



Detector Physics 2020/2021, Lecture 8

Cherenkov radiation and particle identification

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References

many of my slides are taken from

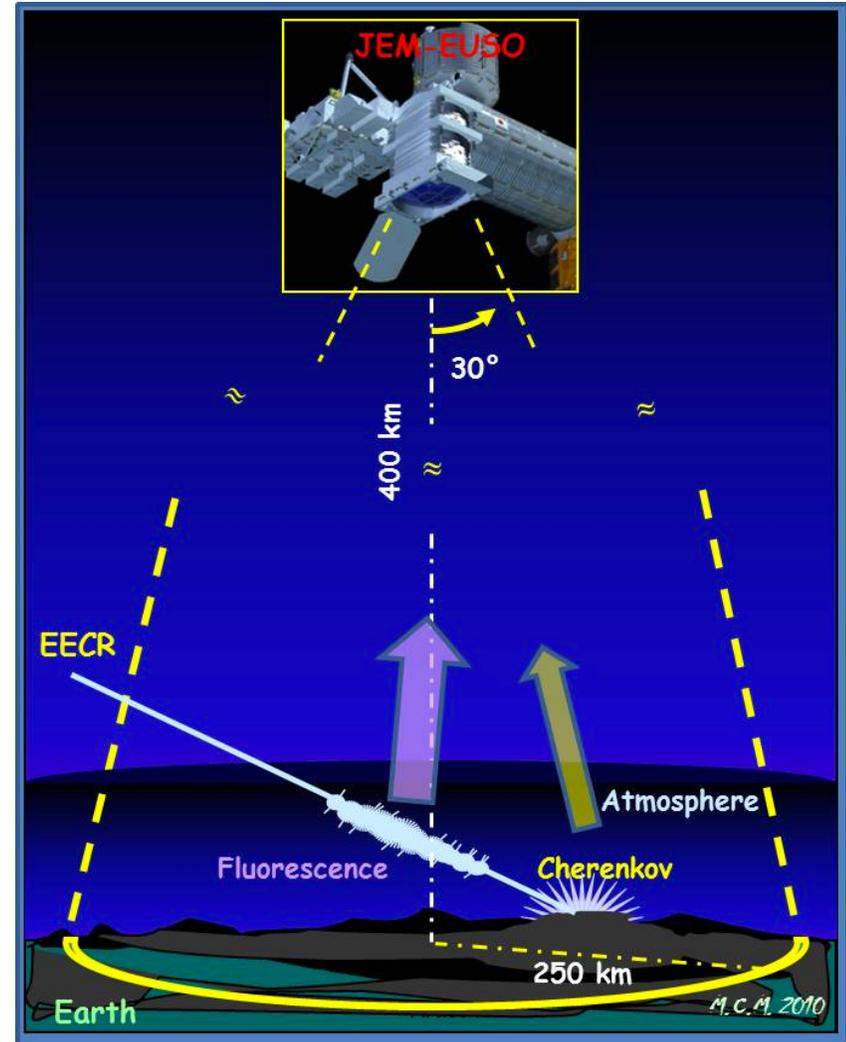
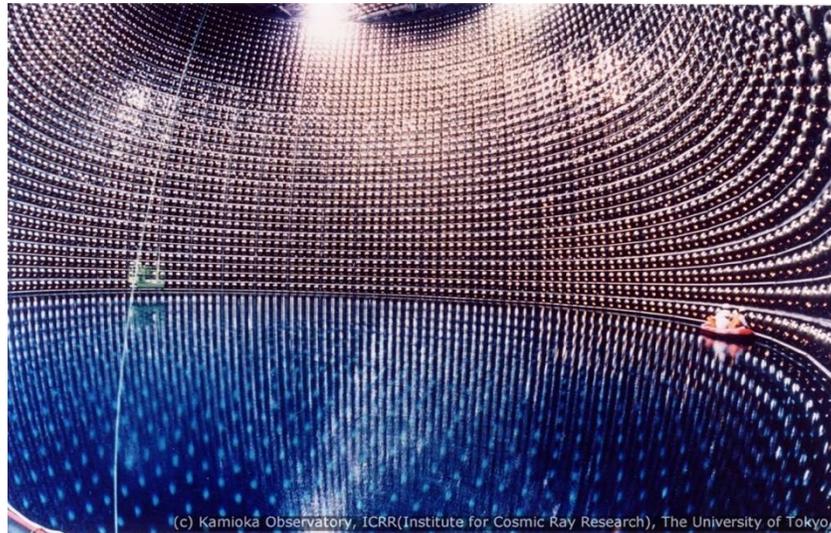
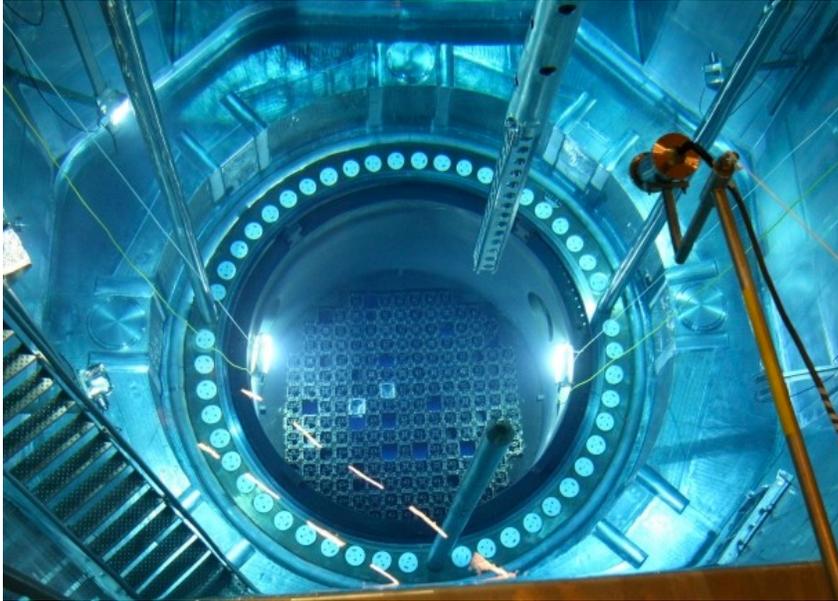
- Thomas Patzak, NPAC Lectures 2019 (thanks!)

<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 price



The Nobel Prize in Physics 1958

"for the discovery and the interpretation of the Cherenkov effect"



Pavel Alekseyevich Cherenkov

🕒 1/3 of the prize

USSR

P.N. Lebedev Physical Institute
Moscow, USSR

b. 1904
d. 1990



Il'ja Mikhailovich Frank

🕒 1/3 of the prize

USSR

University of Moscow; P.N.
Lebedev Physical Institute
Moscow, USSR

b. 1908
d. 1990



Igor Yevgenyevich Tamm

🕒 1/3 of the prize

USSR

University of Moscow; P.N.
Lebedev Physical Institute
Moscow, USSR

b. 1895
d. 1971

Cherenkov radiation: some history



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

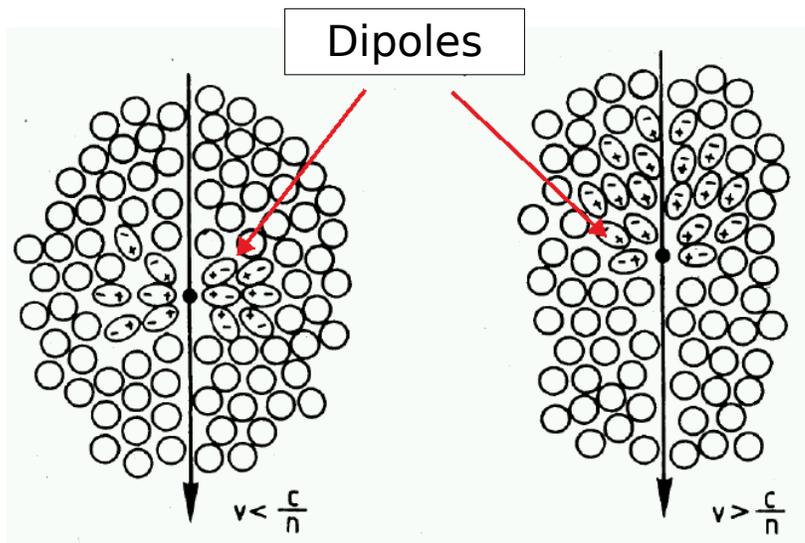
P. Cherenkov established that:

- 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

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

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



Charged particles polarize material
time dependent dipole field \rightarrow dipole radiation

For $v < c/n$:

Induced dipoles symmetrically arranged around particle path \rightarrow no net dipole moment
 \rightarrow no Cherenkov radiation

For $v > c/n$:

Symmetry is broken since the particle goes faster than em waves \rightarrow non-vanishing dipole moment
 \rightarrow Cherenkov radiation

Cherenkov radiation emission

Particle going faster than the speed of light in the material

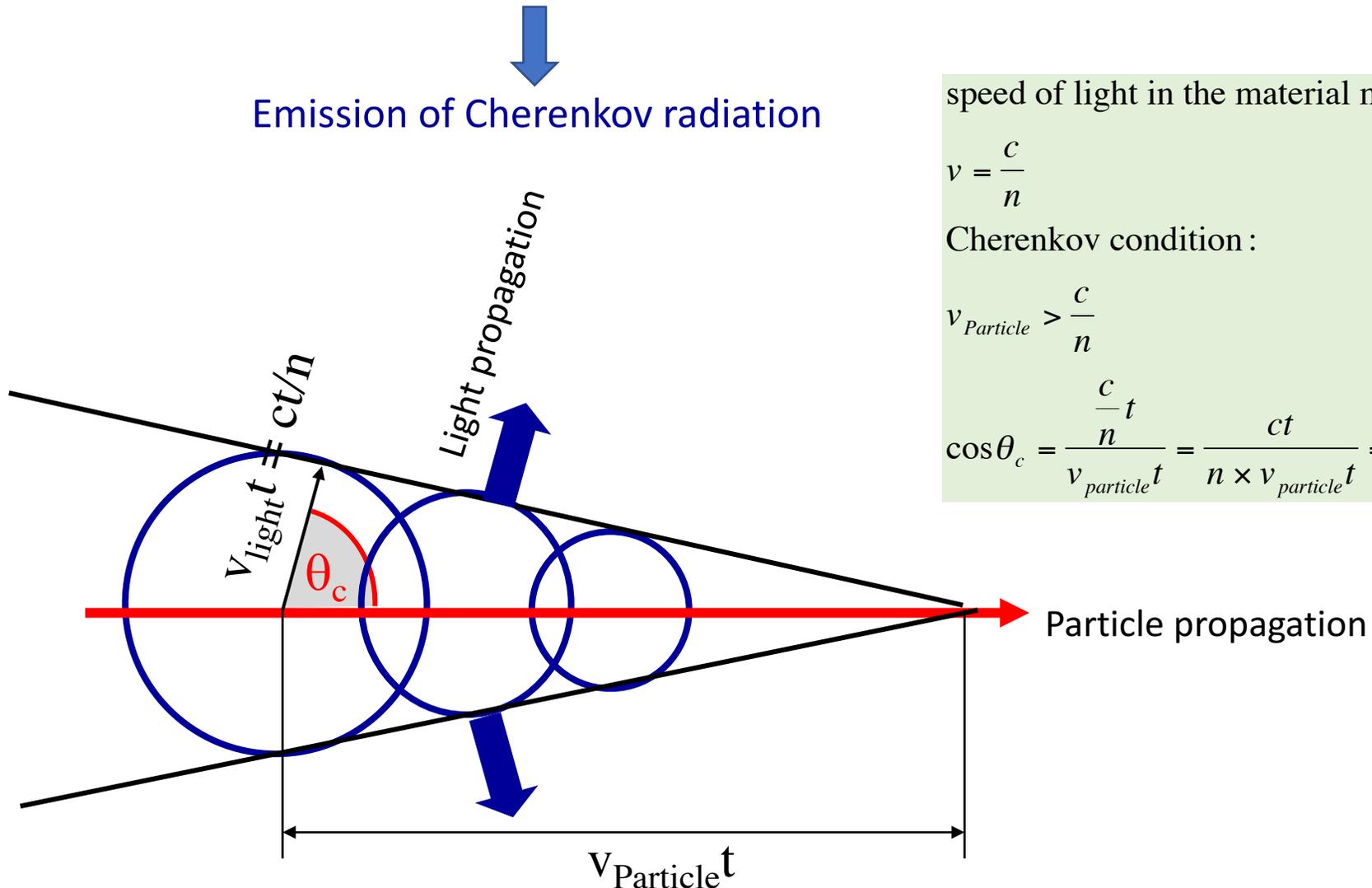
Emission of Cherenkov radiation

speed of light in the material medium:

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

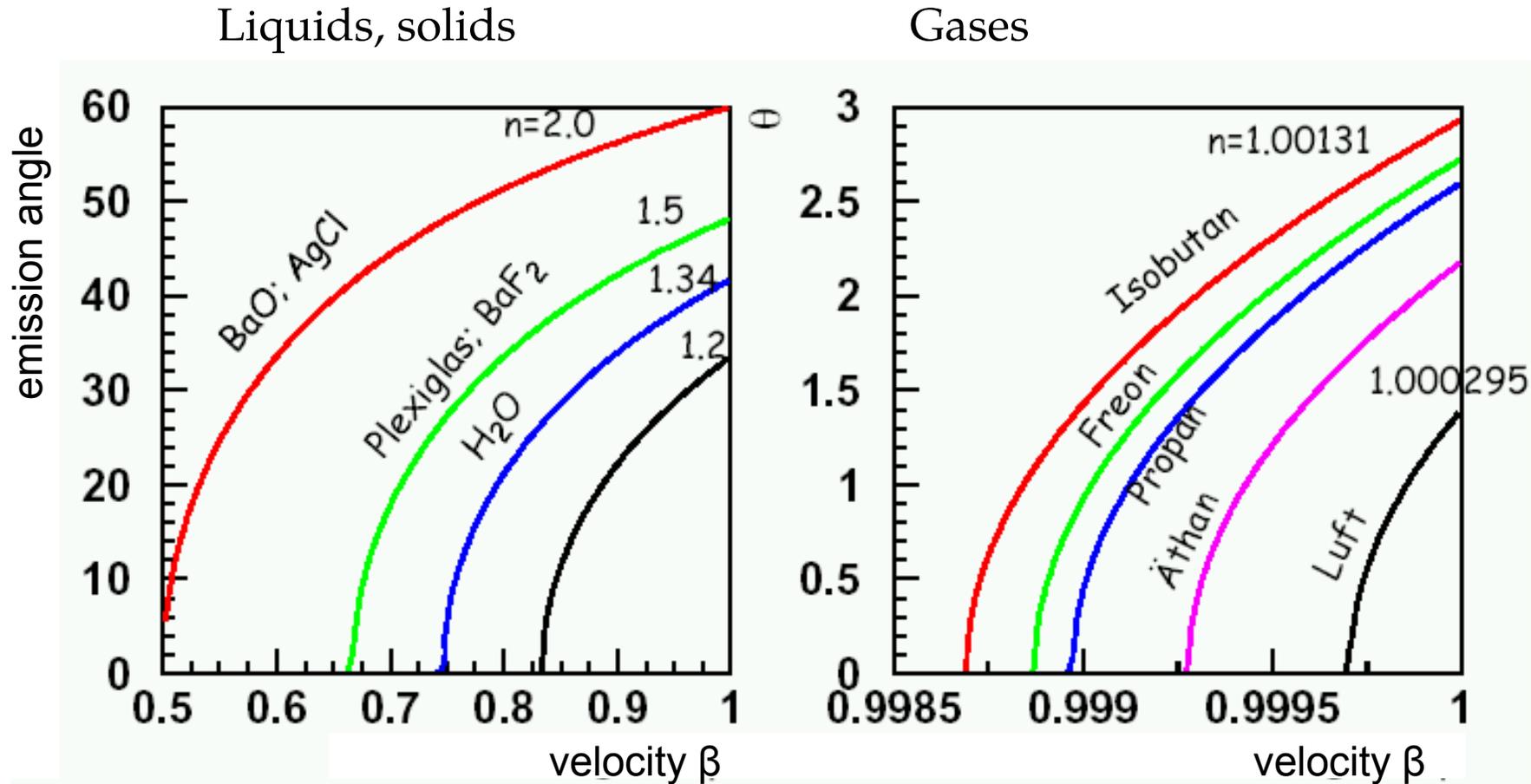
Cherenkov condition:

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

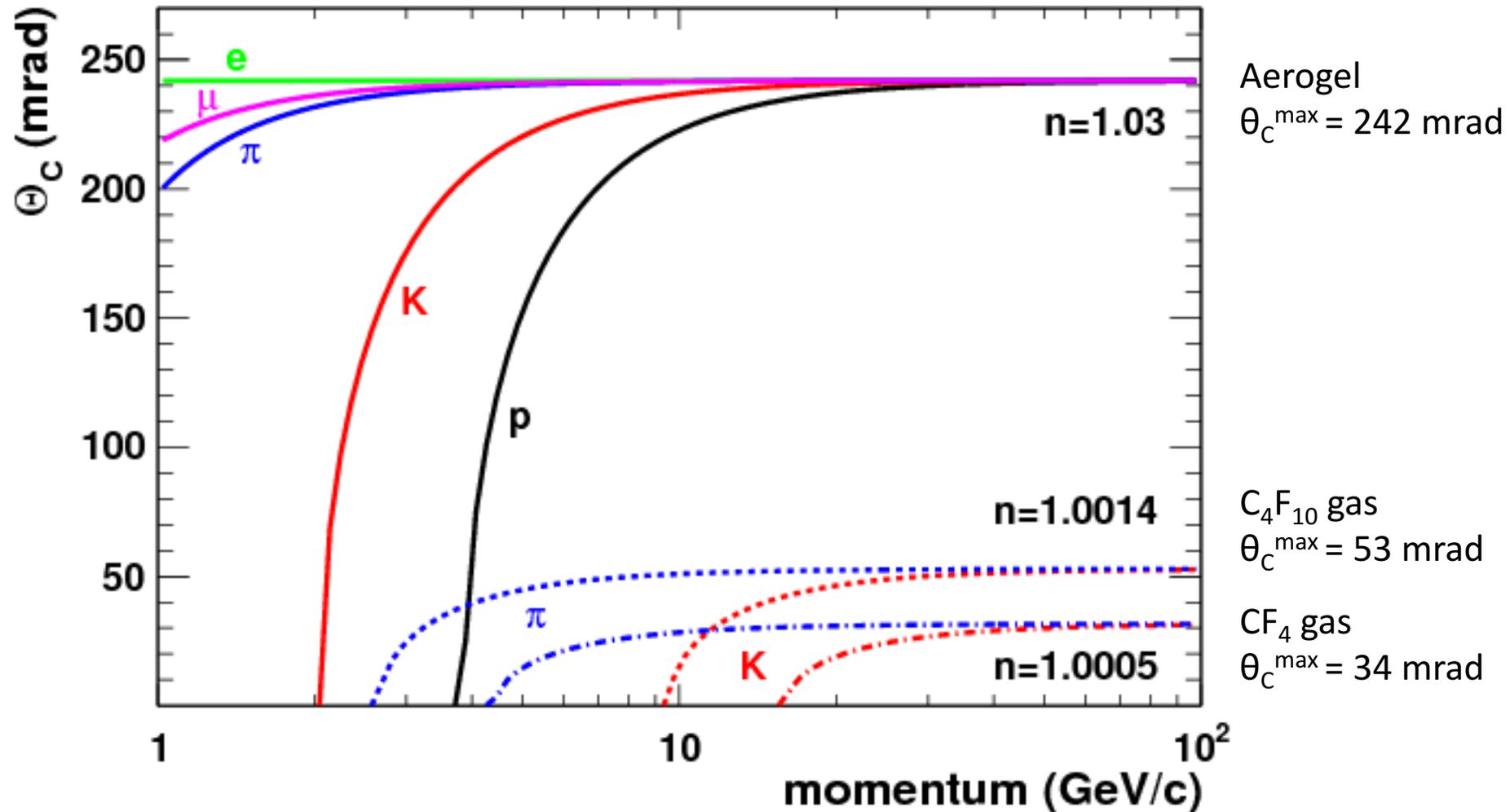
$$\cos \theta_c = \frac{\frac{c}{n}}{v_{\text{particle}} t} = \frac{ct}{n \times v_{\text{particle}} t} = \frac{ct}{n \times \beta_{\text{Particle}} \times ct} = \frac{1}{n \times \beta_{\text{Particle}}}$$


Cherenkov radiation angle

Relation between Cherenkov angle and particle velocity in different materials



Cherenkov radiation angle



Cherenkov radiation

Radiation of “Cherenkov” photons with a continuous 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:

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

to be compared with:

Energy loss by collision in H₂:

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

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

Cherenkov photon density

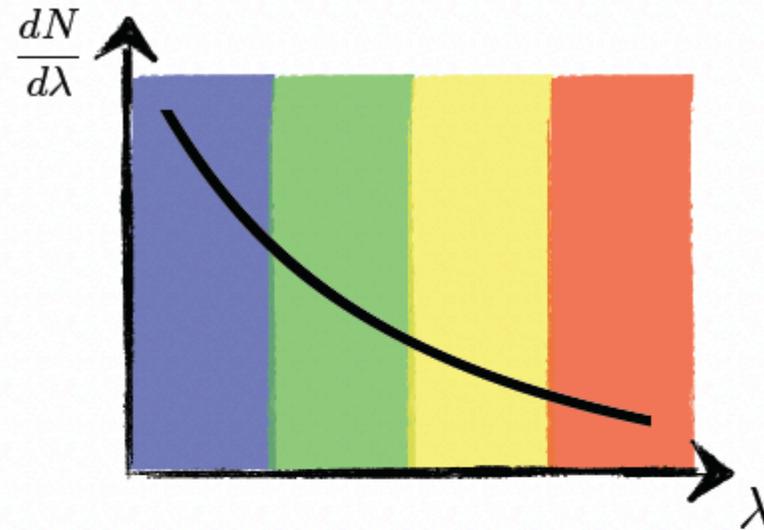
The number of emitted photons per unit length can be obtained from the cross section:

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

→ Number of emitted photons decreases with photon wavelength

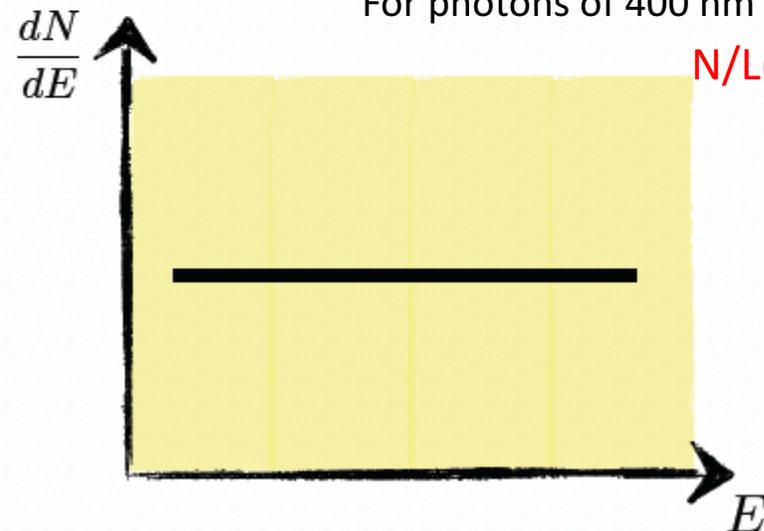
$$\frac{d^2 N}{dE dx} = \frac{z^2 \alpha}{\hbar c} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{z^2 \alpha}{\hbar c} \sin^2 \theta_C \approx \text{const}$$

→ Energy of emitted photons is uniformly distributed



For photons of $400 \text{ nm} < \lambda < 700 \text{ nm}$

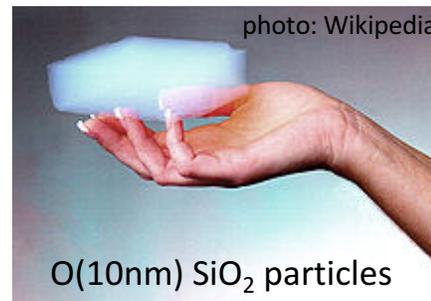
$$N/L(\text{cm}) \approx 490 \sin^2 \theta_c$$



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



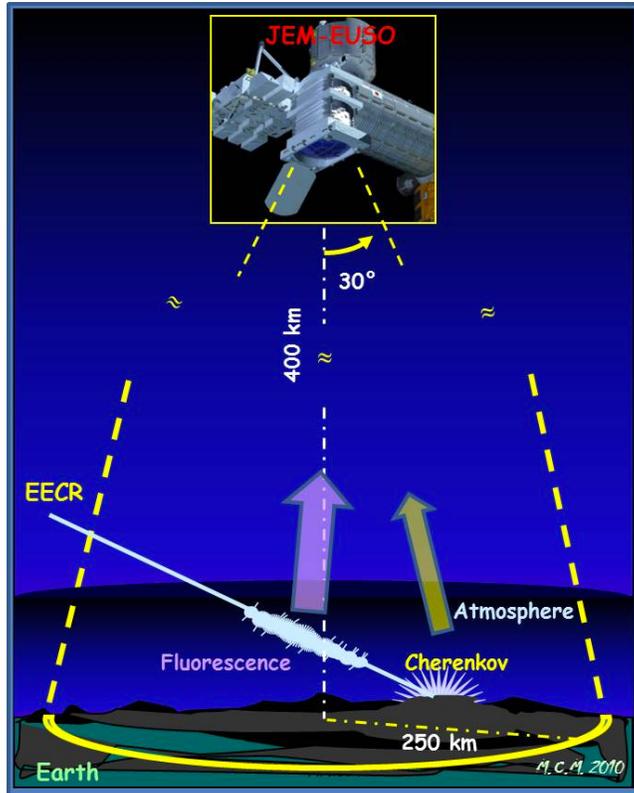
Air, sea-water or ice are exploited as radiators in some astroparticle physics experiments (see next page)

Example of radiators

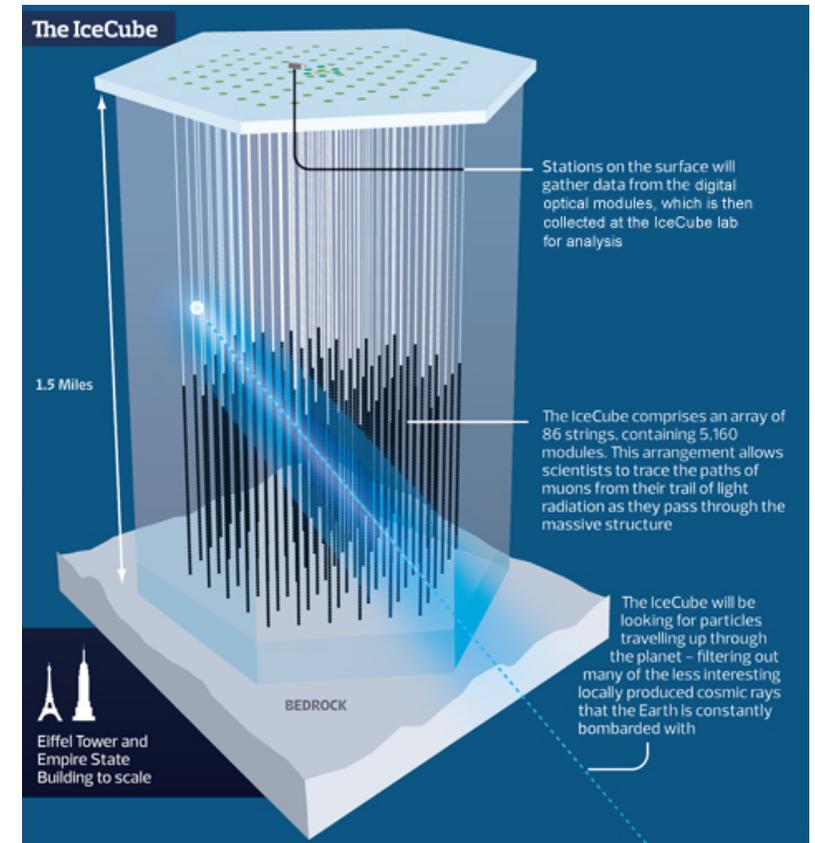
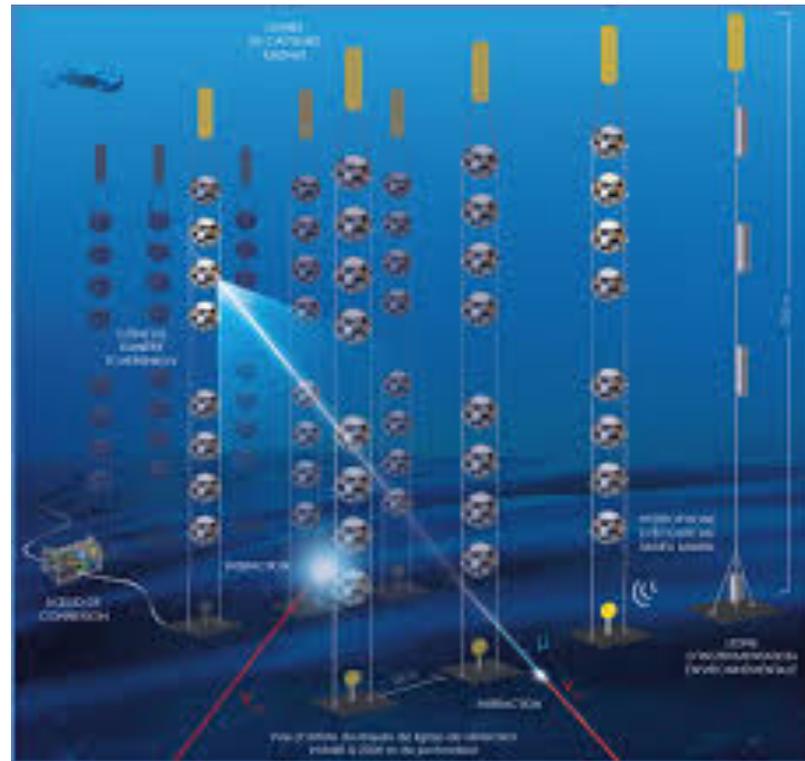
Medium	n-1	$\frac{\gamma_{th} = 1}{\sqrt{1 - \beta_{th}^2}}$	Photons/m
He (STP)	3.5 10 ⁻⁵	120	3
CO ₂ (STP)	4.1 10 ⁻⁴	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

Cherenkov detectors

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



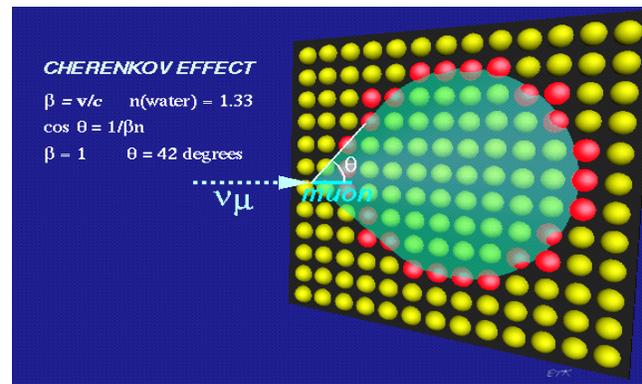
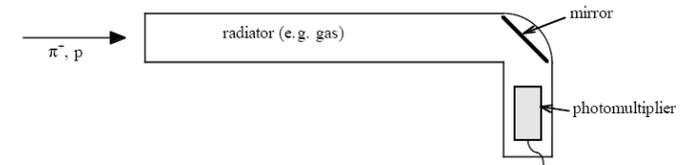
Antares / KM3Net



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)

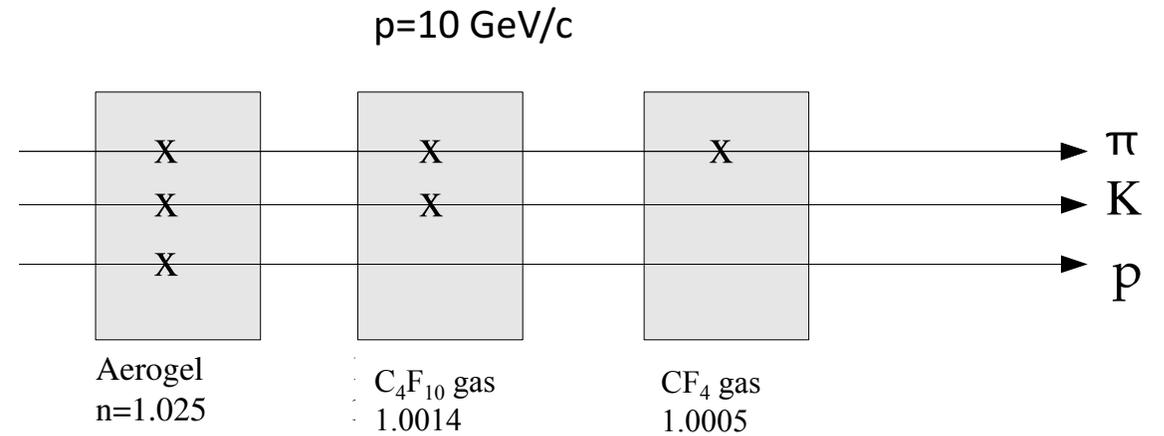
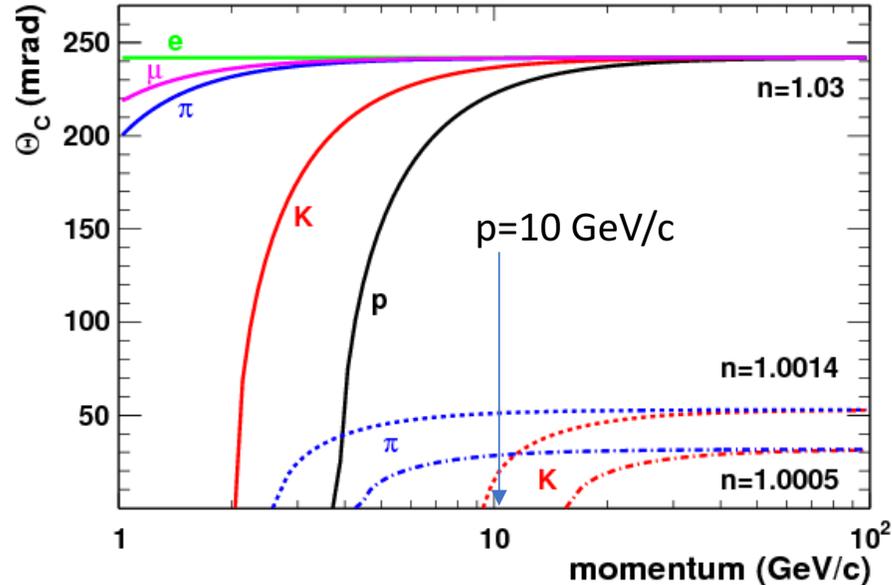


Cherenkov detectors: threshold counters

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



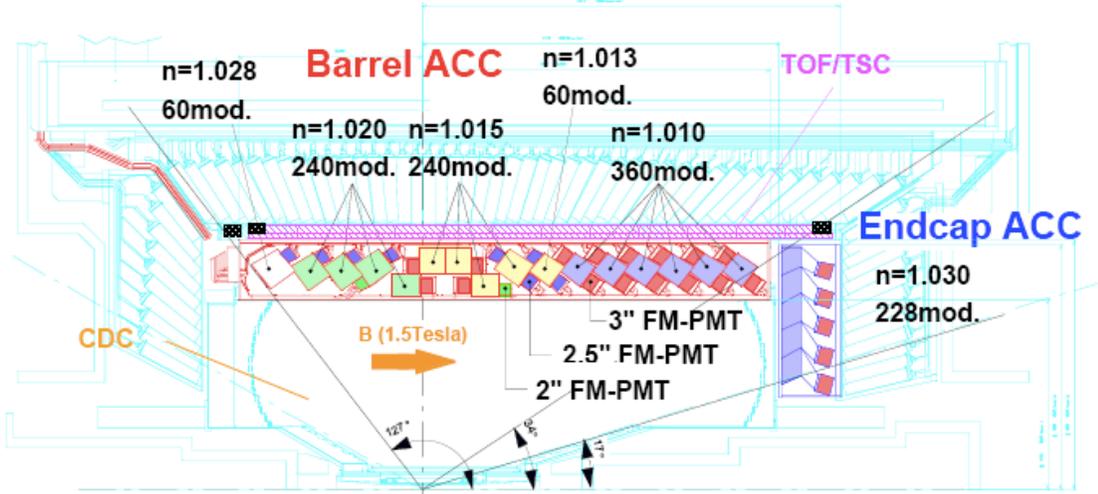
- Improved version: use number of photons (or calibrated pulse) to discriminate particle types.

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

Threshold Cherenkov detectors: examples

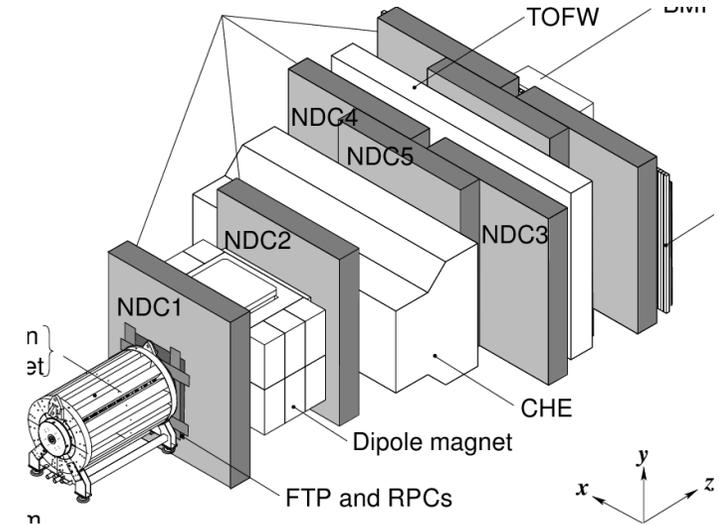
BELLE@KEK (1999-2010)

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

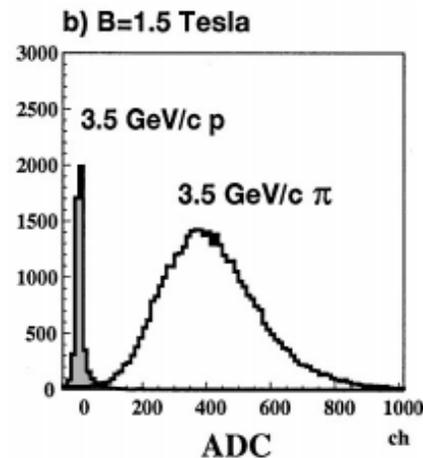


HARP@CERN (2000-2002)

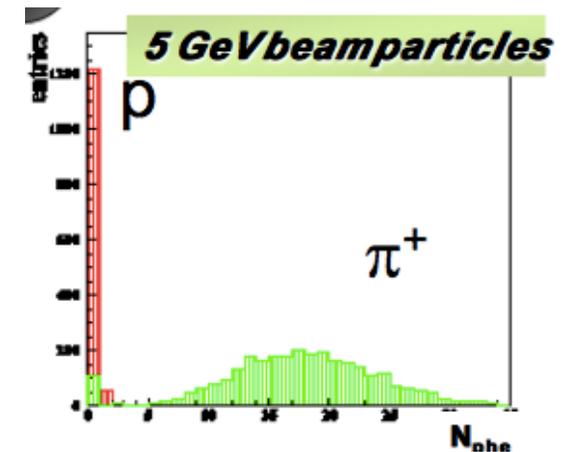
measurement of hadron production on different targets



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



31 m³ filled with C₄F₁₀ (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

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

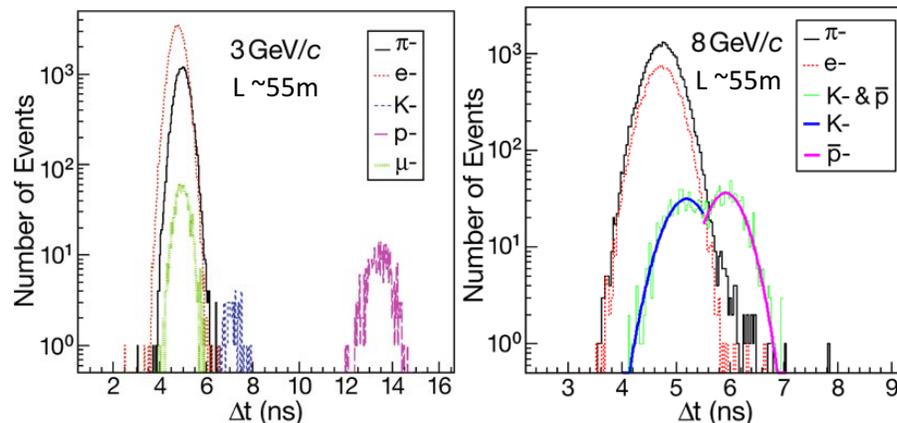
$$= \frac{L}{pc^2} (E_1 - E_2) = \frac{L}{pc^2} \left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4} \right)$$

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

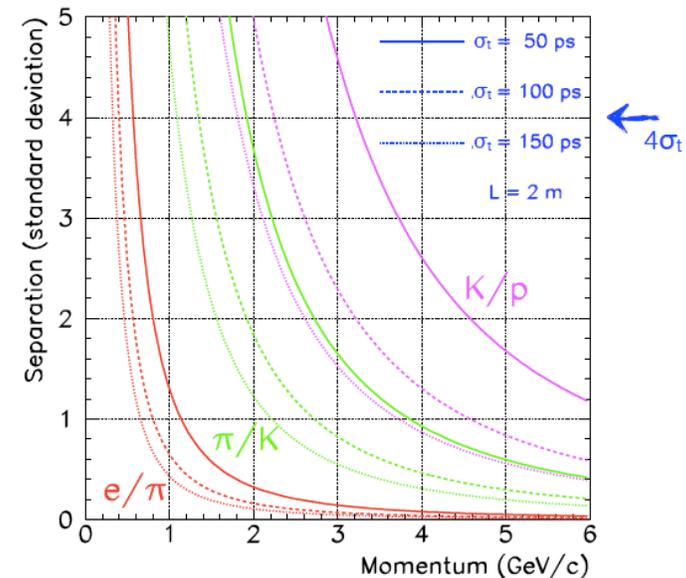
$$\Delta t \approx \frac{L}{pc^2} \left[\left(pc + \frac{m_1^2c^4}{2pc} \right) - \left(pc + \frac{m_2^2c^4}{2pc} \right) \right]$$

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

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



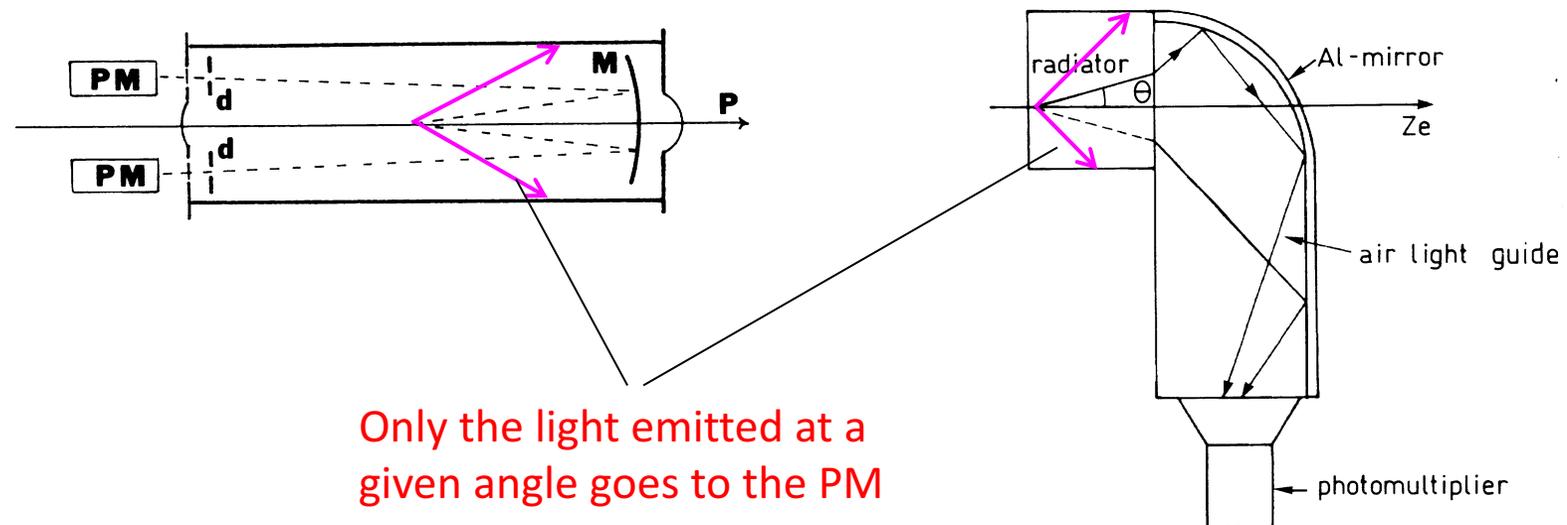
σ_t : time resolution of the detector



Cherenkov detectors: differential counters

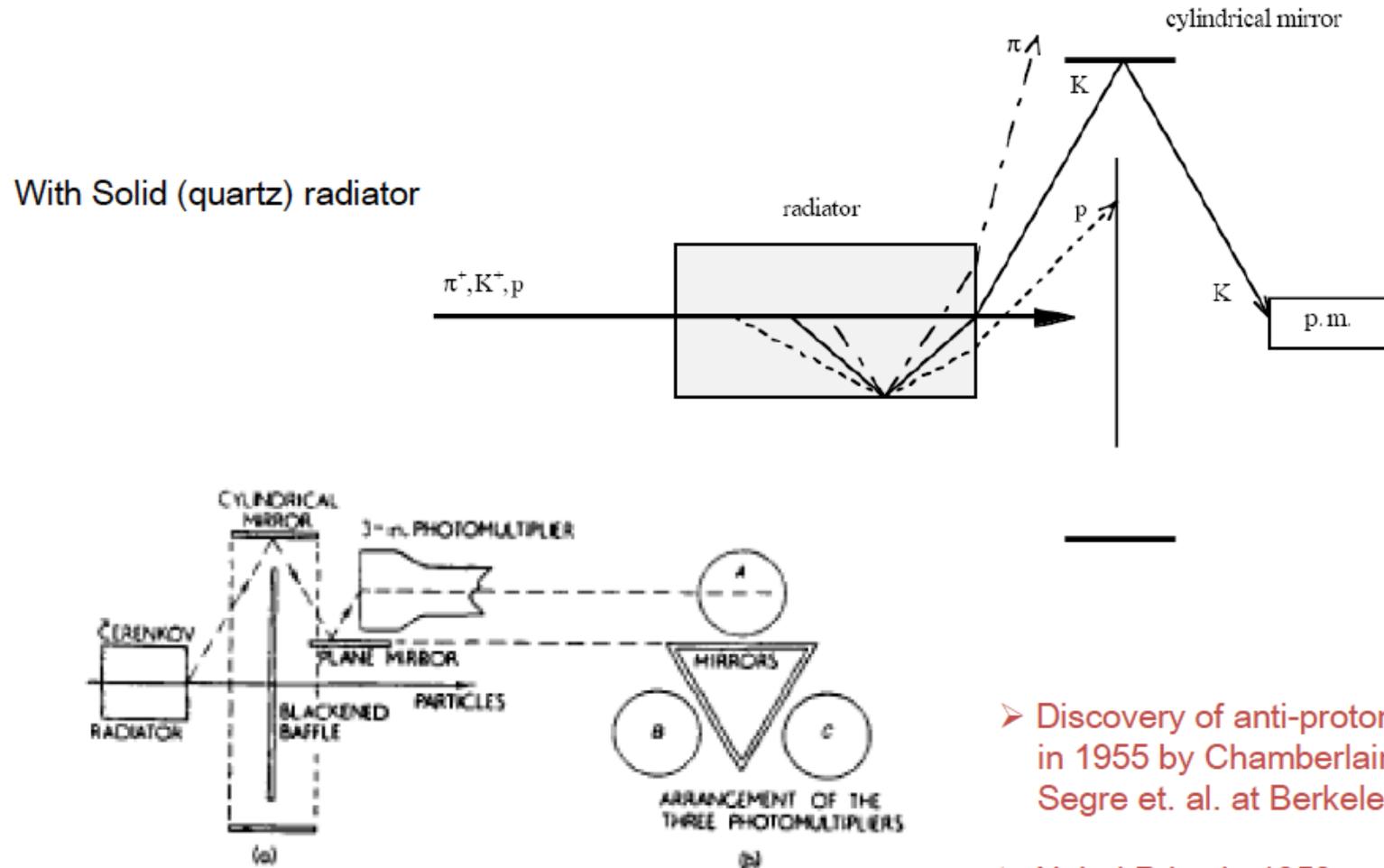
For a given momentum, $\cos\theta$ is function of the mass

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



Differential Cherenkov detectors : example

slide from
S. Easo



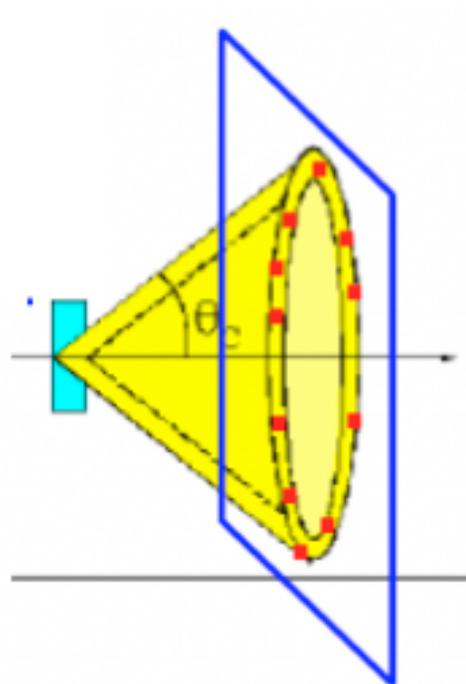
- Discovery of anti-proton in 1955 by Chamberlain, Segre et. al. at Berkeley.
- Nobel Prize in 1959

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

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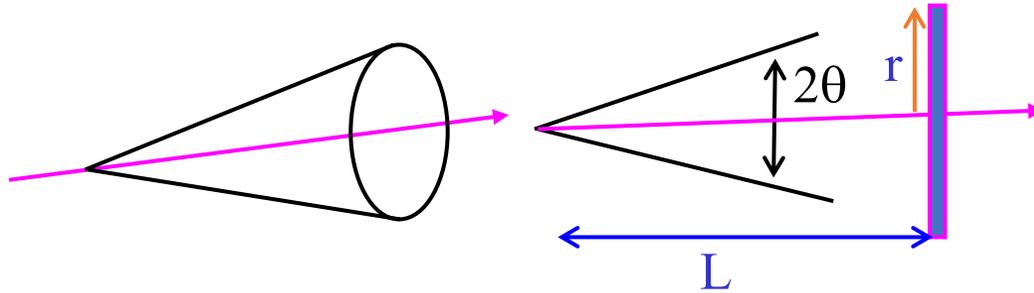
Cherenkov detectors: ring imaging

- Intercept the Cherenkov cone with a plane \rightarrow ring
- Measure both the Cherenkov angle and the number of detected photons
(\rightarrow better resolution on β than equivalent threshold or differential detectors)
- Allows for particle identification over large surfaces
- Requires photodetectors with single photon identification capabilities



Cherenkov radiation and particle identification

RICH and PID



$$r = L \times \tan\theta$$

CHERENKOV EFFECT

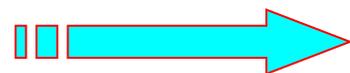
$\beta = v/c$ $n(\text{water}) = 1.33$
 $\cos \theta = 1/\beta n$
 $\beta = 1$ $\theta = 42 \text{ degrees}$

v_μ μon

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

	$\theta(\text{deg})$	$r(\text{m})$
π	43.5	0.95
K	36.7	0.75
P	9.95	0.18

Very good $\pi/K/p$ separation



Particle ID

Tom Ypsilantis



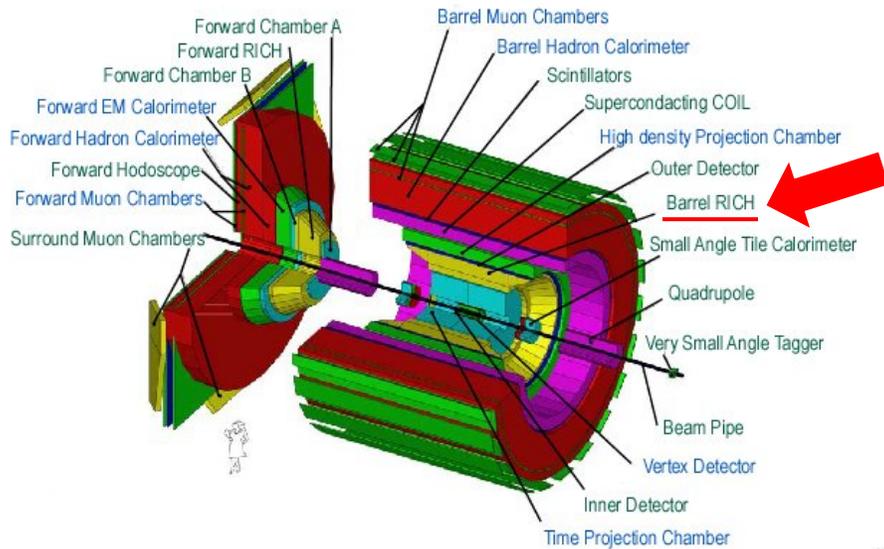
RICH: examples

DELPHI@LEP (CERN, 1988-2000)

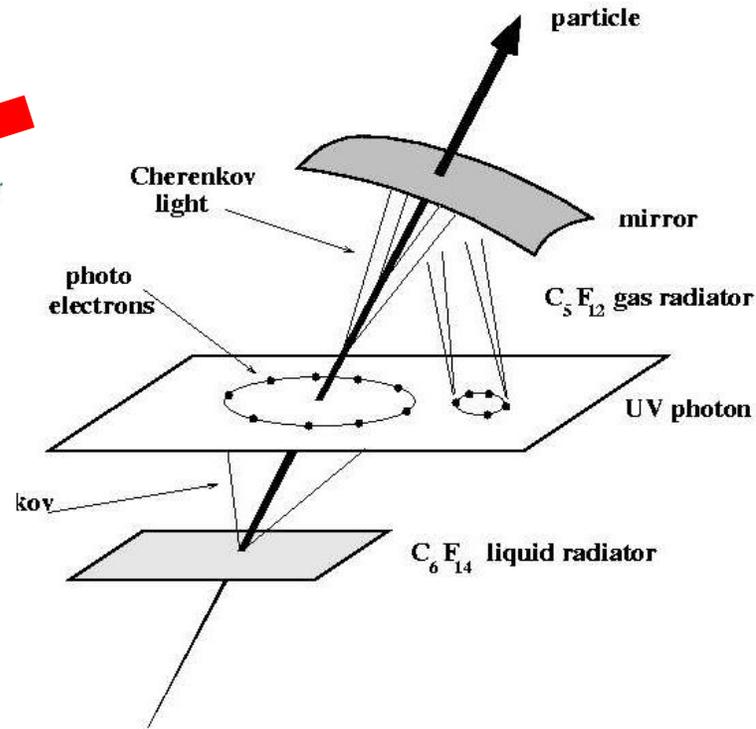
”a Detector with Lepton, Photon and Hadron Identification”

multi-purpose detector for precision EW measurements in e^+e^- collisions at $\sqrt{s}=91\text{-}200$ GeV

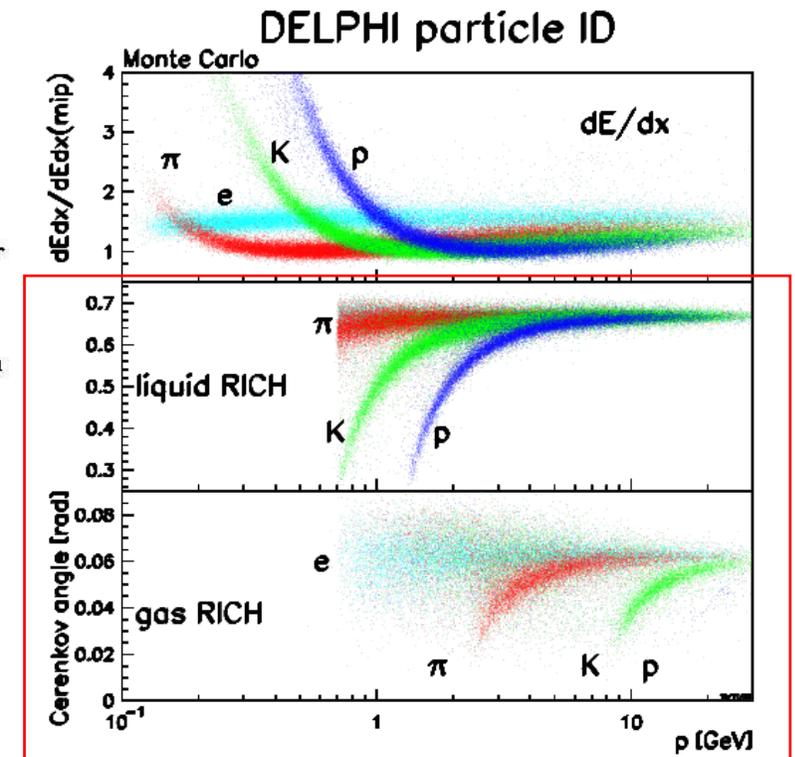
→ one of the first large-size RICH detectors



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



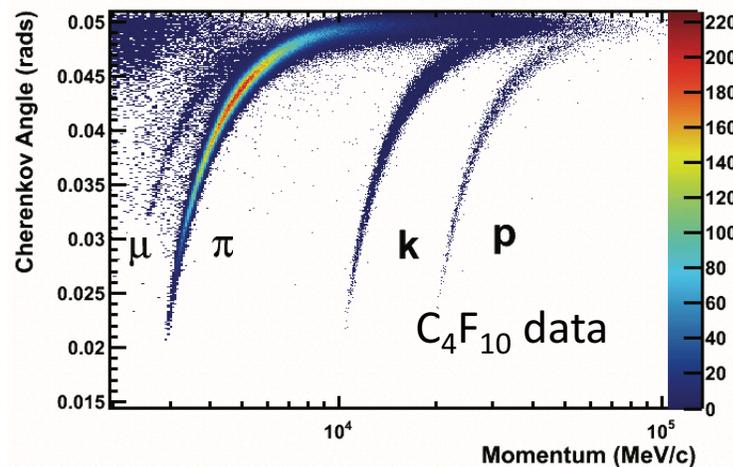
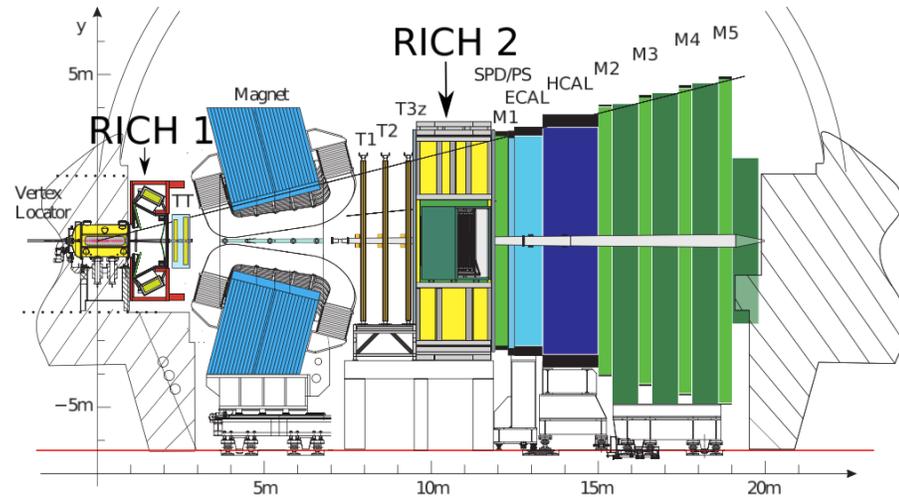
→ $\pi/K/p$ separation over a large momentum range: 0.7-45 GeV/c



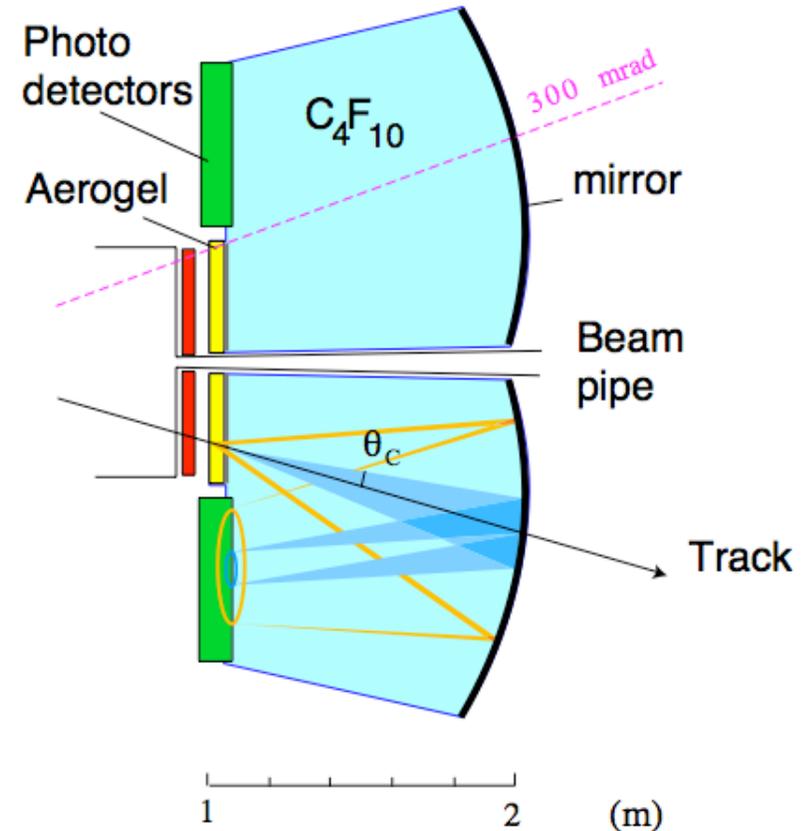
RICH: examples

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+C₄H₁₀/CF₄)
- Photodetectors: HPDs (see next slide)



RICH: examples

LHCb@LHC (CERN)

Hybrid Photon Detectors (HPDs)

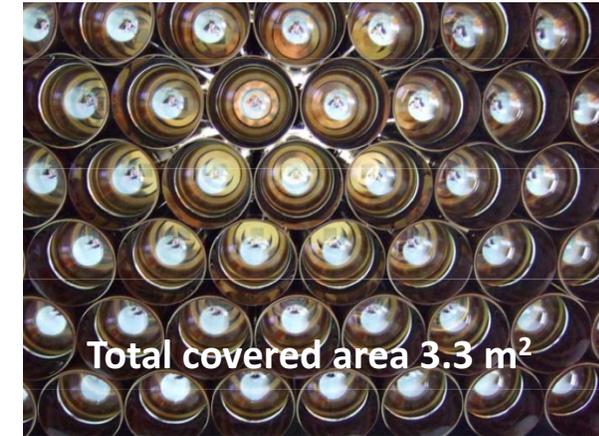
Photoelectric effect +

focusing of photoelectrons to Si sensors

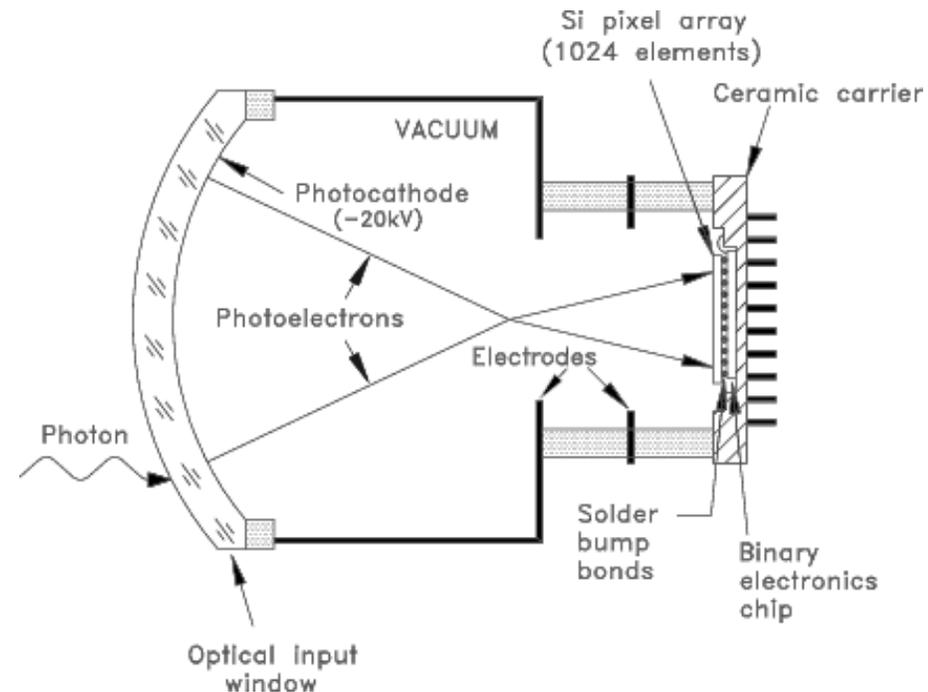
→ Accurate measurement of space and time of photons

→ Short flight path of PEs: reduced sensitivity to magnetic field

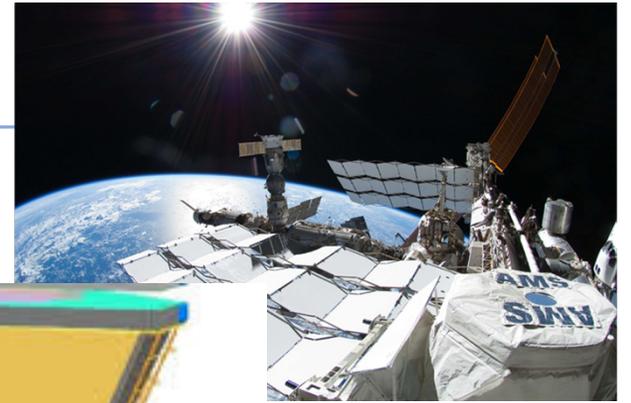
→ Can detect single photons



Total covered area 3.3 m²



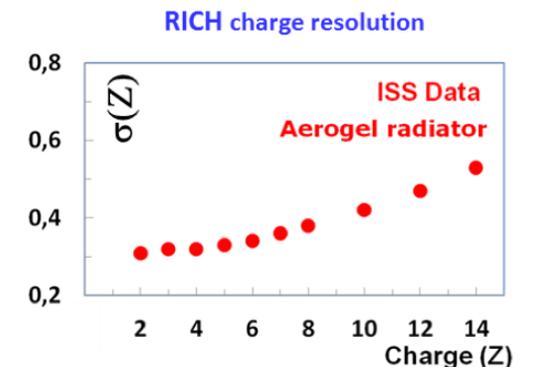
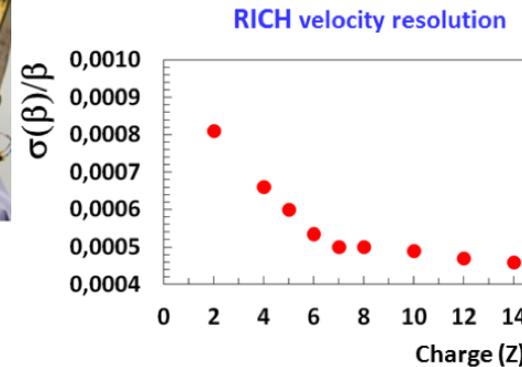
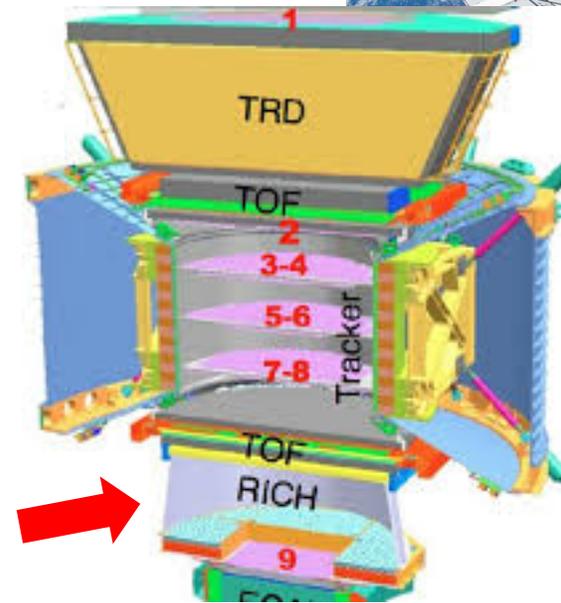
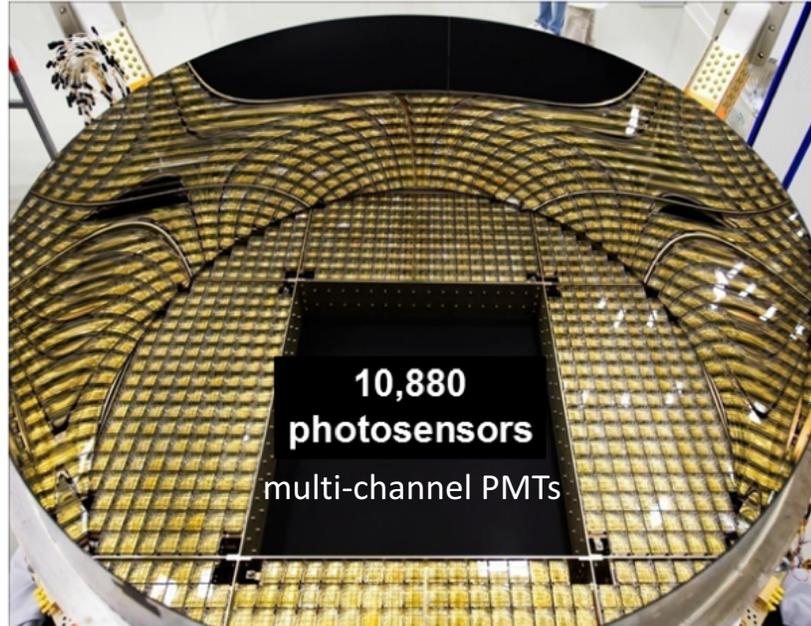
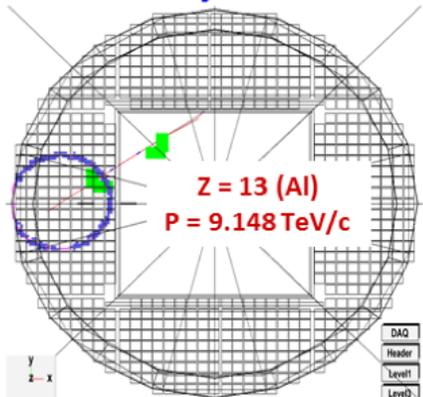
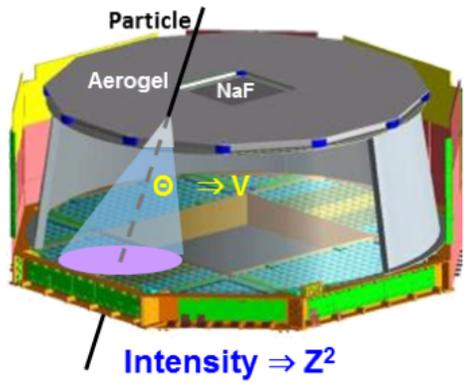
RICH: examples



AMS Ring Imaging Cherenkov (RICH)

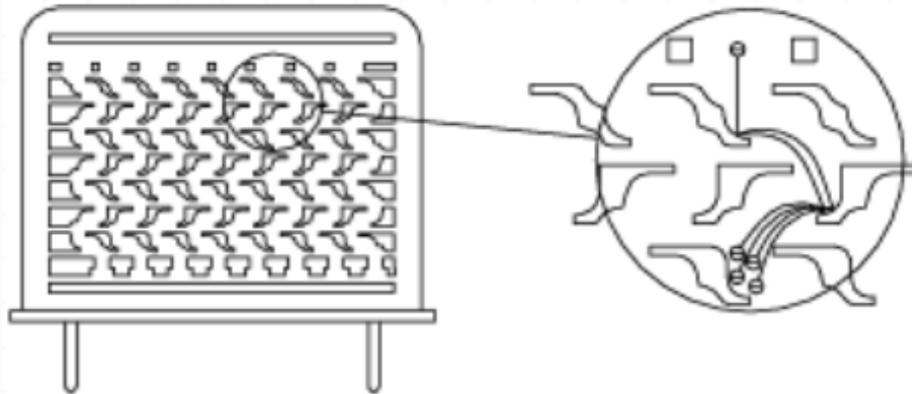
Measurement of Nuclear Charge (Z^2) and its Velocity to 1/1000

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

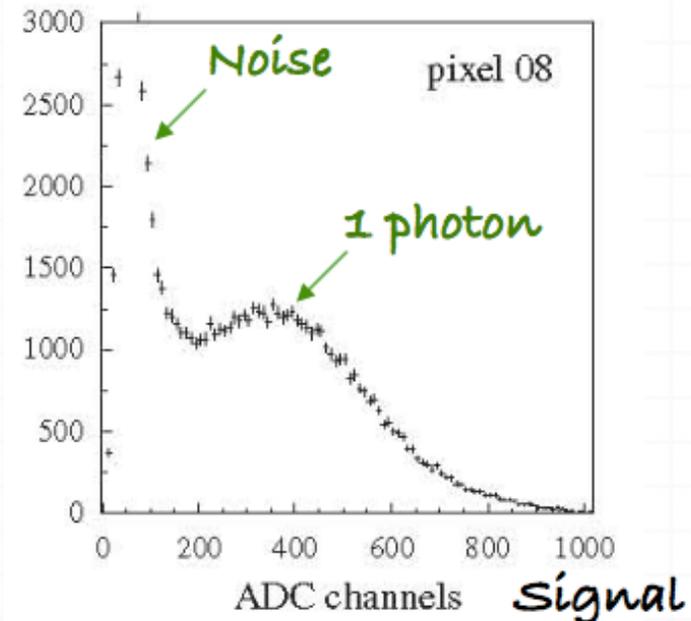
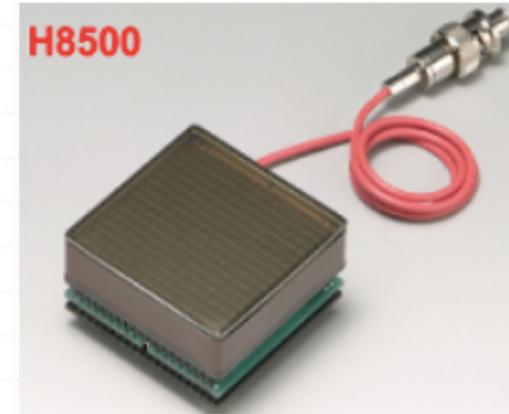


Multi-Anode PMTs

- **Multianode** photomultipliers are a marvel of miniaturization → up to 64 pixels in a single tube, each with size $\sim 2 \times 2 \text{ mm}^2$
- 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:

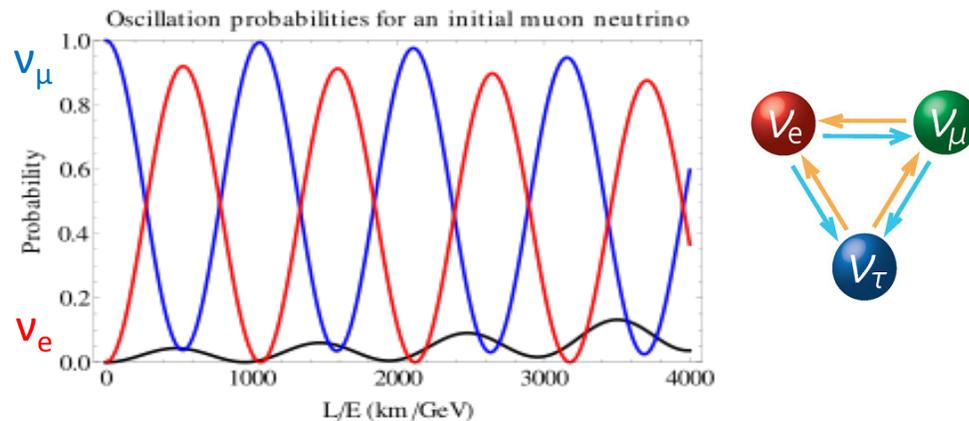
3 flavours (ν_e, ν_μ, ν_τ)

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 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



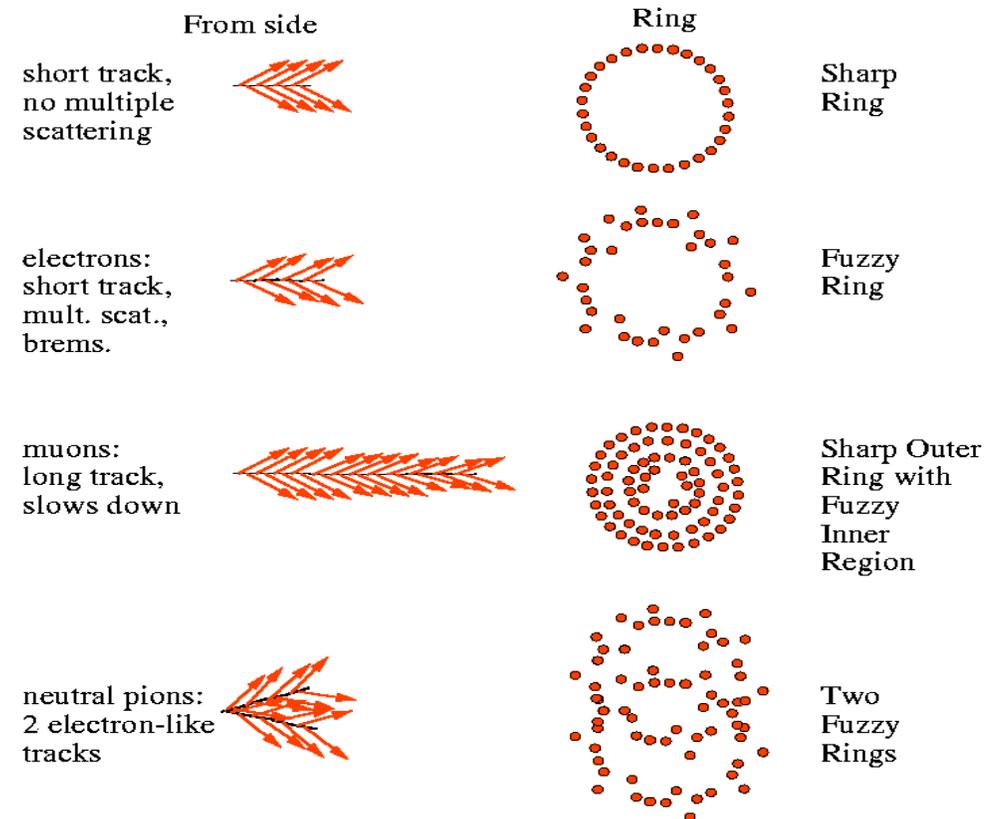
Arthur B. McDonald
Sudbury Neutrino Observatory
Collaboration
Queen's University, Canada

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

Cherenkov PID in neutrino experiments

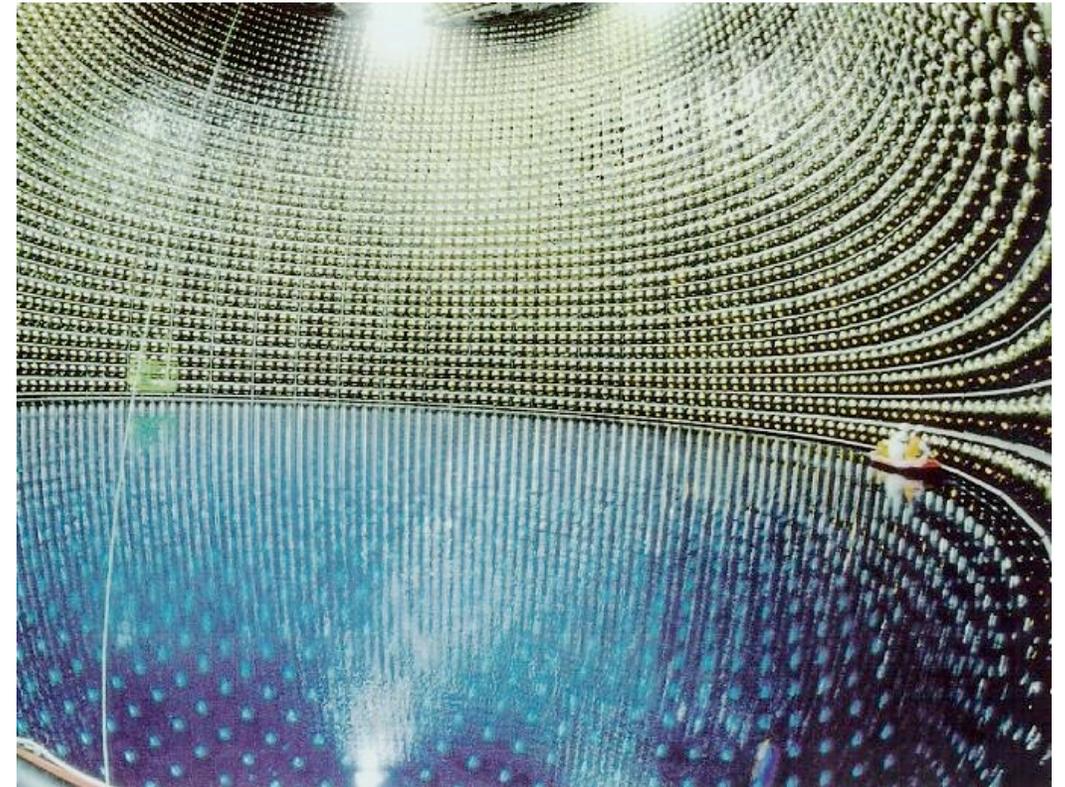
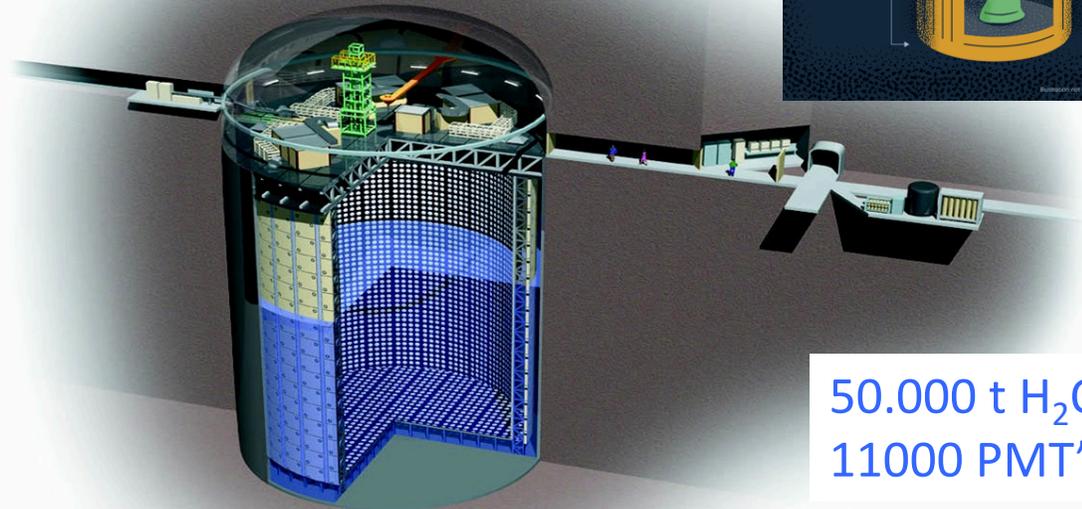
Identification of particles produced in neutrino interactions:
Based on the characteristics of the Cherenkov cone

Particle ID in a Cerenkov Detector:

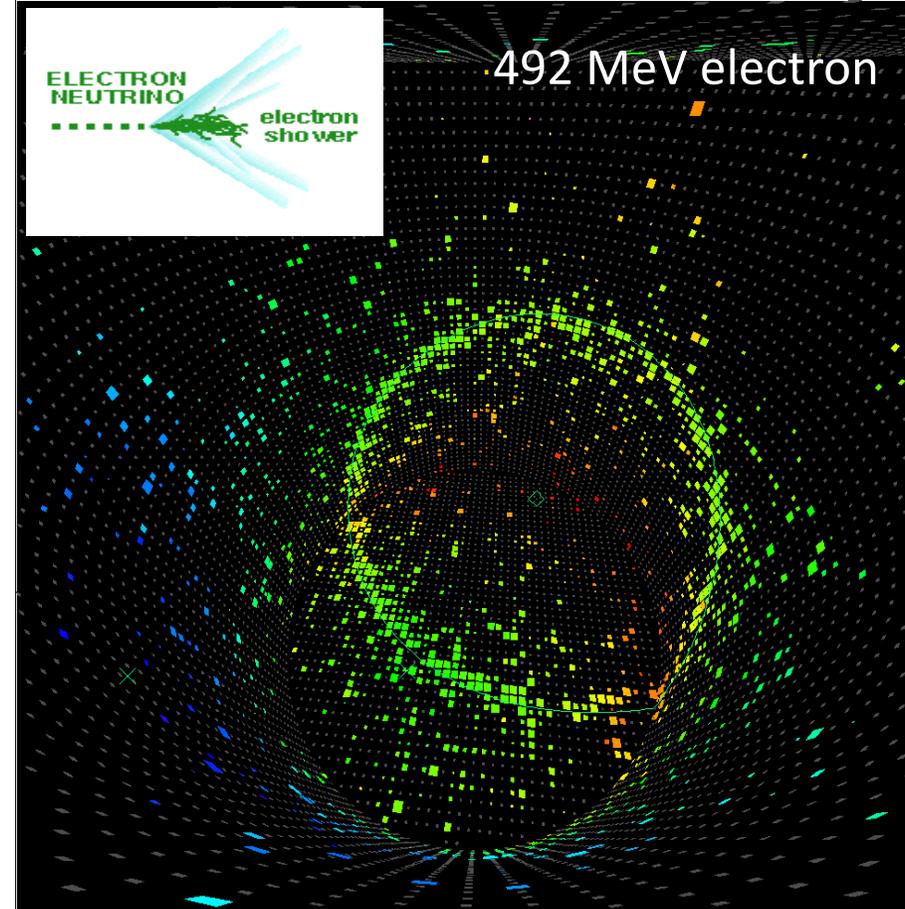
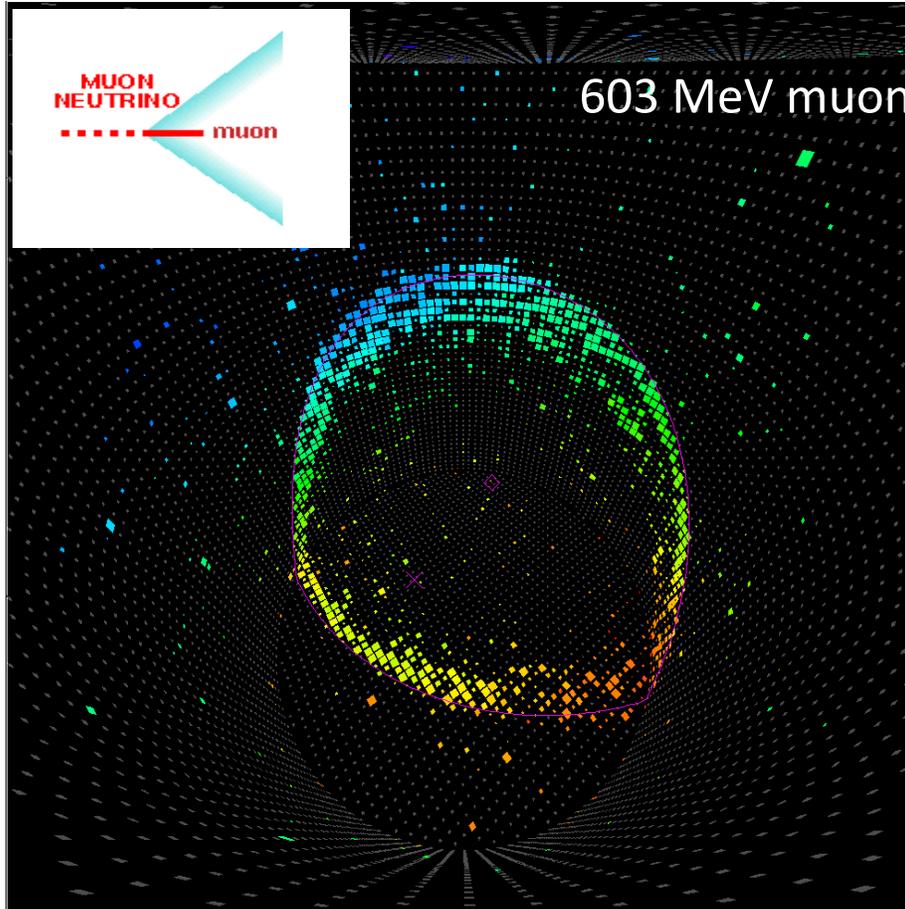
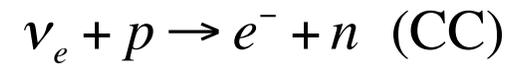
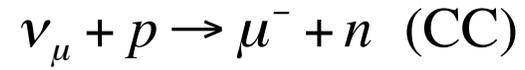


Example: SuperKamiokaNDE

Kamioka mine, Japan
~1000 m under Mount Ikeno



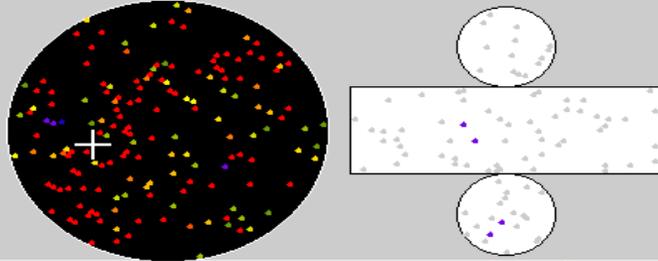
Example: SuperKamiokaNDE



Example: SuperKamiokaNDE

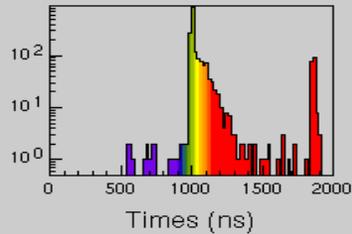
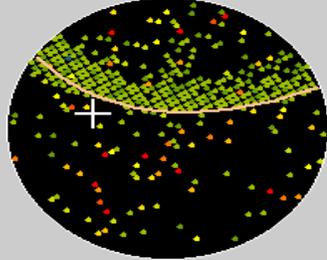
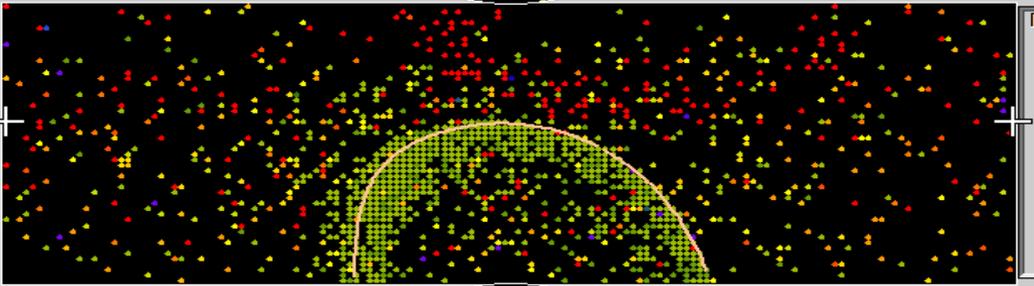
Super-Kamiokande

Run 4234 Event 367257
 97-06-16:23:32:58
 Inner: 1904 hits, 5179 pE
 Outer: 5 hits, 6 pE (in-time)
 Trigger ID: 0x07
 D wall: 885.0 cm
 FC mu-like, $p = 766.0$ MeV/c



Resid(ns)

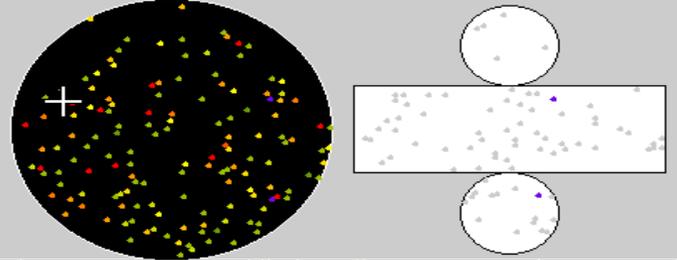
- > 137
- 120- 137
- 102- 120
- 85- 102
- 68- 85
- 51- 68
- 34- 51
- 17- 34
- 0- 17
- -17- 0
- -34- -17
- -51- -34
- -68- -51
- -85- -68
- -102- -85
- <-102



ν_μ

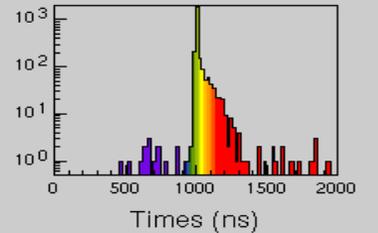
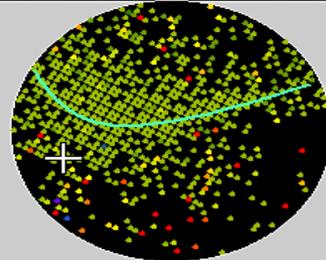
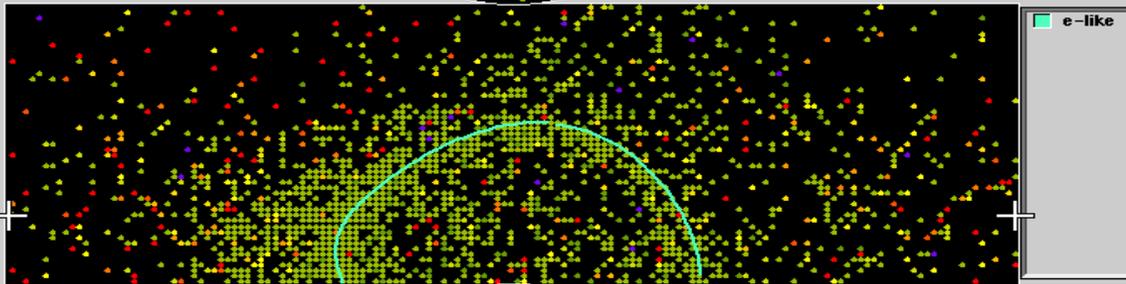
Super-Kamiokande

Run 4268 Event 7899421
 97-06-23:03:15:57
 Inner: 2652 hits, 5741 pE
 Outer: 3 hits, 2 pE (in-time)
 Trigger ID: 0x07
 D wall: 506.0 cm
 FC e-like, $p = 621.3$ MeV/c



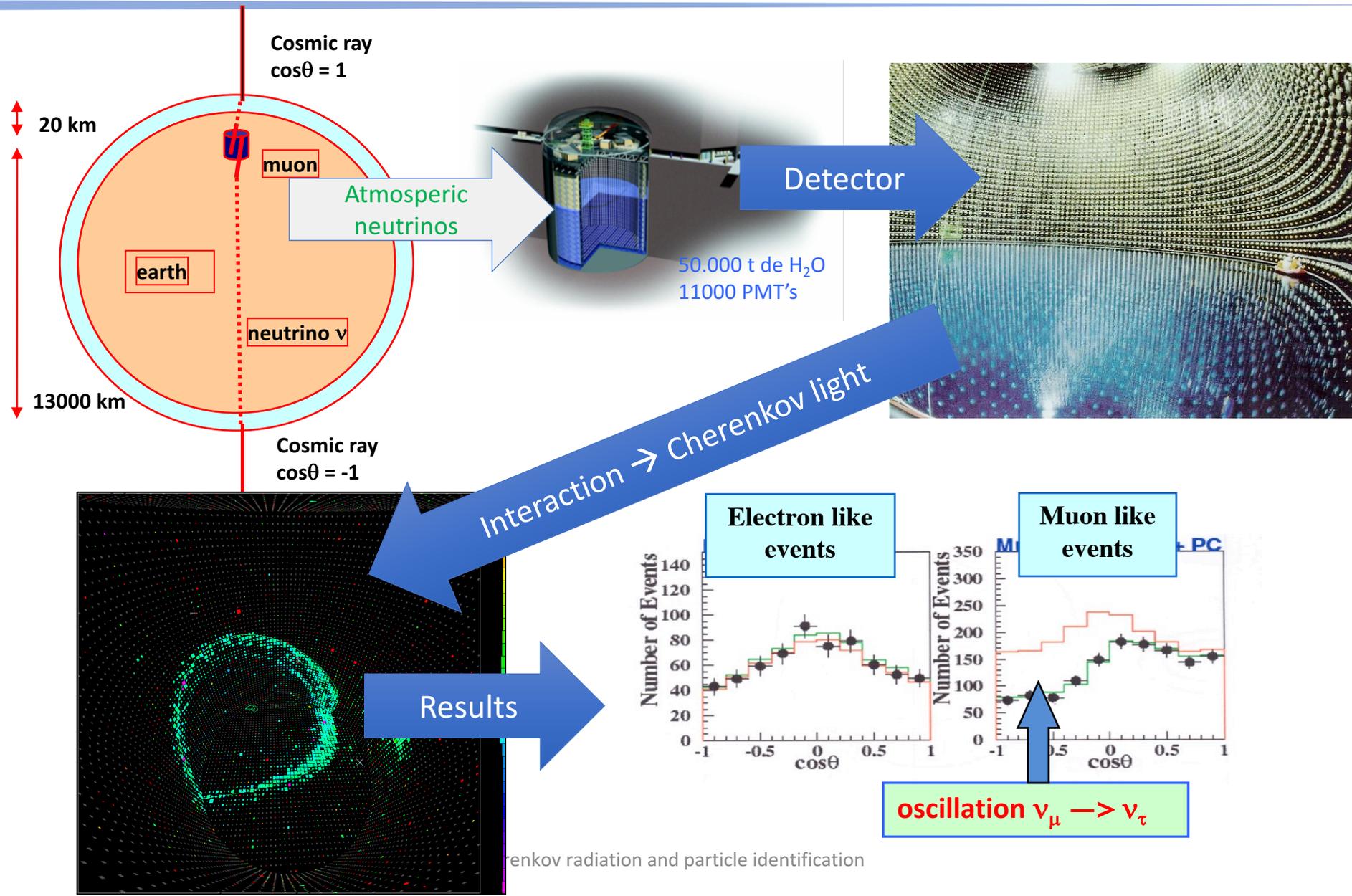
Resid(ns)

- > 137
- 120- 137
- 102- 120
- 85- 102
- 68- 85
- 51- 68
- 34- 51
- 17- 34
- 0- 17
- -17- 0
- -34- -17
- -51- -34
- -68- -51
- -85- -68
- -102- -85
- <-102

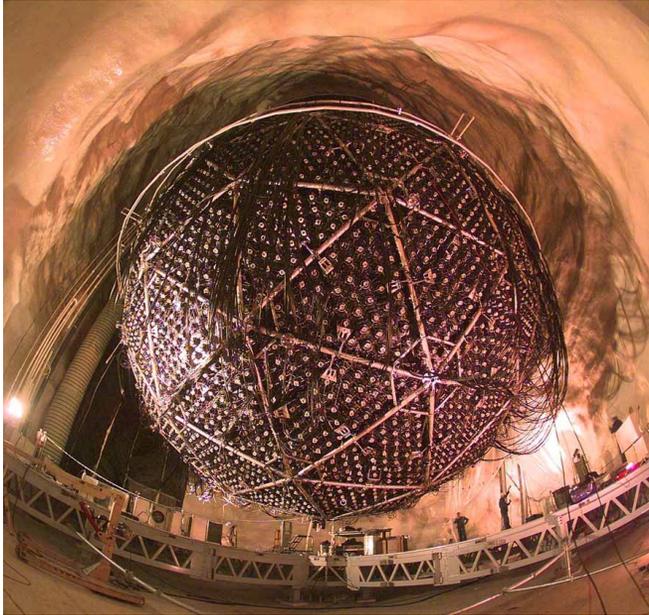


ν_e

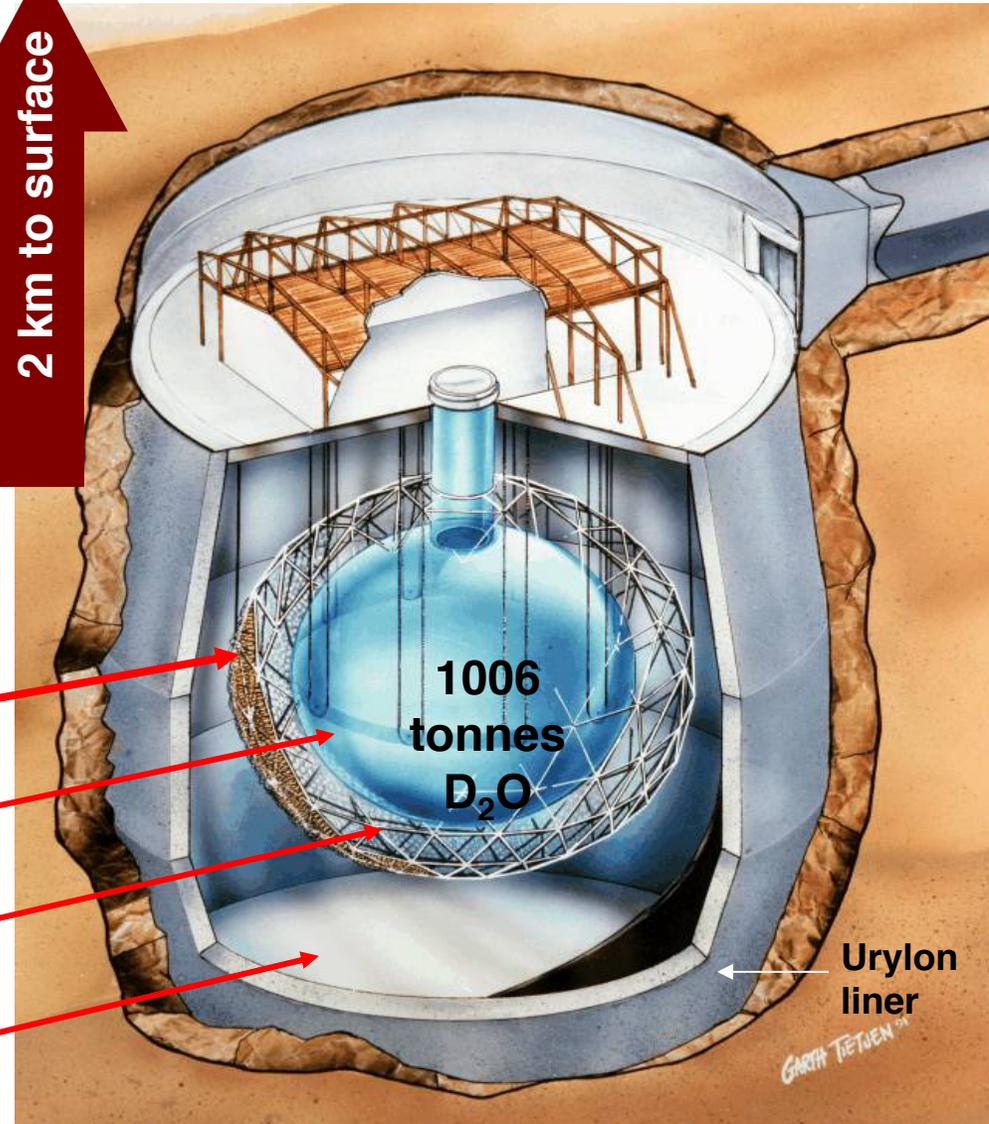
Example: SuperKamiokaNDE



Example: Sudbury Neutrino Observatory (SNO)



2 km to surface



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

12.01m dia. acrylic vessel

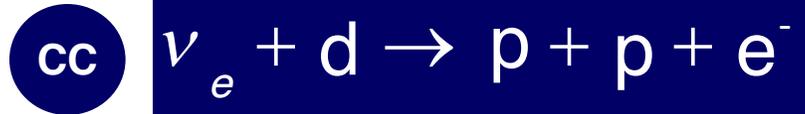
1700 tonnes of inner shielding H₂O

5300 tonnes of outer shielding H₂O

1006
tonnes
D₂O

Urylon
liner

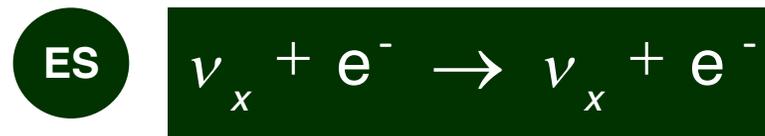
Example: SNO



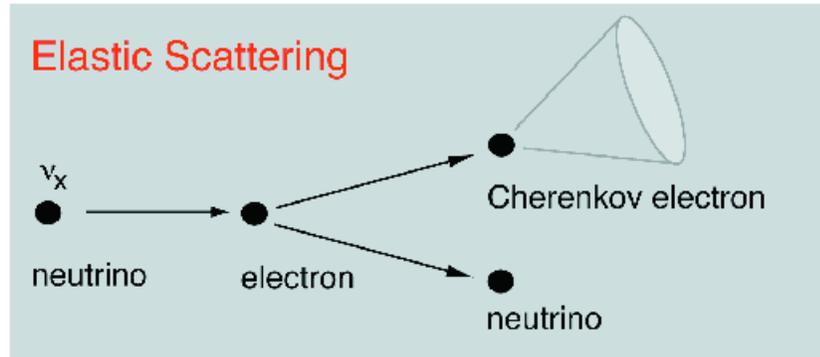
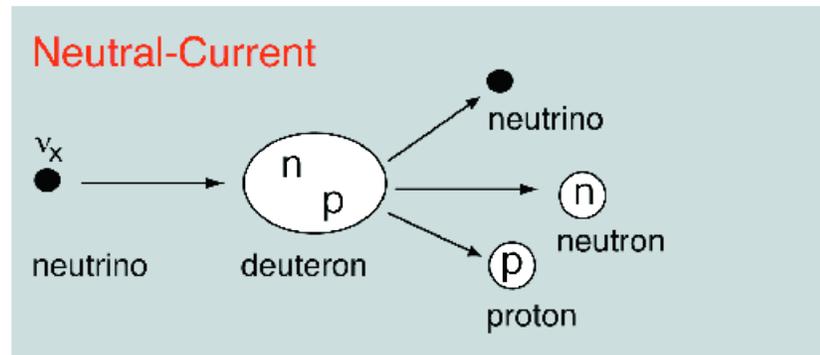
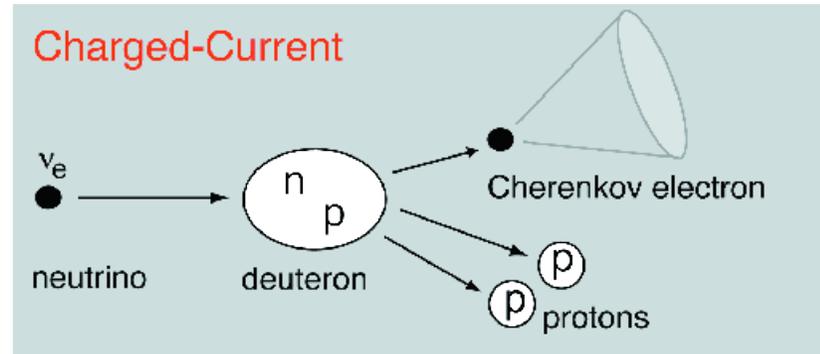
- Measurement of ν_e energy spectrum
- Weak directionality



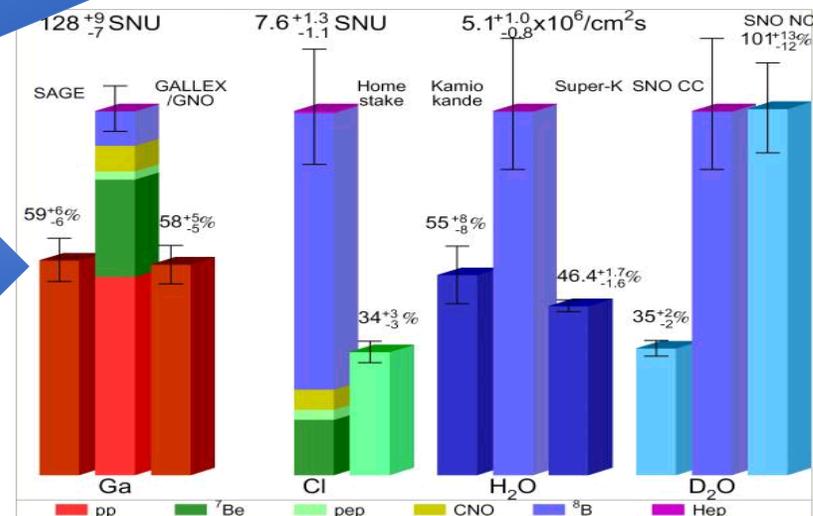
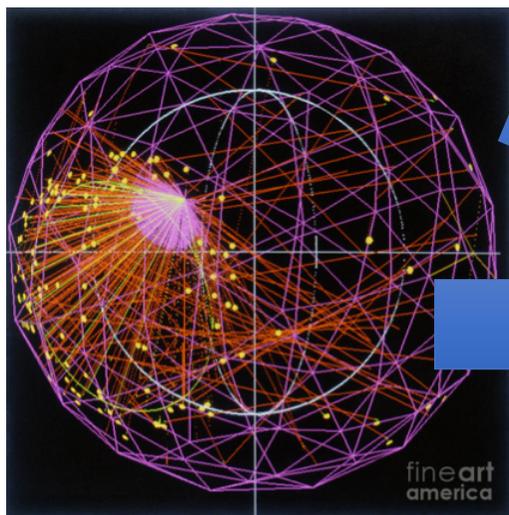
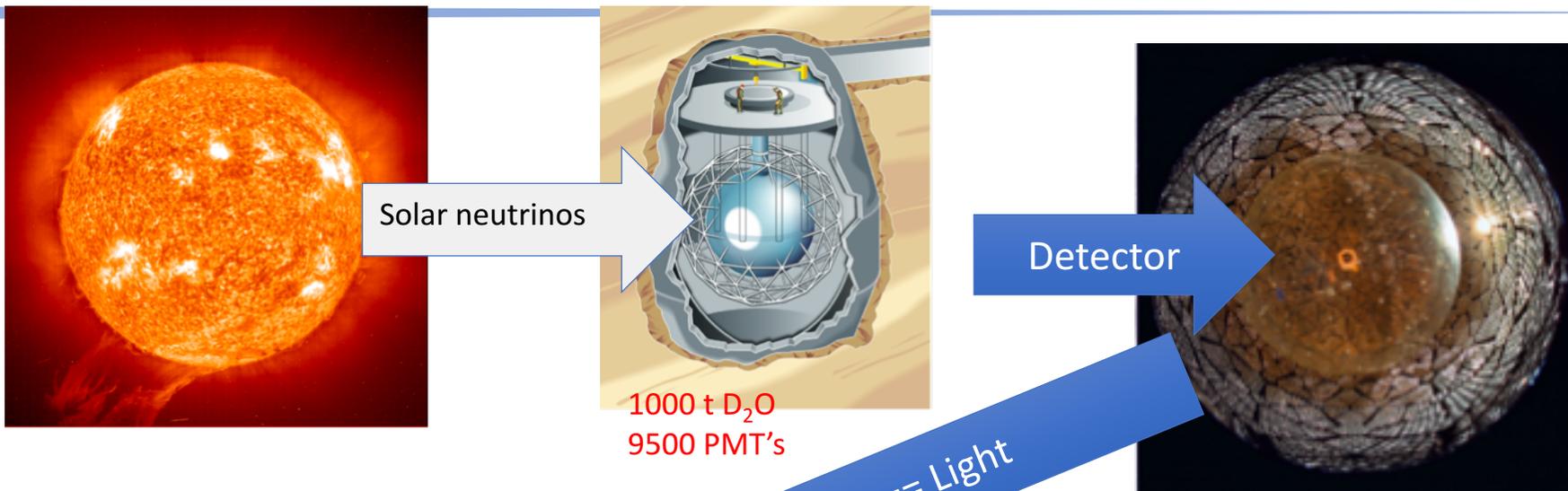
- Measure total ^8B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



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

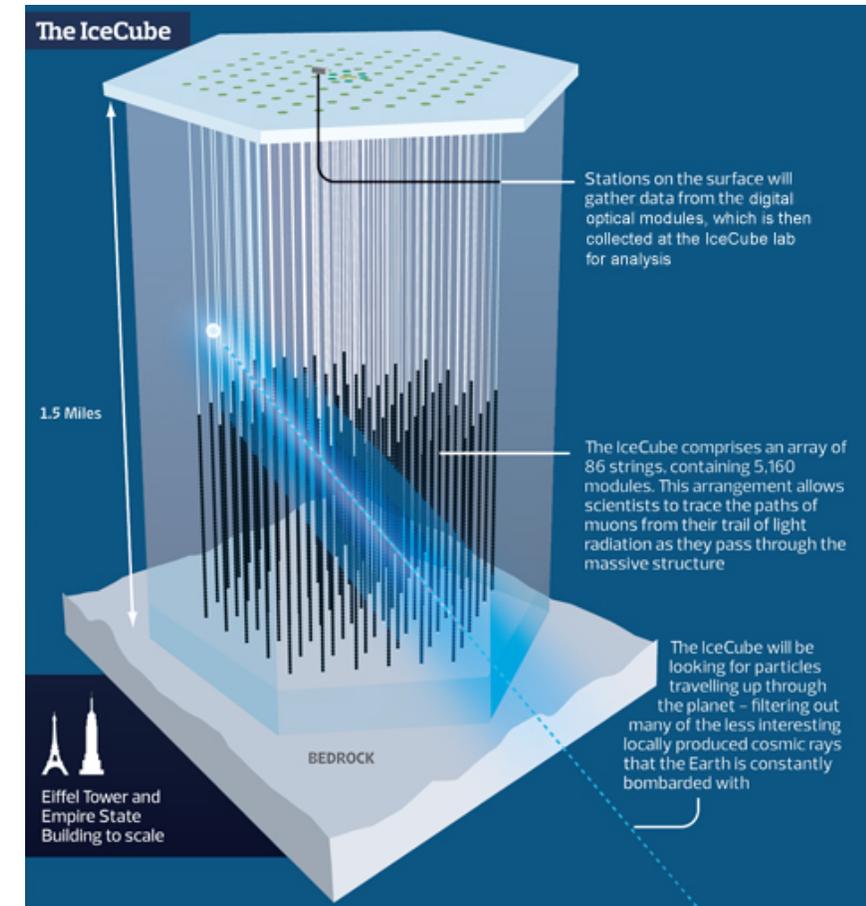
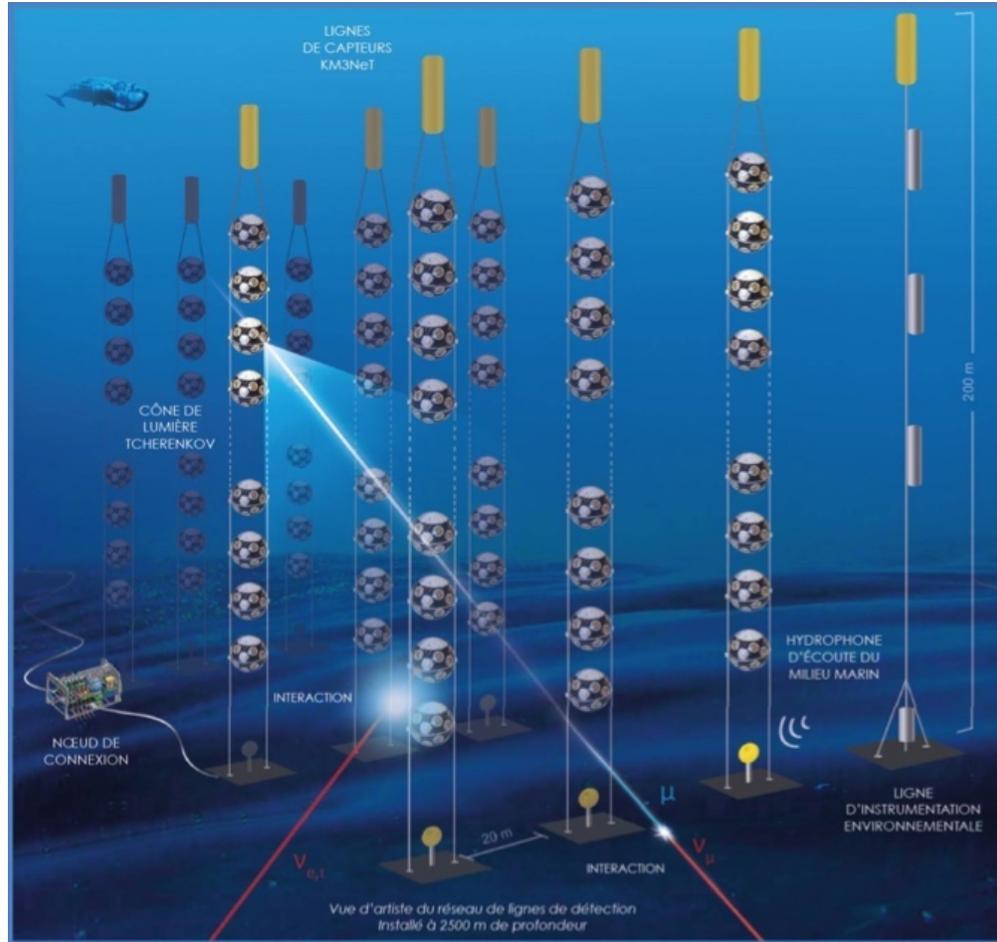


Example: SNO



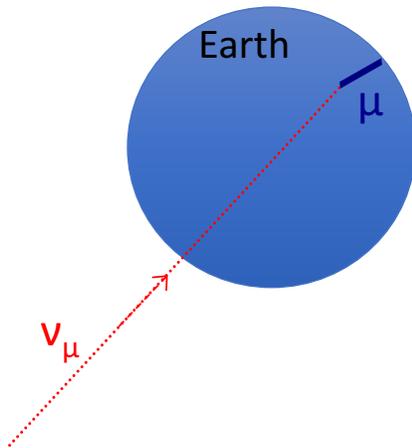
Cherenkov detectors for astroparticle physics

Detection of very high energy neutrinos in sea water / ice
KM3Net / IceCube



Cherenkov detectors for astroparticle physics

Detection of very high energy neutrinos in sea water / ice
KM3Net / IceCube



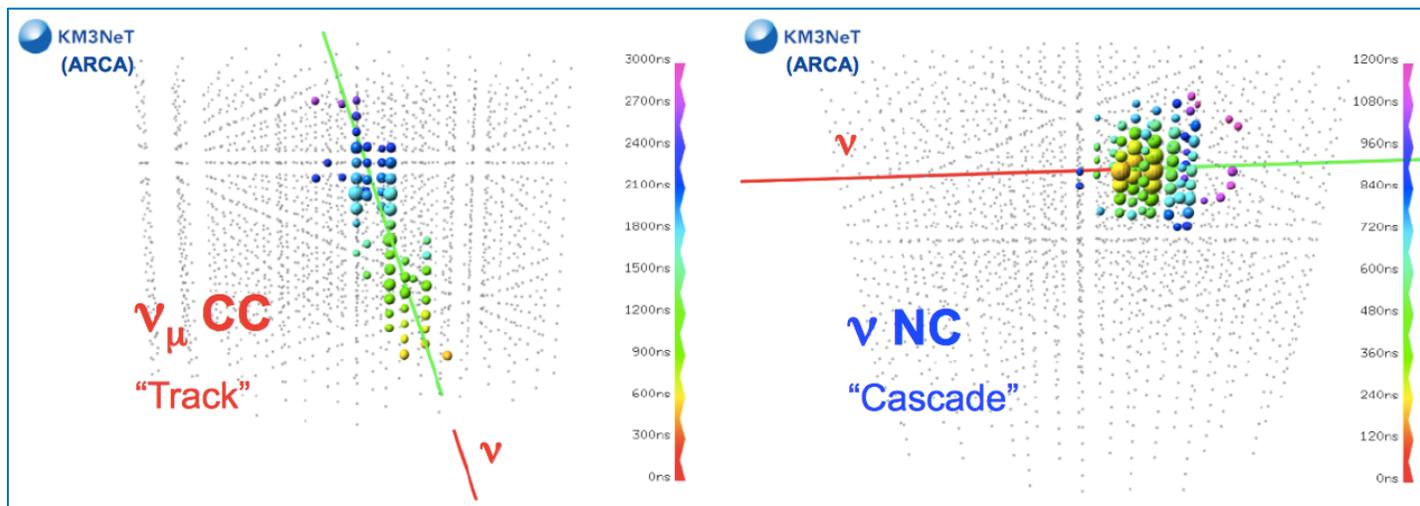
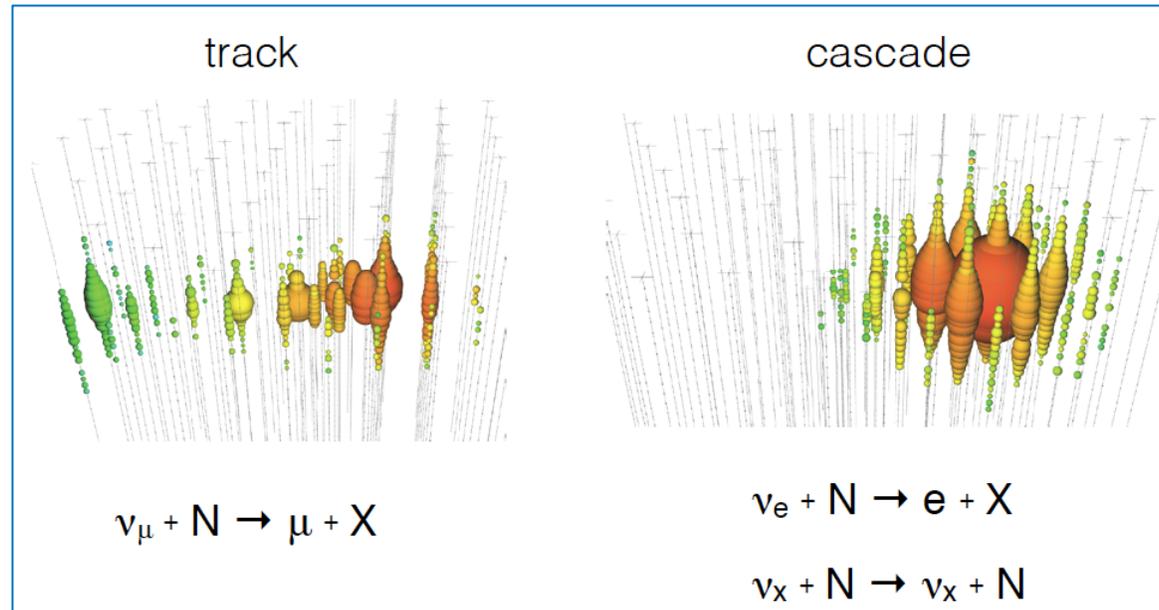
KM3NeT
6210 Digital Optical Modules (DOMs)
43 cm diameter, contains 31 3-inch (7.6 cm)
PMTs with supporting electronics, and is
connected to shore via a high-bandwidth
optical network



[see some neutrino interactions here...](#)

Cherenkov detectors for astroparticle physics

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).

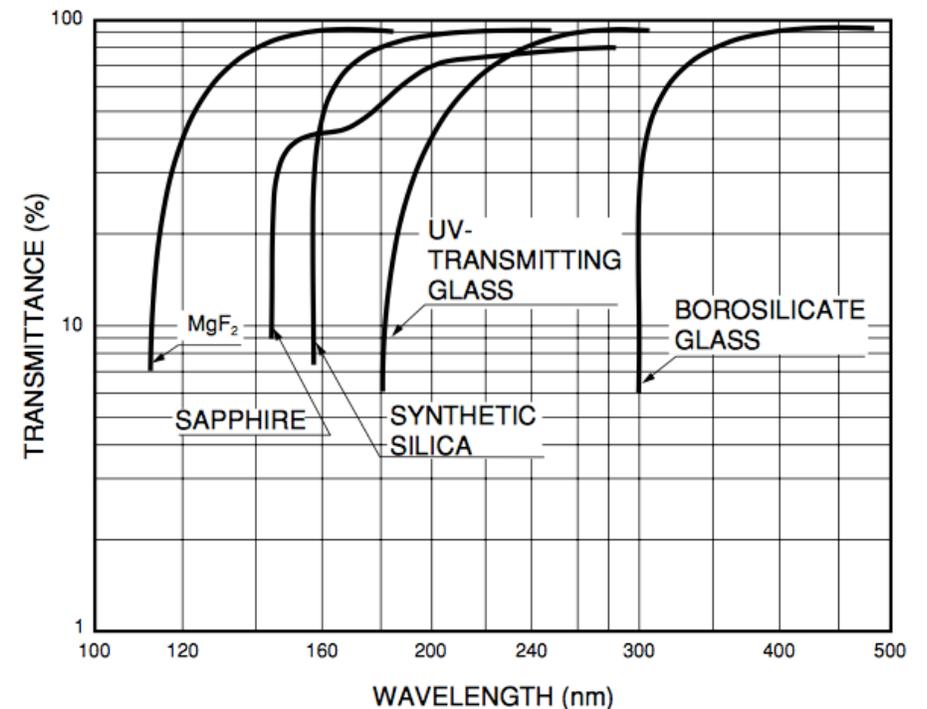
Exercise 2

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.



(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

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

2) uniform distribution in a cylindrical volume

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

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

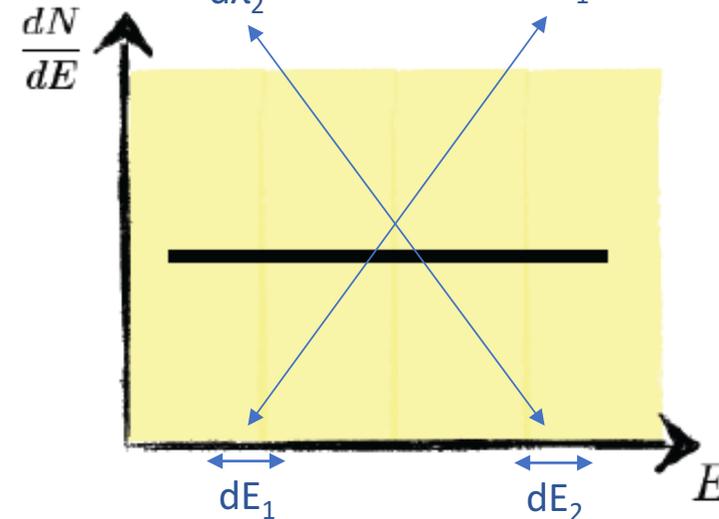
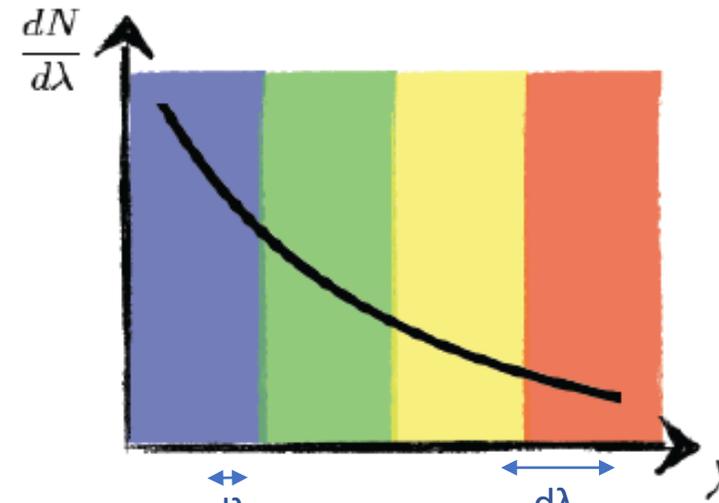
(Appendix: Change of variable in a PDF)

Cherenkov radiation photon spectra:

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

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

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



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

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