Cherenkov and Imaging detectors for HEP and AP

ESIPAP - 2017

François Montanet

Plan of the course

- The Cherenkov effect, theory and phenomenology
- Timing and counting particles
    - The AUGER WCD as an example
- Identifying particles
  - Threshold Cherenkov counters
    - NA9, BELLE
  - Ring Imaging Cherenkov detectors (RICH, DIRC)
    - DELPHI, LHCb, BaBar
  - Measuring charge
    - AMS, CREAM
- VHE gamma rays
    - HESS, MAGIC, VERITAS…
- Neutrino detectors
    - SK, Amanda, Antares, IceCube

THE CHERENKOV EFFECT

2016

Cherenkov Radiation

- Emitted on a cone whose axis is along the particle trajectory and of half oppening angle θ_C such as $\cos\theta_C = 1/(\beta n)$ where β is the particle velocity/c and $n = n(\omega)$ is the frequency dependent refractive index.

- Threshold defined by the condition $1/(\beta n) < 1$

- Emission at all frequencies with $n(\omega) > 1$ (from UV to radio), flat in $h\nu$ in photon yield.

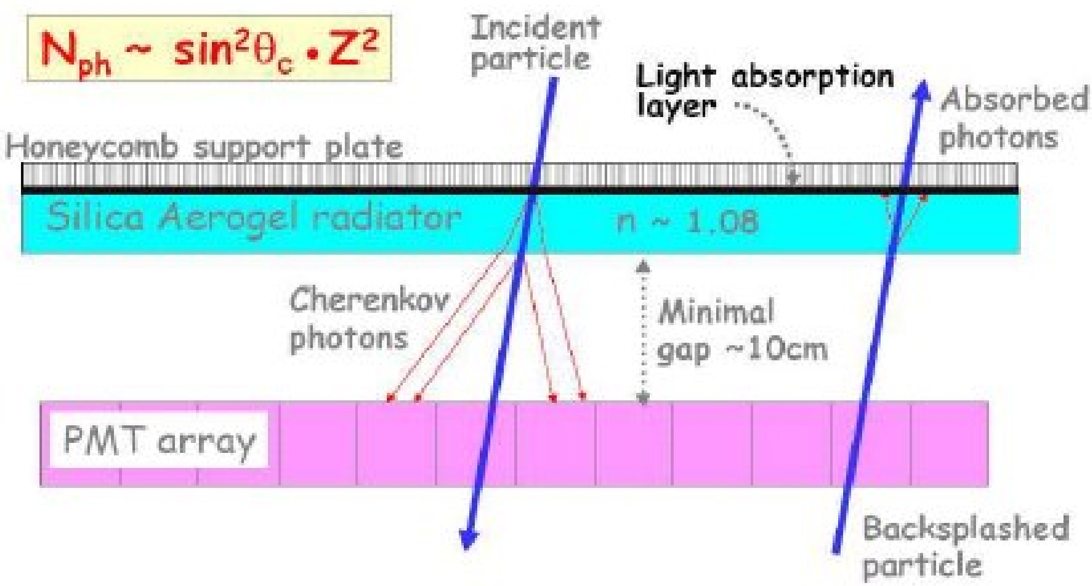
- Generaly detected from near UV to visible light.

$$\frac{dN^2}{dx d\omega} = \frac{\alpha}{c} Z^2 \sin^2\theta_C = \frac{\alpha}{c} Z^2 \left(1 - \frac{1}{\beta n}\right)$$

Cherenkov Radiation

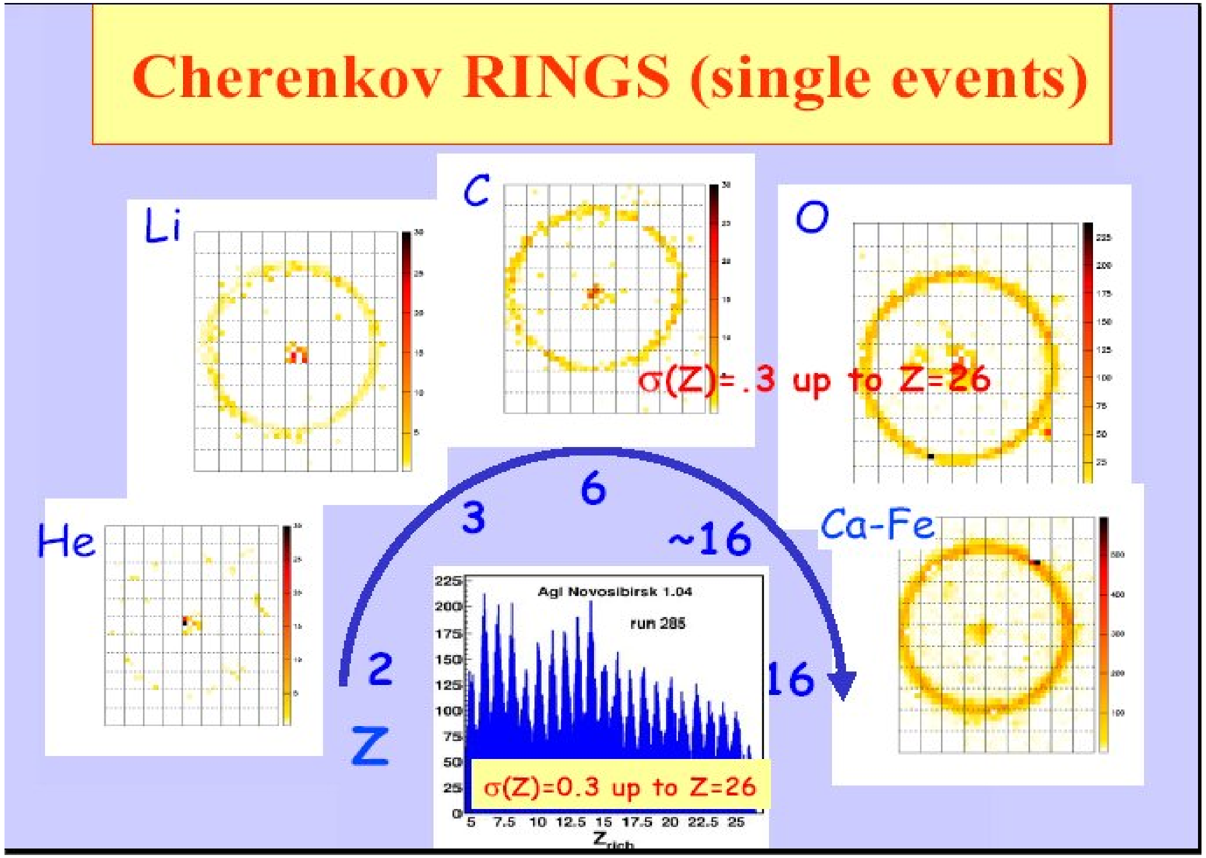
- Allow discrimination between particles with same momentum and ≠ masses (electrons / protons / nuclei) up to energies of the order of 10 GeV/nucleon if $\Delta\beta/\beta \approx 10^{-3}$
- Allow determining the orientation of the particle direction.
- "Ring Imaging Cherenkov" detector or RICH : allow a precise mesurement of the velocity and charge.

RICH principle →



Cherenkov imaging (RICH) and charge measurement

AMS 2 Prototype →



Transition radiation

- Origin : if a particle traverses the boundary between 2 $\neq$ dieletric media, the solution corresponding to each medium do not satisty the boundary. $\rightarrow$ need for an additional " free wave ".

- A dielectric medium is caracterised by its "plasma" frequency ω_p (oscillation frequency of free-like electrons)
  $\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$ or $\hbar\omega_p = 2E_R\sqrt{4\pi n_e a_B^3} \approx 20\text{eV}$
  $n_e =$ electron density ;
  $E_R =$ Rydberg energy $= 13.6\text{eV}$;
  $a_B =$ Bohr radius

- Roughly half of the energy is emitted in the frequency domaine $0.1\gamma\omega_p < \omega < \gamma\omega_p$ for a Lorentz factor $\gamma \approx 1000$, This is the X-ray domaine (2 to 20 keV)

- Energy emitted by the interface if $I = \alpha z^2 \gamma \hbar\omega_p / 3$

Transition radiation (cont)

- Angular distribution peaked at small angles around particle direction: $\theta \approx 1/\gamma$
- Small yield of X-photons per interface : $N \approx \alpha Z^2 \approx 10^{-2} Z^2$
  $\rightarrow$ multiply the number of interfaces
  $\rightarrow$ stack plastic sheets or fibers
- X-ray detection by photo-electric effect: proportional tubes
- Discriminates between particles with same energy and $\neq$ masses at high energies (100 GeV to 1 TeV) (instrumental detection thereshold for X-rays).
- Can measure the Lorentz factor γ up to 10^5. In this case, choose material adequately to have a progressive threshold.

Comptes Rendus (Dokl.) Acad. Sci. URSS *14*, 109–114 (1937)

Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS
1937. Volume XIV, № 3

PHYSICS

COHERENT VISIBLE RADIATION OF FAST ELECTRONS PASSING THROUGH MATTER

By I. FRANK and Ig. TAMM, Corresponding Member of the Academy

In 1934 P. A. Čerenkov has discovered a peculiar phenomenon, whicd he has since investigated in detail (1). All liquids and solids if bombarded by fast electrons, such as β-electrons or Compton electrons produced by γ-rays, do emit a peculiar visible radiation, quite different from the eventual ordinary flourescence. This radiation is partially polarized, the electric oscillation vector being parallel to the electron beam, and its intensity can be reduced neither by temperature nor by addition to the liquid bombarded of quenching substances. The peculiarity of these caracteristics was scrutinized by Wawilow (2) who suggested that this radiation must be connected with the «Bremsung» of fast electrons. Since then a new and undoubtedly the most peculiar characteristic of the phenomenon was discovered, namely, its highly pronounced asymmetry, the intensity of light emitted in the direction of the motion of electrons being many times larger than in the backward direction. It follows that the substance bombarded radiates coherently for the space of at least one wavelength of the visible light.

This peculiar radiation can evidently not be explained by any common mechanism such as the interaction of the fast electron with individual atom or as radiative scattering of electrons on atomic nuclei* On the other hand, the phenomenon can be explained both qualitatively and quantitatively if one takes in account the fact that an electron moving in a medium does radiate light even if it is moving uniformly provided that its velocity is greater than the velocity of light in the medium.

We shall consider an electron moving with constant velocity v along the z axis through a medium characterized by its index of refraction n. The field of the electron may be considered as the result of superposition of spherical waves of retarded potential, which are being continually emitted by the moving electron and are propagated with the velocity $\frac{c}{n}$. It is easy to see that all these consecutive waves emitted

* The intensity of visible light emitted by the last named process is about 10^4 times smaller than the intensity observed.

The Nobel Prize in Physics 1958
Pavel A. Cherenkov, Il´ja M. Frank, Igor Y. Tamm

The Nobel Prize in Physics 1958

Pavel Alekseyevich Cherenkov

Il´ja Mikhailovich Frank

Igor Yevgenyevich Tamm

The Nobel Prize in Physics 1958 was awarded jointly to Pavel Alekseyevich Cherenkov, Il´ja Mikhailovich Frank and Igor Yevgenyevich Tamm *"for the discovery and the interpretation of the Cherenkov effect"*.

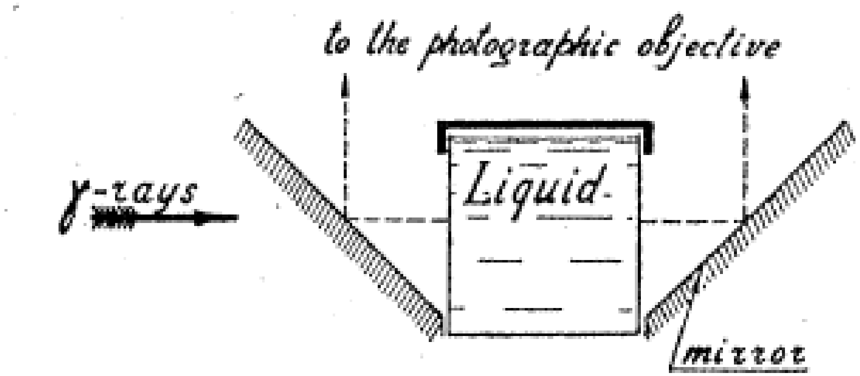


FIG. 1. Arrangement of apparatus.

All the results obtained are in good agreement with I. M. Frank and I. E. Tamm's theory of the coherent radiation of electrons moving in a medium.[6]

P. A. ČERENKOV

The Physical Institute of the Academy of Sciences of U.S.S.R.,
Moscow,
June 15, 1937.

[1] Čerenkov, C. R. Ac. Sci. U.S.S.R. **8**, 451 (1934).
[2] Čerenkov, C. R. Ac. Sci. U.S.S.R. **12** (3), 413 (1936).
[3] Čerenkov, C. R. Ac. Sci. U.S.S.R. **14**, 102 (1937).
[4] Čerenkov, C. R. Ac. Sci. U.S.S.R. **14**, 105 (1937).
[5] Wawilow, C. R. Ac. Sci. U.S.S.R. **8**, 457 (1934).
[6] Frank and Tamm, C. R. Ac. Sci. U.S.S.R. **14**, 109 (1937).
[7] Bull. Ac. Sci. U.S.S.R. No. 7, 919 (1933).
[8] E. Brumberg and S. Wawilow, C. R. Ac. Sci. U.S.S.R. **3**, 405 (1934)

(a)

(b)

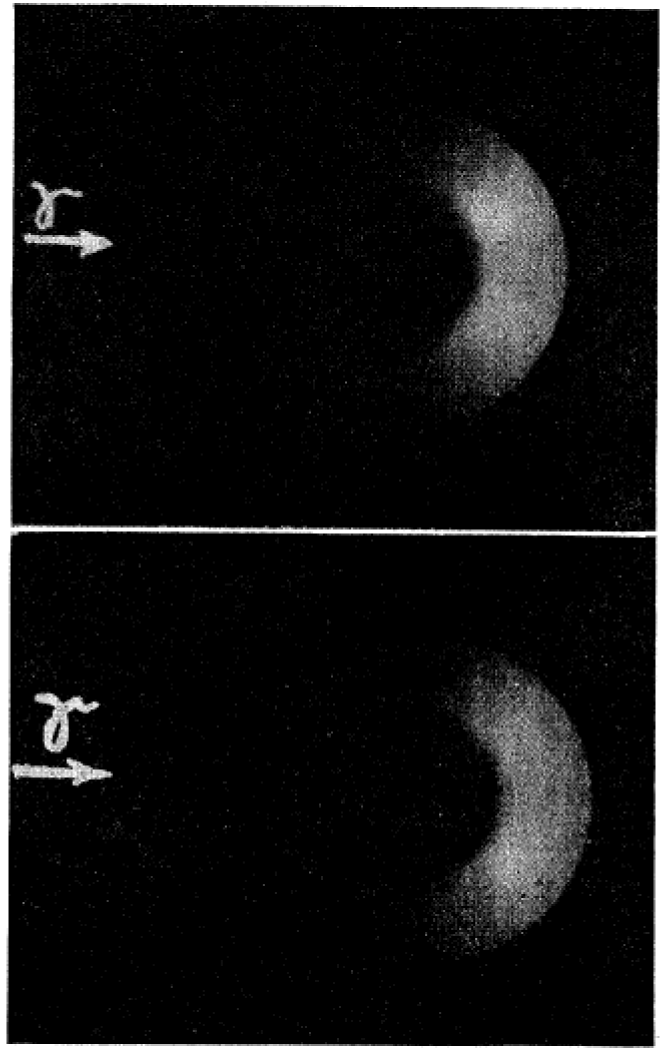
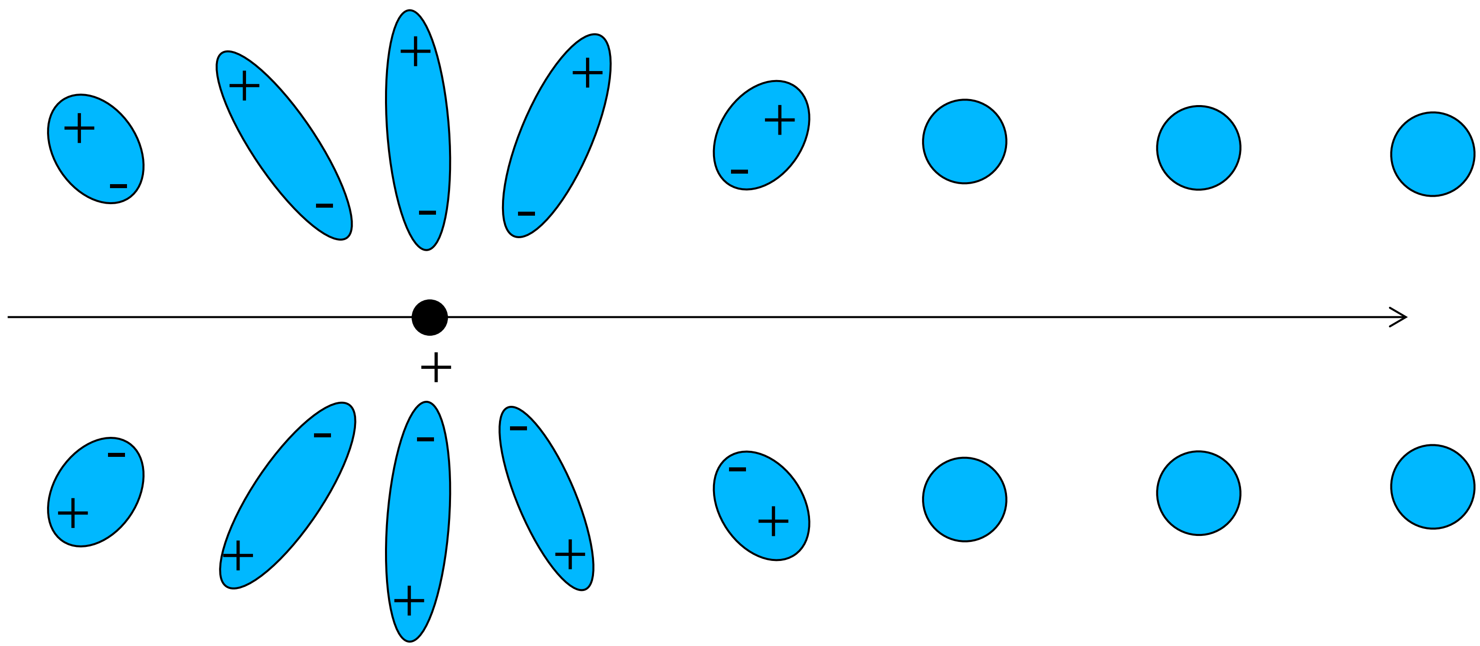


FIG. 2. Photographs showing asymmetry of luminescence. (a) water $n=1.337$; (b) benzene, $n=1.513$.

P.A. Čerenkov Letter to the editor Phys.Rev 53 (1937) 378

Theory of the Cherenkov effect

- Dielectric medium electrons polarized by a moving charged particle.



- De-exitation gives rise to a coherent radiation.
- Same basic process as energy loss (Bethe, Fermi).

The Cherenkov effect

2016

- When a charged particle moves faster than the phase speed of light in a medium, electrons interacting with the particle can emit coherent photons while conserving energy and momentum.
- This process can be viewed as a decay.
- It is actually not the particle that emits light, but the bound electrons of the immediately surrounding (dielectric) medium.
- Emission is coherent because in phase with the particle velocity.
- Pavel A. Čerenkov and Vavilov discovered the radiation in 1934, Igor Tamm and Ilya Frank explained it in 1937.

Ref :

P.A. Čerenkov Letter to the editor Phys.Rev 53 (1937) 378
Frank and Tamm, C.R.Ac.Sci. U.S.S.R. 14, 109 (1937)

The theory of the Cherenkov effect

Igor Tamm and Ilya Frank

The energy emitted per unit length dx travelled by the particle per unit of angular frequency $d\omega$ is:

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

provided that $\beta = \frac{v}{c} > \frac{1}{n(\omega)}$. Here $\mu(\omega)$ and $n(\omega)$ are the frequency-dependent permeability and index of refraction of the medium, q is the electric charge of the particle, v is the speed of the particle, and c is the speed of light in vacuum.

Consequences:

- the **yield** of photons is **flat** versus these photons energy $(h\nu)$.
- the **yield** of photons is $\propto \lambda^{-2} \Rightarrow$ prominent at small wavelengths (UV)
- the spectrum is continuous $\neq$ fluorescence

The Cherenkov effect

The total amount of energy radiated per unit length is:

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

This integral is done over the frequencies ω for which the particle's speed v is greater than speed of light of the media $\frac{c}{n(\omega)}$. The integral is non-divergent because at high frequencies the refractive index becomes less than unity.

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{\beta n(\omega) > 1} \mu(\omega)\omega \left(1 - \frac{1}{\beta^2 n^2(\omega)}\right) d\omega$$

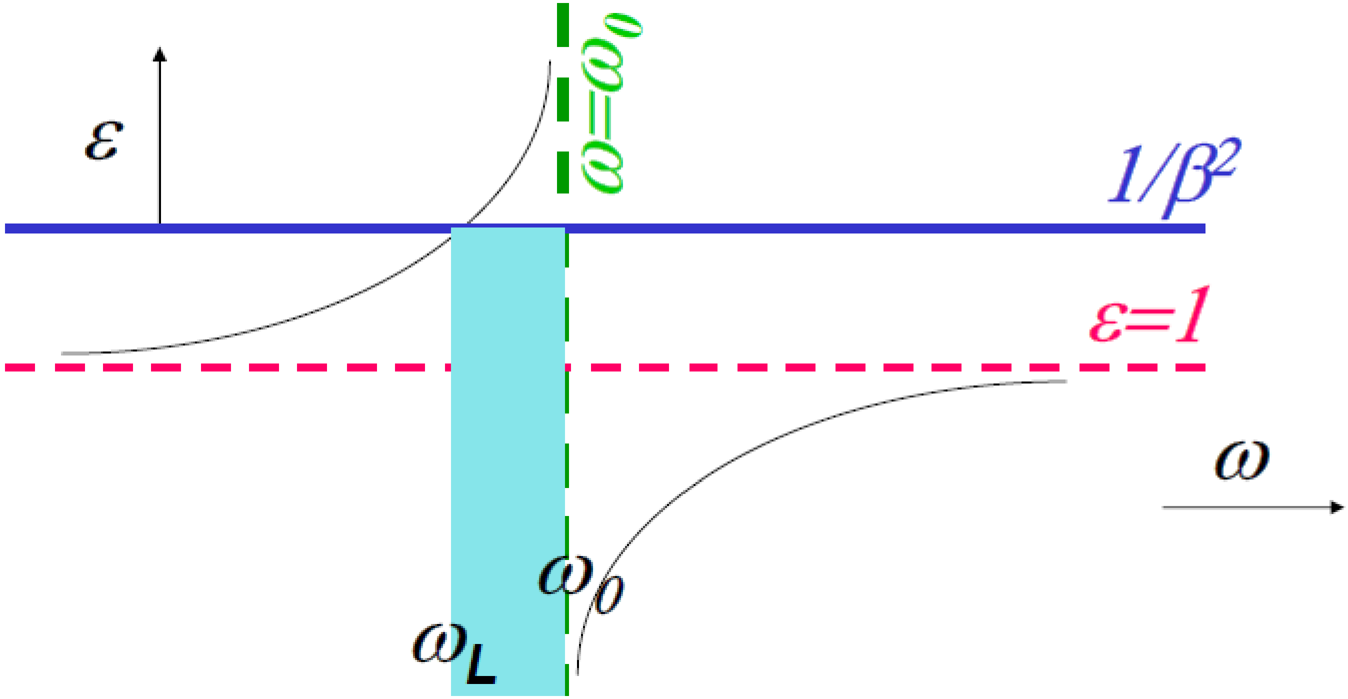
The Cherenkov effect

- Cerenkov radiation consist of a shock wave
- Similar to Doppler effect or Mach shock waves

Dielectrics

- Simple model for dielectric materials

$$\epsilon(\omega) = 1 + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\Gamma}$$



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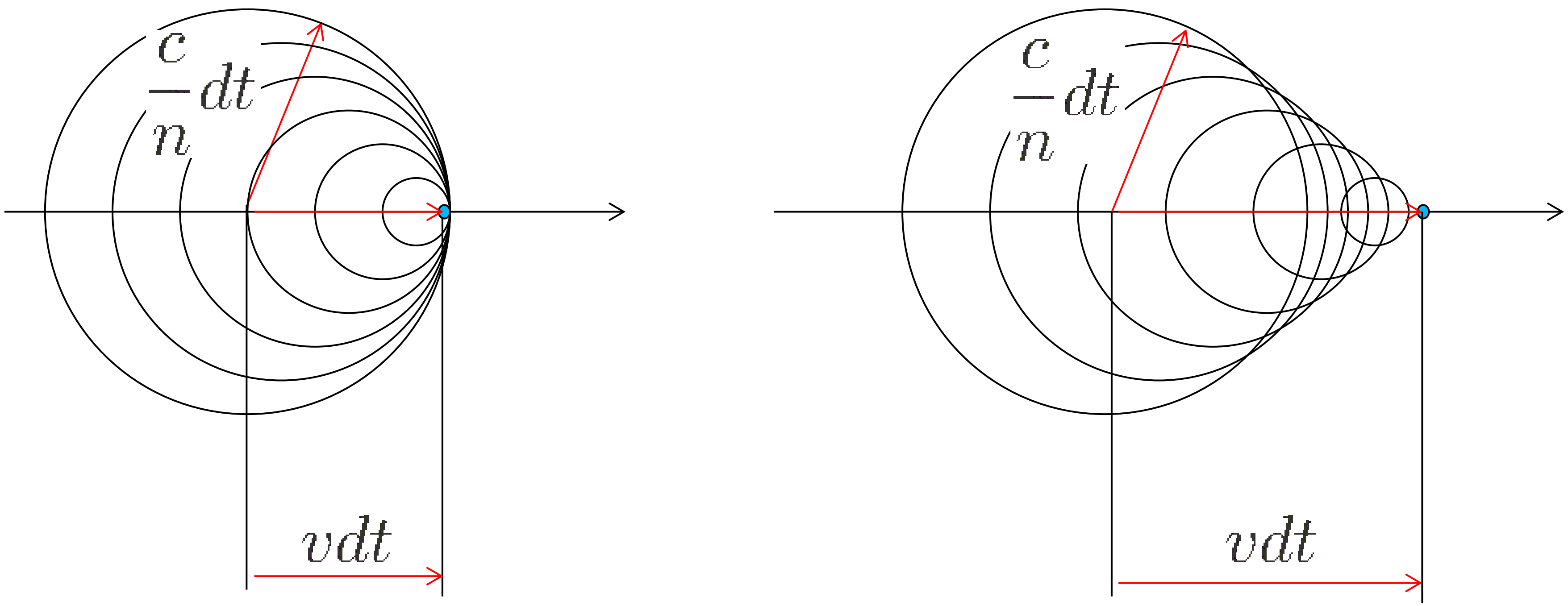

The Cherenkov effect

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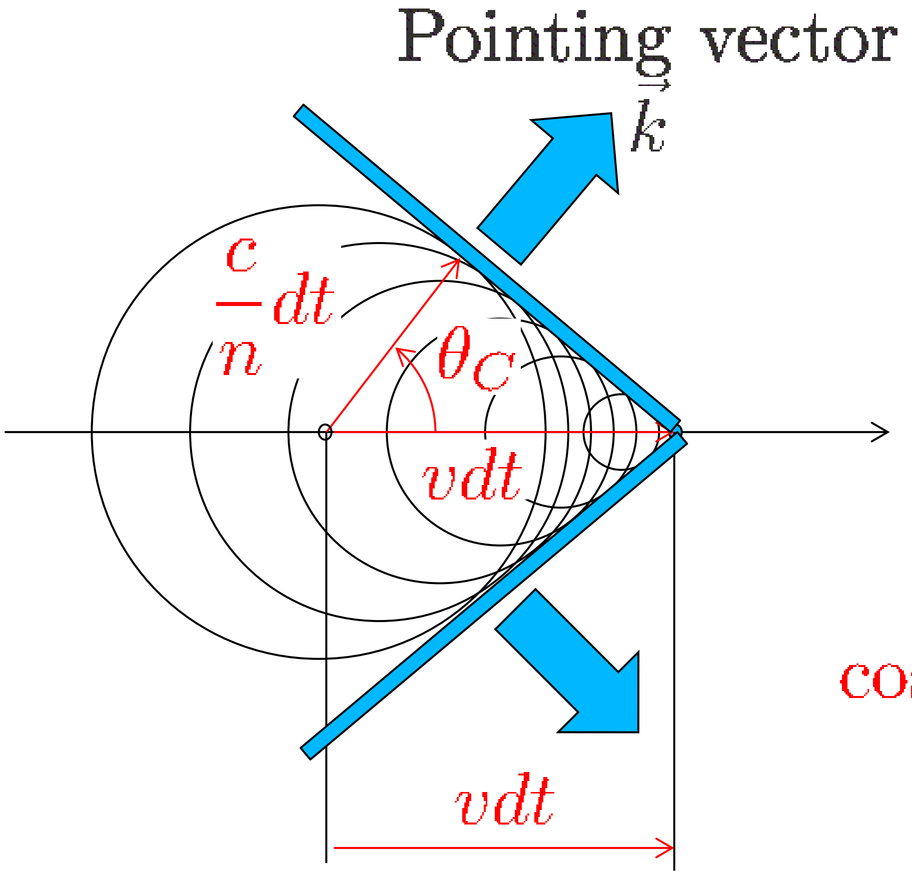


$$\cos\theta_C = \frac{c}{nv} = \frac{1}{n\beta}$$

Cherenkov effect

- Relevant formulae:

The emission angle wrt particle direction:

$$\theta_C = \arccos\left(\frac{1}{n\beta}\right)$$

if $n\beta > 1$.

The threshold velocity:

$$\beta_{\text{th}} = \frac{1}{n}$$

thus the threshold momentum:

$$p_{\text{th}} = m\beta_{\text{th}}\gamma_{\text{th}} = \frac{m}{\sqrt{n^2 - 1}} \approx \frac{m}{\sqrt{2\delta}}$$

with $\delta = n - 1 \ll 1$

Cherenkov effect

- Relevant formulae:

The number of photons produced per unit length and unit of photon energy by a particle with charge Ze:

$$\frac{d^2N}{dEdx} = \frac{\alpha Z^2}{\hbar c}\sin^2\theta_C$$
$$= \frac{\alpha Z^2}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$
$$= 370\ Z^2 \sin^2\theta_C \ \ \mathrm{eV}^{-1}\mathrm{cm}^{-1}$$

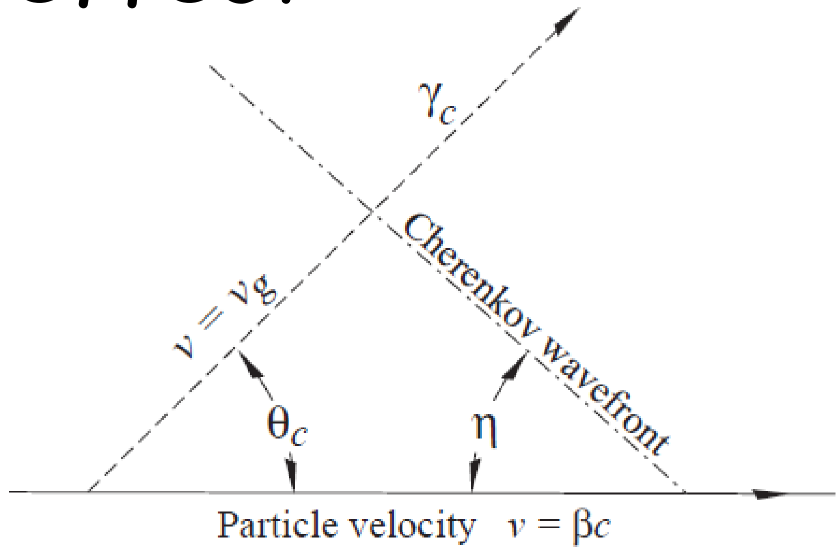
or equivalently:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha Z^2}{\lambda^2}\sin^2\theta_C \approx 4.59\times 10^5\ Z^2\ \sin^2\theta_C \ \ \mathrm{nm}^{-1}\mathrm{cm}^{-1}$$

Cherenkov effect

- Dispersive material:

Important for timing of neutrino telescopes



In dispersive media (where $dn/d\omega \neq 0$) one has to take into account the fact that photons propagate with the **group** velocity. Tamm showed that in that case $\theta_C + \eta \neq 90°$ with η the cone 1/2 opening angle given by:

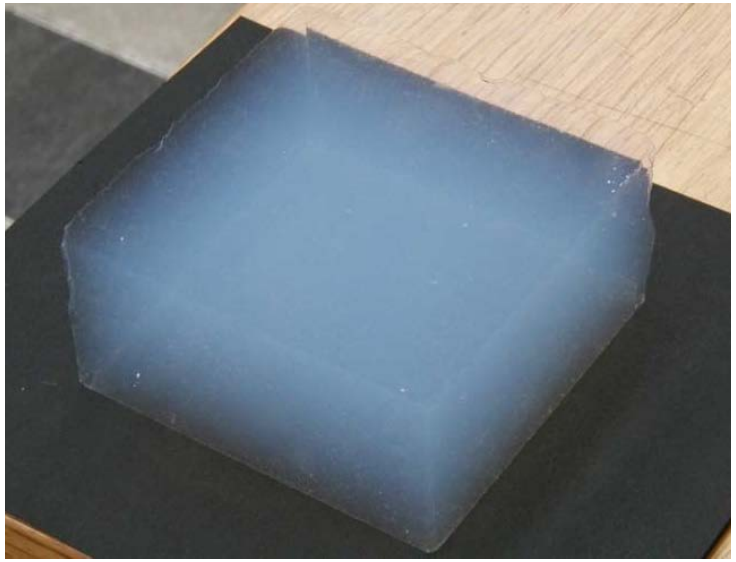
$$\begin{aligned}\cot\eta &= \left[\frac{d}{d\omega}(\omega\tan\theta_C)\right]_{\omega_0} \\ &= \left[\tan\theta_C + \beta^2\omega n(\omega)\frac{dn}{d\omega}\cot\theta_C\right]_{\omega_0}\end{aligned}$$

Radiators

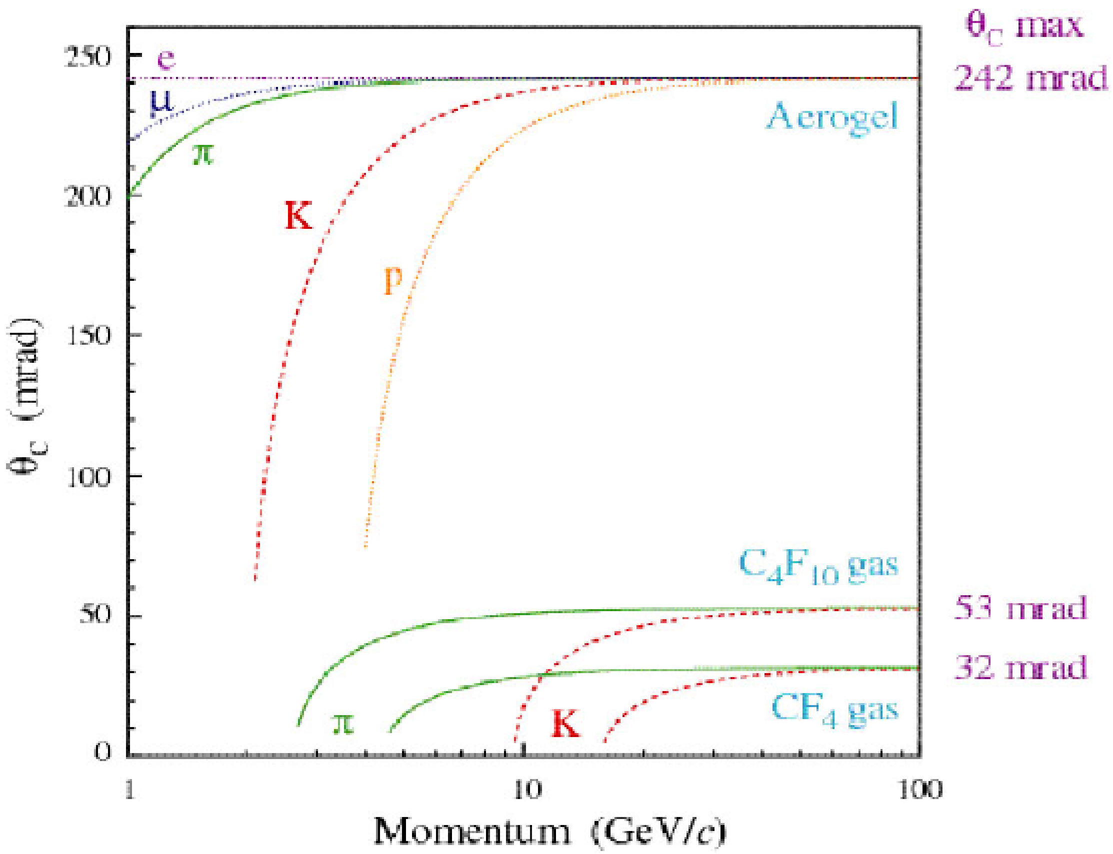
- Matching refractive index to the momentum range.

Medium	$n-1$	γ_{th}	θ_C	Photons/m
He (stp)	$3.5 \cdot 10^{-5}$	120	$0.48°$	3
C_2 (stp)	$4.1 \cdot 10^{-4}$	35	$1.64°$	40
Silica aerogel	$0.025 - 0.075$	$4.6 - 2.7$	$12.7 - 21.5°$	$2400 - 6600$
Water	0.33	1.52	$41.2°$	$2.1 \cdot 10^4$
Glass	$0.46 - 0.75$	$1.37 - 1.22$	$46.8 - 55.1°$	$2.6 - 3.3 \cdot 10^4$

Silica aerogel:
SiO_2 "foam" with
nano-size structure $\ll \lambda$



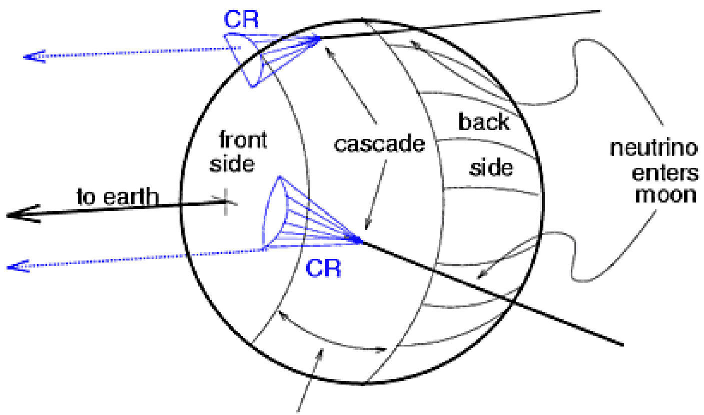
Cherenkov angle vs mass and momentum

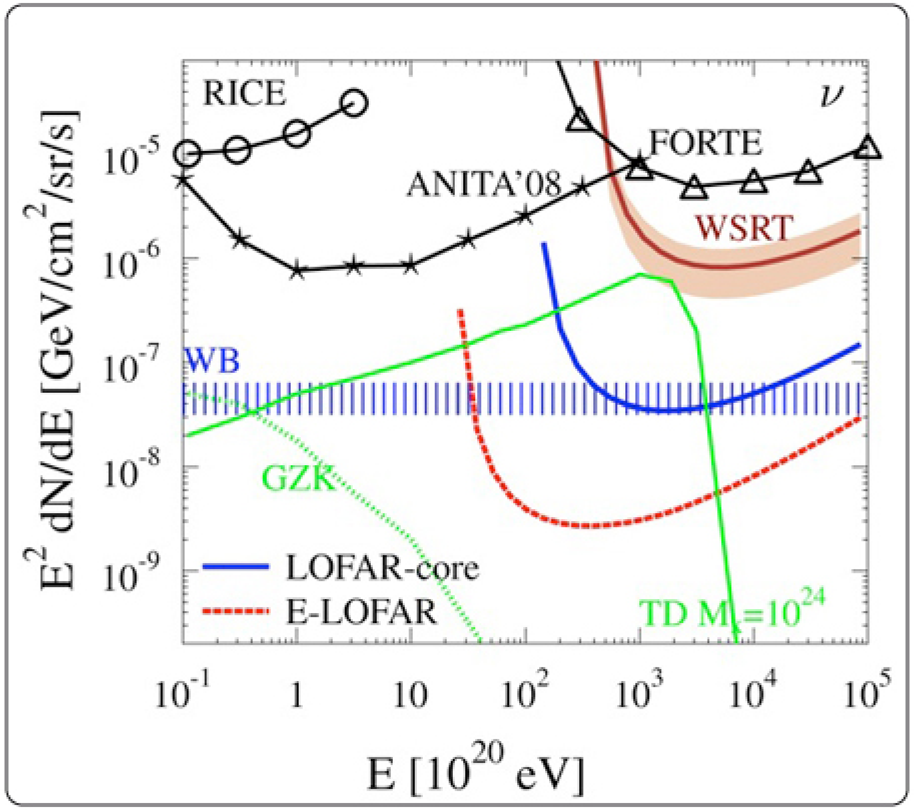


$$\cos\theta_C = \frac{c}{nv} = \frac{1}{n\beta}$$

Cherenkov not only optical

- Radio-wave Cherenkov emission (also called Askarian effect) by EM showers in dense dielectric materials (ice, salt, sand, lunar regolith …)
- Coherent Cherenkov like emission for $\lambda \gg$ shower size $\approx X_0$





TIMING AND COUNTING:
THE AUGER DETECTOR EXAMPLE

Counting particles or timing measurements

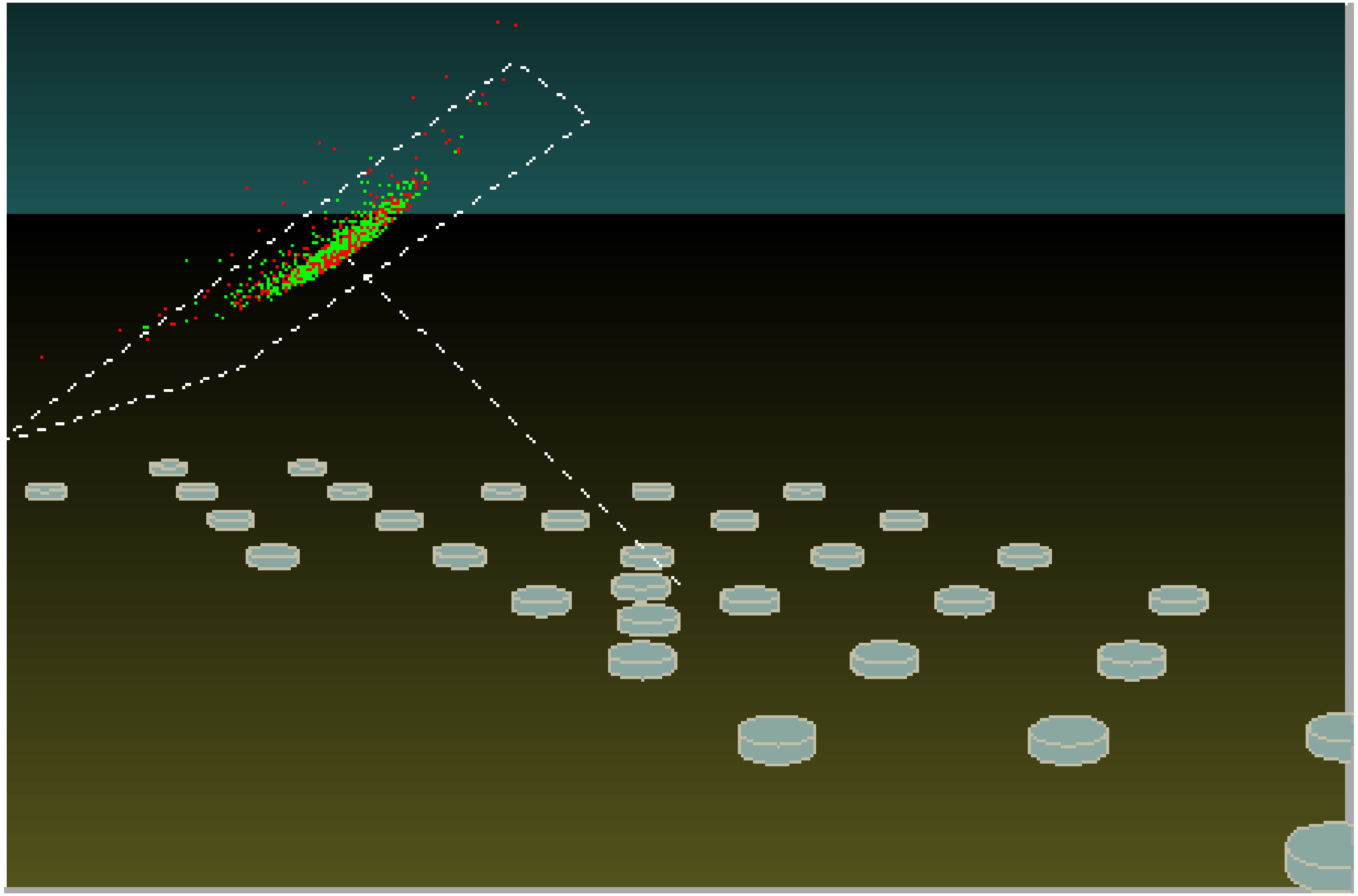
2016

- Example : the Auger Water Cherenkov Tanks

L'Observatoire Pierre Auger

2016

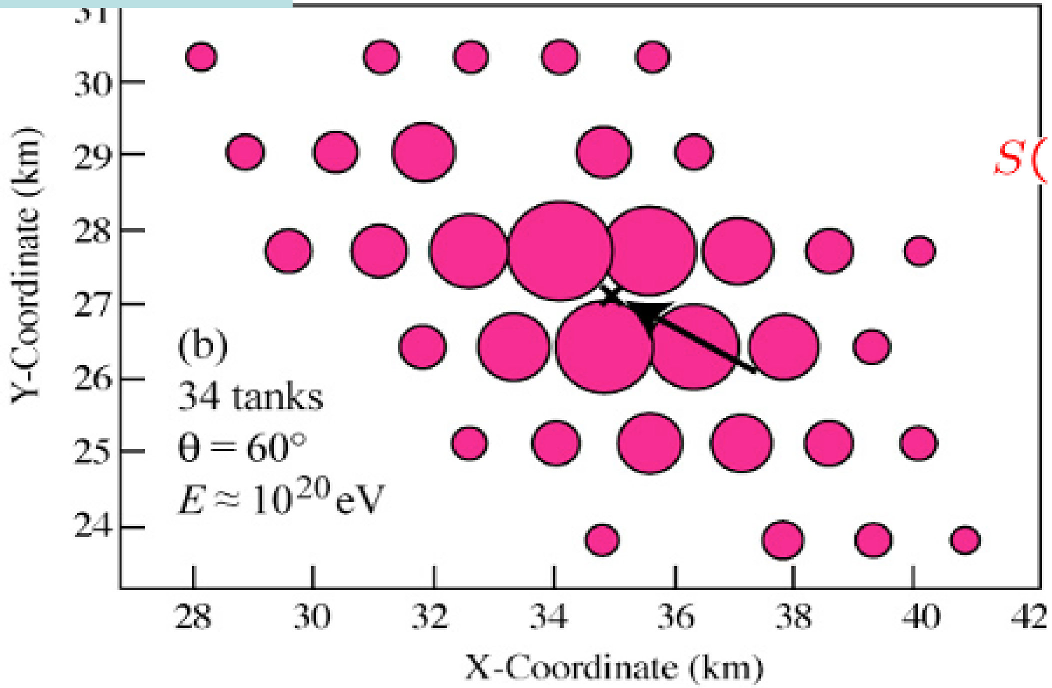
Timing

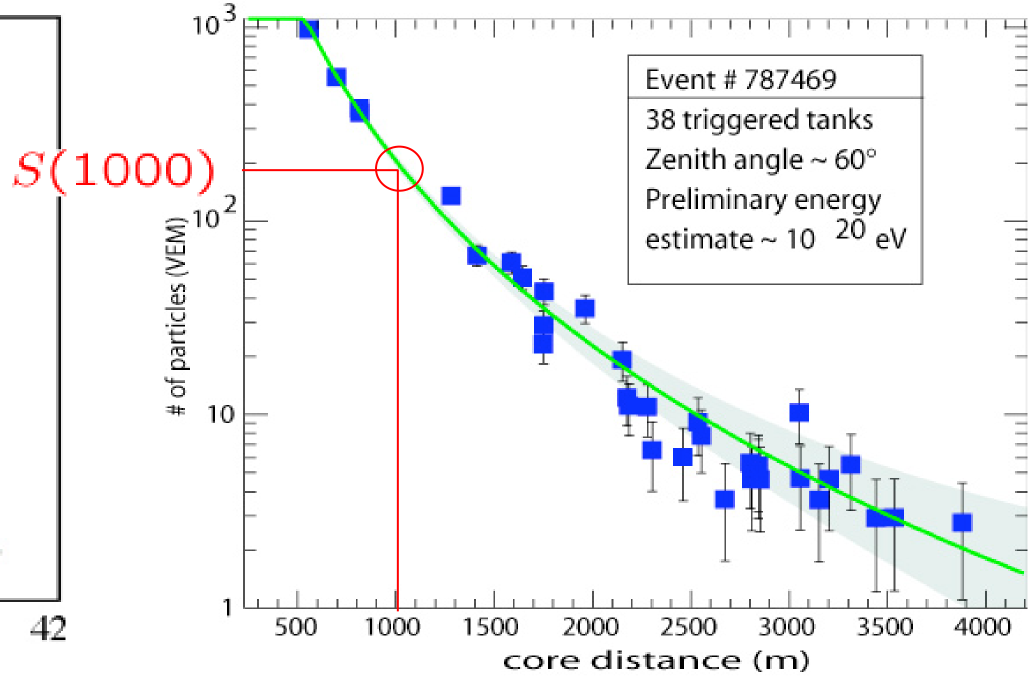


Thin pancake (few tens ns) of particles traveling at speed $v \sim c$. Spacing is 1.5 km $\Rightarrow$ few 10 ns relative timing to achieve 0.1° angular resolution for vertical showers. Acheivable with GPS + flash ADCs.

From EAS footprint and LDF to primary CR energy estimator

AUGER

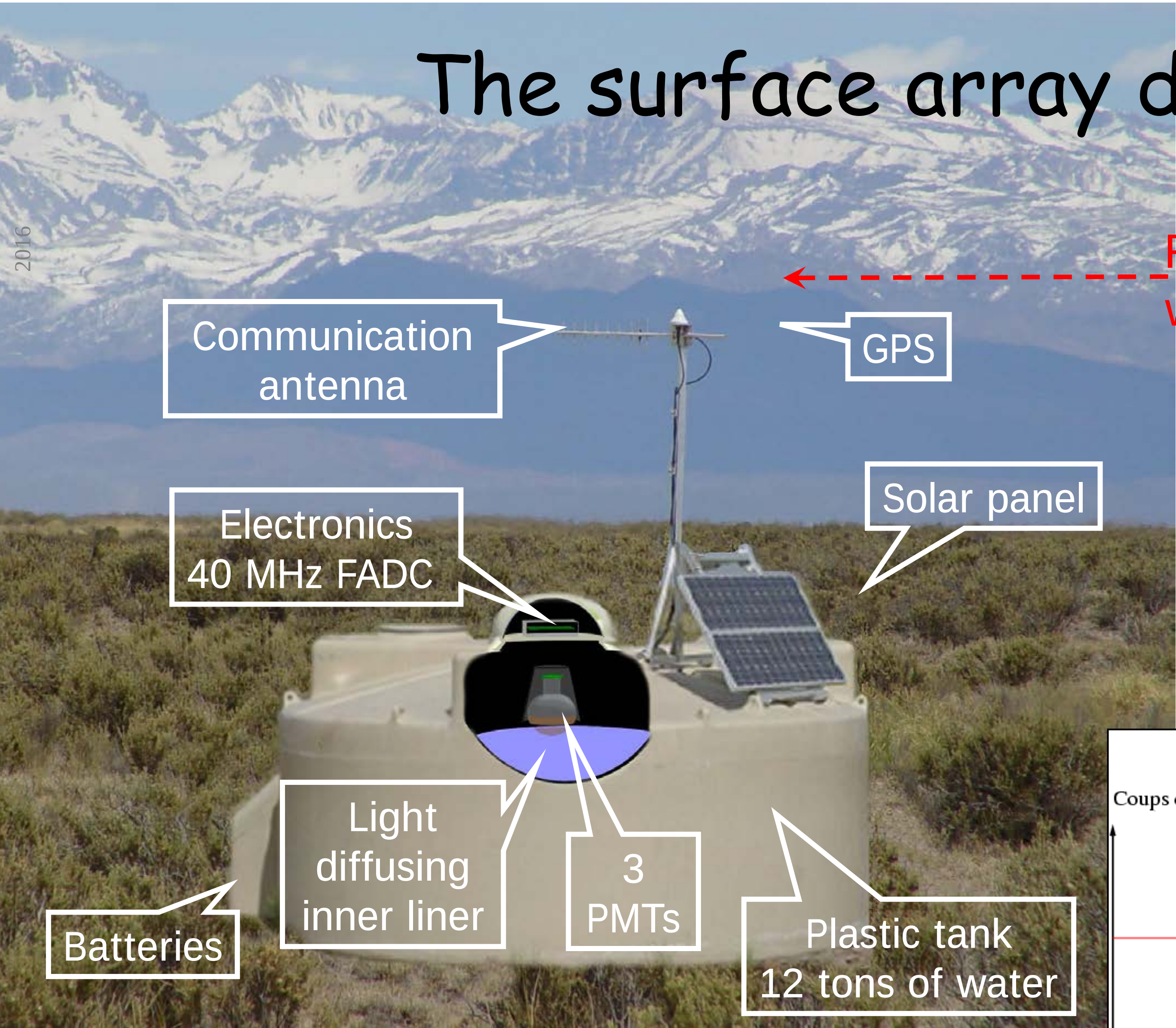




Idea from Hillas 1970 (pioneered by Haverah Park and Agasa)

- energy estimator: signal @ fixed (large) core distance S(R)
- small shower-to-shower fluctuations, depends on primary E only
- Determination of particle density -> LDF -> S(R)
- Largest uncertainty: converting estimator to energy (see later)

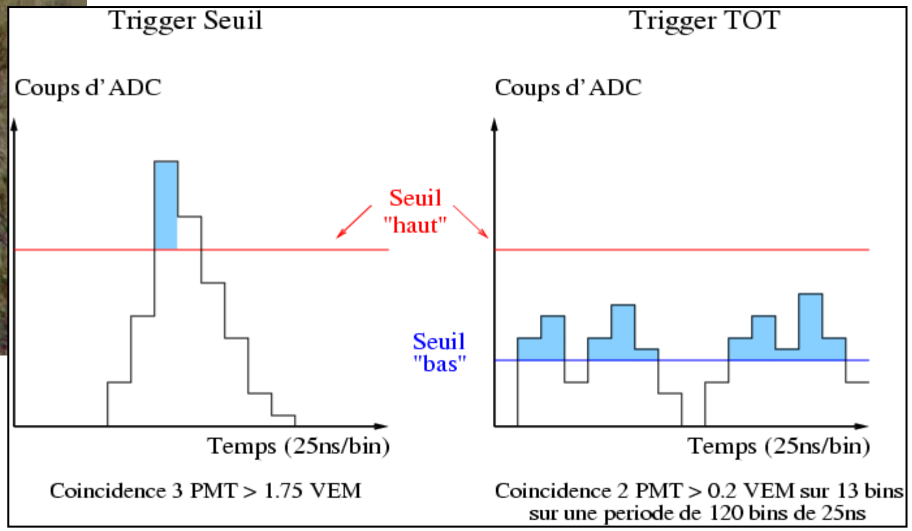
The surface array detectors



Radio
waves

Central DAQ

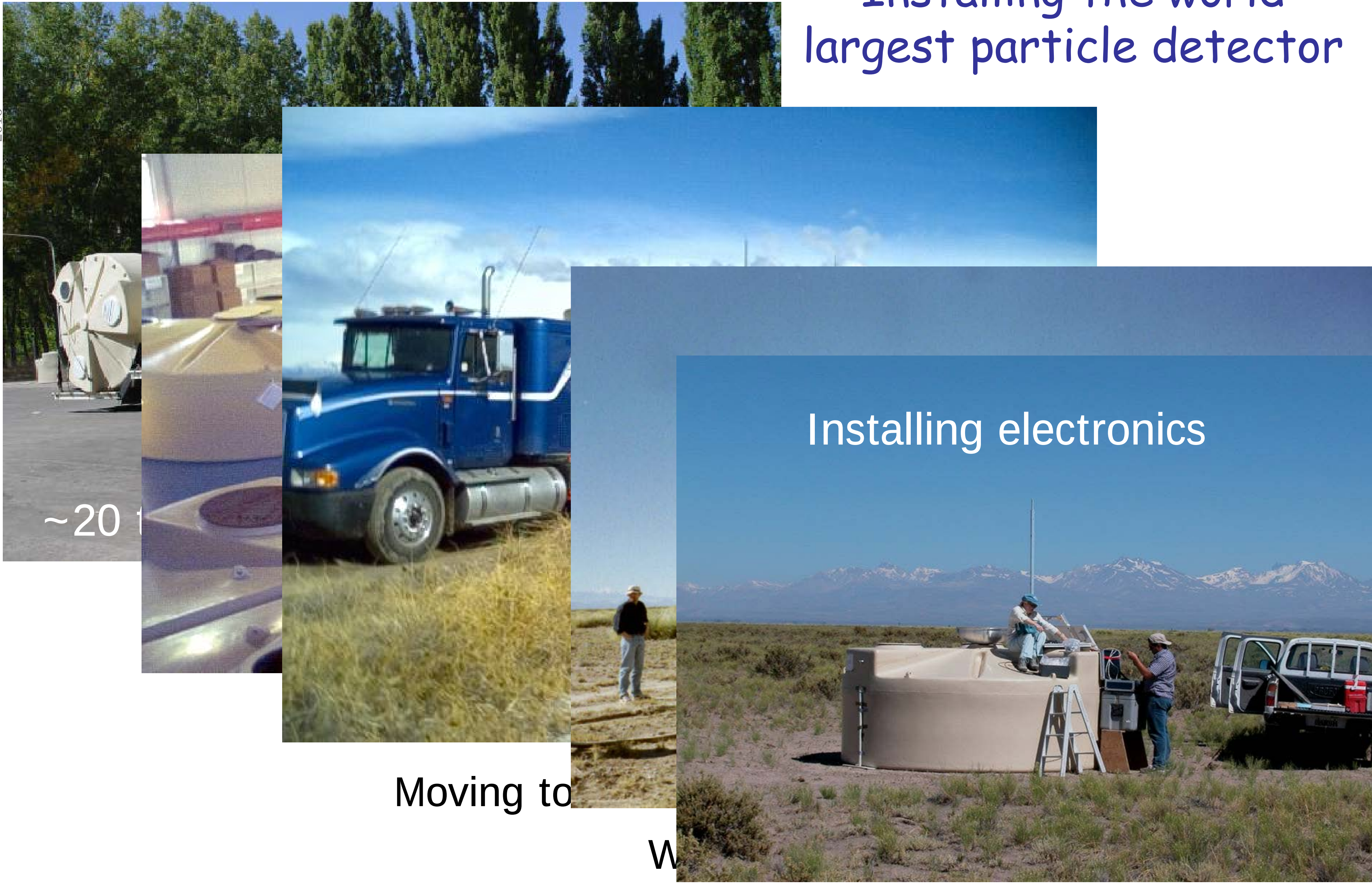
Local trigger



Self-calibration:

1 VEM = average signal from vertical through going muons.

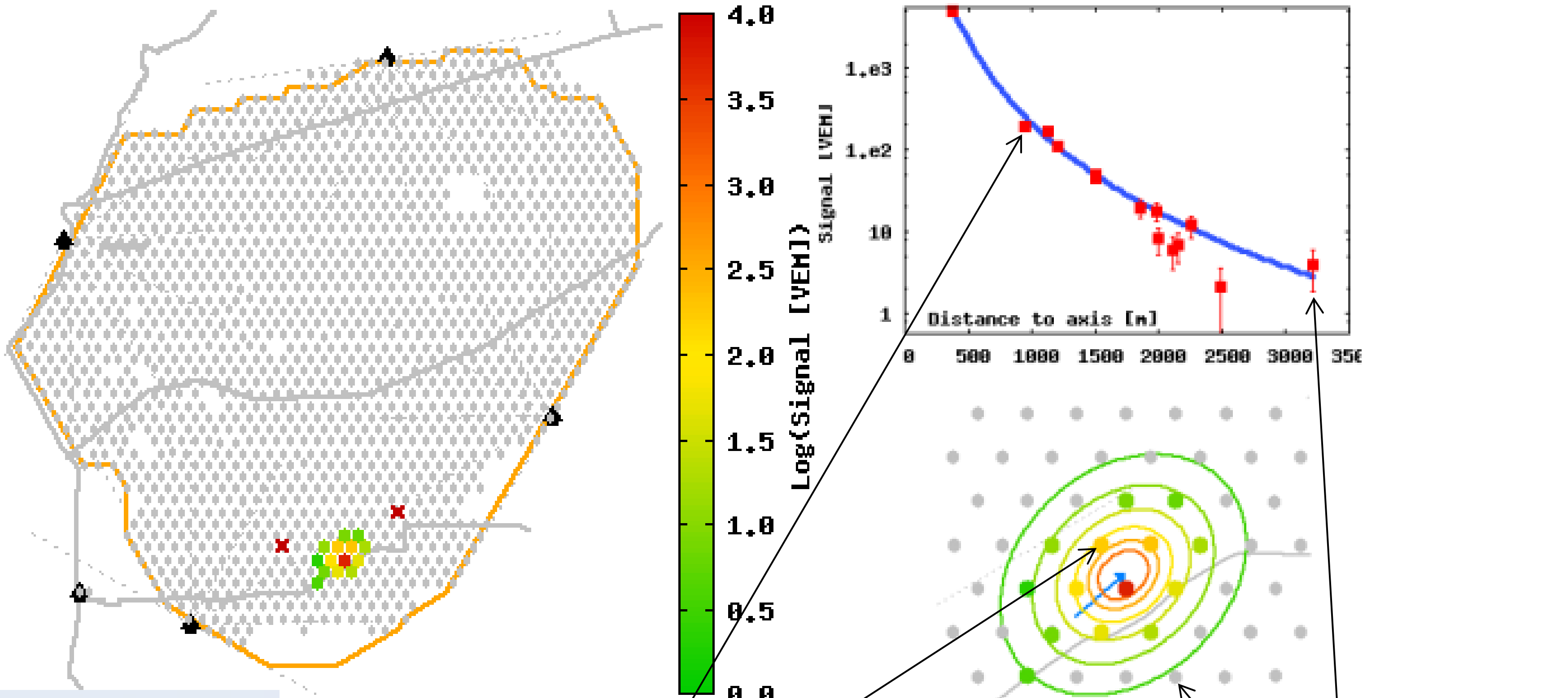
Installing the world largest particle detector



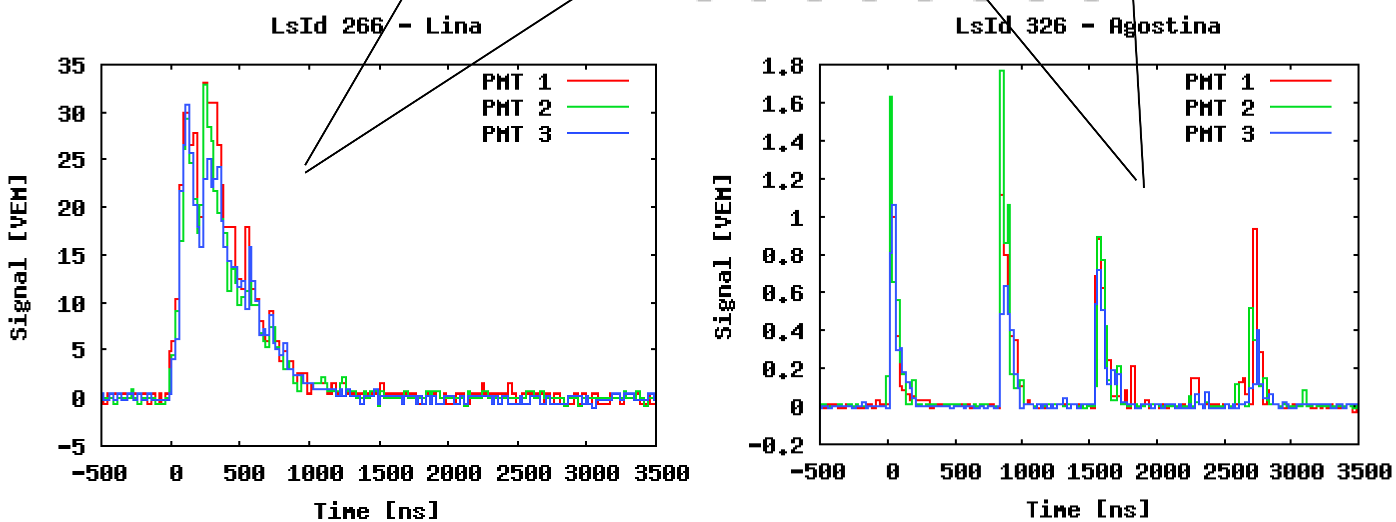
2016

Pierre Auger Observatory surface detectors

An UHECR event



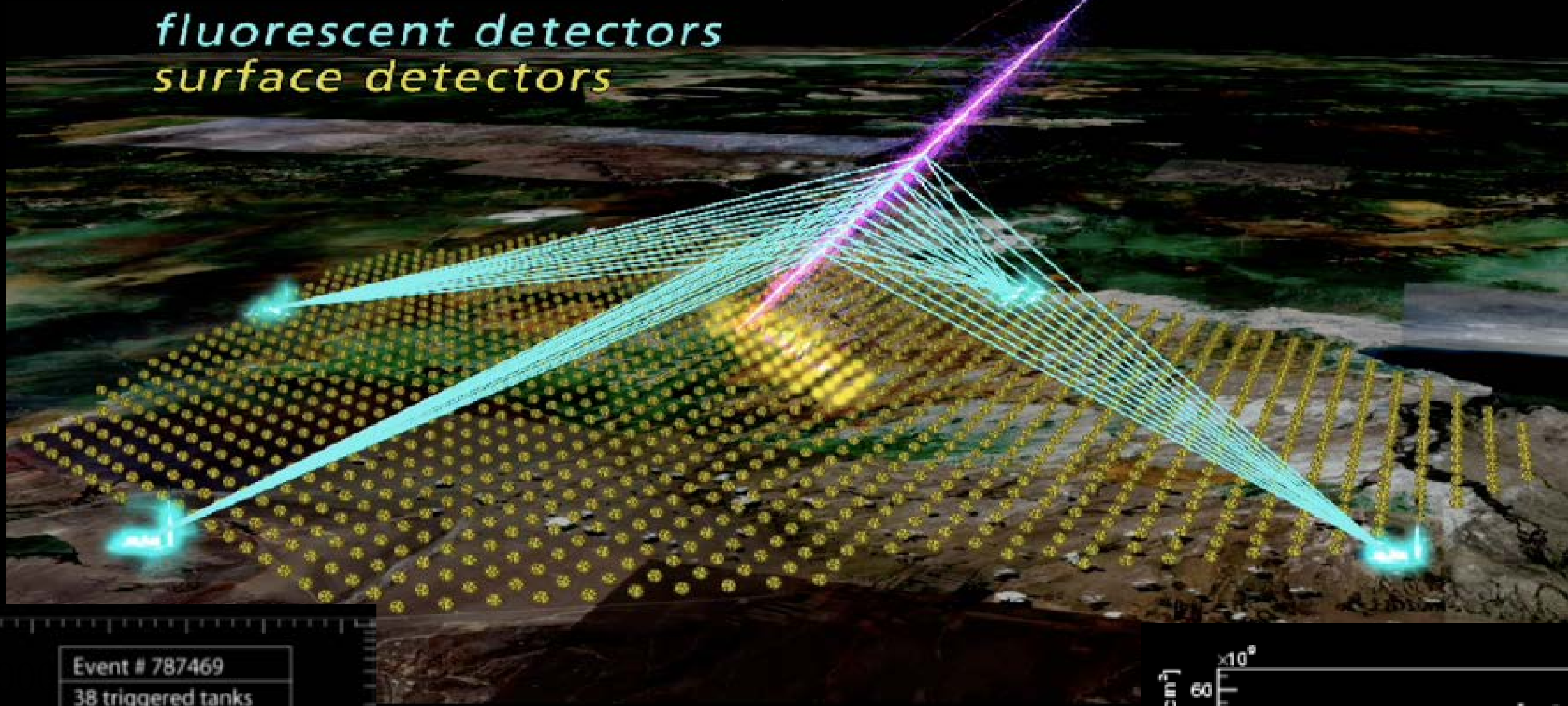
Generic Information	
Id / Date	10485600 / Tue Oct 26 17:39:16 2010
Nb. of stations	14
Energy	49.7 ± 1.9 EeV
Theta	40.2 ± 0.2 deg
Phi	-139.2 ± 0.2 deg
Curvature	10.9 ± 0.5 km
Core Easting	476053 ± 19 m
Core Northing	6079248 ± 12 m
Reduced Chi^2	8.36

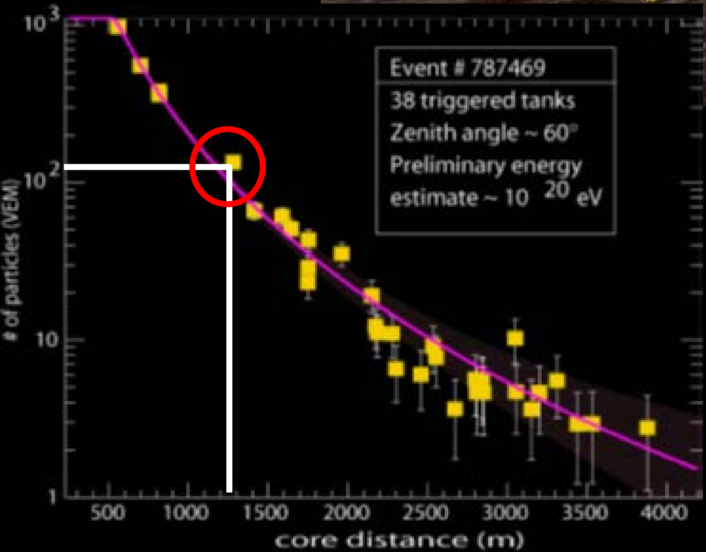


2016

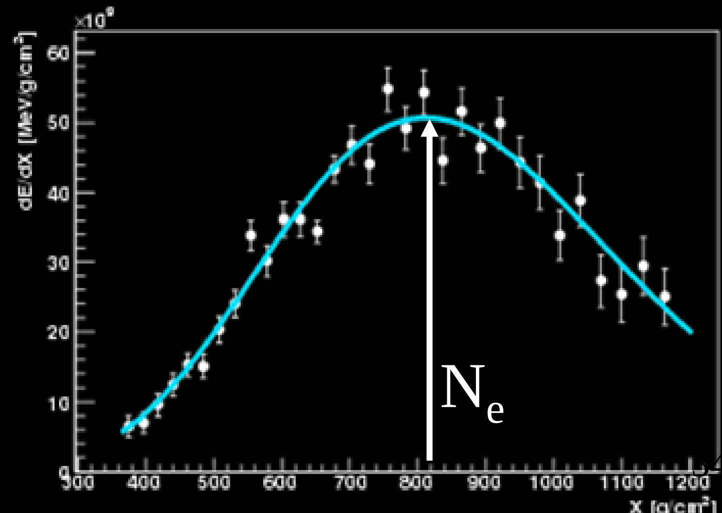
From EAS longitudinal profile to primary CR energy

The Hybrid "image" of the same shower, pioneered by Auger, increases as well the accuracy of the profile measurement.





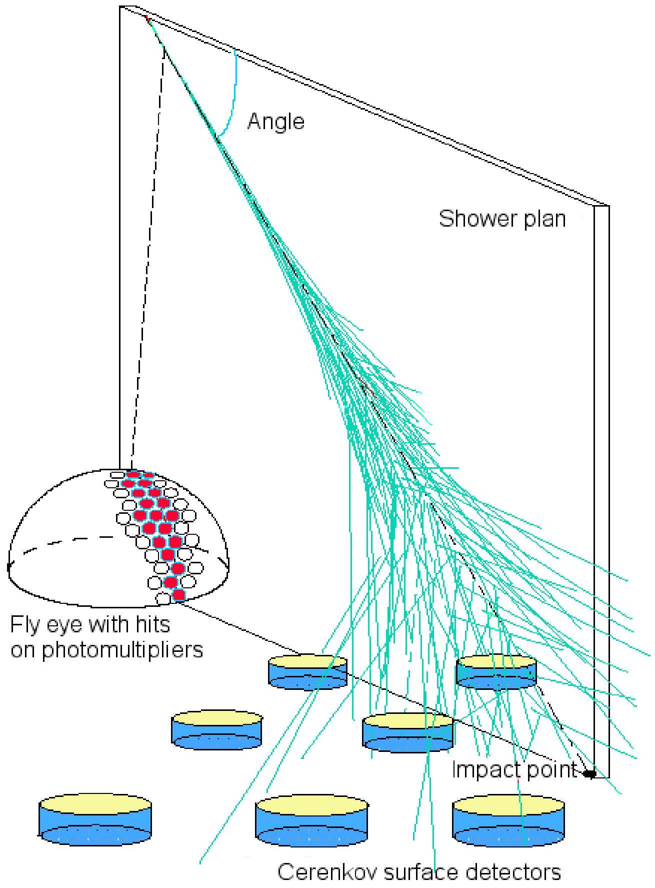
PROGRESS:
Calibration of SD energy estimator through FD



Improving measurements

Fluorescence vs Hybrid techniques :

	Hybrid	SD only	FD only
Angular resolution	0.2°	1-2°	3-5° (0.5° stereo)
Aperture	**Independent on E, mass, models.**	**Independent on E, mass, models.**	**Dependent on E, mass, models, spectral shape.**
Energy	**Independent on mass, models.**	**Dependent on mass, models.**	**Independent on mass, models.**



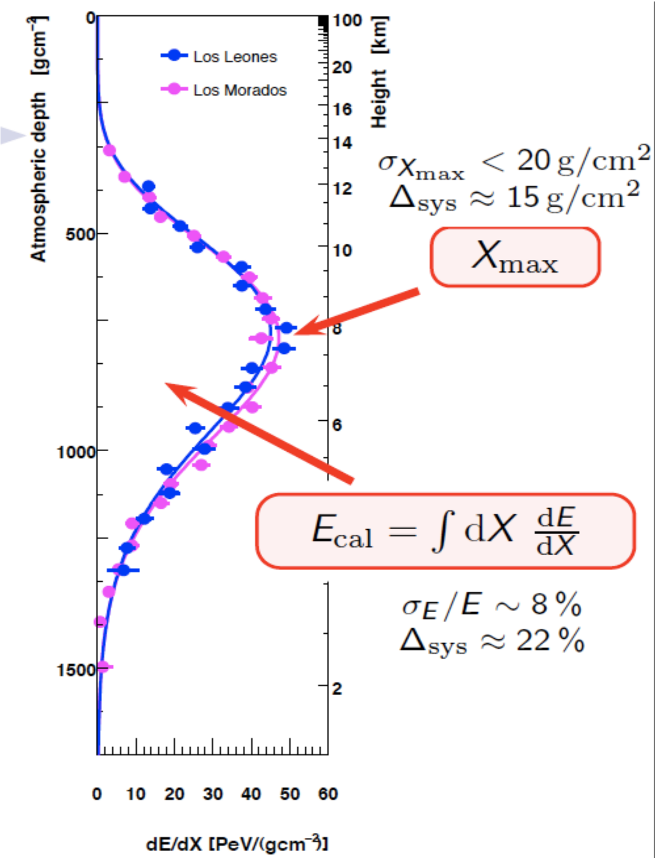
2016

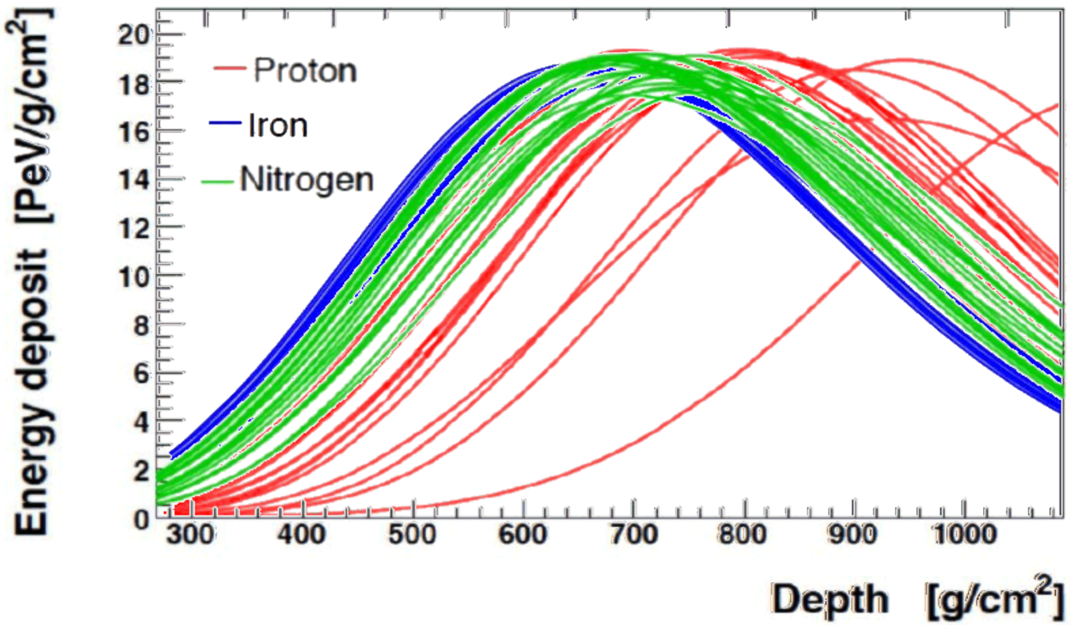
From EAS longitudinal profile to primary CR mass composition

Average depth of shower maximum $<X_{max}>$;

Width of distribution $RMS(X_{max})$ at a certain E

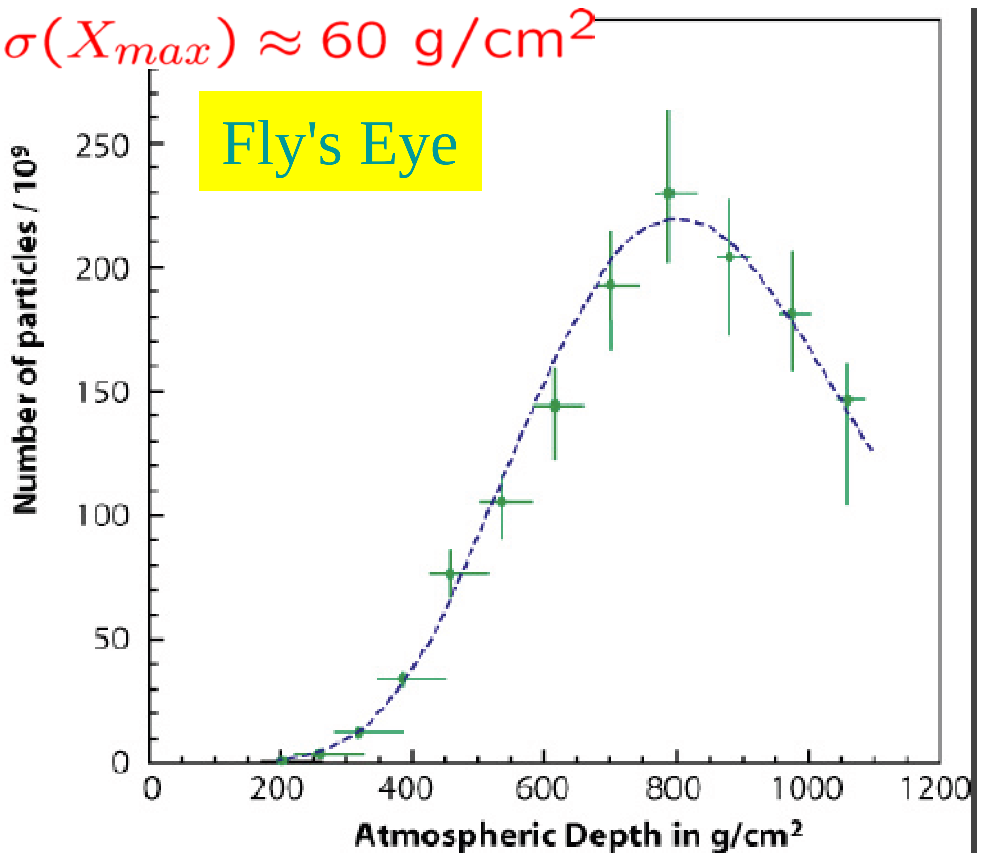
sensitive to primary composition

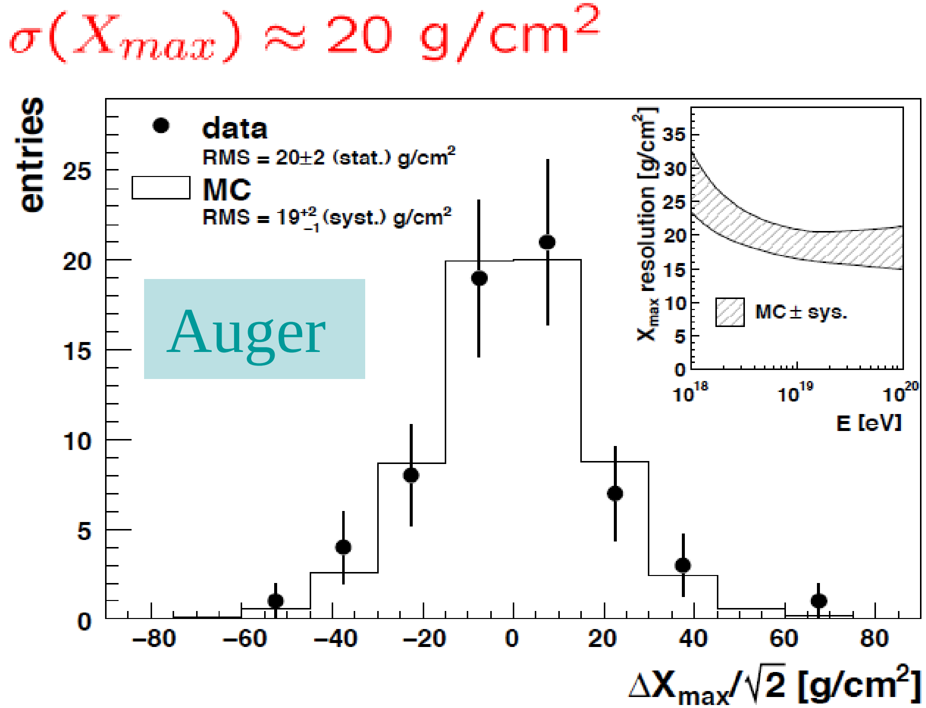




$$X_{max} \propto ln(E_0) - ln(A) \text{ (MC Sim.)}$$

From EAS longitudinal profile to primary CR mass





PROGRESS:

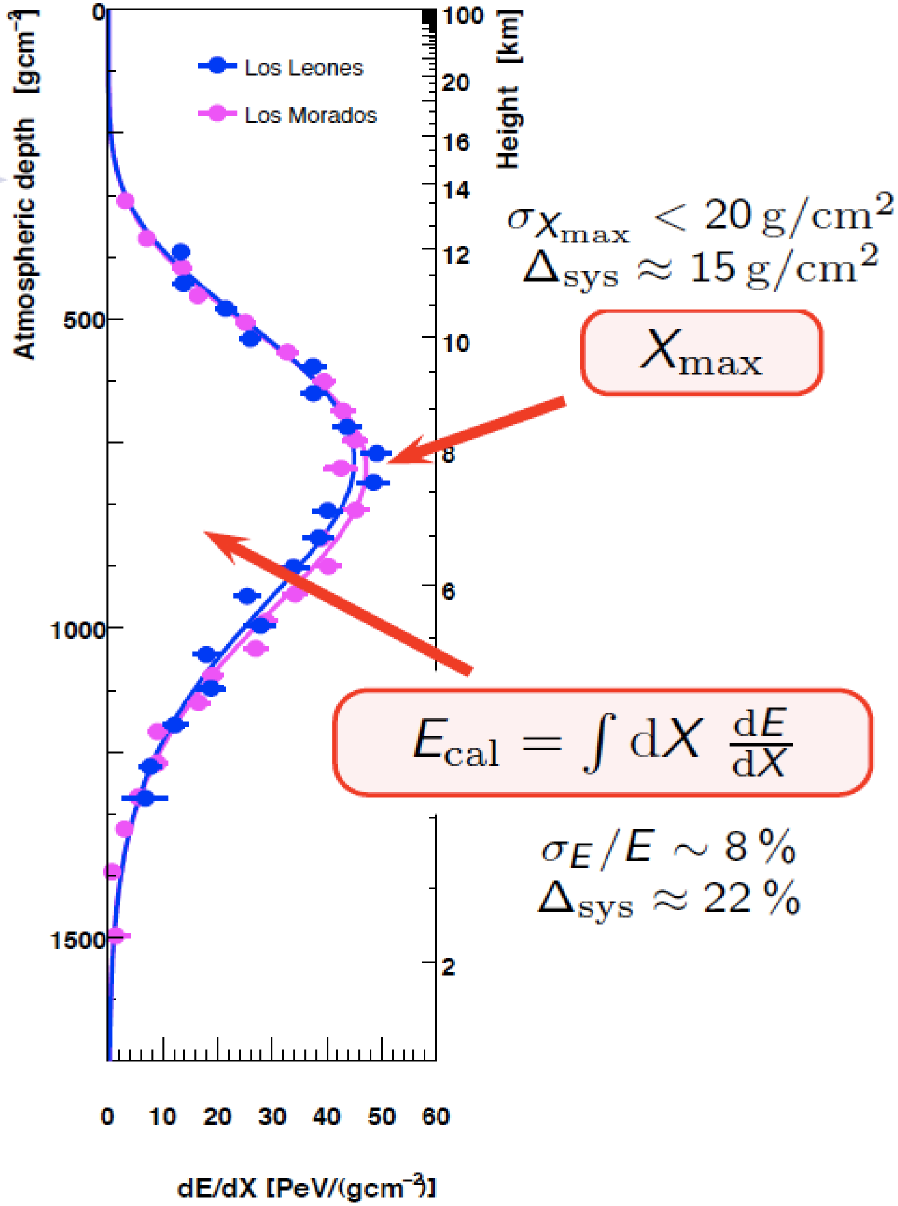
Fly's Eye showed experimental access to X_{max} through fluorescence

High precision now possible through higher resolution + stereo and hybrid measurements (around 20-25 g/cm^2)   N.B. : $< X_{max} >_{proton} - < X_{max} >_{iron} \approx 150$ g/cm^2

Delicate issues: great care in event selection (possible biases)

Important drawback: strong need for models in the interpretation

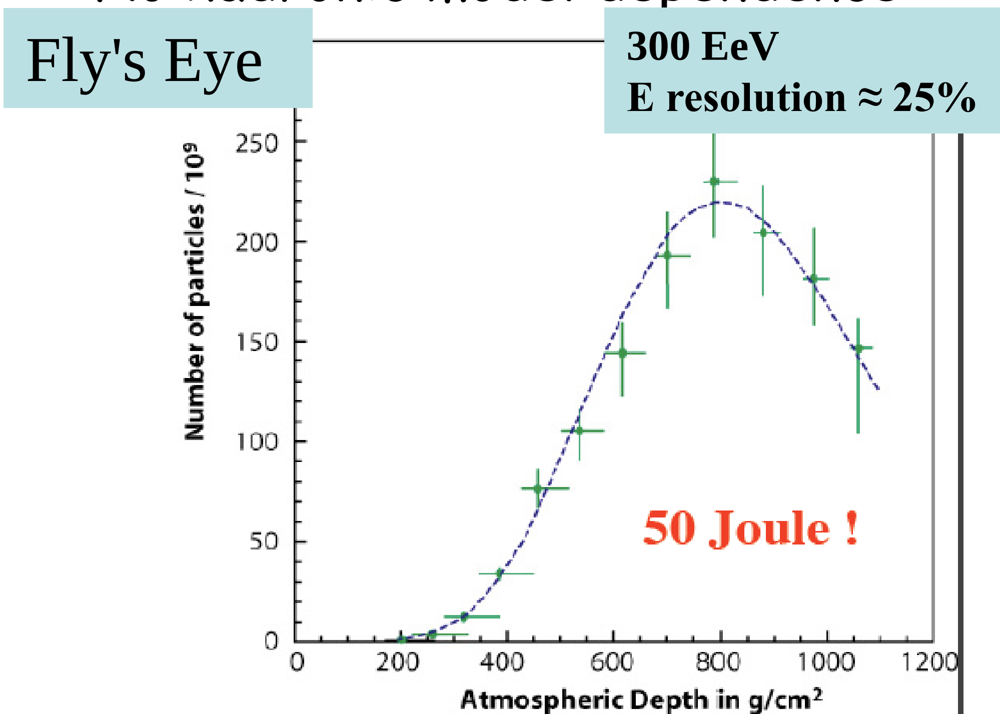
From EAS longitudinal profile to primary CR energy



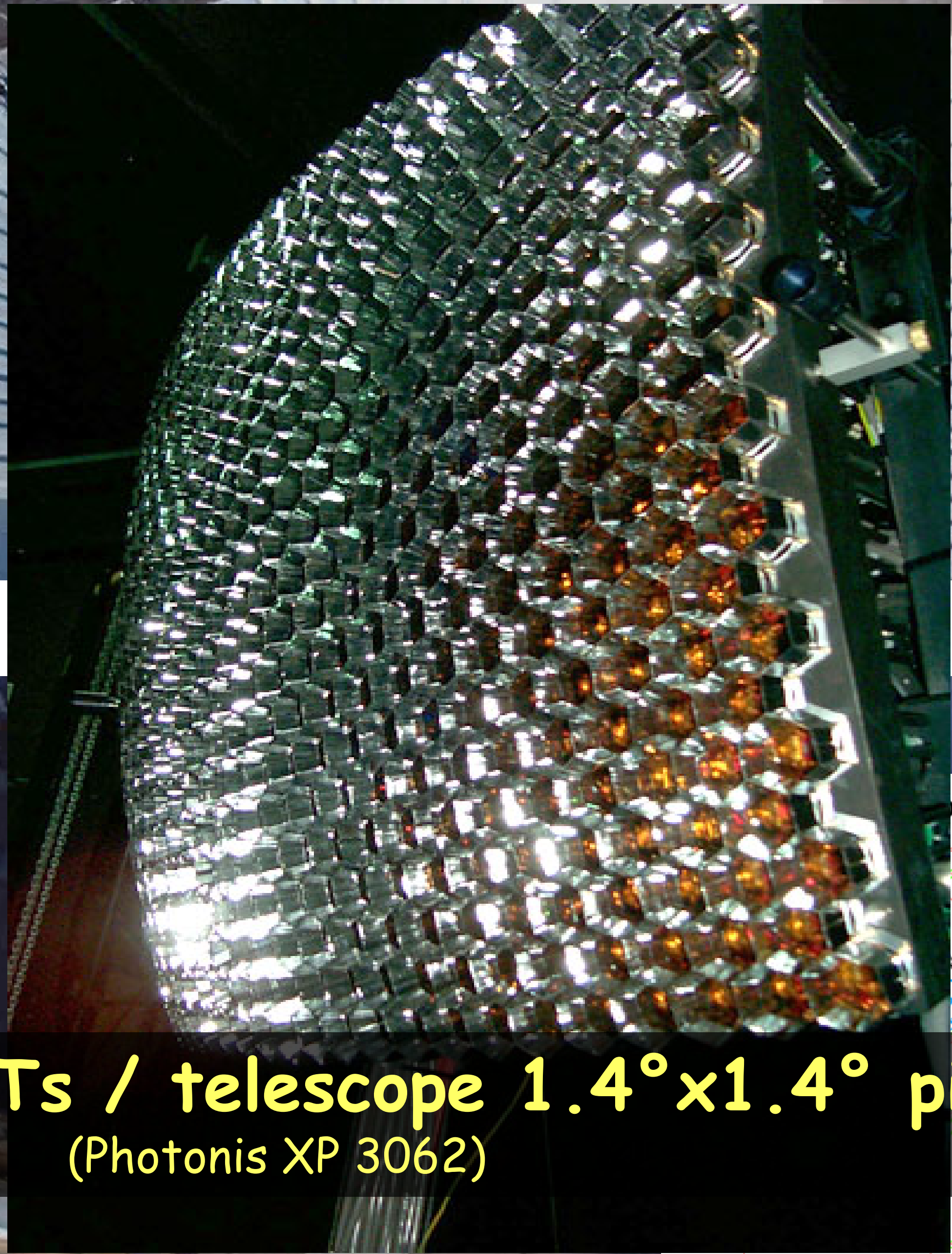
PROGRESS:

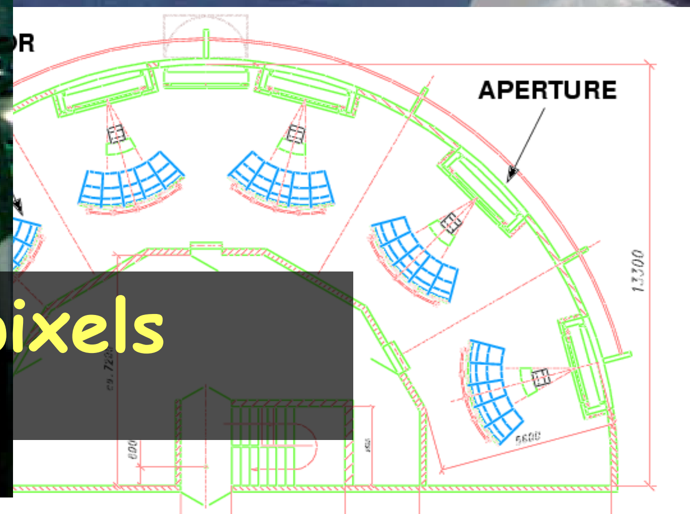
Calorimetric measurement of E with :

- Fluorescence technique
- Validated by Fly's Eye
- Largest uncertainty: fluorescence yield,
- Atmosphere, "missing" energy
- No hadronic model dependence



FD at 4 sites:
each 6 telescopes 30°x30° field of view each





440 PMTs / telescope 1.4°x1.4° pixels

(Photonis XP 3062)

Pierre Auger Observatory fluorescence detectors

2016

Pierre Auger Observatory fluorescence detectors

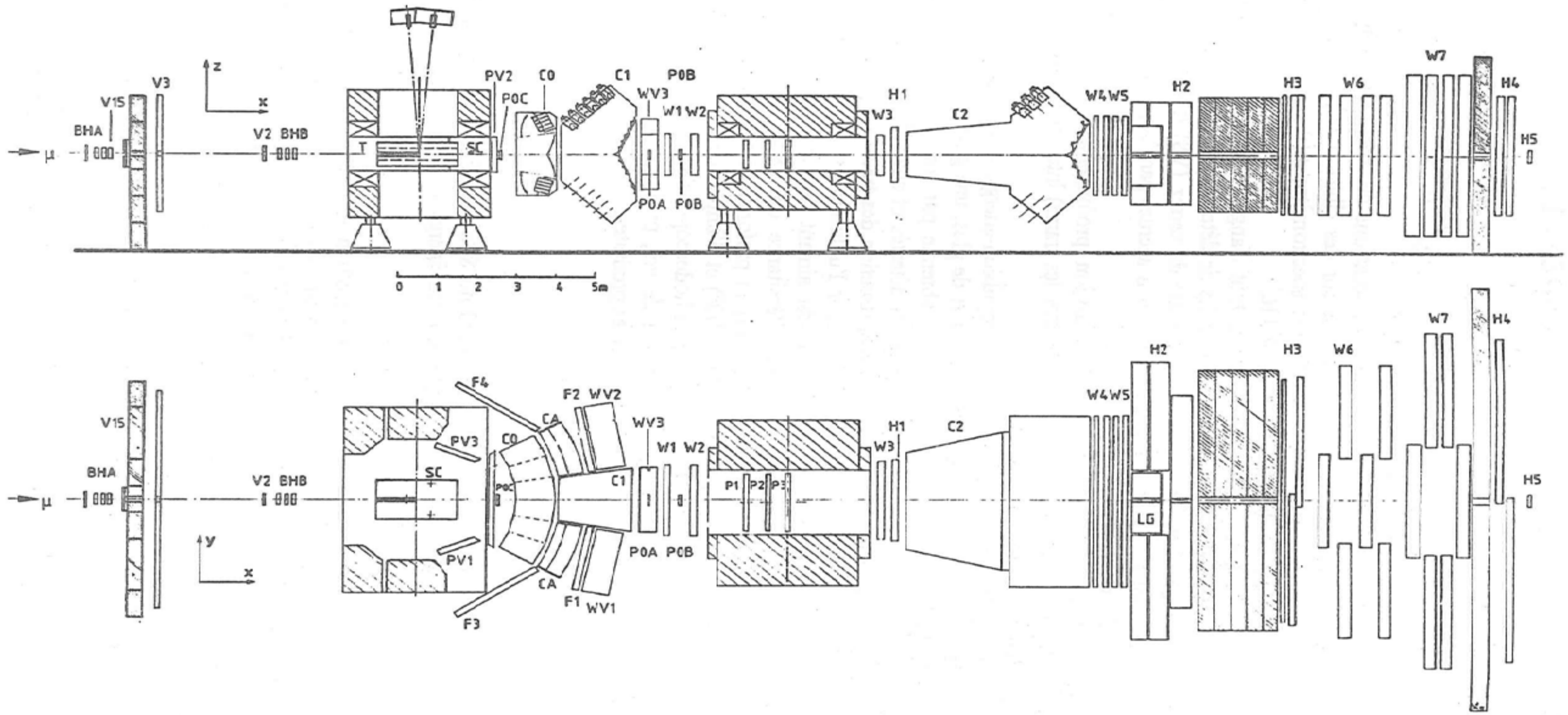
2016

IDENTIFYING PARTICLES MEASURING PARTICLE VELOCITY

Threshold Cherenkov counters

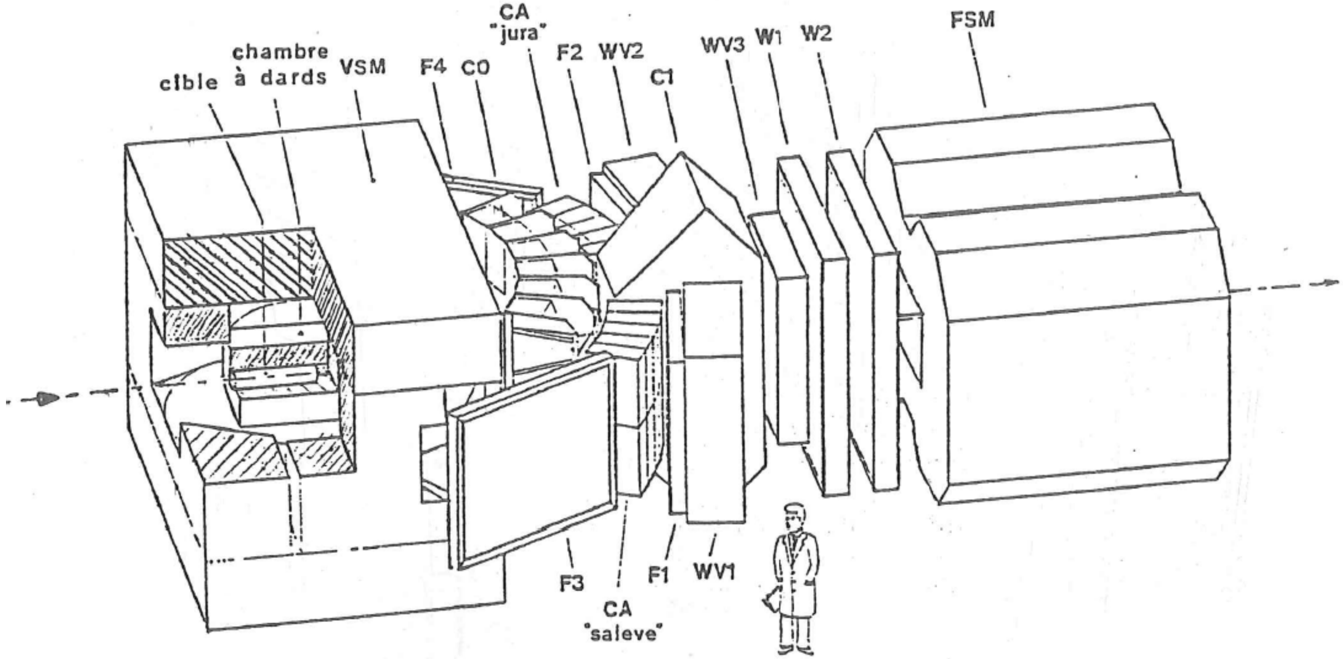
2016

- Hundredth of examples on fix target experiments, where different threshold cherenkov can be used to separate particle masses over a large range of momentum and over large solid angles.
- for example NA9:



Threshold Cherenkov

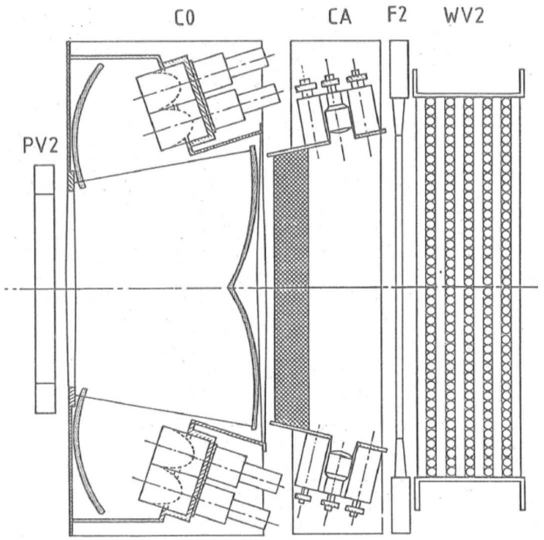
- NA9:



Detecteur	Couverture angulaire horizontale	Zone sensible (cm²)	Taille des cellules	Radiateur n − 1 = (valeurs approximatives)	Valeurs des seuils π/K/p (Gev/c)
F1,F2 F3,F4	±(10 − 34)° ±(32 − 60)°	160× 106 160× 252	160× 10 160× 15	NE 110 NE 110	π/K < 1,5 K/P < 2,5
CA	±(10 − 32)°	2× 150× 130	65× 30	aérogel 0,030	0,6/2/3,8
C0	±32°	2× 300× 100	12× 14 25× 28	néopentane 0,0015	2,6/9,1/17
C1	±9°	109× 143	14× 18	azote 3×10^{-4}	5,6/20/38
C2	±7°	150× 300	23× 25	néon 6×10^{-5}	12/42/79

Threshold Cherenkov

- **NA9:**



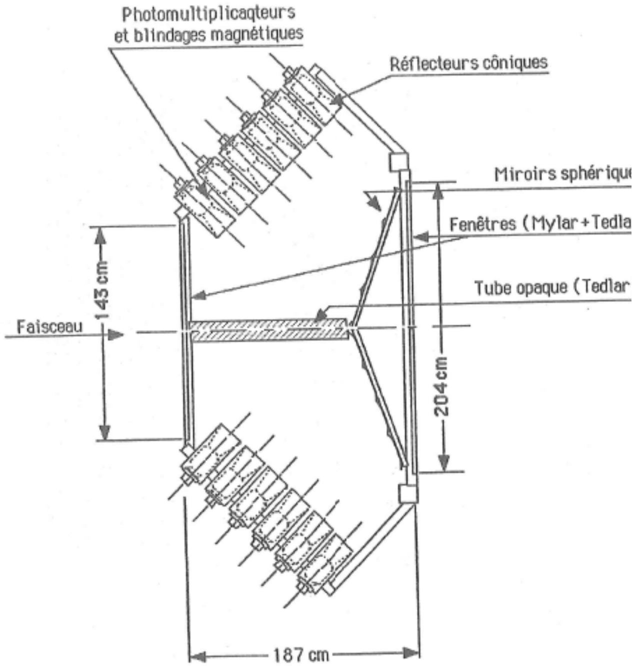


Figure 14: Le compteur Cerenkov C1

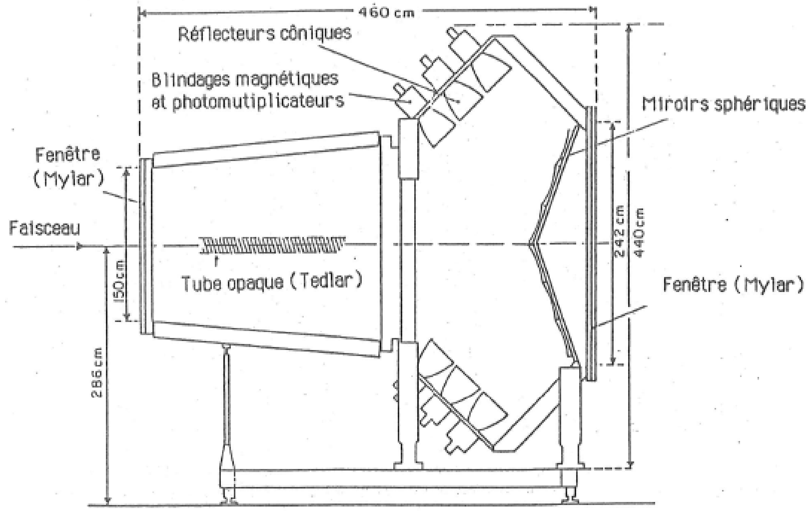


Figure 15: Le compteur Cerenkov C2

Threshold Cherenkov

- NA9:

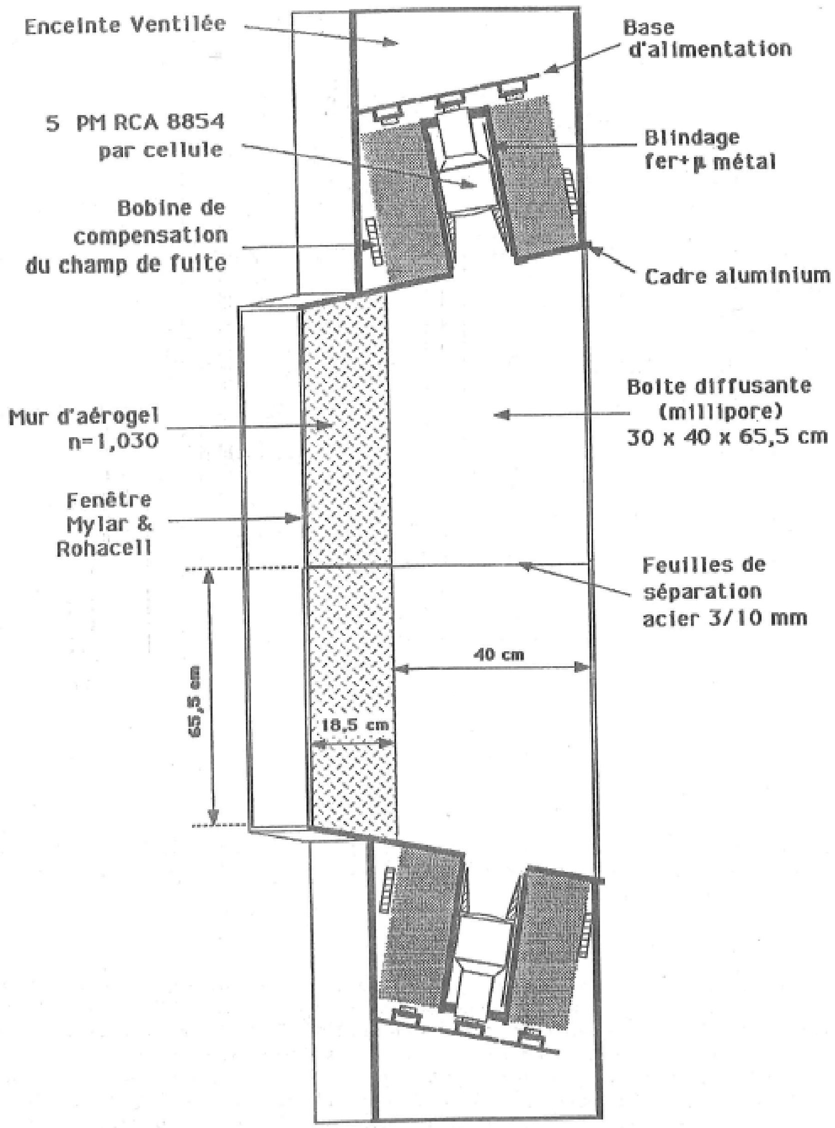
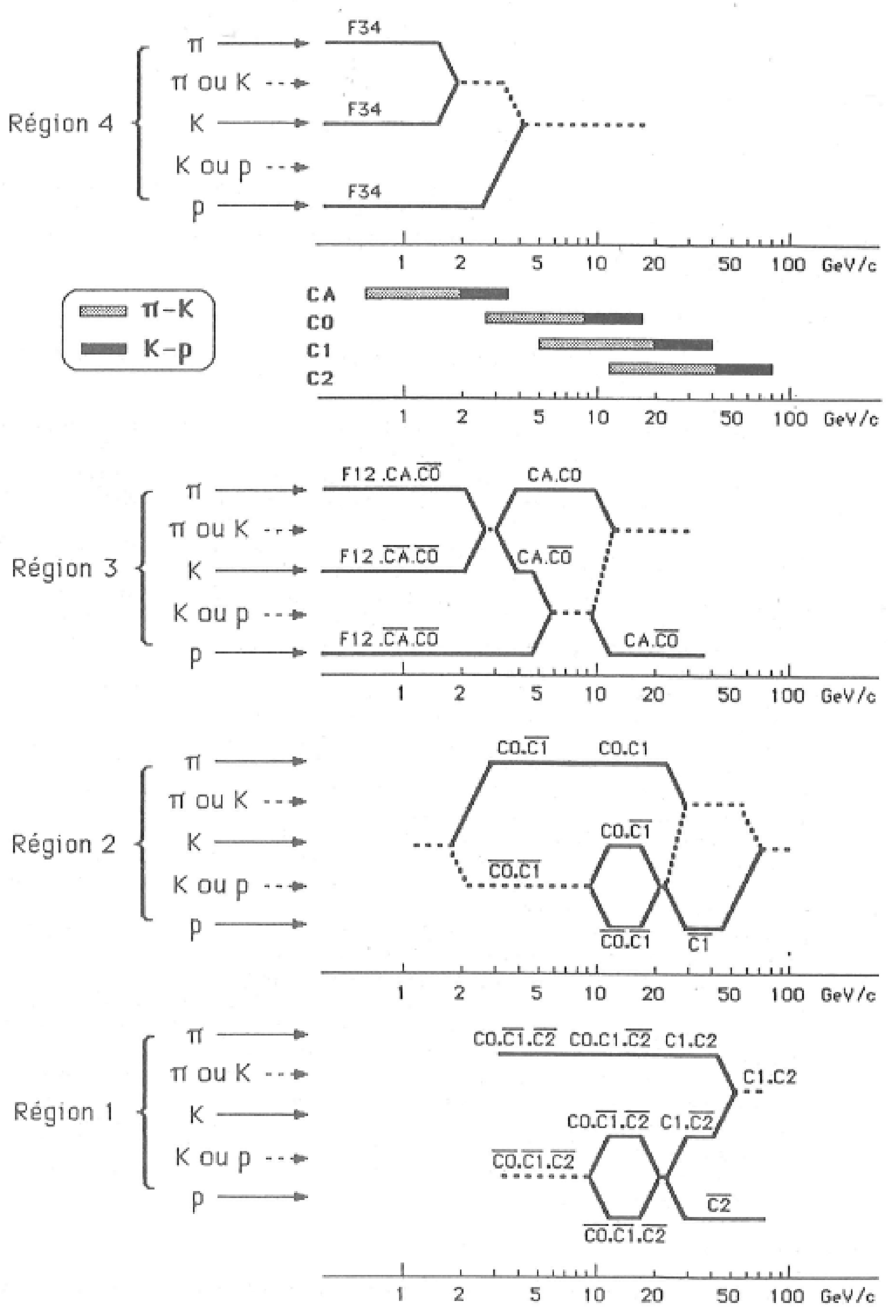


Figure 16: Vue en coupe du compteur Cerenkov à aérogel

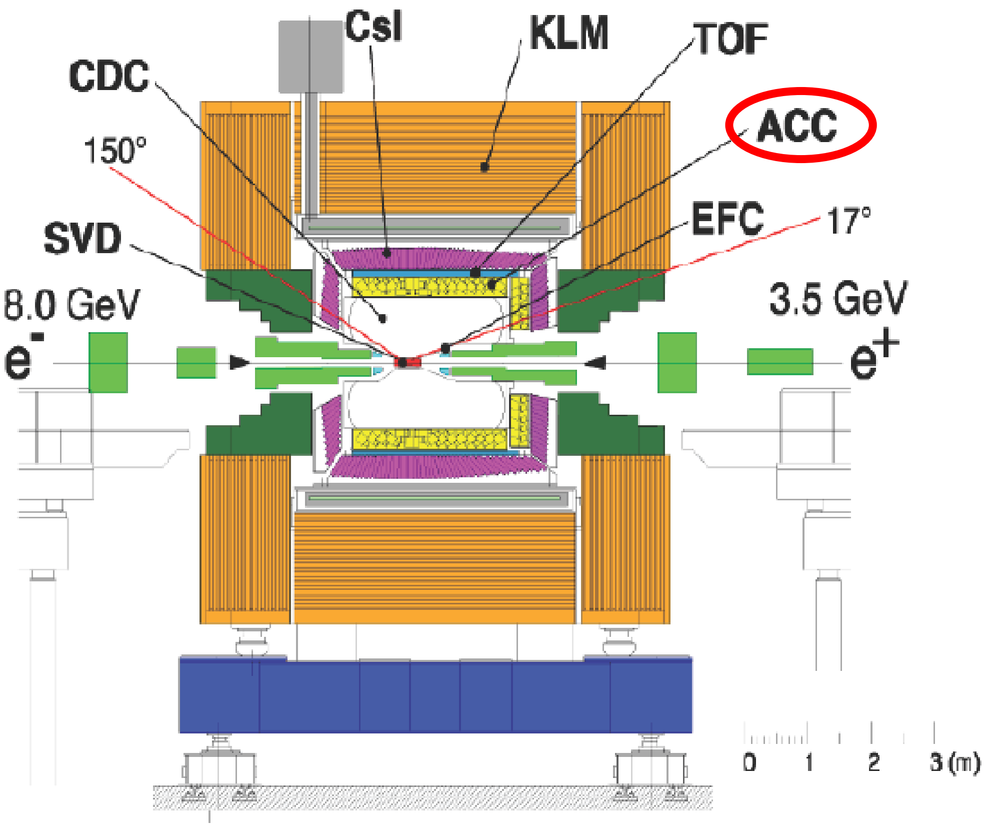
Threshold Cherenkov

- **NA9:**



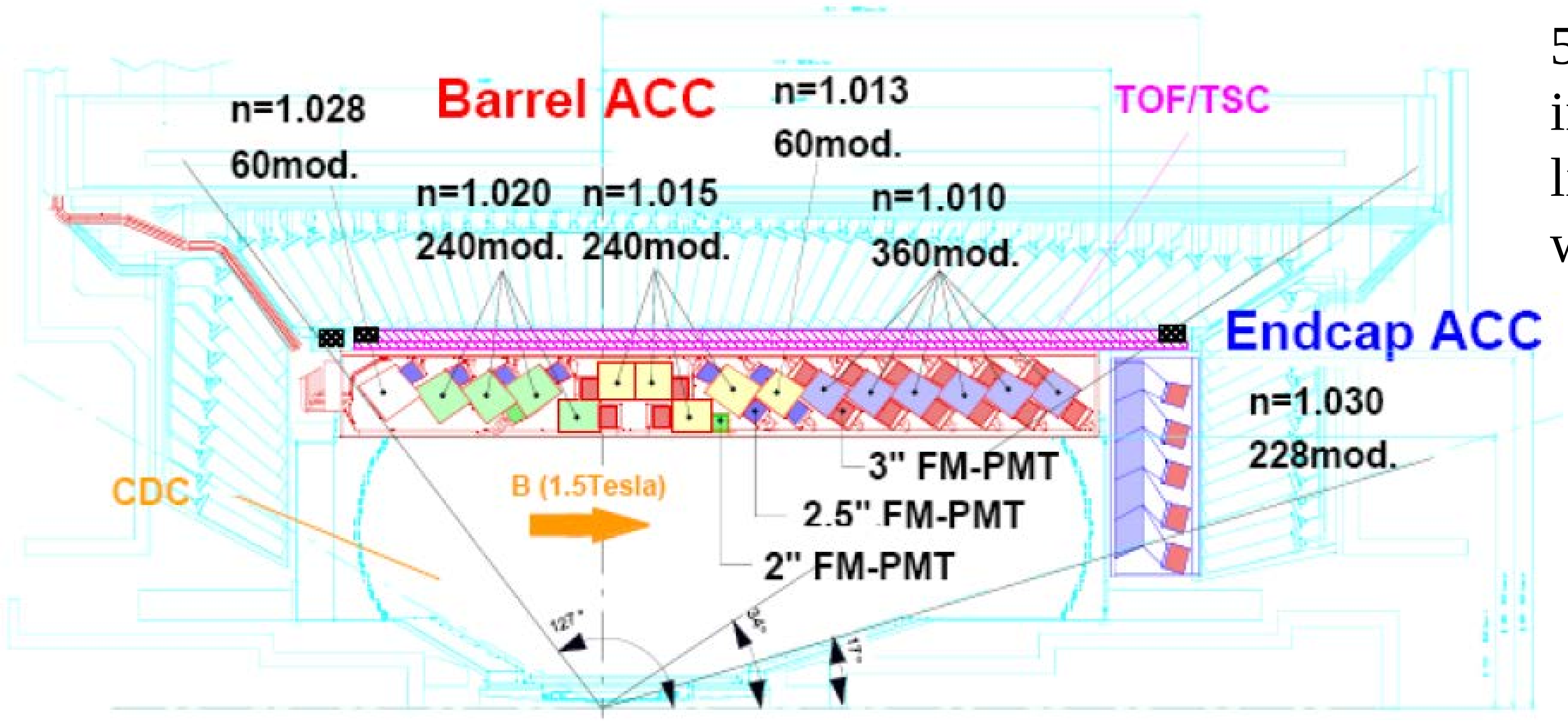
Threshold detectors

- A more recent example BELLE at KEKB
- CP violation in B mesons at e+e- collider.
- Current design: threshold aerogel Cherenkov counters to help discriminate π from K



Threshold detectors

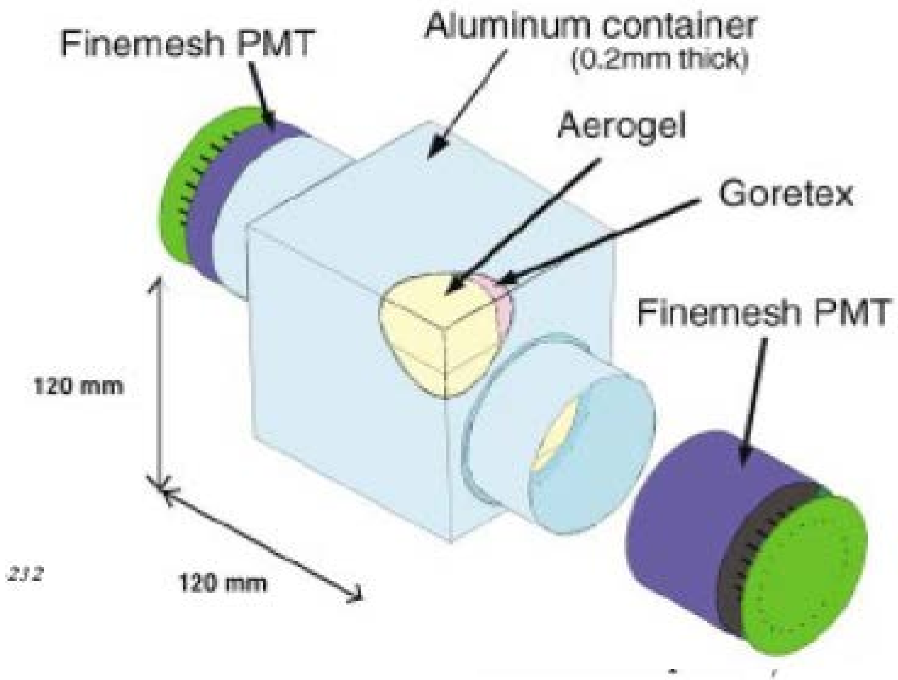
- A more recent example BELLE at KEKB



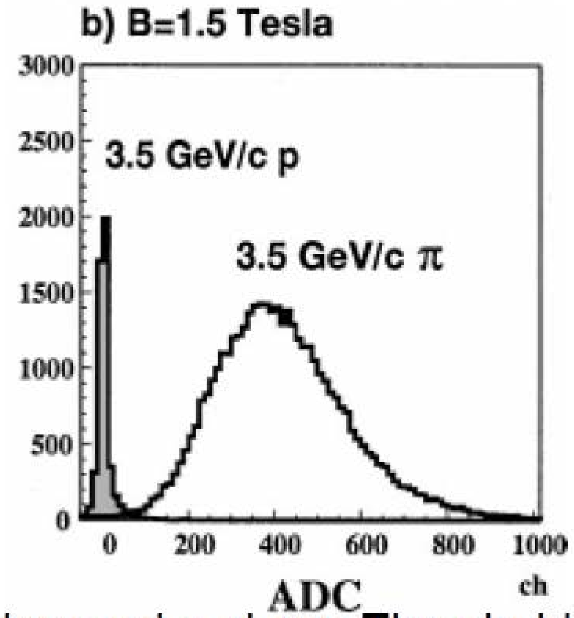
5 aerogel tiles inside a boxed lined with white reflector

Threshold detectors

- A more recent example BELLE at KEKB



- Approx . 20 photoelectrons per Pion detected at 3.5 GeV/c
- More than 3σ separation



p below and π above Threshold

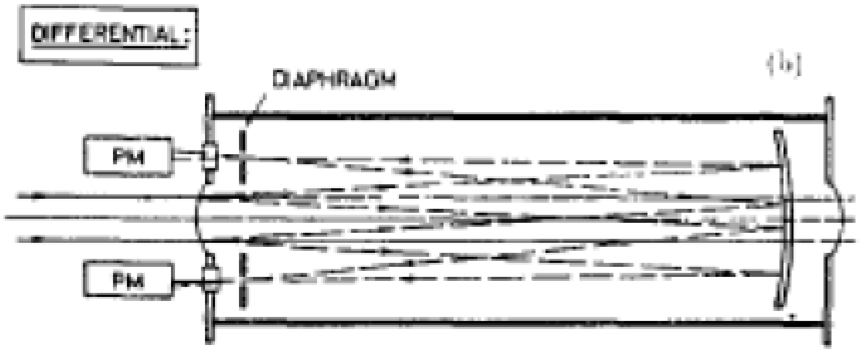
2016

IDENTIFYING PARTICLES

MEASURING THE CHERENKOV ANGLE: DIFFERENTIAL, RICH, DIRC,

Differential Cherenkov Counters

- Used along beam lines to discriminate masses.
- Mesons beams ($\pi^{\pm}$, $K^{\pm}$), hyperon beams etc…
- Example: CEDAR at CERN



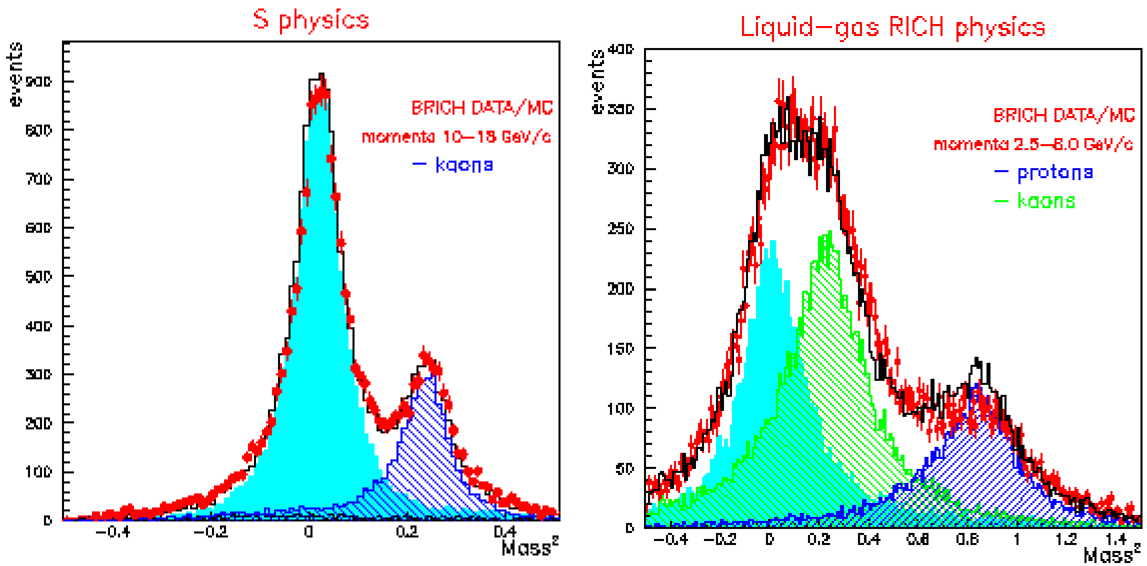
With a Gas radiator

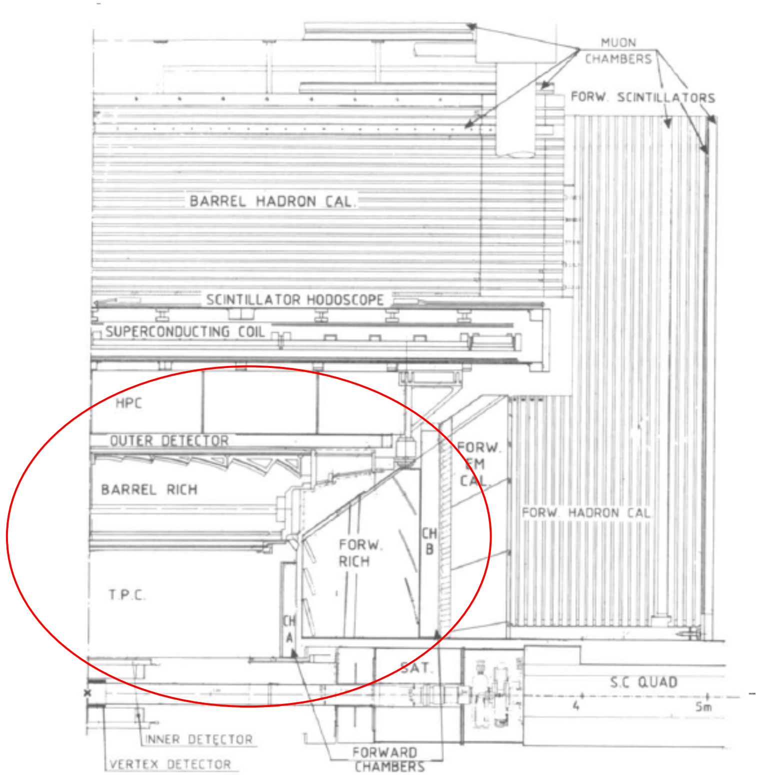
			CEDAR - W	CEDAR - N
Velocity resolution		$\Delta\beta$	$5 \cdot 10^{-6}$	10^{-6}
Radiator	gas		N_2	He
	length	L	5.8 m	5.8 m
	pressure	P	1.6 - 8 bar	10 - 14 bar
	C angle	θ	30.8 mrad	25.8 mrad

RICH detectors

2016

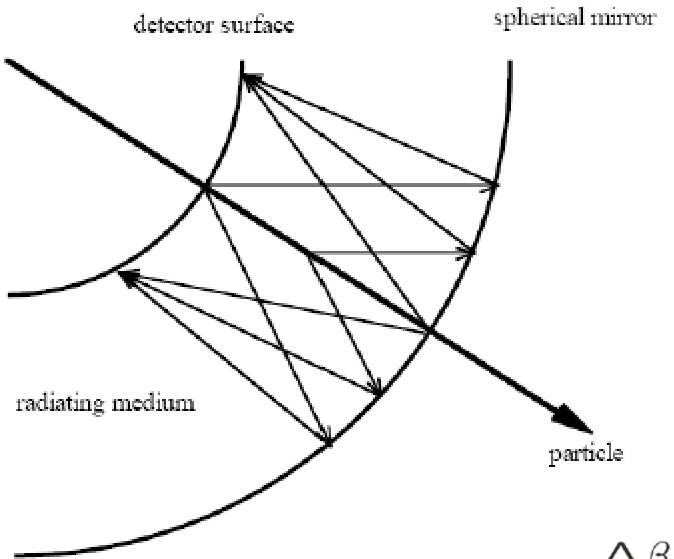
- Ring Imaging Cherenkov detectors
- First used on a fix target experiment, the OMEGA spectrometer at CERN (J. Séguinot & T. Ypsilantis)
- Major breakthrough with the DELPHI RICH
- Liquid and gas fluorocarbon radiators (2 detectors in //)
- Optimized for π / K / p separation up to 30 GeV/c

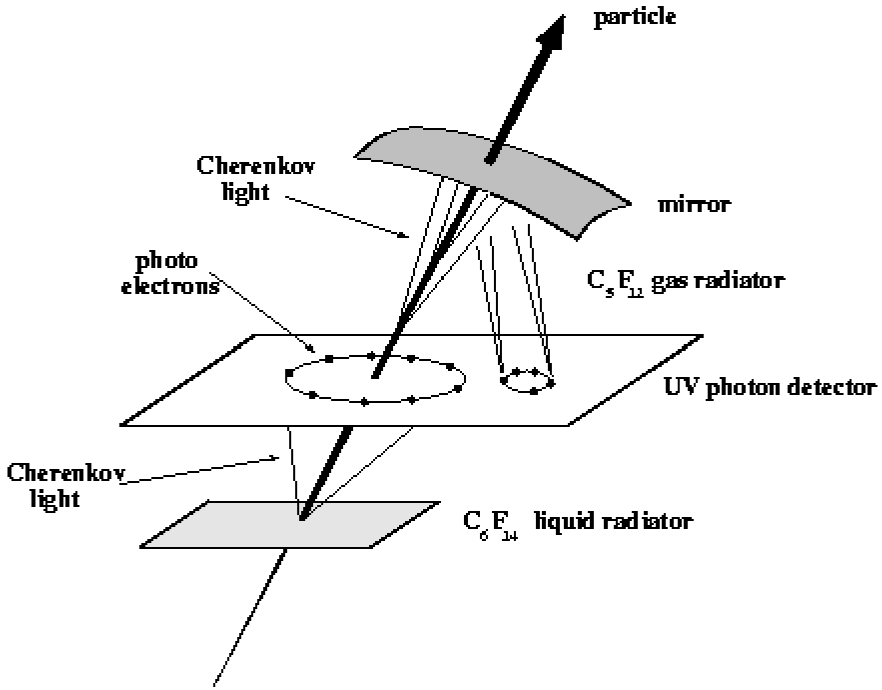




RICH detectors

- Ring Imaging Cherenkov detectors: measure both θ_C and N_{ph}





$$\frac{\Delta\beta}{\beta} = \tan(\theta)\Delta\theta_C$$

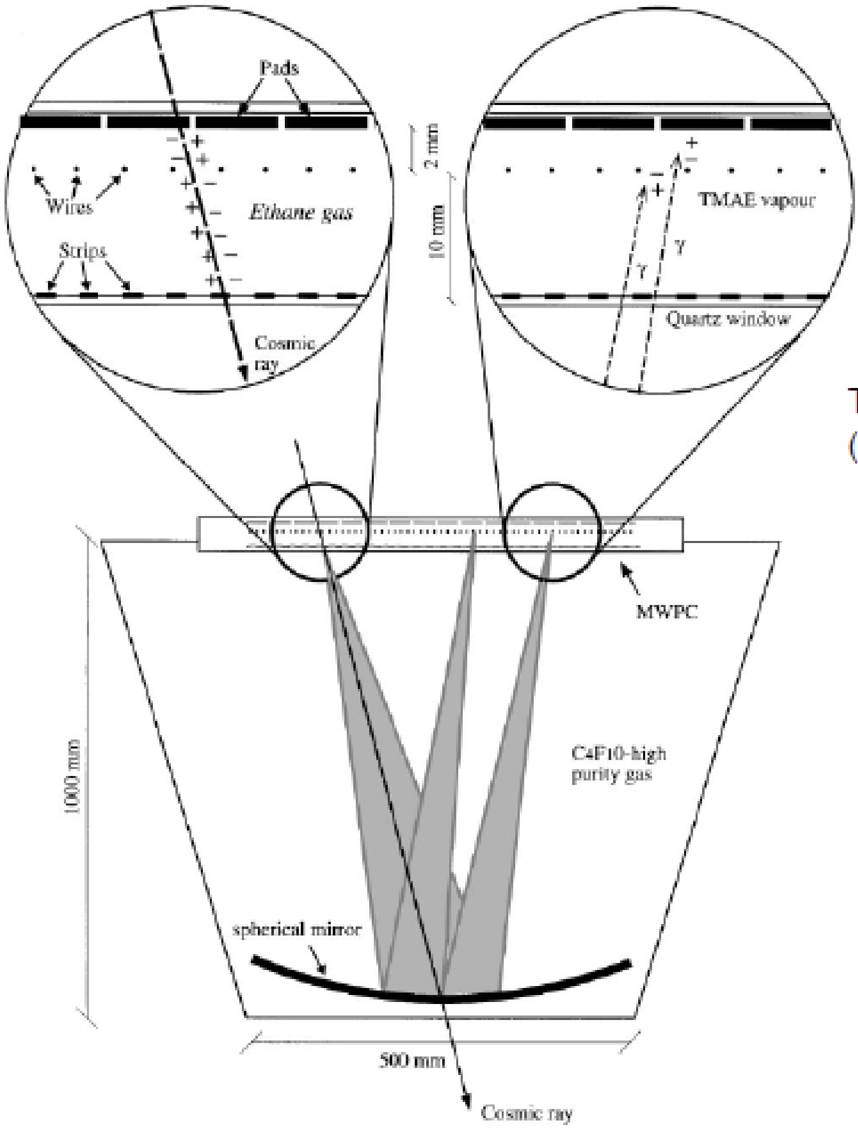
where $\Delta\theta_C = \langle\Delta\theta\rangle/\sqrt{N_{\text{ph}}} + C$

For 1.4m long CF_4 gas radiator at stp and $N_0 = 75\text{cm}^{-1}$,
$\frac{\Delta\beta}{\beta} = 1.6 \cdot 10^{-6}$

RICH also for astroparticles

Balloon Experiment:
RICH detector

CAPRICE Experiment

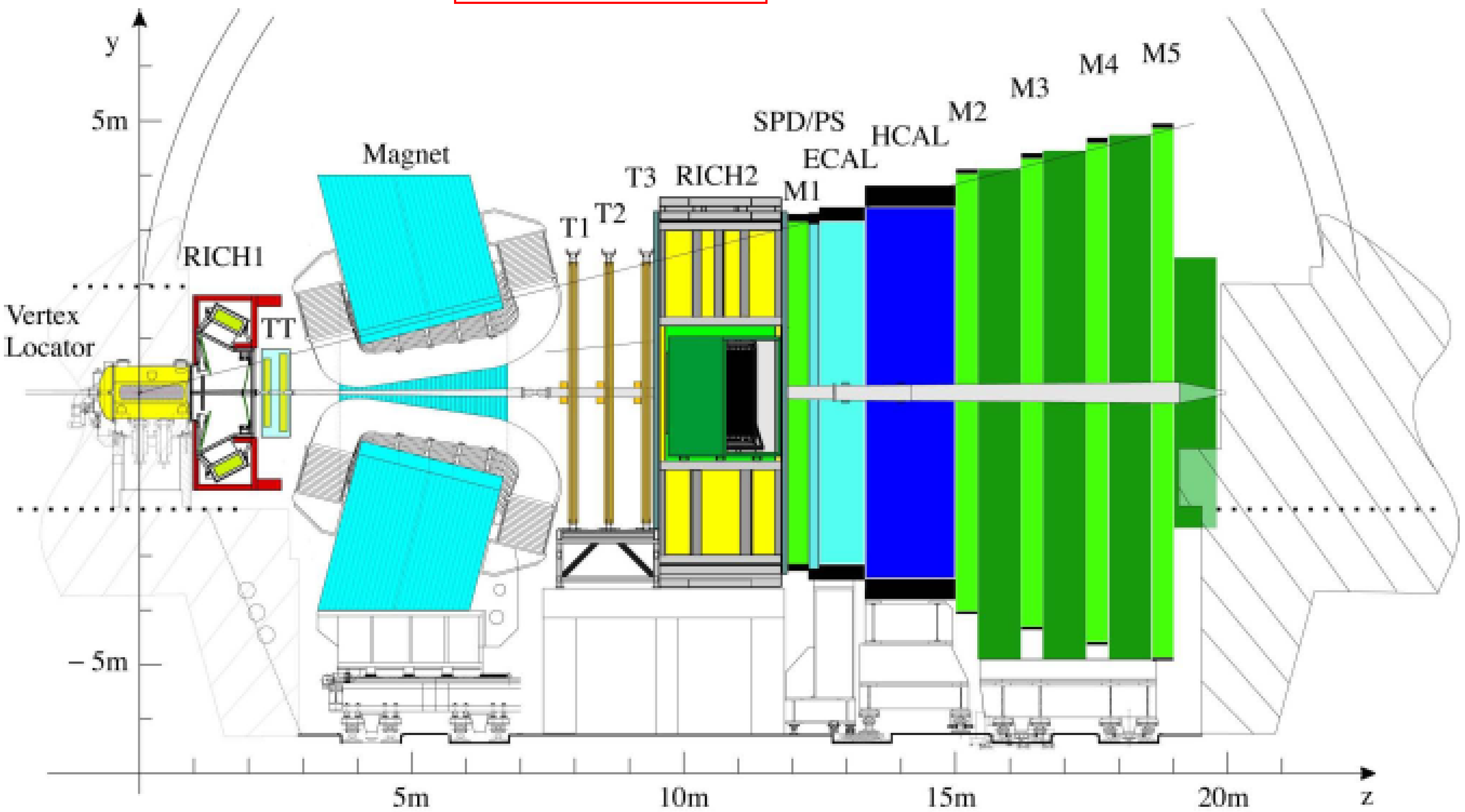


TMAE:
(tetrakis(dimethylamino)
ethylene)

25

LHCb RICH

LHCb Experiment



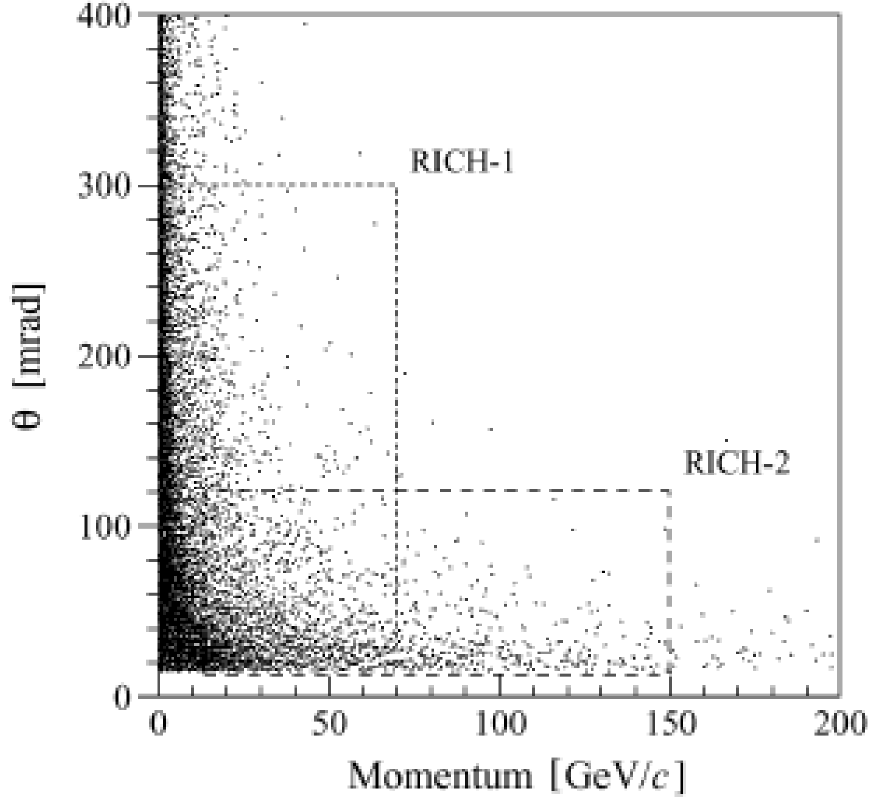
- ➤ Precision measurement of B-Decays and search for signals beyond standard model.
- ➤ Two RICH detectors covering the particle momentum range 1→100 GeV/c using aerogel, C_4F_{10} and CF_4 gas radiators.

LHCb RICH

2016

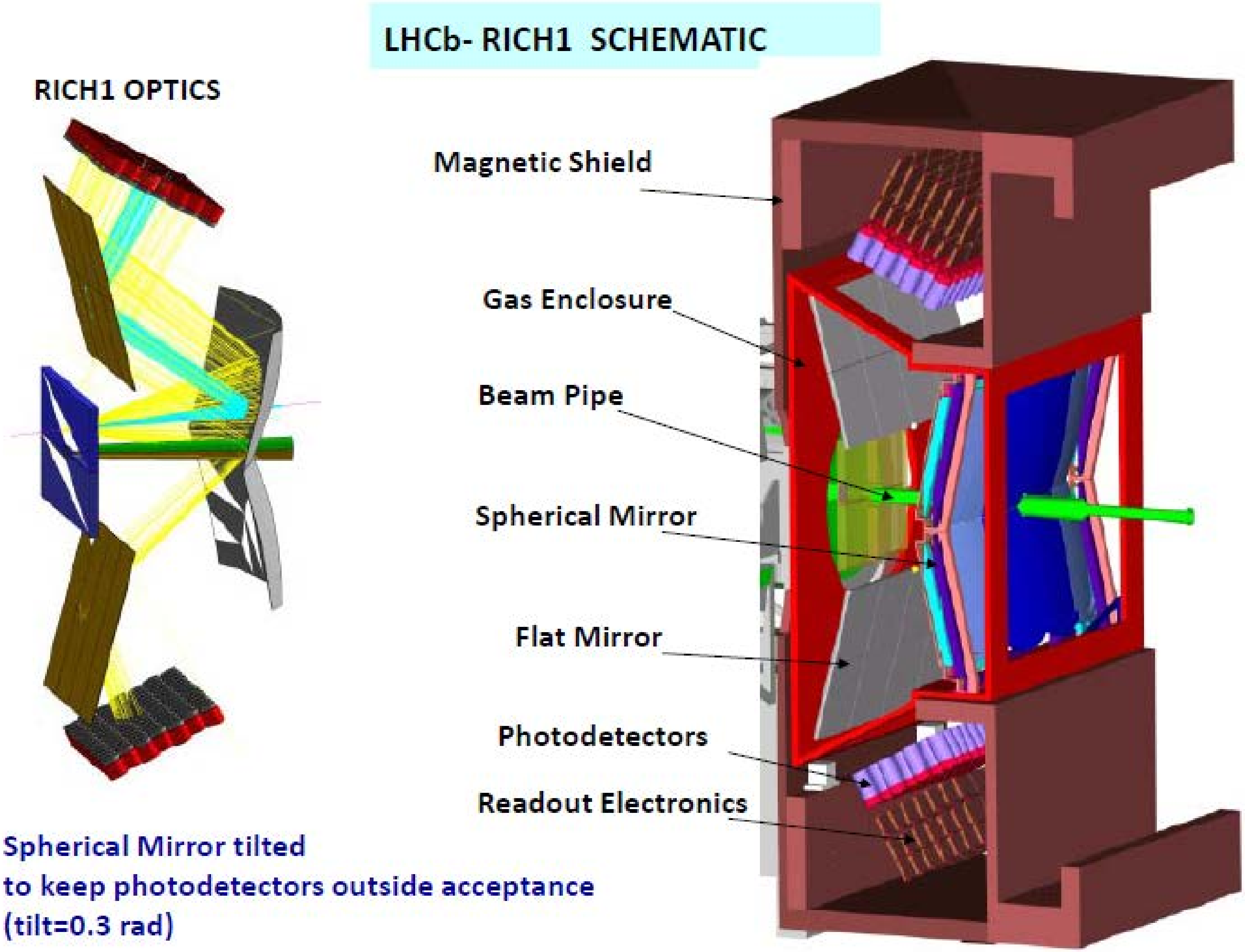
LHCb-RICH Design

RICH1: Aerogel L=5cm p:2→10 GeV/c
n=1.03 (nominal at 540 nm)
C_4F_{10} L=85 cm p: < 70 GeV/c
n=1.0014 (nominal at 400 nm)
Upstream of LHCb Magnet
Acceptance: 25→250 mrad (vertical)
300 mrad (horizontal)
Gas vessel: 2 X 3 X 1 m^3



RICH2: CF_4 L=196 cm p: < 100 GeV/c
n =1.0005 (nominal at 400 nm)
Downstream of LHCb Magnet
Acceptance: 15→100 mrad (vertical)
120 mrad (horizontal)
Gas vessel : 100 m^3

LHCb RICH

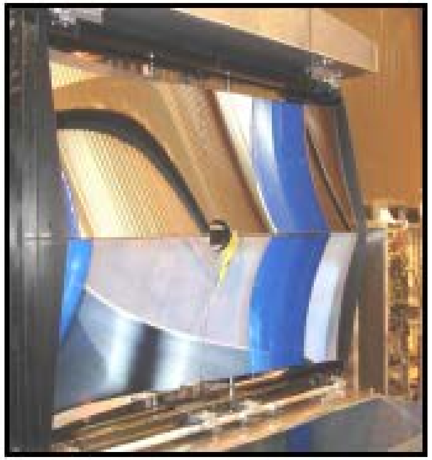


- Spherical Mirror tilted to keep photodetectors outside acceptance (tilt=0.3 rad)

LHCb RICH

RICH1 Photos

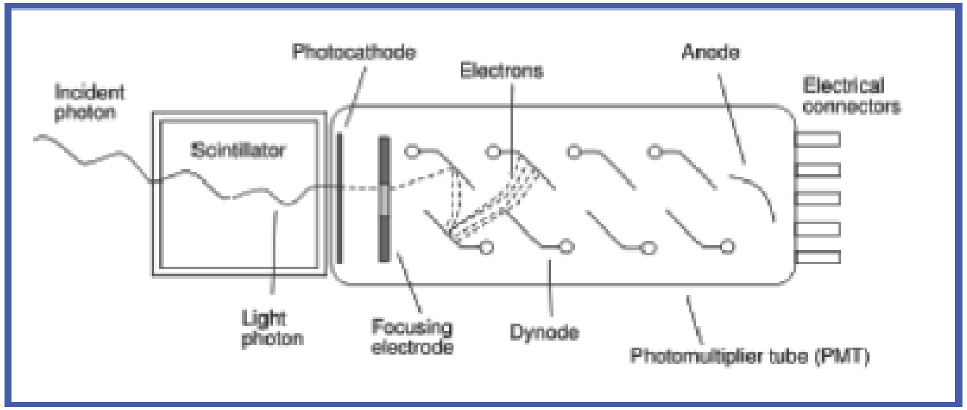
RICH1-HPDs



RICH1 mirrors

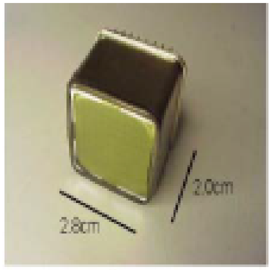
LHCb RICH

Vacuum Based Photodetectors

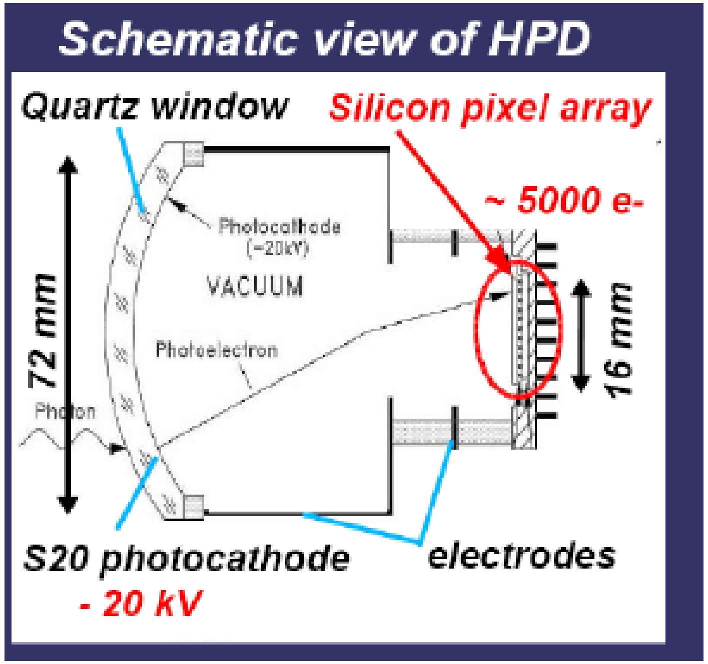


Schematic of a photomultiplier tube coupled to a scintillator.

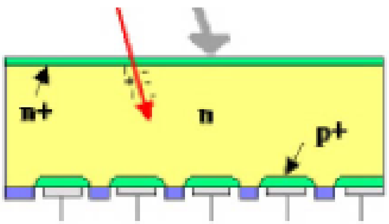
PMTs



MAPMT



- PMTs Commercially produced: more info in www.sales.hamamatsu.com



Silicon detector of HPD

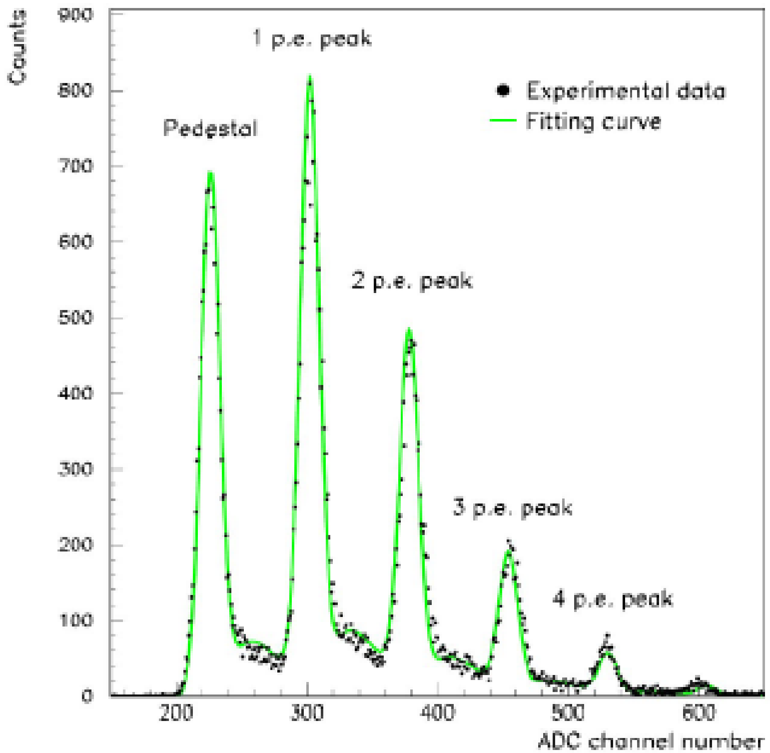
HPD

28

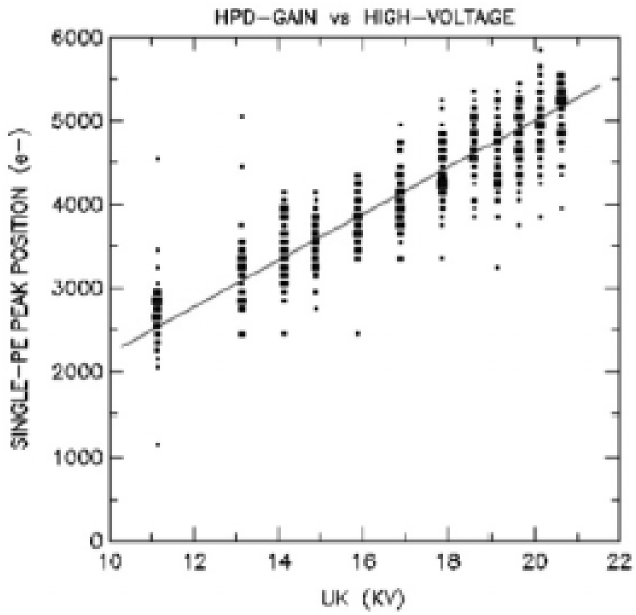
2016

LHCb RICH

Features of HPD

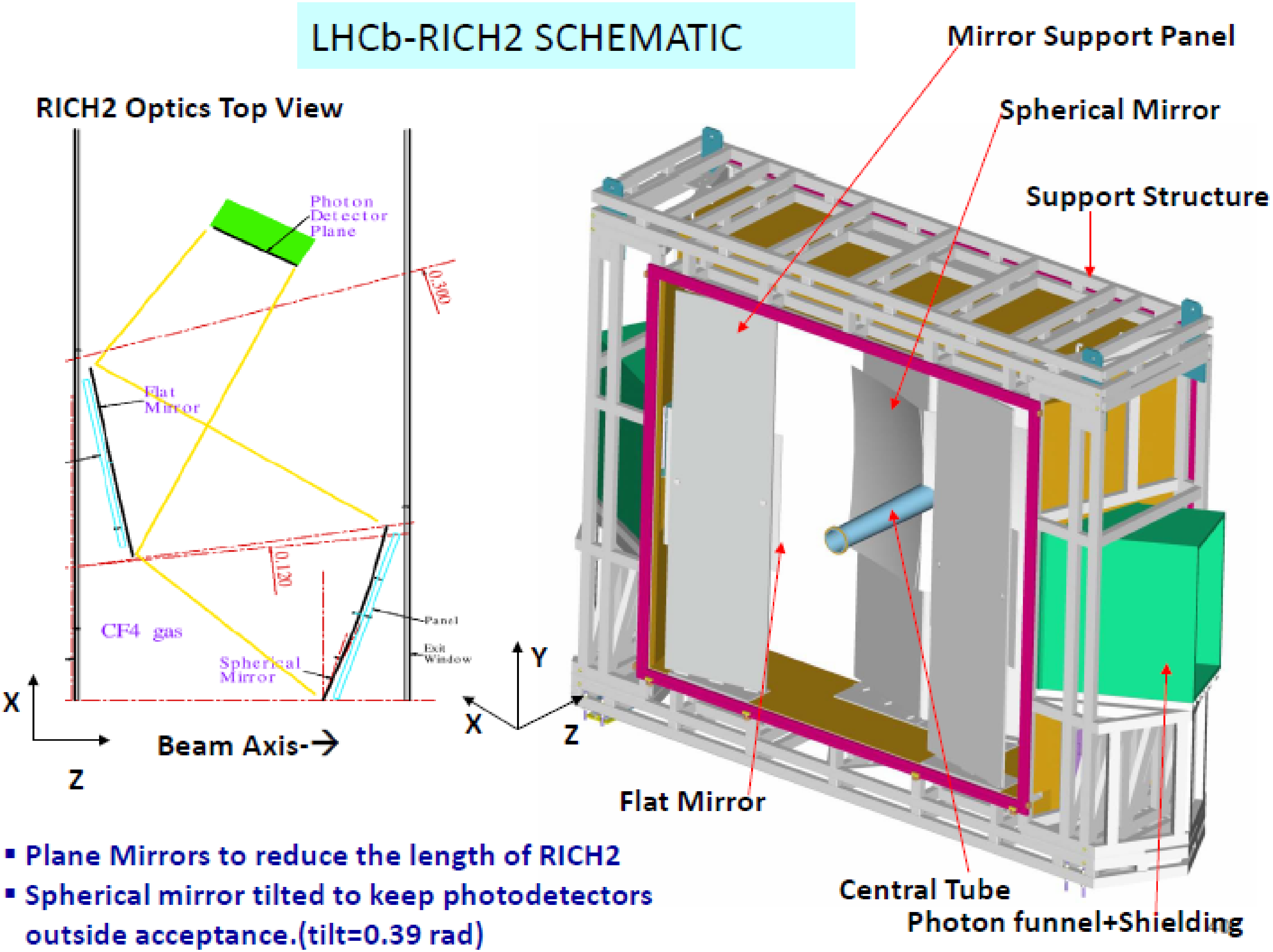


Signal pulse height spectrum of a 61-pixel HPD
Illuminated with Cherenkov photons



- Band gap in Silicon = 3.16eV; Typical Max Gain = 20 keV / 3.16 eV = 5000 (approx)

LHCb RICH



- Plane Mirrors to reduce the length of RICH2
- Spherical mirror tilted to keep photodetectors outside acceptance.(tilt=0.39 rad)

2016

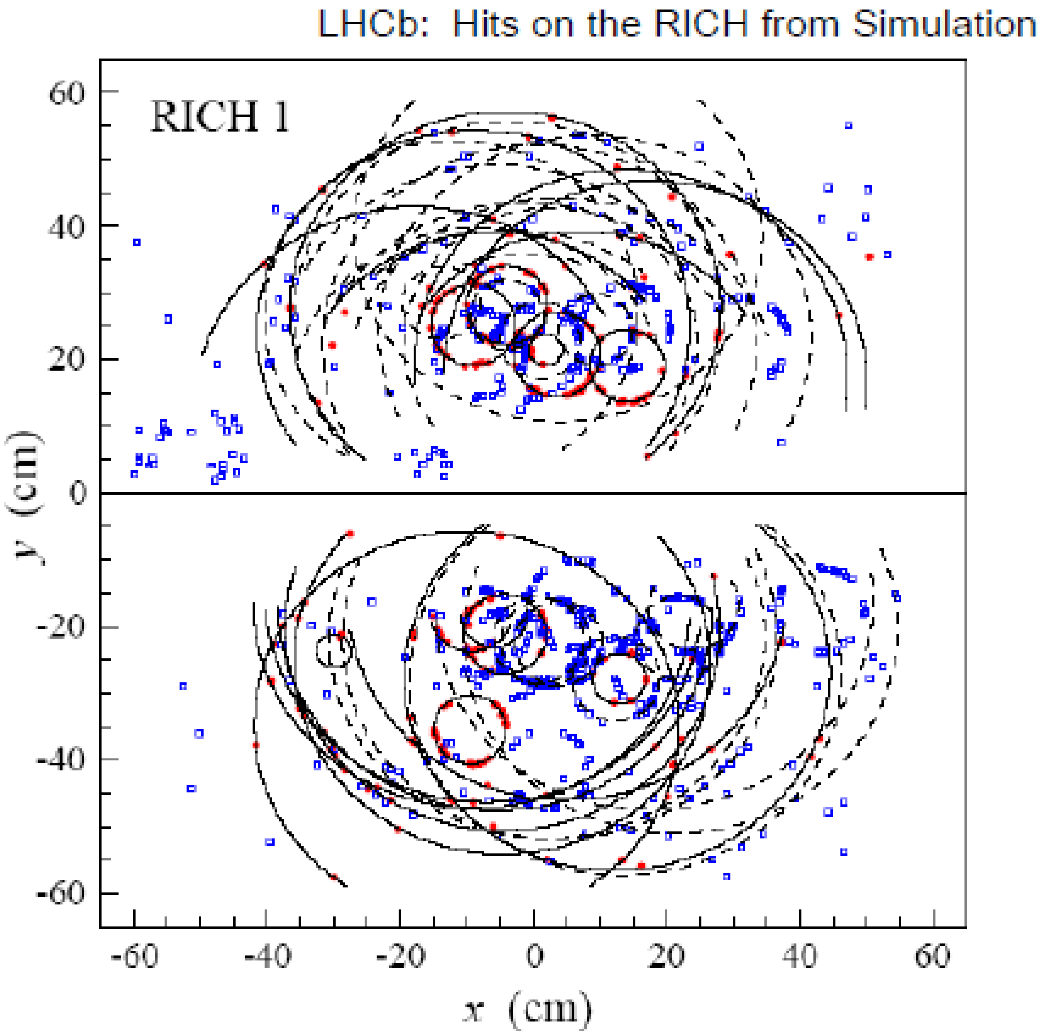
LHCb RICH

LHCb- RICH2 STRUCTURE

Entrance Window
(PMI foam between two
carbon fibre epoxy Skins)

RICH2

LHCb RICH



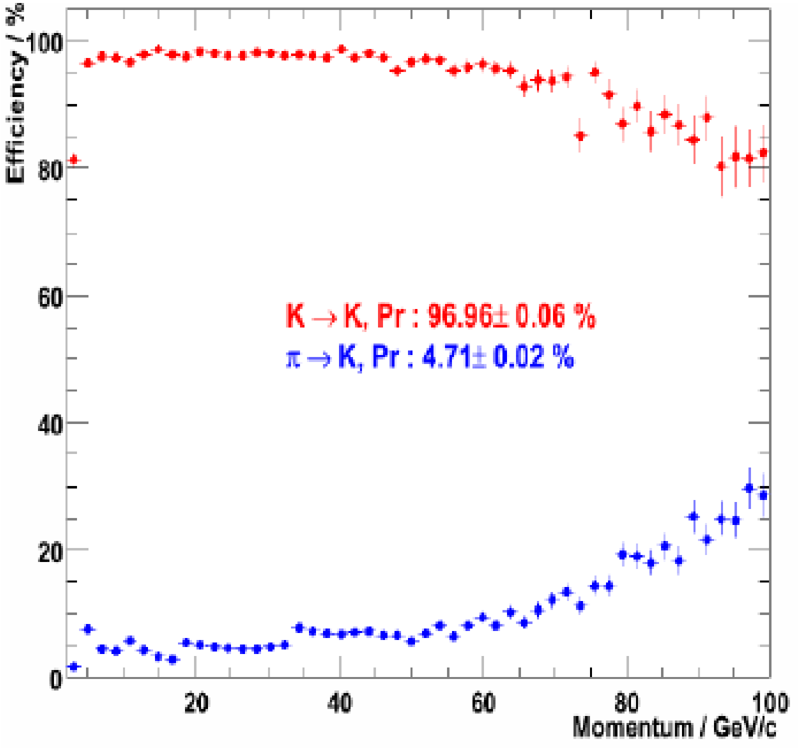
Red: From particles from Primary and Secondary Vertex

Blue: From secondaries and background processes (sometimes with no reconstructed track)

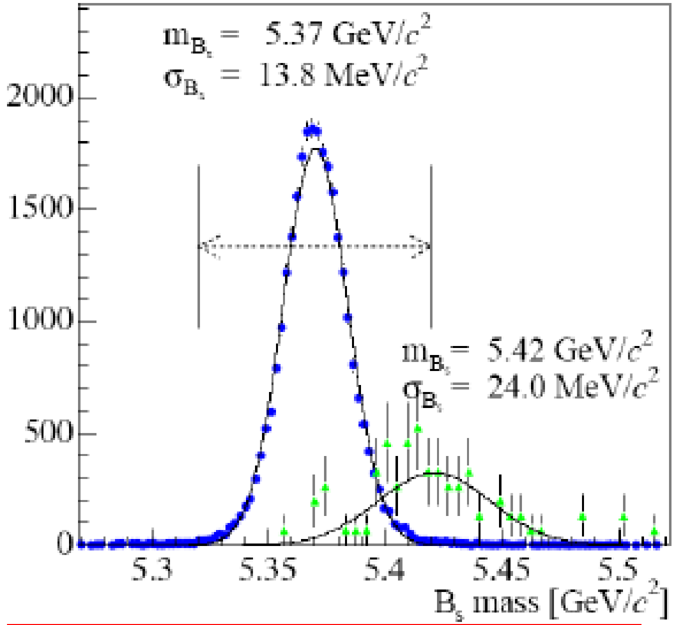
LHCb RICH

LHCb-RICH pattern recognition

Efficiency for identification
and probability for misidentification
vs Particle momentum



Particle Momentum (GeV/c)→



$B^0_s \rightarrow D_s^- K^+$ (signal)

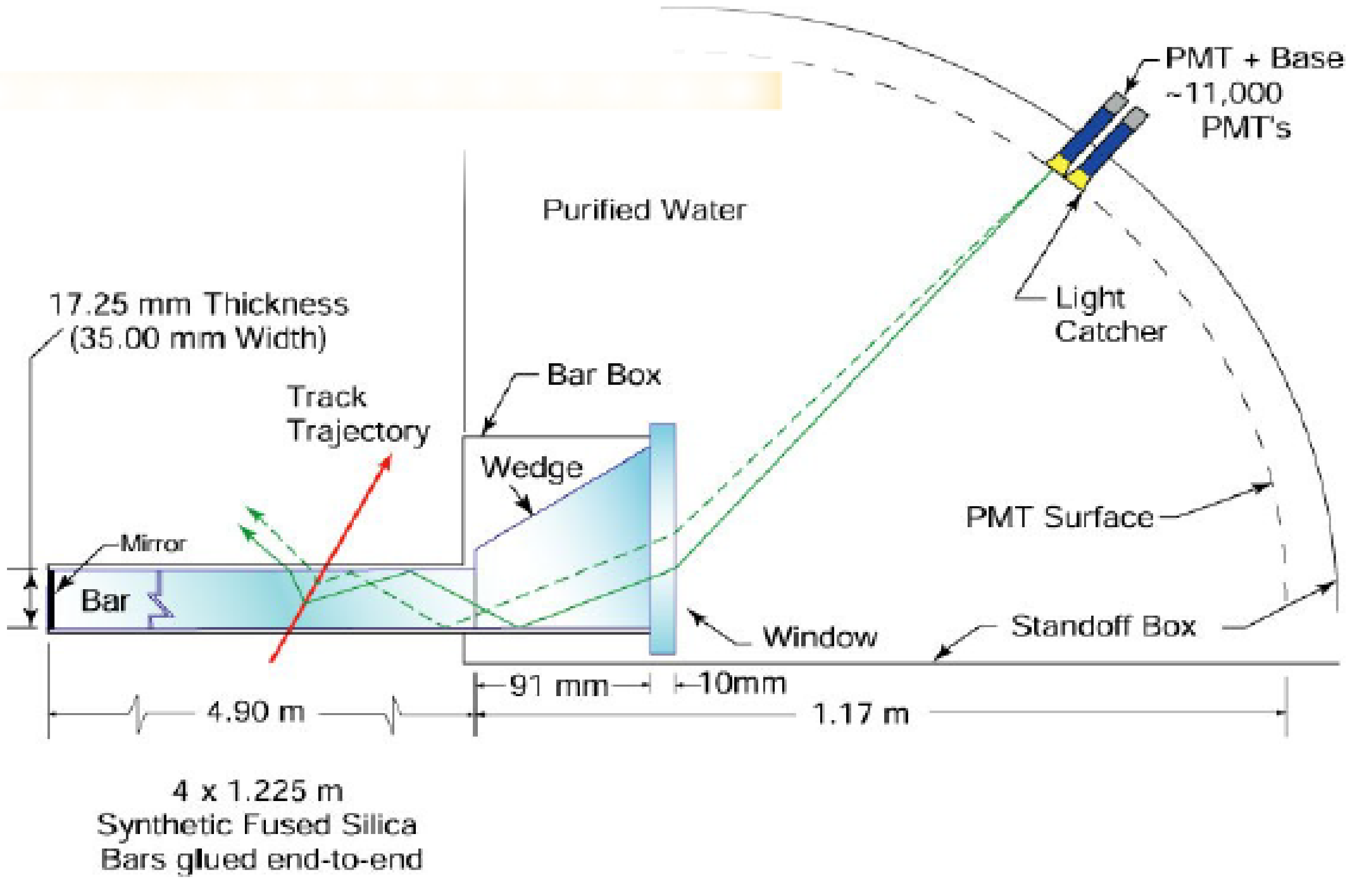
$B^0_s \rightarrow D_s^- \pi^+$) (background

After using RICH, background at 10% level from 10 times level

From simulations

A strange idea: the DIRC

- Detector of Internally Reflected Cherenkov light
- DIRC used at BaBar
- Turned out to be successful and robust for π – K separation.



I. Adam et al. / Nuclear Instruments and Methods in Physics Research A 538 (2005) 281–357

A strange idea: the DIRC

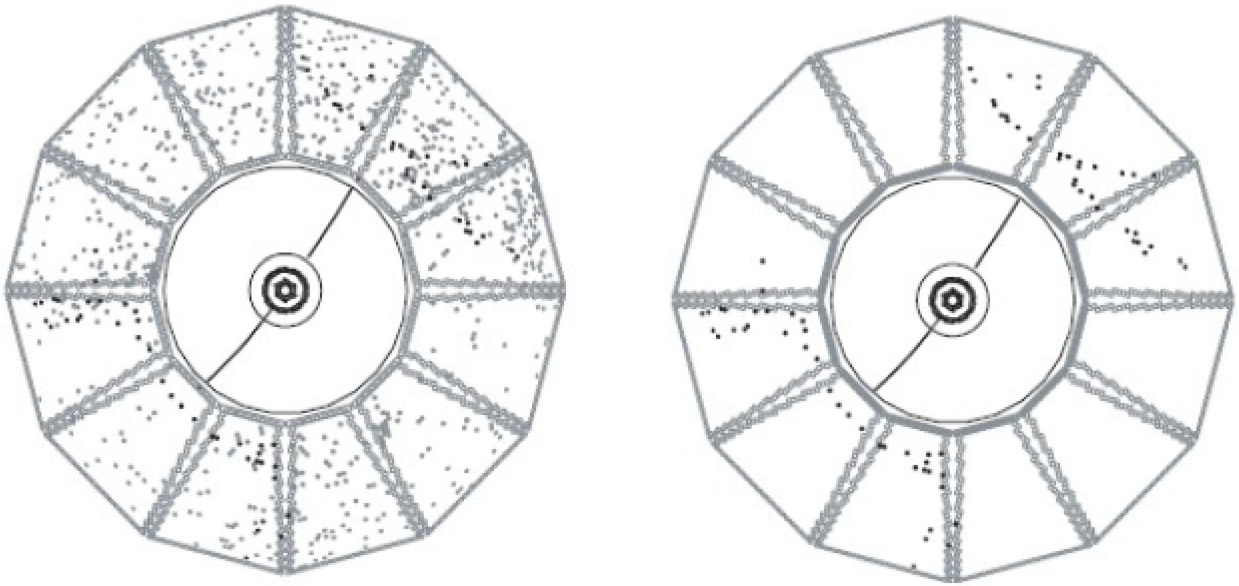
- Detector of Internally Reflected Cherenkov light
- DIRC used at BaBar
- Turned out to be successful and robust for π – K separation.
  - Material is actually synthetic fused silica (Spectrosil)
  - Cross section 17.25 mm x 35.0 mm.
  - Four 1.225 m long bars glued together with Epotek 301-2 optical epoxy to make one 4.9 m long DIRC bar.
  - 99.9±.0.1% transmission per meter at 442 nm
  - 98.9±.0.2% transmission per meter at 325 nm

A strange idea: the DIRC

- Detector of Internally Reflected Cherenkov light

Reconstruction

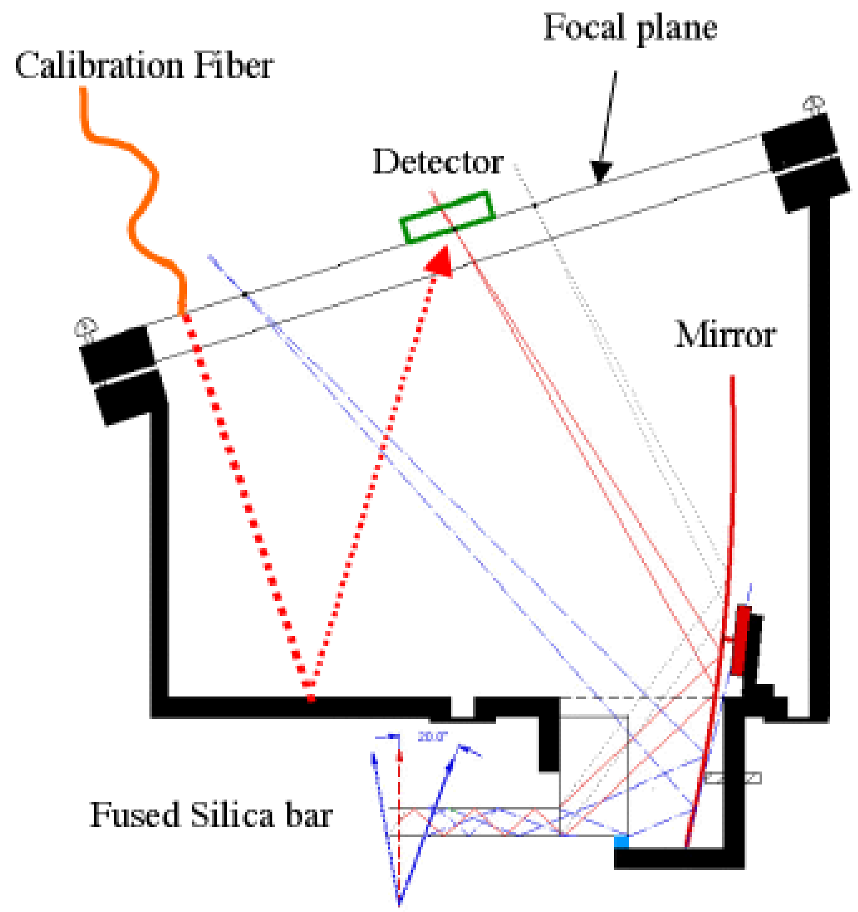
- Arrival time is used to reduce background



- Eliminating the photons outside of a ±300 ns window around the trigger time yields a very clean signal

A strange idea: the DIRC

- Improving the DIRC concept: super-BELLE ?



2016

IDENTIFYING PARTICLES CHARGE MEASUREMENT OF PRIMARY CR

How to characterize the primary particle?

2016

- Mass m
- Electric charge Ze
- Velocity $v = \beta c$
- Lorentz Facteur $\gamma = E/mc^2$
- Momentum $p = mc\beta\gamma$
- Kinetic energy $T = mc^2(\gamma - 1)$

How to characterize the primary particle?

Detector	Observable	Link with the particule
Magnetic spectrometer	Rigidity & Sign of Z	pc/Ze
Time of flight	Velocity/c	β
Proportionnal counters Scintillators Ionisation chamber	Ionisation	$dE/dx = Z^2 f(\beta)$
Čerenkov effect	Č photons density	$dN/dx = Z^2 g(\beta)$
Transition radiation	Nomber of photons X	$N = Z^2 h(\gamma)$
Calorimeter	Deposited energie	$mc^2(\gamma - 1)$

2016

Two important radiations for particle identification

Two effects of the polarization induced by charged particles in dielectric medium

Proportionnal to Z^2

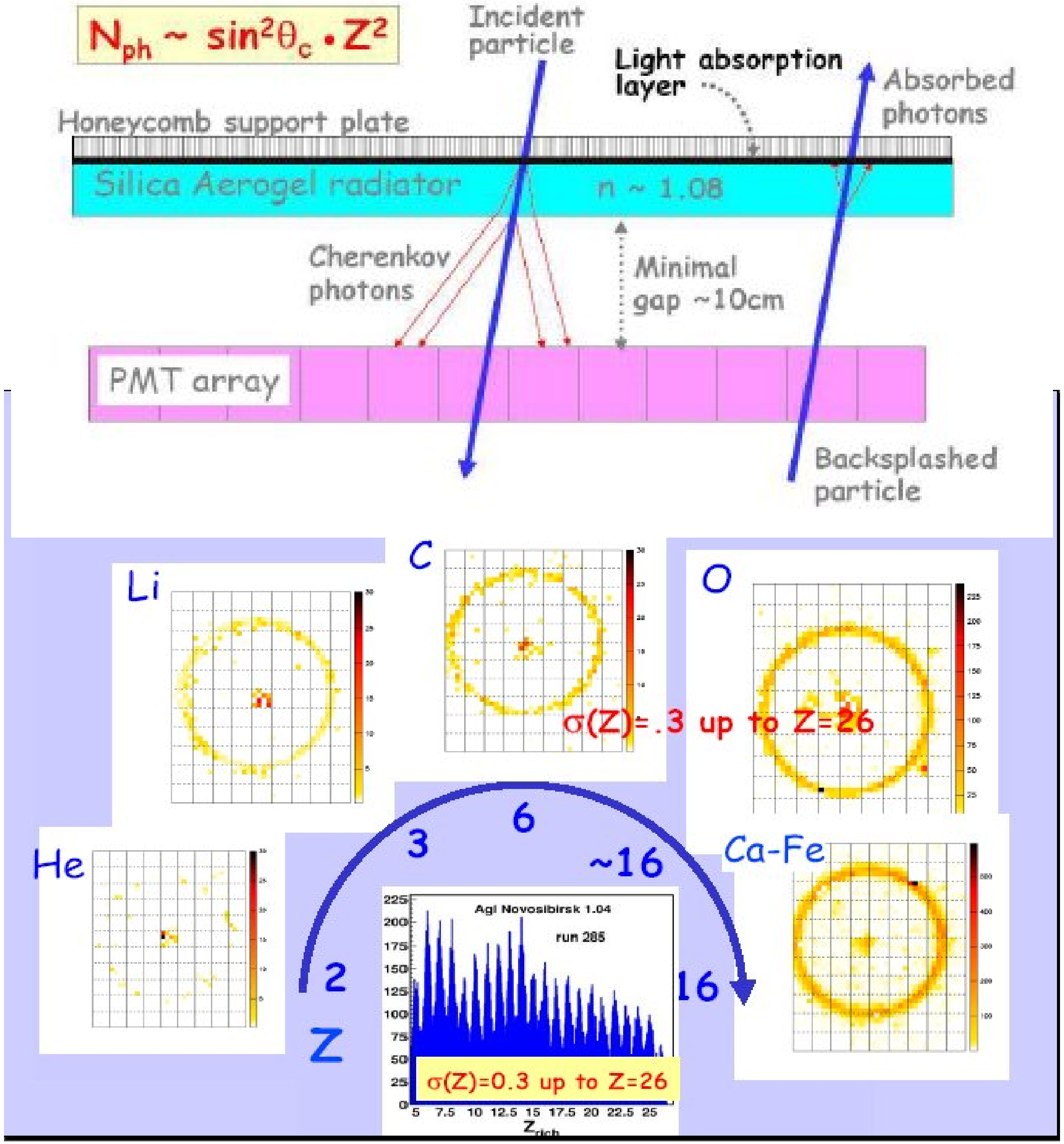
- Čerenkov radiation : si $v > c/n$
  Sensitive to $\beta = v/c$

- Transition radiation : at the interface of $\neq$ dielectric media
  Sensitive to $\gamma = E/(mc^2)$

Cherenkov imaging (RICH) and charge measurement

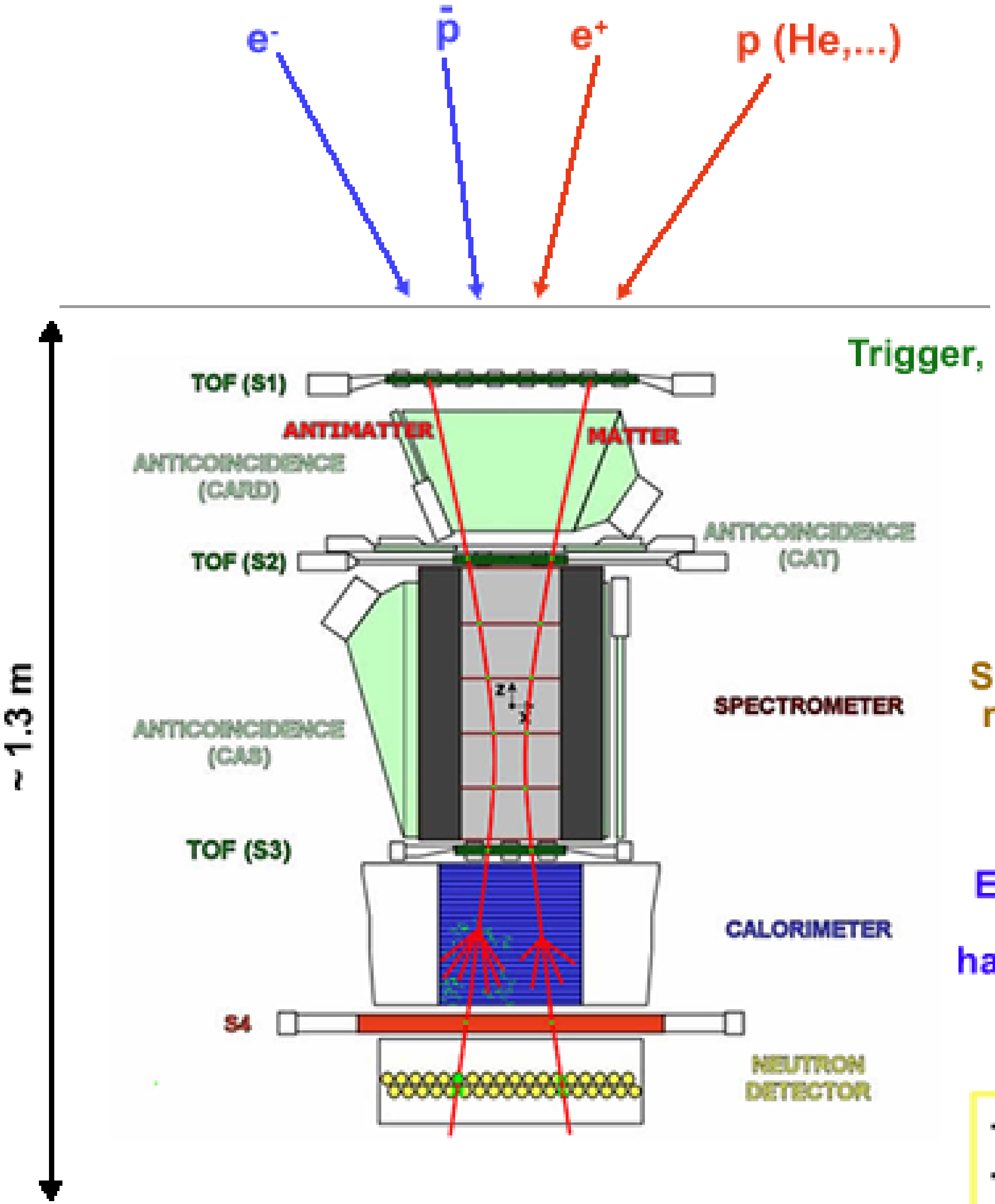
RICH principle →

AMS 2 Prototype →



2016

PAMELA



~470 Kg / ~360 W

Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

AMS-2 On Board ISS

Mission Number: STS-134
Launch: **May 19, 2011**
Orbiter: Endeavour

2016

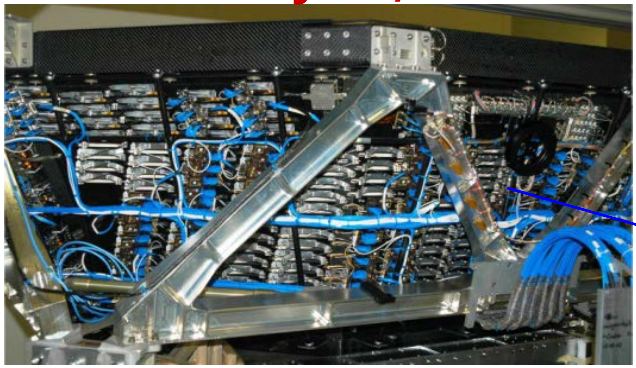
Space spectrometers

	AMS-1 (June 1998)	PAMELA (June 2006 - …)	AMS-2 (May 2011 - …)
Spectrometer Acceptance	0.82 m^2 sr	20.5 cm^2 sr	0.82 m^2 sr
Spectrometer	Permanent magnet Nd Fe B 0.15 T BL^2 = 0,15 T m^2 6 plans (Si)	Permanent magnet Nd Fe B 0.48 T BL^2 = 0,10 T m^2 6 plans (Si)	Permanent magnet Nd Fe B 0.15 T BL^2 = 0,15 T m^2 6 plans (Si)
Time of Flight	yes	yes	yes
Cherenkov	Aerogel (threshold)	-	Ring Imaging Ch.
Transition rad	-	yes	yes
Neutrons det.	-	^3He	-
Anticoincidence	-	yes	yes
Calorimeter	-	16,3 X_0 W+22 plans (Si)	16 X_0 Pb+fibers sc.

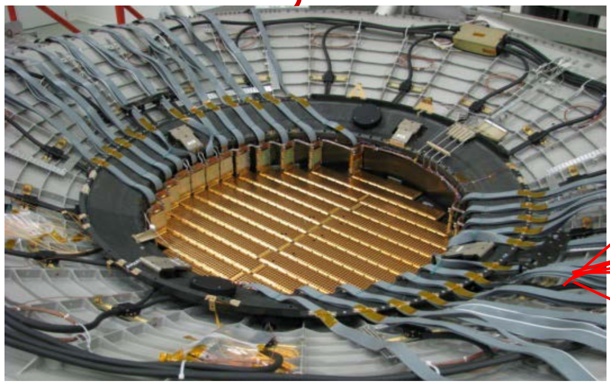
A precision, multipurpose spectrometer up to TeV

2016

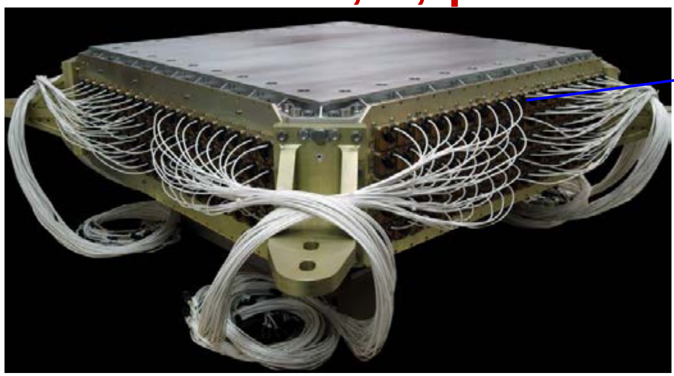
TRD
Identify e^+, e^-

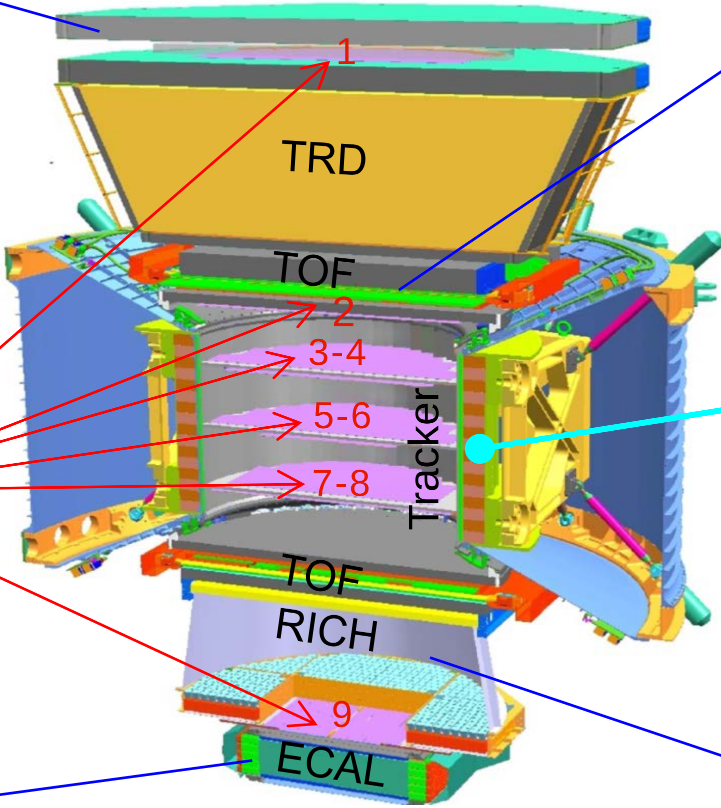


Silicon Tracker
Z, P



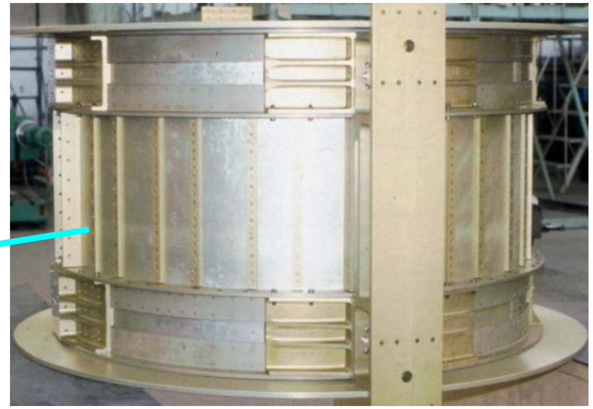
ECAL
E of e^+, e^-, γ



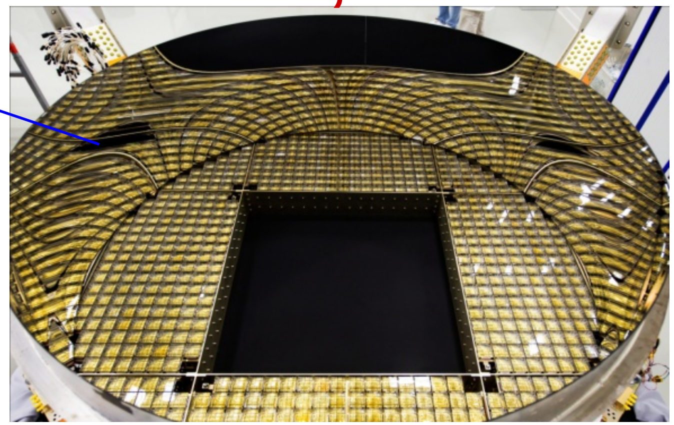


TOF
Z, E

Magnet
±Z



RICH
Z, E

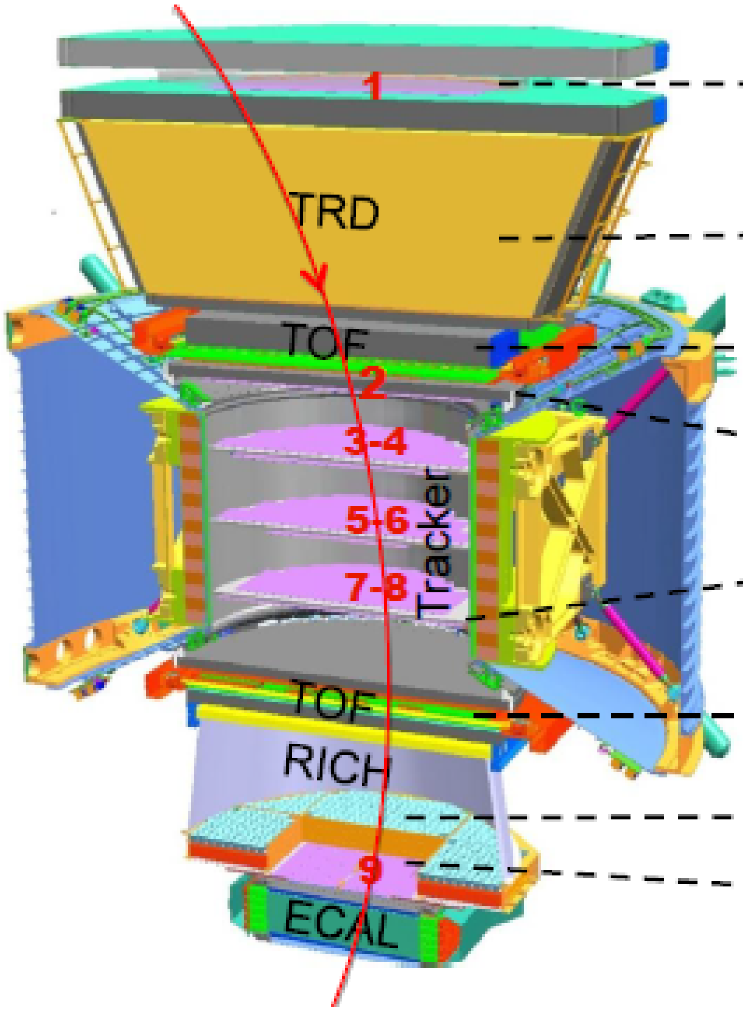


***Z, P** are measured independently by the Tracker, RICH, TOF and ECAL*

AMS charge identification

2016

AMS: Multiple Independent Measurements of the Charge (|Z|)



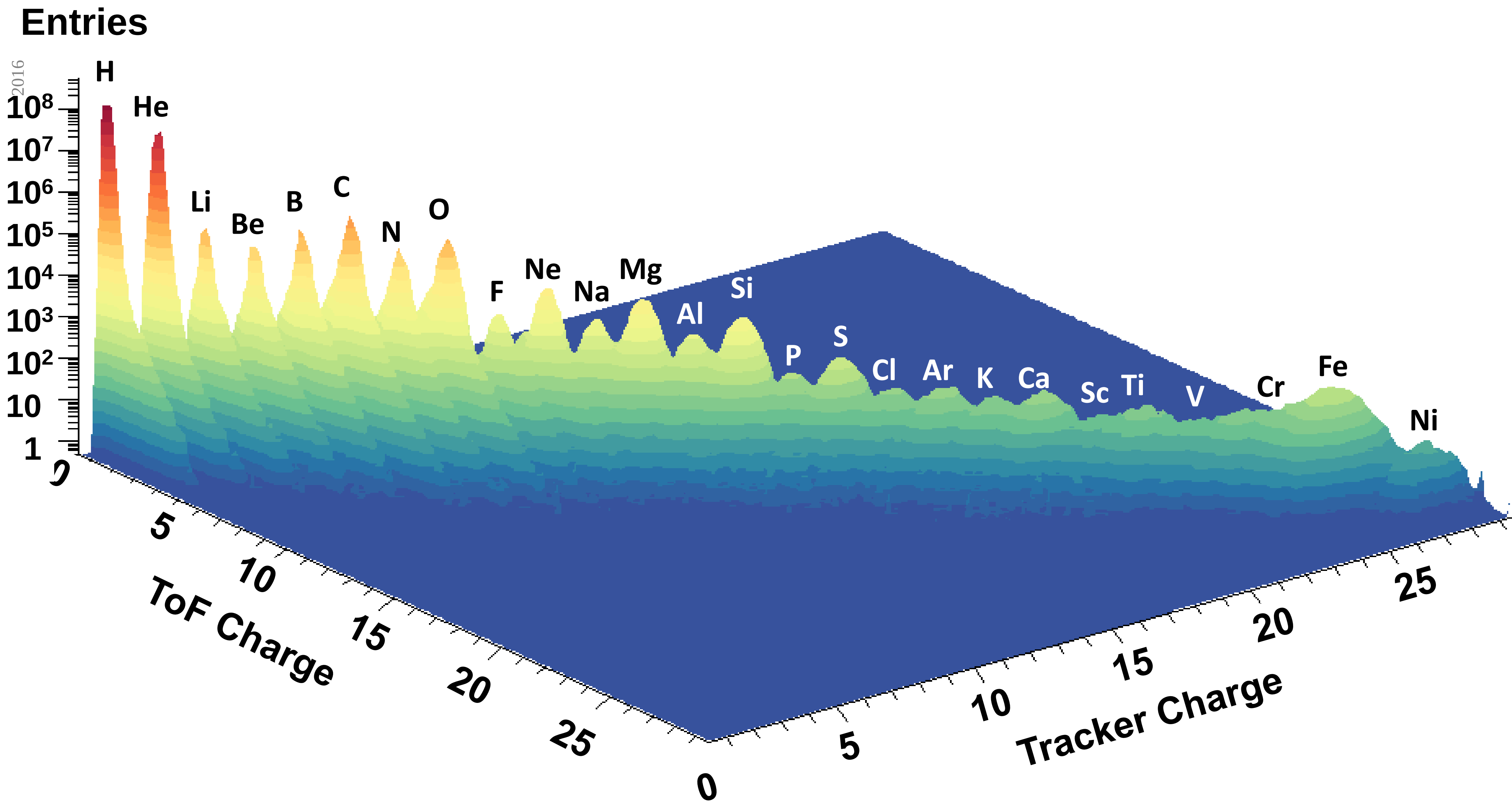
	Carbon (Z=6) ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30

Full coverage of anti-matter & CR physics

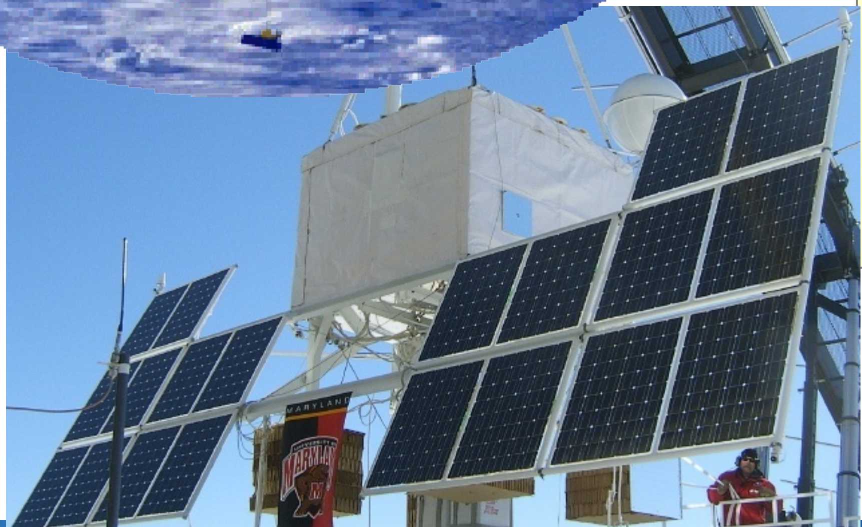
2016

	e^-	P	He,Li,Be,..Fe	γ	e^+	$\bar{P}$, $\bar{D}$	$\overline{He}$, $\bar{C}$
TRD							
TOF							
Tracker							
RICH							
ECAL							
Physics example	**Cosmic Ray Physics**				**Dark matter**		**Antimatter**

AMS Nuclei Measurement on ISS



CREAM



Ultra Long Duration Balloon

ULDB Proj., Adv.Sp.Res33,1633(2004) :

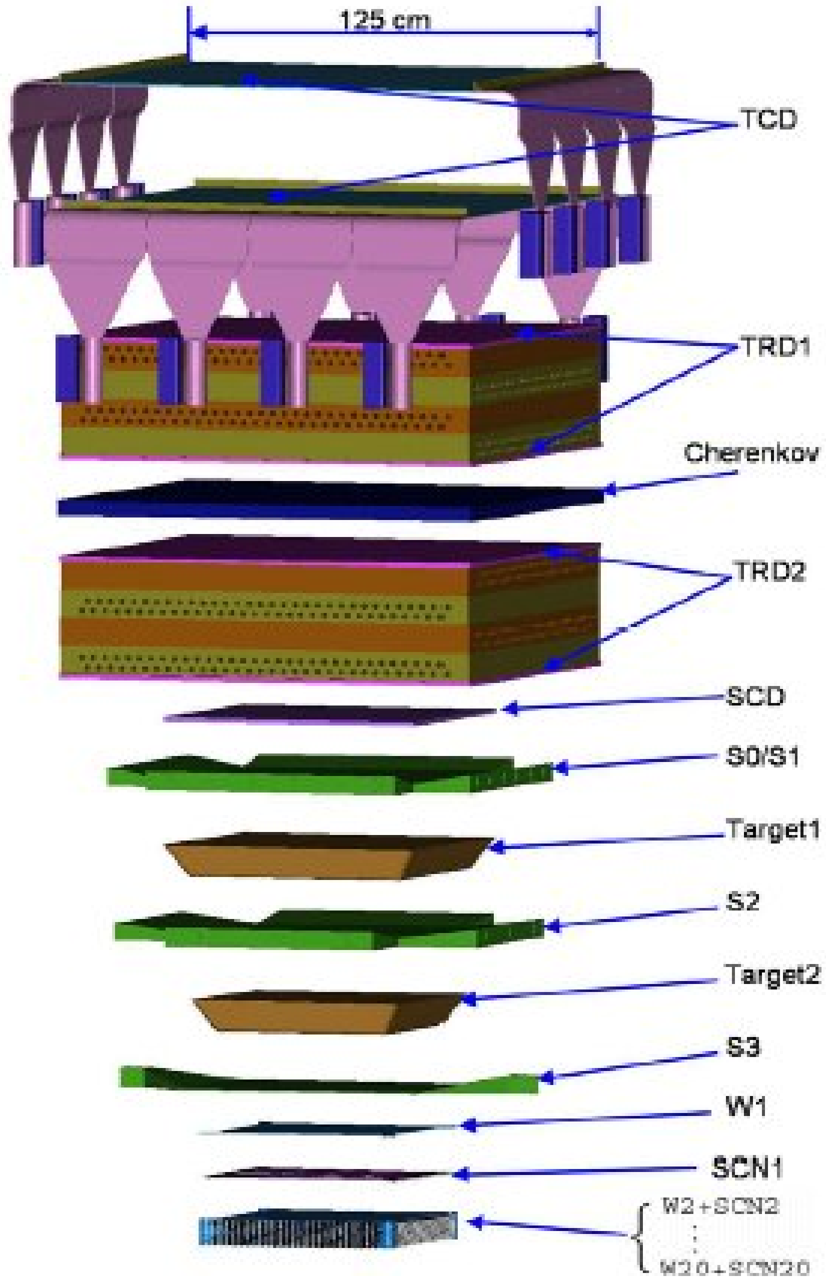
NASA project to develop

- Flight of < 100 days
- Payload $\leq$ 2 tons
- Alt 33000 meter
- CREAM n° 1 : 2006 (2005/LDB)

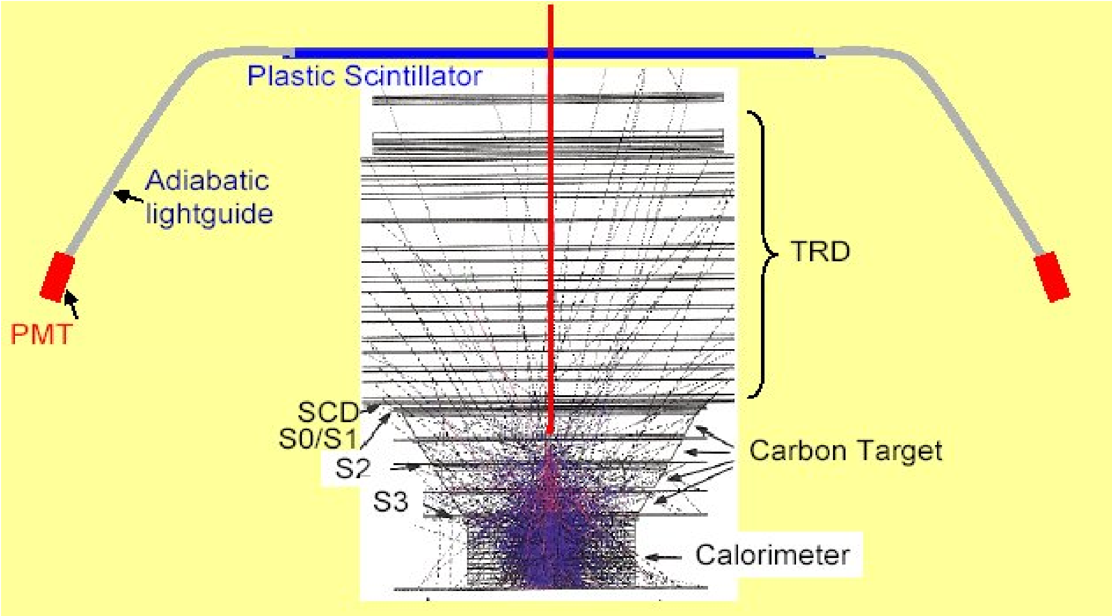
CREAM

Cosmic Ray Energetics and Mass

- Objectives :
  CR composition and spectrum of the different elements
  (from TeV to ~500 TeV)
- Acceptance : 2,2 m^2 sr
- Energy measurement:
  - Calorimeter 20 X_0 (W + scint. fibres)
  - Transition Radiation Detector
- Identification :
  - TRD
  - Cherenkov detector "CHERCAM" similar to AMS-2



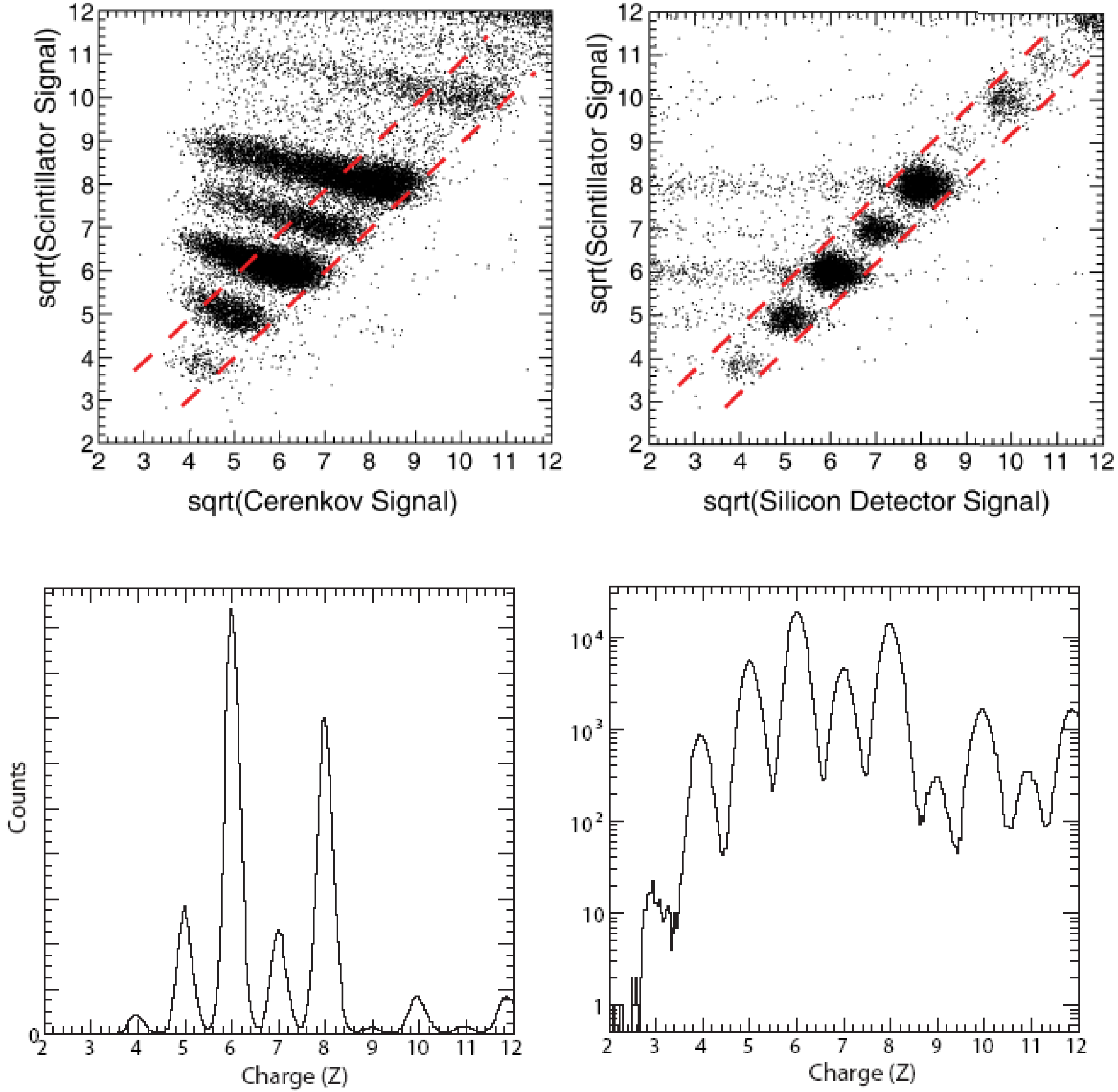
CREAM experiment



- At TeV energies, the interaction of CR in the calorimeter induces many backscattered secondary particles that one have to veto.

- The "CHERCAM" cherenkov solves this problem by measuring accurately the time of any through going particle as well as achieving a precise charge measurement (± 0,3 e)

CREAM experiment

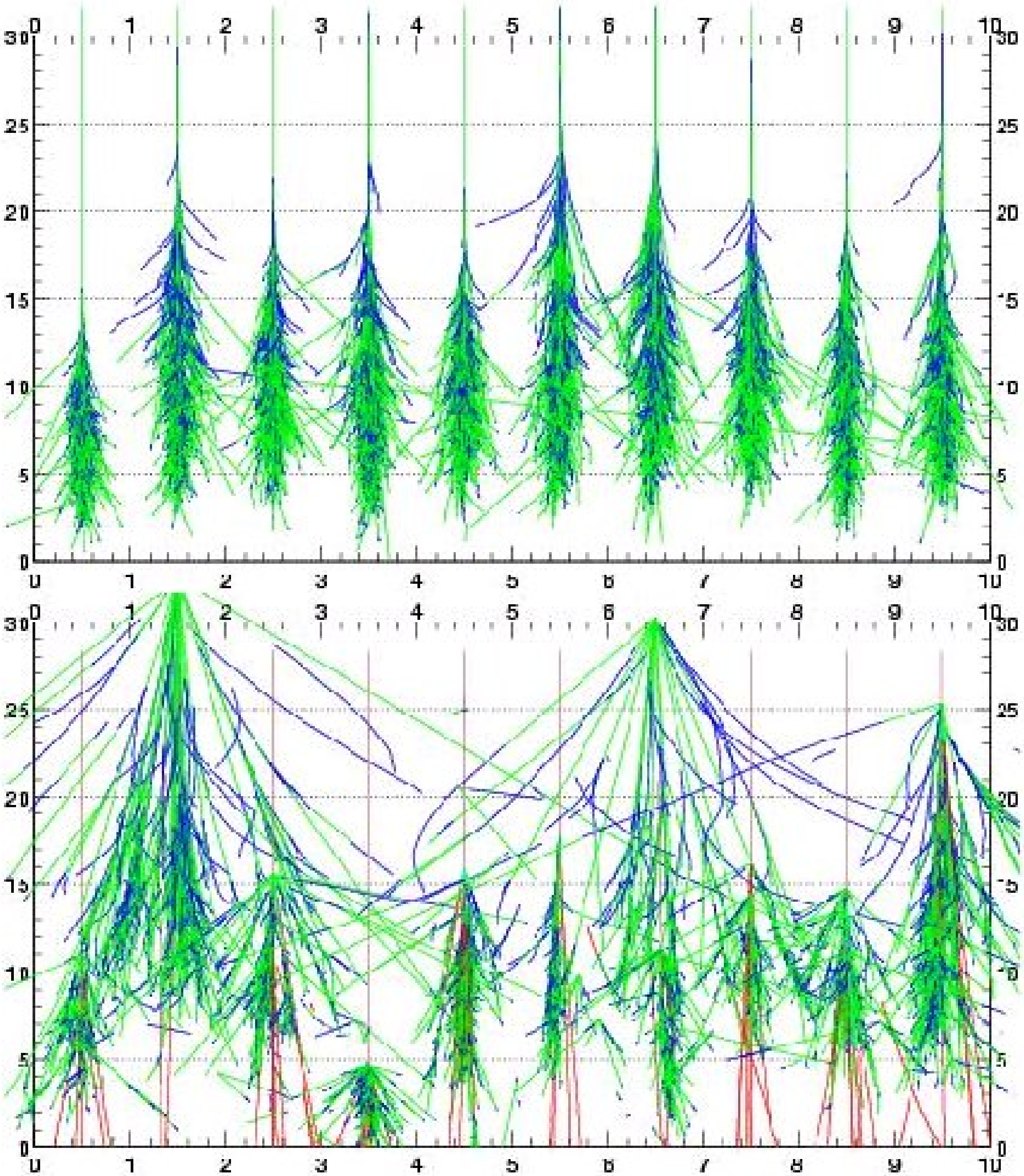


2016

ATMOSPHERIC GAMMA-RAY SHOWERS BY CHERENKOV TELESCOPES

10 γ
300 GeV

10 protons
300 GeV



Simulations de

M. de Naurois

Electromagnetic showers
($e^{\pm}$ or γ primary)

Dominating phenomena

- Radiation processes:
  - Bremsstrahlung of $e^{\pm}$
  - Pair production (>MeV) pairs $e^{+}e^{-}$
- Multiple scattering
  (small angular deflections) of $e^{\pm}$

} In the coulombian field of nuclei

- Energy losses by $e^{\pm}$
  - ionization
  - Atoms excitation

γ induced shower 300 GeV

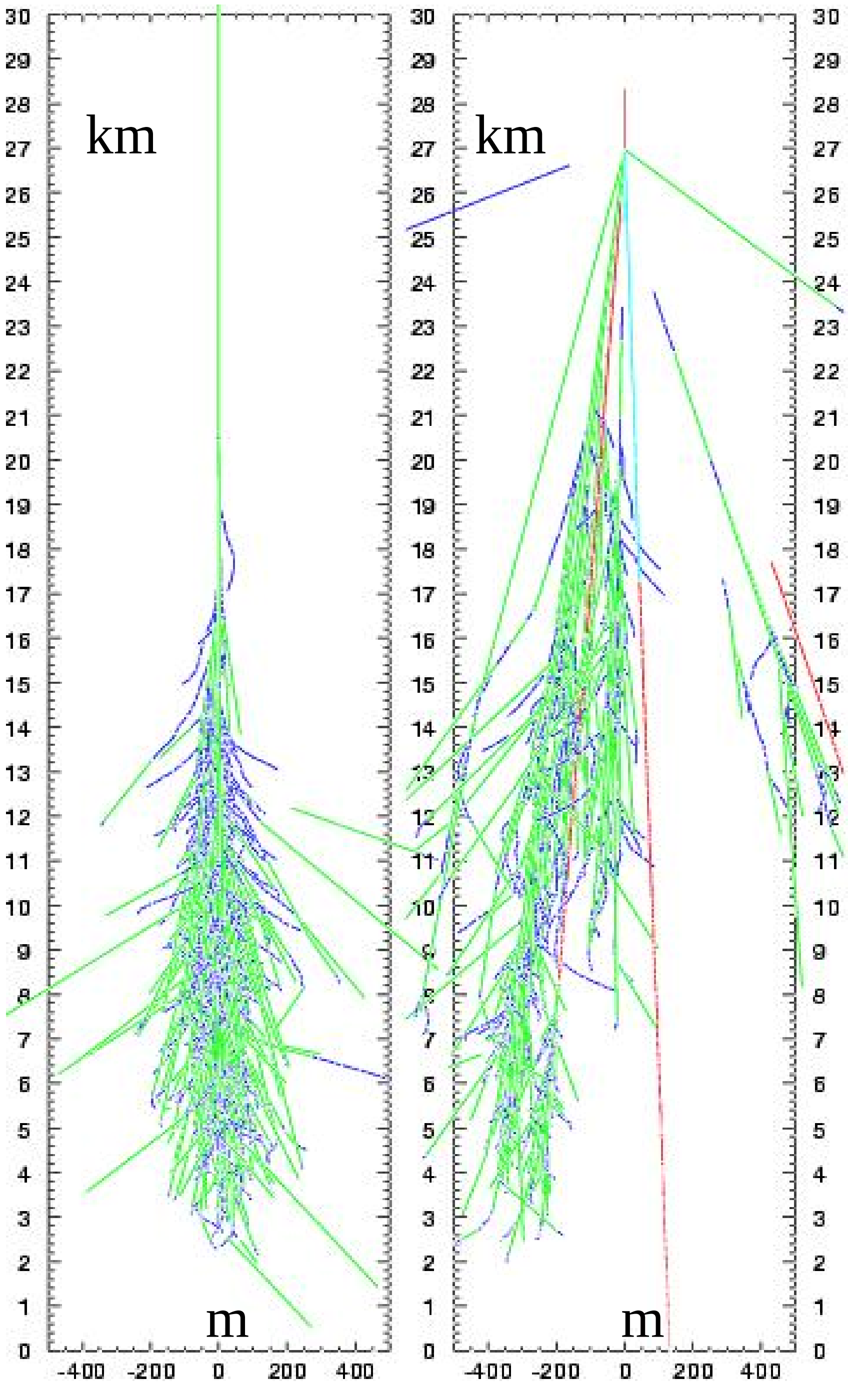
Roughly symmetric around the axis

Small transverse dispersion (multiple scattering)

(almost) no muons unless E_0>1 PeV

Essentially

e+ e- and γ secondaries



proton induced shower 300 GeV

Large transverse momentum

Muon component (from mesons decays)

A hadronic shower does contain EM sub-showers

Optical photon emission by showers

2016

- Showers charged particles emit light:
  - Cherenkov light : very collimated along the shower axis (Cherenkov angle at 1 Atm. ≈ 1°) threshold depending on the altitude : at ground 22 MeV for $e^{\pm}$ et 4.5 GeV for $\mu^{\pm}$

    (20 photons per m per β≈1 charged particle at 1 atm)

    Essentially used for gamma-ray astronomy
  - Nitrogen fluorescence: isotropic emission

    (≈ 4 photons per electron per m)

    Essentially used at UHE ≥ 10^{17}eV.
- This light detected by ground telescopes provides very rich information on the 3D development of the showers.
  It give a quasi calorimetric reliable measurement of the energy.

… but optical detectors can only work during moonless clear sky nights (≈ 10% duty cycle).

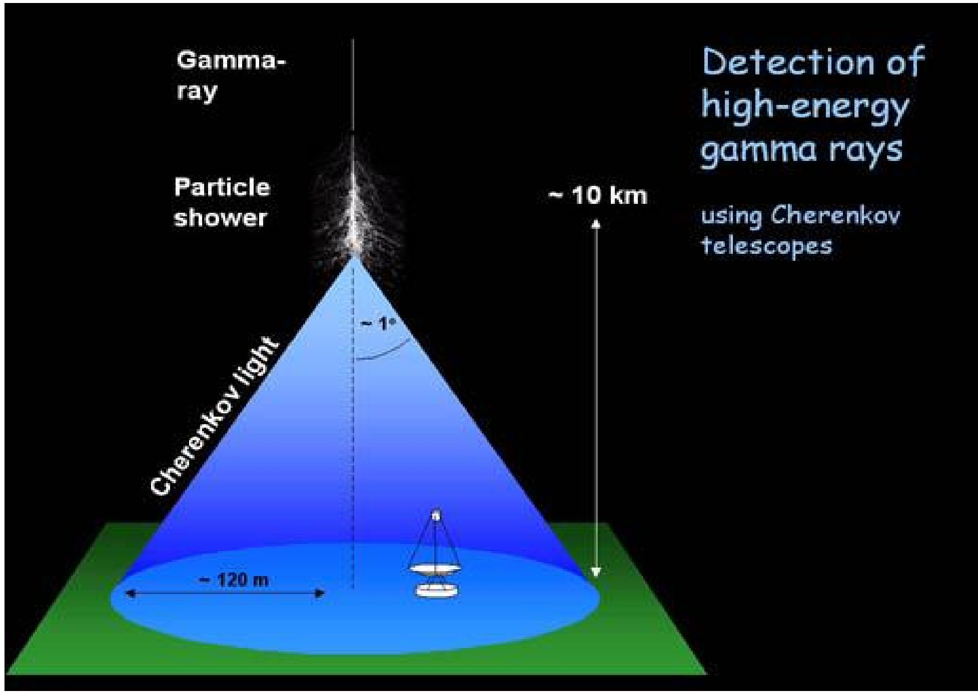
Cherenkov light from VHE gamma rays showers

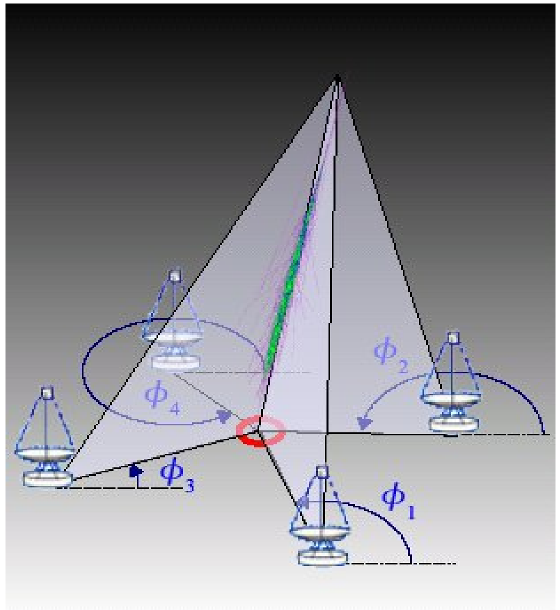
Shower front ≈ conical at energies > TeV,
very well defined in time (few nanoseconds)

… ground enlightened area of 150 m radius
at 1800m asl for TeV showers.

Any large acceptance telescope in this area receive enough photons
→ effective detection area ~ 10^5 m^2

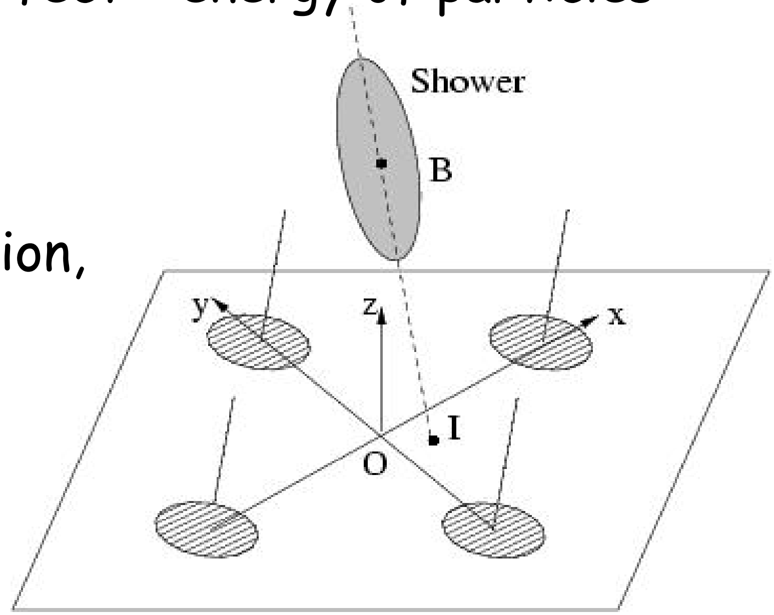
With an array of such telescopes,
3D reconstruction of showers (stereoscopy)
→ total number of Cherenkov photons as an energy estimator).





Showers Cherenkov light

- Longitudinal profile: similar to the particle density profile with a slight shift towards ground of 0.3 X_0 due to the variation of the Cherenkov threshold with altitude.
- Transverse profile: much narrower than that of charged particles ($\sigma_T \approx 10$ to 15 m at 10 km altitude), threshold effect + energy of particles decreasing further away from axis.
- The Cherenkov « photosphere » (origin of photons distribution of EM showers) can be approximated by a 3D gaussian distribution, with axial symmetry for EM showers.
- The measurement of the transverse standard deviation σ_T allows distinguishing narrow EM showers from much wider hadronic showers, (transverse momentum of nuclear interactions $\gg$ QED radiative processes).

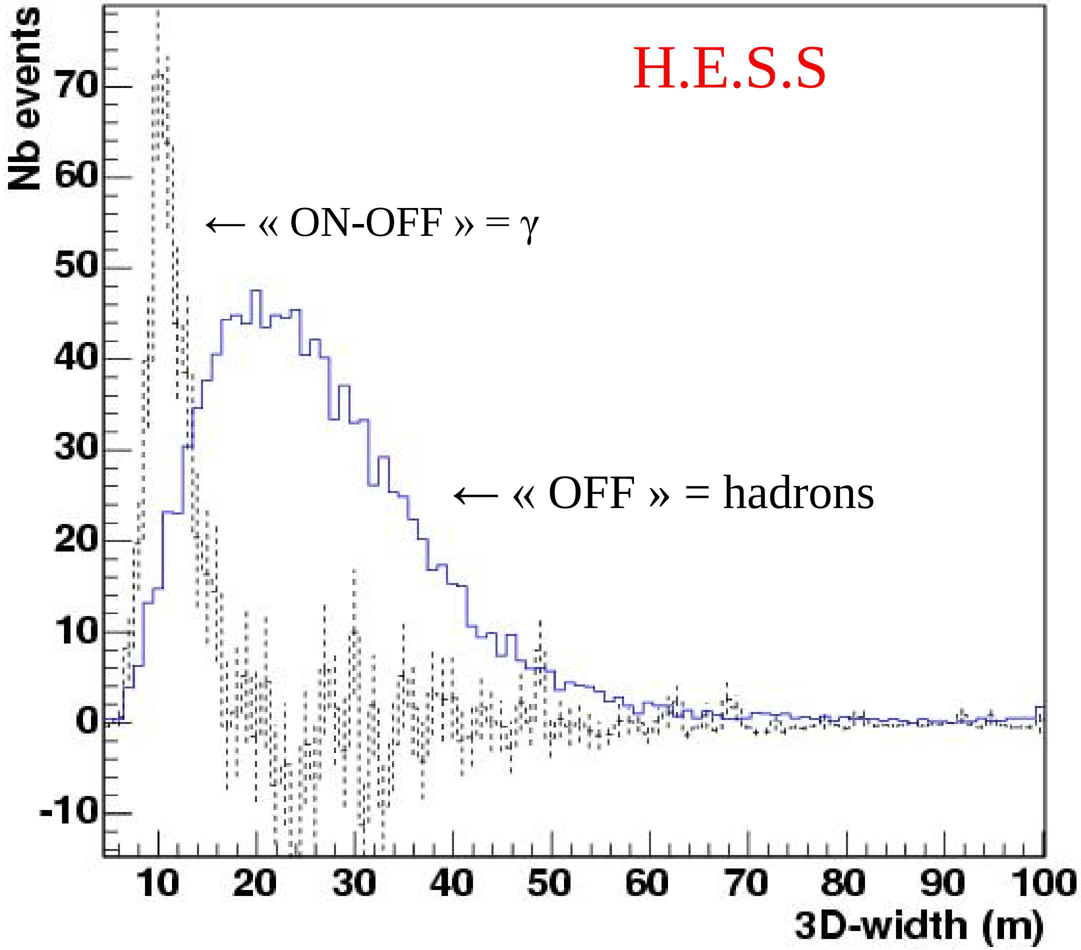


Cherenkov transverse profiles: EM versus hadronic showers

- « OFF » data: showers detected by 3 or 4 telescopes in a zone without γ sources → σ_T distribution for hadronic showers

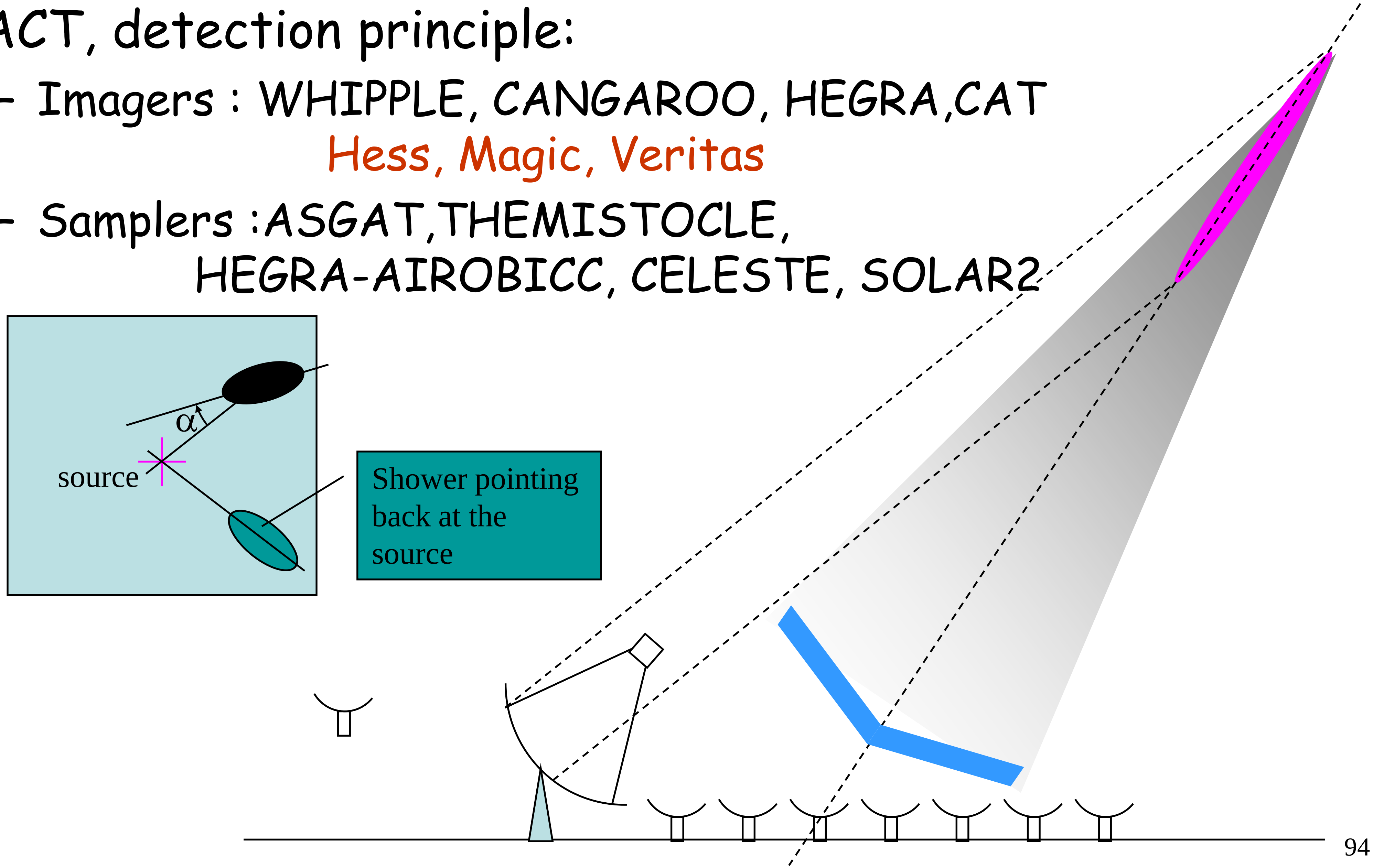
- « ON » data : showers detected by 3 or 4 telescopes in the direction of the γ source PKS2155-304 (a blazar).

- « ON-OFF » distribution : → σ_T distribution for γ showers as seen by 3 or 4 telescopes.



VHE gamma-ray observation

- ACT, detection principle:
  - Imagers : WHIPPLE, CANGAROO, HEGRA,CAT
    Hess, Magic, Veritas
  - Samplers :ASGAT,THEMISTOCLE,
    HEGRA-AIROBICC, CELESTE, SOLAR2



Gamma-ray astronomy above 100 GeV

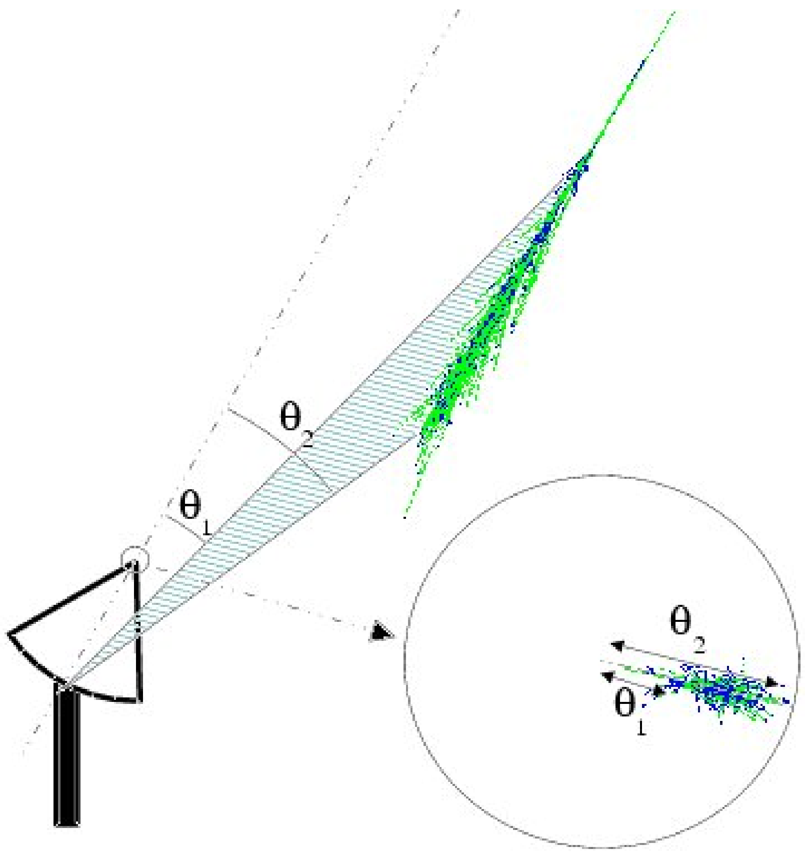
2016

- Atmospheric Cerenkov Detectors (ACTs)
  - Limited field of view instruments (5° for H.E.S.S.),
    ⇒ must follow the source apparent displacement on the sky.
  - Can follow only one source at the time.
  - Only work at clear sky moonless nights.
  - Great γ-hadron discriminating power → most of the TeV sources discoveries.

- Surface detectors (charged particles and γ secondaries at ground level)
  - Large field of view ($\approx$ steradian) instrument
  - High duty cycle
  - Low γ - hadron discrimination power → limited sensitivity.

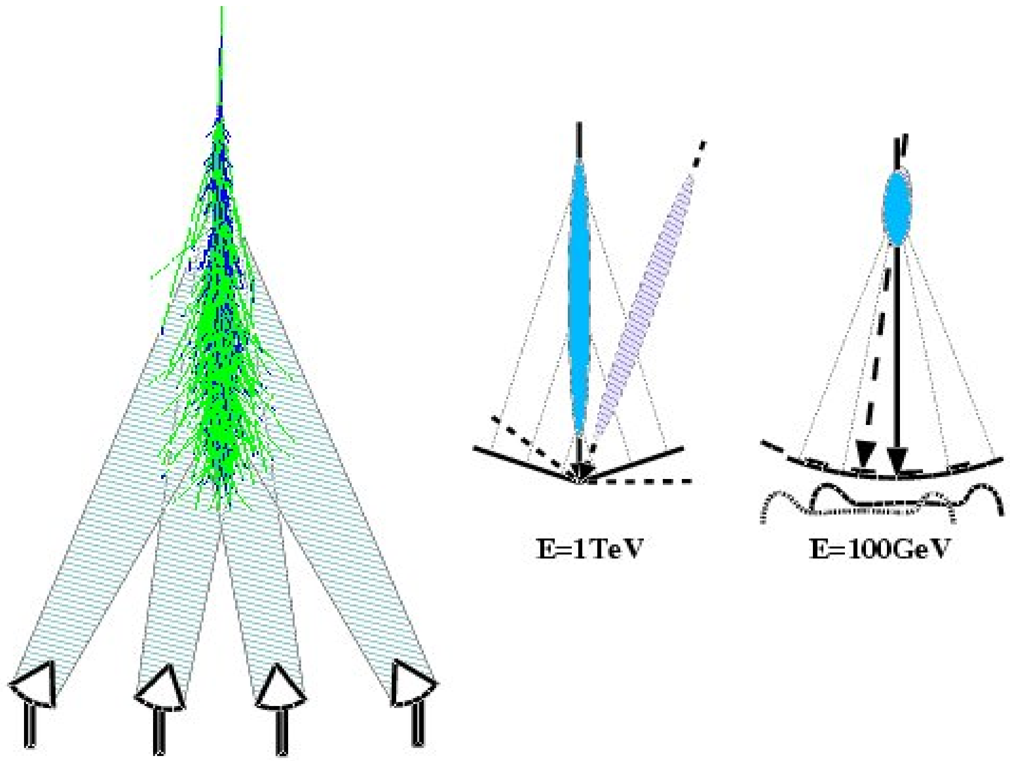
Atmospheric Cerenkov Detectors

Imagers



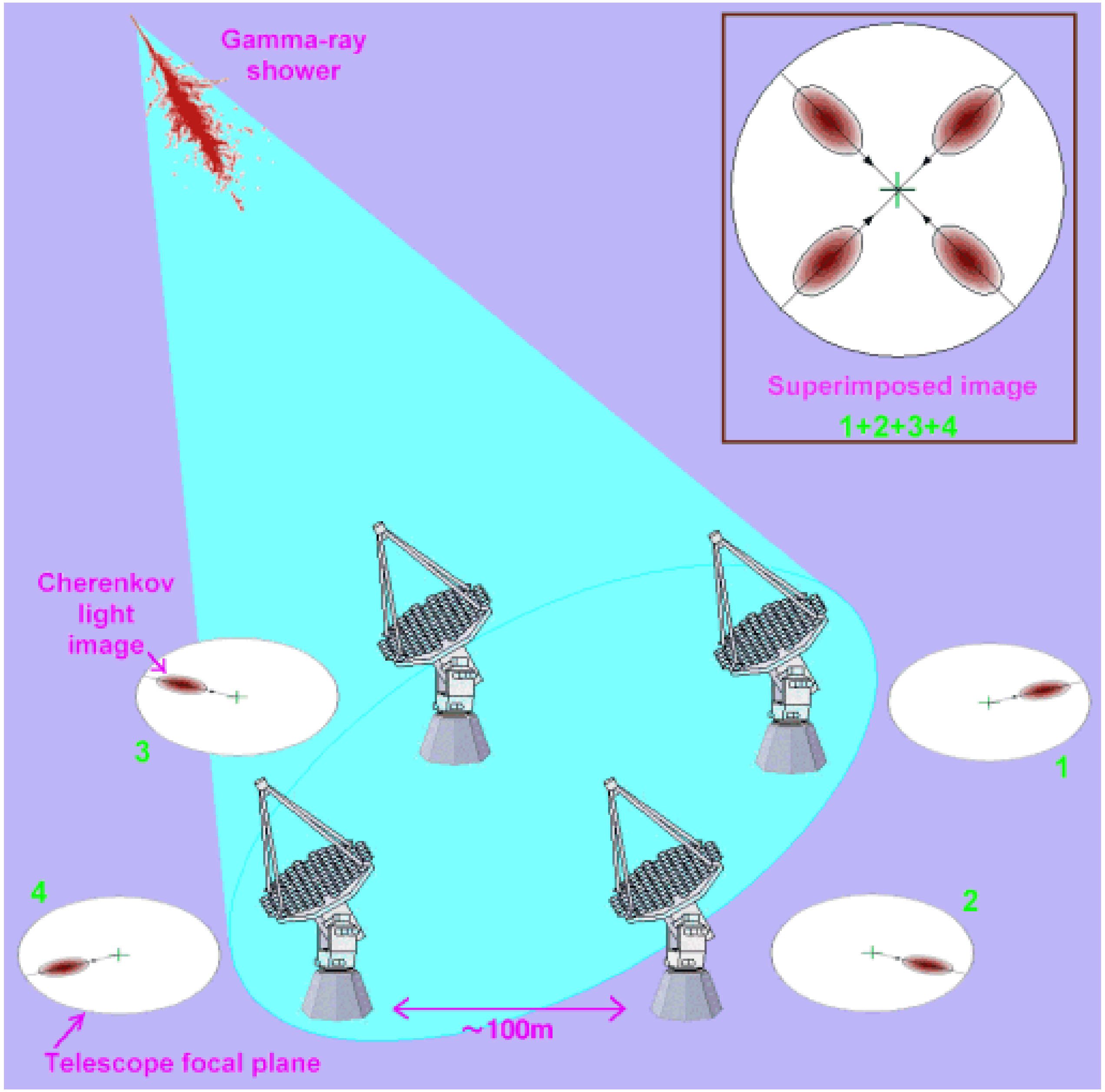
Form the shower image in the focal plane

Samplers



Arrival time + amplitudes on a large number of stations

ACTs in stereoscopic mode

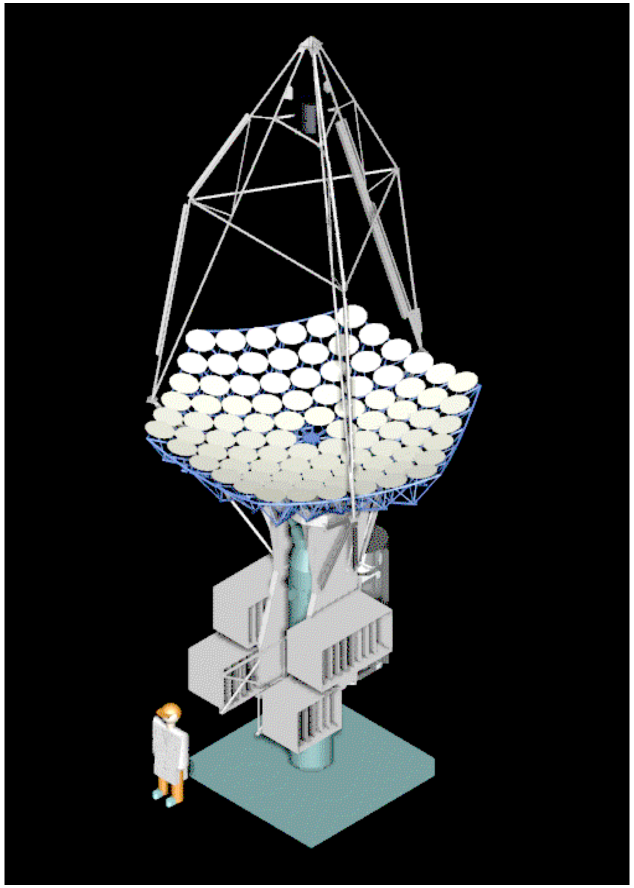


Former ACT

2016

WHIPPLE

CAT



ACTs:
Lowering the energy threshold

Sky background ~ 10^{12} photons m^{-2} sr^{-1} s^{-1}

$$\frac{\text{Signal}}{\sqrt{\text{sky bg}}} \propto \frac{A_{\text{col}}\ \tau\ \Omega_g\ \epsilon}{\sqrt{A_{\text{col}}\ \Delta t\ \Delta\Omega\ \epsilon}} \propto \sqrt{\frac{A_{\text{col}}\ \epsilon}{\Delta t\ \Delta\Omega}}$$

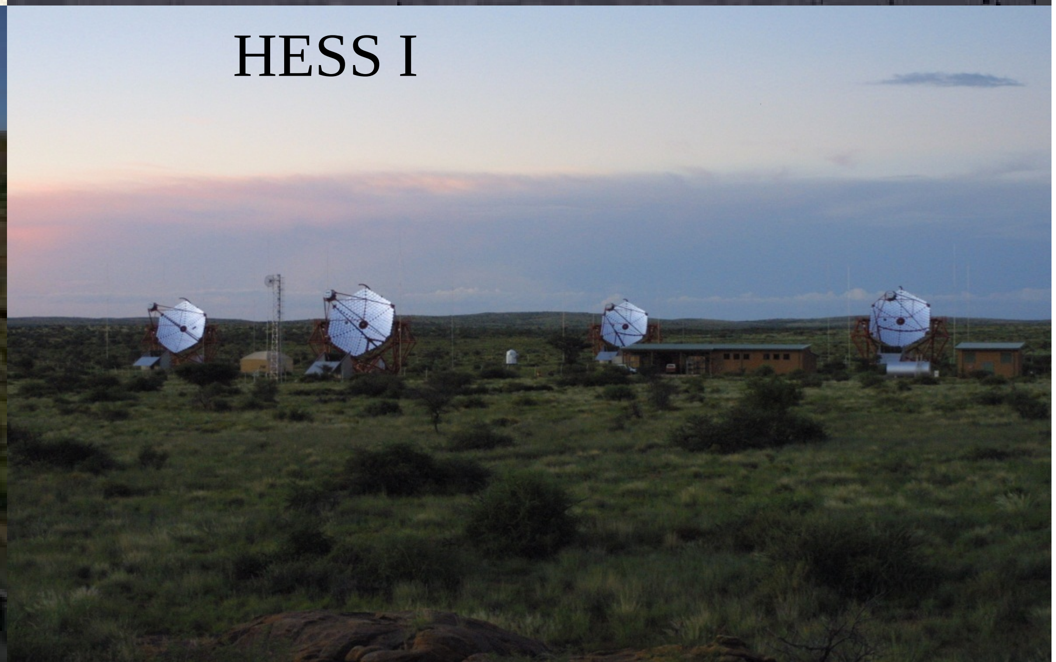
- Increase the photons collection area ≈ reflector area A_{col}
- Increase the photon detection efficiency ϵ (mirror reflectivity, light funnels, PMTs quantum efficiency)
- The coincidence time gate Δt should not exceed by much the Cherenkov characteristic time ($\tau \approx 3$ ns) → isochrones mirror, fast triggering
- The solid angle $\Delta\Omega$ within which the photon signal is integrated should not exceed much the angular size of the shower Ω_g
  → small pixels, triggering by fraction of the field of view or using nearby pixel patterns.

2016

Current ACTs

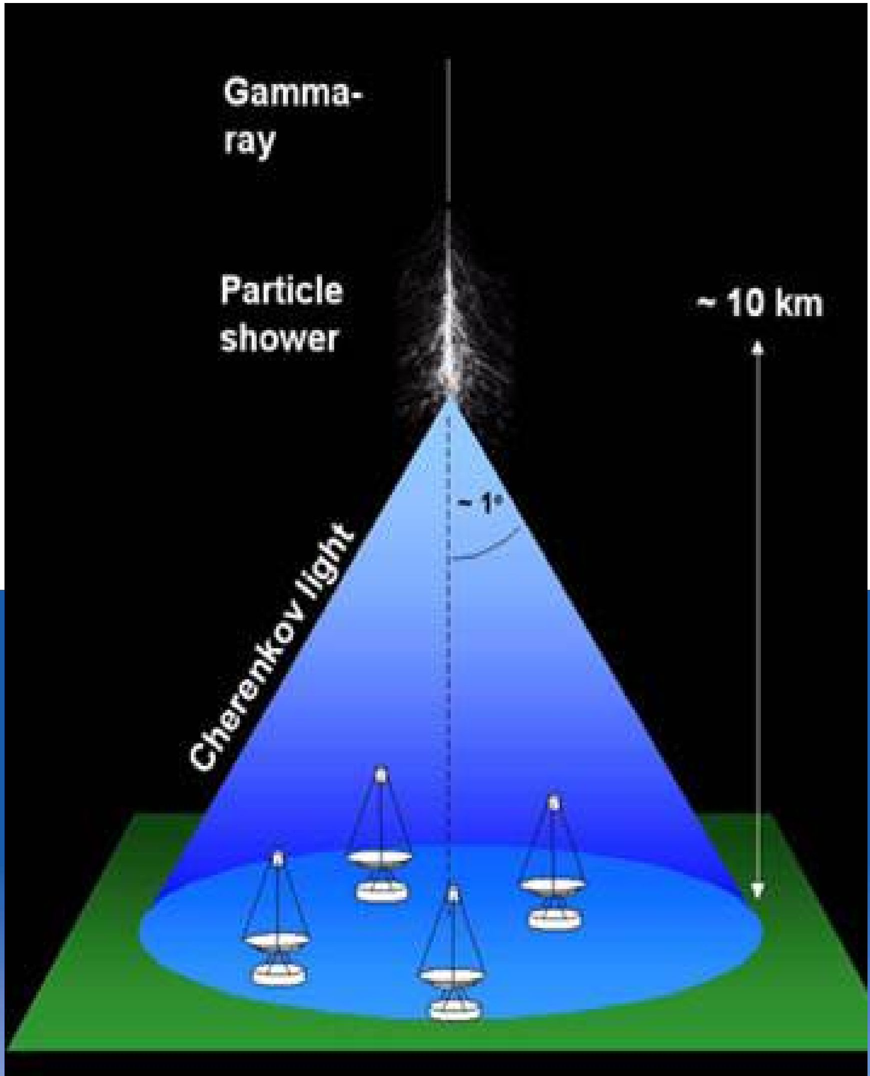
Observatory	# of telescopes	Reflector diameter (m)	Site
CANGAROO III	4	10	Australia
HESS I	4 → 4+1	12 (28)	Namibia
MAGIC	1→2	17	Canaries
VERITAS	2→ 4	12	Arizona

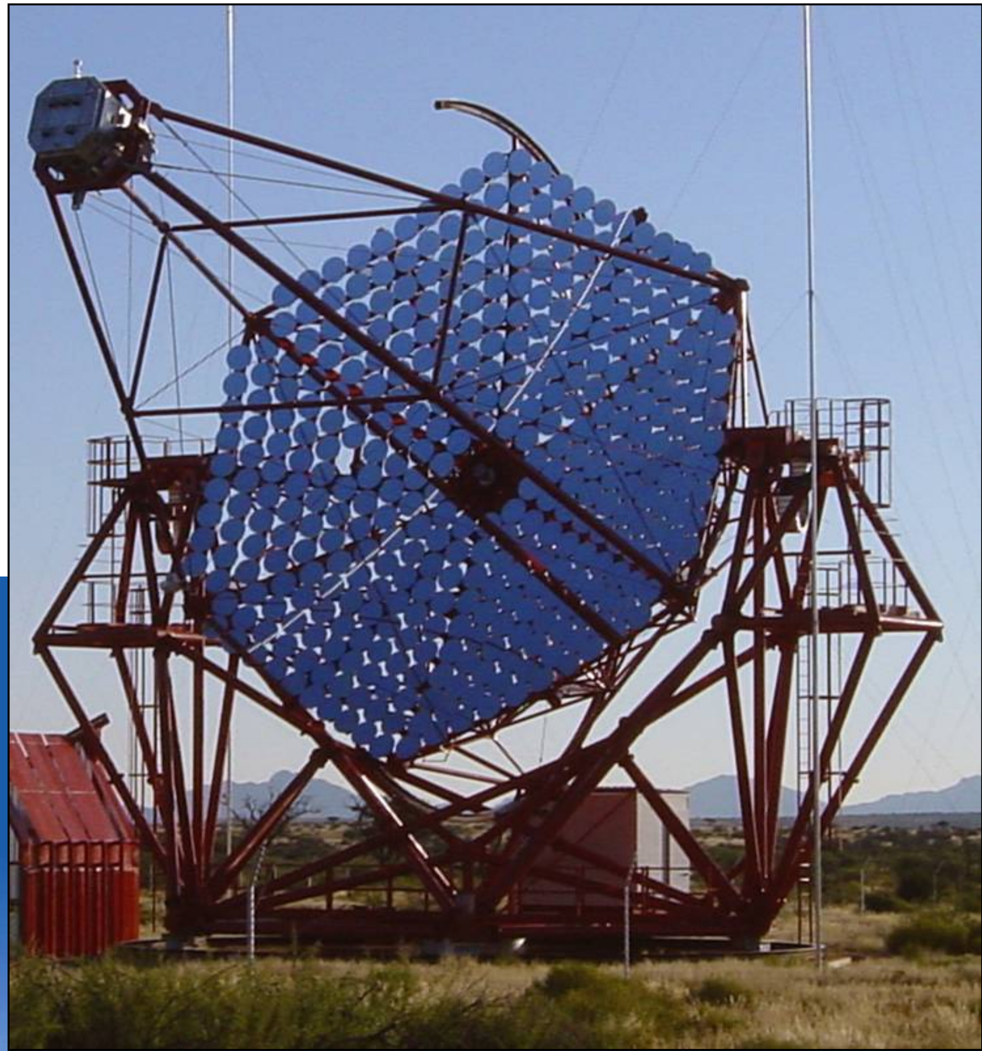
2016



Hess 2004 : x4 telescopes

2016





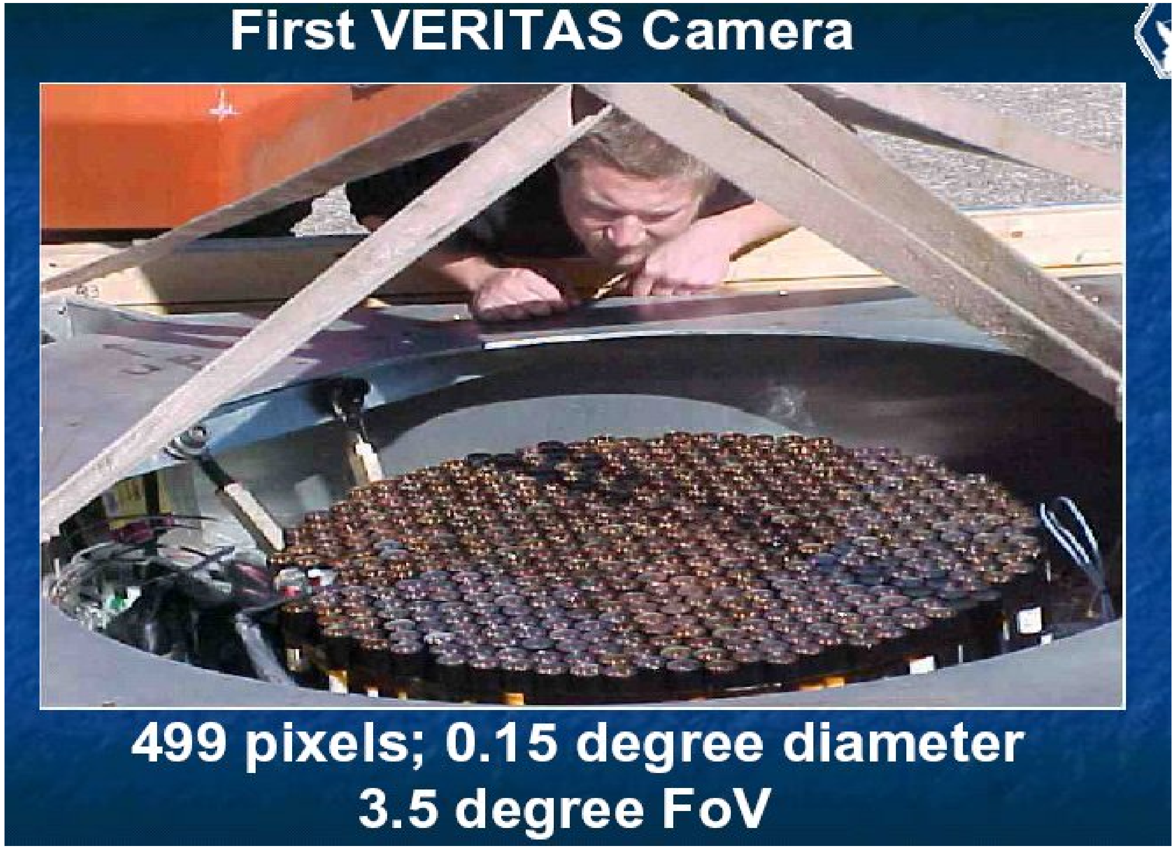
Imaging telescopes: the cameras

2016

Experiment	# pixels	Pixels size	Field of view
CANGAROO III	552	0.115°	3°
HESS I	960	0.16°	5°
MAGIC	396+180	0.08°-0.12°	4°
VERITAS	499	0.15°	3.5°

Imaging telescopes: high resolution cameras

2016



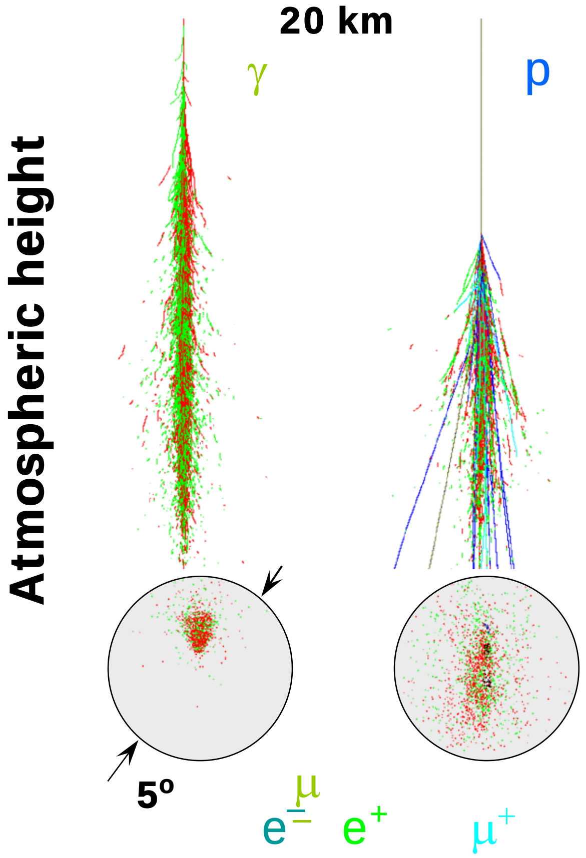
VERITAS

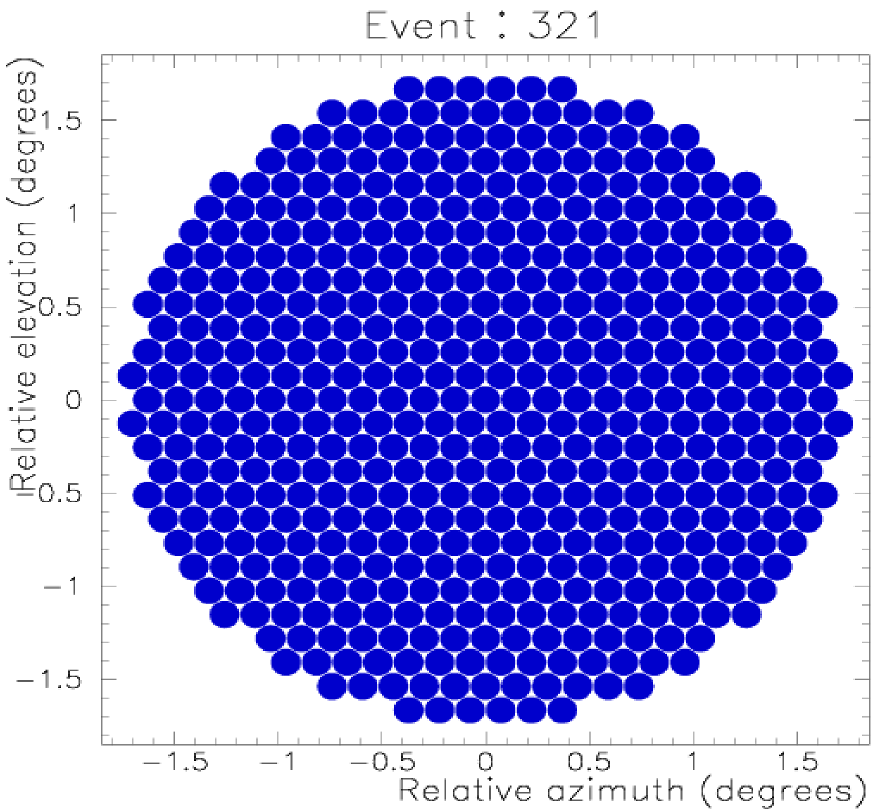
MAGIC

Imaging telescopes: high resolution cameras (H.E.S.S.)

- 960 phototubes equipped with light funnels (Winston cones).
- On board trigger electronics (partially overlapping sectors)
- On board continuous analog memory and fast (Ghz) sampling (Analog Ring Sampler) + integrated signal 12 ns → ADC

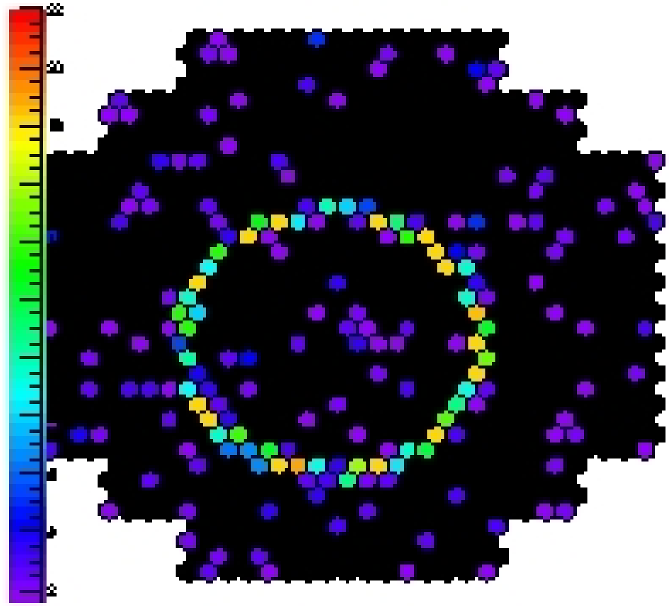
VERITAS Movie Camera

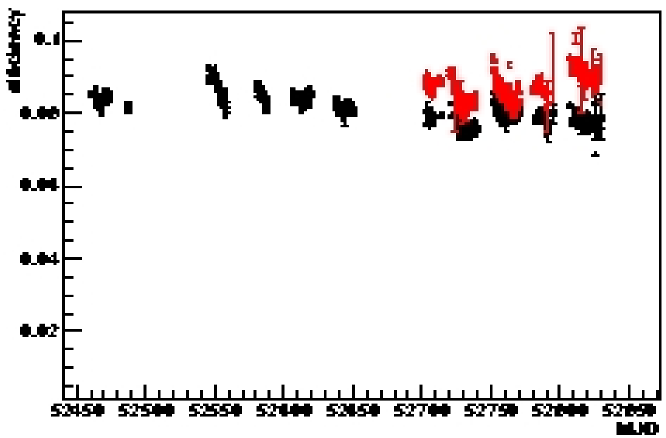




An effective detector monitoring: muon rings

- Muons through the mirror produce a perfect ring image whose light content is completely computable.
- Comparing measured signals with estimations ⇒ global efficiency including effects such as :
  - near atmosphere absorption;
  - mirror reflectivity;
  - light collection;
  - PMTs quantum efficiency .
- The detector monitoring is then automatically taken into account in the data analysis.





Stereoscopic ACTs

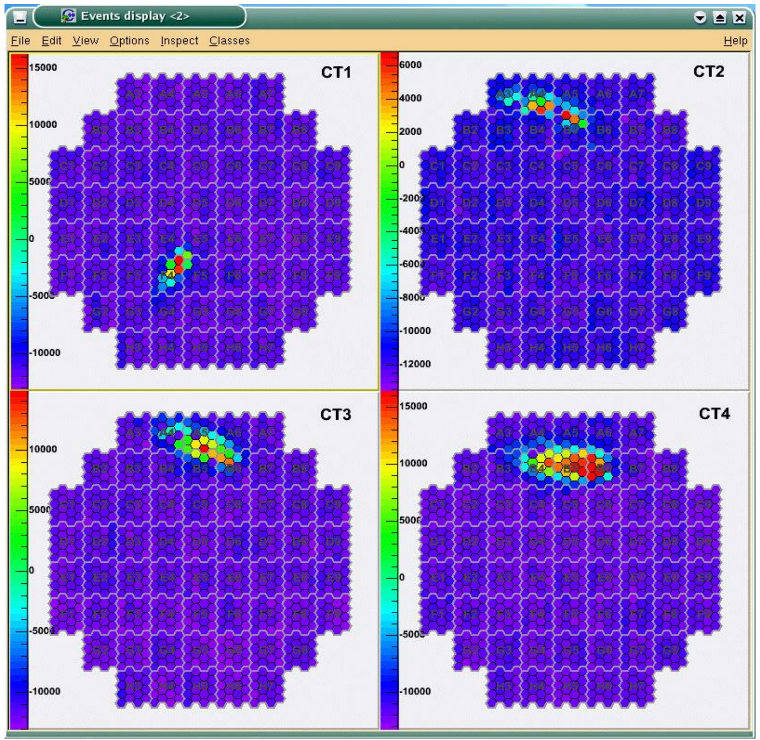
2016

- Each showers is seen by many telescopes

- Very high hadron shower rejection factor
  (> 1000)
  axial symmetry + narrow 3D width
  + punctual source pointing

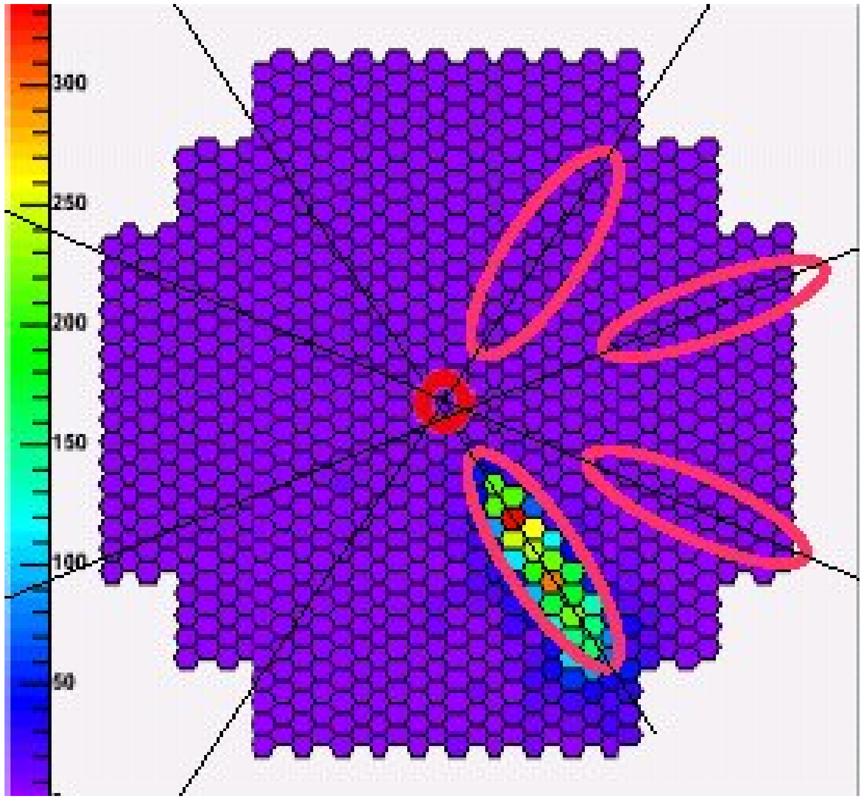
- Much improved angular resolution wrt 1 telescope
  (≈ 4' avec 4 telescopes)

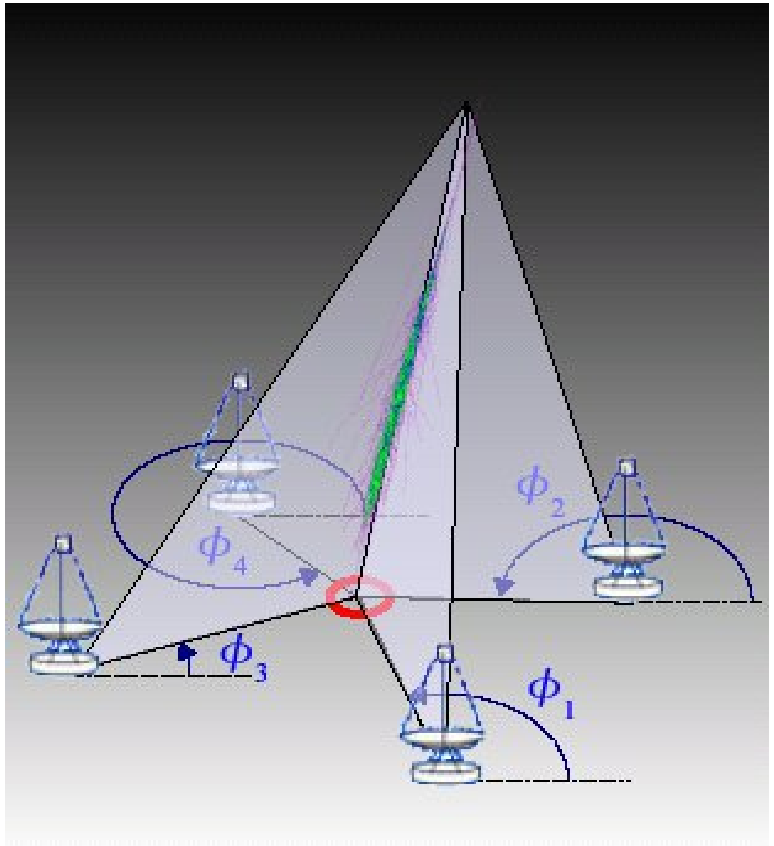
- Better energy resolution
  (≈15%)



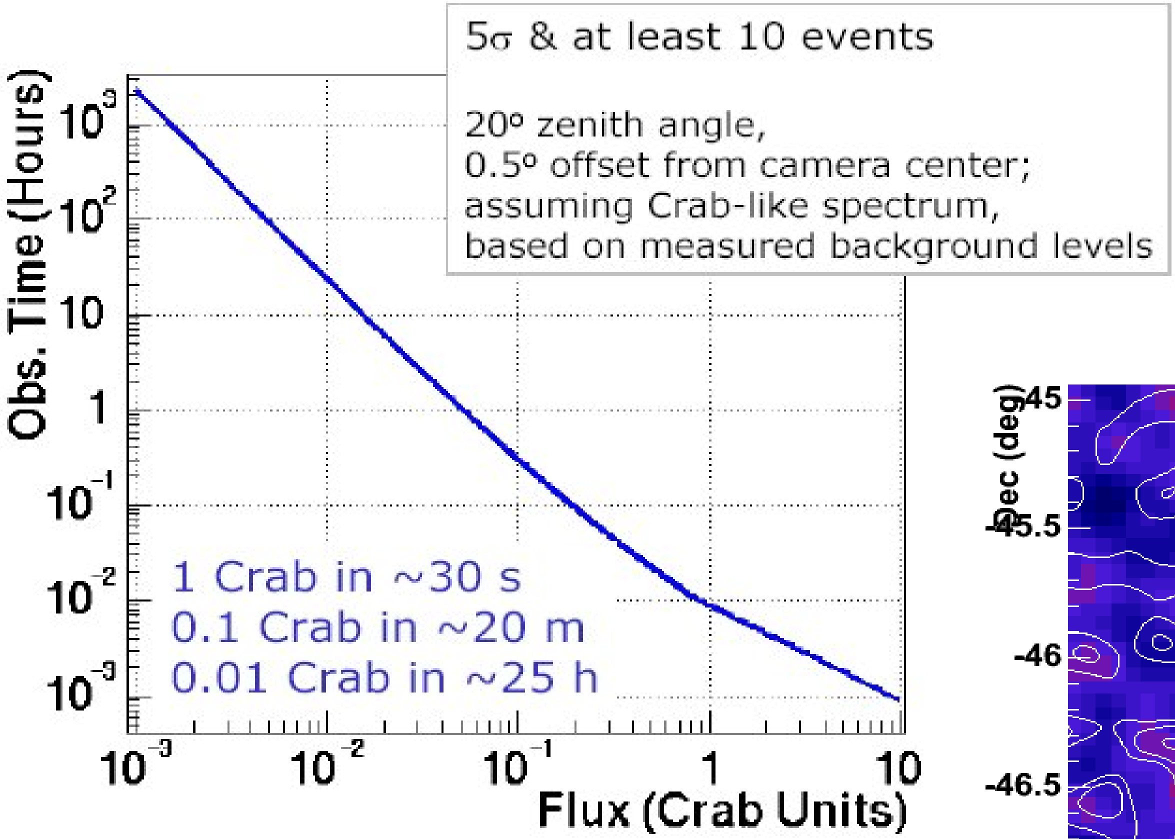
Stereoscopic ACTs

- Direct measurement of the origin of the gamma-ray in the field of view (important for extended sources)
- Direct measurement of the ground impact point (important for the determination of the energy)

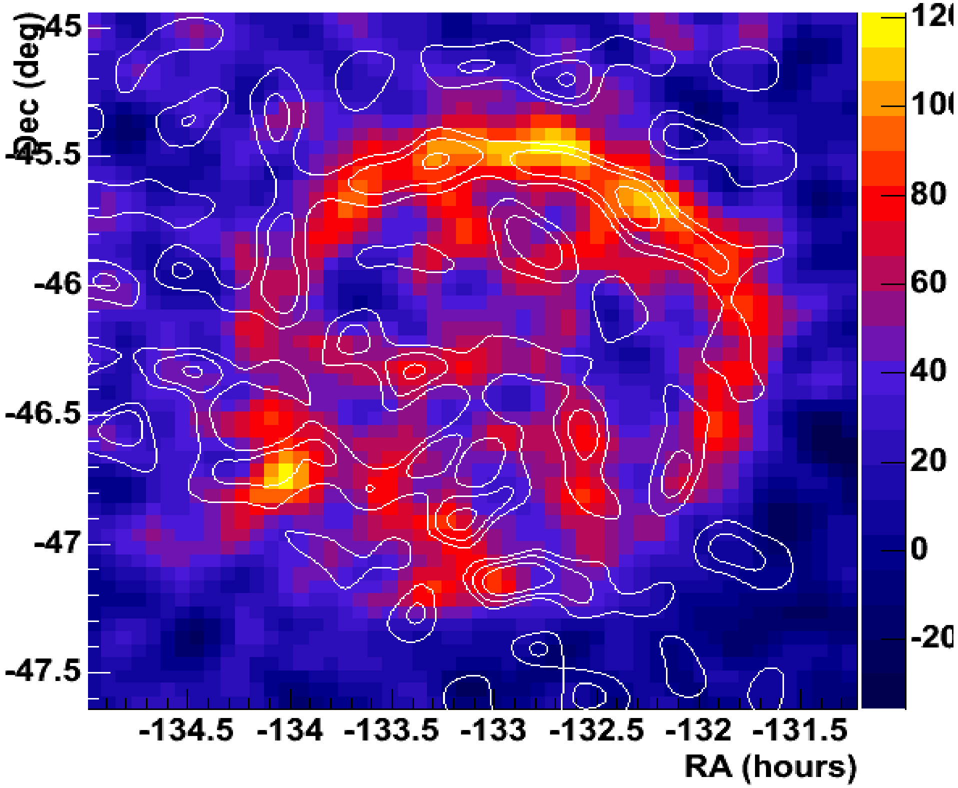




Sensitivity to gamma-ray sources: H.E.S.S.



Extended sources capability e.g. Vela Junior (2° in diameter)

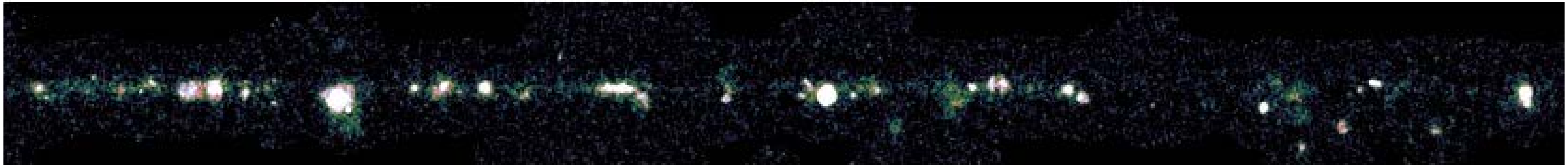


More than hundred TeV-sources

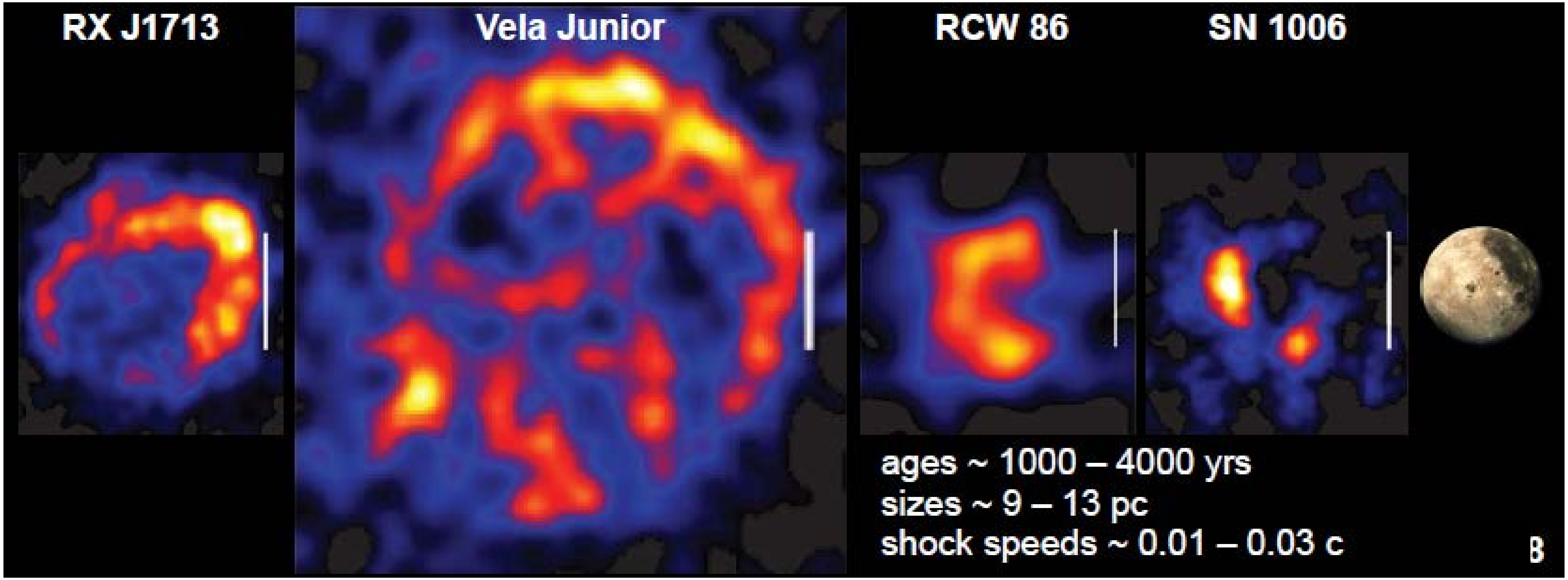
M. Lemoine-Goumard 2006

Galactic Plane Survey with H.E.S.S.

- **~2800 hr of observations of the inner Galaxy (2004–2012)**
  - ~100 sources above the H.E.S.S.-I sensitivity ~1% of Crab
  - Large variety of source types & ~1/3 of unidentified sources



  - 5 resolved shell-type SNRs

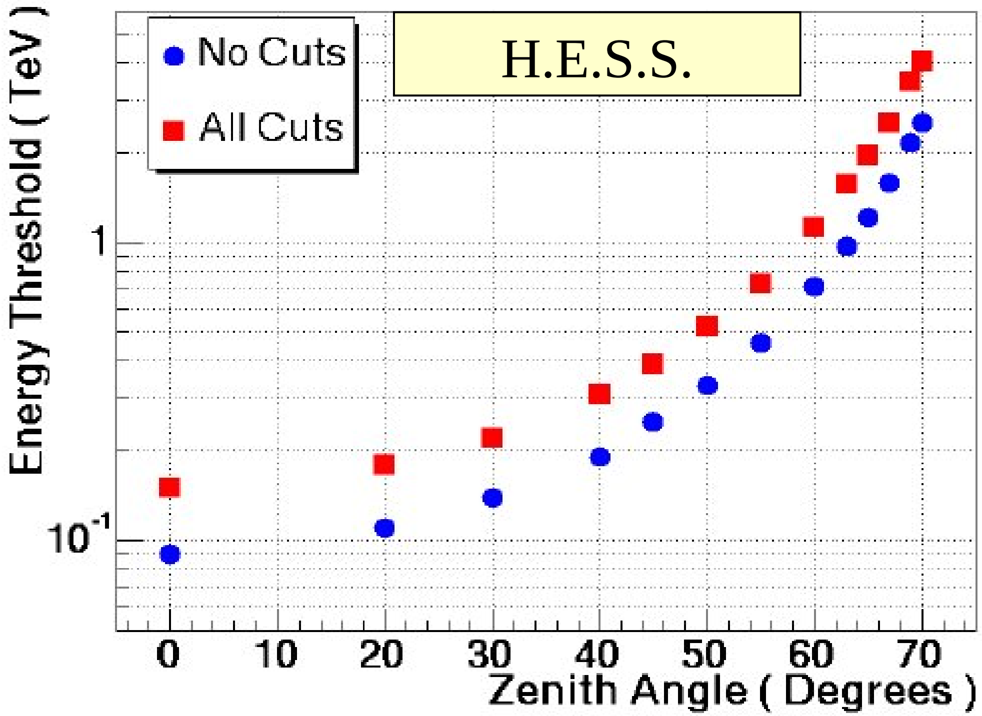


2016

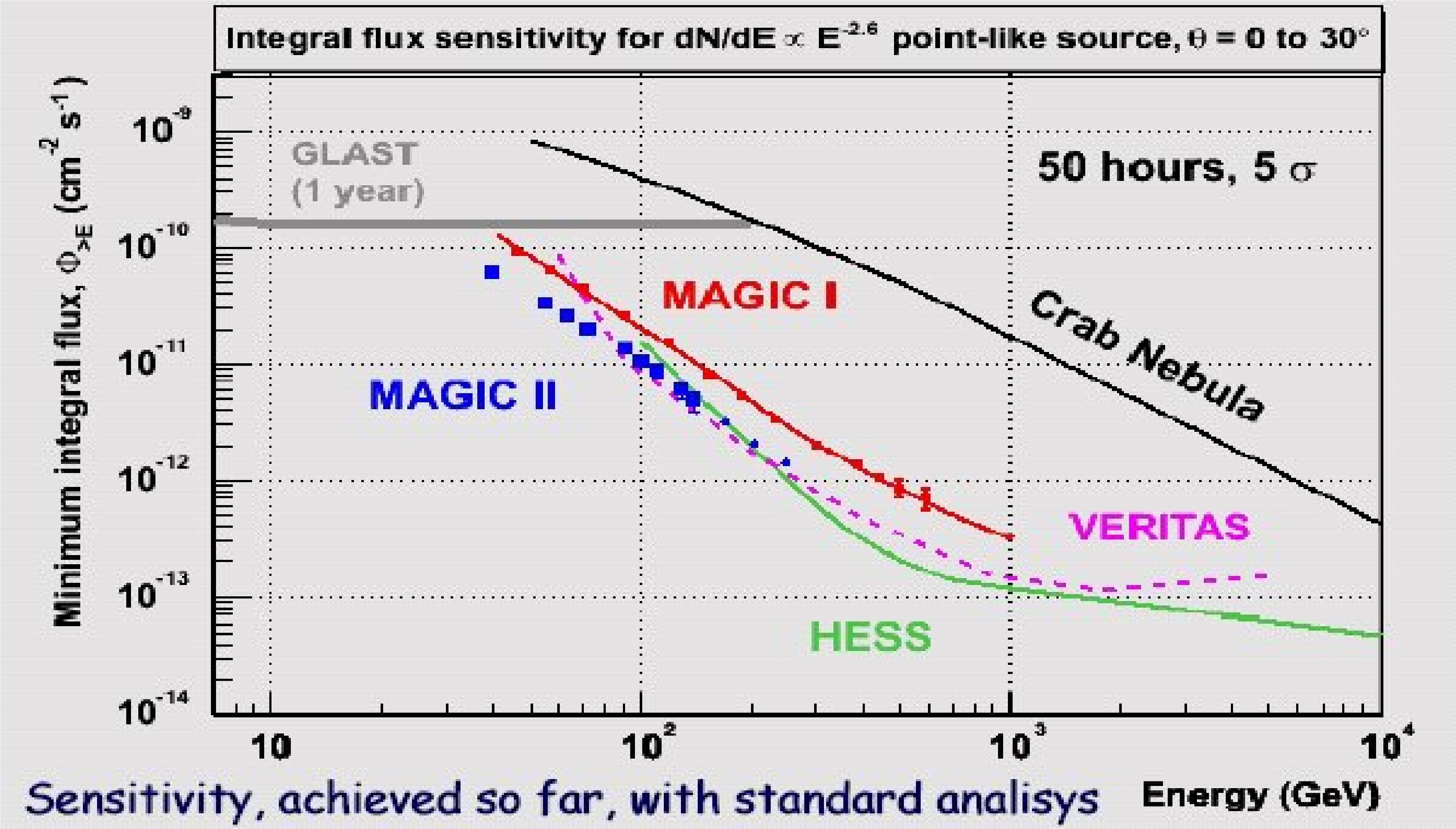
Energy threshold

- The threshold depends on the zenith angle

- Typically 120 GeV
  at the zenith for H.E.S.S.
  and comparable stereoscopic systems.
- MAGIC II (2 identical large telescopes)
  down to 50 GeV.
- Starting now: H.E.S.S. II
  - 50 GeV with a very large telescope
    + les 4xHESS I in stereo
  - 20 GeV expected in « mono »
    with HESS II large telescope
    and a second level trigger.

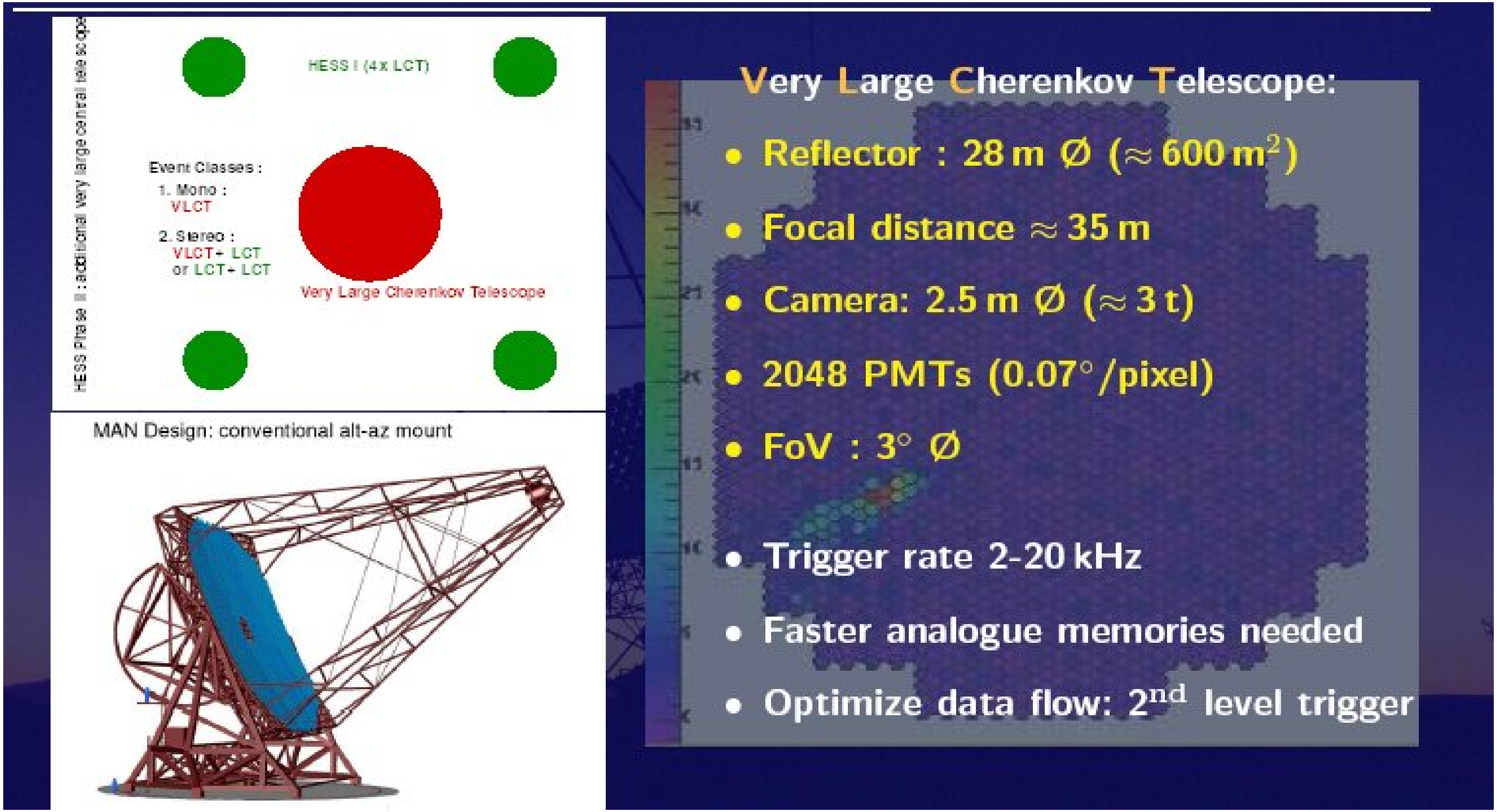


Sensitivity of current imaging telescopes



2016

Down to 20 et 50 GeV with H.E.S.S. II

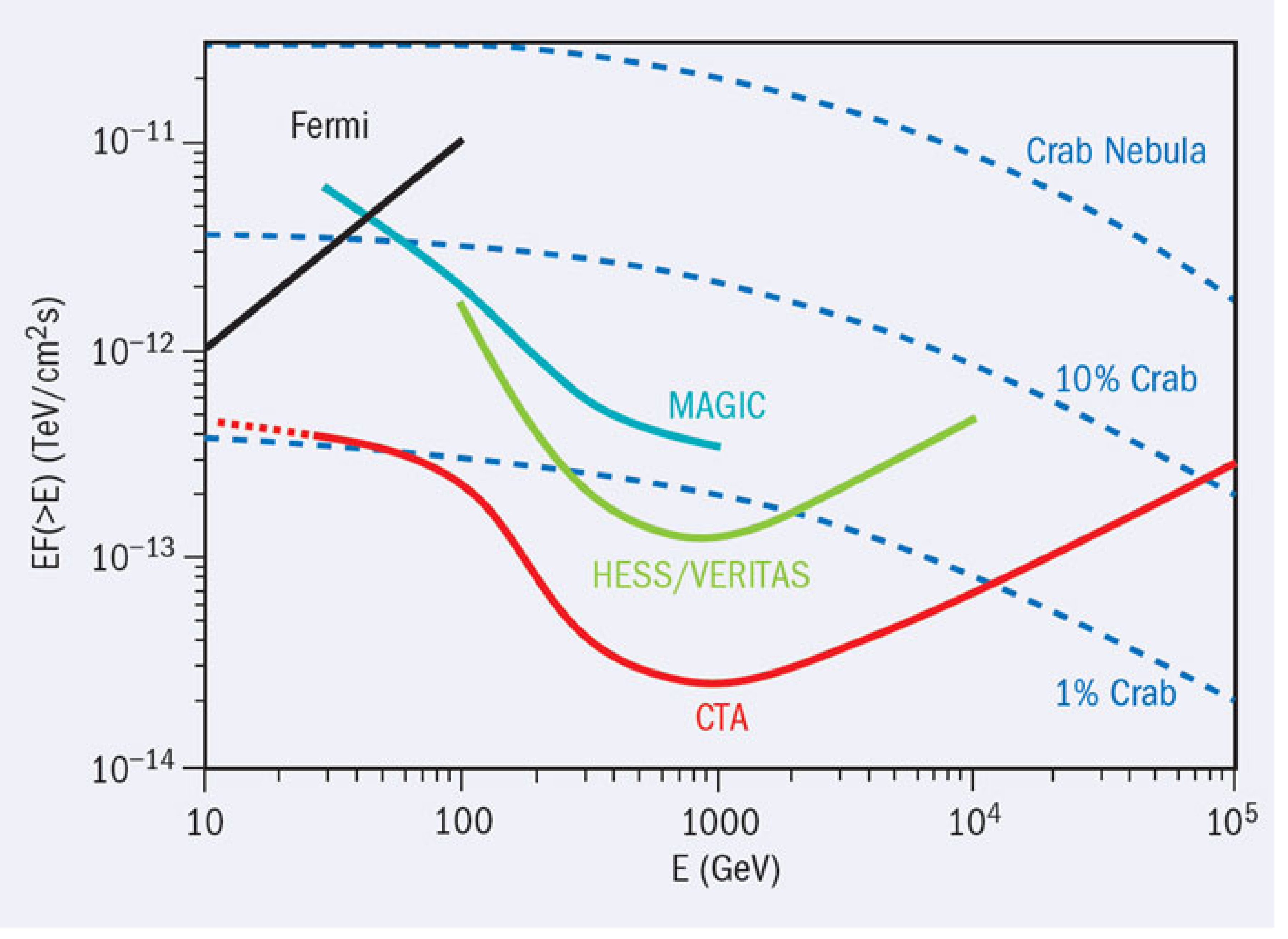


HESS II

2016

- First light July 2012

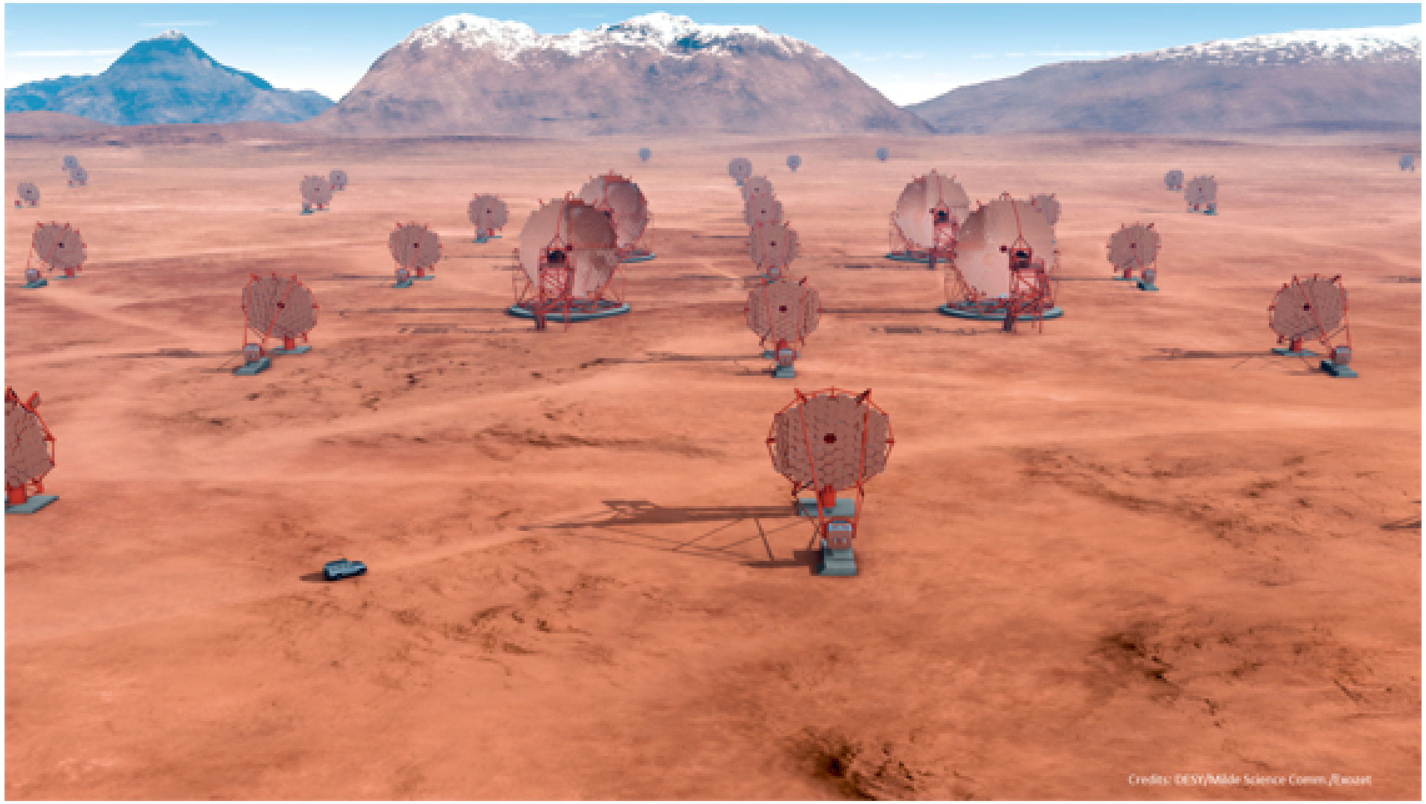
The FERMI, MAGIC , H.E.S.S. II and CTA era



2016

Toward a large array of ATCs : CTA

- Goal : a milli-Crab sensitivity at the TeV
- This could be achieved with 20 to 30 imaging telescopes (HESS-I type)
- The sensitivity is not only increased because of the covered area, but also due to improved stereoscopic quality (improved hadron rejection factors and angular resolution) : 56% of the showers seen by at least 4 tel with 16 in total, up to 2/3 with 36 tel.
- International consortium HESS-MAGIC-VERITAS, 2 sites one north one south: CTA = Cherenkov Telescope Array.



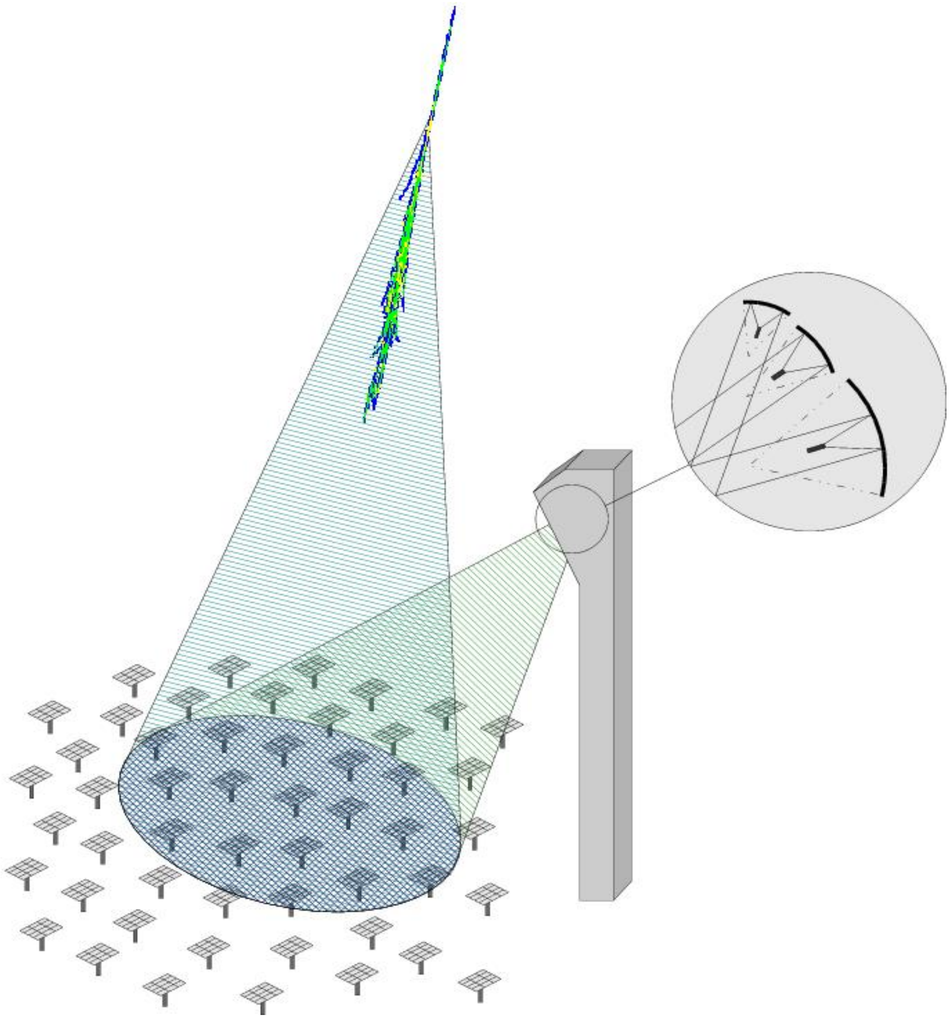
2016

A (once favored) alternative solution: sampling arrays

- To lower threshold, benefit of the very large mirror area from solar power plants
  ~ 2000 - 6000 m^2

- Need to split the beam from the different heliostats
  → Secondary optics

- One PMT per heliostat.



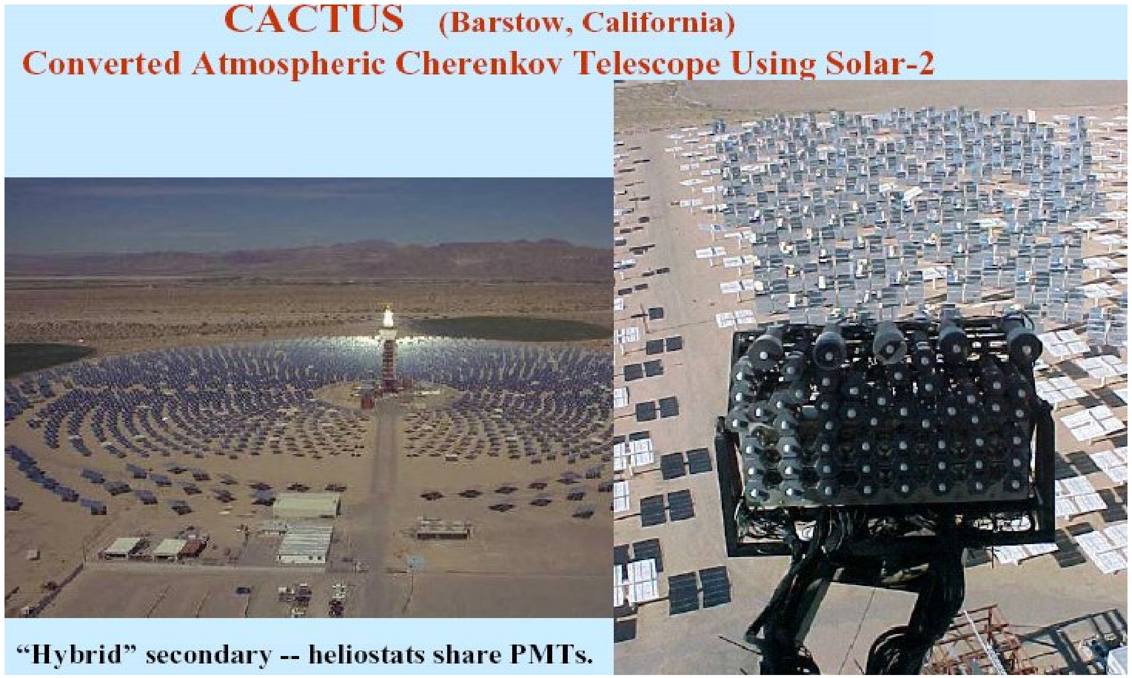
2016

CELESTE (France)

53 ×54 m^2

STACEE (USA)

64 × 40 m2



CACTUS (USA)

160 × 40 m2

Large field of view gamma-ray detectors

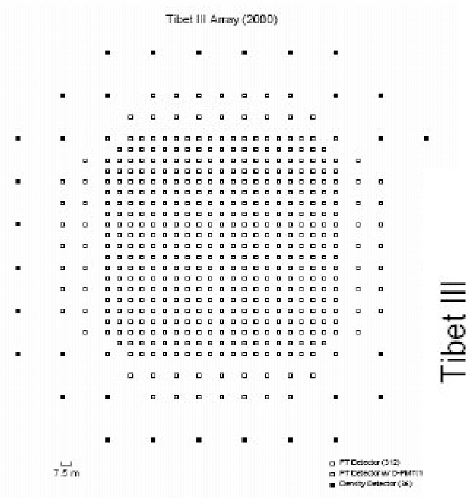
- Detect the shower particle reaching ground (at high altitude) (scintillateurs, RPCs or water Cherenkov detectors)
- Large duty cycle ≈ 90%
- Large solid angle ~ steradian
- Well suited to look for unpredictable transient phenomena (ex: gamma-ray burst)
- … BUT small sensitivity (~0.5 Crabe) because of rather poor hadron shower rejection factor and limited angular resolution (0.5° to 1°) ; (measured from timing in different detectors).
- … as well as rather high threshold (~ 1 TeV)

Large field of view gamma-ray shower detectors

2016

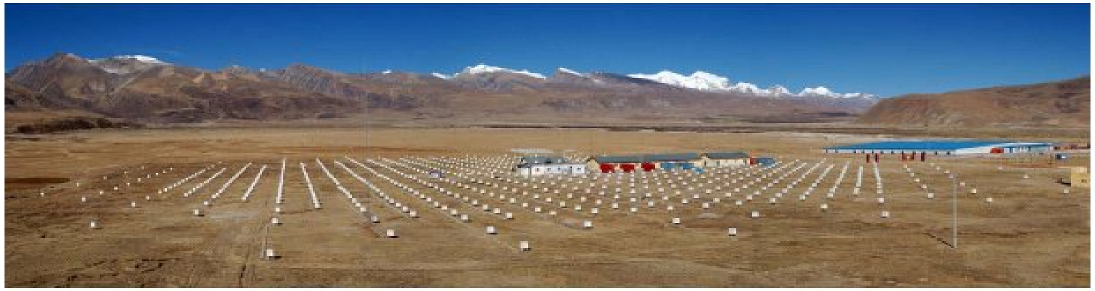
Tibet

- 4300m asl
- Scintillator array
- 497 detectors
  - $0.5 m^2$ each
  - 5mm lead on each
- $5.3x10^4$ m^2 (phys. area)
- 680 Hz trigger rate
- 0.9^o resolution



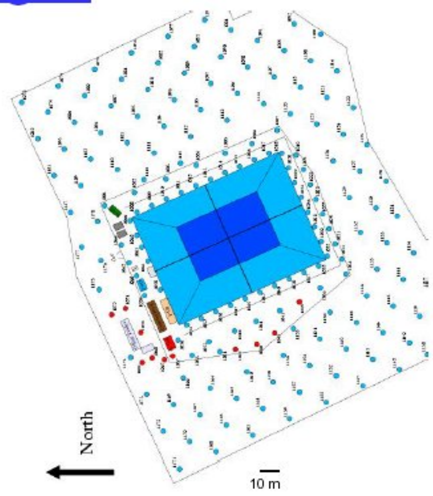
Tibet III

Scintillators

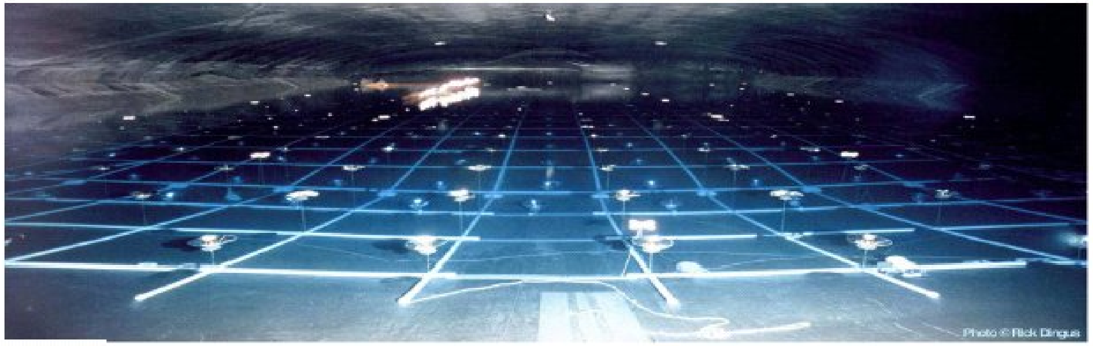


Milagro

- 2600m asl
- Water Cherenkov Detector
- 898 detectors
  - 450(t)/273(b) in pond
  - 175 water tanks
- $3.4x10^4$ m^2 (phys. area)
- 1700 Hz trigger rate
- 0.5^o resolution
- 90% proton rejection



Milagro

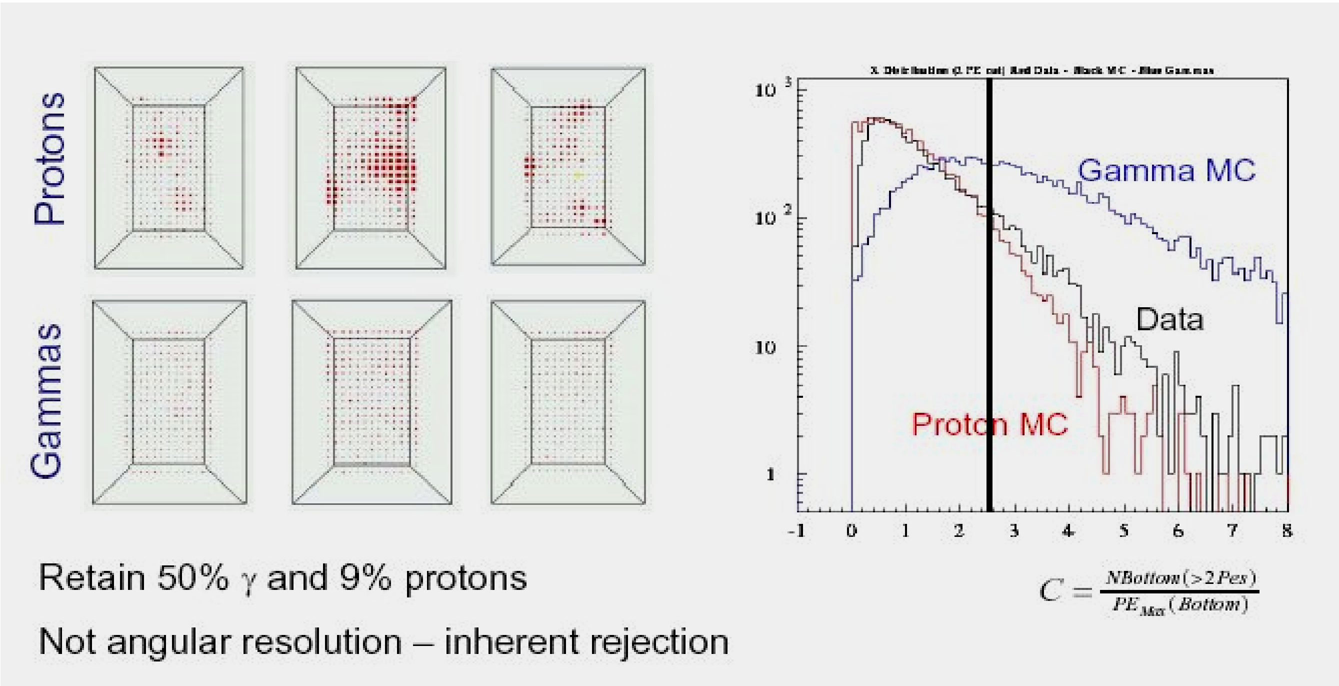


« water pool »

(water Cherenkov detectors)

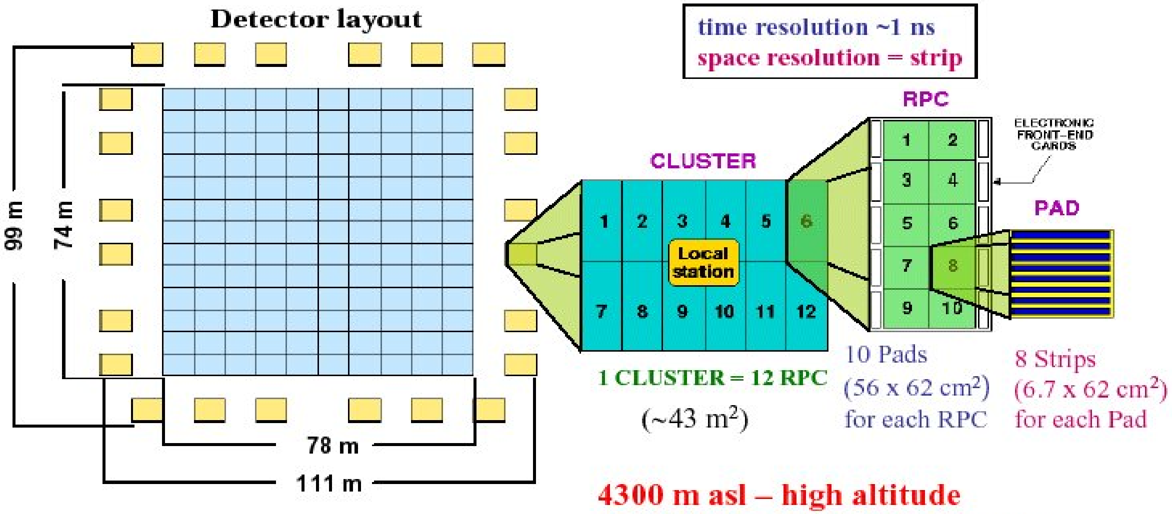
Hadronic background rejection by MILAGRO

- Cherenkov light in the deeper PMTs → hadrons
  (cf. muons that traverses completely the pool).
- Hadronic showers: irregular light distribution → less PMTs hit but larger signal each
- EM showers: more regular light distribution → many more PMTs hit with small signal each PMT.



Proton rejection factor ~ 10

ARGO-Yang Ba Jing (2006)

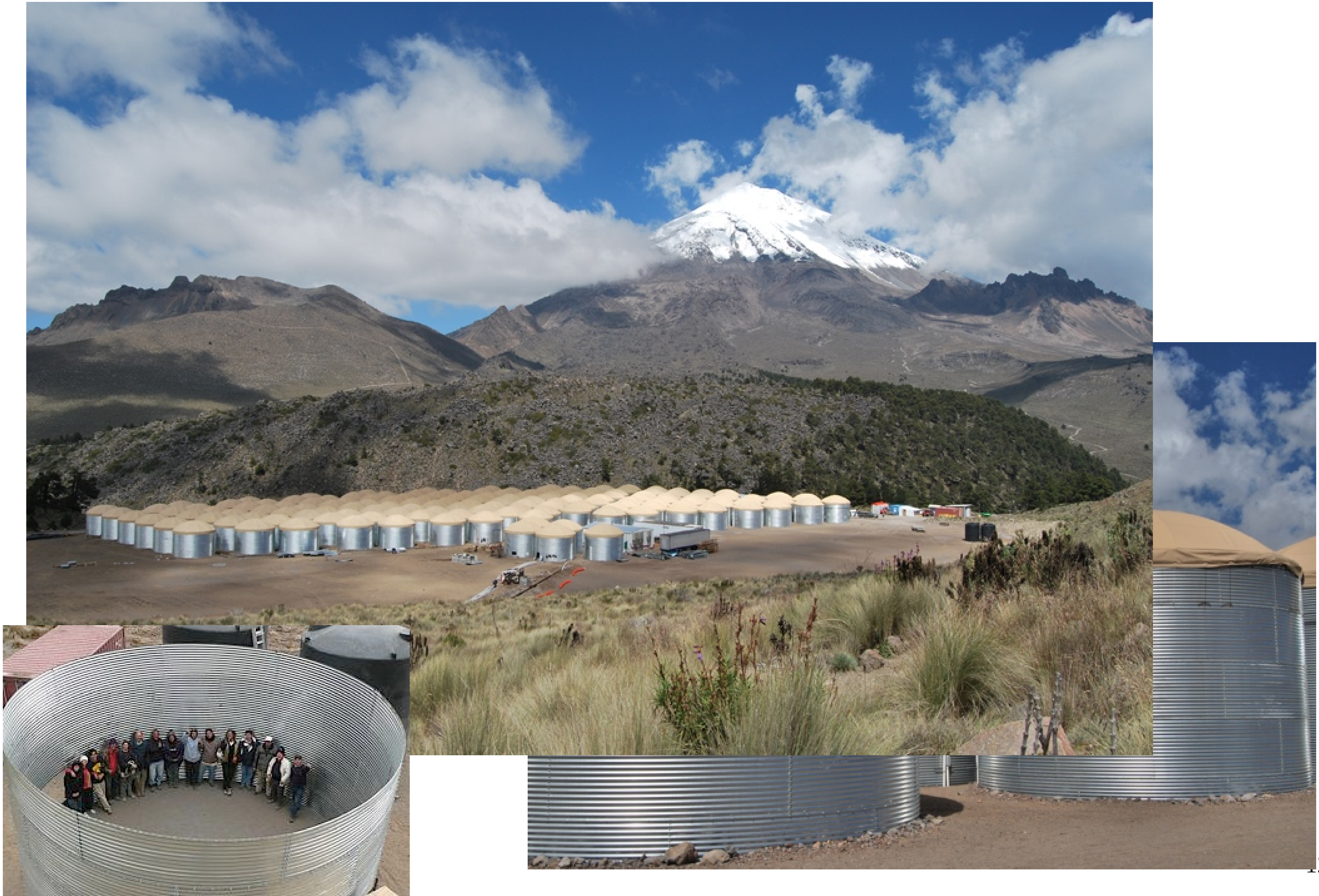


Layer (~92% active surface) of Resistive Plate Chambers (RPC),

4300 m asl – high altitude
5800 m² fully instrumented area
10,000 m² total area
dense sampling of shower

sensitivity (× 3)

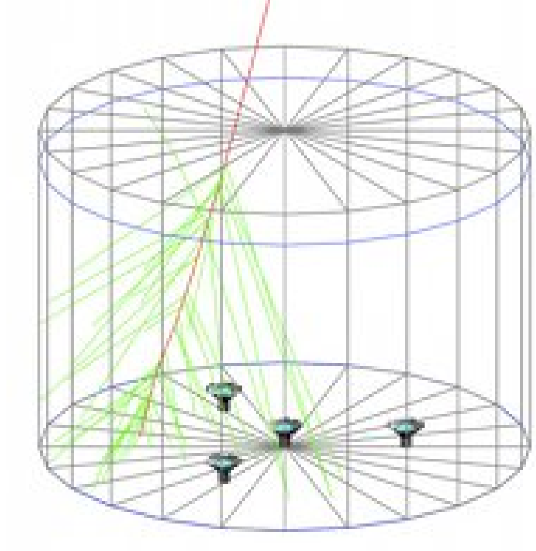
2016

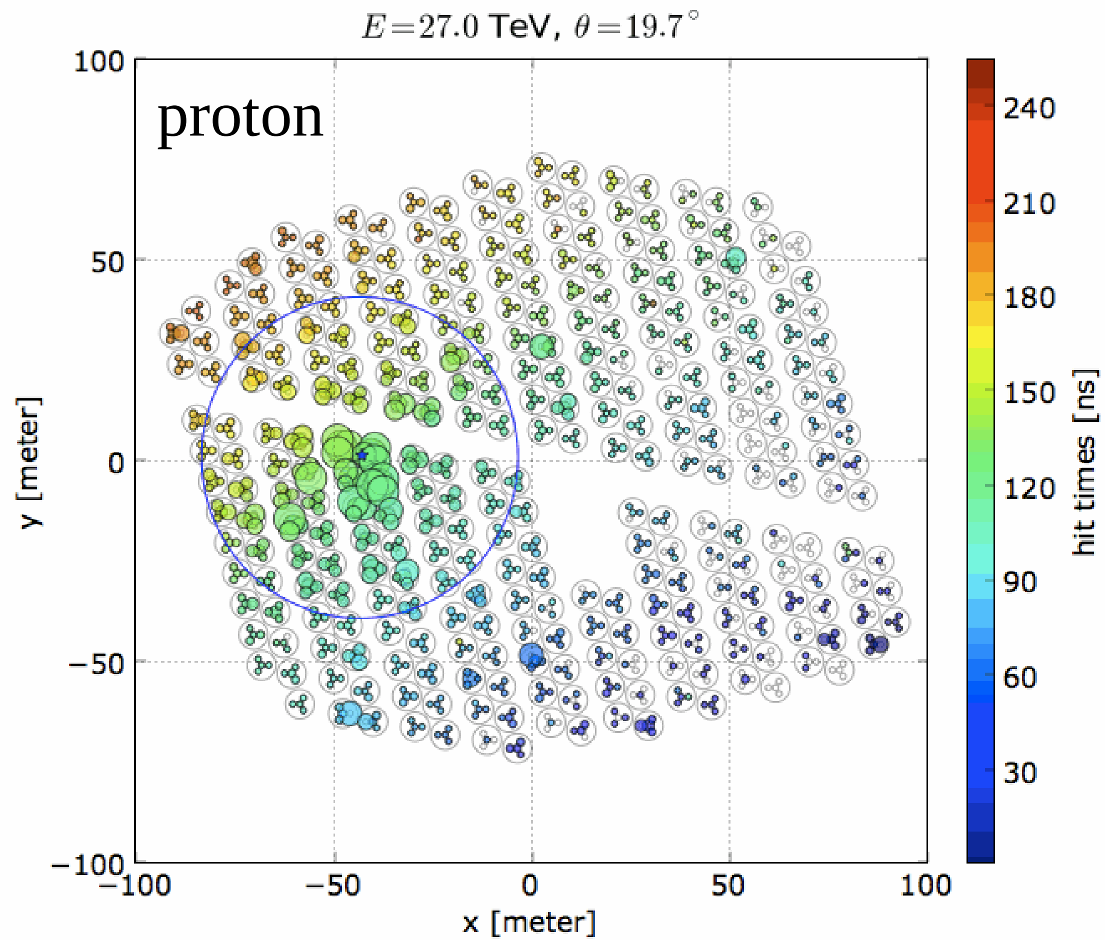


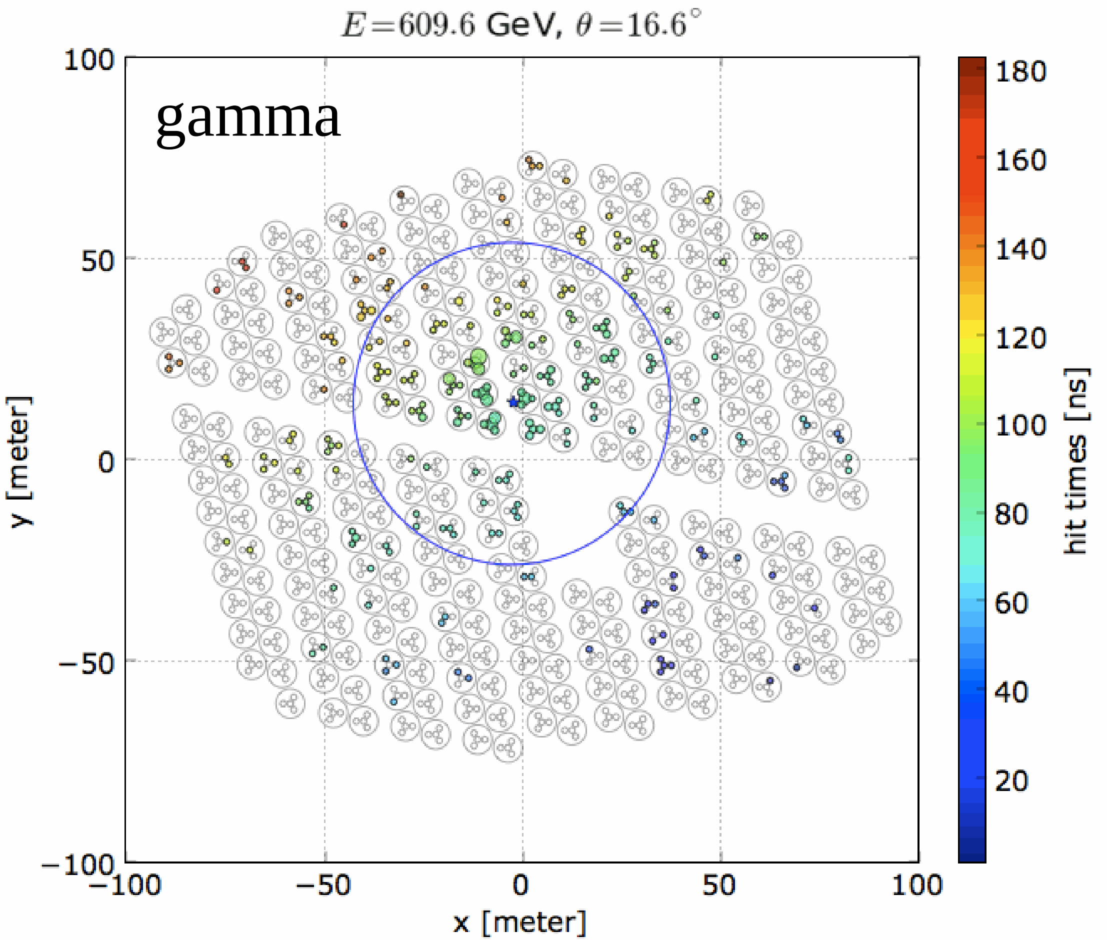

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory
300 tanks completed in Dec.2014
Sierra Negra volcano near Puebla, Mexico.
at an altitude of 4100 meters

2016

Gamma/Hadron rejection

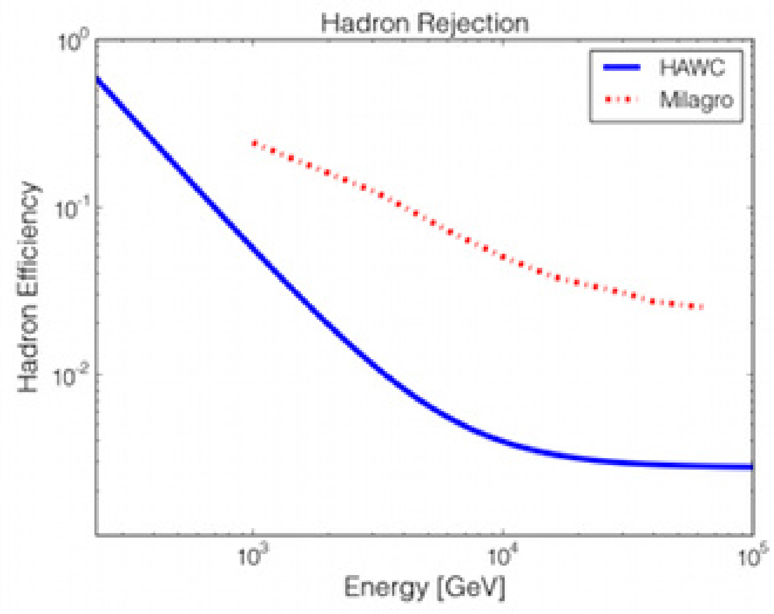


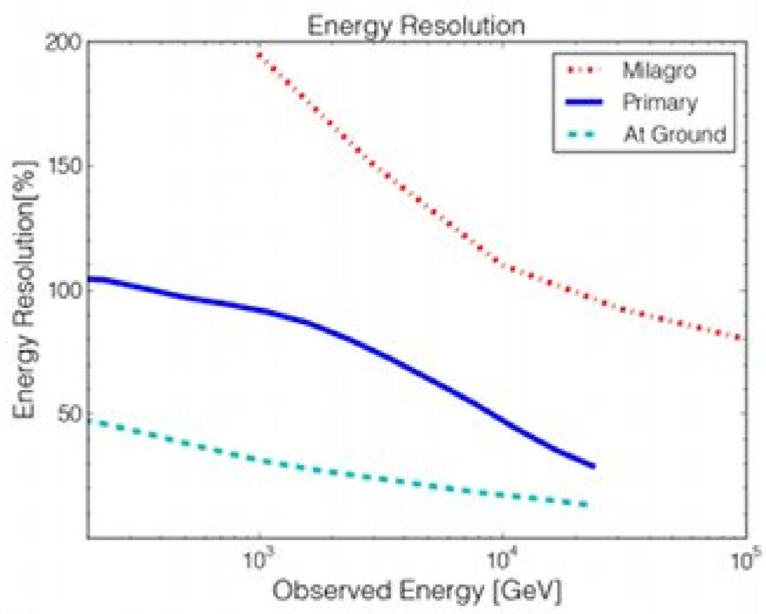


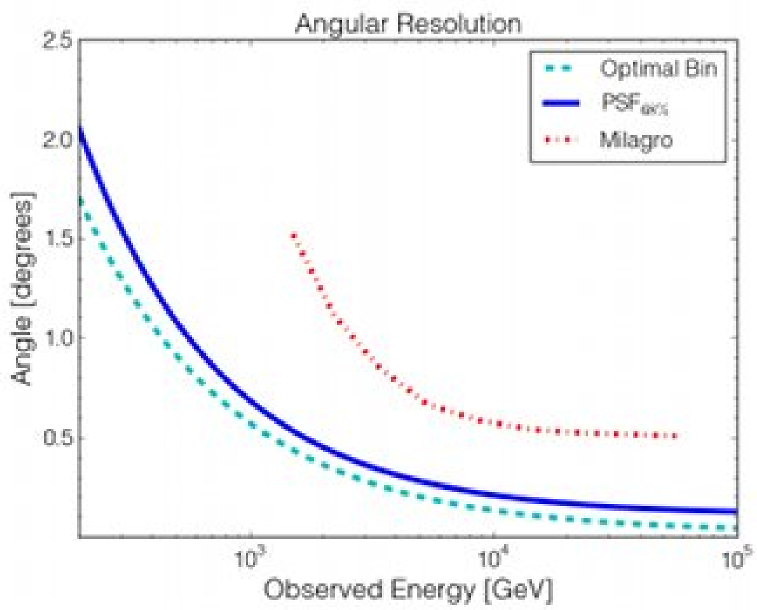


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

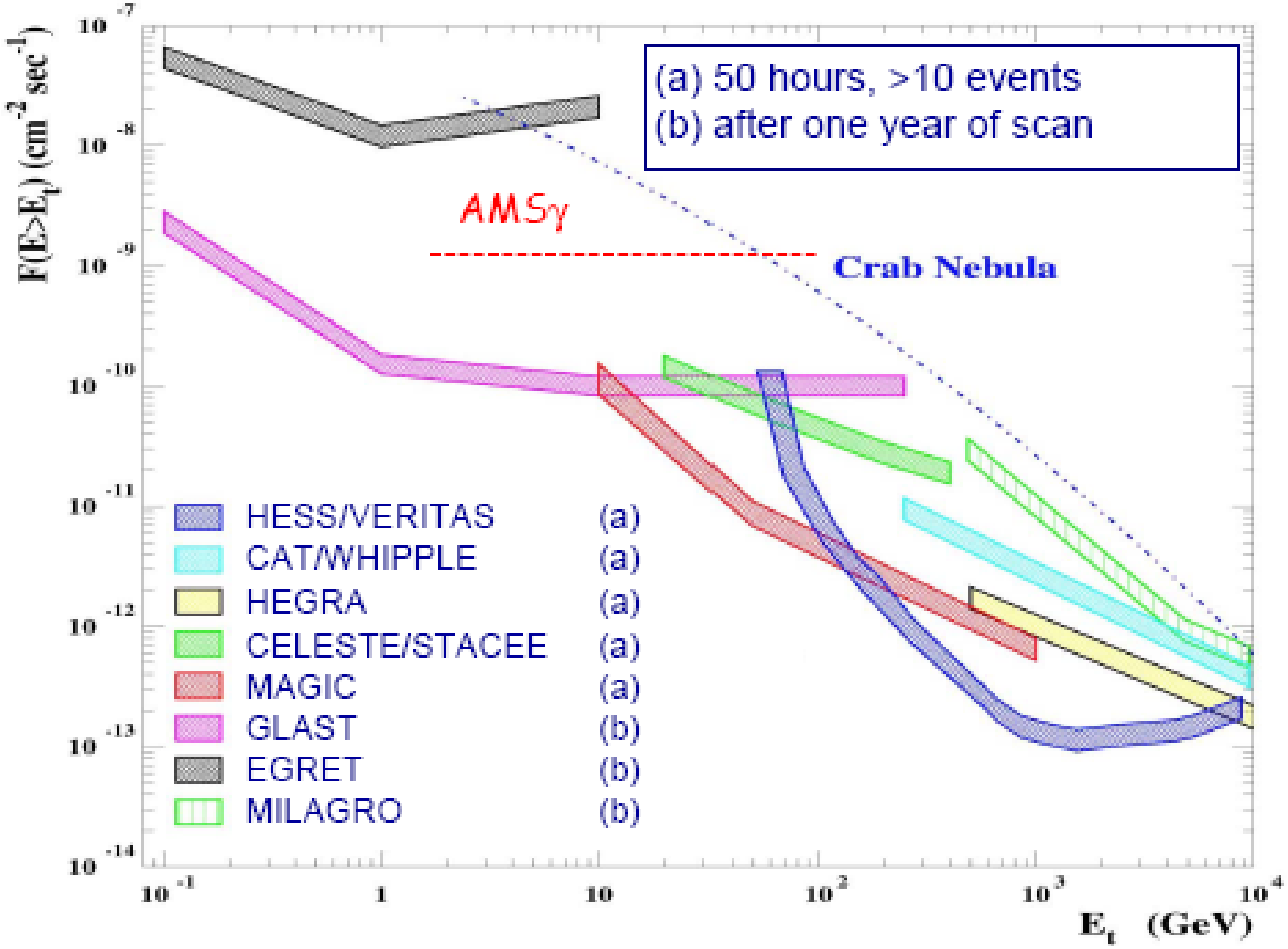
2016



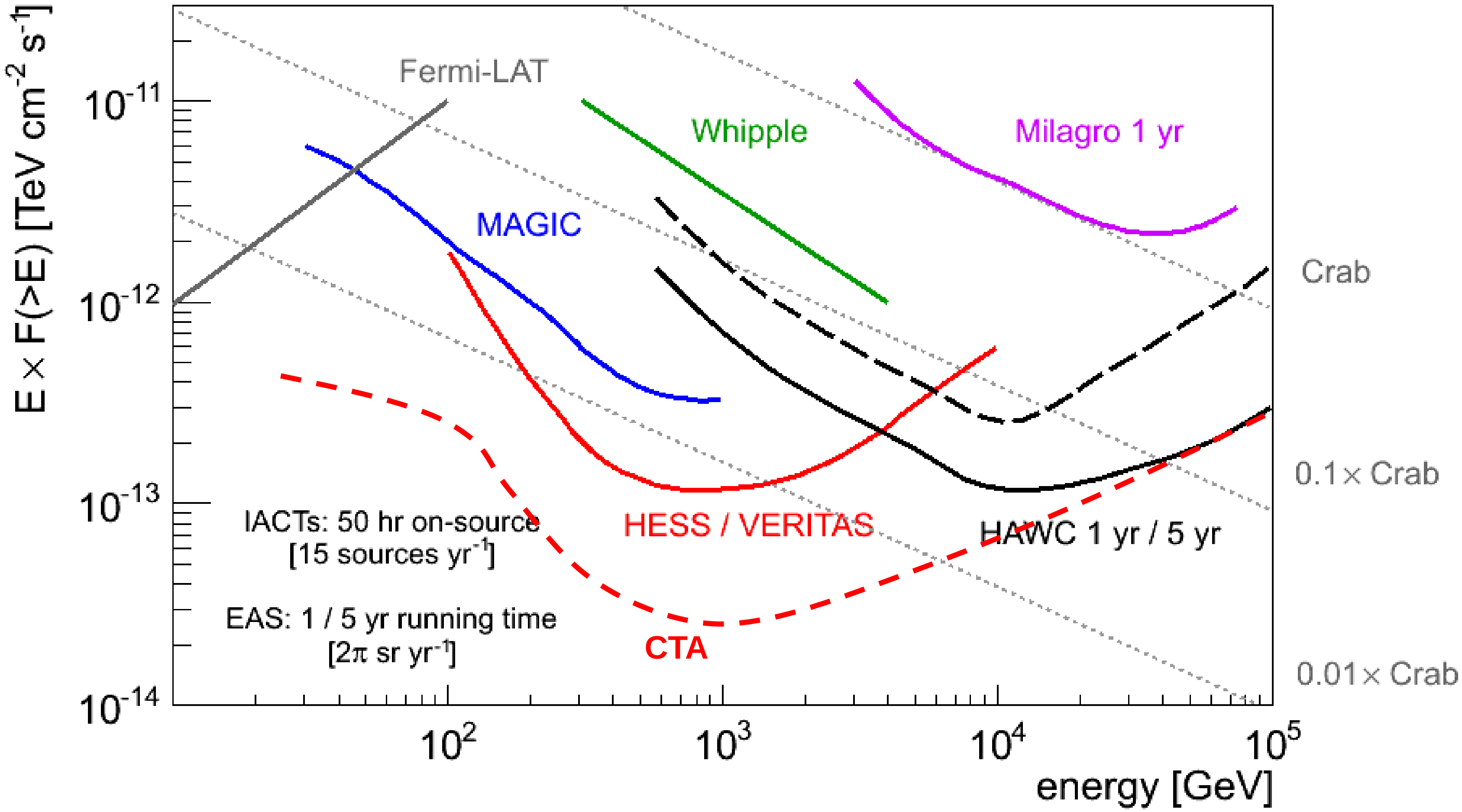




Old and current generation of space and ground γ-telescopes



New and future generation of space and ground γ-telescopes



NEUTRINO TELESCOPES

The cosmic neutrino spectrum, from MeV to EeV

- **MeV-GeV:** Solar neutrinos & super Novæ, atmospheric neutrinos: various detectors but mostly a water Cherenkov domain with SuperKamiokande

- **GeV-TeV:** Cherenkov in natural water or ice, neutrinos atmospheric neutrinos and beyond.
ICECUBE, ANTARES.

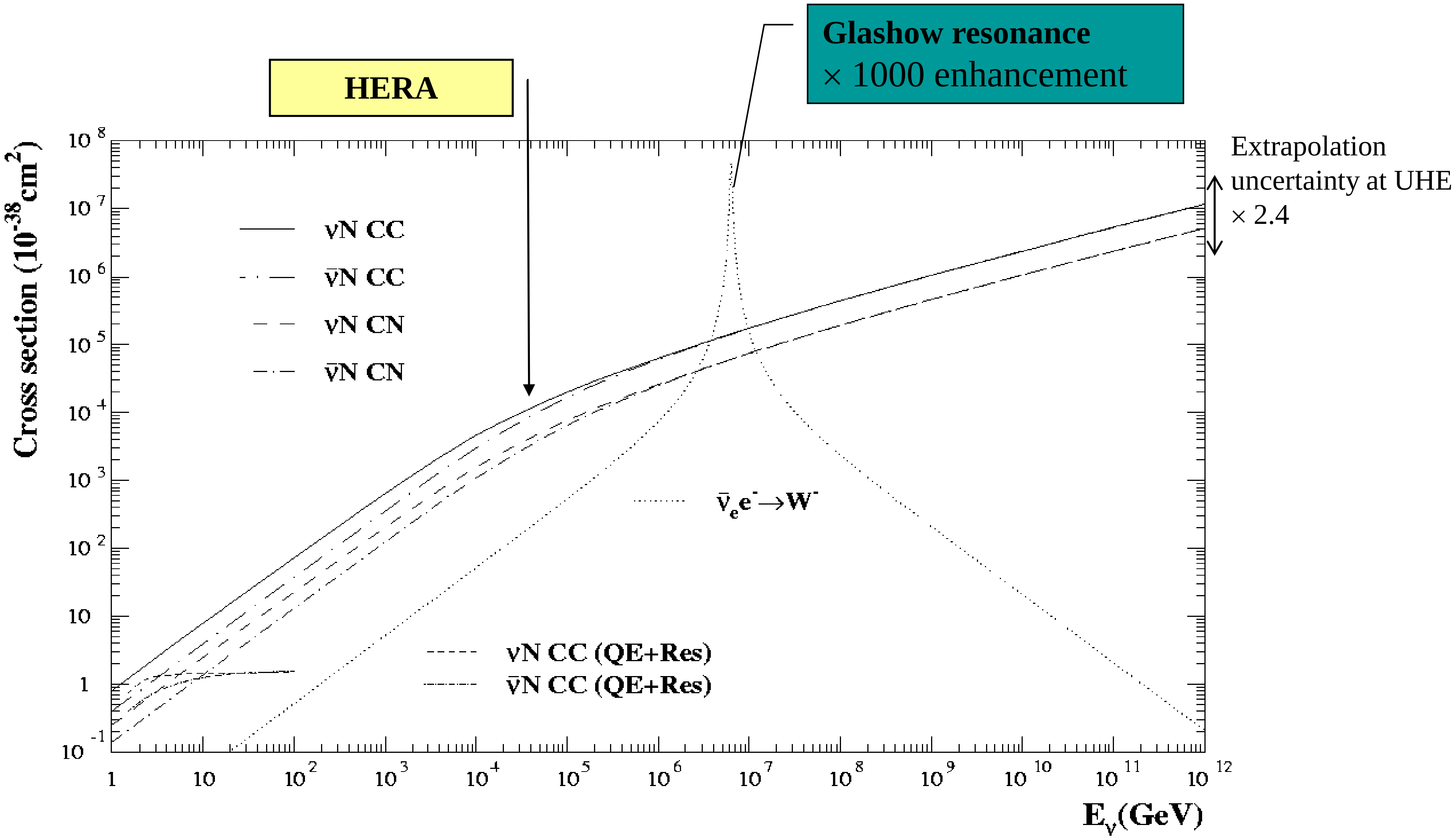
- **TeV-PeV:** the same but extended to 1 km^3 size.
ICECUBE so far the only one.

- **EeV:** arrays foreseen for UHECR detection proved to be very efficient for UHEν's. Observe quasi horizontal showers with AUGER.

2016

Neutrino cross sections

- ν-matter cross sections:



Neutrino detectors

… super heavy weight category !

$$\sigma(\nu N) \sim 0.6 \times 10^{-38} \times \left(\frac{E_\nu}{1\,\mathrm{GeV}} \right) \mathrm{cm}^{-2}$$

<u>ex. the WBB of CERN :</u>

10^{13} 400 GeV protons per extraction

$\Rightarrow \phi_\nu \approx 10^6\, \nu\ \mathrm{cm}^{-2}$ $\quad \langle E_\nu \rangle \approx 20$ GeV

with:

$\sigma_{\nu,N} = 0.6\times10^{-38}$ (E/GeV) cm^2 GeV^{-1}

$N_A = 6.02 \times 10^{23}$ mol^{-1}

With a 100 tons detector, one gets:

$$N_{evt} = N_{nucl} \times \phi_\nu \times \sigma_{\nu,N}$$

$$= 6.02 \times 10^{23} \times 10^8 \times 10^6 \times 0.6\times10^{-38} \times 20$$

$$= 7{,}2 \text{ events / extraction}$$

2016

GeV detection with SuperKamiokande

Atmospheric neutrino flux:

$$\phi \sim 2\ cm^{-2} s^{-1} sr^{-1}$$

$$\lambda = \frac{1}{\sigma n}$$

Interaction probability: $P(x) = 1 - \exp\left(\frac{-x}{\lambda}\right) = 1 - \exp(-n\sigma x)$

$$n = \rho\ N_A$$

Interaction length λ: $\lambda \sim \left(6 \times 10^{23} \times 10^{-38}\right)^{-1} \sim 1.7\ \ 10^{14}\ cm$

2016

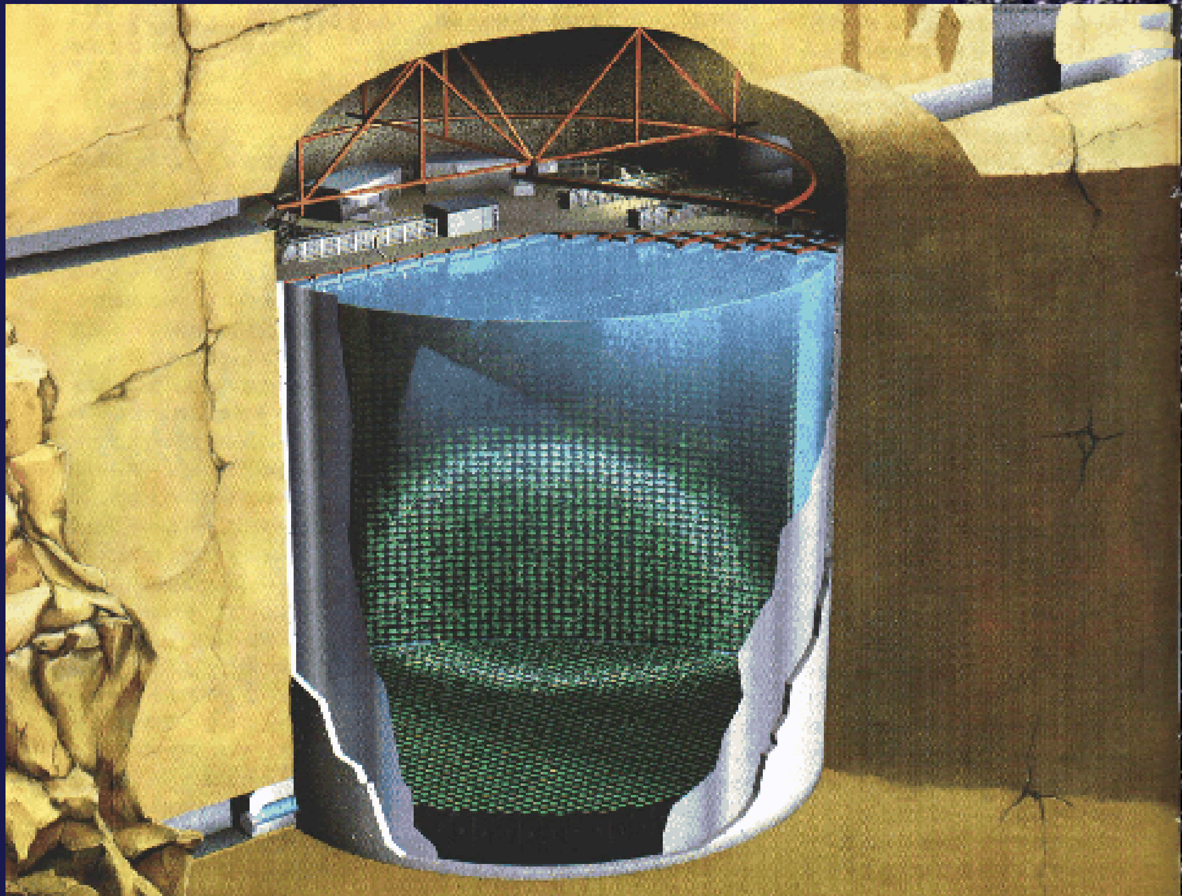
thus : $P(L) \sim \left(\frac{L}{1m}\right) \times 6\ \ 10^{-13}$

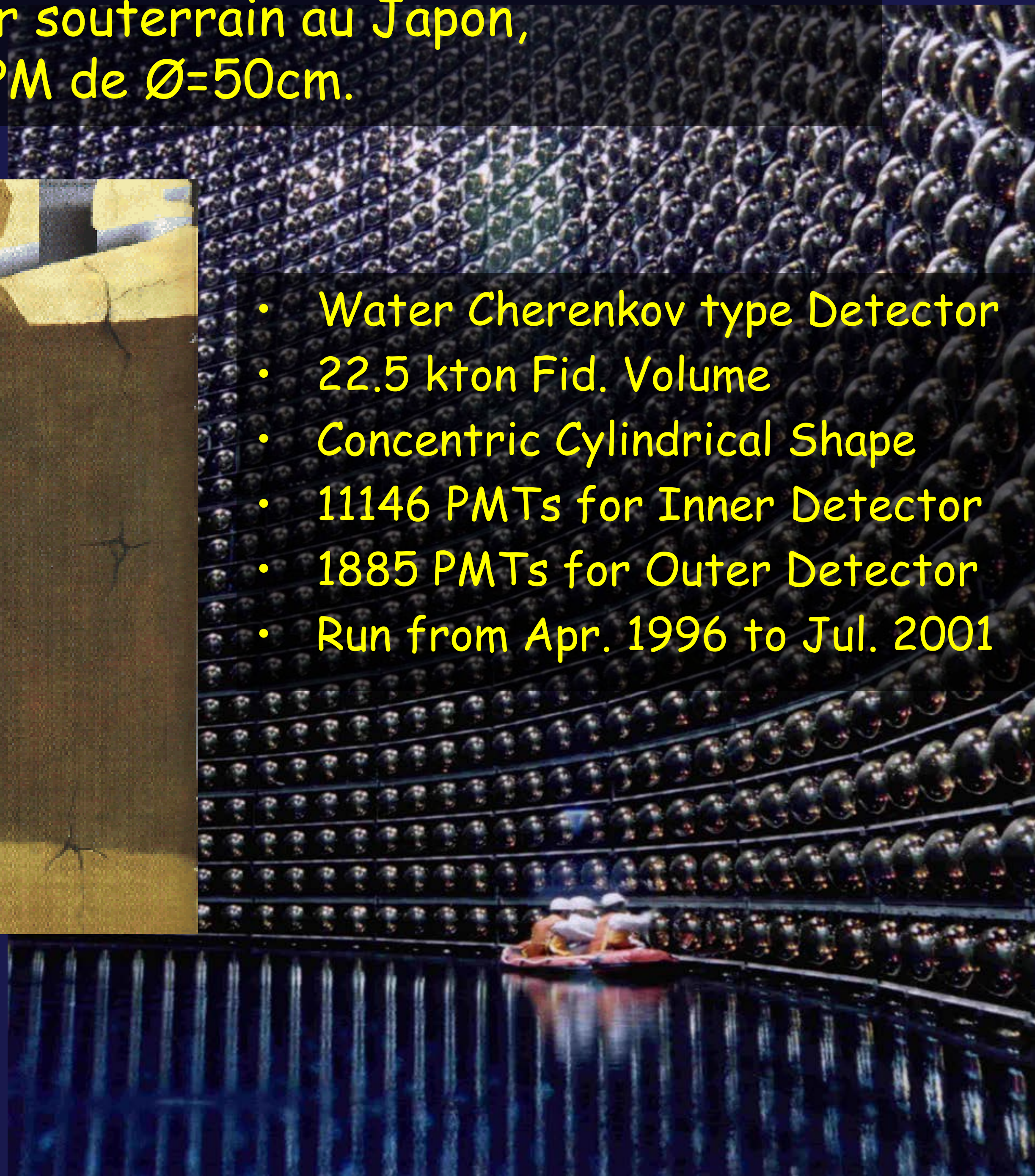
Number of events per day in a detector of volume V=S×L

$$N = \phi\ \Omega\, S\, P(L)$$
$$\approx \left(2.10^{4} m^{-2} sr^{-1} s^{-1}\right) \times (4\pi\ sr) \times \left(8.10^{4}\ s\right) \times 6.10^{-13} \times V$$
$$\approx 1.2 \times 10^{-2}\ \ \text{events/day/m}^{3}\ \text{of water}$$

Super Kamiokande

- Super-Kamiokande, détecteur souterrain au Japon, 50000 tonnes d'eau, 12000 PM de Ø=50cm.



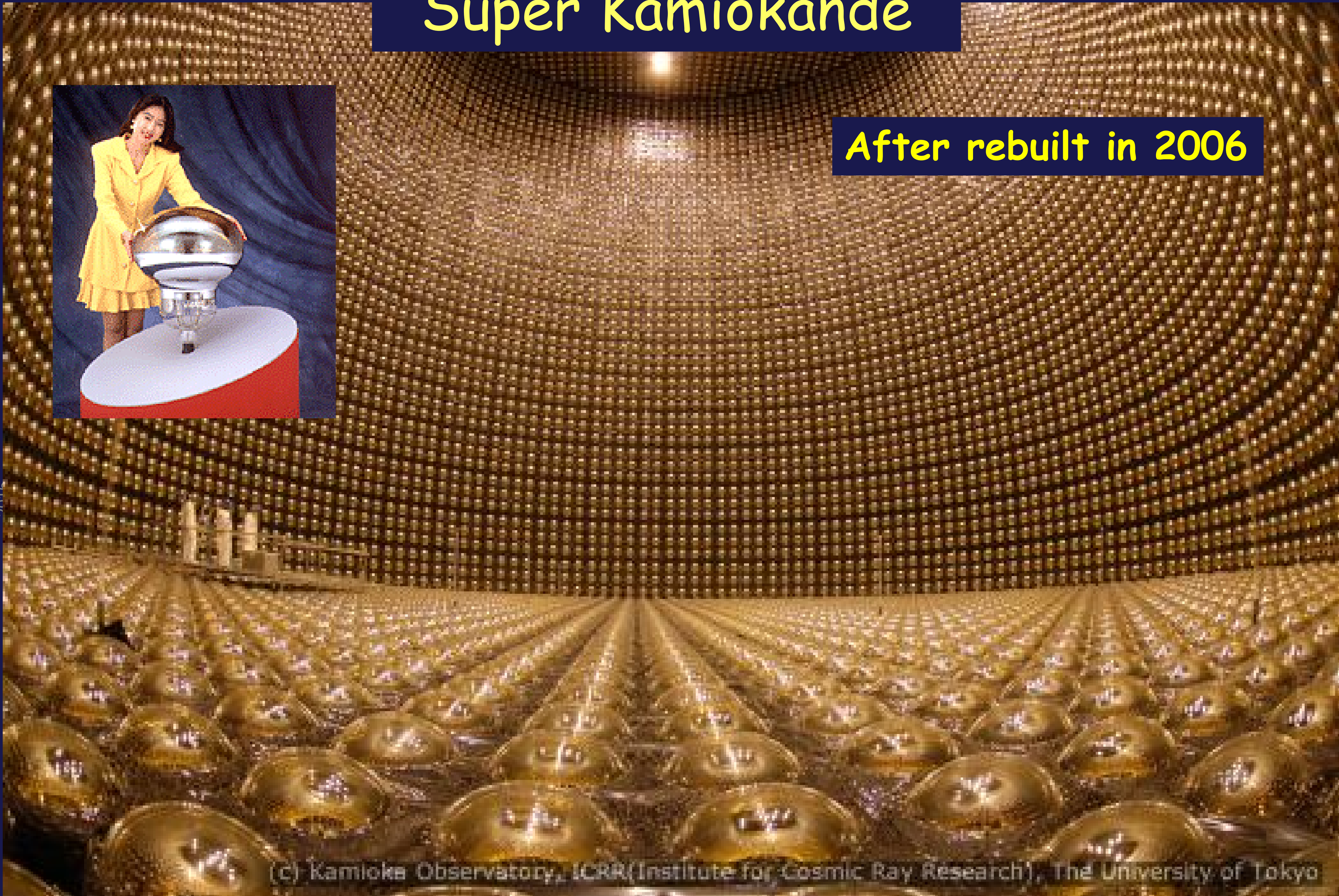


- Water Cherenkov type Detector
- 22.5 kton Fid. Volume
- Concentric Cylindrical Shape
- 11146 PMTs for Inner Detector
- 1885 PMTs for Outer Detector
- Run from Apr. 1996 to Jul. 2001

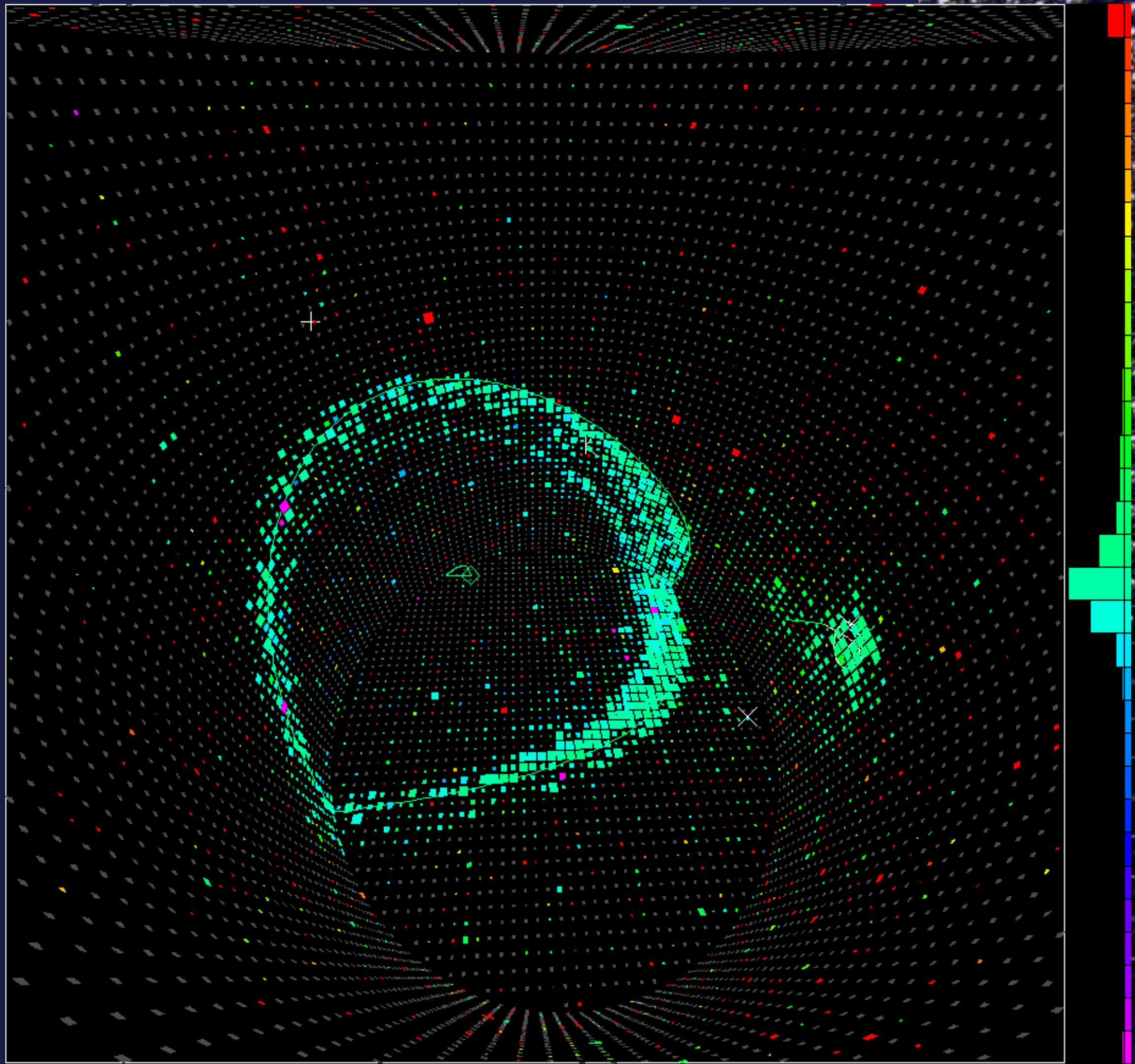
2016

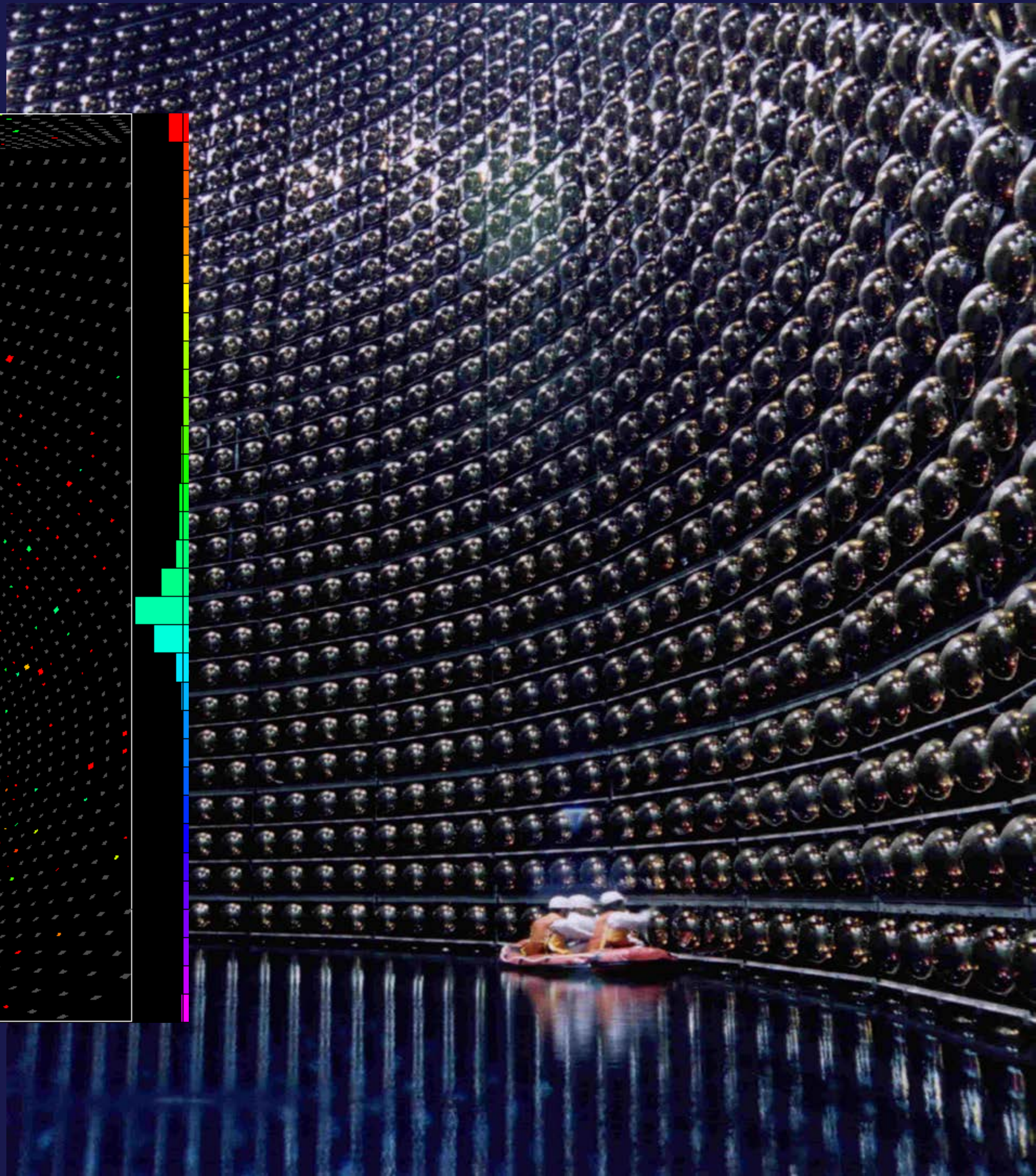
Super Kamiokande

After rebuilt in 2006



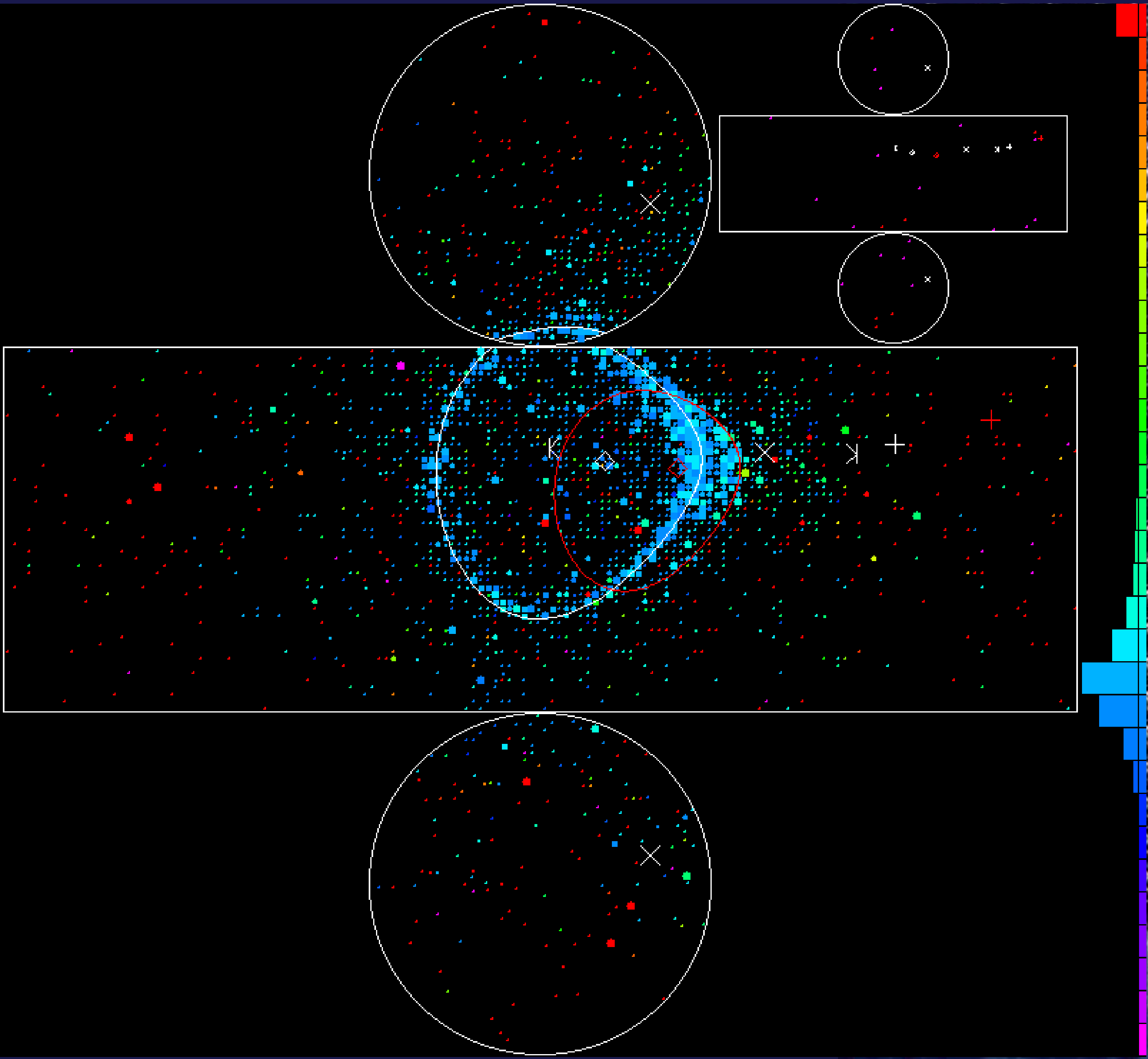
Super Kamiokande

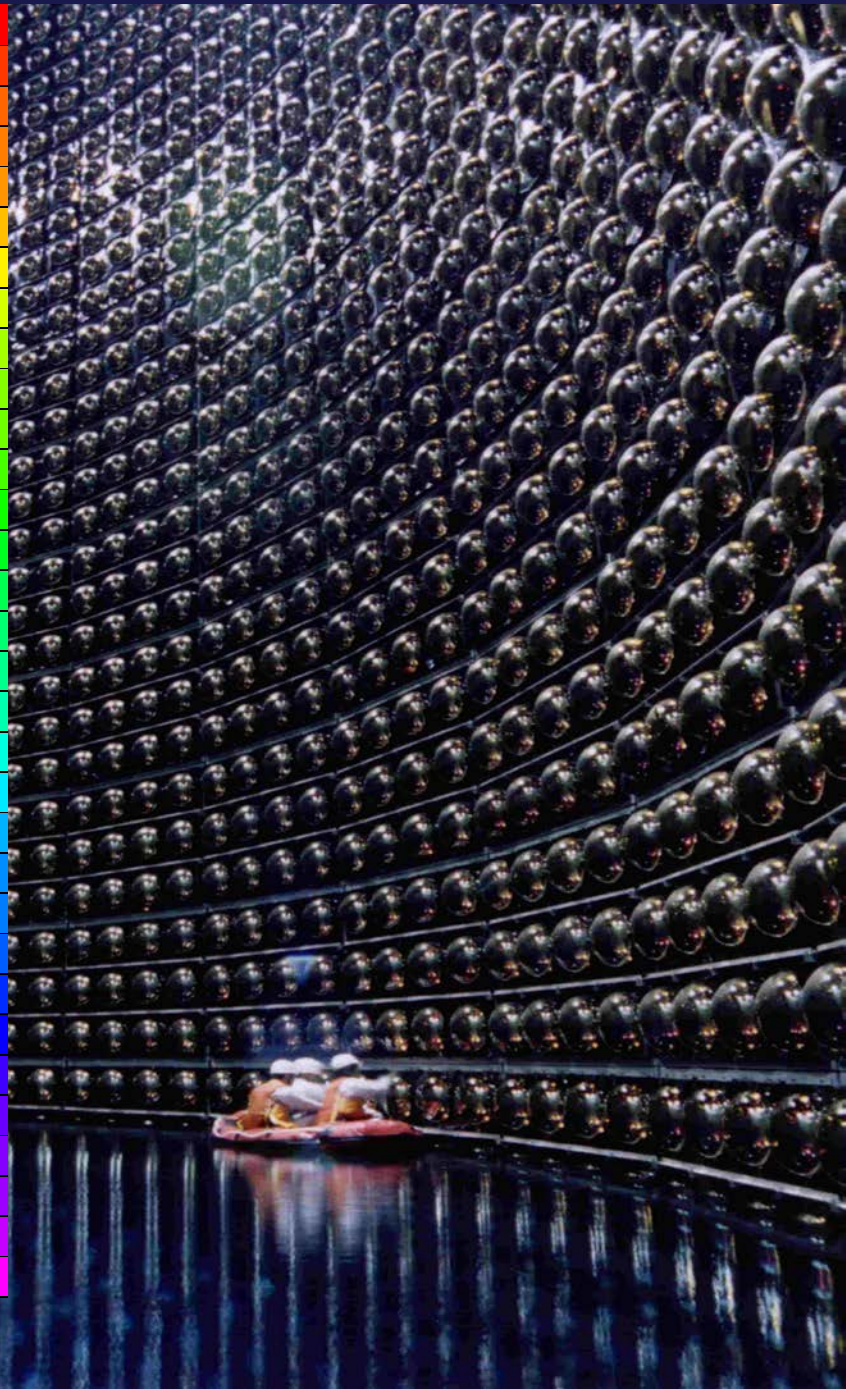




2016

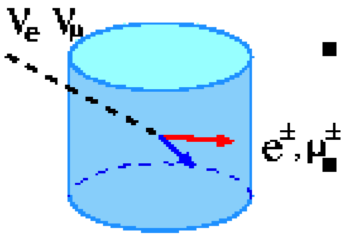
Super Kamiokande





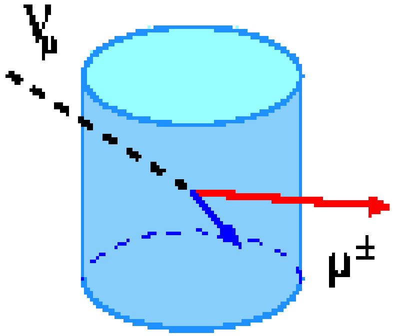
Event patterns in Super-Kamiokande

Fully Contained (FC) event



- All visible particles are contained in the detector
- both ν_μ、ν_e via NC or CC interaction
- Typically E_ν = 1 GeV
- Particle ID

Partially Contained (PC) event



- At least 1 charged particle escapes from detector
- ν_μCC (97%)
- Typically E_ν=10 GeV

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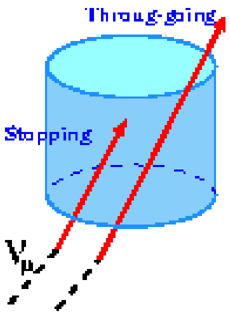
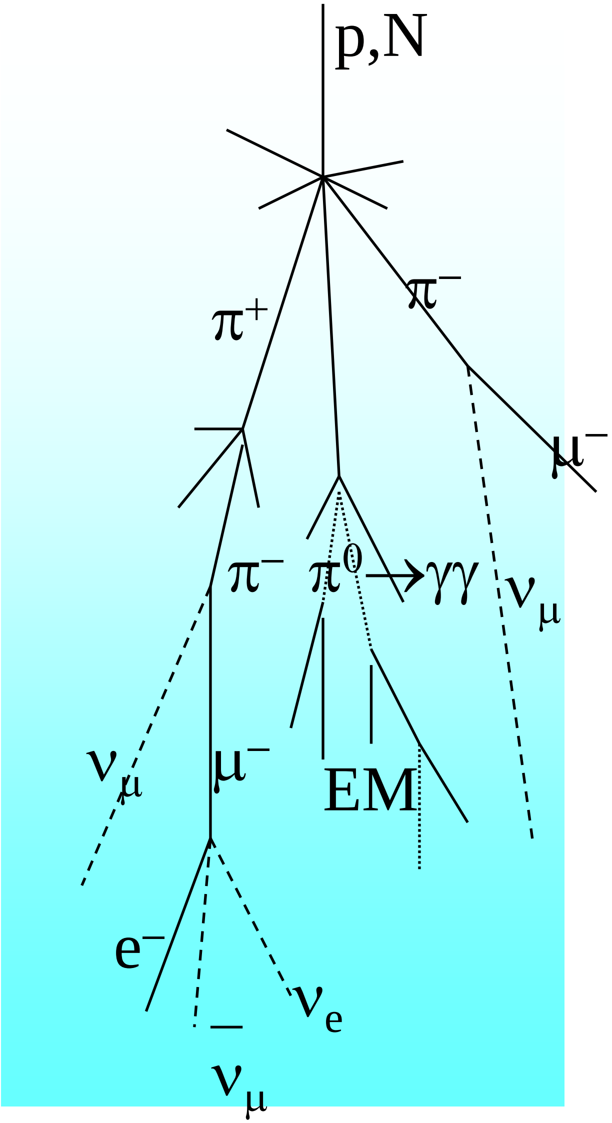
Upward-going muons (Up-mu)



- Entering muon from below
- ν_μ CC only
- E_ν= 10 GeV(stopping),
- 100 GeV(through-going)

Super-Kamiokande covers E_ν = 100 MeV ~ over 1 TeV

Atmospheric neutrinos



- Atmosphere :
  - ~1000 g/cm²
  - ~20 km
  - 11 nuclear λ_{int}

- ν dominated by :

$$\left.\begin{array}{llll} \pi^+ & \rightarrow & \mu^+ & + \nu_\mu \\ & & \hookrightarrow & e^+ + \bar{\nu}_\mu + \nu_e \\ \pi^- & \rightarrow & \mu^- & + \bar{\nu}_\mu \\ & & \hookrightarrow & e^- + \nu_\mu + \bar{\nu}_e \end{array}\right\} \Rightarrow 2\nu_\mu \text{ for } 1\nu_e$$

- Kinematics :

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\langle E_\mu \rangle = 0.787 E_\pi$$
$$\langle E_\nu \rangle = 0.213 E_\pi$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\langle E_\nu \rangle = 1/3 E_\mu$$

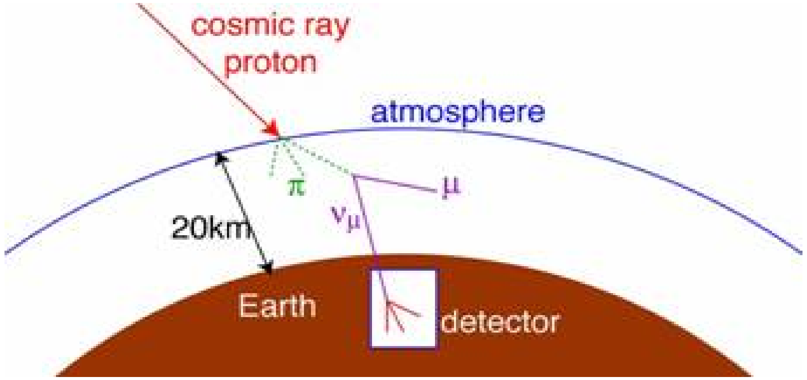
$$\Rightarrow \langle E_{\nu_\mu} \rangle : \langle E_{\nu_e} \rangle : \langle E_{\bar{\nu}_\mu} \rangle \approx 1:1:1$$

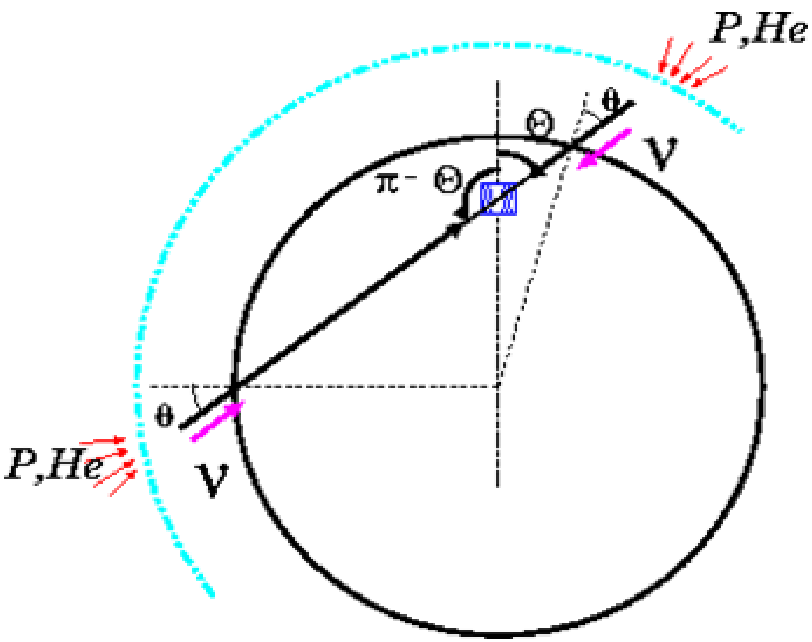
- 1 GeV sea level neutrino fux:

$$\phi \approx 2 \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$$

2016

Atmospheric neutrinos





- **Flavor ratio**

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2 \text{ for } E_\nu \leq \text{qq GeV}$$
$$> 2 \text{ for } E_\nu > \text{qq GeV}$$

- **top down symmetry**

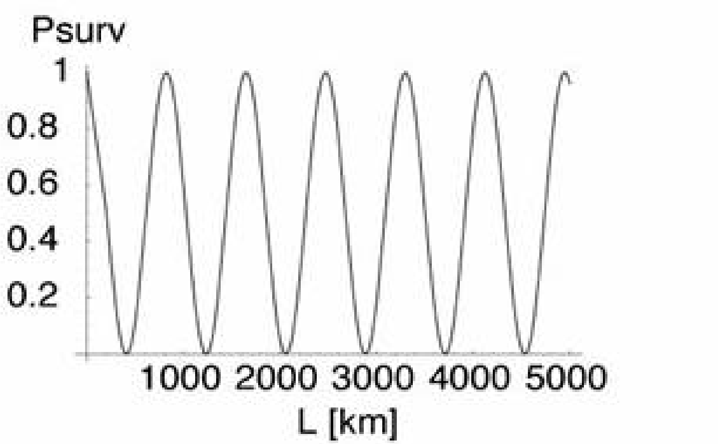
for $E_\nu >$ qq GeV

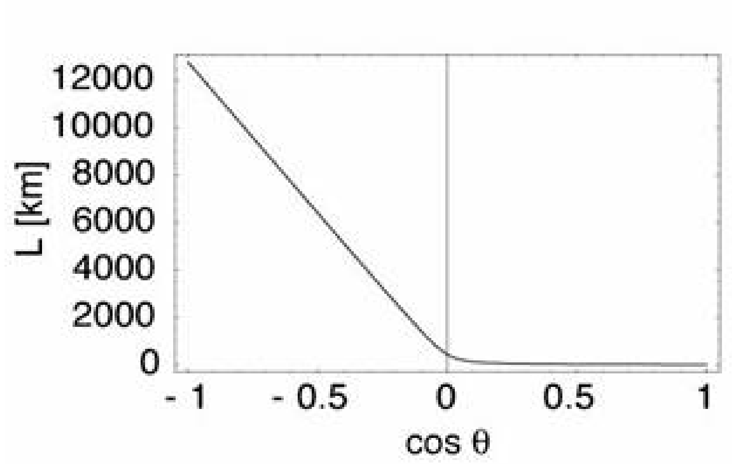
Distance traveled : $L_\nu = 10$ to 13000 km

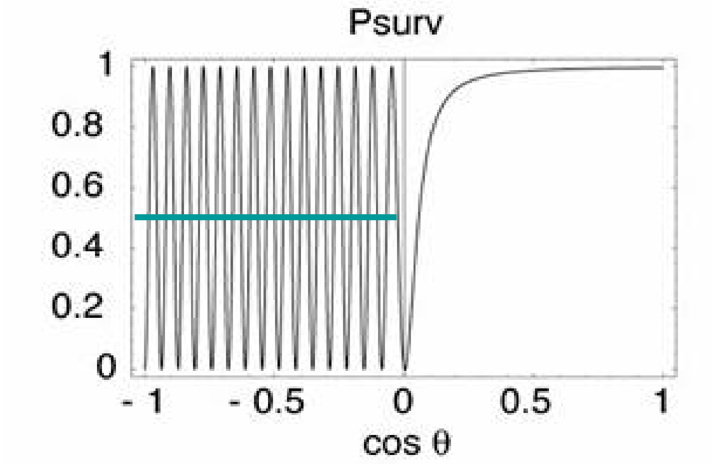
2016

Survival probability

$p = 1\text{GeV/c}\ ,\ \sin^2 2\theta = 1$
$\Delta m^2 = 3 \times 10^{-3}\ (\text{eV/c}^2)^2$

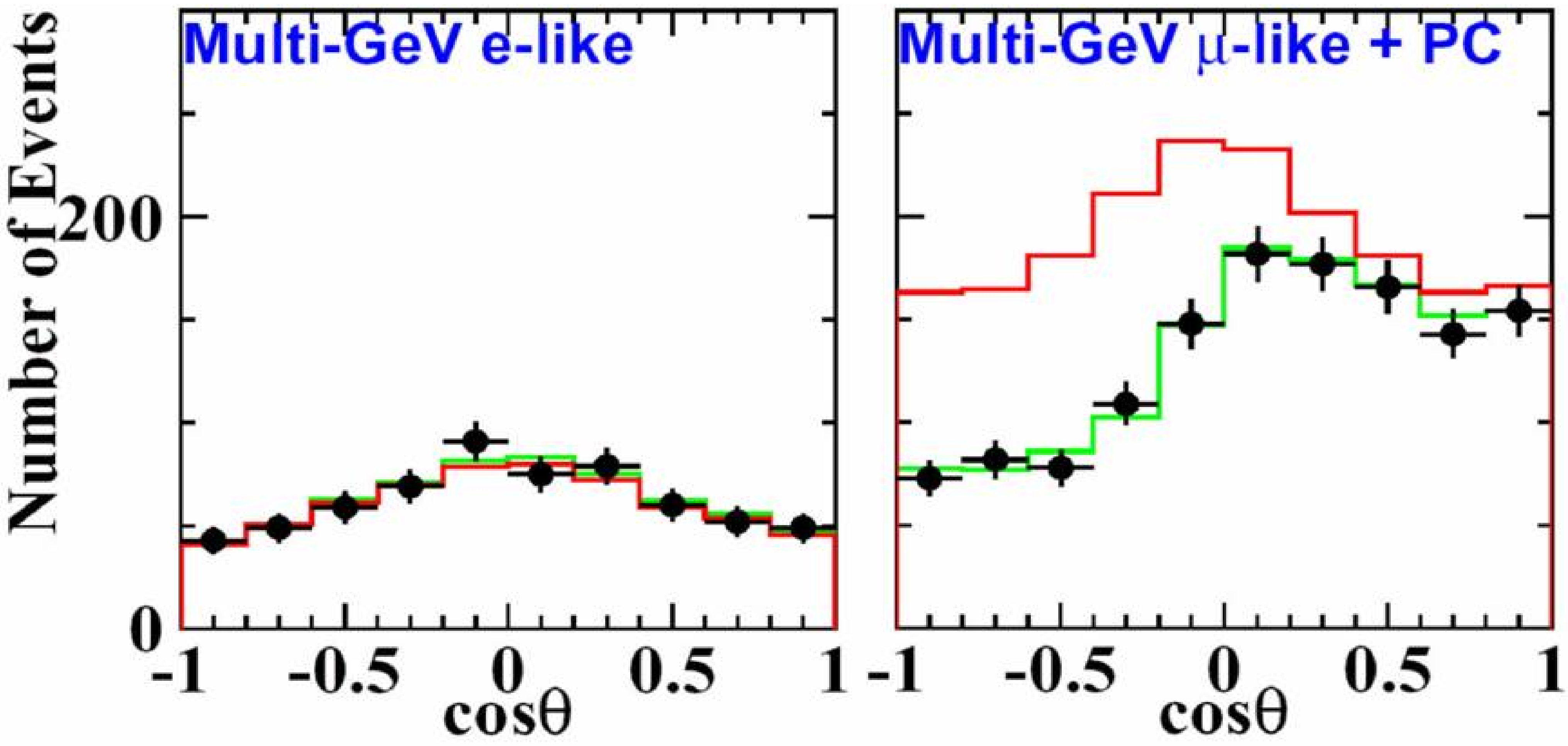




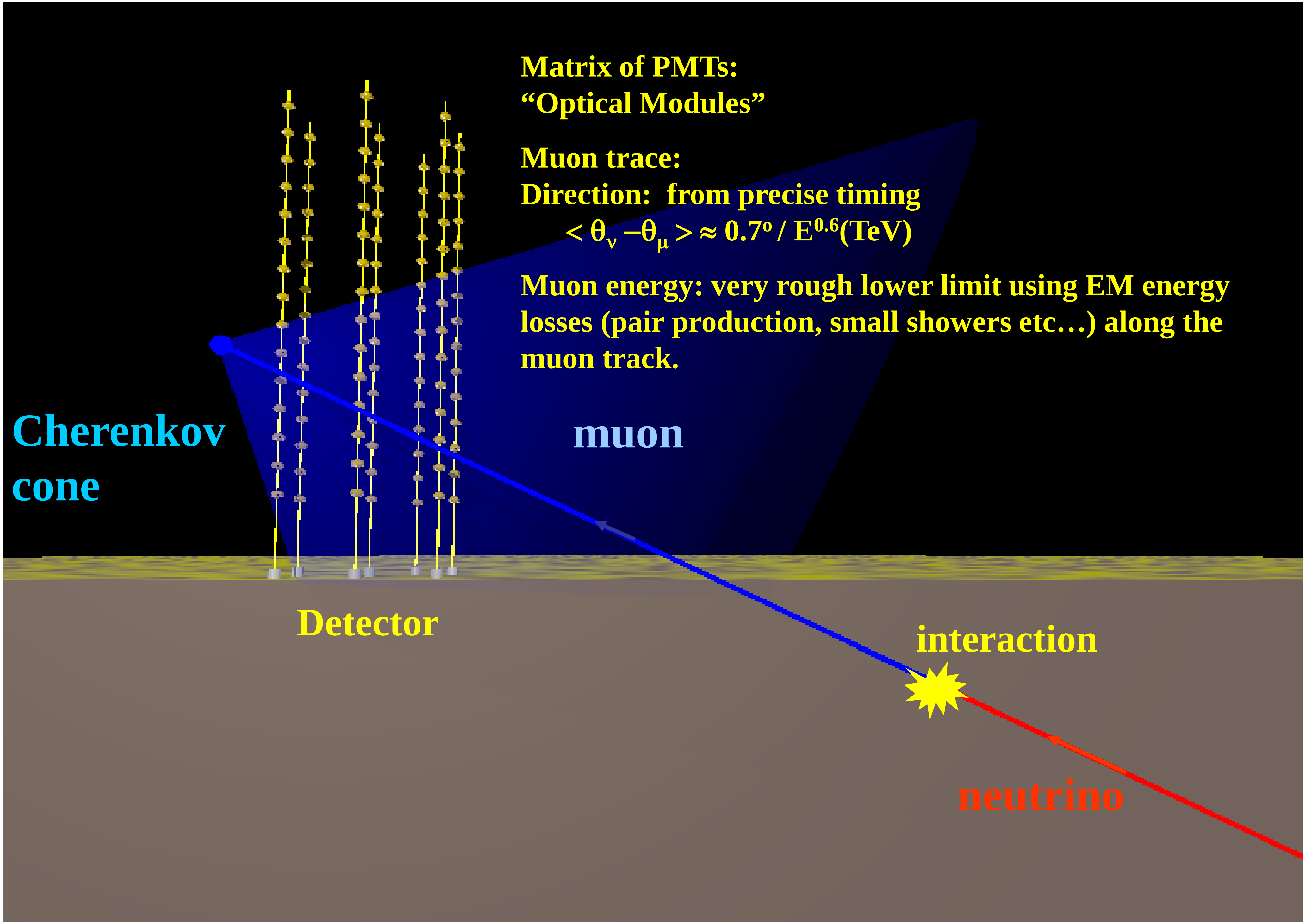


Half of upgoing ν_μ are lost.

Half of ν_μ disappeared !



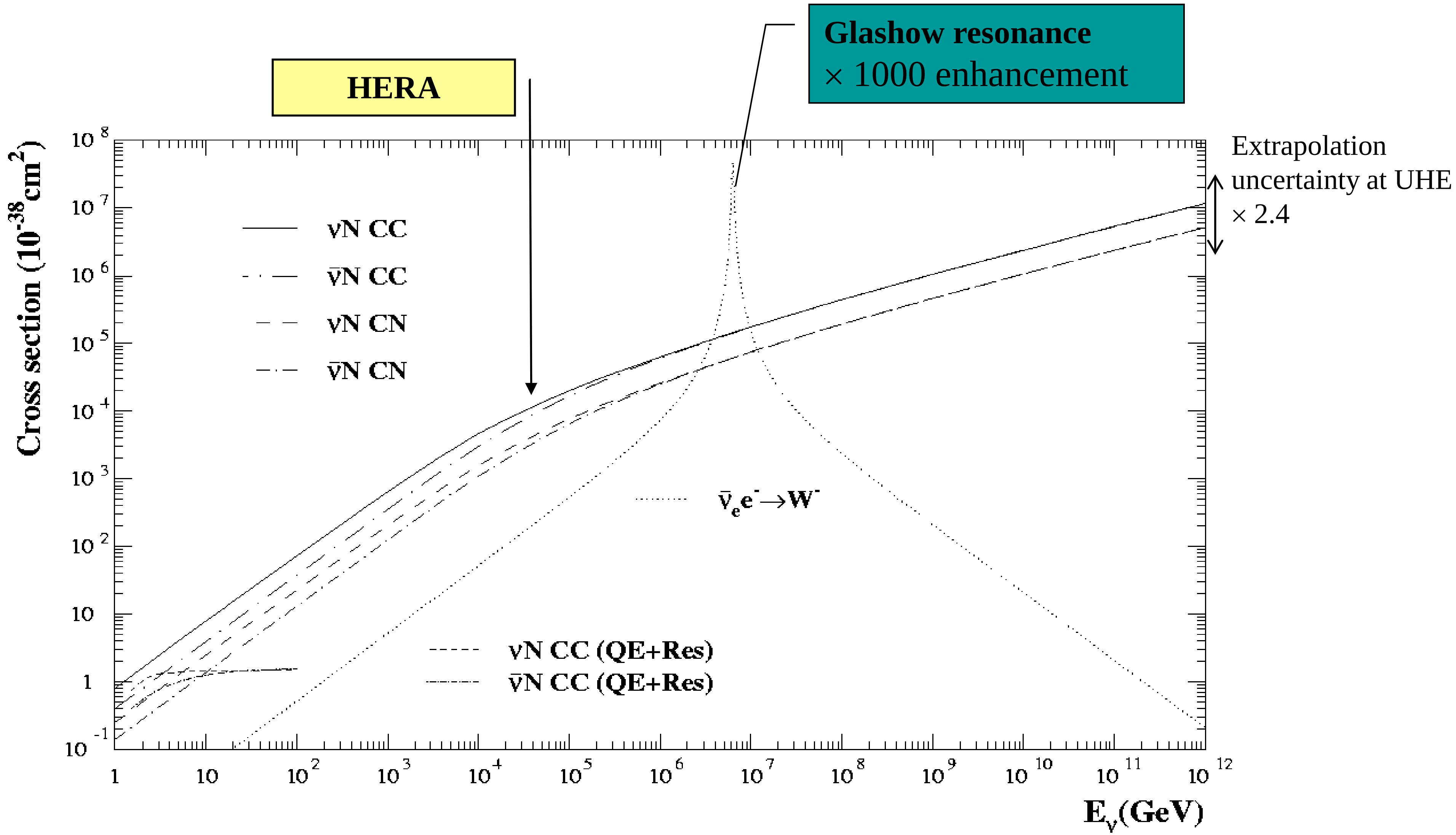
2016


Matrix of PMTs:
“Optical Modules”
Muon trace:
Direction: from precise timing
$< \theta_\nu - \theta_\mu > \approx 0.7^o / E^{0.6}$(TeV)
Muon energy: very rough lower limit using EM energy losses (pair production, small showers etc…) along the muon track.
Cherenkov cone
muon
Detector
interaction
neutrino

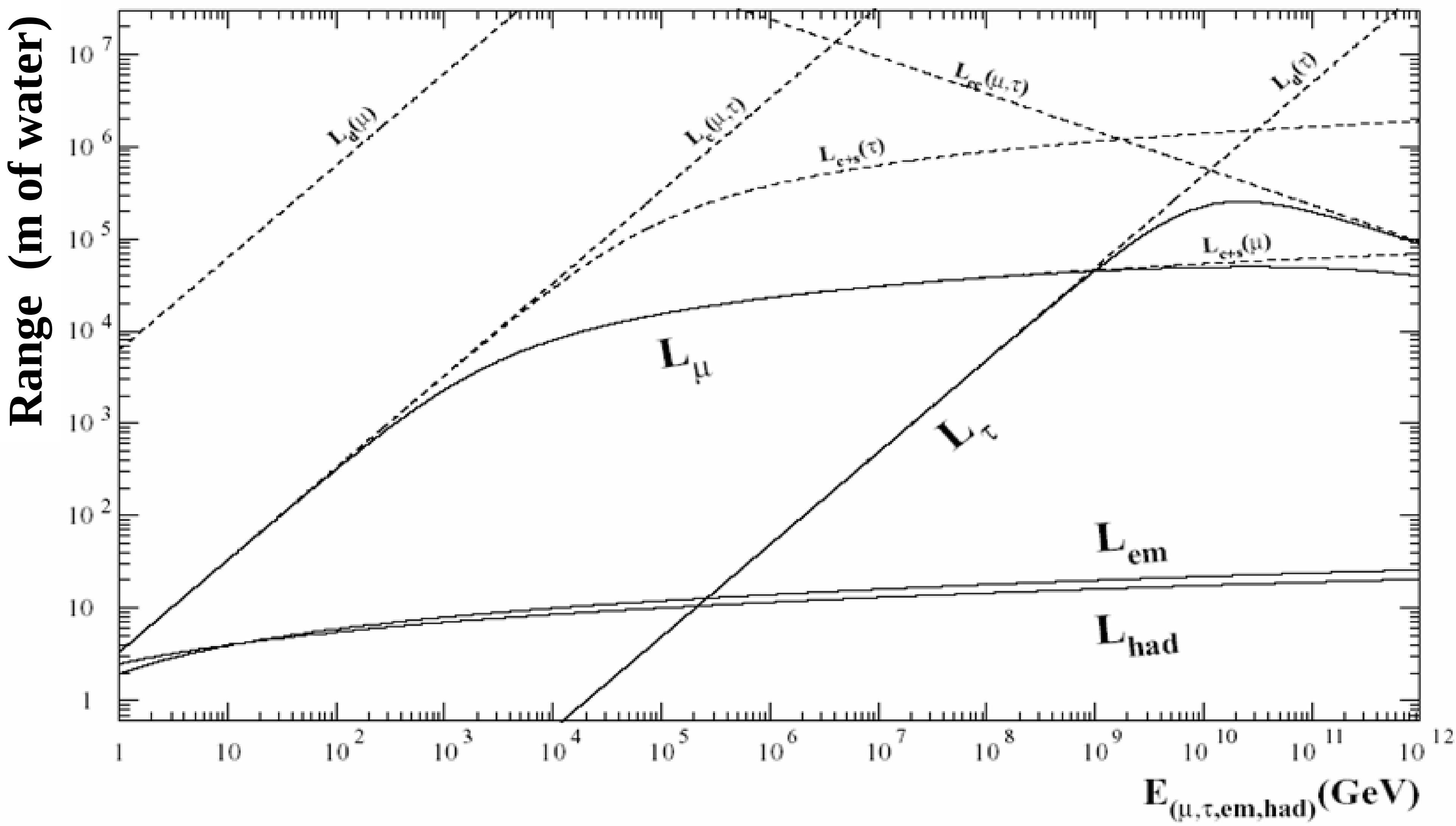
2016

Neutrino cross sections

- ν-matter cross sections:

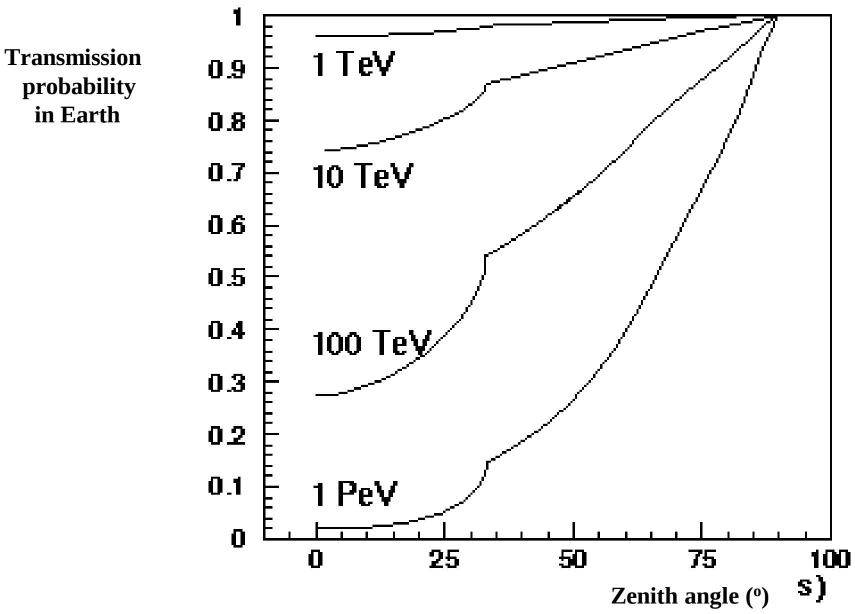


Particle Ranges



Earth opacity

The earth is transparent to ν_μ
< 100 TeV



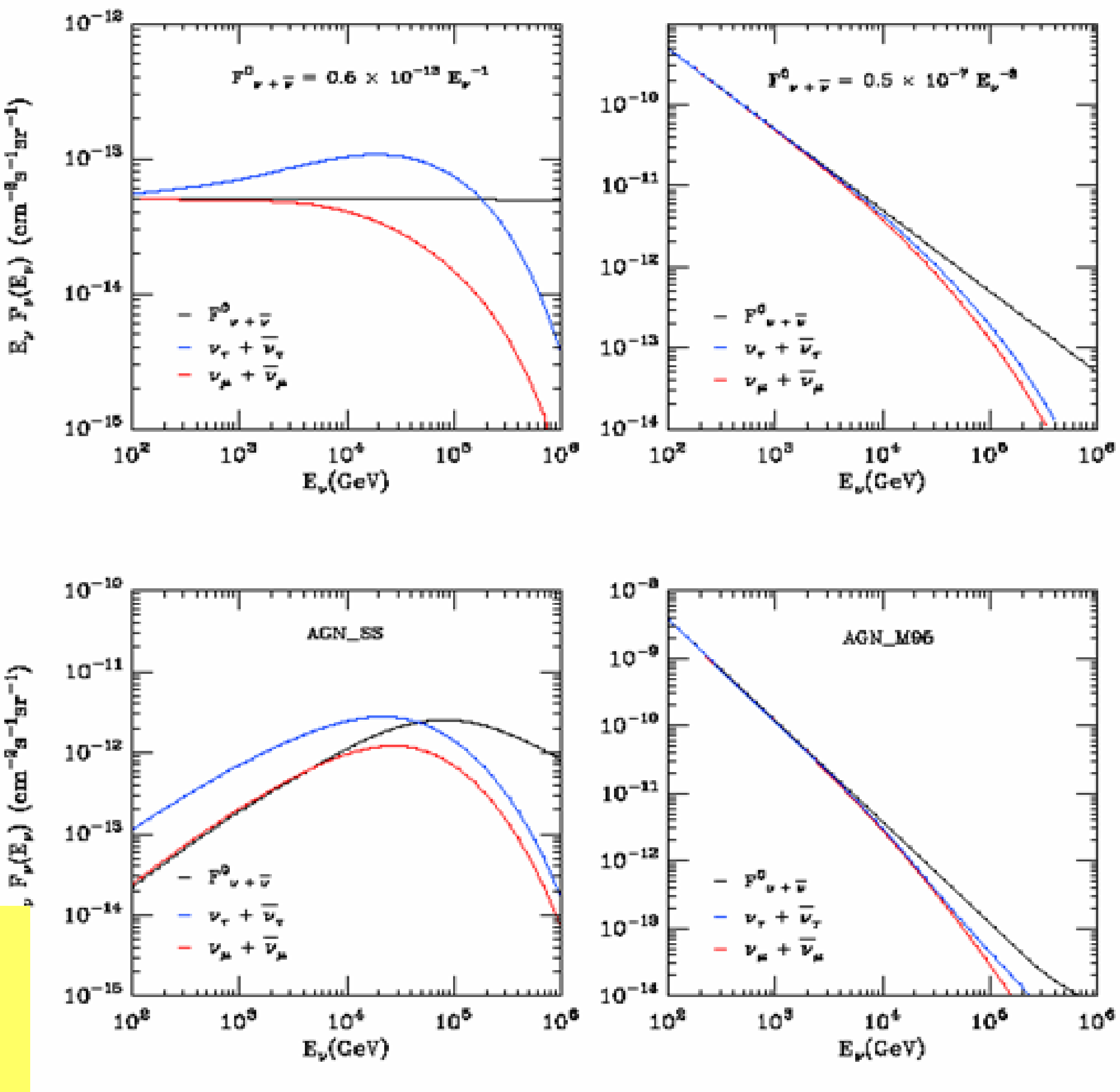


FIG. 2. Muon neutrino plus antineutrino flux (black line), the effect of its attenuation for $\theta = 0°$ (red line) and tau neutrino plus antineutrino upward flux for the same initial flux and the same nadir angle (blue line) for a) E^{-1} flux b) E^{-2} flux c) AGN_SS and d) AGN_M95.

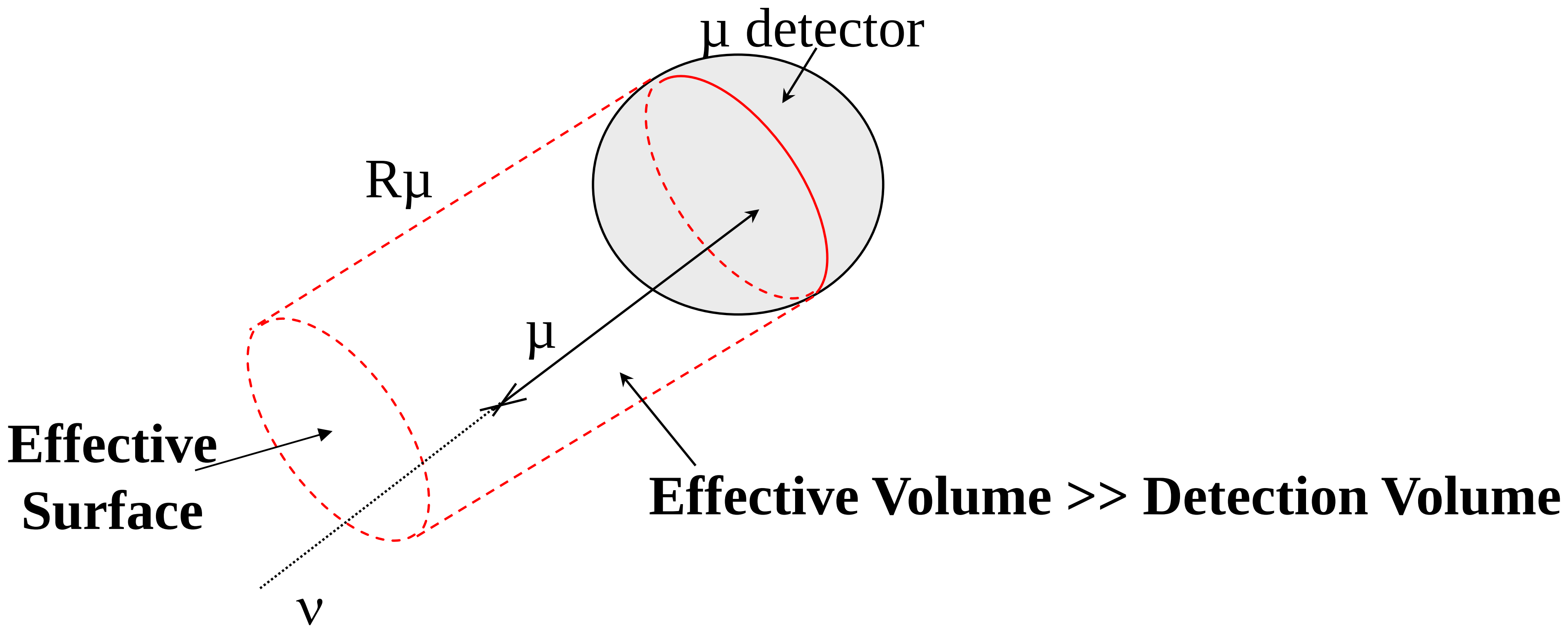
ν_μ absorbed via cc, or regenerated via nc

ν_τ regenerated via cc because $\tau \rightarrow \nu_\tau$ before interacting or significant energy loss.

2016

Detection principles

- The effective target volume is ∝ the muon range



$$V_{eff}(E_\mu) = A_{eff}(E_\mu) \cdot R_\mu(E_\mu)$$

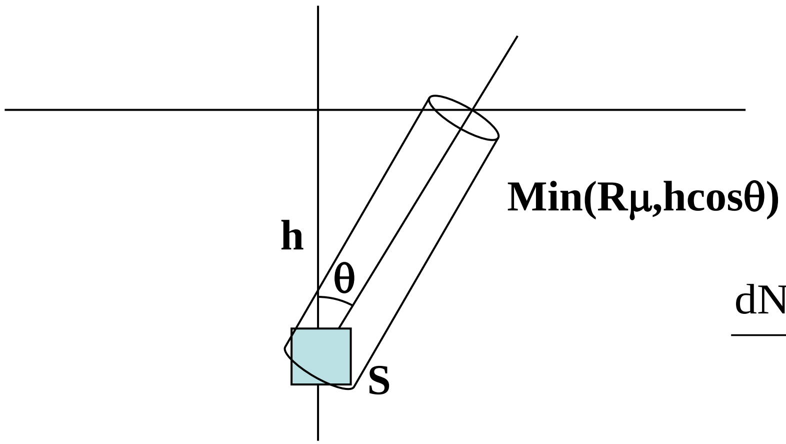
R_μ = 2 km @ 1 TeV

R_μ = 10 km @ 100 TeV

R_μ^{max} = 50 km @ 1 EeV

2016

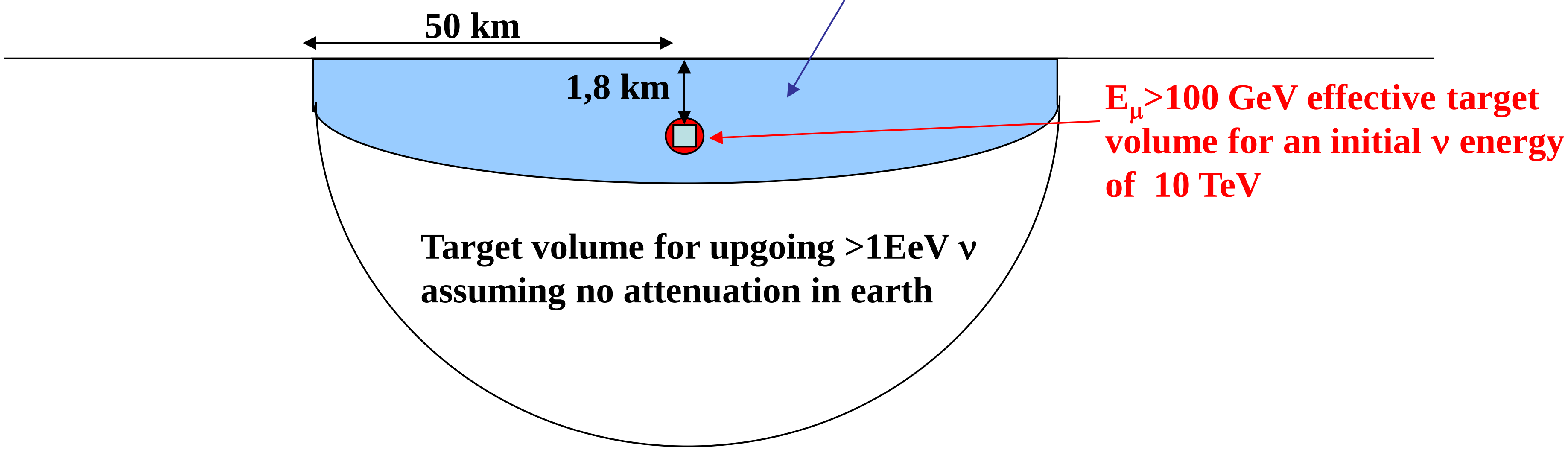
PeV ν_μ in IceCube



$$\frac{\partial \phi_i(E,z)}{\partial z} = -\frac{\partial P^i_{loss}(E,z)\partial z}{\partial z}\phi_i(E,t) + \sum_j \int_E^\infty \frac{\partial P_{j\to i}(E',E,z)}{\partial E \partial z}\phi_i(E',z)dE'$$

$$\frac{dN_{\mu\ E>1PeV}}{dE} = 2\pi\ S\int_{-1}^{1}\frac{\partial \phi_i(E,z(\cos\theta))}{\partial z}\ \sigma_{cc}(E)\ \frac{\rho_{det}}{m_p}\ \mathrm{Min}(R_\mu, z(\cos\theta))\ d(\cos\theta)$$

Target volume accounting for E_μ>1 PeV range and an ν initial energy of 1EeV ~ 10^{13} tons of ice.

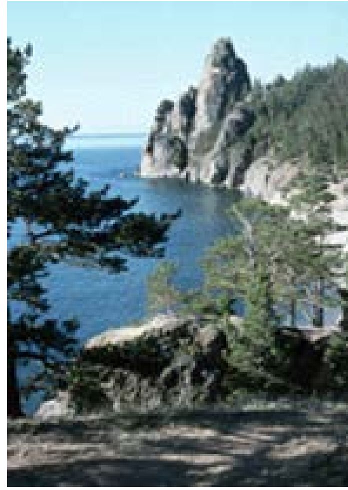


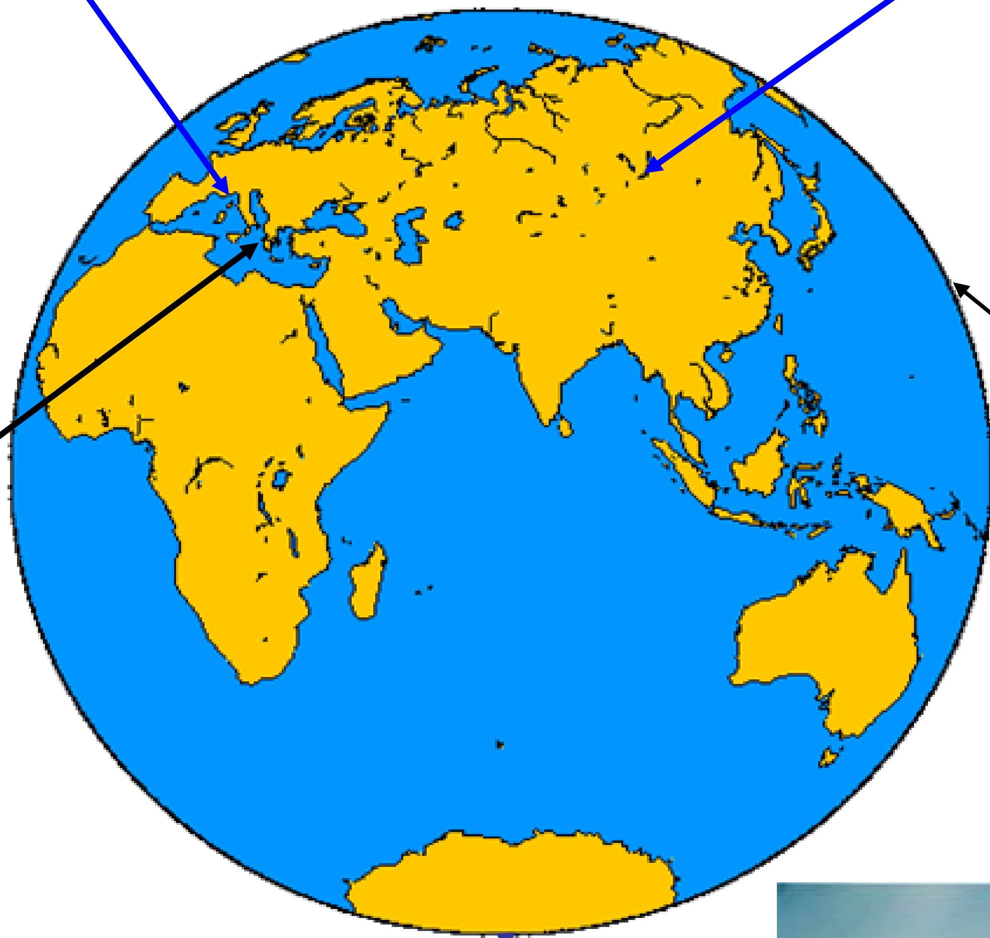
2016

Neutrino Telescope Projects

ANTARES La-Seyne-sur-Mer, France
NEMO Catania, Italy, KM3NET ?

BAIKAL:
Lake Baikal, Siberia





NESTOR : Pylos, Greece

DUMAND, Hawaii
(cancelled 1995)

AMANDA, ICECUBE
South Pole, Antarctica

2016

AMANDA

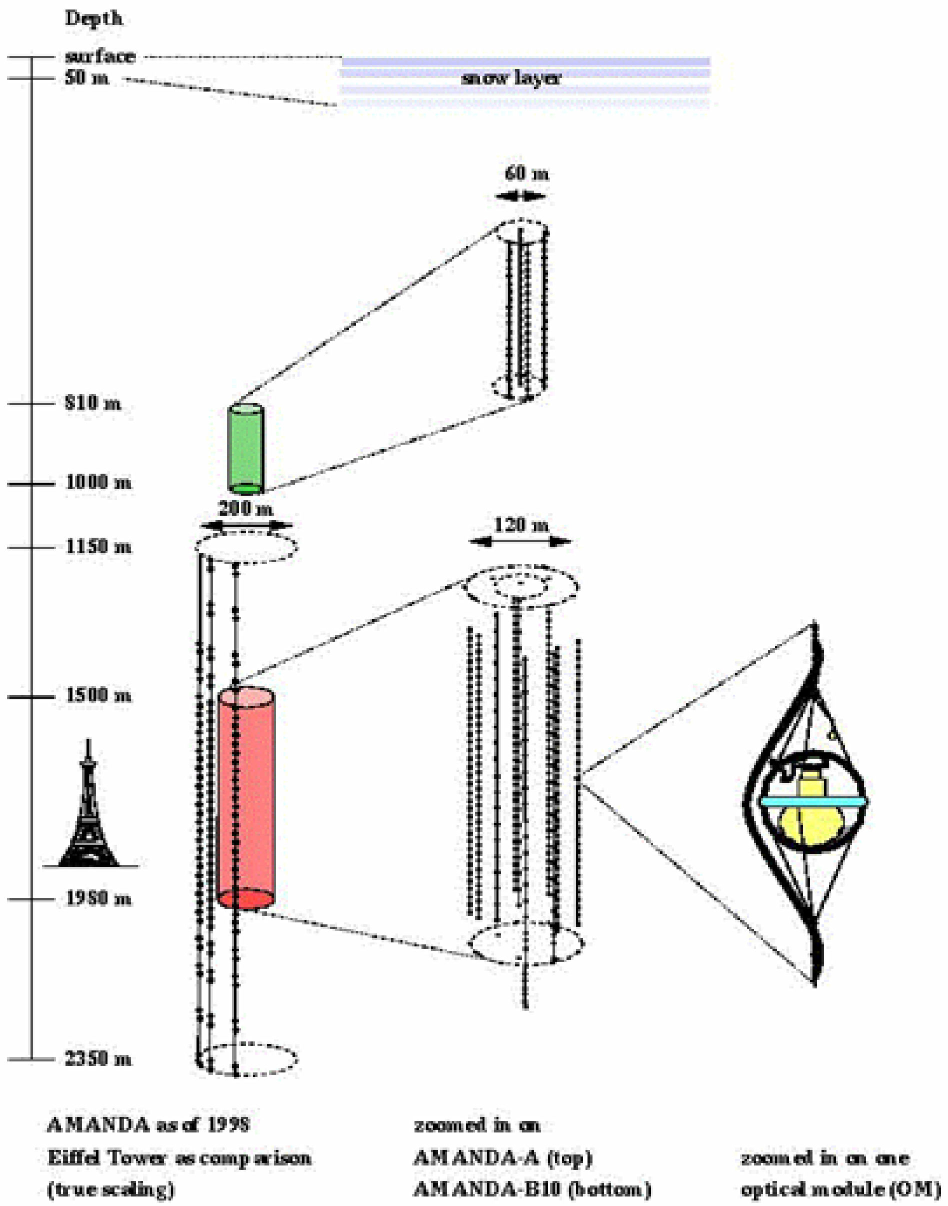
South Pole: glacial ice

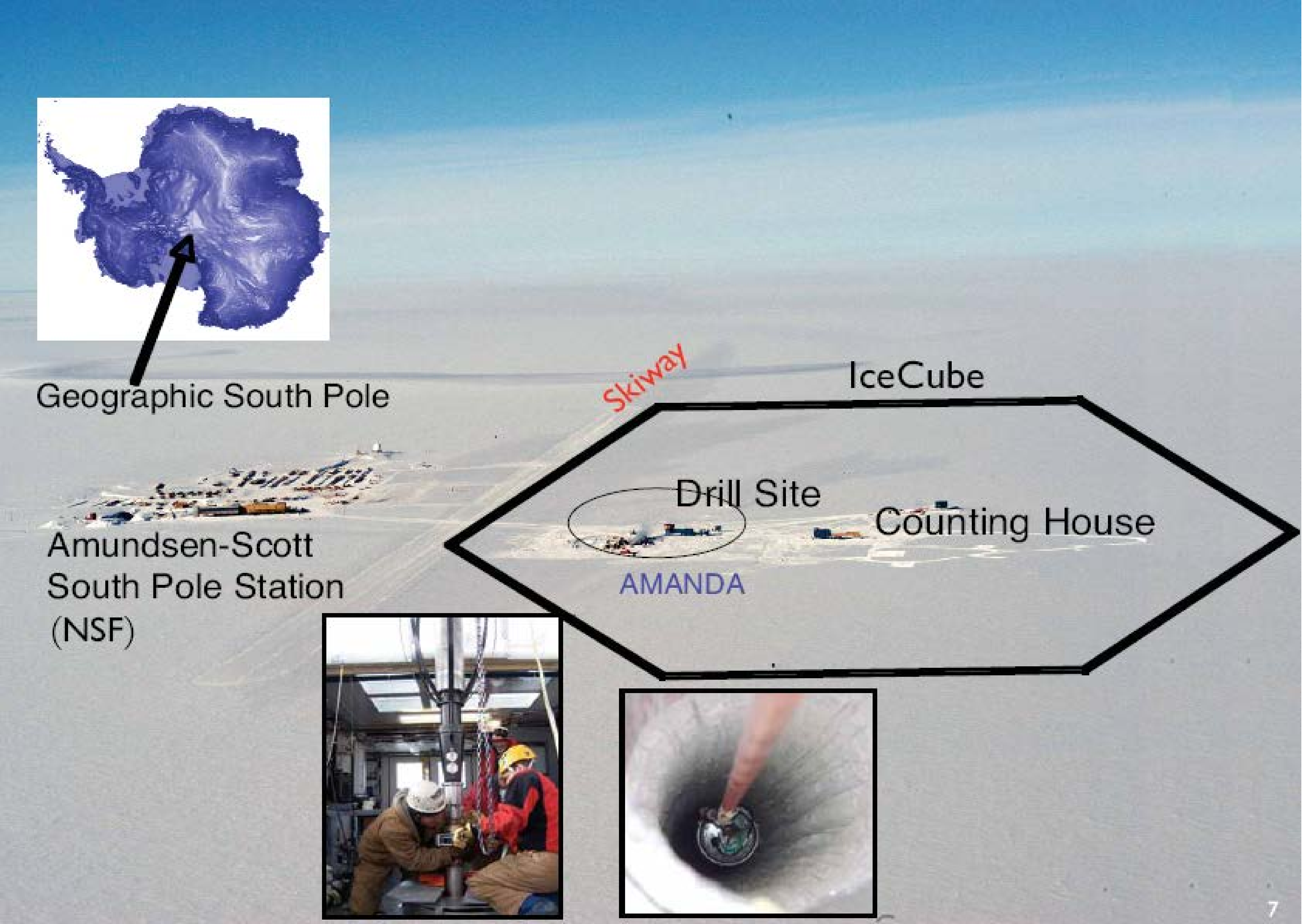
1993 First strings AMANDA A
1998 AMANDA B10 ~ 300 Optical Modules

2000 ~ 700 Optical Modules

→ ICECUBE 8000 Optical Modules

2016

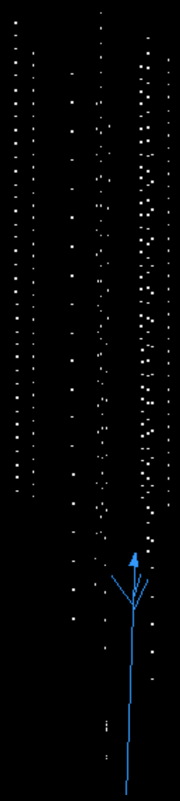



Geographic South Pole
Skiway
IceCube
Drill Site
Counting House
Amundsen-Scott
South Pole Station
(NSF)
AMANDA

AMANDA: **Drill Holes in ice with Hot Water**

2016

Reconstruction d'événement dans Amanda



The IceCube detector

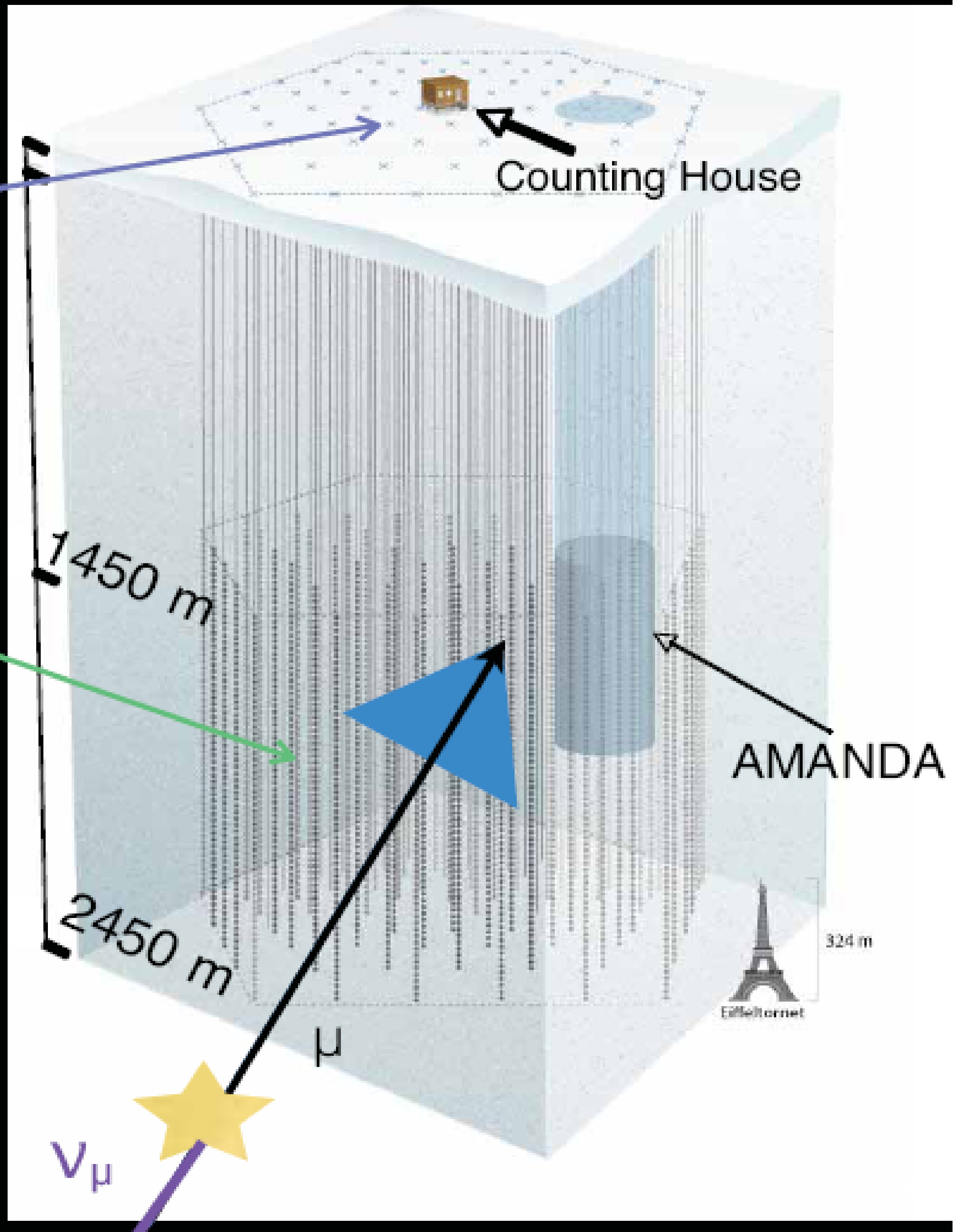
instrumenting 1 km³ of ice

IceTop :
Surface air shower array
Frozen tanks - 2DOMs

InIce :
80 strings each with 60 digital optical modules (DOM)

125m spacing between strings
17m between DOMs

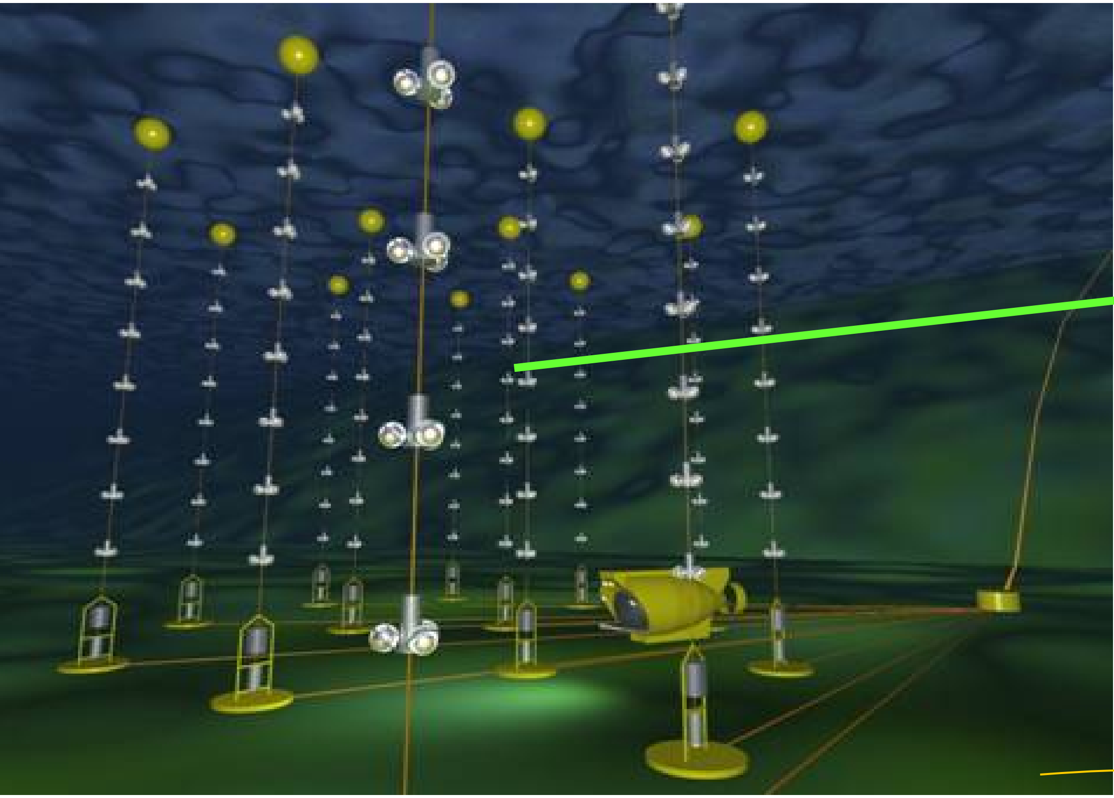
Detect **ν** *of all flavors*
E range : 10^{11} to 10^{20} eV

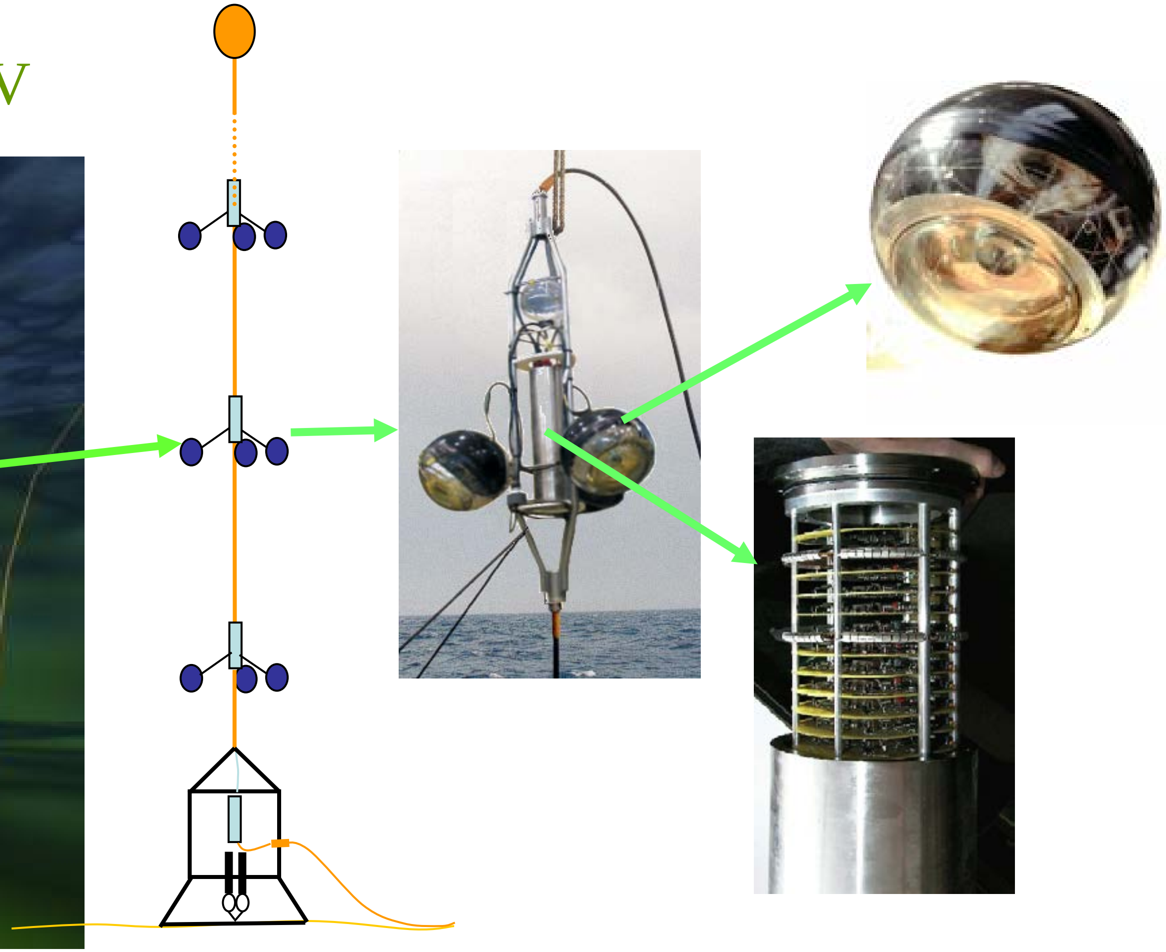


Future in ν telescopes: ANTARES

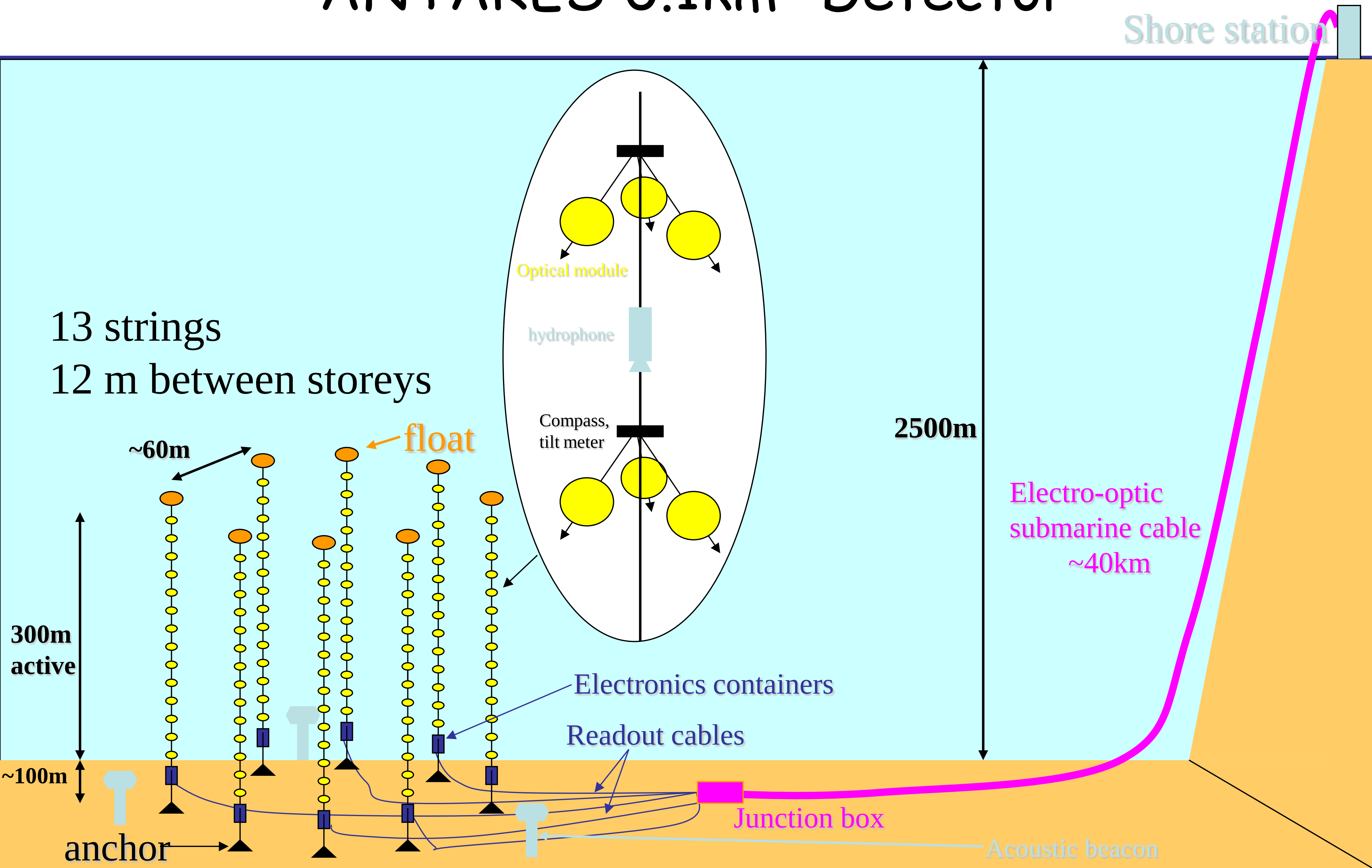
1996	Started
1996 - 2000	Site exploration and demonstrator line
2001 - 2004	Construction of 10 line detector, area ~0.1km^2 on Toulon site
future	1 km^3 in Mediterranean

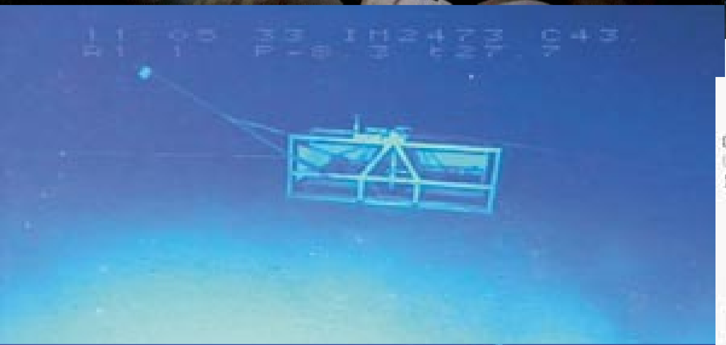
Angular resolution <0.4° for E>10 TeV

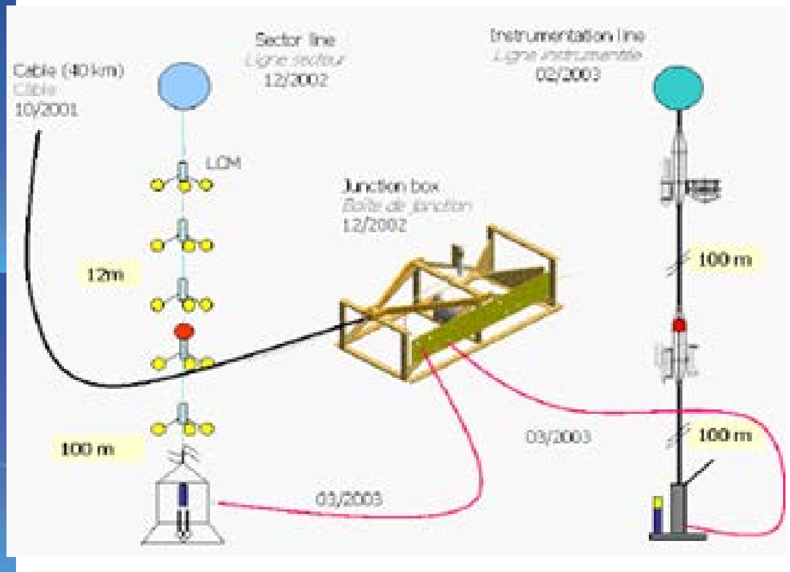




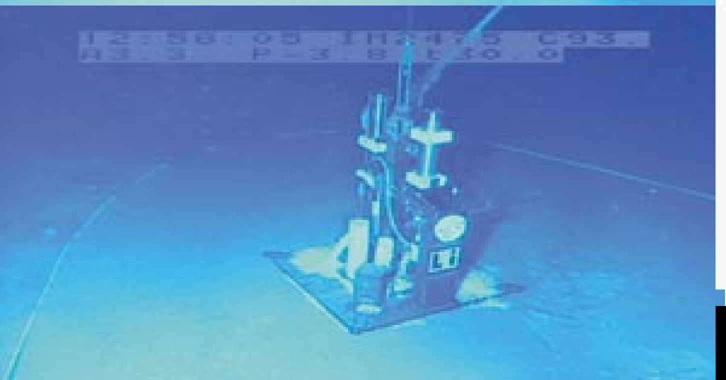
ANTARES 0.1km^2 Detector

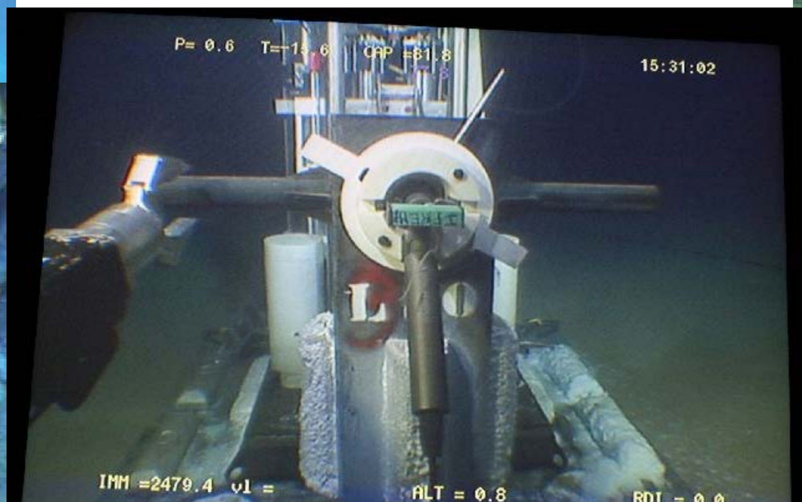




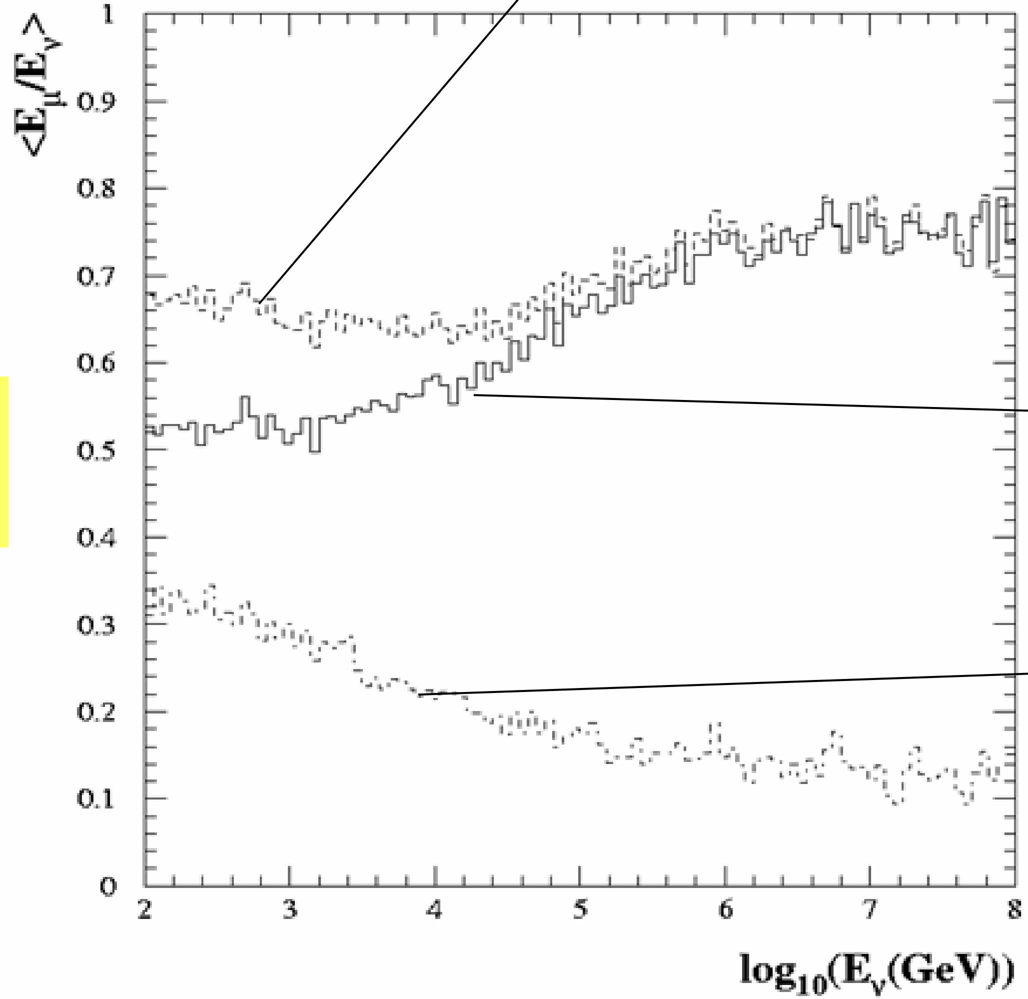

Cable (40 km)
Câble
10/2001
Sector line
Ligne secteur
12/2002
Instrumentation line
Ligne instrumentée
02/2003
LCM
12m
100 m
Junction box
Boîte de jonction
12/2002
100 m
100 m
03/2003
03/2003


Ifremer




P= 0.6
15:31:02
IMM =2479.4
ALT = 0.8

Detection principle



Production energy of μ's reaching the detector

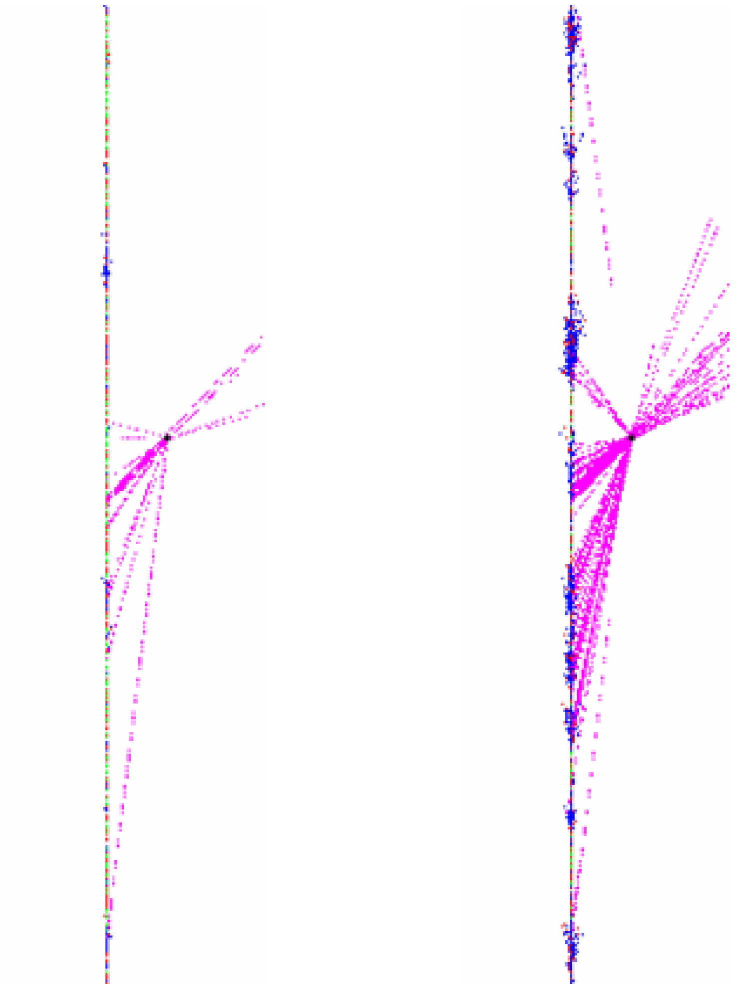
Mean Eμ/Eν ratio versus Eν

Energy of all μ's as produced

Energy of μ's as they reach the detector

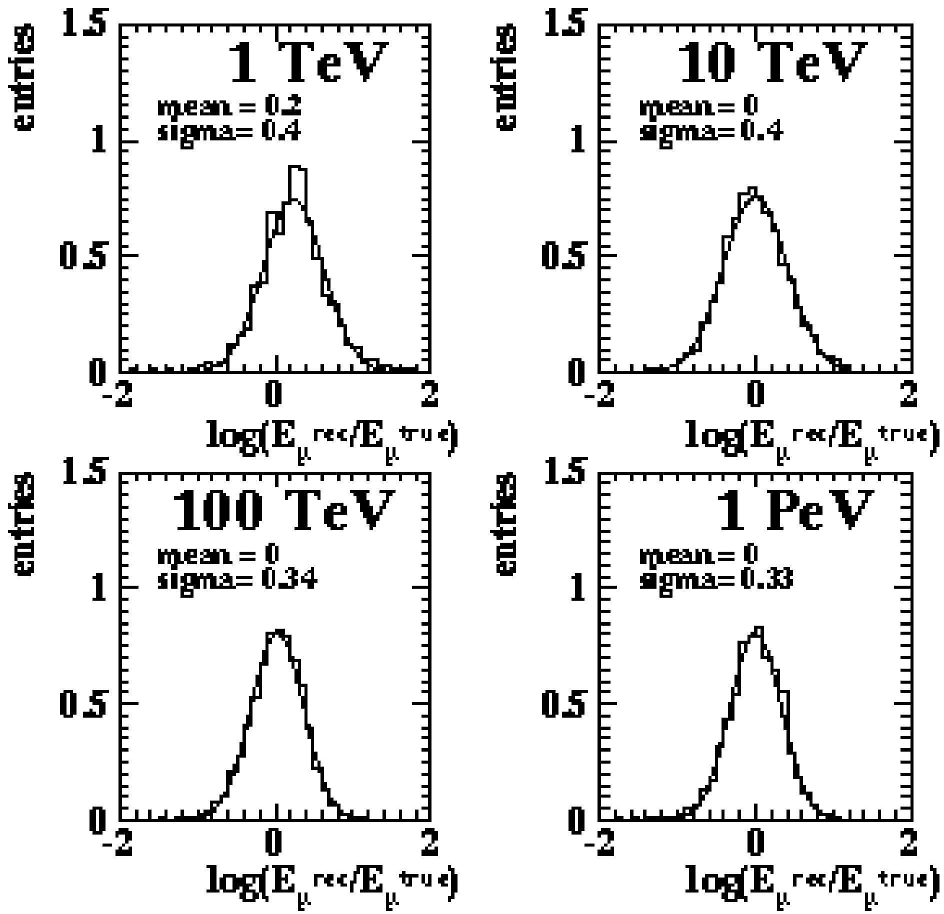
2016

Energy measurement



100 GeV μ   10 TeV μ

(Seuls les photons atteignant un PM sont dessinés)



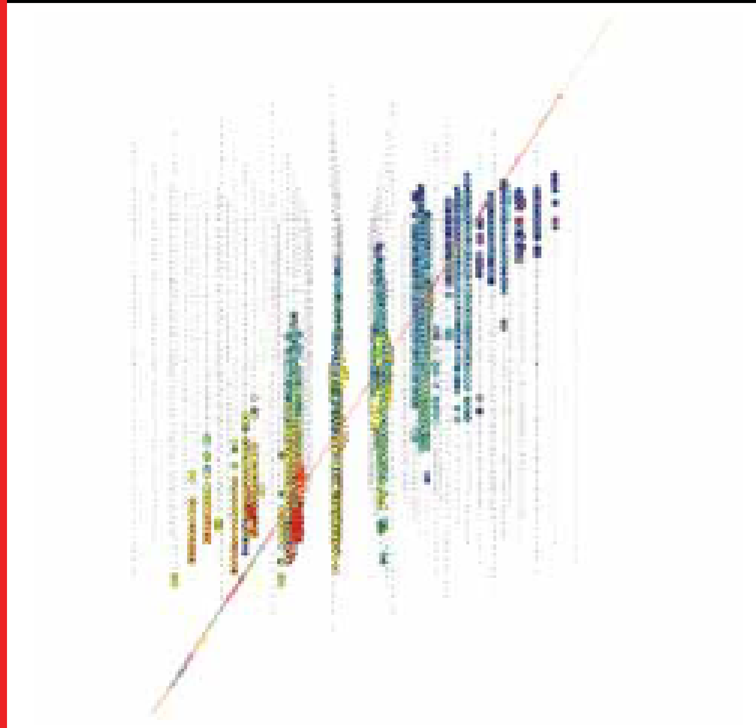
$\Delta E/E = 3 \; (< 10 \text{TeV})$

$= 2 \; (> 10 \text{TeV})$

No real neutrino energy measurement, instead possibility to cut on the muon deposited energy hence on the muon energy (for ex: 1 PeV) and hence to reject muon neutrinos with lower energy.

ν_μ

6x10^{15} eV (6 PeV)
~1000 DOMs hit
~ 20 km



E~dE/dx , e>1TeV
E res. : Δlog(E)~0.3
ang res : 0.8-2 deg

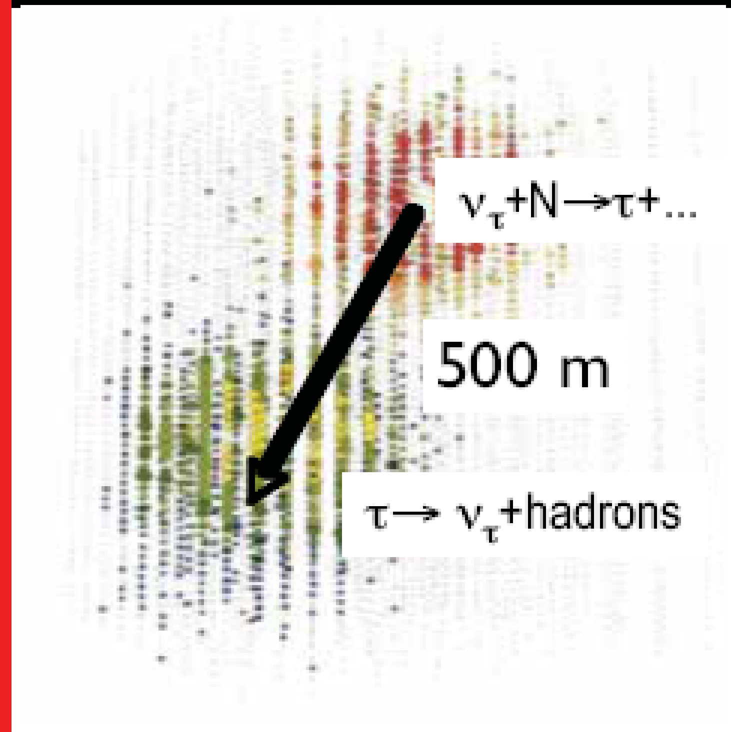
ν_e

E = 375 TeV
"spherical" shell

poor angular resolution
E res : Δlog(E)~0.1-0.2

ν_τ

E = 10 PeV
2 bangs separated by
~ 50*(E_τ/PeV)

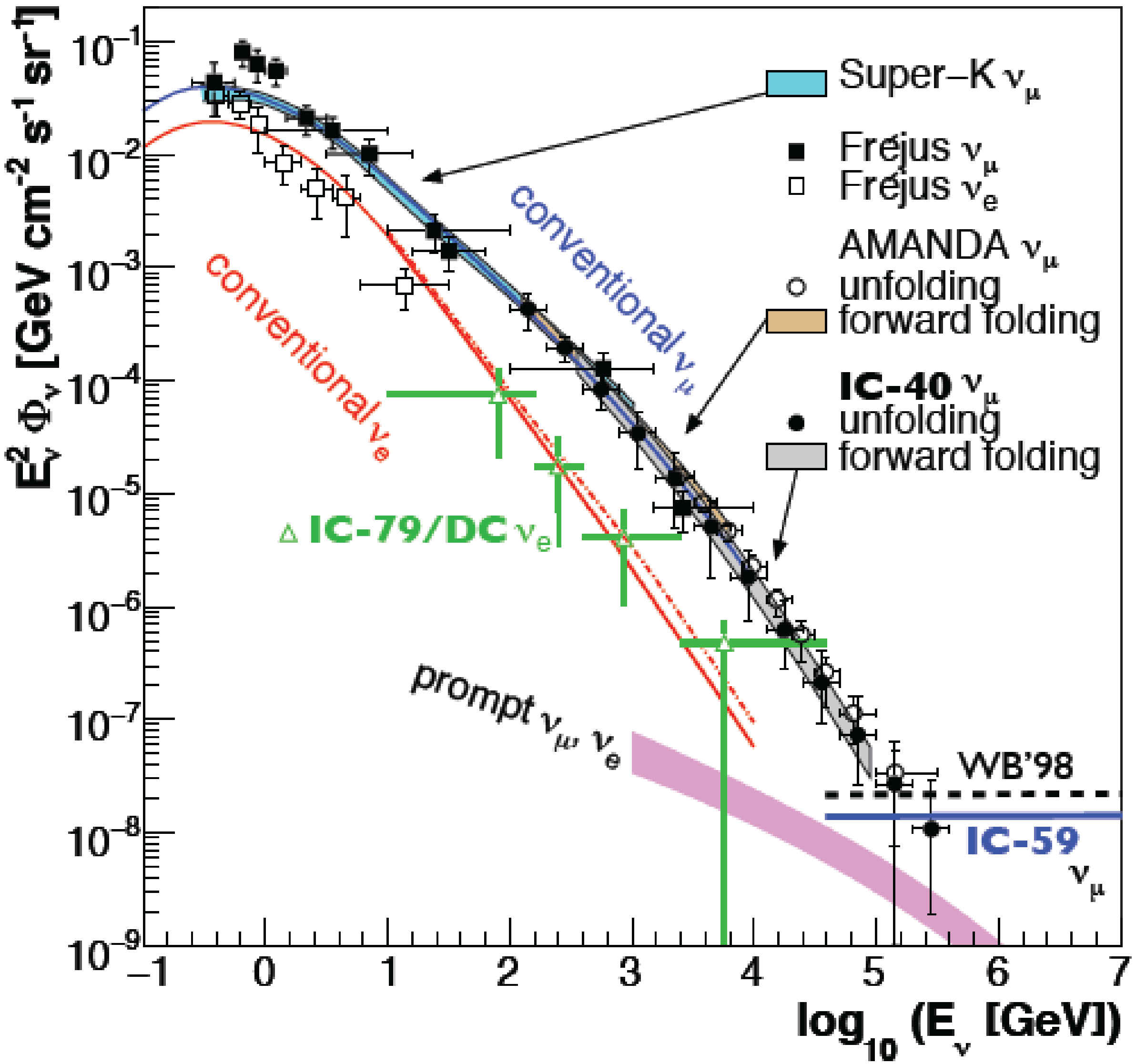


very low background
pointing capability
good E measurement

ICECUBE atmospheric flux

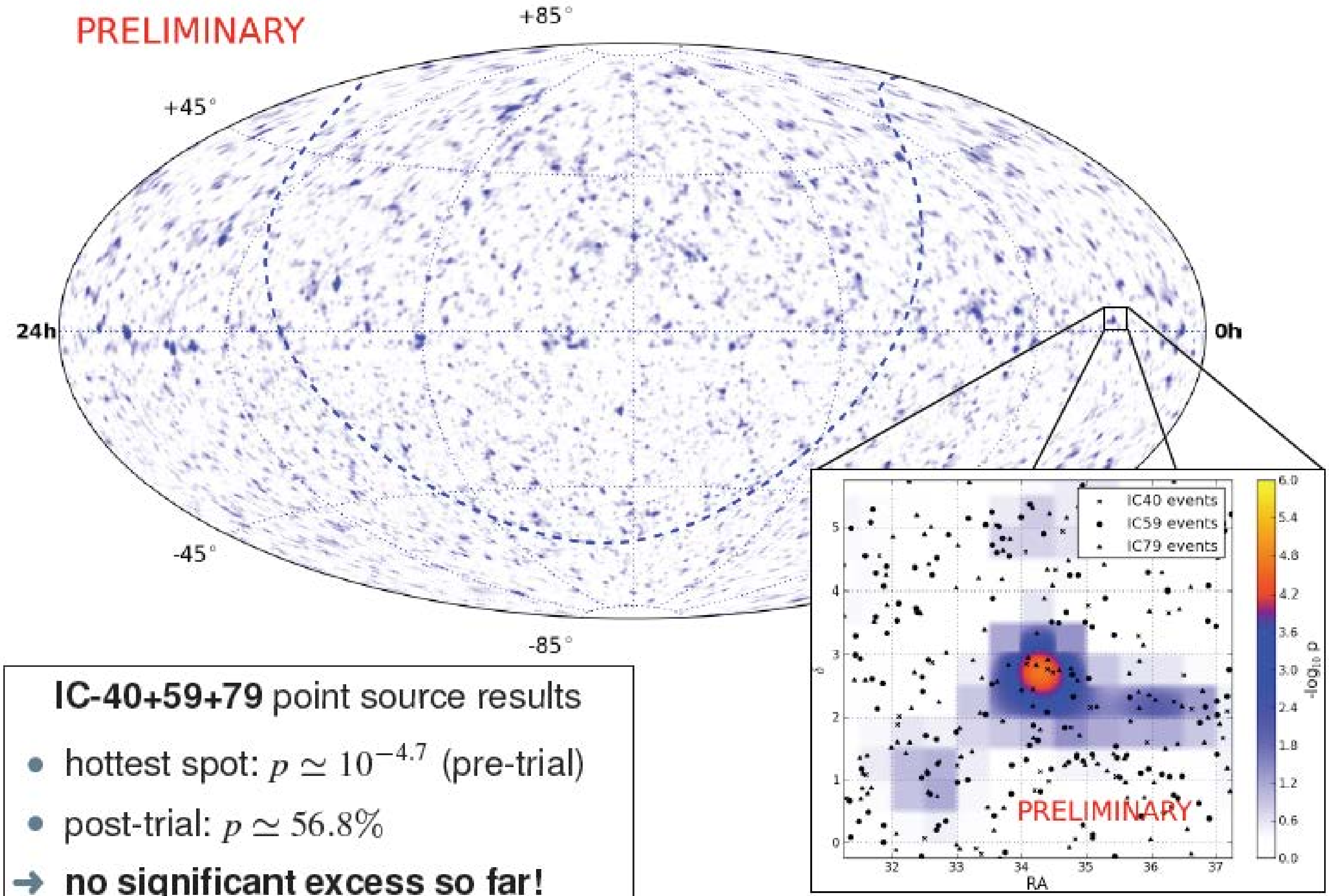
Atmospheric neutrino flux and diffuse limit

- high-energy atmospheric ν_μ/ν_e-spectrum as seen by **IC-40** & **IC-79/DC**
  [IceCube'11,'12]
- diffuse ν_μ limit from **IC-59** (90% C.L.) (**preliminary**)
- predicted prompt atmospheric ν-fluxes (charmed meson decay)
  [Enberg *et al.*'08]
- **theoretical limit** on diffuse astrophysical ν_μ's
  [Waxman&Bahcall '98]



ICECUBE atmospheric flux

Steady point-source search



IC-40+59+79 point source results

- hottest spot: $p \simeq 10^{-4.7}$ (pre-trial)
- post-trial: $p \simeq 56.8\%$

➜ **no significant excess so far!**

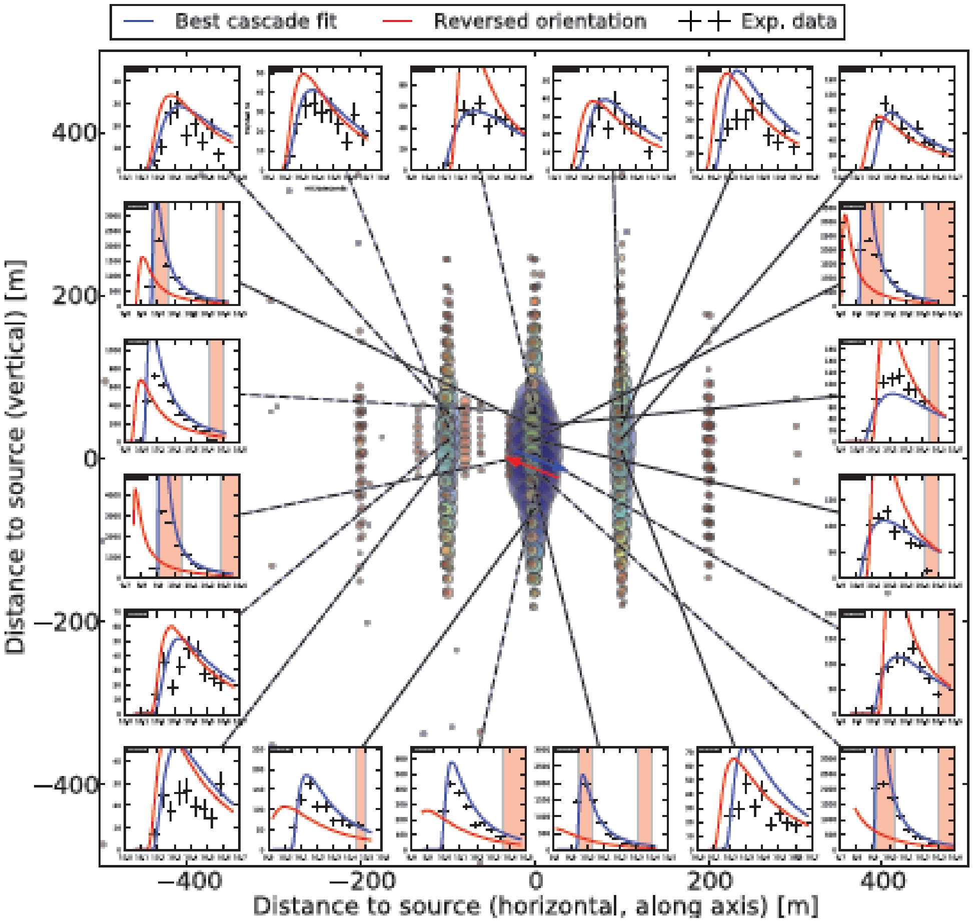
2016

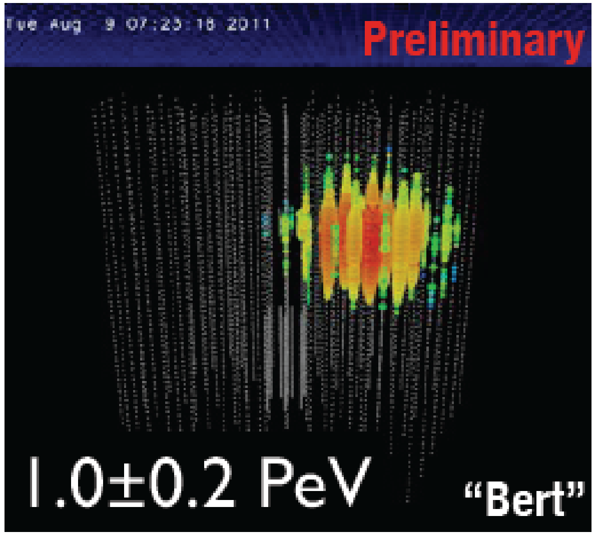
ICECUBE atmospheric flux

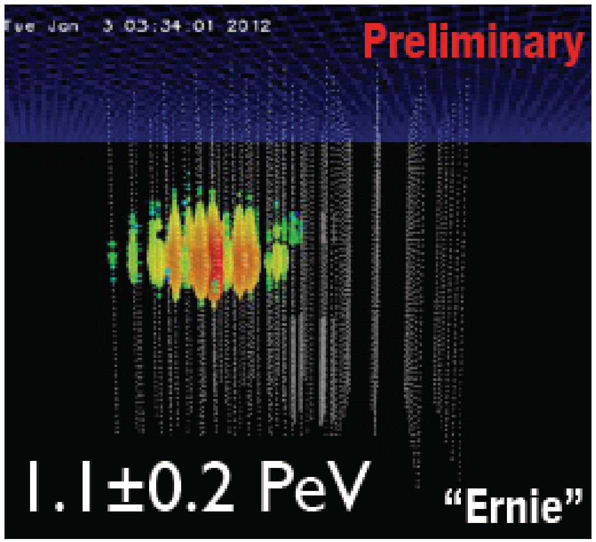
2016

Extremely-high energy analysis

Follow-up studies of background events:
energy, orientation,...
➜ Are there more contained events?





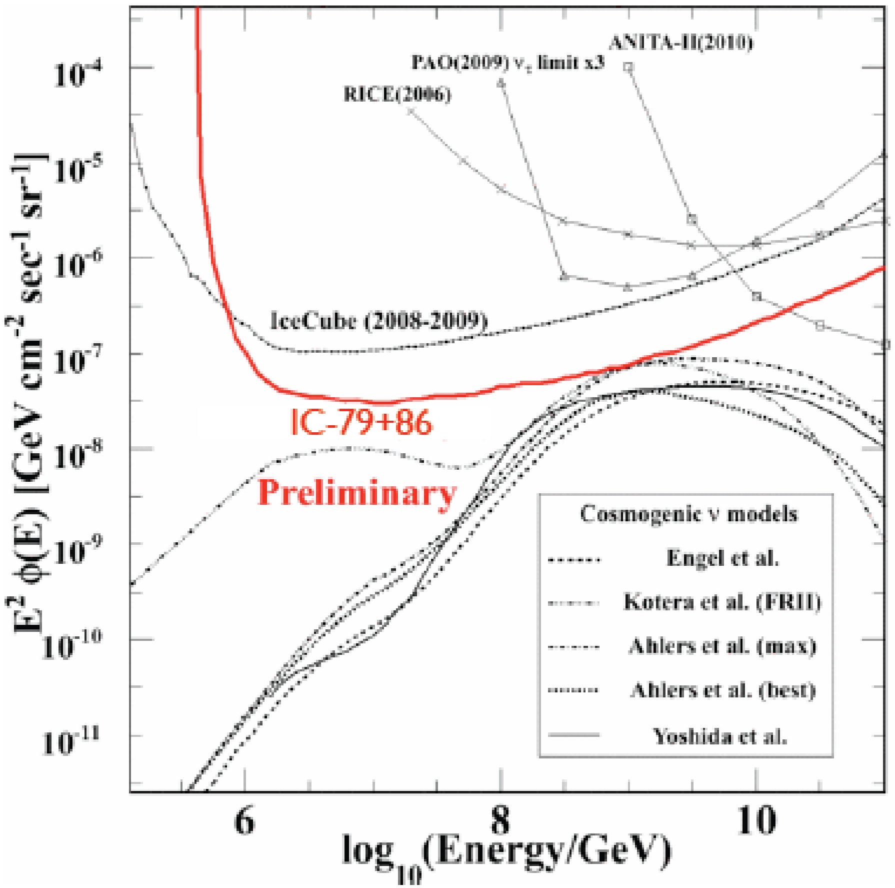


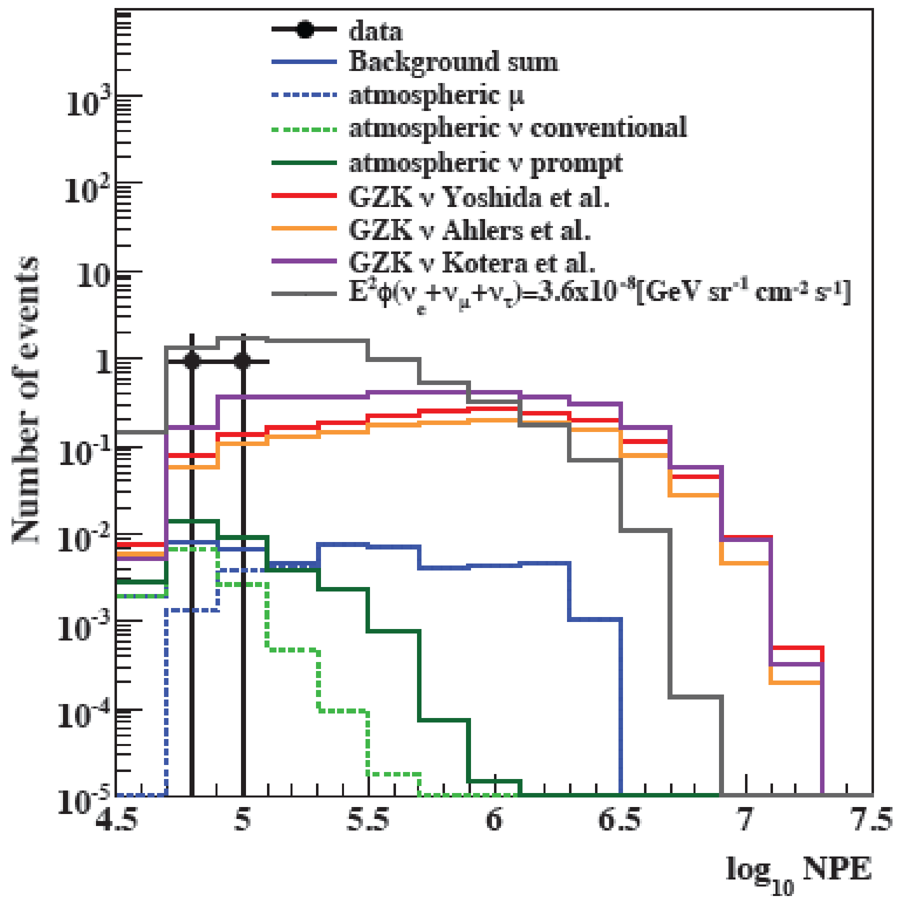
ICECUBE atmospheric flux

Extremely-high energy analysis

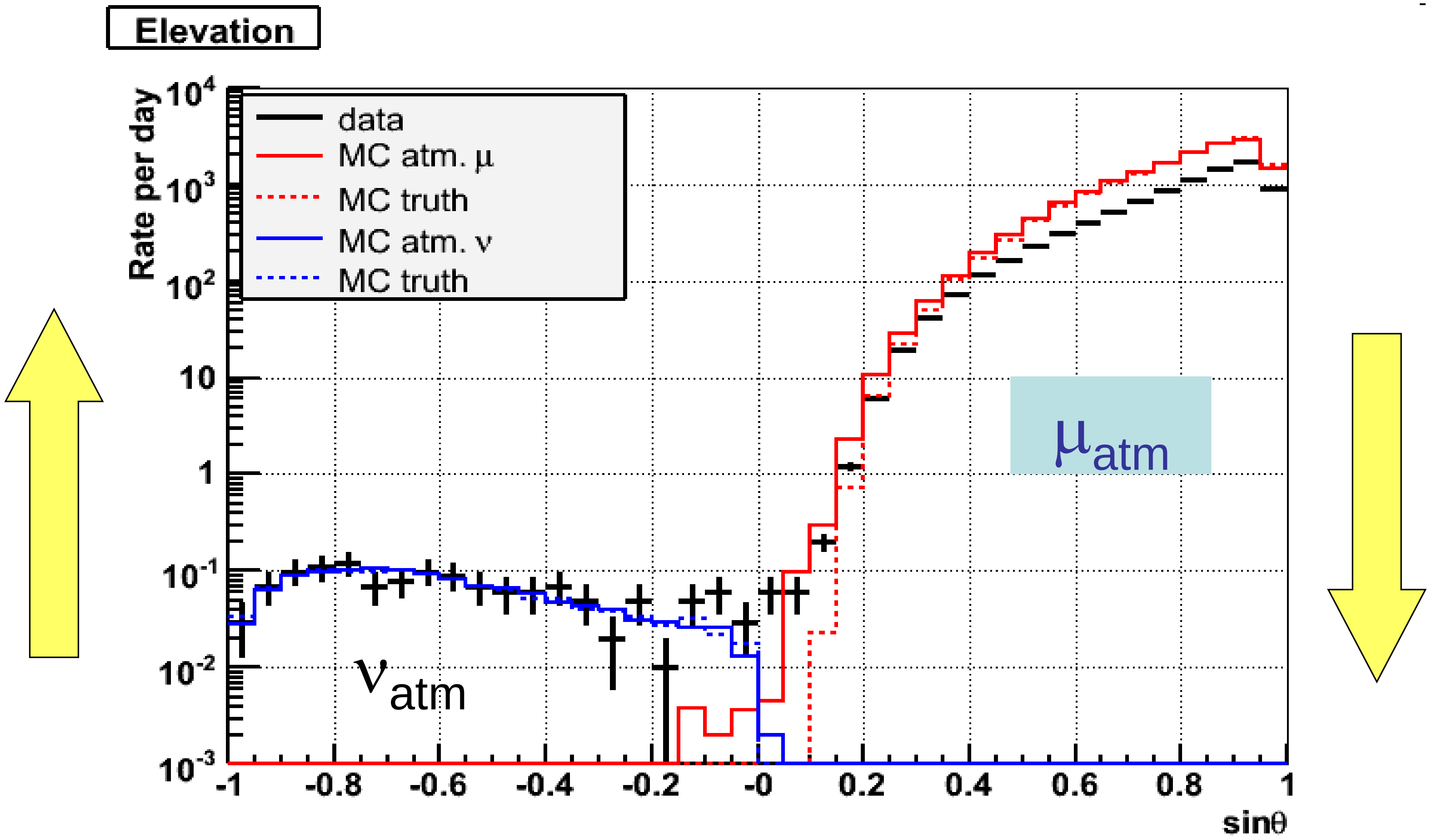
- Study for cosmogenic neutrino fluxes in **IC-79+86**
- optimized cuts on zenith angle and "brightness" (NPE: number of photo-electons)

➜ two "background" events above NPE threshold

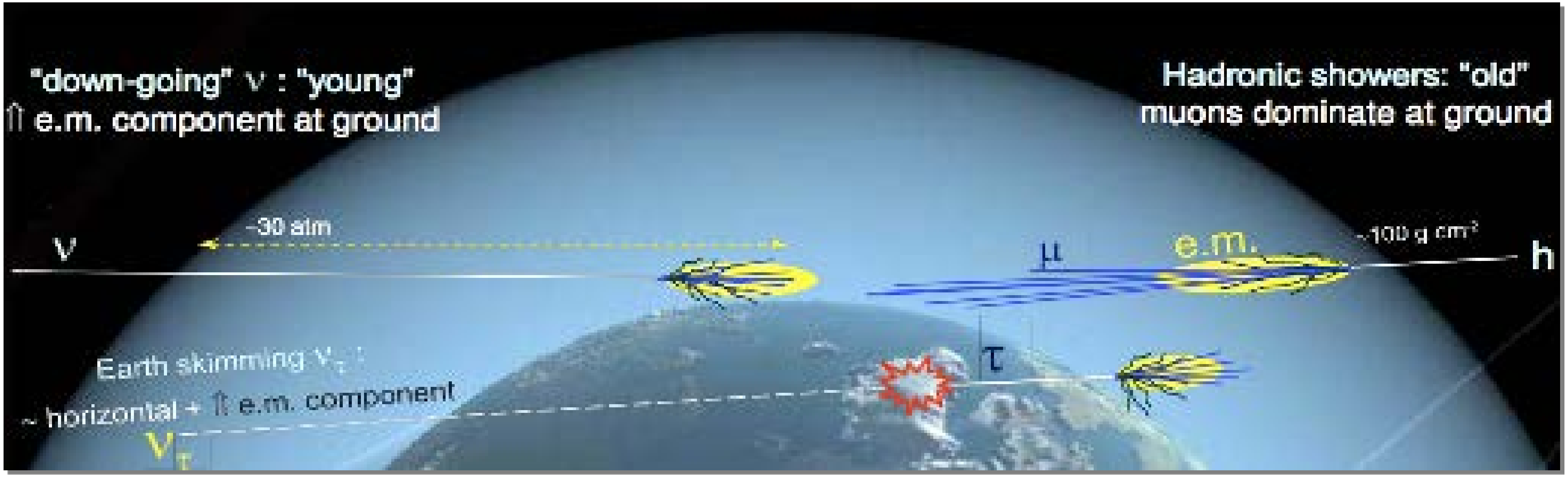




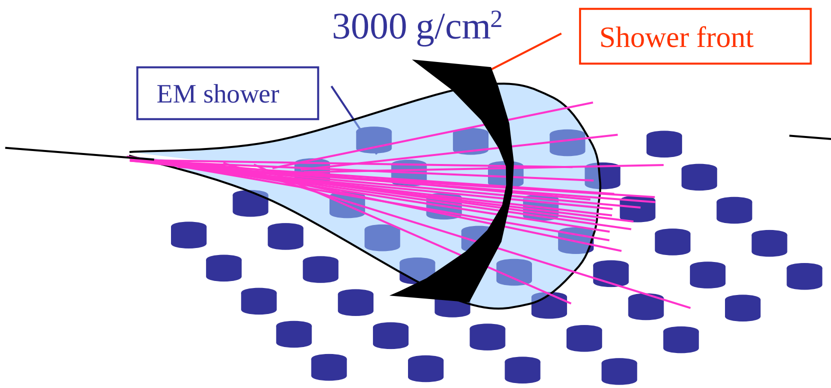
Premiers résultats d'Antares 12 lignes (sur 120 jours actifs)



UHE Neutrinos: Horizontal air showers



ν : “new” showers



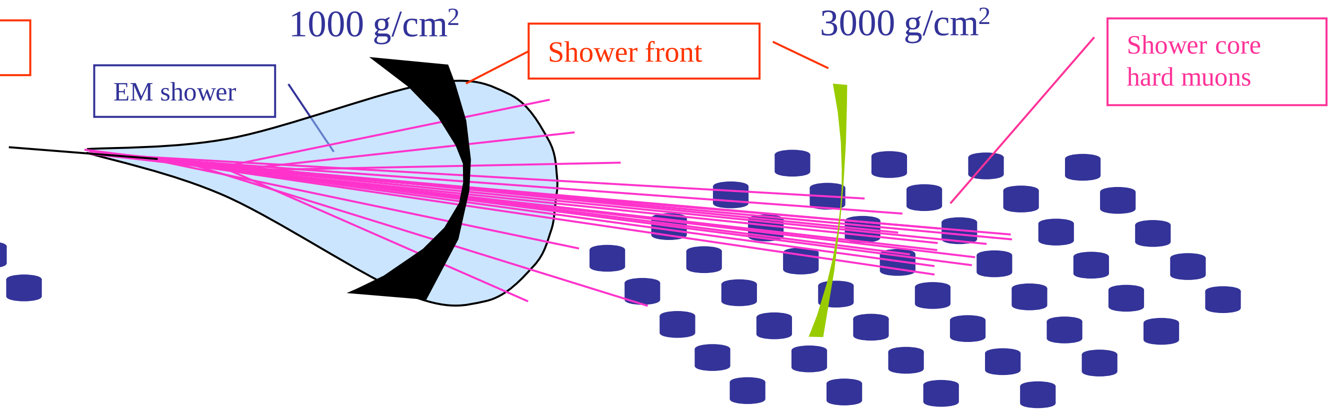
Signal is:

Few events per year

EM rich, curved and thick front

Broad signals

hadrons: “old” showers



Background is:

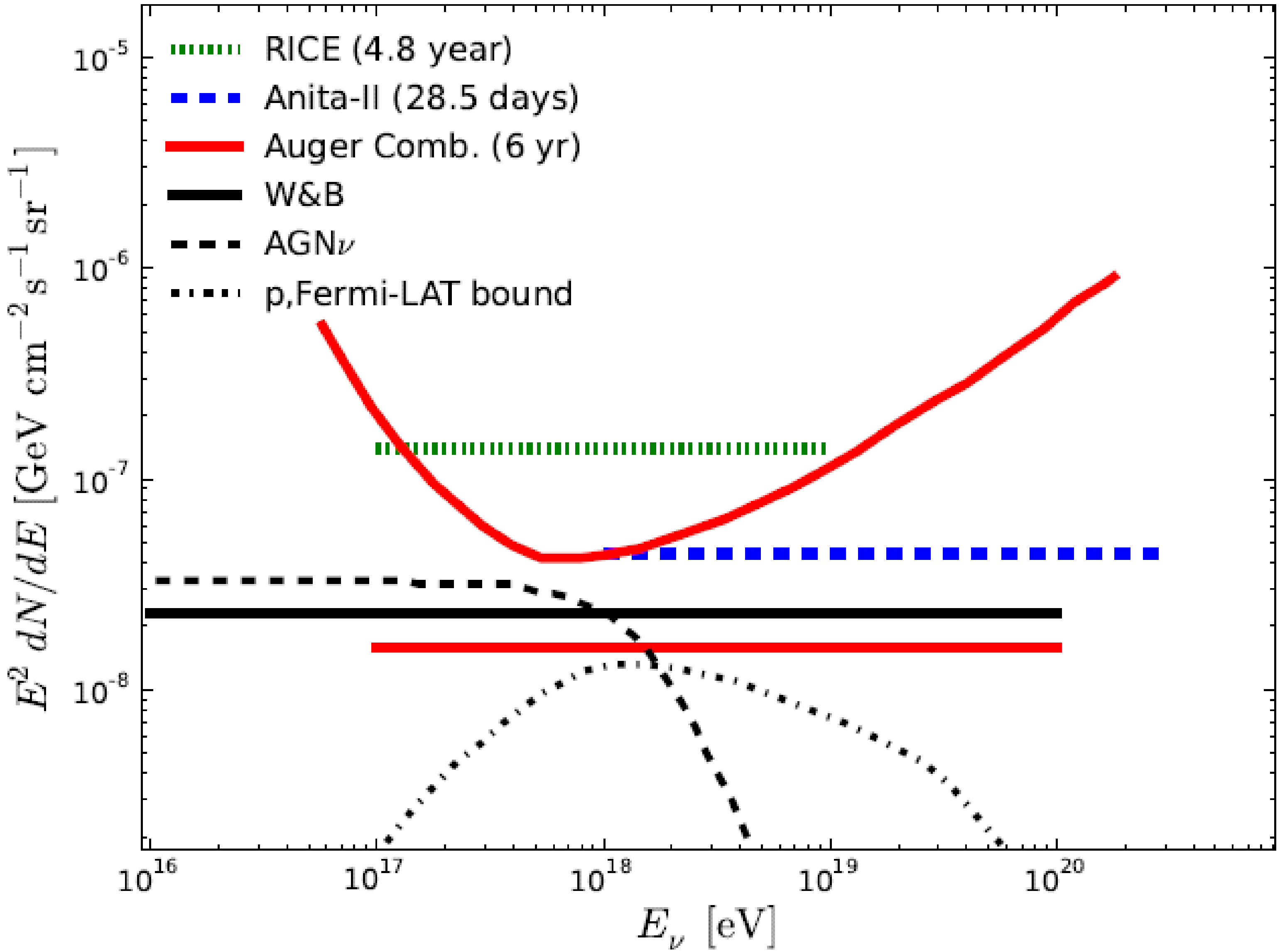
Thousands events per year

EM poor, muon rich, flat and thin front

Prompt signal

2016

AUGER limits



2016