# Astroparticle Physics (Lecture 1)

Lee Thompson
University of Sheffield

Warwick Flavour Week
30th March to 3rd April 2009

# What is Astroparticle Physics?

- A (my) definition:
  - Particle Physics without the (man-made) terrestrial accelerator
- Definitions of which topics fall under ‘astroparticle physics’ or ‘particle astrophysics’ vary according to country and to some extent politics
- Topics generally (sometimes) covered
  - High energy gamma rays
  - High energy cosmic rays
  - High (and ultra-high) energy neutrinos
  - Dark matter
  - (Gravitational waves)
  - (CMBR)
  - (Neutrinoless double beta decay)

# Astroparticle Physics

- Lecture 1, Monday 30th March
  - Introduction to the Cerenkov Effect
    - Threshold Cerenkov, Ring Imaging Cerenkov
  - Use of Cerenkov Effect in Astroparticle Physics
    - Detecting HE Neutrinos, Gamma Rays and Cosmic Rays
- Lecture 2, Tuesday 31st March
  - New Techniques in Astroparticle Physics
    - Acoustic detection of UHE neutrinos in water, ice and salt
    - The Geosynchrotron and Radio Cerenkov Effects and their uses in particle detection, Cosmic Rays and Neutrinos in air, ice and salt
- Lecture 3, Tuesday 31st March
  - The hunt for Dark Matter
    - Why we need Dark Matter
    - Detection techniques for Dark Matter searches

# The Cerenkov Effect

- Named after the famous Russian theorist Pavel Cerenkov who developed the theory of the effect
- Is an electromagnetic phenomenon which takes place when a *charged particle* passes through an *insulator* at a velocity greater than the *velocity of light* in that medium

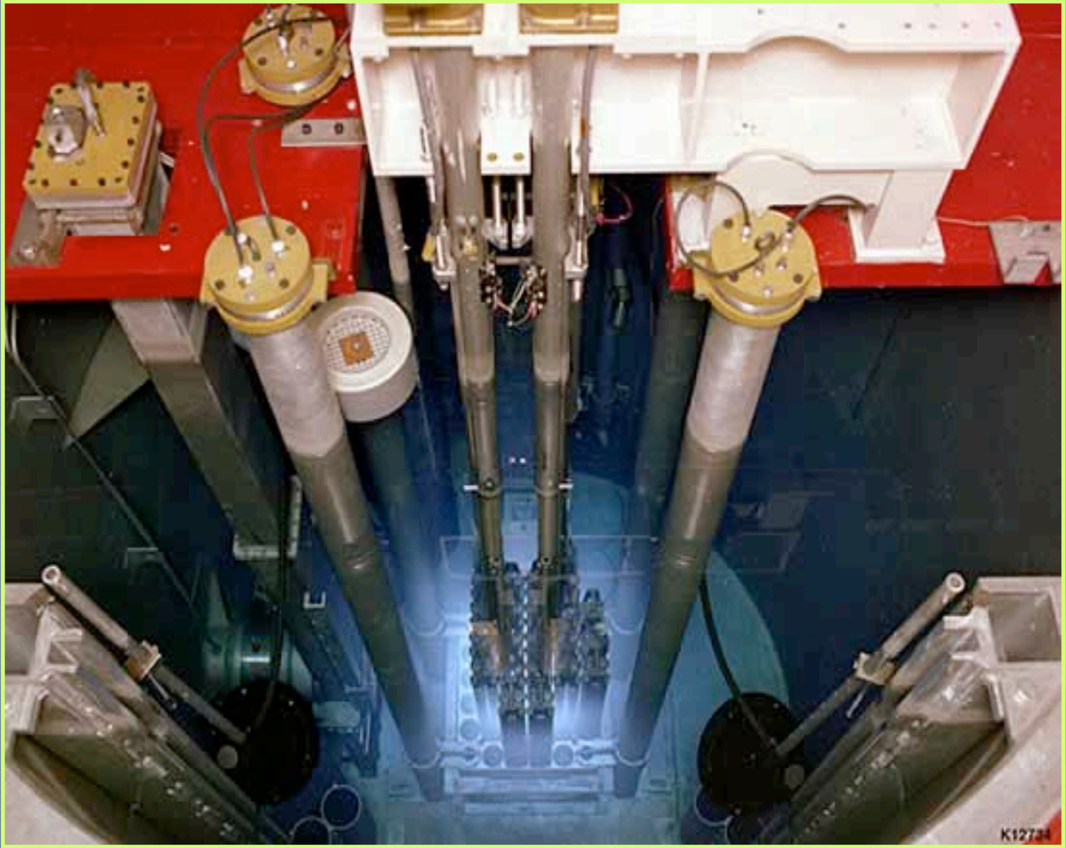
- It is used extensively in particle physics and particle astrophysics as a mechanism by which to detect charged particles travelling relativistically
- 1958 Nobel Prize for Physics

# So what *exactly* happens?

- The charged particle passes through the insulator
- In doing so it perturbs the EM field of the atoms making up the di-electric
- Specifically, the atoms in the medium are polarised (due to simple Coulomb attraction and repulsion)
- After the charged particle has passed through the medium it "relaxes" back to its original state and photons are emitted
- Note: in a *conductor* no photons are emitted

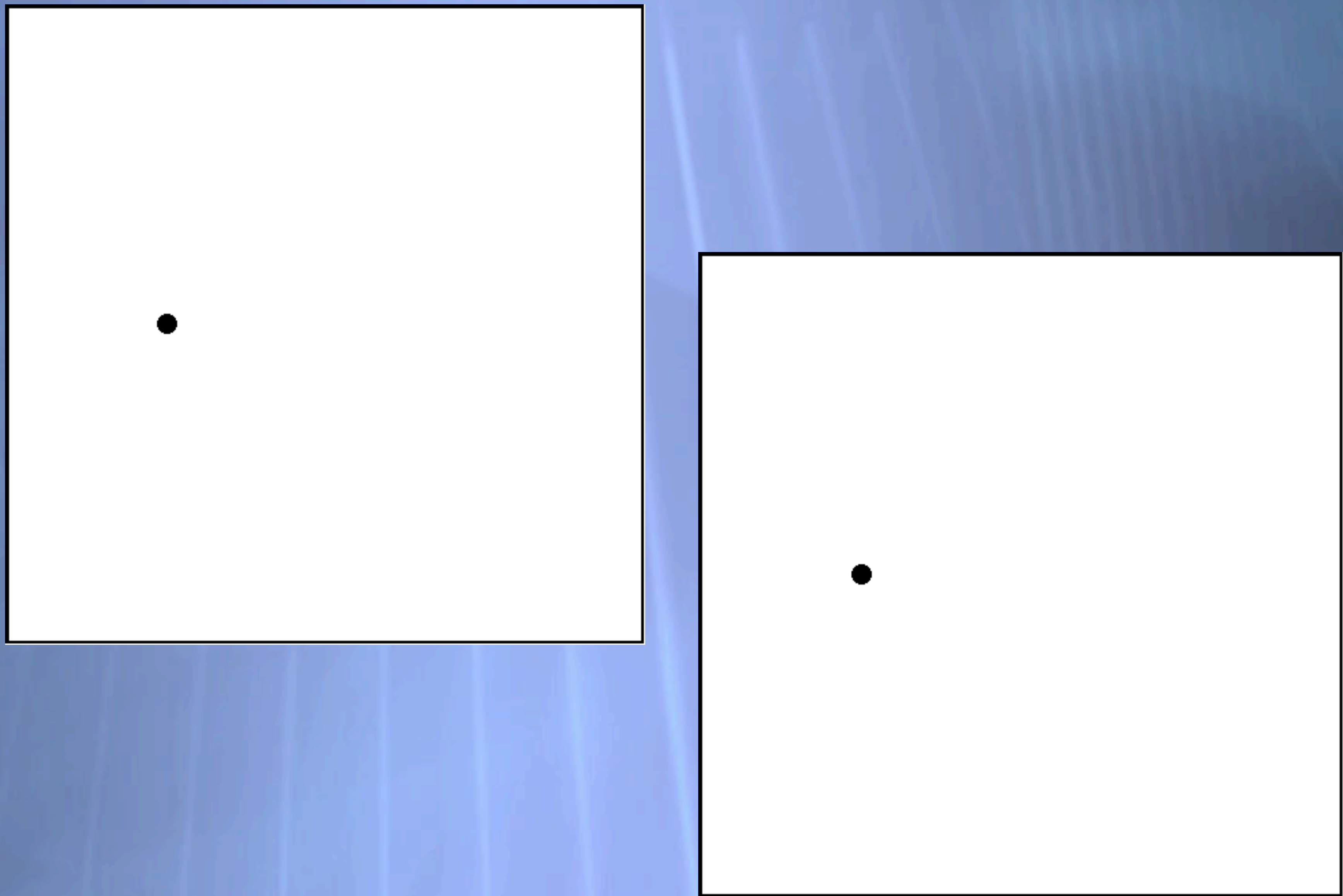
# What *exactly* happens next?

- Under normal circumstances these photons that are emitted would undergo *destructive interference* and no net effect would be seen




- However, when the charged particle causing the disruption is travelling quickly then *constructive interference* of the photons can take place leading to an observable effect

# Visualisation



# Common analogies

- The most common analogy with Cerenkov radiation is that of a *sonic boom* when a plane passes through the sound barrier
- Here a *shock wave* is produced as the sound waves *constructively interfere* as they are unable to escape the supersonic body
- In the same way, a speed boat generates a large bow shock because it travels faster than waves can move on the surface of the water.

# Cerenkov angle

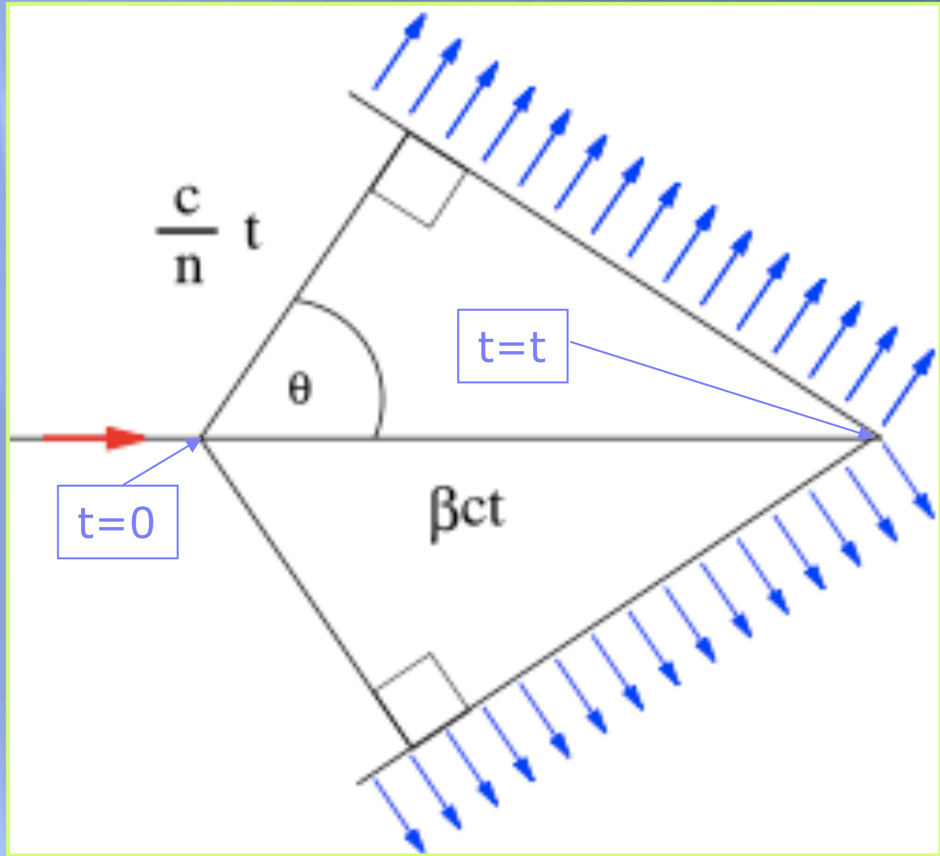
- Consider such a particle travelling through a medium of *refractive index* n
- Distance travelled by the particle is

$$d = x_t = v_p t = \beta c t$$

since $\beta = v_p/c$

- Distance travelled by the EM wave is

$$d_{EM} = v_{EM} t = (c/n)t$$




- Simple geometry then gives us

$$\cos\theta = 1/\beta n$$

# Cerenkov angle and threshold

- Note that this relationship is independent of time
- Considering $\cos\theta = 1/\beta n$ we learn a further 2 things:
  1. There is a threshold velocity below which no Cerenkov radiation will be observed. To see Cerenkov radiation the following must be true: $\beta \geq 1/n$
  2. When a particle is highly relativistic ($v \sim c$) then the Cerenkov angle condition simplifies to: $\cos\theta = 1/n$

# The Tamm-Frank formula

- As well as the Cerenkov angle we also know the number of Cerenkov photons generated as a function of wavelength:

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{v>c/n(\omega)} \mu(\omega)\omega(1 - \frac{c^2}{v^2 n(\omega)^2})d\omega$$

Where:

$\omega$ is the angular frequency of radiation

$\mu(\omega)$ is the permeability of the medium

$n(\omega)$ is the refractive index of the medium

v is the particle's velocity

q is the particle's charge

# Cerenkov radiation - spectrum

- The Tamm-Frank formula has a number of important points:
  1. The radiation is continuous and not peaked at particular wavelengths as is the case for e.g. *fluorescence*
  2. At any frequency the intensity is proportional to the frequency and so higher frequencies (shorter wavelengths) are *more intense*
  3. This results in much C radiation in the UV and/or blue part of the spectrum

# Wavelength dependence

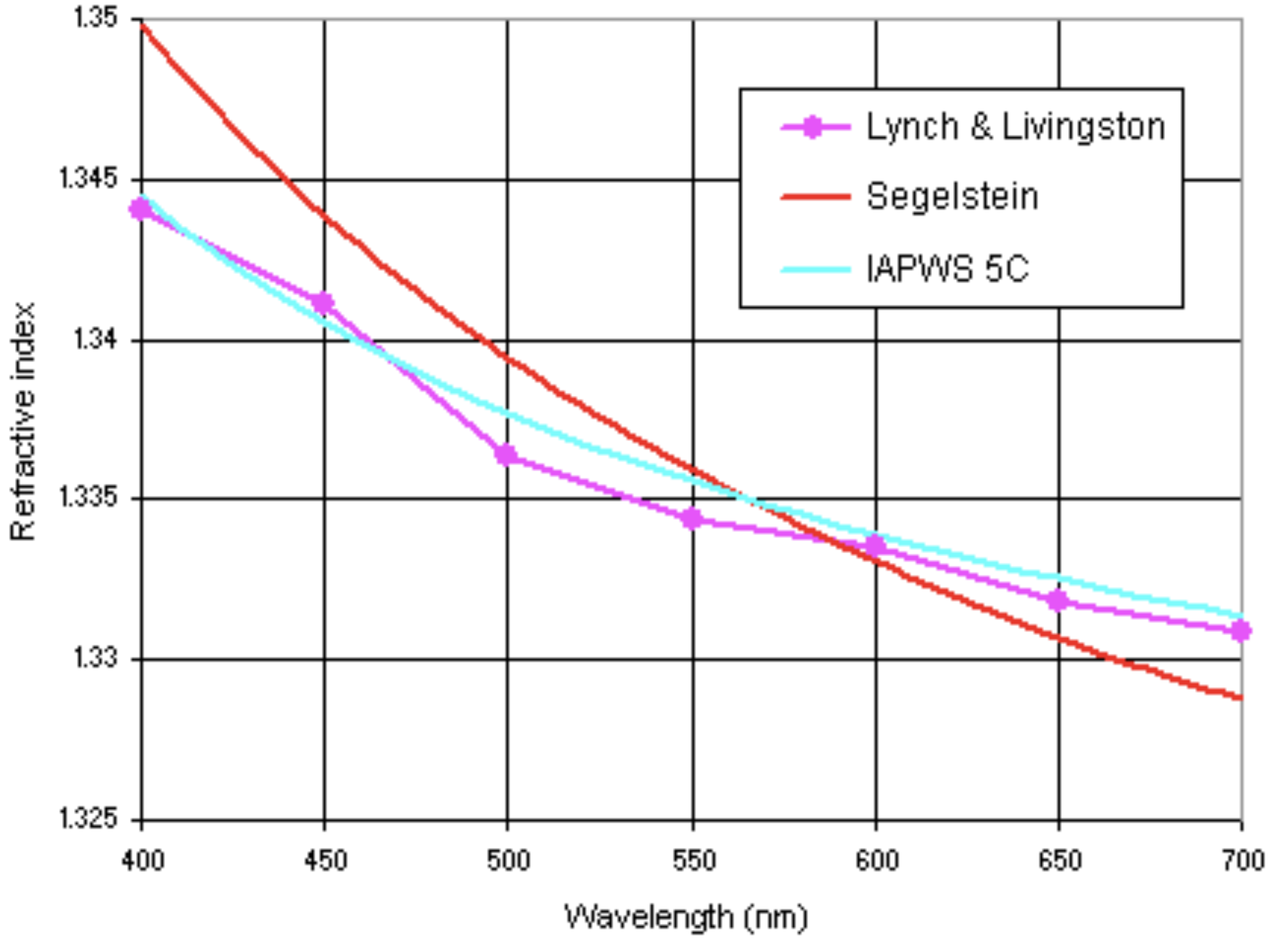



***Fig. 1** Refractive index of water as a function of wavelength*

# Applications of C radiation

- Cerenkov radiation is a powerful tool for the particle phyicist/astroparticle physicist
  - It appears only for charged particles
  - Secondly, it is only produced by particle travelling with very high velocity - so it is a good indicator of the passage of a relativistic charged particle through some experimental apparatus
  - You can use Cerenkov radiation to determine the $\beta$ - and hence the velocity - of a particle
  - If you can determine the particle’s momentum by other means (say, in a magnetic spectrometer) then the combination of the knowledge of the particle’s velocity and momentum allows its *rest mass* - and hence the particle type to be determined

# Building a C detector

- There are 2 basic components to a Cerenkov detector:
  1. A suitable medium, probably (but not necessarily) located in a suitable container. In these lectures we will focus on:
     - Water
     - Ice
     - The atmosphere
  2. A photosensor capable of detecting ideally single photons and being sensitive in the wavelength domain that C photons are produced. The detector of choice is *the photomultiplier tube (PMT)*

# Threshold Cerenkov Detectors

- These are not seen so often these days
- Used to be present in, e.g. fixed target beam lines at CERN
- Usually these beam lines supply particles of a known momentum

- As illustrated schematically above, by choosing a number of (usually gases) with different refractive indices then the presence (or not) of Cerenkov light in co-incidence with some trigger signal allowed particle types to be determined

# Ring Imaging C Detectors

- Known as RICH or CRID
- Rather than just a binary device they set out to record the cone of C light, focus it and record it in some way
- Used in PP experiments at CERN, e.g. WA69, DELPHI, ALICE and elsewhere

- CASE STUDY (DELPHI)
- Hybrid gas and liquid detector
- Gives particle ID over a wide momentum range
- Liquid (1cm),

  $n = 1.2718$:

  $\pi = 0.17$GeV/c,

  $K = 0.7$ GeV/c,

  $p = 1.7$GeV/c
- Gas (40cm)

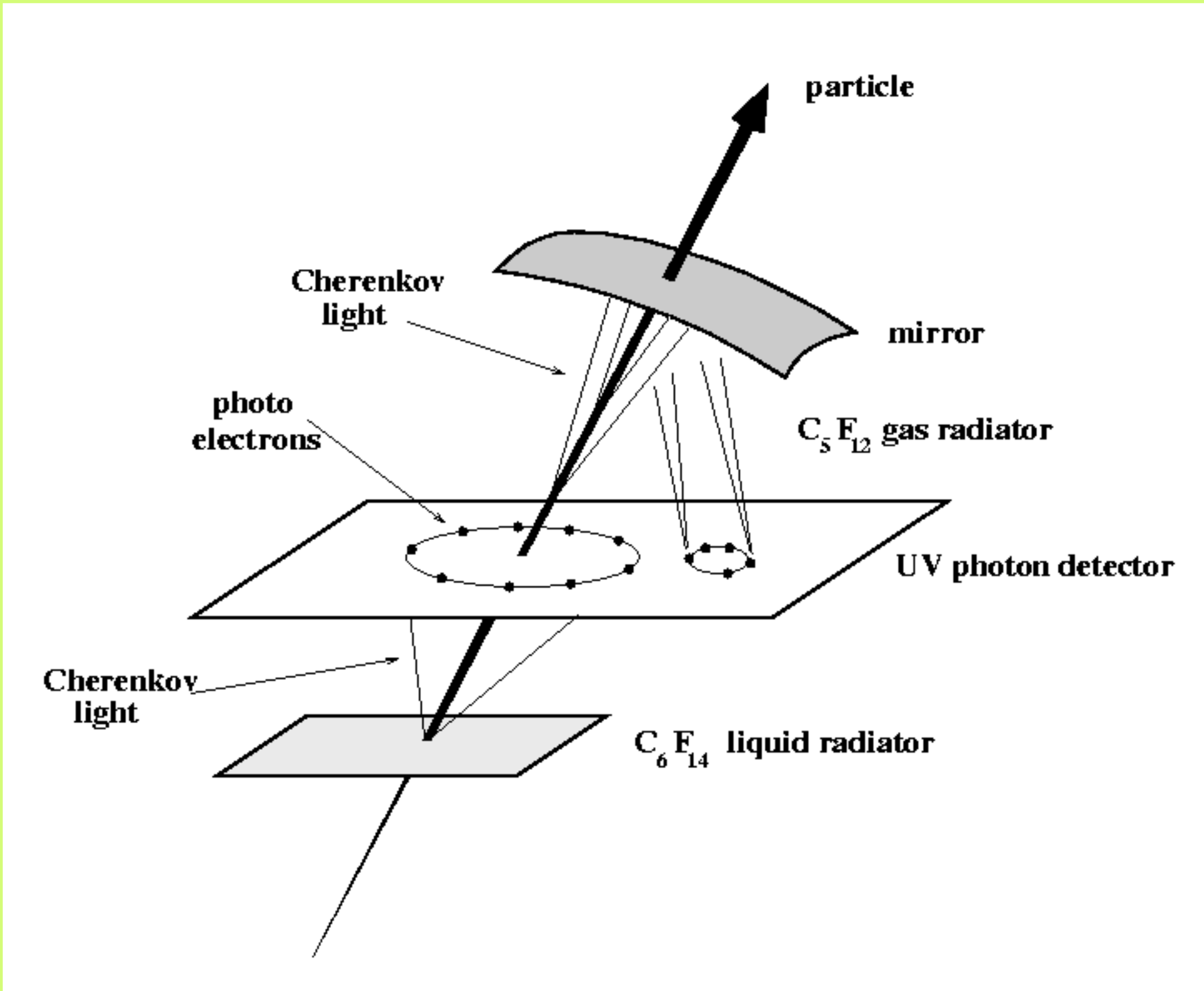
  $n = 1.00194$:

  $\pi = 2.3$ GeV/c

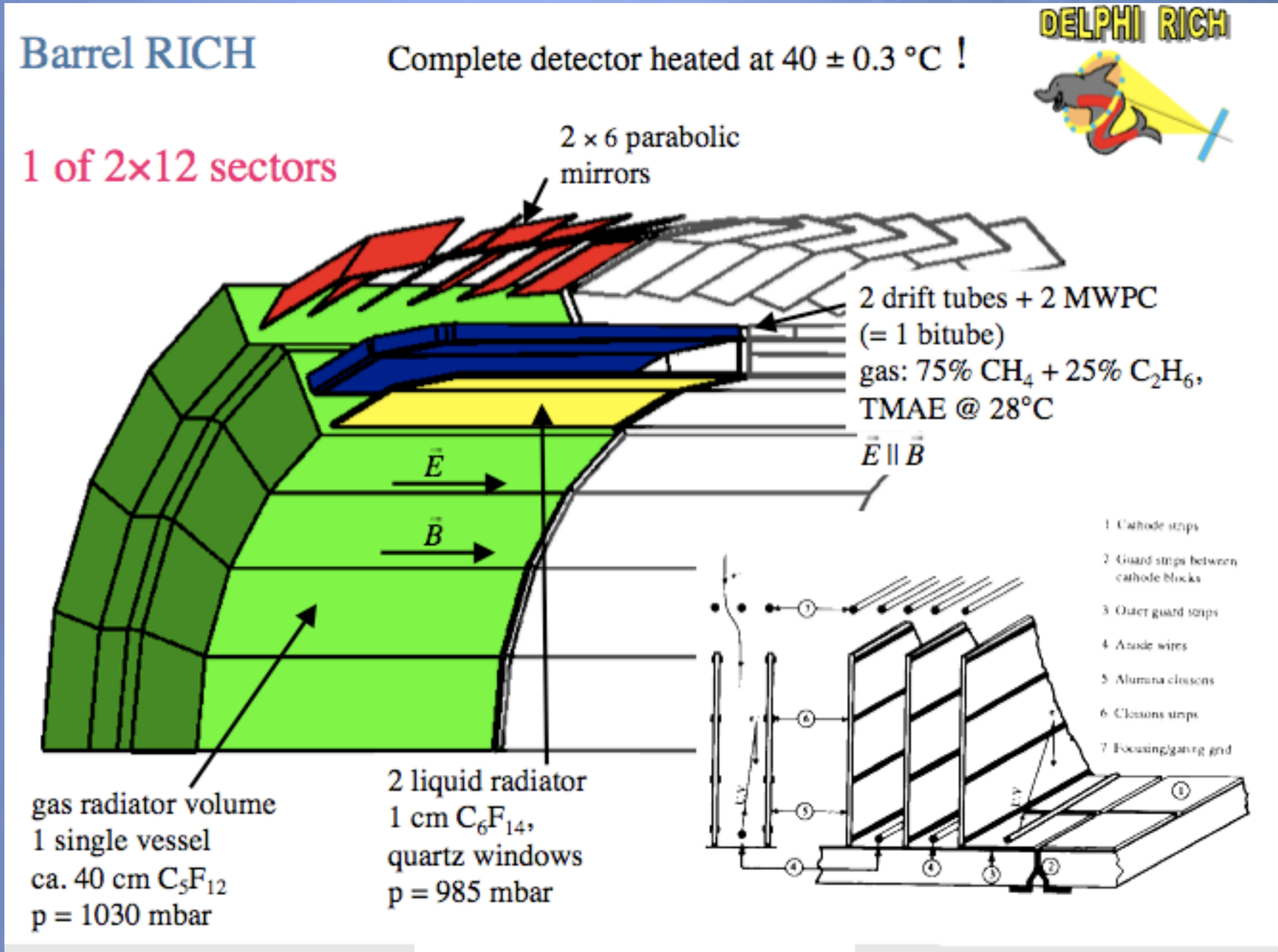
  $K = 8.2$ GeV/c

  $p = 16.0$ GeV/c

# Case study (DELPHI)

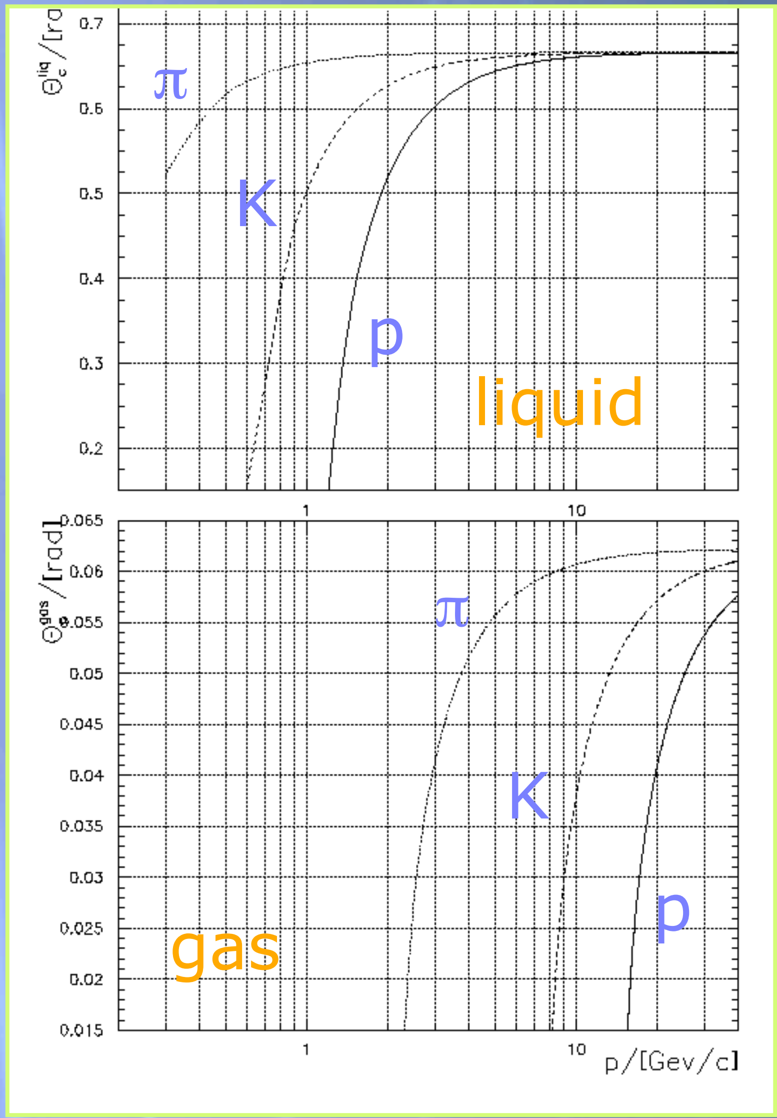


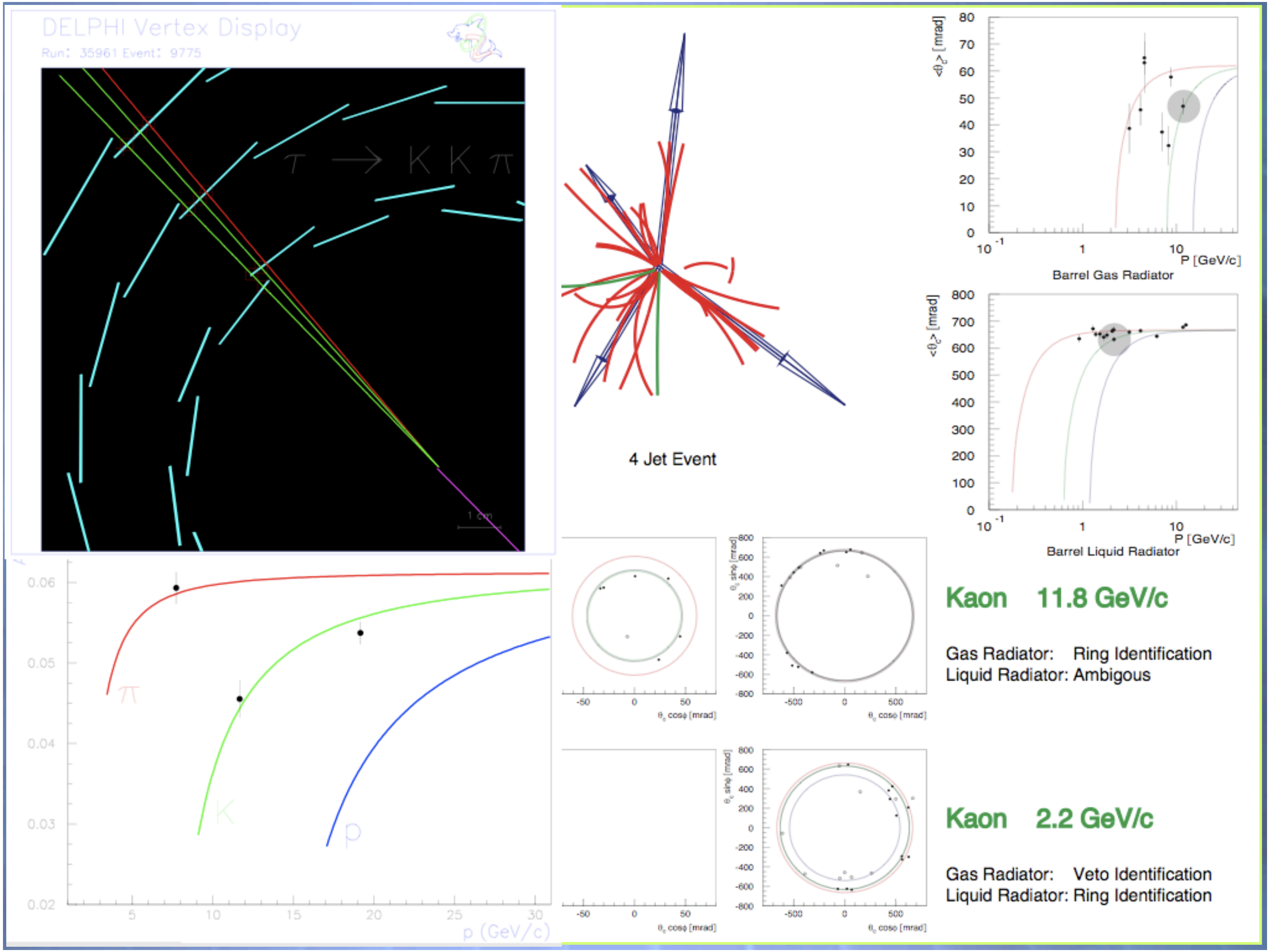
# The DELPHI RICH



# DELPHI RICH Sensitivity

- Cerenkov angle changes with momentum and particle type
- Enables curves for both liquid and gas RICHs to be predicted
- Event-by-event particle identification is thus possible

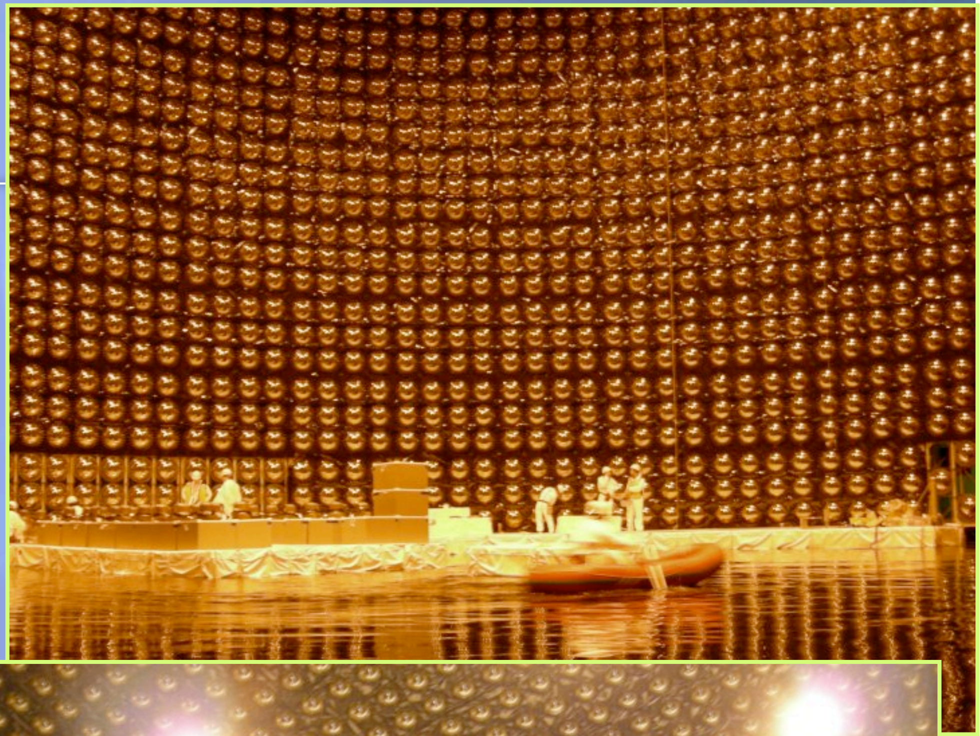


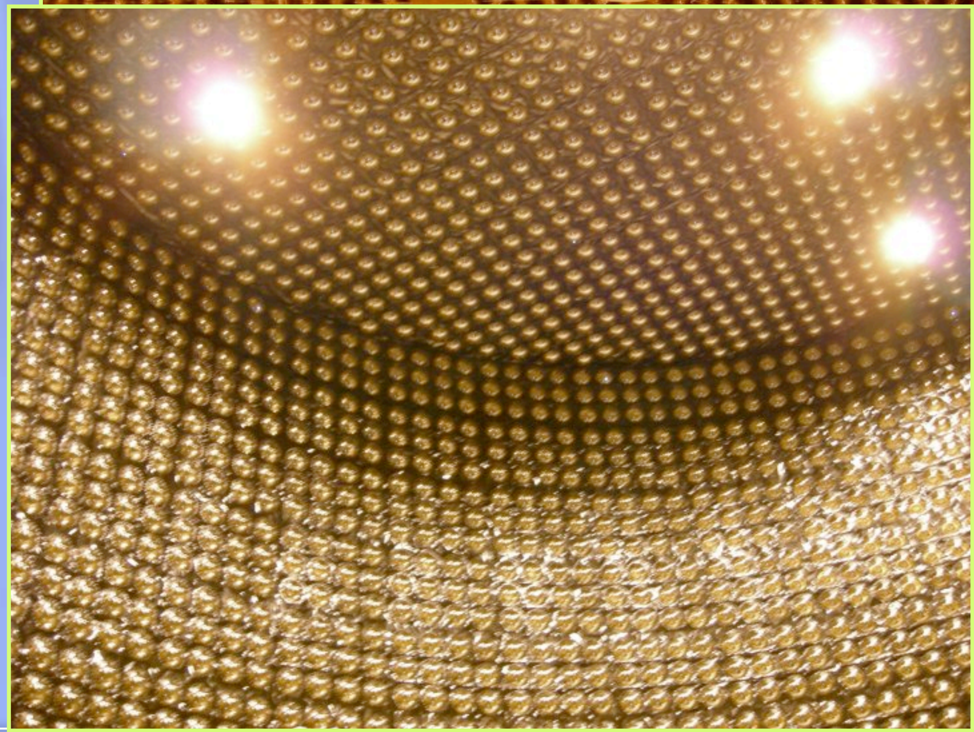


DELPHI Vertex Display
Run: 35961 Event: 9775
τ → K K π
1 cm
π
K
p
p (GeV/c)
4 Jet Event
Barrel Gas Radiator
Barrel Liquid Radiator
P [GeV/c]
Kaon 11.8 GeV/c
Gas Radiator: Ring Identification
Liquid Radiator: Ambigous
Kaon 2.2 GeV/c
Gas Radiator: Veto Identification
Liquid Radiator: Ring Identification

# Super-K

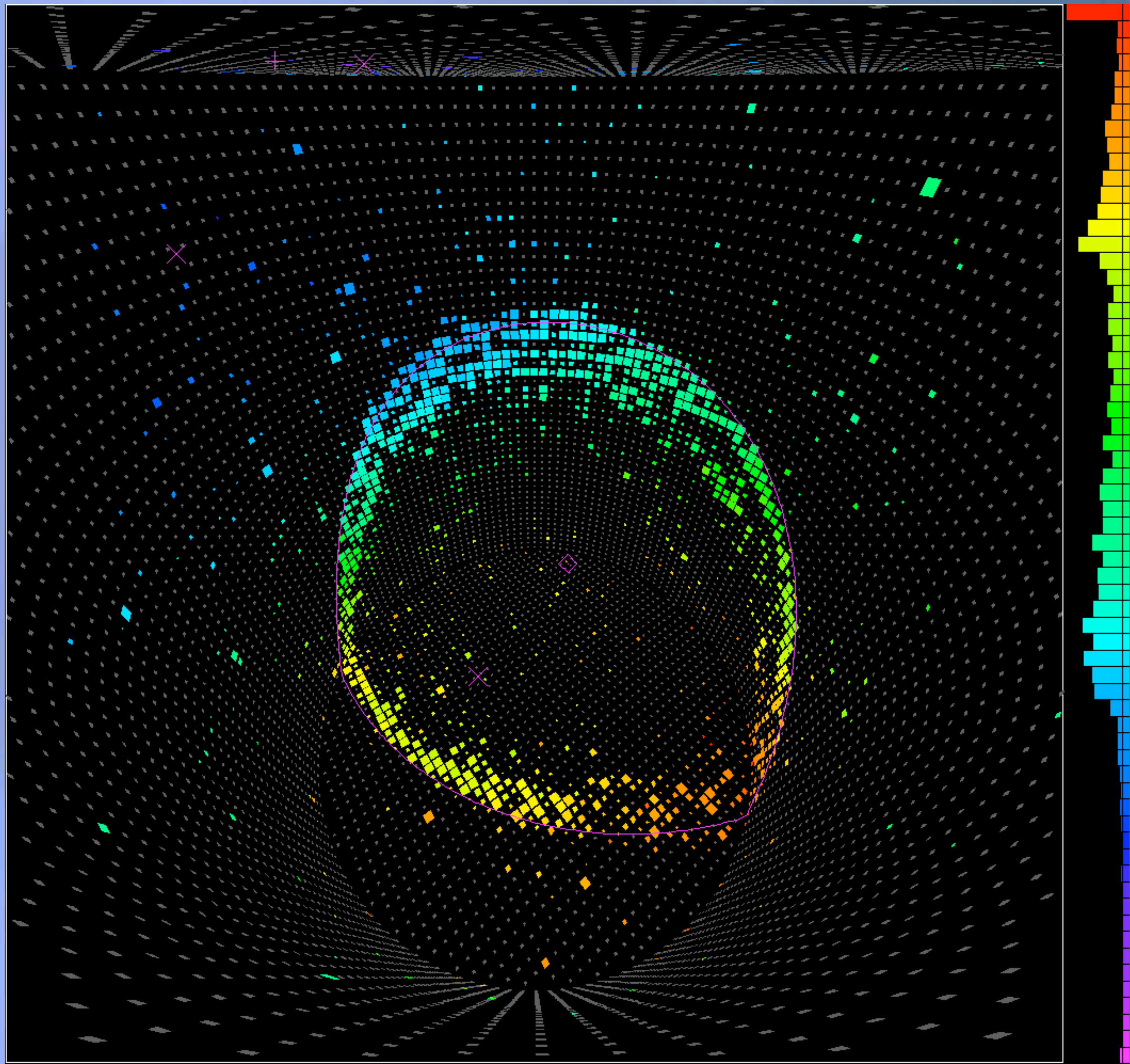
- Super-K started data taking in the mid 1990s
- 40m tall x 40m diameter water tank under a Japanese mountain
- 50,000 tons of water
- 11,200 20" Hamamatsu phototubes
- Built as a neutrino observatory (atmospheric, solar)
- Muon/electron discrimination via ring "fuzziness"





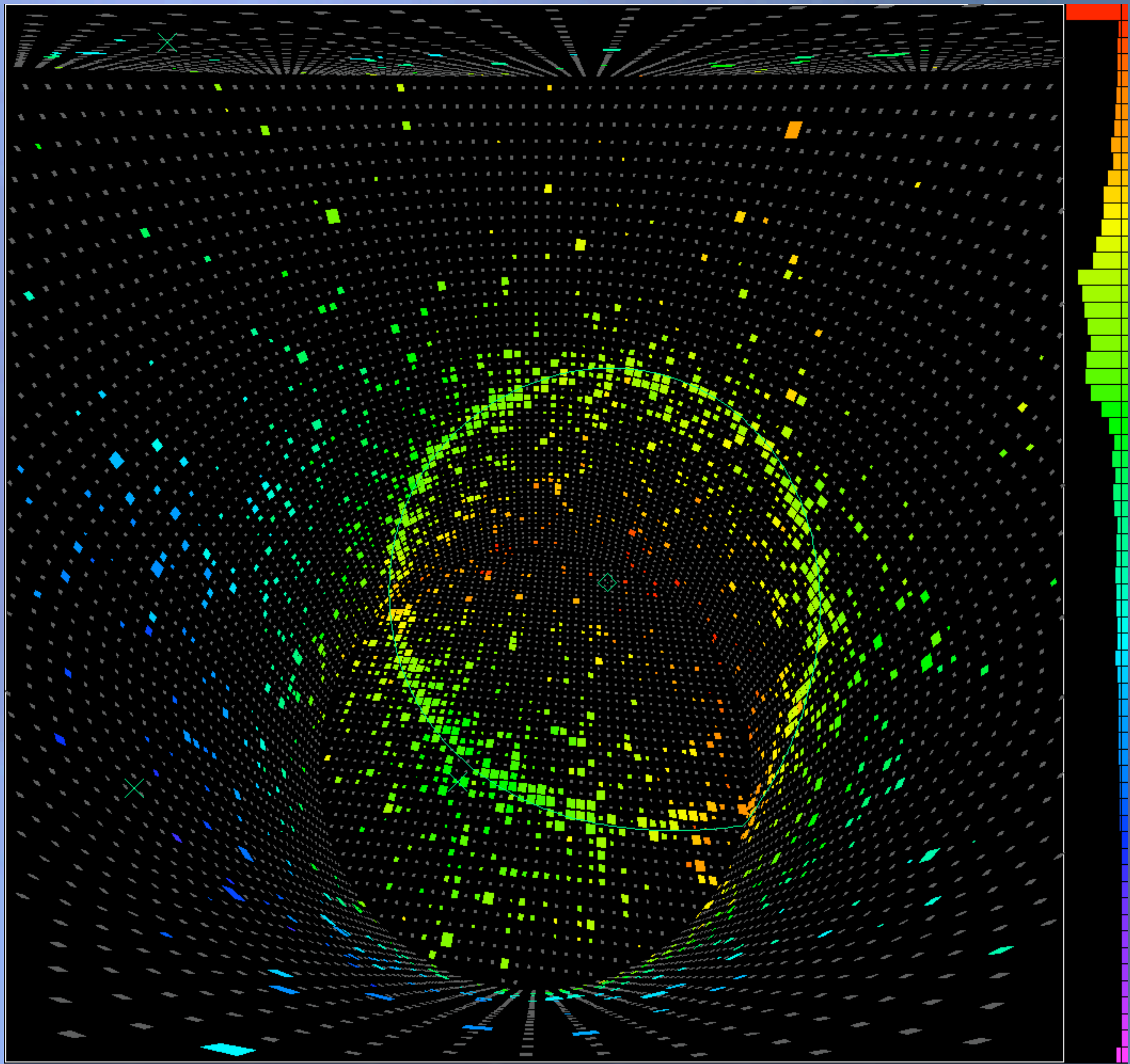
# Examples of SK events

- This is a muon - characterised by the relatively sharp ring
- Colours represent *timing* not *signal amplitude*



# Examples of SK events

- This is an electron as recorded in SK
- Note that the C ring in this case is more spread out
- This results from scattering of the electron



# C radiation - a 2nd Nobel Prize

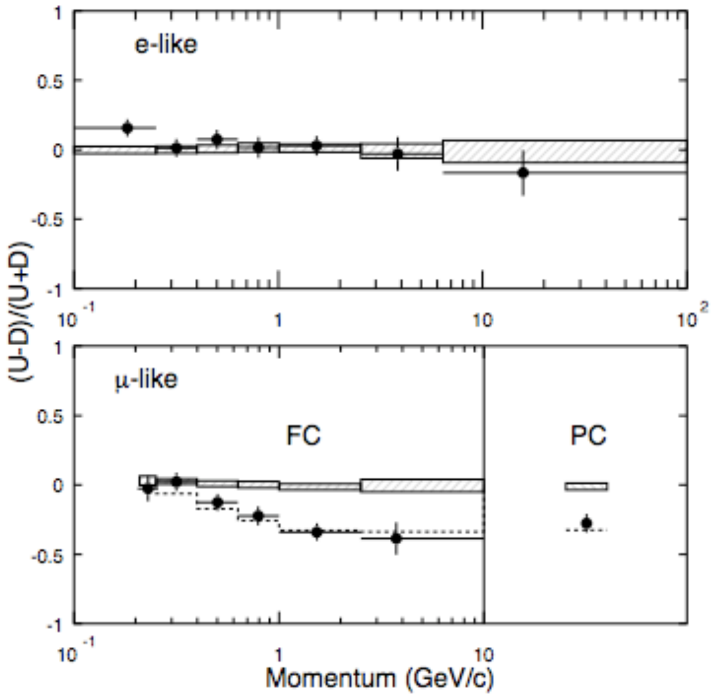



FIG. 1. The $(U - D)/(U + D)$ asymmetry as a function of momentum for FC $e$-like and $\mu$-like events and PC events. While it is not possible to assign a momentum to a PC event, the PC sample is estimated to have a mean neutrino energy of 15 GeV. The Monte Carlo expectation without neutrino oscillations is shown in the hatched region with statistical and systematic errors added in quadrature. The dashed line for $\mu$-like is the expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.2 \times 10^{-3}\ \mathrm{eV}^2)$.

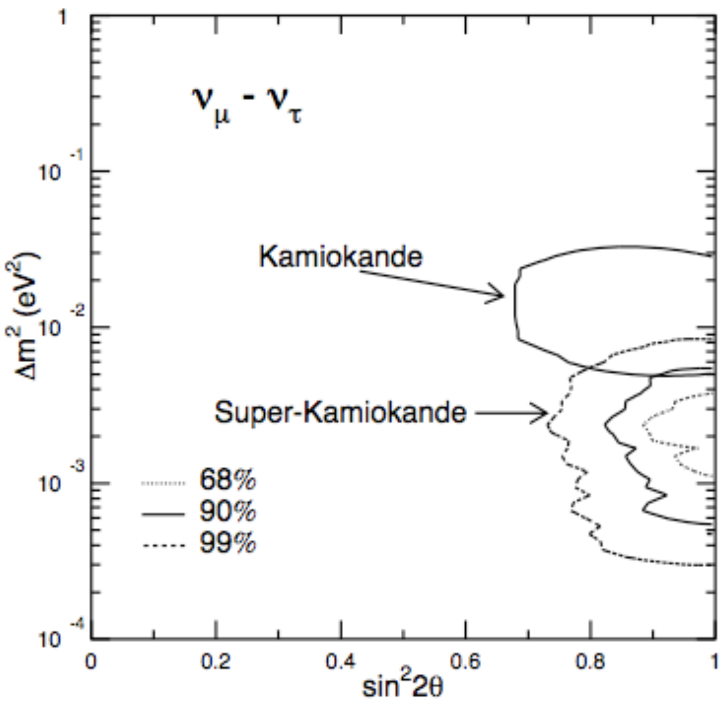
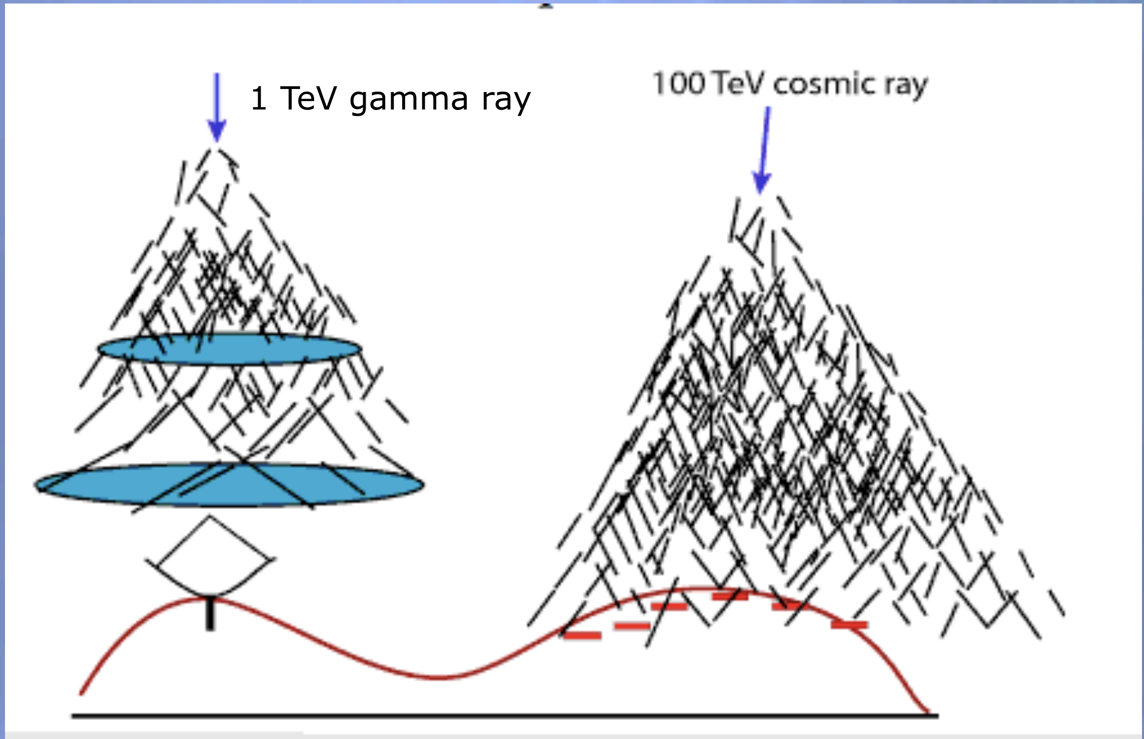



FIG. 2. The 68%, 90% and 99% confidence intervals are shown for $\sin^2 2\theta$ and $\Delta m^2$ for $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillations based on 33.0 kiloton-years of Super Kamiokande data. The 90% confidence interval obtained by the Kamiokande experiment is also shown.

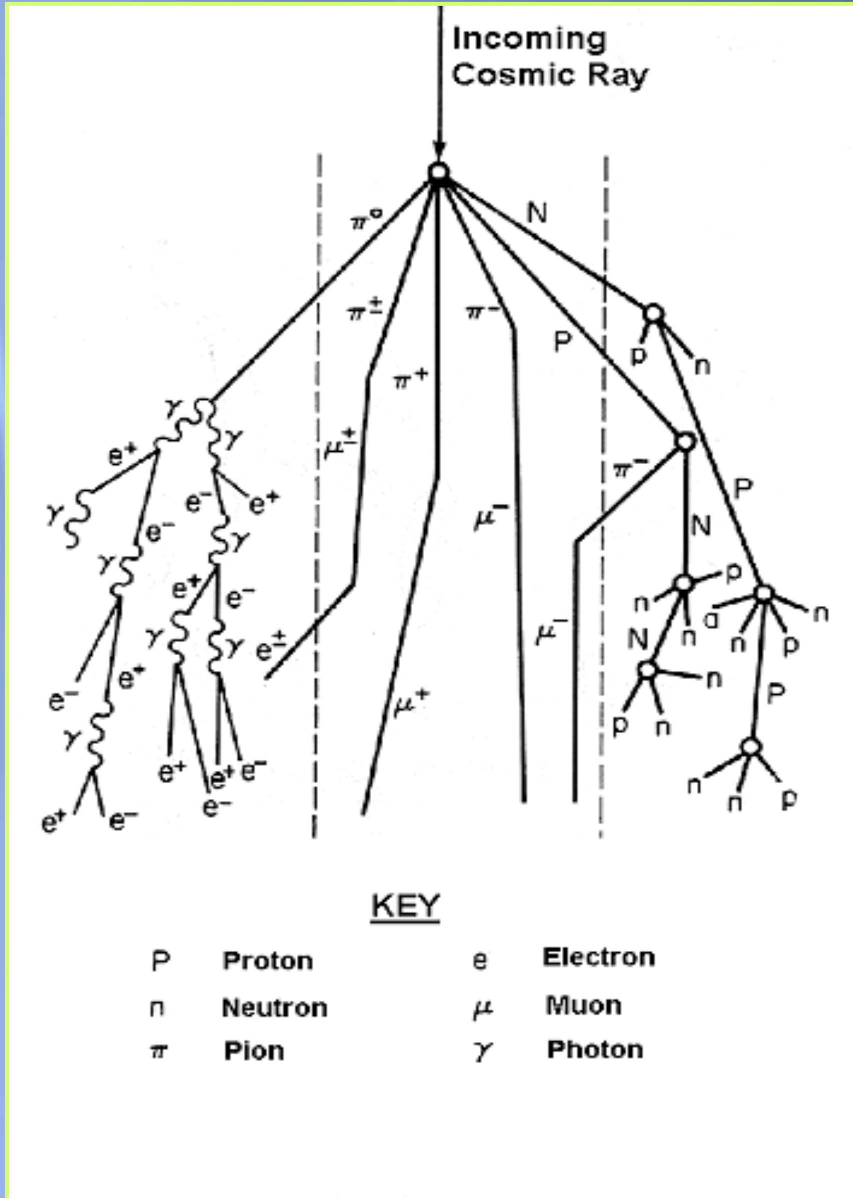
# C effect in Astroparticle Physics: EAS array vs IACT




- Advantages and disadvantages to both techniques:
- IACT: lower threshold, small field of view, low duty cycle
- EAS array: higher threshold, large field of view, large duty cycle

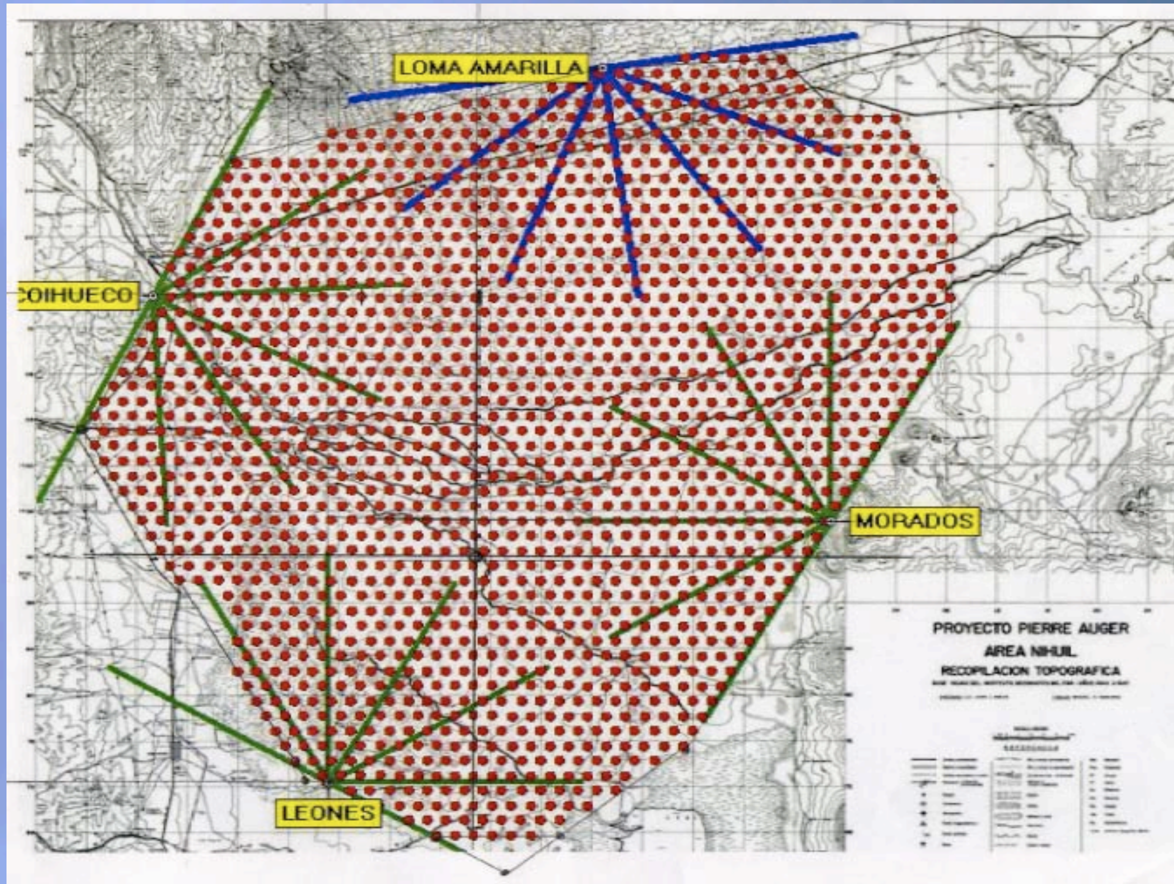
# C detectors for EAS

- When a *primary cosmic ray* or *high energy gamma ray* enters the atmosphere it triggers a series of particle physics reactions that result in a shower of elementary particles (EAS)
- (Many of) these *secondaries* are charged and travelling at relativistic speeds
- Some EAS detectors set out to sample these secondaries at ground level using C radiation



# What cosmic rays do NOT do

# The AUGER project

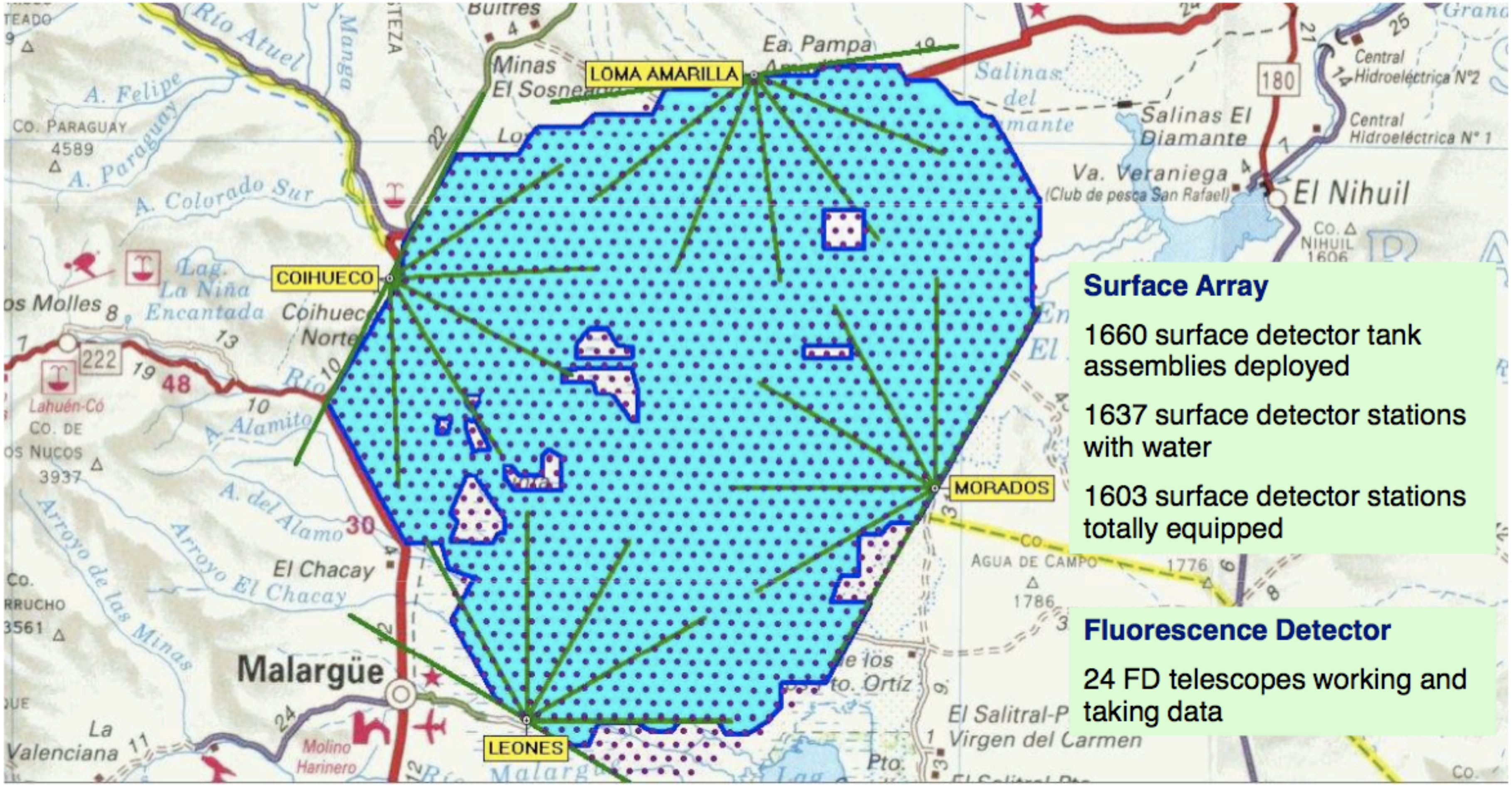




- AUGER set out to build a huge effective area cosmic ray detector combining both Cerenkov and fluorescence techniques for the first time
- Note in this case Cerenkov tanks *sample* the signal

# AUGER Status

## Pierre Auger Observatory: Status

**June 11 2008**




**Surface Array**

1660 surface detector tank assemblies deployed

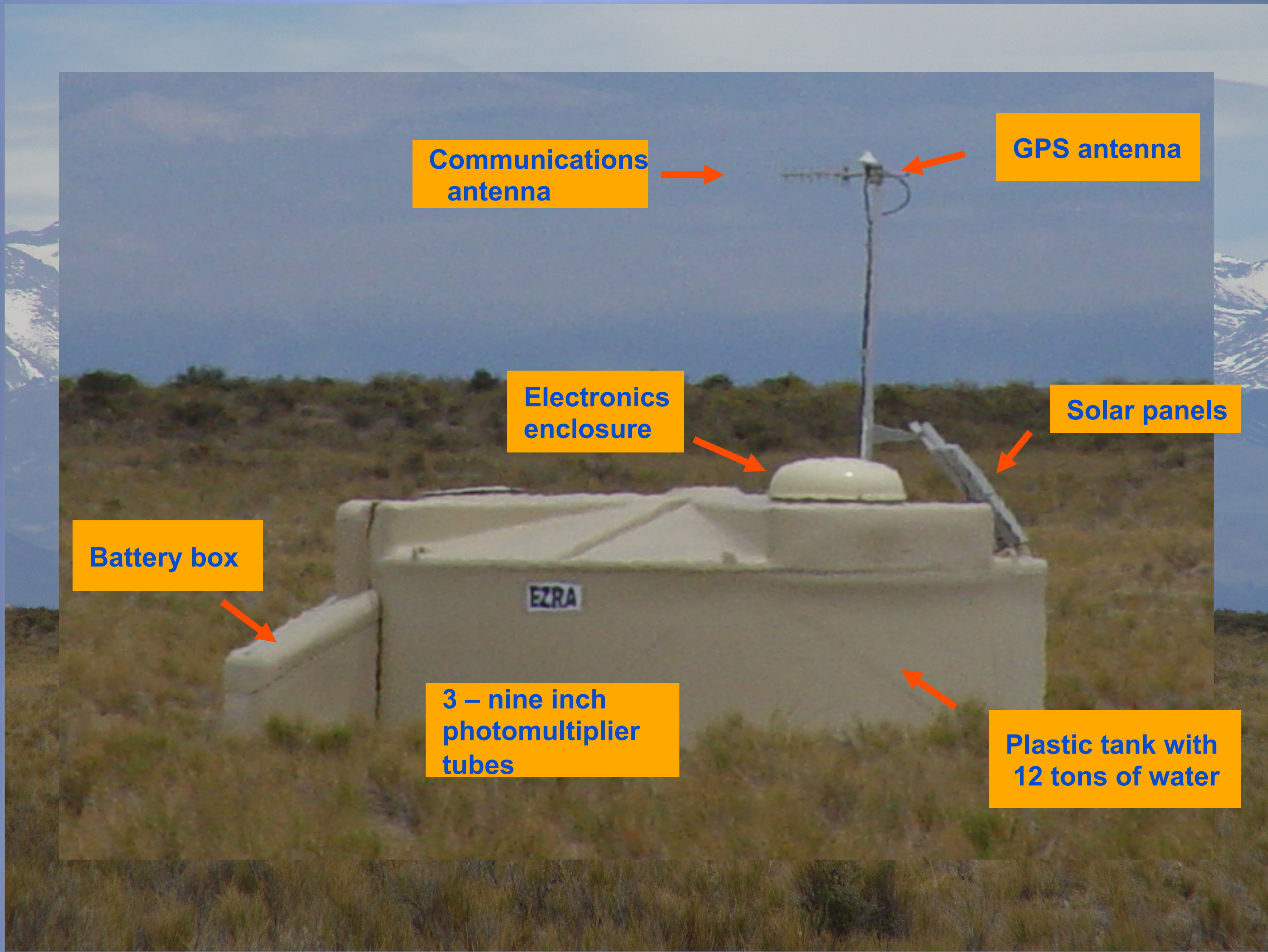
1637 surface detector stations with water

1603 surface detector stations totally equipped

**Fluorescence Detector**

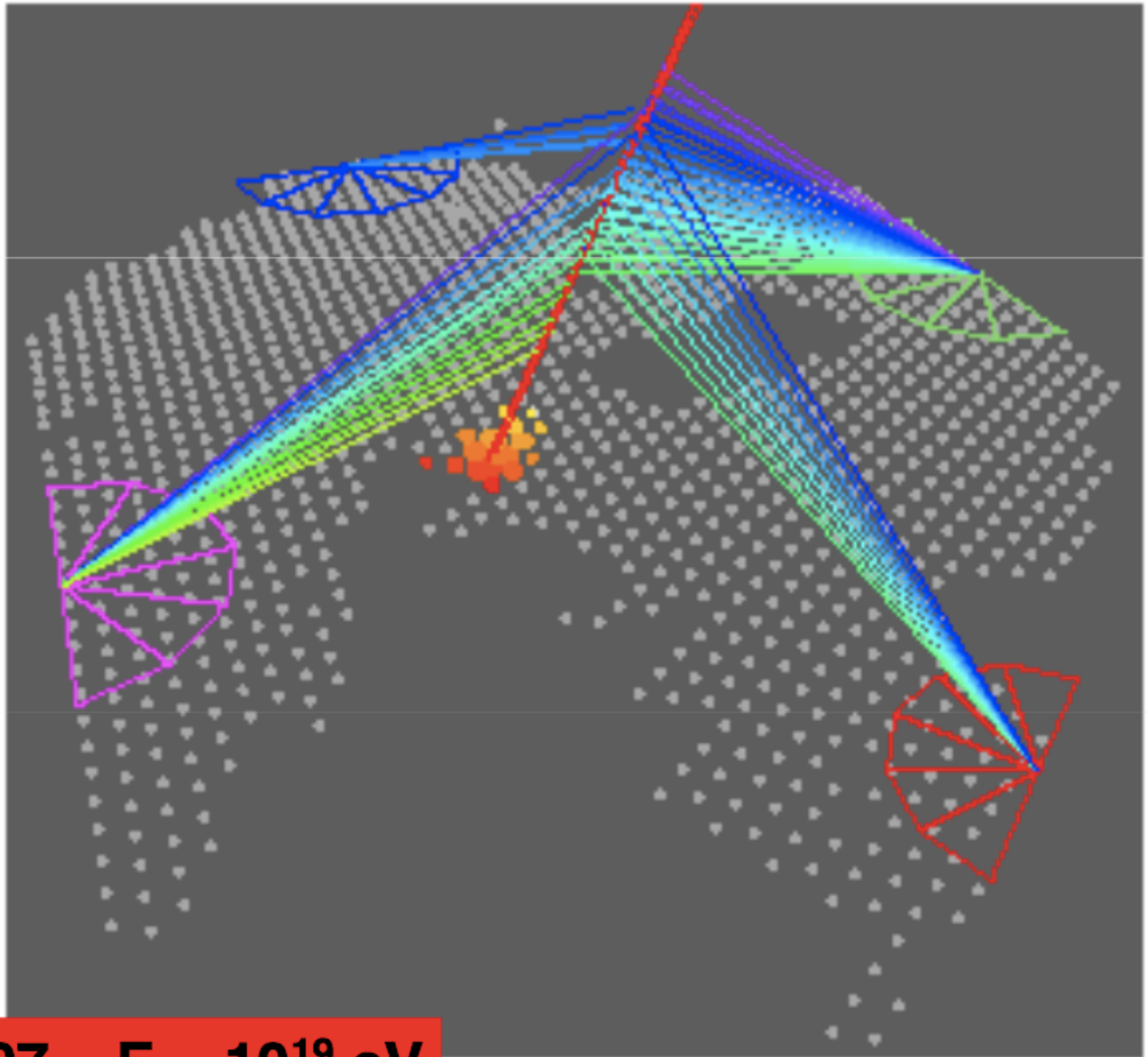
24 FD telescopes working and taking data

# AUGER's C detectors



# Hybrid event detected with 4 FD eyes & surface detector

Miguel Mostafá

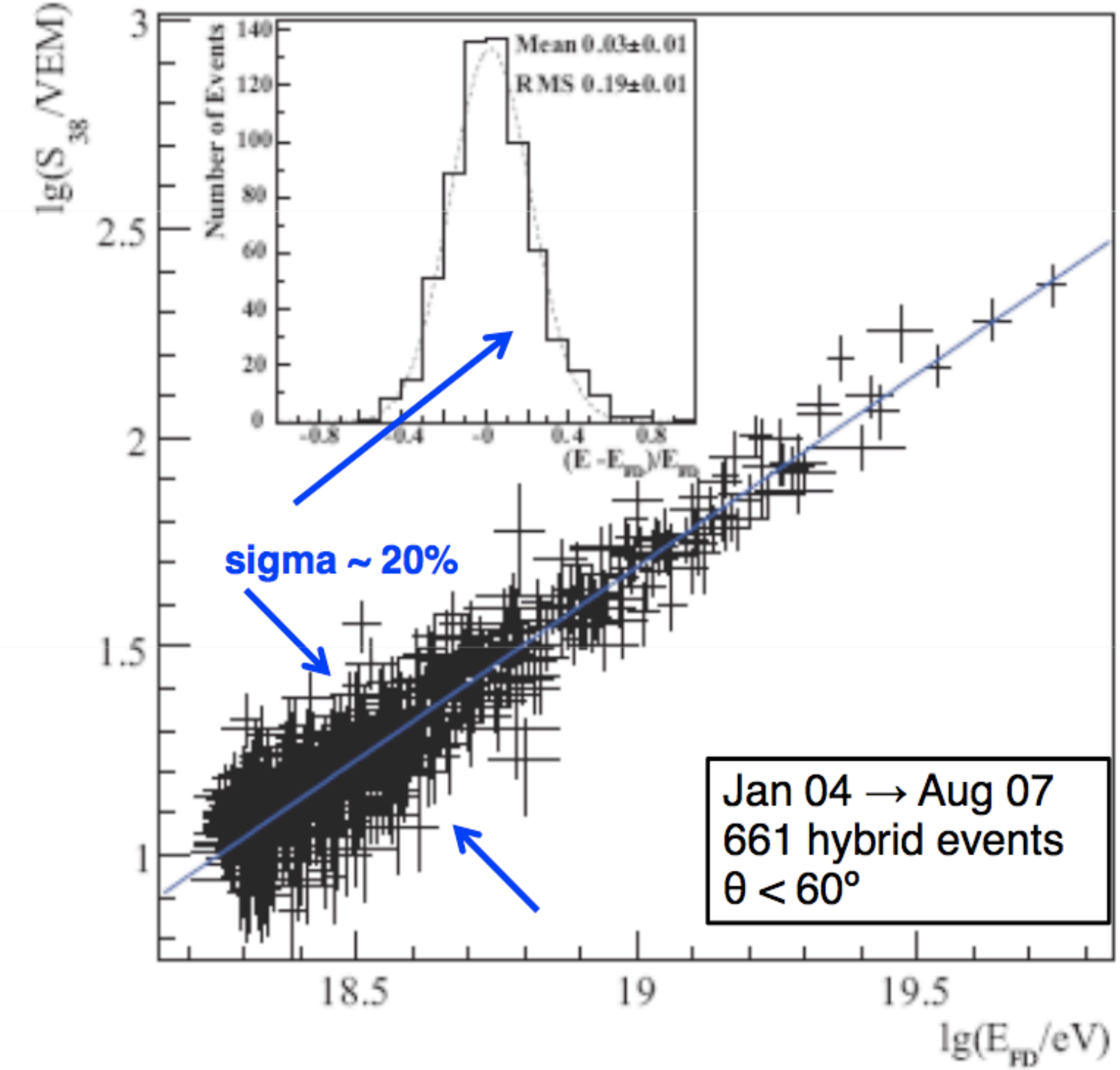


**20 May 2007 E ~ $10^{19}$ eV**

# Hybrid detectors

- AUGER is an excellent example of a *hybrid* detector combining more than one detection technique - in this case *Cerenkov radiation* and *fluorescence*
- A number of hybrid detectors are being proposed for the future - optical-acoustic, optical-radio, etc

# Energy estimation




**Linear correlation between $E_{FD}$ and S(1000)**

**Energy scale determined with hybrid events:**

**~ 20% E resolution.**

**Extrapolate calibration to events observed with the Surface Detector only**

**Minimises Monte Carlo and mass composition dependence**

**S(1000): Lateral energy distribution function**

# Angular Resolution

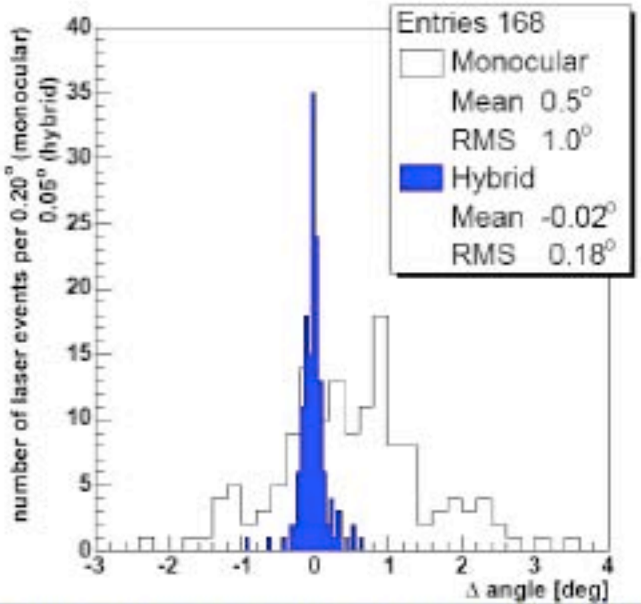
## Surface Detectors

determined by timing uncertainties

(~ 12 ns)

< 1° E > 10EeV

| A.R. (68% CL) | # of tanks | Typical if |
|---|---|---|
| < 2.2° | 3 | E < 3 EeV |
| < 1.7° | 4 | 3 EeV < E < 8 EeV |
| < 1.4° | 5 or more | E > 8 EeV |

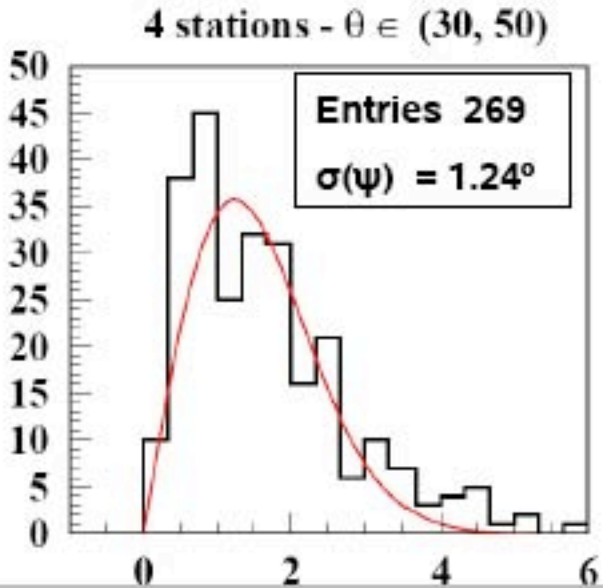



Angle in laser beam /FD detector plane

## Hybrid events

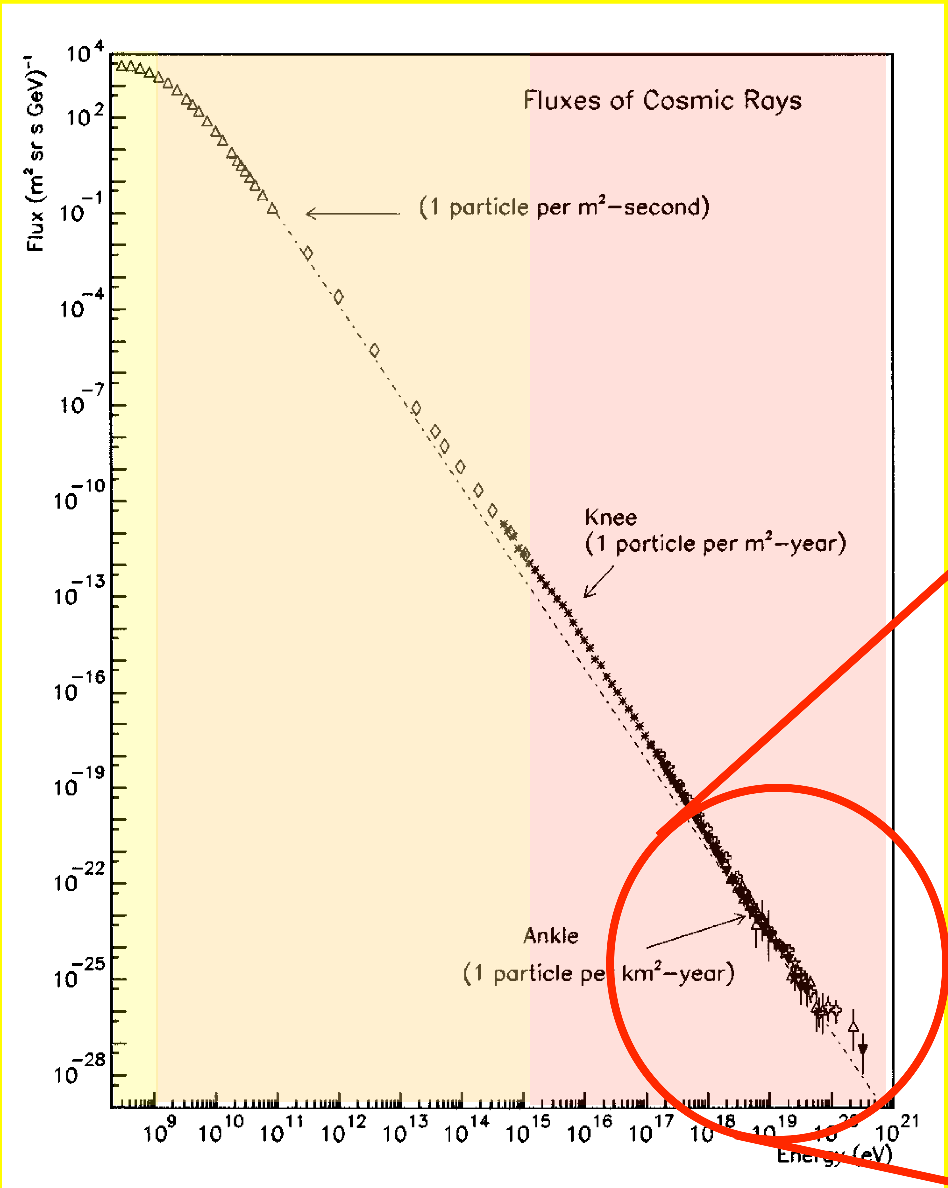
0.6° (mean)

Consistency →

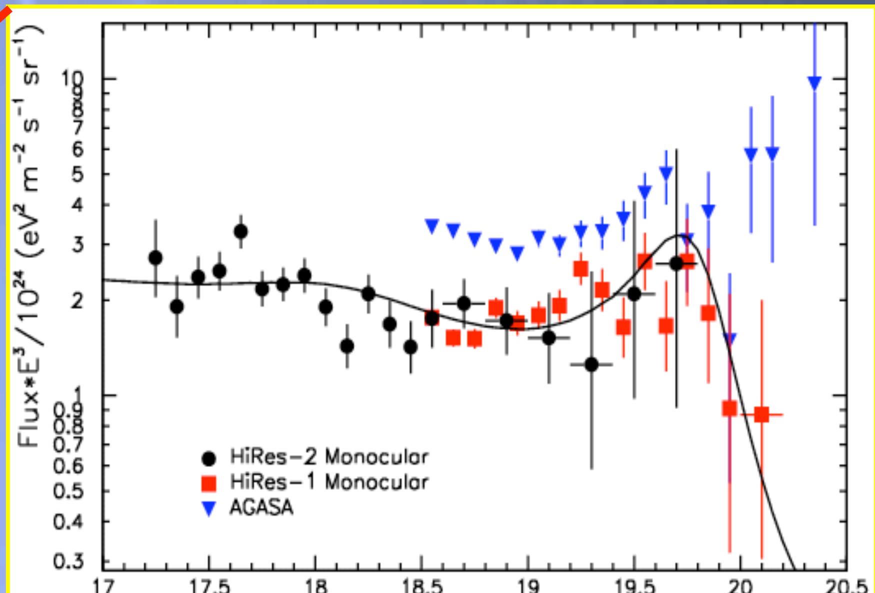



Hybrid-SD only space angle difference

# Highest Energy Cosmic Rays



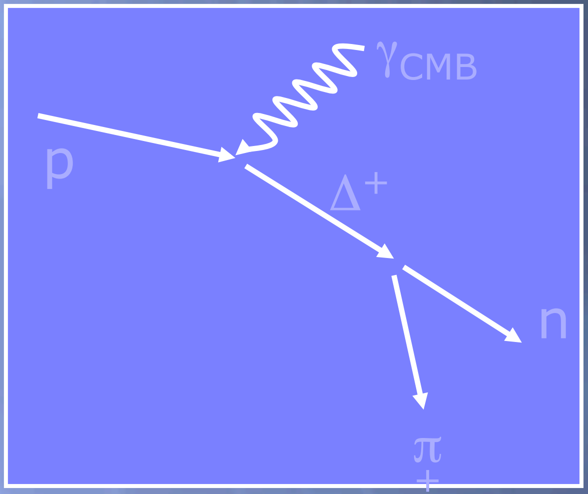

- Far less is know about the highest energy cosmic rays
  - Up to tens of Joules per cosmic ray primary
  - Where do they come from?
  - What produces them?
  - Do they “cut-off” or not?

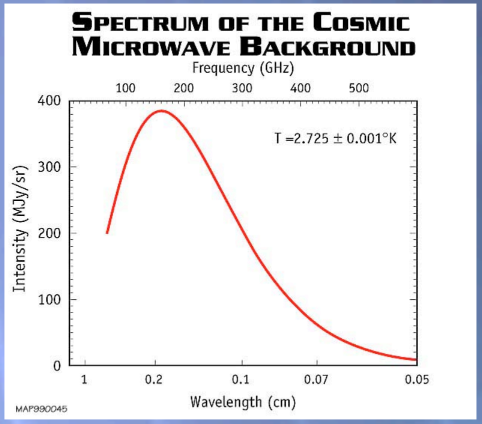



astro-ph/0208301

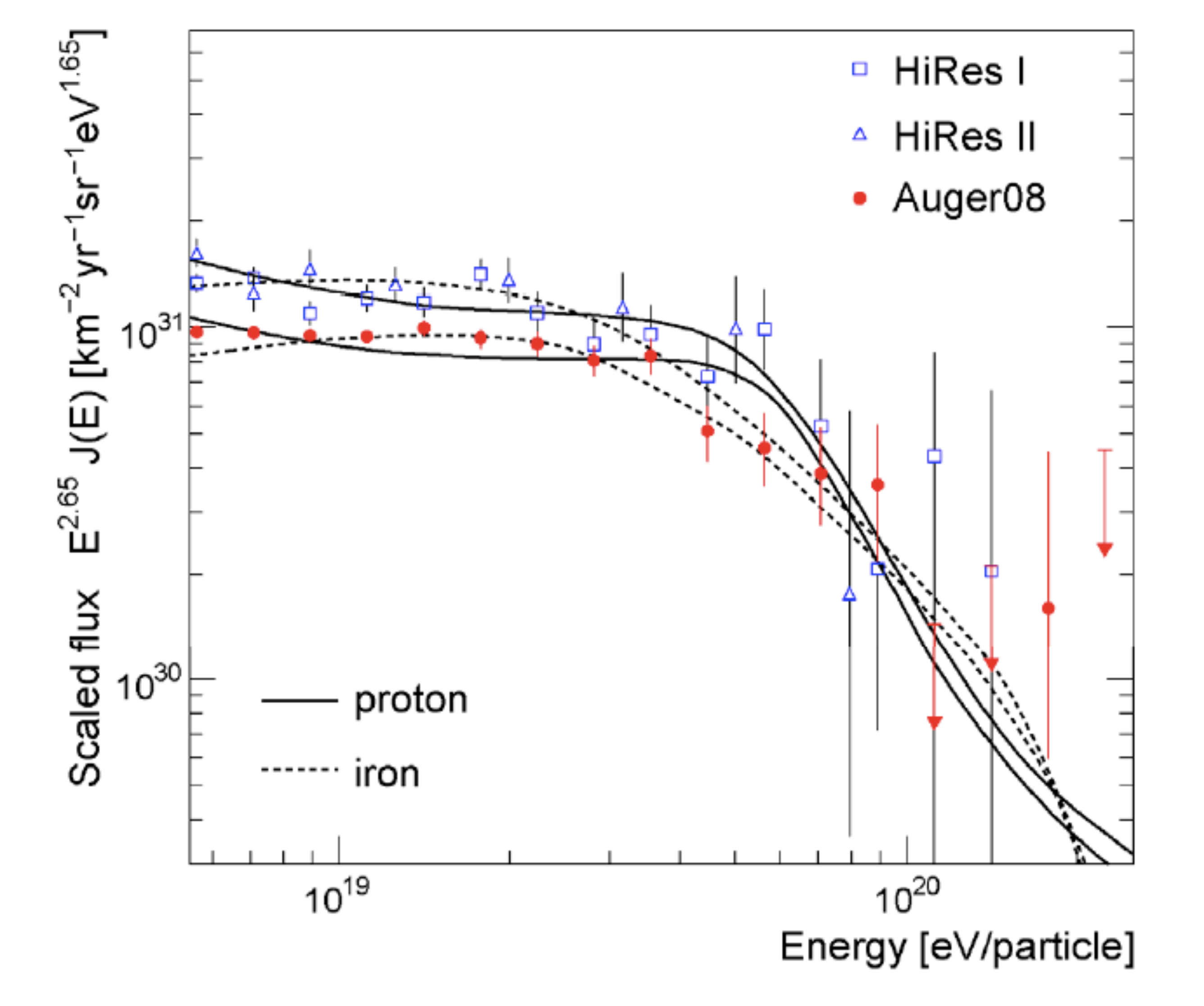
# The GZK effect

- Cosmic ray protons above a certain energy shouldn't be observed due to the so-called GZK effect
- Protons with E ~ $4\times10^{19}$eV interact with CMB photons
- Rest mass energy is exactly equivalent to that of the $\Delta^+$ resonance (a baryon)

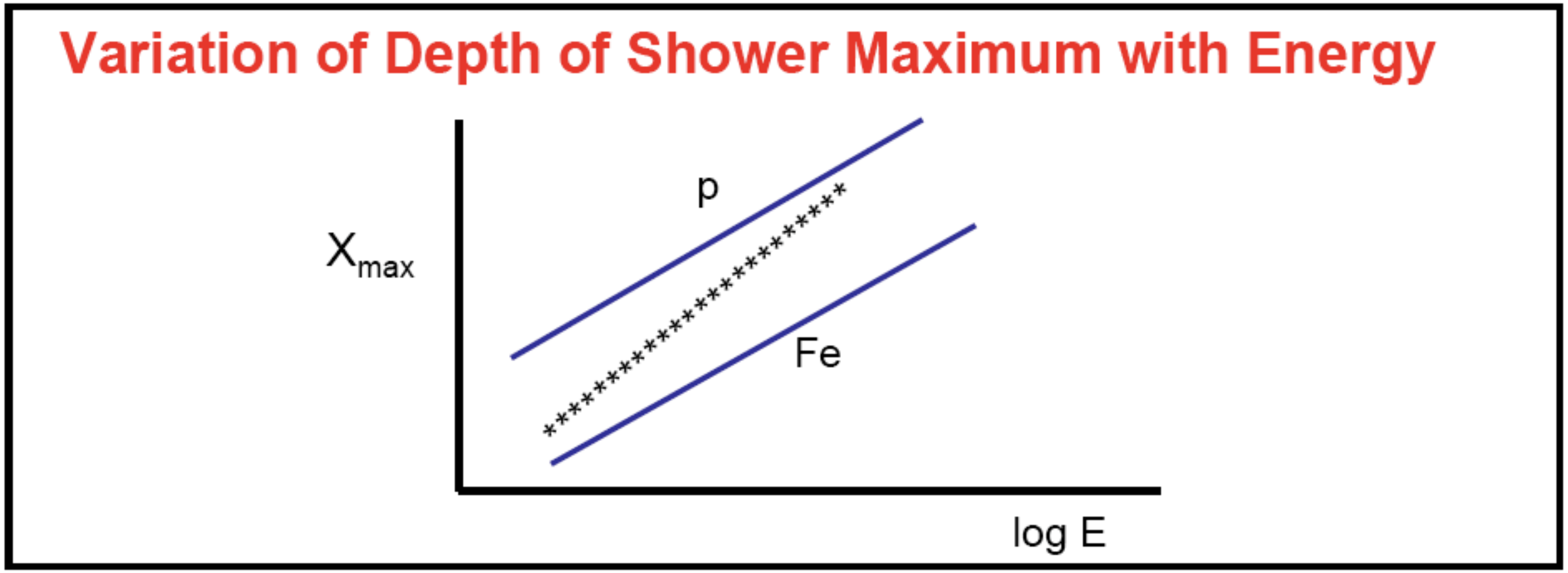


# AUGER High Energy Result



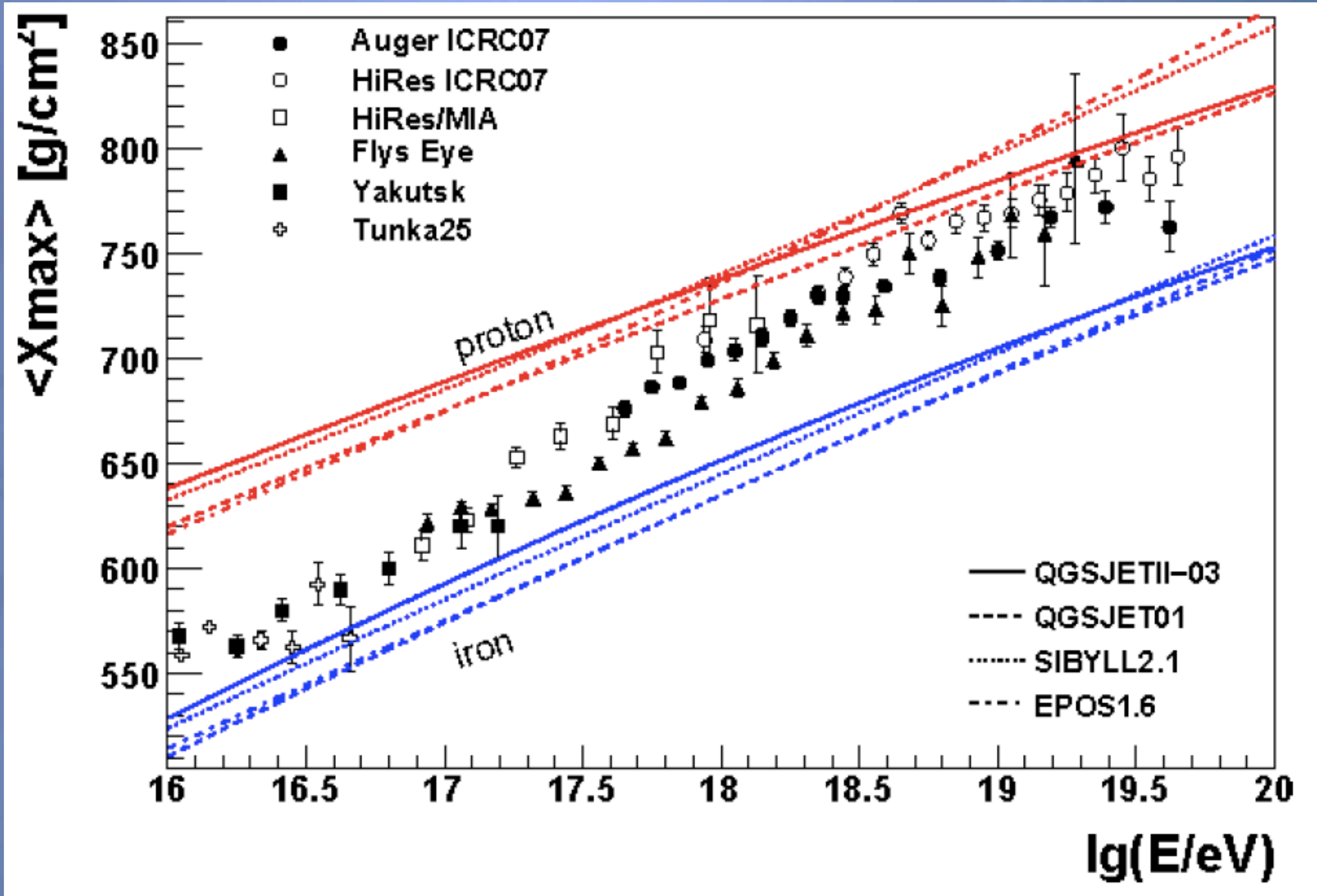
# AUGER composition




protons
nuclei
neutrinos
photons

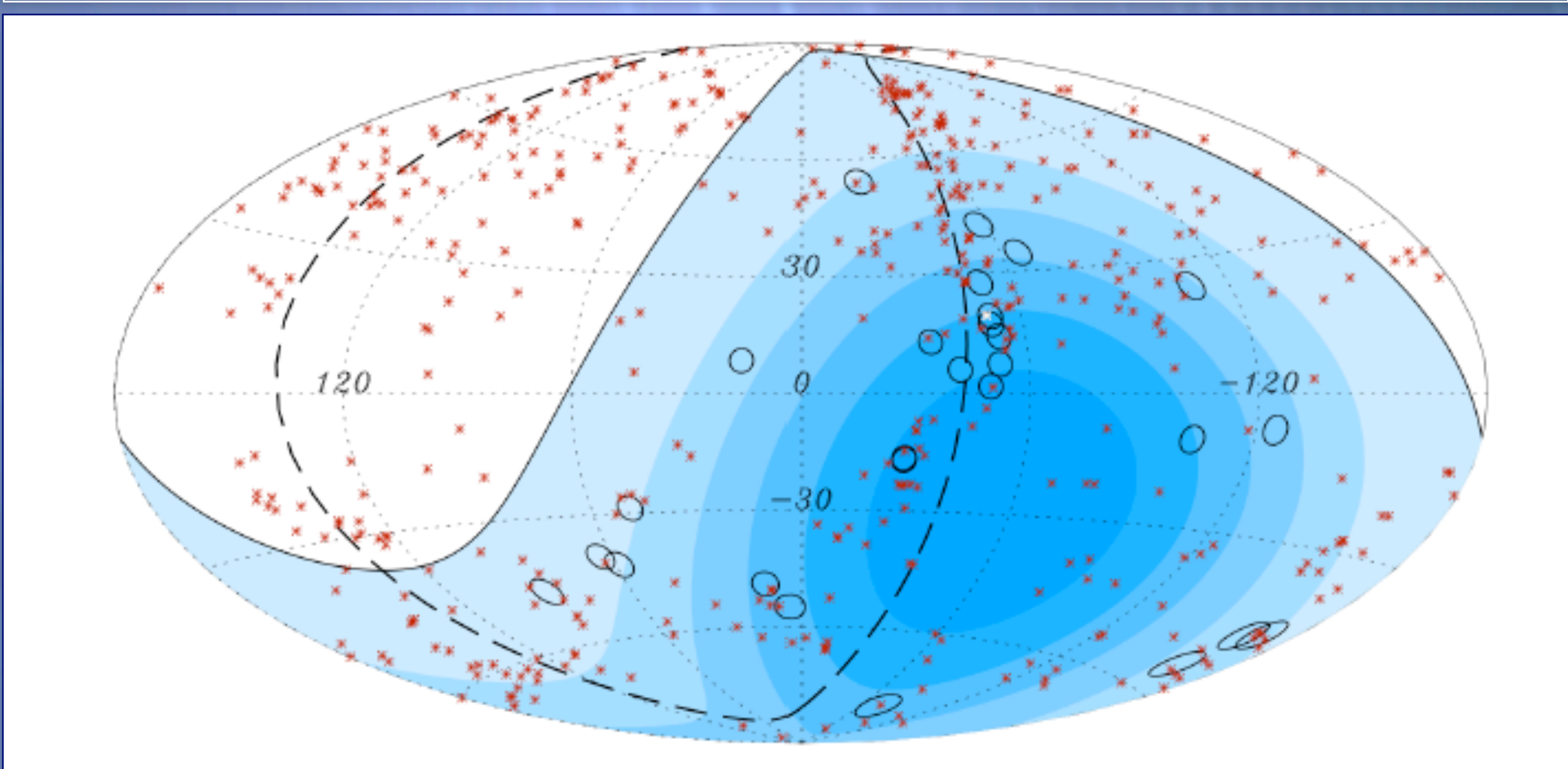
**Different cross-sections give different depths of shower maximum**

# Composition results



# AUGER and AGN

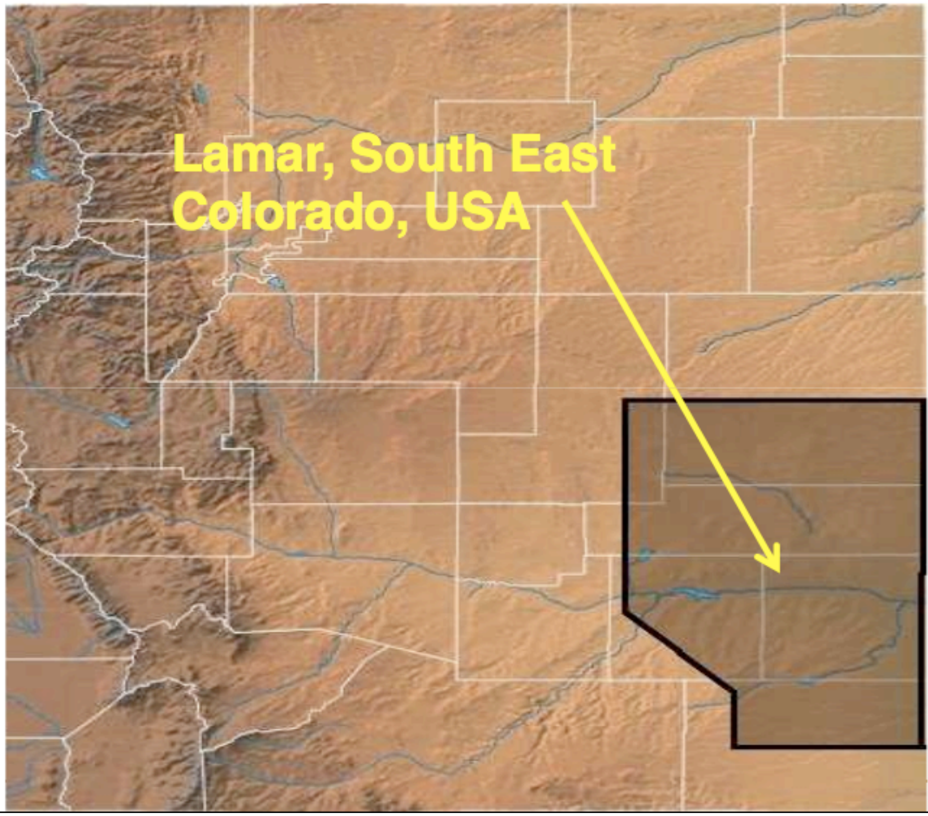
- 2007 AUGER Science paper correlates 20 out of 27 UHE events with known AGN

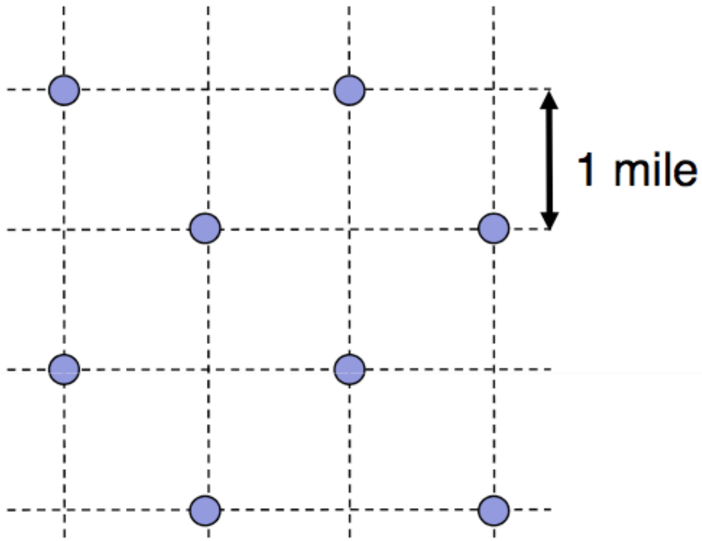



- Cen A has 2 events within $3.1^0$, no events from Virgo region

# The future?

| | AUGER SOUTH | AUGER NORTH |
|---|---|---|
| SD units: | 1,600 | 4,400 |
| SD area: | 3,000 km$^2$ | 20,000 km$^2$ |
| # PMT/tank: | 3 | 1 |
| Type of tank: | Non-insulated | Insulated |



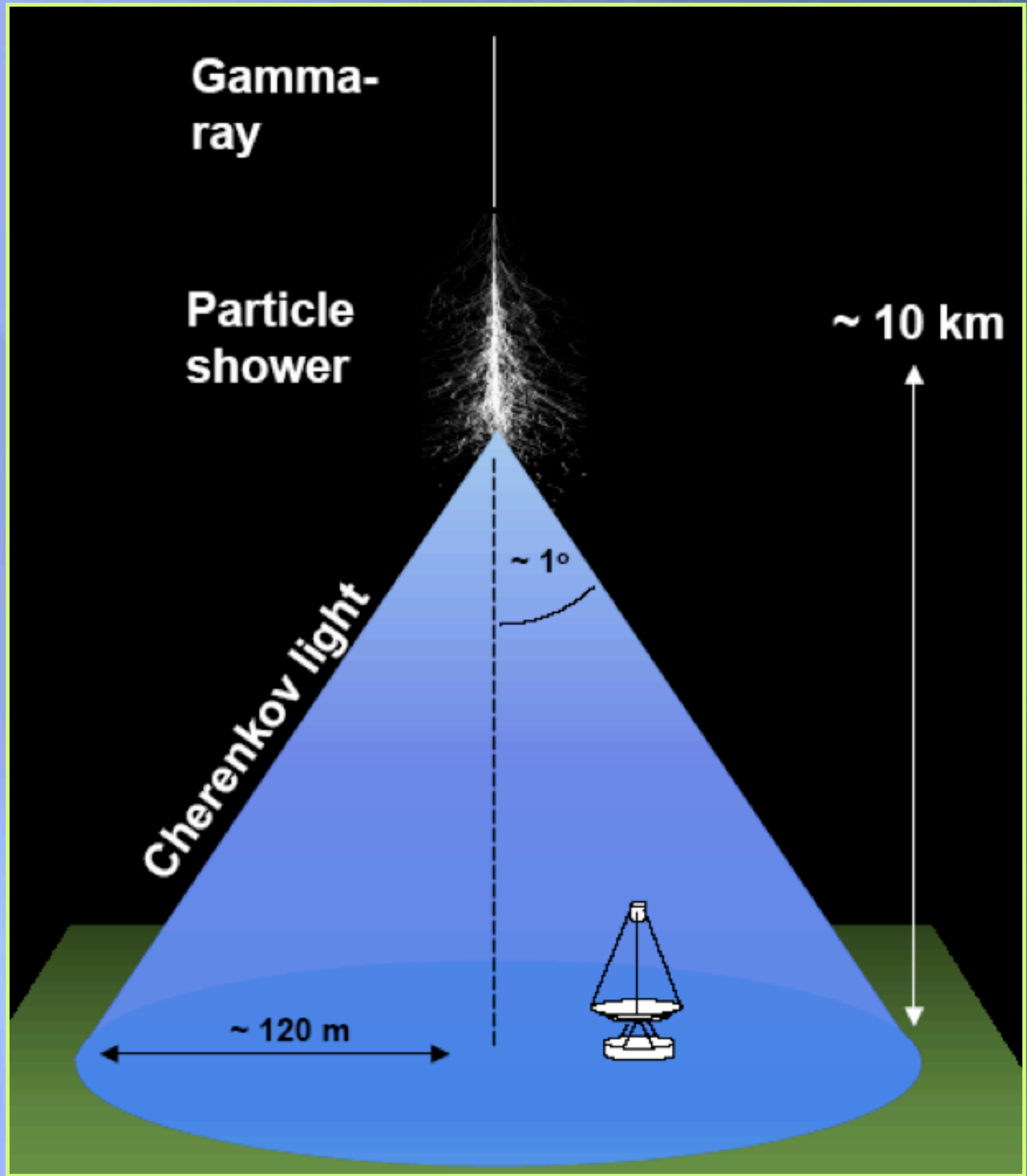

+ several Fluorescence Telescopes

# High Energy Gamma Rays

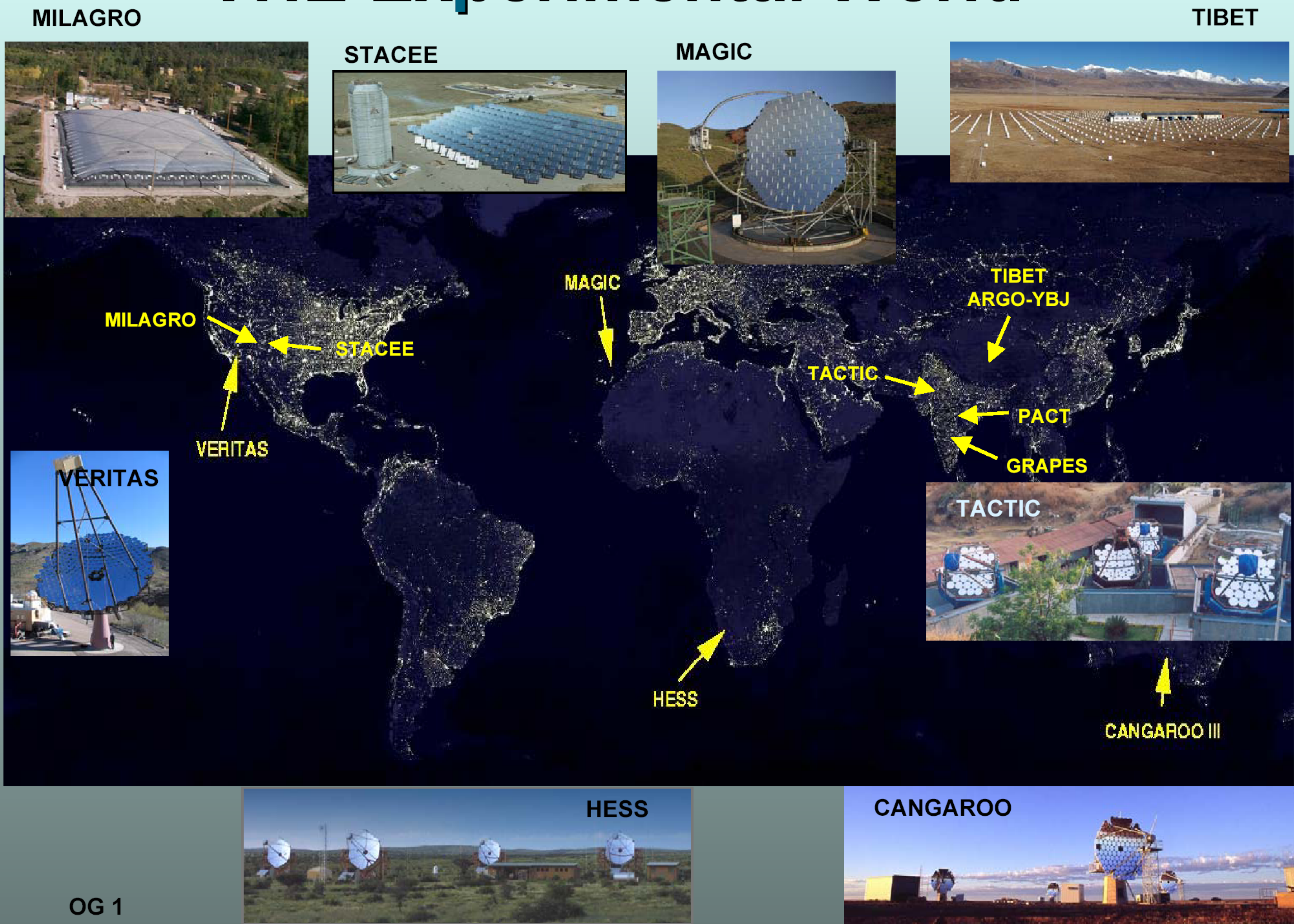
- In a similar way to UHECRs then high energy gamma rays can initiate a particle shower in the upper atmosphere
- The difference here is that in the case of HE gamma ray telescopes they record the C light produced in the atmosphere
- Note that in this case the detection medium is the air with a refractive index of 1.0004 c.f. ~1.3 for water

# IACT detection principle

- The schematic shows the principle behind HE gamma ray detection with a single telescope
- Cerenkov light created in the atmosphere is focussed by a mirror onto a photodetector - usually an array of PMTs

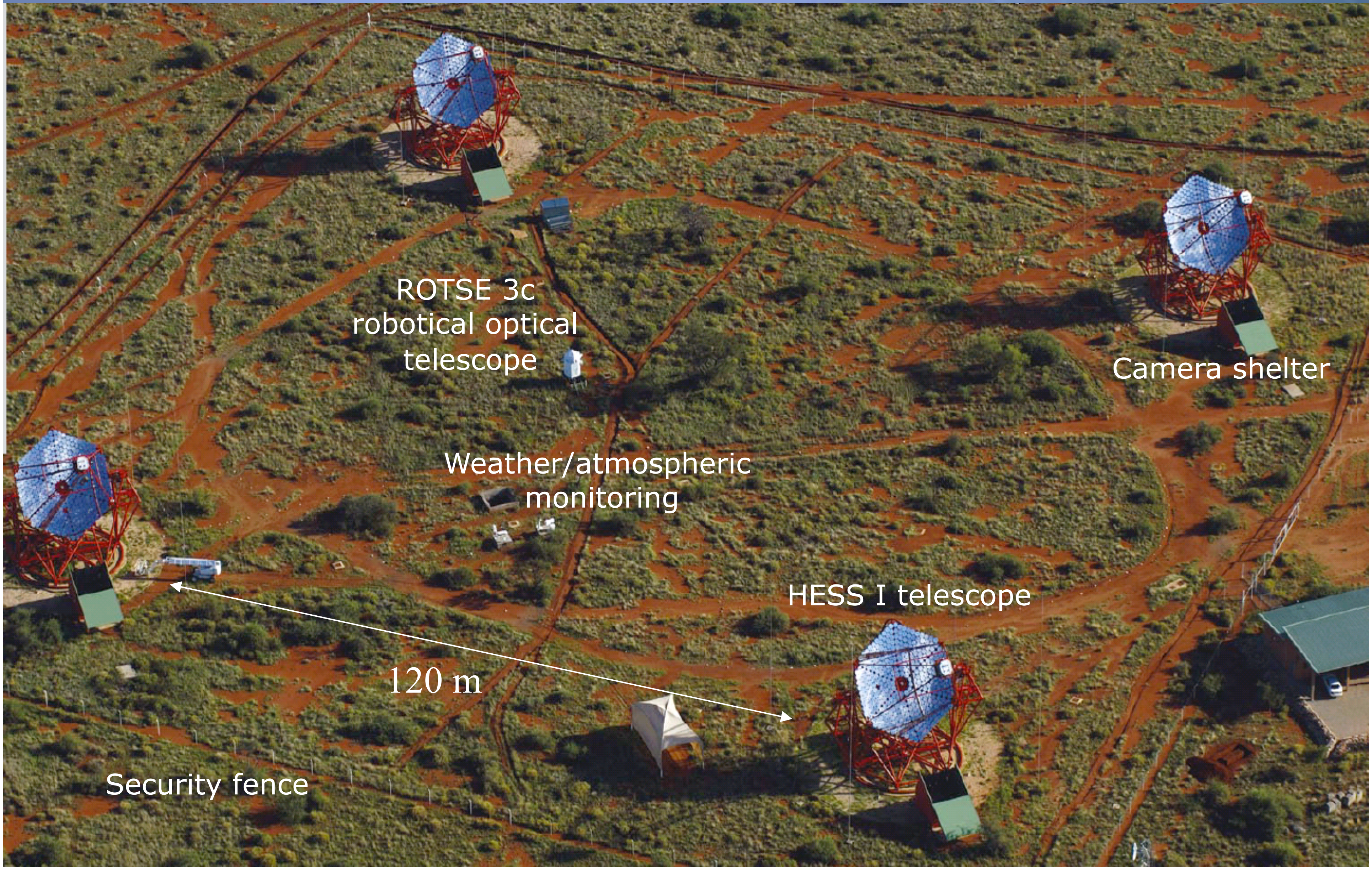


# VHE Experimental World



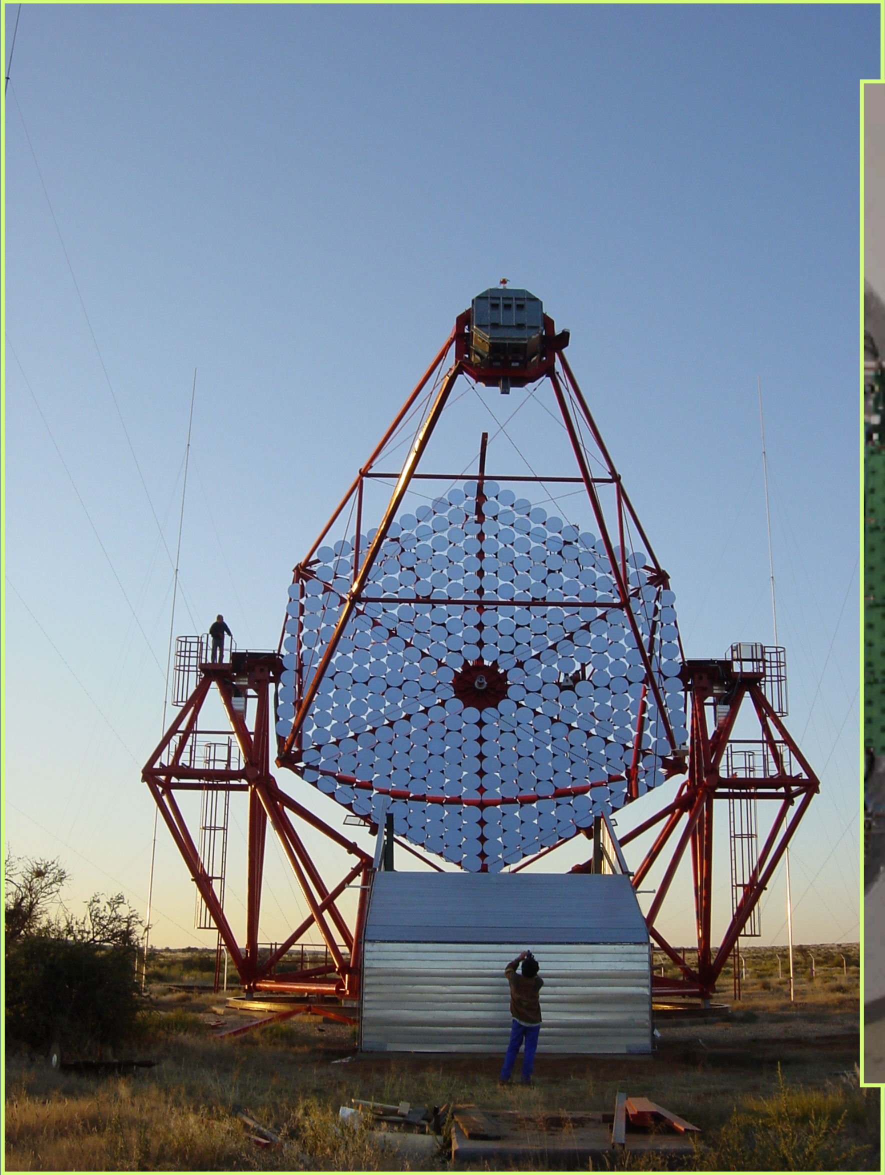

OG 1

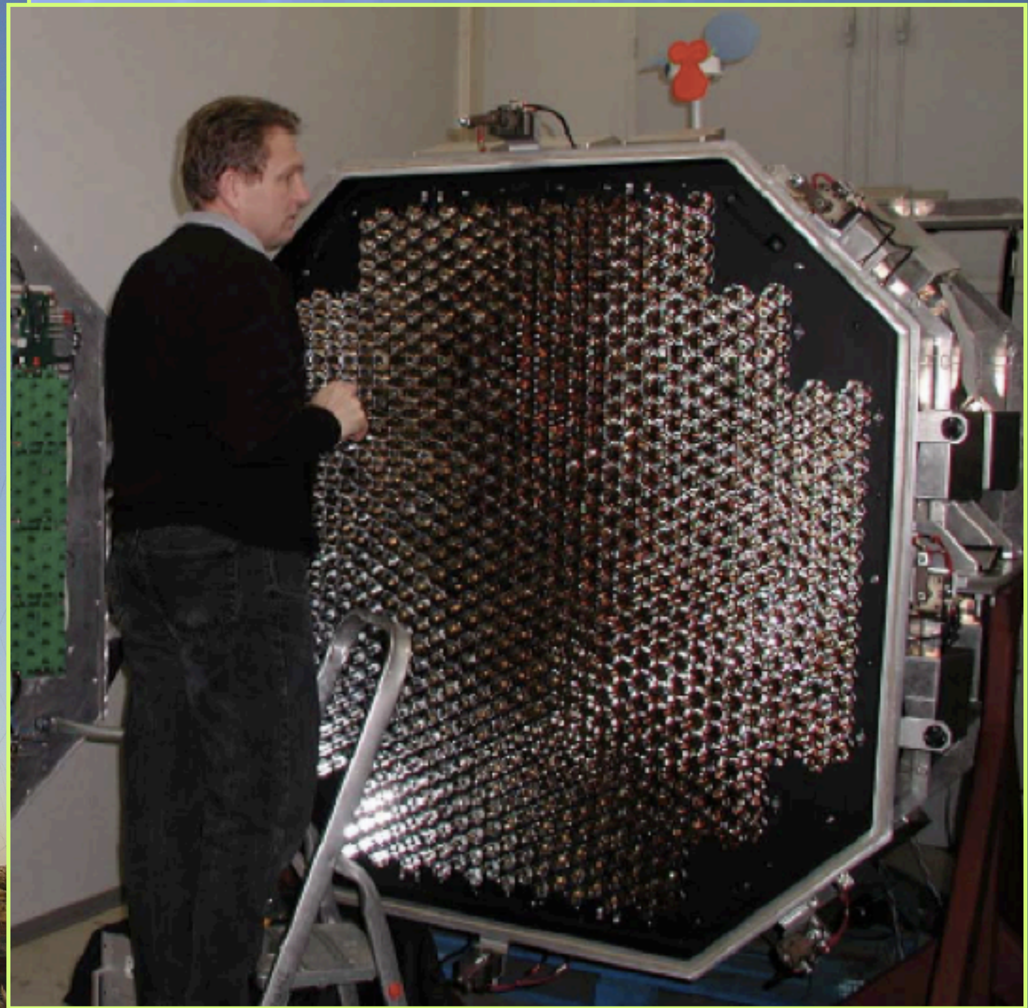
# H.E.S.S. Site



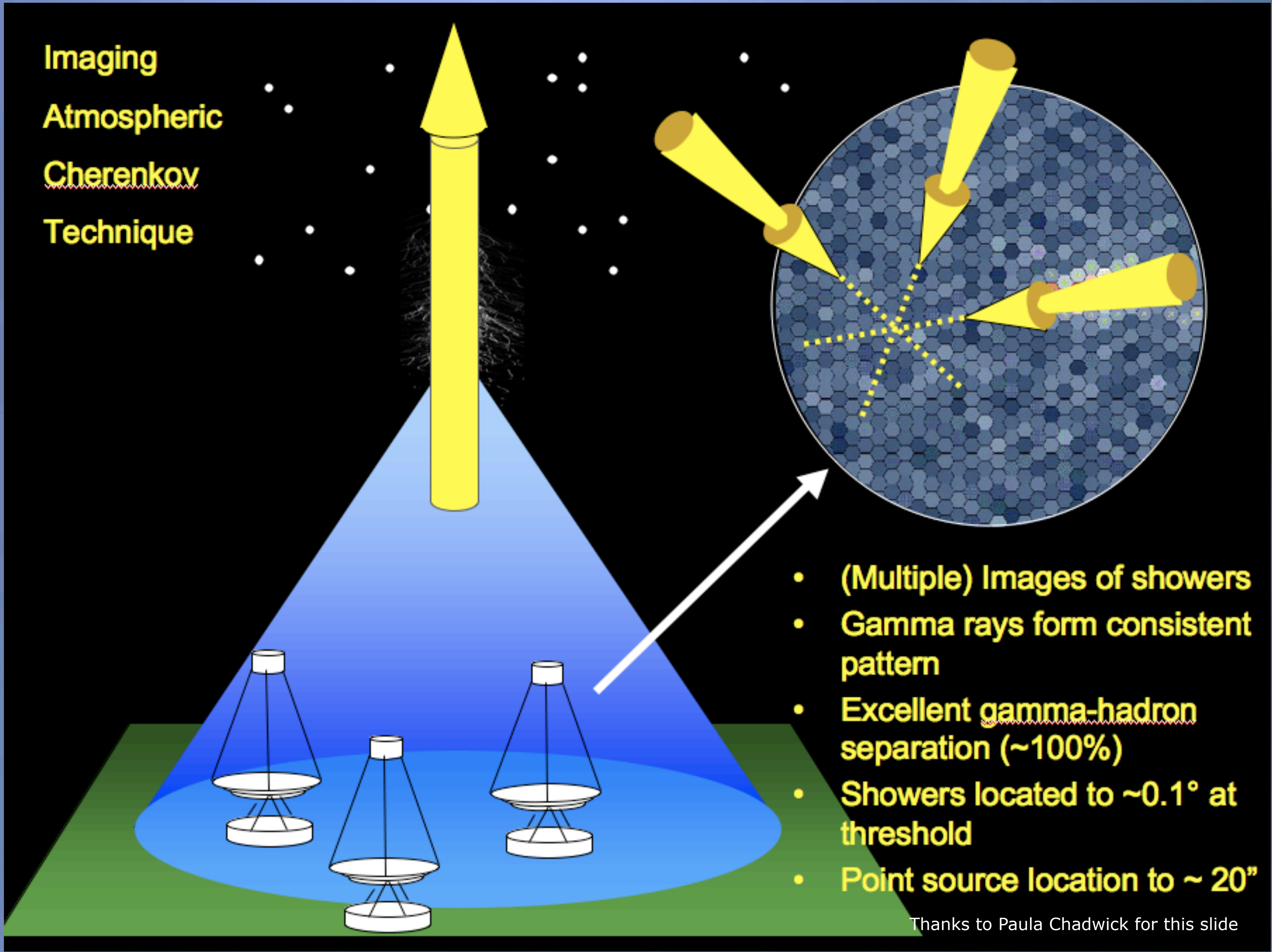
ROTSE 3c
robotical optical
telescope
Camera shelter
Weather/atmospheric
monitoring
HESS I telescope
120 m
Security fence

# H.E.S.S. telescope and “camera”



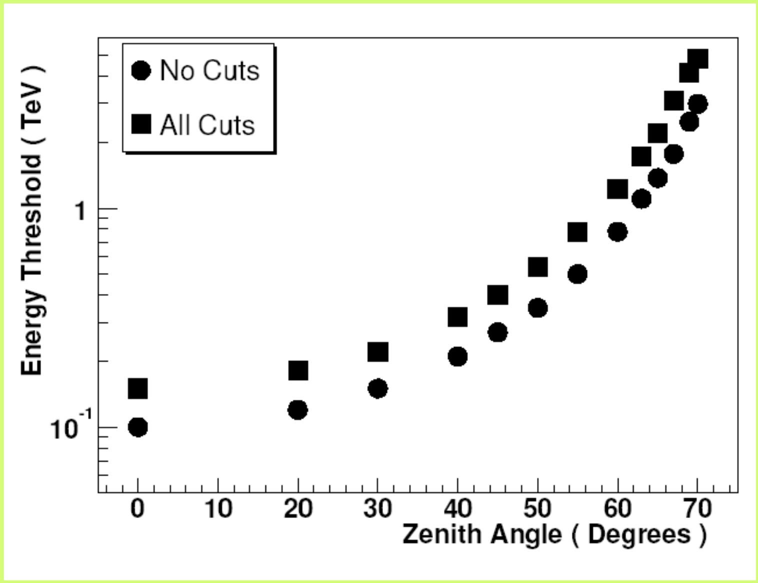


# Advantages from >1 telescope

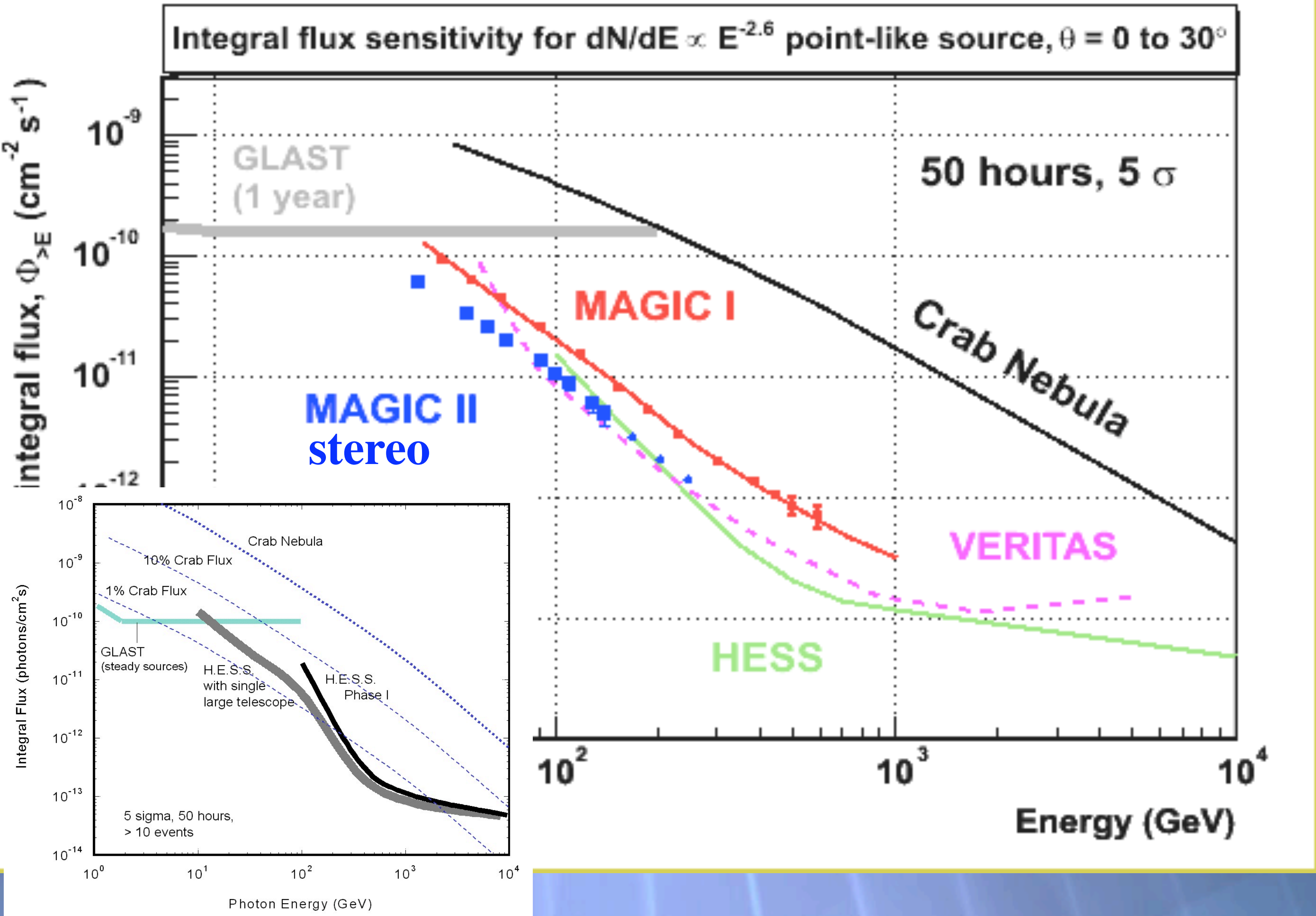


# IACT Features

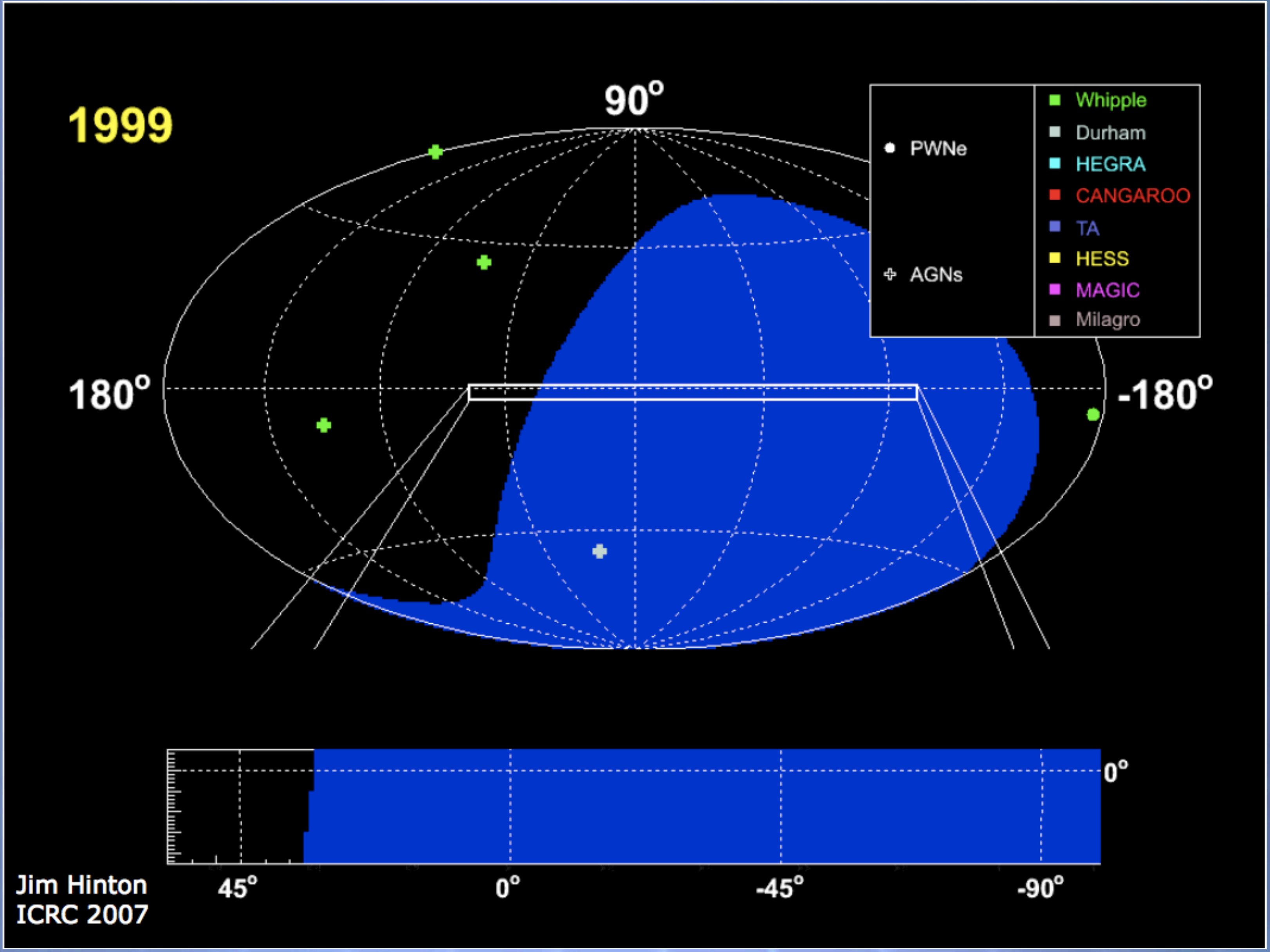
- Excellent source location
- IACTs are *pointing* instruments
- Very large effective area can be achieved
- Energy threshold (and collection area) increase with zenith angle
- Cannot observe during full moon and when there is cloud cover



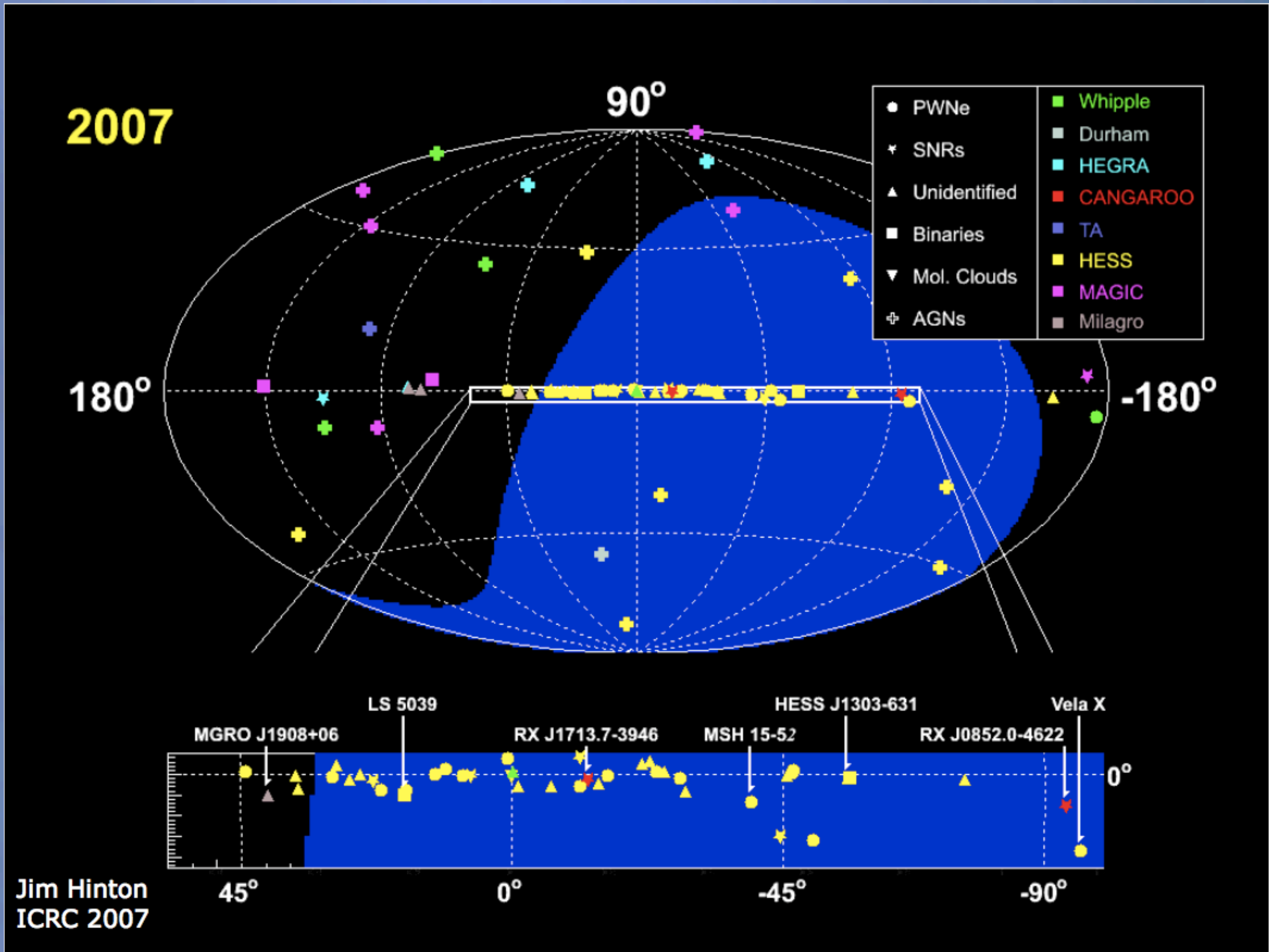
# IACT Performance



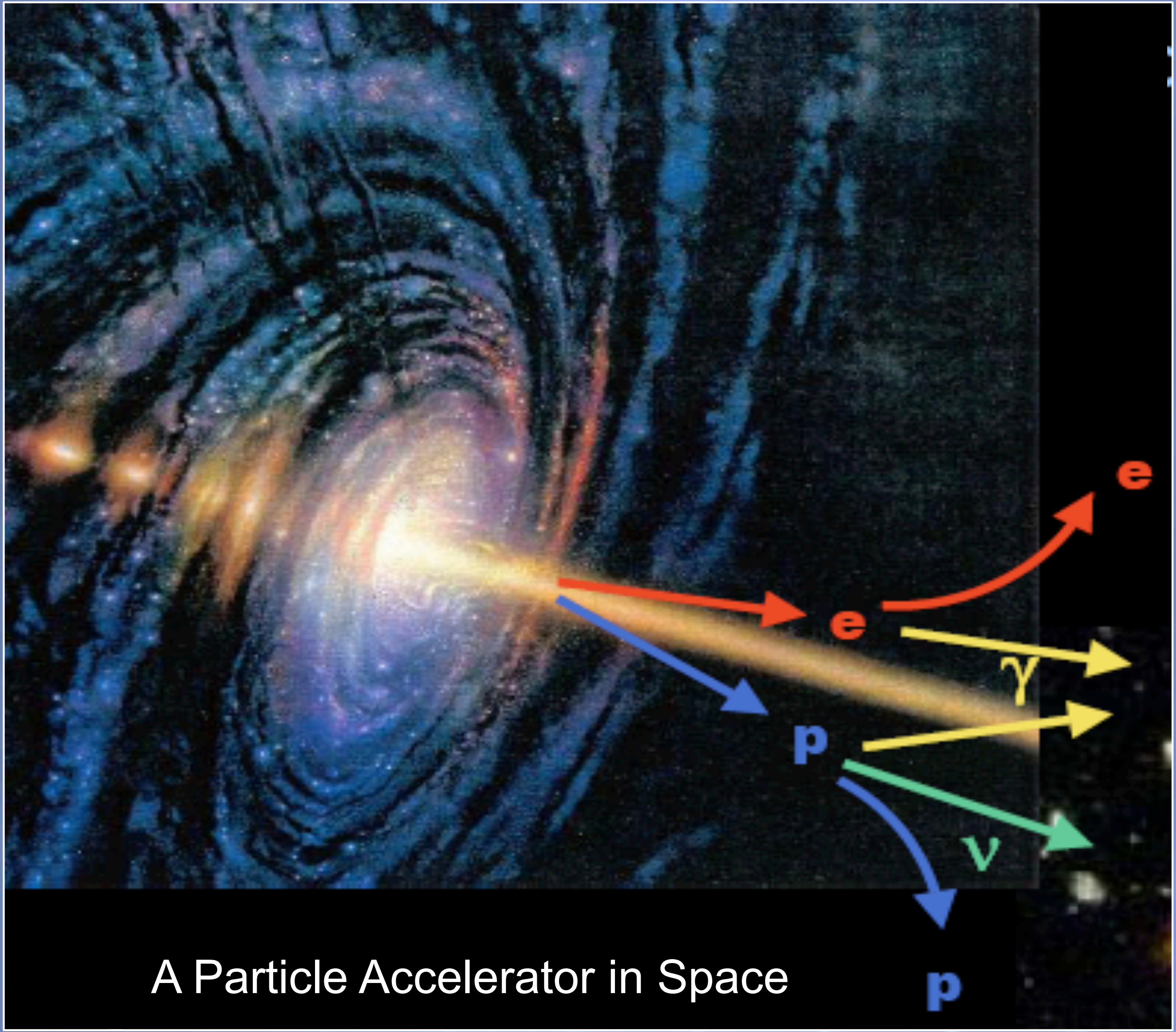
# High energy γ ray sources '99



# High energy γ ray sources '07



# High energy $\gamma$ ray sources '07

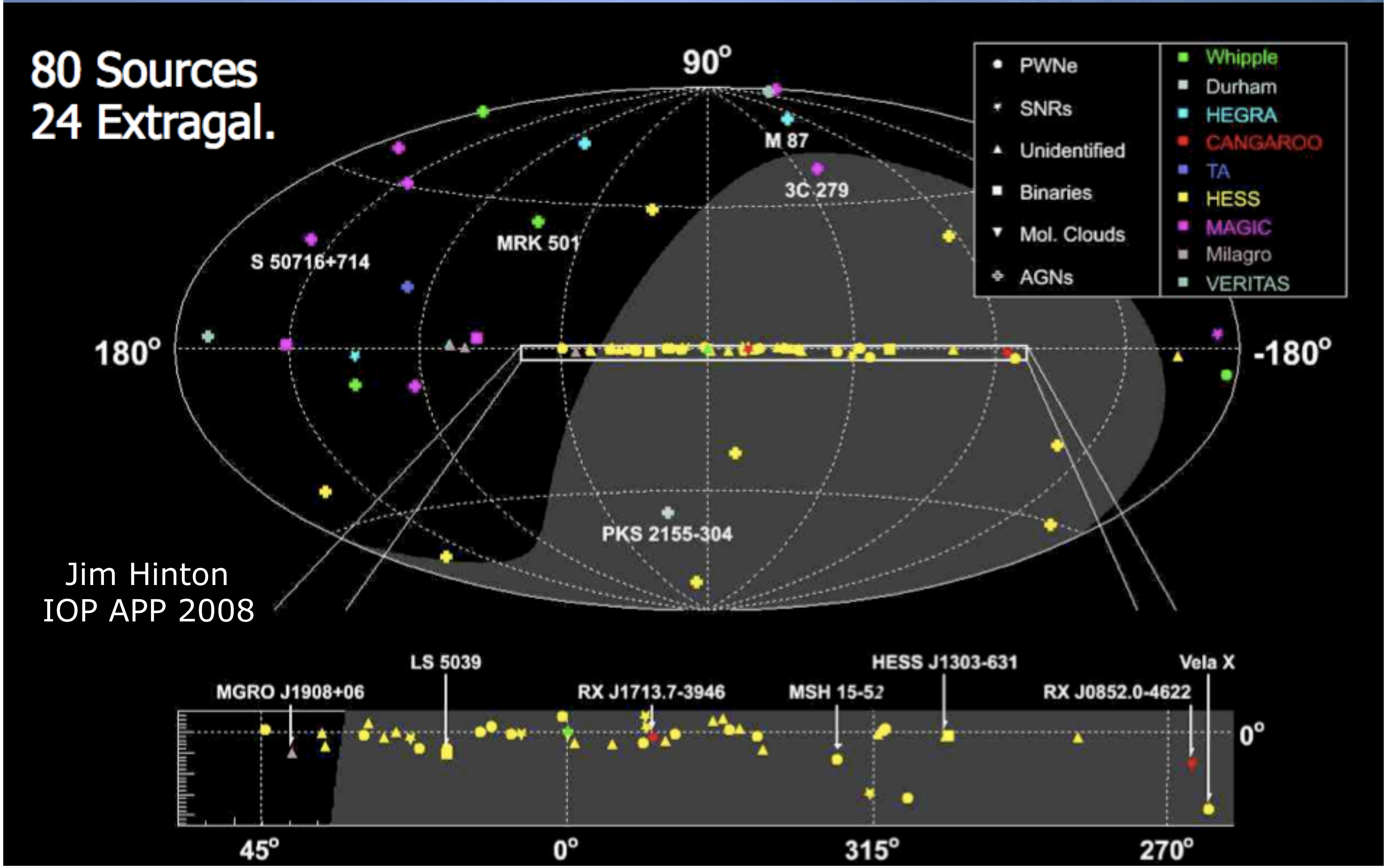



71 sources:

- 7 SNR
- 18 PWN
- 21 Un.Gal.
- 2 Diffuse
- 4 Binary
- 19 AGN
- 3 in Gal. plane have <u>no</u> counterparts

- Each of these sources is a high energy cosmic accelerator of primary electrons or nuclei

# High energy γ ray sources '08

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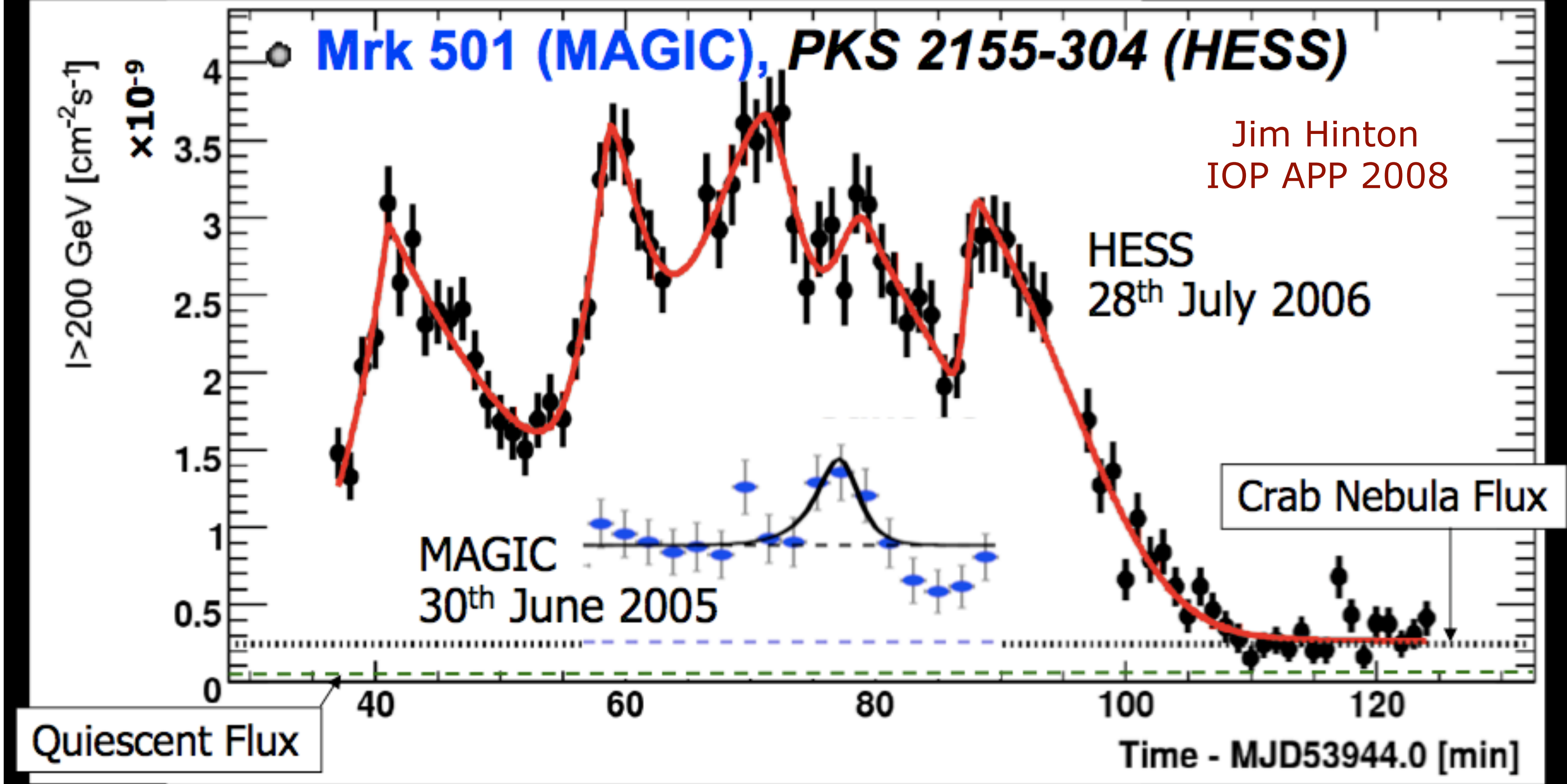
# Short term variability




- ***2 minute variability timescales***
  - *Very constraining for models, implies $\Gamma > 50$*
  - *can be used as a probe of fundamental physics: c(E)*

e.g. Begelmann, Fabian, Rees 2007

# Energy dept. morphology

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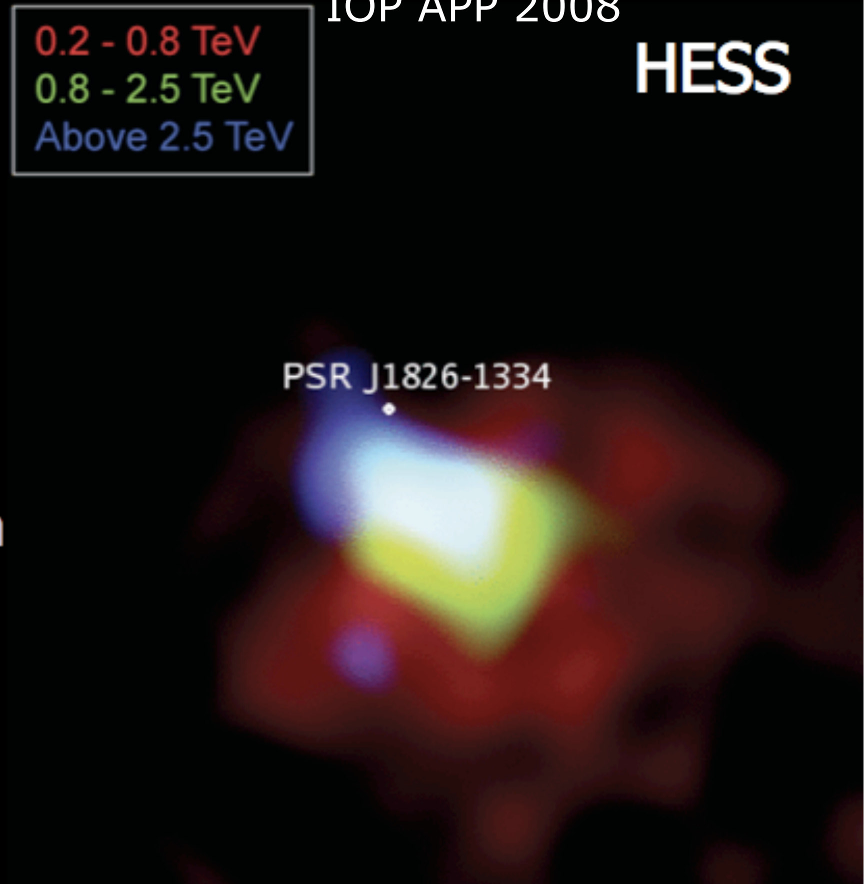
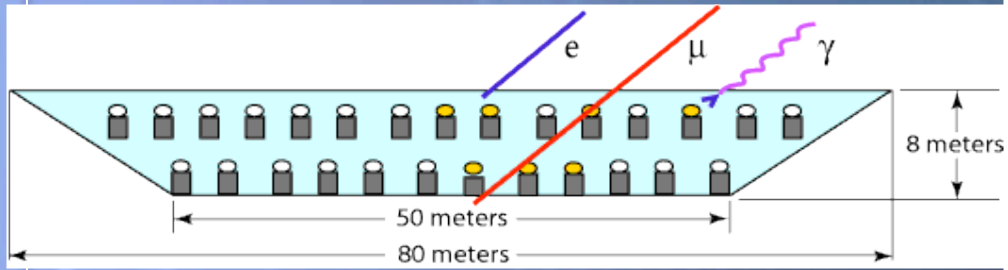
- **Large sources + good angular + energy resolution**
  - **Sensitivity to energy dep. Morph.**
- **First case: HESS J1825-137**
  - **PWN associated with energetic young pulsar PSR J1826-1334**
  - **Interpreted as IC emission from electrons "cooling" as they propagate away from pulsar? ($t_{cool} \propto 1/E$)**
- **In general**
  - **A lot of astrophysics can be probed, energy dep. of particle losses, *cosmic ray diffusion*…**



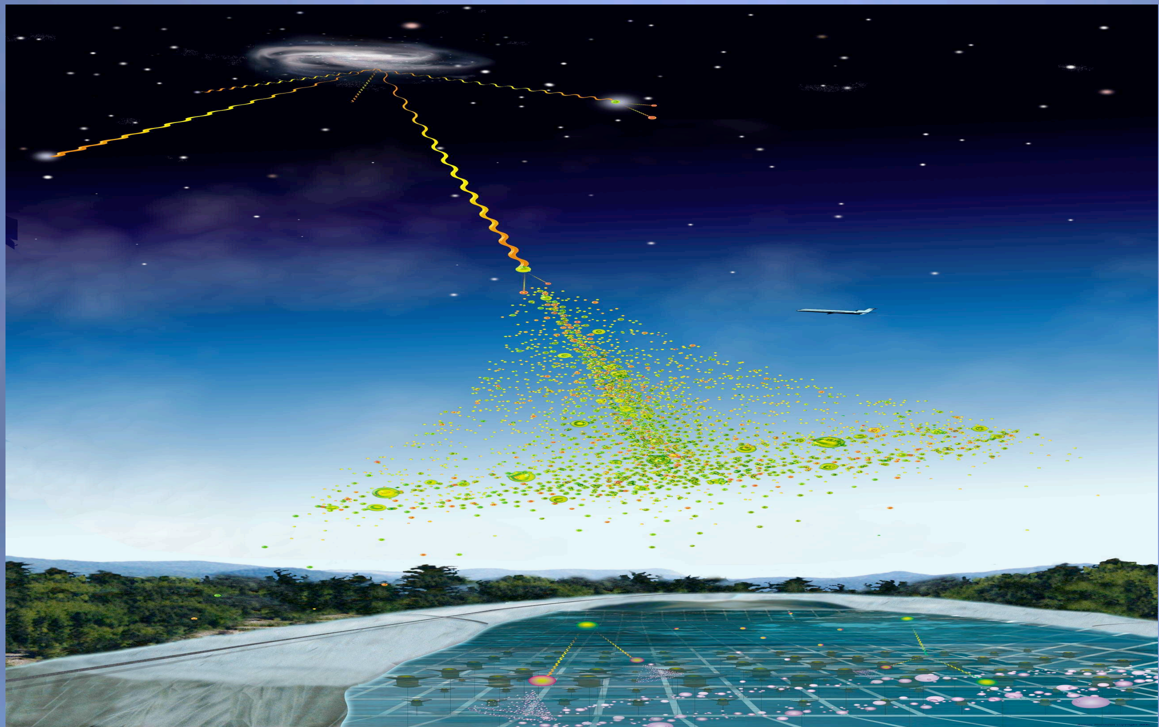

***→ Requires large area (statistics) and good angular resolution***

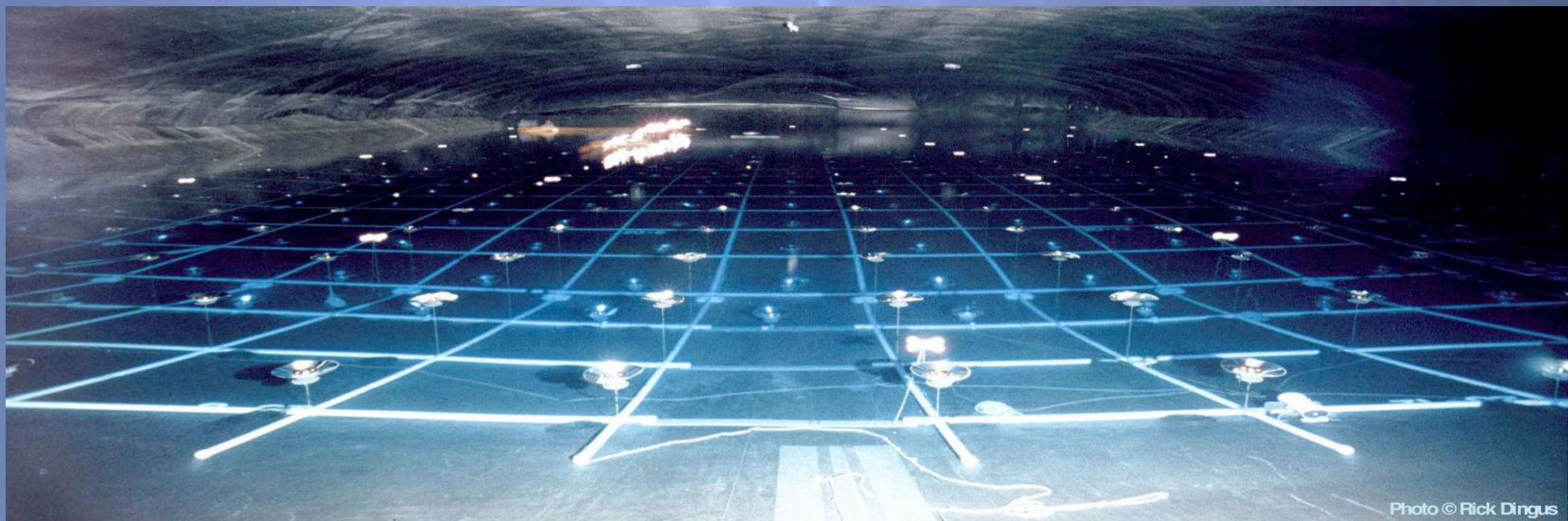
# MILAGRO

- A large area(50m x 80m x 8m) Cerenkov water tank at high altitude (2630m) in the Jemez mountains of New Mexico
- Many "out-rigger" tanks to increase coverage area to ~ 40000m$^2$
- Has continuous wide field coverage
- Sensitive to >TeV sources
- Transients to 100s of GeV

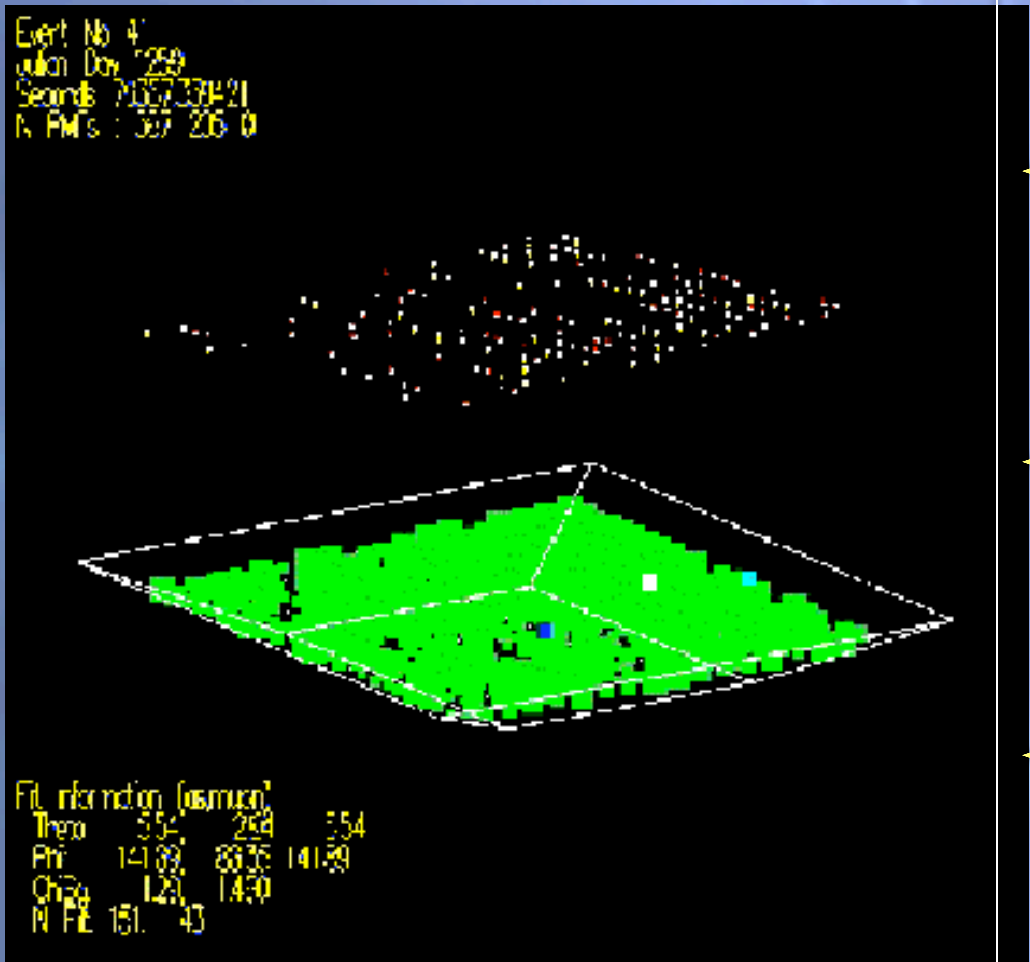



# MILAGRO



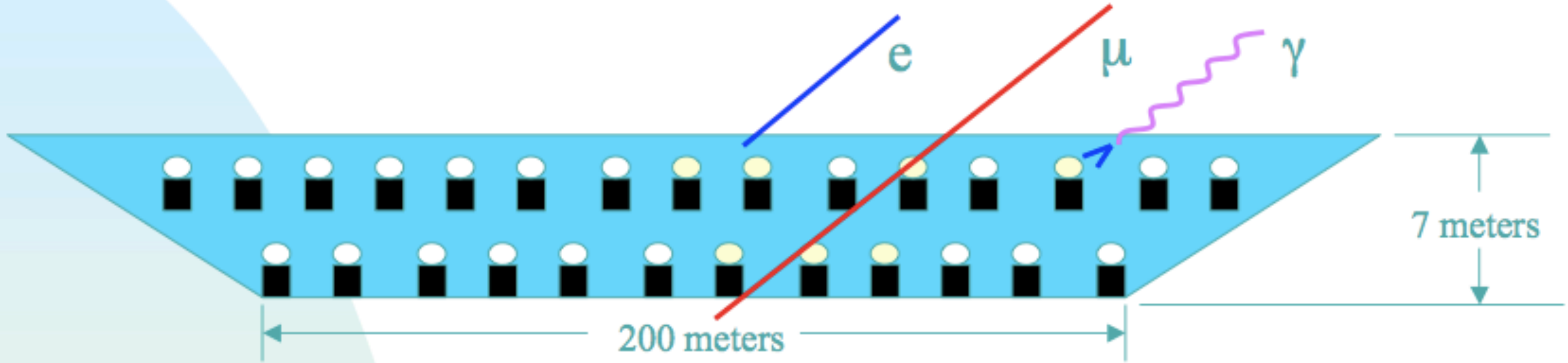


# MILAGRO event



- Visualization of an actual event as seen by MILAGRO
- The green boxes in the pond represent the amount of light received by each PMT
- The white dots hovering above the pond are the individual PMT arrival times fit to a plane
- This plane is a measurement of the front edge of the pancake of relativistic particles

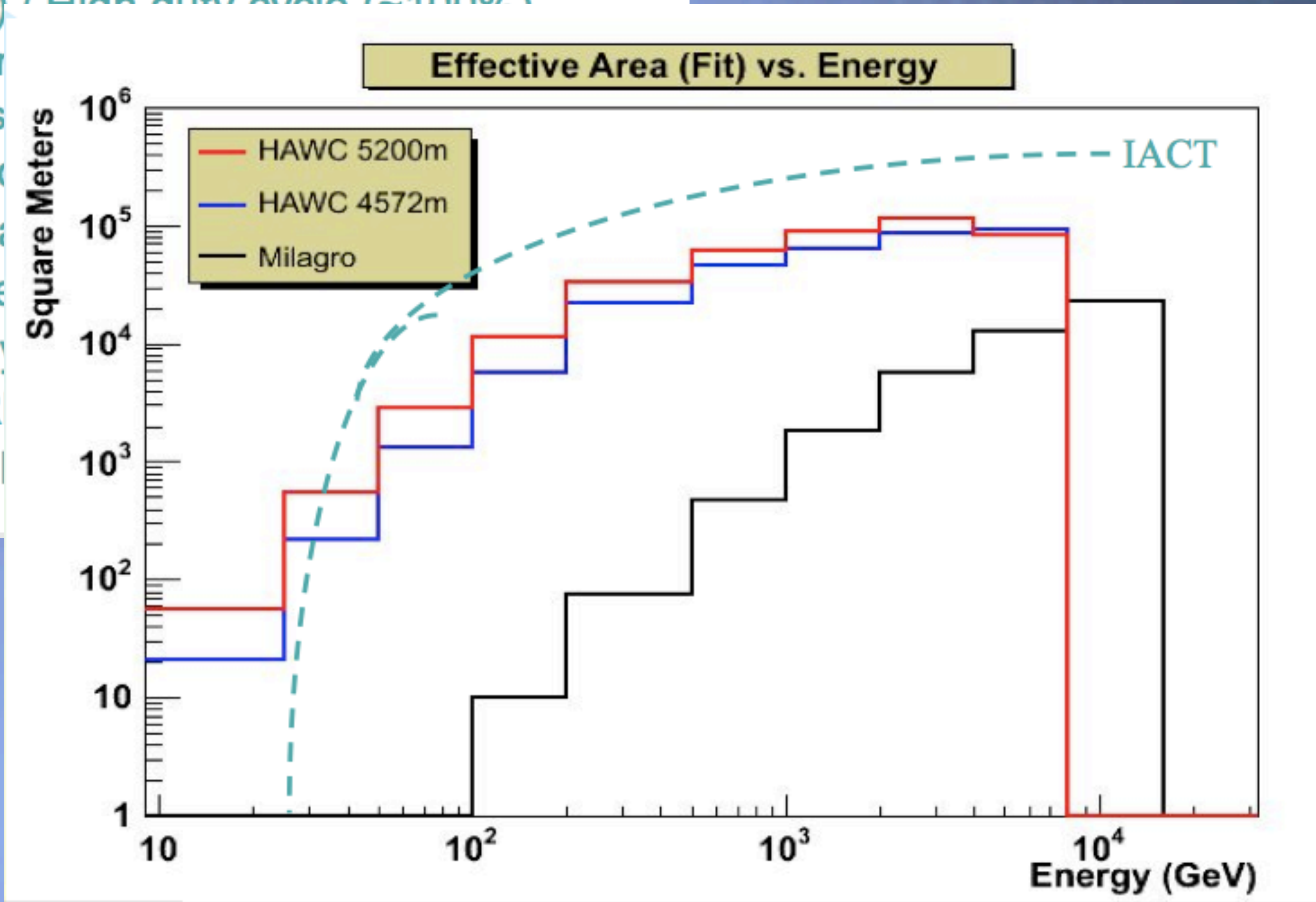
# Next generation - HAWC



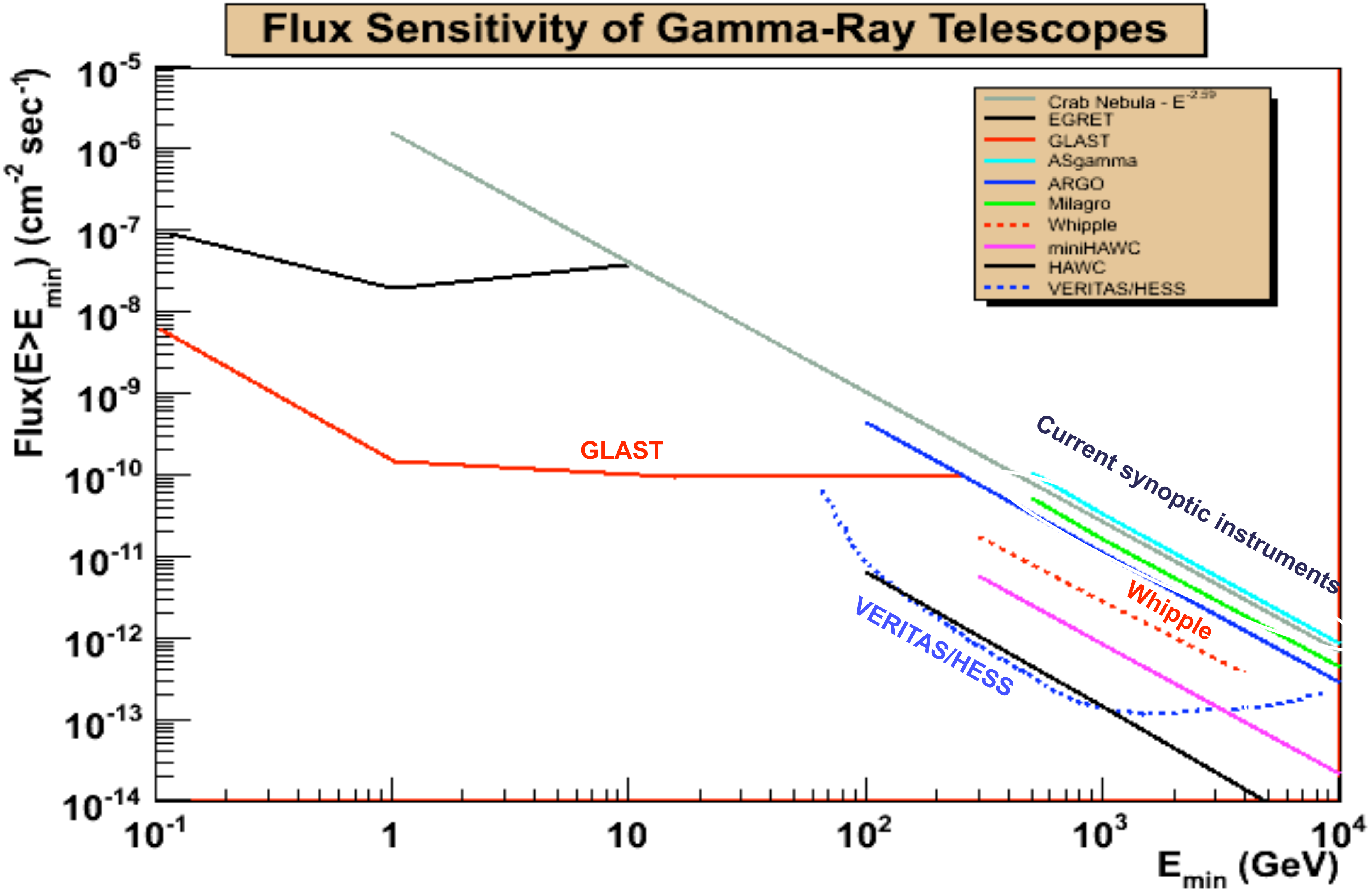

- 200m x 200m water Cherenkov detector
- Two layers of 8” PMTs on a 3 meter grid
  - Top layer under 1.5m water (trigger & angle)
  - Bottom layer under 6m water (energy & particle ID)
- Two altitudes investigated
  - 4500 m (Tibet, China)
  - 5200 m (Altacama desert Chile)

# HAWC

- Energy Threshold ~20 GeV
  - GRBs visible to redshift ~1
  - Near known GRB energy
  - AGN to redshift ~0.3
- Large fov (~2 sr)
  - GRBs pro
  - AGN trans
- Large Area / Go
  - High signal r
  - Ability to dete
- Moderate Energy
  - Measure GR
  - Measure AG



# Overall Performances



# Extending the Low Energy Domain

- Image quality is limited by the number of photons and air shower fluctuation

- Increase photo-collection efficiency x ~30
  - Increase telescope density (gain x 4)
    - ~100m spacing → ~50m spacing
  - Increase telescope diameter (gain x 3)
    - 12m-17m φ → 20-30m φ
  - Increase Q.E. of photo-detectors (gain x 3)
    - Q.E. 20% → 60-80%
    - (Current status HPD 53%, SiPM ~40%)

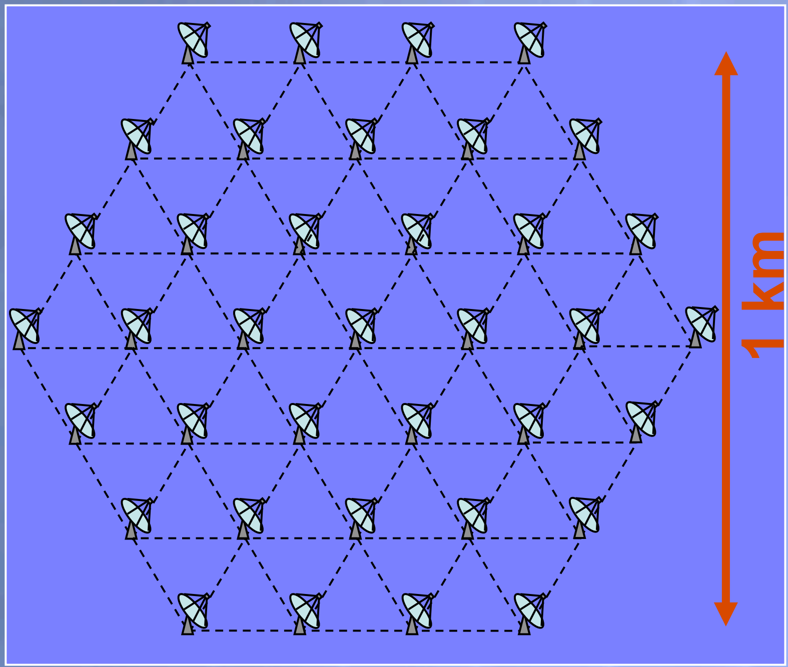
- Photon sampling rate: HESS, MAGIC, VERITAS ~ 1/1000
- Photon sampling rate in CTA can be ~1/30 (10% mirror area, 50% Q.E.)
- Significant improvement in data quality is expected

# Extending the High Energy Limit

- Statistics limits the sensitivity (>100km$^2$hr)
- Two major possibilities
  - Large array of small IACTs (~100 IACTs over a few km$^2$ area)
  - HAWC or HAWC-II (wide angle, non-bias all sky survey)
  - Both are complimentary

IACT PARAMETERS
Mirror 18 m2
F/D≈ 1,2-1.4
Camera FOV: 5-7°
Pixels 0.25°
Pmts: hemispherical
32%QE at 400 nm
500 Mhz ringsampling FADC
Threshold 250-300 GeV
Cost/telescope < 200 k€
Construction ≈ as HEGRA IAC

**CTA-HE(ULTRA), HE-ASTRO, GRATIS**




**HAWC, HAWC-II: High Altitude at 4000~5000m**

# The future?

- **Two major efforts beyond HESS-2, MAGIC-2:**
- **CTA (Europe) and AGIS (US)**
  - ***Both* have base-line designs with ≥ 50 telescopes**
  - ***Both* aim for ~1 order of magnitude sensitivity improvement**
  - ***Both* aim for substantial (>factor 2) improvement in angular resolution**
  - ***Both* aim for a *core* energy range 0.1-10 TeV**
- **But there are differences!**

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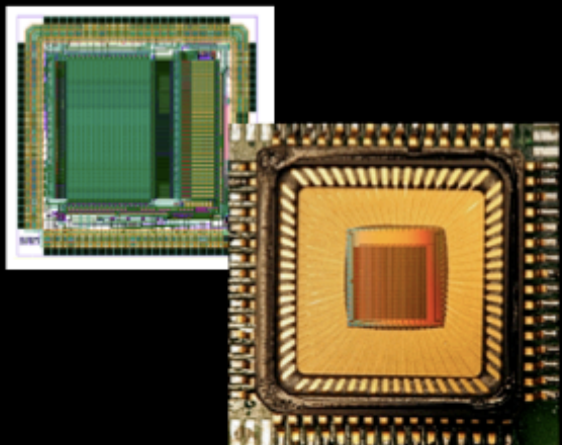
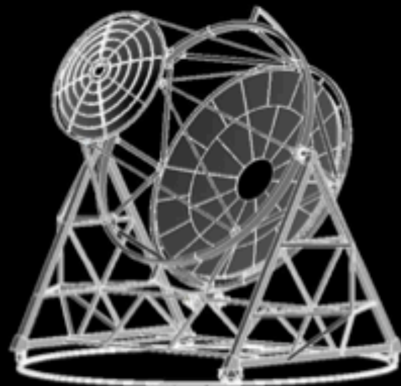
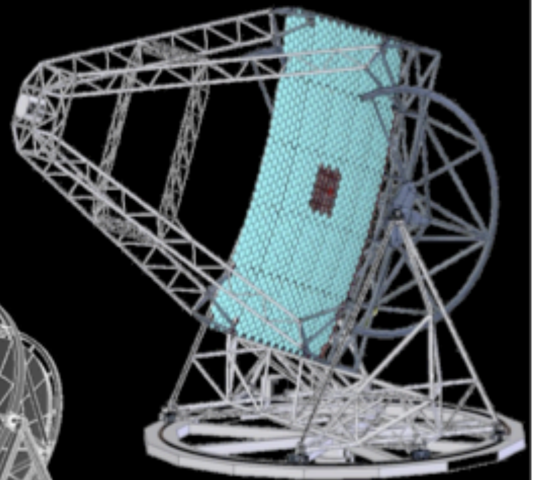




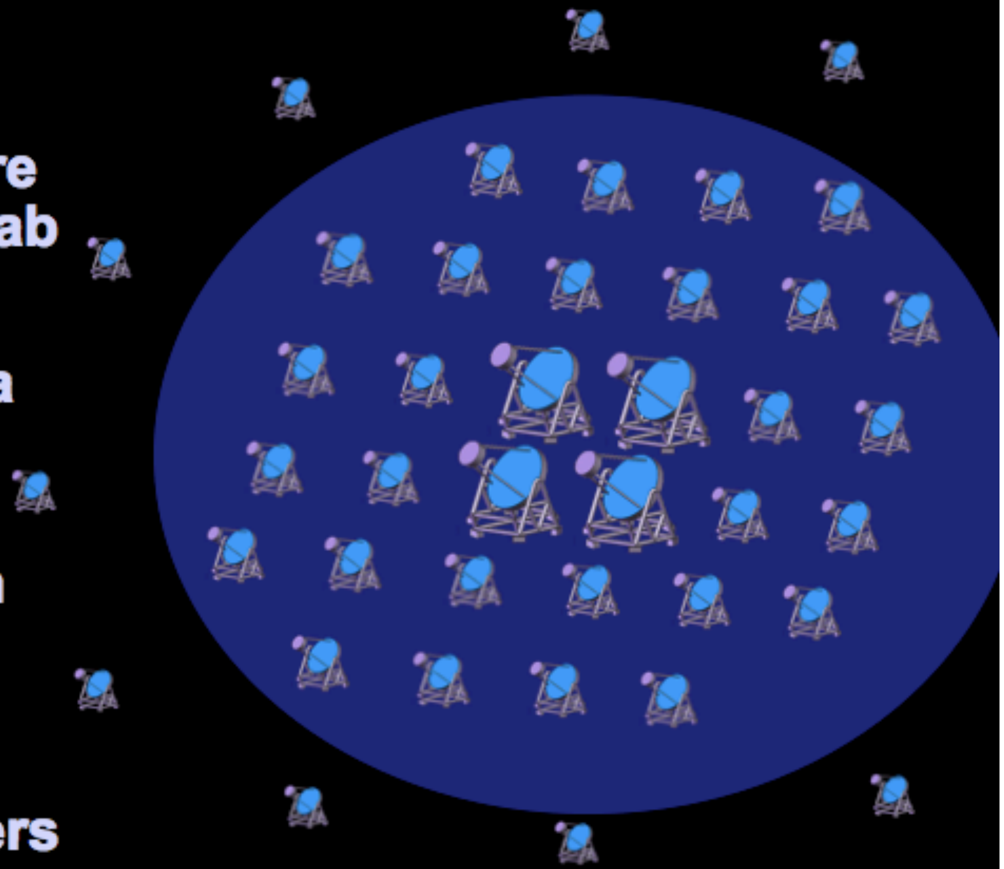


# The future?

- **Concept**
  - **An IACT array *observatory***
  - **one order of magnitude more sensitive than HESS: 1 mCrab**
  - **wide energy coverage:**

**~0.03-100 TeV, achieved with a mixture of telescope sizes, spacings**

  - **sites in the North and South**
- **Consortium**
  - **European Led**
  - **HESS + MAGIC + many others**
  - **15 countries currently involved**



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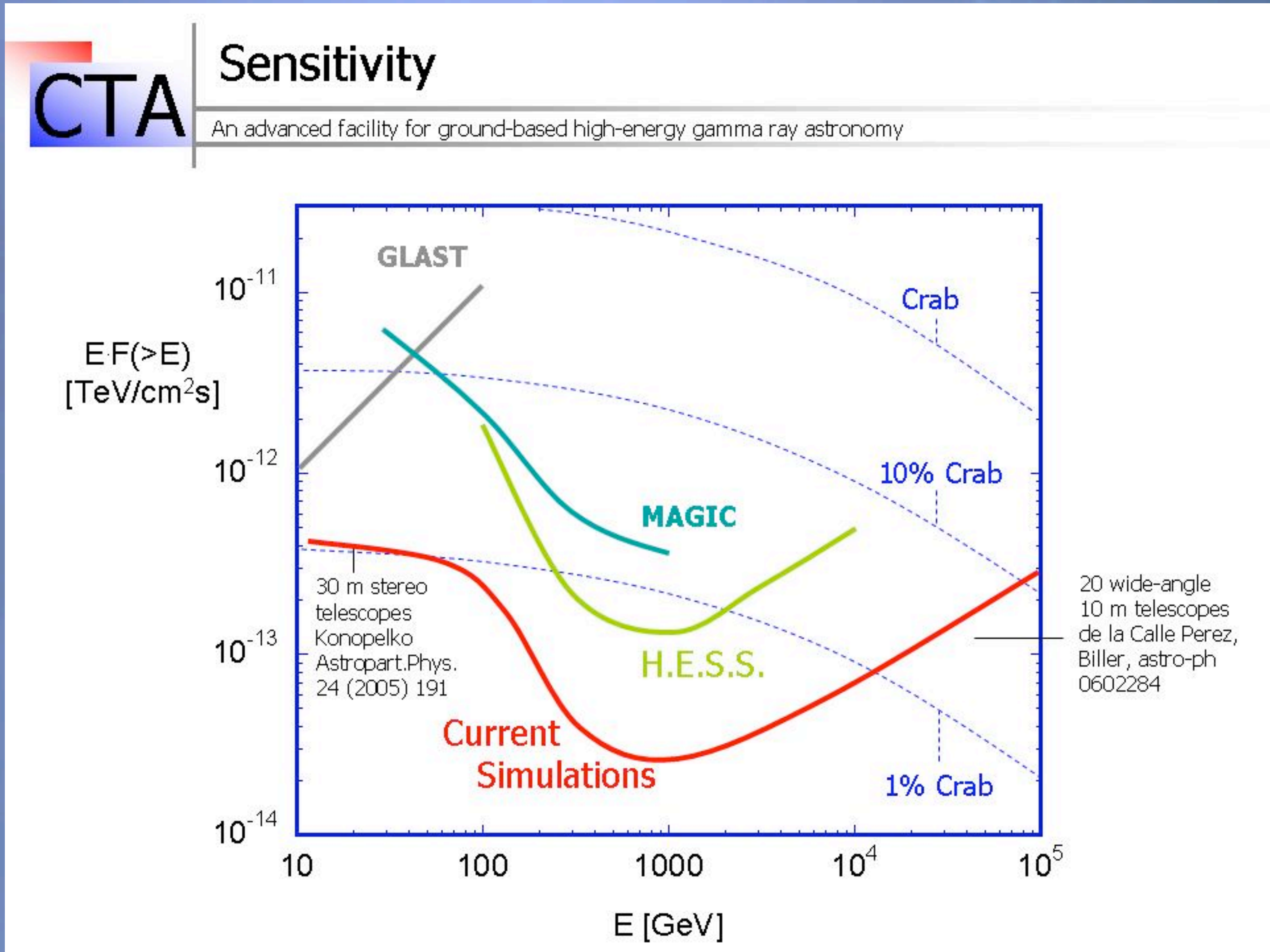
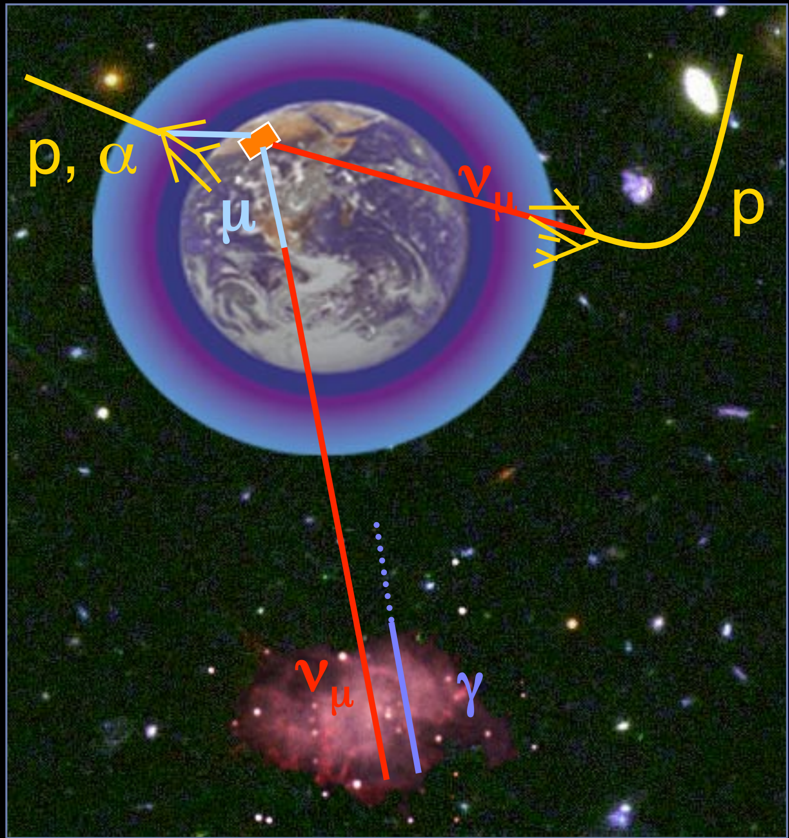
# The future?


CTA
Sensitivity
An advanced facility for ground-based high-energy gamma ray astronomy
GLAST
E·F(>E)
[TeV/cm2s]
10-11
10-12
10-13
10-14
Crab
10% Crab
1% Crab
MAGIC
H.E.S.S.
Current
Simulations
30 m stereo
telescopes
Konopelko
Astropart.Phys.
24 (2005) 191
20 wide-angle
10 m telescopes
de la Calle Perez,
Biller, astro-ph
0602284
10
100
1000
10^4
10^5
E [GeV]

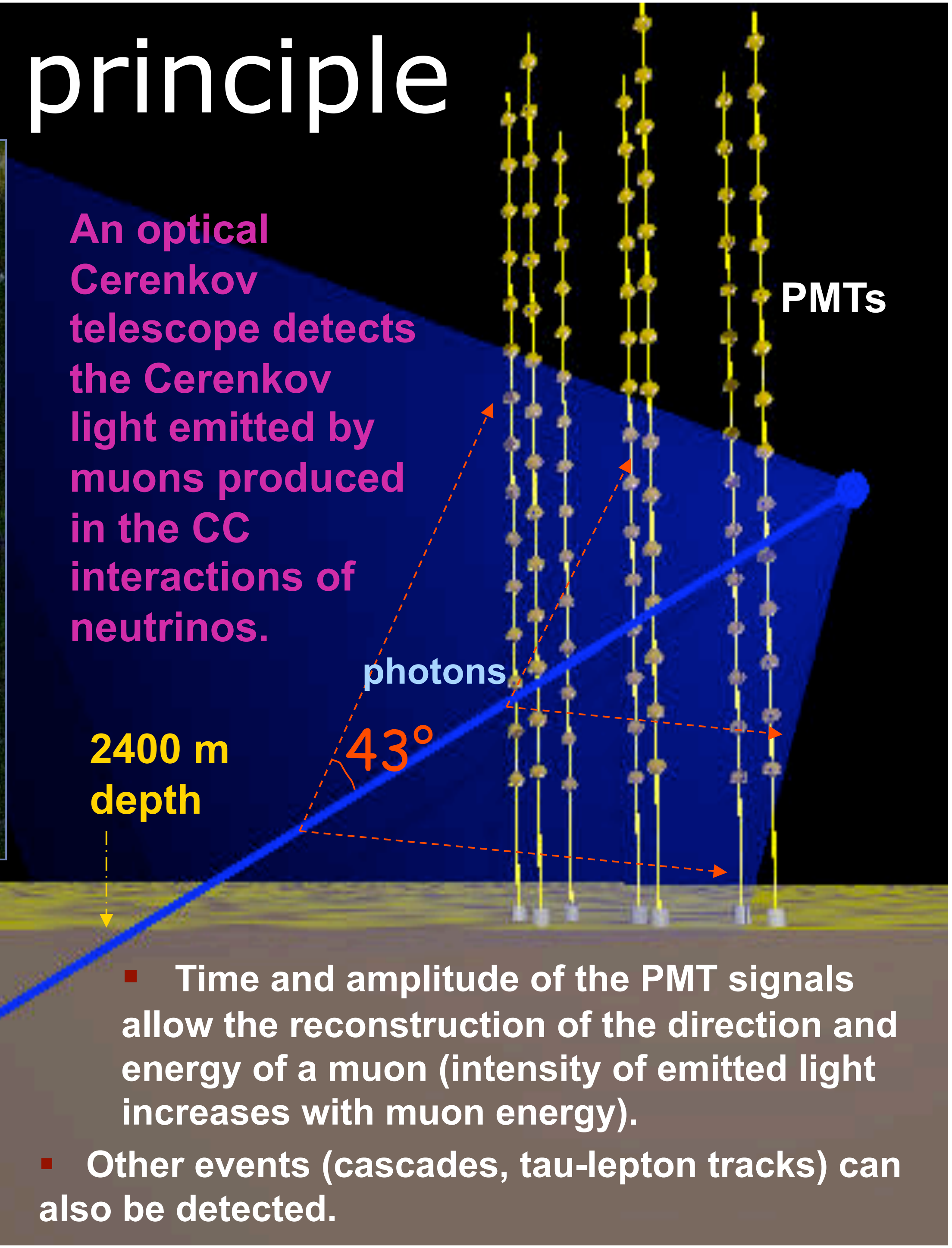
# HE neutrino detection

- We now turn our attention to higher energy neutrinos (typically in the GeV-TeV scale)
- Here the detection principle is different
  - Neutrino cross-sections are low so huge effective volume detectors are needed - economically impossible to do with a man-made "container"
  - Therefore a natural medium is needed which
    - Produces C photons efficiently
    - Allows those photons to be detected
  - Both water and ice are suitable media

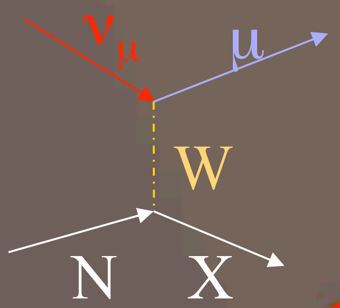
# Detection principle




An optical Cerenkov telescope detects the Cerenkov light emitted by muons produced in the CC interactions of neutrinos.

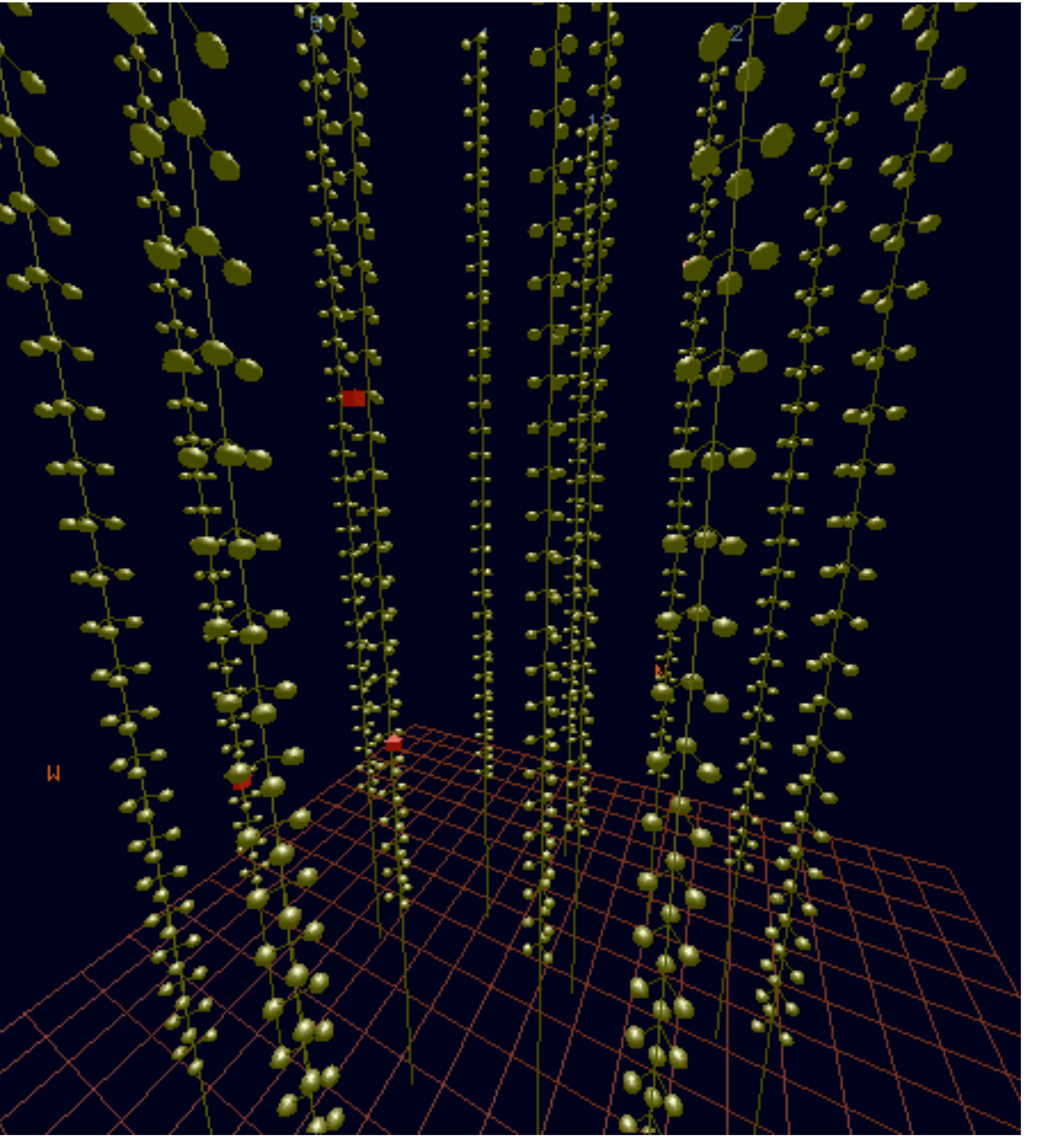



**Both $\sigma_{\nu N}$ & μ range $\propto E_\nu$**




- Time and amplitude of the PMT signals allow the reconstruction of the direction and energy of a muon (intensity of emitted light increases with muon energy).
- Other events (cascades, tau-lepton tracks) can also be detected.

A simulated ANTARES event showing the muon trajectory, Cerenkov light rays and PMT hits

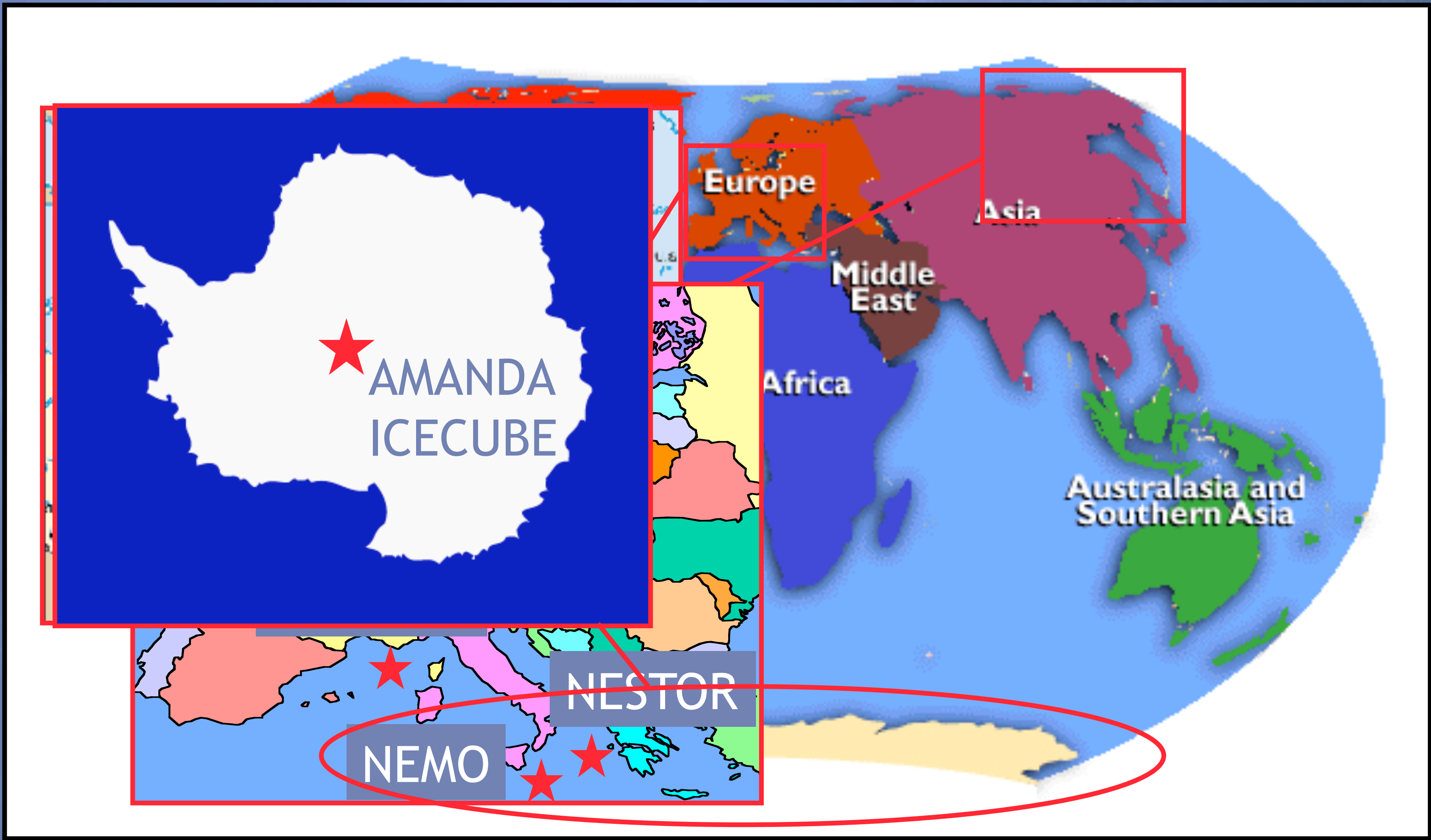


# What are the issues when designing a neutrino telescope?

- Optical properties of the detection medium:
  - Absorption
  - Scattering

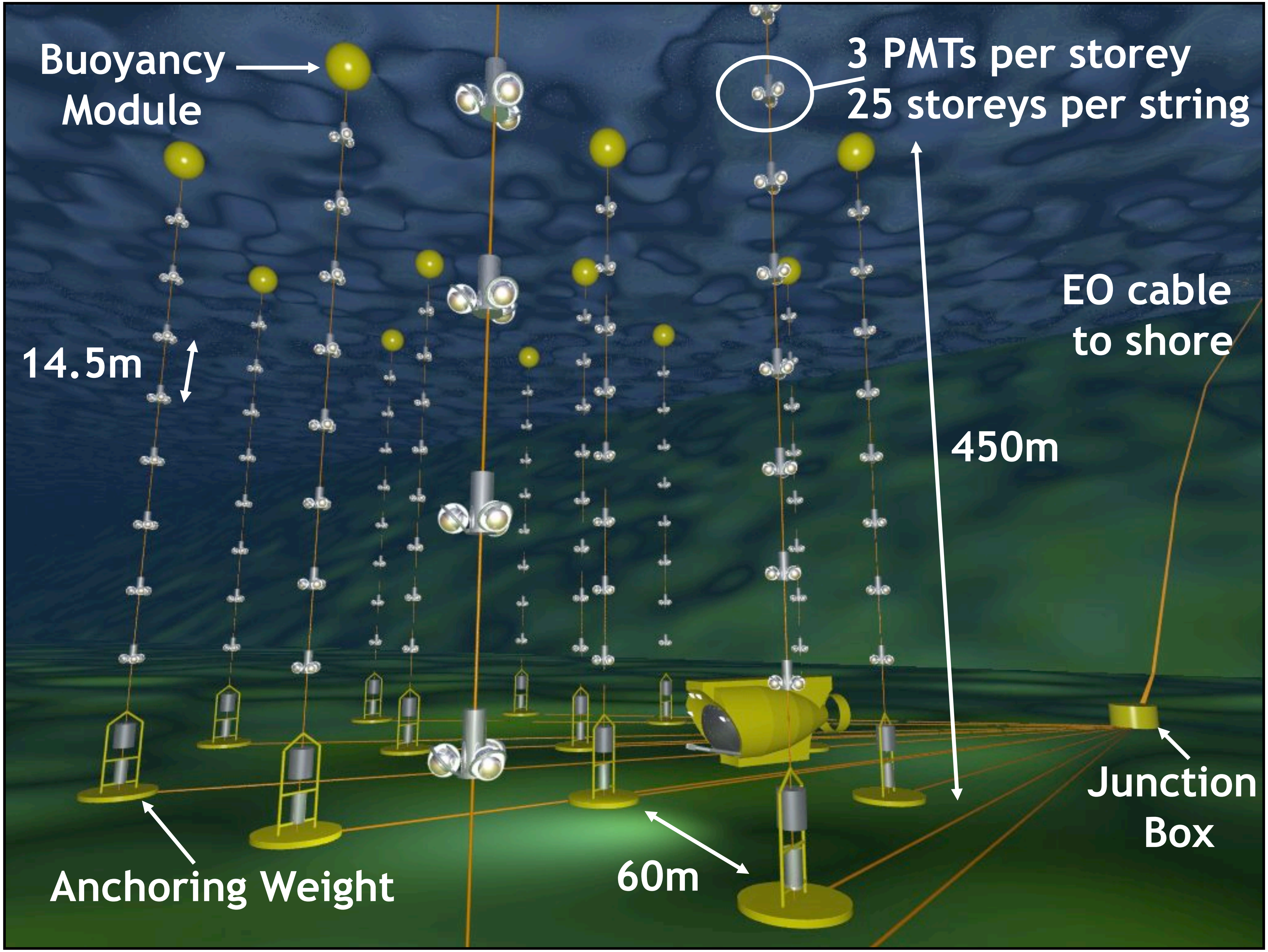
  … these ultimately determine the performance of the detector (effective area, pointing accuracy) and dictate the economics of the venture (e.g. photosensor spacing)
- Optical backgrounds
  - Bioluminescence
  - Potassium-40
- Attenuation of C photons elsewhere
  - Biofouling

# Current projects

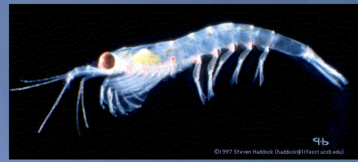


# Media Comparison

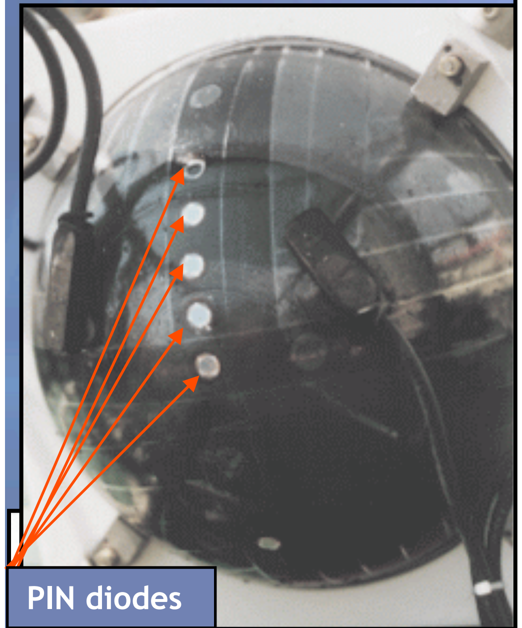
| Ice (AMANDA, ICECUBE) | Sea Water (ANTARES, NEMO, NESTOR, KM3NeT) | Fresh Water (Baikal) |
|---|---|---|
| Long absorption length (fewer PMTs required) | Short absorption length (more expensive) | Unlike ice the absorption length is short: (22±2m) |
| Short scattering length - poor angular resolution | Very long scattering length (>~200m) | Scattering length is (16 ÷ 70)m at 490nm |
| No Potassium-40 present - low noise environment | Potassium-40 present | Little Potassium-40 present - low noise environment |
| No bioluminescence | Bioluminescent burst activity observed and understood | No bioluminescence |
| No repair of detector components possible | Surfacing, repair and re-deployment of strings possible | As for sea water during summer months |

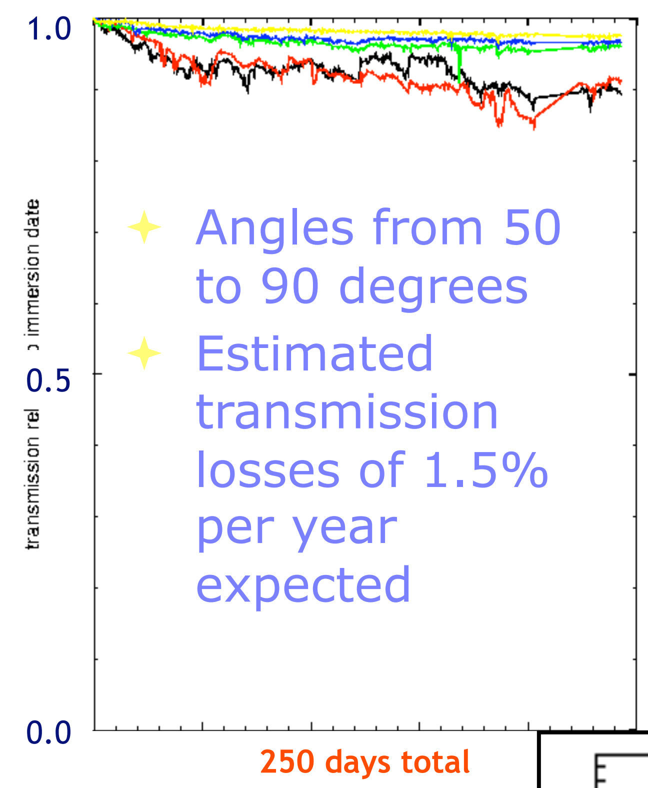

Buoyancy Module
3 PMTs per storey
25 storeys per string
EO cable to shore
14.5m
450m
Junction Box
Anchoring Weight
60m

# Site Evaluation

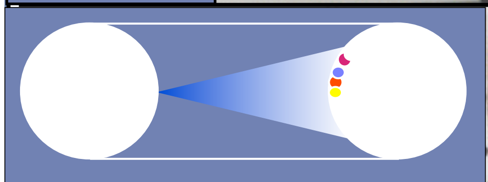


## Sedimentation Biofouling



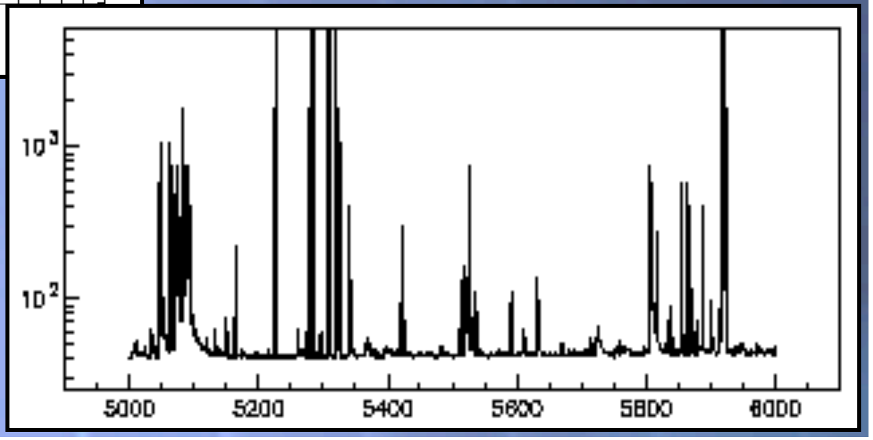




- Angles from 50 to 90 degrees
- Estimated transmission losses of 1.5% per year expected

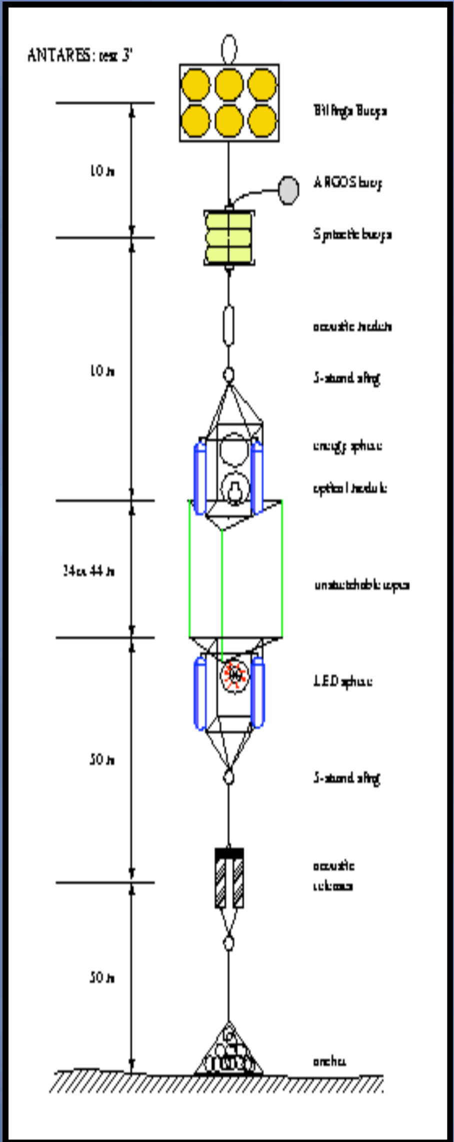


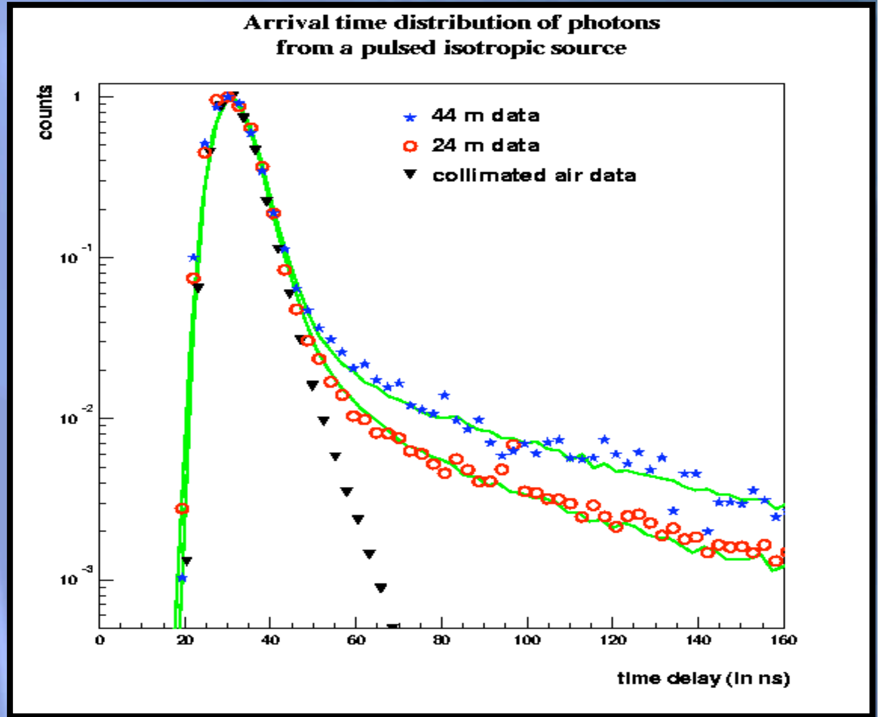
## Optical Backgrounds

- Typical time profile of single hits on a PMT at 0.3 photo-electron threshold
- Observed background activity shows two distinct components with respect to time:
  1. continuous (slowly varying)
  2. burst regime: bioluminescence from fish, bacteria.
- Optical background rate due to $^{40}K$ is constant and is typically 40kHz (8” PMT) to 60kHz (10” PMT)

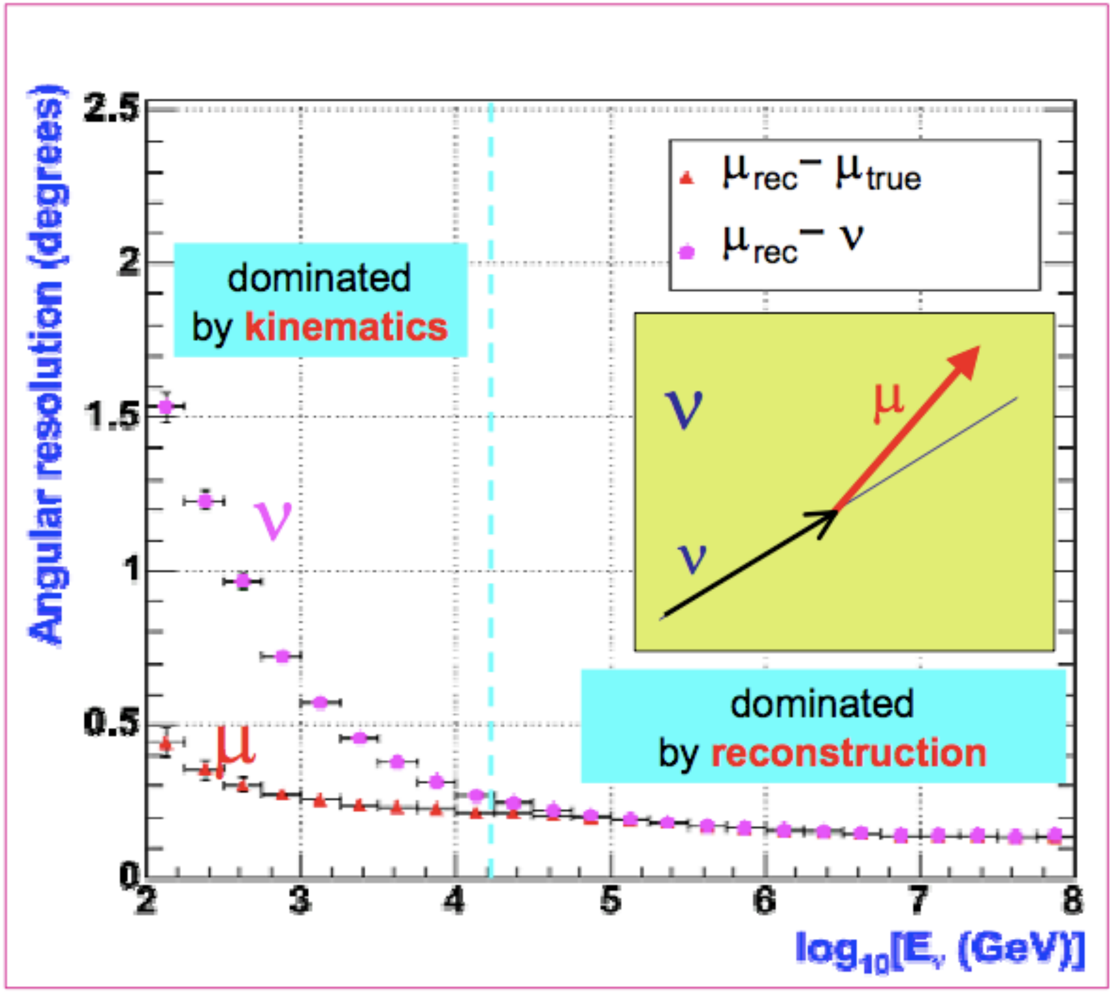


# Water Quality



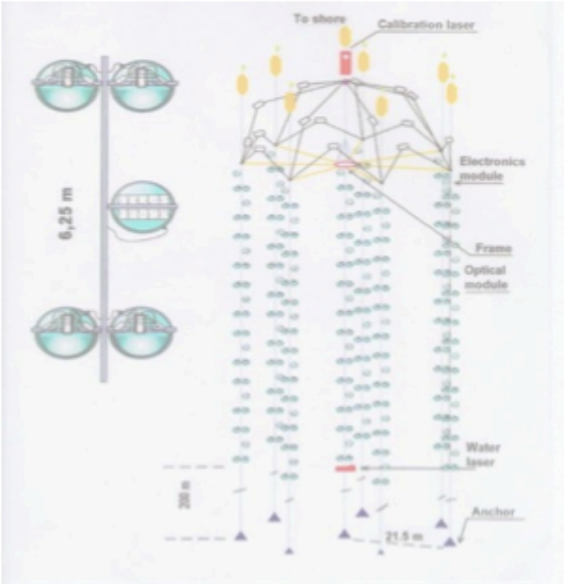



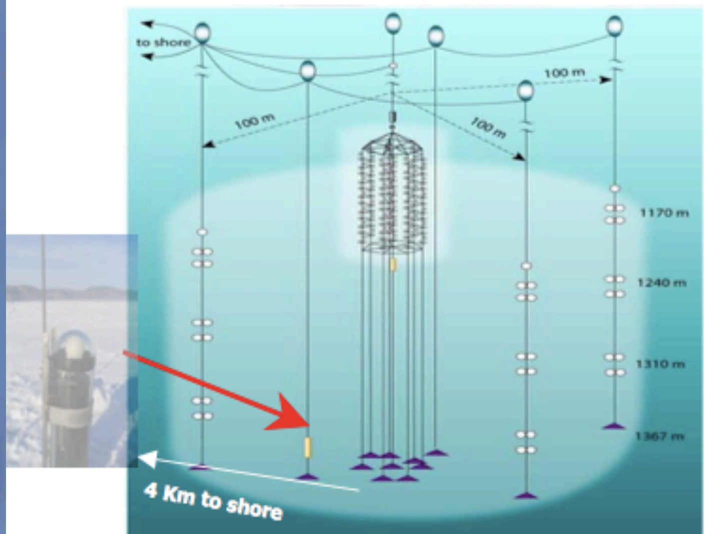
# Angular Resolution




At 100 TeV: Amanda ~2°
Antares ~ 0.2°

# Lake Baikal




**NT200** *running since 1998*

- 8 strings with 192 optical modules
- 72m height, R=20m, 1070m depth, $V_{geo}$=0.1Mton
- $\mu$ effective area: >2000 $m^2$ ($E_\mu$>1 TeV)
- Shower Eff Volume: ~1 Mton at 1 PeV

**NT200+** *commissioned April 9, 2005*

- 3 new strings, 200 m height, 36 OMs
- 1 new bright Laser for time calibration
  imitation of 10 PeV-500 PeV cascades,
  >10^13 photons/pulse w/ diffusor, ← **SNO-Calib**
- 2 new 4km cables to shore
- DAQ – New Underwater & Shore Station: Underwater Linux embedded PCs, Industrial Ethernet Systems

NT200+ is tailored to UHE $\nu$-induced cascades

- 5 Mton equipped volume
- Veff >10 Mton at 10 PeV

→ 4fold sensitivity gain with only 20% additional PMTS

# Lake Baikal - Future Plans

Sparse instrumentation:

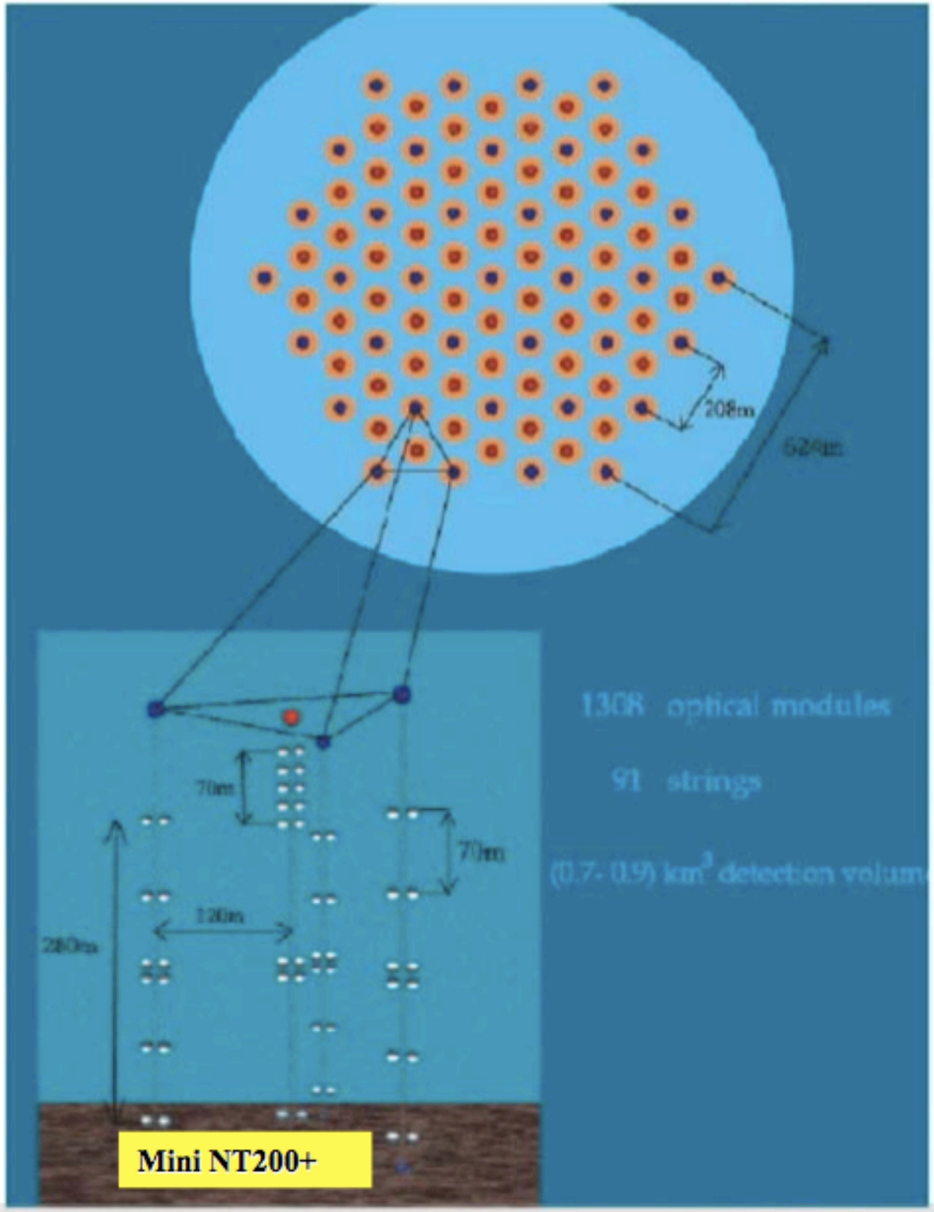
91 strings with 12/16 OM = 1308 OMs

→ Casacde effective volume for 100 TeV: ~ 0.5 -1.0 km$^3$

→ Muon threshold between 10 and 100 TeV

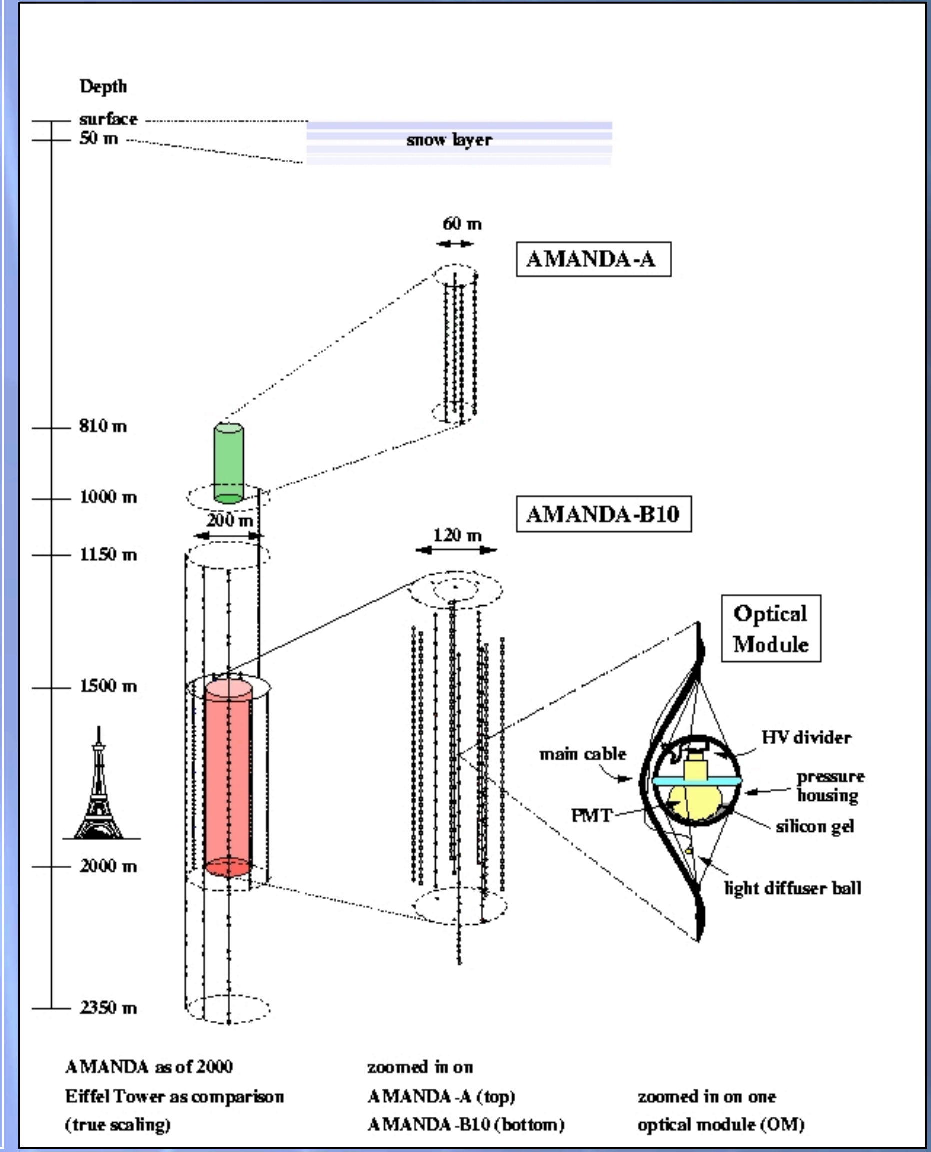
Baseline schedule:

- R&D +TDR 2006-08. Funded.
- Construction ≥2009.

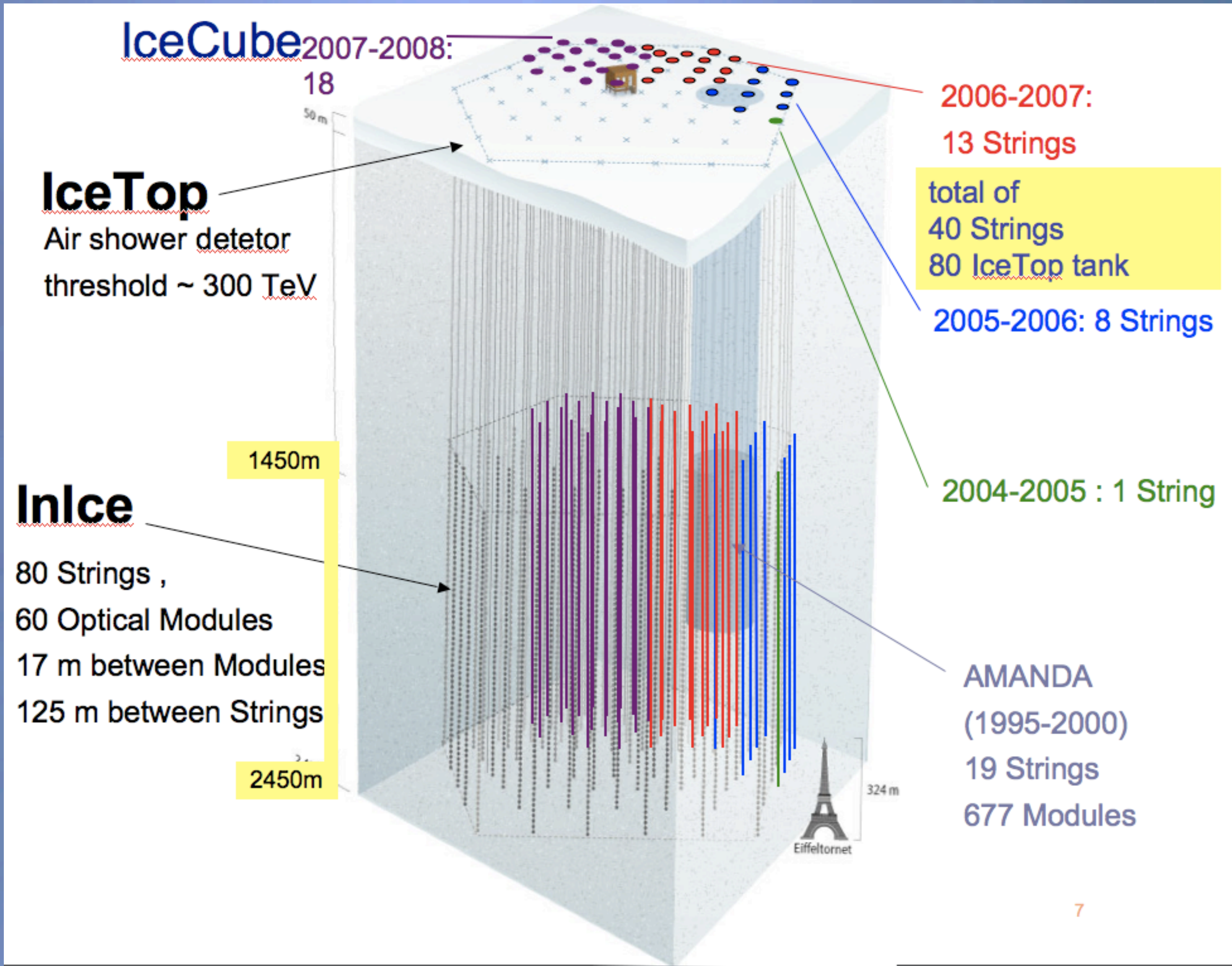


# AMANDA

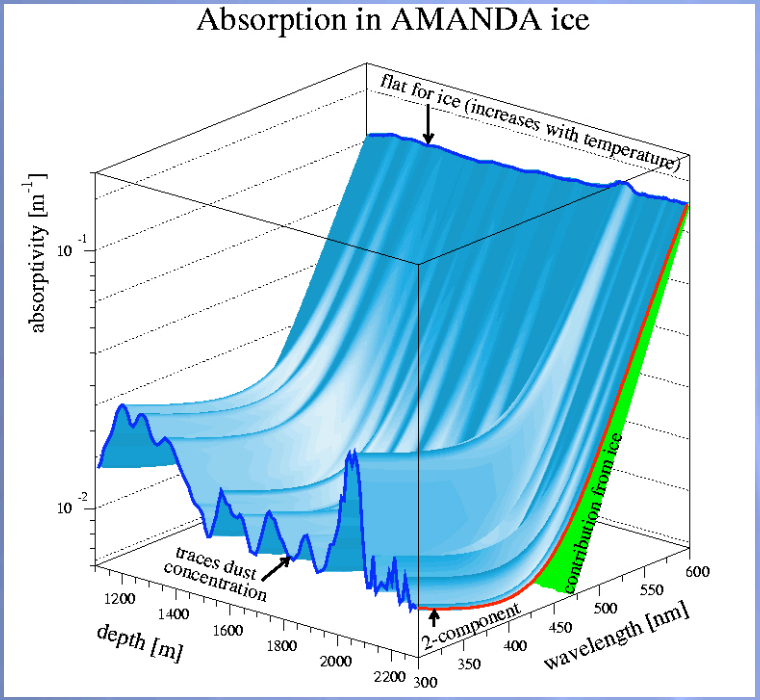
- 677 analog OMs deployed along 19 strings
  - 10 strings 1997 (AMANDA B10)
  - 3 strings 1998 (AMANDA B13)
  - 6 strings 2000 (AMANDA II)
- Analog PMT signals using electrical and optical transmission lines.
- 200 m diameter, 500 metres height; AMANDA II encompasses 20 Mton instrumented ice volume.
- AMANDA will remain operational and form IceCube *Inner Core Detector* for low E physics (~ 100 GeV)
- IceCube surrounding strings provide effective veto – lower background and can push AMANDA energy threshold down.
- Conventional TDC / ADC technology for AMANDA has been entirely replaced by TWR system.
- Beginning 2007 season, AMANDA / IceCube data streams were be conjoined; detector subsystems will share trigger information.

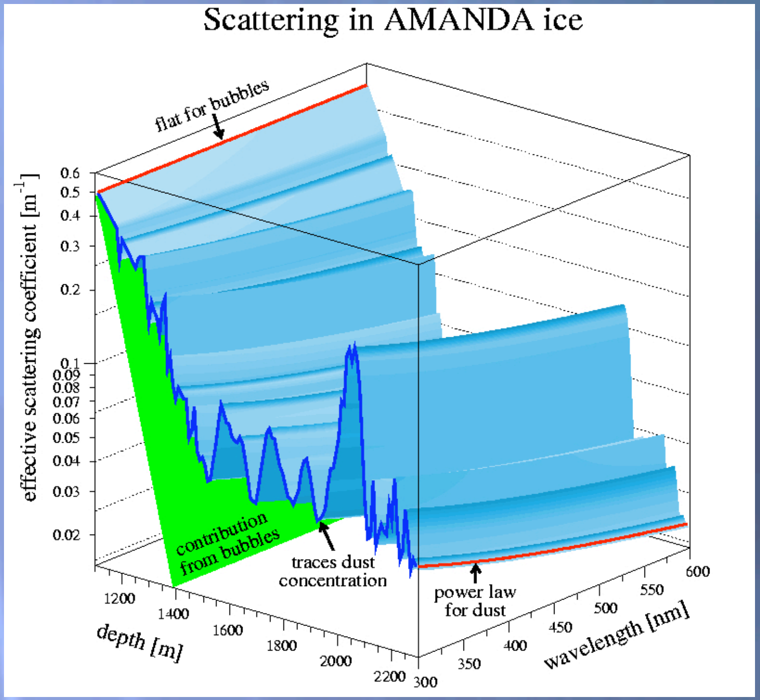


# ICECUBE


IceCube2007-2008:
18
2006-2007:
13 Strings
total of
40 Strings
80 IceTop tank
2005-2006: 8 Strings
IceTop
Air shower detetor
threshold ~ 300 TeV
1450m
InIce
80 Strings ,
60 Optical Modules
17 m between Modules
125 m between Strings
2450m
2004-2005 : 1 String
AMANDA
(1995-2000)
19 Strings
677 Modules
324 m
Eiffeltornet
7

# Medium Properties (again)

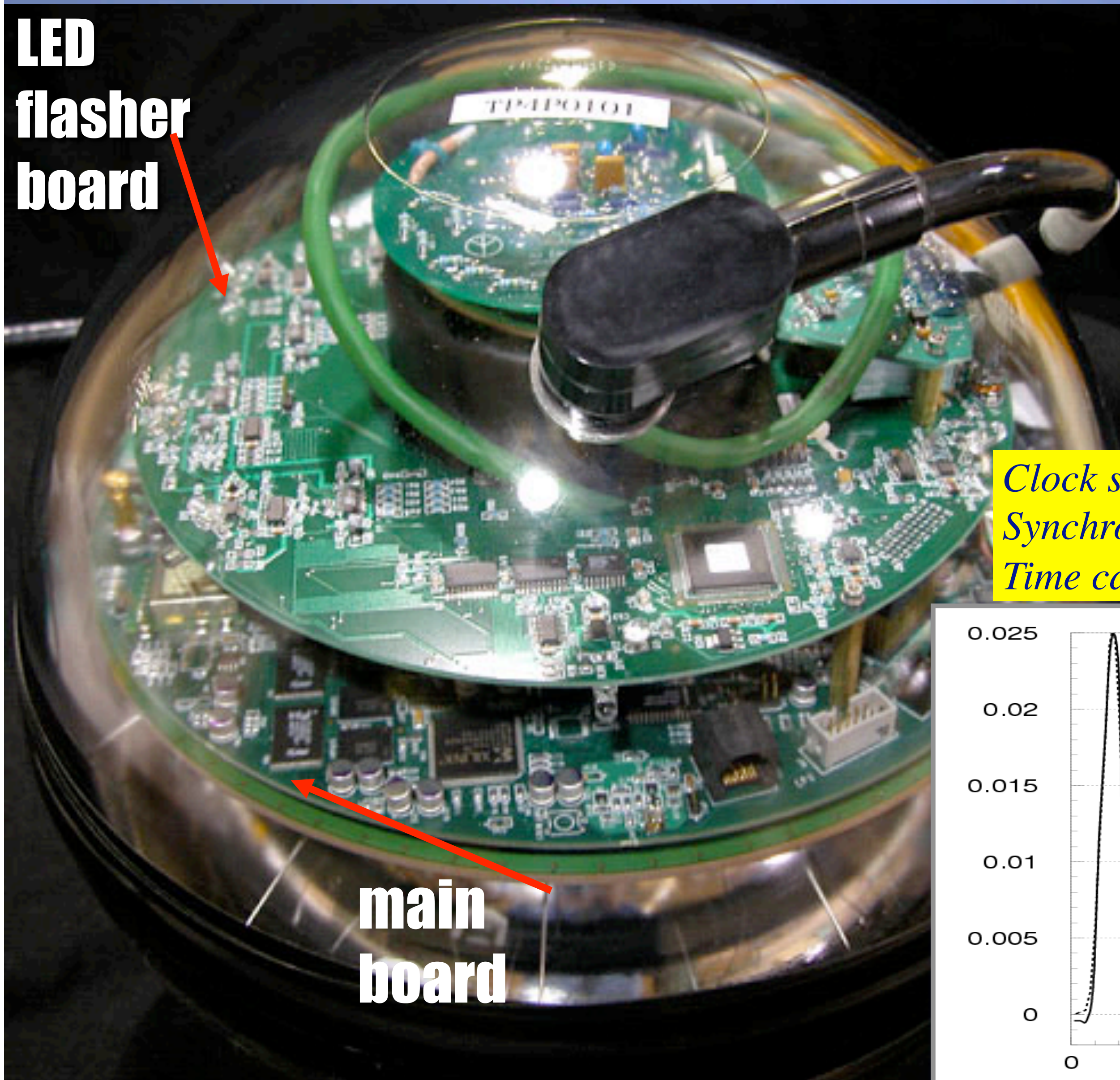



Why deploy in ice? Deep glacial ice is optically transparent. Two mechanisms: scattering length ~ 20 m, absorption ~ O(100) m. Ice has several layers of dust from prehistoric events. Monte Carlo detector simulation must account for this. Reconstruction methods involving maximum likelihood tests against hypotheses have been developed to overcome difficulties posed by photon scattering.

Plots above from *in situ* measurements using artificial light sources in AMANDA. “Hole ice” around deployed modules must also be taken into account.

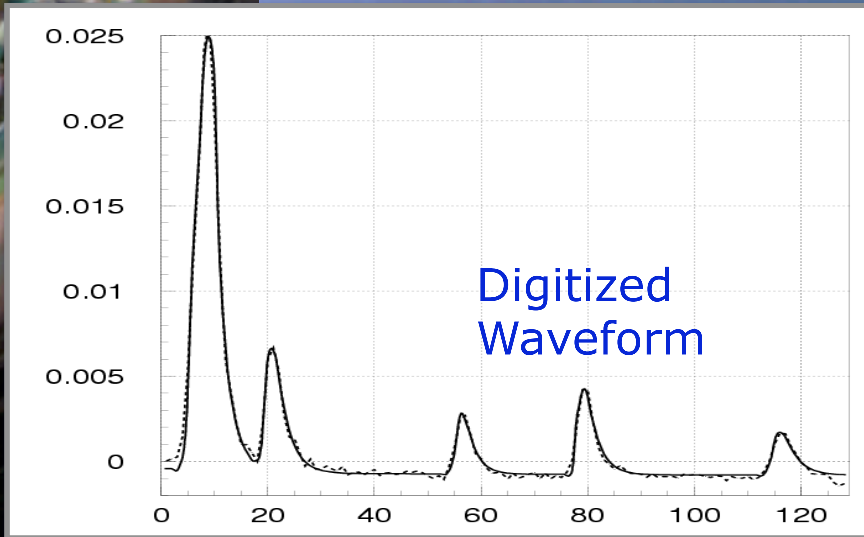
# ICECUBE Digital OM




PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 μs with fast ADC
Dynamic range 500pe/15 nsec

Send all data to surface over copper
2 sensors/twisted pair.
Flasherboard with 12 LEDs
Local HV

*Clock stability: $10^{-10} \approx 0.1$ nsec / sec*
*Synchronized to GPS time every $\approx$10 sec*
*Time calibration resolution = 2 nsec*

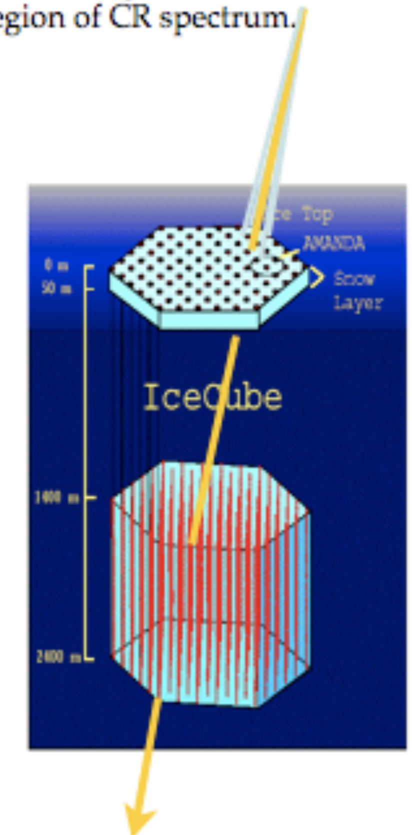


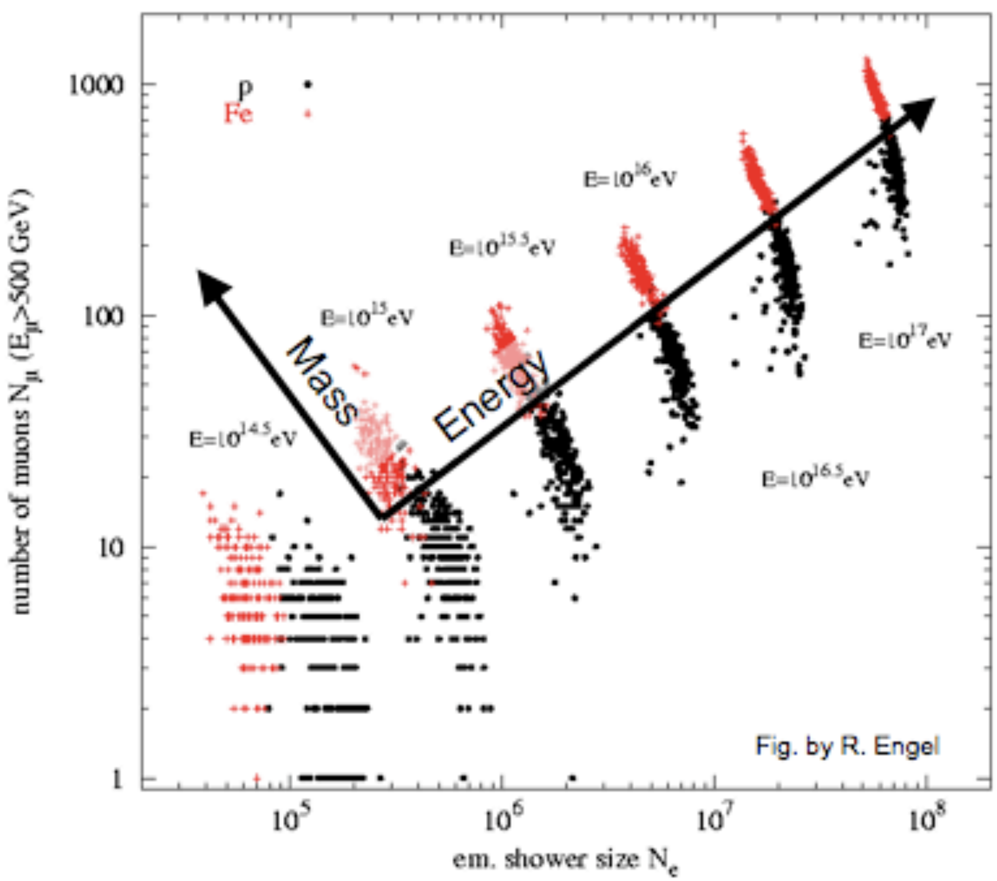
# ICETOP

# ICECUBE+ICETOP=CRs

Deep-ice array + IceTop form 3D airshower detector with 0.3 km²·sr acceptance – very powerful combination for cosmic ray physics.

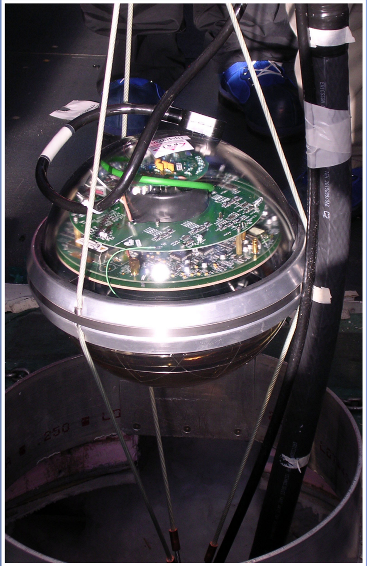
South Pole altitude near shower max for 10 PeV primaries – almost perfect placement from standpoint of minimizing fluctuations in "knee" region of CR spectrum.

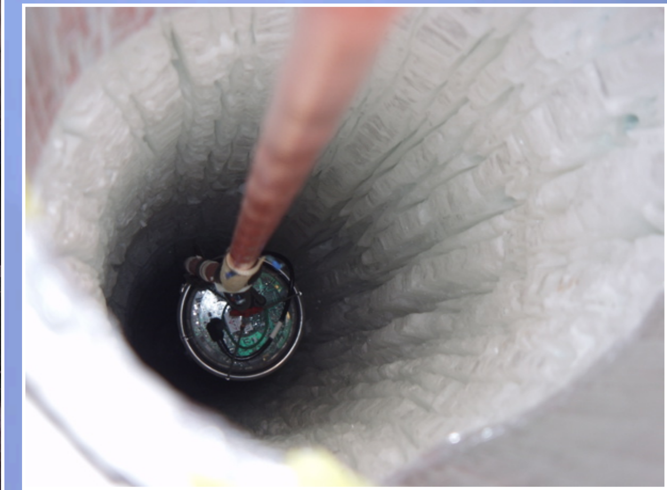


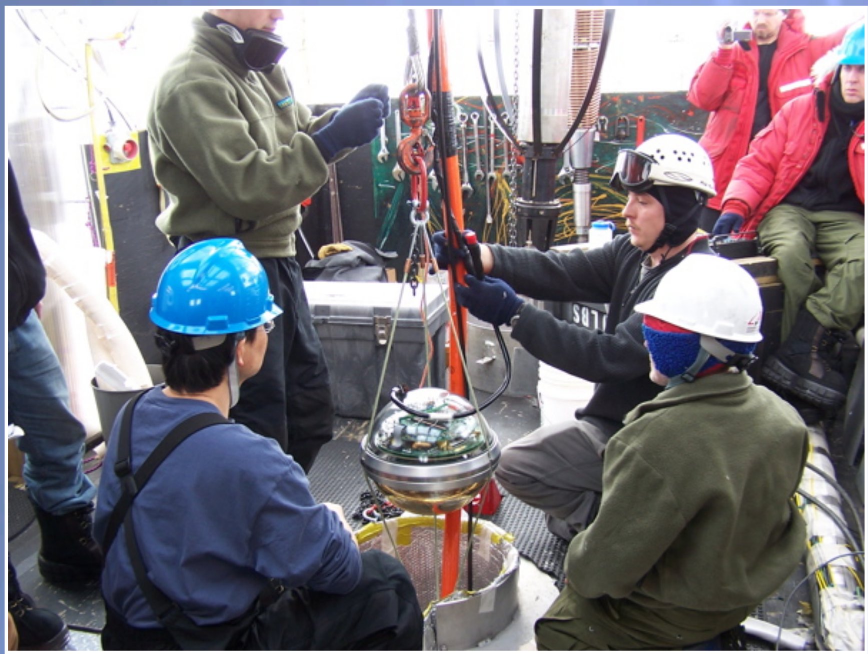



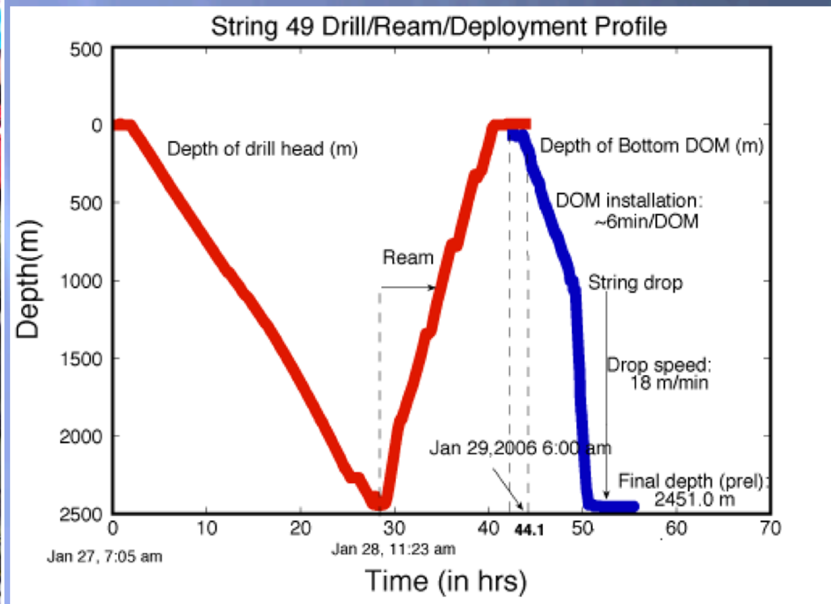

As shown in plot above Z, $E_{CR}$ by simultaneous measurement of deep-ice detector response ($N_\mu$) and surface array ($N_e$). SPASE-AMANDA published result: Astropart. Phys. **21** (565)

# Deployment





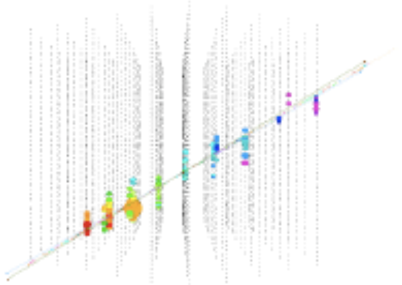



String 49 Drill/Ream/Deployment Profile
Depth of drill head (m)
Depth of Bottom DOM (m)
DOM installation: ~6min/DOM
Ream
String drop
Drop speed: 18 m/min
Jan 29,2006 6:00 am
Final depth (prel): 2451.0 m
Depth(m)
500
0
500
1000
1500
2000
2500
0
10
20
30
40
44.1
50
60
70
Jan 27, 7:05 am
Jan 28, 11:23 am
Time (in hrs)

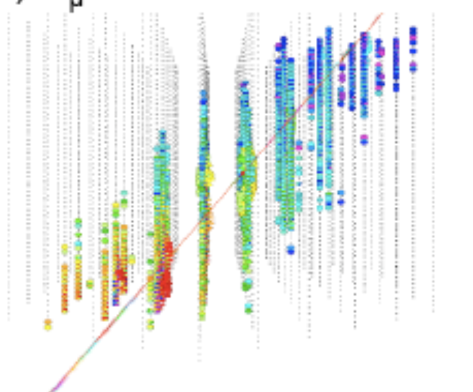
# Neutrino Topologies

## Muon neutrino

a) $E_\mu$=10 TeV ~ 90 hits



b) $E_\mu$=6 PeV ~1000 hits

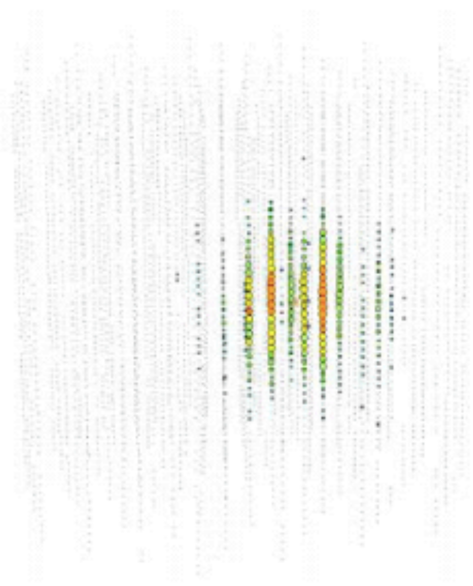


E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3
Angular Res.: 0.8 -2 deg

## Electron neutrino

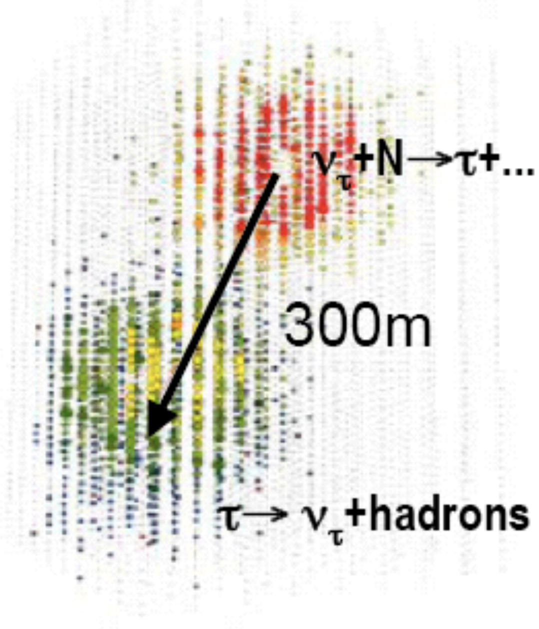
E = 375 TeV



Energy Res. log(E)~0.1-0.2
Poor Angular Resolution

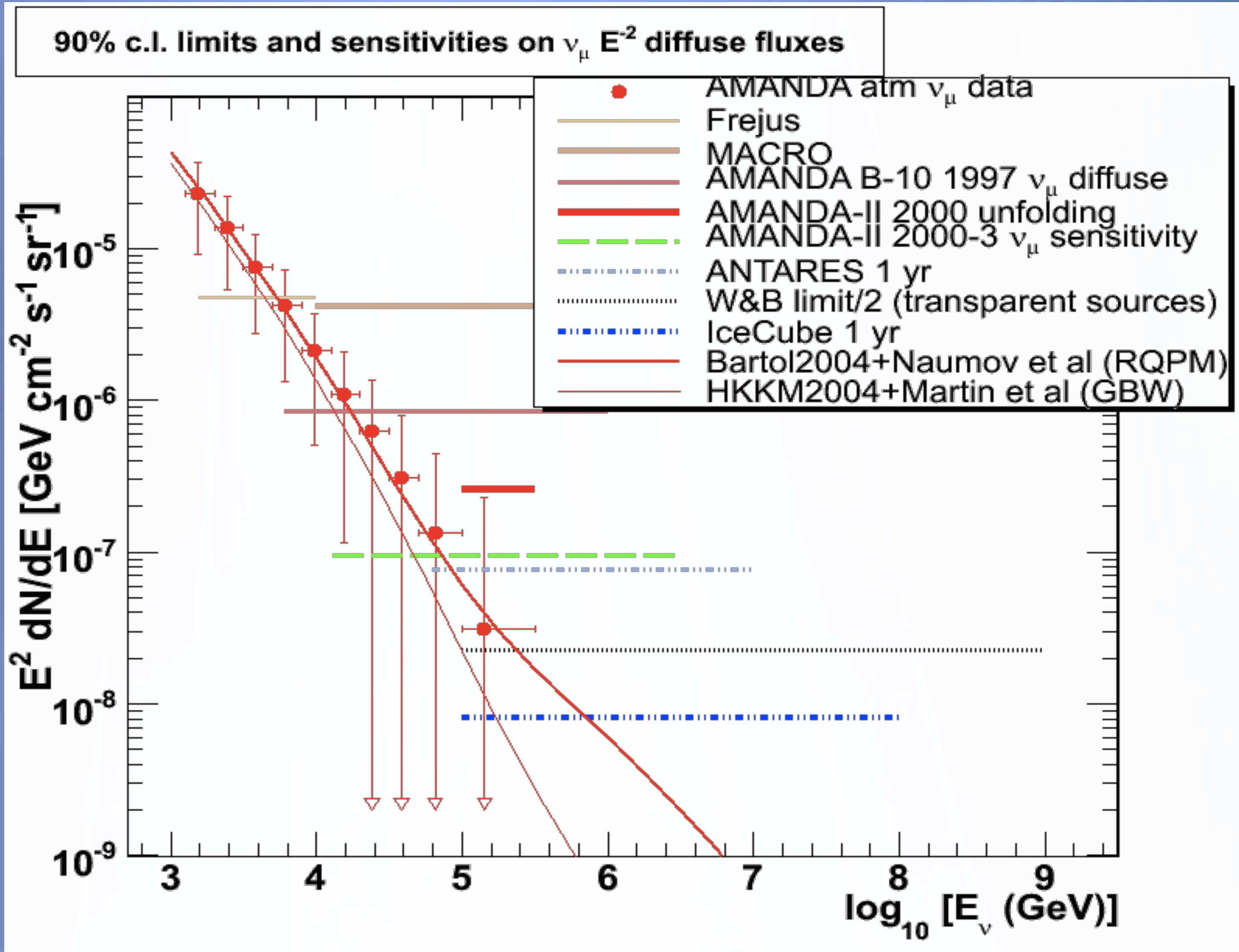
## Tau neutrino

E = 10 PeV



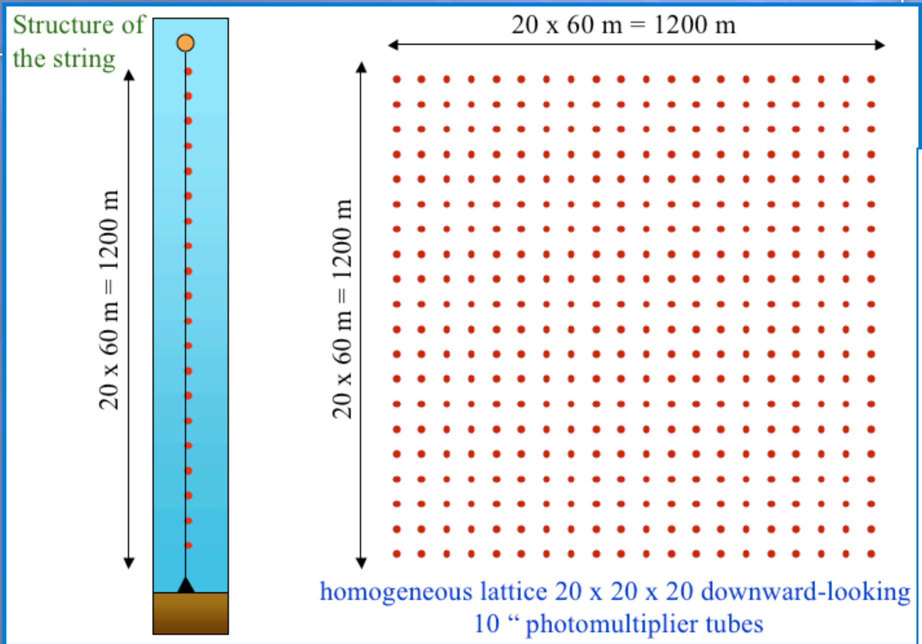

Double-bang signature above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

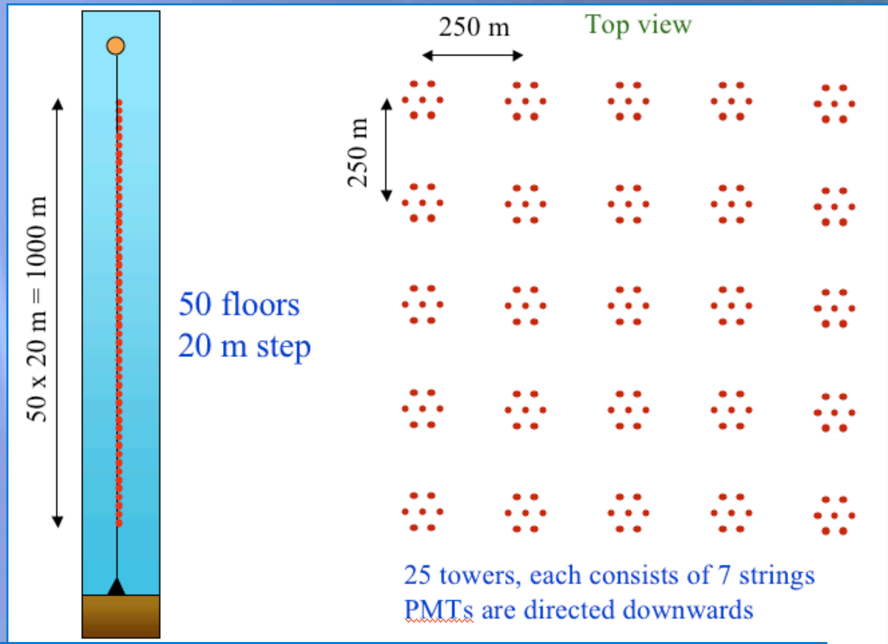
# Physics Reach - Point Sources

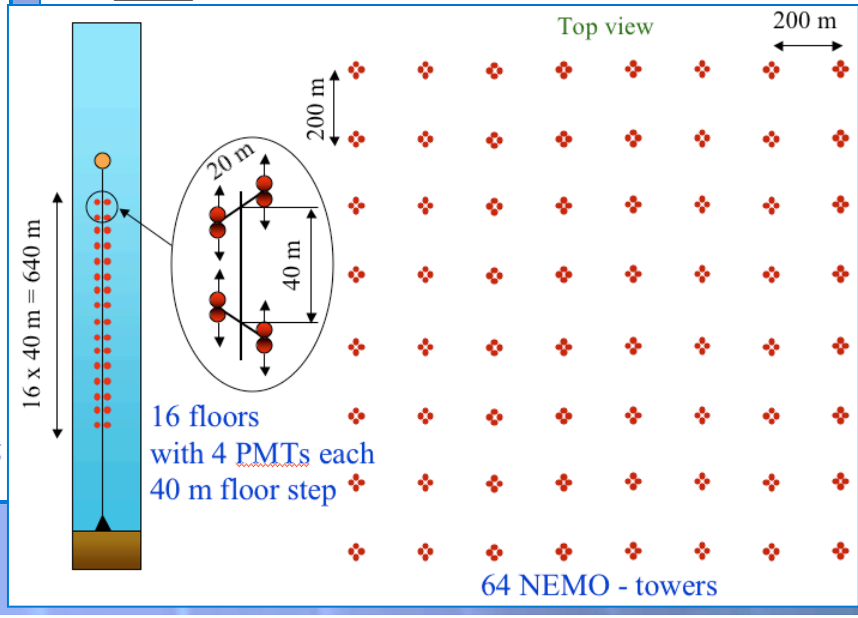


# KM3NeT - KM3 in the Med

- Basically a grouping of ANTARES, NEMO and NESTOR
- In the Design study Phase



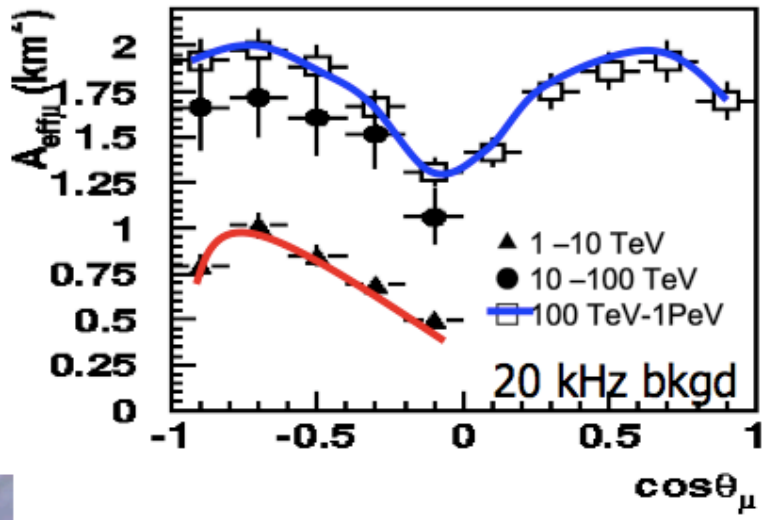



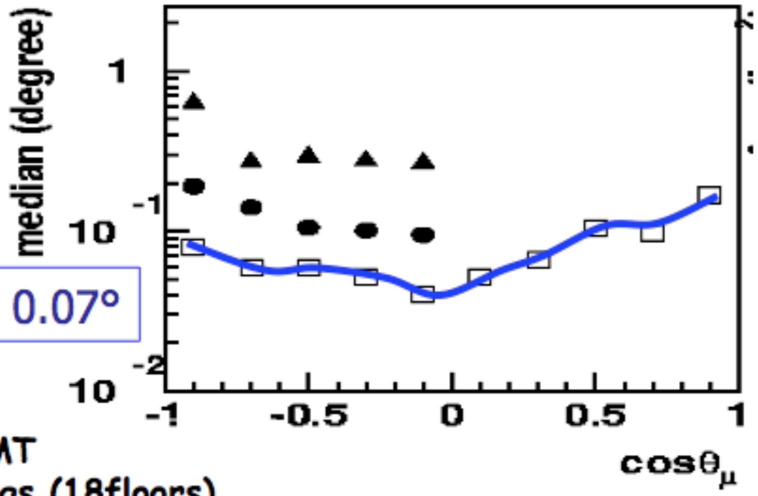




- No decision on site(s) yet

# KM3NeT-ICECUBE performance

KM3NET (one example)

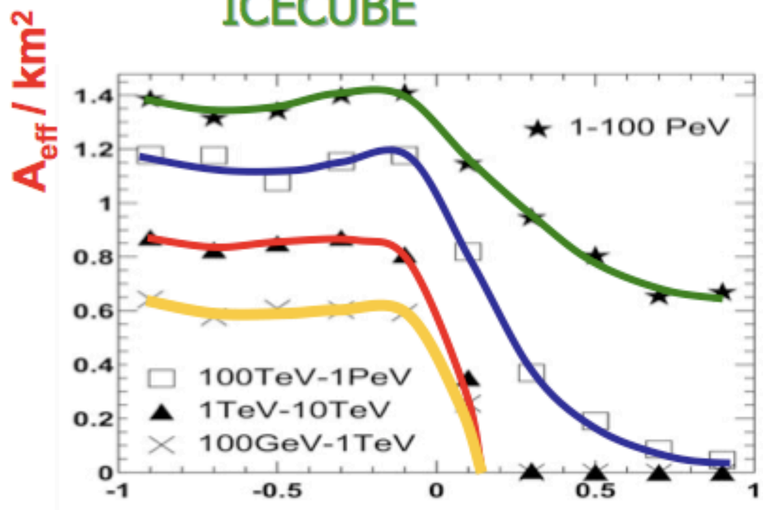


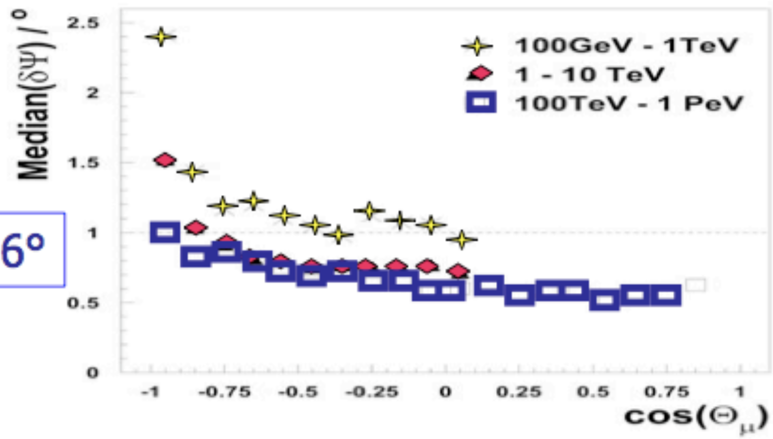




0.07°

5832 PMT
81 strings (18floors)
String height 680m

ICECUBE

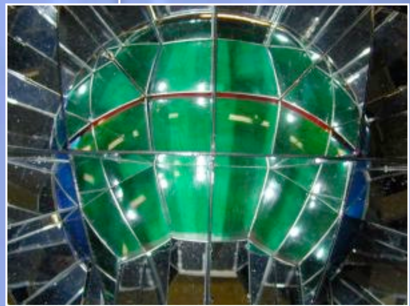


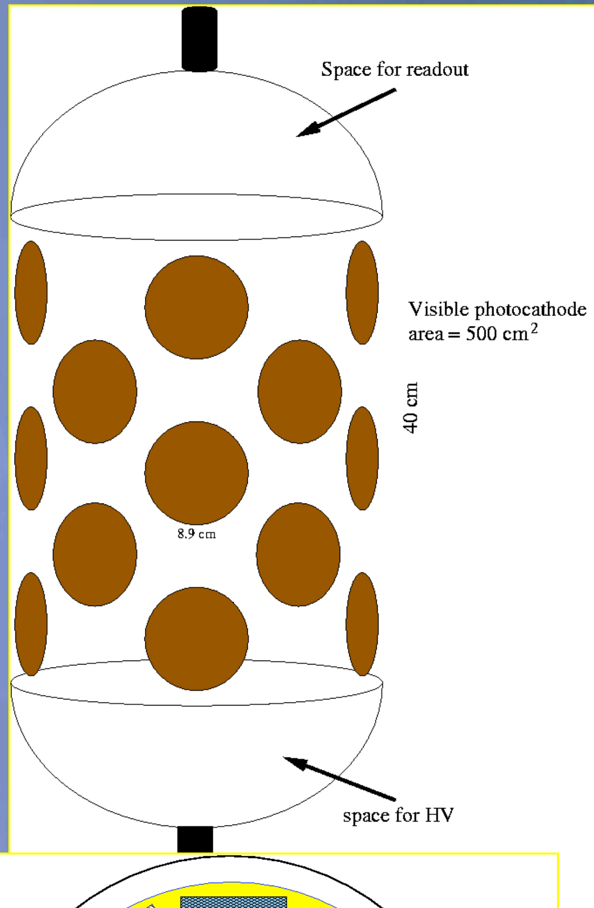



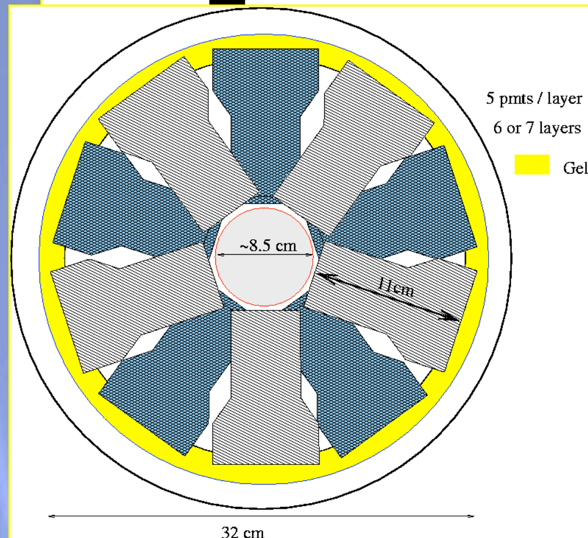

0.6°

# New Methods: Photosensors

- Much R&D into different aspects of detection design
- E.g. novel photodetection techniques
- Improve quantum efficiency
- Add directionality



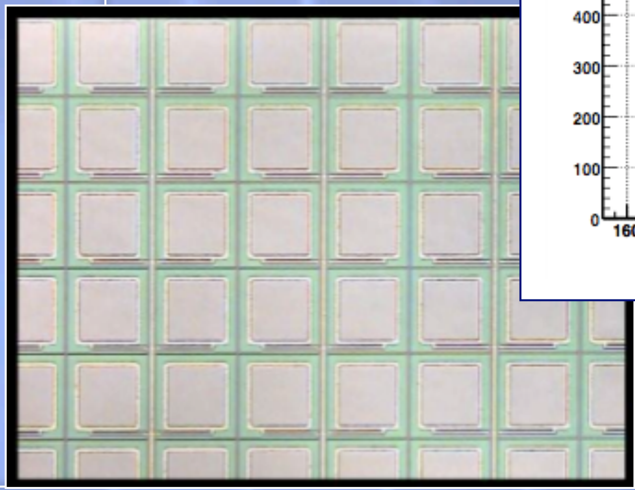


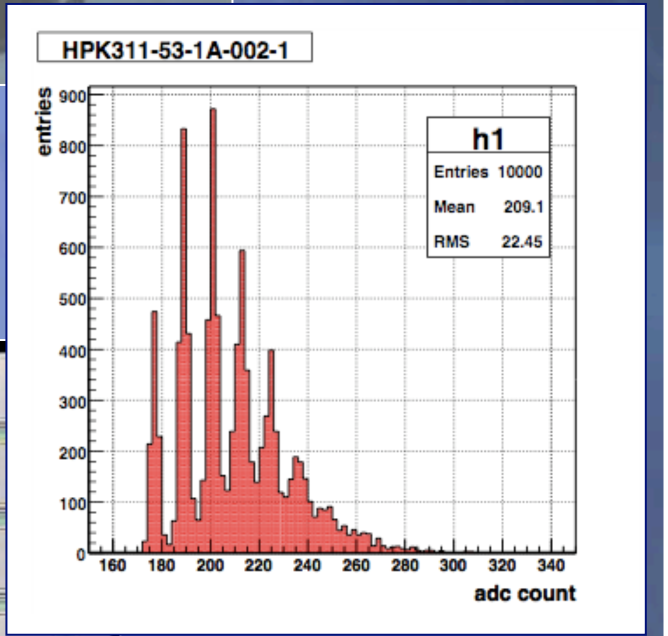



# New Methods: Photosensors

MPPCs

- Multi-pixel devices
- Cheap
- Fast
- Run in Geiger mode
- Excellent single photon counting
- Low gain
- Temperature dependent





# Conclusions

- Cerenkov radiation is a naturally occurring phenomenon that has been actively utilised by particle and astroparticle physicists for particle detection and identification
- In Astroparticle Physics it is used, in particular, for the detection of High Energy Gamma Rays, Ultra High Energy Cosmic Rays and High Energy Neutrinos
- In all of these cases working first/second generation experiments are delivering exciting results
- The next generation of devices utilising Cenenkov radiation are being planned and, in some case are under construction (AUGER North, HAWC, CTA, ICECUBE, KM3, etc.)
- These detectors will provide plenty of interesting data for the next generation of astroparticle physicists