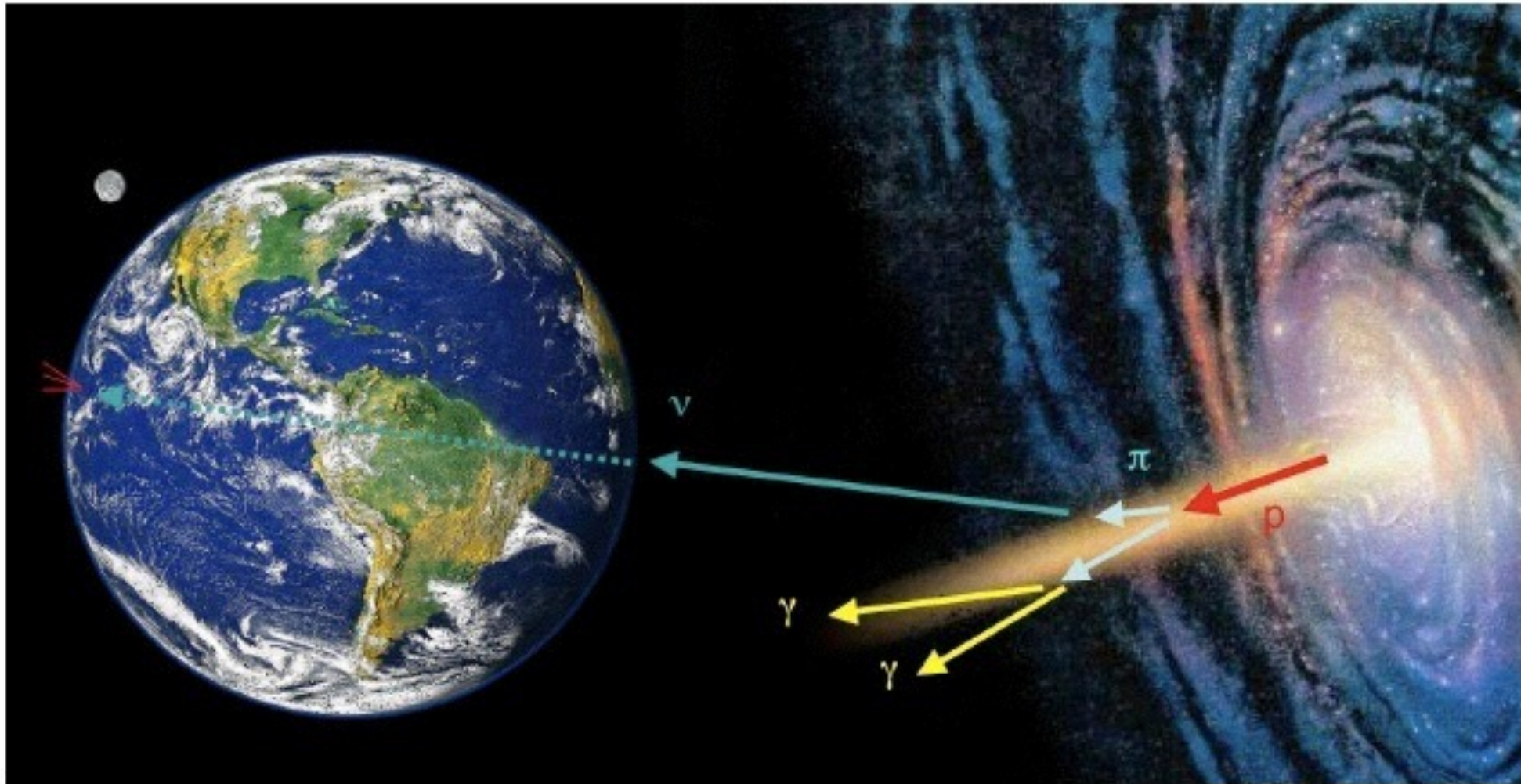


Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



03. Detectors in Particle & Astroparticle Physics

25.04.2016



Overview

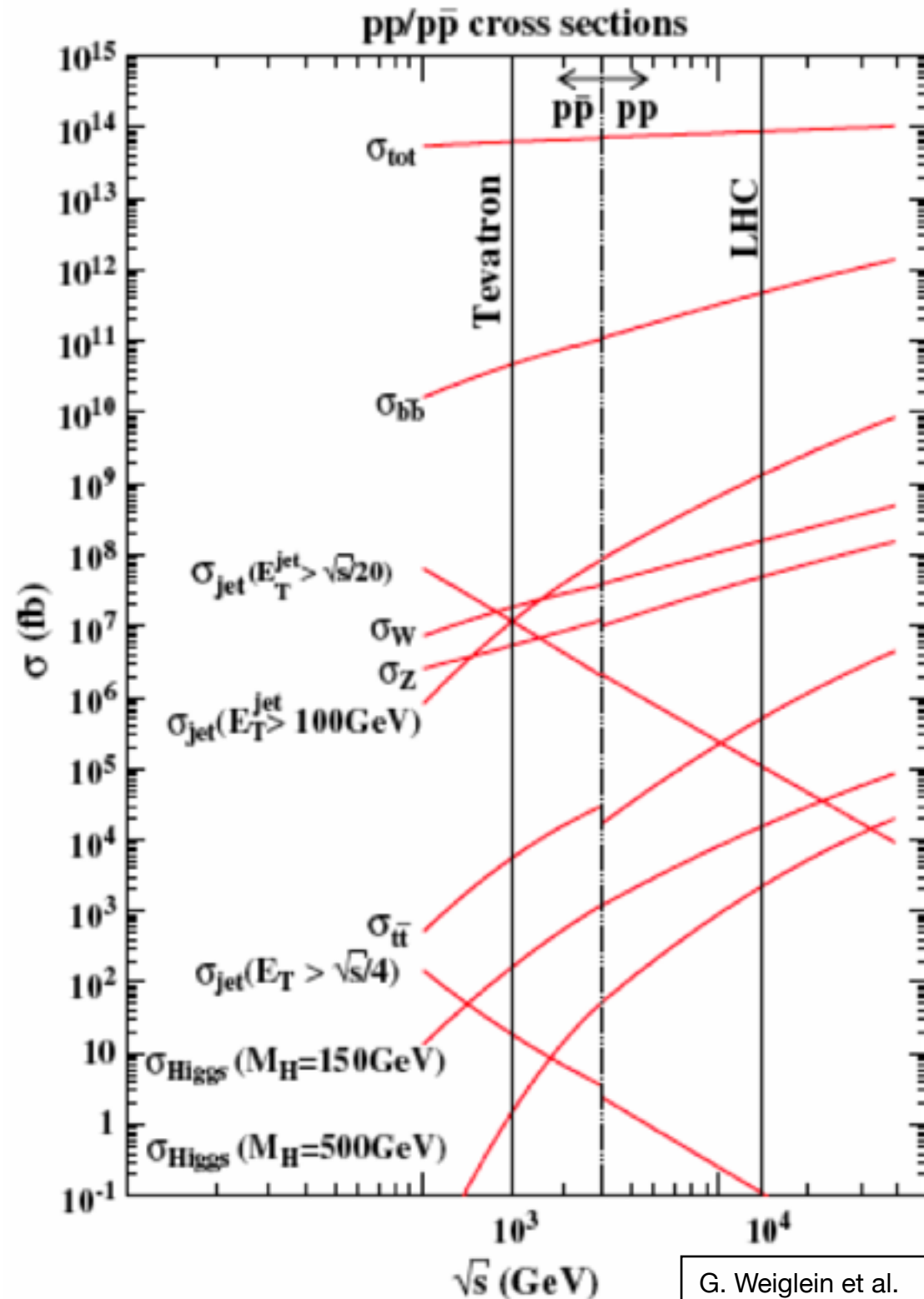
- Detectors in Particle and Astroparticle Physics
 - Large Detector Systems at LHC
 - Large Detectors in Astroparticle Physics
- Basics: Interaction of Particles with Matter
- Detection Techniques
- A Few Examples



Overview:

Detectors in Particle and Astroparticle Physics

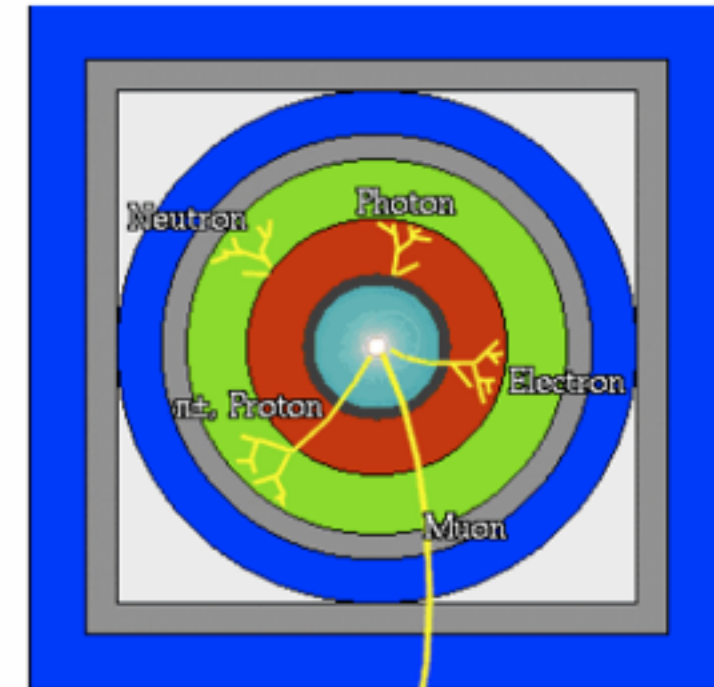
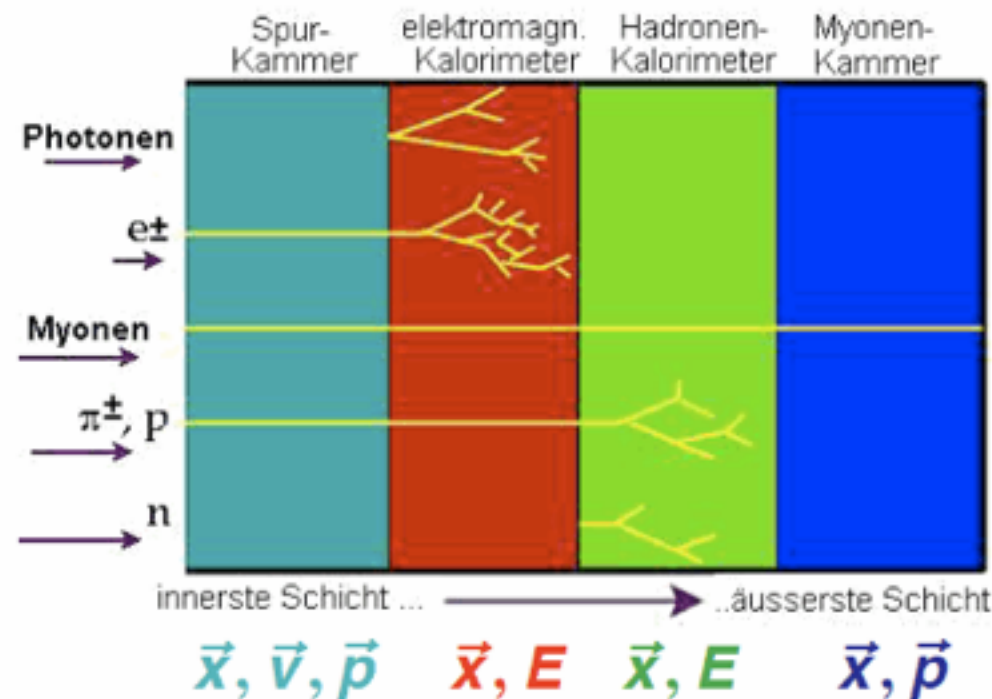
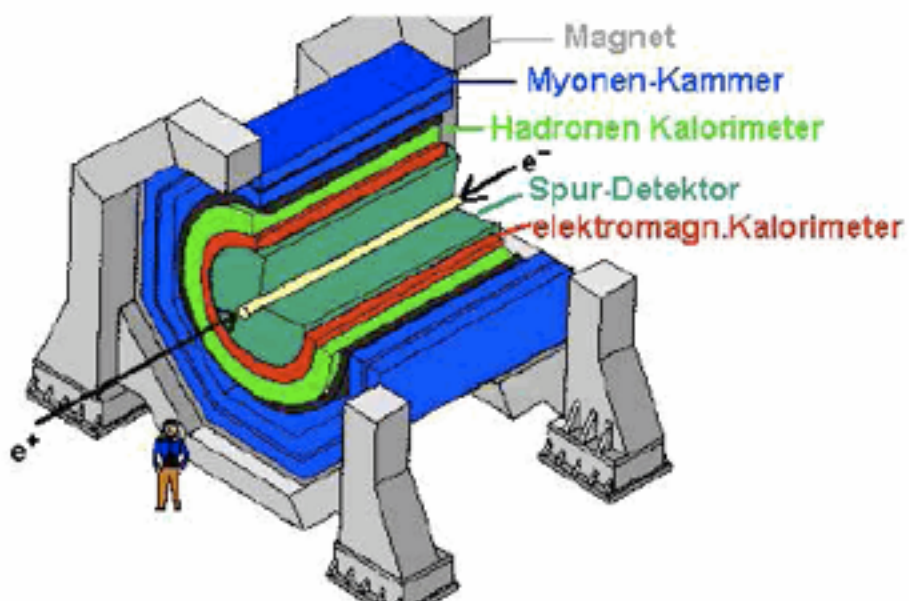
Challenges at Hadron-Colliders



- At Hadron-Colliders:
 - Extreme event rates:
Interesting processes are much rarer than “normal” processes
 - Detectors are optimized to cope with very high event rates and high particle density, and for picking up rare signatures out of large backgrounds

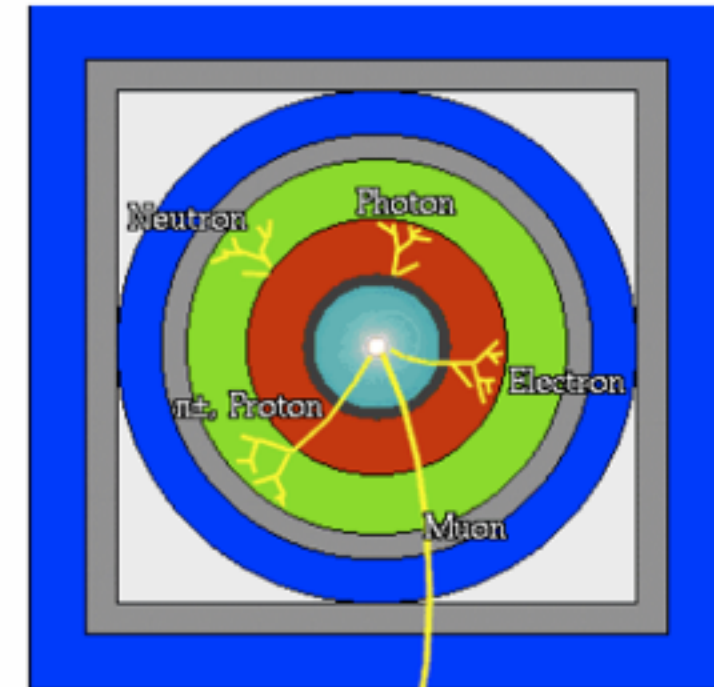
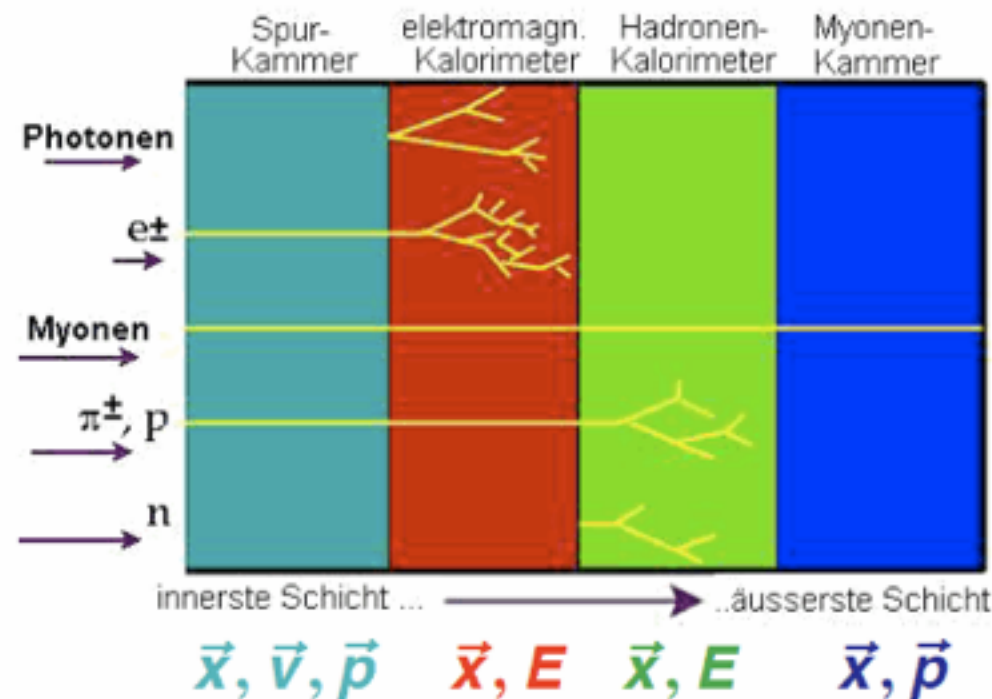
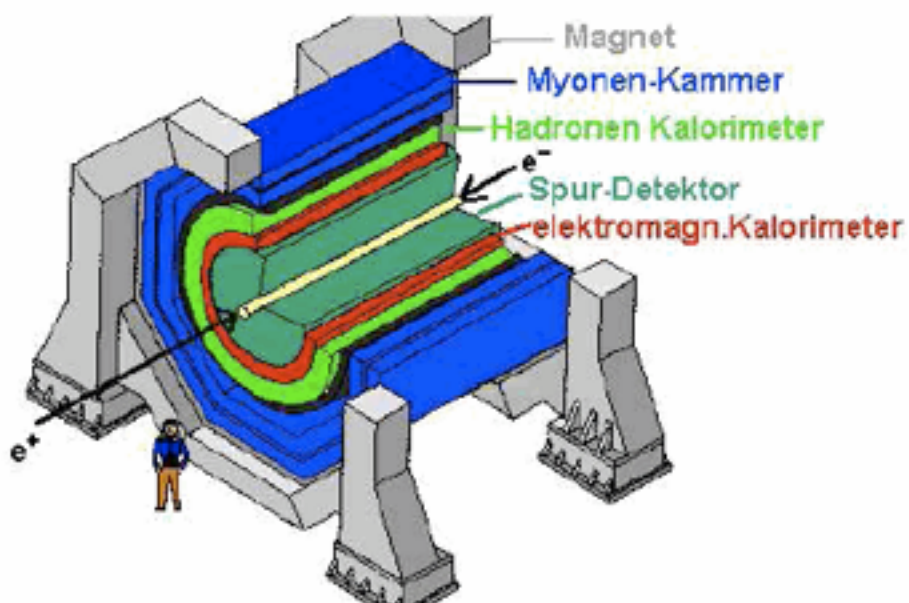
Detectors in Particle Physics

- Detection of the products of particle collisions in the detector system
 - Signals are obtained via electromagnetic interactions with the detector material



Detectors in Particle Physics

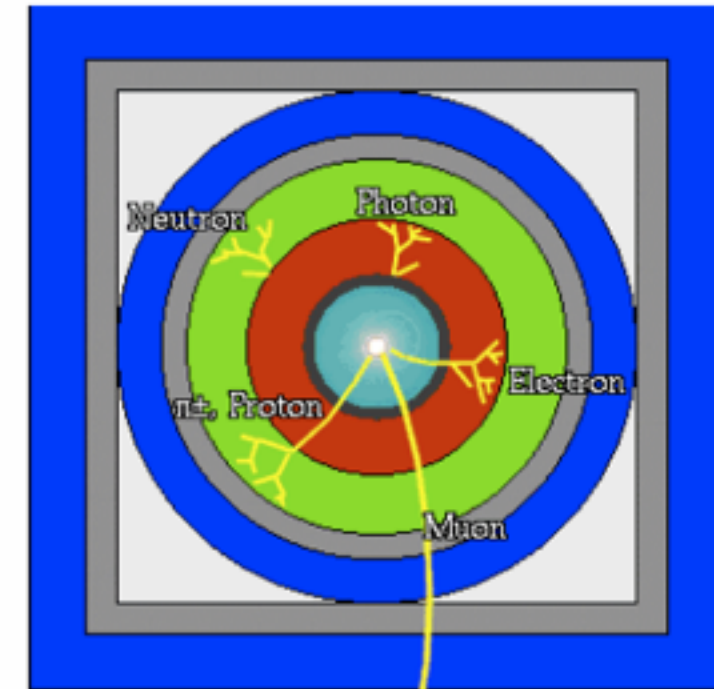
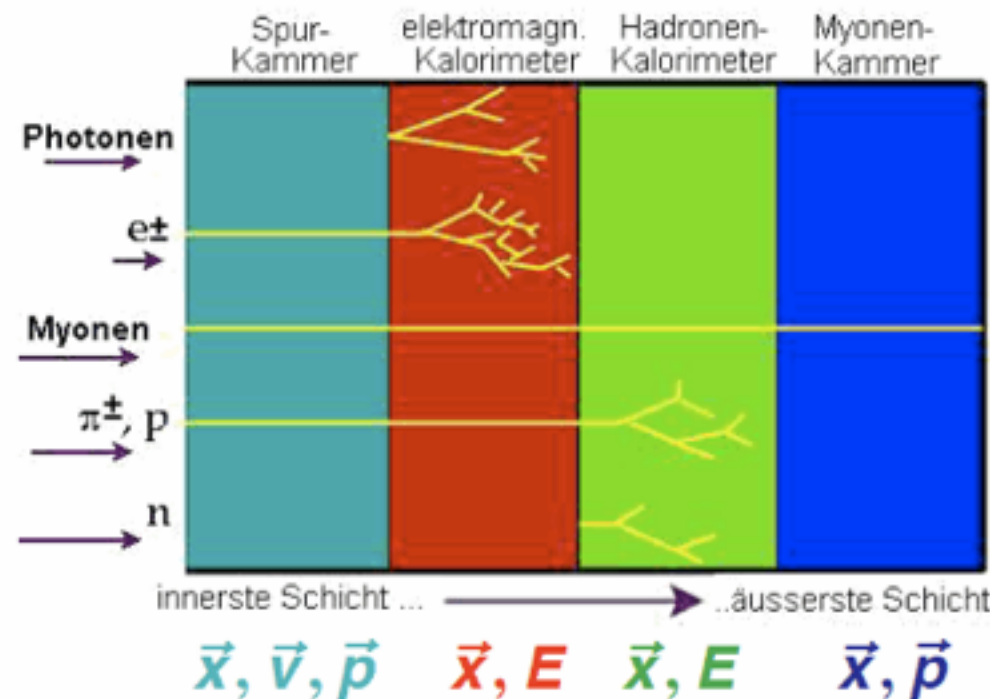
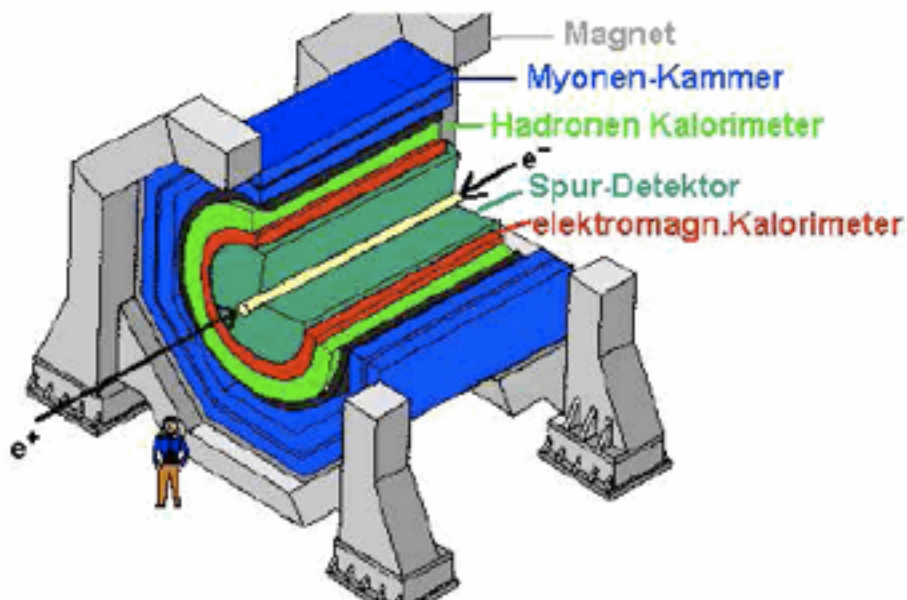
- Detection of the products of particle collisions in the detector system
 - Signals are obtained via electromagnetic interactions with the detector material



Tracker: Momentum of charged particles via deflection in magnetic field and precise track reconstruction

Detectors in Particle Physics

- Detection of the products of particle collisions in the detector system
 - Signals are obtained via electromagnetic interactions with the detector material

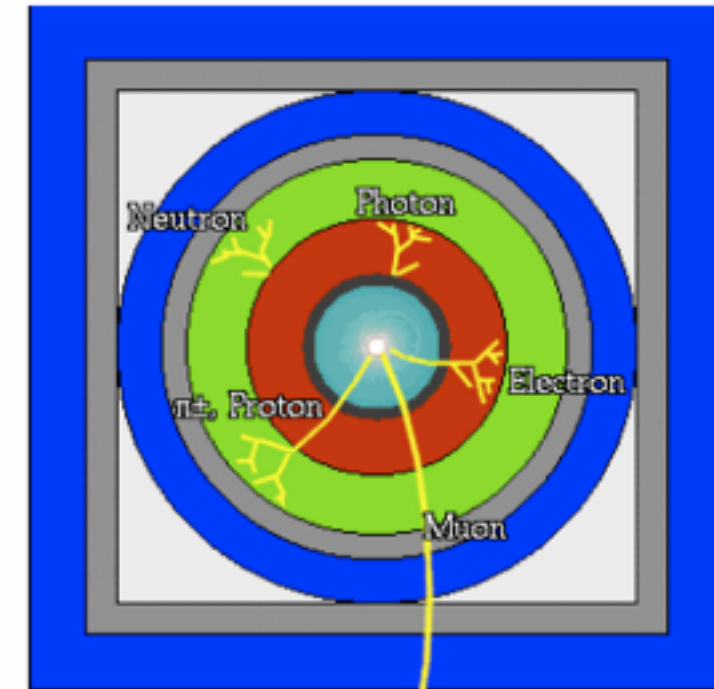
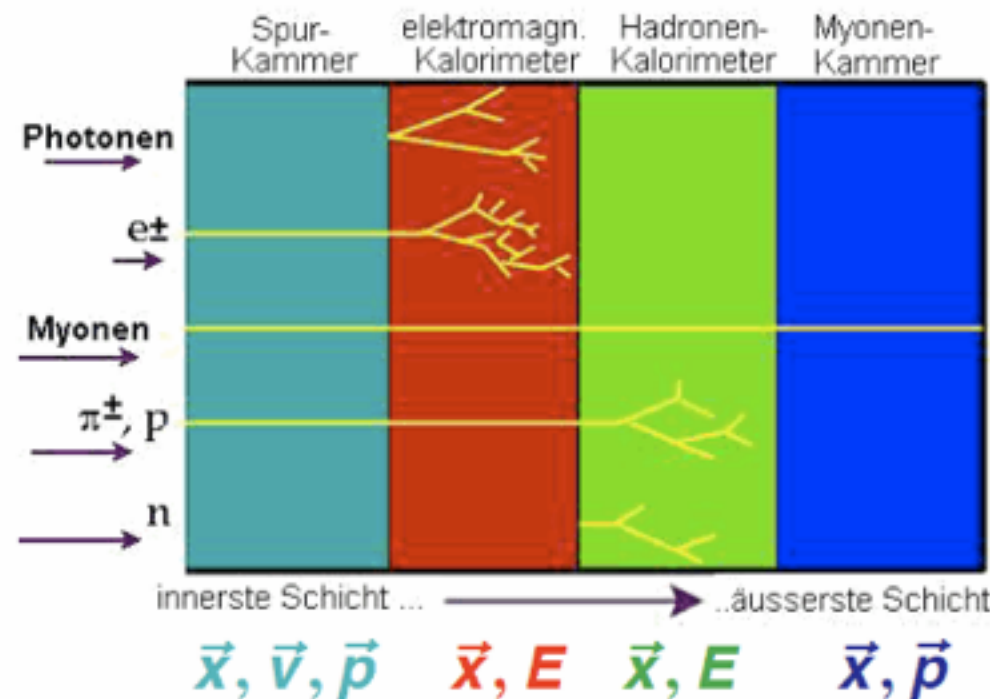
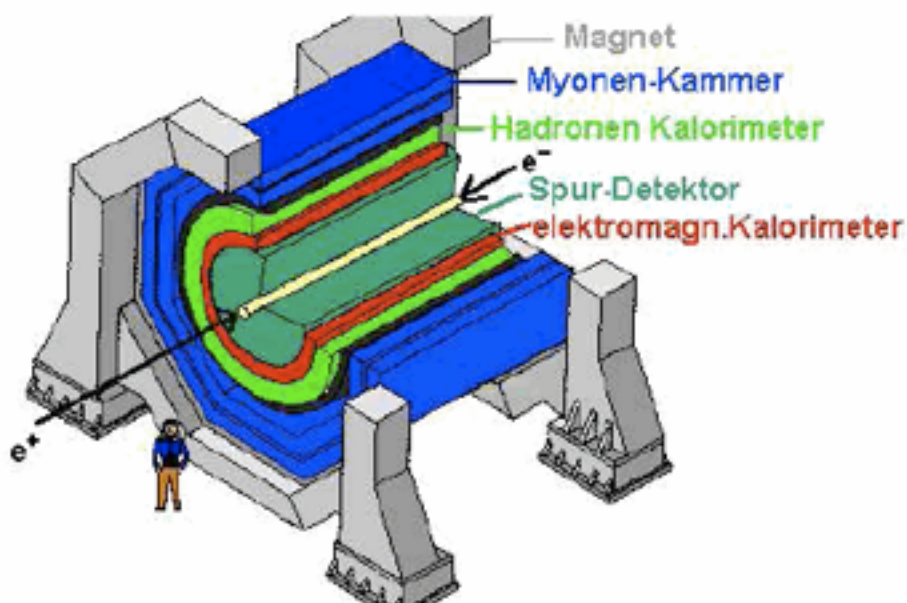


Tracker: Momentum of charged particles via deflection in magnetic field and precise track reconstruction

Calorimeter: Energy measurement of photons, electrons and hadrons via total absorption

Detectors in Particle Physics

- Detection of the products of particle collisions in the detector system
 - Signals are obtained via electromagnetic interactions with the detector material

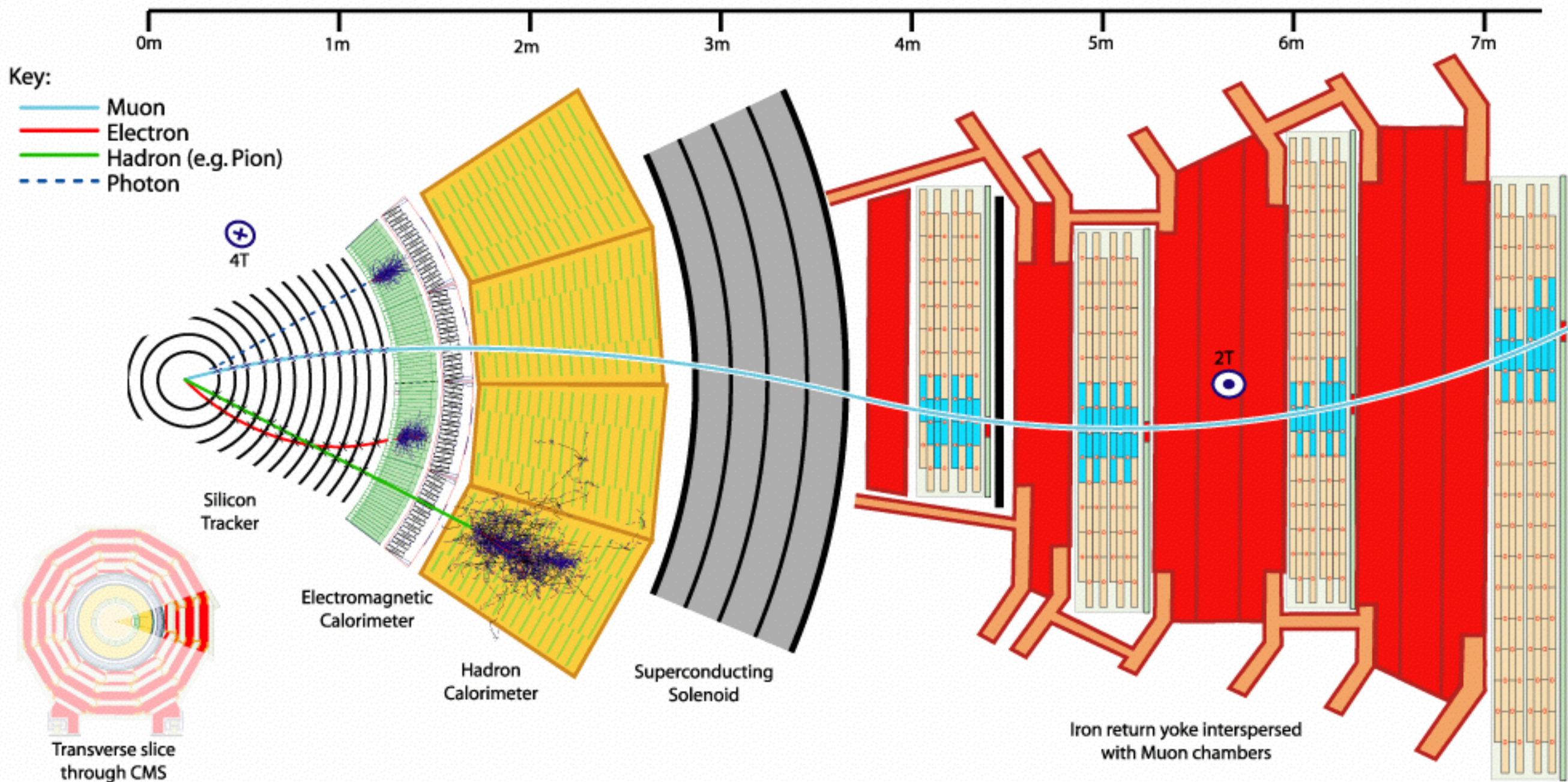


Tracker: Momentum of charged particles via deflection in magnetic field and precise track reconstruction

Calorimeter: Energy measurement of photons, electrons and hadrons via total absorption

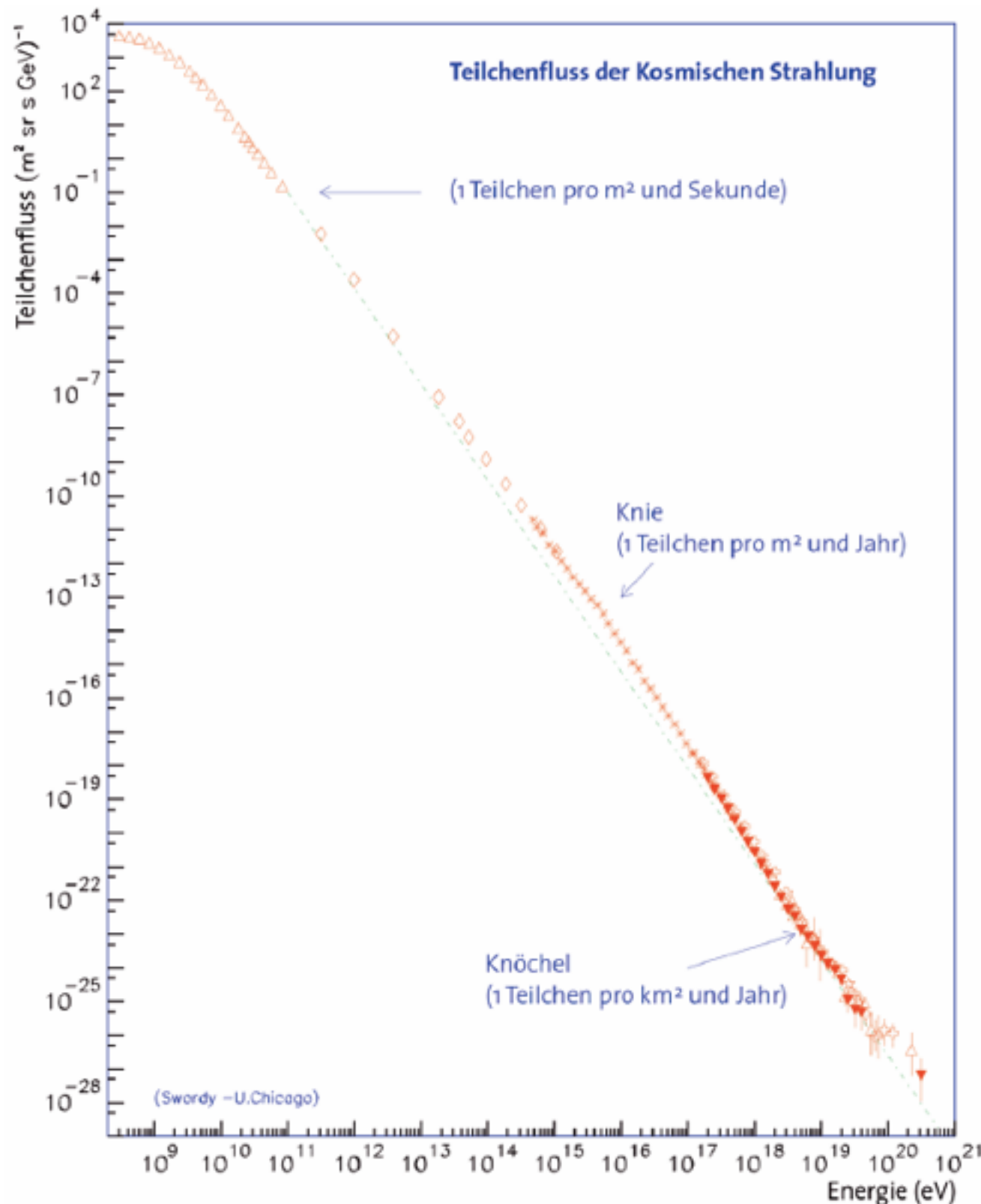
Muon Detectors: Identification and momentum measurement of muons

Collider-Detectors: Cross Section [CMS]



- High energies require high magnetic fields and large detectors
- Shown here: CMS, (C is for Compact!)

Challenges in Astroparticle Physics



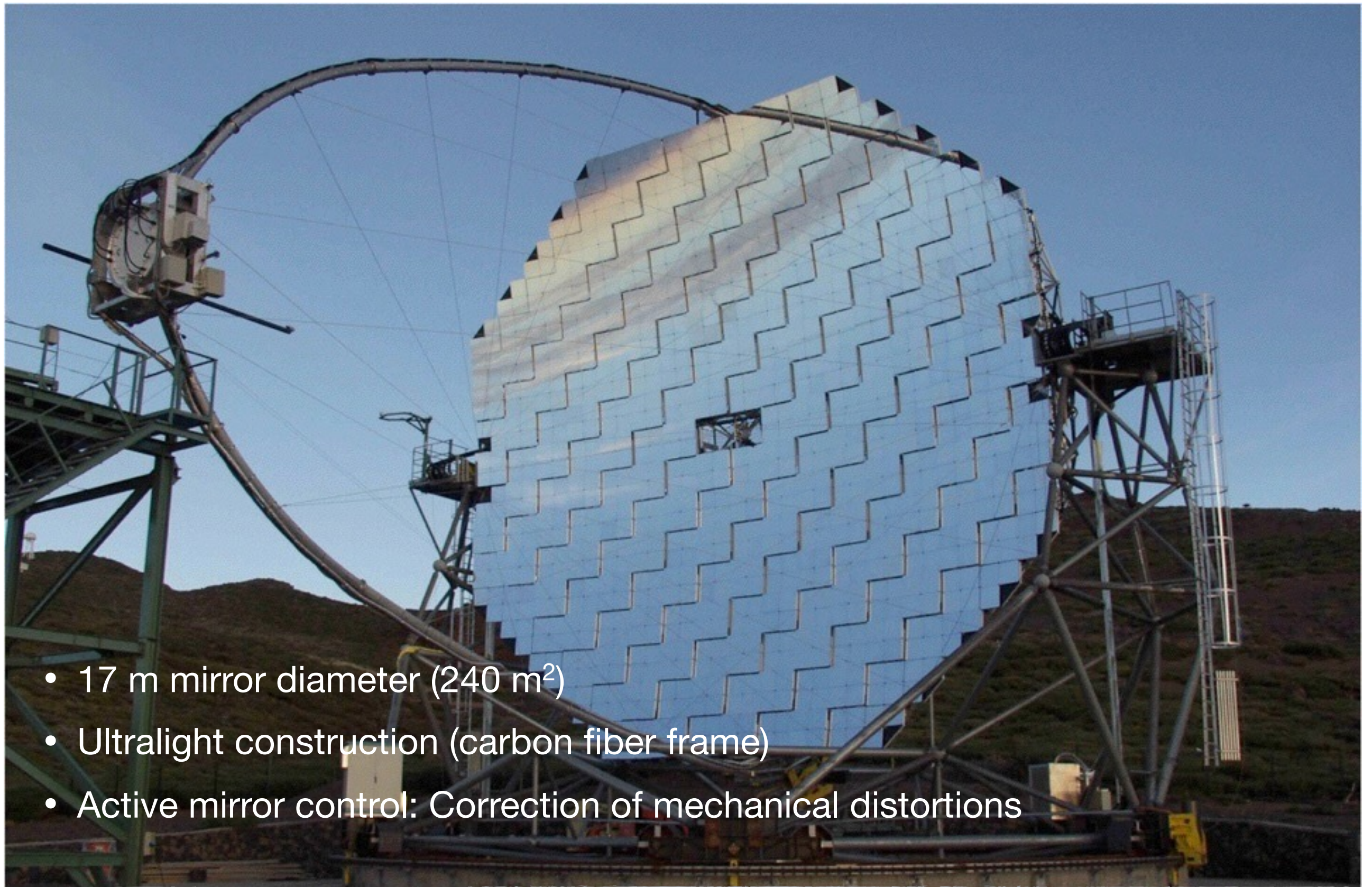
- Search for very rare events
 - ▶ Large areas / volumes have to be covered
 - ▶ Good suppression of background
 - ▶ High efficiency: Can not afford to lose events
 - ▶ Data rates, radiation damage, ... usually not an issue

What do we want to measure?

- Highly energetic particles from cosmic sources: hadrons, photons
 - Either: Measurement outside of the atmosphere
 - Or: Use of the atmosphere as detector, particle detectors via air showers
- Neutrinos
 - Low cross section => Large detector volumes
- Dark Matter
 - Low cross sections => large sensitive volumes / masses, extreme suppression of background

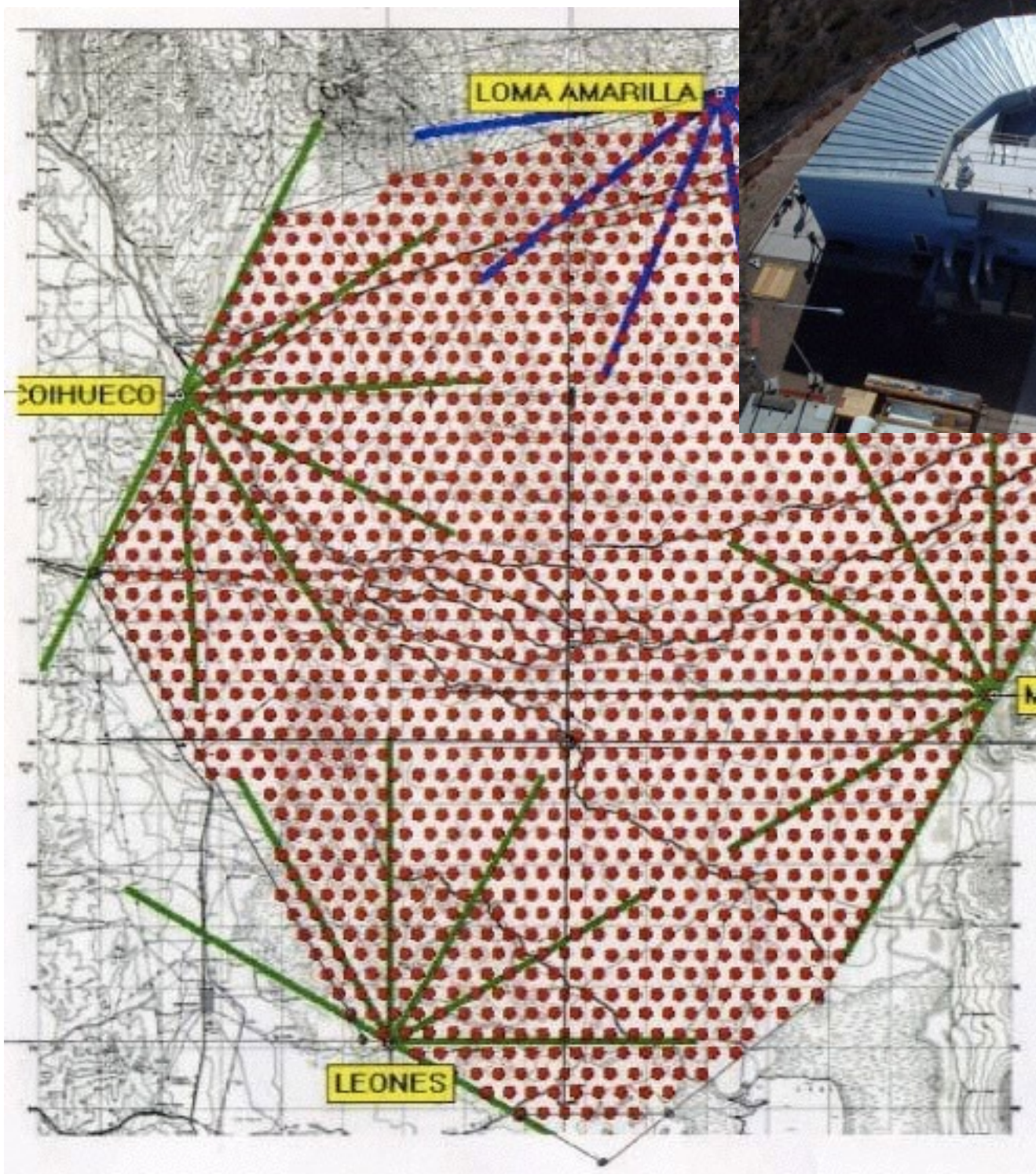


MAGIC: High-Energy Gammas



- 17 m mirror diameter (240 m²)
- Ultralight construction (carbon fiber frame)
- Active mirror control: Correction of mechanical distortions

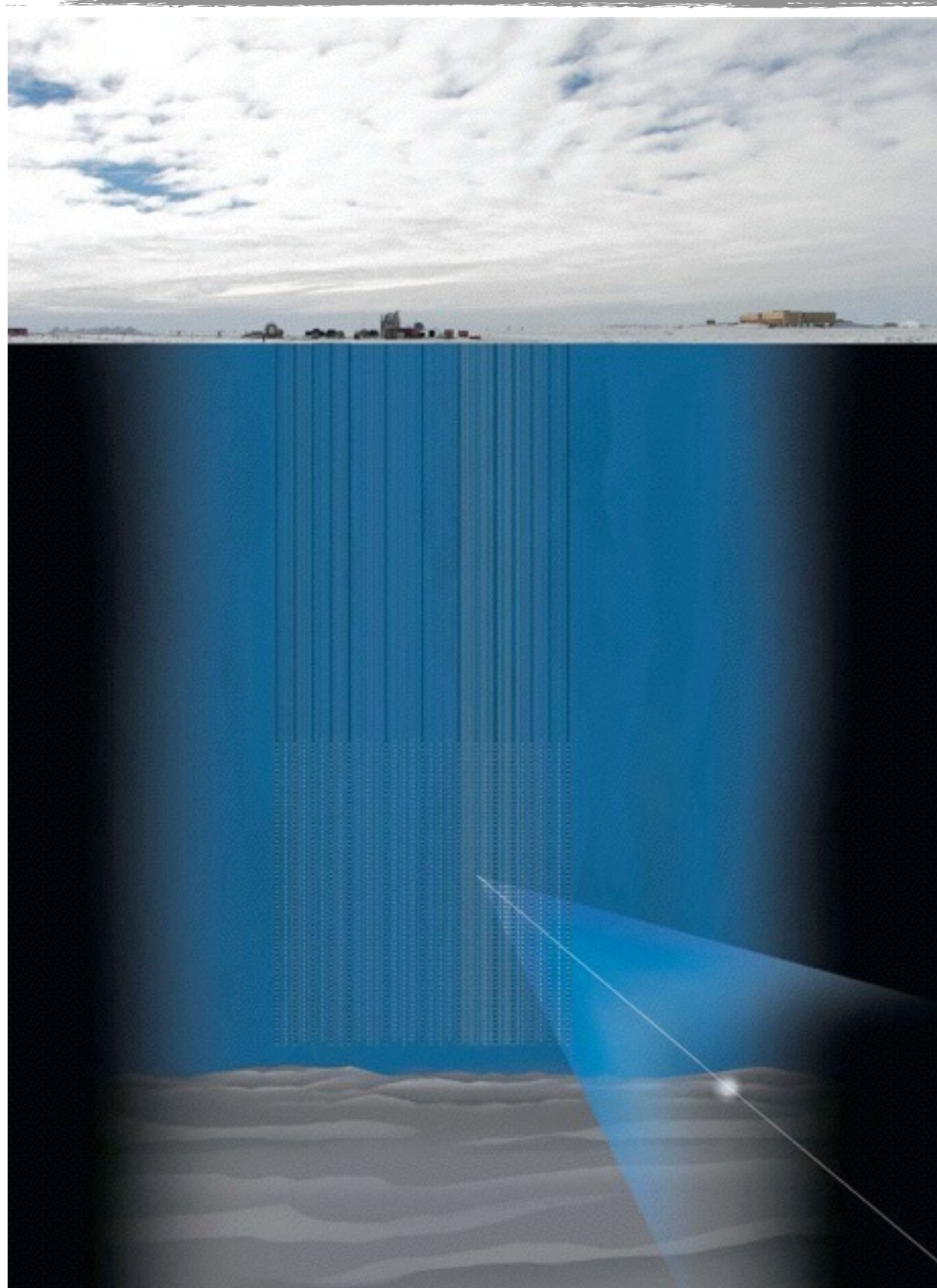
AUGER: Highly Energetic Charged Particles



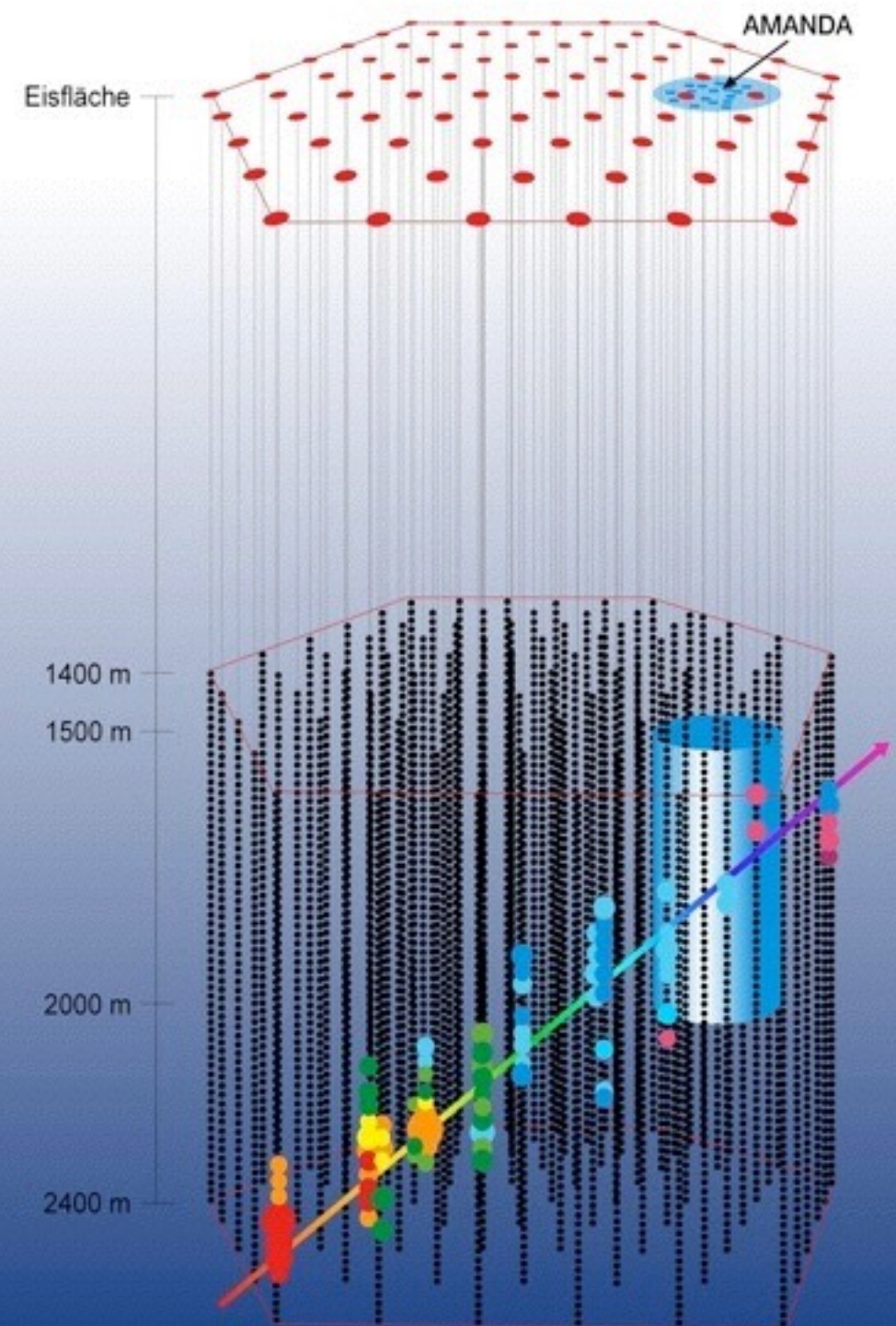
- 1600 Water-Cherenkov-detectors on the ground
- 4 fluorescence stations with 6 telescopes each
- 3000 km²



Amanda/IceCube



IceCube: 1 km³ instrumented volume

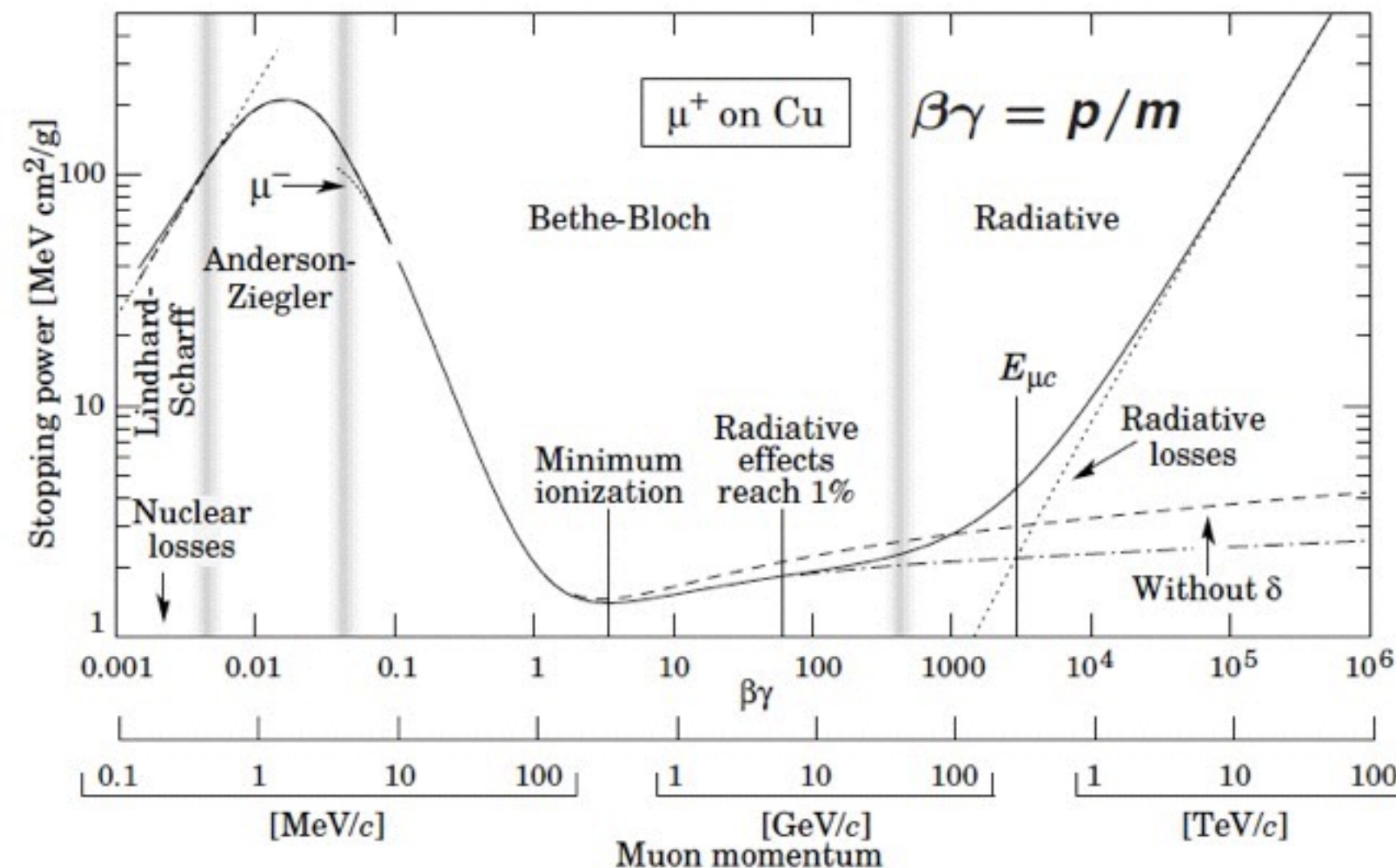


The Basics of Particle Detection: Interaction of Particles with Matter

Energy Loss in Matter: Bethe-Bloch

- The Bethe-Bloch equation describes energy loss through ionization

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



- Valid in intermediate energy range: $\sim 0.1 < \beta\gamma < \sim 1000$
 - at low energies: atomic effects
 - at high energies: radiative energy loss in addition
- Z/A Dependence: high energy loss in H**
- $1/\beta^2$ for low momenta: Heavy particles lose more energy
- Minimum at $p/m \sim 3-4$: minimum ionizing particle MIP
- Logarithmic rise for high energy
- Additional density effect due to polarization of absorber

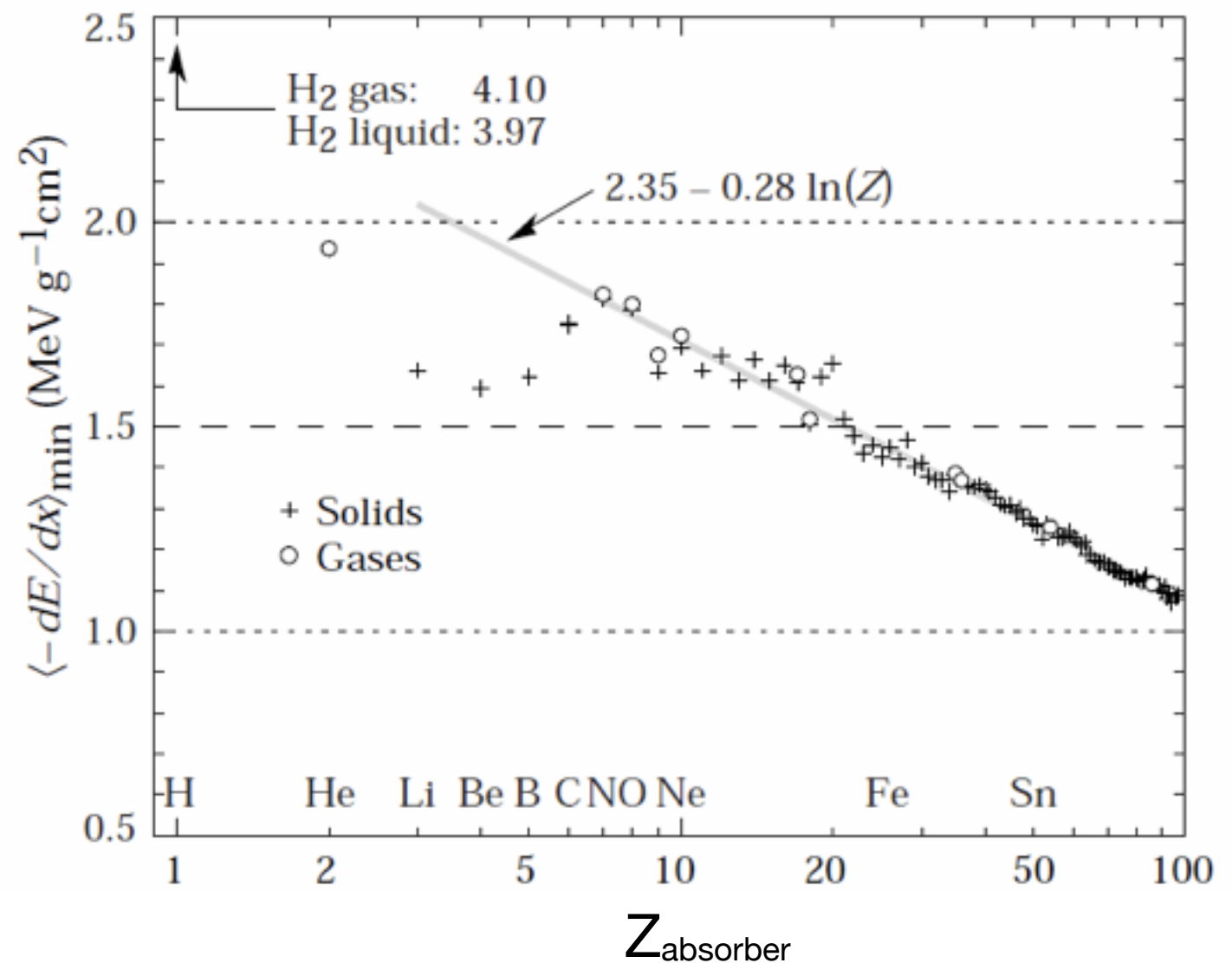
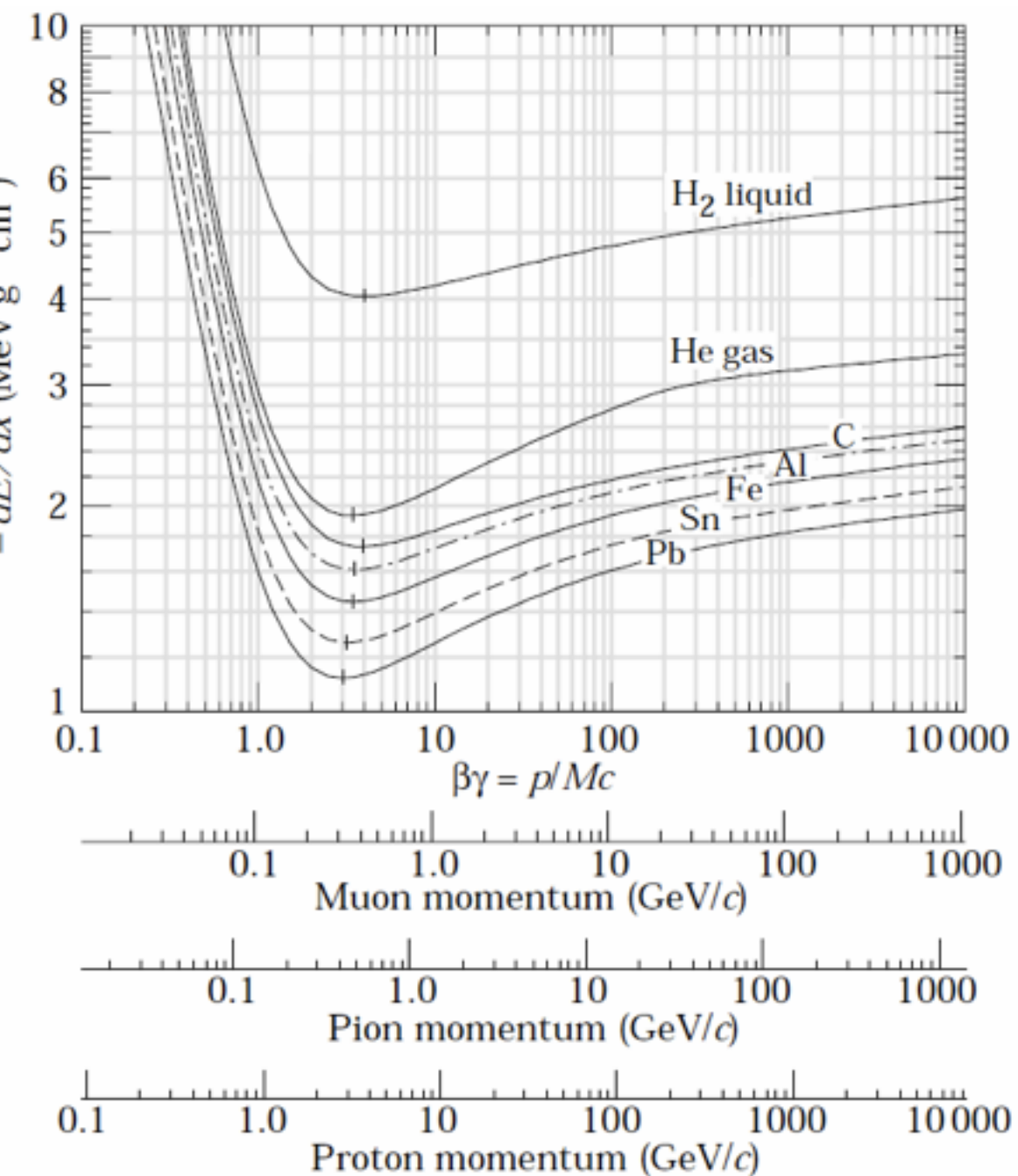
Important Constants

Symbol	Definition	Wert und/oder Dimension
α	Feinstrukturkonstante	$1/137.03599976(50)$
m	Masse des einfallenden Teilchens	MeV/c^2
E	Energie des Teilchens	MeV
T	kinetische Energie des Teilchens	MeV
$z \cdot e$	Ladung des Teilchens	$z \cdot 1.6021 \cdot 10^{-19} \text{ C}$
r_e	klassischer Elektronenradius	$2.817940285(31) \text{ fm}$
N_A	Avogadro-Zahl	$6.02214199(47) \cdot 10^{-23} / \text{mol}$
$Z; A$	Atomzahl; Atomgewicht des Absorbers	—; g/mol
K	$4\pi N_A r_e m_e c^2$	$0.307075 \text{ MeV cm}^2$
δ	Dichtekorrektur zur Ionisation	
E_p	Plasmaenergie	$28.816 \sqrt{\rho \langle Z/A \rangle} \text{ eV}, \rho \text{ in g/cm}^3$
X_0	Strahlungslänge	g/cm^2
λ_a	Absorptionslänge	g/cm^2
T_{max}	Maximal übertragbare kinetische Energie	MeV
I	Mittlere Ionisationsenergie	eV
$E_c; E_{\mu c}$	Kritische Energie für Elektronen; Myonen	$\text{MeV}; \text{GeV}$

- Mean ionization energy:

$$I \sim 16 Z^{0.9} \text{ eV for } Z > 1$$

Material Dependence of Energy Loss



- Ballpark number to remember:
Energy loss of MIPs ($\beta\gamma \sim 3$):
1-2 MeV g⁻¹ cm² (exception: H)

Electrons & Photons: Radiation Length

- The relevant material constant: ***radiation length X_0***
 - Describes high-energy electrons and photons (energy loss via Bremsstrahlung and e^+e^- - pair creation)

Electrons & Photons: Radiation Length

- The relevant material constant: ***radiation length X_0***
 - Describes high-energy electrons and photons (energy loss via Bremsstrahlung and e^+e^- - pair creation)
- Defined as the amount of matter that has to be traversed so that
 - an electron loses all but $1/e$ of its energy via Bremsstrahlung
 - $7/9$ of the mean free path of photons for pair creation



Electrons & Photons: Radiation Length

- The relevant material constant: ***radiation length X_0***
 - Describes high-energy electrons and photons (energy loss via Bremsstrahlung and e^+e^- - pair creation)
 - Defined as the amount of matter that has to be traversed so that
 - an electron loses all but 1/e of its energy via Bremsstrahlung
 - 7/9 of the mean free path of photons for pair creation

empirical formula:
$$X_0 = \frac{716.4 A}{Z(1+Z) \ln(287/\sqrt{Z})} \frac{g}{cm^2} \propto \frac{A}{Z^2}$$

Electrons & Photons: Radiation Length

- The relevant material constant: ***radiation length X_0***
 - Describes high-energy electrons and photons (energy loss via Bremsstrahlung and e^+e^- - pair creation)
 - Defined as the amount of matter that has to be traversed so that
 - an electron loses all but $1/e$ of its energy via Bremsstrahlung
 - $7/9$ of the mean free path of photons for pair creation

empirical formula:
$$X_0 = \frac{716.4 A}{Z(1+Z) \ln(287/\sqrt{Z})} \frac{g}{cm^2} \propto \frac{A}{Z^2}$$

- Also relevant for the description of low-angle multiple scattering

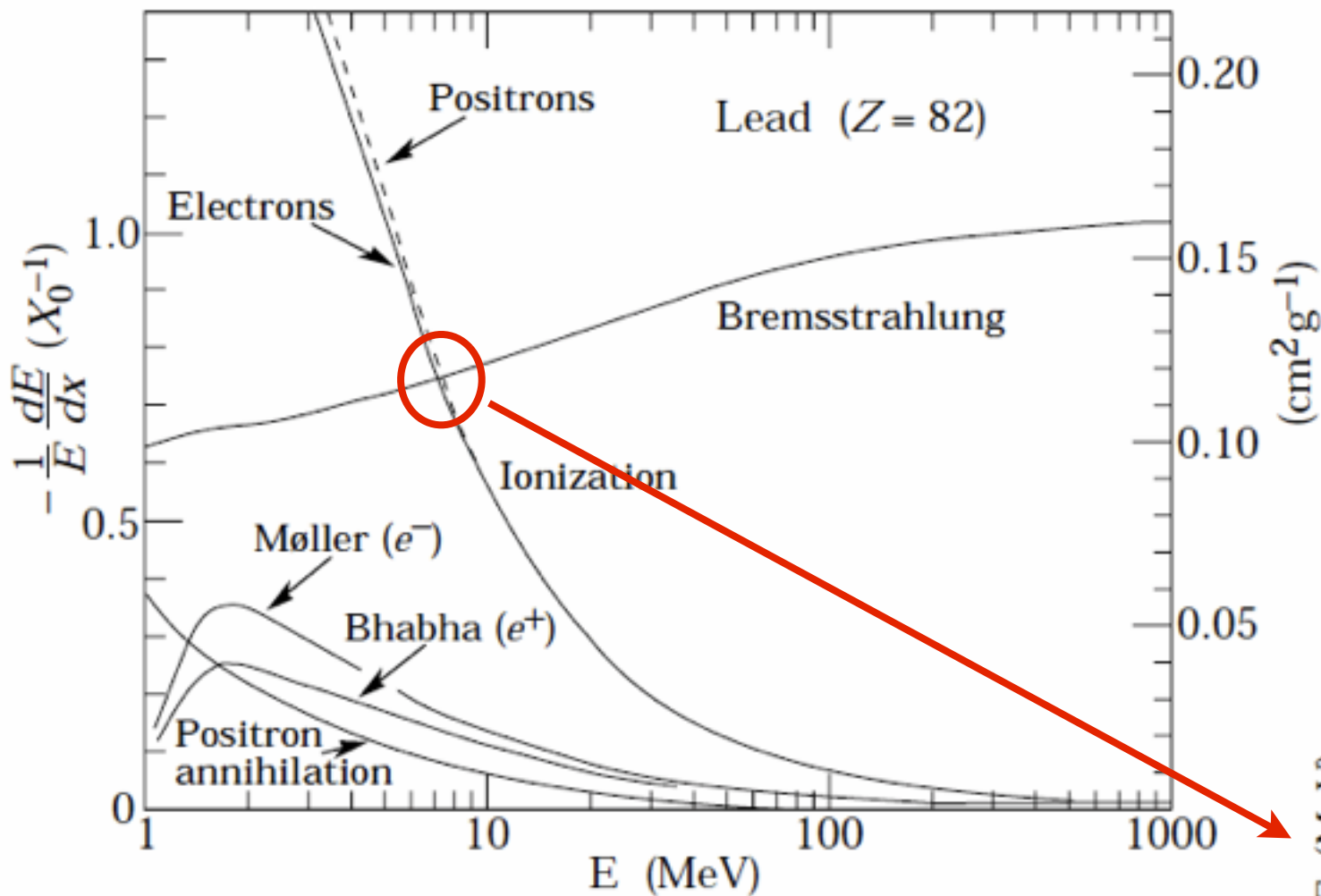
Electrons & Photons: Radiation Length

- The relevant material constant: **radiation length X_0**
 - Describes high-energy electrons and photons (energy loss via Bremsstrahlung and e^+e^- - pair creation)
 - Defined as the amount of matter that has to be traversed so that
 - an electron loses all but 1/e of its energy via Bremsstrahlung
 - 7/9 of the mean free path of photons for pair creation

empirical formula:
$$X_0 = \frac{716.4 A}{Z(1+Z) \ln(287/\sqrt{Z})} \frac{g}{cm^2} \propto \frac{A}{Z^2}$$

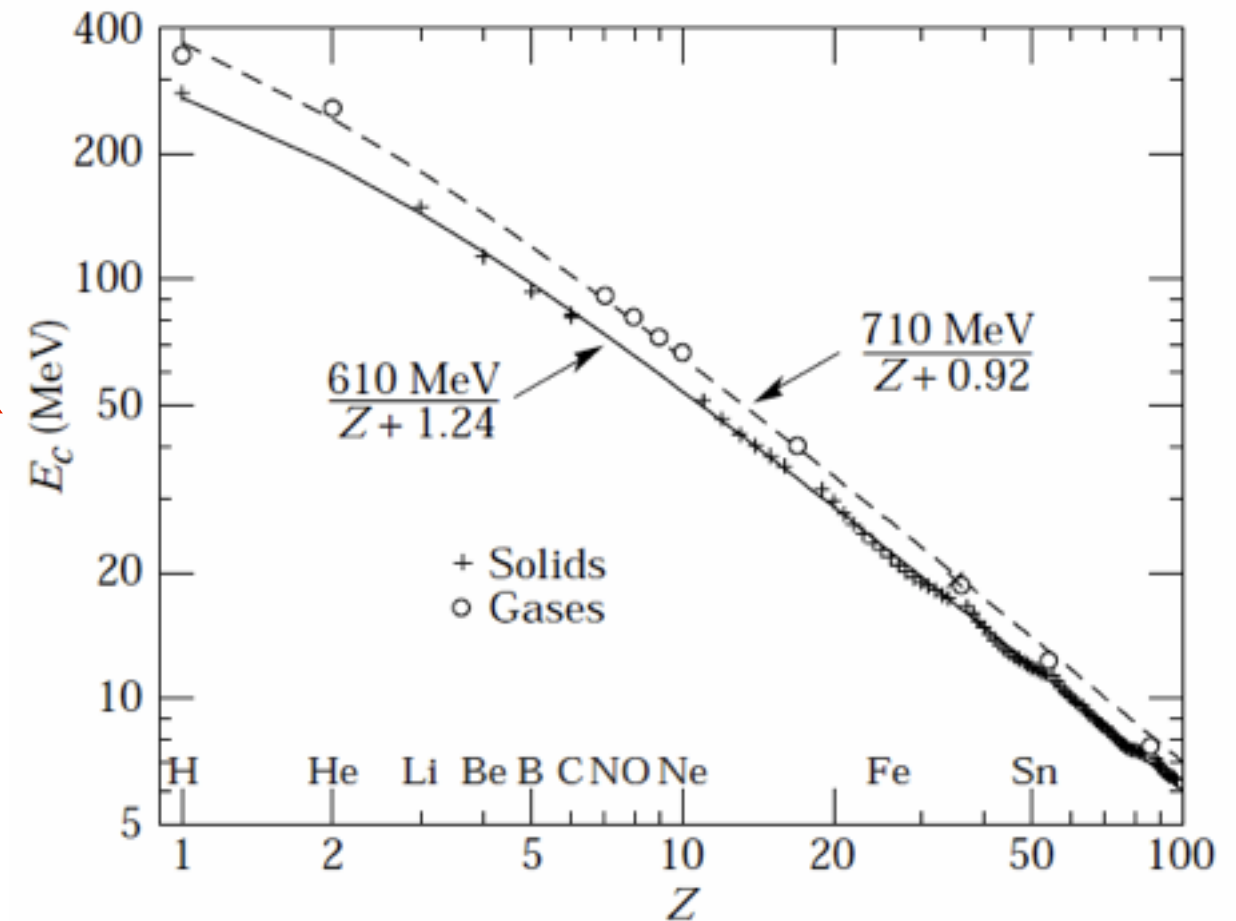
- Also relevant for the description of low-angle multiple scattering
- Usually given in g/cm², typical values for some materials:
 - Air: 36.66 g/cm², corresponds to ~ 300 m
 - Water: 36.08 g/cm², corresponds to ~ 36 cm
 - Aluminum: 24.01 g/cm², corresponds to 8.9 cm
 - Tungsten: 6.76 g/cm², corresponds to 0.35 cm

Electrons: Energy Loss



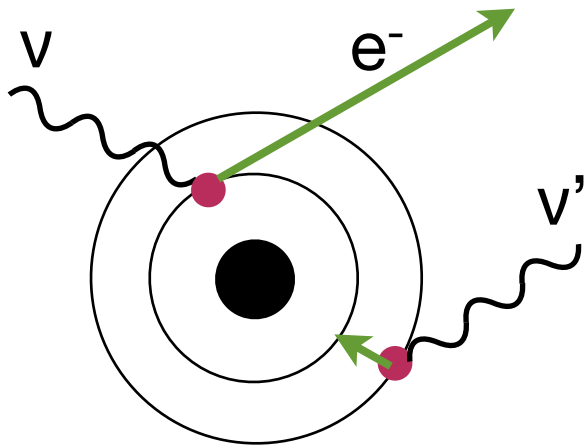
- Bremsstrahlung dominates at high energies
- At low energies: Ionization, scattering

- Critical energy: The energy where ionization and radiative energy loss are equal

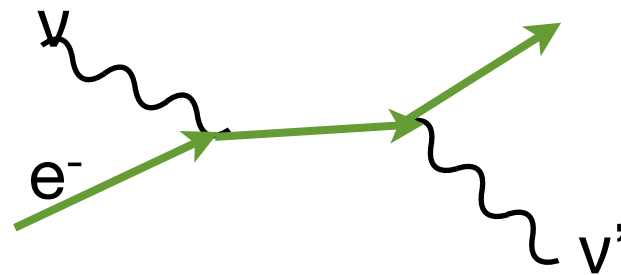


Photons: Interaction

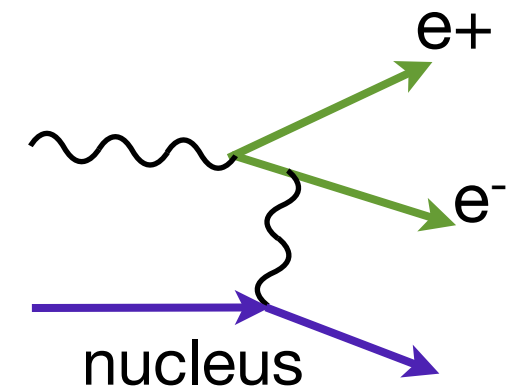
Photo effect



Compton scattering



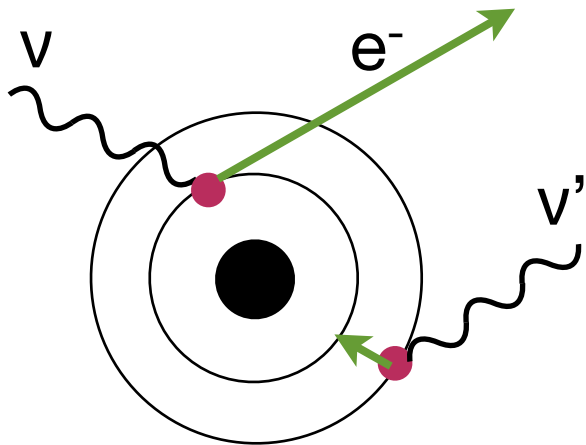
Pair creation



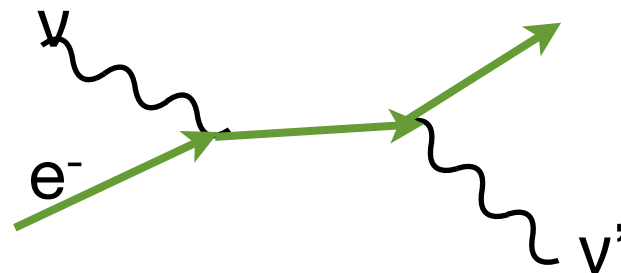
energy threshold:
 $2 m_e = \sim 1.022 \text{ MeV}$

Photons: Interaction

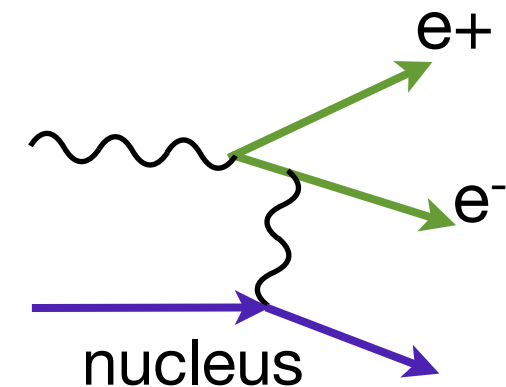
Photo effect



Compton scattering



Pair creation

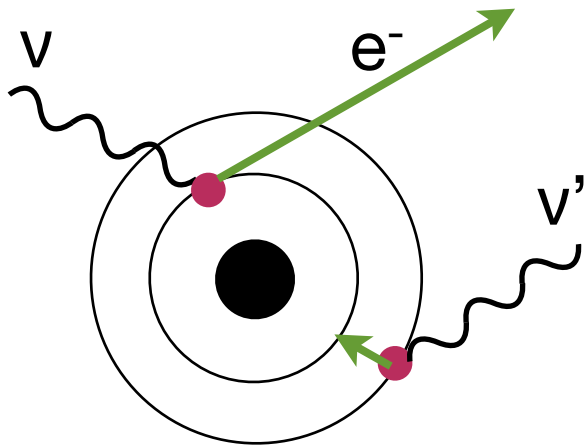


energy threshold:
 $2 m_e = \sim 1.022 \text{ MeV}$

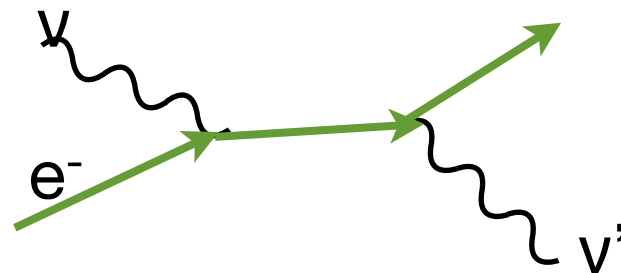
- In contrast to dE/dx of charged particles:
“all-or-nothing” reactions with a certain probability

Photons: Interaction

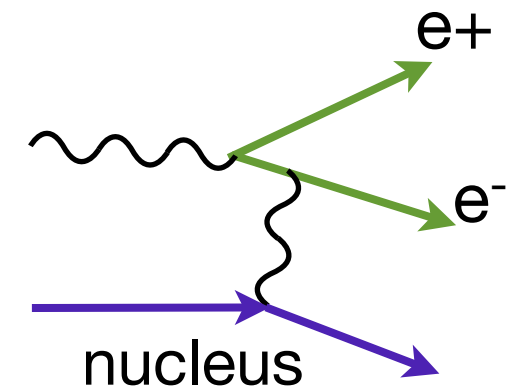
Photo effect



Compton scattering



Pair creation



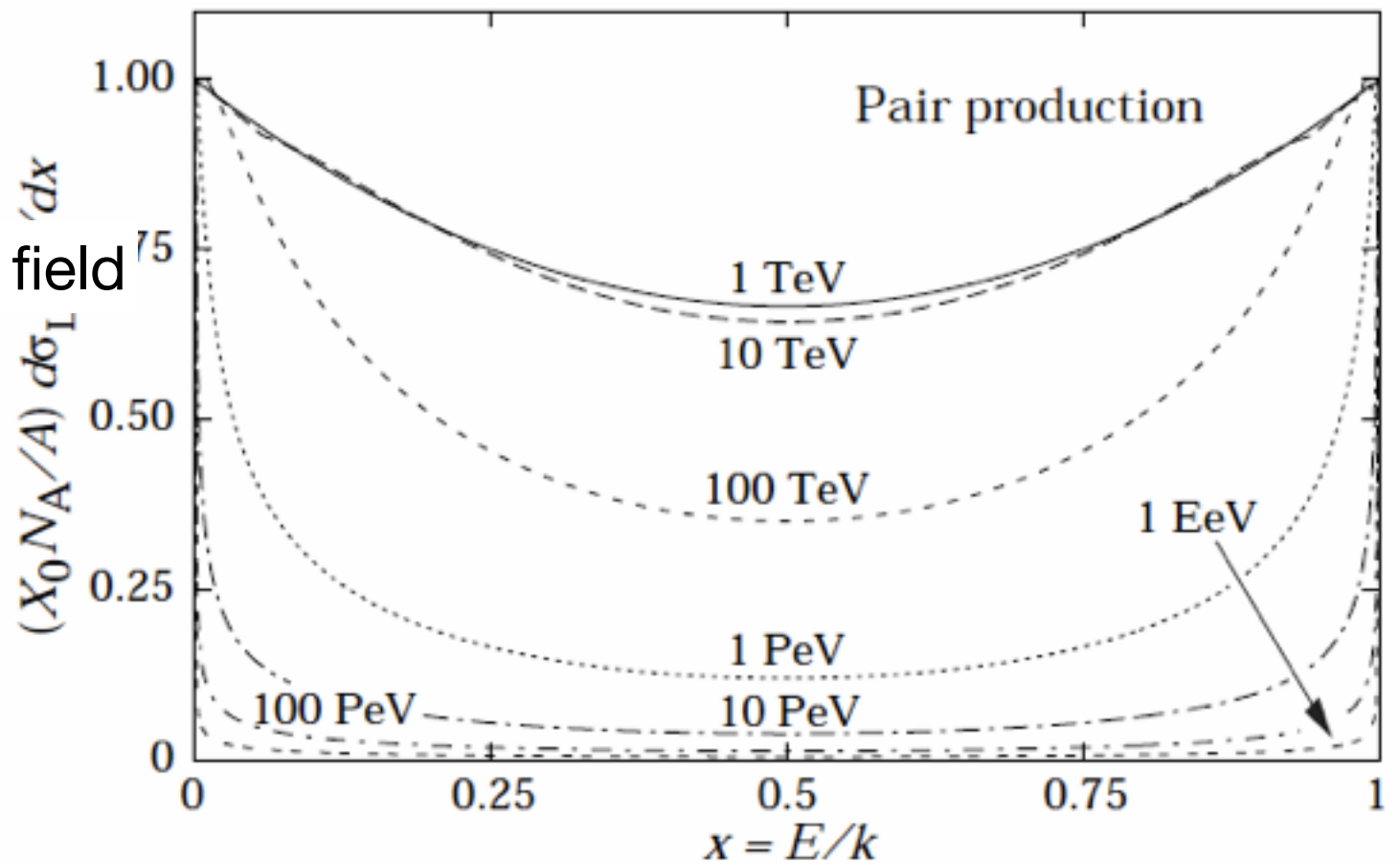
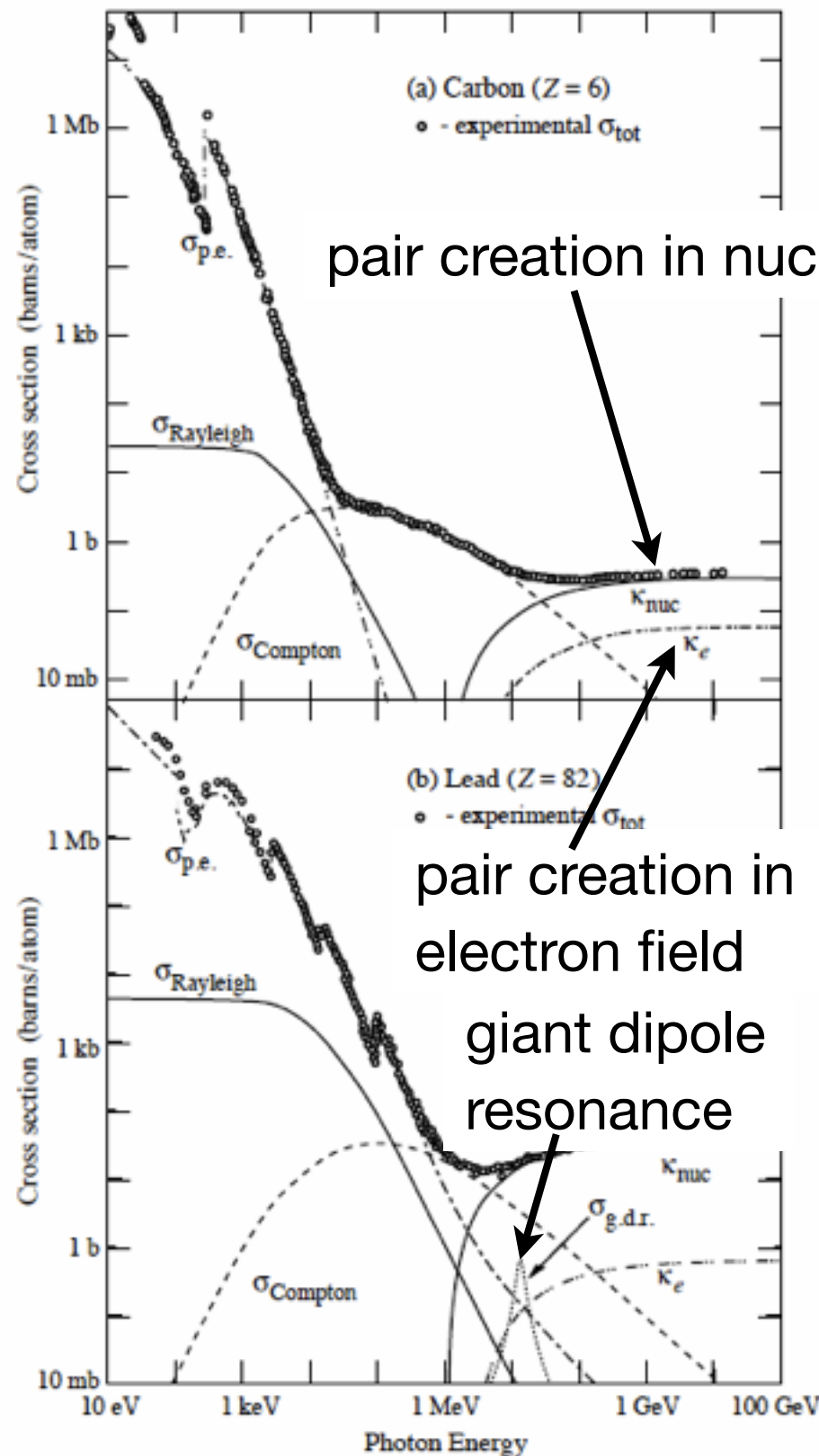
energy threshold:
 $2 m_e = \sim 1.022 \text{ MeV}$

- In contrast to dE/dx of charged particles:
“all-or-nothing” reactions with a certain probability

⇒ Decrease of photon intensity with material thickness

$$I(x) = I_0 e^{-\mu x}$$

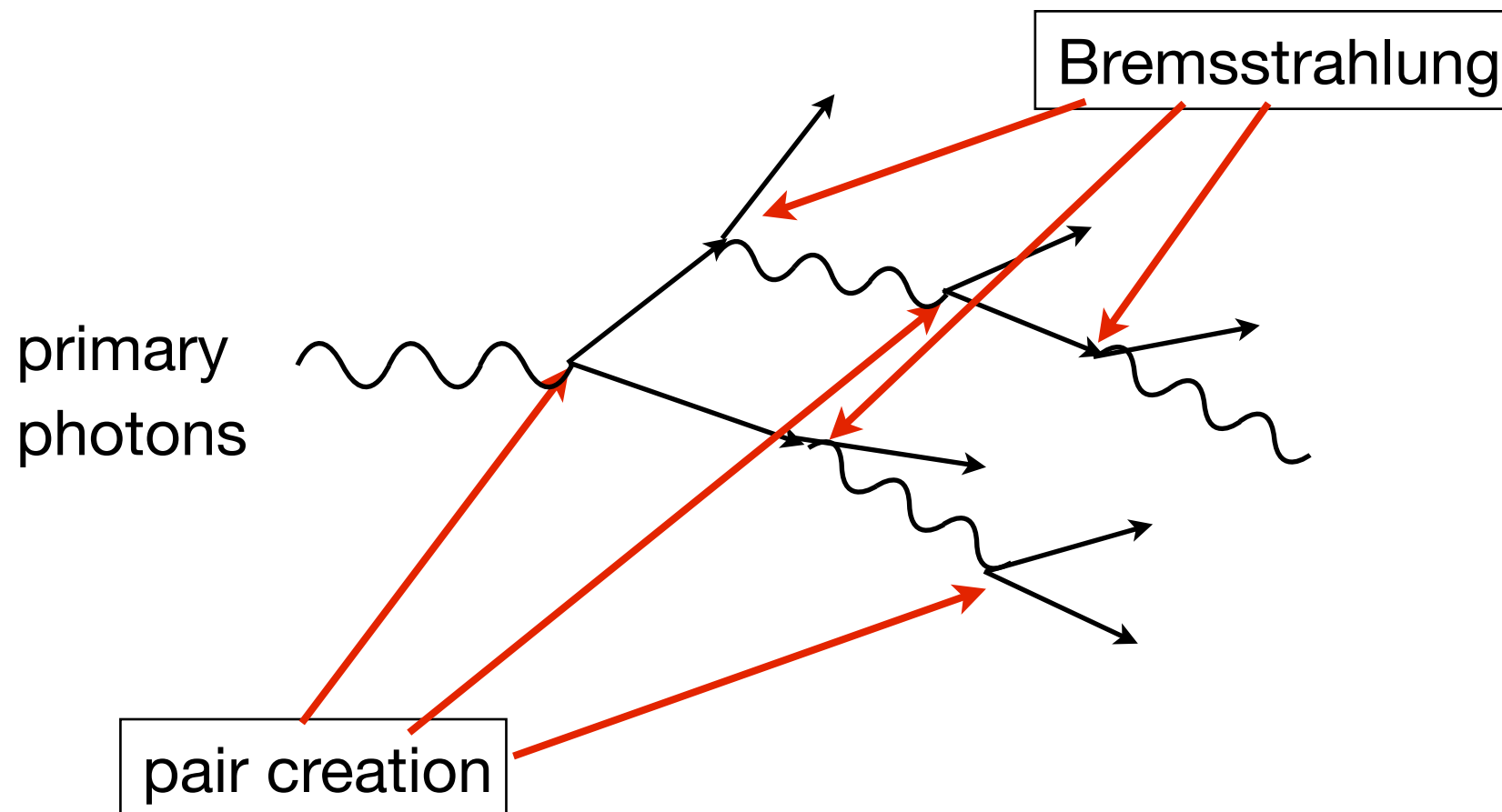
Photons in Matter



- At high energies pair production dominates
- Lower energies:
 - photo-electric effect
 - coherent scattering: Rayleigh scattering
 - Compton scattering
 - nuclear excitation

Electromagnetic Cascades

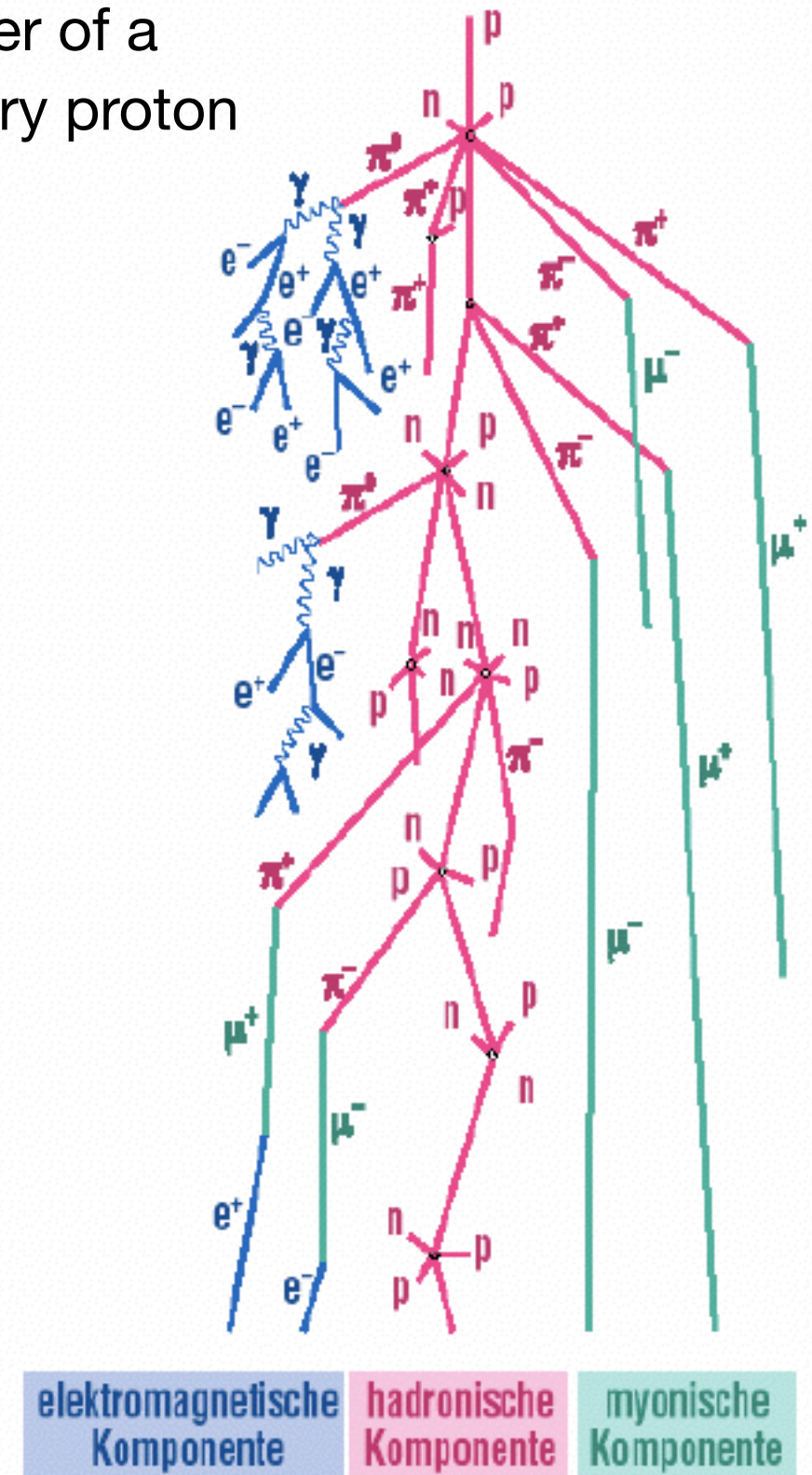
- Highly energetic electrons and photons (energies substantially above the pair creation threshold, i.e. several MeV) lead to electromagnetic showers in matter:
- A combination of Bremsstrahlung und pair creation until the initial energy is used up



Particle Showers

- Highly energetic charged particles and photons from space create a shower in the atmosphere
- A cascade of particles, the number of particles is proportional to the energy of the primary particle: 1-1.5 particles / GeV in shower maximum

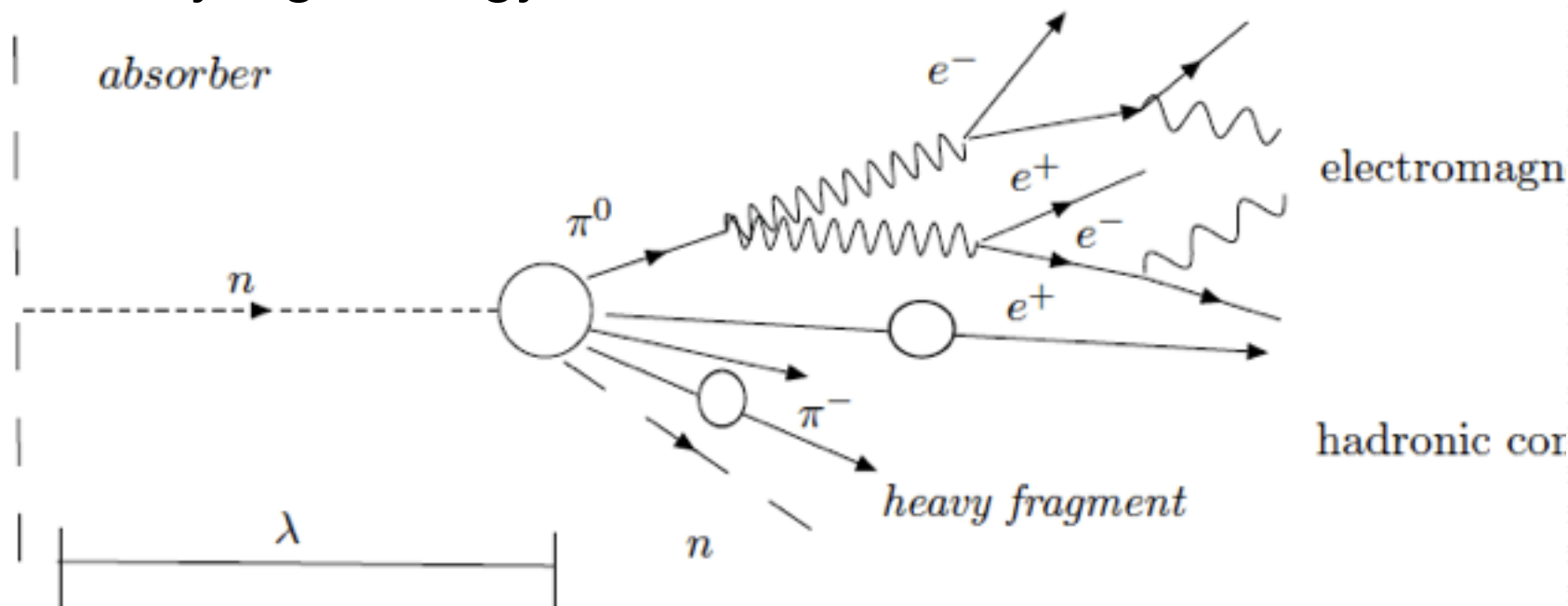
shower of a primary proton



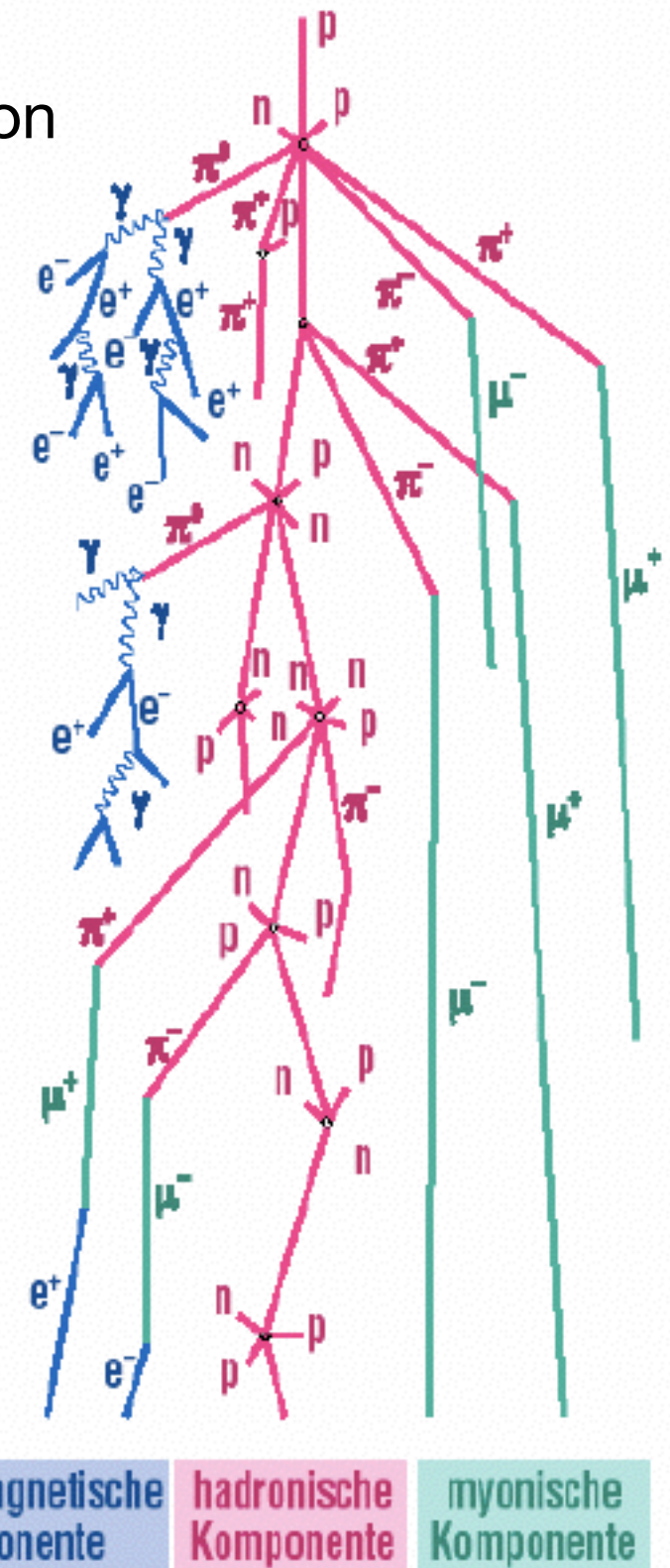
Particle Showers

- Highly energetic charged particles and photons from space create a shower in the atmosphere
- A cascade of particles, the number of particles is proportional to the energy of the primary particle: 1-1.5 particles / GeV in shower maximum

Also hadronic showers have mostly EM-character at very high energy

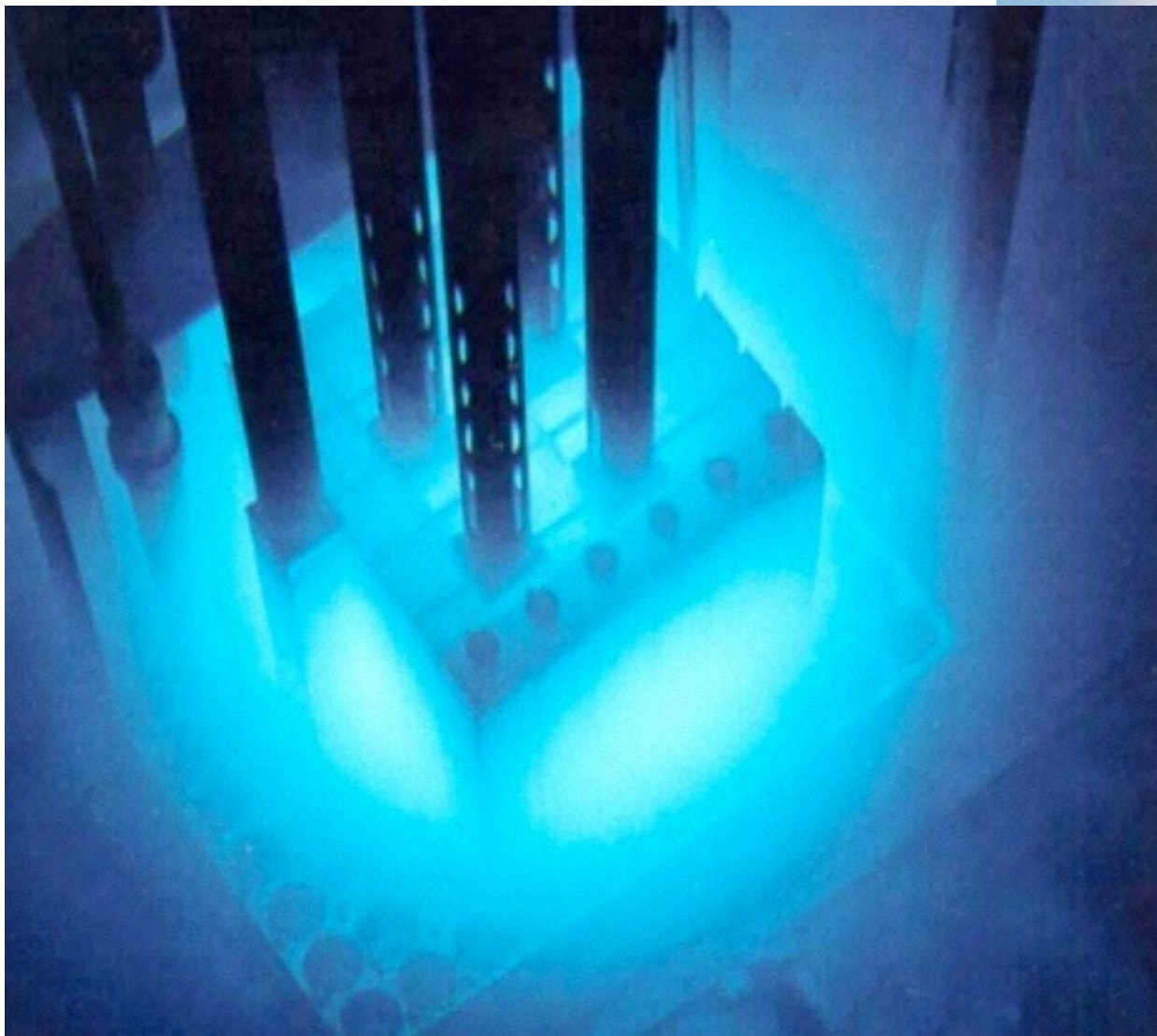


shower of a primary proton

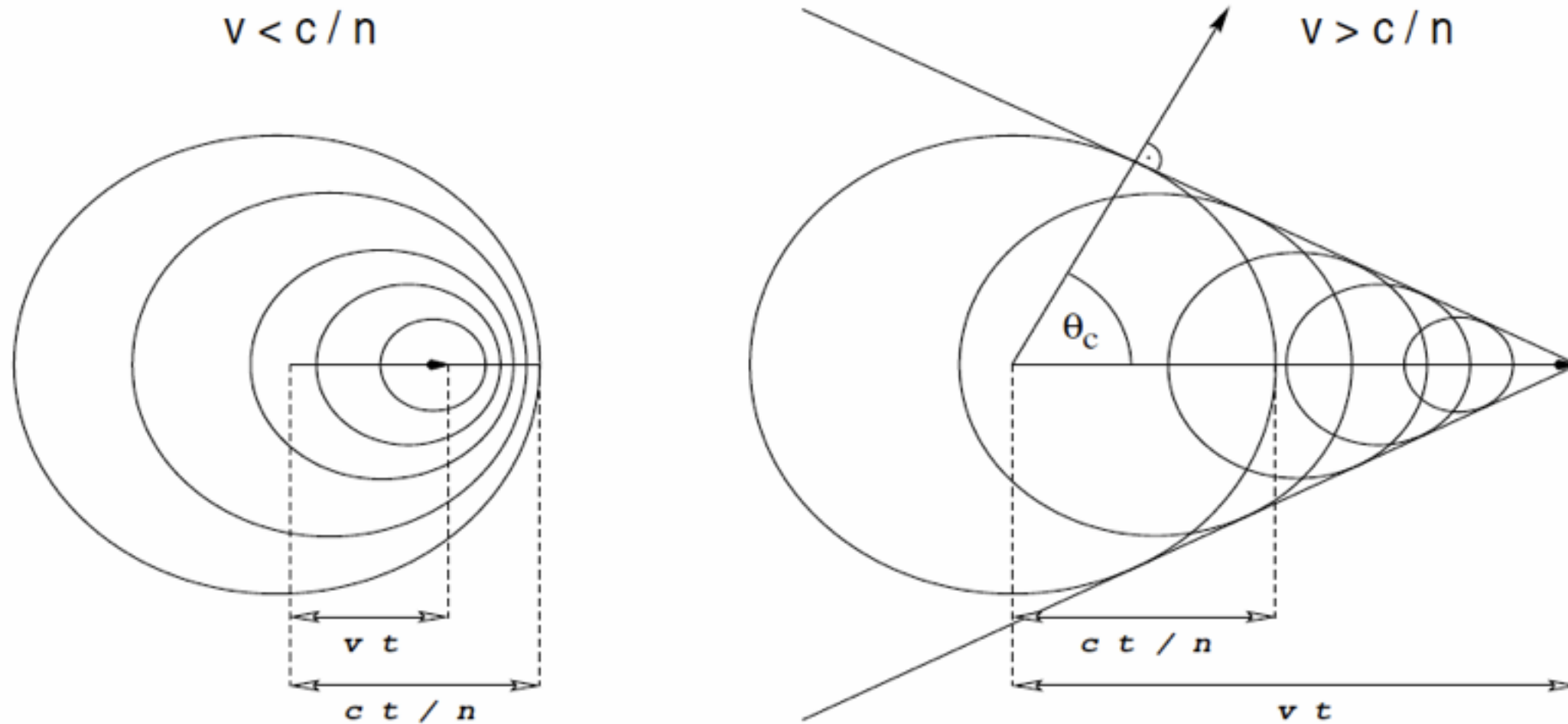


elektromagnetische Komponente hadronische Komponente myonische Komponente

Cherenkov-Light: “Supersonic Boom” with Photons



Cherenkov Light



D. Kranich,
Dissertation

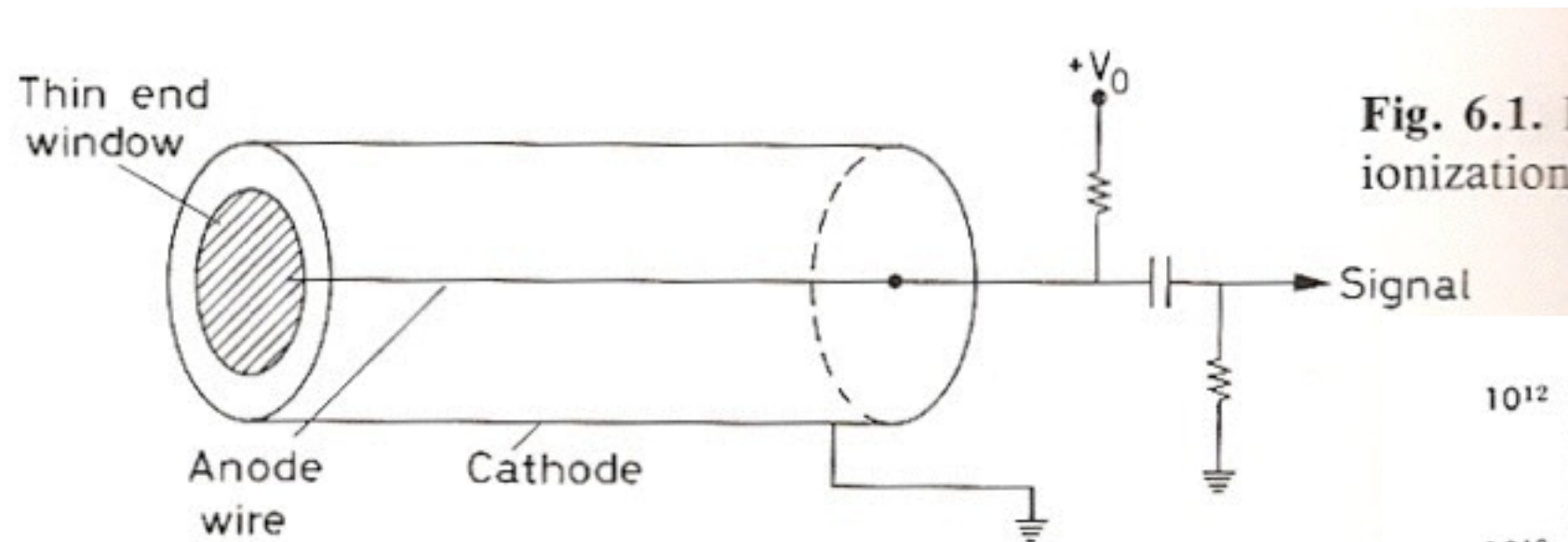
- Emission of photons by charged particles which are faster than the speed of light in the medium: constructive interference

Emission with a characteristic angle:

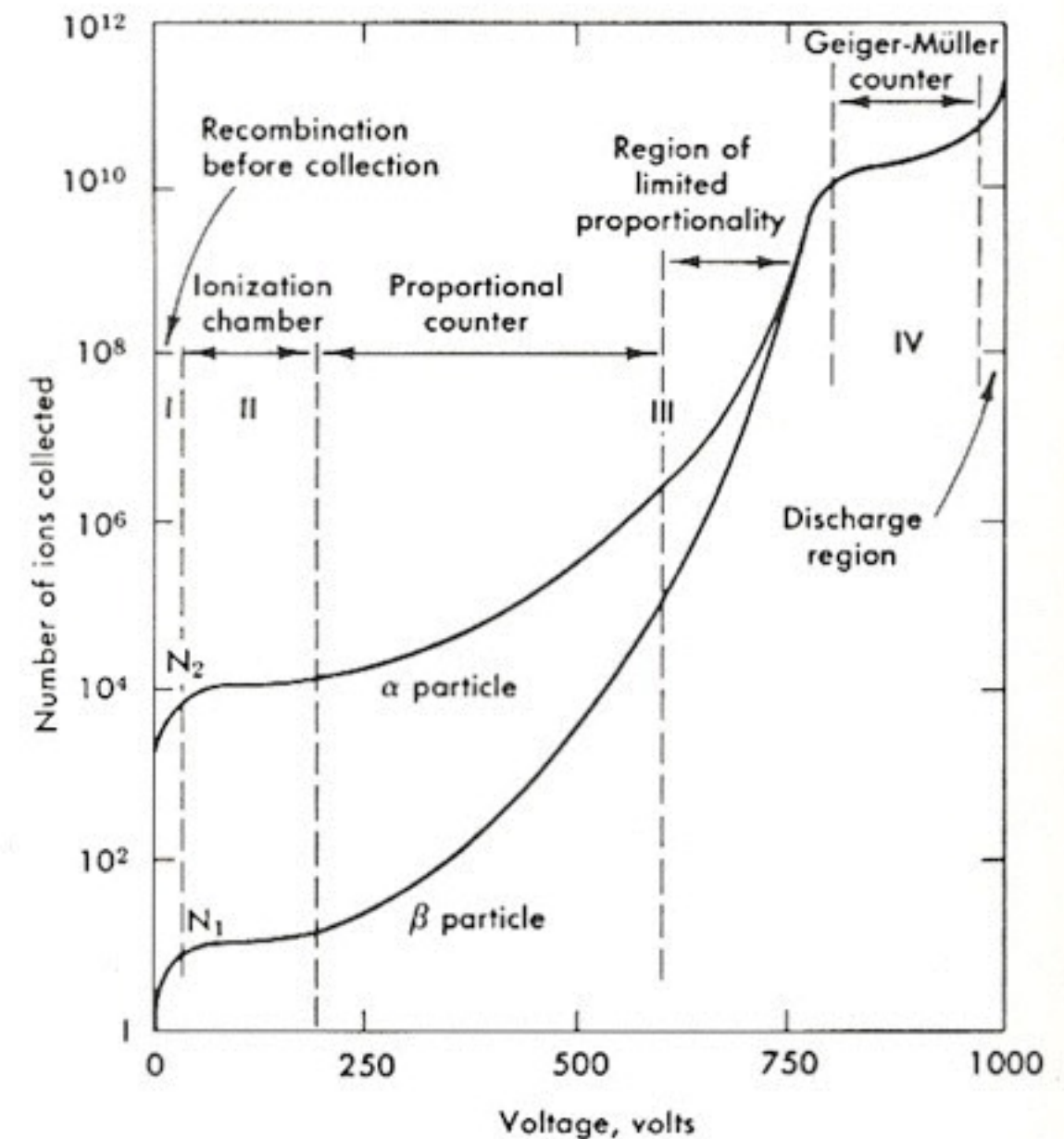
$$\cos\theta_c = \frac{ct/n}{vt} = \frac{1}{n\beta}$$

Detection Methods

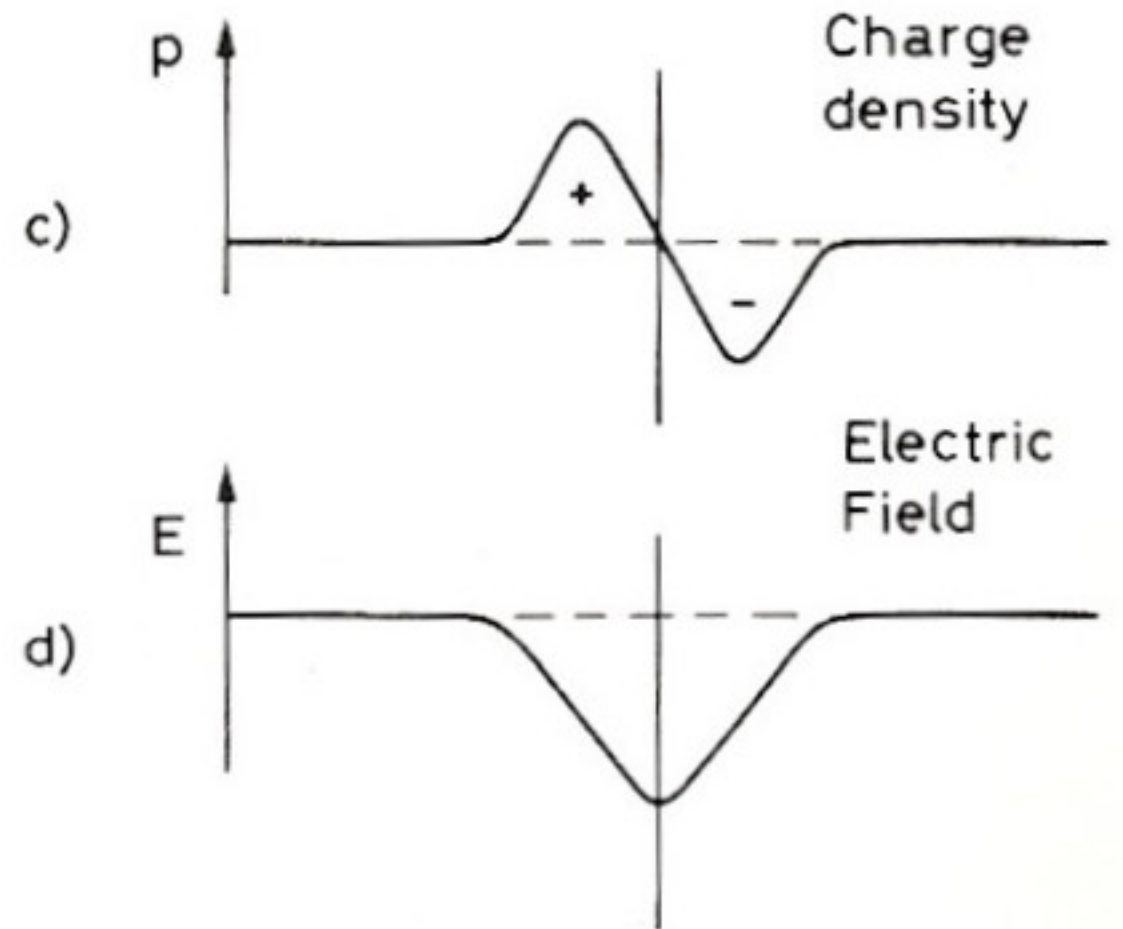
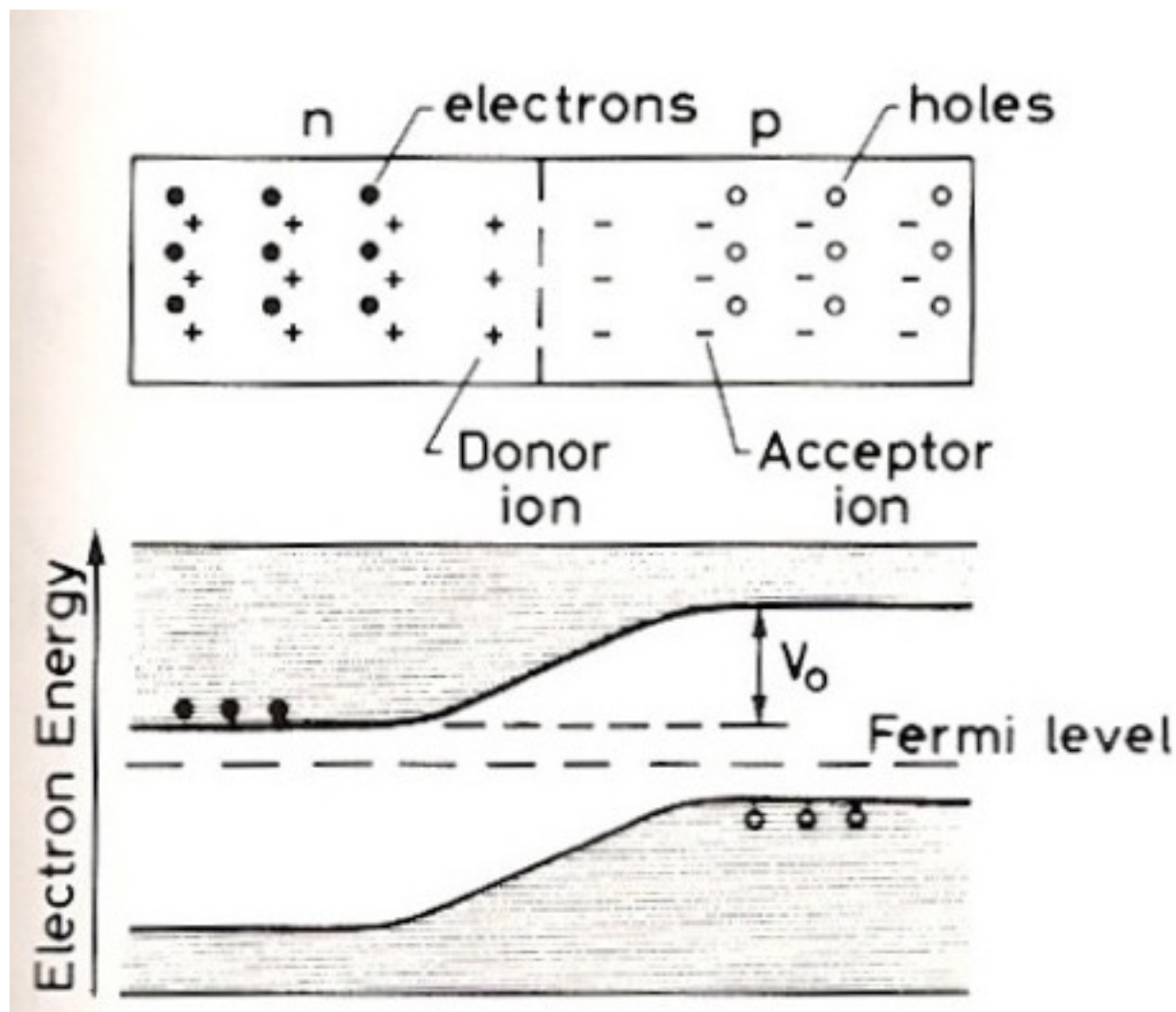
Ionization Chamber: A Classic



- Passage of particles creates electron-ion pairs in the gas volume
- Electrons are accelerated by strong electric field - avalanche multiplication takes place
- Depending on the voltage the signal is either proportional to the originally deposited charge, or goes into saturation

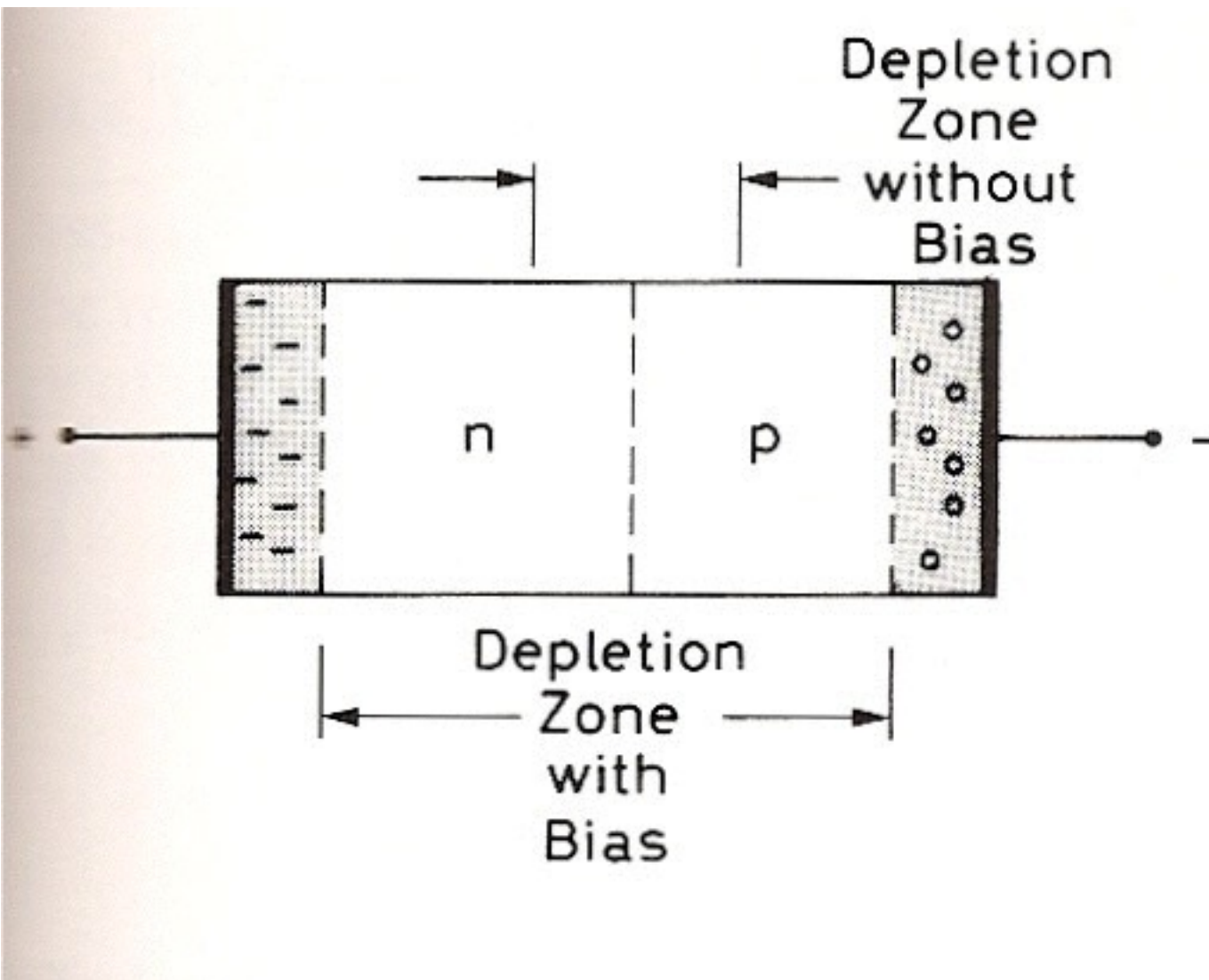


Semiconductor Detectors - PN Junction



- Interfaces between differently doped silicon forms a PN junction
 - Donators (for ex. Phosphorous) provides electrons: n - doping
 - Acceptors (for ex. Boron) provides holes: p - doping
 - The charge excesses equalize by diffusion, a depletion zone and a corresponding field form at the interface

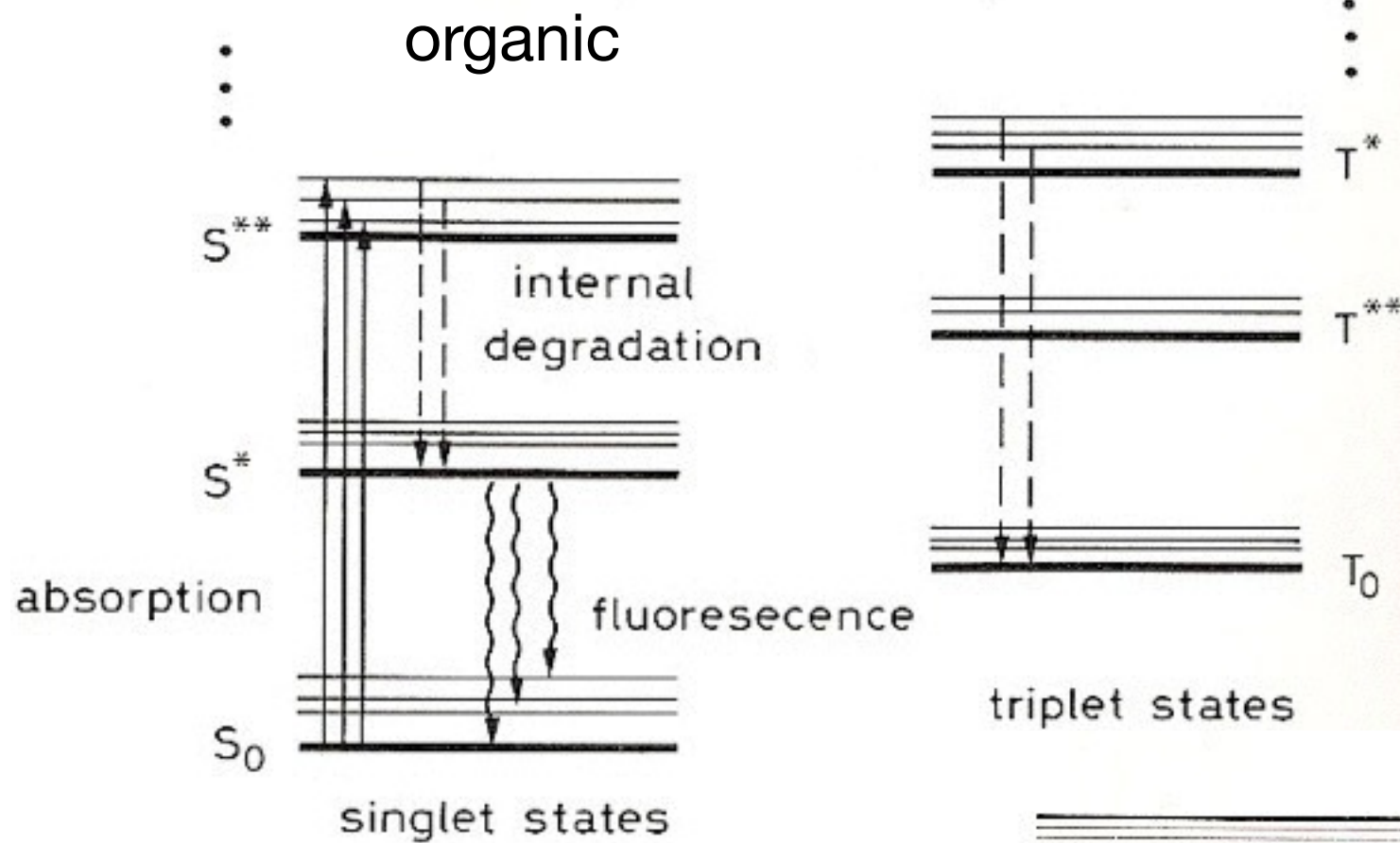
Semiconductor Detectors: Charge Collection



- An external bias voltage increases the depletion zone: All free charge carriers are removed
- Created electrons and holes travel to the electrodes before they can recombine with the silicon: Signals can be read out

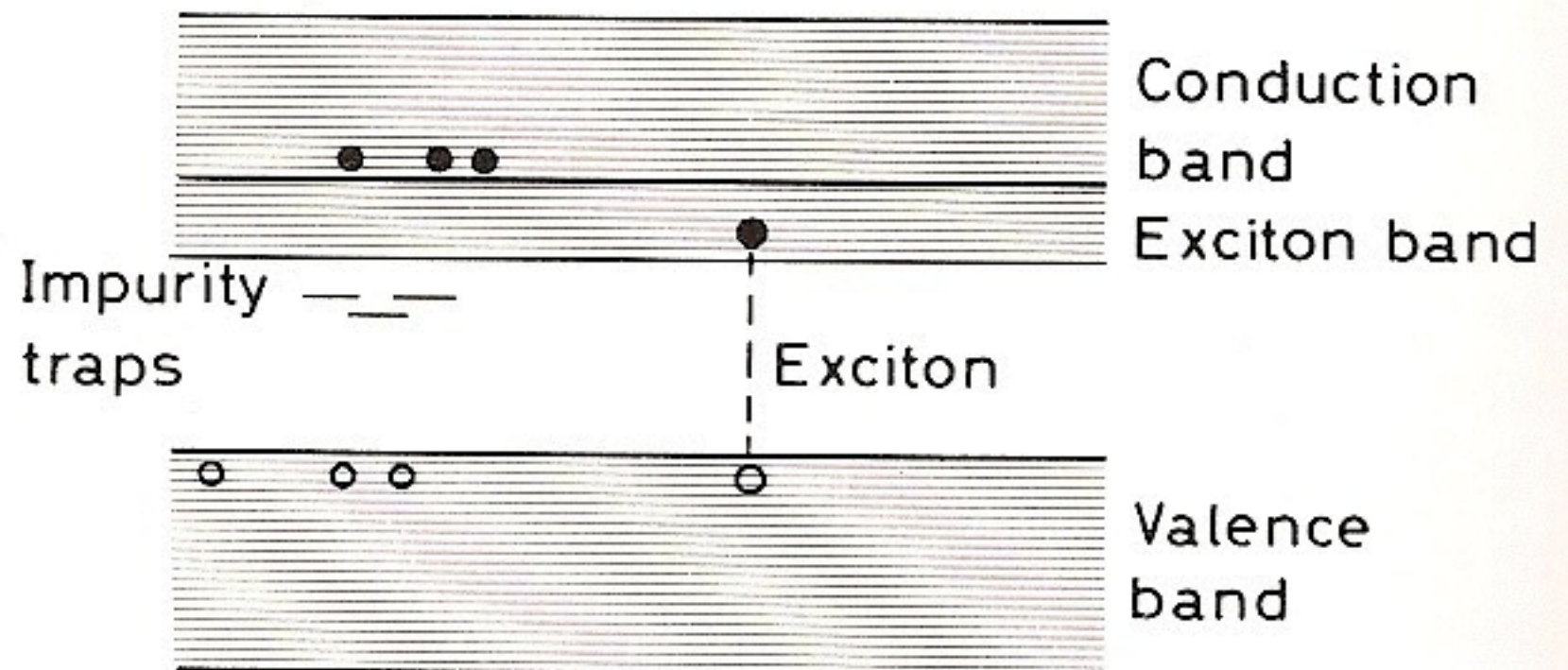
- Traversing particles create electron-hole pairs (in Si: 3.6 eV per pair required, compared to 20 eV - 40 eV in gaseous detectors)
 - High density and low ionization threshold allow thin detectors with high spatial resolution

Scintillation

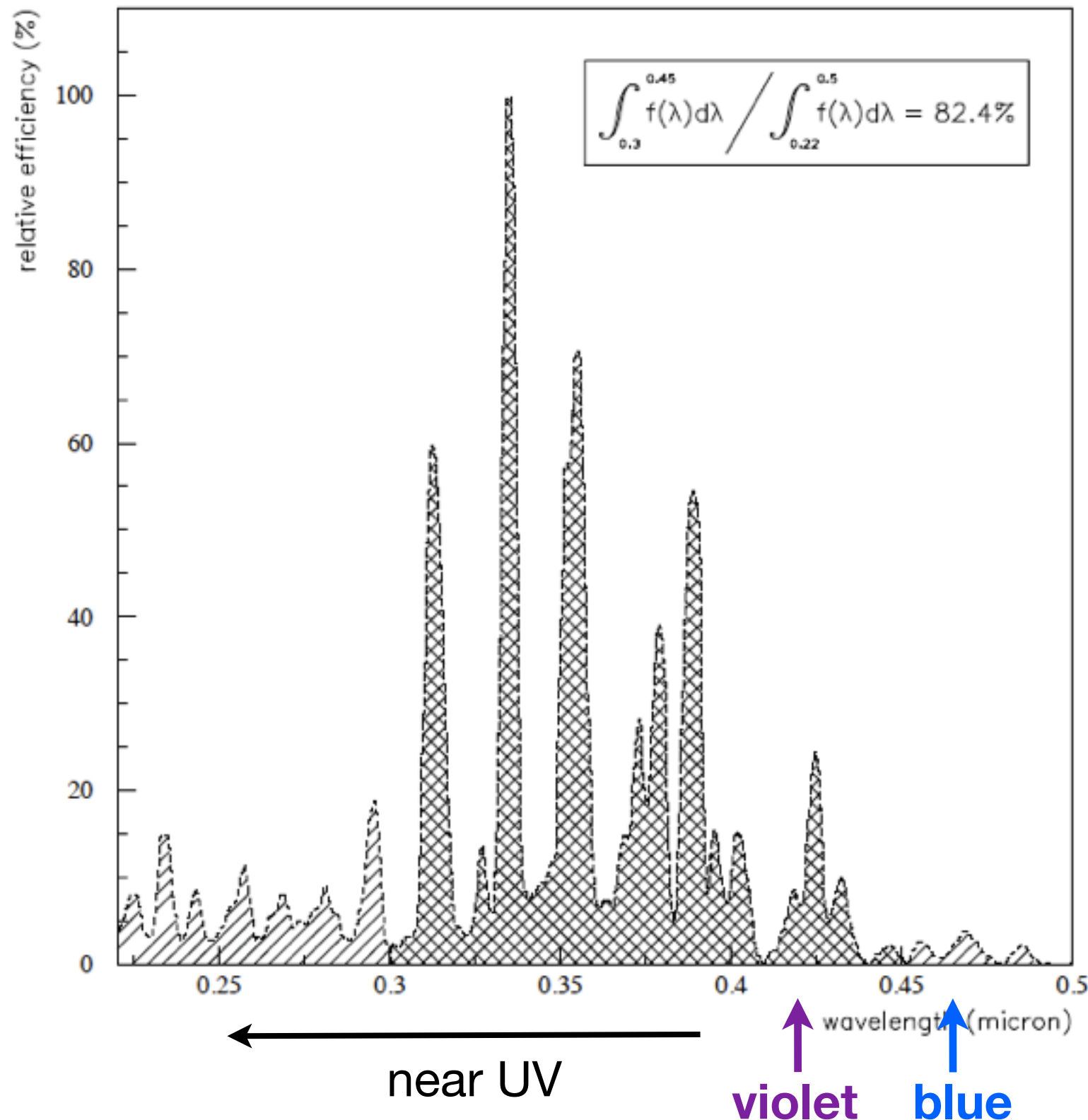


- Scintillators emit light when crossed by ionizing particles
 - Excitation of metastable states in molecules (organic scintillator) or defects in crystals (inorganic scintillator)

inorganic:



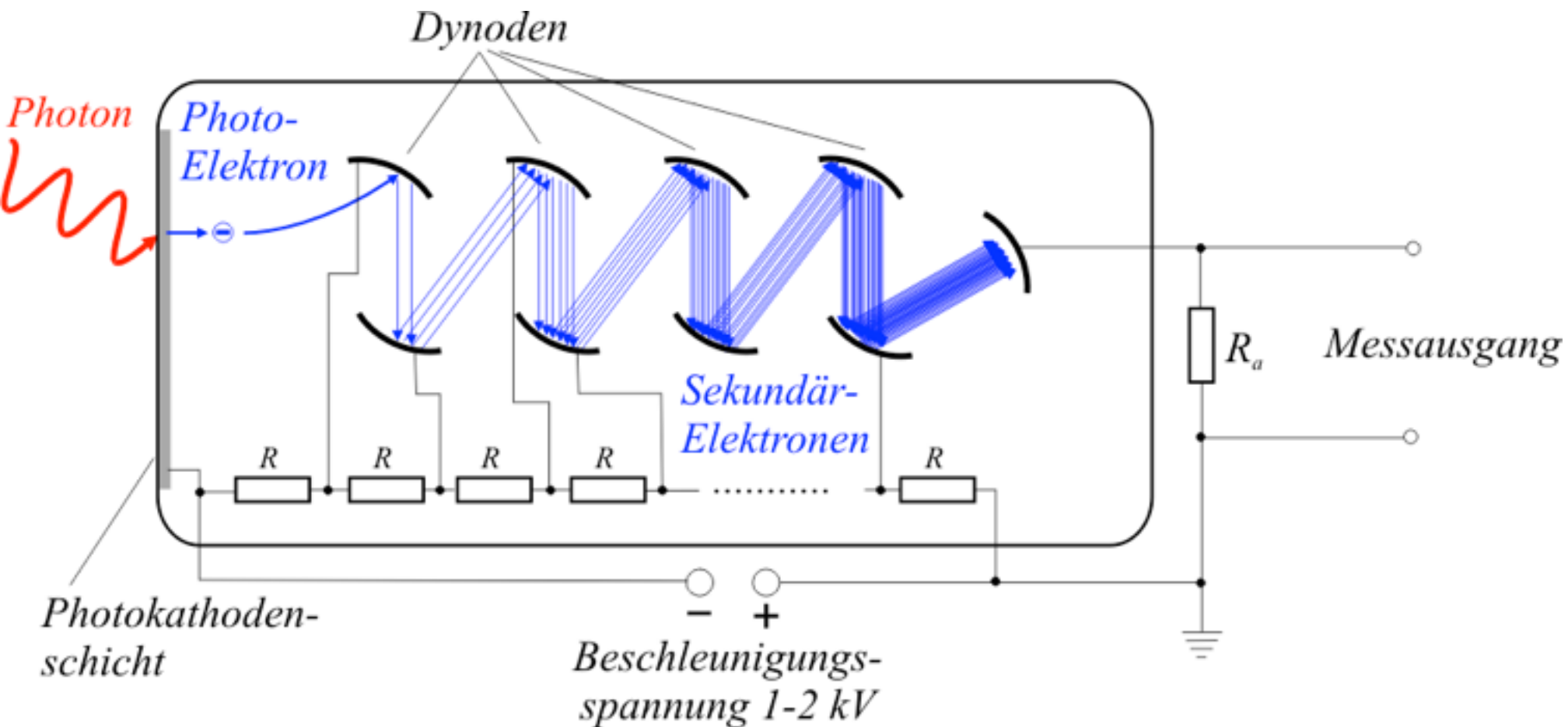
Fluorescence of Air



- Excitation of nitrogen in the atmosphere (2P - orbital of N₂, 1N orbital of N₂⁺)
- 80% of the photons are emitted in the range of 300 nm bis 450 nm
- Only ~ 5x10⁻⁵ of all deposited energy in air is emitted as fluorescence photons
 - Emission is isotropic: Can only be used for very high energies!

Detection of Photons: The Photo-Multiplier

- The classic way to detect visible (or near-visible) photons:



- Conversion of the photon to a photo-electron on a photo-cathode
 - Amplification of single-electron signal to a detectable signal with several dynodes
- Suited for a wide range of wavelengths ranging from UV to IR, good efficiency, up to ~ 25% (with special techniques up to ~ 40%), single photons can be detected
 - Large active areas are possible: SuperKamiokande uses PMTs with an active area 460 mm in diameter

Photon Detection with Silicon

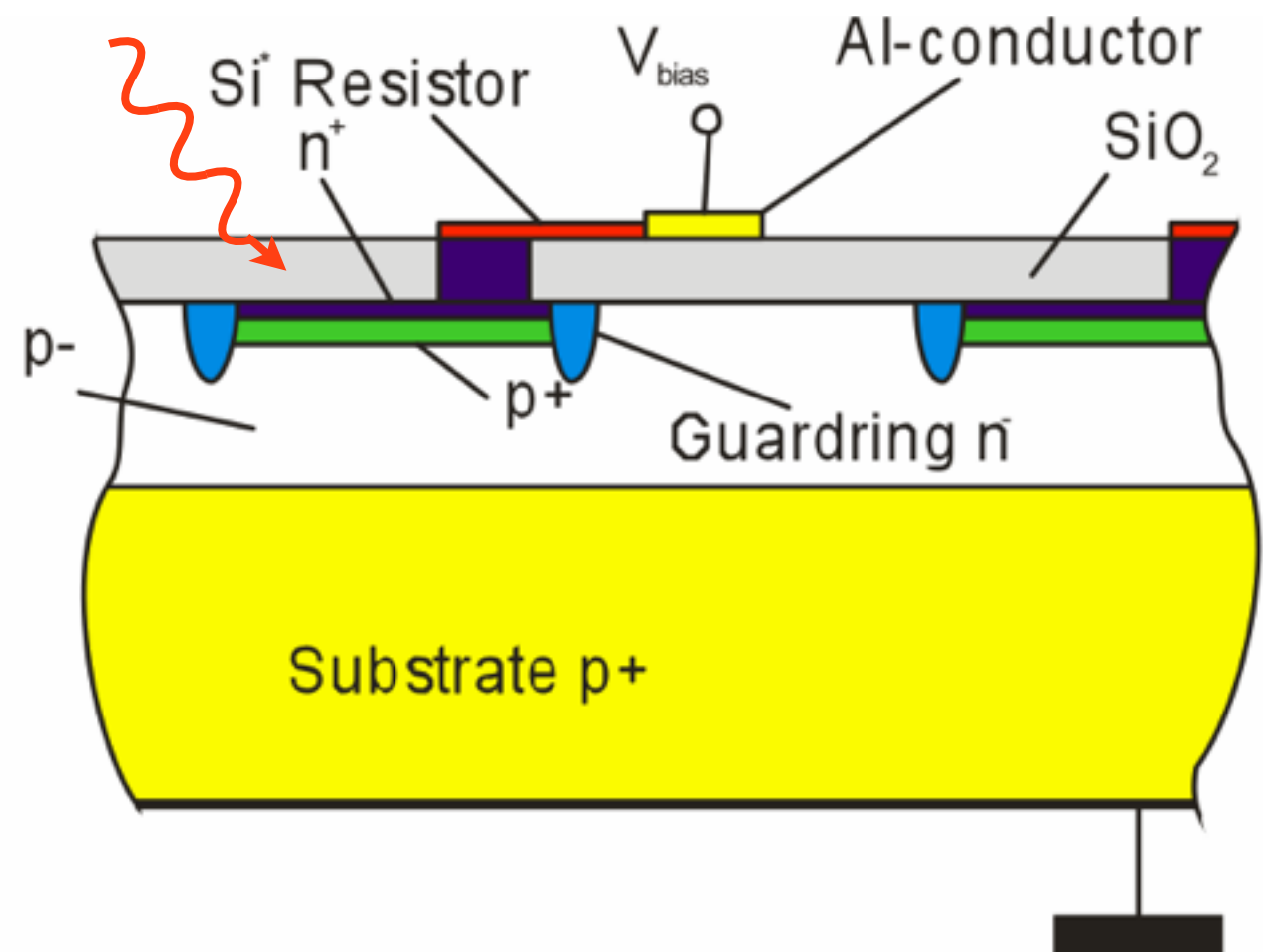
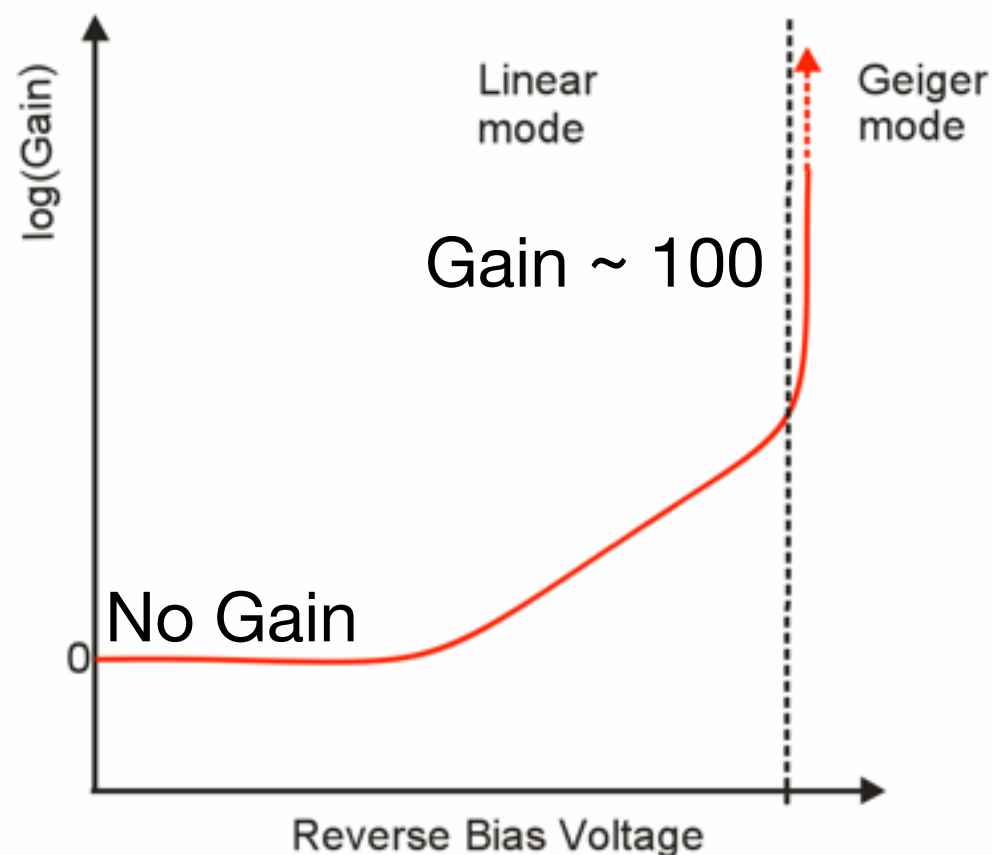
- Silicon detectors can also be used to detect visible photons, but:
 - Photo effect only creates a single electron-hole pair (very different from the situation with charged particles): Amplification is crucial!
 - ▶ The usual charge amplification of up to ~ 100 reachable in silicon is insufficient to detect single photons with high efficiency



Photon Detection with Silicon

- Silicon detectors can also be used to detect visible photons, but:
 - Photo effect only creates a single electron-hole pair (very different from the situation with charged particles): Amplification is crucial!
 - ▶ The usual charge amplification of up to ~ 100 reachable in silicon is insufficient to detect single photons with high efficiency

Avalanche Photo Diode APD

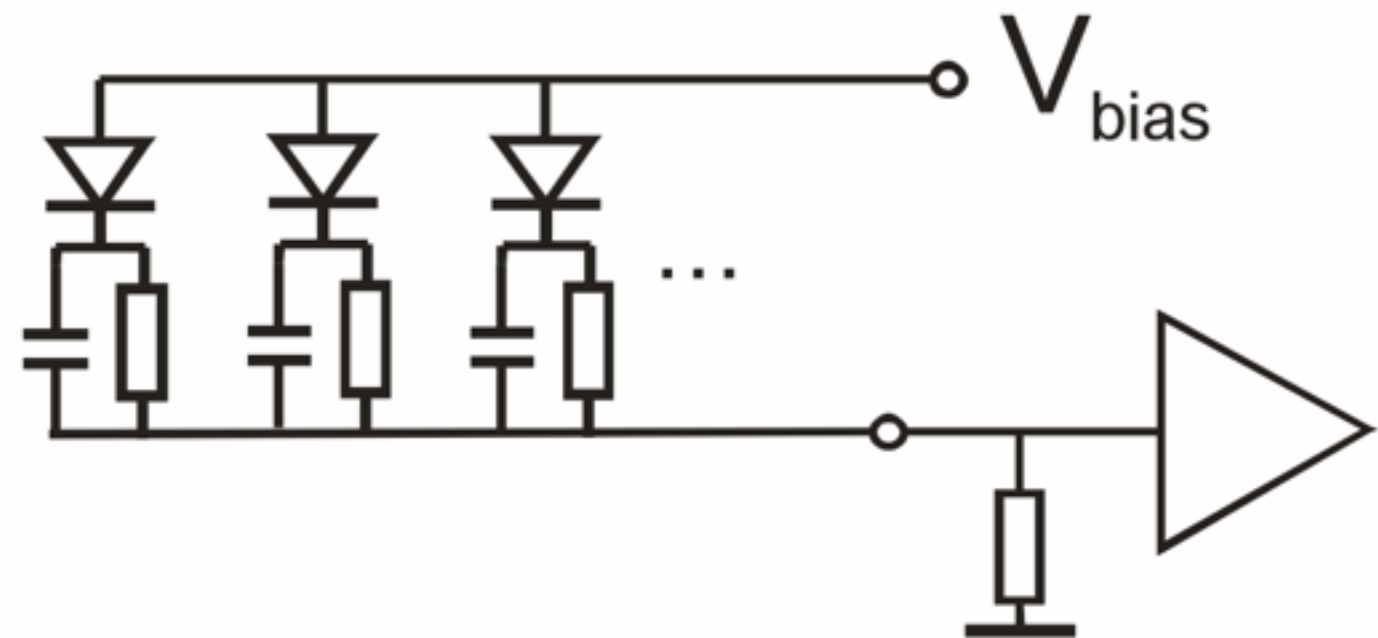
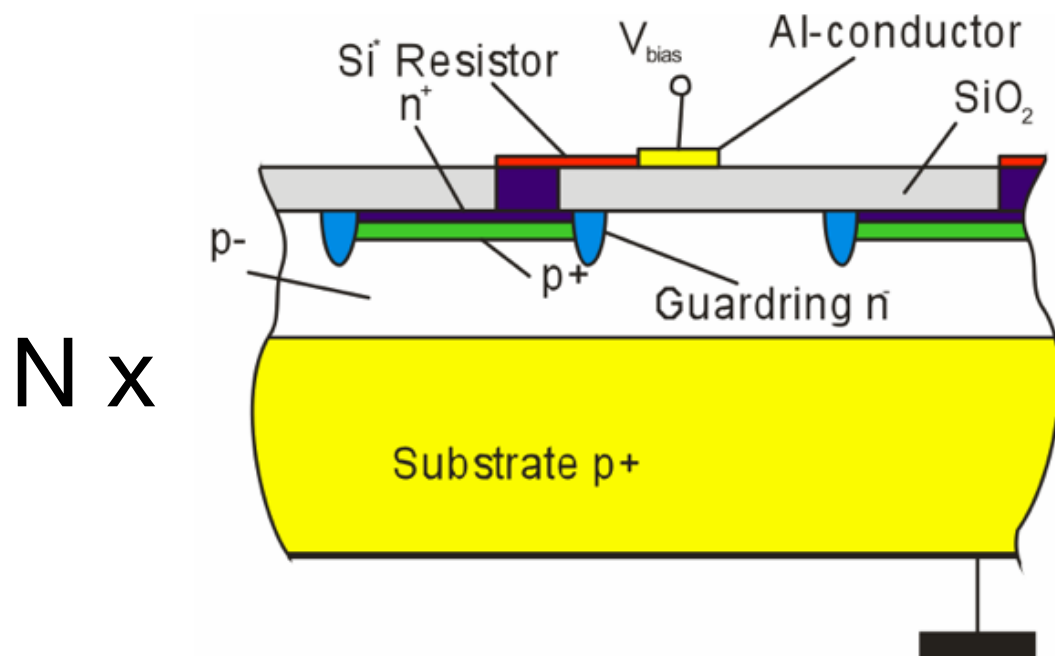


New Photon Sensors: Silicon Photomultipliers

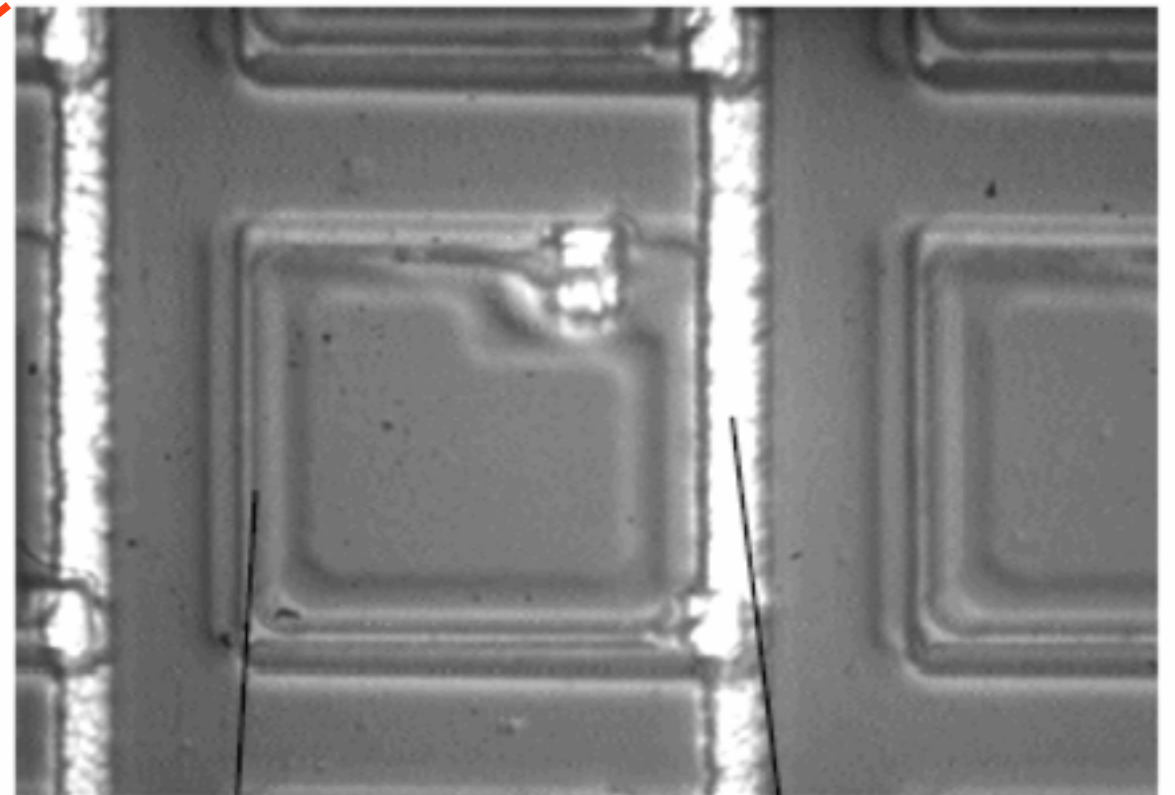
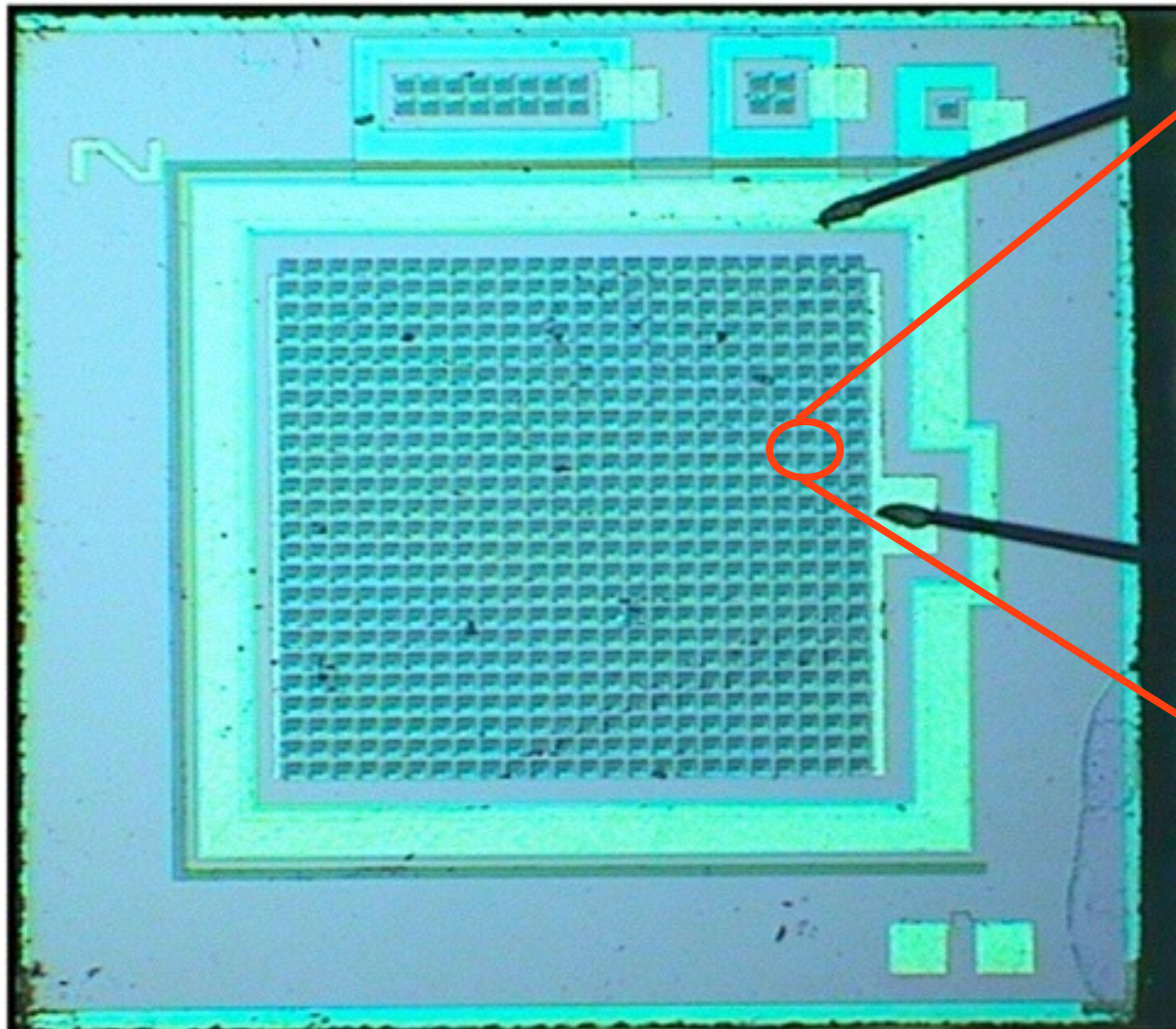
- Highest amplification ($\sim 10^6$) by running APDs in Geiger mode: a single photon triggers a discharge, the diode operates in digital mode: Yes/No, no dependence of the current on the number of photons

New Photon Sensors: Silicon Photomultipliers

- Highest amplification ($\sim 10^6$) by running APDs in Geiger mode: a single photon triggers a discharge, the diode operates in digital mode: Yes/No, no dependence of the current on the number of photons
- The trick: Put many small APDs on a chip, read out the summed-up signal
 - Easy handling: Only one channel (as a PMT, hence the name)
 - Extreme amplification: Detection of single photons not a problem!



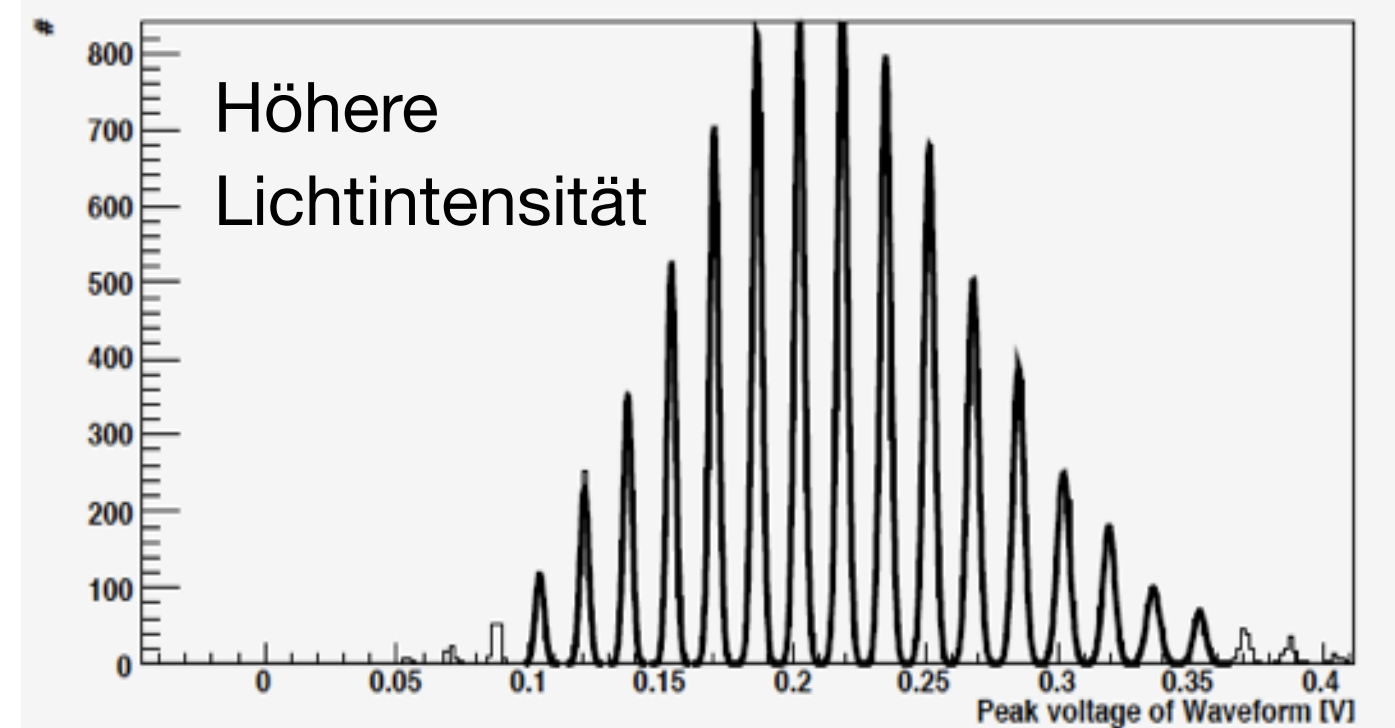
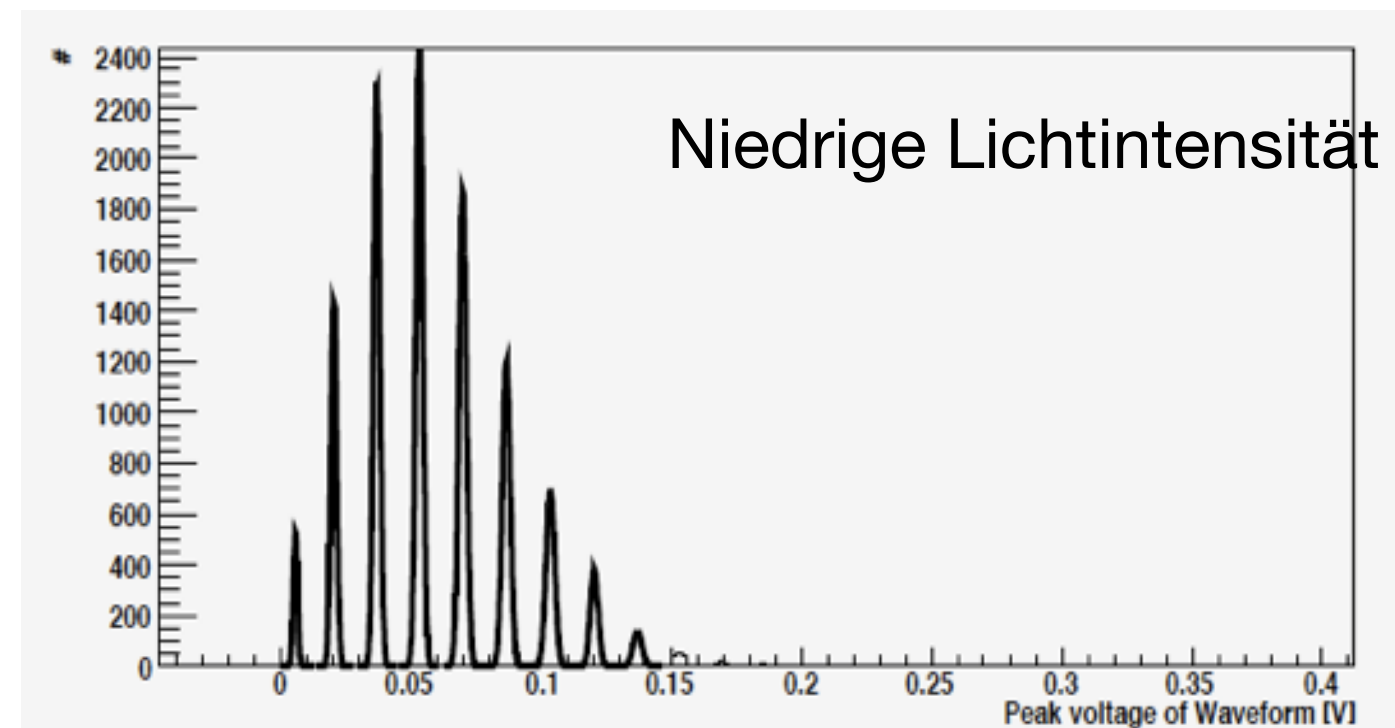
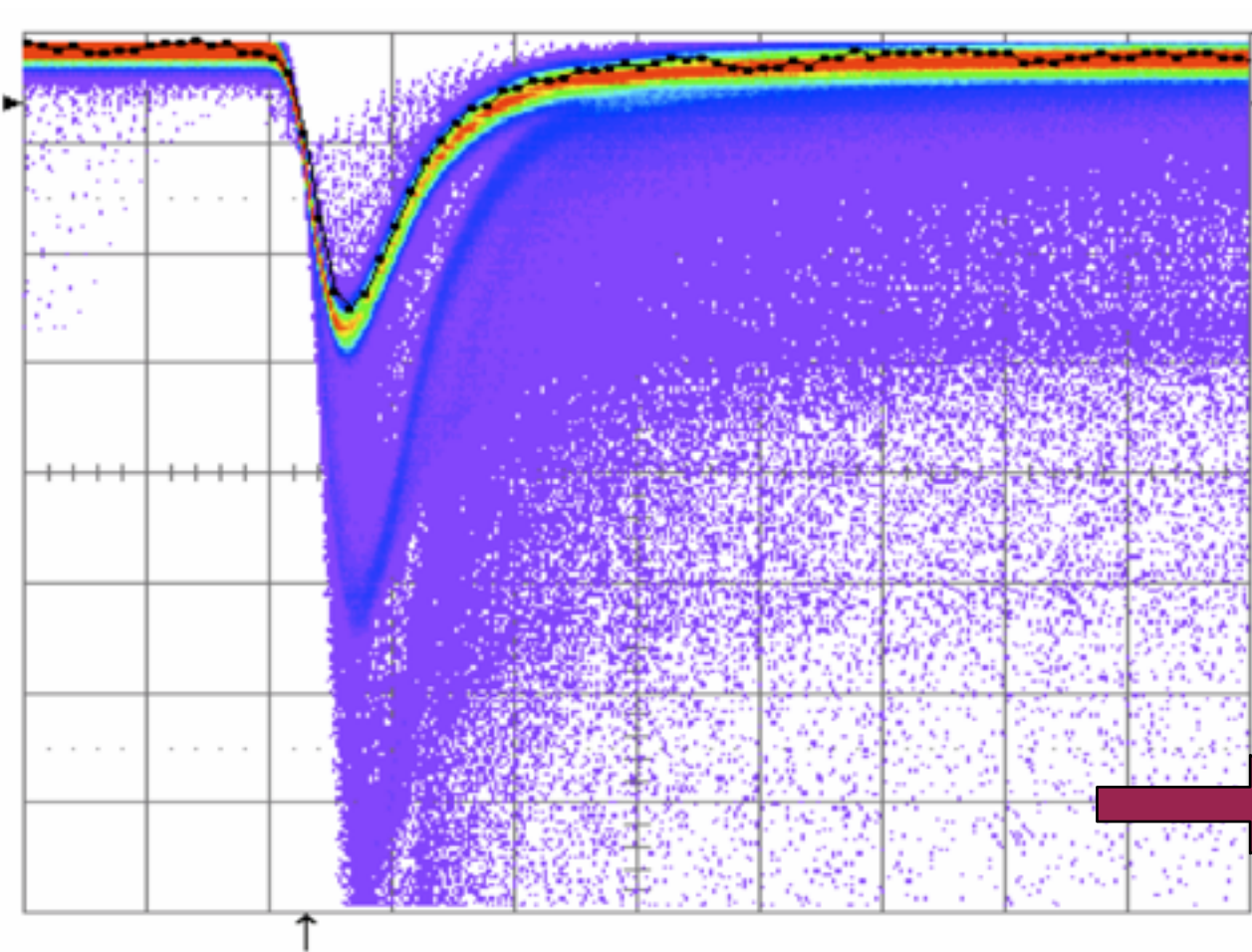
Silicon Photomultiplier: SiPM



Si^* Resistor

Al - conductor

SiPM Signals



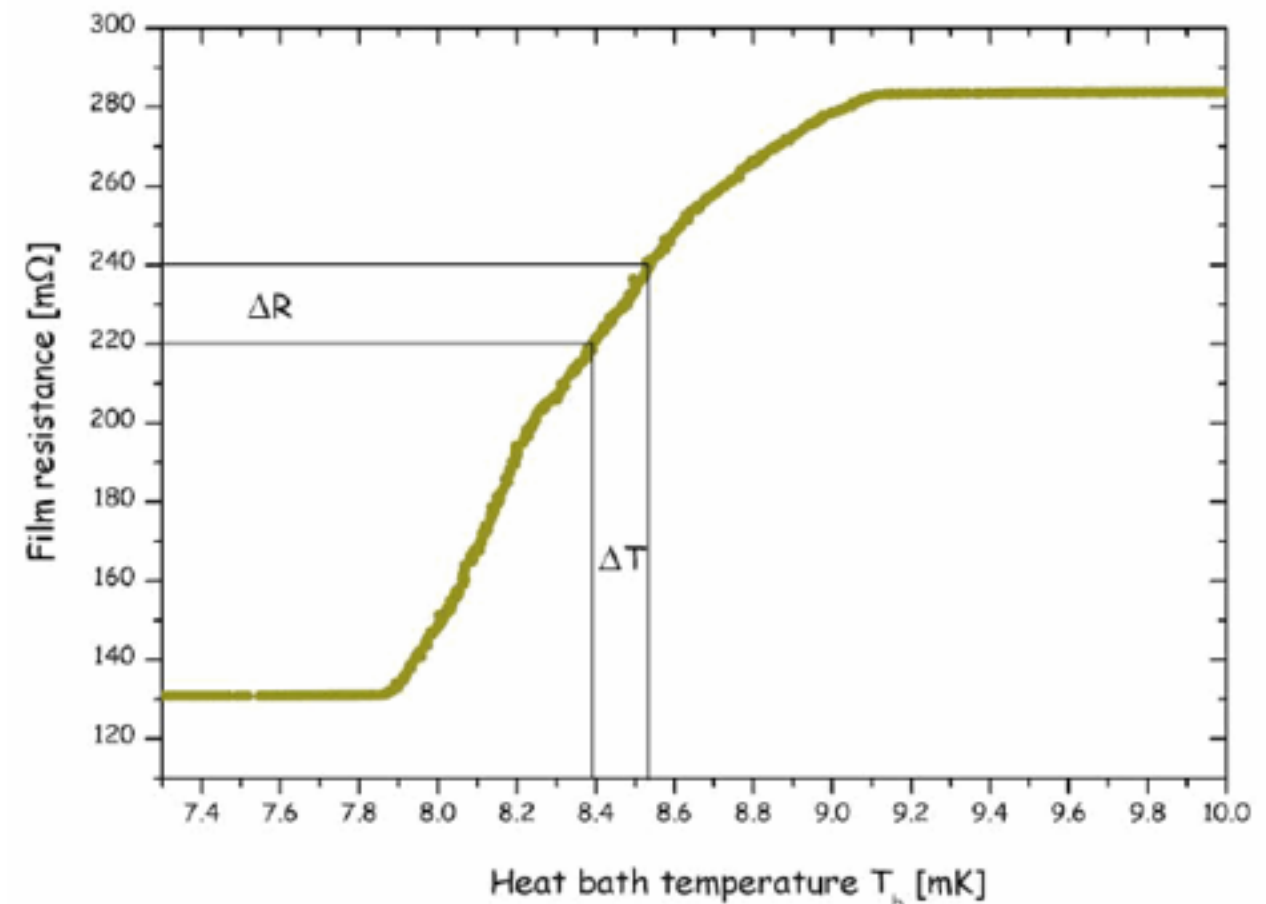
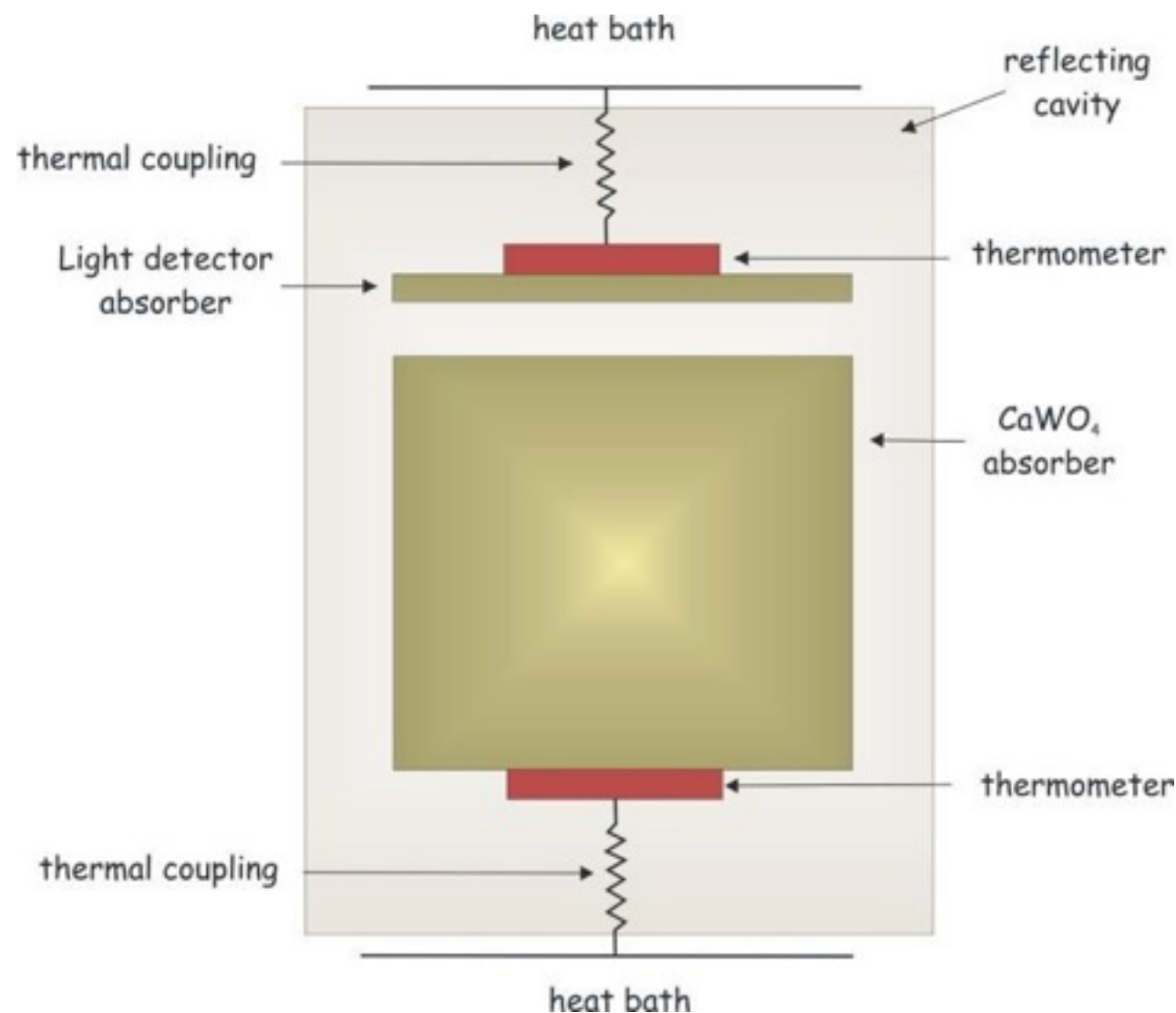
Single photons can be resolved

Experimental Applications

A Few Examples

Cryogenic Detectors: CRESST

- Cryogenic Rare Event Search with Superconducting Thermometers
- Search for weakly interacting massive particles (WIMPs)
- Detection via nuclear recoil in crystals, measured with superconducting thermometers
 - Recoil energy is transformed to phonons, increases temperature of thermometer, change of resistance is detected with SQUIDs



Cherenkov Detectors

- Detection of Cherenkov light: Possibility to measure particle velocity, well suited for particle detection since the light is focused and emitted instantaneously

Cherenkov angle: $\cos\theta_c = \frac{1}{n\beta}$

Cherenkov threshold: $\beta > c/n$

Cherenkov Detectors

- Detection of Cherenkov light: Possibility to measure particle velocity, well suited for particle detection since the light is focused and emitted instantaneously

Cherenkov angle: $\cos\theta_c = \frac{1}{n\beta}$

Cherenkov threshold: $\beta > c/n$

- The simplest detector: Threshold counter - only detected light to give lower limit on velocity

Cherenkov Detectors

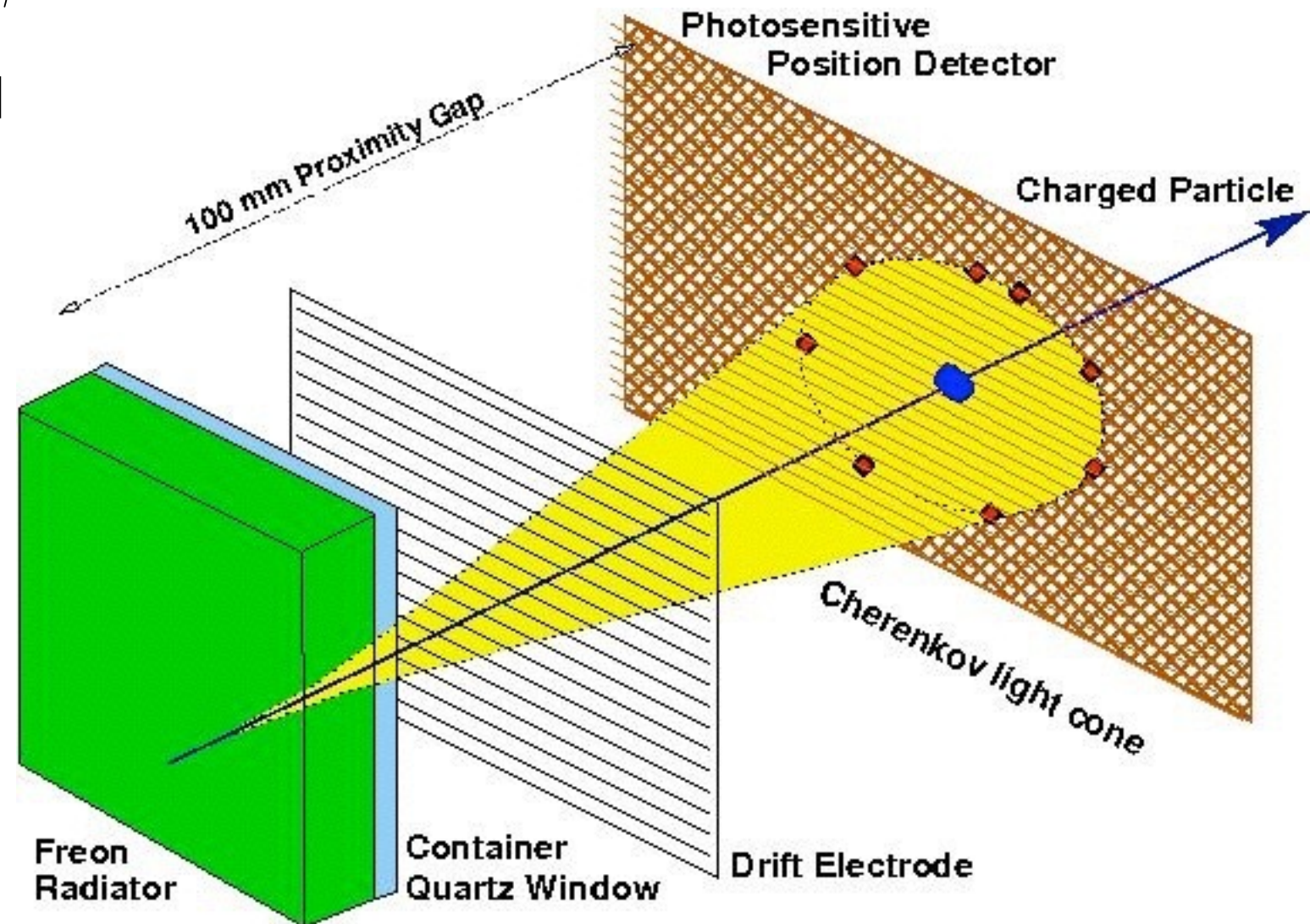
- Detection of Cherenkov light: Possibility to measure particle velocity, well suited for particle detection since the light is focused and emitted instantaneously

Cherenkov angle: $\cos\theta_c = \frac{1}{n\beta}$

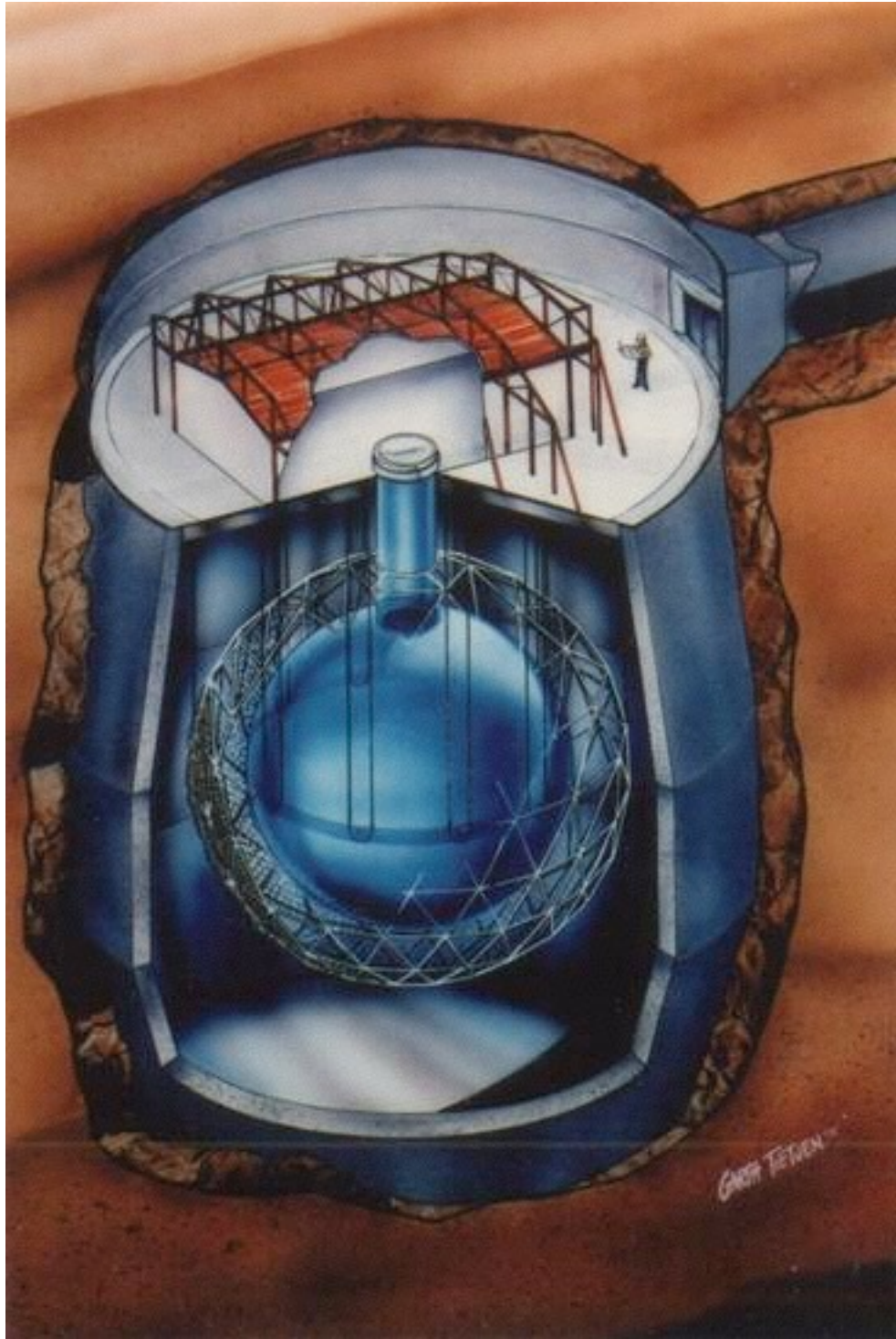
Cherenkov threshold: $\beta > c/n$

- The simplest detector: Threshold counter - only detected light to give lower limit on velocity
- Velocity measurement: Determination of Cherenkov angle by measurement of parameters of a ring

Ring **I**maging **C**herenkov Counter

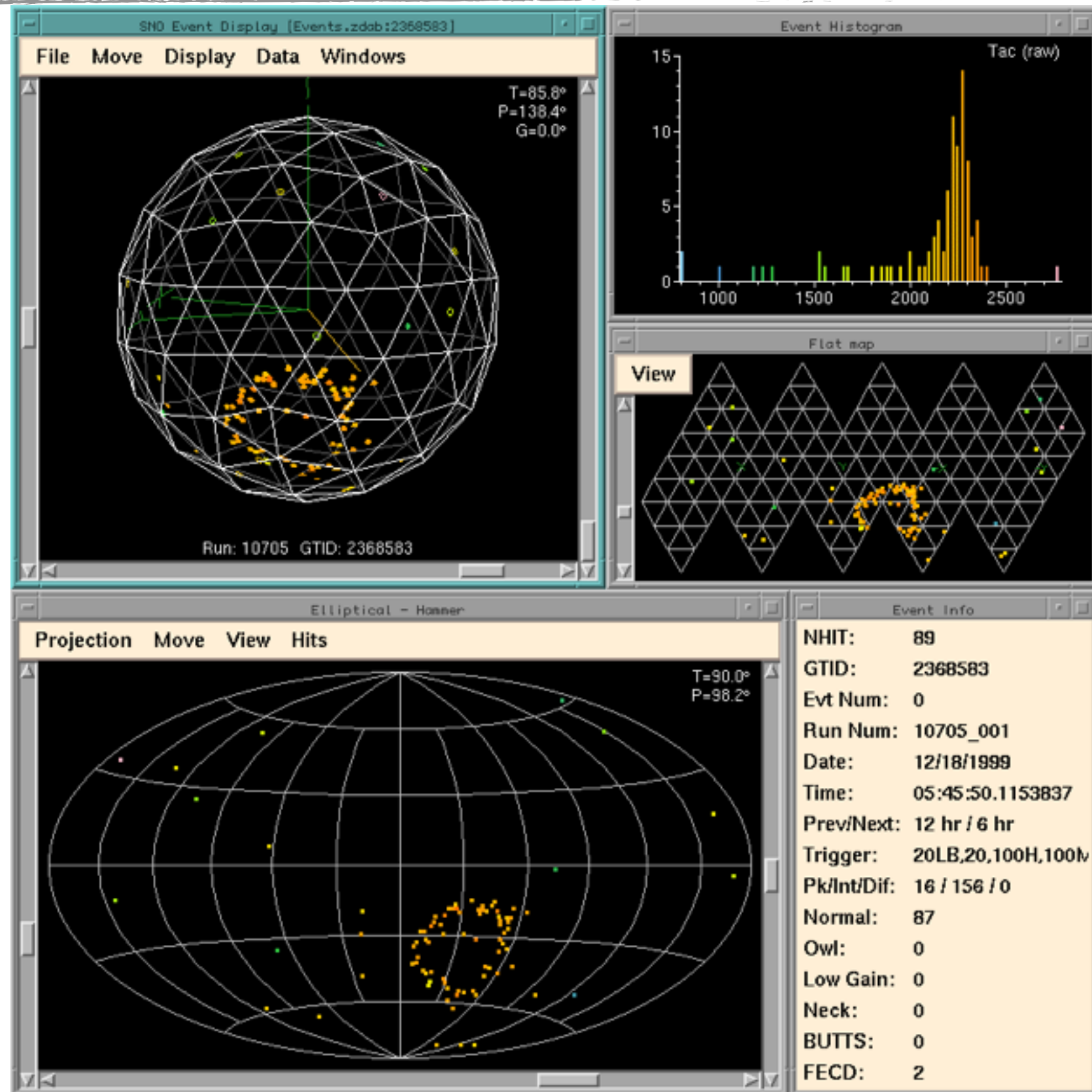
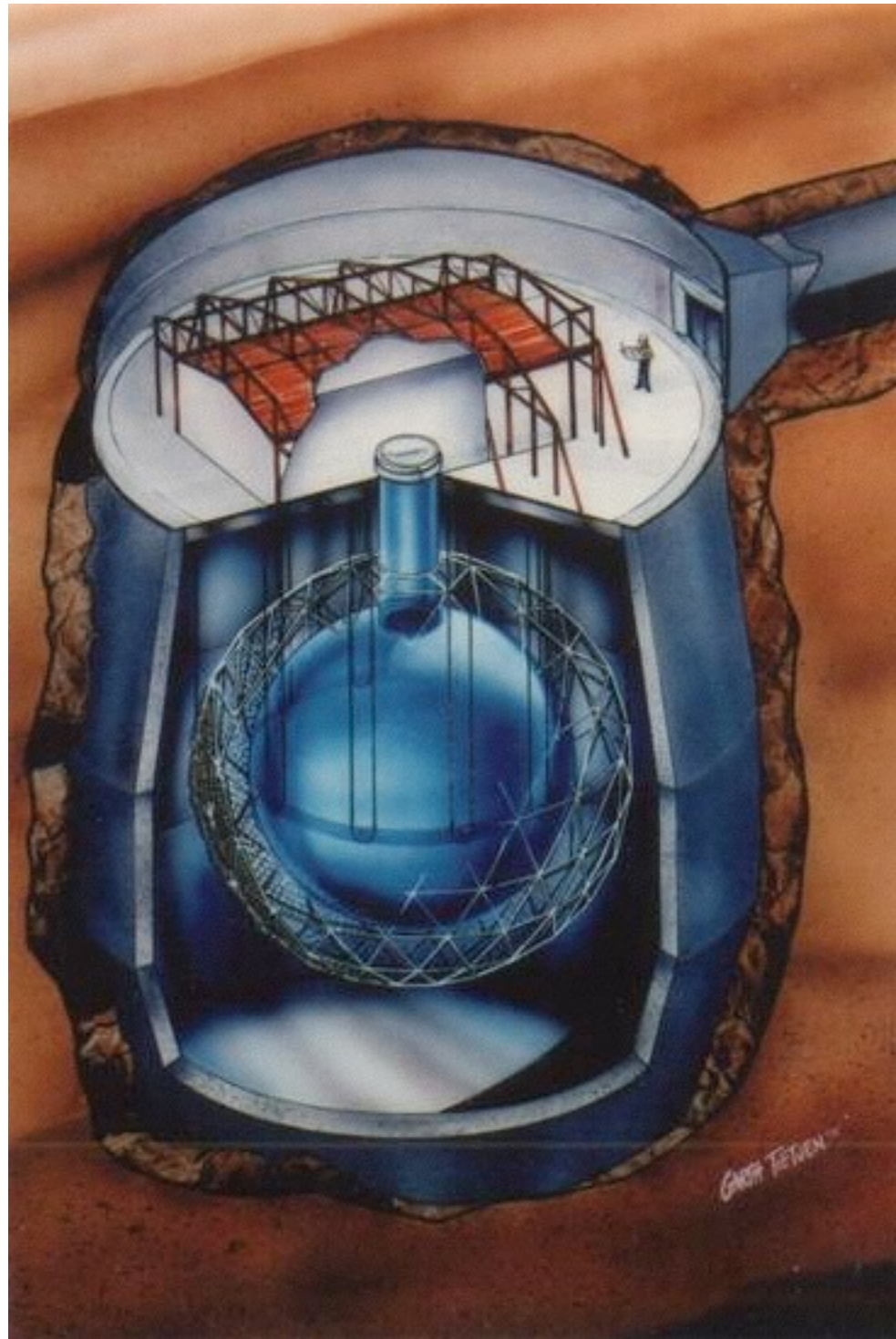


Cherenkov Detectors for Neutrinos

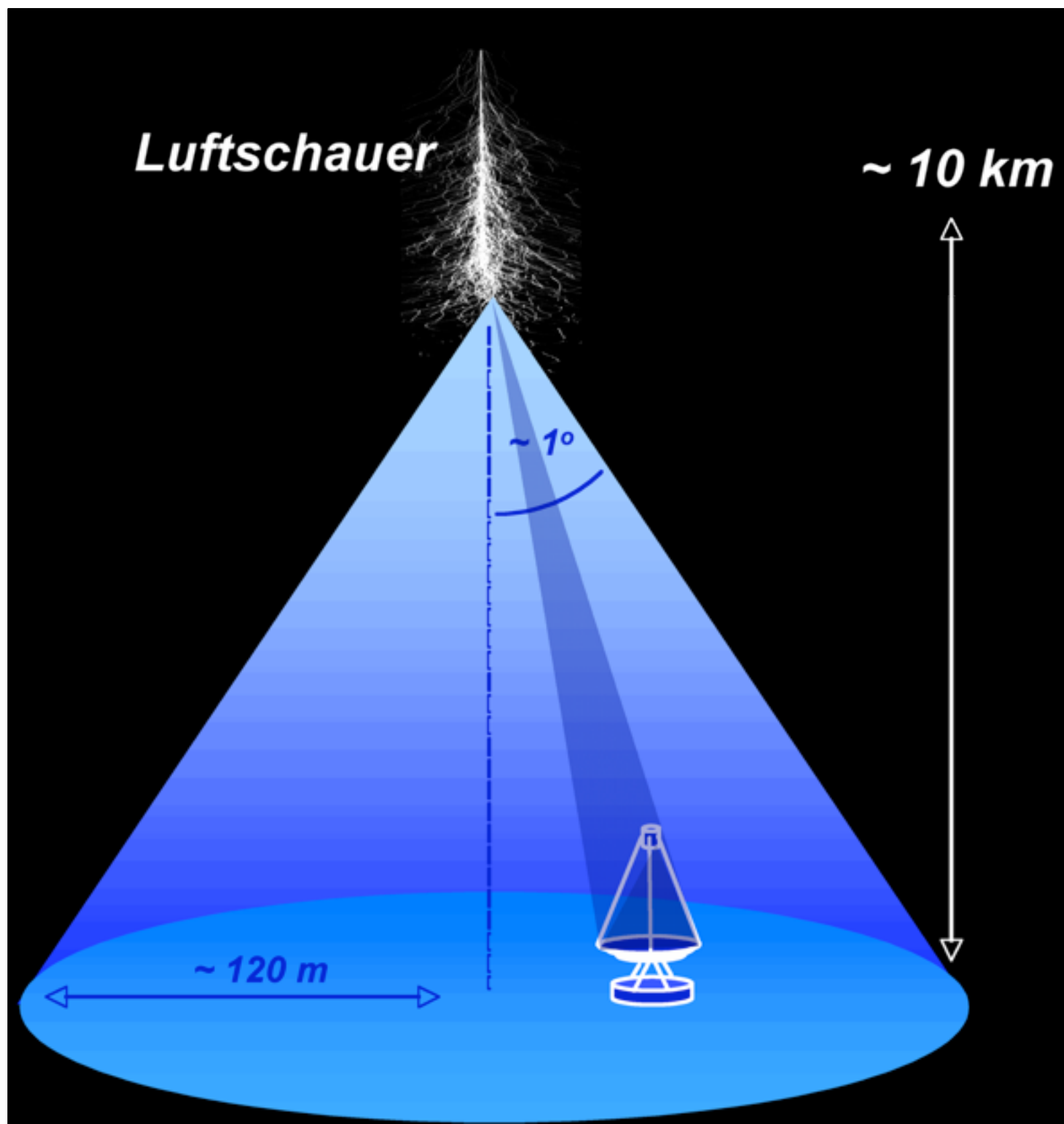


- Detection of electrons and muons created by charged current neutrino reactions:
Emission of Cherenkov light in water, energy measurement by measurement of Cherenkov angle

Cherenkov Detectors for Neutrinos



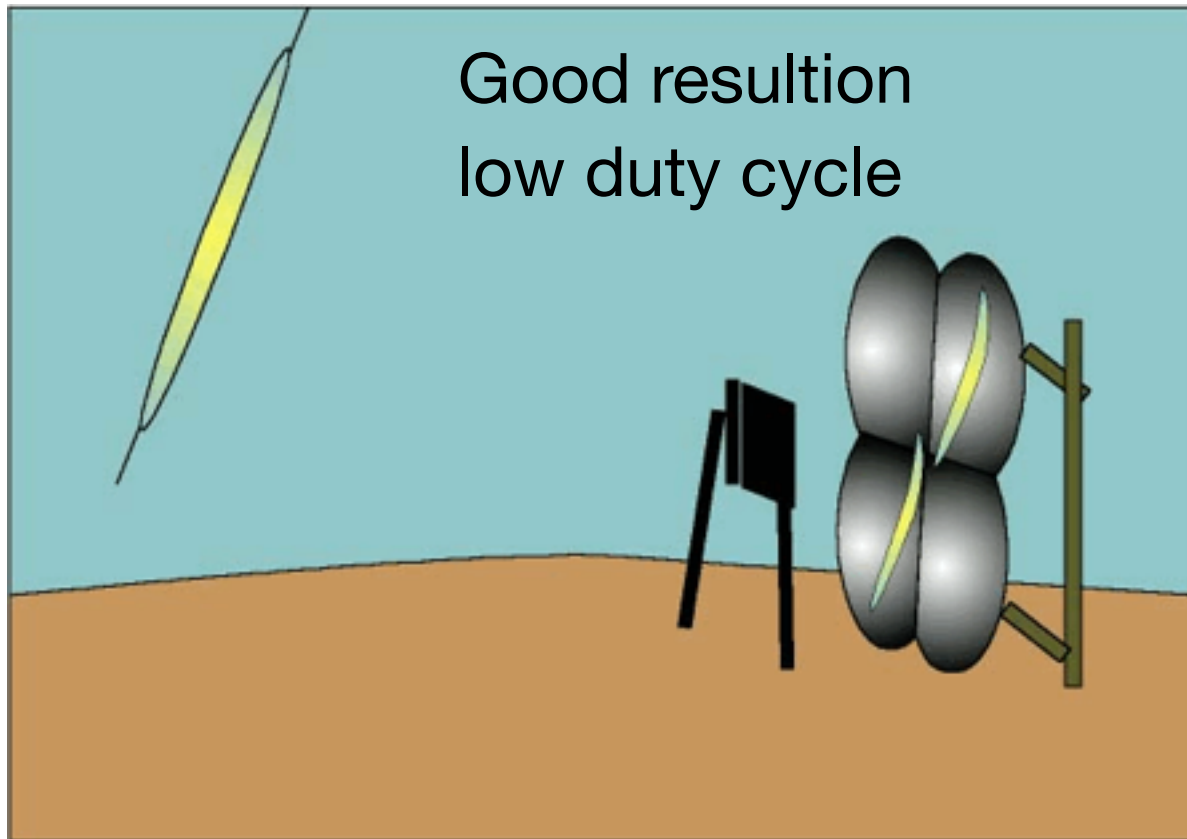
Cherenkov Telescopes for Air Showers



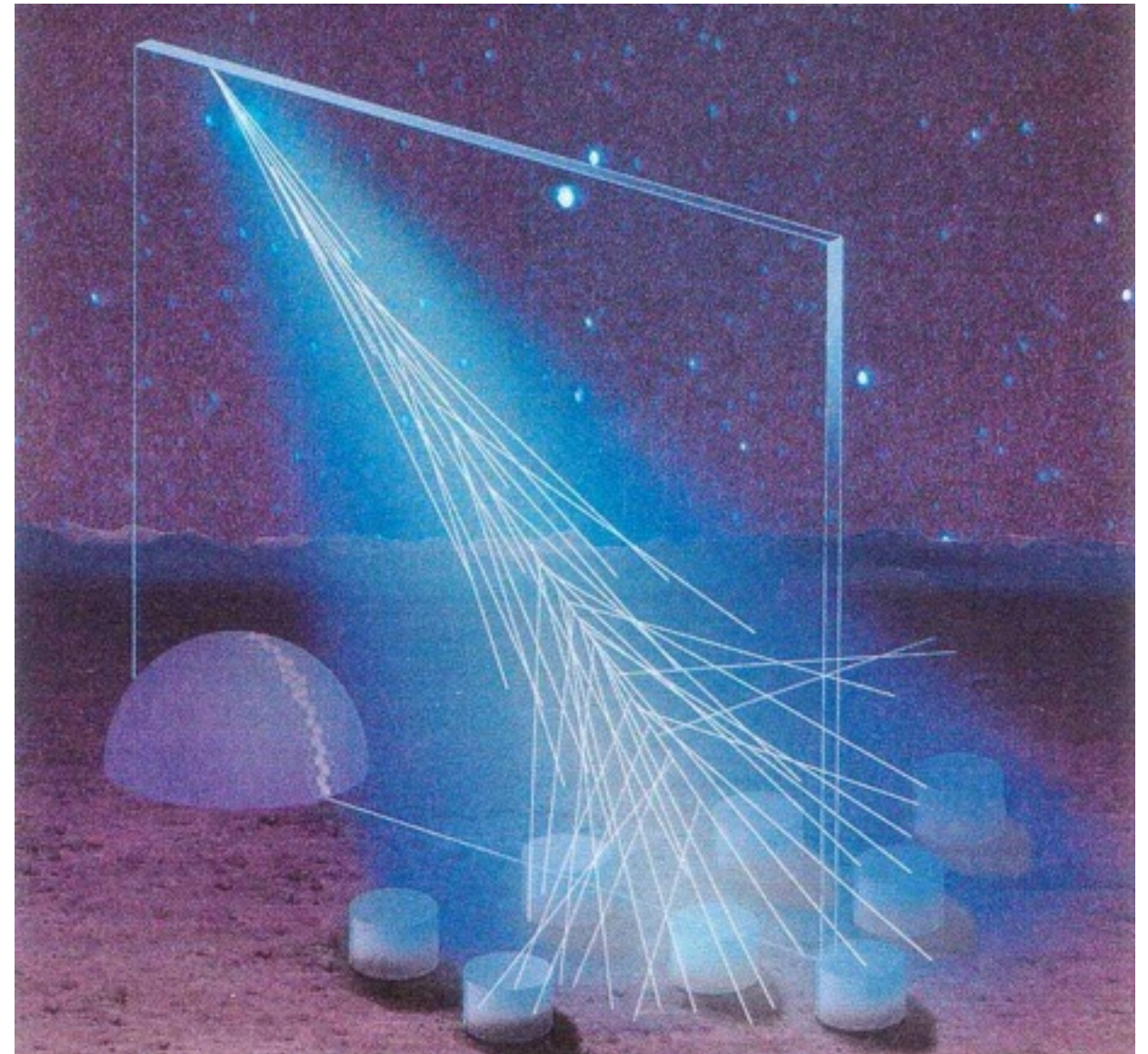
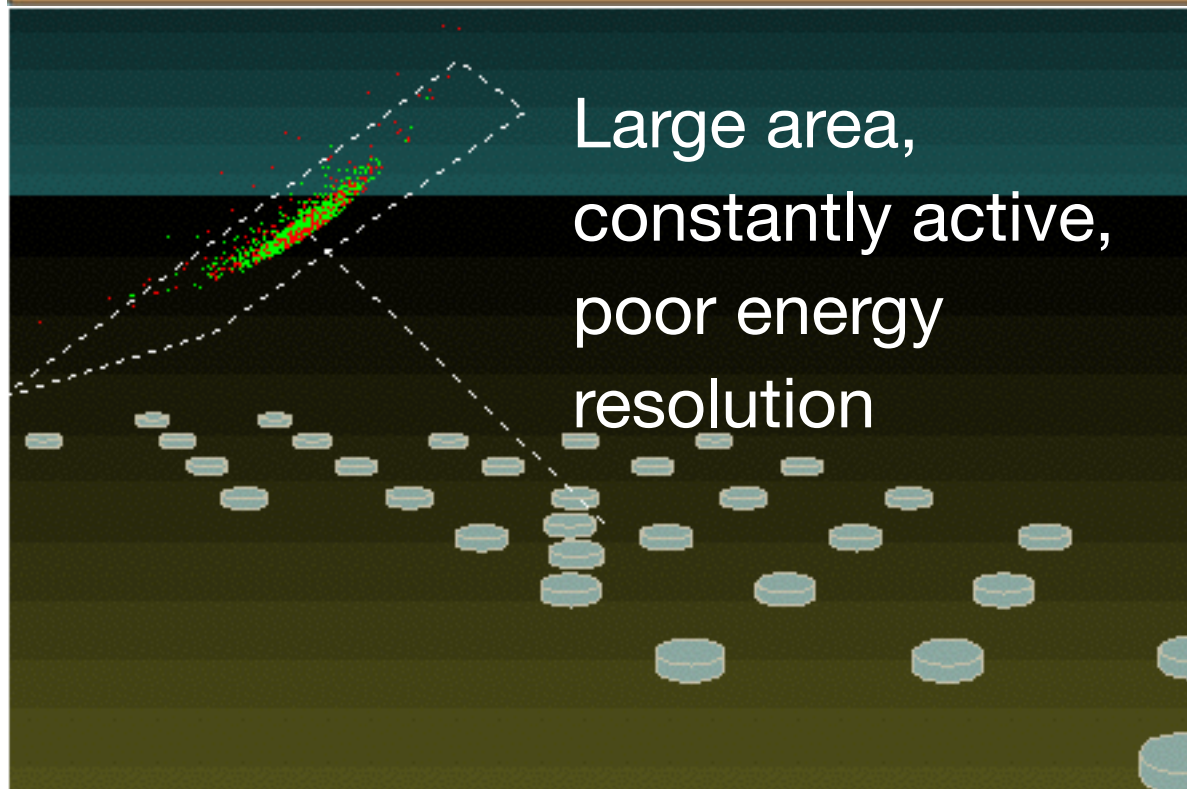
- Cherenkov light is created by electrons in the shower at an altitude of $\sim 10 \text{ km}$
- ▶ On the ground the light spreads over an area with a radius of $\sim 120 \text{ m}$
- ▶ Detection possible with a telescope within this area

Giant Air Shower Arrays

Good resolution
low duty cycle



Large area,
constantly active,
poor energy
resolution



- Two methods for energy measurement
 - Particle multiplicity on the ground
 - Fluorescence light in the atmosphere

Summary

- Differing requirements for detectors in accelerator-based particle physics and astroparticle physics:
 - Extreme rates vs rare events
- Common basis: Interaction of particles with matter
 - Ionization energy loss: Bethe-Bloch
 - Photons: pair production at high energies ($> \text{few MeV}$)
 - Formation of particle showers for highly energetic hadrons, electrons, photons
- Detection techniques
 - Charge collection in gaseous and semi-conductor detectors
 - Light detection, for example for fluorescence / scintillation and Cherenkov detectors



Summary

- Differing requirements for detectors in accelerator-based particle physics and astroparticle physics:
 - Extreme rates vs rare events
- Common basis: Interaction of particles with matter
 - Ionization energy loss: Bethe-Bloch
 - Photons: pair production at high energies ($> \text{few MeV}$)
 - Formation of particle showers for highly energetic hadrons, electrons, photons
- Detection techniques
 - Charge collection in gaseous and semi-conductor detectors
 - Light detection, for example for fluorescence / scintillation and Cherenkov detectors

Next Lecture: 02.05.,
“Cosmic Accelerators”, F. Simon

Topics Overview

11.04.	Einführung / Introduction
18.04.	Erdegebundene Beschleuniger / Accelerators
25.04.	Detektoren in der Nicht-Beschleuniger-Physik / Detectors
02.05.	Kosmische Beschleuniger / Cosmic Accelerators
09.05.	Das Standardmodell / The Standard Model
16.05.	Pfingsten - Keine Vorlesung! No Lecture
23.05.	QCD und Jet Physik an Lepton Beschleunigern / QCD and Jets
30.05.	Präzisionsexperimente (g-2) / Precision Experiments
06.06.	Gravitationswellen / Gravitational Waves
13.06.	Kosmische Strahlung I / Cosmic Rays I
20.06.	Kosmische Strahlung II / Cosmic Rays II
27.06.	Dunkle Materie & Dunkle Energie / Dark Matter & Dark Energy
04.07.	Neutrinos I
11.07.	Neutrinos II

