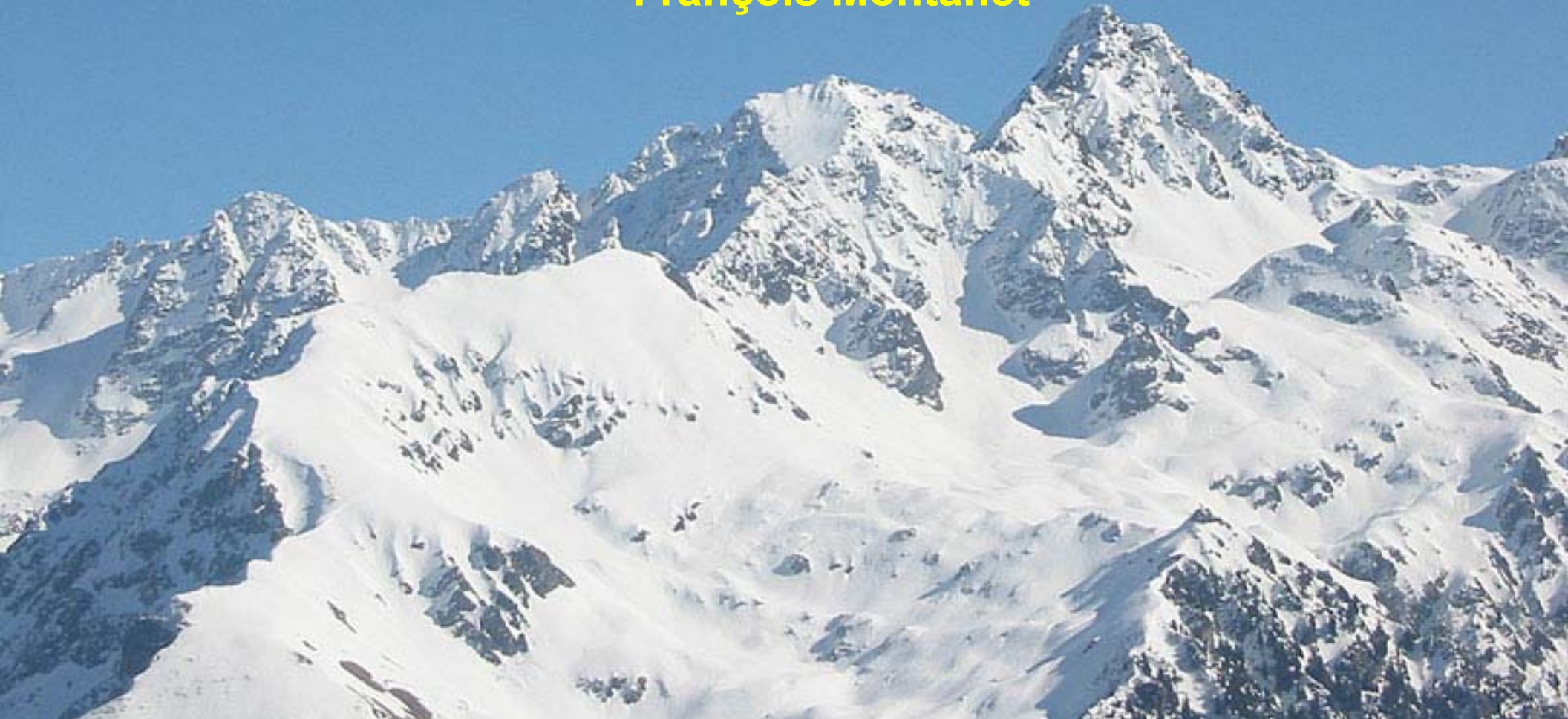


Cherenkov and Imaging detectors for HEP and AP

ESIPAP - 2020

François Montanet



Plan of the course

- The Cherenkov effect, theory and phenomenology
- Timing and counting particles
 - The AUGER WCD as an example, plus FD
- 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, CTA...
- Neutrino detectors
 - SK, Amanda, Antares, IceCube

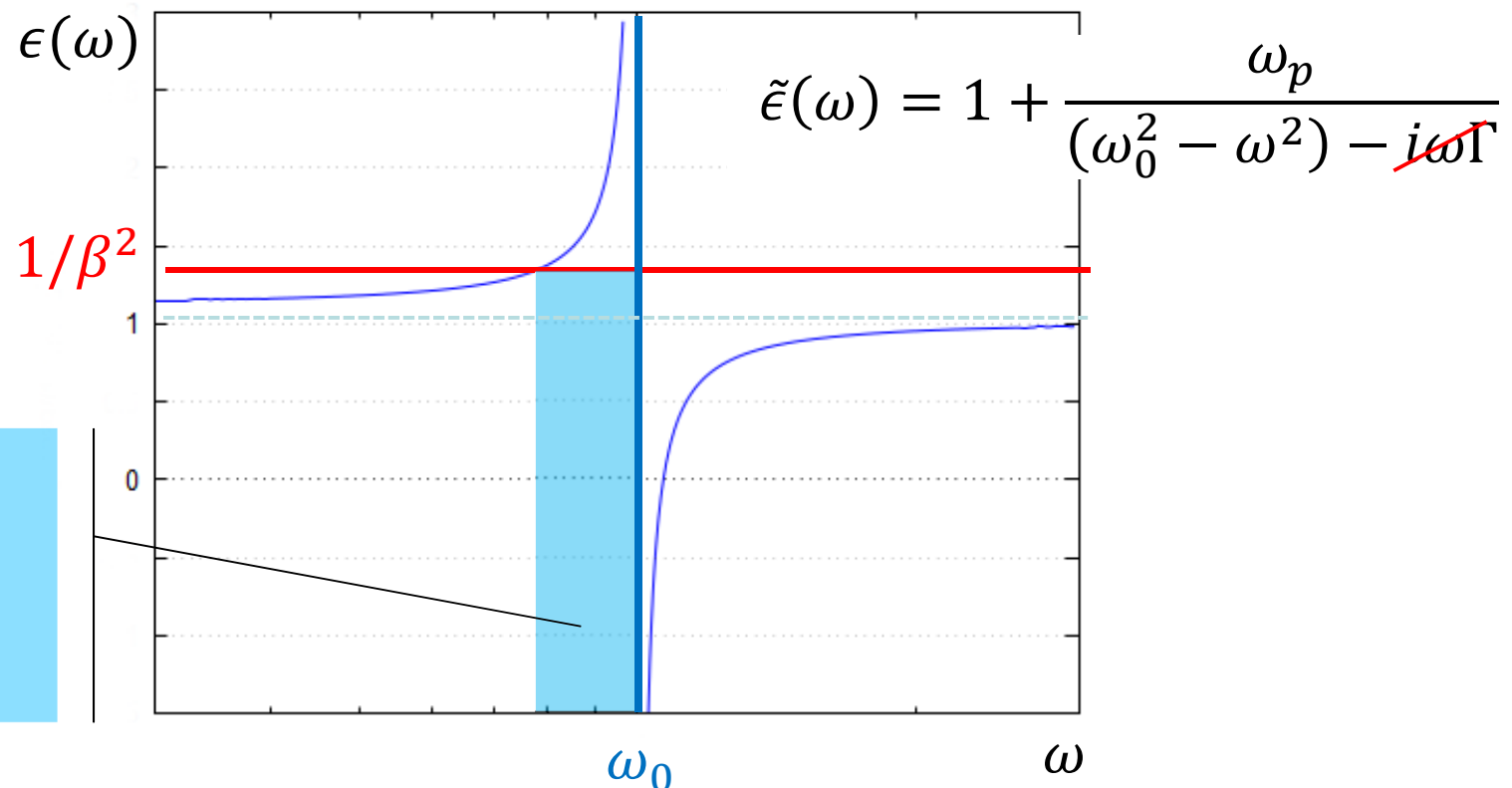
THE CHERENKOV EFFECT

Cherenkov Radiation

Coherent emission of photons by a dielectric medium due to charged particles with velocities $>$ local phase velocity of light in that medium.

$$\tilde{\epsilon} = \epsilon_1 + i\epsilon_2 = (n + i\kappa)^2$$

Transparent medium
=> no absorption



Frequency
(wavelength)
domain in which
Cherenkov
radiation occurs

Cherenkov Radiation

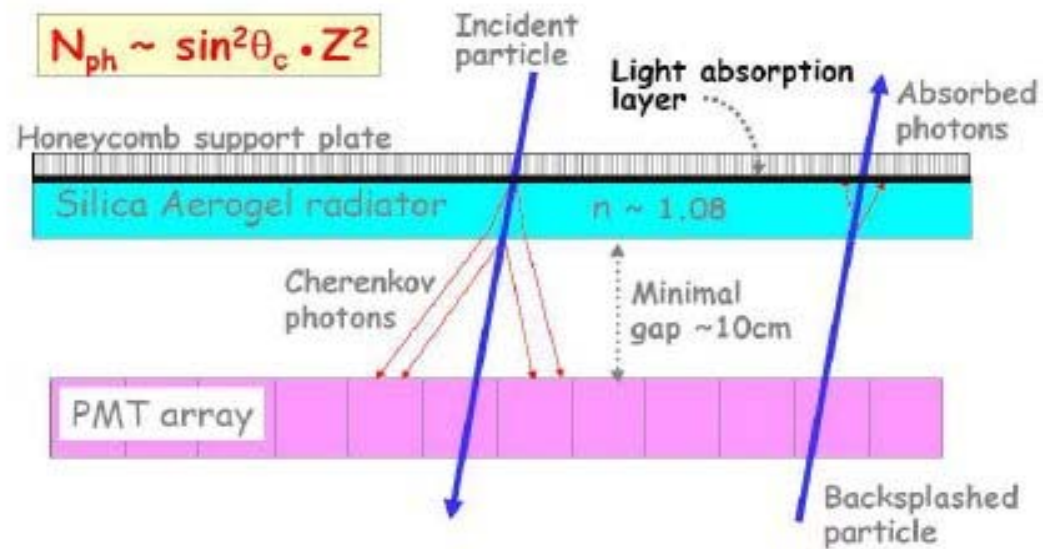
- Emitted on a cone whose axis is along the particle trajectory and of half opening angle θ_C such as $\cos(\theta_C) = 1/(\beta n)$ where β is the particle velocity/ c and $n = n(\omega)$ is the frequency dependent refractive index.
- Threshold defined by the condition $\frac{1}{\beta n} < 1 \Rightarrow \beta > \frac{1}{n}$
- Emission at all frequencies with $n(\omega) > 1$ (from UV to radio), with a flat photon yield as function of $h\nu$.
- Generally detected from near UV to visible light (but not only).

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

Cherenkov Radiation

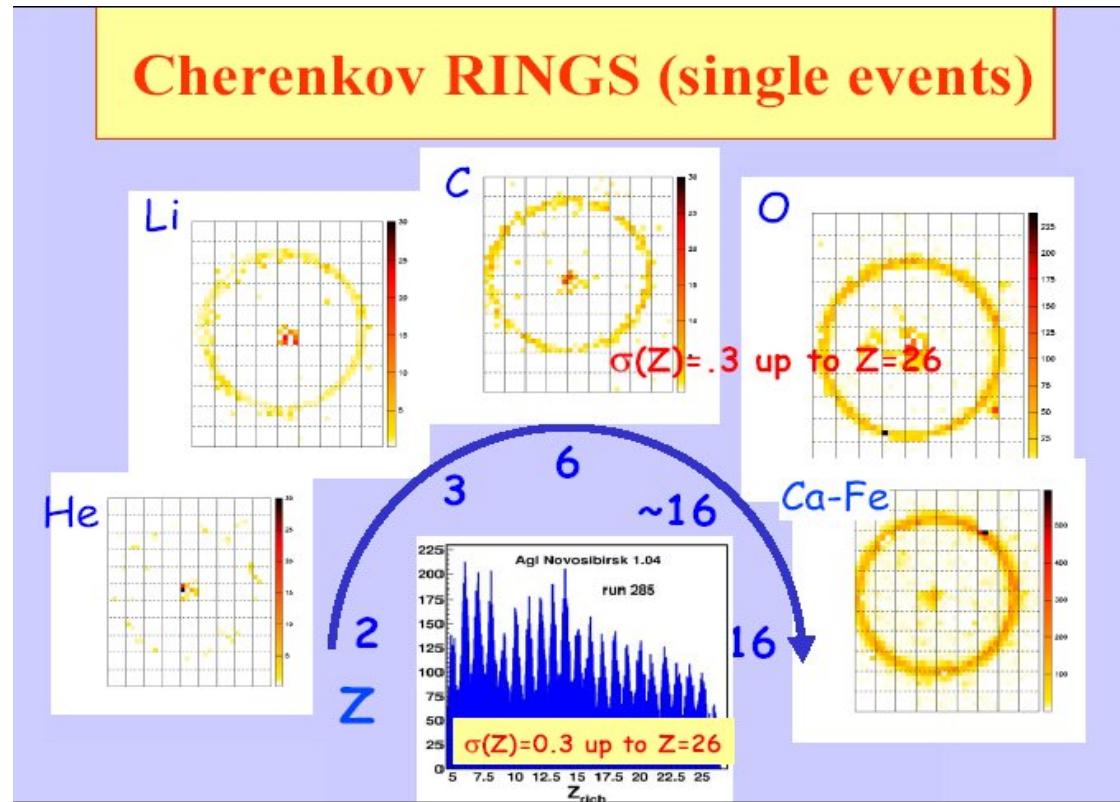
- Allow discrimination between particles with same momentum and \neq masses (electrons / protons / nuclei)
- Up to energies of the order of 10 GeV/nucleon if $\frac{\Delta\beta}{\beta} \approx 10^{-3}$
- Allow determining the orientation of the particle direction.
- "Ring Imaging Cherenkov" detector or "RICH" allow a precise measurement 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 dielectric media, the solution corresponding to each medium does not satisfy the boundary condition \Rightarrow need for an additional "free wave".
- A dielectric medium is characterized by its "plasma" frequency ω_p (oscillation frequency of free-like electrons)

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad \Rightarrow \quad \hbar \omega_p = 2 E_R \sqrt{4 \pi n_e a_B^3} \approx 20 \text{ eV}$$

where n_e = electron density

E_R = Rydberg energy = 13.6 eV ;

a_B = Bohr radius

- Roughly half of the energy is emitted in the frequency domain
 $0.1 \gamma \omega_p < \omega < \gamma \omega_p$
- For a Lorentz factor $\gamma \approx 1000$, this is the X-ray domain (2 to 20 keV)
- Energy emitted by the interface is $I = \alpha Z^2 \gamma \hbar \frac{\omega_p}{3}$

Transition radiation (cont)

- Angular distribution peaked at small angles around particle direction:

$$\theta \approx 1/\gamma$$

- Small yield of X-photons per interface : $N \approx \alpha Z^2 \approx 10^{-2} Z^2$

→ multiply the number of interfaces

→ 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 threshold 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 (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, which 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 fluorescence. 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 characteristics 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".

Photos: Copyright © The Nobel Foundation

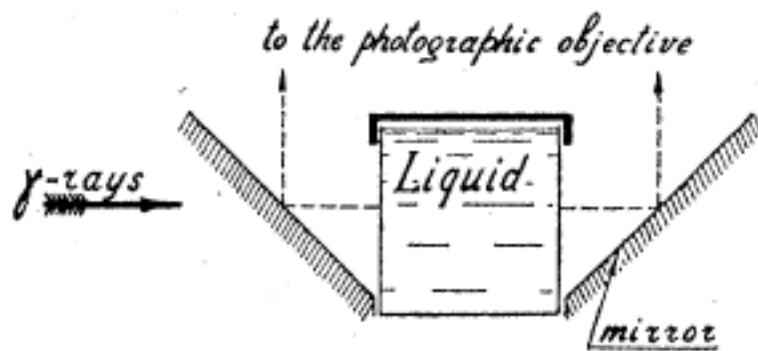


FIG. 1. Arrangement of apparatus.

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)

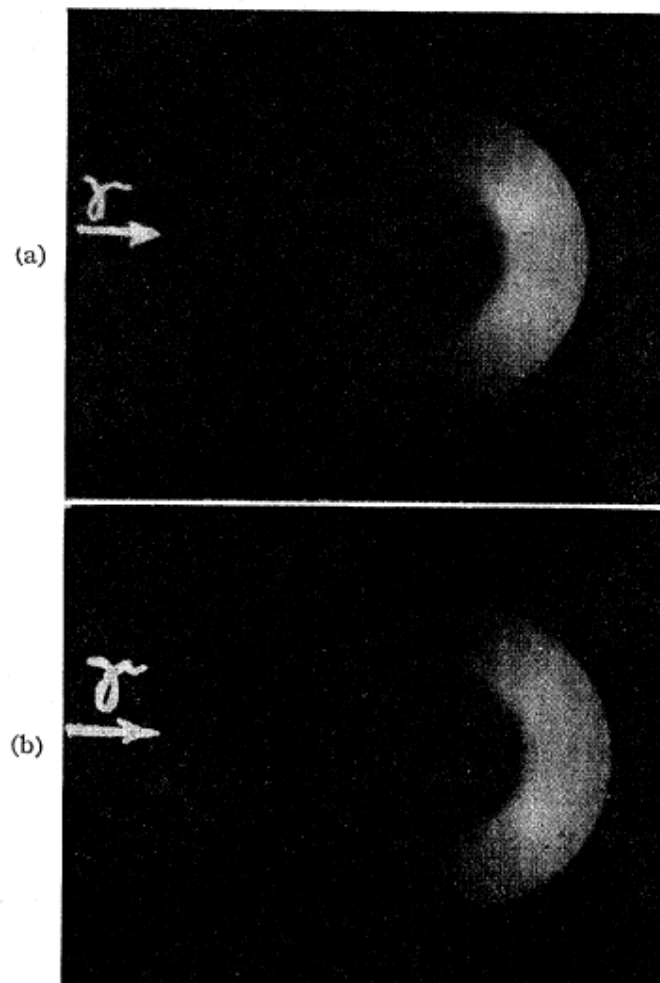
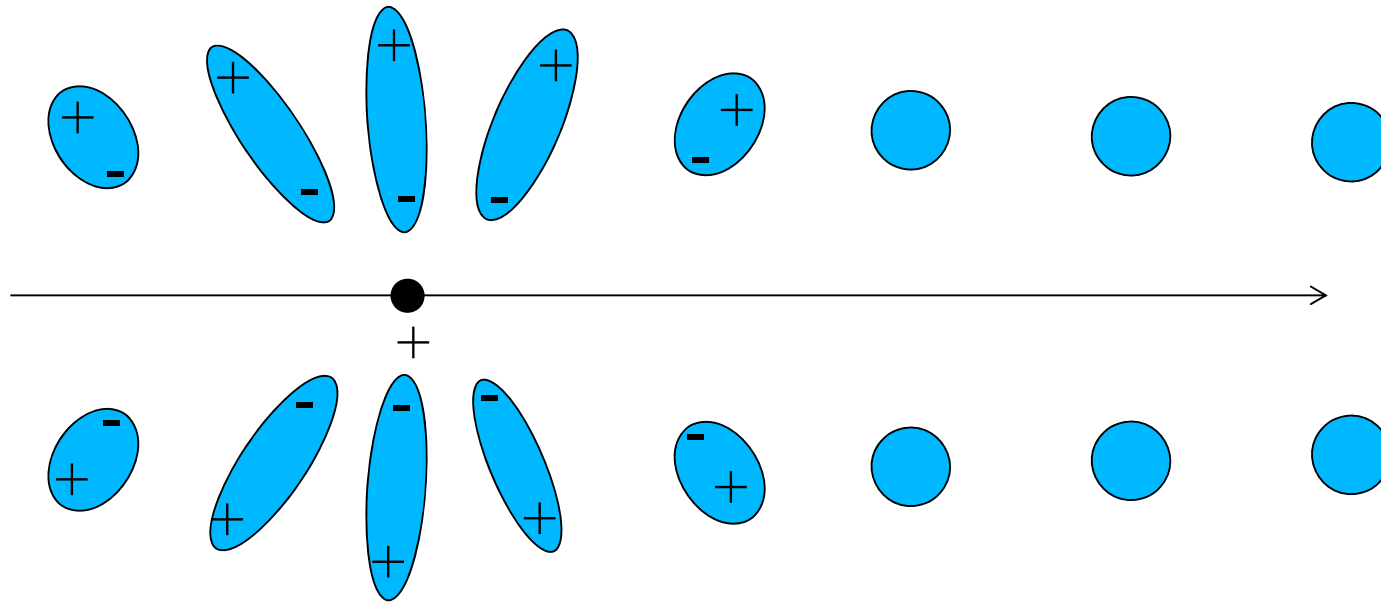


FIG. 2. Photographs showing asymmetry of luminescence. (a) water, $n = 1.337$; (b) benzene, $n = 1.513$.

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

The Cherenkov effect

- 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

Igor Tamm and Ilya Frank

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 velocity v is greater than speed of light in the medium $c/n(\omega)$. This integral is non-divergent because at high frequencies the refractive index becomes less than unity.

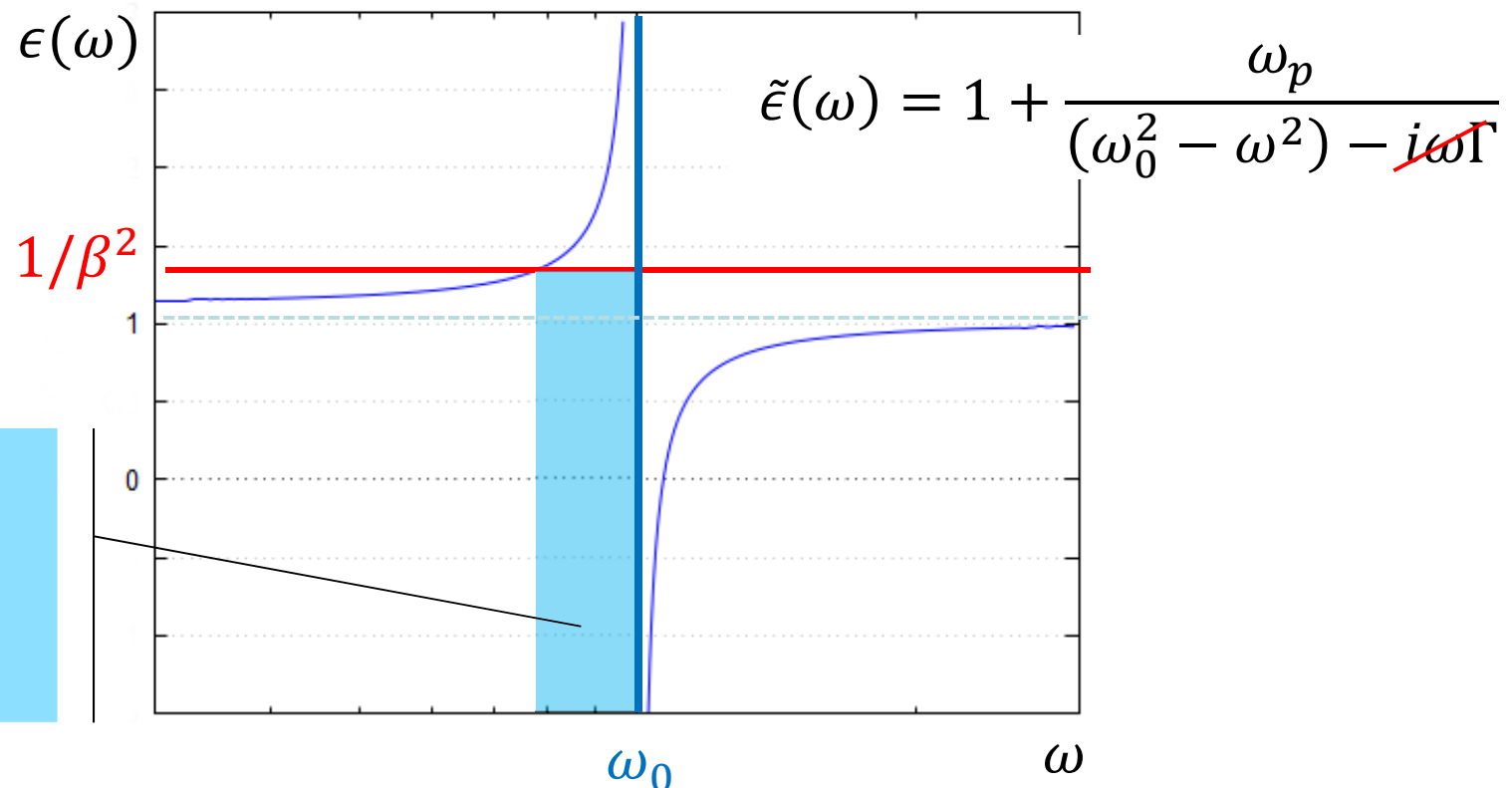
$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{\beta n(\omega) > 1} \mu(\omega) \omega \left(1 - \frac{1}{\beta^2 n^2(\omega)} \right) d\omega$$

Cherenkov Radiation

Coherent emission of photons by a dielectric medium due to charged particles with velocities $>$ local phase velocity of light in that medium.

$$\tilde{\epsilon} = \epsilon_1 + i\epsilon_2 = (n + i\kappa)^2$$

Transparent medium
=> no absorption



Frequency
(wavelength)
domaine in which
Cherenkov
radiation occurs

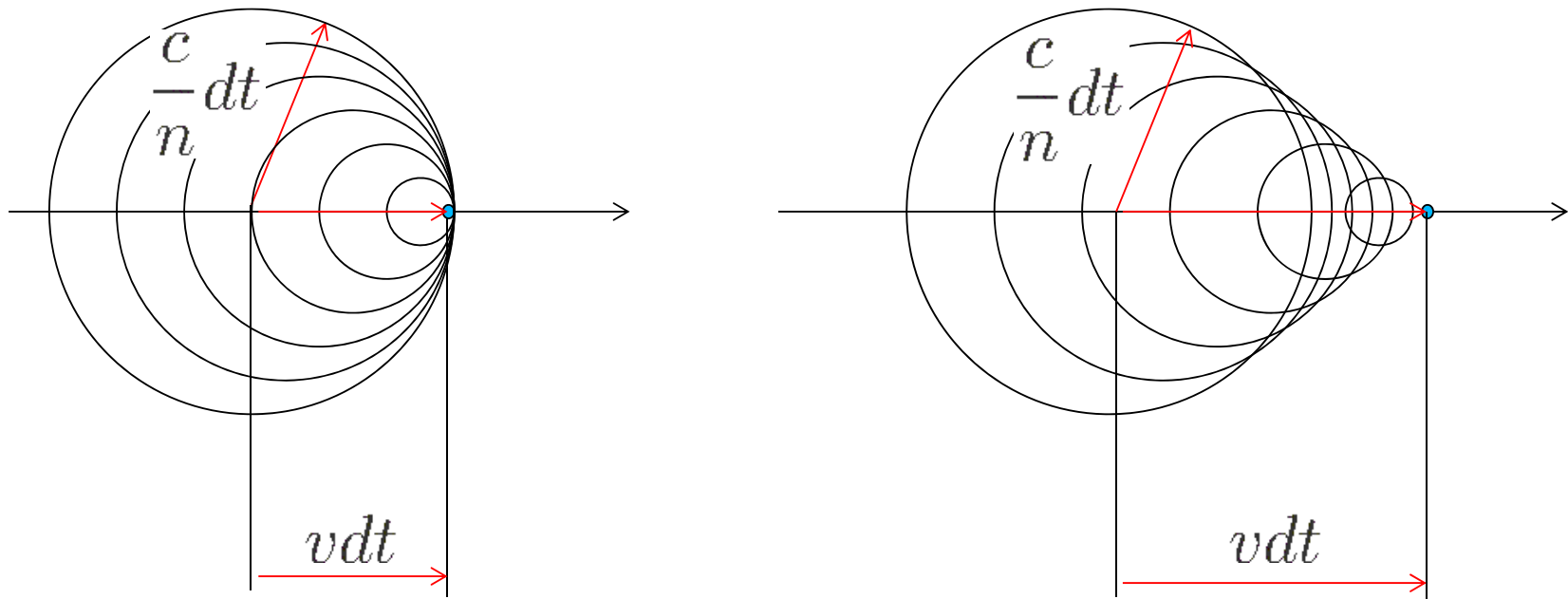
The Cherenkov effect

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



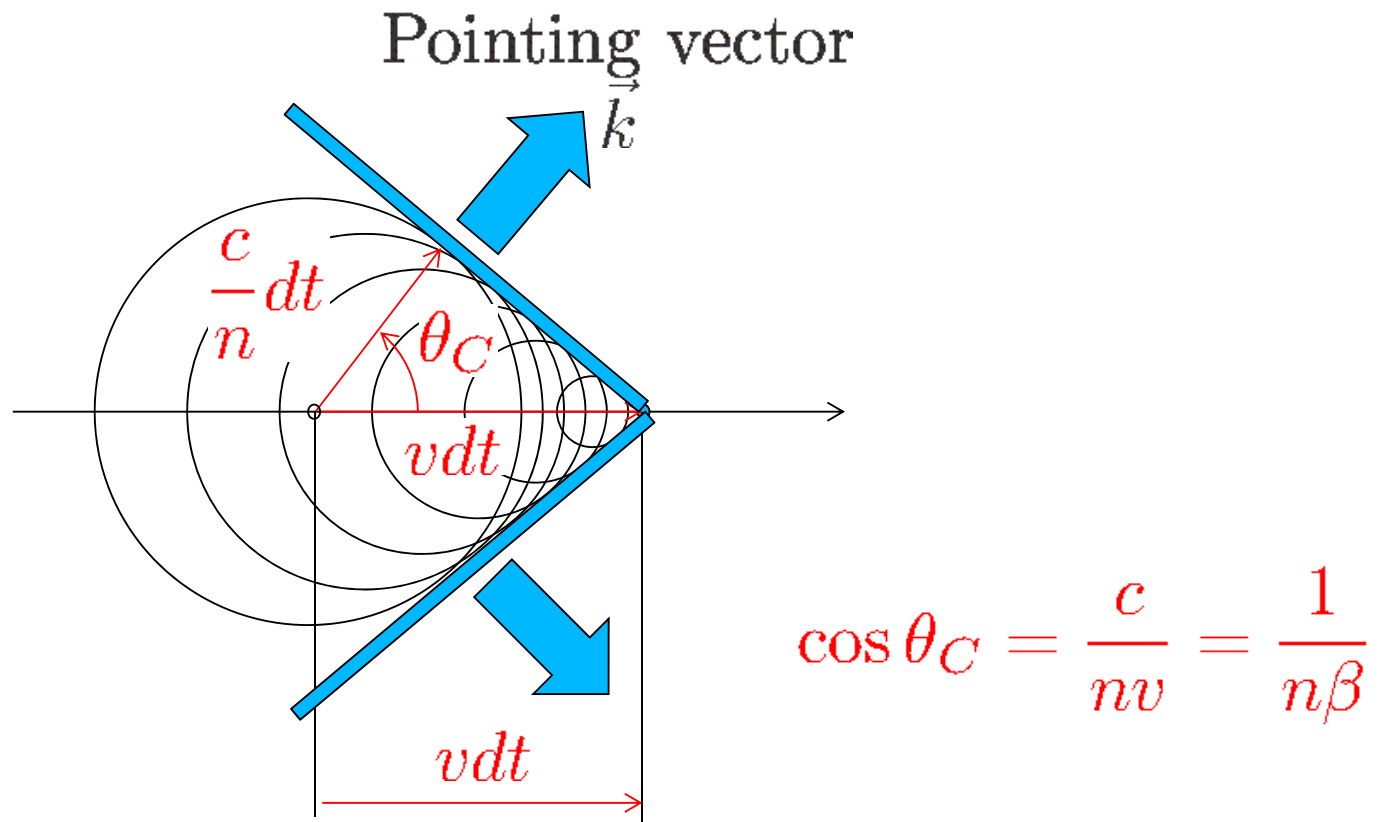
The Cherenkov effect

- Cerenkov radiation consist of a shock wave
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The Cherenkov effect

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



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:

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

thus the threshold momentum:

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

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

Cherenkov effect

Relevant formulae (cont):

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

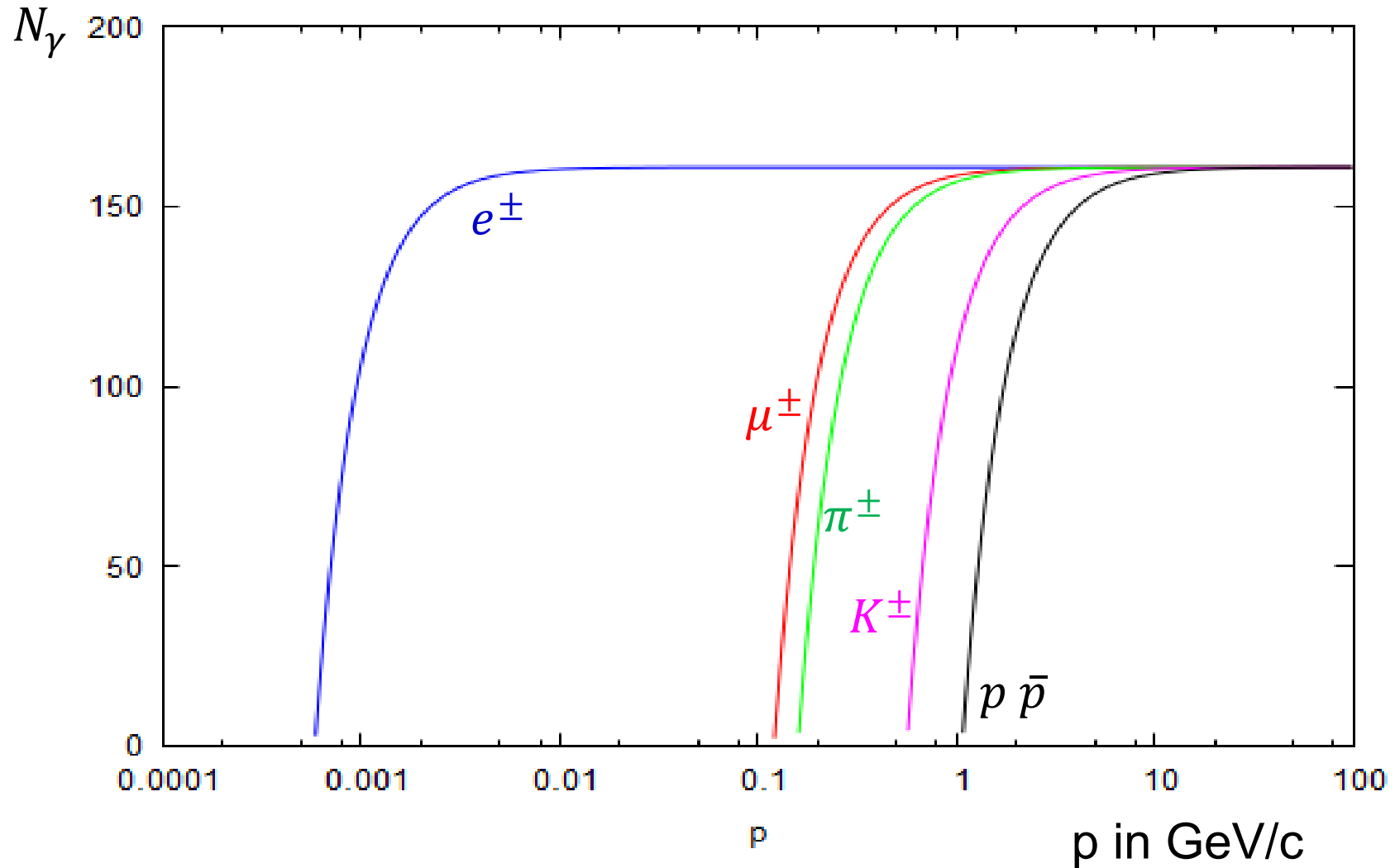
$$\begin{aligned}\frac{d^2N}{dEdx} &= \frac{\alpha Z^2}{\hbar c} \left(1 - \frac{1}{\beta^2 n^2(E)} \right) \\ &= \frac{\alpha Z^2}{\hbar c} \sin^2 \theta_C \\ &= 370 Z^2 \sin^2 \theta_C \text{ eV}^{-1} \text{ cm}^{-1}\end{aligned}$$

or equivalently:

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

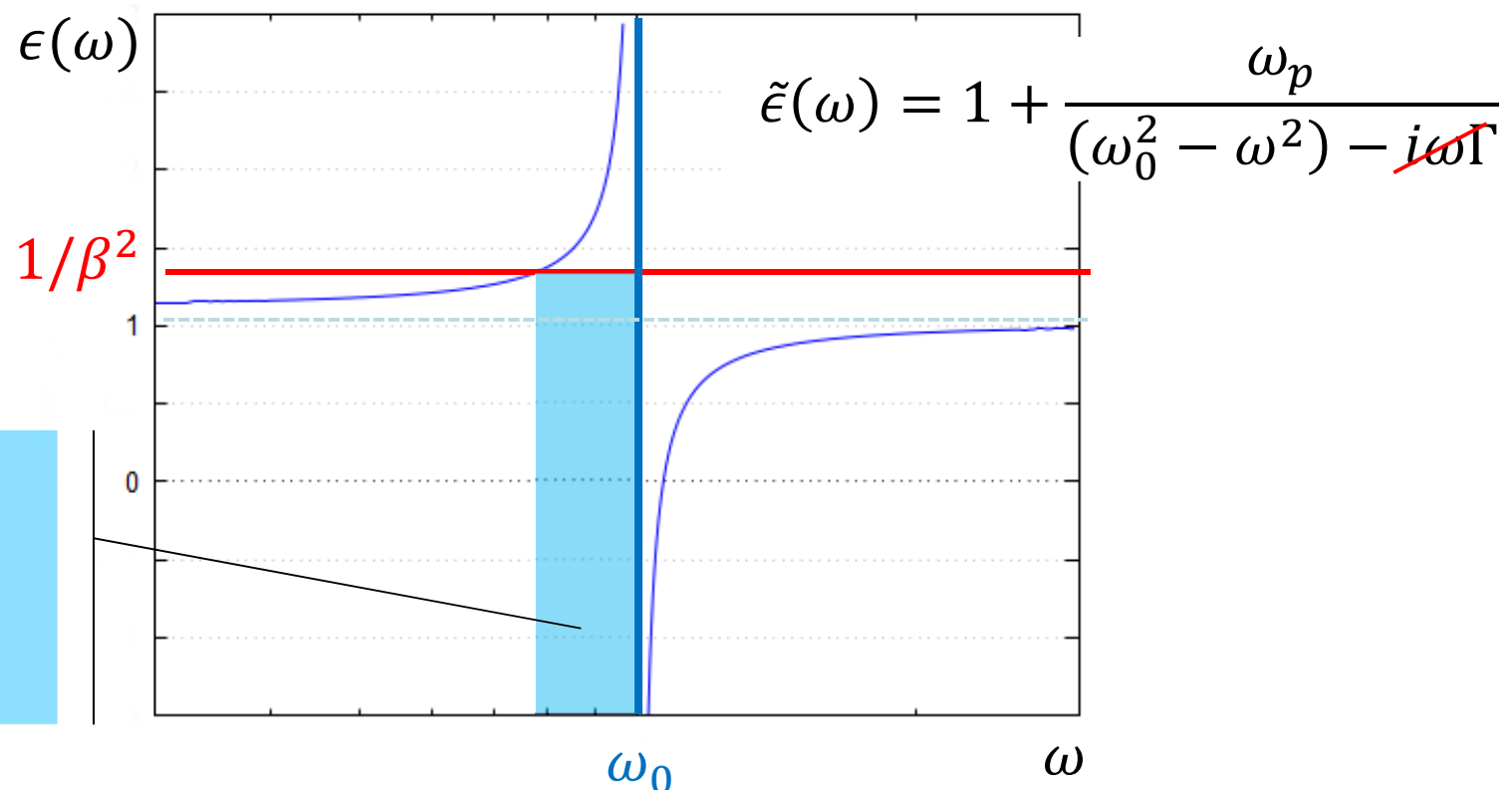
Cherenkov effect

Photon yield for 1 cm of water ($n = 1.33$) and 1 eV spectral band.



Dispersion in dielectrics

- Dielectric constant and index of refraction depending on light frequency or wavelength
⇒ phase velocity and group velocity

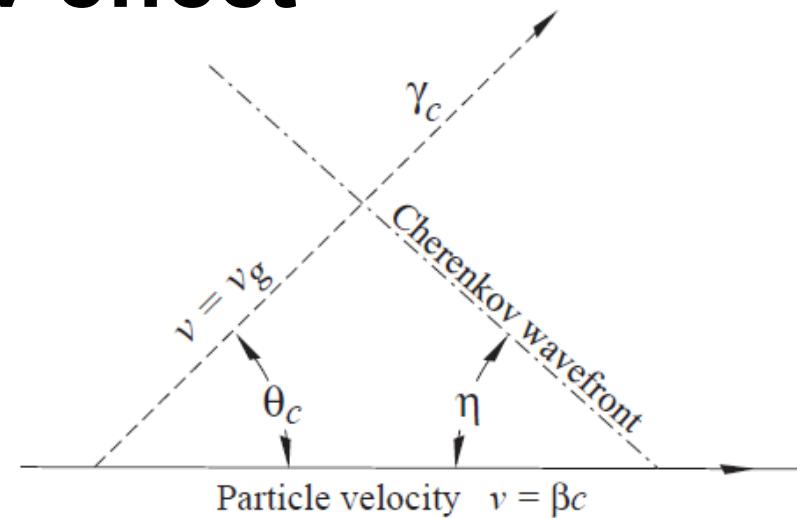


Frequency
(wavelength)
domaine in which
Cherenkov
radiation occurs

Cherenkov effect

- Dispersive material:

Indeed important for the precise 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 $\theta_C + \eta \neq 90^\circ$ with η the cone 1/2 opening angle given by:

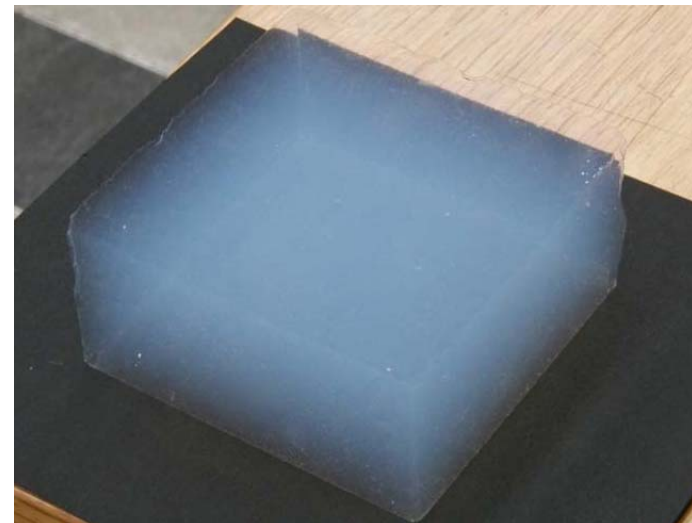
$$\begin{aligned} \cot \eta &= \left[\frac{d}{d\omega} (\omega \tan \theta_C) \right]_{\omega_0} \\ &= \left[\tan \theta_C + \beta^2 \omega n(\omega) \frac{dn}{d\omega} \cot \theta_C \right]_{\omega_0} \end{aligned}$$

Radiators

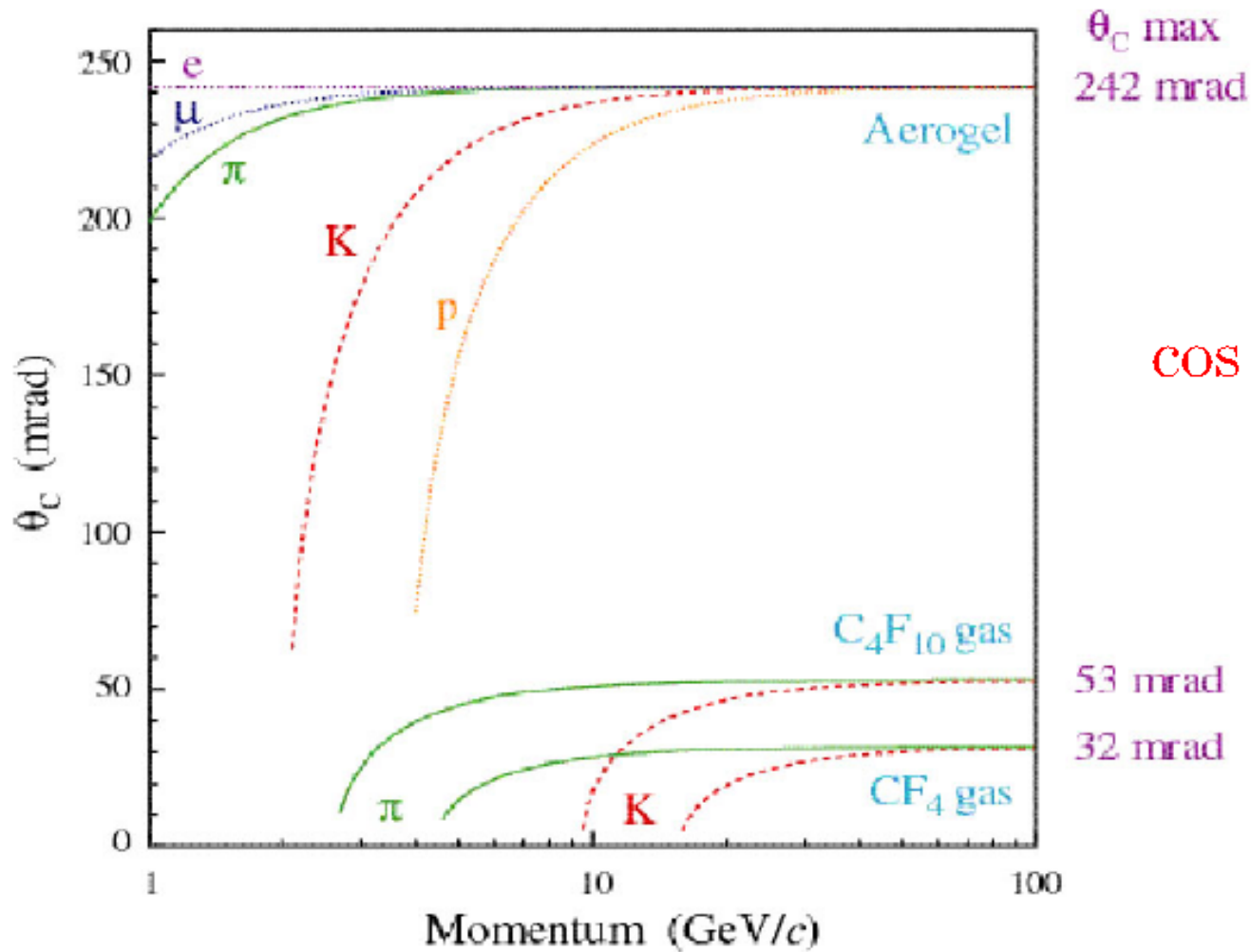
- Matching refractive index to the momentum range.

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	$12.7 - 21.5^\circ$	2400 – 6600
Water	0.33	1.52	41.2°	$2.1 \cdot 10^4$
Glass	0.46 – 0.75	1.37 – 1.22	$46.8 - 55.1^\circ$	$2.6 - 3.3 \cdot 10^4$

Silica aerogel:
SiO₂ "foam" with
nano-size structure λ ,



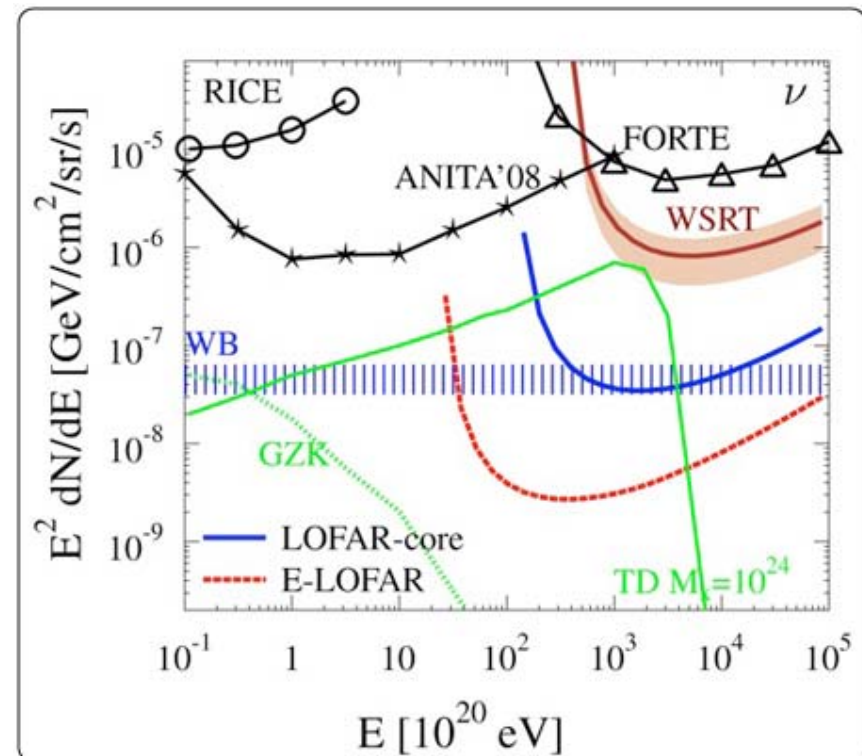
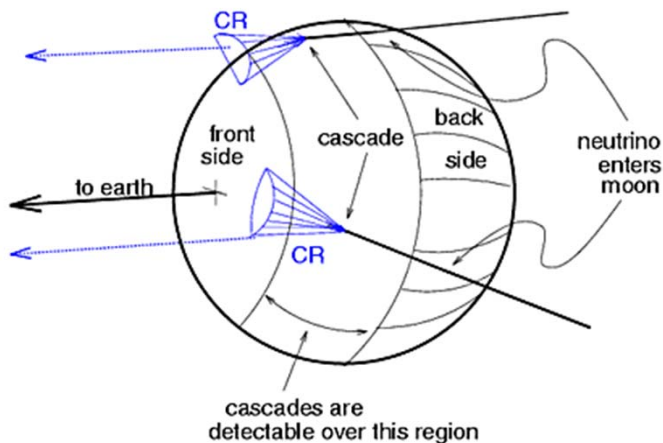
Cherenkov angle vs mass and momentum



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

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

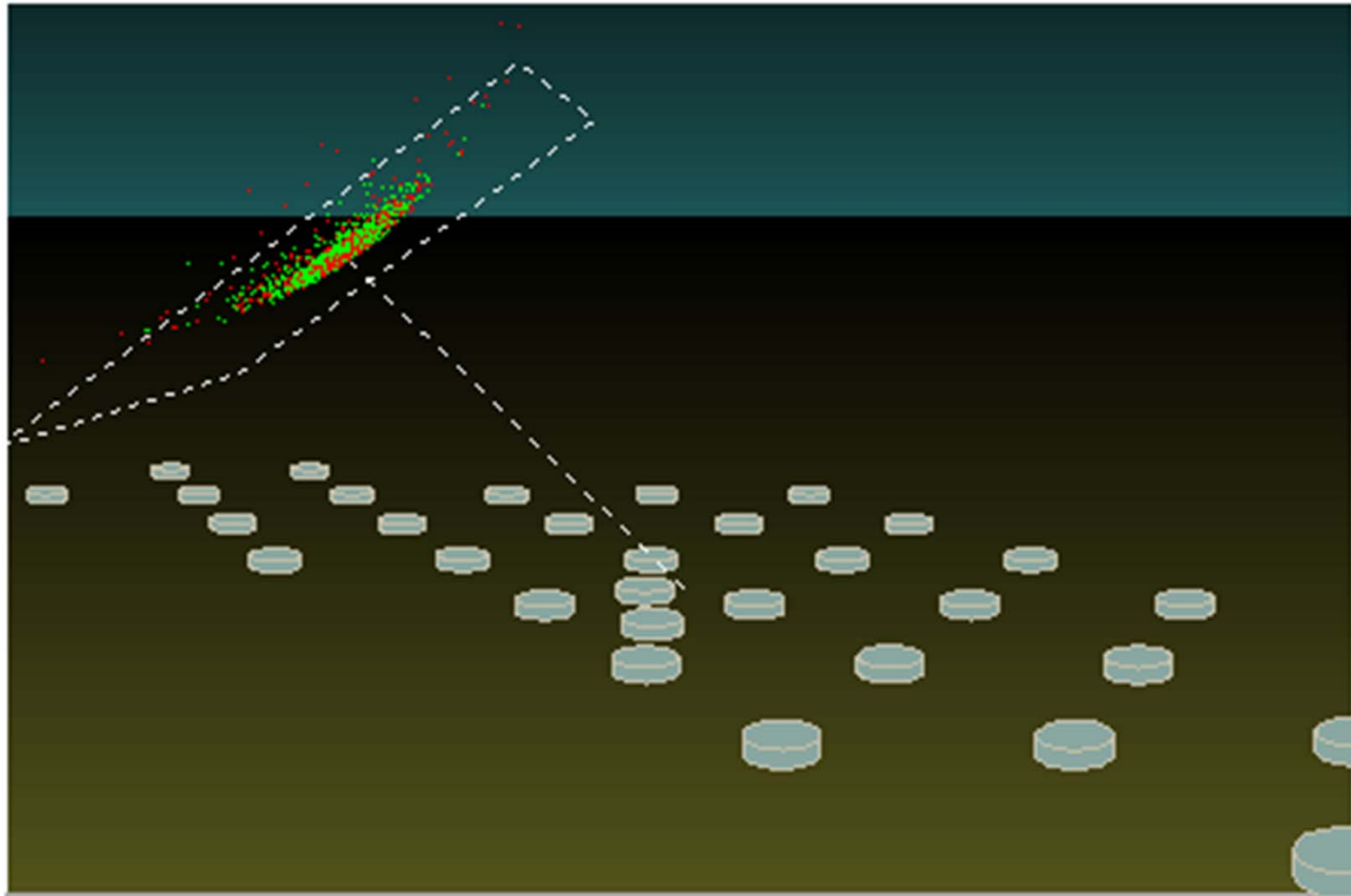
- Example : the Auger Water Cherenkov Tanks



Pierre Auger observatory



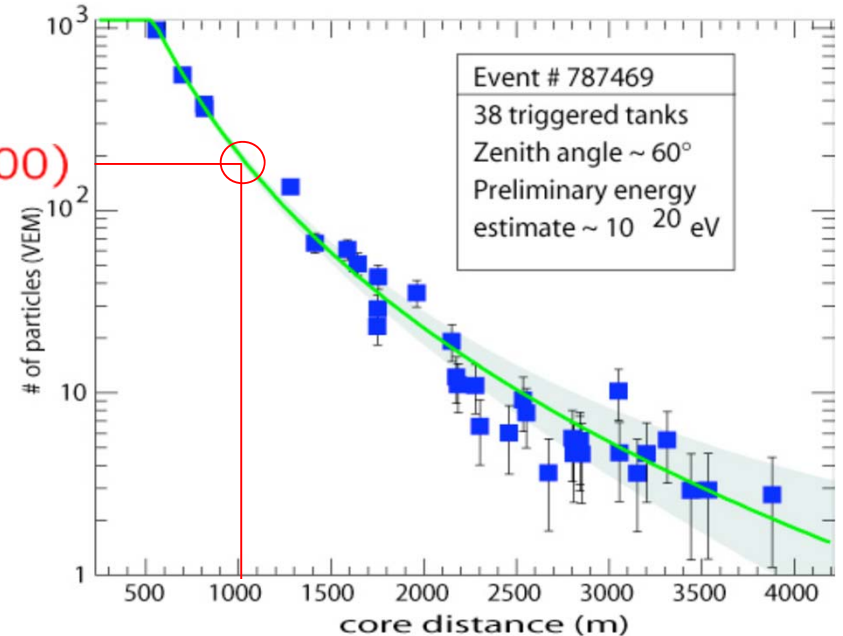
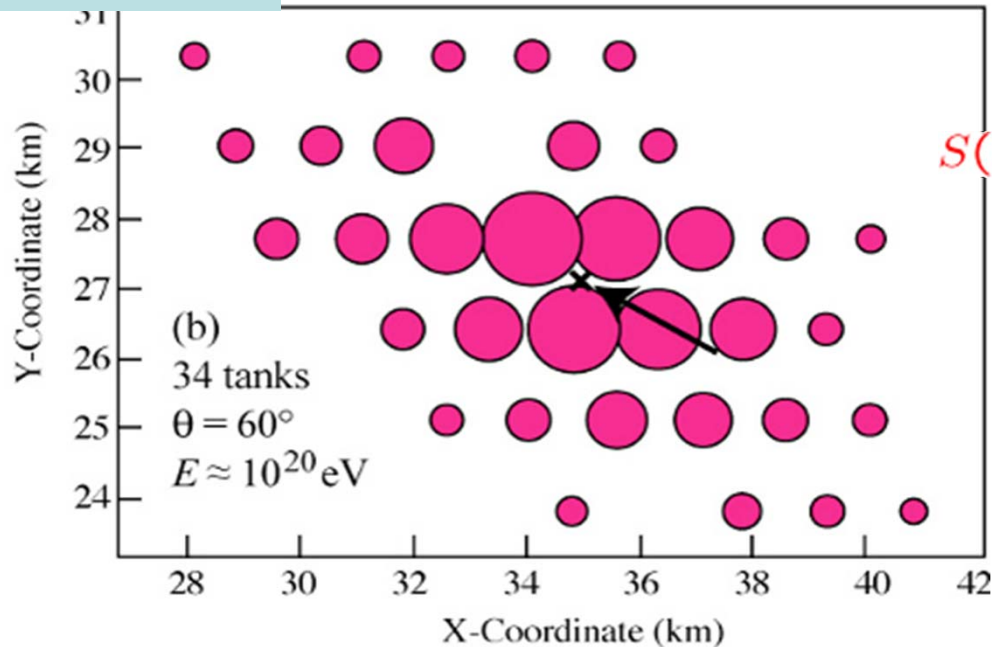
Timing



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. Achievable with GPS + flash ADCs.

From EAS footprint and LDF to primary CR energy estimator

AUGER

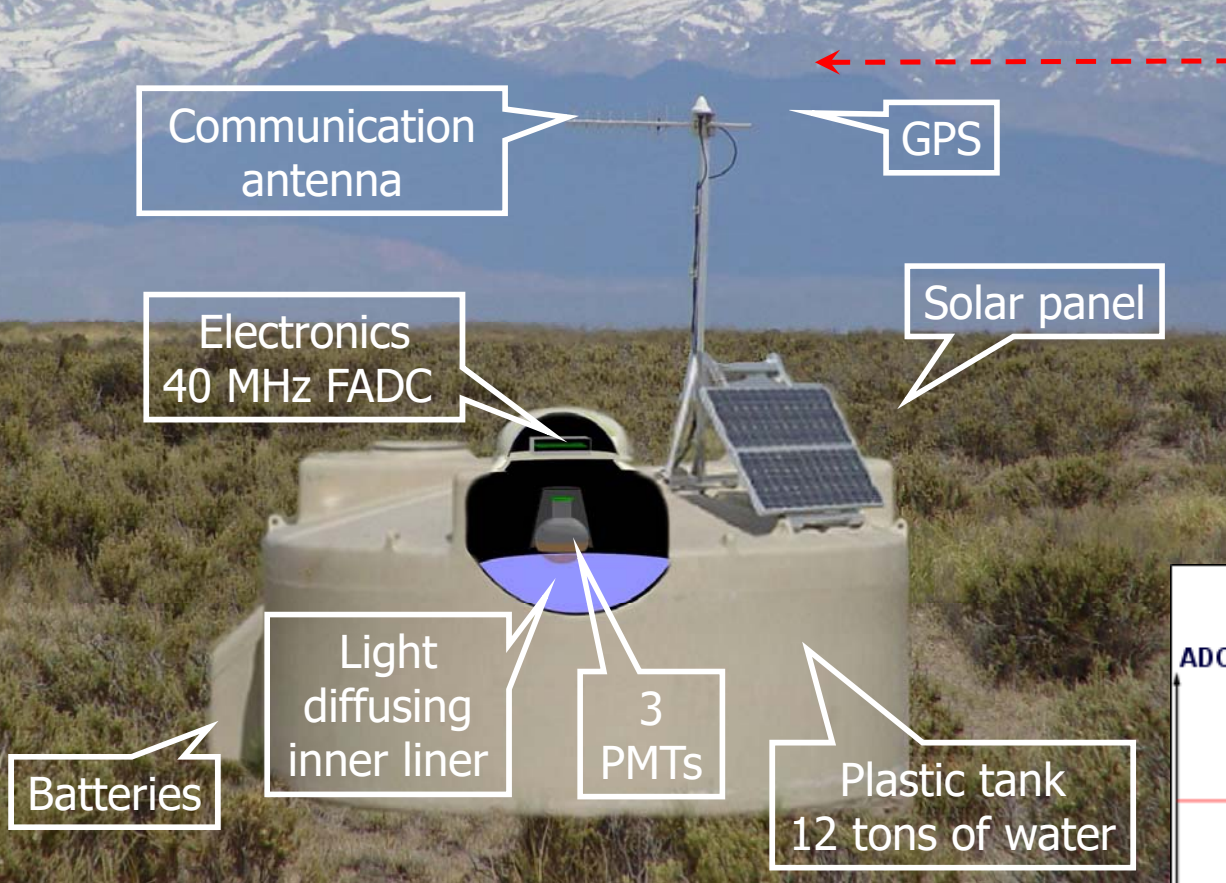


Idea from Hillas 1970 (pioneered by Haverah Park and Agasa)

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

The surface array detectors

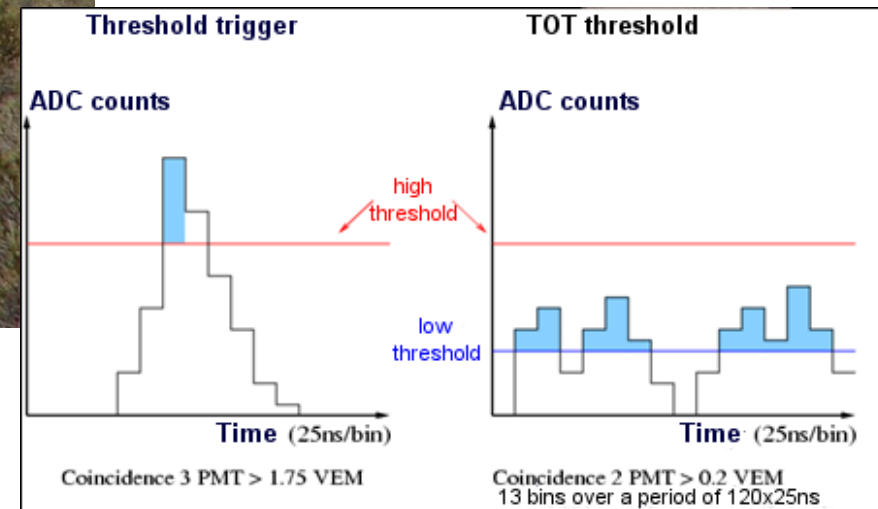
© Montanari-CHDHEAP-ESIPAP 2020



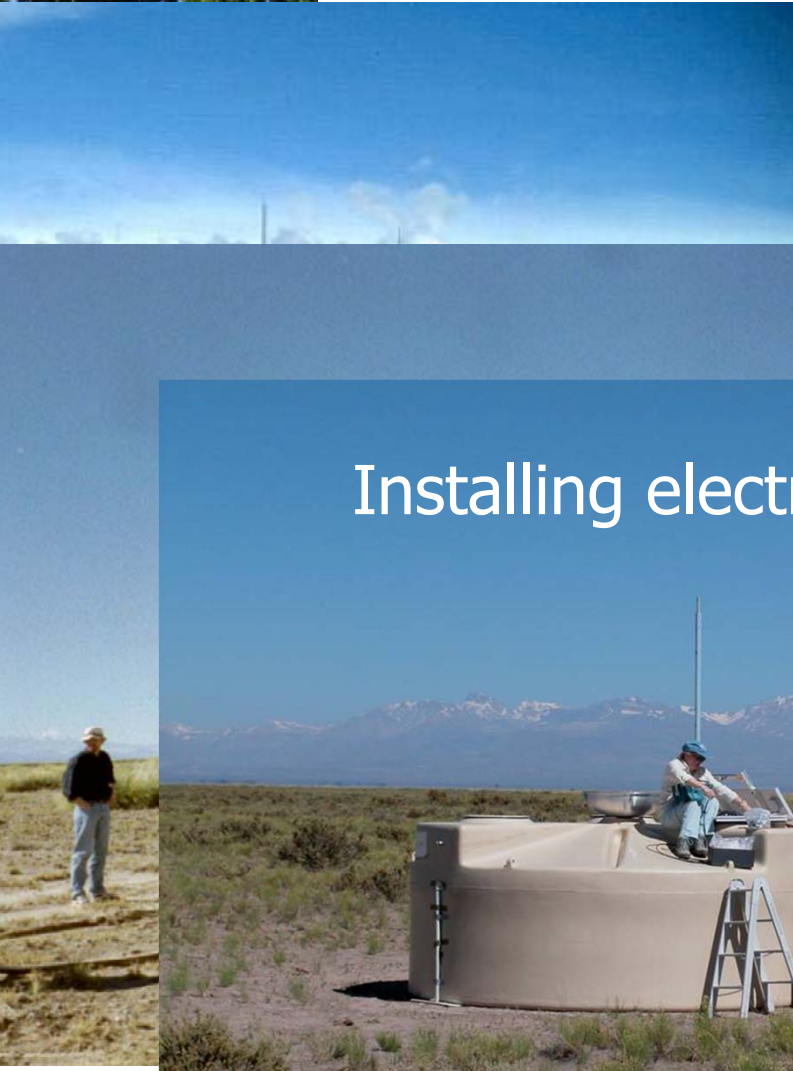
Central DAQ

Local trigger

Self-calibration:
 1 VEM = average signal from vertical through going muons.



Installing the world largest particle detector



Installing electronics

Moving to

W

2020
F. Montanet CIDHEAP ESIPAP

~20 t

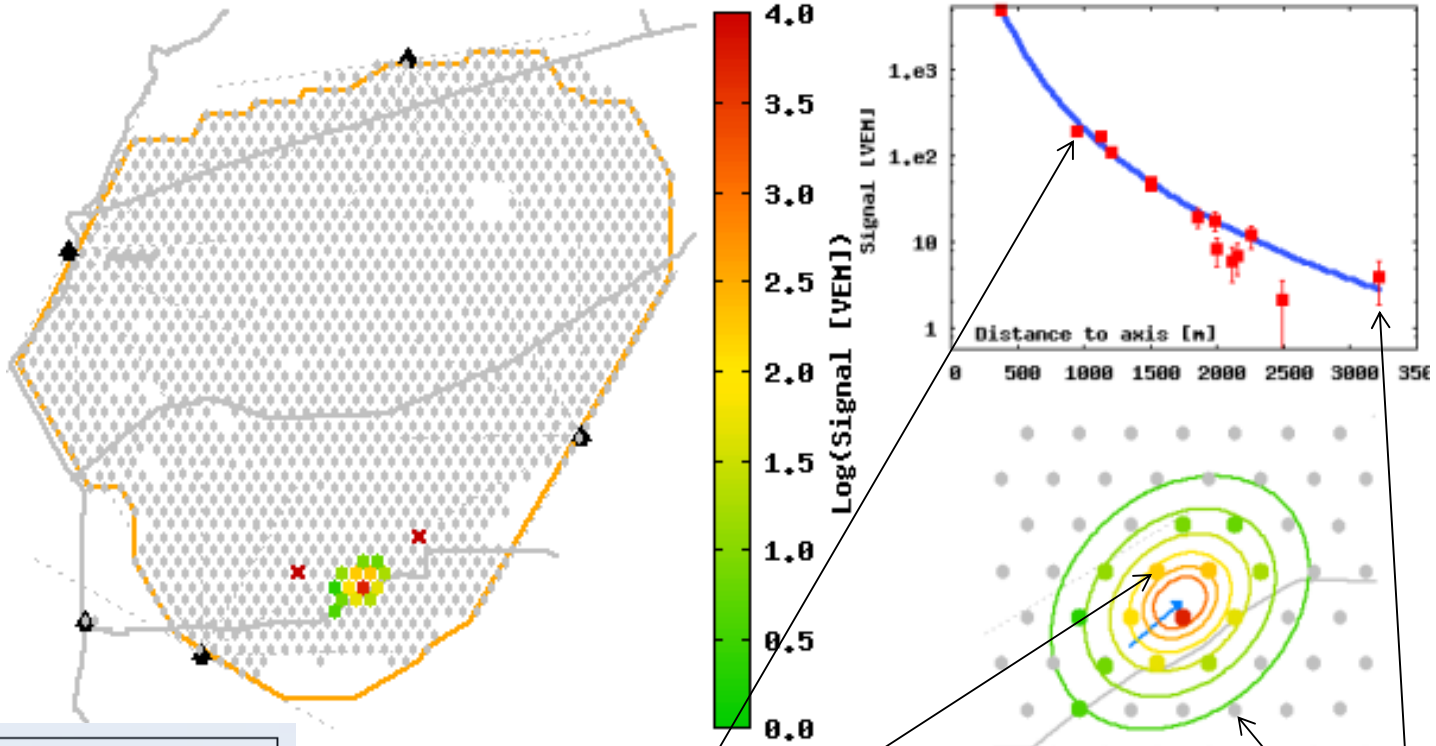
Installing the world largest particle detector



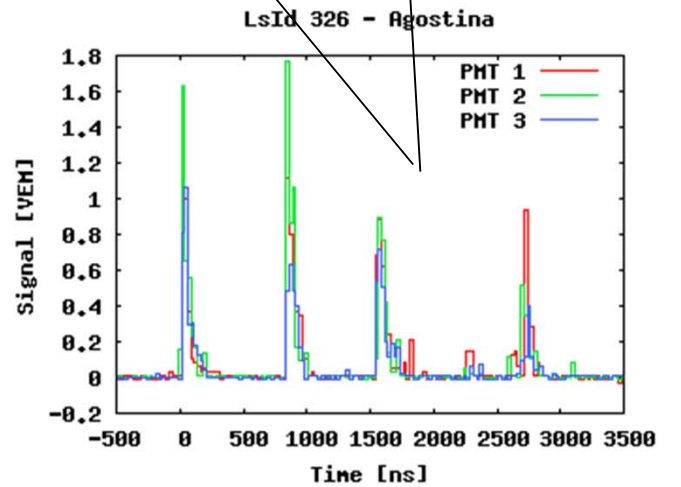
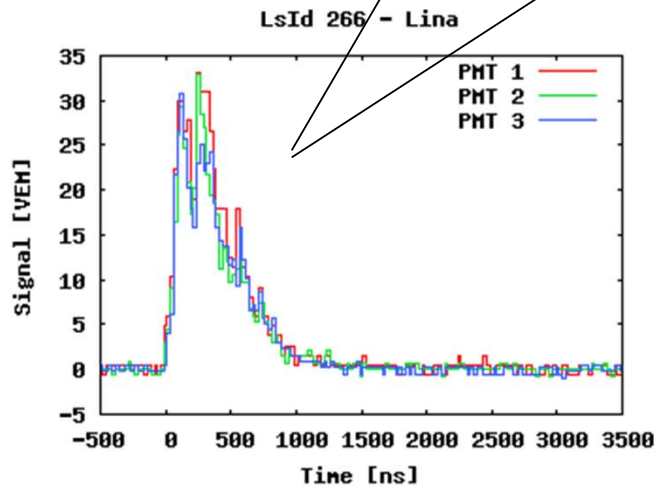
Pierre Auger Observatory surface detectors



UHECR event

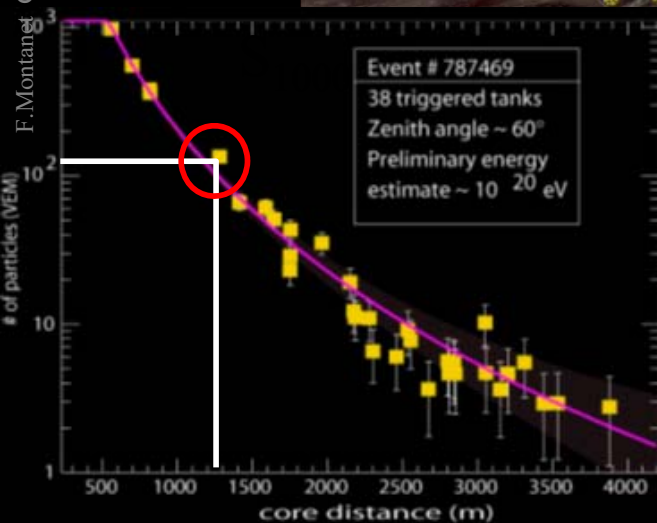
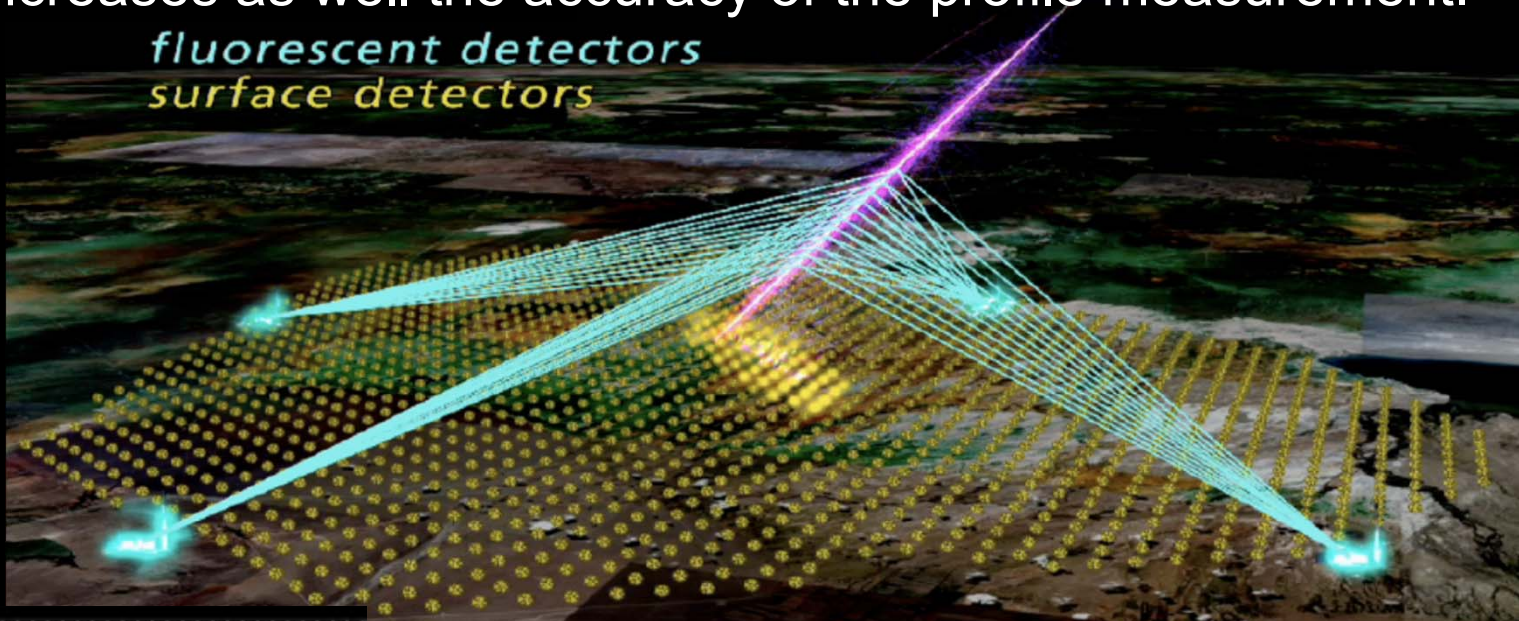


Generic Information	
Id / Date	10485600 / Tue Oct 26 17:39:16 2010
Nb. of stations	14
Energy	49.7 ± 1.9 EeV
Theta	40.2 ± 0.2 deg
Phi	-139.2 ± 0.2 deg
Curvature	10.9 ± 0.5 km
Core Easting	476053 ± 19 m
Core Northing	6079248 ± 12 m
Reduced χ^2	8.36

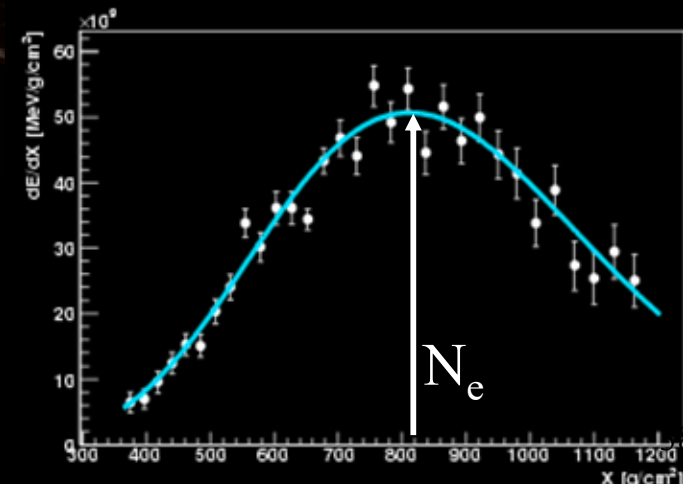


From EAS longitudinal profile to primary CR energy

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



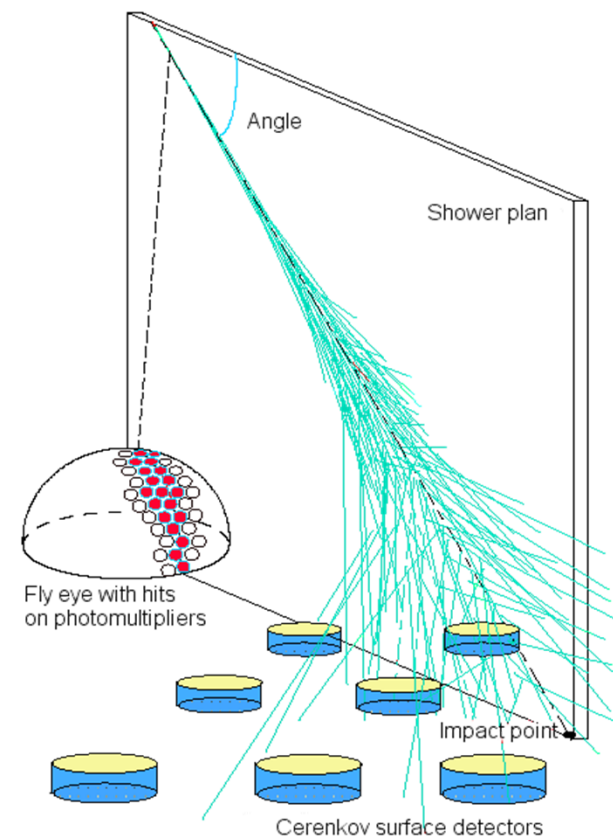
PROGRESS:
Calibration of SD energy estimator through FD



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.

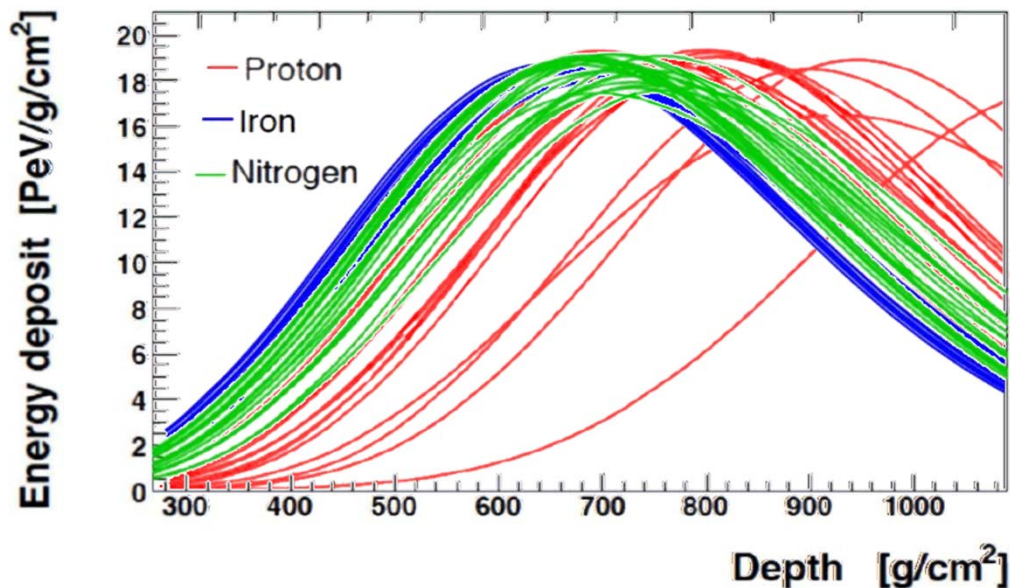
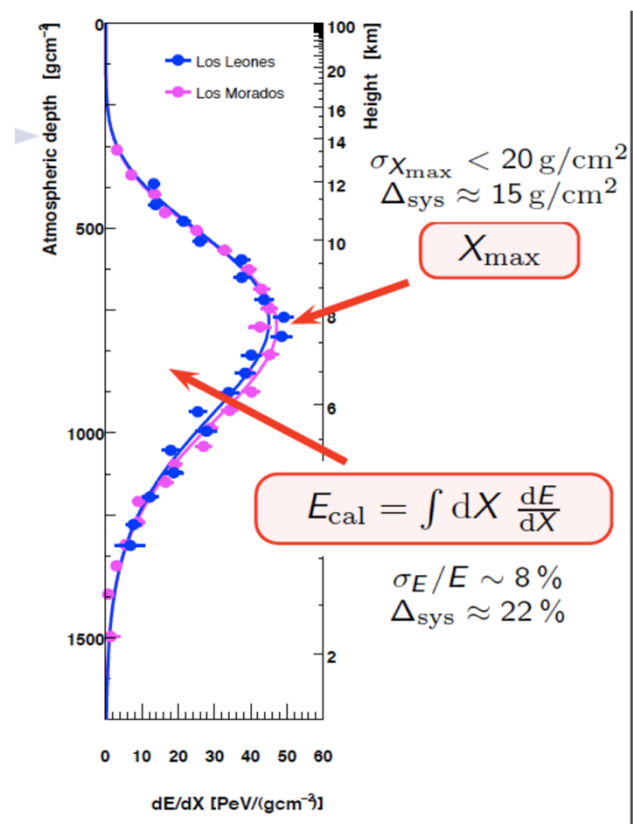


From EAS longitudinal profile to primary CR mass composition

Average depth of shower maximum $\langle X_{\max} \rangle$;

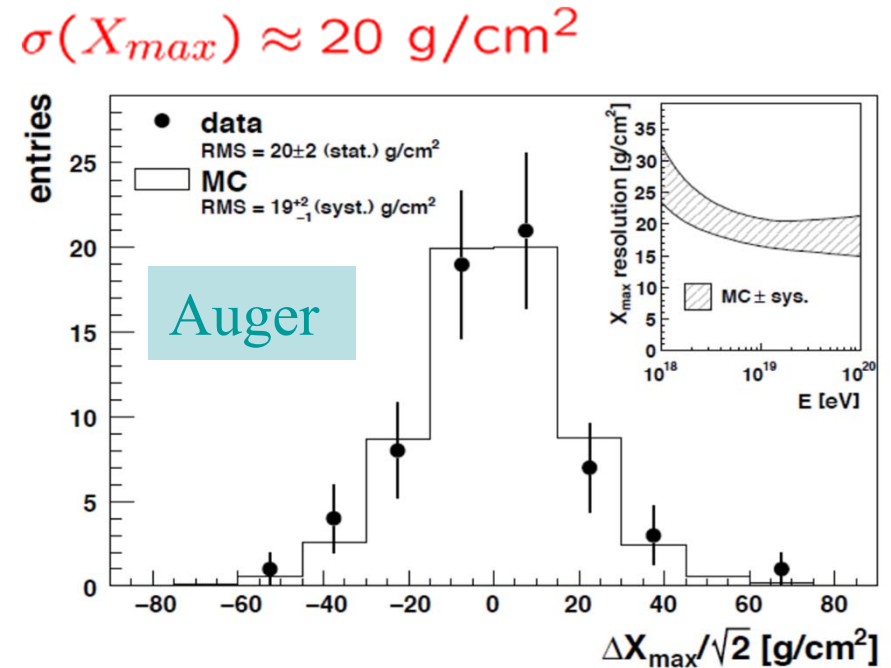
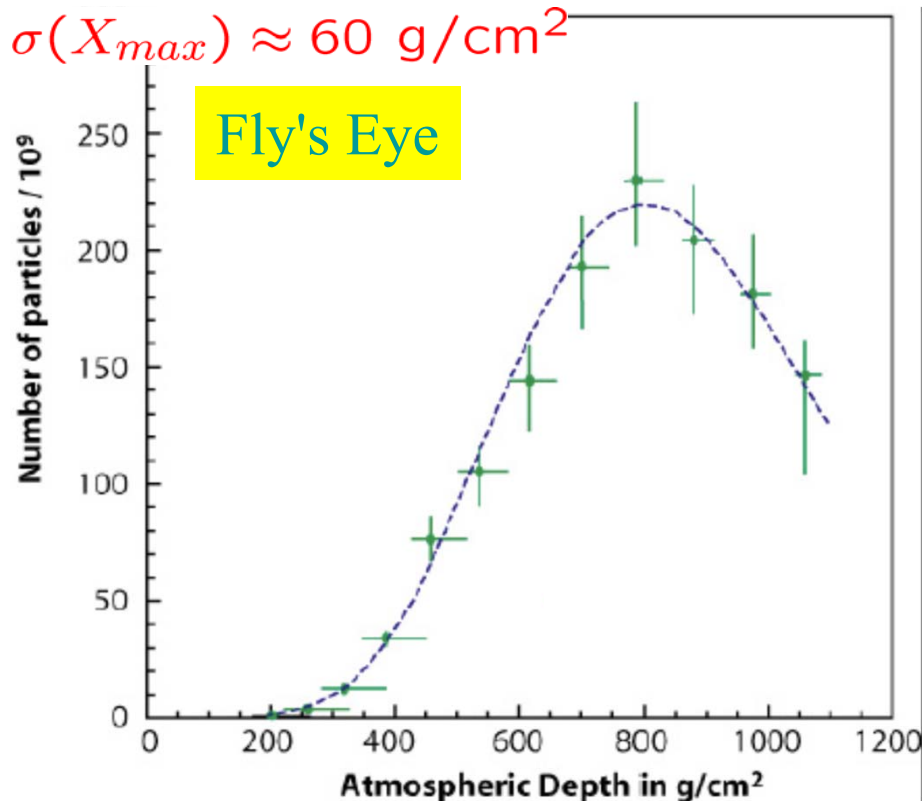
Width of distribution $\text{RMS}(X_{\max})$ at a certain E

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

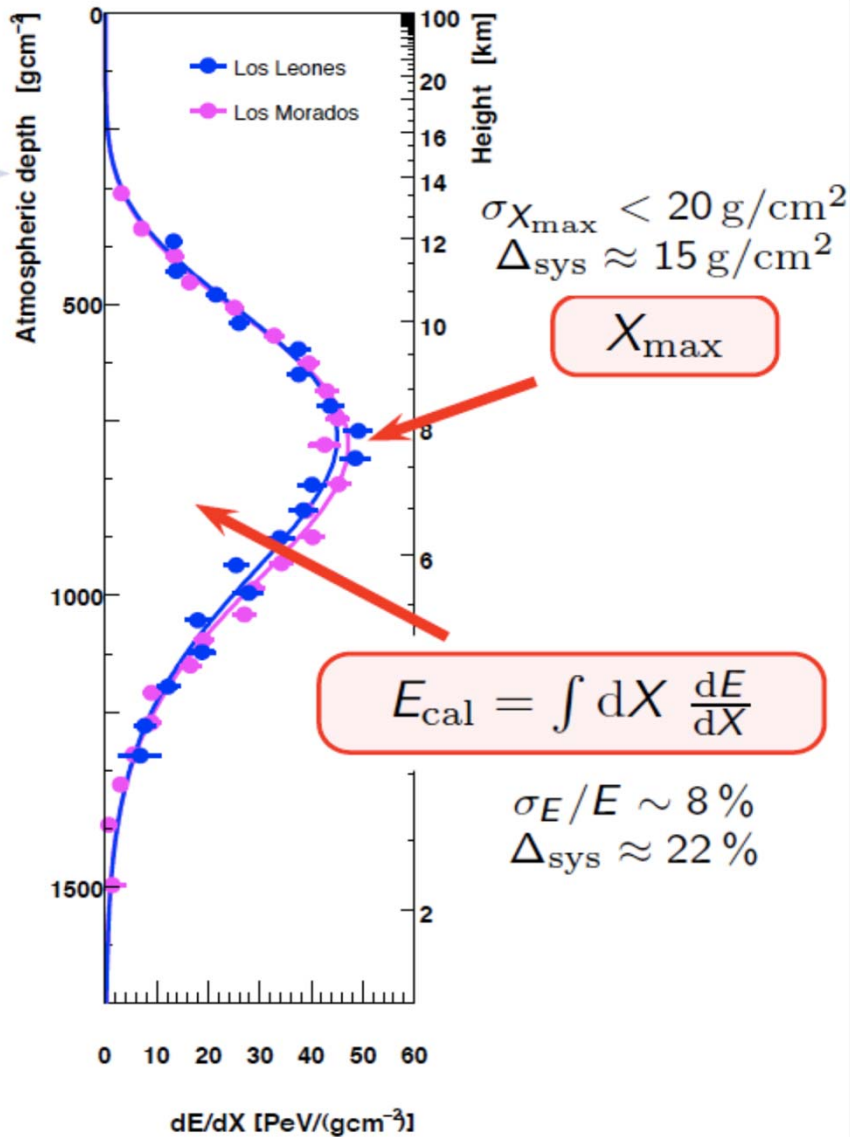
High precision now possible through higher resolution + stereo and hybrid measurements (around $20\text{-}25 \text{ g/cm}^2$)

N.B. : $\langle X_{max} \rangle_{proton} - \langle X_{max} \rangle_{iron} \approx 150 \text{ g/cm}^2$

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



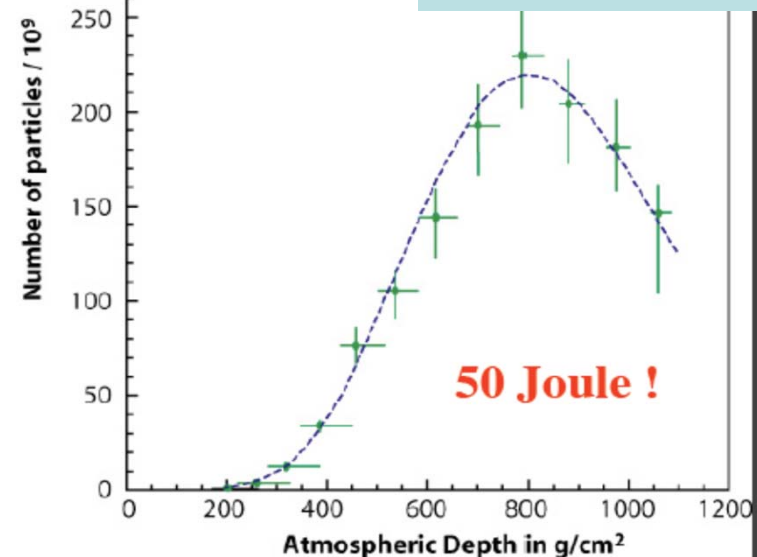
PROGRESS:

Calorimetric measurement of E with :

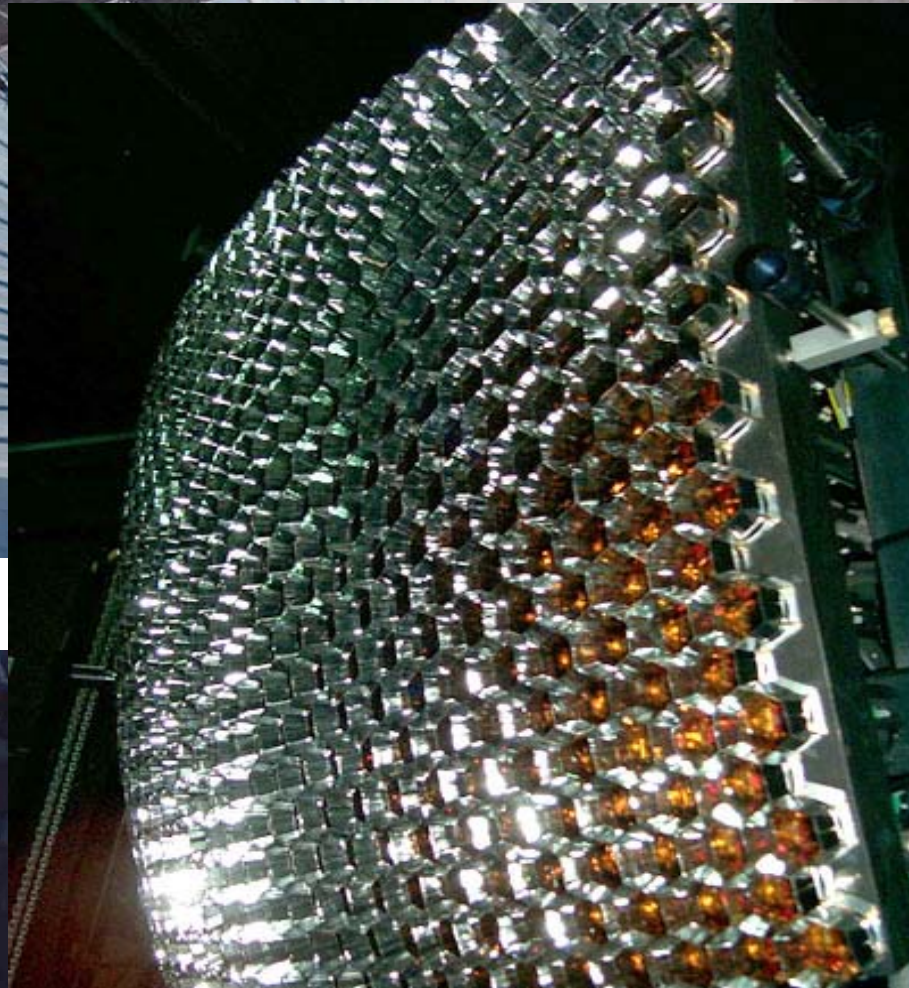
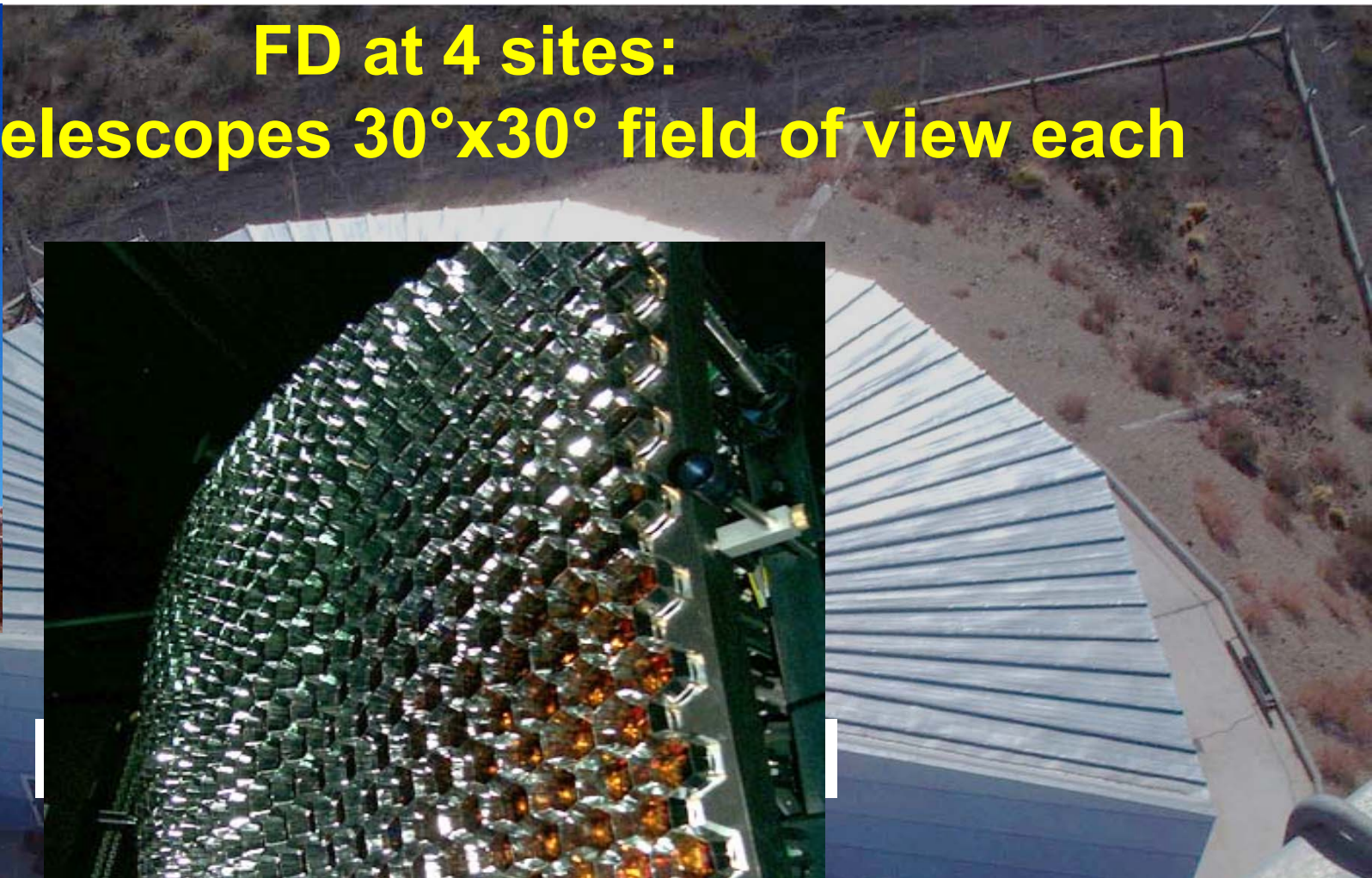
- Fluorescence technique
- Validated by Fly's Eye
- Largest uncertainty: fluorescence yield,
- Atmosphere, "missing" energy
- No hadronic model dependence

Fly's Eye

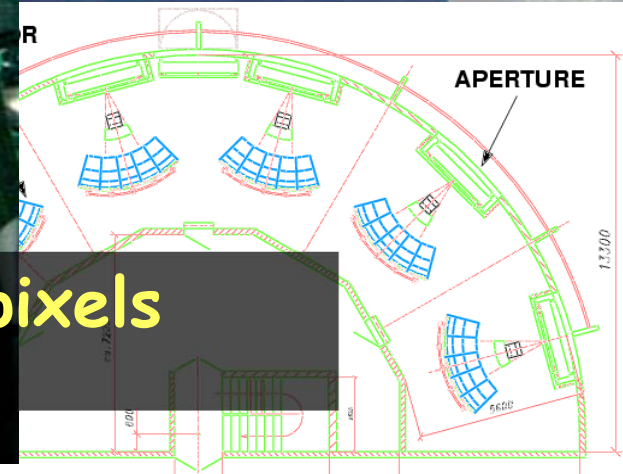
300 EeV
E resolution $\approx 25\%$



**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



Pierre Auger Observatory fluorescence detectors

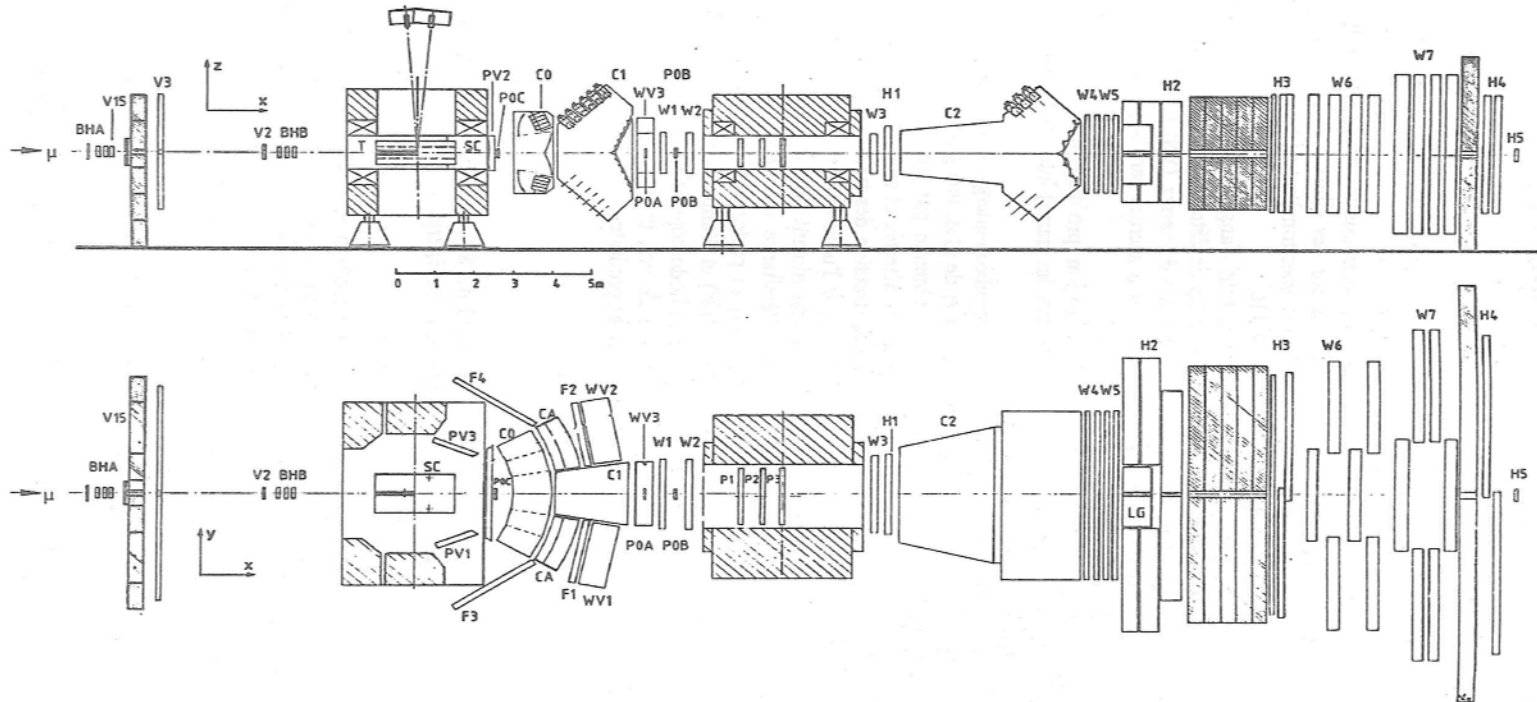


IDENTIFYING PARTICLES

MEASURING PARTICLE VELOCITY

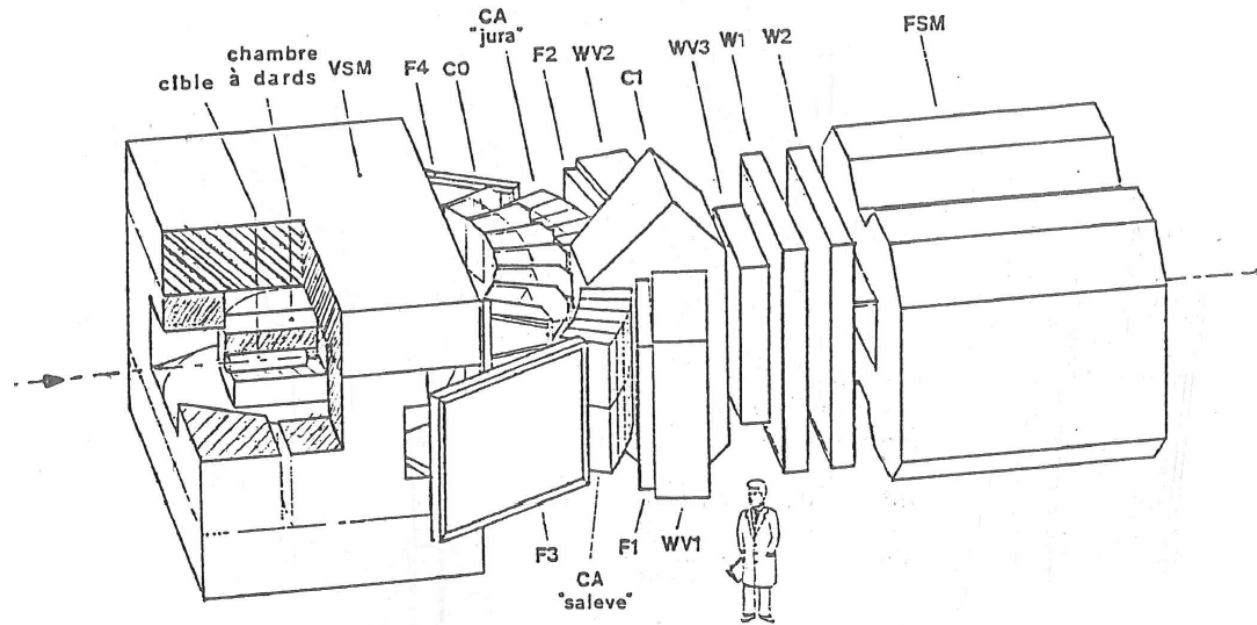
Threshold Cherenkov counters

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

Threshold Cherenkov

- NA9:

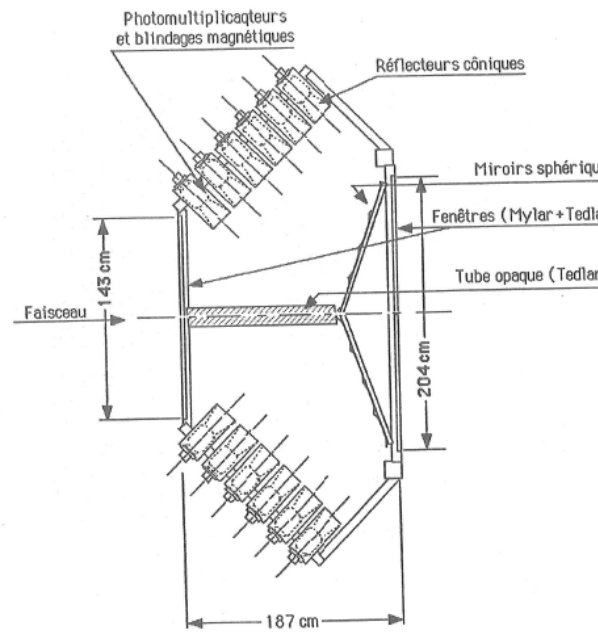
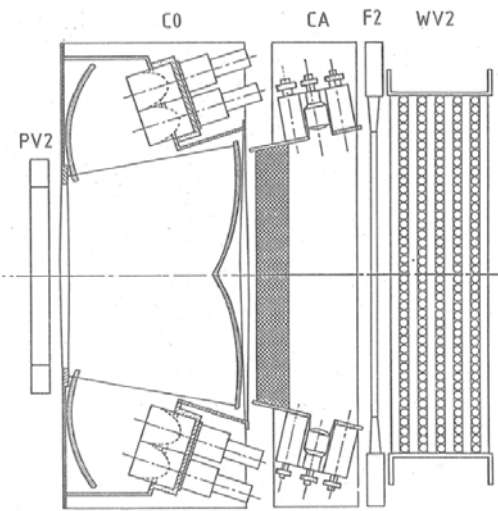


Figure 14: Le compteur Cerenkov C1

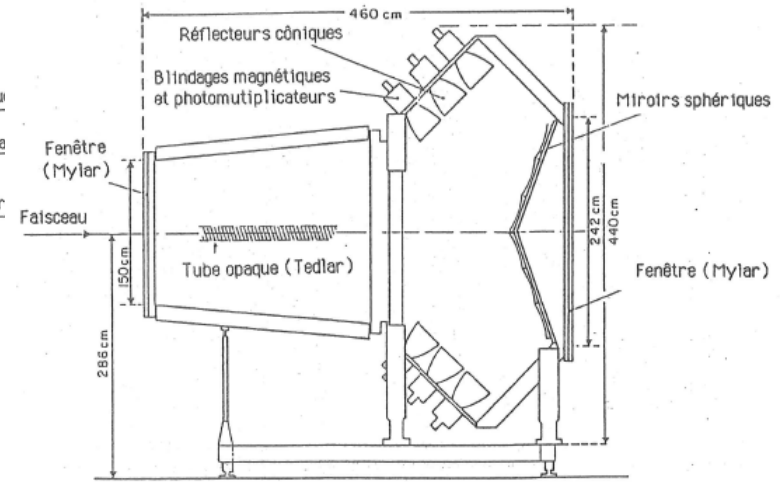


Figure 15: Le compteur Cerenkov C2

Threshold Cherenkov

- NA9:

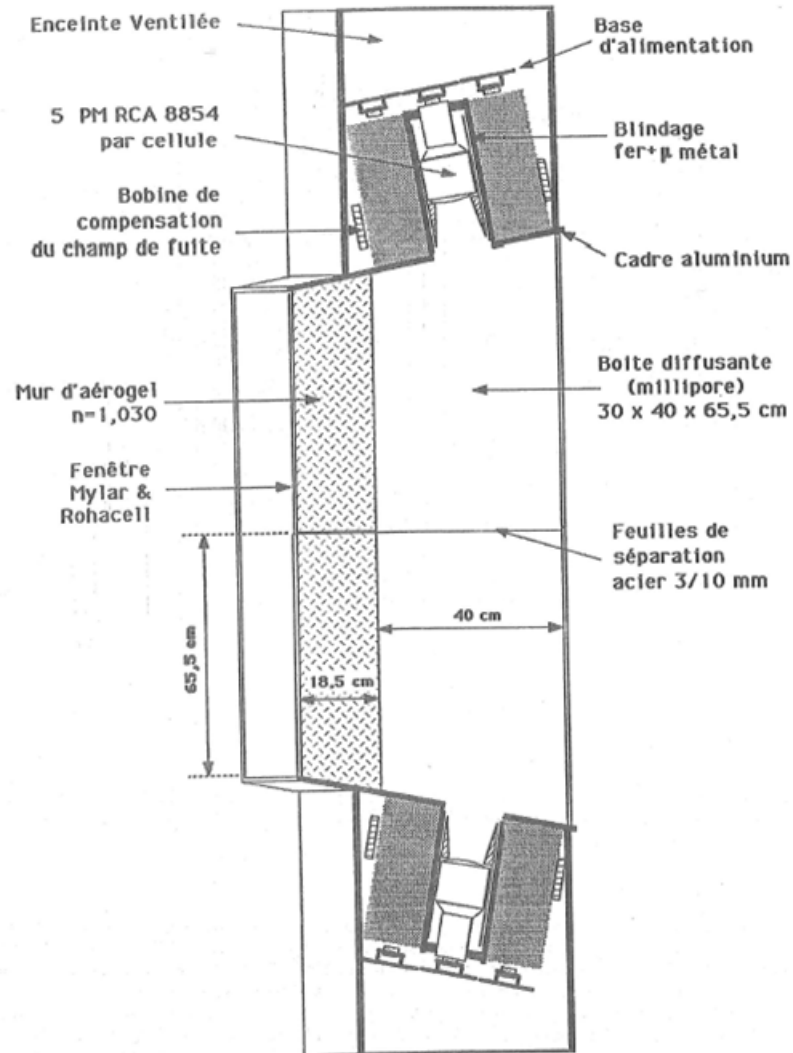
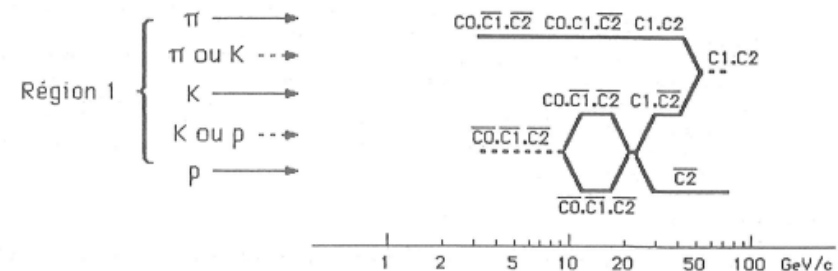
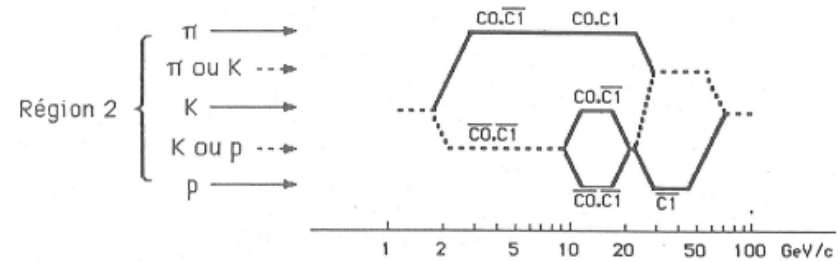
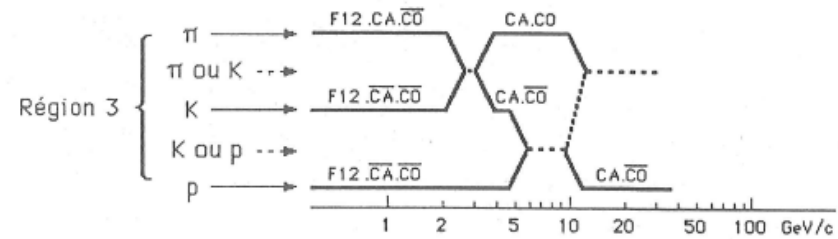
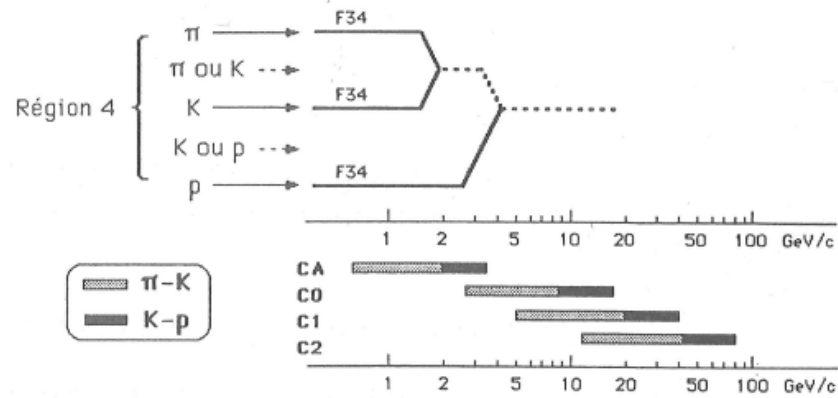


Figure 16: Vue en coupe du compteur Cherenkov à aérogel

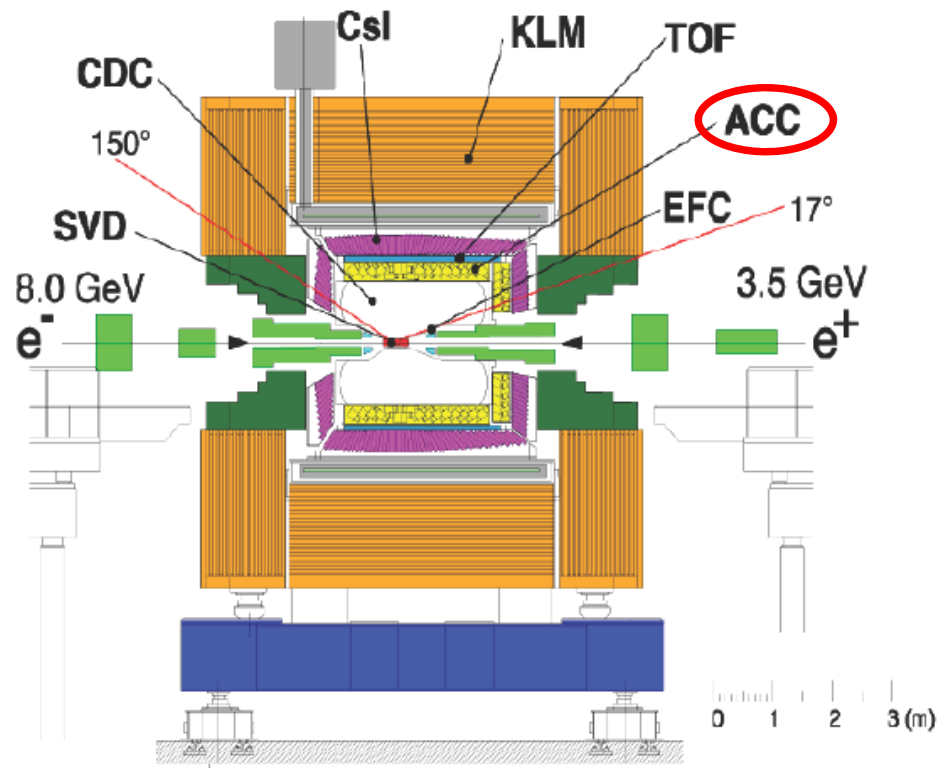
Threshold Cherenkov

- NA9:



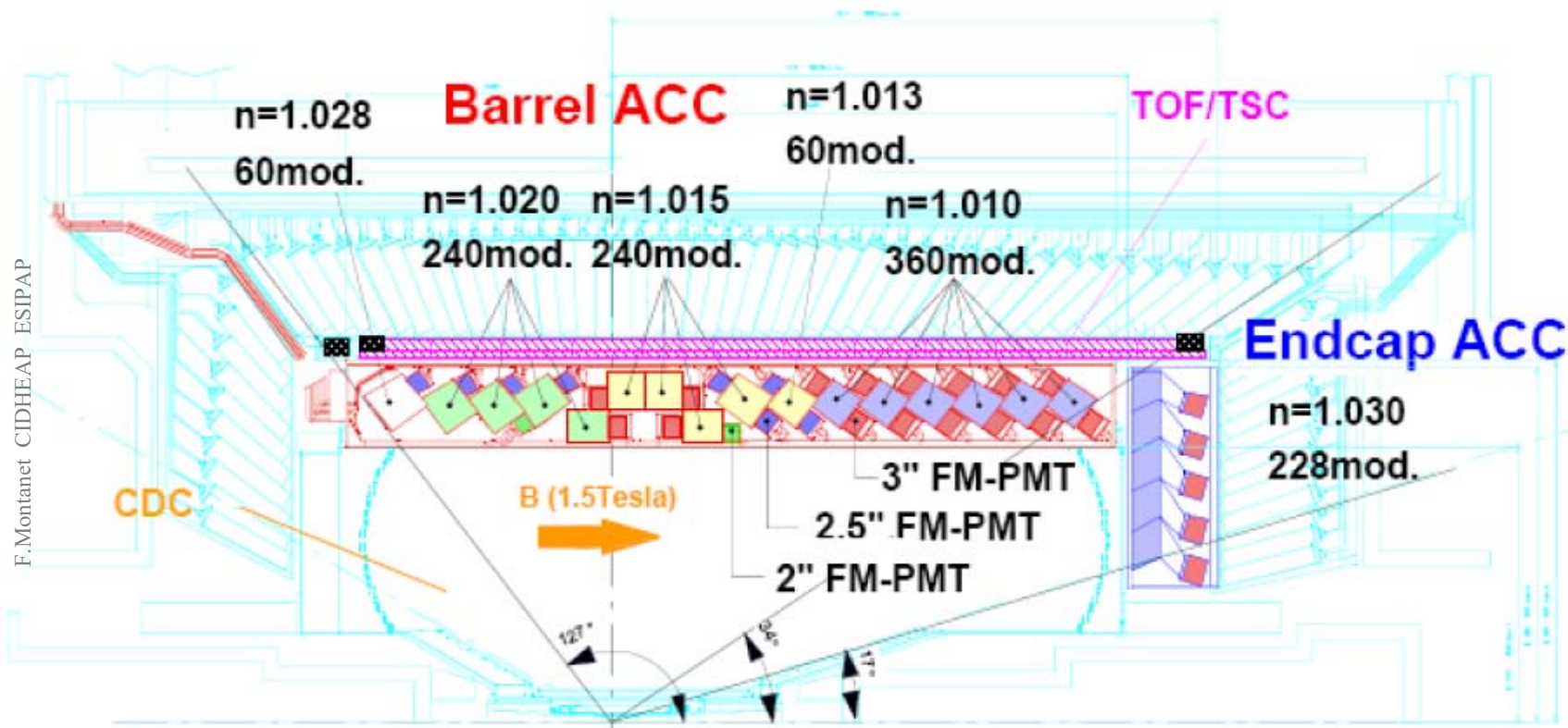
Threshold detectors

- 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 $\frac{1}{4}$ from K



Threshold detectors

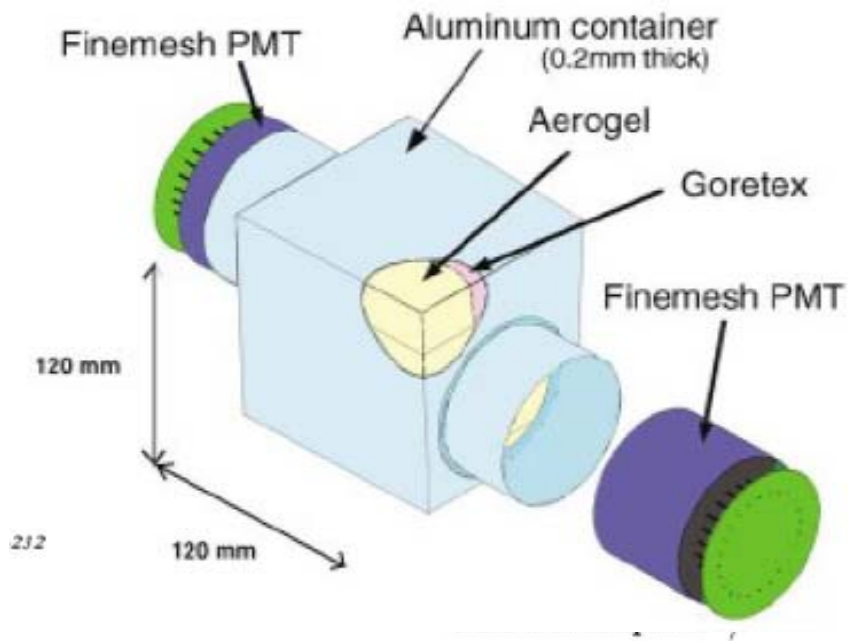
- A more recent example BELLE at KEKB



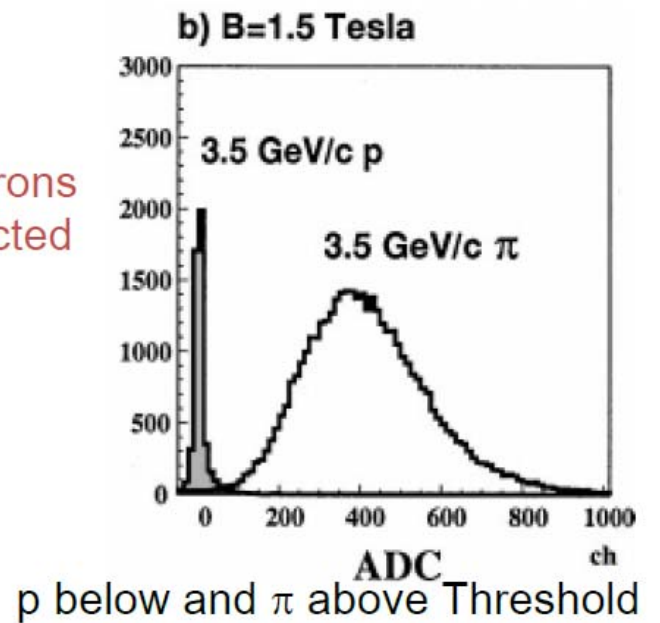
5 aerogel tiles
inside a boxed
lined with
white reflector

Threshold detectors

- A more recent example BELLE at KEKB



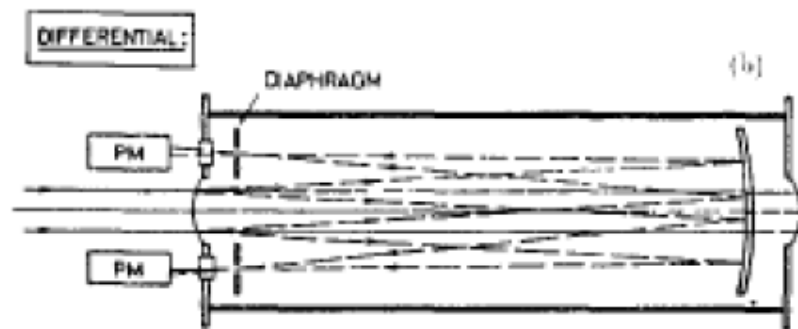
- Approx . 20 photoelectrons per Pion detected at 3.5 GeV/c
- More than 3σ separation



IDENTIFYING PARTICLES MEASURING THE CHERENKOV ANGLE: DIFFERENTIAL, RICH, DIRC,

Differential Cherenkov Counters

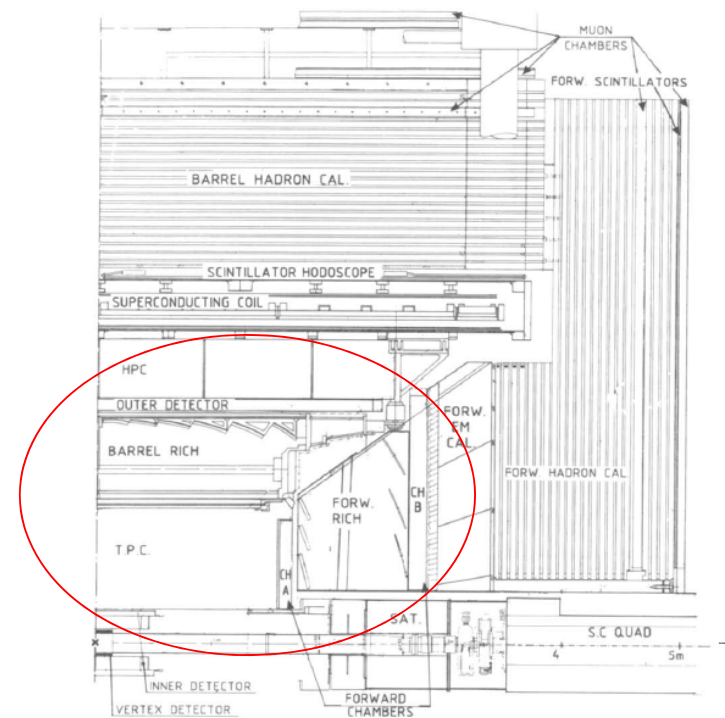
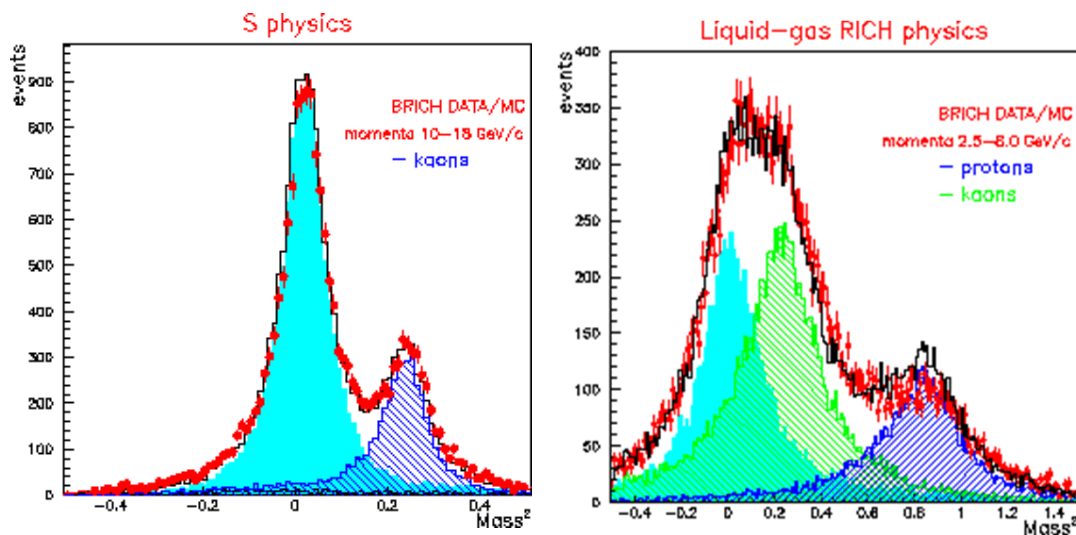
- Used along beam lines to discriminate masses.
- Mesons beams (π^\pm, K^\pm), hyperon beams etc...
- Example: CEDAR at CERN



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

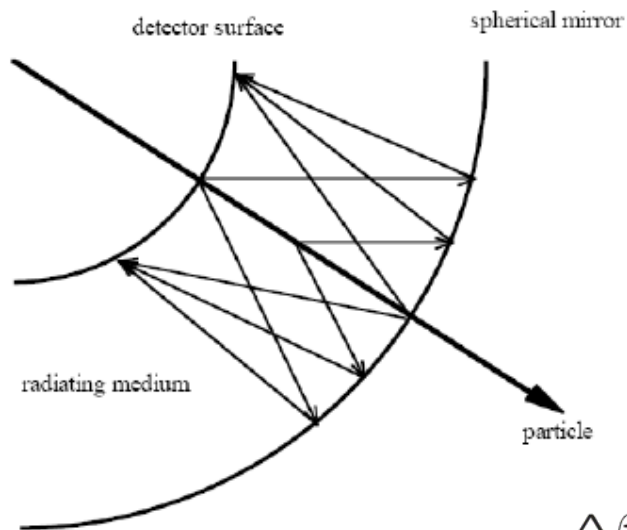
RICH detectors

- 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 μ_C and N_{ph}



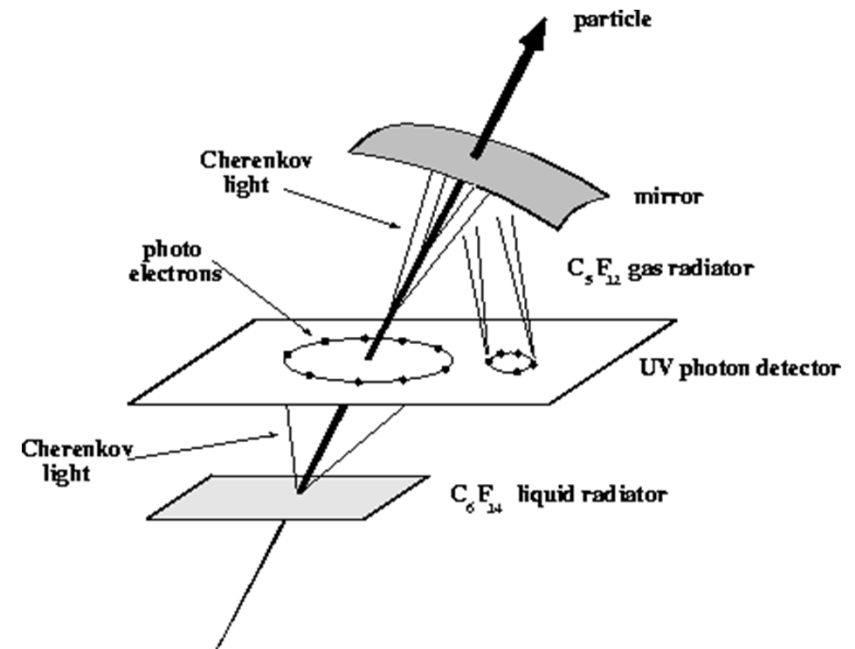
$$\frac{\Delta\beta}{\beta} = \tan(\theta)\Delta\theta_C$$

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

For 1.4m long CF_4 gas radiator at

stp and $N_0 = 75\text{cm}^{-1}$,

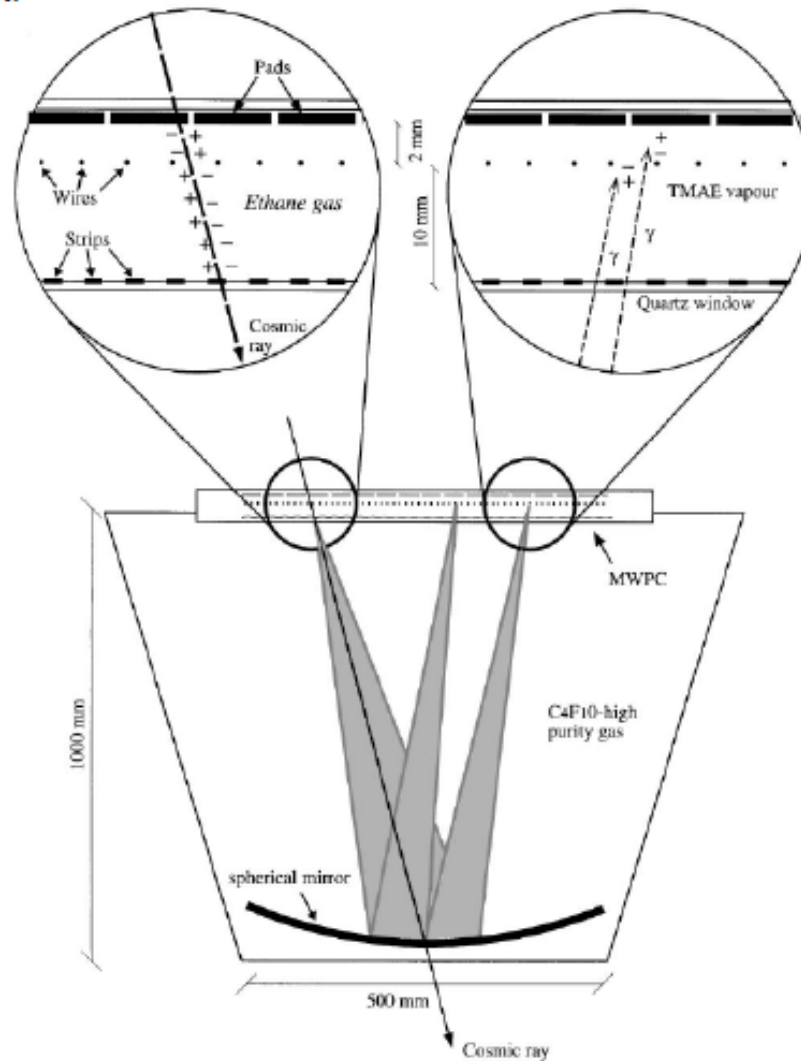
$$\frac{\Delta\beta}{\beta} = 1.6 \cdot 10^{-6}$$



RICH also for astroparticles

Balloon Experiment:
RICH detector

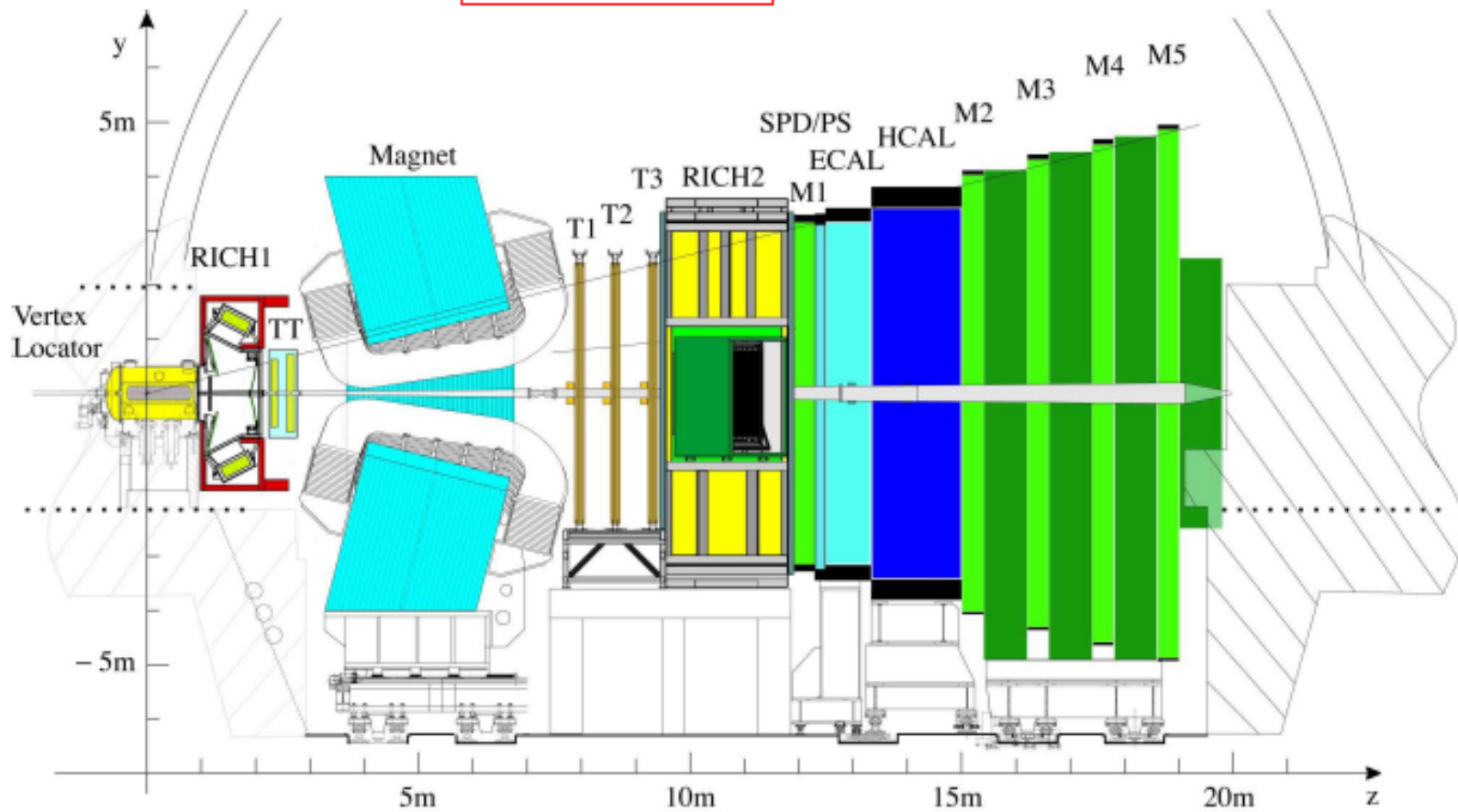
CAPRICE Experiment



TMAE:
(tetrakis(dimethylamino)
ethylene)

LHCb RICH

LHCb Experiment



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

LHCb RICH

LHCb-RICH Design

RICH1: Aerogel L=5cm p:2→10 GeV/c
n=1.03 (nominal at 540 nm)
C₄F₁₀ 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)

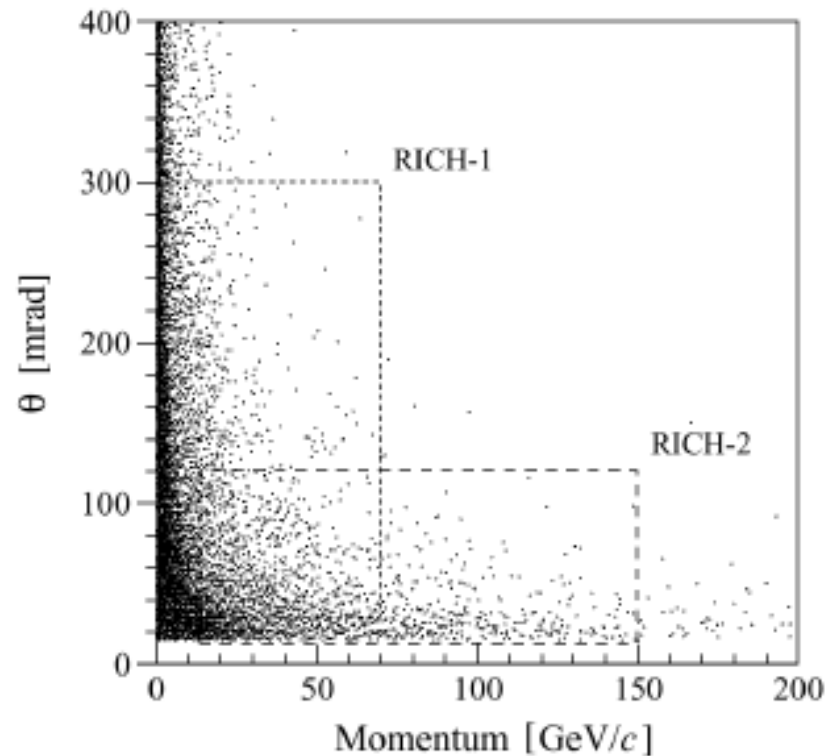
Gas vessel: 2 X 3 X 1 m³

RICH2: CF₄ 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)

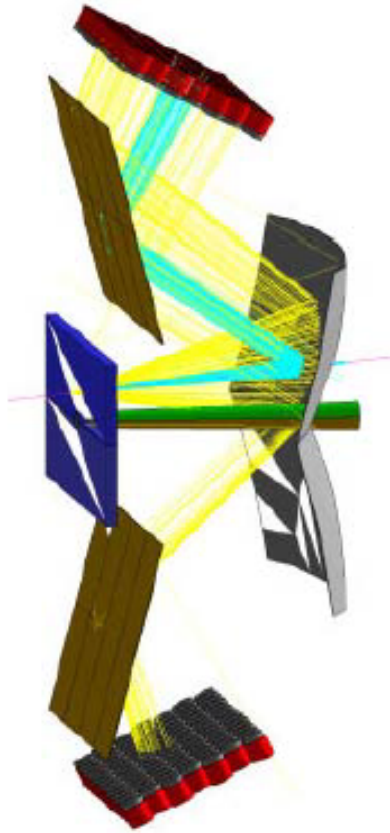
Gas vessel : 100 m³



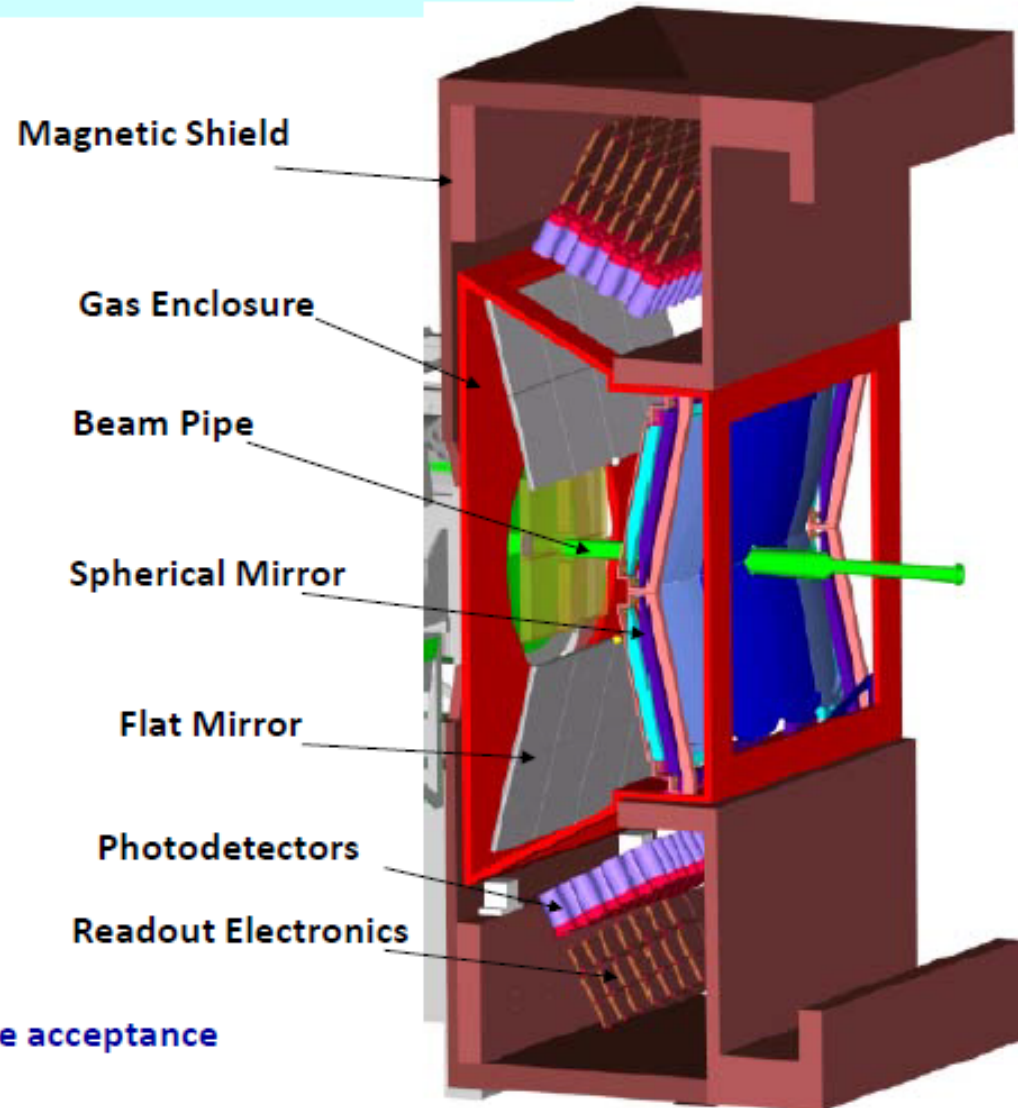
LHCb RICH

LHCb- RICH1 SCHEMATIC

RICH1 OPTICS



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



LHCb RICH

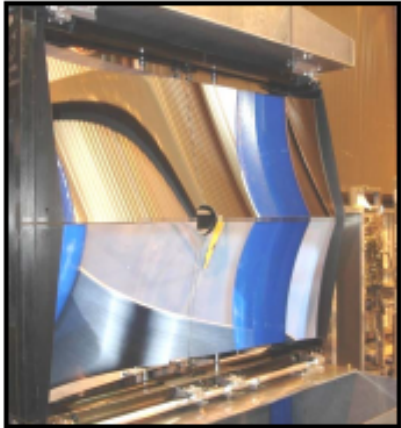
RICH1 Photos



RICH1-HPDs

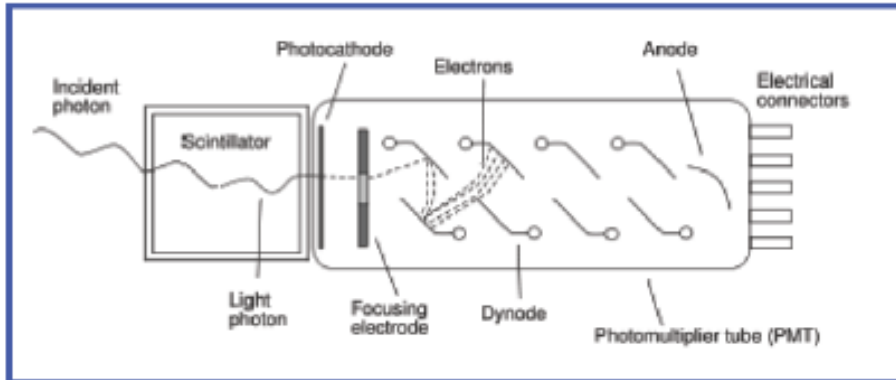


RICH1 mirrors



LHCb RICH

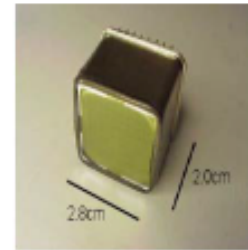
Vacuum Based Photodetectors



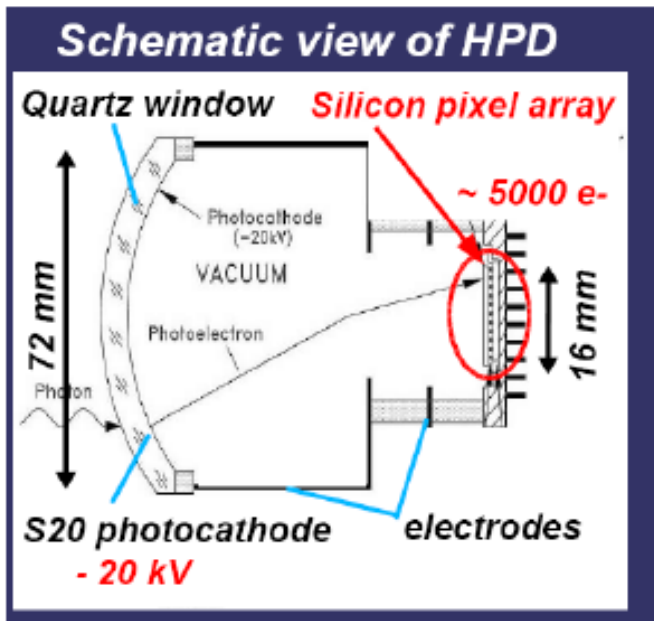
Schematic of a photomultiplier tube coupled to a [scintillator](#).



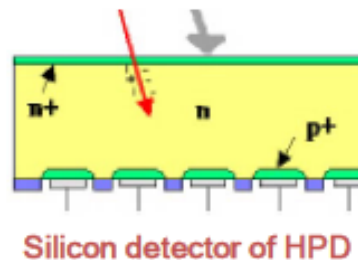
PMTs



MAPMT



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

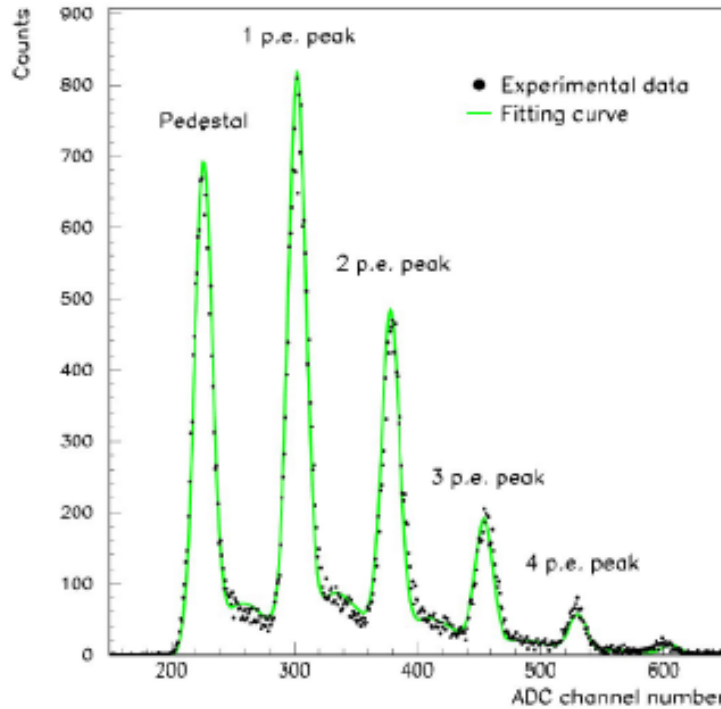


HPD

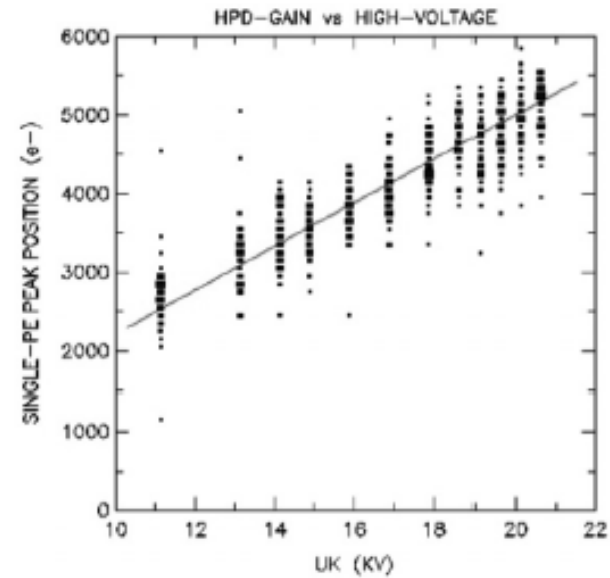
28

LHCb RICH

Features of HPD



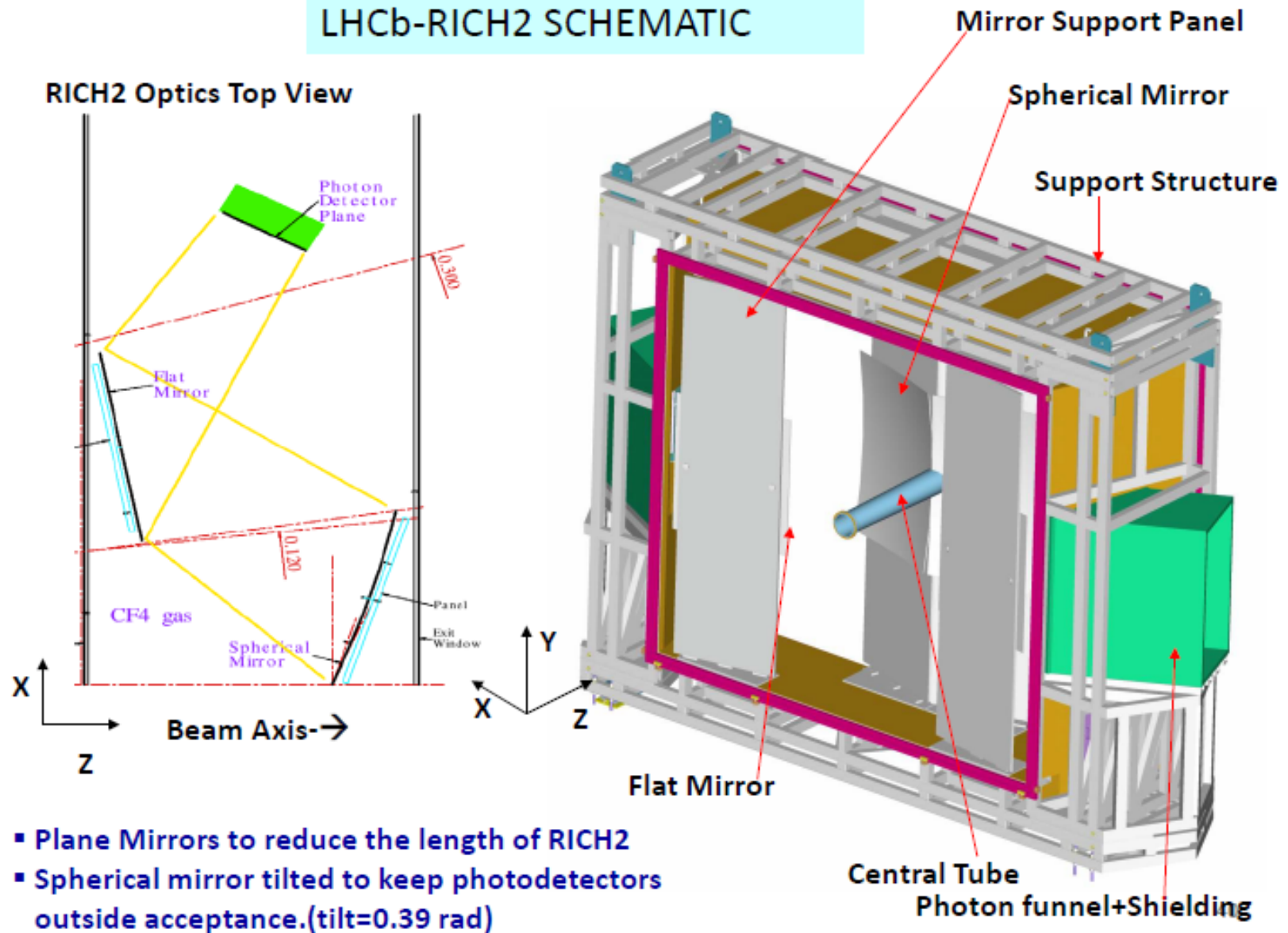
Signal pulse height spectrum of a 61-pixel HPD
Illuminated with Cherenkov photons



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

LHCb RICH

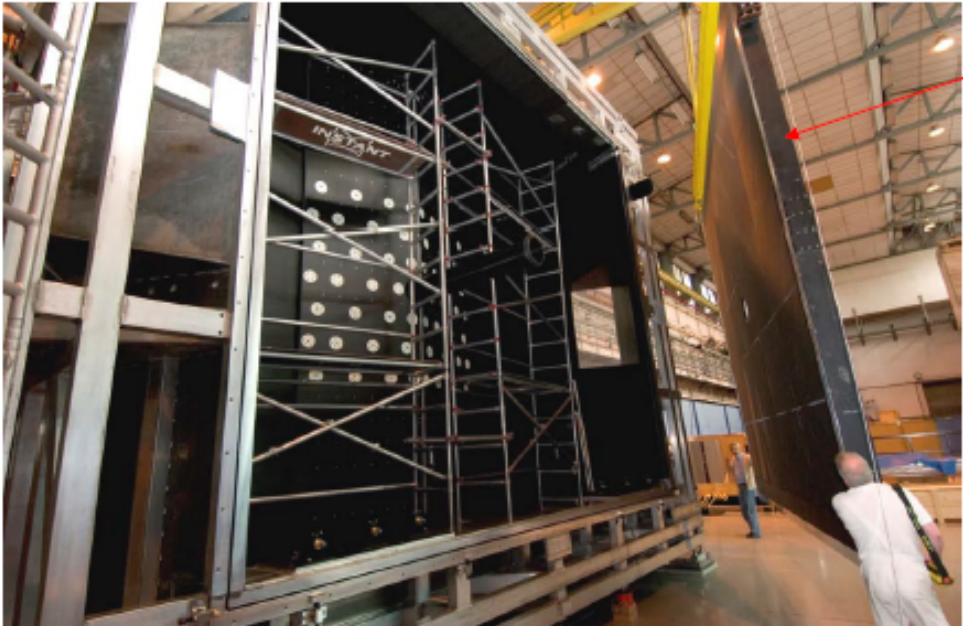
LHCb-RICH2 SCHEMATIC



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

LHCb RICH

LHCb- RICH2 STRUCTURE



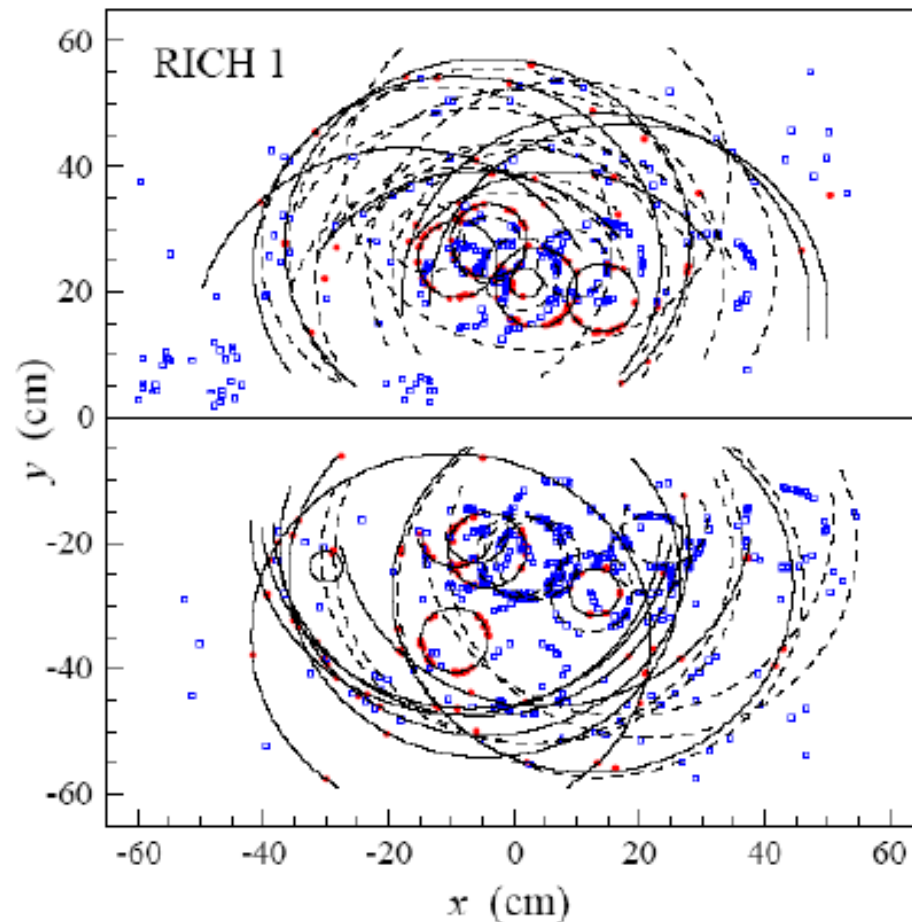
Entrance Window
(PMI foam between two
carbon fibre epoxy Skins)



RICH2

LHCb RICH

LHCb: Hits on the RICH from Simulation



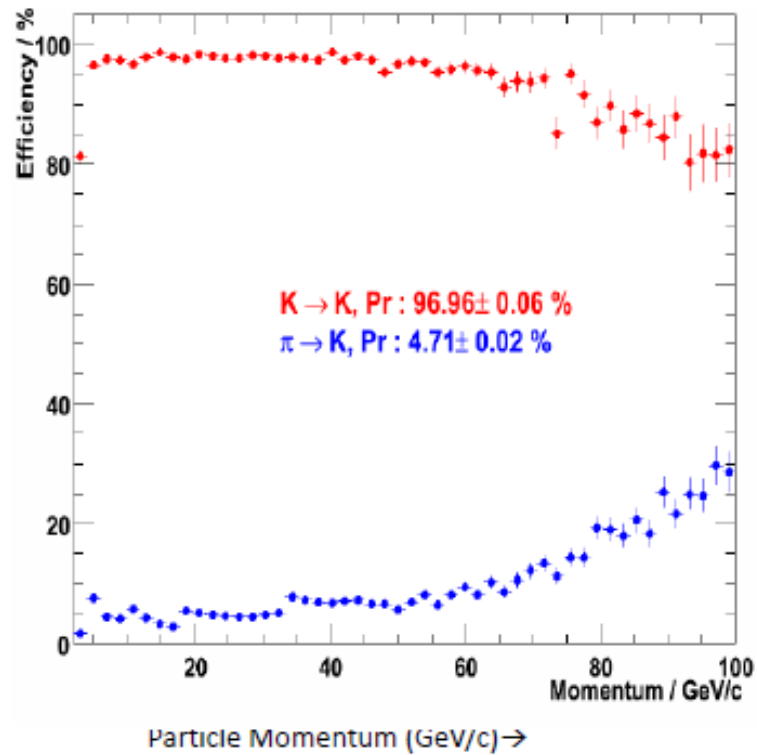
Red: From particles from Primary and Secondary Vertex

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

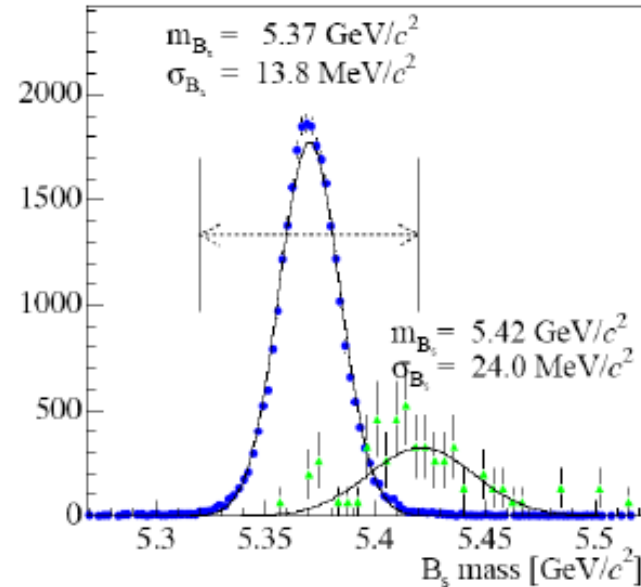
LHCb RICH

LHCb-RICH pattern recognition

Efficiency for identification and probability for misidentification vs Particle momentum



From simulations



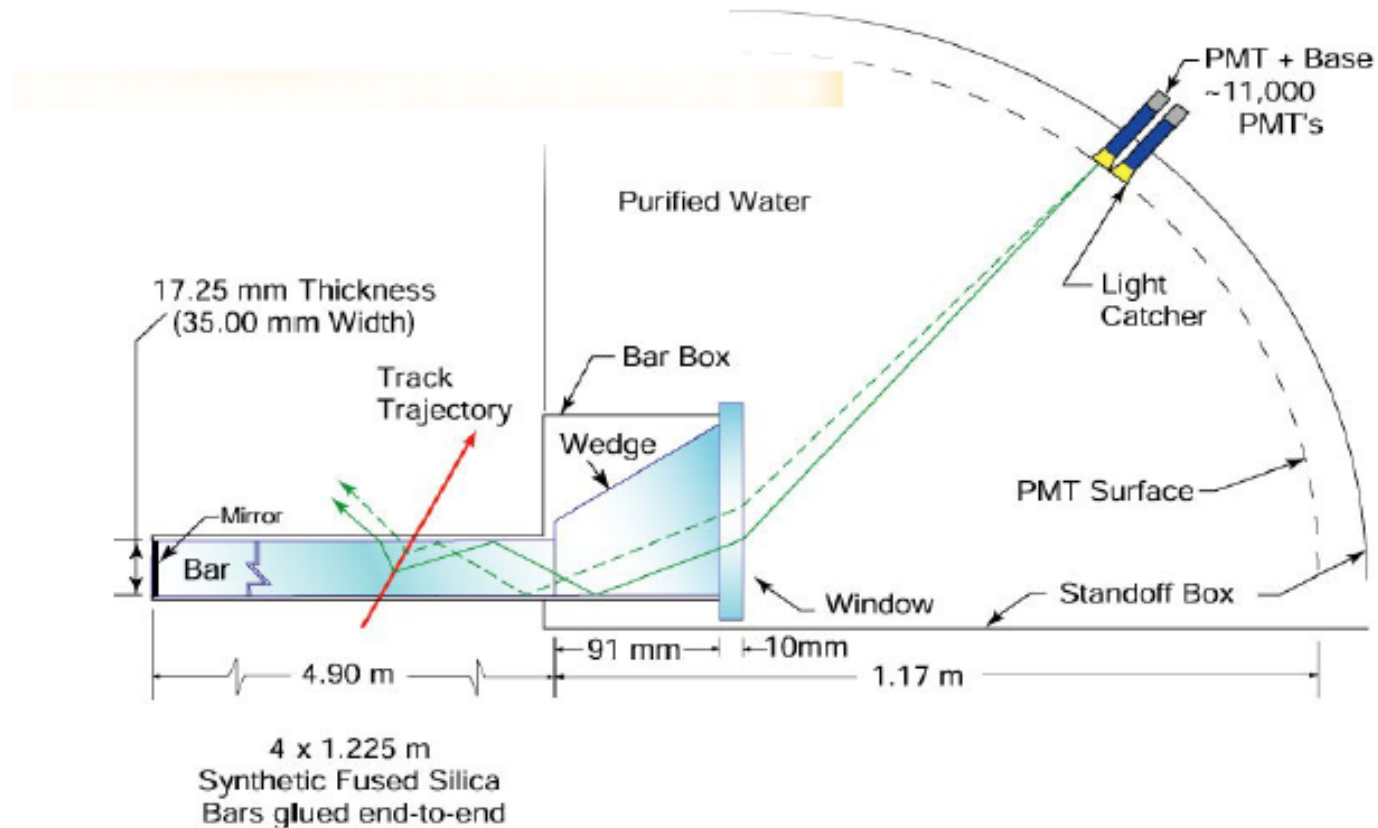
$B_s^0 \rightarrow D_s^- K^+$ $B_s^0 \rightarrow D_s^- \pi^+$

(signal) (background)

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

A strange idea: the DIRC

- Detector of Internally Reflected Cherenkov light
- DIRC used at BaBar
- Turned out to be successful and robust for $\pi - K$ 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 $\pi - K$ 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.
 - $99.9 \pm 0.1\%$ transmission per meter at 442 nm
 - $98.9 \pm 0.2\%$ transmission per meter at 325 nm

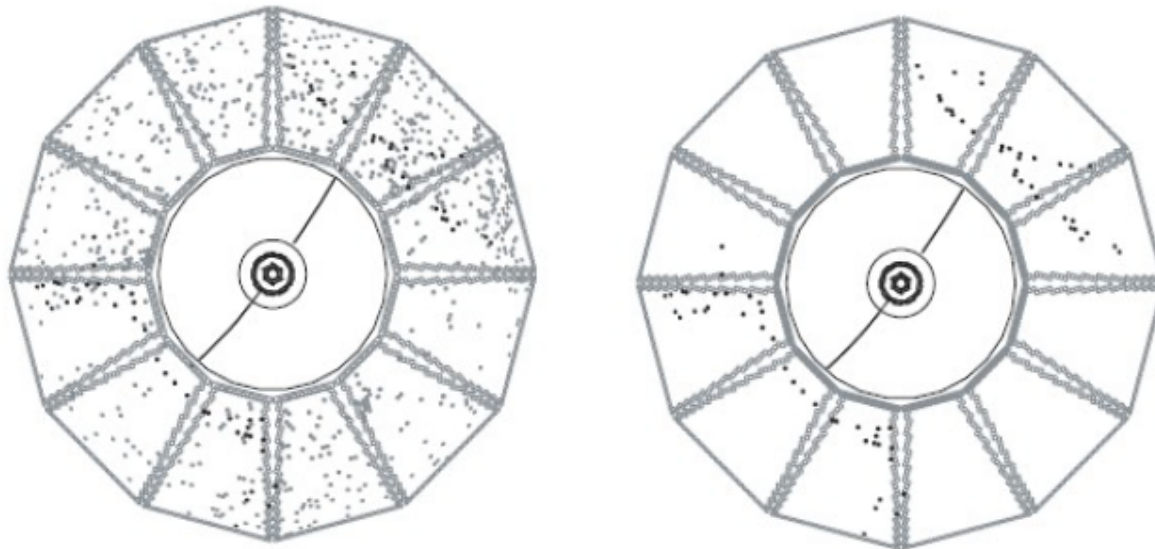


A strange idea: the DIRC

- Detector of Internally Reflected Cherenkov light

Reconstruction

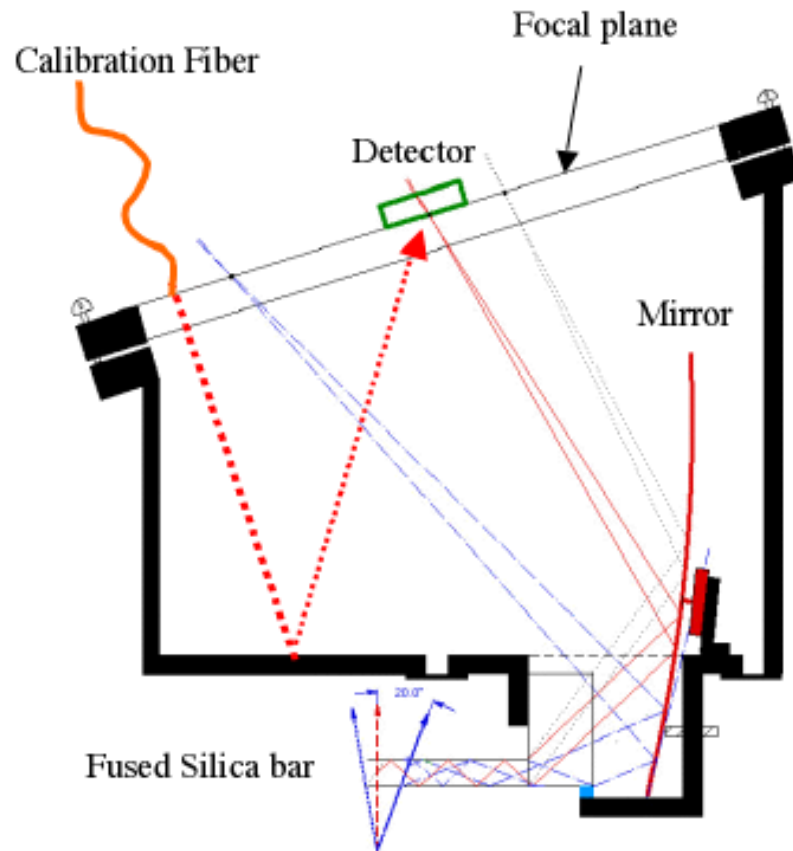
- Arrival time is used to reduce background



- 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 ?



IDENTIFYING PARTICLES CHARGE MEASUREMENT OF PRIMARY CR

How to characterize the primary particle?

- 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	Number of photons X	$N = Z^2 h(\gamma)$
Calorimeter	Deposited energie	$mc^2(\gamma - 1)$

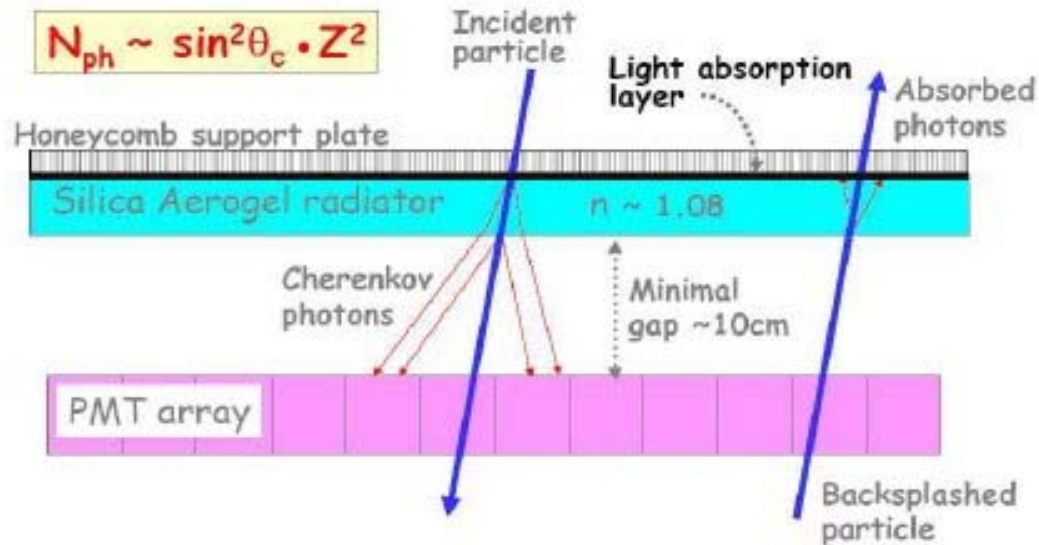
Two important radiations for particle identification

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

Proportionnal to Z^2

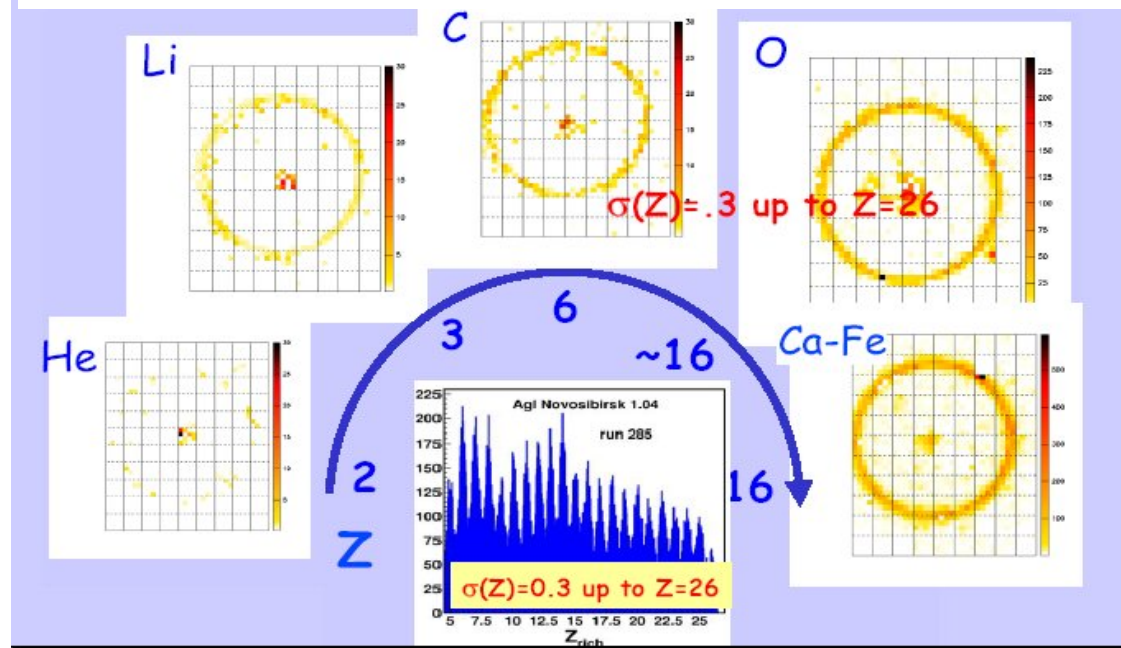
- Čerenkov radiation : si $v > c/n$
Sensitive to $\beta = v/c$
- Transition radiation : at the interface of \neq dielectric media
Sensitive to $\gamma = E/(mc^2)$

Cherenkov imaging (RICH) and charge measurement

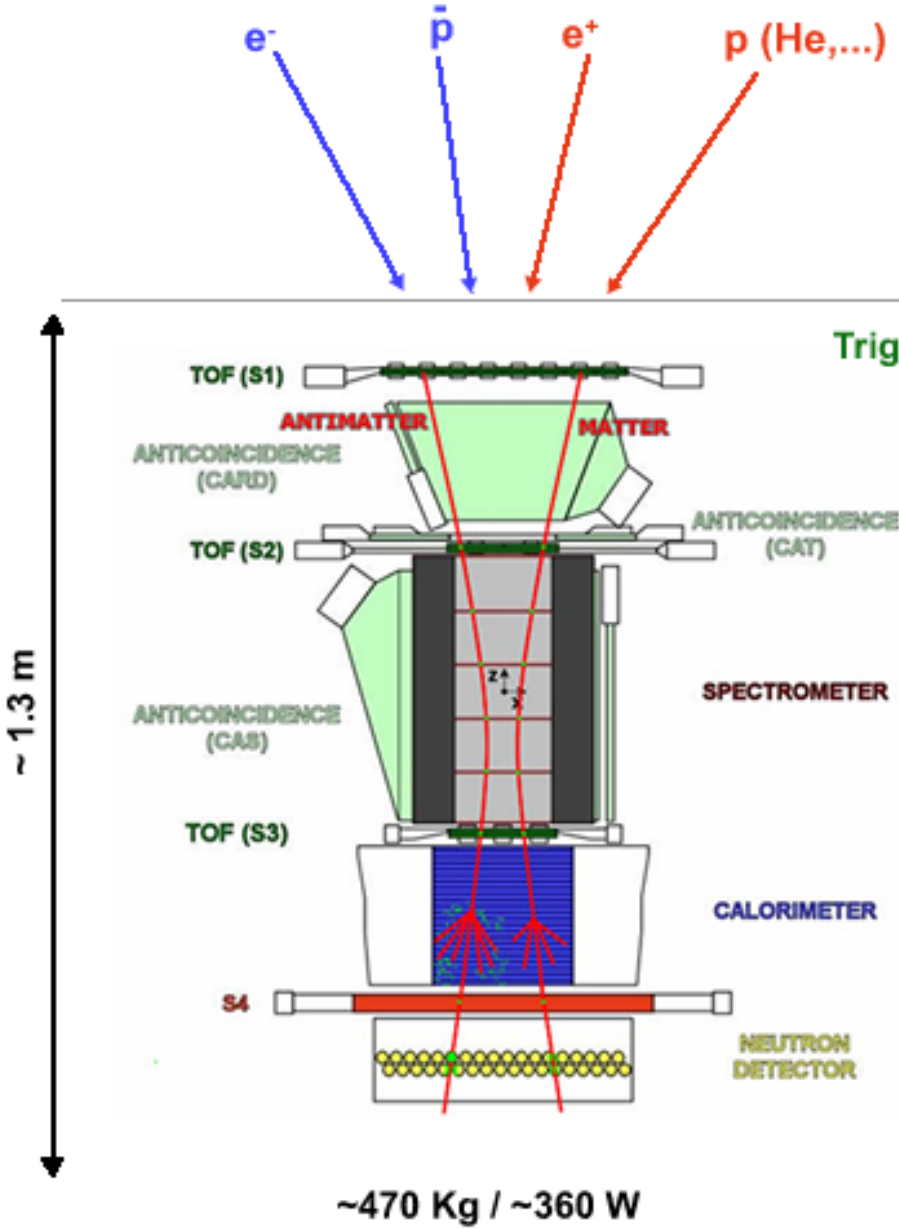


RICH principle →

AMS 2 Prototype →



PAMELA



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)

- Permanent magnet, 0.43 T
- 21.5 cm² 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)

Sign of charge, rigidity, dE/dx

- 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 cm² sr

Electron energy, dE/dx, lepton-hadron separation

- 36 ³He counters
- ³He(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



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.	-	³ He	-
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

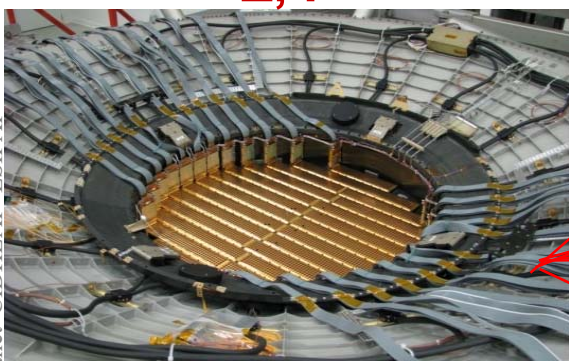
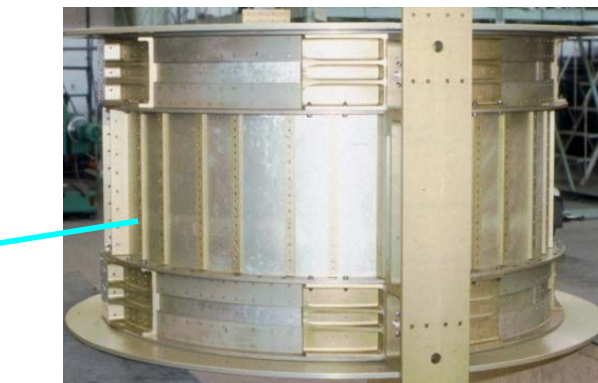
TRD

Identify e^+ , e^-



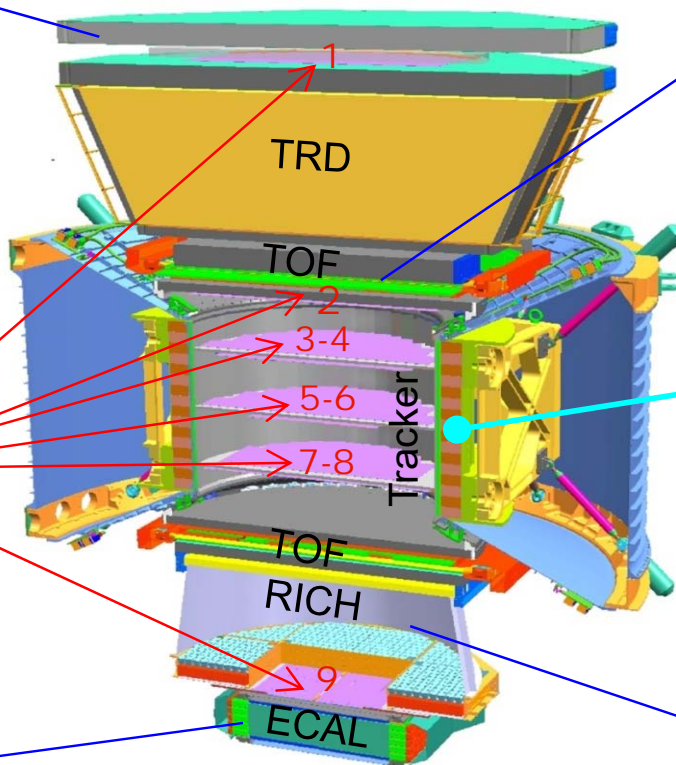
TOF
 Z, E

Magnet
 $\pm Z$

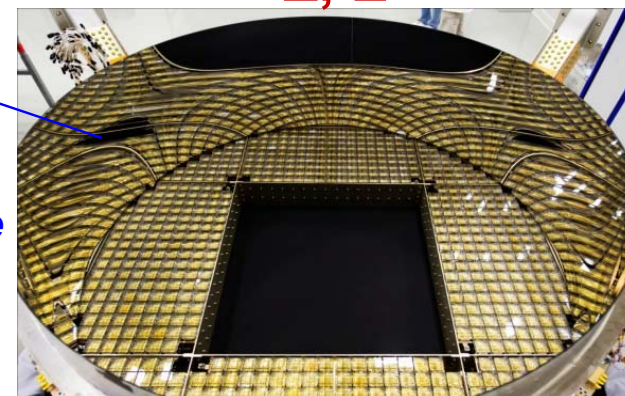


ECAL

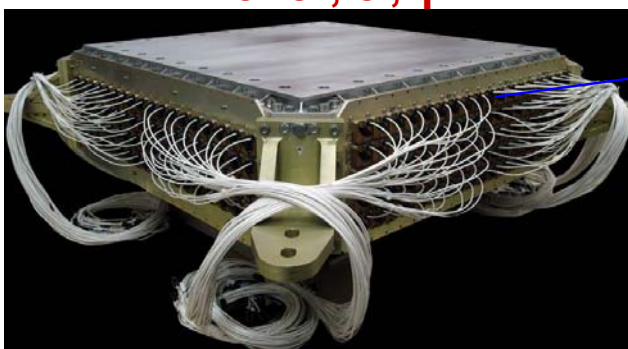
E of e^+ , e^- , γ



RICH
 Z, E

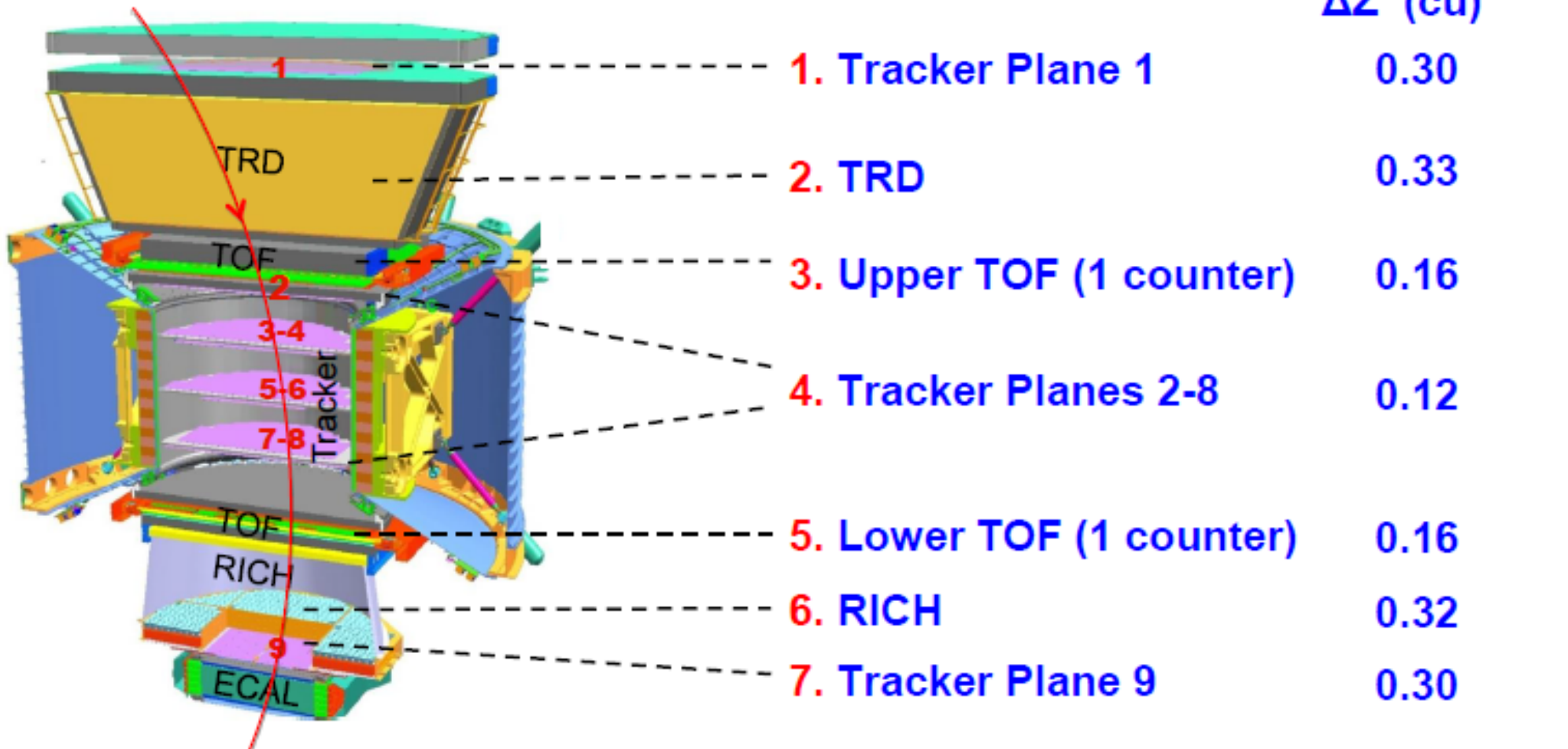


Z, P are measured independently by the Tracker, RICH, TOF and ECAL



AMS charge identification

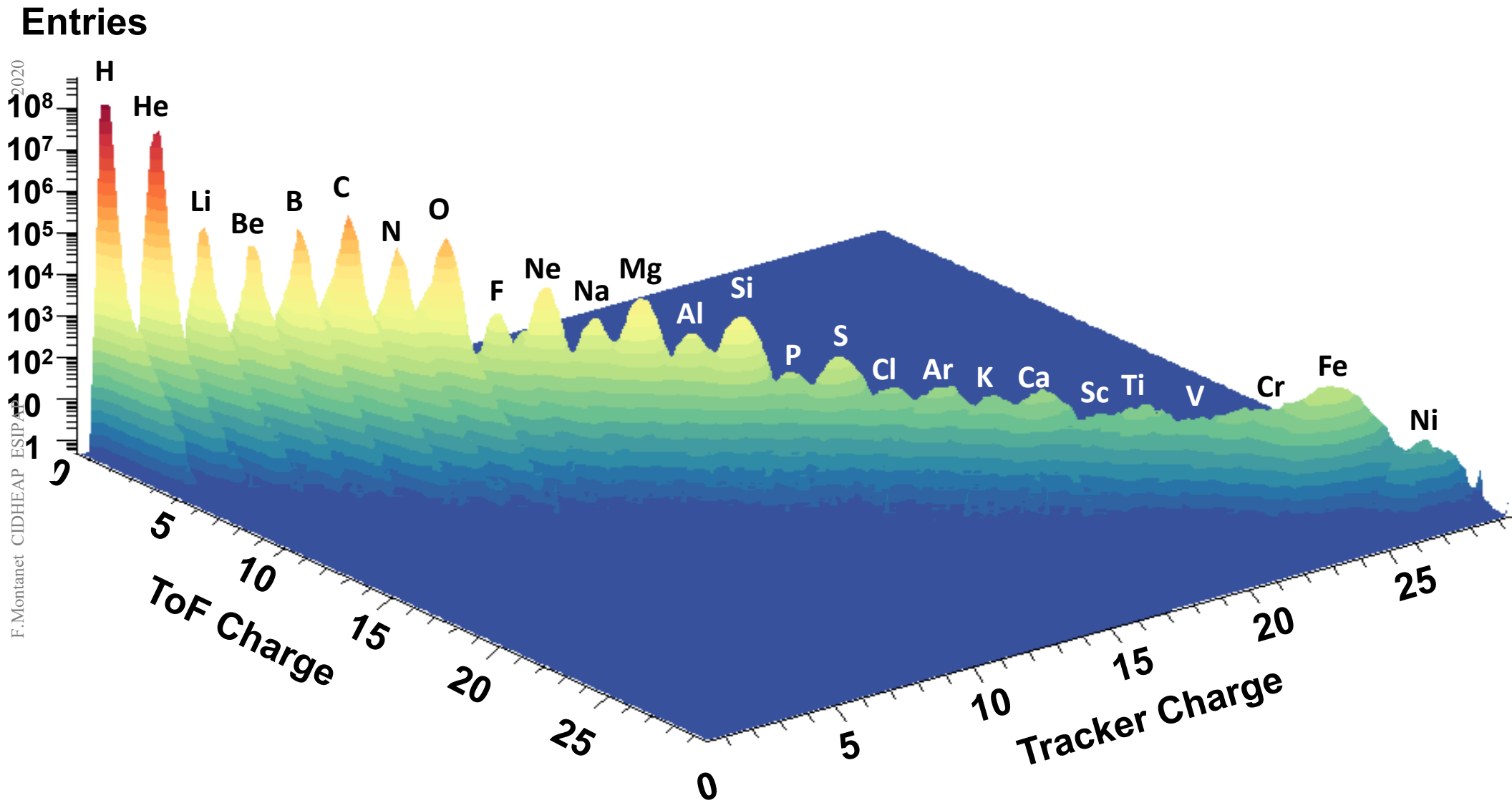
AMS: Multiple Independent Measurements of the Charge ($|Z|$)



Full coverage of anti-matter & CR physics

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

AMS Nuclei Measurement on ISS

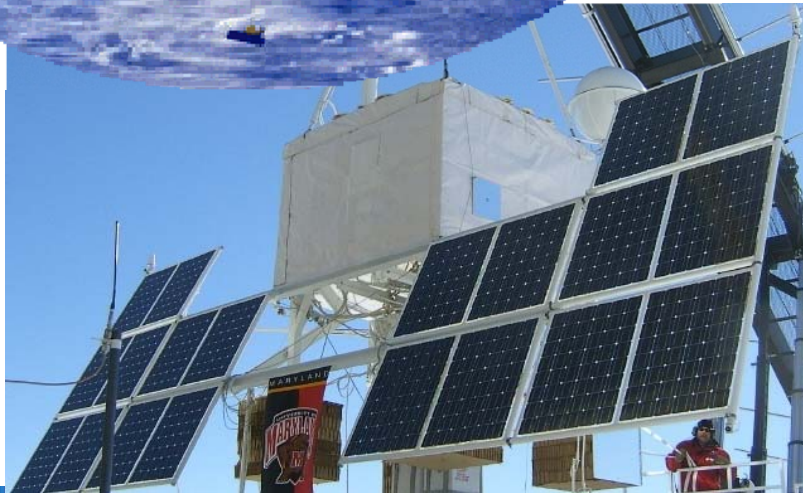


CREAM



Ultra Long Duration Balloon
ULDB Proj., Adv.Sp.Res33,1633(2004) :
NASA project to develop

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

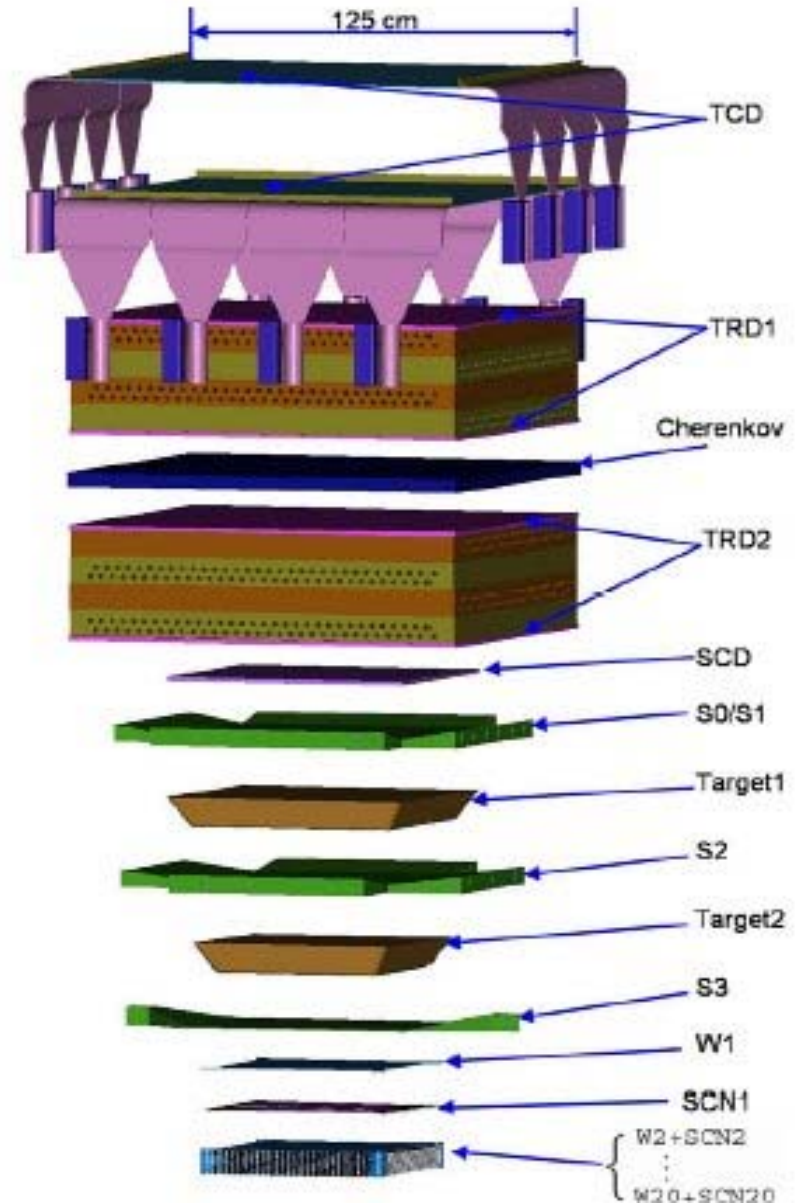


F.Montanet CIDHEAP ESIPAP

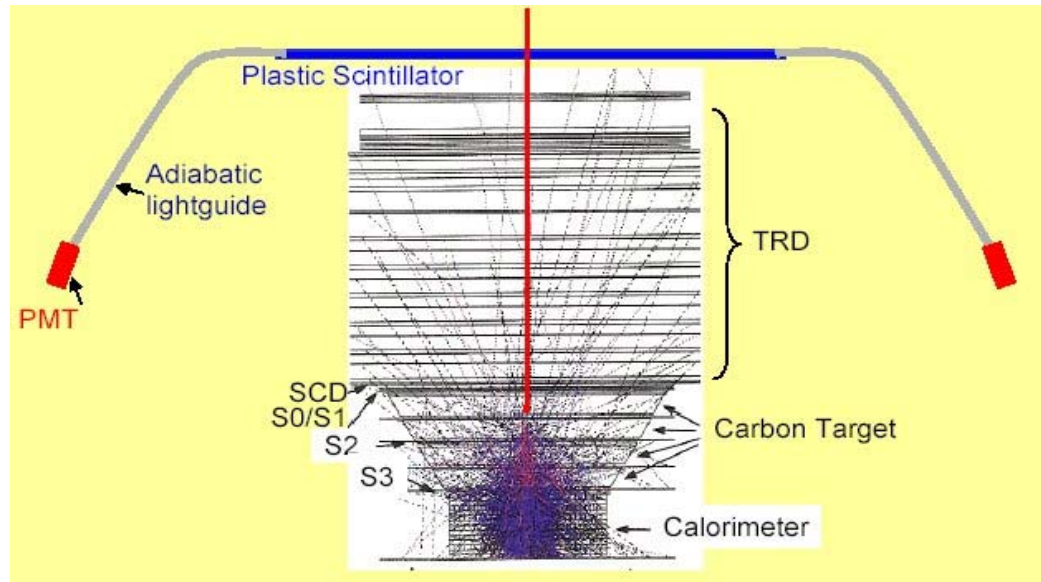
CREAM

Cosmic Ray Energetics and Mass

- **Objectives** :
CR composition and spectrum of the different elements (from TeV to ~500 TeV)
- **Acceptance** : 2,2 m² sr
- **Energy measurement**:
 - Calorimeter 20 X₀ (W + scint. fibres)
 - Transition Radiation Detector
- **Identification** :
 - TRD
 - Cherenkov detector "CHERCAM" similar to AMS-2

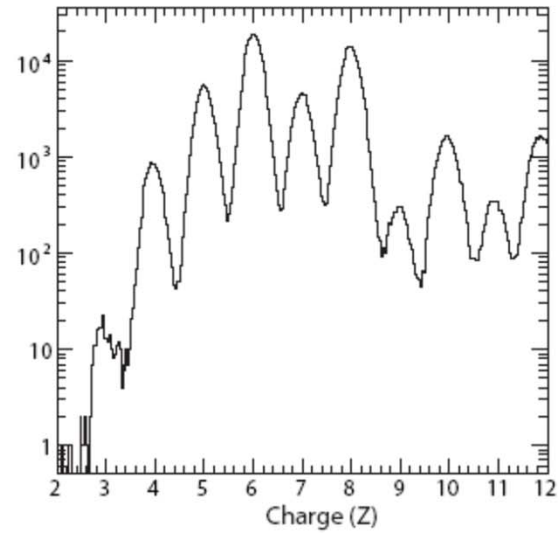
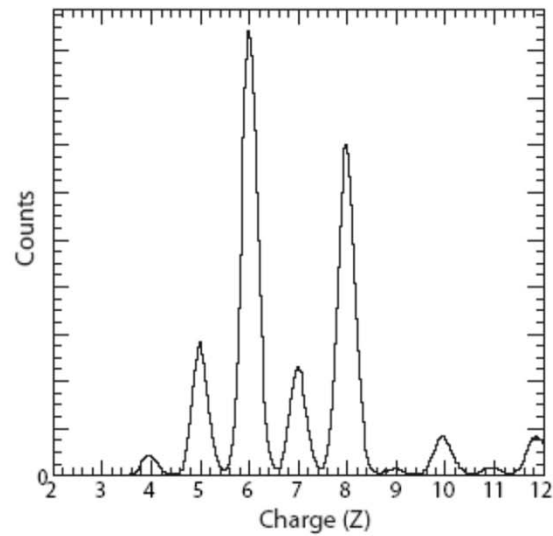
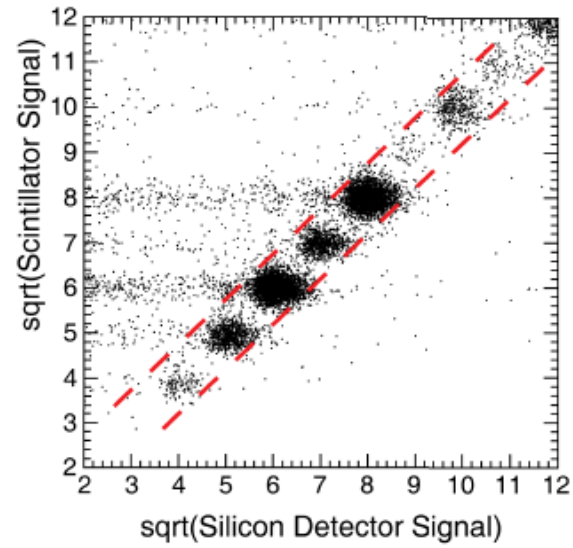
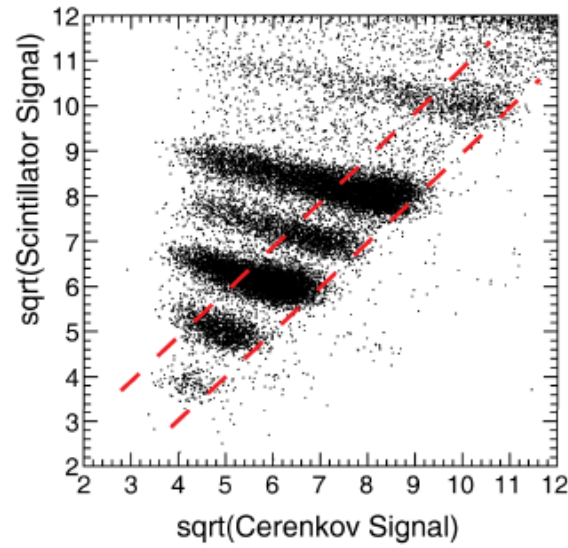


CREAM experiment



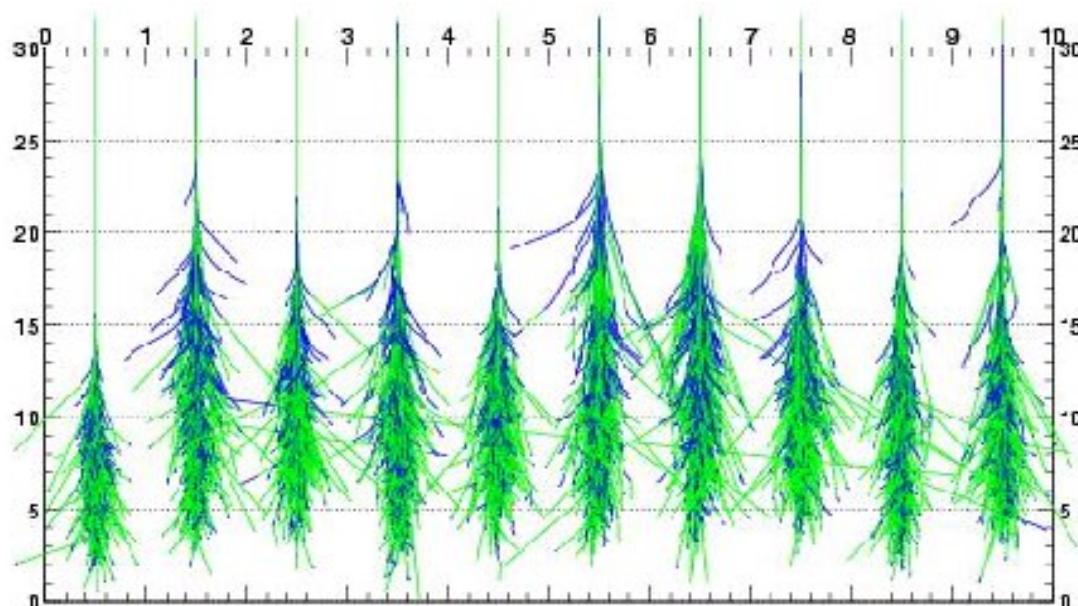
- **At TeV energies**, the interaction of CR in the calorimeter induces **many backscattered secondary particles** that one have to veto.
- **The "CHERCAM" cherenkov** solves this problem by measuring accurately the time of any through going particle as well as achieving a precise charge measurement ($\pm 0,3 e$)

CREAM experiment

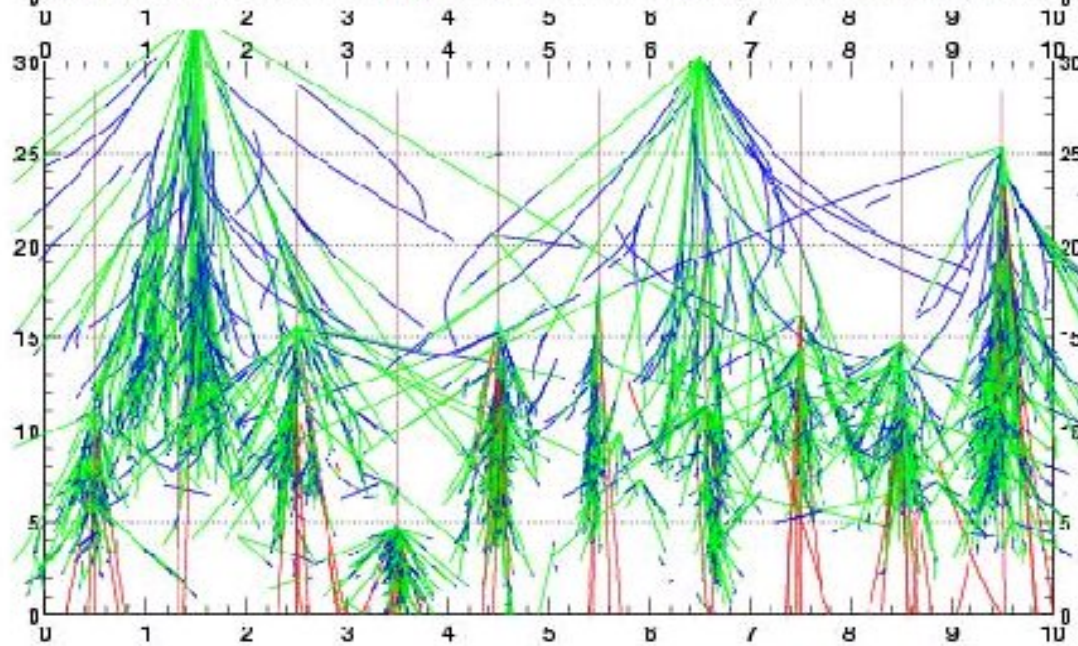


ATMOSPHERIC GAMMA-RAY SHOWERS BY CHERENKOV TELESCOPES

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
- Energy losses by e^\pm
 - ionization
 - Atoms excitation

In the coulombian
field of nuclei

γ induced
shower 300 GeV

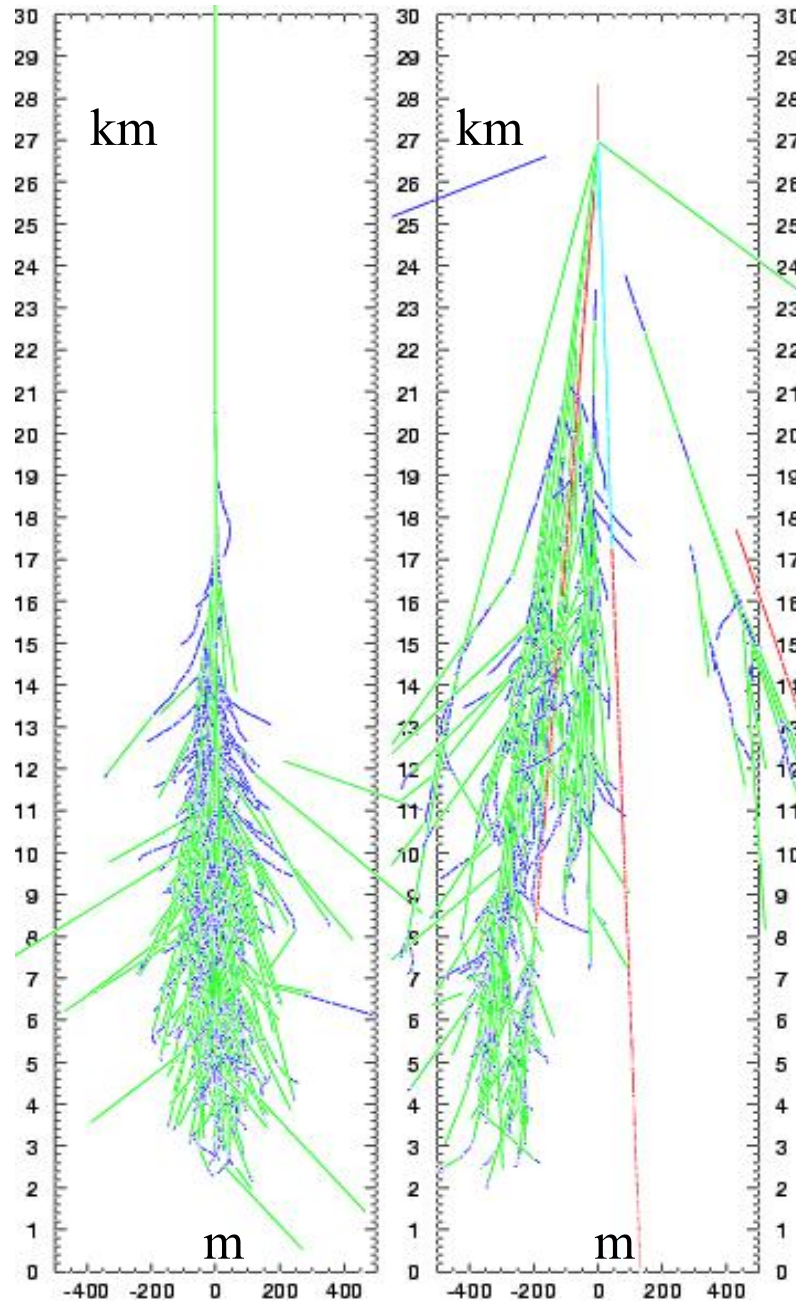
Roughly
symmetric
around the axis

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

- Showers charged particles emit light:
 - **Cherenkov light** : **very collimated** along the shower axis (Cherenkov angle at 1 Atm. $\approx 1^\circ$) **threshold depending on the altitude** : at ground 22 MeV for e^\pm et 4.5 GeV for μ^\pm
(20 photons per m per $\beta \approx 1$ charged particle at 1 atm)
Essentially used for gamma-ray astronomy
 - **Nitrogen fluorescence**: **isotropic emission**
($\frac{1}{4}$ 4 photons per electron per m)
Essentially used at UHE $\geq 10^{17}$ 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 ($\approx 10\%$ duty cycle).**

Cherenkov light from VHE gamma rays showers

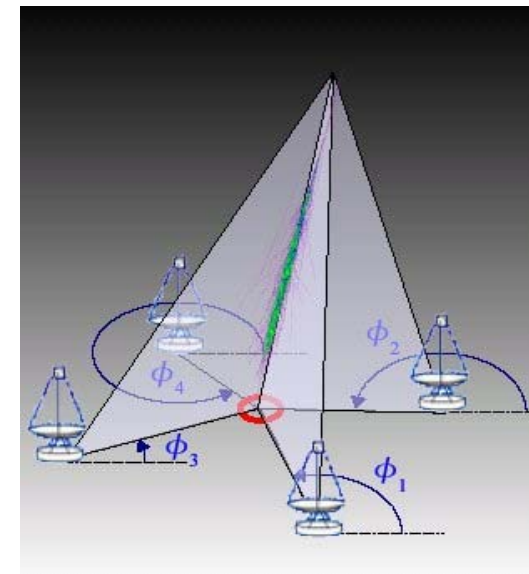
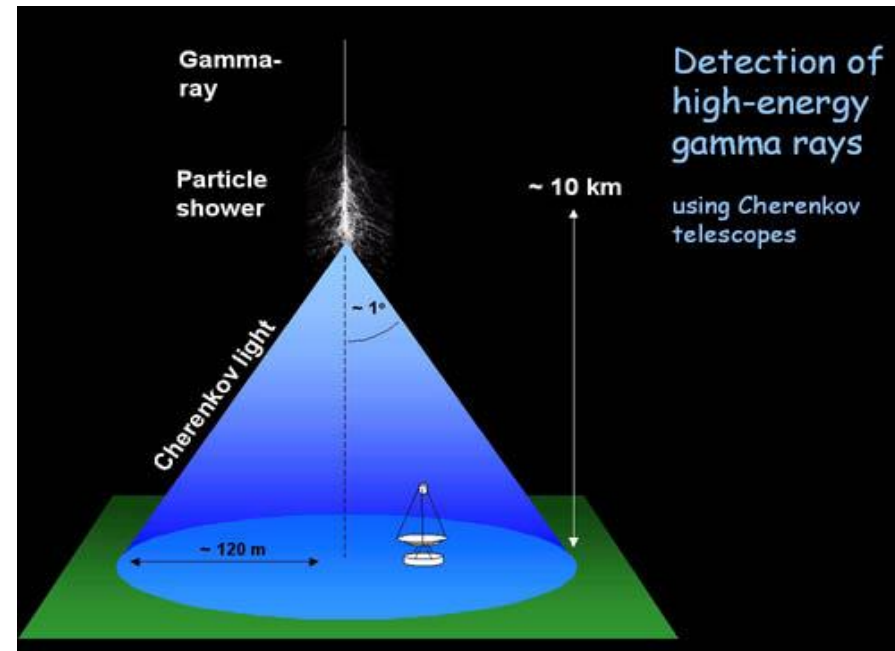
Shower front \approx conical at energies $>$ TeV, **very well defined in time** (few nanoseconds)

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

Any large acceptance telescope in this area receive enough photons

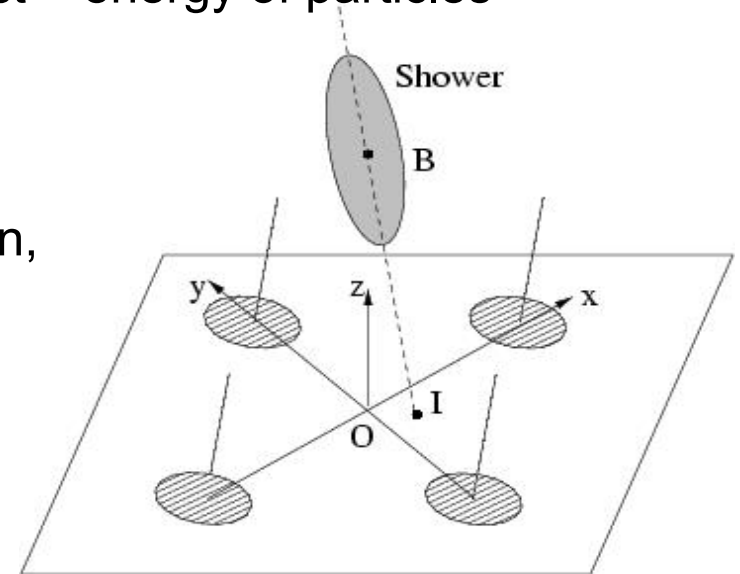
→ **effective detection area $\sim 10^5 \text{ m}^2$**

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



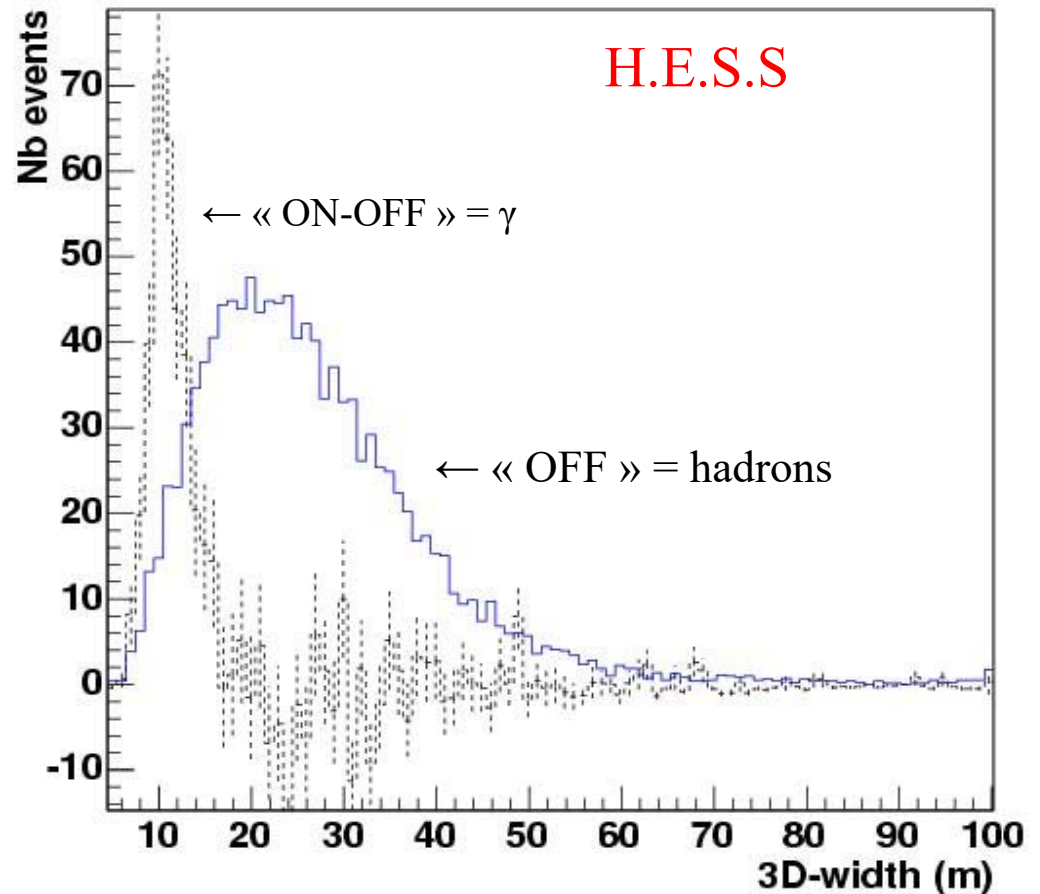
Showers Cherenkov light

- **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 \rightarrow QED radiative processes).



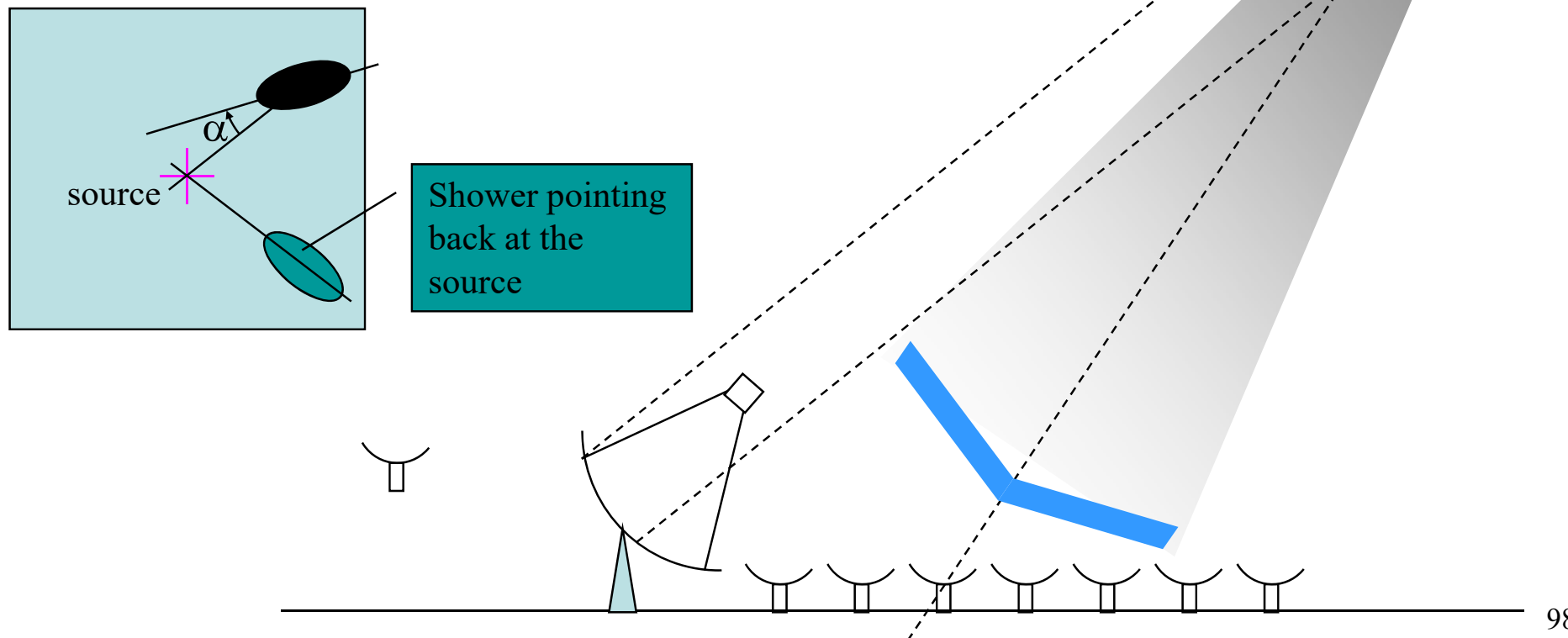
Cherenkov transverse profiles: EM versus hadronic showers

- « OFF » data: showers detected by 3 or 4 telescopes in a zone without ° sources
→ σ_T distribution for hadronic showers
- « ON » data : showers detected by 3 or 4 telescopes in the direction of the ° 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

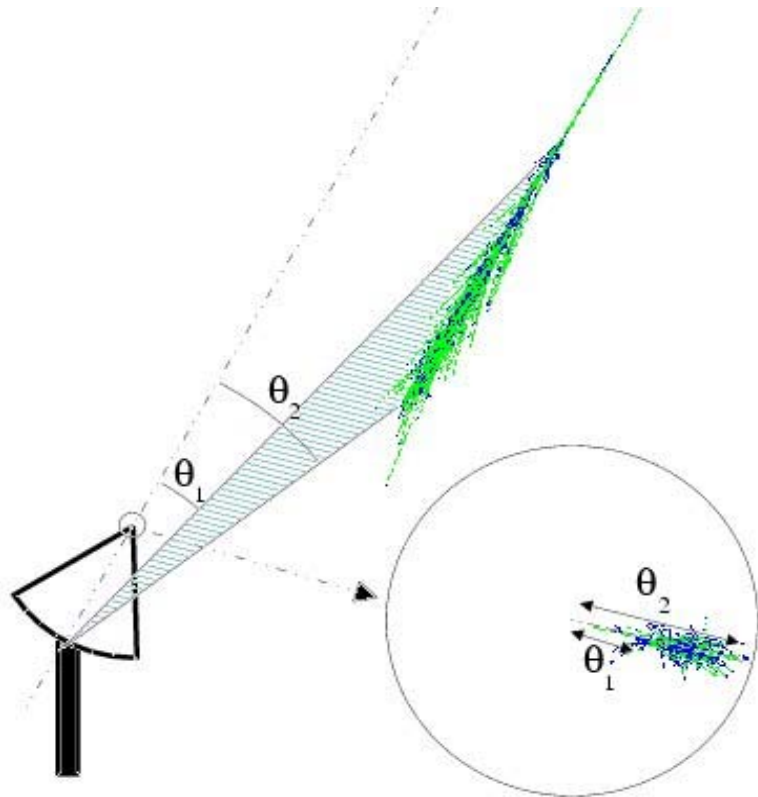


Gamma-ray astronomy above 100 GeV

- **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** \rightarrow 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 \rightarrow limited sensitivity.

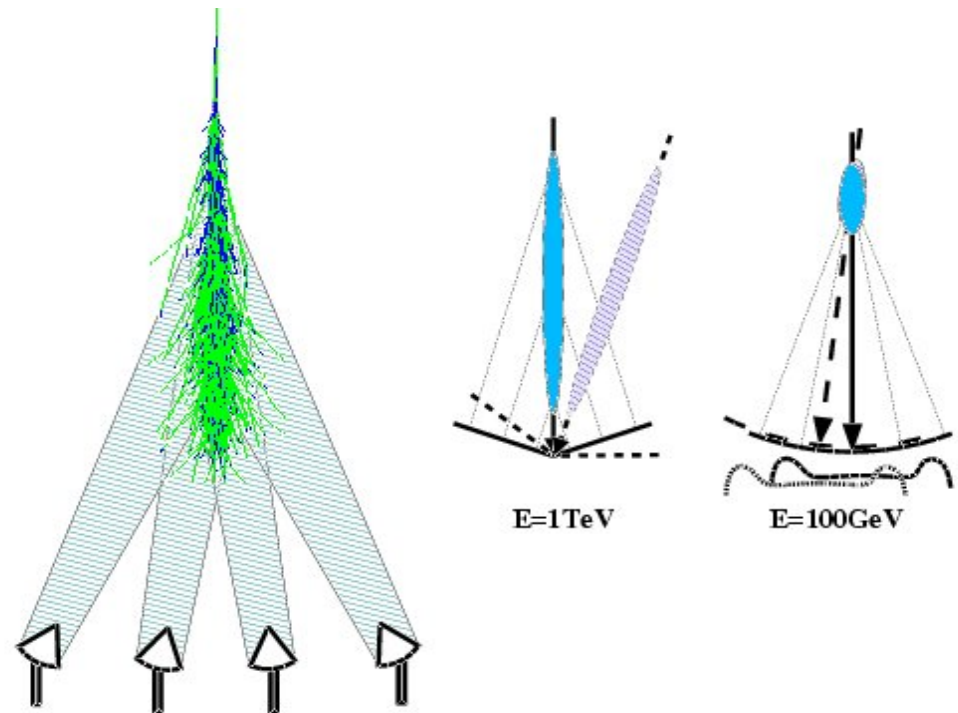
Atmospheric Cerenkov Detectors

Imagers



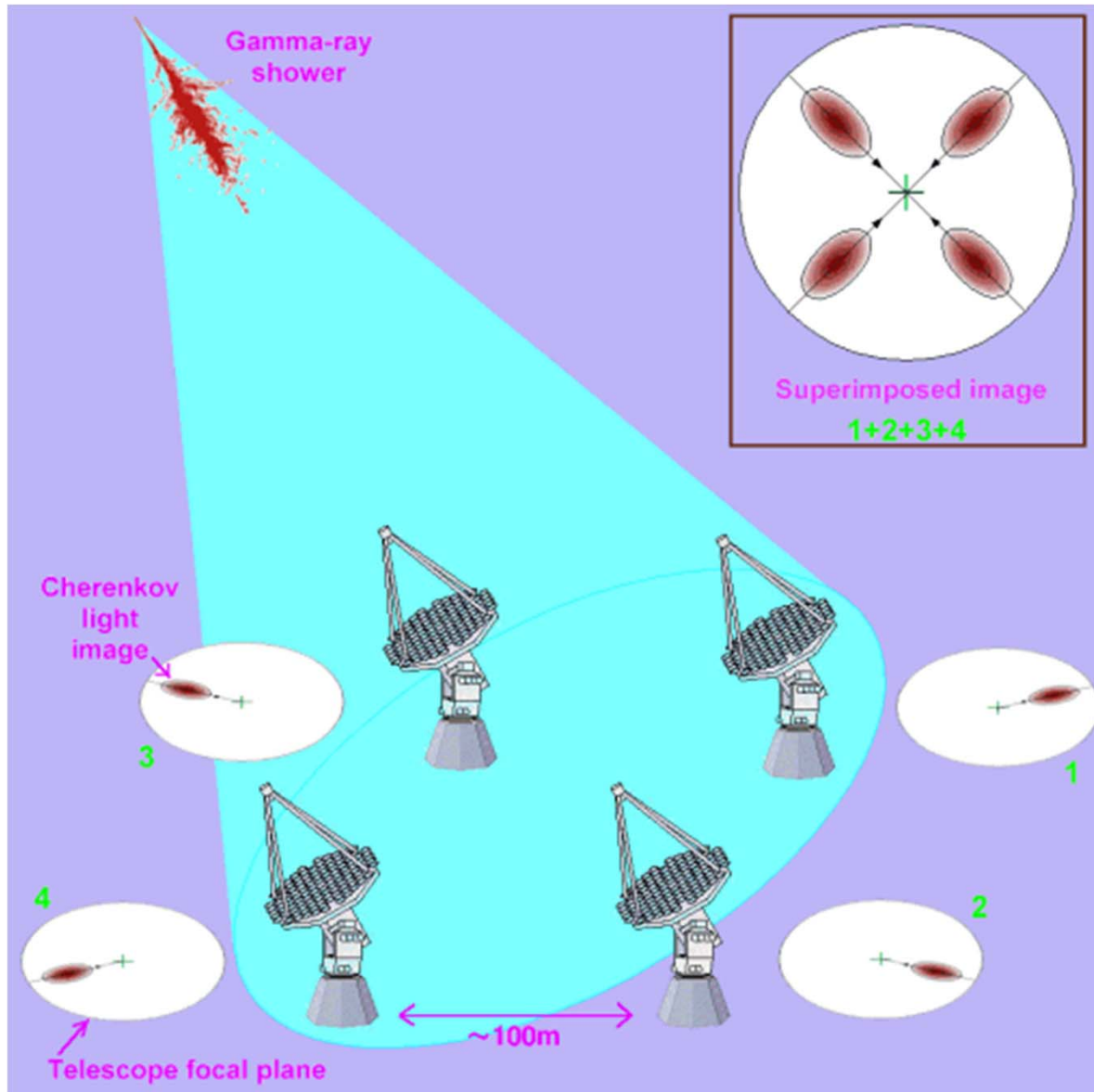
Form the shower image in the focal plane

Samplers



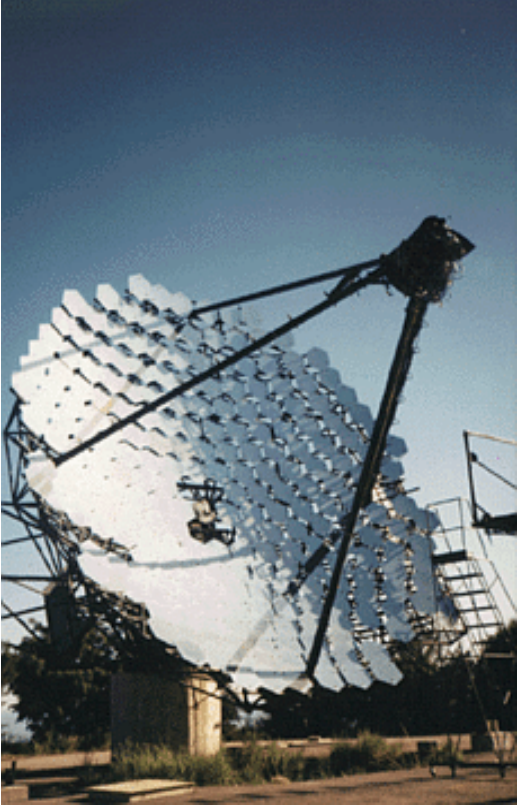
Arrival time + amplitudes on a large number of stations

ACTs in stereoscopic mode

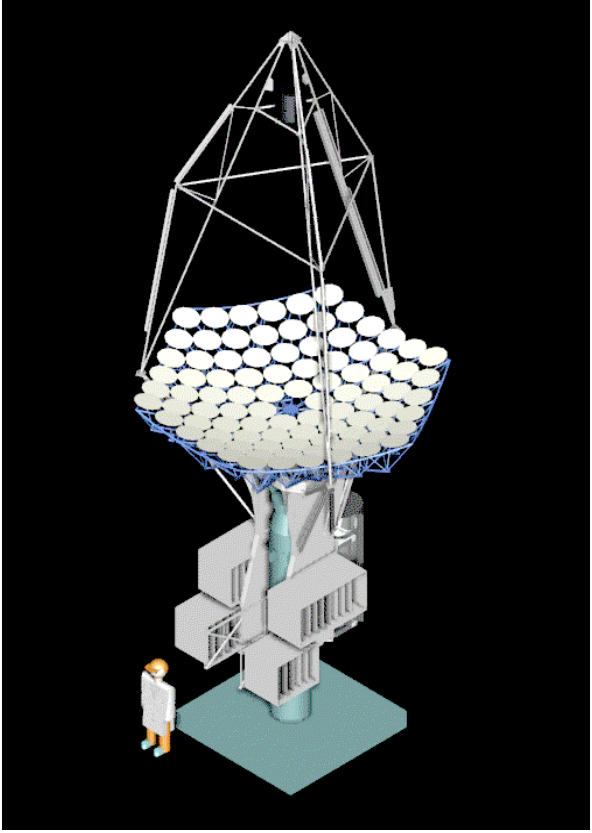


Former ACT

WHIPPLE



CAT



ACTs:

Lowering the energy threshold

Sky background $\sim 10^{12}$ photons $\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}$

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

- Increase the photons collection area \approx reflector area A_{col}
- Increase the photon detection efficiency ² (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) \rightarrow 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
 \rightarrow small pixels, triggering by fraction of the field of view or using nearby pixel patterns.

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

VERITAS



CANGAROO III



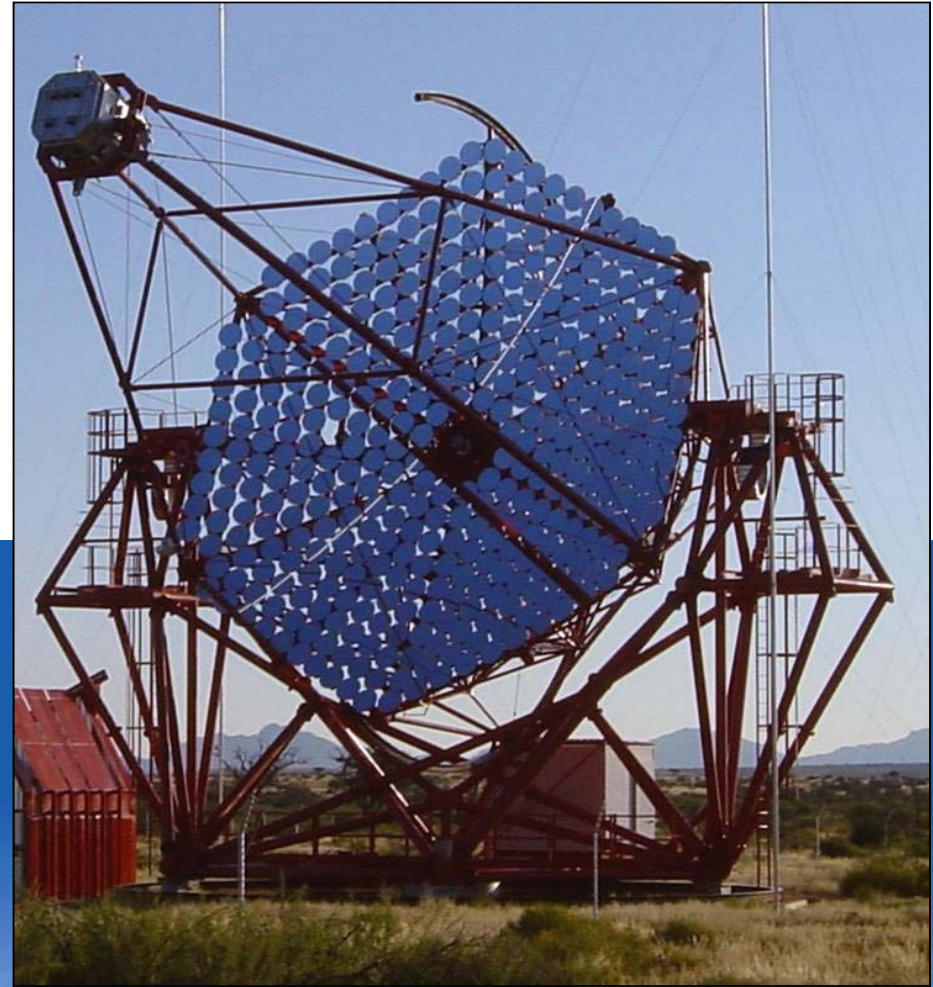
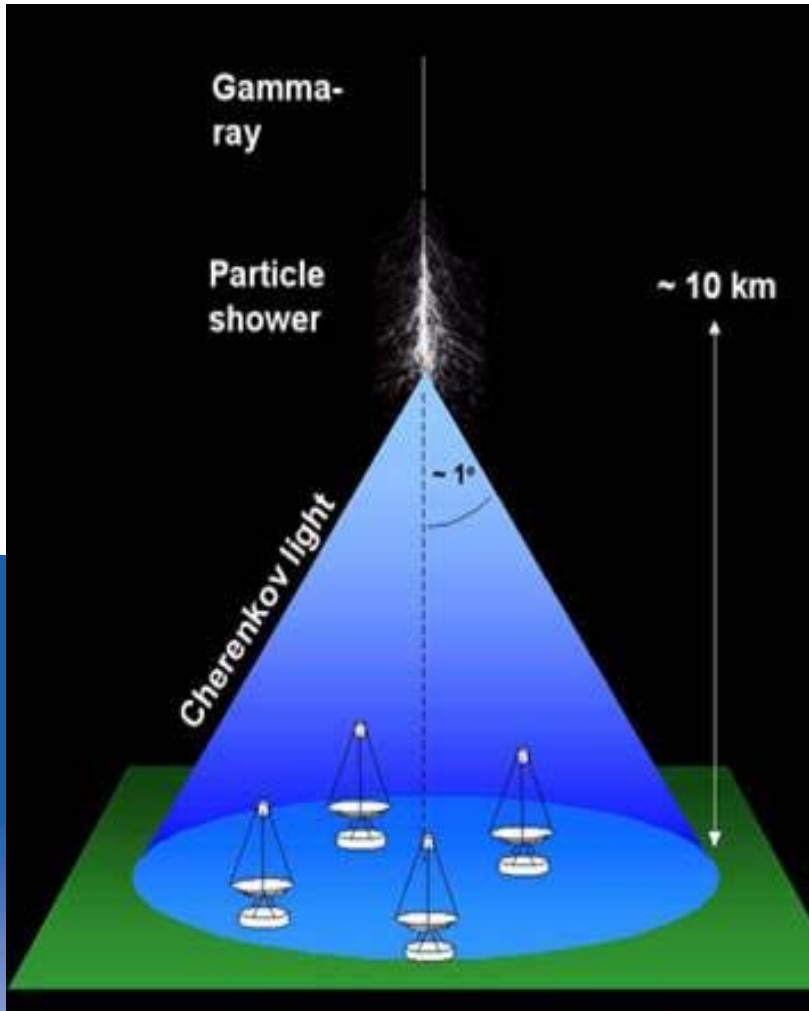
MAGIC



HESS I



Hess 2004 : x4 telescopes



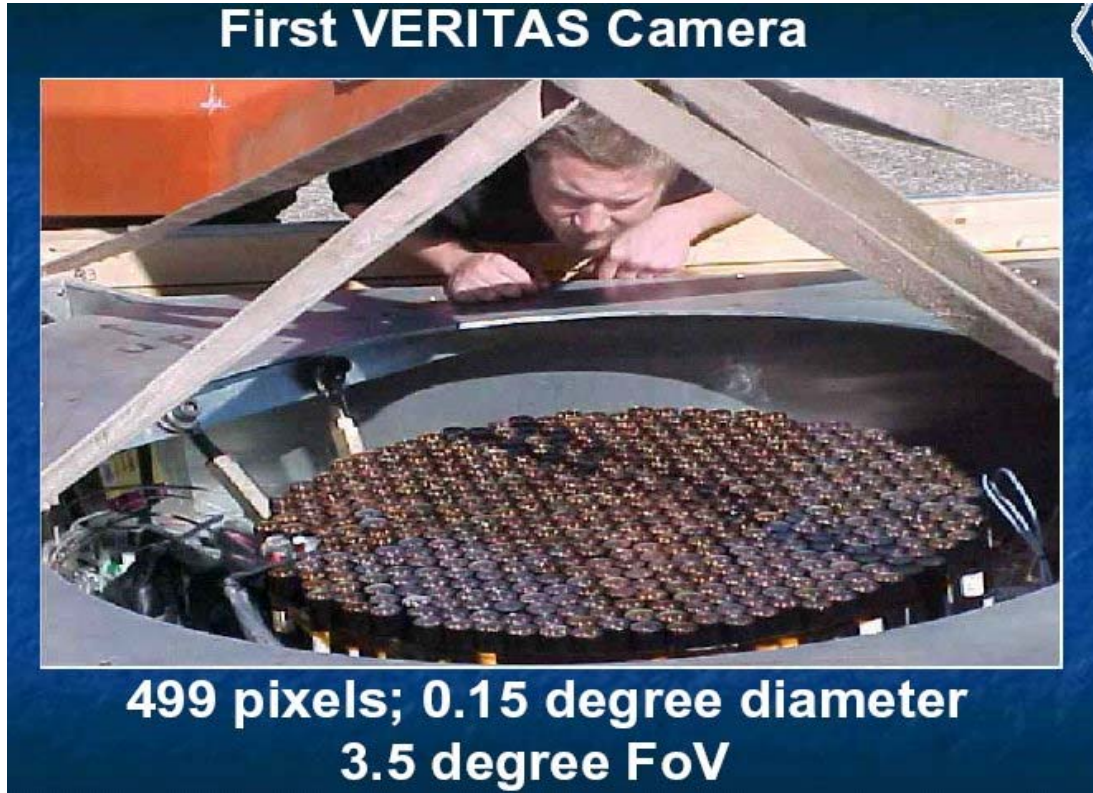
Imaging telescopes: the cameras

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

2020

F.Montanet CIDHEAP ESIPAP



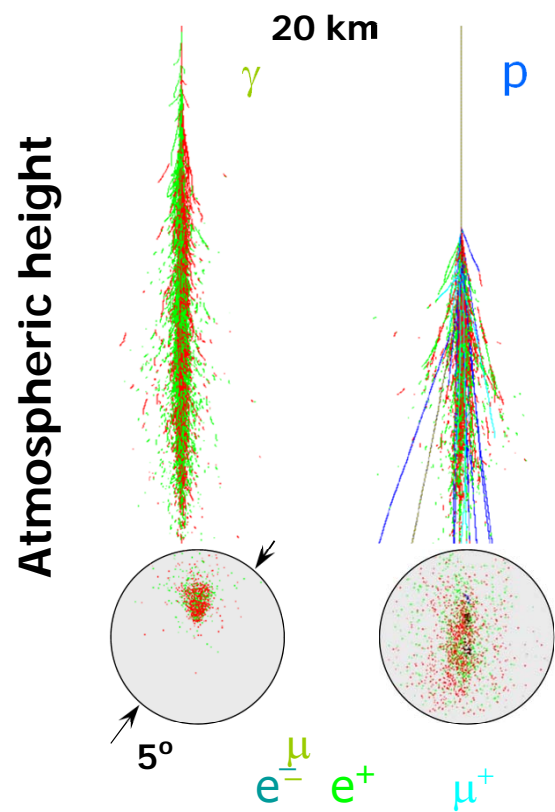
VERITAS

MAGIC

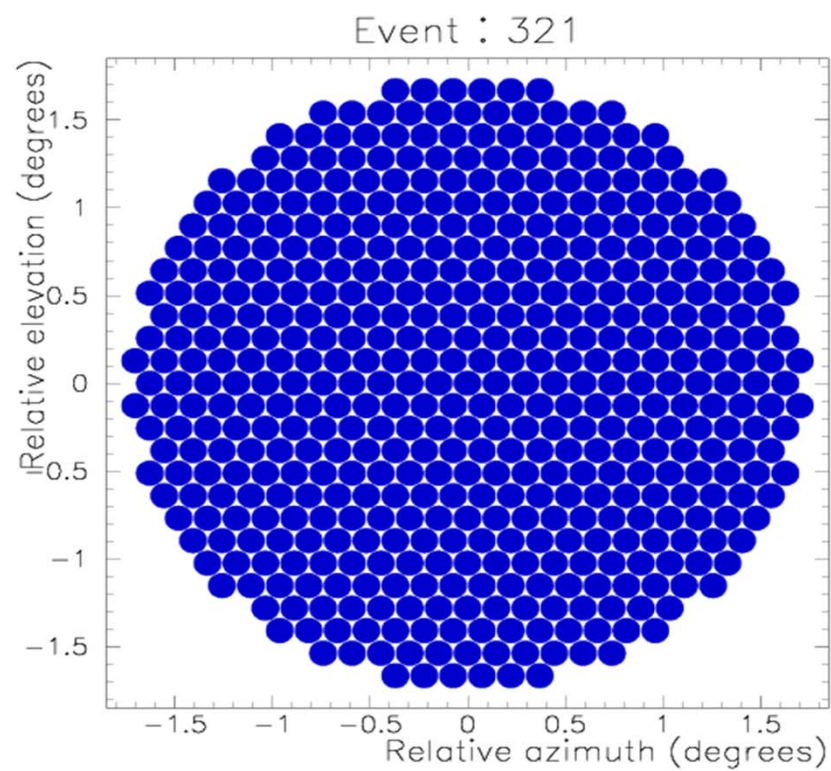
Imaging telescopes: high resolution cameras (H.E.S.S.)

- 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 \rightarrow ADC



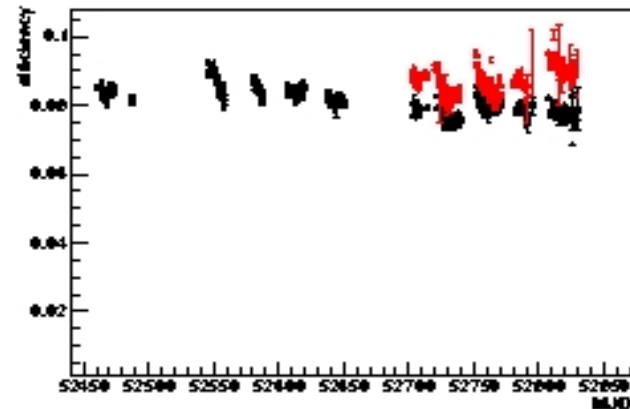
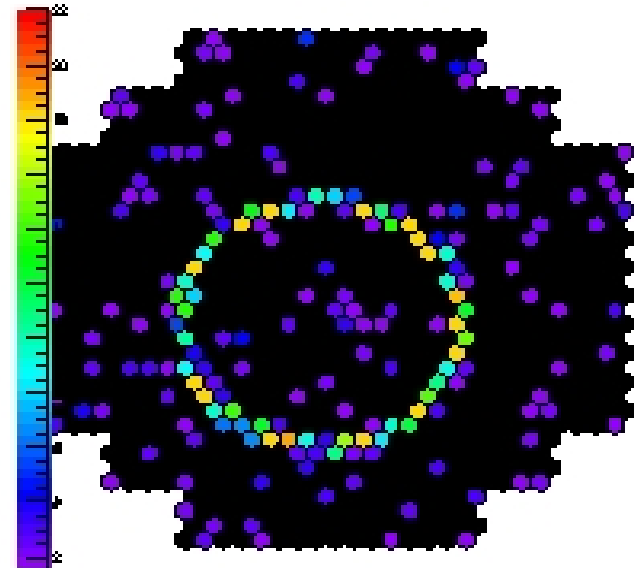


VERITAS Movie Camera



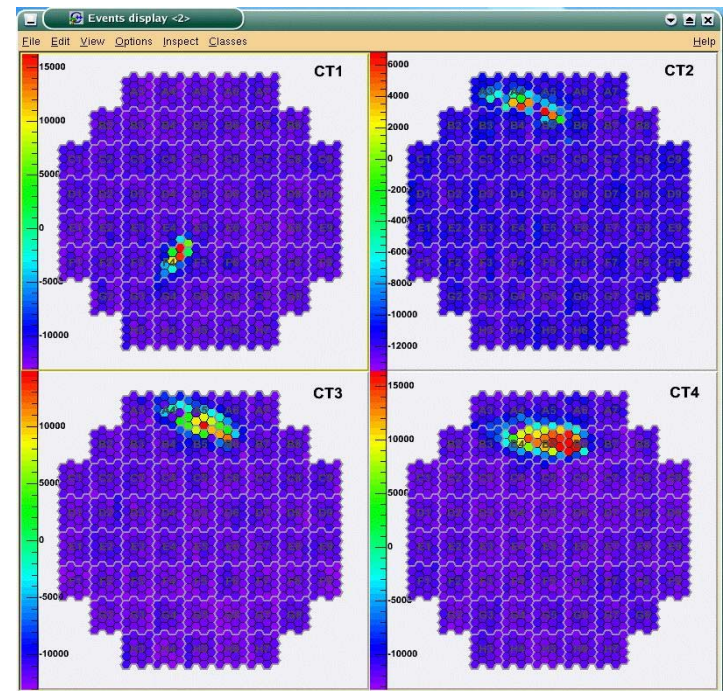
An effective detector monitoring: muon rings

- 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.



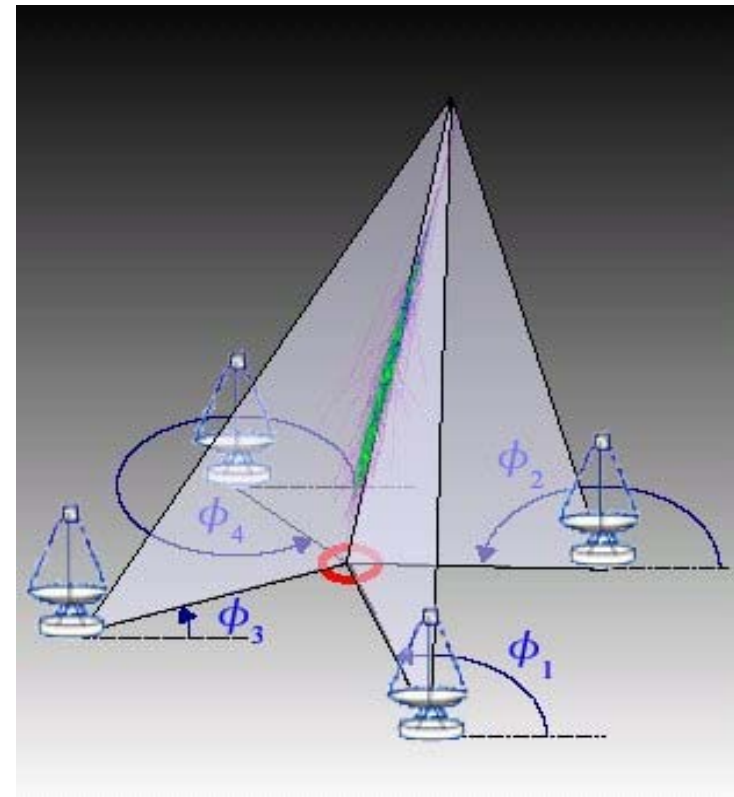
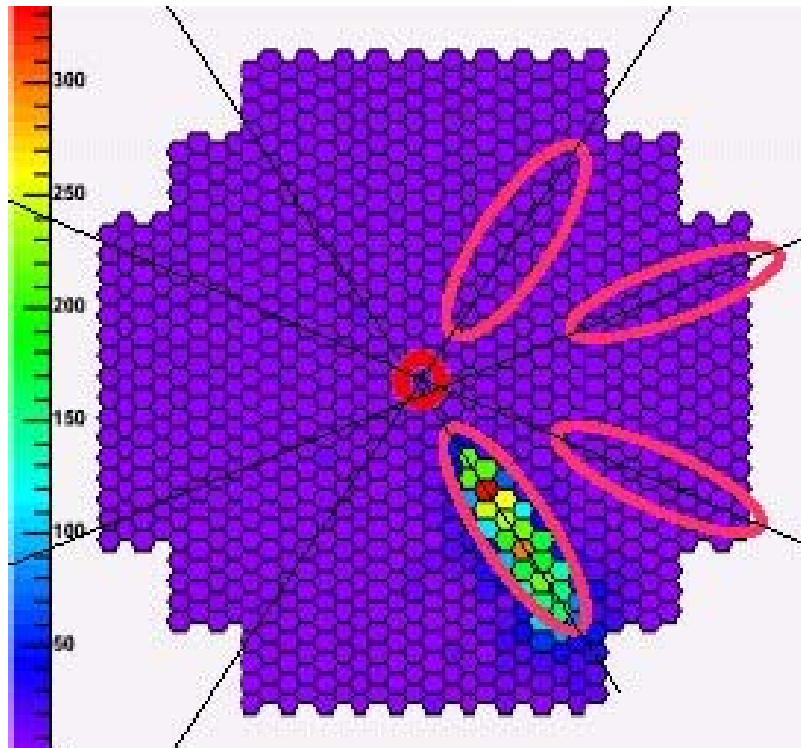
Stereoscopic ACTs

- 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
($\approx 4'$ avec 4 telescopes)
- **Better energy resolution** ($\approx 15\%$)

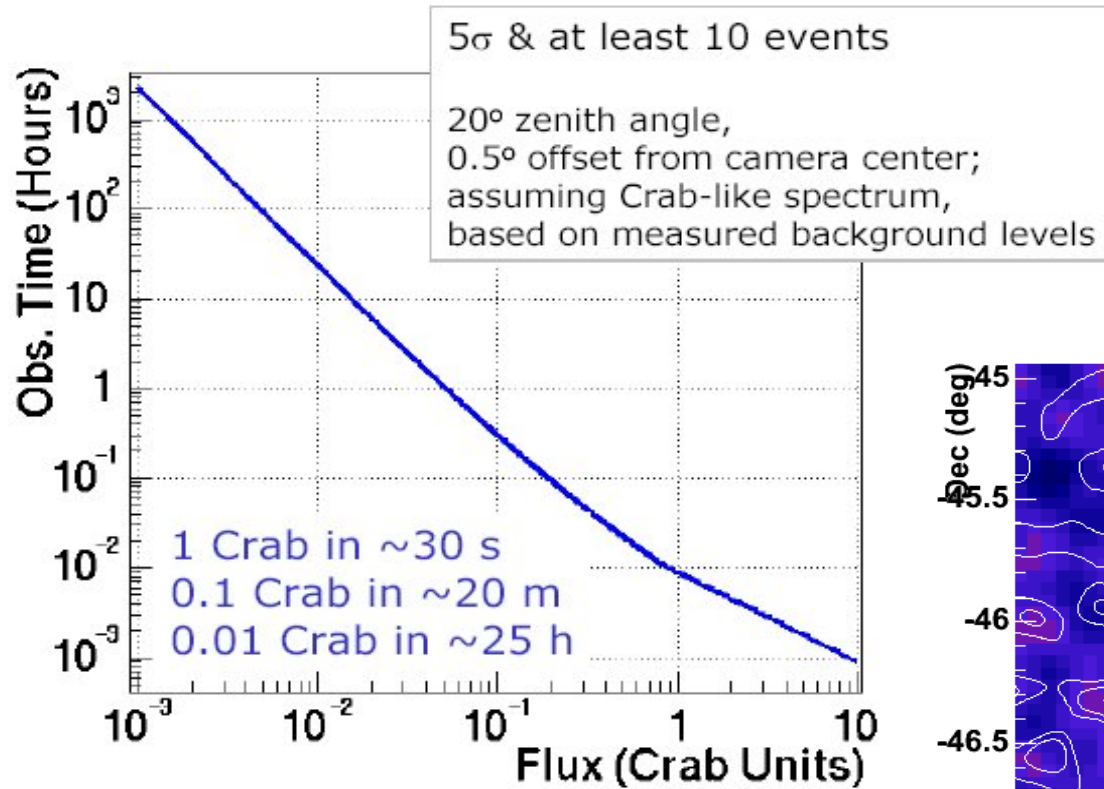


Stereoscopic ACTs

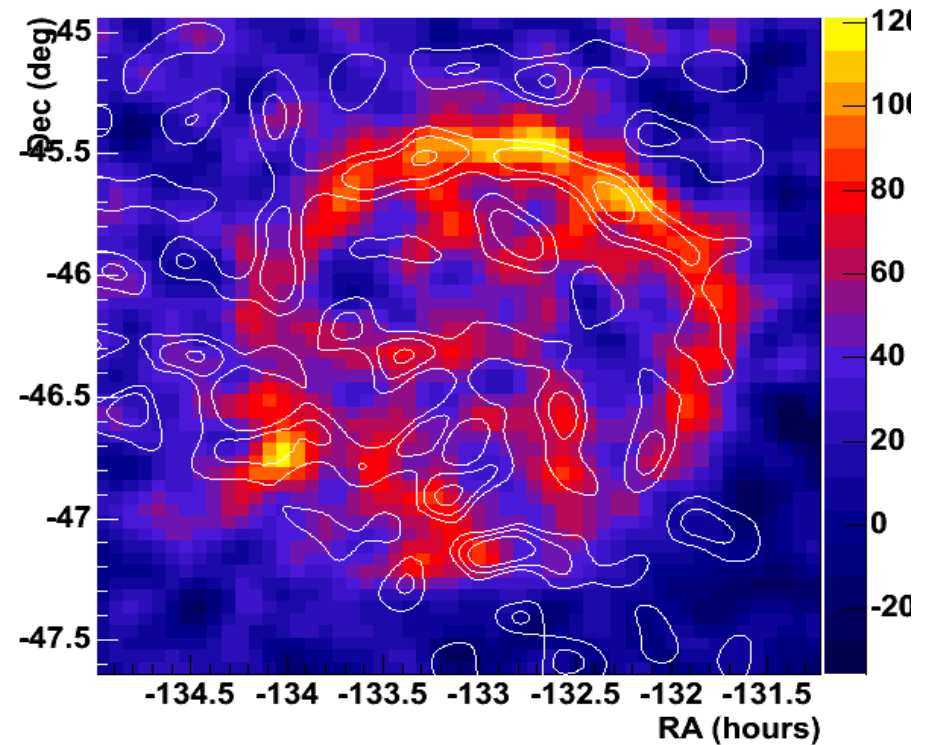
- Direct measurement of the **origin of the gamma-ray** in the field of view (important for **extended sources**)
- Direct measurement of the **ground impact point** (important for **the determination of the energy**)



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



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

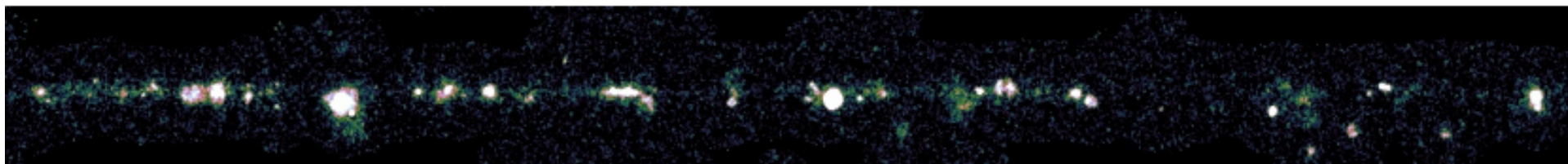


More than hundred TeV-sources

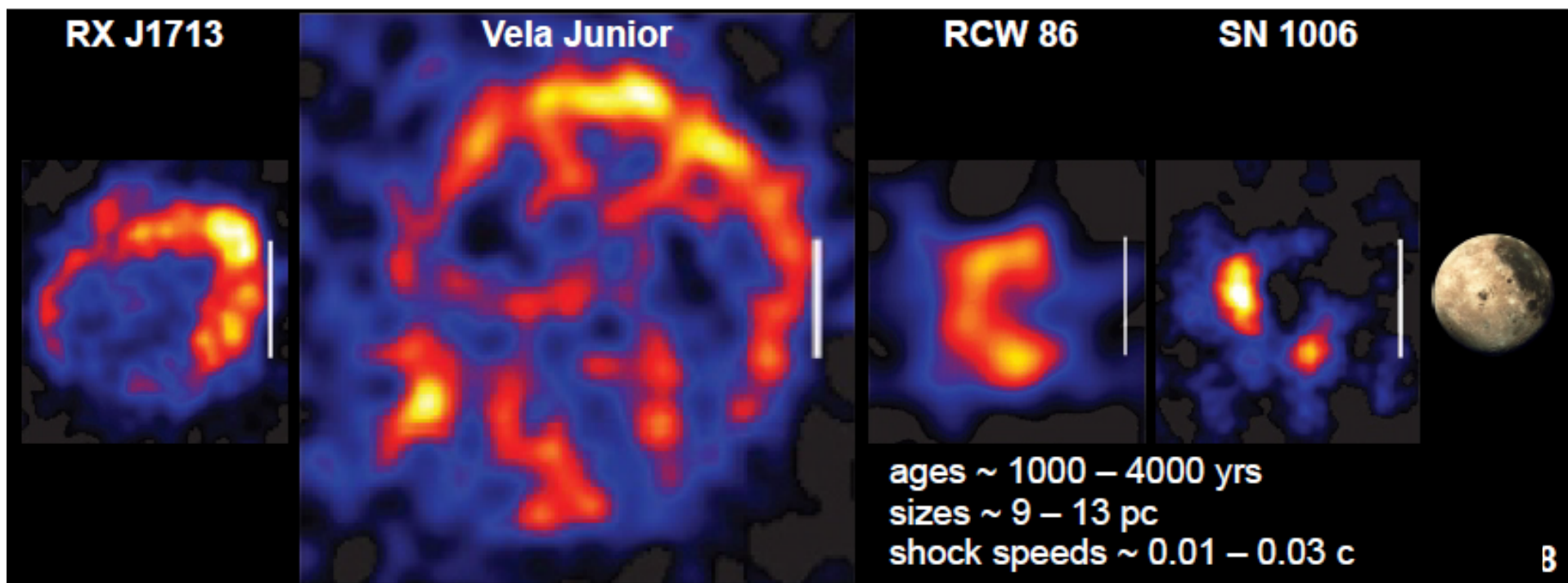
M. Lemoine-Goumard 2006

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

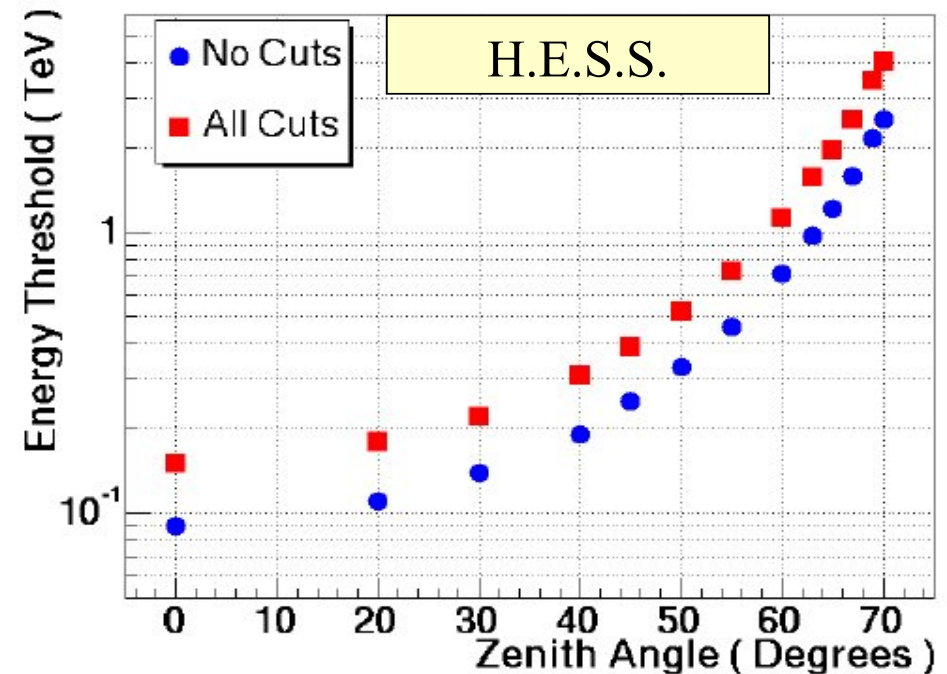


- 5 resolved shell-type SNRs



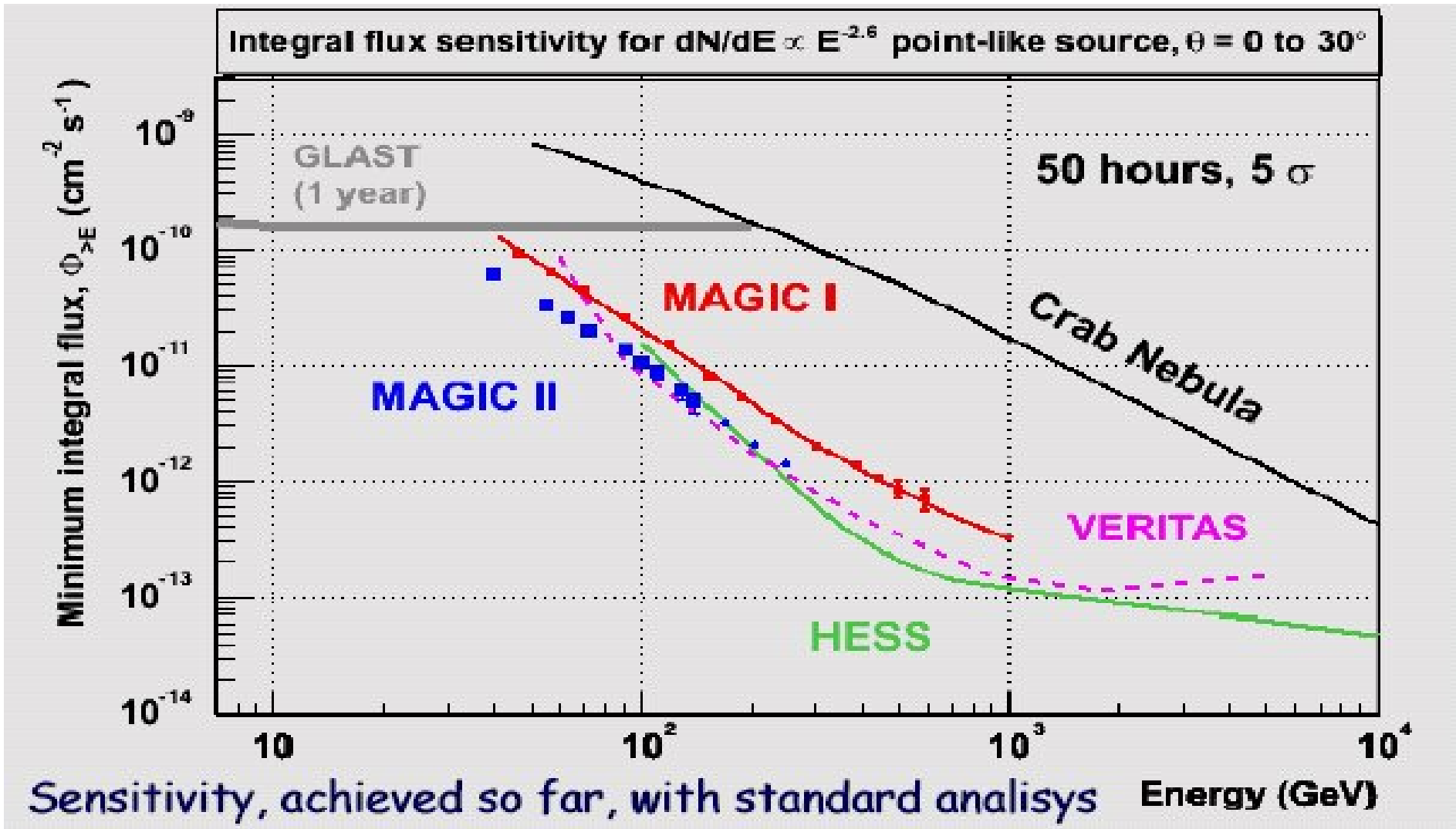
Energy threshold

- 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

2020
F. Montanet CIDHEAP ESIPAP



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

HESS Phase II : additional very large central telescope


HESS I (4x LCT)

Event Classes :

1. Mono : VLCT
2. Stereo : VLCT+ LCT or LCT+ LCT

Very Large Cherenkov Telescope

MAN Design: conventional alt-az mount



Very Large Cherenkov Telescope:

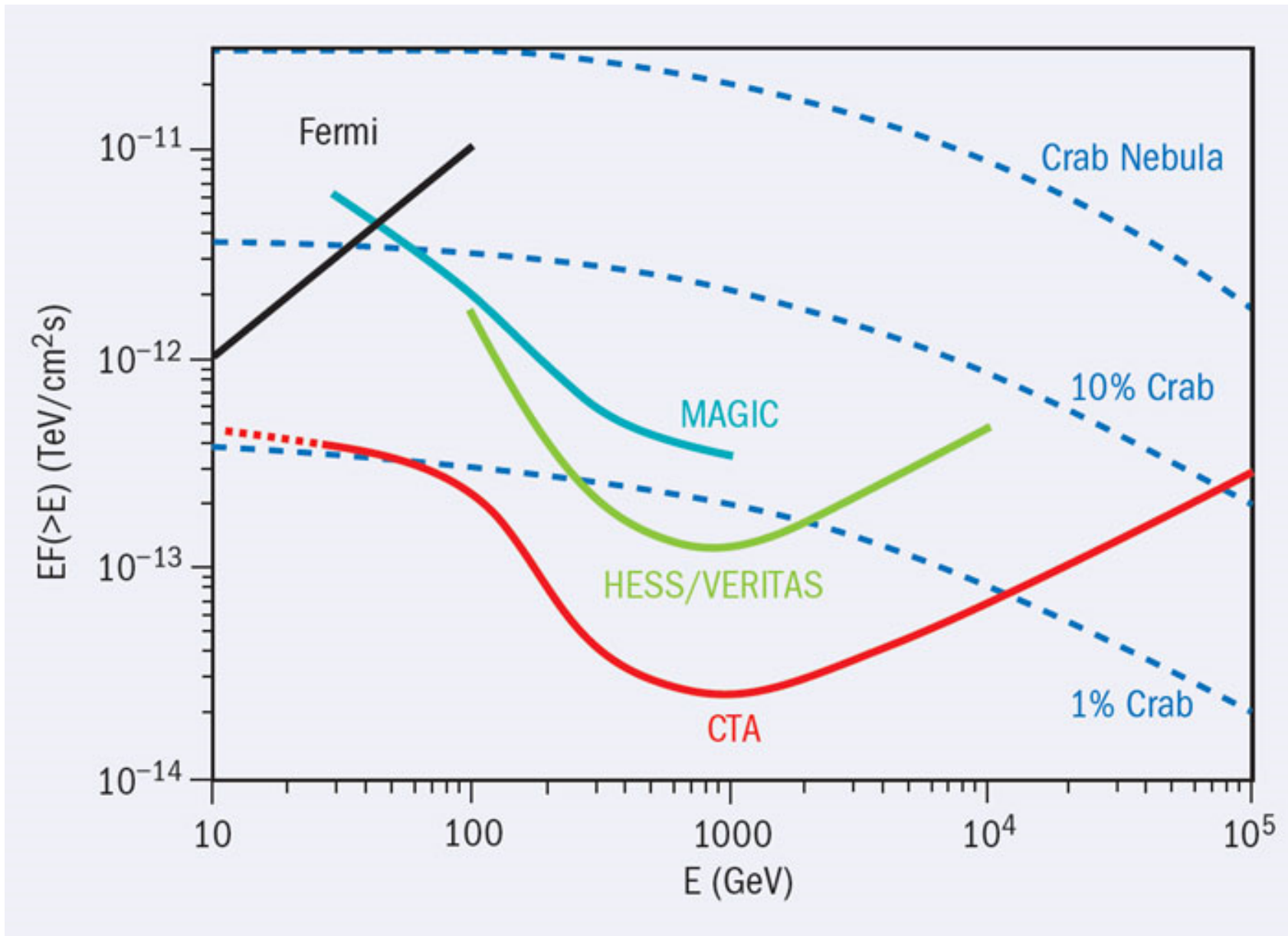
- Reflector : 28 m \varnothing ($\approx 600 \text{ m}^2$)
- Focal distance $\approx 35 \text{ m}$
- Camera: 2.5 m \varnothing ($\approx 3 \text{ t}$)
- 2048 PMTs (0.07° /pixel)
- FoV : $3^\circ \varnothing$
- Trigger rate 2-20 kHz
- Faster analogue memories needed
- Optimize data flow: 2nd level trigger

HESS II

- First light July 2012



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



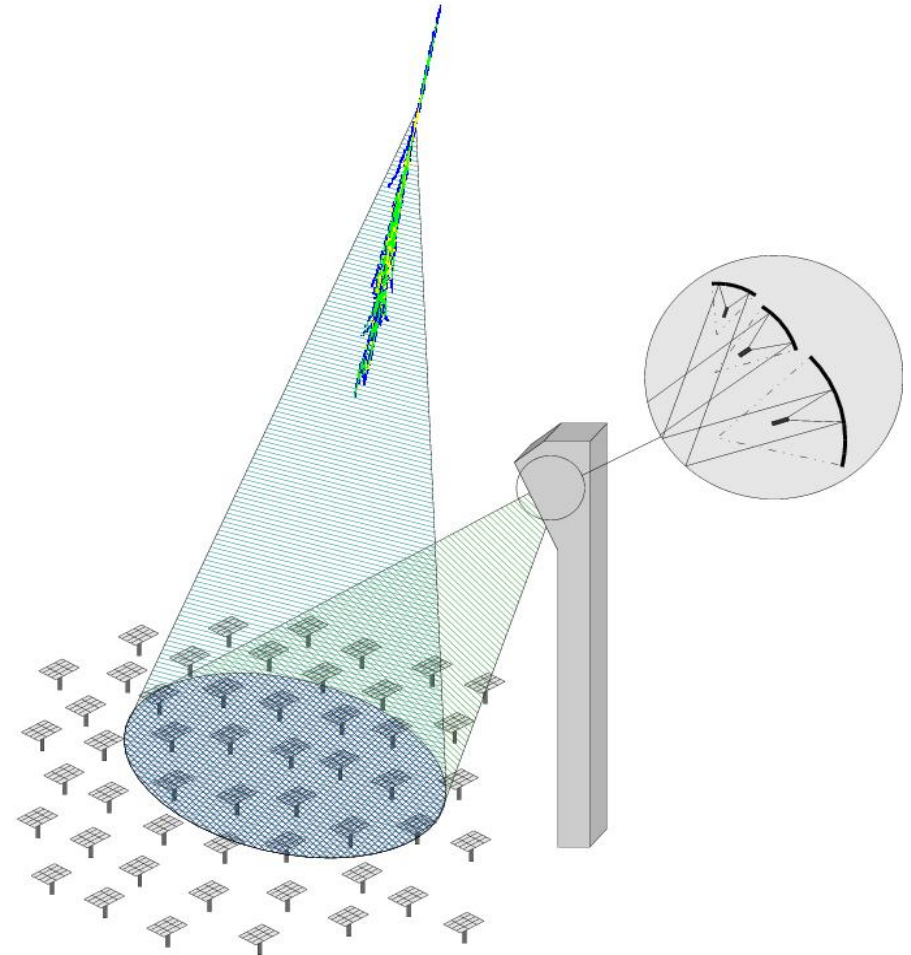
Toward a large array of ATCs : CTA

- **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.



A (once favored) alternative solution: sampling arrays

- To lower threshold, benefit of the very large mirror area from solar power plants
~ 2000 - 6000 m²
- Need to split the beam from the different heliostats
→ Secondary optics
- One PMT per heliostat.



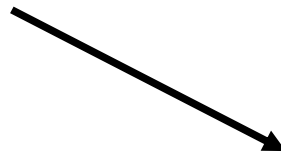
CELESTE (France)

$53 \times 54 \text{ m}^2$



STACEE (USA)

$64 \times 40 \text{ m}^2$



STACEE experiment, Sandia Laboratory, New Mexico

CACTUS (Barstow, California)

Converted Atmospheric Cherenkov Telescope Using Solar-2



“Hybrid” secondary -- heliostats share PMTs.



CACTUS (USA)

$160 \times 40 \text{ m}^2$

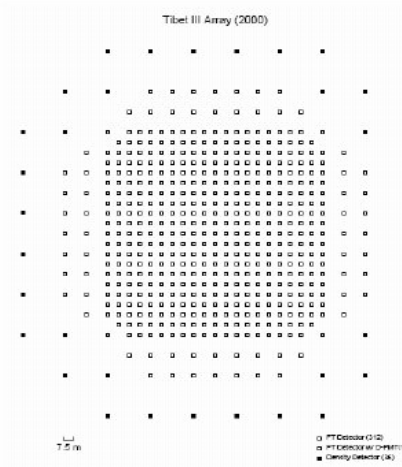
Large field of view gamma-ray detectors

- Detect the shower particle reaching ground (at high altitude) (scintillateurs, RPCs or water Cherenkov detectors)
- Large duty cycle $\approx 90\%$
- Large solid angle \sim 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

Tibet

- 4300m asl
- Scintillator array
- 497 detectors
 - 0.5m² each
 - 5mm lead on each
- 5.3x10⁴ m² (phys. area)
- 680 Hz trigger rate
- 0.9° resolution



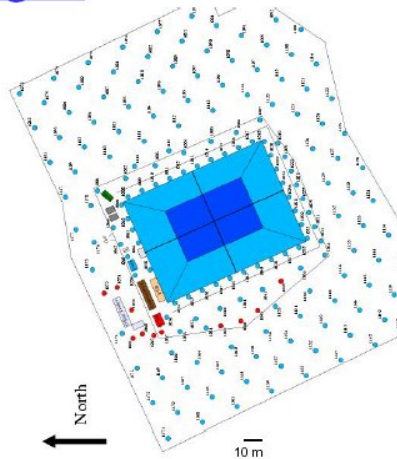
Tibet III

Scintillators



Milagro

- 2600m asl
- Water Cherenkov Detector
- 898 detectors
 - 450(t)/273(b) in pond
 - 175 water tanks
- 3.4x10⁴ m² (phys. area)
- 1700 Hz trigger rate
- 0.5° resolution
- 90% proton rejection



Milagro

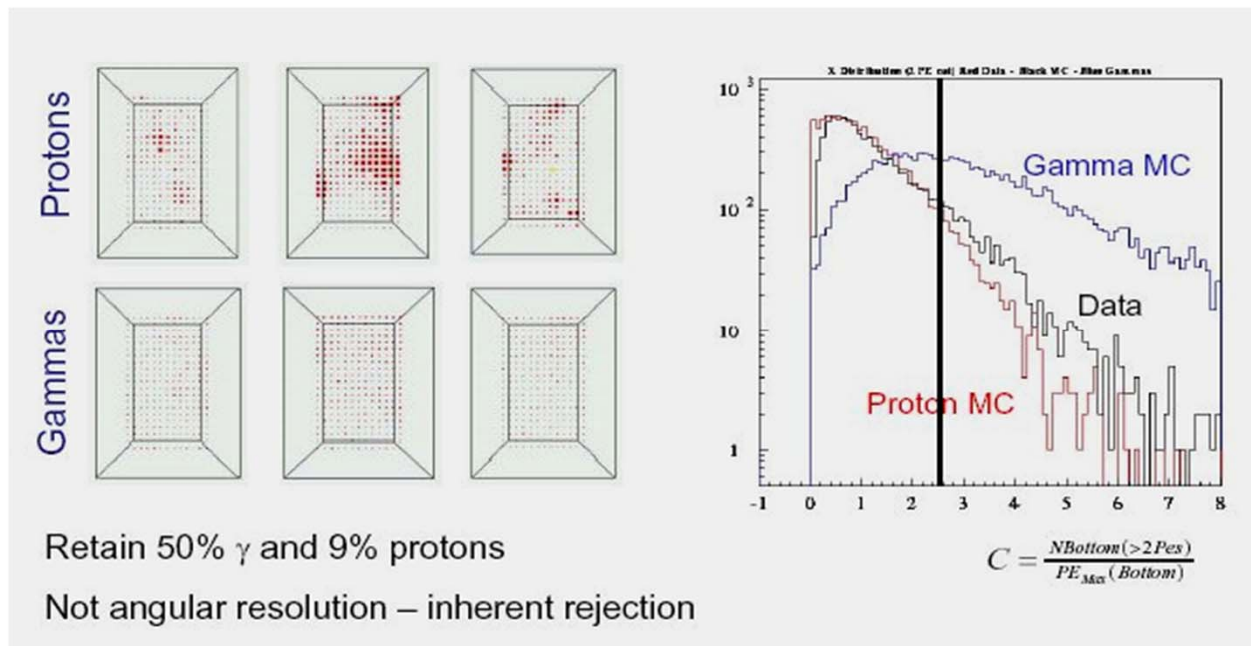


« water pool »

(water Cherenkov detectors)

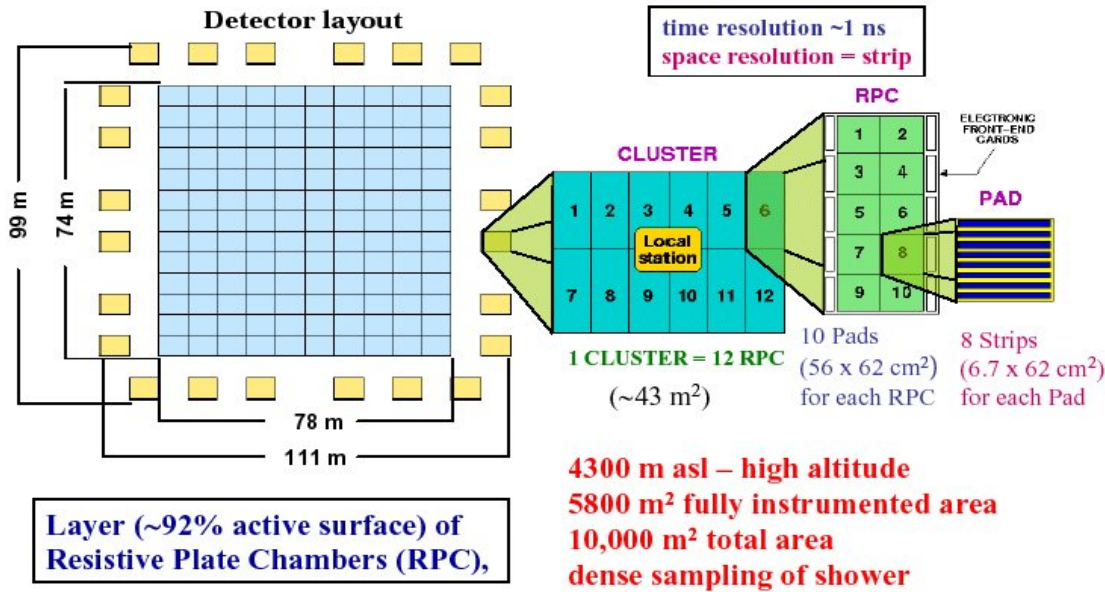
Hadronic background rejection by MILAGRO

- 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)



sensitivity (× 3)





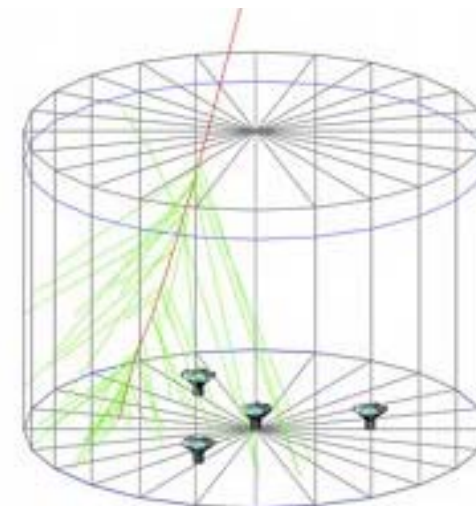
F.M. CIDHEAP / ESIPAP



300 tanks completed in Dec.2014

Sierra Negra volcano near Puebla, Mexico.
at an altitude of 4100 meters



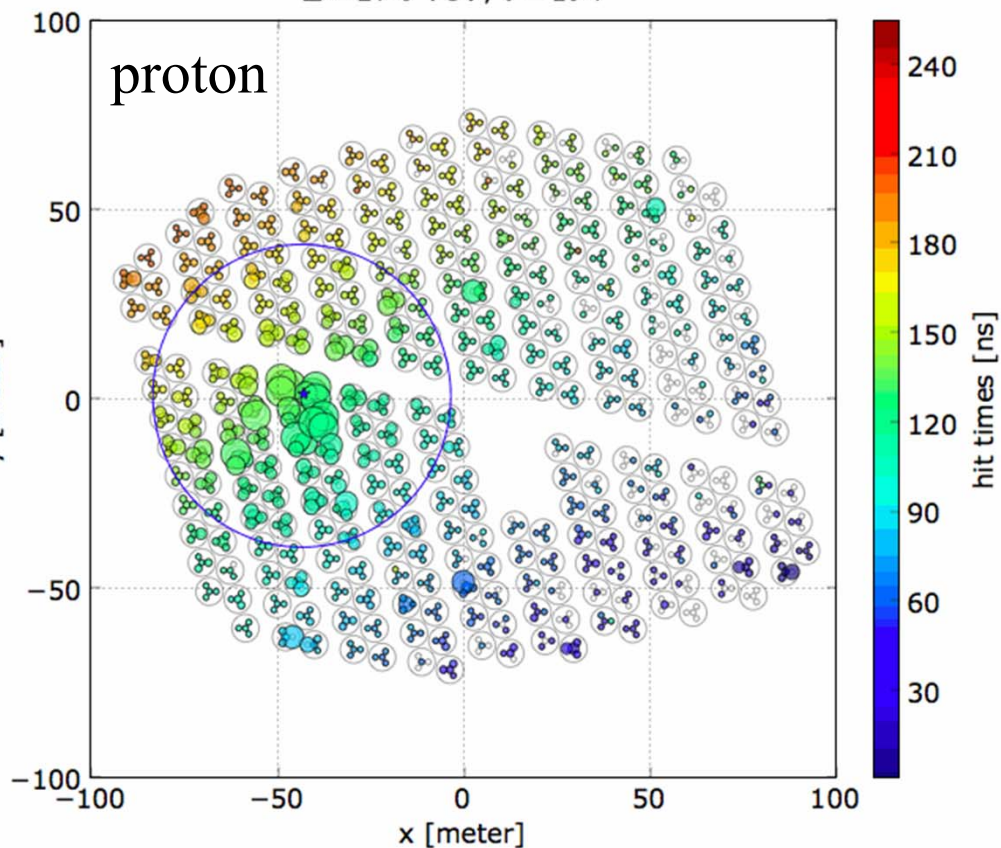


Gamma/Hadron rejection

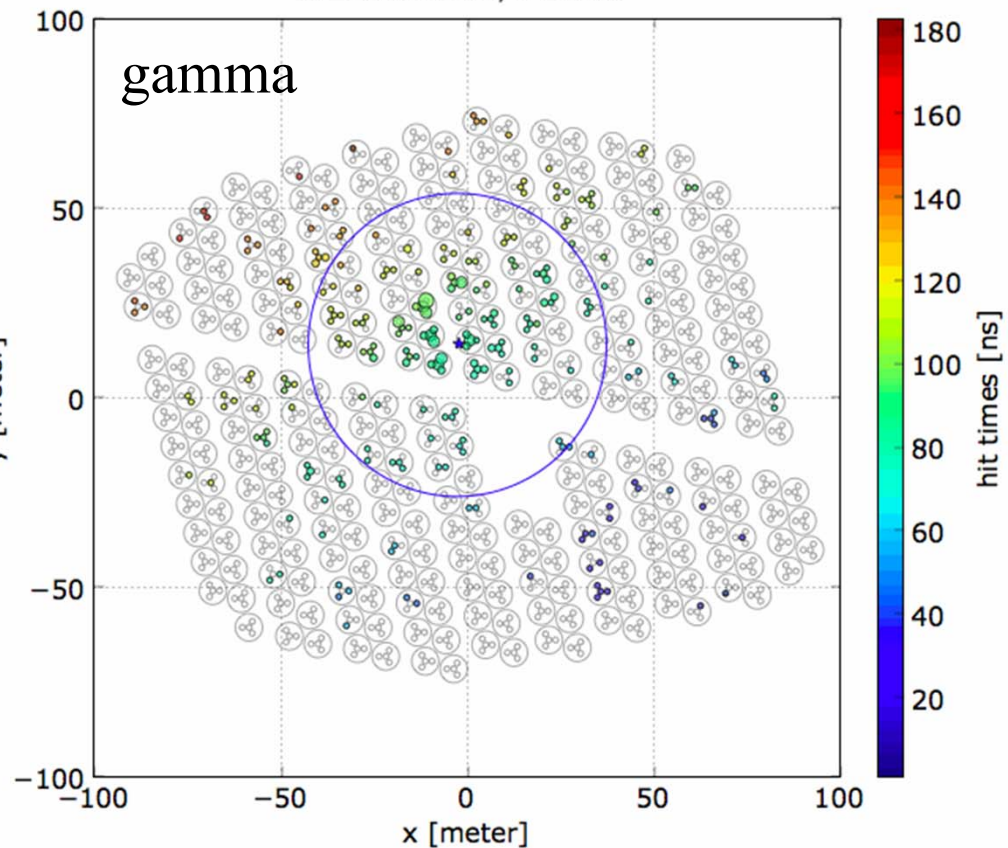
2020

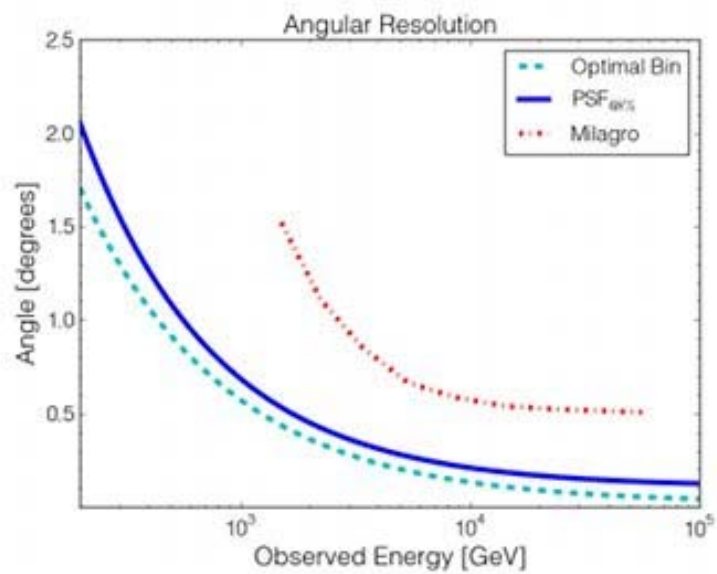
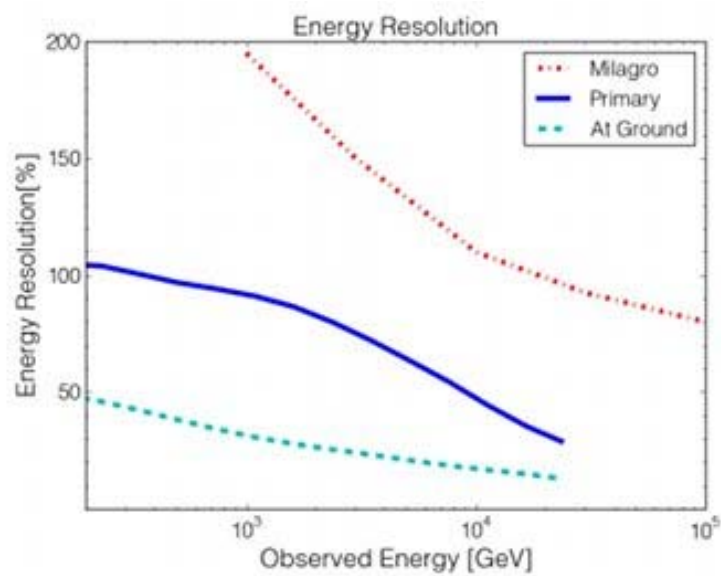
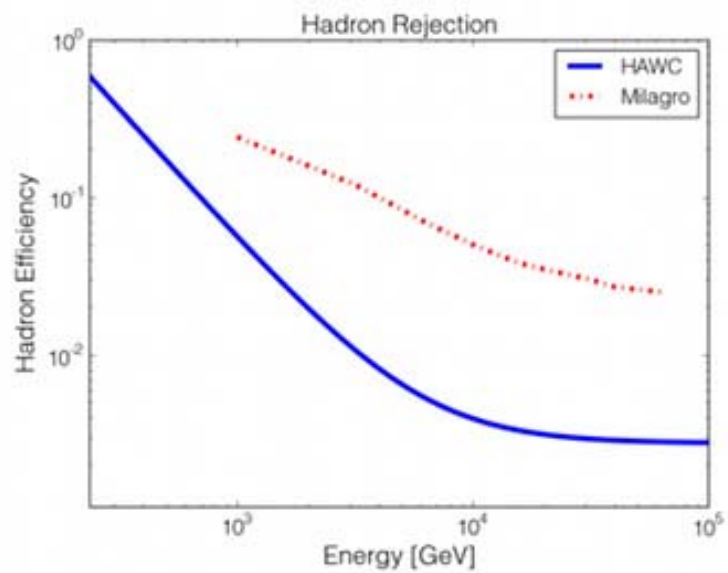
F. Y. M. HAWC ESIPAP

$E=27.0 \text{ TeV}, \theta=19.7^\circ$

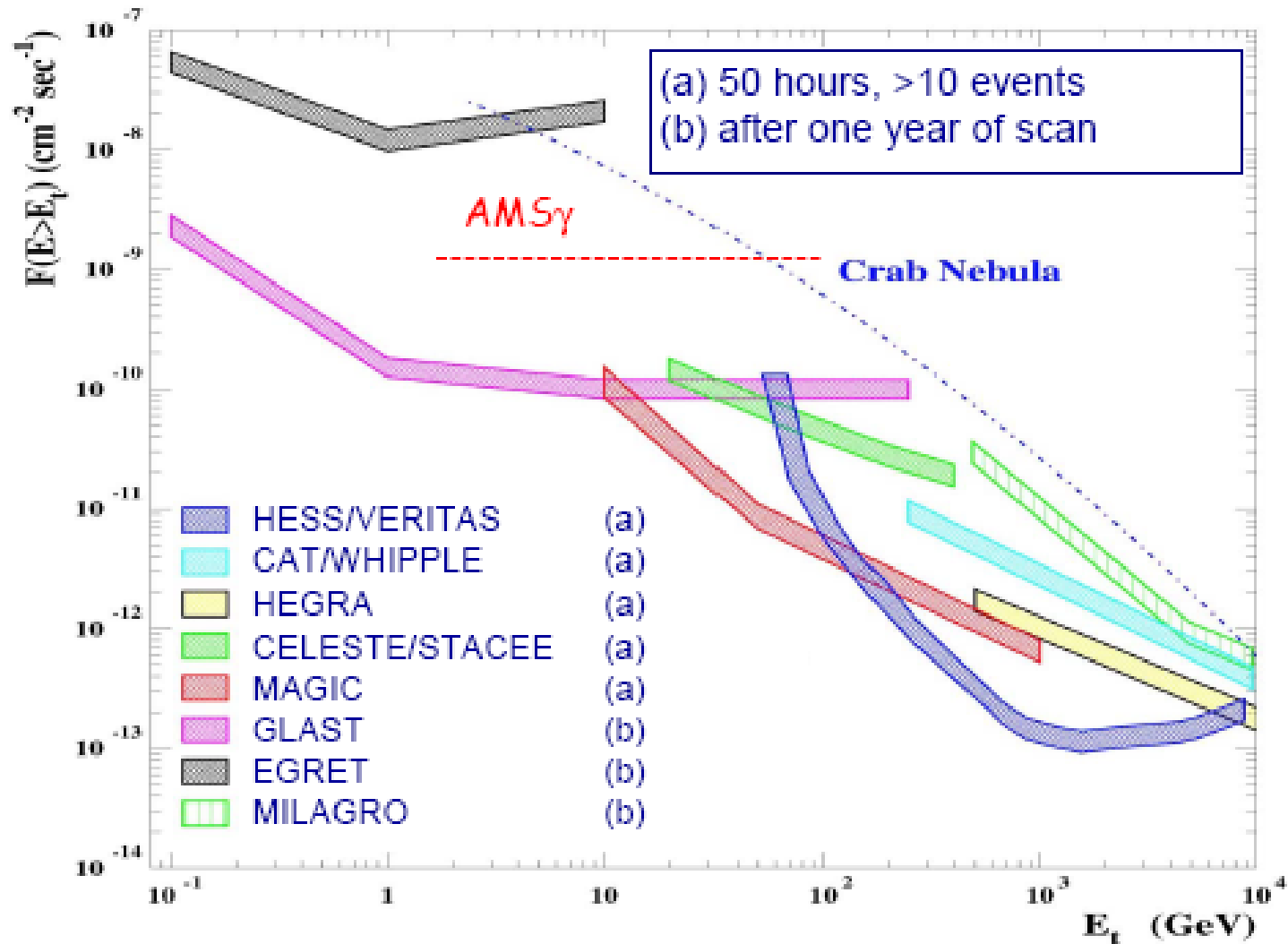


$E=609.6 \text{ GeV}, \theta=16.6^\circ$

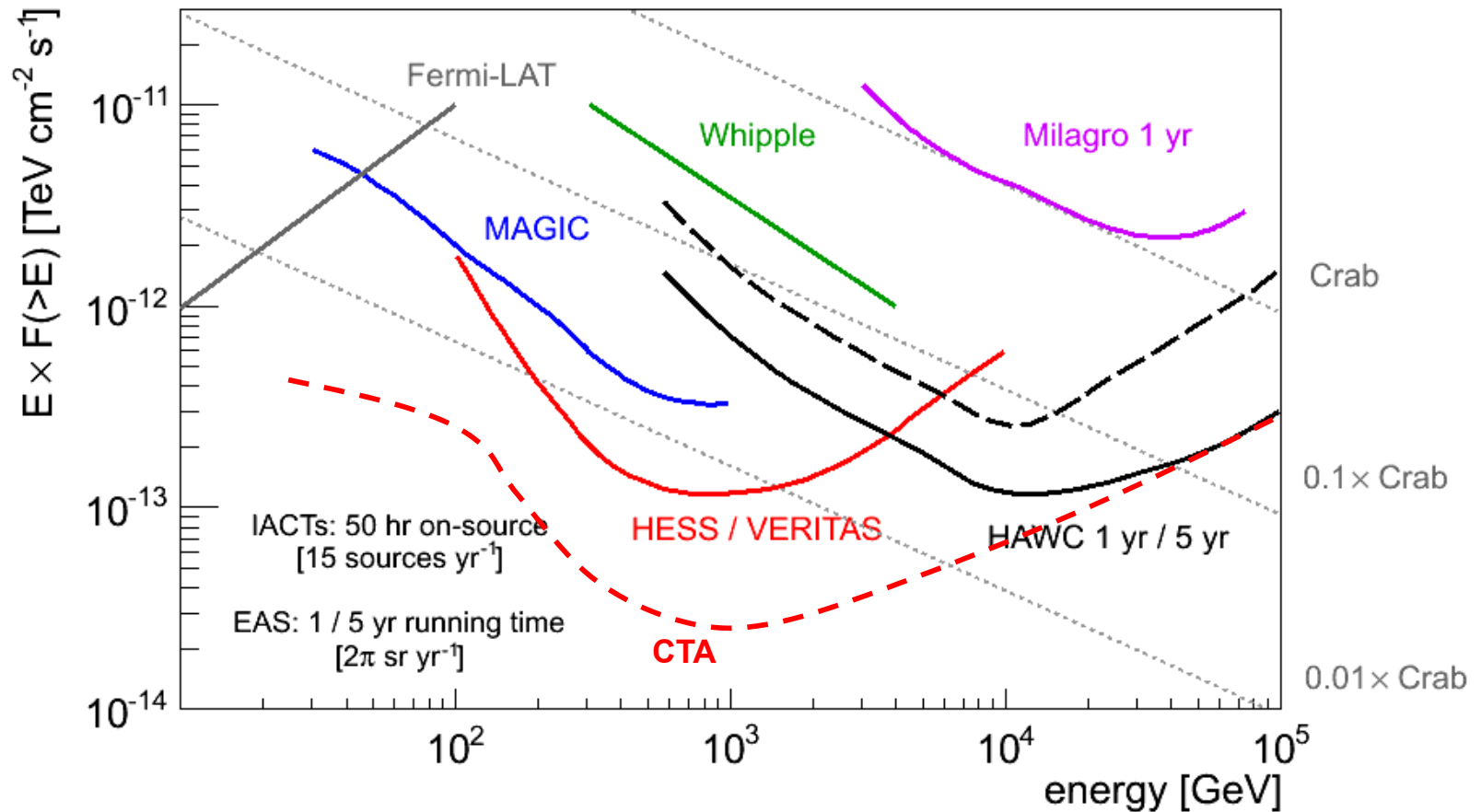




Old and current generation of space and ground γ -telescopes



New and future generation of space and ground γ -telescopes



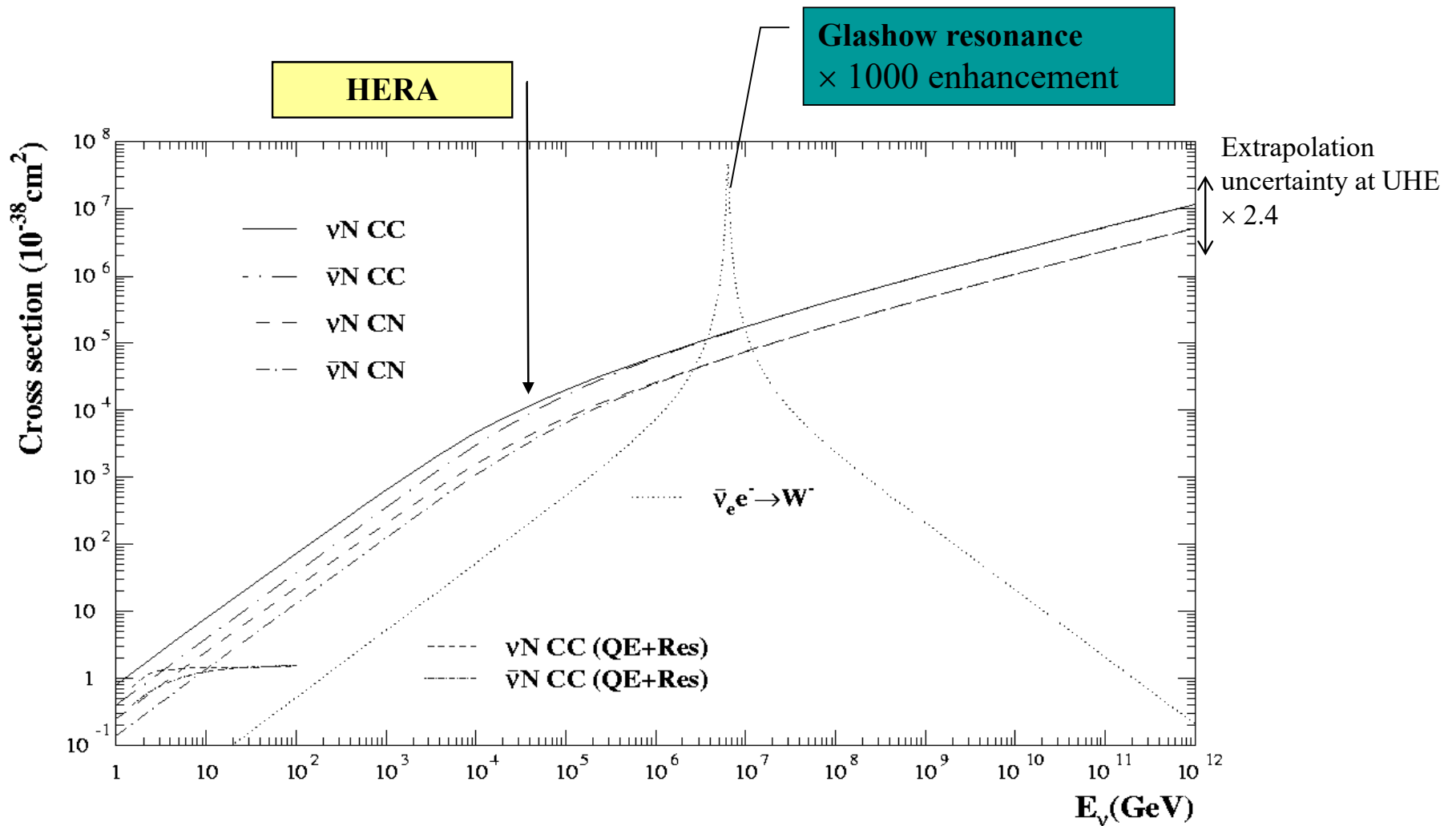
NEUTRINO TELESCOPES

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 km³ size.
ICECUBE so far the only one.
- **EeV:** arrays foreseen for UHECR detection proved to be very efficient for UHE⁰'s. Observe quasi horizontal showers with **AUGER.**

Neutrino cross sections

- ν -matter cross sections:



Neutrino detectors

... super heavy weight category !



ex. the WBB of CERN :

10^{13} 400 GeV protons per extraction

$\Rightarrow \phi_\nu \approx 10^6 \text{ v cm}^{-2}$ $\langle E_\nu \rangle \approx 20 \text{ GeV}$

with:

$\sigma_{\nu,N} = 0.6 \times 10^{-38} (E/\text{GeV}) \text{ cm}^2 \text{ GeV}^{-1}$

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

With a 100 tons detector, one gets:

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

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

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

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

GeV detection with SuperKamiokande

Atmospheric neutrino flux:

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

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

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

$$n = \rho N_A$$

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

thus :

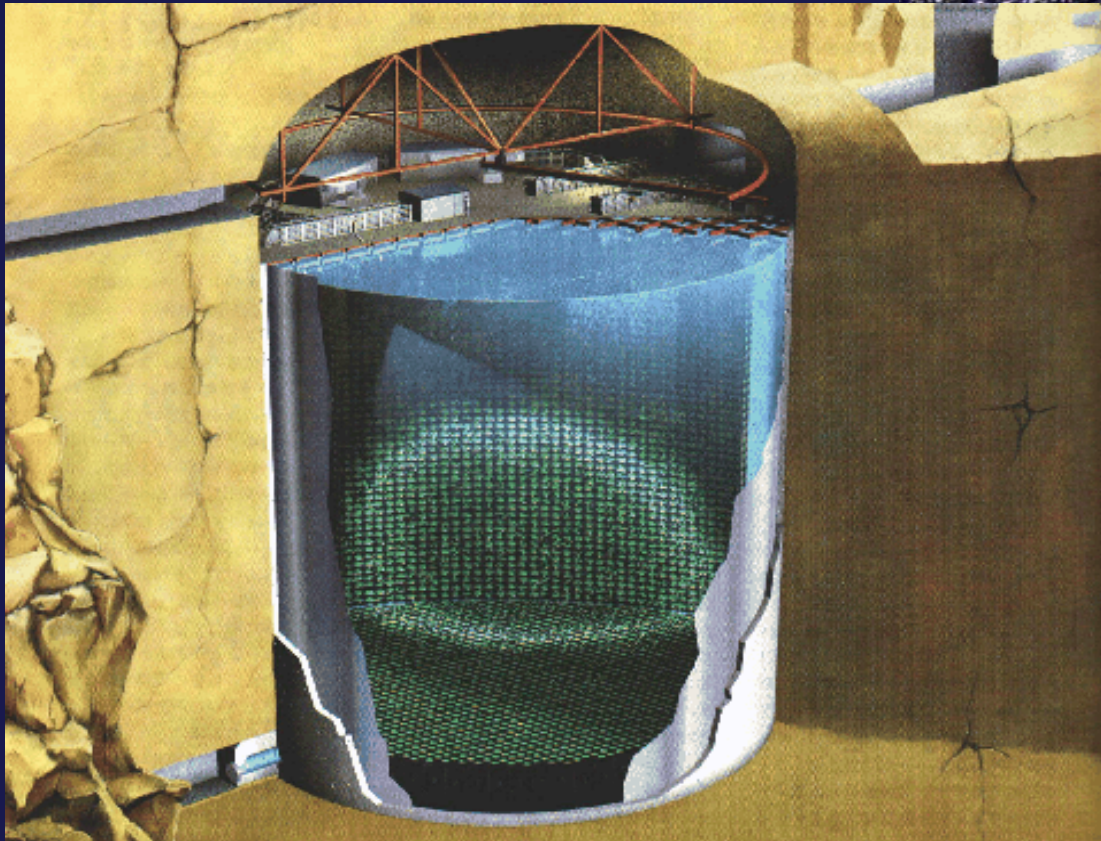
$$P(L) \sim \left(\frac{L}{1m}\right) \times 6 \cdot 10^{-13}$$

Number of events per day in a detector of volume $V=S \times L$

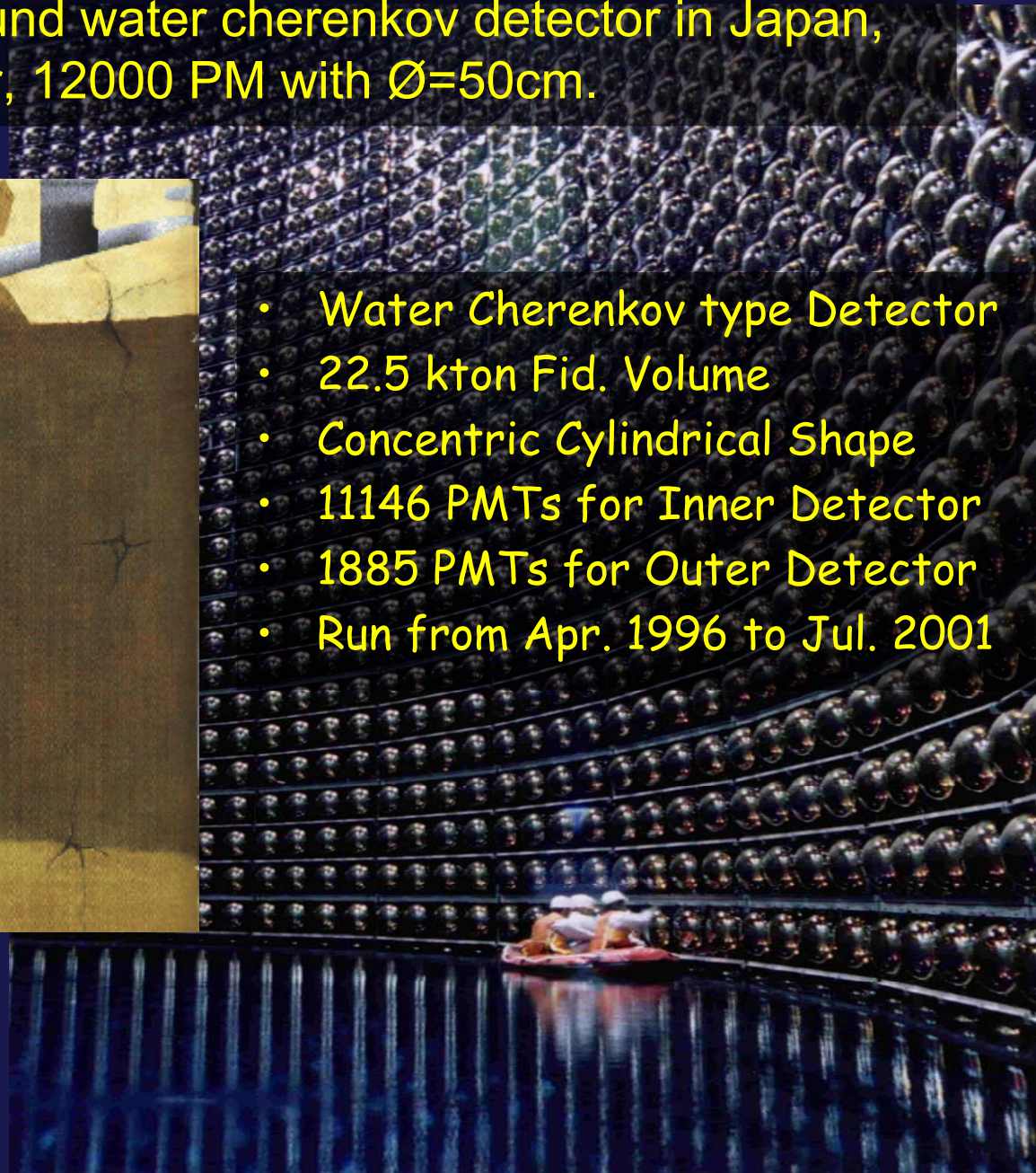
$$\begin{aligned} N &= \phi \Omega S P(L) \\ &\approx (2 \cdot 10^4 \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}) \times (4\pi \text{ sr}) \times (8 \cdot 10^4 \text{ s}) \times 6 \cdot 10^{-13} \times V \\ &\approx 1.2 \times 10^{-2} \text{ events/day / m}^3 \text{ of water} \end{aligned}$$

Super Kamiokande

- Super-Kamiokande, underground water cherenkov detector in Japan, 50000 tons of ultra pure water, 12000 PM with $\text{Ø}=50\text{cm}$.



- 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

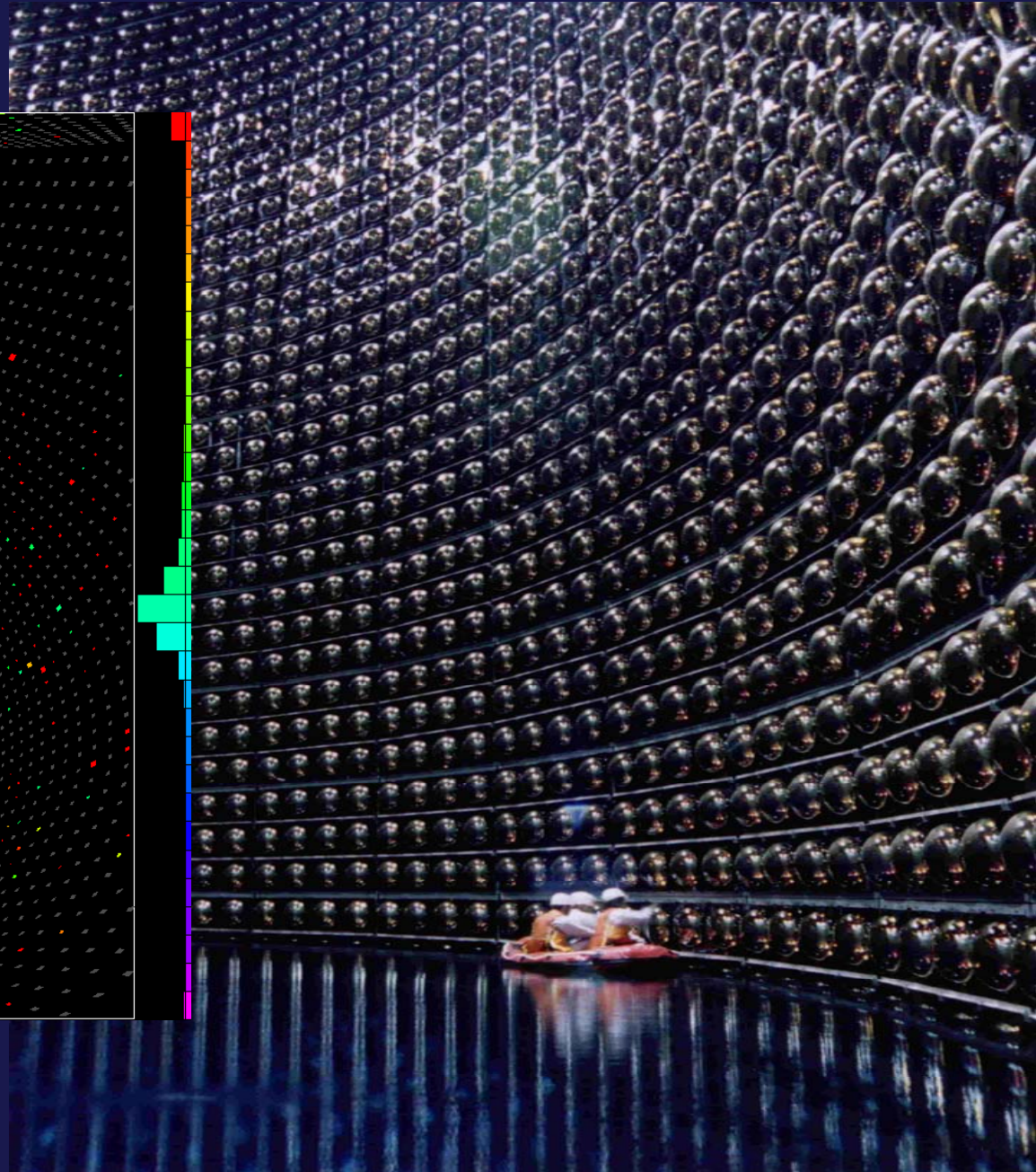
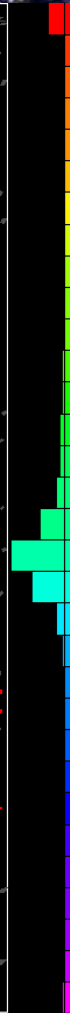
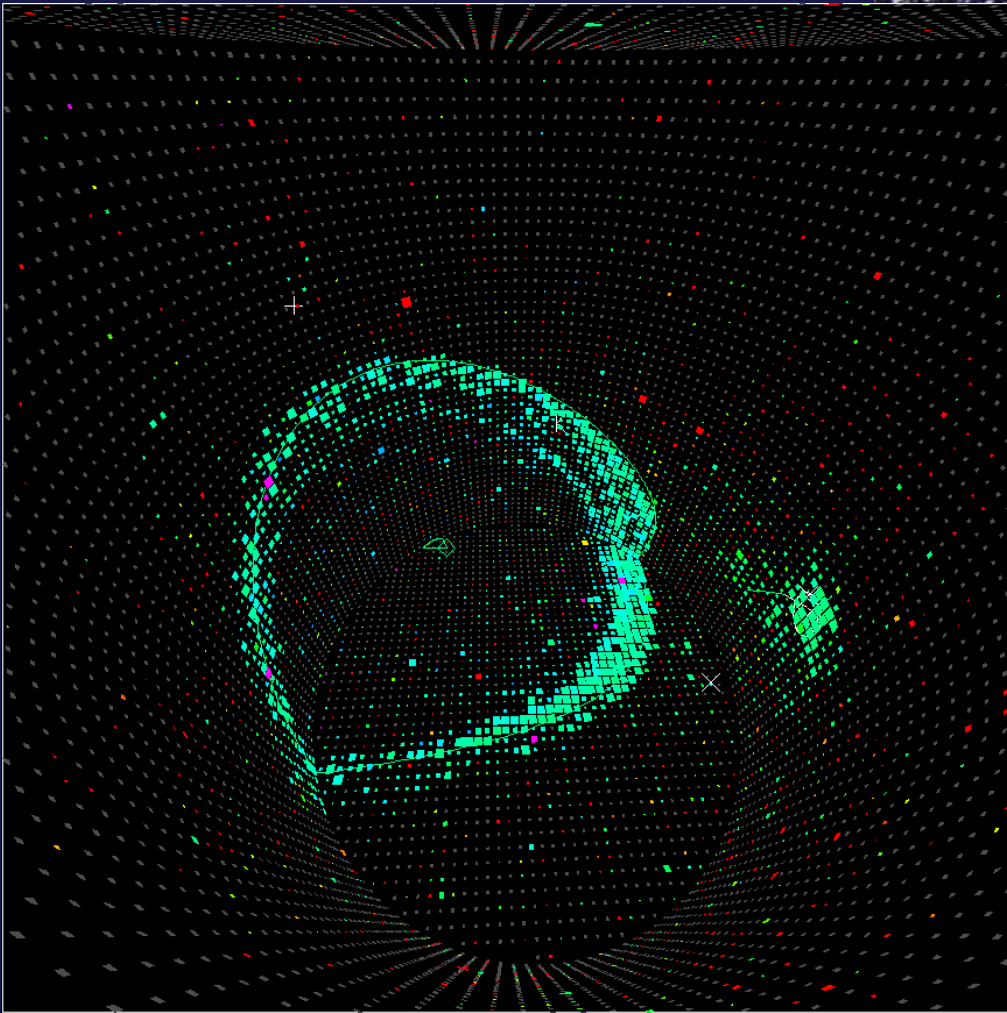


Super Kamiokande

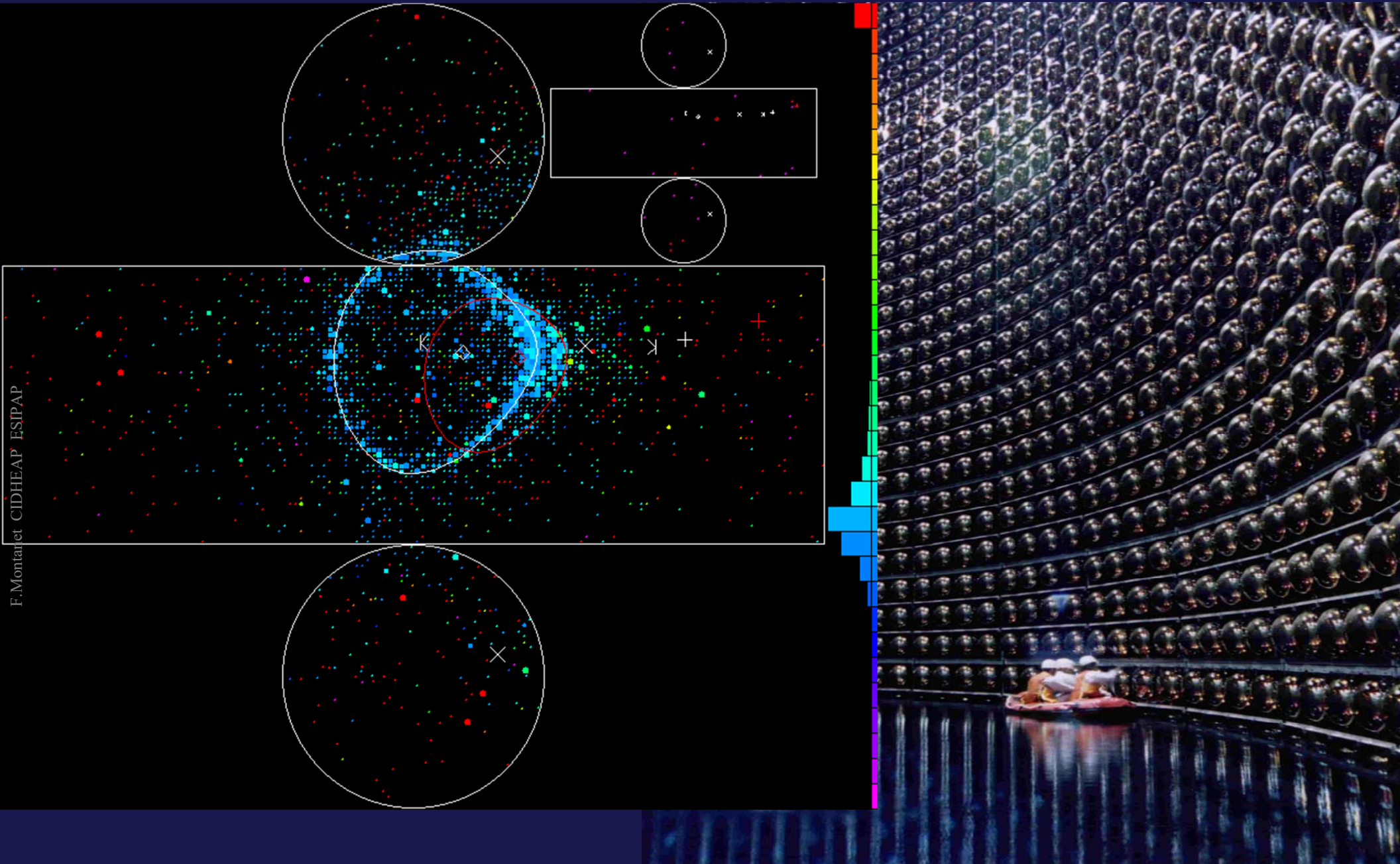
After rebuilt in 2006



Super Kamiokande

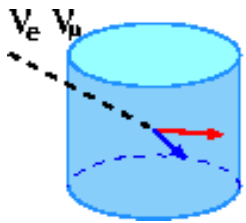


Super Kamiokande



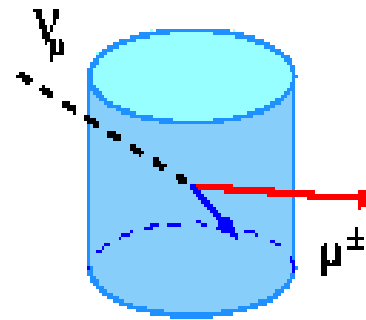
Event patterns in Super-Kamiokande

Fully Contained (FC) event



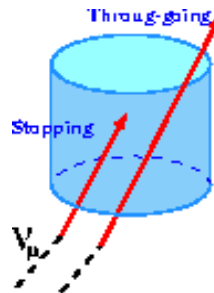
- All visible particles are contained in the detector
- both ν_μ, ν_e via NC or CC interaction
- Typically $E_\nu = 1$ GeV
- Particle ID

Partially Contained (PC) event



- At least 1 charged particle escapes from detector
- ν_μ CC (97%)
- Typically $E_\nu = 10$ GeV

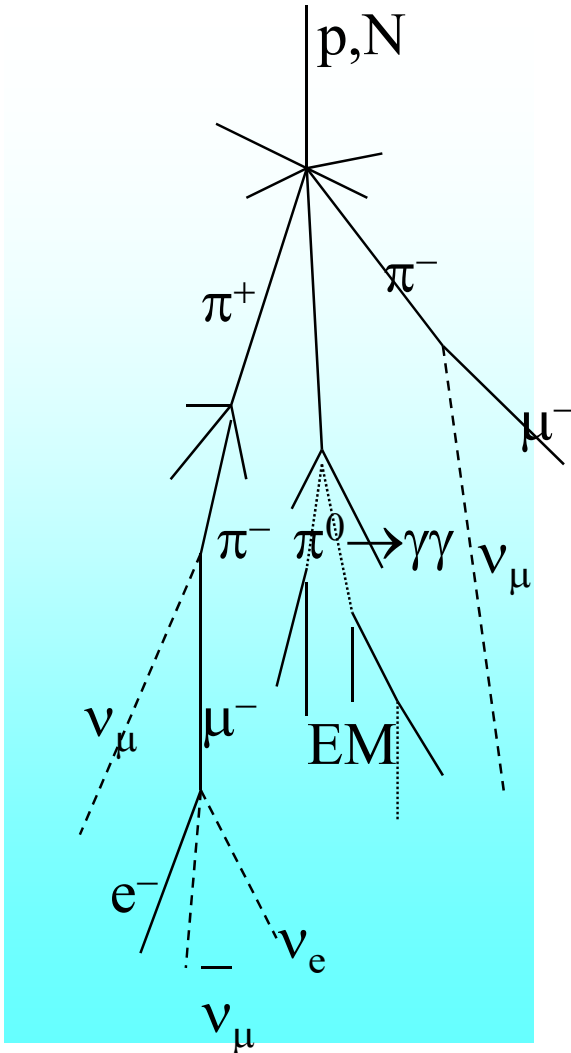
Upward-going muons (Up-mu)



- Entering muon from below
- ν_μ CC only
- $E_\nu = 10$ GeV (stopping),
100 GeV (through-going)

Super-Kamiokande covers $E_\nu = 100$ MeV \sim over 1 TeV

Atmospheric neutrinos



– Atmosphere :

- $\sim 1000 \text{ g/cm}^2$
- $\sim 20 \text{ km}$
- 11 nuclear λ_{int}

– ν dominated by :

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

– Kinematics :

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\langle E_\mu \rangle = 0.787 E_\pi$$

$$\langle E_\nu \rangle = 0.213 E_\pi$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

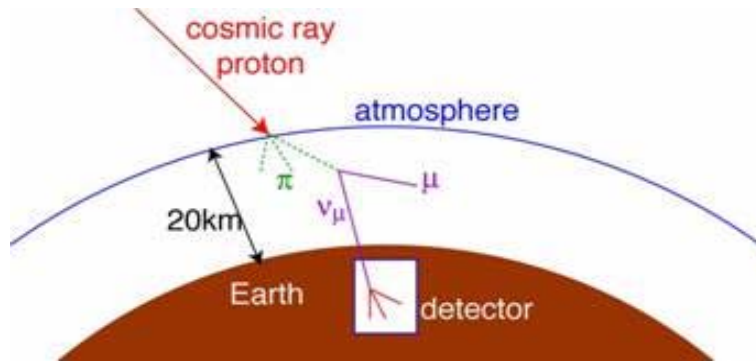
$$\langle E_\nu \rangle = 1/3 E_\mu$$

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

– 1 GeV sea level neutrino flux:

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

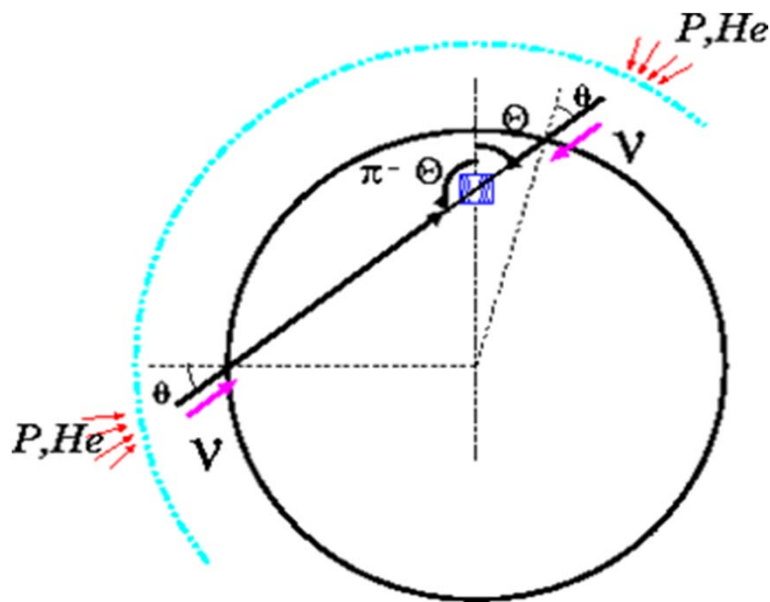
Atmospheric neutrinos



- Flavor ratio

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

$$> 2 \text{ for } E_{\nu} > \text{qq GeV}$$



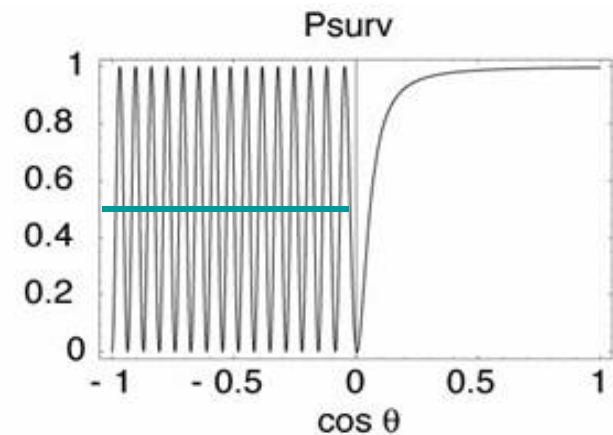
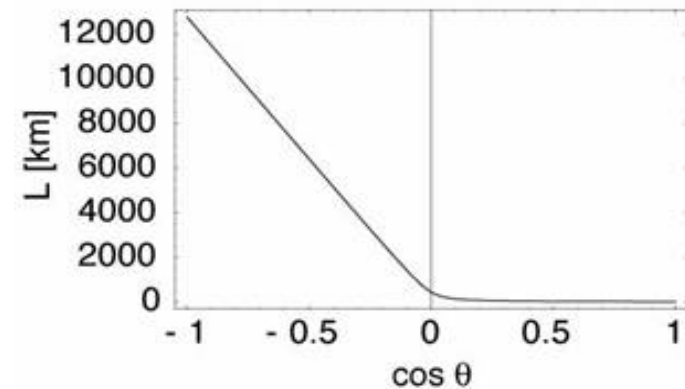
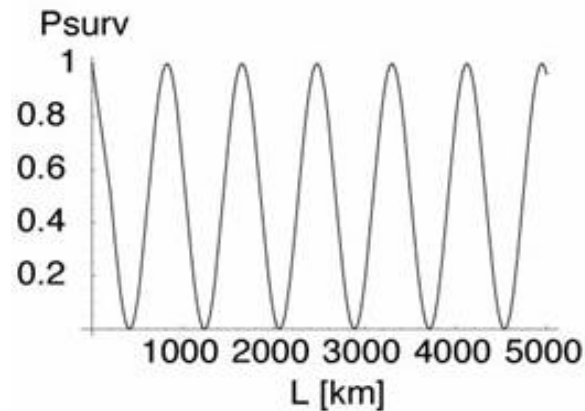
- top down symmetry

for $E_{\nu} > \text{qq GeV}$

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

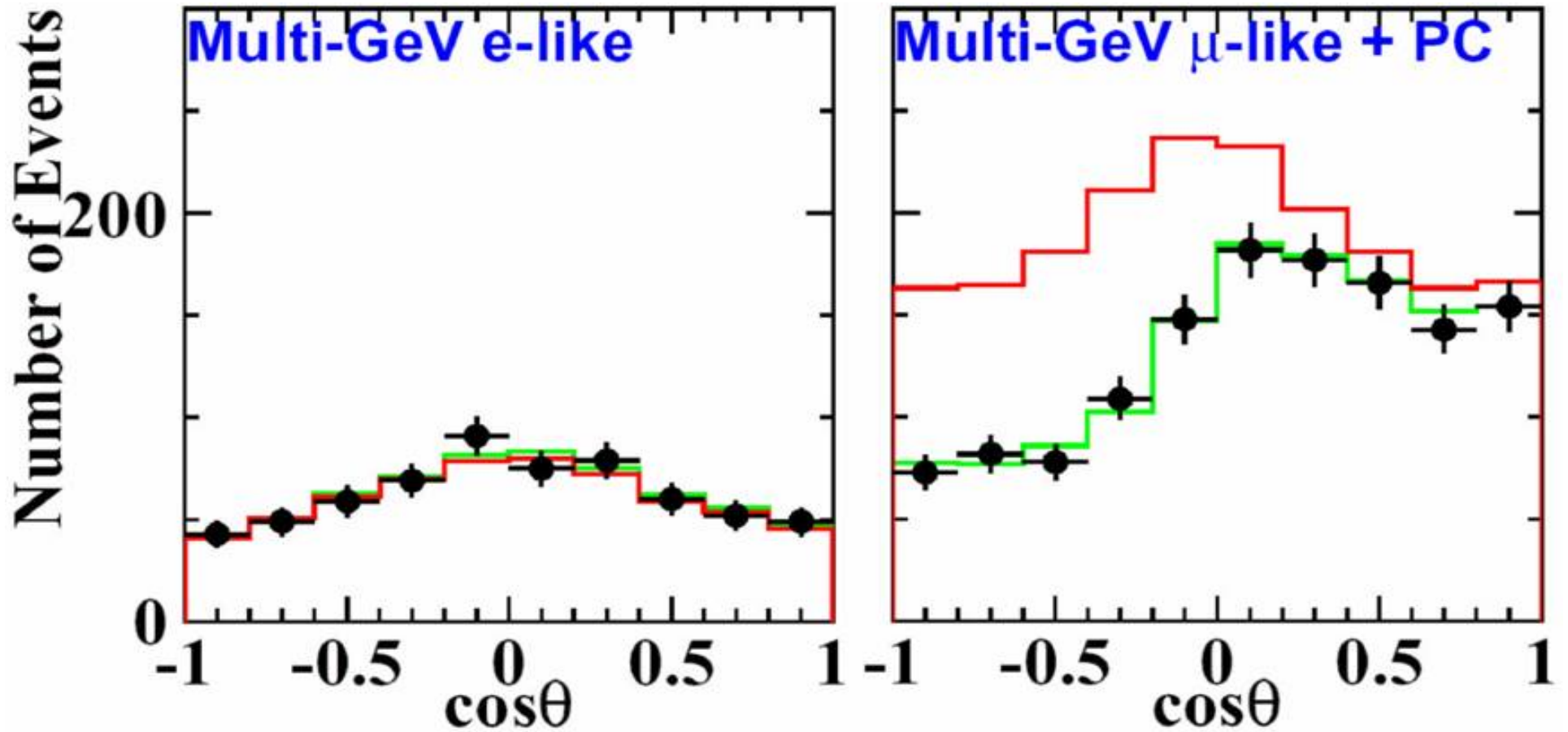
Survival probability

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



Half of upgoing ν_{μ}
are lost.

Half of ν_μ disappeared !



**Matrix of PMTs:
“Optical Modules”**

Muon trace:

Direction: from precise timing

$$\langle \theta_\nu - \theta_\mu \rangle \approx 0.7^\circ / E^{0.6}(\text{TeV})$$

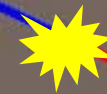
Muon energy: very rough lower limit using EM energy losses (pair production, small showers etc...) along the muon track.

**Cherenkov
cone**

muon

Detector

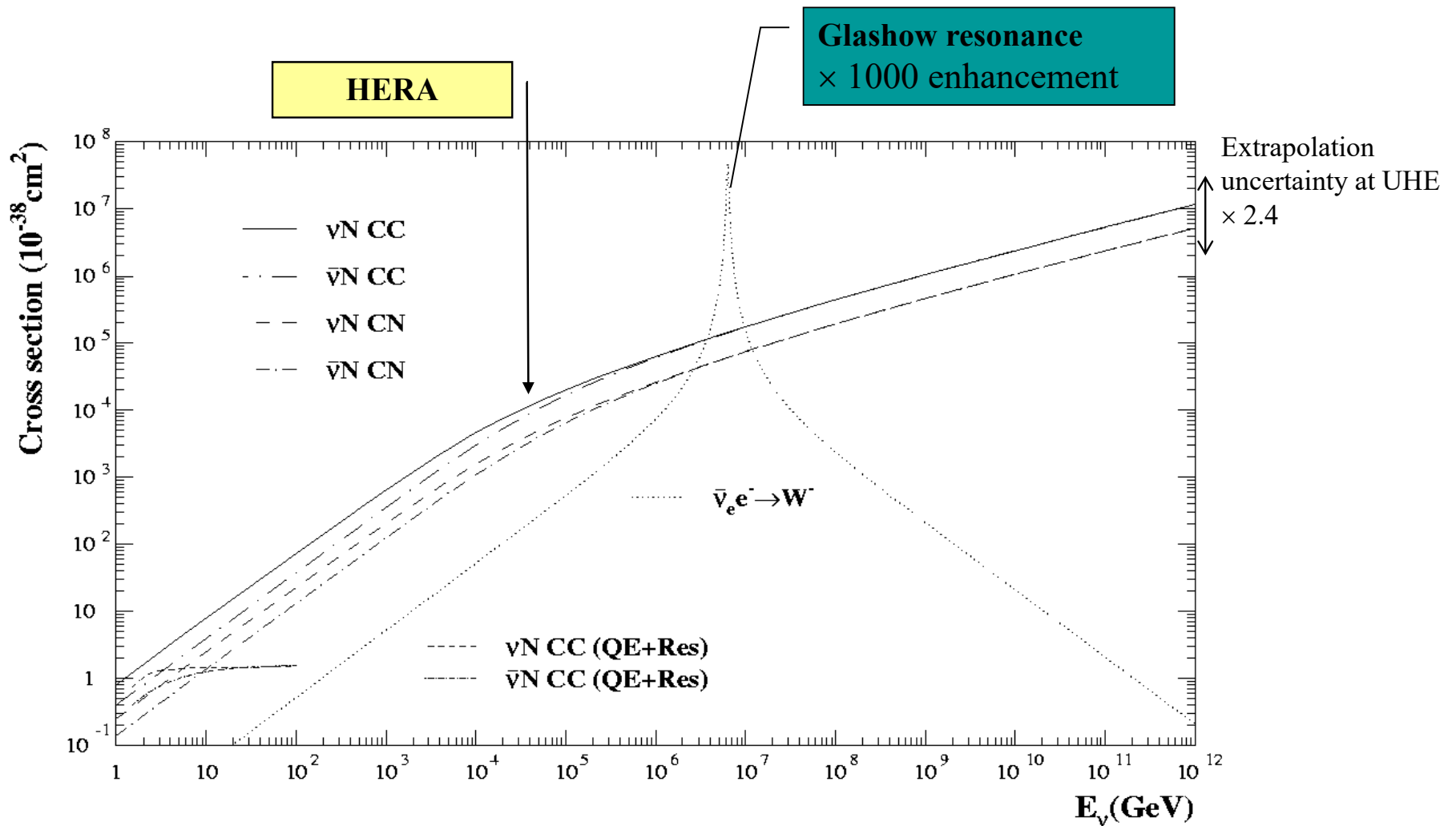
interaction



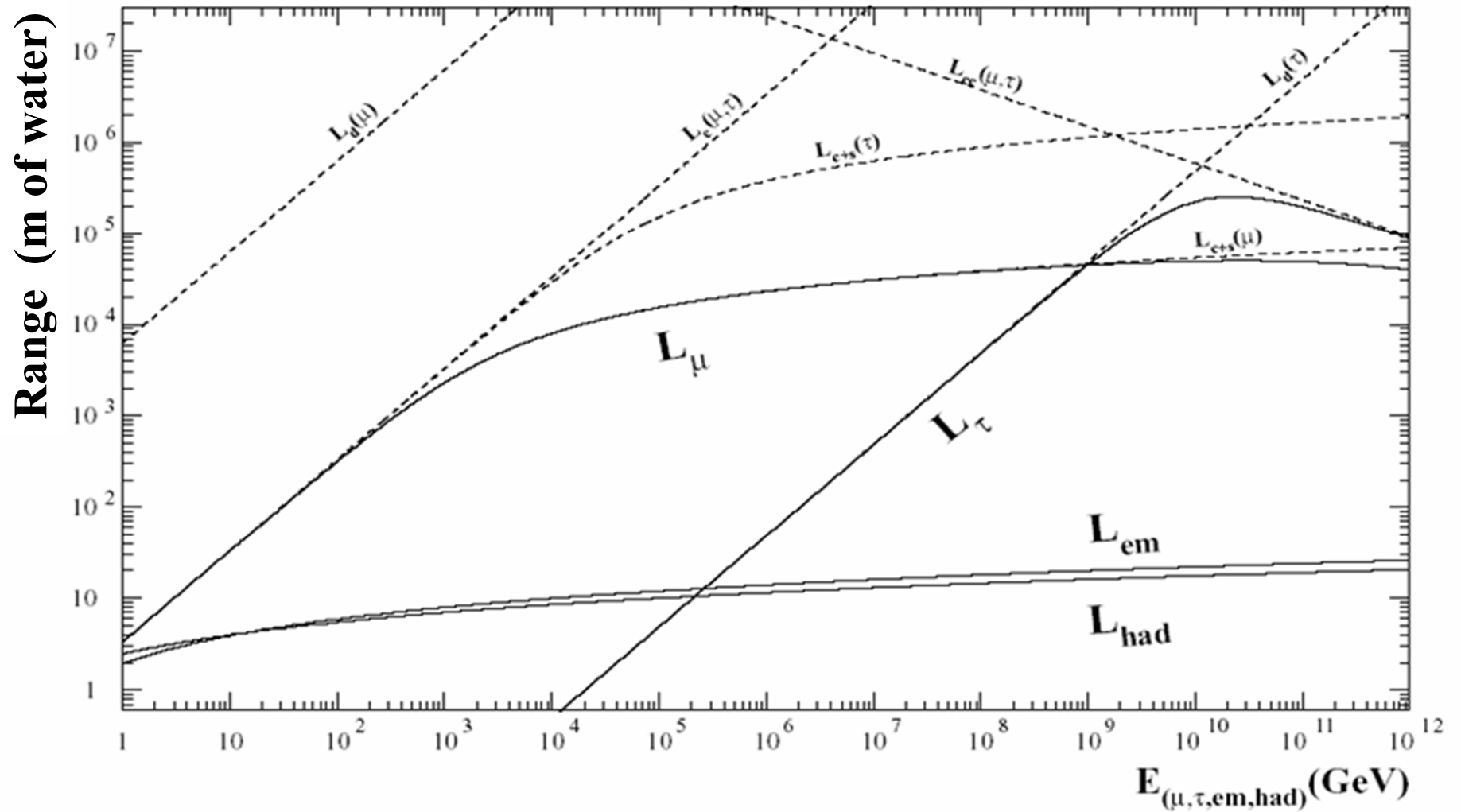
neutrino

Neutrino cross sections

- ν -matter cross sections:

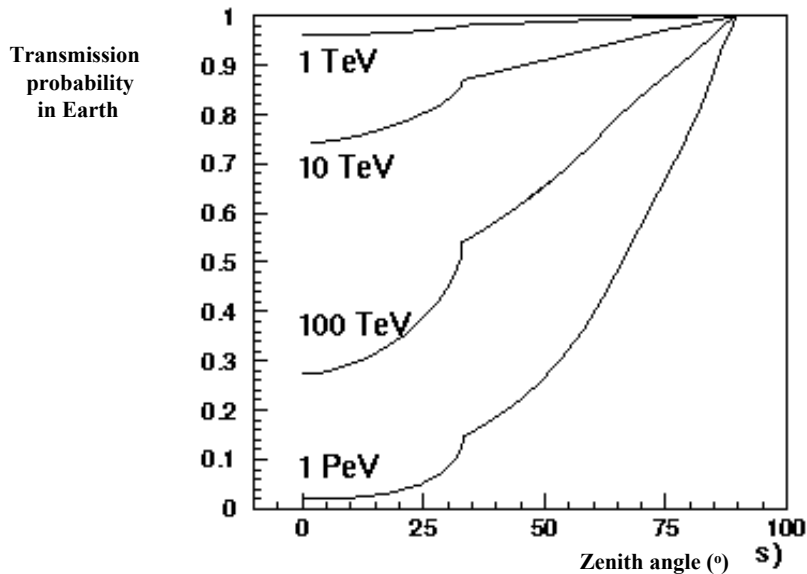


Particle Ranges



Earth opacity

The earth is transparent to ν_μ
 < 100 TeV



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.

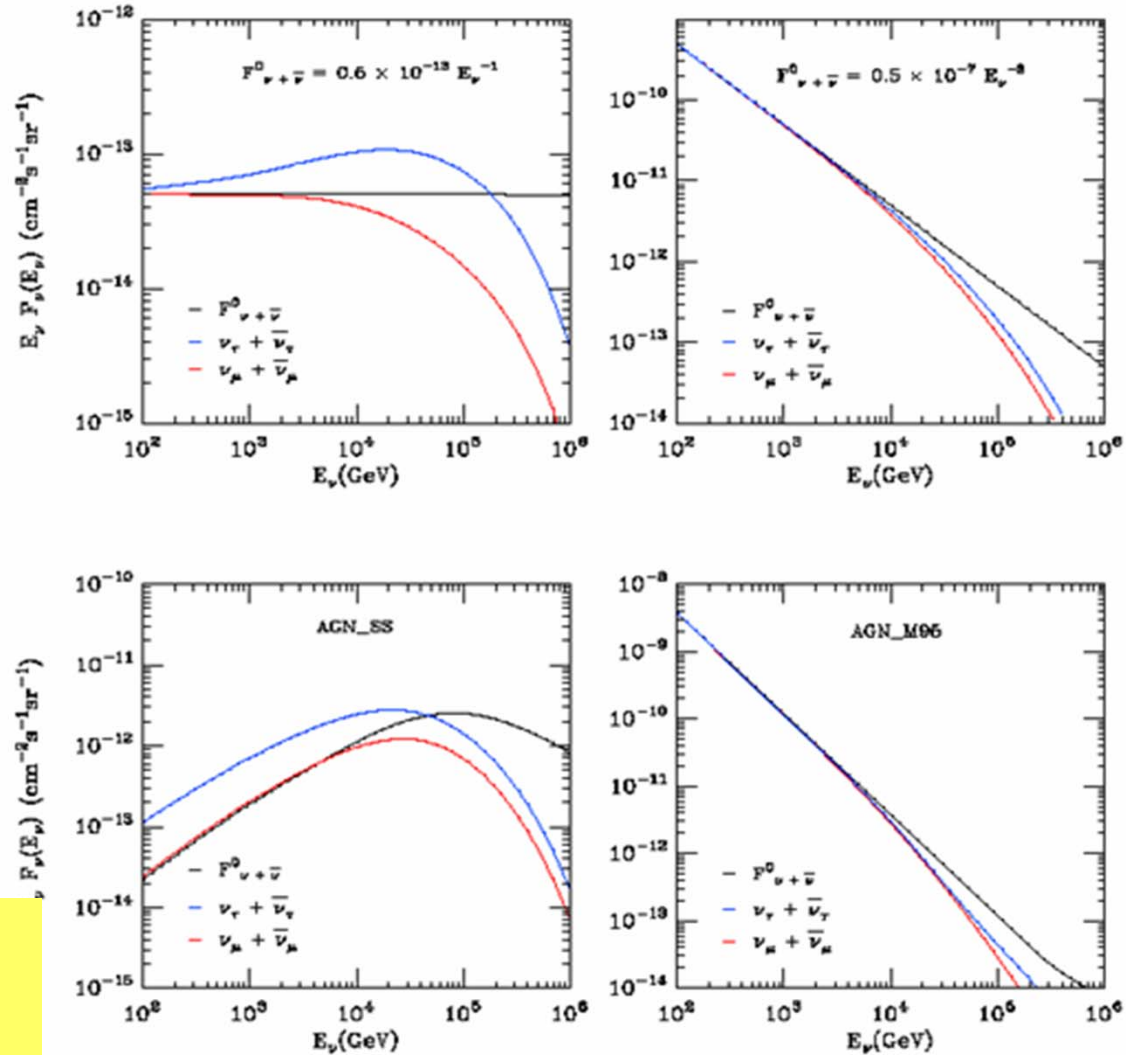
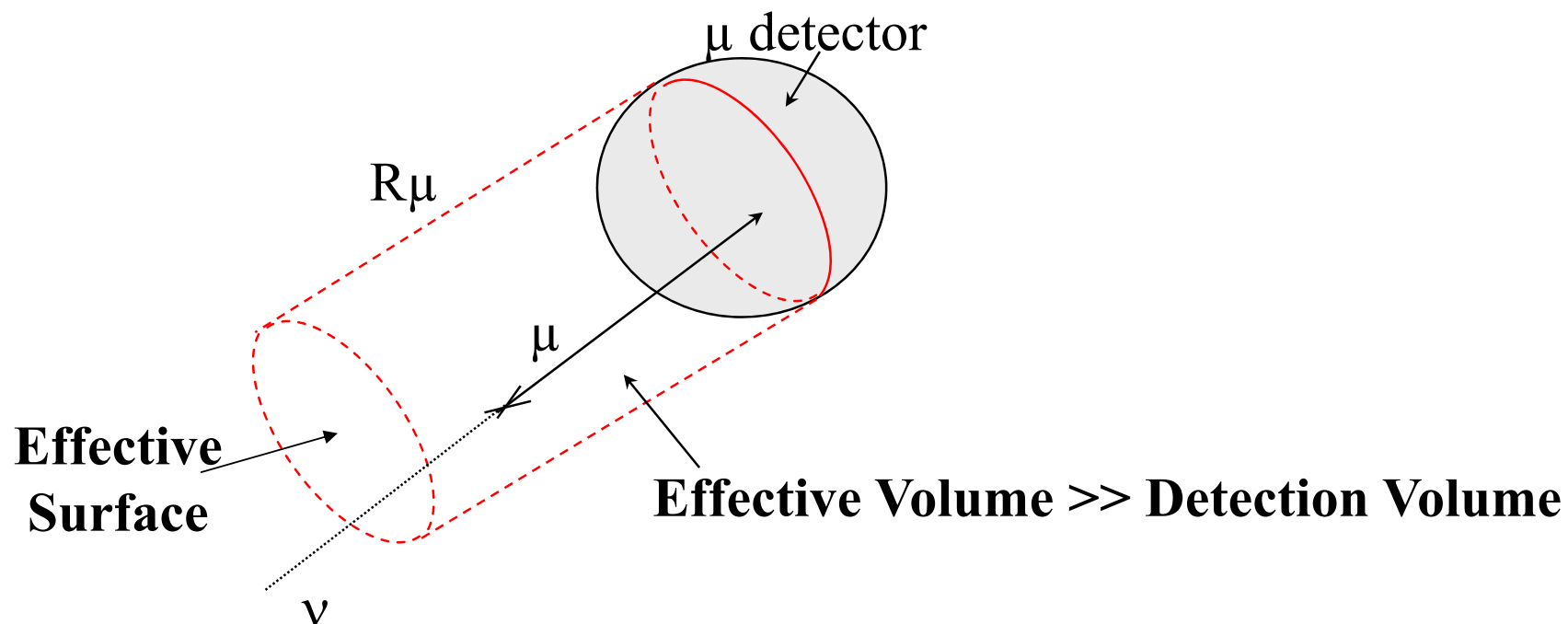


FIG. 2. Muon neutrino plus antineutrino flux (black line), the effect of its attenuation for $\theta = 0^\circ$ (red line) and tau neutrino plus antineutrino upward flux for the same initial flux and the same nadir angle (blue line) for a) E^{-1} flux b) E^{-2} flux c) AGN_SS and d) AGN_M96.

Detection principles

- The effective target volume is / the muon range



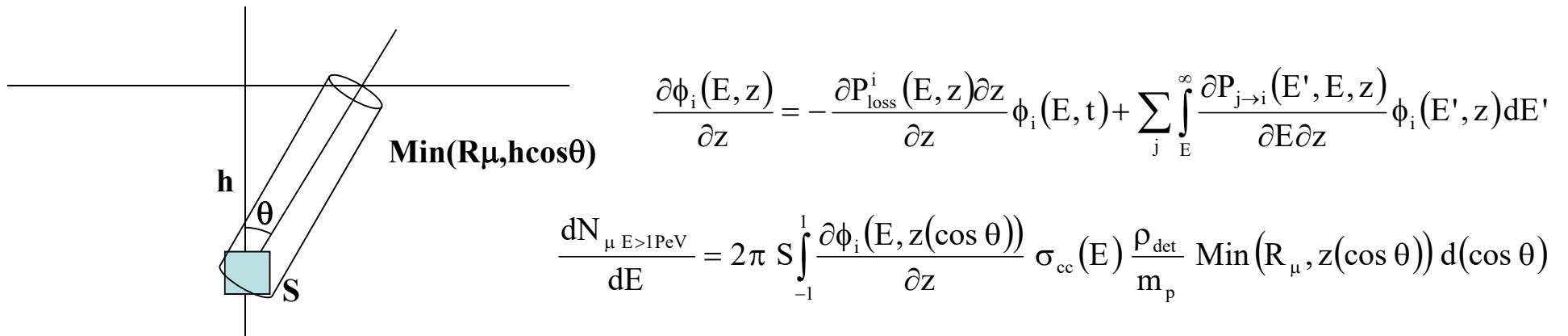
$$V_{\text{eff}}(E_\mu) = A_{\text{eff}}(E_\mu) \cdot R_\mu(E_\mu)$$

$$R_\mu = 2 \text{ km @ 1 TeV}$$

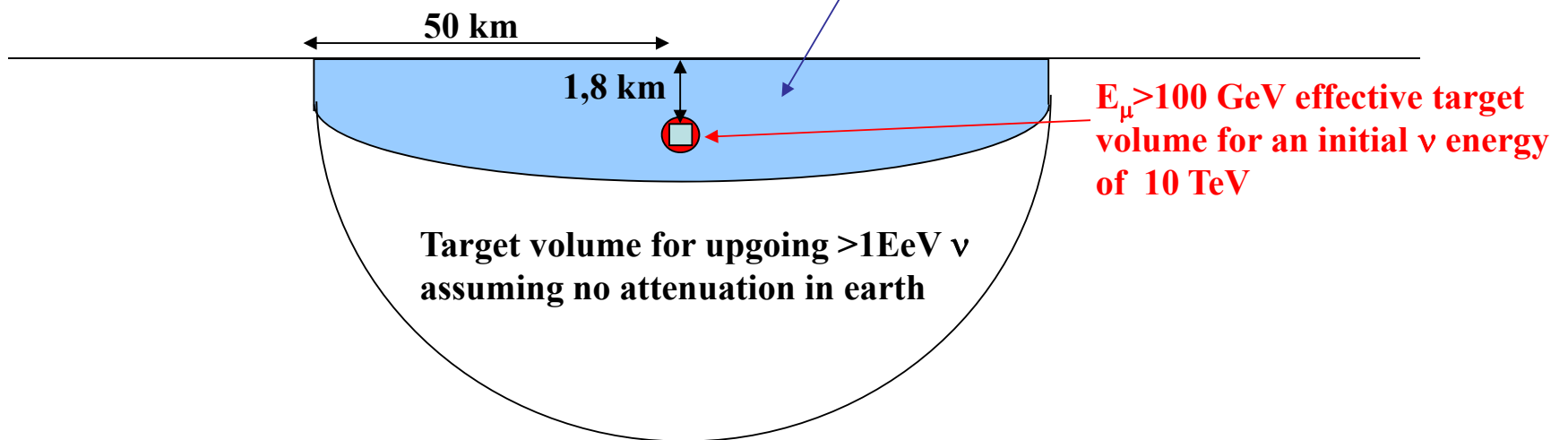
$$R_\mu = 10 \text{ km @ 100 TeV}$$

$$R_\mu^{\text{max}} = 50 \text{ km @ 1 EeV}$$

PeV ν_μ in IceCube



Target volume accounting for $E_\mu > 1 \text{ PeV}$ range and an ν initial energy of $1 \text{ EeV} \sim 10^{13}$ tons of ice.



Neutrino Telescope Projects

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

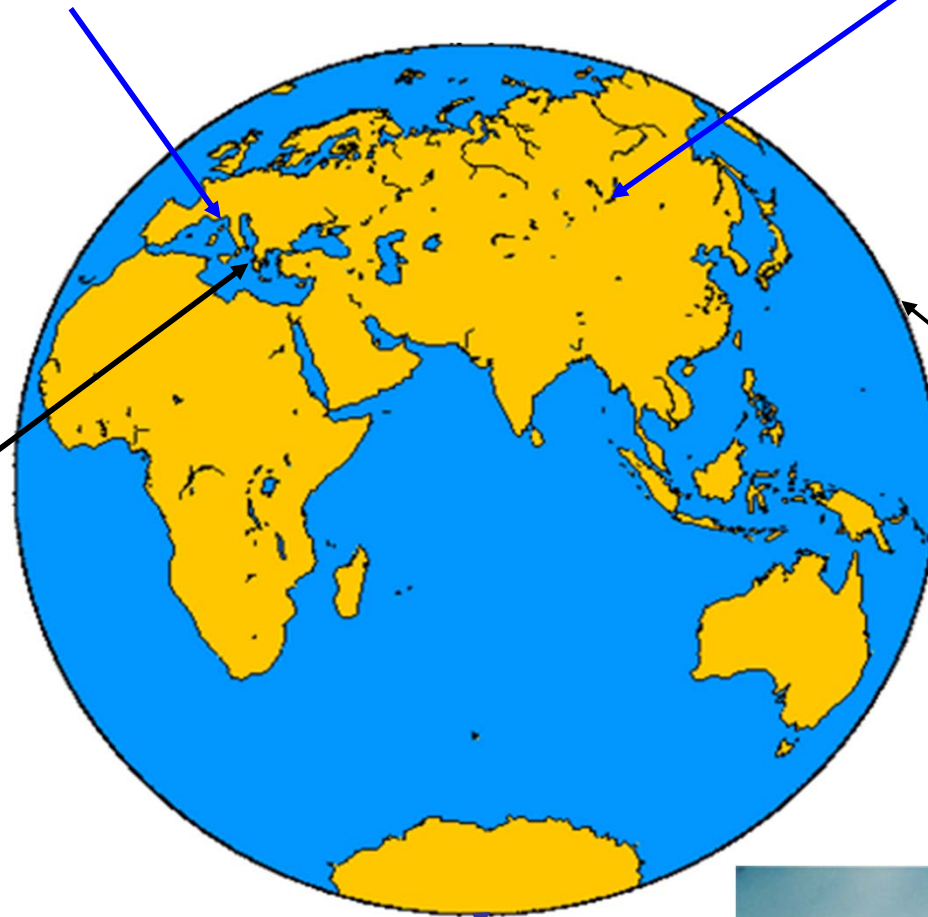
BAIKAL:
Lake Baikal, Siberia



NESTOR : Pylos, Greece

DUMAND, Hawaii
(cancelled 1995)

AMANDA, ICECUBE
South Pole, Antarctica



AMANDA

South Pole: glacial ice

1993 First strings AMANDA A

1998 AMANDA B10 ~ 300 Optical Modules

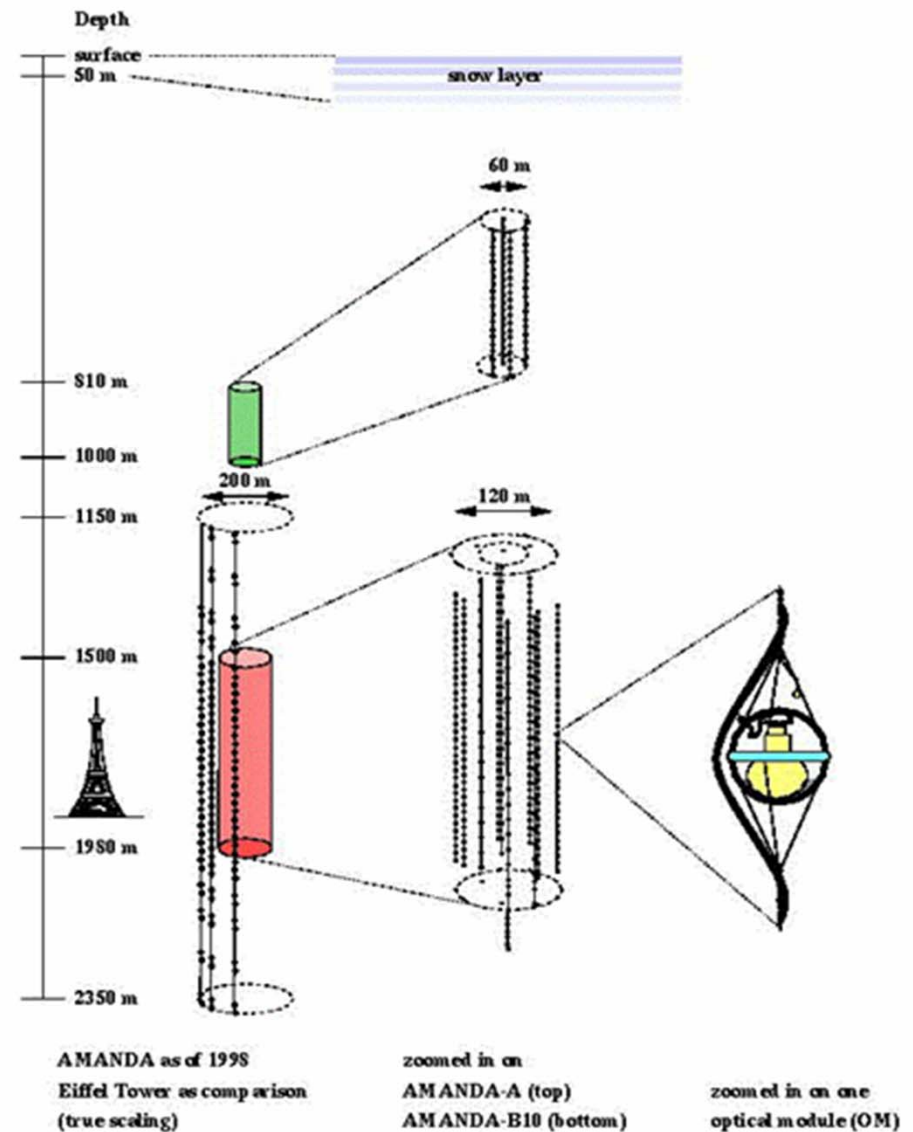
2000 ~ 700 Optical Modules

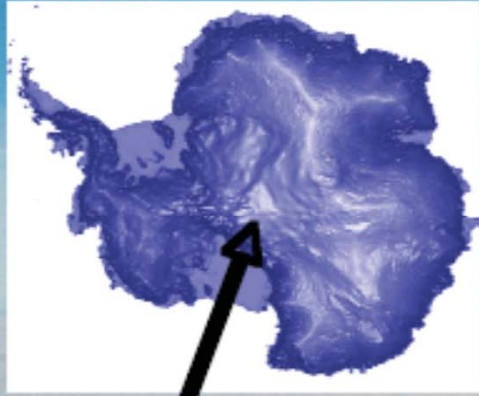
→ ICECUBE 8000 Optical Modules

F. Montanet CIDHE2020ESIPAP



AMANDA
 $\nu > 50\text{GeV}$





Geographic South Pole

Amundsen-Scott
South Pole Station
(NSF)

Skiway

IceCube

Drill Site

Counting House

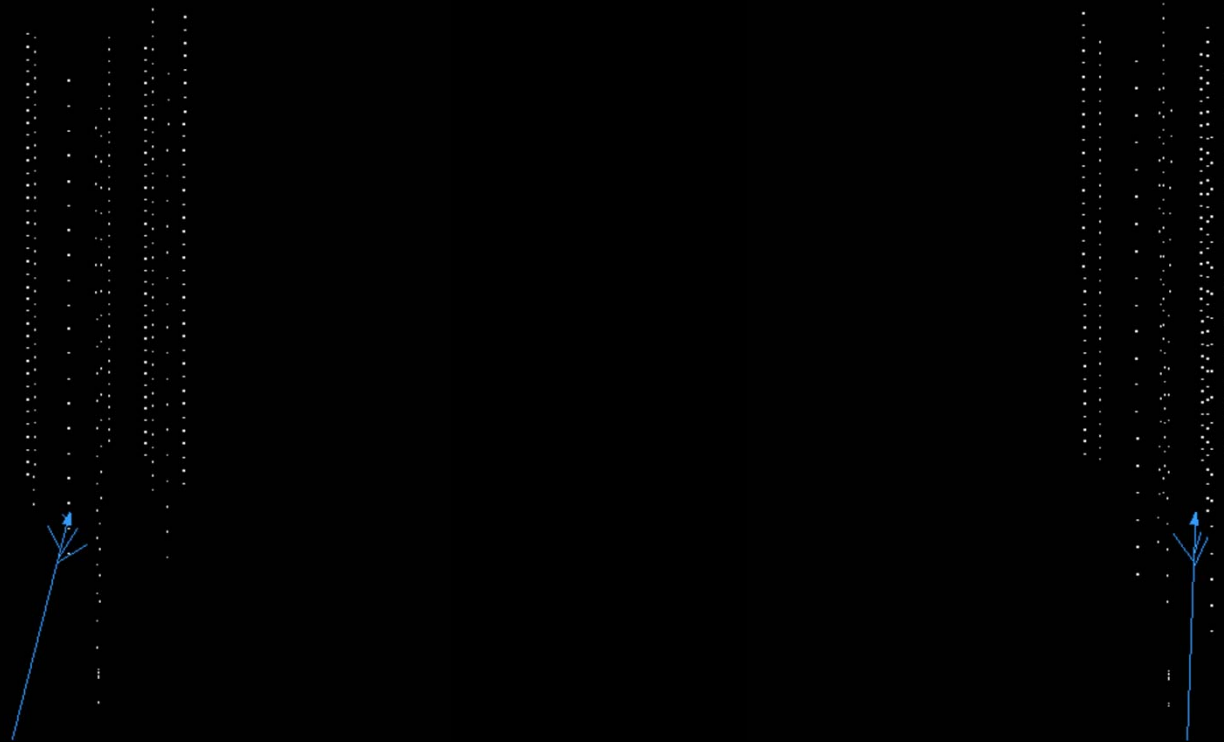
AMANDA



AMANDA: Drill Holes in ice with Hot Water



Reconstruction d'événement dans Amanda



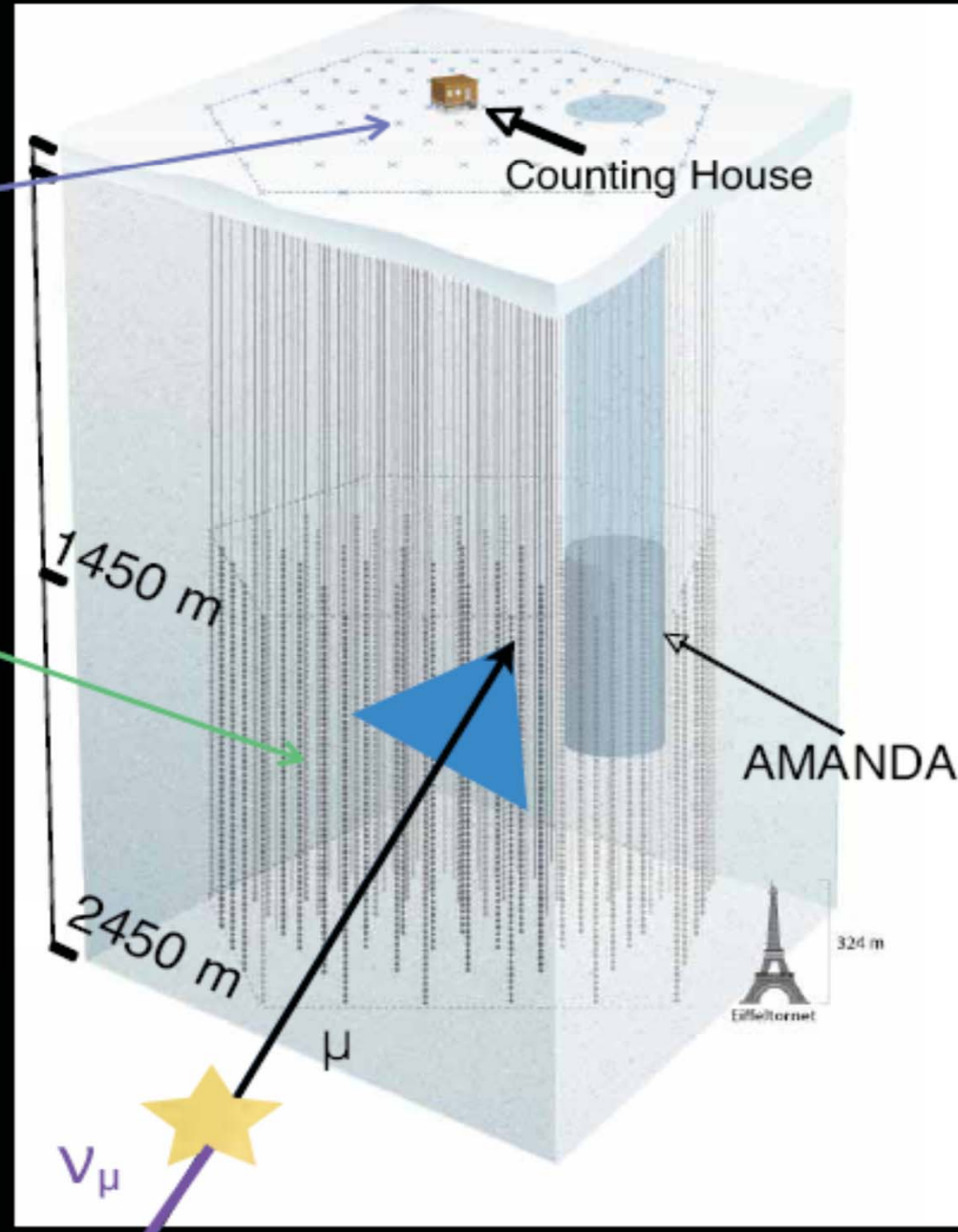
The IceCube detector

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



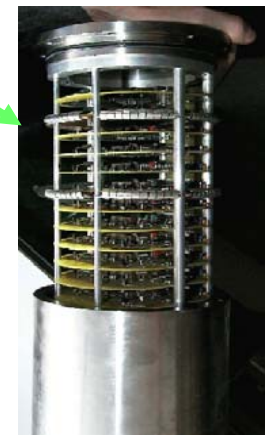
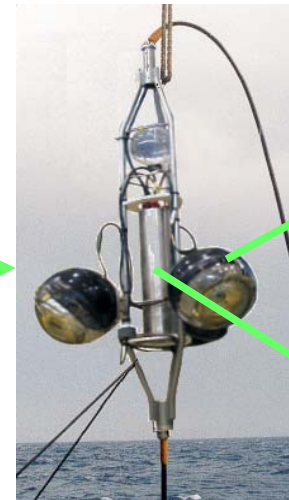
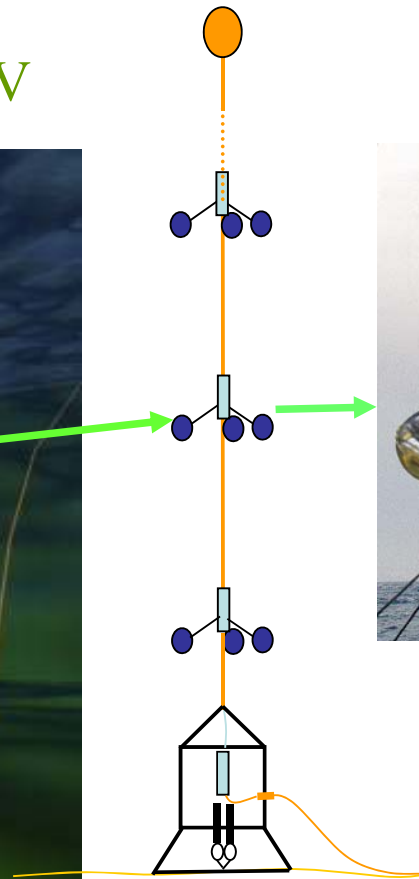
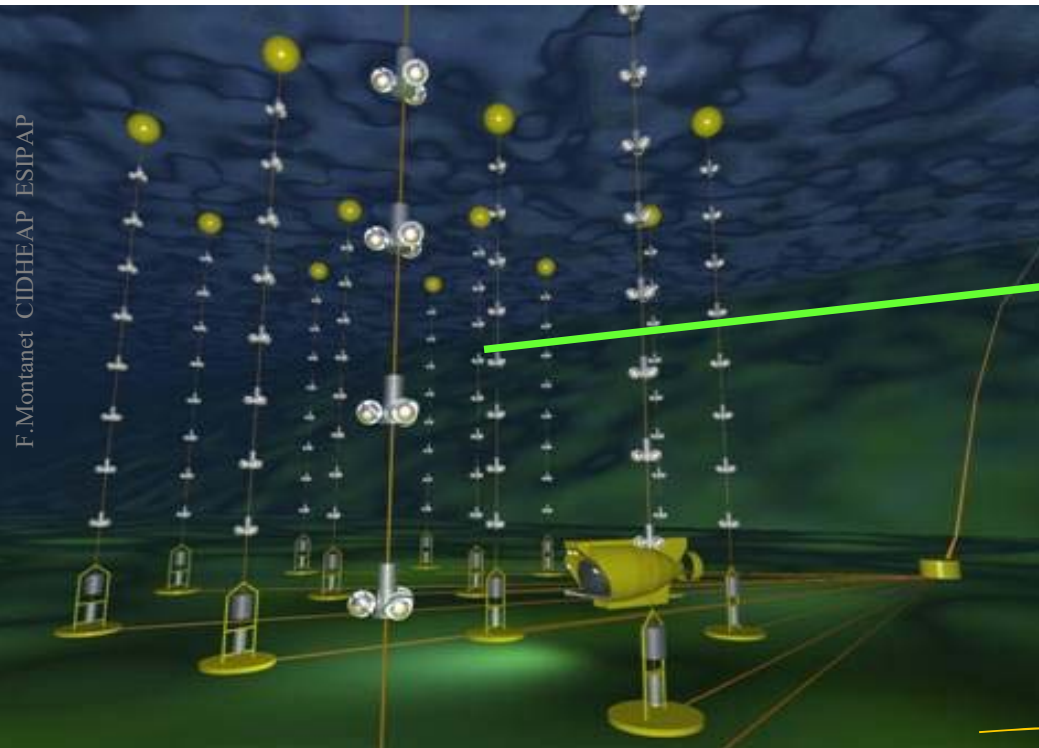
F. Montanet CIDHEAP ESPAP

Future in ν telescopes: ANTARES



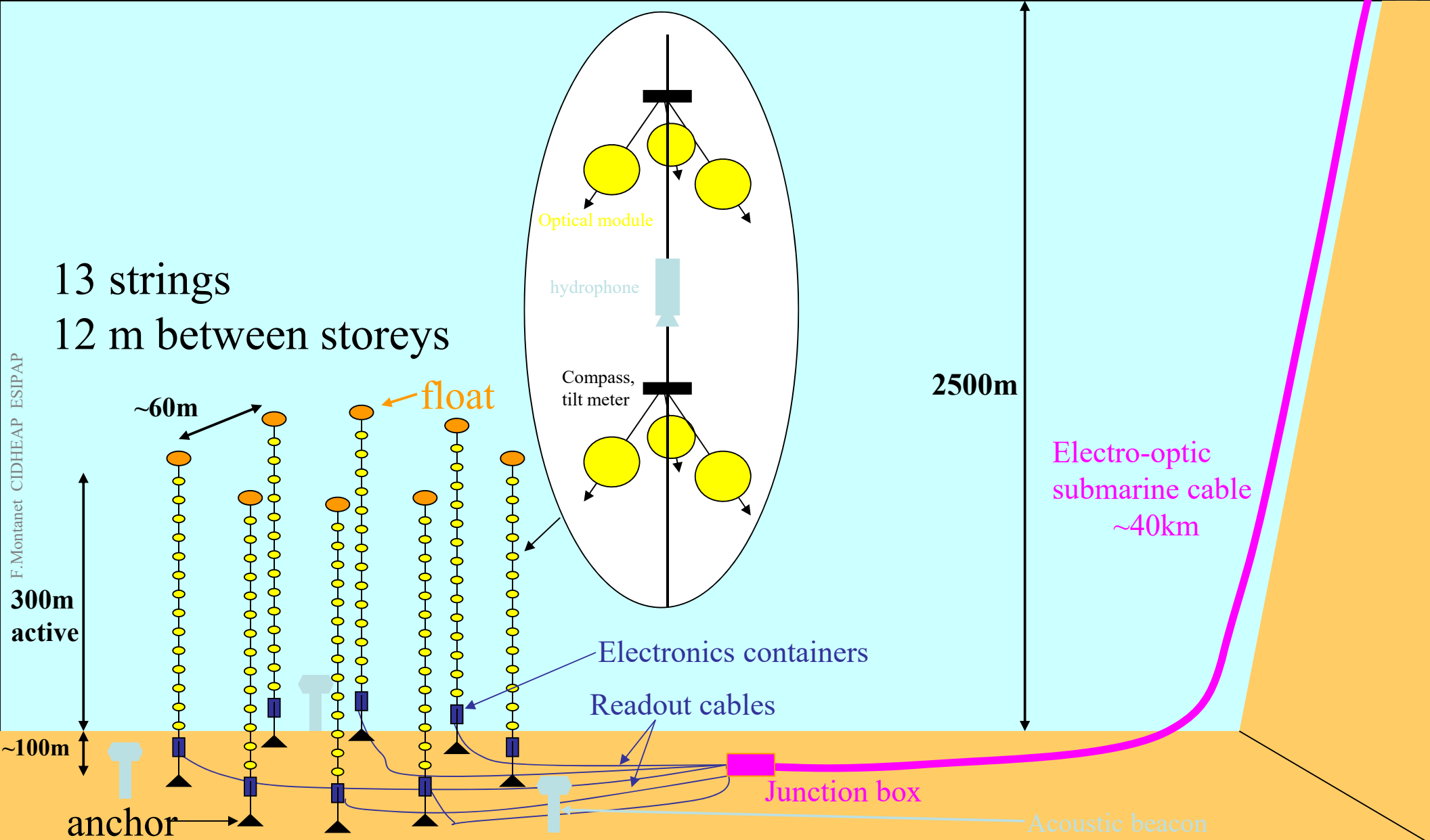
- 1996 Started
- 1996 - 2000 Site exploration and demonstrator line
- 2001 - 2004 Construction of 10 line detector, area $\sim 0.1\text{km}^2$ on Toulon site
- future 1 km^3 in Mediterranean

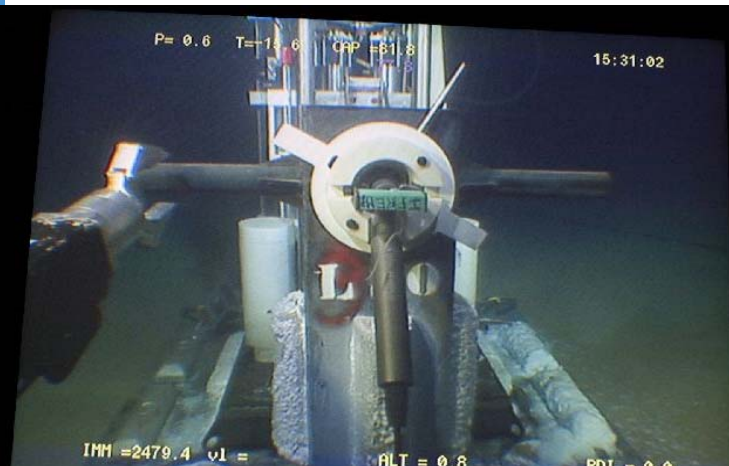
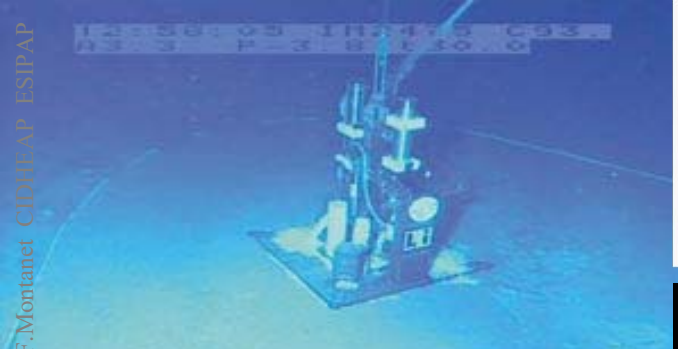
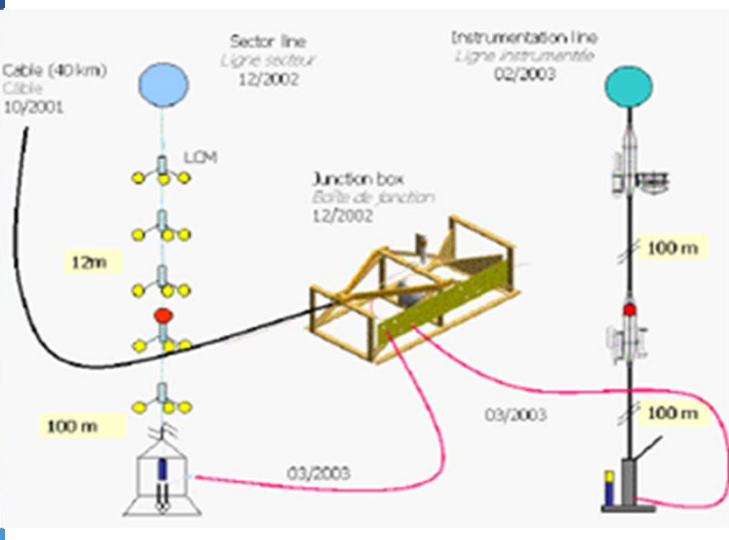
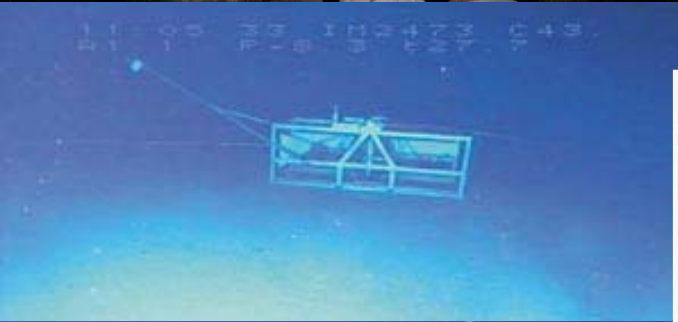
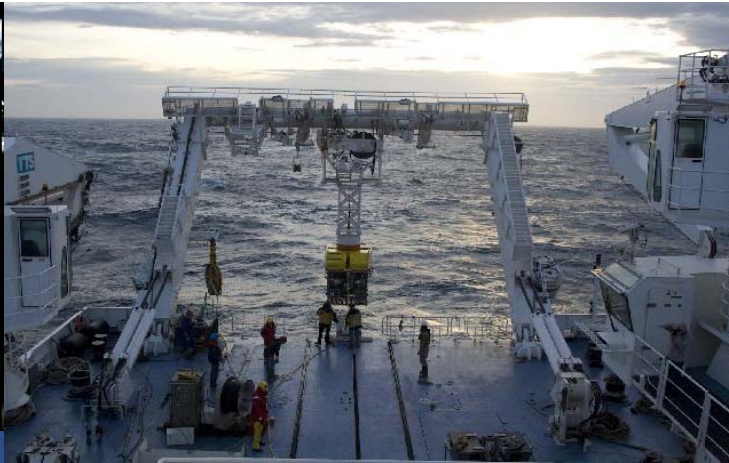
Angular resolution $< 0.4^\circ$ for $E > 10\text{ TeV}$



ANTARES 0.1km² Detector

Shore station

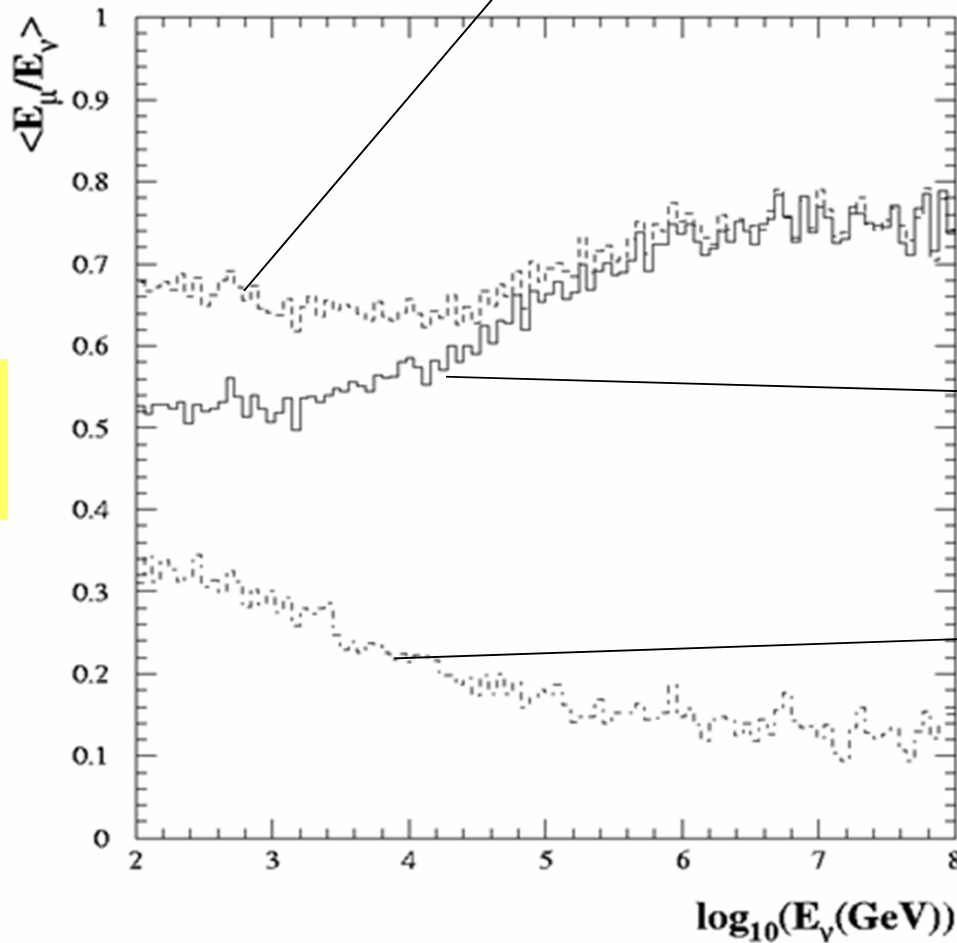




F. Montanet CIDREAP ESIPAP

Detection principle

Production energy of μ 's reaching the detector

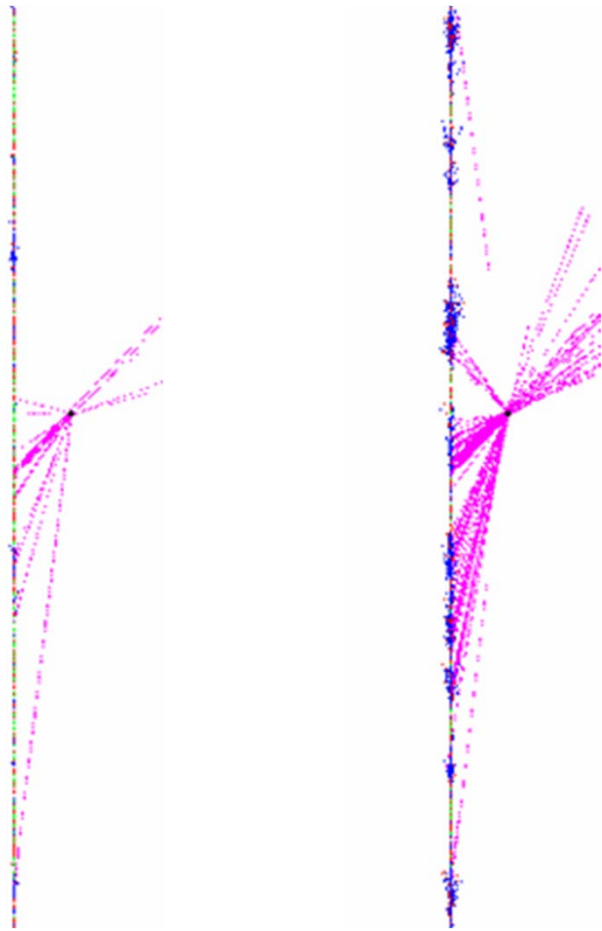


Mean E_μ/E_ν ratio versus E_ν

Energy of all μ 's as produced

Energy of μ 's as they reach the detector

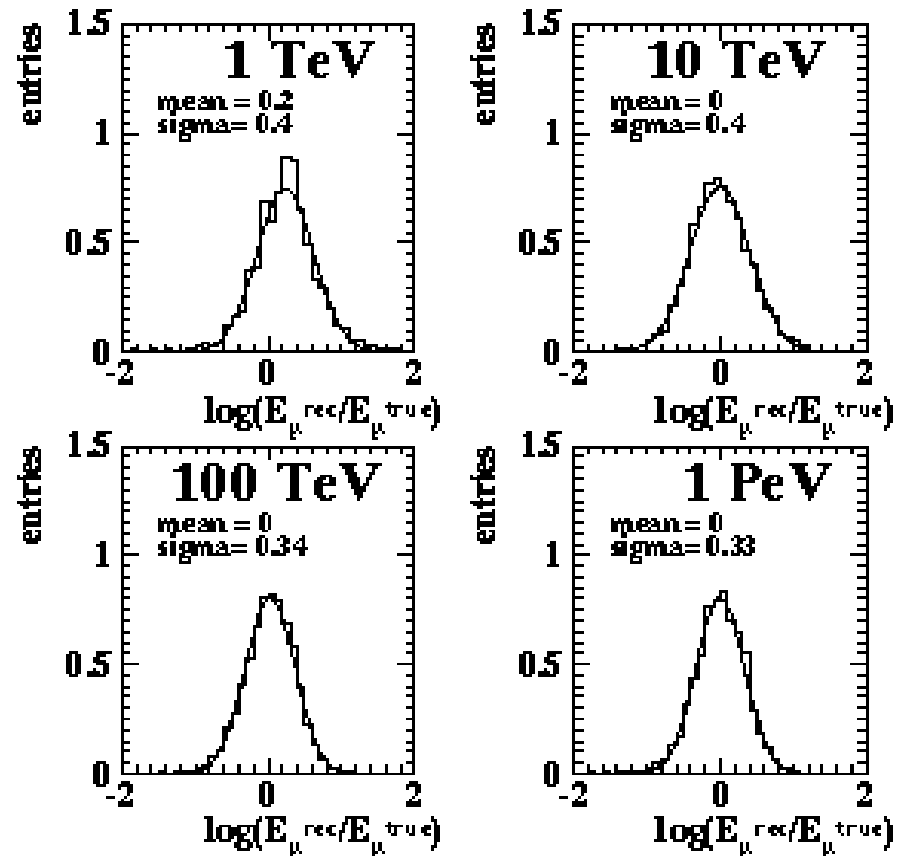
Energy measurement



100 GeV μ

10 TeV μ

(Seuls les photons atteignant un PM sont dessinés)

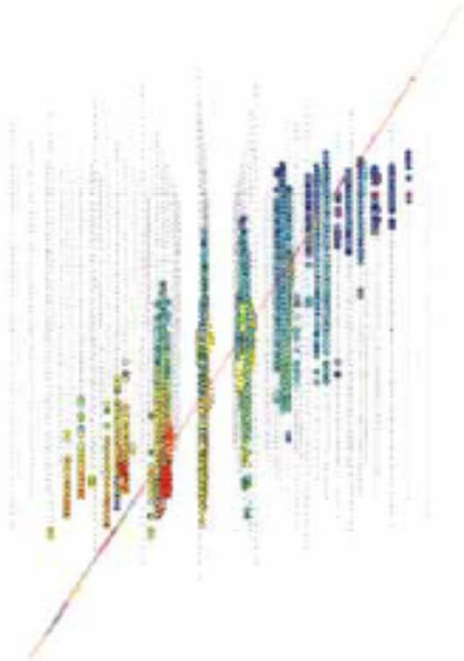


$$\begin{aligned} \Delta E/E &= 3 \quad (< 10\text{TeV}) \\ &= 2 \quad (> 10\text{TeV}) \end{aligned}$$

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

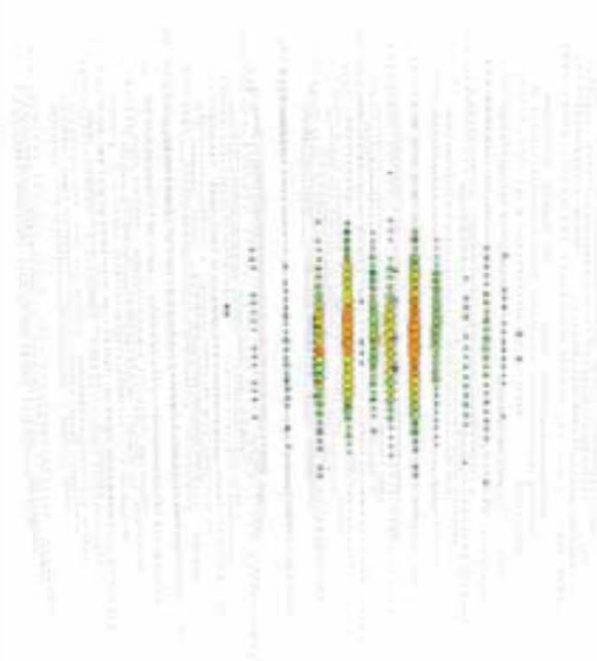
6×10^{15} eV (6 PeV)
 ~1000 DOMs hit
 ~ 20 km



$E \sim dE/dx$, $E > 1$ TeV
 E res. : $\Delta \log(E) \sim 0.3$
 ang res : 0.8-2 deg

 ν_e

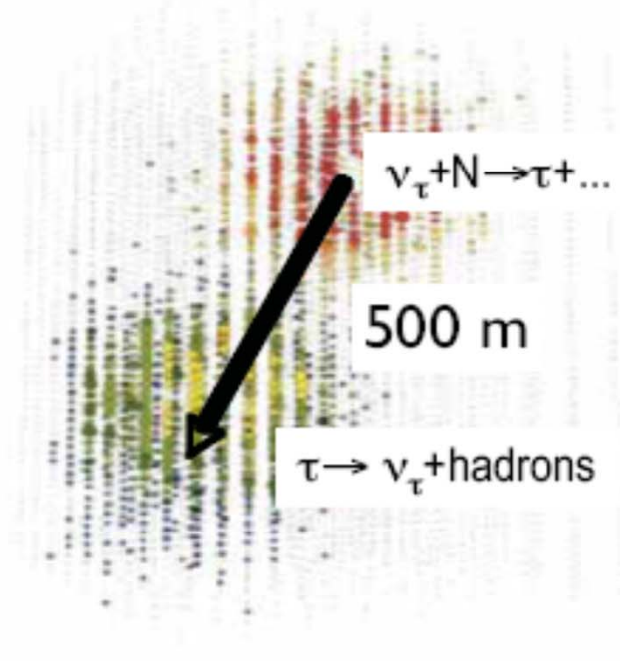
$E = 375$ TeV
 "spherical" shell



poor angular resolution
 E res : $\Delta \log(E) \sim 0.1-0.2$

 ν_τ

$E = 10$ PeV
 2 bangs separated by
 ~ $50 * (E_\tau / \text{PeV})$

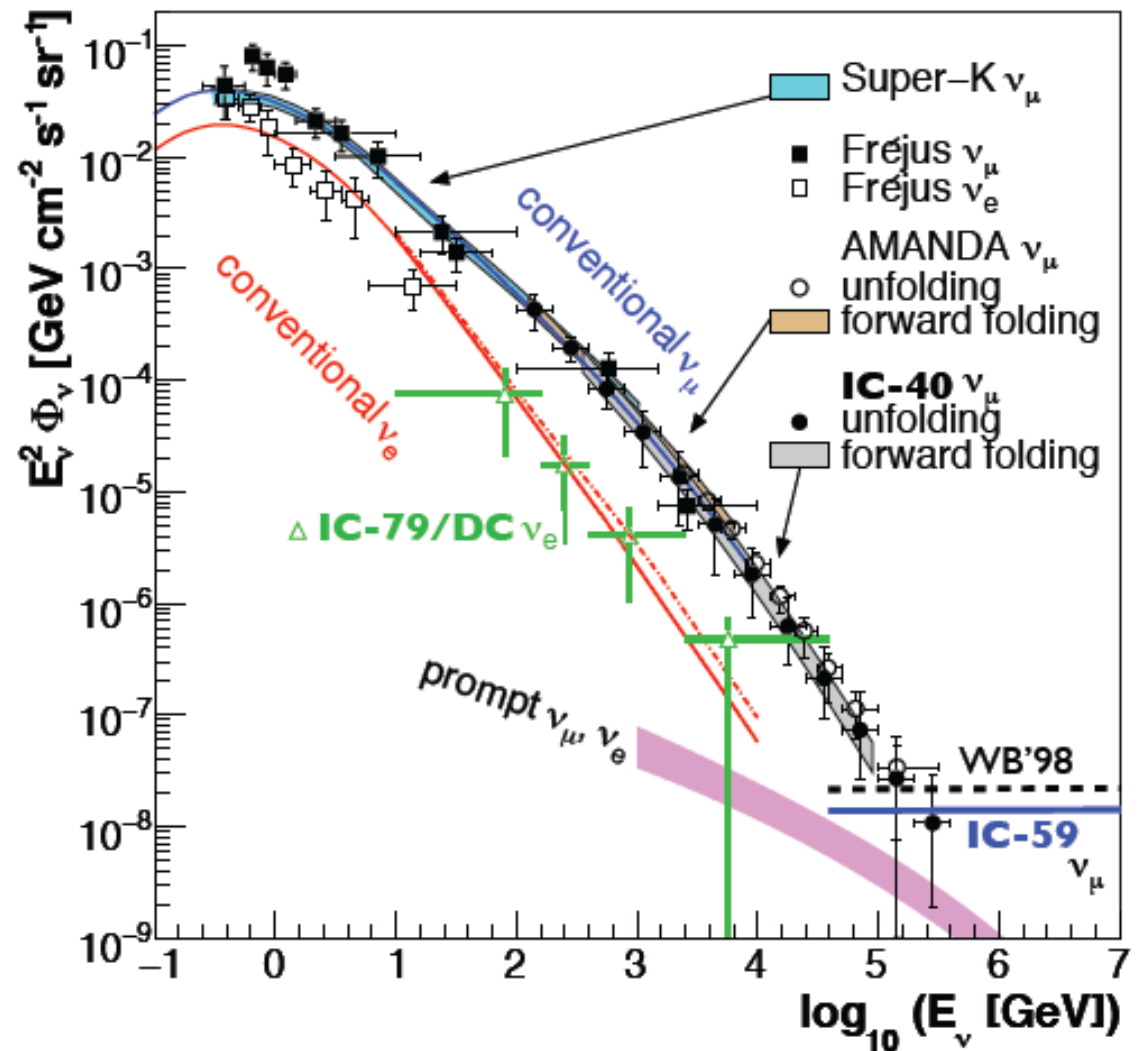


very low background
 pointing capability
 good E measurement

ICECUBE atmospheric flux

Atmospheric neutrino flux and diffuse limit

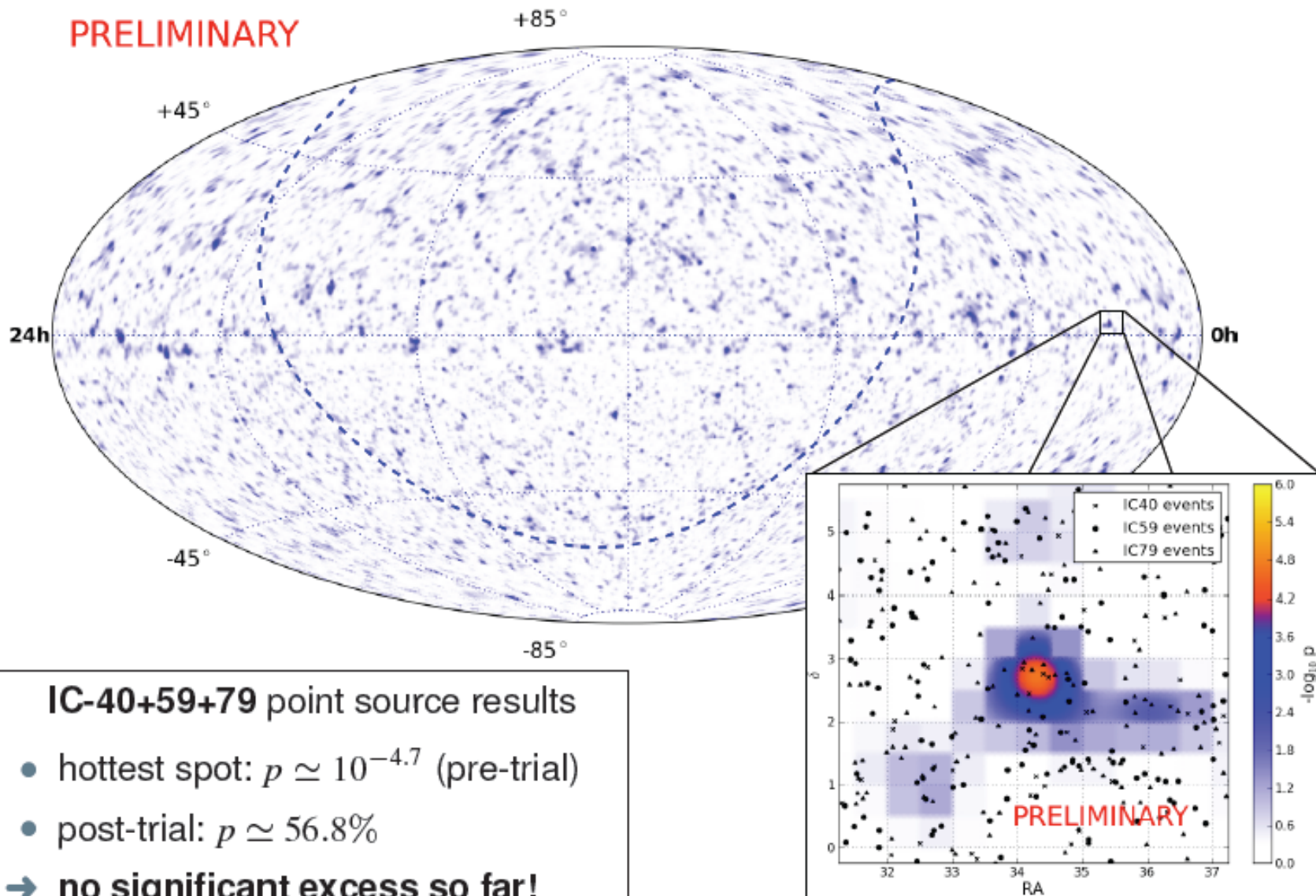
- high-energy atmospheric ν_μ/ν_e -spectrum as seen by IC-40 & IC-79/DC
[IceCube'11,'12]
- diffuse ν_μ limit from IC-59 (90% C.L.) (preliminary)
- predicted prompt atmospheric ν -fluxes (charmed meson decay)
[Enberg *et al.*'08]
- theoretical limit on diffuse astrophysical ν_μ 's
[Waxman&Bahcall '98]



ICECUBE atmospheric flux

Steady point-source search

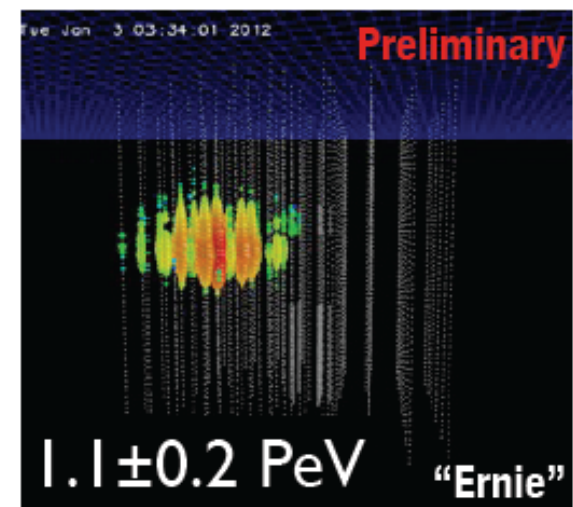
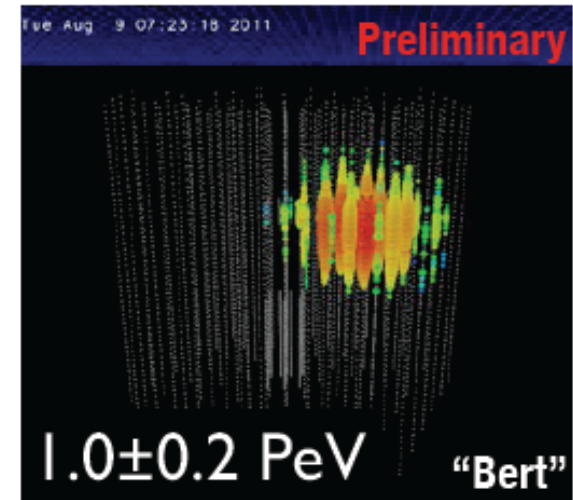
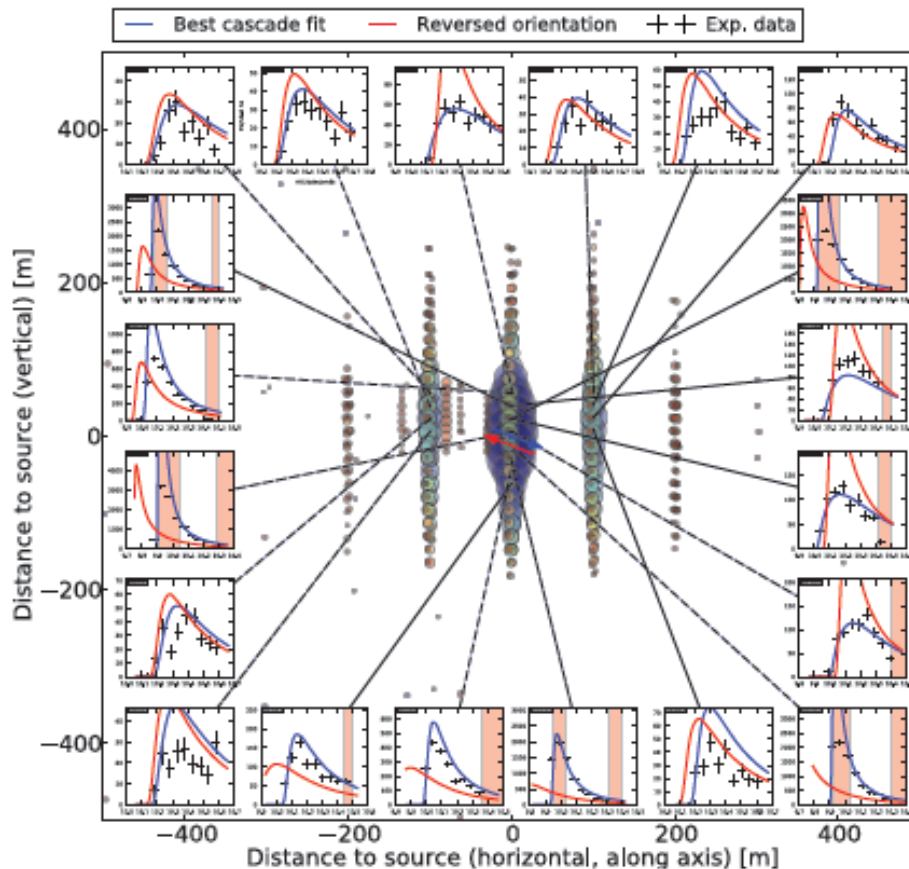
PRELIMINARY



ICECUBE atmospheric flux

Extremely-high energy analysis

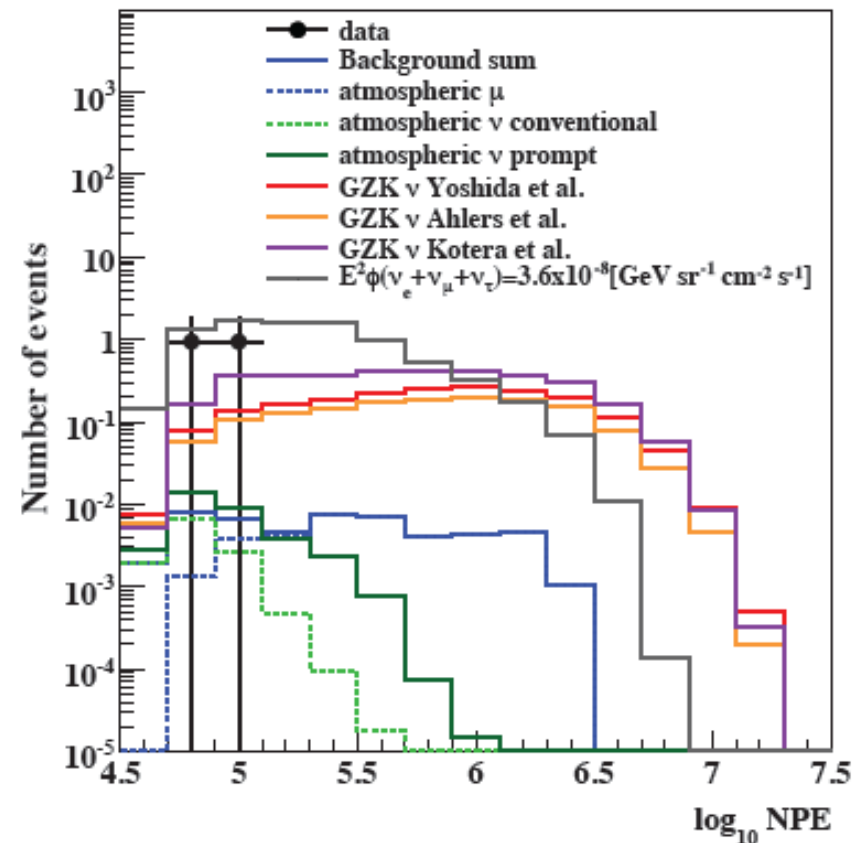
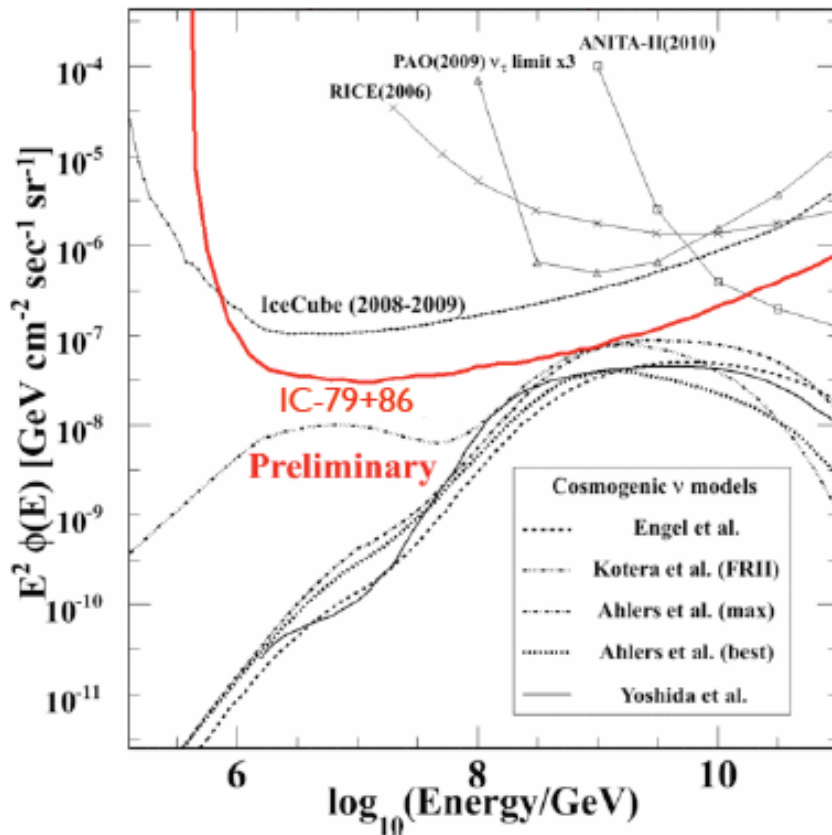
Follow-up studies of background events:
energy, orientation,...
→ Are there more contained events?



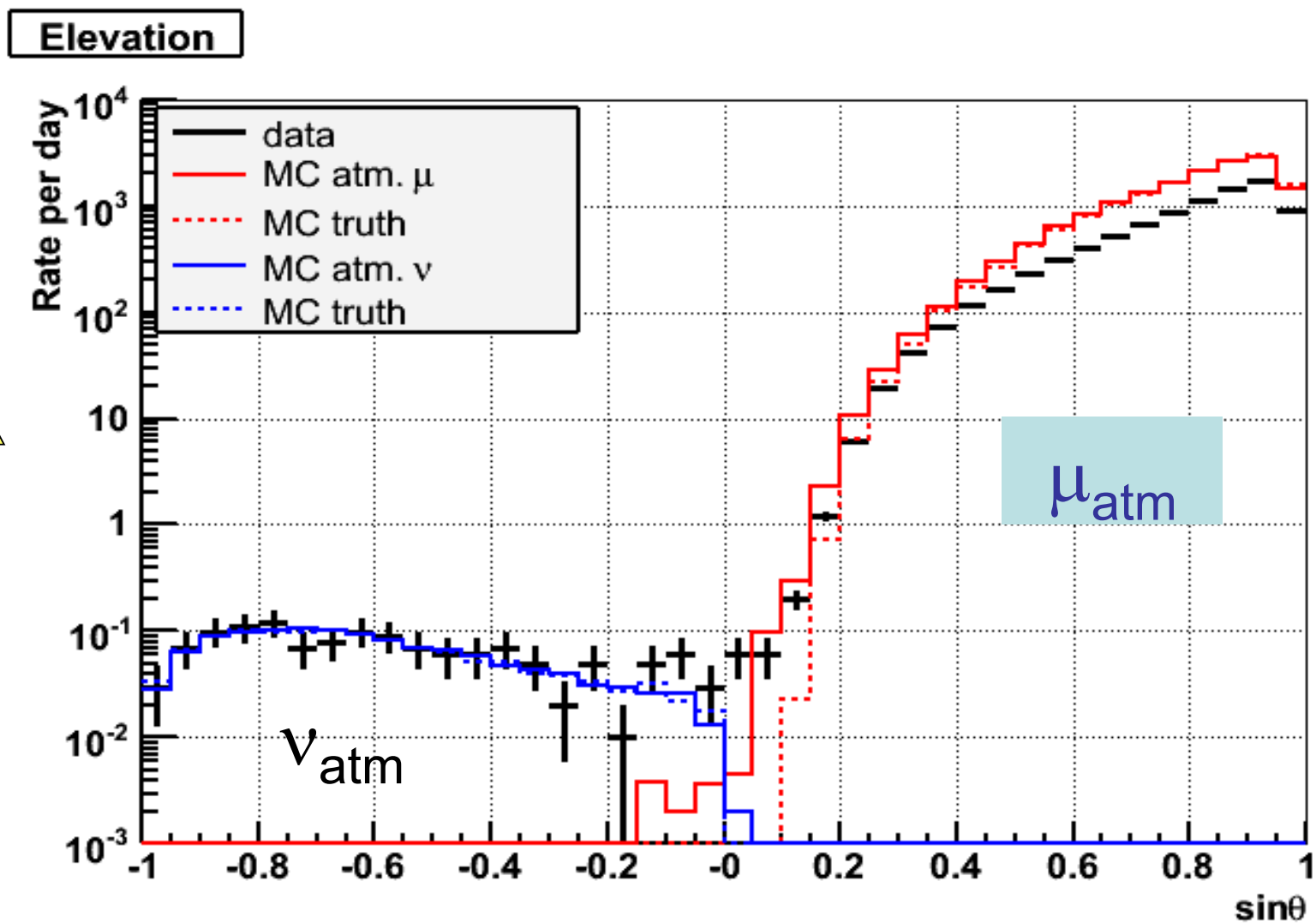
ICECUBE atmospheric flux

Extremely-high energy analysis

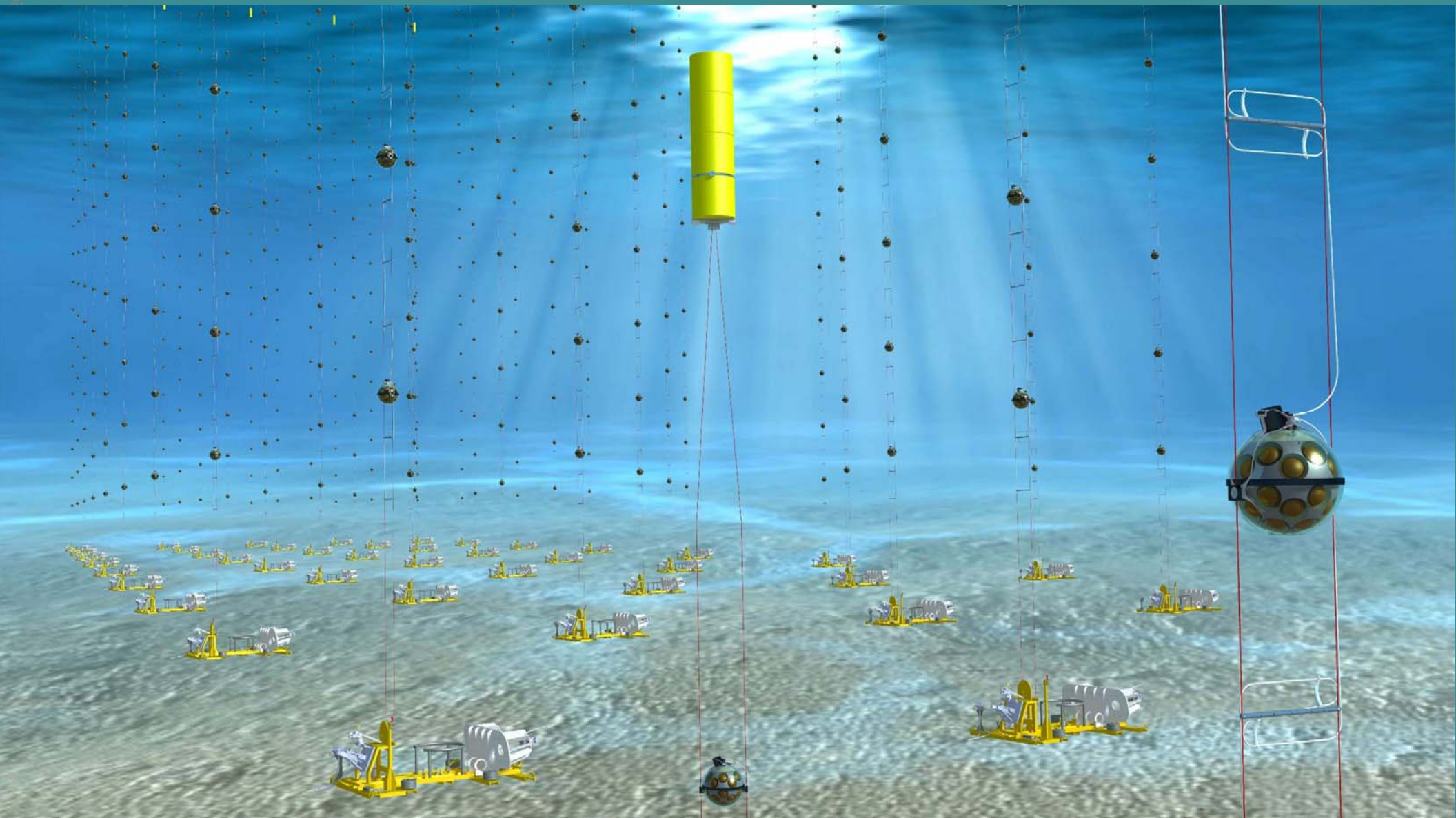
- Study for cosmogenic neutrino fluxes in **IC-79+86**
- optimized cuts on zenith angle and “brightness” (NPE: number of photo-electrons)
- two “background” events above NPE threshold



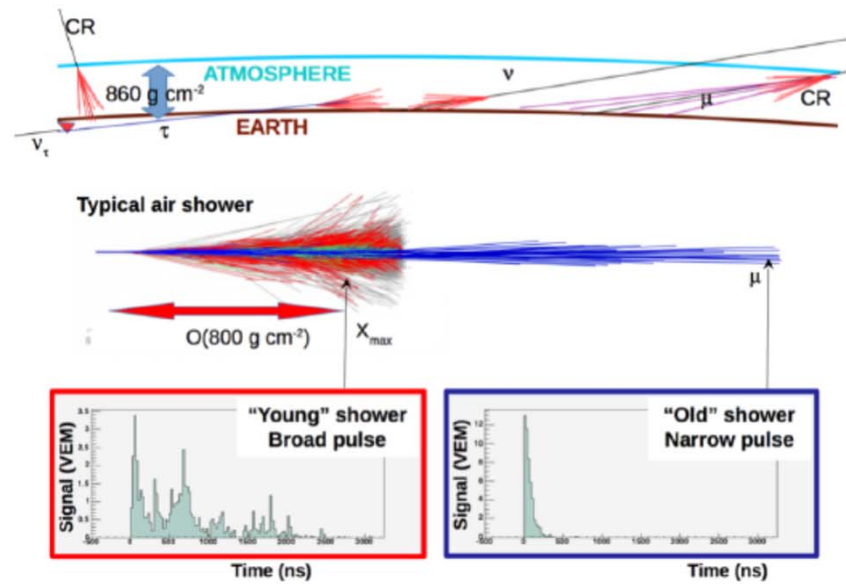
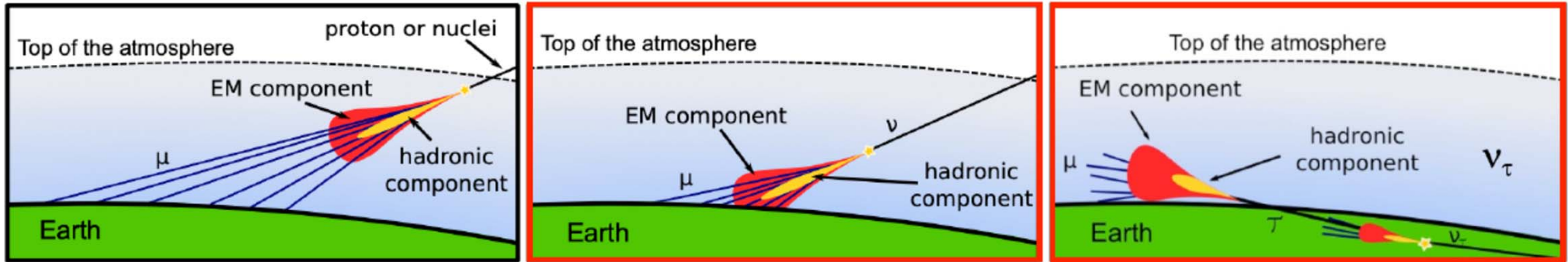
Premiers résultats d'Antares 12 lignes (sur 120 jours actifs)



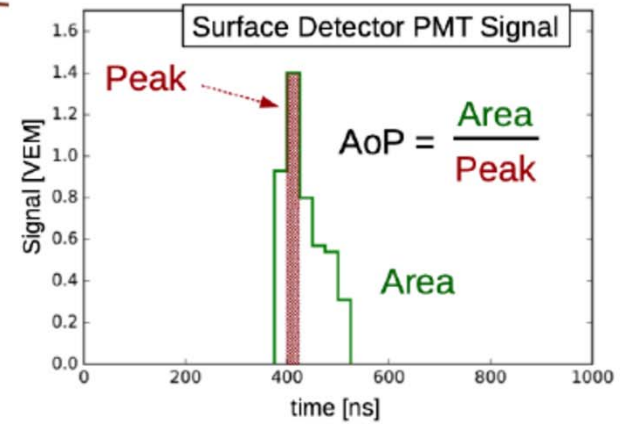
KM3NET (ORCA & ASCA)



Neutrinos in Auger



Searching for neutrinos = look for inclined showers with em component

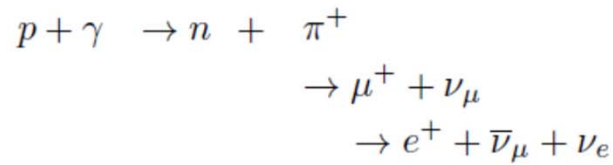


with large area/peak (A/P ~ 1 for muons)

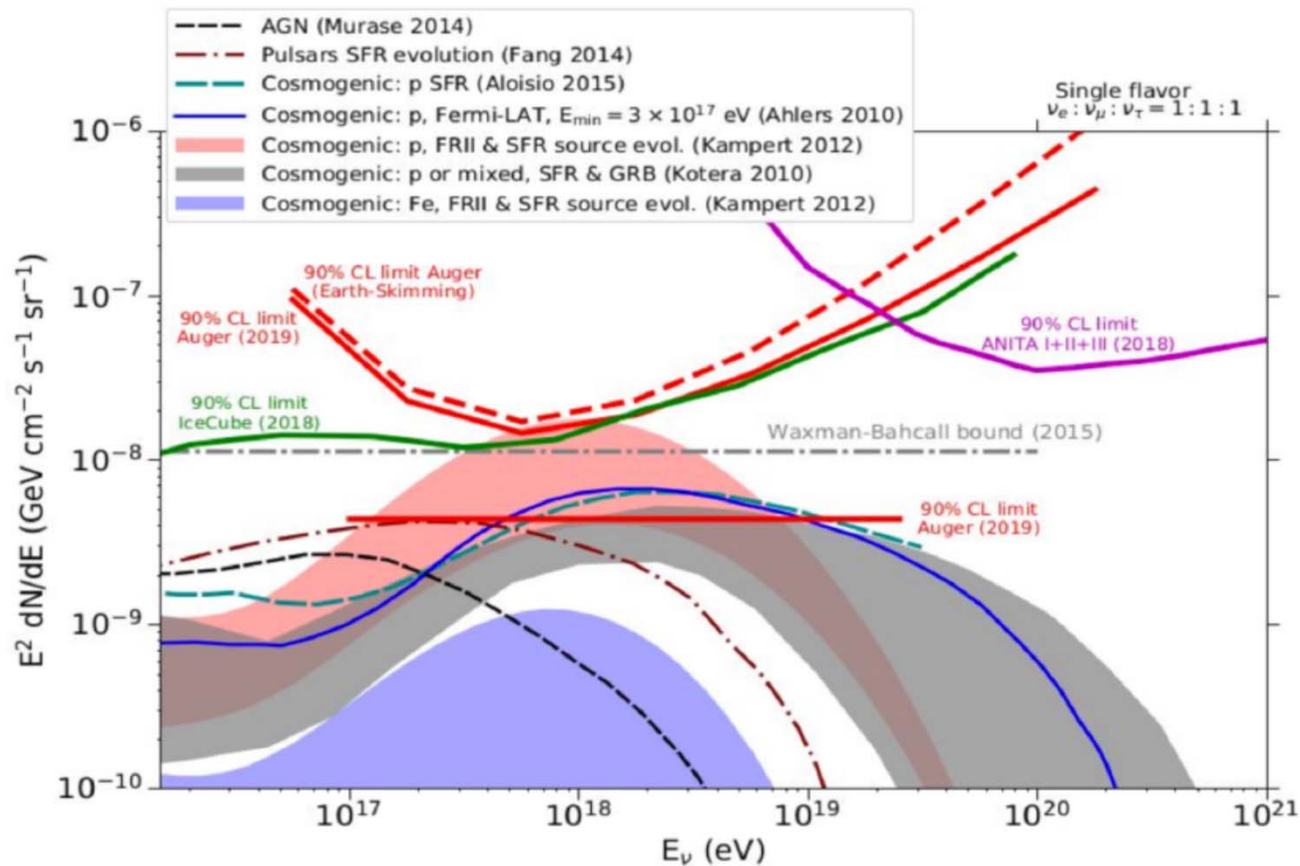
Complementary properties to other neutrino telescopes

- largest exposure at EeV energies
- different flavour response wrt under-water or under-ice telescopes: higher sensitivity to ν_τ , lowest to ν_μ

Neutrino diffuse flux



$$k = \frac{N_{up}}{\int_{E_\nu} E_\nu^{-2} \epsilon_{tot}(E_\nu) dE_\nu}$$

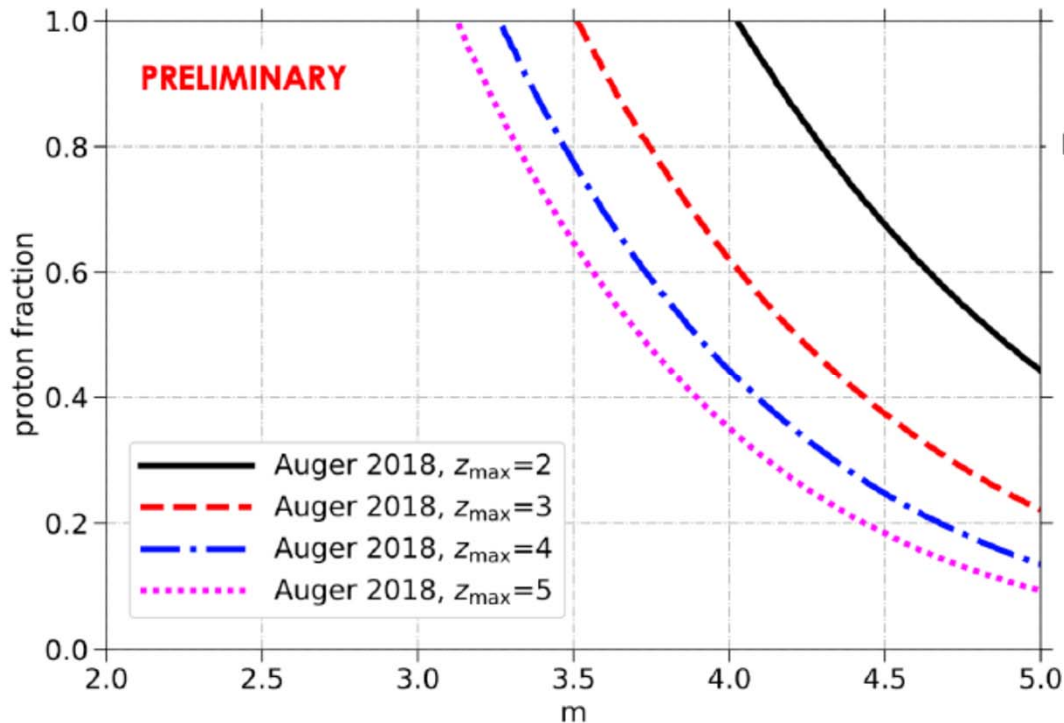
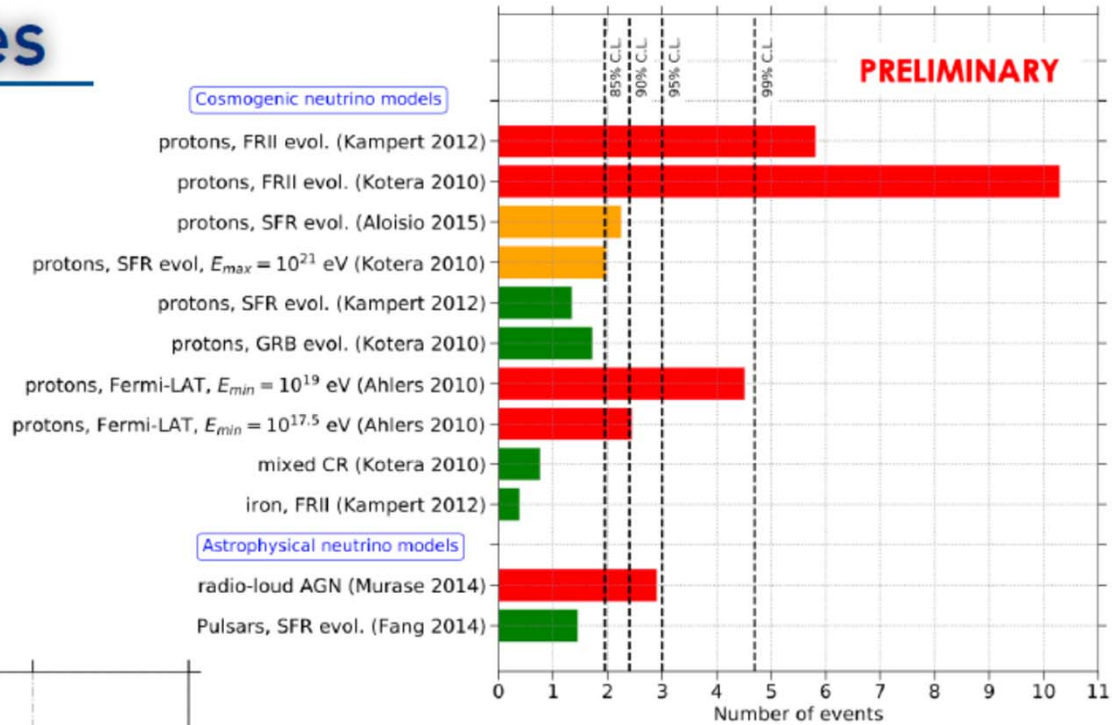


Maximum sensitivity around EeV
 k (90% CL) $< 4.4 \cdot 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

Constraints on sources

From the expected event rates in Auger, different models of cosmogenic and astrophysical neutrino production are

- excluded (red)
- disfavoured (orange)

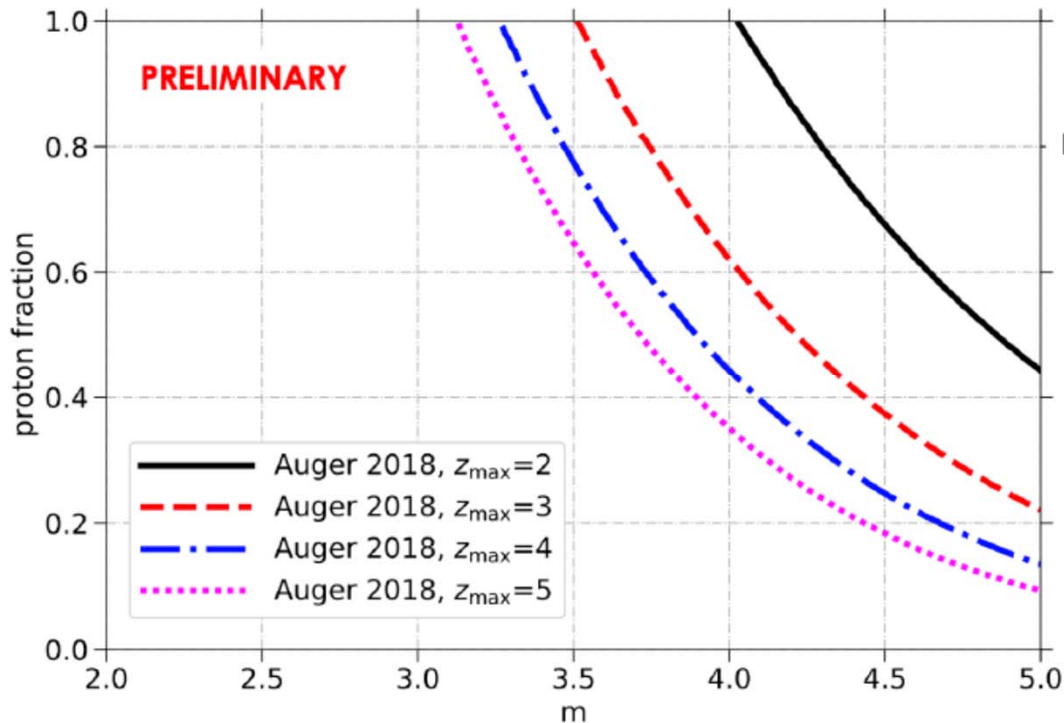
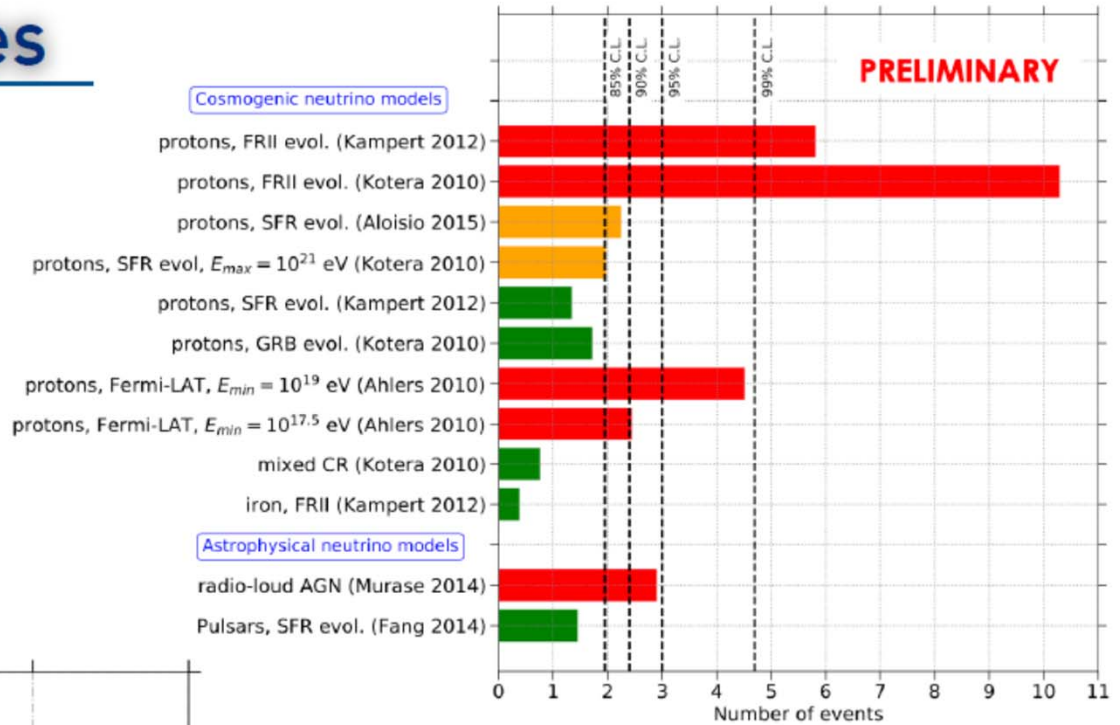


Large proton fractions and strong evolution of sources are disfavoured at 90% C.L.
[assuming sources evolving as $(1+z)^m$]

Constraints on sources

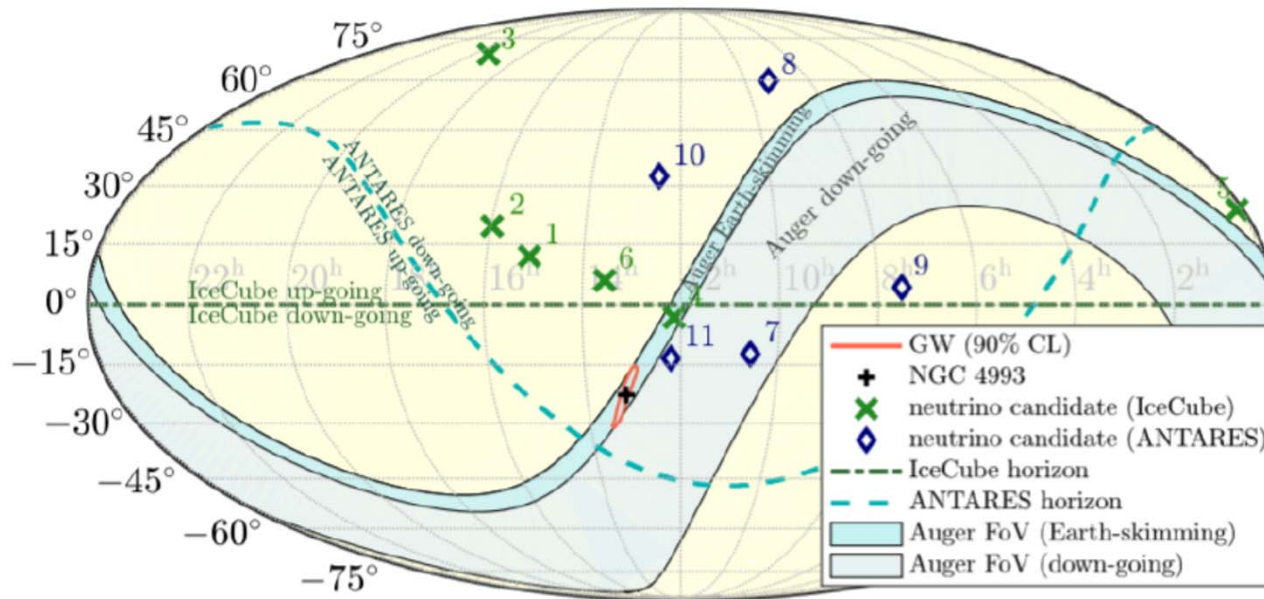
From the expected event rates in Auger, different models of cosmogenic and astrophysical neutrino production are

- excluded (red)
- disfavoured (orange)



Large proton fractions and strong evolution of sources are disfavoured at 90% C.L.
[assuming sources evolving as $(1+z)^m$]

Follow up of the GW170817 event



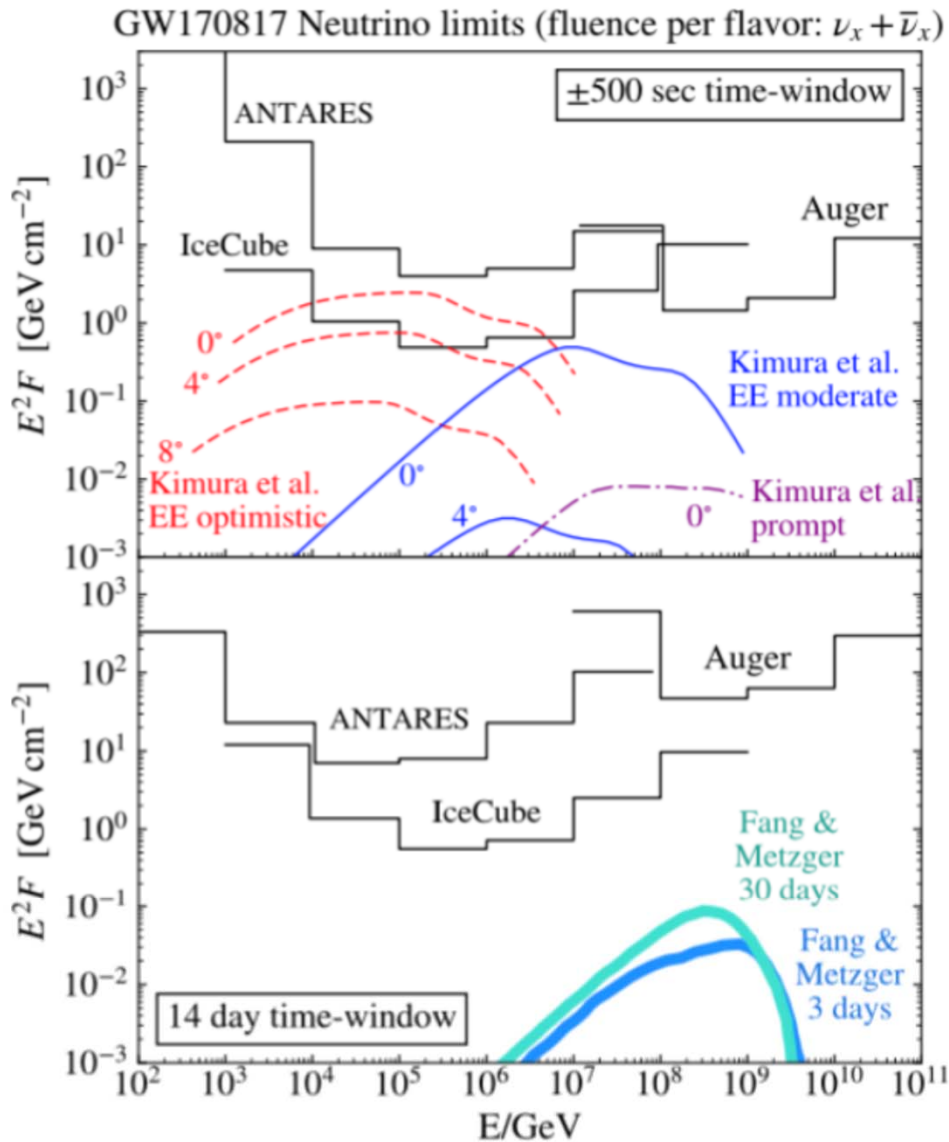
No UHE neutrino candidate found
either in the coincidence window ± 500 s around the GW events
or in the 14-days search period after it

In the energy range $10^{17} - 2.5 \cdot 10^{19}$ eV, the total energy emitted in $\nu\tau$ is

± 500 s : $< 6.9 \cdot 10^{-4} M_{\odot}$

+14 days : $< 2.3 \cdot 10^{-2} M_{\odot}$

Constraints to models



sGRBs

- prompt emission (due to internal energy dissipation in the jet), extended emission (afterglow due to forward shocks around the burst)
- viewed on-axis or off-axis
- neutrinos can arise from closely GRBs or EE

S.Kimura et al., ApJ Lett.848: L4 (2017)

msec Magnetar remnants

- promising site for accelerating particles to UHE
- neutrino late production from UHECRs interactions with ambient photons and baryons
- strong neutrino signal at 10¹⁸ eV if large contribution of magnetars to the bulk of UHECRs (light nuclei at 10^{17.5}-10¹⁸ eV)

K.Fang, B.Metzger, ApJ 849 (2017) 153