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Labex

USPC Université Sorbonne Paris Cité

Advanced Gamma-Ray Science

Methods and Tools

K.Kosack, J.Decock

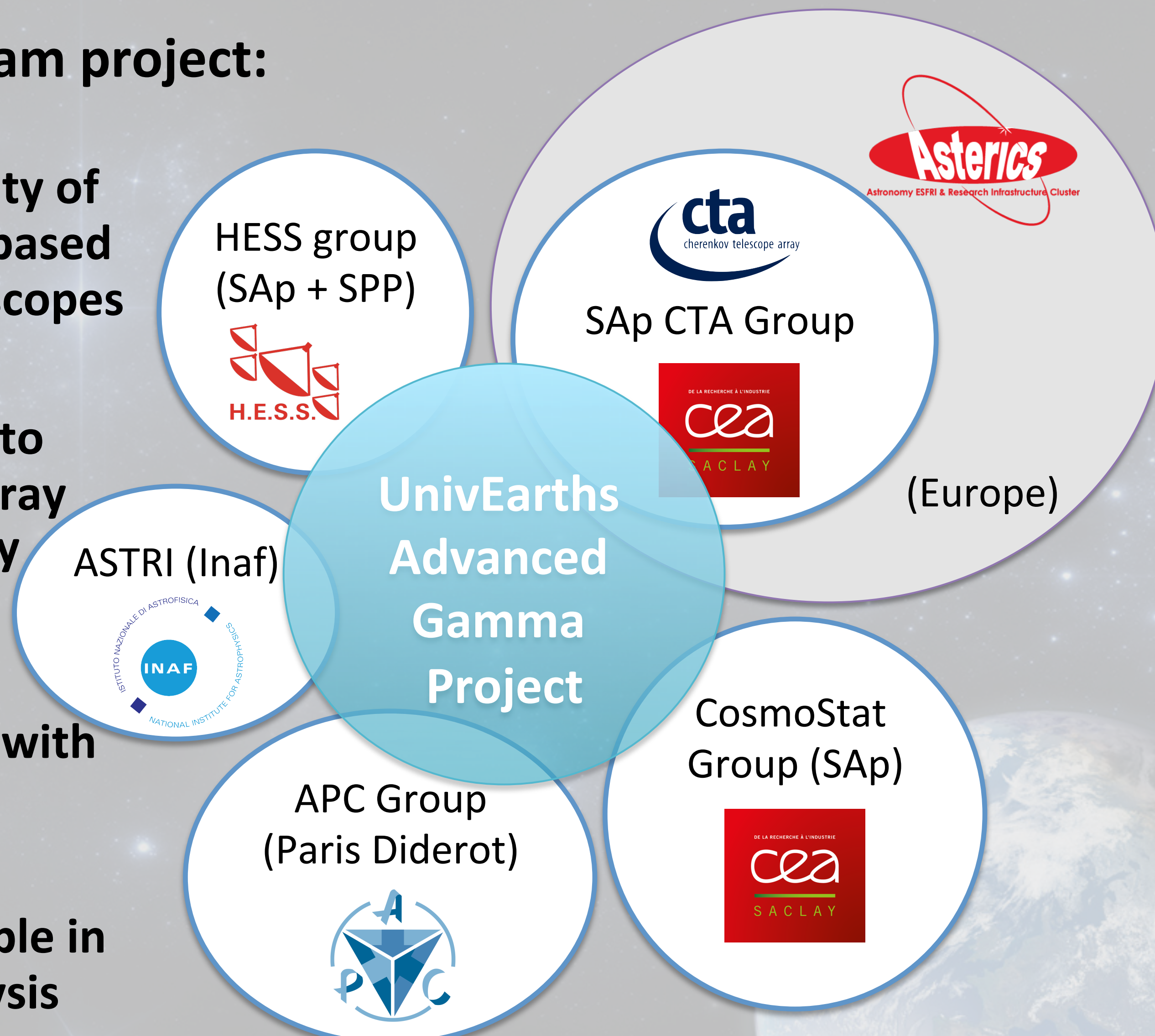
CEA Saclay – Irfu/Sap

November 29, 2016

PROJECT CONTEXT: GROUP DEVELOPMENT

Goal of young-team project:

- ✓ Improve sensitivity of modern ground-based Gamma-ray telescopes
- ✓ Develop a group to work on gamma-ray techniques locally at CEA
- ✓ Improve overlap with related groups
- ✓ Involve new people in gamma-ray analysis



PROJECT MANAGEMENT:
THE TEAM

Jérémie Decock

UnivEarths post-doc

- Doctor of Computer Science, Inria
- Numerical techniques and software development
- Mathematical optimization
- Signal processing

\+

WP Leader
Karl Kosack

CEA/AIM

HESS, CTA

Tino Michael

CEA/AIM

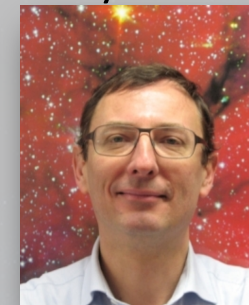
CTA, ASTERICS

Fabio Acéro

CNRS/AIM

CTA, Fermi

Thierry Stolarczyk



CEA/AIM

CTA (leader)

Bruno Khélifi

CNRS/APC

HESS, CTA

Sandrine Pires

CEA/AIM

CosmoStat
Euclid, Kepler

David Landriu

CEA/AIM

Fermi, CTA

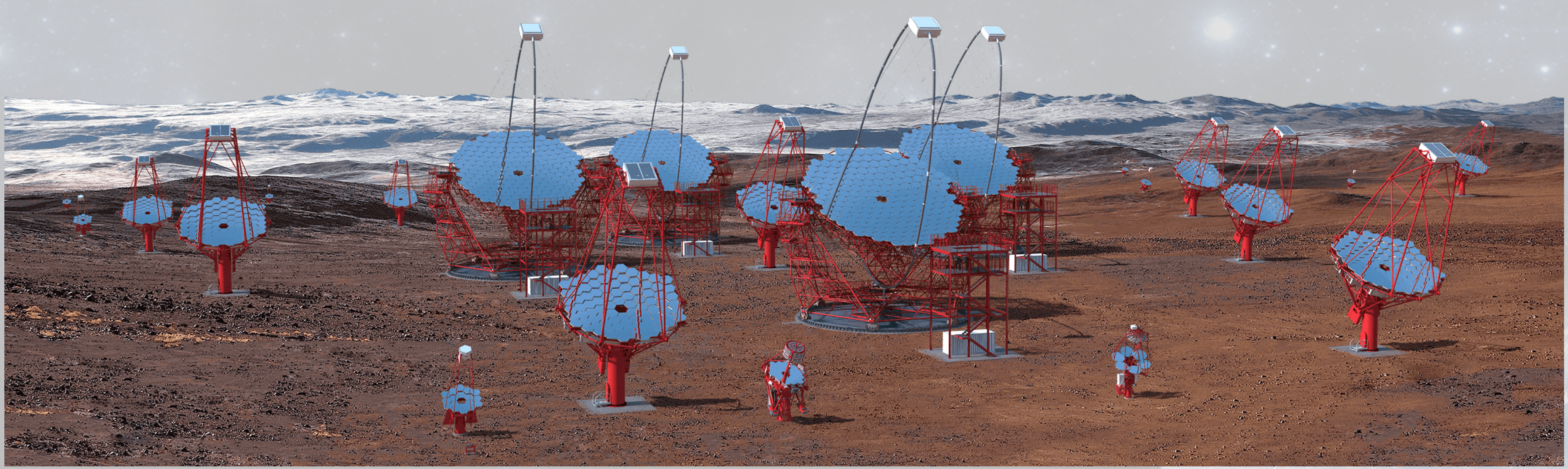
Fabian Schüssler

CEA/SPP

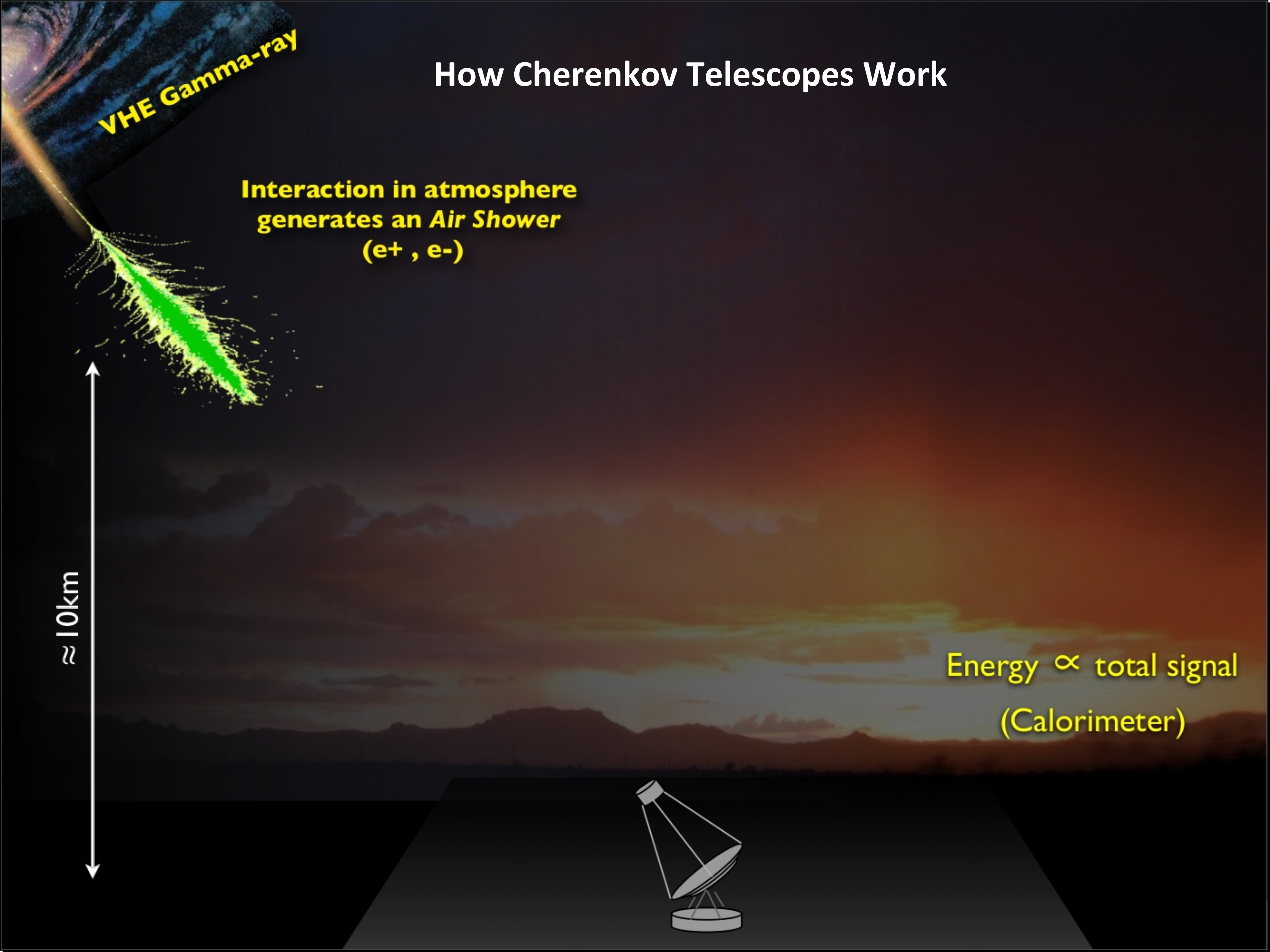
HESS

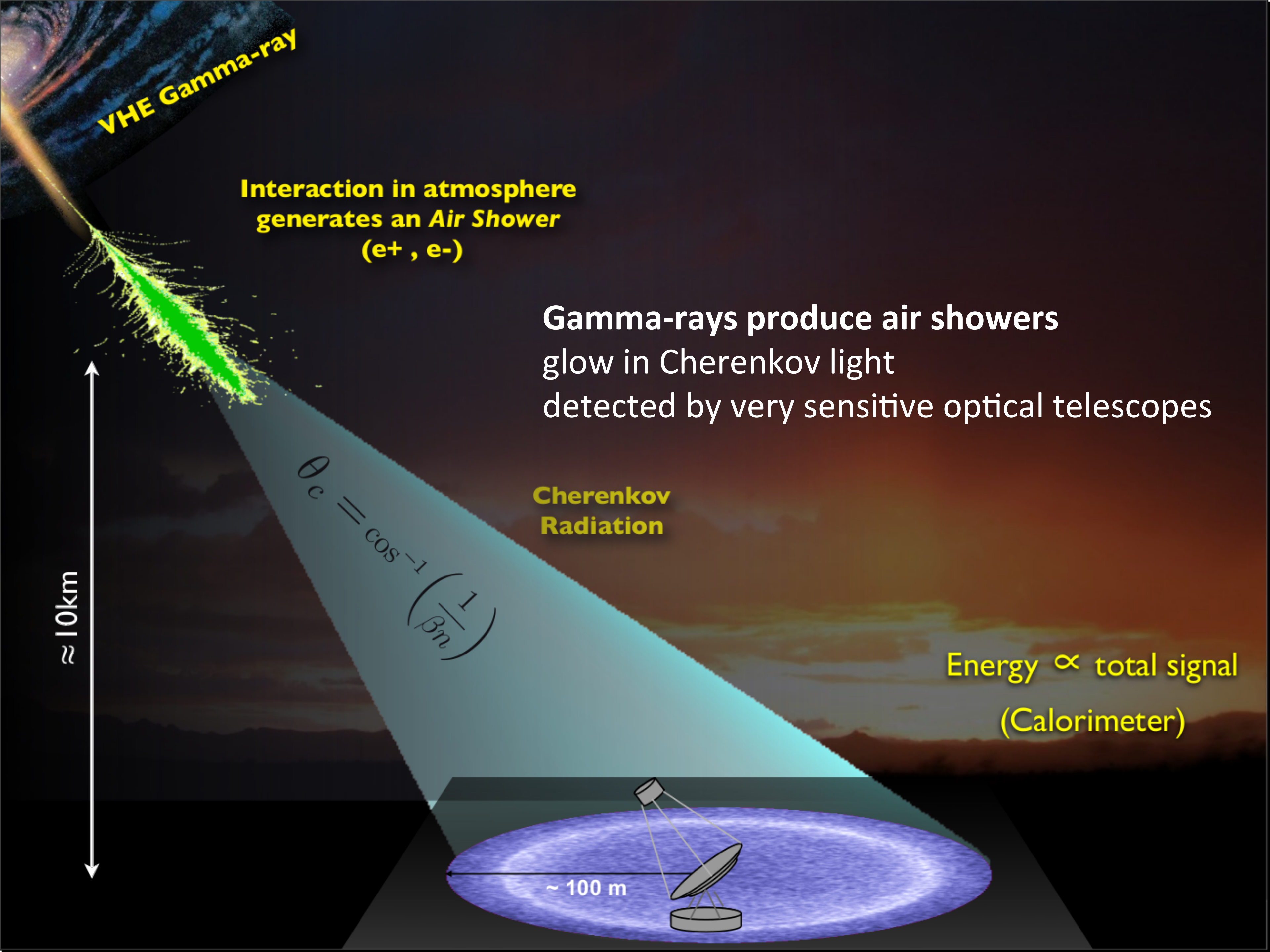
OBSERVATORIES:
HESS

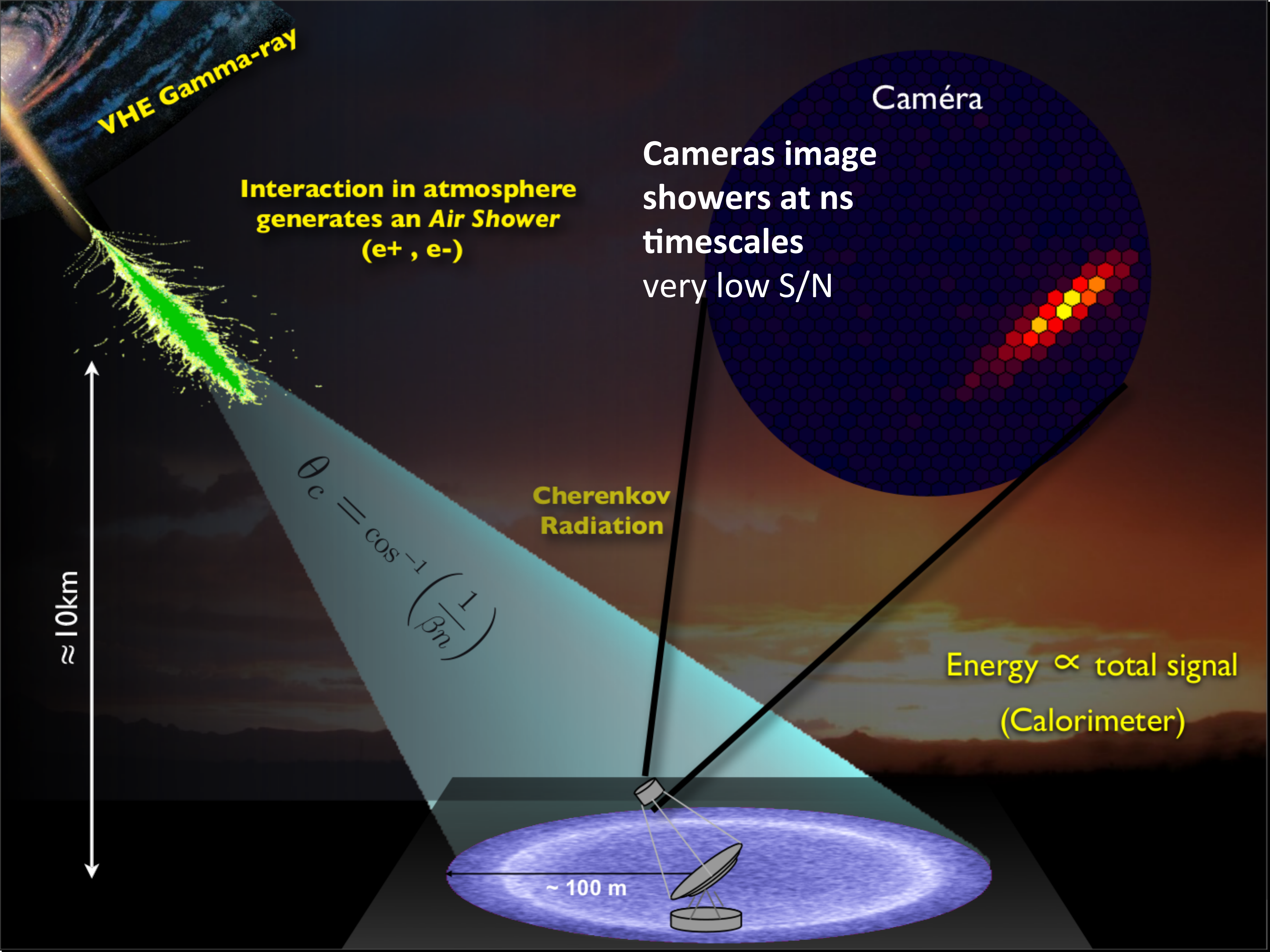
OBSERVATORIES:
CTA



How Cherenkov Telescopes Work

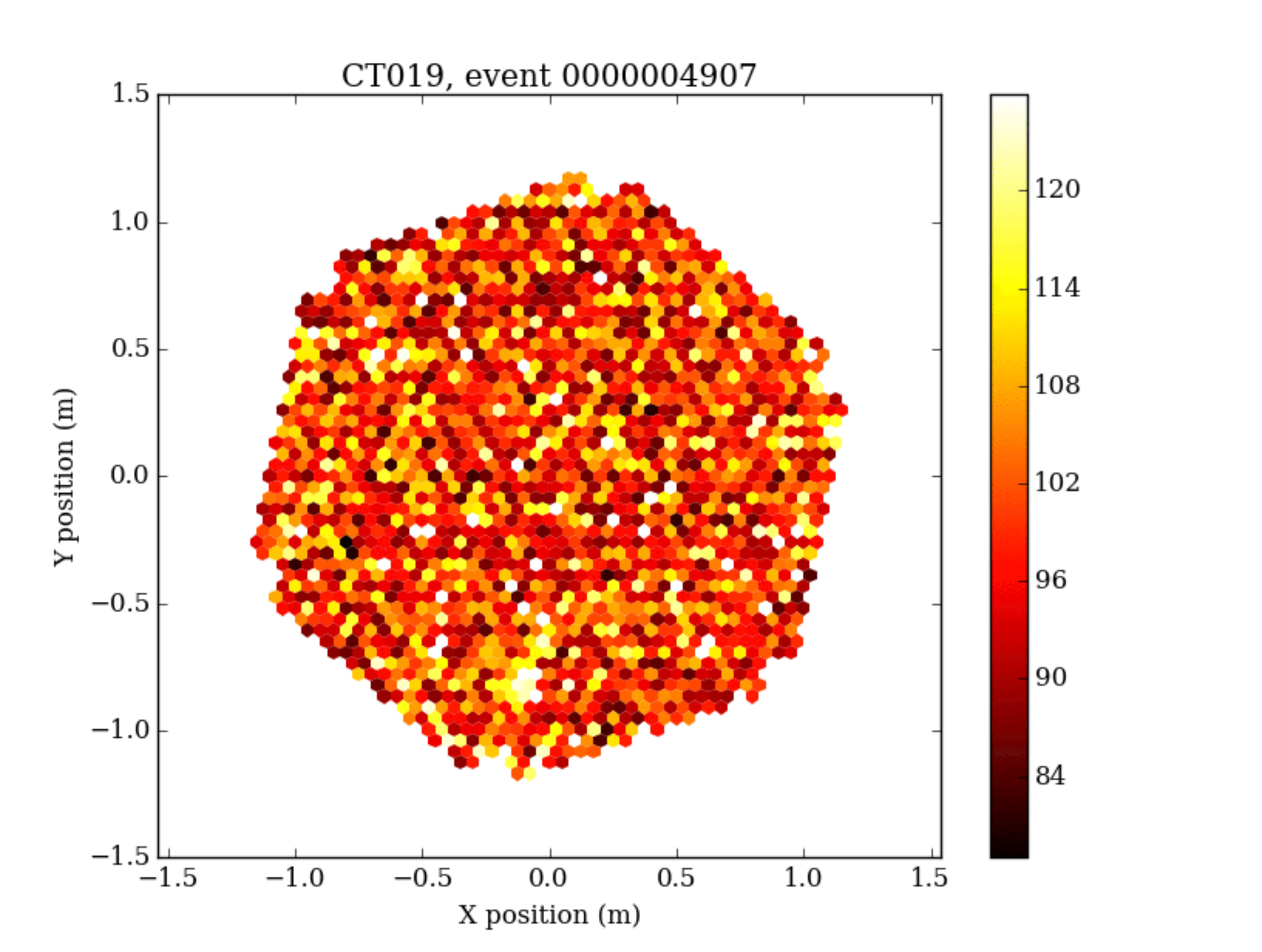



VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
Gamma-rays produce air showers
glow in Cherenkov light
detected by very sensitive optical telescopes
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
Cherenkov
Radiation
≈10km
Energy ∝ total signal
(Calorimeter)
~ 100 m

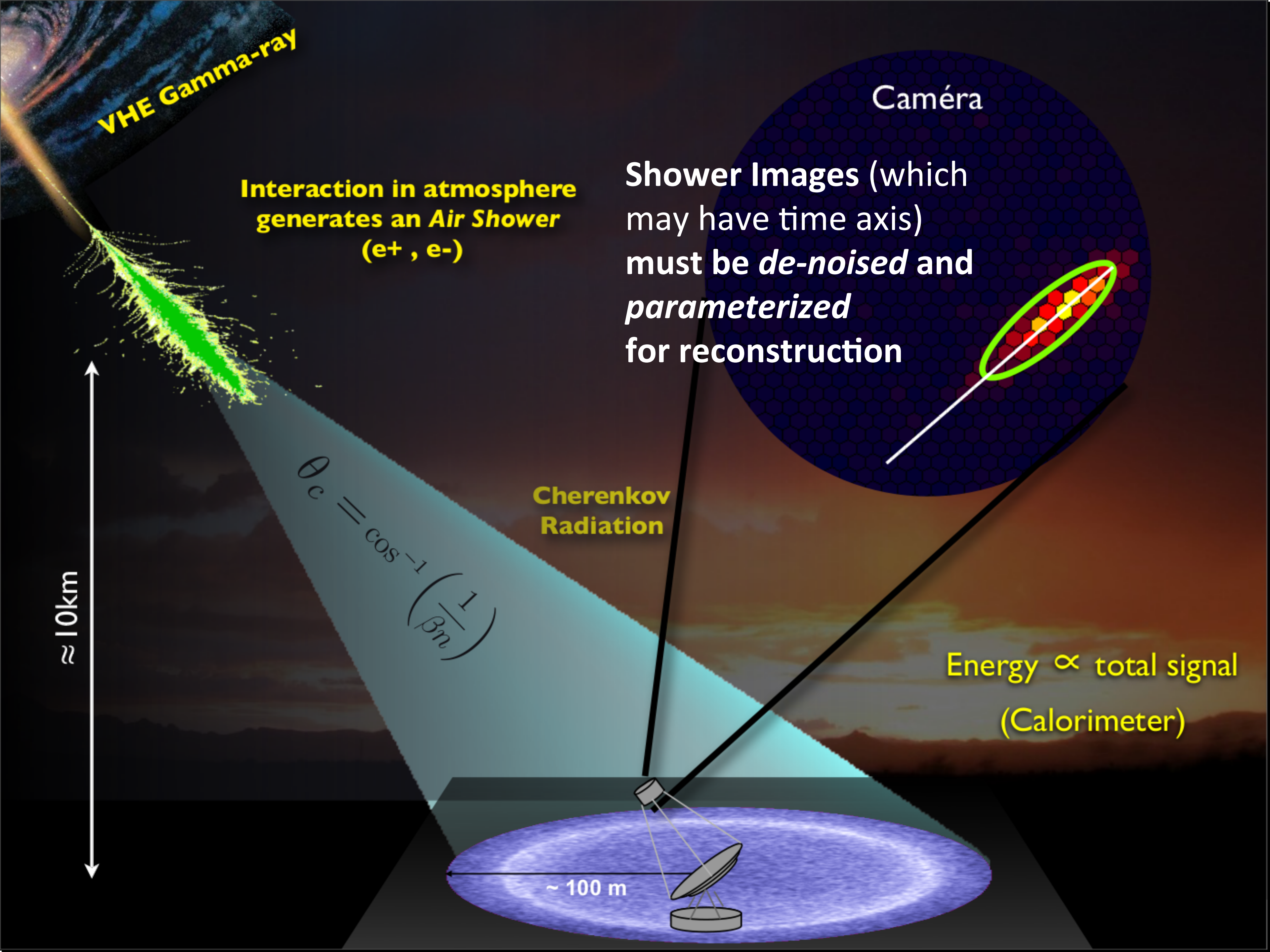


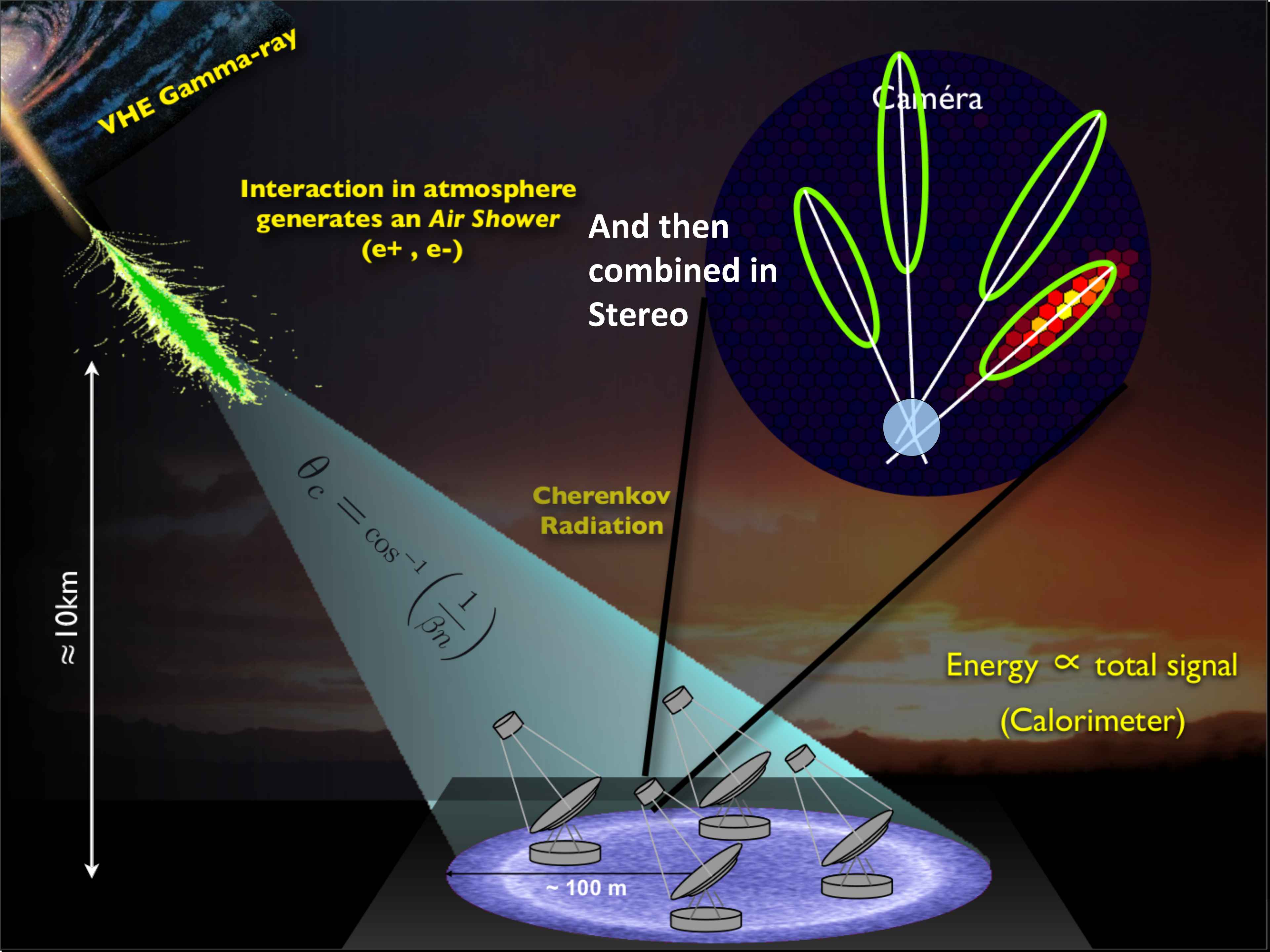
VHE Gamma-ray
Interaction in atmosphere generates an *Air Shower* (e+ , e-)
Caméra
Cameras image showers at ns timescales
very low S/N
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
Cherenkov Radiation
≈ 10km
Energy ∝ total signal
(Calorimeter)
~ 100 m

EXAMPLE



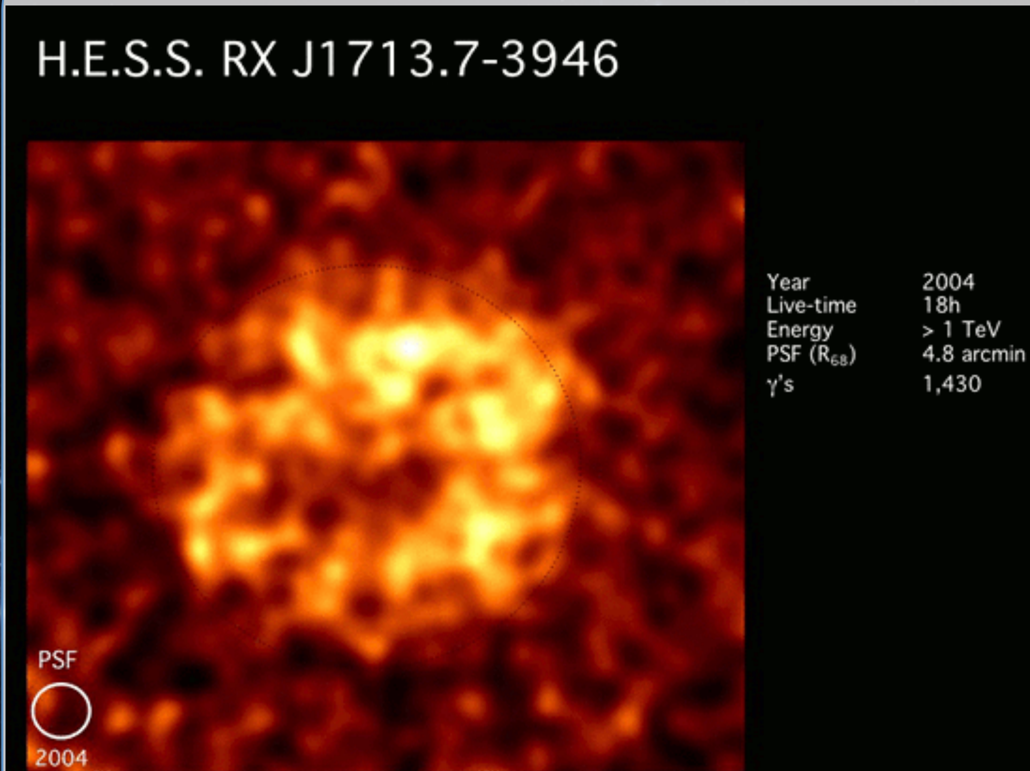
CT019, event 0000004907
Y position (m)
X position (m)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
120
114
108
102
96
90
84

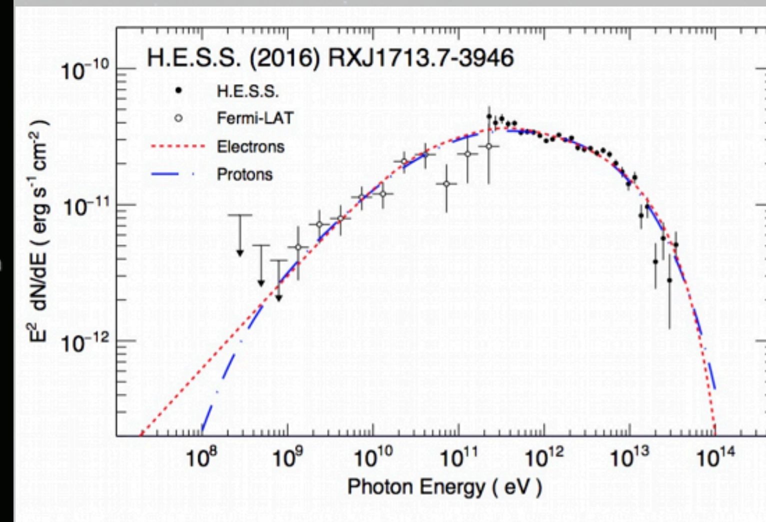

VHE Gamma-ray
Interaction in atmosphere generates an *Air Shower* (e+ , e-)
Caméra
Shower Images (which may have time axis) **must be *de-noised* and *parameterized* for reconstruction**
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
Cherenkov Radiation
≈ 10km
Energy ∝ total signal
(Calorimeter)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



VHE Gamma-ray
Interaction in atmosphere generates an *Air Shower* (e+ , e-)
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



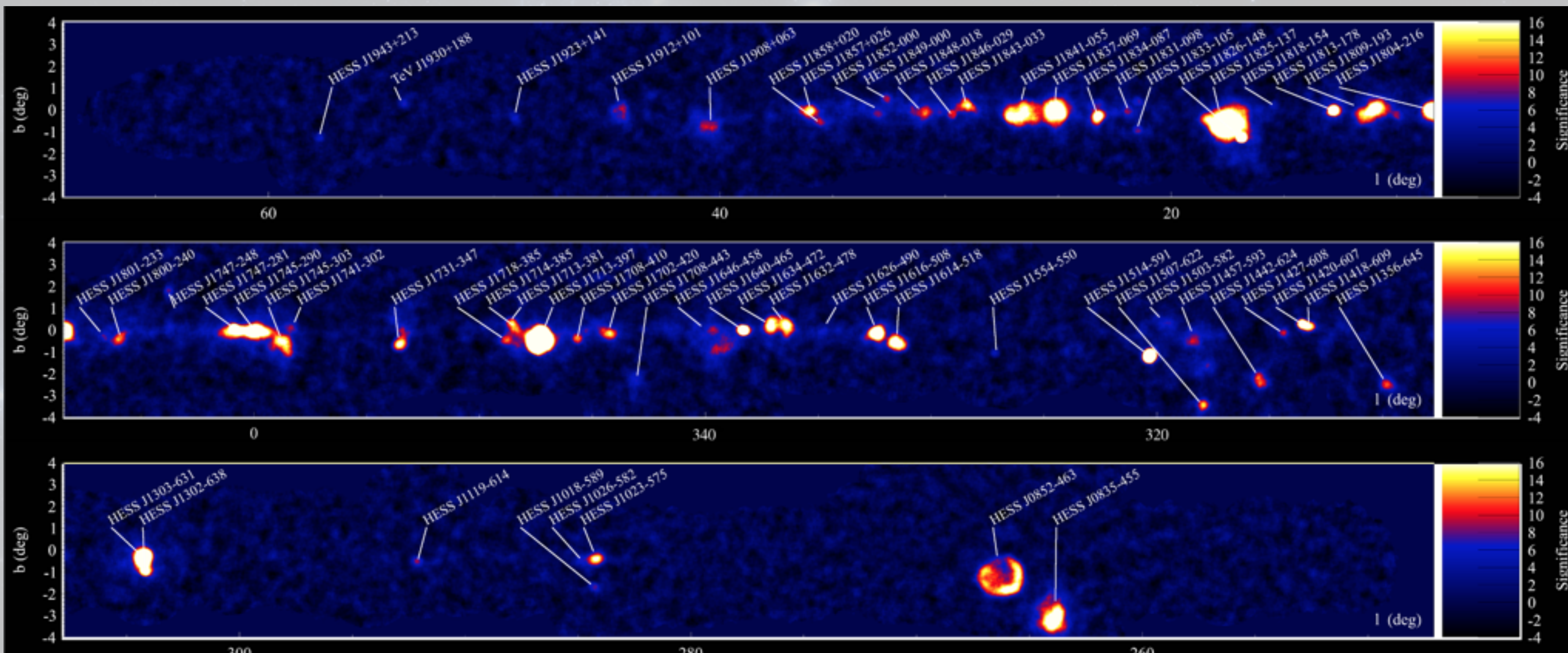


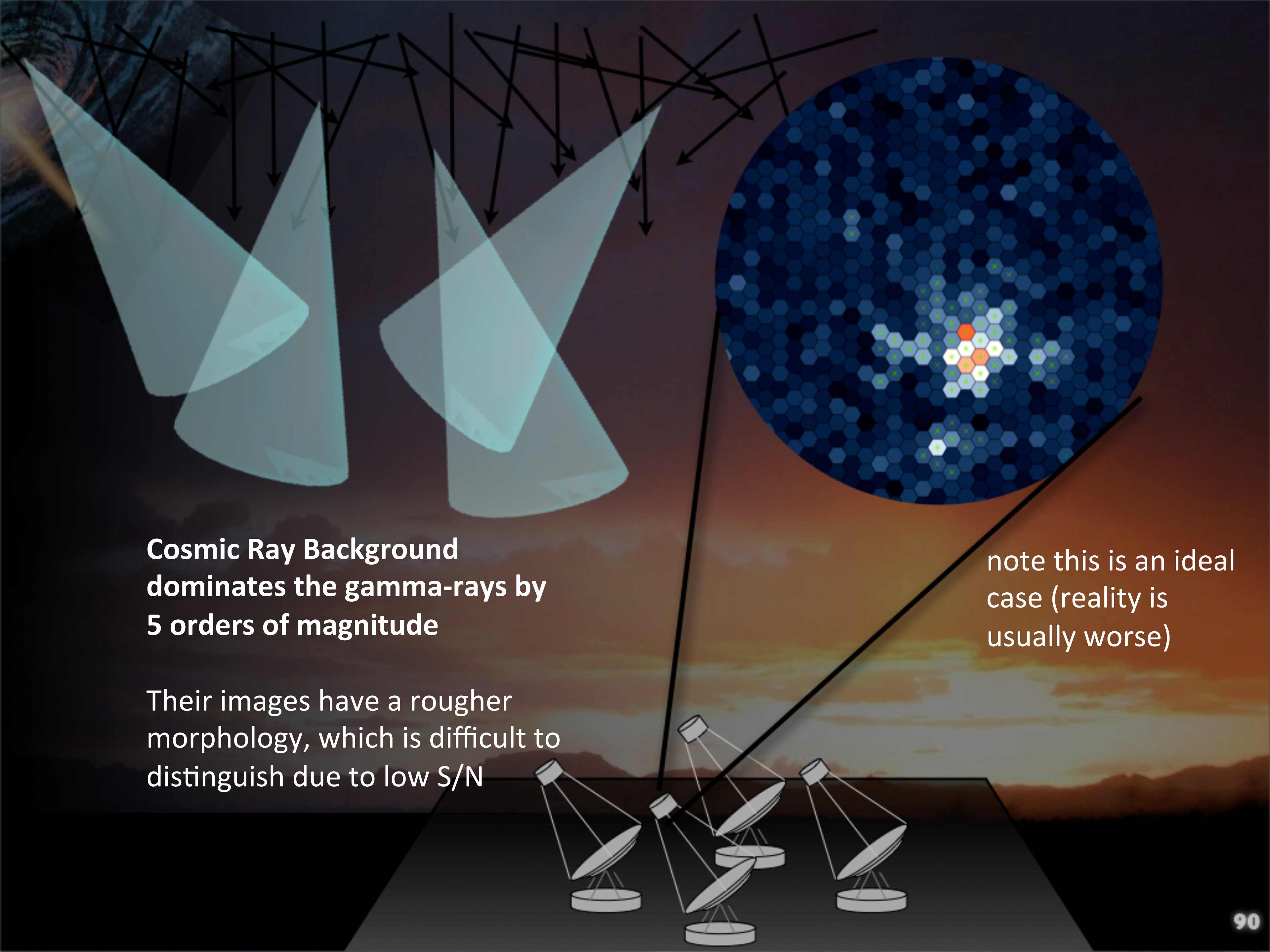
Very steep ($\approx E^{-2.5}$ spectra)
so low-energy threshold important

Could use this to show what a final sky map looks like (after reconstruction many 1000s of gamms rays)

This is a supernova remnant shell

SKY MAPS


HESS J1943+213
TeV J1930+188
HESS J1923+141
HESS J1912+101
HESS J1908+063
HESS J1858+020
HESS J1857+026
HESS J1852-000
HESS J1849-000
HESS J1848-018
HESS J1846-029
HESS J1843-033
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1831-098
HESS J1833-105
HESS J1826-148
HESS J1825-137
HESS J1818-154
HESS J1813-178
HESS J1809-193
HESS J1804-216
HESS J1801-233
HESS J1800-240
HESS J1747-248
HESS J1747-281
HESS J1745-290
HESS J1745-303
HESS J1741-302
HESS J1731-347
HESS J1718-385
HESS J1714-385
HESS J1713-381
HESS J1713-397
HESS J1708-410
HESS J1702-420
HESS J1708-443
HESS J1646-458
HESS J1640-465
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1616-508
HESS J1614-518
HESS J1554-550
HESS J1514-591
HESS J1507-622
HESS J1503-582
HESS J1457-593
HESS J1442-624
HESS J1427-608
HESS J1420-607
HESS J1418-609
HESS J1356-645
HESS J1303-631
HESS J1302-638
HESS J1119-614
HESS J1018-589
HESS J1026-582
HESS J1023-575
HESS J0852-463
HESS J0835-455
b (deg)
l (deg)
Significance
60
40
20
0
340
320
300
280
260



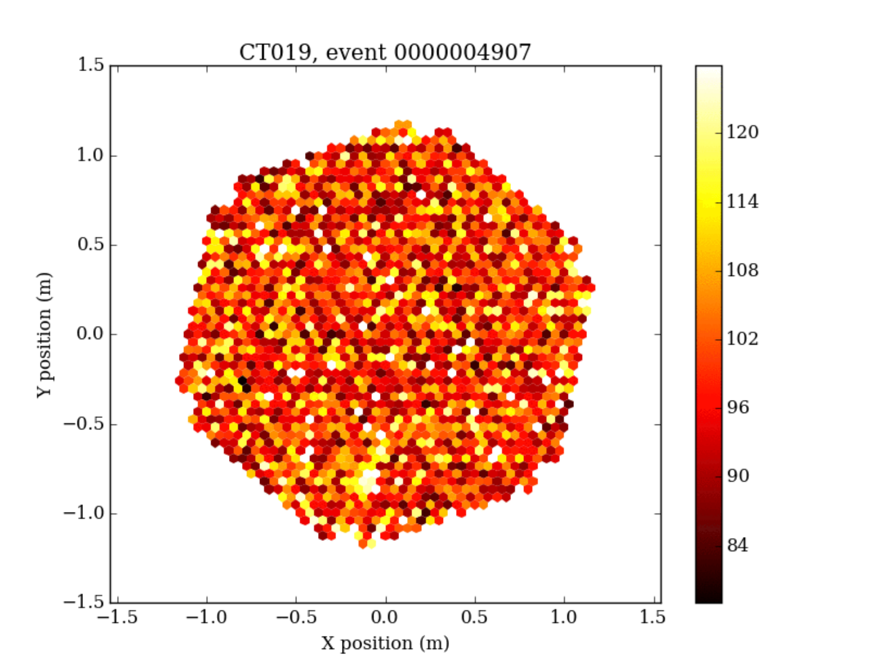
Cosmic Ray Background dominates the gamma-rays by 5 orders of magnitude

Their images have a rougher morphology, which is difficult to distinguish due to low S/N

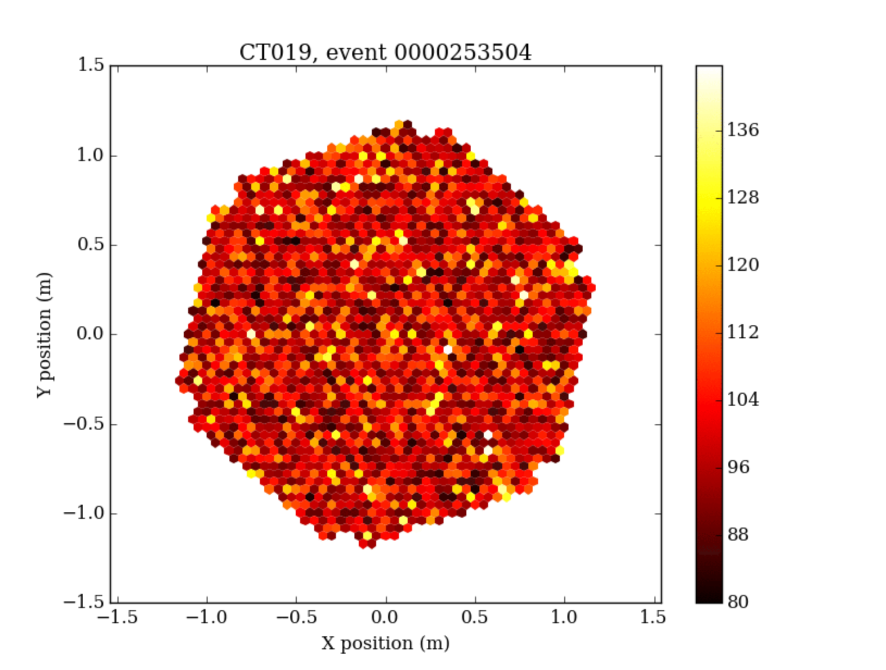
note this is an ideal case (reality is usually worse)

EXAMPLES

Gamma rays



Protons



PROJECT:
FOCUS ON TWO ASPECTS FOR CHERENKOV TELESCOPES

✓ **Gamma-ray reconstruction and discrimination**

- Better de-noising and image characterization
- Improve PSF and energy threshold
- Improve data volume reduction with less loss for CTA (factor of 100x needed)

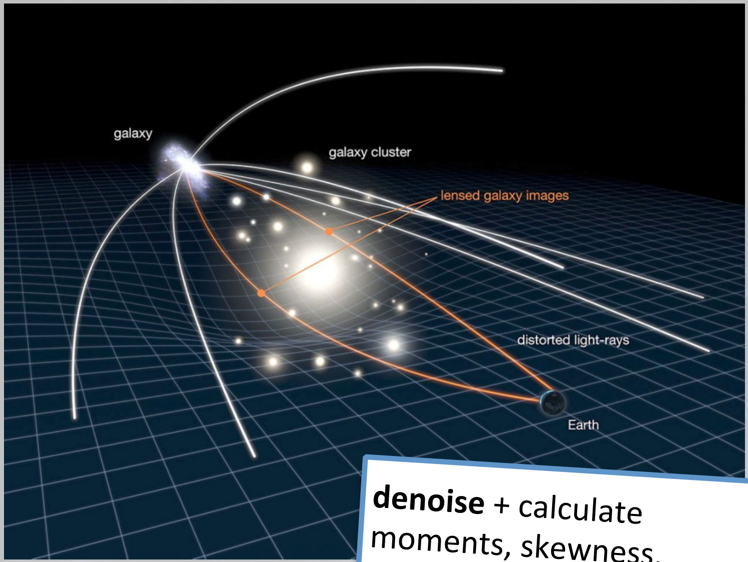
✓ **Realtime transient detection**

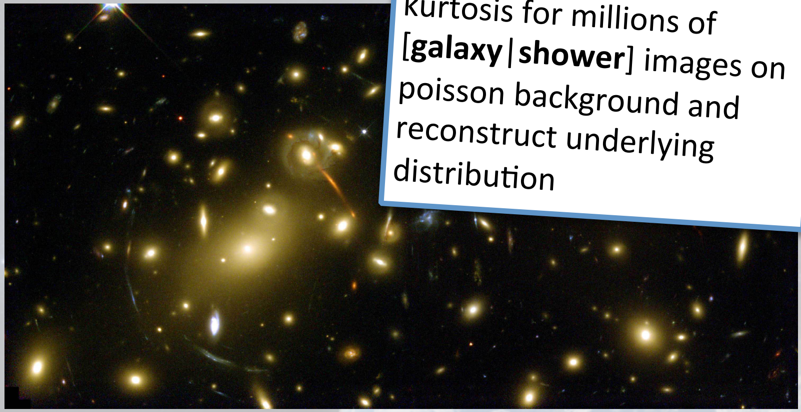
- Wide field-of-view
- Changing detector conditions (atmosphere)
- Complex detector response
- Reduce reliance on calibration and pre-calculated instrumental response functions

THE IDEA:
SYNERGIES WITH OTHER FIELDS

An example: Weak Gravitational Lensing

- **Look for and parameterize *minute shears* in images of galaxies**
- **Galaxy images are low Gaussian signals on high-noise background**
  - This is nearly identical to the problem we have when reconstructing Cherenkov-light images of showers
  - Very **different physics, same mathematics**…
  - The techniques developed for Weak lensing are **far more advanced** than what are currently used for gamma rays and **can be exploited**





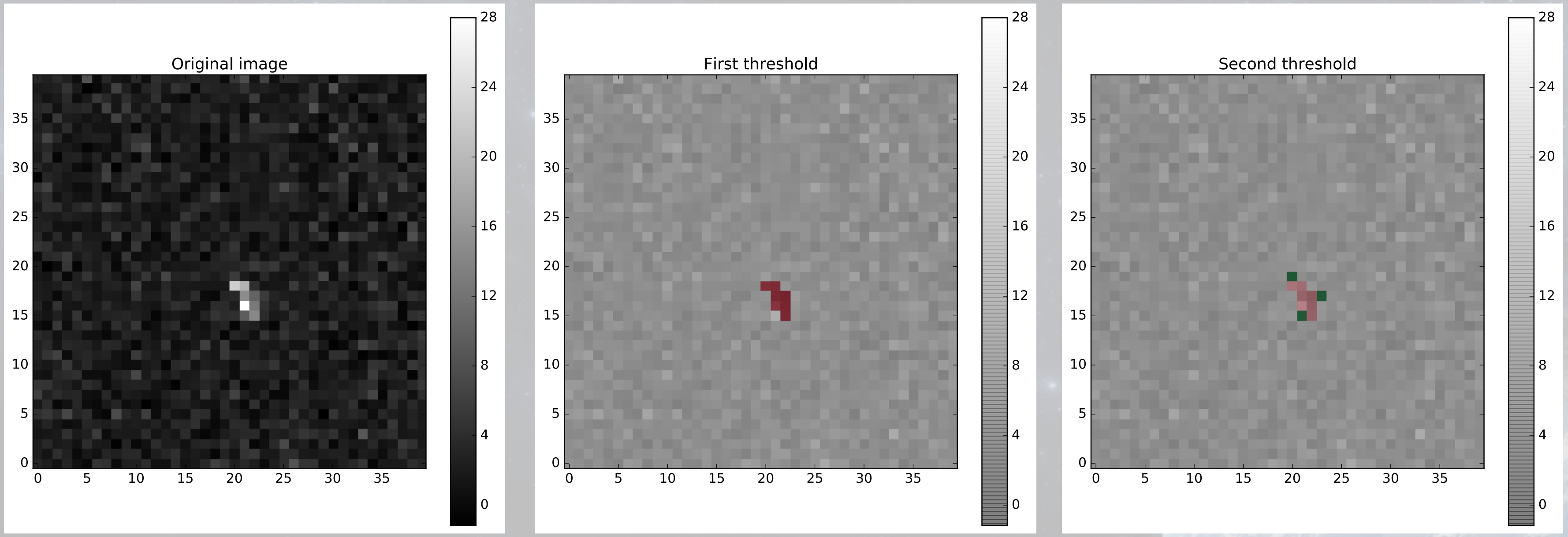
denoise + calculate moments, skewness, kurtosis for millions of [**galaxy**|**shower**] images on poisson background and reconstruct underlying distribution

e.g "Weak Lensig Mass Reconstrcution using Wavelets", J.-L. Starck, S. Pires, and A. Refregier, A&A, 451, 3, 1139-1150, 2006

METHODS CURRENTLY USED FOR GAMMA RAYS IMAGES CLEANING

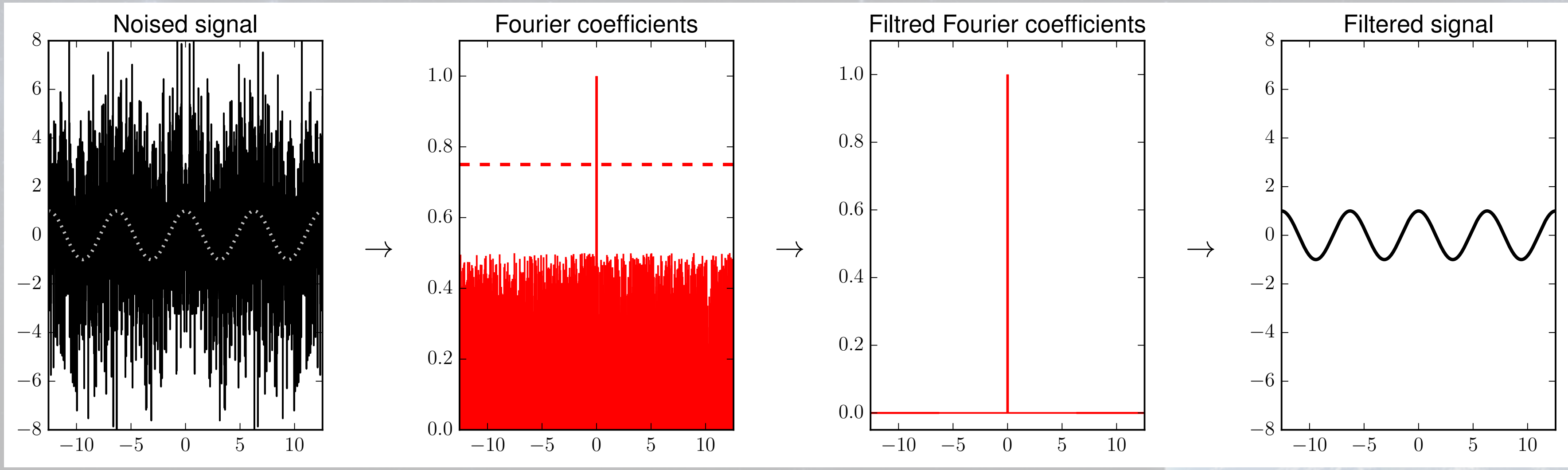
A very simple cleaning procedure:

- 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)



Sparse image and signal processing:

- Remove noise in direct space can be difficult
- Remove noise in the transformed space can be easier (Fourier, Wavelets, ...):
  - noise is uniformly distributed on small coefficients
  - signal is defined by few big coefficients

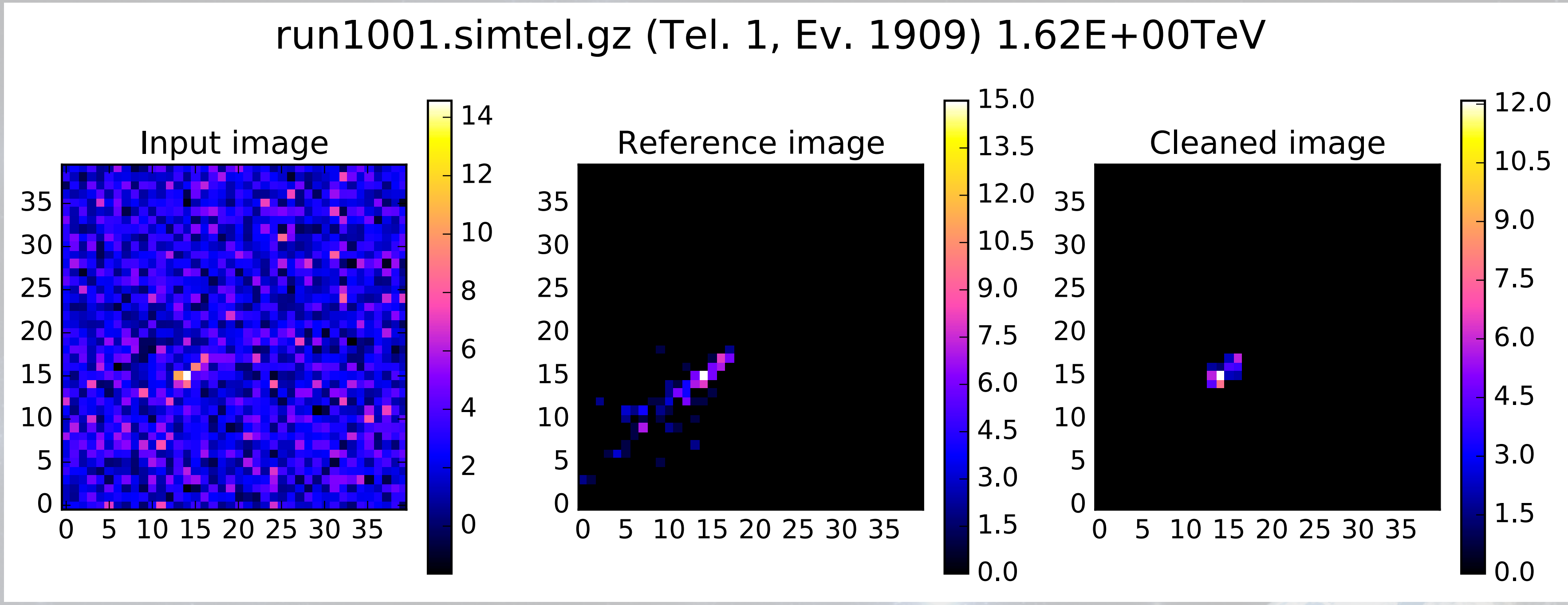


ADVANTAGES

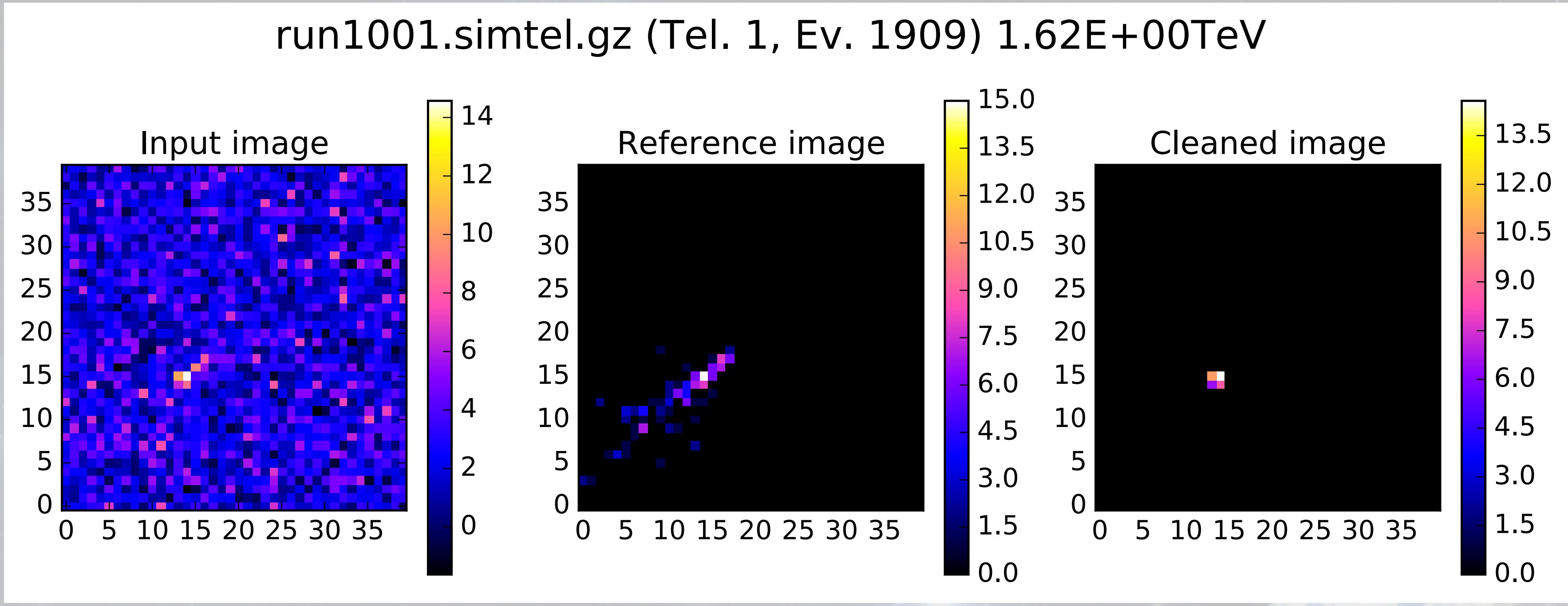
- **Sparse methods:**
  - Wavelets
  - Curvelets
  - Shearelets
  - Shapelets
  - ...

- Better noise separation
- Keep large and small scales
- Gamma/Hadron discrimination
- Fainter features

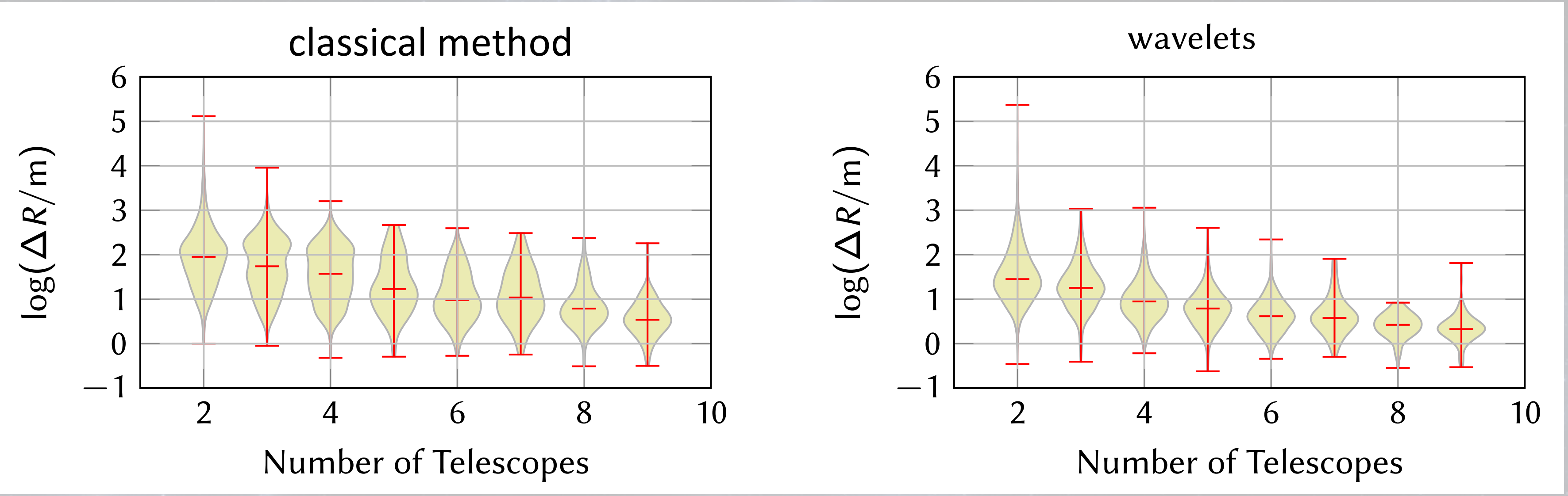
EXAMPLE: IMAGE CLEANING WITH WAVELETS



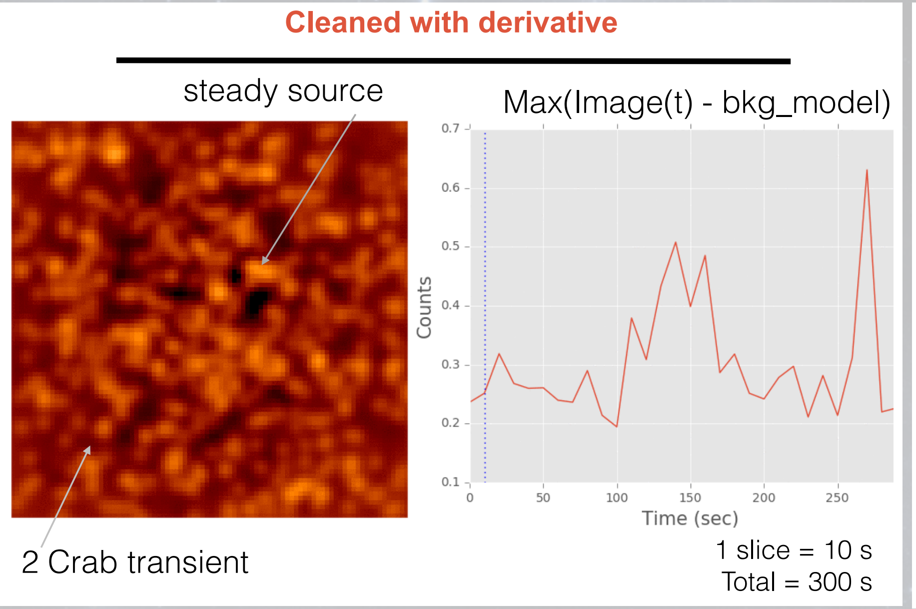
EXAMPLE:
FORMER IMAGE CLEANING METHOD

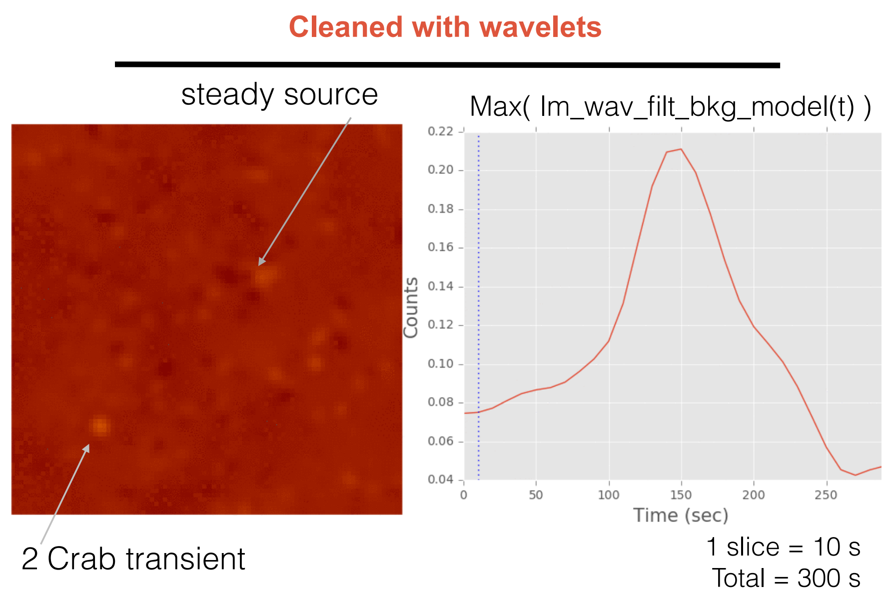


PROGRESS IN EVENTS RECONSTRUCTION (TINO MICHAEL)



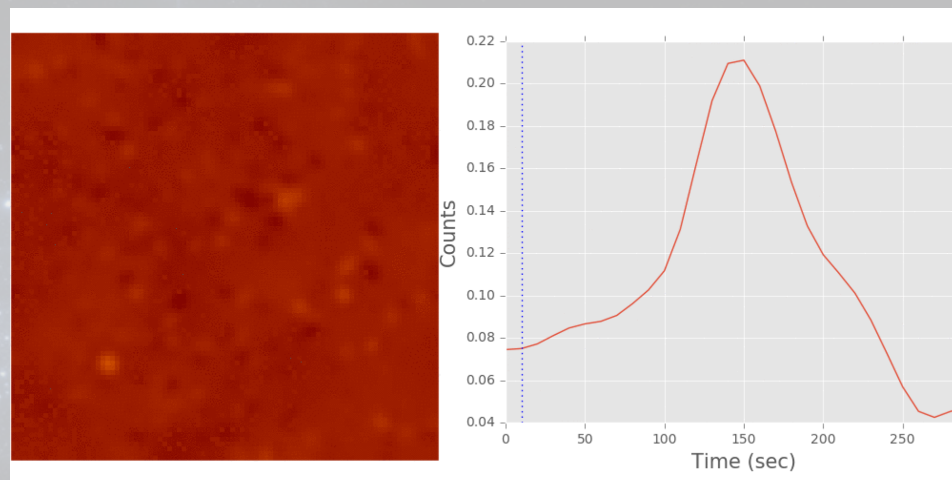
PROGRESS IN TRANSIENT DETECTION (FABIO ACERO)

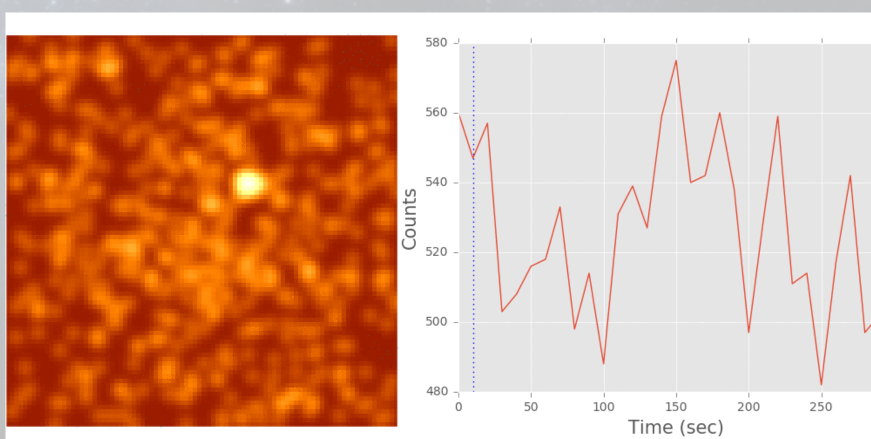




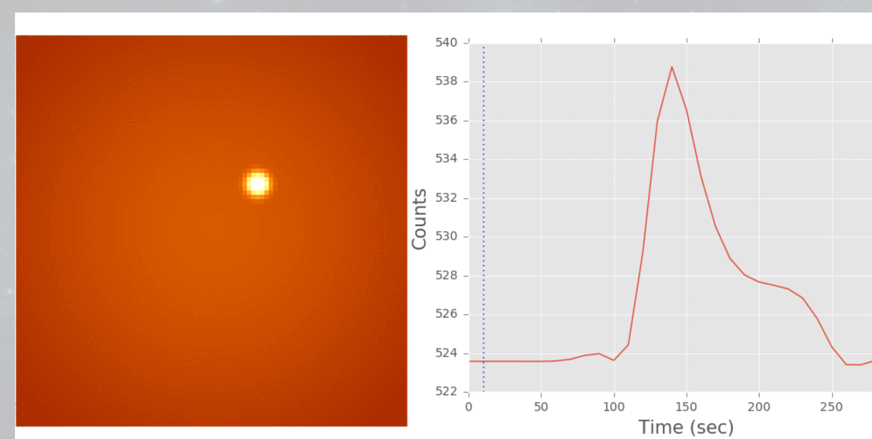
PROGRESS IN TRANSIENT DETECTION (FABIO ACERO)

Toy model





Toy model + noise



Cleaned toy model with wavelets

PROJECT:
PLAN/TIMELINE

	Q1 2015	Q2 2015	Q3 2015	Q4 2015	Q1 2016	Q2 2016	Q3 2016	Q4 2016	Q1 2017	Q2 2017	Q3 2017	Q4 2017	Q1 2018
Postdoc Search													
Postdoc employment				delay									
Technique Study													
Implementation & test (*recon*), simplified data													
Implementation & test (recon) with realistic data								delay					
Implementation & test (transients)													
Final Validation								delay	delay				
Technique Publication													

✓ **Main Deliverables:**

- Code library adapted for use for Cherenkov Telescopes (open-source, python)
- Validation report (plots and results for realistic data, MC for CTA or real for HESS if possible)
- Publication on technique / documentation

✓ **Schedule notes:**

- Some unforeseen delays at start of project
- Challenges to finish on time:
  - *Adapt techniques to realistic data (see later)*
  - *Validation of technique*

SUMMARY

- **Modern signal processing techniques appear to be very useful for Cherenkov Telescope data**
  - Improve PSF
  - Improve low energy sensitivity
  - Immediate applications to CTA and HESS
  - Perhaps provide faster data processing
- **This Work has piqued the interest of other members, started new projects and fostered inter-group work**

Thank you

SUBJECT

Try to improve image cleaning before reconstruction (*Hillas*)

Improve methods to remove:

- Instrumental noise
- Background noise

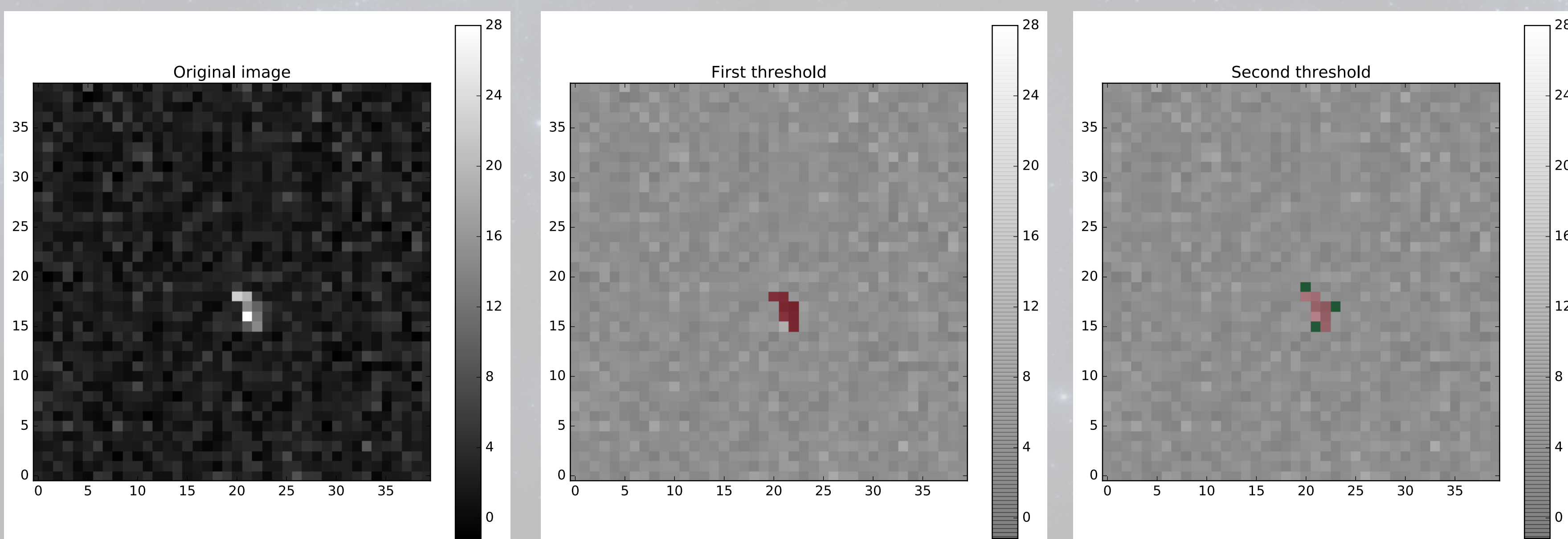
Motivations:

- Keep more signal (deeper into the noise)
- Reduce threshold
- Maybe eventually do cleaning and time-integration all at once

THE "TAILCUT CLEAN" ALGORITHM

A very simple cleaning procedure:

- Keep pixels above a given threshold (e.g. 50% max)
- Keep some neighbors of these selected pixels: those above a second (lower) threshold (e.g. 25% max)



REMARKS

- Fast and simple
- Sufficient for bright showers
- But surely we can do better for faint showers

BASIC IDEA TO GO BEYOND

- **Tailcut method: threshold in the main space**
- **Better idea: threshold 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

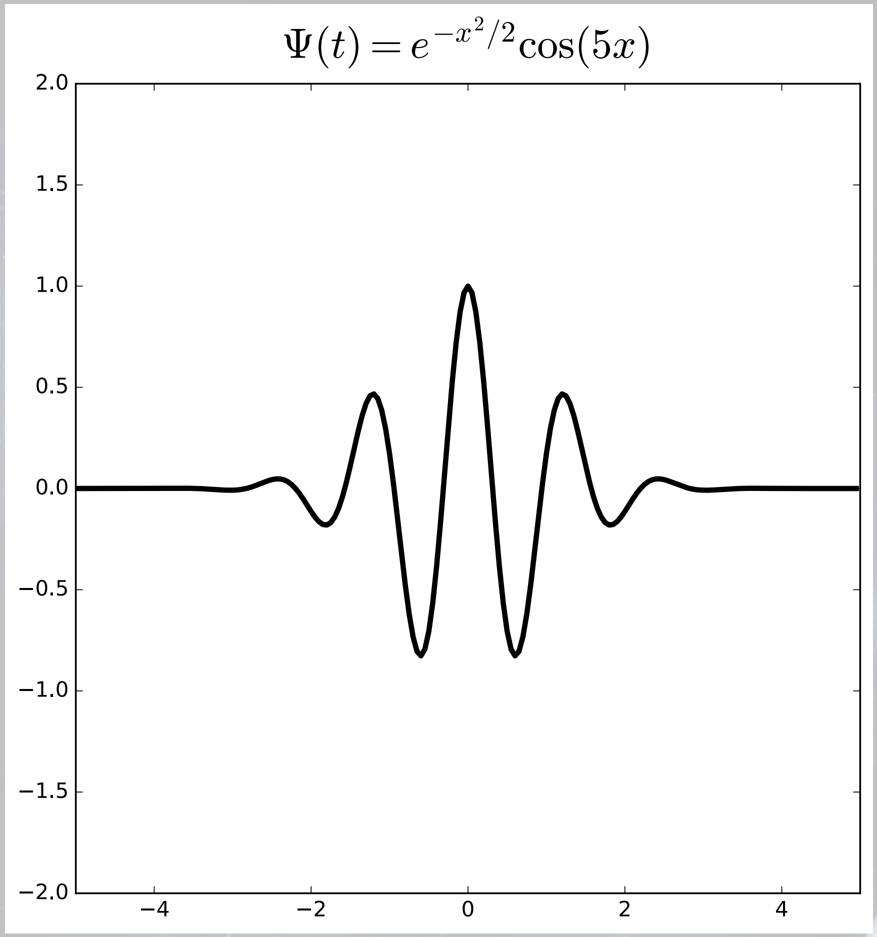
Roughly the same idea than doing filtering with Fourier Transform

- 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

- Use functions named wavelets instead sin and cos functions as new bases in the transformed space
- The transformed space contains spatial information

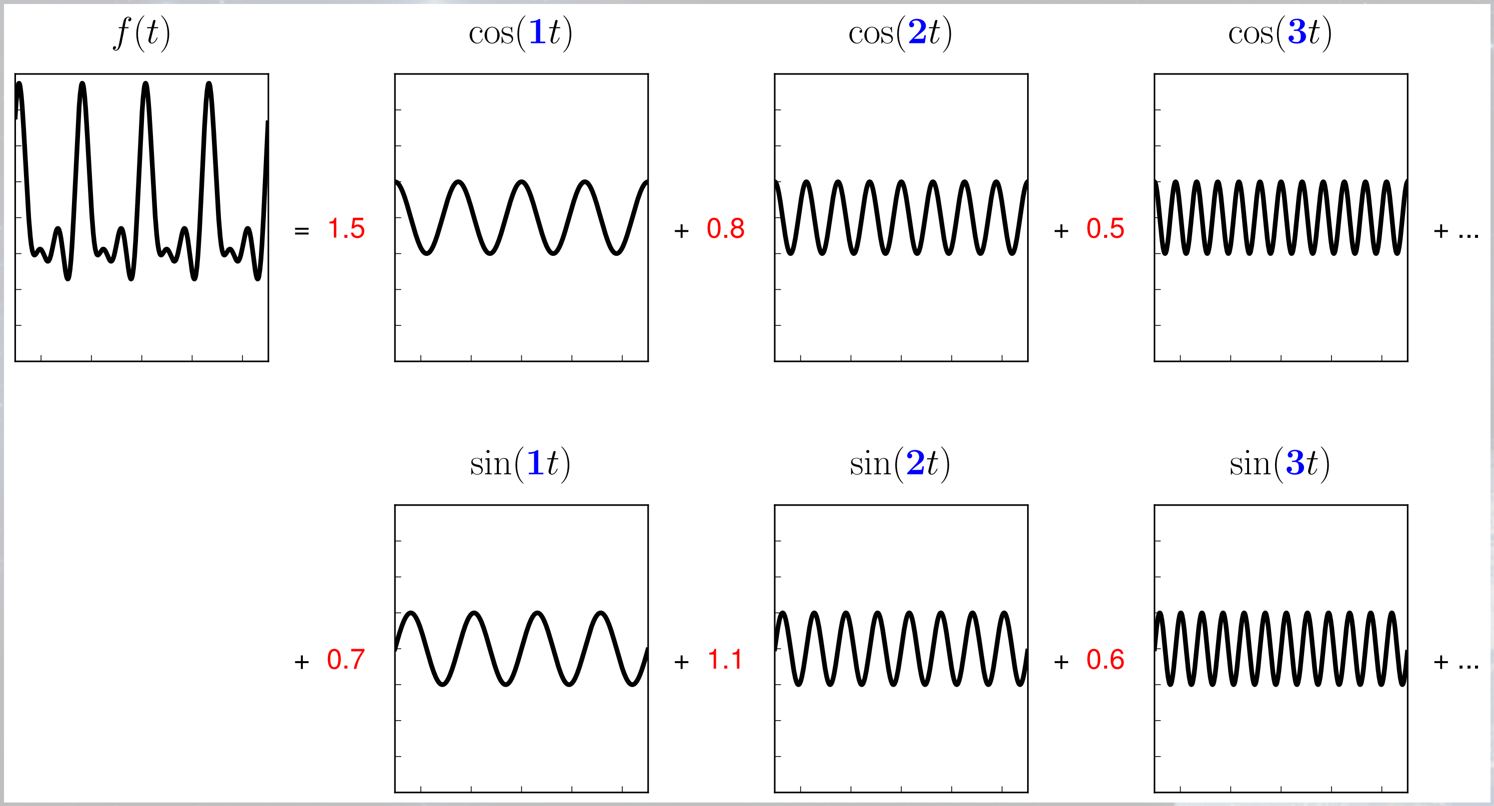
EXAMPLE OF WAVELET FUNCTION (MORLET WAVELET)



"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, ...)



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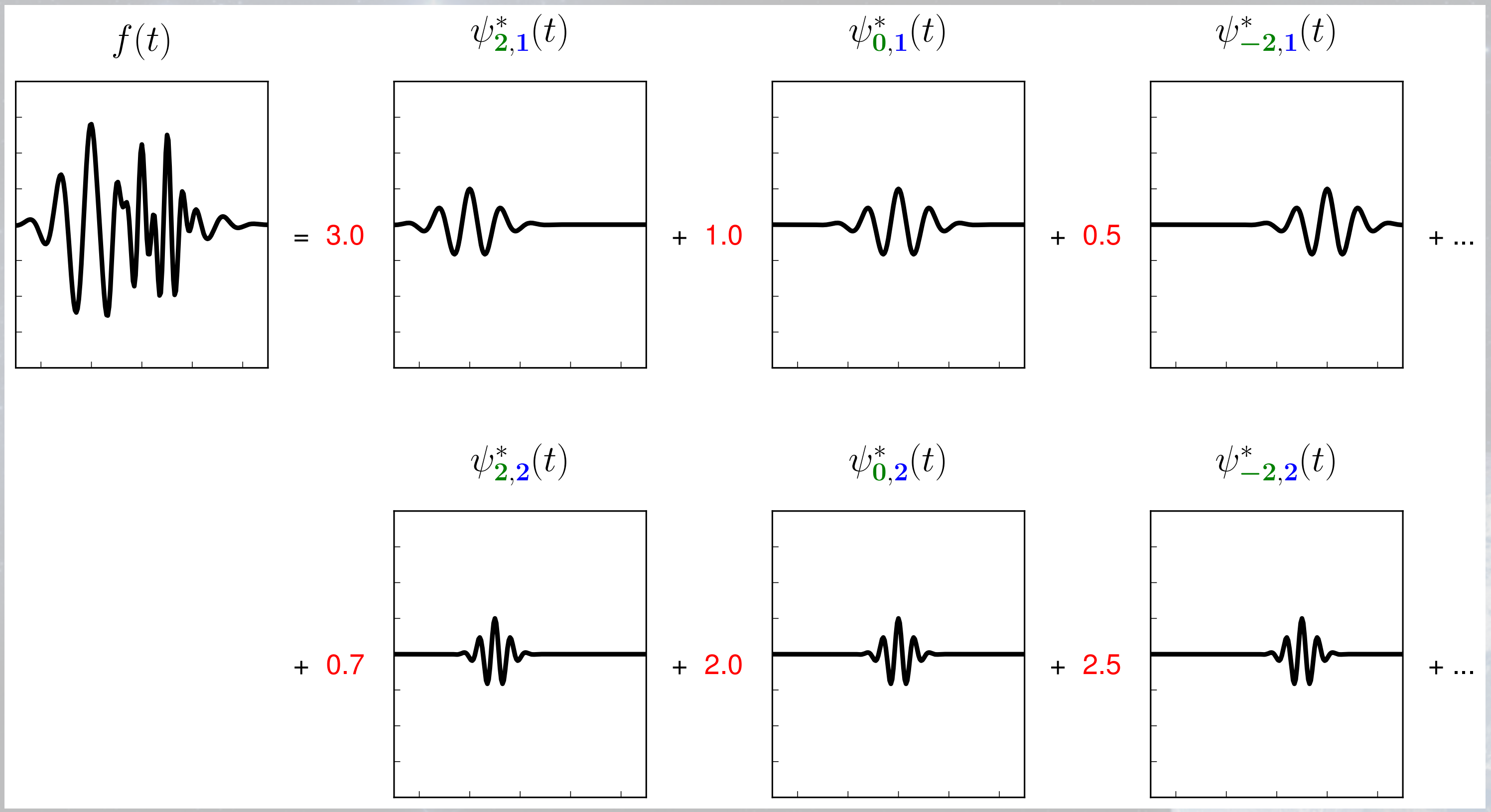
CLEANING PROCEDURE: GENERAL IDEA WITH WAVELET TRANSFORM

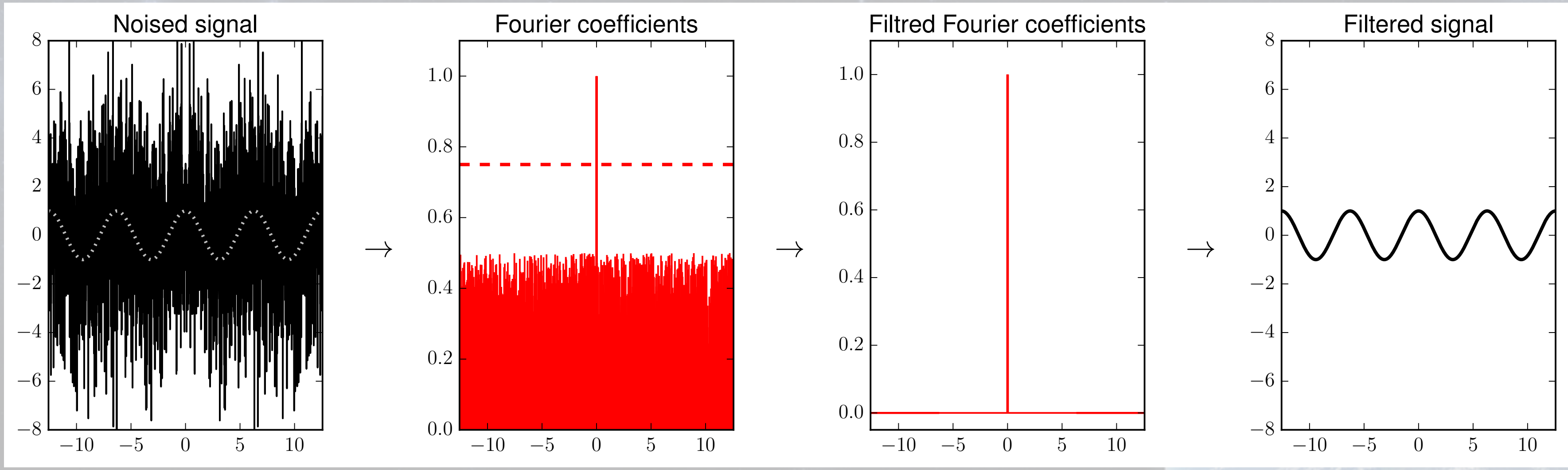
- Input signal is converted to a weighted sum of these wavelet functions at different scales (dilate factor) and positions (translate factor)
- Threshold is applied on these weights to remove locally (in space or time) some frequencies (or scales) in the input signal



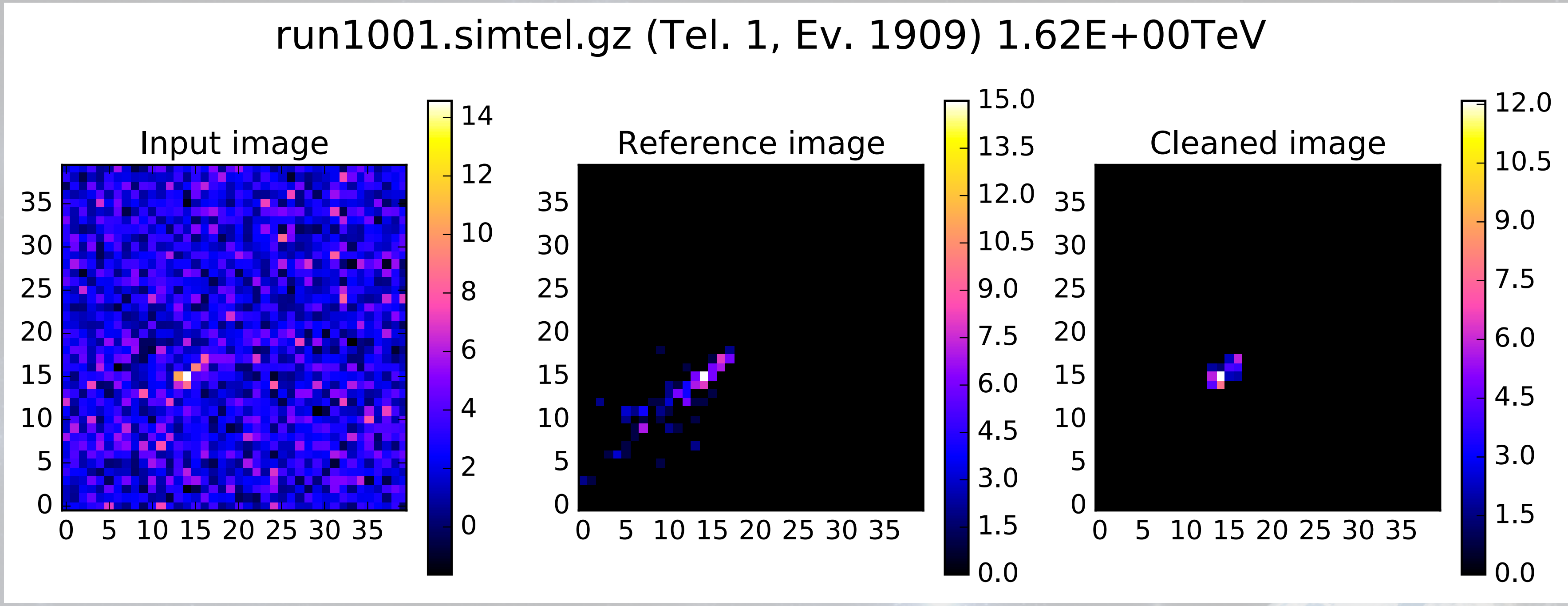
FIND A BASE WHERE SIGNAL AND NOISE CAN BE EASILY SEPARATED

In this example:

- Remove noise in direct space is difficult
- Remove noise in the transformed space is easy:
  - noise is uniformly distributed on small coefficients
  - signal is defined by few big coefficients



EXAMPLE


run1001.simtel.gz (Tel. 1, Ev. 1909) 1.62E+00TeV
Input image
Reference image
Cleaned image
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10
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0
2
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12
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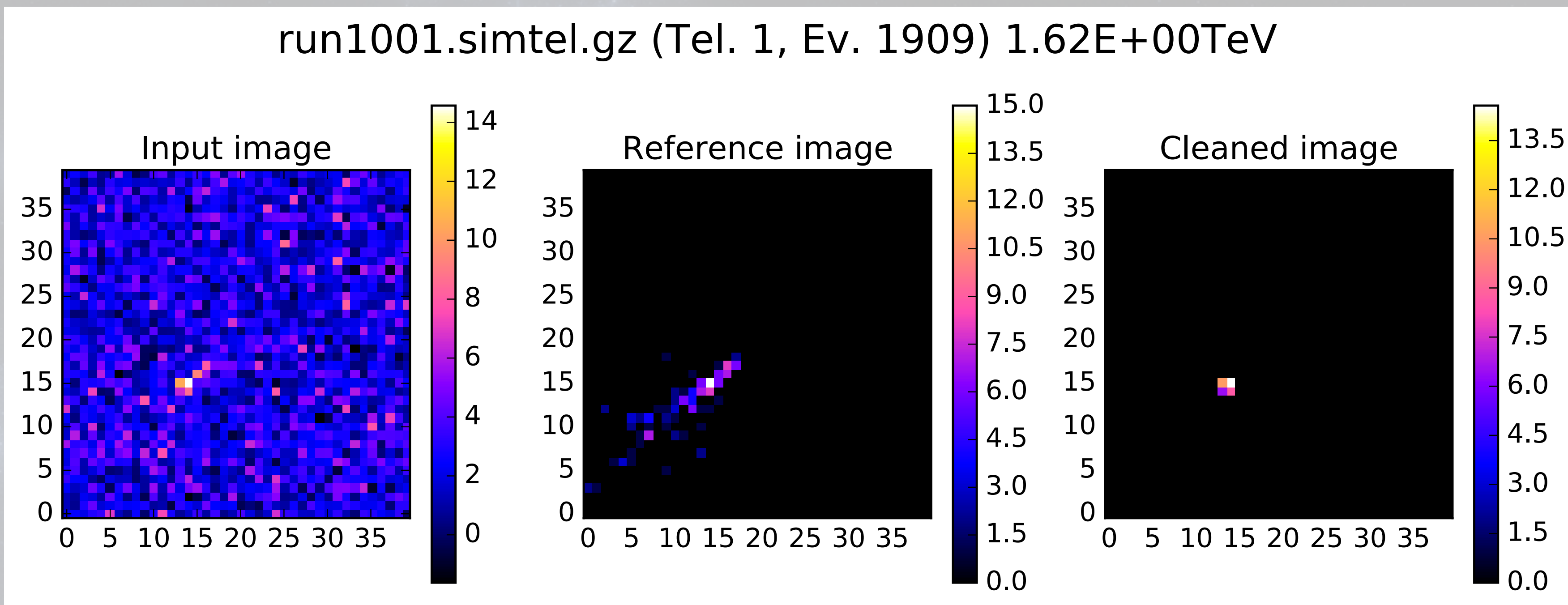
6.0
7.5
9.0
10.5
12.0
13.5
15.0

EXAMPLE


run1001.simtel.gz (Tel. 1, Ev. 1909) 1.62E+00TeV
Input image
Reference image
Cleaned image
0 5 10 15 20 25 30 35
0 2 4 6 8 10 12 14
0.0 1.5 3.0 4.5 6.0 7.5 9.0 10.5 12.0 13.5 15.0
0.0 1.5 3.0 4.5 6.0 7.5 9.0 10.5 12.0 13.5