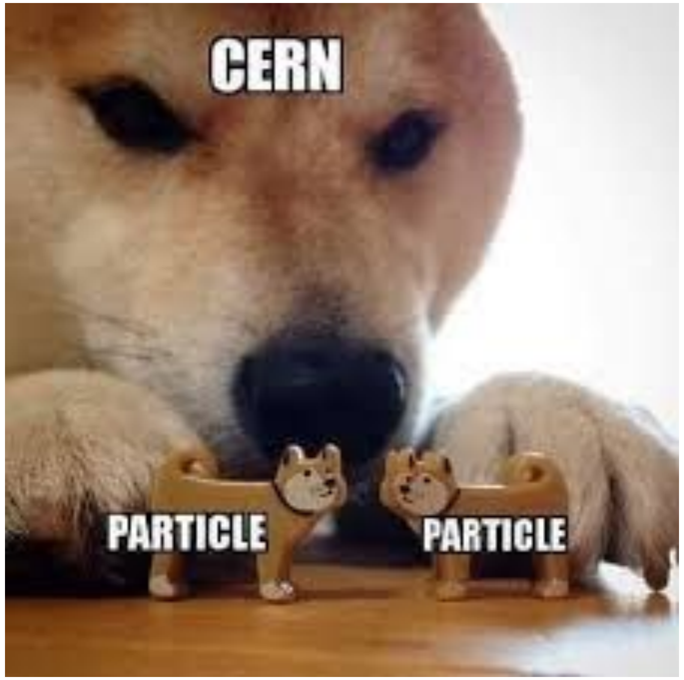
Transient gamma-ray sky with the future Cherenkov Telescope Array and validation tests with the NectarCAM camera

Anastasiia Mikhno, 2nd year PhD
LPNHE, IJCLab (Paris, France)

Supervisors:
Jenan-Philippe Lenain, Jonathan Biteau

We are not the same...

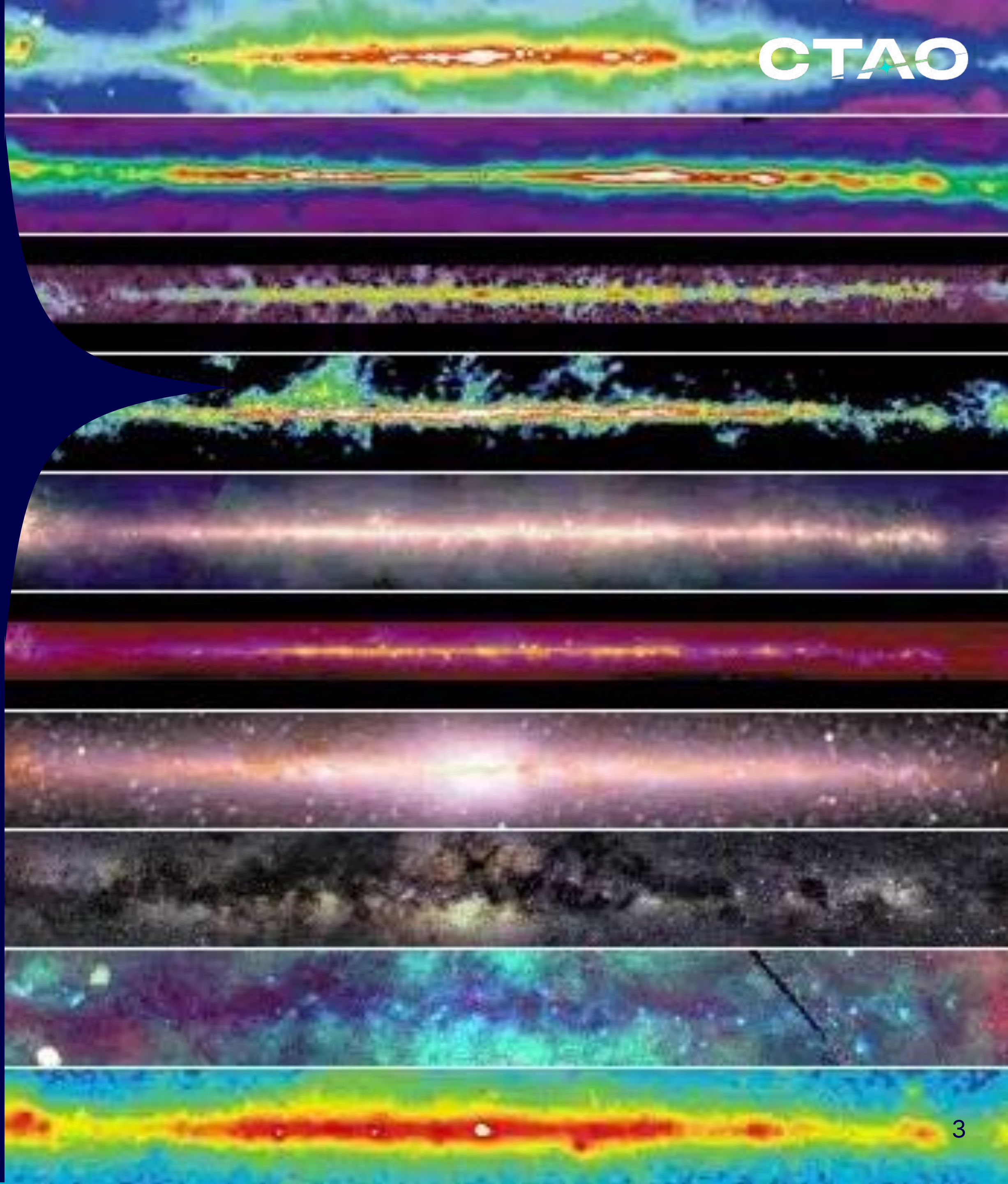
Particle physics



Astroparticle physics

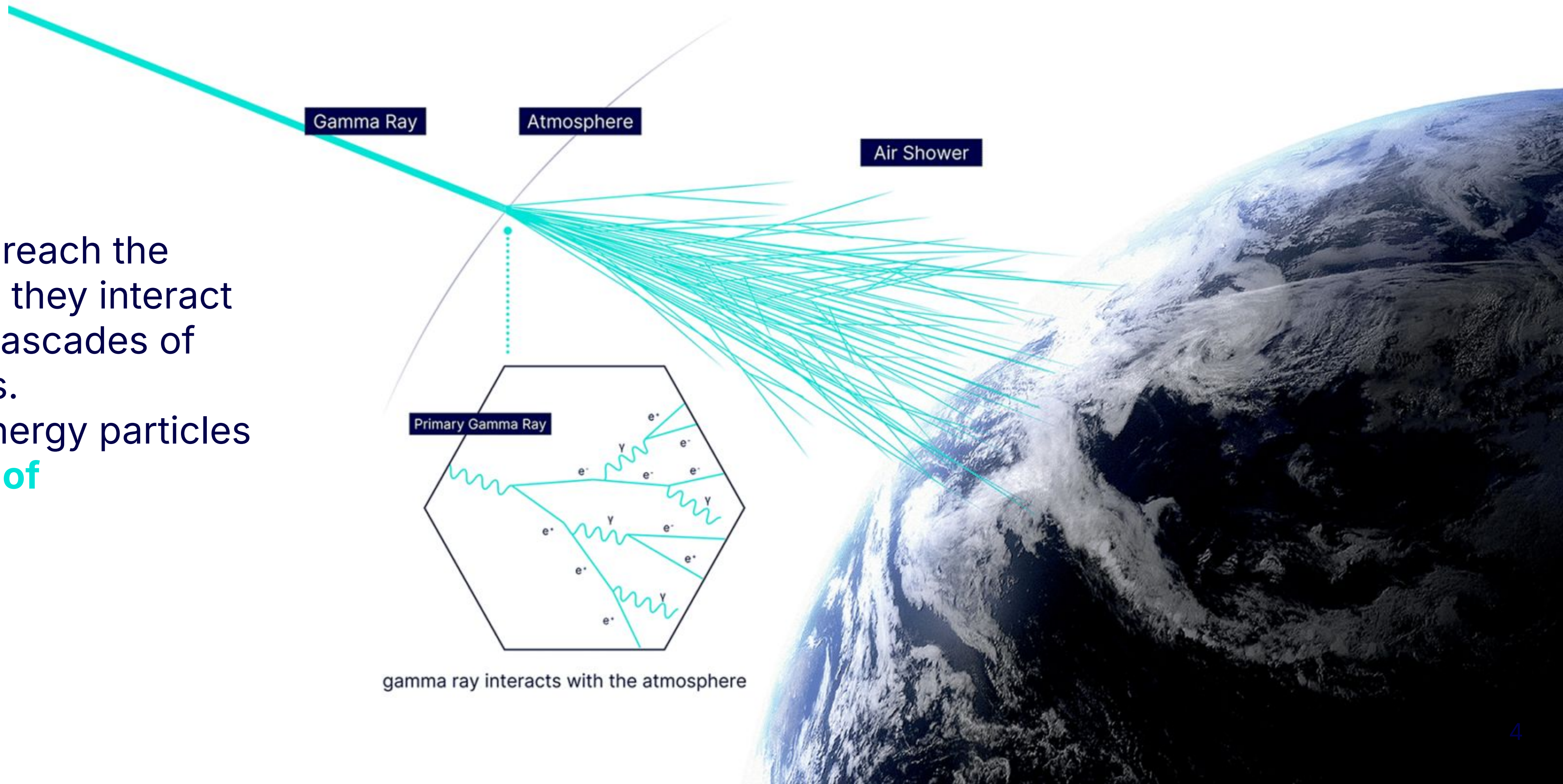
Oh boy, we look!

This image shows the Milky Way in different wavelengths, from radio waves at the top, to gamma rays at the bottom.

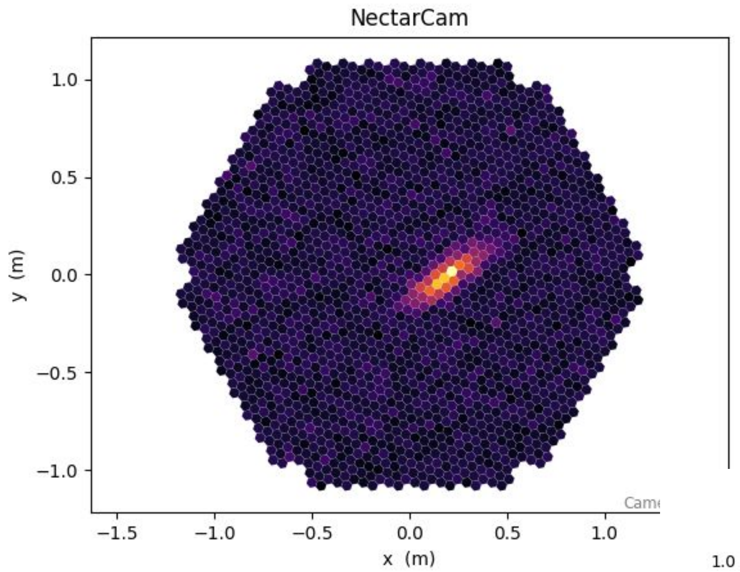


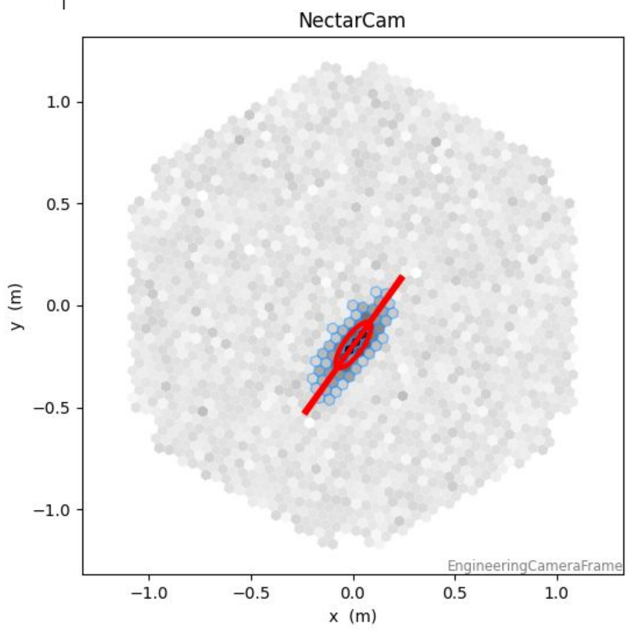
The Cherenkov Effect

When gamma rays reach the Earth’s atmosphere they interact with it, producing cascades of subatomic particles.
These ultra-high energy particles create **a blue flash of “Cherenkov light”**



Catching the Light



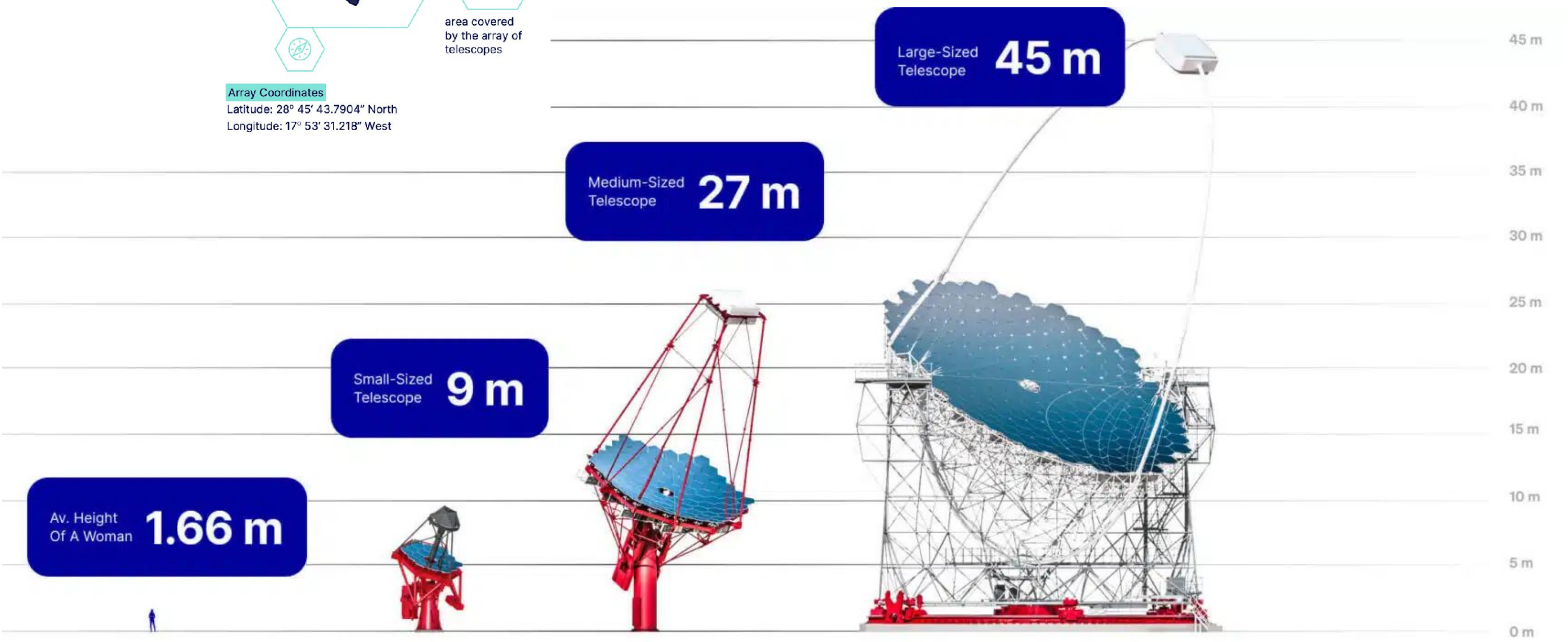


When the Cherenkov light reaches the CTAO's telescopes, the mirrors reflect the light so the cameras can record the event, capturing a billion frames per second.

Watch the film to learn more.

The array and the site

These cascades are so rare that the CTAO will be using **more than 60 telescopes spread between two array sites** in the northern and southern hemispheres to improve billion frames per second.

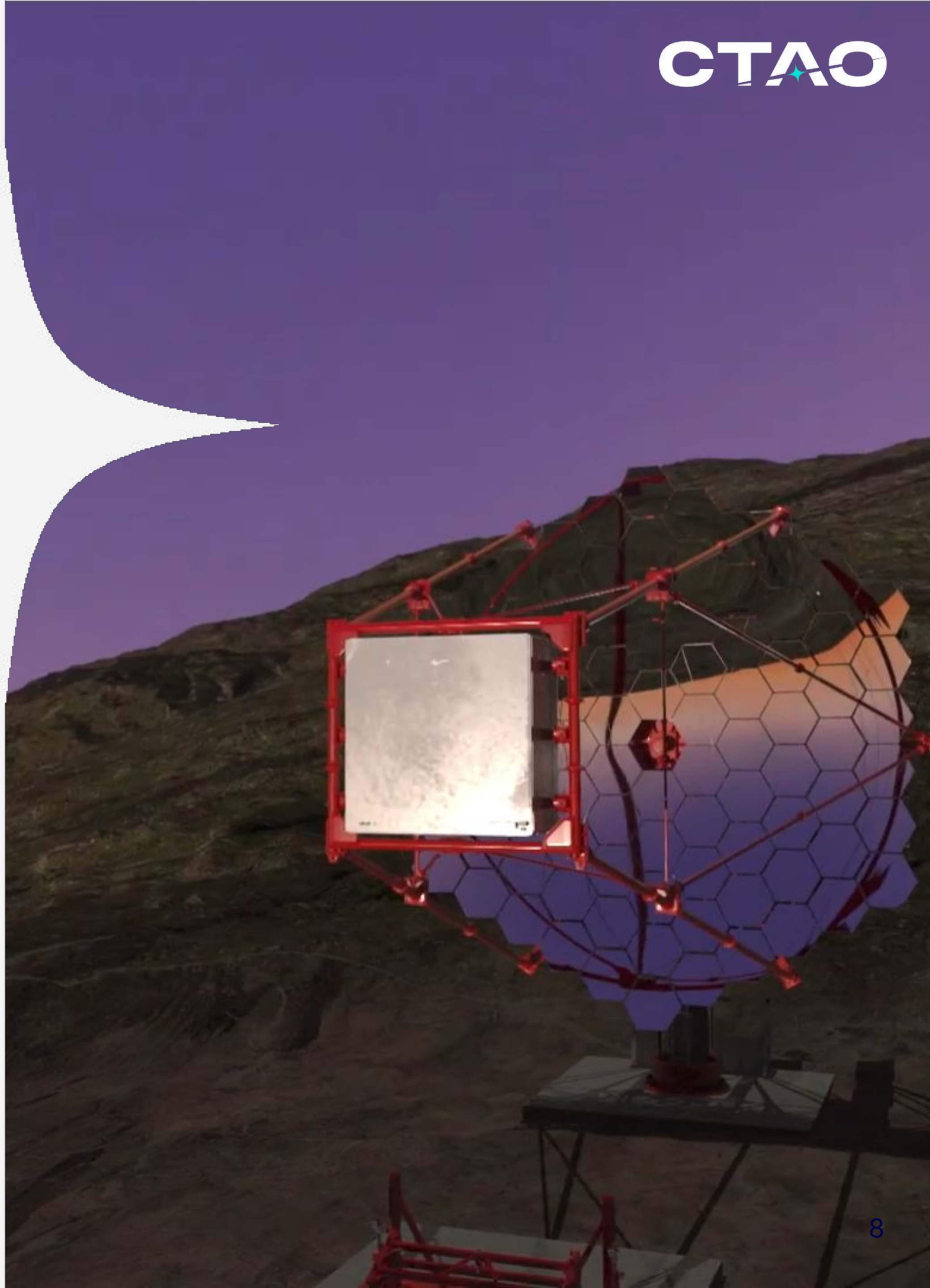


2 Aspects:

- Validation tests of NectarCAM
- Simulation and analysis of response to AGNs

Medium-Sized Telescope (MST)

- Optimized energy range: 150 GeV - 5 TeV
- Location: CTAO-North and CTAO-South



NectarCAM calibration

Will equip medium-sized telescopes MST.

Flat-Field calibration:

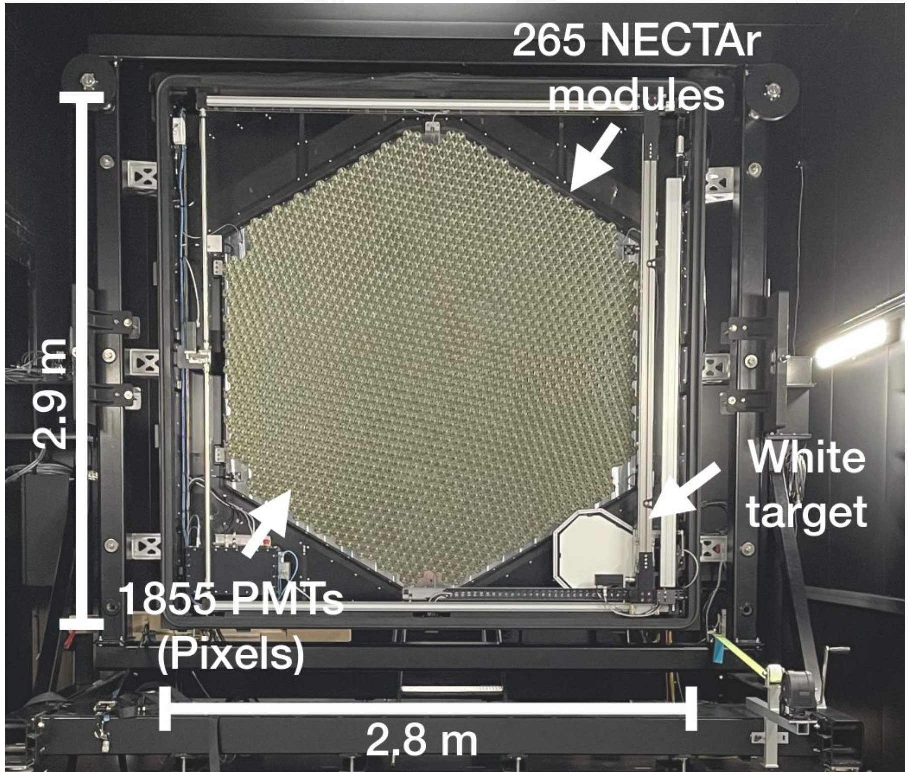
Is required for mitigating differences in light-collection efficiency of all the pixels of the camera.

Goal:

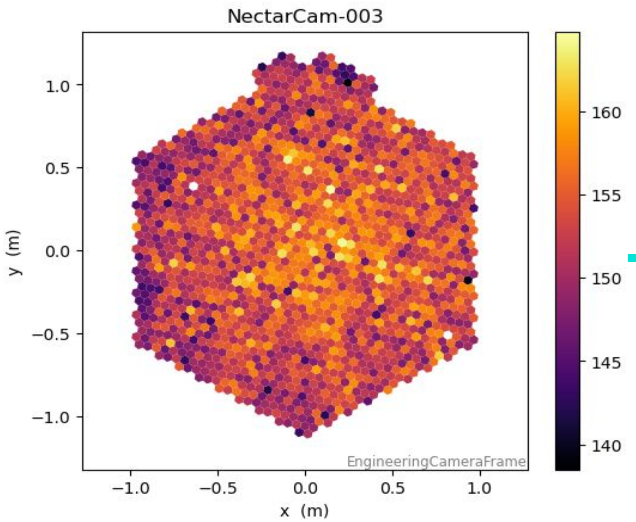
Improve flat-field calibration by taking into account **Flasher's light-front shape → 2D Gaussian**

to have control of **2% over the light front** → the **uncertainty on the model** should be **2%**

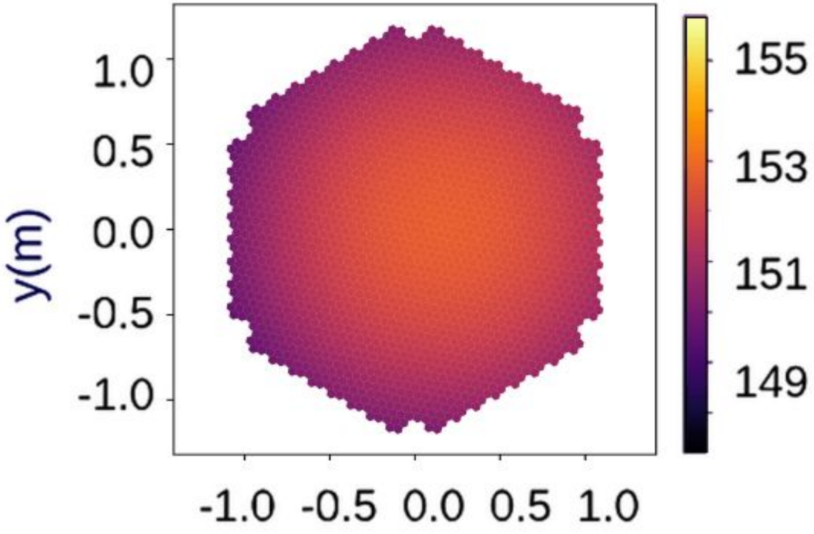
CEA camera setup



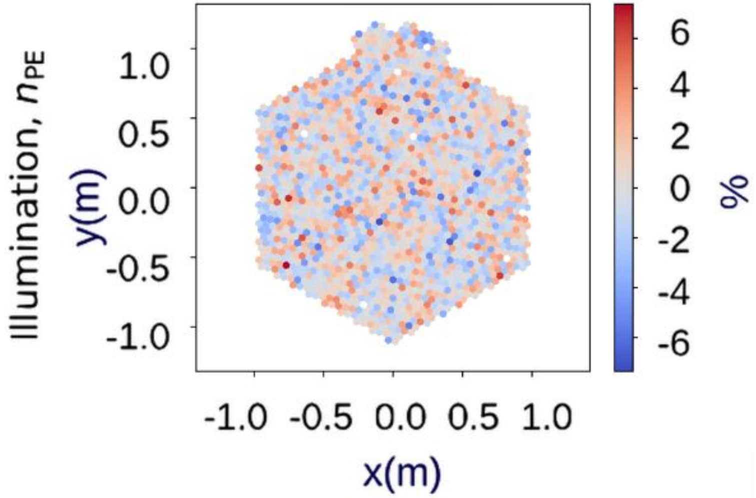
NectarCAM calibration



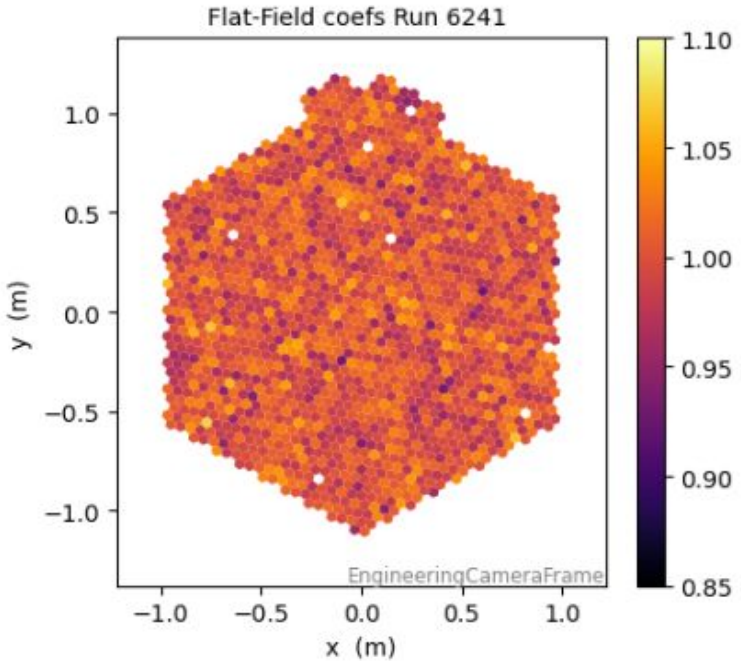
Data



Fit



Residuals

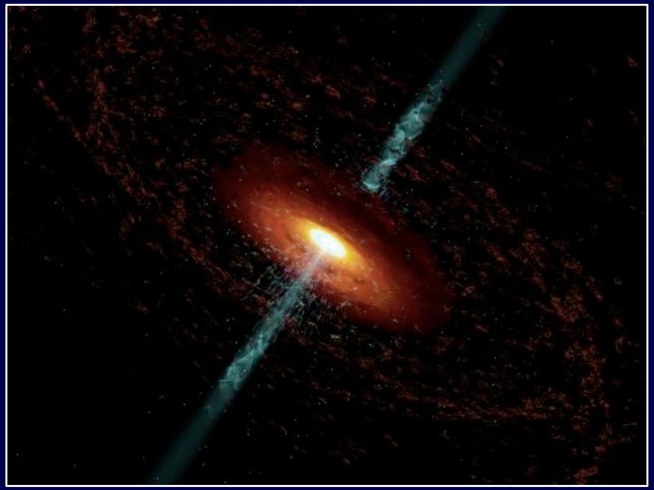


- Flat-field coefficients can be obtained:
  - FF = data/model

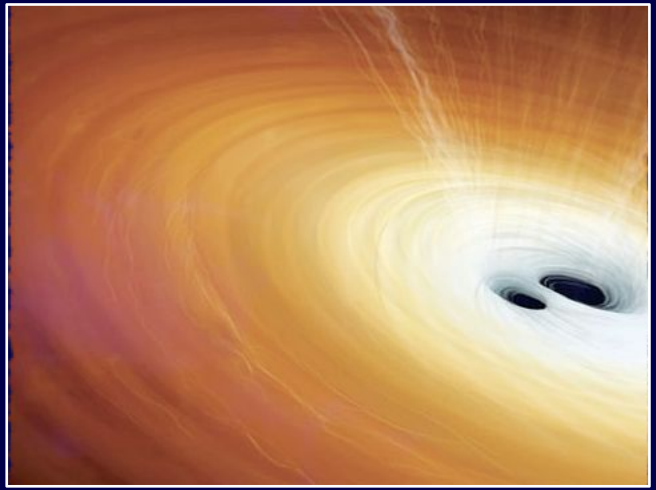
2nd aspect

Simulation and analysis of response to AGNs

Universe of High Energy events



Active Galactic Nuclei

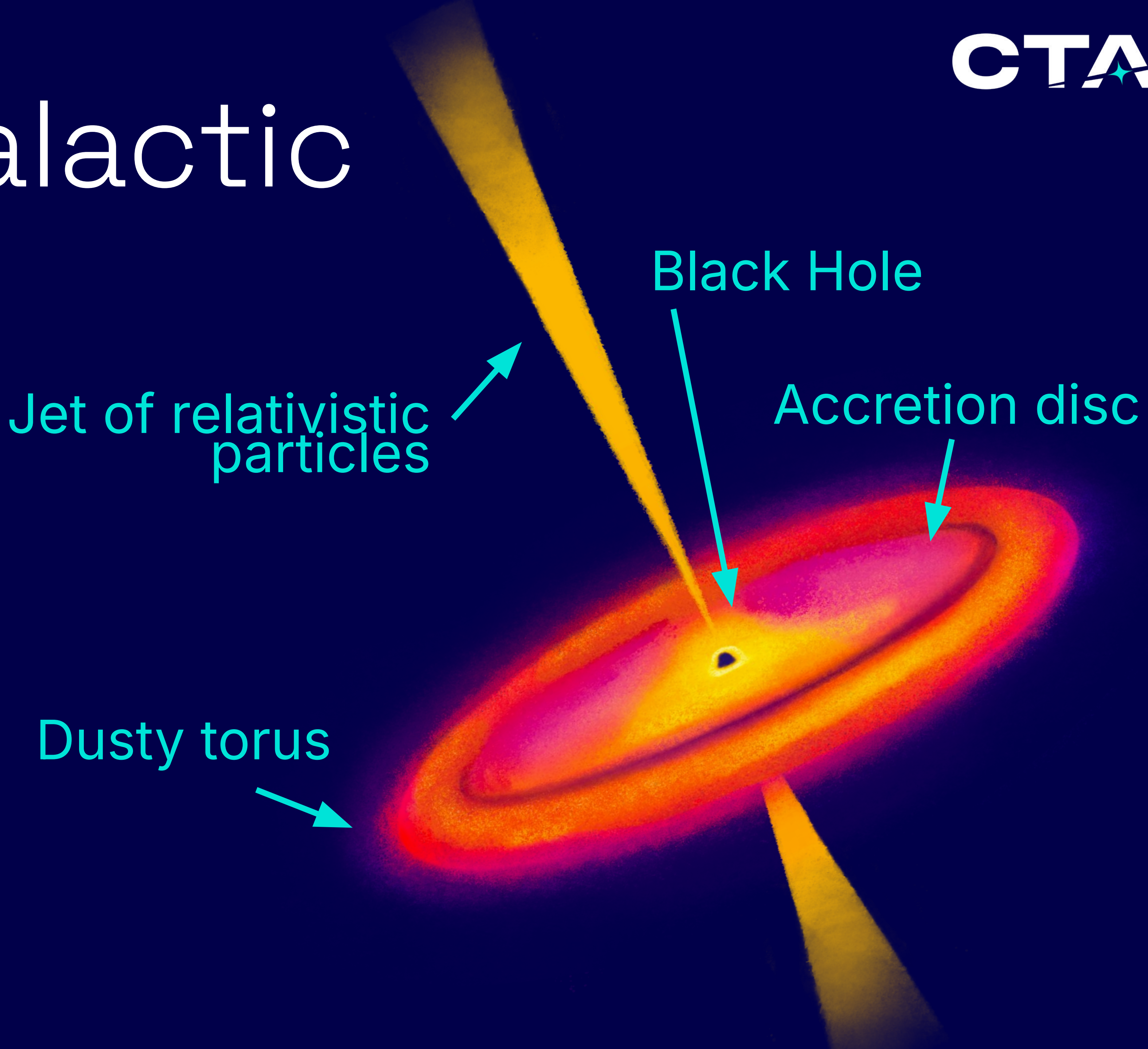


Black holes/neutron stars mergers

Gamma-ray bursts

Active Galactic Nuclei

- extremely bright central region of a galaxy, it is typically variable and very bright compared to the rest of the galaxy



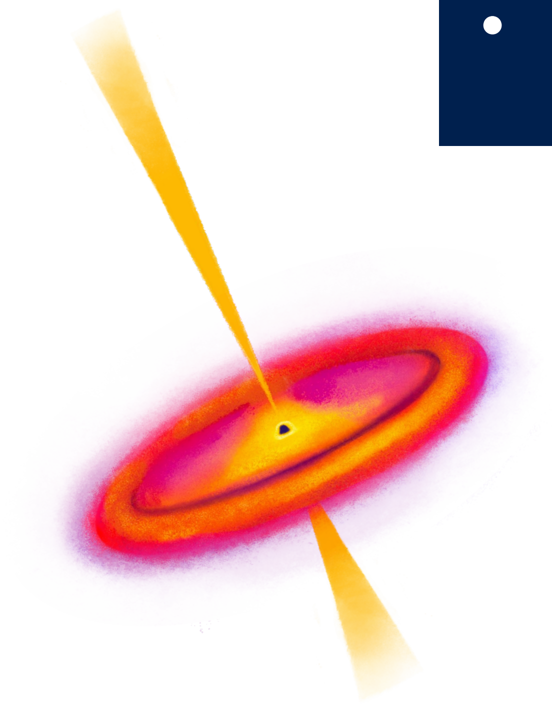
Simulation and analysis of response to AGNs

Long Term Monitoring

- Measure (unbiased) the duty-cycle of AGNs;
- Locate the gamma-ray emission region within the AGN

AGN Flares

- Provides constraints on the physics in vicinity of SMBH;
- Distinguish between emission mechanisms (leptonic vs hadronic)



CTA-AGN-VAR Pipeline

A python package based on Gammapy.

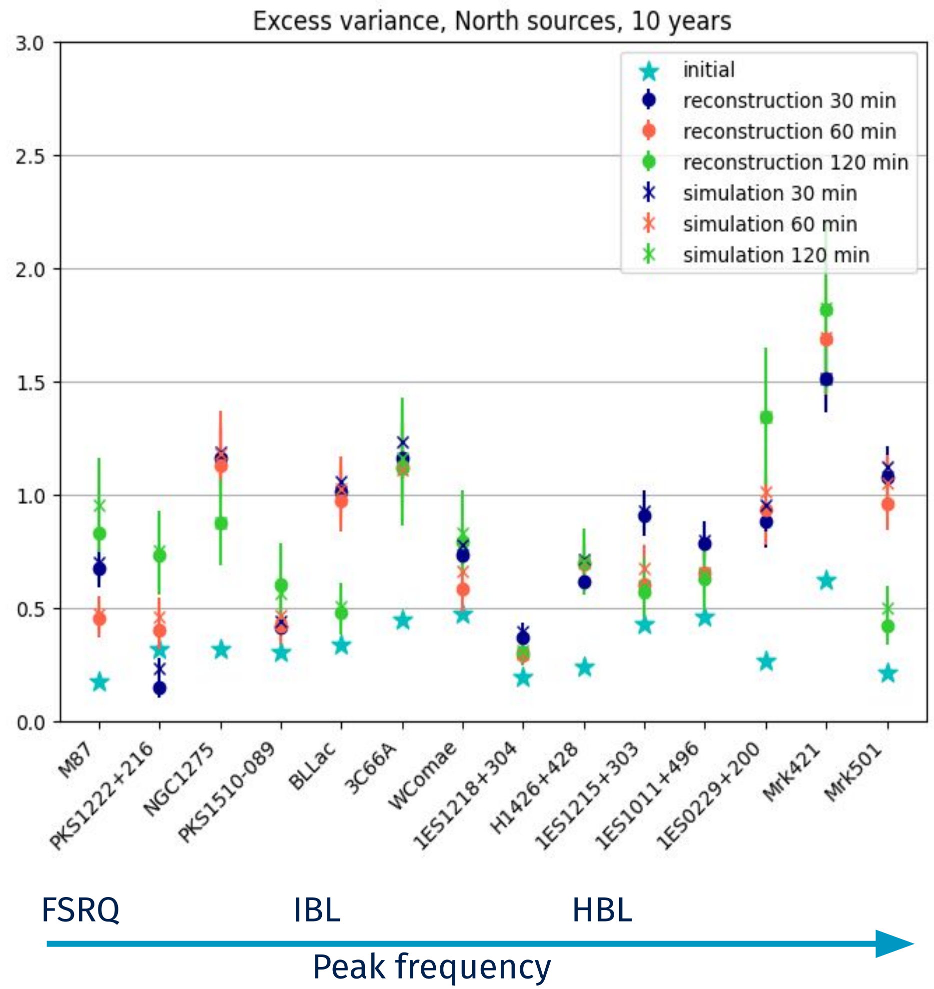
- ❑ Simulate gamma-like events from AGN observations with CTAO.
- ❑ Takes into account observational constraints.
- ❑ Light curve reconstruction from input model.
- ❑ Fits “Realistic” light-curve.

Grolleron, G (2024)

Observational program

Long-term monitoring:
4 strategies for 10-years monitoring, with observation windows of :
10 min, 30 min, 1 h, 2 h

- Define best observational strategy for AGNs of interest:
  - tested excess variance as a metric → shown to be biased
  - in process of testing probability density function (for the flux) as an alternative metric



Thank you

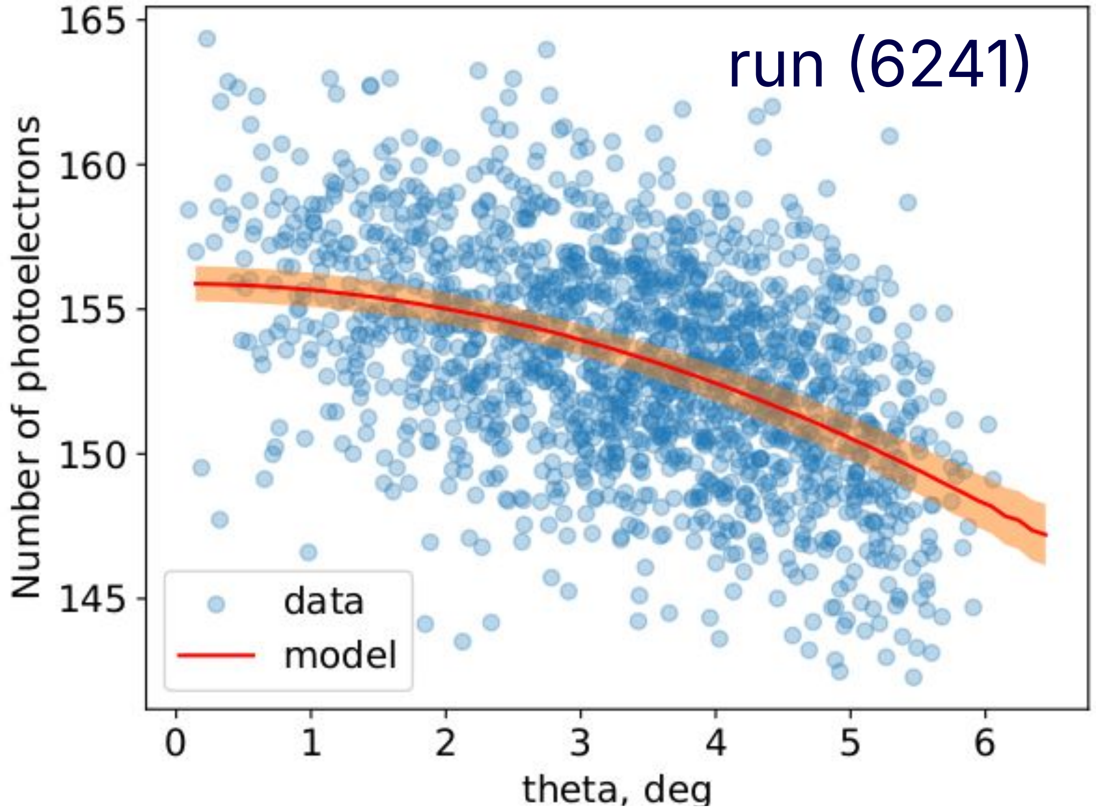
Backup

Flat-Field calibration

- Outliers are deleted (3 sigma away from the rest of data points);

The resulting uncertainty on the model is: 0.4%

- Flat-field coefficients can be obtained:
  - FF = data/model



Additionally: we can add parameter V_int to the likelihood to take into account intrinsic scatter or systematic uncertainties ->method is currently under validation using toy Monte Carlo

Flat-Field calibration

SPE run

Pedestal run

Flat-Field run

Photostatistics

$$g^{(*)} = \frac{\sigma_x^2 - \sigma_{\text{ped}}^2}{\langle x \rangle (1 + \beta^2)}$$

Illumination per pixel (N_photoelectrons)

Flat-field coefficients

$\bar{x}_j$ - mean charge in each pixel (over all events)

$\bar{\bar{x}}$ - mean signal over all pixels and events

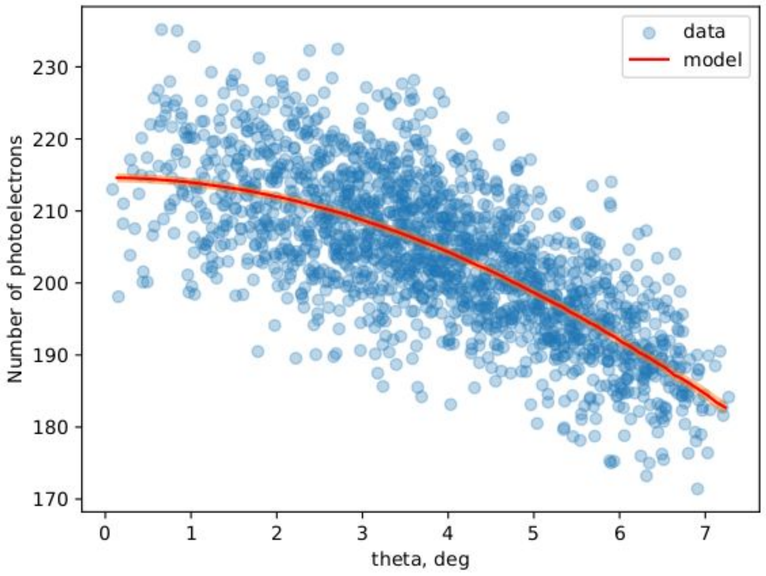
$$\hat{\rho}_j^{(A)} = \frac{\bar{x}_j}{\bar{\bar{x}}} \qquad (1)$$

(1) Internal note: Gain estimation with a light pulser by Stephen Fegan

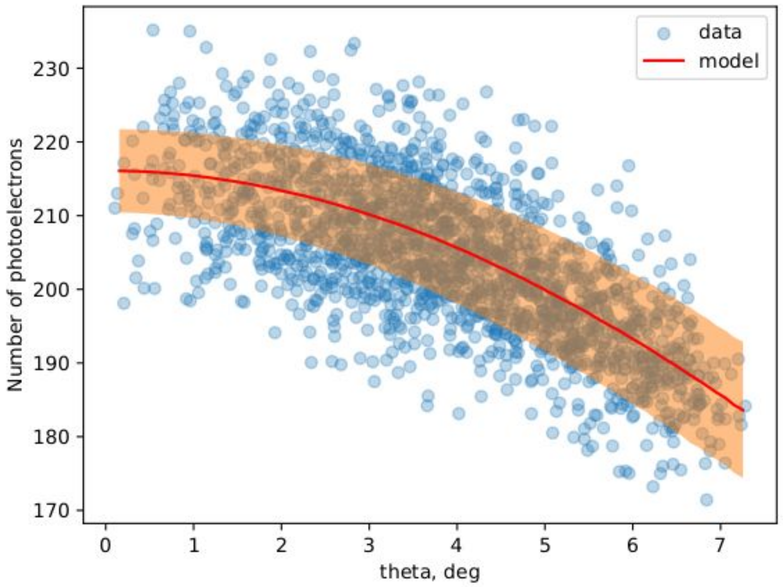
Model with intrinsic variance

The additional variance term Vint introduced in the **Likelihood** required to account for **intrinsic scatter** or **systematic uncertainties** in the data that are **not captured** by the statistical errors alone.

$$L = \prod_i \frac{1}{\sqrt{2\pi(\sigma_i^2 + V_{\text{int}})}} \exp\left[-\frac{(y_i - f(x_i))^2}{2(\sigma_i^2 + V_{\text{int}})}\right]$$



Without V_int



With V_int

Power Spectral Density and variability

Variability of a blazar is a stochastic process ~ noise.
PSD qualitatively characterises the variability

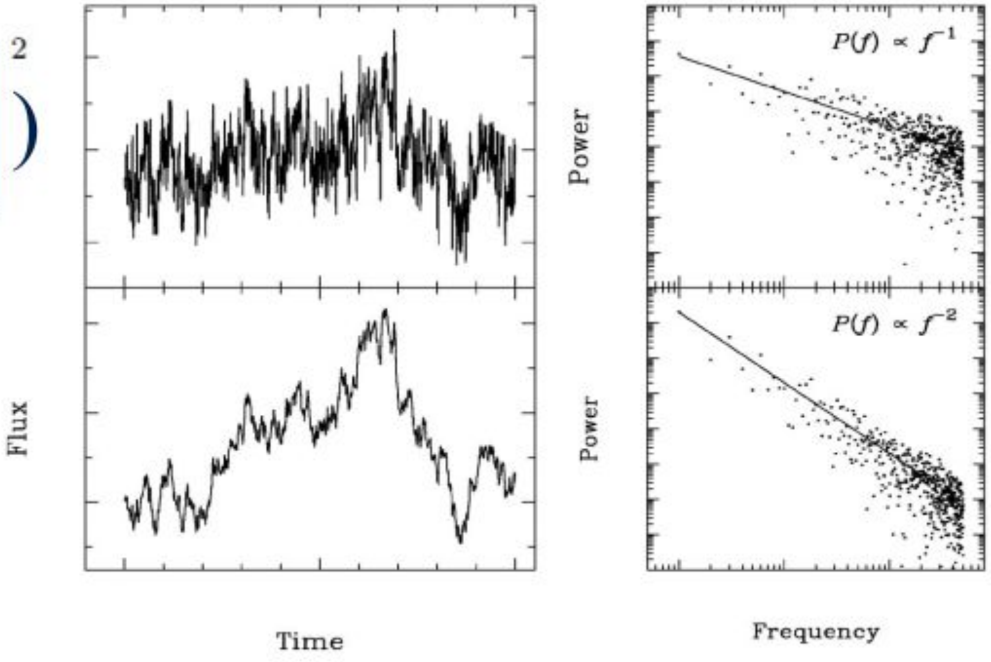
$$P(\nu) = A\|\mathrm{DFT}(\nu)\|^2 = \frac{2\delta \mathrm{T}}{\mathrm{N}} \left(\left[\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i} \cos(2\pi\nu \mathrm{t_i}) \right]^2 + \left[\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i} \sin(2\pi\nu \mathrm{t_i}) \right]^2 \right)$$

Mean variance from PSD:

$$\langle S^2 \rangle = \sum_{j=1}^{N} P(\nu)\delta\nu \quad \delta\nu = 1/N\delta T$$

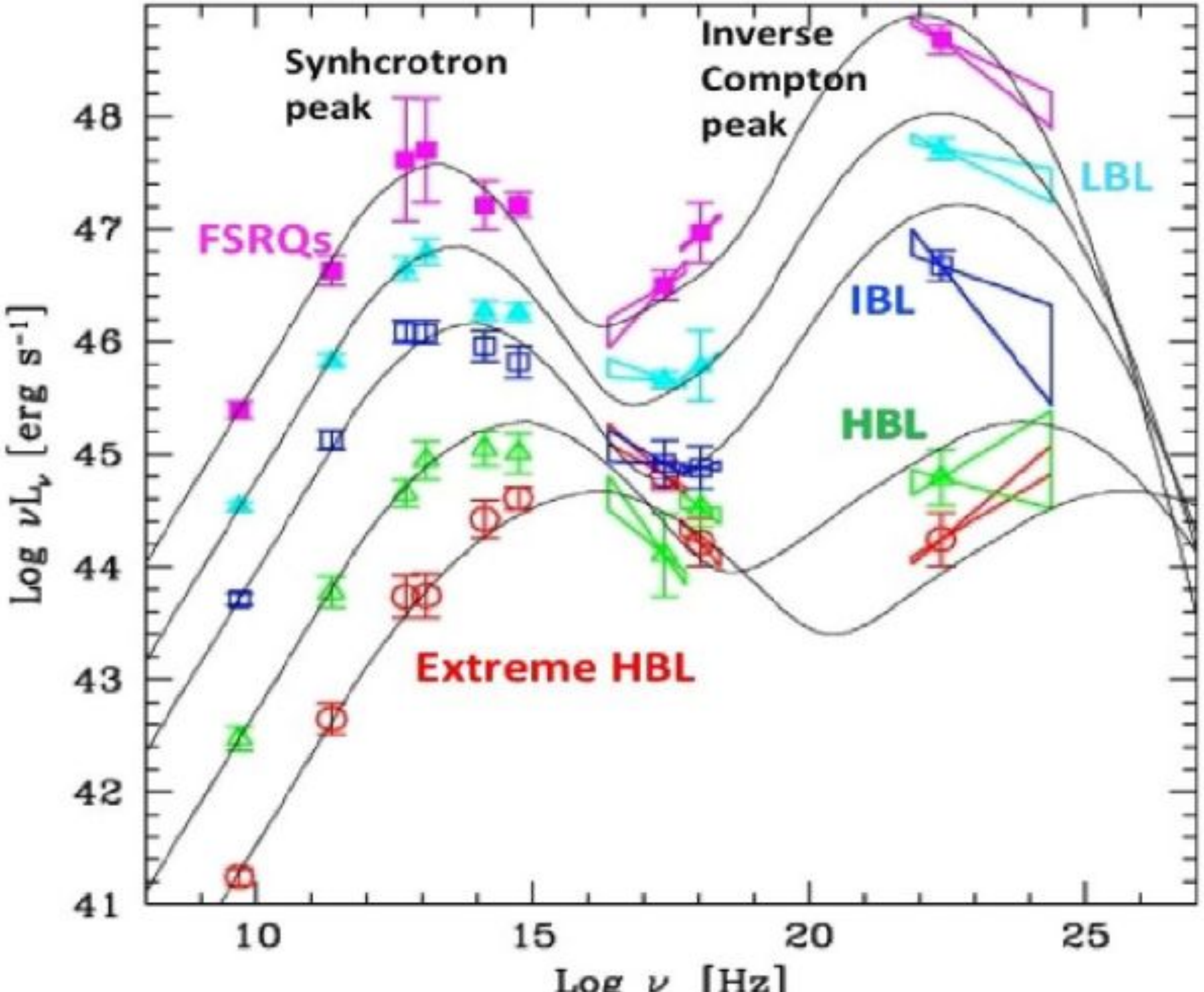
Excess variance characterizes **intrinsic source variance,** taking into account uncertainties on the individual flux measurements:

$$\sigma^2_{\mathrm{NXS}} = \frac{S^2 - \overline{\sigma^2_{\mathrm{err}}}}{\bar{x}^2}$$



AGN types

- **BLLacs** are radio-loud, variable and polarized
- **Flat-Spectrum Radio Quasar (FSRQ)** - distinguished by prominent emission lines



CTAO

The CtaAgnVar Pipeline

Input:
- IRFs
- visibility tables
- Spectral model (SED)
- parametrization of Power Spectrum
+Log-normal distribution
+Harder-when- brighter

→

Simulation

of gamma-like events based on a selected spectral model

→

Fit

- Several models are fitted to the data,
- The best SEDs are selected based on the test:

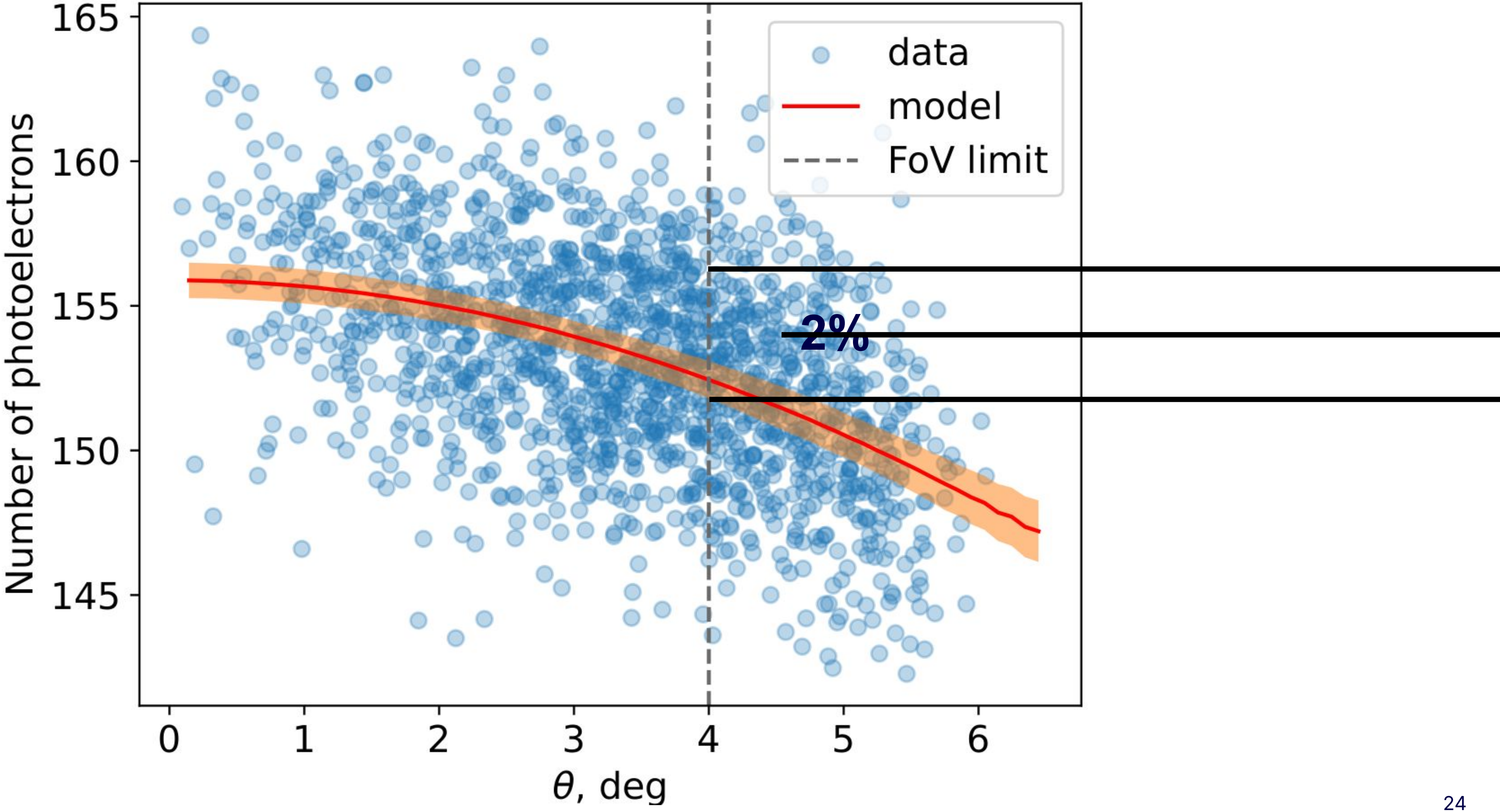
$$-2log\frac{L(H_1)}{L(H_0)}$$

→

Analysis

computation of:
- PSDs
- Spectral index
- Excess variance

Example of spectral model: $\phi_z(E,t) = \phi_0(t)\left(\frac{E}{E_0}\right)^{-\Gamma(t)-\beta ln\frac{E}{E_0}} e^{-\frac{E}{E_{\rm cut}}} e^{-\tau_{\gamma\gamma}(E,z)}$


165
160
155
150
145
Number of photoelectrons
0
1
2
3
4
5
6
θ, deg
data
model
FoV limit
2%