III. Physikalisches Institut A

RWTH AACHEN UNIVERSITY

Experimental Techniques in Particle Physics (WS 2020/2021)

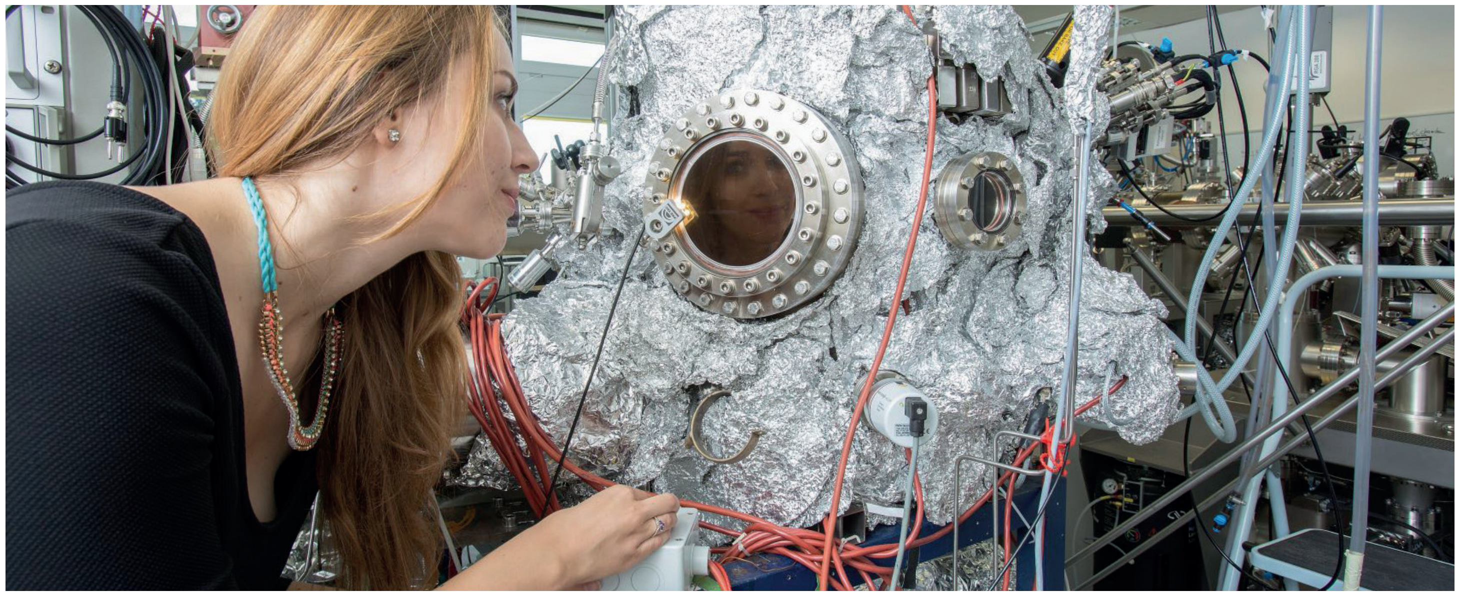
Calorimeters and Cherenkov Detectors

Prof. Alexander Schmidt

19.01.2021

SUMMER STUDENTS.

DESY International Summer Student Program 2020
21 July to 10 September



DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics.
Each summer DESY offers students in physics, related natural science disciplines or computing the opportunity to participate in its research activities. About 100 students from all over the world take part in DESY's research and attend the lecture program.

www.desy.de/summerstudents

Photon Science
Summer students join groups at DESY and European XFEL which address fundamental and applied questions in the fields of physics, biology, chemistry, crystallography, materials and geological sciences, computing and engineering. This includes research with synchrotron radiation on molecules, soft matter, solid-state and nanomaterials, the development of new experimental techniques based on synchrotron radiation and lasers and the theory of interaction of matter and light.

Elementary Particle Physics, Astroparticle Physics and Accelerators
Projects in the analysis, software or detector related fields of experiments in elementary particle physics (ATLAS, CMS, ILC, BELLE II, ALPS II) and astroparticle physics (CTA, IceCube), development of particle accelerators and detectors, theory or computing.

Application Deadline is 31 January 2020.
Qualified applicants should have completed three years of full time studies at university level by summer 2020.
All participating students will obtain financial support.

Deutsches Elektronen-Synchrotron DESY
Ein Forschungszentrum der Helmholtz-Gemeinschaft

statement from DESY: “Due to the covid-19 pandemic situation there has not yet been yet a decision taken if a regular DESY summer student programme will take place in 2021. We are currently working towards setting up a programme with online and hybrid formats. Final decisions and announcements on the programme are expected for early february 2021.”

CERN summer student programme

(deadline for application:
31. Jan. 2021)

About HR | My Career | Students and Apprentices | My Benefits | Joining or leaving CERN | Key Resources

CERN activities during the programme

Home » Students and Apprentices » Summer Students » CERN activiti

- Lectures Programme
- CERN IT Lectures (Openlab Programme)
- Workshops
- Poster Session
- Student Session
- Visits
- CERN Summer Student Webfest
- Group Photo
- Lost & Found

3.6 Calorimetry

Calorimeter:

- Detector, which absorbs particles completely
- Measurement of particle energy
- Calor (Latin) = Heat
  $\leftrightarrow$ but $1\ GeV$ particle in $1\ l$ water only $\Delta T = E/C_V = 3.8 \cdot 10^{-14} K$!

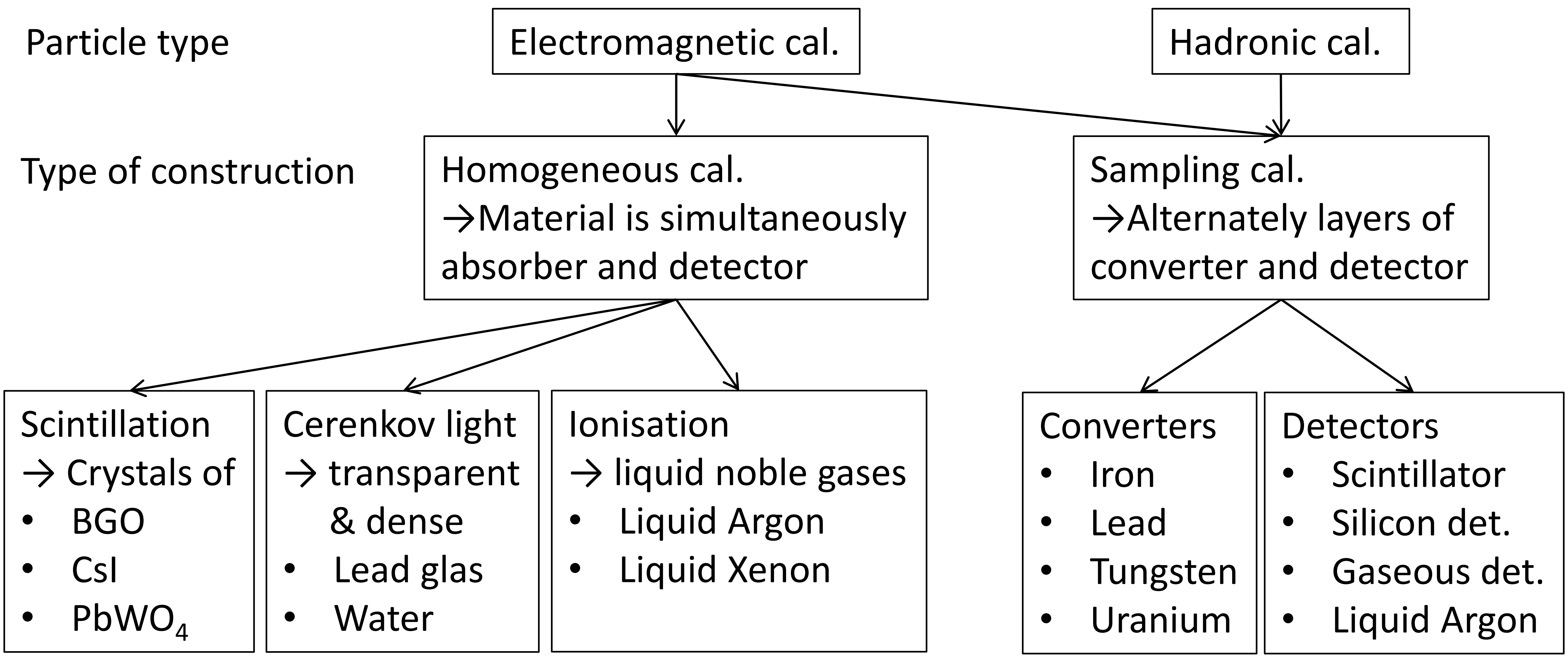
Measured values:

- Energy via shower size
  $\rightarrow$ Ionization, Cerenkov and scintillation light
- Position via shower center
- Important: good energy resolution and linearity

Advantage with respect to tracking detectors:

- Measures the energy also of neutral particles (γ, π^0, K^0)
- Resolution of calorimeter improves with particle energy: $\sigma_E/E \propto 1/\sqrt{E}$
  $\leftrightarrow$ Resolution of spectrometer worsens with particle momentum: $\sigma_p/p \propto p$

Classification



Homogeneous vs. Sampling Calorimeter

Homogeneous

+ best possible energy resolution

+ complete shower is detected

– expensive

Sampling

– worse energy resolution

– only part of shower detected

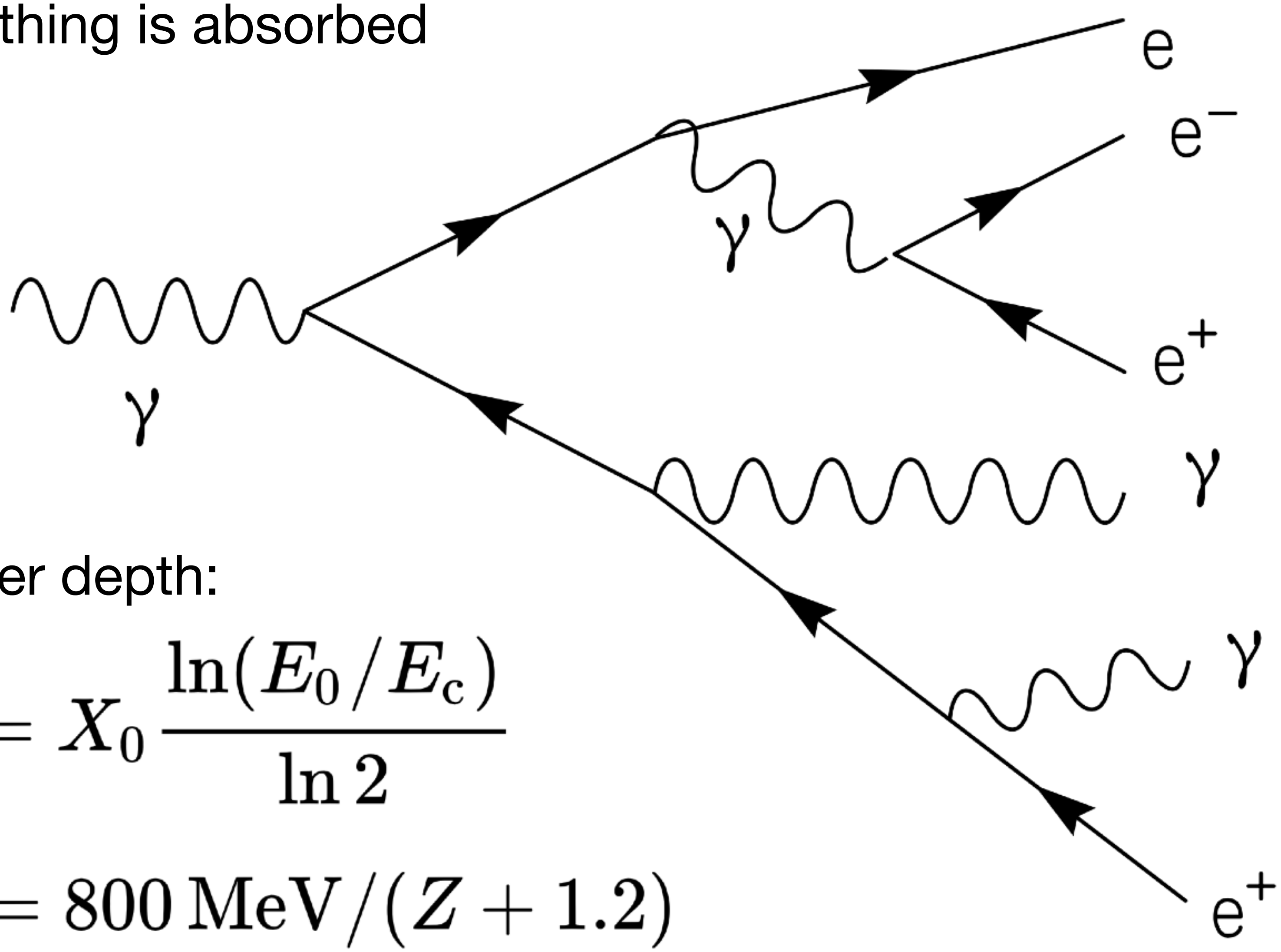
+ not so expensive

+ absorber with high denisty possible
→ compact size

+ Seperation of active and passive parts
→ flexibilty in choice of material

Photon interactions: showers

- high-energy photons can create long cascades of interactions until everything is absorbed



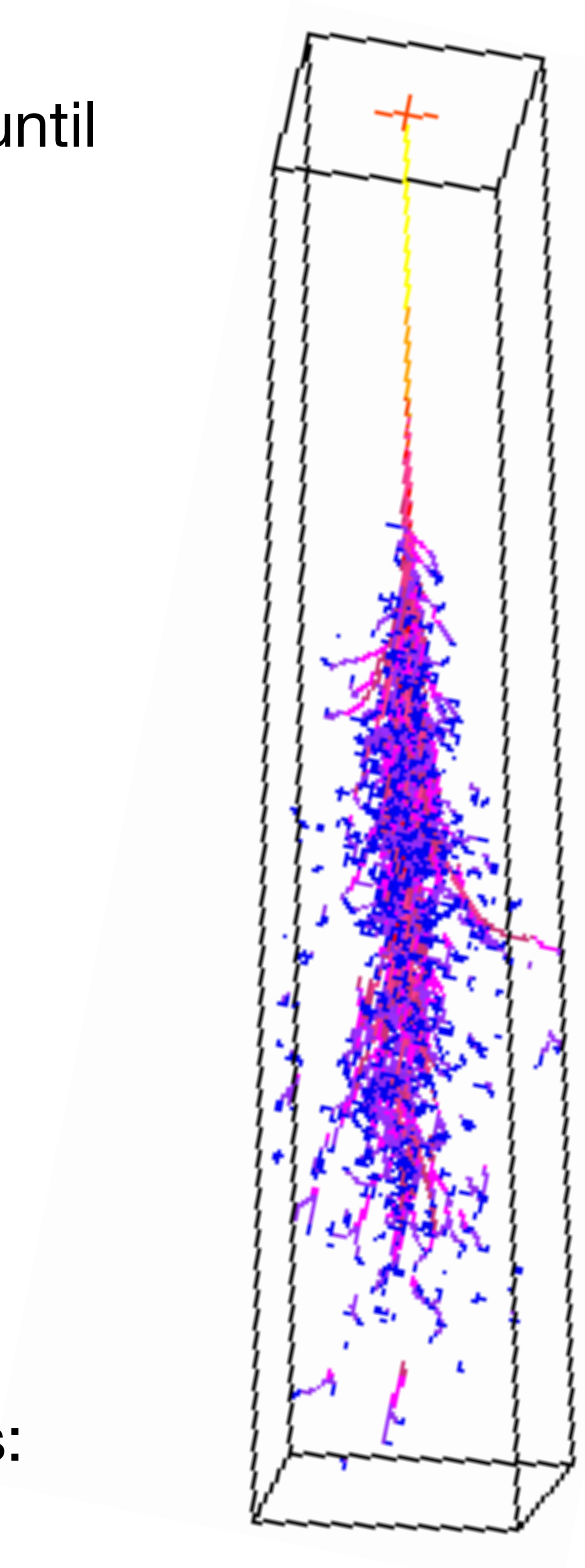
- shower depth:

$$X = X_0 \frac{\ln(E_0/E_c)}{\ln 2}$$

$$E_c = 800\,\mathrm{MeV}/(Z+1.2)$$

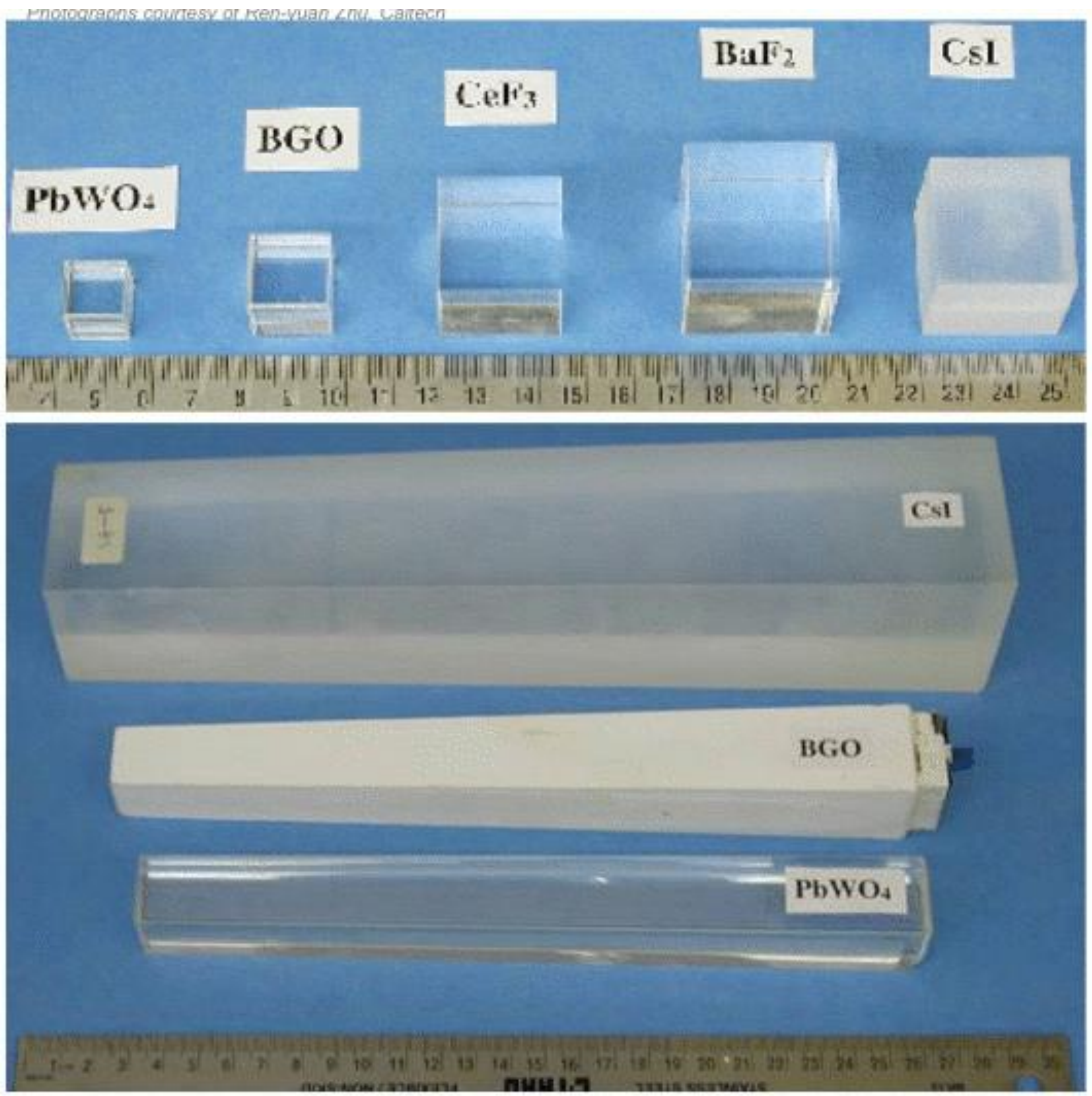
- transverse size of the shower is characterized by Moliere radius:

$$R_m = \frac{21\,\mathrm{MeV}}{E_C} X_0$$

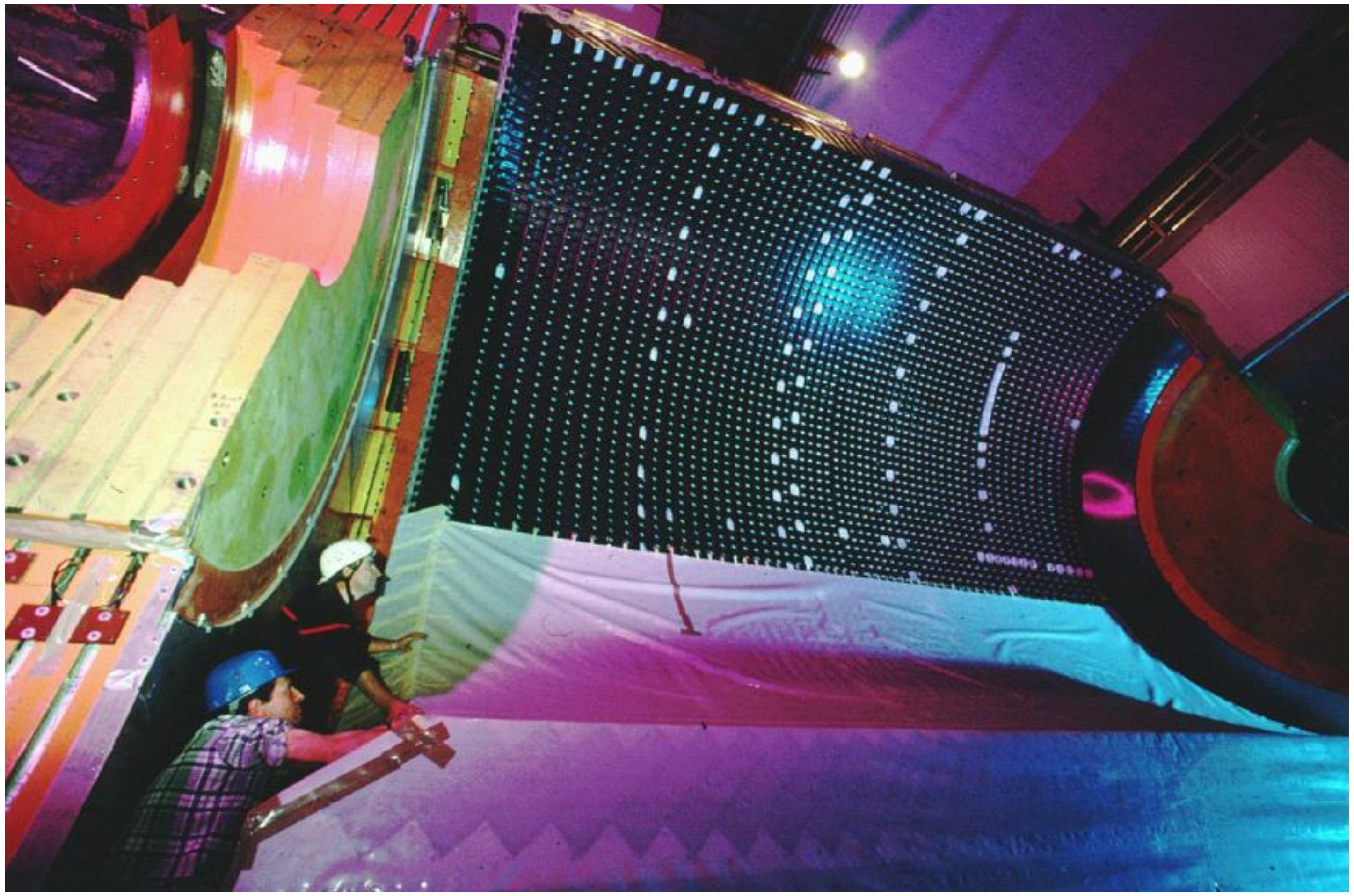


Homogeneous Calorimeter

Scintillator crystals

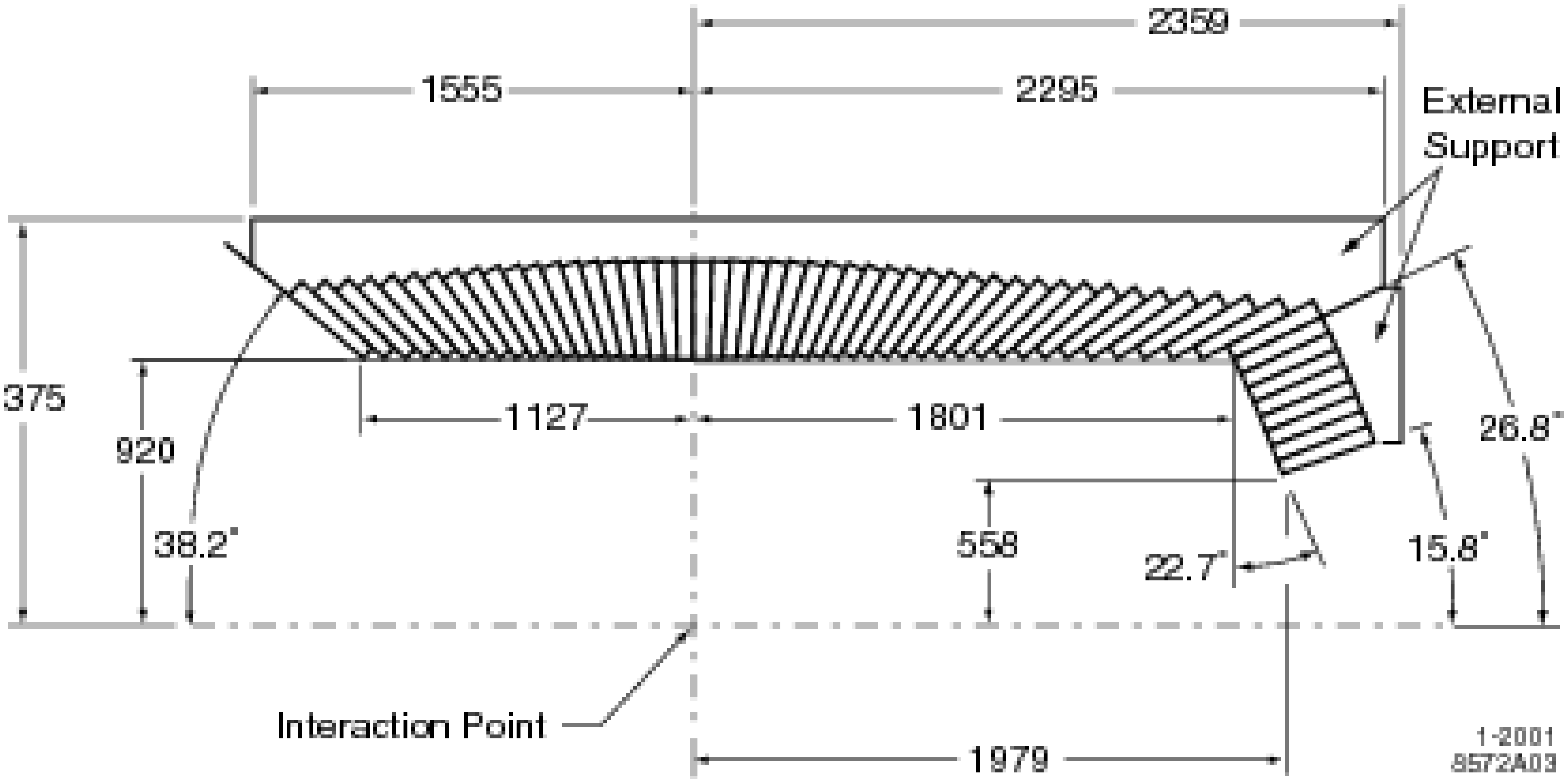


OPAL lead glas calorimeter



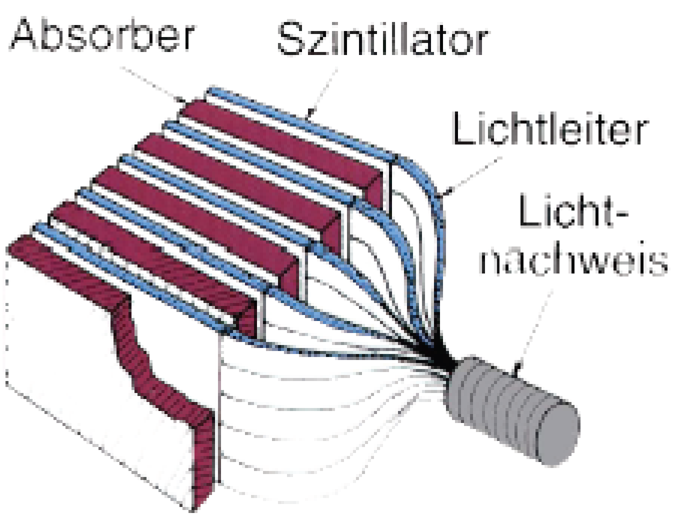
Homogeneous Calorimeter

Optimum shower reconstruction → Projective geometry



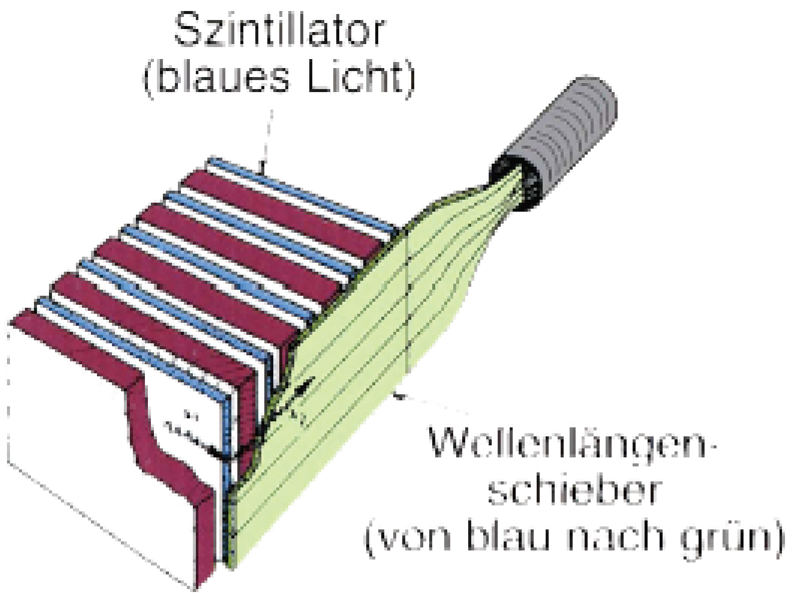
<u>But:</u> Danger of particle loss through gaps

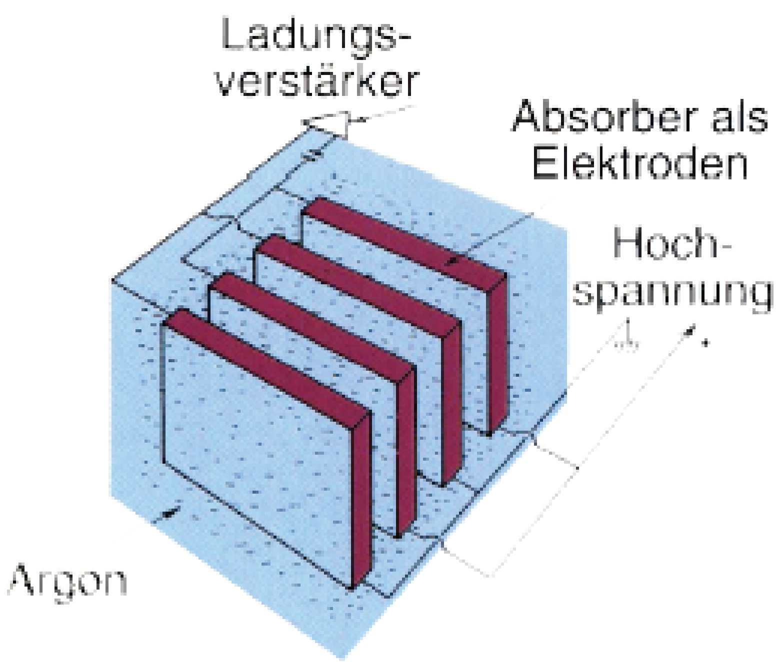
Sampling calorimeters (sandwiches)



Left: active regions are made of scintillators. The signal is read out through fibres and photo multipliers.

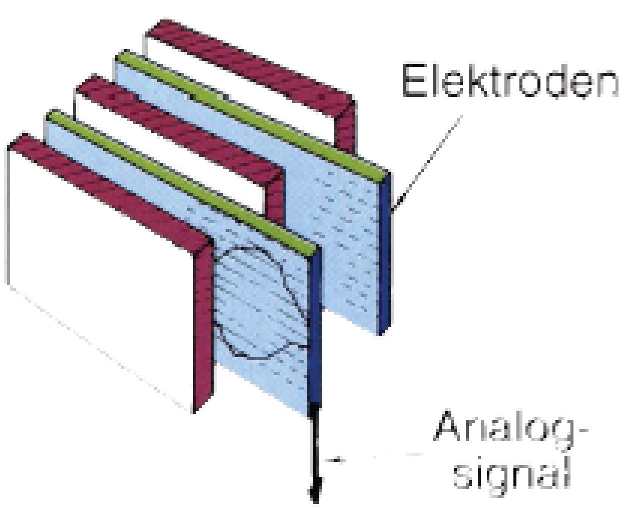
This can be combined with wavelength shifters (**right** picture)





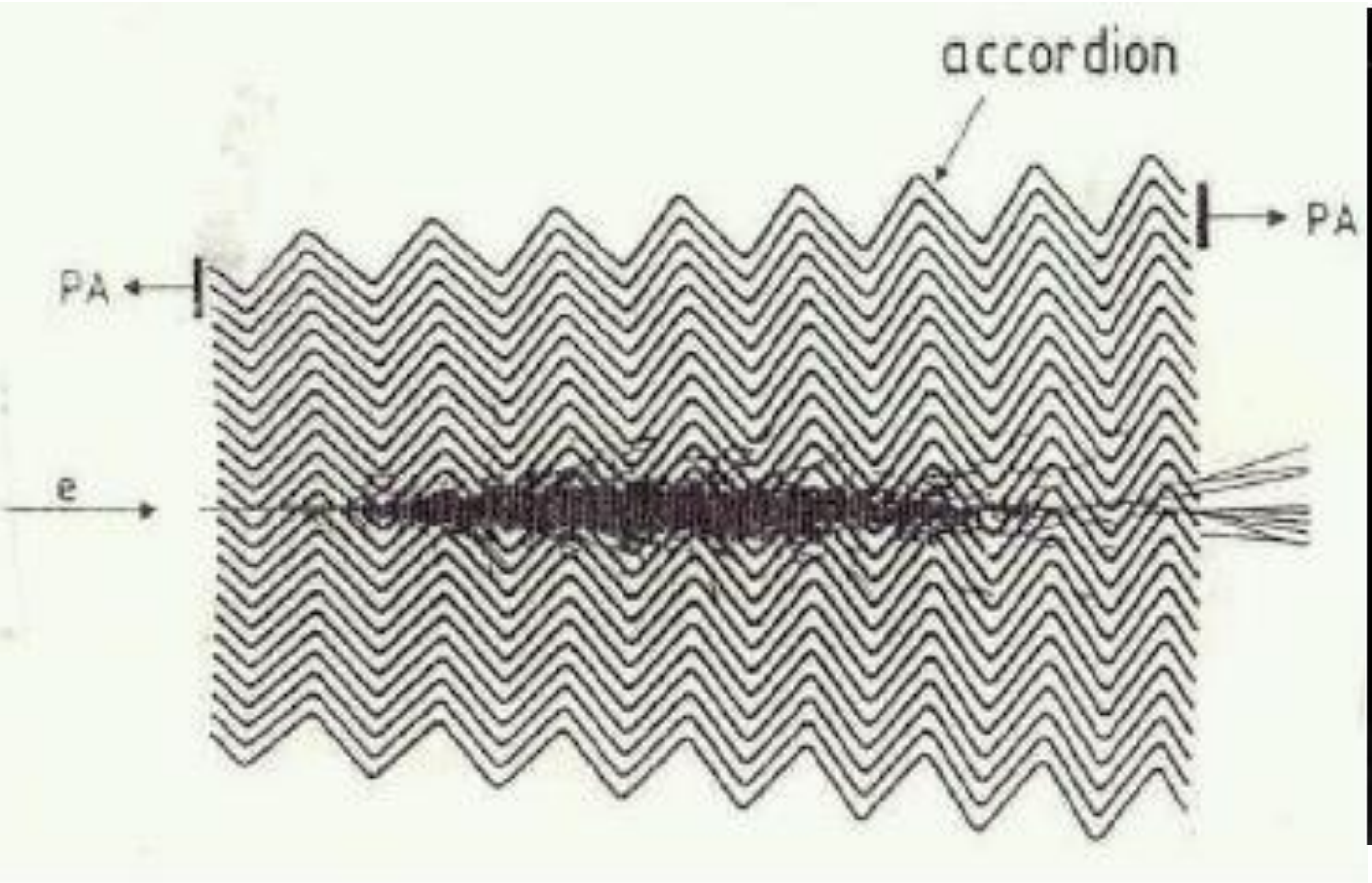
Left: the active regions are made of liquid argon. The absorbers are embedded in the liquid argon and act as readout electrodes to record the ionisation (instead of the scintillating light)

Right: ionisation chambers (gas detectors) are embedded between the absorbers.

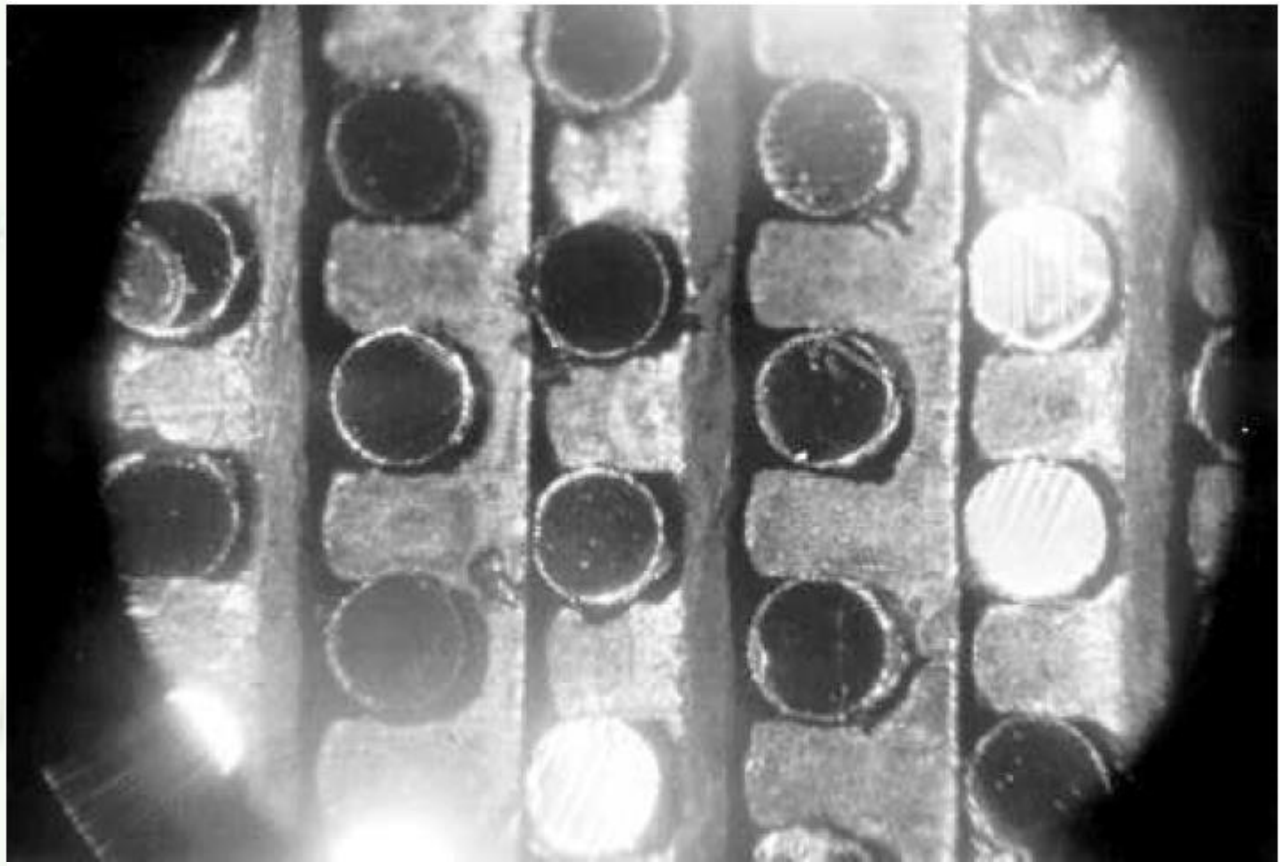


Sampling Calorimeter

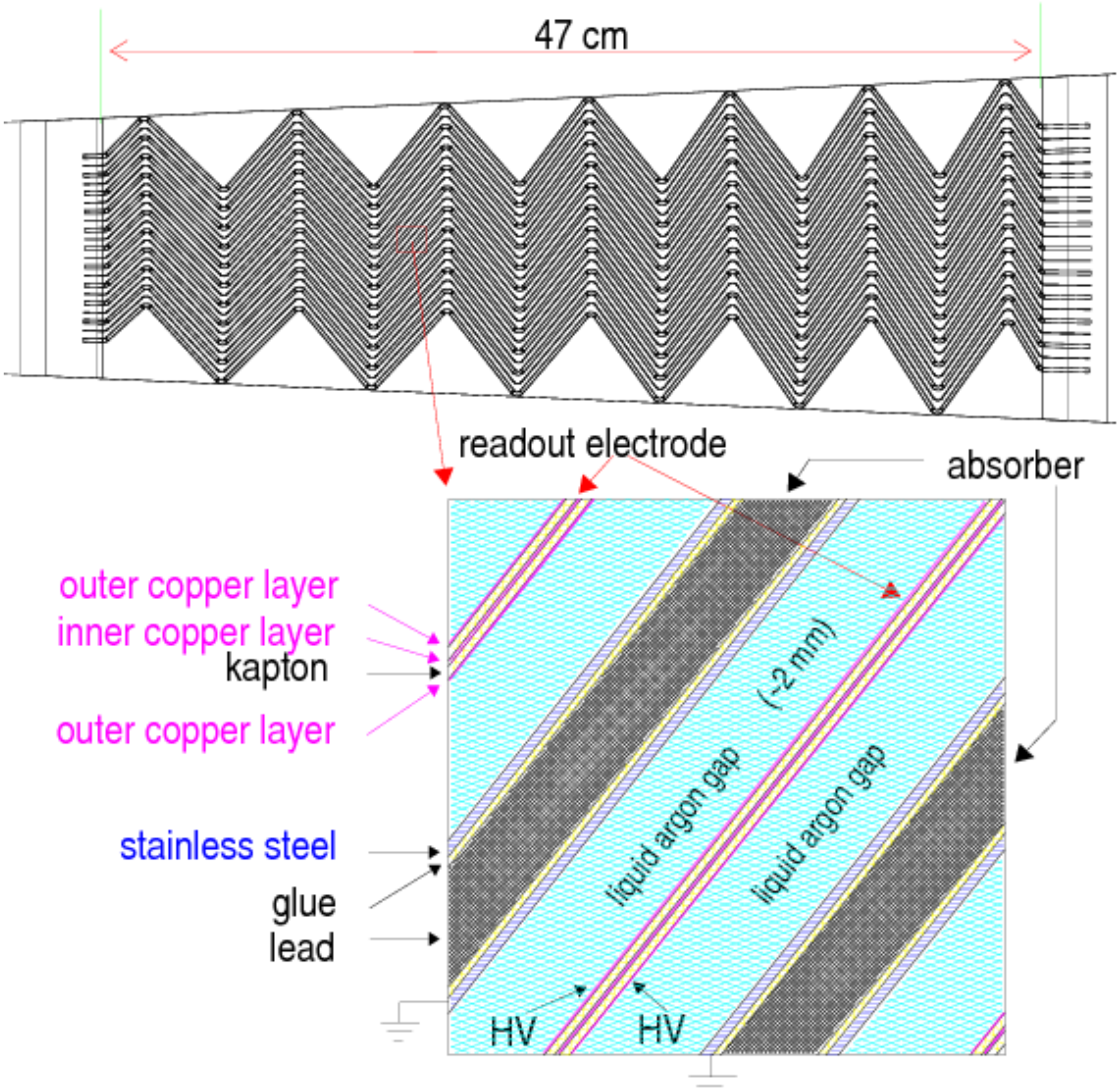
Accordeon calorimeter



Spagetti calorimeter (SPACAL)

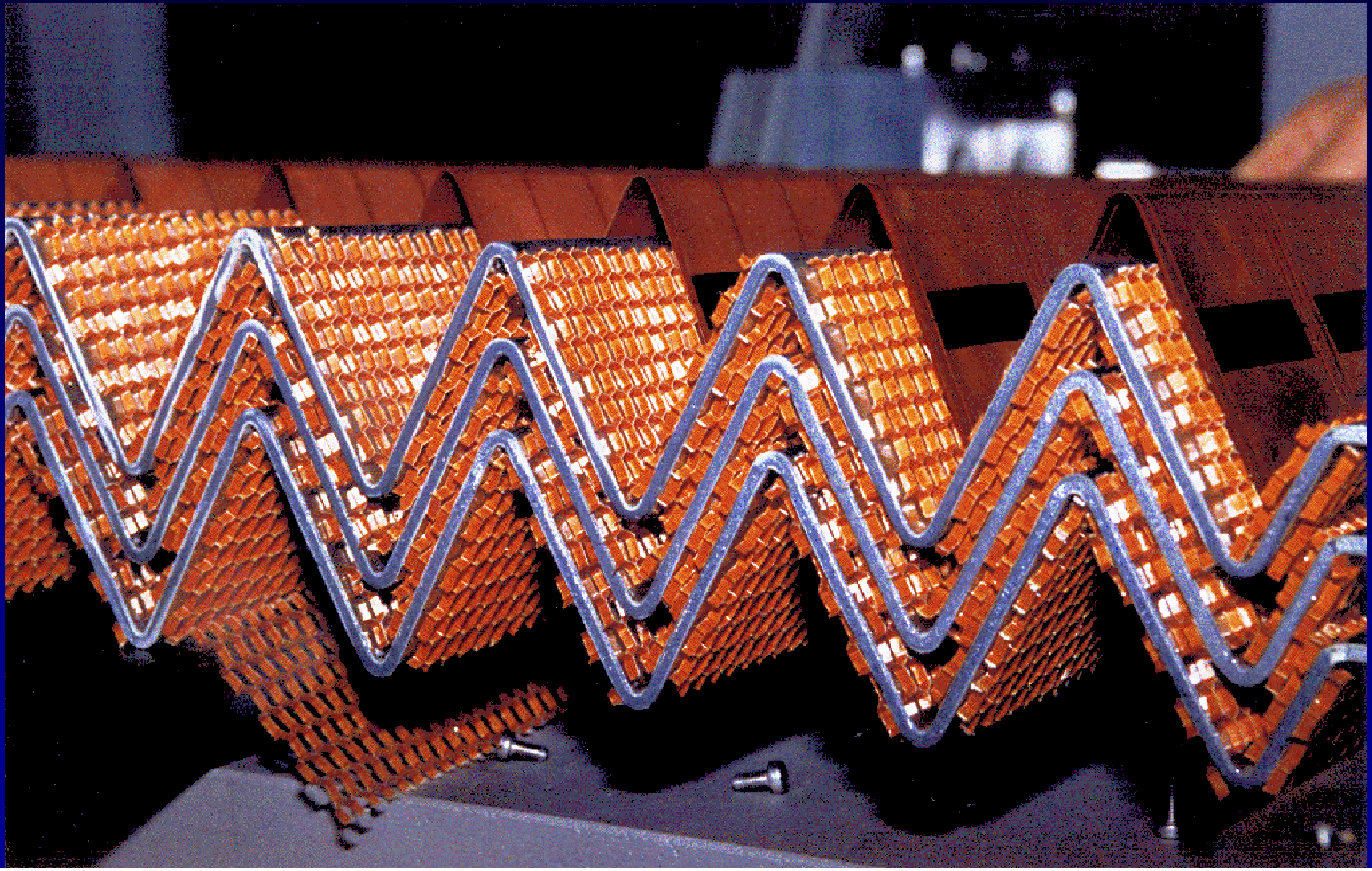


ATLAS electromagnetic calorimeter (accordeon):



- lead is the absorber (to create the shower)
- ionisation happens in argon
- high voltage applied to copper layers to make ions drift
- read out happens at inner copper layer through capacitive coupling

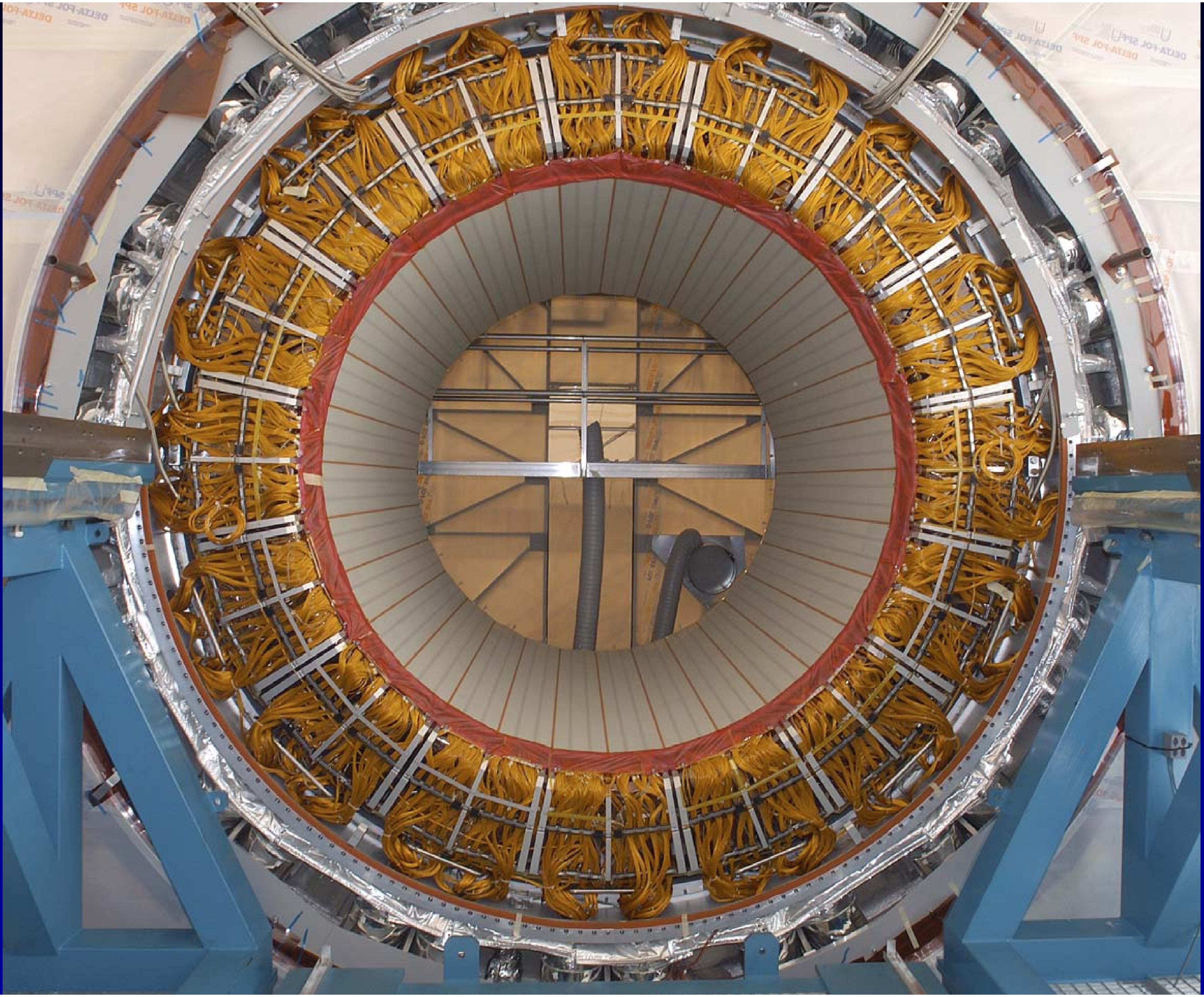
ATLAS electromagnetic calorimeter (accordeon):



- ~ 20 000 m² of honeycomb spacers to maintain flexible electrodes centered in the gap.
- After commissioning (at 87K) and before final installation in the pit:
  - 31 dead readout channels in the EM barrel (0.03%)
  - 14 dead readout channels in the EM end-caps (0.025%)

ATLAS electromagnetic calorimeter (accordeon):

ATLAS electromagnetic calorimeter (accordeon):



Energy resolution

- Statistical component $\Delta E \propto \sqrt{N} \;\Rightarrow\; \sigma_E/E \propto 1/\sqrt{E}$
- Limited quantum efficiency
- Shower losses („leakage“)
- Sampling fluctuations

  → Division of energy absorption between converter and detector varies event by event

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \equiv \sqrt{\left(\frac{a}{\sqrt{E/GeV}}\right)^2 + b^2}$$

Electromagnetic calorimeter

CMS ($PbWO_4$): $$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\%$$

ATLAS (liq. Ar): $$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$$

E_0 = deposited Energy

Extension in length from: $$T(95\%) = \ln\frac{E_0}{E_C} + B + 0.08\,Z + 9.6 \quad [X_0] \quad \begin{cases} B = -0.5 \text{ for } e^{\pm} \\ B = +0.5 \text{ for } \gamma \end{cases}$$

E_C = critical Energy (Bremsstrahlung equal to Ionisation)

→ Length which contains 95% of shower energy
→ Energy resolution improves with energy containment

Angular granularity from: $$R(95\%) = 2\rho_M$$ ρ_M: Moliere radius

→ transverse dimension which contains 95% of shower energy
→ Position resolution improves with angular granularity

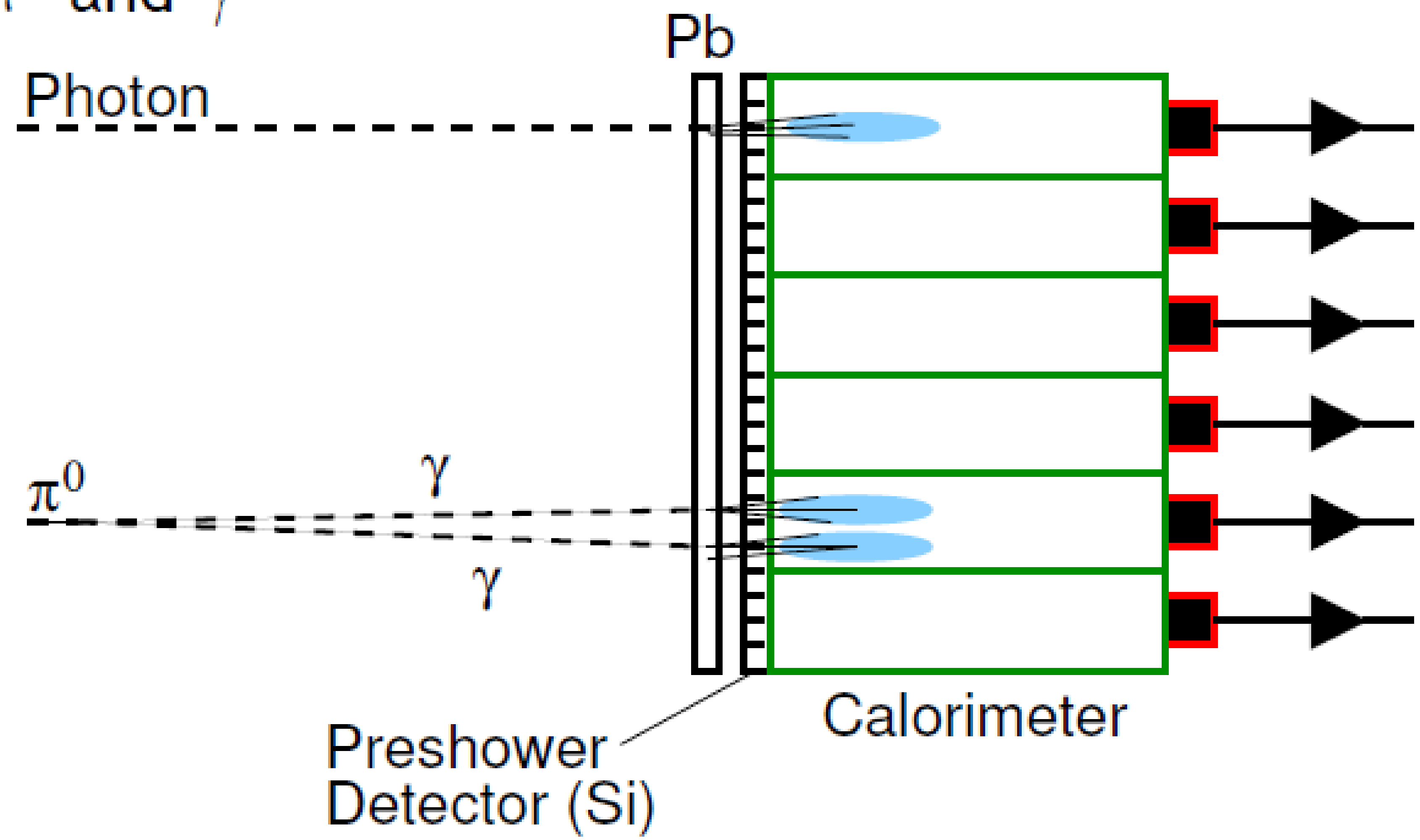
Moliere radius:

The **Molière radius** is a characteristic constant of a material giving the scale of the transverse dimension of the fully contained electromagnetic showers initiated by an incident high energy electron or photon. By definition, it is the radius of a cylinder containing on average 90% of the shower's energy deposition.

$$\rho_{\mathrm{M}} = 0.0265\, X_0\, (Z + 1.2)$$

Preshower Detector

Unterscheidung von π^0 and γ



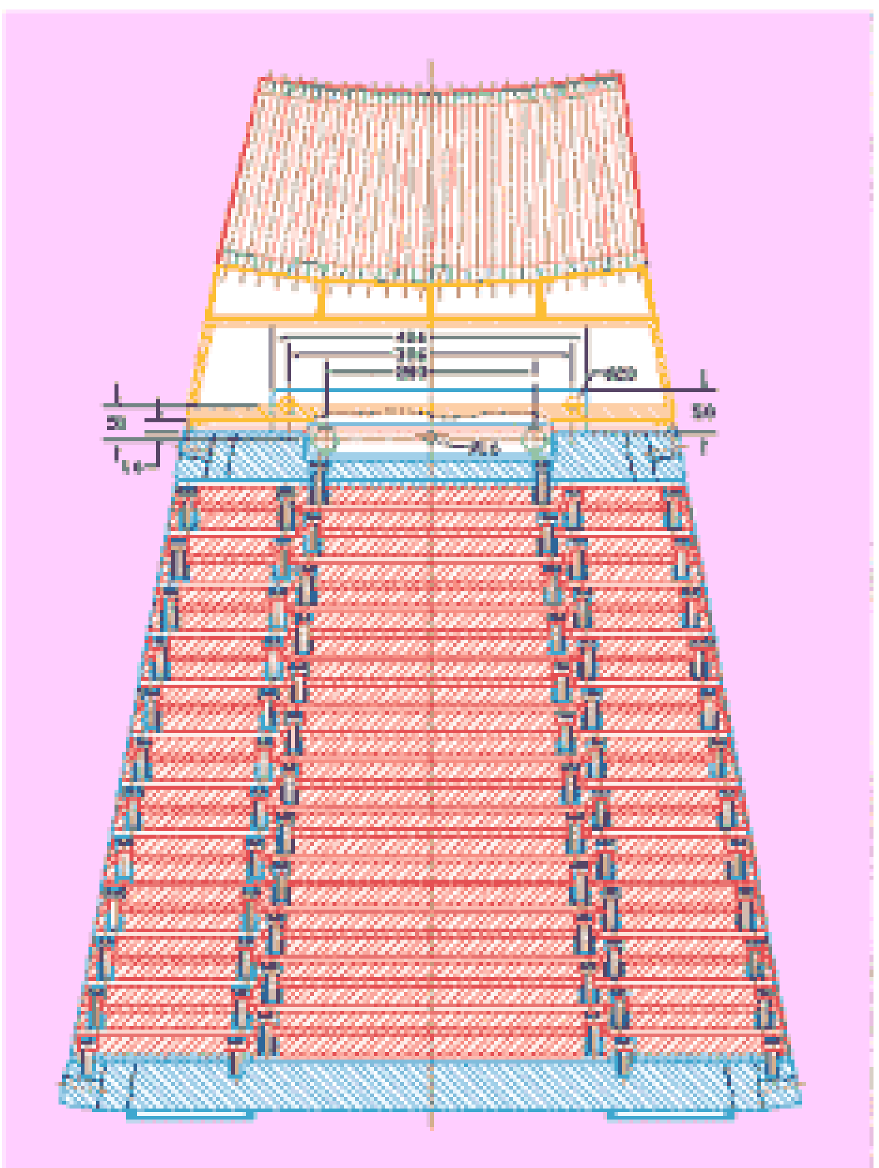
- Improved position resolution
- Photon idetification
- γ/π^0 Seperation

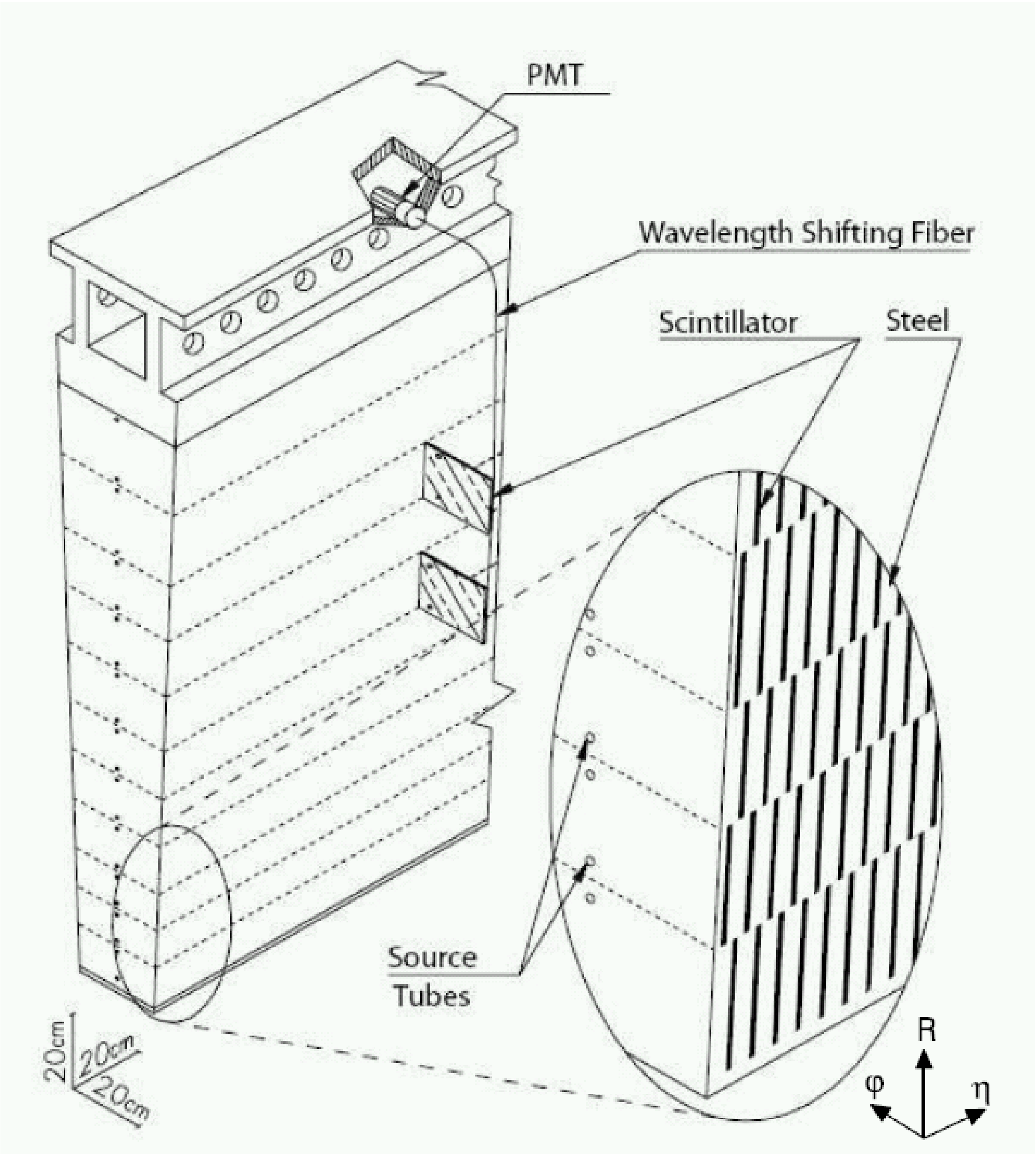
Hadronic Calorimeter

Shower depth given by hadronic absorption length λ_i

CMS: Brass, Plastic scintillator — $8\lambda_i$

ATLAS: Steel, Plastic scintillator — $10\lambda_i$

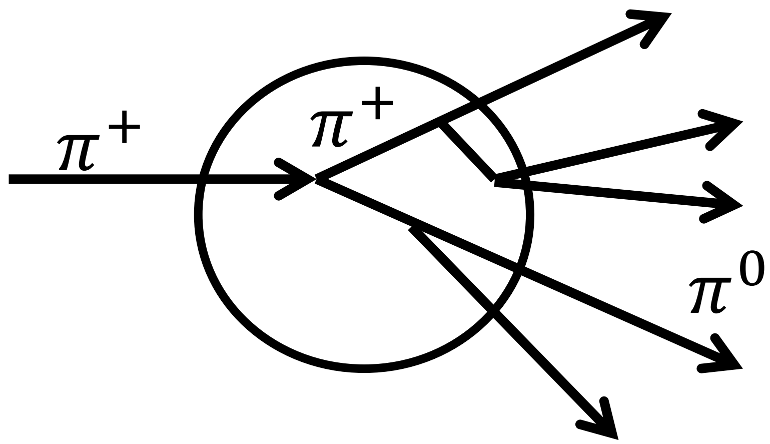




Shower components

Hadron → absorber → inelastic scattering with nuclei

- Generation of mesons and baryons in nuclear matter

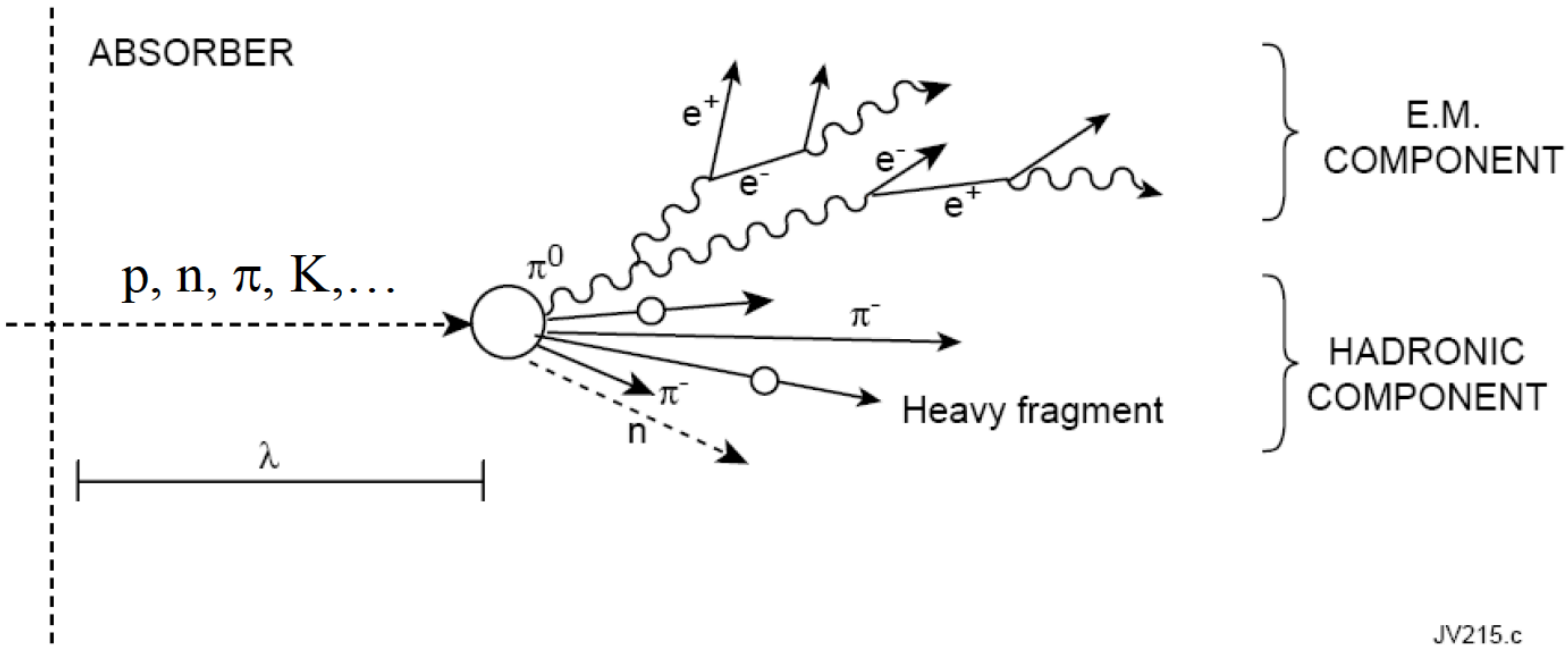


- Spallation
- Nuclear excitation

→ There are also <u>neutral</u> mesons generated (π^0, η, ...)
$\pi^0 \rightarrow \gamma\gamma$: electromagnetic shower component

→ Also K_L, muons, neutrinos are generated

→ not or badly detected shower components



ABSORBER
p, n, π, K,…
λ
π0
e+
e-
e-
e+
π-
π-
n
Heavy fragment
E.M.
COMPONENT
HADRONIC
COMPONENT
JV215.c

Electromagnetic and hadronic shower components

Problem: Different calorimeter signal regarding shower components f_e and f_h

$$S = S_e + S_h = \varepsilon_e f_e E + \varepsilon_h f_h E = \varepsilon_h \left(\frac{\varepsilon_e}{\varepsilon_h} f_e + f_h \right) E \equiv \varepsilon_h \left(\frac{e}{h} f_e + f_h \right) E$$

Favored: $\frac{e}{h} = 1$

- Electron and pion of same energy generate same signal
- Fluctuations between f_e and f_h do not change the signal

Problem: $\frac{e}{h} > 1$ in most cases

- Concept of „Compensation“
- Compensating Calorimeter
  achieved by optimizing materials, thicknesses,…

Overview of Calorimeters

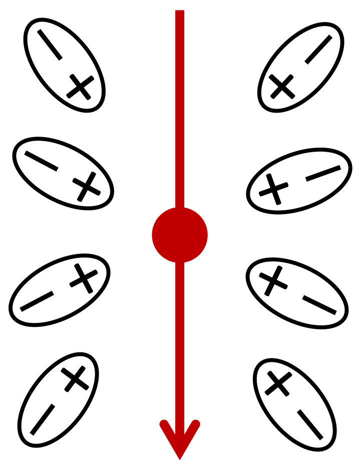
Experiment	Electromagnetic Cal.	Hadronic Cal.
CMS	$PbWO_4$ crystals	brass / scintillator
ATLAS	Pb / liq. Ar	steel / scintillator
BABAR	CsI (Tl) crystals	-
H1	Pb / liq. Ar	Pb / liq. Ar
ZEUS	U / scintillator	U / scintillator
ALEPH	Pb / prop. tubes	Fe / scintillating tiles
DELPHI	Pb / gas chambers	Fe / streamer tubes
L3	BGO crystals	U / prop. tubes
OPAL	lead glas	Fe / prop. tubes

Cerenkov Radiation to determine β

The speed of the propagation of light in water is only 0.75c. Matter can be accelerated beyond this speed easily.

A charged particle passes a medium faster than the speed of light in this medium

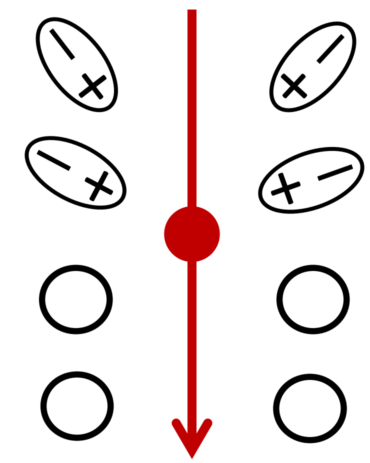
$$v < \frac{c}{n}$$



Symmetric
charge distribution

- ➢ Dipol moment vanishes
- ➢ No radiation

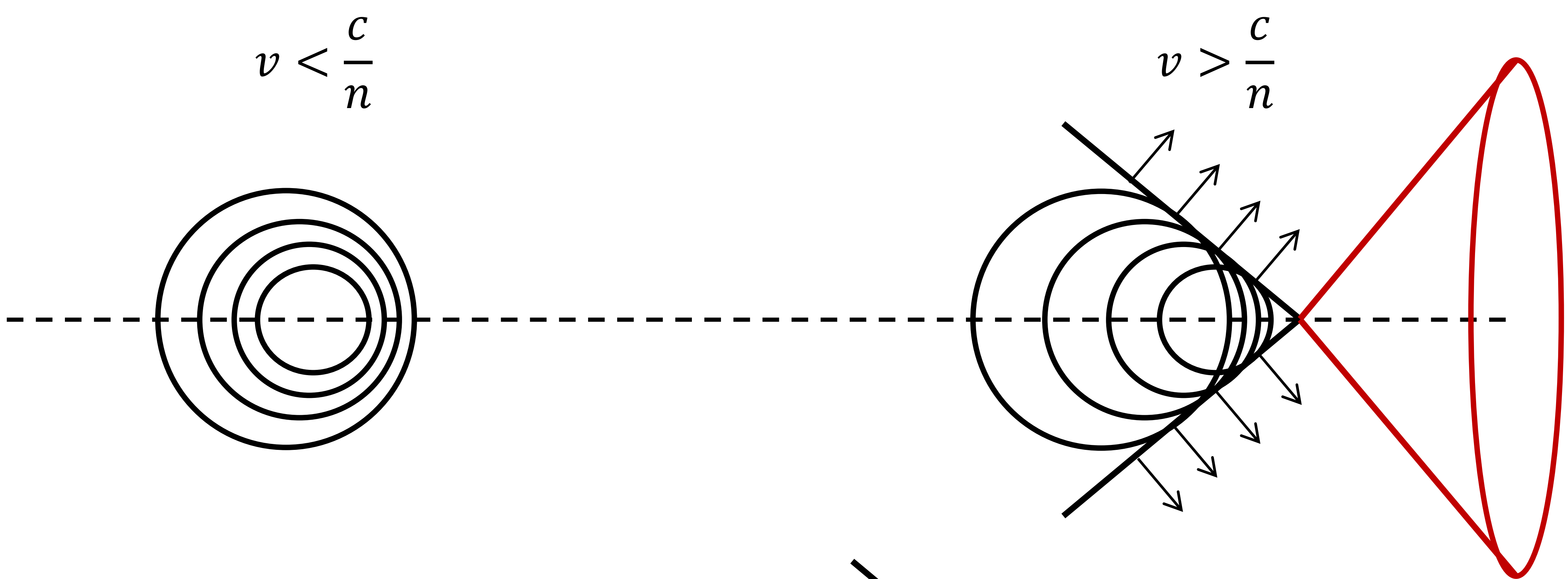
$$v > \frac{c}{n}$$



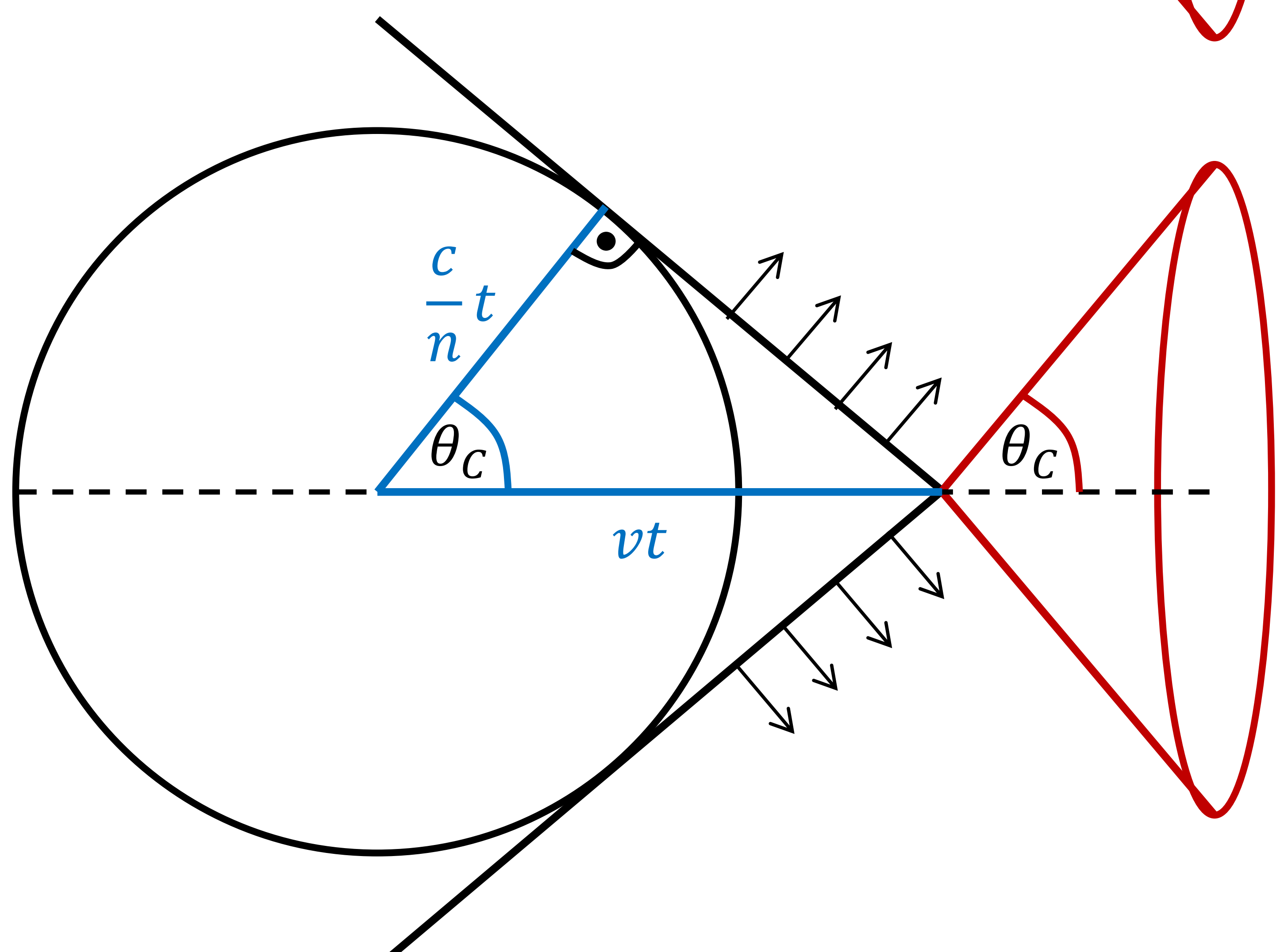
Asymmetric
charge distribution

- ➢ Moving dipol moment
- ➢ Radiation of Cerenkov light

Cerenkov radiation

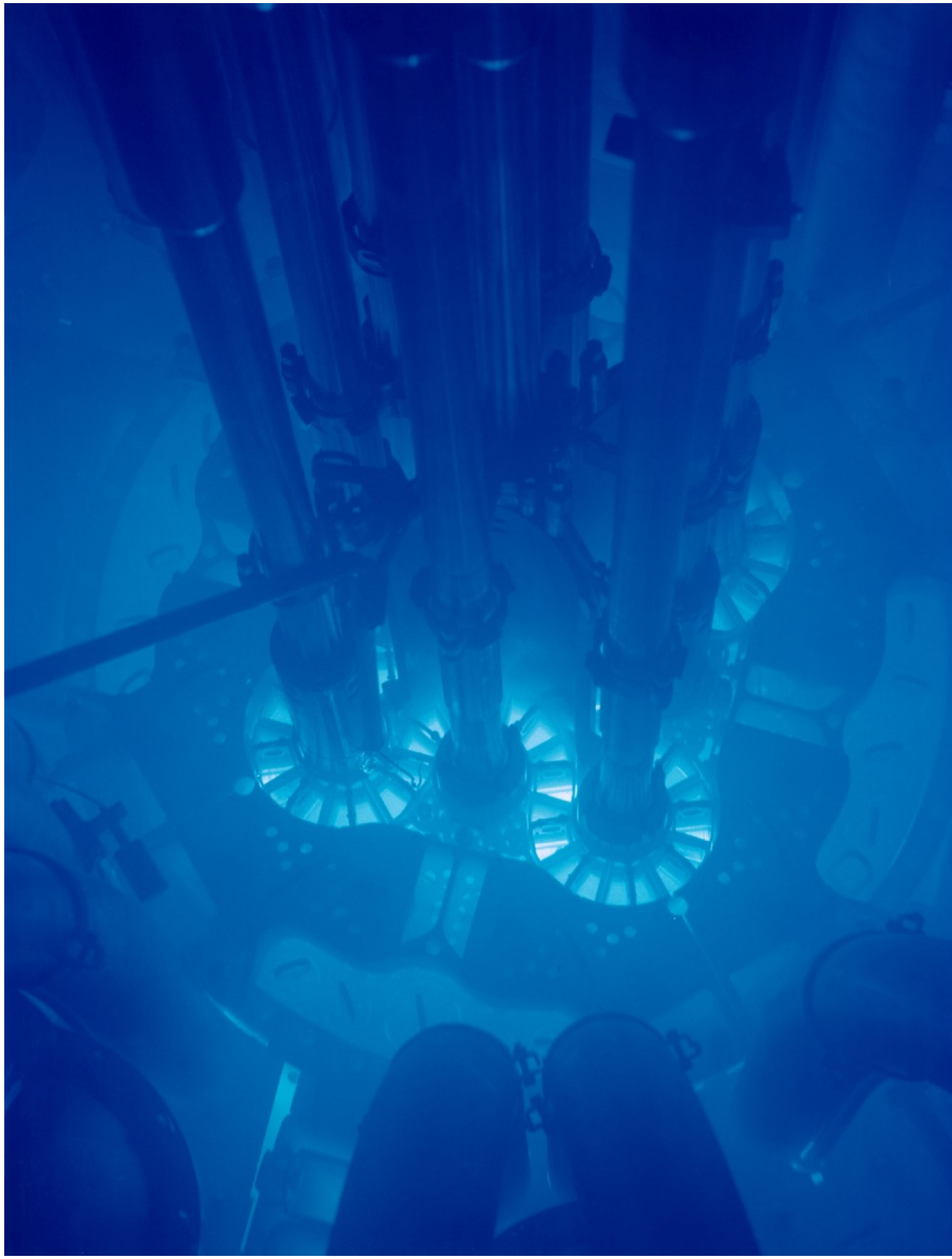


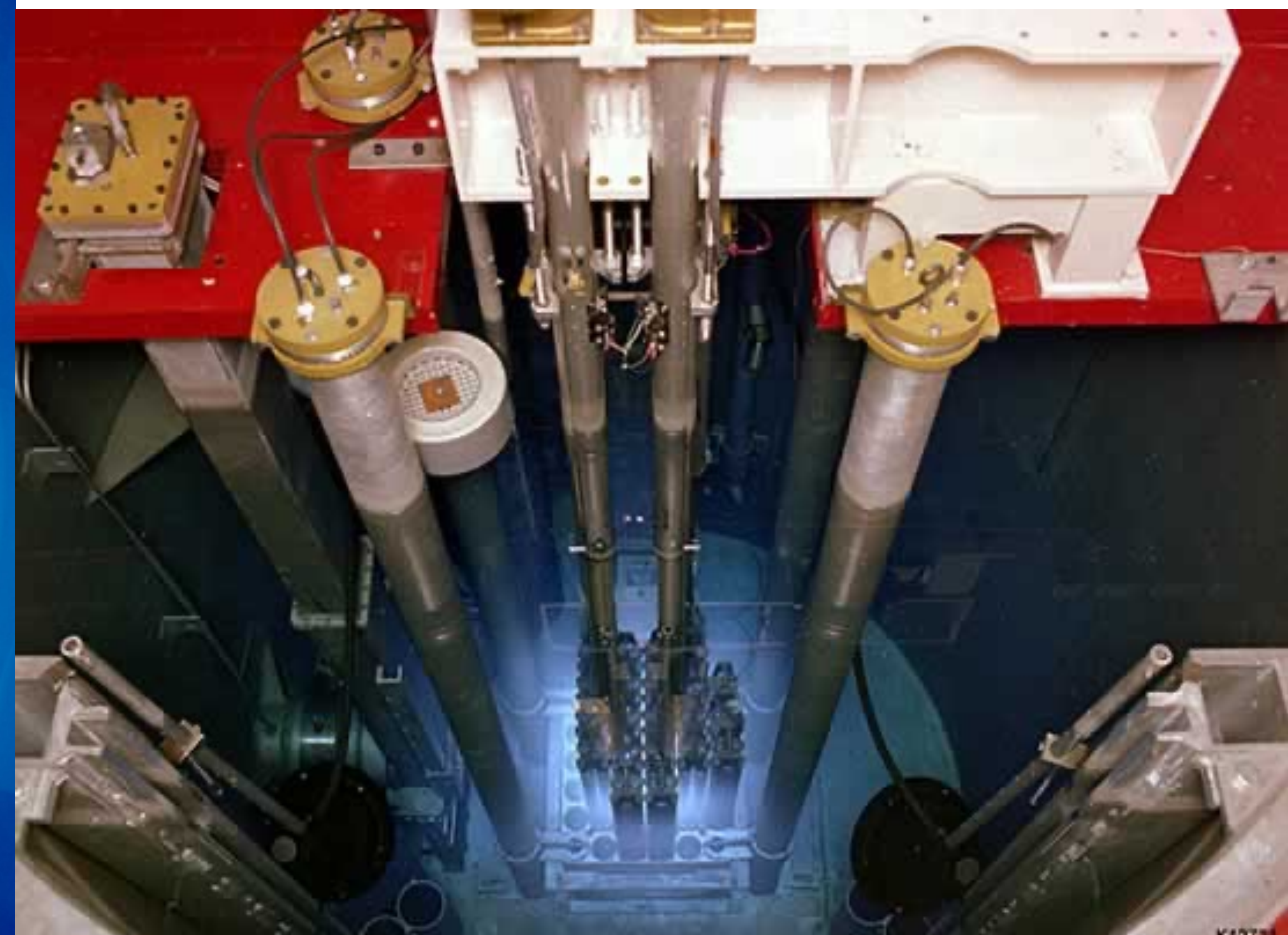
$$\cos\theta_C = \frac{\frac{c}{n}t}{vt} = \frac{c}{n\,v} = \frac{1}{\beta n}$$



Light cone with
half opening angle θ_C

Cerenkov radiation in underwater nuclear reactors:

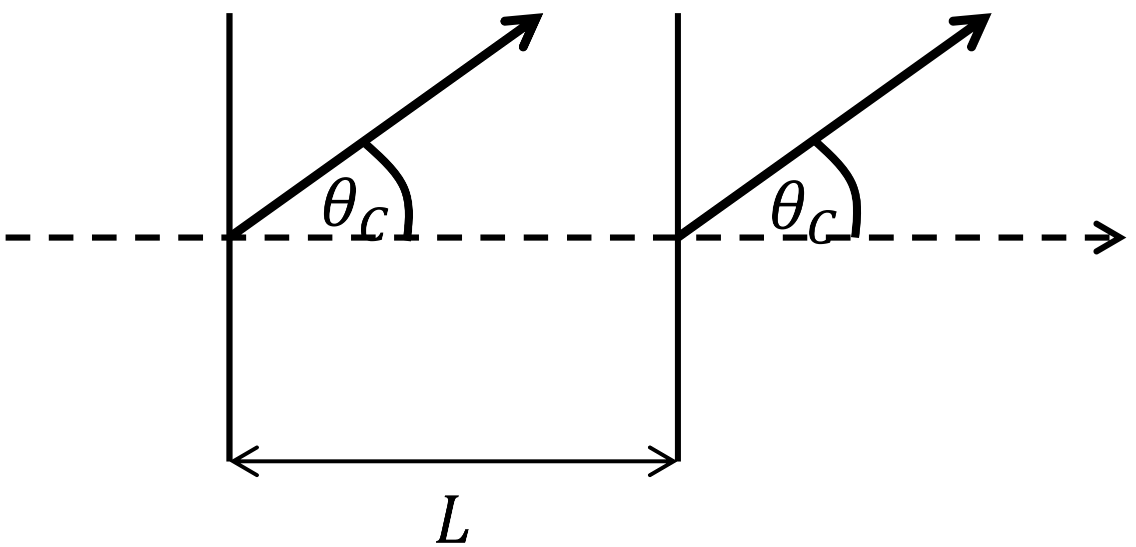




- Usage of Cerenkov radiation:
  - Particle ID (see later)
  - Large volume neutrinos detectors (Cones in water / ice)
  - Calorimetry (Lead glass, earth‘s atmosphere)

- Cerenkov radiation is independent of ρ, Z, I and other material constants
  - It only depends on the refractive index $n = \mathrm{n}(\omega) \Rightarrow \theta_C(\omega)$

- Limited material thickness leads to refraction:



Smearing of the light cone: $\Delta\theta_C \approx \lambda / L$

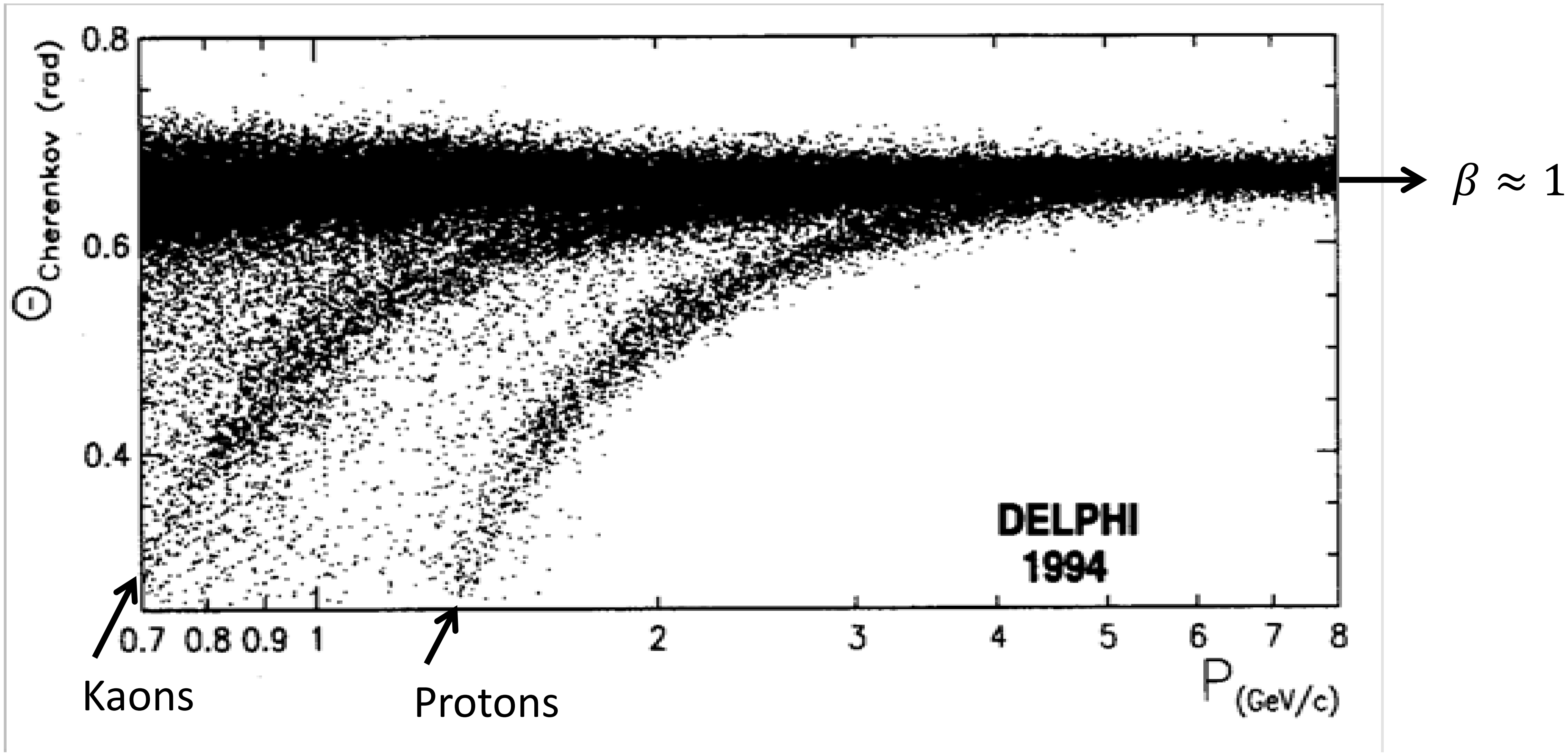
- Photon spectrum:
  - All photon energies with about equal probability
  - Numer of photons: $N_C = \frac{\alpha}{c} \sin^2 \theta_C \, \Delta x \, \Delta\omega$ mit $\sin^2 \theta_C = 1 - \frac{1}{\beta^2 n^2}$
  - Try to detect all photons up to the UV region:

$N_C \approx 365 \sin^2 \theta_C$ photons per eV energy intervall and per cm material

For $\beta \to 1$: $\sin^2 \theta_C \to 1 - \frac{1}{n^2}$ $\begin{cases} \text{Gases: } n \approx 1 \Rightarrow N_C \to 0 \\ \text{Water: } n \approx 1.3 \Rightarrow N_C \to \frac{3}{4} \cdot 365 \end{cases}$

  - Relativistic particles in water: about 200 photons per cm
  - Energy loss $\sim 500 \; eV/cm$ $\rightarrow$ negligible compared to $\frac{dE}{dx}$ from ionisation

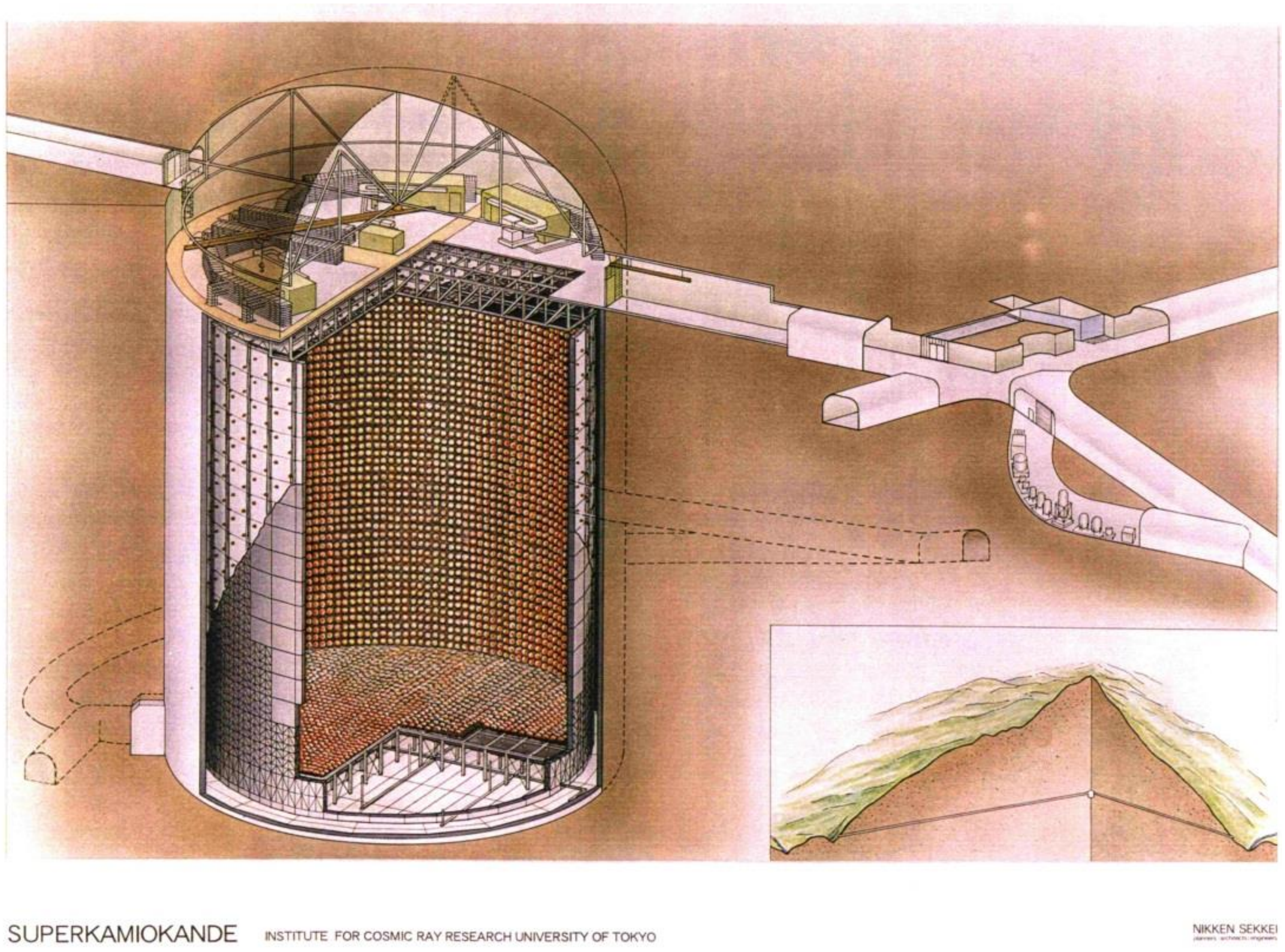
- Diameter of ring → Cerenkov angle θ_C → β

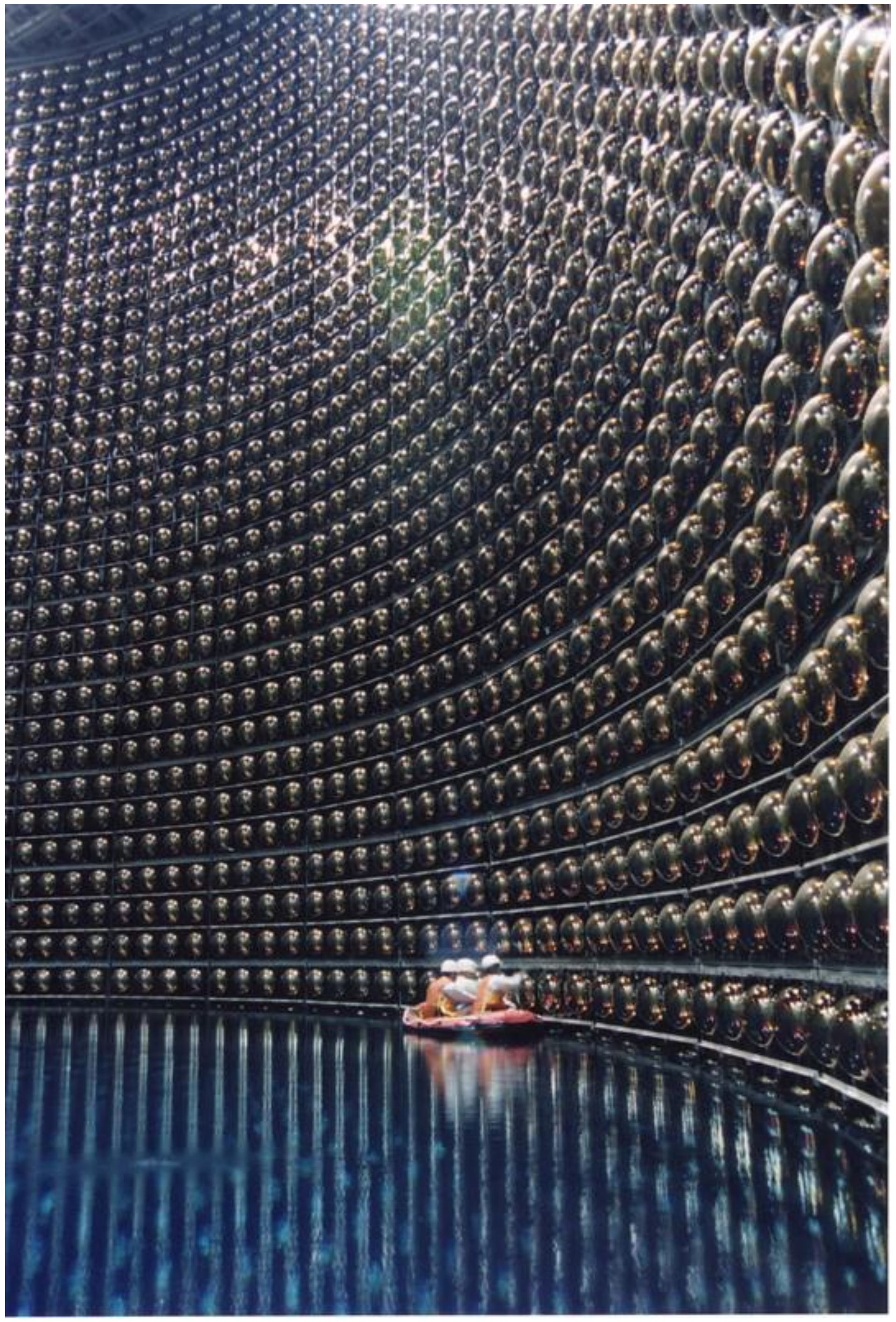


$$\cos\theta_C = \frac{1}{\beta n} \;\Rightarrow\; \cos 0.68 = \frac{1}{n} \;\Rightarrow\; n \approx 2$$

Insertion: Cerenkov cones in neutrino detectors

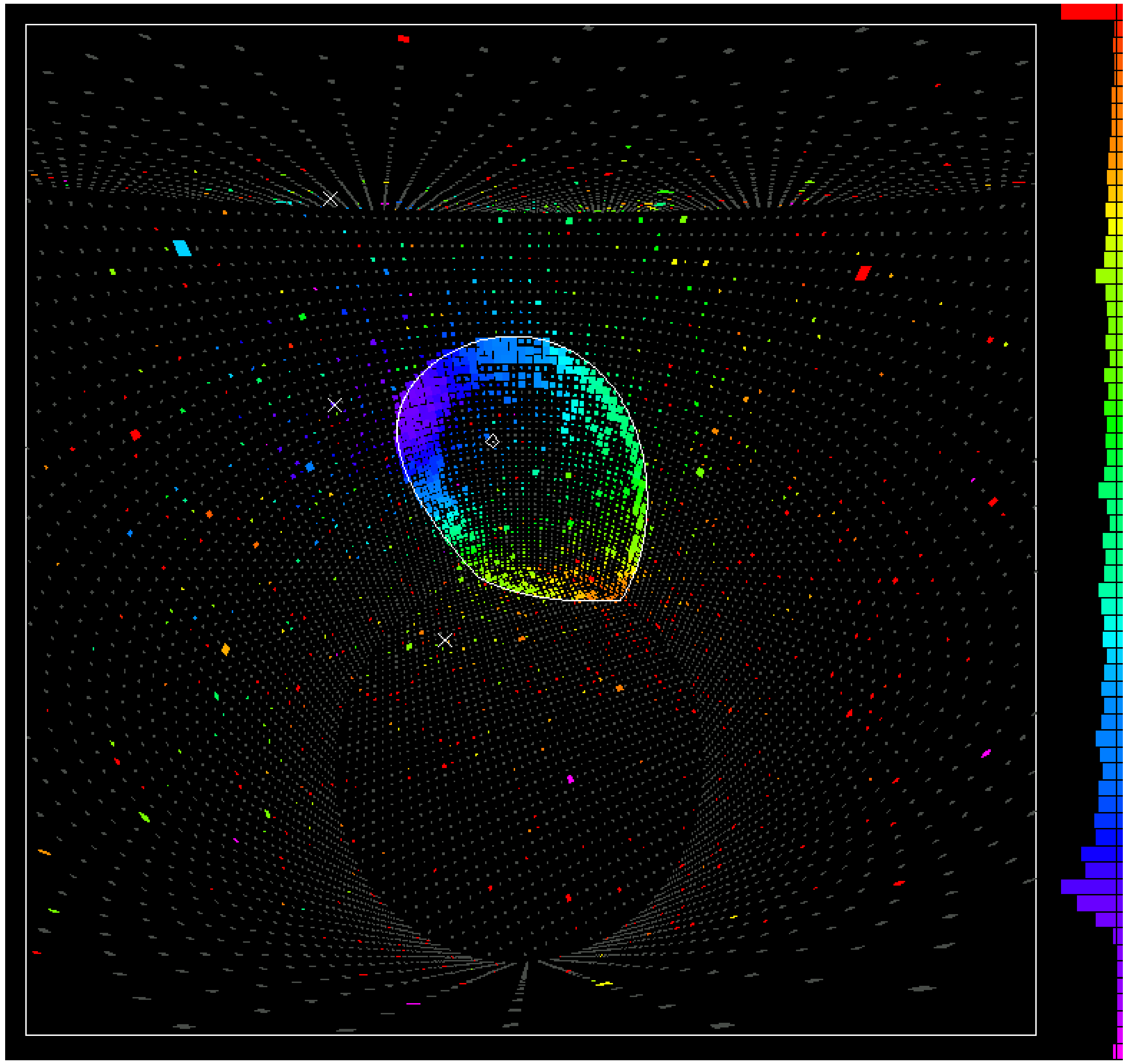
Super-Kamiokande is a 50,000 ton water Cherenkov detector, with 11,000 photomultiplier tubes, which started observation in 1996 after 5 years of construction



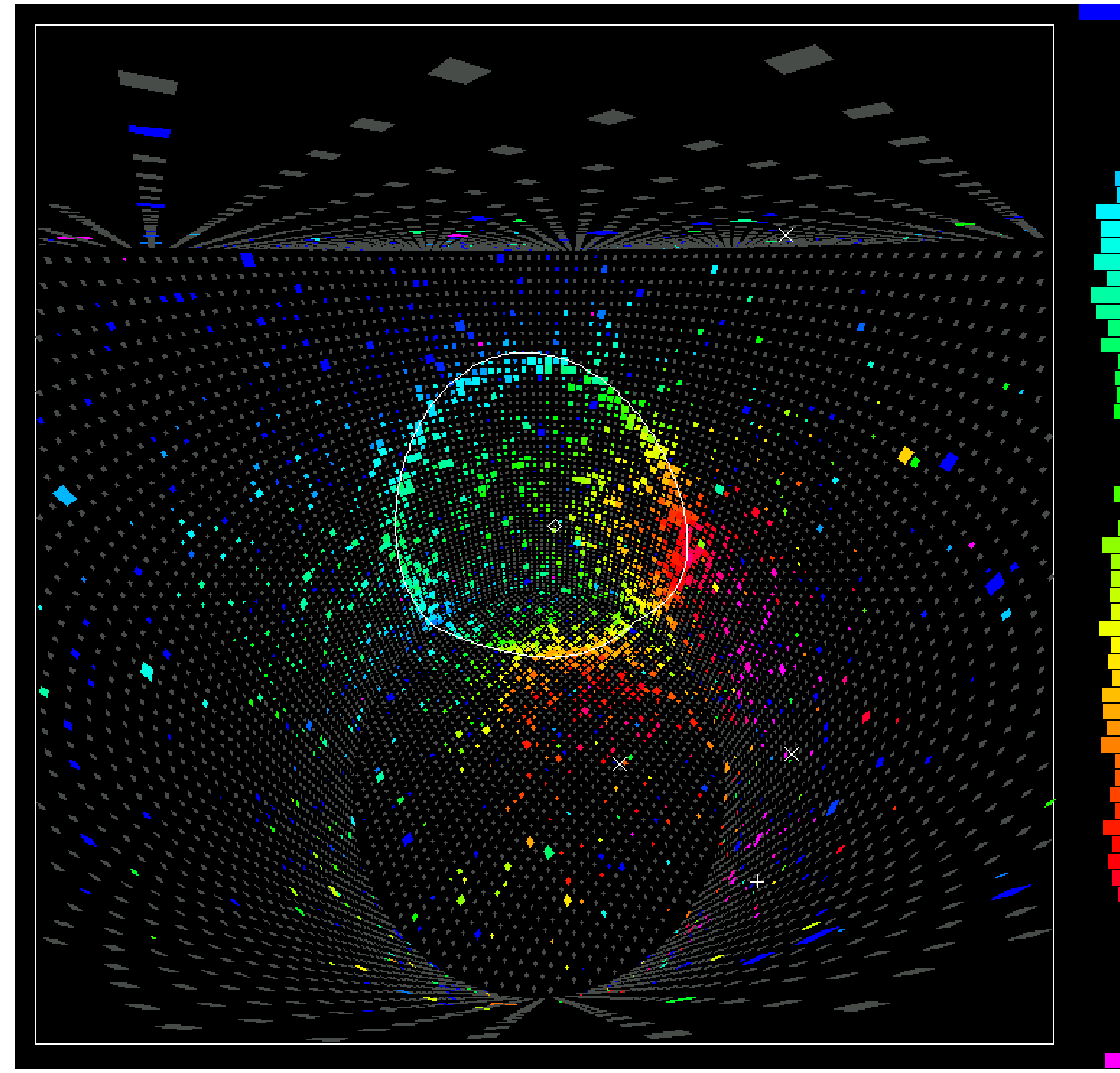


Insertion: Cerenkov cones in neutrino detectors

Muon



Electron



- Rings on tank walls, because particle tracks very short (otherwise discs)
- Sharp ring for muons ⟷ fuzzy ring for electrons due to bremsstrahlung
- Different kind of particle ID! → Has nothing to do with a measurement of β