(Future) Experiments for gamma-ray detection

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McGill University

ISSS (GSSI) June 2017

“Cosmic Ray Physics in Space”

Menu

- Antipasti – Introduction & motivation: why study GeV/TeV gammas?
- Primi – Ground-based techniques: the present generation
- Secondi – The way forward: the road to CTA
- Contorni – Other approaches
- Digestivo – Conclusions

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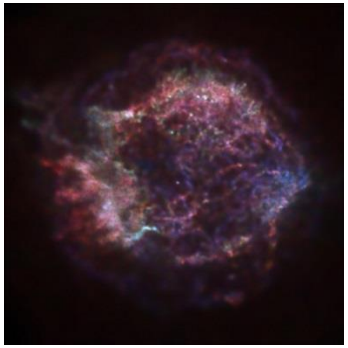
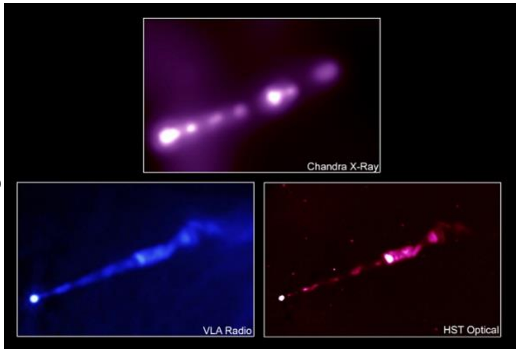
Very high-energy (VHE) gamma-ray astrophysics

- At E> 100 GeV (VHE), several classes of sources known…
  - Galactic:
    - Supernova Remnants
    - Pulsar Wind Nebulae
    - Binary systems
  - Extragalactic:
    - Active Galactic Nuclei
    - Starburst galaxies

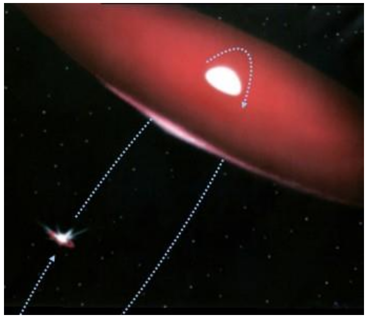
- …or possible:
  - Gamma-Ray Bursts?
  - Dark-matter annihilation?
  - FRBs?
  - GW/ν counterparts?


Cas A – XMM Newton

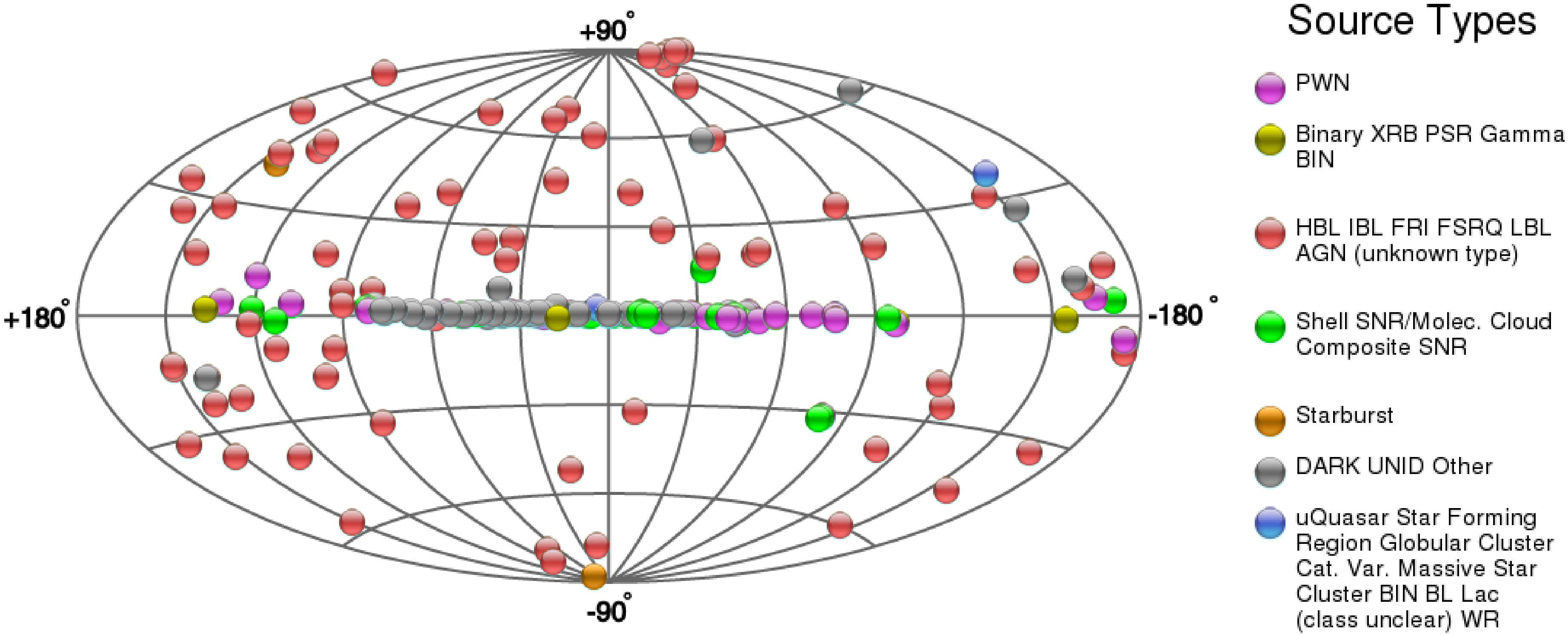

Crab: HST + Chandra



M87


PSR B1259

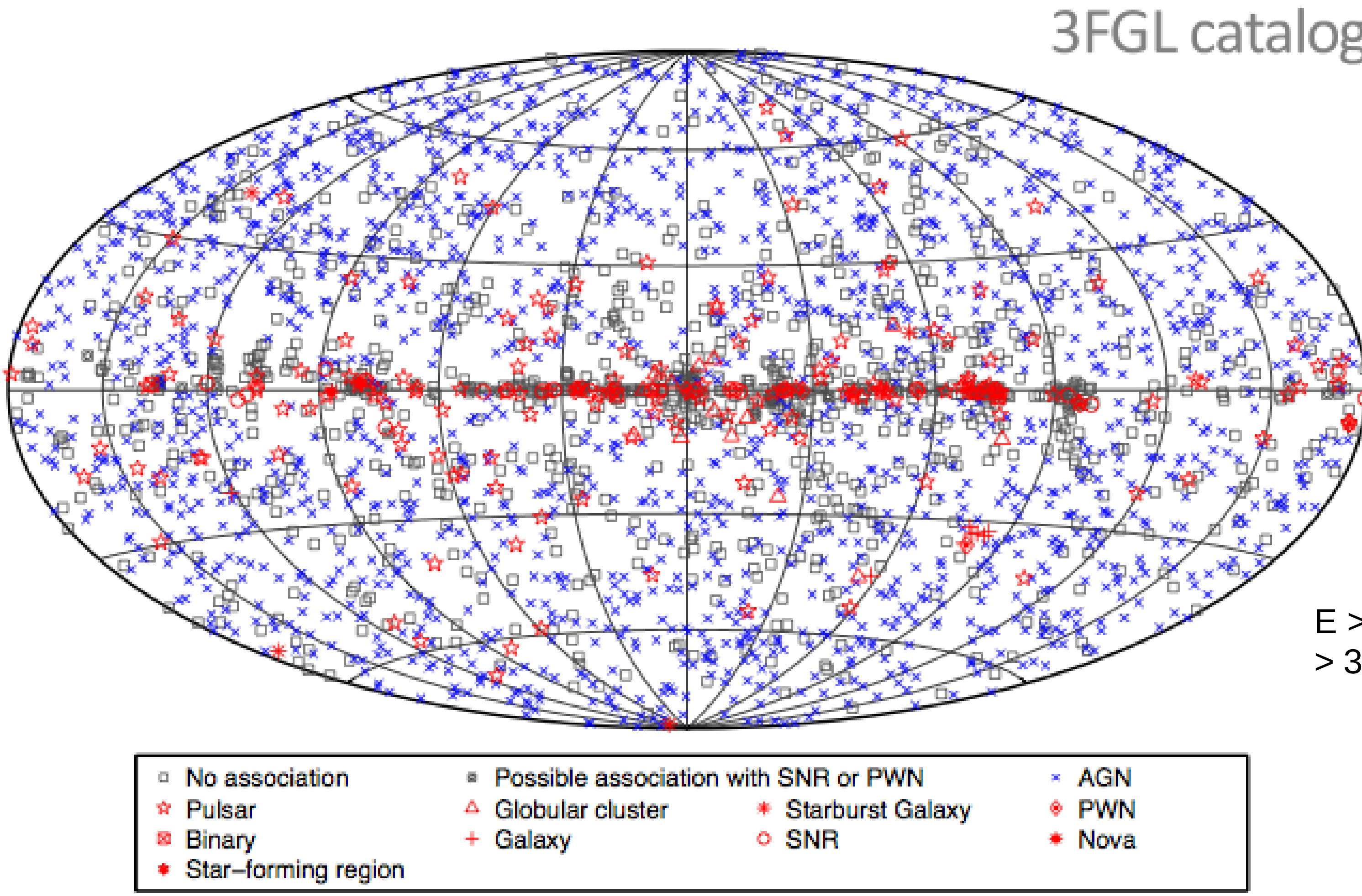
The VHE sky



tevcat.uchicago.edu

~ 200 confirmed sources (up from ~10 at turn of the millenium)

The gamma-ray sky (*Fermi*-LAT 3FGL)



E > 100 MeV
> 3000 sources

VHE gamma-ray sources: the physics

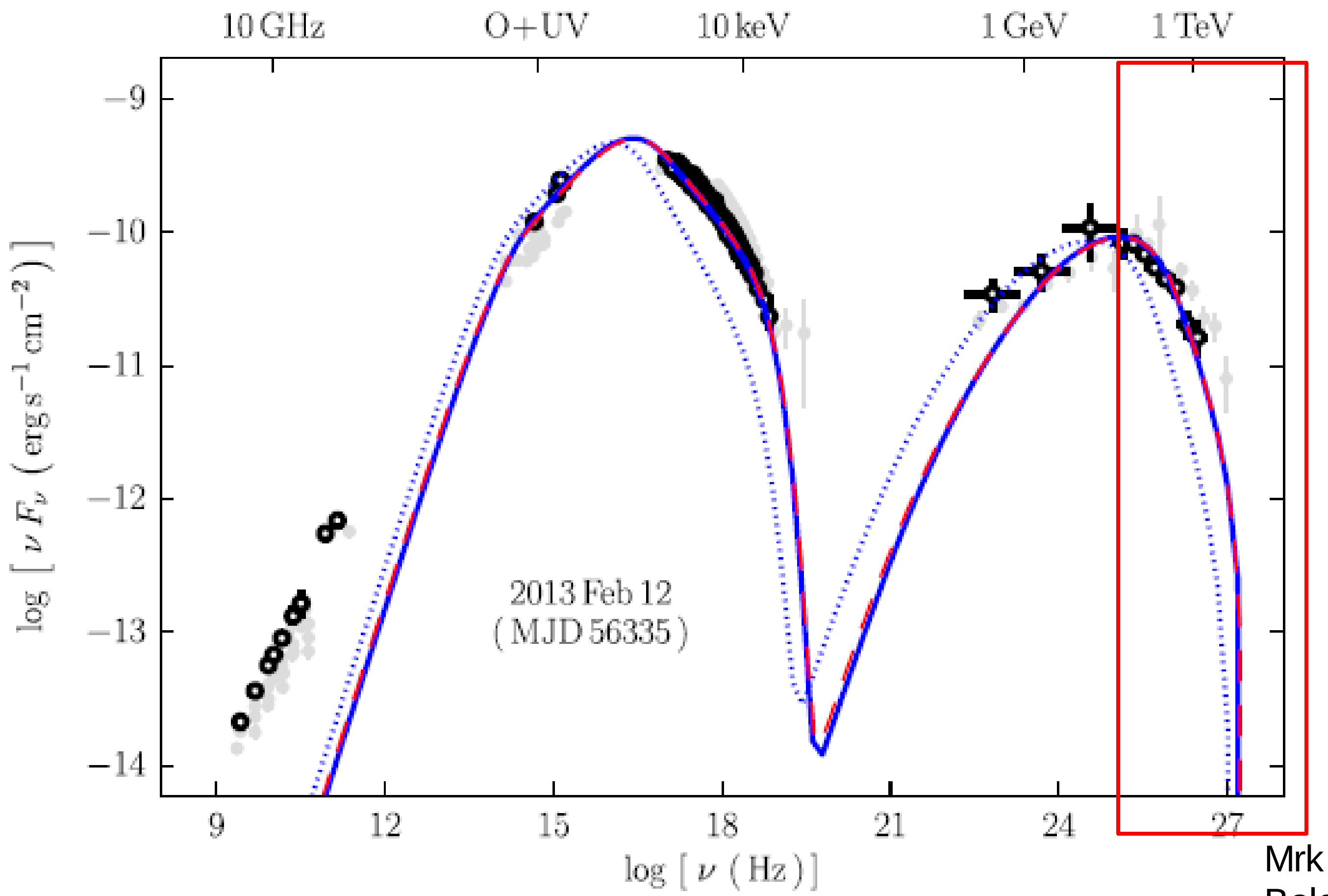
- Crab (nebula) is most constant source in sky;
  Flux (E> 1 Tev) ~ 2×10^{-7} $\gamma/m^2/s$ (~ a few $\gamma/ m^2/yr$)

- All sources have two-component SEDs and ~power law ($E^{-\gamma}$) spectra in VHE regime

- Multi TeV γ imply source populations (p, e) at higher energy
  - What is the source population?
  - How do they get accelerated to these energies?

- Dominant production processes believed to be:
  - Inverse Compton scattering (of lower energy photon population)
  - π^0 production & decay

"Typical" spectral energy distribution



Mrk 421
Balokovic et. al. 2016

VHE gamma-ray production

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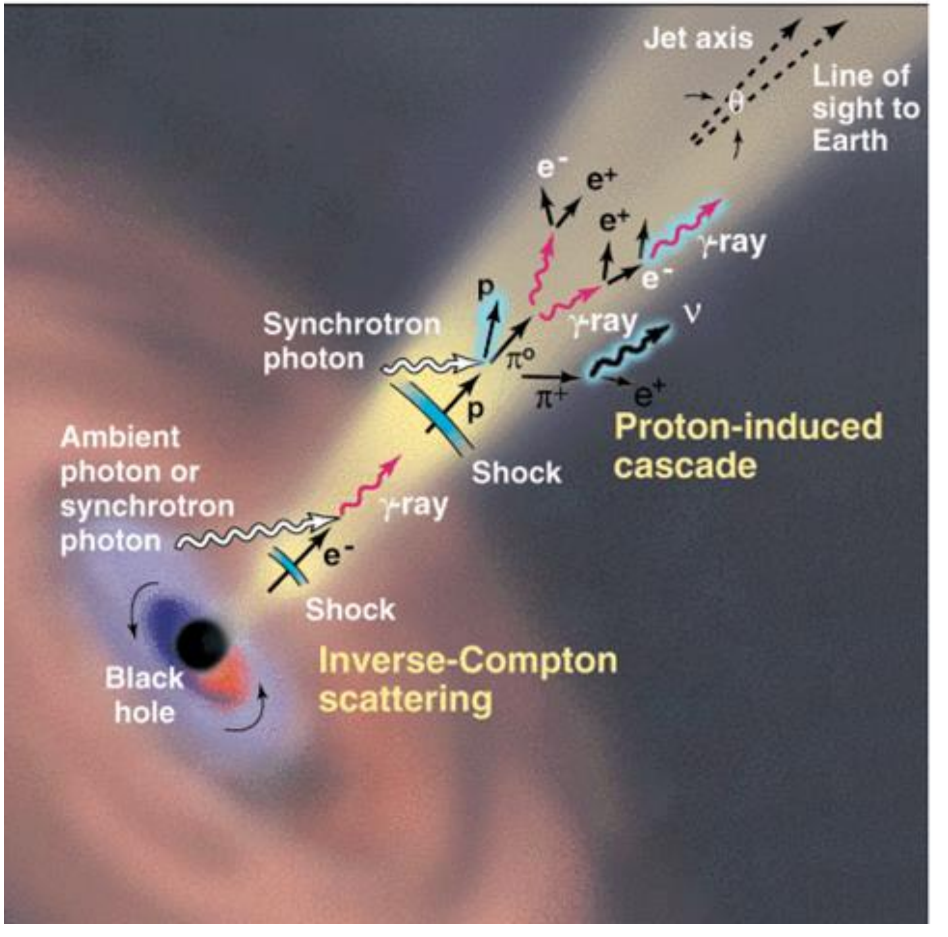
  - π^0 production & decay



VHE gamma-ray sources as a tool

- Multi-wavelength, multi-particle studies to disentangle production issues
- Potential VHE emission from transients/other phenomena:
  - GRBs
  - FRBs
  - gravitational wave events
  - high energy neutrinos (IceCube, Km3Net)
- Sensitivity to other fundamental particle physics issues…:
  - dark matter annihilation
  - primordial black holes
  - energy-dependent *c*
- *…*and even to cosmic-ray issues:
  - high-energy electron spectrum
  - high-Z flux (Fe)

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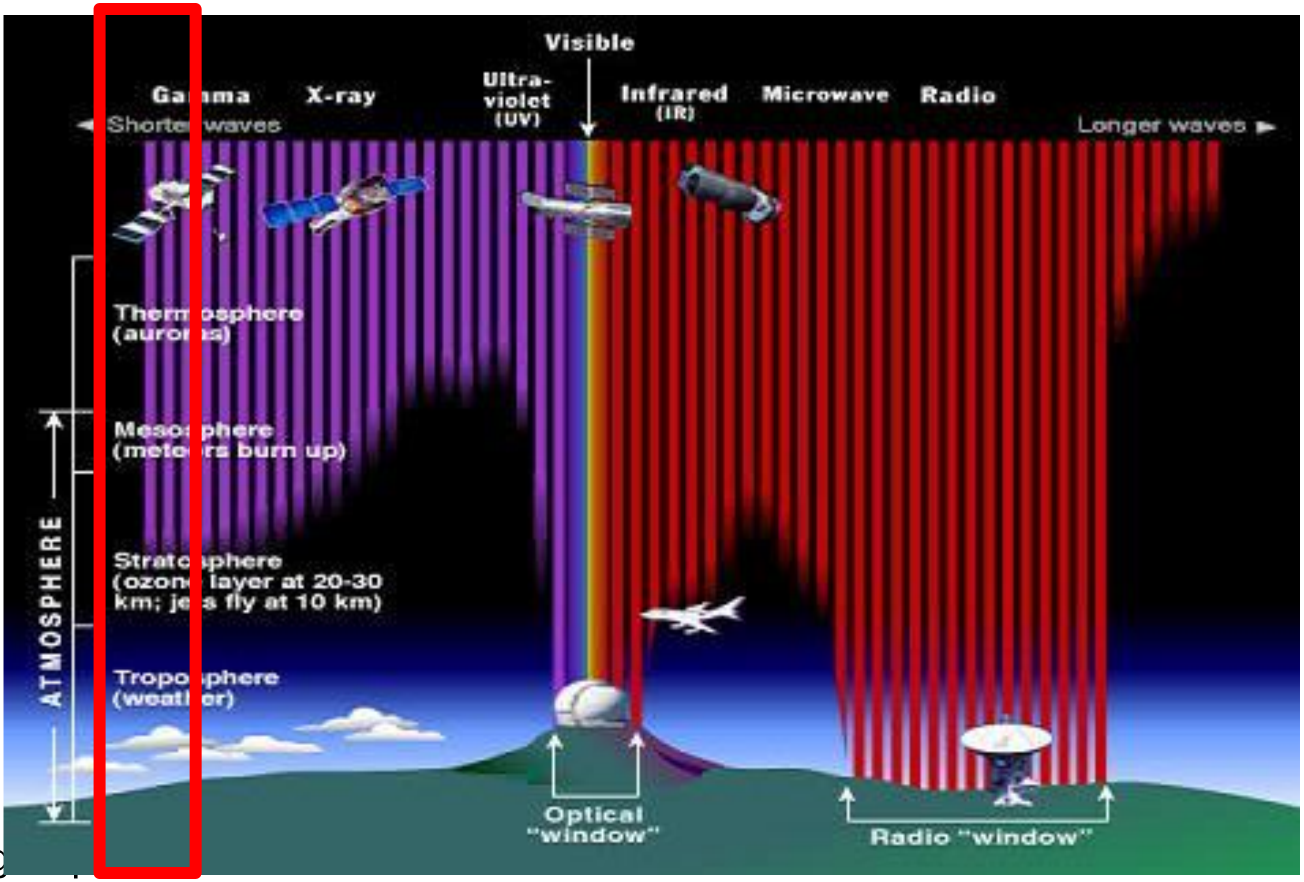
The VHE regime: three major challenges

- Fluxes are low: Crab in VHE is ~ a few γ/ m^2/yr
- VHE gamma-rays are a small part (~10^{-4}) of the *cosmic ray* flux
- Atmosphere is opaque in VHE regime:



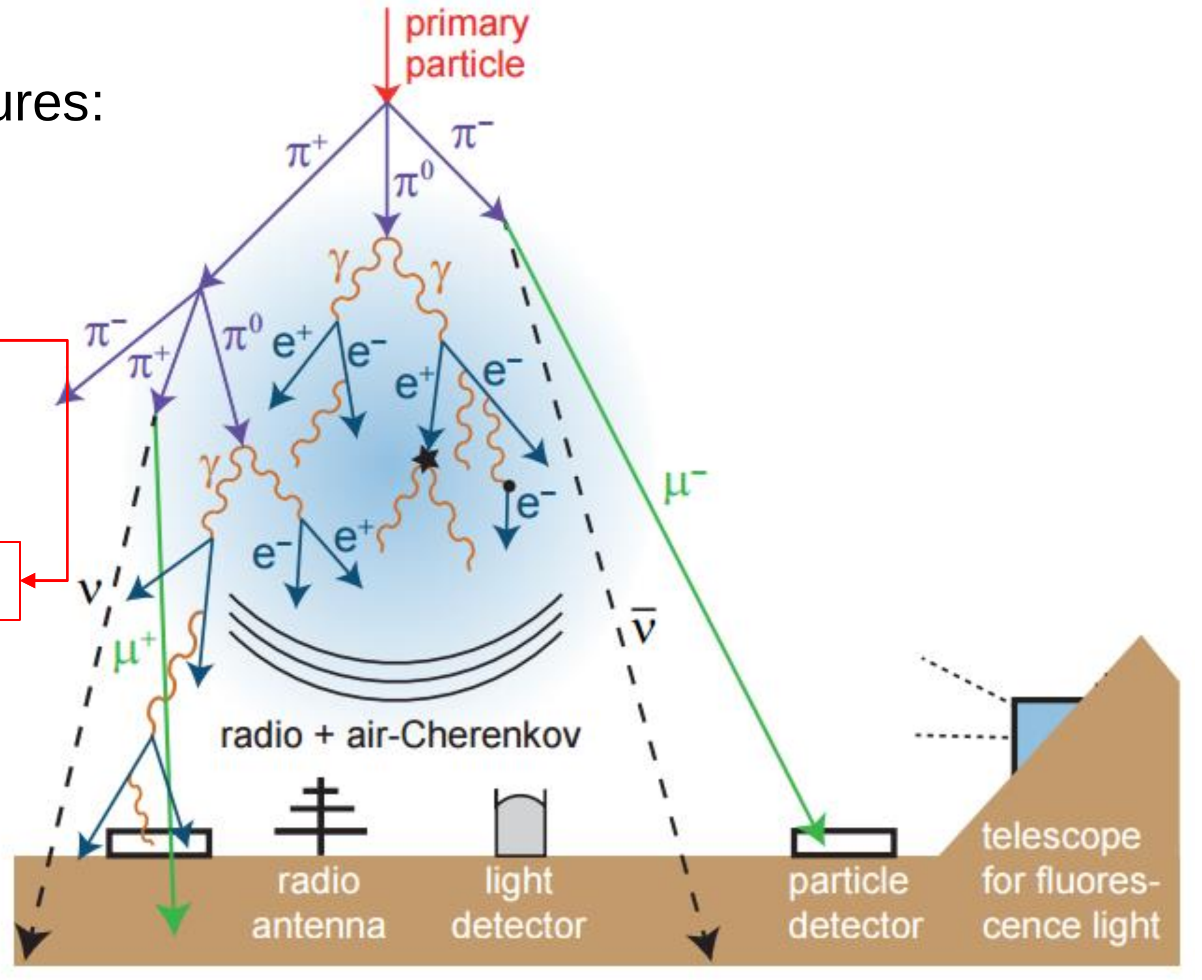
Cosmic ray interactions in the atmosphere

Multiple possible experimental signatures:

- radio
- particles
- Cherenkov light
- air fluoresence

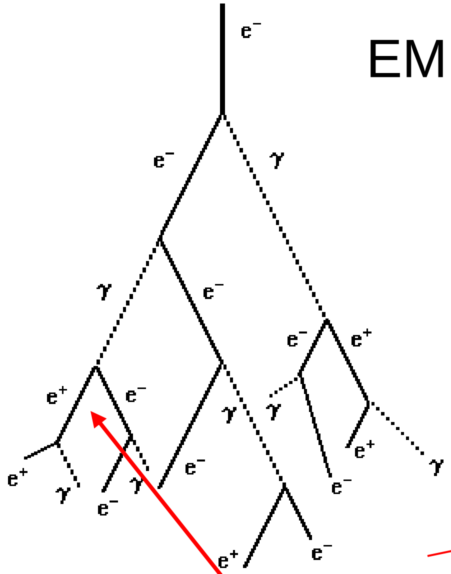
most of this talk

See 'contorni' later



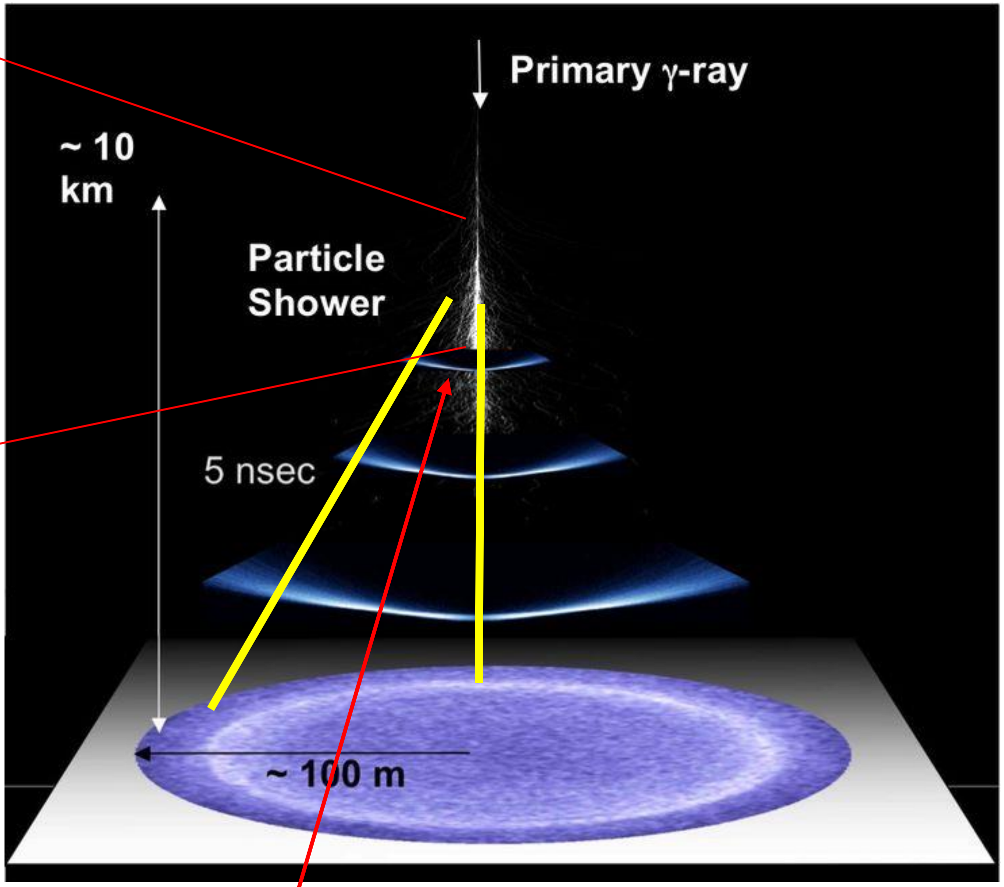
Schroder (2017)

Gamma-ray interactions in the atmosphere



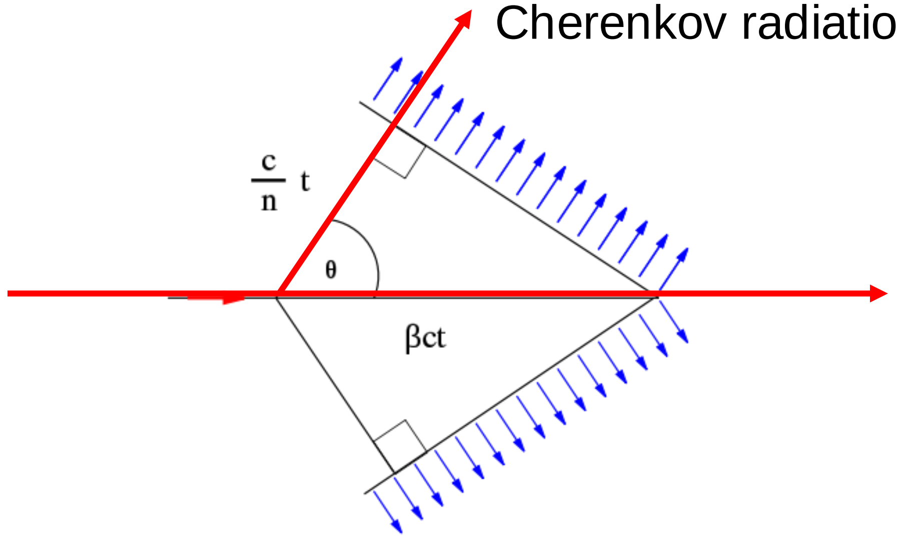
EM shower

Charged secondaries
produce Cherenkov light



Cherenkov angle = ~ 1°

Cherenkov radiation



Cherenkov angle: $\cos(\theta) = 1/n\beta$

$n_{atmosphere} \sim 1.000x \rightarrow \theta \sim 1^o$

Number of photons:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Cherenkov light: the atmosphere as calorimeter

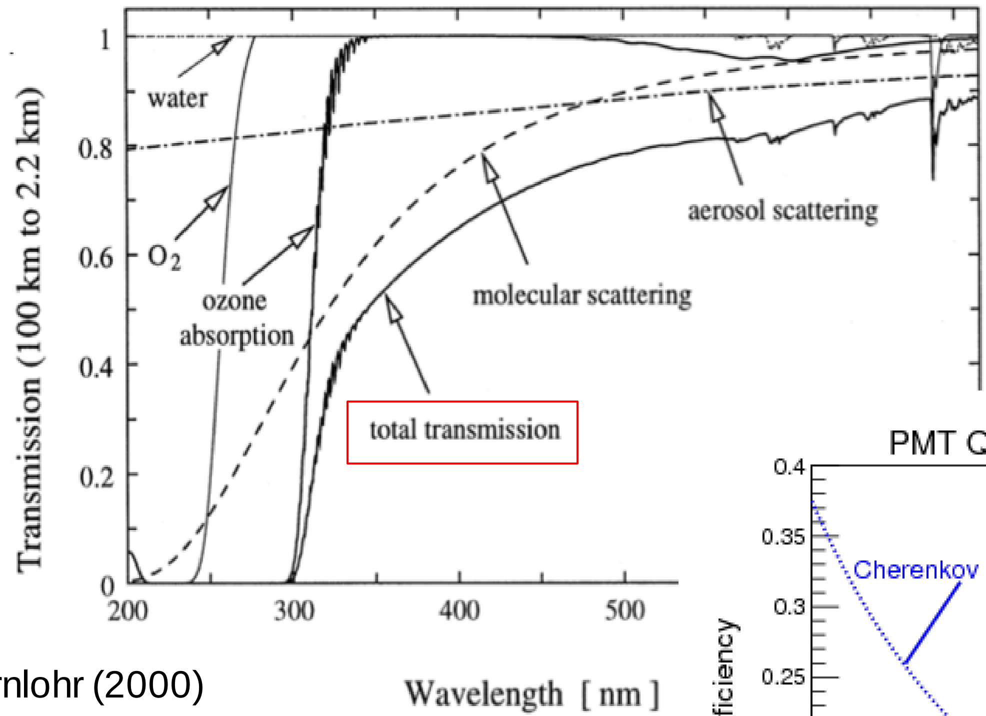
- λ^{-2} spectrum extends into regime of atmospheric transparency and "easy" photon detection
- Small Cherenkov angle – i.e., directional
- Light pool: large area on ground (~10^5 m^2)
- Light output ~ proportional to primary energy ("calorimetric")
- Fast signal ('pancake' ~5 ns in thickness)

Cherenkov light: well-suited to gamma-ray detection

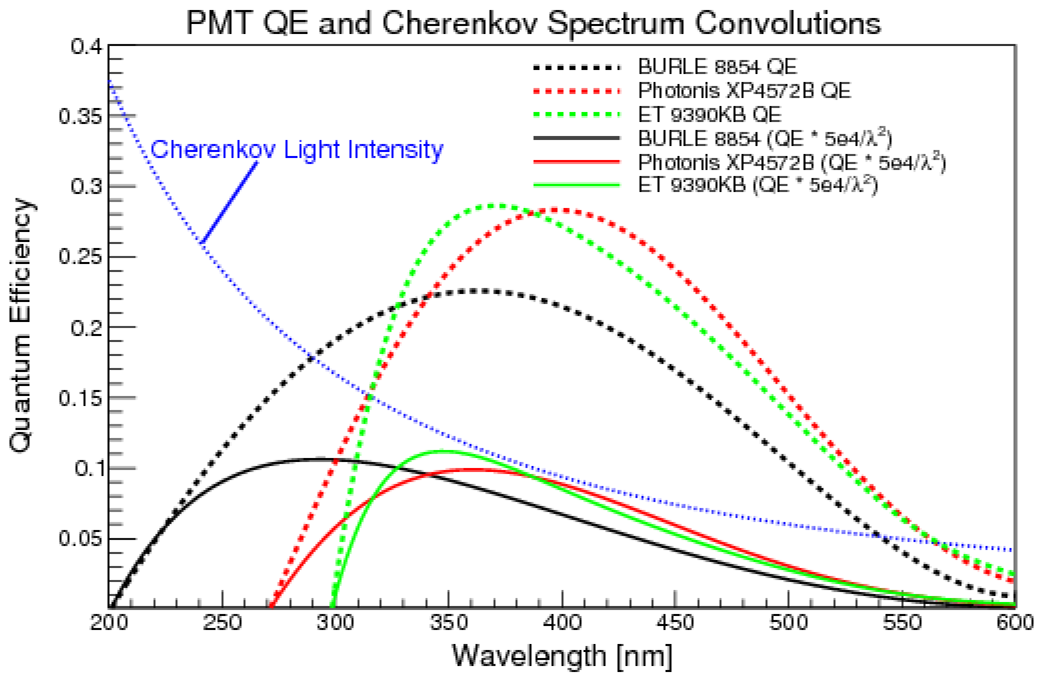
The atmosphere:
- ~ 27 Xo
- ~ 11 λ_I

Pretty good (EM) calorimeter

Atmospheric transmission & PMT response



Bernlohr (2000)



Convergence

Atmospheric Cherenkov Technique (ACT) is a happy convergence of

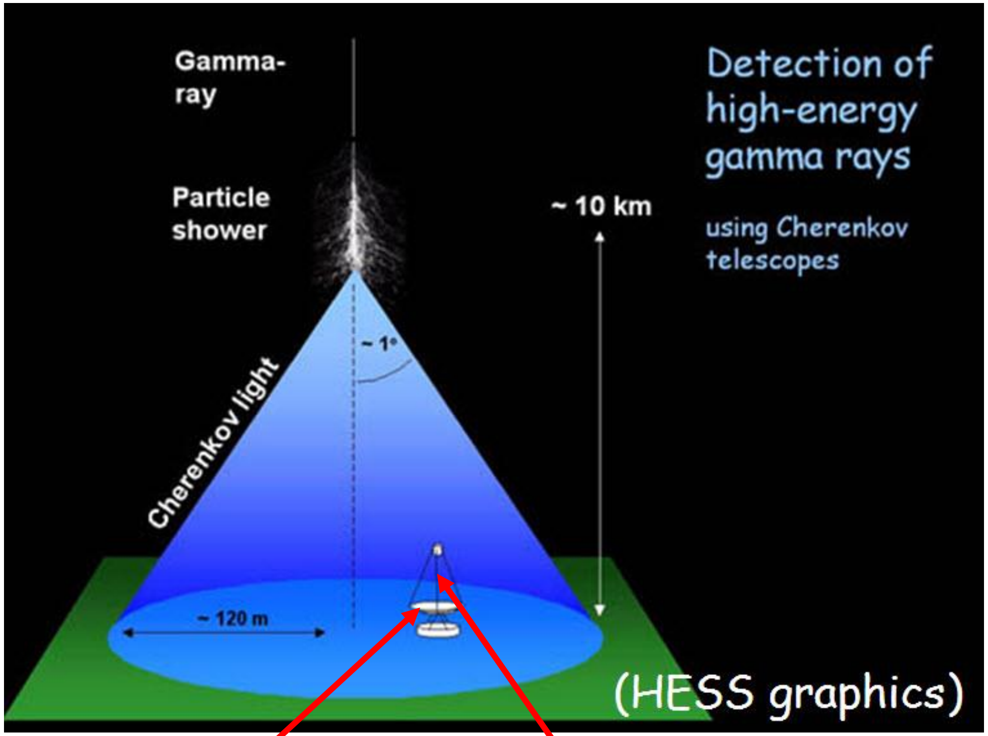
- Small Cherenkov angle → directionality/pointing

- Cherenkov spectrum (λ^{-2})
- Atmospheric transmission (λ >300 nm)
- Photomultiplier quantum efficiency window

- Photomultiplier response
  - in time (t < 10 ns is "easy") → triggerability
  - to single photons → sensitivity

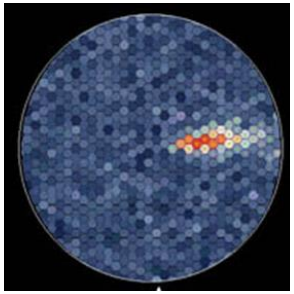
Result is a sensitive, robust means of detecting showers.

The atmosphere becomes part of our detector



- Every point in the Cherenkov light pool “sees” the shower, so effective area becomes size of light pool ~ 10^5 m^2
- Size of shower image will be ~Molière radius/few km ~ 1/2°
- Photon density in the light pool will be energy estimator – better light collection will lower the threshold

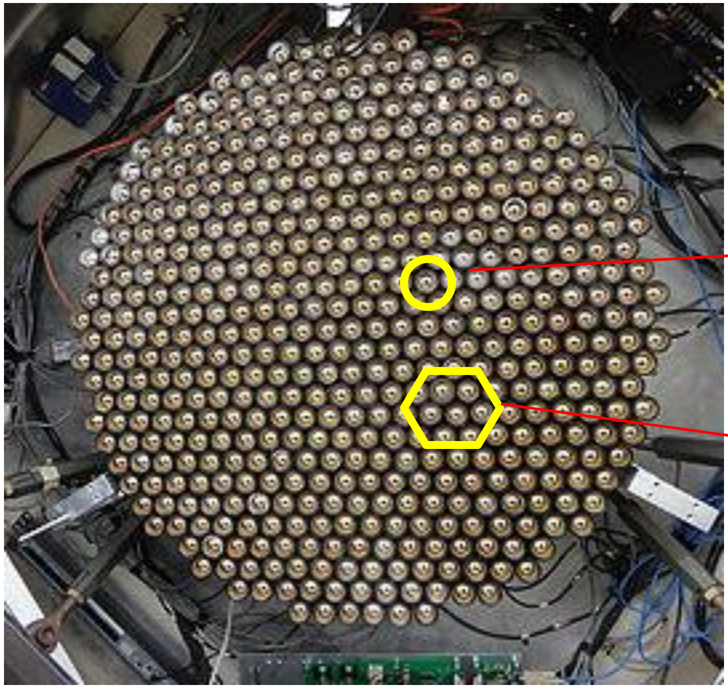
Telescope to image Cherenkov light



View of shower in focal plane of telescope

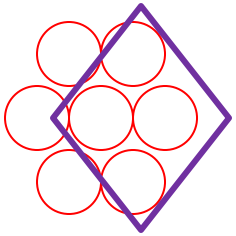
Pixelated cameras can detect individual air showers

Rapidity of Cherenkov signal (~5 ns):
- well-matched to PMT response times
- allows detector to be triggered on individual showers


VERITAS camera, 499 PMTs

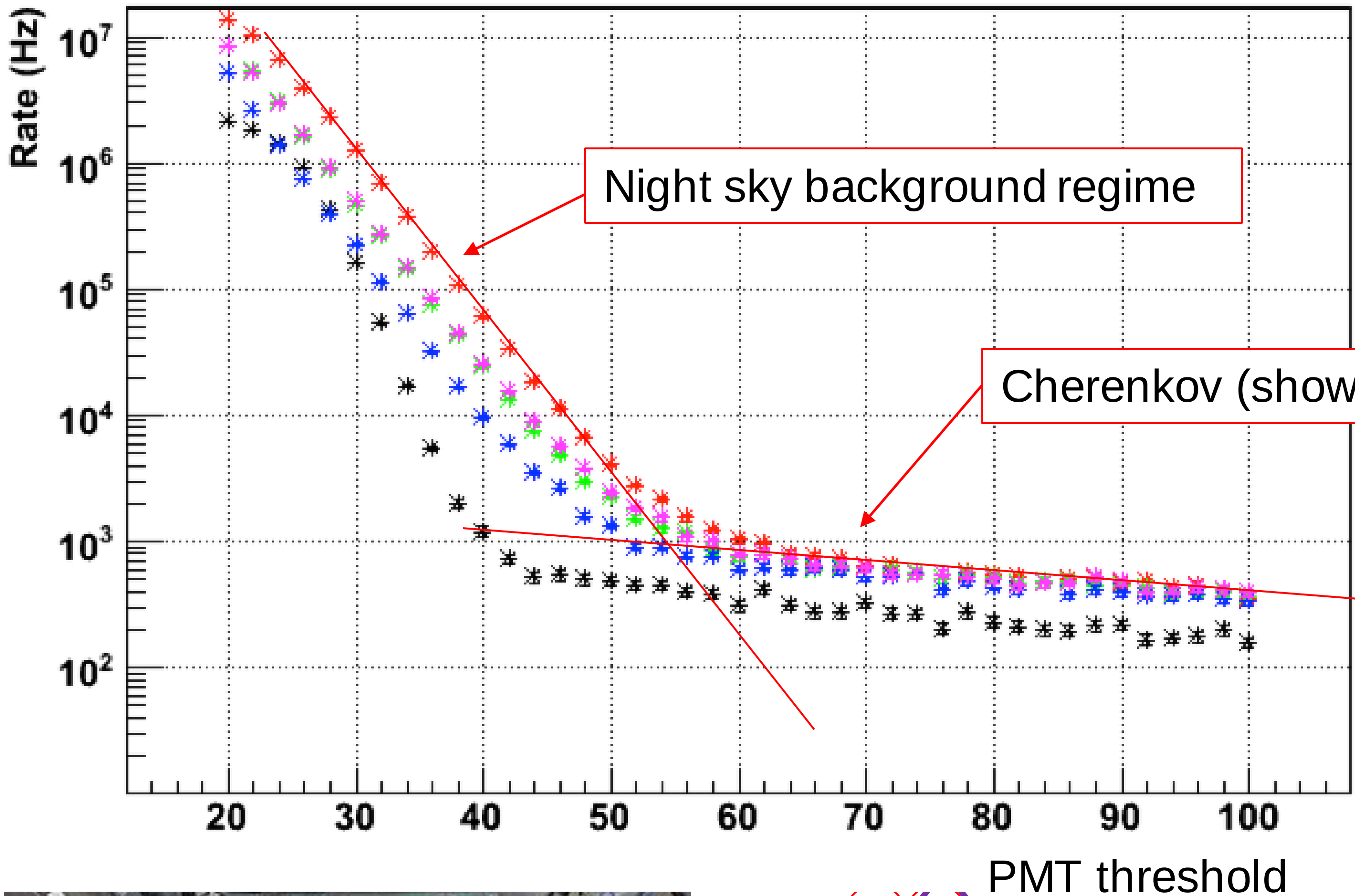
Individual PMT sees night sky background at ~10^5 Hz

Hexagonal unit cell tiled by (overlapping) trigger groups of four (require three to be hit)



ers

VERITAS telescope trigger rate curve



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Hz

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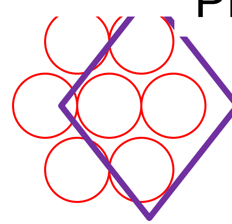
VERITAS camera, 499 PMTs



What about CR background?

Cherenkov radiation provides a means of detecting gammas – what about the *cosmic ray background*?

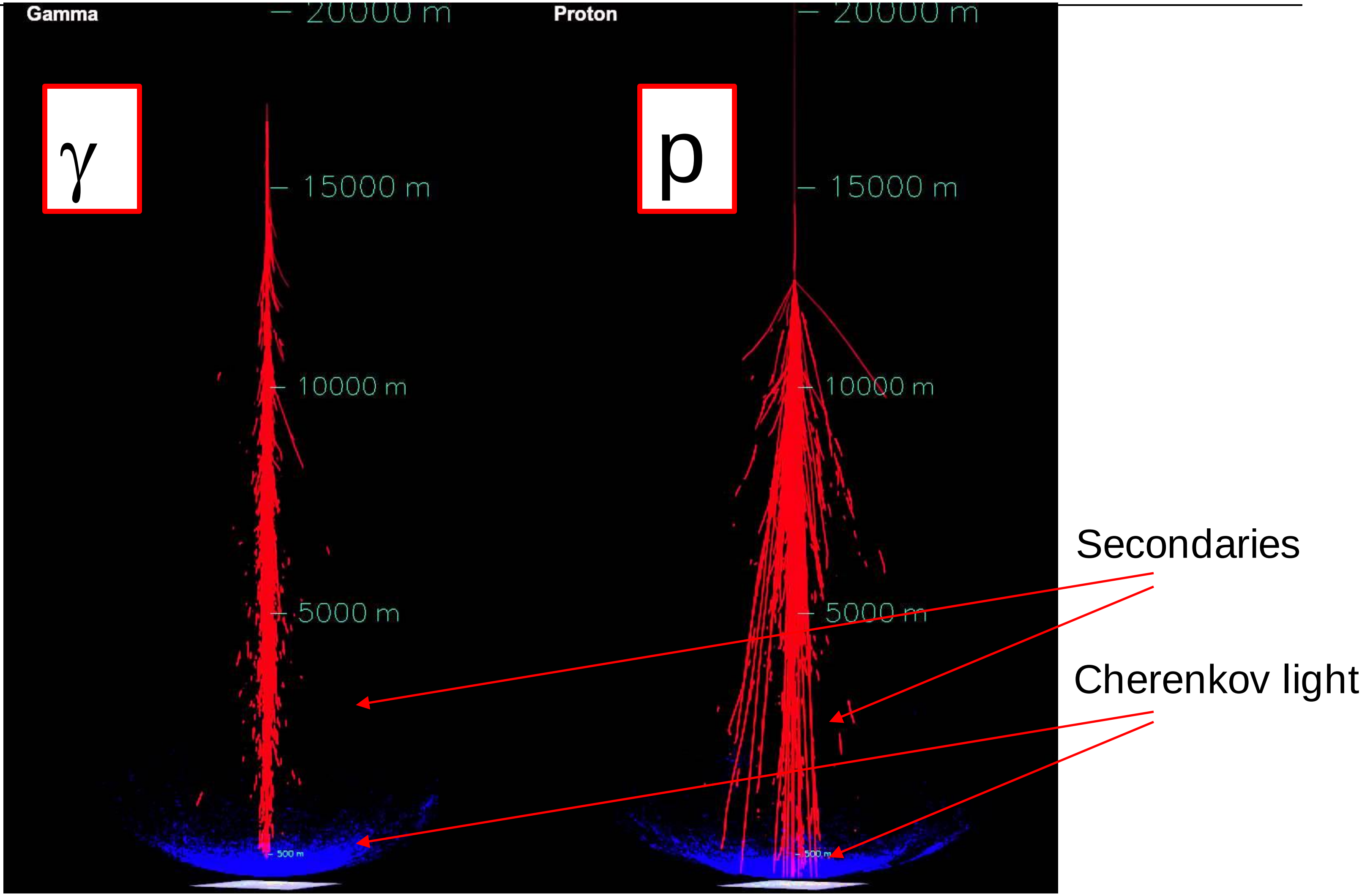
Recall: CR are ≥10^4 times more common than gamma rays.

Use differences between CR showers and gamma-ray showers – i.e. between hadronic showers, and EM showers:

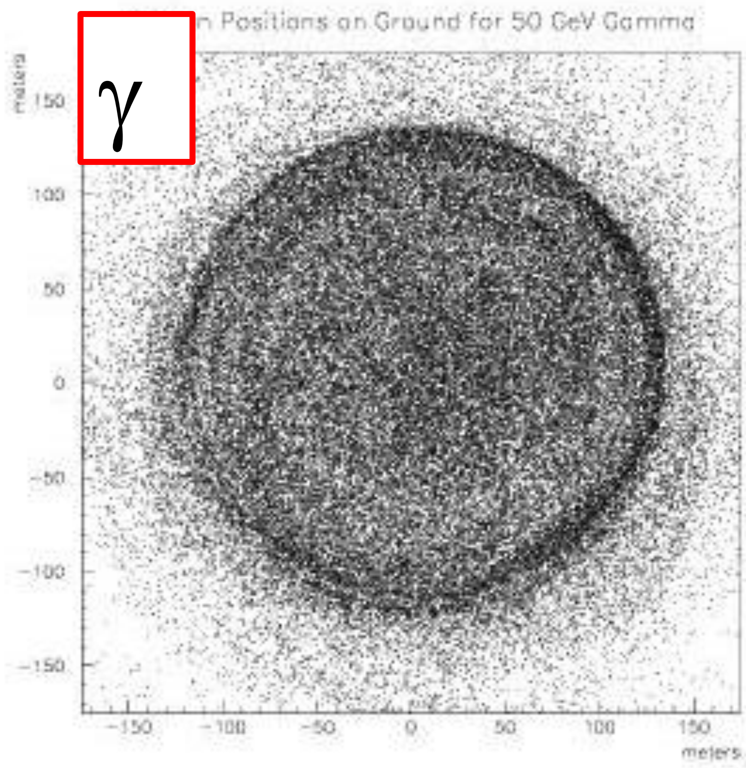
EM: uniform, compact
CR: more irregular, broader

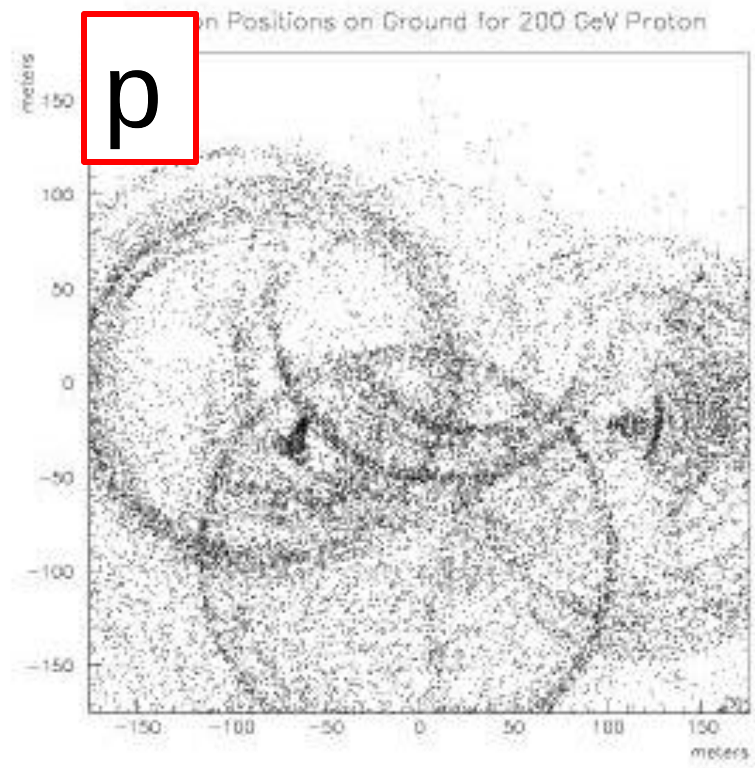
Image analysis is a key part of the ACT: need fine-grained cameras

EM vs. hadronic showers: simulations

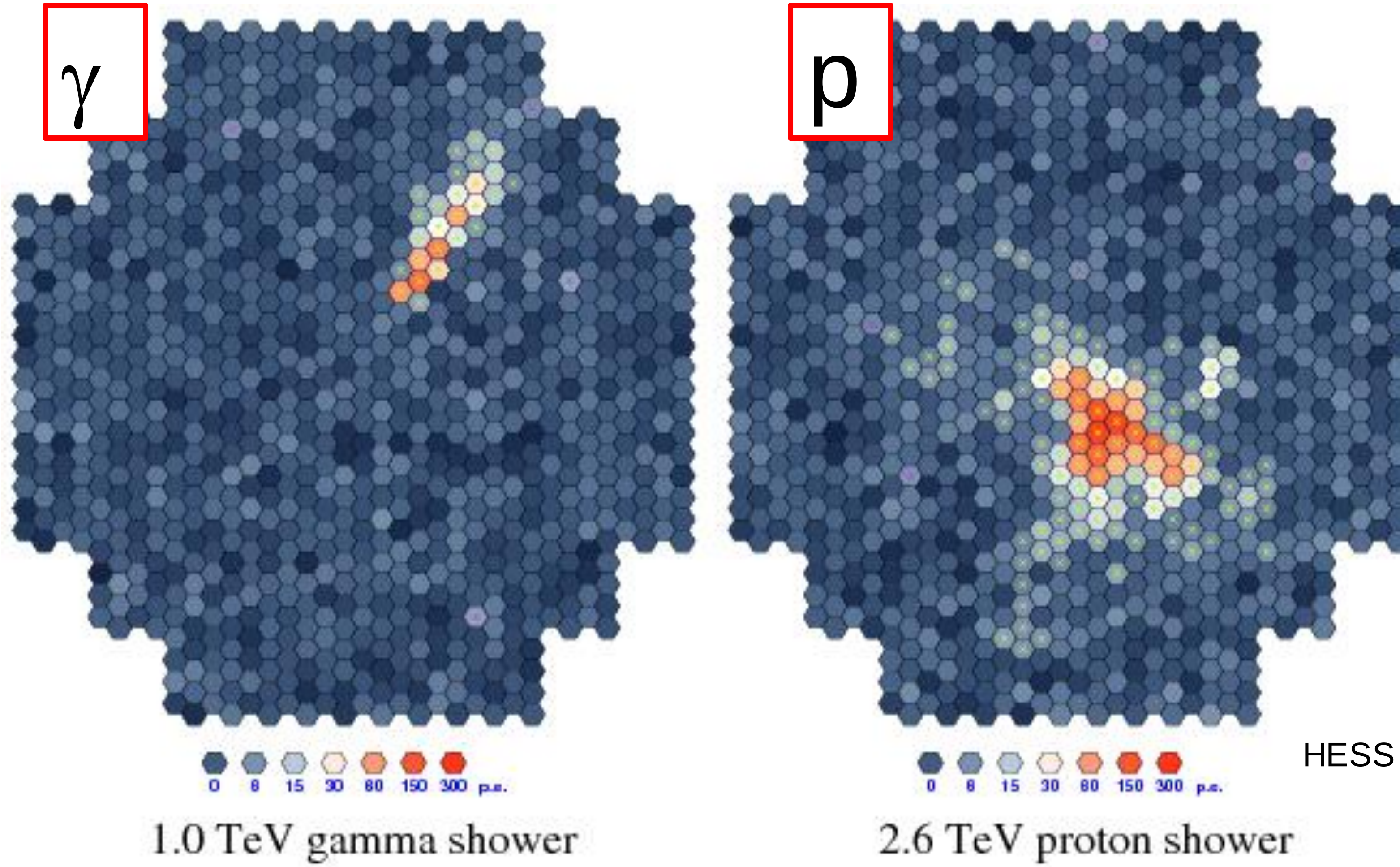


Shower footprints on the ground





Showers can be reconstructed in the focal plane

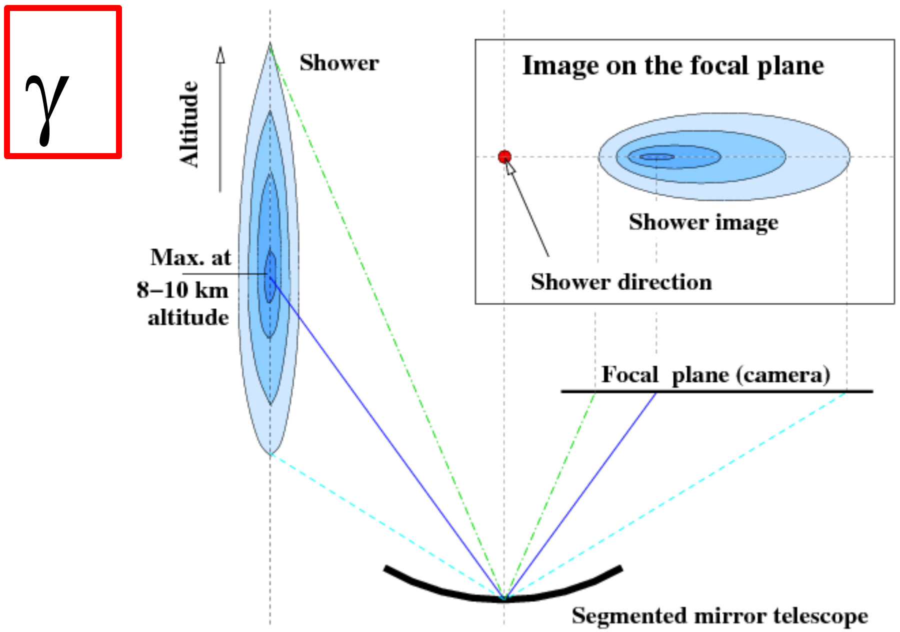


HESS cameras

Gamma-ray reconstruction

Image analysis allows reconstruction of gamma-ray characteristics:

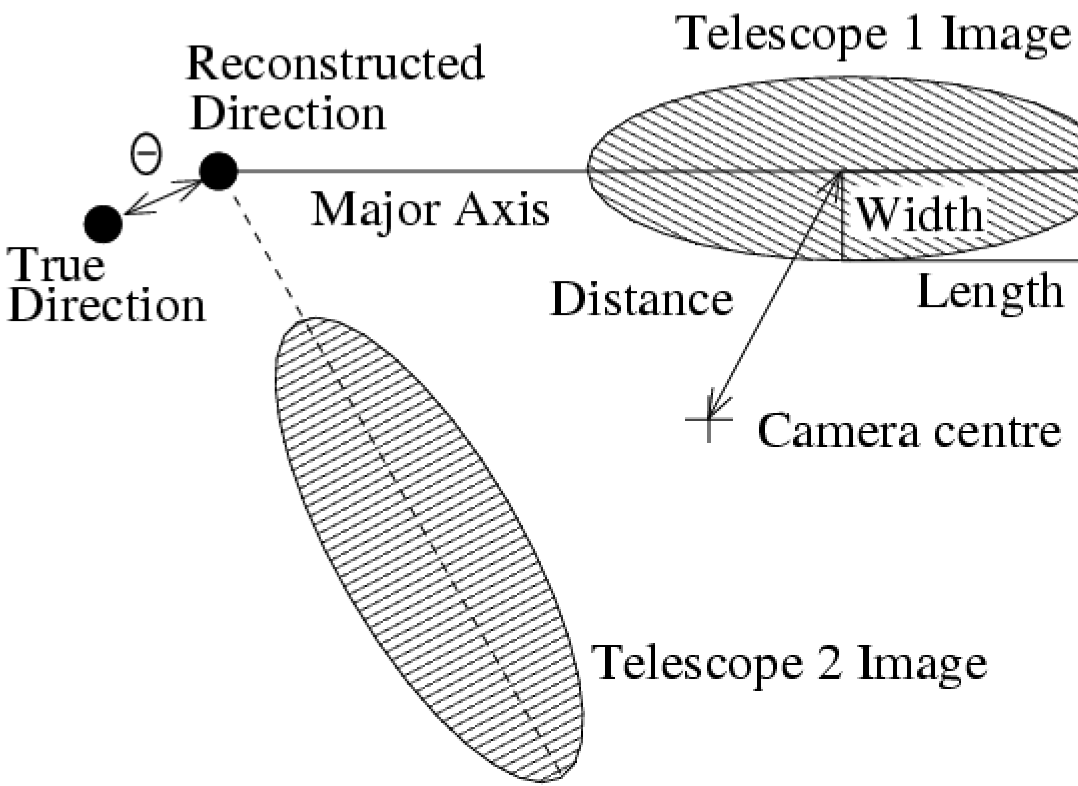
- parametrize showers as ellipses (“moment analysis”)
- orientation of ellipse indicates shower direction in sky
- amount of light in image is energy estimator

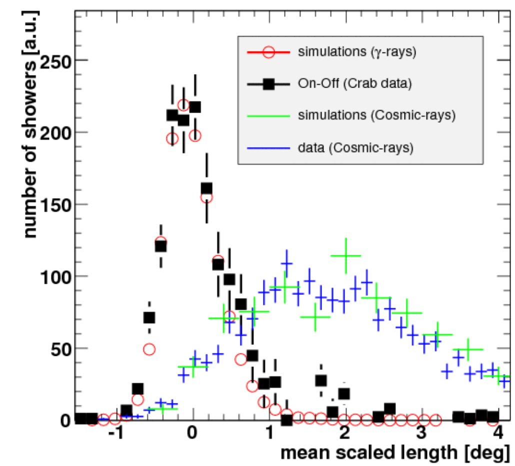


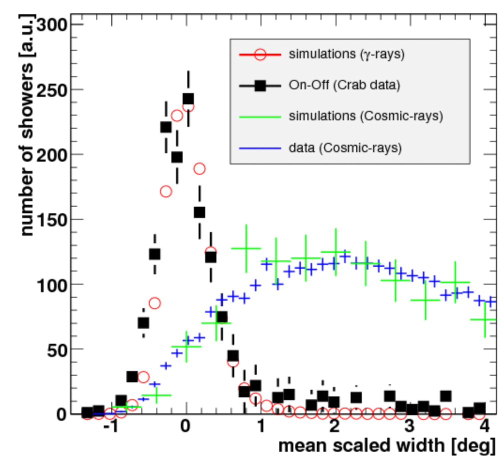
Hillas parameters for background rejection

Image analysis allows reconstruction of gamma-ray characteristics:

- parametrize showers as ellipses ("moment analysis")







Presto: VHE astronomy comes of age!

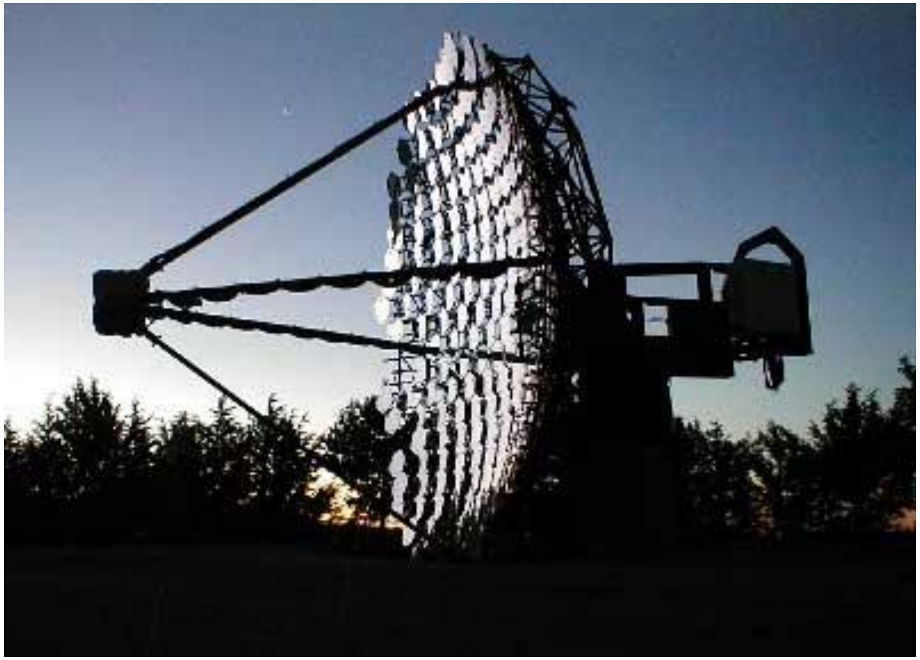
Combination of:

- Large telescopes
- Multi-PMT, triggerable cameras
- Image analysis

led to first reproducible, high-significance detections of VHE sources by the Whipple telescope:

1989: Crab
1992: Mrk 421

The start of VHE astronomy !



Whipple 10-m telescope, Davies-Cotton optical design

Intermezzo: the Crab

Crab Nebula is result of a supernova event observed on Earth in 1054.
Now the 'standard candle' in VHE astronomy:

- bright ~ 2 x 10^{-7} $\gamma/m^2/s$ (~ a few $\gamma/m^2/yr$) (E>1 TeV)
- constant flux

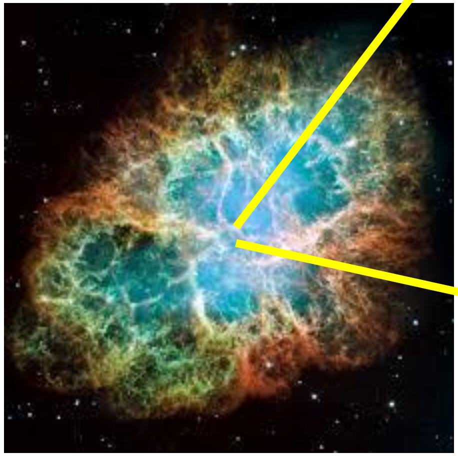
Whipple Crab discovery:

9σ in 163 hours of data
ie: $0.7\sigma \cdot \sqrt{t}$ (t in hrs)

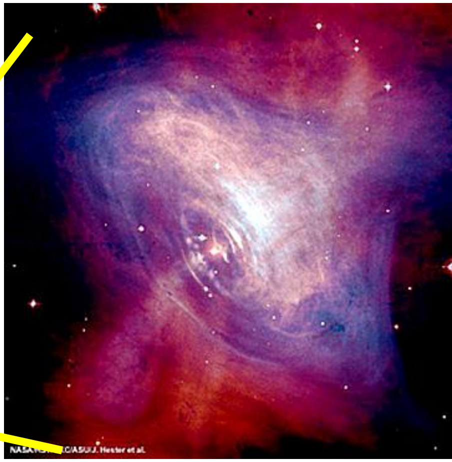
WEEKES *ET AL.*

TABLE 4
Azwidth DISCRIMINATION

Epoch	ON	OFF	All (%)	Difference	OFF (%)	Significance
No Selection (All)						
1986–1988	652,974	651,801	100.0	+1173	0.2	+1.03
Azwidth Selection						
1986–1988	9092	7929	1.2	+1163	14.7	+8.91



HST WFPC2



Chandra (X-ray)

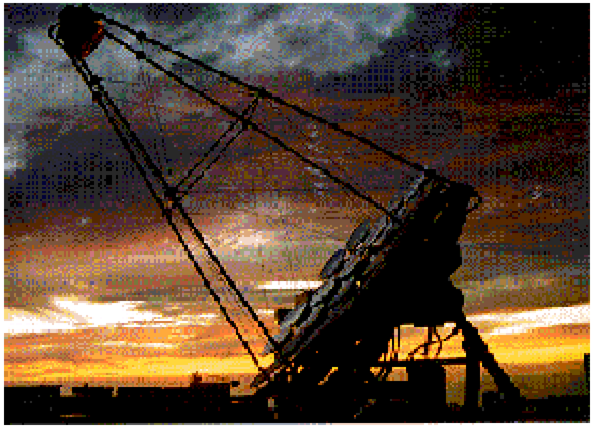
First generation ACT telescopes: single dishes

First generation of ACT (1980s, 1990s) telescopes were single dishes:

Whipple (10m) – Arizona	(US, UK, Ireland)
Cangaroo (3.8m) – Australian outback	(Japan, Australia)
CAT (5m) – Pyrenees	(France)
HEGRA (3.5m) – Canary Islands	(Germany, Spain)

HEGRA pioneered the concept of the Cherenkov array in the 1990's

CAT



HEGRA

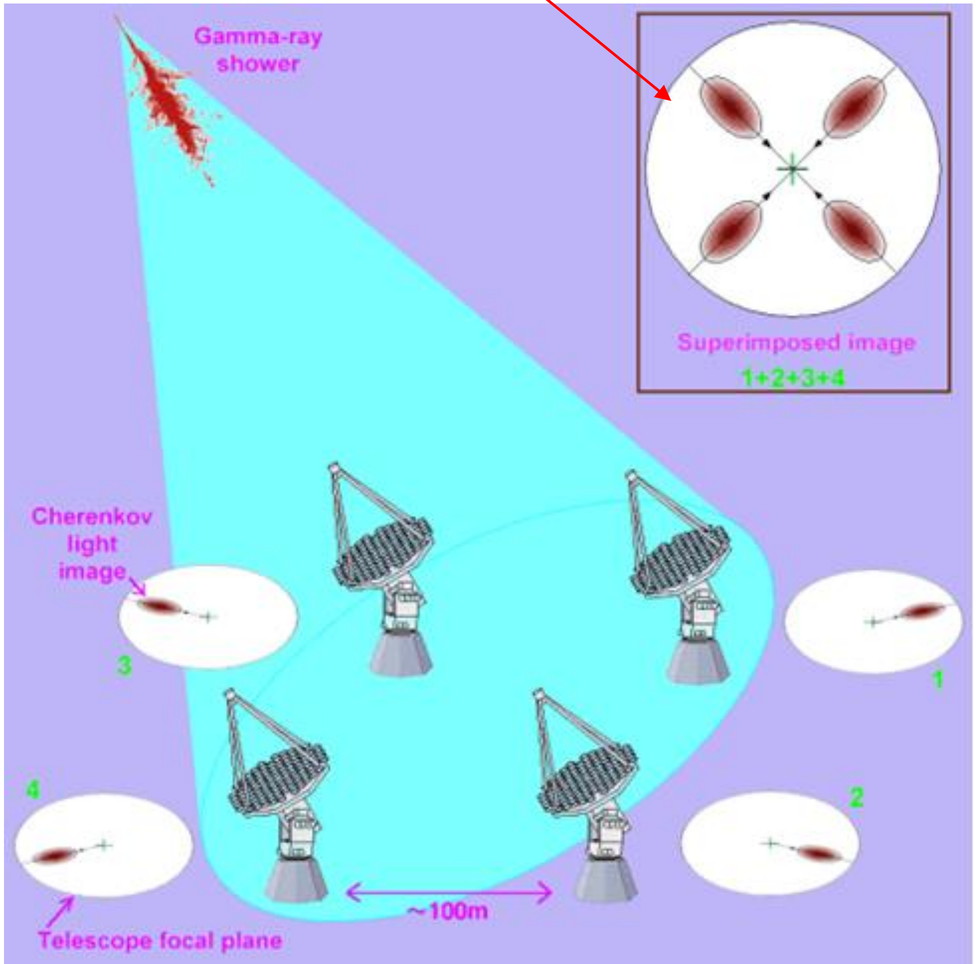
Multiple telescopes

An array of telescopes gives multiple views of the same shower.

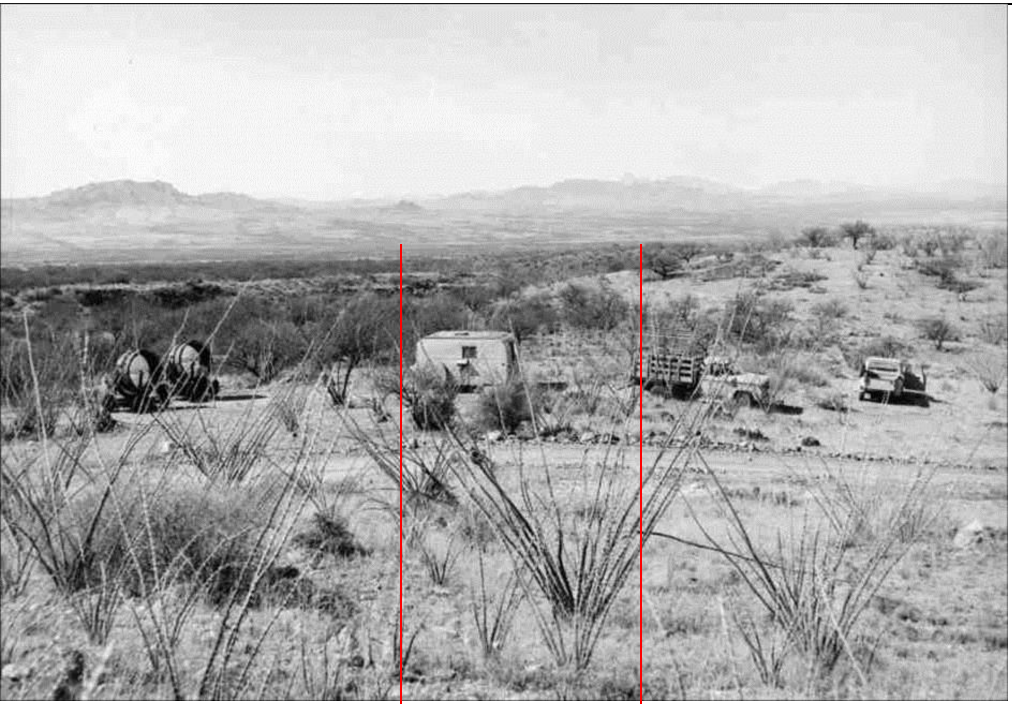
Modest increase in effective area, but dramatic improvements in:

- Background rejection
- Angular resolution (<< 1°)
- Energy resolution (~15%)

Multiple views allow reconstruction of gamma-ray origin



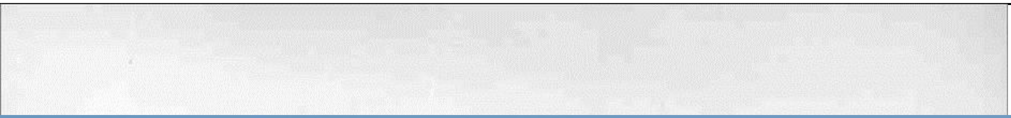
Cherenkov telescopes come full circle in 50 years…



1967

2014

Cherenkov telescopes come full circle in 50 years…



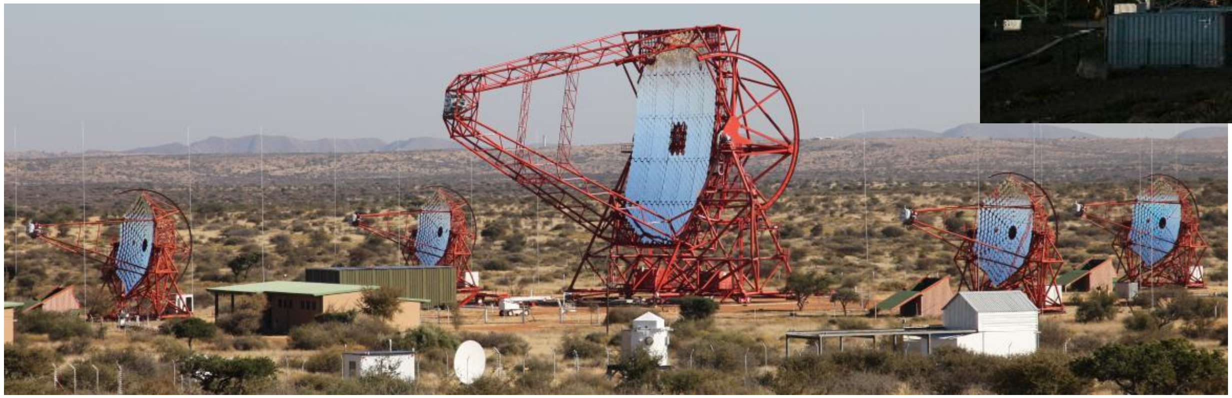
1967

Current ACT Arrays

VERITAS: 4 x 12 m, Arizona

MAGIC: 2 x 17m, Canary Islands

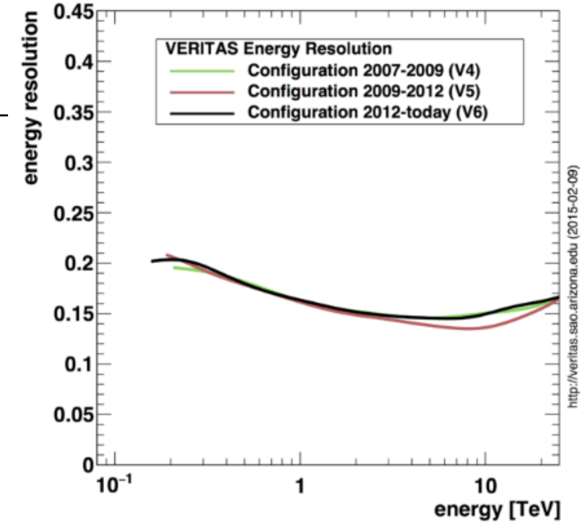
H.E.S.S. (4 x 12 m + 1 x 28 m, Namibia)

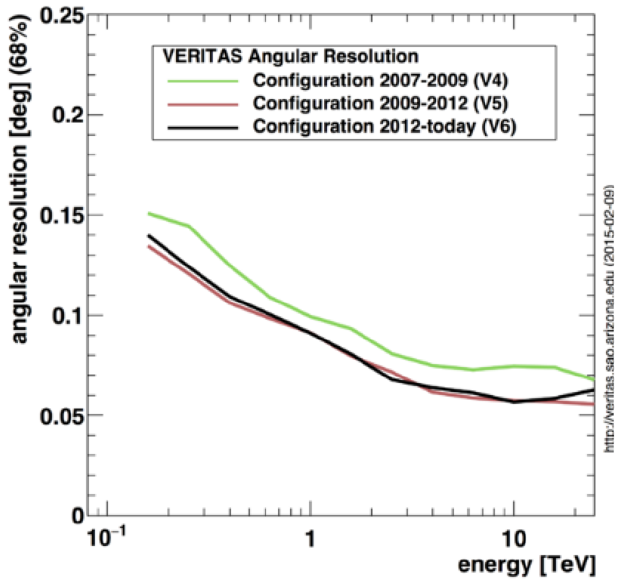


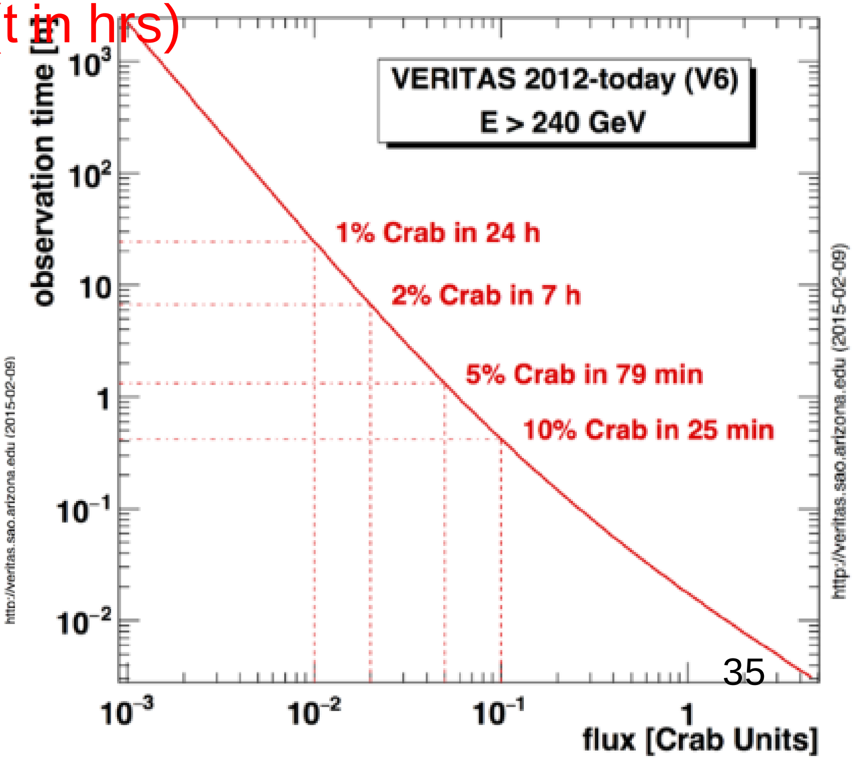
Array Performance

eg. VERITAS:

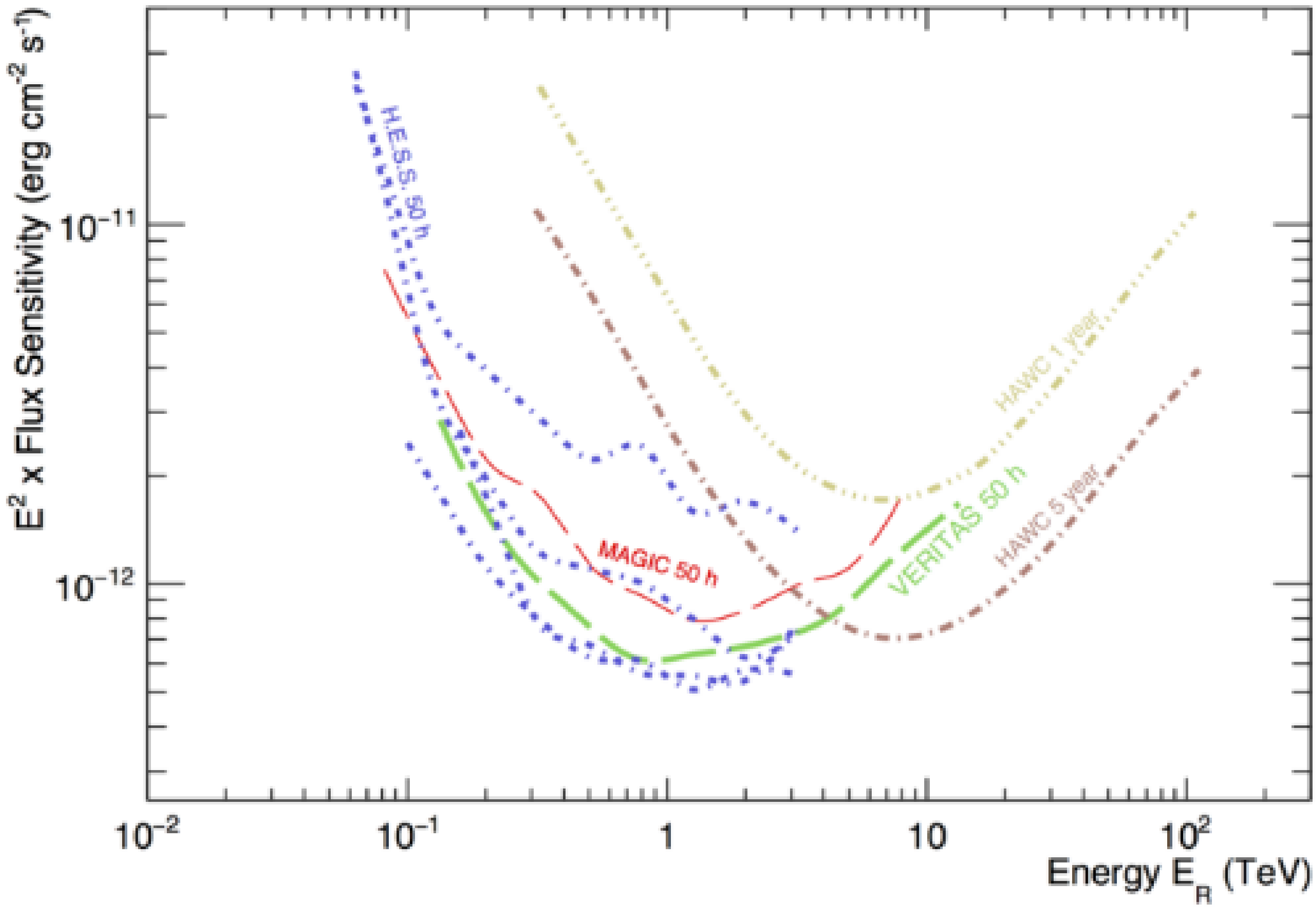
- Energy range: 100 GeV → 30 TeV
- Angular resolution: < 0.1° (68% containment)
- Energy resolution: 15%-25%
- Field of view: 3.5°
- Sensitivity (5σ detection):
  - Crab Nebula: ~ 60 sec: $40\sigma \cdot \sqrt{t}$ (t in hrs)
  - 1% Crab Nebula flux: < 25 h
- Source localization <50 arc sec



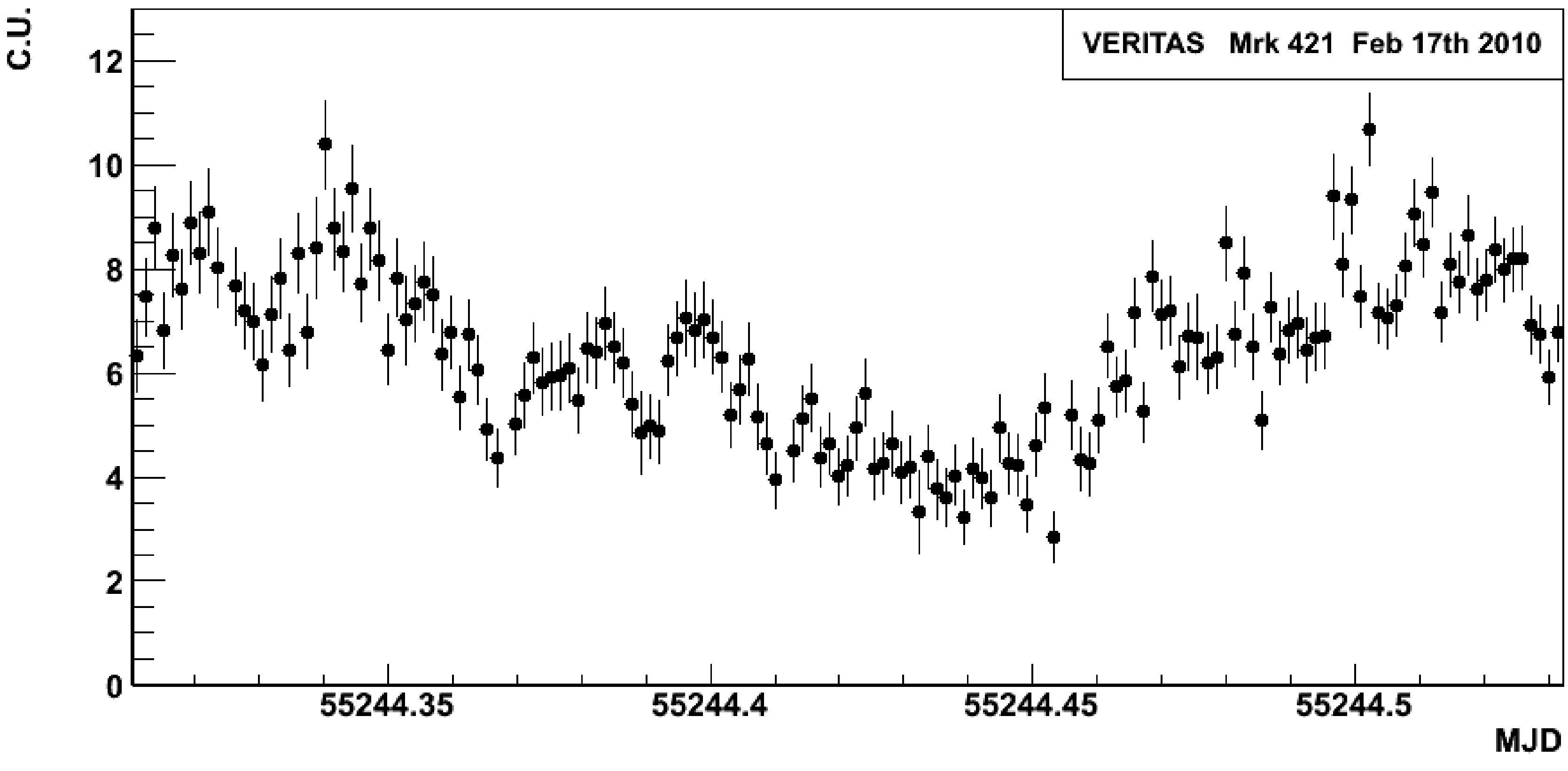




Comparative sensitivities

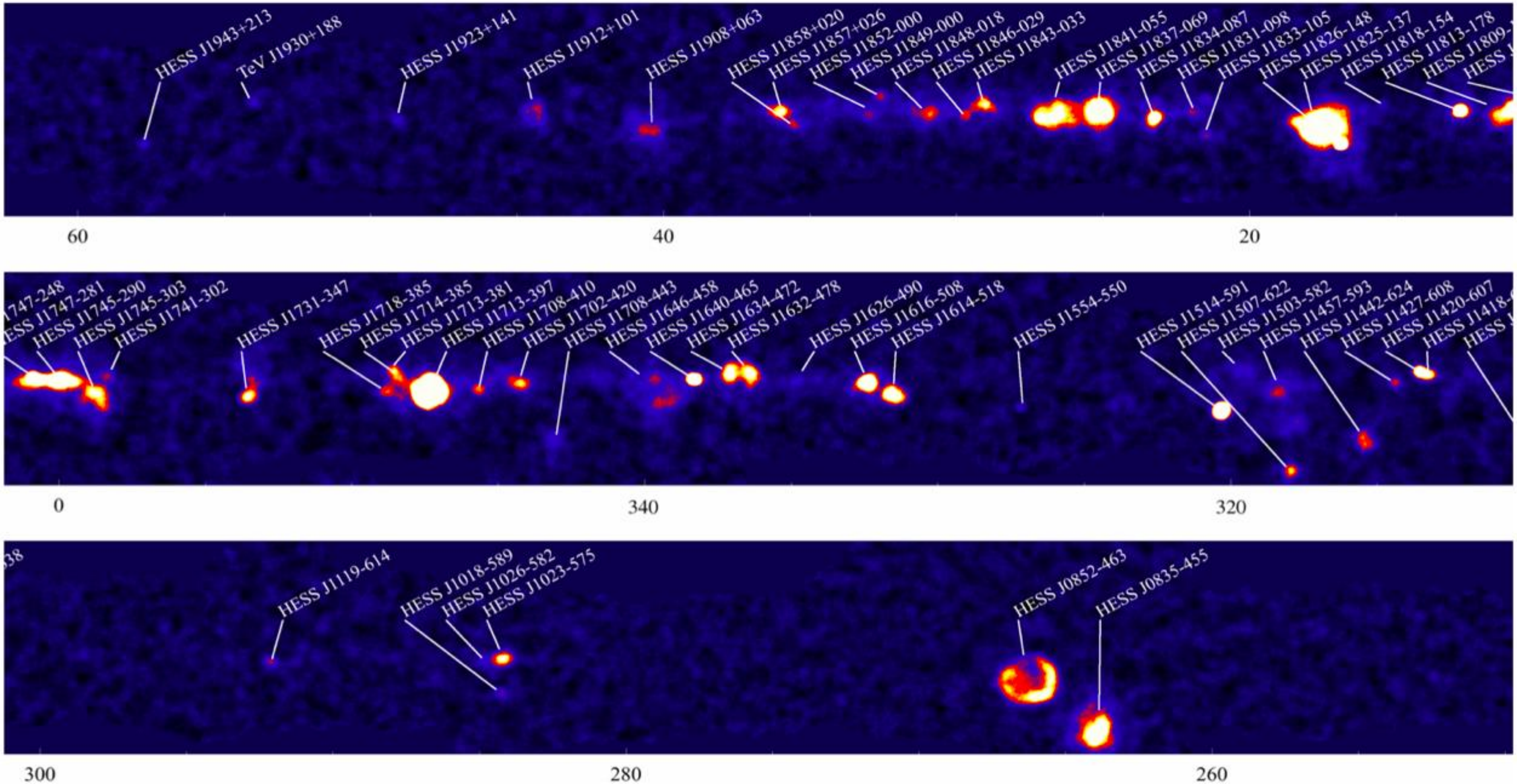


Eg. Sensitivity to variable sources



2 minute binning!

Eg. HESS Galactic Plane Survey



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What do we want to do better?

Wish list:

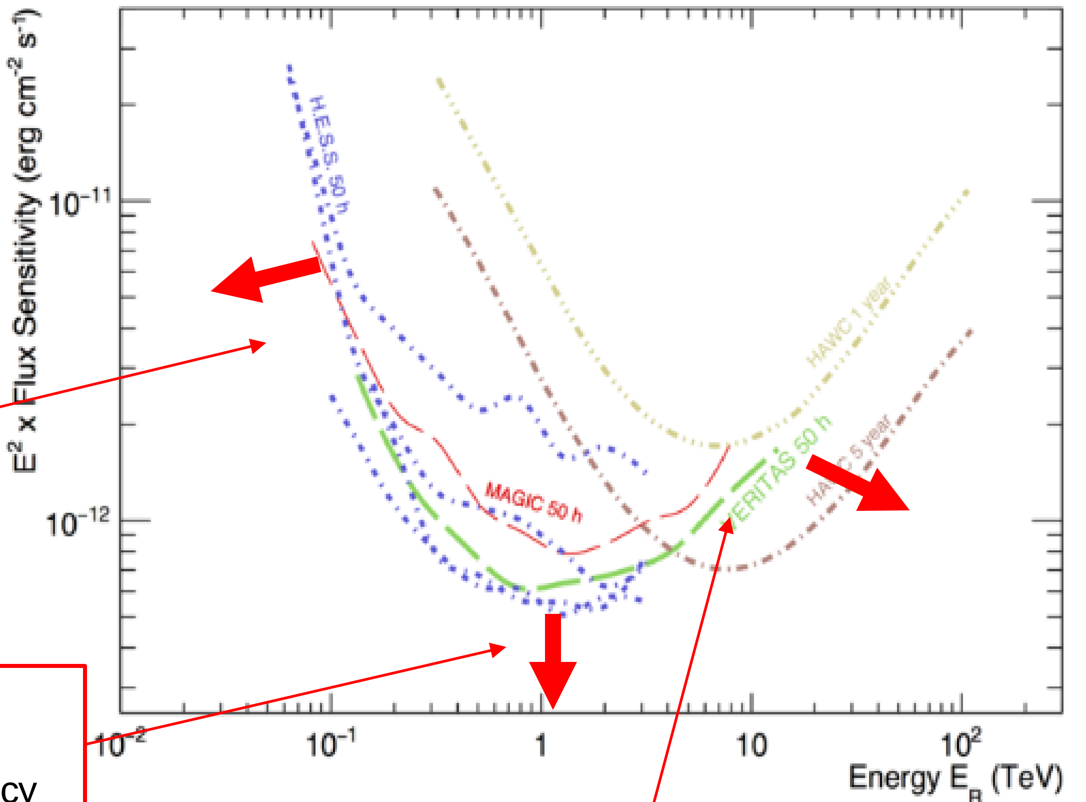
- Improve sensitivity
  - Increase photon rate to improve sensitivity to variable sources
  - Increase number of sources
- Extend energy range
  - At low E end, where sources have higher fluxes
  - At upper E end, if sensitivity is sufficiently good to see EBL-cutoff sources at high redshift
- Improve reconstruction precision
  - In angular resolution for morphology
  - In energy, for improved spectral studies to understand acceleration
- Larger field of view (for surveys)

Cherenkov technique is mature, but can be improved

How to do it?

Cherenkov technique is mature, but can be improved

Current sensitivity



Below ~200 GeV: limited by shower brightness: go to bigger dishes

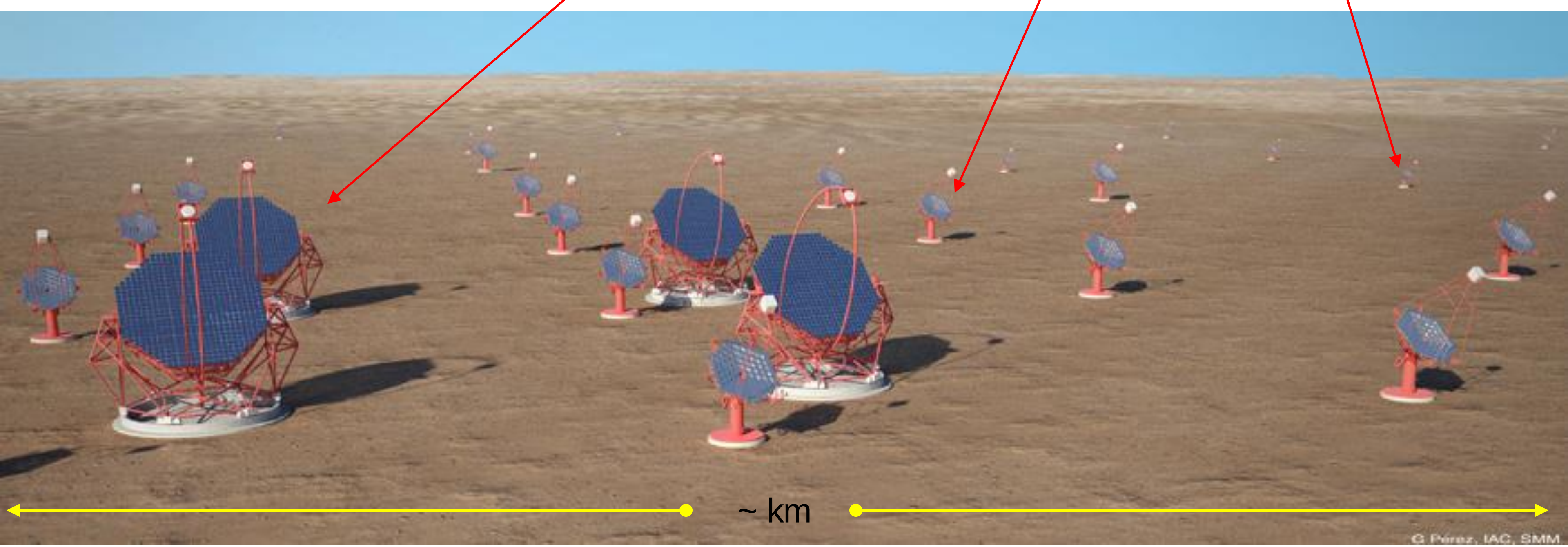
Overall improved sensitivity by increased photo detection efficiency

Above several TeV: limited by effective area: increase size of array

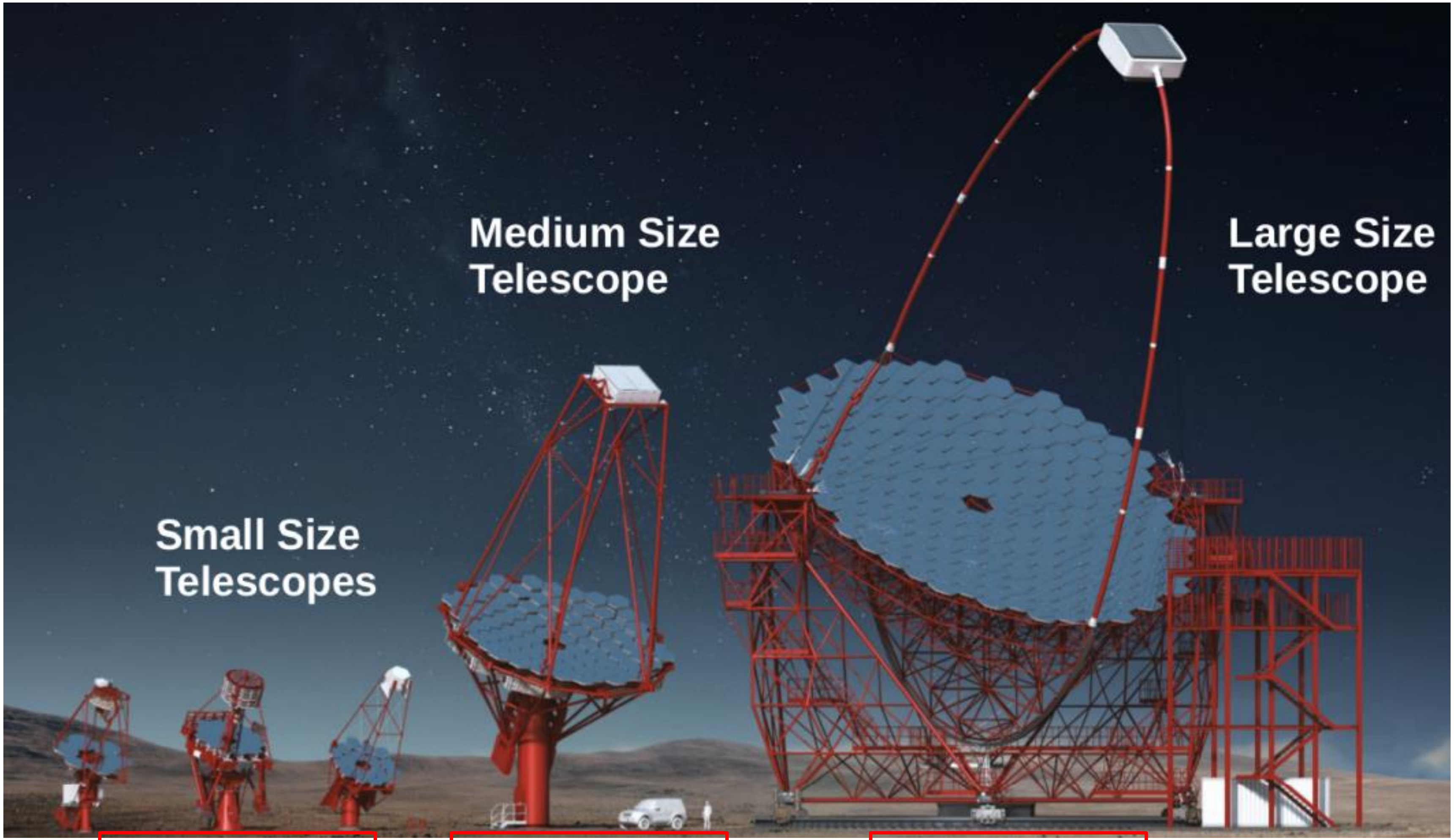
The Cherenkov Telescope Array (CTA)

Goals:

- improve sensitivity by ~ order of magnitude
- extend energy reach to << 100 GeV, and >100 TeV
- improve angular and energy resolution
- increase field of view
- cover full sky



Three different telescope sizes



Small (3-4 m) | Medium (12 m) | Large (23 m)

Three different telescope sizes

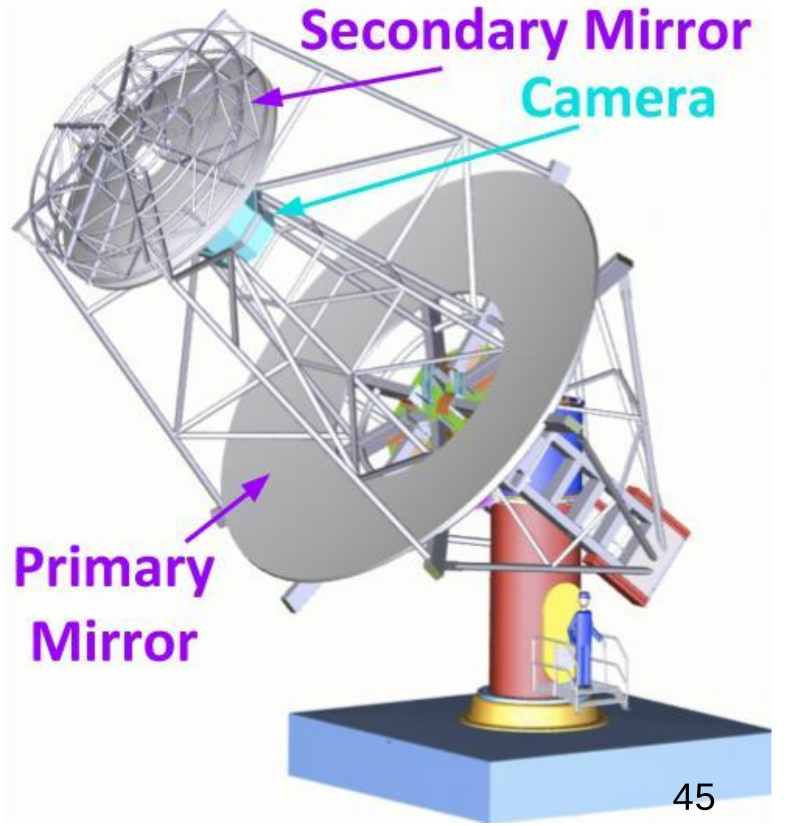
LST:
- Optimized for 20 GeV – few hundred GeV
- 23m diameter, 4^o field of view
- Fast slewing for transients à la MAGIC

MST:
- Optimized for 100 GeV – 10 TeV
- 12-m diameter, 8^o field of view
- Choice between "classic" (Davies-Cotton optical design like VERITAS & H.E.S.S) or more technically challenging Schwarzschild-Couder design with SiPM camera

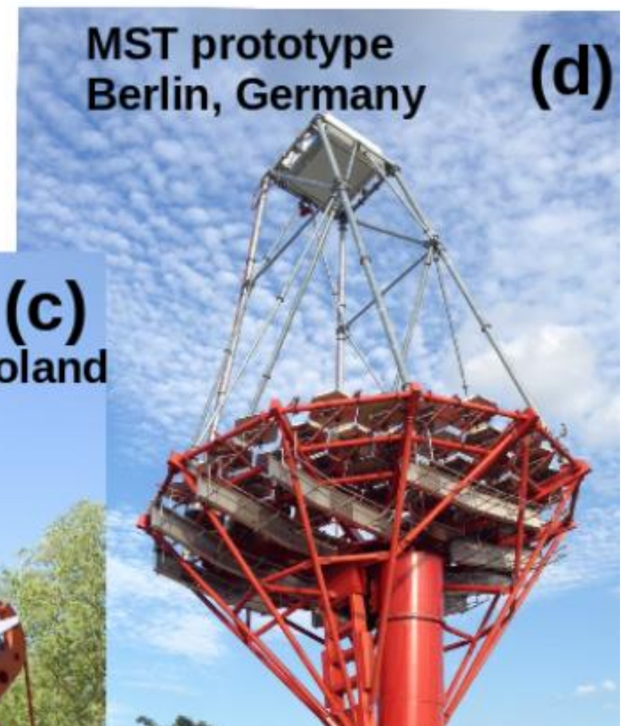
SST:
- Optimized for > 10 TeV
- 3 to 4 m primary, 9^o field of view
- Again, choice between Davies-Cotton & Schwarzschild-Couder design, and PMT or SiPM camera

Schwarzschild-Couder optical design

- Two-mirror design
- Superior to 'classic' Davies-Cotton (much reduced coma and spherical aberration) for wide field of view
- Isochronous
- Small plate scale (compact cameras)
- Cost is extremely tight tolerances on optical surfaces



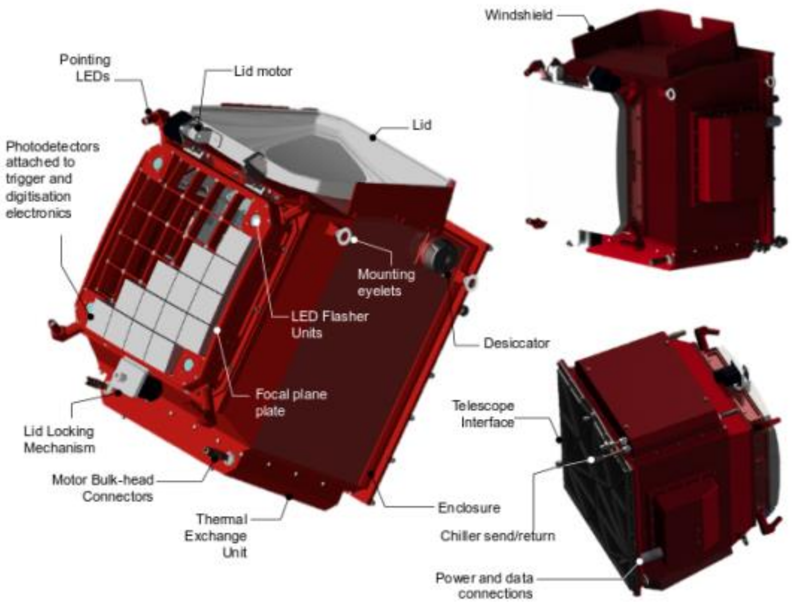
Prototypes: telescopes (SST, MST):

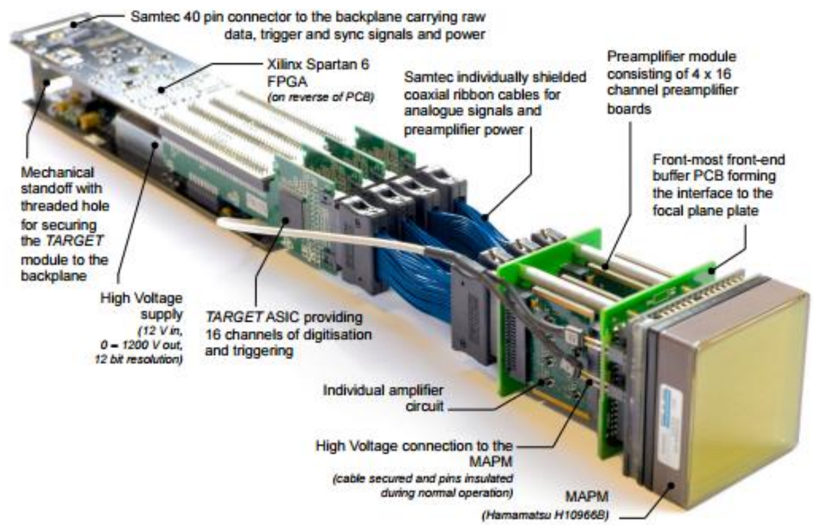


Prototypes: cameras

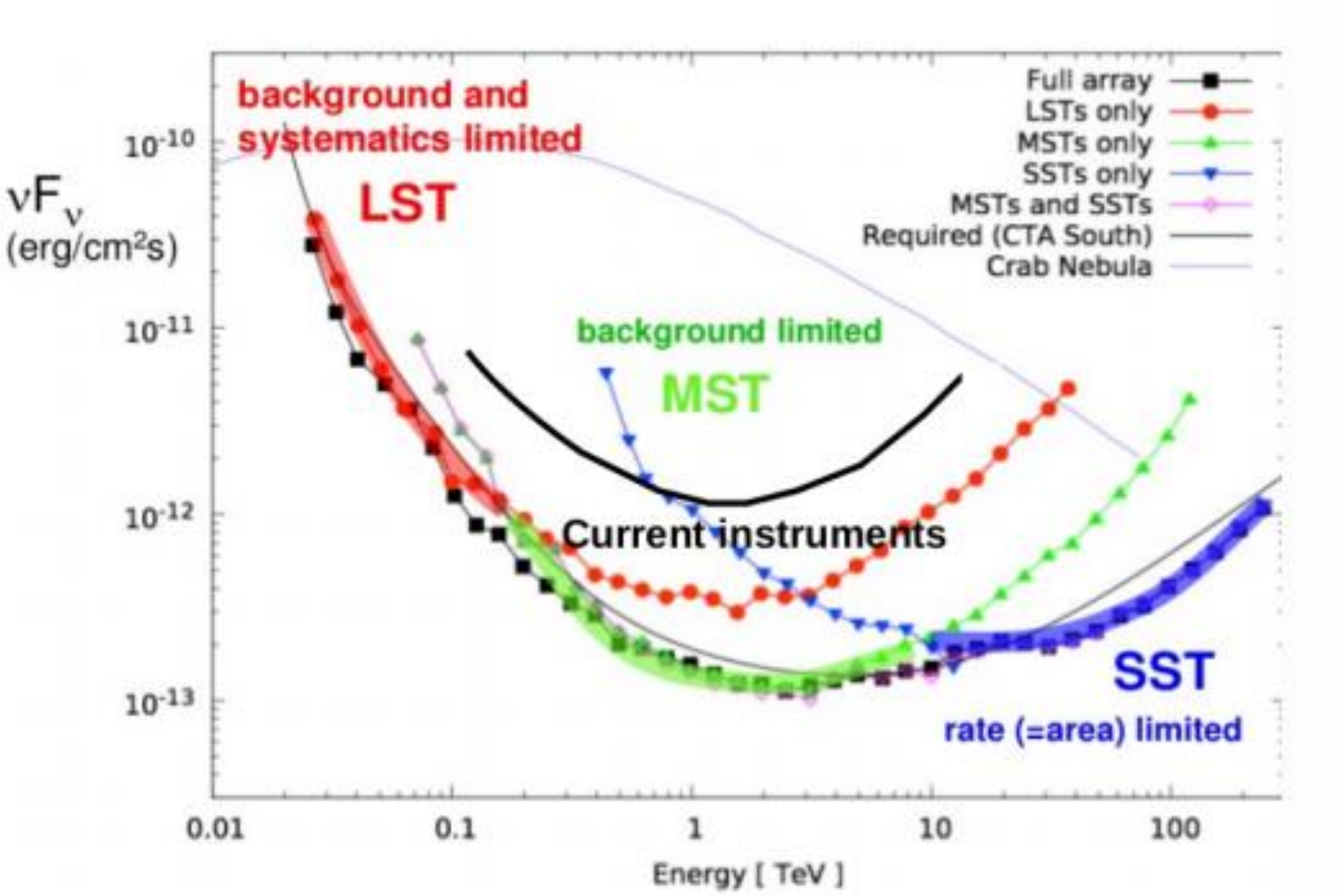
Prototypes exist for SST and MST cameras, based on both ‘classic’ phototubes and SiPM

eg: SST camera





Telescope sensitivities



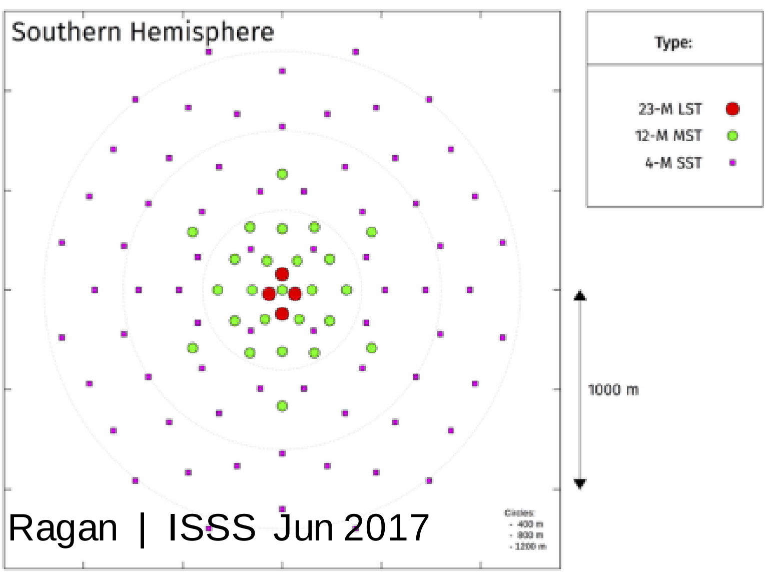
Two different sites for full-sky coverage

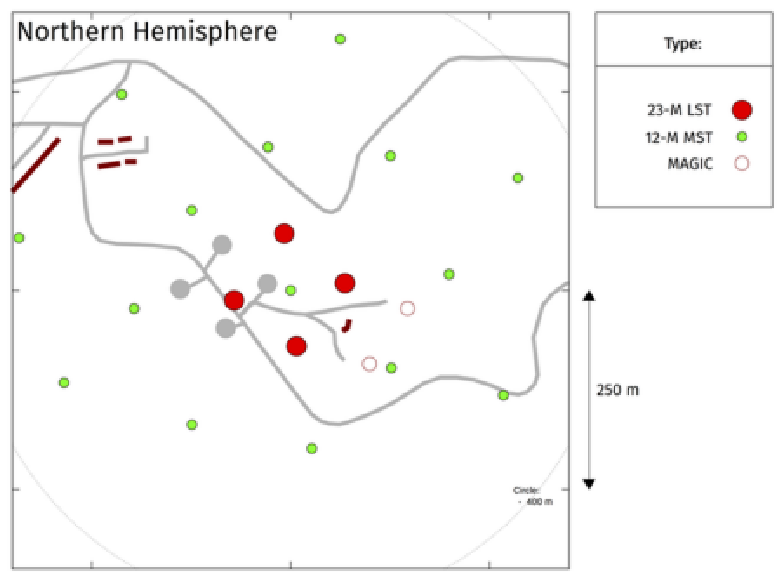
Northern site:

- Smaller array for extra-galactic sources: 4 LSTs, 15 MSTs
- 20 GeV to 20 TeV
- La Palma (Canary Islands), co-sited with MAGIC

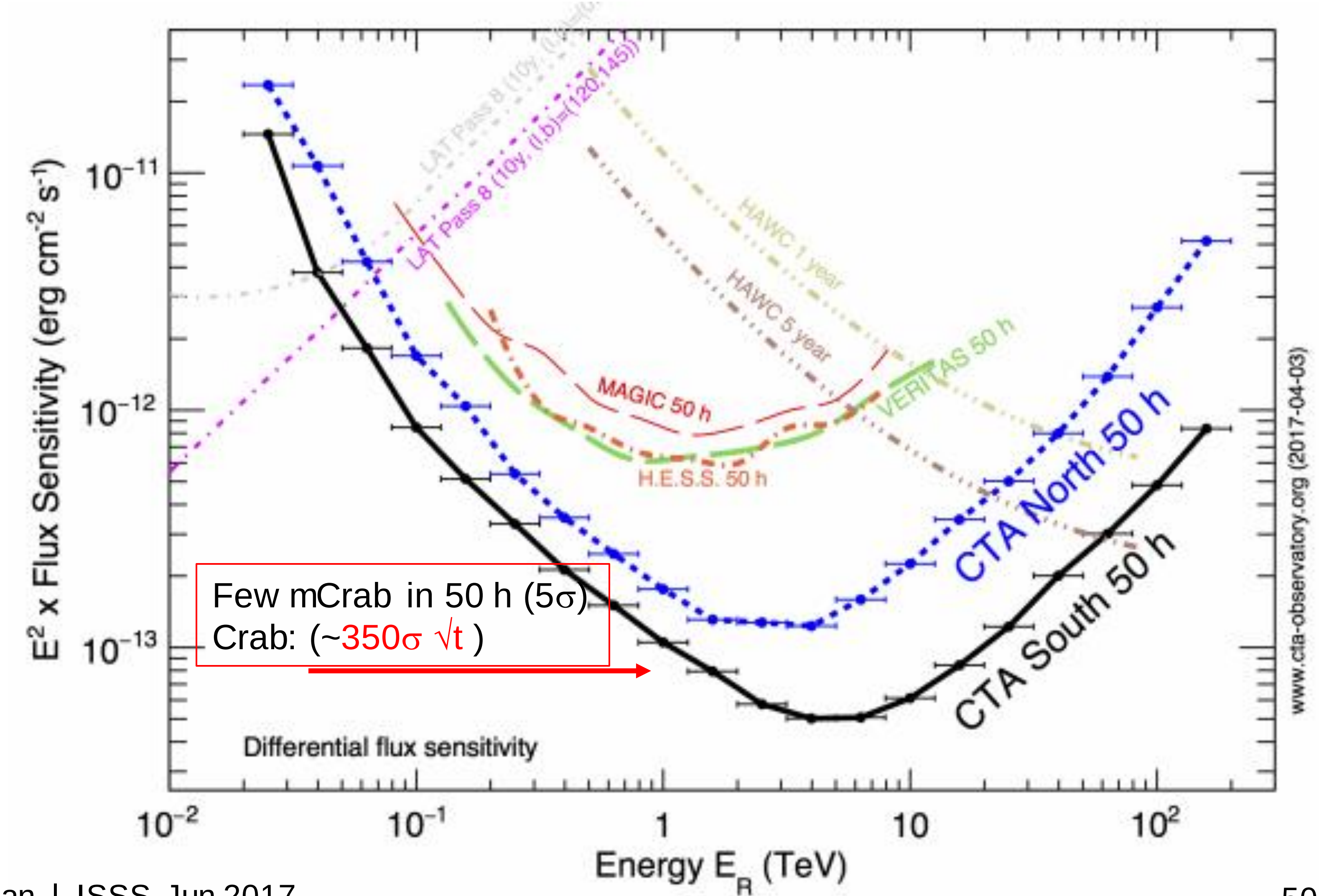
Southern site:

- Larger array: 4 LSTs, 25 MSTs, 70 SSTs
- Full energy range and access to the Galactic Centre region
- Paranal, Chile (ESO site)



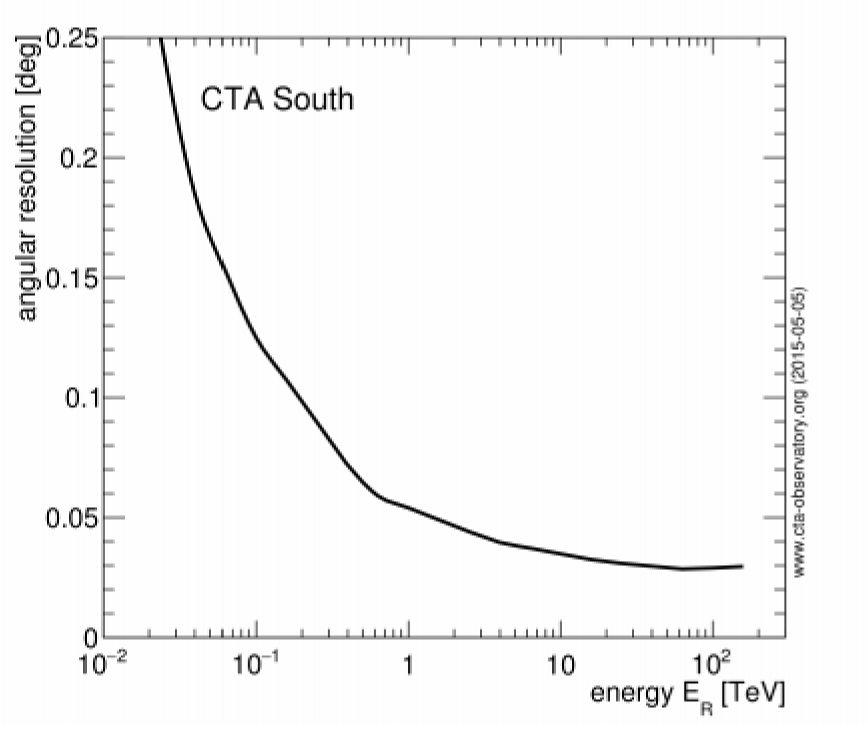


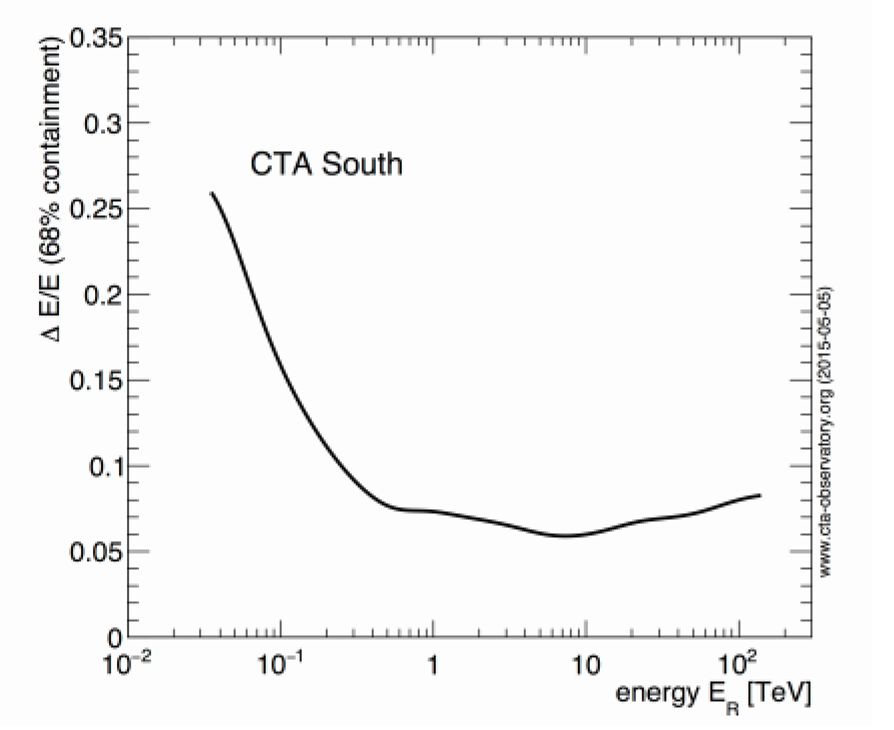
Array sensitivities



Resolution

- ~ few arc minute angular resolution at highest energies
- Substantially better energy resolution than current arrays





Status

- Prototypes of SSTs, MSTs exist – ‘downselect’ still to come
- Site selection finalized
- Construction started at CTA-North on LST prototype
- Funding situation complicated, but progressing
- By early 2020’s, VHE gamma-ray astronomy will be taking its next great stride forward

Menu

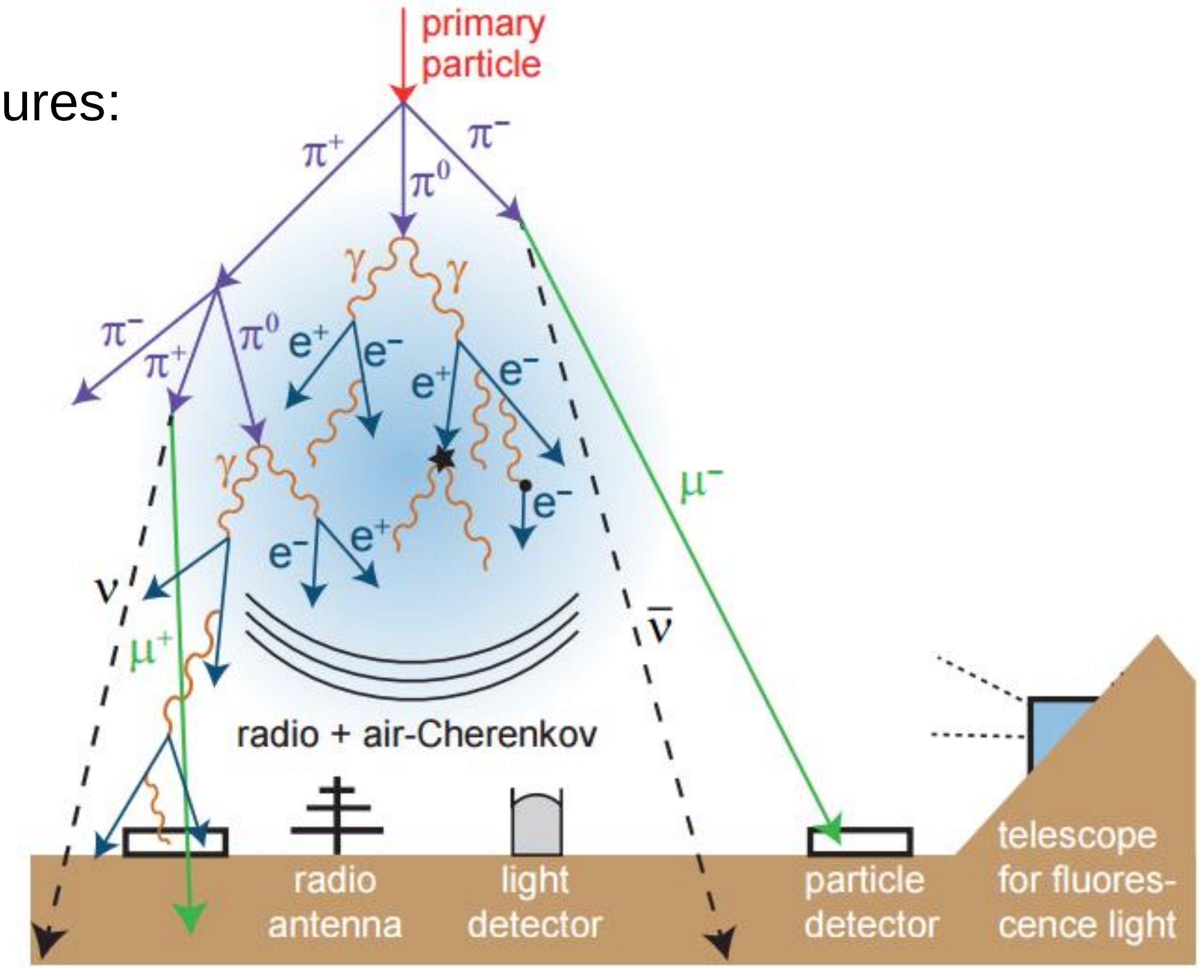
- Antipasti – Introduction & motivation: why study GeV/TeV gammas?
- Primi – Ground-based techniques: the present generation
- Secondi – The way forward: the road to CTA
- Contorni – Other approaches
- Digestivo – Conclusions

Reminder: cosmic ray interactions in the atmosphere

Multiple possible experimental signatures:

- radio
- particles
- Cherenkov light
- air fluoresence

See 'contorni' later



Schroder (2017)

At very high energies, particles propogate to ground

Detection on ground allows reconstruction of primary. Methods are generally complementary to air Cherenkov instruments (larger field of view, higher duty cycle, but lower sensitivity):

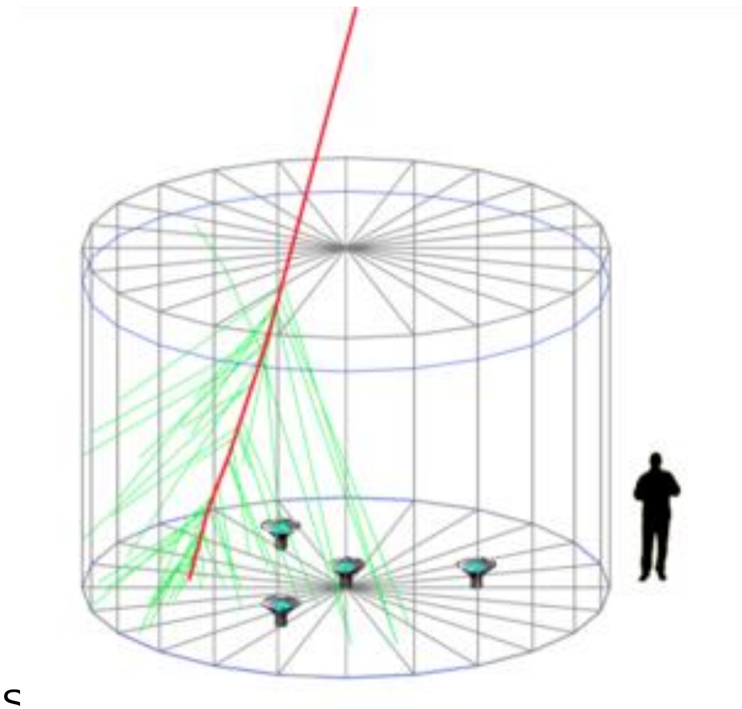
- using charged particle detectors (eg. ARGO-YBJ)
- using water Cherenkov technique (eg. HAWC, LHAASO)
- combined arrays (eg. Tunka-TAIGA) – particle detectors & Cherenkov

Background (CR) rejection by uniformity of particles on ground and lack of penetrating particles (muons from CR)

HAWC

Array of water Cherenkov detectors:

- 300 water tanks, each of ~150 m^3, equipped with 4 PMTs
- located at Sierra Negra, Mexico, 4100 m altitude
- very wide field-of-view, nearly-continuous duty cycle
- lower instantaneous flux sensitivity than atmospheric Cherenkov

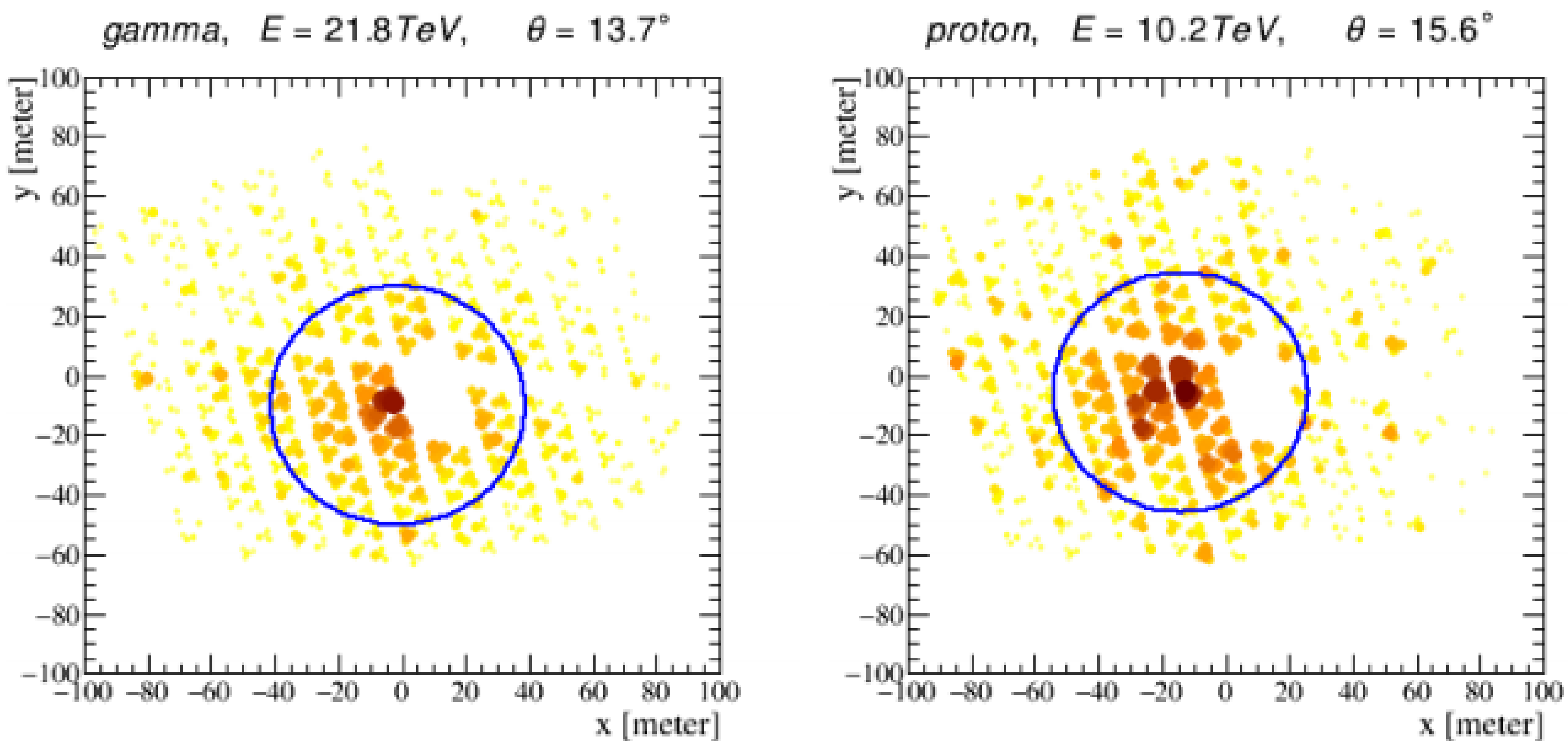


HAWC

~150 m

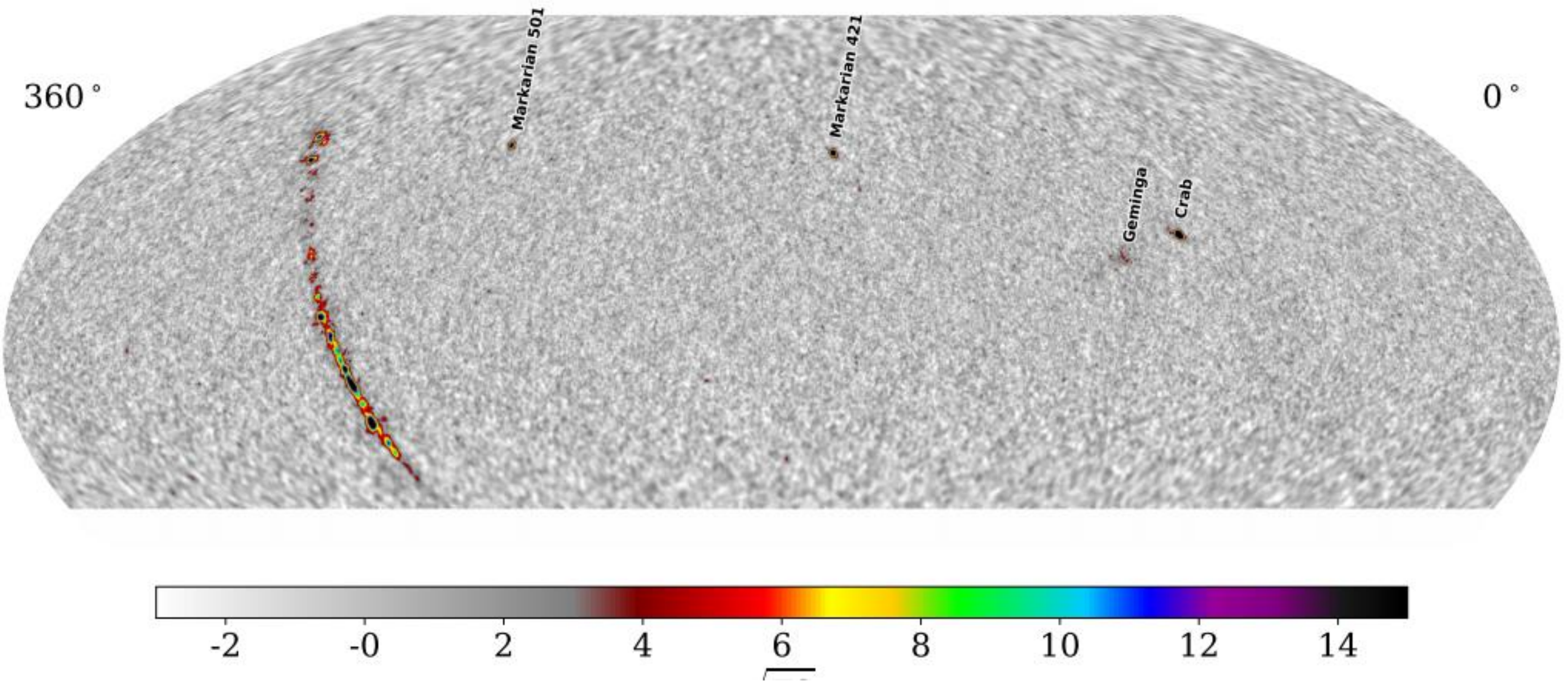
HAWC

Background (CR) rejection by uniformity of tank hits on ground
E resolution ~ 100% at low E, 50% at E> 10 TeV
Angular resolution at highest E better than 0.2°

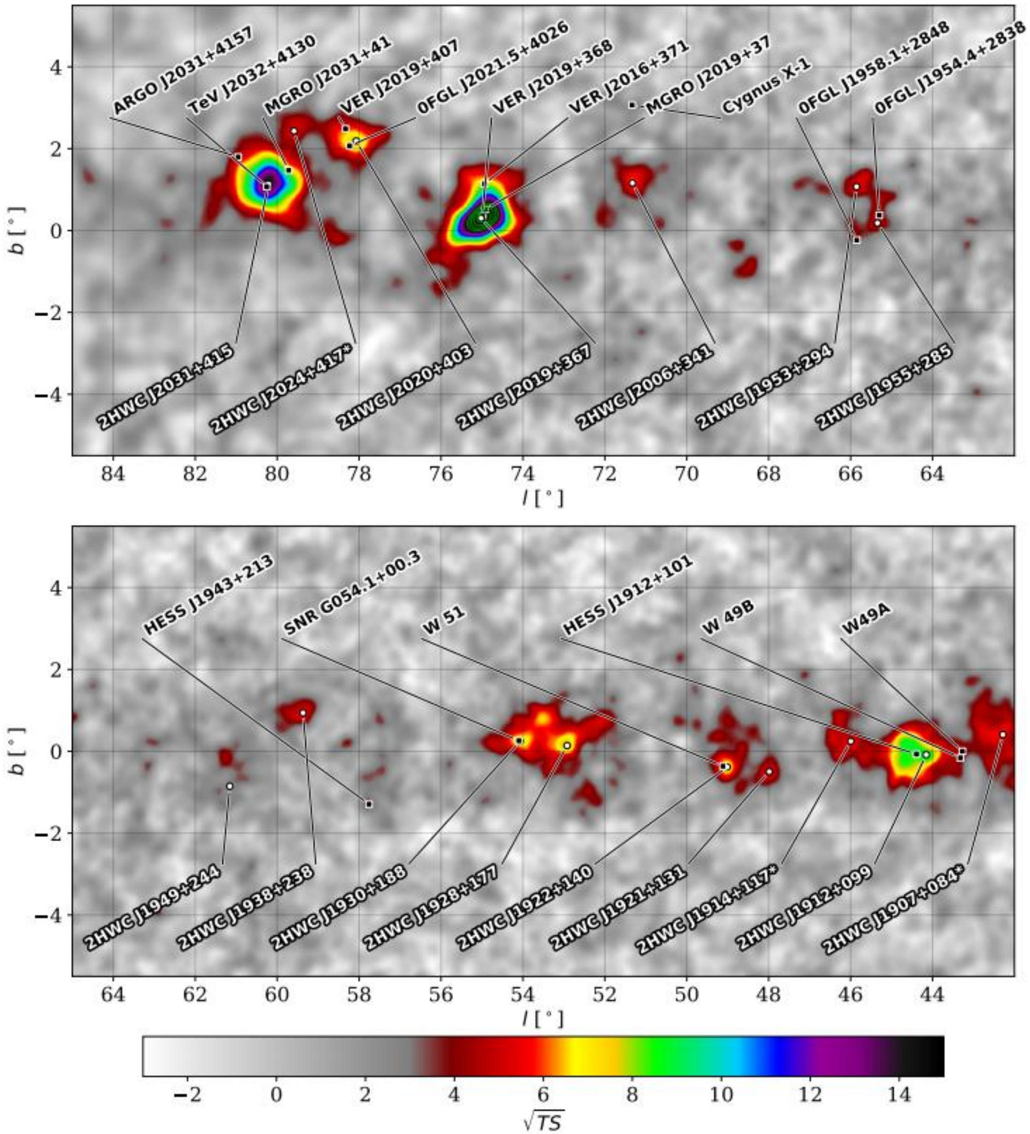


HAWC Sky Map

Based on ~1.5 years of data; 39 detections



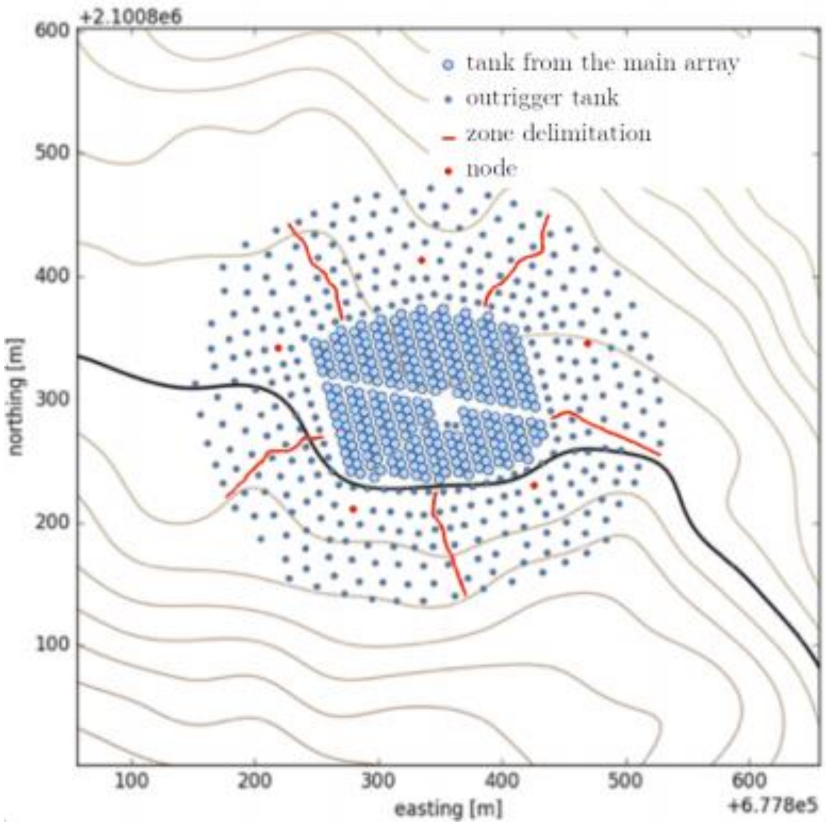
HAWC Sky Map – Inner Galactic Plane



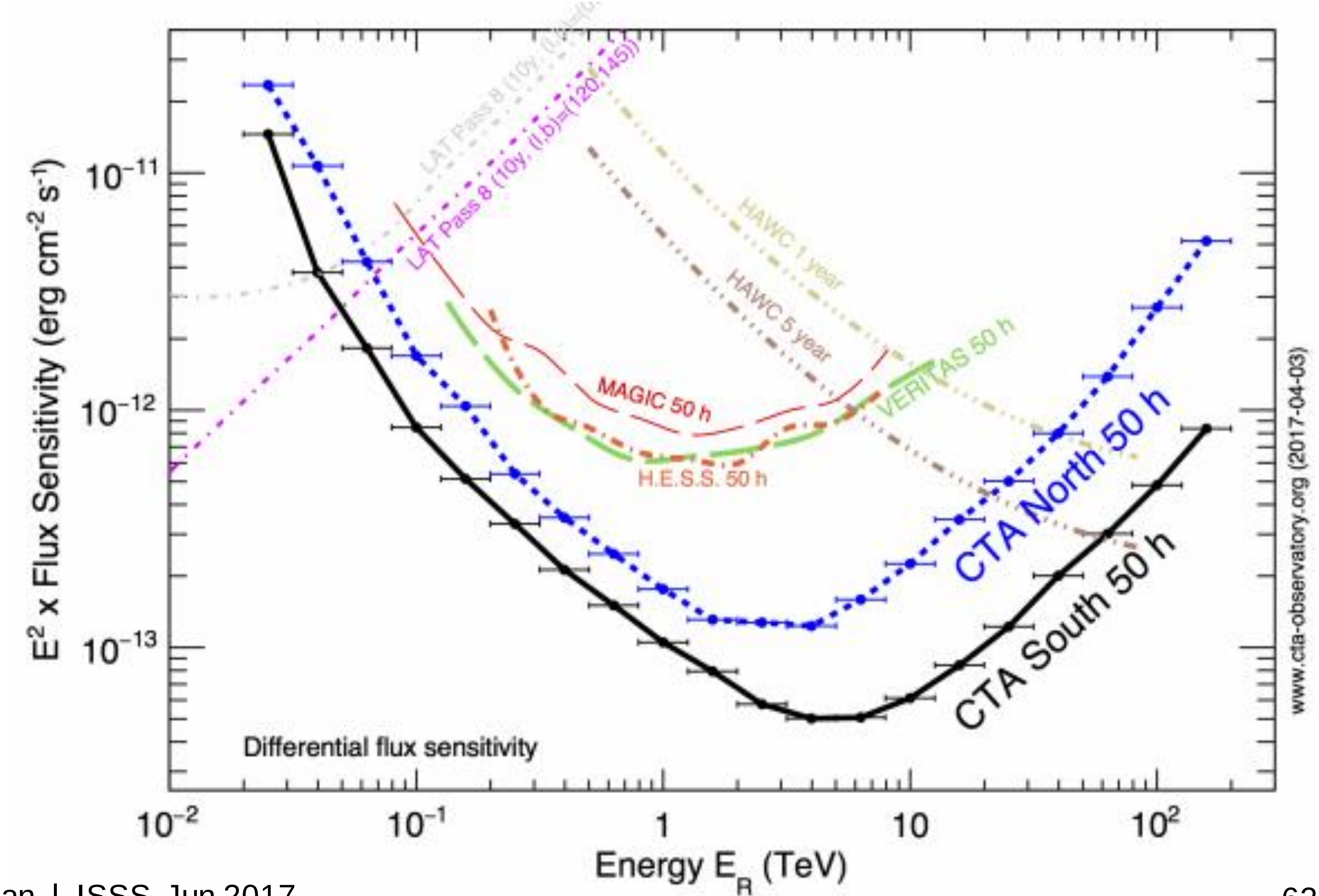
HAWC upgrade – outrigger array

At high energies, shower footprint becomes ~ size of HAWC array.

Add outriggers (smaller tanks, single PMT) to improve core position reconstruction to ~ 10 m



HAWC sensitivity



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Conclusions

- VHE gamma-ray astronomy has grown from a handful of sources to ~200 over the last 15 years;
- Atmospheric Cherenkov Technique is mature
- CTA will improve on current instruments by ~ factor of 10, through larger arrays, optimized telescopes
- Other complementary approaches with high duty cycles, nearly-all-sky coverage exist
- The short-term future of VHE astronomy appears bright!