drifts across the camera.

An “On-Off” strategy, e.g. where a source fills a field of view, would require dedicated observations of an ON region followed by dedicated observations of an OFF (empty) sky region taken under similar conditions (zenith angle etc.)

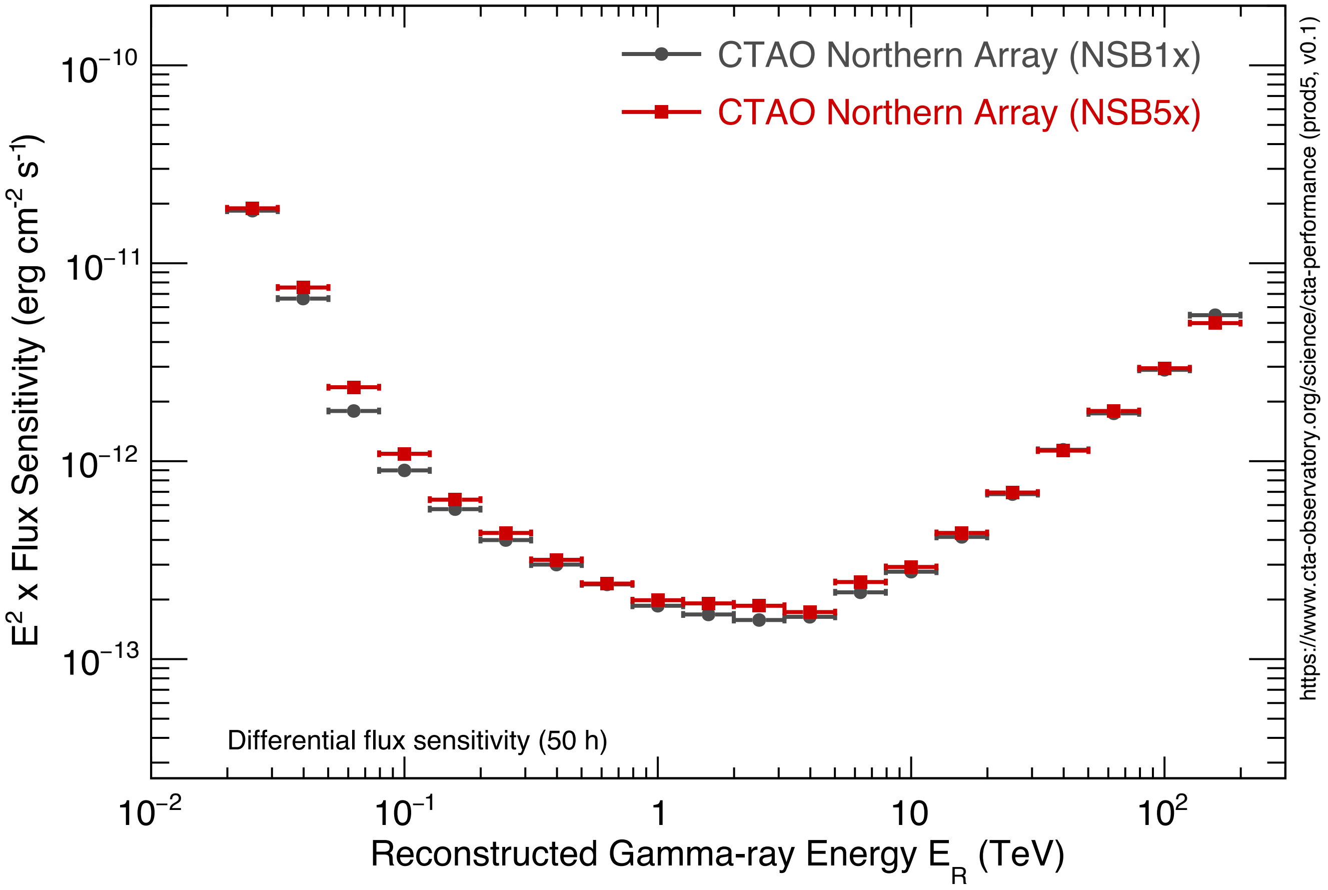
Influence of Night Sky Background

Sources of night sky background include bright stars, diffuse air glow and moonlight.

LSTs and MSTs are required by CTA to continue data taking under NSB up to 5x the nominal dark level.

SSTs are required to continue data taking under NSB conditions up to 30x the nominal dark level.

This increases the available observing time, at the cost of sensitivity.



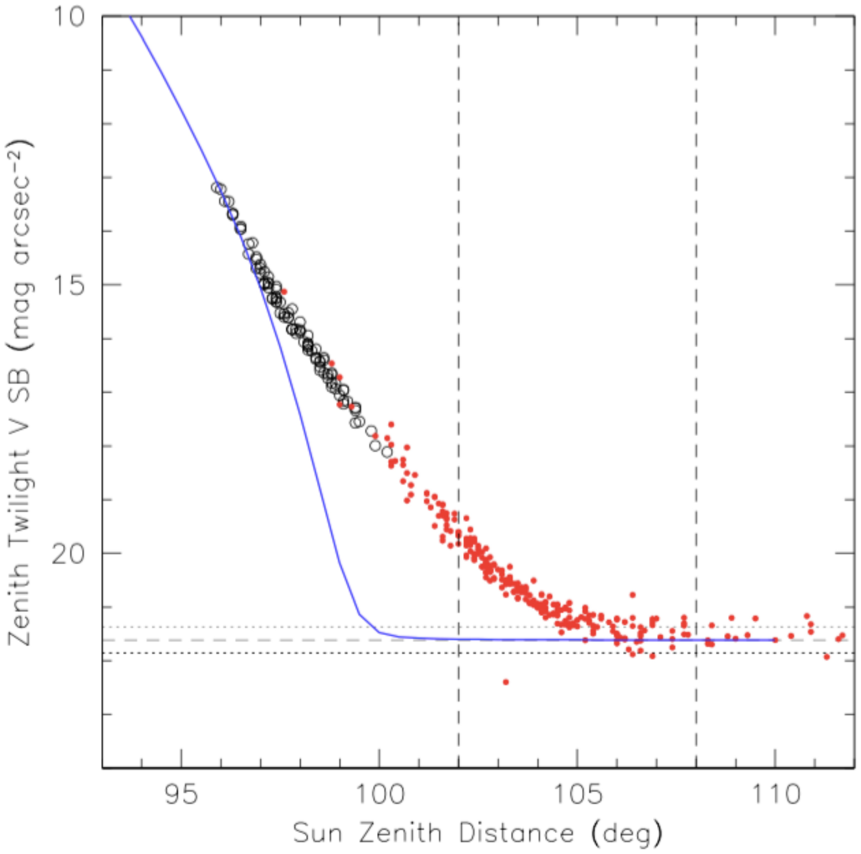
Night Sky Background

Motivation —> more challenging observing conditions, but much more observing time available.

Astronomical twilight: sun more than 18° below the horizon
Nautical twilight: sun more than 12° below the horizon
Civil twilight: sun more than 6° below the horizon

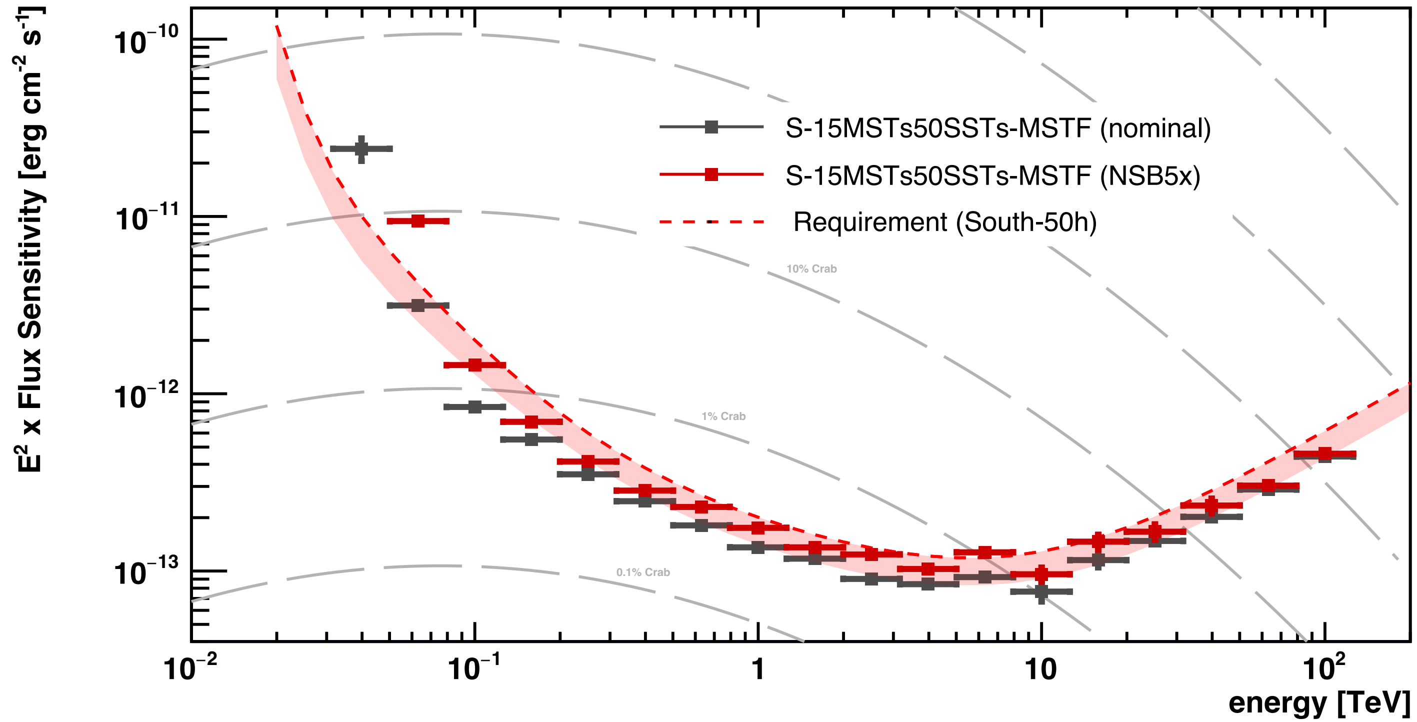
Days since new Moon	FLI	NSB (mag/arcsec^2)	Brightness Increase
0	0	22.05	-
10	0.781	18.71	21.68
14	0.997	17.06	99.08

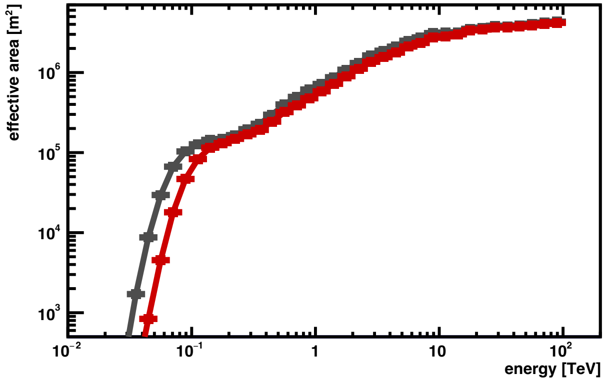
	Paranal		La Palma	
Dark Time	Extra hours	% increase	Extra hours	% increase
Standard (sun $< -18°$)	(1593)	0	(1564)	0
Sun $< -15°$	82	5.1	86	5.5
NSB $\times 5$ (Moon)	960	60.3	943	60.3
NSB $\times 30$ (Moon)	1679	105	1657	106

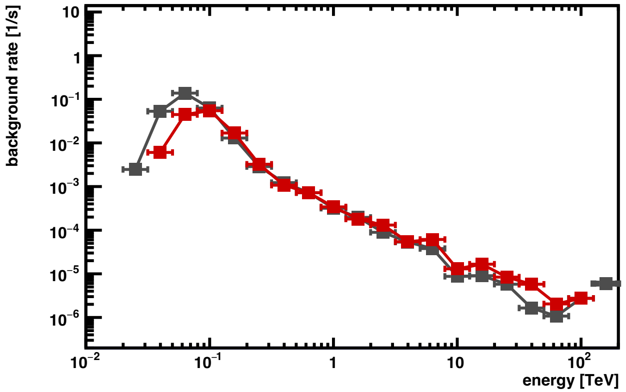


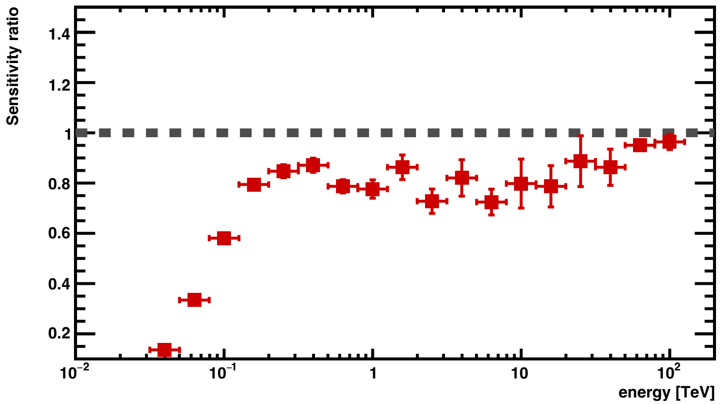
Influence of Night Sky Background

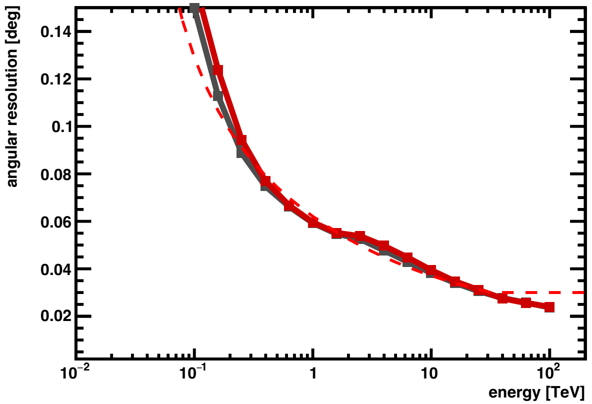
CTA-South (G. Maier)

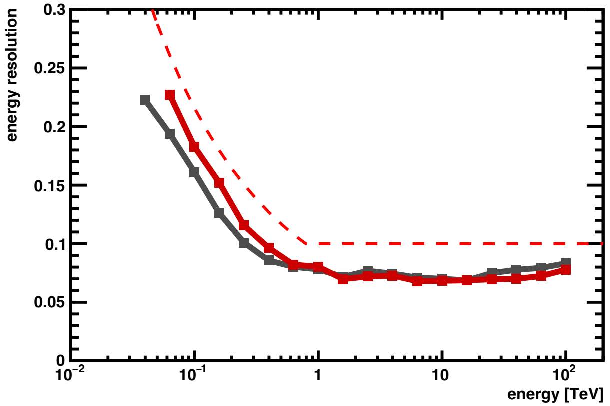












Major caveat: LST-1 vs 4xLST sub-array

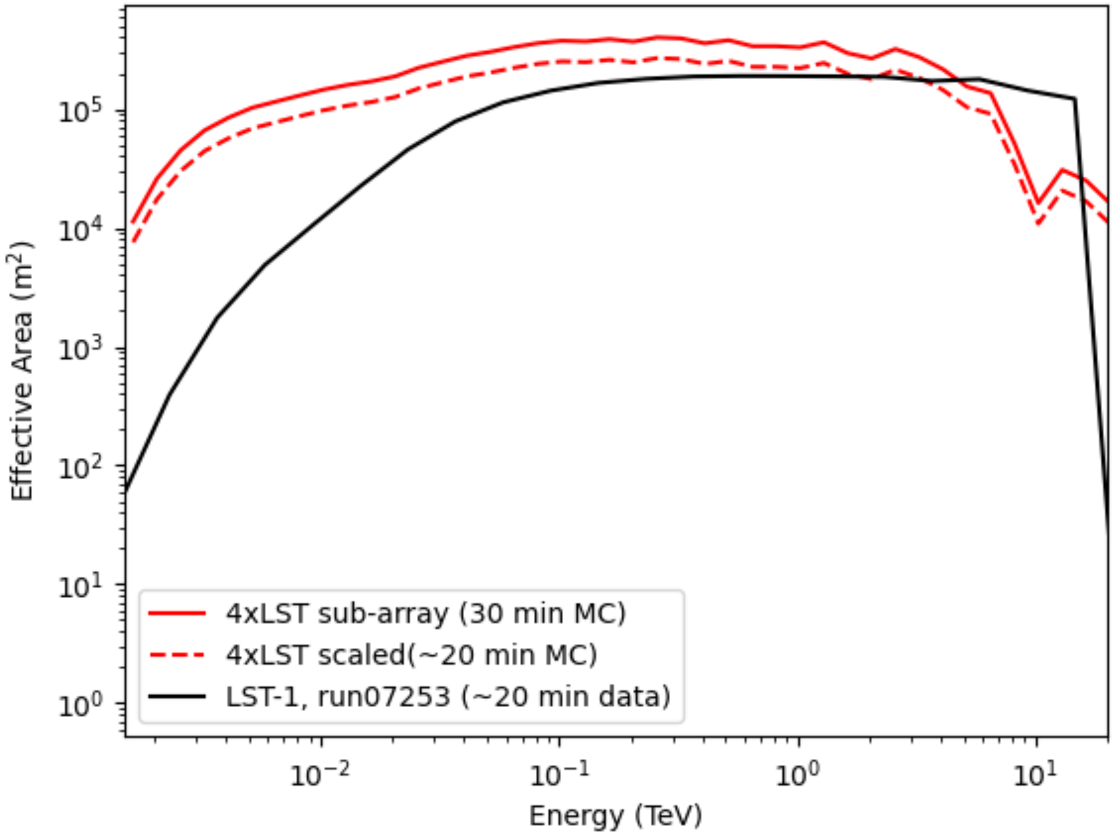
Notebook 5 — scale time

You should have already noticed a major issue:
the IRFs from MC are for a 4 telescope sub-array, but we want to estimate the observing time required by LST-1 as a single telescope. How to approximate this?

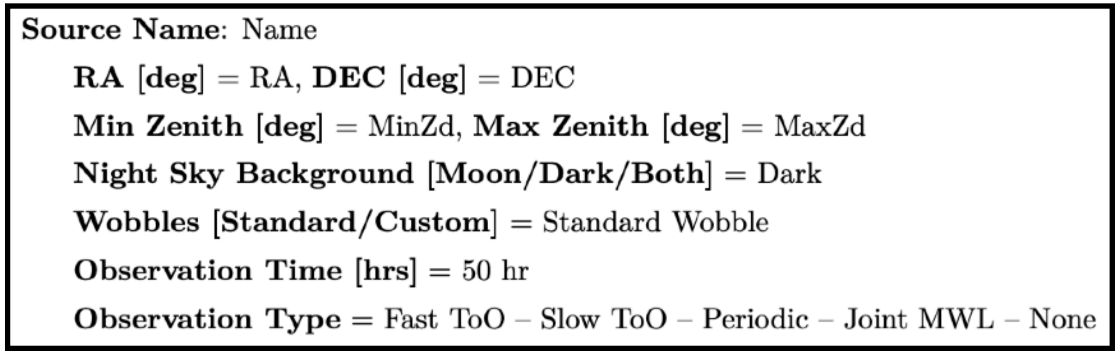
Two adjustments: scaling the effective area and accounting for changes in background rate. We will look at the first as a *minimum* increase to the required exposure.

In a nutshell: the units of flux normalisation are 1/(cm s), governed by the effective area and exposure.
Therefore, to reach an equivalent flux sensitivity, we must increase the exposure by a factor that at least compensates for the reduced effective area.

$$\phi_1 = \phi_4 \rightarrow A_1 t_1 = A_4 t_4 \text{ and hence } t_1 = \frac{A_4}{A_1} t_4$$



Putting it all together…



Source Name: Name

RA [deg] = RA, **DEC** [deg] = DEC

Min Zenith [deg] = MinZd, **Max Zenith** [deg] = MaxZd

Night Sky Background [Moon/Dark/Both] = Dark

Wobbles [Standard/Custom] = Standard Wobble

Observation Time [hrs] = 50 hr

Observation Type = Fast ToO – Slow ToO – Periodic – Joint MWL – None

- **Target Name**
- **Sky location:** Choose e.g. centre-of-gravity if not a point-source
- **Zenith angle range:** min = 5° likely always;
  max ≤ 70° depends on energy threshold & visibility
- **NSB:** dark only or both (only moon = only for technical reasons)
- **Wobbles:** standard for point sources = 0.4° for LST. Would recommend larger wobble for any extended source
- **Observation time:**
  In case of “wobble” pointing, this is the total as derived from the sensitivity calculations. In case of “grid” (scan) pointings, this is the time derived from the sensitivity calculations multiplied by the number of pointing positions.
- **Observation type:** Fast ToO = e.g. GRB / GW alert (recommend: wobble / scan);
  Slow ToO = less time critical; Periodic / Joint MWL = needs to be scheduled on a fixed timetable (i.e. regular monitoring or external constraints); “None” = standard

Note: data quality selection cuts may further restrict the usable exposure for analysis once observations have been taken. Consider an overhead of ~10-20%.

When to observe: ToOs (Target of Opportunity observations)

Examples

For Target of Opportunity observations, it is of paramount importance to clearly state the trigger criteria and expected duration of observations / strategy per ToO trigger.

e.g. GRB alert: automatically observe any GRB alert issued by the GCN (Gamma-ray Coordination Network) that is visible for > 30 minutes at zenith angles < 60° (and angle > 30° away from the moon) within 4 hours of the alert.

Motivation —> unlikely to have TeV emission at late times.

Revision of criteria through experience: TeV emission observed up to 3 days post alert!
—> Extend time after alert when observations are conducted.
—> Continue over multiple nights *if* there is a detection in the real-time analysis

<u>Other types of ToOs:</u>

AGN flares (use MWL data e.g. radio / X-ray)
Stellar novae (use MWL data e.g. optical magnitude / spectroscopy)
GW / neutrino follow-up (use multi-messenger data & catalogues / algorithms to optimise strategy)
etc.

General tips

- You know your science case best!
- Don’t propose data that won’t be useful (e.g. too high energy threshold / too low sensitivity)
- Proposal should be convincing enough for a review committee:
  that you understand the caveats and how to analyse the data
  well-motivated science case and the context of previous observations taken into account
- Common sense: don’t propose targets that are not visible from CTA-N!!
- In general, will need an approximate spectrum / flux level to estimate the required time.
  —> Use previous gamma-ray data if available
  —> Use MWL data (e.g. Fermi-LAT?) and extrapolate under reasonable models
  —> Use comparable sources to estimate a reasonable range of fluxes
- Pointing strategy: wobble for point-sources
  —> wobble should always be larger than the source size for extended sources
  —> double-check the positions; avoid pointing directly at a source, e.g. in crowded regions such as the galactic plane.
  (Remember, there could be a neighbouring source!)

alison.mw.mitchell@fau.de