Detector Physics 2022/2023, Lecture 8

Cherenkov radiation and particle identification

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References

many of my slides are taken from

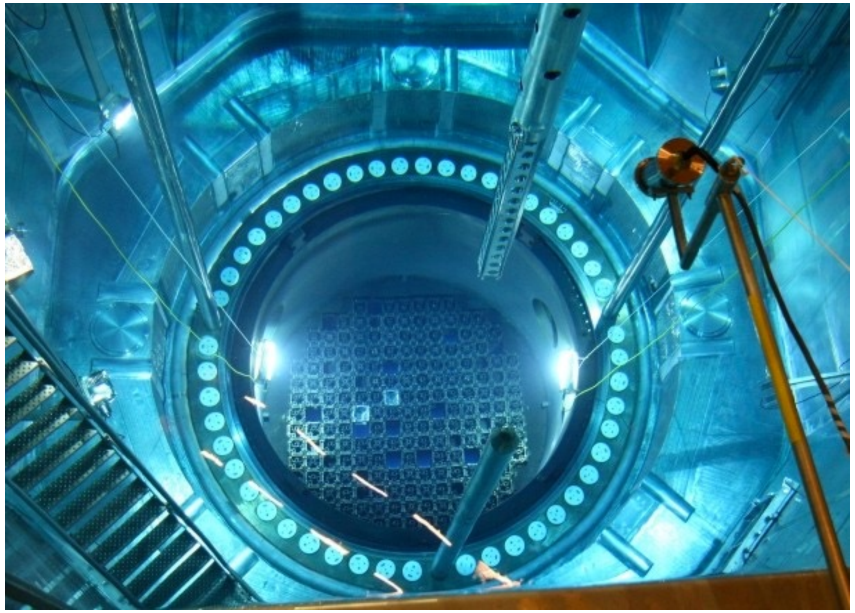
- Thomas Patzak, NPAC Lectures 2019 (thanks!)

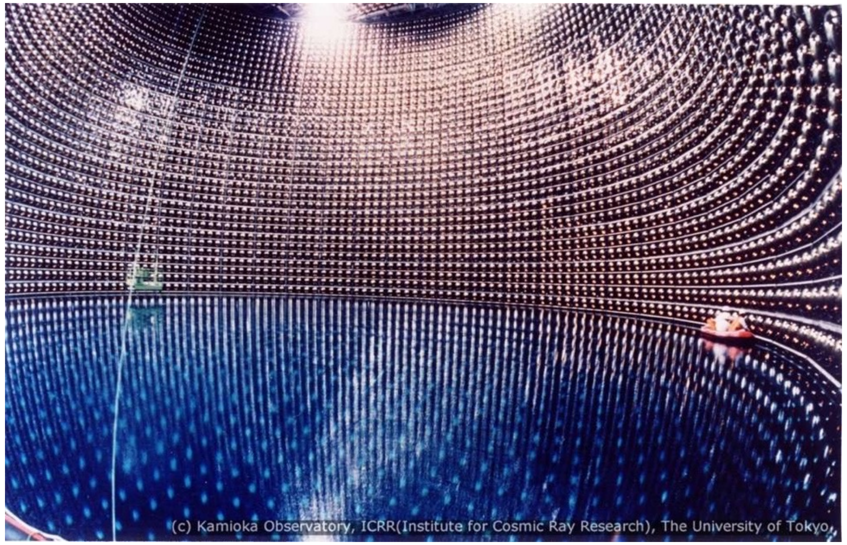
https://npac.lal.in2p3.fr/1st-semester-lectures-1920/

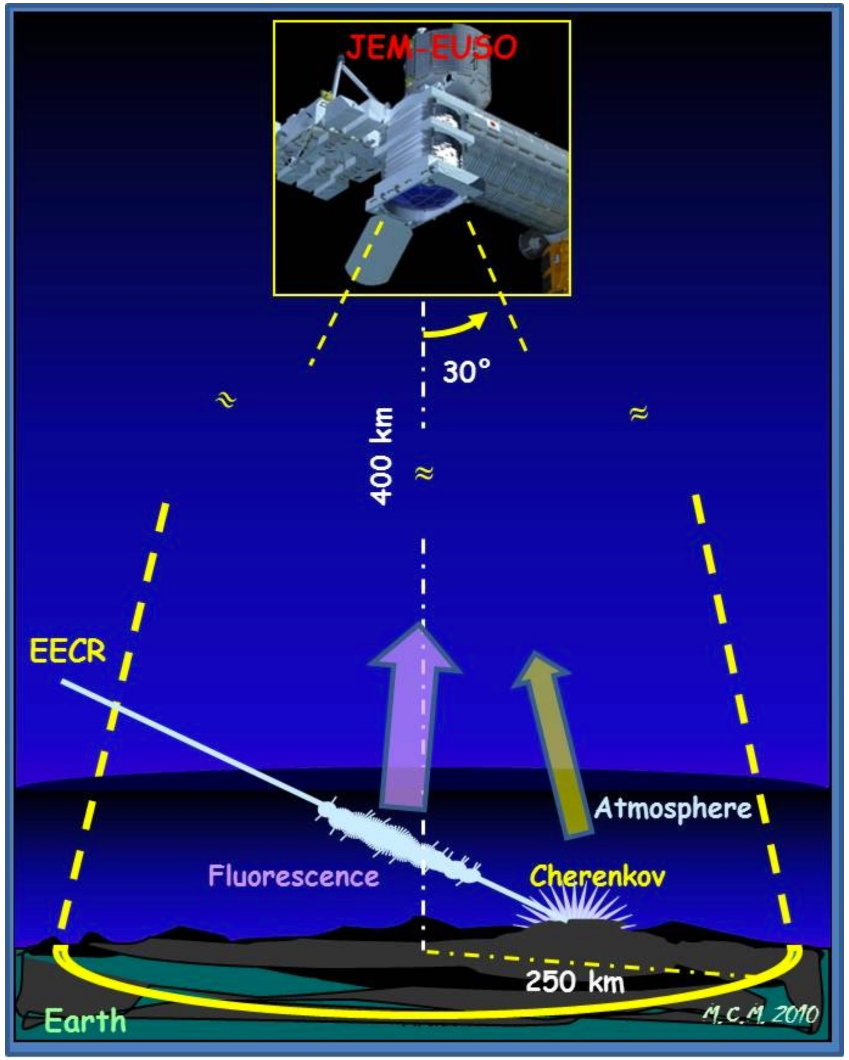
- S. Easo (RAL) Graduate Student Lecture 2011

https://warwick.ac.uk/fac/sci/physics/staff/academic/gershon/gradteaching/warwickweek/material/detectors/warwick_week_pid_lecture_2011_pdf.pdf

Cherenkov radiation







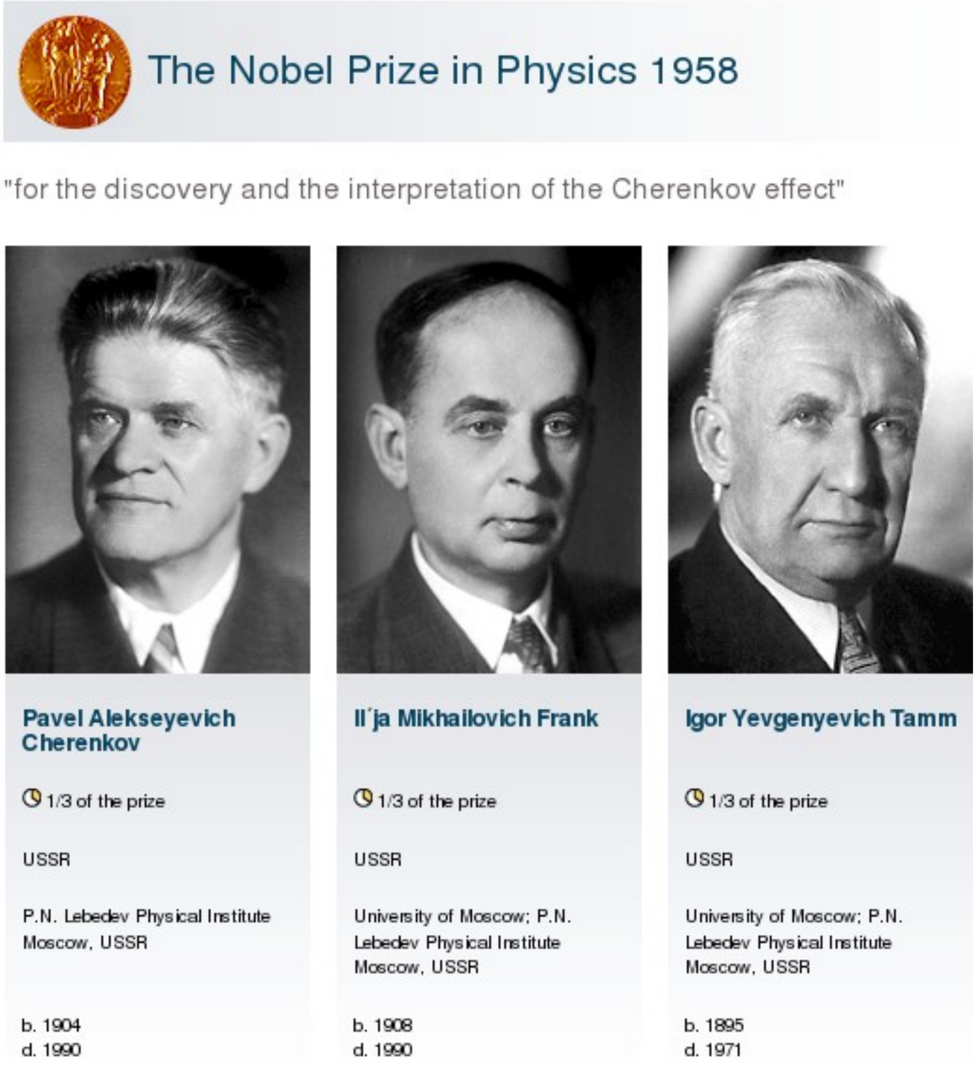
Cherenkov radiation: some history

1888 predicted by O. Heaviside
Deformation of the electromagnetic field of a charged, moving particle
1901 predicted by Kelvin
1904 predicted by Sommerfeld

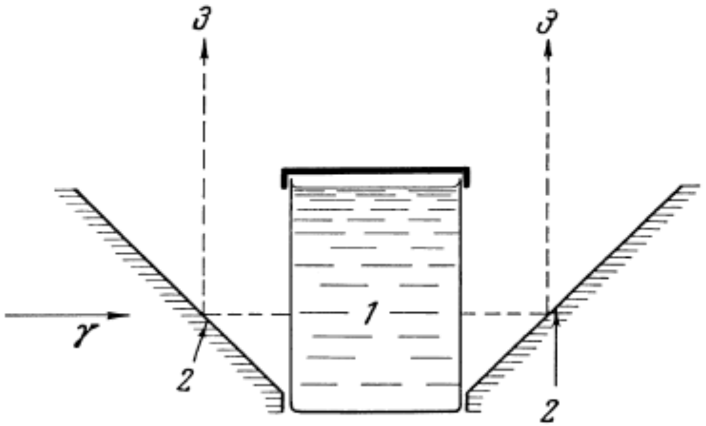
Cherenkov:
1934 experimentally observed

Frank & Tamm
1937 theoretical explanation

1958 Nobel prize



Cherenkov radiation: some history



- 1: vessel with liquid
- 2 mirror
- 3: Cherenkov photons towards the photographic plate

Typical Apparatus used by Cherenkov to study the angular distribution of Cherenkov photons.
(Incident γ ray produces electrons by compton scattering in the liquid).

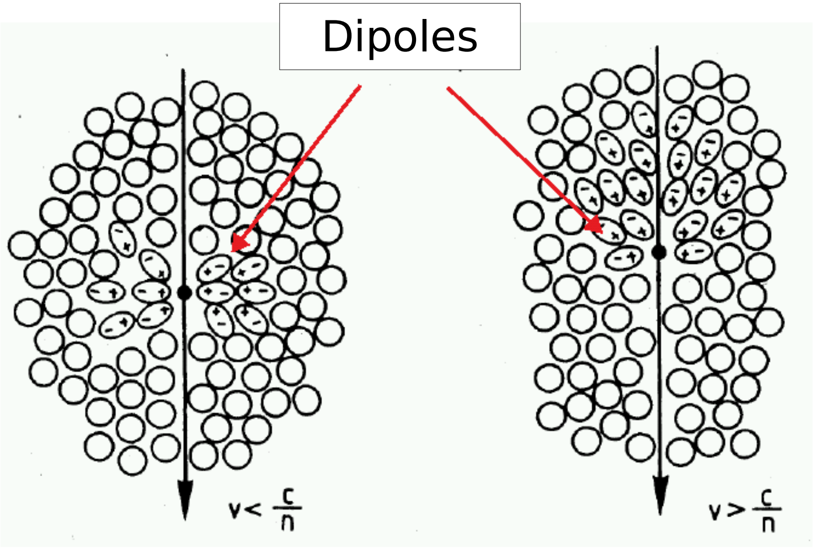
P. Cherenkov established that:

- Light Intensity is proportional to the electron path length in the medium.
- Light comes only from the 'fast' electrons above a velocity threshold, in his Apparatus.
- Light emission is prompt and the light is polarized.
- The wavelength spectrum of the light produced is continuous. No special spectral lines.
- The angular distribution of the radiation, its intensity, wavelength spectrum and its dependence on the refractive index agree with the theory proposed by his colleagues Frank and Tamm.

Cherenkov radiation

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Density correction due to polarization of the material results in an attenuation of the relativistic rise.



Charged particles polarize material
time dependent dipole field → dipole radiation

<u>For v < c/n:</u>
Induced dipoles symmetrically arranged around particle path -> no net dipole moment
→ no Cherenkov radiation

<u>For v > c/n:</u>
Symmetry is broken since the particle goes faster then em waves -> non-vanishing dipole moment
→ Cherenkov radiation

Cherenkov radiation emission

Particle going faster than the speed of light in the material

↓

Emission of Cherenkov radiation

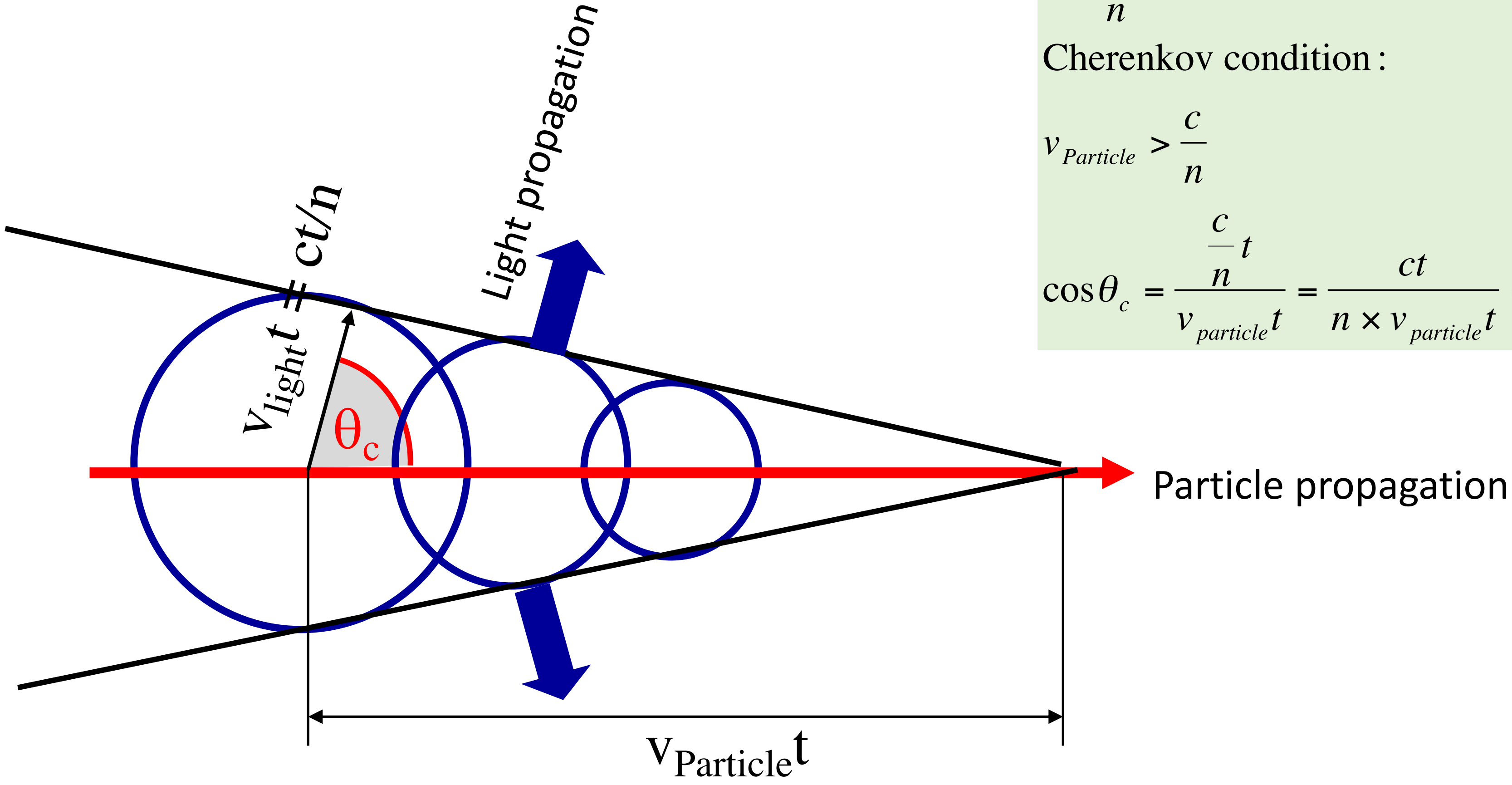
speed of light in the material medium:

$$v = \frac{c}{n}$$

Cherenkov condition:

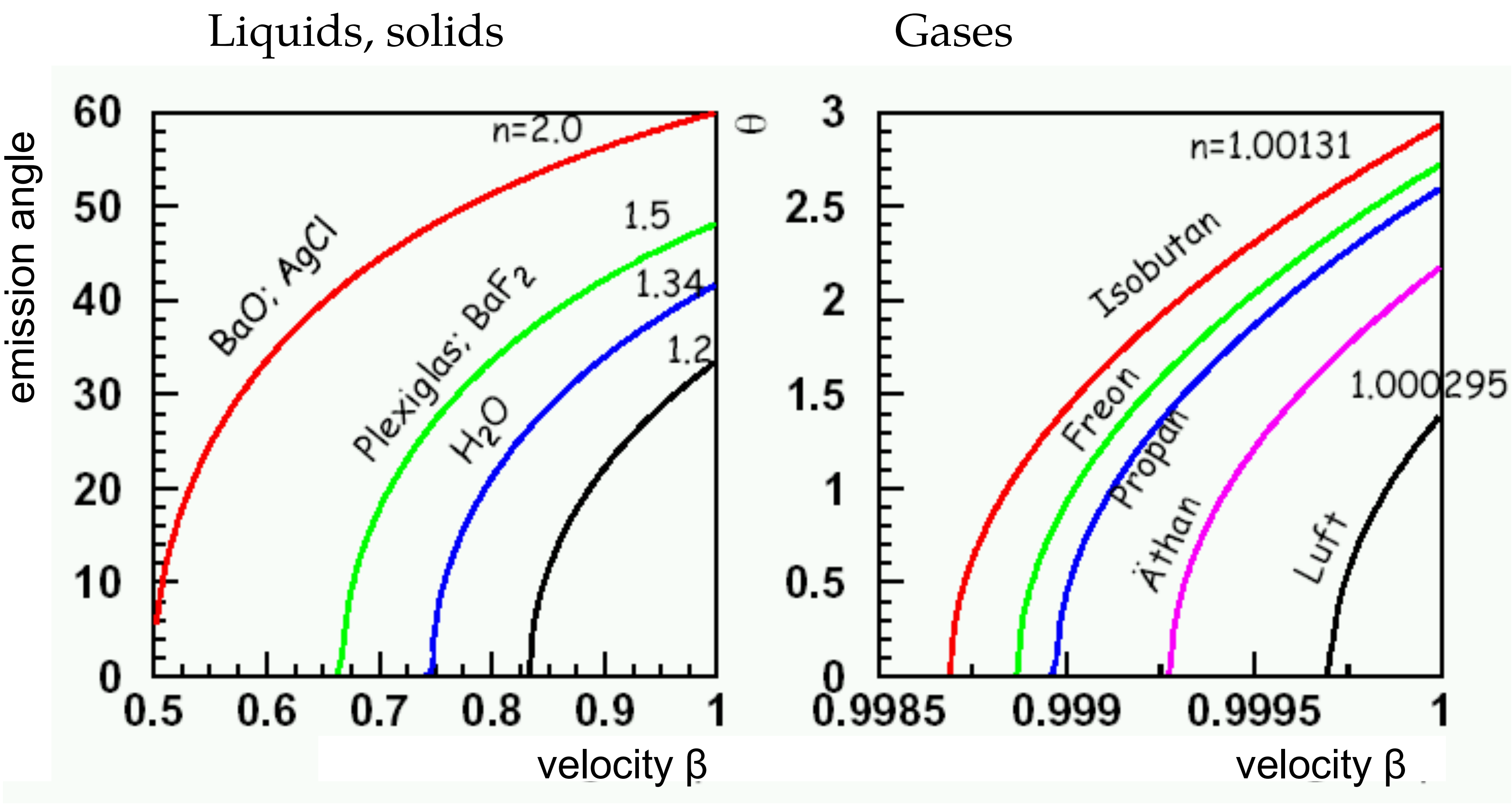
$$v_{Particle} > \frac{c}{n}$$

$$\cos\theta_c = \frac{\frac{c}{n}t}{v_{particle}t} = \frac{ct}{n \times v_{particle}t} = \frac{ct}{n \times \beta_{Particle} \times ct} = \frac{1}{n \times \beta_{Particle}}$$

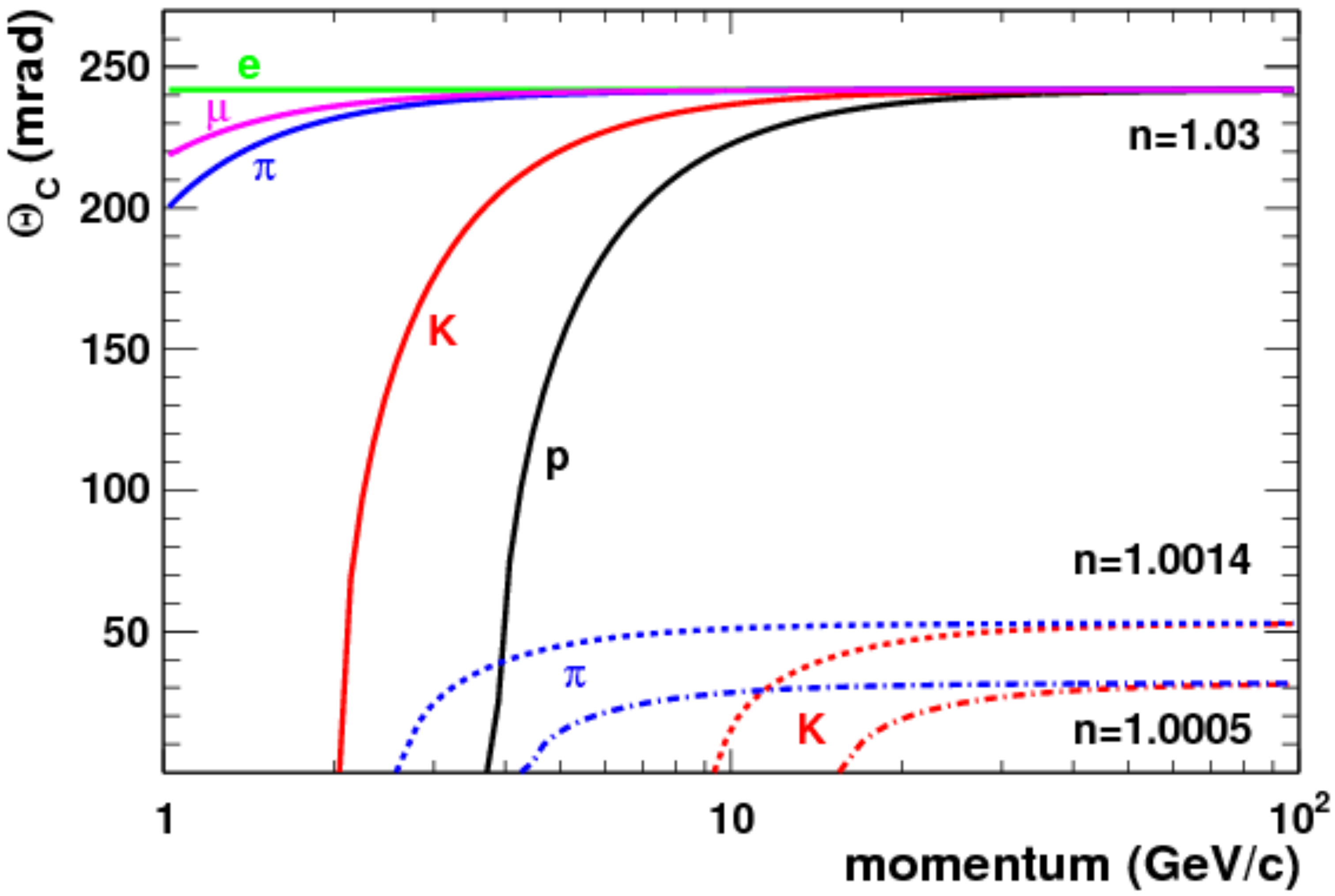


Cherenkov radiation angle

Relation between Cherenkov angle and particle velocity in different materials



Cherenkov radiation angle



Aerogel
θ_C^{max} = 242 mrad

C_4F_{10} gas
θ_C^{max} = 53 mrad

CF_4 gas
θ_C^{max} = 34 mrad

Cherenkov radiation

Radiation of “Cherenkov” photons with a continuos spectrum
The photons are polarized

First theory by Tamm and Frank

$$\left(-\frac{dE}{dx}\right)_{\text{Cherenkov}} = \frac{4\pi e^2}{c^2}\int \omega d\omega\left(1-\frac{1}{\beta^2 n^2}\right)$$

This is already included in the dE/dx by Bethe & Bloch (relativistic rise)

Energy loss by Cherenkov radiation:

$$-\left(\frac{dE}{dx}\right)_{\text{Cherencov}} \cong 10^{-3}\ \text{MeVcm}^2\text{g}^{-1}$$

to be compared with:

Energy loss by collision in H_2: $-\left(\frac{dE}{dx}\right)_{Coll} \cong 0{,}1\ \text{MeVcm}^2\text{g}^{-1}$

Energy loss by collision in a gas with large Z: $-\left(\frac{dE}{dx}\right)_{Coll} \cong 0{,}01\ \text{MeVcm}^2\text{g}^{-1}$

Cherenkov photon density

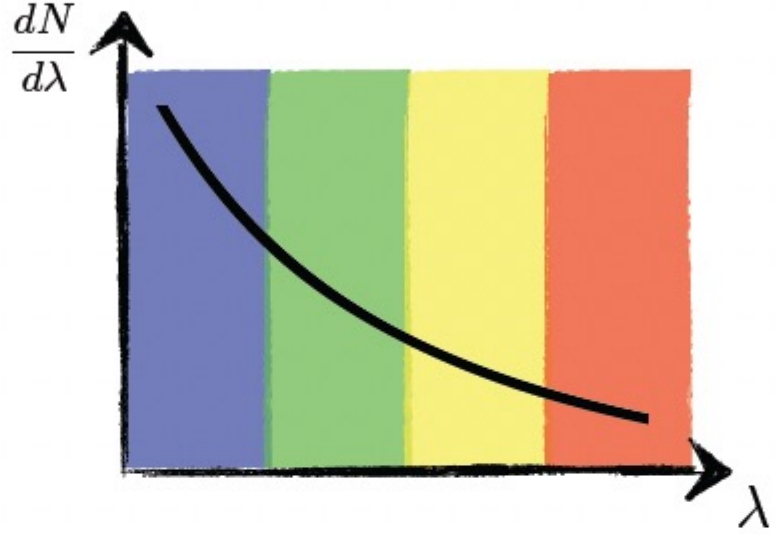
The number of emitted photons per unit length can be obtained from the cross section:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

→ Number of emitted photons decreases with photon wavelength

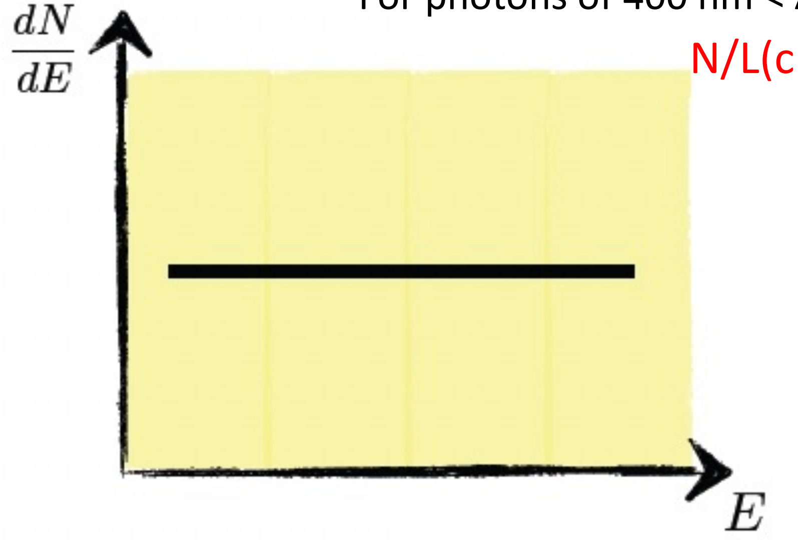
$$\frac{d^2N}{dE dx} = \frac{z^2\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{z^2\alpha}{\hbar c}\sin^2\theta_C \approx \text{const}$$

→ Energy of emitted photons is uniformly distributed



For photons of 400 nm < λ < 700 nm

N/L(cm) ≈ 490 $\sin^2\theta_c$



R. De Vita, INFN Genova

Cherenkov detectors

<u>Main components</u> of a Cherenkov detector

- **Radiator** to produce the Cherenkov photons
- **Mirror, lens, etc.** to collect/transport the photons
- **Photodetector** to detect the photons

- The radiator is chosen based on its refractive index

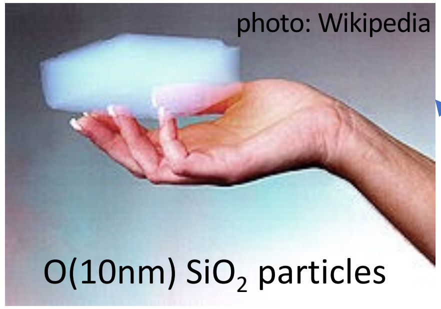


photo: Wikipedia

O(10nm) SiO_2 particles

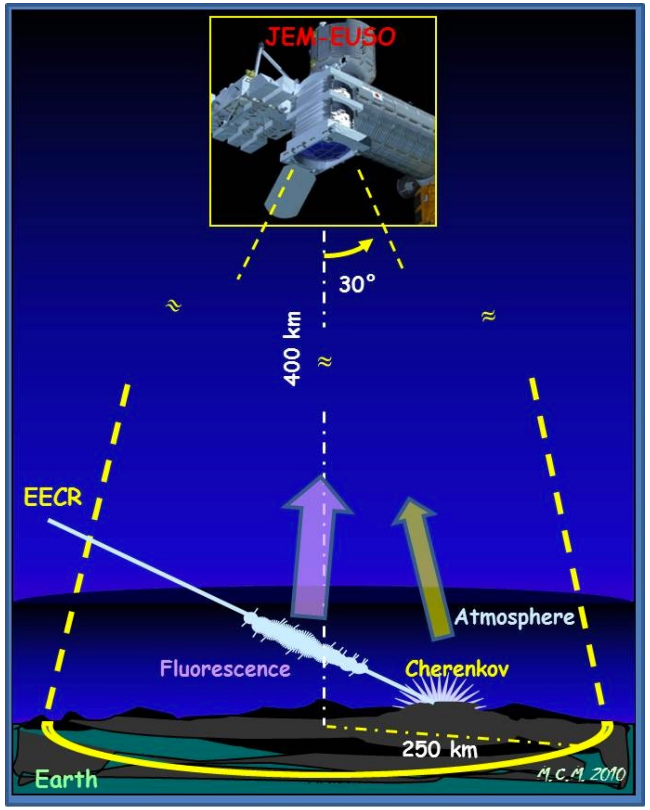
Example of radiators

Medium	n-1	$\gamma_{th} = 1/\sqrt{1-\beta_{th}^2}$	Photons/m
He (STP)	$3.5\ 10^{-5}$	120	3
CO_2 (STP)	$4.1\ 10^{-4}$	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

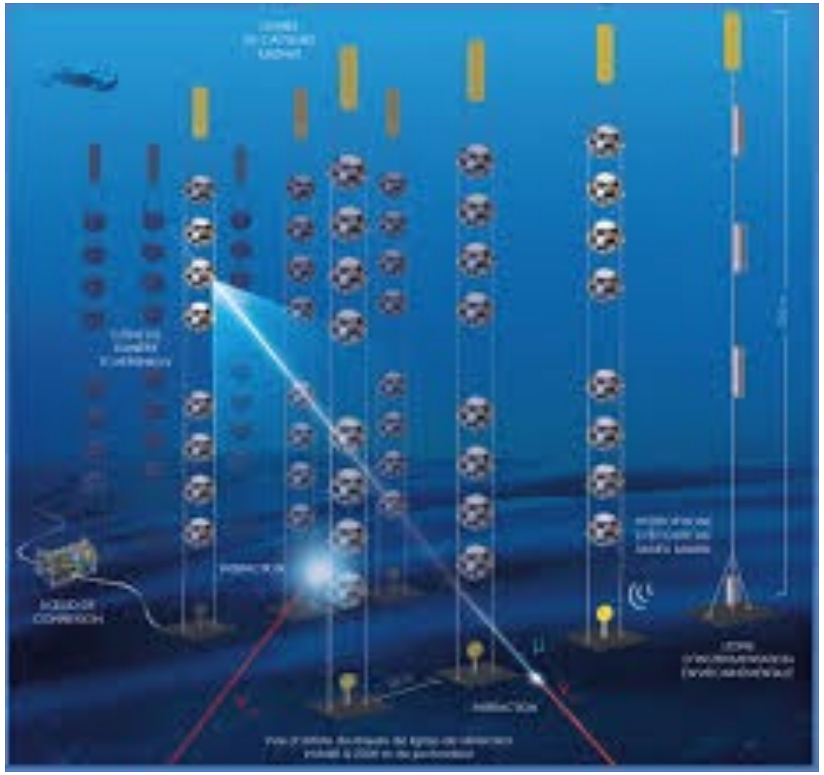
Air, sea-water or ice are exploited as radiators in some astroparticle physics experiments (see next page)

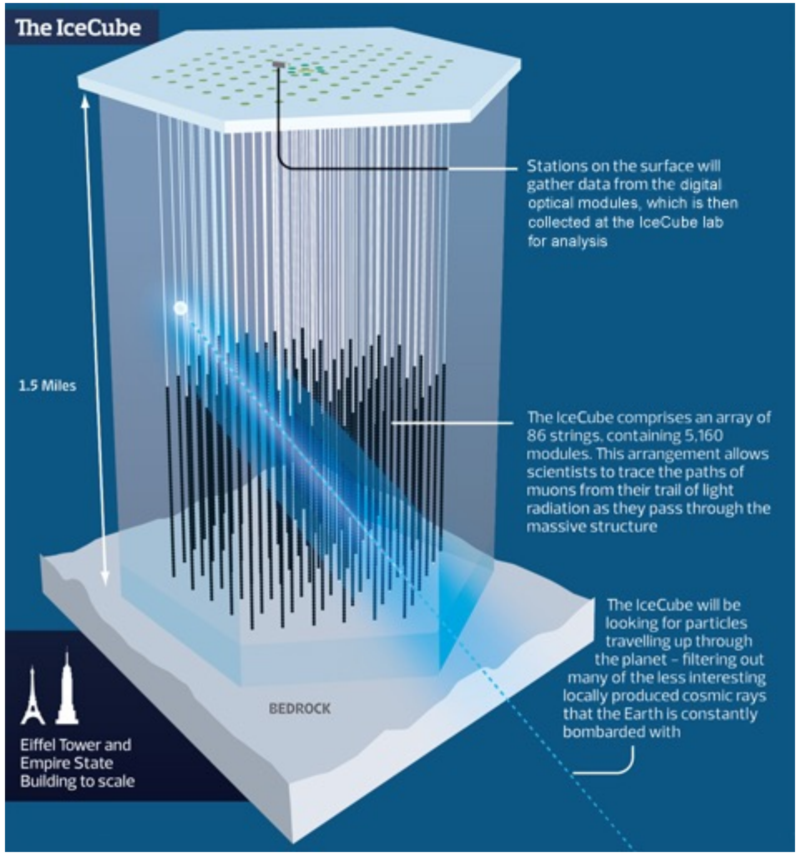
Cherenkov detectors

Air, sea-water or ice are exploited as radiators in some astroparticle physics experiments



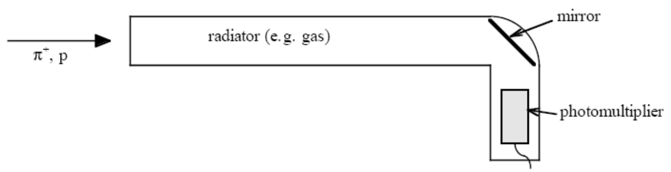
Antares / KM3Net



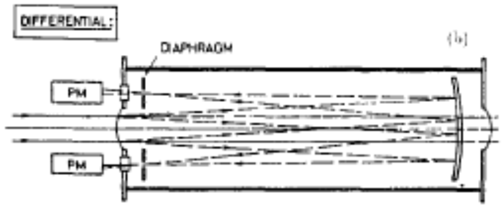


Cherenkov detectors

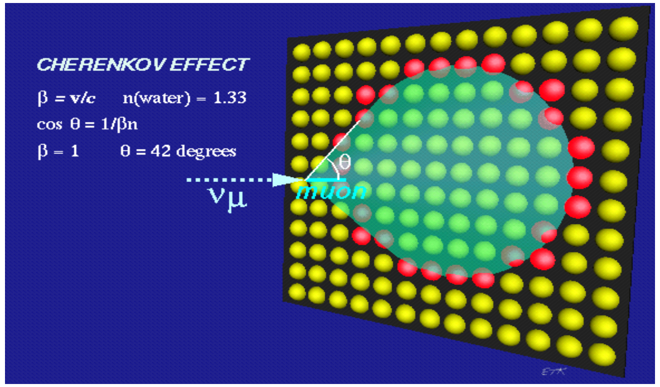
Detectors based on Cherenkov radiation are of 3 types



- **Threshold counters** (yes/no Cherenkov radiation)



- **Differential counters** (measures the Cherenkov angle in a given range)
- **Ring imaging counters** (reconstruct the image of the Cherenkov ring)

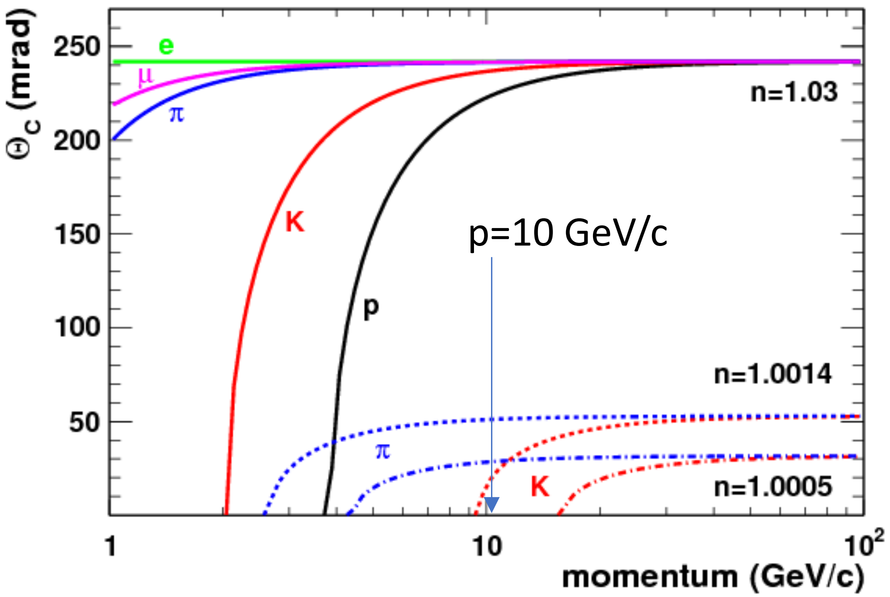


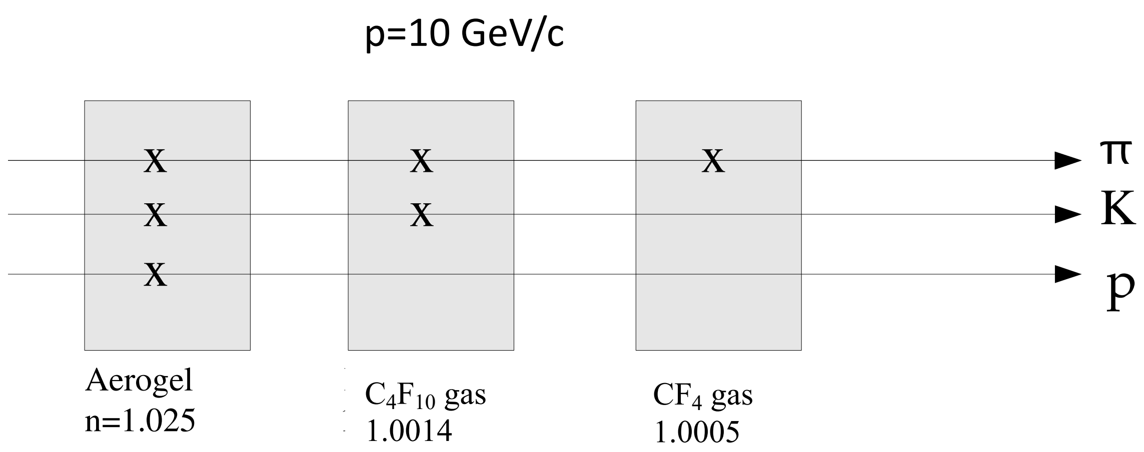
Cherenkov detectors: threshold counters

- Separation of particles with the same momentum but different masses

Cherenkov radiation only if $\beta > \frac{1}{n}$

for a given momentum p, since $\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2+m^2}} = \frac{1}{\sqrt{1+(m/p)^2}}$, Cherenkov radiation only if $m < p\sqrt{n-1}$





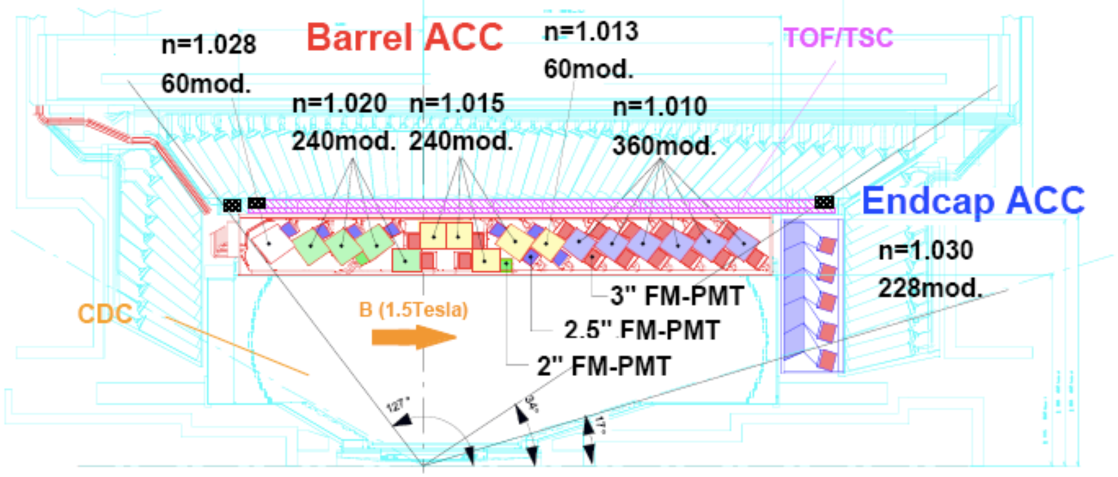
- Improved version: use number of photons (or calibrated pulse) to discriminate particle types.

$$N \approx 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\left(1 + \frac{m^2}{p^2}\right)$$

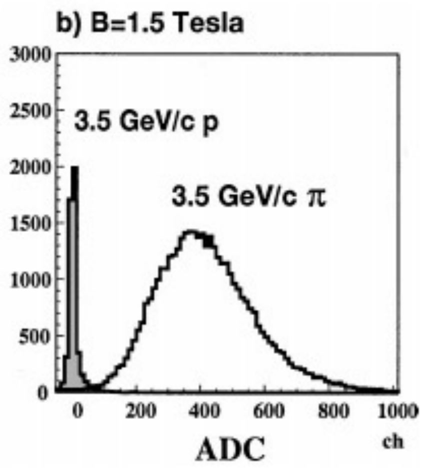
Threshold Cherenkov detectors: examples

BELLE@KEK (1999-2010)

to observe CP violation in B decays at an e+e- collider

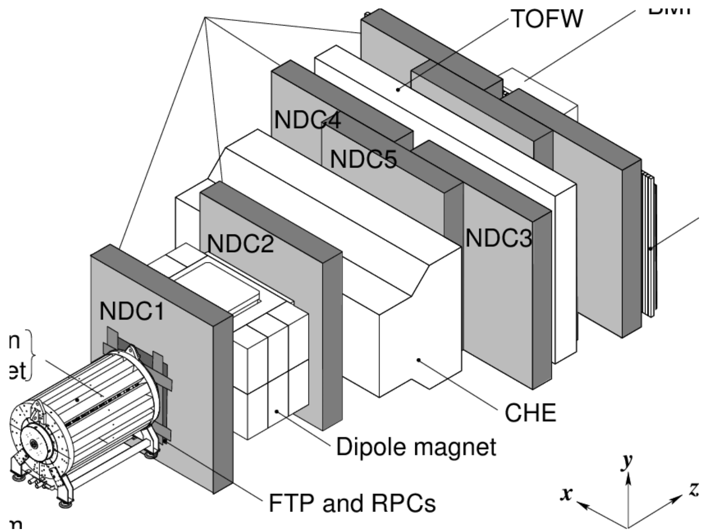


Five aerogel tiles inside an Al box lined with a white reflector(Goretex)

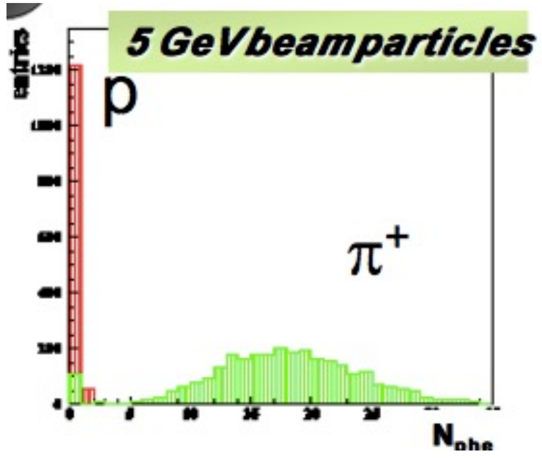


HARP@CERN (2000-2002)

measurement of hadron production on different targets



31 m^3 filled with C_4F_{10} (n=1.0014)



(Complementing Cherenkov PID : Time-of-Flight)

Distinguishing particles with ToF:
[particles have same momentum p]

Particle 1 : velocity v_1, β_1; mass m_1, energy E_1
Particle 2 : velocity v_2, β_2; mass m_2, energy E_2

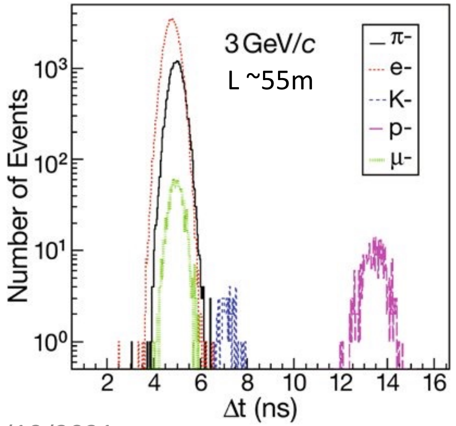
Distance L : distance between ToF counters

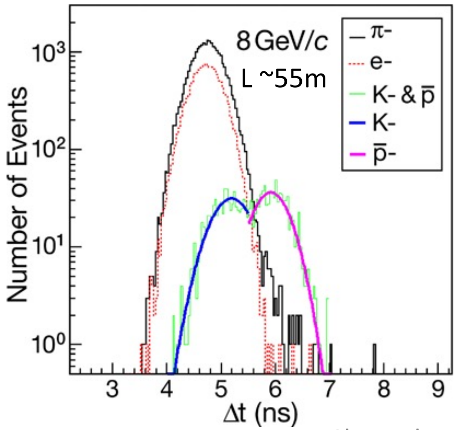
$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$
$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

Relativistic particles, $E \simeq pc \gg m_i c^2$:

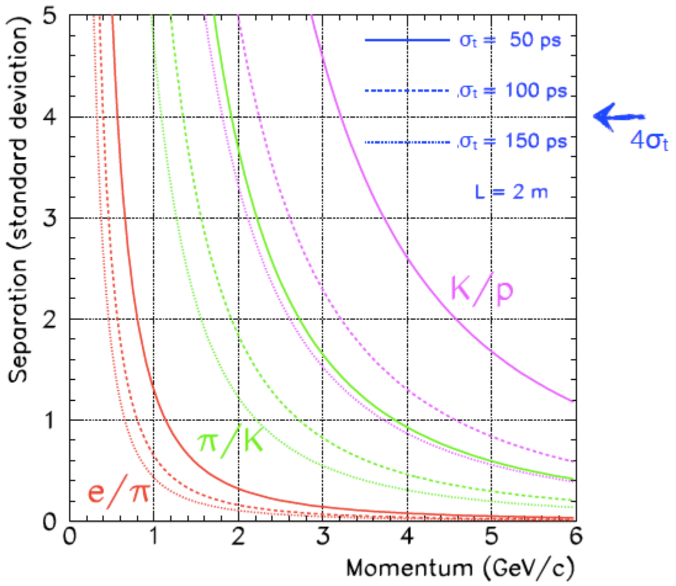
$$\Delta t \approx \frac{L}{pc^2}\left[\left(pc + \frac{m_1^2c^4}{2pc}\right) - \left(pc + \frac{m_2^2c^4}{2pc}\right)\right]$$
$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

Cherenkov + TOF routinely used for beam monitoring in fixed-target experiments





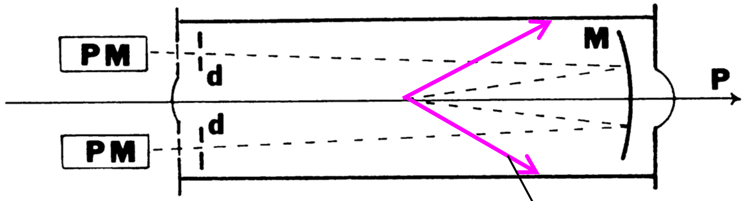
σ_t : time resolution of the detector

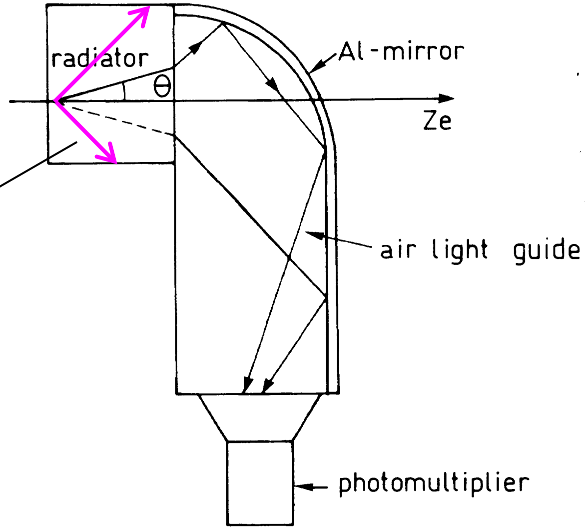


Cherenkov detectors: differential counters

For a given momentum, cosθ is function of the mass

$$\cos\theta = \frac{1}{n\beta} = \frac{1}{n(p/E)} = \frac{\sqrt{m^2 + p^2}}{np}$$



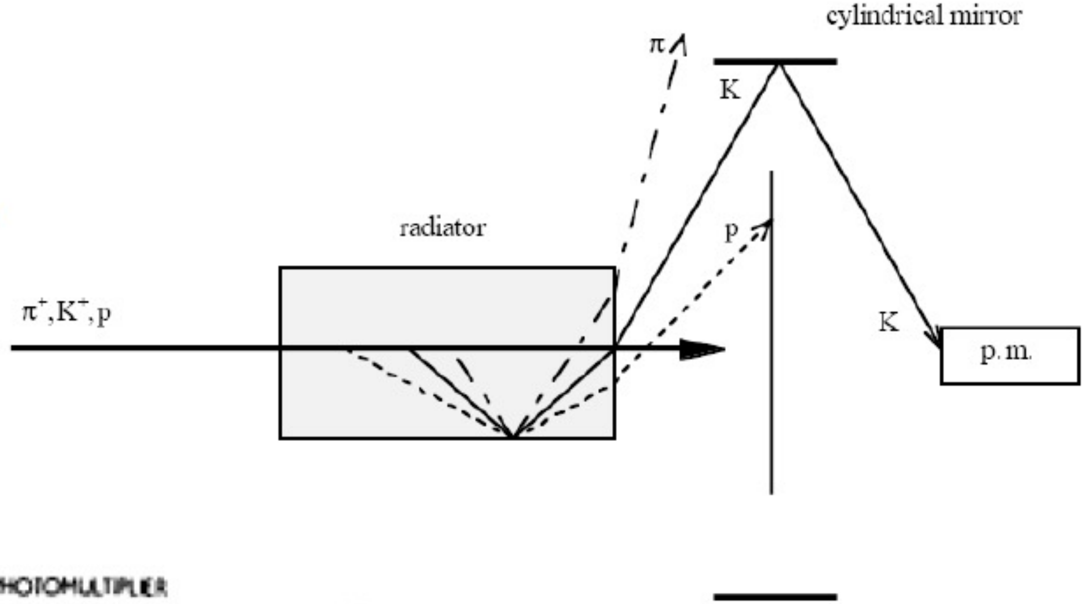


Only the light emitted at a
given angle goes to the PM

Differential Cherenkov detectors : example

slide from S. Easo

With Solid (quartz) radiator



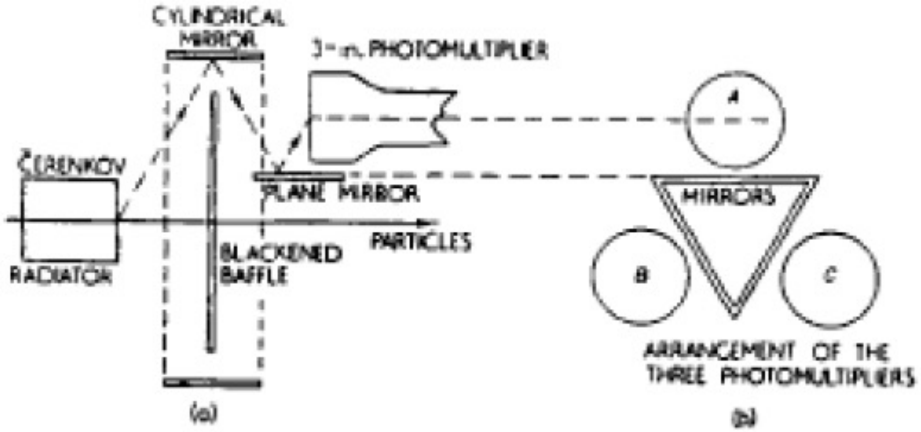


Fig. 2. The differential Cherenkov counter used in the antiproton discovery experiment: (a) side view; (b) end view.

- Discovery of anti-proton in 1955 by Chamberlain, Segre et. al. at Berkeley.
- Nobel Prize in 1959

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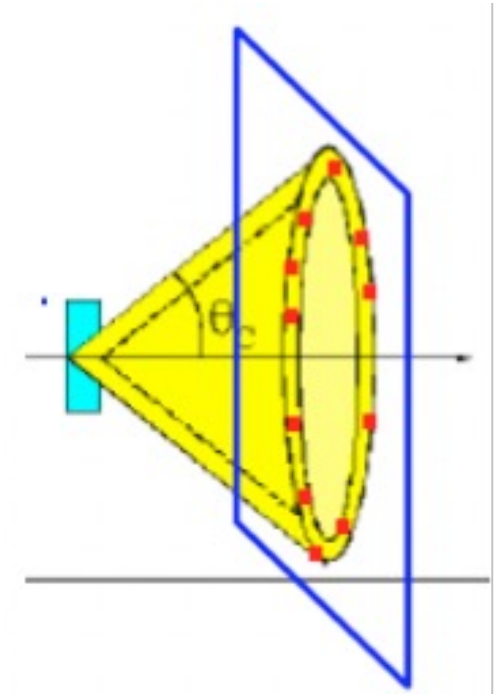
Cherenkov detectors: ring imaging

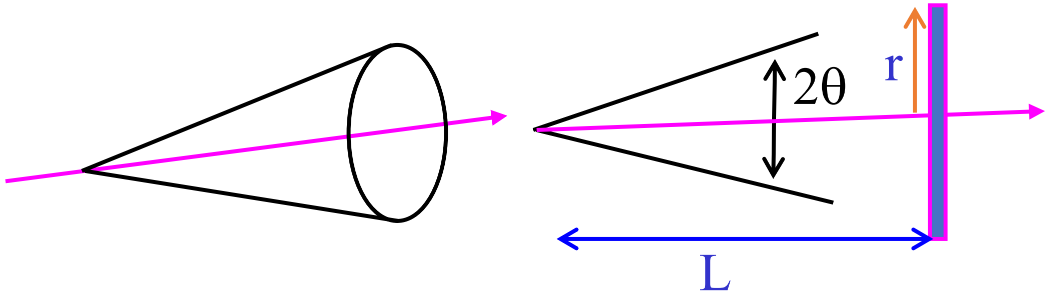
- Intercept the Cherenkov cone with a plane → ring
- Measure both the Cherenkov angle and the number of detected photons

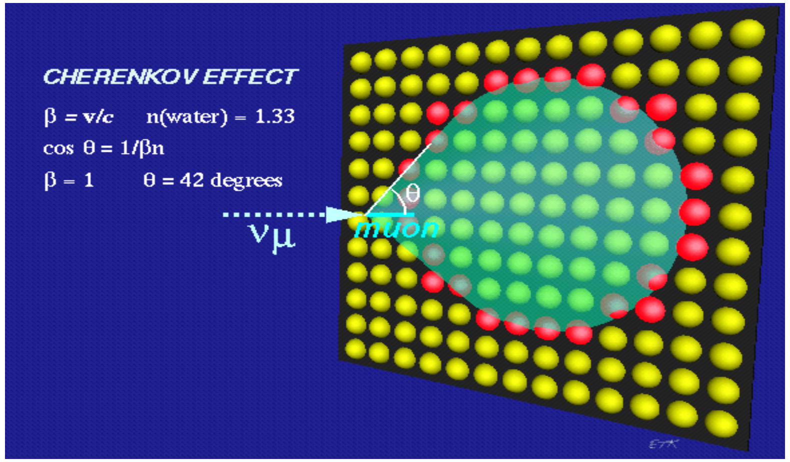
    (➔ better resolution on β than equivalent threshold or differential detectors)

- Allows for particle identification over large surfaces
- Requires photodetectors with single photon identification capabilities



RICH and PID





$r = L \times \tan\theta$

Example : Incoming particle with p = 1GeV/c, L = 1 m, in LiF (n = 1.392):

	θ(deg)	r(m)
π	43.5	0.95
K	36.7	0.75
P	9.95	0.18

Very good π/K/p seperation

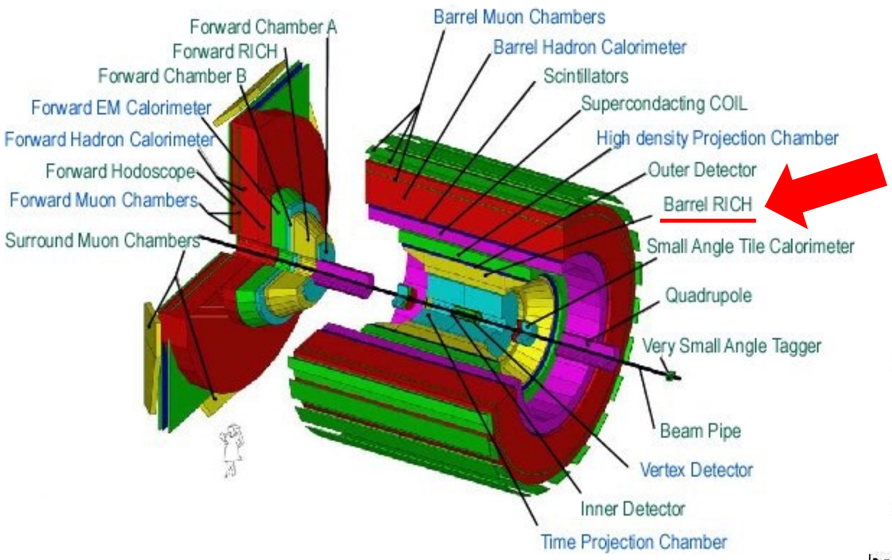
Particle ID

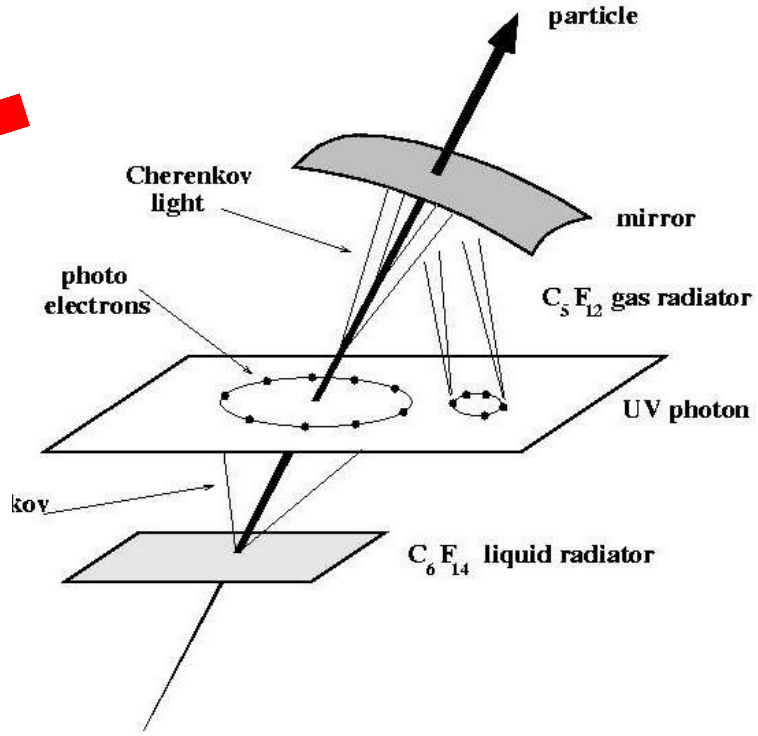
Tom Ypsilantis

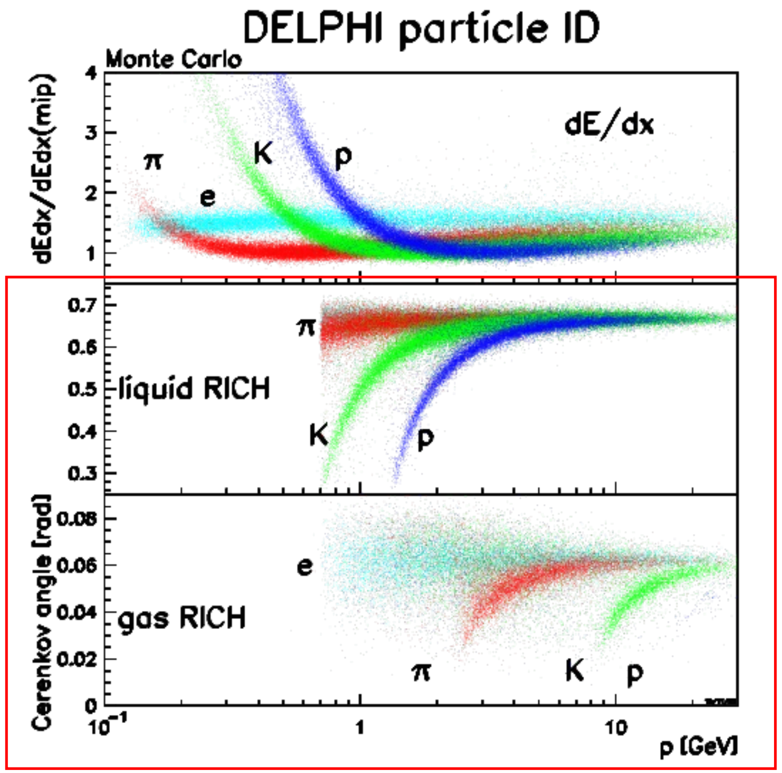
RICH: examples

DELPHI@LEP (CERN, 1988-2000)
"a Detector with Lepton, Photon and Hadron Identification"
multi-purpose detector for precision EW measurements in e^+e^- collisions at sqrt(s)=91-200 GeV
→ one of the first large-size RICH detectors

→ π/K/p separation over a large momentum range: 0.7-45 GeV/c







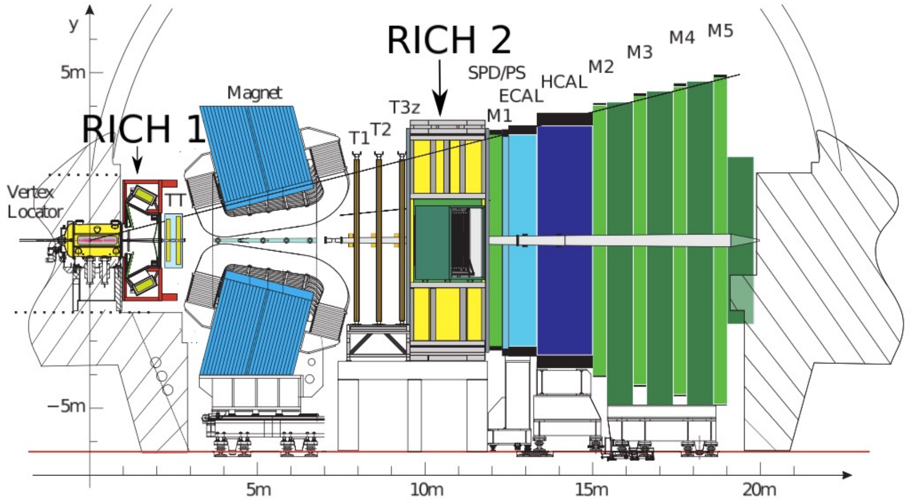
- 2 radiators:
  C_5F_{12} gas, n=1.241
  C_6F_{14} liquid, n=1.2834
- 288 parabolic mirrors
- photodetector: gas+TMAE+MWPCs

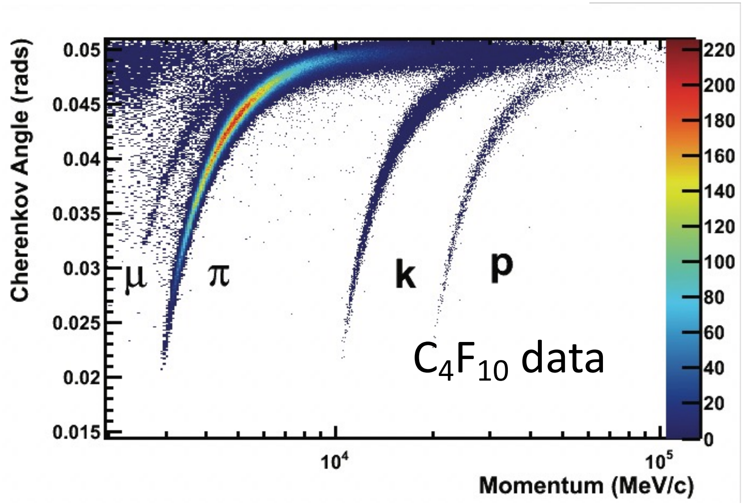
RICH: examples

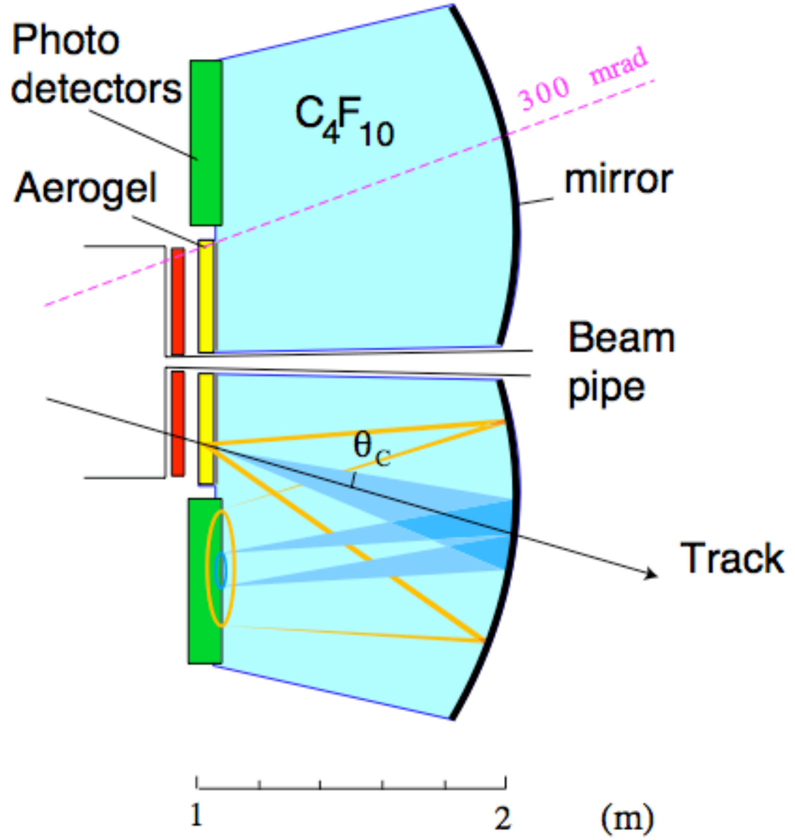
LHCb@LHC (CERN)

Identify charged hadrons (π,K) in B (and D) meson decays

- 2 RICH detectors to cover different momentum and polar angle ranges
- 2 radiators in each RICH (Aerogel+C_4H_{10}/CF_4)
- Photodetectors: HPDs (see next slide)



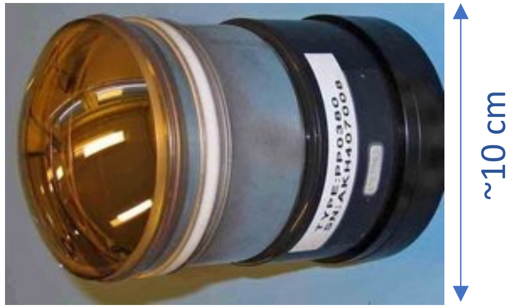


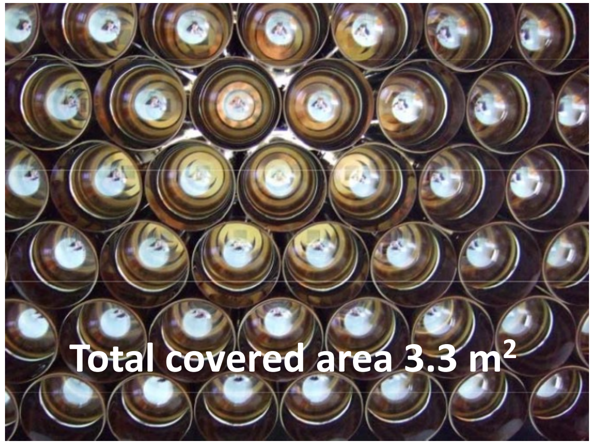


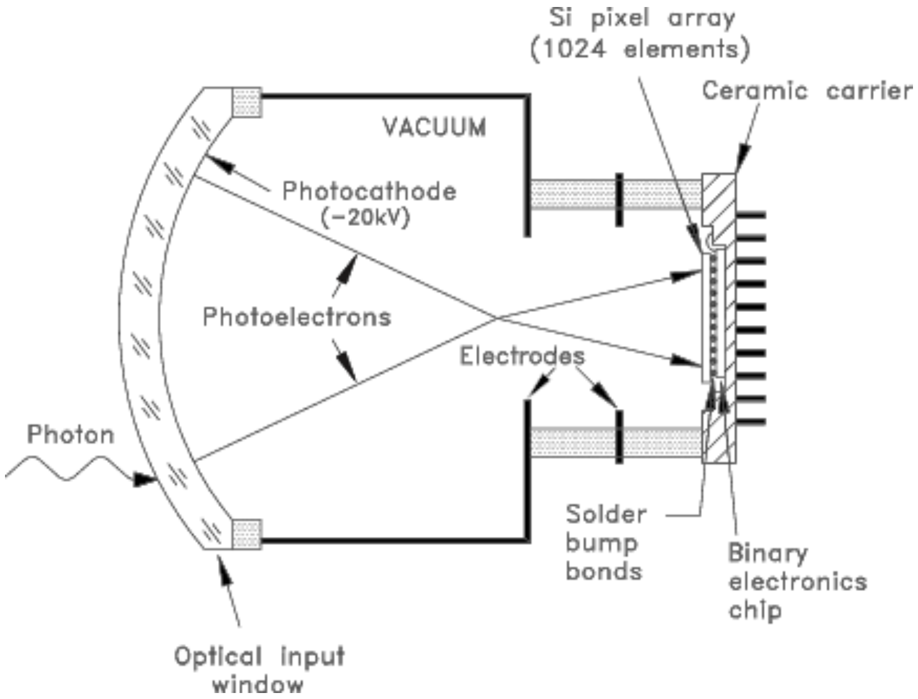
RICH: examples

LHCb@LHC (CERN)

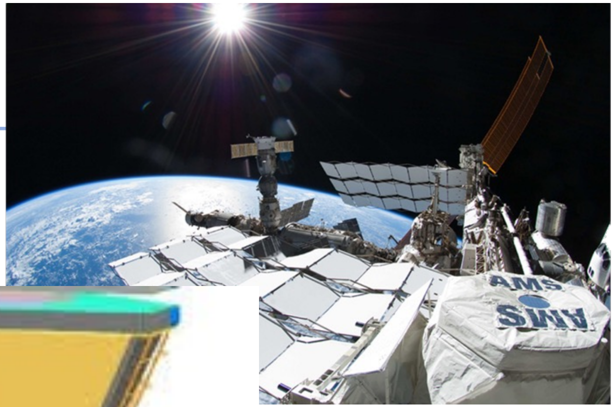
Hybrid Photon Detectors (**HPDs**)
Photoelectric effect +
focusing of photoelectrons to Si sensors
→ Accurate measurement of space and time of photons
→ Short flight path of PEs: reduced sensitivity to magnetic field
→ Can detect single photons





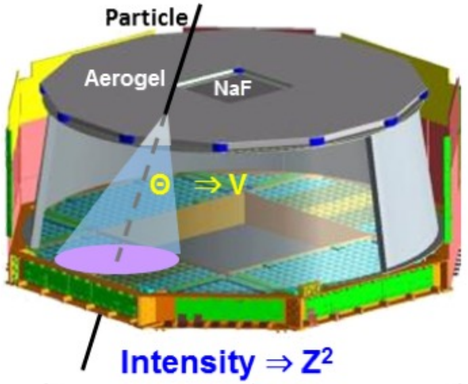


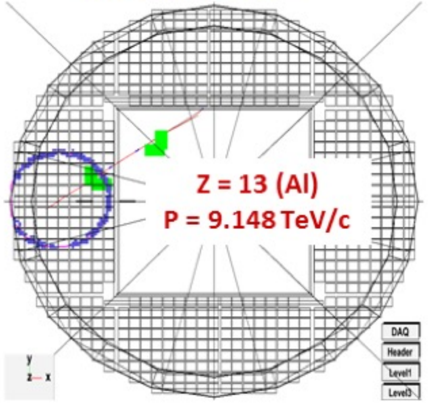
RICH: examples



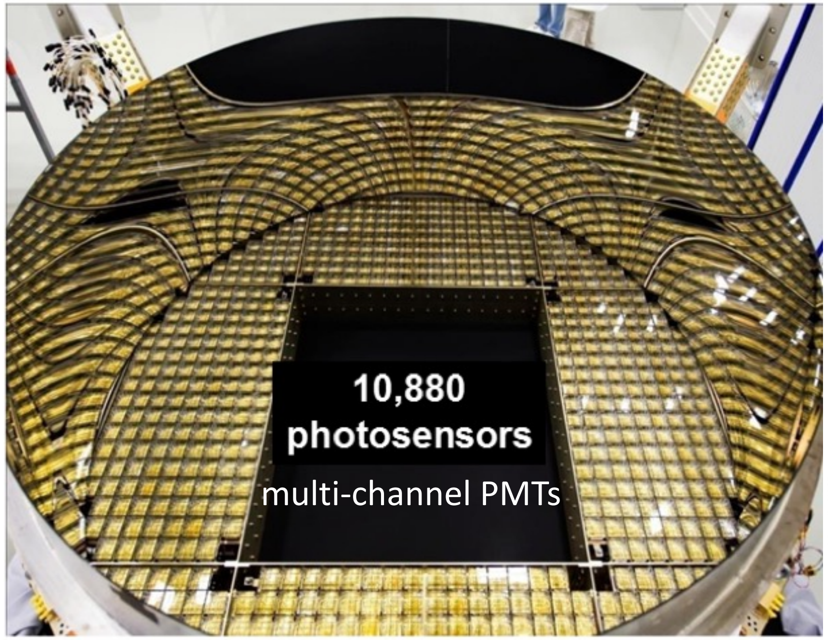
AMS Ring Imaging CHerenkov (RICH)

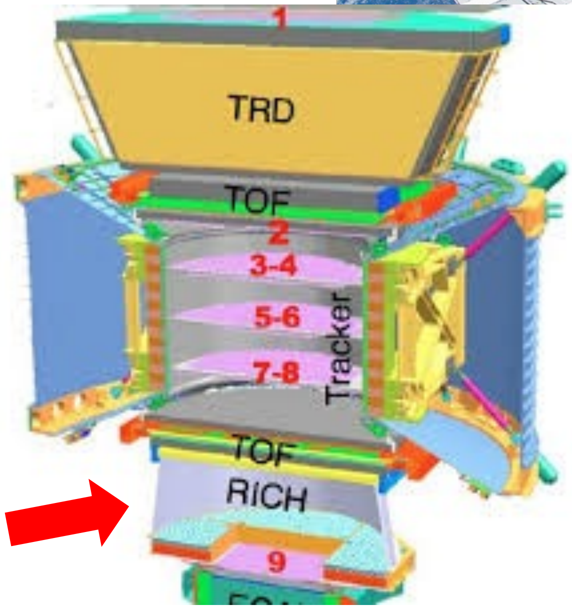
Measurement of Nuclear Charge (Z^2) and its Velocity to 1/1000

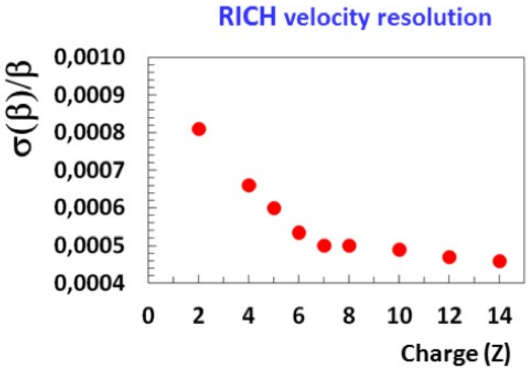


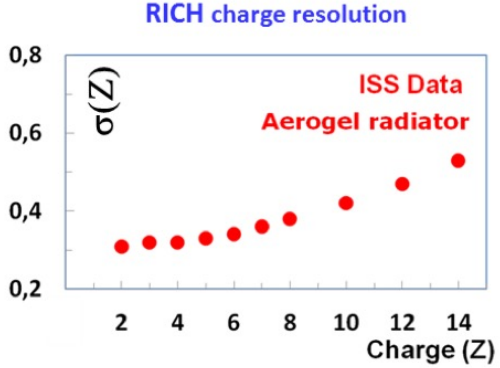


- 2 radiators:
  16 tiles of NaF tiles, n=1.33
  92 tiles of Aerogel, n=1.05
- 470mm expansion volume + mirrors



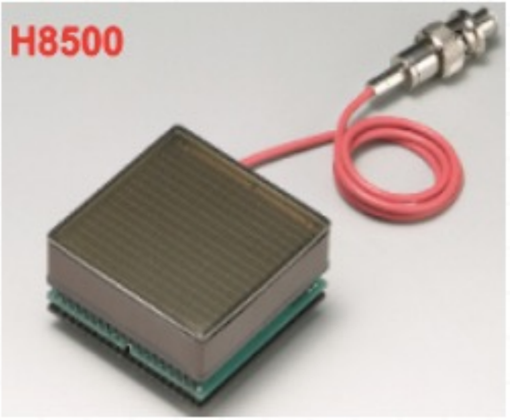


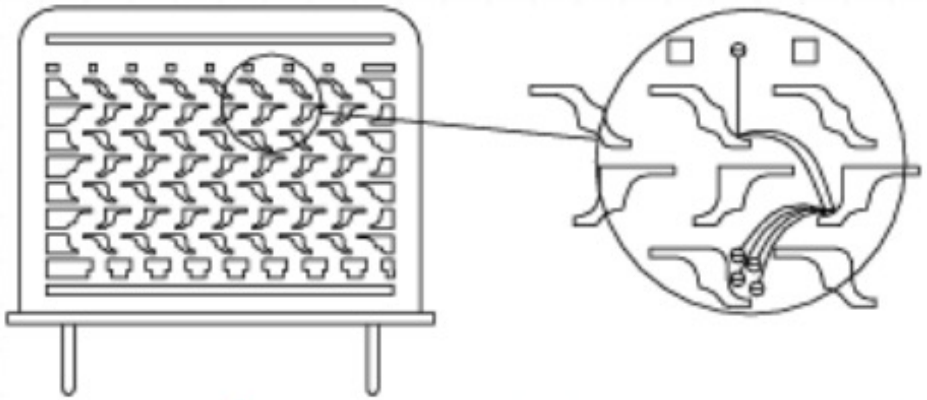




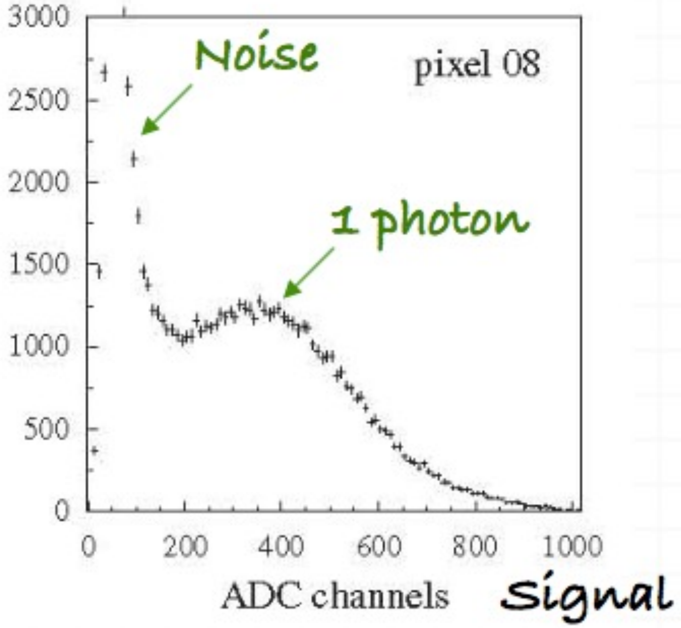
Multi-Anode PMTs

- *Multianode* photomultipliers are a marvel of miniaturization → up to 64 pixels in a single tube, each with size ~ 2x2 mm^2
- Dynode structure formed from a stack of perforated metal foils
- Signal width dominated by fluctuations in the charge multiplication of the first dynodes





Multianode PM (Hamamatsu)

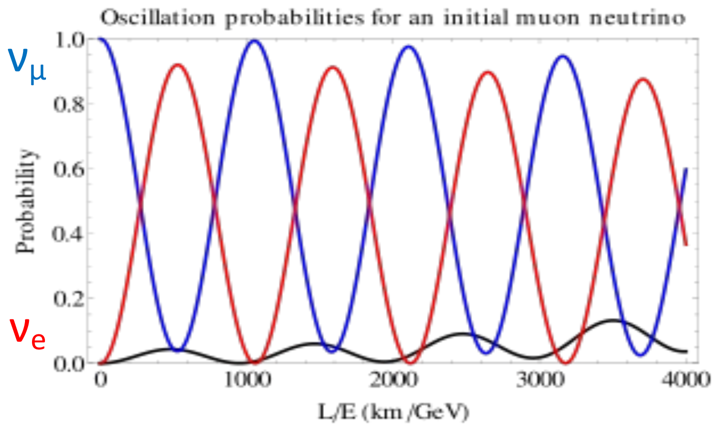


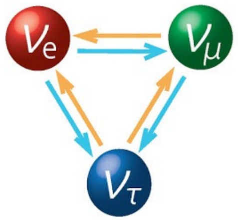
R. De Vita, INFN Genova

Cherenkov PID in neutrino experiments

Neutrinos:
3 flavours (ν_e,ν_μ,ν_τ)
3 mass eigenstates (ν_1,ν_2,ν_3)

Observation of neutrino oscillations
→ flavour eigenstates are superposition of mass eigenstates
→ neutrinos have mass





Neutrino experiments need to identify the <u>flavour of the neutrino</u> == <u>flavour of the lepton</u> produced in CC interactions

The Nobel Prize for Physics 2015

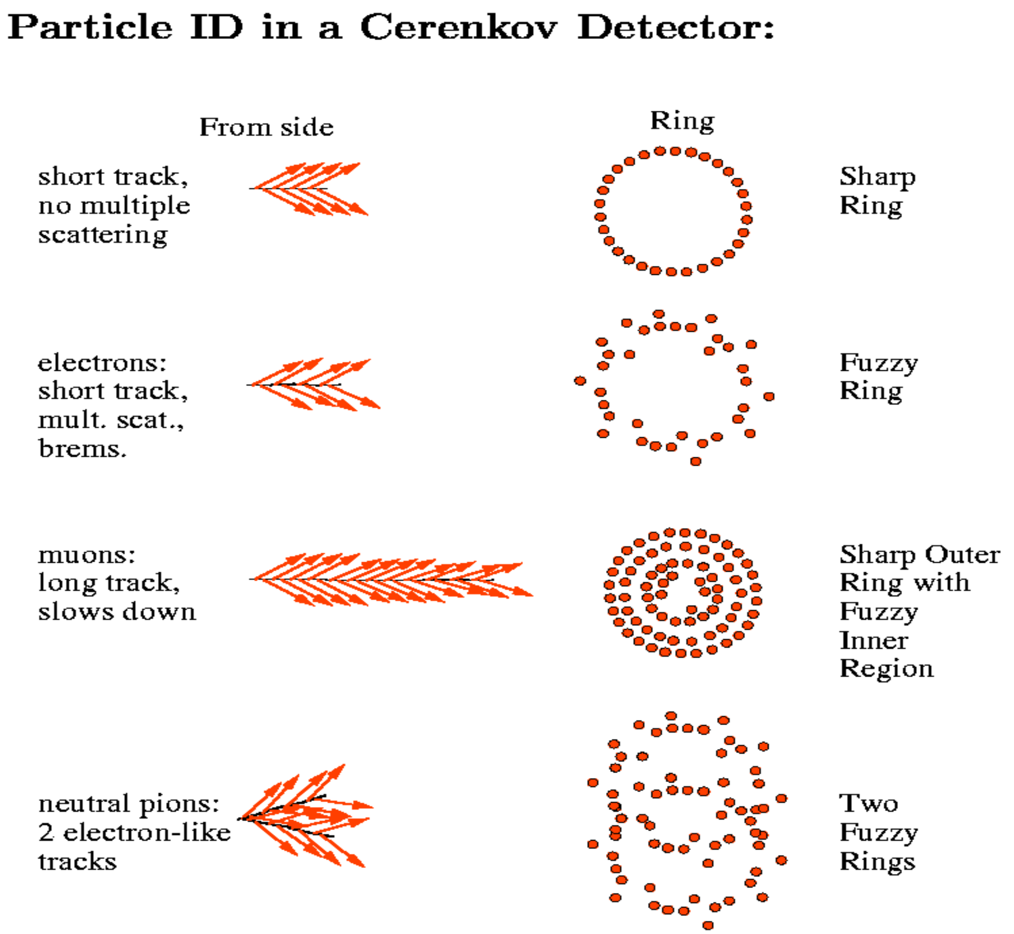
Takaaki Kajita
Super Kamiokande Collaboration
University of Tokyo, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Canada

« For the discovery of neutrino oscillations, which shows that neutrinos have mass. »

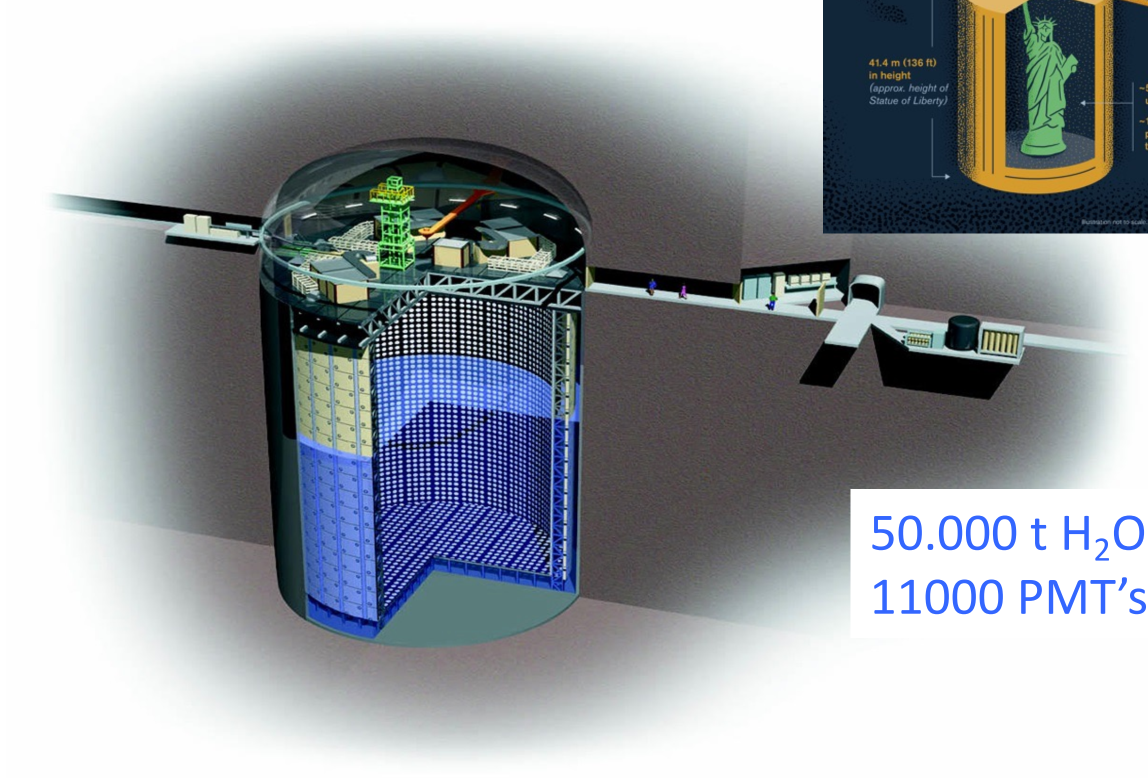
Cherenkov PID in neutrino experiments

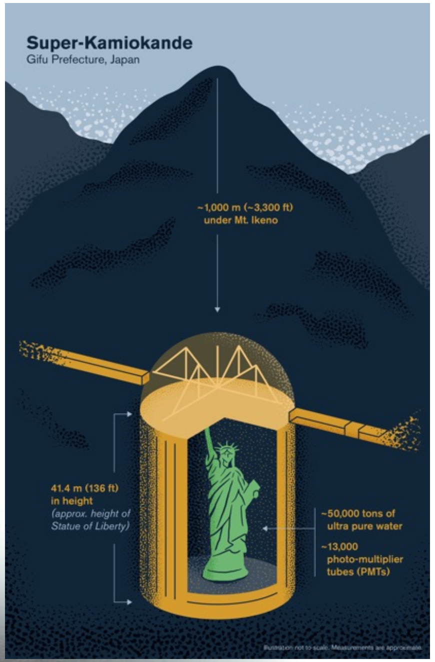
Identification of particles produced in neutrino interactions:
Based on the characteristics of the Cherenkov cone



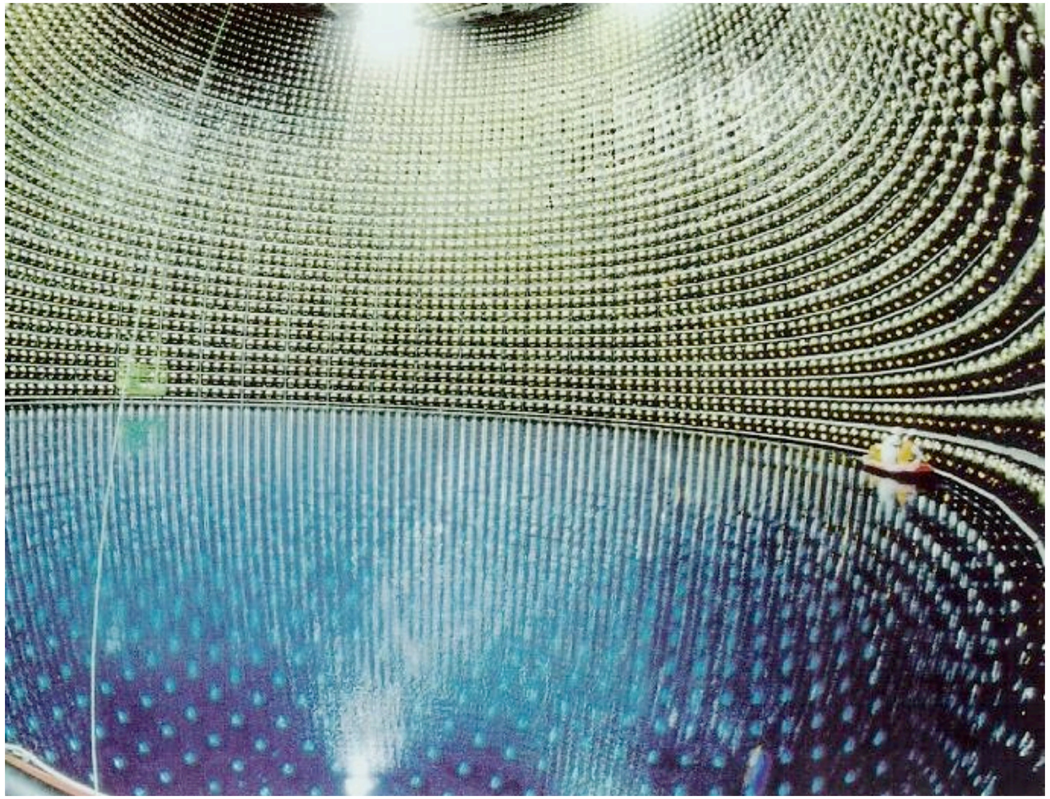
Example: SuperKamiokaNDE

Kamioka mine, Japan
~1000 m under Mount Ikeno



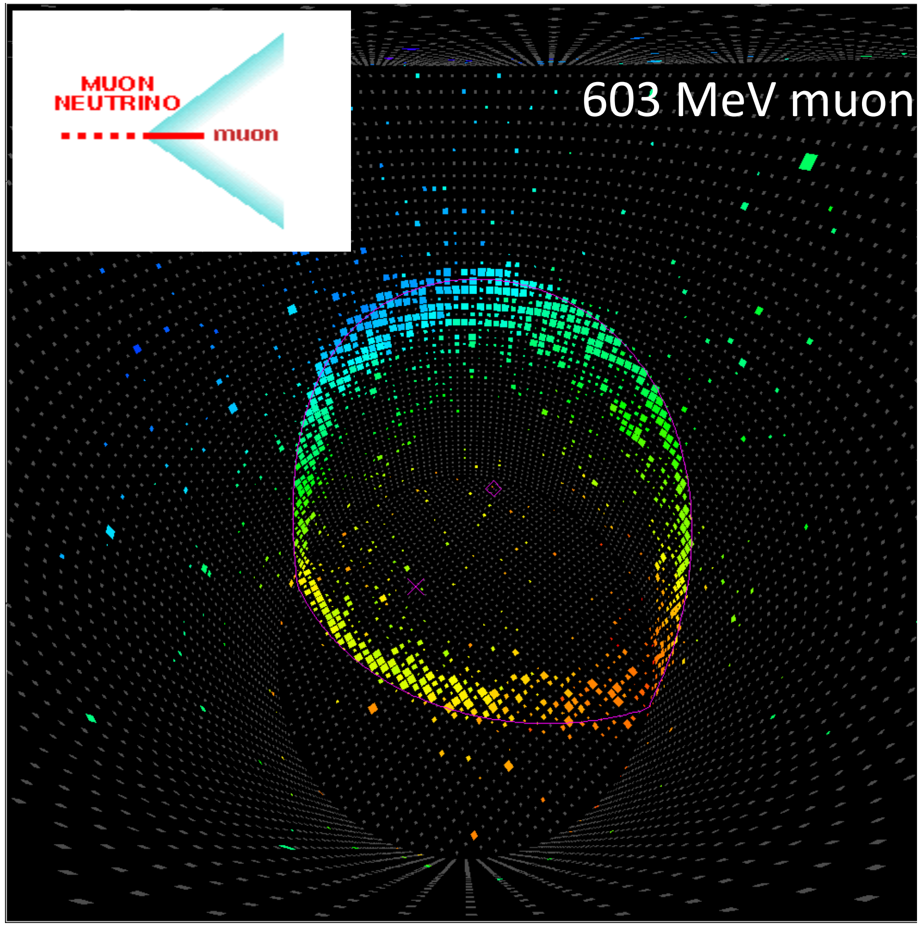


50.000 t H_2O
11000 PMT's

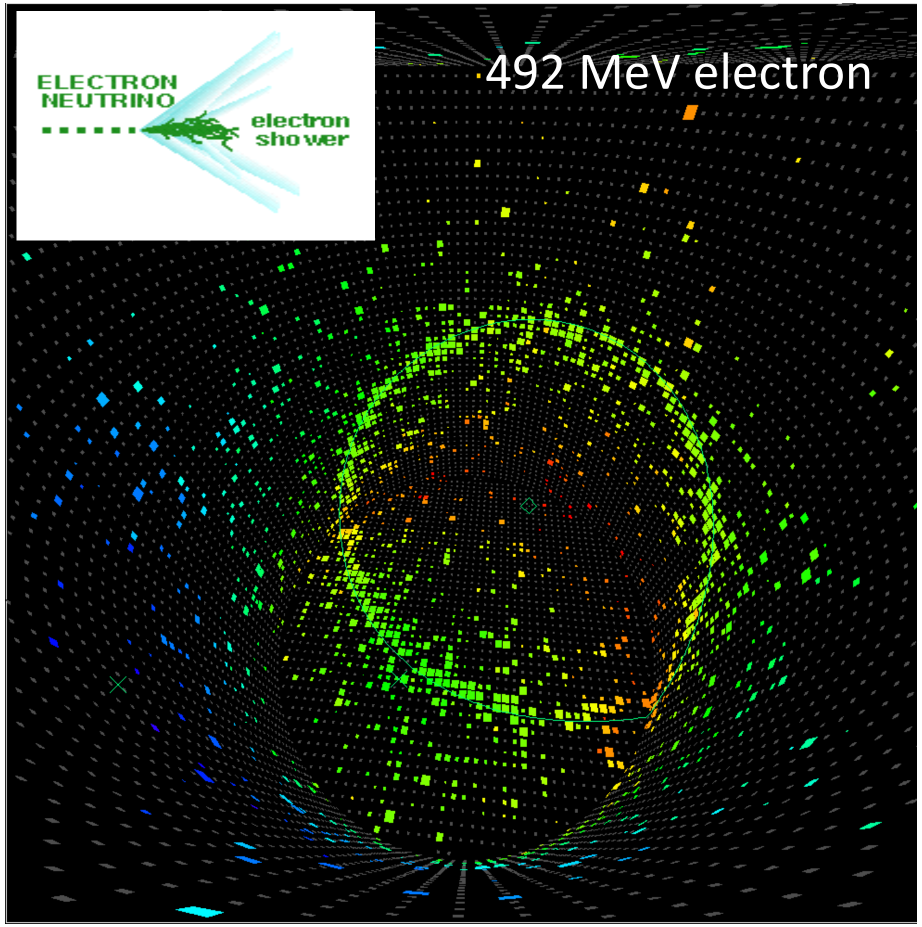


Example: SuperKamiokaNDE

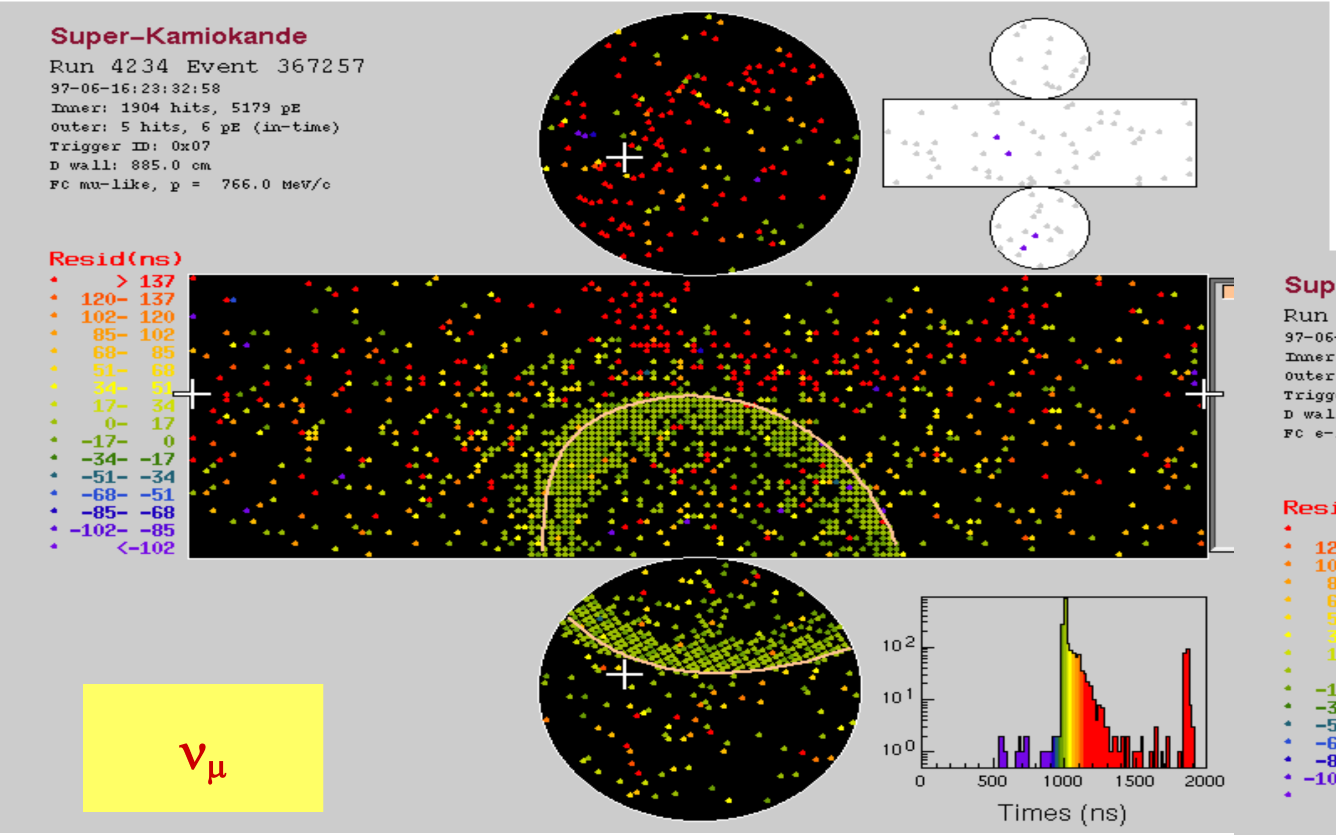
$$\nu_\mu + p \rightarrow \mu^- + n \quad \text{(CC)}$$

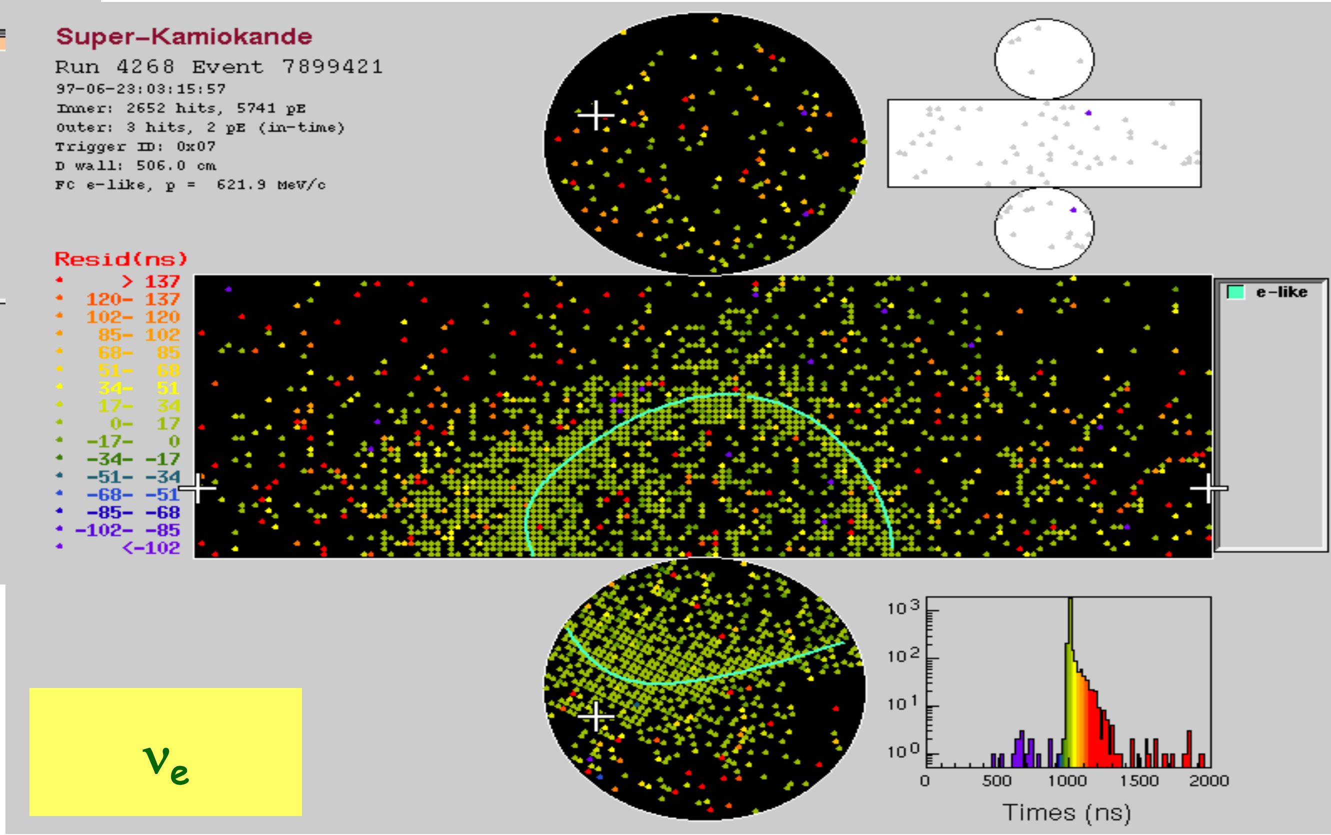


$$\nu_e + p \rightarrow e^- + n \quad \text{(CC)}$$

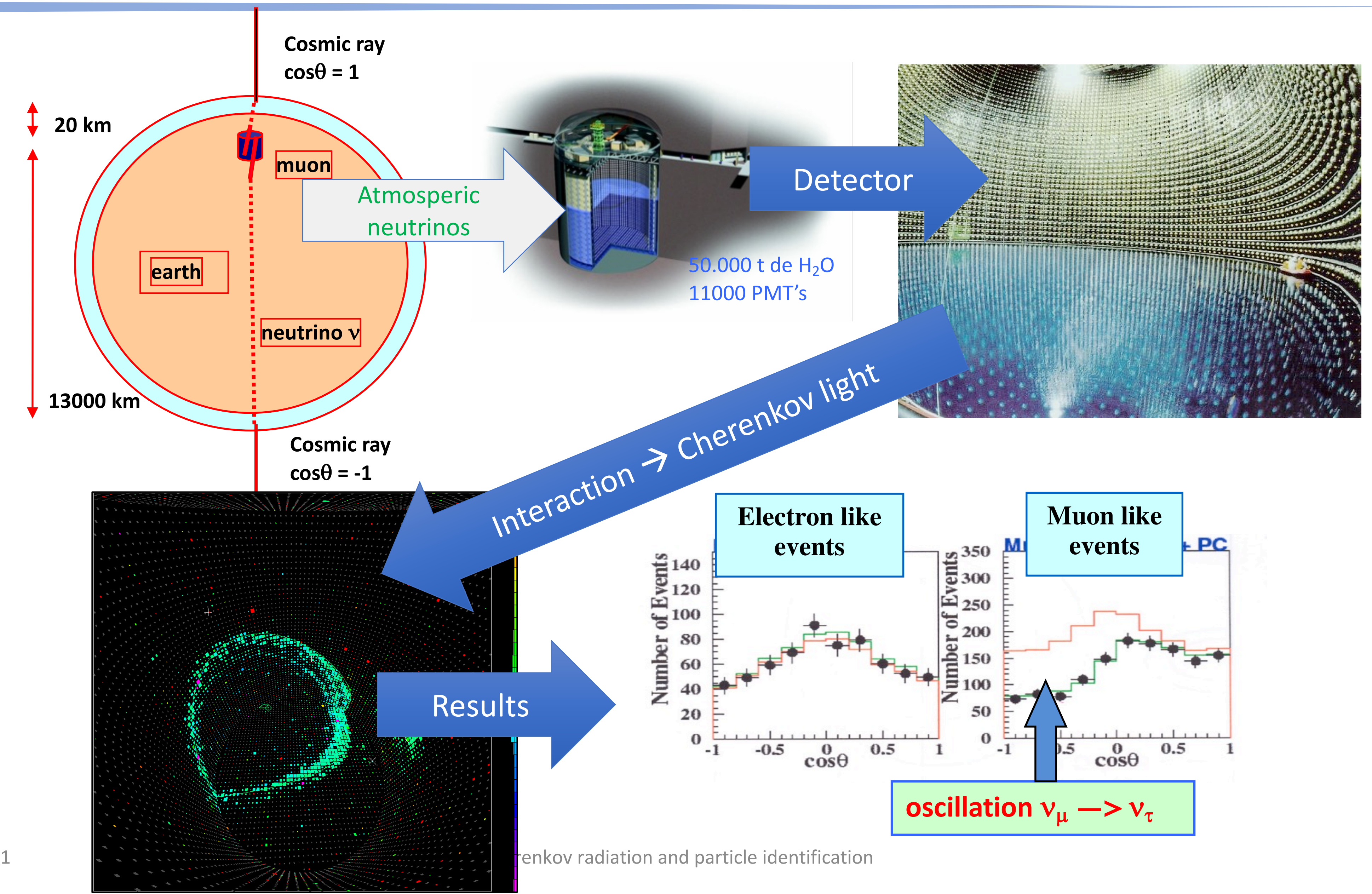


Example: SuperKamiokaNDE

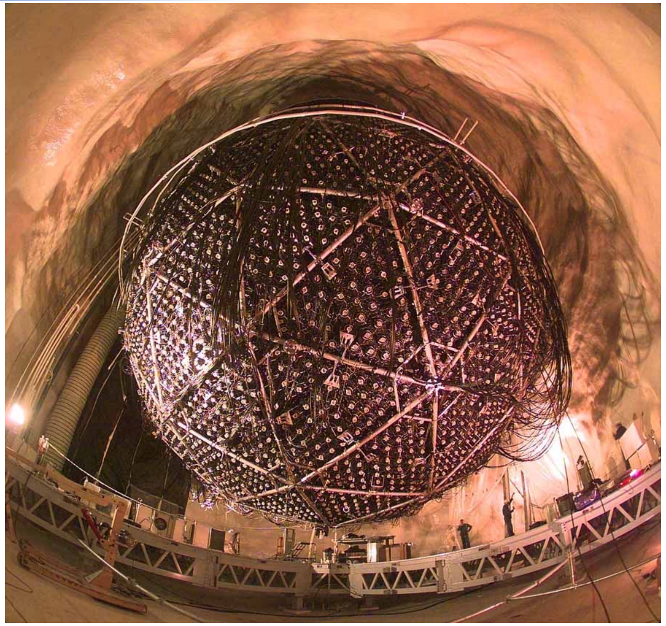


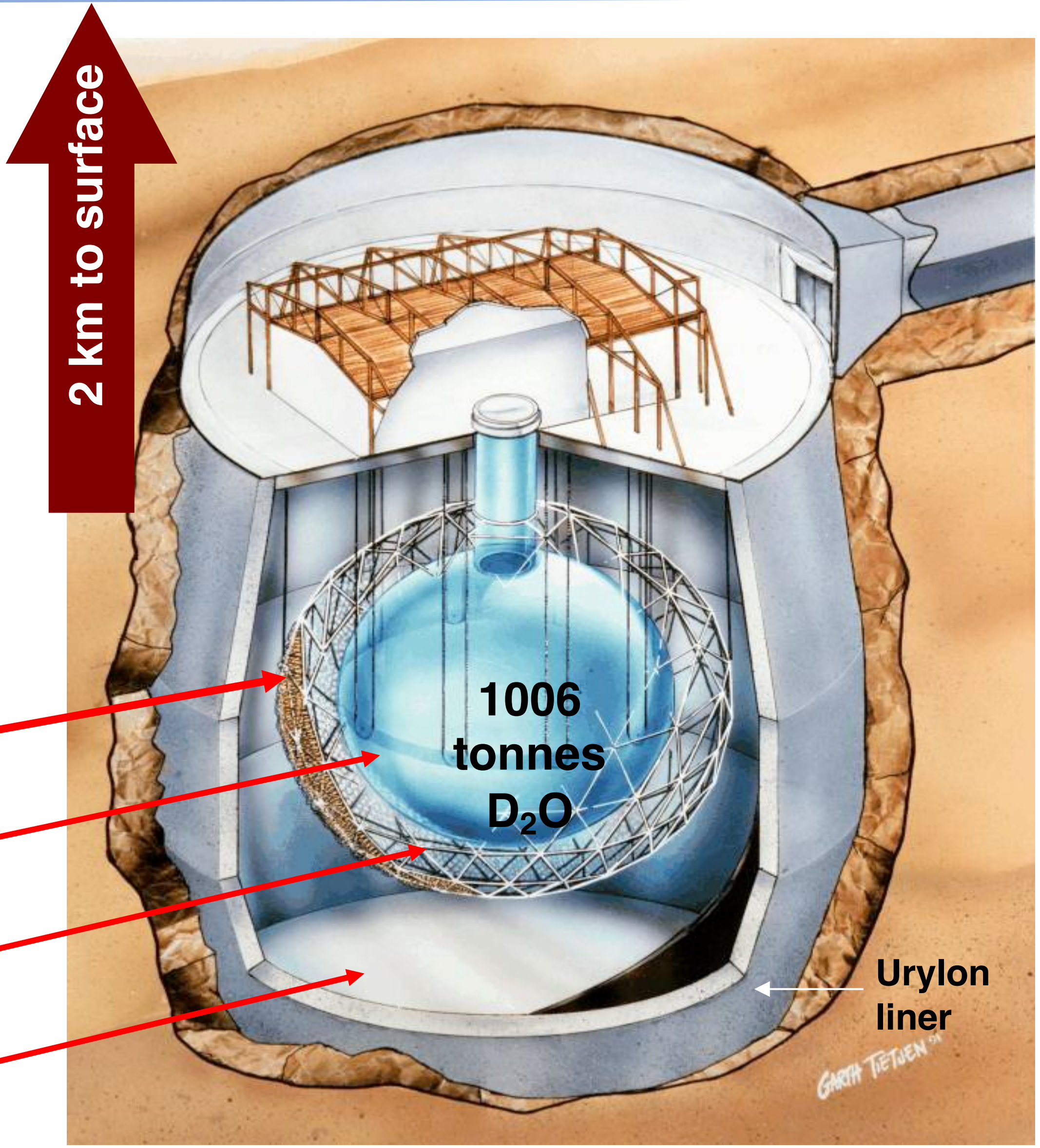


Example: SuperKamiokaNDE



Example: Sudbury Neutrino Observatory (SNO)





17.8m dia. PMT Support Structure
9456 20-cm dia. PMTs
56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H_2O

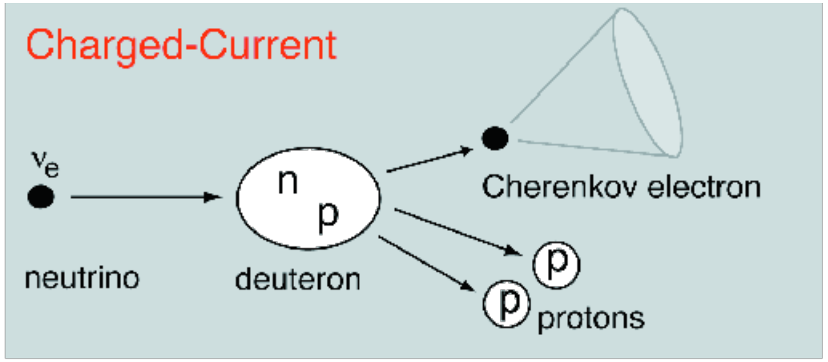
5300 tonnes of outer shielding H_2O

Nucl. Inst. Meth. A449, 127 (2000)

Example: SNO

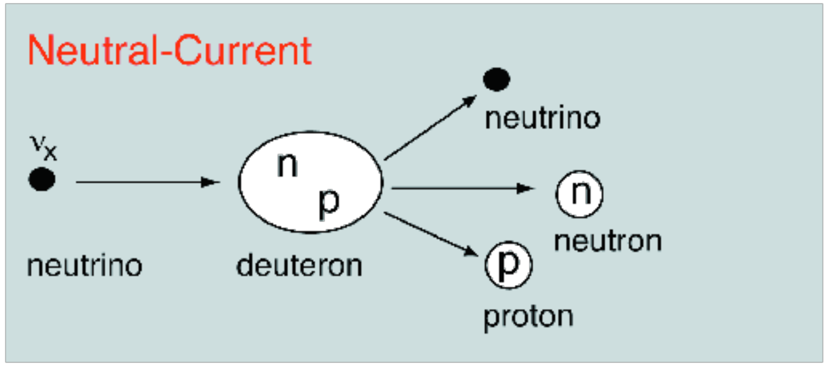
CC $\nu_e + d \rightarrow p + p + e^-$

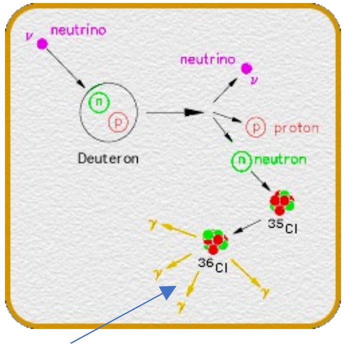
- Measurement of ν_e energy spectrum
- Weak directionality



NC $\nu_x + d \rightarrow p + n + \nu_x$

- Measure total ^8B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

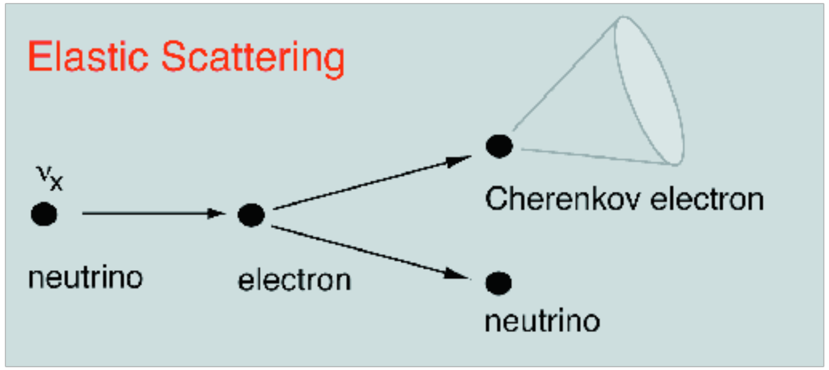




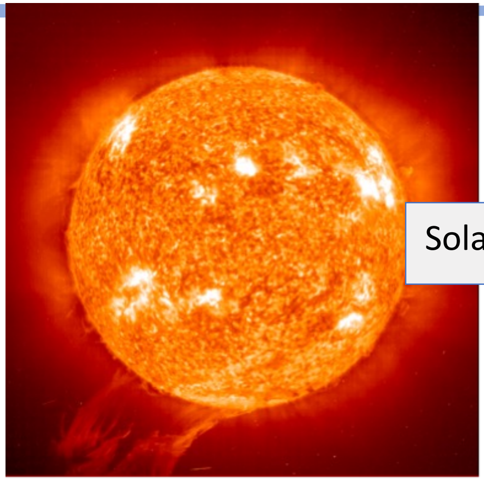
gamma rays which are emitted when the neutron is finally captured by another nucleus. The gamma rays will scatter electrons which produce detectable light via the Cherenkov process

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

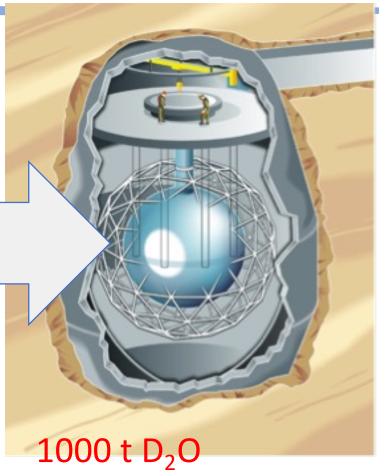
- Low Statistics
- $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
- Strong directionality



Example: SNO

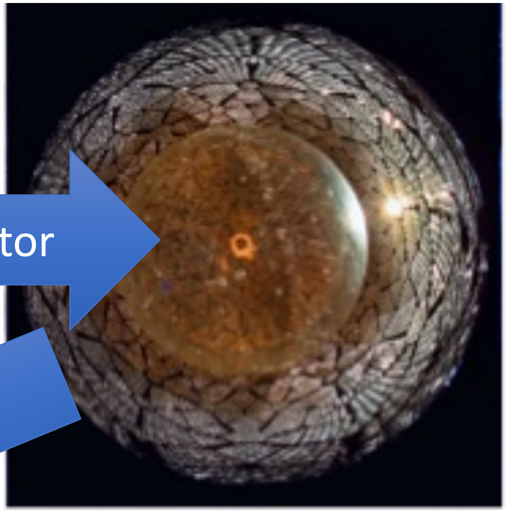


Solar neutrinos

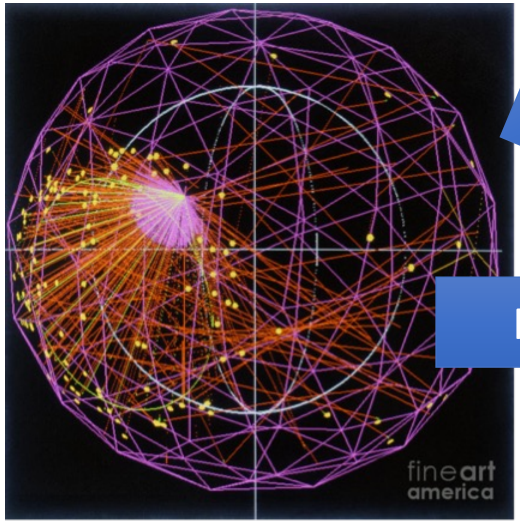


1000 t D_2O
9500 PMT's

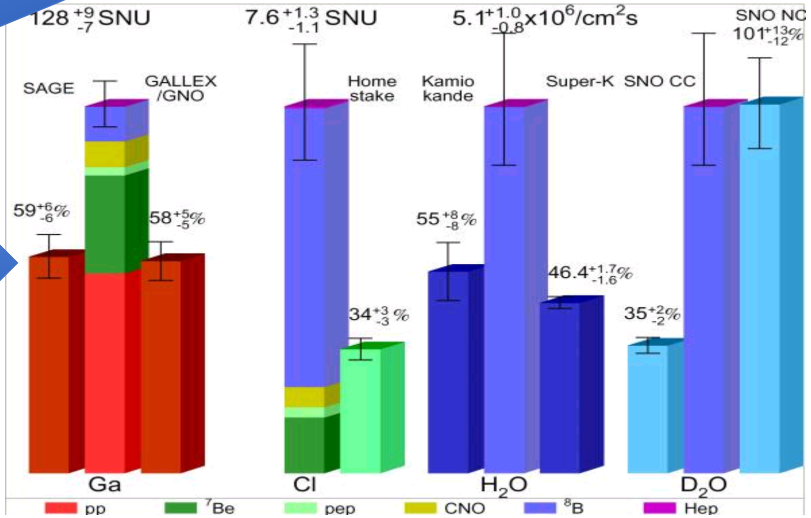
Detector



Interactions == Light



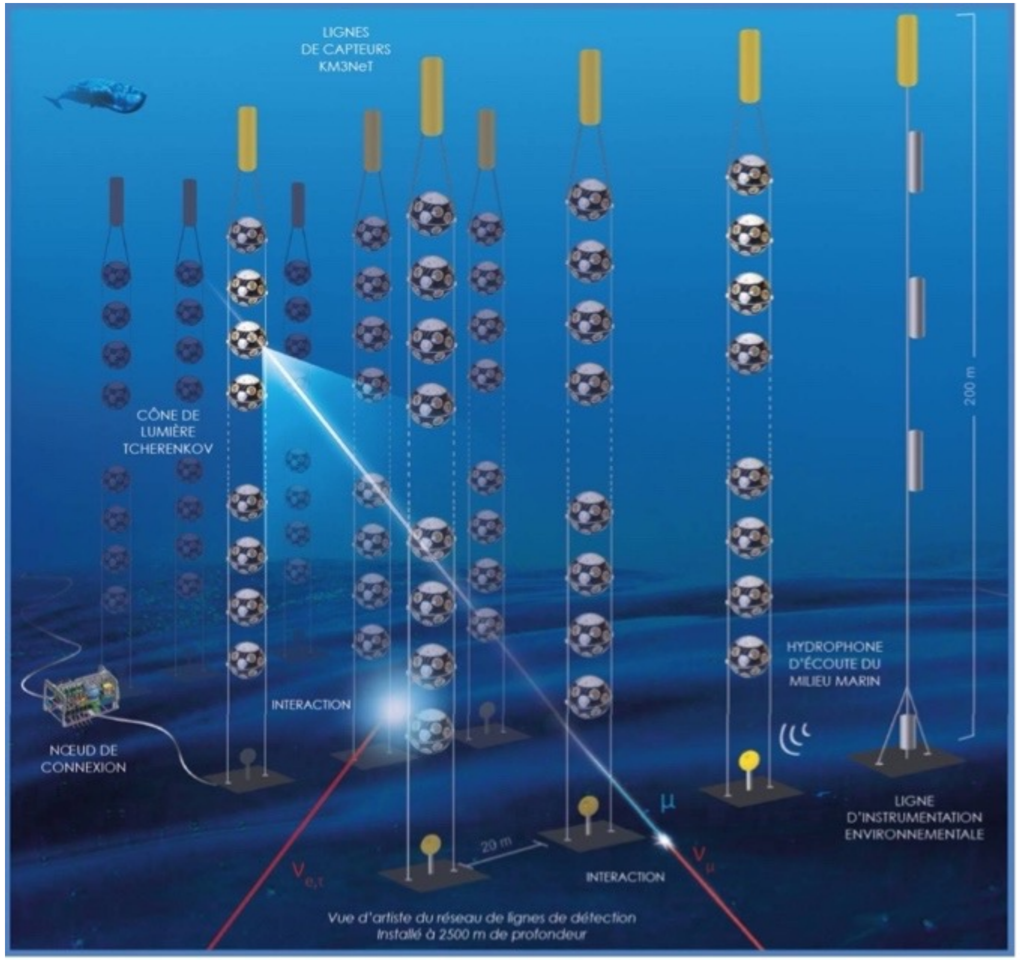
Results

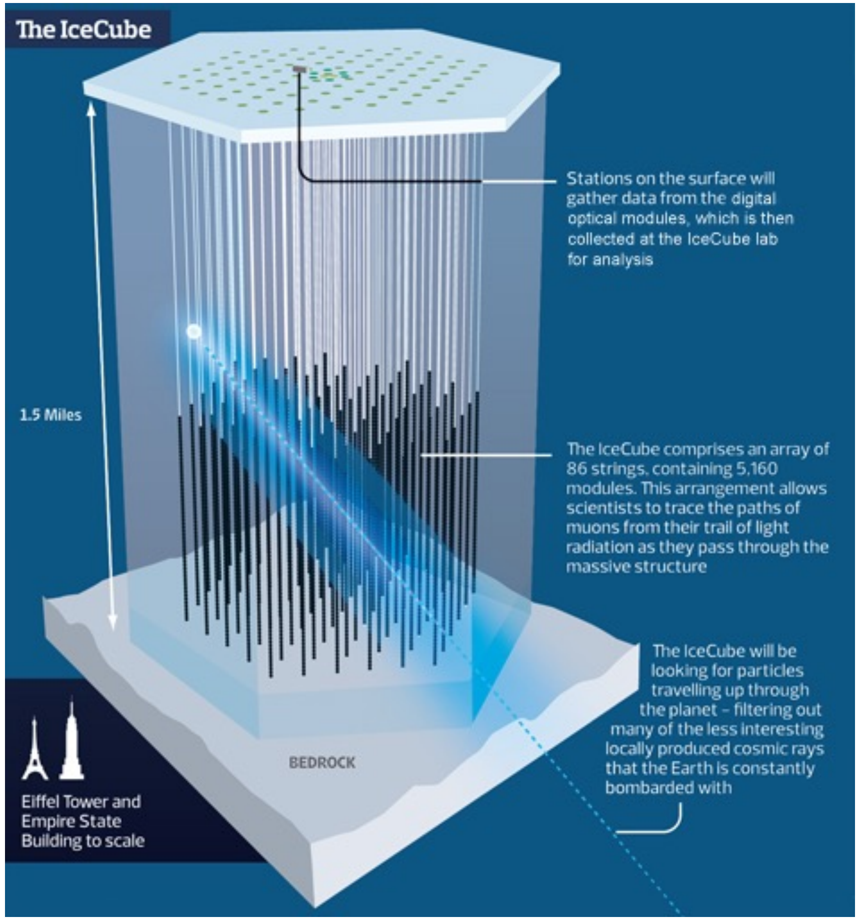


Cherenkov detectors for astroparticle physis

Detection of very high energy neutrinos in sea water / ice

KM3Net / IceCube

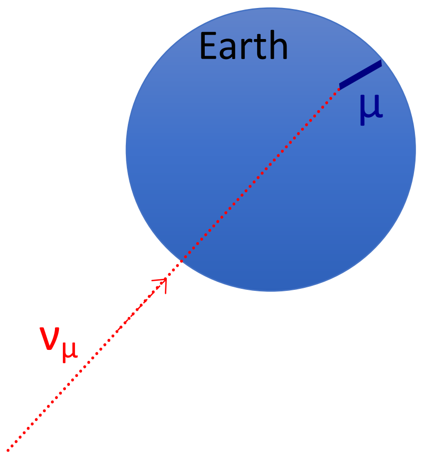




Cherenkov detectors for astroparticle physis

Detection of very high energy neutrinos in sea water / ice

KM3Net / IceCube



KM3NeT

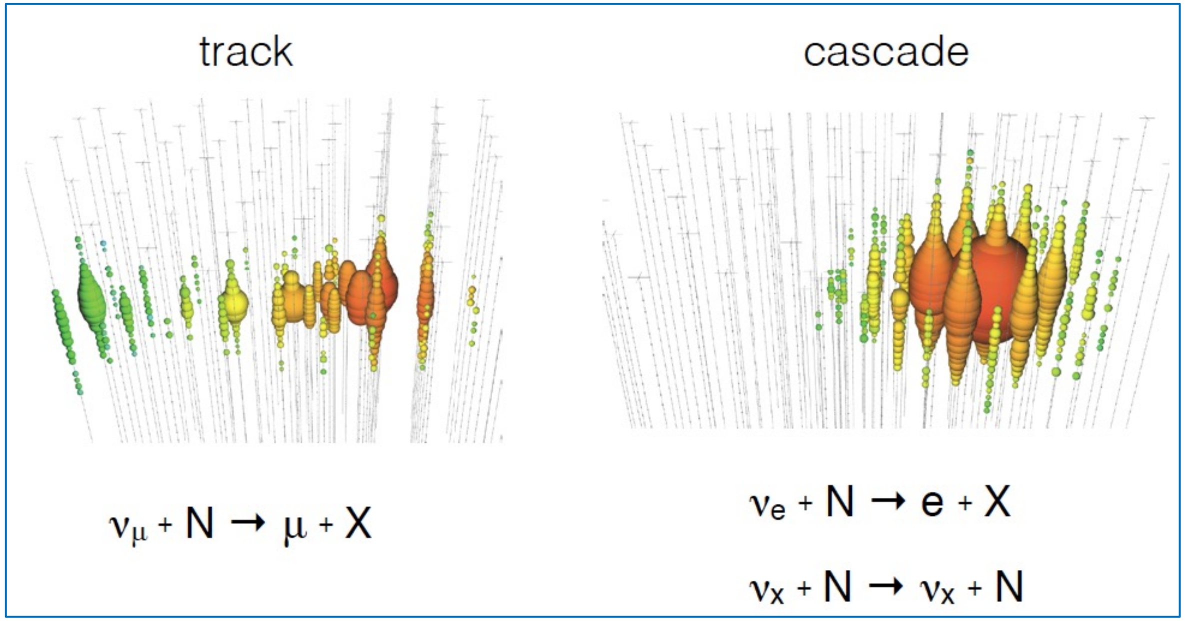
6210 Digital Optical Modules (**DOMs**)

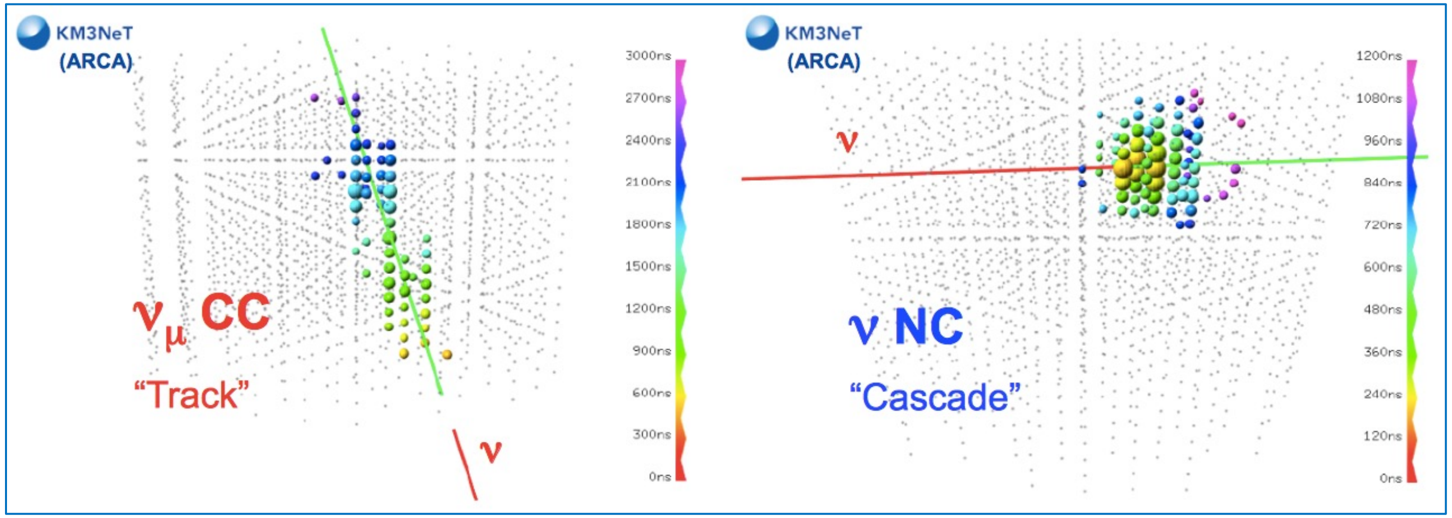
43 cm diameter, contains 31 3-inch (7.6 cm) PMTs with supporting electronics, and is connected to shore via a high-bandwidth optical network

see some neutrino interactions here…

Cherenkov detectors for astroparticle physis

IceCube





Cherenkov radiation and detectors: summary

- Charged particles travelling through a medium at a speed larger than that of light in the medium produce Cherenkov radiation
- Light emission at angle $\cos\theta_C = \frac{1}{n\,\beta}$
- Used for particle identification in different types of detectors
  - Threshold
  - Differential
  - Ring Imaging (RICH)
- Combined with Time-of-Flight, dE/dx (+ calorimetry etc.) for particle identification over wide momentum range
- Development of different types of photosensors

Exercises

Exercise 1

Compare the number of Cherenkov photons expected from a 2 MeV electron interacting in water to the number of scintillation photons expected from the same energy electron interacting in NaI(Tl).

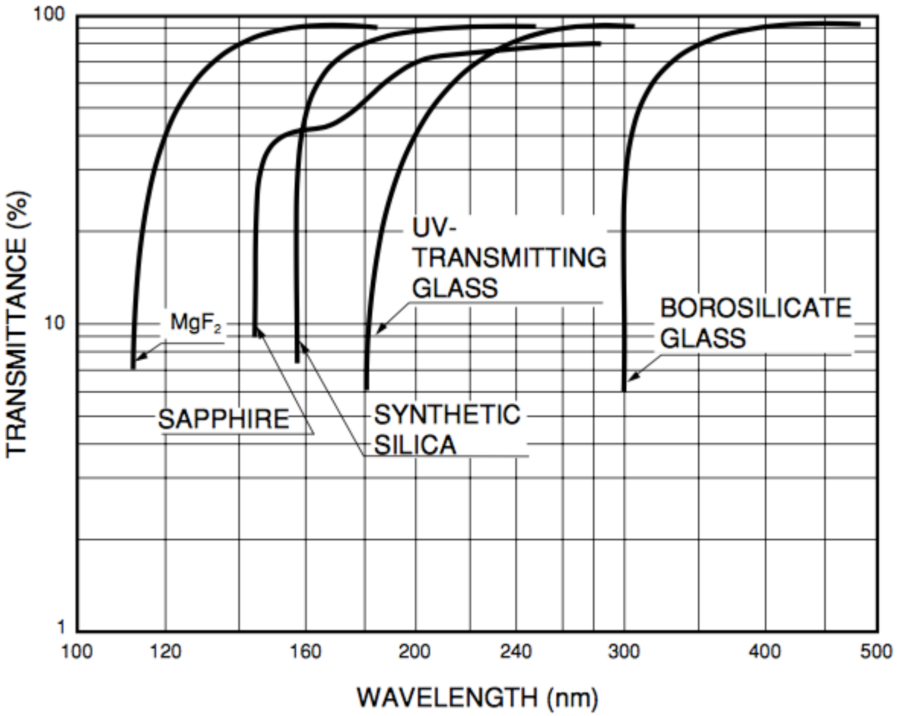
Exercise 2

We want build a huge detector filled with water to detect the Cherenkov light from charged particles. Should we use ”UV-transmitting glass” glass or ”Borosilicate glass” for the PMT photocatodes?

The photon density per unit length can be expressed as

$$\frac{dN}{dx} = 2\pi\, z^2\, \alpha\, \sin^2\theta \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} \quad \text{with} \quad 2\pi\, z^2\, \alpha = 4{,}584 \times 10^{-2}$$

The refractive index of water is 1.33.



Exercises

Exercise 3 (exam 2020-2021)

A 500 MeV electron interacts in the water (n=1.3) of the SuperKamiokande experiment at a distance of 5 m from the detector wall. The number of Cherenkov photons it produces per unit path (in nm) and wavelength (in nm) is

$$\frac{d^2N}{dx\, d\lambda} = 2\pi\, \alpha\, sin^2\theta_C \frac{1}{\lambda^2}$$

where α is the fine structure constant (∼7.3×10^{-3}).

The range of 500 MeV electrons in water is about 1m.

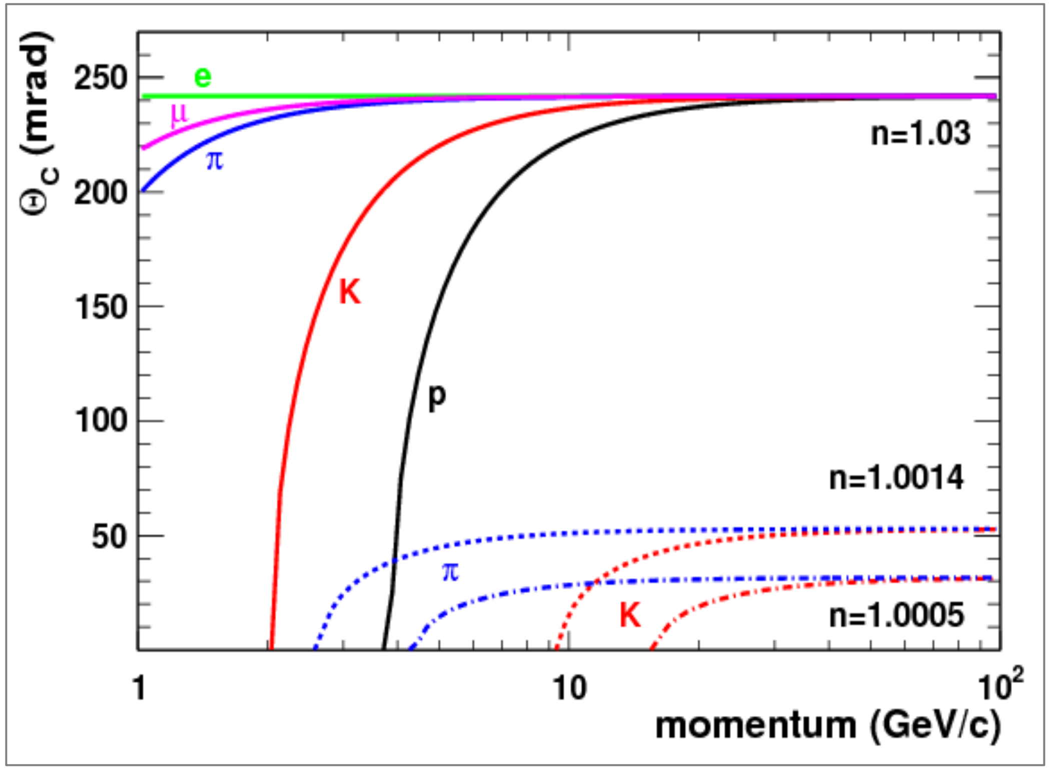
- Compute:
  - the radius of the Cherenkov ring on the detector wall (neglect deformations, i.e. assume the wall to be flat and perpendicular to the electron trajectory);
  - the number of detected photons, if the PMTs detect photons of wavelengths between 300 and 500 nm with an average Quantum Efficiency of 20% and provide 40% geometrical coverage.

Exercises

<u>Exercise 4</u> (exam 2020-2021)

The figure on the right shows the Cherenkov angle as a function of momentum for different kinds of particles in media with different refraction indices: Aerogel (n=1.03), C_4F_{10} gas (n=1.0014) and CF_4 gas (n=1.0005).

Which combination of these radiators would you choose to discriminate pions from kaons in a particle beam with a momentum of 5 GeV/c? Explain.



(Appendix: Change of variable in a PDF)

- Probability density function (PDF) of the variable *x, P(x).*
- How to compute the PDF of a new variable *y*, if we know the dependence *y(x)*?

$$\frac{dN}{dy} = \frac{dN}{dx}\frac{dx}{dy} = \frac{\frac{dN}{dx}}{\left|\frac{dy}{dx}\right|} = \frac{P(x(y))}{|J|}$$

J is the "Jacobian" of the transformation

Examples:

1) zenith angle distribution of cosmic rays

$$\frac{dN}{d\vartheta} \propto (\cos\vartheta)^2 \qquad \frac{dN}{d\cos\vartheta} = \frac{dN}{d\vartheta}\frac{d\vartheta}{d\cos\vartheta} \propto \frac{(\cos\vartheta)^2}{|\sin\vartheta|} = \frac{x^2}{\sqrt{1-x^2}}$$

2) uniform distribution in a cylindrical volume

$\frac{dN}{dV} = C'$ with $dV = h\,2\pi\,r\,dr = h\,\pi\,d(r^2)$ so $\frac{dN}{dr^2} = C$

but $\frac{dN}{dr} = \frac{C}{\left|\frac{dr}{d(r^2)}\right|} = C\left|\frac{d(r^2)}{dr}\right| = 2C\,r$

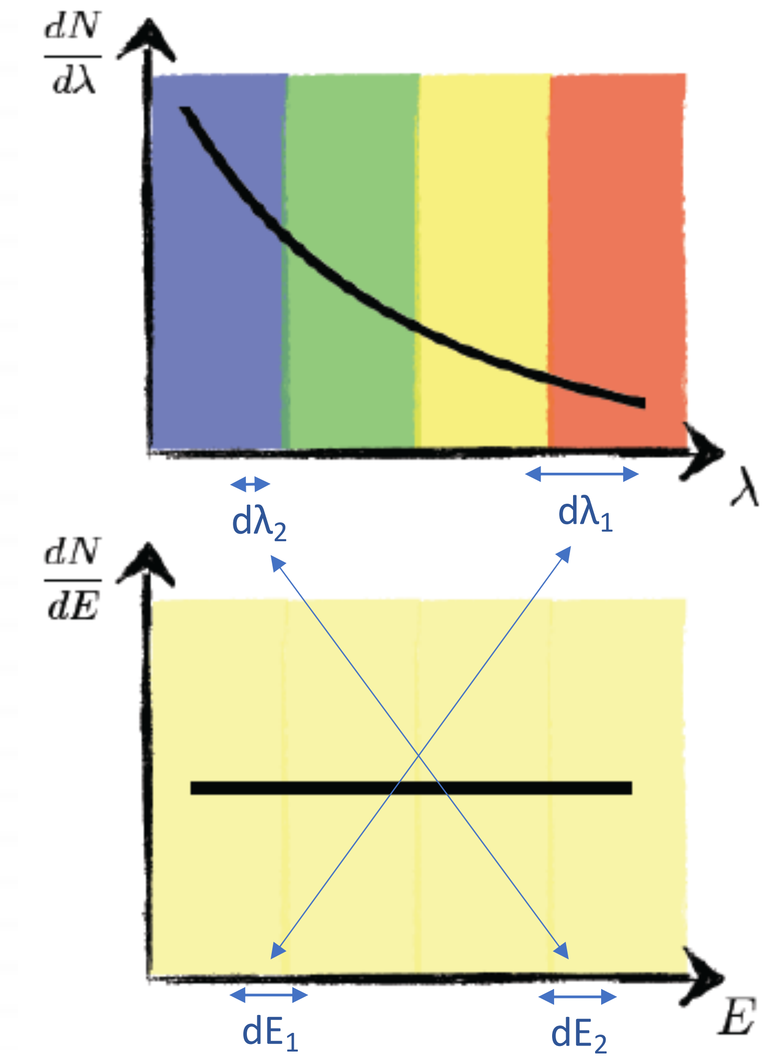
(Appendix: Change of variable in a PDF)

Cherenkov radiation photon spectra:

$$\frac{dN}{d\lambda} = \frac{C}{\lambda^2}$$

change variable to $E = \frac{hc}{\lambda}$ $\quad \frac{dE}{d\lambda} = \frac{hc}{\lambda^2}$

$$\frac{dN}{dE} = \frac{\frac{dN}{d\lambda}}{\left|\frac{dE}{d\lambda}\right|} = \frac{\frac{C}{\lambda^2}}{\frac{hc}{\lambda^2}} = constant$$



$$dE \propto \frac{1}{\lambda^2} d\lambda$$

$$d\lambda \propto \frac{1}{E^2} dE$$