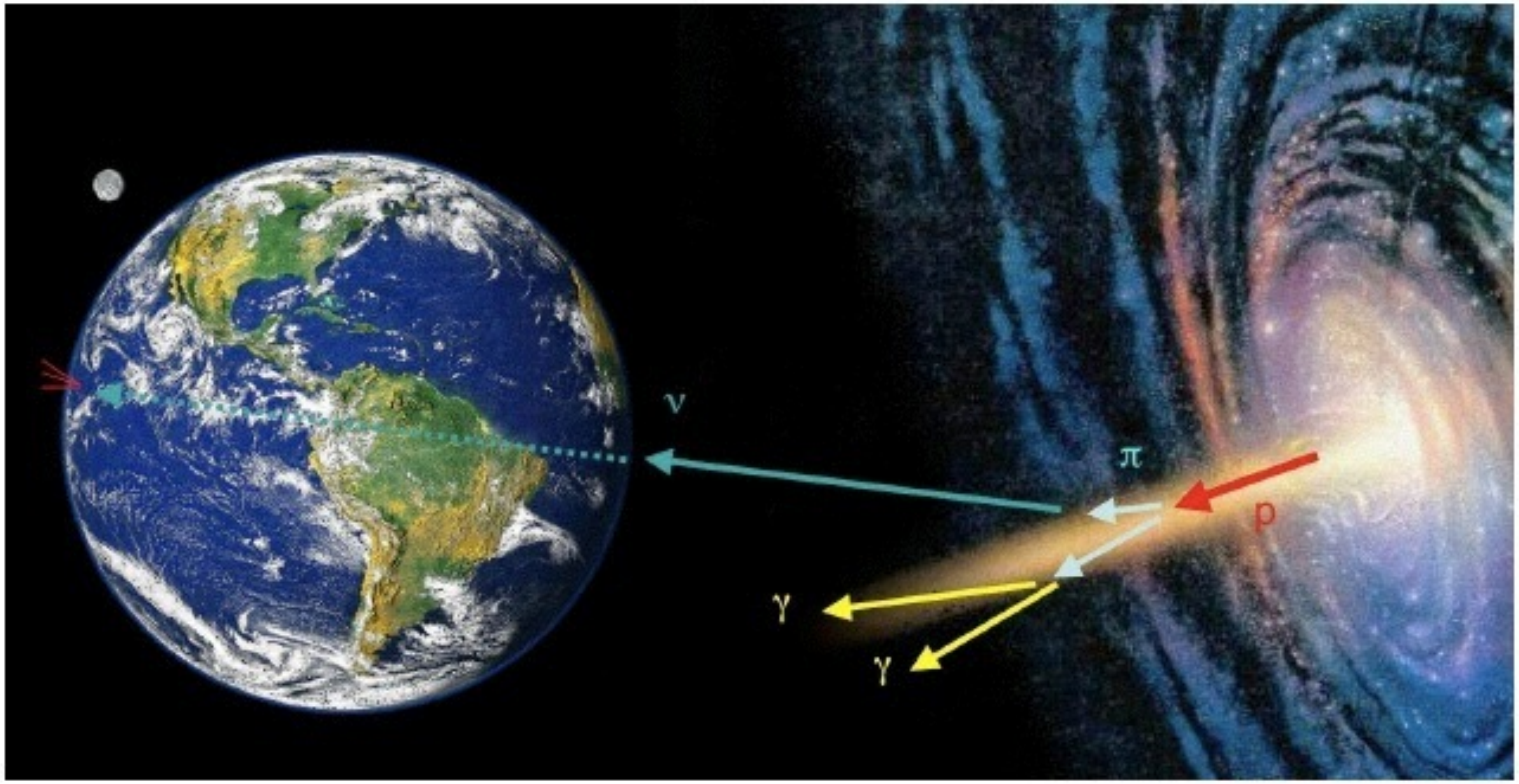
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



03. Detectors in Particle & Astroparticle Physics

27.04.2014

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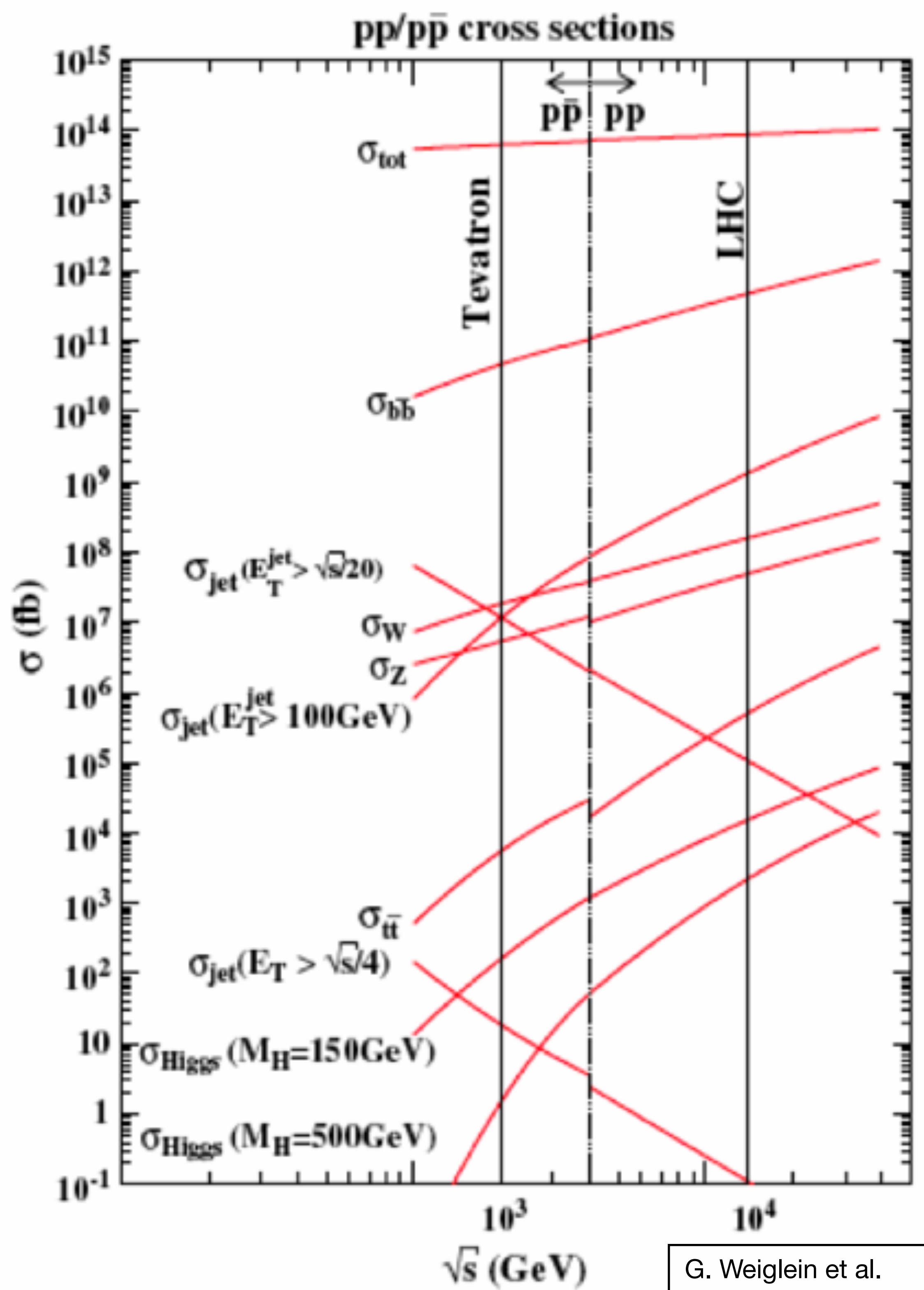
Prof. Dr. Siegfried Bethke
Dr. Frank Simon

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

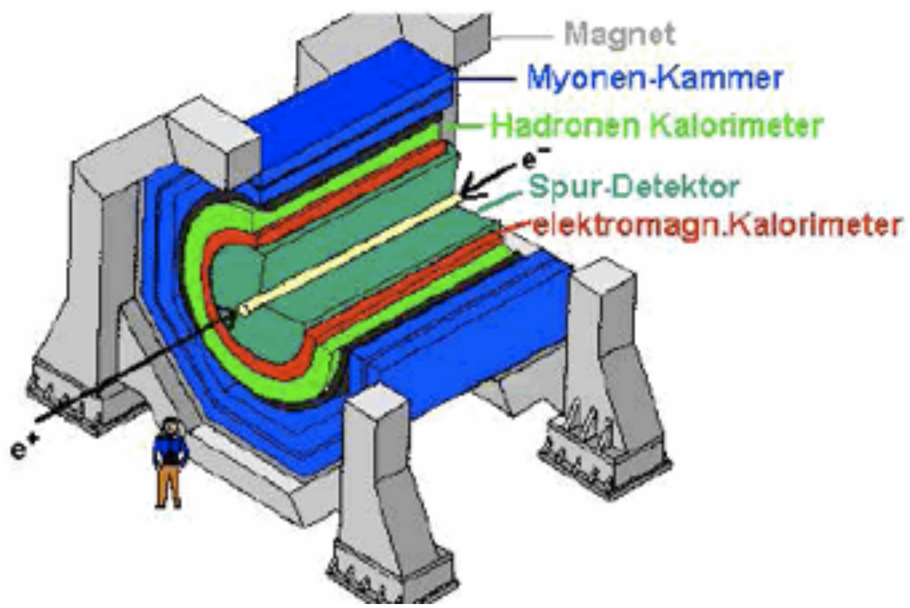


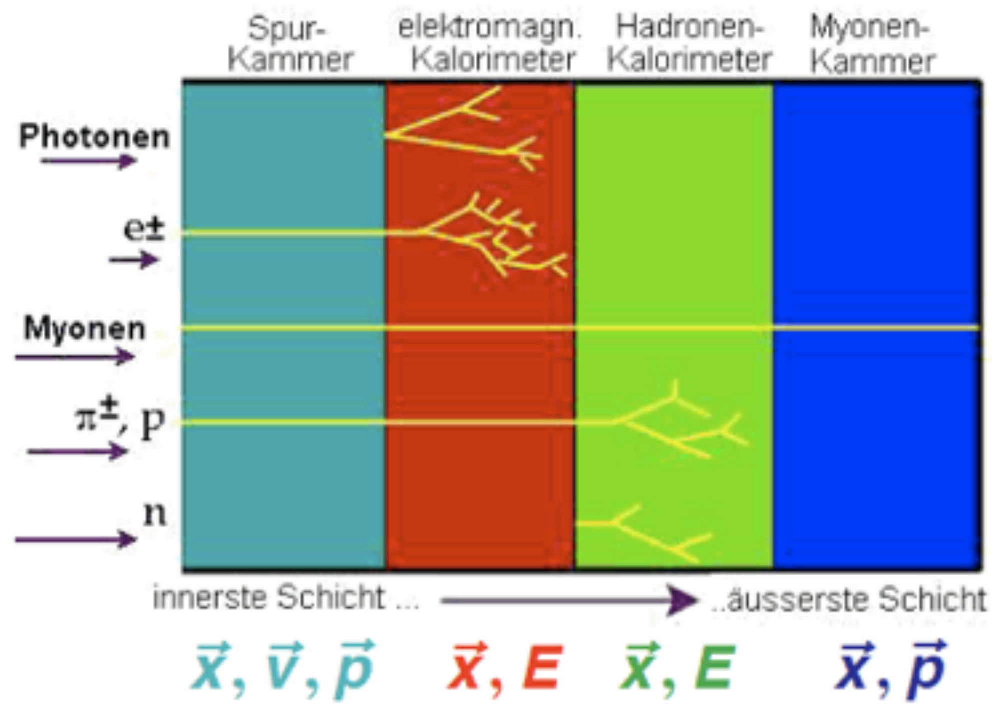
G. Weiglein et al.
Physics Reports 426 (2006) 47–358

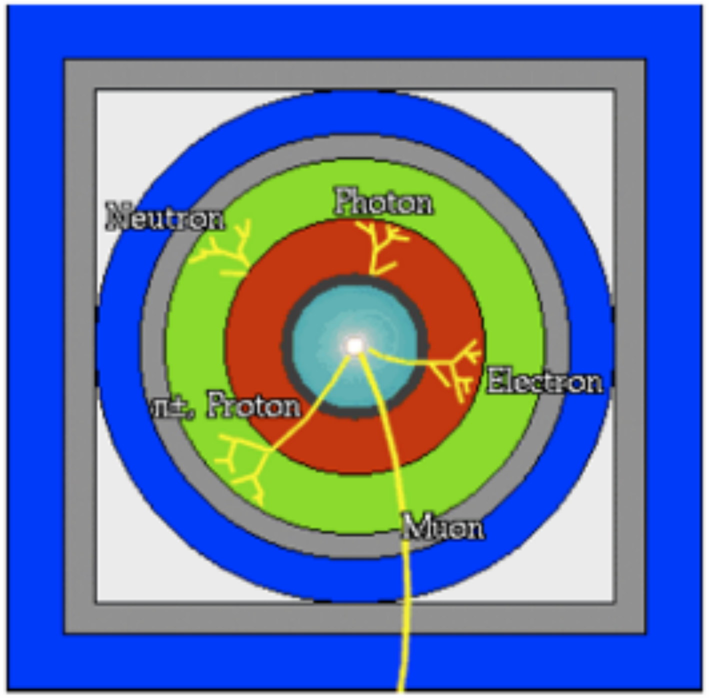
- At Hadron-Colliders:
  - Extreme event rates:
    Interesting processes are much rarer than “normal” processes
  - Detectors are optimized to cope with very high event rates and high particle density, and for picking up rare signatures out of large backgrounds

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







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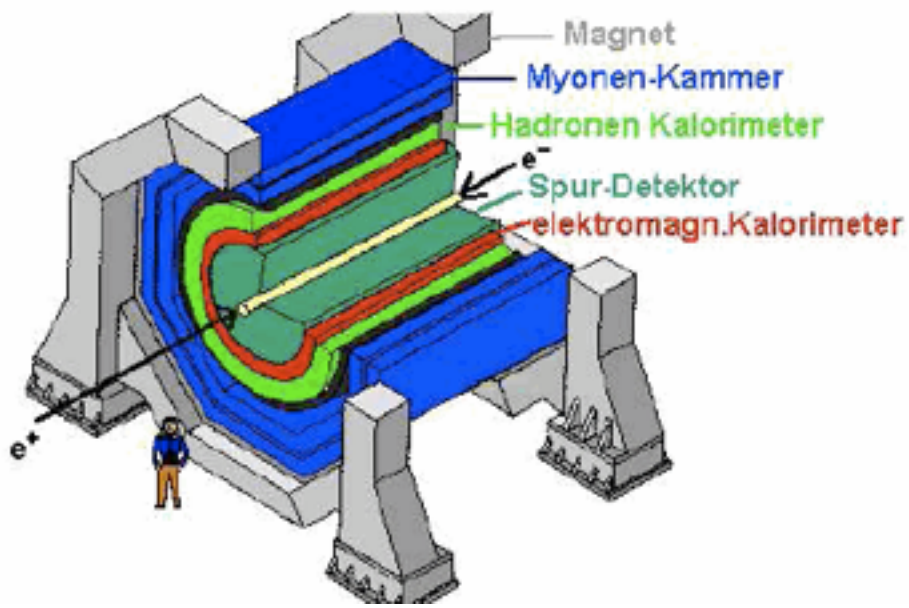

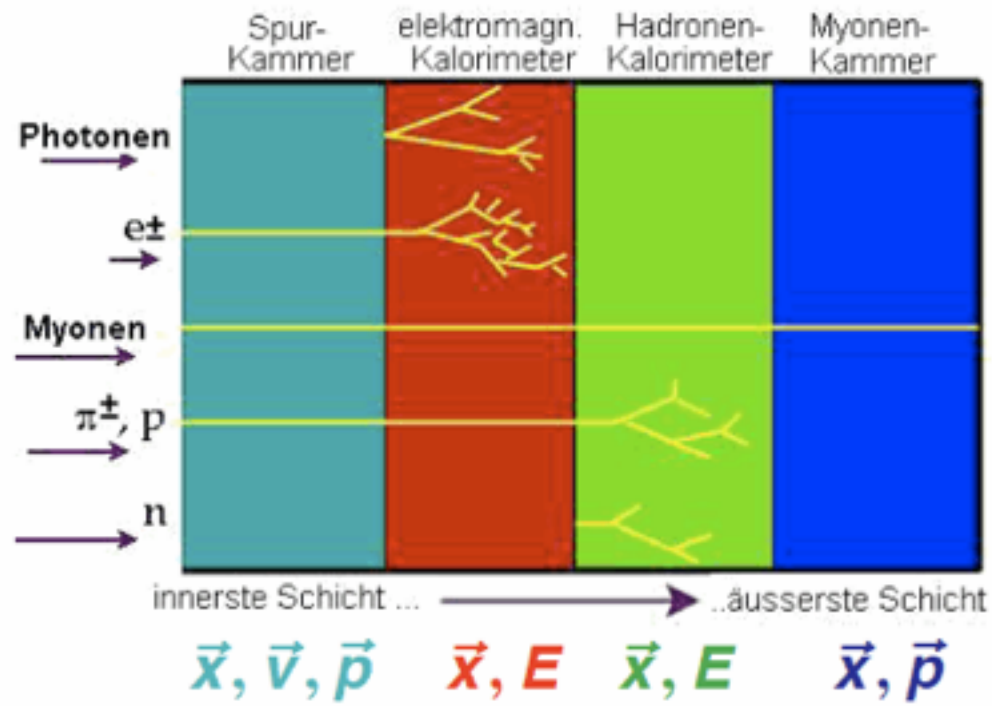

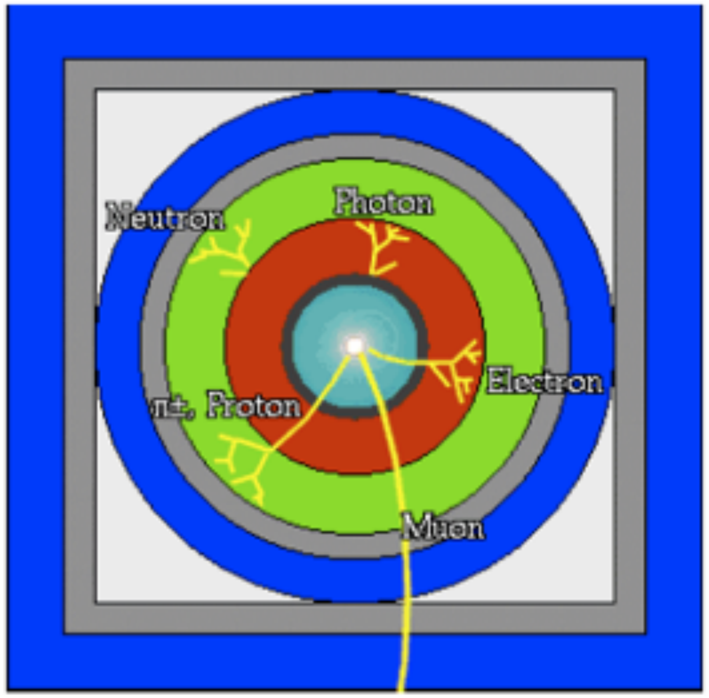

Tracker: Momentum of charged particles via deflection in magnetic field and precise track reconstruction

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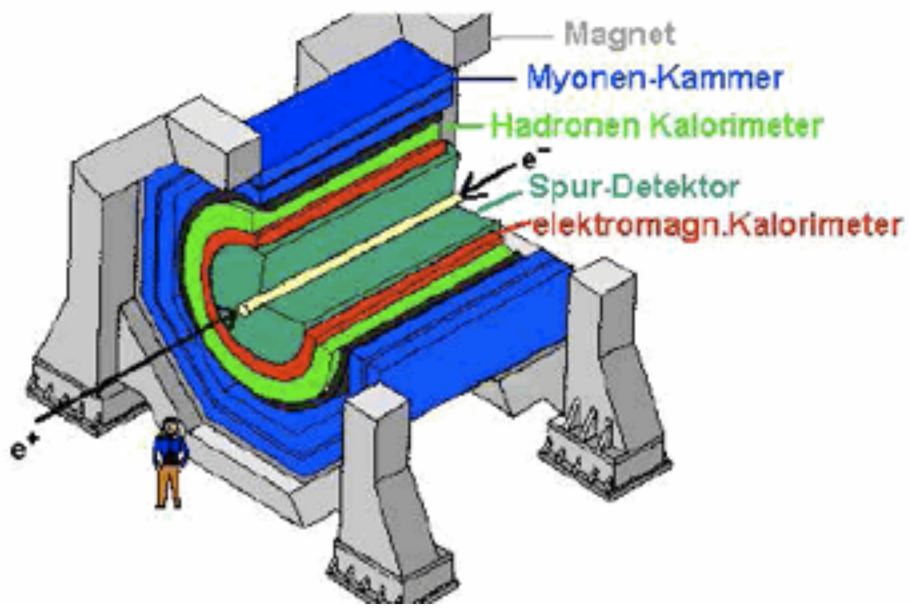

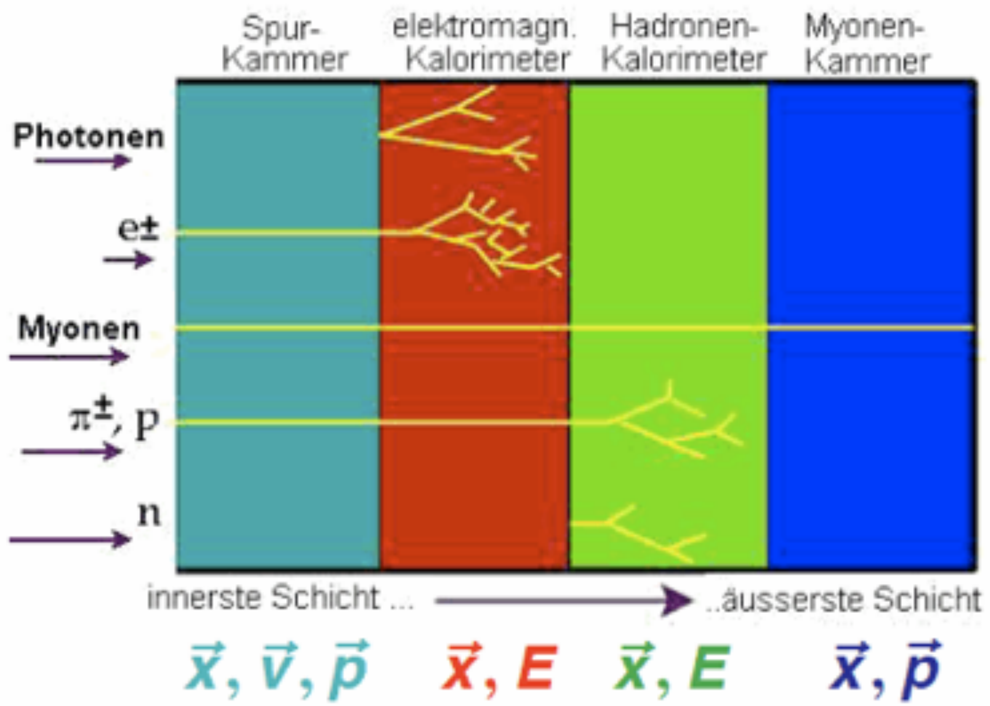

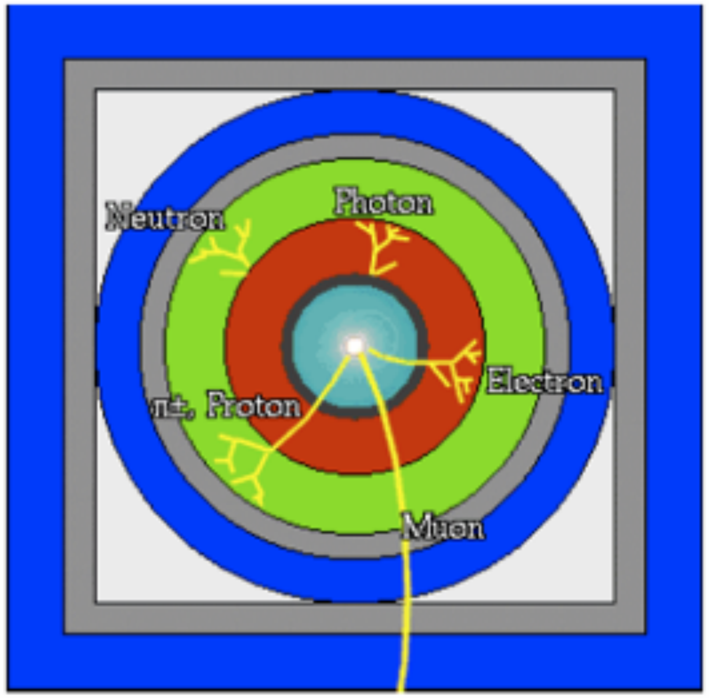

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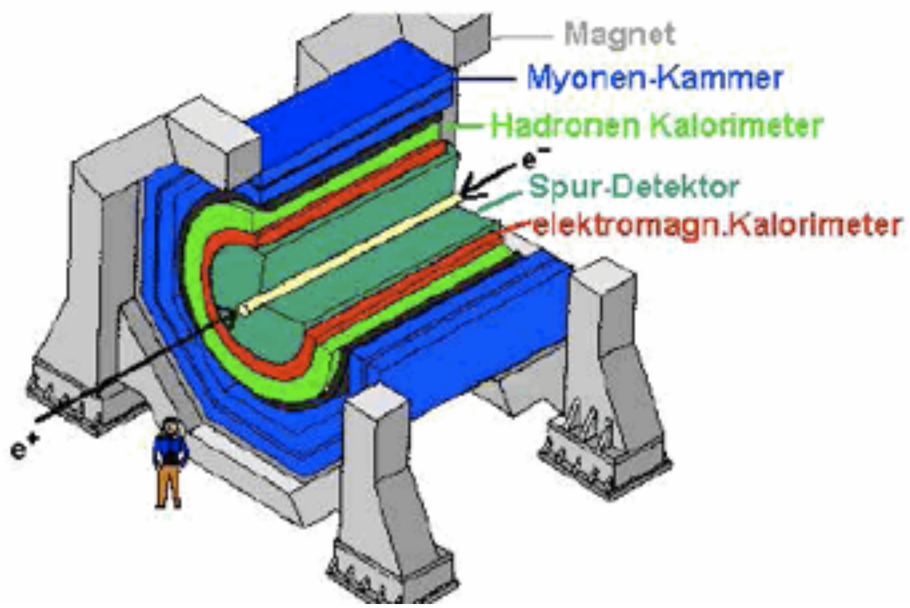

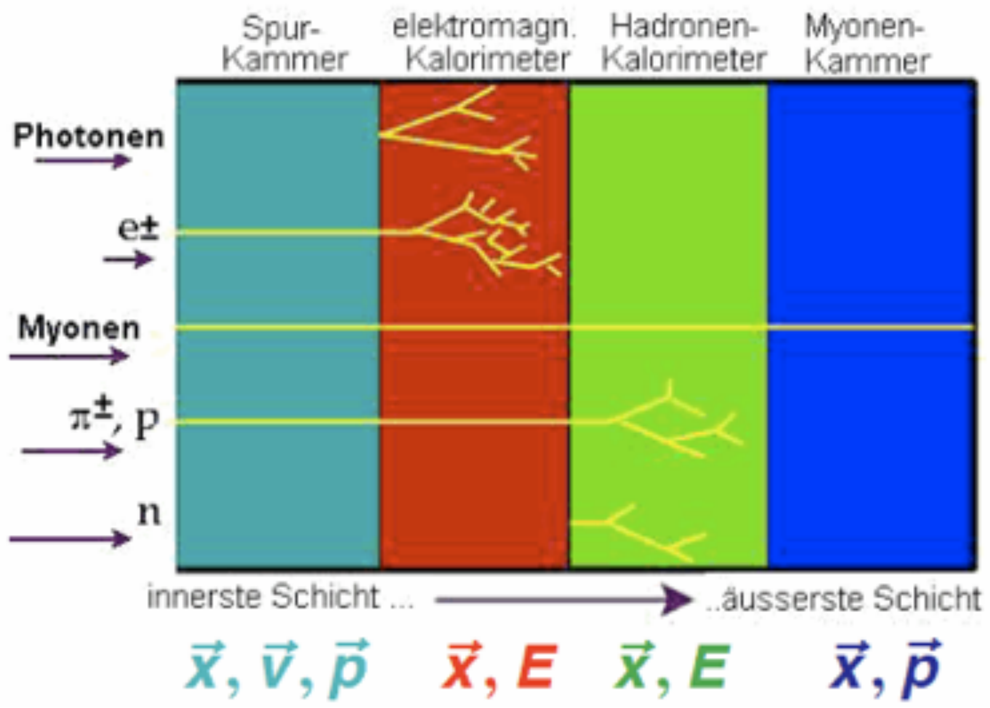

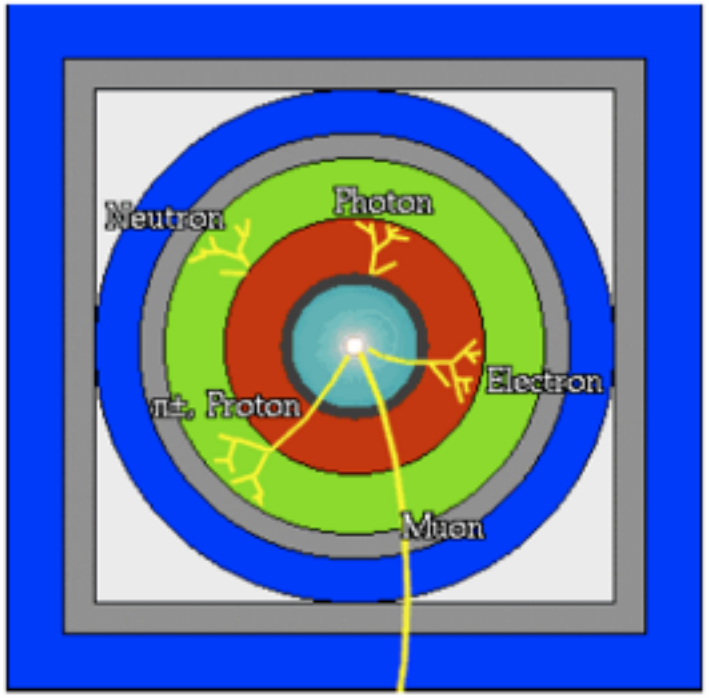

Tracker: Momentum of charged particles via deflection in magnetic field and precise track reconstruction

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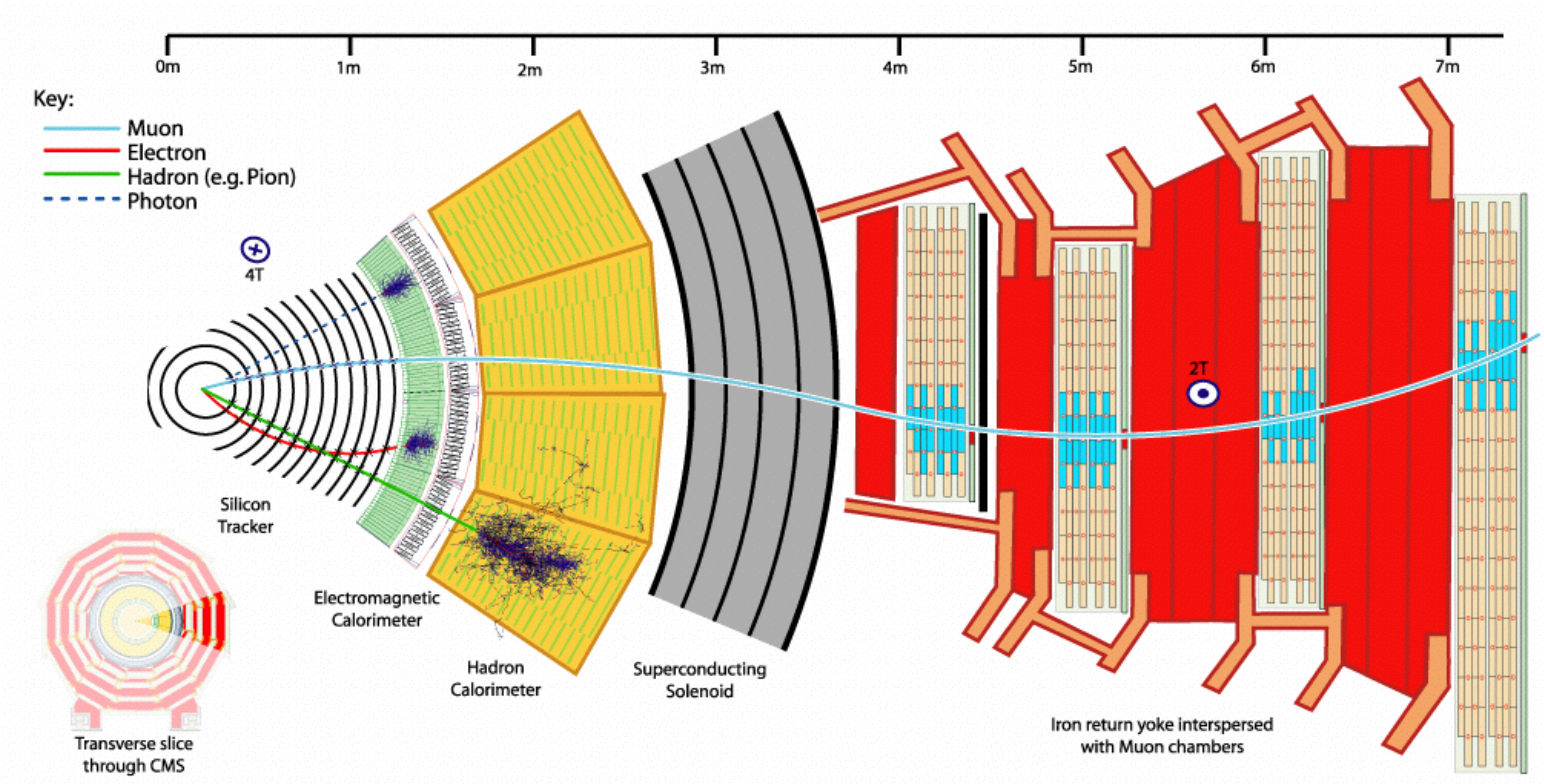
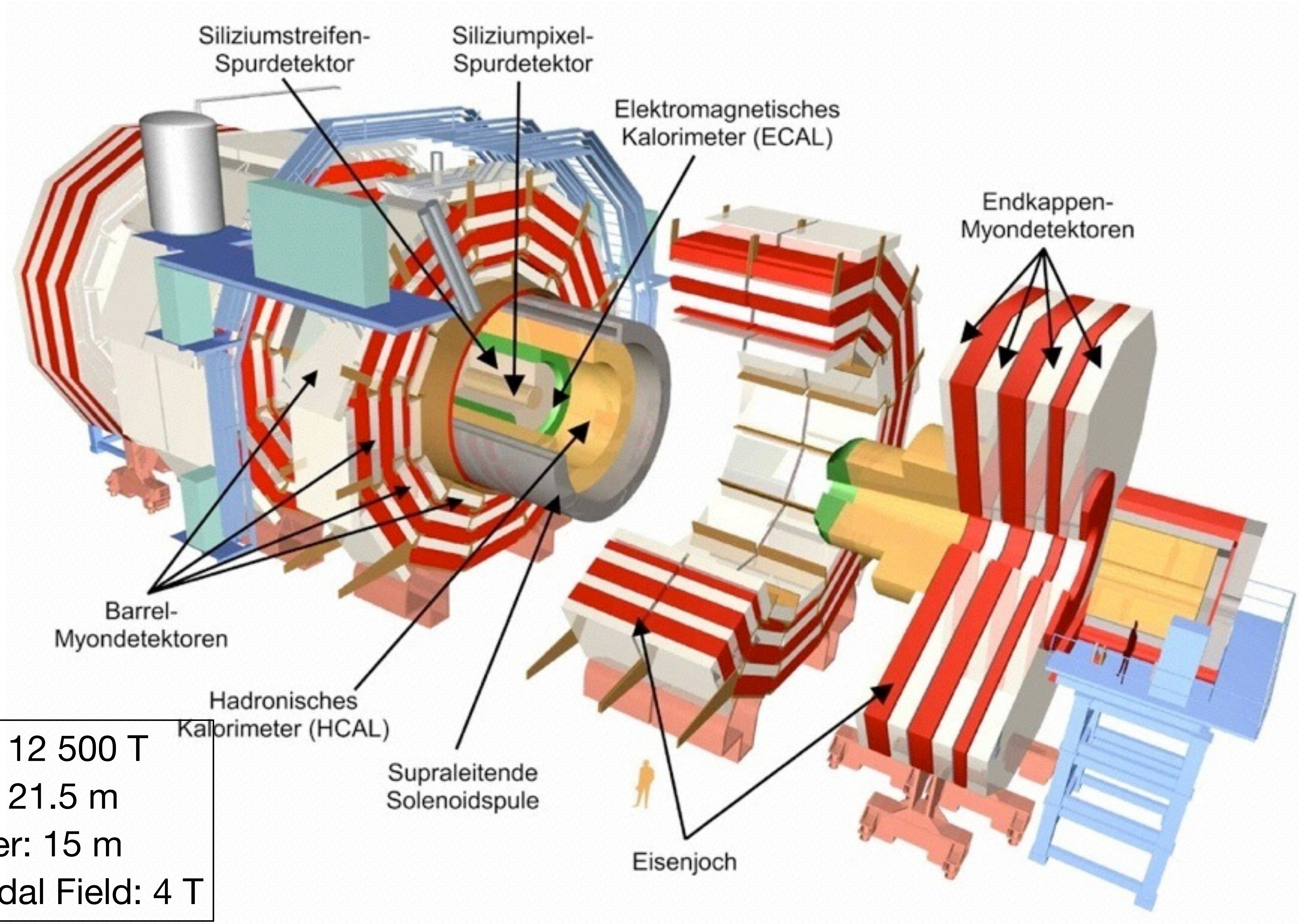
Muon Detectors: Identification and momentum measurement of muons

Collider-Detectors: Cross Section [CMS]



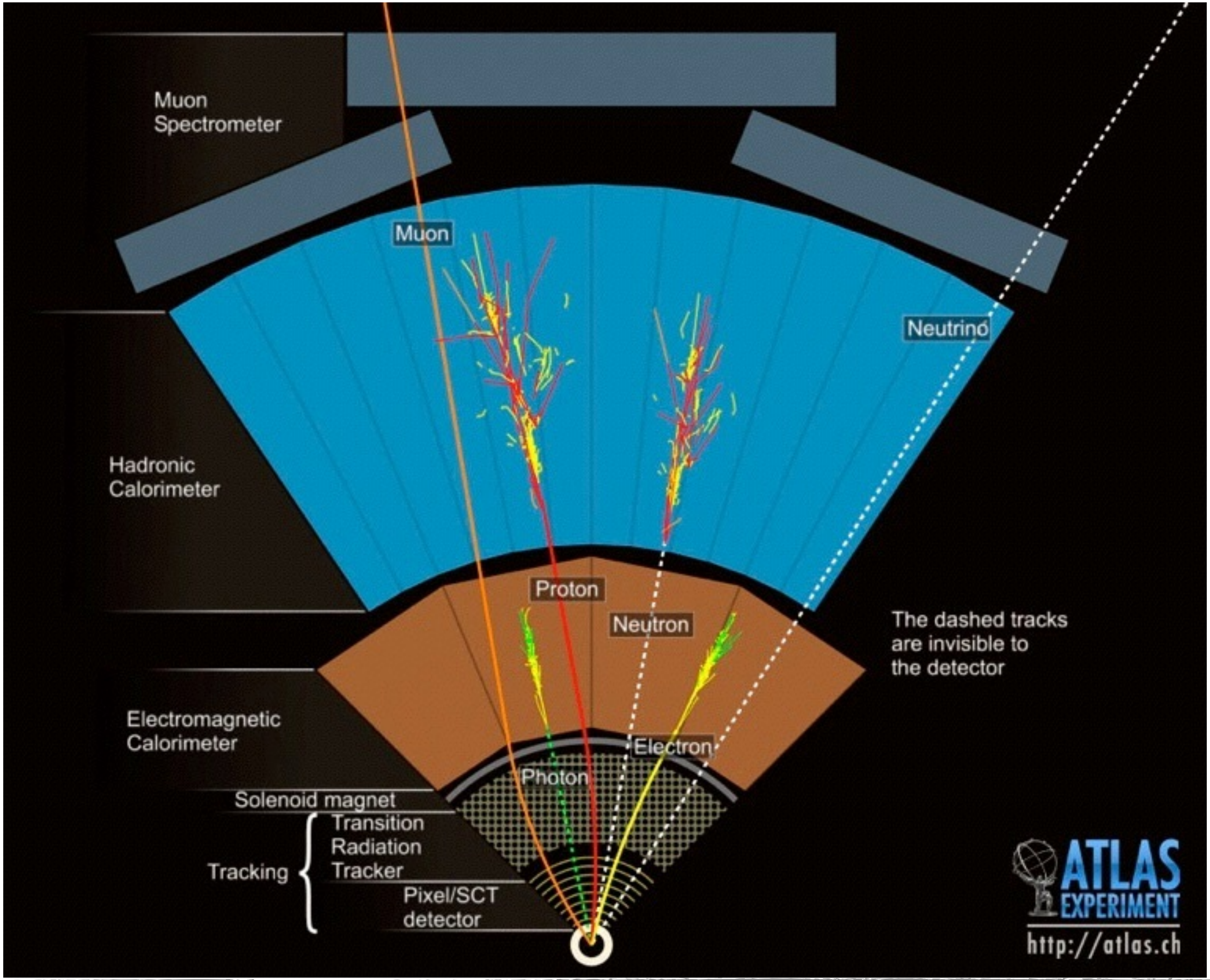
- High energies require high magnetic fields and large detectors
- Shown here: CMS, (C is for Compact!)

CMS: The Heavy Weight

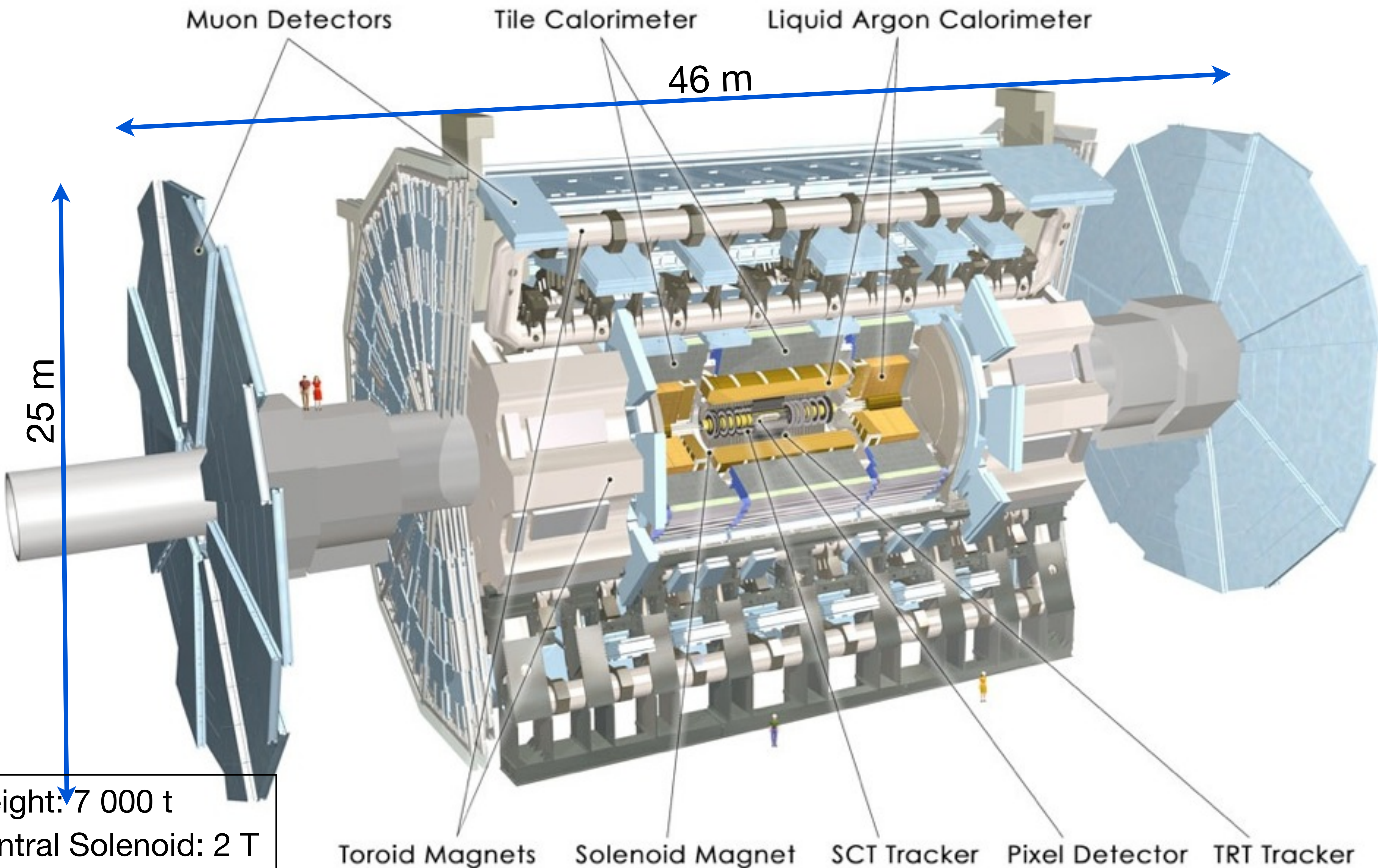


Weight: 12 500 T
Length: 21.5 m
Diameter: 15 m
Solenoidal Field: 4 T

Particles in ATLAS



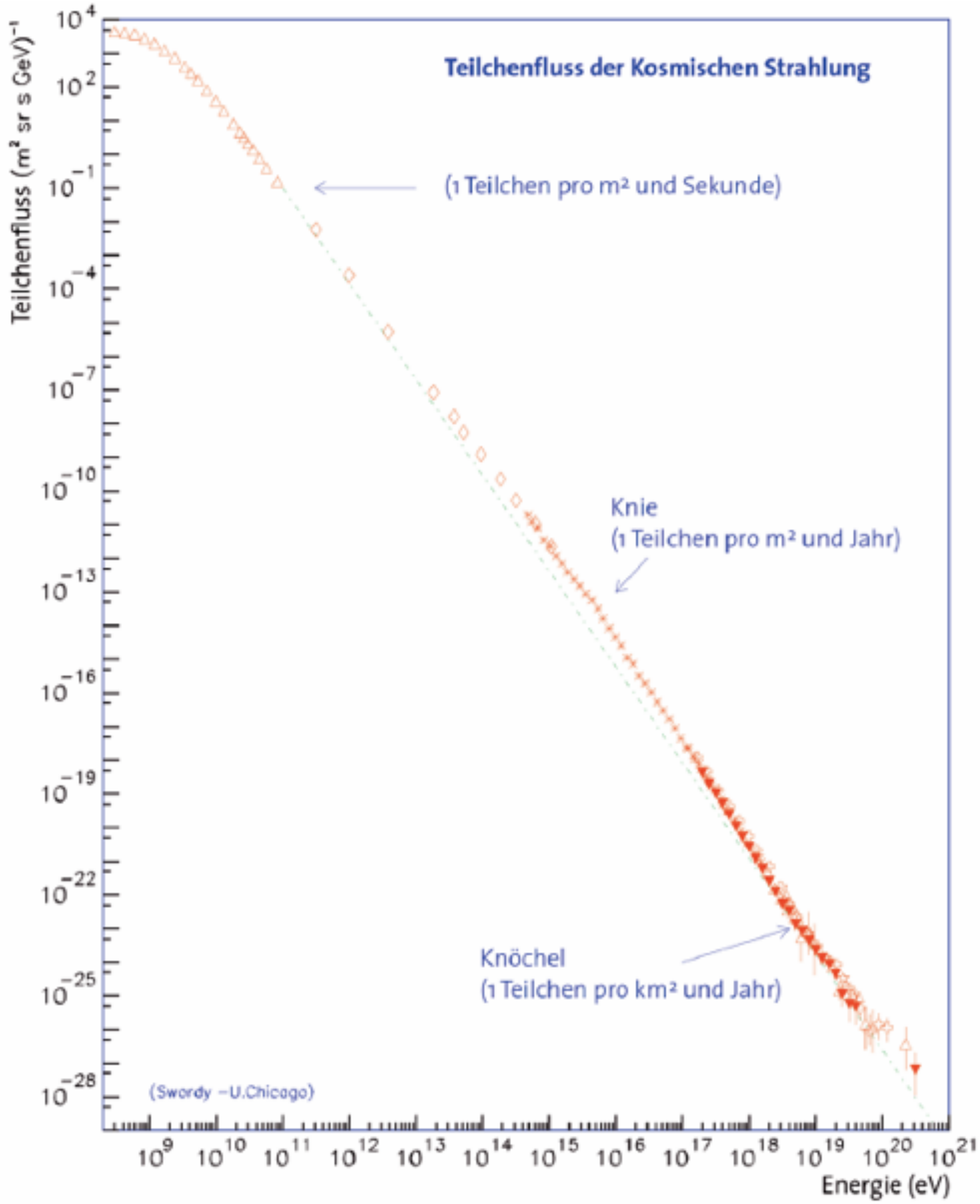
ATLAS: The Biggest Collider Detector



Weight: 7 000 t
Central Solenoid: 2 T
Muon-Toroid: 4 T

Illustration: CERN

Challenges in Astroparticle Physics

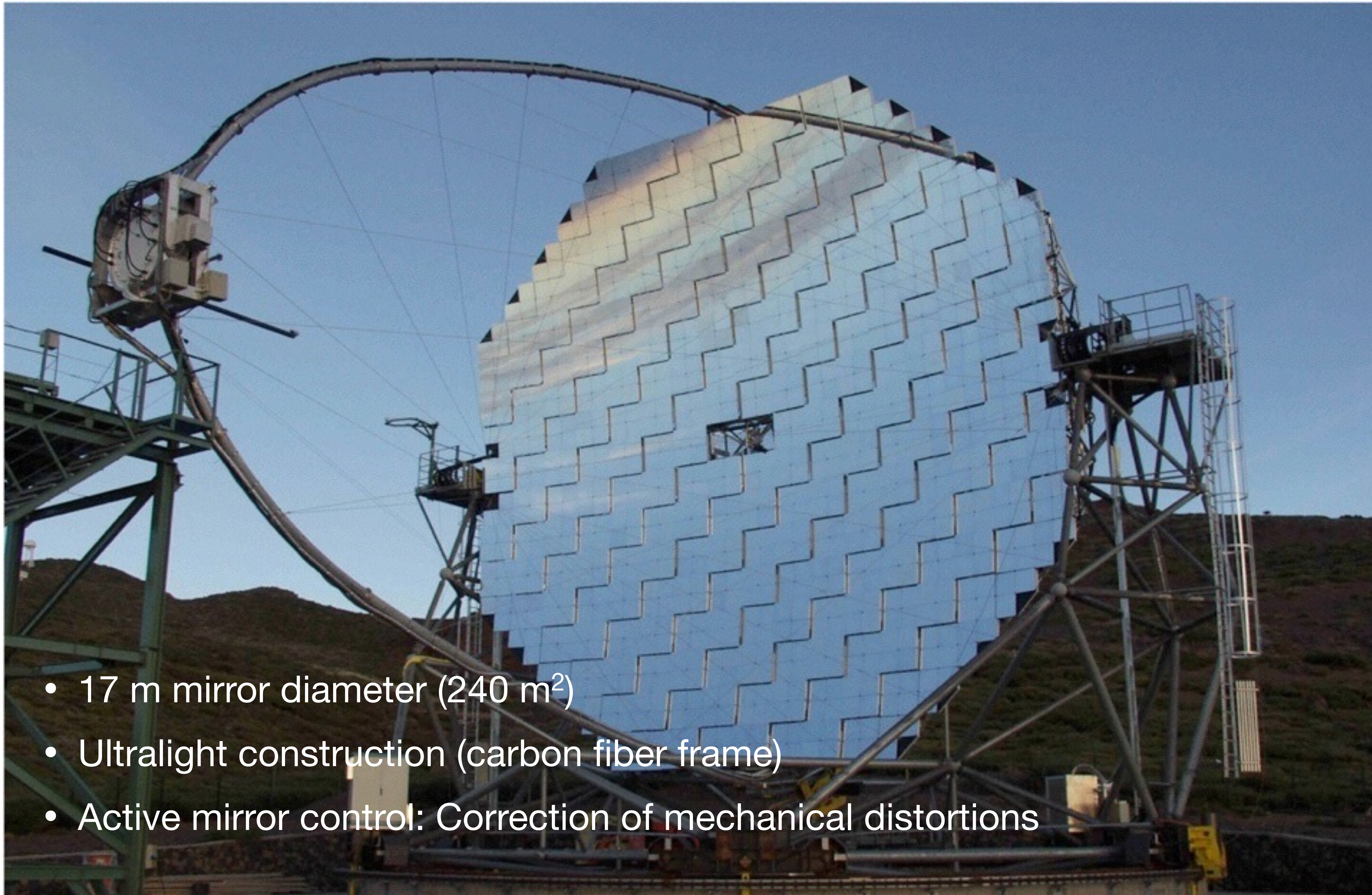


- Search for very rare events
  - Large areas / volumes have to be covered
  - Good suppression of background
  - High efficiency: Can not afford to loose events
  - Data rates, radiation damage, ... usually not an issue

What do we want to measure?

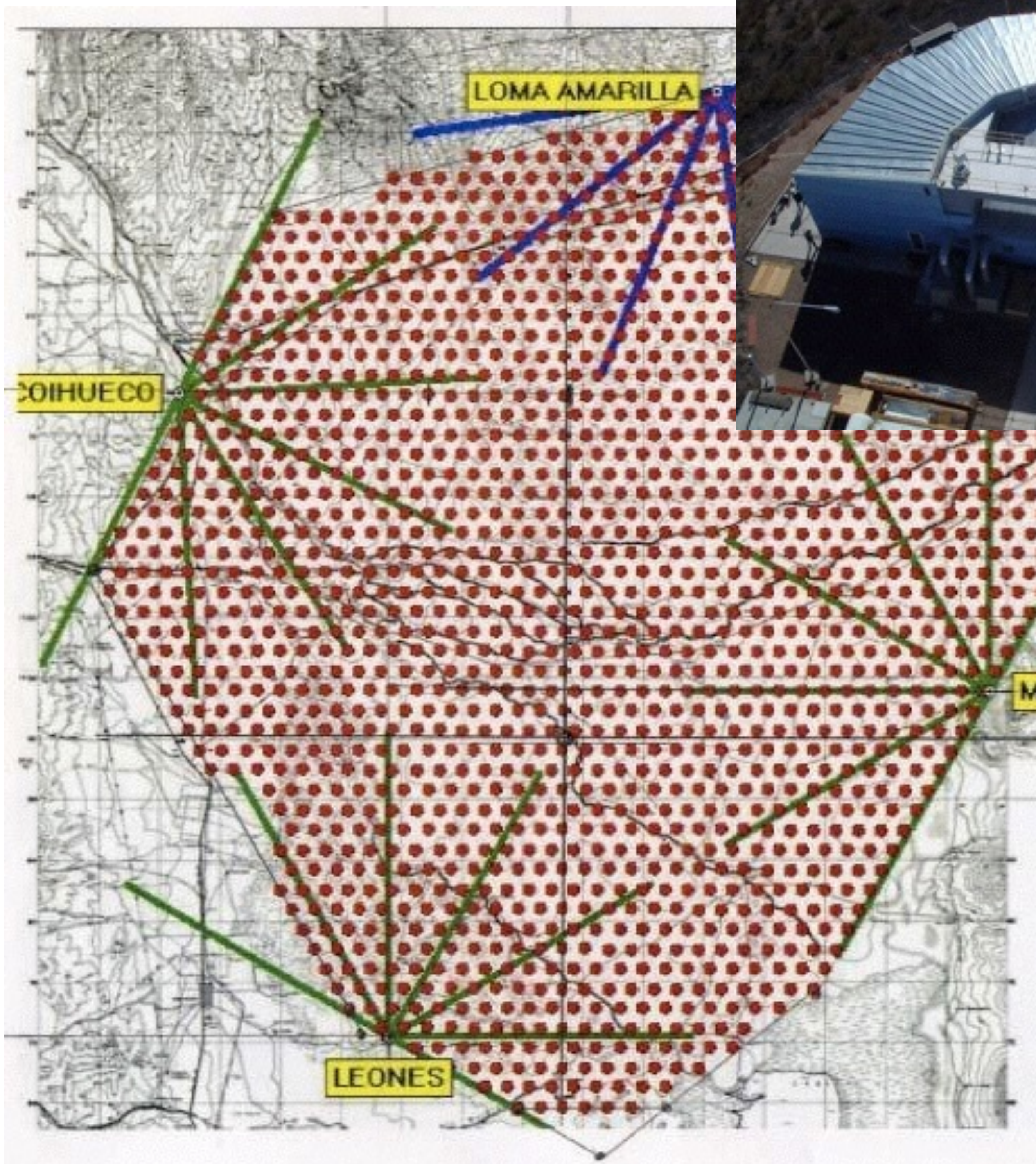
- Highly energetic particles from cosmic sources: hadrons, photons
  - Either: Measurement outside of the atmosphere
  - Or: Use of the atmosphere as detector, particle detectors via air showers
- Neutrinos
  - Low cross section => Large detector volumes
- Dark Matter
  - Low cross sections => large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

MAGIC: High-Energy Gammas



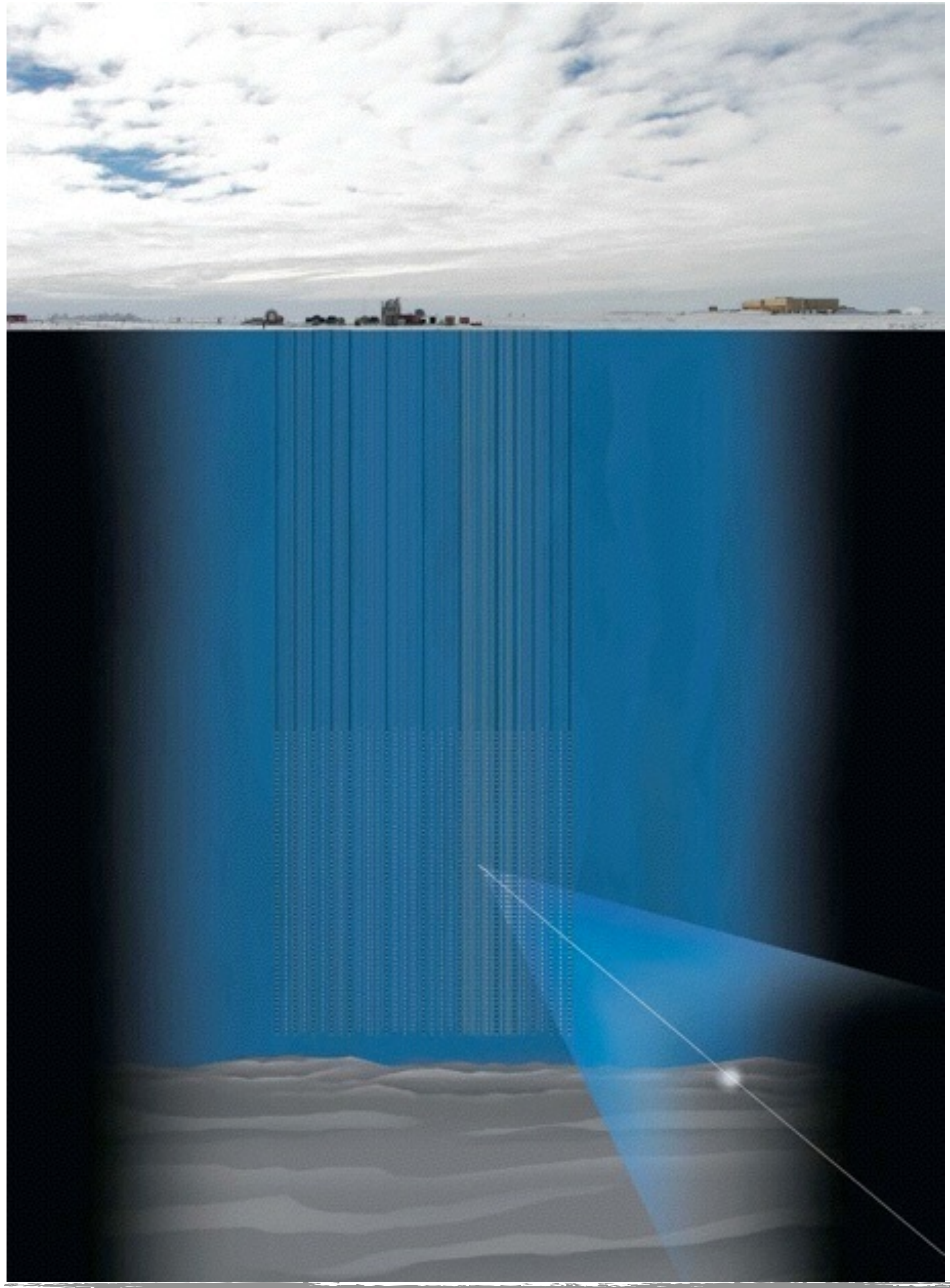
- 17 m mirror diameter (240 m^2)
- Ultralight construction (carbon fiber frame)
- Active mirror control: Correction of mechanical distortions

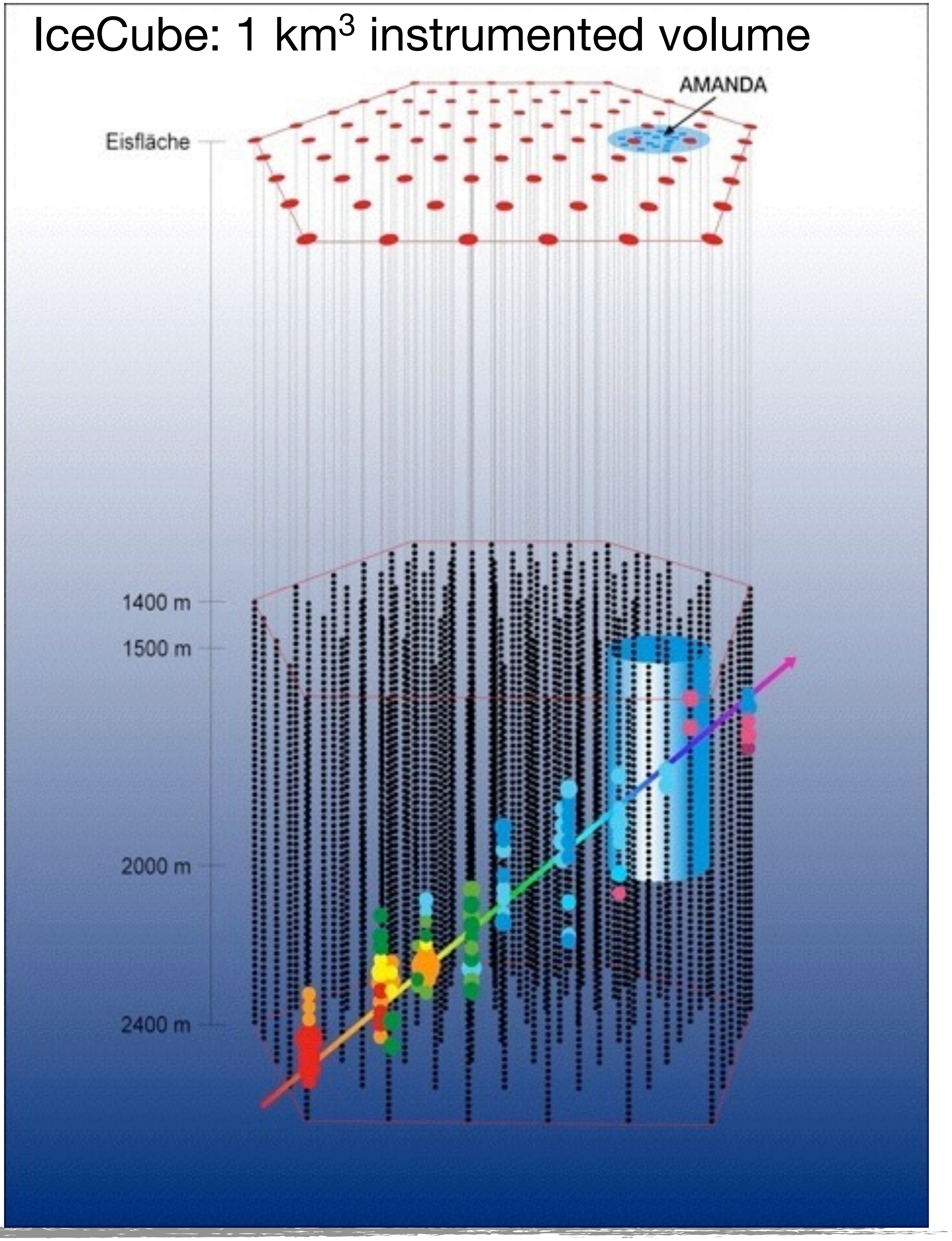
AUGER: Highly Energetic Charged Particles



- 1600 Water-cherenkov-detectors on the ground
- 4 fluorescence stations with 6 telescopes each
- 3000 km^2

Amanda/IceCube



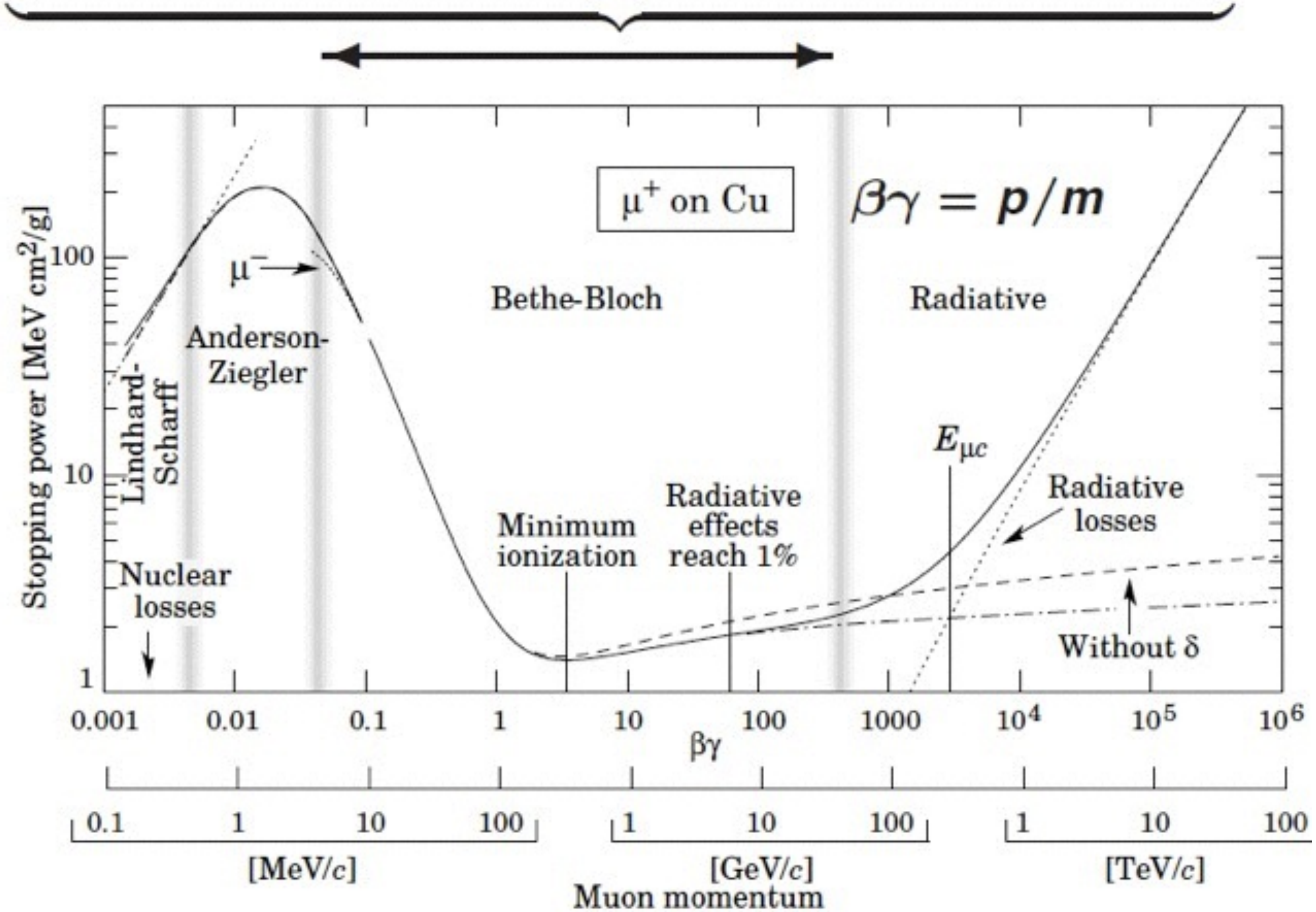


The Basics of Particle Detection: Interaction of Particles with Matter

Energy Loss in Matter: Bethe-Bloch

- The Bethe-Bloch equation describes energy loss through ionization

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



- Valid in intermediate energy range: ~0.1 < βγ < ~ 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 loose more energy
- Minimum at p/m ~ 3-4: minimum ionizing particle MIP
- Logarithmic rise for high energy
- Additional density effect due to polarization of absorber

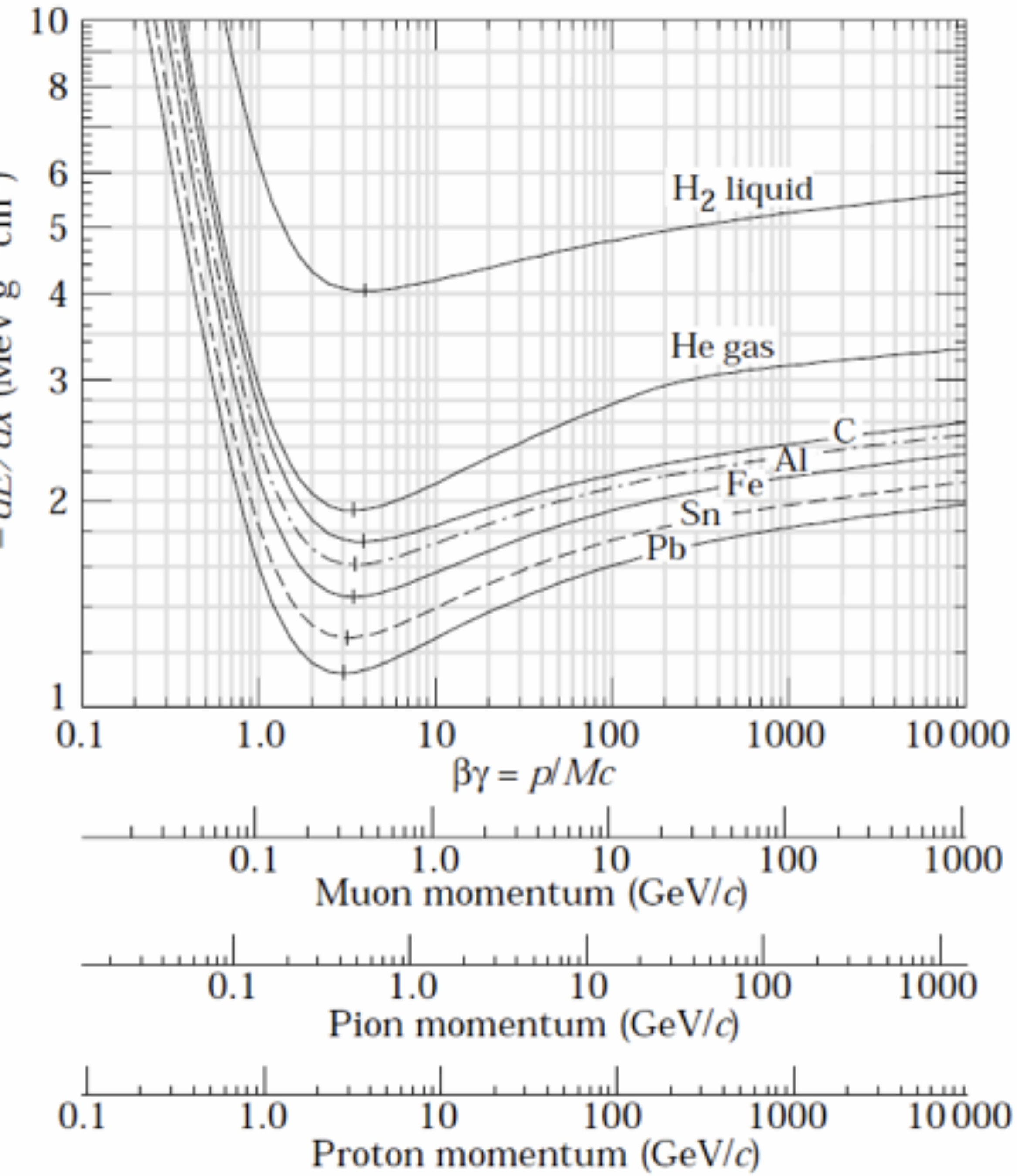
Important Constants

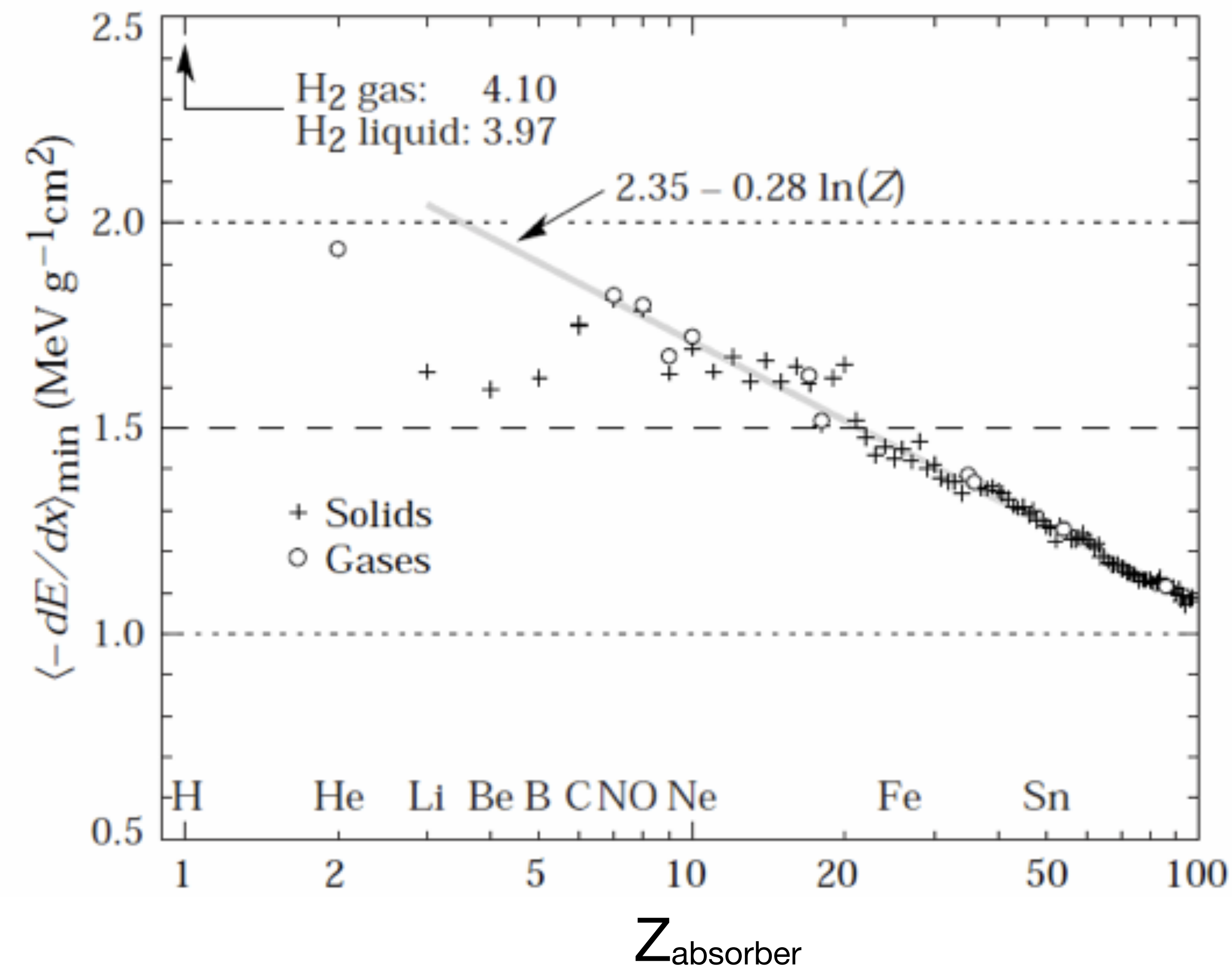
Symbol	Definition	Wert und/oder Dimension
α	Feinstrukturkonstante	1/137.03599976(50)
m	Masse des einfallenden Teilchens	$\mathrm{MeV/c^2}$
E	Energie des Teilchens	MeV
T	kinetische Energie des Teilchens	MeV
$z \cdot e$	Ladung des Teilchens	$z \cdot 1.6021 \cdot 10^{-19}$ C
r_e	klassischer Elektronenradius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

- Mean ionization energy:

  $I \sim 16\ Z^{0.9}$ 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} cm^2 (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)

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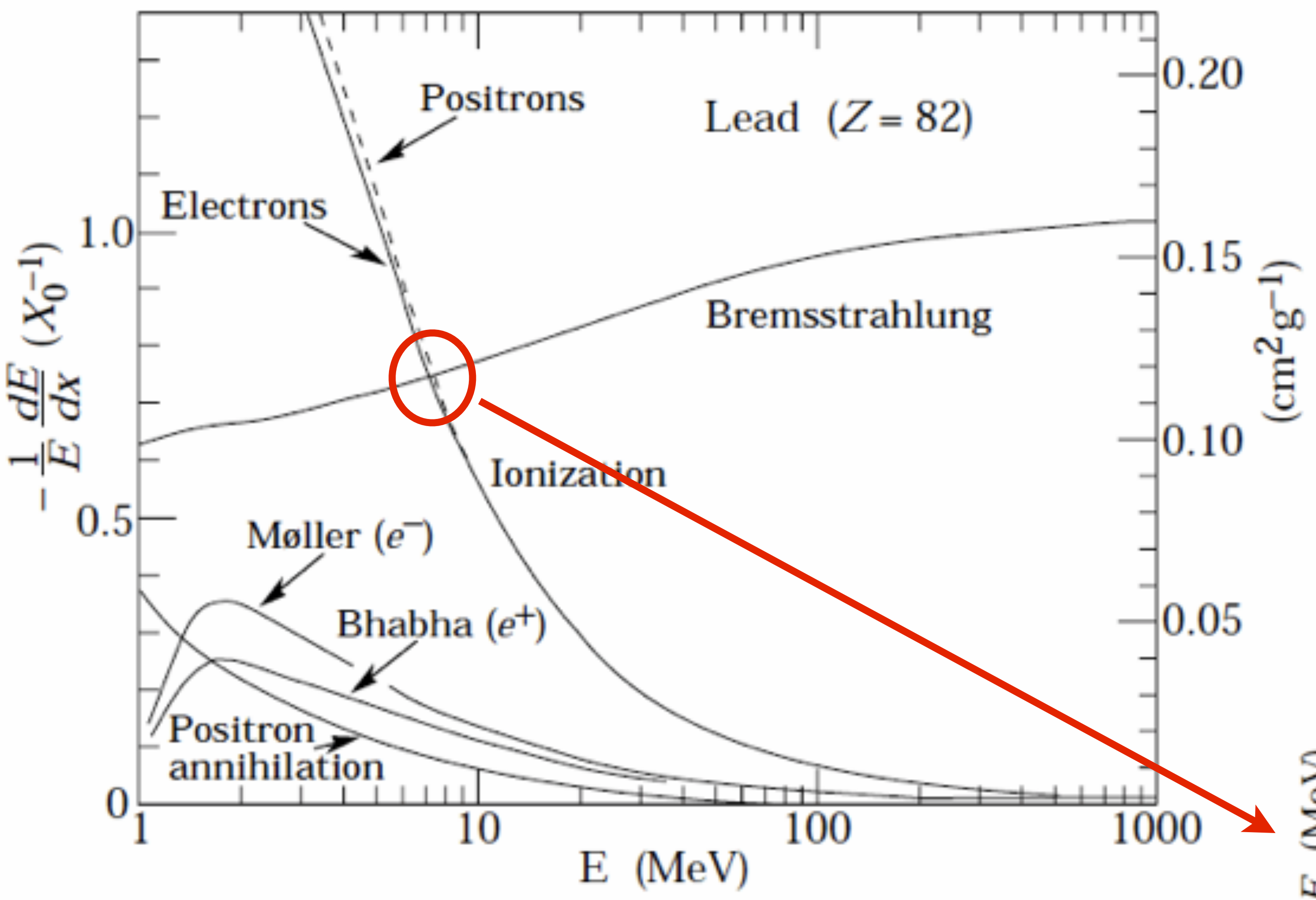
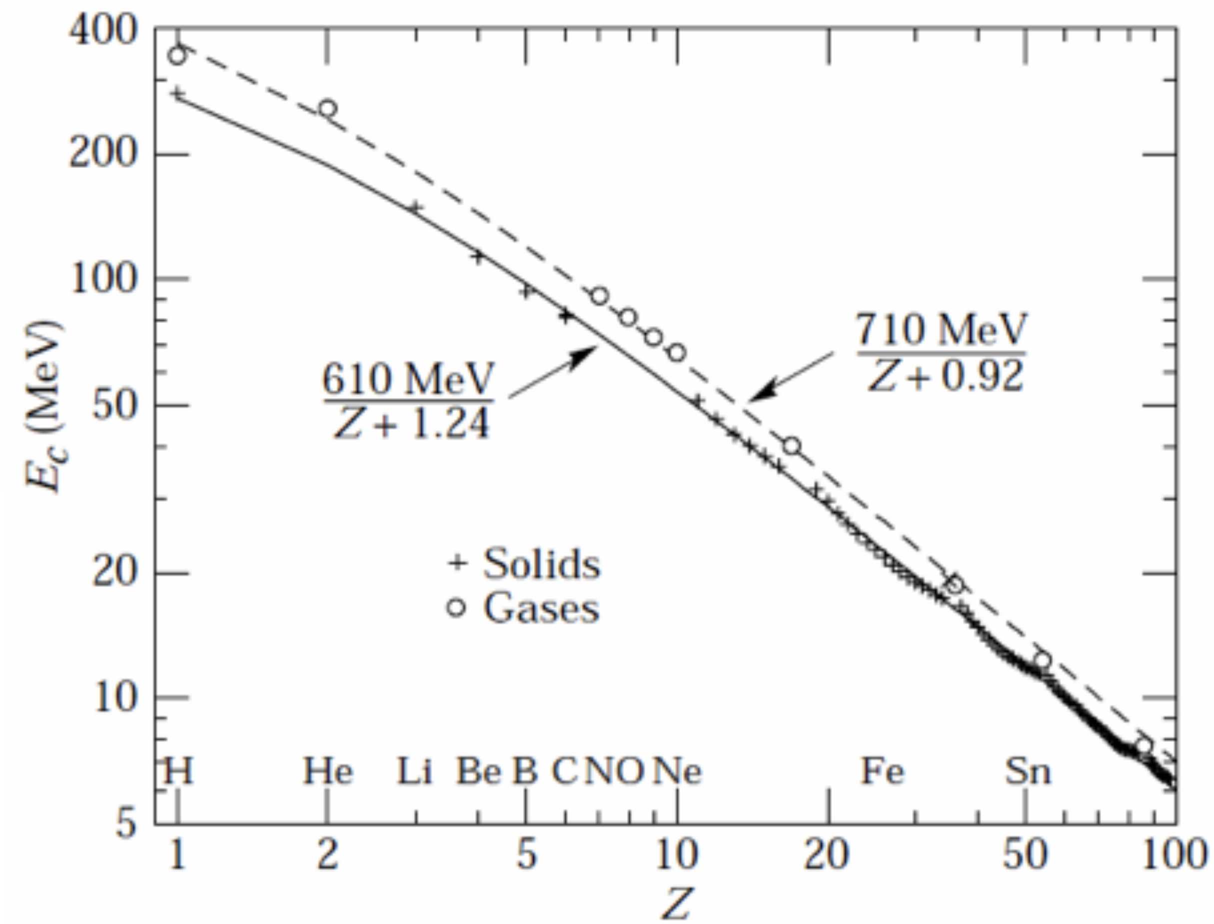
  - Also relevant for the description of low-angle multiple scattering
  - Usually given in g/cm², typical values for some materials:
    - Air: 36.66 g/cm², corresponds to ~ 300 m
    - Water: 36.08 g/cm², corresponds to ~ 36 cm
    - Aluminum: 24.01 g/cm², corresponds to 8.9 cm
    - Tungsten: 6.76 g/cm²,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

Electrons: Energy Loss



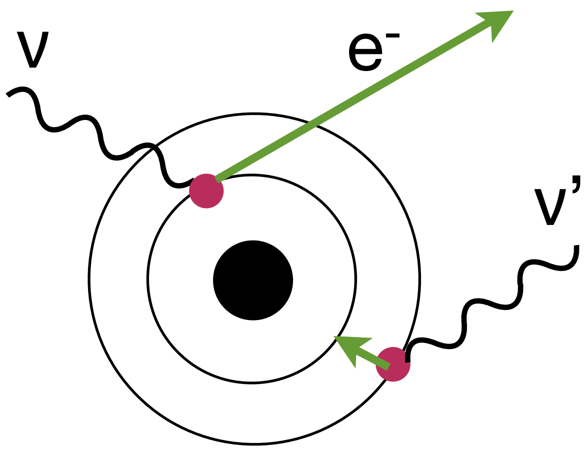
- Bremsstrahlung dominates at high energies
- At low energies: Ionization, scattering



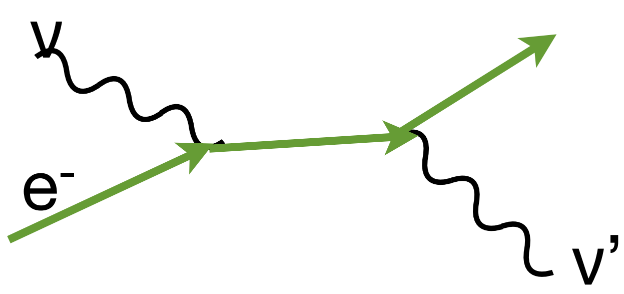
- Critical energy: The energy where ionization and radiative energy loss are equal

Photons: Interaction

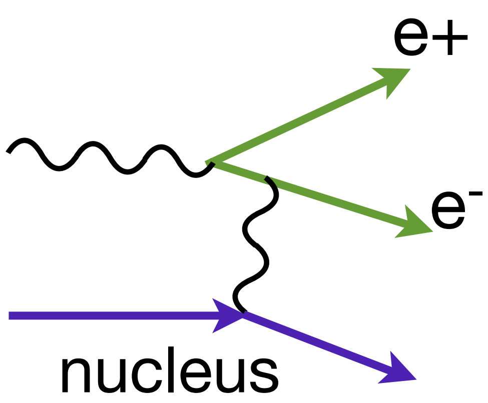
Photo effect



Compton scattering



Pair creation



energy threshold:

$2\ m_e = \sim 1.022$ MeV

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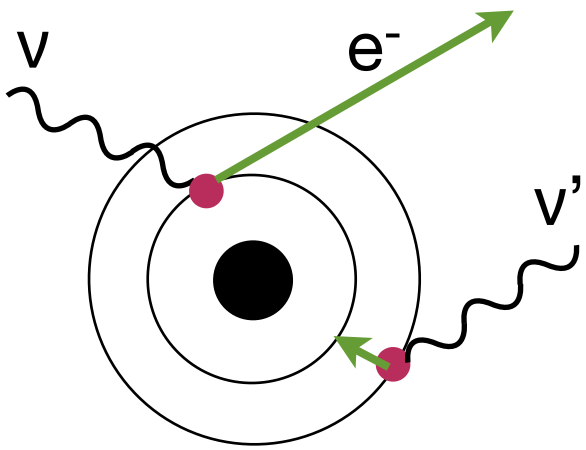

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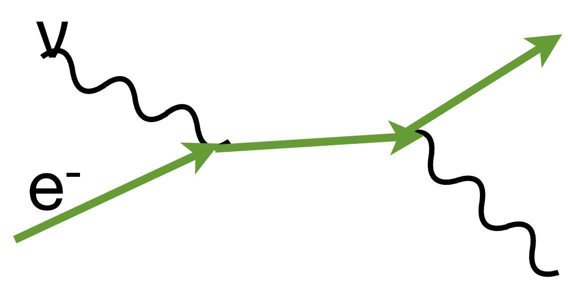

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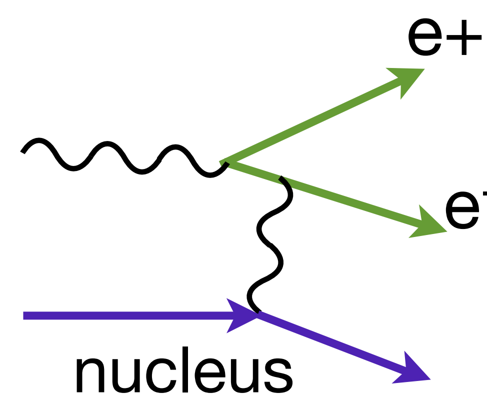

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- In contrast to dE/dx of charged particles:
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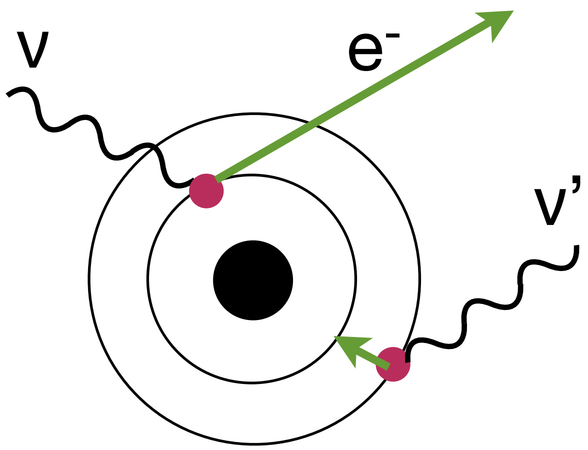

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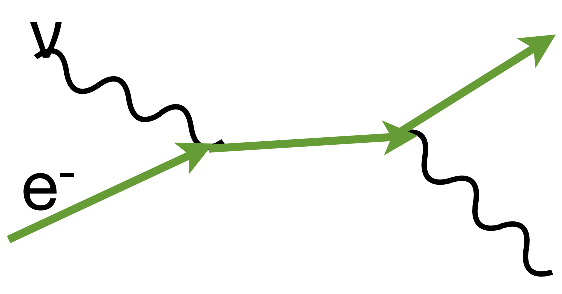

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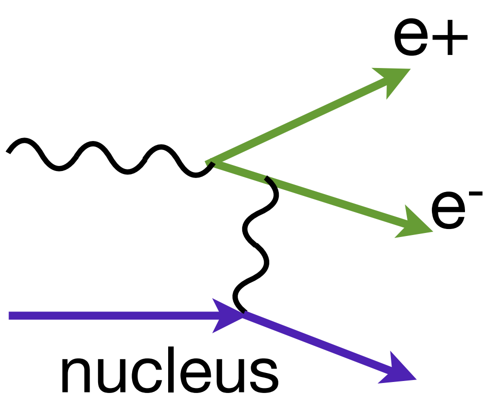

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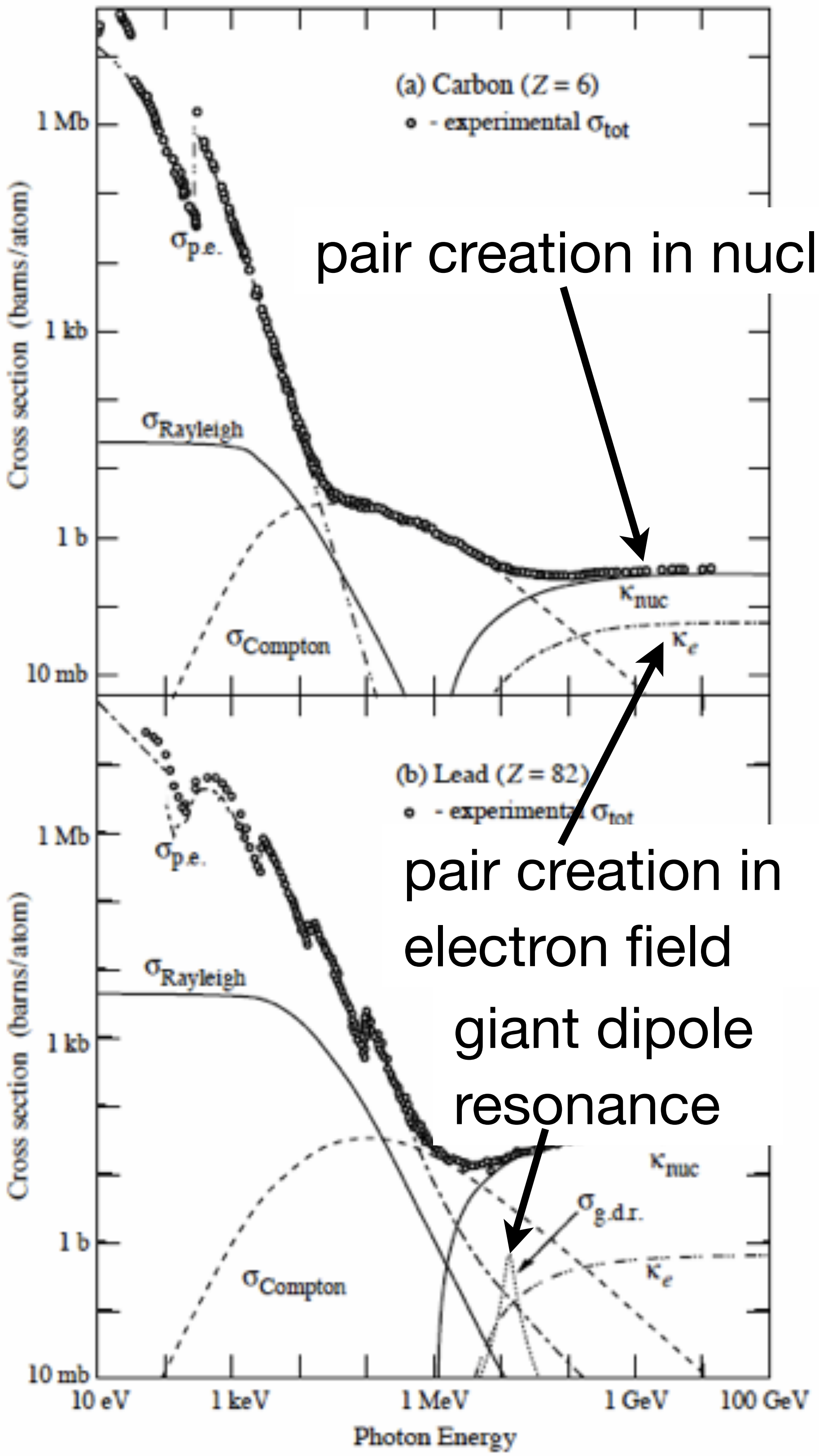
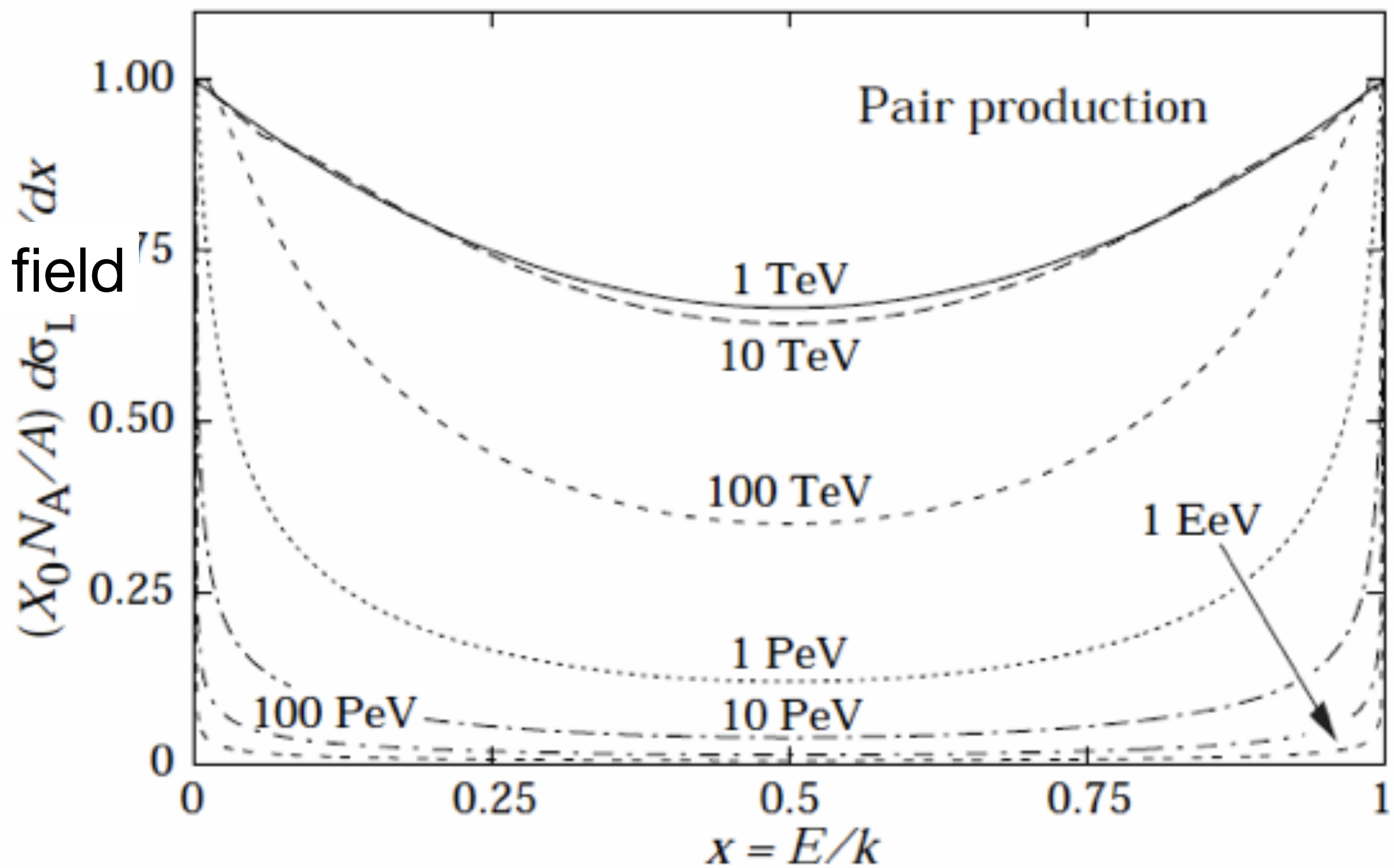
➩ Decrease of photon intensity with material thickness

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

Photons in Matter

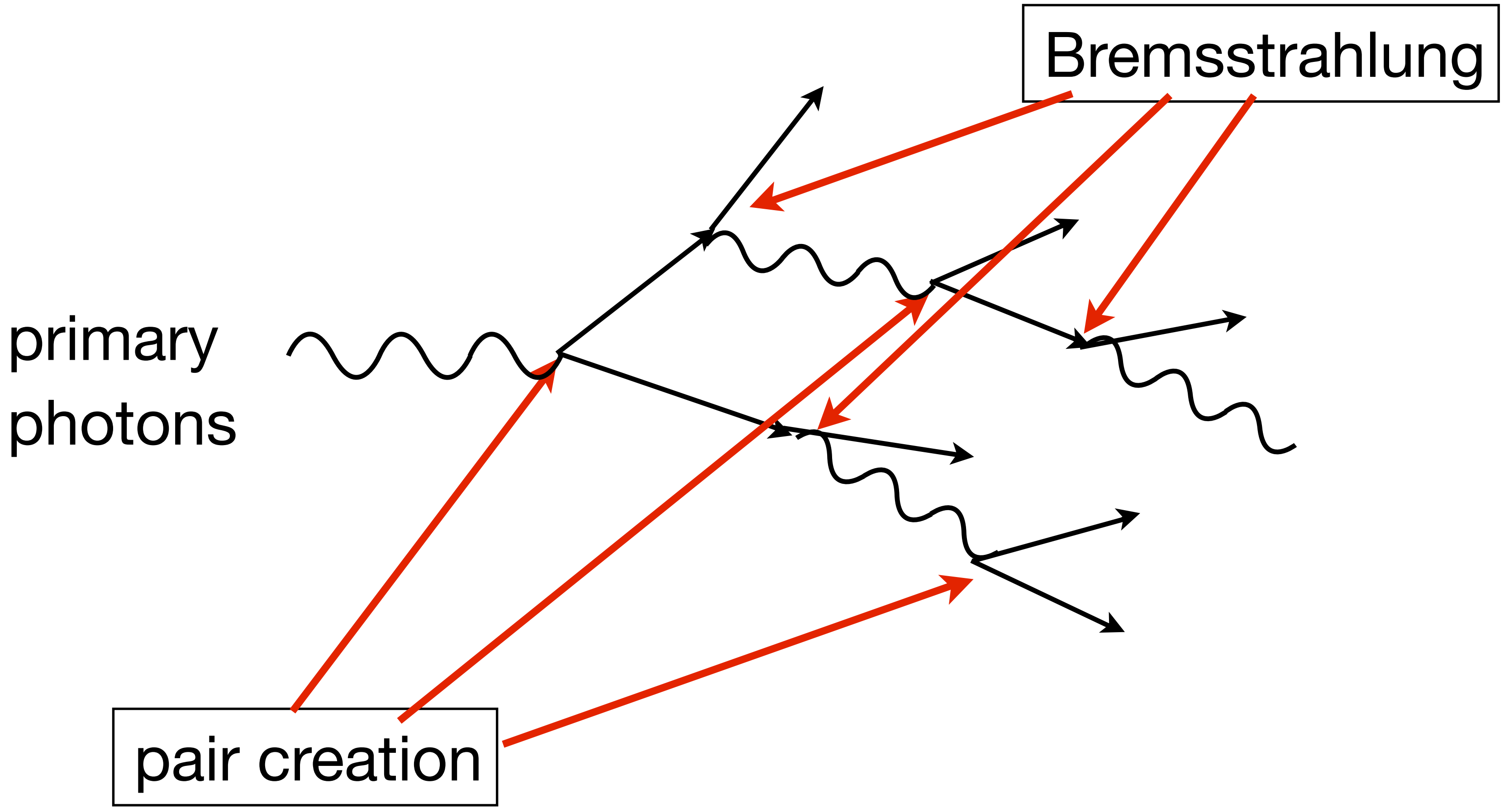




- At high energies pair production dominates
- Lower energies:
  - photo-electric effect
  - coherent scattering: Rayleigh scattering
  - Compton scattering
  - nuclear excitation

Electromagnetic Cascades

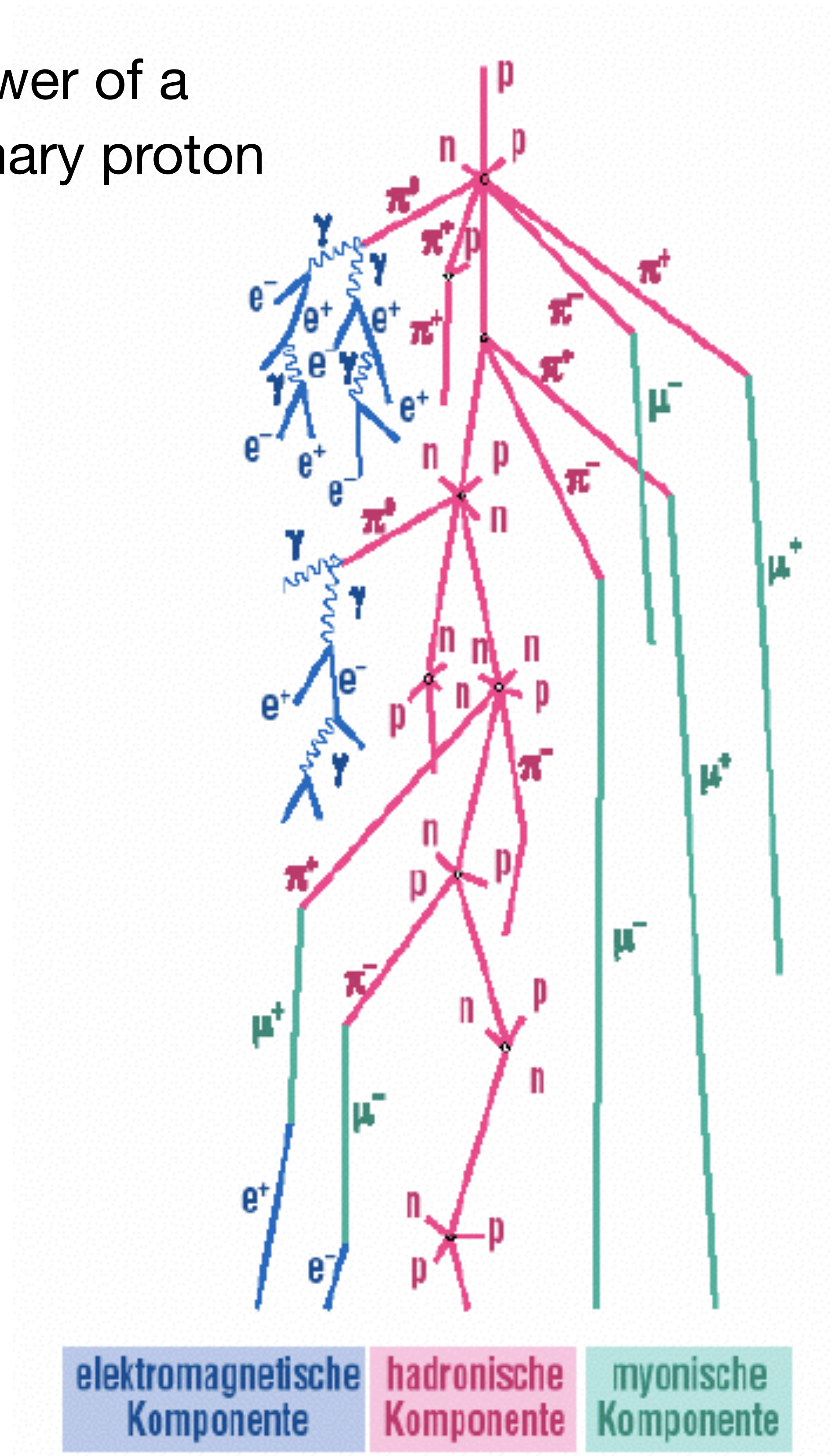
- Highly energetic electrons and photons (energies substantially above the pair creation threshold, i.e. several MeV) lead to electromagnetic showers in matter:
  - A combination of Bremsstrahlung und pair creation until the initial energy is used up



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



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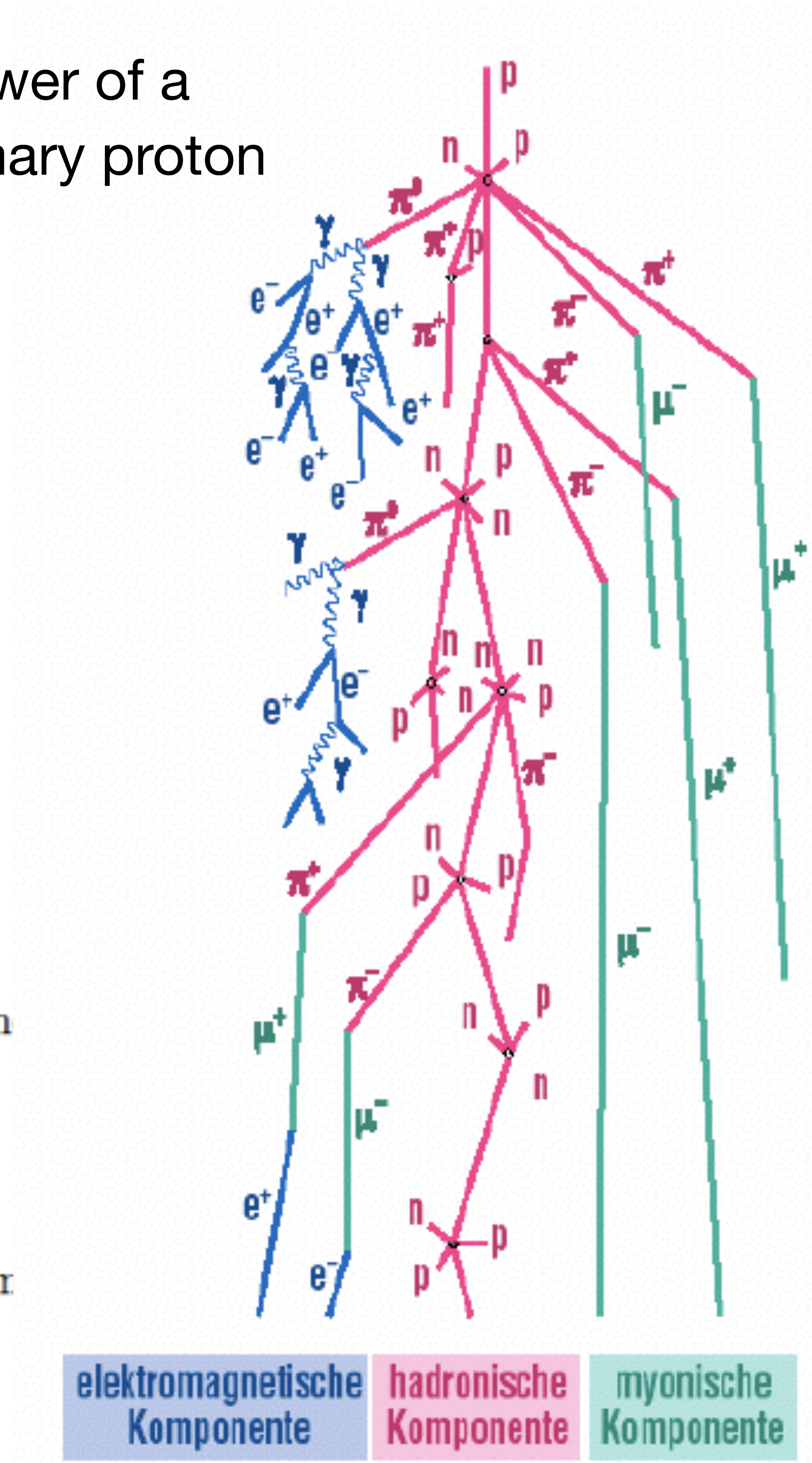
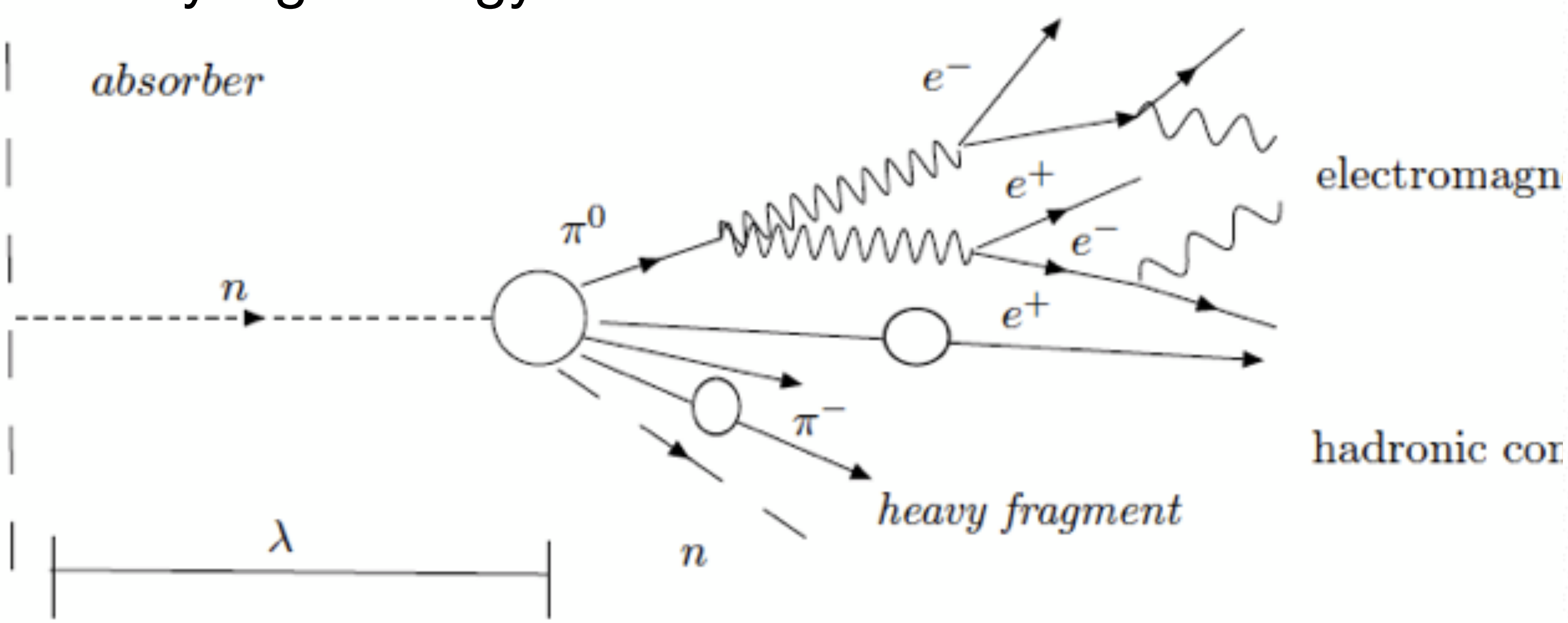
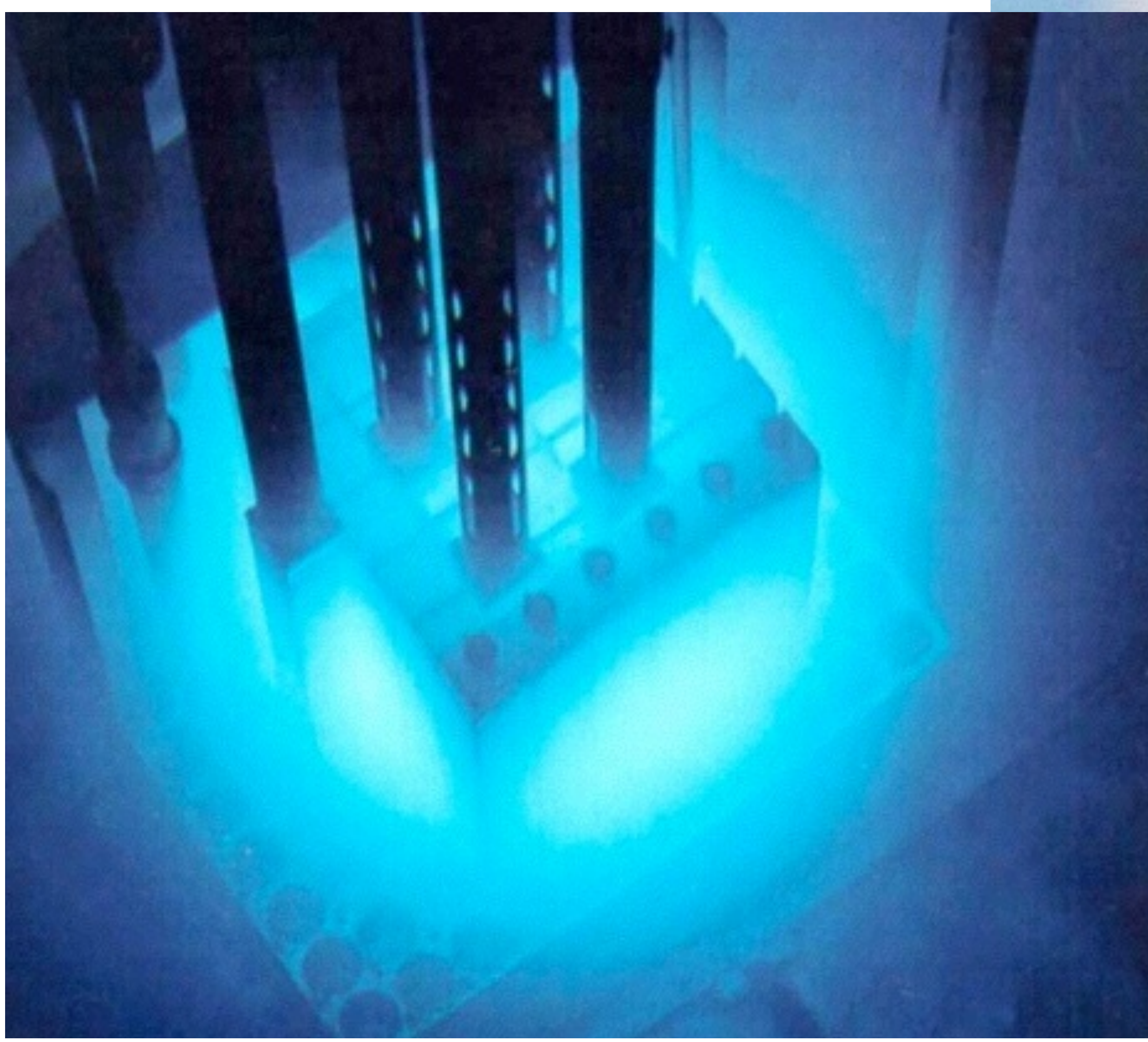


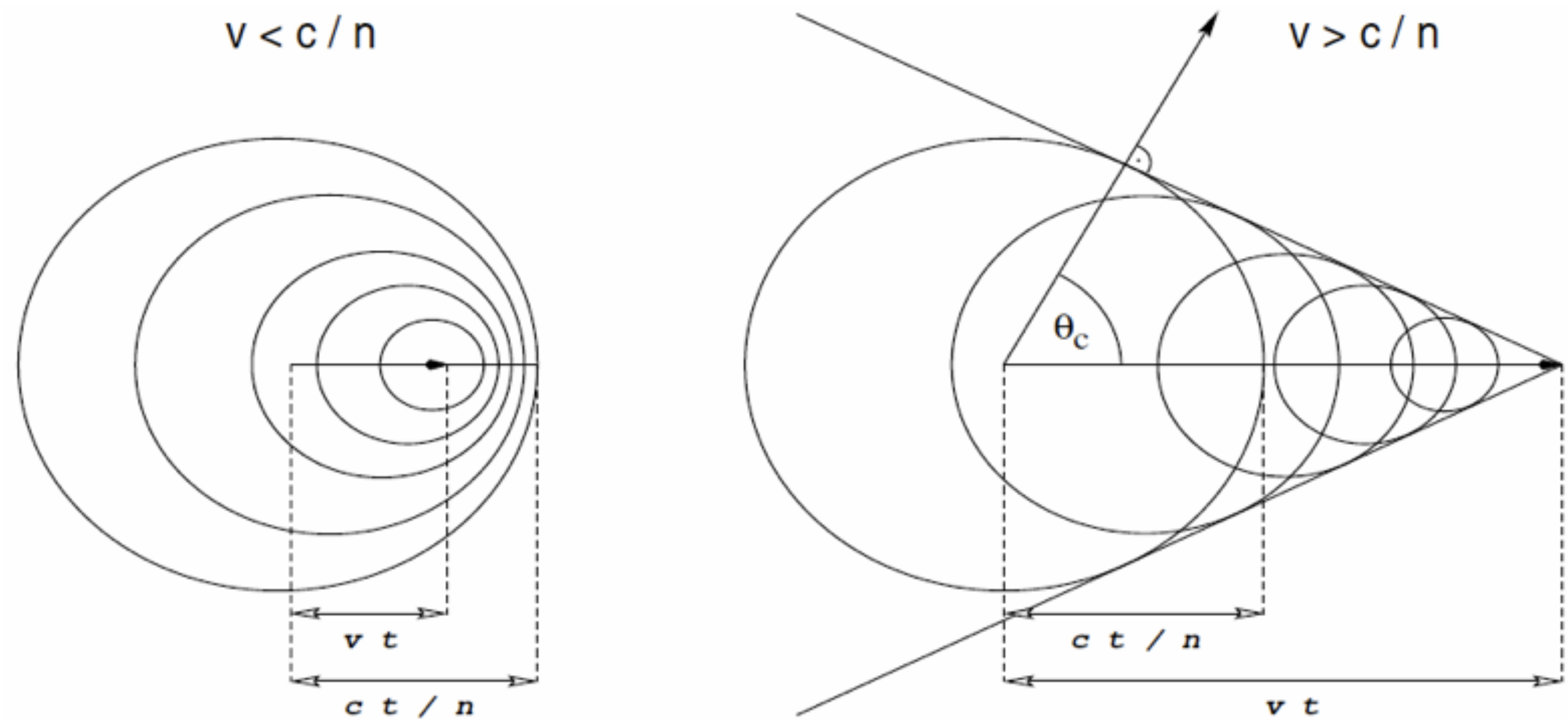
Also hadronic showers have mostly EM-character at very high energy



Cherenkov-Light: "Supersonic Boom" with Photons



Cherenkov Light



D. Kranich, Dissertation

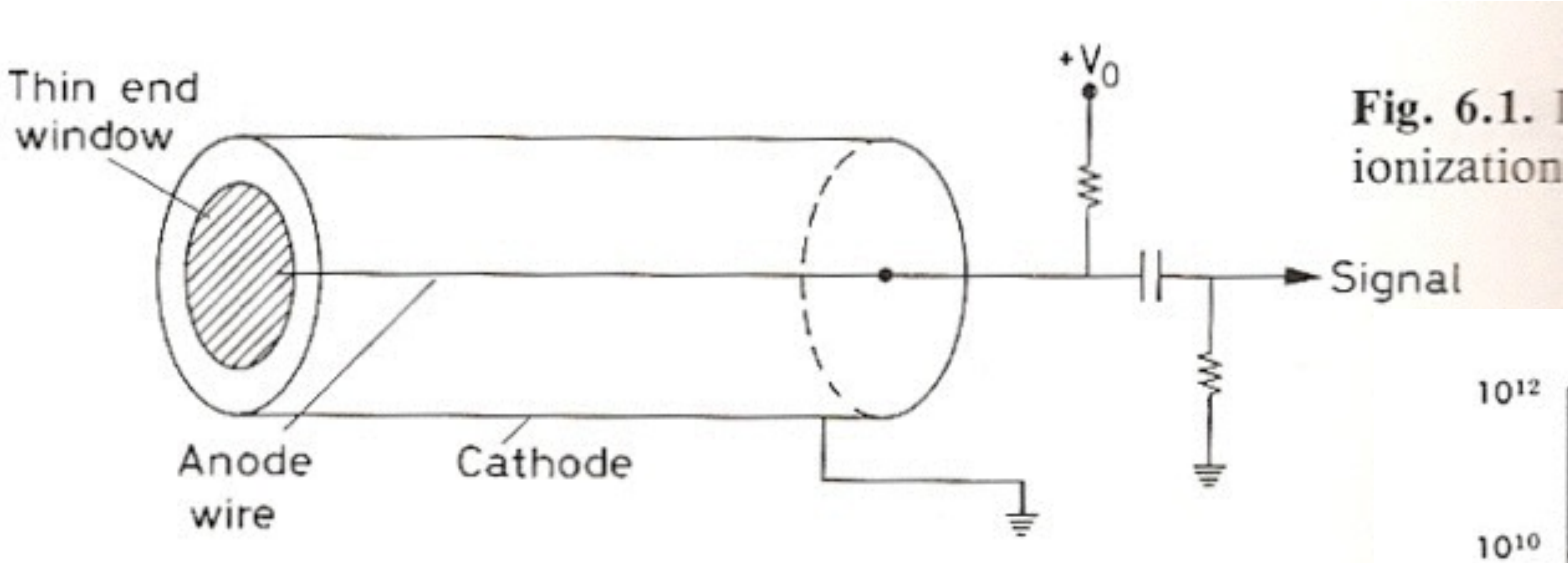
- Emission of photons by charged particles which are faster than the speed of light in the medium: constructive interference

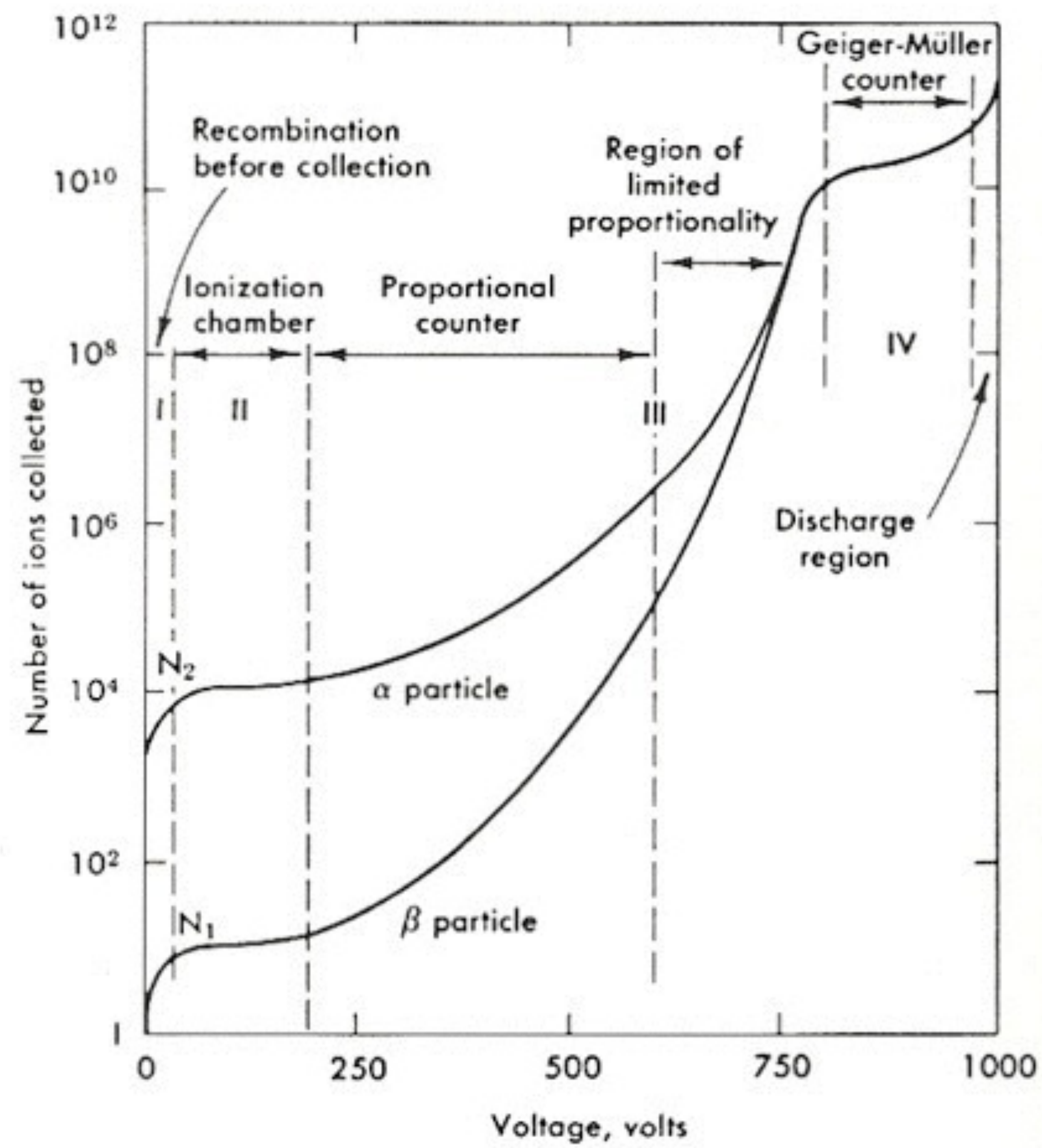
Emission with a characteristic angle:

$$cos\theta_c = \frac{c\,t\,/\,n}{v\,t} = \frac{1}{n\beta}$$

Detection Methods

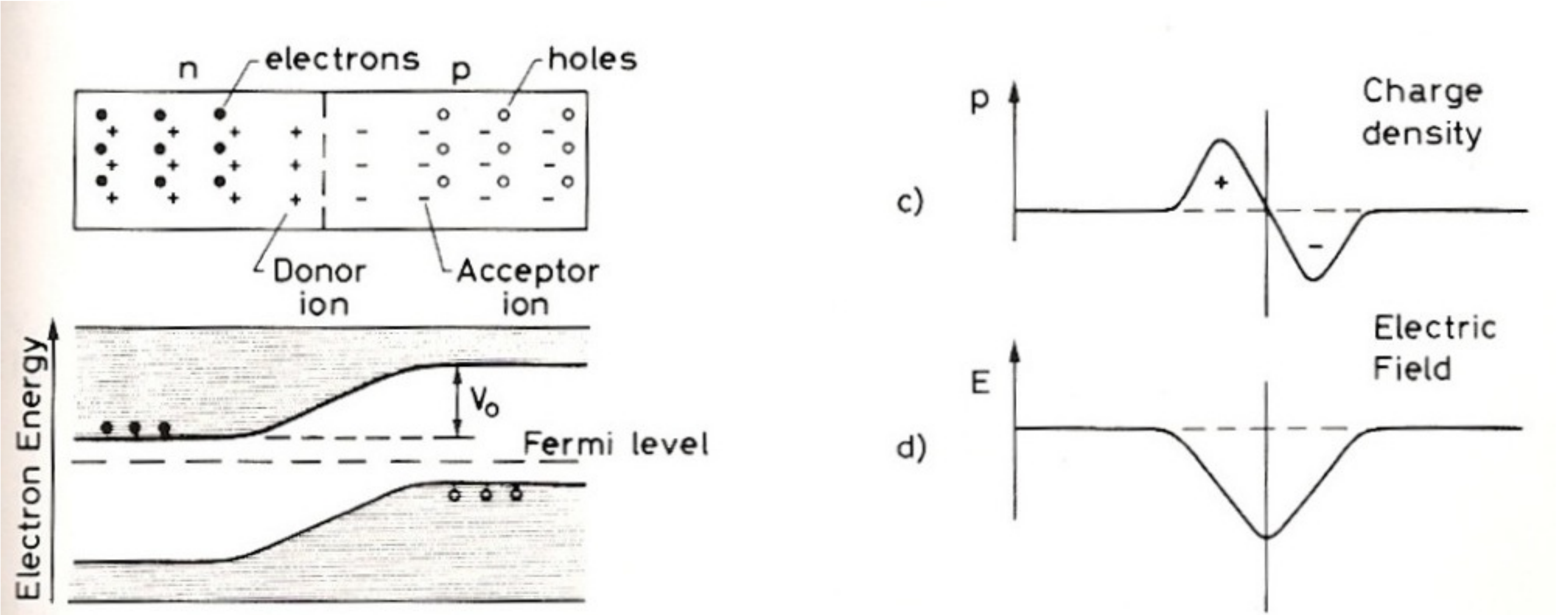
Ionization Chamber: A Classic





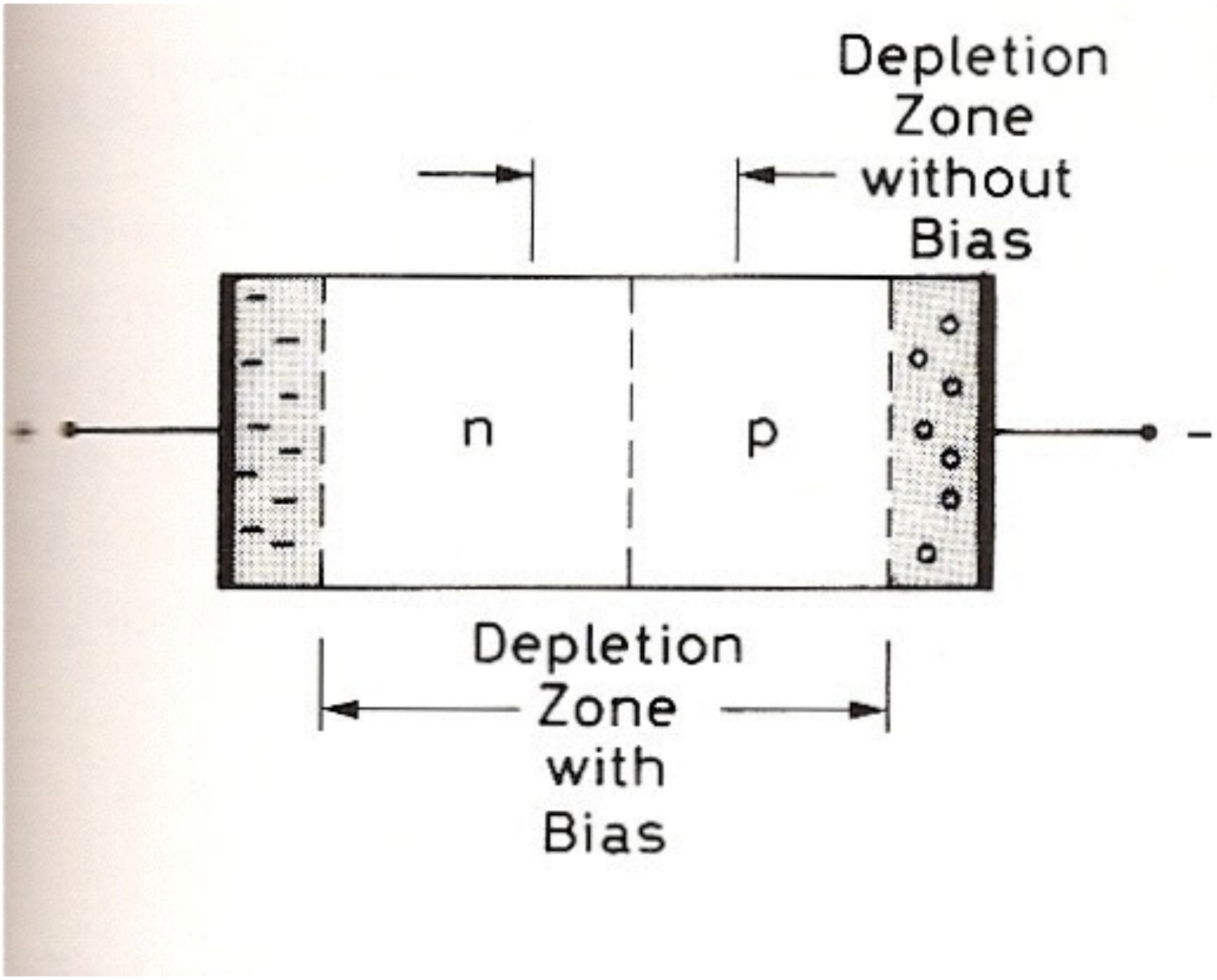
- Passage of particles creates electron-ion pairs in the gas volume
- Electrons are accelerated by strong electric field - avalanche multiplication takes place
- Depending on the voltage the signal is either proportional to the originally deposited charge, or goes into saturation

Semiconductor Detectors - PN Junction



- Interfaces between differently doped silicon froms a PN junction
  - Donators (for ex. Phosphorous) provides electrons: n - doping
  - Aceptors (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

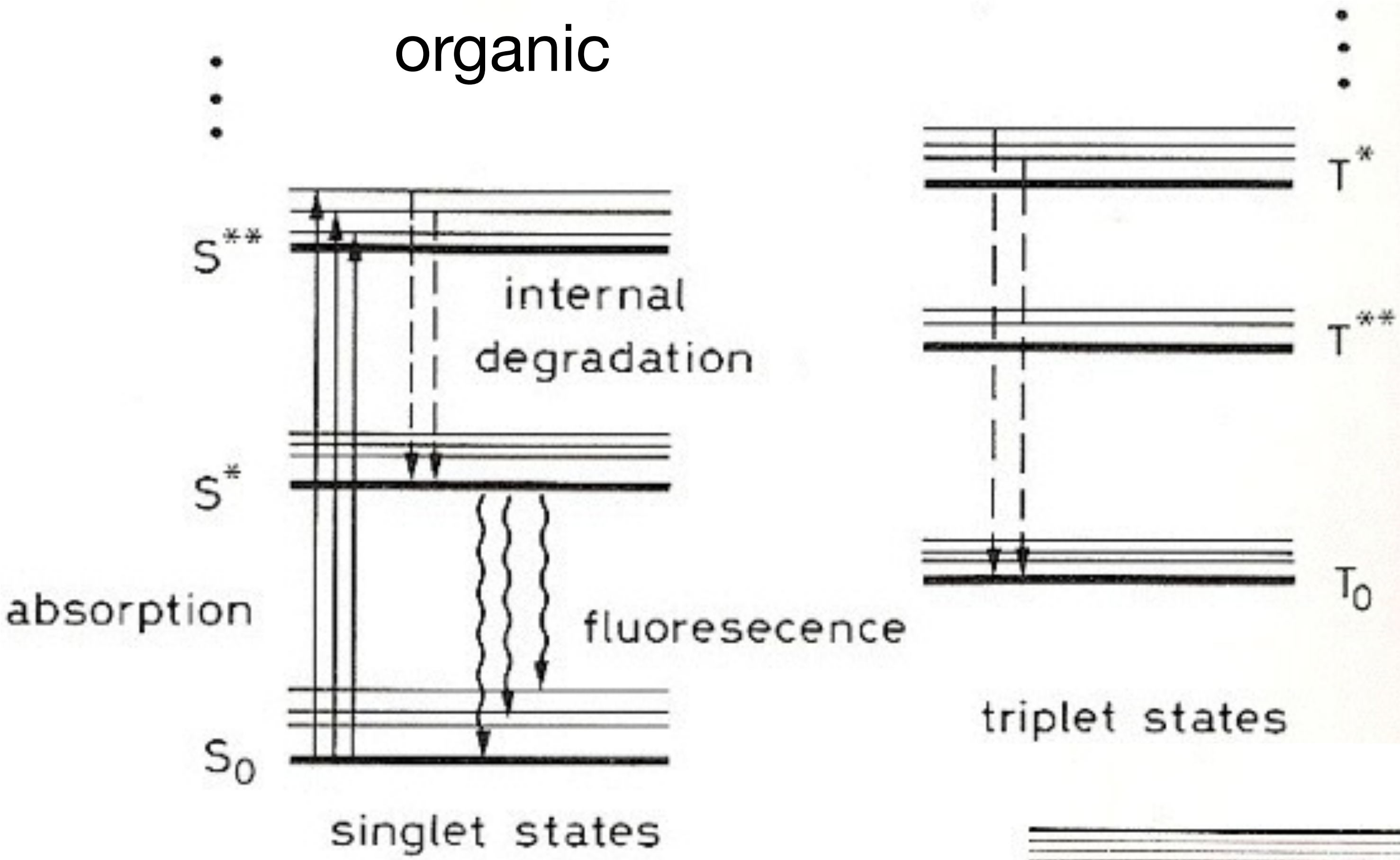


- An external bias voltage increases the depletion zone: All free charge carriers are removed
  - Created electrons and holes travel to the electrodes before they can recombine with the silicon: Signals can be read out

- 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

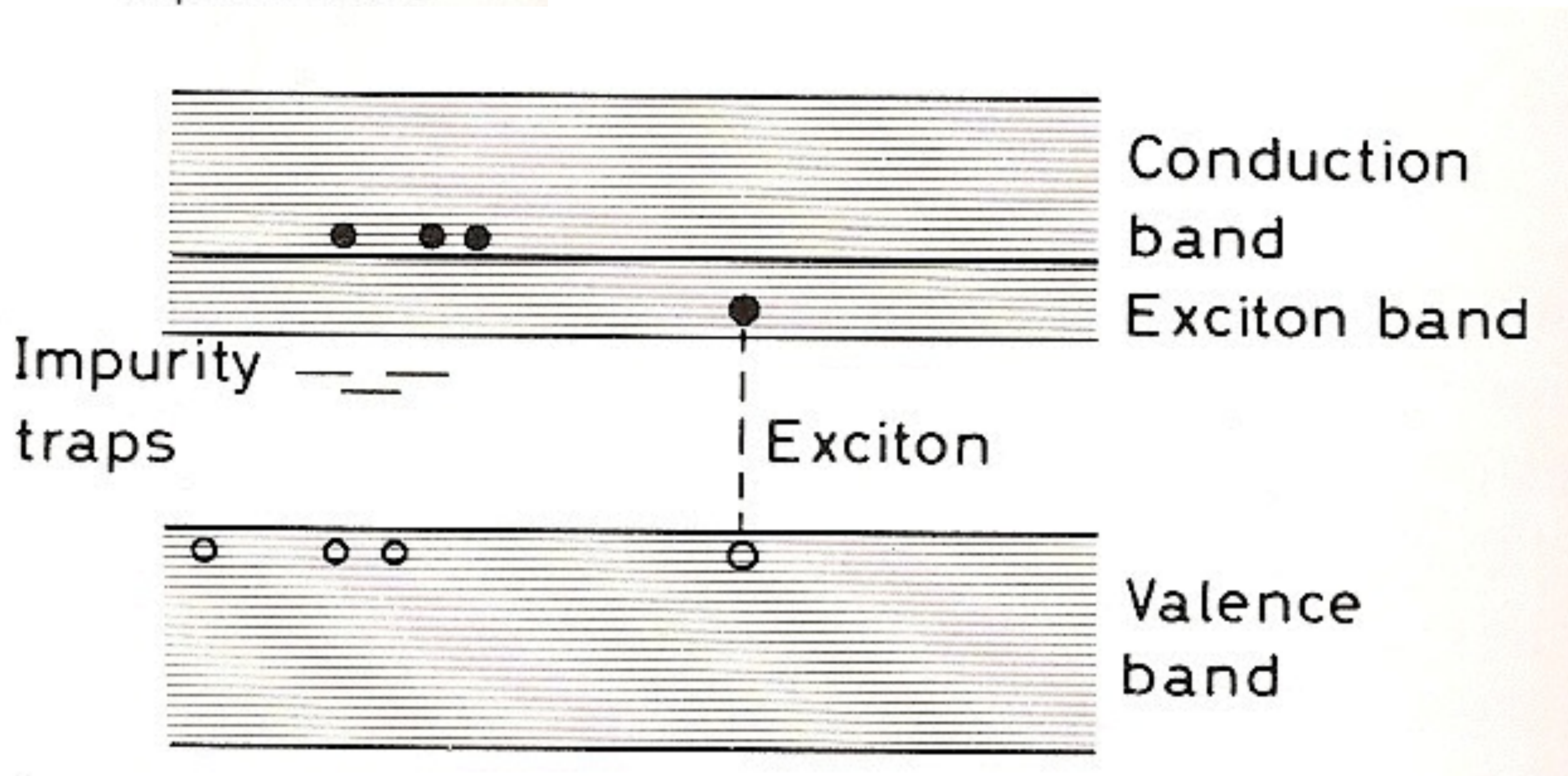
Scintillation

organic

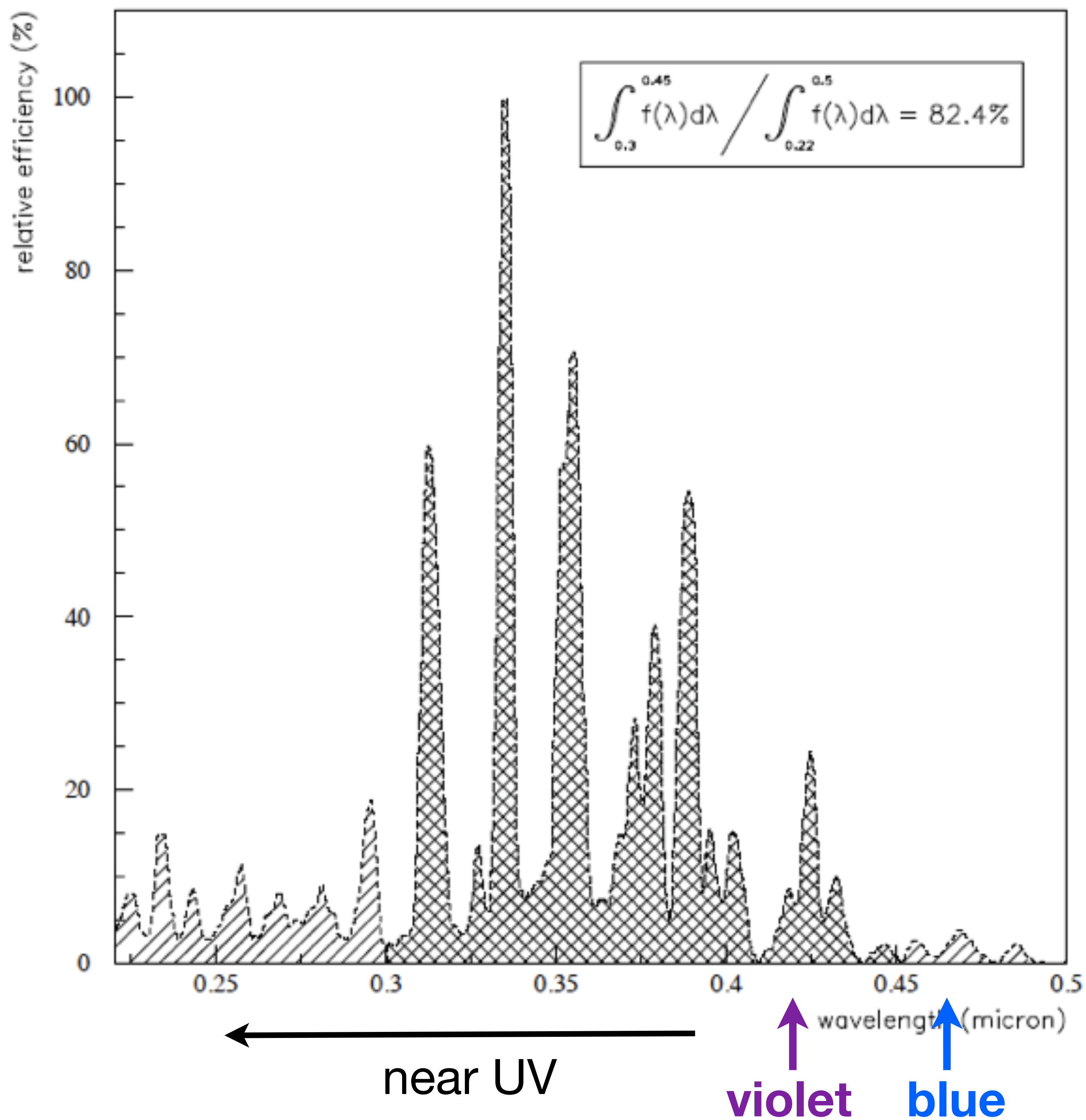


- Scintillators emit light when crossed by ionizing particles
  - Excitation of metastable states in molecules (organic scintillator) or defects in crystals (inorganic scintillator)

inorganic:



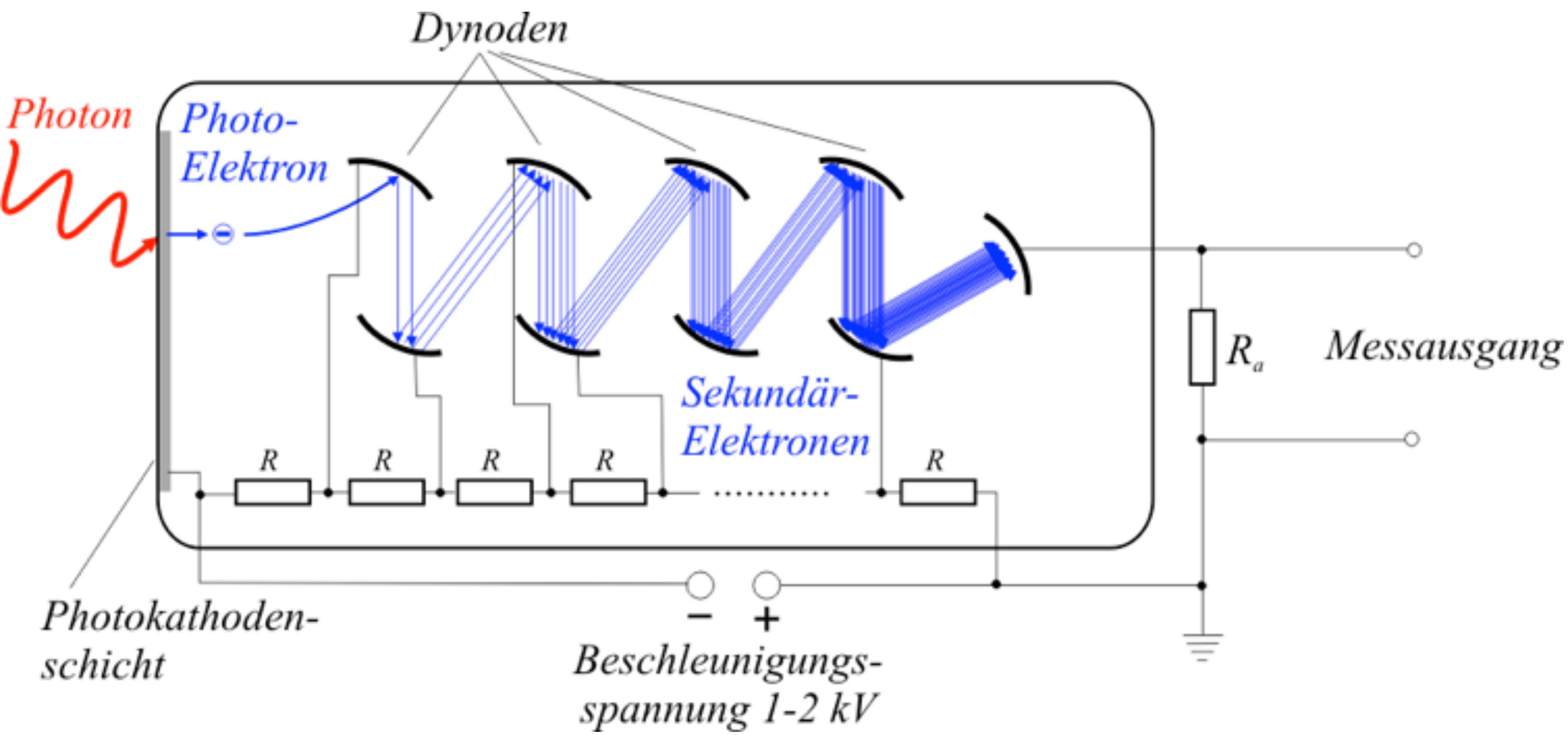
Fluorescence of Air



- Excitation of nitrogen in the atmosphere (2P - orbital of N_2, 1N orbital of N_2^+)
- 80% of the photons are emitted in the range of 300 nm bis 450 nm
- Only ~ 5×10^{-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 n

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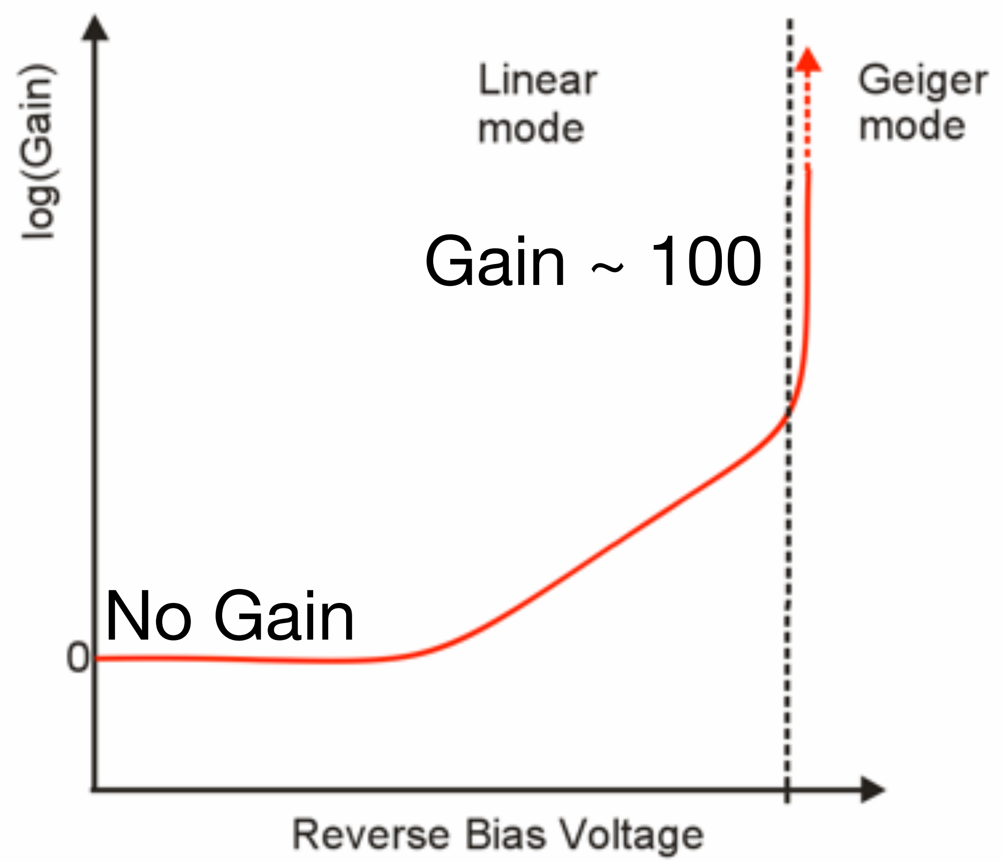
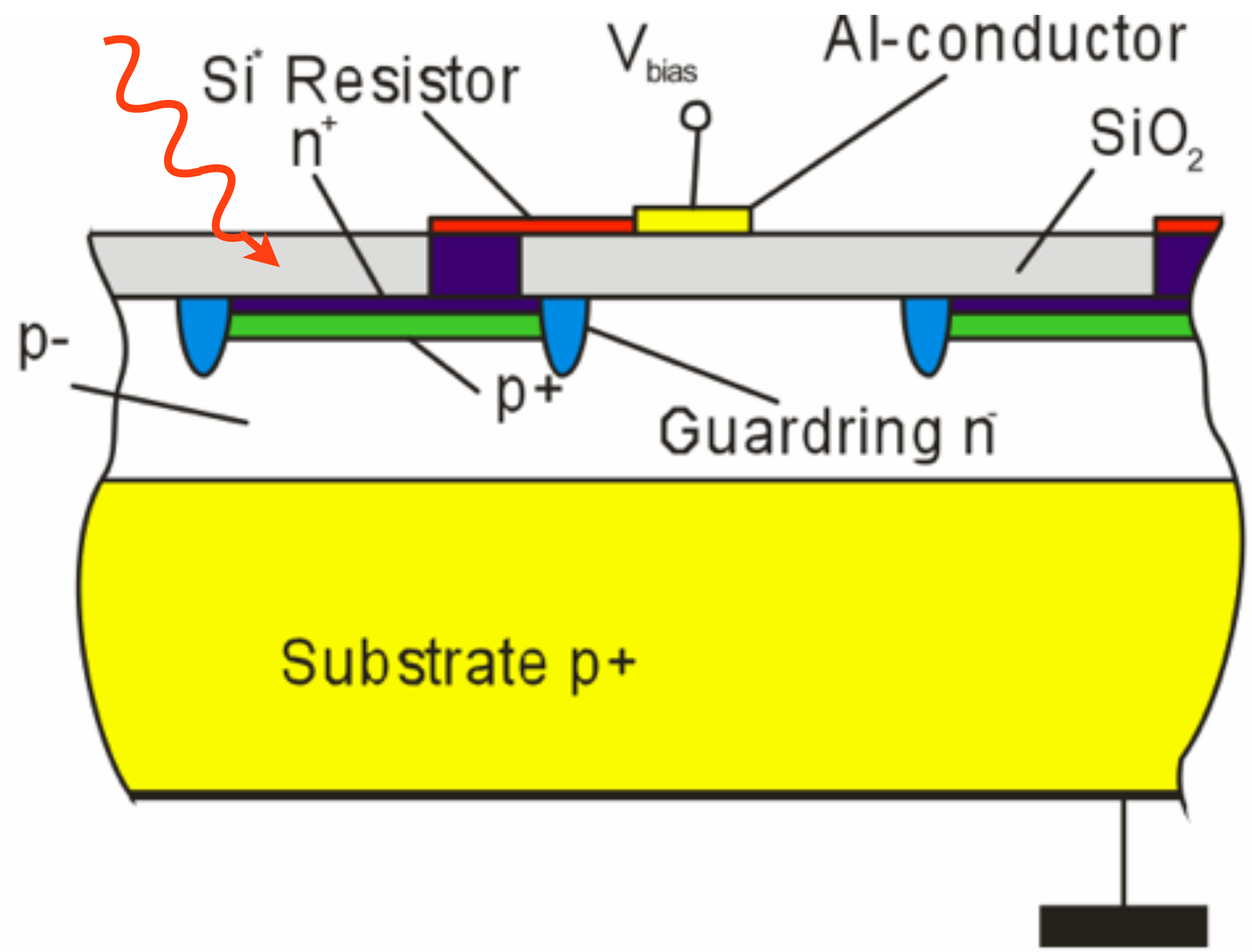
Avalanche Photo Diode APD





New Photon Sensors: Silicon Photomultipliers

- Highest amplification (~ 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

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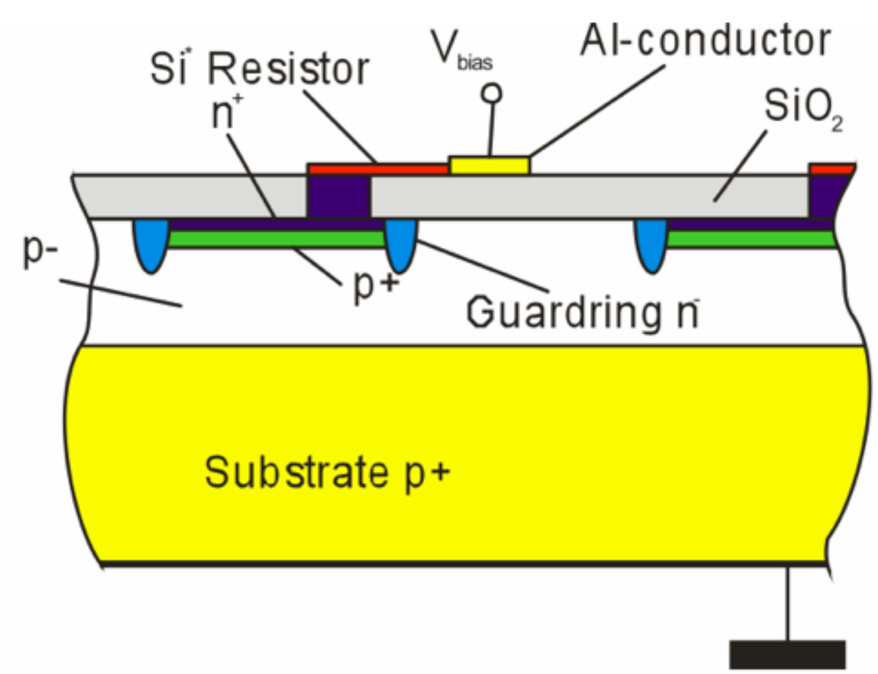
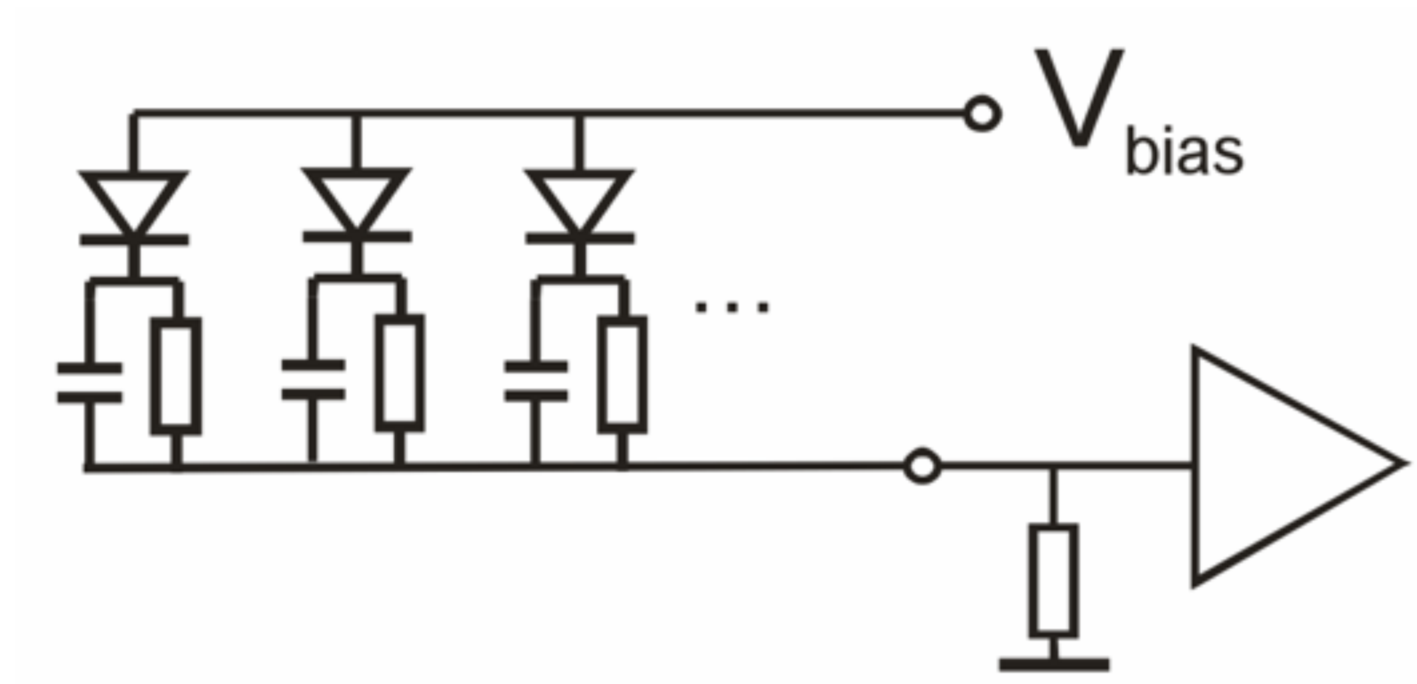
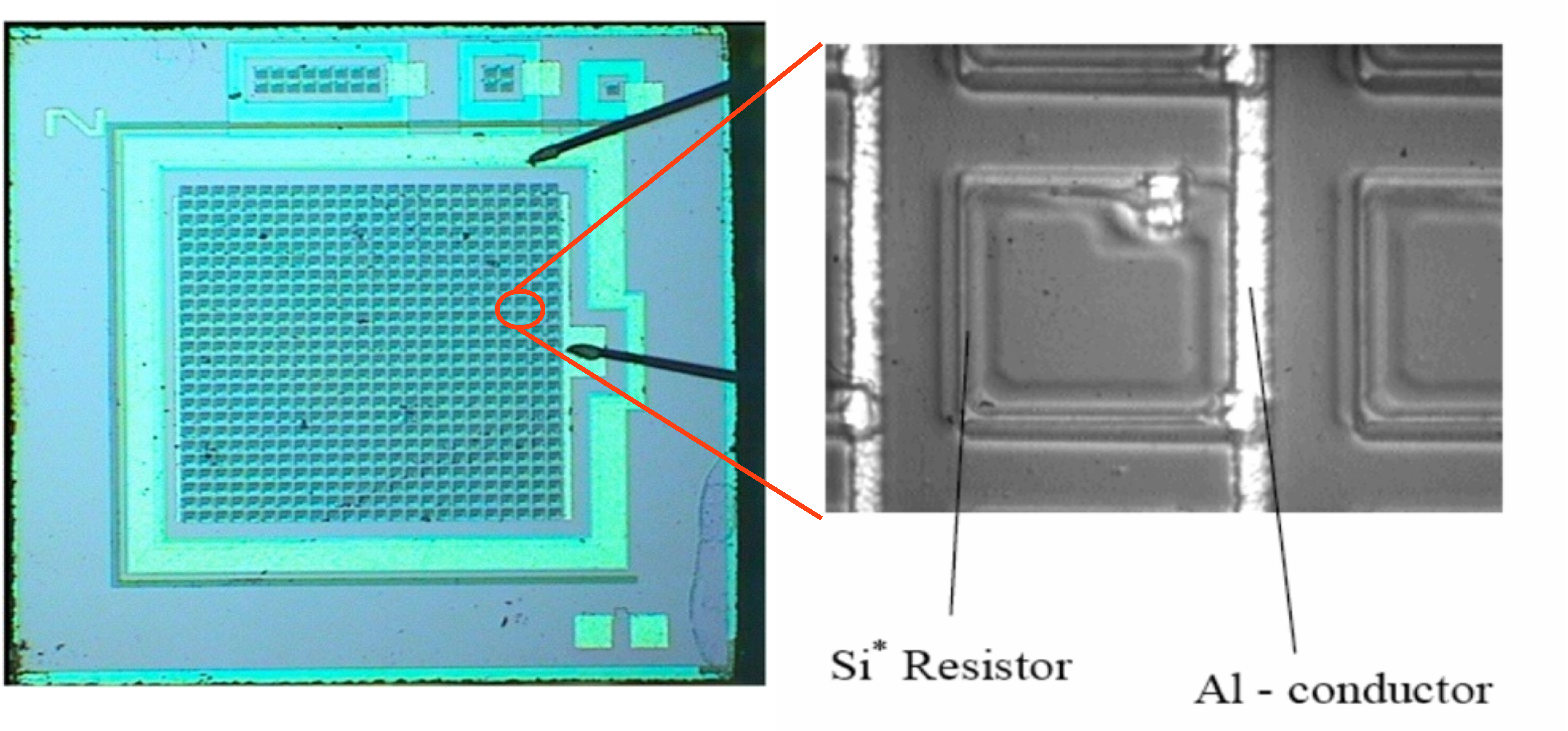
- Highest amplification (~ 10^6) by running APDs in Geiger mode: a single photon triggers a discharge, the diode operates in digital mode: Yes/No, no dependence of the current on the number of photons
- The trick: Put many small APDs on a chip, read out the summed-up signal
  - Easy handling: Only one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

N x

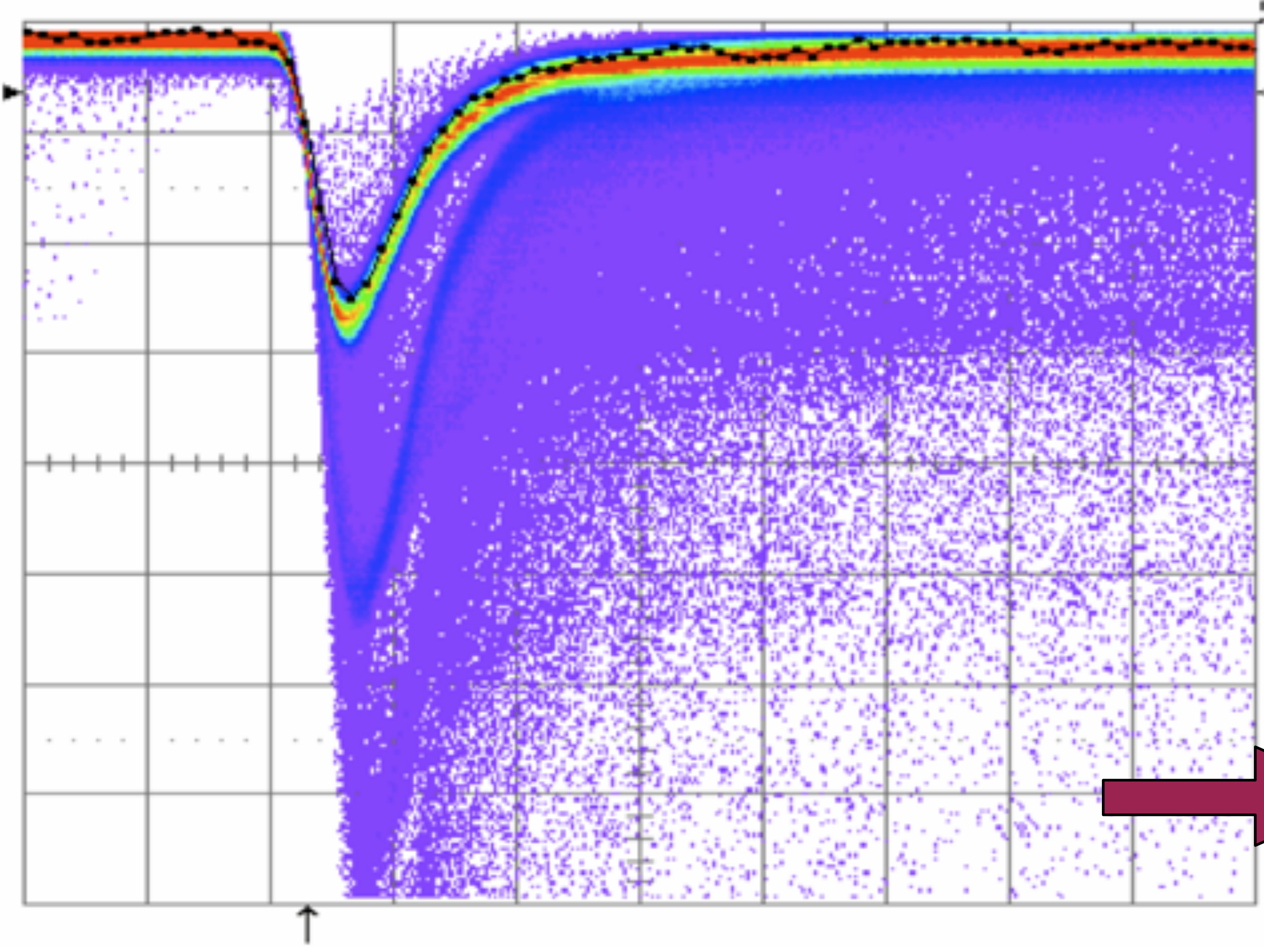


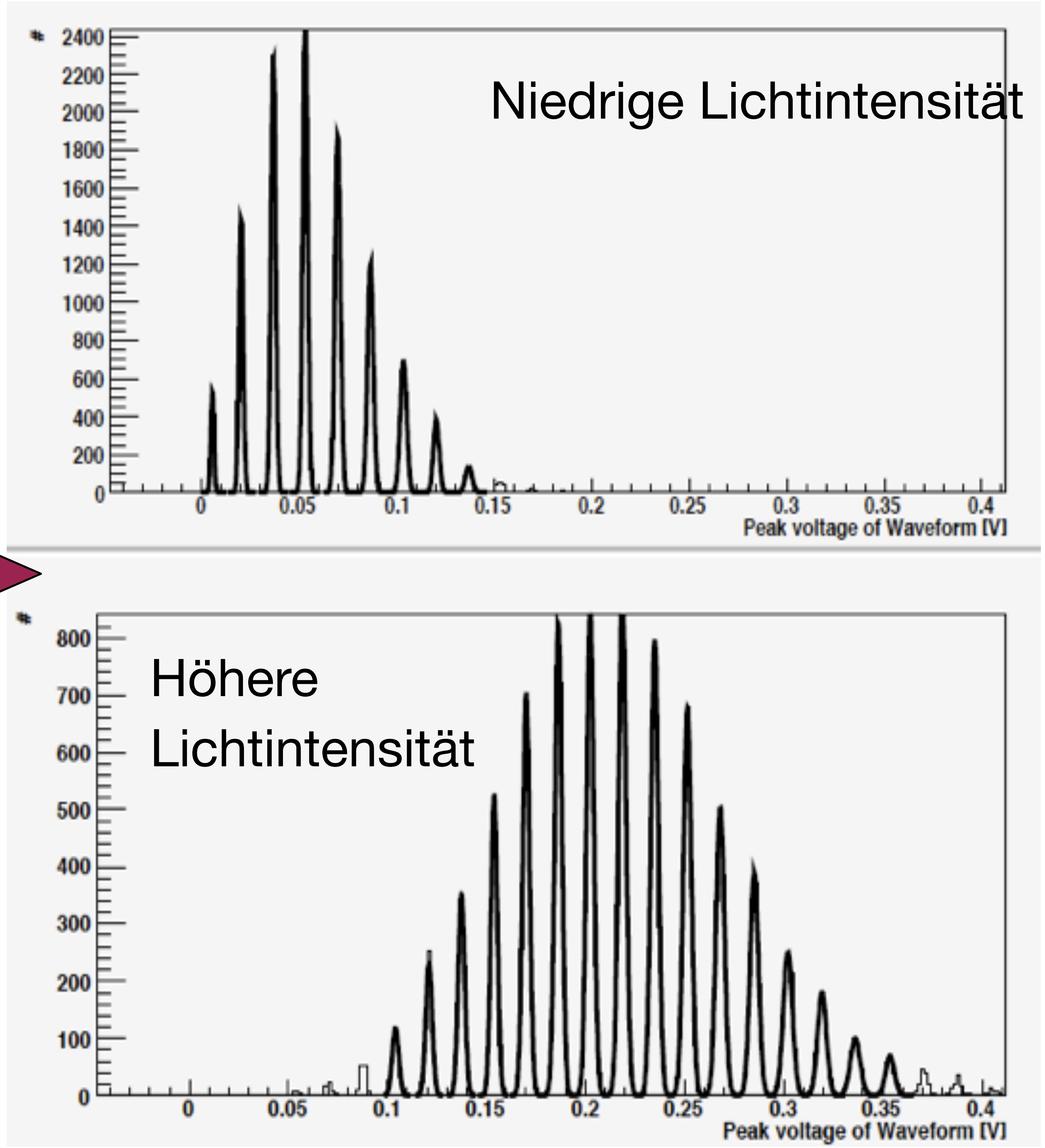


Silicon Photomultiplier: SiPM



SiPM Signals



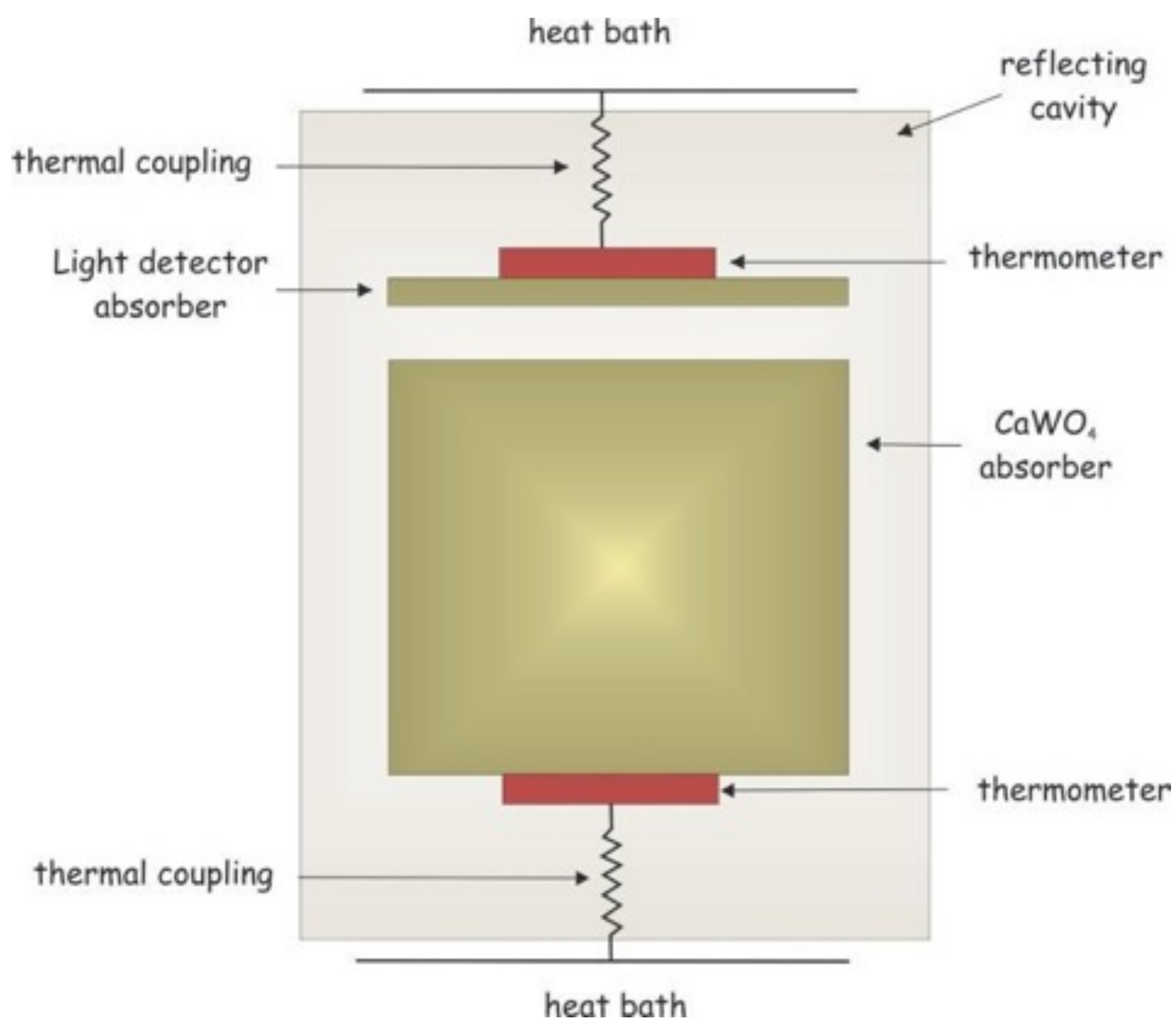


Single photons can be resolveds

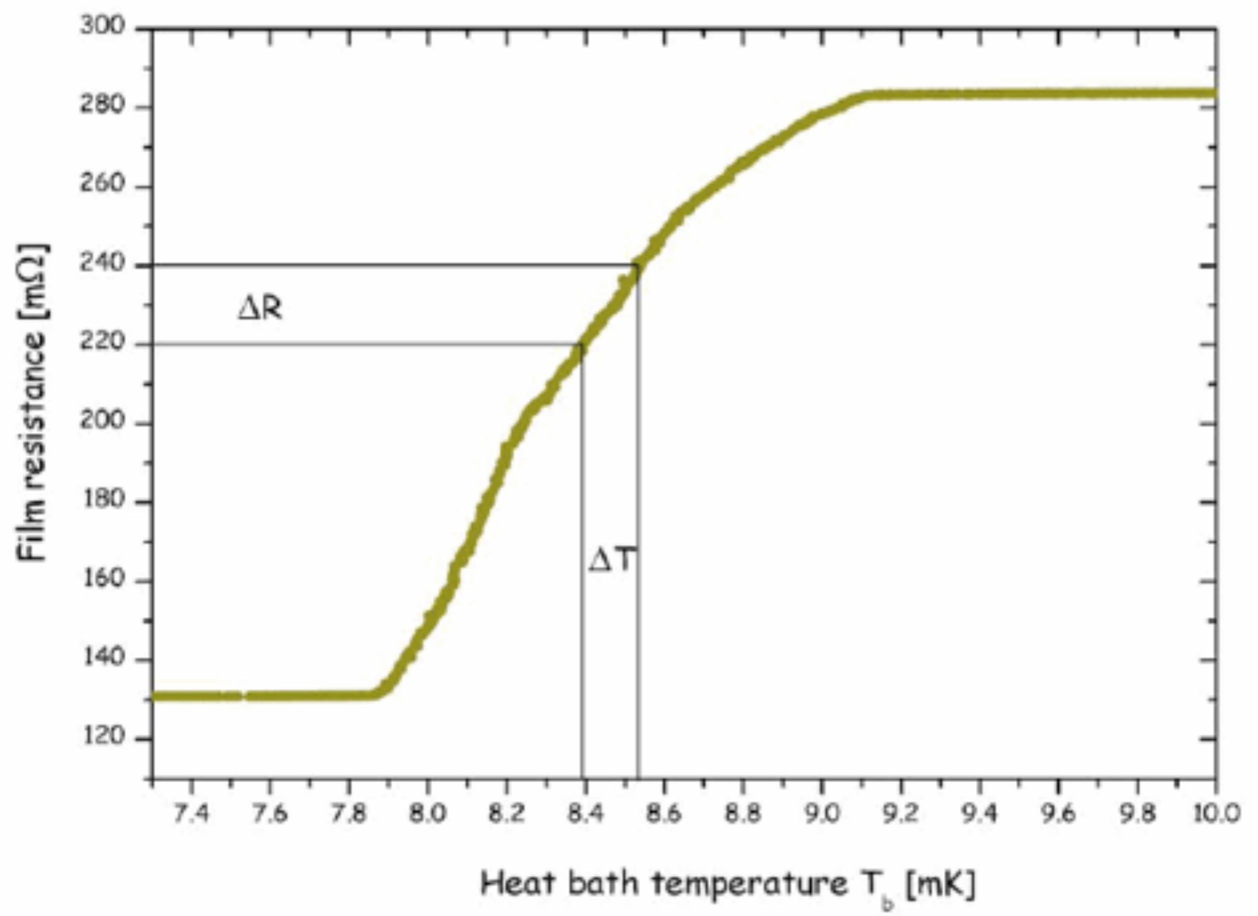
Experimental Applications
A Few Examples

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: $\beta > c/n$

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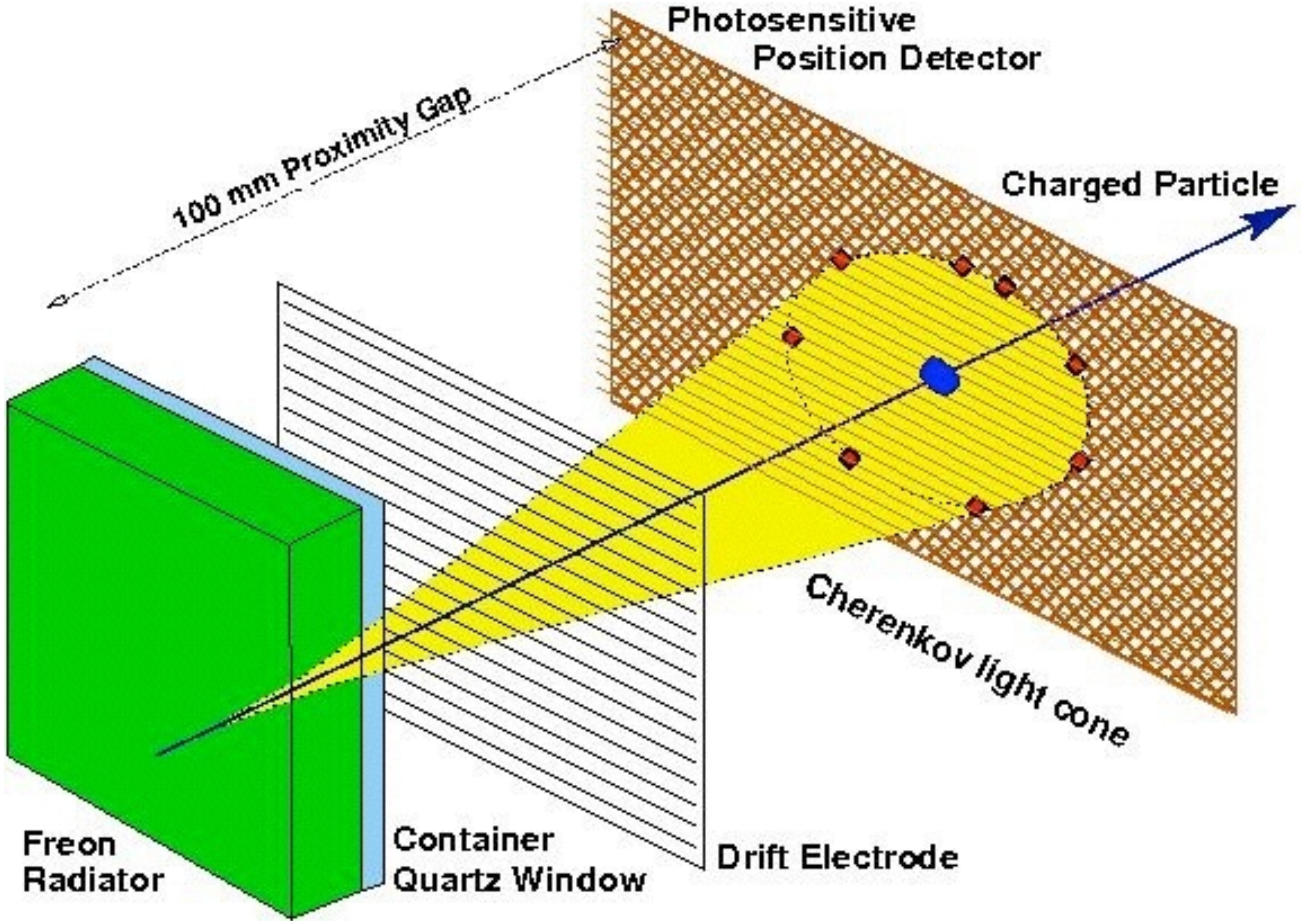
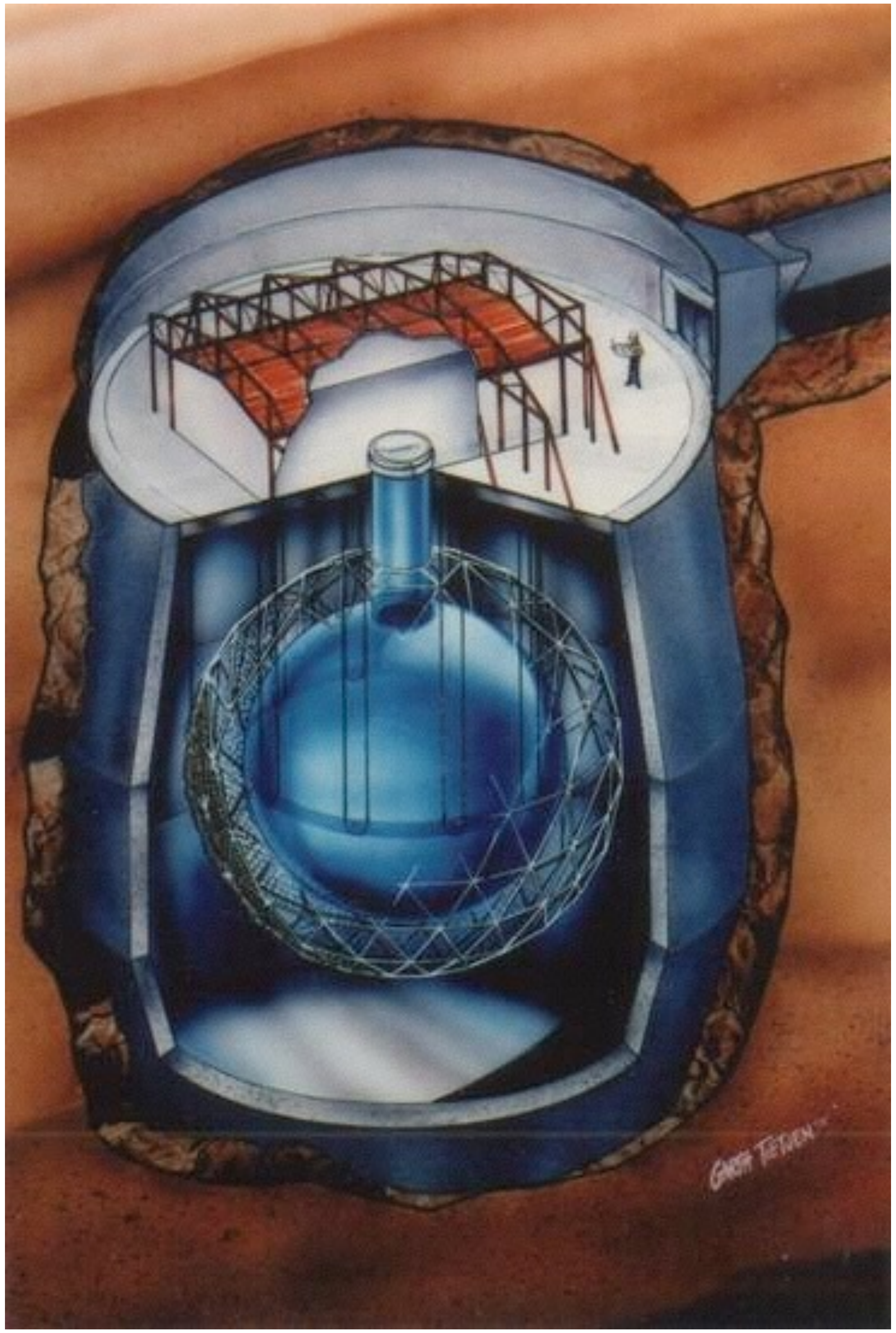
- Velocity measurement: Determination of Cherenkov angle by measurement of parameters of a ring

Ring **I**maging **CH**erenkov Counter

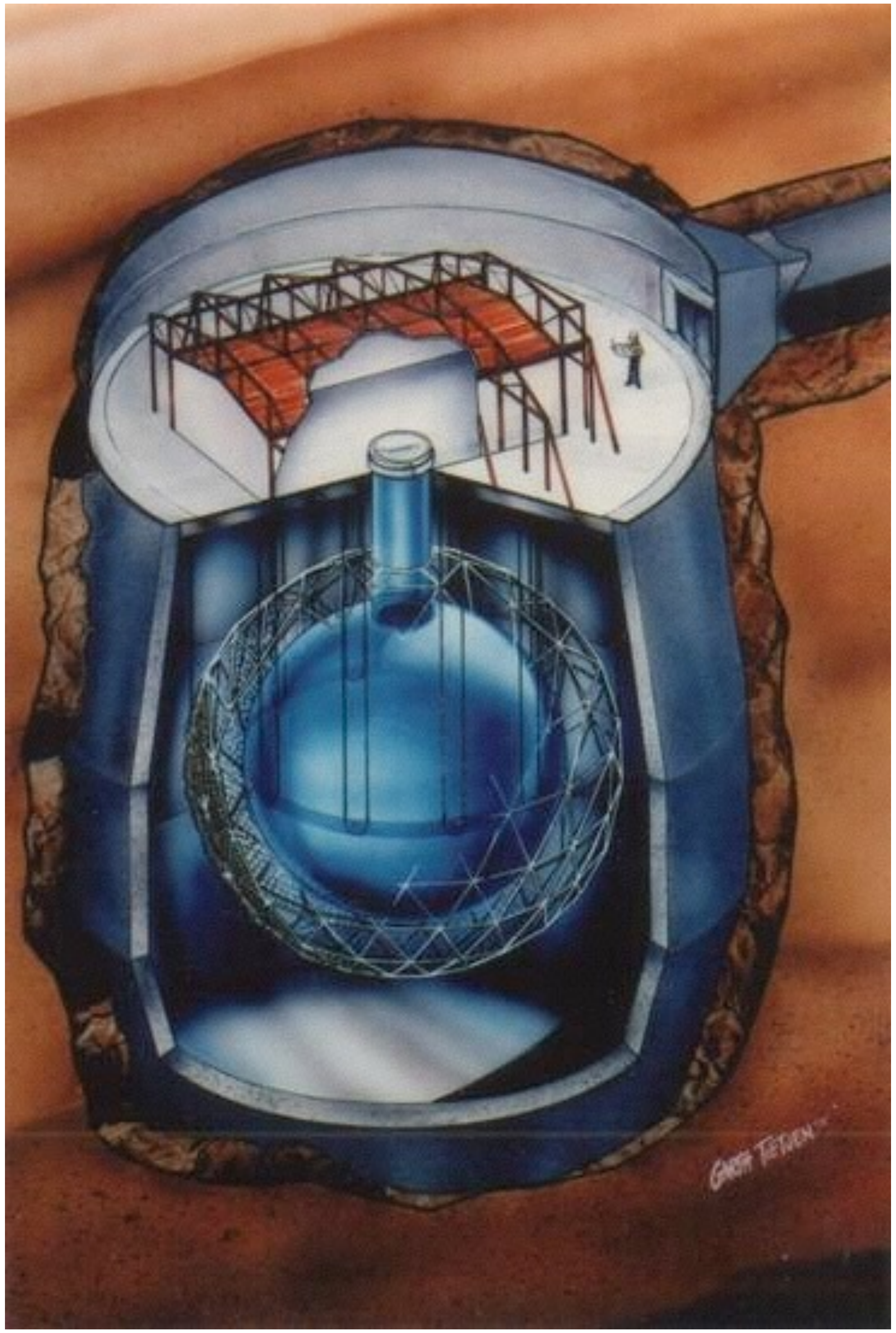


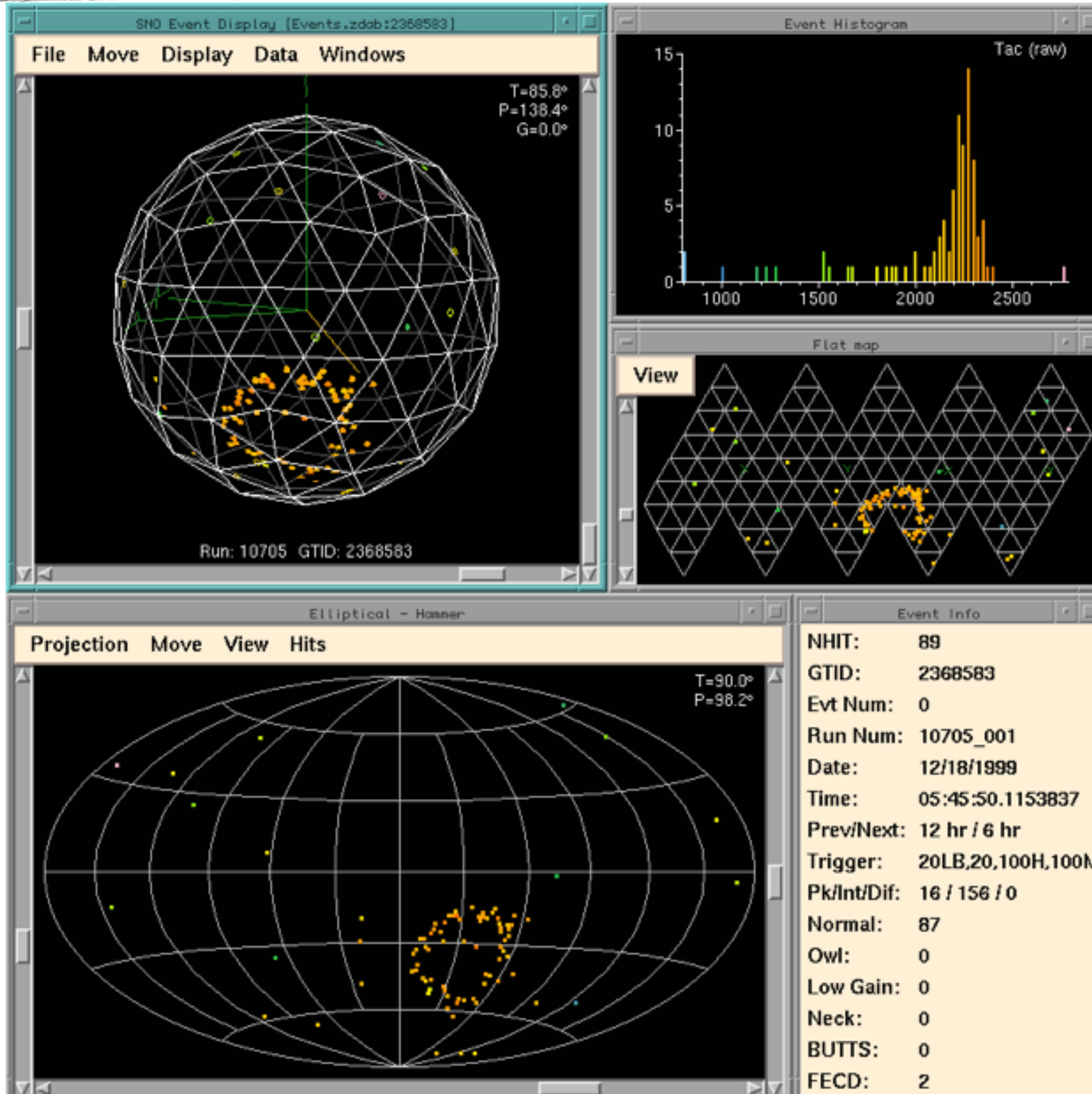
Cherenkov Detectors for Neutrinos



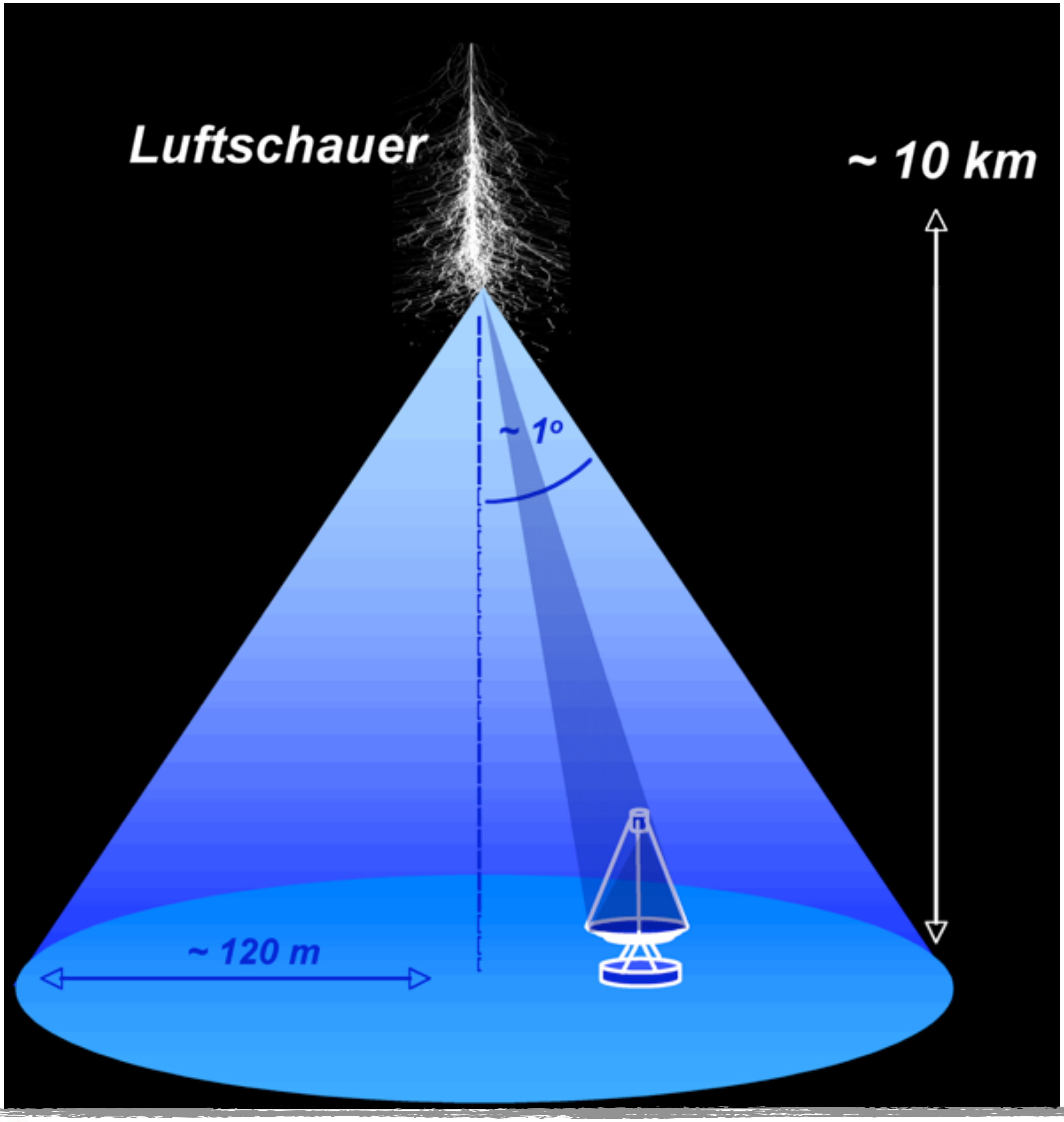
- Detection of electrons and muons created by charged current neutrino reactions: Emission of Cherenkov light in water, energy measurement by measurement of Cherenkov angle

Cherenkov Detectors for Neutrinos



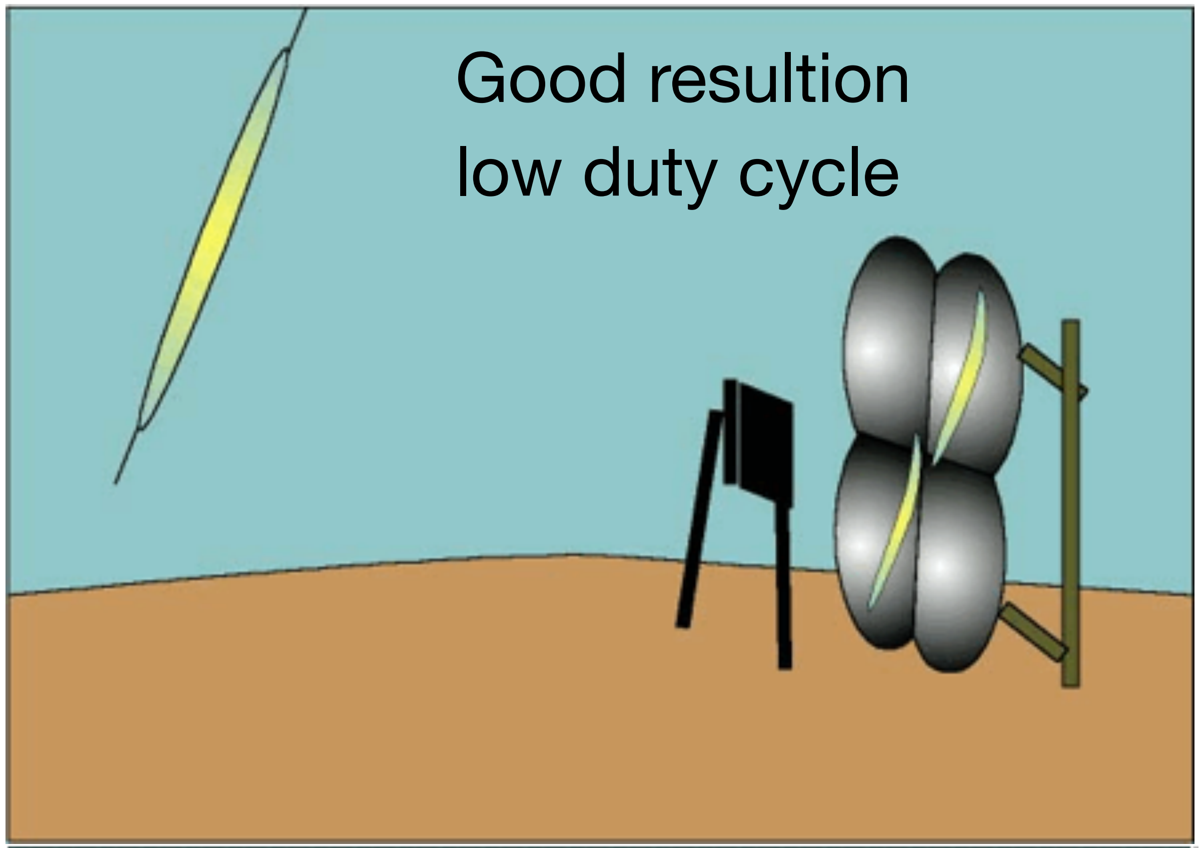


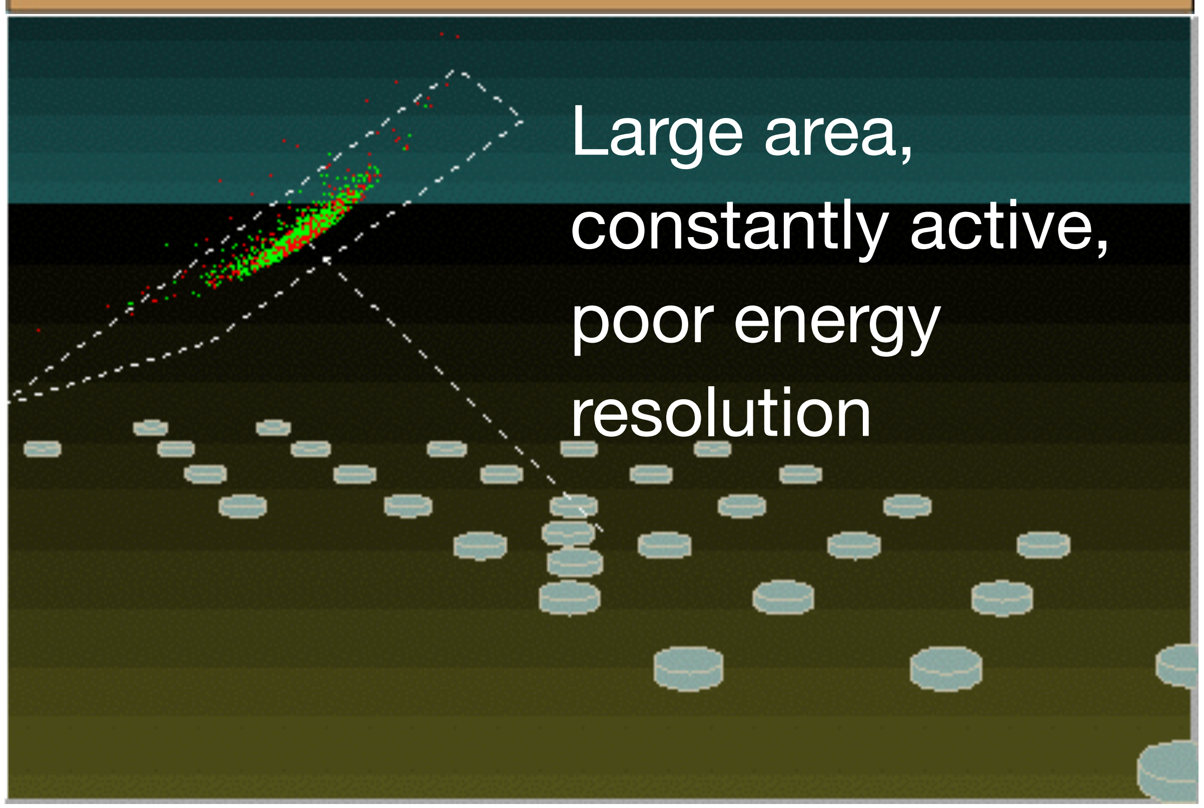
Cherenkov Telescopes for Air Showers

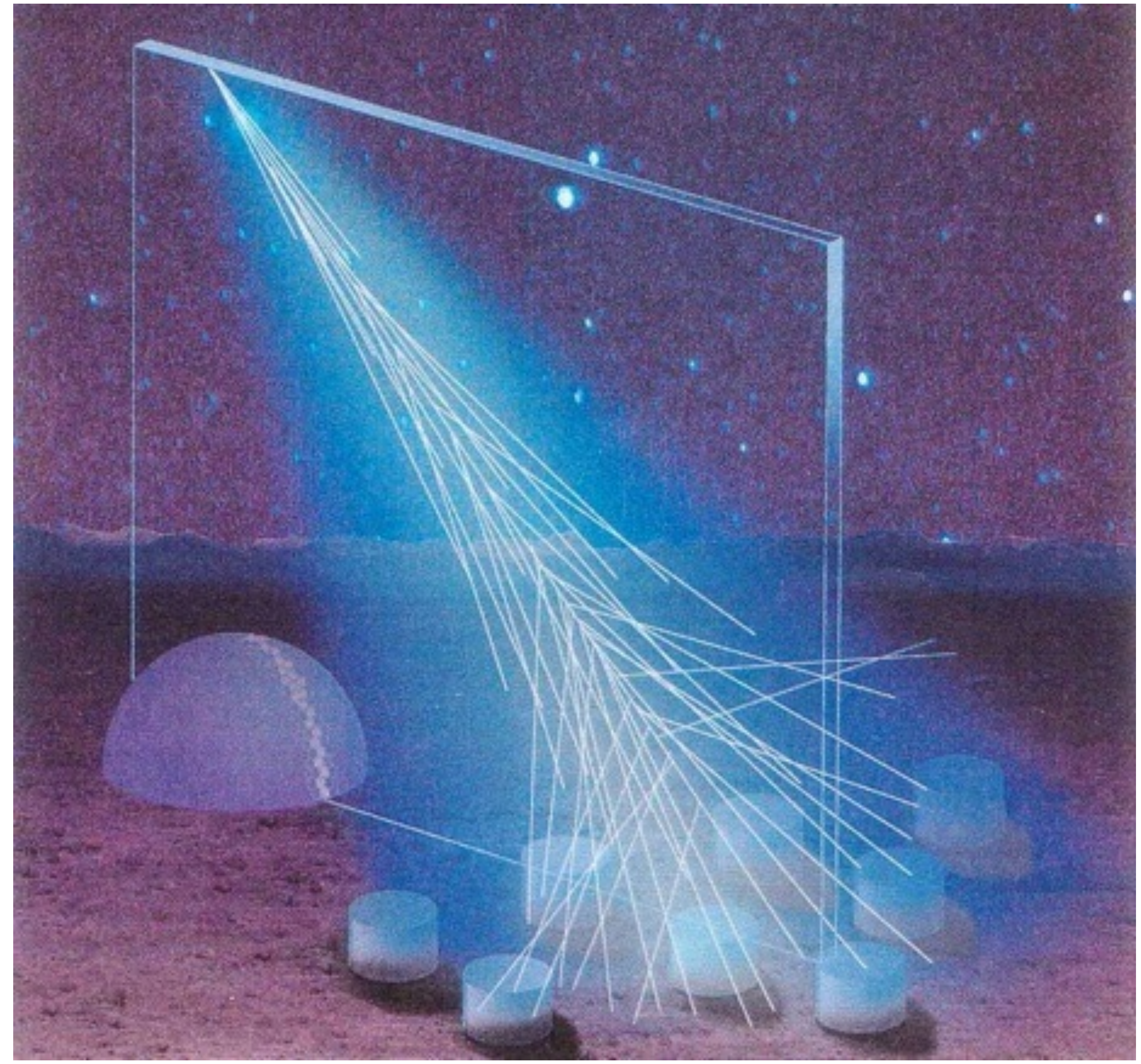


- Cherenkov light is created by electrons in the shower at an altitude of ~10 km
  - On the ground the light spreads over an area with a radius of ~120 m
    - Detection possible with a telescope within this area

Giant Air Shower Arrays







- 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 (> few MeV)
    - Formation of particle showers for highly energetic hadrons, electrons, photons

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    - Charge collection in gaseous and semi-conductor detectors
    - Light detection, for example for fluorescence / scintillation and Cherenkov detectors

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Next Lecture: 05.05.,
“Cosmic Accelerators”, F. Simon

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