Detector Physics 2022/2023, Lecture 8

Cherenkov radiation and particle identification

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References

many of my slides are taken from

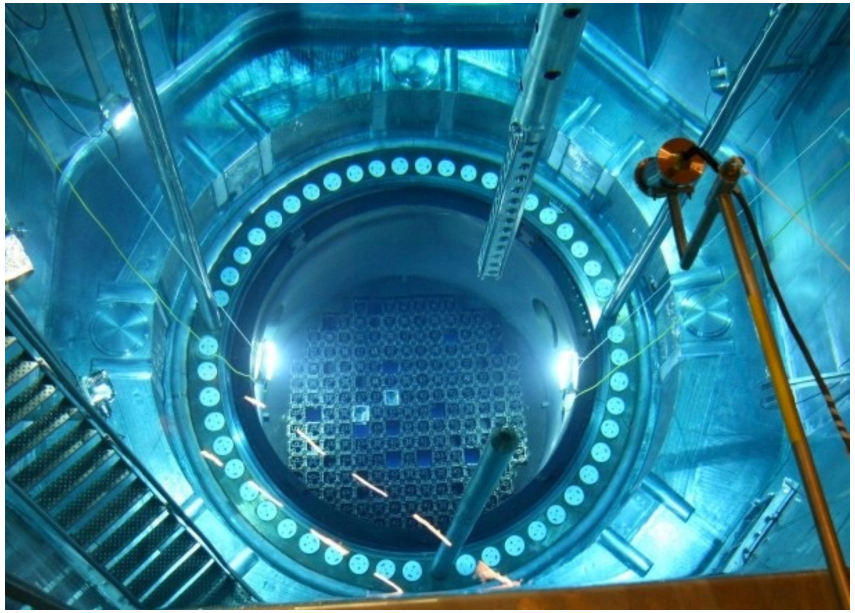
- Thomas Patzak, NPAC Lectures 2019 (thanks!)

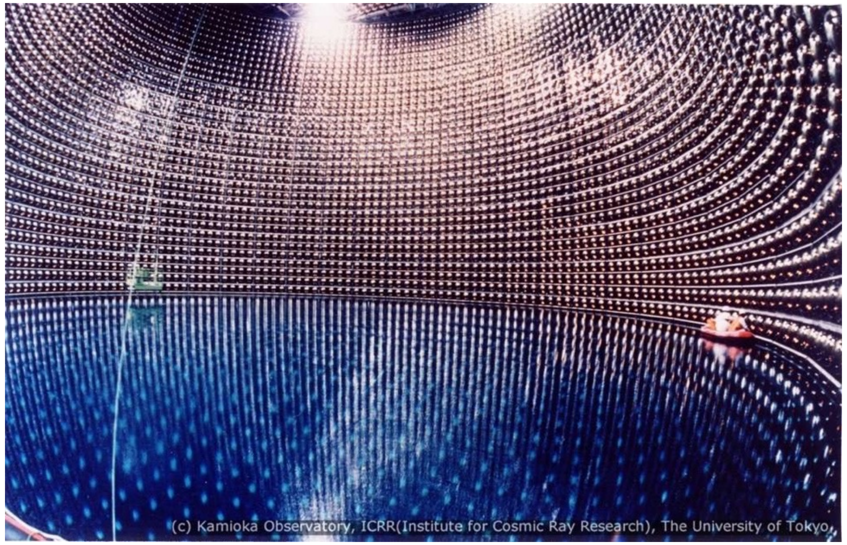
https://npac.lal.in2p3.fr/1st-semester-lectures-1920/

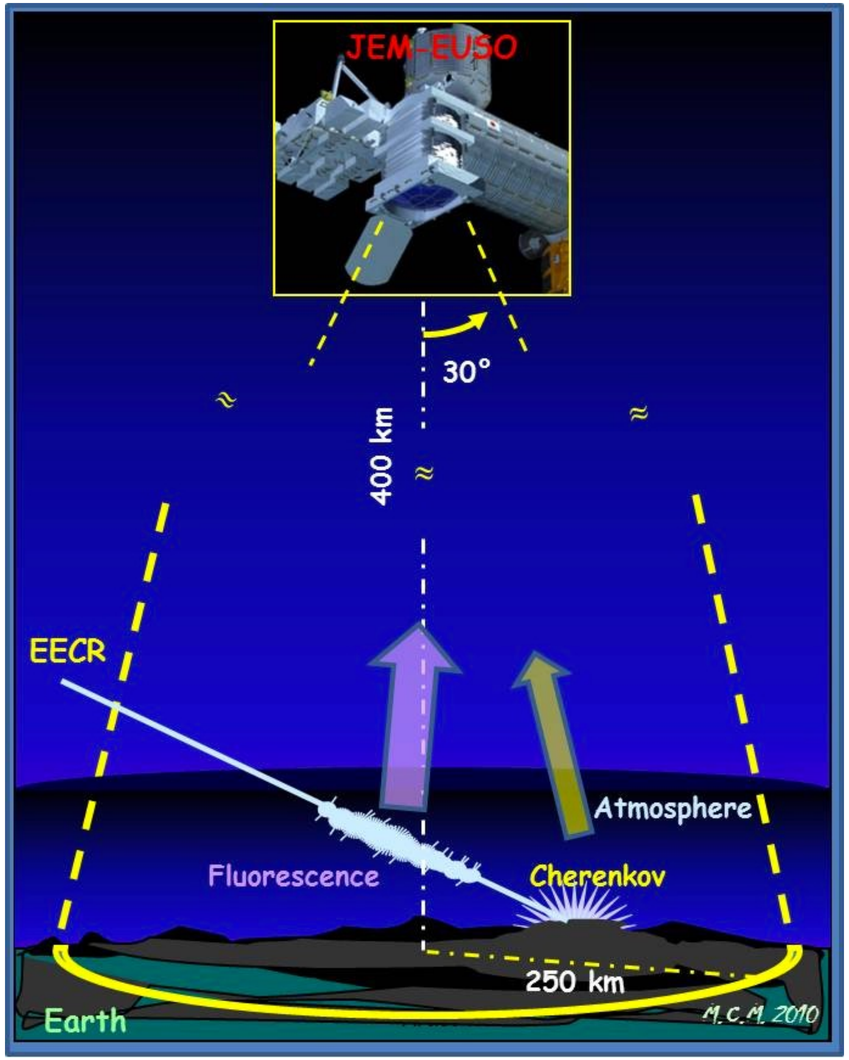
- S. Easo (RAL) Graduate Student Lecture 2011

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

Cherenkov radiation







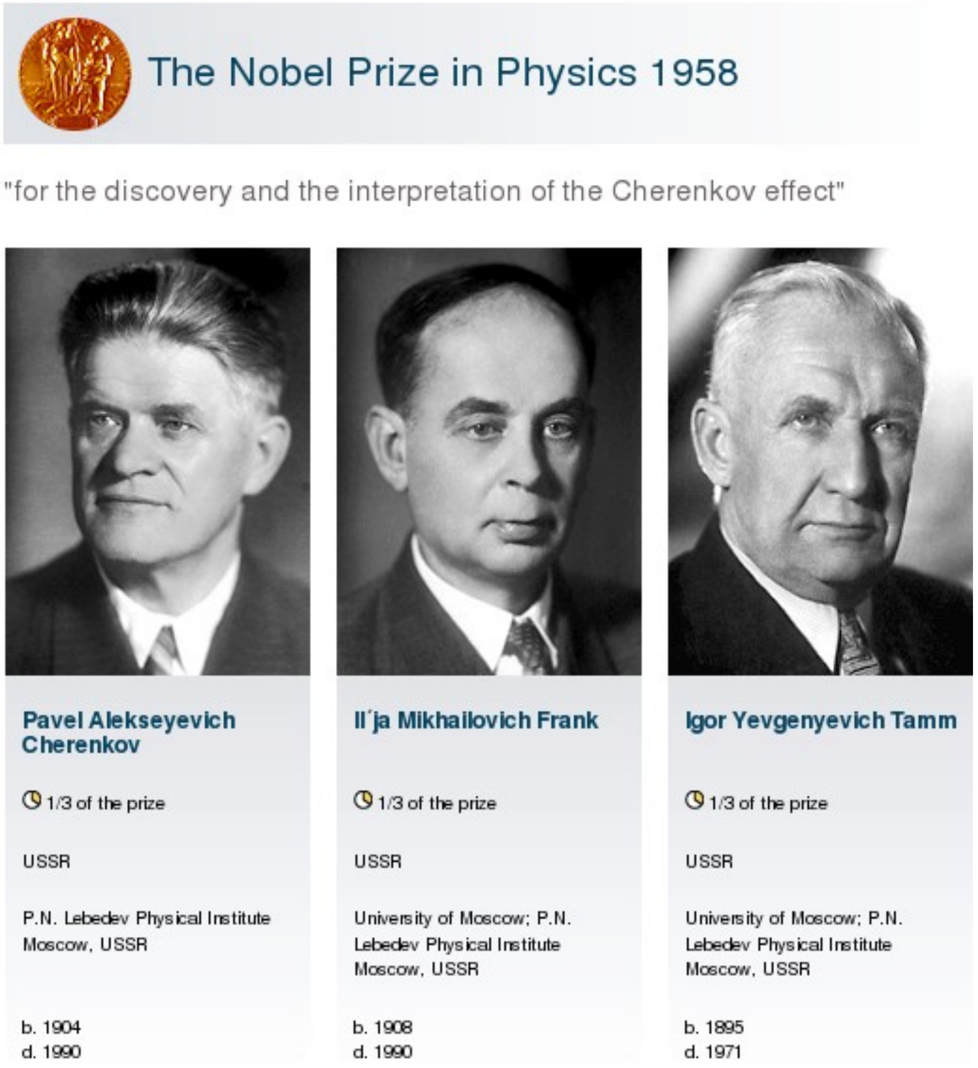
Cherenkov radiation: some history

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

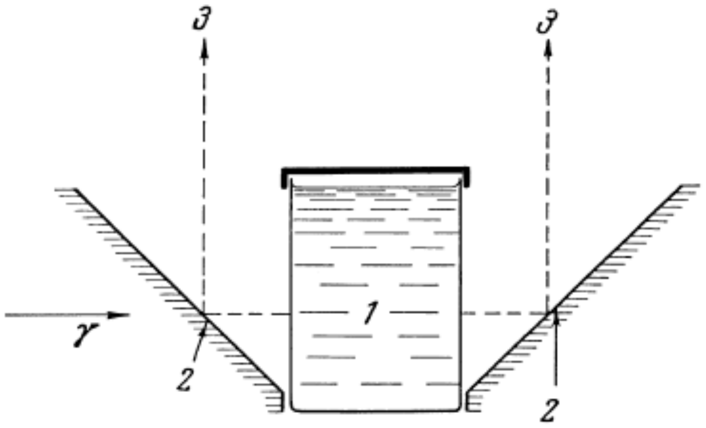
Cherenkov:
1934 experimentally observed

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).

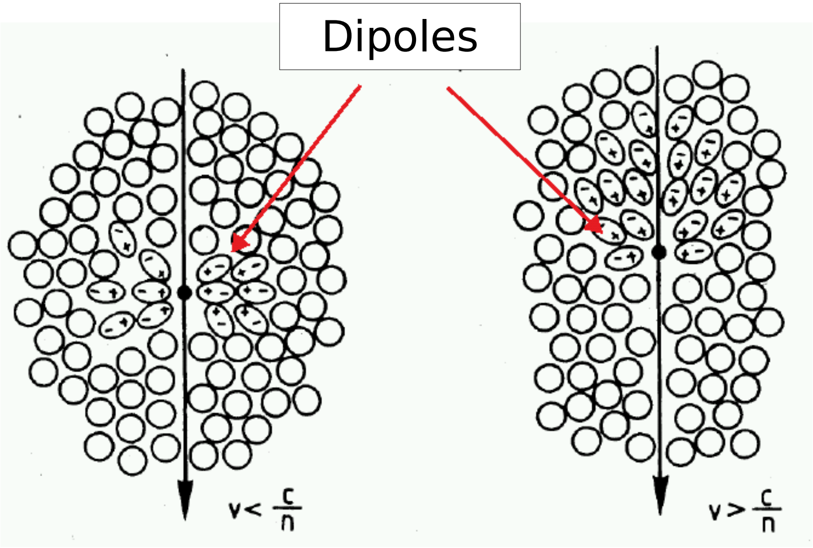
P. Cherenkov established that:

- 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

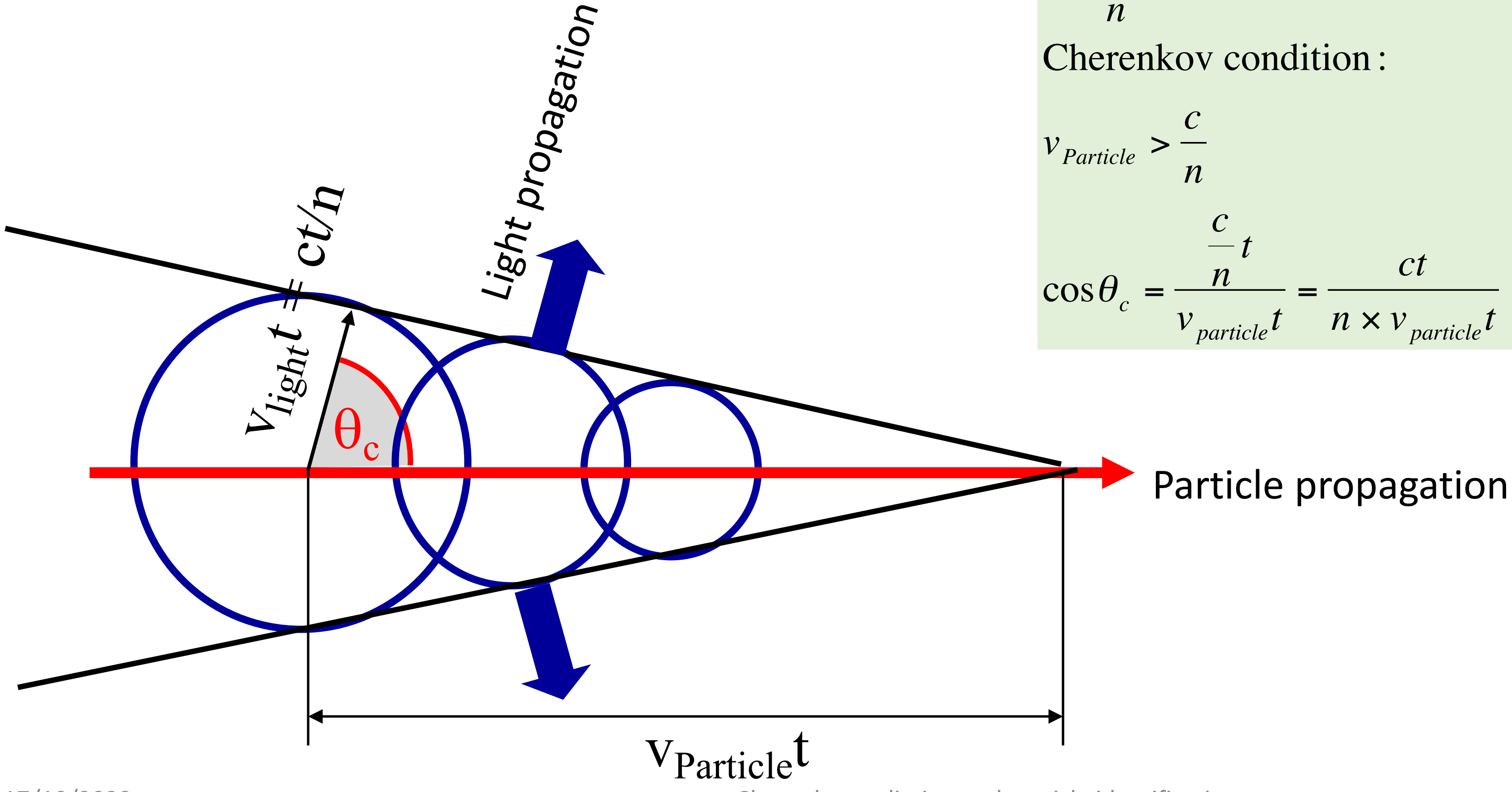
For v < c/n:
Induced dipoles symmetrically arranged around particle path -> no net dipole moment
→ no Cherenkov radiation

For v > c/n:
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:

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

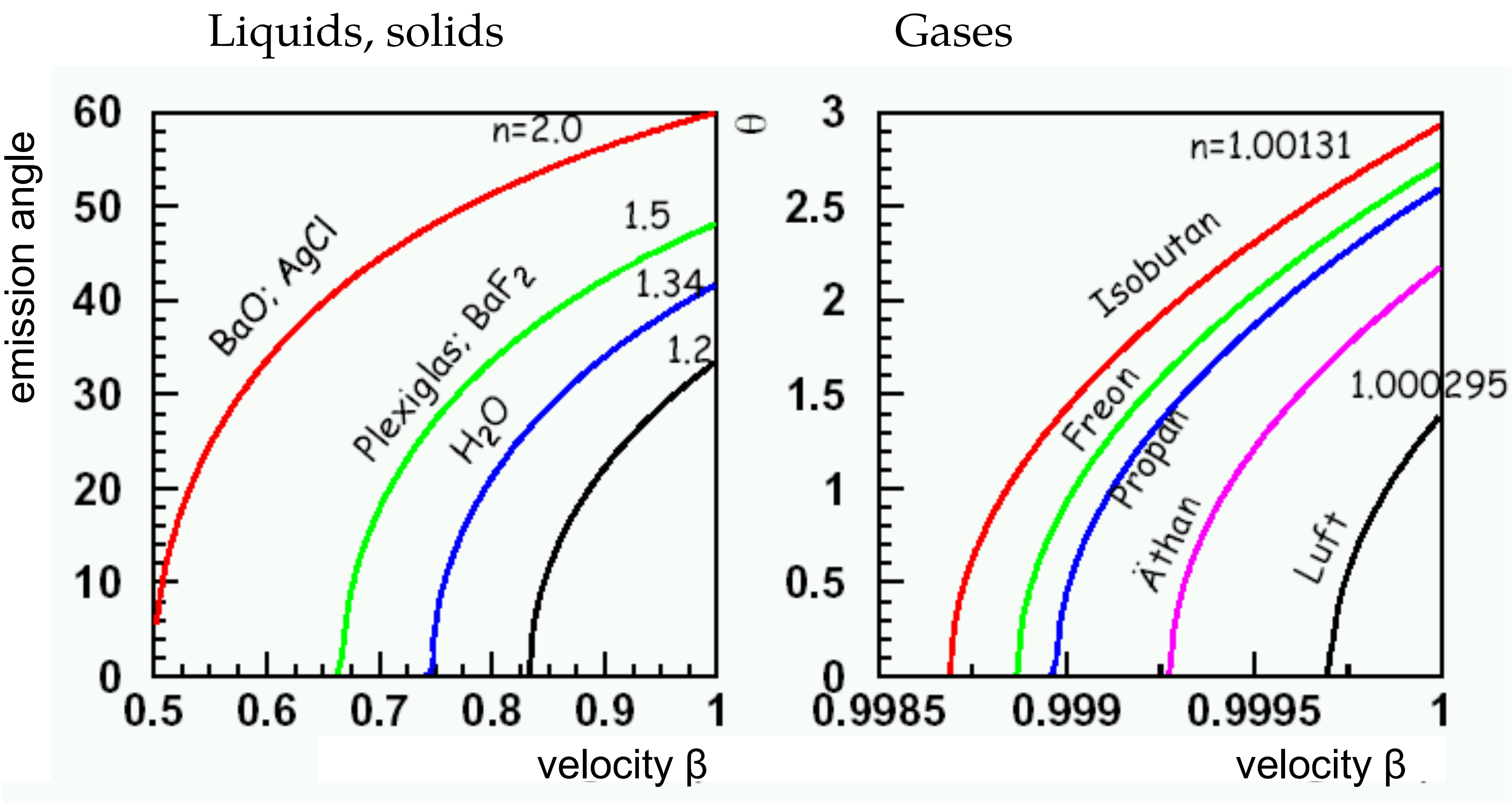
Cherenkov condition:

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

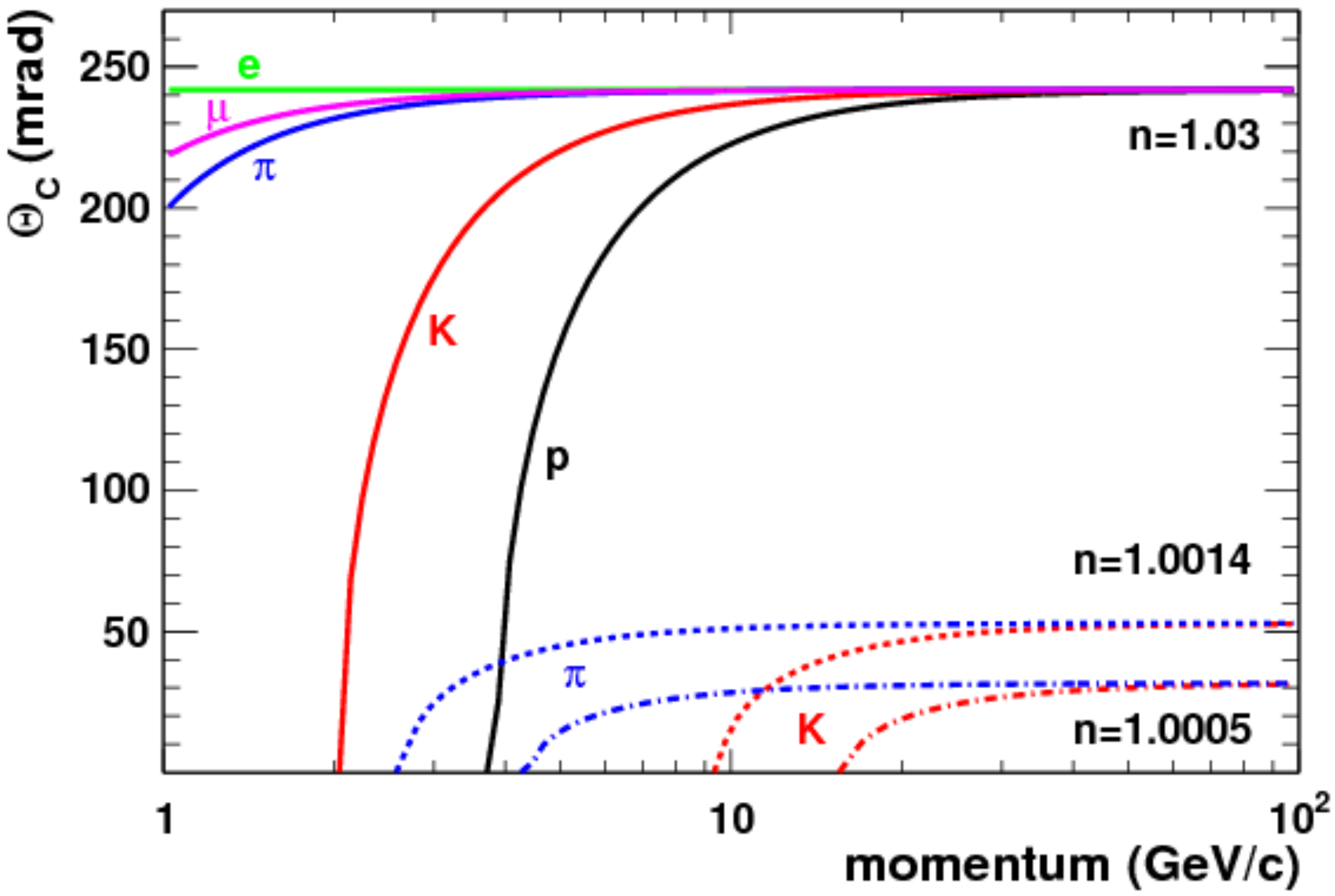
$$\cos\theta_c = \frac{\frac{c}{n}t}{v_{particle}t} = \frac{ct}{n \times v_{particle}t} = \frac{ct}{n \times \beta_{Particle} \times ct} = \frac{1}{n \times \beta_{Particle}}$$

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

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

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

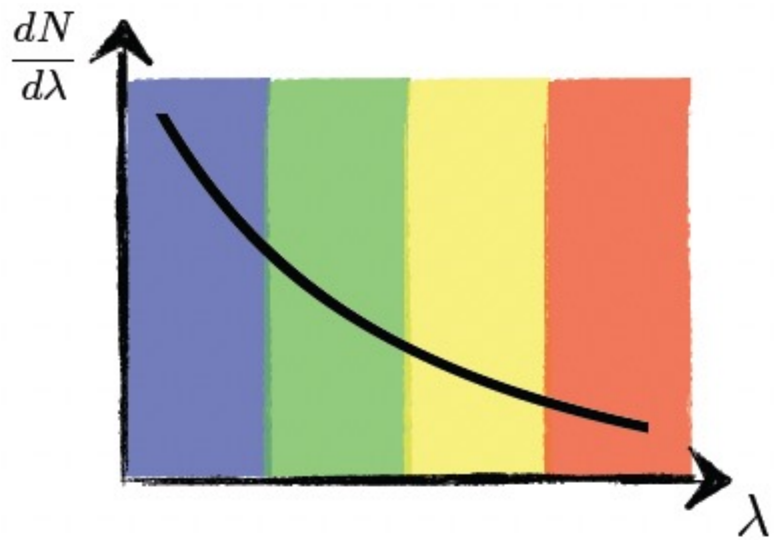
Energy loss by collision in a gas with large Z: $$-\left(\frac{dE}{dx}\right)_{Coll} \cong 0{,}01\ \text{MeVcm}^2\text{g}^{-1}$$

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

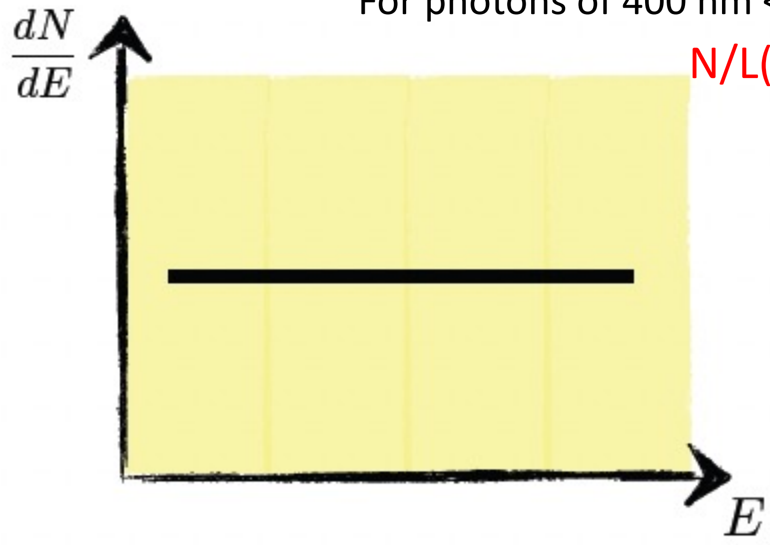


For photons of 400 nm < λ < 700 nm

N/L(cm) ≈ 490 $\sin^2\theta_c$

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

→ Energy of emitted photons is uniformly distributed



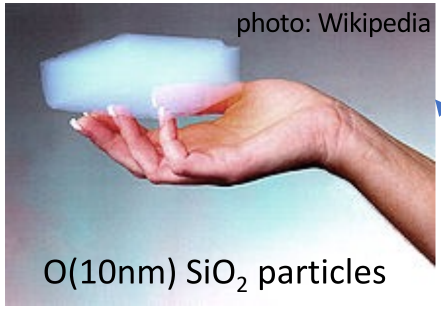
R. De Vita,
INFN Genova

Cherenkov detectors

Main components 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



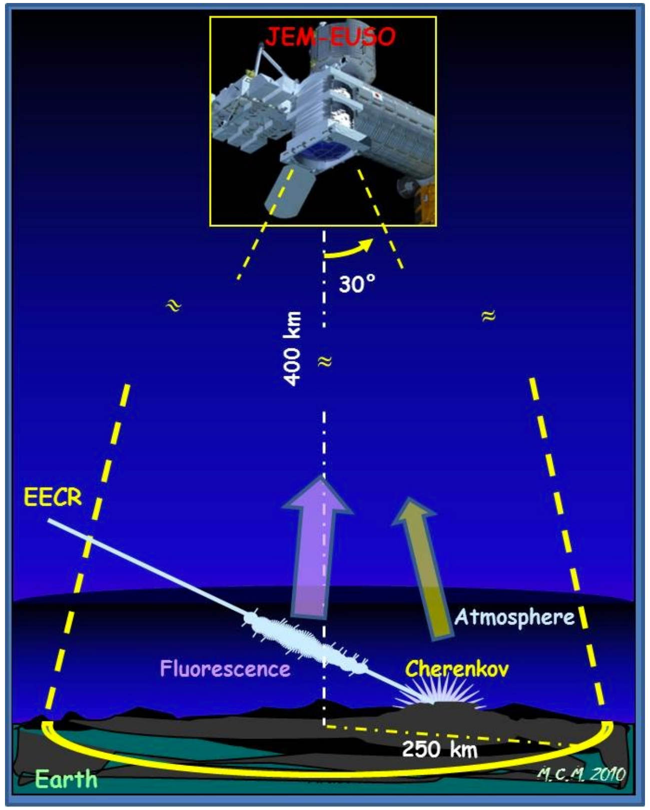
Air, sea-water or ice are exploited as radiators in some astroparticle physics experiments (see next page)

Example of radiators

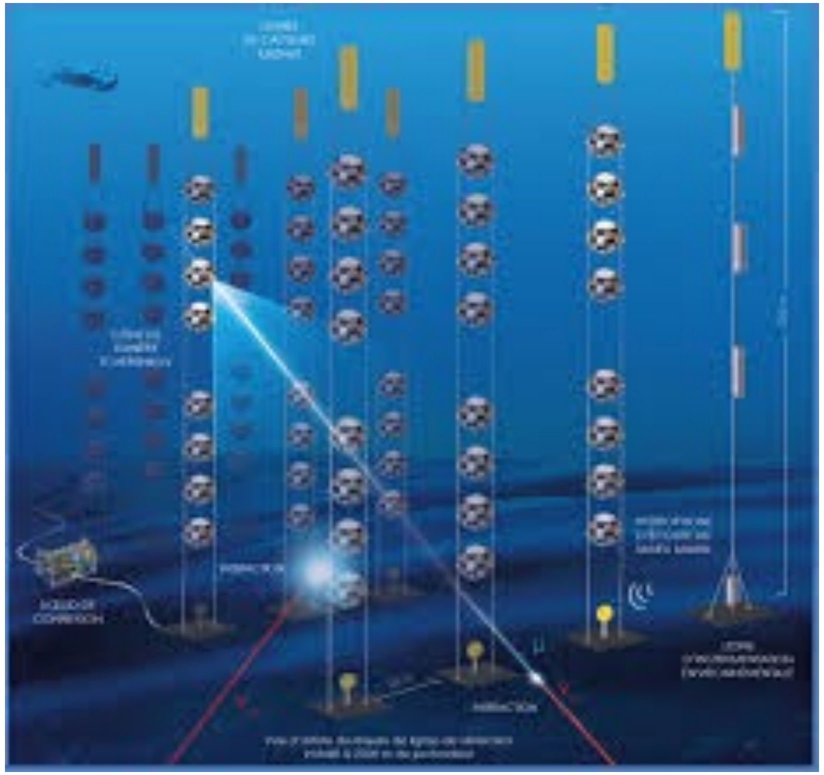
Medium	n-1	$\gamma_{th} = 1/\sqrt{1-\beta_{th}^2}$	Photons/m
He (STP)	3.5 10^{-5}	120	3
CO_2 (STP)	4.1 10^{-4}	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

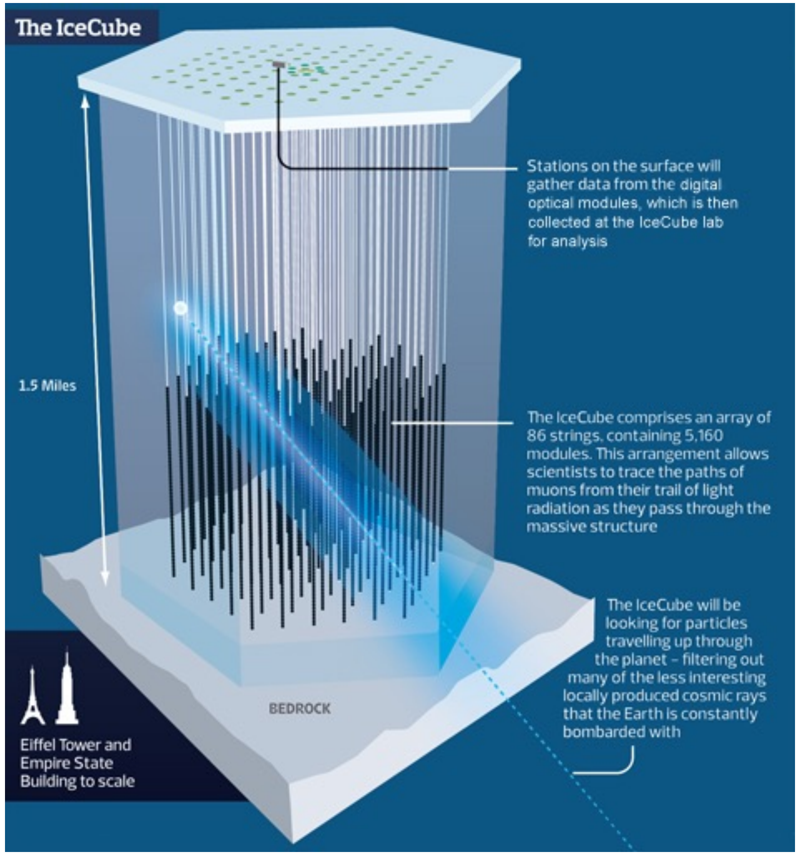
Cherenkov detectors

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



Antares / KM3Net

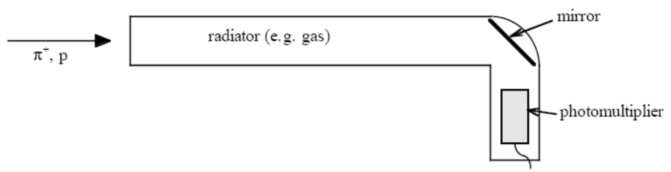




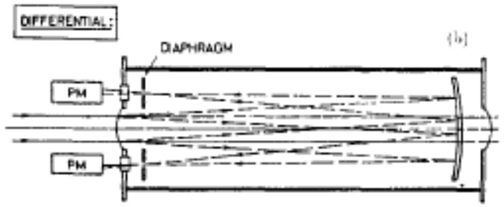
Cherenkov detectors

Detectors based on Cherenkov radiation are of 3 types

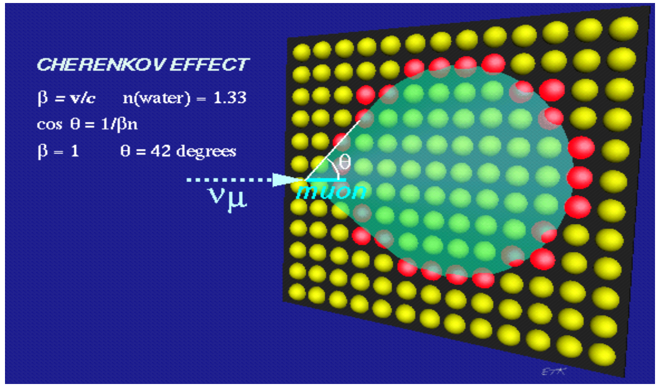
- **Threshold counters** (yes/no Cherenkov radiation)



- **Differential counters** (measures the Cherenkov angle in a given range)



- **Ring imaging counters** (reconstruct the image of the Cherenkov ring)

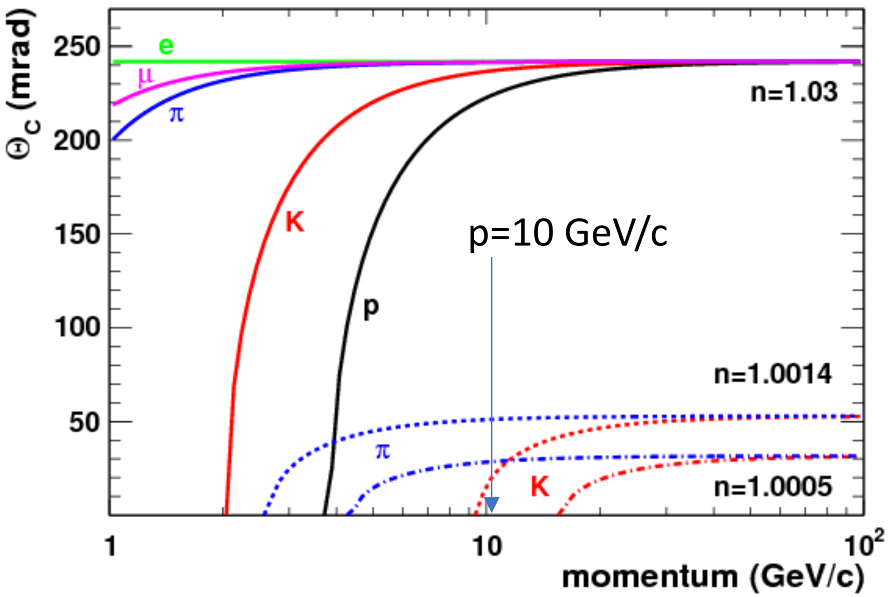


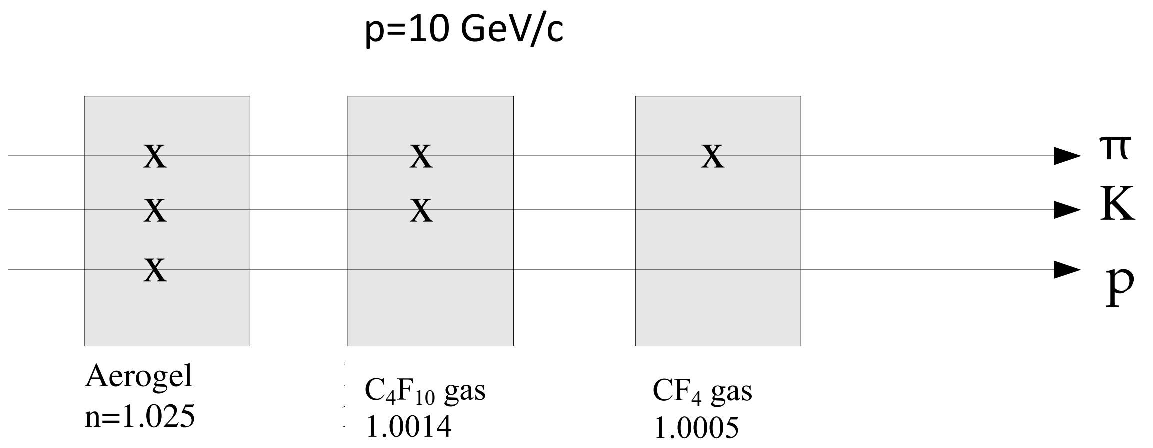
Cherenkov detectors: threshold counters

- 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 $m < p\sqrt{n-1}$



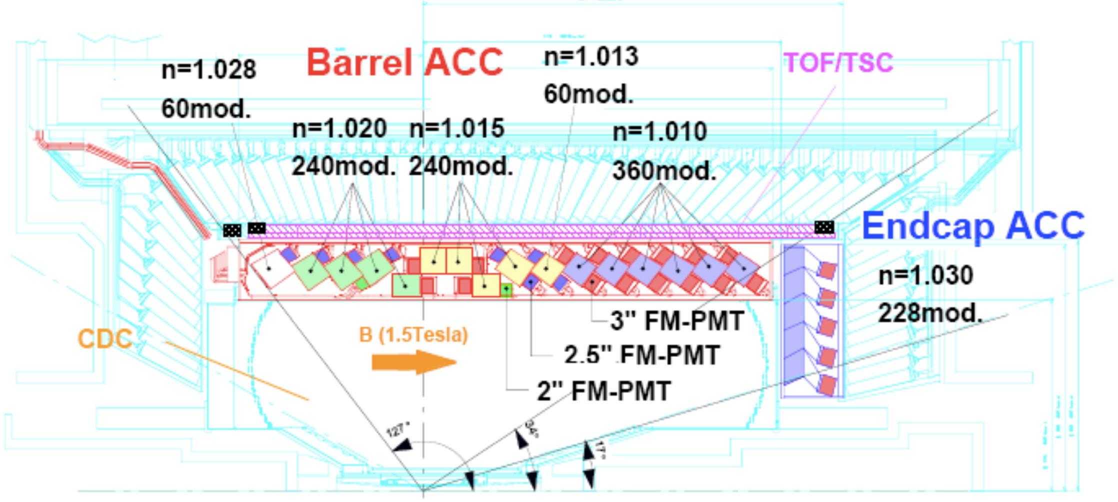


- Improved version: use number of photons (or calibrated pulse) to discriminate particle types.

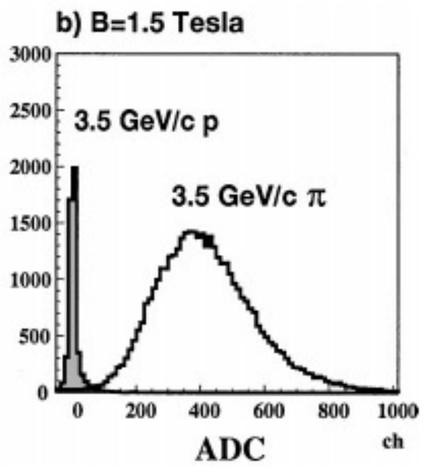
$$N \approx 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\left(1 + \frac{m^2}{p^2}\right)$$

Threshold Cherenkov detectors: examples

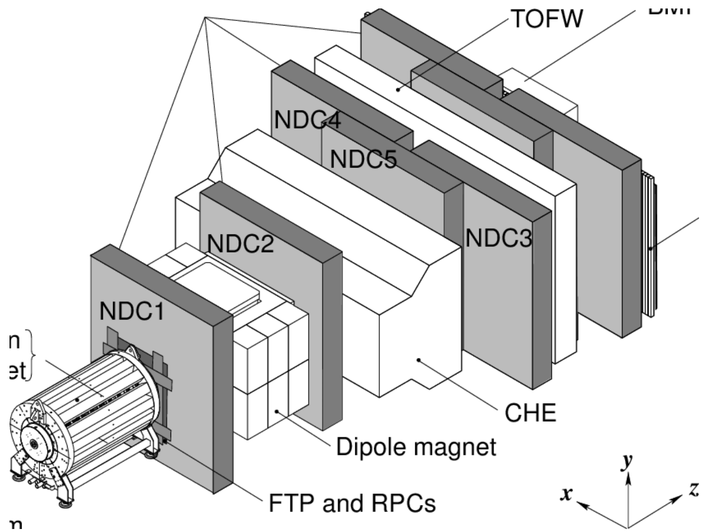
BELLE@KEK (1999-2010)
to observe CP violation in B decays at an e+e- collider



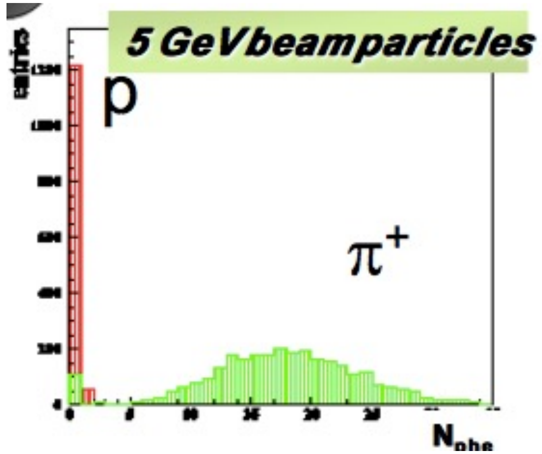
Five aerogel tiles inside an Al box lined with a white reflector(Goretex)



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

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

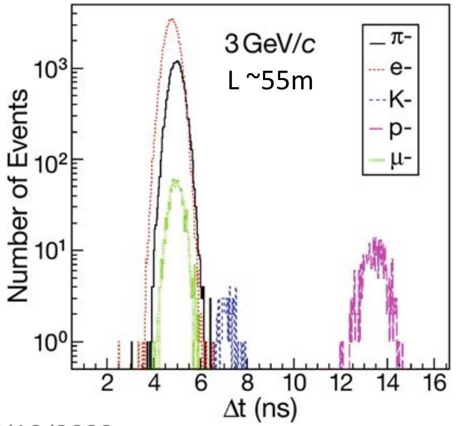
$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

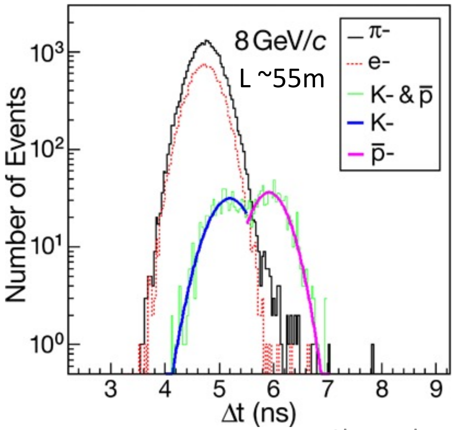
Relativistic particles, $E \simeq pc \gg m_i c^2$:

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

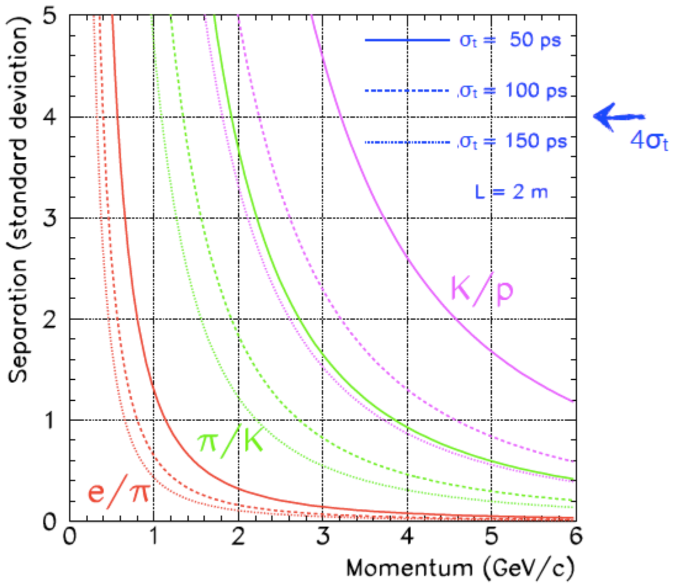
$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

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





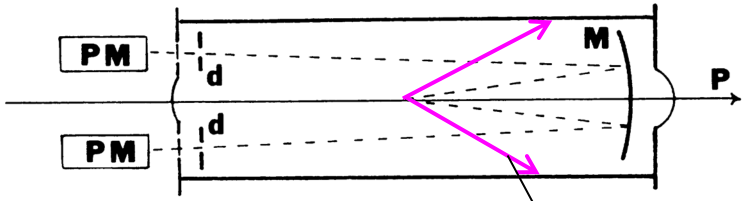
σ_t : time resolution of the detector

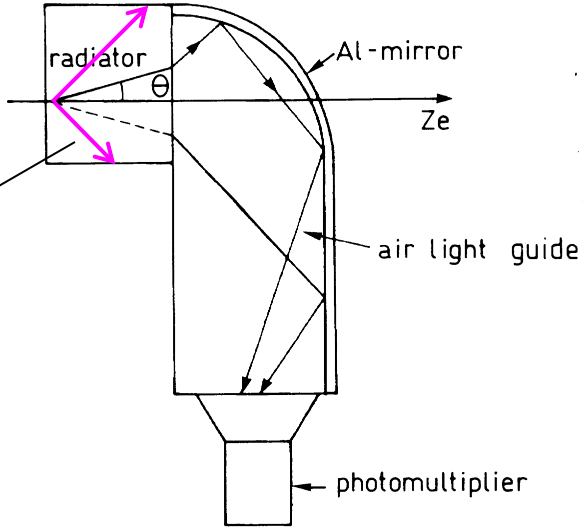


Cherenkov detectors: differential counters

For a given momentum, cosθ is function of the mass

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



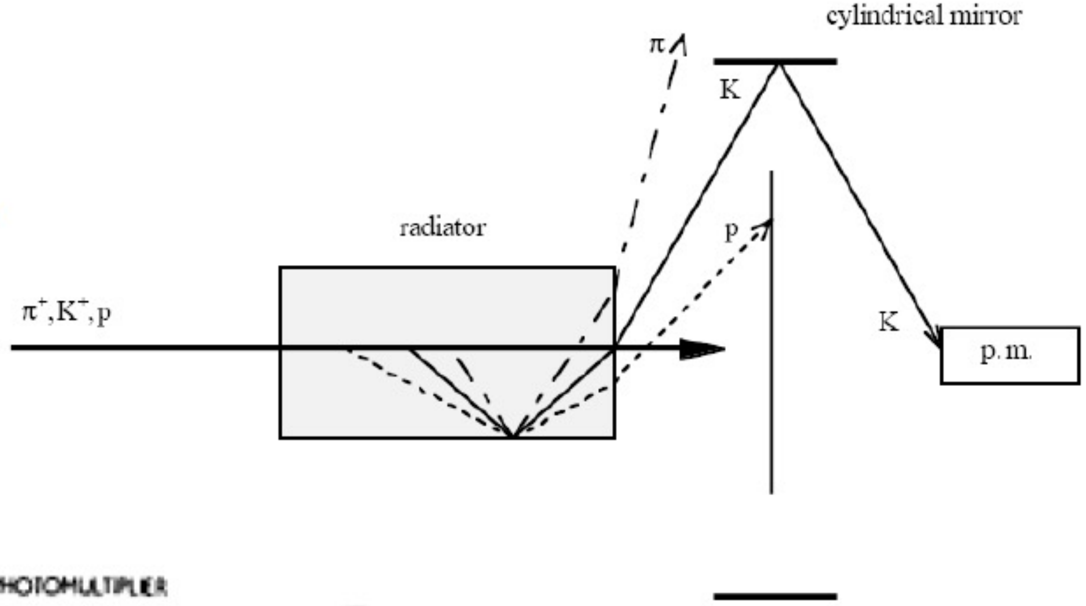


Only the light emitted at a given angle goes to the PM

Differential Cherenkov detectors : example

slide from S. Easo

With Solid (quartz) radiator



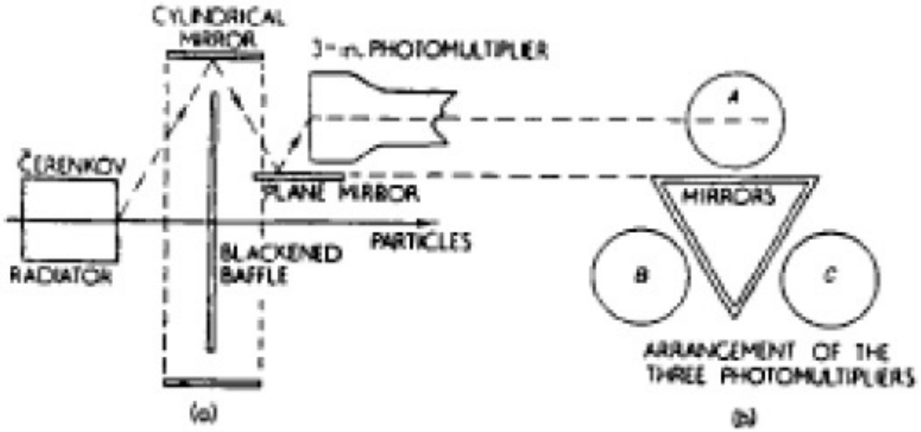


Fig. 2. The differential Cherenkov counter used in the antiproton discovery experiment: (a) side view; (b) end view.

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

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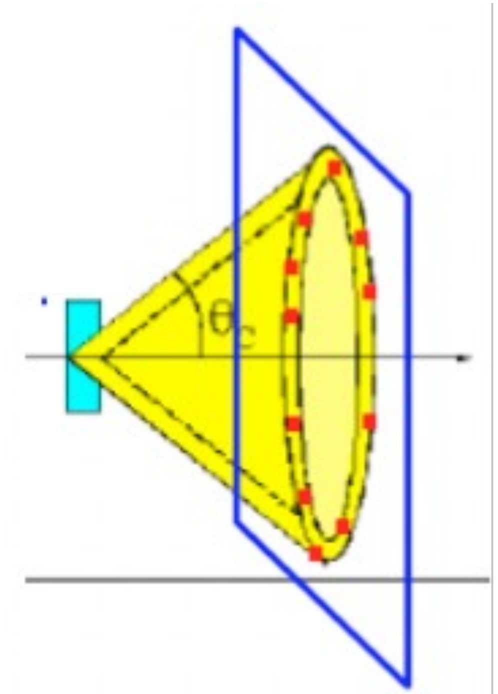
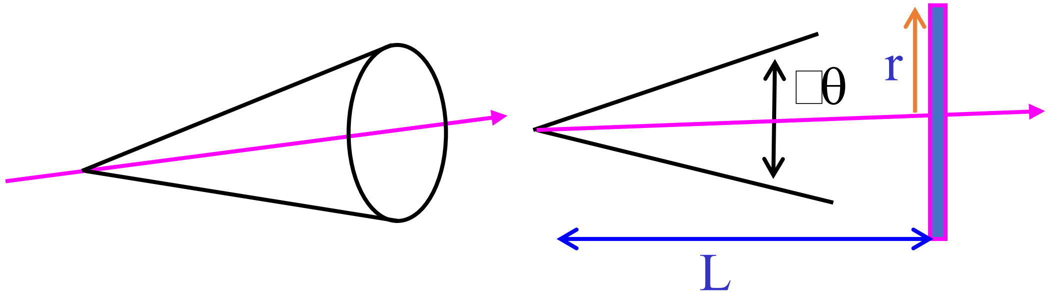
Cherenkov detectors: ring imaging

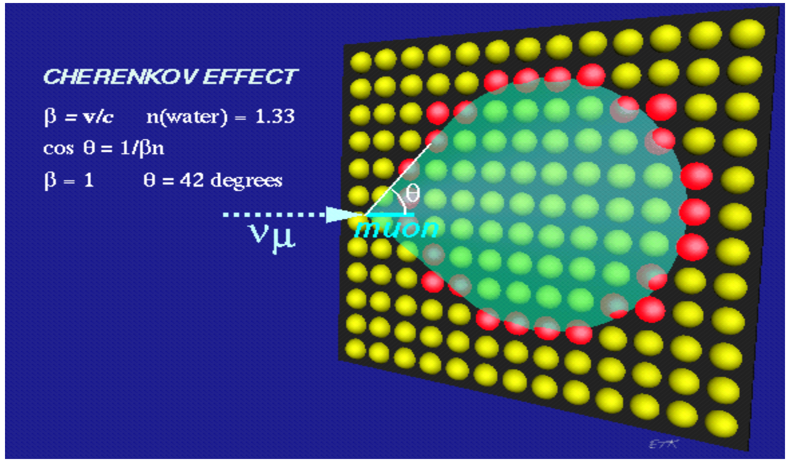
- Intercept the Cherenkov cone with a plane → ring
- Measure both the Cherenkov angle and the number of detected photons

  (➔ 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 x tanθ

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

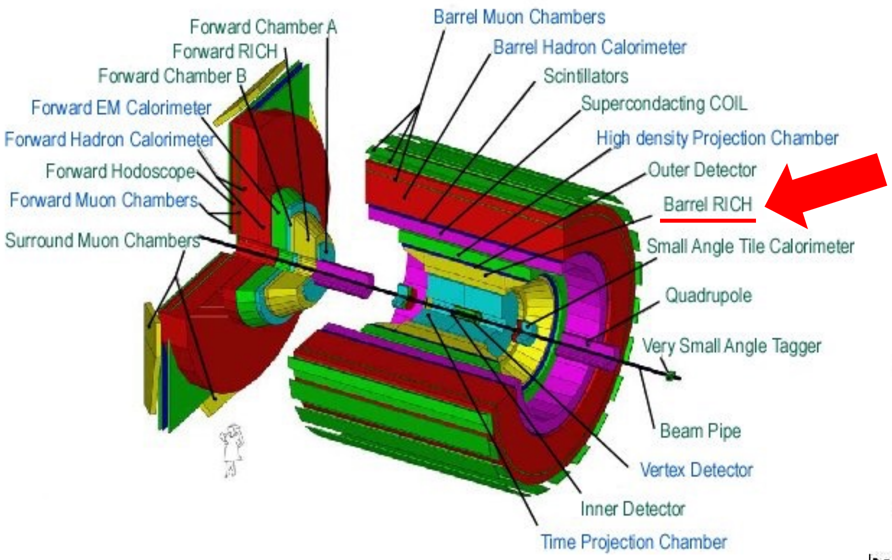
Very good π/K/p seperation

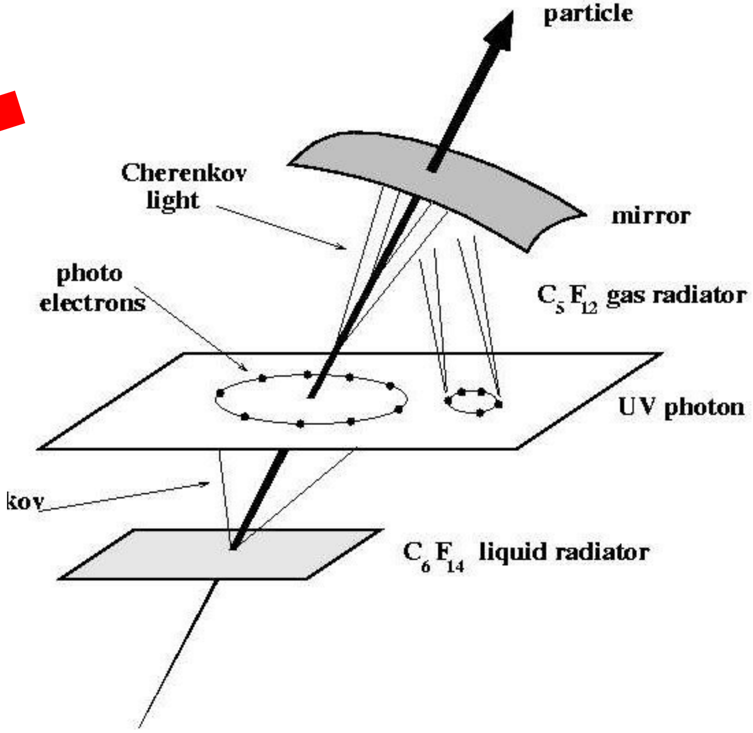
Particle ID

Tom Ypsilantis

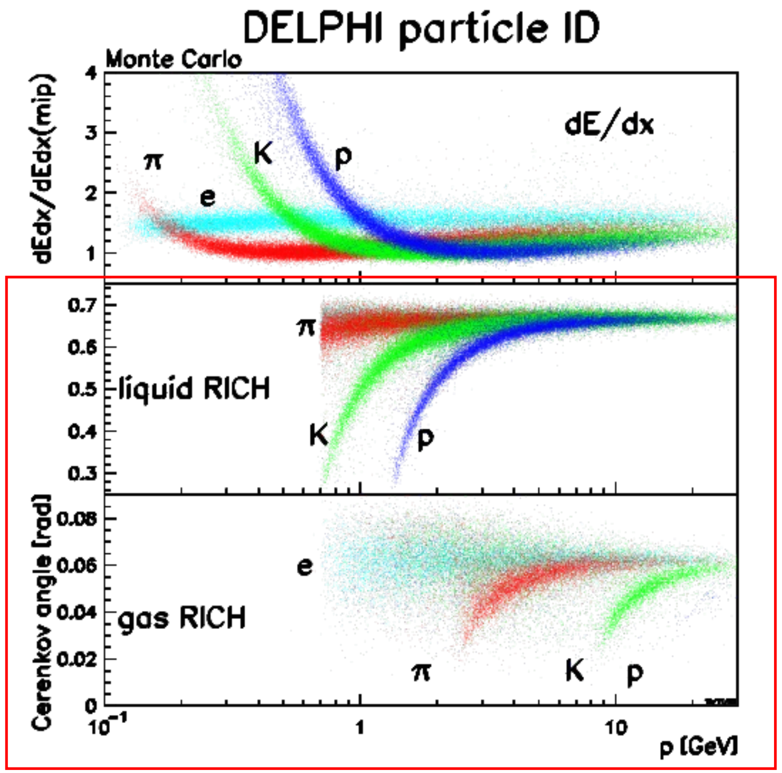
RICH: examples

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





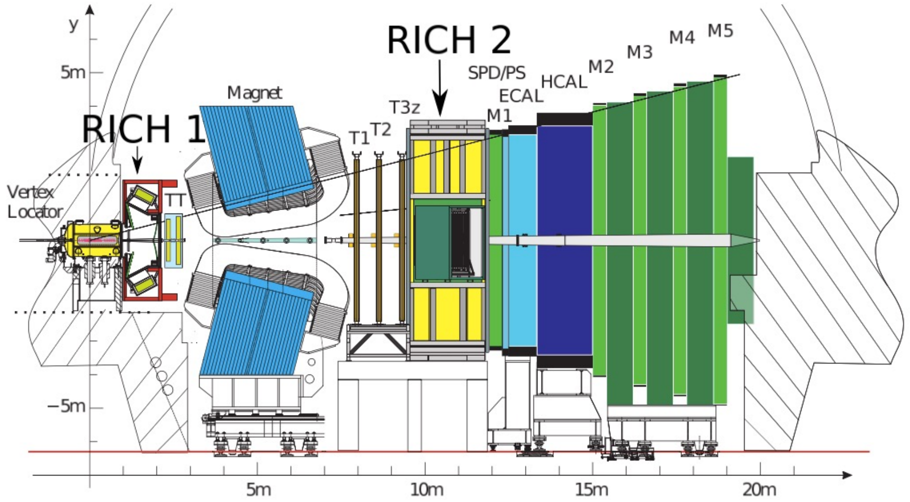
→ π/K/p separation over a large momentum range: 0.7-45 GeV/c

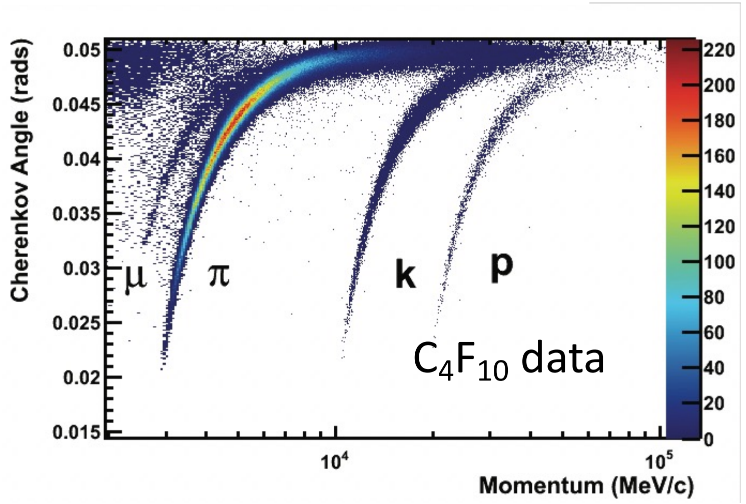


- 2 radiators:
  C_5F_{12} gas, n=1.241
  C_6F_{14} liquid, n=1.2834
- 288 parabolic mirrors
- photodetector: gas+TMAE+MWPCs

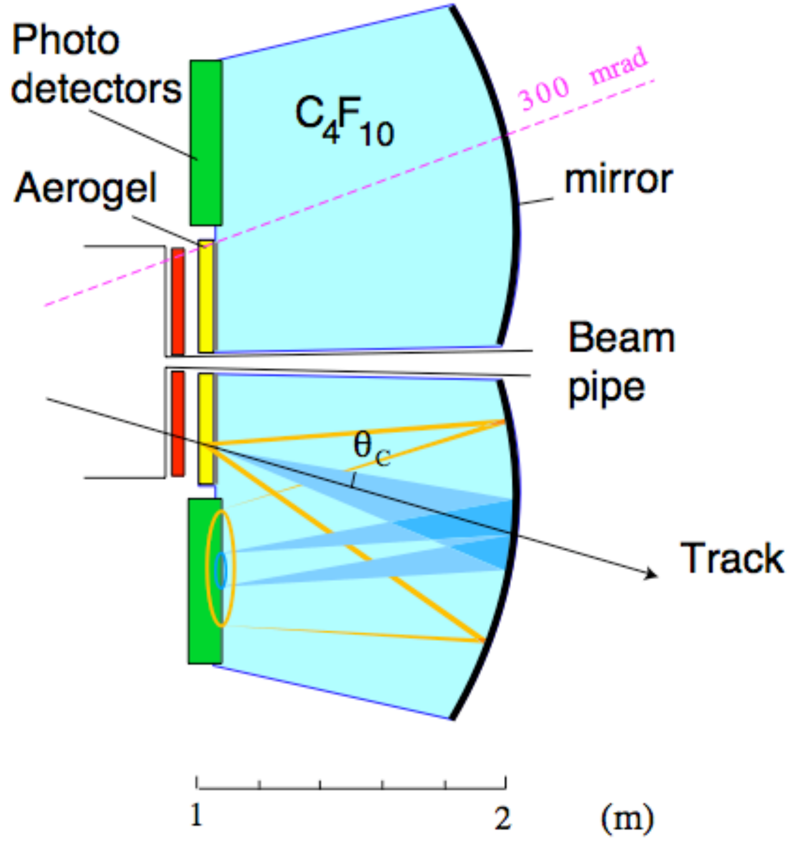
RICH: examples

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)

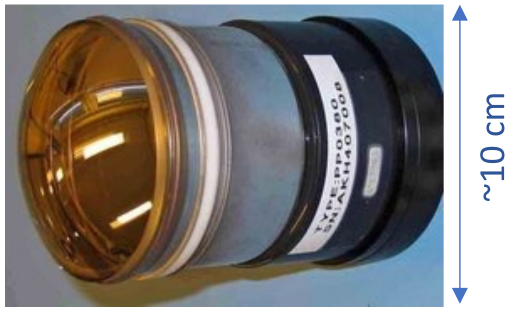


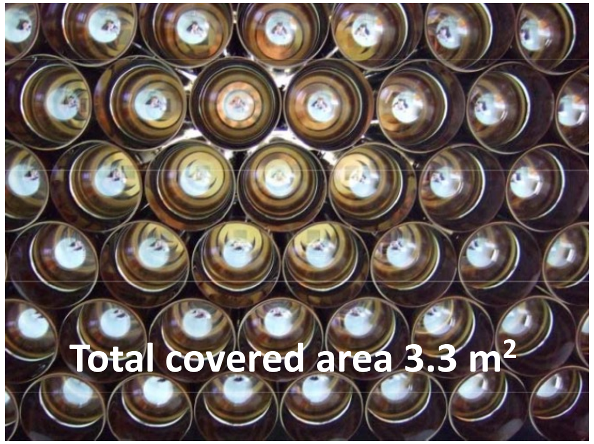
RICH: examples

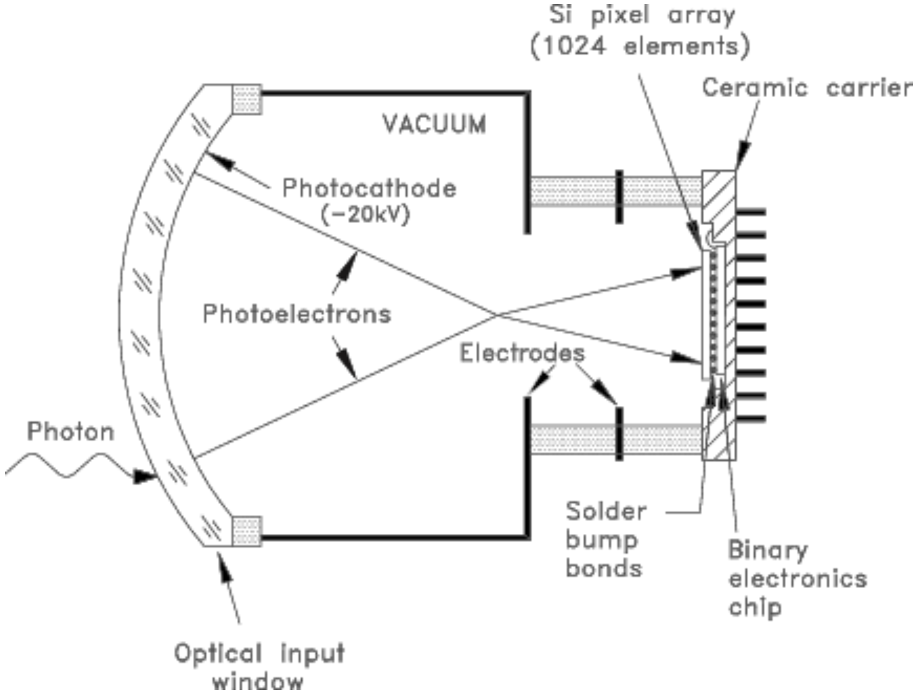
LHCb@LHC (CERN)

Hybrid Photon Detectors (**HPDs**)
Photoelectric effect +
focusing of photoelectrons to Si sensors

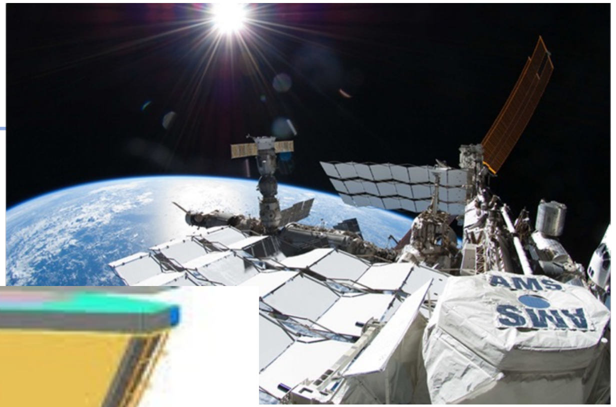
→ Accurate measurement of space and time of photons
→ Short flight path of PEs: reduced sensitivity to magnetic field
→ Can detect single photons







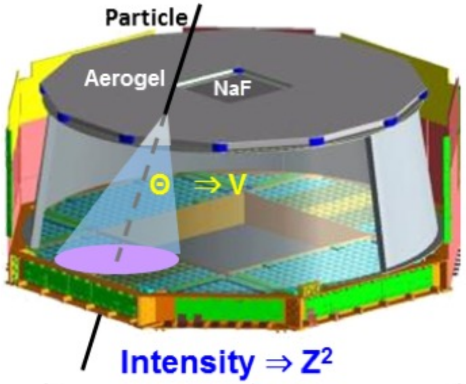
RICH: examples

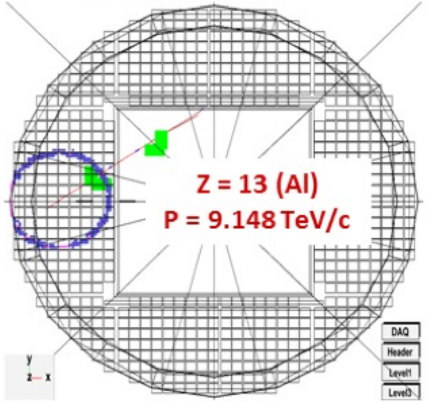


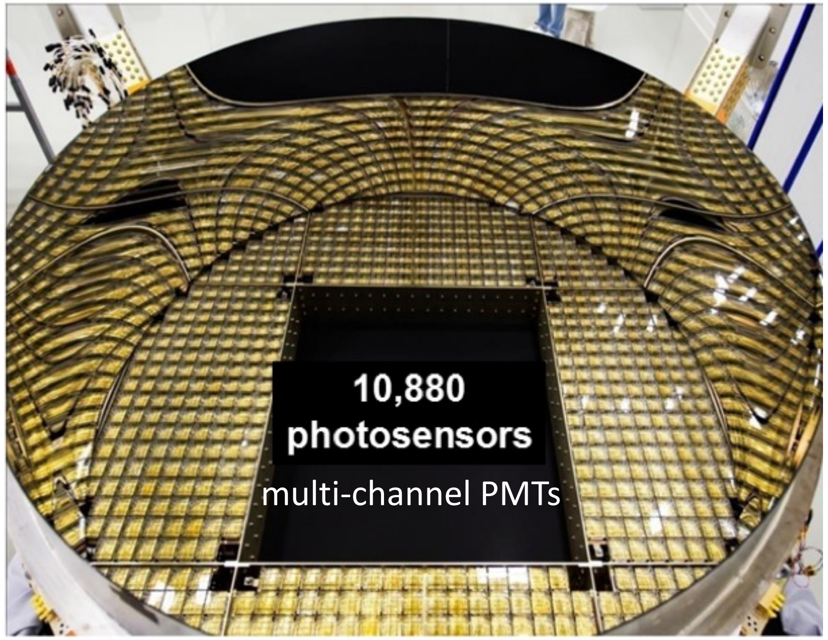
AMS Ring Imaging CHerenkov (RICH)

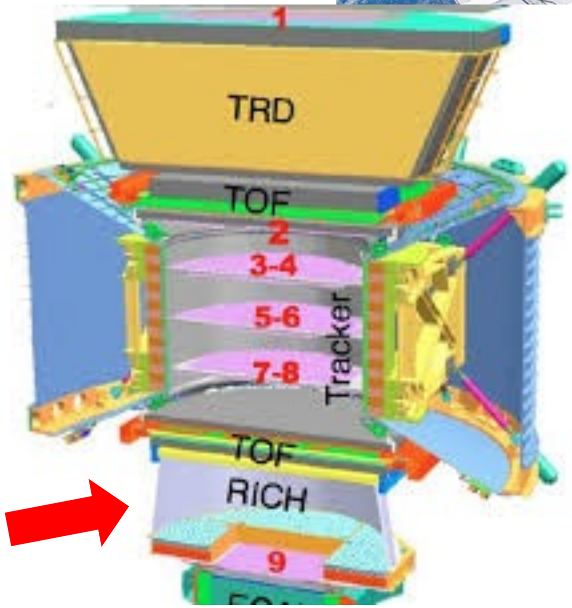
Measurement of Nuclear Charge (Z^2) and its Velocity to 1/1000

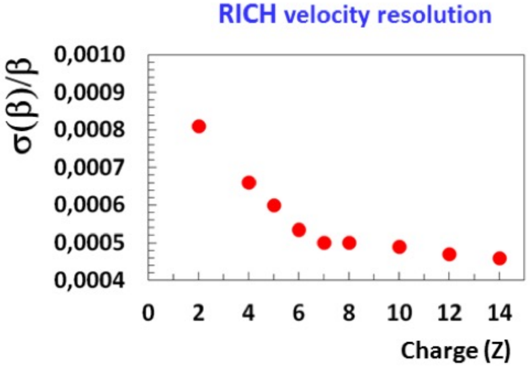
- 2 radiators:
  - 16 tiles of NaF tiles, n=1.33
  - 92 tiles of Aerogel, n=1.05
- 470mm expansion volume + mirrors

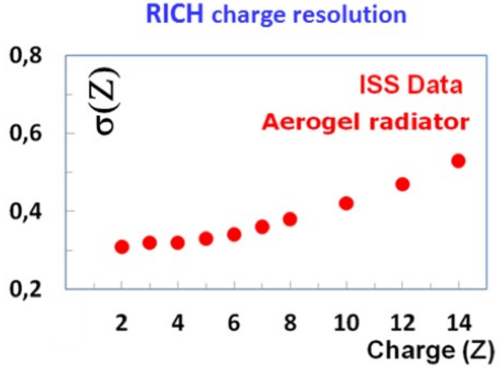






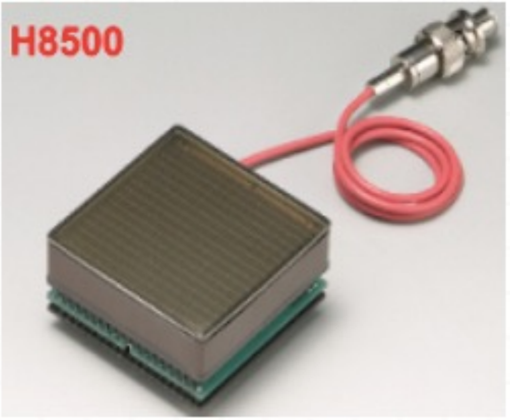


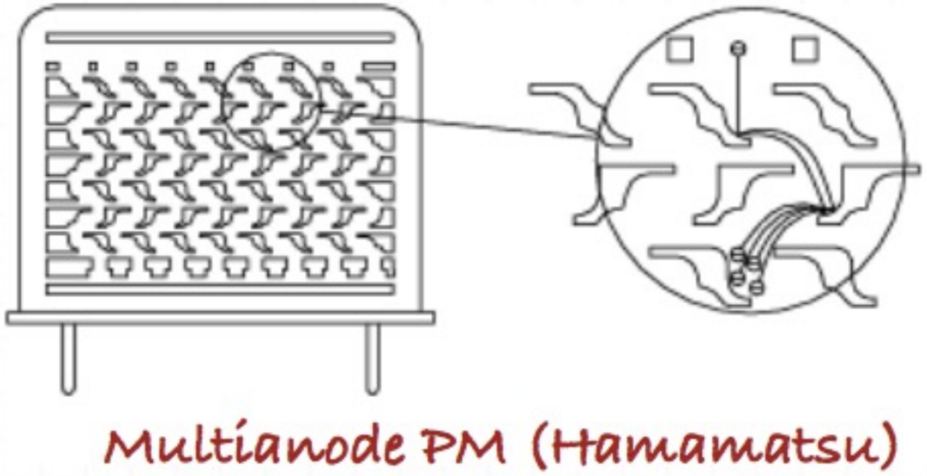


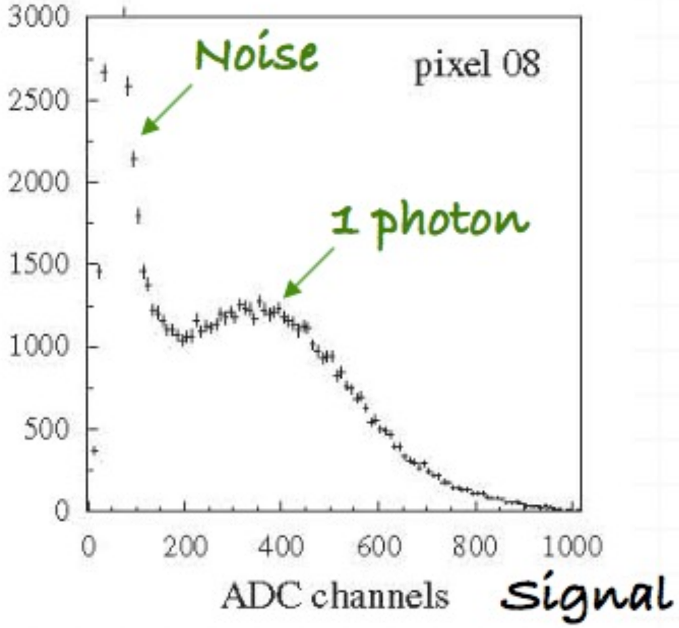


Multi-Anode PMTs

- *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





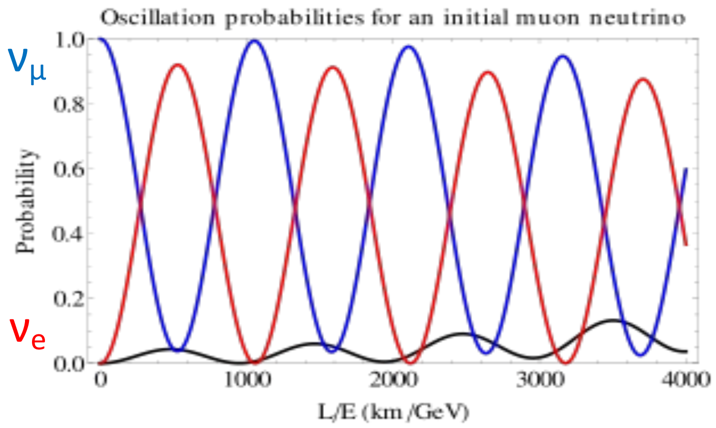


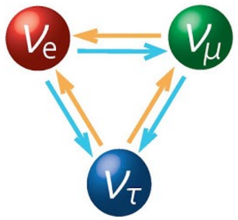
R. De Vita, INFN Genova

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 flavour of the neutrino == flavour of the lepton produced in CC interactions

The Nobel Prize for Physics 2015

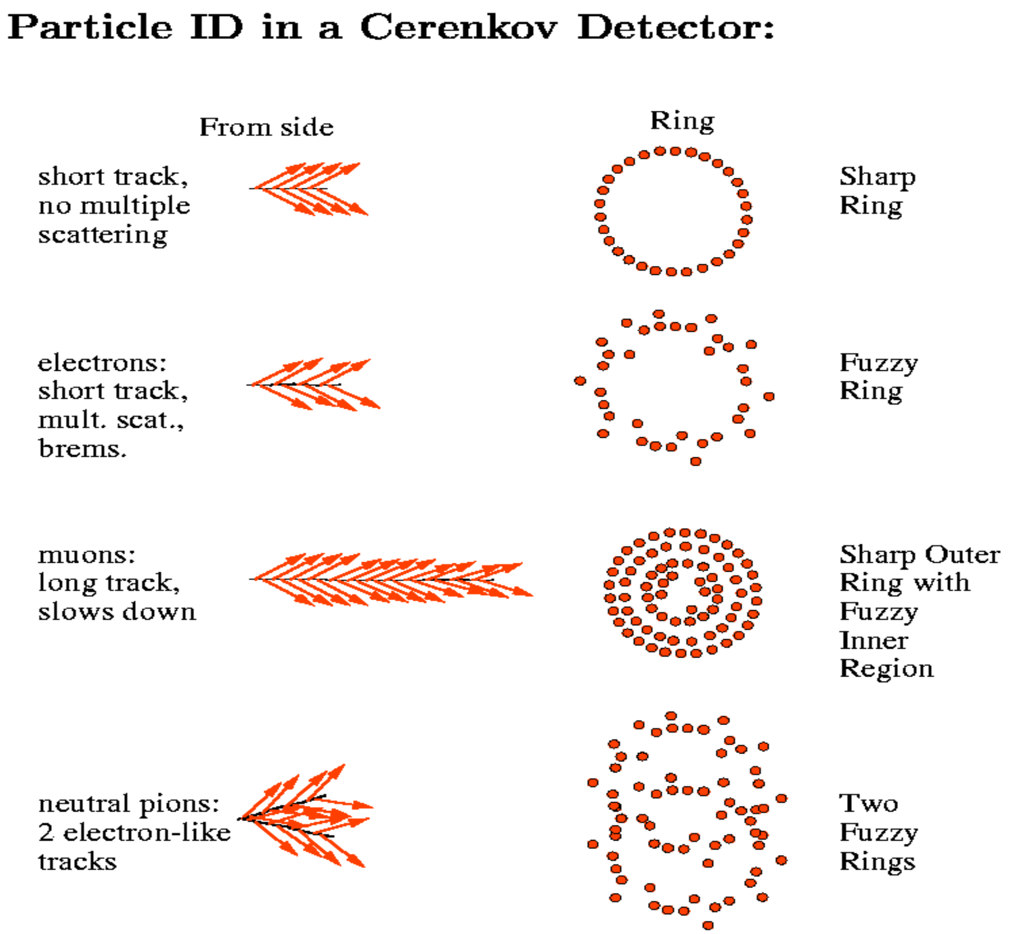
Takaaki Kajita
Super Kamiokande Collaboration
University of Tokyo, Japan

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

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

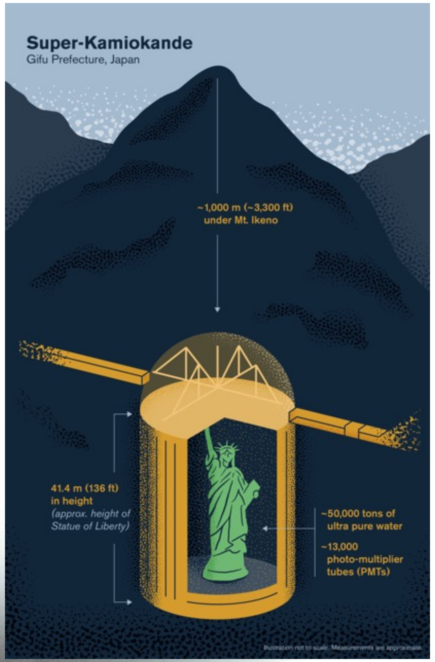
Cherenkov PID in neutrino experiments

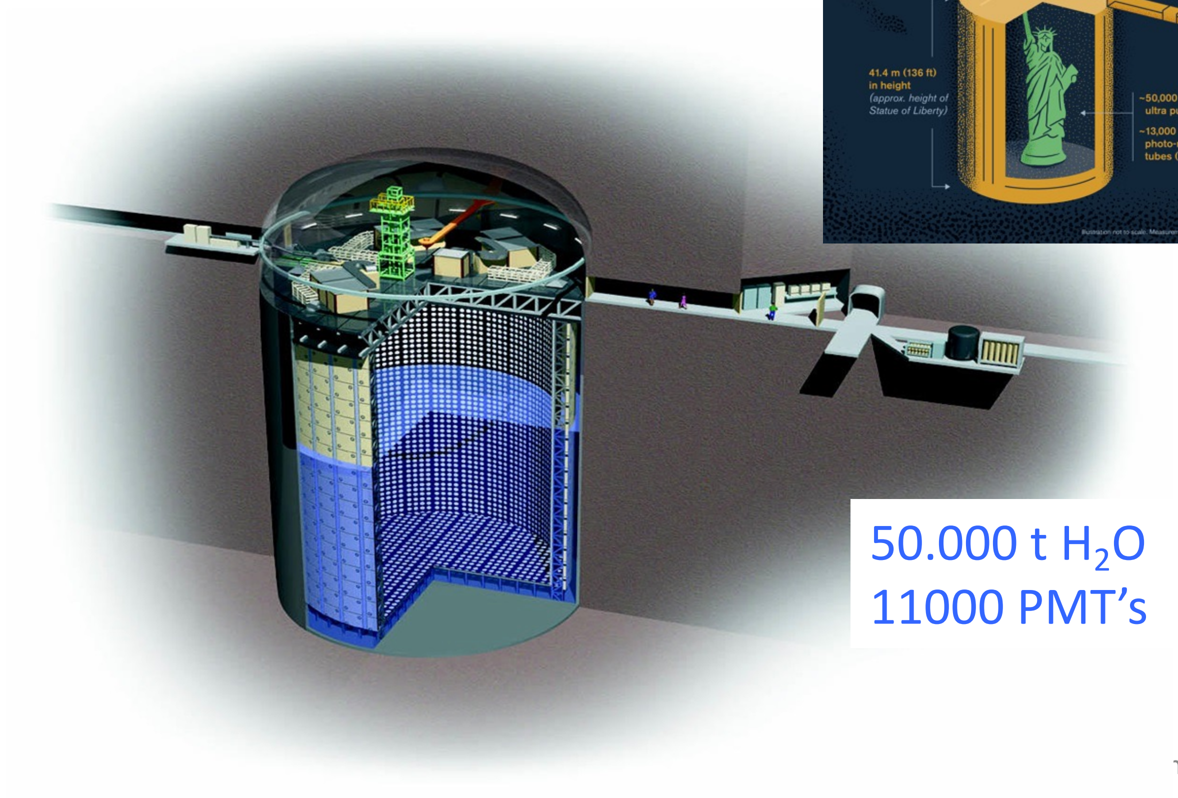
Identification of particles produced in neutrino interactions:
Based on the characteristics of the Cherenkov cone



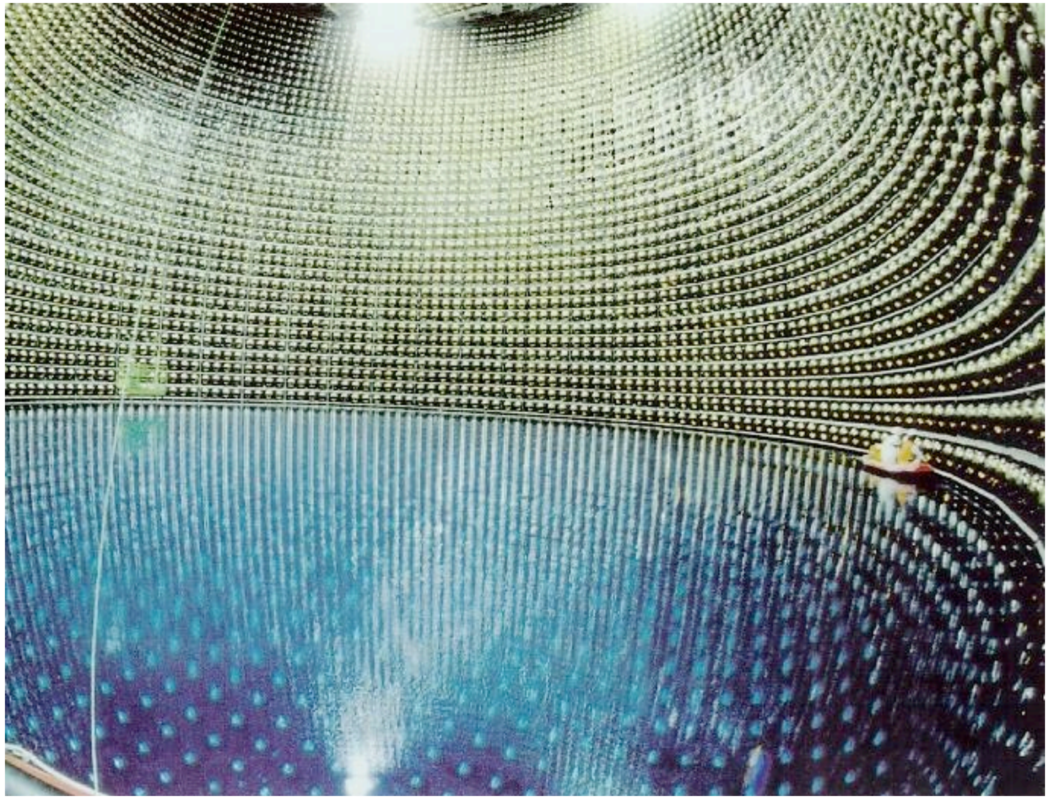
Example: SuperKamiokaNDE

Kamioka mine, Japan
~1000 m under Mount Ikeno





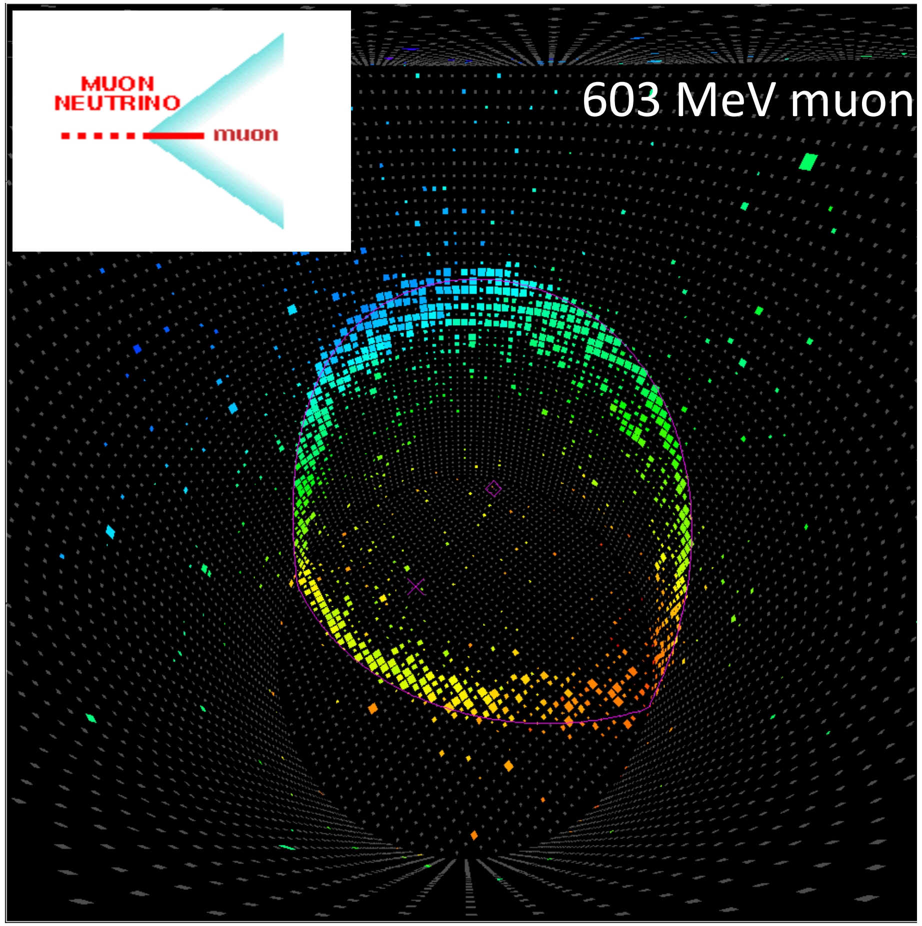
50.000 t H_2O
11000 PMT's

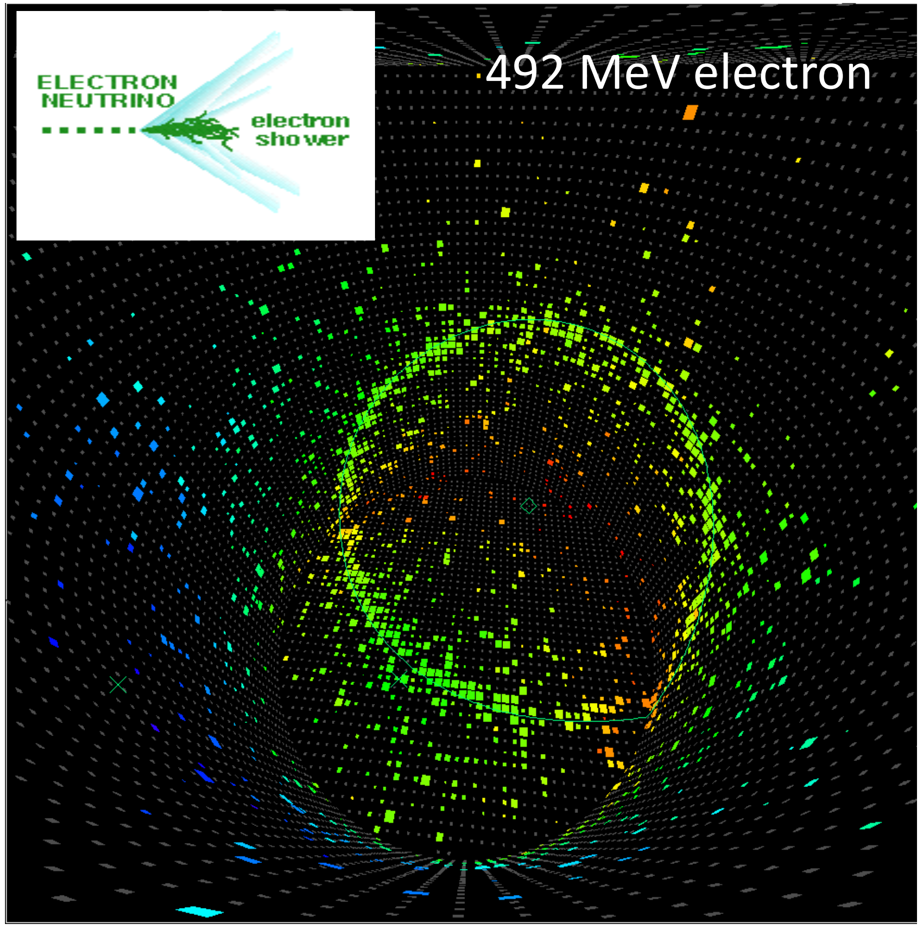


Example: SuperKamiokaNDE

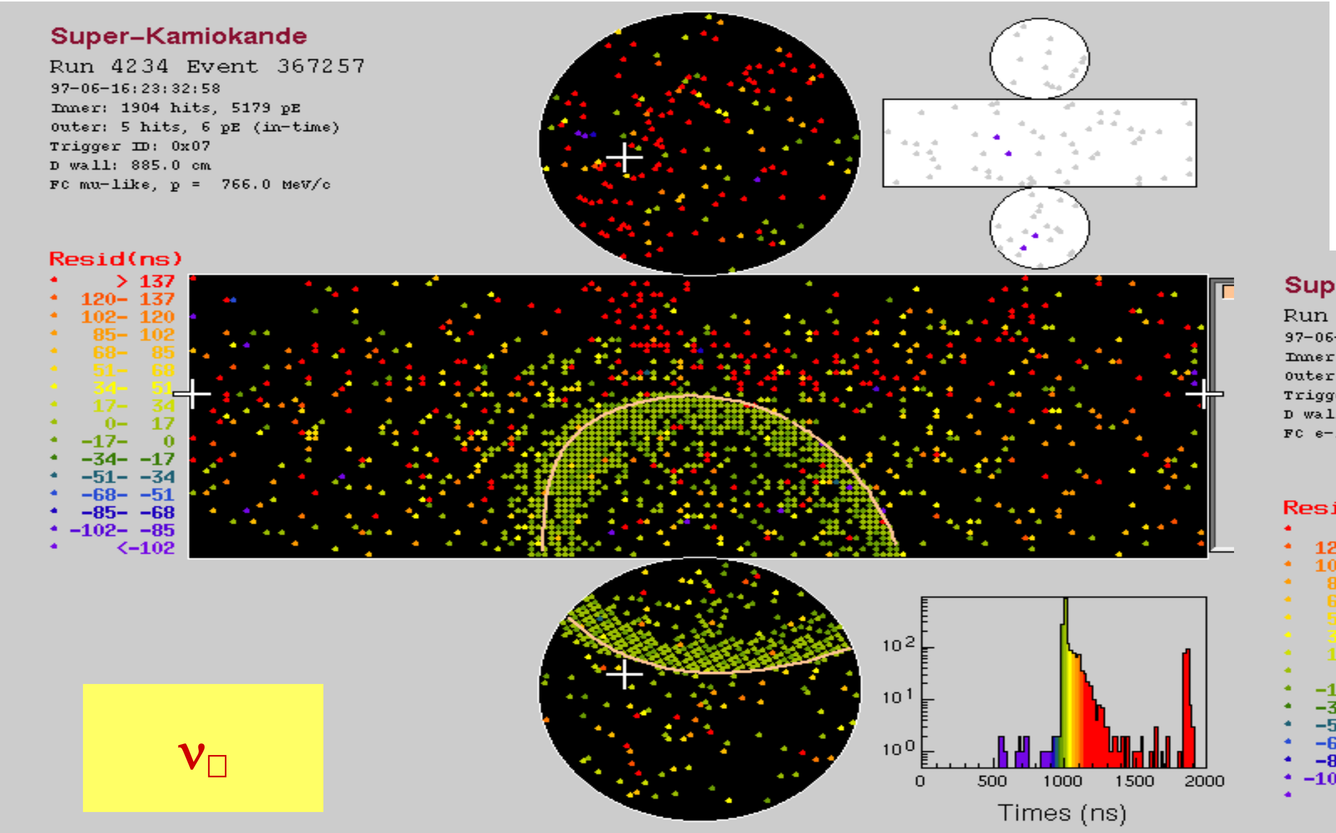
$$\nu_\mu + p \rightarrow \mu^- + n \quad \text{(CC)}$$

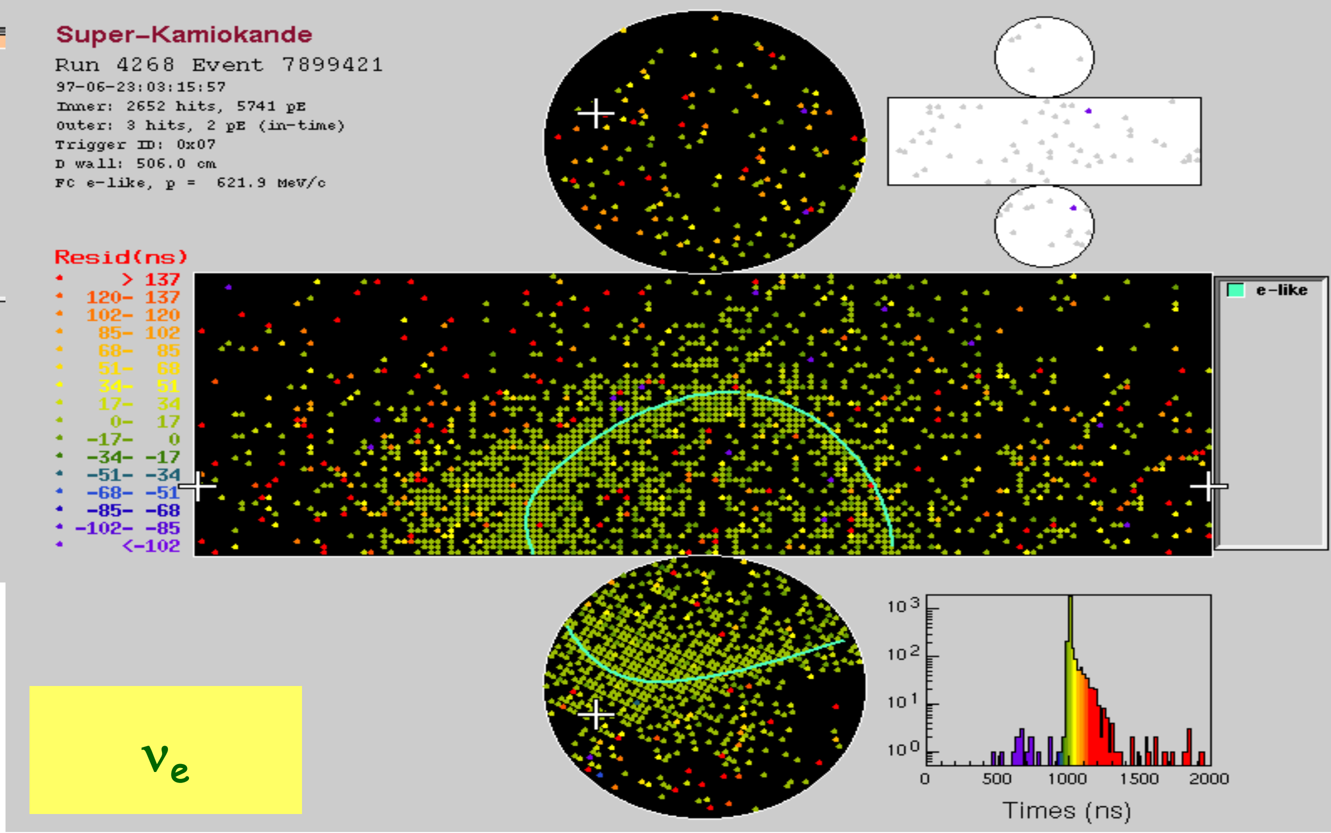
$$\nu_e + p \rightarrow e^- + n \quad \text{(CC)}$$



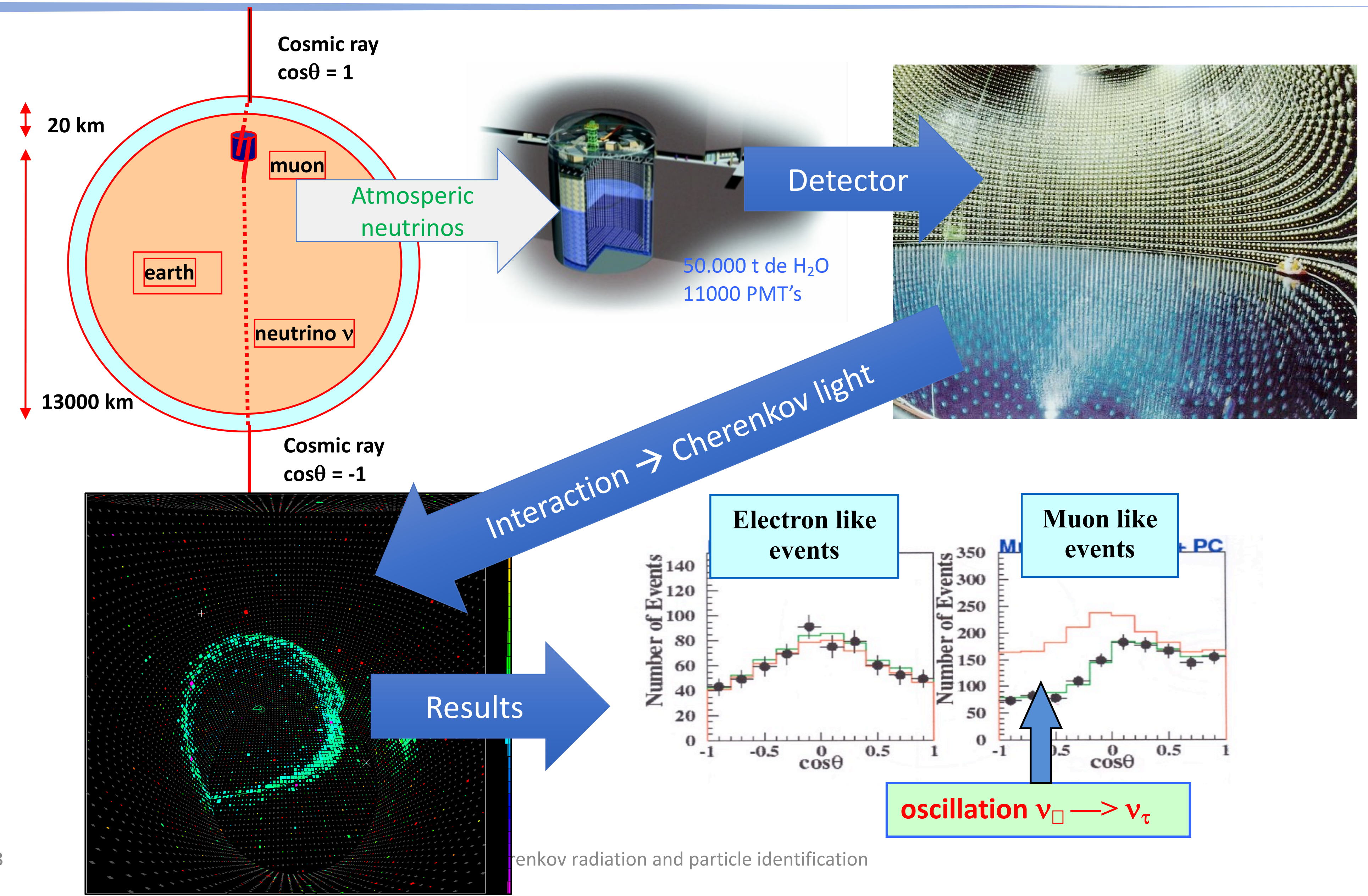


Example: SuperKamiokaNDE

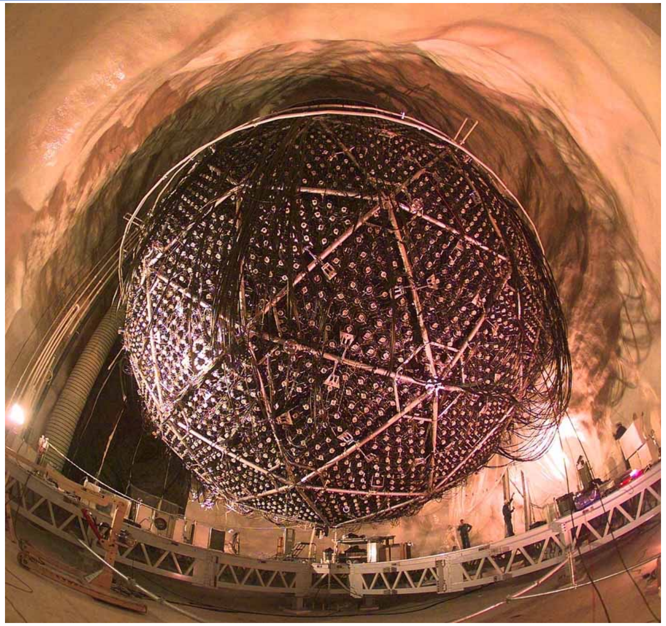


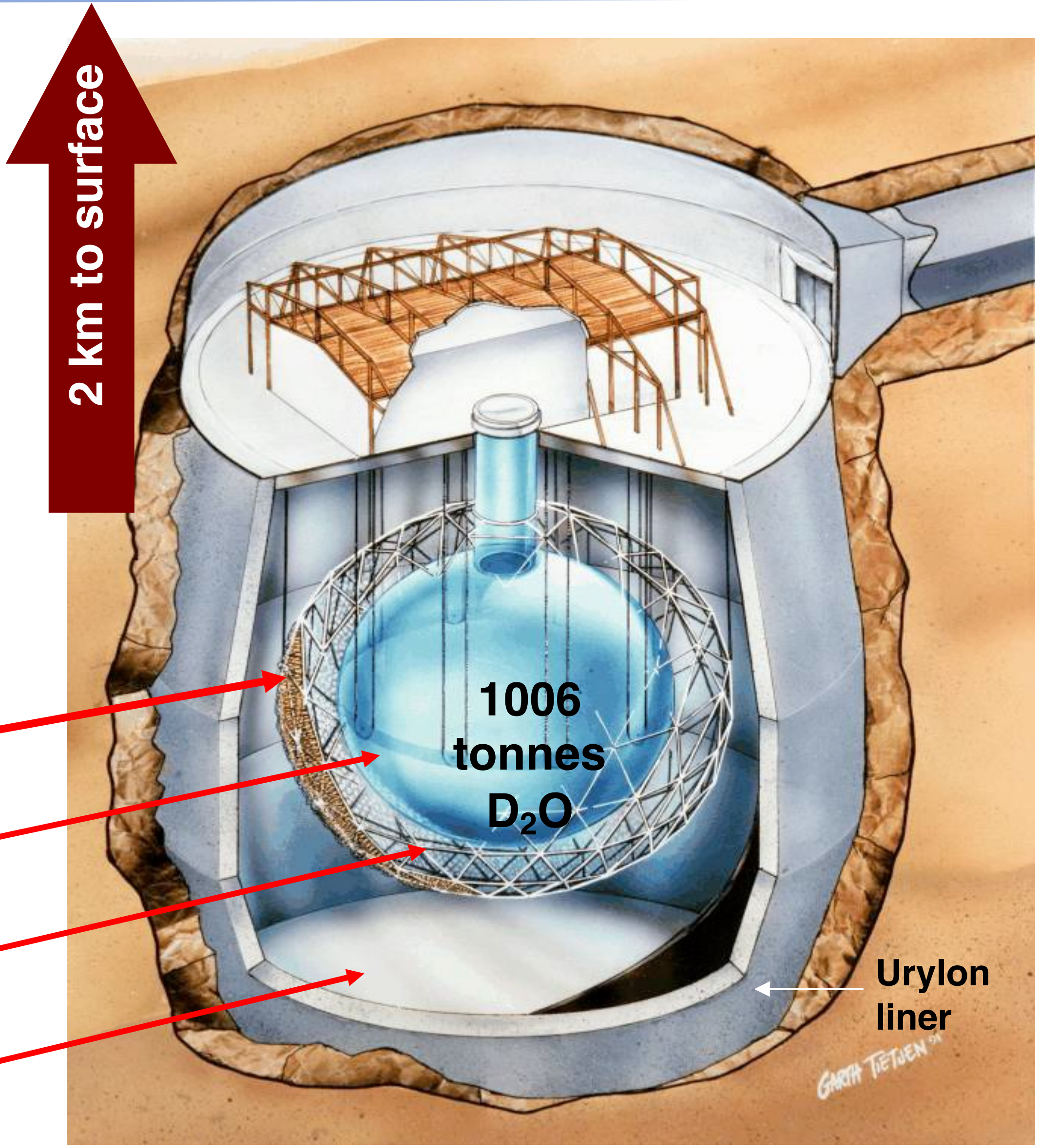


Example: SuperKamiokaNDE



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

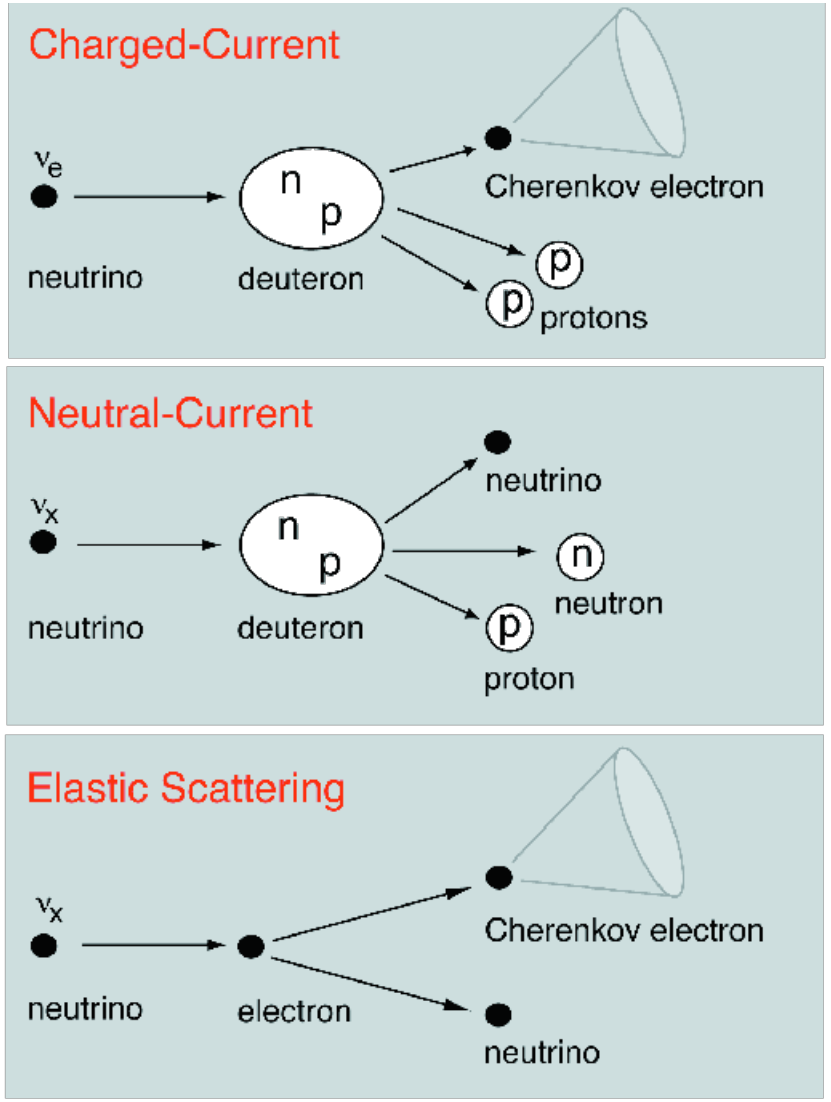
- Measurement of ν_e energy spectrum
- Weak directionality

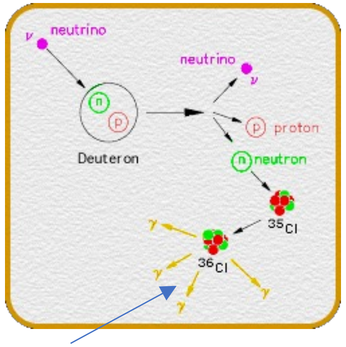
NC $\nu_x + d \rightarrow p + n + \nu_x$

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

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

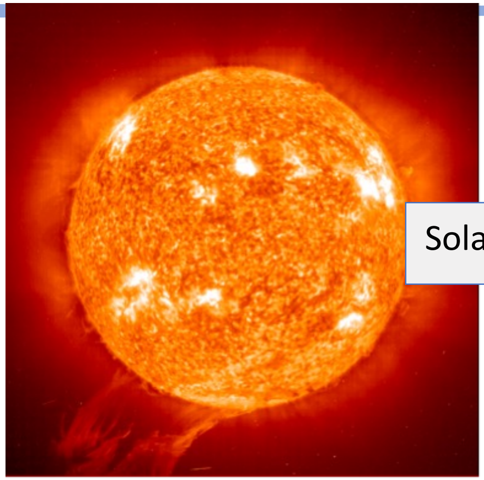
- Low Statistics
- $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
- Strong directionality



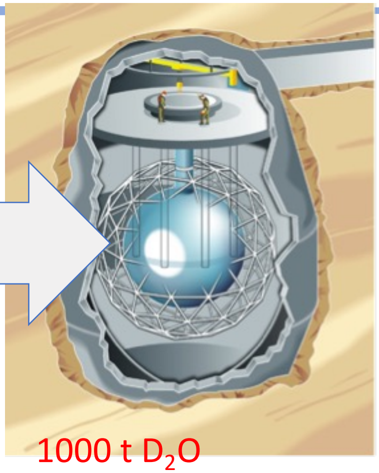


gamma rays which are emitted when the neutron is finally captured by another nucleus. The gamma rays will scatter electrons which produce detectable light via the Cherenkov process

Example: SNO

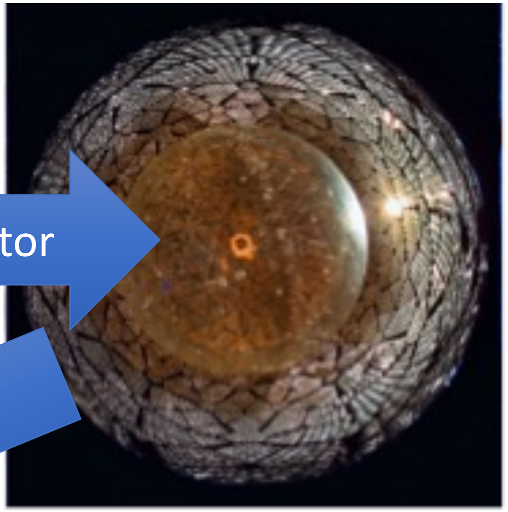


Solar neutrinos

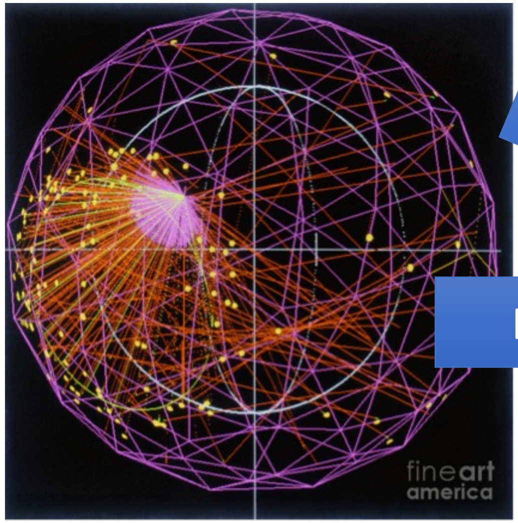


1000 t D_2O
9500 PMT's

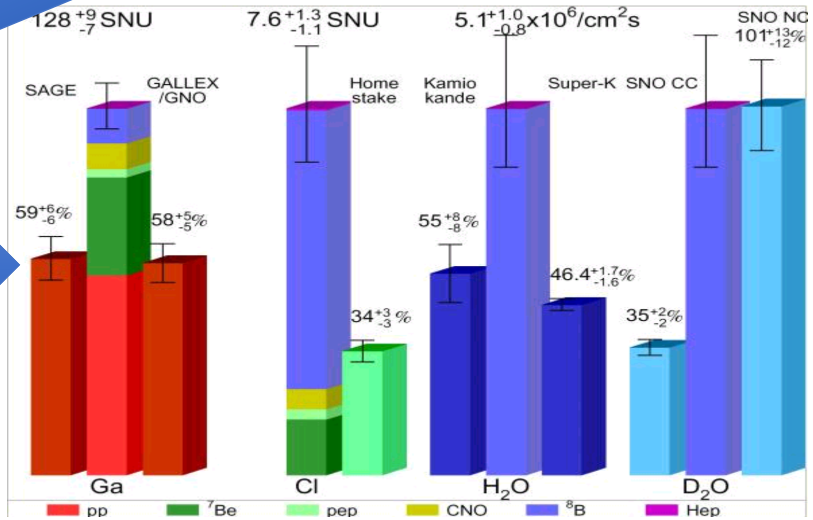
Detector



Interactions == Light



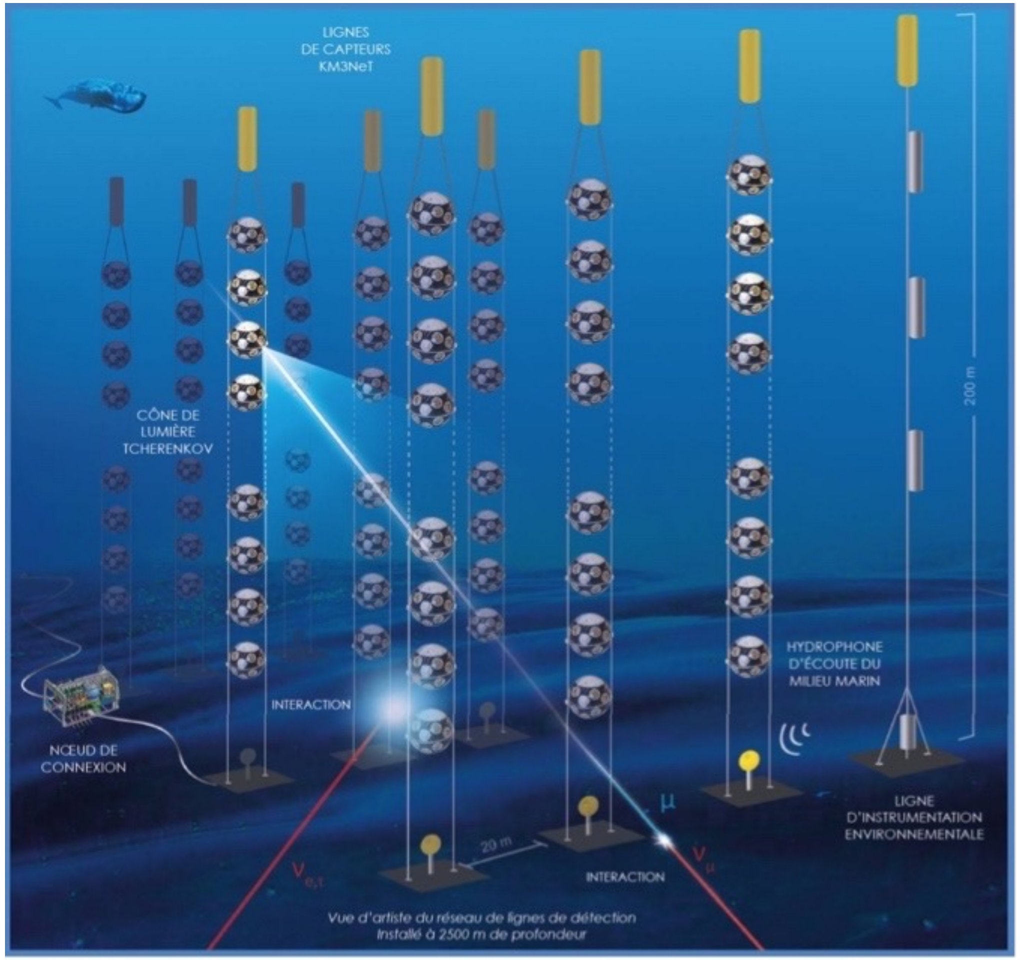
Results

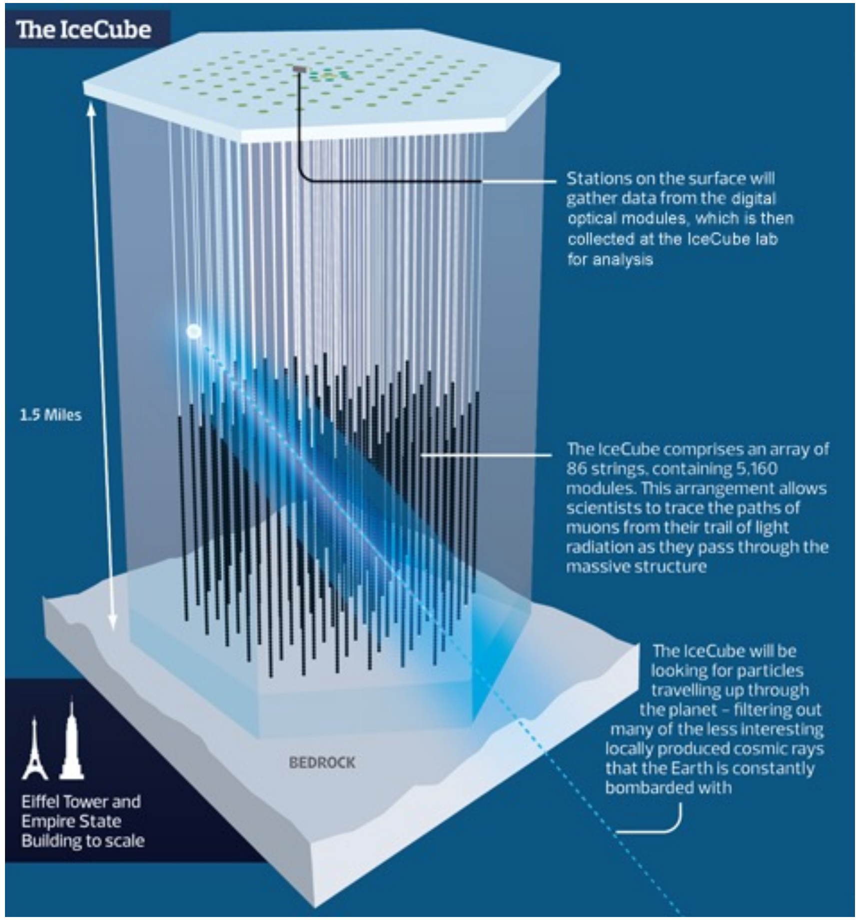


Cherenkov detectors for astroparticle physis

Detection of very high energy neutrinos in sea water / ice

KM3Net / IceCube





Cherenkov detectors for astroparticle physis

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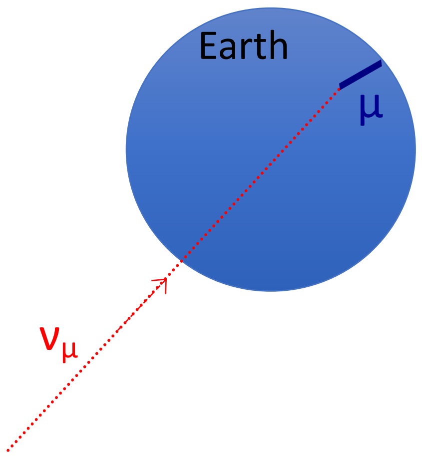
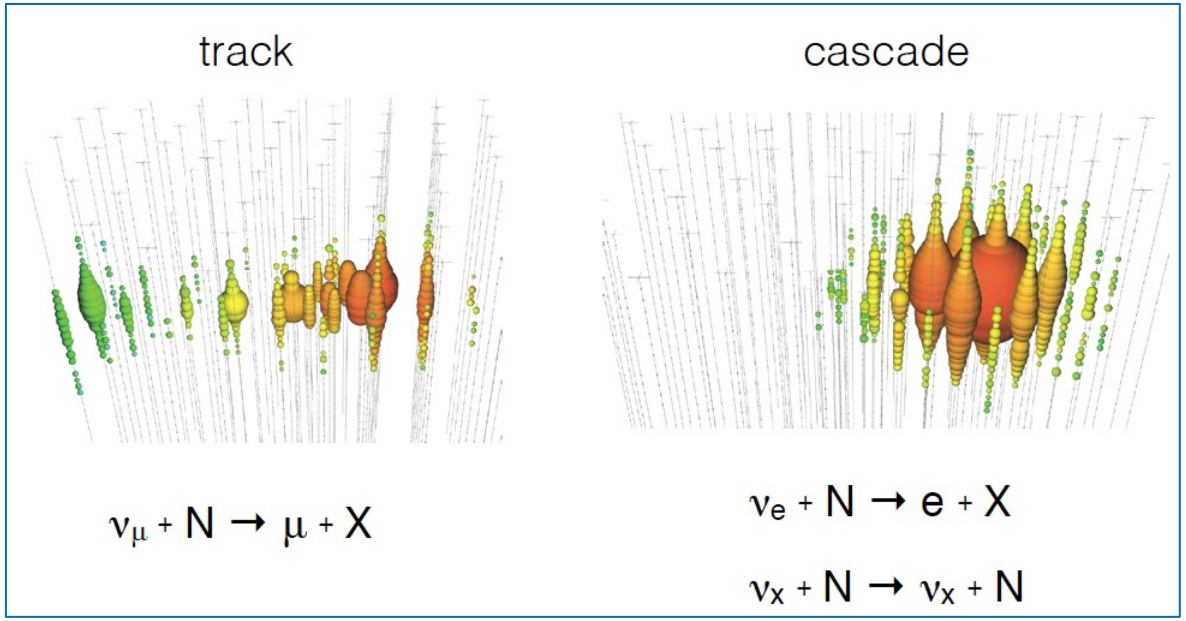


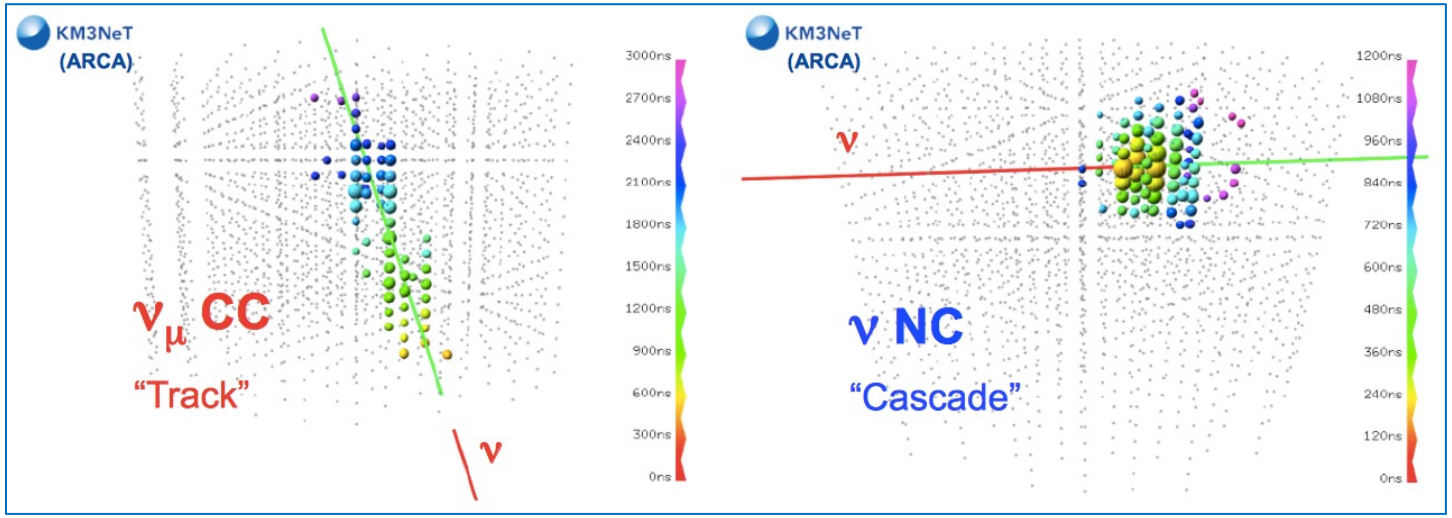
KM3NeT
6210 Digital Optical Modules (**DOMs**)
43 cm diameter, contains 31 3-inch (7.6 cm) PMTs with supporting electronics, and is connected to shore via a high-bandwidth optical network

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).

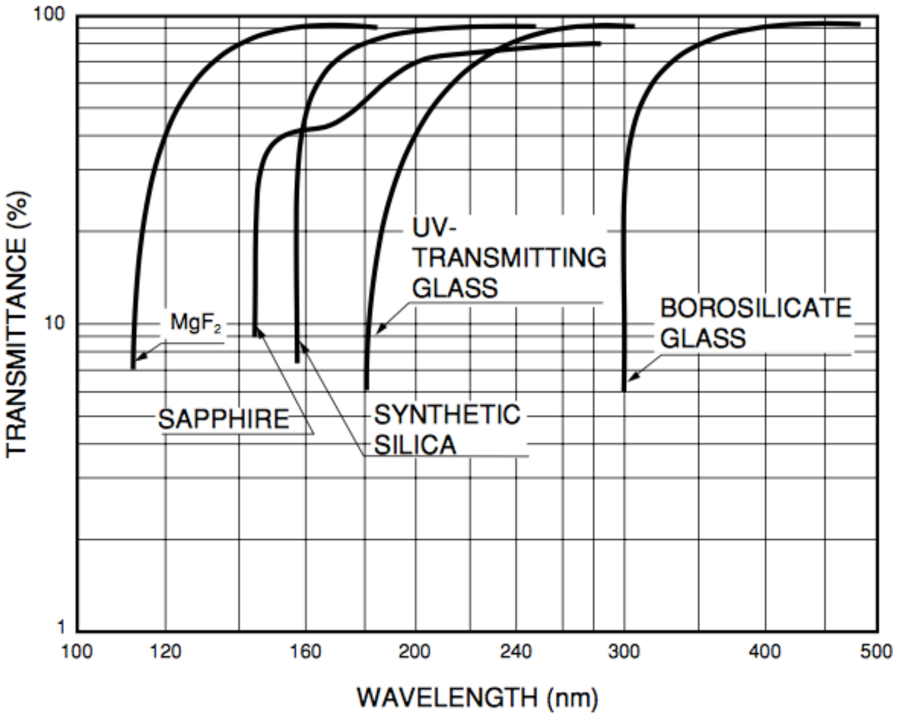
Exercise 2

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

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

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 (~$7.3\text{x}10^{-3}$).

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

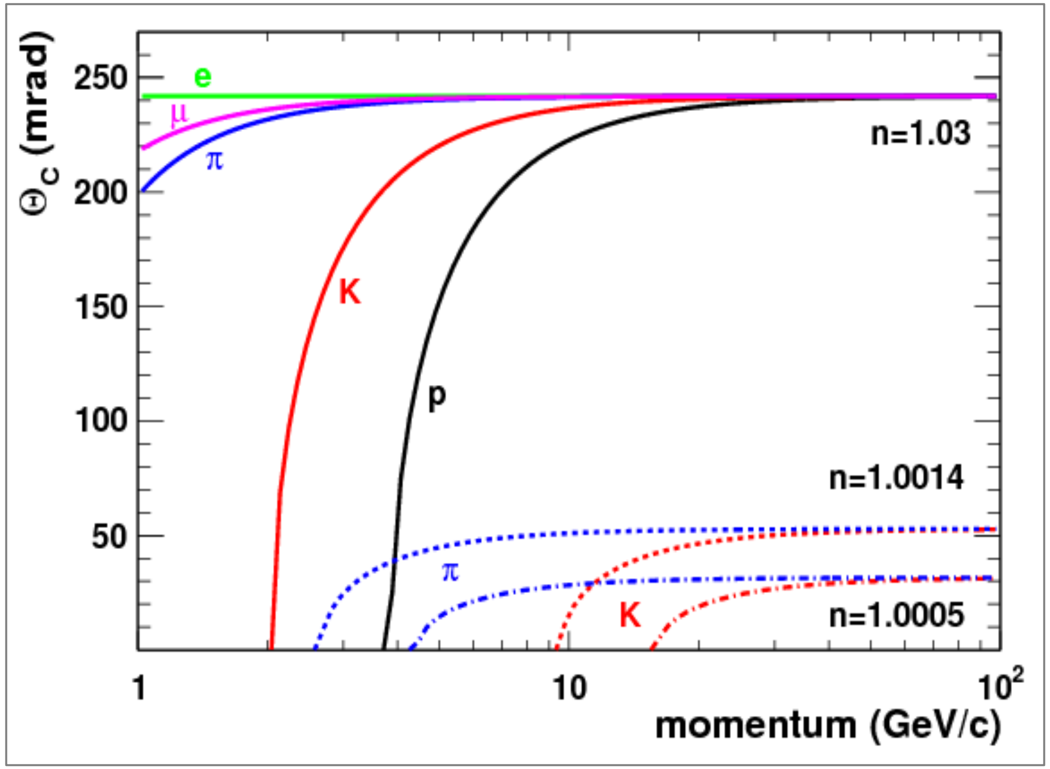
- Compute:
  - the radius of the Cherenkov ring on the detector wall (neglect deformations, i.e. assume the wall to be flat and perpendicular to the electron trajectory);
  - the number of detected photons, if the PMTs detect photons of wavelengths between 300 and 500 nm with an average Quantum Efficiency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

<u>Examples</u>:

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

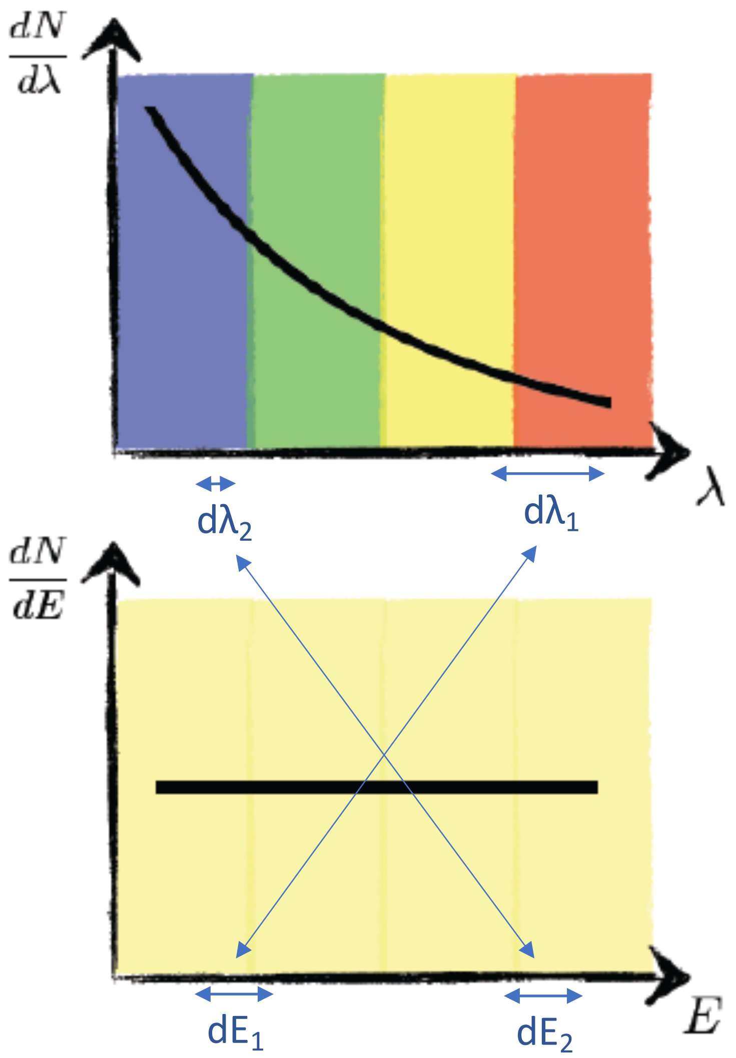
(Appendix: Change of variable in a PDF)

Cherenkov radiation photon spectra:

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

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

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



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

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