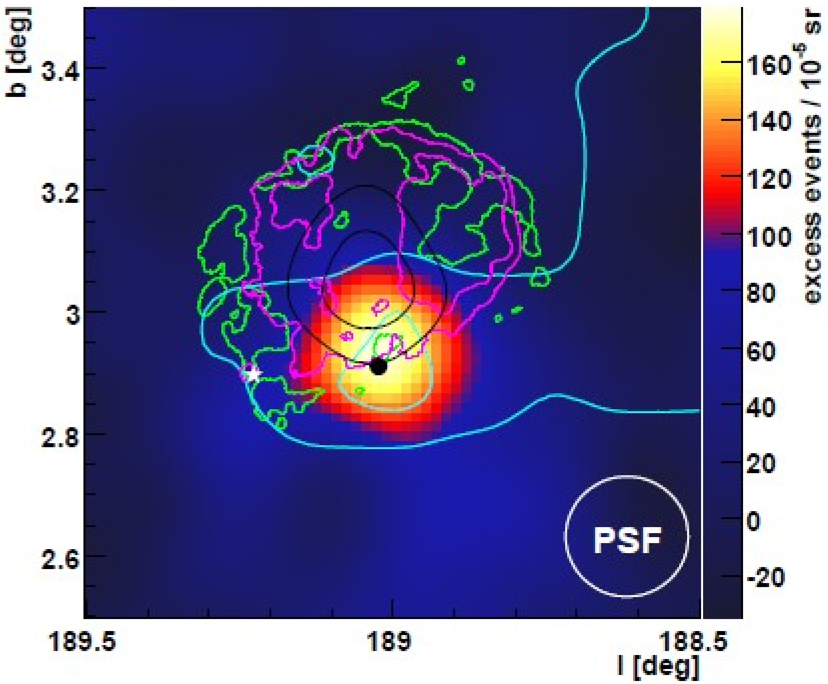
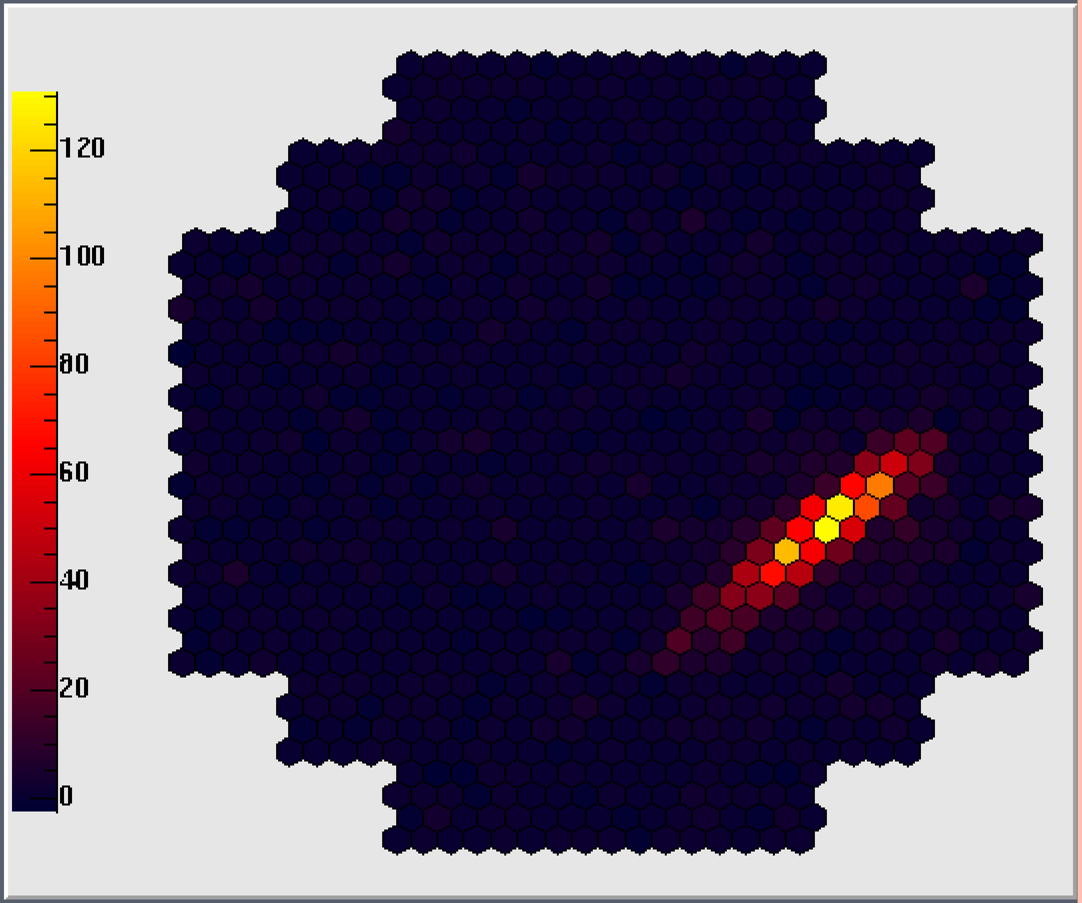


ASTROPARTICLE PHYSICS LECTURE 2

Matthew Malek

University of Sheffield

1



High Energy Astroparticle Physics

Acceleration Mechanisms
Sources
Detection

Detection of High Energy Astroparticles

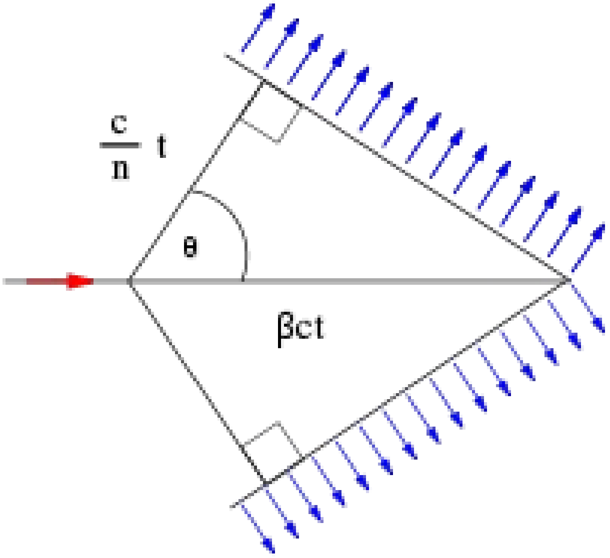
- Basic principles
  - Cosmic rays and high-energy γs shower in the atmosphere
    - detect light emitted or induced by the shower
      - Cherenkov radiation
      - fluorescence
    - detect shower particles that reach the ground
      - much more likely for hadron-induced showers
  - Neutrinos (in general) do not shower
    - detect products of charged-current interactions (e, μ, τ)
  - Ultra-high-energy neutrinos *will* shower in matter
    - acoustic detection of shower energy

Detection of Air Showers

- Cherenkov radiation
  - emitted by charged particles in the shower travelling at speeds > *c*/*n* where *n* is refractive index
    - forward peaked
    - faint, so requires dark skies
    - relatively low energy threshold
    - works for both hadron and photon cascades—basis of ground-based γ-ray astronomy
- Nitrogen fluorescence
  - UV radiation emitted by excited nitrogen molecules
    - isotropic
    - requires dark skies
- Detection of shower particles on ground
  - using water Cherenkov detectors or scintillator panels
    - higher threshold
    - not dependent on sky conditions
    - works better for hadron-induced showers

Cherenkov Radiation

- Radiation emitted by charged particle travelling faster than speed of light in a medium
  - wavefronts constructively interfere to produce cone of radiation
  - angle of cone given by
    - $\cos\theta = 1/\beta n$
    - for astroparticle
    - applications usually
    - $\beta \approx 1$
    - hence in air $\theta \approx 1.3°$
    - (depends on temperature);
    - in water $\theta \approx 41°$ (40° for ice)



Cherenkov Radiation

Spectrum of radiation is given by Frank-Tamm formula:

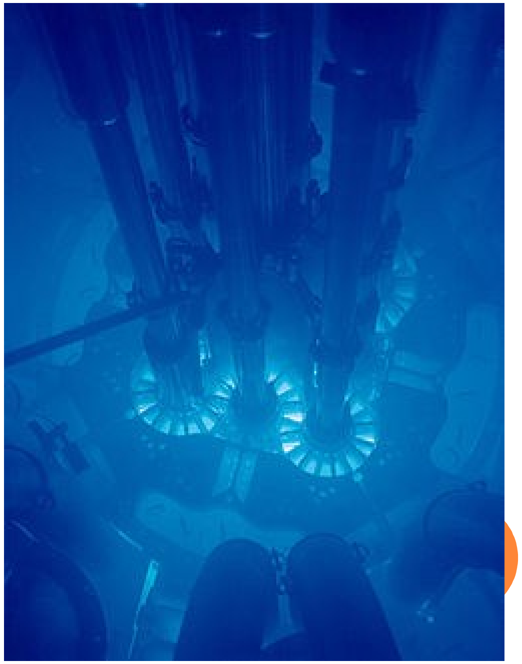
$$\frac{\partial^2 E}{\partial x\, \partial \omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

- μ is permeability of medium, n its refractive index, q charge of particle, β its speed, ω emitted angular frequency, x length traversed
- note that $dE \propto \omega$; spectrum is continuous, but
- in general radiation is most intense at
  - high frequencies

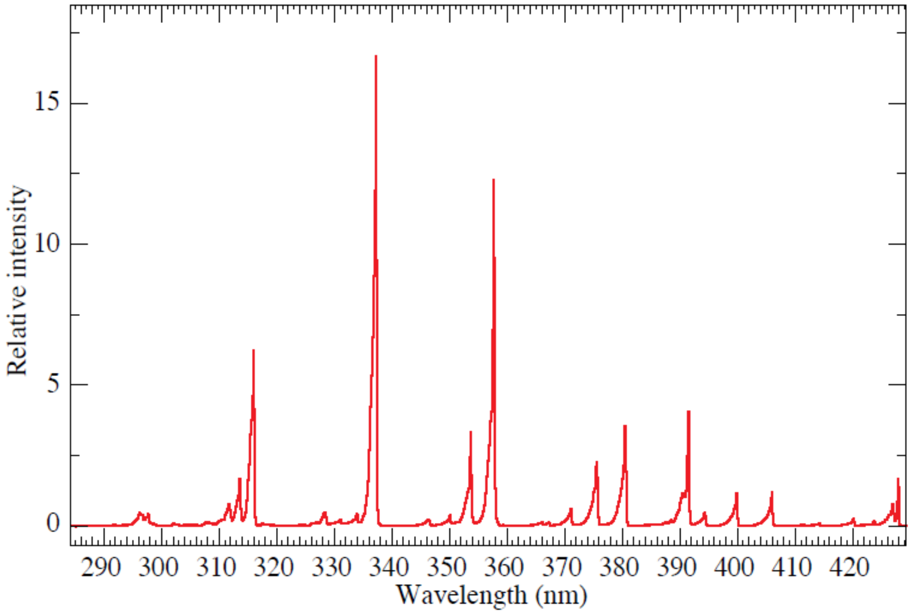
◦ Threshold given by $\beta > 1/n$

◦ below this no Cherenkov radiation

- emitted
- basis of “threshold Cerenkov counters” used
  - for particle ID in particle physics experiments



M. Ave *et al.*, *[AIRFLY Collab.]*, *Astropart. Phys.* **28** (2007) 41.

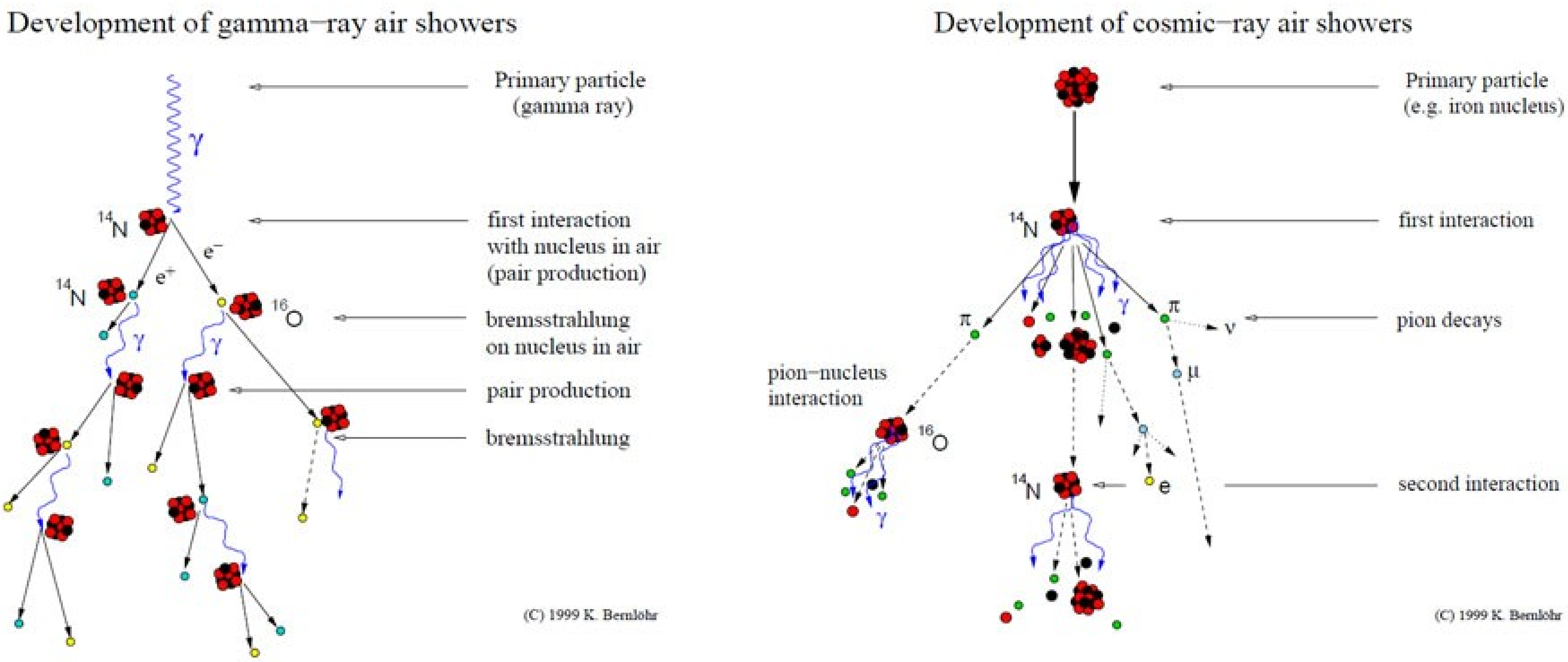


Fluorescence spectrum excited by 3 MeV electrons in dry air

Fluorescence

- Misnamed!
  - it’s really scintillation
- Emitted isotropically
  - in contrast to Cherenkov
  - Almost independent of
- primary particle species
  - exciting particles are mainly e± which are produced by both electromagnetic and hadronic cascades
  - light produced $\propto$ energy deposited in atmosphere
- Emitted light is in discrete lines in near UV
  - detection requires clear skies and nearly moonless nights

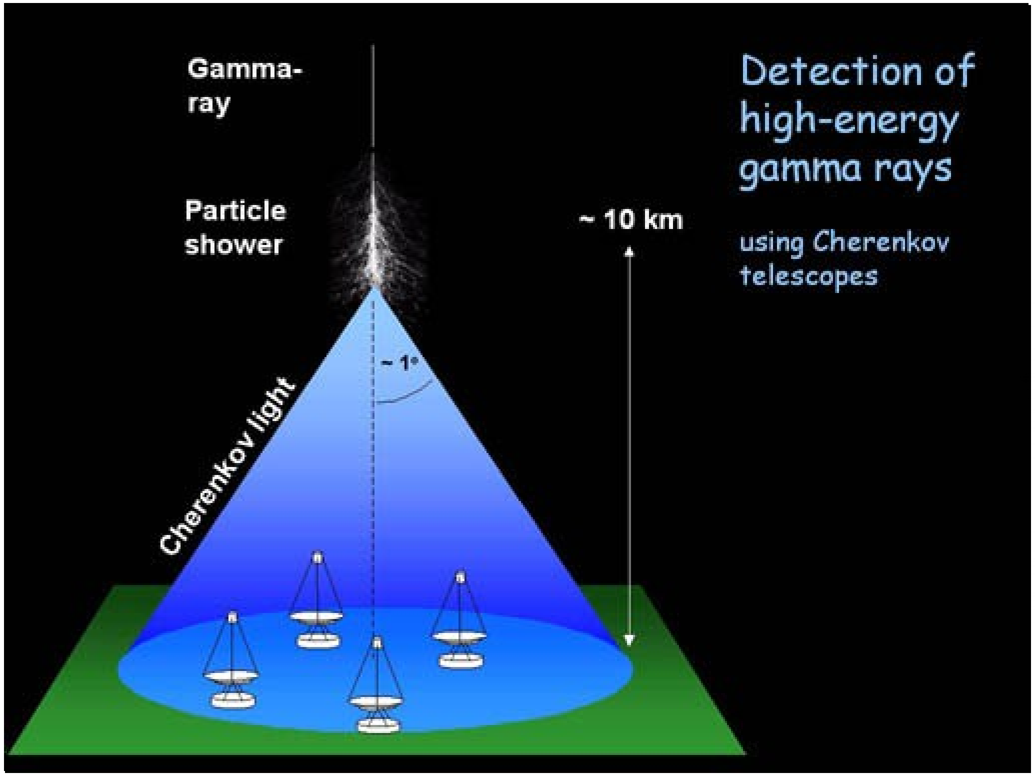
Schematic of Air-Shower Development

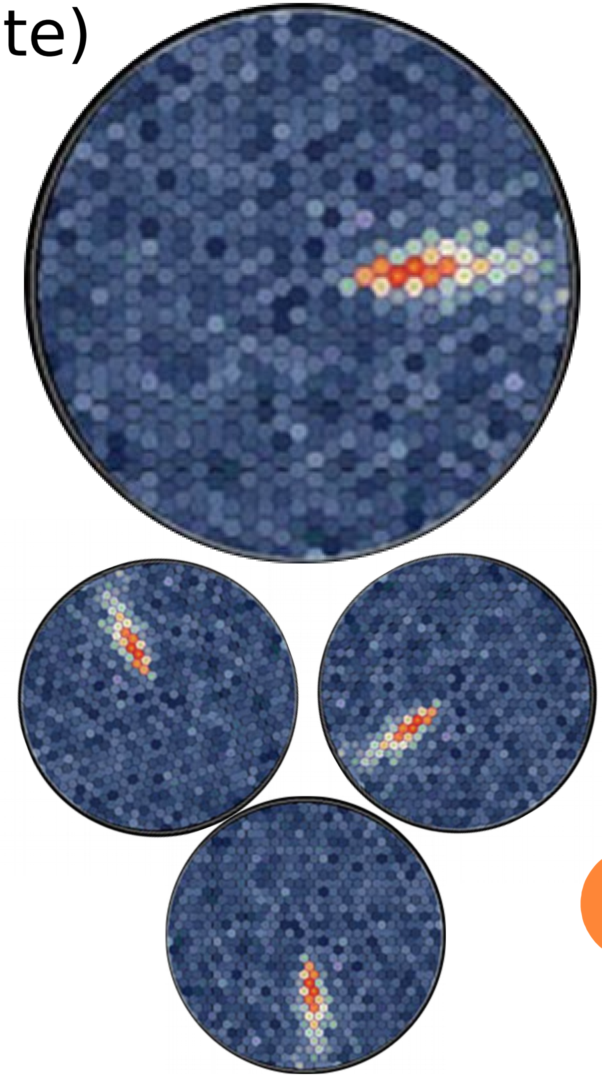


Gamma-induced showers have different particle content and will peak at a different height from hadron-induced showers. They also have a different morphology—note the subshowers in the hadron-induced cascade.

TeV Gamma-Ray Astronomy: Imaging Atmospheric Cherenkov Telescopes

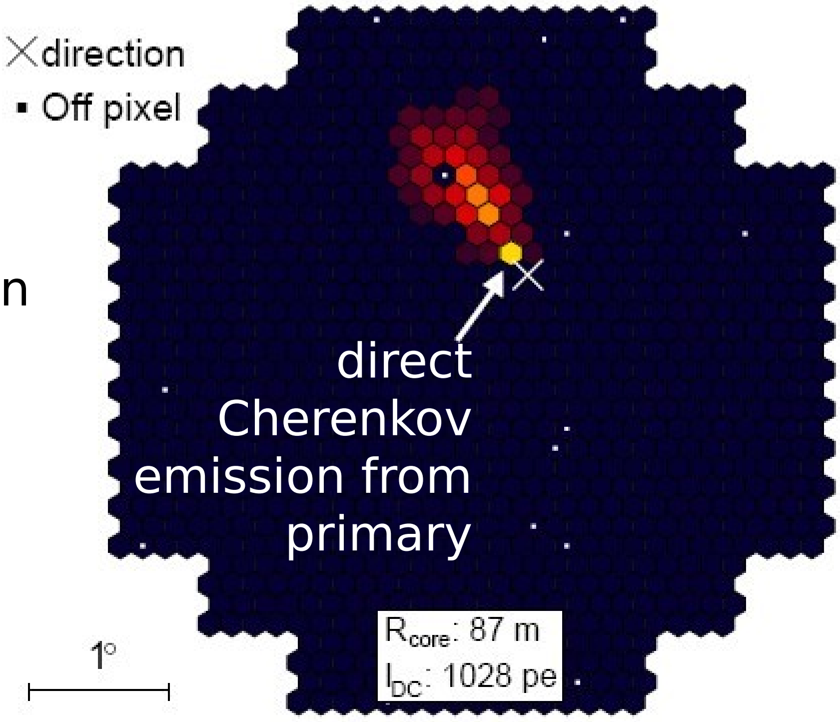
- Principles (from H.E.S.S. website)





TeV Gamma-Ray Astronomy: Imaging Atmospheric Cherenkov Telescopes

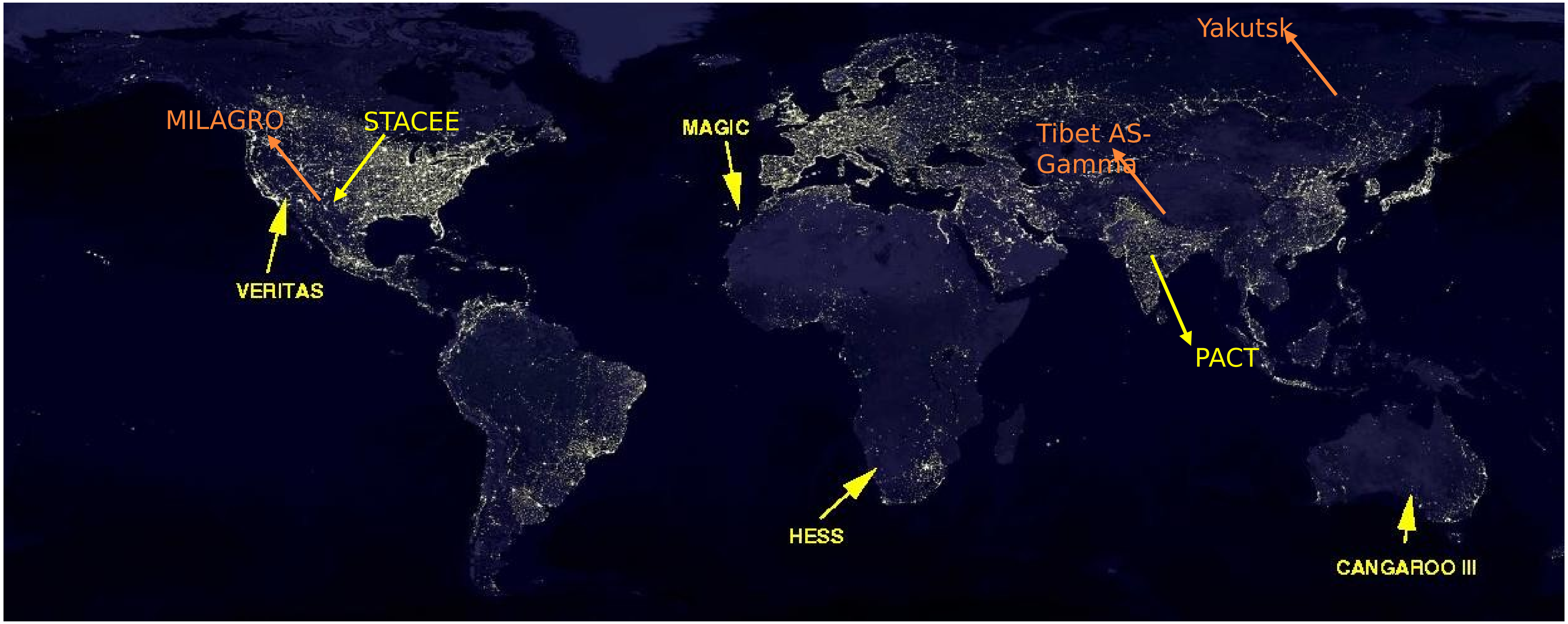
- Particle identification
  - shower shape
  - broader and less regular for
    - hadron-induced showers
    - narrow cone of direct emission
    - from heavy nucleus
- Energy reconstruction
- total Cherenkov light yield
  - $\propto$ energy of primary
    - resolution typically 15-20%
    - threshold given by:
    -
    - $$E_T \propto \frac{1}{C(\lambda)}\sqrt{\frac{B(\lambda)\Omega\tau}{\eta(\lambda)A}}$$



Heavy nucleus signal in HESS

where *C* is Cherenkov yield, *B* sky background,
- η photon collection efficiency, *A* mirror area, Ω solid angle,
- τ integration time

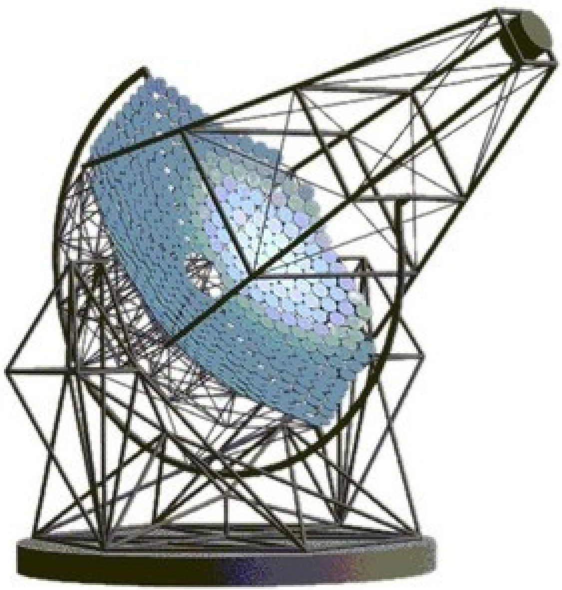
TeV Gamma-ray Observatories



Main sites: VERITAS, HESS, CANGAROO III (stereo systems);
MAGIC (single dish)

two since 2009

IACT Technology: H.E.S.S. (Namibia)
[IACT = Imaging Air Cherenkov Telescope]

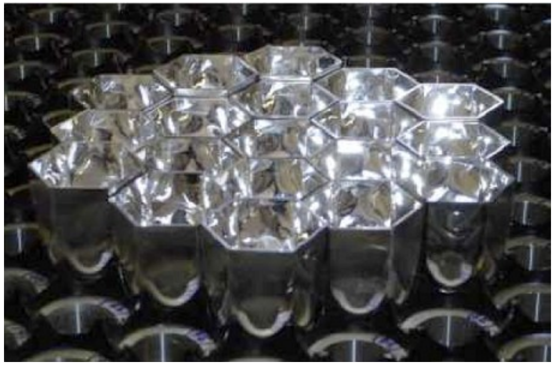


4 telescopes each of 108 m^2 aperture
(12 metres diameter each)

Camera array of 2048 pixels (0.07°)

H.E.S.S. II: New 28 metre telescope
operational since July 2012
(lowers energy threshold to 30 GeV)

IACT Technology: VERITAS (USA)



Very similar to H.E.S.S.

4 telescopes each 110 m^2

499 pixel camera

IACT Technology: MAGIC (Canary Islands)

Larger telescopes (236 m^2), hence lower threshold (25 GeV); also fast slew to respond to GRB alerts

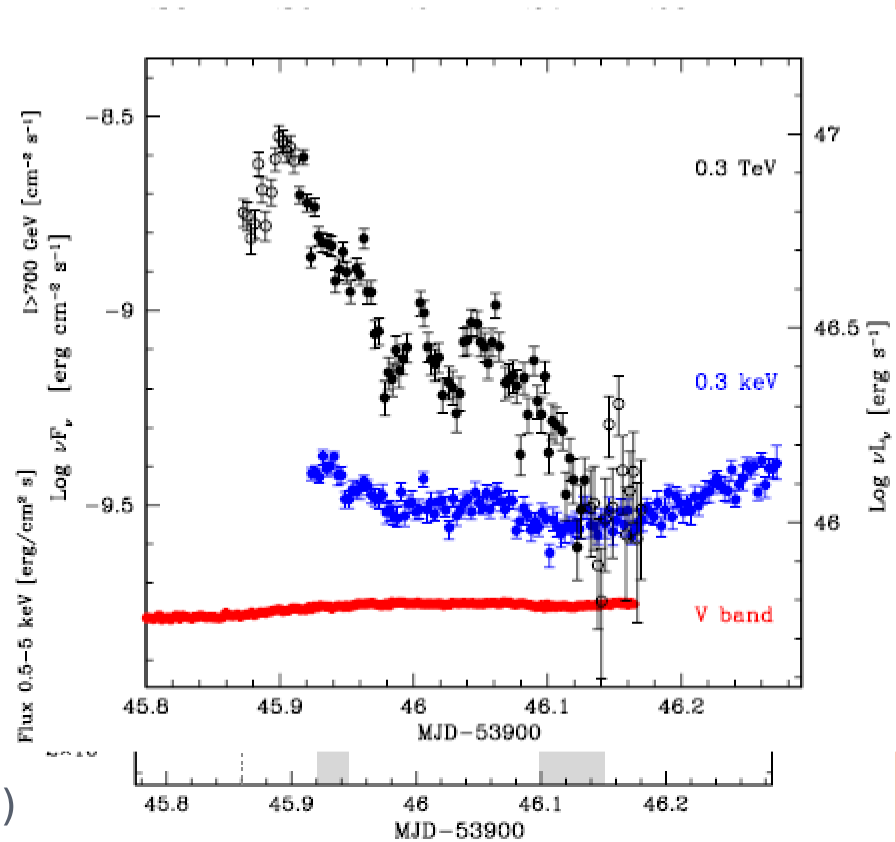
The two telescopes can operate independently

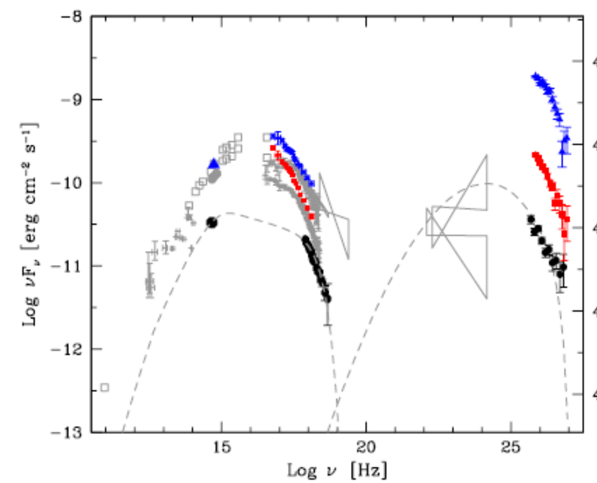
Camera has inner core of 396 1” PMTs, outer ring of 180 1.5" PMTs.

Some Results

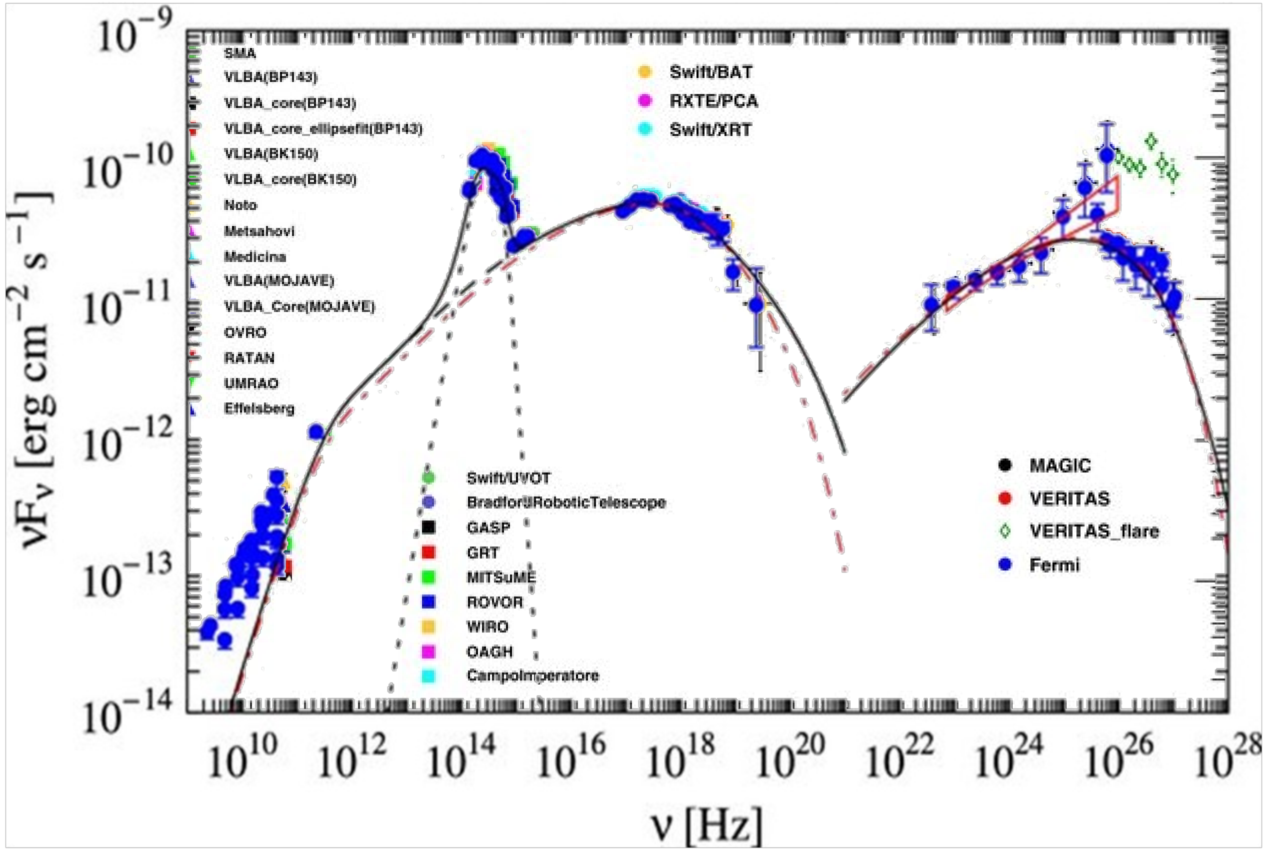
Some blazar sources seen to vary on *very* short timescales

- (few minutes)
- plots show PKS 2155−304
- observed by HESS and Chandra
  - (Aharonian et al., *A&A* **502** (2009) 749)
  - flare is much larger at TeV energies
  - but TeV & x-rays correlated
  - Explaining these fast flares is a
  - major challenge for models



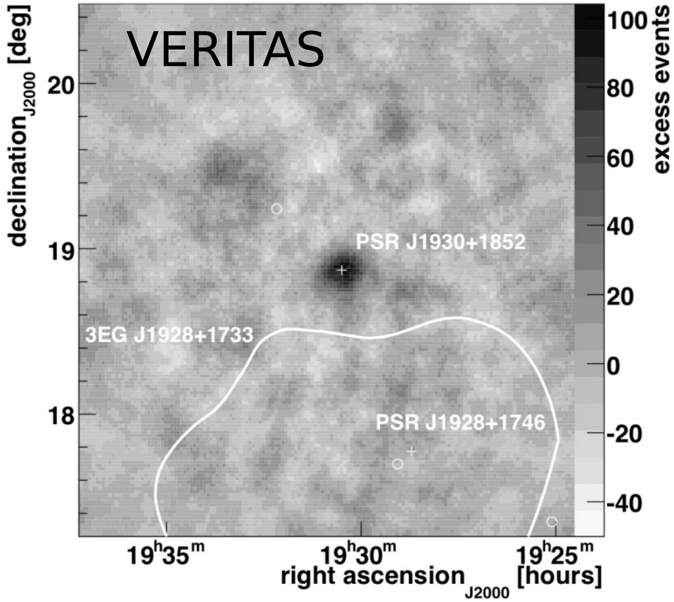


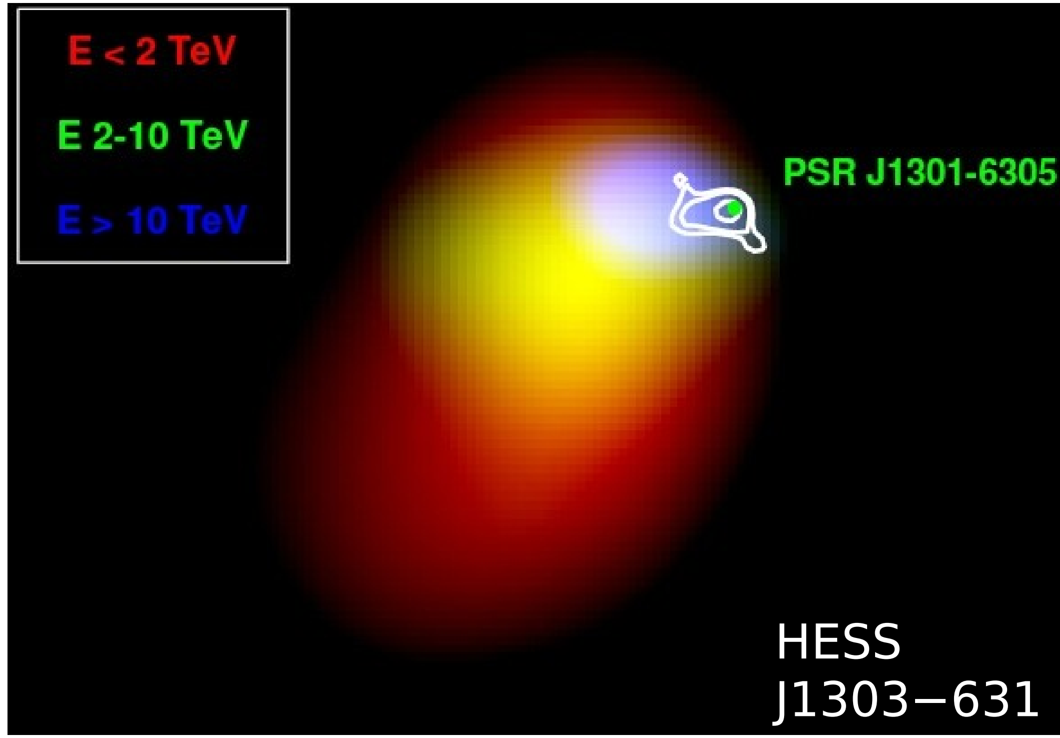
More Results



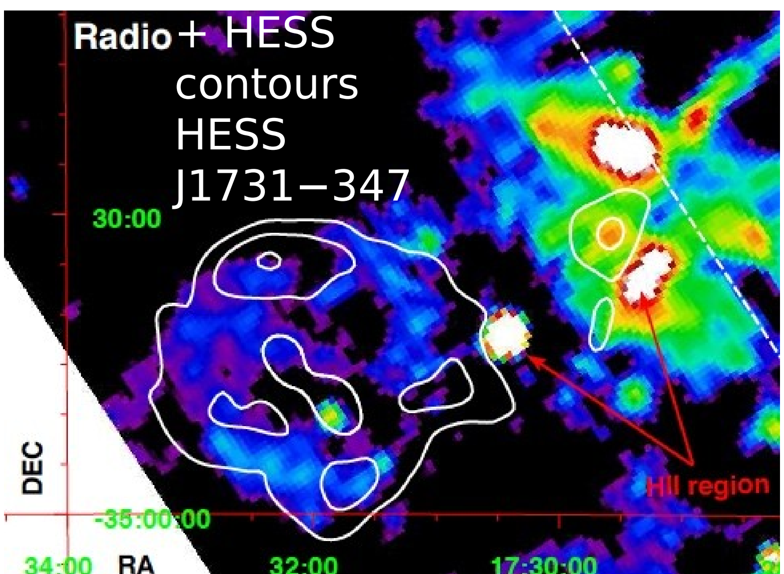
Multiwavelength study of Mkn 501 (Abdo et al, *ApJ* **727**

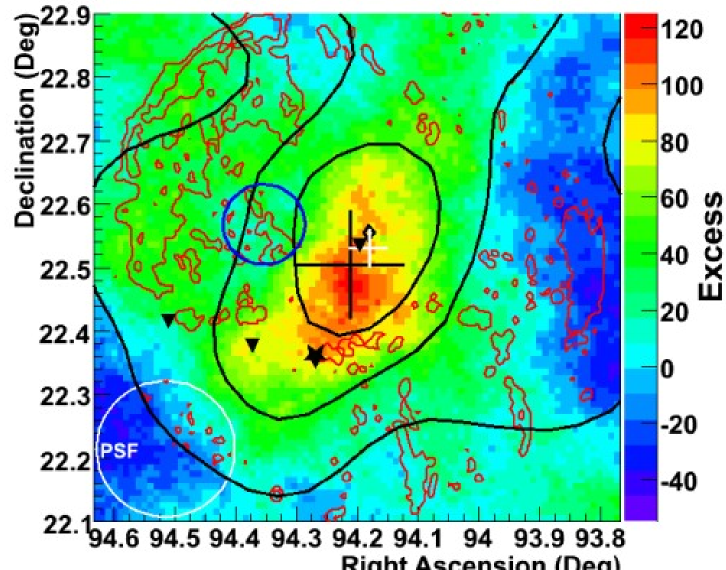
- (2011) 129)
- Note TeV flare
  - see by VERITAS
  - Modelled by
- one-zone SSC
- Fit parameters:
  - jet Doppler factor δ, emitting region radius R, magnetic field B, ratio of electron and magnetic field comoving energy densities η, plus electron spectral distribution (modelled as broken power law in γe with exponential cut-off at high energies)
  - find δ = 12, R = 1.3×10^{12} km (9 AU), B = 0.015 G, η = 56, ⟨γe⟩ = 2400
    - ultrarelativistic electrons in near-equipartition with mildly relativistic protons?
    - consistent with shock acceleration





Images of TeV sources associated with pulsars and SNRs

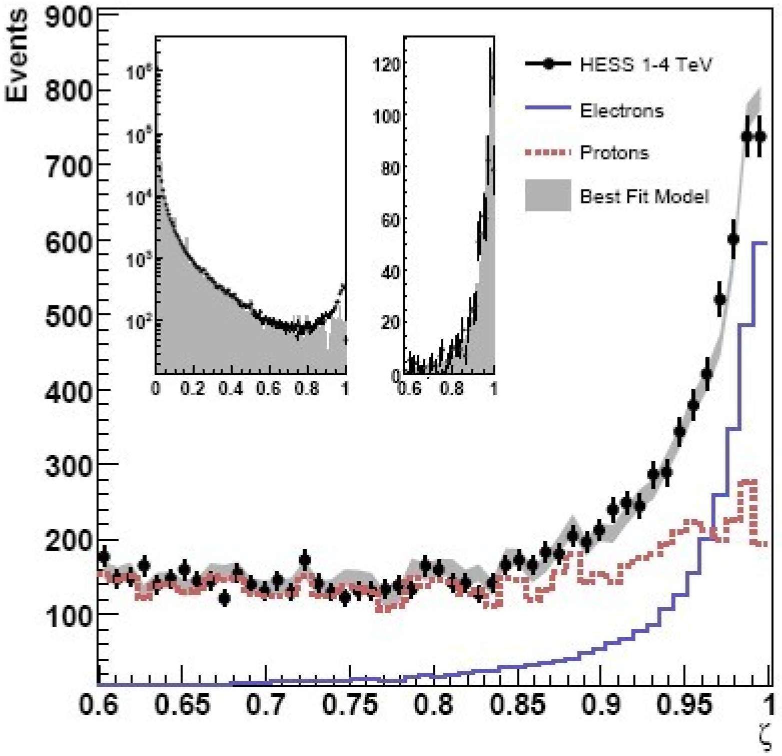


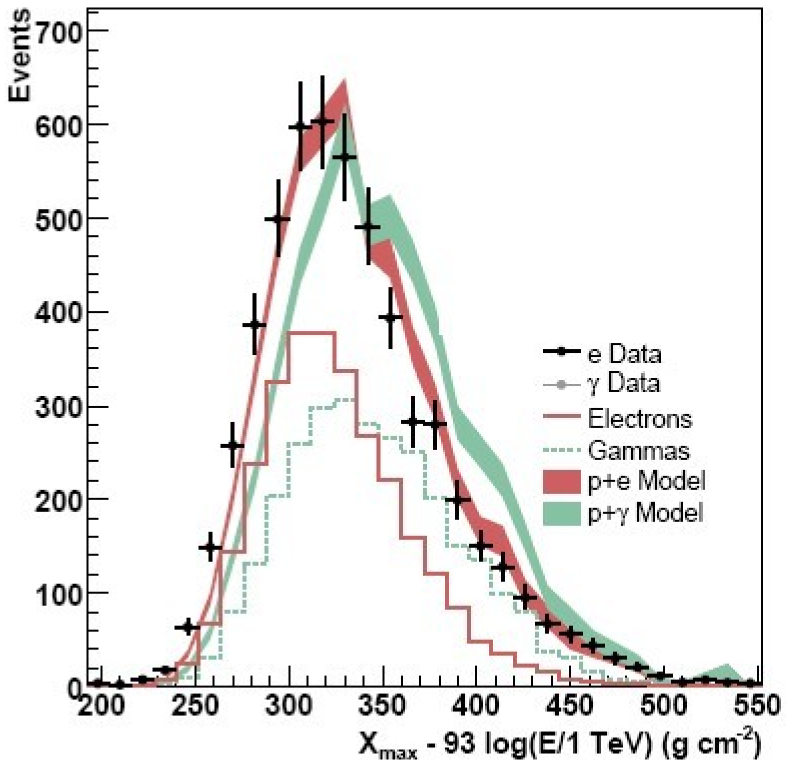


VERITAS
SNR IC443
optical

Fermi 95%
MAGIC
(white +)

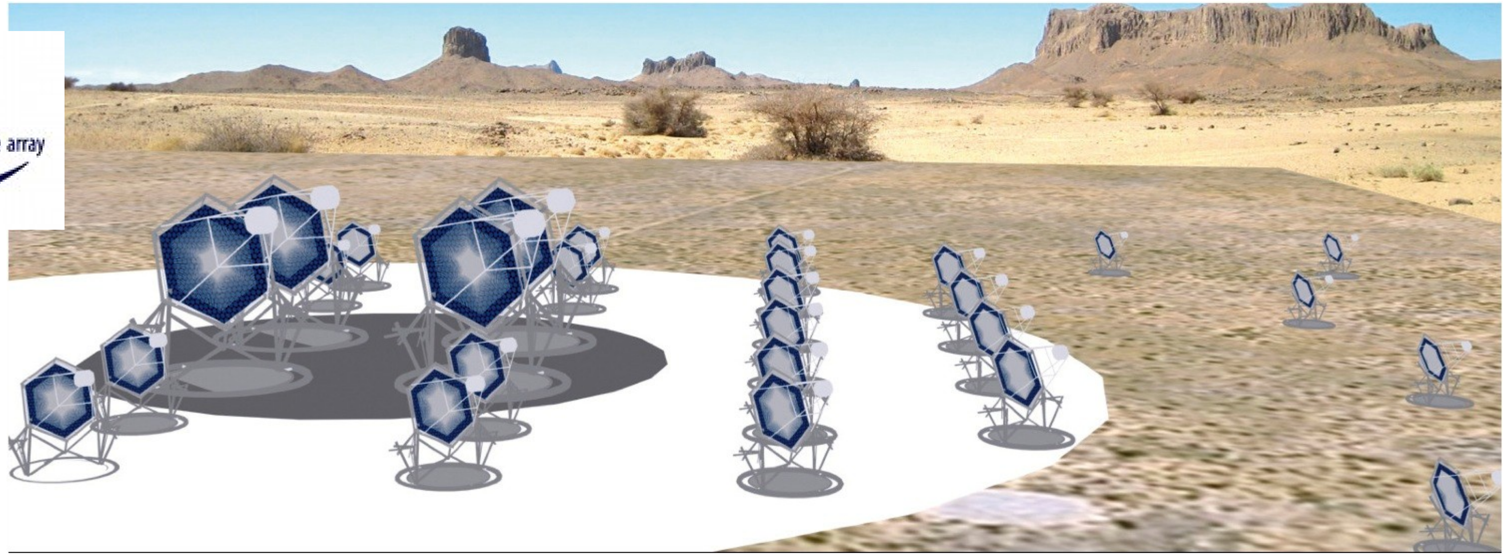
HESS as a detector of cosmic-ray electrons



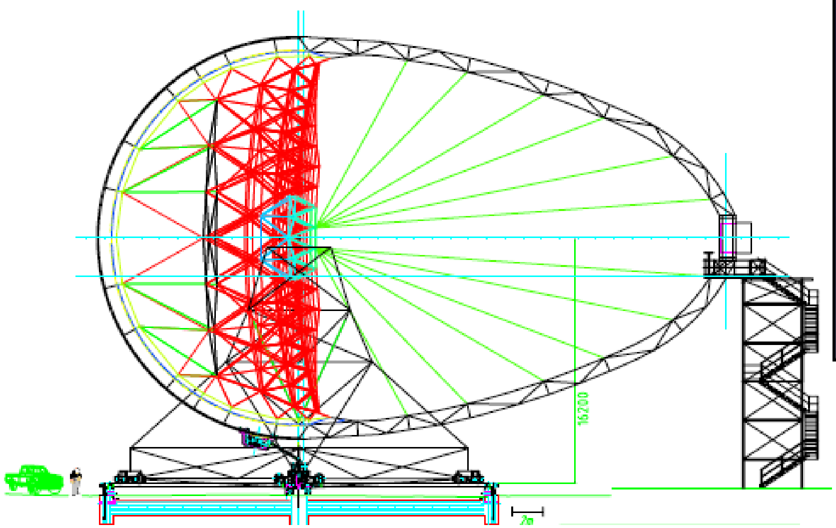


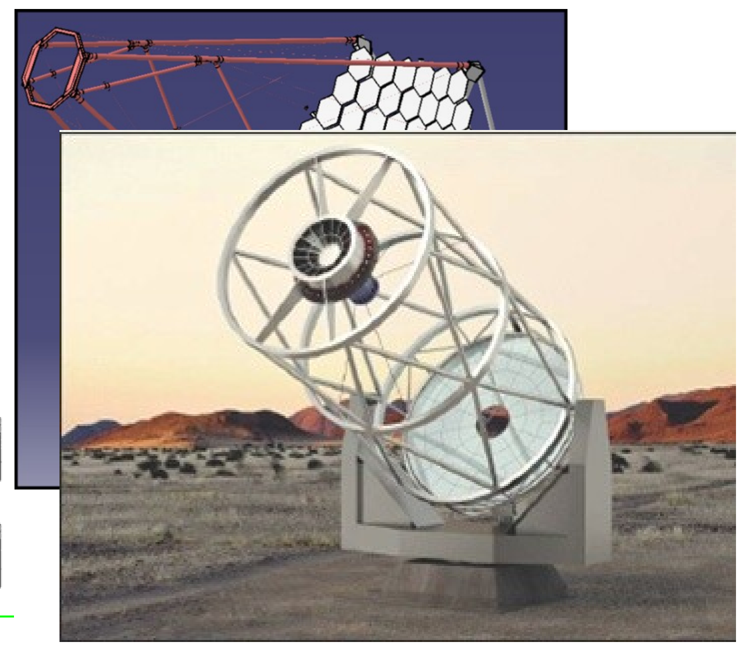
Separation of electron and proton showers using multivariate analysis

Separation of electron and photon showers using *X*max (depth of shower maximum): electrons shower earlier than photons cta cherenkov telescope array



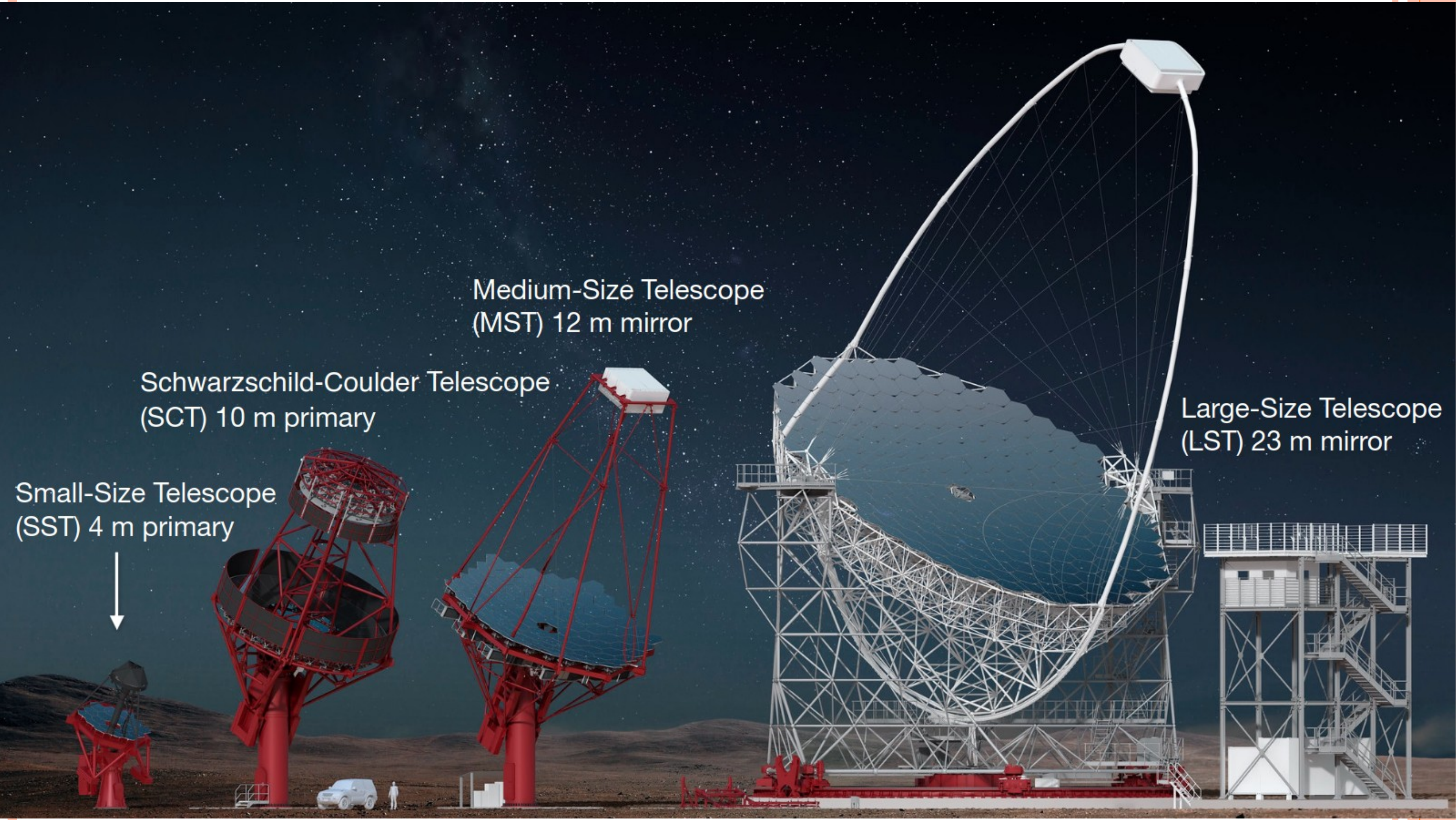
- Future facility for TeV gamma-ray astronomy
  - three different telescope designs optimised for different energies
  - in design phase



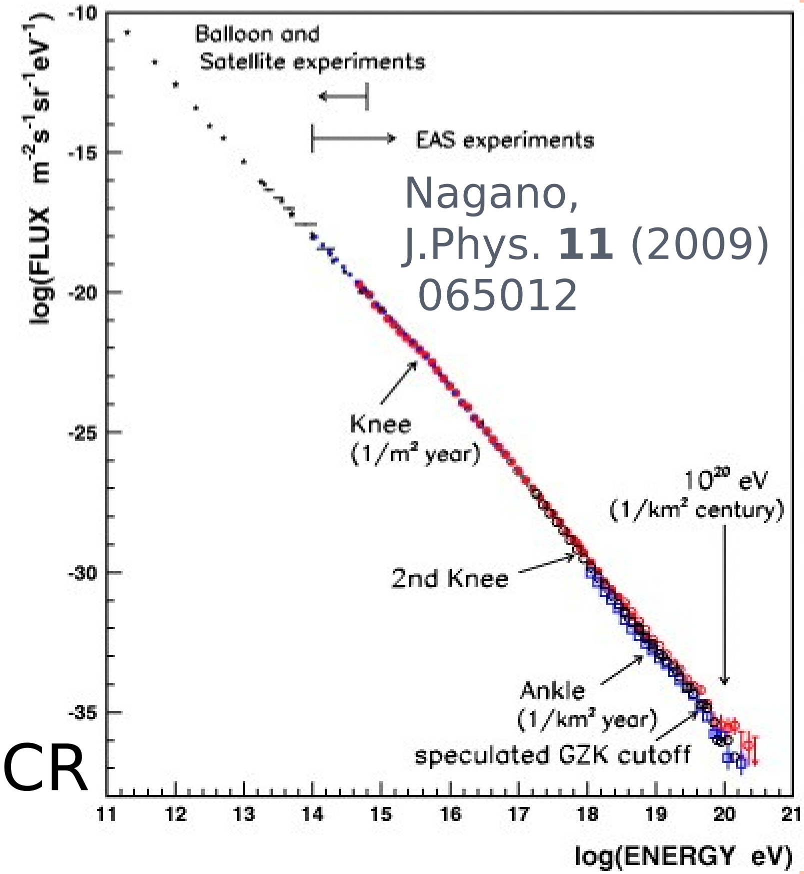


CTA-North Site
La Palma, Spain

CTA-South Site
ESO Chile


Medium-Size Telescope
(MST) 12 m mirror
Schwarzschild-Coulder Telescope
(SCT) 10 m primary
Large-Size Telescope
(LST) 23 m mirror
Small-Size Telescope
(SST) 4 m primary

Cosmic Ray Detectors



Nagano, J.Phys. **11** (2009) 065012

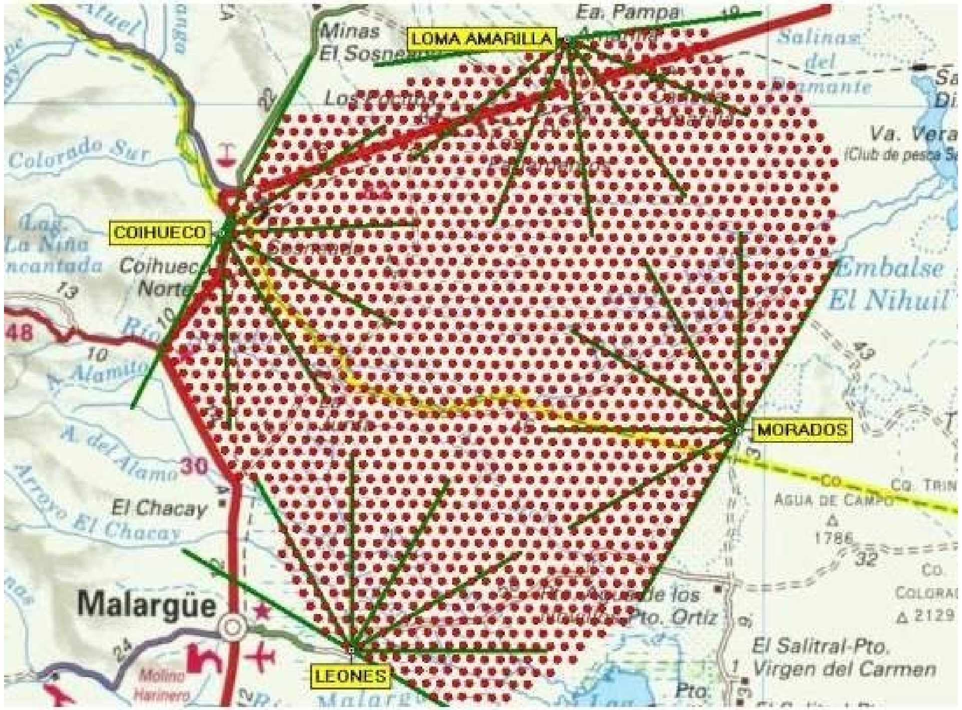
- Focus in recent years on UHECR
- rare, so require very large area
  - detectors
  - fluorescence detectors “see” large
  - effective area, but have limited
    - duty cycle
    - ground-based shower sampling has
    - good duty cycle, but requires
    - genuinely large area coverage to have large effective area

Ground Array Technology

- Large area ground arrays consist of multiple small stations whose data are combined to reconstruct the shower
  - detector technology scintillator (SUGAR, AGASA) or water Cherenkov (Haverah Park, Auger)
    - some detectors (AGASA, Yakutsk) also include underground muon detectors
  - individual detectors need to be robust and self-contained
- Energy reconstruction by
  - conversion from shower size
    - estimated number of electrons, N_e, combined with muons, N_μ, for those experiments with muon detectors
  - particle density at a given (large) distance from core
    - smaller fluctuations, and less sensitive to primary particle type, than shower core

Example of Ground Array

- Pierre Auger Observatory, Argentina
  - 1600 water Cherenkov tanks
  - solar powered with GPS



Example of Ground Array

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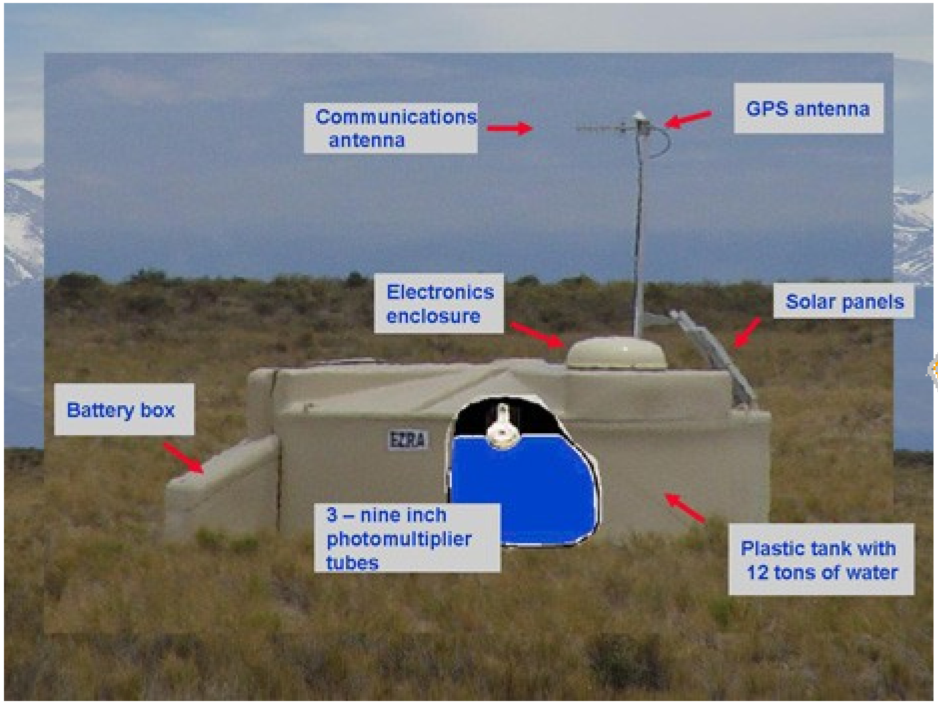
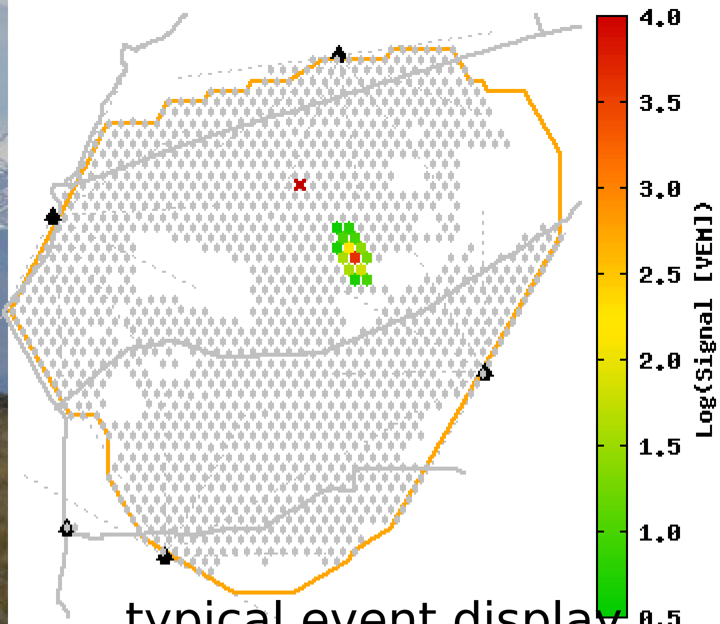
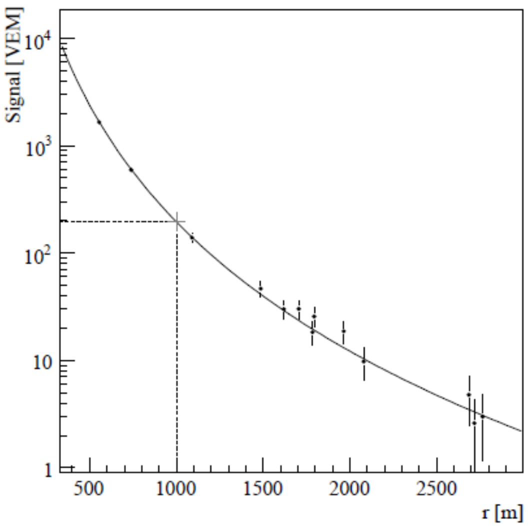


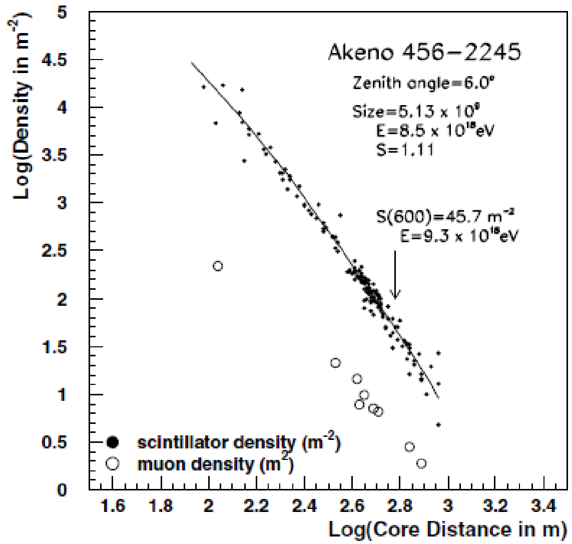


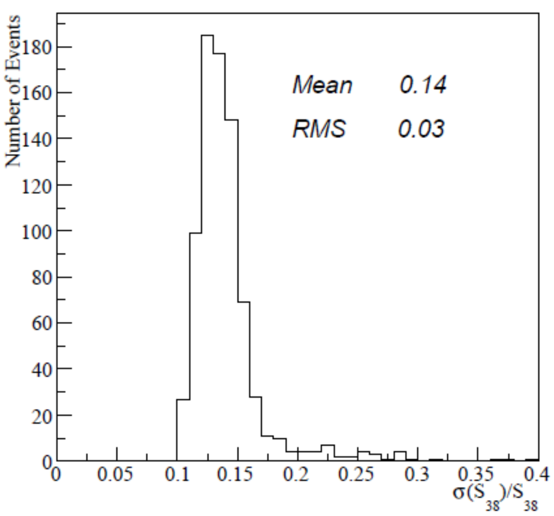
typical event display

Energy Reconstruction in Ground Arrays

- Auger fits *S*(1000), shower density 1 km from core, and corrects for inclination to get *S*(38°)
  - calibrated by comparison with fluorescence
- AGASA used *S*(600), verified by comparison with *N*e and *N*μ
- Significant systematic errors (~20% quoted)



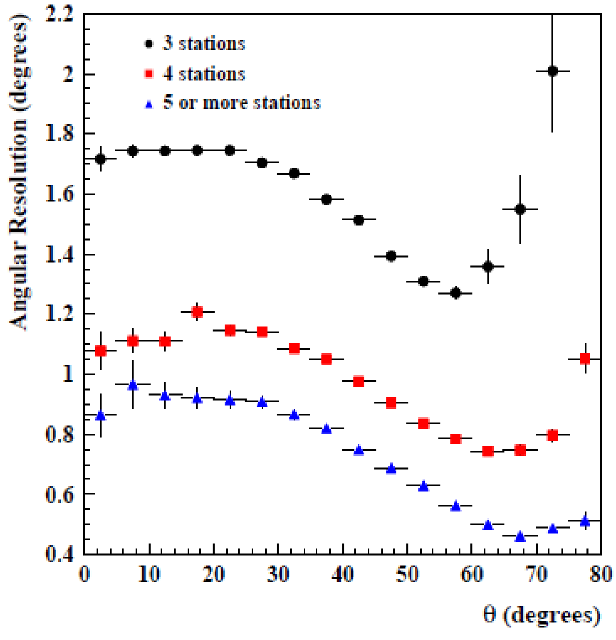


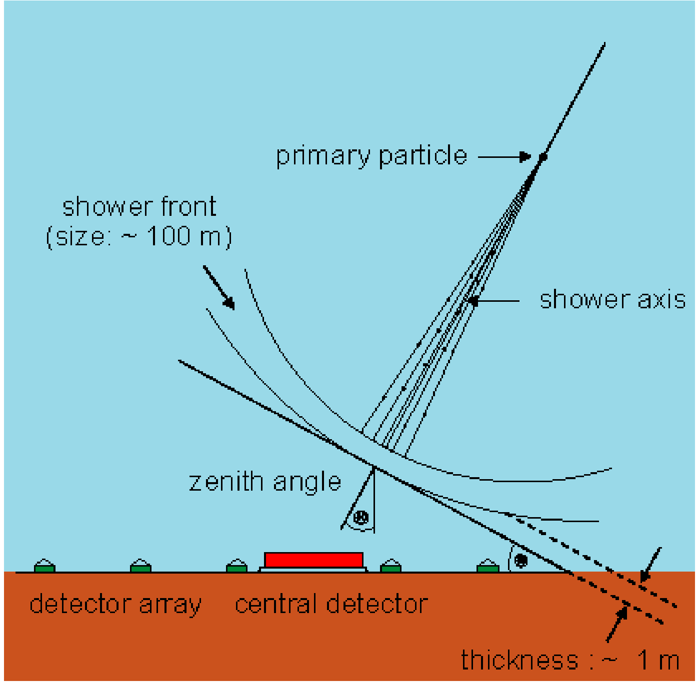


Direction Reconstruction in Ground Arrays

Direction is reconstructed from arrival time of shower

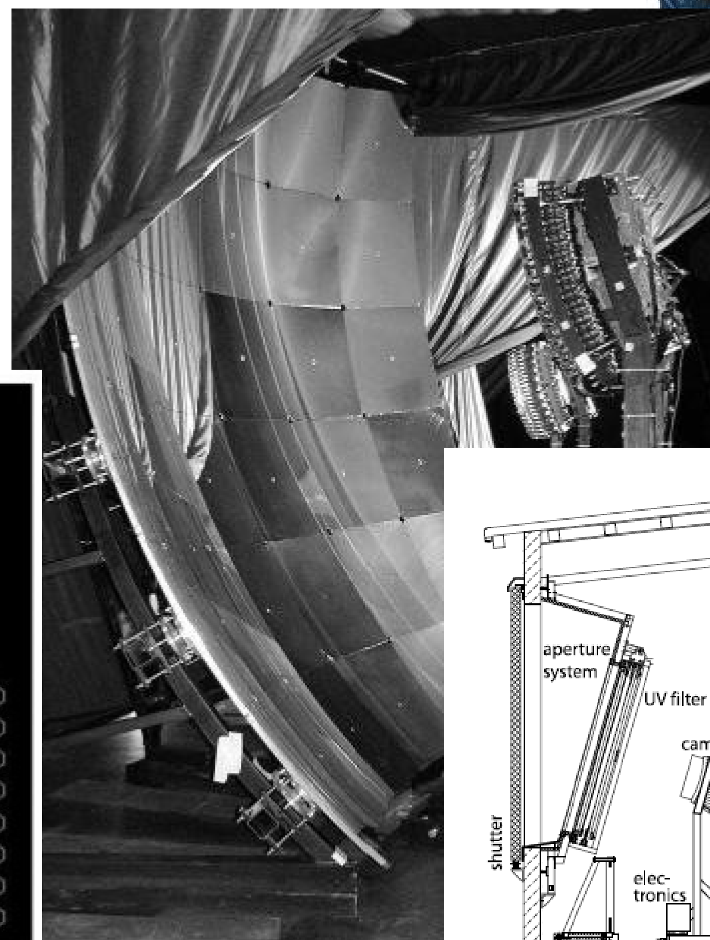
- at different ground stations
- better than 1° if >4 stations fire
  - (E > 8 EeV)

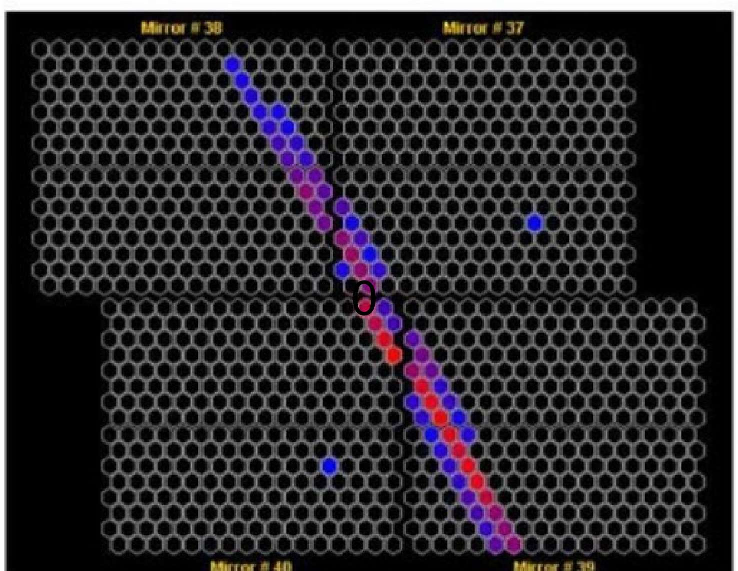


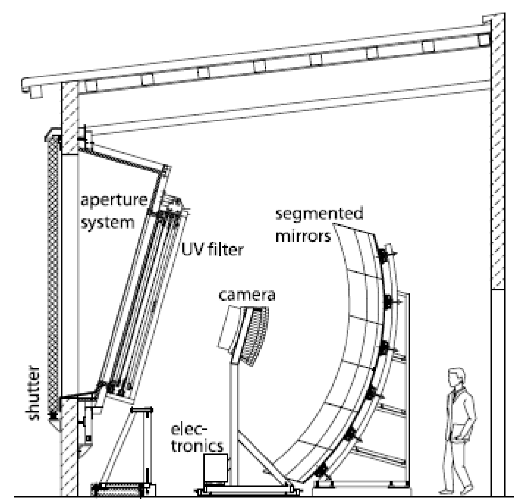


Fluorescence Detector Technolo

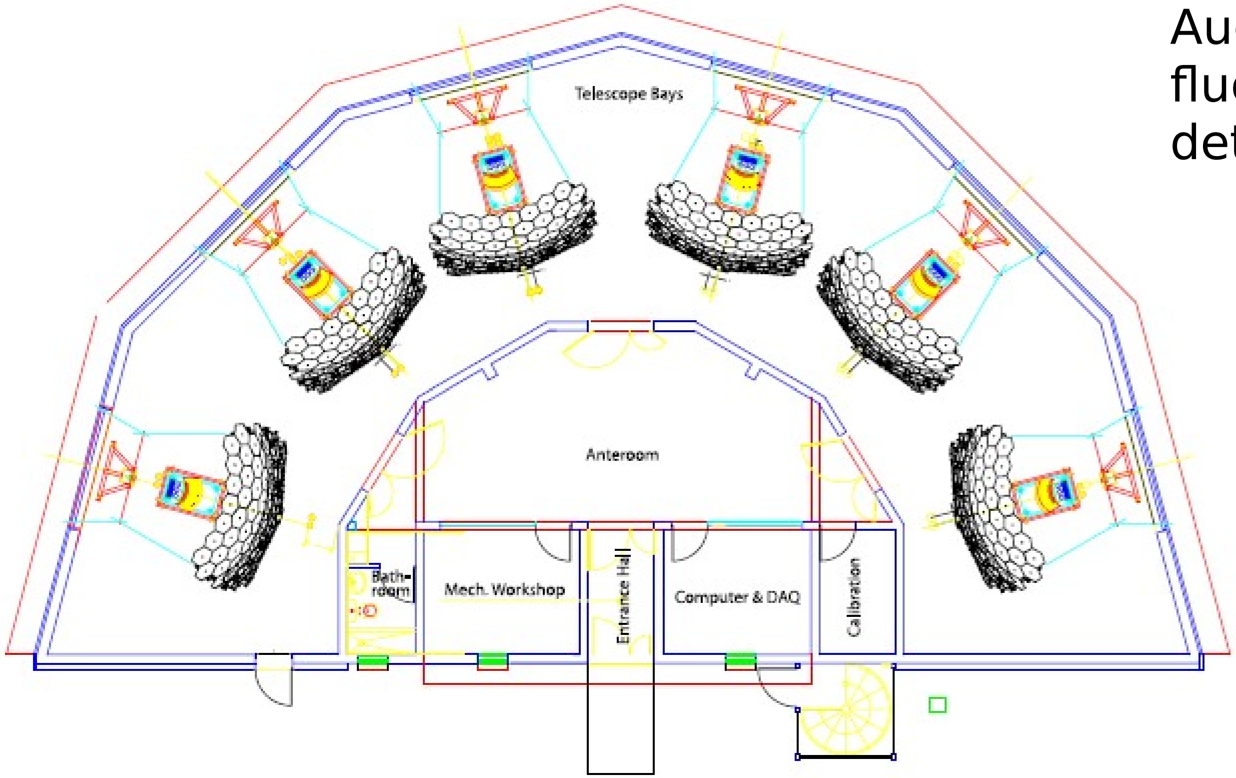
- Broadly similar to Cherenkov telescop
- Expect to see
- “stripe” of light
- corresponding to
  - shower







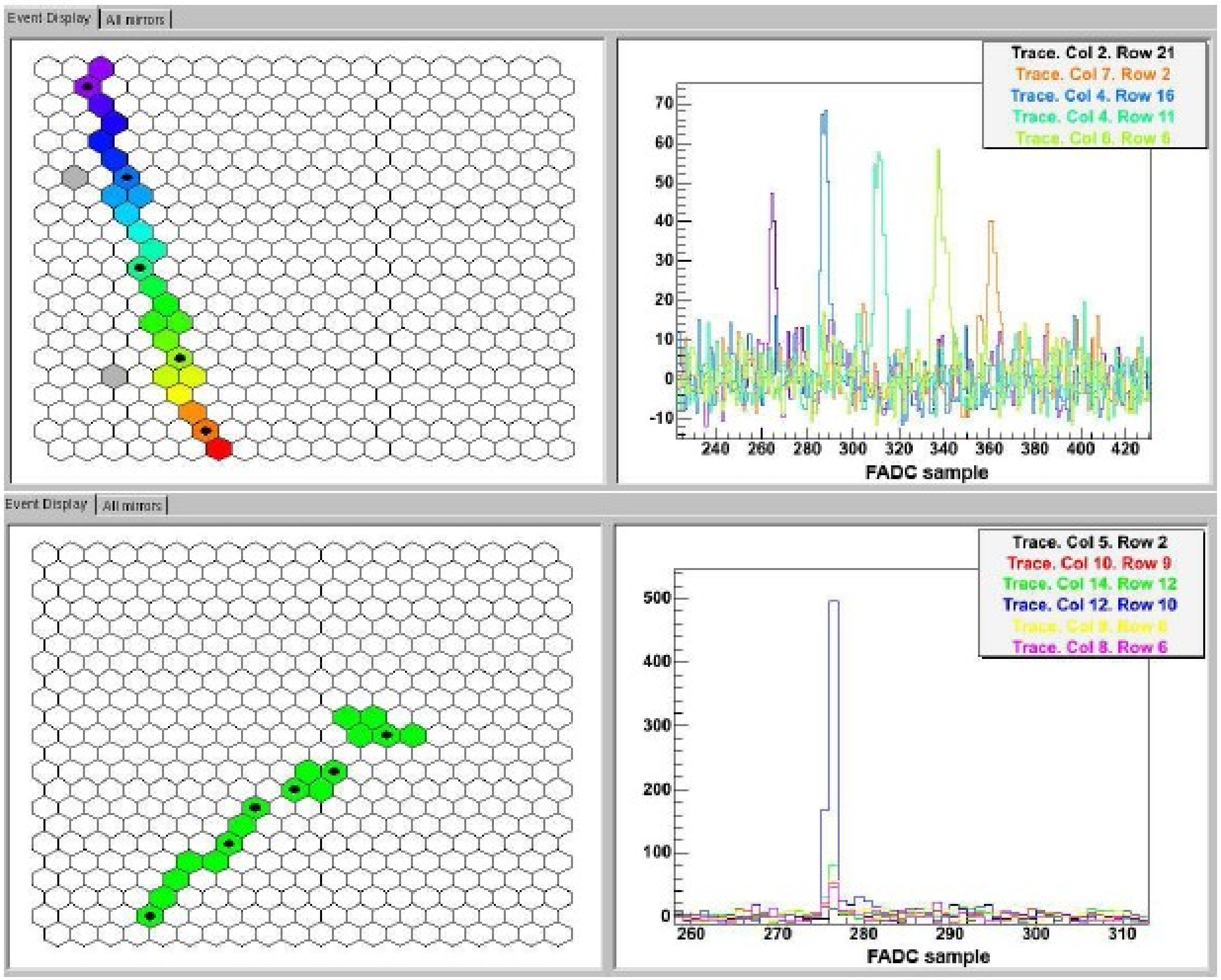
Fluorescence Detector Technology



Auger fluorescence detector layout

Auger Coll., *Nucl. Instrum.Meth.* **A620** (2010) 227

Background Rejection

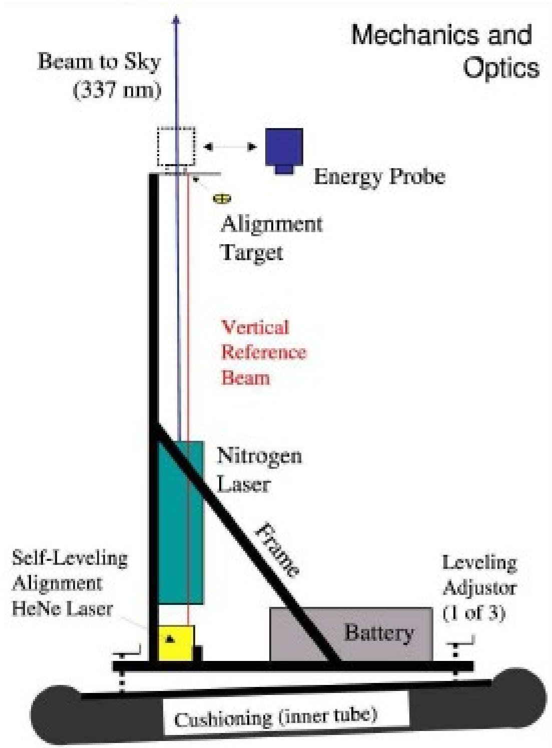


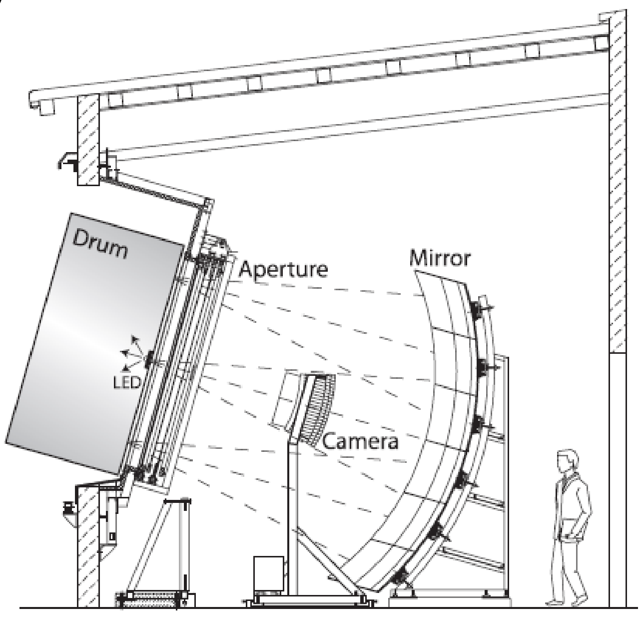
Genuine event with colours showing time progression

Fake event probably caused by cosmic ray muon interacting directly in detector

Energy Reconstruction in Fluorescence Detector

- Calorimetric detector: total light intensity measures electromagnetic energy in shower
- response calibrated using artificial
- light source and
- direct
- excitation of
- fluorescence
- with nitrogen
  - laser

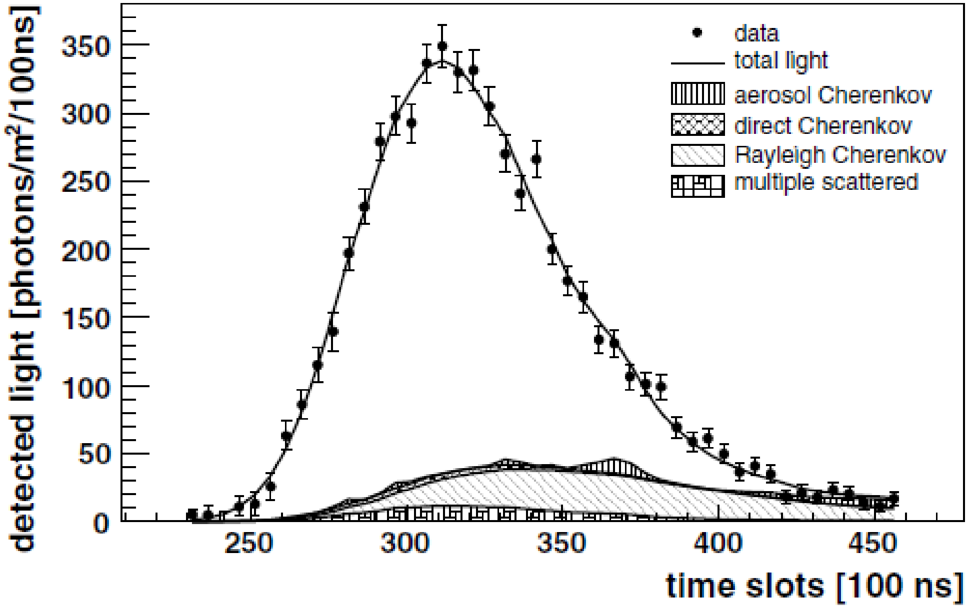


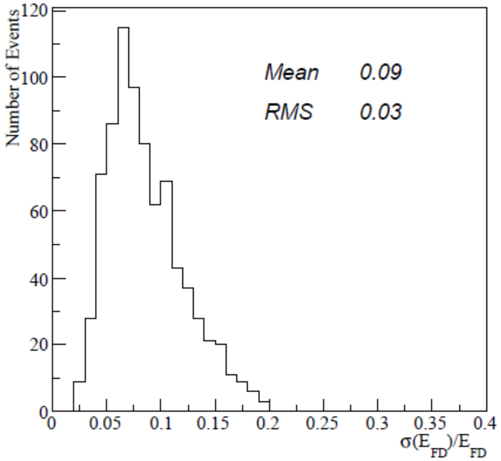


Auger Collab.

Energy Reconstruction in Fluorescence Detector

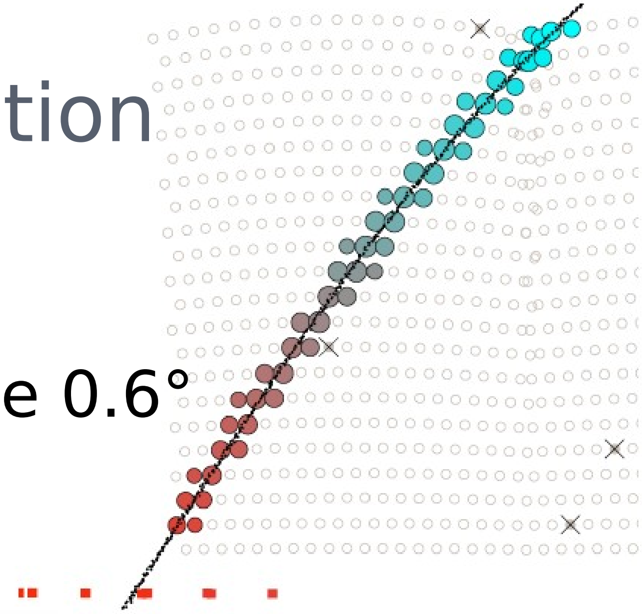
Measure longitudinal
- shower profile
- Fit to standard
- profile (Gaisser-
  - Hillas function)
  - Correct for
  - non-electromagnetic
  - energy
    - Resulting statistical error is about 10%
    - Used to calibrate ground array

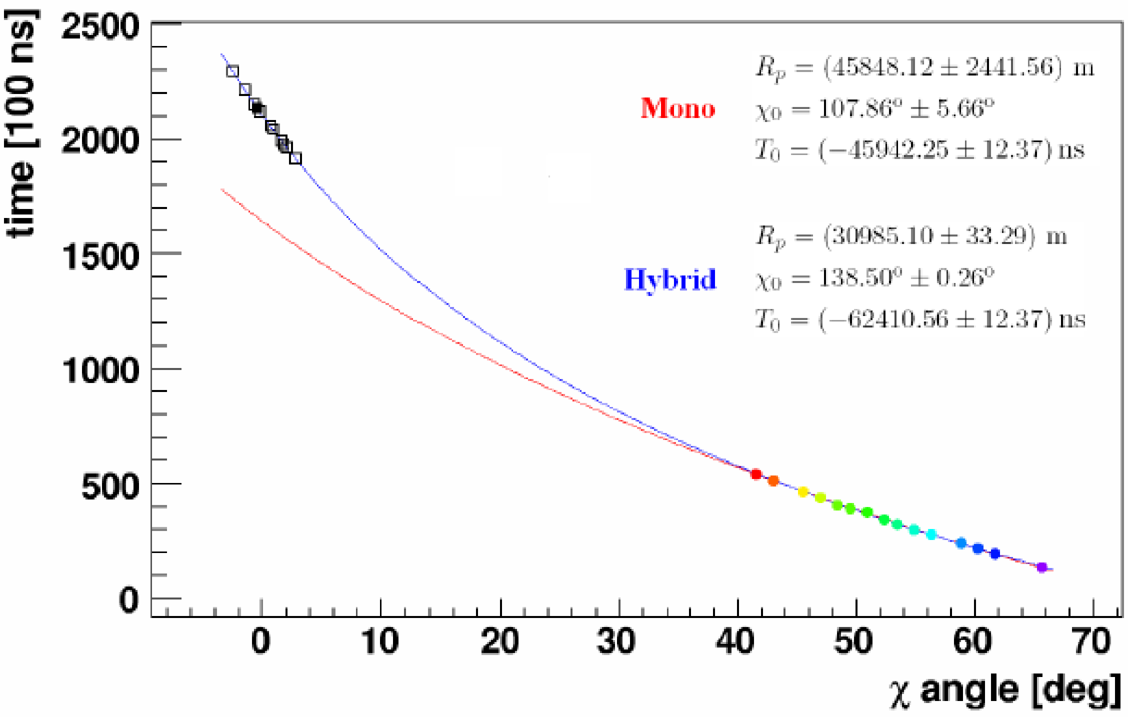


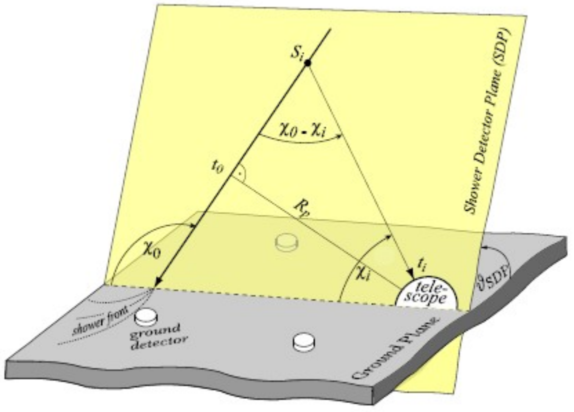


Hybrid Detector Reconstruction

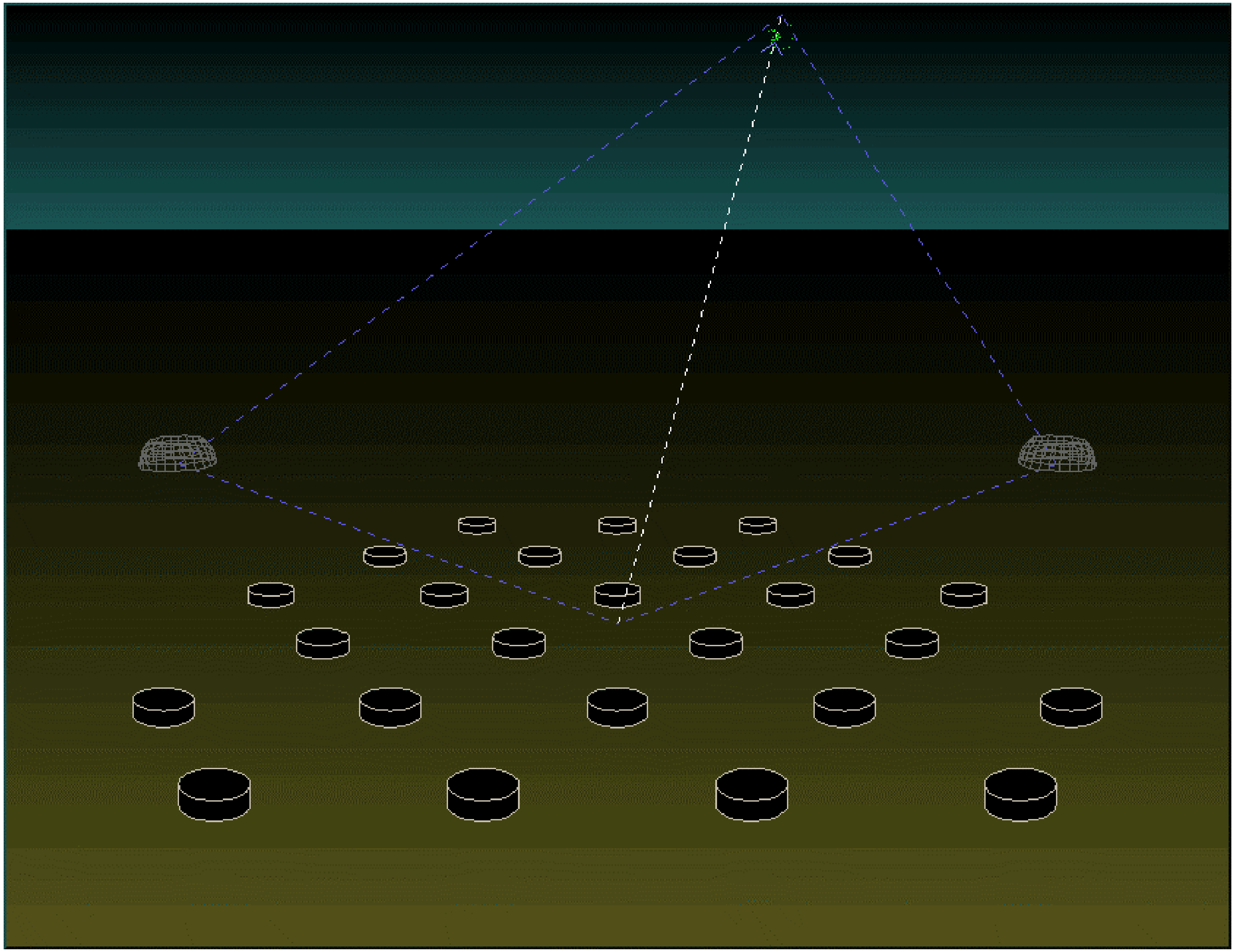
Combining detectors improves
- performance
- Angular resolution in hybrid mode 0.6°





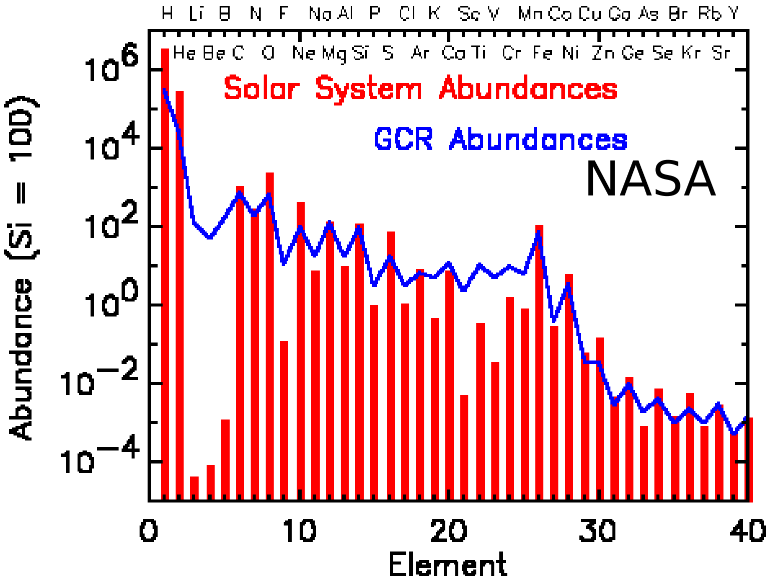


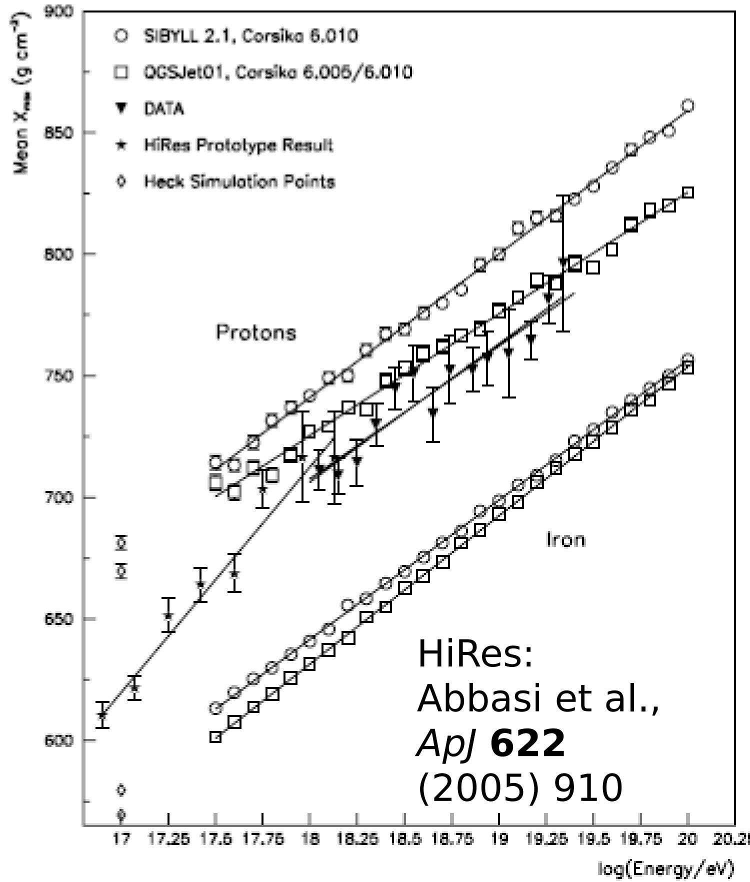
Hybrid Event Schematic



Properties of Primary Cosmic Rays: Particle Content

- Particle identification by mean and variance of shower depth *X*max
- At low energies similar to
- solar system, but enhanced
  - in low Z spallation products
  - at higher energy nearly pure
  - protons

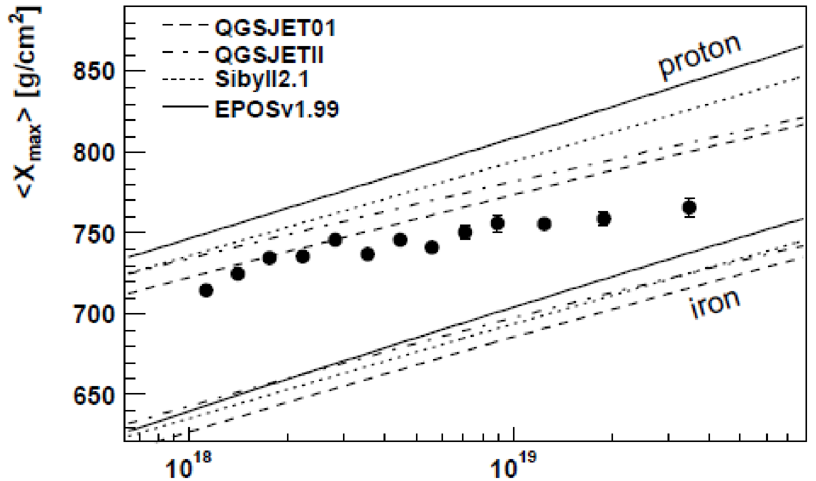


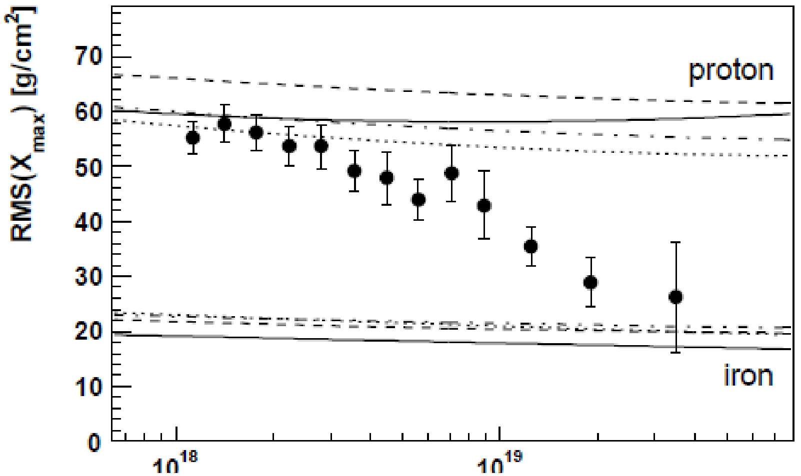


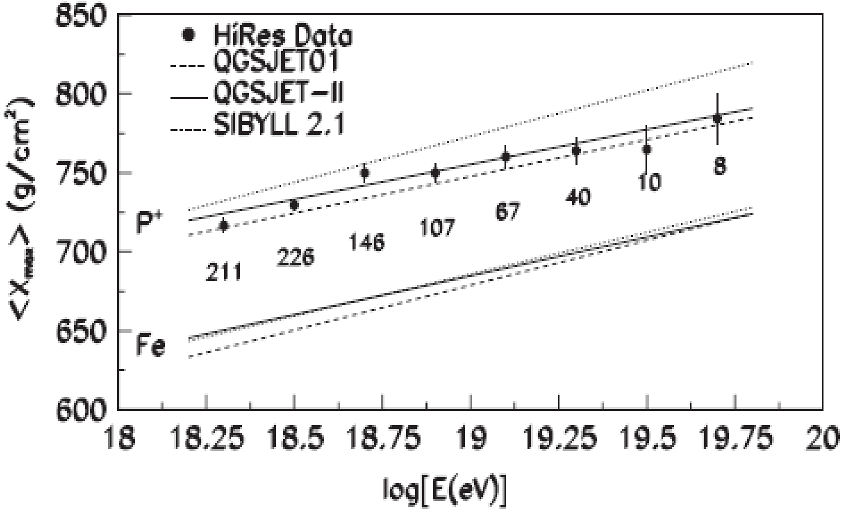
Properties of Primary Cosmic Rays: Particle Content

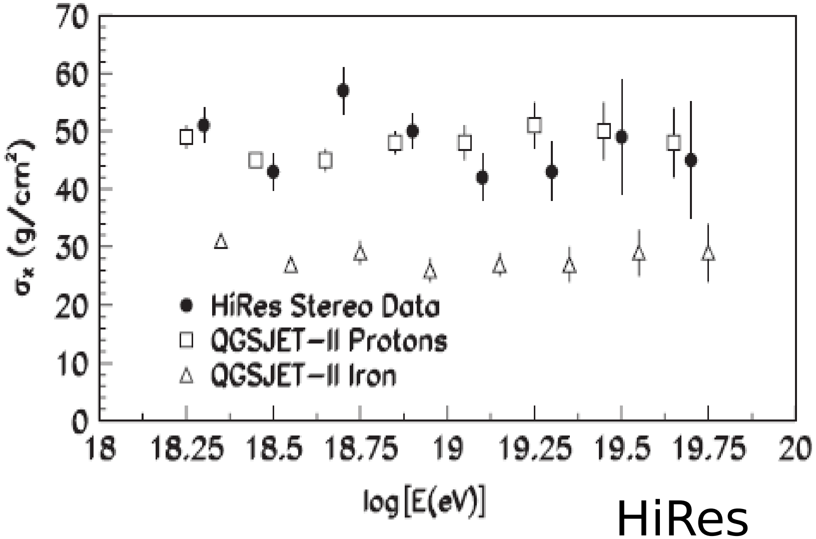
Some disagreement at highest energies!

Auger









HiRes

Energy Spectrum of UHECRs

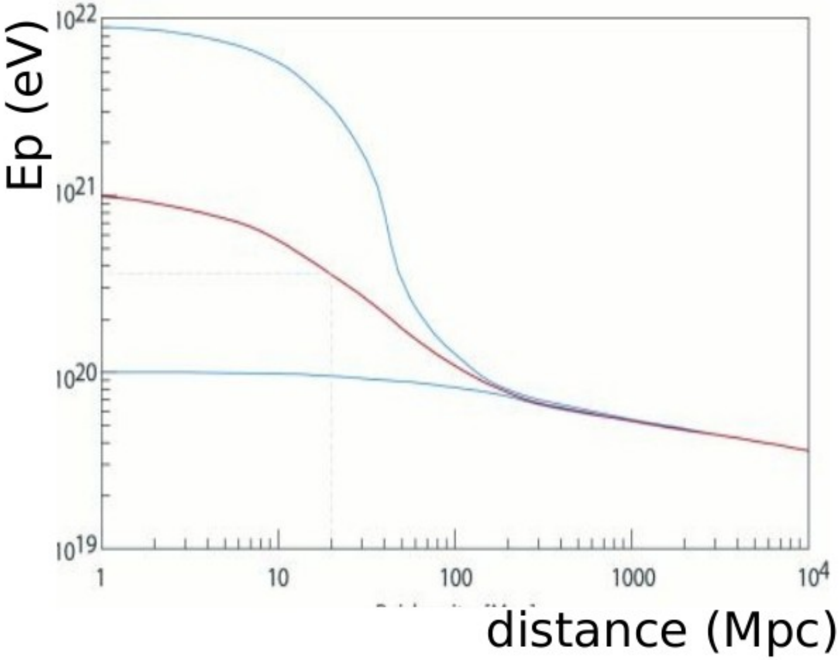
- Expect **GZK cut-off** at high energy owing to pion photoproduction via Δ resonance
  - $\gamma + p \to \Delta+ \to p + \pi0$ (or $n + \pi+$)
  - requires $E\gamma$ = 145 MeV (150 MeV) for proton at rest
    - energy of CMB photon ~3 kB T = $7\times10-4$ eV on average
    - so require proton $\gamma \sim 2\times10^{11}$, i.e. $E_p \sim 2\times10^{20}$ eV
    - this is an overestimate, because protons will see high-energy tail of CMB blackbody—true cutoff is about 5×10^{19} eV

Result: protons with energies > 10^{20} eV lose energy as they travel

- effective range of >GZK protons ~100 Mpc essentially independent of initial energy

Energy Spectrum of UHECRs

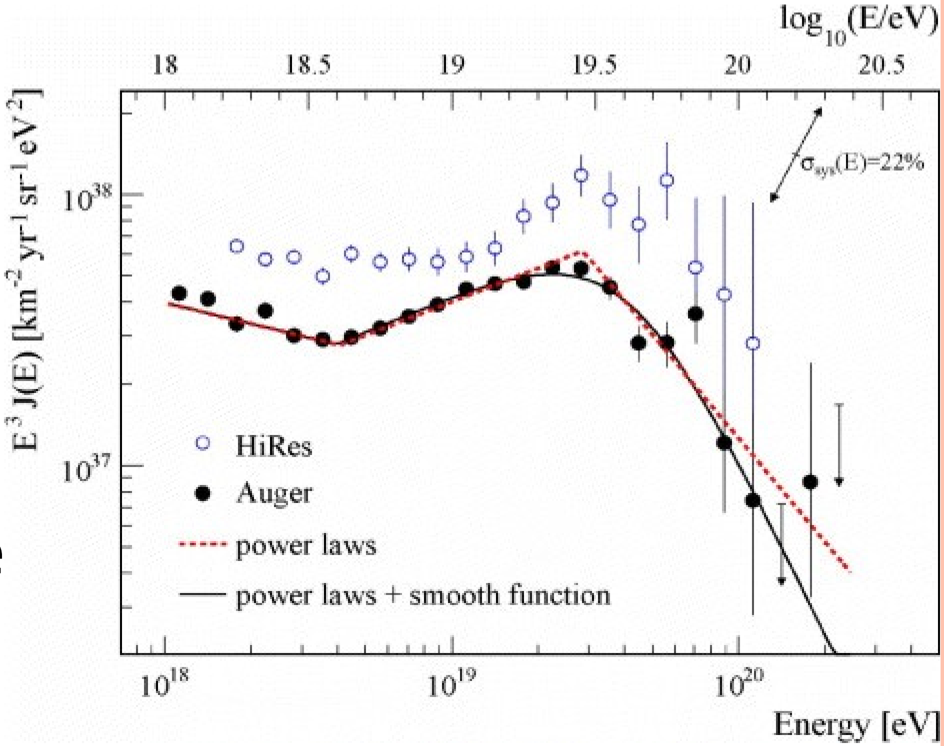
- Expect **GZK cut-off** at high energy owing to pion photoproduction via Δ resonance



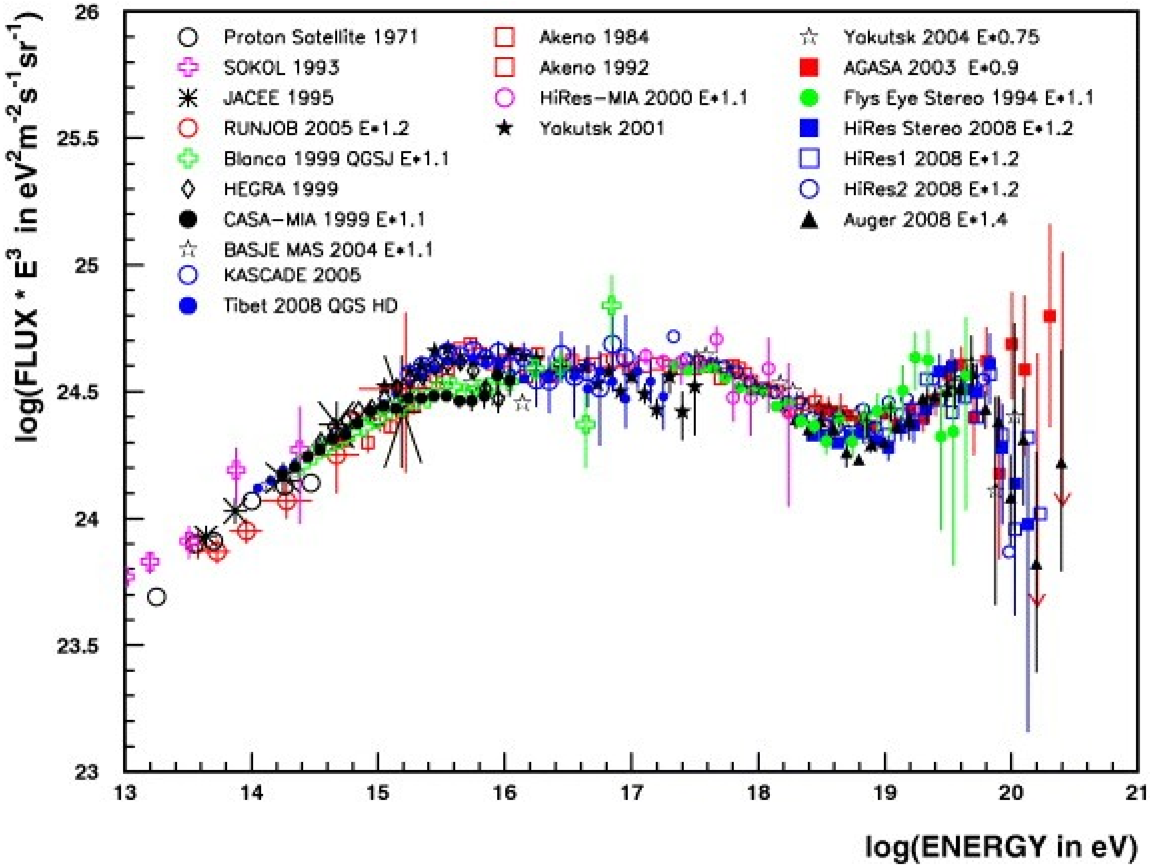
- Result: protons with energies > 10^{20} eV lose energy as they travel

Observation of GZK Cutoff

- Seen by both Auger
- and HiRes
- apparent difference is
- consistent with
- systematic error in
  - energy scale
  - This implies that source
  - of UHECRs are genuinel
- astrophysical objects
  - local sources, e.g. decay of some kind of superheavy metastable dark matter, would not show cutoff

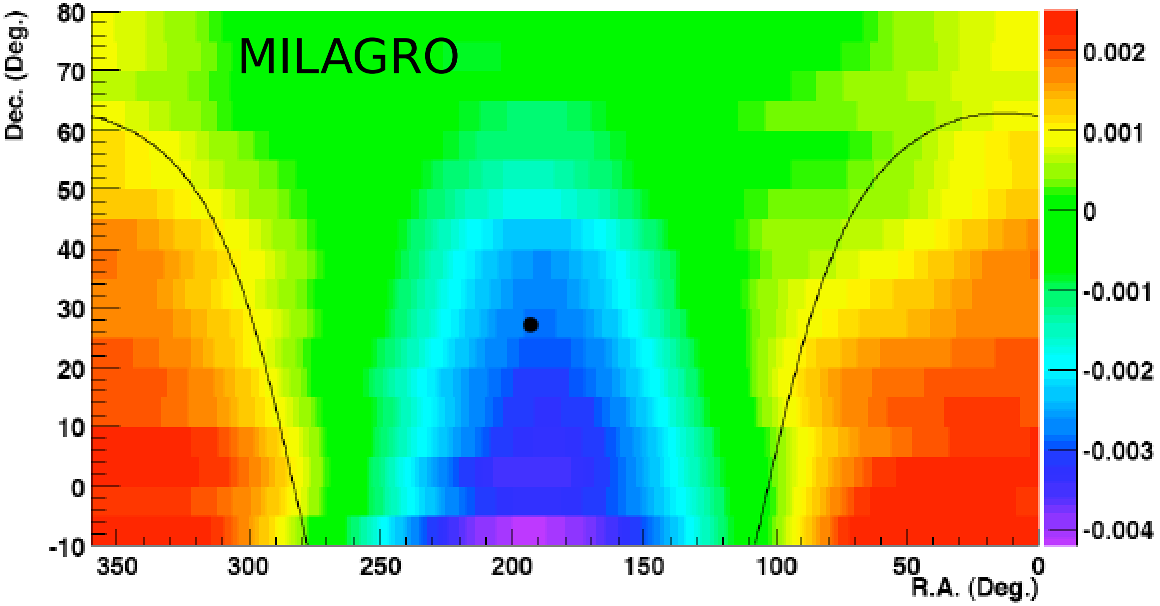


Combined CR Energy Spectrum

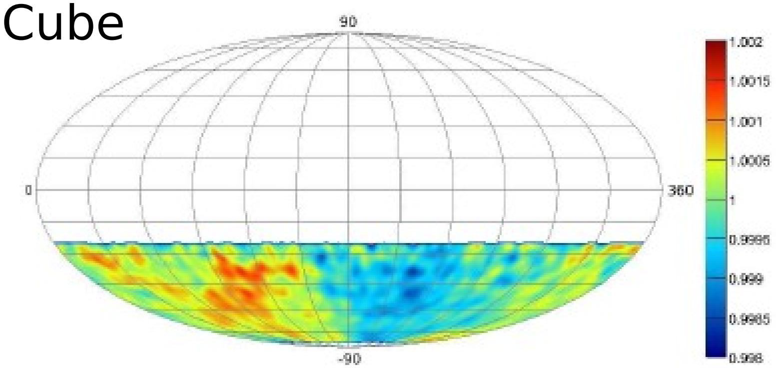


Energy scales adjusted based on pair-production dip just below 10^{19} eV.
Taken from Nagano (2009)

Cosmic Ray Anisotropy: Dipole



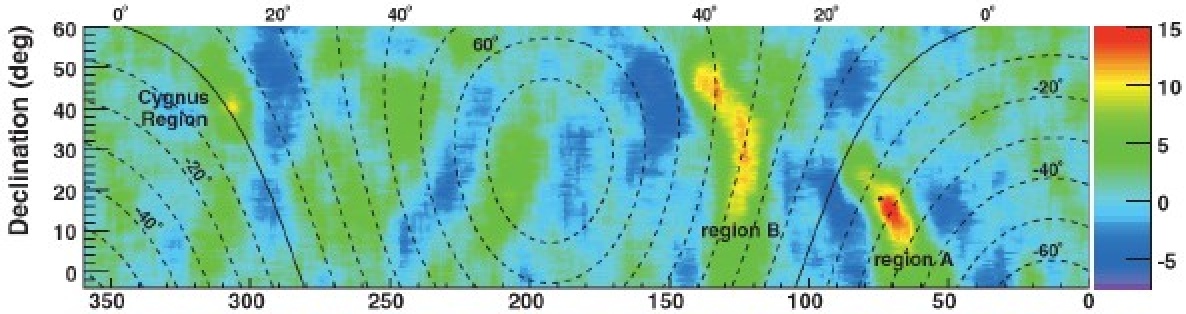
IceCube



Consistently observed by many experiments.

Probably caused by Sun's orbital motion

Cosmic Ray Anisotropy



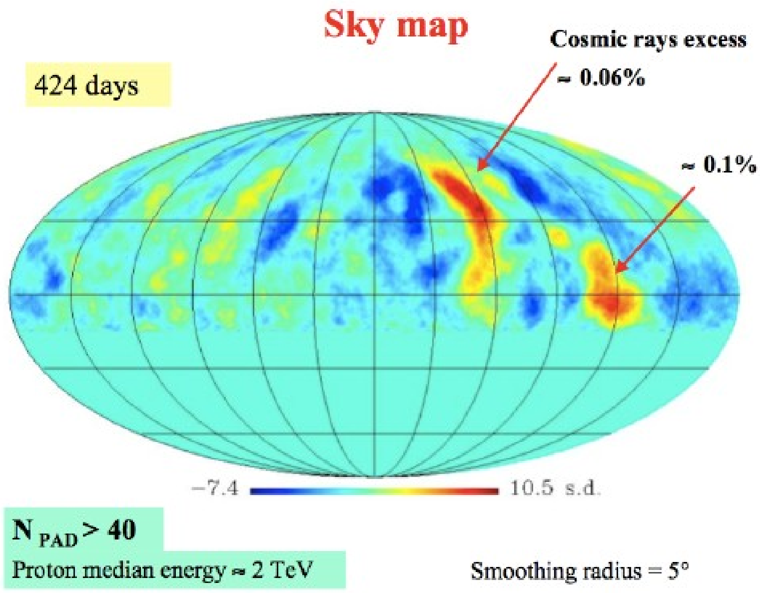
MILAGRO

Small-scale anisotropy

Local source?

Magnetic field effects?

Heliotail?



S. Vernetto for ARGO-YBJ Collaboration RICAP 2009

Detection of UHE Gammas and CRs: Summary

- UHE astroparticles are easier to detect from the ground than from space
  - Putting large detectors covering large effective areas into space is non-trivial!
- Cherenkov, fluorescence and ground-array technologies all well established
  - each technique has advantages and disadvantages
  - “hybrid” detectors using multiple techniques are effective
- Multiwavelength studies of interesting objects provide increasingly good constraints on models
  - relevant for TeV γ-rays, not for CRs because of lack of directionality