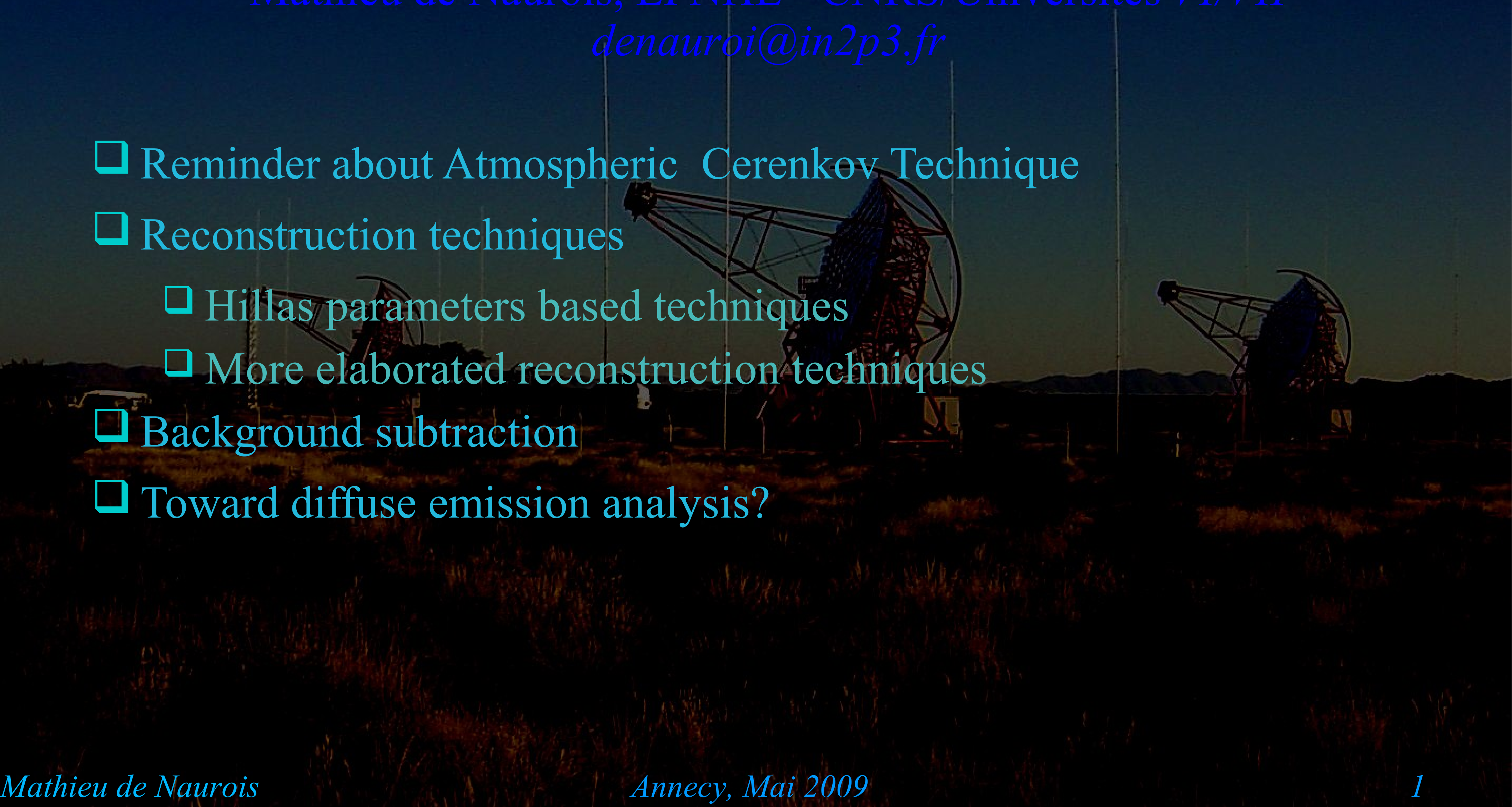


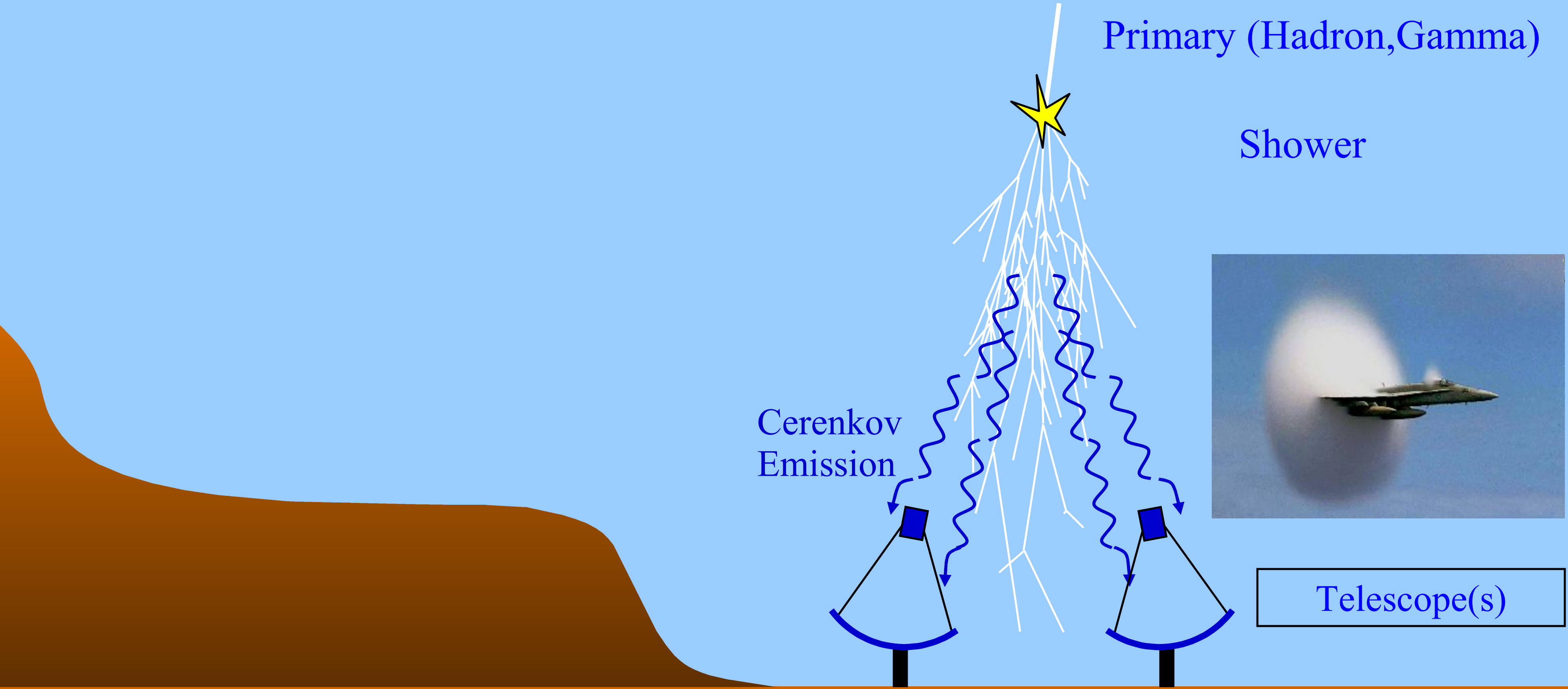
Analysis techniques for HESS

Mathieu de Naurois, LPNHE - CNRS/Universités *VI/VII*
denauroi@in2p3.fr

- Reminder about Atmospheric Cerenkov Technique
- Reconstruction techniques
  - Hillas parameters based techniques
  - More elaborated reconstruction techniques
- Background subtraction
- Toward diffuse emission analysis?

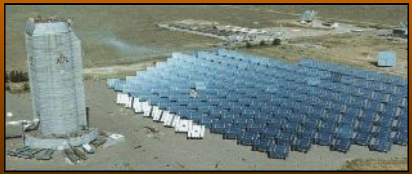
Crab > 1 TeV : ~ 1 γ/century/m^2

Need for huge collection area



HESS, VERITAS, MAGIC, CANGAROO

STACEE, CELESTE, SOLAR II, GRAAL



An electromagnetic shower

~ 10 km

From below

~ 300 m

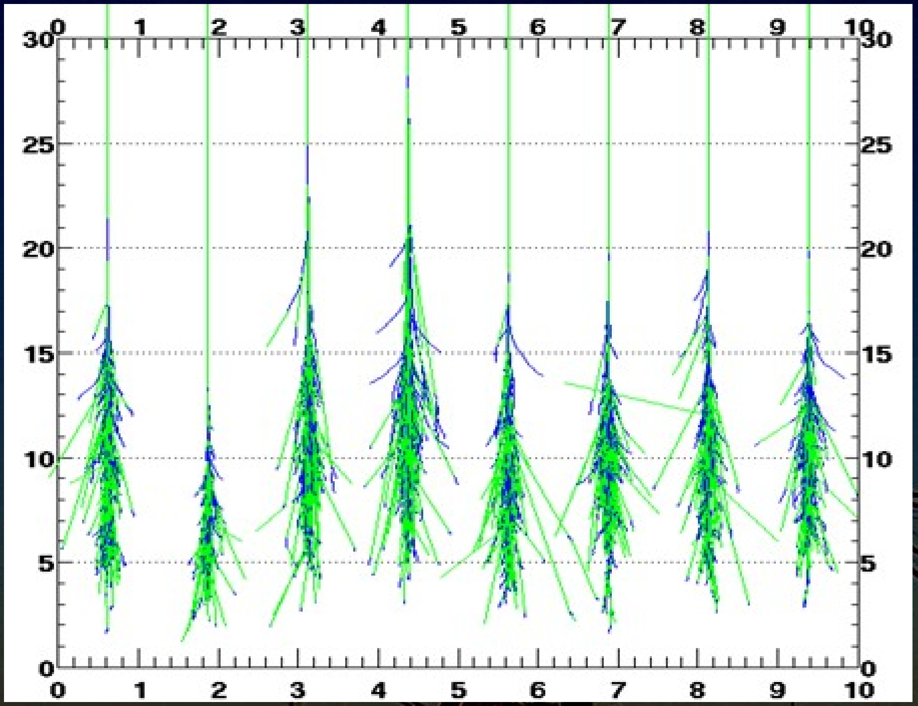
Variability of showers

γ, 100 GeV

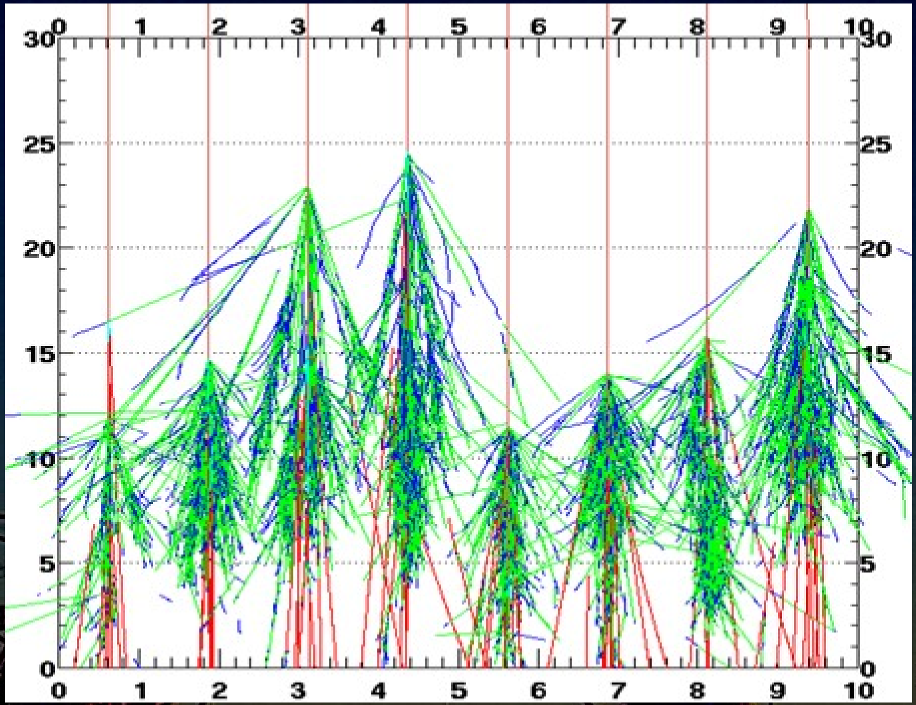
Protons, 500 GeV

Variability of showers

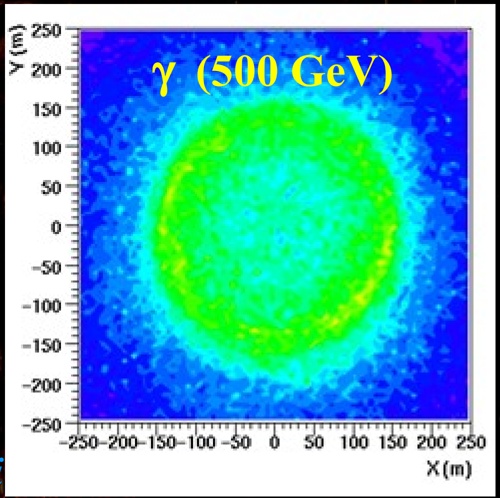
γ, 100 GeV

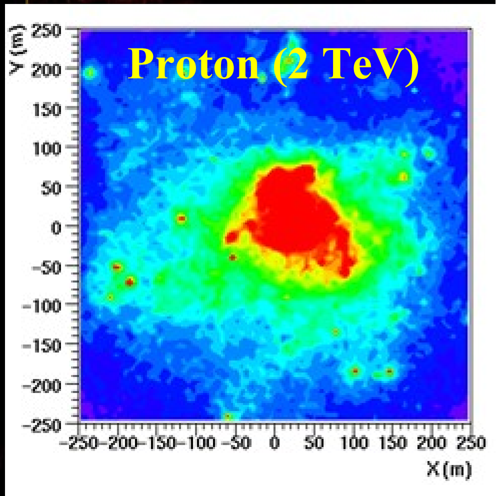


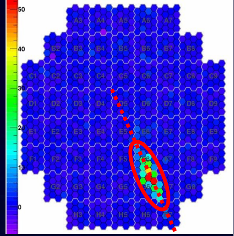
Protons, 500 GeV



- ❑ Hadronic showers fluctuate more (Good for discrimination)
- ❑ Contain some muons



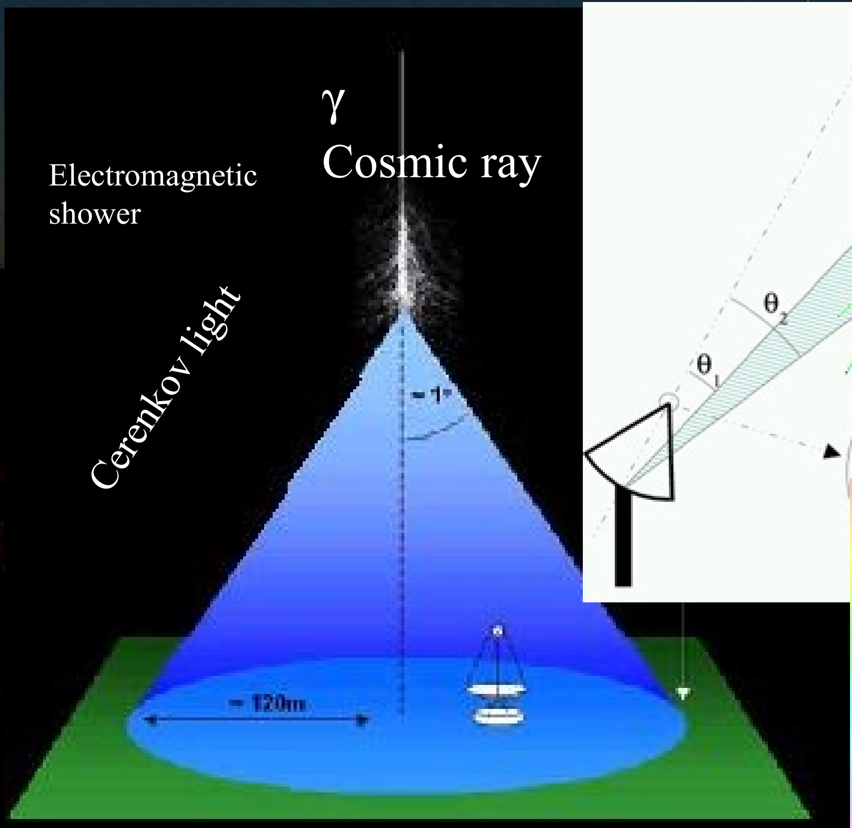


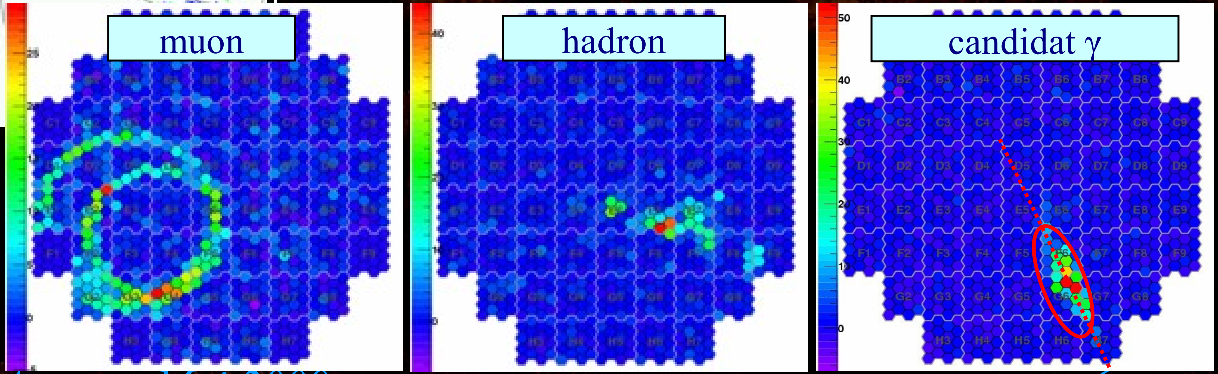


Atmospheric Cherenkov Imaging

- ☐ Cherenkov flash spread over ~120 m r. r
- ☐ Image the shower on a very fast camera (ΔT ~ 2ns)
- ☐ Large effective area (10^5 m^2) even with modest size telescopes

- ☐ Key point : speed (< 10 ns)
- ☐ Image shape used in γ/hadrons separation





I – "Hillas Parameters" based techniques

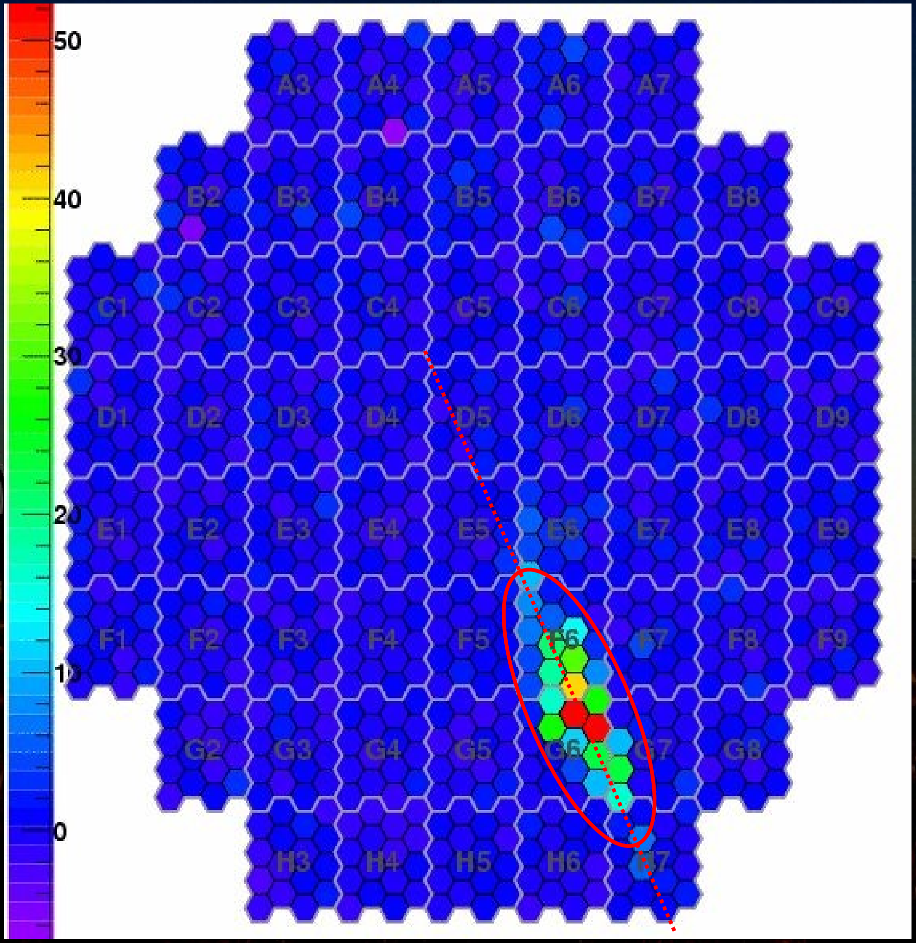
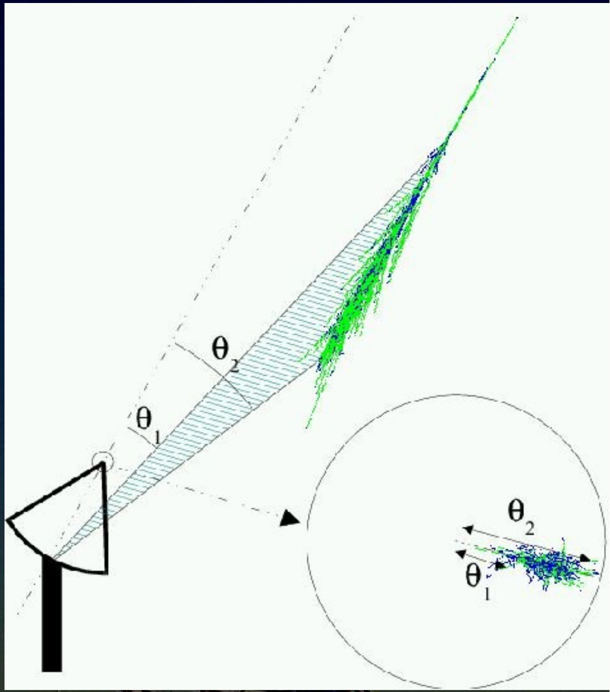
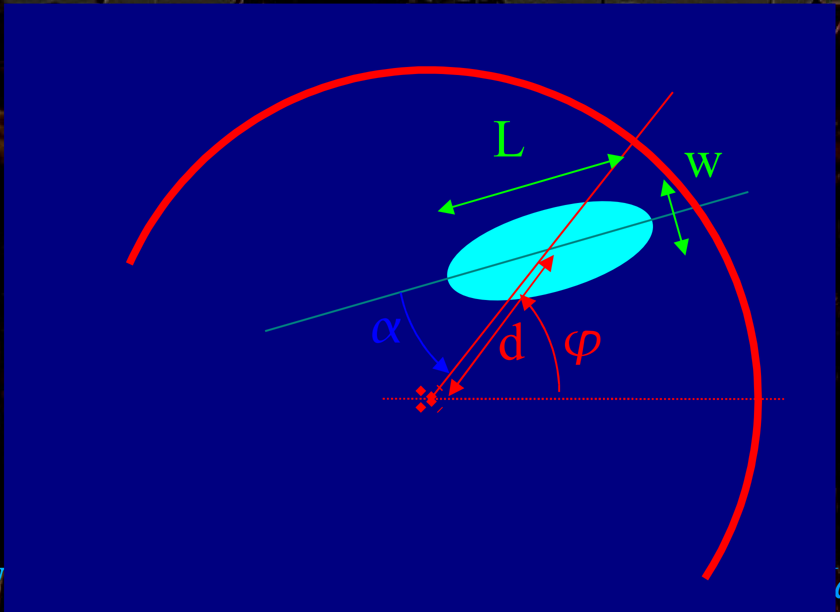
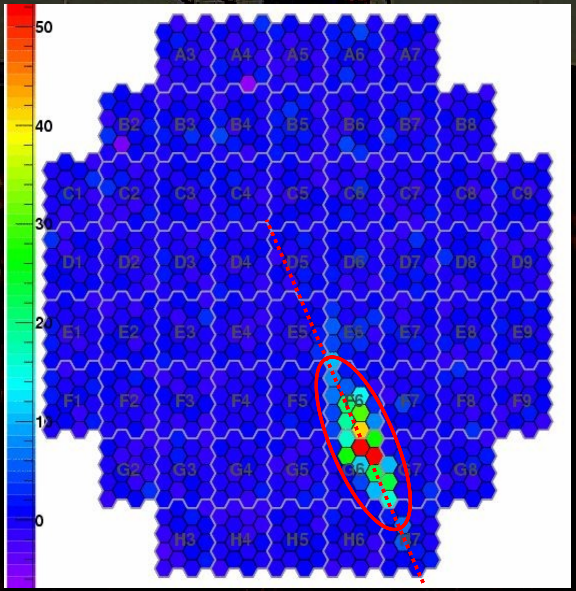


Image parametrisation

- Hillas Parameters (1984):
  γ images are ~ elliptical
  ⇒ reduce information to a few numbers:
  - Length (L) & Width (w)
  - Amplitude (size)
  - Nominal Distance (d)
  - Azimuthal Angle (φ), pointing angle (α)
- Additional parameters : asymmetry, …
- Need pixel-in-shower identification (cleaning)

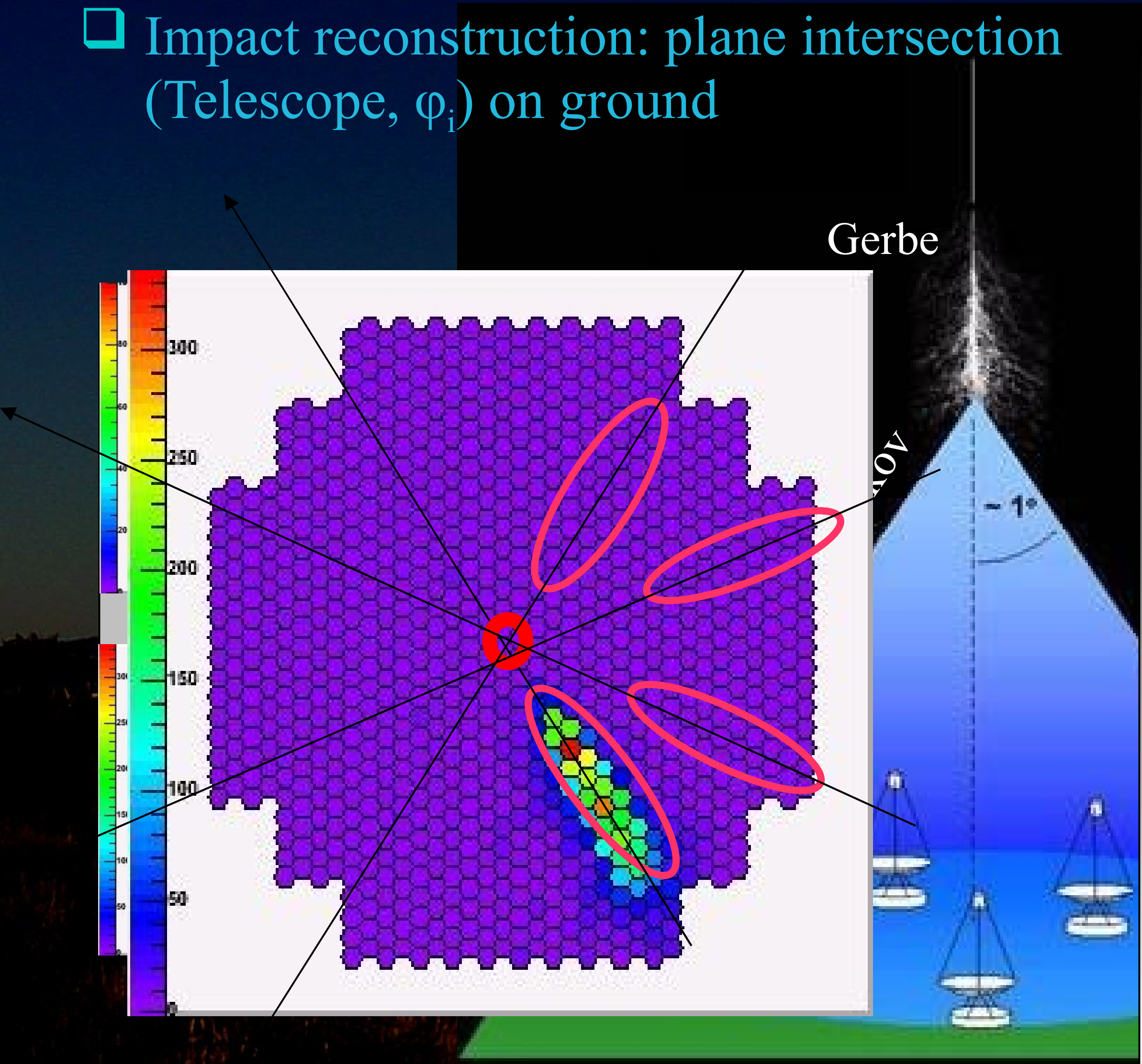


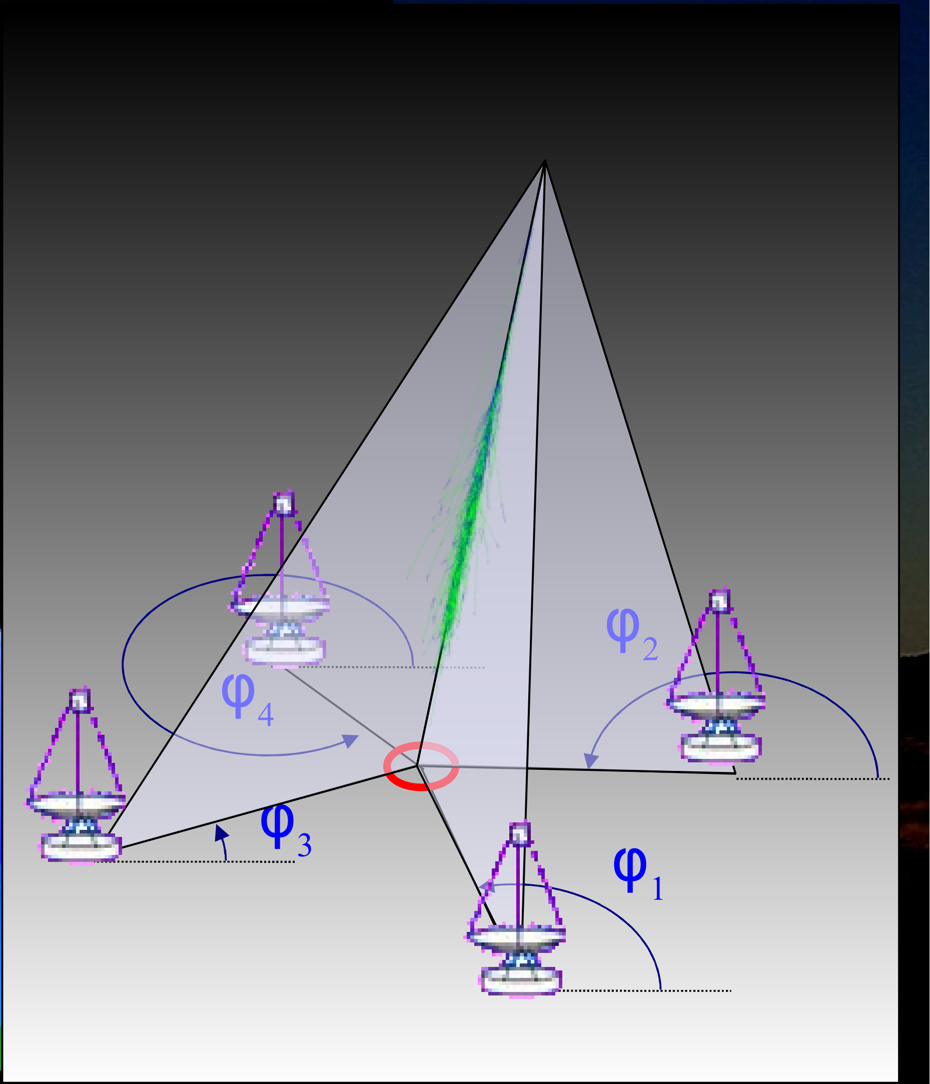




Stereoscopy

- ☐ Direction reconstruction: intersection of image main axis (angular space)
- ☐ Impact reconstruction: plane intersection (Telescope, φ_i) on ground



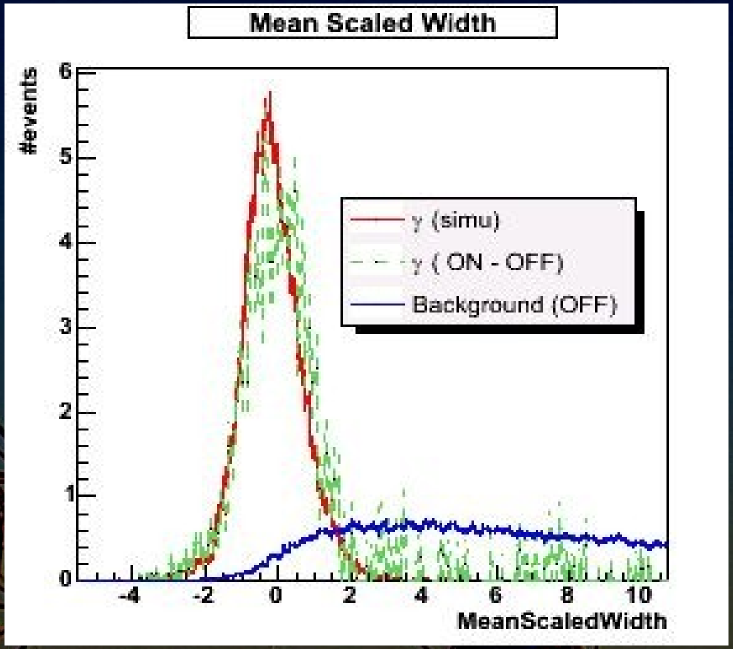


γ/h Separation – Energy reconstruction

- MC => lookup table
  (width, length = f(impact, size))
  $\langle w\rangle(\rho,I)$, $\sigma_w(\rho,I)$...
- Normalized parameter, averaged over telescopes

$$S_w = \frac{\left(w - \langle w\rangle\right)}{\sigma_w}$$

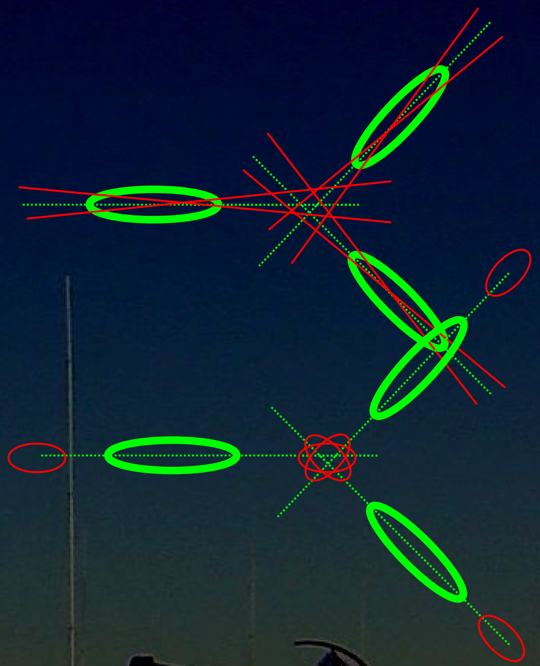
$$MSW = \sum_{tels} S_w / \sqrt{ntels}$$



- MeanScaledWidth and MeanScaledLength most discriminant (factor ~ 100)
- Energie : Similar technique : Lookup tables (Image Size, Impact distance)
  ⇒ Energy and σ_{Energy}
  - Resolution 20 - 25%
  - Can be improved using additional variables
    e.g. Depth of shower maximum

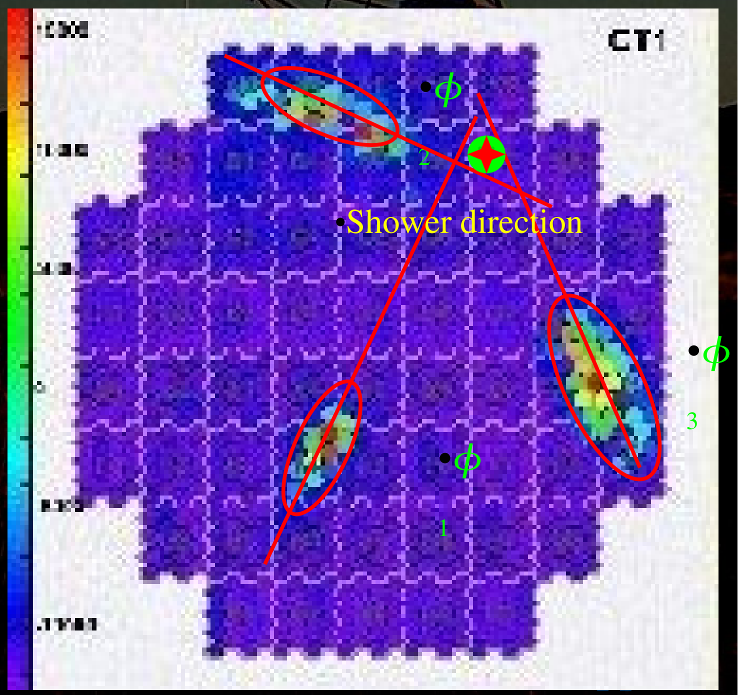
Possible improvements

- ❑ Some possible improvements in reconstruction (Hofmann et al, 1999)
  - ❑ Uncertainty on Hillas Parameters
  - ❑ Constrains on nominal distance



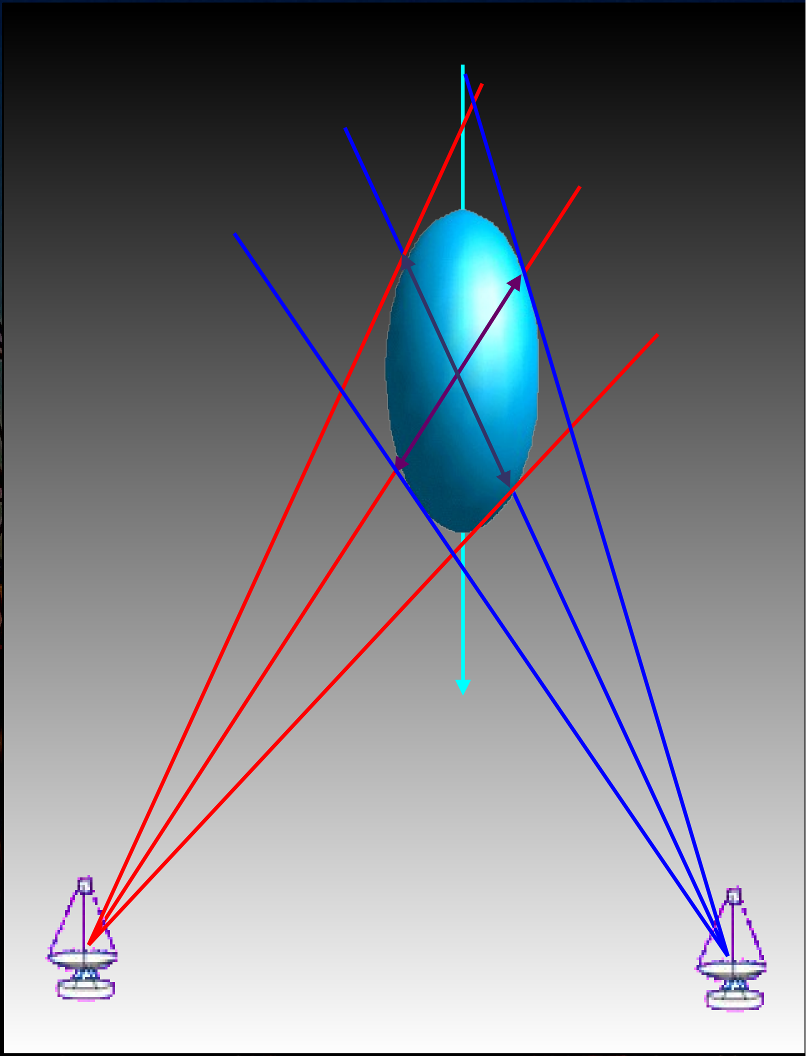
- ❑ Discrimination: additional informations can help
  - ❑ Depths of shower maximum
  - ❑ Consistency between telescopes (i.e. energy reconstruction)
  - ❑ Temporal structure (time gradient in images)

- ❑ Significant improvement (~ 2) only in single telescope mode



3D Model Analysis

- Principle: extend Hillas parameters using correlations between several telescopes
- Model the shower by a 3D Gaussian photosphere
- Intensity in each pixel : line of sight integral of photosphere
- Fit model to actual images (after cleaning) (log-likelihood)



8 parameters fit

Altitude, impact, direction,
width, length, brightness

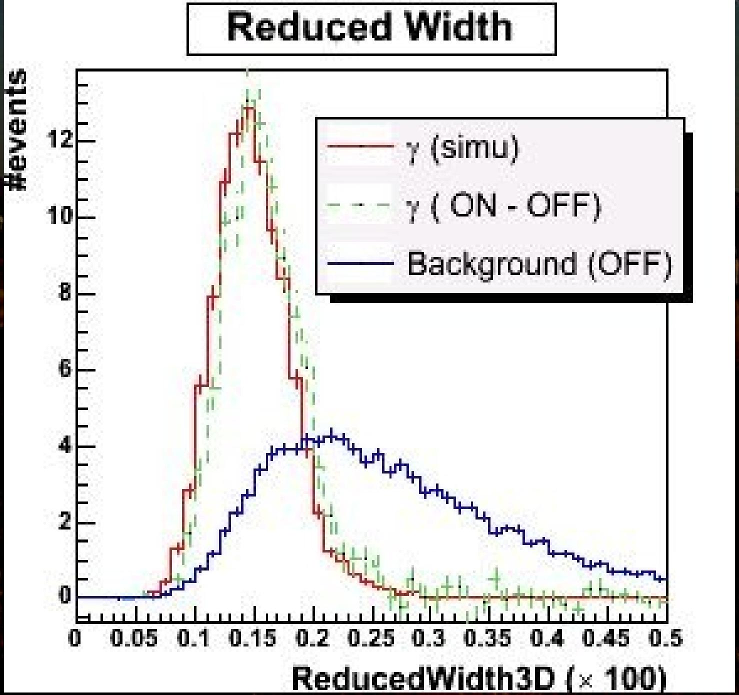
Lemoine-Goumard, Degrange, Tluczykont,
Astropart Phy 25 (2005)

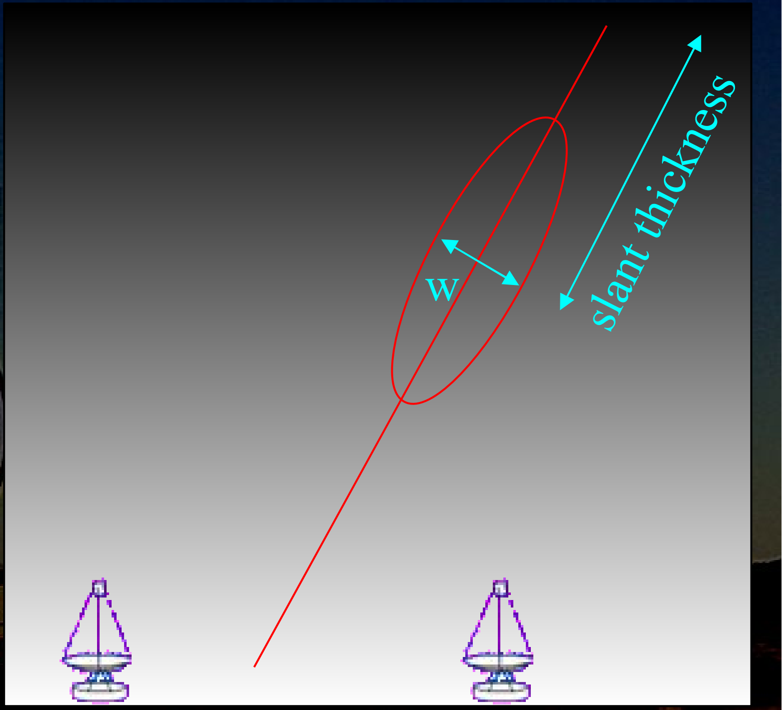
Discrimination

- Width (en units or radiation length) proportional to slant thickness
- Reduced width:

$$\omega = \frac{w \times \rho\left(z_{max}\right)}{thickness}$$

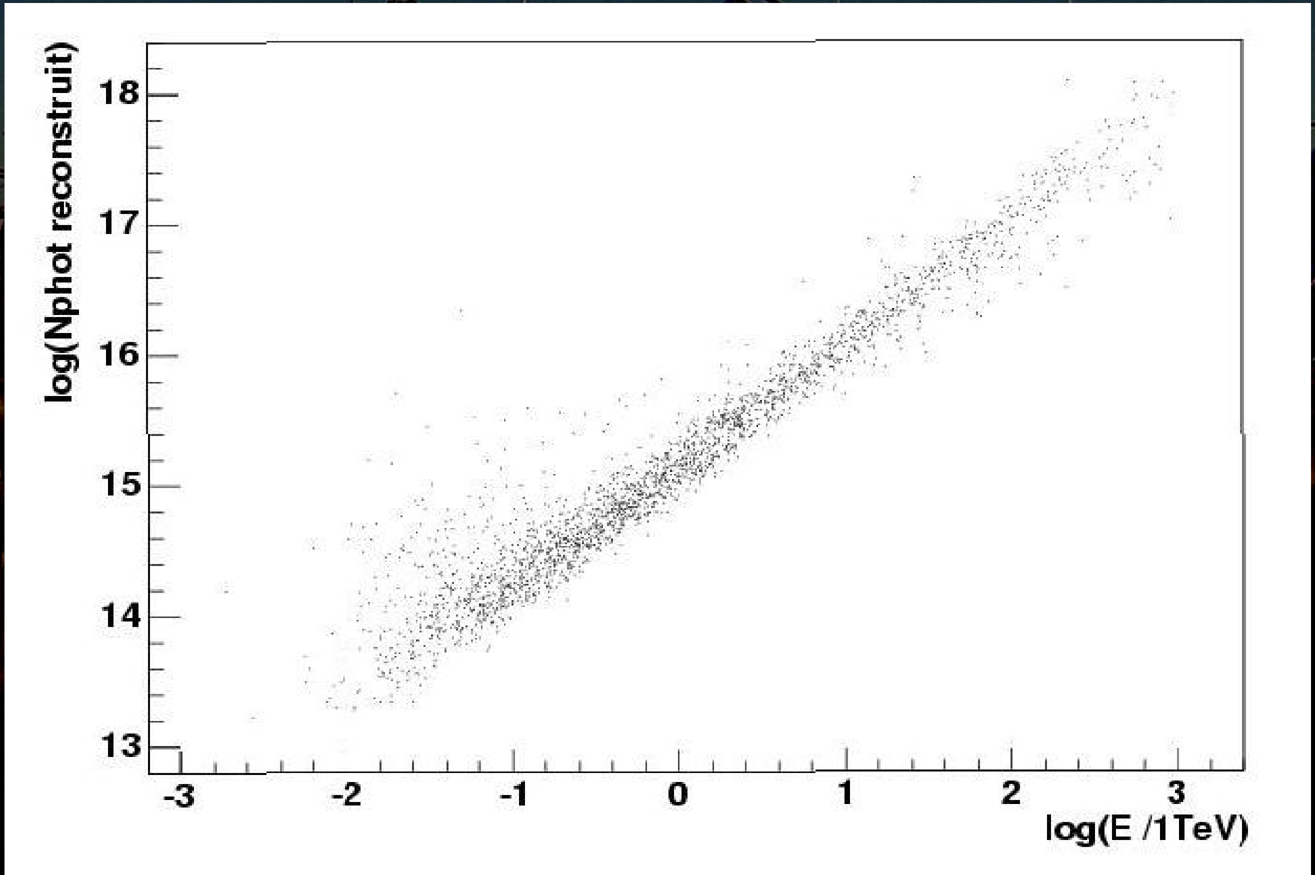
- Rejection factor O(100)



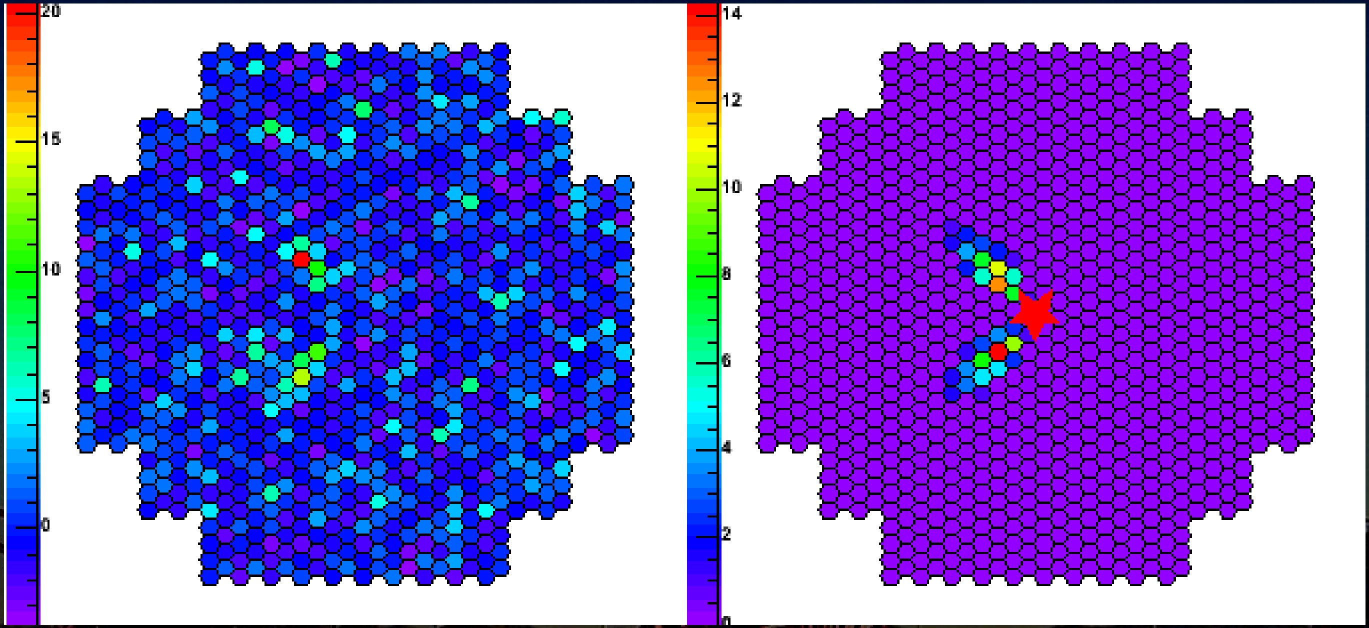


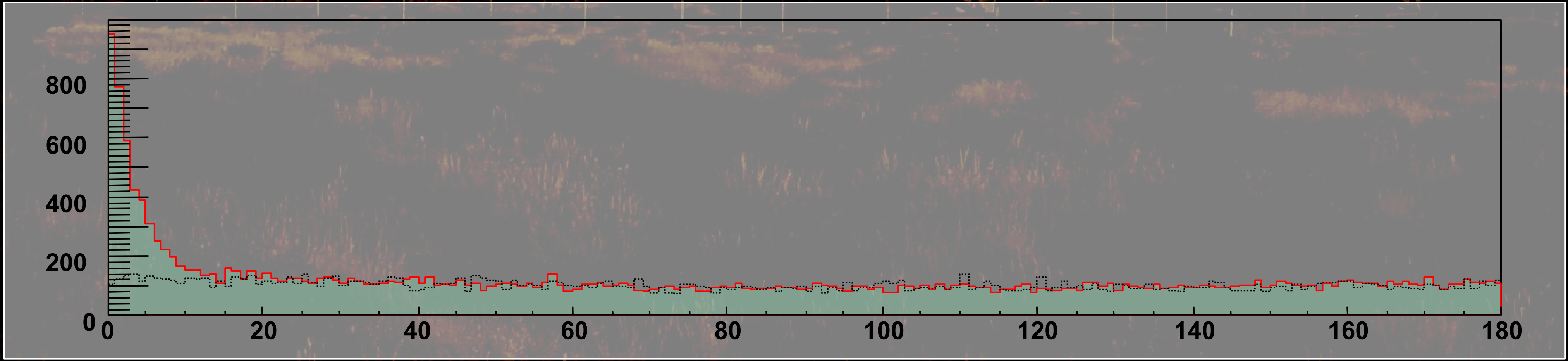
Energy reconstruction

- Result of shower fit: number of photons in shower
- Empirical relation to energy : ln(E) = a + b * ln(Nphot)
  a and b function of zenith angle (from MC)
- Resolution < 15% in [800 GeV – 50 TeV], no bias, worsen at lower energies



III – Model Analysis





Principles

- Fit the raw (uncleaned) images to a precalculated shower model
  - Semi-analytical shower model, function of shower true parameters (energy, direction, impact,...), done once for all
  - Log-likelihood fit, using actual noise distribution in every pixel (=> more precise)

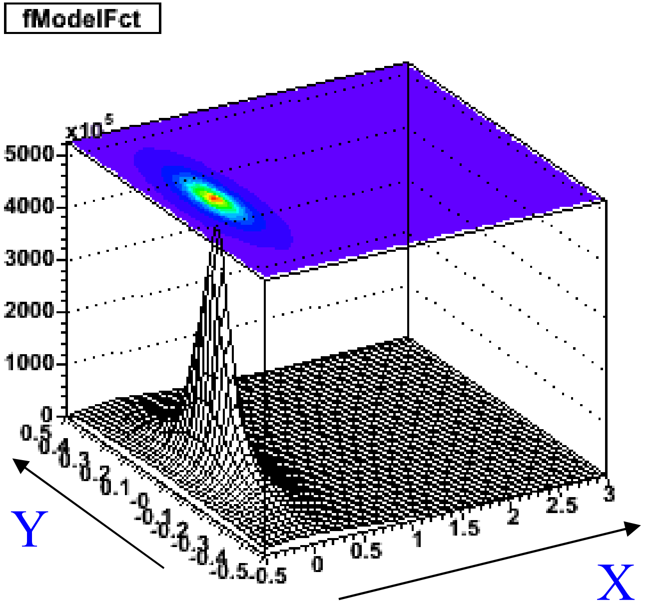
Prob. of observing x when μ is expected

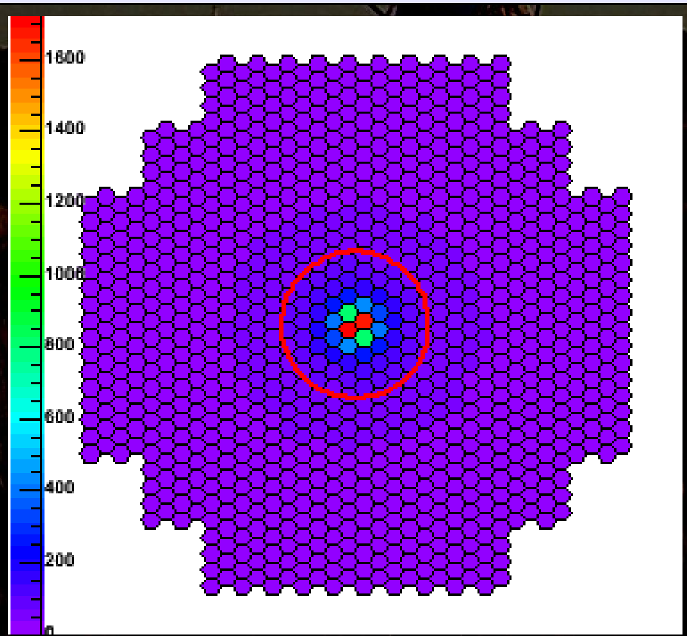
$$P_{df}(x,\mu,\sigma_p)=\sum_n \frac{\mu^n e^{-\mu}}{n!\sqrt{2\pi(\sigma_p^2+n\,\sigma_\gamma^2)}}\exp\left(\frac{-(x-n)^2}{2(\sigma_p^2+n^2\sigma_\gamma^2)}\right)$$

$\sigma_p = Pedestal\ width\ (NSB + electronic\ noise)$

$\sigma_\gamma = PMT\ resolution$

Model image for each
- zenith angle
- energy
- impact distance
- first interaction depth





Discrimination: goodness-of-fit

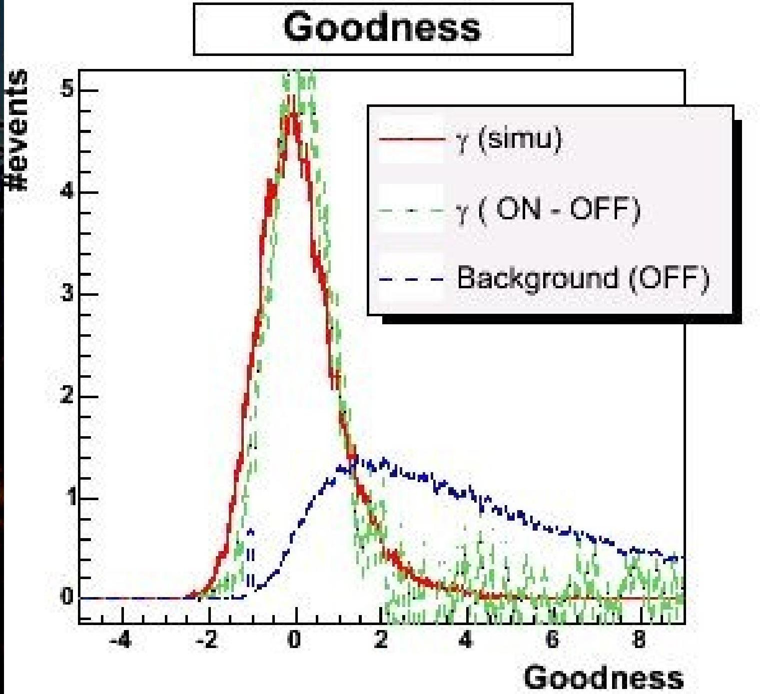
- ☐ NOT a likelihood ratio (no alternate hypothesis)
- ☐ Comparison of actual log-likelihood with expectation value (analytically calculated)

$$\langle \ln L \rangle = \int_x \ln\left(P_{df}\left(x,\mu,\sigma_p\right)\right) \times P_{df}\left(x,\mu,\sigma_p\right) \times dx$$

- ☐ Goodness-of-fit

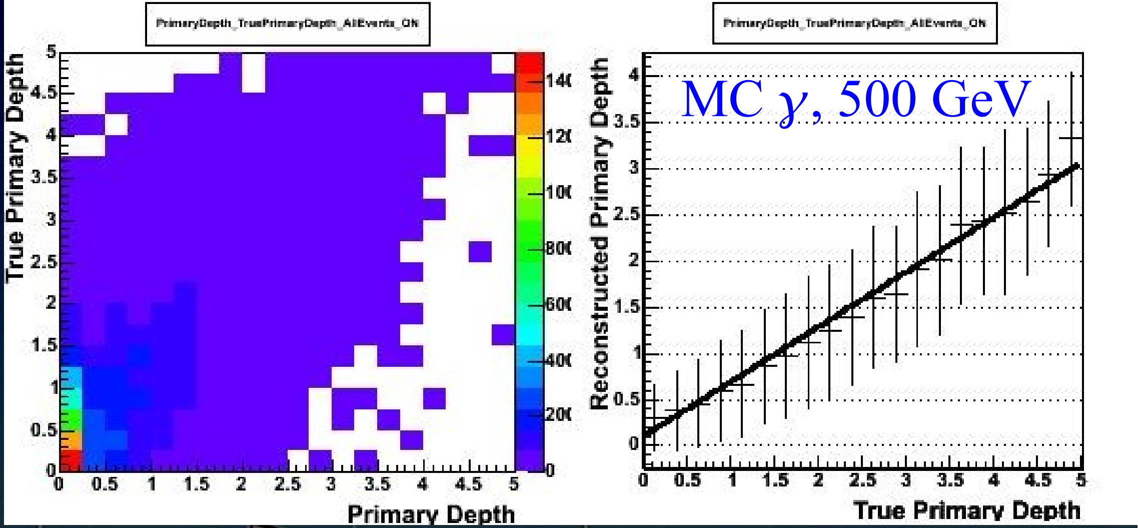
$$g = -\left(\frac{\ln L - \langle \ln L \rangle}{\sqrt{\quad \times NDof}}\right)$$

(~ normal variable)

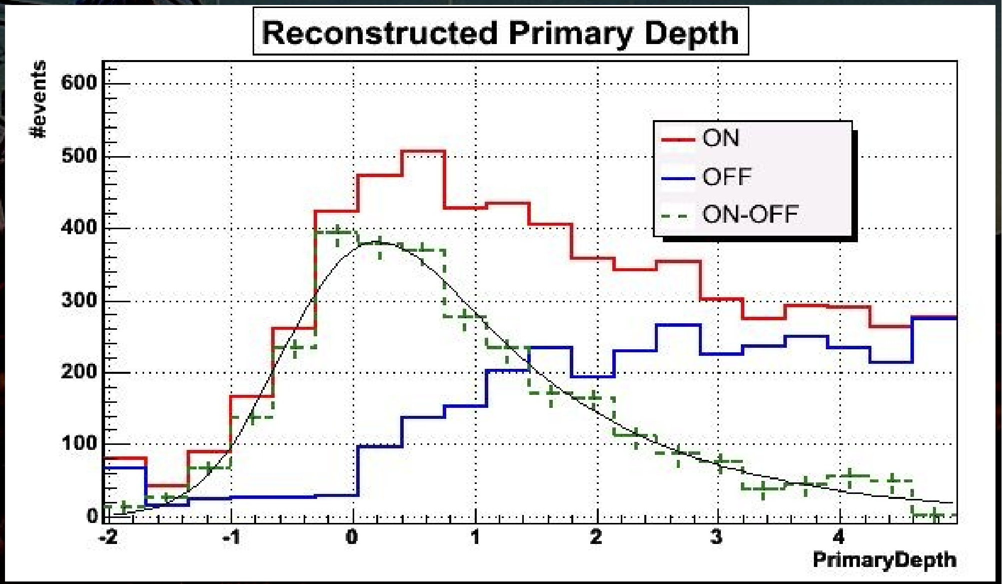


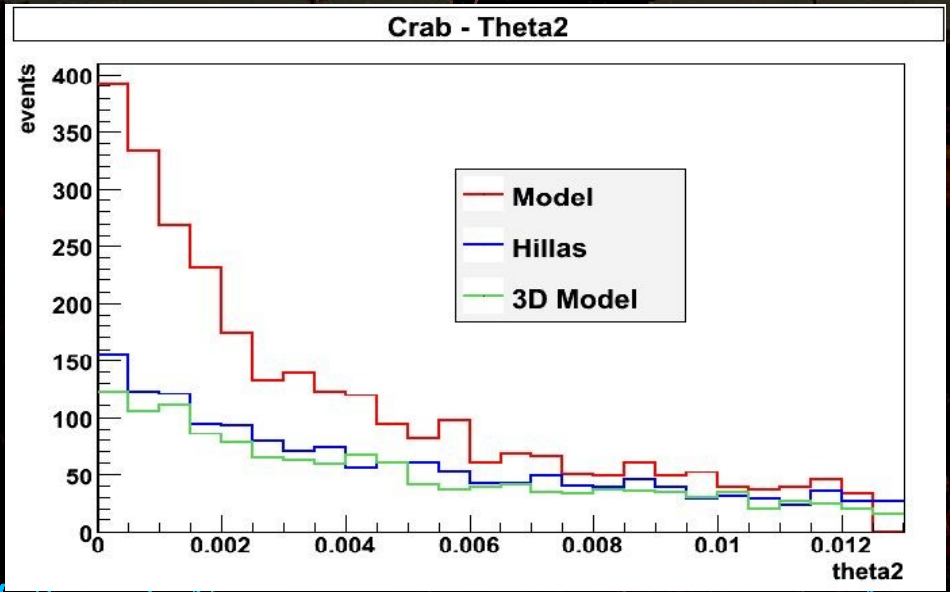
Performances

- Resolution on first interaction point ~0.5 X_0
- Good energy resolution
  15% @ 80 GeV, 8% @ 2 TeV
- Improved angular resolution
- Improved rejection, in particular at low energy

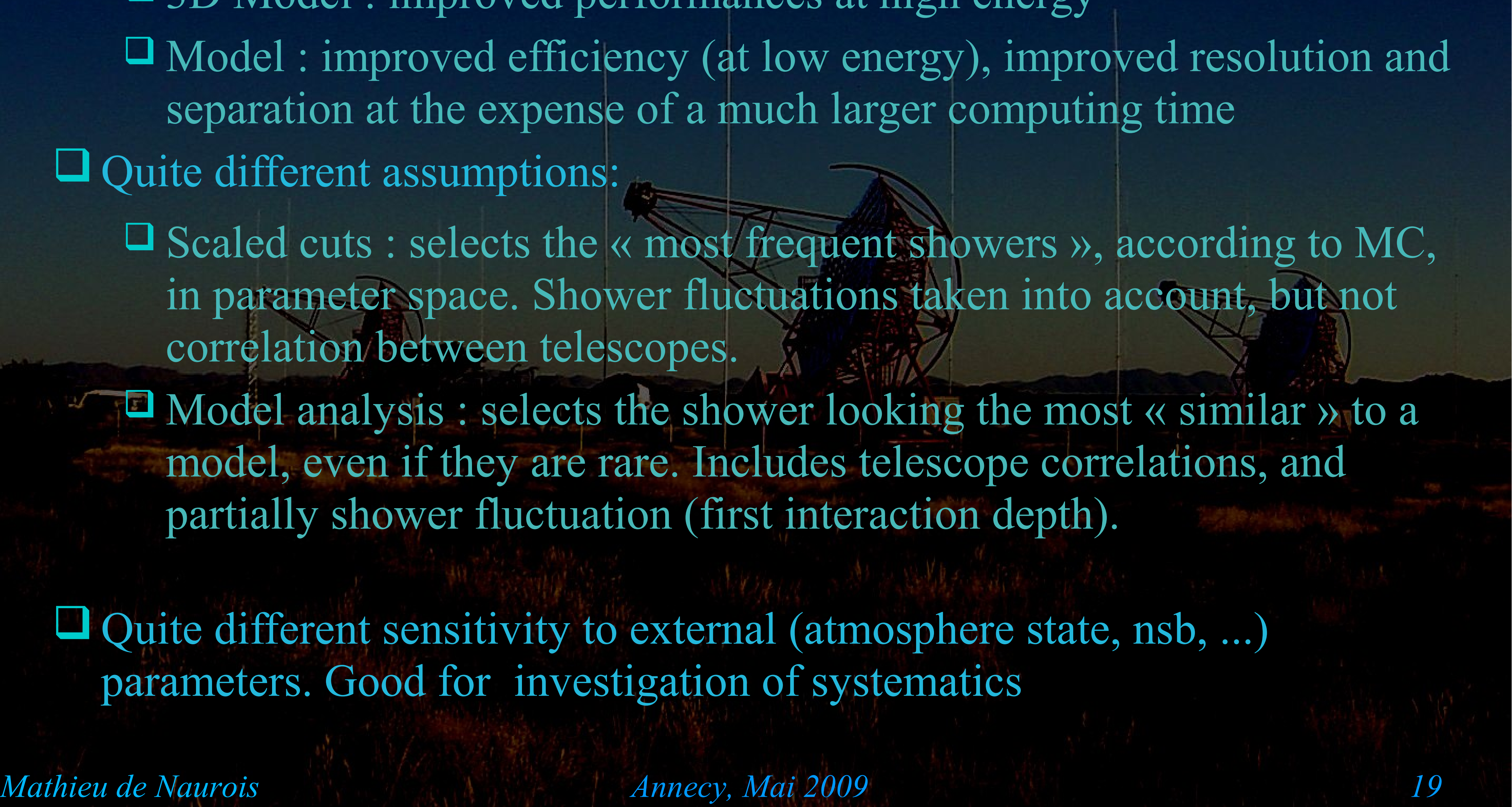


MC γ, 500 GeV





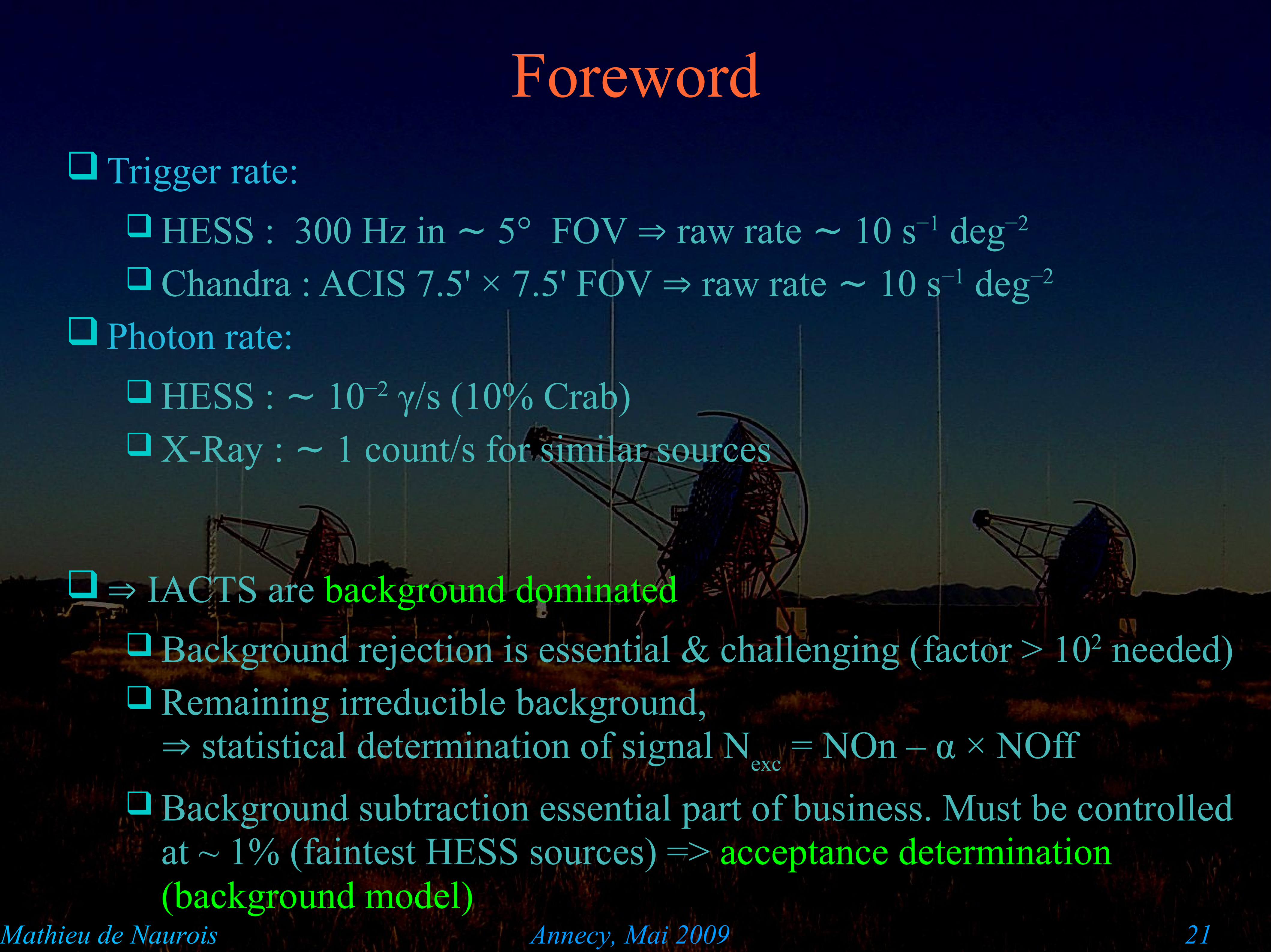
Conclusion on reconstructions



- 3 different techniques:
  - Hillas / Scaled cuts : robust, quite stable and fast
  - 3D Model : improved performances at high energy
  - Model : improved efficiency (at low energy), improved resolution and separation at the expense of a much larger computing time
- Quite different assumptions:
  - Scaled cuts : selects the « most frequent showers », according to MC, in parameter space. Shower fluctuations taken into account, but not correlation between telescopes.
  - Model analysis : selects the shower looking the most « similar » to a model, even if they are rare. Includes telescope correlations, and partially shower fluctuation (first interaction depth).

- Quite different sensitivity to external (atmosphere state, nsb, ...) parameters. Good for investigation of systematics

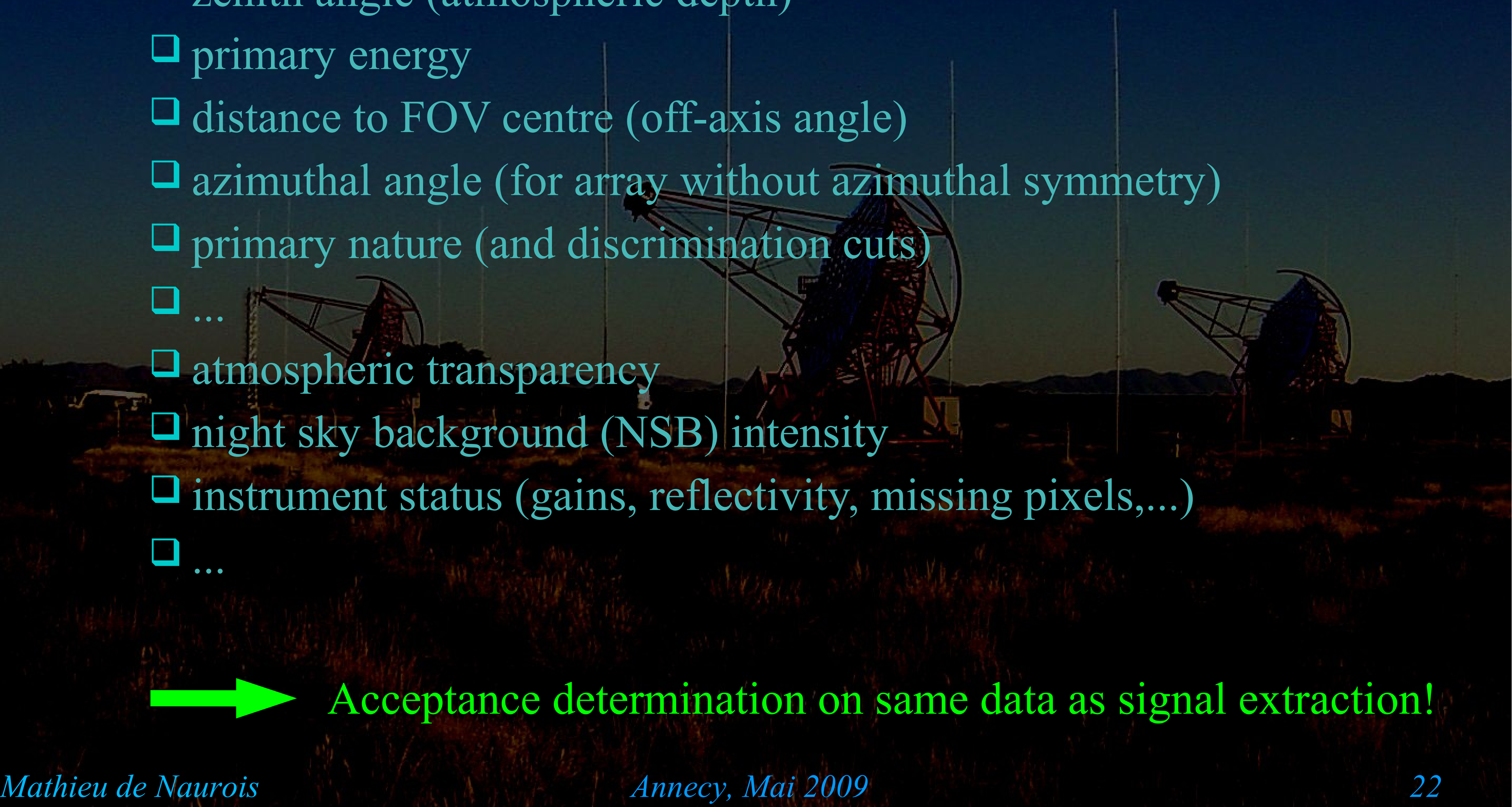
Background subtraction



Foreword

- Trigger rate:
  - HESS : 300 Hz in ~ 5° FOV ⇒ raw rate ~ $10\ \mathrm{s}^{-1}\ \mathrm{deg}^{-2}$
  - Chandra : ACIS 7.5' × 7.5' FOV ⇒ raw rate ~ $10\ \mathrm{s}^{-1}\ \mathrm{deg}^{-2}$
- Photon rate:
  - HESS : ~ 10^{-2} γ/s (10% Crab)
  - X-Ray : ~ 1 count/s for similar sources
- ⇒ IACTS are background dominated
  - Background rejection is essential & challenging (factor > 10^2 needed)
  - Remaining irreducible background,
    ⇒ statistical determination of signal $N_{exc} = NOn - \alpha \times NOff$
  - Background subtraction essential part of business. Must be controlled at ~ 1% (faintest HESS sources) => acceptance determination (background model)

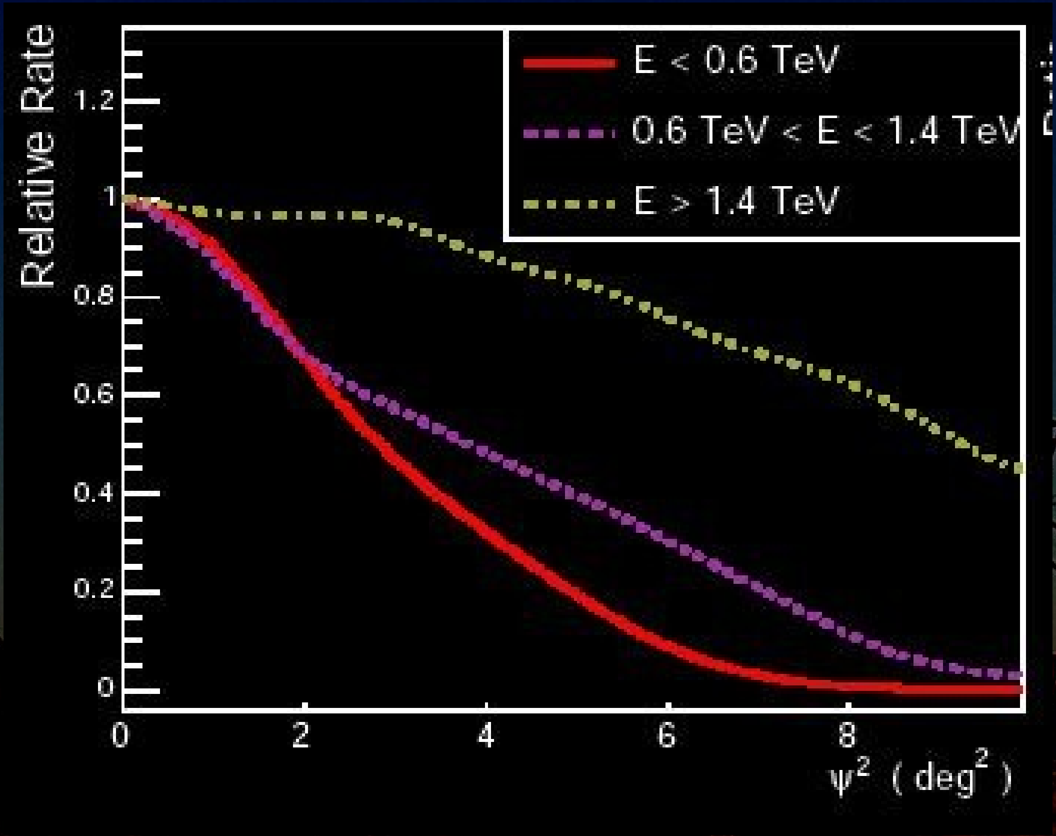
Background model?



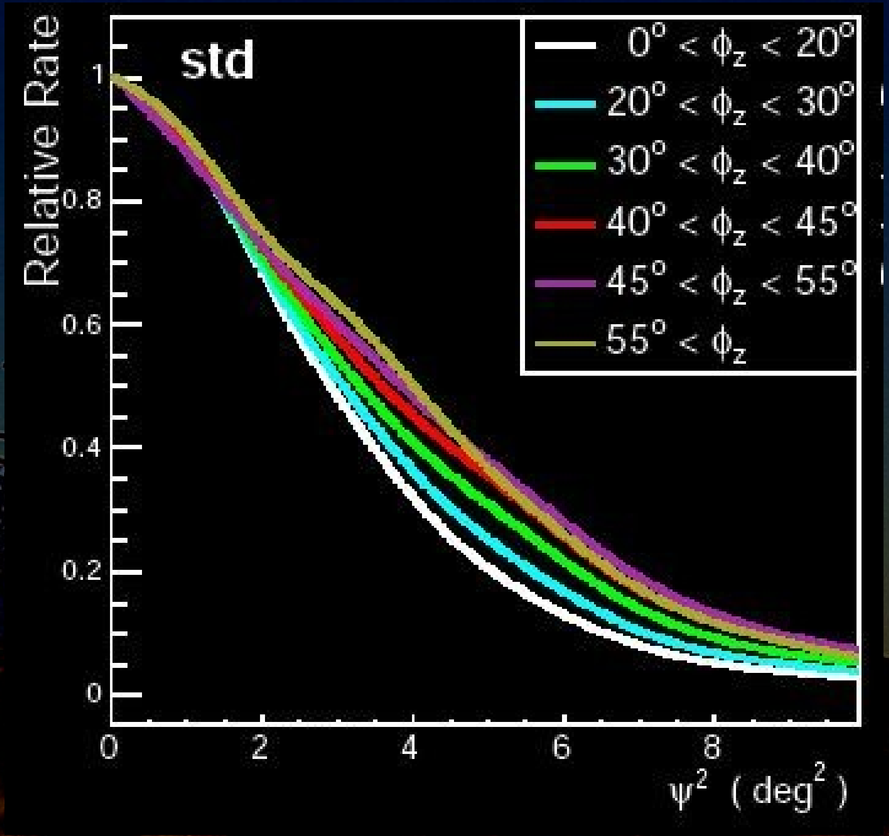
- Acceptance (= expected background) depends on:
  - zenith angle (atmospheric depth)
  - primary energy
  - distance to FOV centre (off-axis angle)
  - azimuthal angle (for array without azimuthal symmetry)
  - primary nature (and discrimination cuts)
  - …
  - atmospheric transparency
  - night sky background (NSB) intensity
  - instrument status (gains, reflectivity, missing pixels,...)
  - …

→ Acceptance determination on same data as signal extraction!

Radial (= off-axis) acceptance



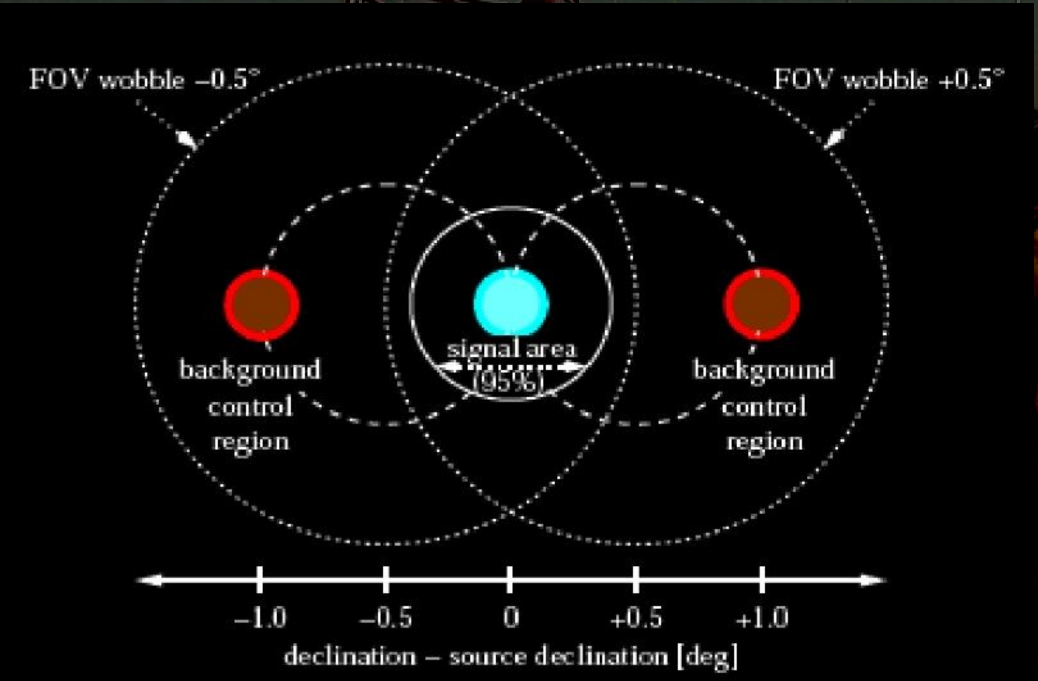
As function of energy

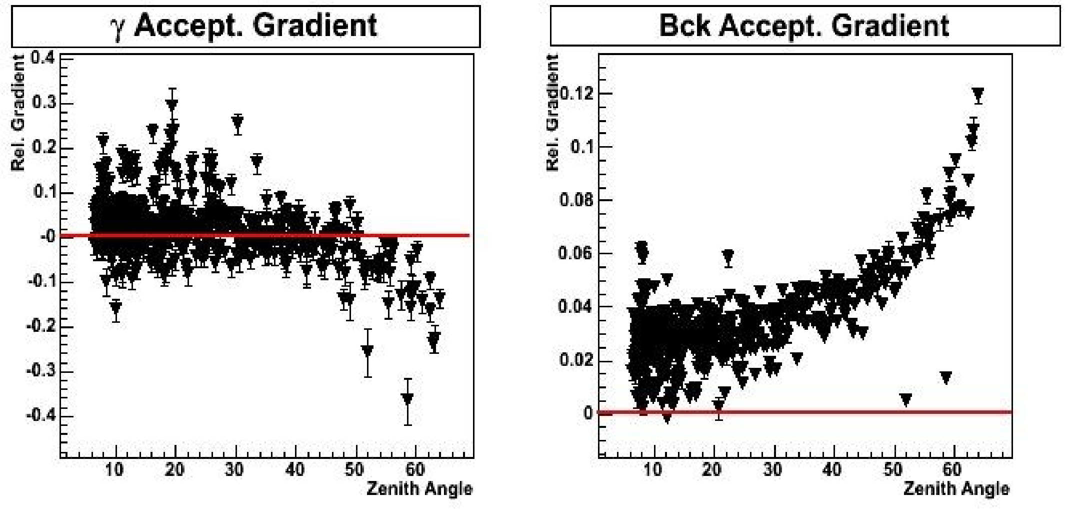


As function of zenith angle

Wobble observation mode

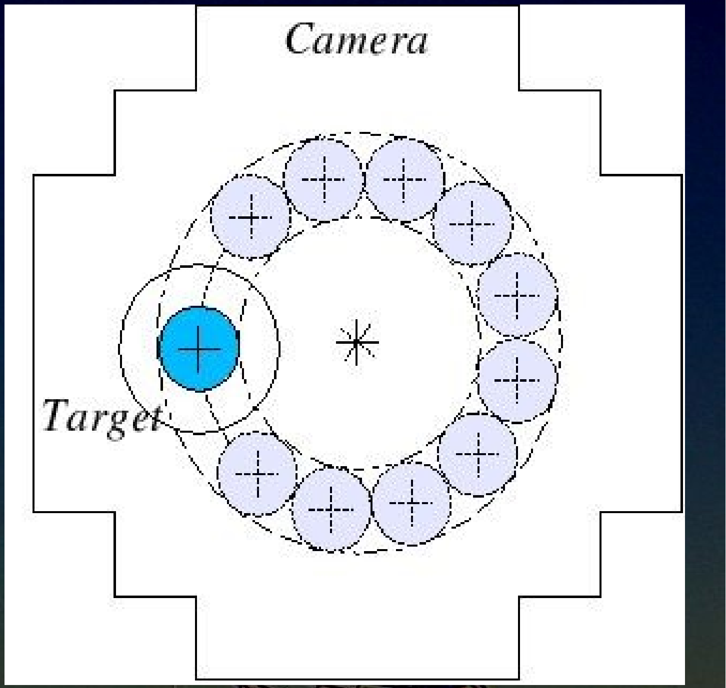
- Pioneered by Whipple / HEGRA
  - Alternating observation position, shifted in FOV (±0.5°)
  - Background from mirror region in FOV
  - Rely on azimuthal symmetry of acceptance. ~ True in single telescope, not in stereo. Zenith angle gradient.
  - Can derive a signal, a spectra, but not map (no mirror for centre)

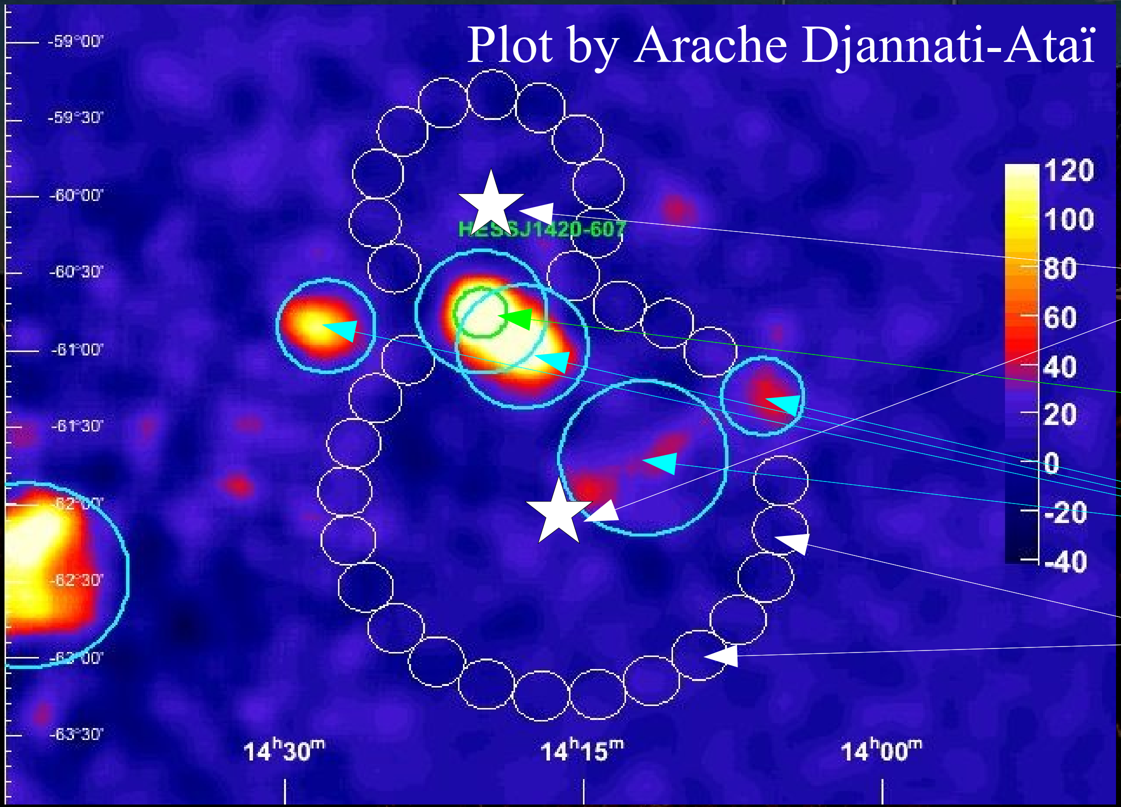




Multiple Off Background

- ❑ Extension of wobble mode:
  - ❑ Several OFF regions distributed at equal distance to camera centre
  - ❑ *a priori* exclusion of known source (iterative process)
  - ❑ No map...




Plot by Arache Djannati-Ataï

pointing

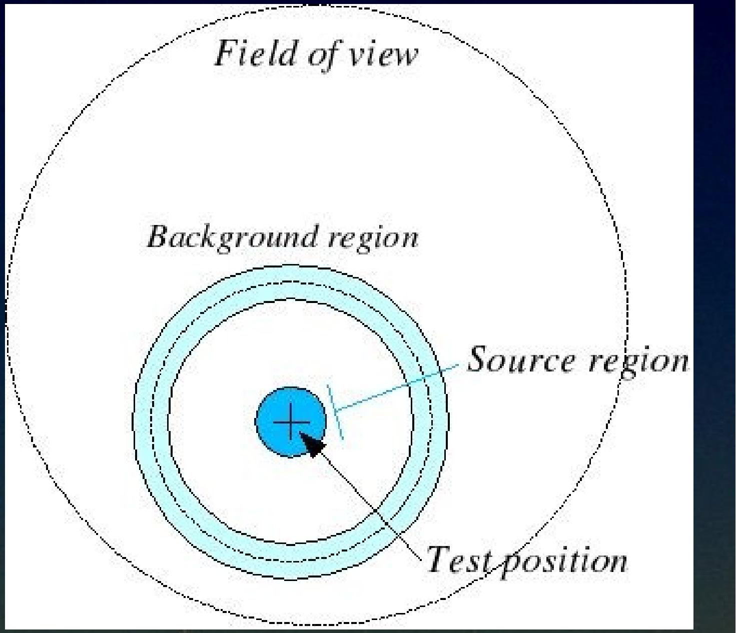
Target Region

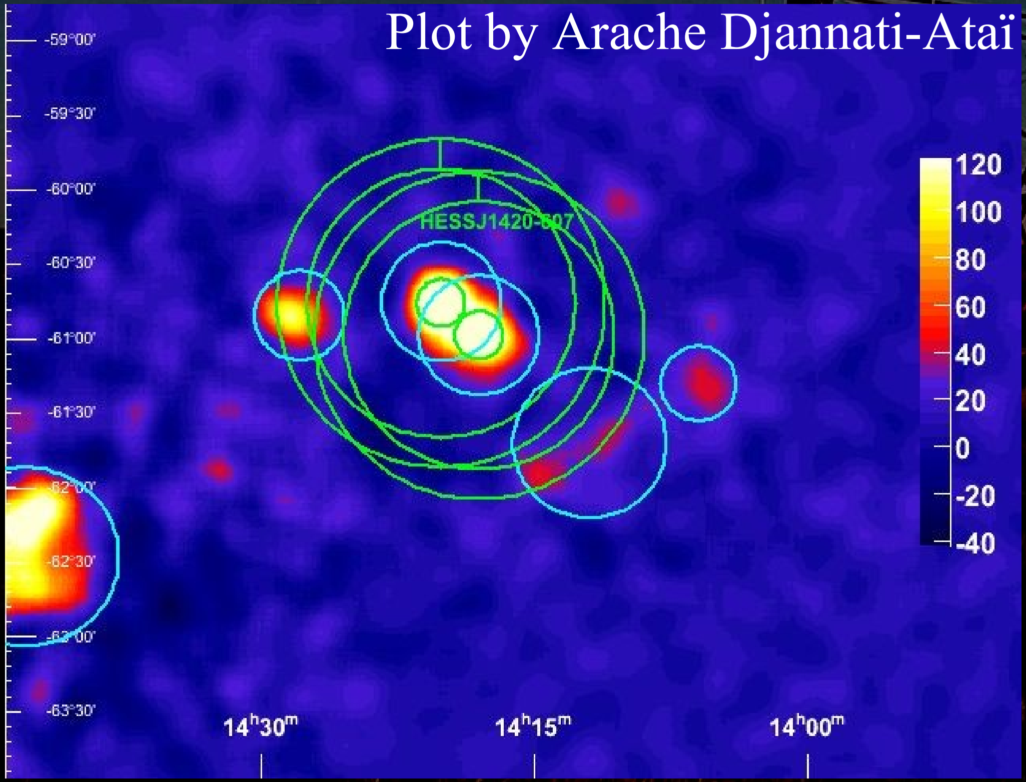
Excluded Regions

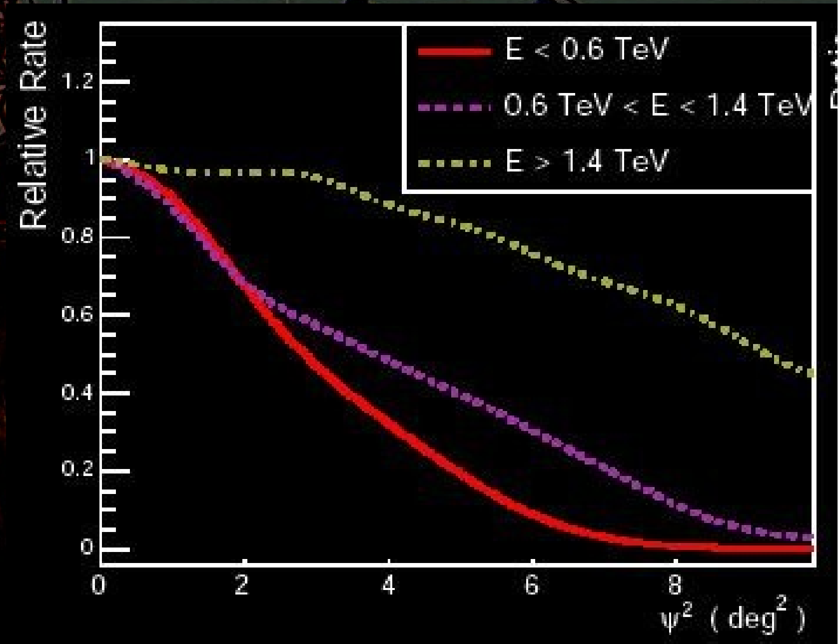
OFF Regions

Ring Background

- ❑ Background from a ring centred on each test position. Not at equal distance to centre
- ❑ Radial acceptance correction (averaged)
- ❑ Energy dependency of radial acceptance not taken into account (yet) ⇒ no spectra, just maps

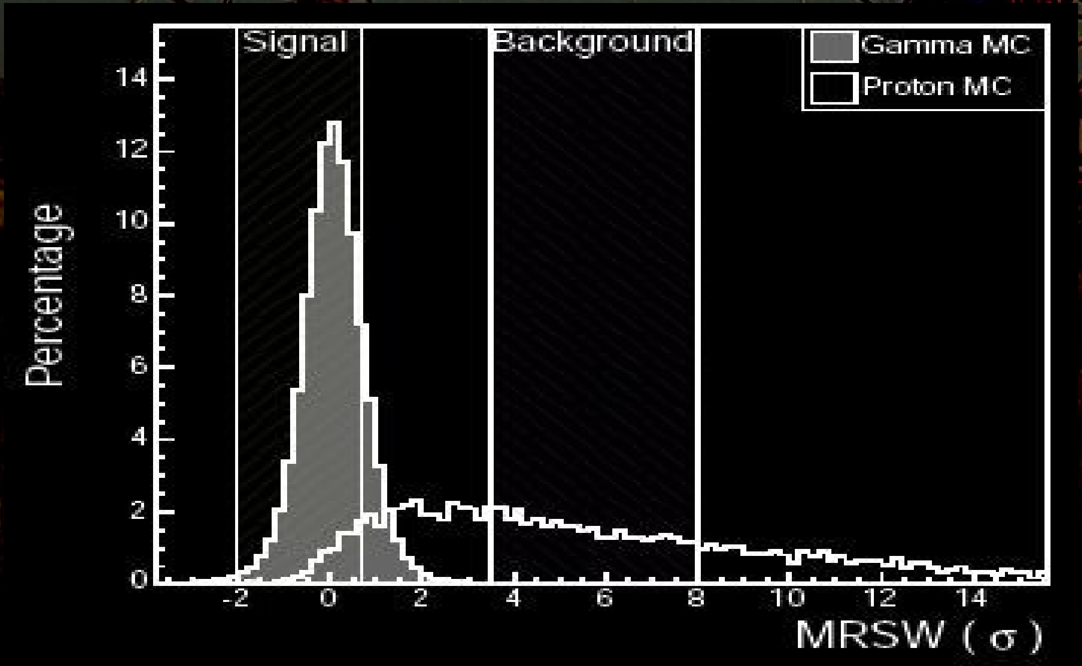


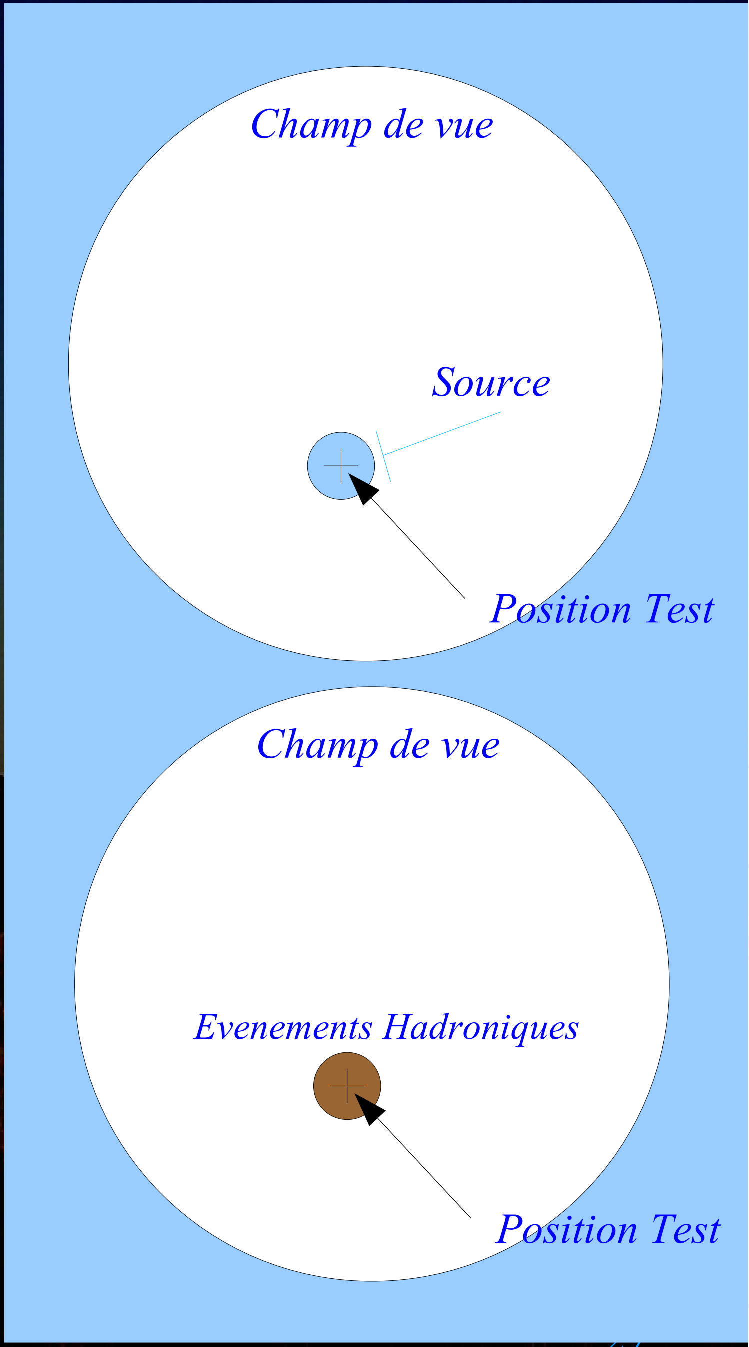

Plot by Arache Djannati-Ataï



Template Model

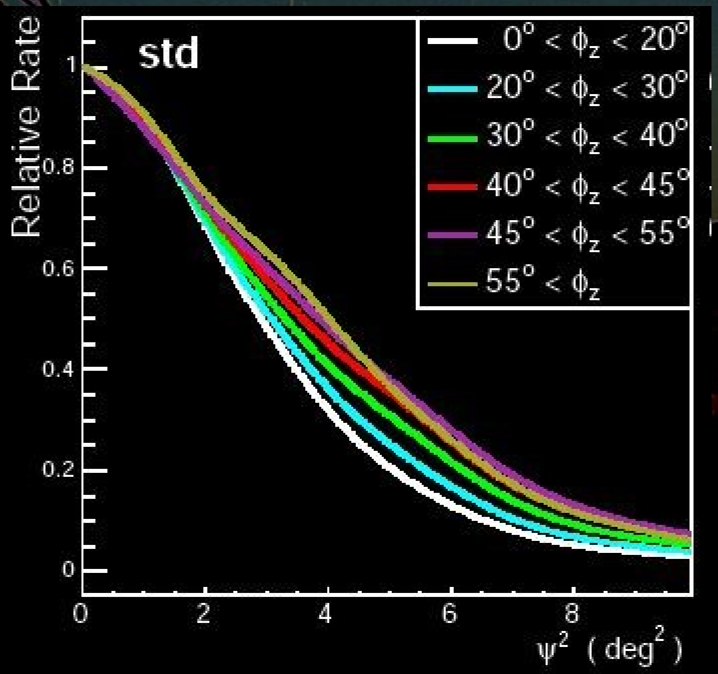
- Use an alternate (“hadron-like”) population at the same position
- ⇒ Acceptance needed for both populations
- Only map (energy badly controlled for hadrons)
- Good for large sources and/or crowded FOV (RXJ 1713,...)





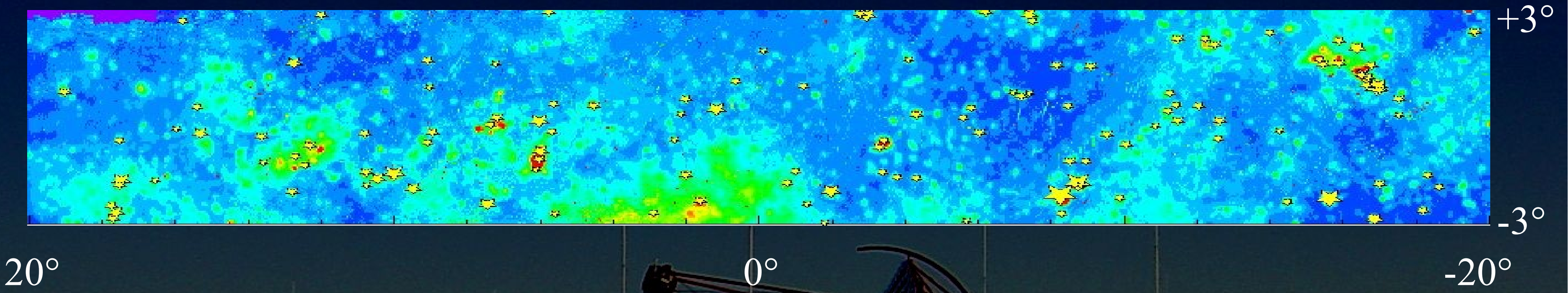
Field-of-view background
Toward diffuse emission?

- ❑ To be able to detect large structure, one need to derive the acceptance from alternate data (or MC)
  - ❑ Precalculated acceptance curves (as function of zenith)
  - ❑ Still need normalisation on a fraction of FOV (absolute level) ⇒ signal free region needed in FOV
- ❑ Good for large sources (and for diffuse?)
- ❑ But control of systematics (NSB,...) very tricky, not reliable yet for faint sources
- ❑ Need large amount of data taken with similar conditions (NSB, reflectivity, ...) and without source



Night sky background measurement (NSB)

- HESS estimation from pedestal width (noise dist. in PMTs)

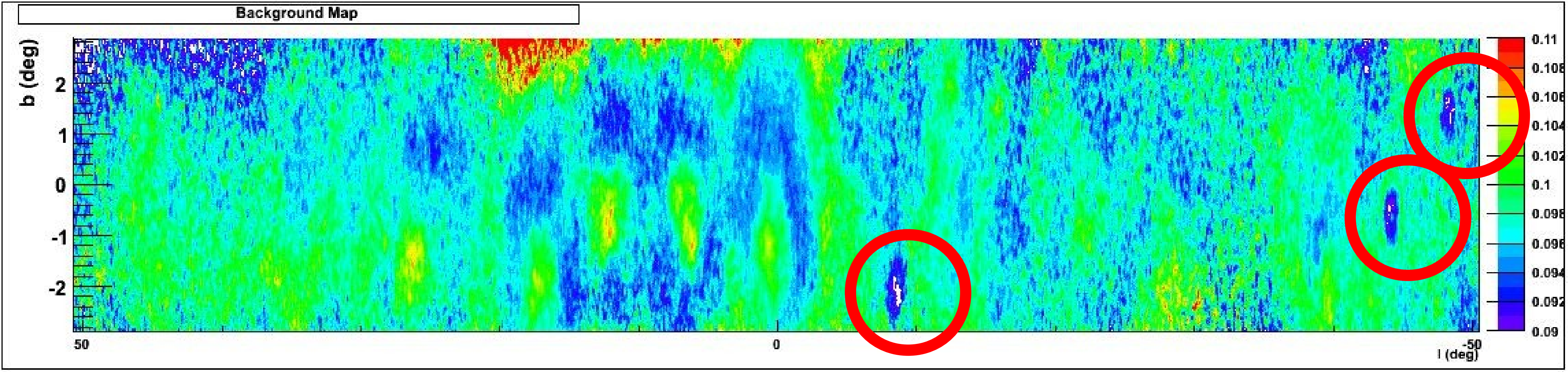


- Good correlation with optical

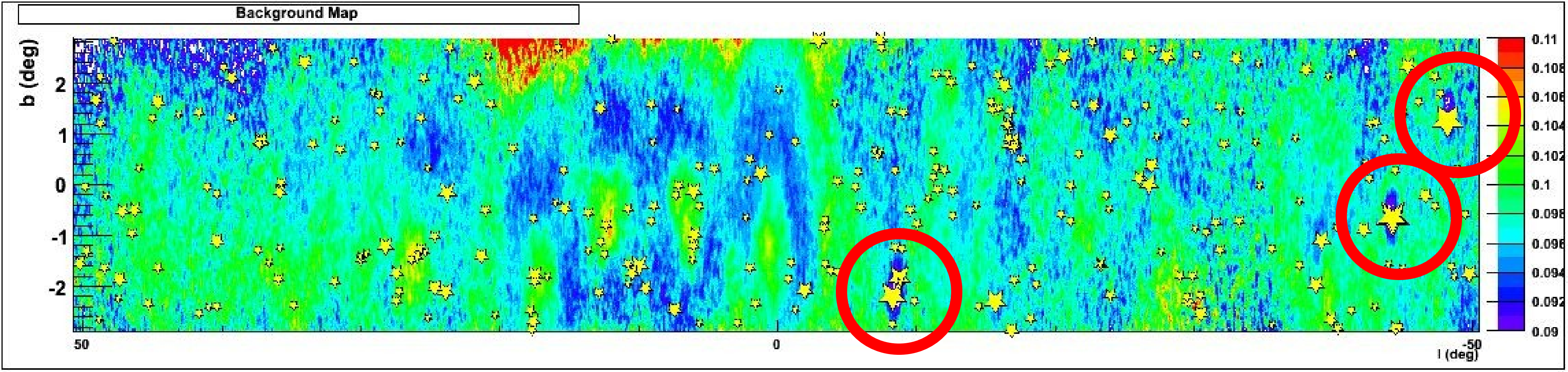
Plot: Aldée Charbonnier

NSB anisotropies effect

- Acceptance to hadrons in Galactic plane: ± 3%(RMS) fluctuations

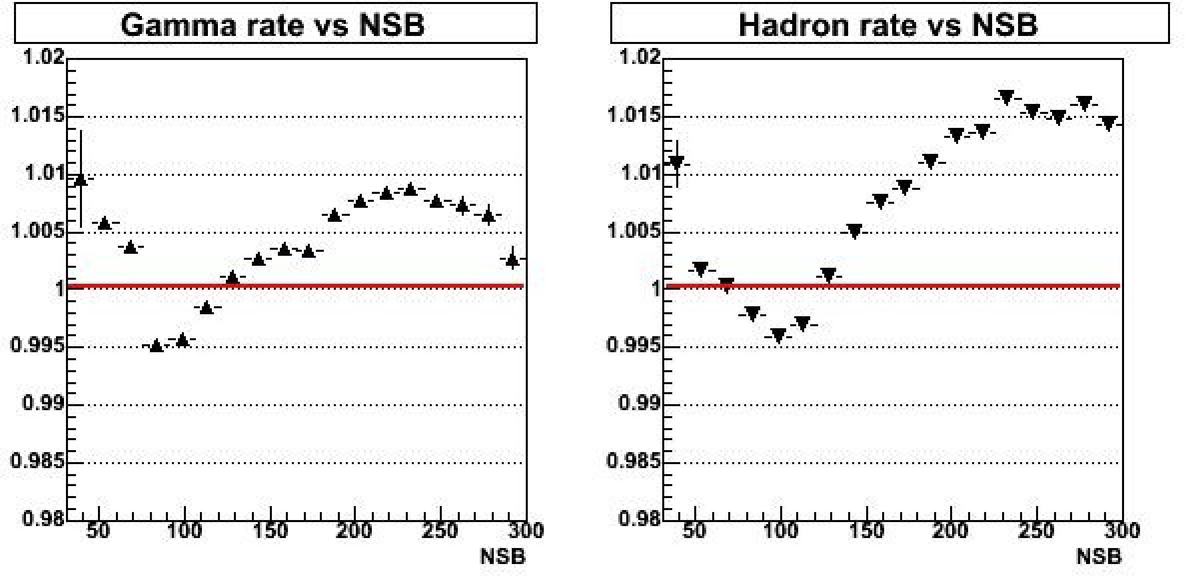


- some "holes"
- ... correlated with bright stars : pixels switched off



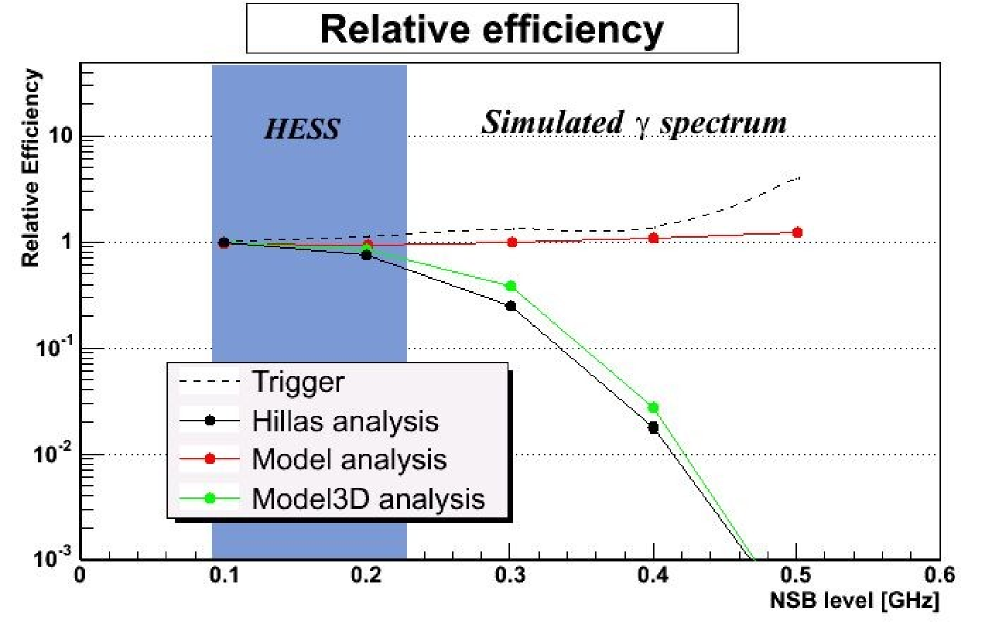
NSB effect on event rate in cuts

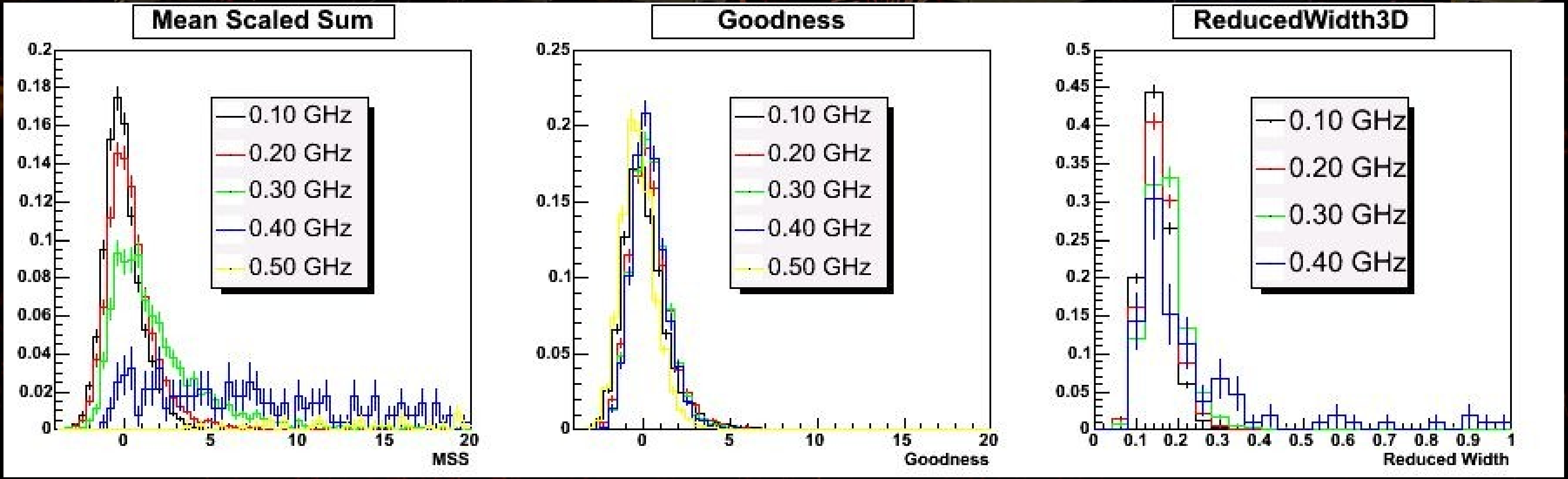
- ☐ Correlated fluctuations at the level of 1%
- ☐ Does not account for all discrepancies...



NSB effect on discrimination

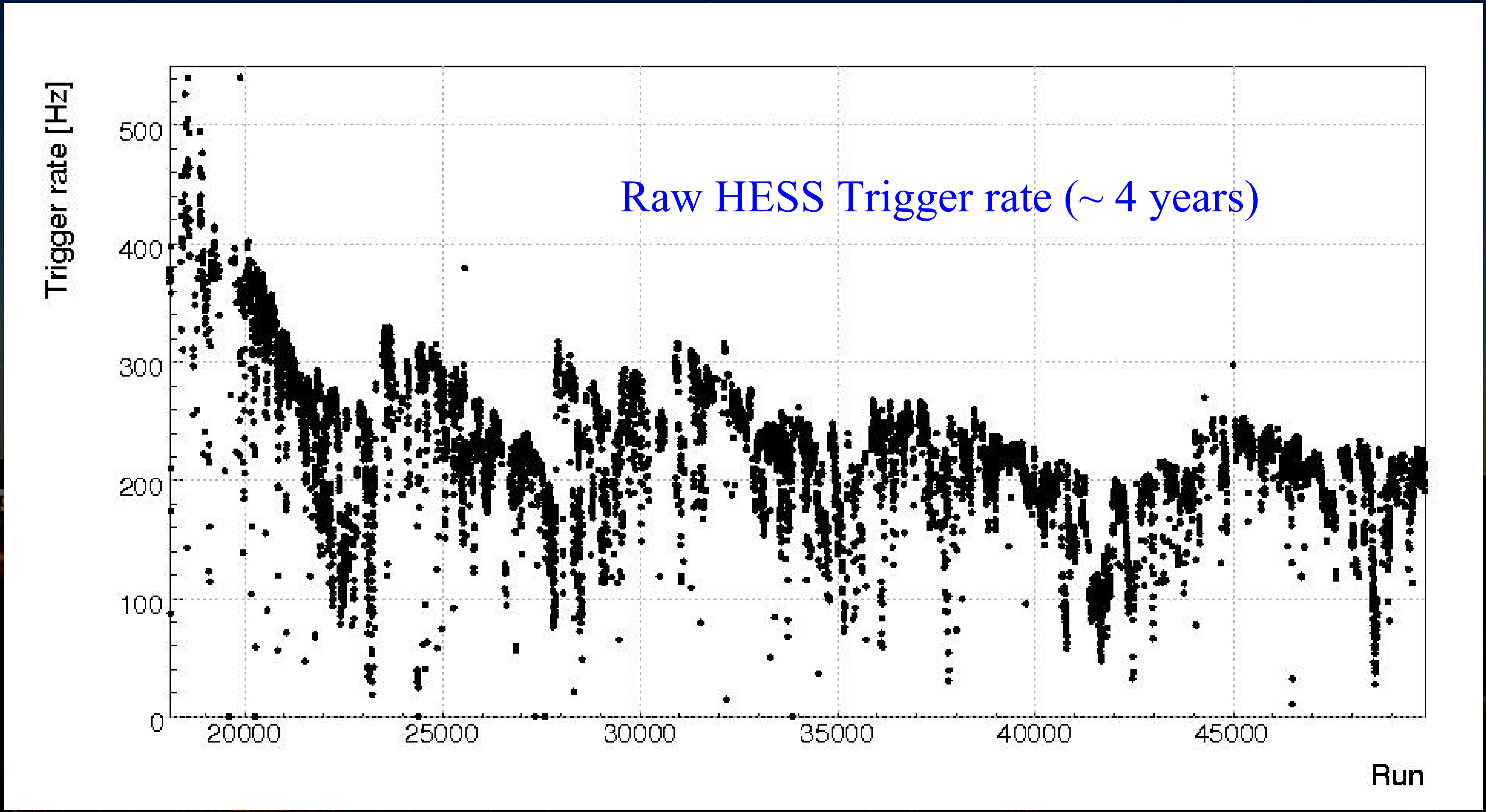
- Effect on acceptance to γ
  - Hillas: Scaled parameters degraded
  - Model : goodness stable
  - Model 3D : worse fit convergence
- Quite similar effect on hadrons





Toward a diffuse emission analysis

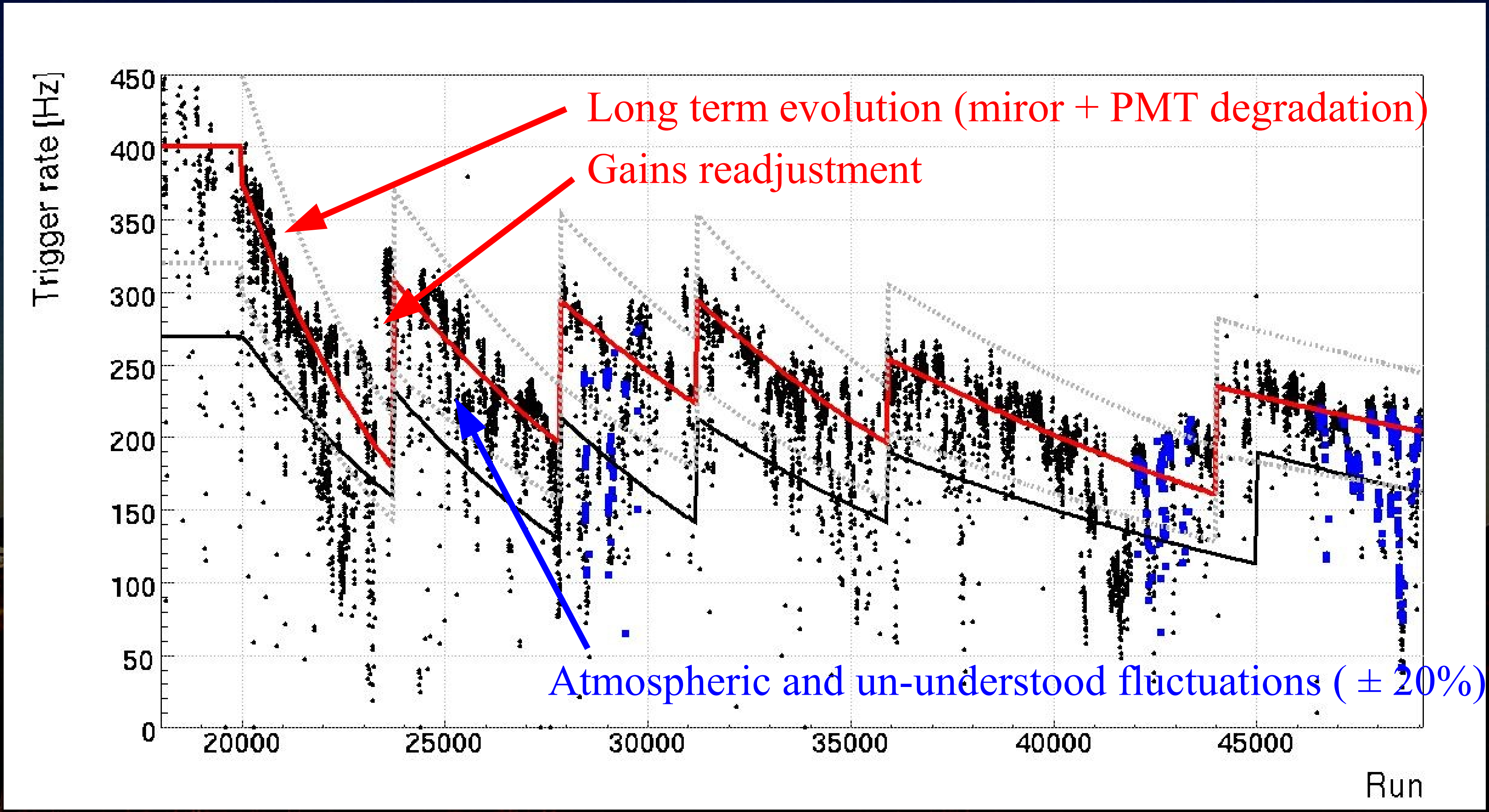
- ☐ Is diffuse emission analysis possible?
- ☐ i.e. Do we understand the instrument enough ?



Raw HESS Trigger rate (~ 4 years)

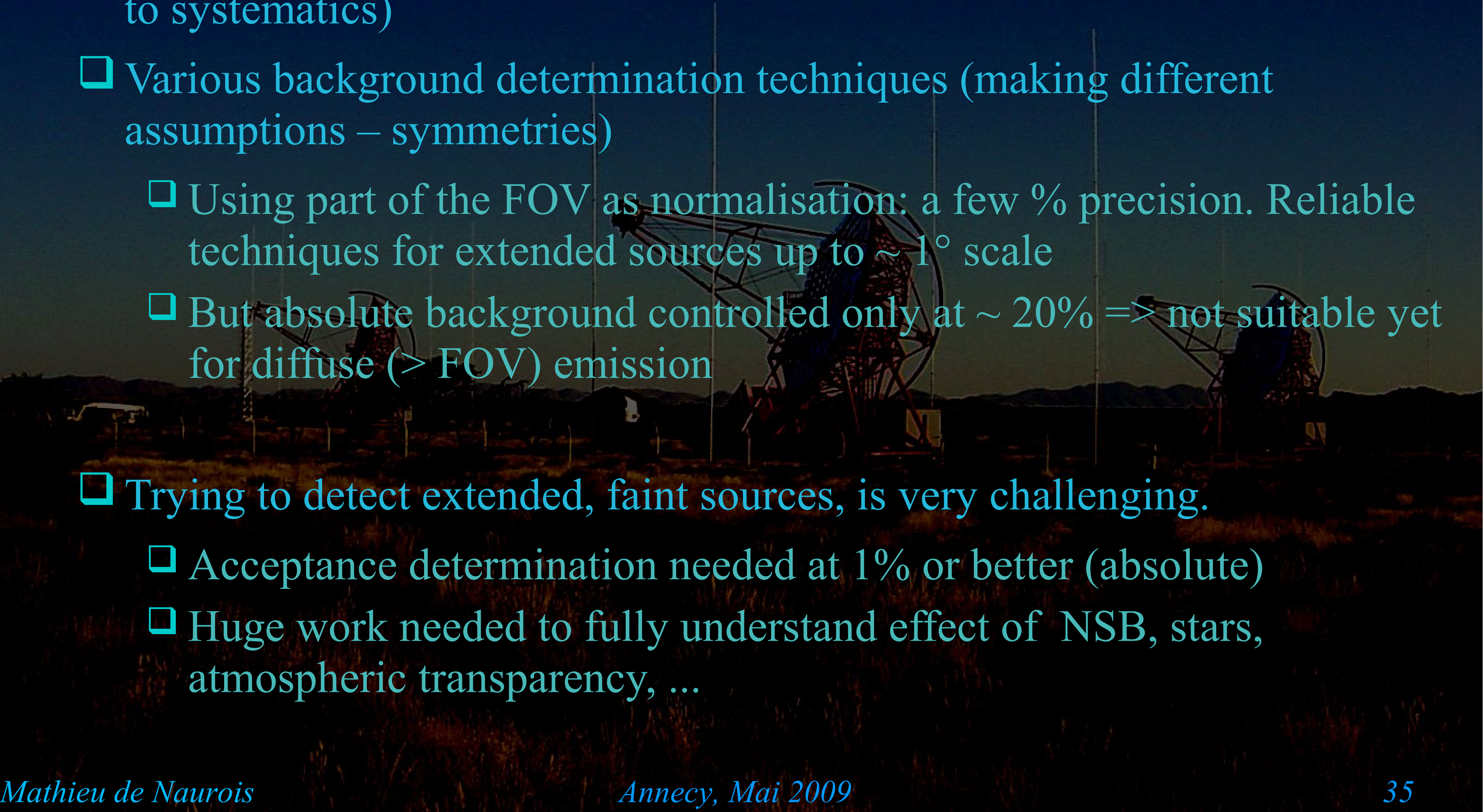
Trigger rate

- With zenith angle correction



- Only partially correlated with meteorological measurement (backscattered light, radiometers, …)

Conclusions



- Various reconstruction techniques (different performances and sensitivity to systematics)
- Various background determination techniques (making different assumptions – symmetries)
  - Using part of the FOV as normalisation: a few % precision. Reliable techniques for extended sources up to ~ 1° scale
  - But absolute background controlled only at ~ 20% => not suitable yet for diffuse (> FOV) emission
- Trying to detect extended, faint sources, is very challenging.
  - Acceptance determination needed at 1% or better (absolute)
  - Huge work needed to fully understand effect of NSB, stars, atmospheric transparency, ...