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Detecting Gamma Rays

Part II: Very High Energy Gamma rays

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International School of Astro-Particle Physics, Paris 2012

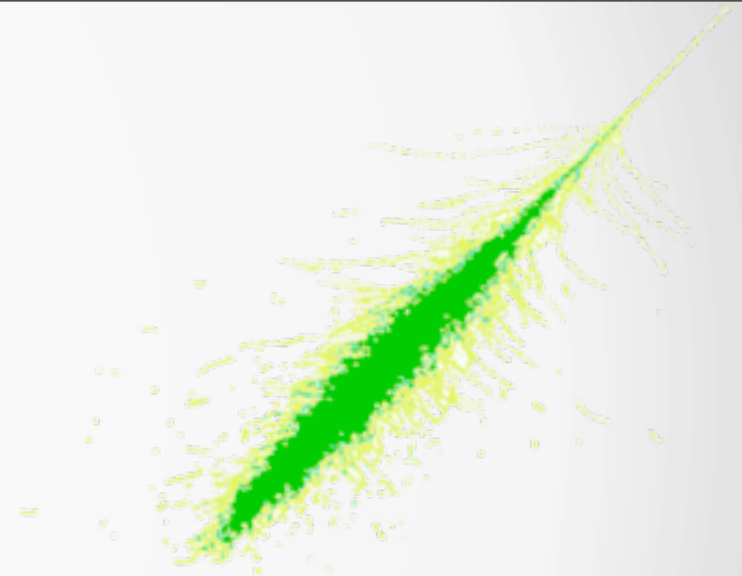
Last Time...

Sources of non-thermal radiation

The detection of high-energy (MeV-GeV) gamma rays

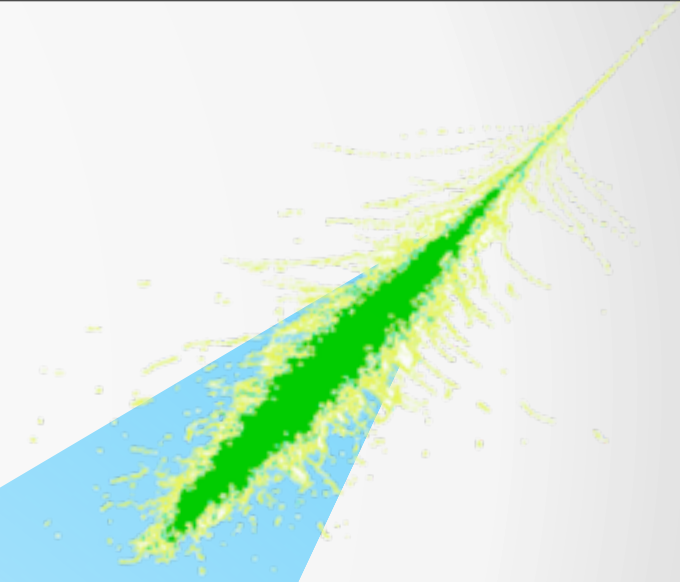
- MeV gammas: Compton-scatter in satellite
- GeV gammas: pair-production in satellite
- TeV gammas:
  - would pass right through satellite
  - need *much larger* collection area

Extensive air showers generated by gamma and cosmic rays in the atmosphere



IACT Technique

Detecting Very-High-Energy (VHE) gamma rays from the ground with *Imaging Atmospheric Cherenkov Telescopes*



IACT Technique

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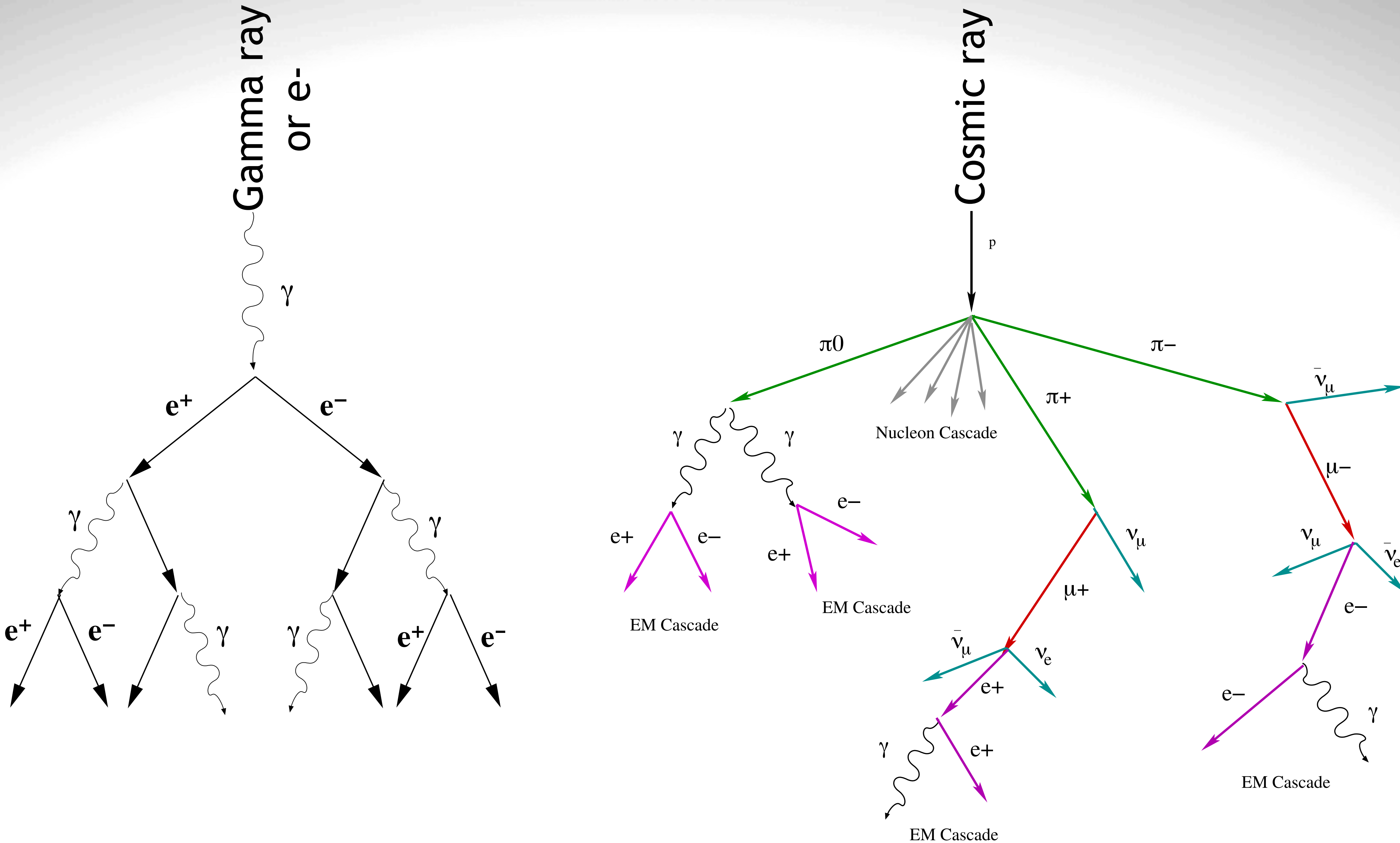
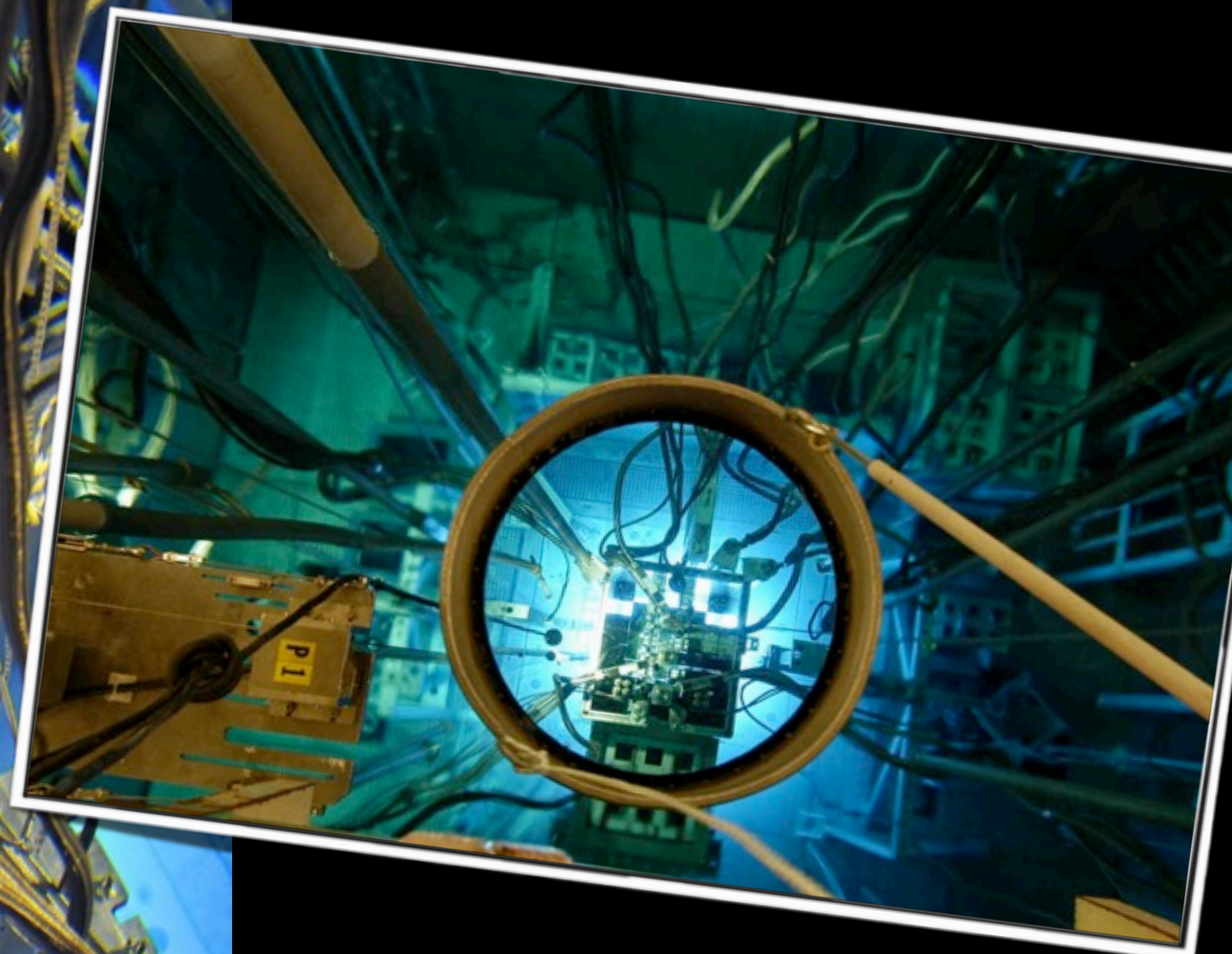
Recall: Air showers



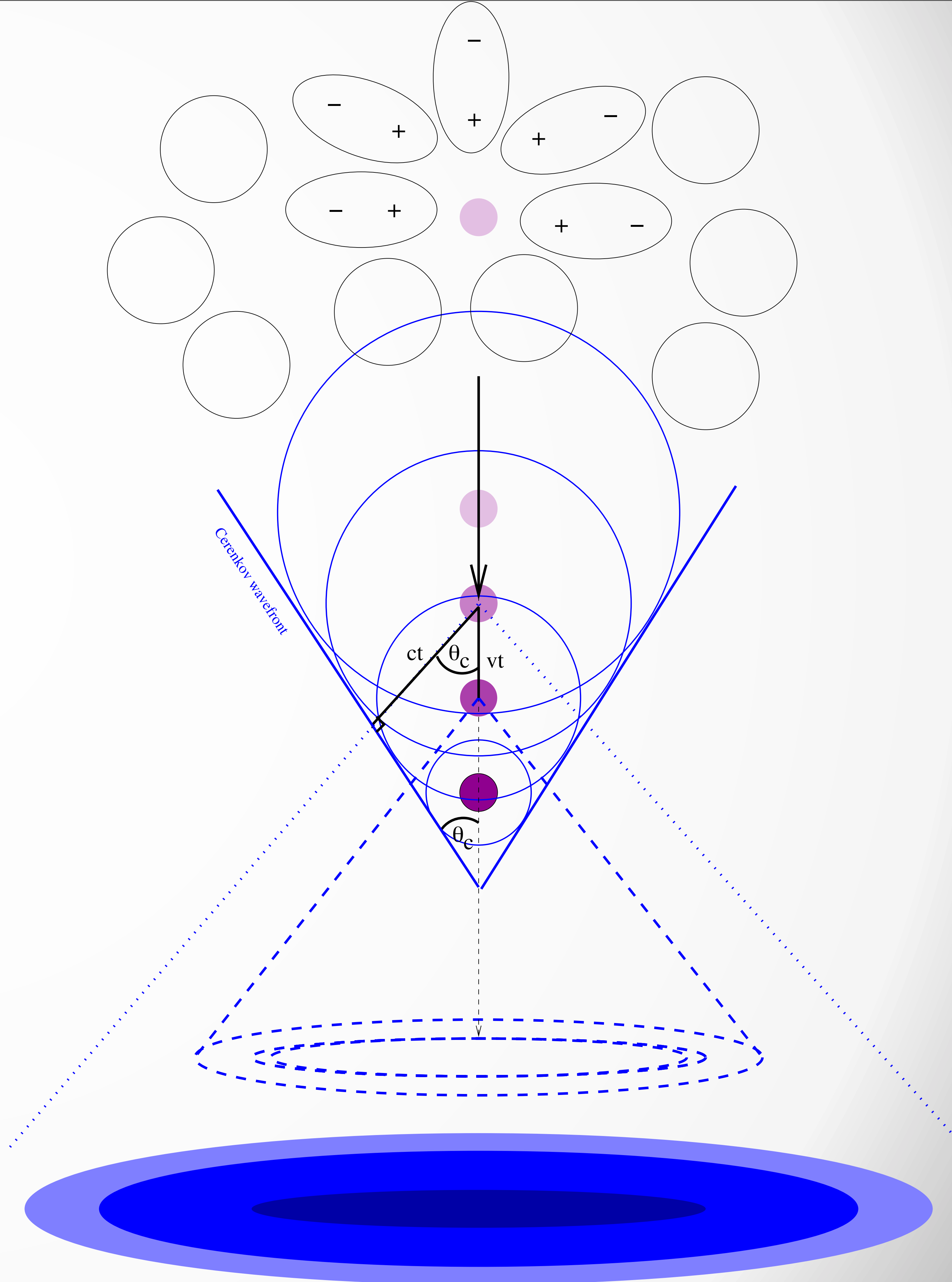
- Hadronic showers have larger transverse momentum, sub-showers that look like EM showers
- From Heitler Model of EM showers: max number of particles in shower is proportional to the incident energy

Detecting Extensive Air Showers



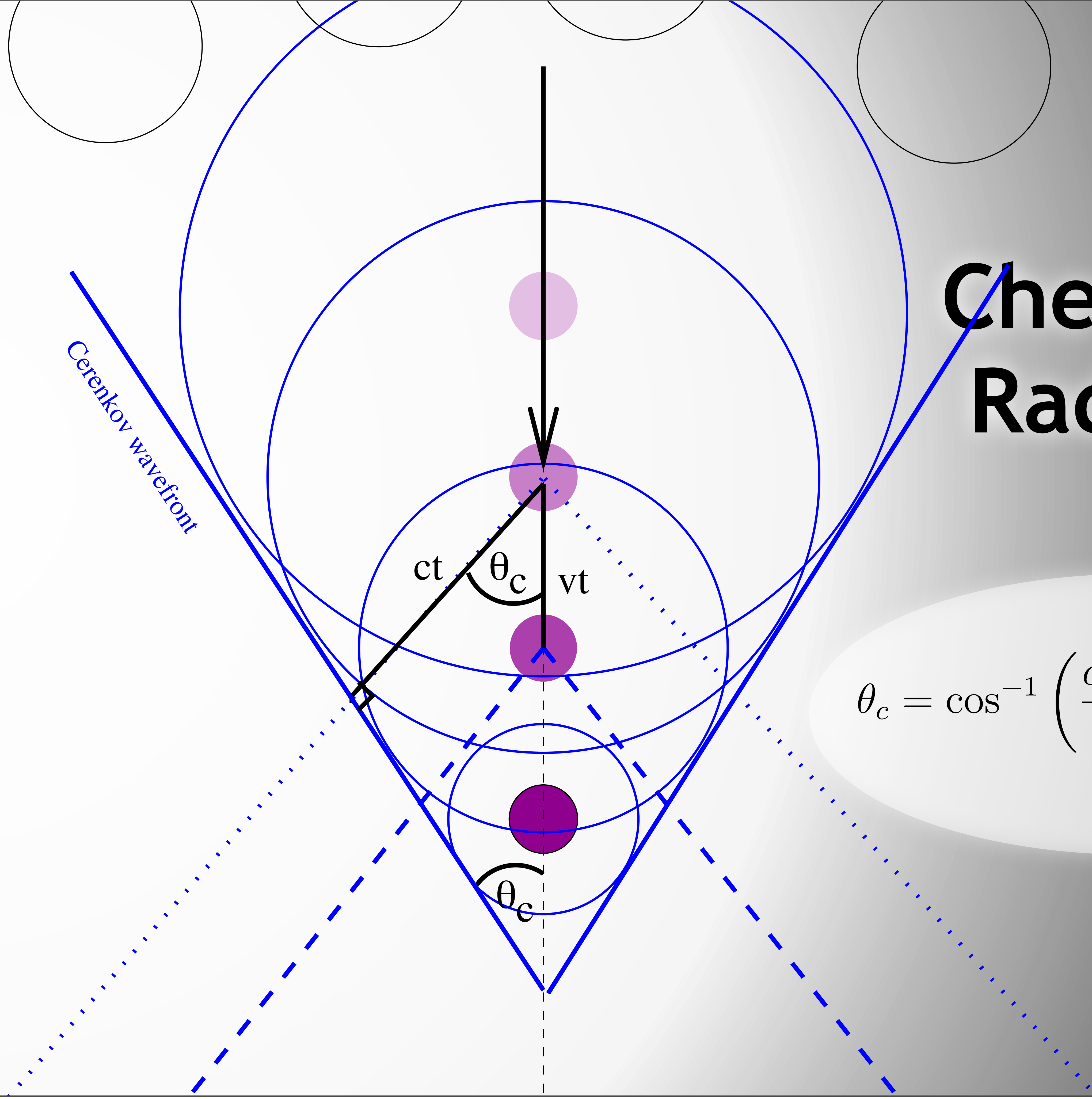
Core of the *Osiris* reactor, CEA Saclay

Cherenkov Radiation



- Charged particle momentarily polarizes surrounding molecules, which then snap back to equilibrium
- Normally, no radiation due to destructive interference
- When $v > c_m$, interference is no longer destructive, and radiation is emitted
- P. Cherenkov, Frank & Tamm (nobel prize in 1958)

Cherenkov Radiation



$$\theta_c = \cos^{-1}\left(\frac{c_{\mathrm{m}}t}{vt}\right) = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

Cherenkov Radiation in atmosphere

Jelley, 1958

$$\cos(\theta) = \frac{1}{\beta n}$$

$$n = 1 + \epsilon_0 e^{-h/h_0}$$ variation of IOR in atmosphere

$$h_0 \simeq 8.4\,\mathrm{km}$$ scale height

$$\epsilon_0 \simeq 2.8 \times 10^{-4}$$ at sea level

n_{air} @ sealevel ≈ 1.0003

θc = 1.4˚

(smaller higher up due to lower density)

Number of photons emitted per pathlength per frequency:

$$\frac{dN^2}{\partial x \partial \lambda} = \frac{2\pi\alpha Z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2\, n^2(\lambda)}\right)$$

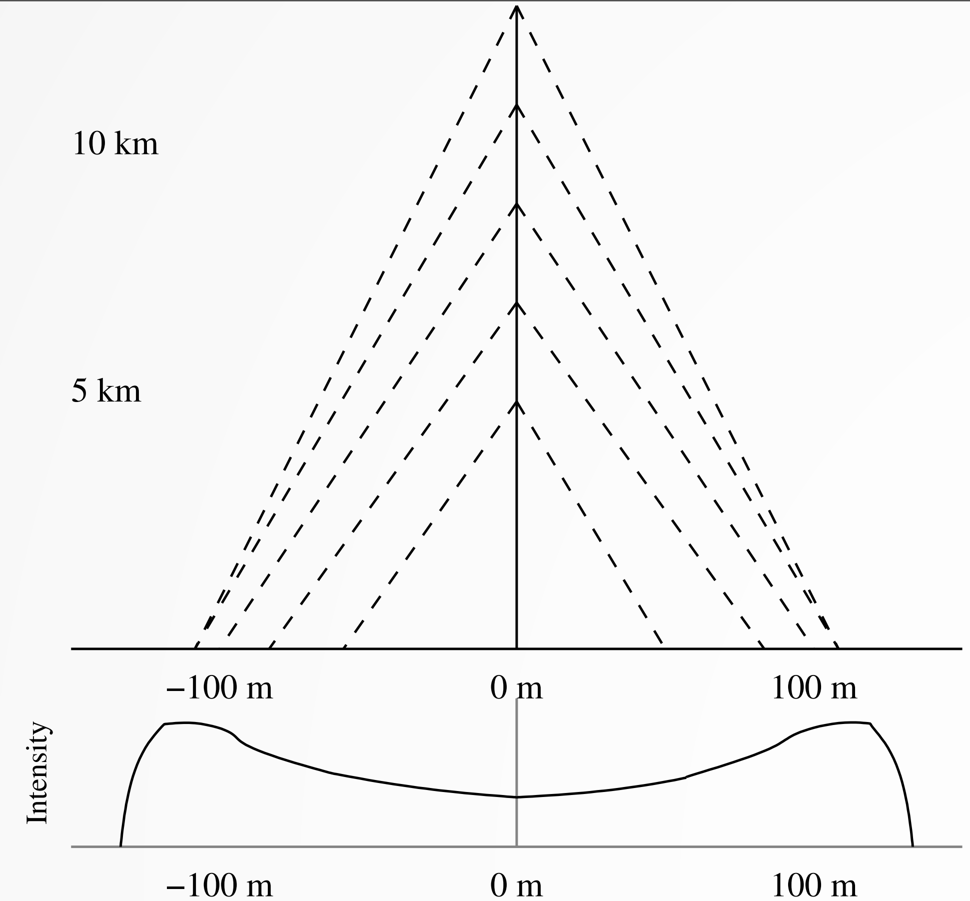
$$N = 2\pi\alpha l \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\left(1 - \frac{1}{\beta^2\, n^2(\lambda)}\right)$$

Peaks in the UV/blue in atmosphere

Threshold Energy:

$m_0c^2[1/\sqrt{2(n-1)} - 1])$ ≈ 21 MeV for e-

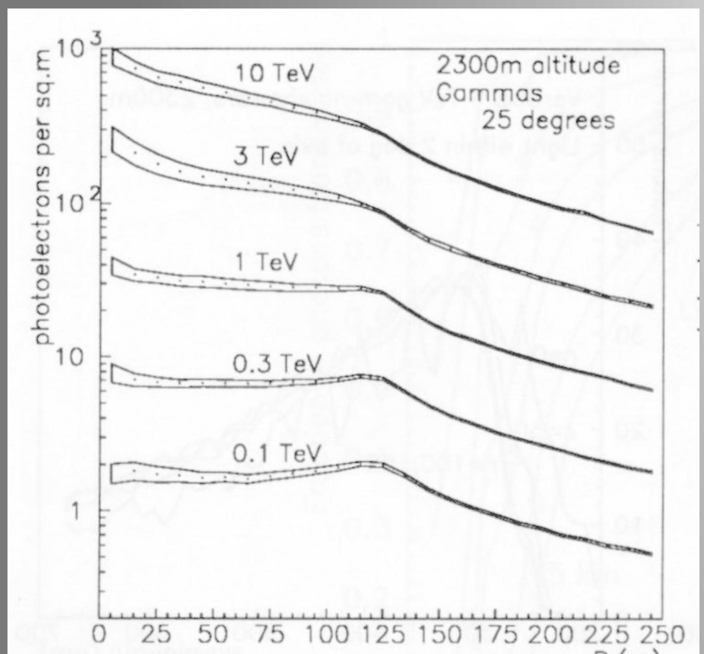
Cherenkov light from Air Showers



“light pool” on ground

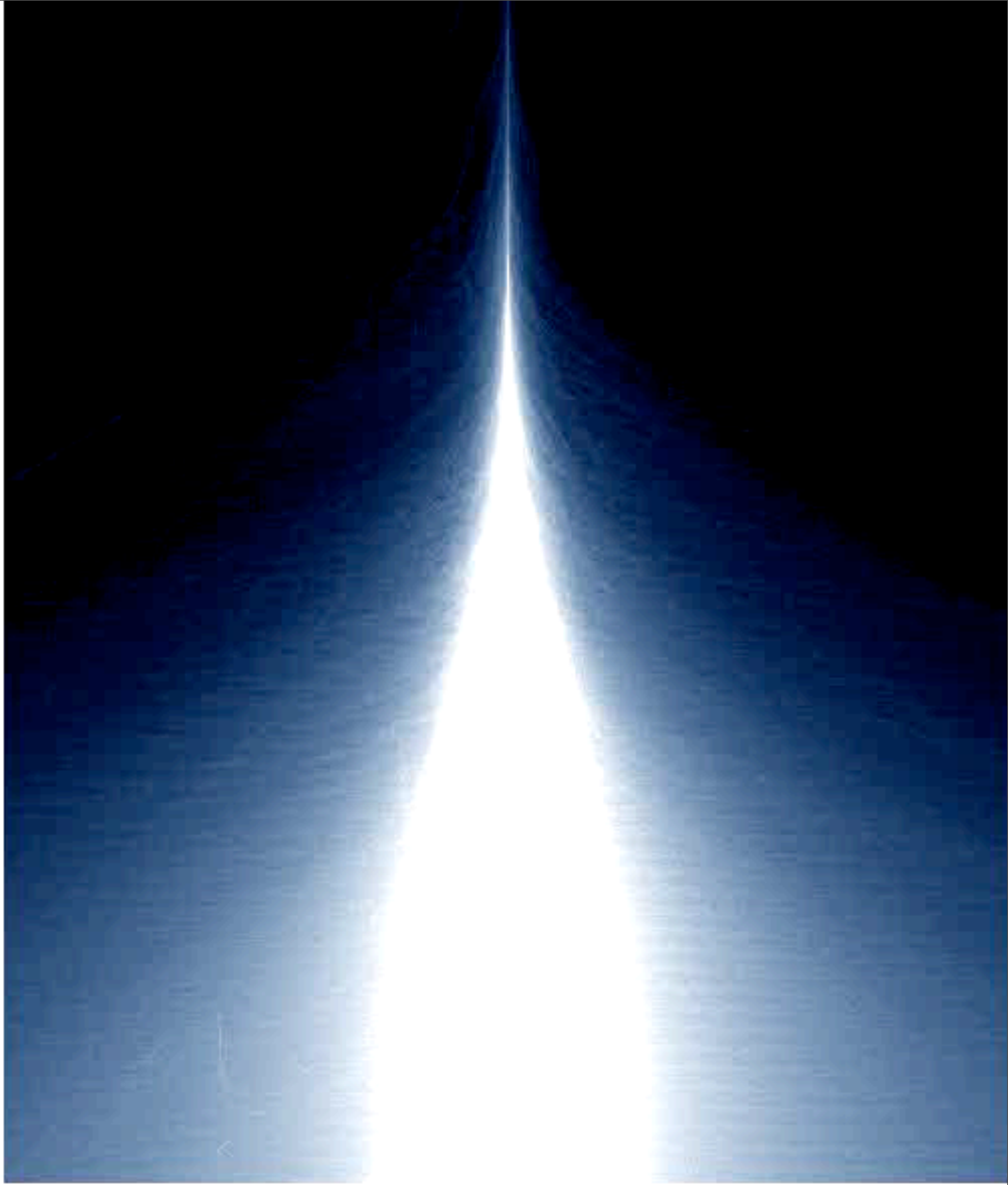
Ensemble of electrons/positrons:

- change in Cherenkov angle + multiple Coulomb-scattering washes out the ring shape of the Cherenkov light
- faint elliptical shaft of UV light
- lateral width determined by the Coulomb-scattering angle
  - $\theta \approx (R_m/h_{max})$
  - Rm = “Molière Radius” of the shower (characteristic width)
- Time structure of **flash ≈ 20 ns**
- Light pool is **≈120 m radius** at 2km



Hillas et al

Animation by
K. Bernlöhr,2000



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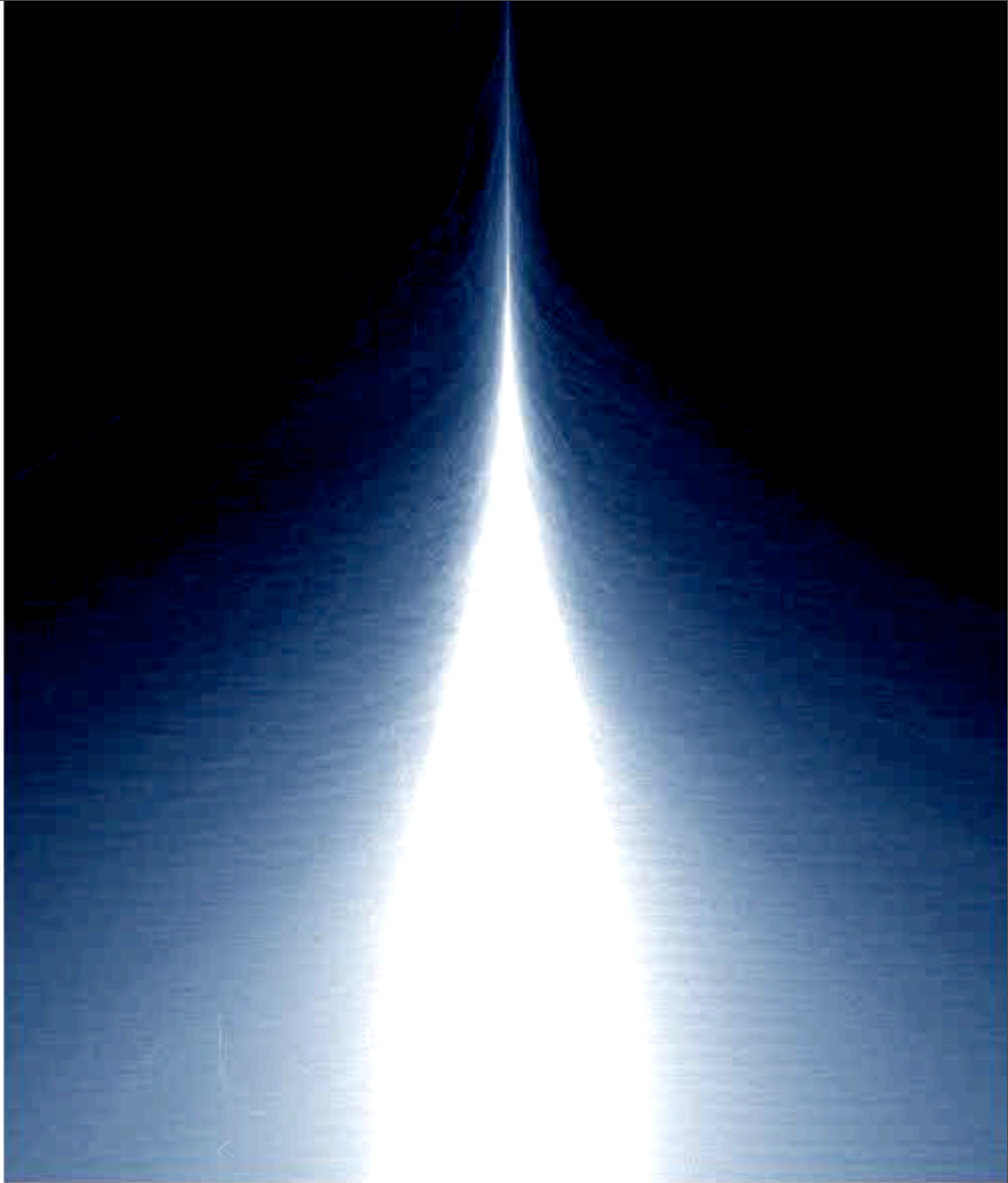

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Some history…

History of detection

- Idea to use photon detector to see Cherenkov light from showers
- From searchlights to modern Imaging Atmospheric Cherenkov Telescopes

Detecting Cosmic Rays from Air Showers

Galbraith & Jelley, 1953

February 21, 1953 NATURE

Light Pulses from the Night Sky associated with Cosmic Rays

IN 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

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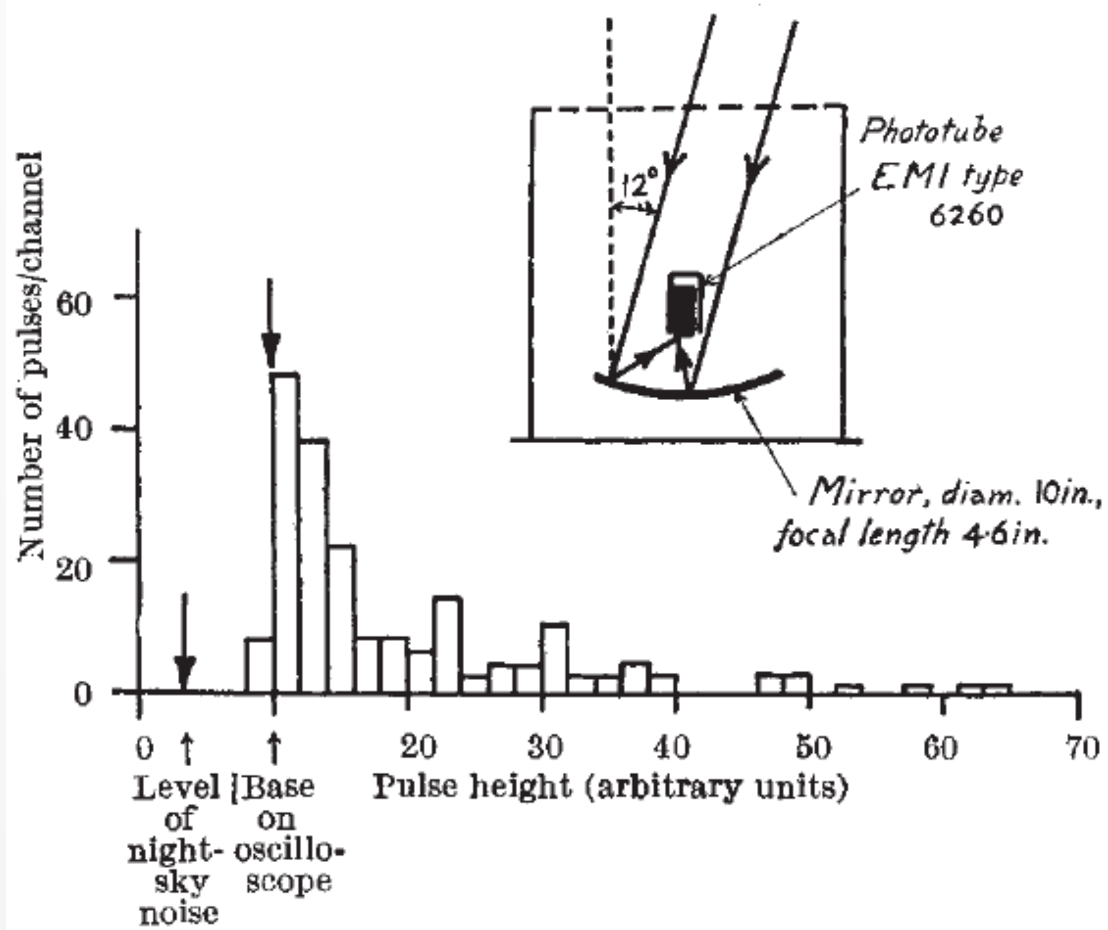
W. GALBRAITH
J. V. JELLEY



Galbraith & Jelley, 1953

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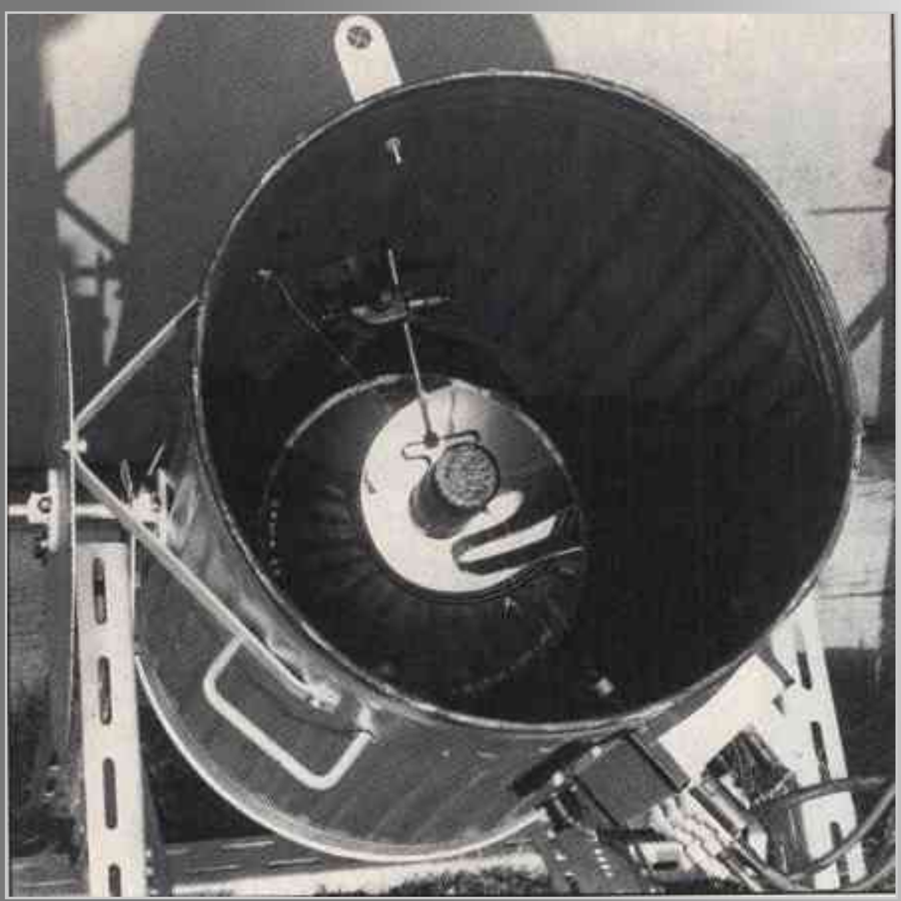

yes, this is a trash can

February 21, 1953 NATURE

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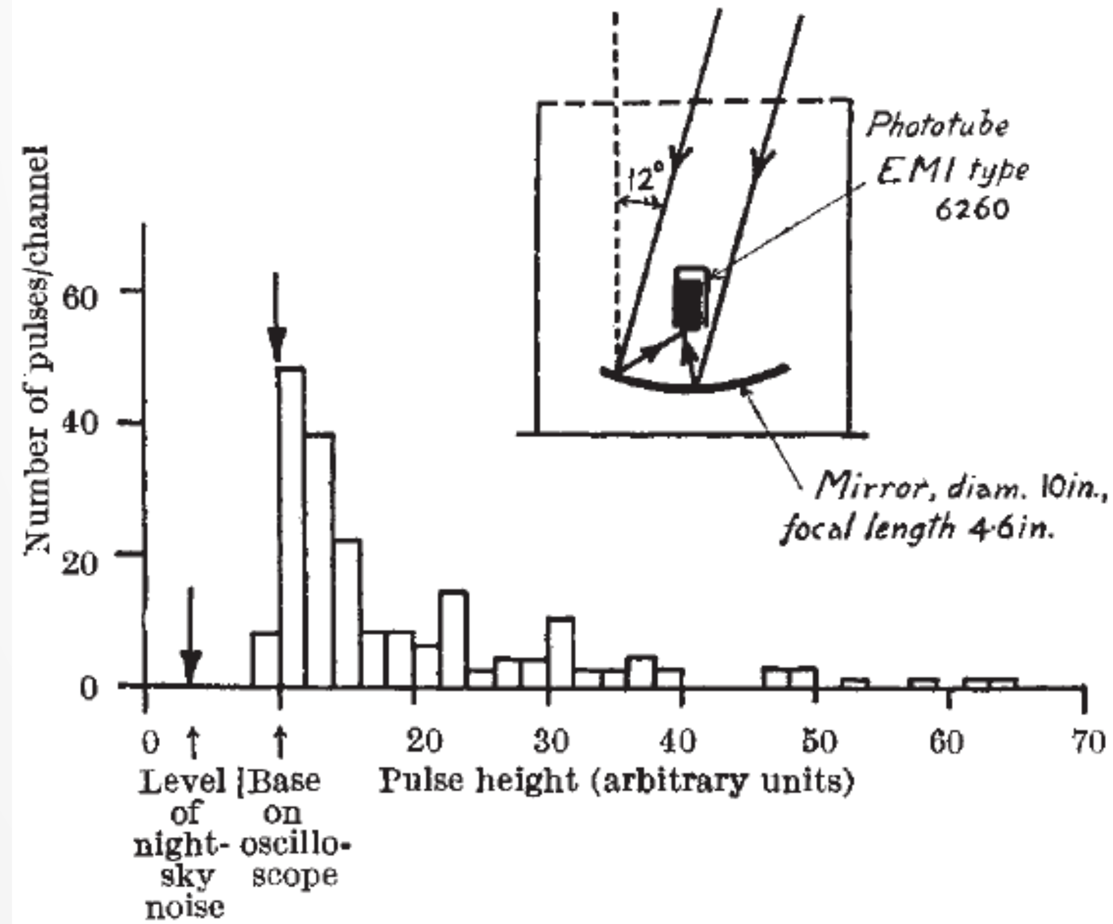
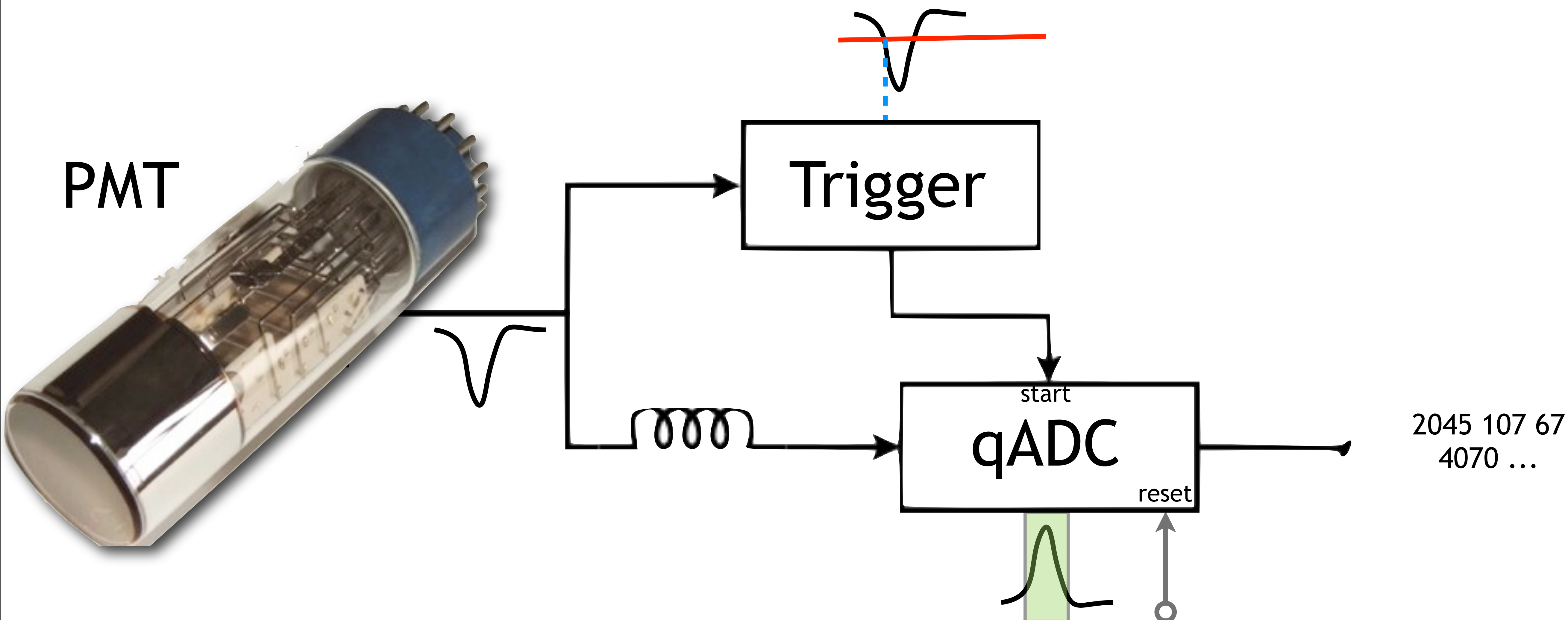


Simple Detector



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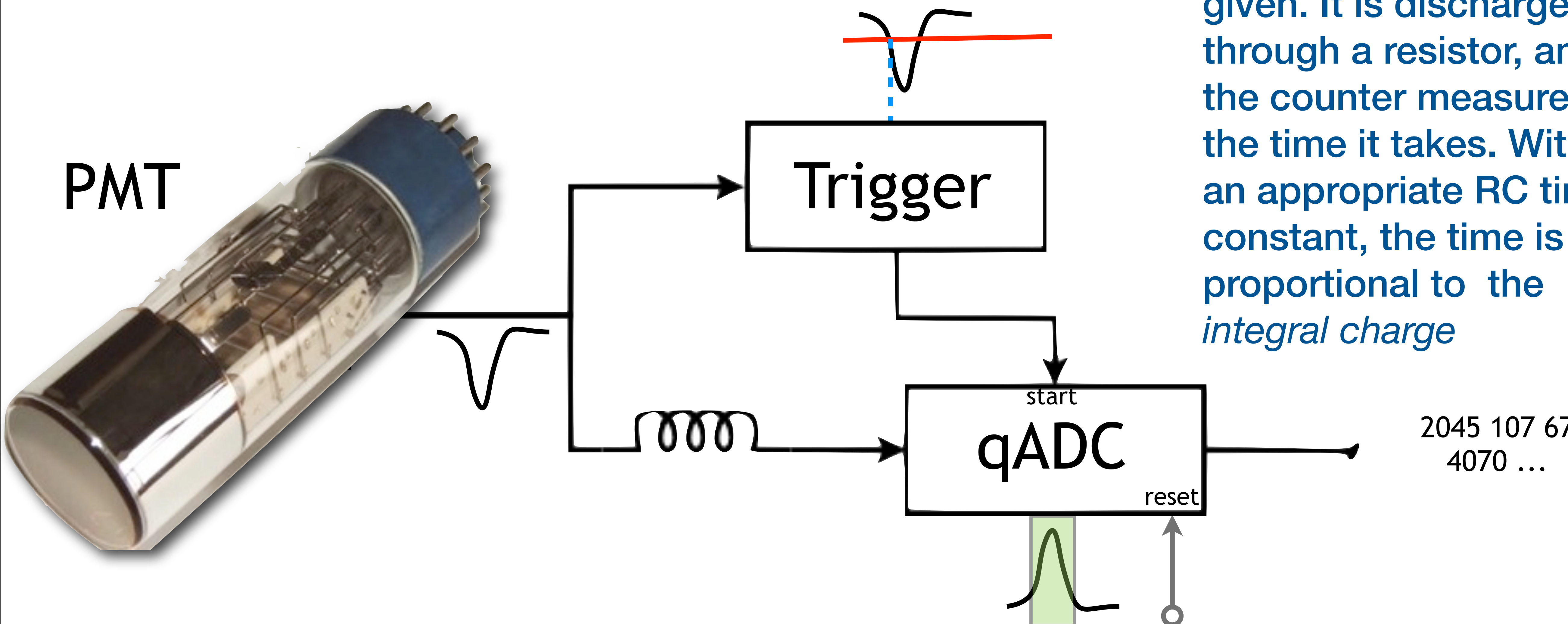

A **qADC** is essentially a *capacitor* with a *counter* attached. Charge builds up on the capacitor until a readout signal is given. It is discharged through a resistor, and the counter measures the time it takes. With an appropriate RC time constant, the time is proportional to the *integral charge*

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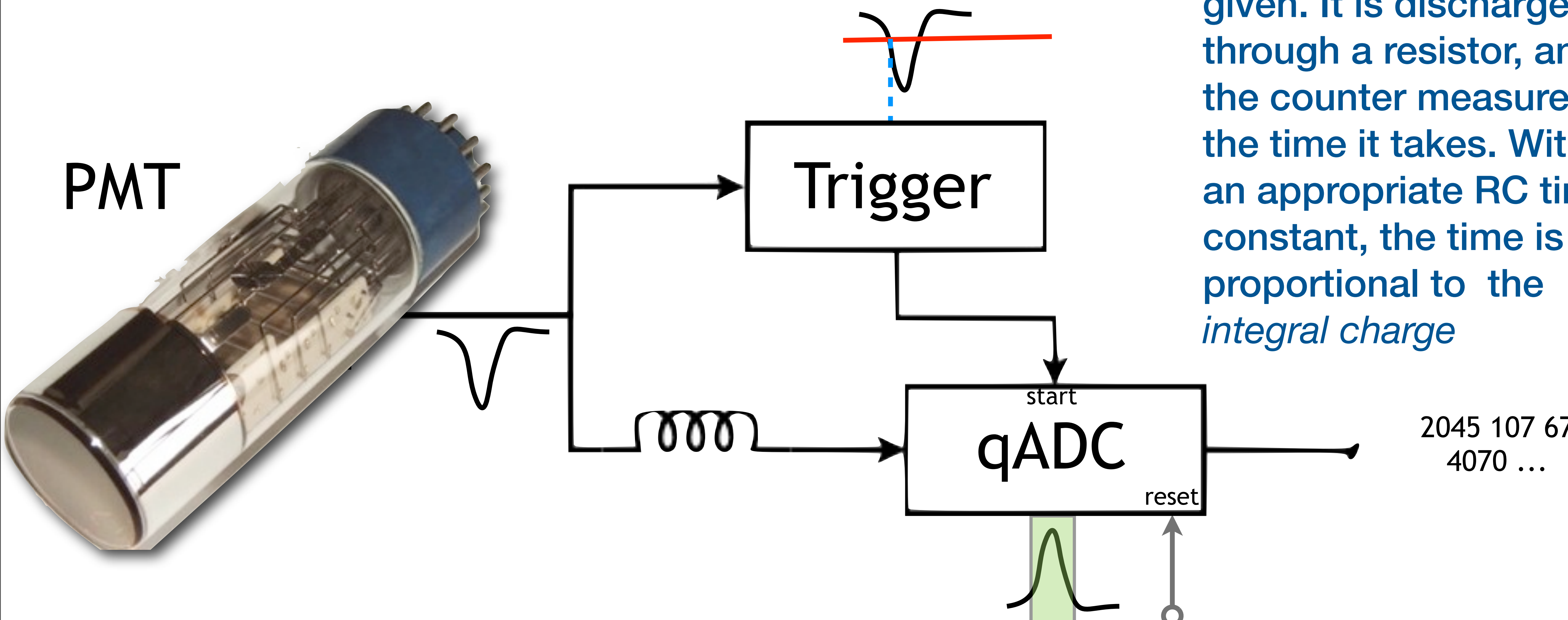

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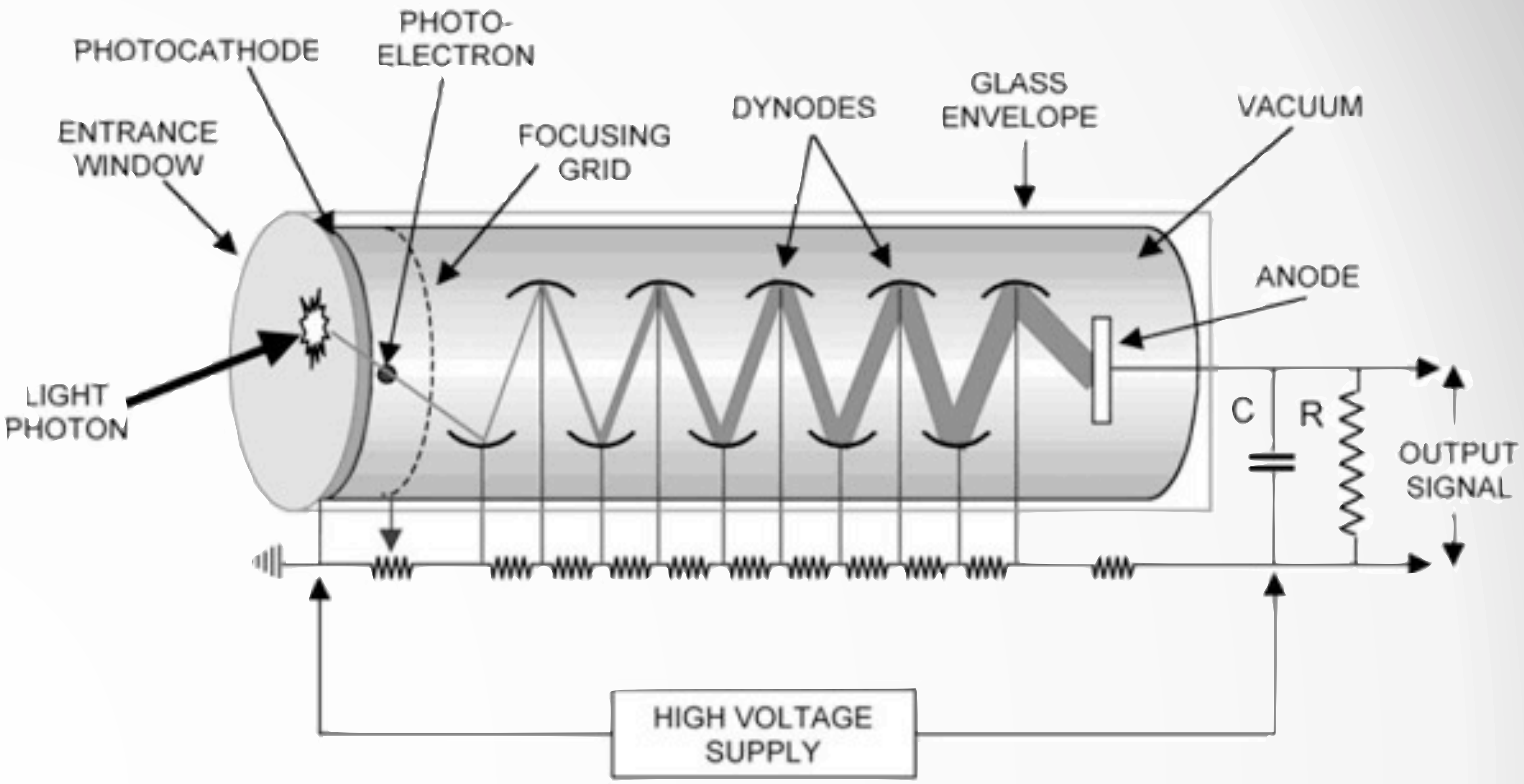
Width of the integration time window determines the signal/noise ratio (smaller is better)



Aside: The Photo-multiplier Tube

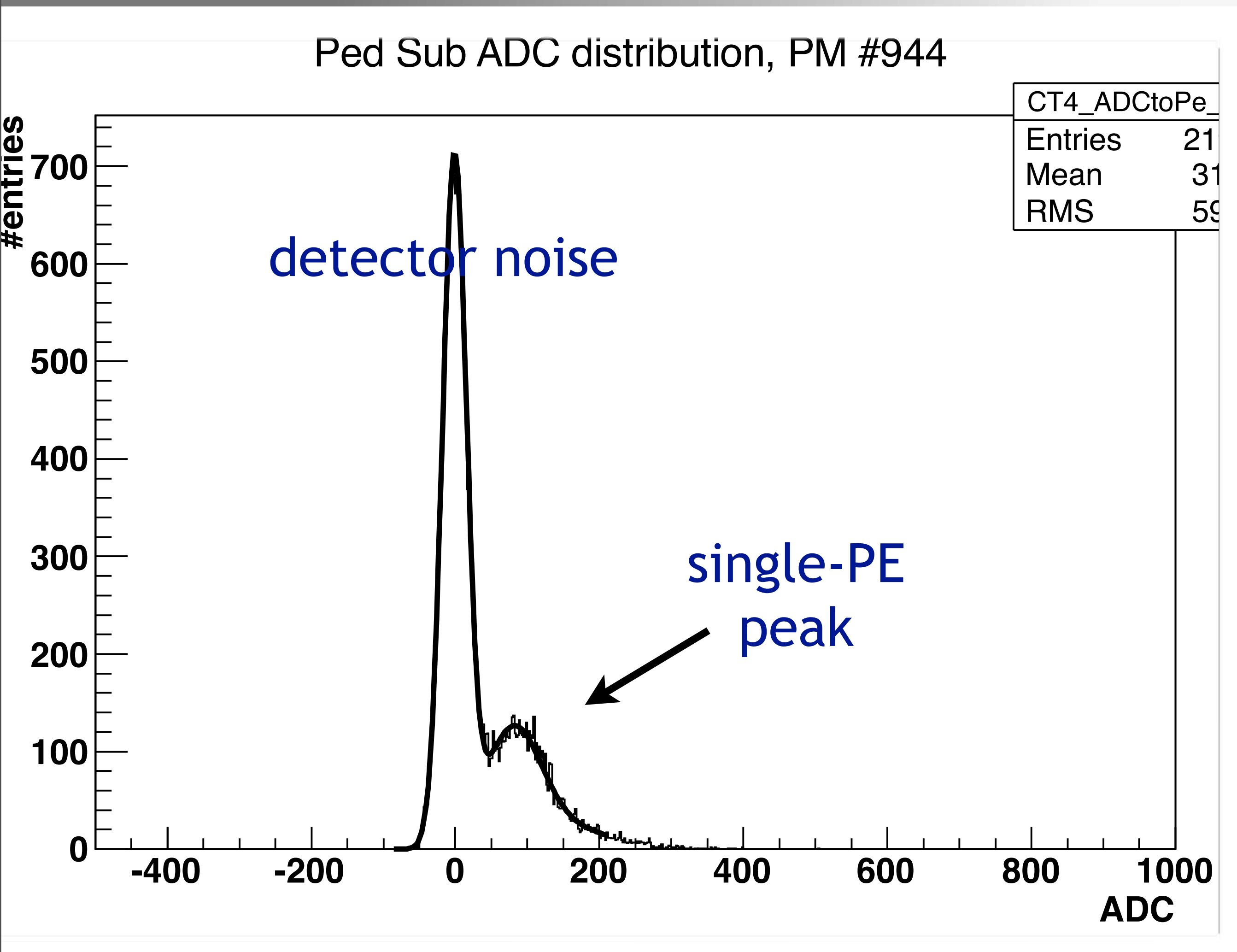
Why not use CCDs?

- simply not sensitive enough to detect Cherenkov flashes above the night-sky-background light! (too much noise)

PMTs are extremely sensitive detectors

- can detect single photons of light!

Want a detector that can resolve a single photo-electron



- minimum detectable level
- at typical HV level, cherenkov light flashes are only a few PEs above the night-sky-background light level
- the count distribution (measured in total darkness + a weak LED) allows one to measure the PE/DC ratio: photoelectrons per digital count
  - part of the calibration process for a single pixel detector
  - inter-calibration of multiple pixel detectors... (coming soon)

Detecting Gamma-rays

Detecting Gamma-rays

Cosmic ray showers are detectible using the Atmospheric Cherenkov technique.

- They are isotropic over the sky (they do not point-back to a source due to magnetic fields)

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Jelley proposed: gamma rays from an astrophysical source should be too.

- they do point back to a source
- alternate between signal (point at the source) and background (point-away from source)
- if you count events long enough, signal should dominate over the background

Even ignoring stars, the sky is not dark:

- **Night Sky Background** (NSB) light is always present
- Collective unresolved visible/UV light from optical sources (stars, Milky Way, etc)
- Glow from moon, nearby light pollution

aside: NSB noise

ON/OFF observations

Method to extract a weak signal over a background of cosmic rays + NSB

ON observation:

- point at the source (e.g. Crab Nebula) for 28 minutes

OFF observation:

- take up to 2 minutes to slew backward 30 min in Right Ascension
  - therefore you are looking at the same position in the atmosphere as the ON observation was 30 minutes ago
  - assume atmospheric variations are small over 30 minute timescale
- take another 30 minute observation of this (presumably) blank part of the sky

Statistics:

- N_{on} - N_{off} gives you the excess count rate
- with enough repeated exposures of ON and OFF, signal should peek through the background

Weekes, 1967
“the early days”

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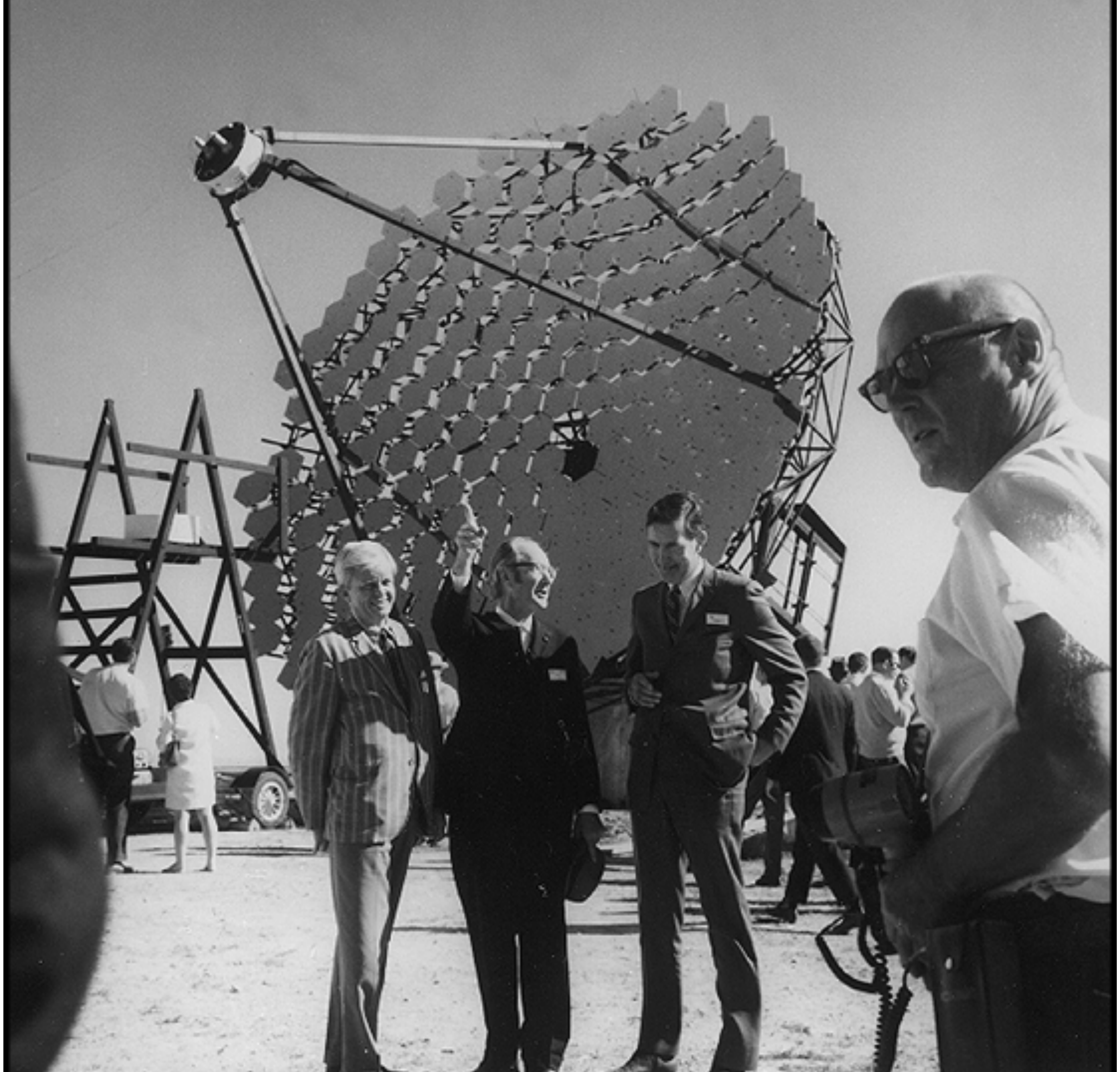
“the early days”


Mount Hopkins,
Arizona, USA
Photo by K. Kosack

The Whipple 10 m Telescope, 1968



The Whipple 10 m Telescope, Today

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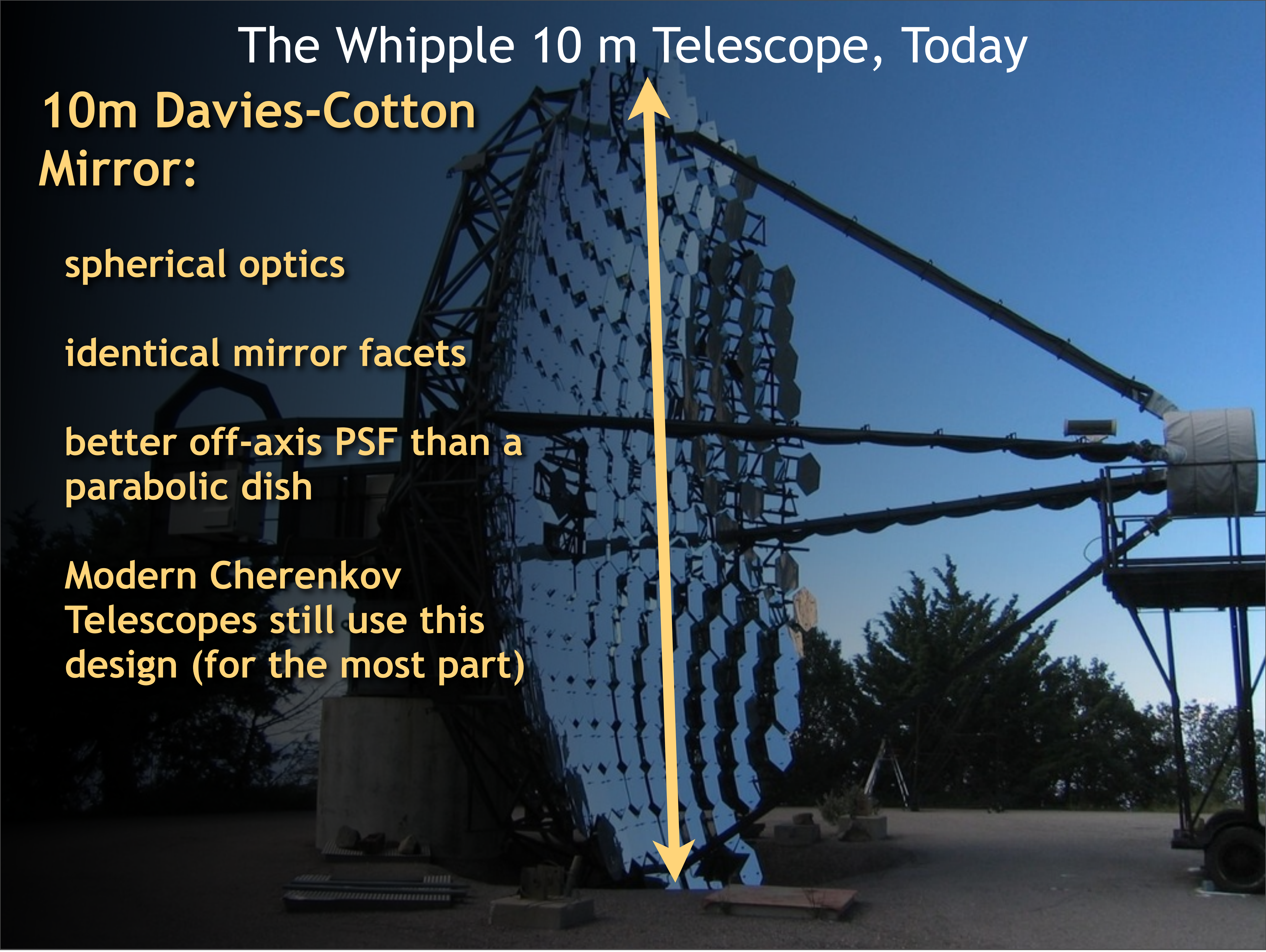
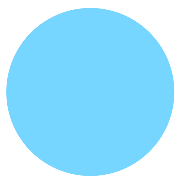
Friday, July 6, 2012


The Whipple 10 m Telescope, Today
10m Davies-Cotton Mirror:
spherical optics
identical mirror facets
better off-axis PSF than a parabolic dish
Modern Cherenkov Telescopes still use this design (for the most part)

Single-Pixel Detector



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How can it be improved?

- **Imaging**! Use multiple pixels to image the full shower
- Use shape of the image to reject hadronic showers

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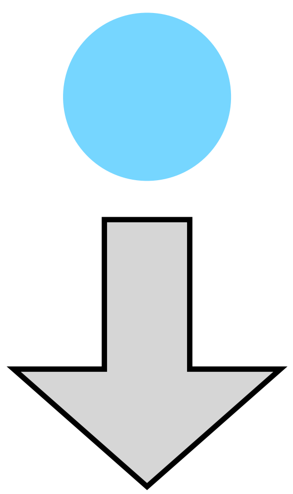

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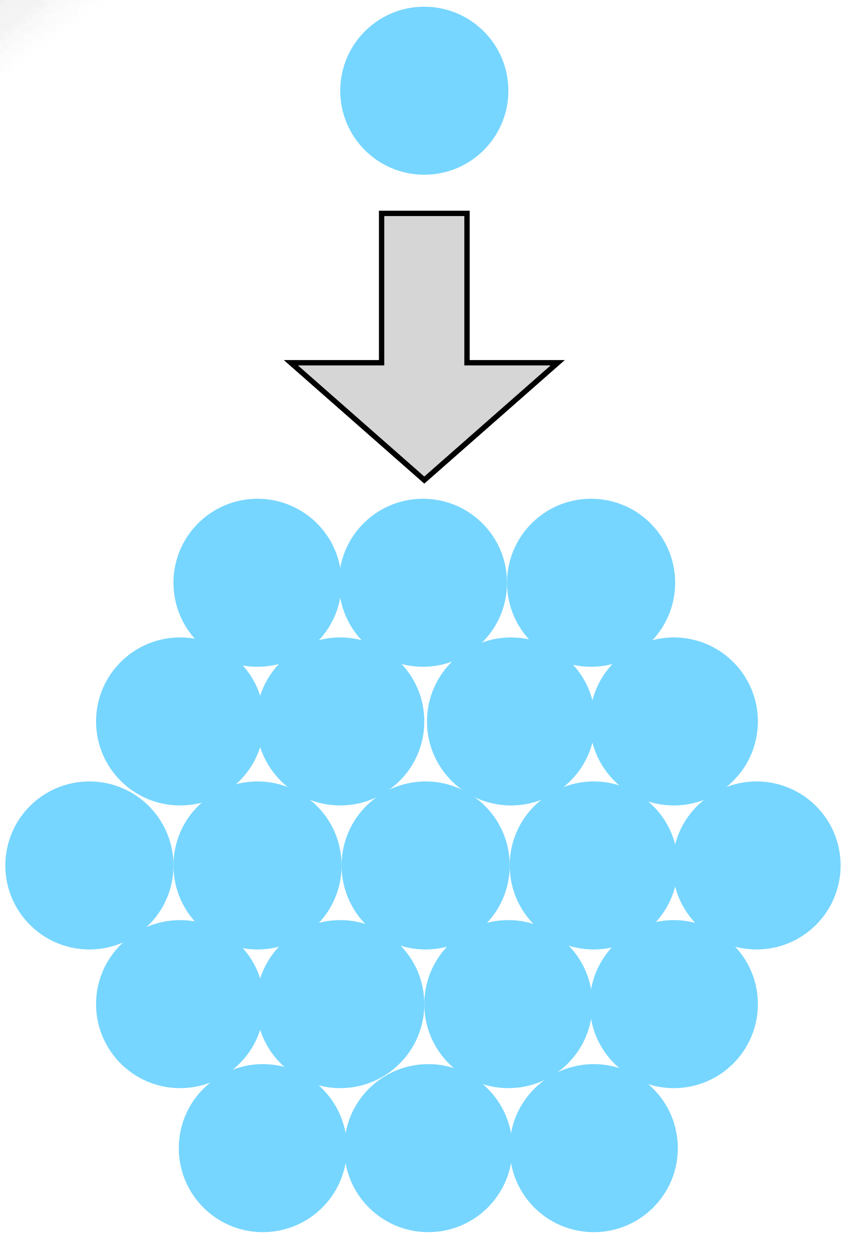

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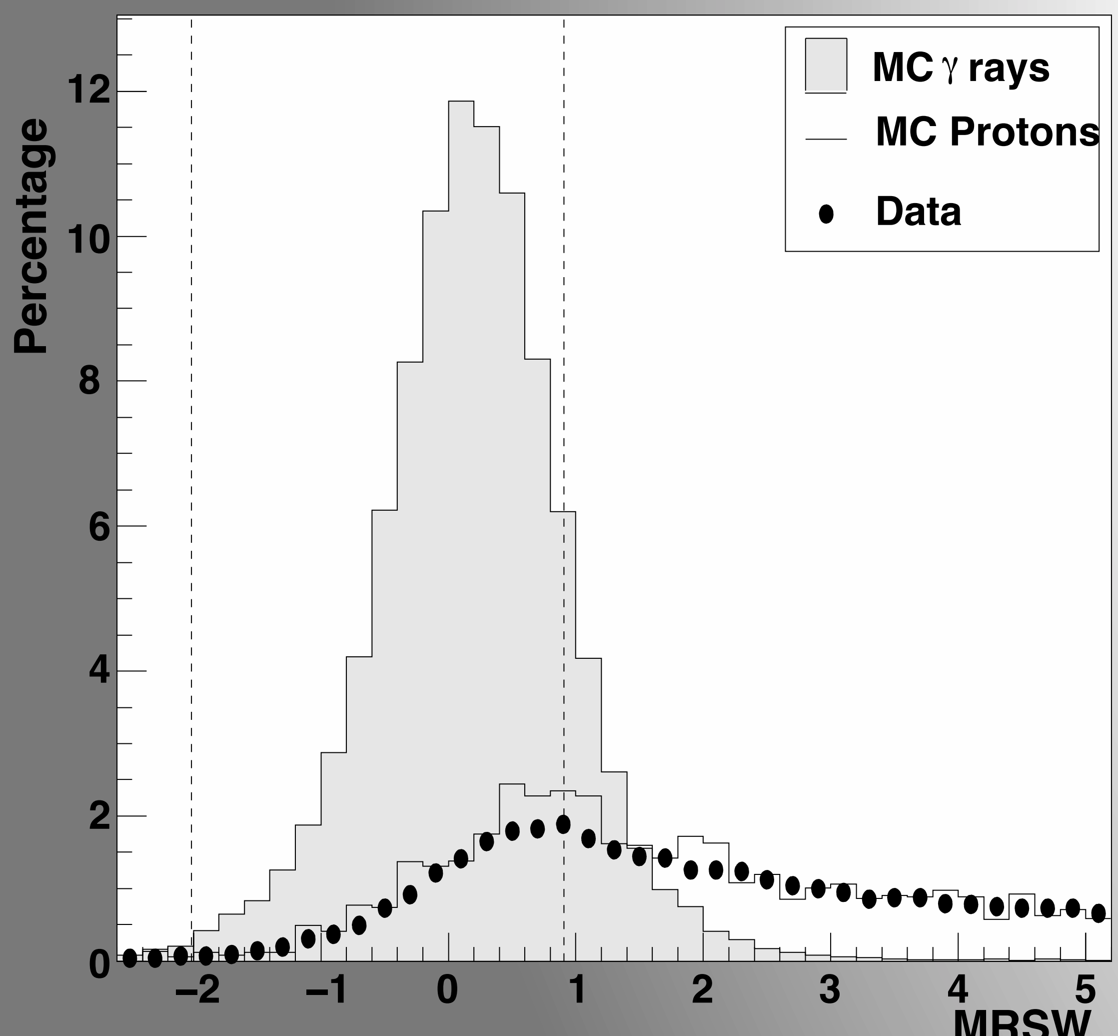
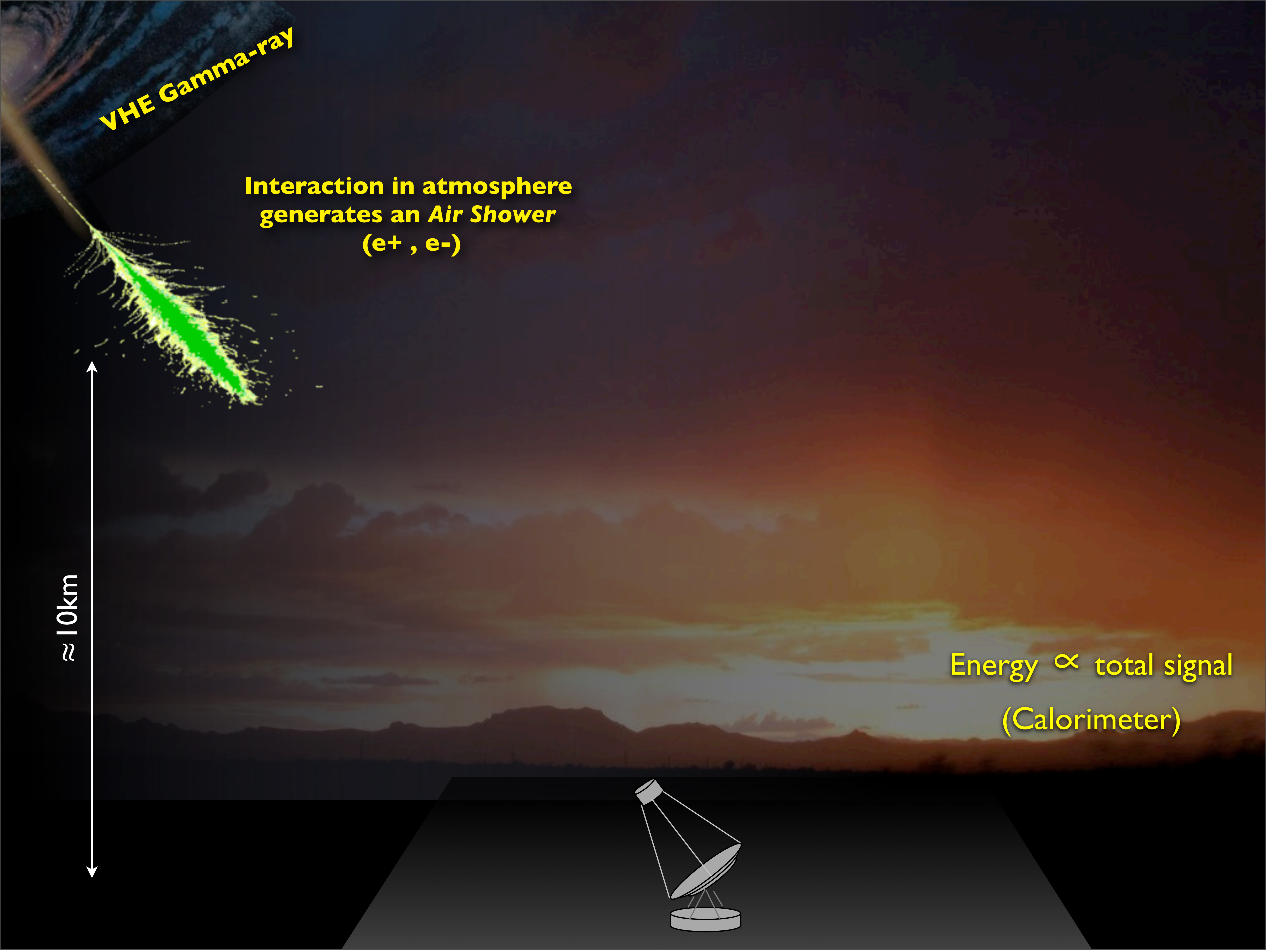
The Imaging Technique

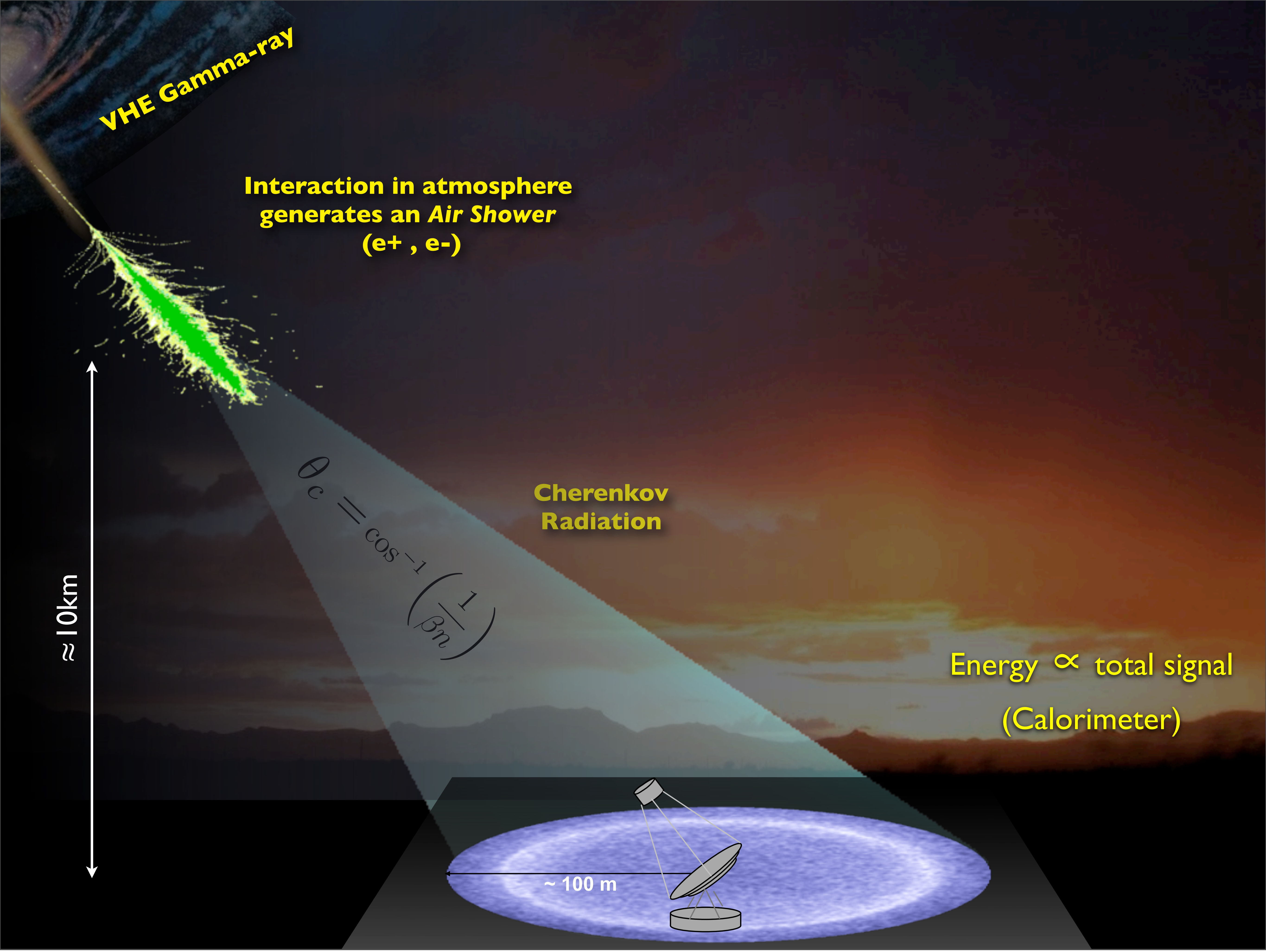


Breakthrough:

- use multiple pixels to try to see an image of the shower!
- Recall that the width of the shower for EM cascades is related to the Moliere radius (Coulomb scattering), and is fairly narrow
- For hadronic showers, the higher transverse momentum from pion production and sub-showers produces a wider shower.
- **the width of the shower can be used to discriminate gammas from hadrons**



VHE Gamma-ray
Interaction in atmosphere
generates an *Air Shower*
(e+ , e-)
≈ 10km
Energy ∝ total signal
(Calorimeter)


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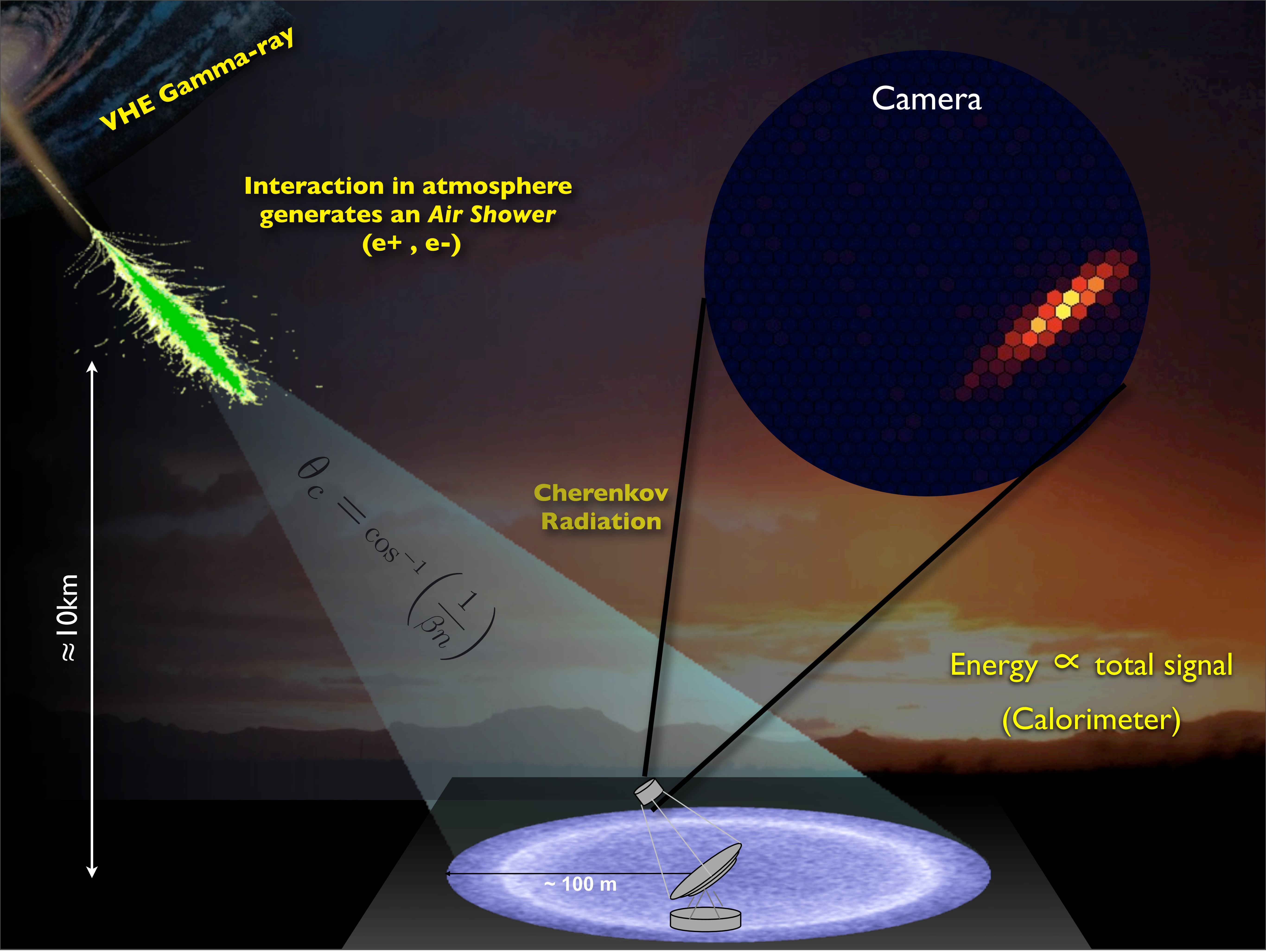
VHE Gamma-ray
Interaction in atmosphere generates an *Air Shower* (e+ , e-)
Camera
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Energy ∝ total signal
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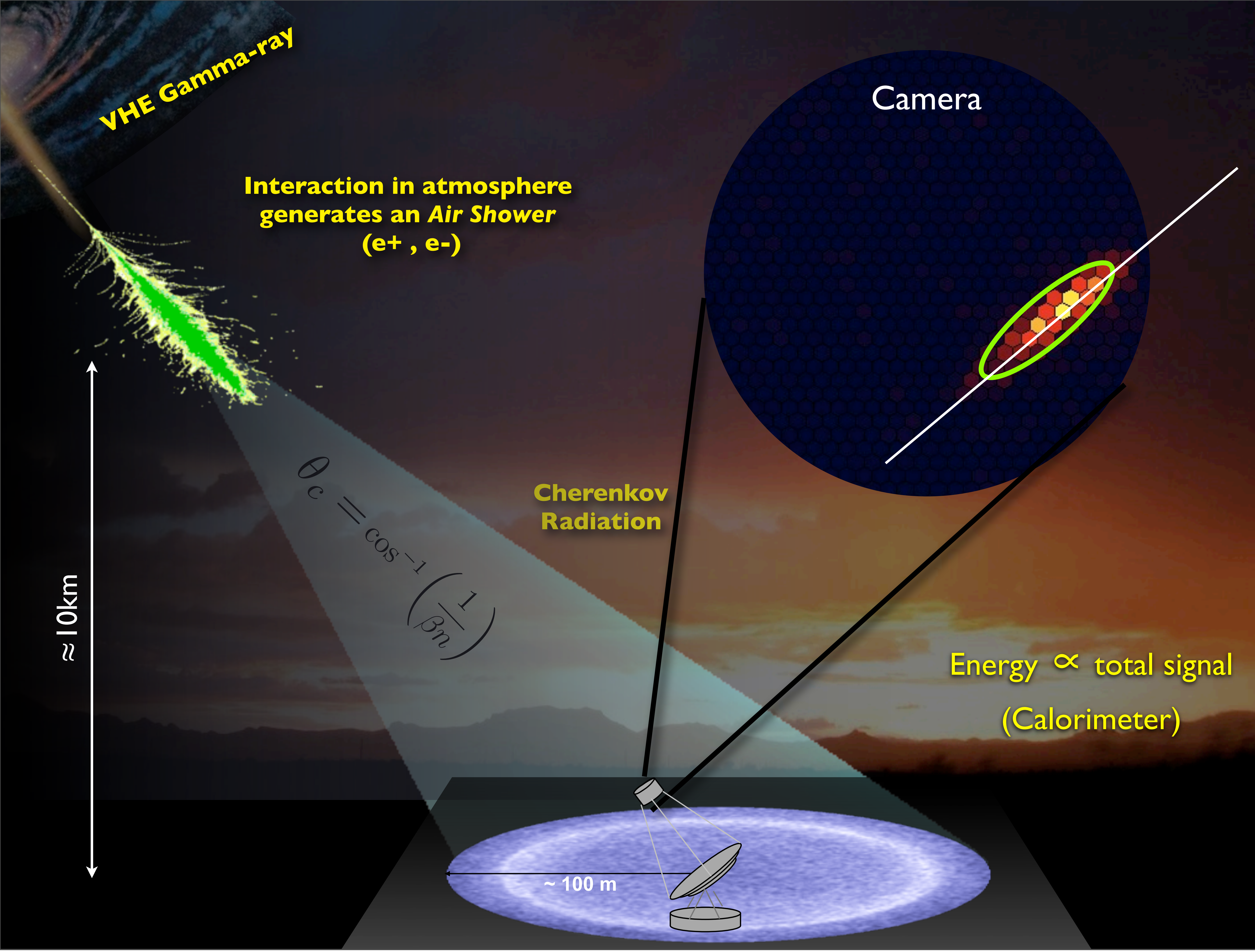
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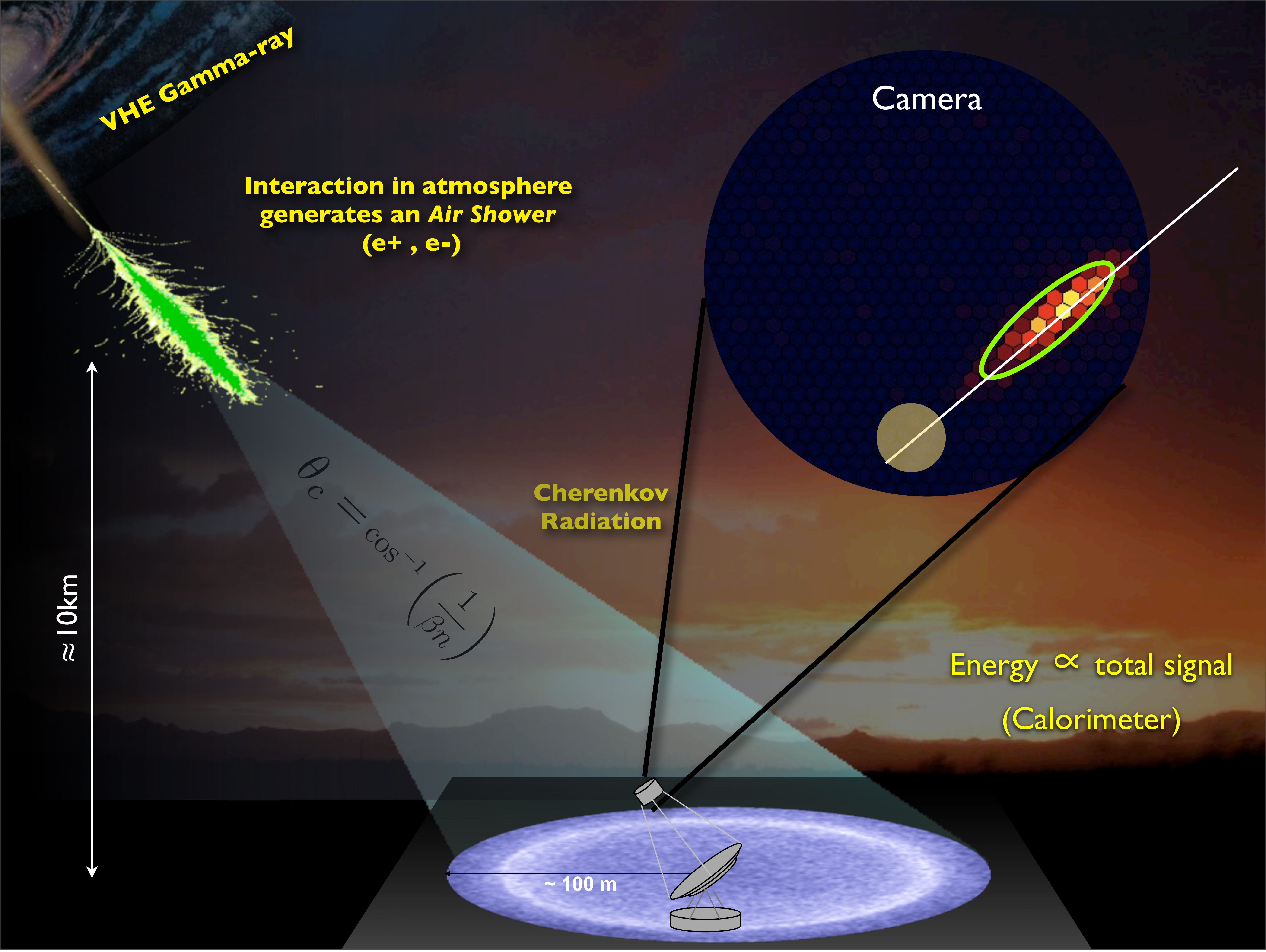
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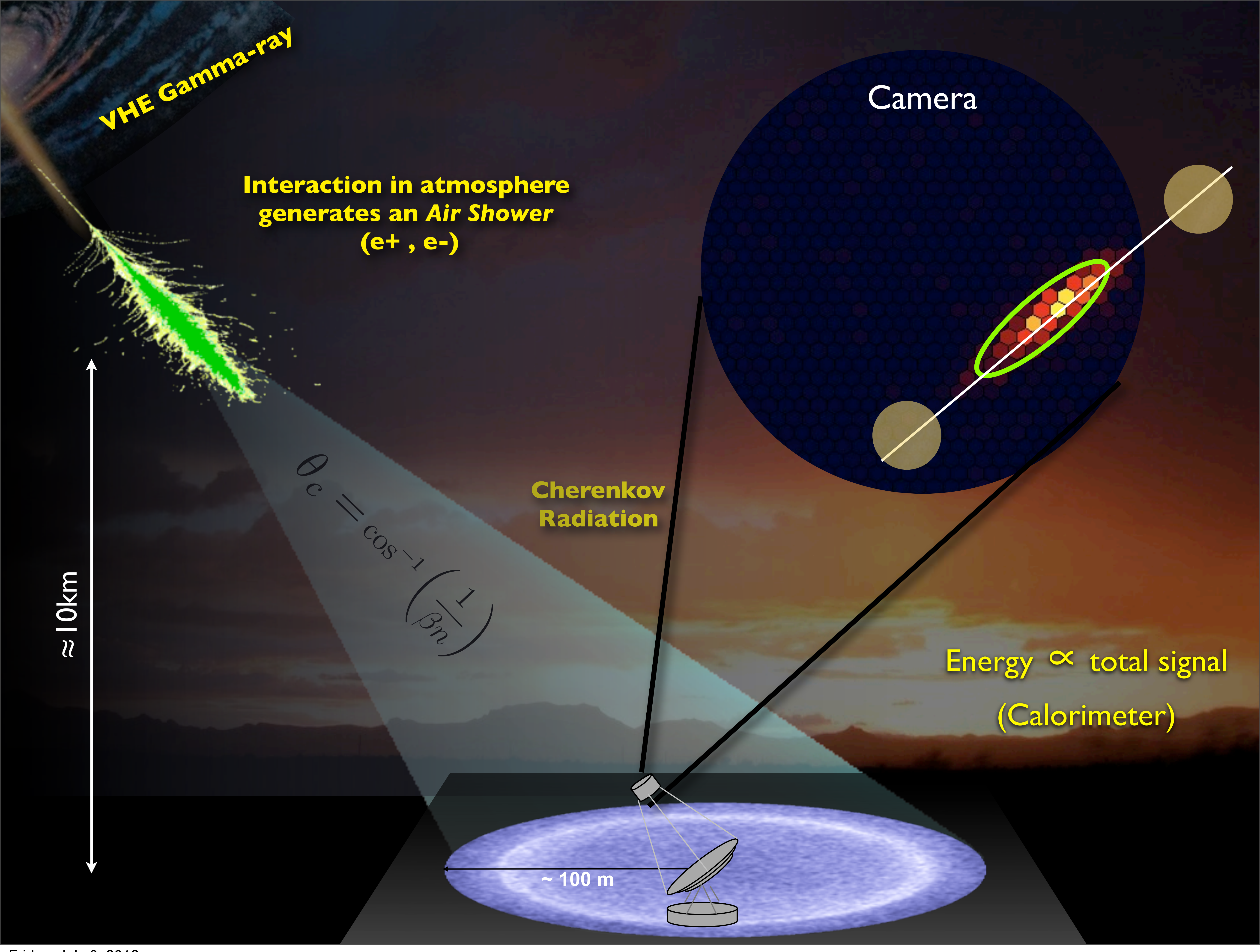
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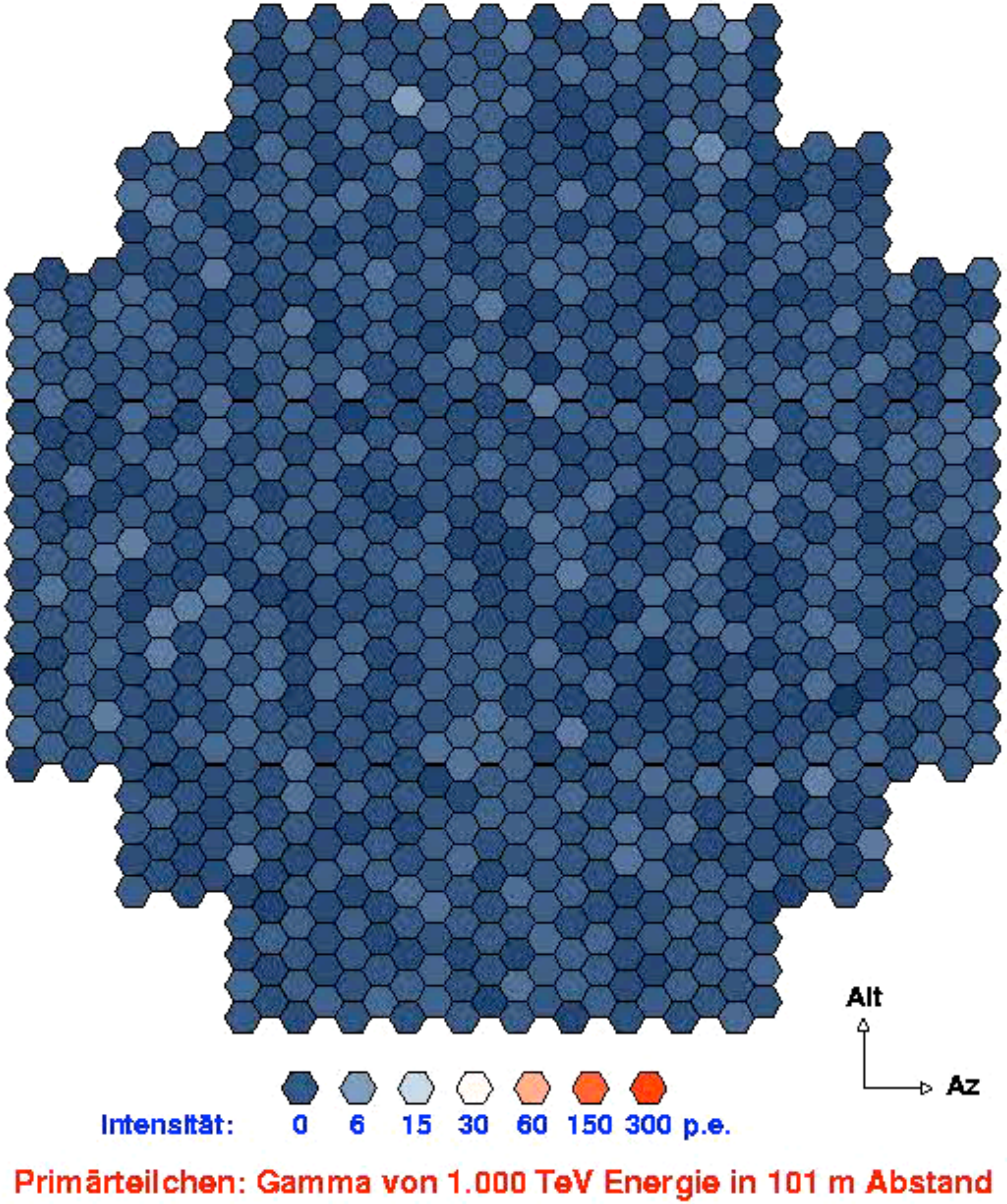
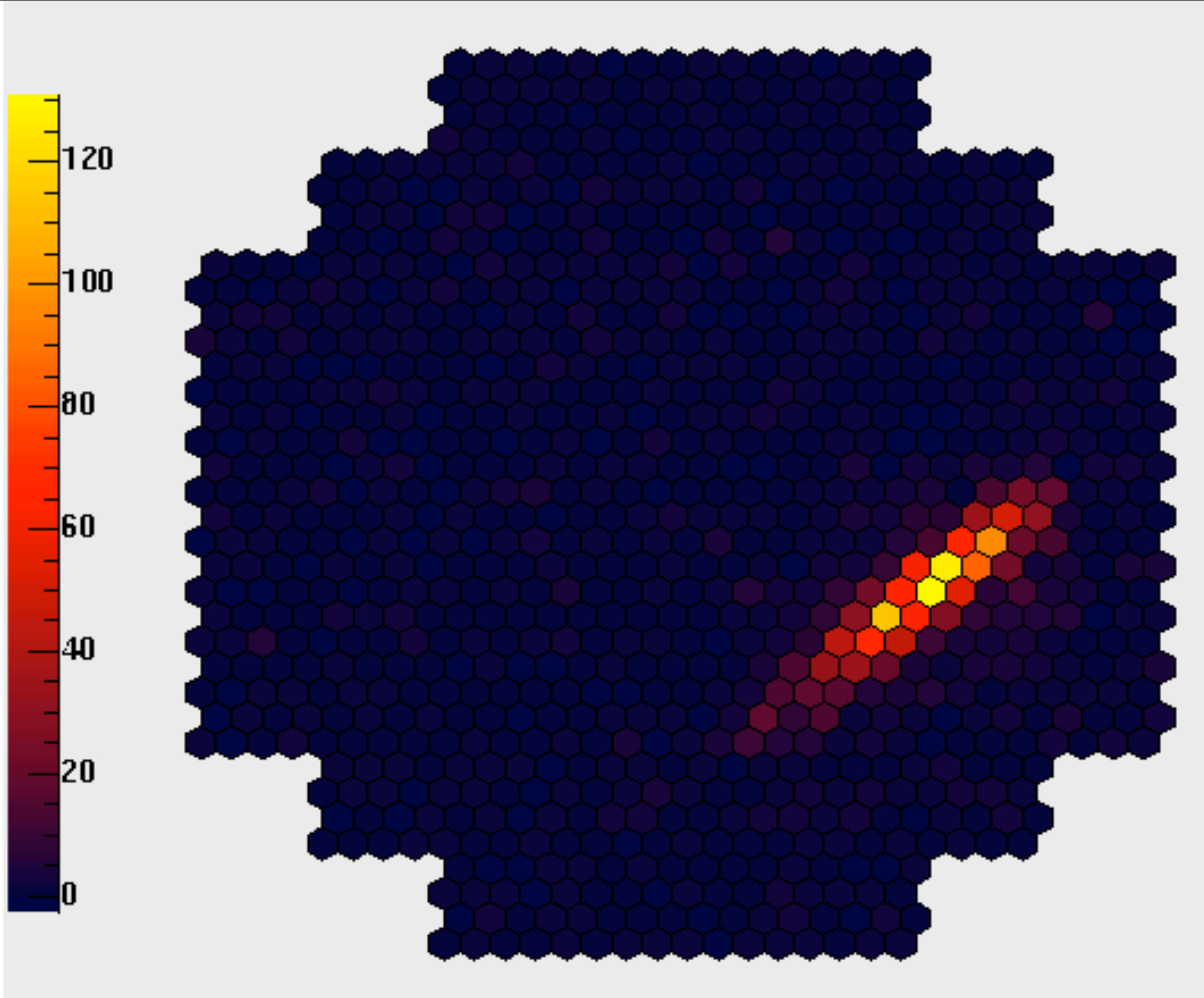
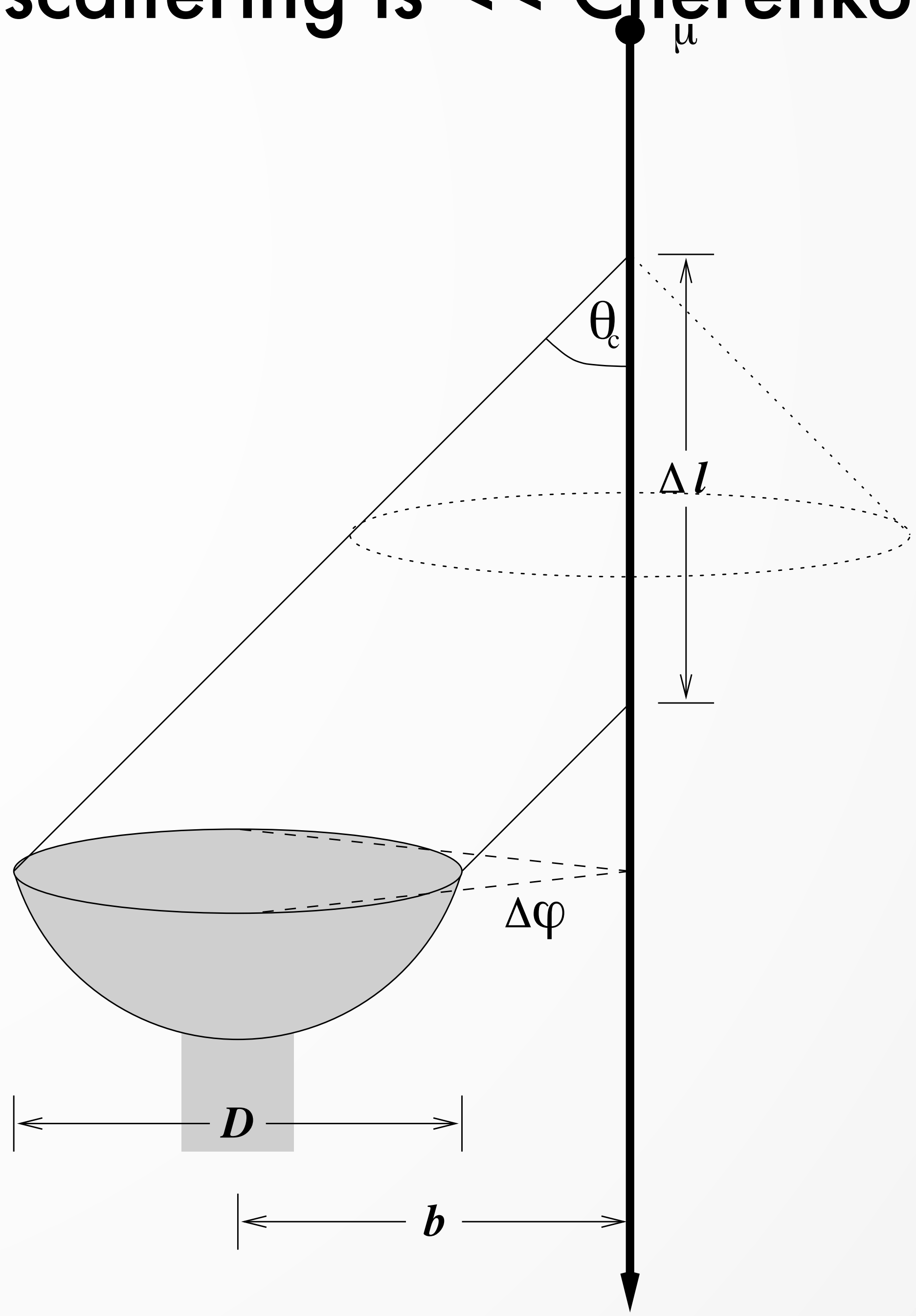


Animation from K. Bernlöhr


120
100
80
60
40
20
0

What are those ring things?

- muons produced in hadronic sub-showers
- heavier than electrons, so Coulomb scattering is << Cherenkov angle



Aside: Muons!

Frank and Tamm '37:

- Cherenkov light per pathlength (dL/dl) emitted by a muon is proportional to $\sin^2\theta_c$
- Pathlength $\Delta l = D/\tan\theta_c$
- Total light falling on telescope:

$$L \simeq \frac{\partial L}{\partial l} \cdot \Delta l \cdot \frac{\Delta\phi}{2\pi}$$
$$= \sin^2\theta_c \cdot \frac{D}{\tan\theta_c} \cdot \frac{\Delta\phi}{2\pi}$$

- arclength prop to $\Delta\Phi$, so:

$$\frac{L}{\text{arclength}} \simeq \sin^2\theta_c \cdot \frac{D}{\tan\theta_c} \cdot \frac{\Delta\phi}{2\pi} \cdot \frac{1}{\Delta\phi},$$

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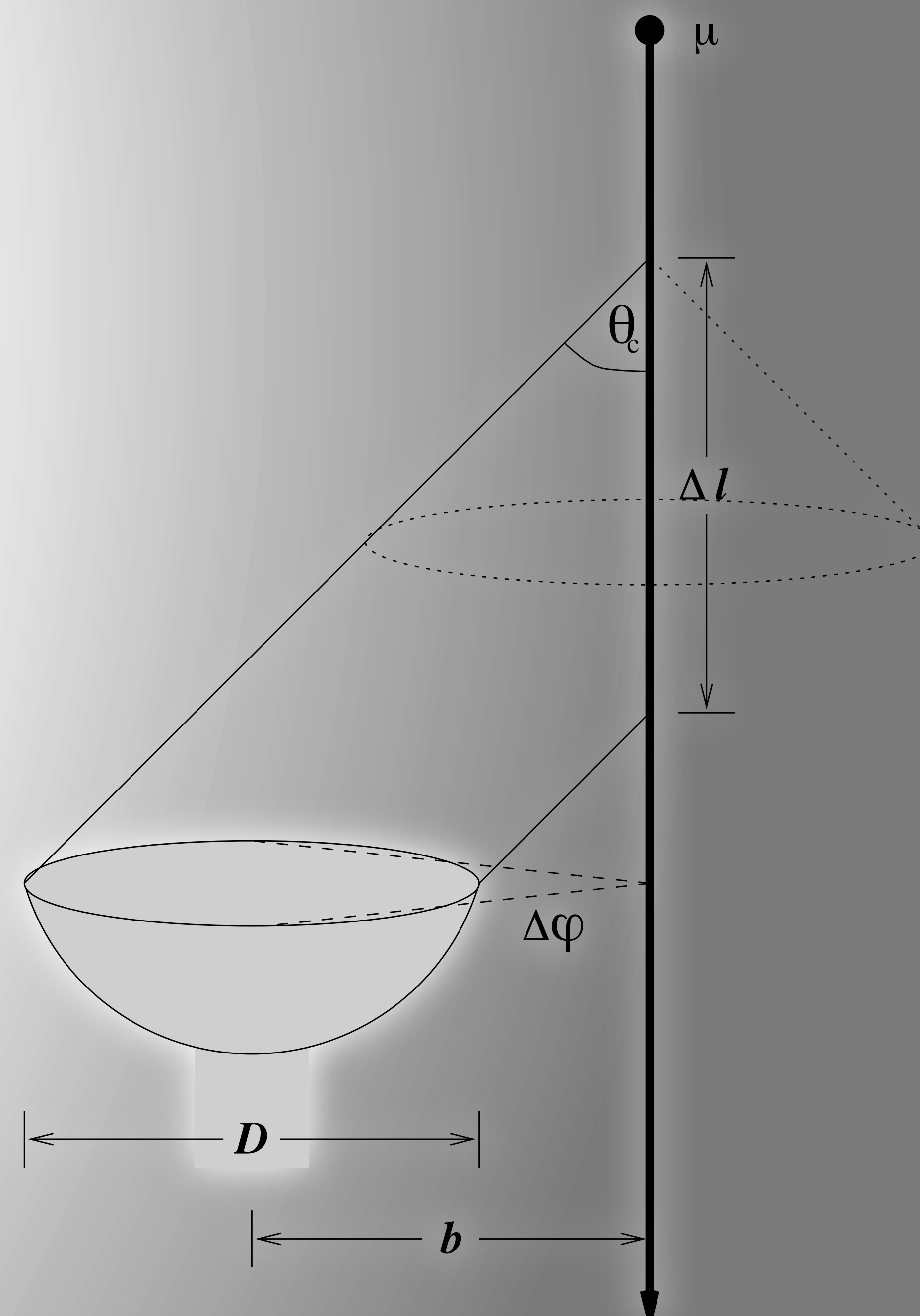

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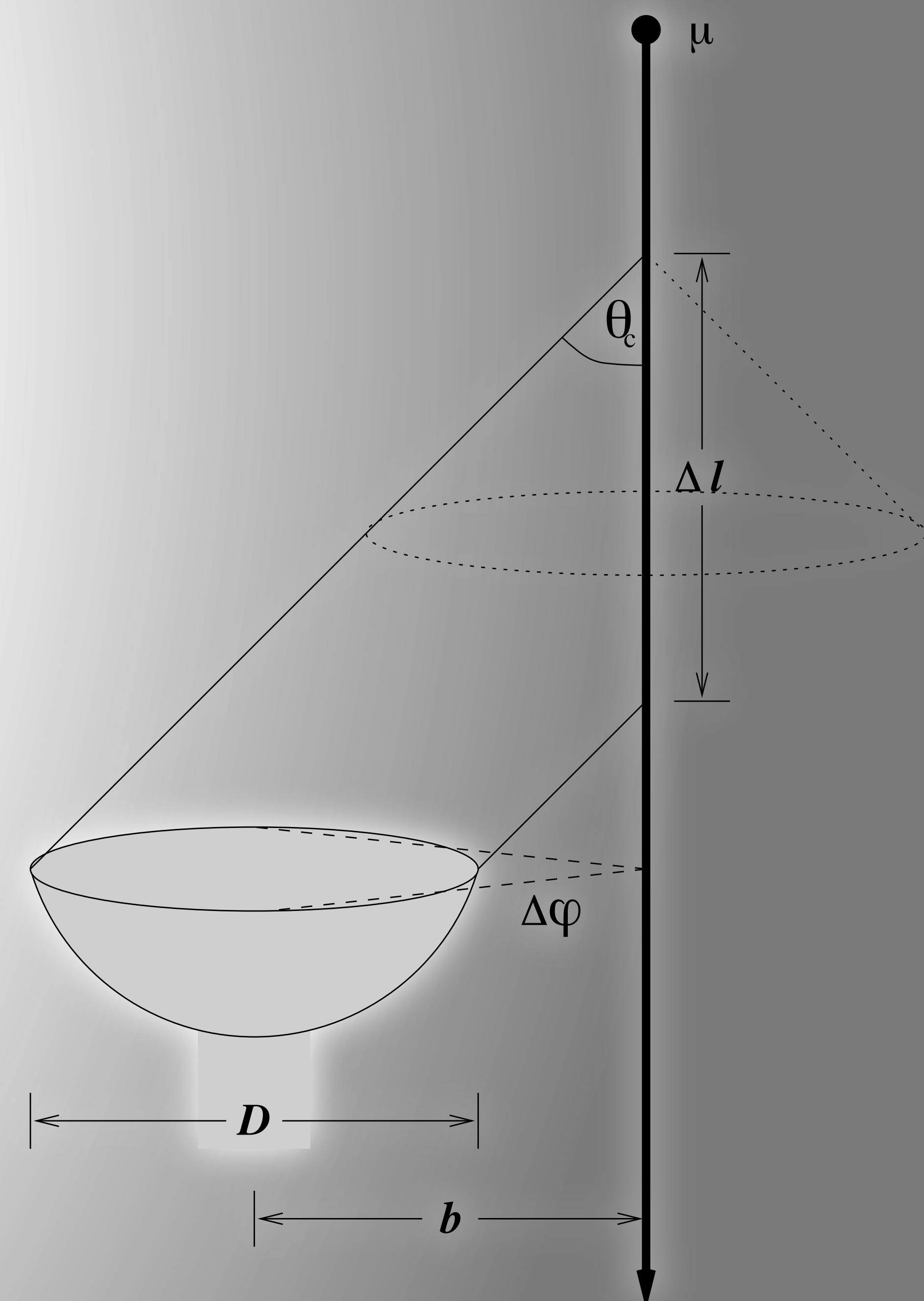

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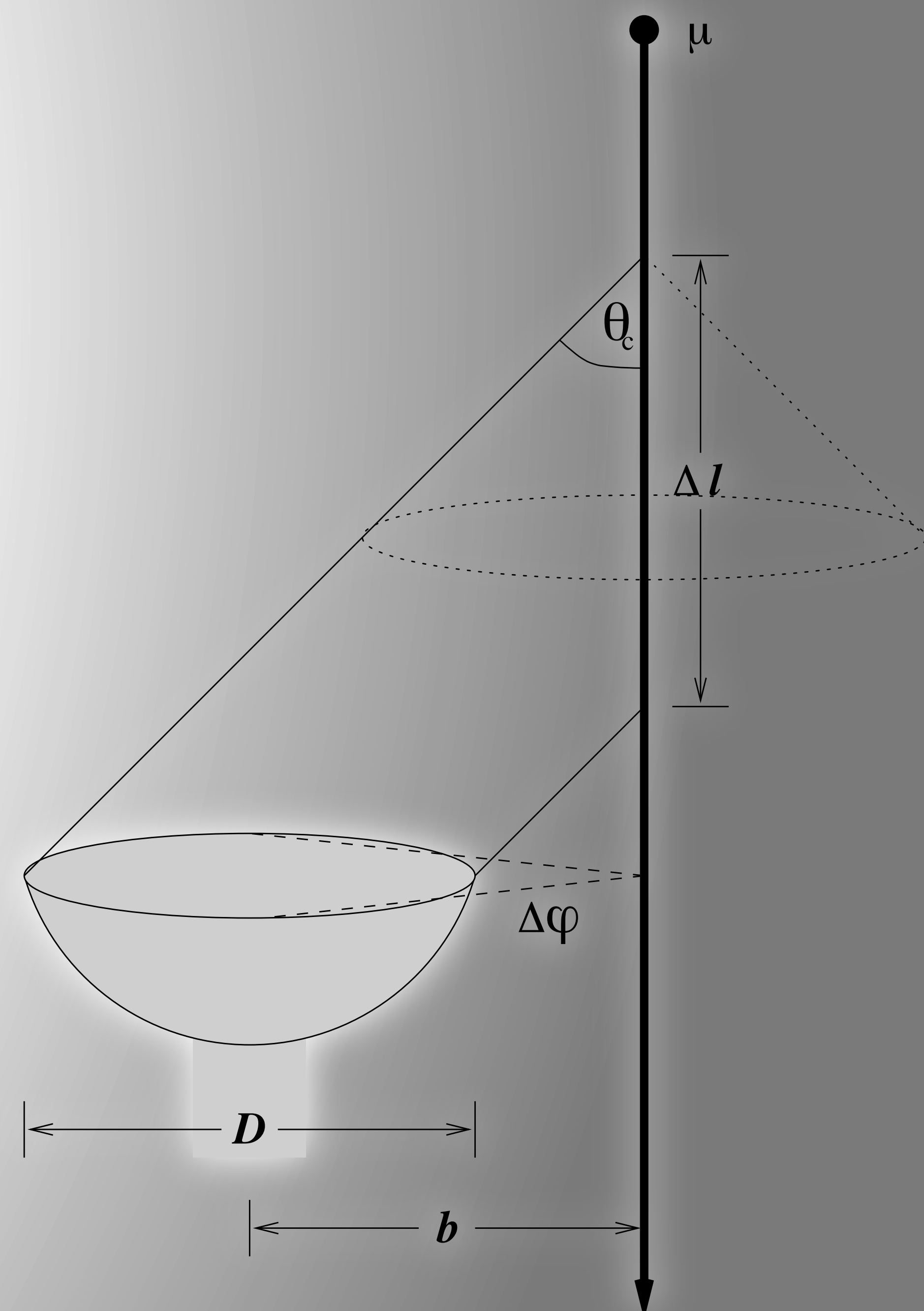


- arclength prop to ΔΦ, so:

$$\frac{L}{\text{arclength}} \simeq \sin^2\theta_c \cdot \frac{D}{\tan\theta_c} \cdot \frac{\cancel{\Delta\phi}}{2\pi} \cdot \frac{1}{\cancel{\Delta\phi}},$$

constant

Muons

The Good:

- Can be used to determine the optical efficiency of the system
- Constant signal/arclength gives a measure of the total gain of the telescope system.

The Bad:

- Partial muon arcs look much like EM showers, particularly a problem at ≈100 GeV

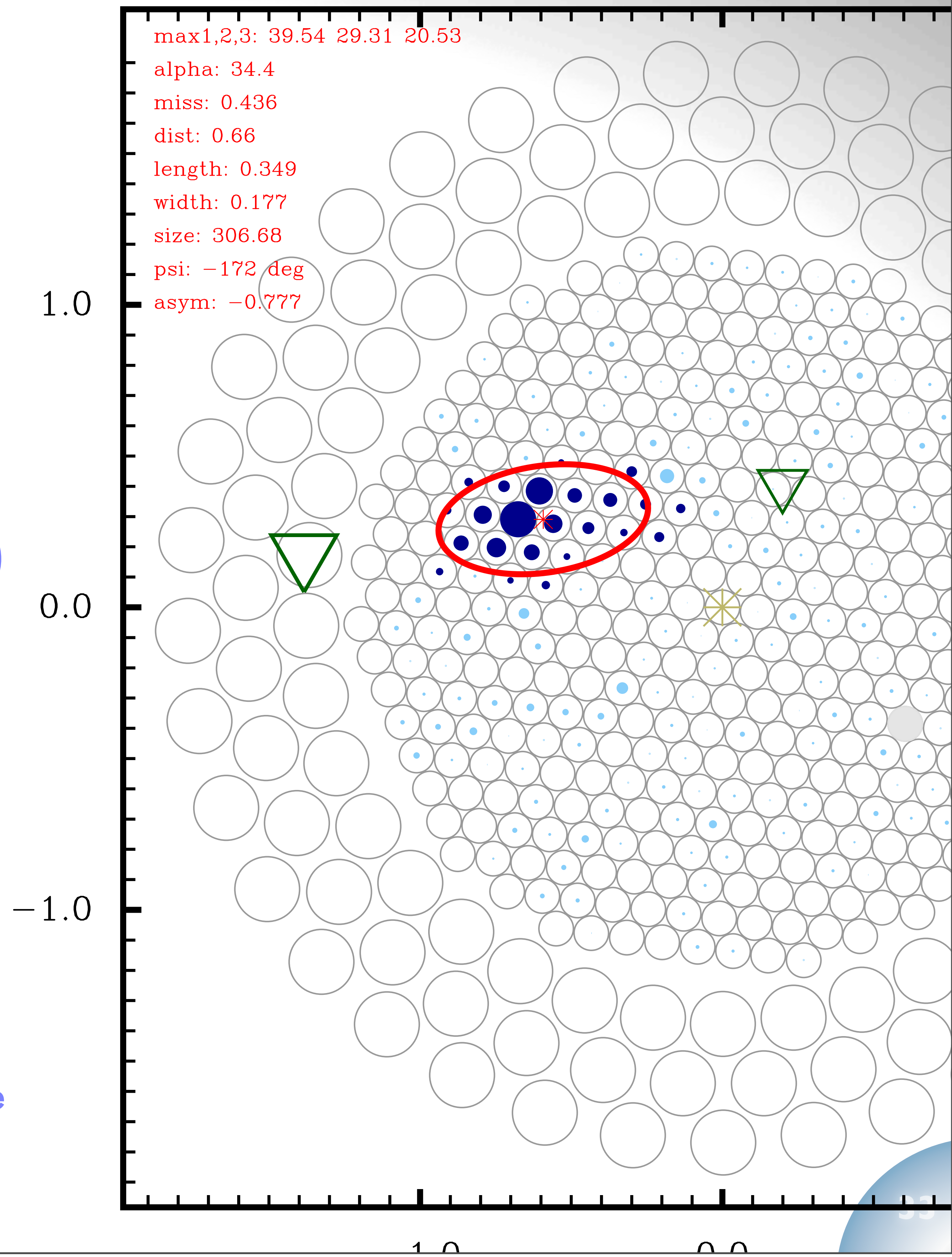
Hillas Parameterization

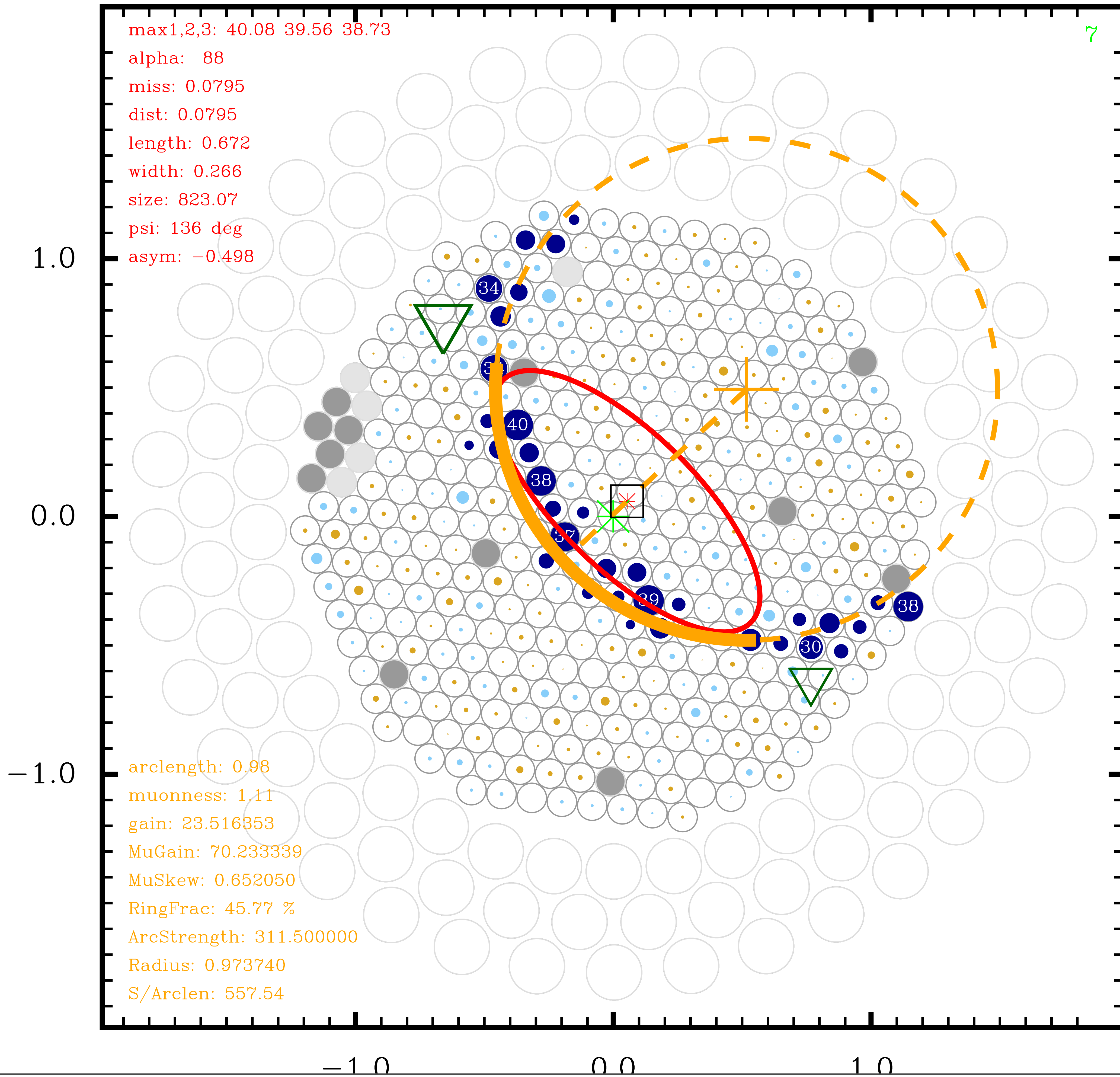
Image Cleaning:

- remove pixels corresponding to night-sky-background noise before calculating image moments
- 2-step threshold:
  - keep all pixels above high threshold (say 7 PE)
  - keep all pixels above lower threshold (5 PE) that have neighbors with a high-threshold pixel.

Moment Analysis:

- Calculate the 2D moments of the remaining pixels (up to 3rd order)
  - 1st order: image centroid
  - 2nd order: image elongation (ellipse)
  - 3rd order: skewness and kurtosis provide the asymmetry of the image





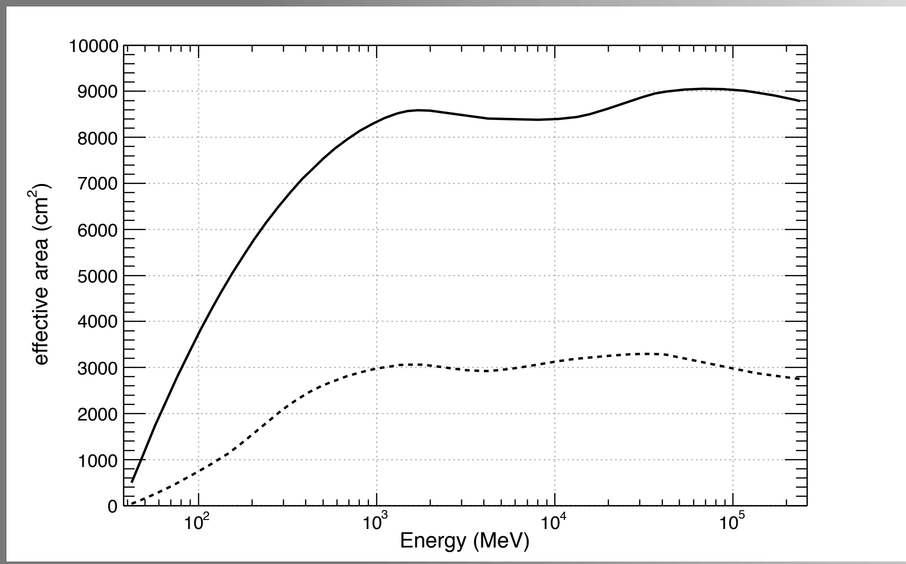
Friday, July 6, 2012

Rejecting Hadrons

Imaging allows the physical characteristics of the shower to be determined

- Moment analysis (Michael Hillas) provides a set of parameters that can be used for gamma/hadron discrimination:
  - **WIDTH**: the primary **hadron rejection parameter**. Hadronic showers are wider due to larger transverse momentum and sub-showers
  - **LENGTH**: lesser rejection power, but helps
  - **LENGTH/SIZE** is a good veto for muon ring images.
- Also provide a method for energy reconstruction:
  - **SIZE** and **DISTANCE** (which is prop to impact parameter) can be used to determine the *energy*
  - at fixed impact parameter, E ≈ SIZE

Limiting Effects



rsus energy at normal incidence (solid curve) and at 60° off-axis (dashed curve) for Source analysis class.

Threshold energy:

- Larger dishes mean fainter showers can be seen (fainter=lower energy). So the dish size sets the energy threshold
- Astrophysical sources have steep power-law spectra (E^{-2} - E^{-4}), so there is a great advantage in signal when going to lower energies

Effective Collection Area:

- For ACTs, it's not the size of the mirror: one can detect any shower where the mirror is in the light pool...
  - prop to size of light pool for a single telescope (≈ **10^5 m^2 !**)
  - Recall A_{eff} for e.g. Fermi: ≈ **1 m^2**
- Having multiple telescopes, widely spaced, also increases the effective area
- since at high-energies, there is little signal, larger effective areas are important

THE ASTROPHYSICAL JOURNAL, 342:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

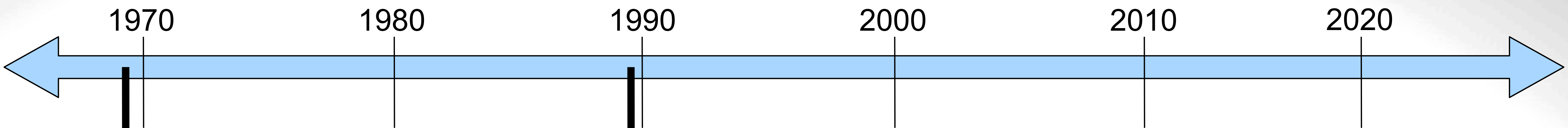
Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

The Detection of the Crab Nebula

Successful detection in 1989! with the Whipple 10 m

- 50 hours of observation time
- 5 sigma signal
  - (counts as a function of alpha only, no image)

Historical Summary

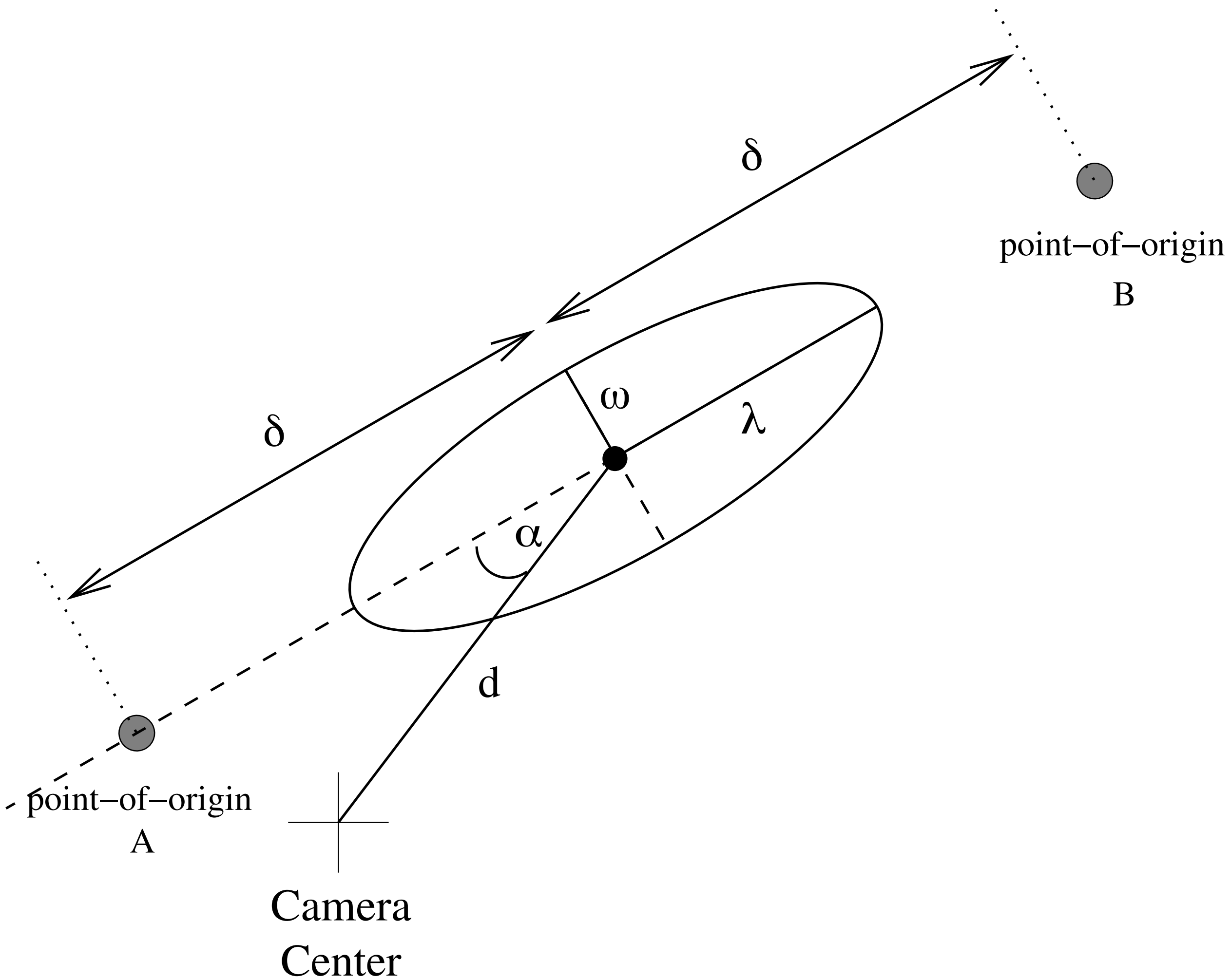


1968: Whipple 10 M Telescope Constructed (single-pixel-camera)

1989: Whipple 10 M Detects 1st Gamma-ray source!
(The Crab Nebula, Weekes et al)

Thanks to the *imaging technique* (multiple pixel camera)

Alpha Plots

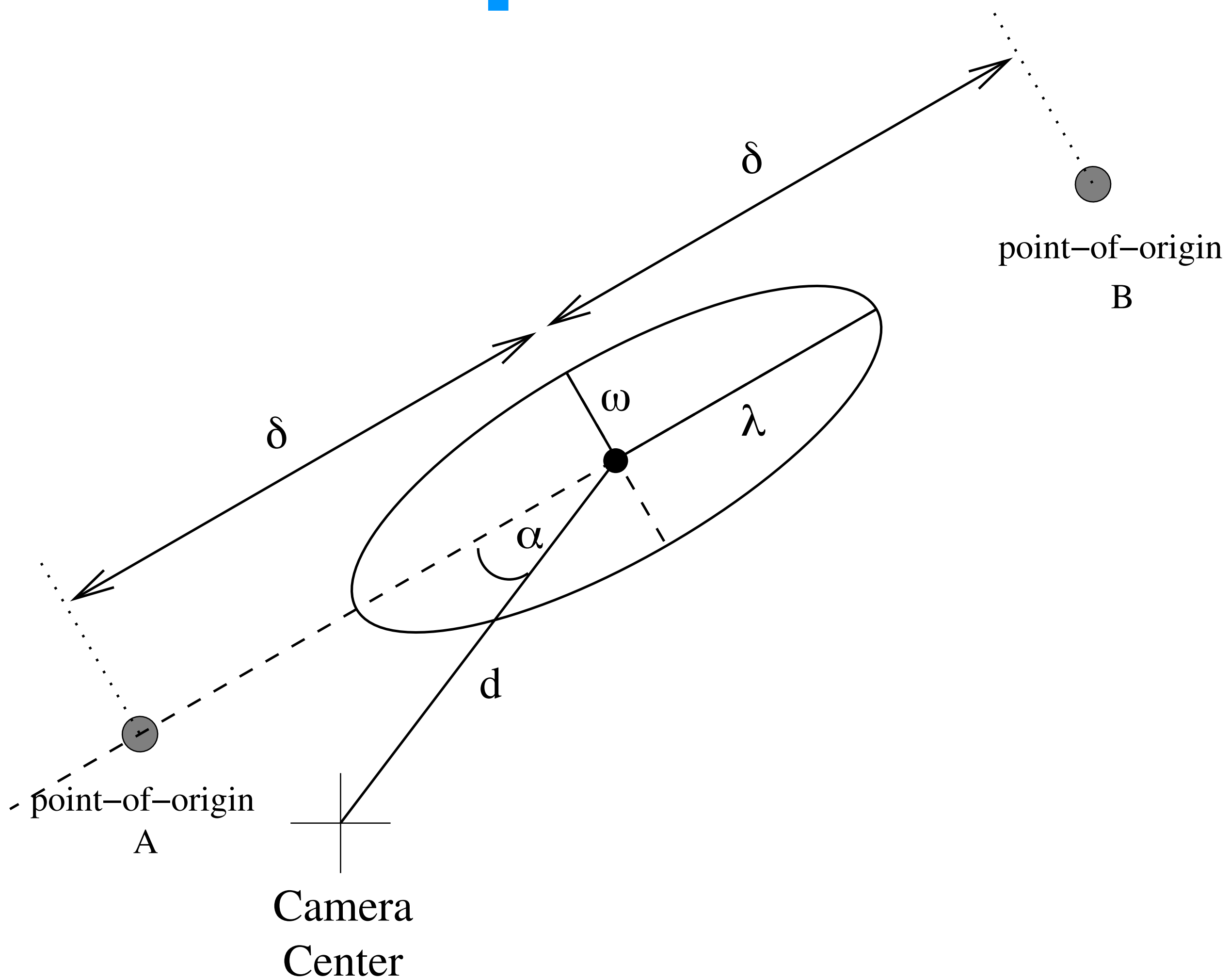


Early IACTs imaged the showers, but didn't produce gamma-ray images!

- simple ON-OFF mode, with the source candidate at the center of the FOV
- the ALPHA parameter (ellipse angle wrt source candidate position) was used for localizing the signal

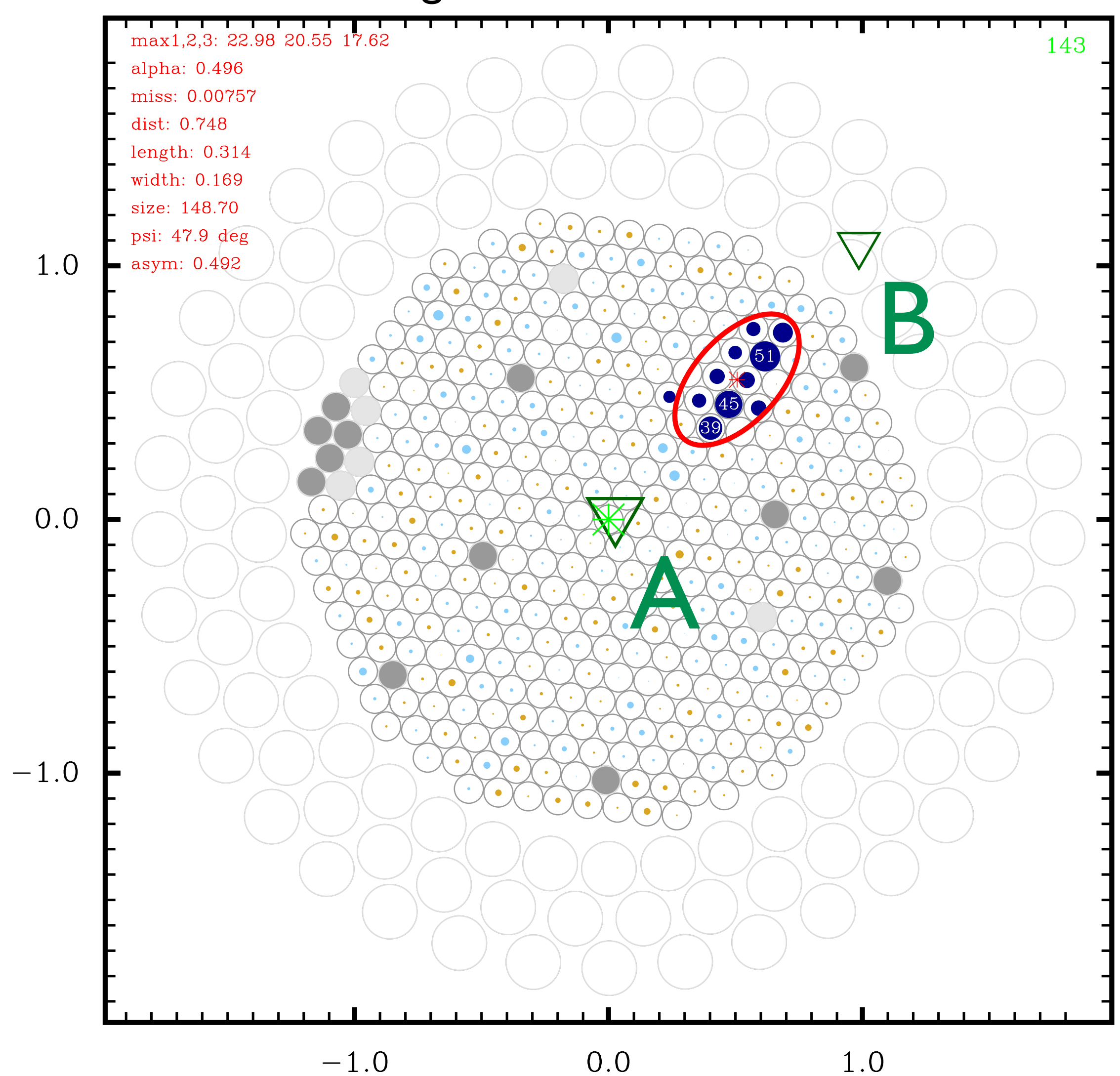
Displacement Method

However, gamma-ray sky images still can be produced with a single-dish telescope:



$$\delta = \epsilon(\log S)\left|1 - \frac{\omega}{\lambda}\right|$$

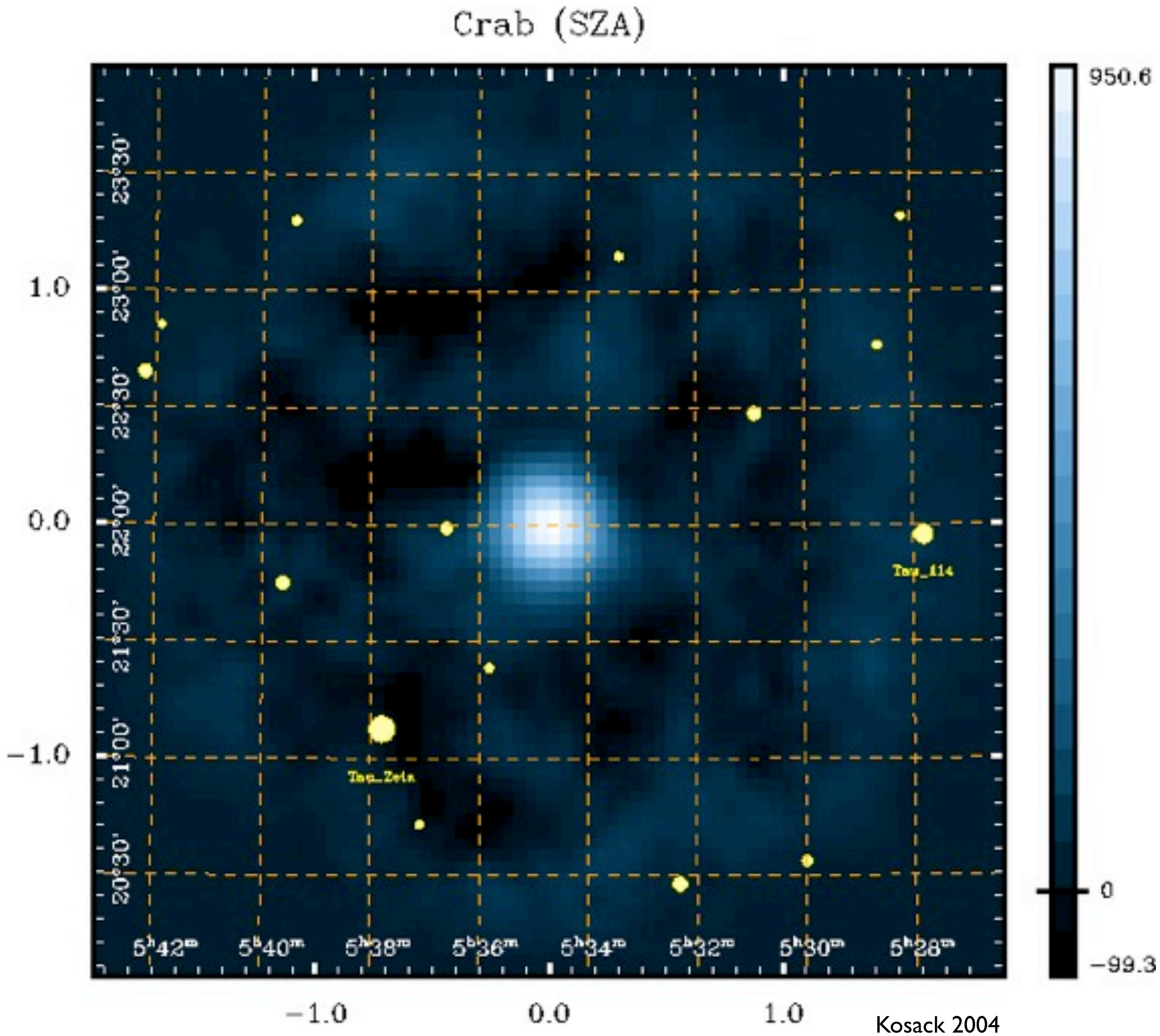
Cherenkov event in the Whipple 10m telescope, with generation 4 camera



Figures from Kosack 2004

Crab Nebula

ON-OFF Background-subtracted gamma-ray image of the Crab Nebula (pointlike) with the Whipple 10M using the displacement method



Kosack 2004

More single-dish imagers...

CAT, 5m
Themis, France
1996-2002

CANGAROO, 4m, 7m, 10m
Australia
1992-200X

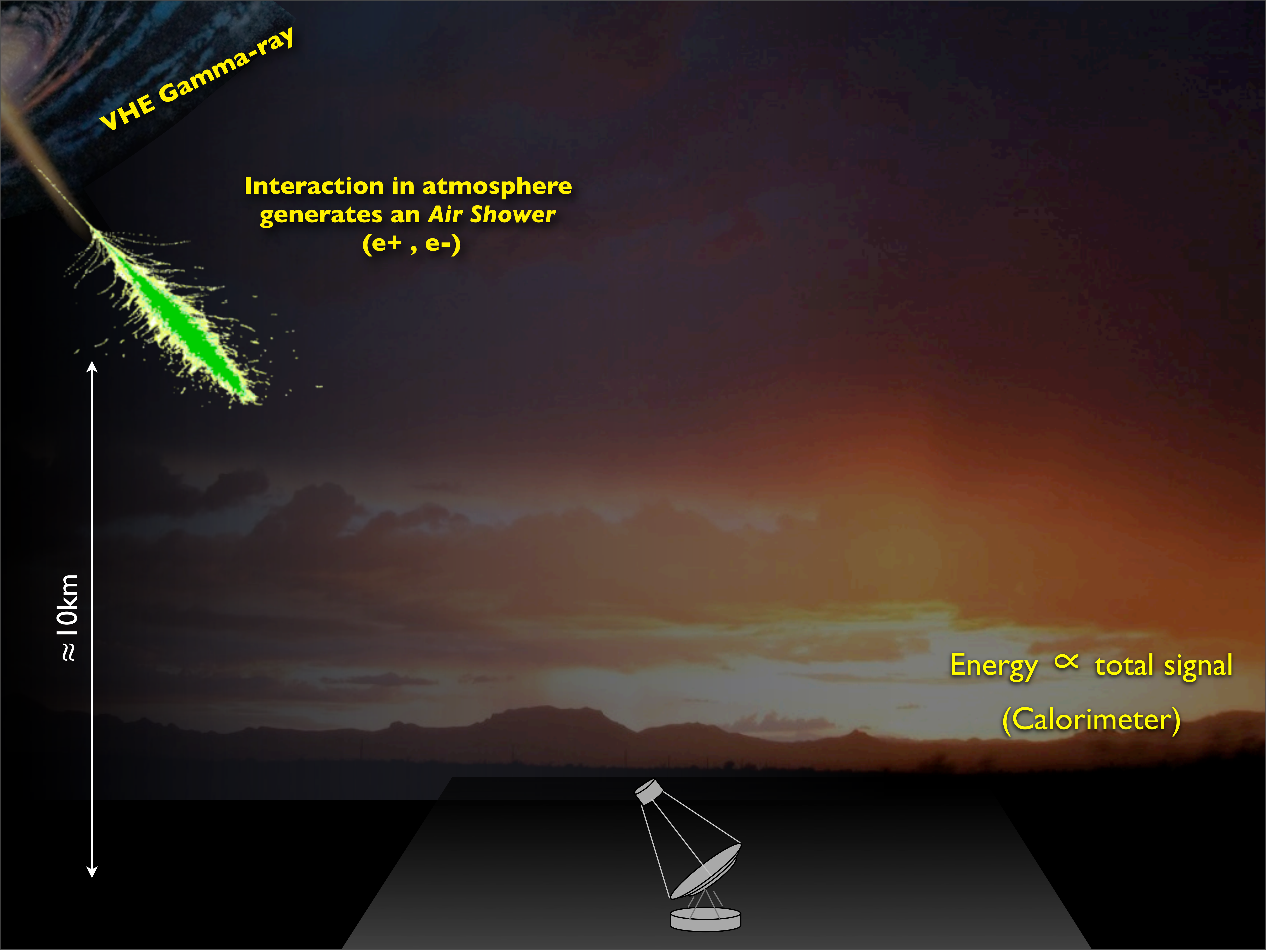
Telescope Arrays

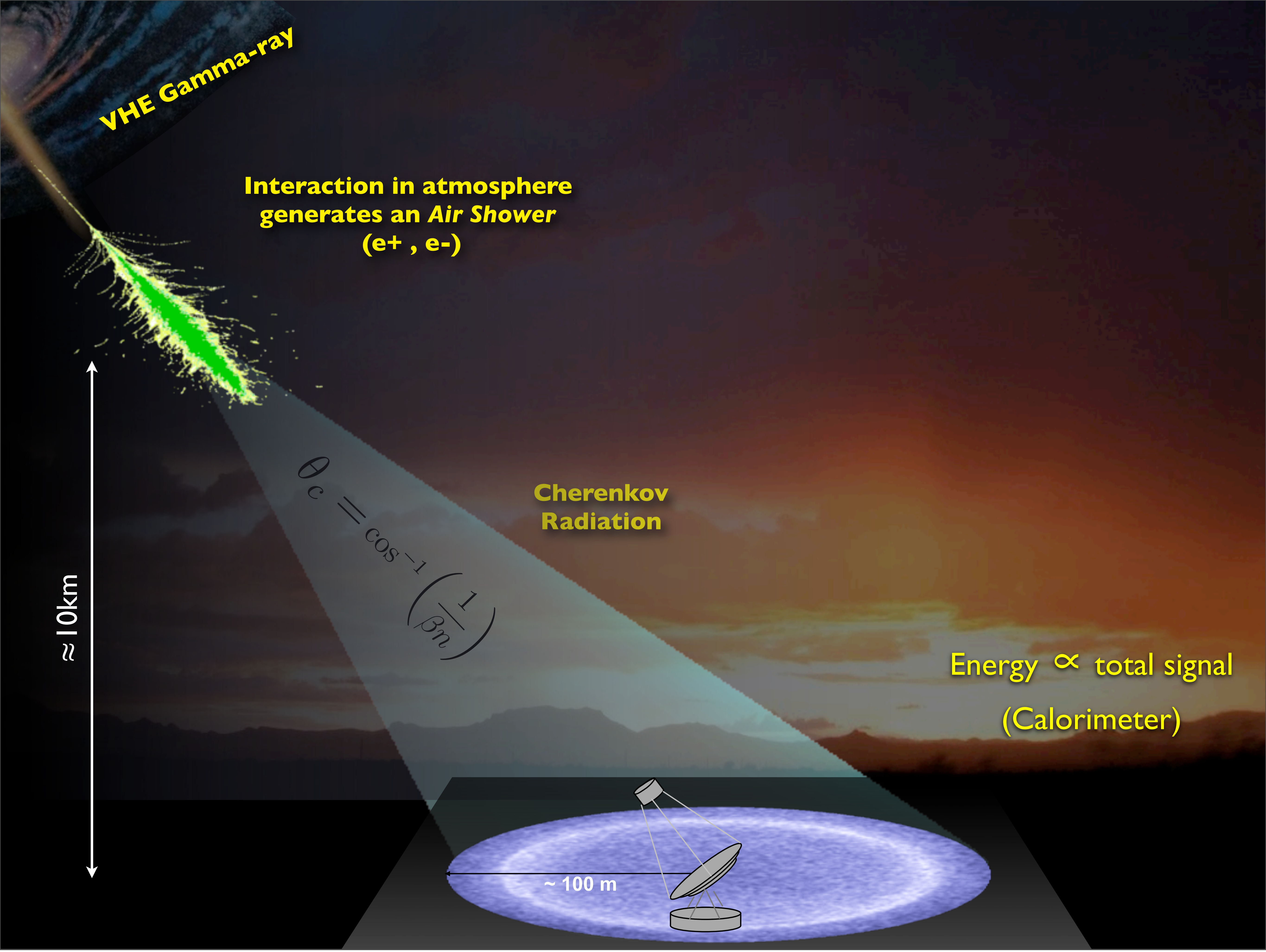
Single dish instruments work well, but:

- have poor angular resolution
- can't determine full shower geometry
- still have quite large background level

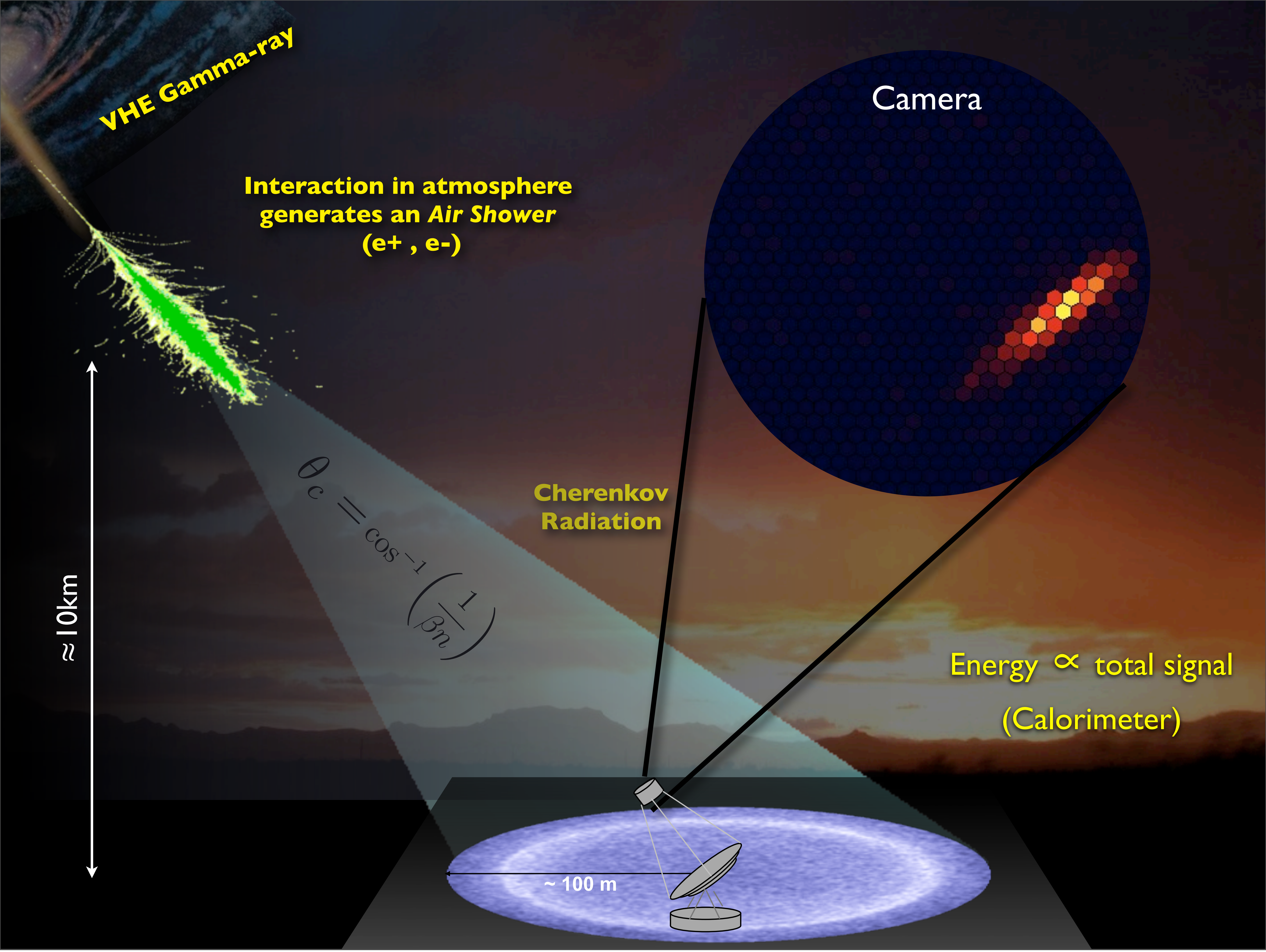
Imaging the shower from multiple viewpoints

- greatly reduces the background at the trigger level (requiring 2-tel coincidence)
- significantly improves shower reconstruction, PSF, etc


VHE Gamma-ray
Interaction in atmosphere generates an *Air Shower* (e+ , e-)
≈ 10km
Energy ∝ total signal
(Calorimeter)



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



VHE Gamma-ray
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Camera
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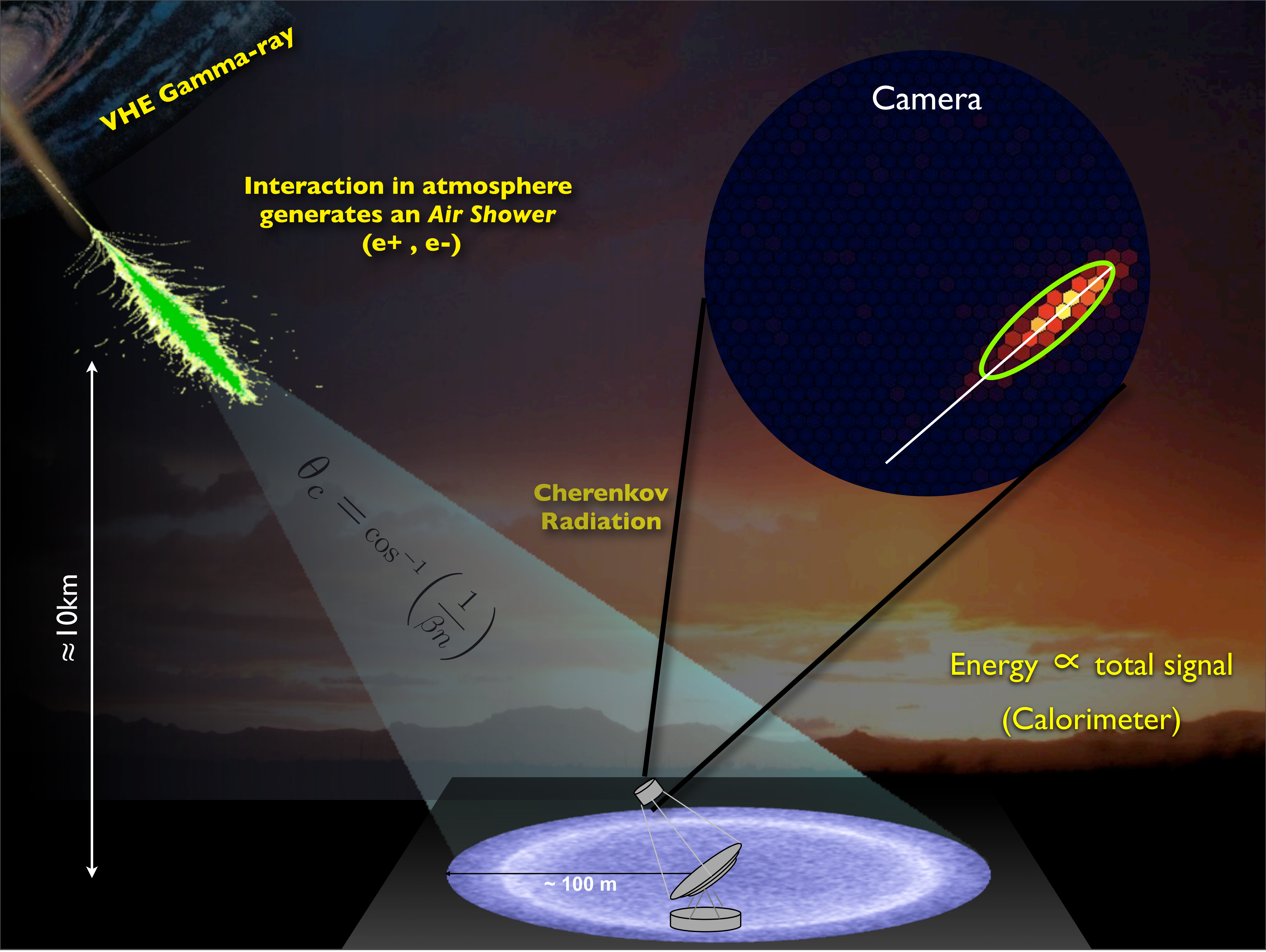
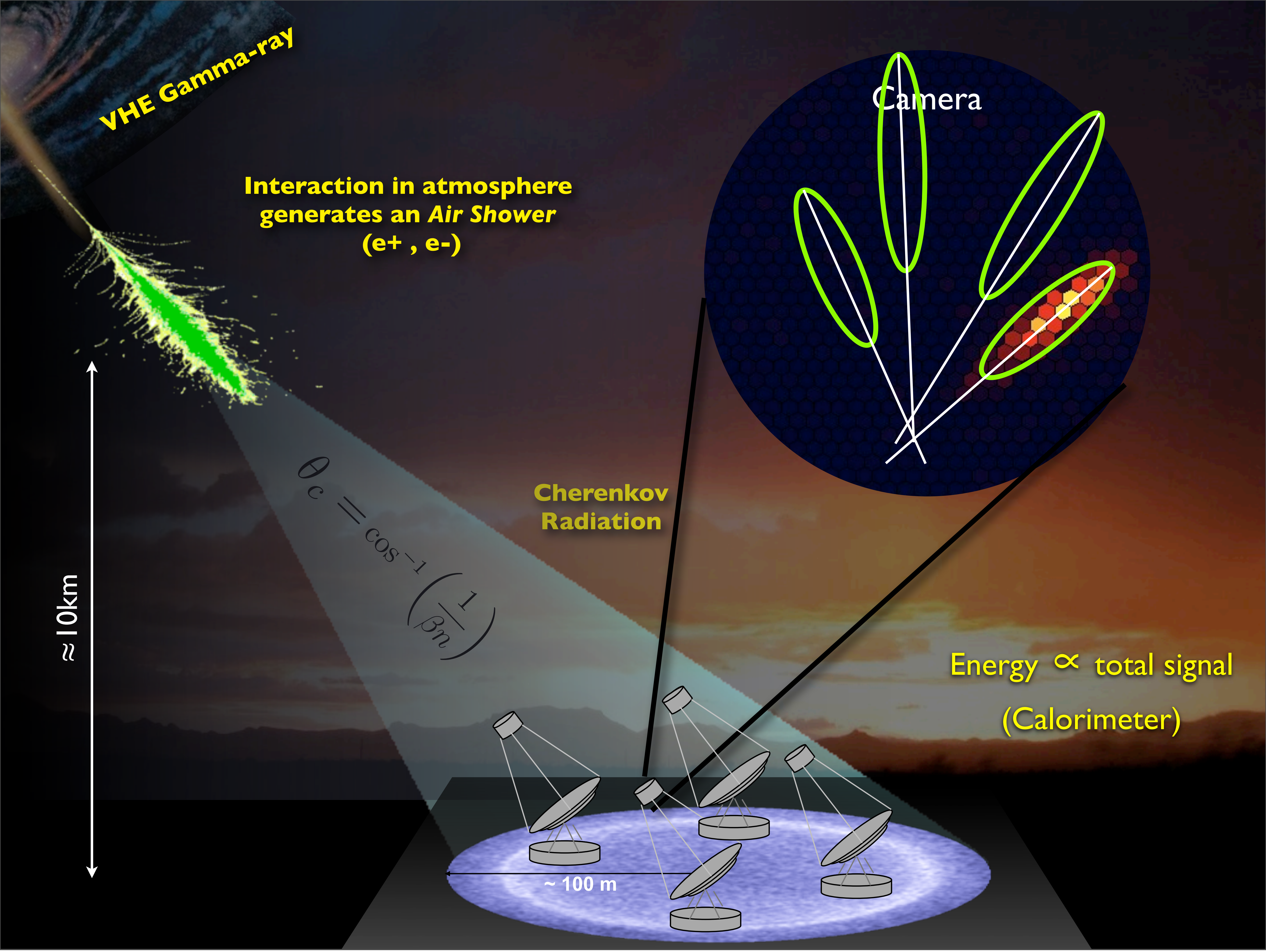
Cherenkov Radiation
≈ 10km
Energy ∝ total signal
(Calorimeter)
~ 100 m


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



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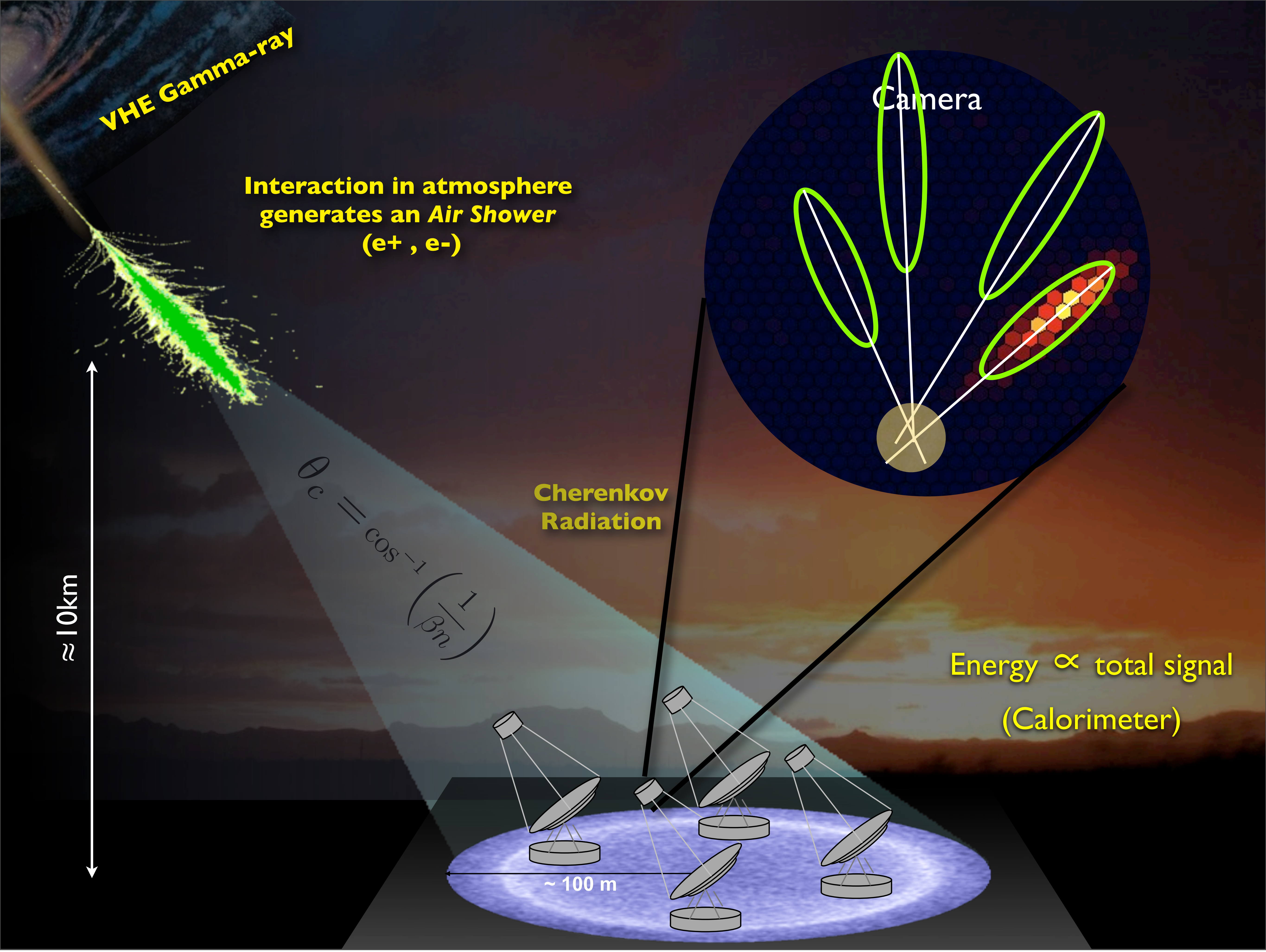

VHE Gamma-ray
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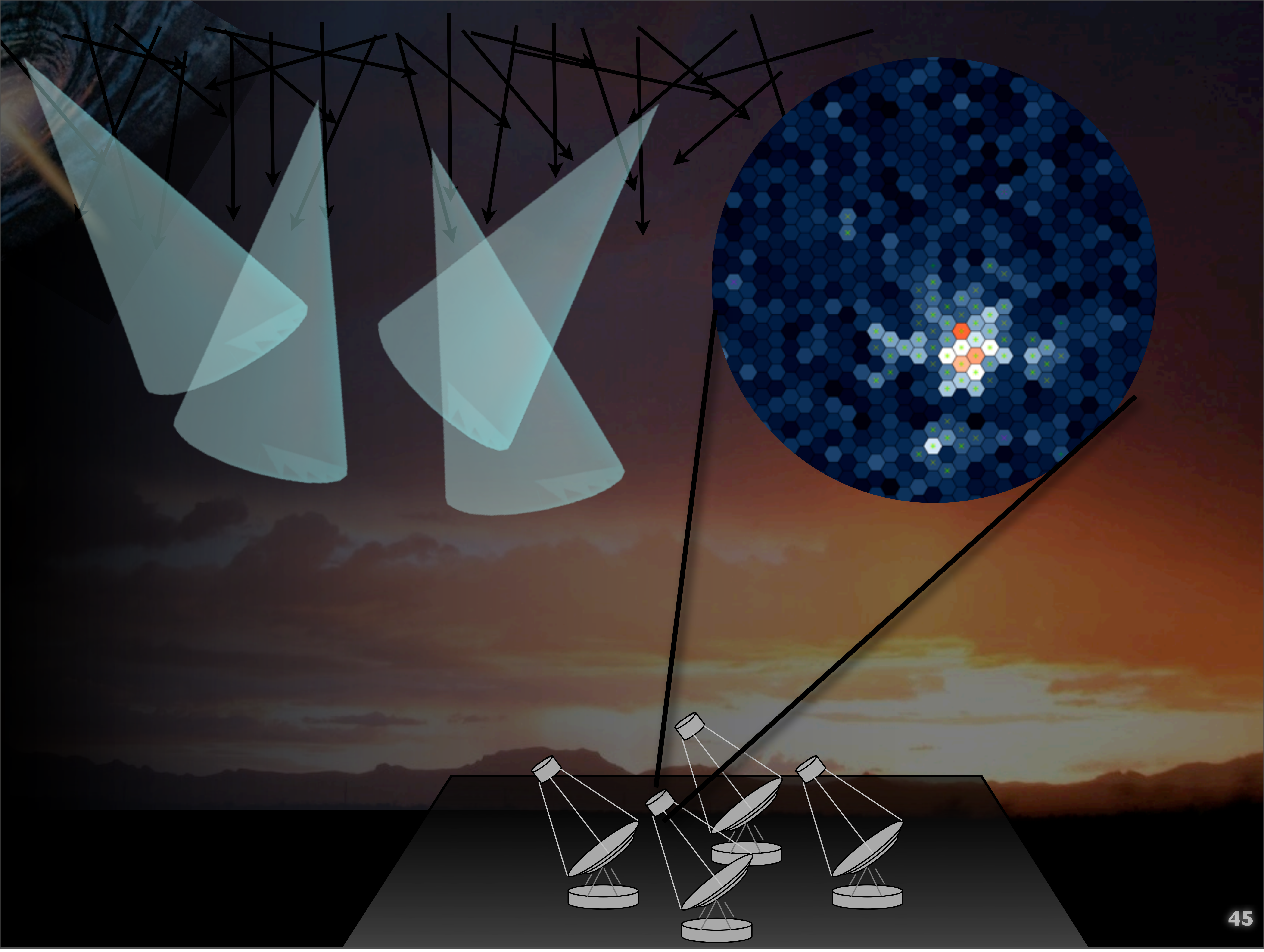
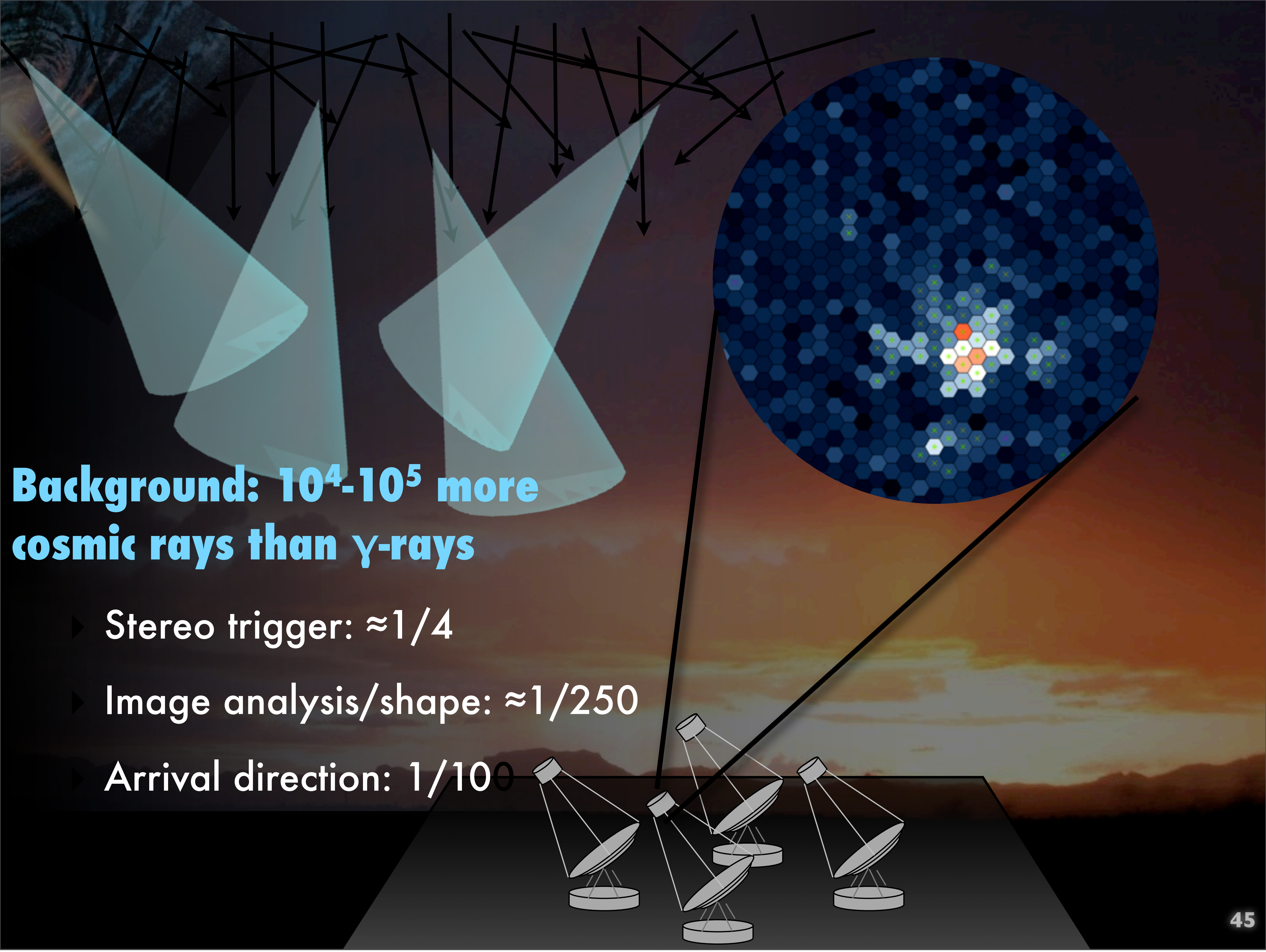
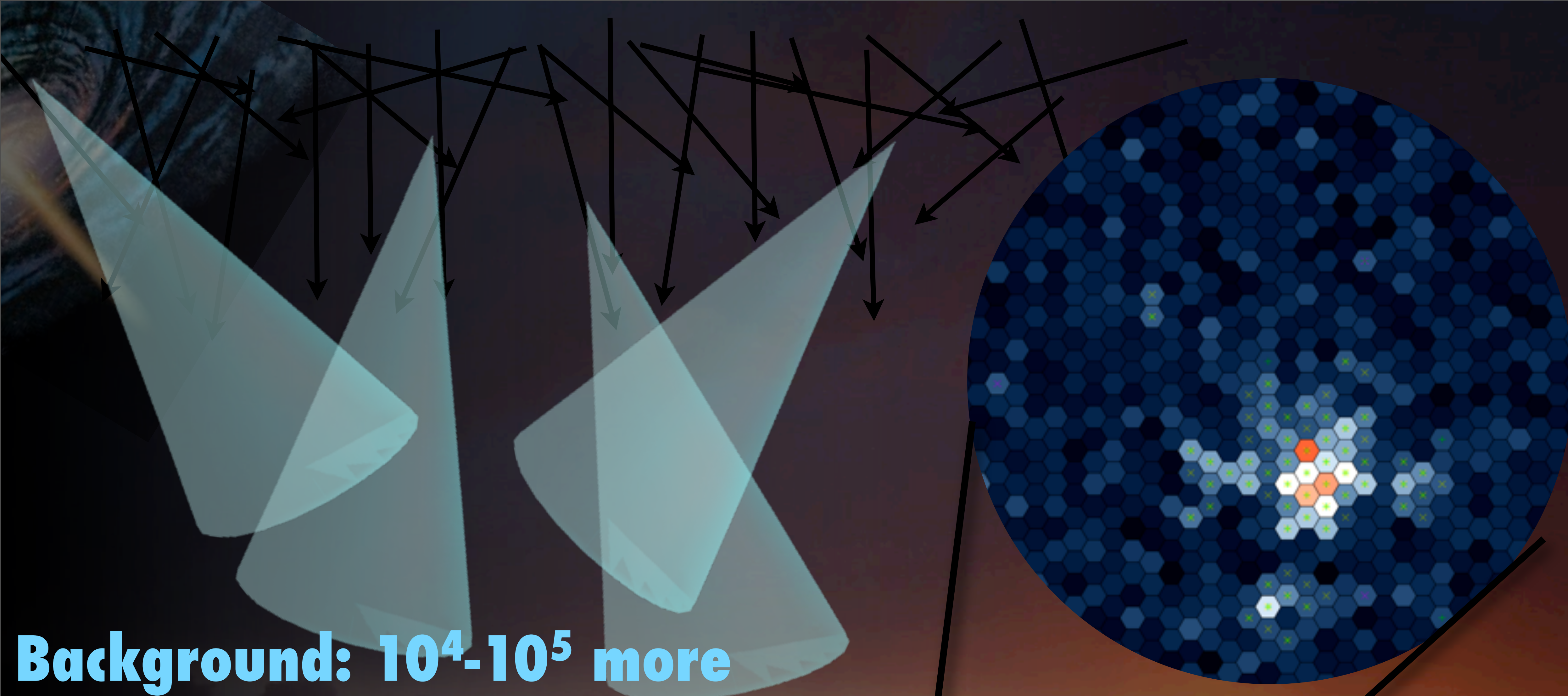



Background: 10^4-10^5 more cosmic rays than γ-rays
Stereo trigger: ≈1/4
Image analysis/shape: ≈1/250
Arrival direction: 1/100
45



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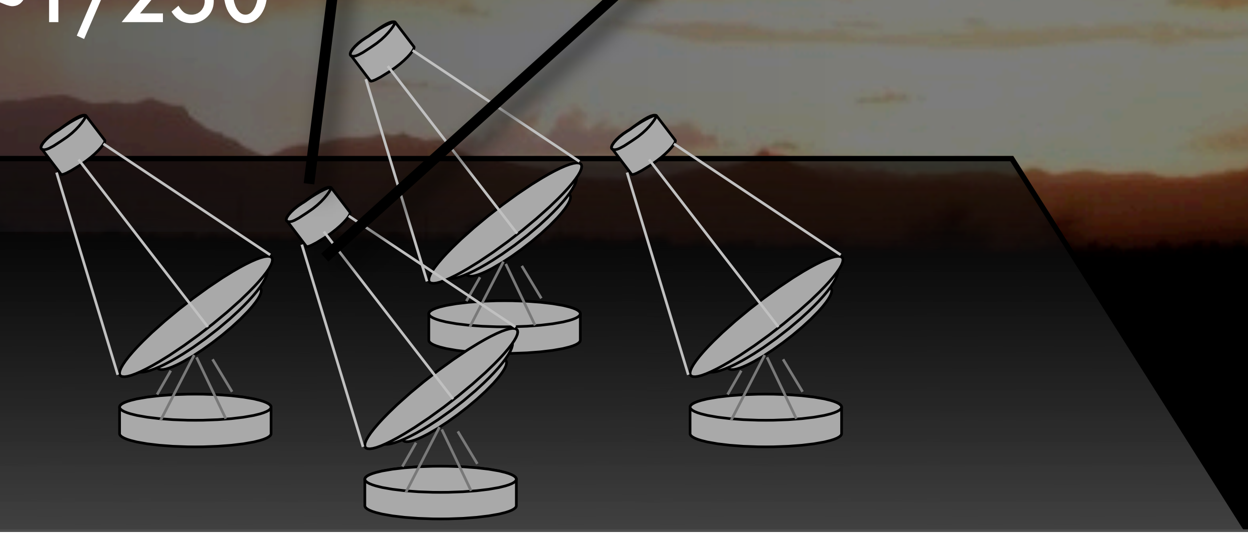
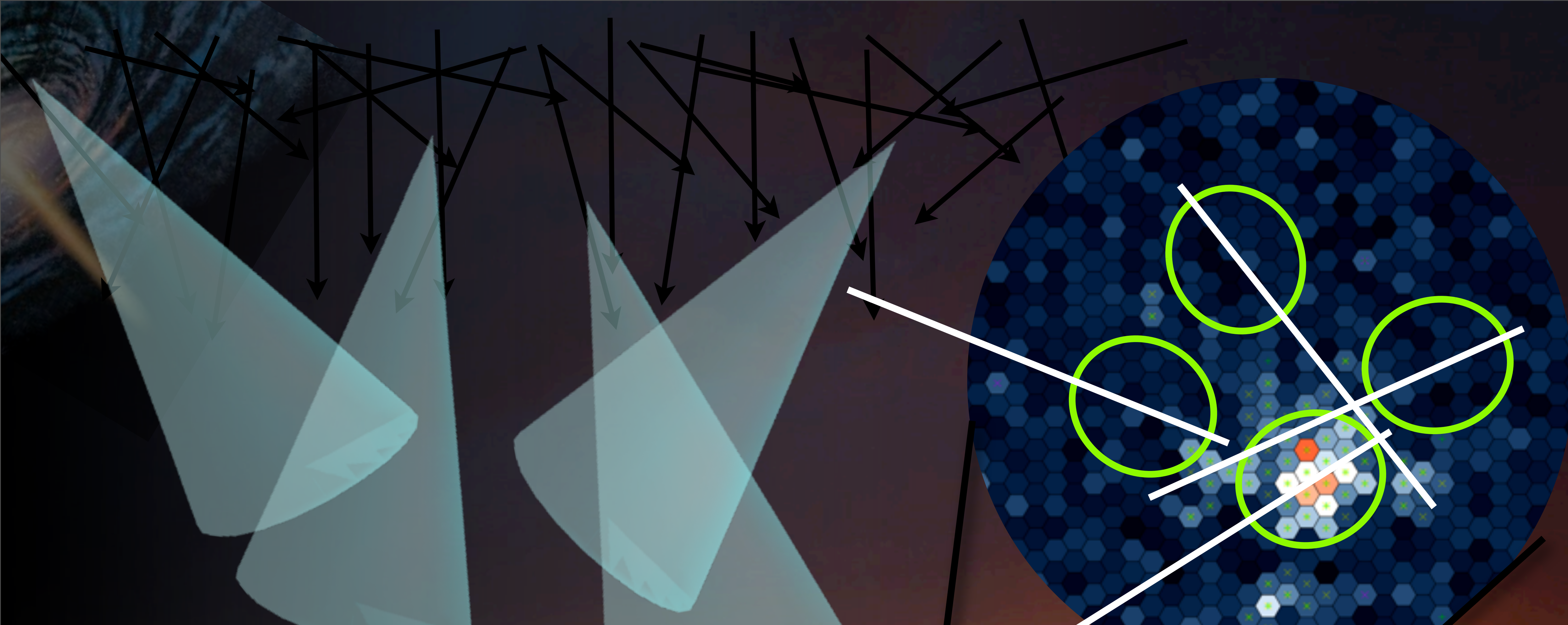


After analysis: S/N≈1.0!



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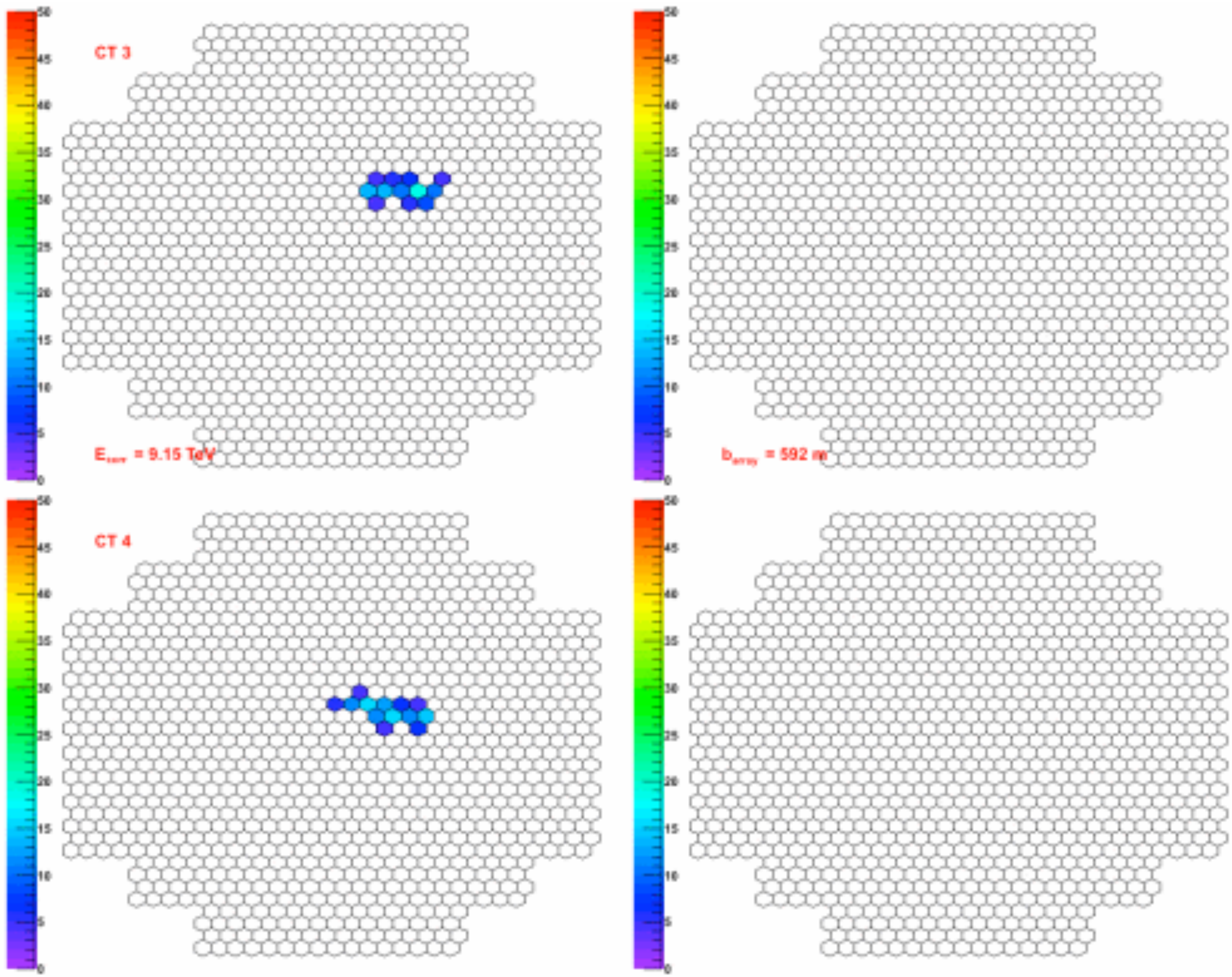

CT 3
E = 9.15 TeV
b_array = 592 m
CT 4

Trigger Levels:

- **L1**: pixel trigger
  - is the signal in a single pixel (or trigger sector in some cases) above a threshold?
- **L2**: telescope trigger
  - have enough pixels/sectors triggered?
- **L3**: array trigger
  - has more than one telescope triggered within a small time window?
  - Rejects most muons
  - drastically reduces triggers due to NSB fluctuations

Triggering a modern ACT Array

Modern Electronics

Still basically the same as the old ones:

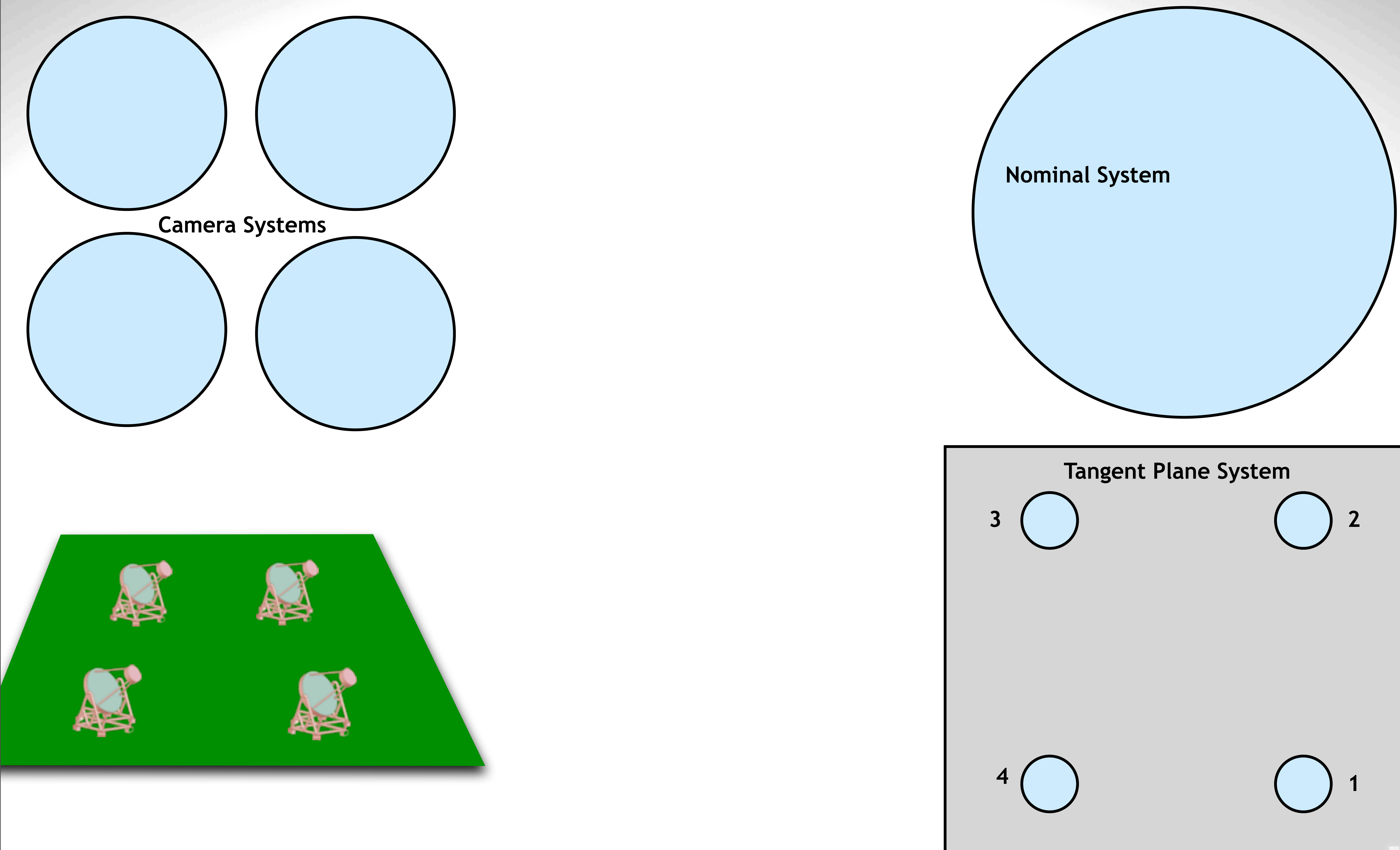
- PMT + Trigger + digitizer circuit

but, now we have fancier digitizers

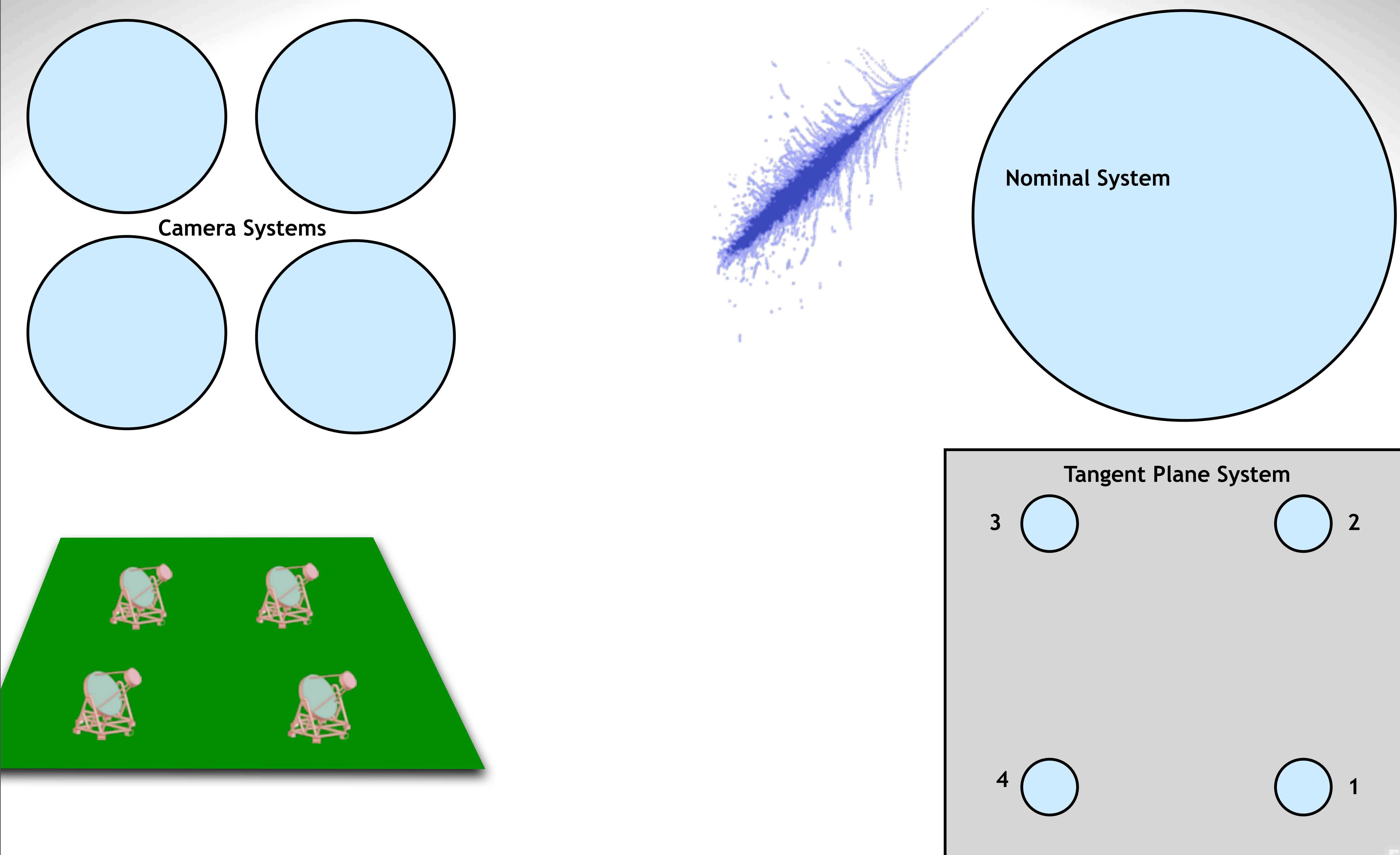
- Analog Ring Samplers
  - like a series of qADC capacitors on a chip. Readout can be done in time-slices, or with a variable integration window
  - provides a delay buffer of a few microseconds
  - cheap
- FlashADCs
  - digitize a signal continuously
  - Full waveform readout (all time-slices)
  - delay buffer limited only by memory

Reconstructing the physical properties of Extensive Air Showers

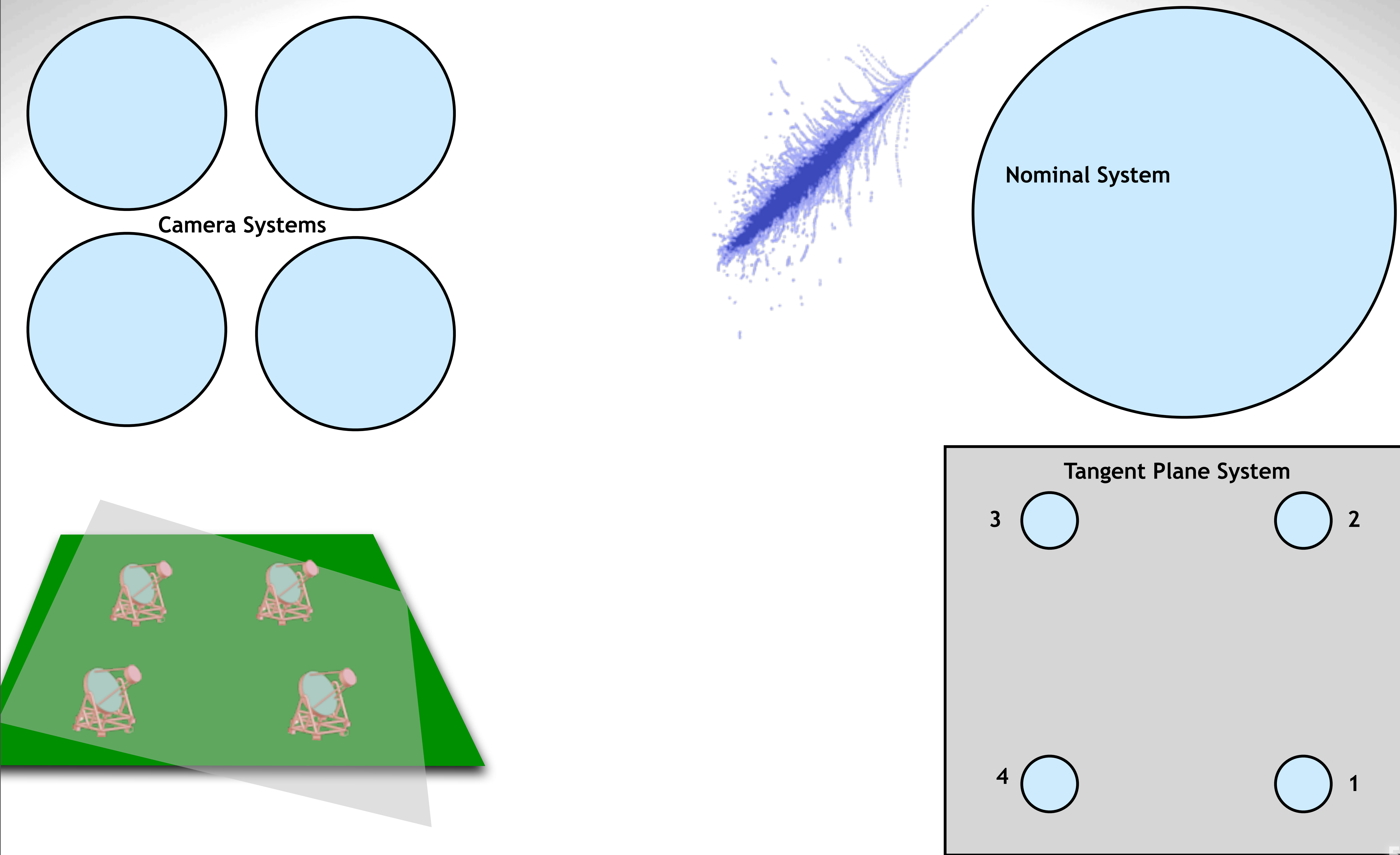
Simple Stereo Reconstruction



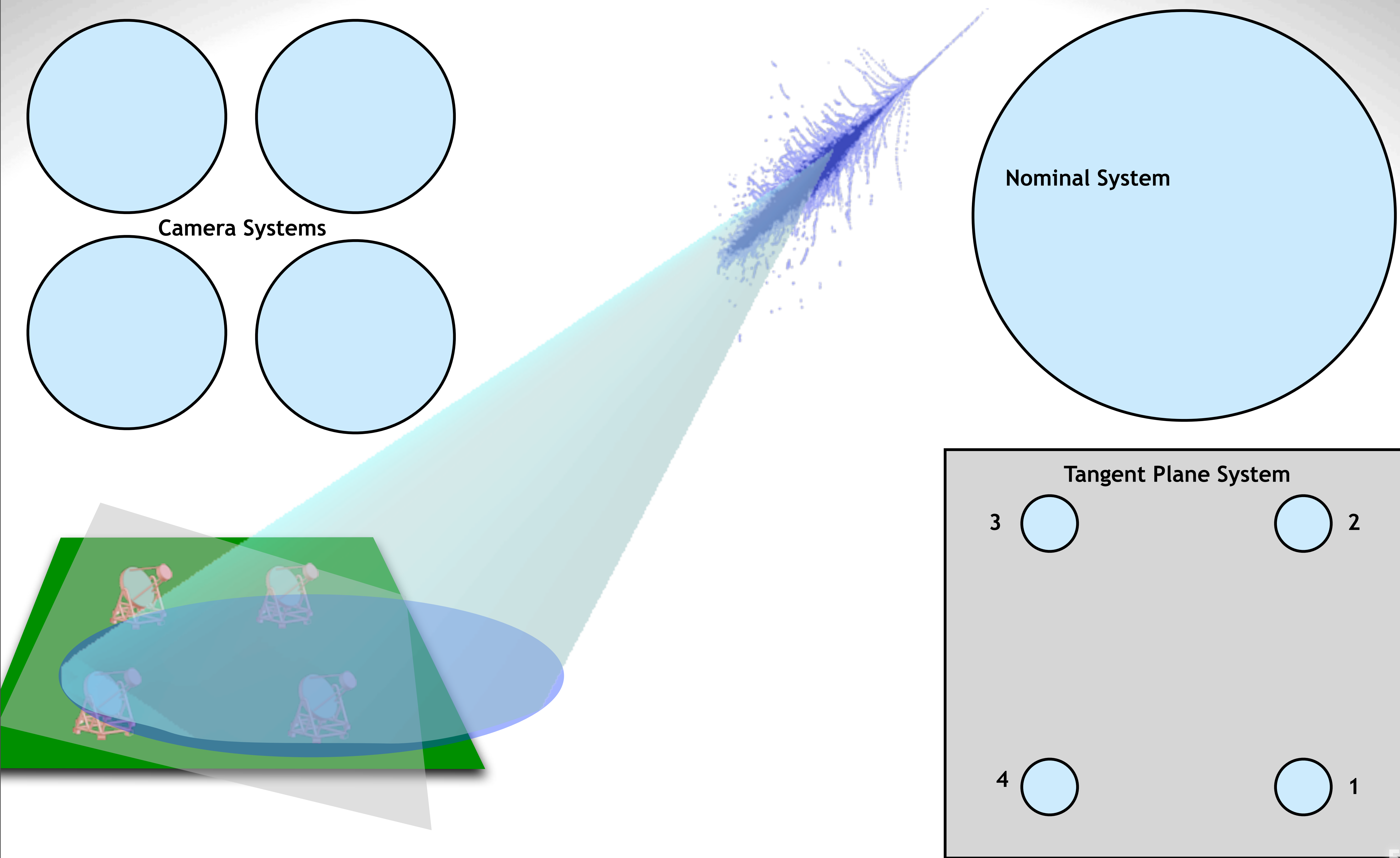
Simple Stereo Reconstruction



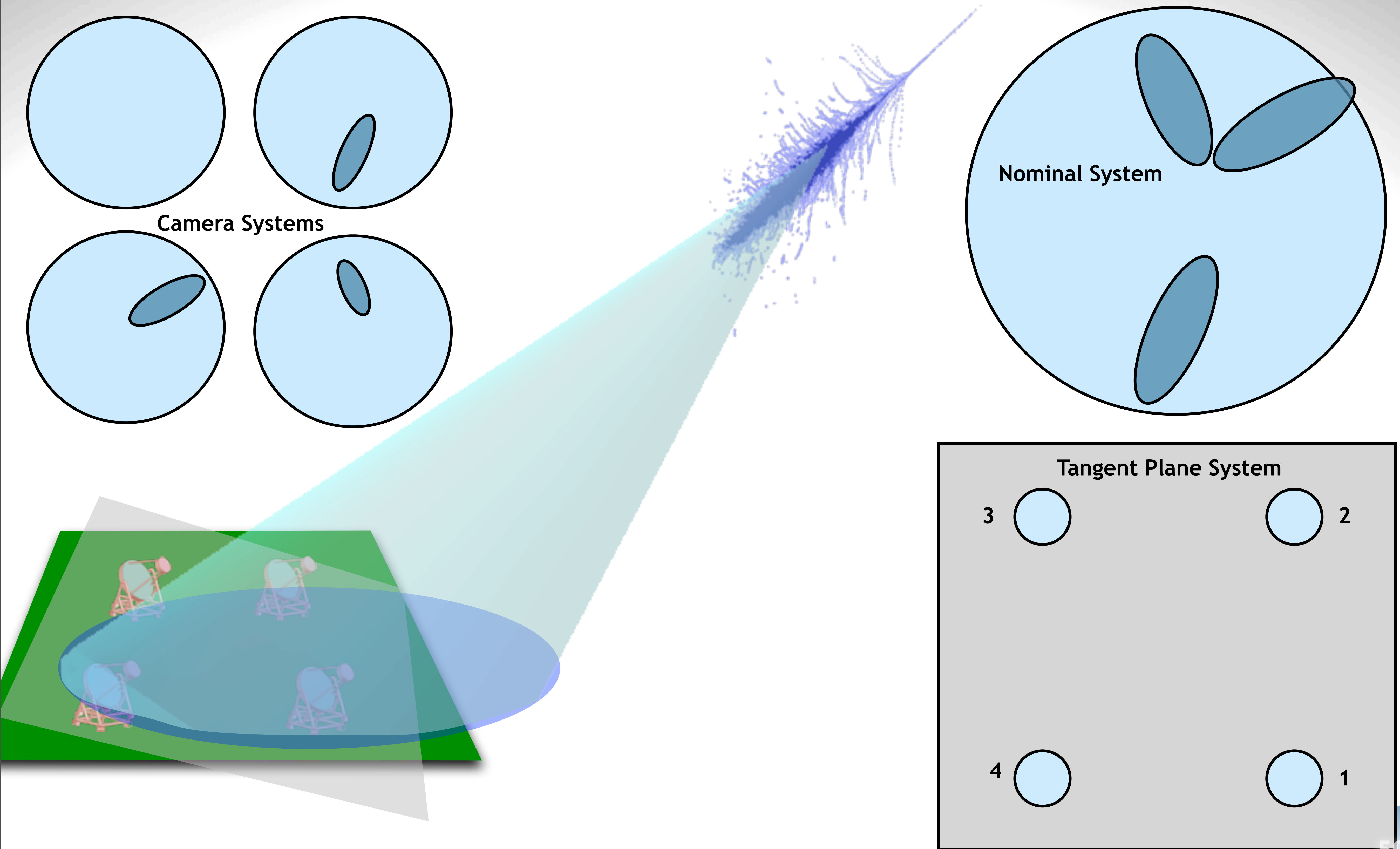
Simple Stereo Reconstruction



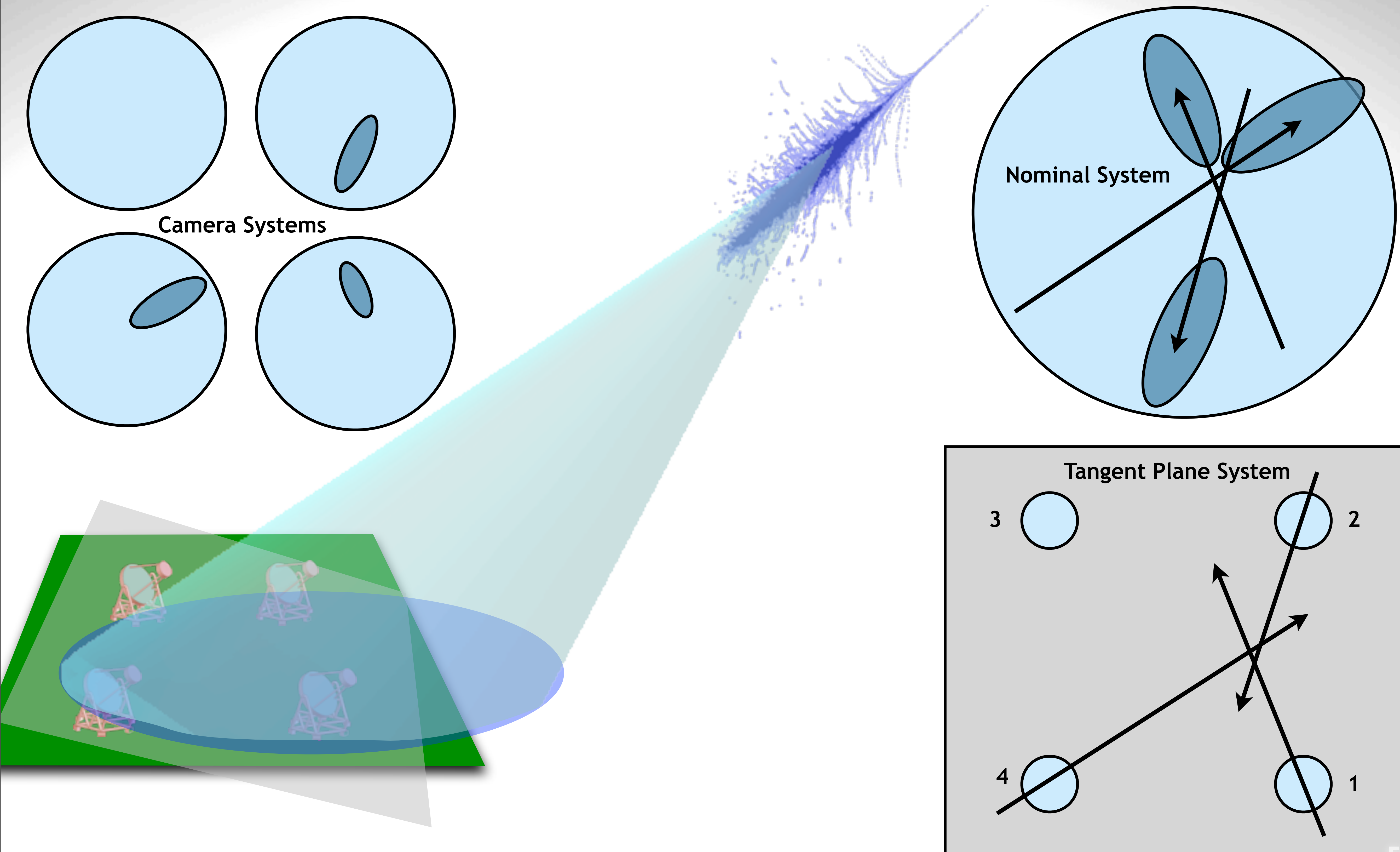
Simple Stereo Reconstruction



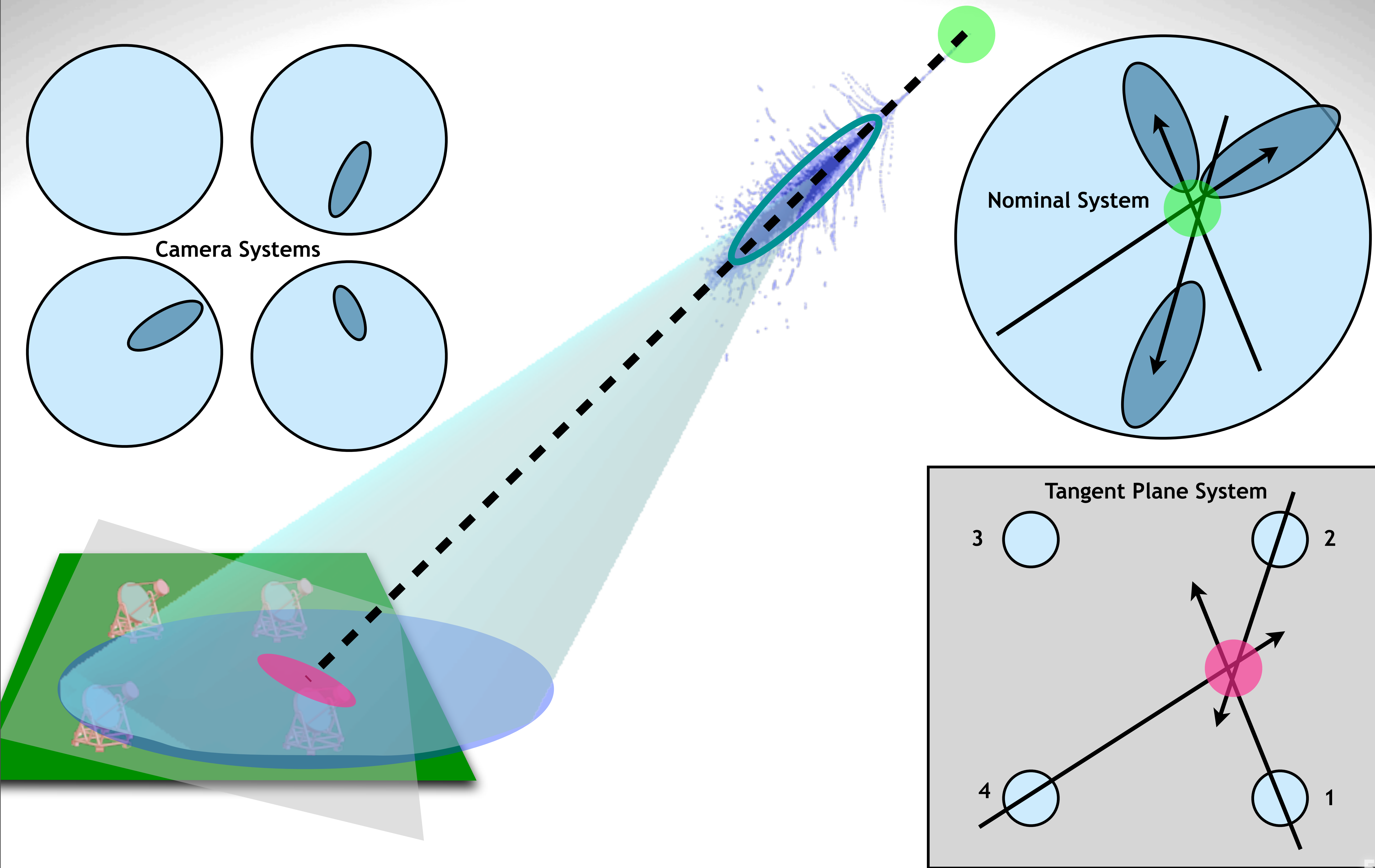
Simple Stereo Reconstruction



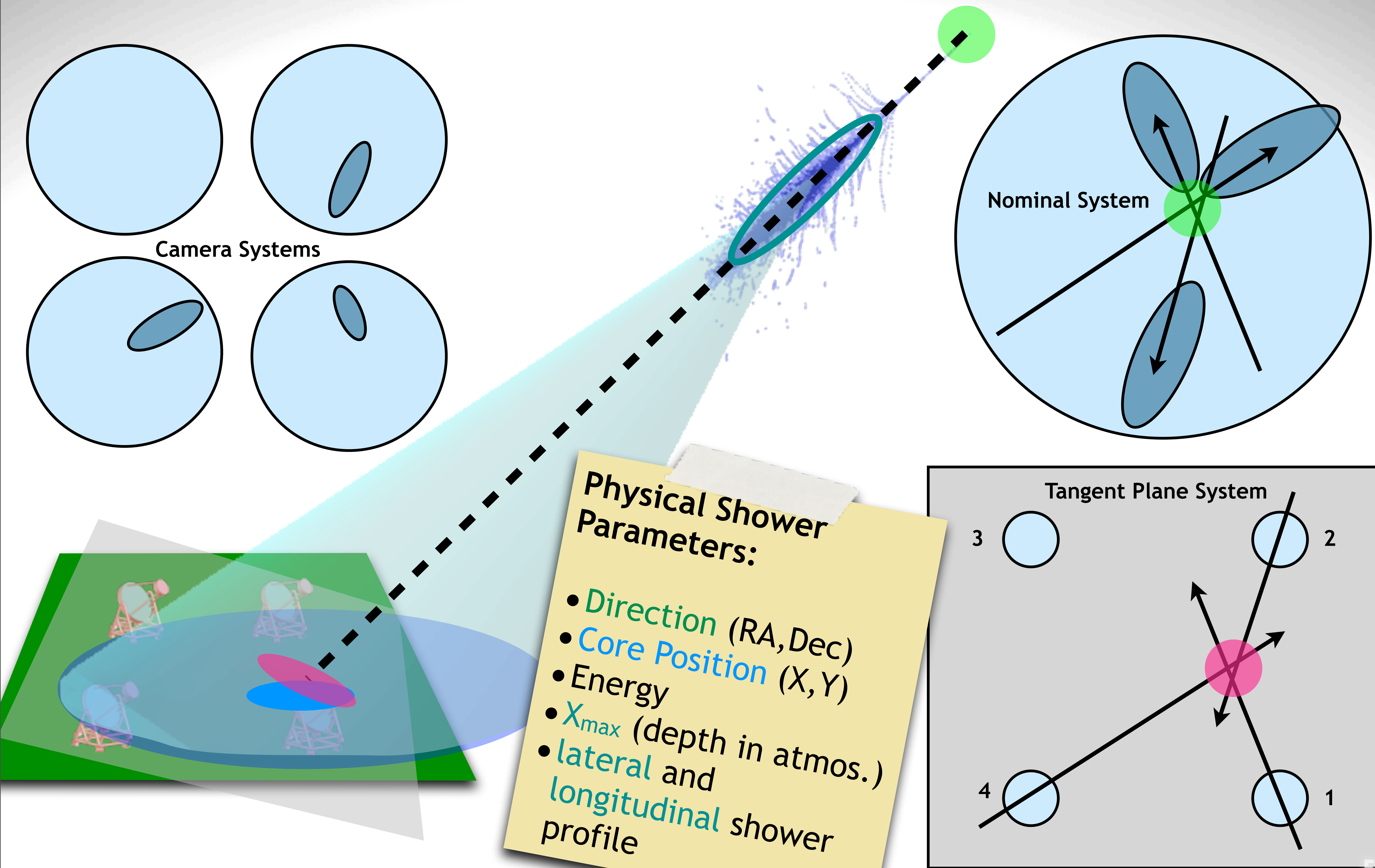
Simple Stereo Reconstruction



Simple Stereo Reconstruction

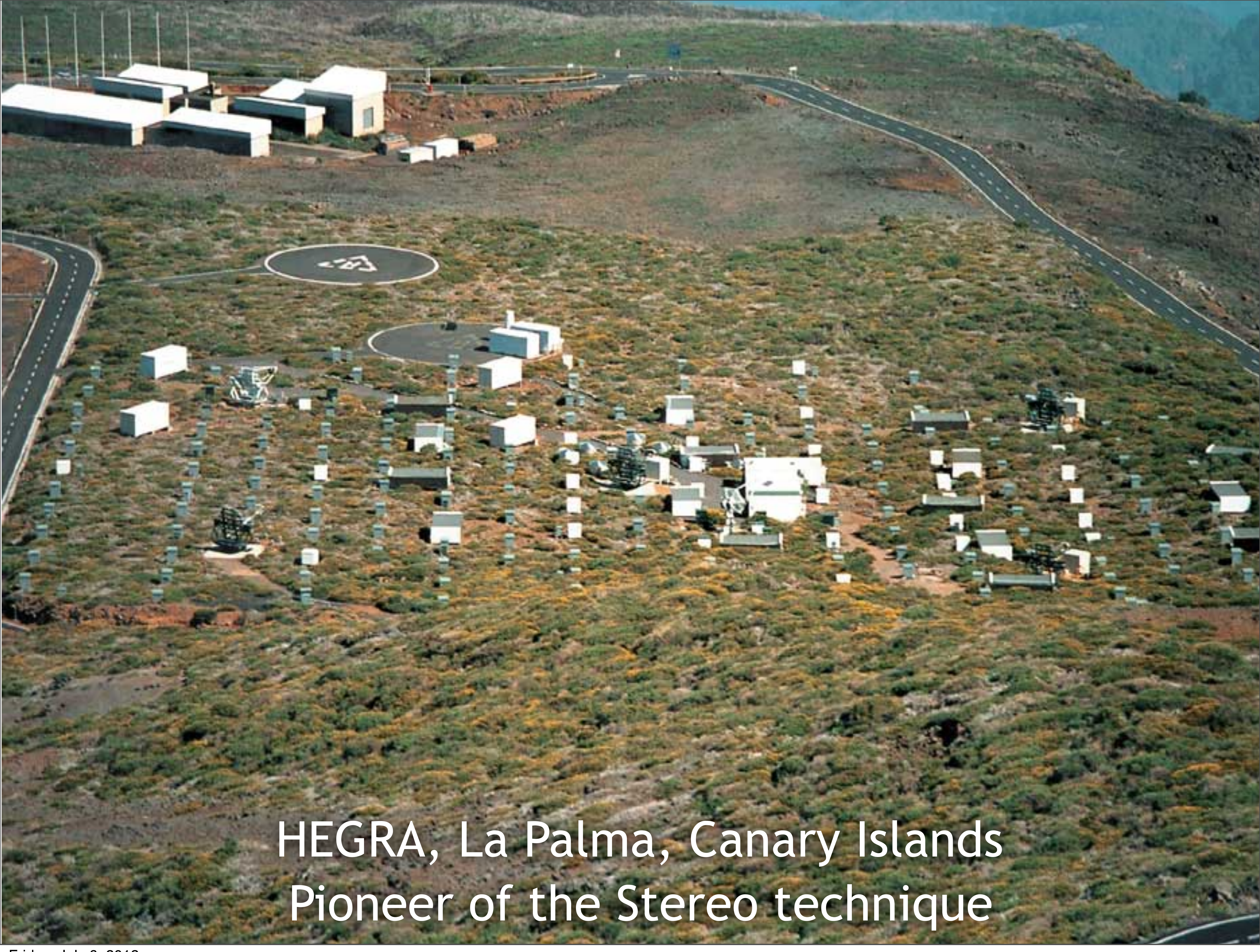


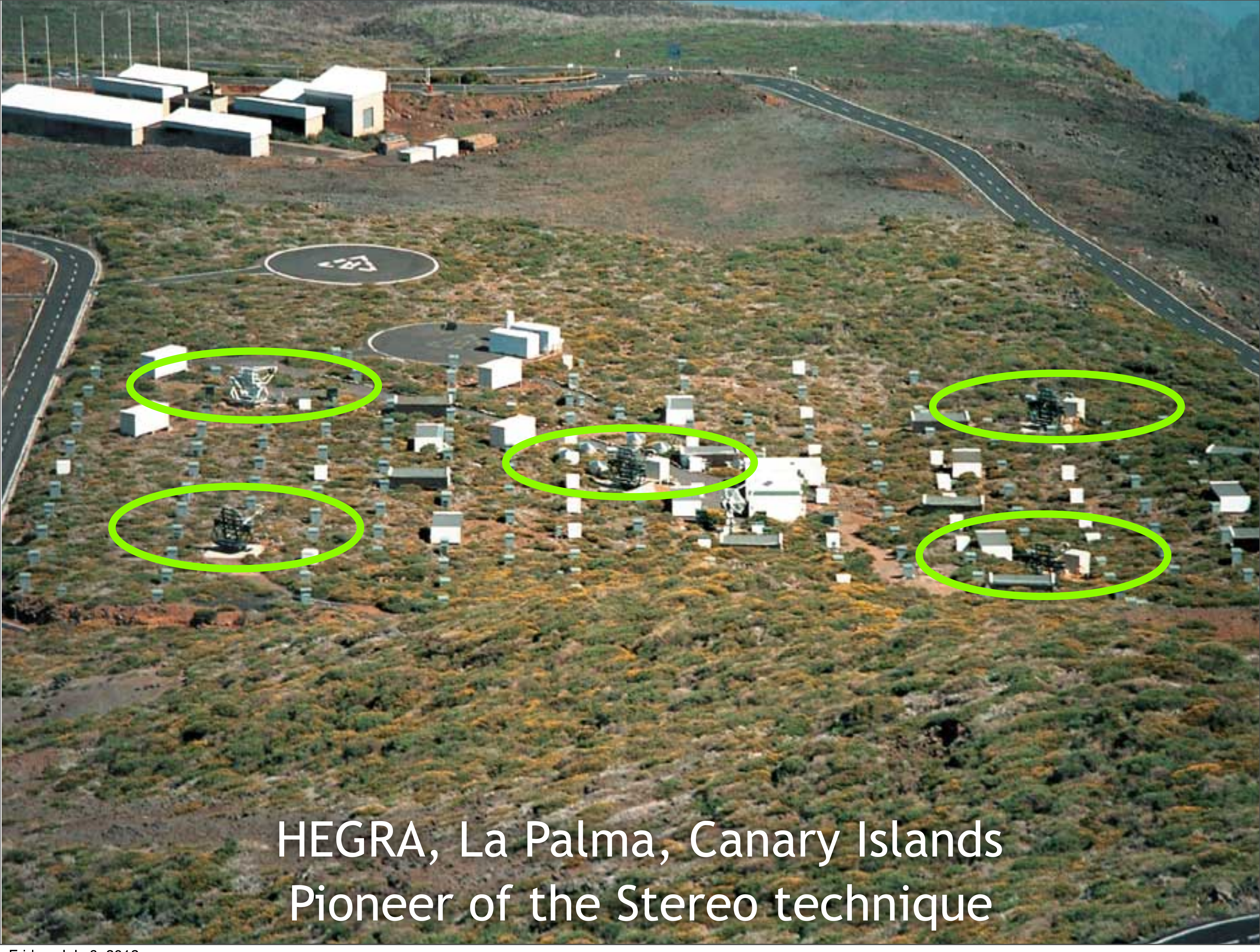
Simple Stereo Reconstruction



Physical Shower Parameters:

- Direction (RA,Dec)
- Core Position (X,Y)
- Energy
- X_{max} (depth in atmos.)
- lateral and longitudinal shower profile


HEGRA, La Palma, Canary Islands
Pioneer of the Stereo technique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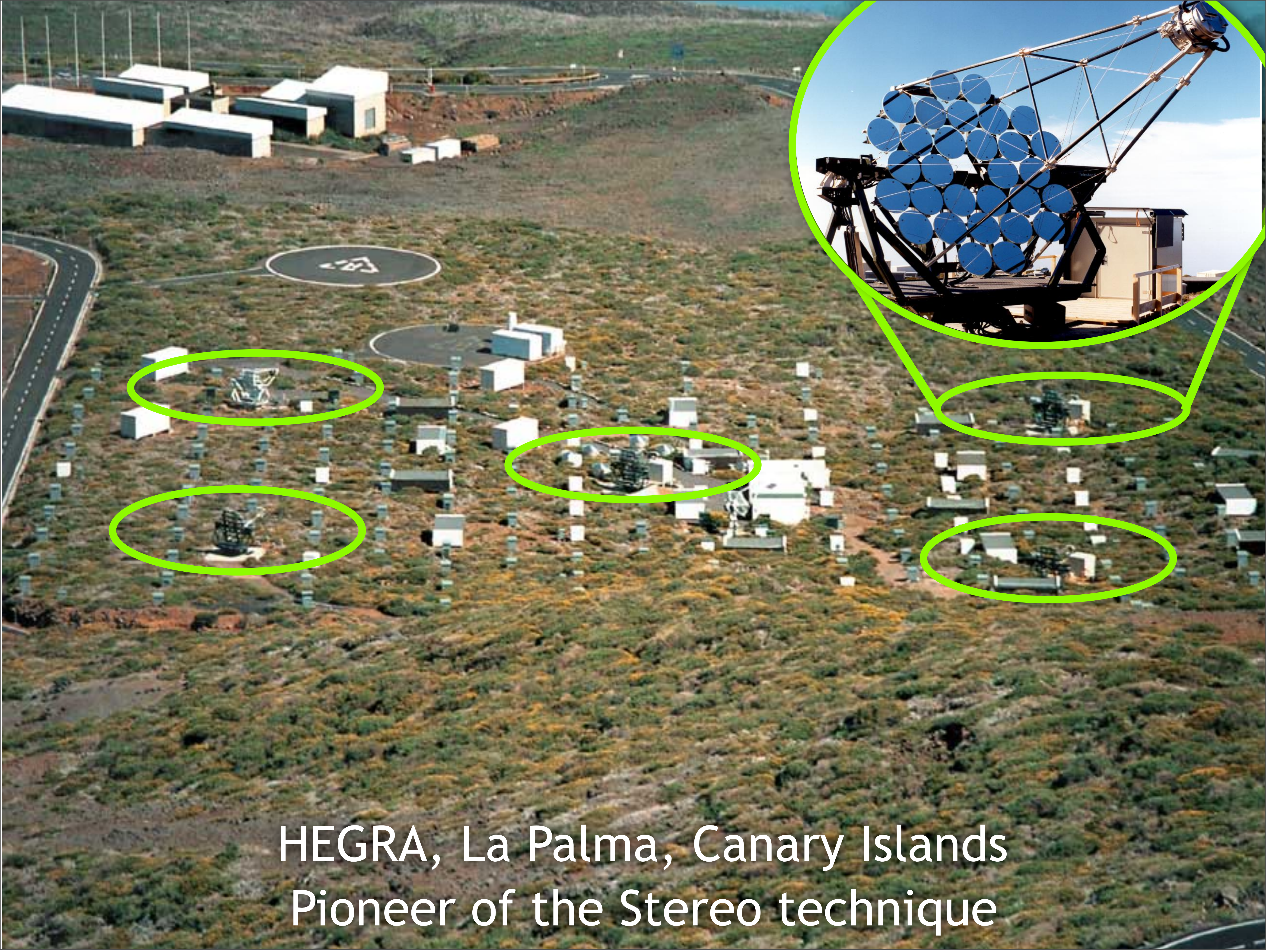

HEGRA, La Palma, Canary Islands
Pioneer of the Stereo technique

Modern Atmospheric Cherenkov Telescopes

Bigger Dishes:

- Image fainter showers, go to lower energies (10s of GeV)
- generally smaller field-of-view than smaller-dish telescopes

or Larger Arrays:

- more smaller dish telescopes allow greater sensitivity at medium to high energies
- Large (5° Fields of view)
  - Obviously you would want the best: lots of big-dish telescopes, but money is always a limitation!
  - Cost increases with size of dish or number of telescopes


MAGIC
VERITAS
H.E.S.S.

Crab Nebula again...

Recall original Whipple detection:

- 5 sigma in 50 hours

Crab with HESS:

- 5 sigma in 30 seconds!

Shower Recon: Analytical Model

Simplest model:

- Assume:
  - the shower is a 3D Gaussian
  - angular distribution of Cherenkov light is only zenith-angle dependent
- Given a set of shower parameters, calculate the predicted images in each pixel of the cameras
- Minimize χ2 between real and predicted images

Fancier models can use some shower physics to give more realistic model

$$q_{\mathrm{th}} = \int_0^\infty n_c(r) r^2 \, \mathrm{d}r \, \Delta\omega_{\mathrm{pix}} I(\varepsilon) \frac{S_{\mathrm{tel}} \cos\theta}{r^2}$$

$$= S_{\mathrm{tel}} \Delta\omega_{\mathrm{pix}} I(\varepsilon) \cos\theta \int_0^\infty n_c(r) \, \mathrm{d}r. \qquad (1)$$

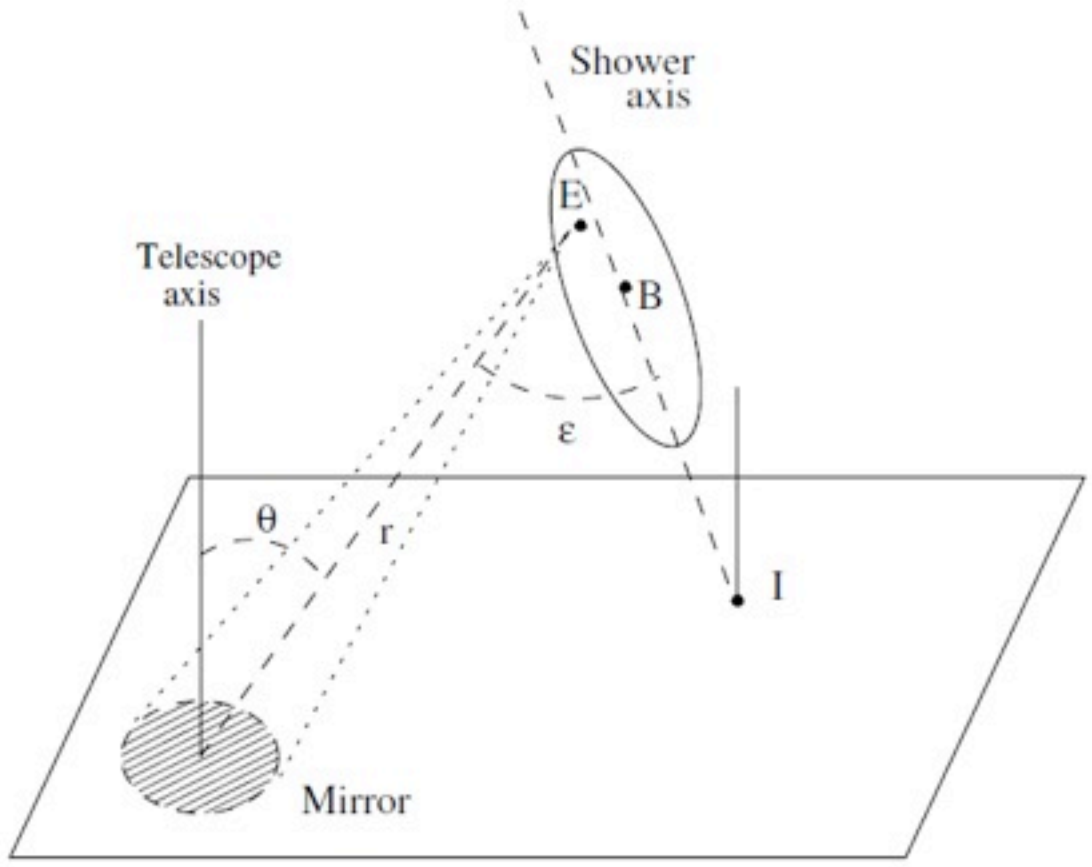
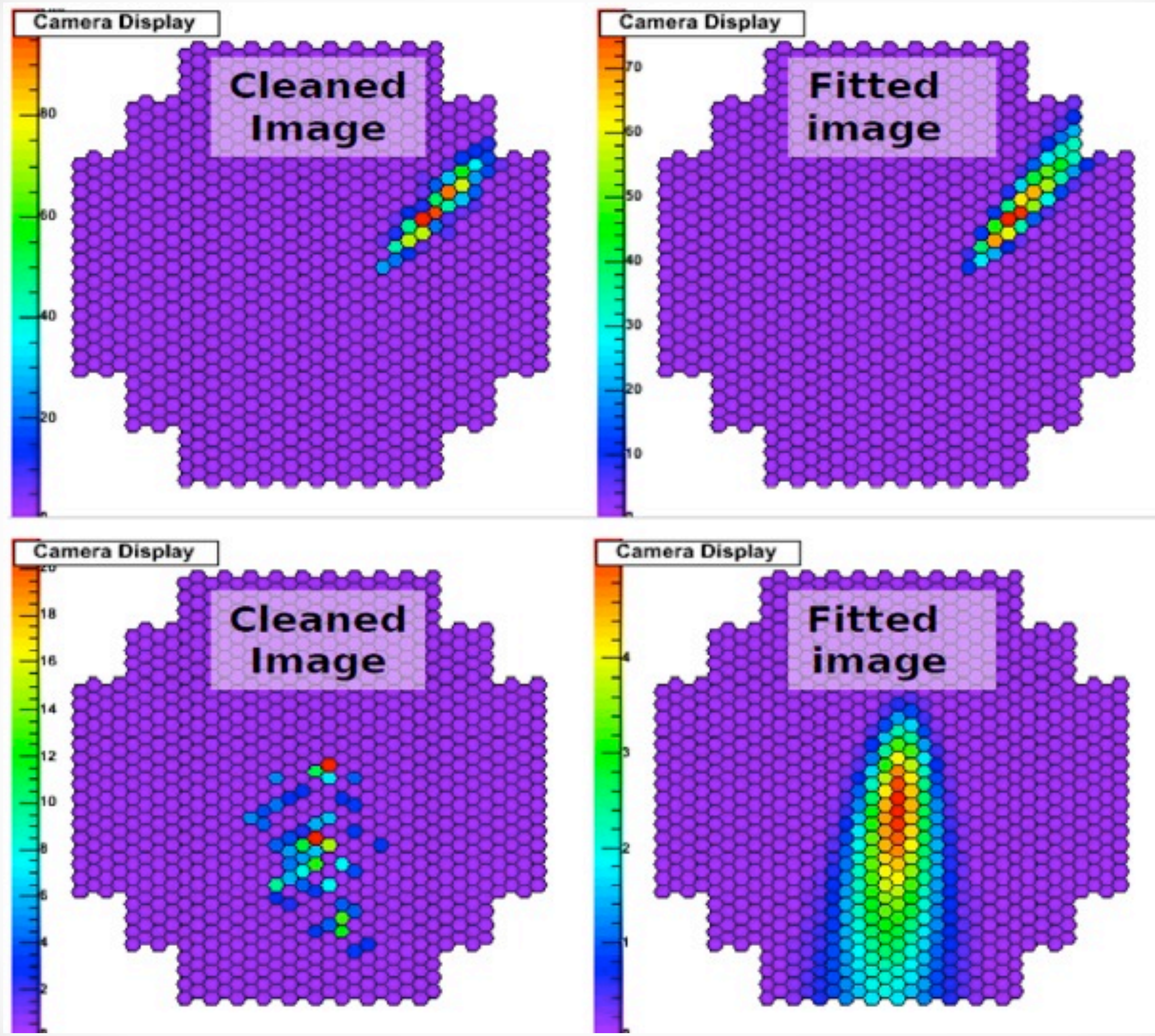


Fig. 4. Calculation of the expected number of collected photons in a pixel, as a function of the shower parameters.

Gamma Ray:

Hadron:



Y. Becherini

Recon: Simulation Templates

We have full, detailed, first-principle shower simulations... why not use them?

- Build a set of shower profiles: (longitudinal, latitudinal, angular) using simulations
- Take into account varying:
  - Optical efficiency
  - Atmospheric absorption
  - Detector calibration (missing pixels, etc)
  - NSB noise in each pixel
  - Detector properties (QE, PSF, etc)
  - Pointing direction (Zenith angle, azimuth)

Simulation Templates

Generate database of shower template images as a function of:

- Primary Energy
- Interaction Depth
- Zenith Angle
- Azimuth angle wrt B field
- Impact distance
- Position in camera

In the end: **1M shower image templates**

- All are for on-axis shower, can translate for off-axis

Simulation Templates

Define:

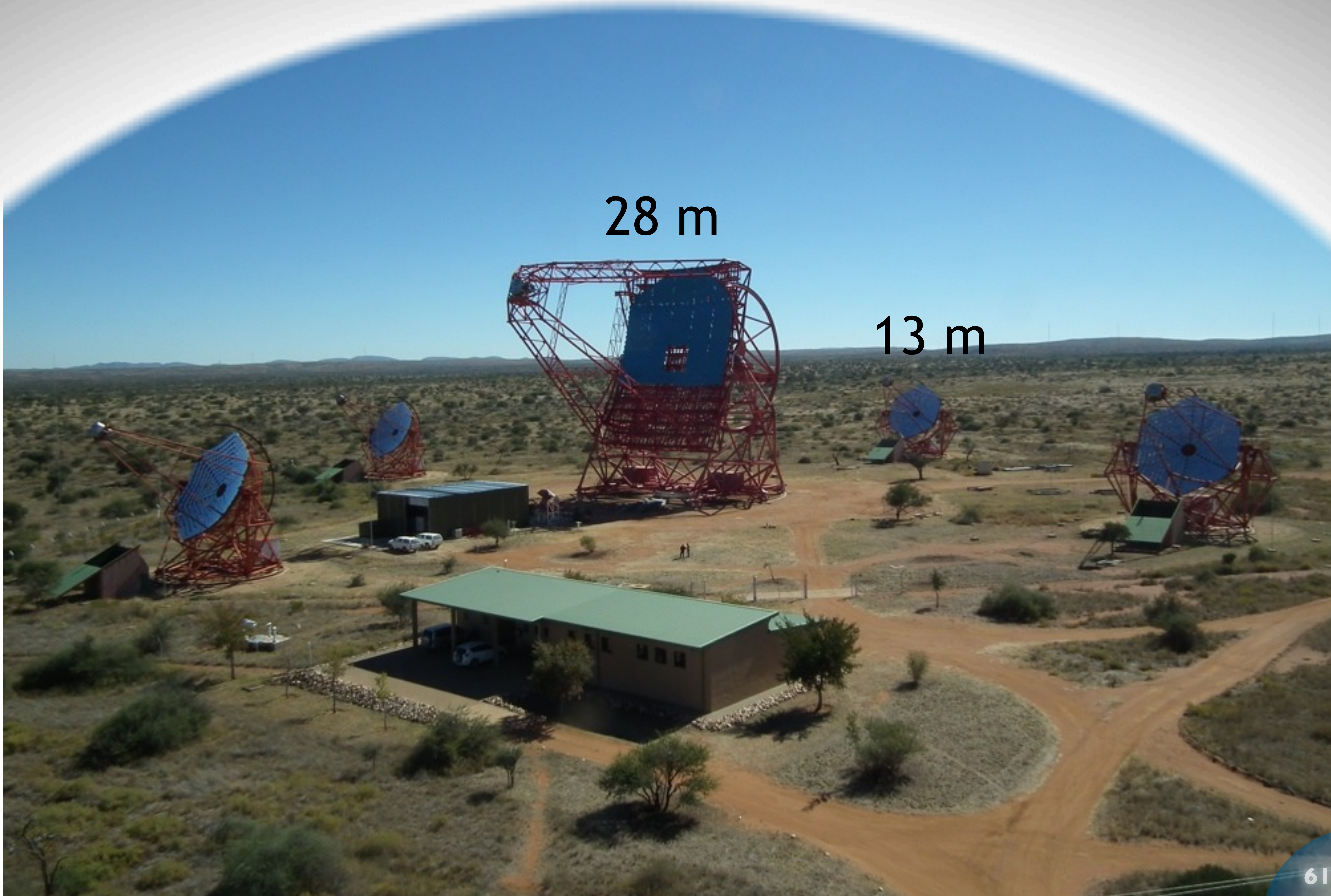
- Pixel log(likelihood):
  - probability that the pixel fits the template,
  - taking into account NSB level, electronic noise pedestals, etc (no "image cleaning" needed: raw images)
- Telescope log(likelihood):
  - probability that the full image fits a template
- Goodness of fit (combination of the two likelihoods)

Minimize the likelihoods and extract goodness

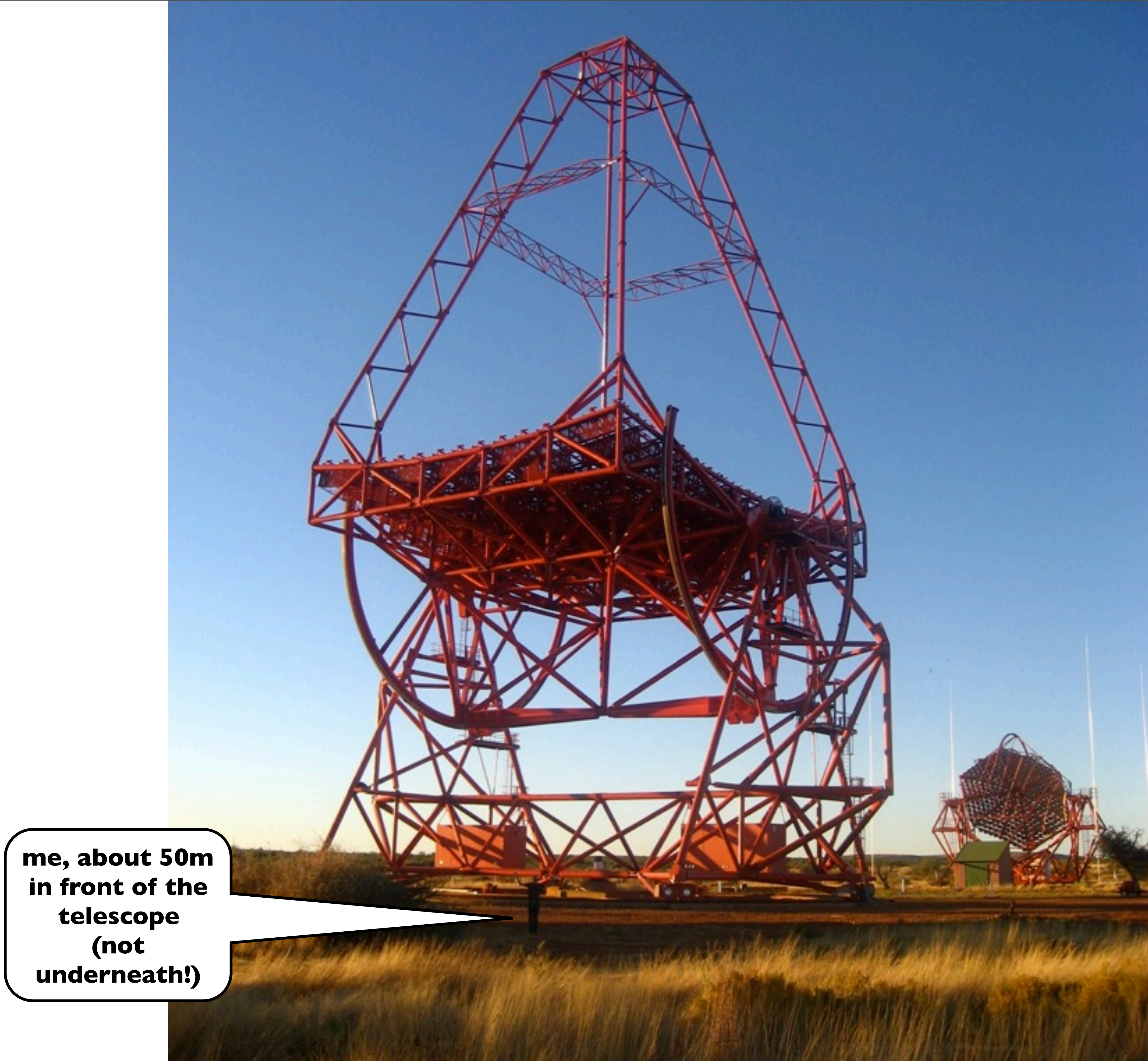
- Final result uses all information avilable from the simulations
- "goodness" is a hadron discrimination parameter that works well
- **advantage**: use all info about NSB levels, instrumental performance, has low energy threshold!
- **disadvantage**: large CPU and memory requirements

Upcoming and Future IACT Instruments

HESS-II: July 2012!



HESS-II: July 2012!


me, about 50m
in front of the
telescope
(not
underneath!)

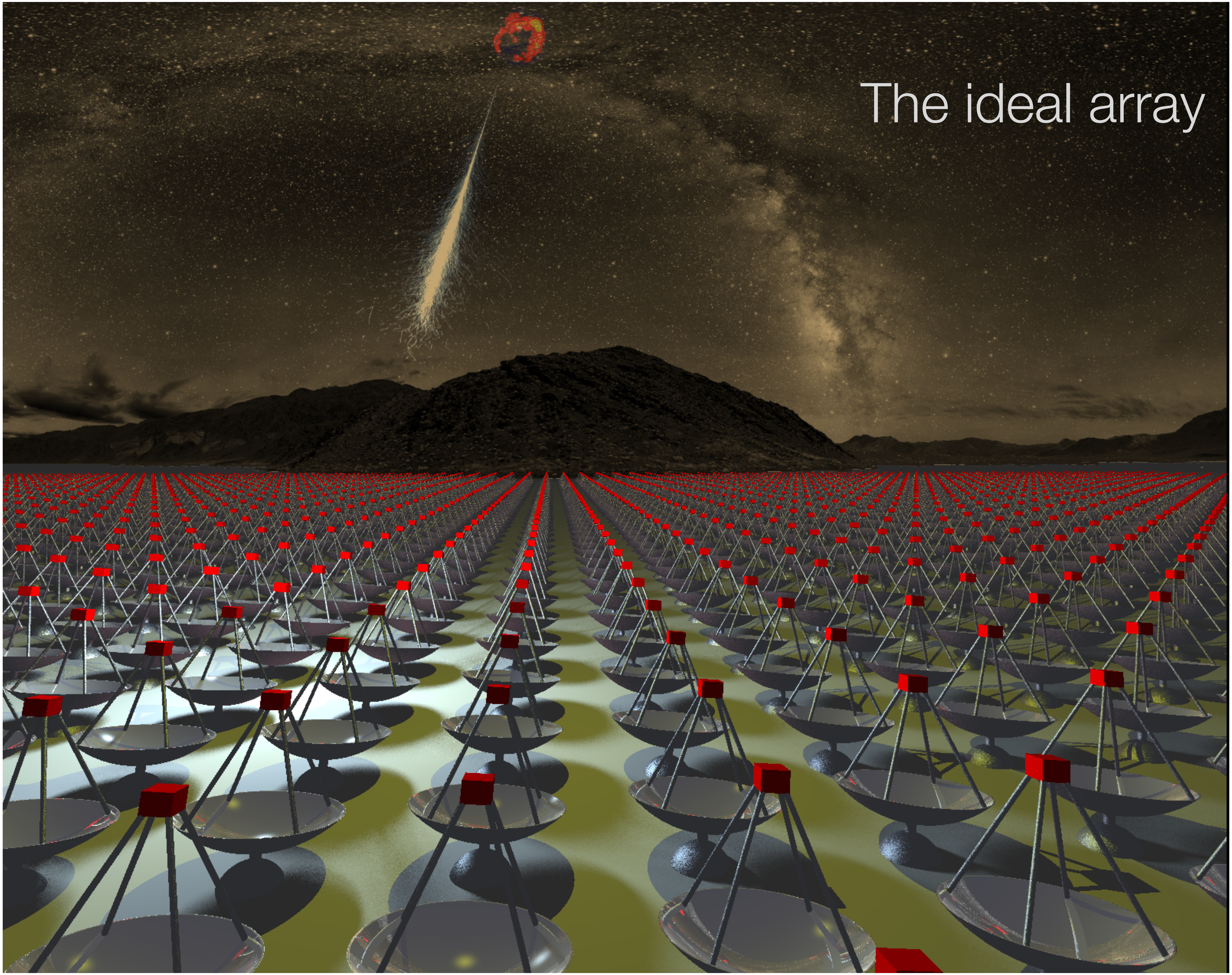
CTA: 2014+

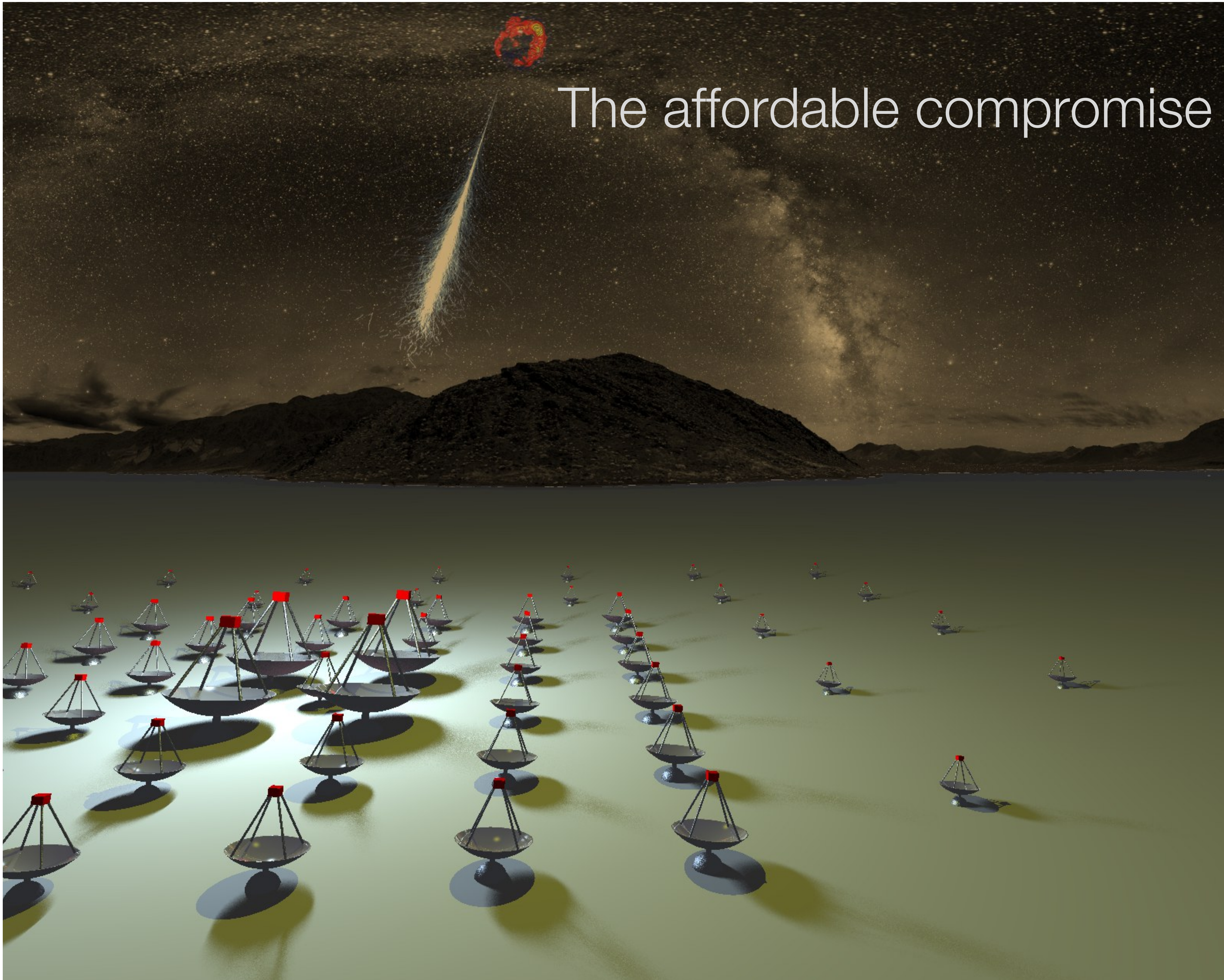
Next Generation Instrument:

- want **10x sensitivity** of current telescopes in core energy range, and similar at low and high energies
- want better angular resolution

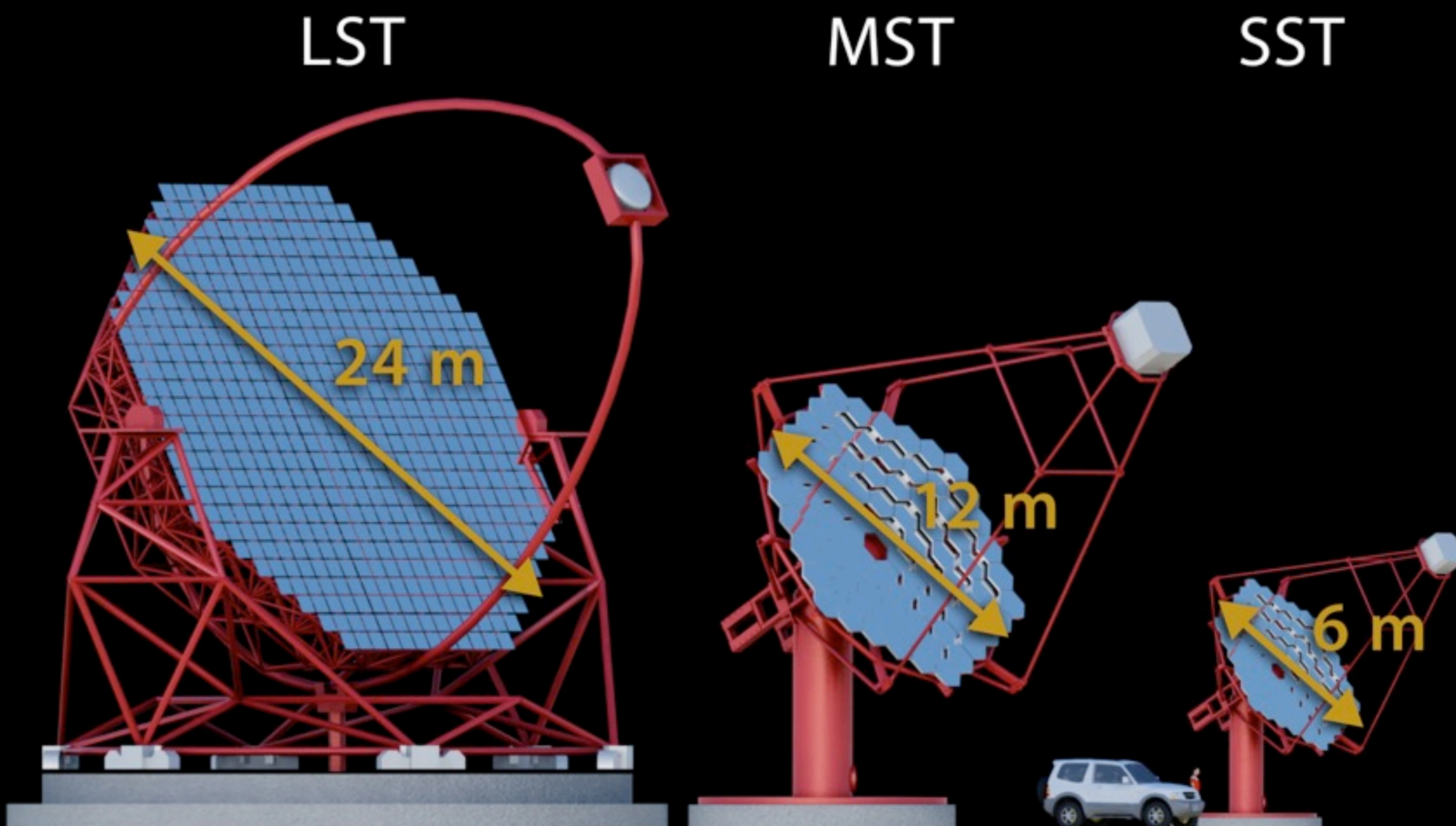
How to achieve it:

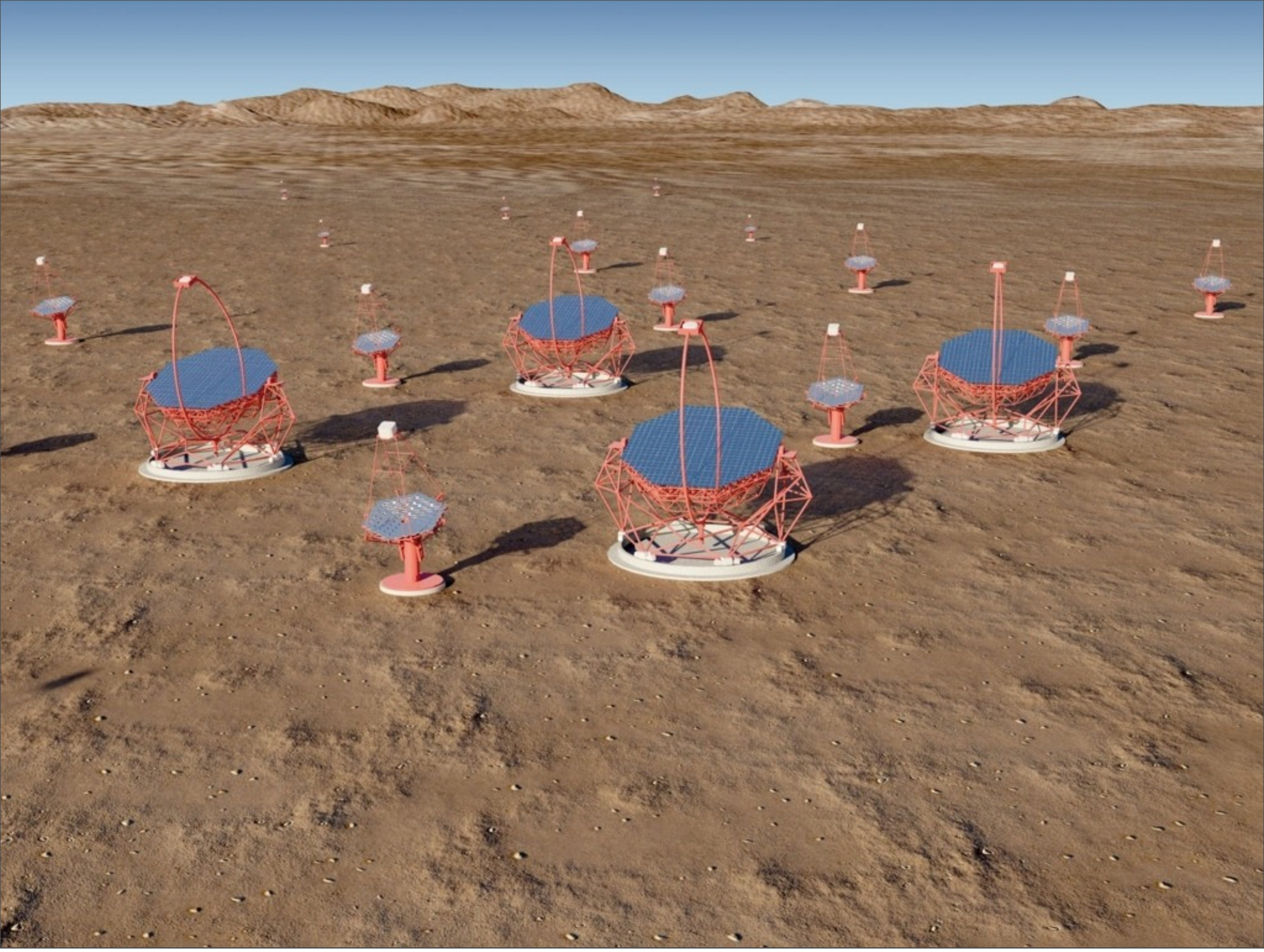
- Many telescopes over square kilometer: **bigger effective area**
- More Larger telescopes: **Lower energy threshold**
- Telescopes closer packed: **better angular resolution**

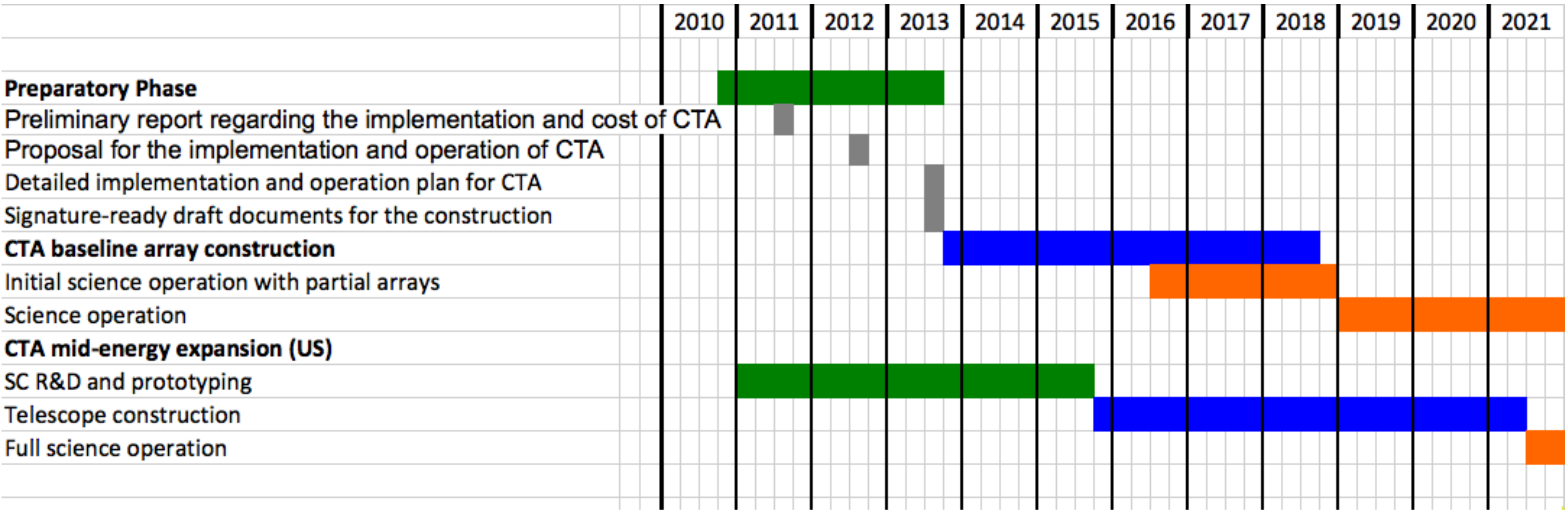

The ideal array


The affordable compromise


cta
cherenkov telescope array


LST
MST
SST
24 m
12 m
6 m




2010
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2016
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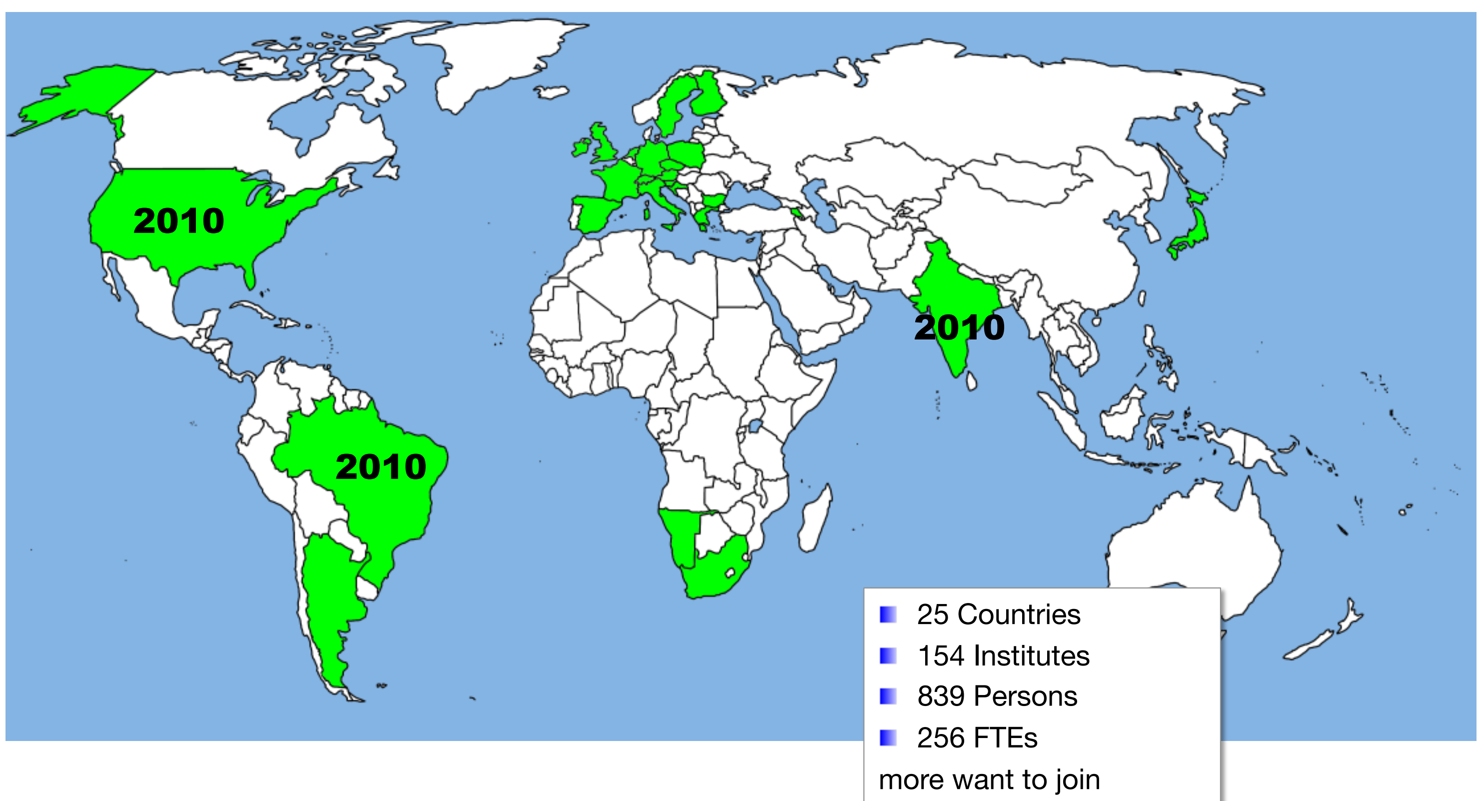
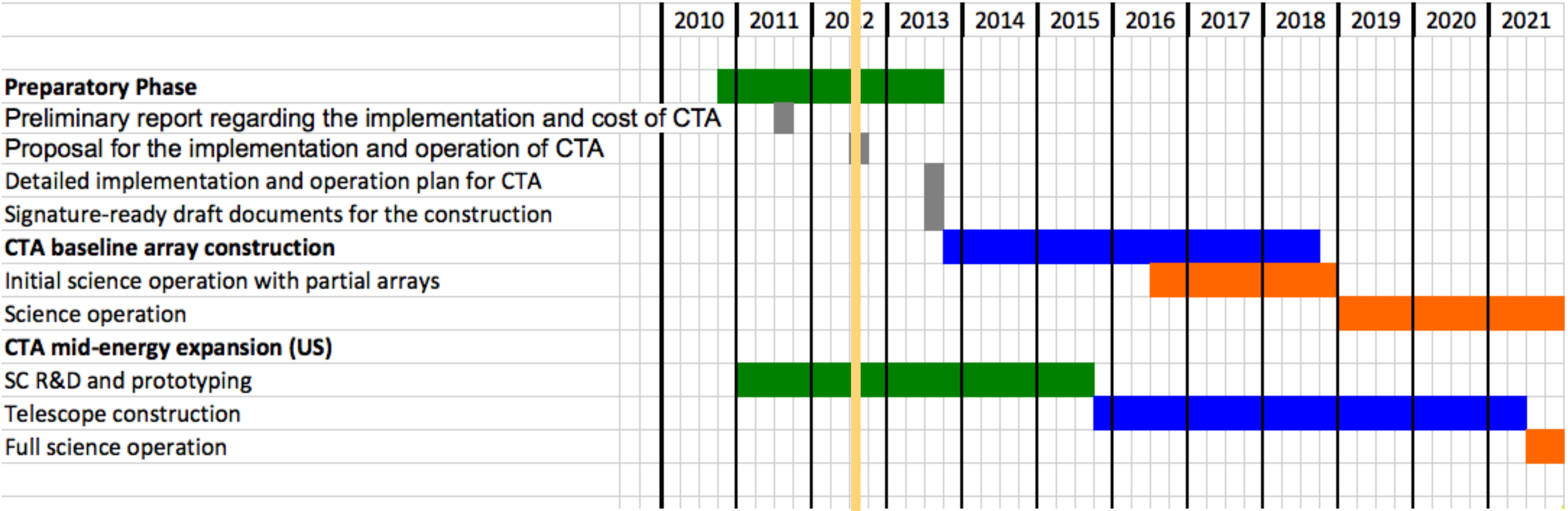
2018
2019
2020
2021
Preparatory Phase
Preliminary report regarding the implementation and cost of CTA
Proposal for the implementation and operation of CTA
Detailed implementation and operation plan for CTA
Signature-ready draft documents for the construction
CTA baseline array construction
Initial science operation with partial arrays
Science operation
CTA mid-energy expansion (US)
SC R&D and prototyping
Telescope construction
Full science operation


2010
2010
2010
25 Countries
154 Institutes
839 Persons
256 FTEs
more want to join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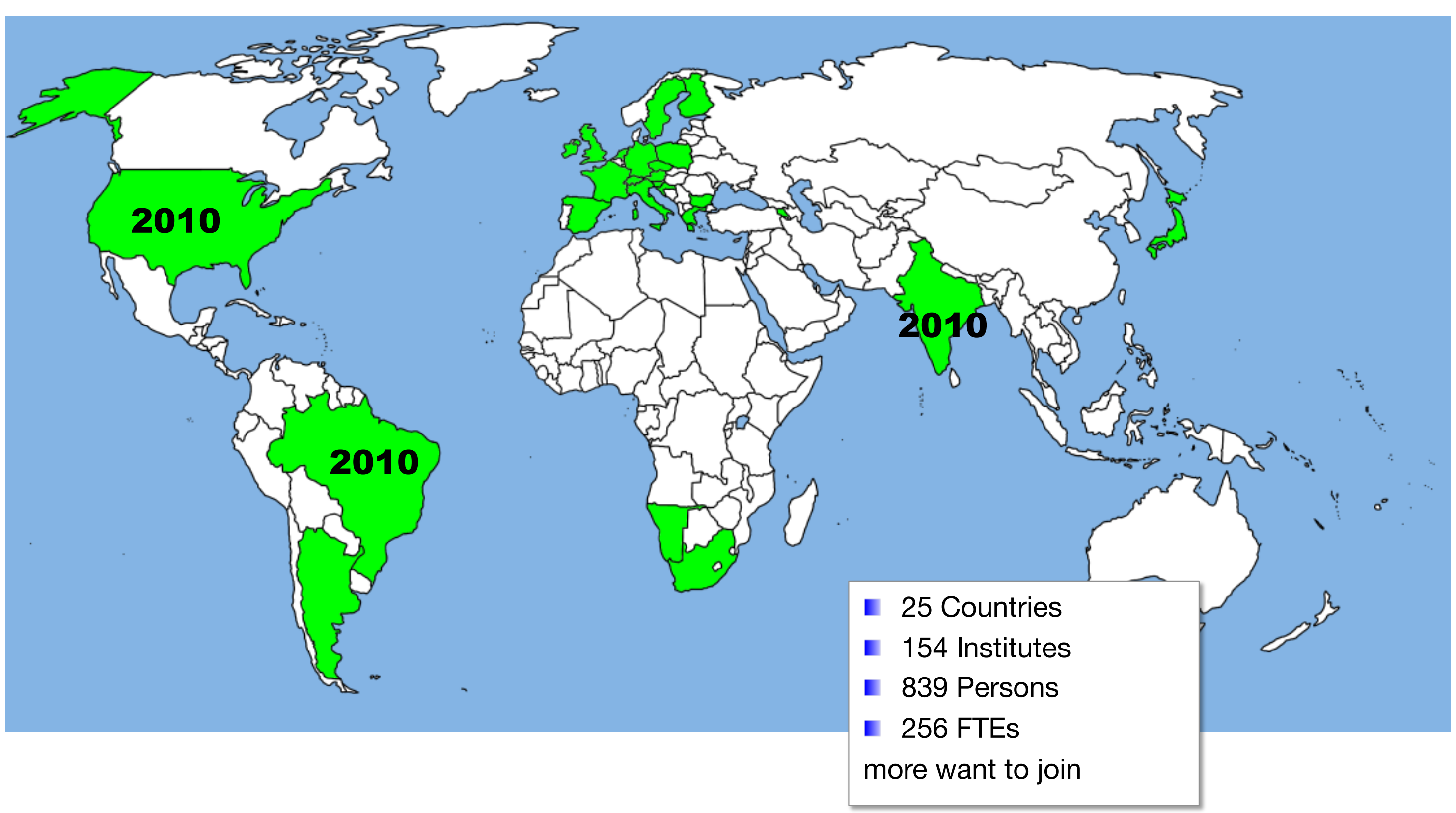
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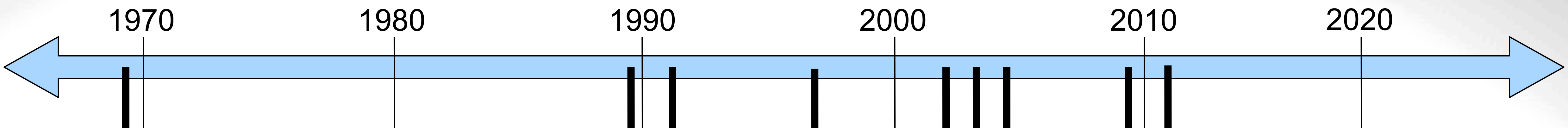


20XX: CTA

1968: Whipple 10 M Telescope Constructed (single-pixel-camera)

1989: Whipple 10 M Detects 1st Gamma-ray source! (The Crab Nebula, Weekes et al)

Thanks to the *imaging technique* (multiple pixel camera)

1992: HEGRA CT1, CANGAROO-I Begin operation
1996: HEGRA *stereo array*

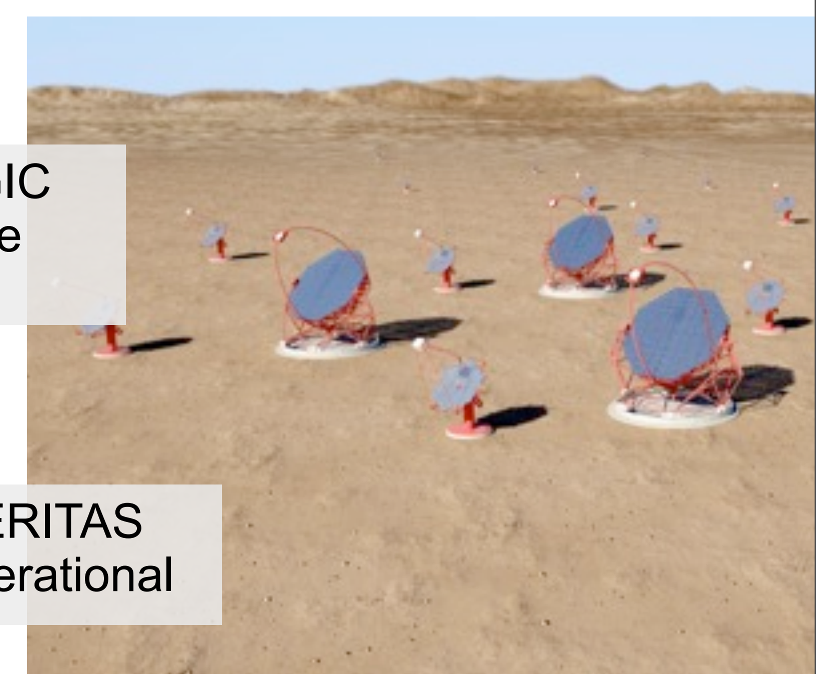
2003: HESS Begins stereo (4-tel) operation

2004: MAGIC (large single telescope)

2005: VERITAS Array operational

2009: MAGIC II

2012: HESS II



Note: this simplified timeline does not incude several other Cherenkov telescopes (CAT, Mark-II, Tactic) as well as wavefront-sampling telescopes (PACT, HAGAR)

Historical Summary

Number of detected sources: 0 — 1 — ≈10 — ≈30 — ≈100 — 1000?

1970 — 1980 — 1990 — 2000 — 2010 — 2020

1968: Whipple 10 M Telescope Constructed (single-pixel-camera)

1989: Whipple 10 M Detects 1st Gamma-ray source! (The Crab Nebula, Weekes et al)

Thanks to the *imaging technique* (multiple pixel camera)

1992: HEGRA CT1, CANGAROO-I Begin operation
1996: HEGRA *stereo array*

2003: HESS Begins stereo (4-tel) operation

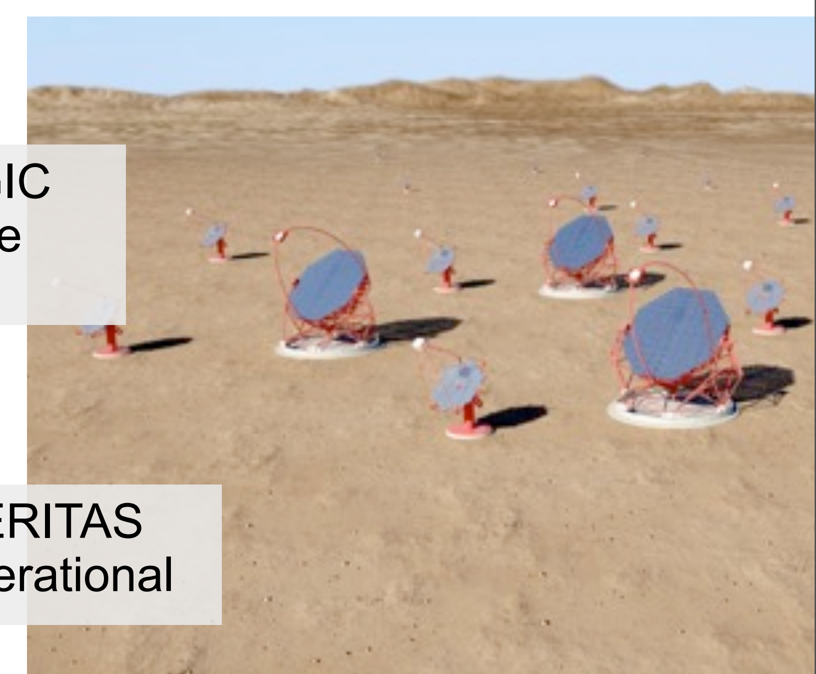
2004: MAGIC (large single telescope)

2005: VERITAS Array operational

2009: MAGIC II

2012: HESS II

20XX: CTA



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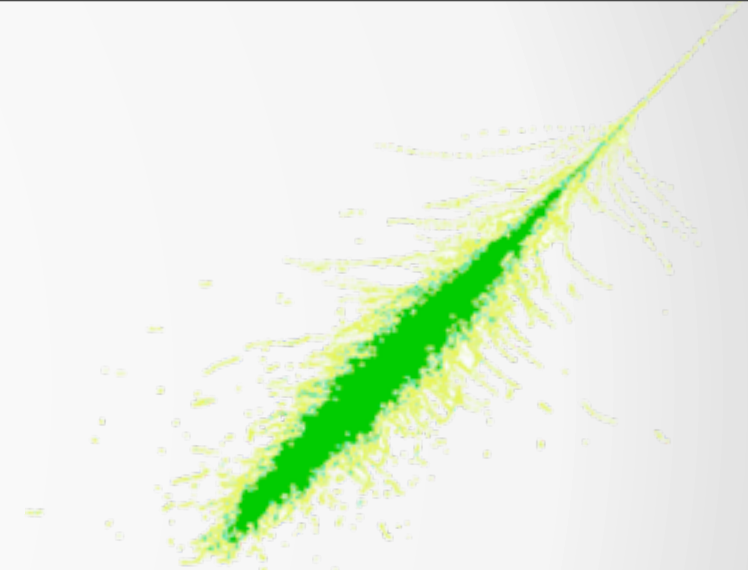
The imaging technique made detecting VHE gamma-rays possible

- Took 20 years to go from idea to detection!
- Only the brightest sources were visible (a handful up until 2003), most ~1 Crab flux

The stereo technique + larger telescopes made VHE Astronomy possible

- Better background rejection and higher sensitivities
- Now have nearly **100 sources! 1% Crab!**



Other Methods

Water Cherenkov Telescopes

Wavefront sampling telescopes

Other Methods

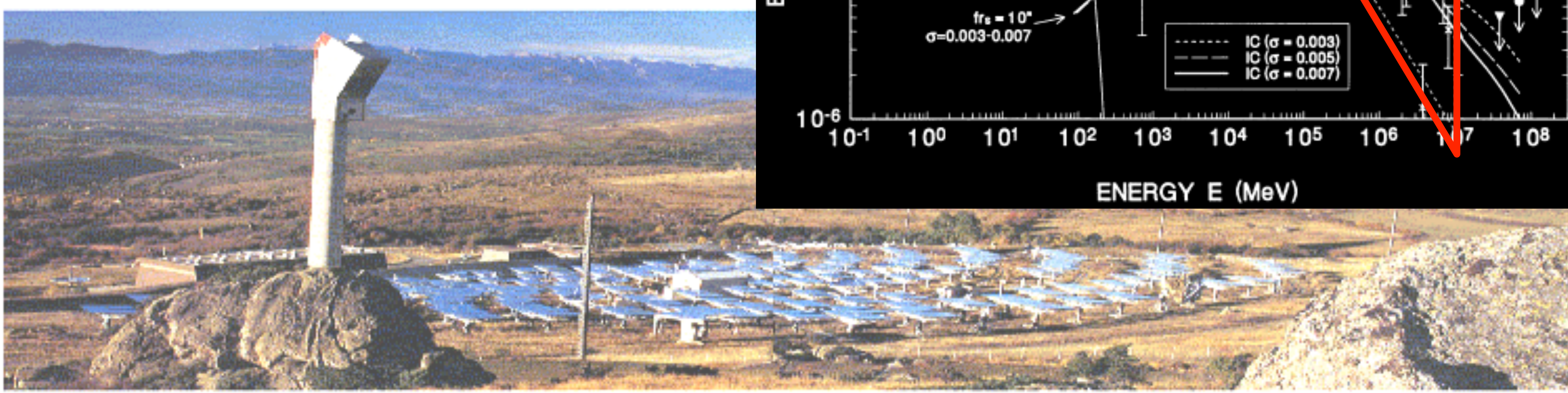
Water Cherenkov Telescopes

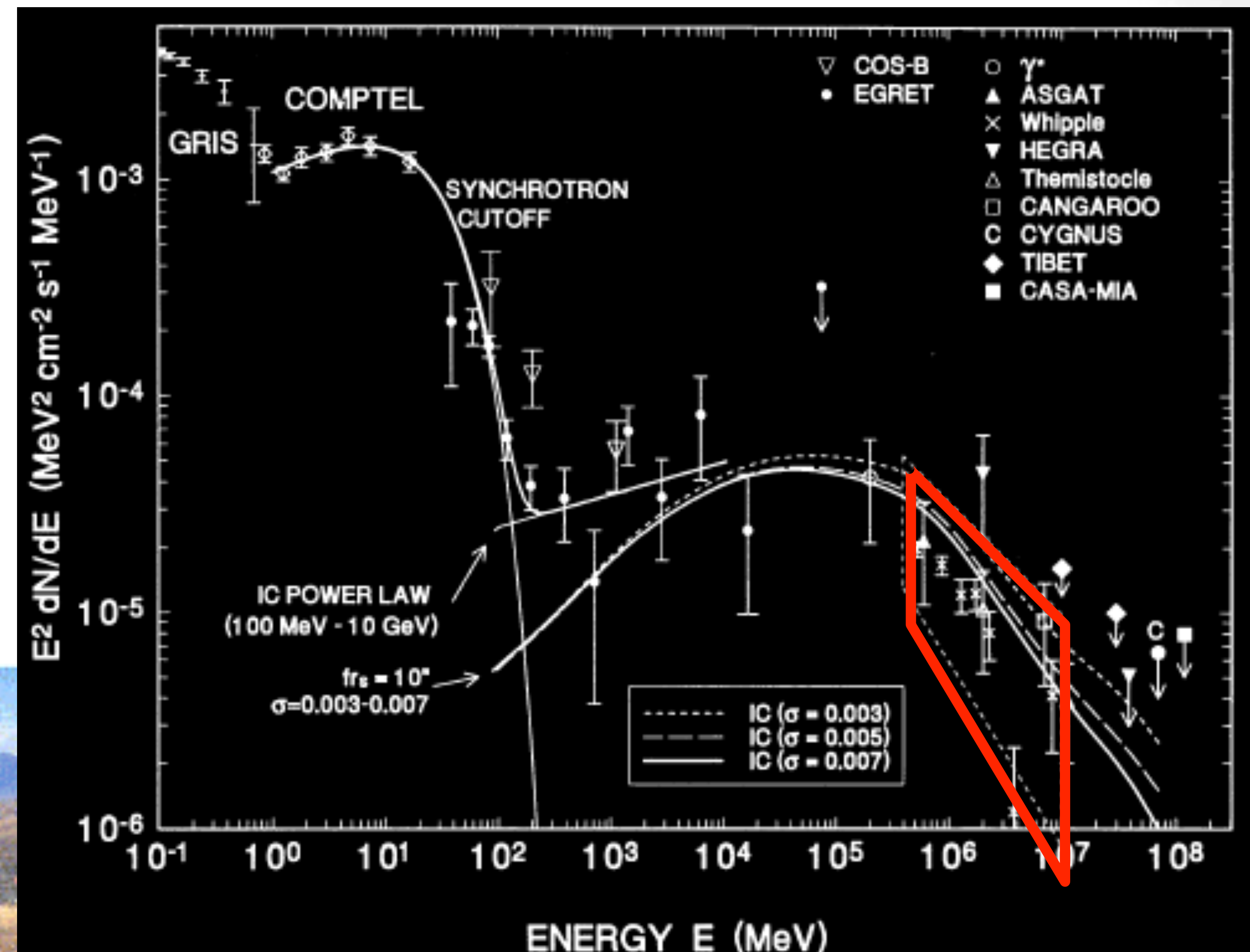
Wavefront sampling telescopes

Solar Towers

Pioneered here in France (Themistocle)

(Stacee, in US)



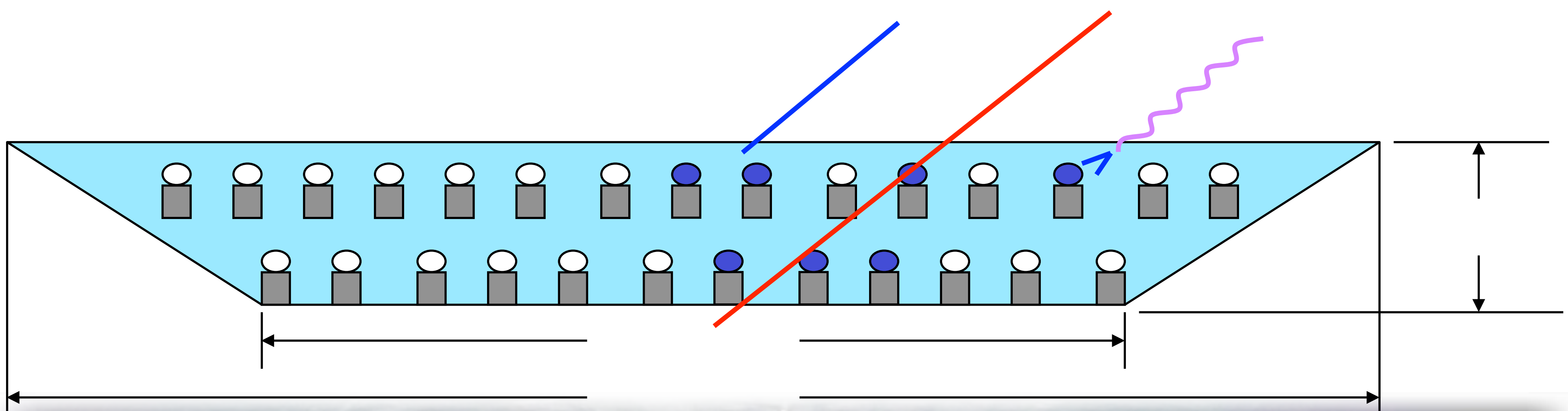


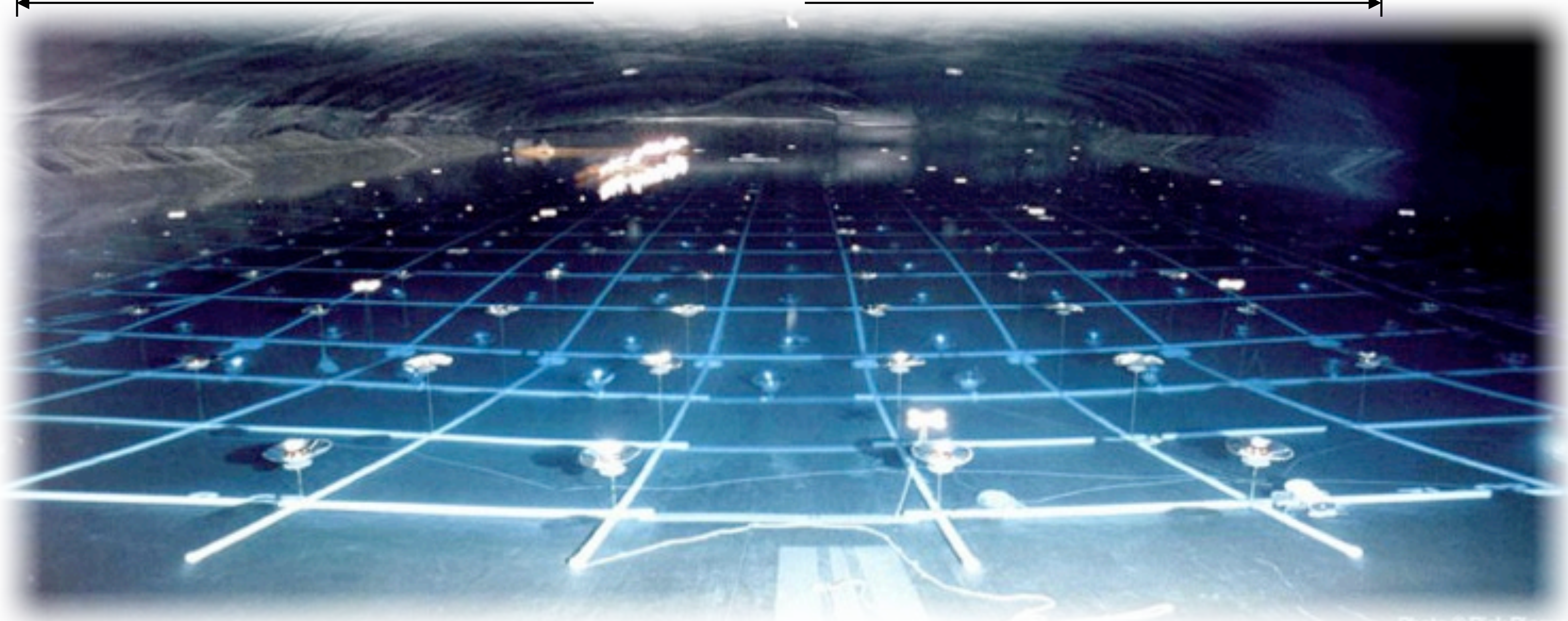
Water Cherenkov Telescopes

As in atmosphere, the particles in a shower will create Cherenkov light as they pass through water

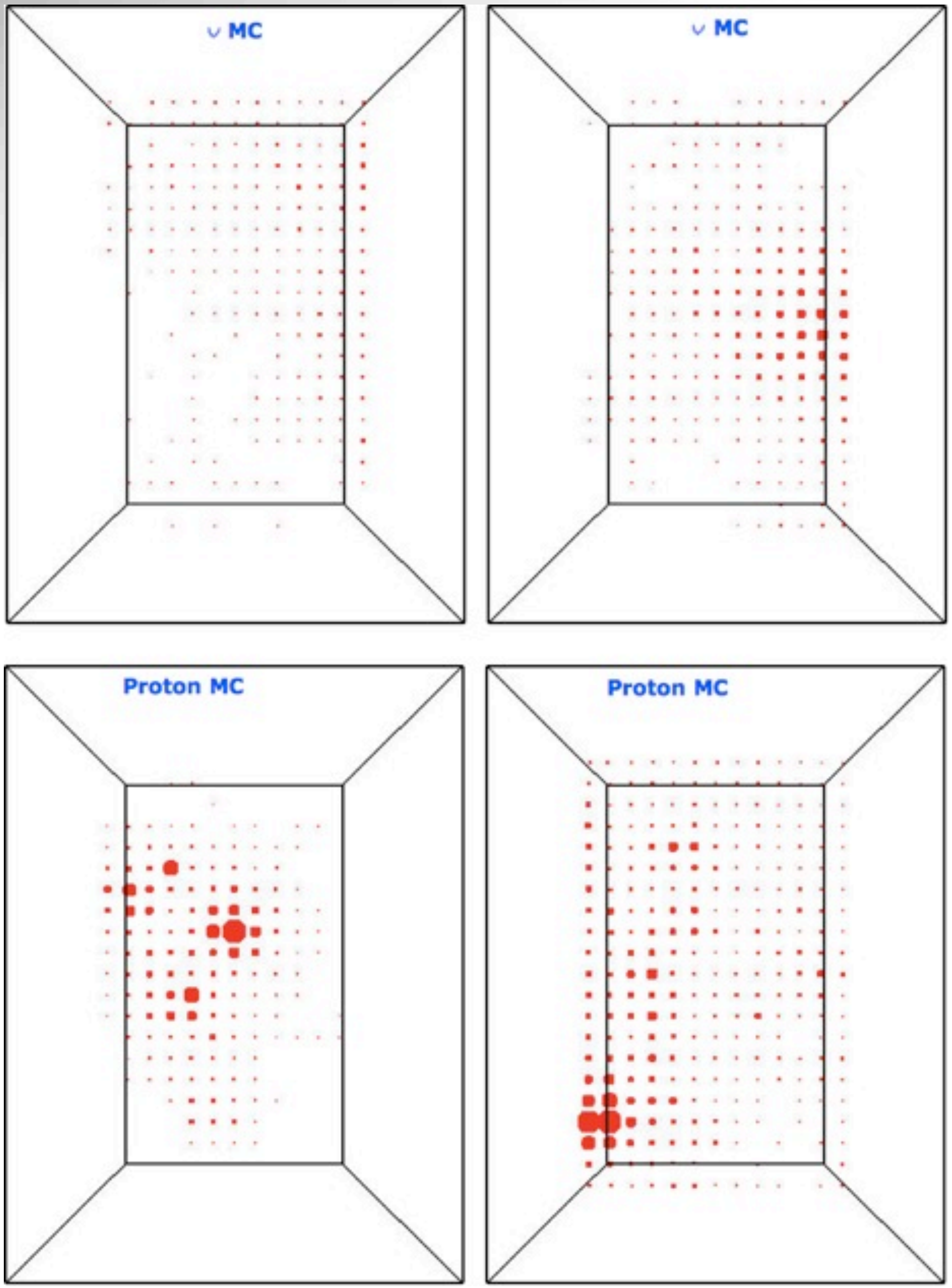
- an easier to control detector: fully contained water tank, with photomultiplier tubes inside
- only sees the electrons/positrons generated in the shower that strike the detector (at ground level)
- Therefore need a detector that is large area on ground

Milagro





Background Rejection



Water Cherenkov Telescopes

Advantages:

- Works in the day time! (high duty cycle)
- no moving parts
- Large FOV compared to pointed telescopes

Disadvantages:

- poor energy and spatial resolution
- very high energy threshold (>TeV)

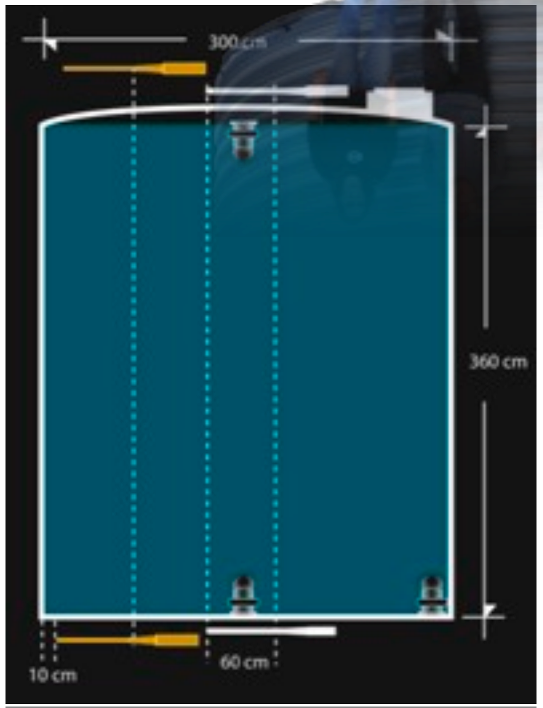
HAWC

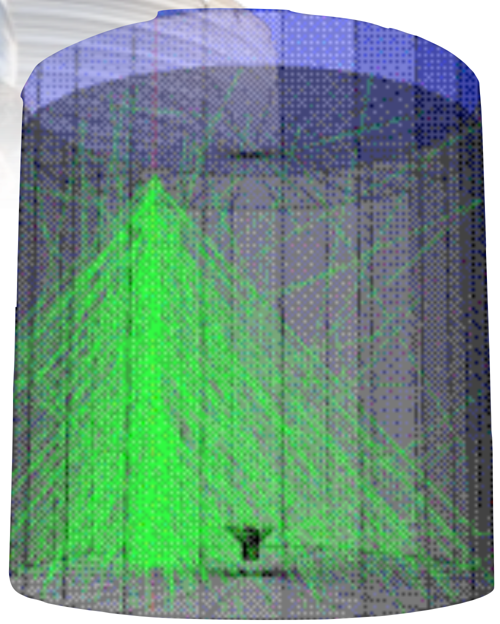
900 3m plastic water tanks or 300 larger 7.5m tanks

- No “pond” as with Milagro
- each tank is isolated
- Milagro front-end electronics + new trigger

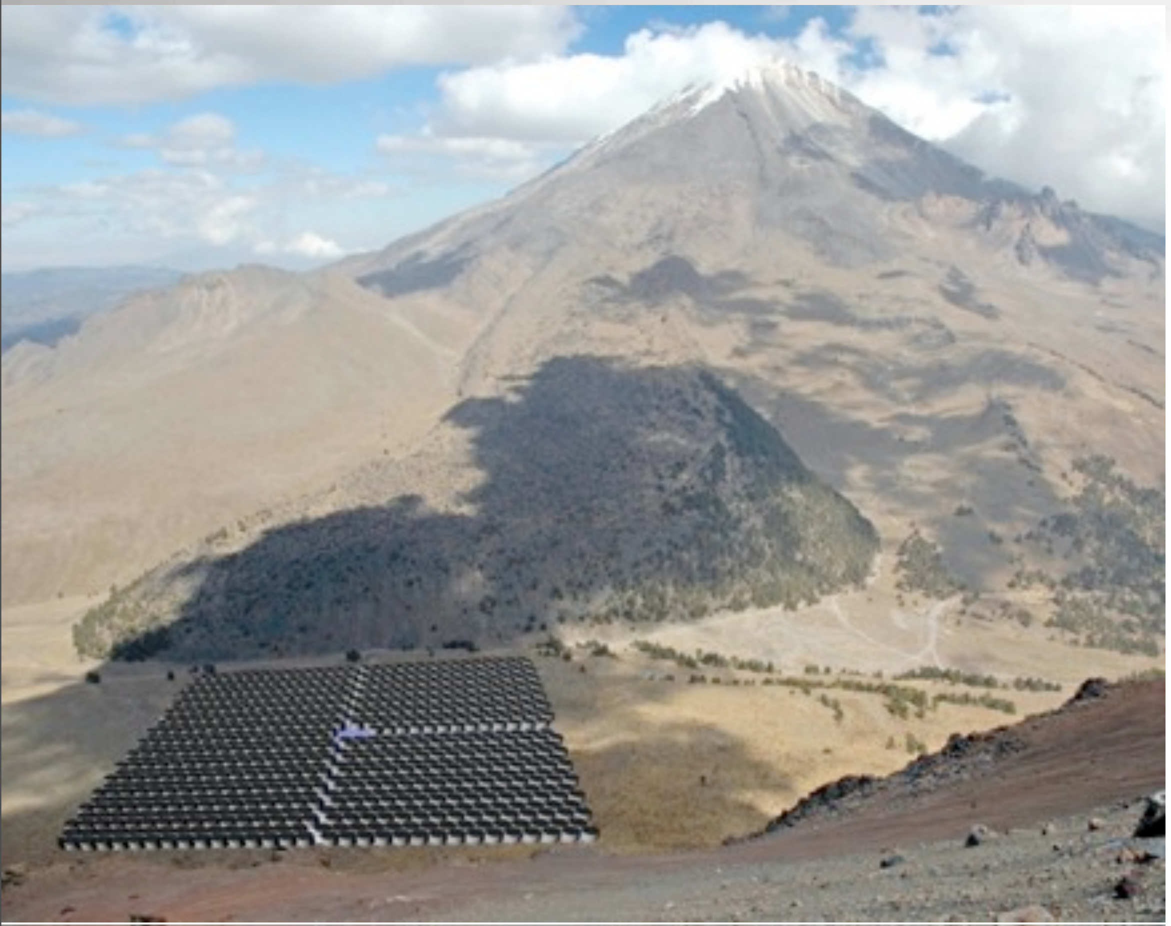
Performance

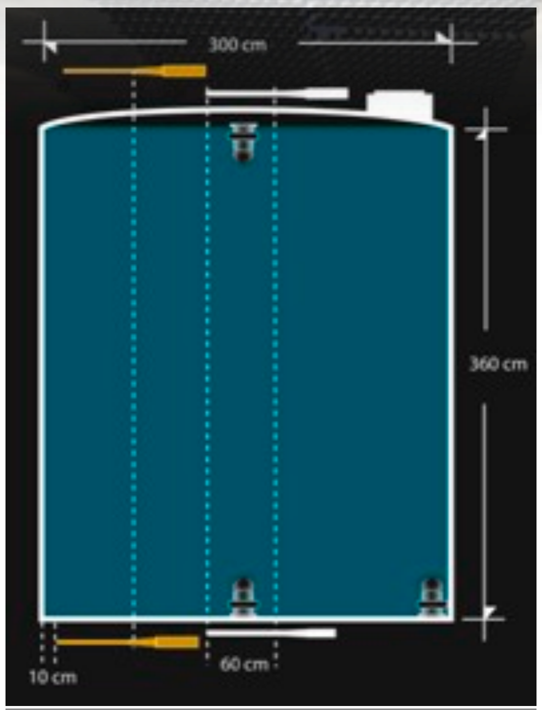
- Very wide field of view (full sky in hemisphere)
- Continuous observation and monitoring
- Low angular res/sensitivity compared to pointed telescopes

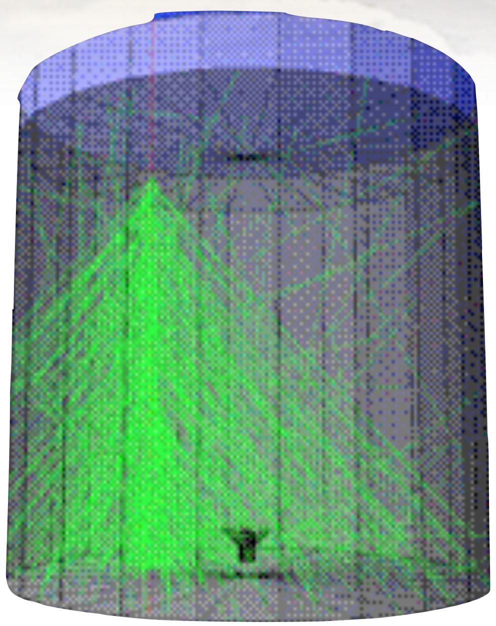




HAWC







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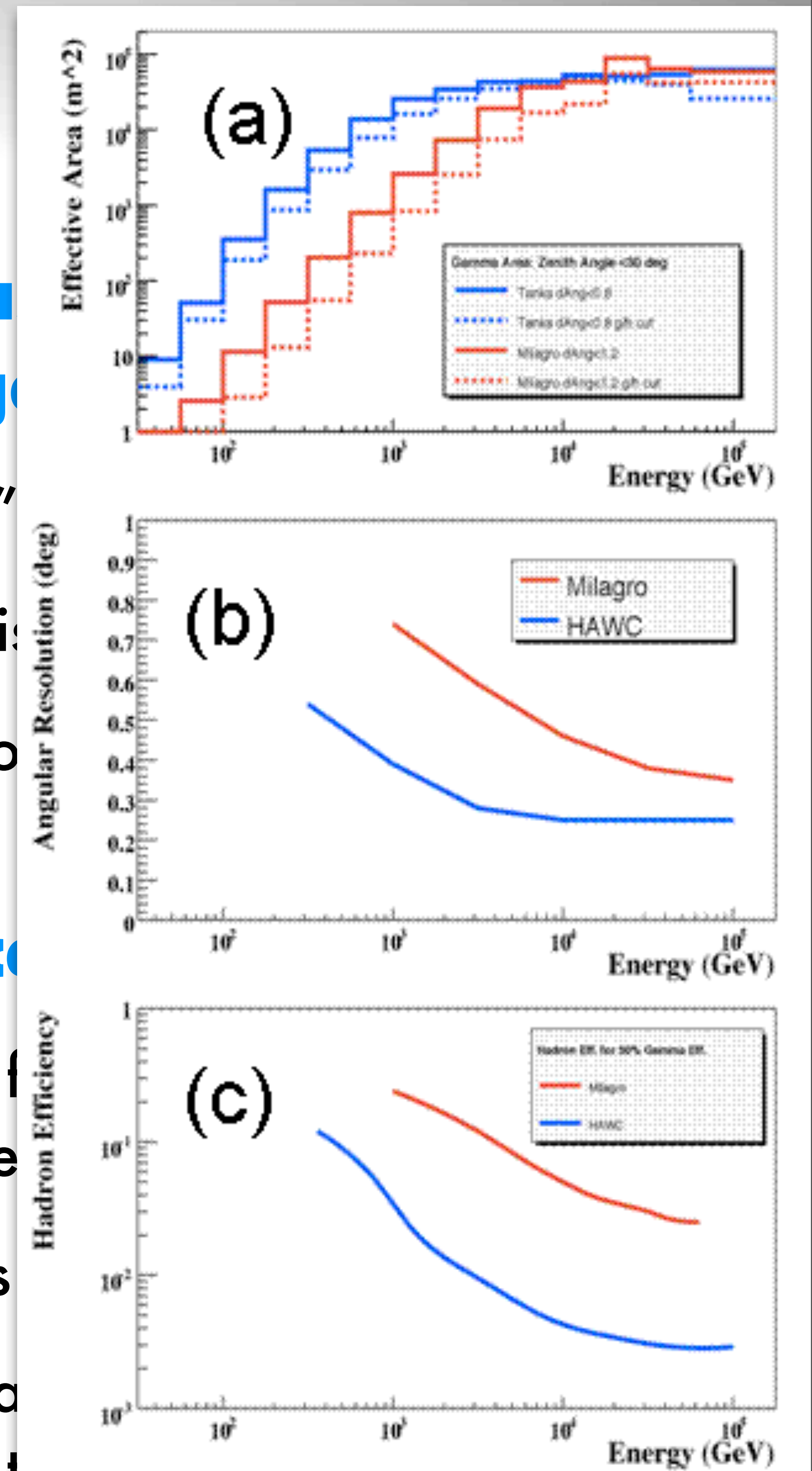
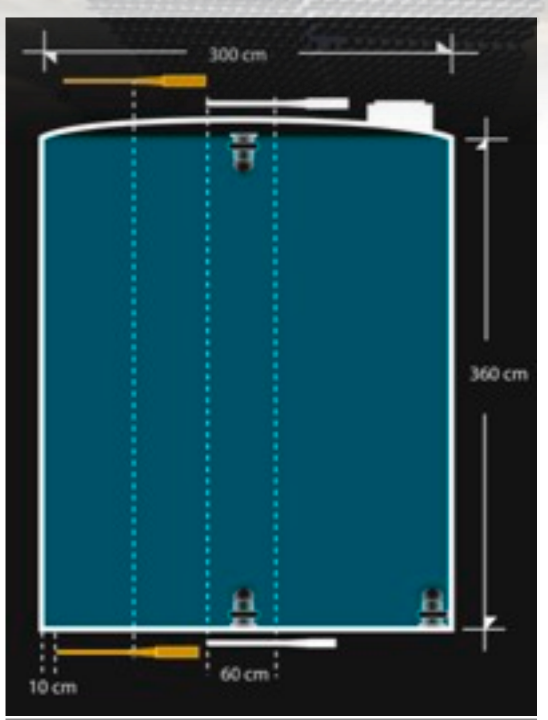
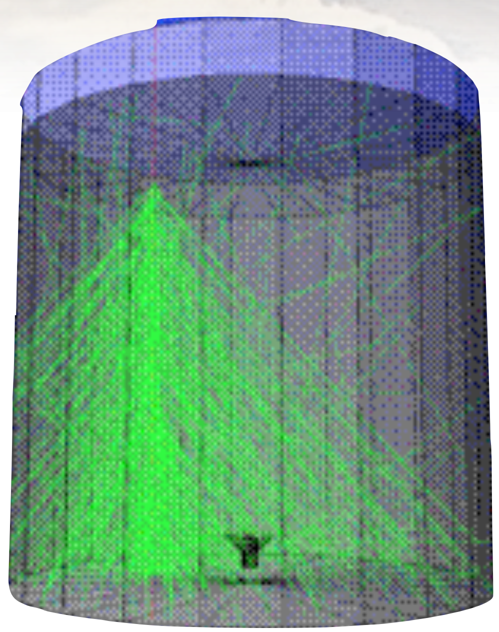
- Very wide f hemisphere
- Continuous
- Low angula to pointed telescopes







Comparison

	Atmospheric Cherenkov Telescopes (ACTs)	**Water Cherenkov Telescopes (WCTs)**
Cherenkov medium	Atmosphere / particles in shower	Water / particles at ground-level
Direction Reconstruction	Via 3-D imaging of shower	From timing
Energy Reconstruction	Atmosphere as calorimeter, good energy resolution, (spectra)	poor energy resolution (total flux)
Hadron rejection	via image shape, stereo fit	distribution of secondaries, muon veto layer
Sensitivity	**high**	low
Energy Range	**Wide** (50 GeV - 100 TeV)	> few TeV
Angular resolution	**high** (<0.1°)	low (≈ 0.5°)
Duty cycle	low (nightime, good weather)	**high** (operates in daylight too)
Field-of-view	2-6°	**50°** (equiv)

Analysis

We've detected them.... now what?

Previously:

We know how to detect showers from *gamma rays* and *cosmic rays*

We can reject a large fraction of the cosmic rays via the stereo trigger and imaging technique

BUT: we are still left with a mixture of

- gamma rays from our source
- background gamma rays
- electrons
- gamma-like hadrons
- gamma-like muons

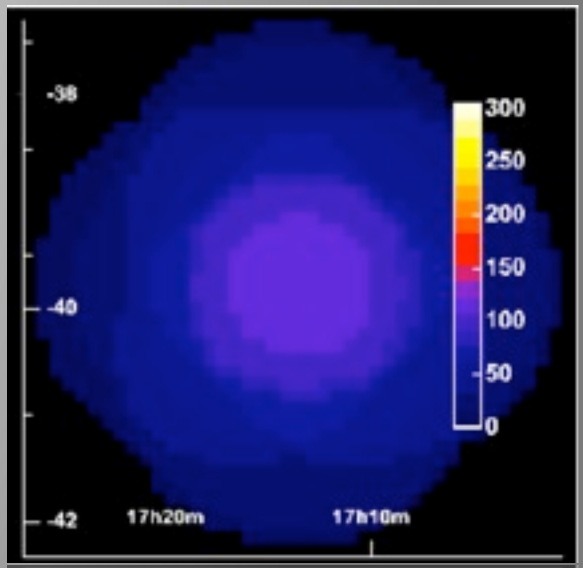
Gamma-Hadron separation:

- separation of cosmic-ray-like from gamma-ray-like shower events
- reduces the cosmic ray background significantly, but does not eliminate it

Background modeling

- determination of the characteristics of the residual cosmic-ray background in the gamma-ray-like sample
- allows the calculation of a gamma-ray signal on a statistical basis (never event-by-event)

Some terminology



Modern methods of gamma-hadron separation

The various reconstruction methods all provide parameters that can help distinguish signal from background

- goodness of model fit
- mean scaled width
- difference between reconstructions at multiple cleaning thresholds, etc.

Phase space is quite large!

- simple "box" cuts on each parameter quickly become complicated

Leveraging all this information requires multi-variate analysis techniques

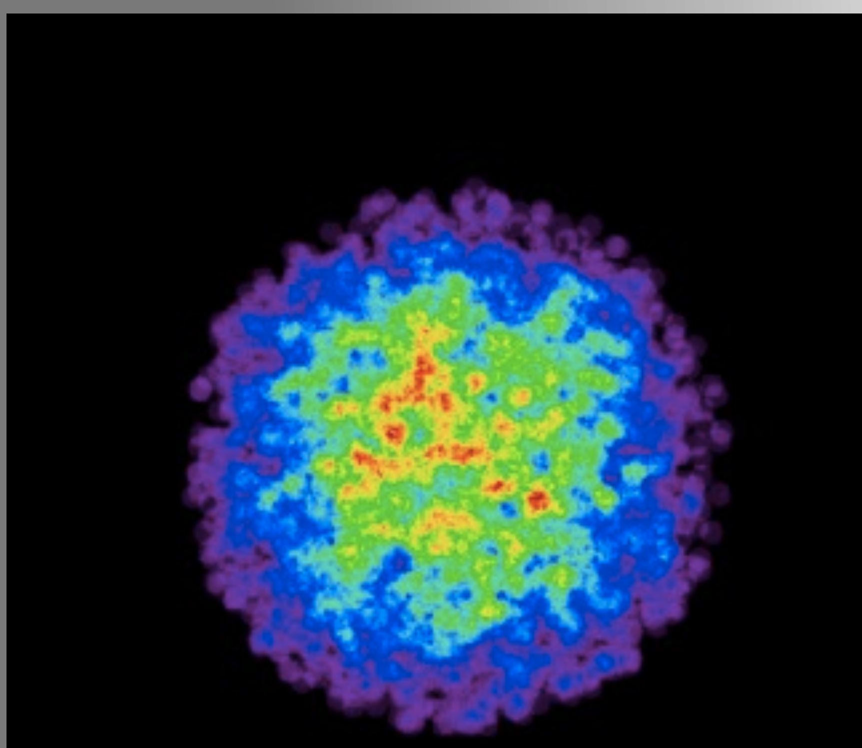
Like the Fermi analysis, need to select a weak signal over a large background using large parameter space:

- Boosted Decision Trees
- Neural Networks
- other multi-variate tools

Multivariate optimization

Background components

Events for a 28min exposure, with no source



Again, even after effective gamma/hadron separation, one is always left with a large residual background level

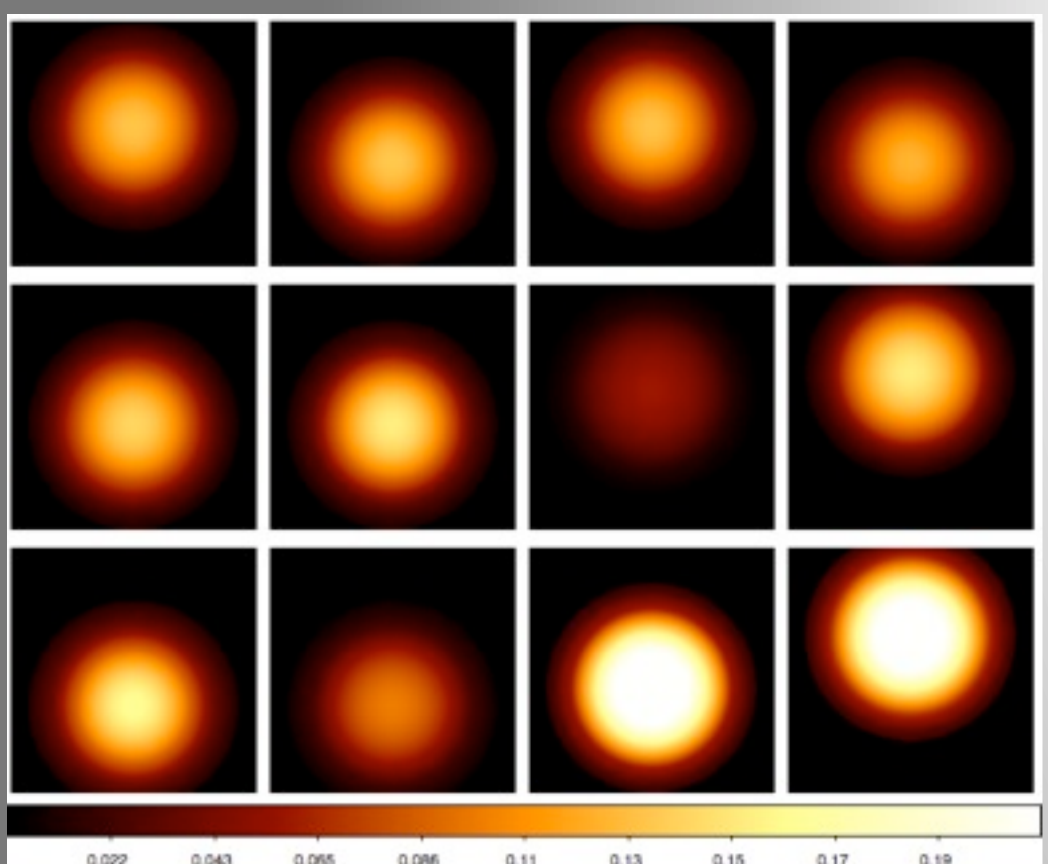
- due to cosmic ray events that look like gamma rays!
  - protons (mostly)
  - electrons (some)
  - muons (rarely)

What is a background model?

Background Modeling

- A measure of what the instrument sees when exposed to hadronic events (ignoring any gamma-ray background for now)
- The response to residual hadronic events is not the same as to actual gamma-ray events
- Analogous to the "effective collection area" for hadrons
- minimally a function of
  - position in FOV
  - energy
  - Alt/Az of pointing direction
  - telescope configuration

Combining Multiple exposures



Exposure maps for a series of 28-min observations. The variations are due to atmospheric changes

Understanding the hadronic background isn't just important for subtracting it...

Atmosphere transparency/density/etc is an unknown part of the detector!

- simulations are for an *average* atmosphere
- nightly variations are normal
  - density
  - temperature
  - haze
  - aerosols
  - turbulence/seeing
- Reflected mainly in the trigger rate
- note that 30 minute exposure on one night ≠ 30 minute exposure on another
  - "time" isn't really a good exposure measurement!

Defining exposure

Personal camera:

- simply time •ISO
- given an f-stop, you get an appropriate exposure time, knowing the effective “film speed” (a constant) of your CCD

Telescopes with fancier optics

- time • acceptance(r,phi,E)

ACTs:

- time • acceptance(r,phi,E,pointing) • throughput(t)

2D efficiency

variations in atmosphere

Acceptance

efficiency of photon detection across the field-of-view

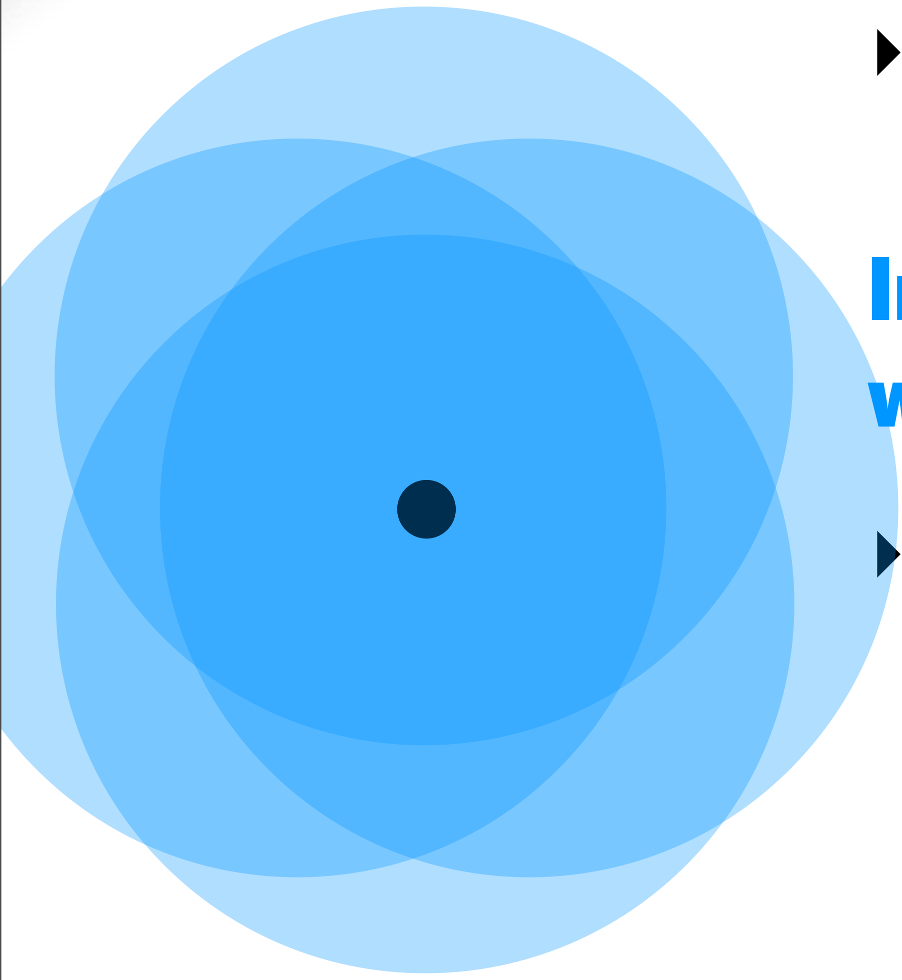
Is it the same for signal and background? (gamma-rays vs cosmic rays)?

- [show acceptance plots]
- NO!

How do we model it?

- Gamma-rays: from simulations, point-source at multiple positions in the FOV
- Cosmic rays: could do the same... but very CPU intensive!
  - instead: we have lots of background data, so just accumulate it!

Estimating the Background



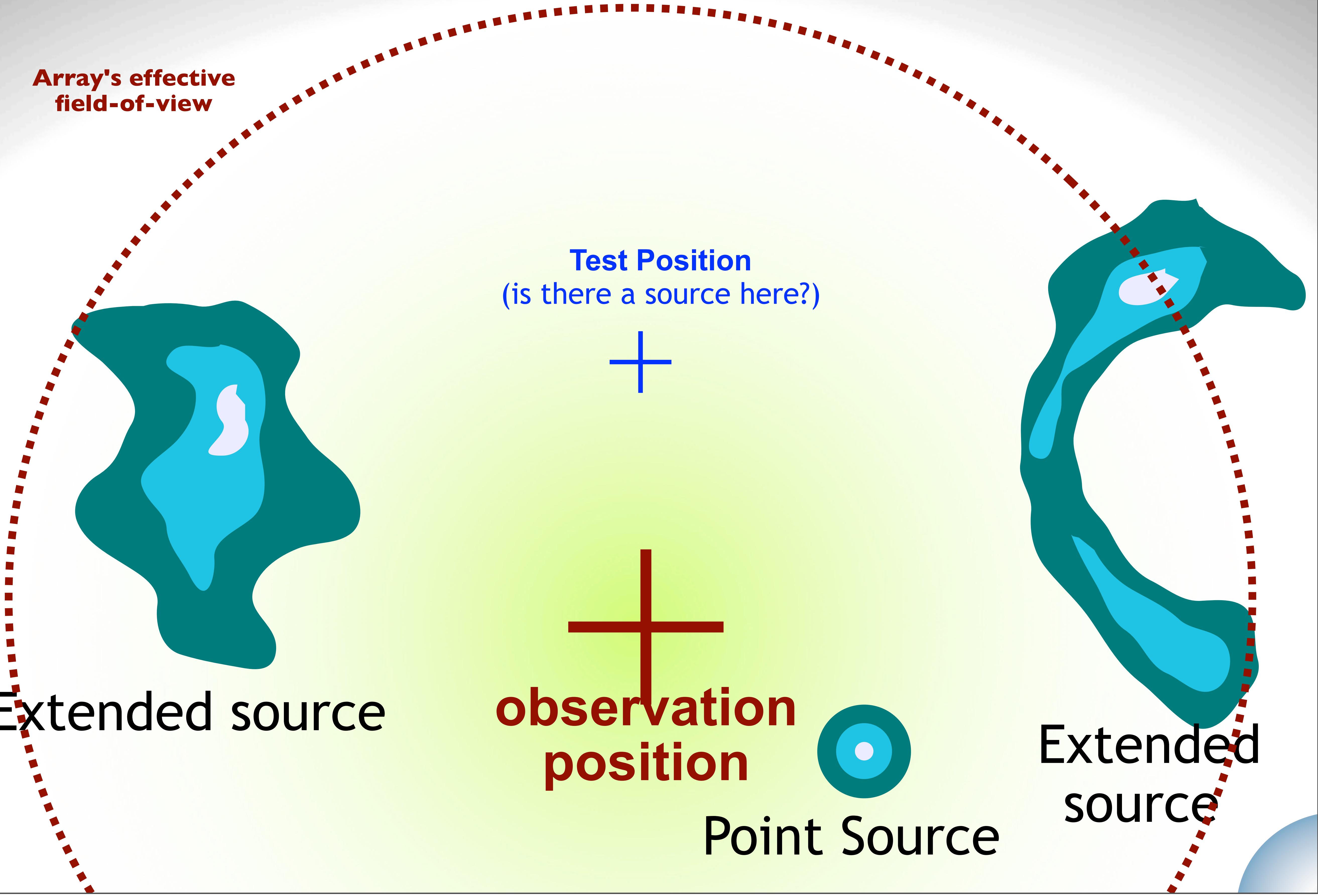
Taking ON/OFF observations like in the past wastes too much exposure time

- remember these instruments only work in total darkness! (small duty cycle)

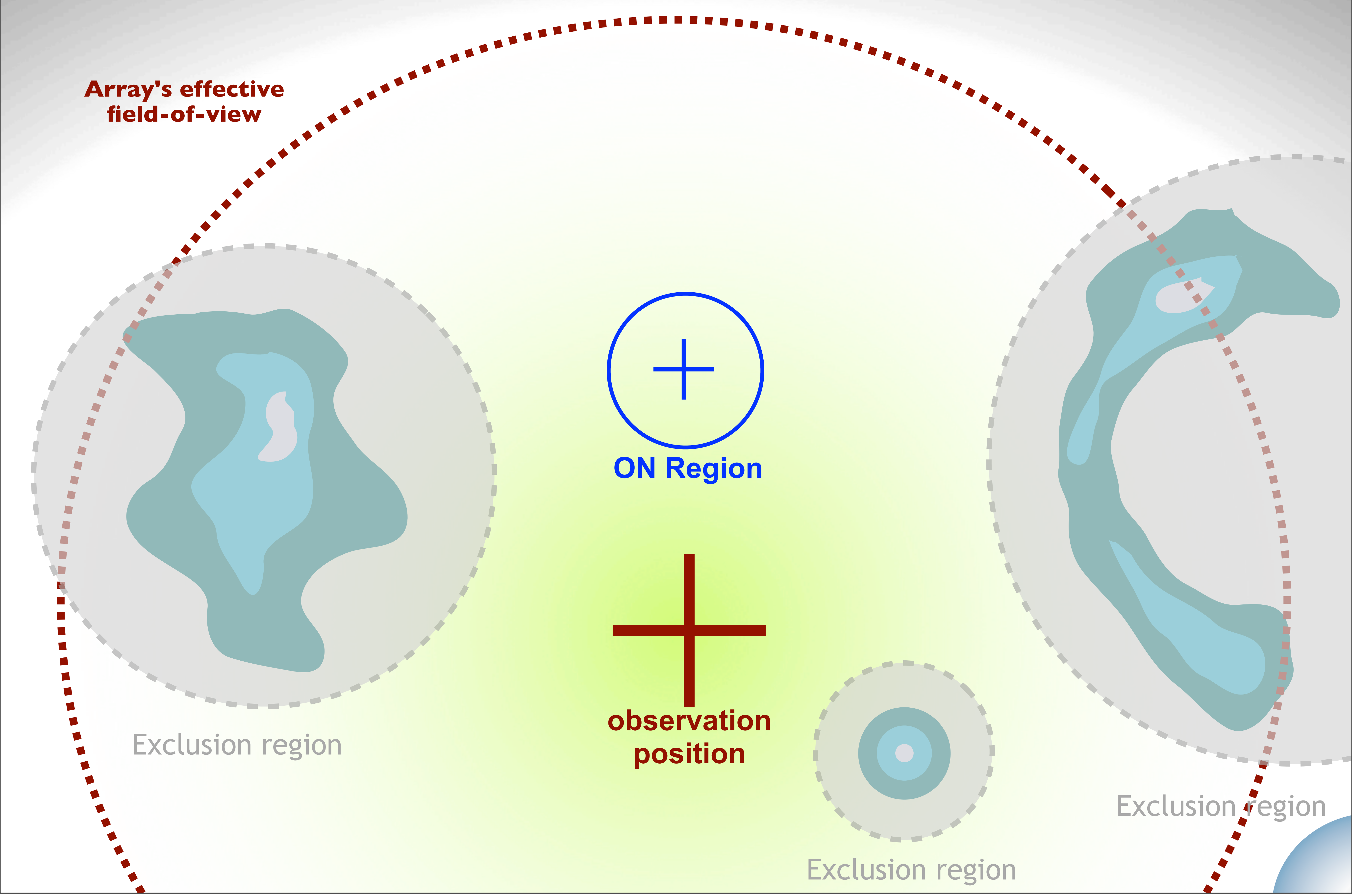
Instead, want to take background from within the field-of-view if possible

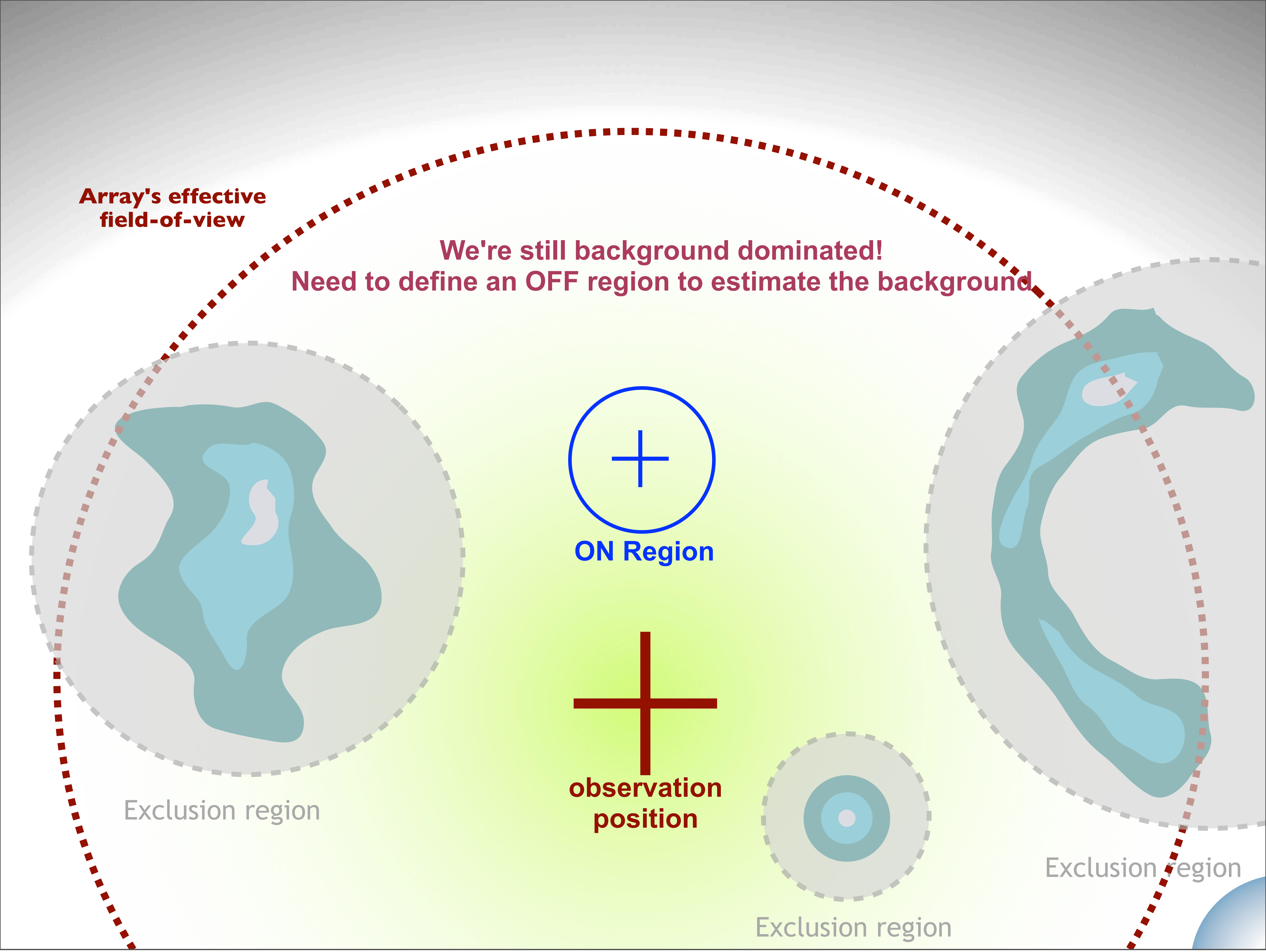
- need a new method of observation **Wobble Mode**:
  - point slightly away from the source of interest (>0.5°)
  - alternate north,south,east,west with each exposure.
  - non-radial effects average out (mostly)

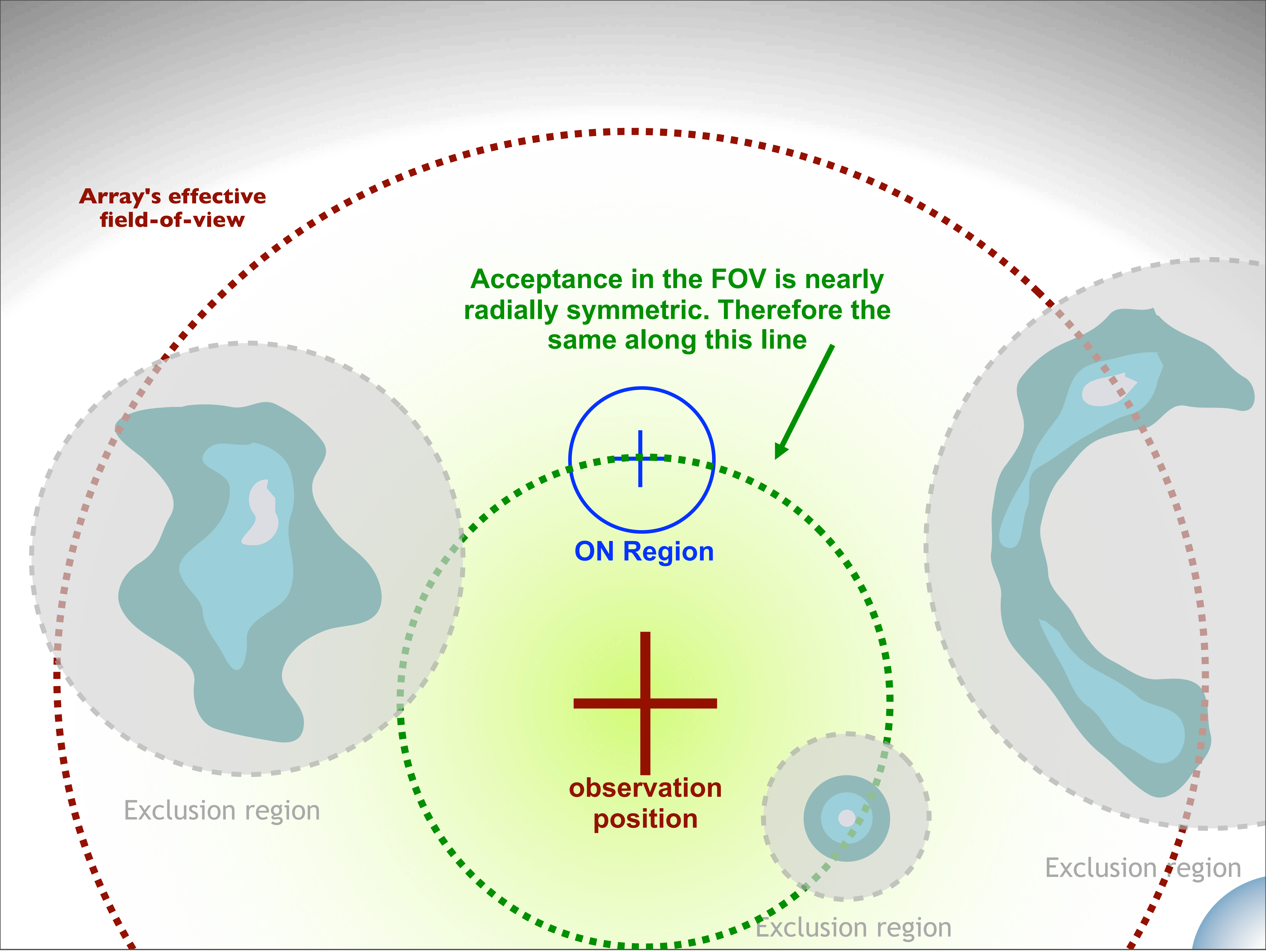
A piece of the VHE sky...



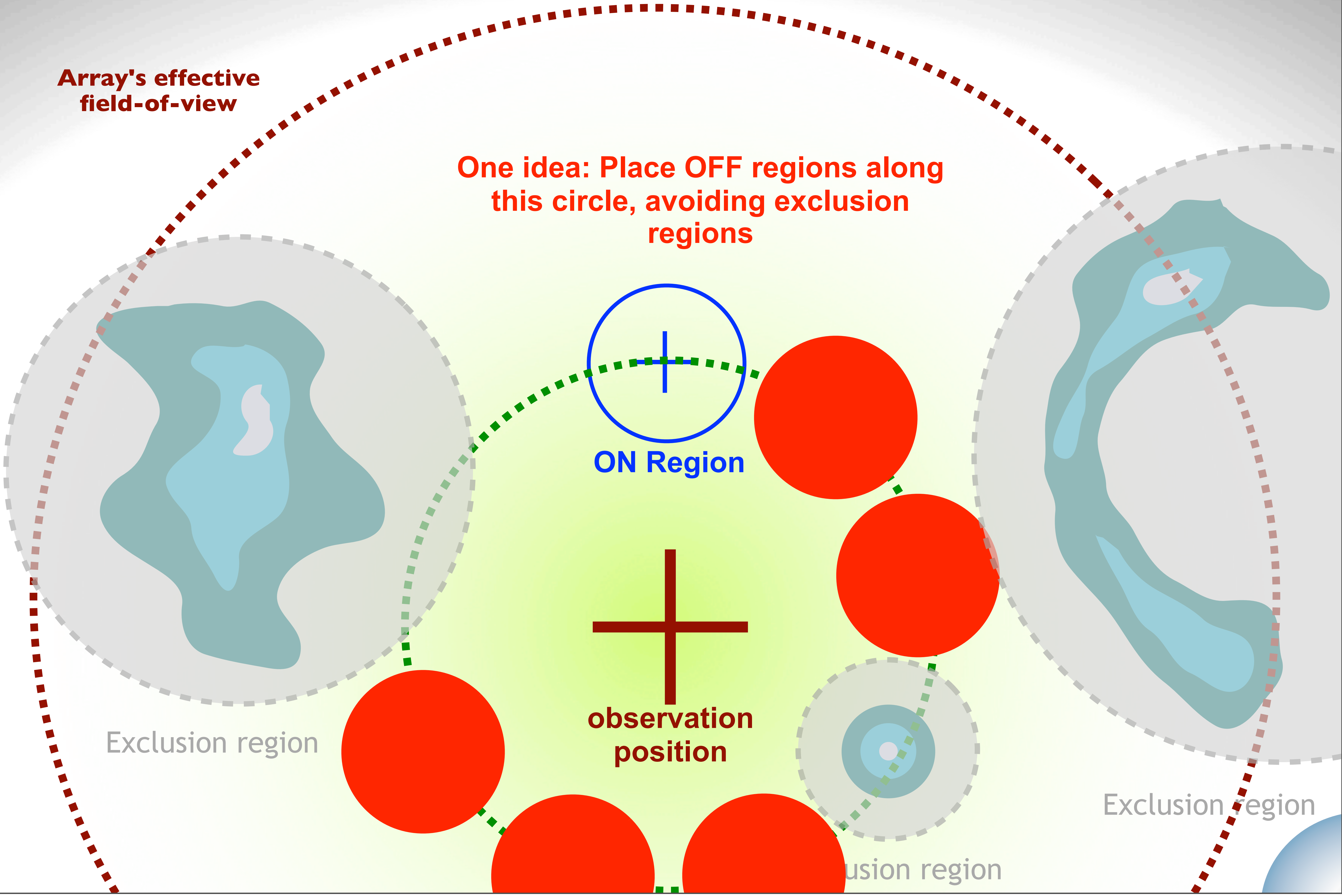
Test Region: is there a source?



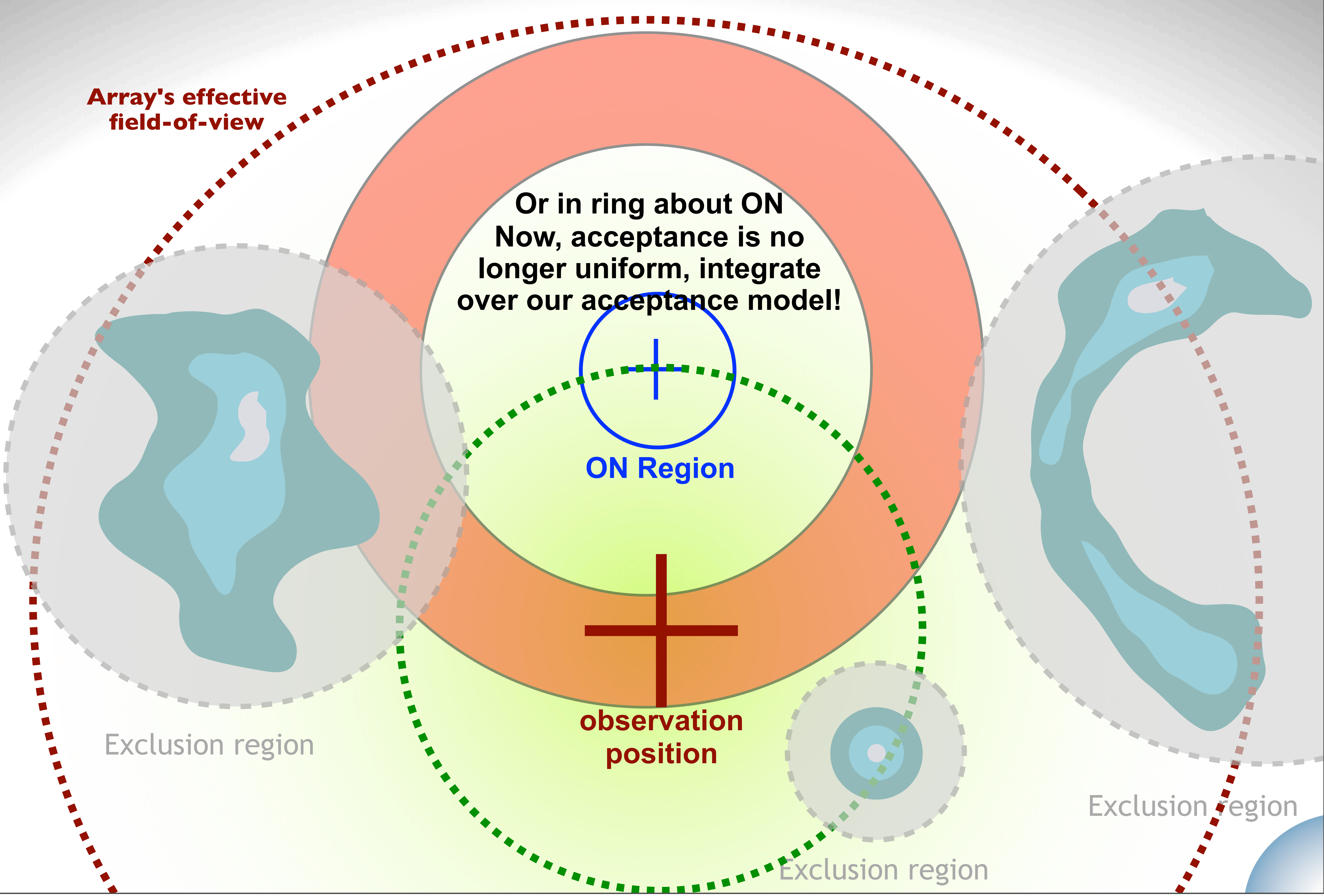

Array's effective field-of-view
We're still background dominated!
Need to define an OFF region to estimate the background
ON Region
observation position
Exclusion region
Exclusion region
Exclusion region


Array's effective field-of-view
Acceptance in the FOV is nearly radially symmetric. Therefore the same along this line
ON Region
observation position
Exclusion region
Exclusion region
Exclusion region

“Reflected Region” Background



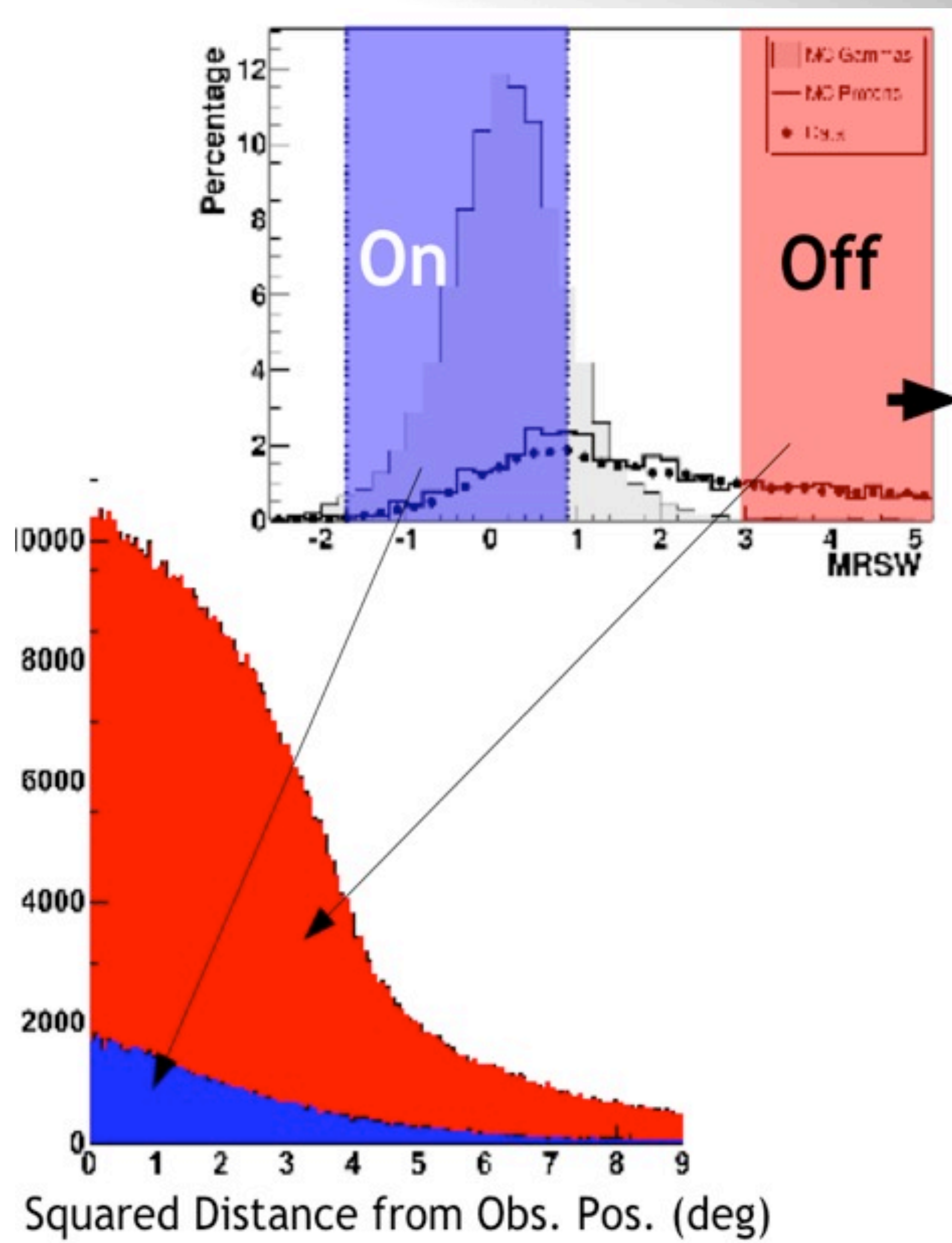
Ring Background



Phase-space Template Background

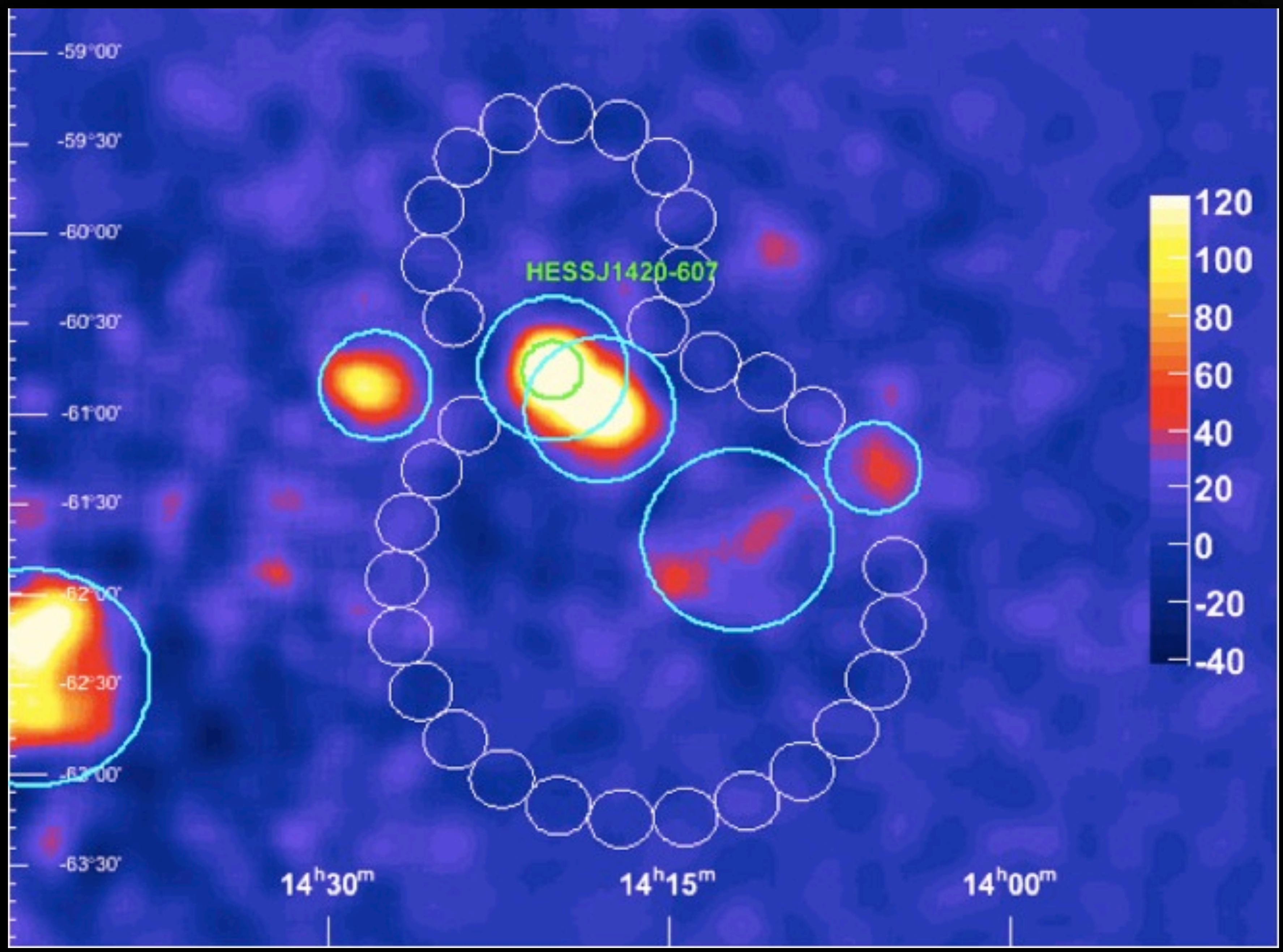
Select OFF events from a region in parameter space

- e.g. using the mean scaled width



Concrete example:

Kookaburra Nebula with H.E.S.S.



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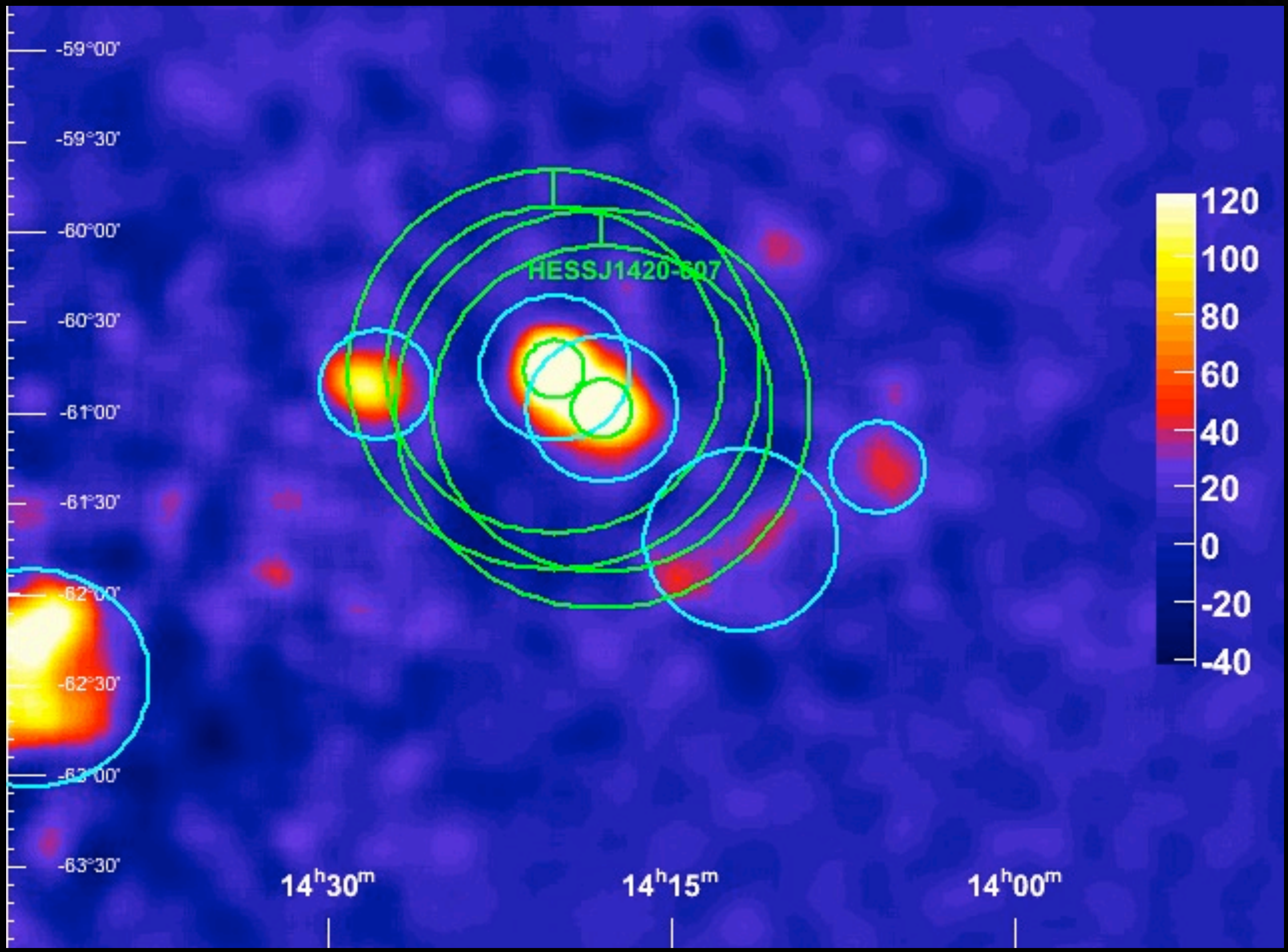


Detecting a source

We now have

- a measure of the total detected counts
- a model for the number of background counts
- NOTE: we *never* have a count of "photons"! We can only talk statistically about gamma rays.

We would like to calculate:

- the "excess" gamma-like events above the background
- the statistical significance of the excess
- NOTE: we *never* have a list of photons!
  - Non = Nsignal + Nbackground
  - Noff = Nbackground

Excess and Significance

$N_{excess} = N_{on} - \alpha N_{off}$

- α is the ratio of the ON/OFF exposure: it includes the area of the regions and acceptance differences

Significance?

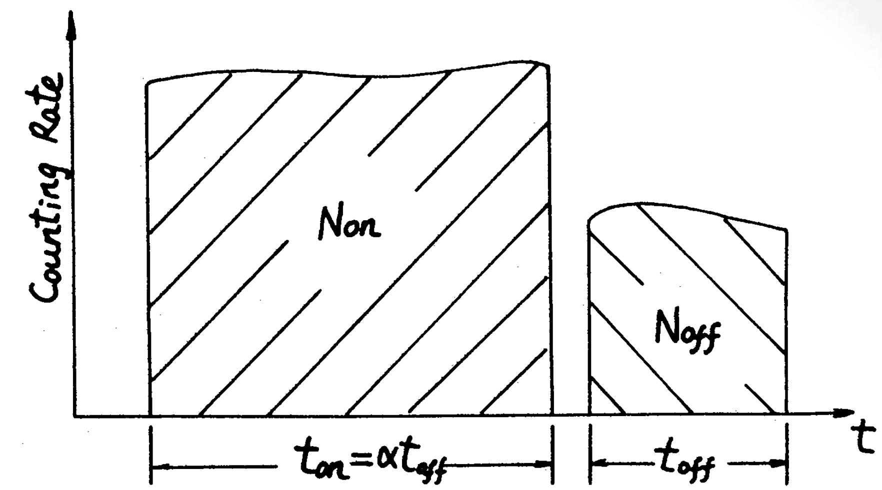


FIG. 1.—A typical observation in γ-ray astronomy

- Naively:
  - $\sigma^2_{excess} = \sigma^2_{on} + \alpha^2\, \sigma^2_{off}$
  - std deviation is sqrt(N_{excess}), assuming poisson statistics

$$\sigma^2(N_S) = \sigma^2(N_{\text{on}}) + \sigma^2(\alpha N_{\text{off}}) = \sigma^2(N_{\text{on}}) + \alpha^2\sigma^2(N_{\text{off}})$$

$$\hat{\sigma}(N_S) = \sqrt{\hat{\sigma}^2(N_{\text{on}}) + \alpha^2\hat{\sigma}^2(N_{\text{off}})} = \sqrt{N_{\text{on}} + \alpha^2 N_{\text{off}}}$$

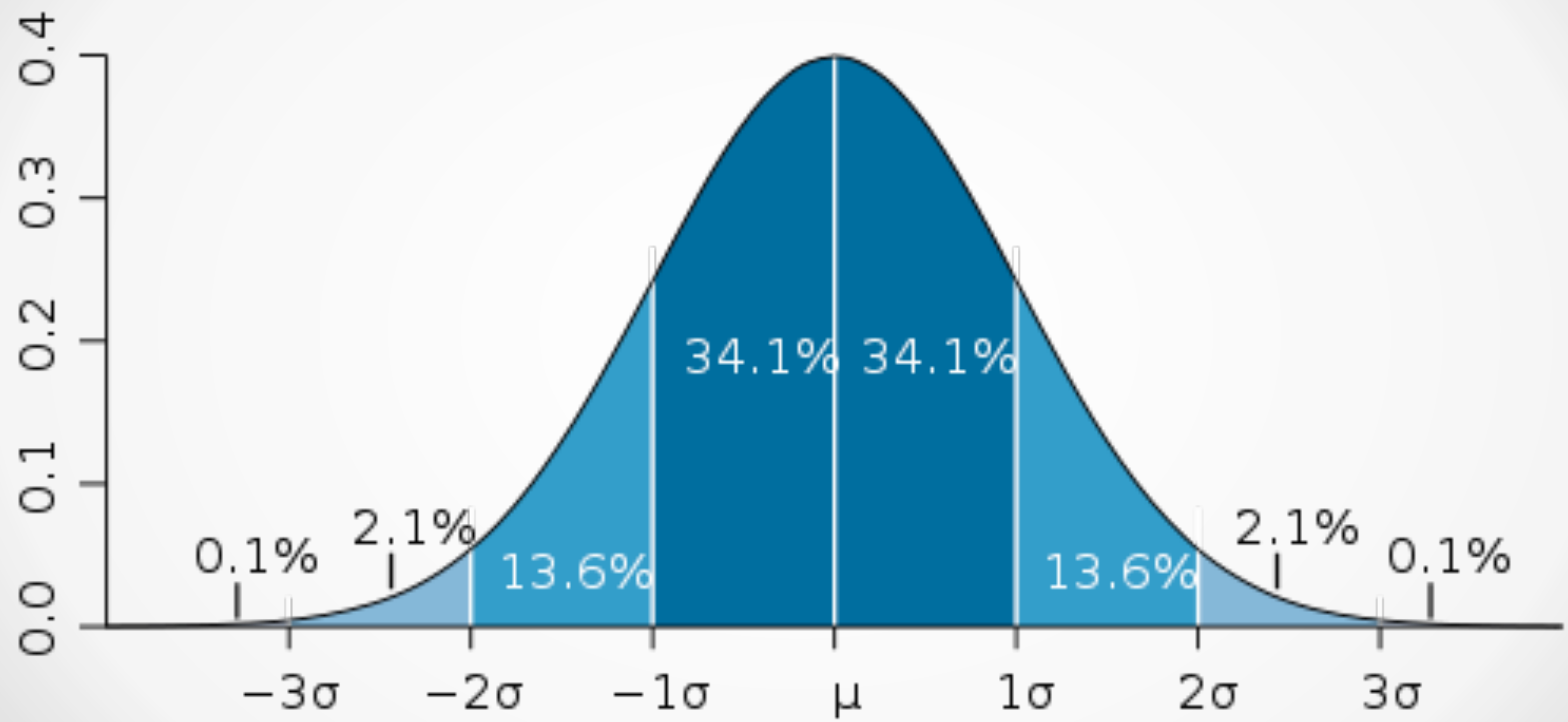
$$S = \frac{N_S}{\hat{\sigma}(N_S)} = \frac{N_{\text{on}} - \alpha N_{\text{off}}}{\sqrt{N_{\text{on}} + \alpha^2 N_{\text{off}}}}$$

- But this has a problem: for alpha ≠1, the underlying distribution for S is definitely not Gaussian! Want S to have mean=0 and stddev of 1.0 when no source is present

Significance

A better formulation:

- assume that Non as well as Noff are due to background (since you want to test whether the signal is consistent with noise):
- Then, $\sigma^2(N_S) = \sigma^2(N_{\text{on}}) + \alpha^2\sigma^2(N_{\text{off}}) = (1+\alpha)\langle N_B\rangle$
- $$S = \frac{N_S}{\hat{\sigma}(N_S)} = \frac{N_{on} - N_{off}}{\sqrt{\alpha(N_{on} + N_{off})}}$$
  .
- Better, matches monte-carlo sims more closely when Non and Noff are large, but still not perfect


0.4
0.3
0.2
0.1
0.0
34.1%
34.1%
13.6%
13.6%
2.1%
2.1%
0.1%
0.1%
−3σ
−2σ
−1σ
μ
1σ
2σ
3σ

Li and Ma Significance

Li and Ma 1983, ApJ 272:317-324

Null hypothesis: $E = E_0 = (\epsilon_{10}, \epsilon_{20}, \ldots, \epsilon_{r0})$,
Alternative hypothesis: $E \neq E_0$,
define the maximum likelihood ratio

$$\lambda = \frac{L(X|E_0, \hat{T}_c)}{L(X|\hat{E}, \hat{T})} = \frac{P_r(X|E_0, \hat{T}_c)}{P_r(X|\hat{E}, \hat{T})}, \tag{13}$$

where $L(X|\Theta')$ is the likelihood function of N observed values X given parameters $\Theta = \Theta'$, that is, the probability of experimental results X given $\Theta = \Theta'$; $\hat{E}$ and $\hat{T}$ are the maximum likelihood estimates of parameters E and T; $\hat{T}_c$ are the conditional maximum likelihood estimates given $E = E_0$. On condition of null hypothesis $E = E_0$ being true, variable $-2 \ln \lambda$ will asymptotically follow a χ^2 distribution with r degrees of freedom, while $N \to \infty$, as denoted by

$$-2 \ln \lambda \sim \chi^2(r) .$$

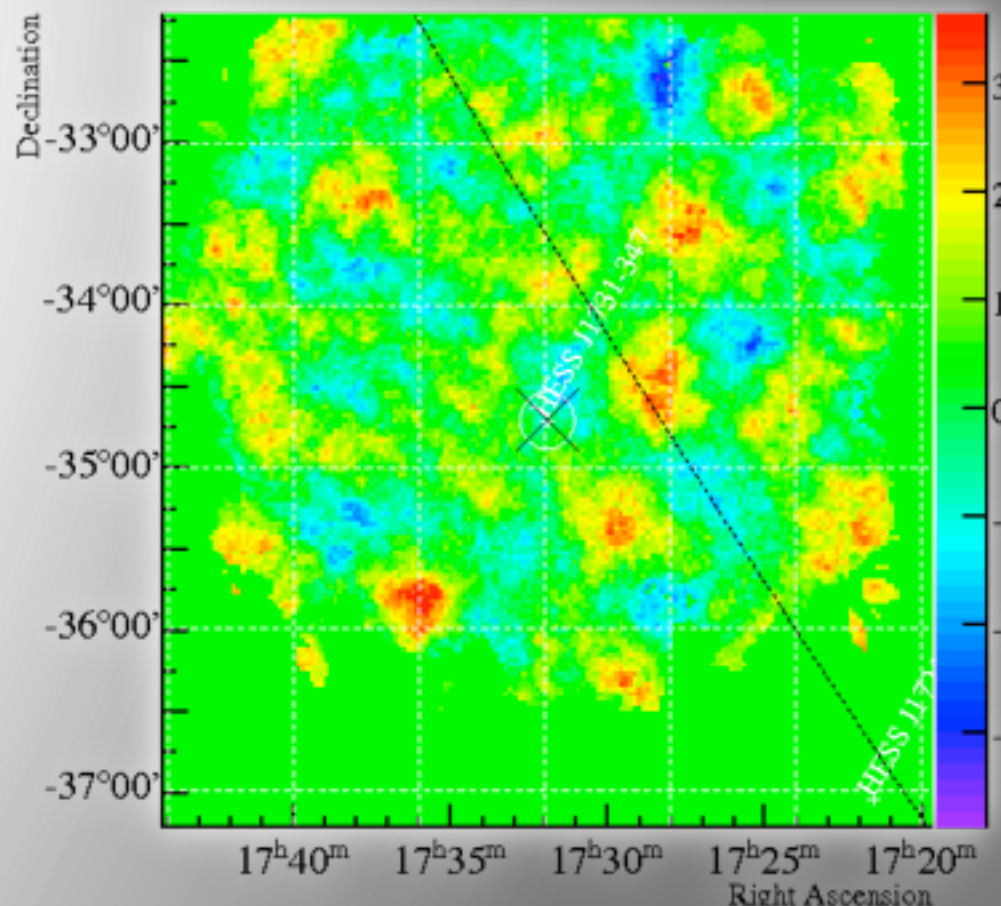
In our case, the observed data $X = (N_{\rm on}, N_{\rm off})$, estimated unknown parameters $\Theta = (\langle N_S \rangle, \langle N_B \rangle)$, and
Null hypothesis: $\langle N_S \rangle = 0$,
Alternative hypothesis: $\langle N_S \rangle \neq 0$.

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

Blind searches can lead to false positives!

- What is the chance probability of detecting a 3σ (or even 5σ) source in a large field of view?
- What if we test every position in the sky for gamma-ray emission?
  - recall that significance has a normal distribution mostly in the ±1 range, but there are always fluctuations above and below
- The probability that we hit an upward fluctuation increases with every position that is tested!
- Without an *a priori* position, 5σ is not a true detection!

aside: **Trials Factors**



Probability that a signal is not a fluctuation:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{S} e^{\frac{t^2}{2}} \, dt$$

aside: Trials Factors

Probability of finding a fake source with significance S_{pre} in N trials:

- $1 - P_N = (1-P)^N$

How many trials?

- For the HESS galactic plane survey, ≈ number of bins in survey! ($>10^6$)
- One for every position you tried
- One for every time range tried
- Careful of anything that could cause you to optimize on a signal!

Significance	
Pre-trials	Post-trials
5.0	0.4
6.0	3.0
7.0	4.6
7.5	5.3
8.0	6.0
9.0	7.3
10.0	8.5

Making a Sky Map

Up to now, we have only a single set of statistics relating to the question "is there a source in our ON region"

The source position is not always known *a priori*.

- new source discoveries
- unknown source morphologies/sizes
- transients with large error-box

It's nice to see what the sky looks like...

For this we need images!

Imaging Analysis

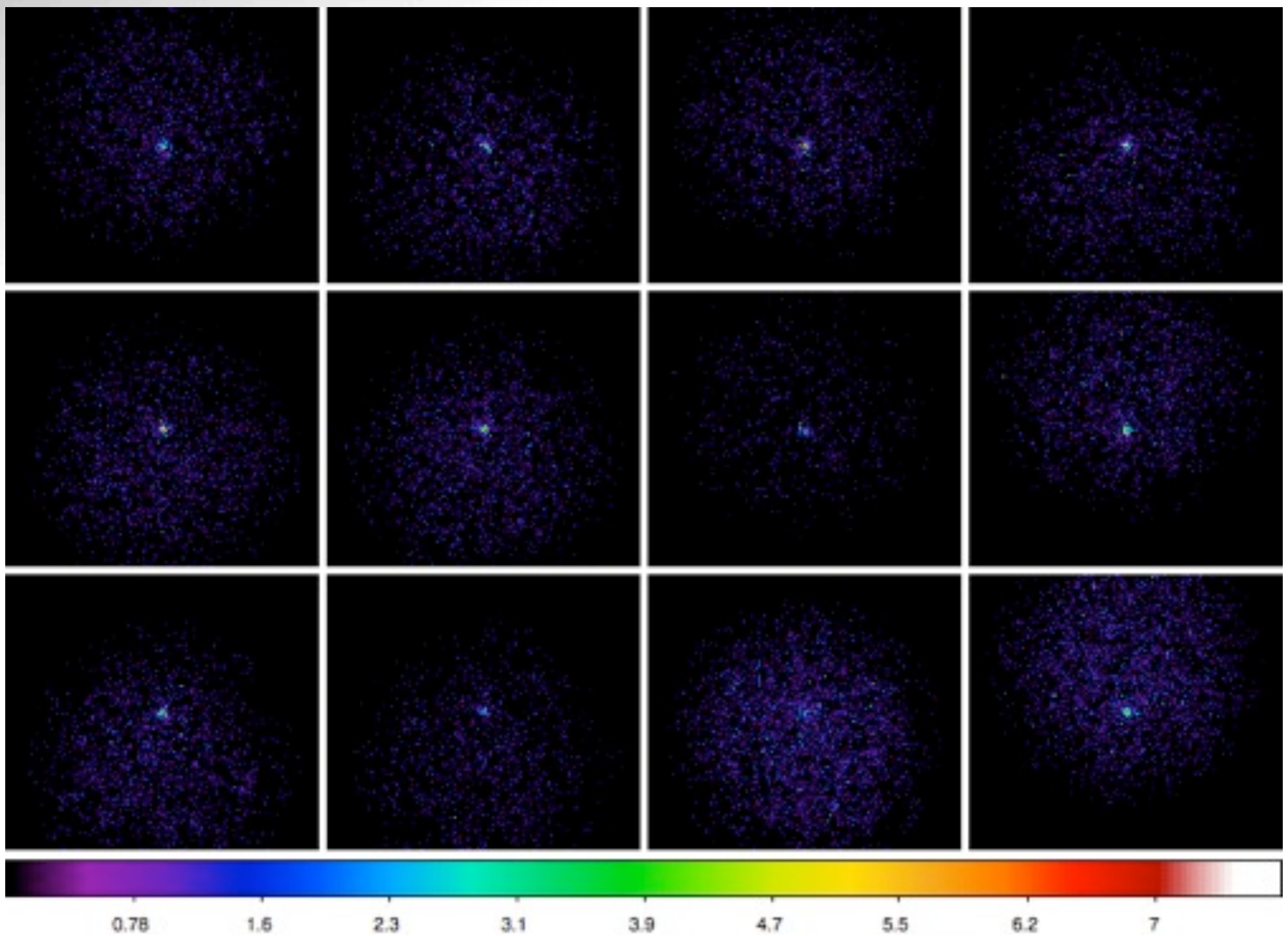
Instead of using spatial regions for each observation, generate a background model at each point in space, using the same methods as before...

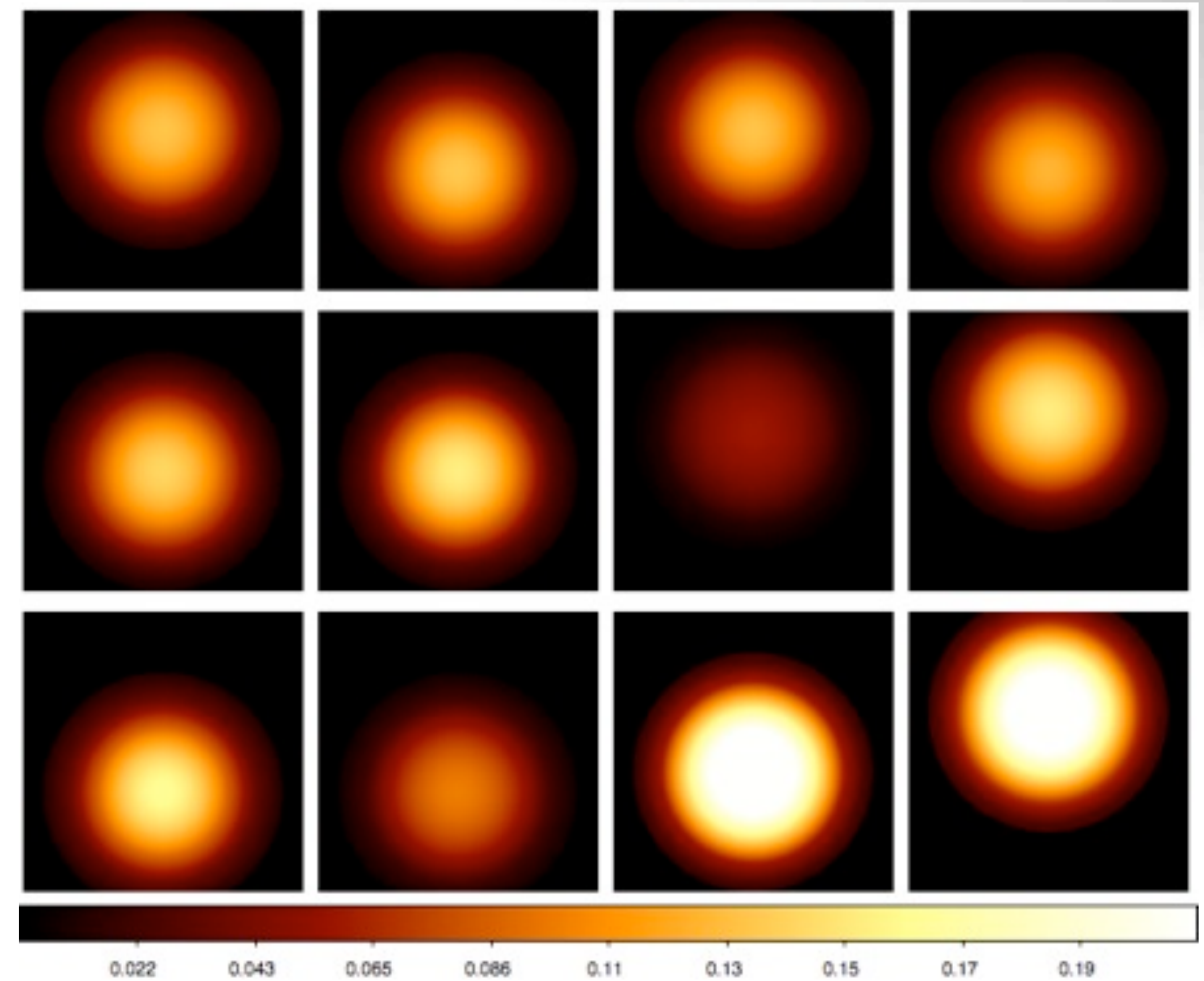
In all cases you still need OFF-source regions (or a source exclusion mask) to normalize the background!

- This is due to the atmosphere throughput, which is generally unknown and must be measured

Let’s analyze some real data..

Again, the Crab Nebula (north/south wobble)





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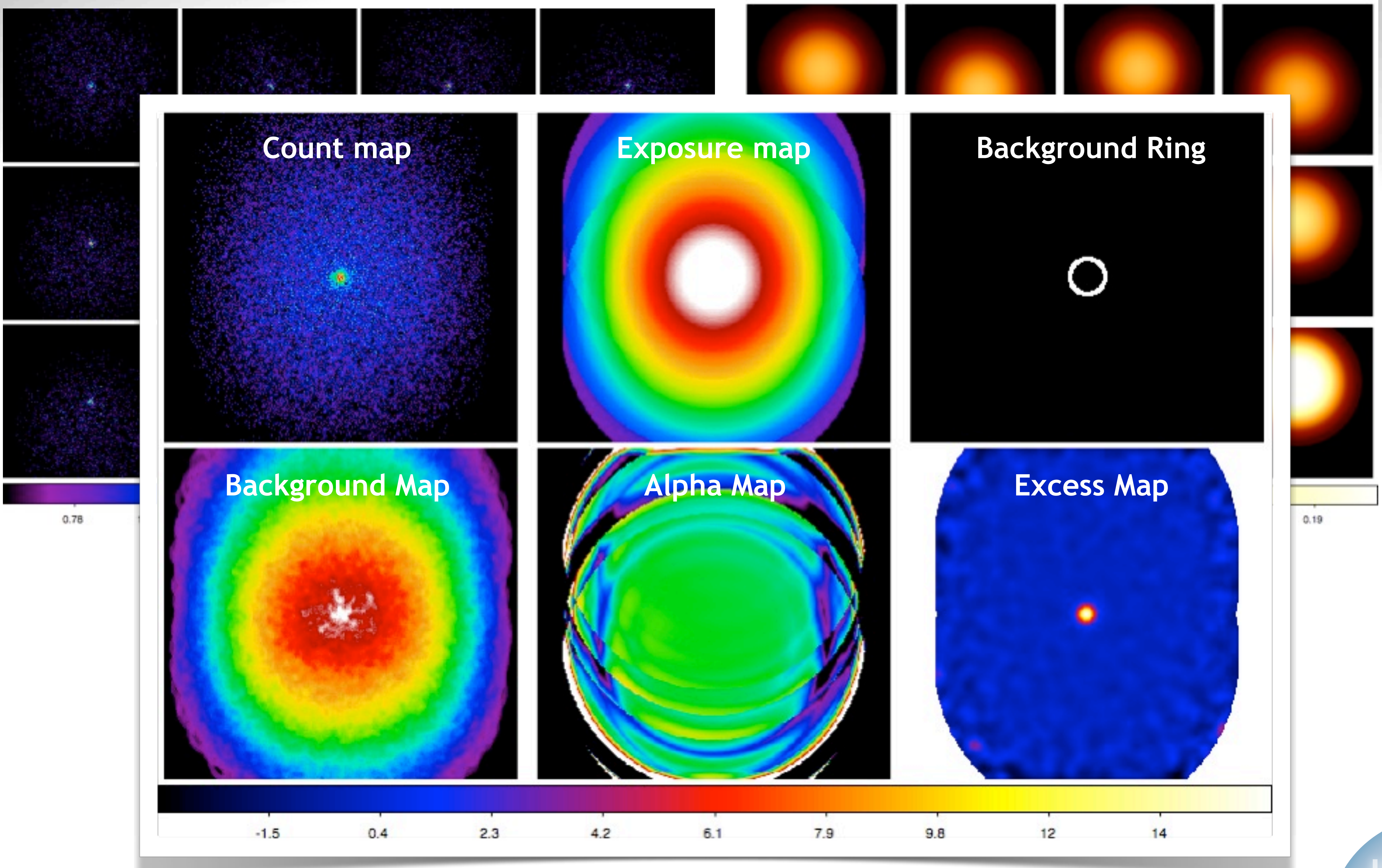


Spectral Analysis

Let's say we have detected a source, and have an image (or known position)

- How do we calculate a flux?
- We Have distributions of the following parameters (as a function of reconstructed energy):

$$\sum_{\text{runs}} \left\{ \right.$$

  - Non
  - Noff
  - Live-time
  - Exposure ON/Exposure OFF ratio (depends on Background method)
  - Effective area (from simulations)
  - gamma/hadron efficiency (from simulations)

Instrumental Responses

Effective Area

- The collection area for gamma rays
- ≈ size of the light pool on the ground for a single telescope

Point-Spread-Function

- How well we can reconstruct the direction
- $P(\mathbf{r}_{reco} \mid \mathbf{r}_{true})$

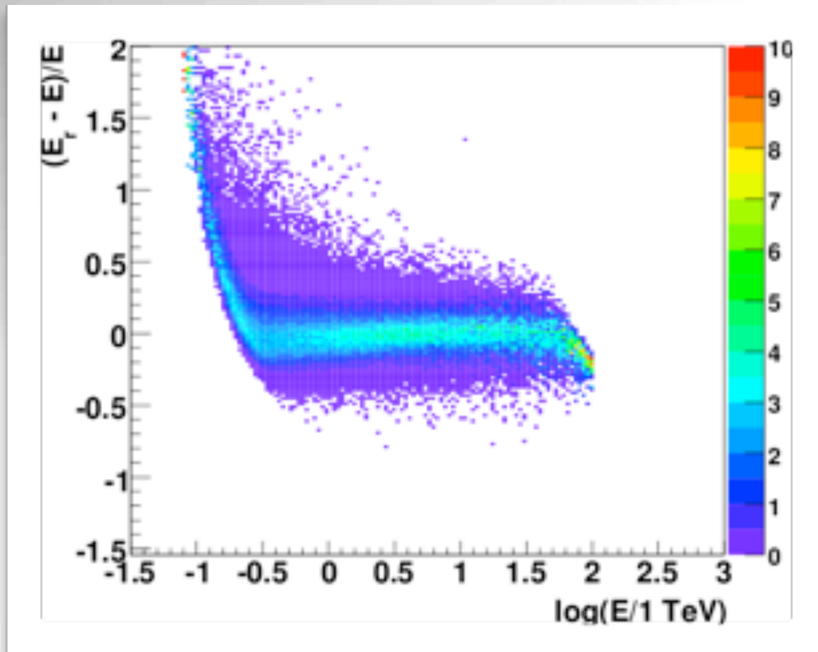
Energy Migration

- How well we can reconstruct the energy
- $P(E_{reco} \mid E_{true})$

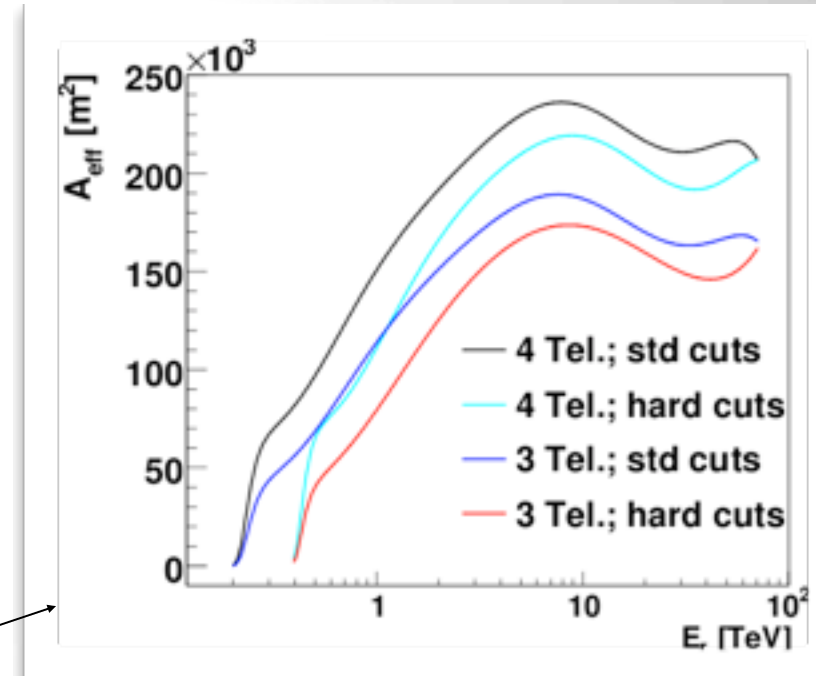
Background acceptance

- How efficiently we detect background events in the FOV (similar to the effective area, but for non-gamma events)

What the flux?!



$$F(E) = \frac{dN_\gamma}{dE\,dt\,dA}$$



$$\frac{dN_\gamma}{dE_{\rm r}dt} = \int_0^\infty P(E, E_{\rm r}, \theta_{\rm z}, \psi, \nu_{\rm az})\tilde{A}_{\rm eff}(E, \theta_{\rm z}, \psi, \nu_{\rm az})\epsilon(E, \theta_{\rm z}, \psi, \nu_{\rm az})F(E)dE$$

Differential gamma-ray rate

Probability of reconstructing true energy E

True effective area

Gamma-ray selection efficiency

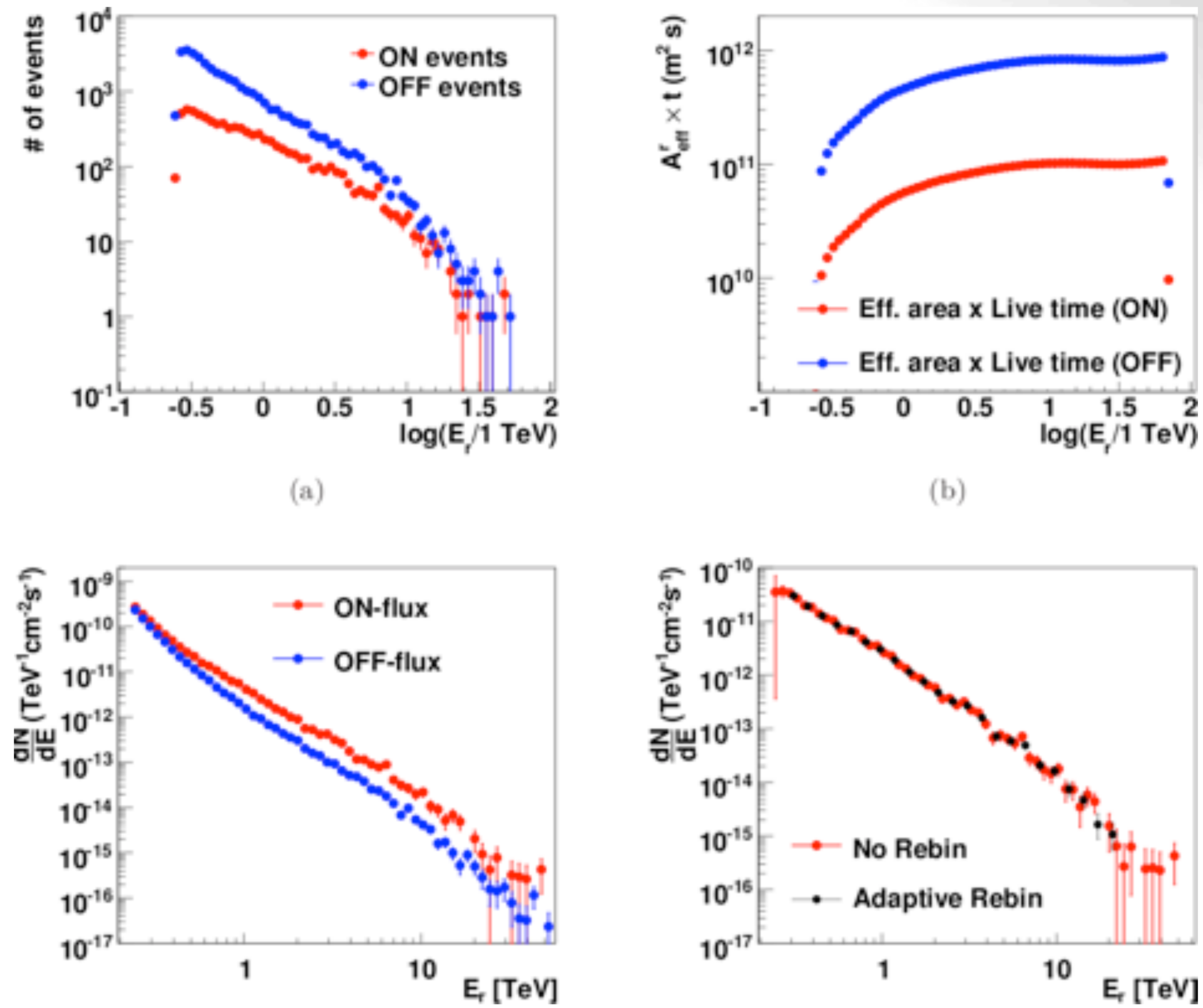
$$F(E_{\rm r}) = \frac{1}{A_{\rm eff}(E_{\rm r}, \theta_{\rm z}, \psi, \nu_{\rm az})}\frac{d^2N_\gamma}{dE_{\rm r}dt}$$

Not trivial to invert!

Spectral Analysis

Basic method:

- Bin the ON and OFF events by energy
  - (corrected by ON/OFF exposure factor)
- Look up effective area based on zenith-angle/offset distributions of the events
- Calculate ON and OFF flux, subtract
- Fit a function



$$\Phi_i = \frac{(N_i^{\mathrm{ON}} - \alpha_i N_i^{\mathrm{OFF}})}{A_{\mathrm{eff}}^i \tau_i}$$

Spectral Analysis

Forward folding method

- Assume underlying spectrum shape
- Calculate expected gamma-ray count
-
$$
\begin{aligned}
n_\gamma\Big|_{E_{\mathrm{r,i}}}^{E_{\mathrm{r,i+1}}} &= \sum_{\mathrm{runs},\theta,\psi} t_{\theta,\psi} \int_{E_{\mathrm{r,i}}}^{E_{\mathrm{r,i+1}}} dE_{\mathrm{r}} \\
& \int_0^\infty dE \cdot \phi_{\mathrm{fit}}(E) A_{\mathrm{eff}}(E,\theta,\psi) P(E_{\mathrm{r}}, E, \theta, \psi) \\
C &= \alpha(N_{\mathrm{on}} + N_{off}) - (1+\alpha) n_\gamma \\
D &= C^2 + 4\alpha(\alpha+1) N_{off} n_\gamma \\
n_h\Big|_{E_{\mathrm{r,i}}}^{E_{\mathrm{r,i+1}}} &= \frac{C+D}{2\alpha(\alpha+1)}
\end{aligned}
$$
- Poisson probability: $$P(N_{\mathrm{on}}, N_{off} | n_\gamma, n_h) = \frac{(n_\gamma + \alpha n_h)^{N_{\mathrm{on}}}}{N_{\mathrm{on}}!} \exp(-(n_\gamma + \alpha n_h)) \cdot \frac{n_h^{N_{off}} \exp(-n_h)}{N_{off}!}$$
- Expected background count (maximizing P analytically)

Spectral Analysis

... forward folding method:

- Then, knowing the estimated signal and background (n_γ,n_h), maximize the likelihood, varying the parameters of the assumed source spectrum (in n_γ):

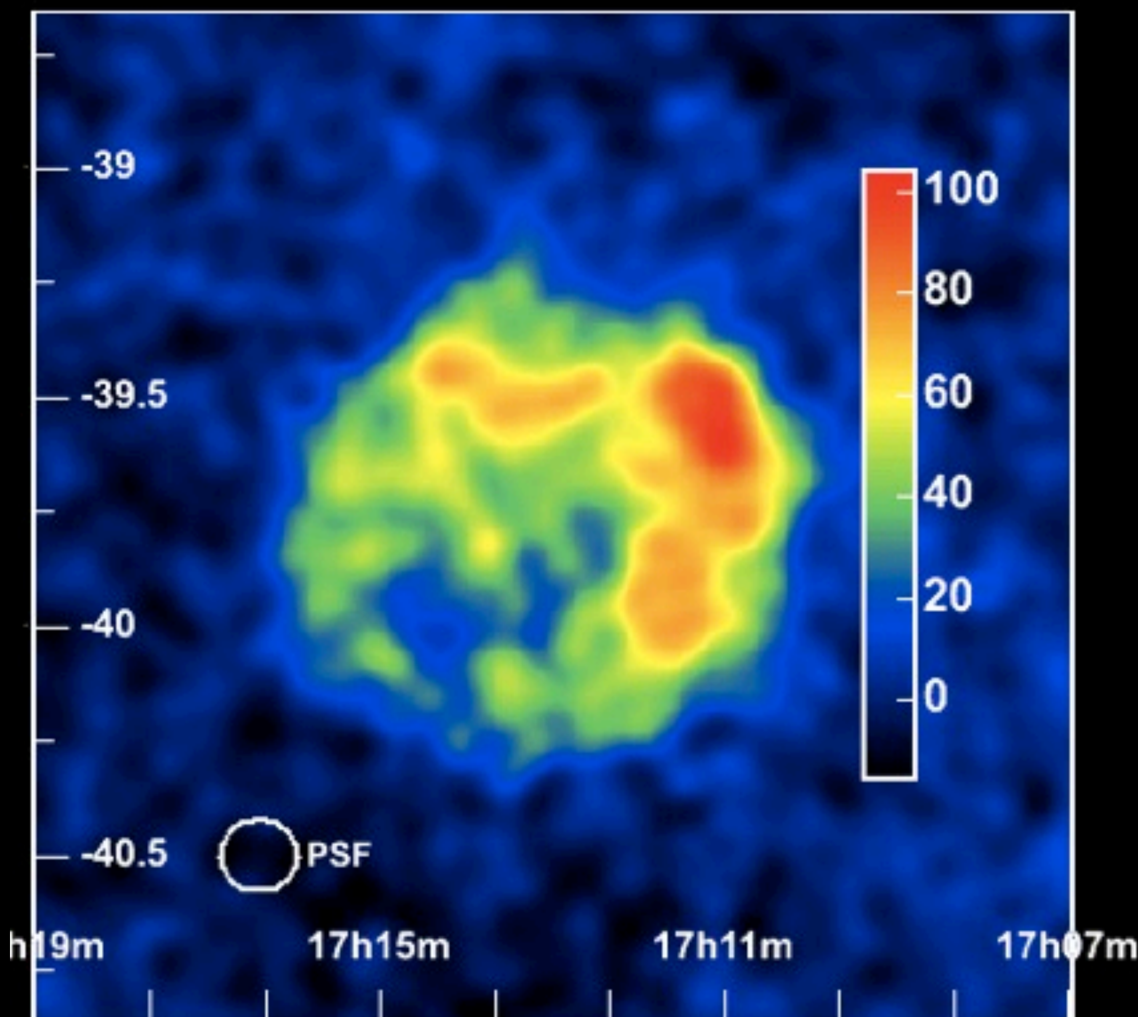
$$
\begin{aligned}
-L = -log(P) \quad \sim \quad & N_{on} \cdot \log(n_\gamma + \alpha n_h) + N_{off} \cdot \log(n_h) \\
& -((1+\alpha)n_h + n_\gamma)
\end{aligned}
$$

- The answer is then your fitted function, residuals can be used to make flux points.
- Advantages: Non and Noff used directly for the fit, no need for large re-binning and flux-point calculation.

Results

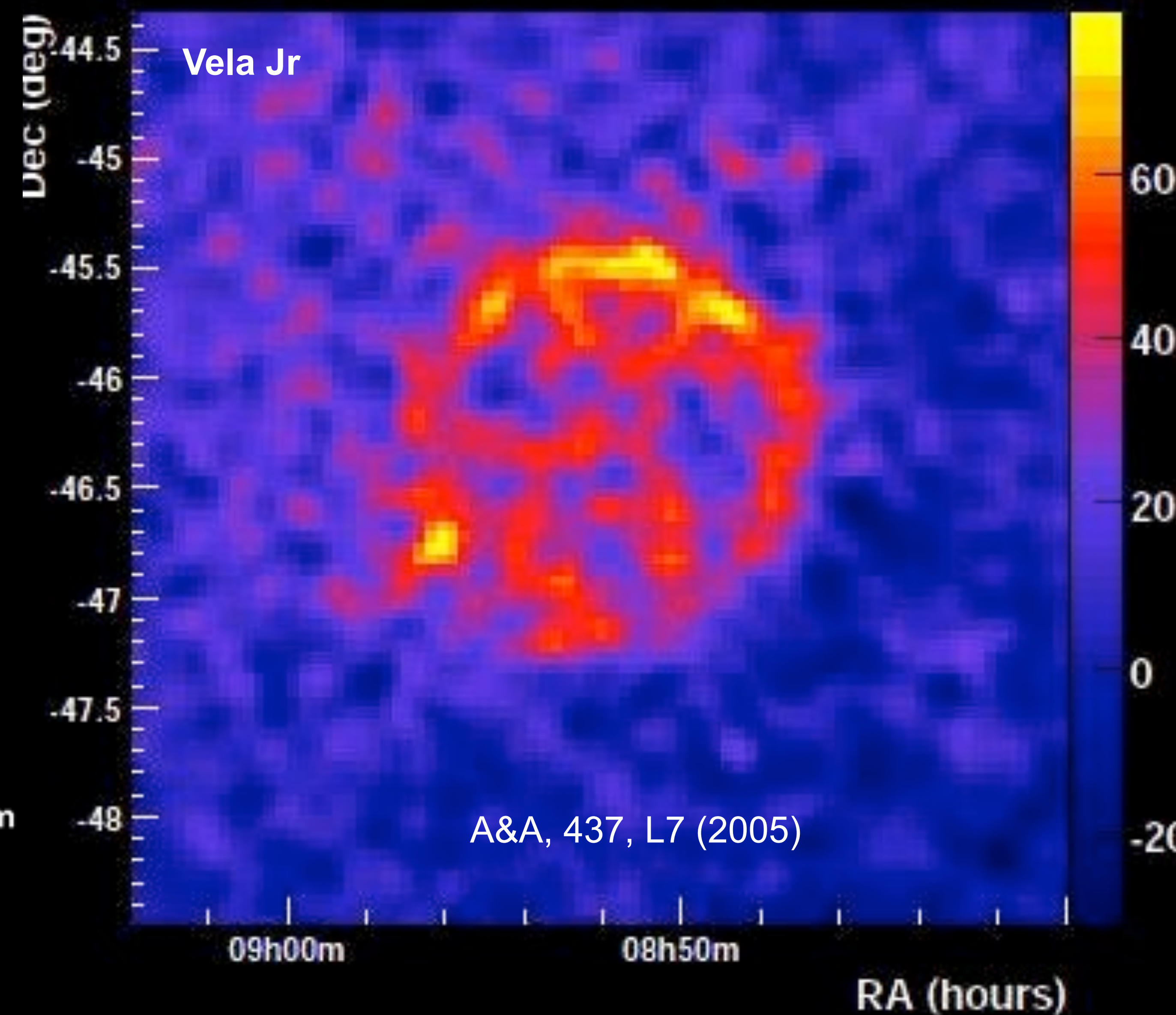
A few examples of VHE gamma ray detections...

Supernova Remnants



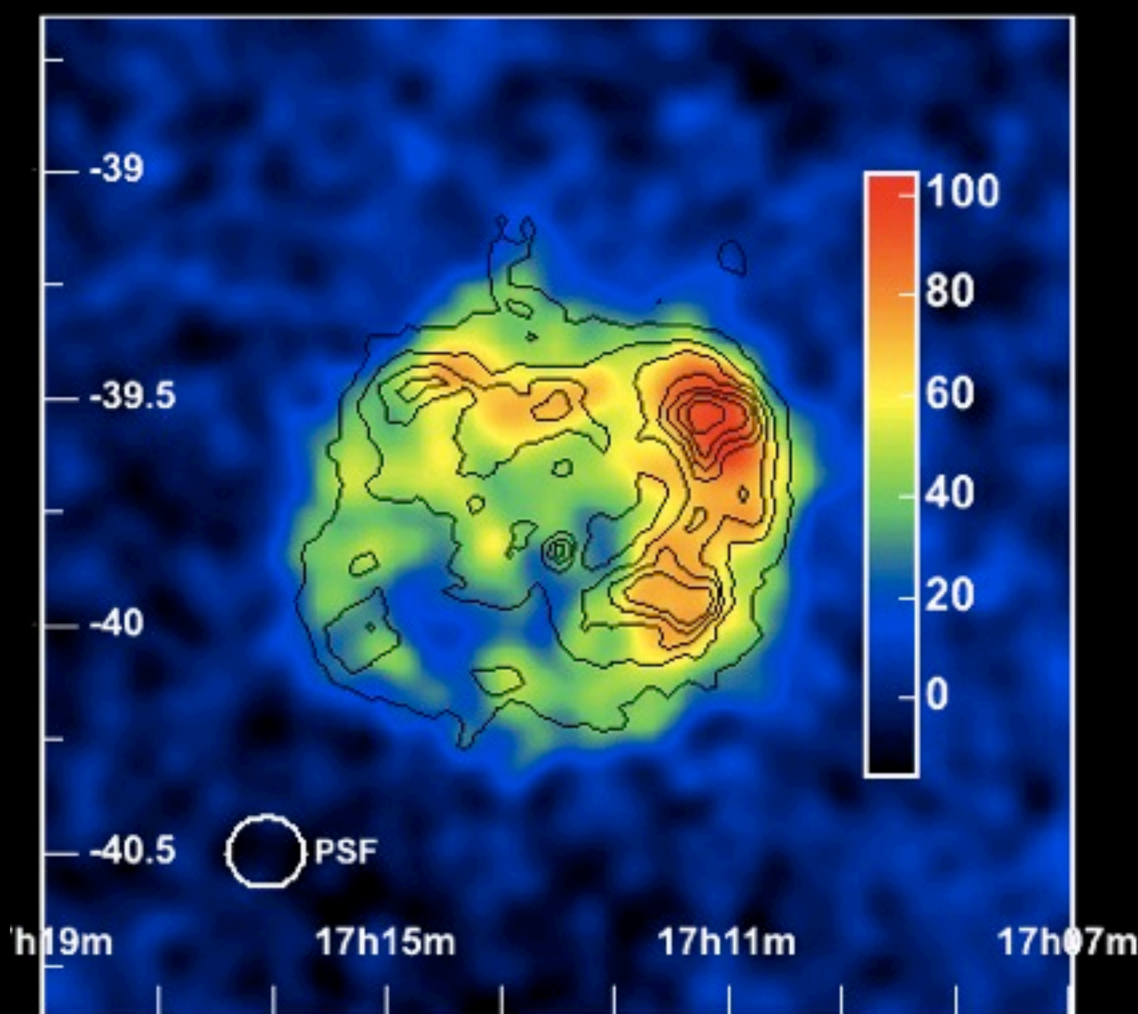
RX J1713

Aharonian et al., 2004, *Nature*, 432, 75



First resolved extended TeV source!
Correspondance with X-Ray morphology: implies gamma/X-ray production mechanism linked

Supernova Remnants



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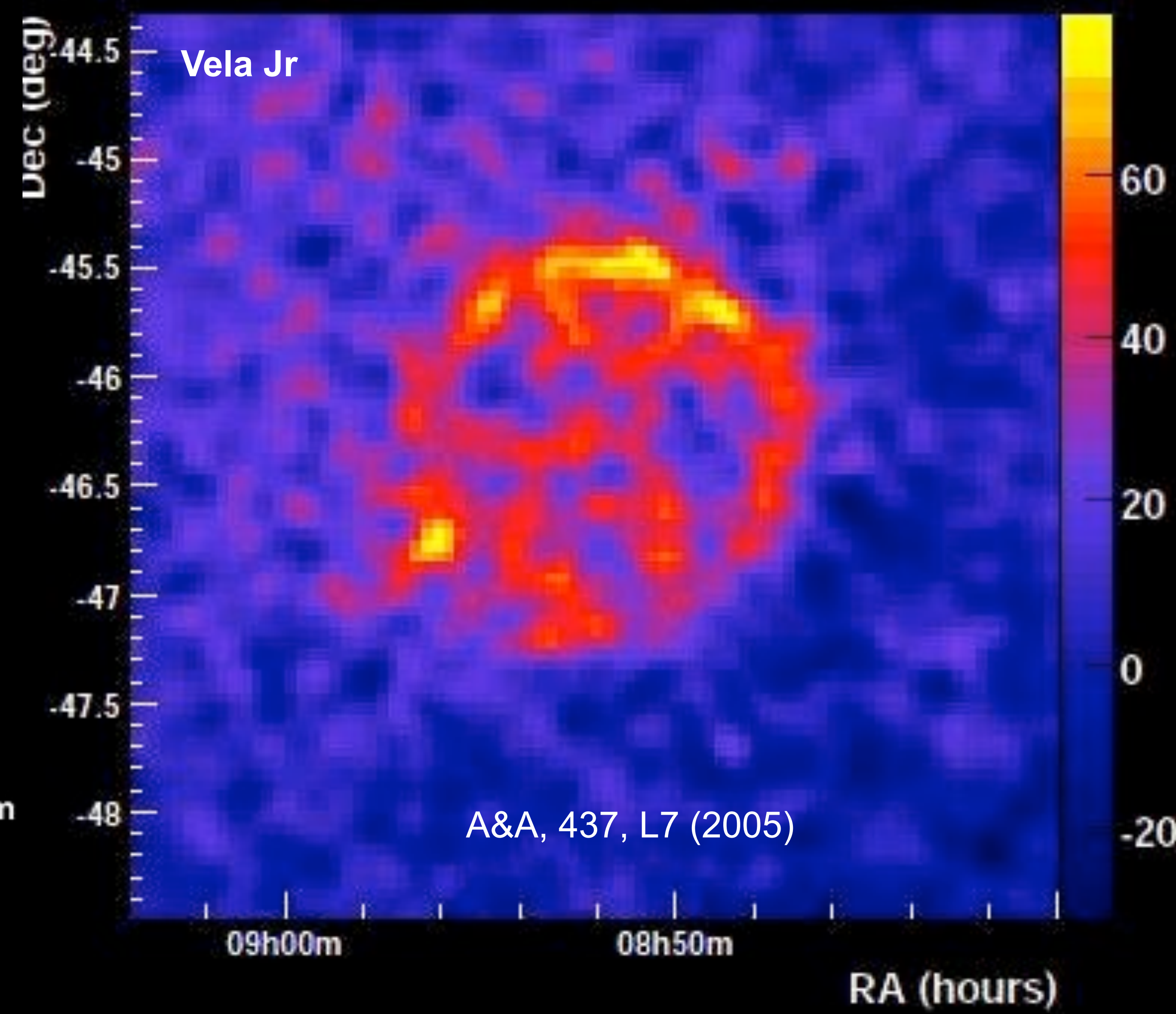

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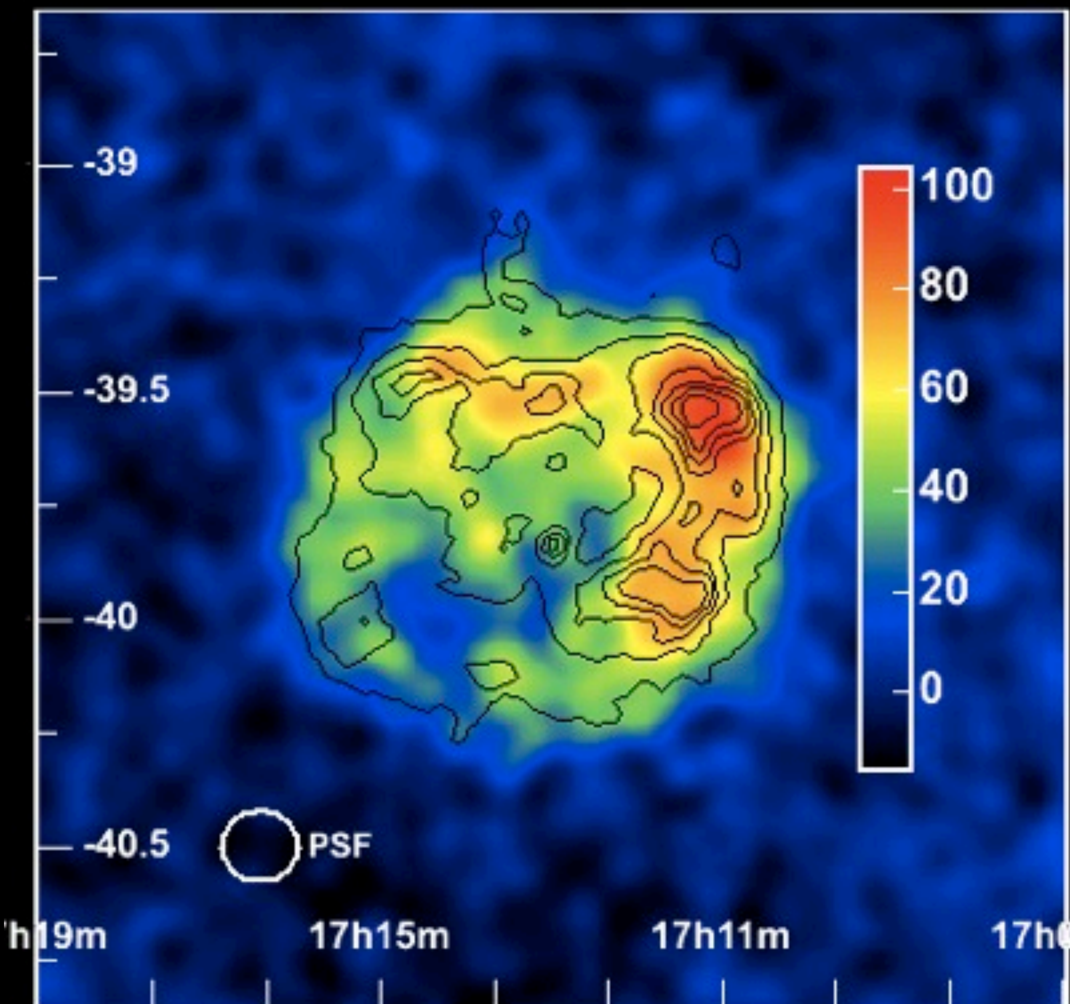

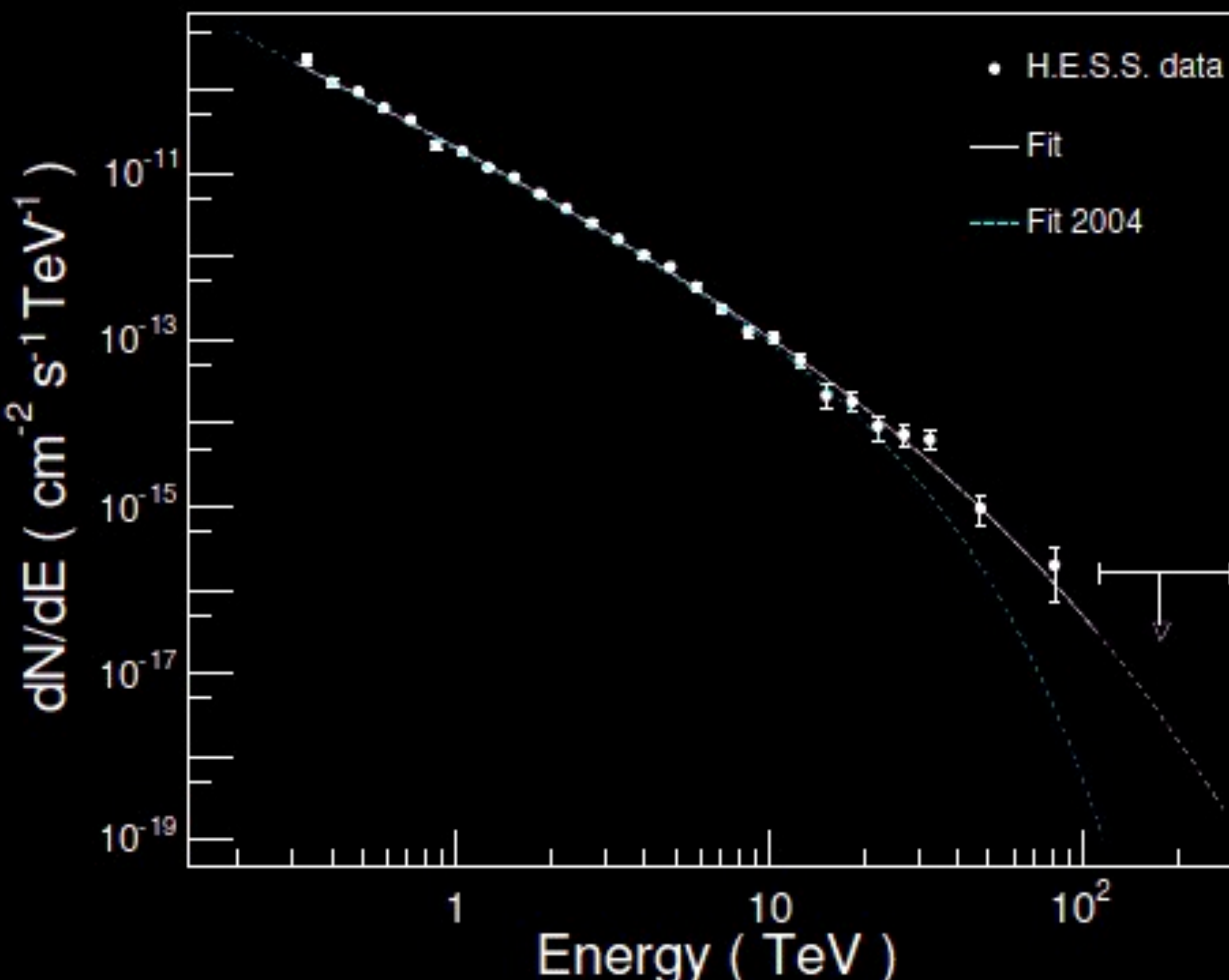

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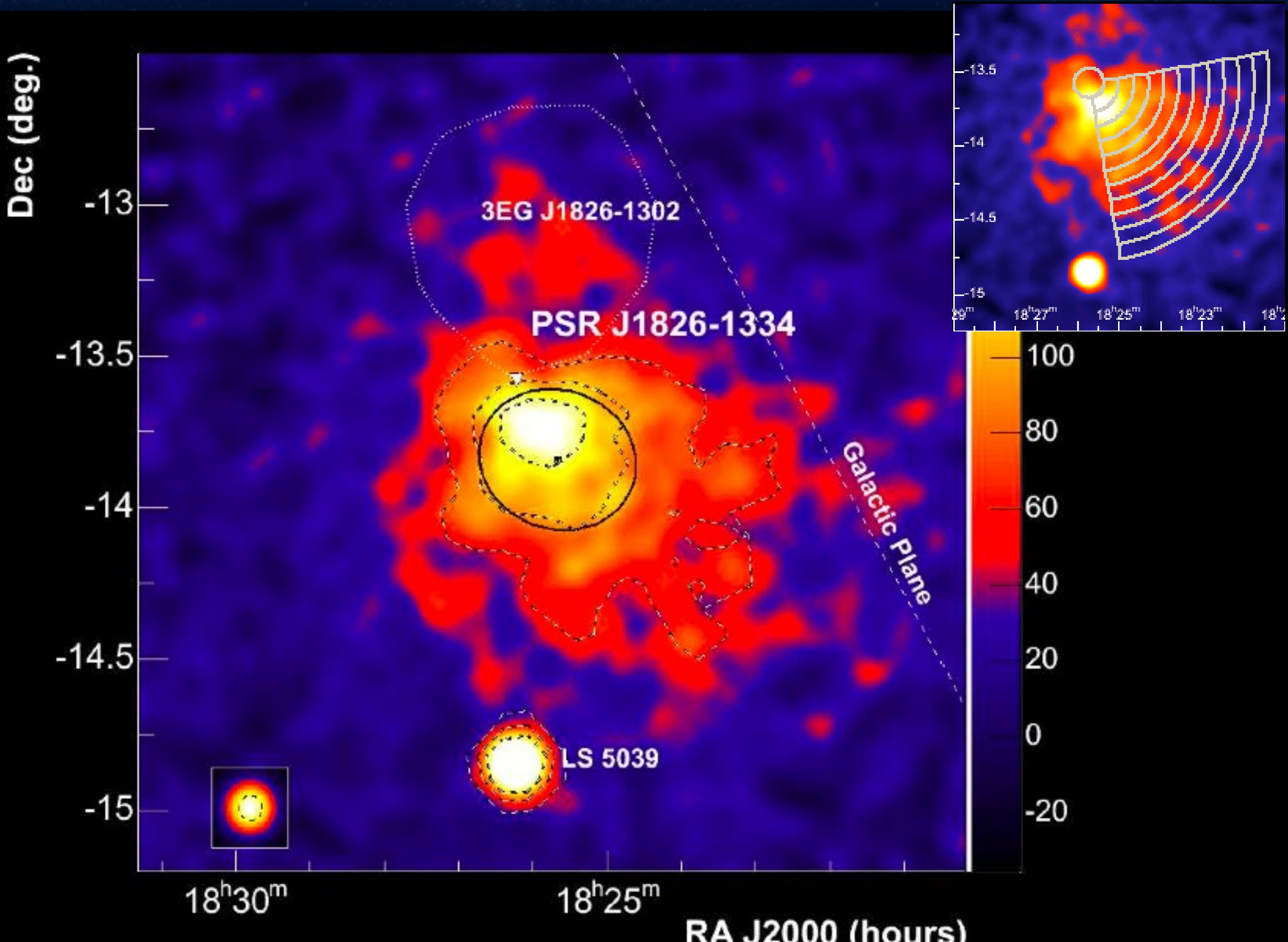
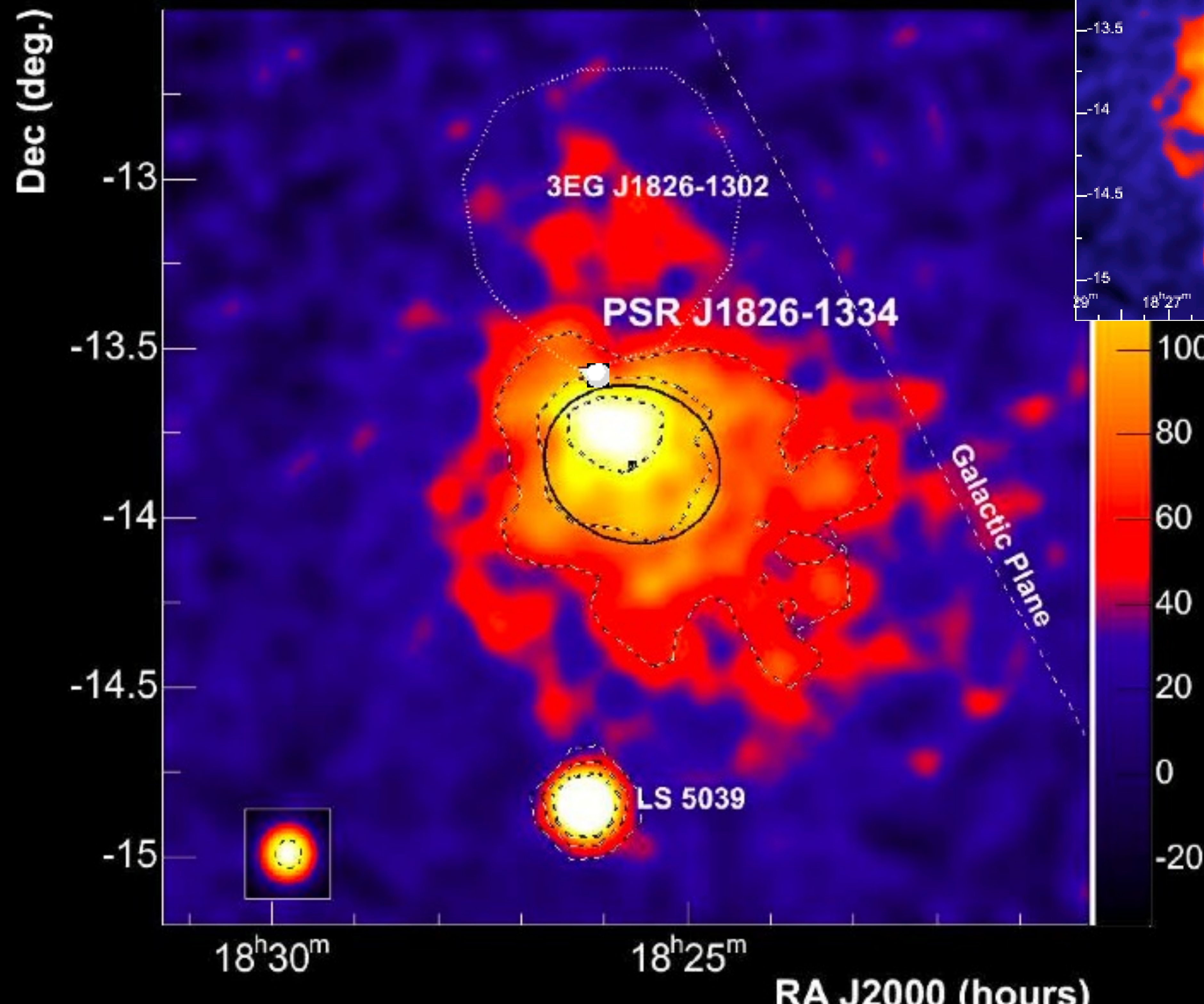
HESS J1825


Dec (deg.)
-13
-13.5
-14
-14.5
-15
3EG J1826-1302
PSR J1826-1334
Galactic Plane
LS 5039
100
80
60
40
20
0
-20
18h30m
18h25m
RA J2000 (hours)
-13.5
-14
-14.5
-15
18h27m
18h25m
18h23m

HESS J1825



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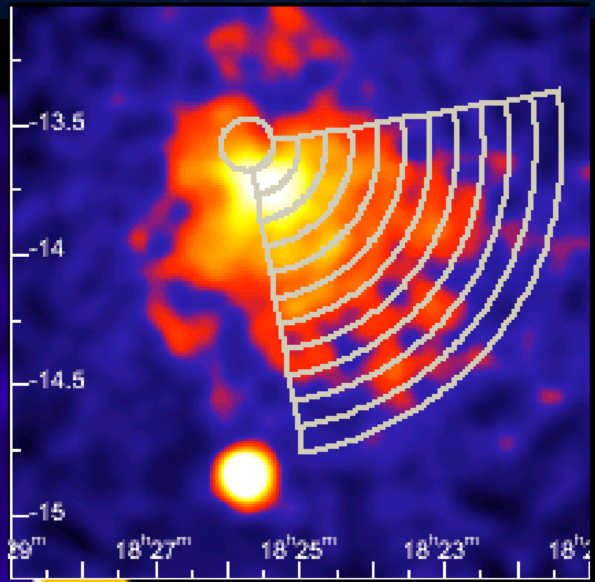
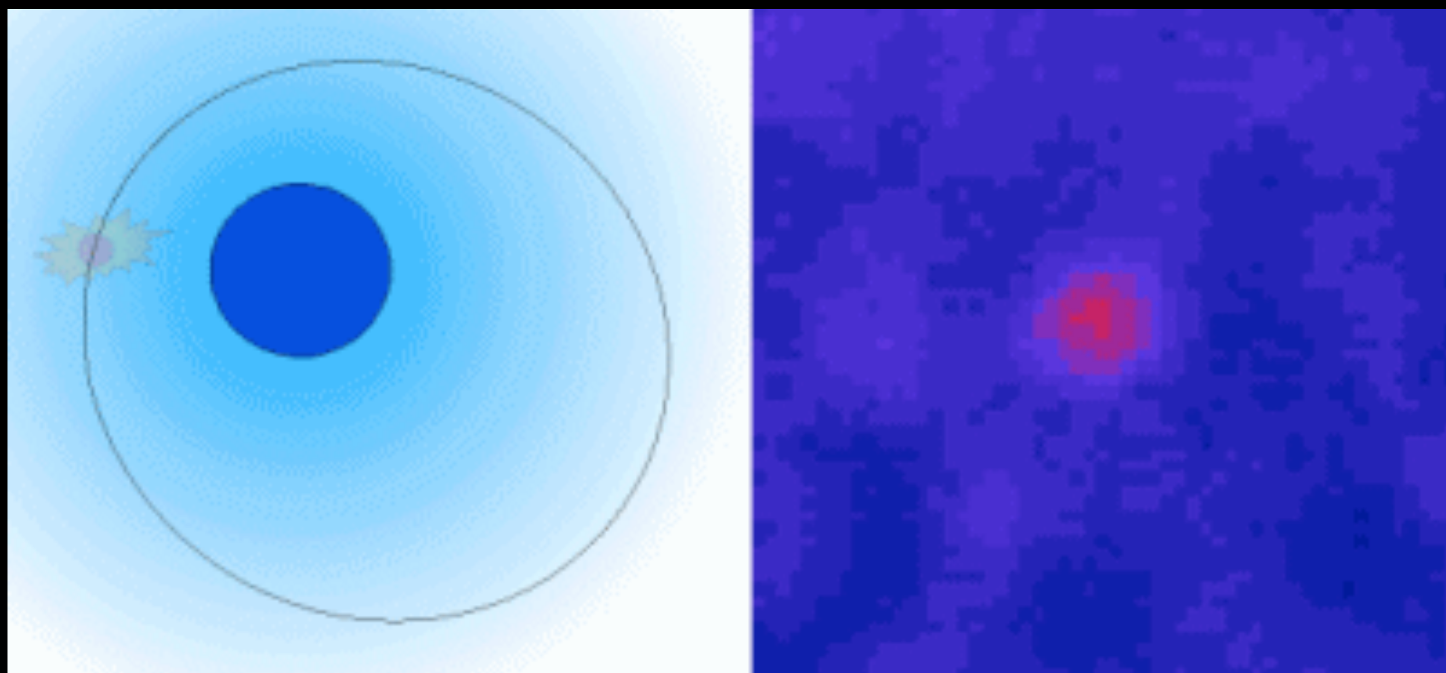
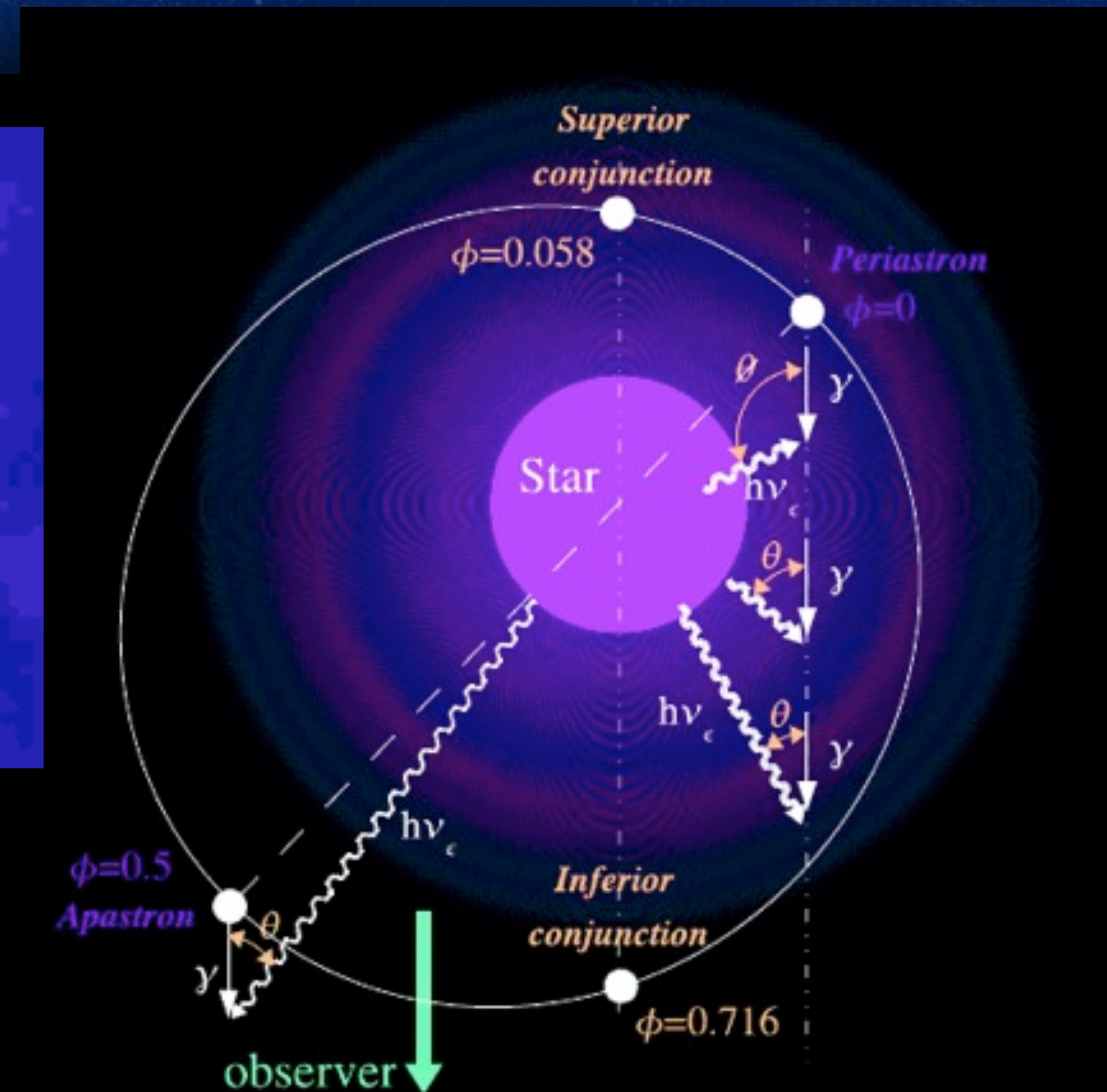
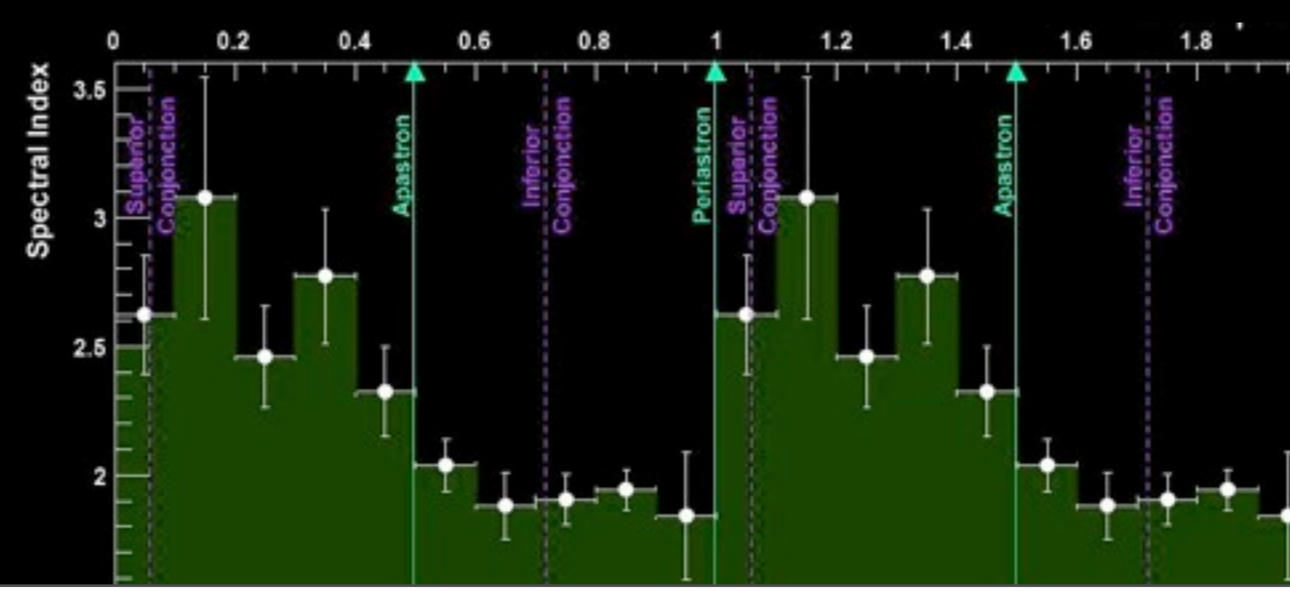


LS 5039

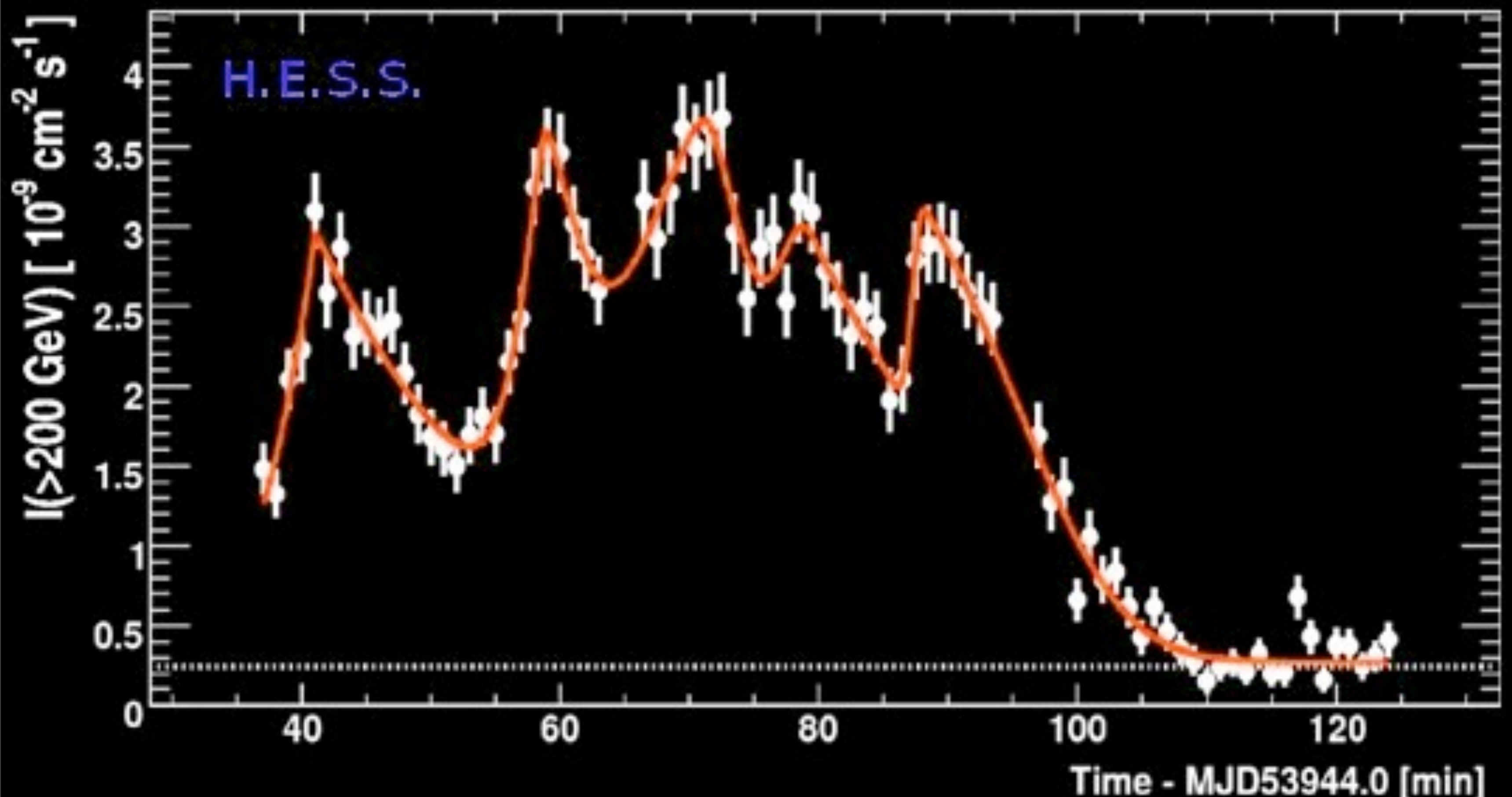




Period:
<u>HESS</u>: 3.908(2) d
<u>Optical</u>: 3.9060 d



AGN Flaring: PKS 2155



F(>200GeV) in 5 minute bins

Aharonian et al ApJL 664, 2007

- **First major AGN flare for Southern hemisphere source**
  - 15x Crab Nebula flux!
- **Variability on 200s timescales! (fastest ever in the field)**
  - Spectra on same timescales!
  - Very small emission region or very high Lorentz factor!

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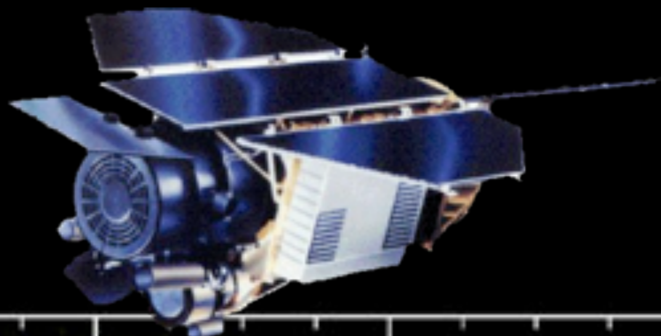

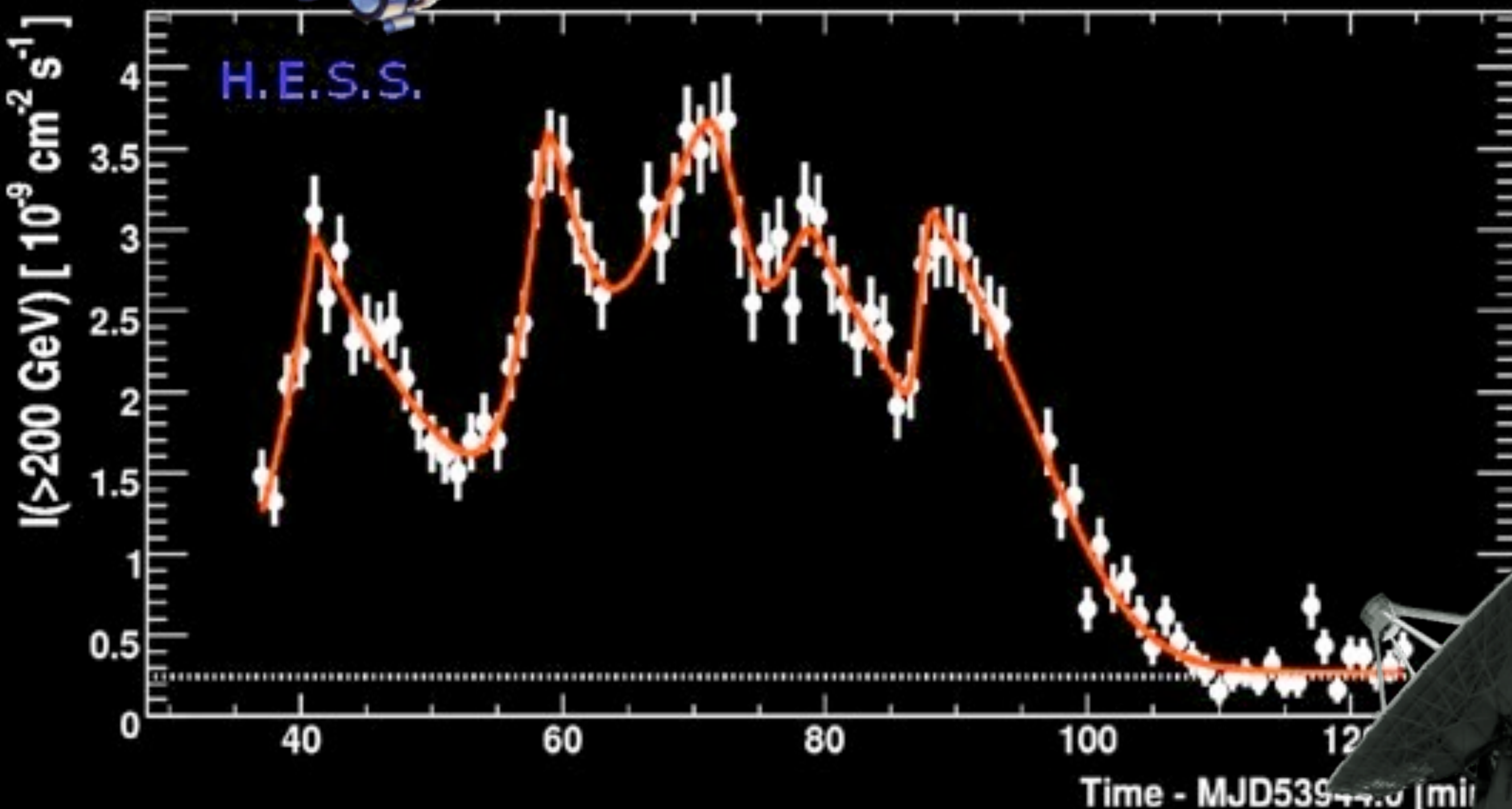

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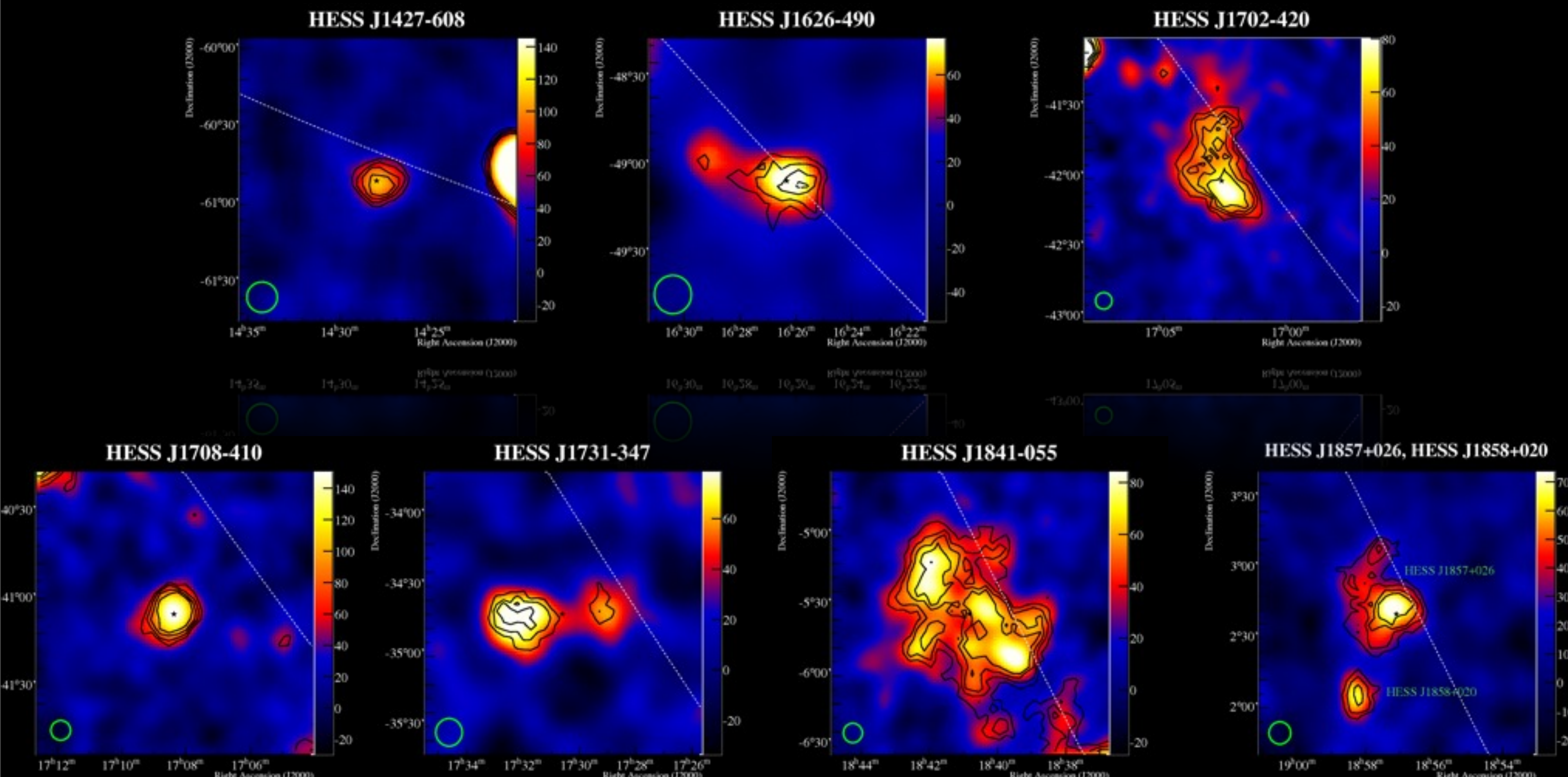
Some Unidentified Sources

Aharonian et al 2008, A&A [K. Kosack]



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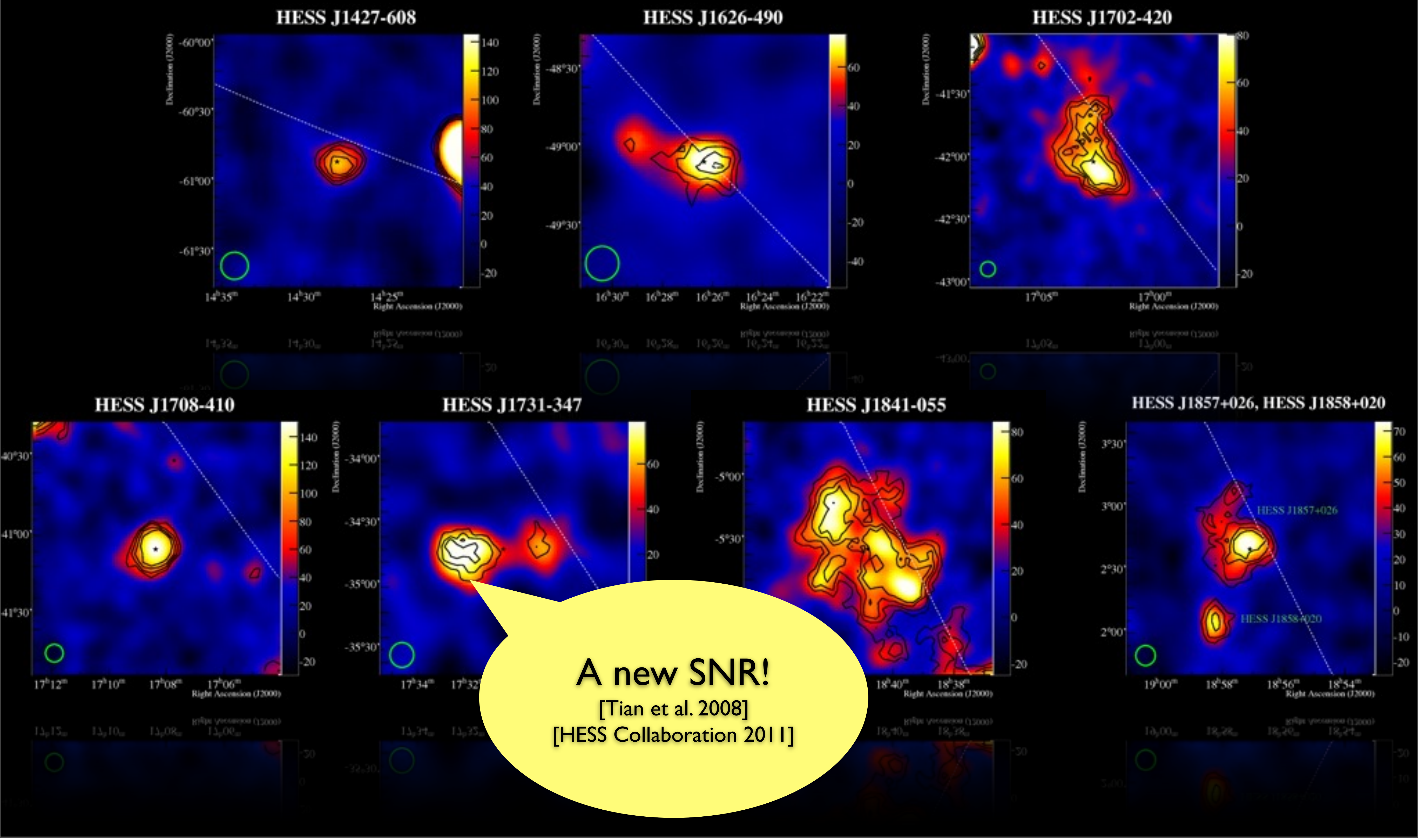

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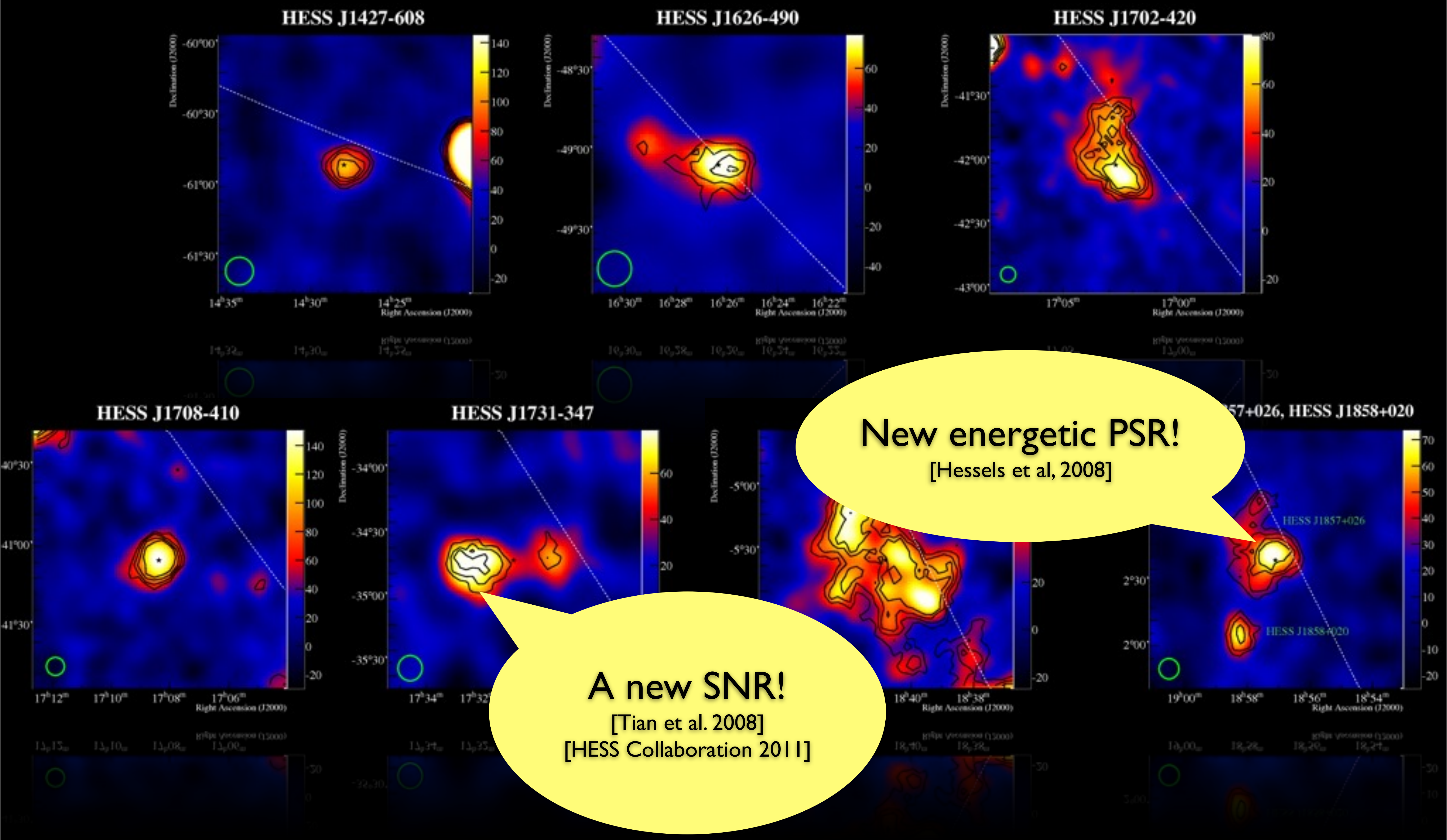
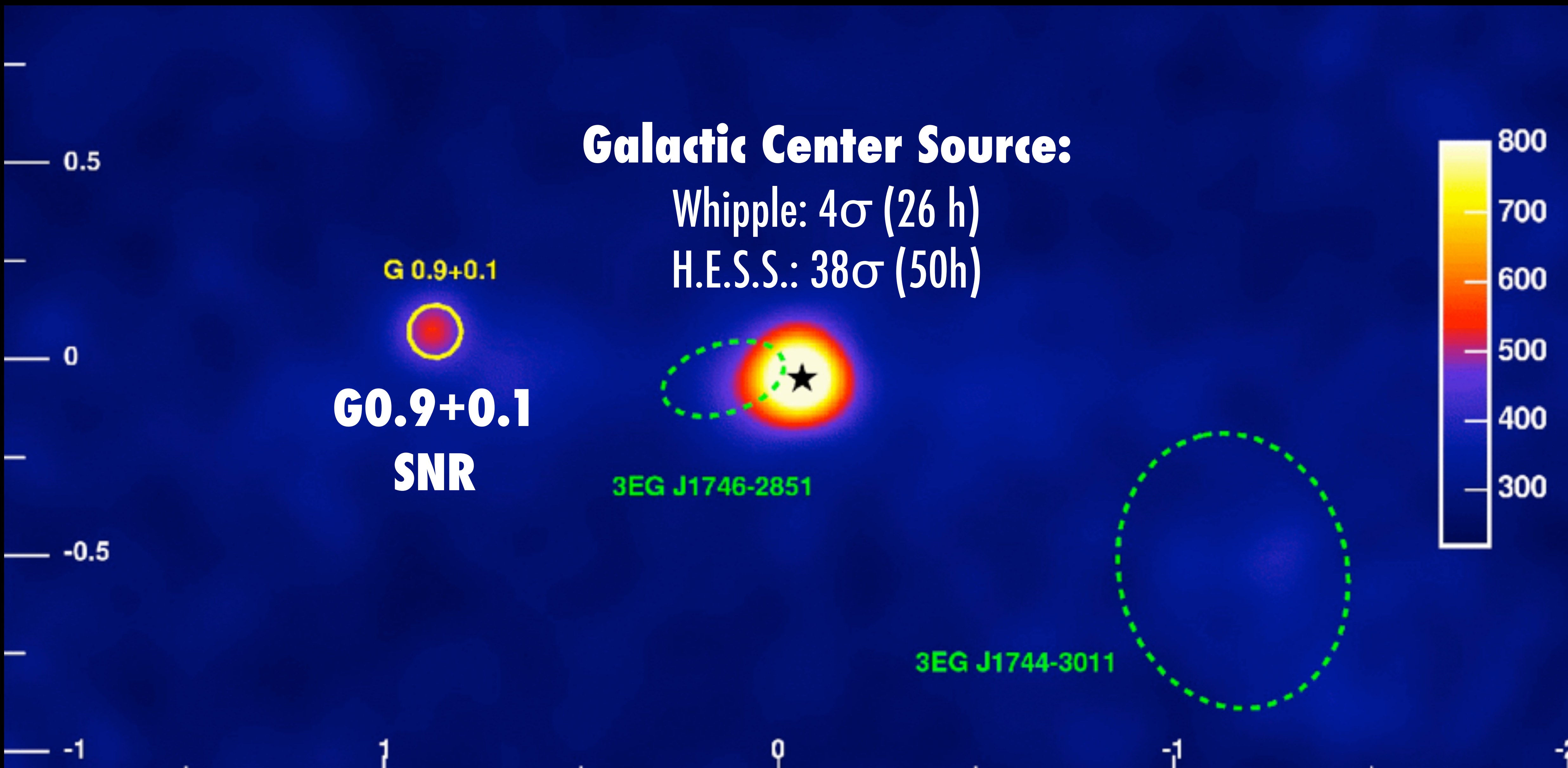


Crab Pulsar

- **Expect to see pulsations from the Crab Pulsar in the GeV energy range...**
  - confirmed by MAGIC in 20XX: first detection of pulsed emission by a VHE gamma-ray telescope
- **The unexpected:**
  - detection above 100 GeV by VERITAS!
  - not predicted by any theoretical model

The Galactic Center



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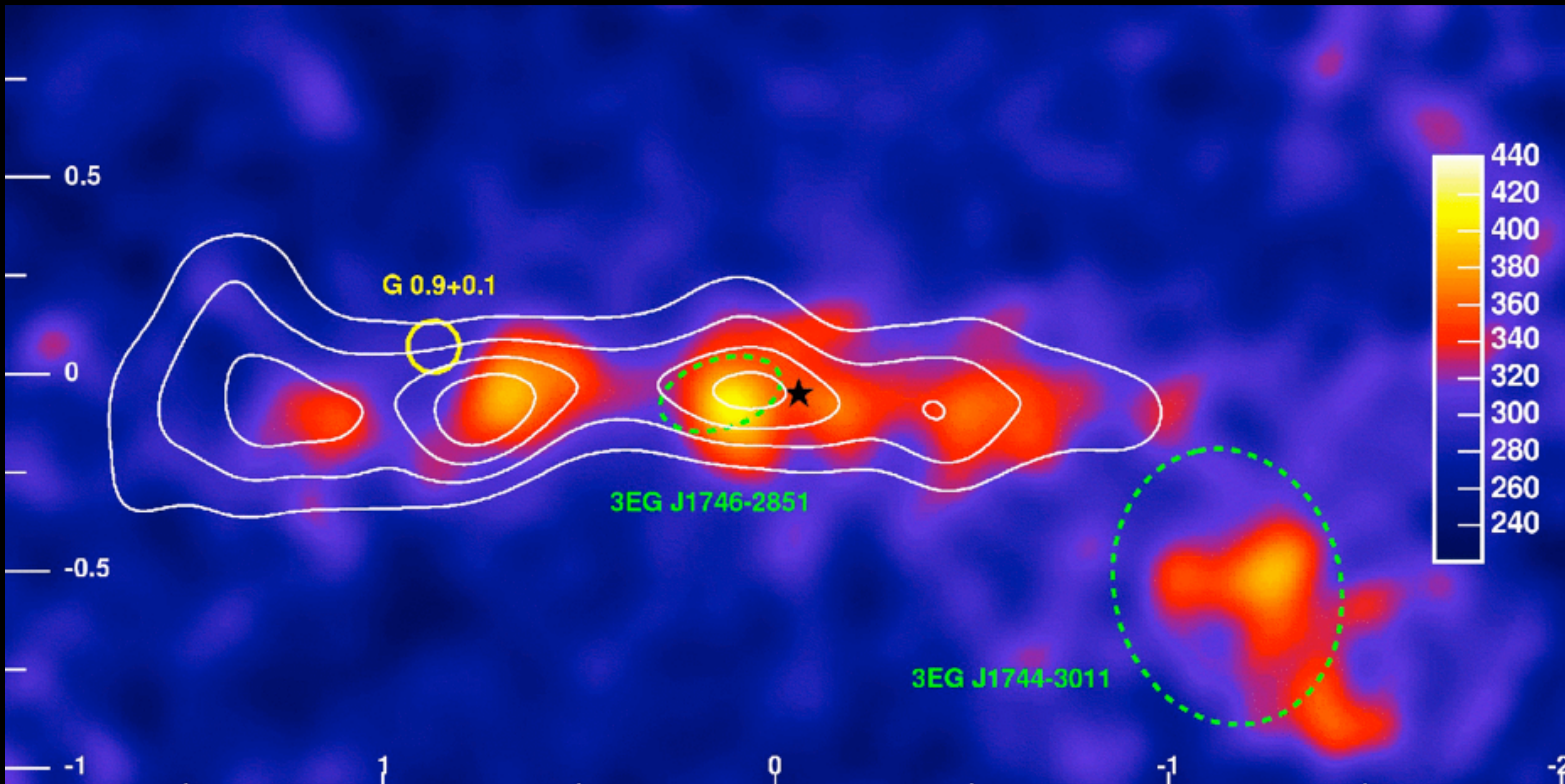

- GC + G0.9 Subtracted: Diffuse emission!
- Interaction of CRs with molecular clouds
  - not consistent with passive illumination (spectral index ≈2.3)

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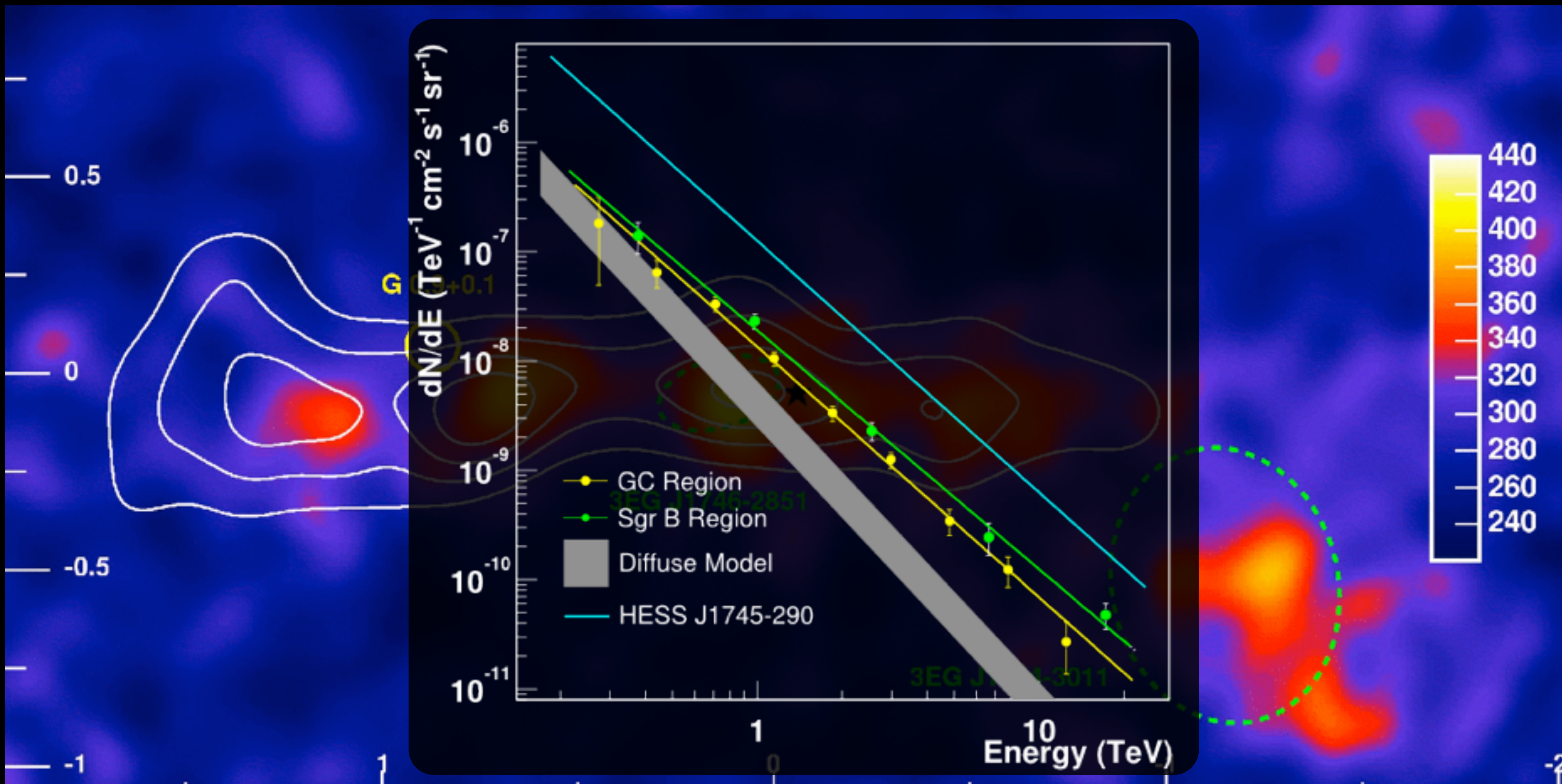

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HESS Galactic Plane Survey