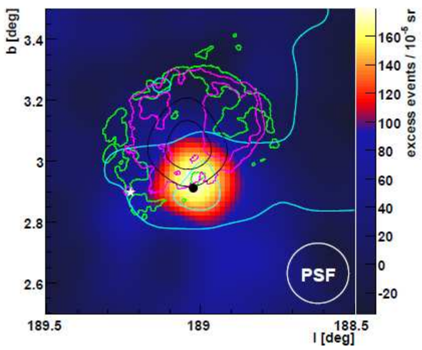
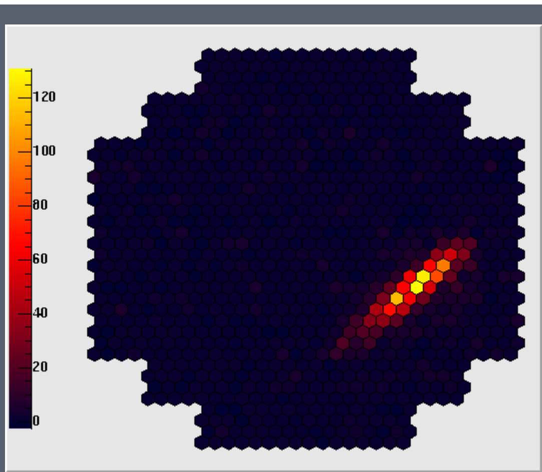



# ASTROPARTICLE PHYSICS LECTURE 2

1


Susan Cartwright

University of Sheffield


# HIGH ENERGY ASTROPARTICLE PHYSICS

2

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 don't shower
    - detect products of charged-current interactions (e, μ, τ)
  - Ultra-high-energy neutrinos *will* shower in matter
    - acoustic detection of shower energy

3

## 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
  - usually using water Cherenkov detectors
    - higher threshold
    - not dependent on sky conditions
    - works better for hadron-induced showers

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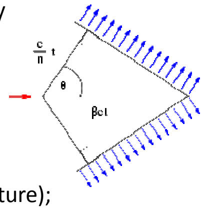
## CHERENKOV RADIATION

- 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 $\cos \vartheta = 1/\beta n$
    - for astroparticle applications usually $\beta \approx 1$
    - hence in air $\vartheta \approx 1.3°$ (depends on temperature); in water $\vartheta \approx 41°$ (40° for ice)

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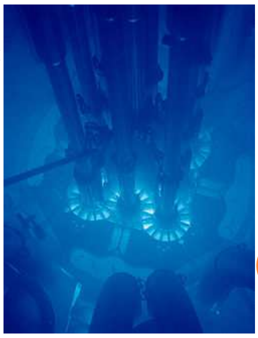
## CHERENKOV RADIATION

- Spectrum of radiation is given by Frank-Tamm formula

$$\mathrm{d}E = \frac{\mu(\omega) q^2}{4\pi}\omega\left(1 - \frac{1}{\beta^2 n^2(\omega)}\right)\mathrm{d}x\,\mathrm{d}\omega$$

  - $\mu$ is permeability of medium, $n$ its refractive index, $q$ charge of particle, $\beta$ its speed, $\omega$ emitted angular frequency, $x$ length traversed
    - note that $\mathrm{d}E \propto \omega$; 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



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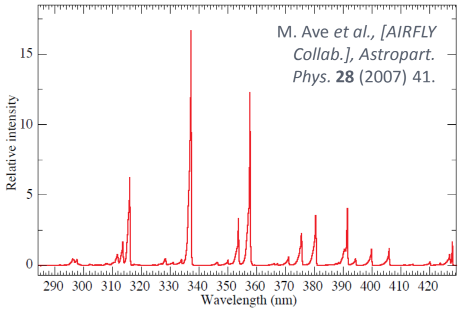
## Fluorescence

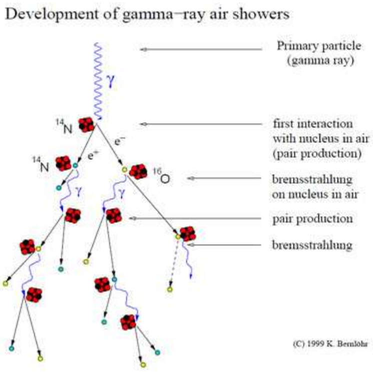


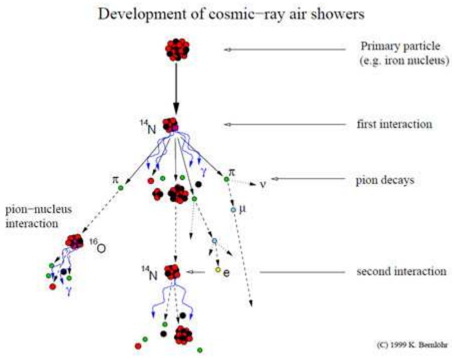

Fluorescence spectrum excited by 3 MeV electrons in dry air

- Misnamed!
  - it's really scintillation
- Emitted isotropically
  - in contrast to Cherenkov
- Almost independent of primary particle species
  - exciting particles are mainly $e^{\pm}$ 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

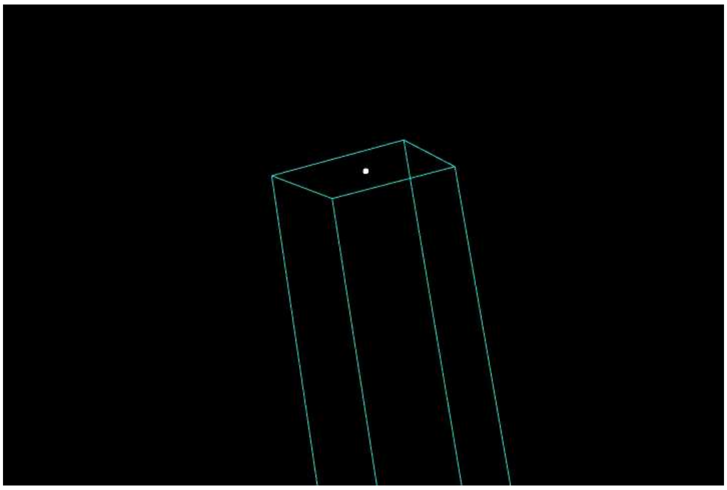



Gamma-induced showers have different particle content and will peak at a different height from hadron-induced showers. They also have a different morphology—note the subshowers in the hadron-induced cascade.

## AIR SHOWER ANIMATION

http://astro.uchicago.edu/cosmus/projects/aires
Ave, Surendran, Yamamoto, Landsberg, SubbaRao (animation); Sciutto (AIRES simulation)



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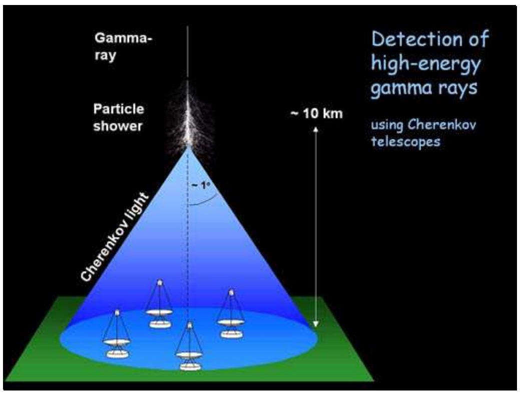
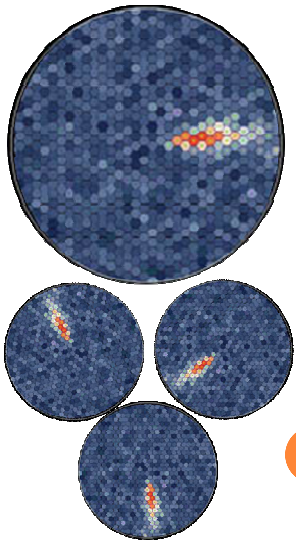
## TEV GAMMA-RAY ASTRONOMY: IMAGING ATMOSPHERIC CHERENKOV TELESCOPES

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



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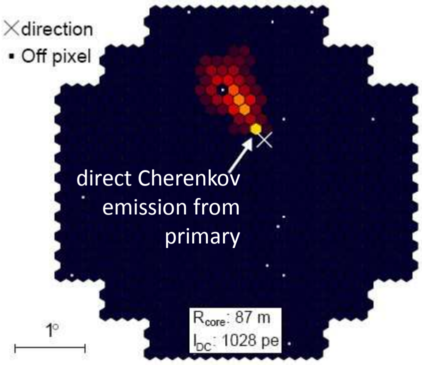
## TeV Gamma-Ray Astronomy: Imaging Atmospheric Cherenkov Telescopes

- 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 ∝ energy of primary
    - resolution typically 15-20%
    - threshold given by




Heavy nucleus signal in HESS

$E_T \propto \frac{1}{C(\lambda)}\sqrt{\frac{B(\lambda)\Omega\tau}{\eta(\lambda)A}}$ where *C* is Cherenkov yield, *B* sky background, η photon collection efficiency, *A* mirror area, Ω solid angle, τ integration time

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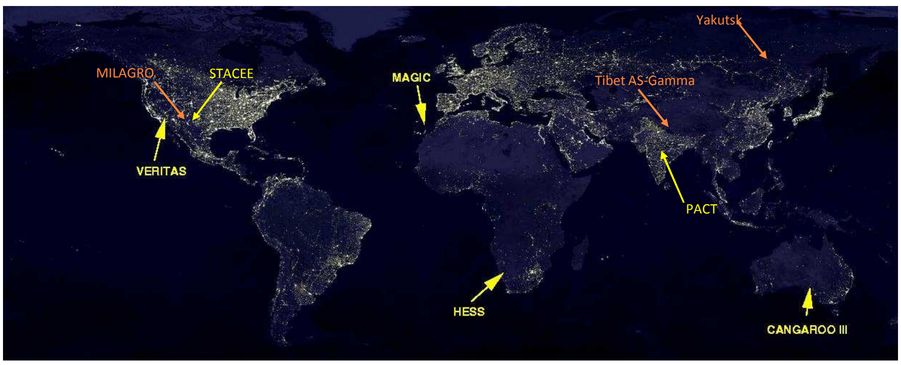
## TeV Gamma-ray Observatories




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

two since 2009

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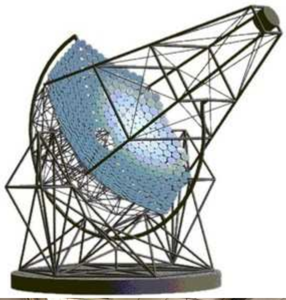
## IACT Technology: H.E.S.S. (Namibia)



4 telescopes each of 108 $m^2$ aperture

Camera array of 2048 pixels (0.07°)

New 30-m telescope under construction (will reduce energy threshold to 30 GeV)

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## IACT Technology: VERITAS (USA)

Very similar to H.E.S.S.

4 telescopes each 110 $m^2$

499-pixel camera

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## IACT Technology: MAGIC (Canary Islands)

Larger telescopes (236 m$^2$), hence lower threshold; 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"

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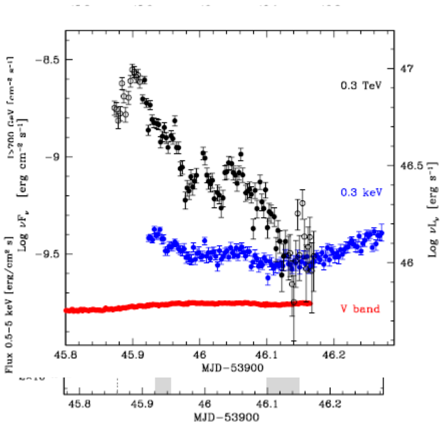
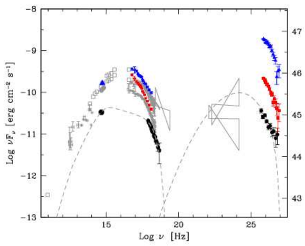
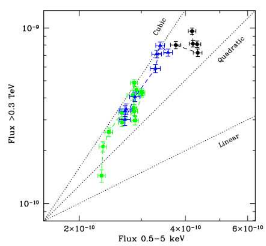
## Some Results

- 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

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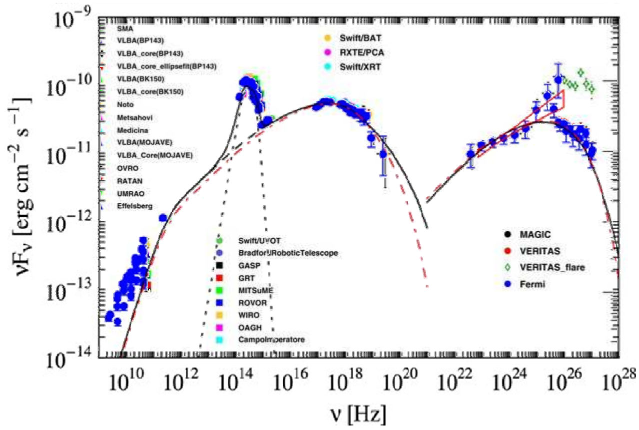
## Some Results

- 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 $\gamma_e$ with exponential cut-off at high energies)
  - find δ = 12, R = $1.3\times10^{12}$ km (9 AU), B = 0.015 G, η = 56, $\langle\gamma_e\rangle$ = 2400
    - ultrarelativistic electrons in near-equipartition with mildly relativistic protons?
    - consistent with shock acceleration

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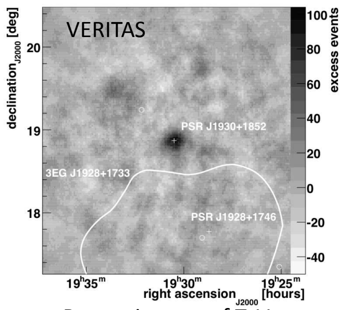
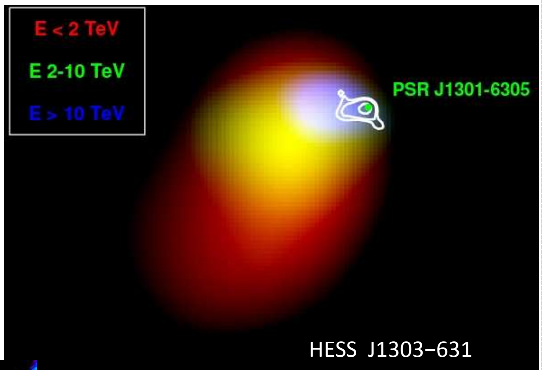
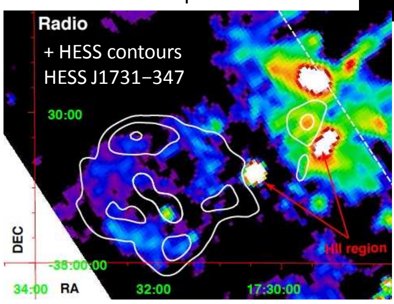
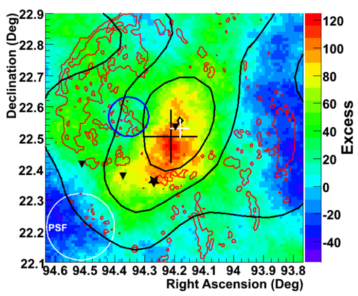



Recent images of TeV sources associated with pulsars and SNRs




VERITAS
SNR IC443
optical
CO
Fermi 95%
MAGIC
(white +)

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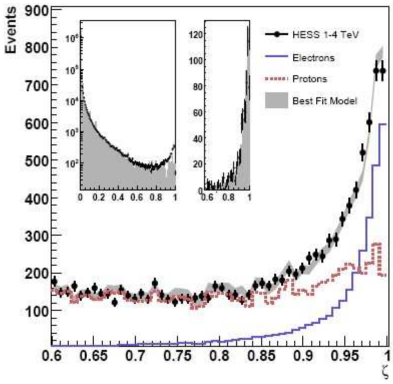
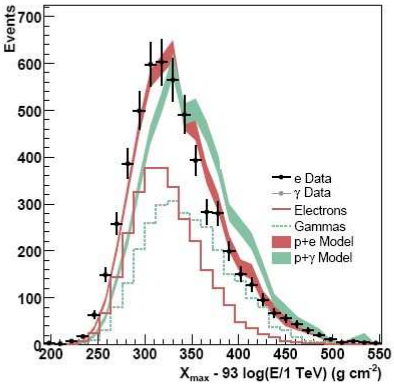
## HESS AS A DETECTOR OF COSMIC-RAY ELECTRONS



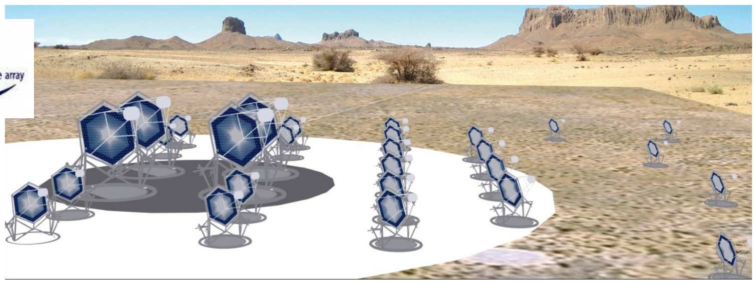

Separation of electron and proton showers using multivariate analysis



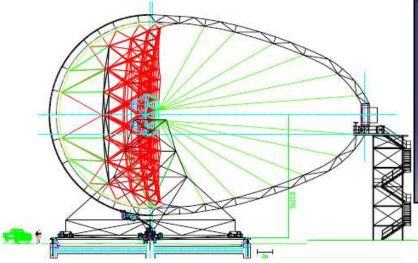

Separation of electron and photon showers using $X_{max}$ (depth of shower maximum): electrons shower earlier than photons

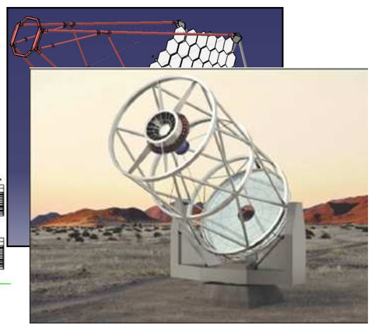


cta
cherenkov telescope array

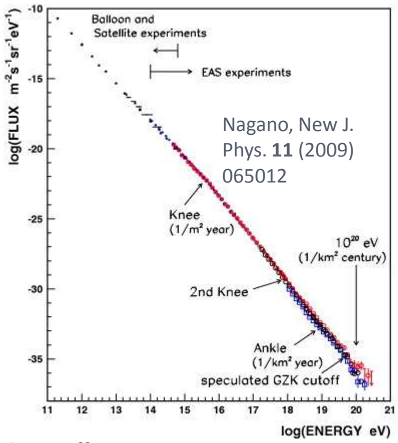


- Future facility for TeV gamma-ray astronomy
  - three different telescope designs optimised for different energies
  - in design phase



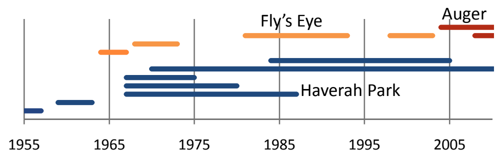


## Cosmic Ray Detectors




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

- Focus in recent years on UHE CRs
  - 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




**Hybrid**
**Fluorescence**
**Ground array**
(after Nagano 2009)

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## 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, $N_\mu$, 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

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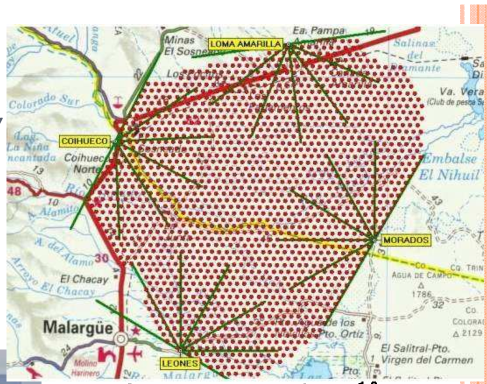
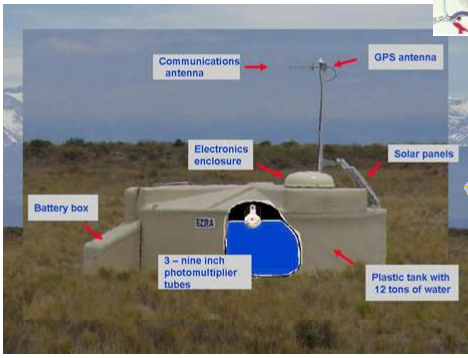
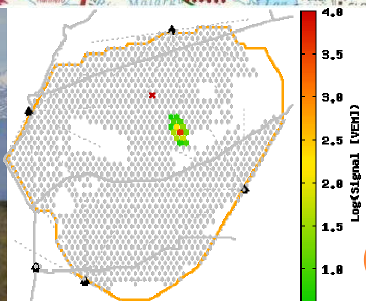
## Example of Ground Array

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



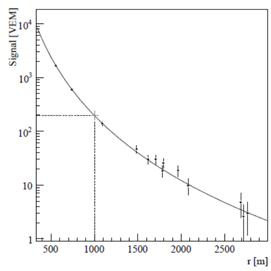



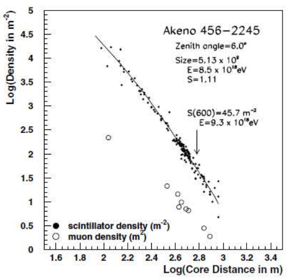

typical event display

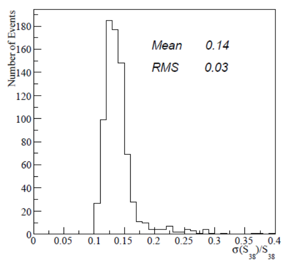


## Energy Reconstruction in Ground Arrays

- 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 $N_\mu$
- Significant systematic errors (~20% quoted)

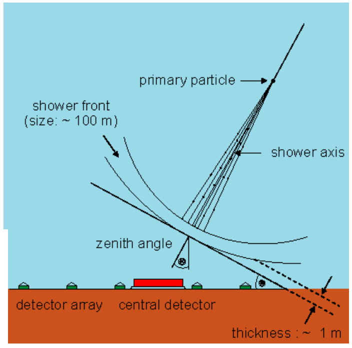


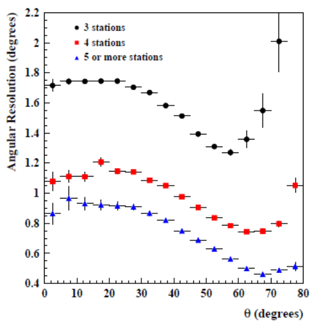



## Direction Reconstruction in Ground Arrays

- Direction is reconstructed from arrival time of shower at different ground stations
  - better than 1° if >4 stations fire ($E$ > 8 EeV)

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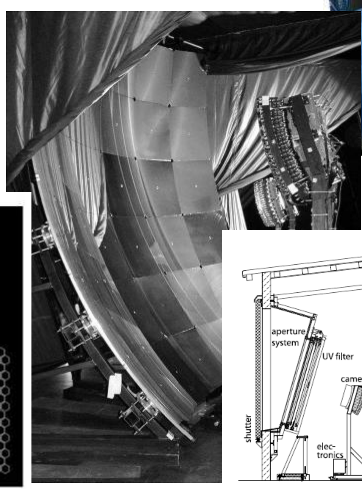
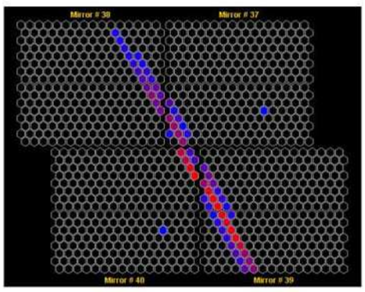
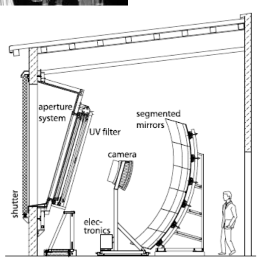
## Fluorescence Detector Technology

- Broadly similar to Cherenkov telescope
  - Expect to see "stripe" of light corresponding to shower



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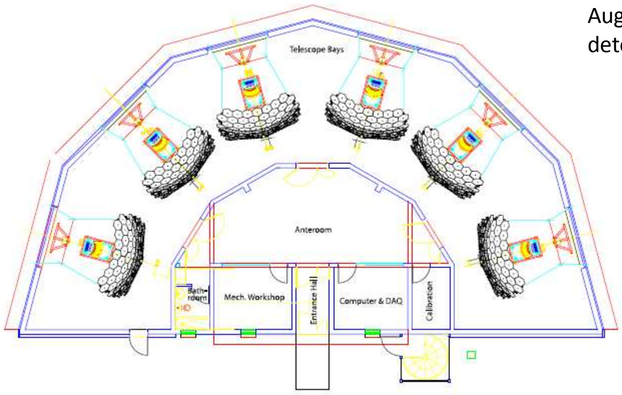
## Fluorescence Detector Technology




Auger fluorescence detector layout

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

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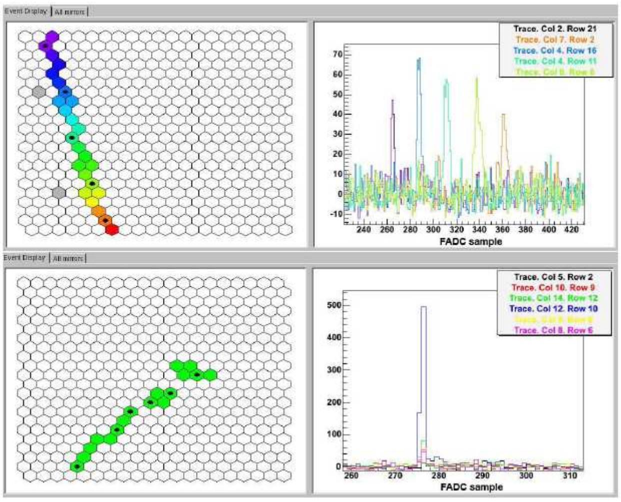
## Background Rejection




Genuine event with colours showing time progression

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

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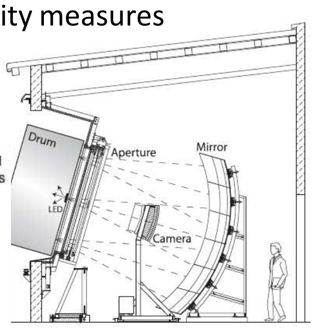
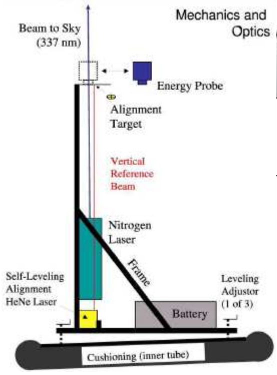
## Energy Reconstruction in Fluorescence Detector

- 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 Coll.

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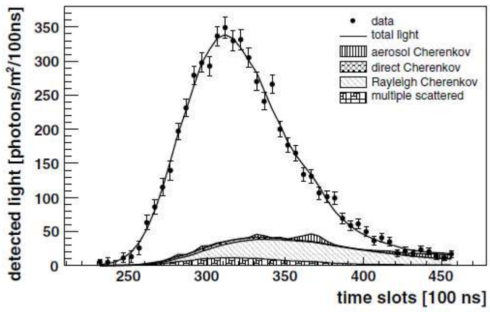
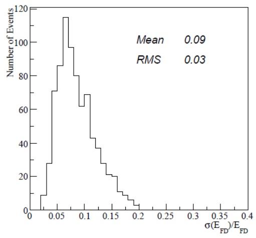
## Energy Reconstruction in Fluorescence Detector

- Measure longitudinal shower profile
  - Fit to standard profile (Gaisser-Hillas function)
  - Correct for non-electromagnetic energy
    - resulting statistical error is about 10%
    - good agreement with ground array

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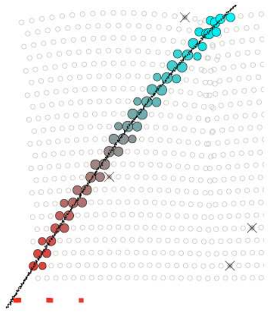
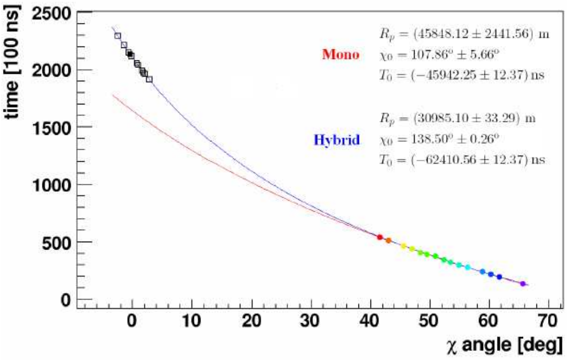
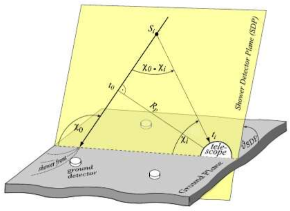
## Hybrid Detector Reconstruction

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





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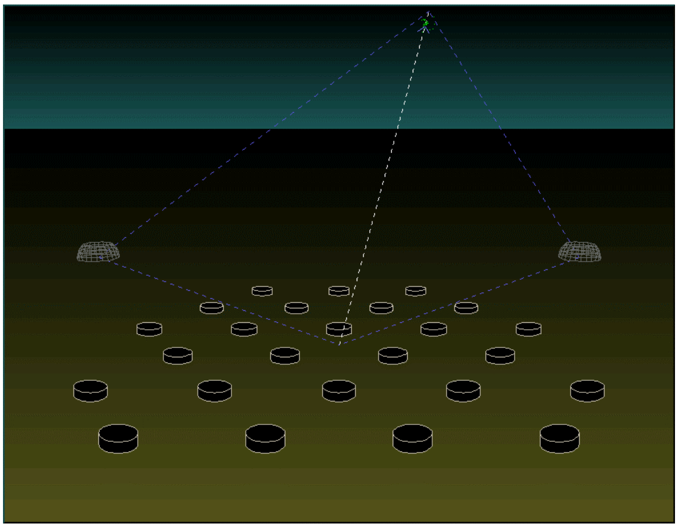
## Hybrid Event Schematic



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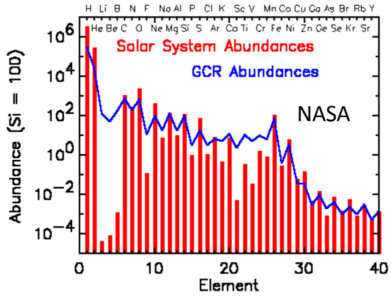
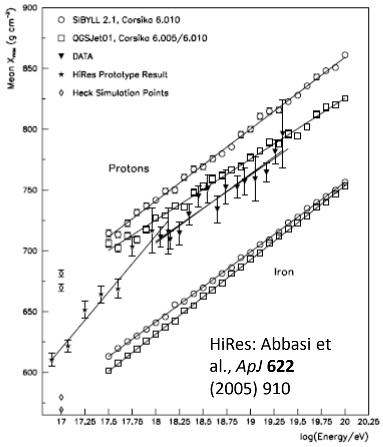
## Properties of Primary Cosmic Rays: Particle Content

- 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




HiRes: Abbasi et al., *ApJ* **622** (2005) 910

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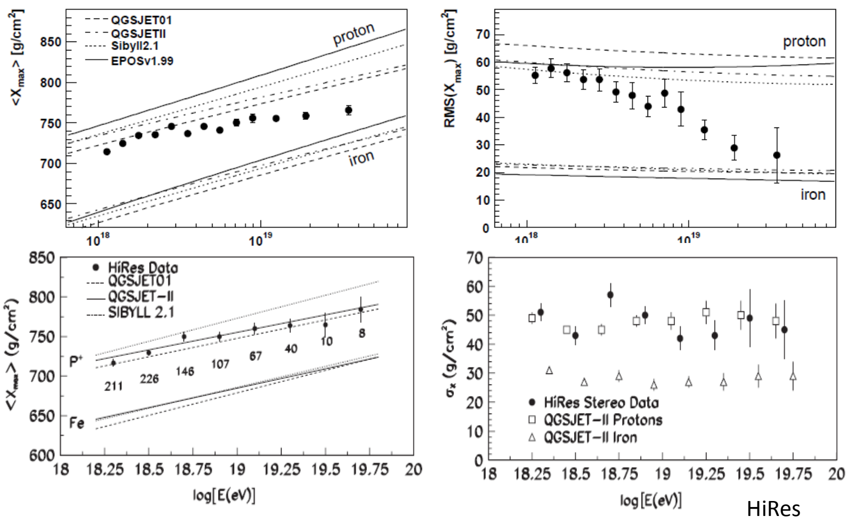
## Properties of Primary Cosmic Rays: Particle Content

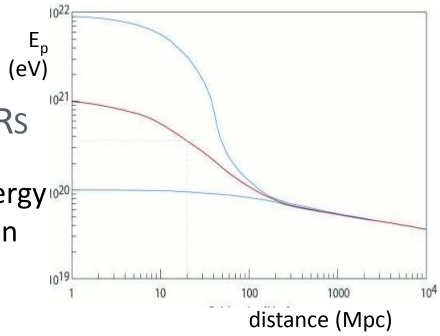
Some disagreement at highest energies!

Auger




HiRes

## Energy Spectrum of UHECRs




- Expect **GZK cut-off** at high energy owing to pion photoproduction via Δ resonance
  - $\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$ (or $n + \pi^+$)
  - requires $E_\gamma$ = 145 MeV (150 MeV) for proton at rest
    - energy of CMB photon ~3 $k_B T = 7\times10^{-4}$ 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 $5\times10^{19}$ 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

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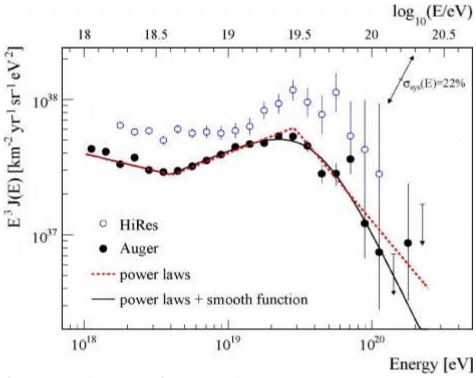
## Observation of GZK Cutoff

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

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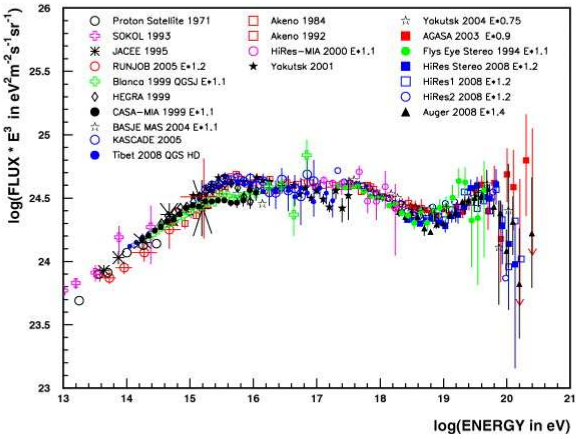
## COMBINED CR ENERGY SPECTRUM




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

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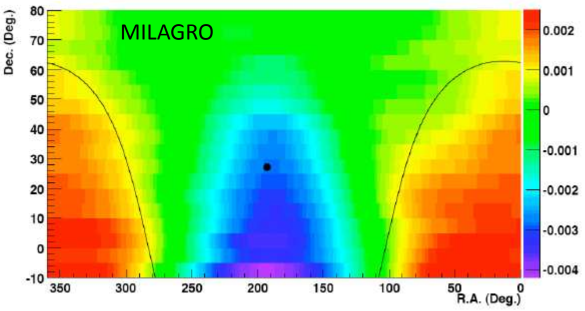
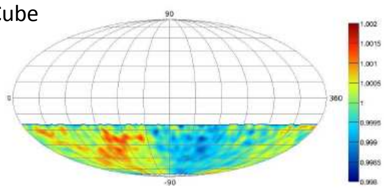
## COSMIC RAY ANISOTROPY: DIPOLE




Consistently observed by many experiments.

Probably caused by Sun's orbital motion

IceCube



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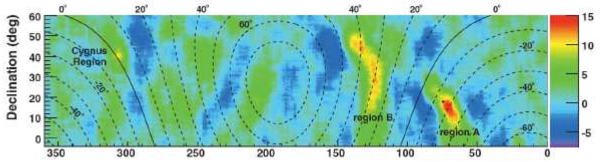
## Cosmic Ray Anisotropy



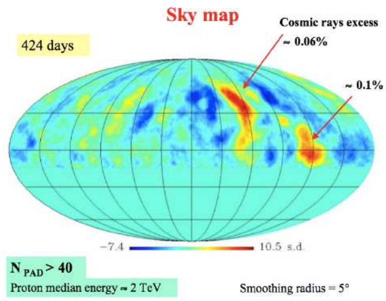

MILAGRO

Small-scale anisotropy

Local source?

Magnetic field effect?

Heliotail?




S. Vernetto for ARGO-YBJ Collaboration RICAP 2009

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## Detection of UHE Gammas and CRs: Summary

- UHE astroparticles are easier to detect from the ground than from space
  - large detectors covering large effective areas are not easy to put into orbit
- 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

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