Advanced Image Cleaning for Cherenkov Telescopes

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LEPCHE

B. 709 p. 120

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The road so far

2008

- Master degree in Computer Science (Paris V)

2011

- Master degree in Artificial Intelligence (UPMC, Paris VI)
  - Mathematical optimization
  - Machine learning (classification + regression)

The road so far

2014

- PhD at Inria Saclay (LRI)
- TAO team

  Mathematical Optimization + Machine Learning

The road so far 臺灣

2014

- PhD at Inria Saclay (LRI)
- TAO team

  Mathematical Optimization + Machine Learning
- 5 months in Taiwan

The road so far

- Subject: *Hybridization of dynamic optimization methodologies*
  - Sequential decision making (a.k.a. multistage optimization) and reinforcement learning
  - Mainly applied to power systems and energy stock management (hydropower), in front of stochastic demand and production

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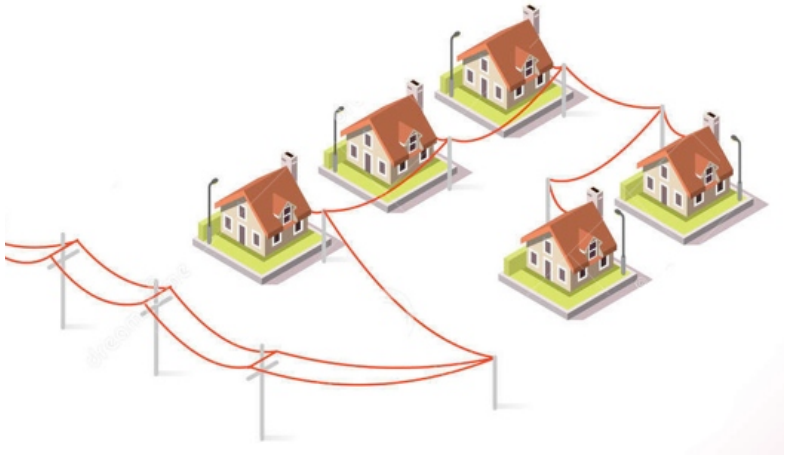

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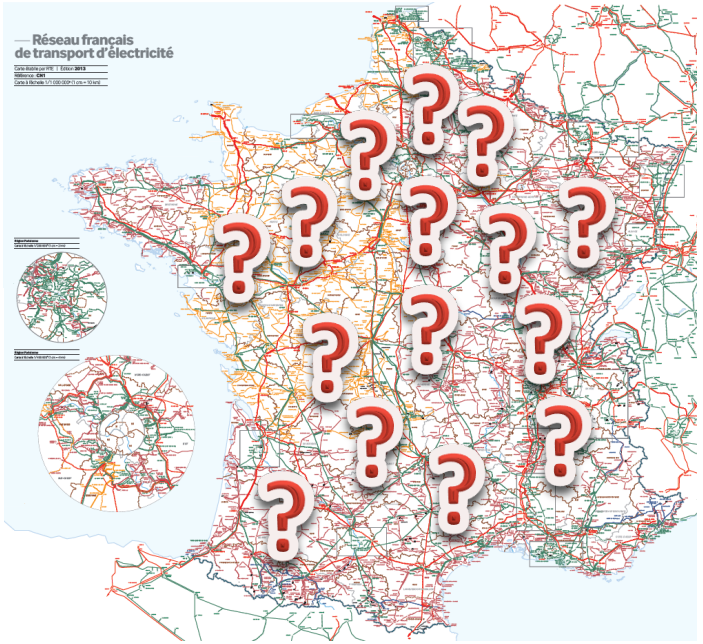

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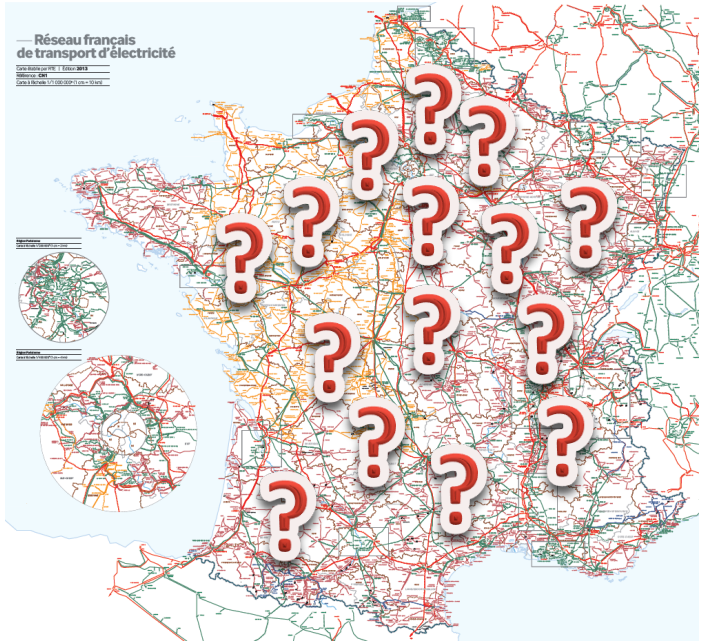

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Manuscript: http://www.jdhp.org/phd.pdf

The road so far

2015

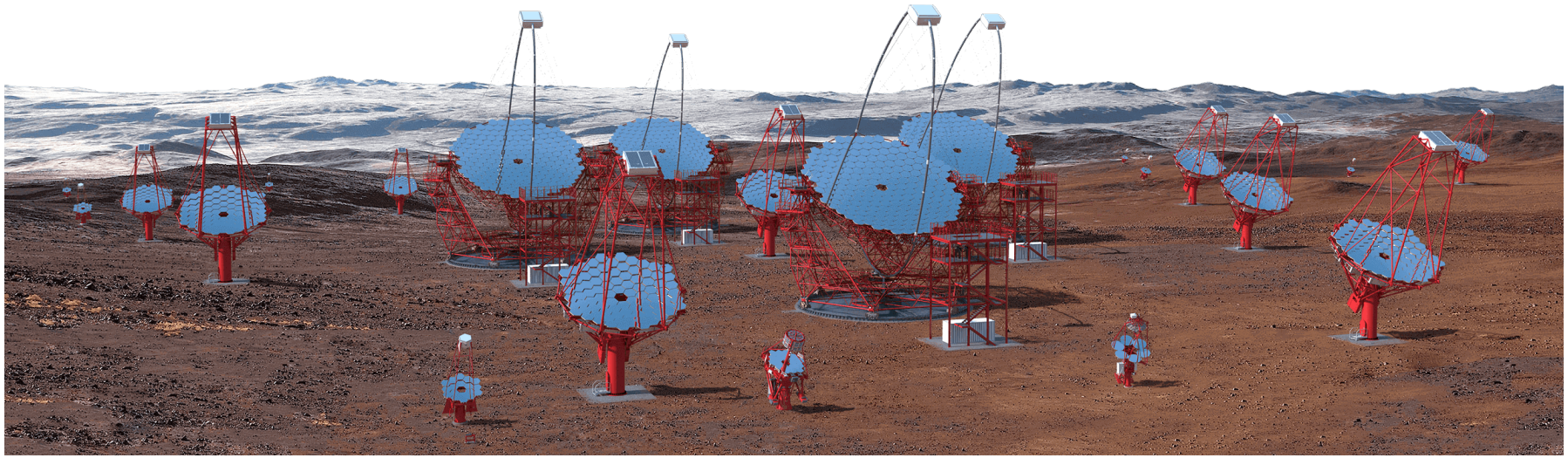
- Postdoc at Inria
- Parallelization of "Cutting Plane" methods

2016

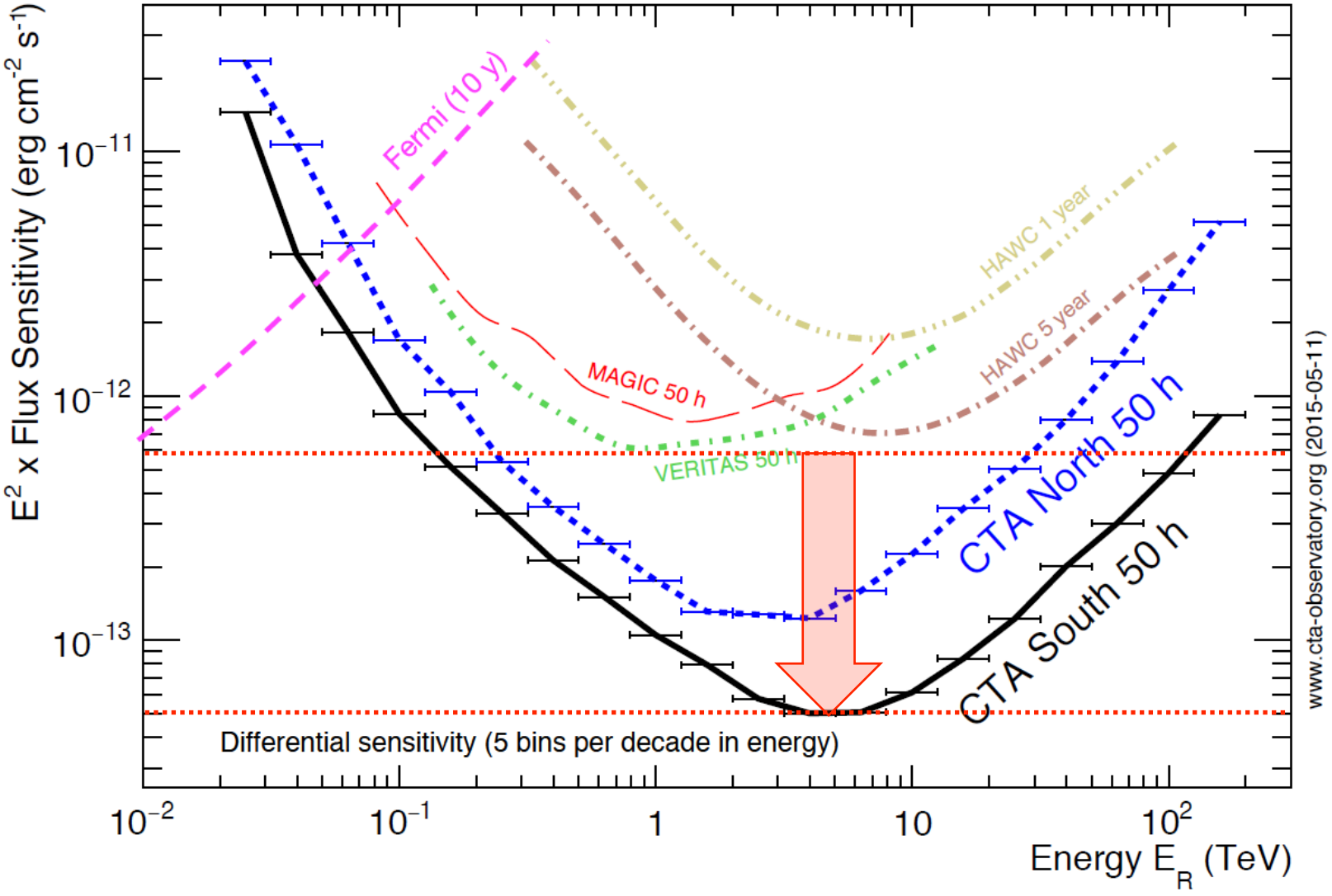
- CTA group at CEA, pipeline team
  - F.Acero, K.Brugge, K.Kosack, D.Landriu, T.Michael, T.Stolarczyk
  - Collaboration with Cosmostat
- New methods to improve the signal to noise ratio at the level of instruments

Context: CTA

cherenkov telescope array

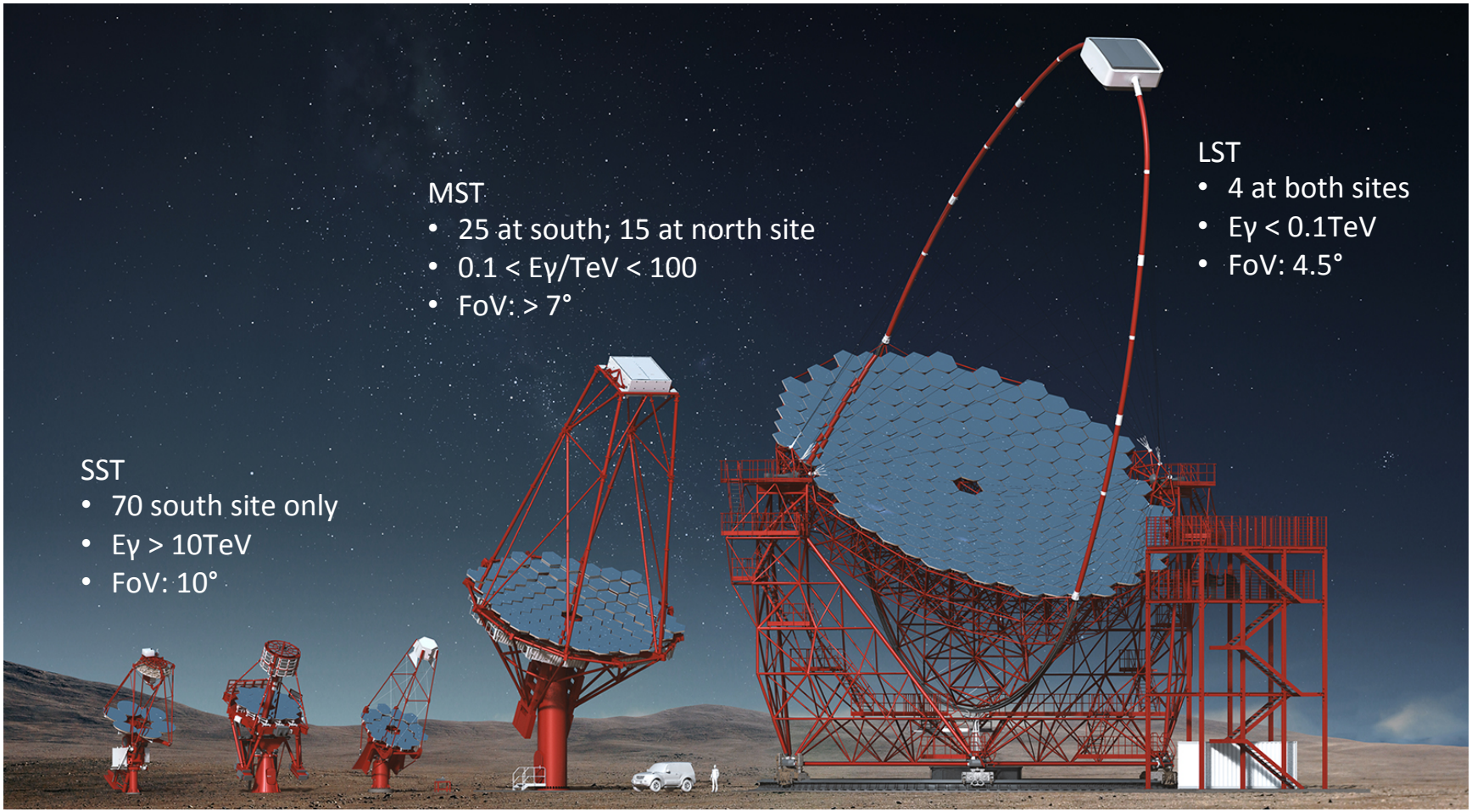


Performance - Sensitivity



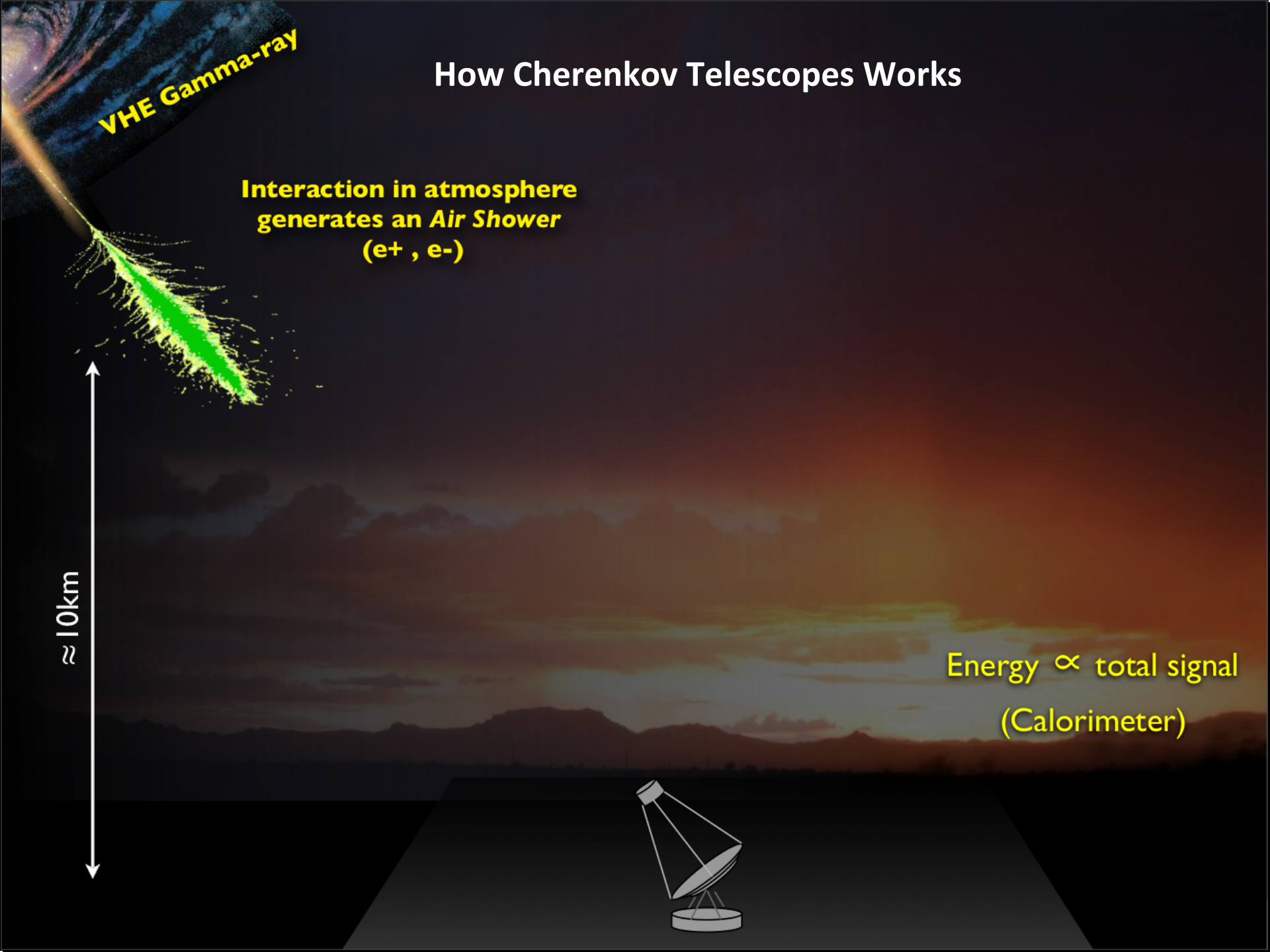
2 sites: La Palma (Spain) and Paranal (Chile)

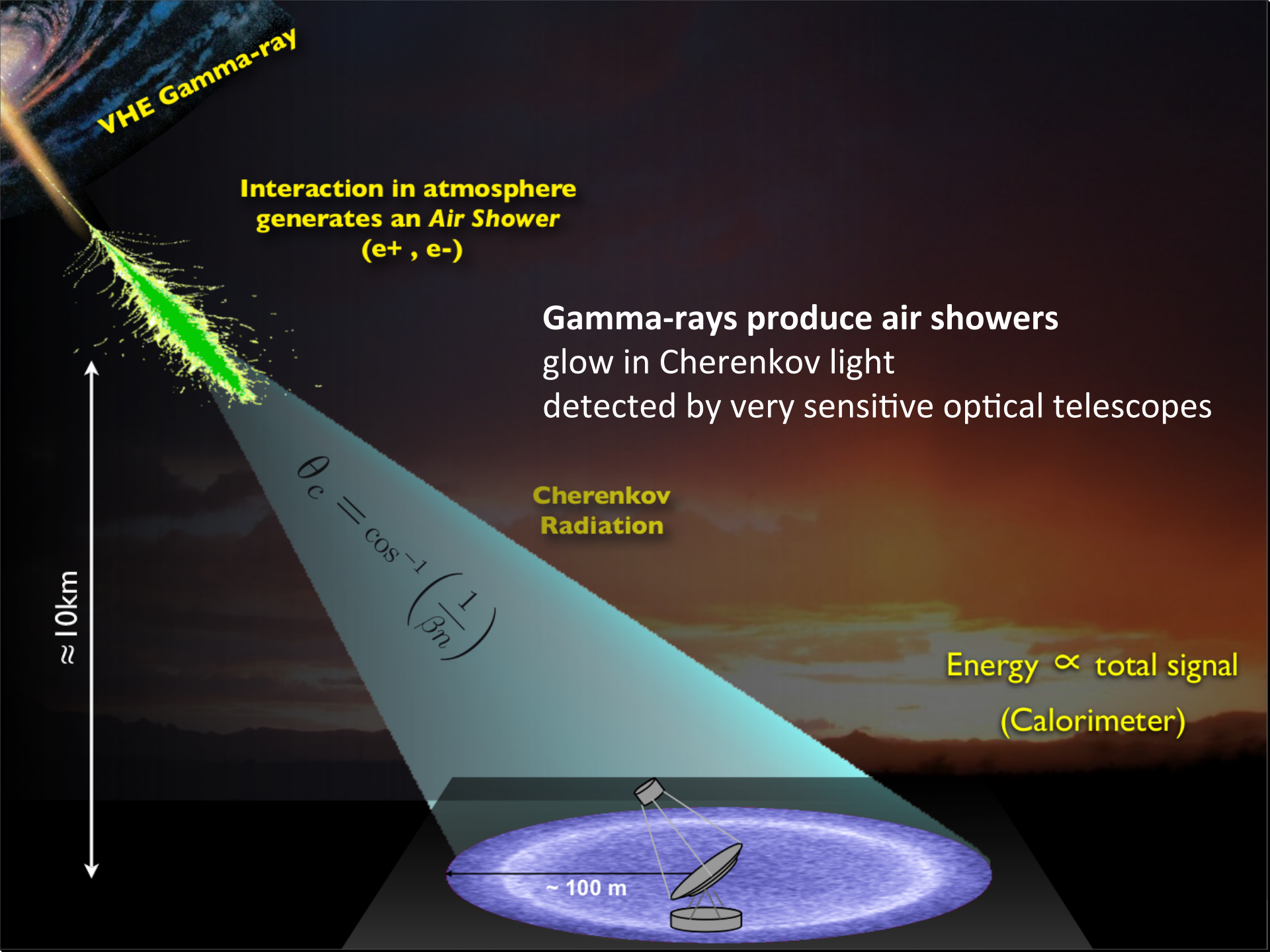
3 telescope size

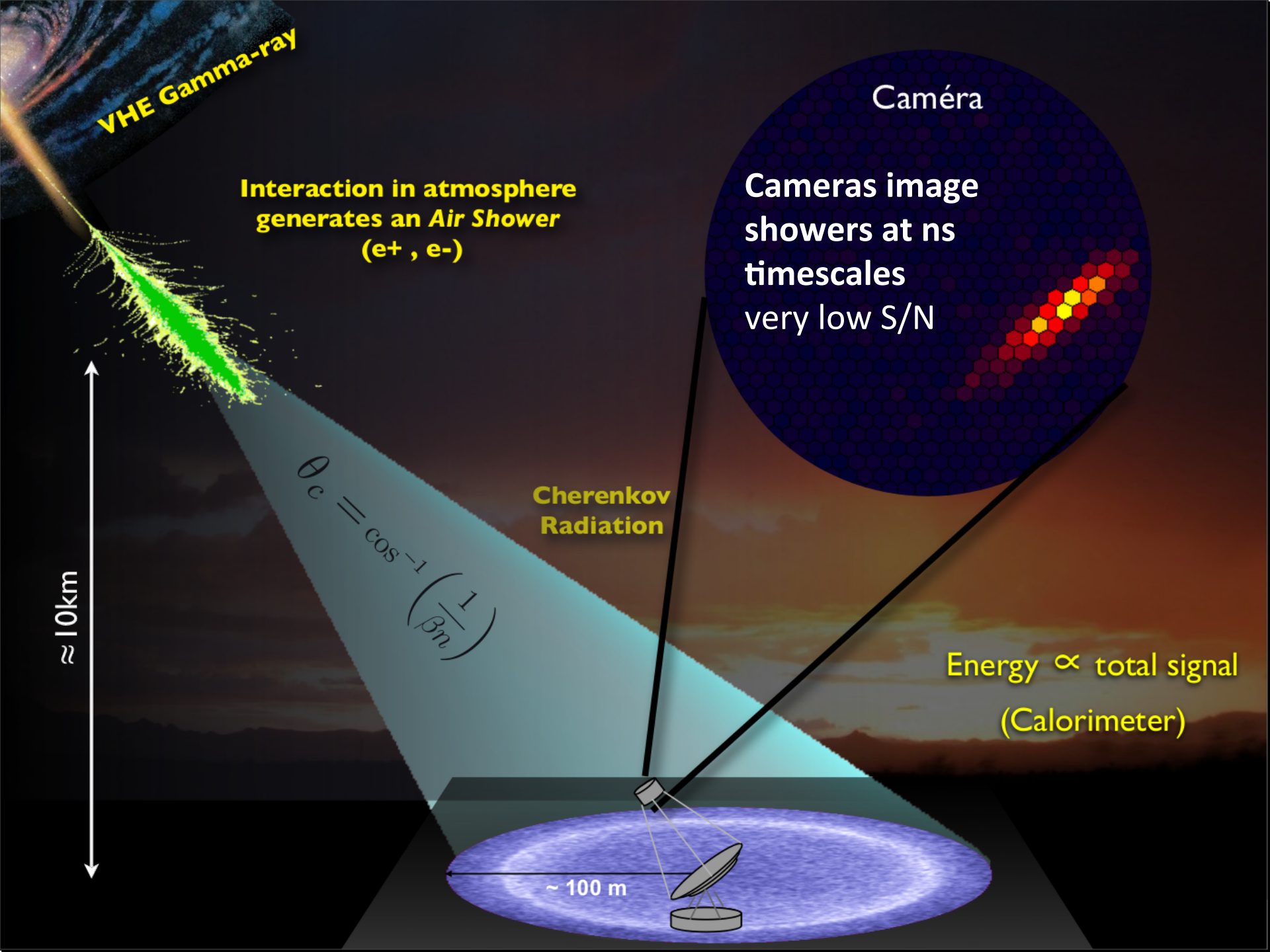


Construction started

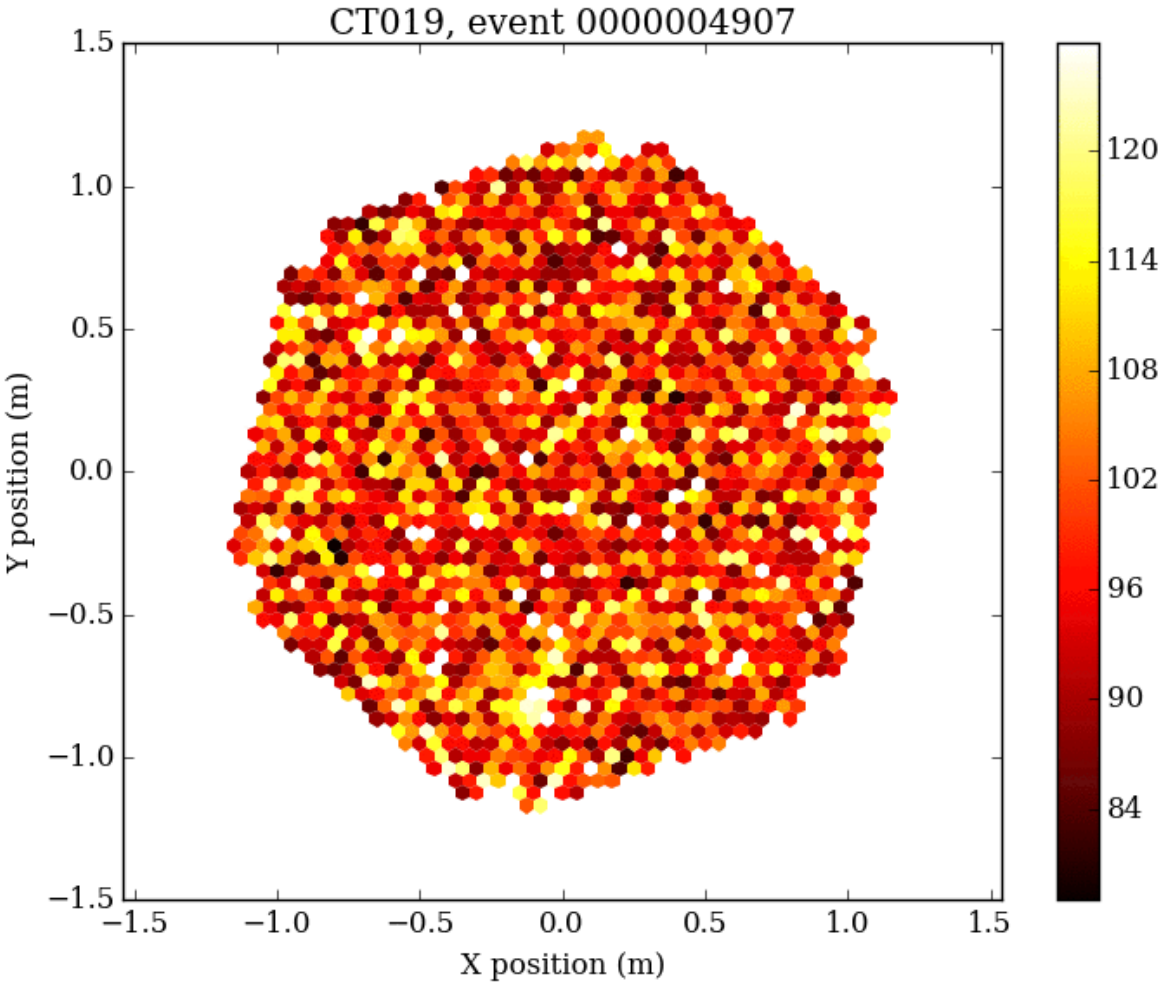
How Cherenkov Telescopes Works

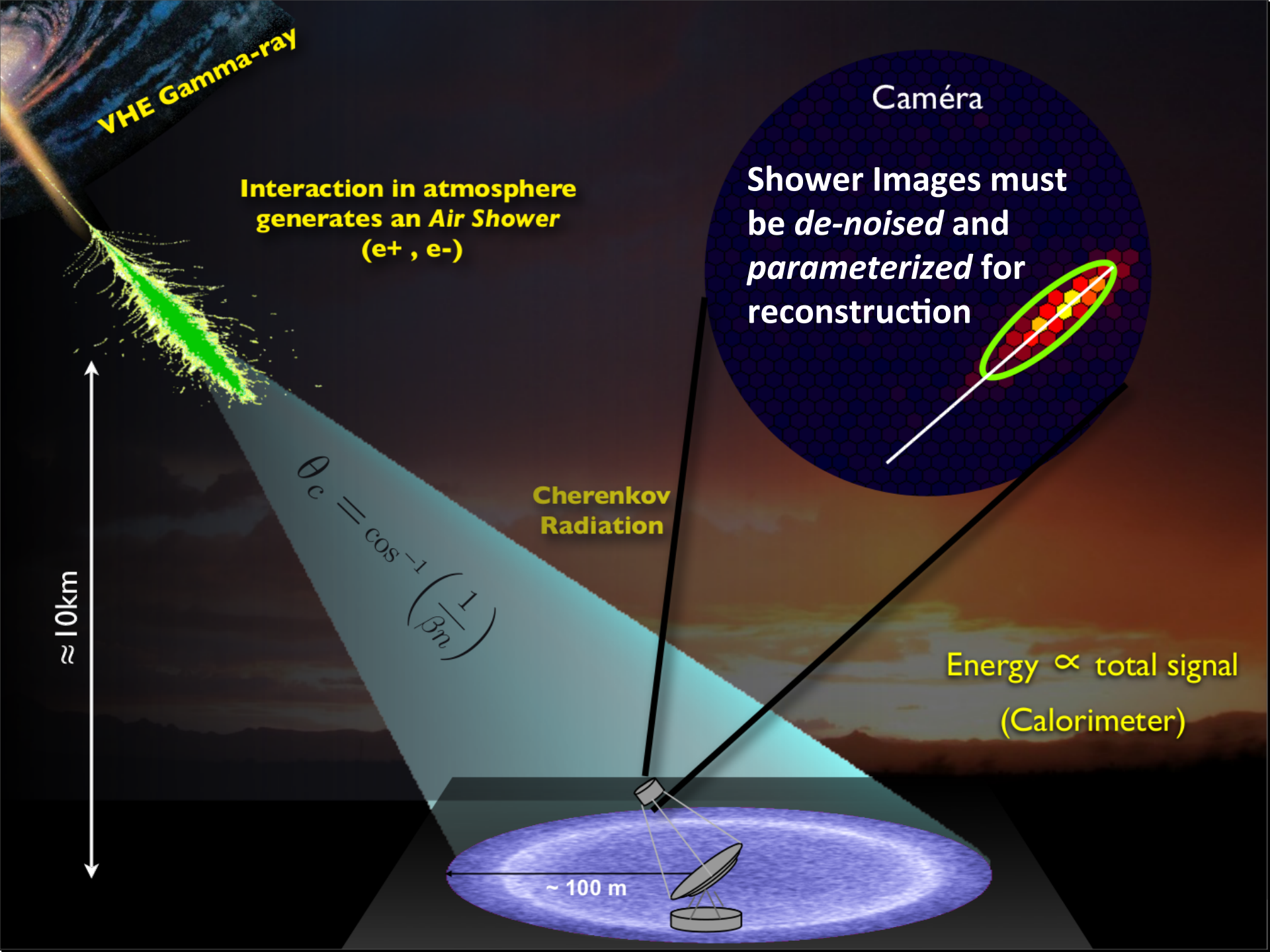


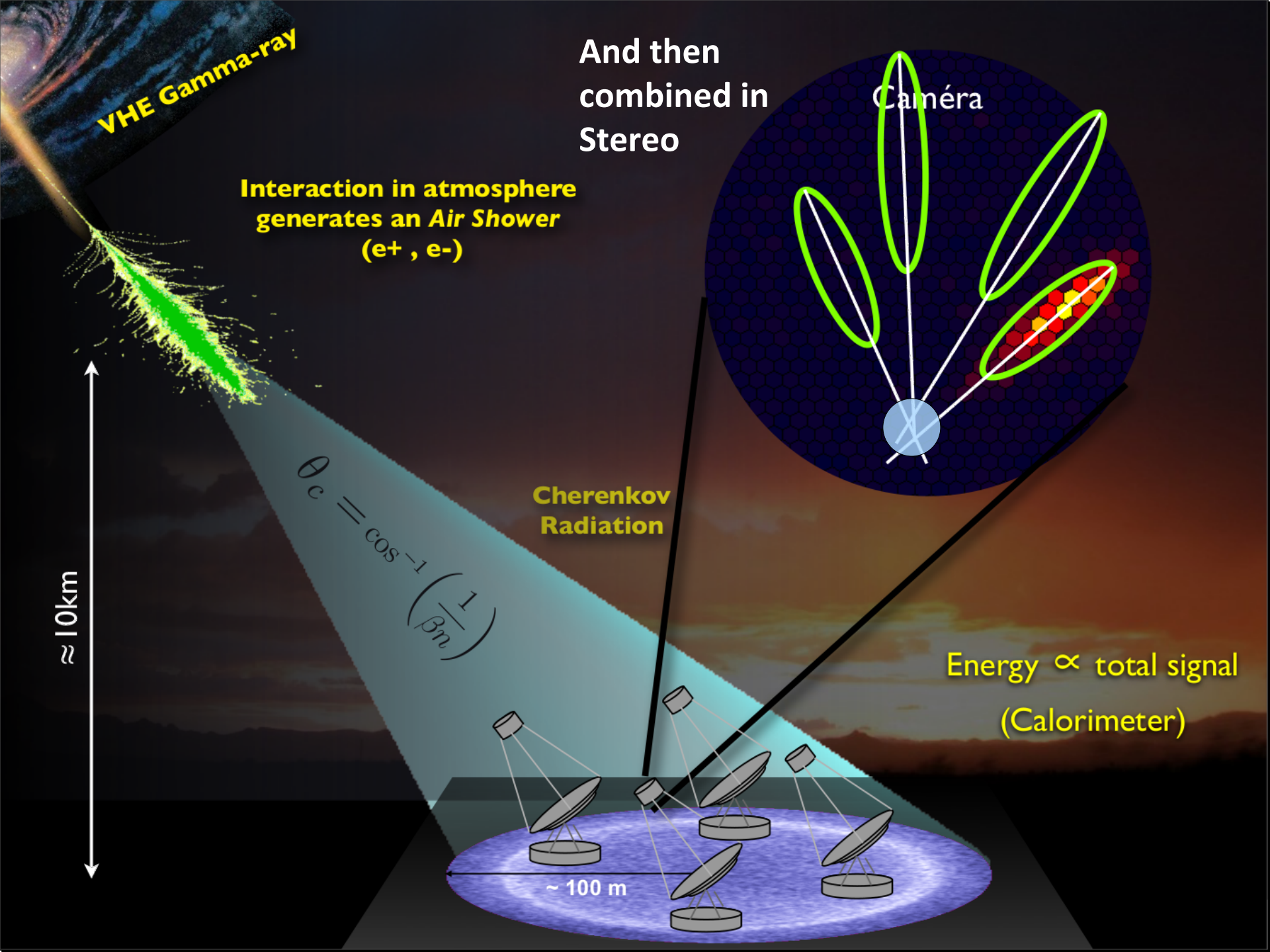

VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
Gamma-rays produce air showers
glow in Cherenkov light
detected by very sensitive optical telescopes
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
Cherenkov
Radiation
≈ 10km
Energy ∝ total signal
(Calorimeter)
~ 100 m


VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
Caméra
Cameras image
showers at ns
timescales
very low S/N
Cherenkov
Radiation
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
≈ 10km
Energy ∝ total signal
(Calorimeter)
~ 100 m

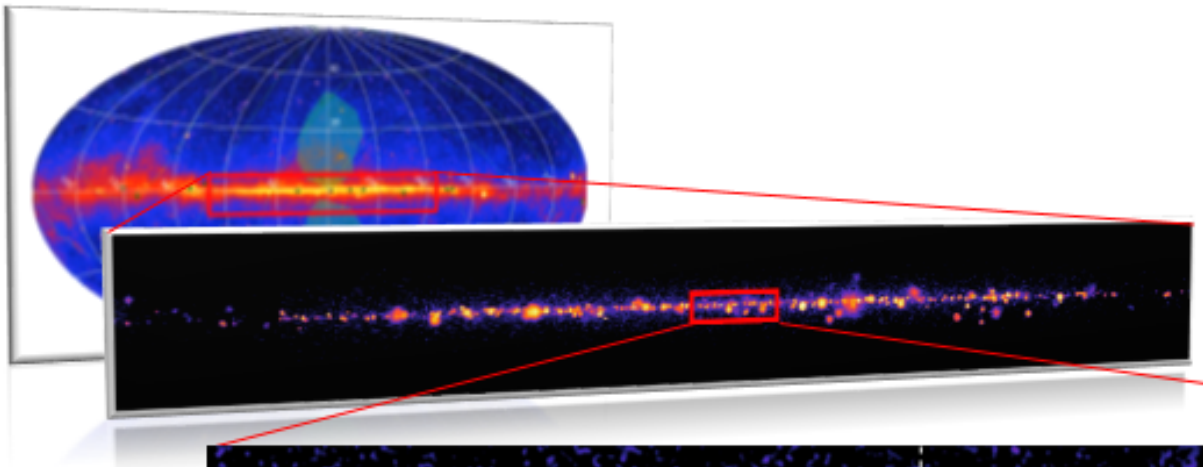
Example

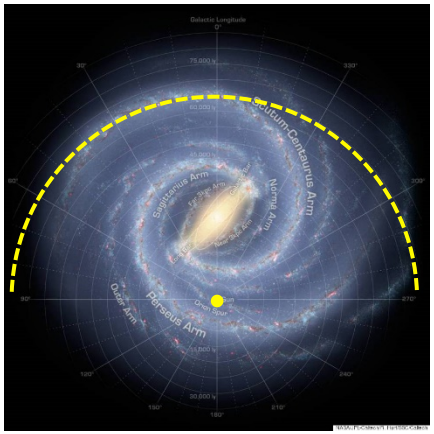

CT019, event 0000004907
Y position (m)
X position (m)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
120
114
108
102
96
90
84

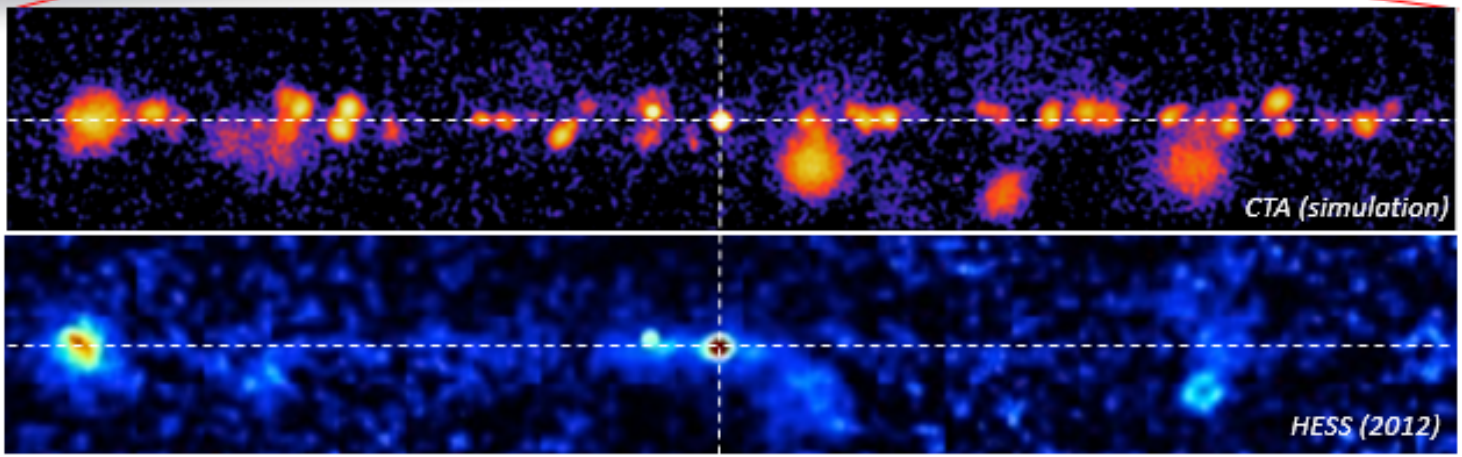

VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
Caméra
Shower Images must
be *de-noised* and
parameterized for
reconstruction
Cherenkov
Radiation
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
≈ 10km
~ 100 m
Energy ∝ total signal
(Calorimeter)

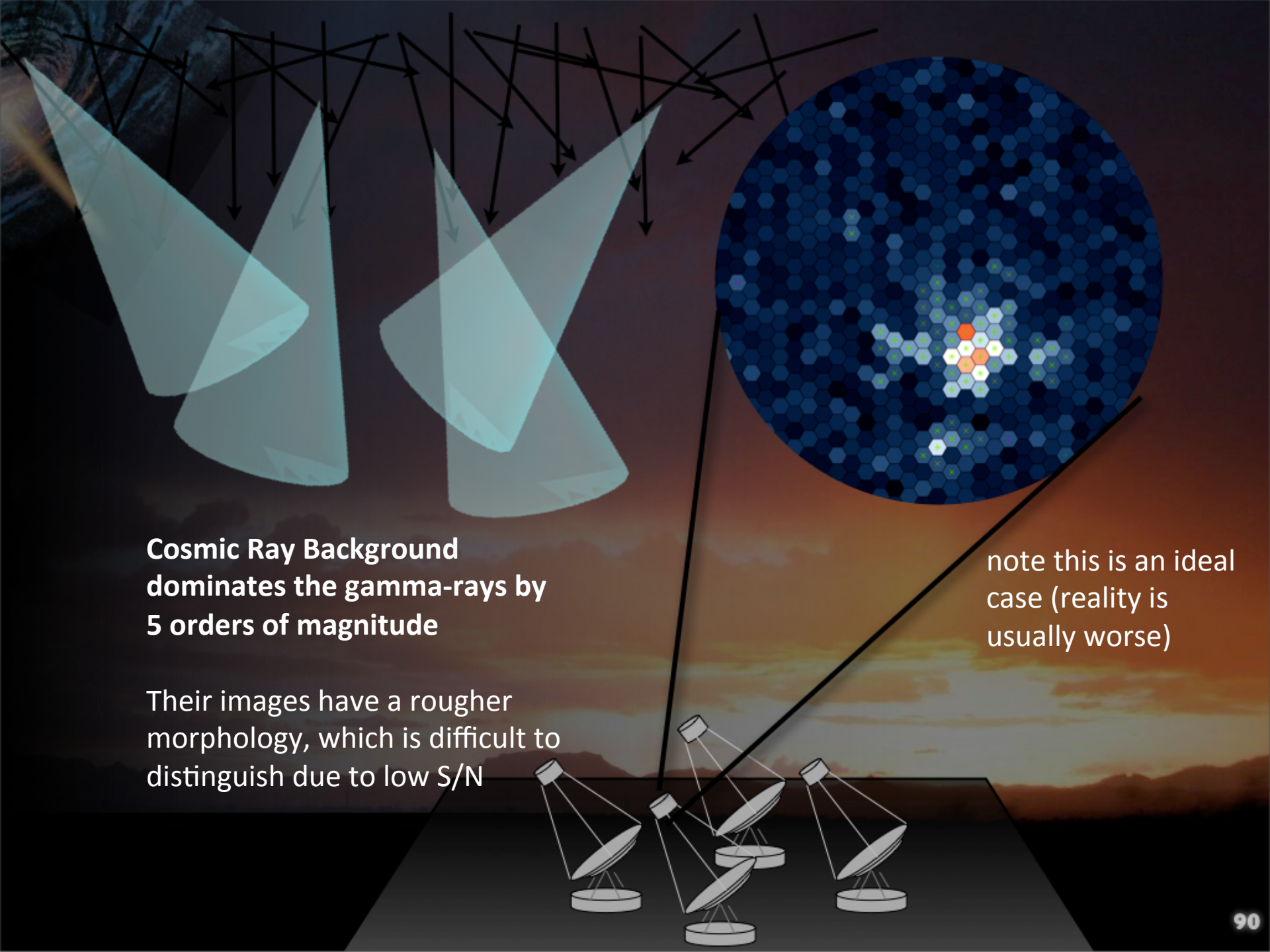

VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
And then
combined in
Stereo
Caméra
Cherenkov
Radiation
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
≈ 10km
~ 100 m
Energy ∝ total signal
(Calorimeter)

Sky maps



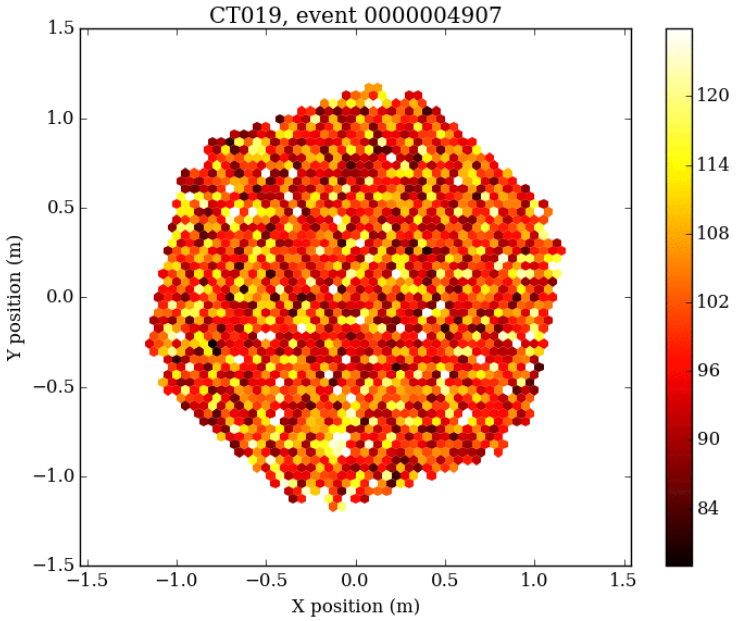

Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm


CTA (simulation)
HESS (2012)

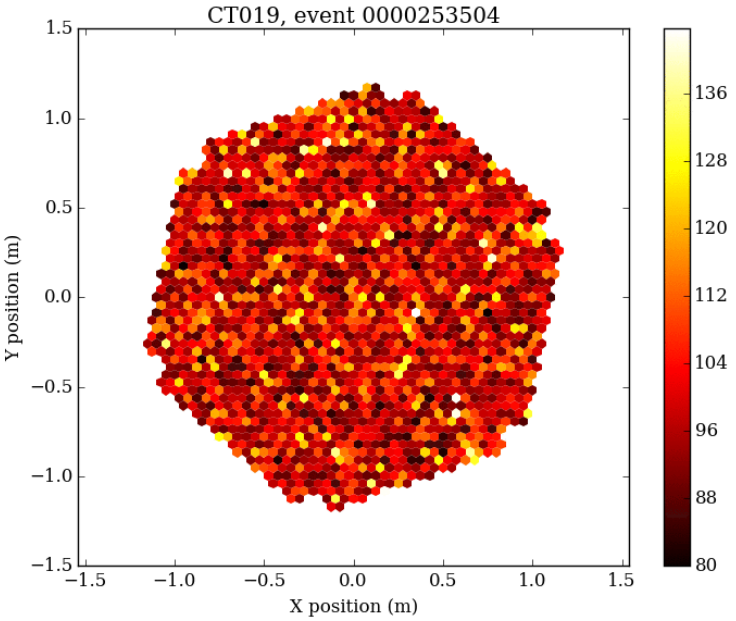

Cosmic Ray Background dominates the gamma-rays by 5 orders of magnitude
Their images have a rougher morphology, which is difficult to distinguish due to low S/N
note this is an ideal case (reality is usually worse)

Examples

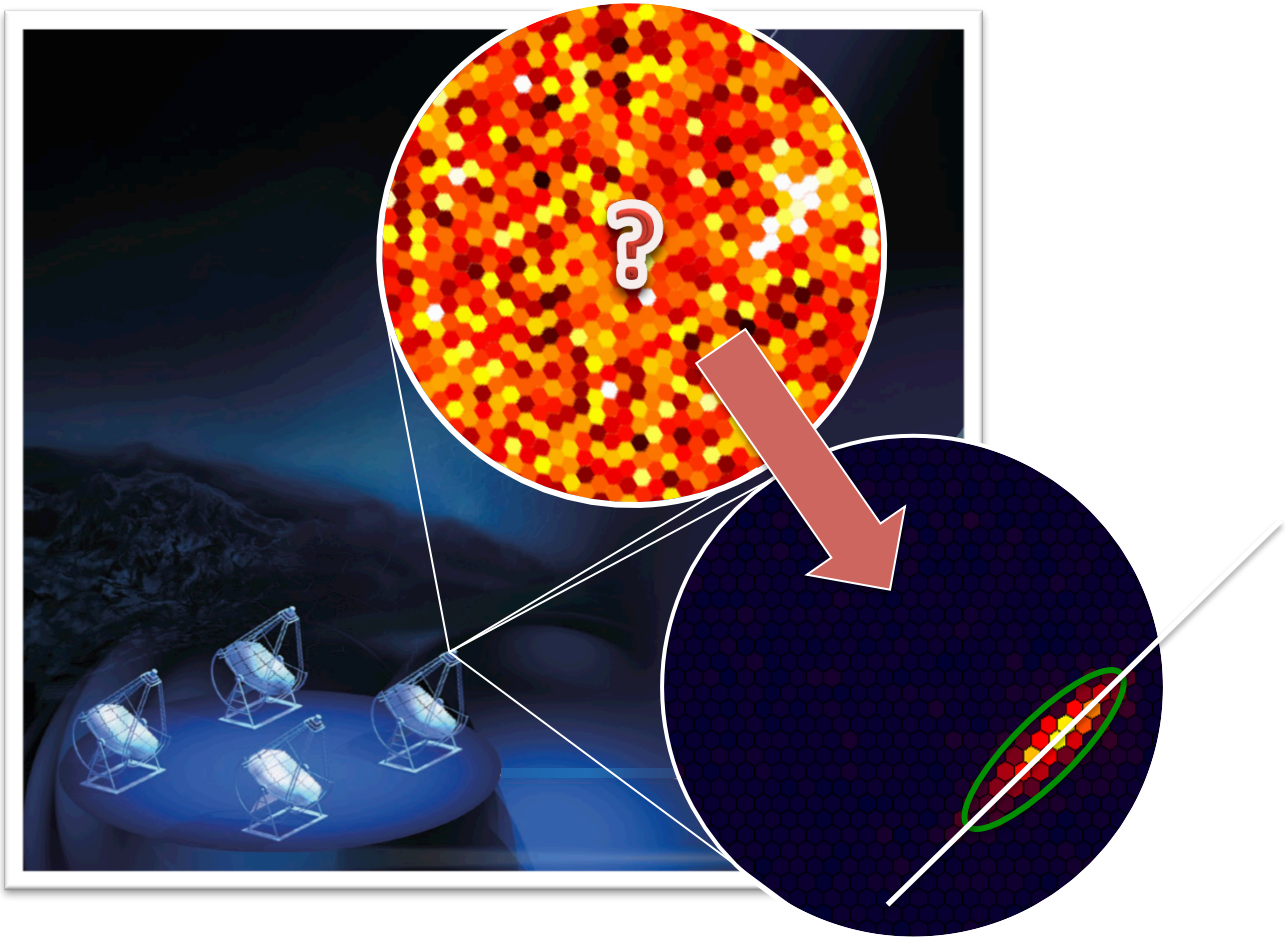
Gamma rays



Protons



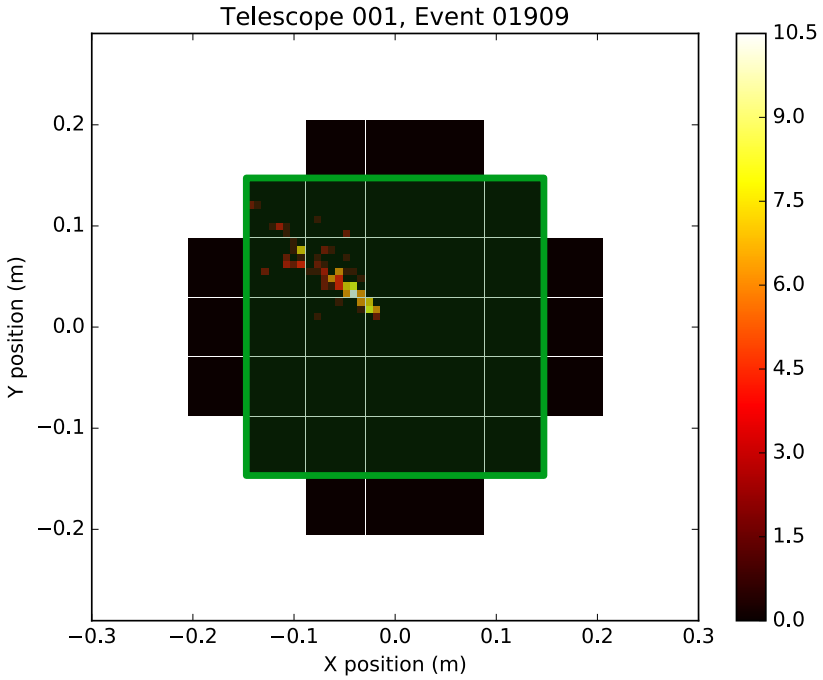
My task: image cleaning



Experimental setting

Dataset used to assess cleaning algorithms

- Monte-Carlo simulations: gamma-ray 100 GeV up to 100 TeV + protons
- ASTRI telescopes
- Cropped to get squared pixel arrays

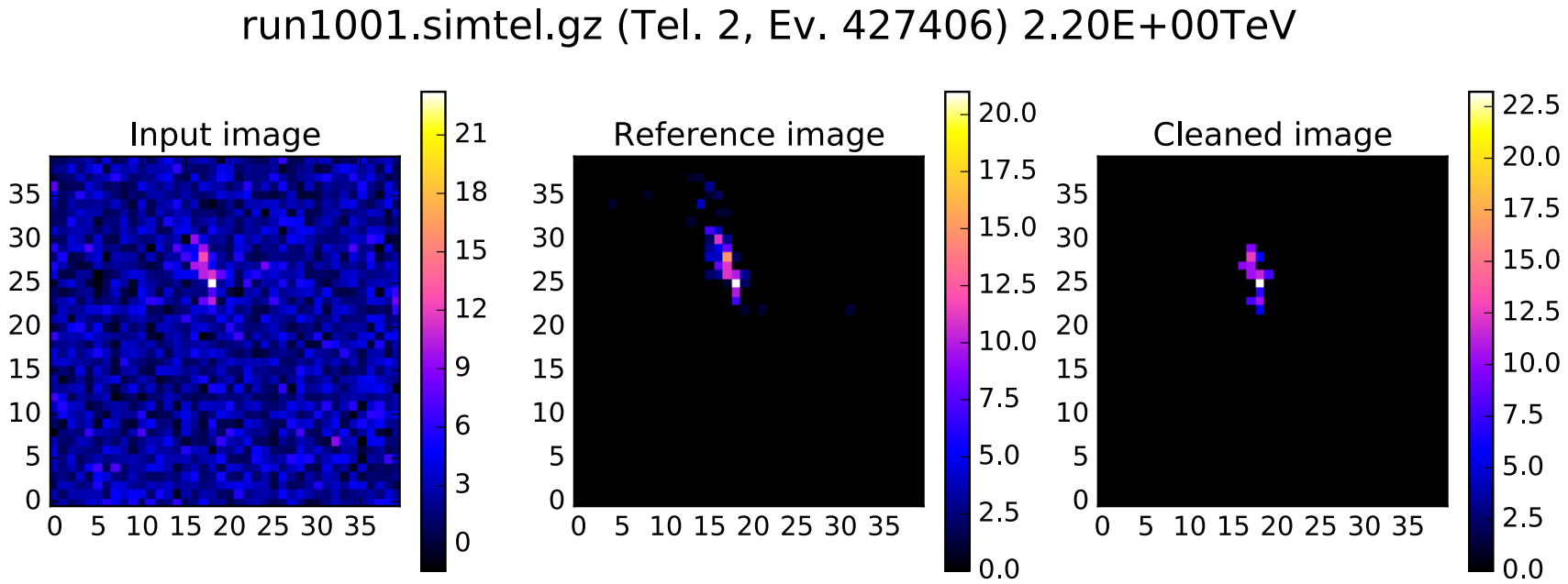


Methods currently used for gamma rays images cleaning (Tailcut)

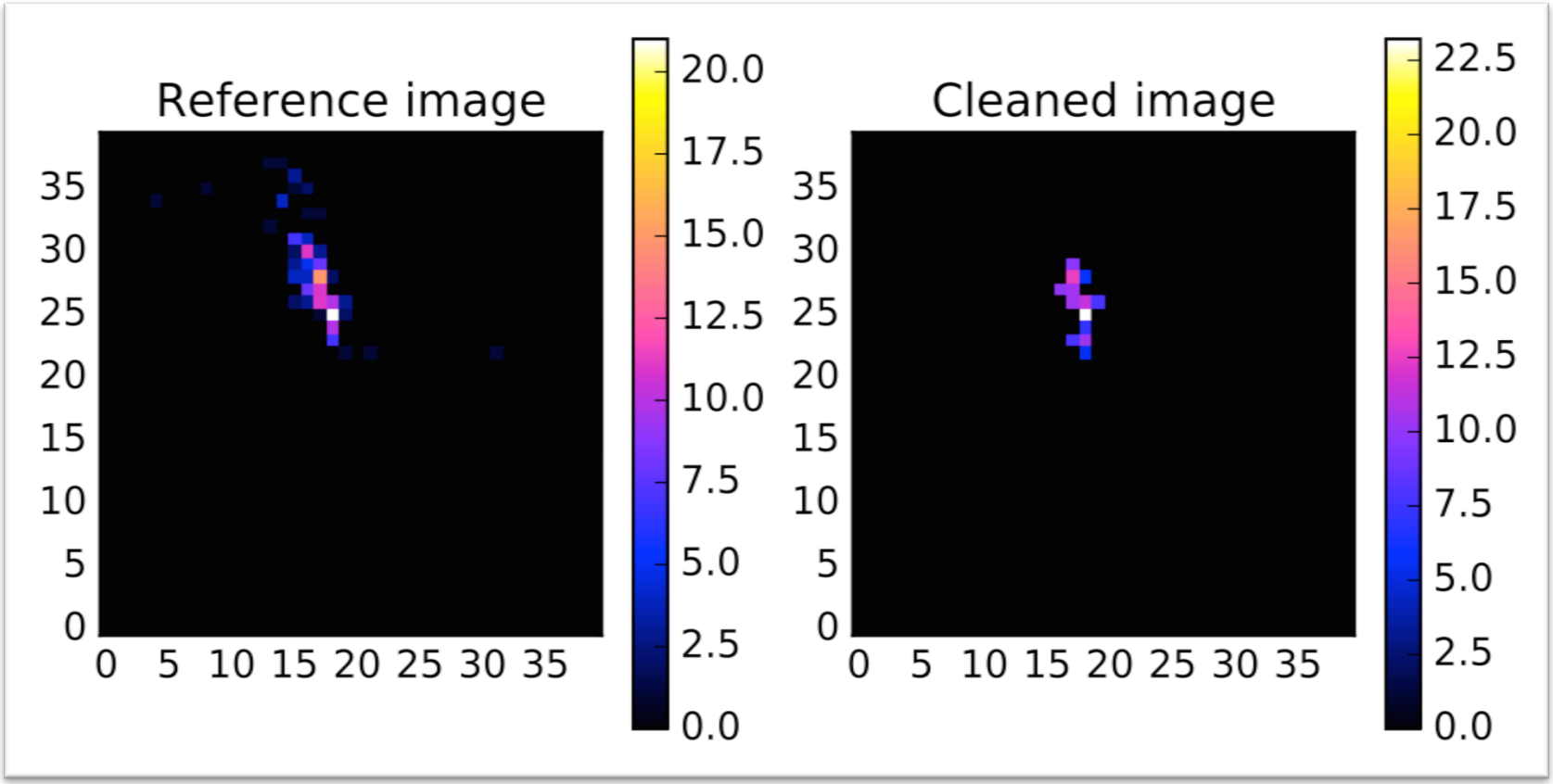
A very simple cleaning procedure:

- Keep pixels above a given threshold (e.g. 10 photoelectrons)
- Keep some neighbors of these selected pixels: those above a second (lower) threshold (e.g. 5 photoelectrons)

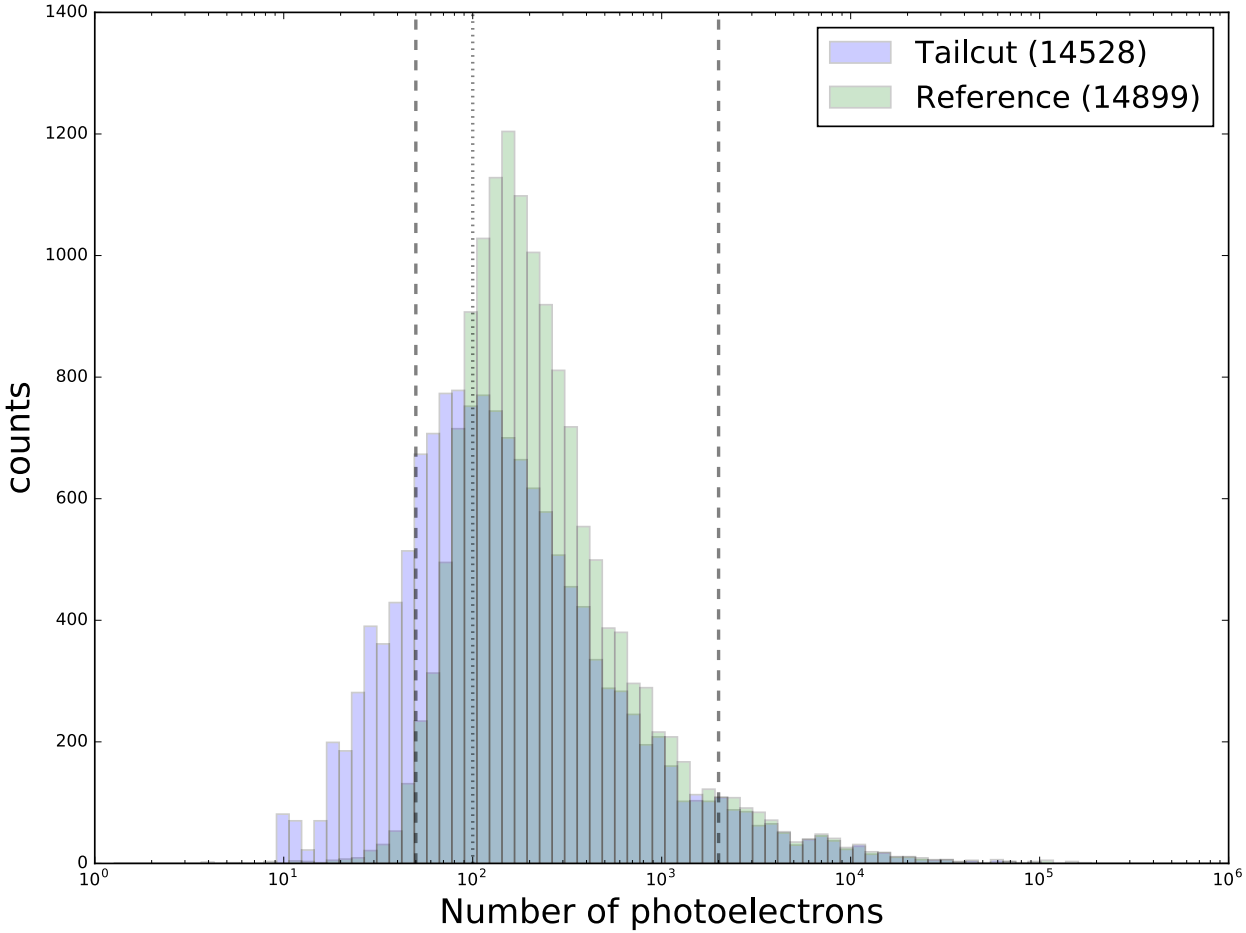
Methods currently used for gamma rays images cleaning (Tailcut)



Tailcut
Information loss



Tailcut
Information loss



Basic idea to go beyond

- Tailcut method: thresholds in the main space
- Better idea: thresholds in a different space where signal and noise can be easily separated
  - Wavelet transform
  - Cosmostat tools (iSAP/Sparse2D)

    (http://www.cosmostat.org/software/isap/)

We are considering Wavelet Transform method

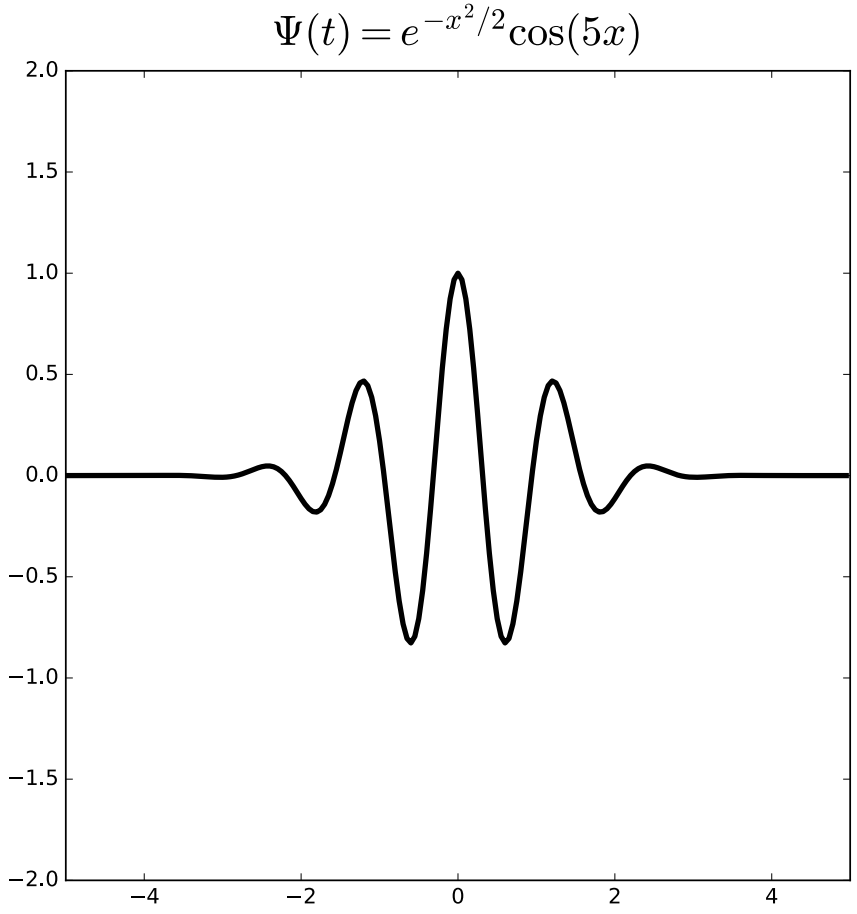
Idea: similar to Fourier Transform filtering

- Apply the transform on the signal
- Apply a threshold in the transformed space
- Invert the transform to go back to the original signal space

Differences with Fourier Transform

- Bases: wavelets functions instead sin and cos
- Spatial information

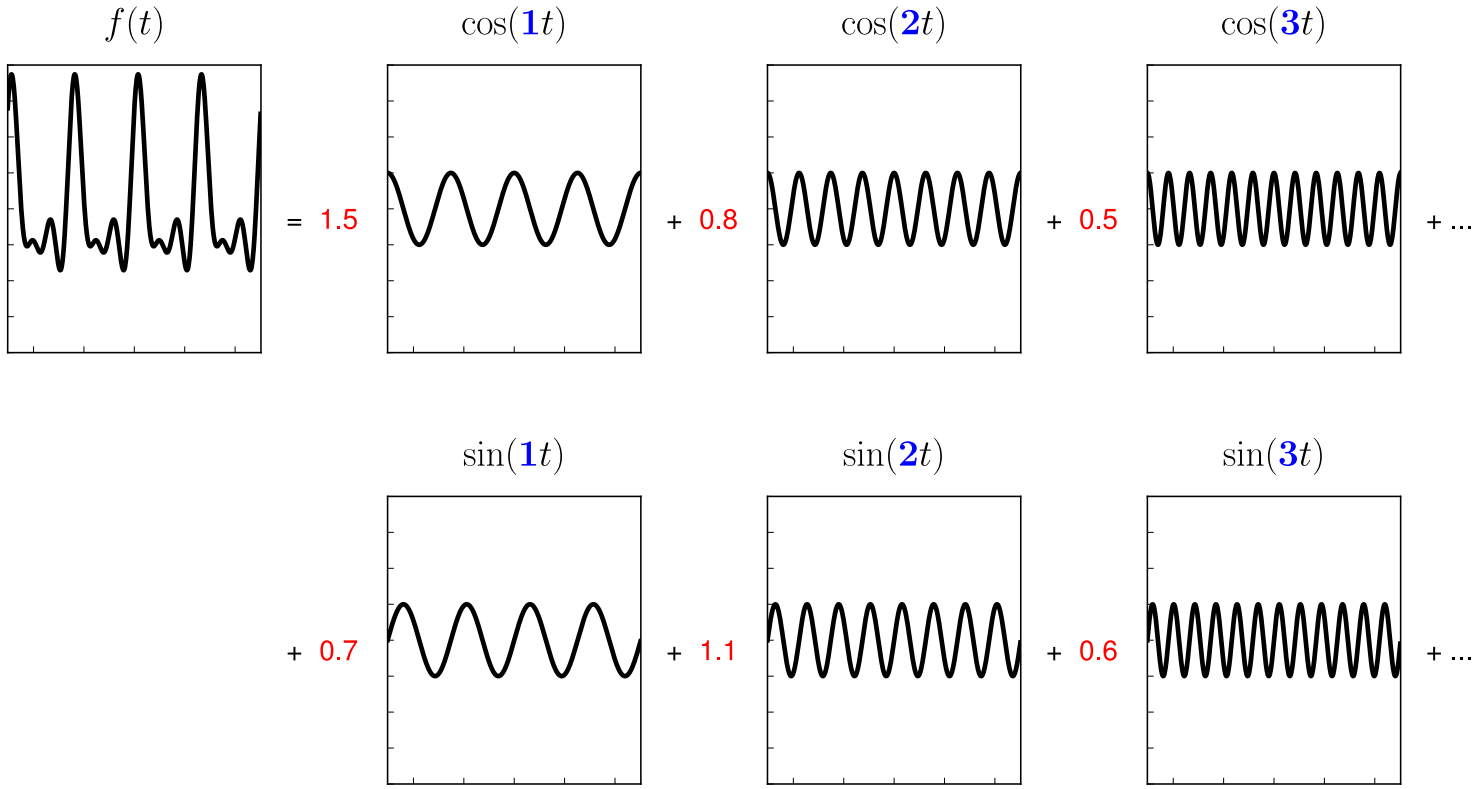
Example of wavelet function (Morlet wavelet)



"A short wave-like oscillation with a beginning and an end"

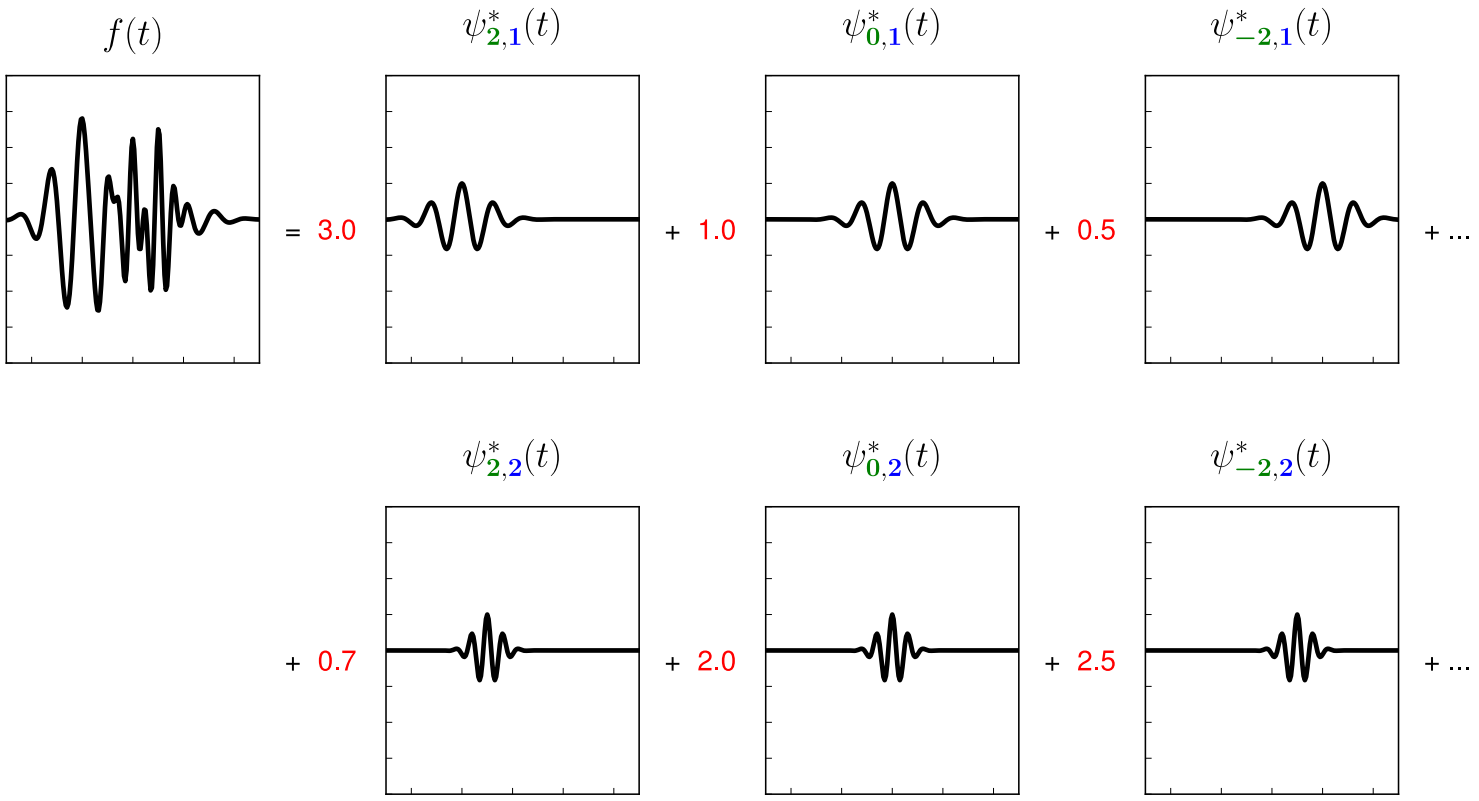
Cleaning procedure: general idea with Fourier Transform

- Input signal is converted to a weighted sum of sin and cos at different frequencies
- Threshold is applied on these weights to remove some frequencies in the input signal (e.g. high pass filter, low pass filter, ...)

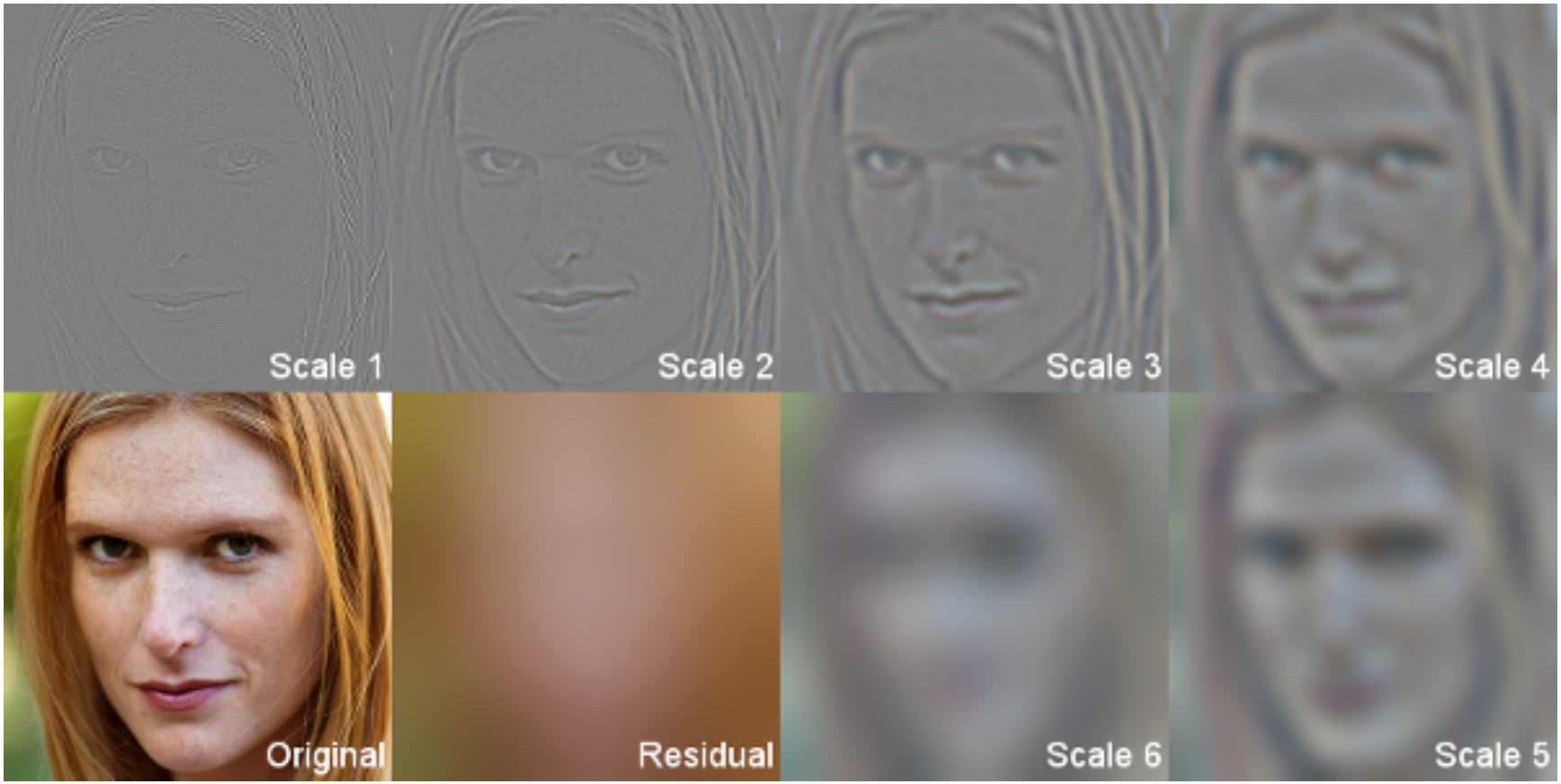


Cleaning procedure: general idea with Wavelet Transform

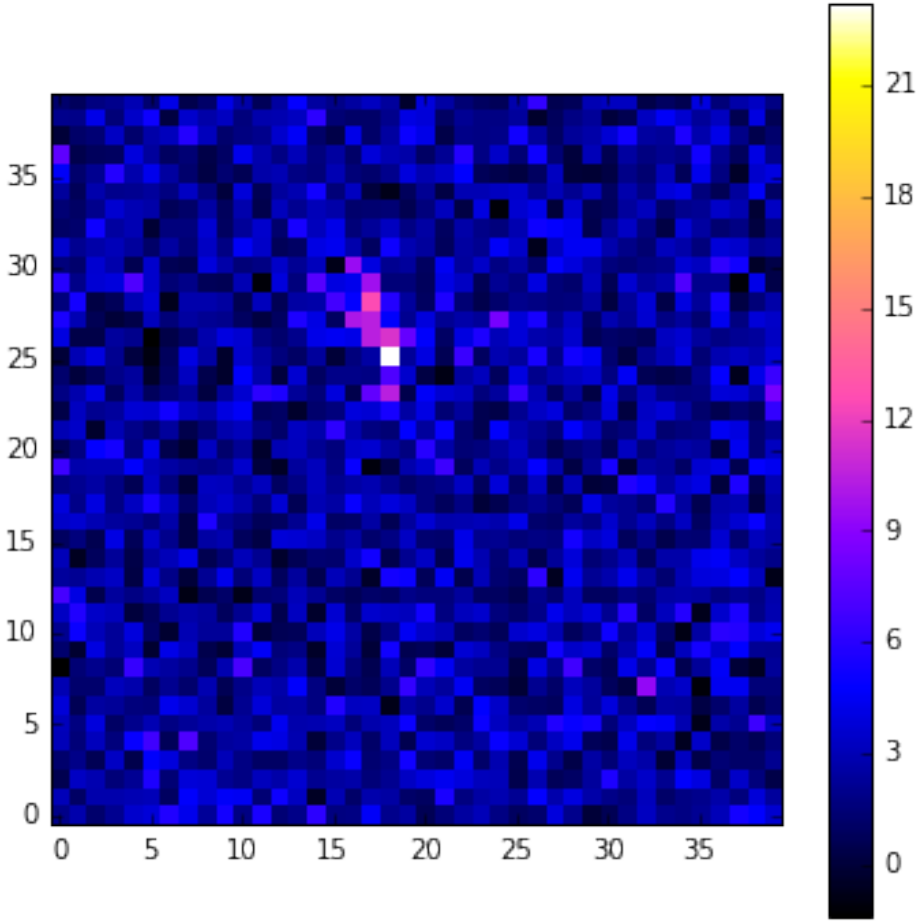
- Input signal is converted to a weighted sum of these wavelet functions at different scales (dilate factor) and positions (translate factor)
- Threshold is applied on these weights to remove locally (in space or time) some frequencies (or scales) in the input signal



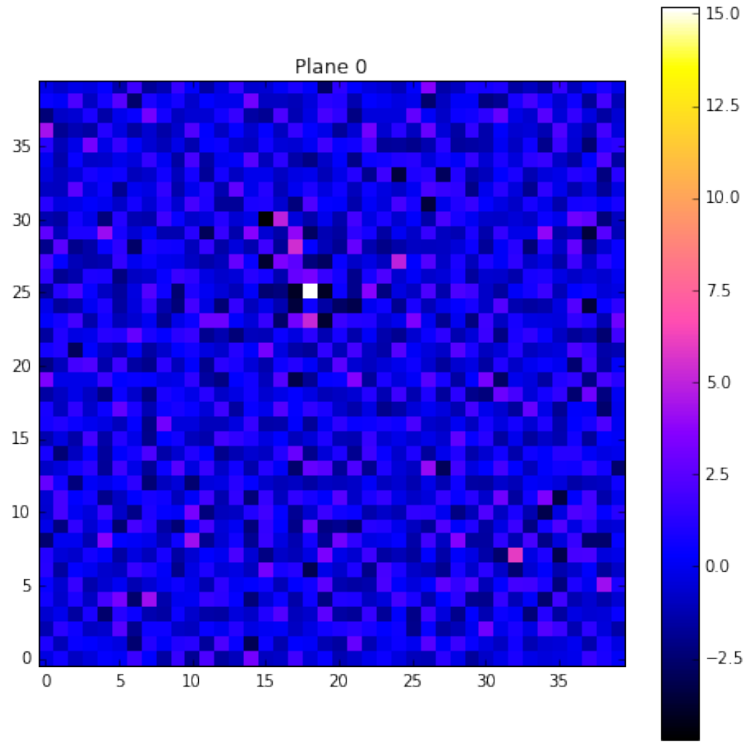
Example

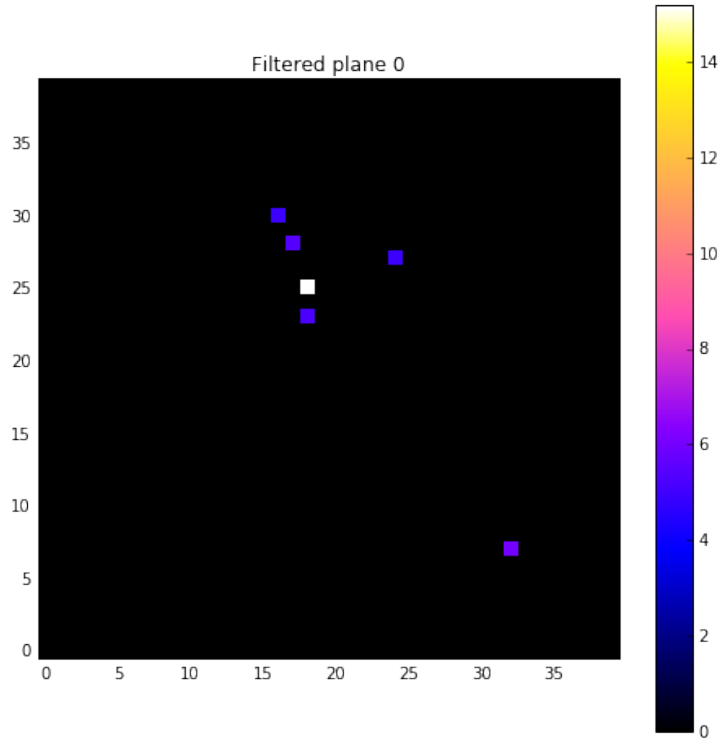

Scale 1
Scale 2
Scale 3
Scale 4
Original
Residual
Scale 6
Scale 5

Cleaning with wavelets: example

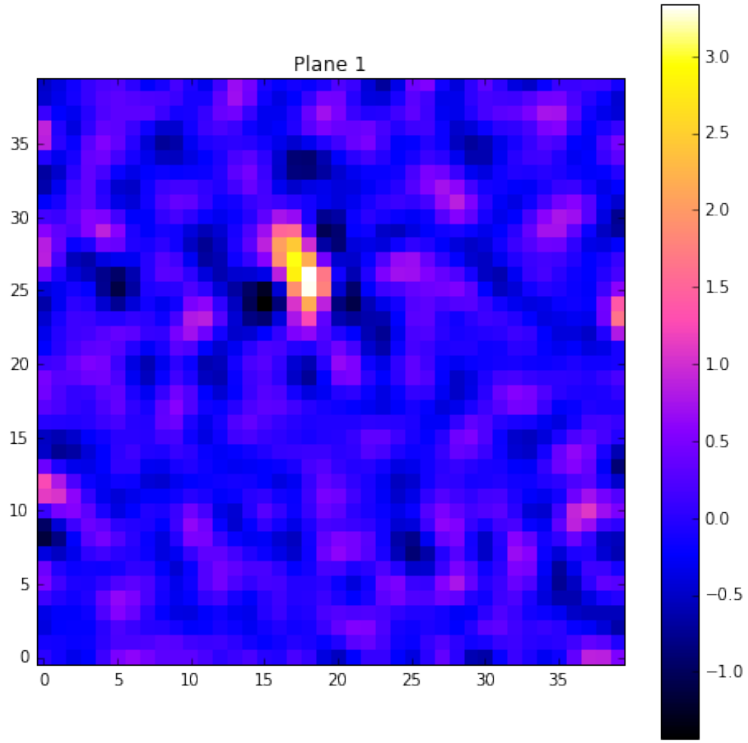


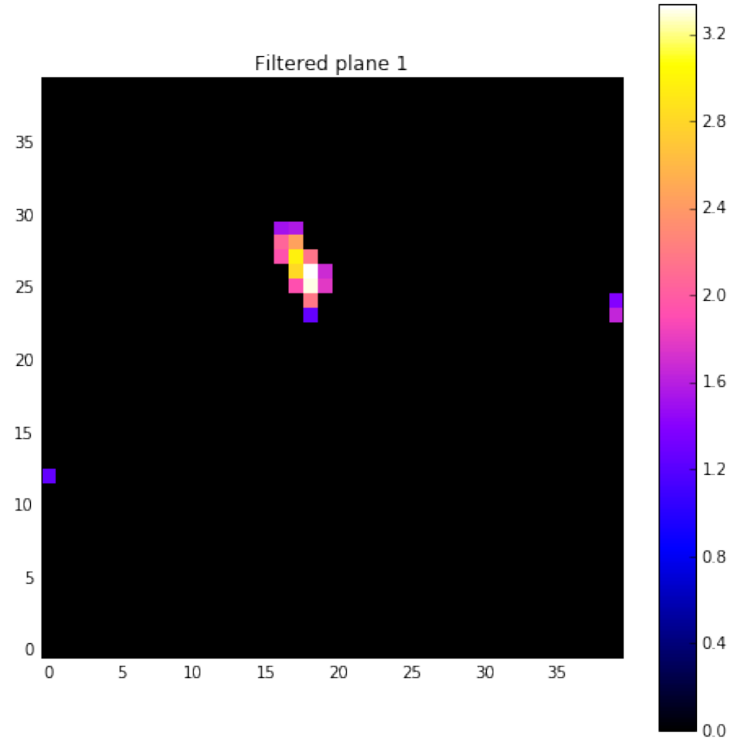
1st Plane (small scale)



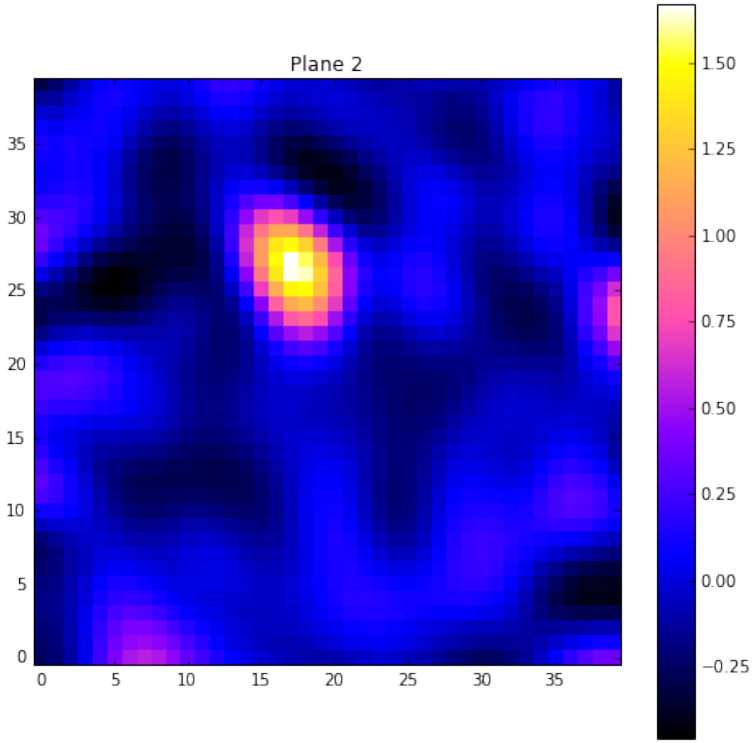


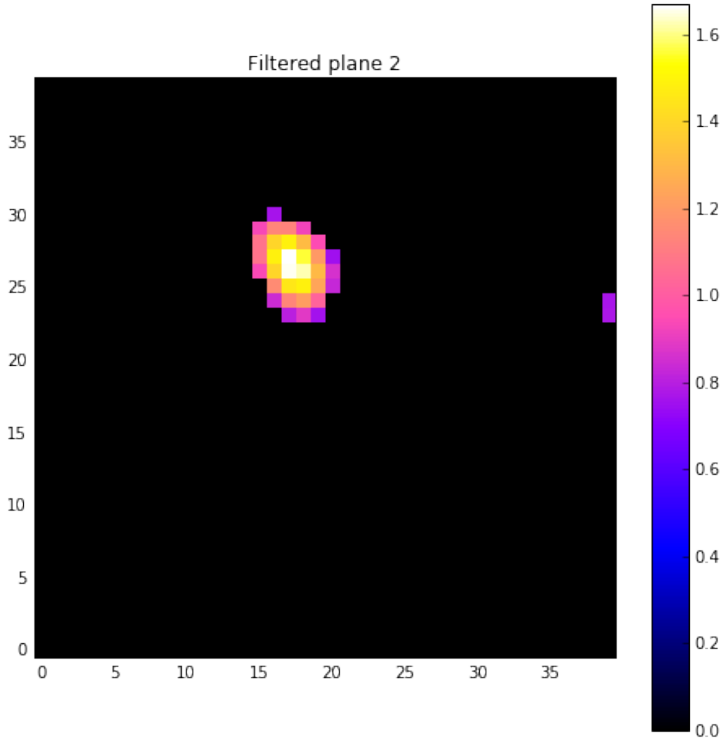
2nd Plane


Plane 1
0
5
10
15
20
25
30
35
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0

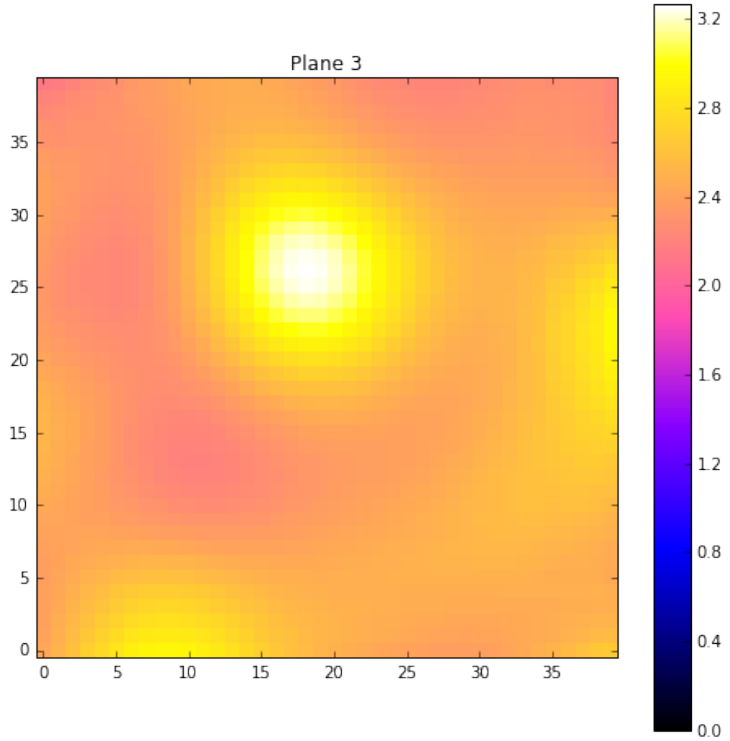

Filtered plane 1
0
5
10
15
20
25
30
35
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

3rd Plane

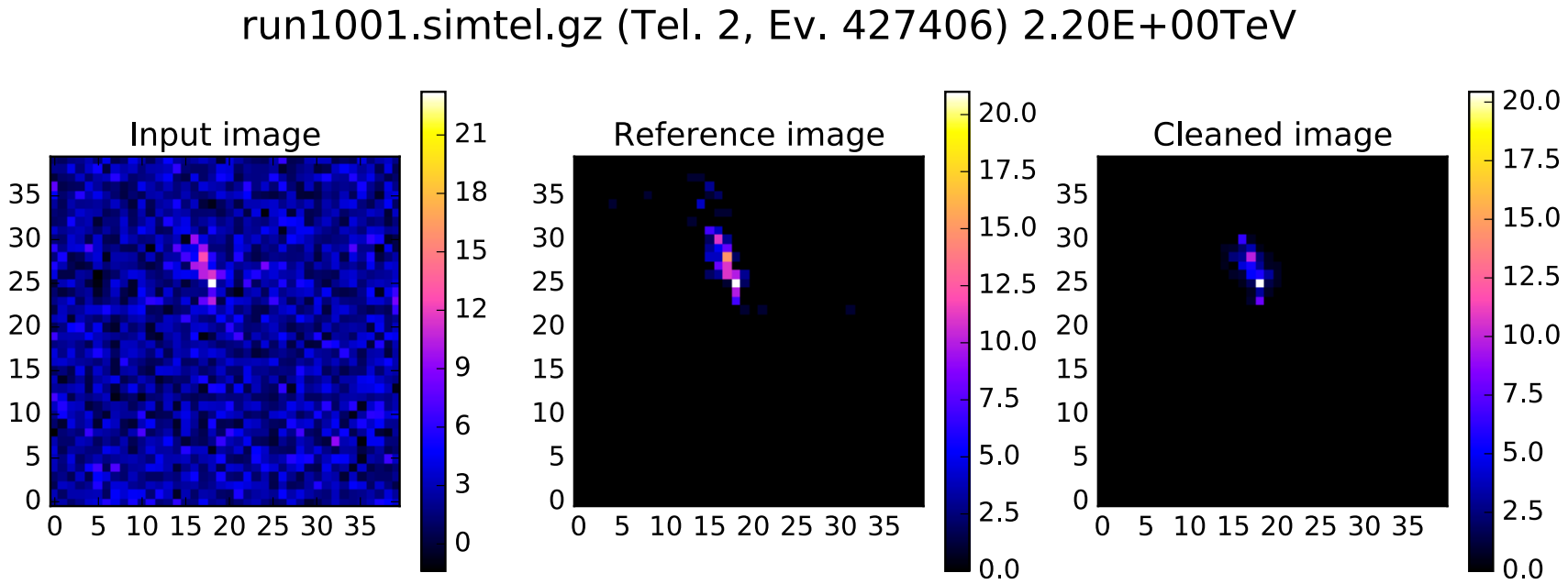

Plane 2
0
5
10
15
20
25
30
35
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25


Filtered plane 2
0
5
10
15
20
25
30
35
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

4th Plane (large scale)



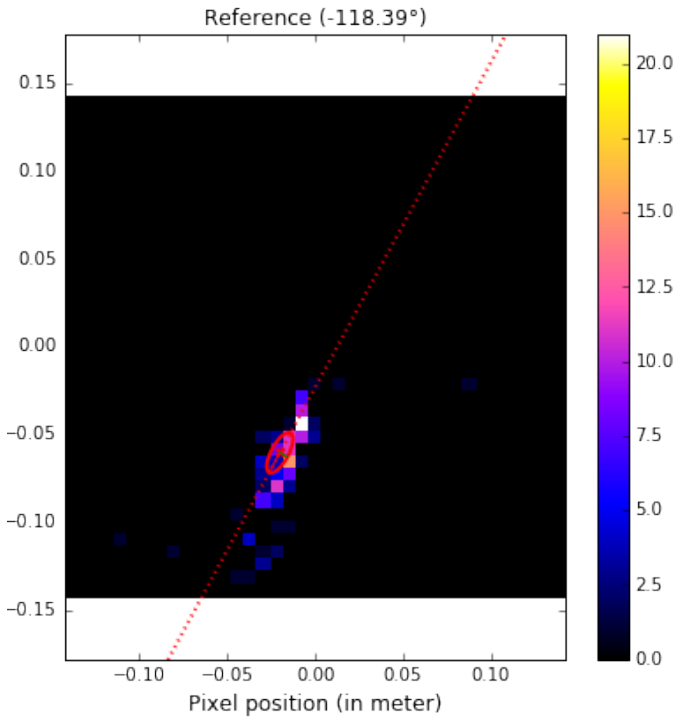
Cleaning with wavelets: example

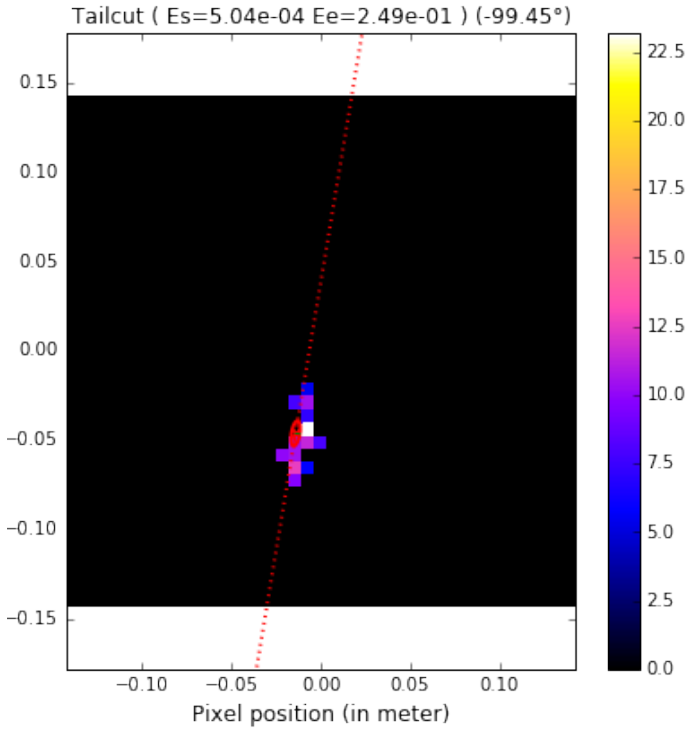


Preliminary results for gammas

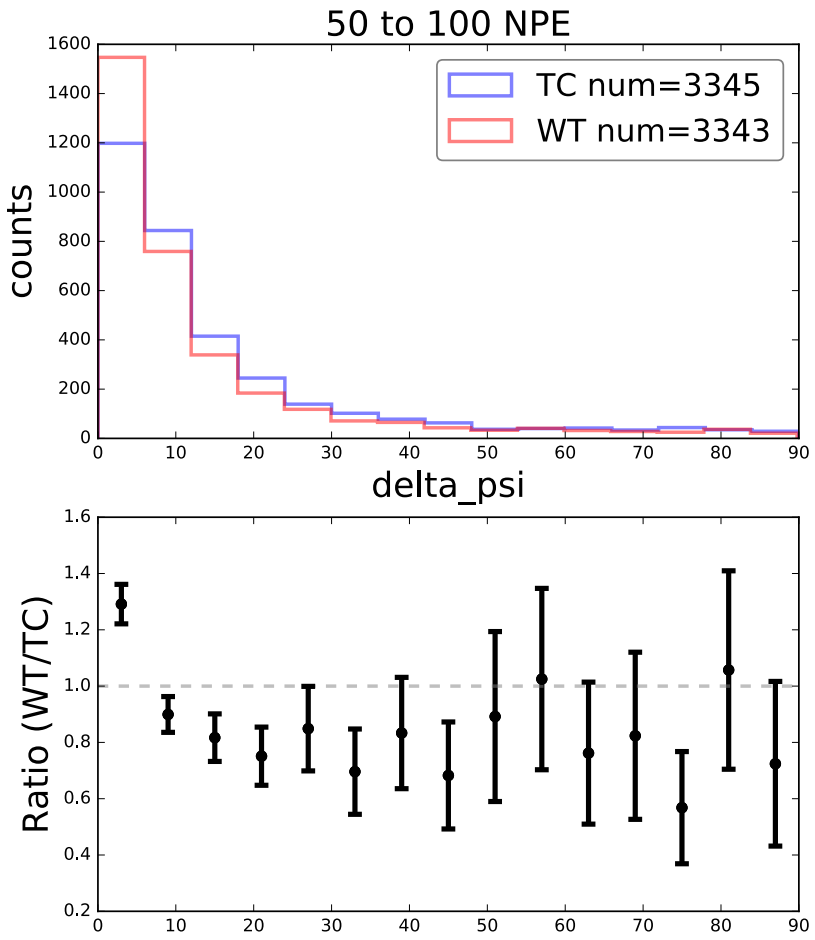
Does it work well on large statistics ?

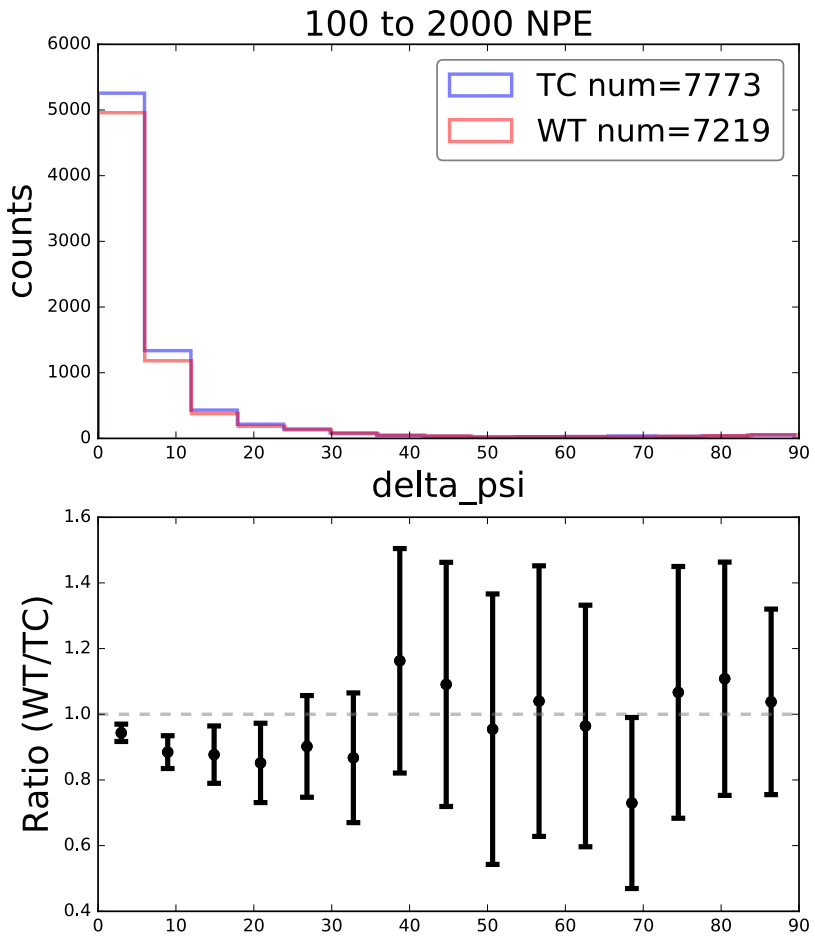
Estimator of performance at the level of images



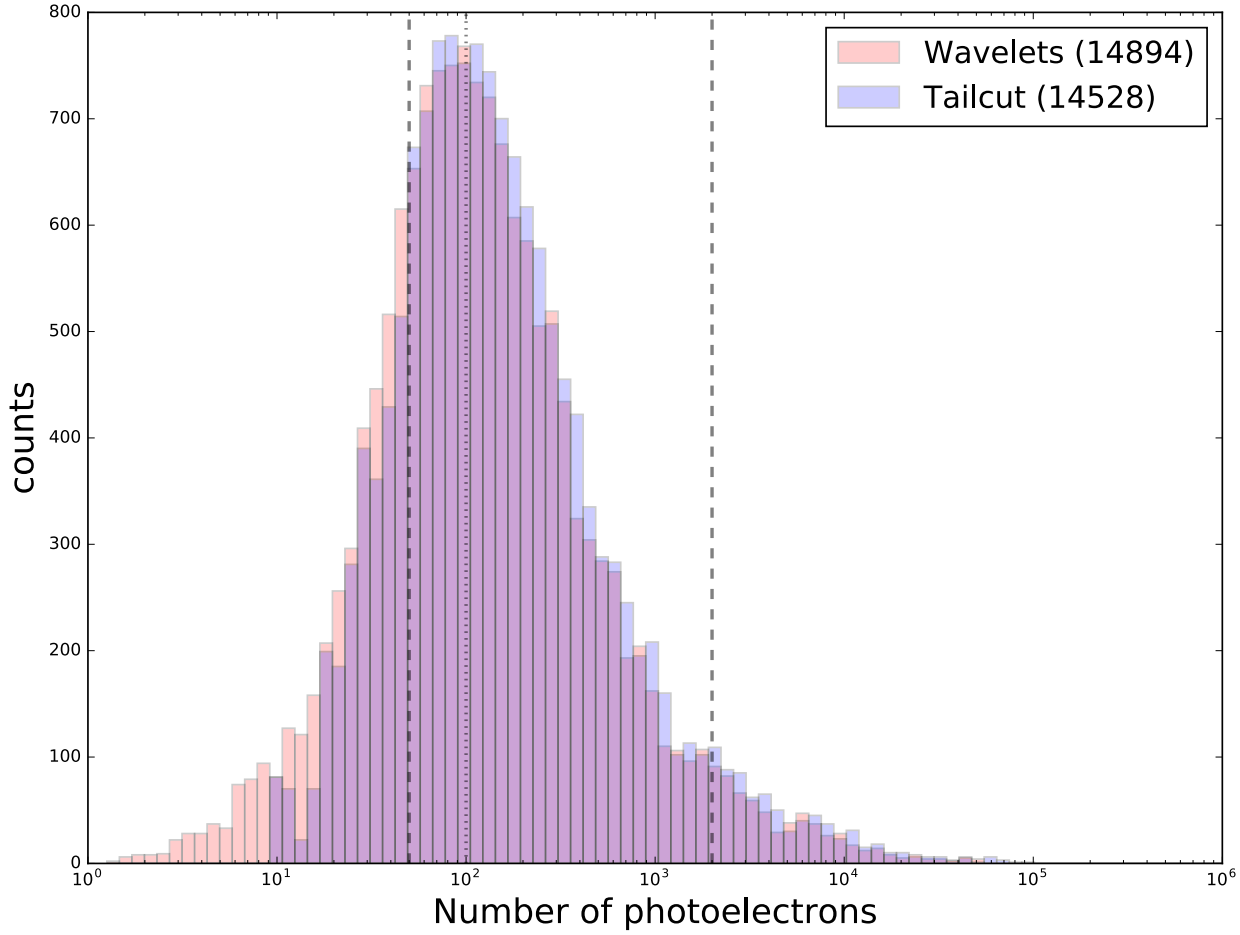


B-spline wavelets « à-trous »
Shower axis reconstruction





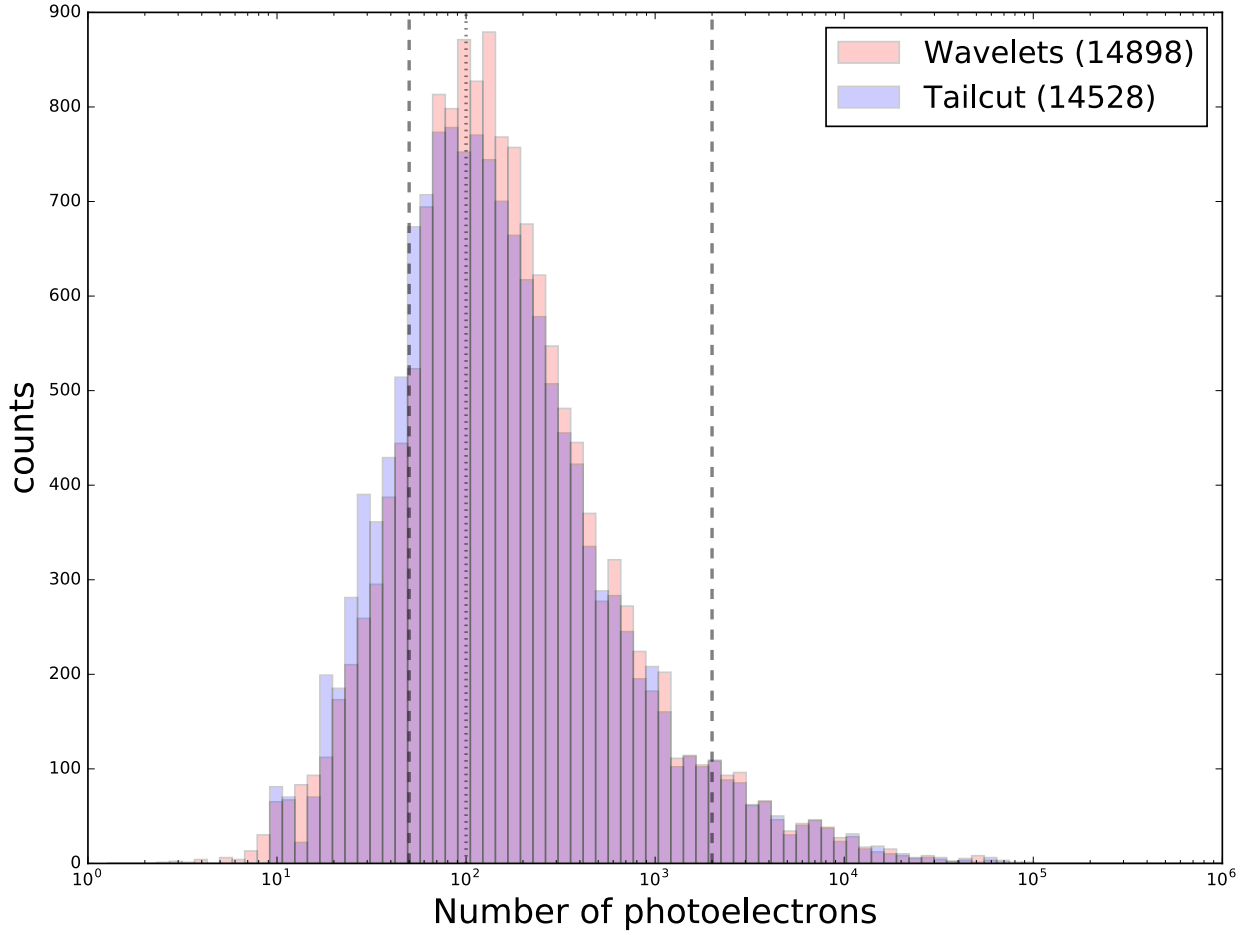
B-spline wavelets « à-trous »
Information loss



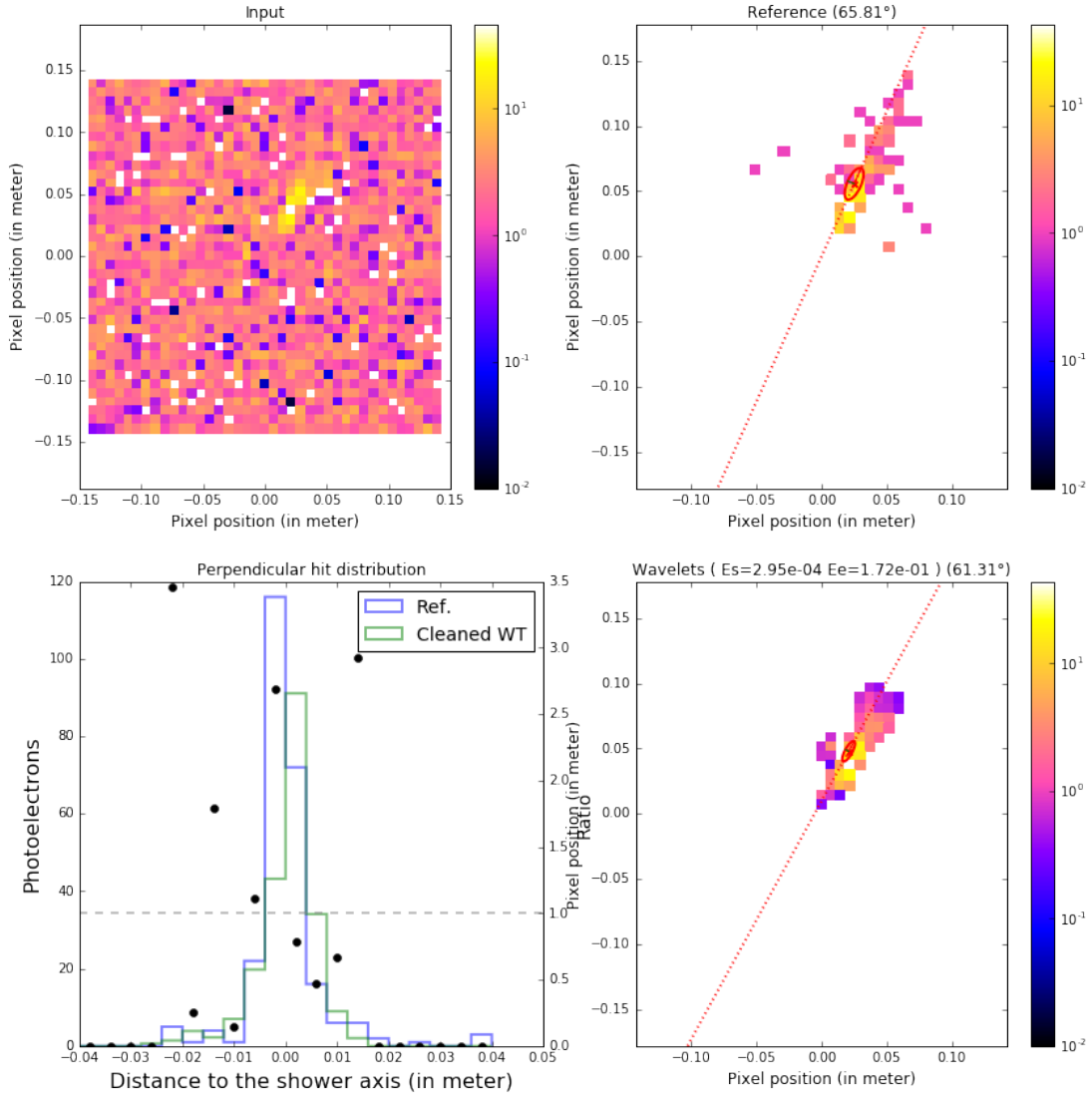
A possible solution ?

Anisotropic wavelets

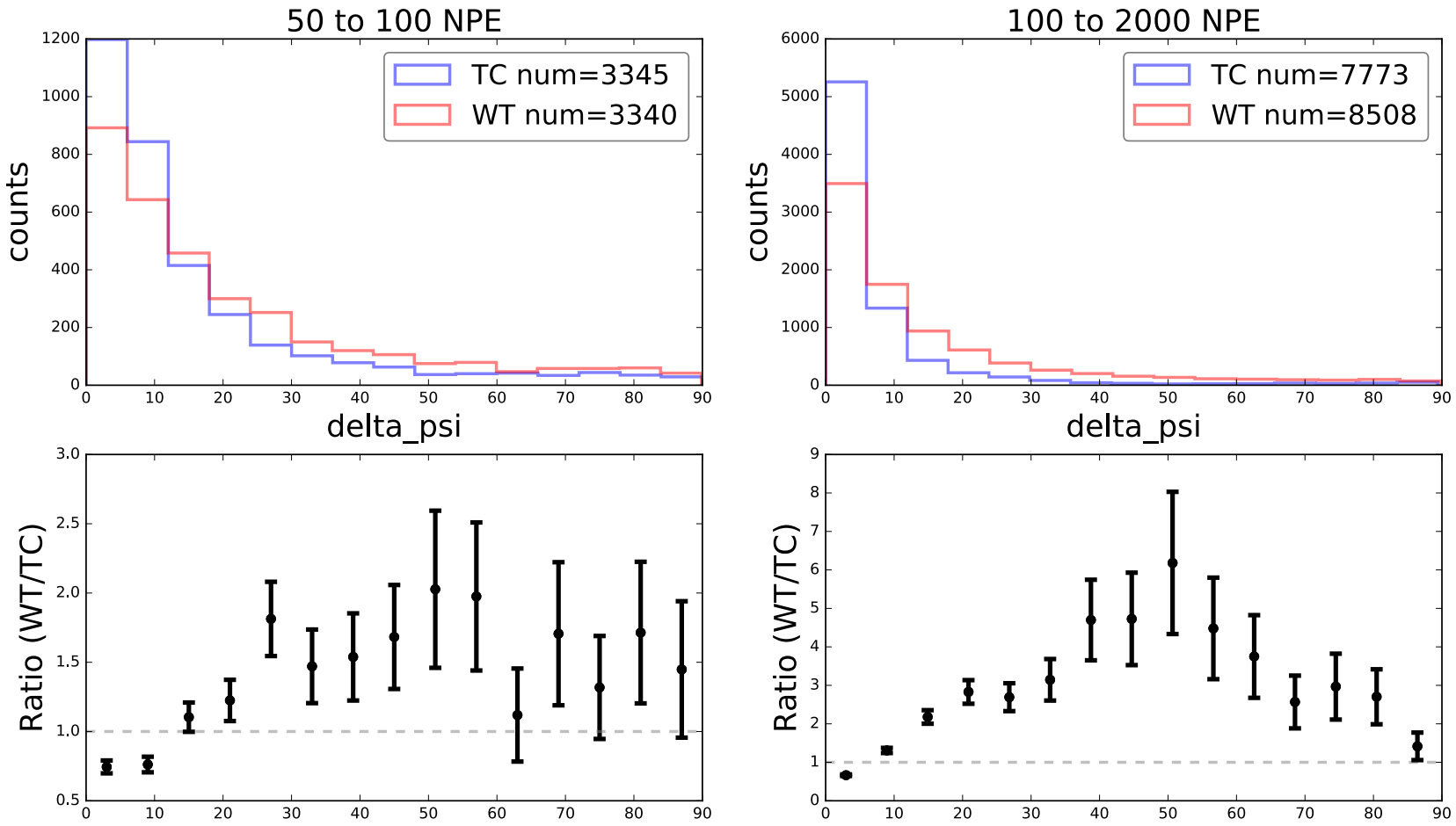
Bi-orthogonal wavelet transform Information loss



1.591 TeV (259 photoelectrons in reference image) - Event 454807 - Telescope 1



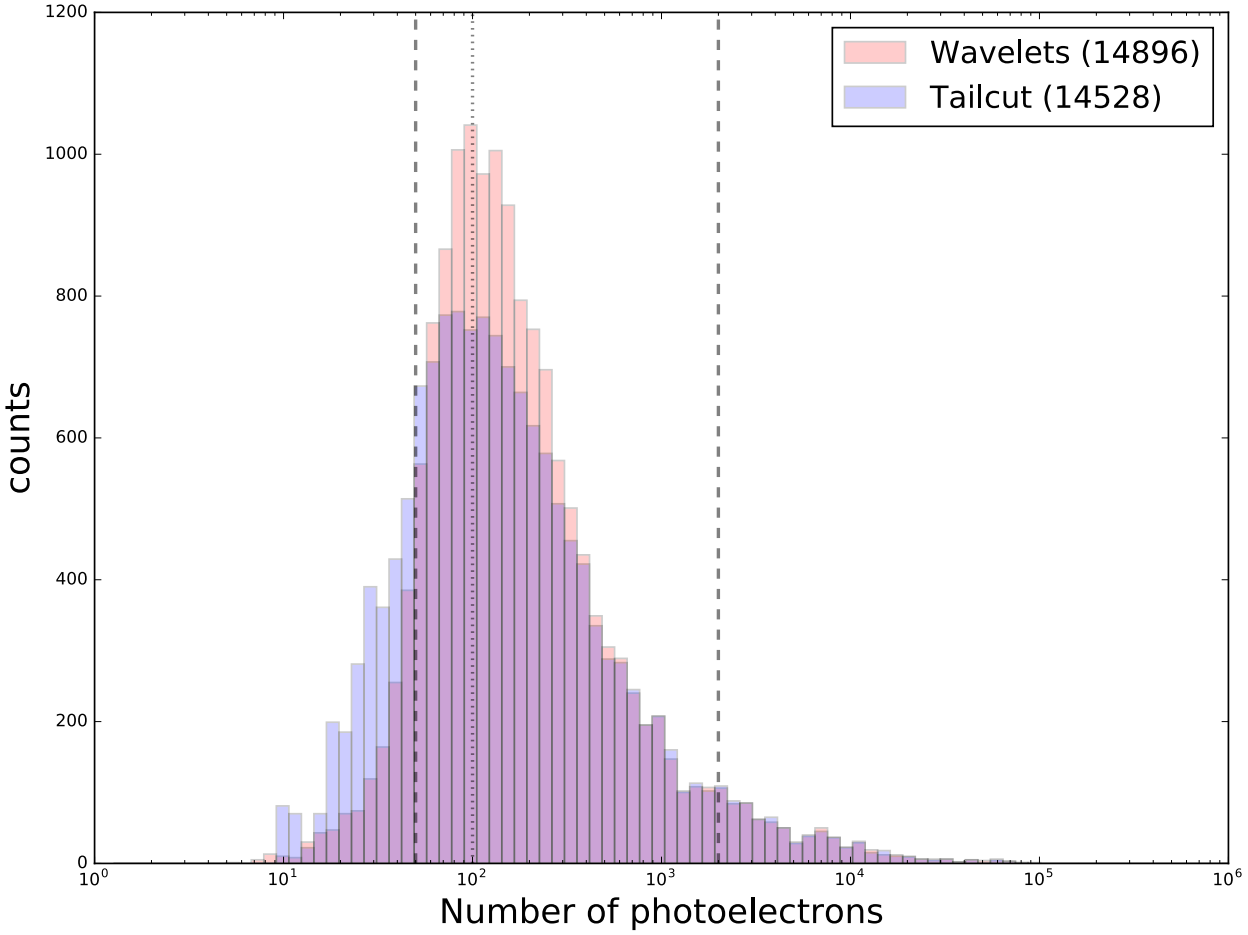
Bi-orthogonal wavelet transform
Shower axis reconstruction



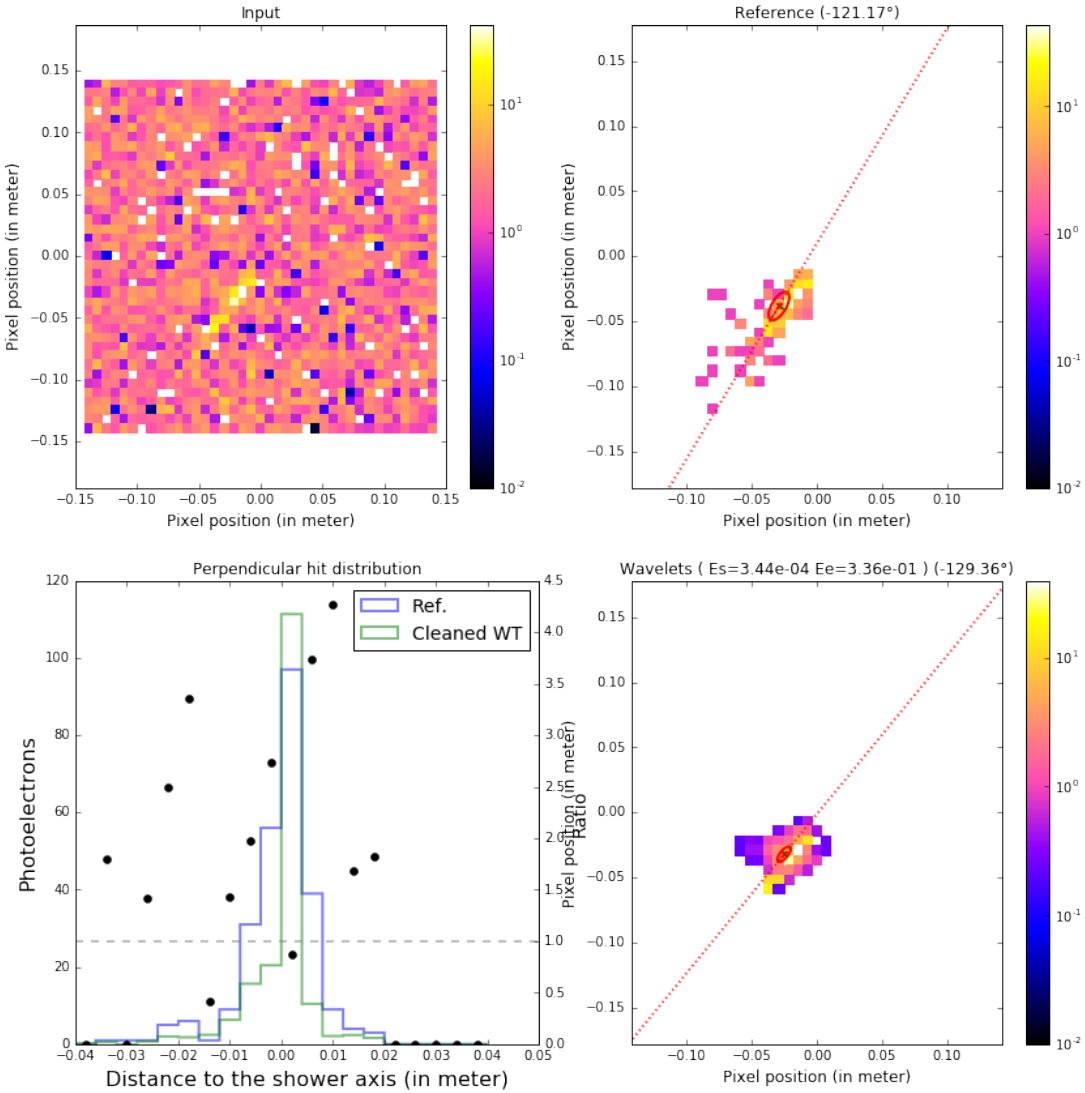
Another track

Iterative Multiresolution Thresholding

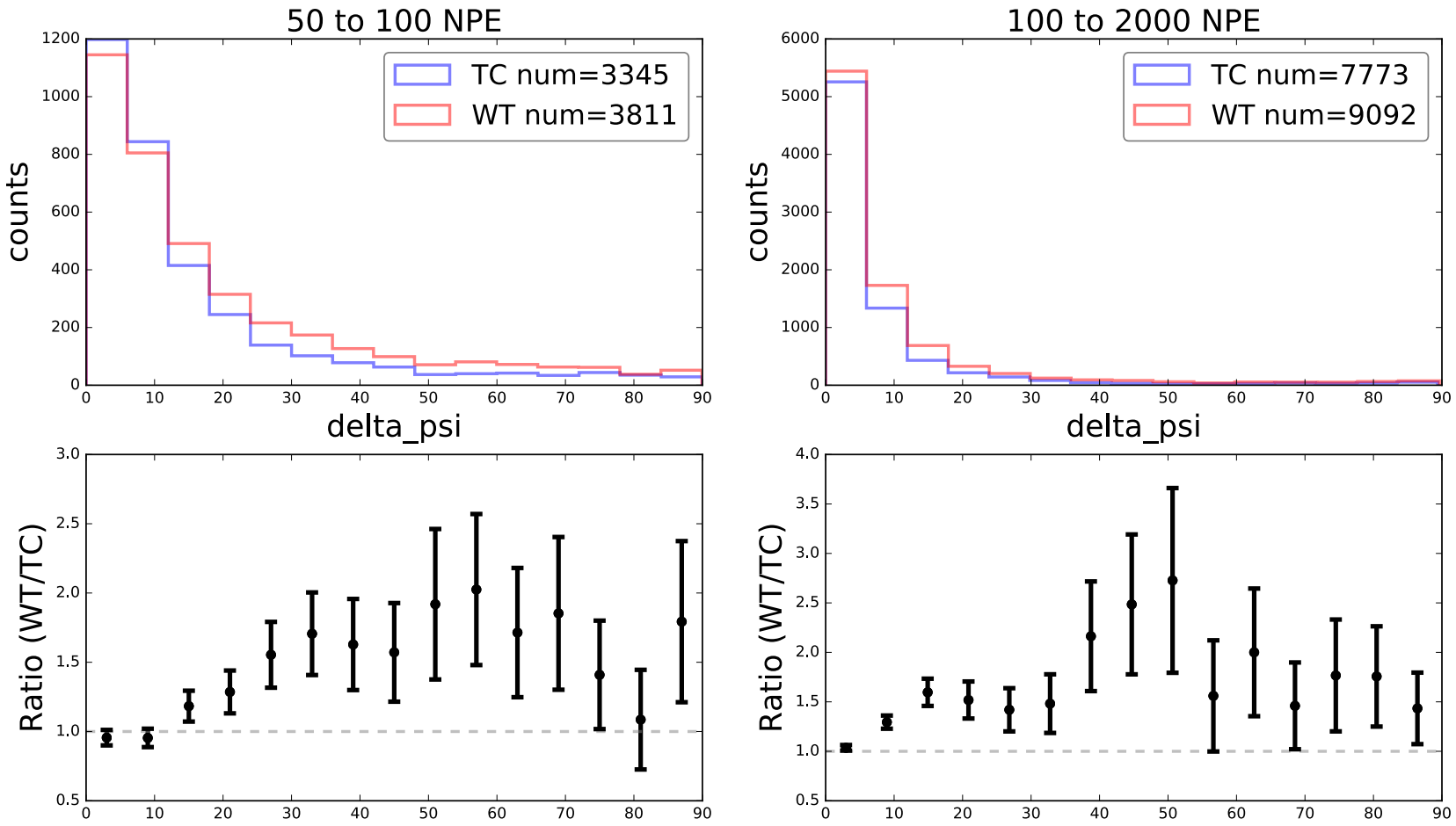
Iterative Multiresolution Thresholding Information loss



2.198 TeV (268 photoelectrons in reference image) - Event 427404 - Telescope 1



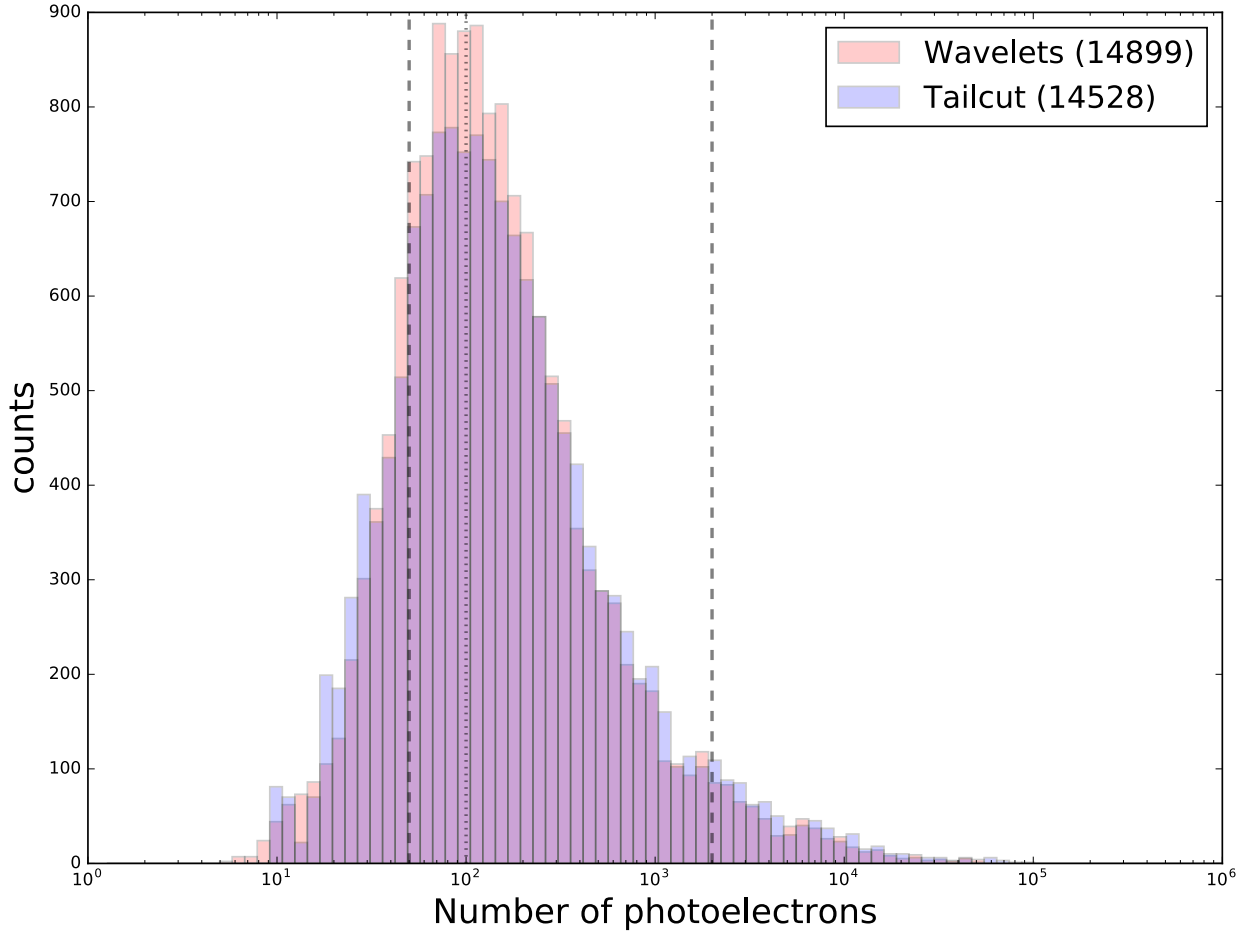
Iterative Multiresolution Thresholding Shower axis reconstruction



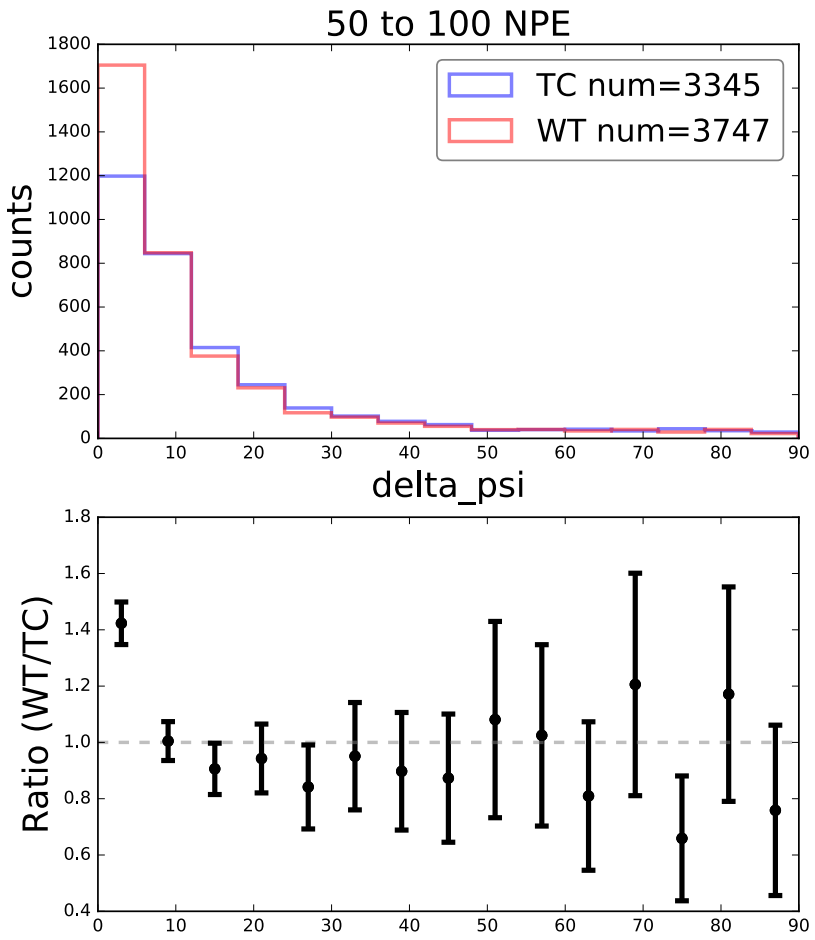
An alternative

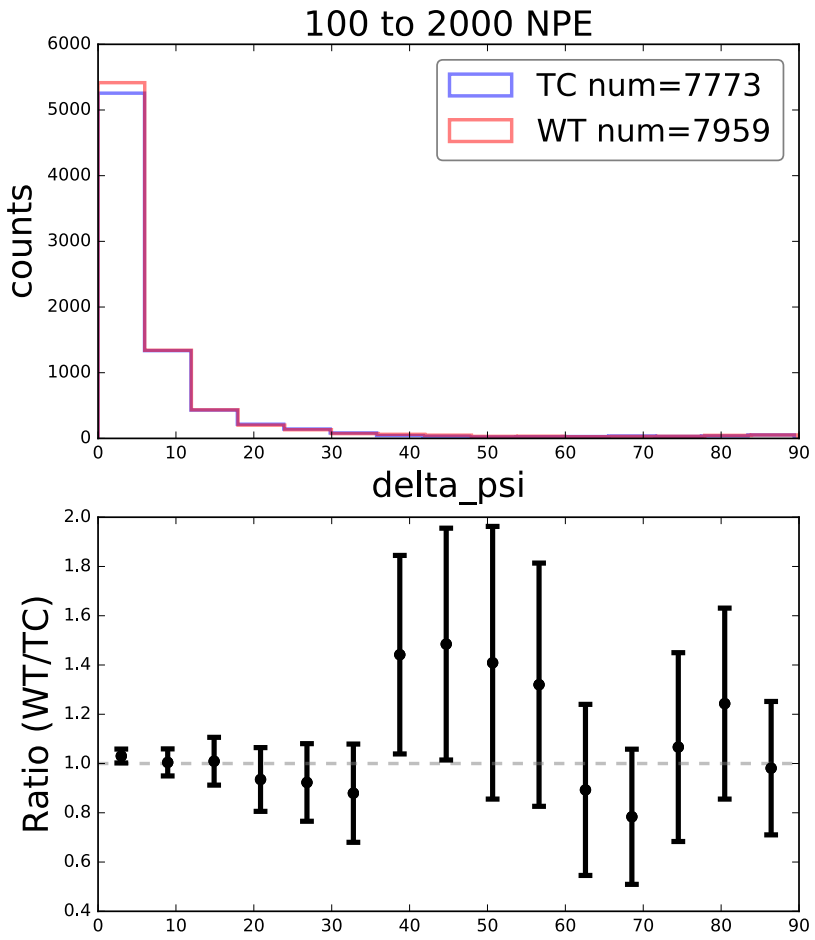
Explicitly reduce the filtering on small scales

Lower the filtering threshold for small scales
Information loss



Lower the filtering threshold for small scales
Shower axis reconstruction





Is it better ?

Yes it is !

Progress in events reconstruction (Tino Michael)

- What about stereoscopy ?
- What about the actual sensitivity gain ?

Next steps

- Multiplicity: check performances on the full telescope array
- Investigate on other configurations
  - Anisotropic wavelets
  - Curvlets
- Apply the cleaning methods to telescopes having hexagonal grid of pixels