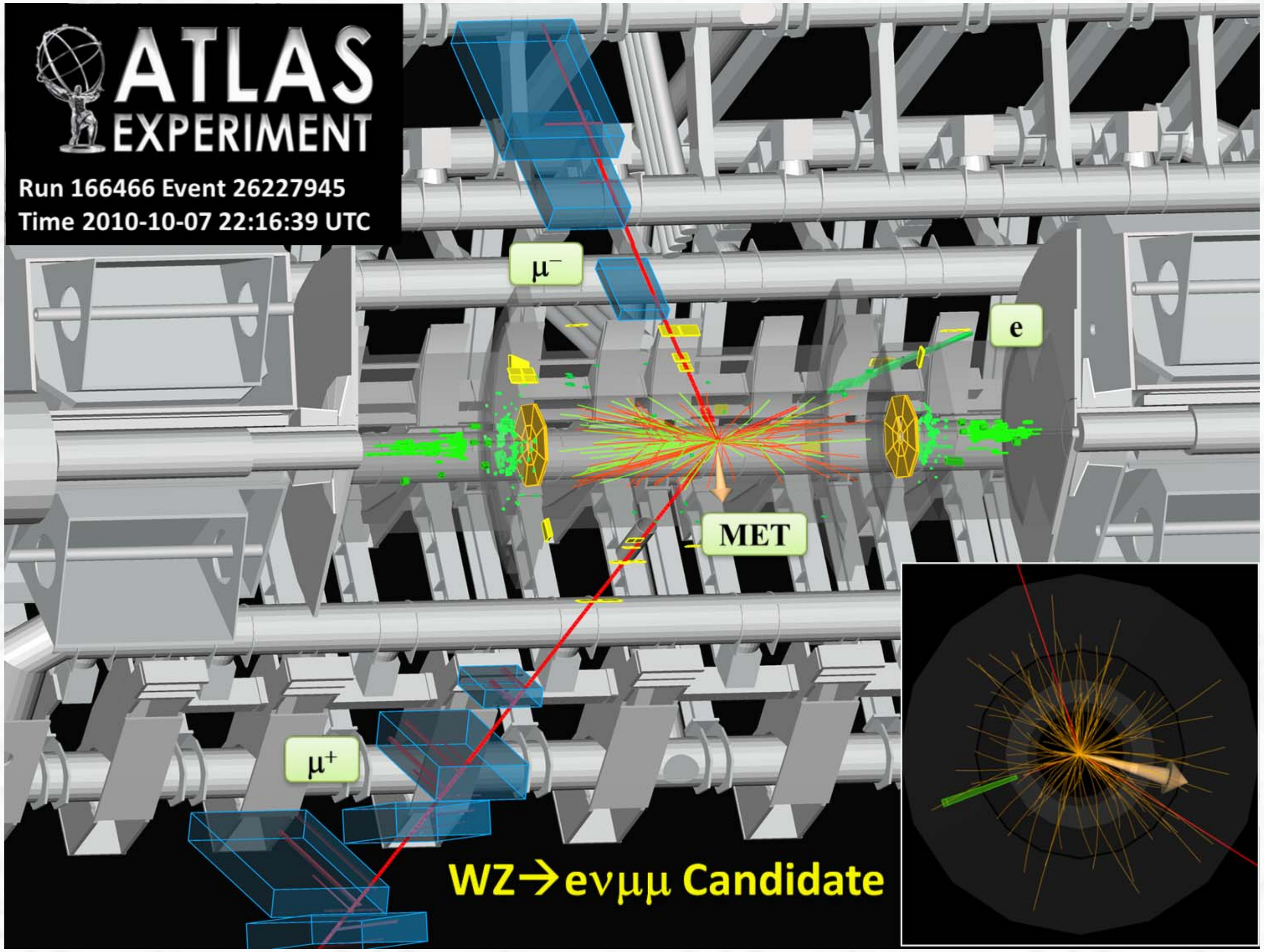
Particle Detectors



1. Introduction

1.1 Historical developments

1.2 Today's fields of application of particle detectors

1.3 Observables, parameters of measurements

1.4 Radiation sources

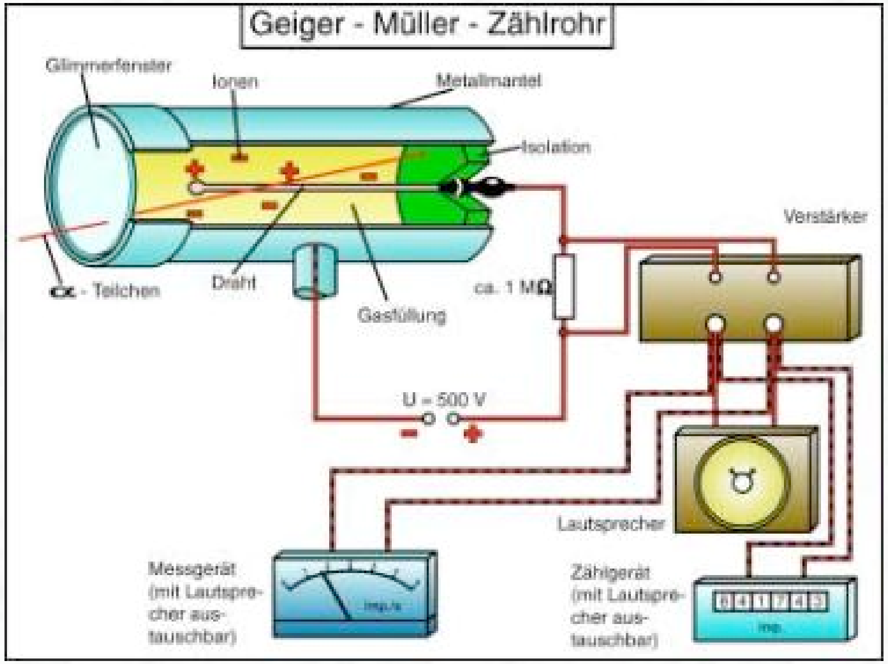
- Particle detectors have plenty of applications in science and technology

- In order to carry out experimental measurements in many areas of physics, particle detectors have to be used

  - Detection of photons (light) → Photo multiplier (photo-electric effect)
    → electrical signal → Electronic (amplification, signal for readout)

  - Detection of direct electrical signals,
    e.g. via Ionisation of gases (Ar, Xe,..),
    liquids (e.g. liquid argon) or
    solid materials
    (semiconductors: Si, Ge, GaAs, ...)

  → detection of ionising radiation (α, β)



1.1 History of Instrumentation

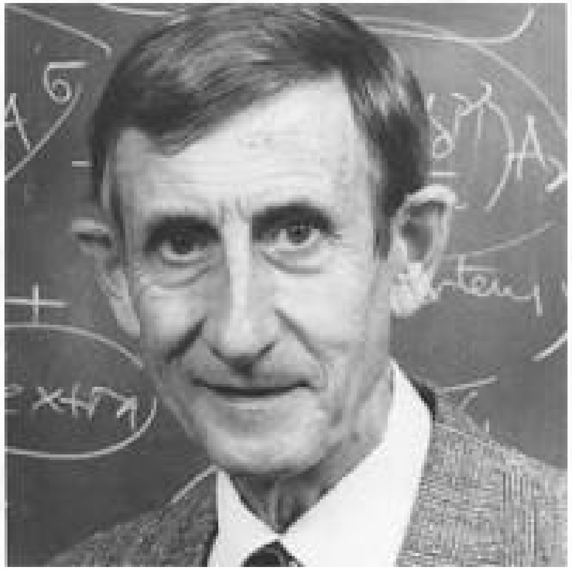
1906:	Geiger Counter	H. Geiger, E. Rutherford
1910:	Cloud Chamber	C.T.R. Wilson
1912:	Tip Counter	H. Geiger
1928:	Geiger-Müller Counter*	W. Müller
1929:	Coincidence Method	W. Bothe
1930:	Emulsion	M. Blau
1940/50:	Scintillator, Photomultiplier*	
1952:	Bubble Chamber	D. Glaser
1962:	Spark Chamber	
1968:	Multi-Wire Prop. Chamber*	G. Charpak
1972:	Drift Chamber*	F. Sauli, J. Heintze et al.
1974:	Time Projection Chamber*	D. Nygren
1983:	Silicon strip detectors*	J. Kemmer, R. Klanner, G. Lutz et al.
1990:	Silicon pixel detectors*	

*covered during this lecture series

Ideas and tools: both are important

"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson



→New tools and technologies developed over more than 20 years (for the large detector concepts) will hopefully lead to exciting discoveries at the LHC beyond the already discovered Higgs boson !

Physics Nobel Prizes for Instrumentation

1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron & Discoveries

1948: P.M.S. Blacket, Cloud Chamber & Discoveries

1950: C. Powell, Photographic Method & Discoveries

1954: Walter Bothe, Coincidence method & Discoveries

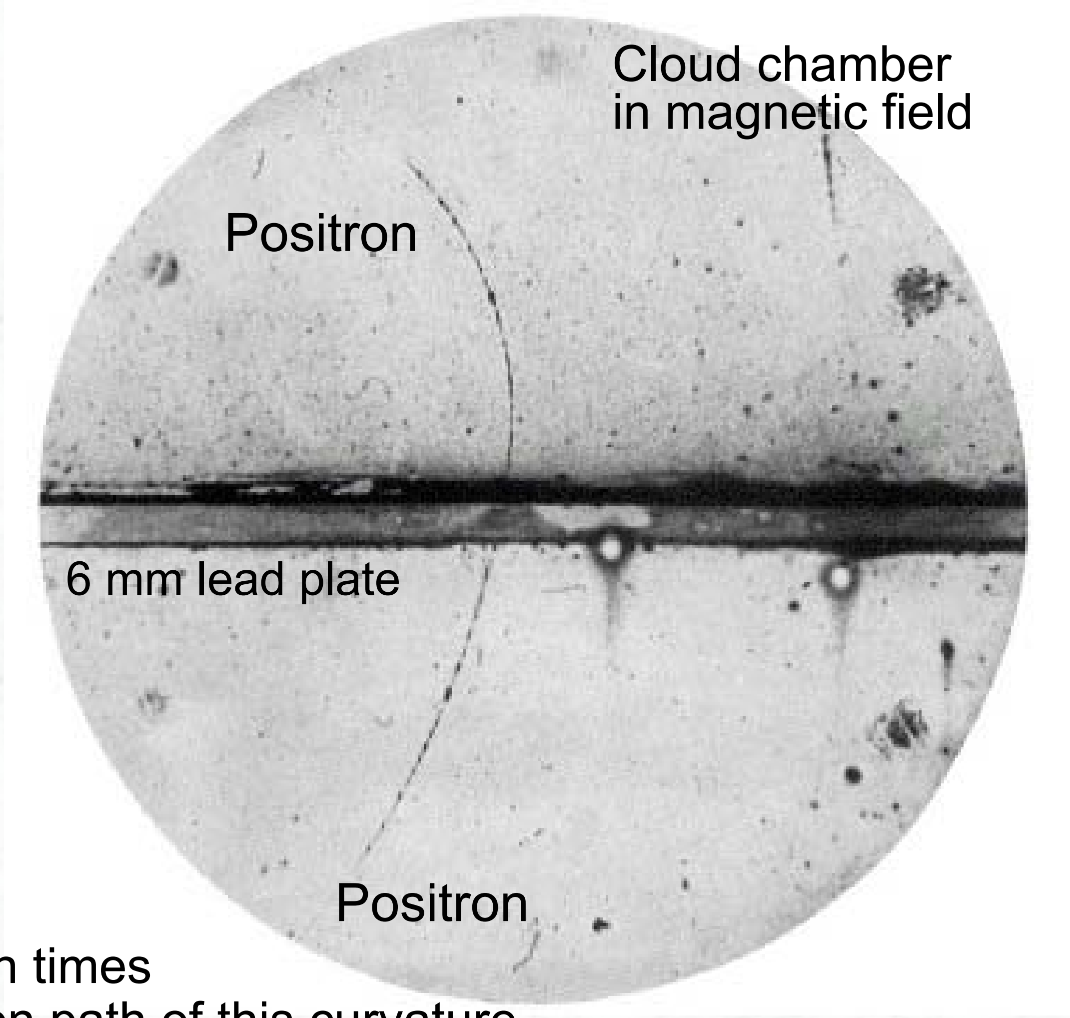
1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries

1992: Georges Charpak, Multi-Wire Proportional Chamber

Historical Developments

Discovery of antimatter
[Anderson 1932; Nobel prize 1936]



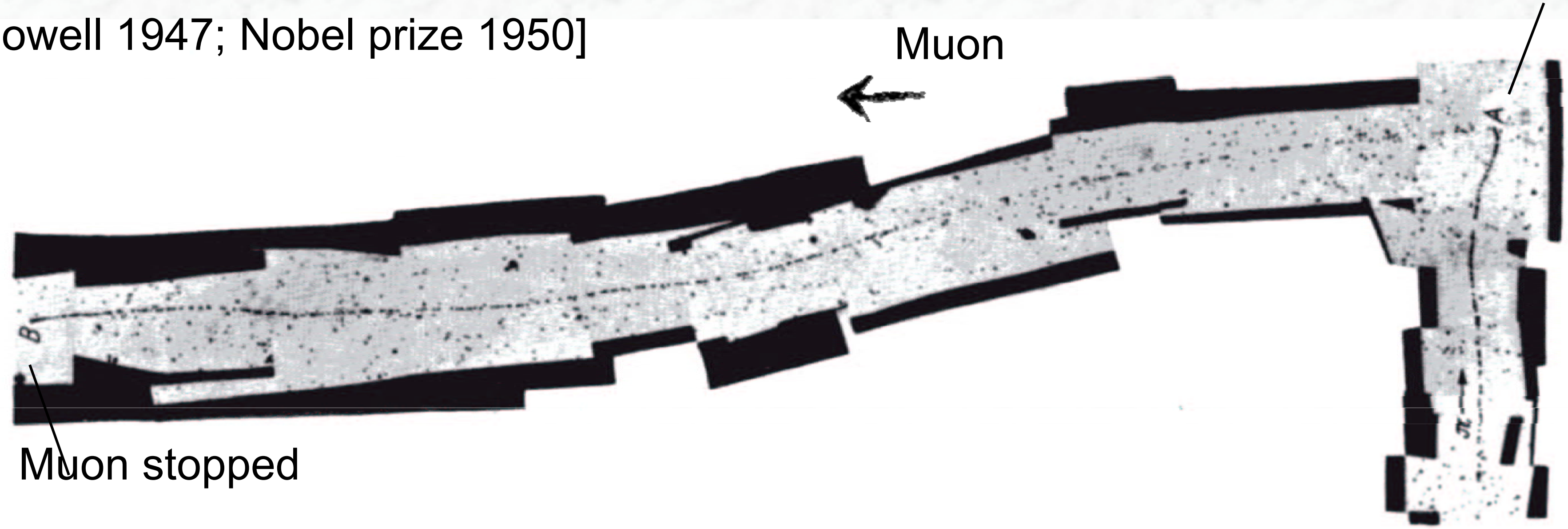
63 MeV positron passing through a lead plate emerging as 23 MeV positron.

The length of this latter pass is at least ten times greater than the possible length of a proton path of this curvature.

Historical Developments

Discovery of the pion
Nuclear emulsion technique

[Powell 1947; Nobel prize 1950]



Pion
at rest

Muon

Muon stopped

π → $\mu\nu$

$\mu \rightarrow e\nu\nu$ [not seen]

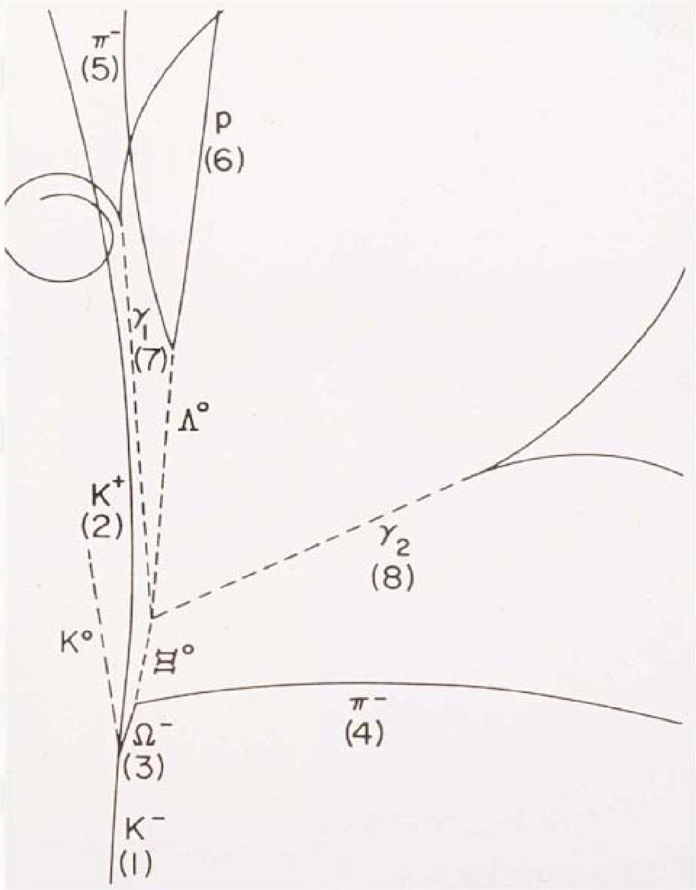
Pion

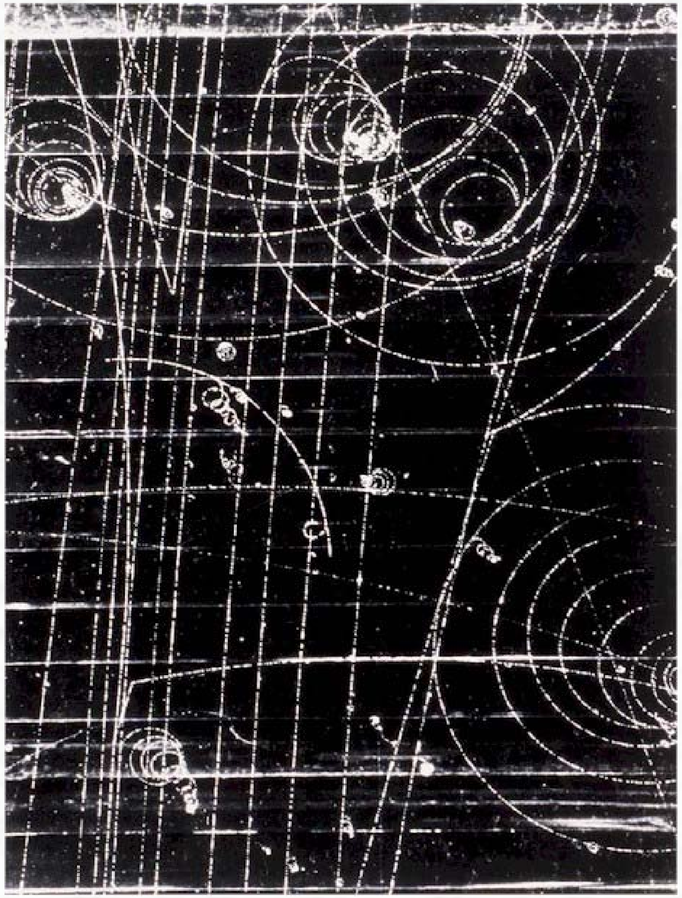
Historical Developments

1964: Brookhaven, AGS accelerator. 80 inch bubble chamber, liquid hydrogen

Observation of the reaction $K^- + p \rightarrow K^0\ K^+\ \Omega^-$

Strangeness S = -3, (sss), cascade decays → new particle, $m(\Omega) = 1.672$ GeV/c^2





First observed Ω^- event
[BNL Bubble Chamber]

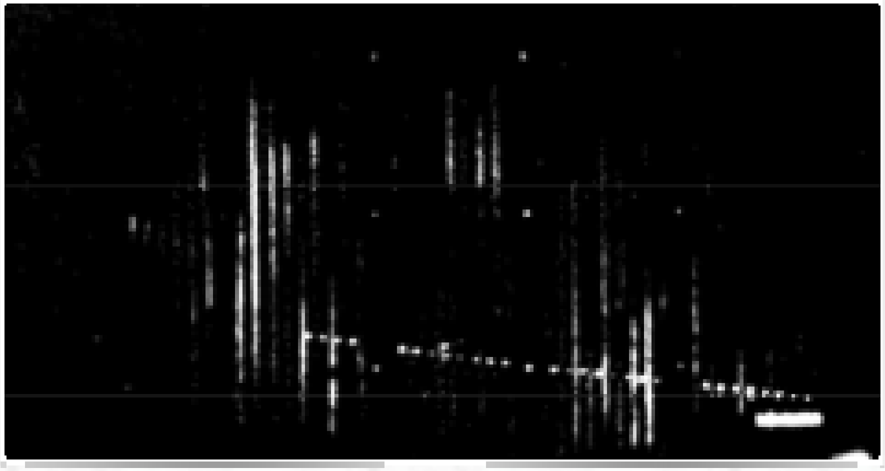
Historical Developments

Melvin Schwartz in front of the spark chamber used to discover the muon neutrino

Discovery of the muon neutrino (1962)

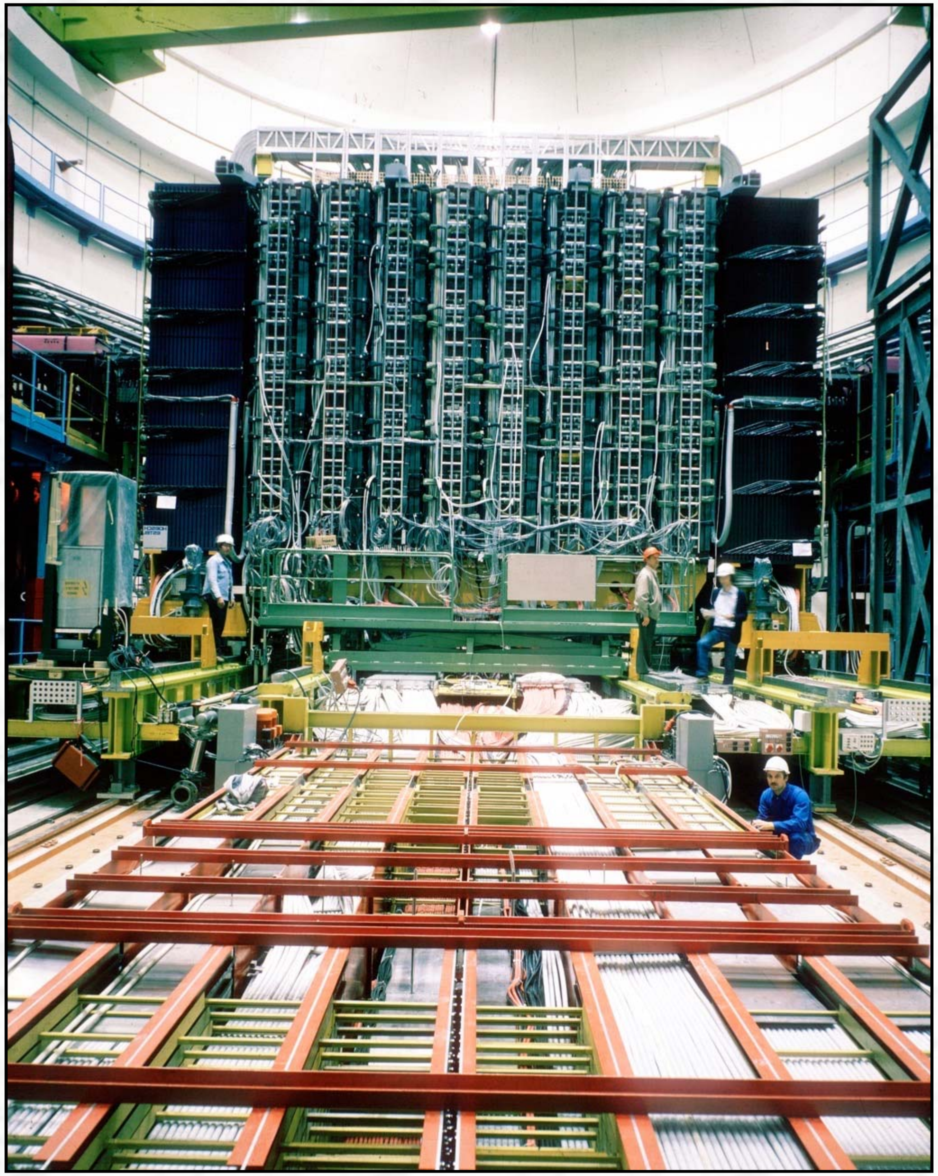
Leon M. Lederman
Melvin Schwartz
Jack Steinberger

[Nobel prize 1988]



Single muon event from the original publication

Historical Development



UA1

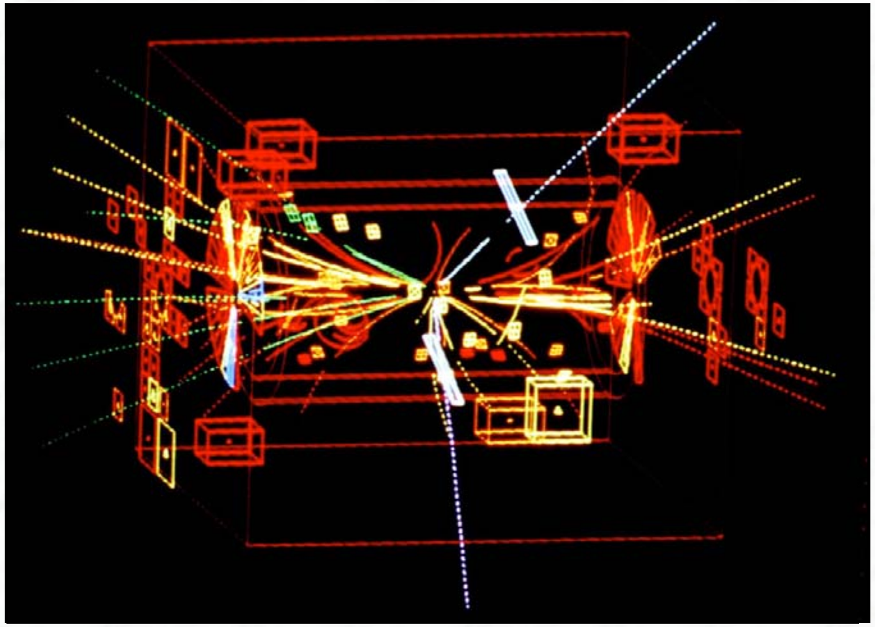
Detector

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

First Z^0 particle seen by UA1



(i)Elementary Particle Physics

Detection and precise measurement of reactions (collisions) at particle accelerators

- Measurement of final state particles (momenta, energies, ..)

- Identification of final state particles (e, γ, μ, τ, jets, …)

- Energy balance

  (total energy or energy in the transverse plane)

  → identification of only weakly interacting particles (e.g. neutrinos)

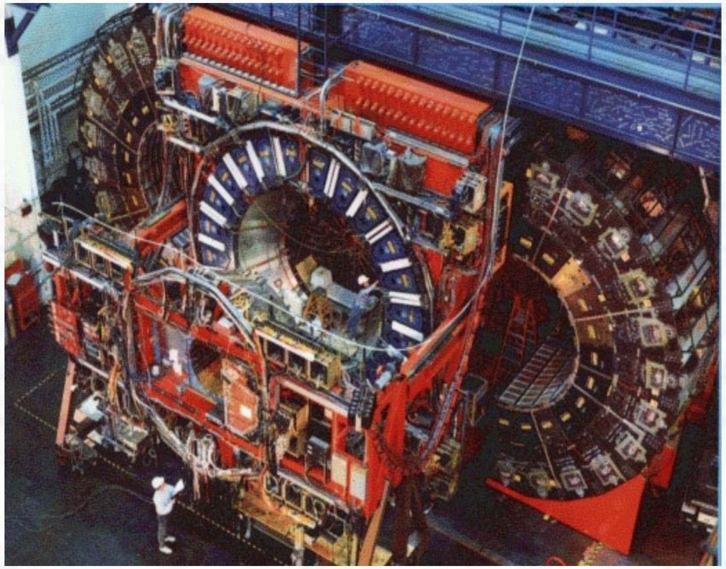
- Energy range: 0.2 MeV → 5 TeV

High Energy Particle Accelerators (last 25 years):

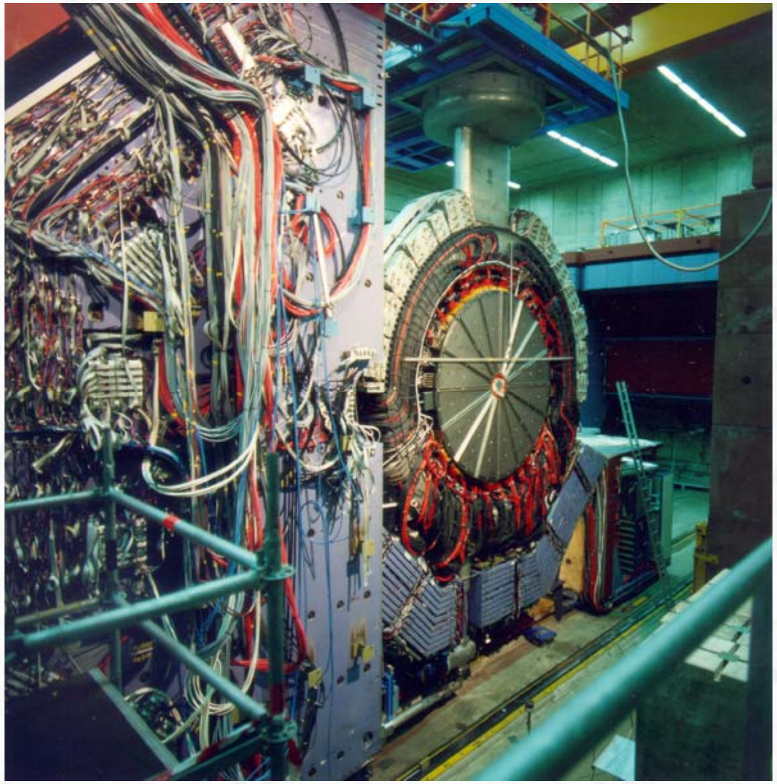
Accelerator	**type, laboratory**	**energy $\sqrt{s}$**	**years of operation**
LEP-I	e^+e^- collider, CERN	91 GeV	1989 - 1994
LEP-II	e^+e^- collider, CERN	209 GeV	1995 - 2000
HERA-I	ep collider, DESY	27 + 800 GeV	1992 - 2000
HERA-II	ep collider, DESY	27 + 920 GeV	2002 - 2007
TeVatron Run I	ppbar collider, Fermilab	1.8 TeV	1987 - 1996
TeVatron Run II	ppbar collider, Fermilab	1.96 TeV	2002 - 2011
LHC, Run 1	pp collider, CERN	7 TeV	2010- 2012
LHC, Run 2	pp collider, CERN	13 - 14 TeV	2015- …….

In addition: high intensity B factories at SLAC (1998 – 2007) and KEK (1998 - …)

Large Detector Systems in Particle Physics

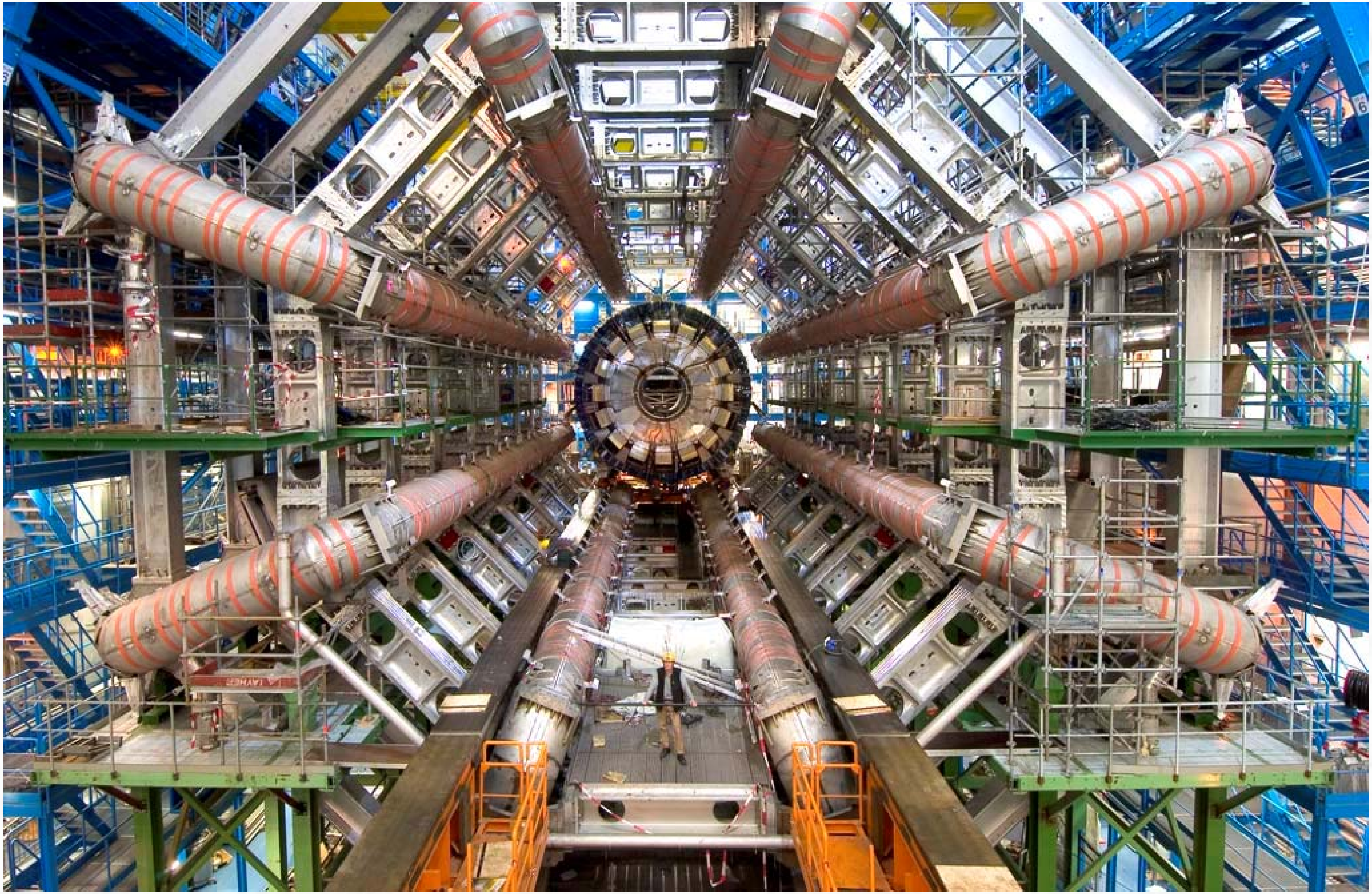


CDF-Experiment, Fermilab / USA

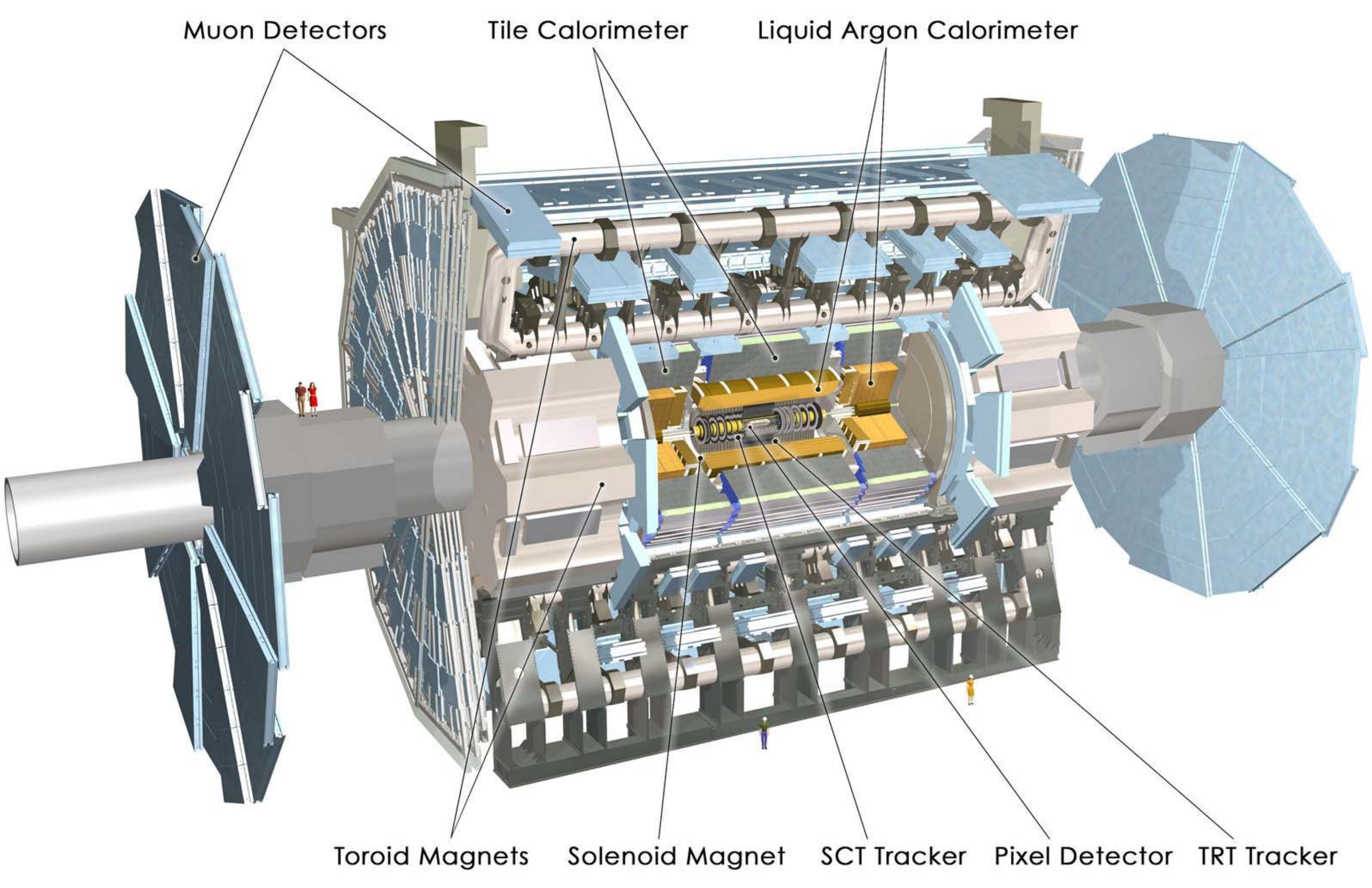


H1-Experiment, DESY / Hamburg

The ATLAS experiment at the Large Hadron Collider during assembly (October 2005)



The ATLAS experiment



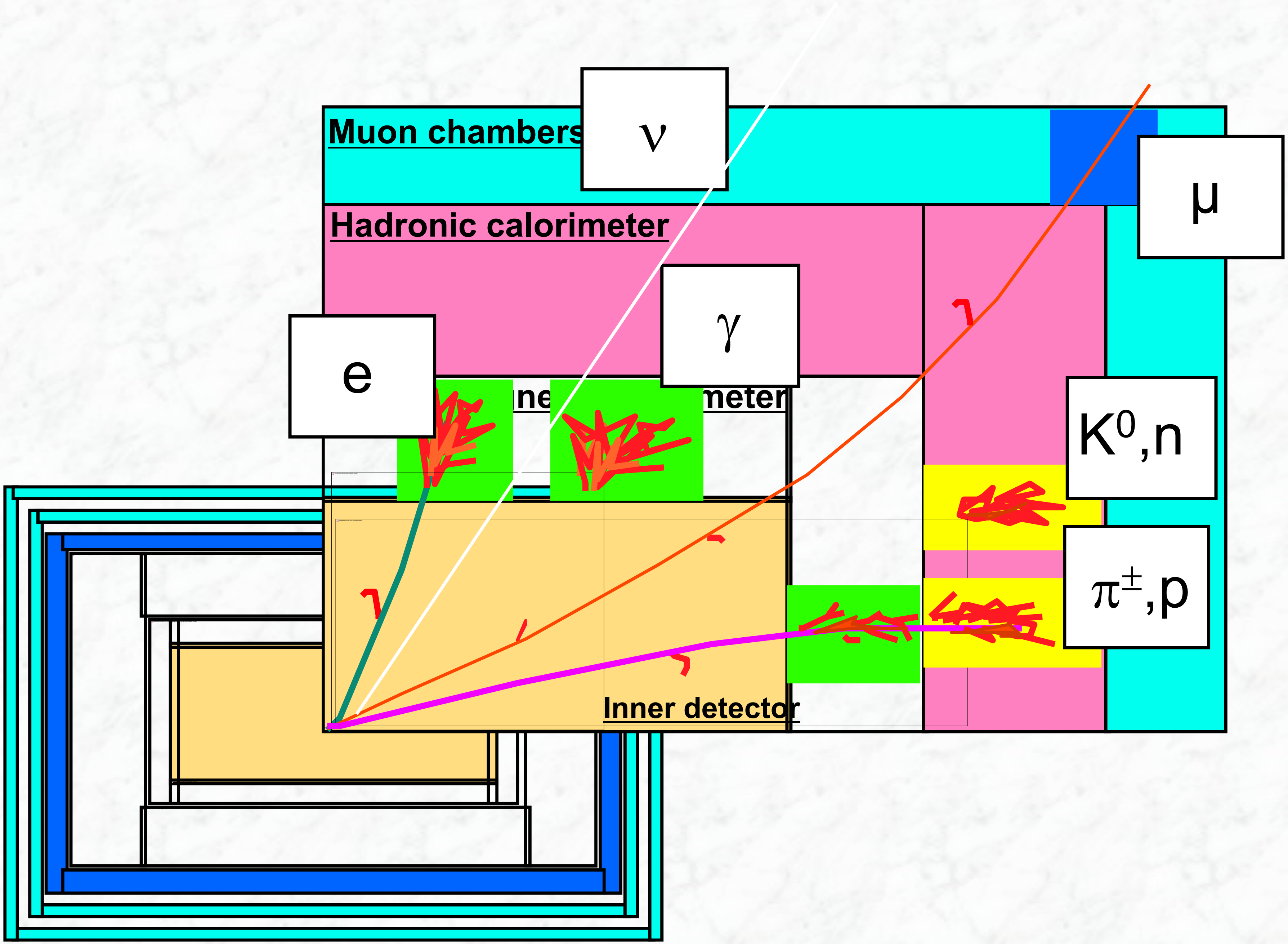
- Solenoidal magnetic field (2T) in the central region (momentum measurement)
- Independent muon spectrometer (supercond. toroid system)
- High resolution silicon position detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

  space resolution: ~ 15 μm
- Liquid argon calorimeter (high granularity) Energy measurement down to 1° to the beam line

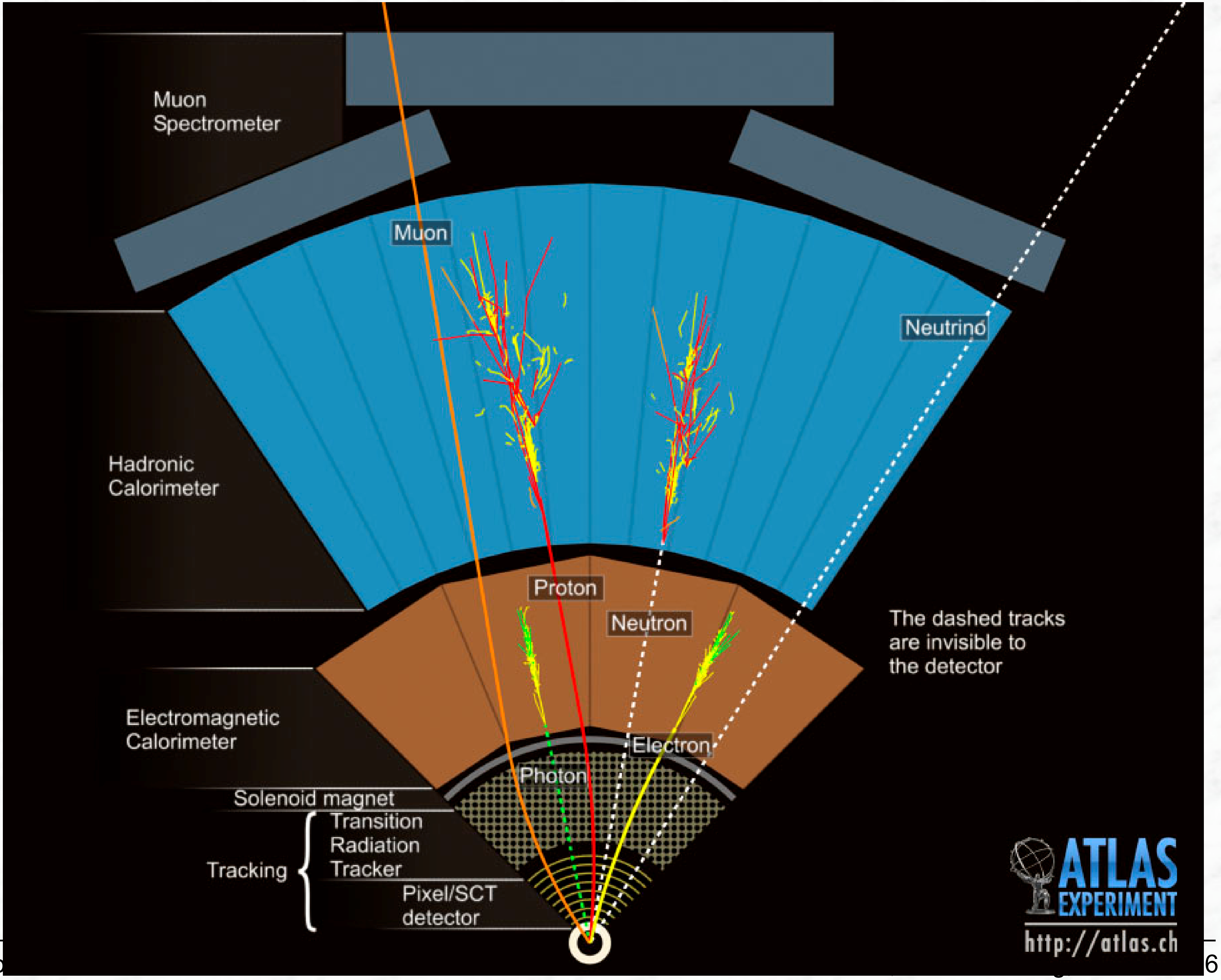
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

More than 200 Mio electronic readout channels

The interplay of the various detector layers

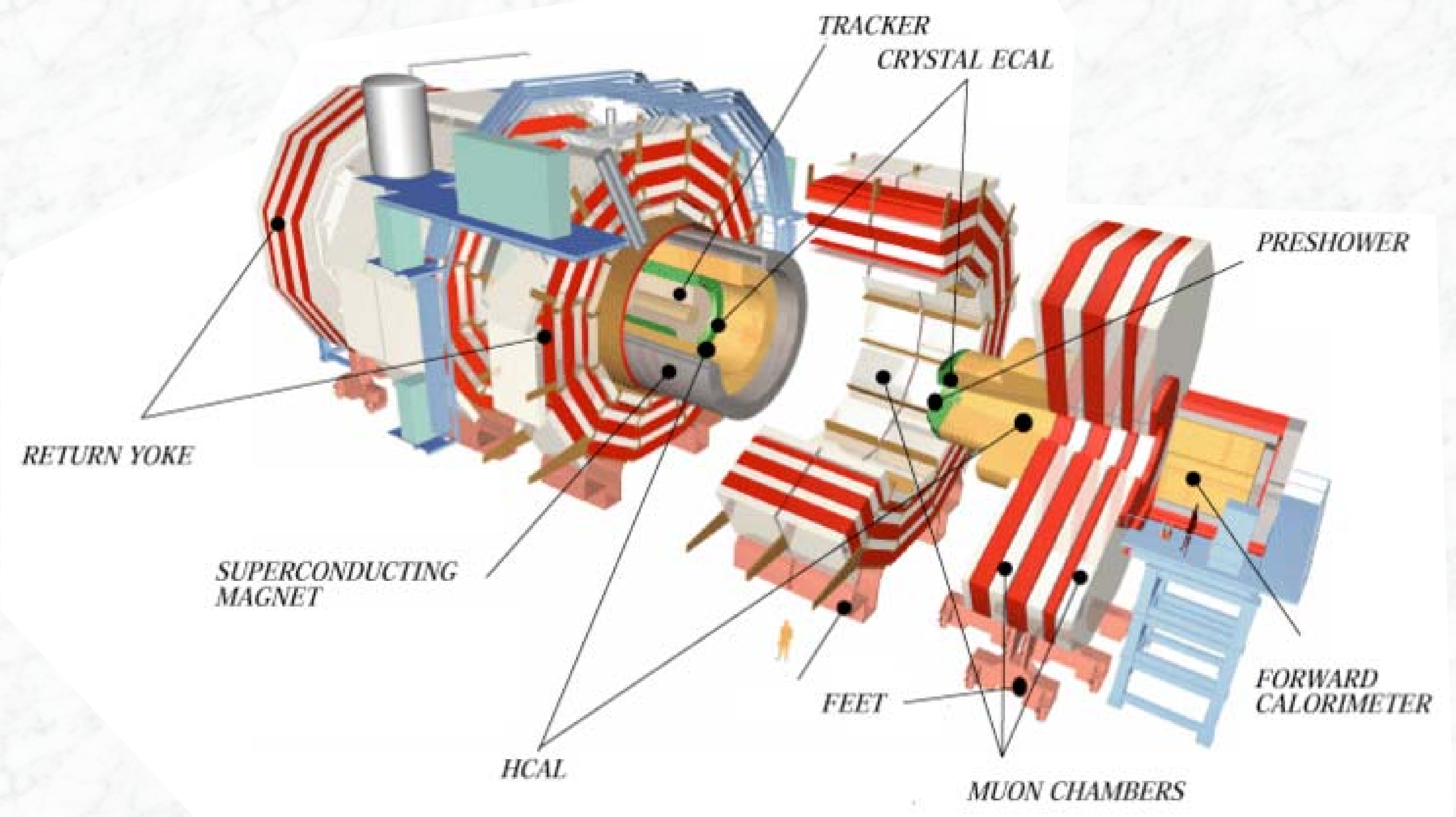


Layers of the ATLAS detector

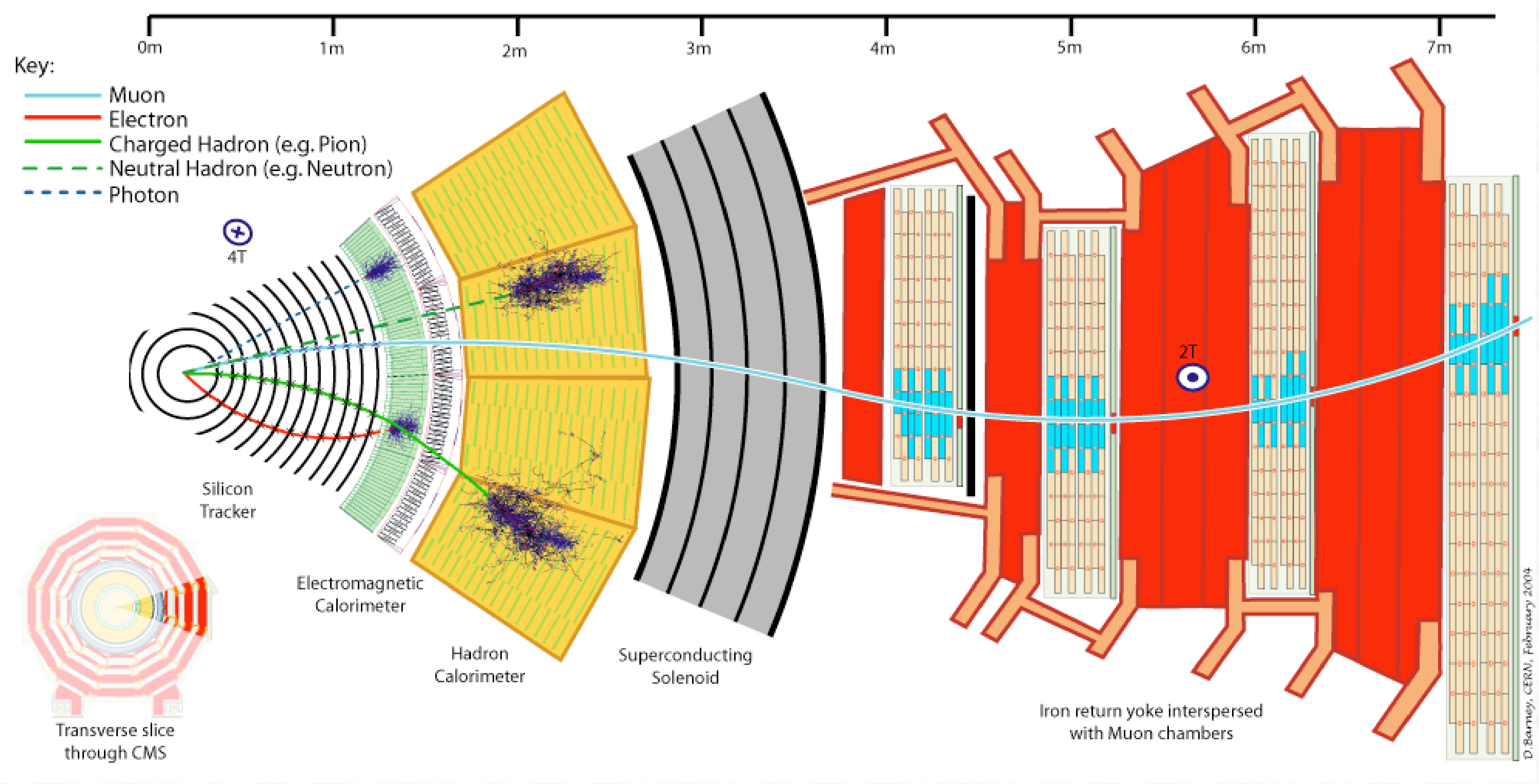


The dashed tracks are invisible to the detector

The CMS Detector



The CMS Detector



(ii) Astro-Particle Physics

Detection and measurement of cosmic rays
(ground based and satellite experiments)

Important observables: direction, energy,
composition (particle identification), ….

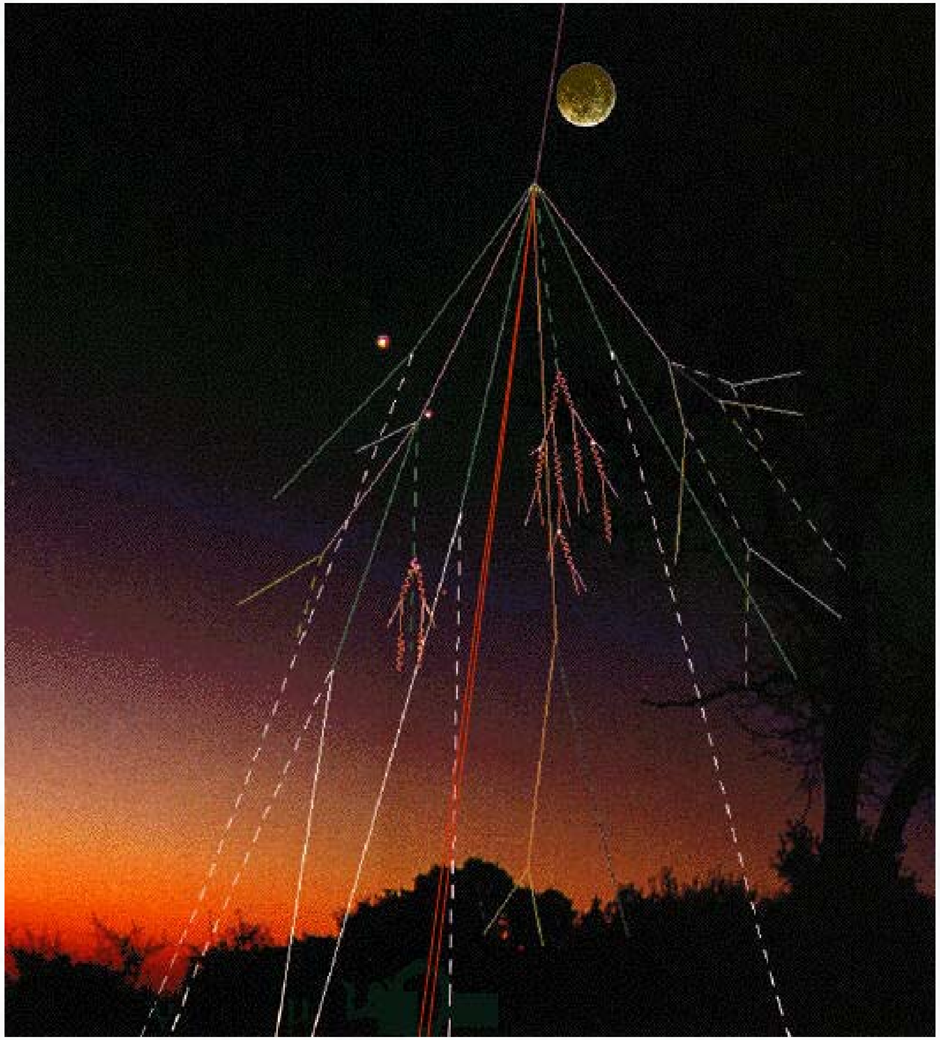
- Detection of high energy γ rays (γ ray bursts)

- Detection of antiparticles (e^+, antiprotons, …)
  (Signals from Dark Matter annihilation)

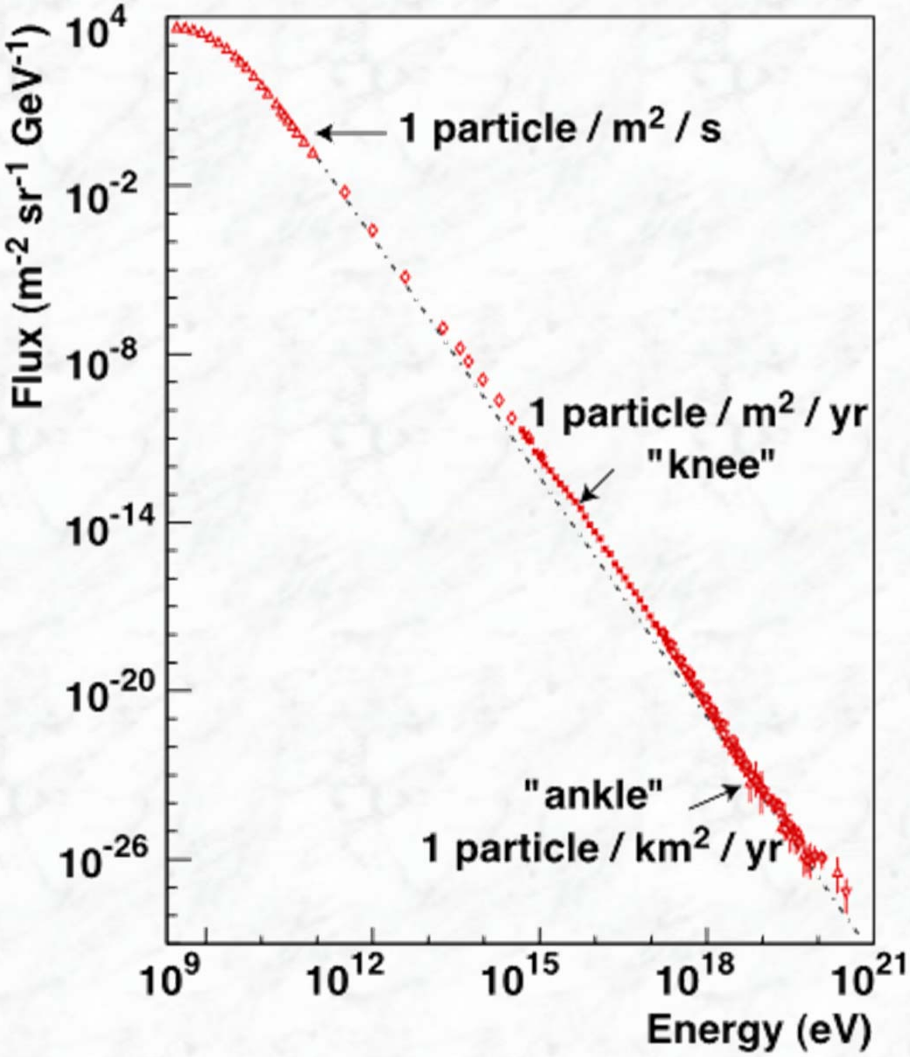
- Detection of neutrinos from solar, galactic and extragalactic sources

- Energy range: up to 10^{21} eV

Cosmic Rays

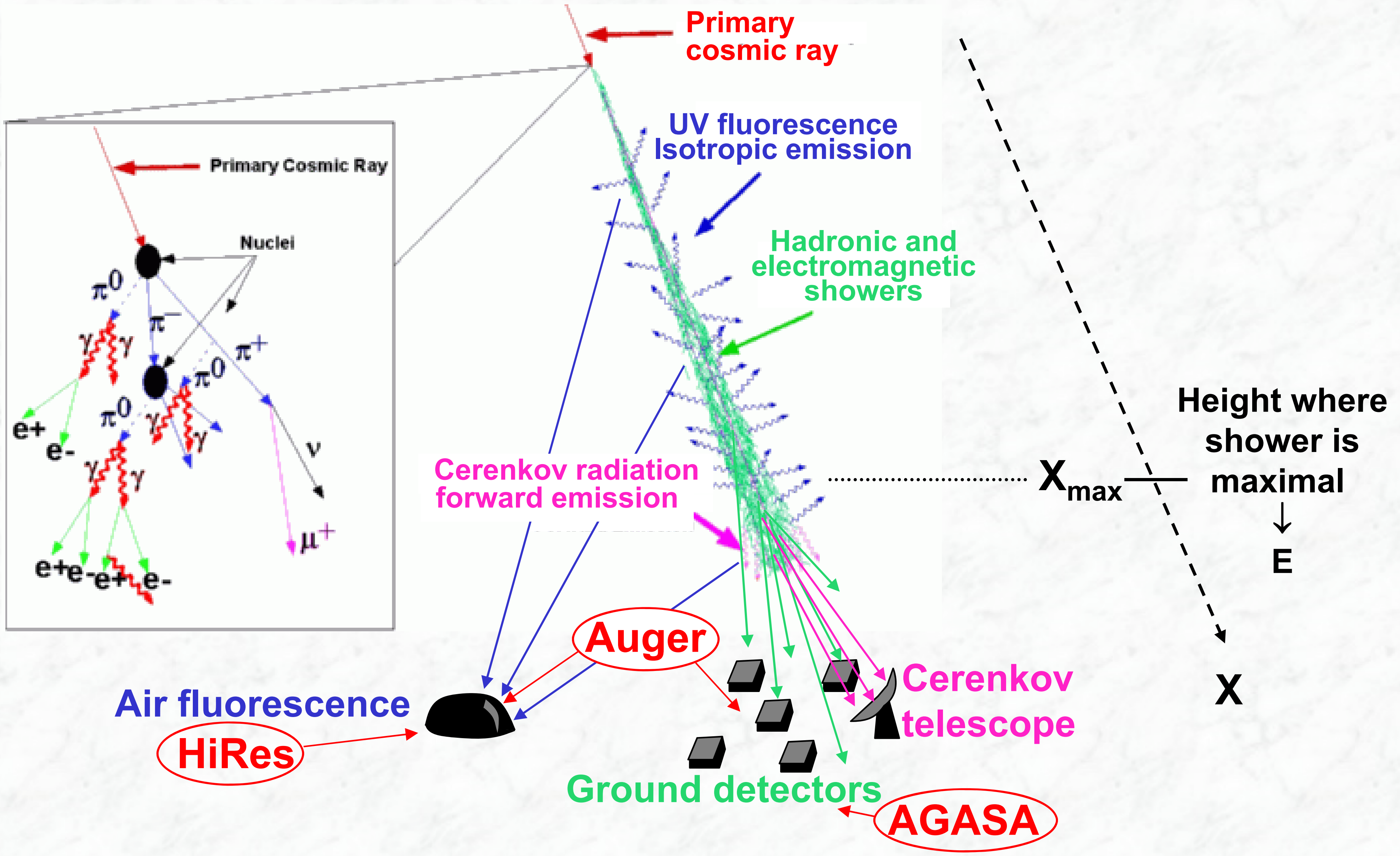


Energy spectrum of cosmic rays



E_{max} = 3.2 10^{20} eV = 50 J !

Ground-based detection methods



Primary cosmic ray

UV fluorescence
Isotropic emission

Hadronic and electromagnetic showers

Cerenkov radiation forward emission

X_{max}

Height where shower is maximal
↓
E

X

Auger

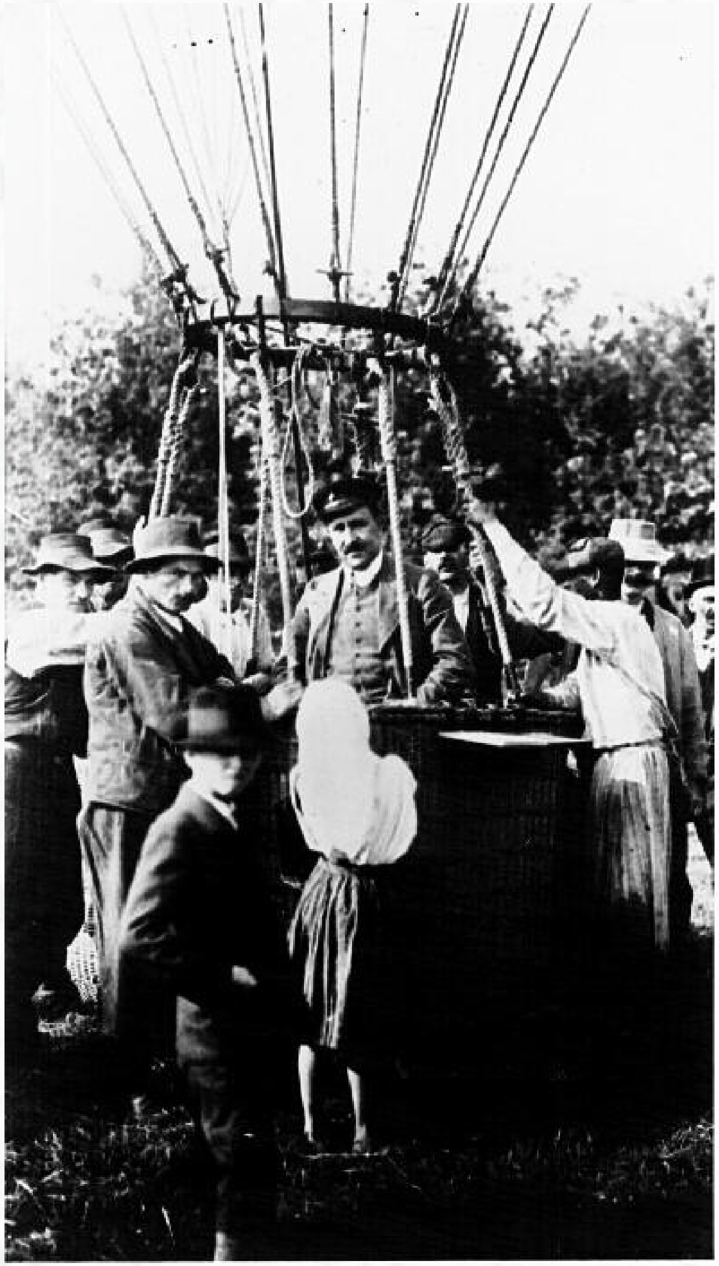
Air fluorescence

HiRes

Ground detectors

AGASA

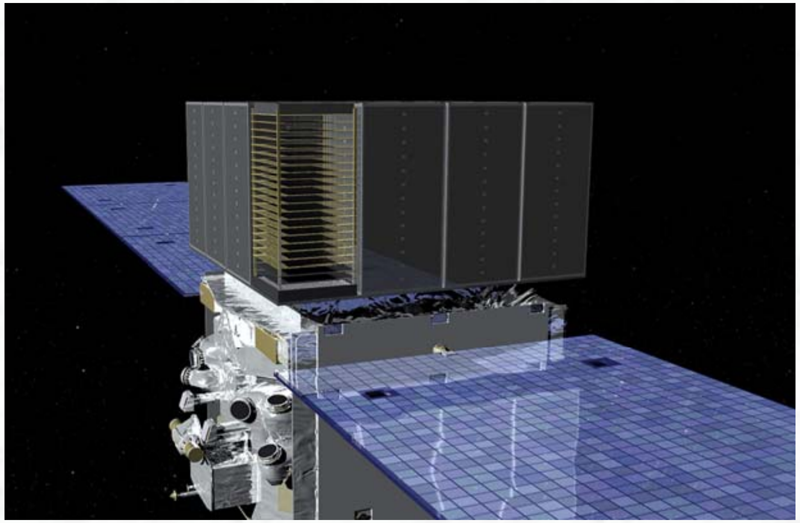
Cerenkov telescope



Victor Hess, 1912
Untersuchung der kosmischen Strahlung

The HESS experiment, Namibia (2008)
Max-Planck-Institut für Physik, Heidelberg and others

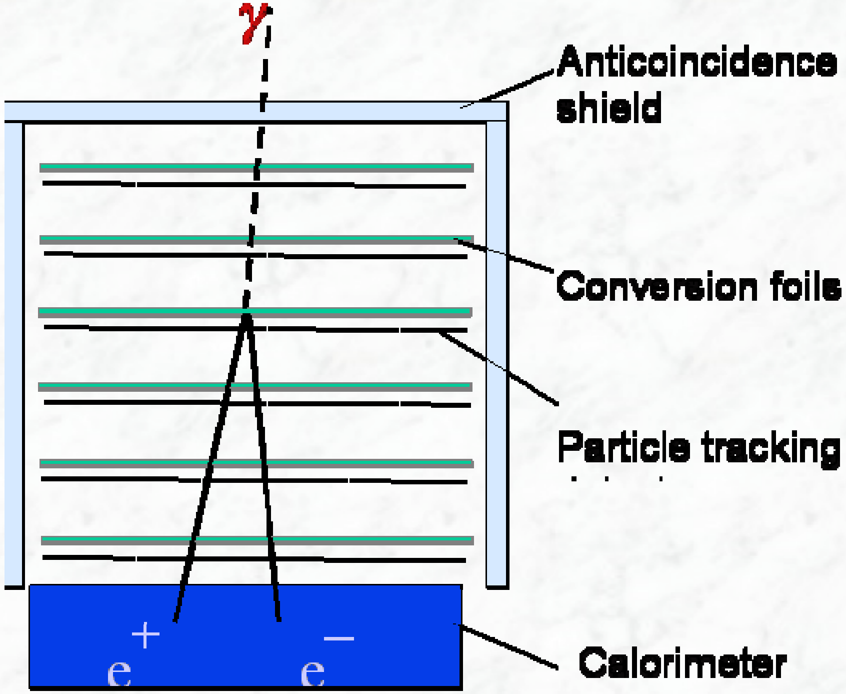
Example: GLAST / FERMI



The Gamma Ray Large Area Space Telescope

Comprised of four key components:

- Precision Tracker
- Calorimeter
- Data Acquisition System
- Anti-coincidence Detector

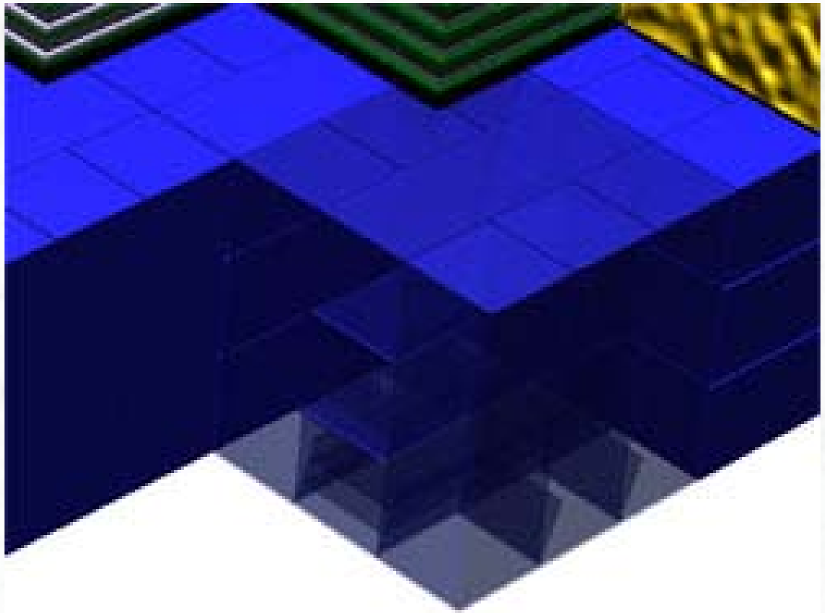


GLAST / FERMI Calorimeter:

- The calorimeter design for GLAST produces flashes of light that are used to determine how much energy is in each gamma-ray. A calorimeter is a device that measures the energy (heat in calories) of a particle when it is totally absorbed.

- CsI(TI) bars, arranged in a segmented manner, give both longitudinal and transverse information about the energy deposition pattern.

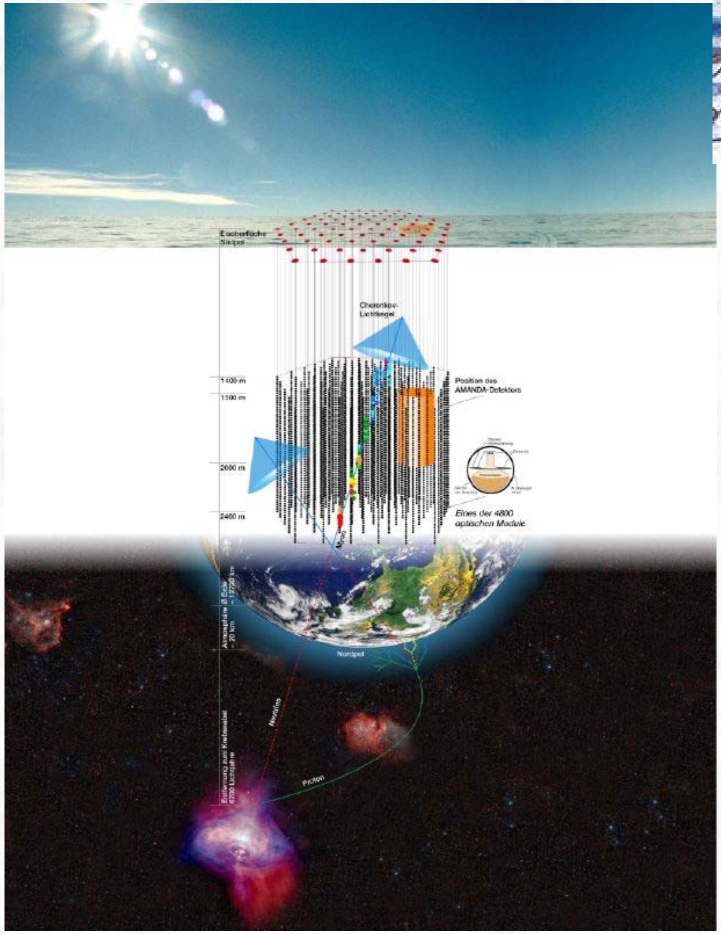
- Once a gamma ray penetrates through the anticoincidence shield, the silicon-strip tracker and lead converter planes, it then passes into the cesium-iodide calorimeters. This causes a scintillation reaction in the cesium-iodide, and the resultant flash is converted to a voltage. This voltage is then digitized, recorded and relayed to earth.



Cesium-iodide blocks (segmentation) provide additonal positional information about the shower.

Detektoren in der Antarktis,
das Neutrino-Experiment AMANDA

AMANDA (Südpol)



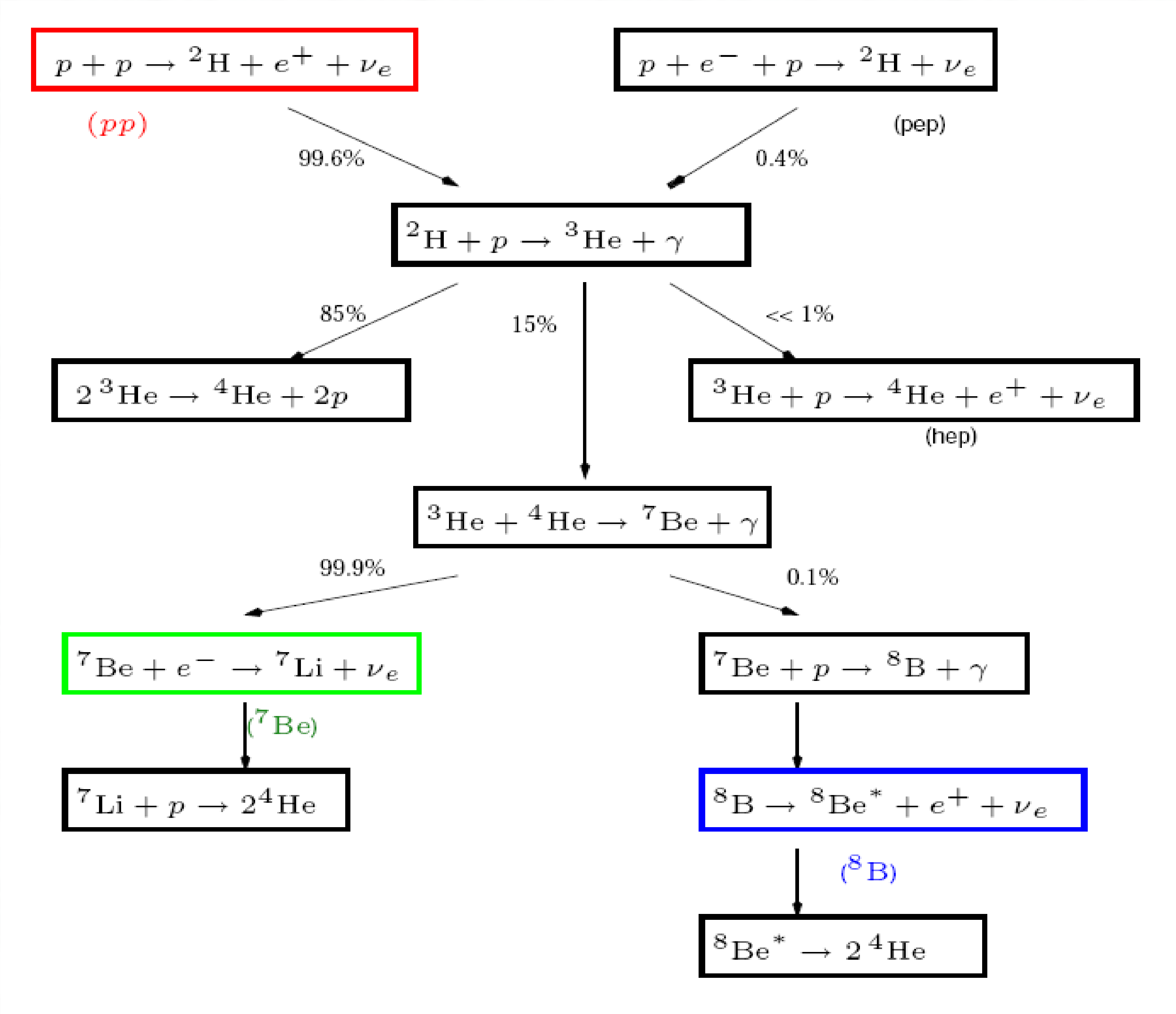
(iii) Neutrino Physics (properties of neutrinos)

Detection of solar and atmospheric neutrinos as well as neutrinos from accelerators

Important observables: direction, neutrino flavour, (energy), …..

- Energy range: 100 μeV up to 1 TeV

Energy and neutrino production in the sun



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

(pp)

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

(pep)

99.6%

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

15%

<< 1%

$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

(hep)

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.9%

0.1%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

$({}^7\mathrm{Be})$

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

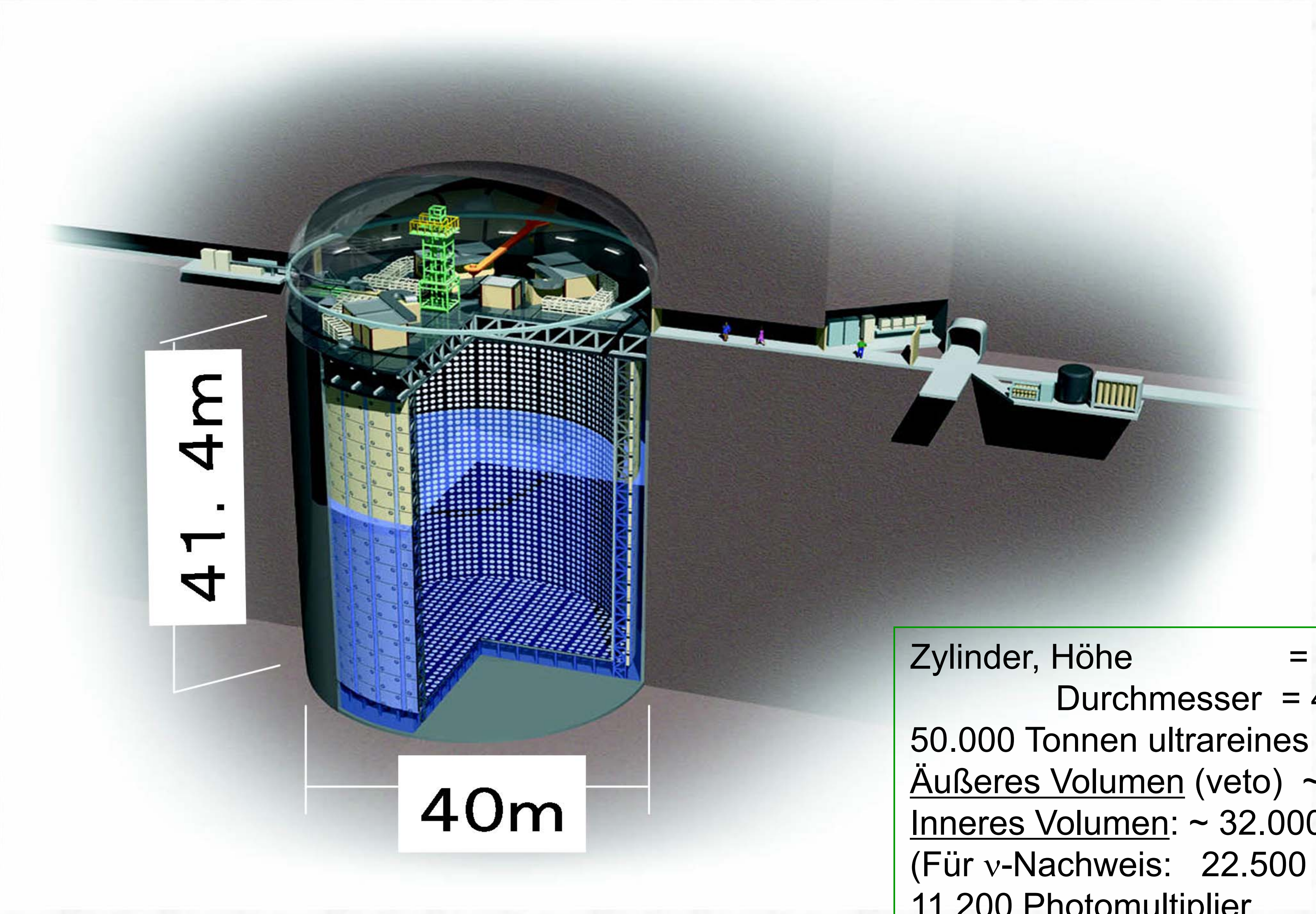
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

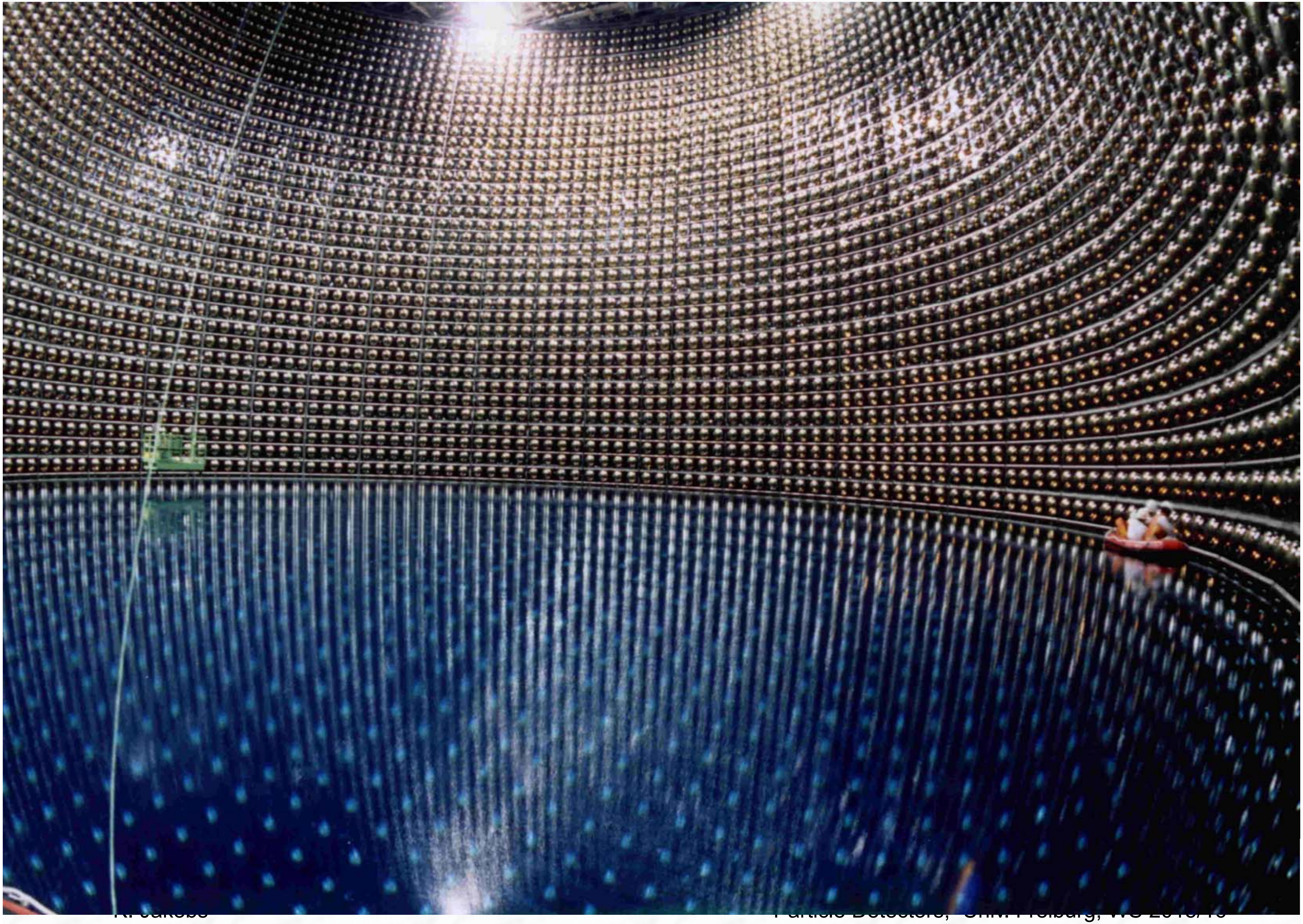
$({}^8\mathrm{B})$

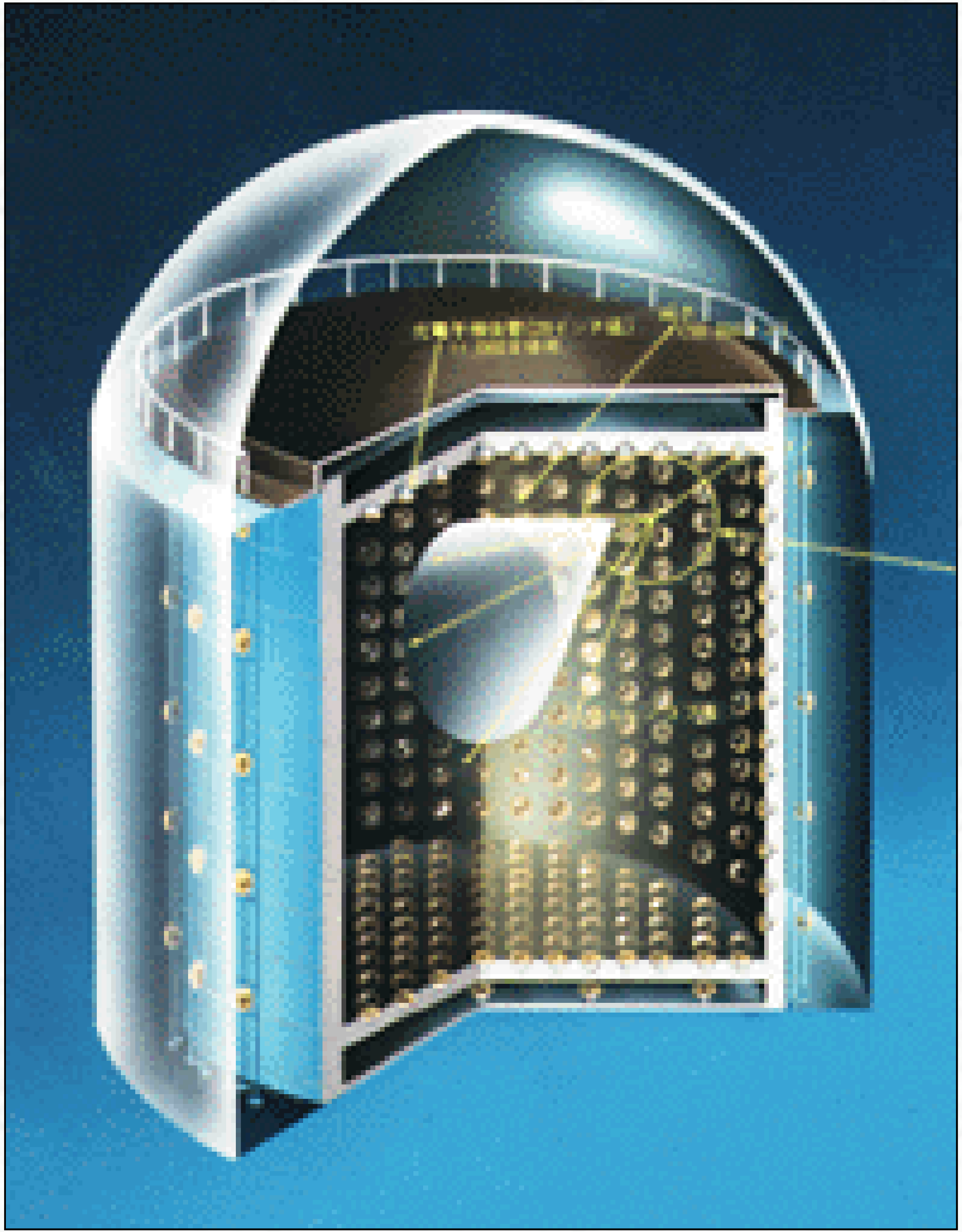
${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

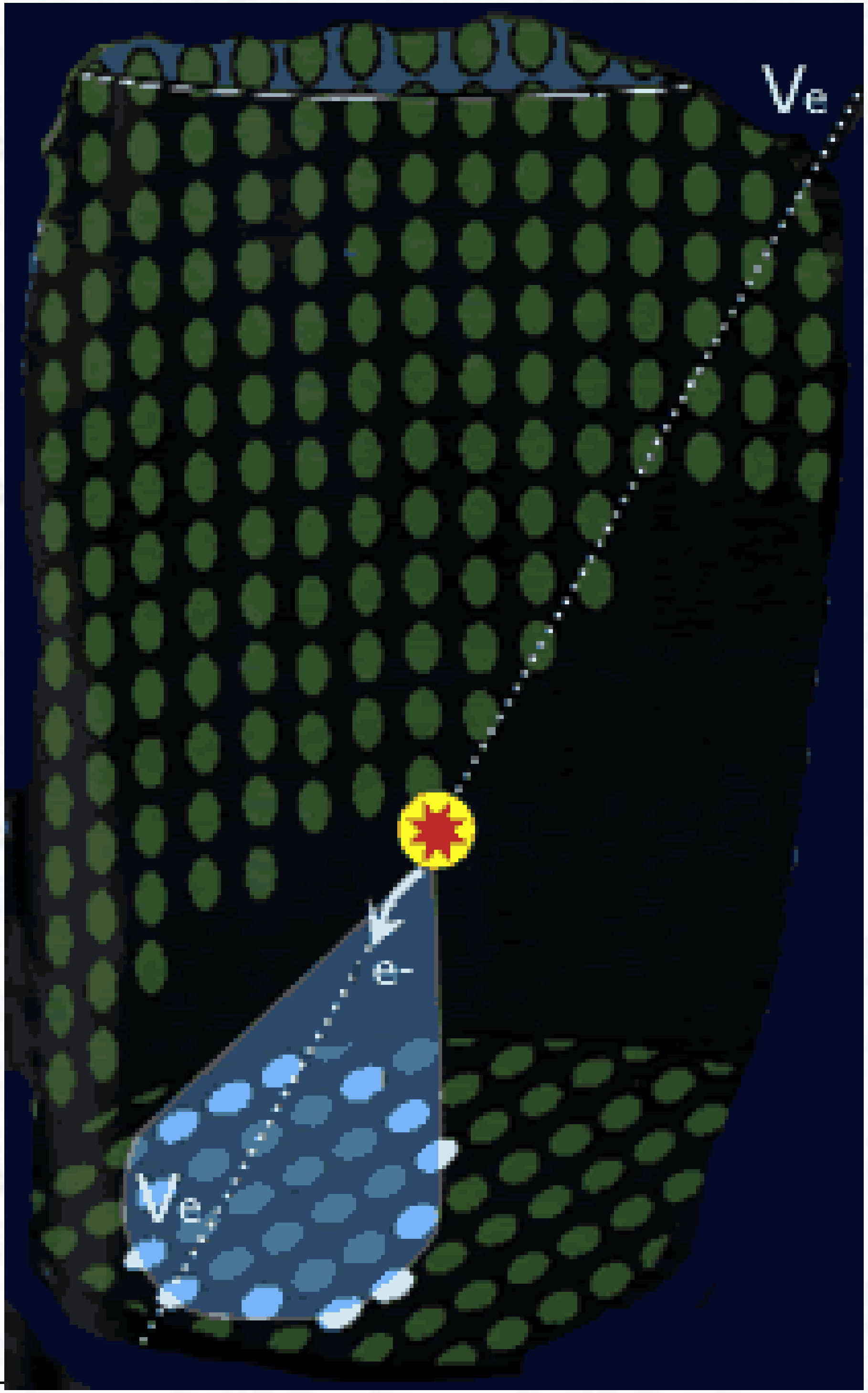
Superkamiokande-Detektor (Japan)



Zylinder, Höhe = 41.4 m
Durchmesser = 40 m
50.000 Tonnen ultrareines Wasser
Äußeres Volumen (veto) ~2.7 m dick
Inneres Volumen: ~ 32.000 Tonnen
(Für ν-Nachweis: 22.500 Tonnen)
11.200 Photomultiplier
Durchmesser = 50 cm



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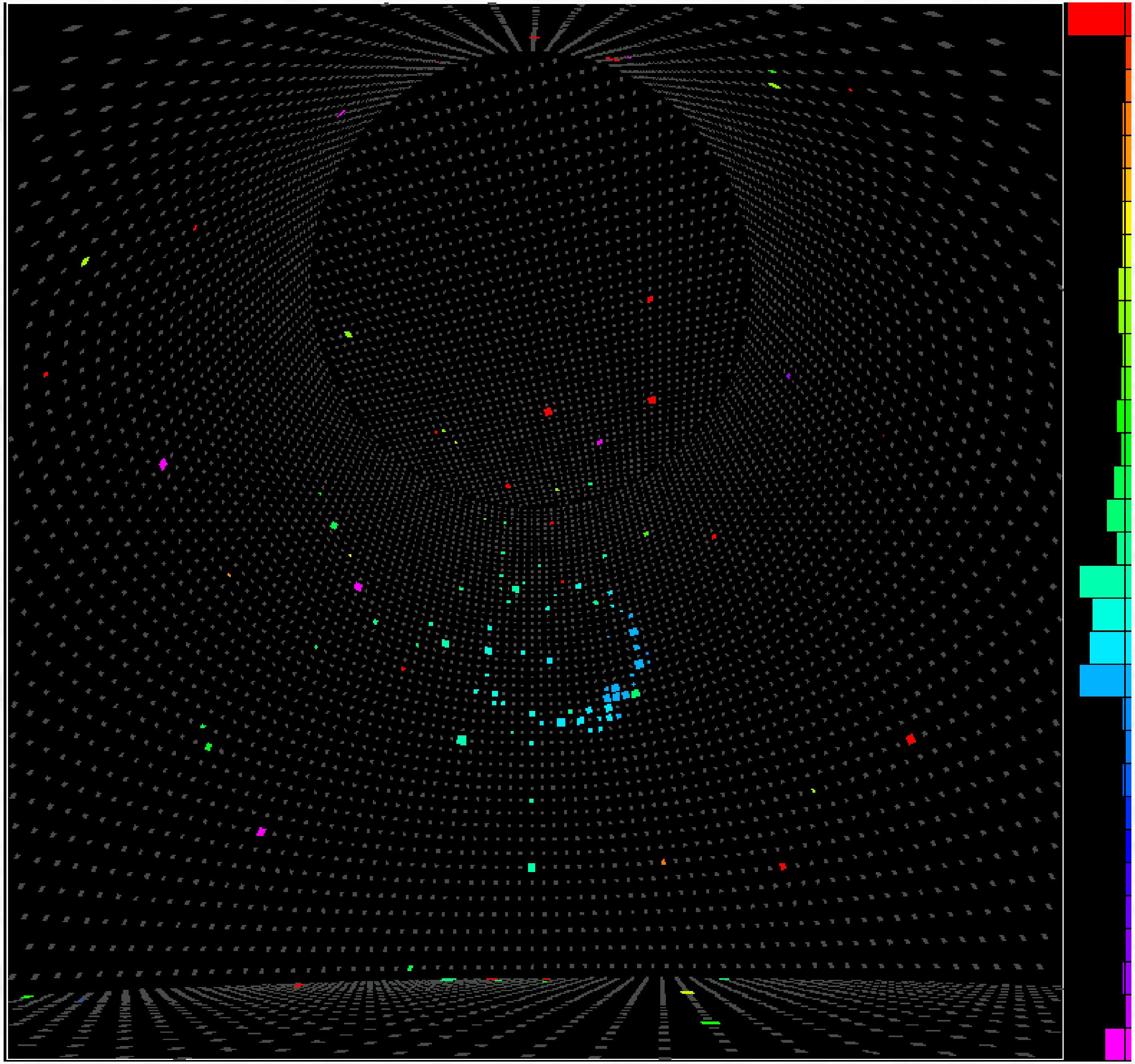
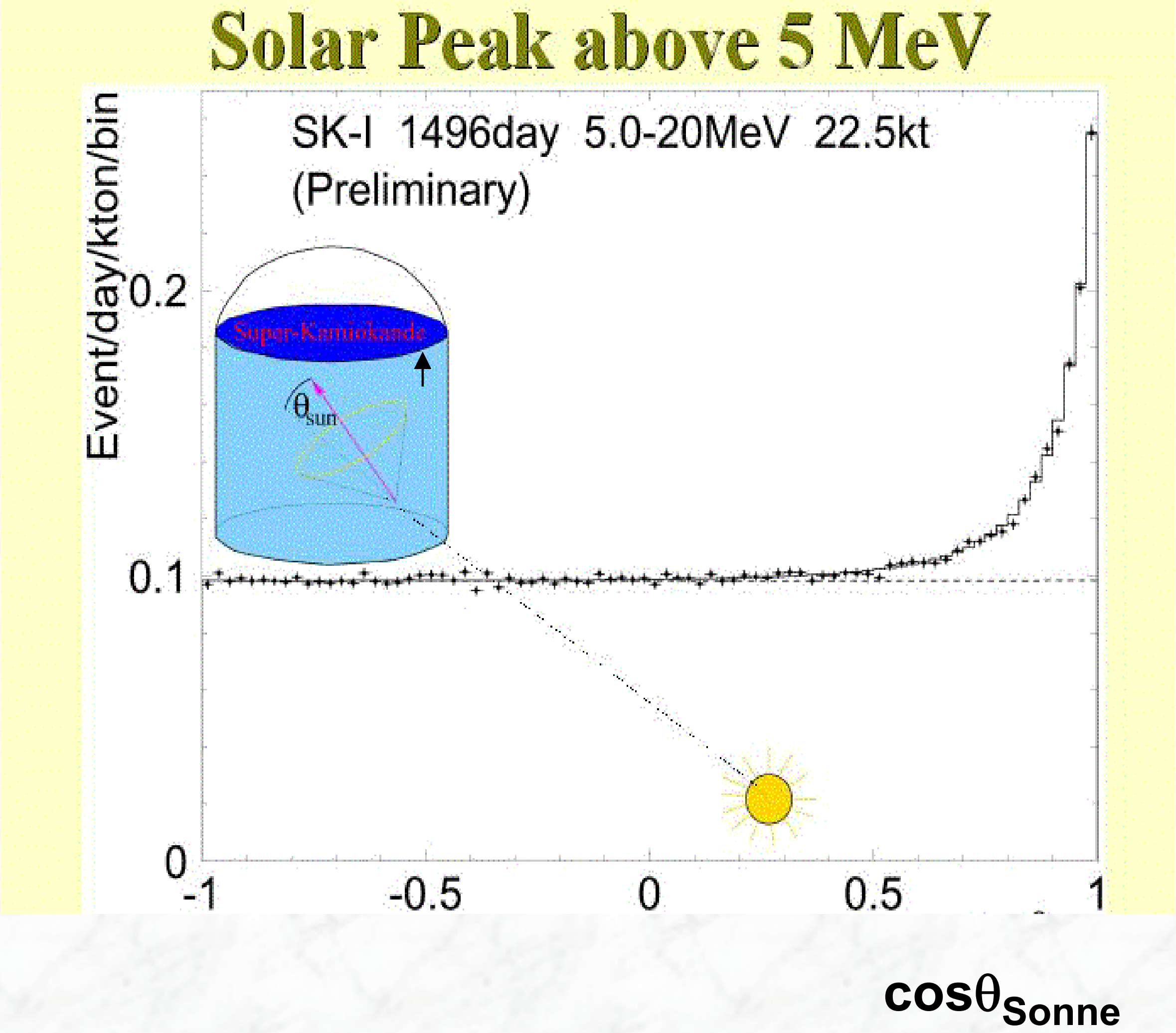


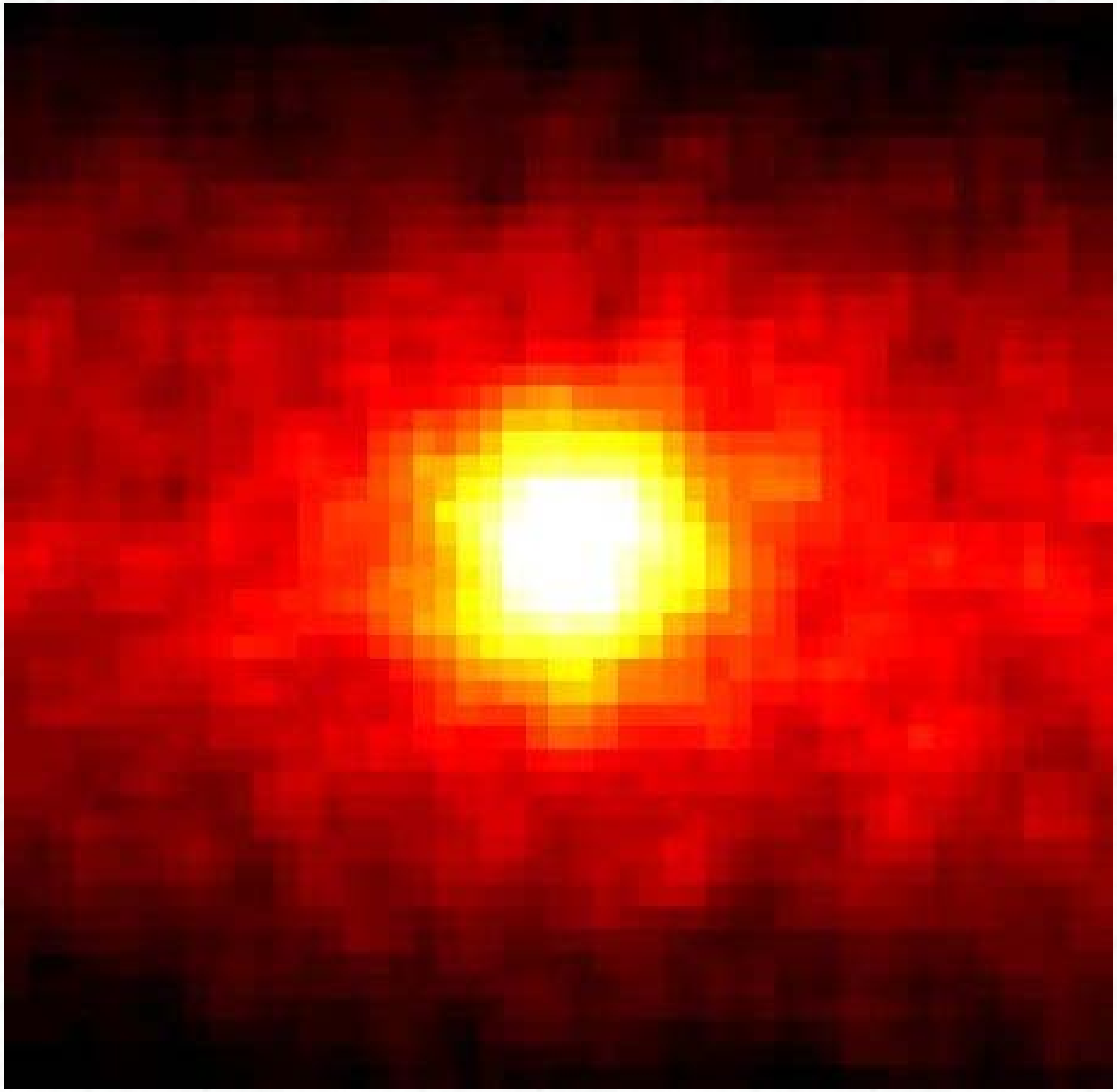
12 MeV
Neutrino
von der Sonne
im SK-Detektor



Bestätigung des solaren Ursprungs der nachgewiesenen Neutrinos:

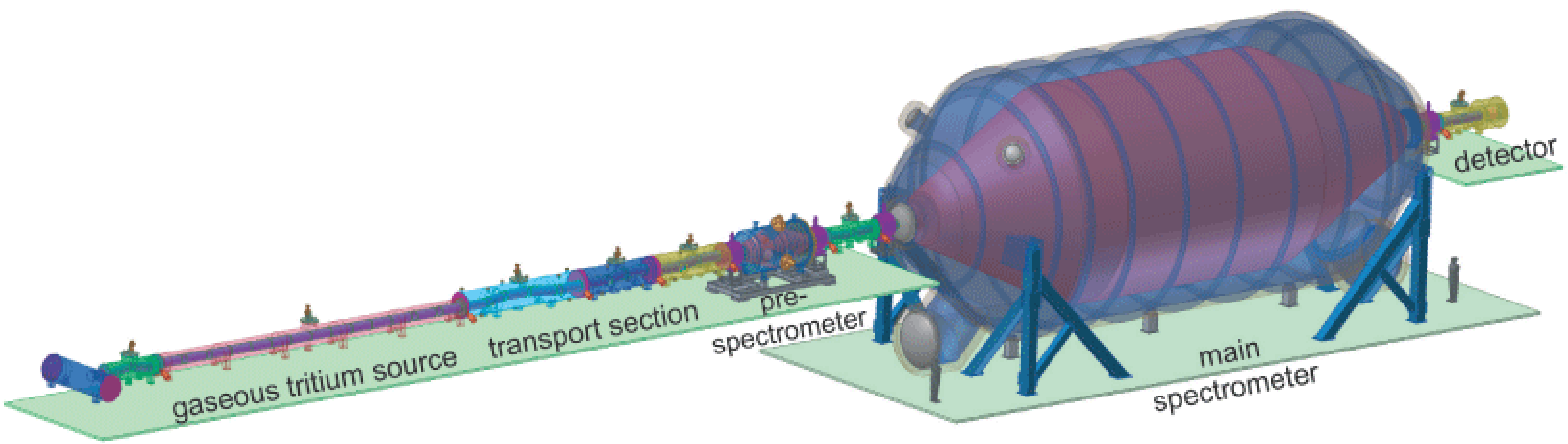
Winkelkorrelation zwischen der Neutrino-Richtung und der Richtung des gestreuten Elektrons

The sun in the light of neutrinos (“viziualized” by the Super-Kamiokande experiment)



KATRIN: Karlsruhe Tritium Neutrino Experiment

Direct neutrino mass measurment in the KATRIN-Experiment
via end-point of the electron energy spectrum from tritium β decay

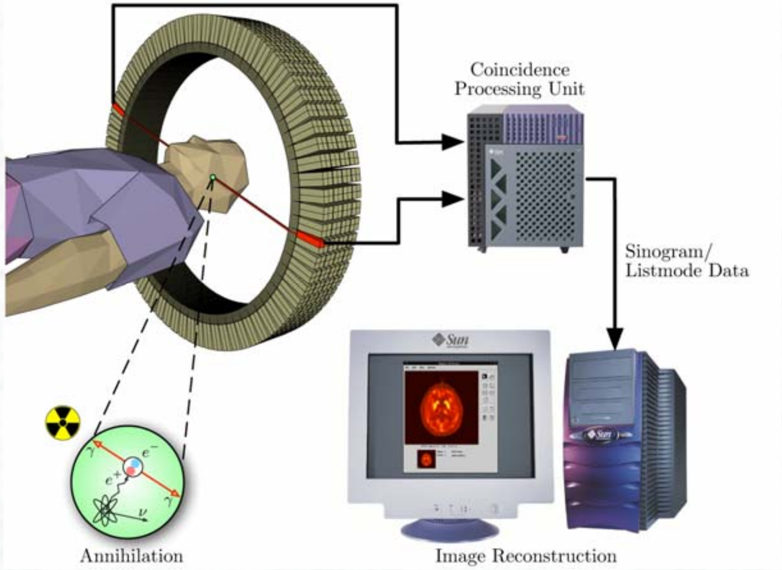


(iv) Anwendungen in der Medizin

- Röntgenuntersuchungen (γ-Strahlen, Photoplatten, mittlerweile digitales Röntgen)

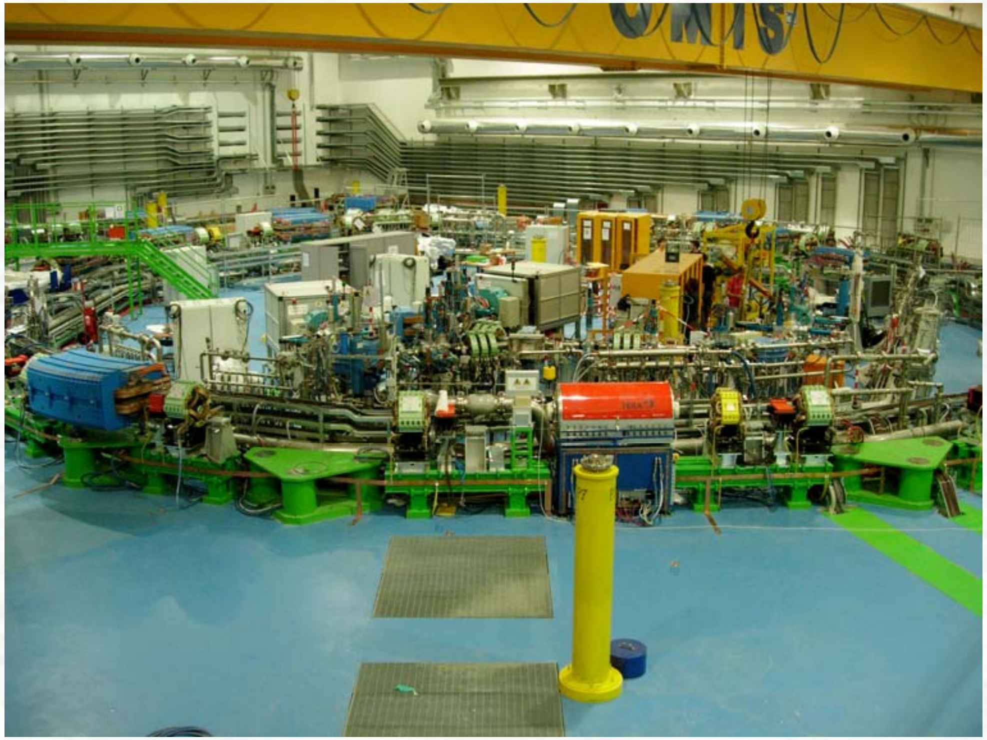
- Nuklearmedizin (Nachweis von γ-Strahlung, z.B. nach Anreicherung von entsprechenden radioaktiven Isotopen in Organen (z.B. Schilddrüse)

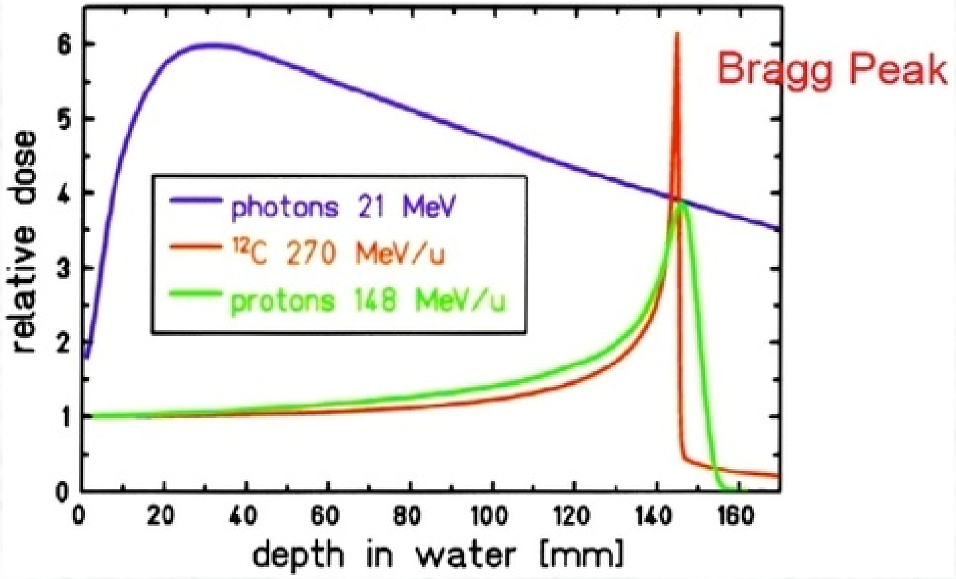
- Positronen-Emissions-Tomographie
  (Bildgebendes Verfahren, Sichtbarmachung der Verteilung von radioaktiven Substanzen (Radiopharmaka, β^+-Strahler) im Organismus über die Vernichtungsreaktion $e^+e^- \rightarrow \gamma\,\gamma$
  → Rückschüsse auf biochemische und physiologische Reaktionen



- Tumortherapie mit Hadronen (π+ oder p) oder Ionen

Energiedeposition am Ort des Tumors;
Erfordert Beschleuniger, die Strahlen geeigneter Energie zur Verfügung stellen

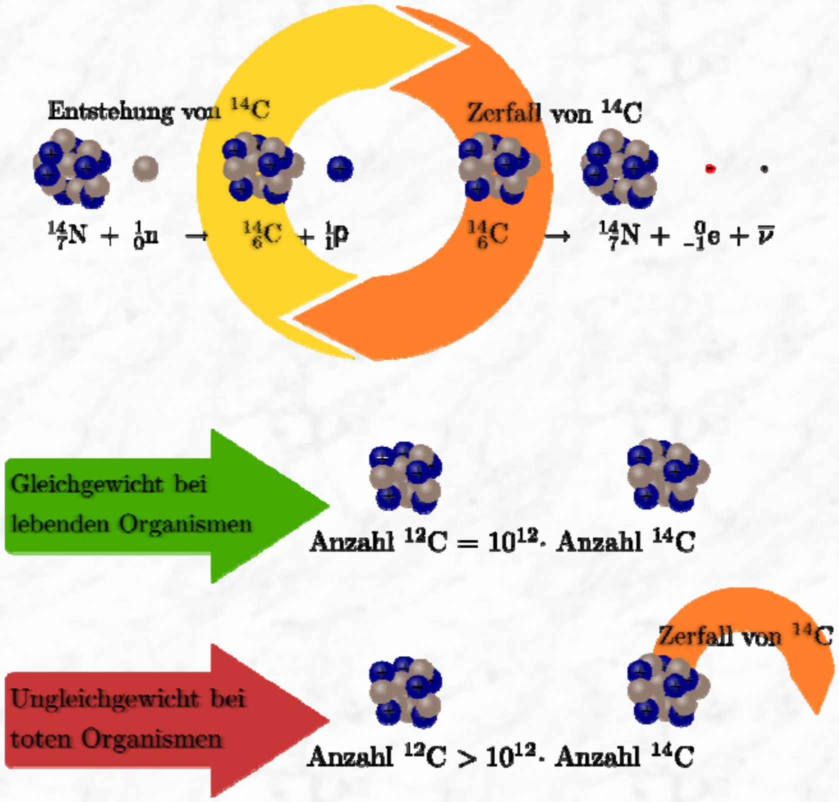


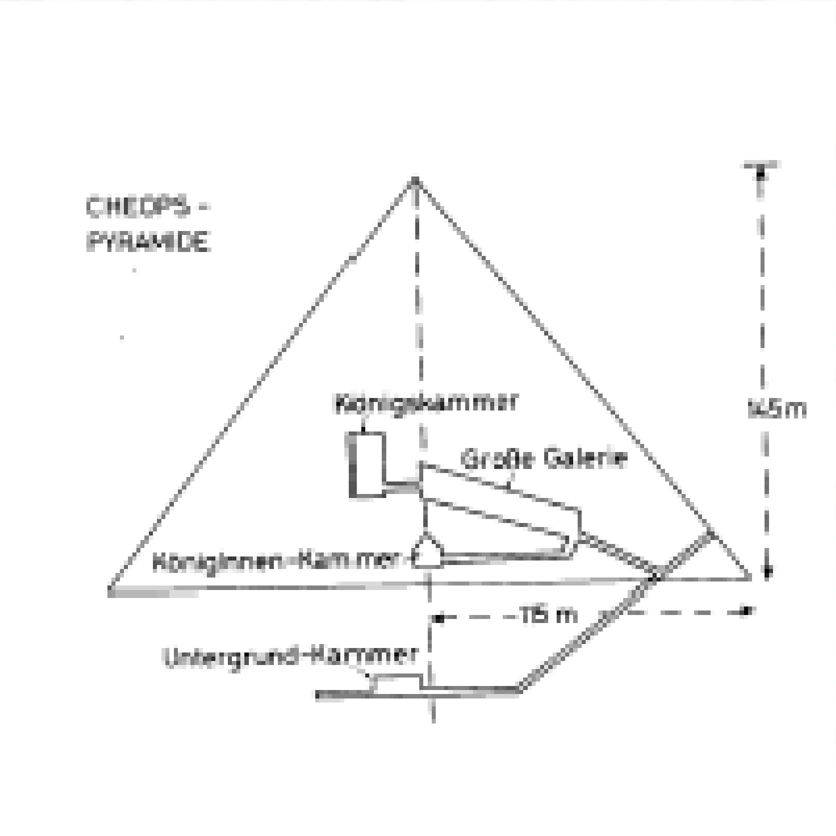


(v) Archäologie

- Altersbestimmung über die C^{14}-Methode

- „Röntgen“ der Pyramiden im „Lichte kosmischer Myonen“





(vi) Umweltphysik

- Vermessung natürlicher und künstlicher Radioaktvität oder Strahlenbelastung

1.2 Wichtige Messgrößen

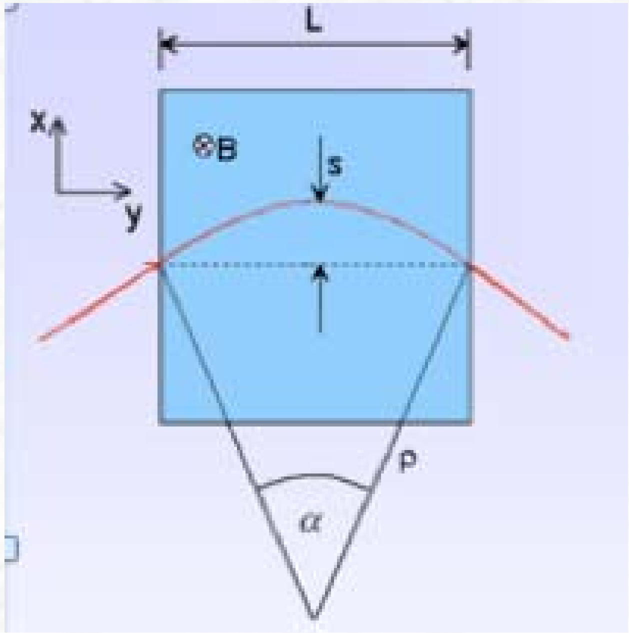
- Impuls von Teilchen:

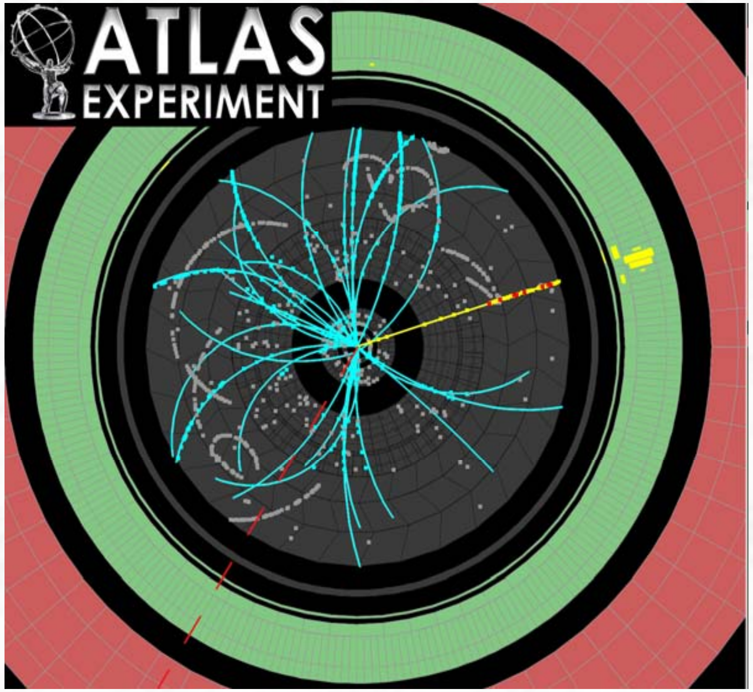
Vermessung der Bahnkurve elektrisch geladener Teilchen in einem bekannten Magnetfeld

Lorentzkraft: $F = q\,(v \times B)$

Spezialfall: homogenes Magnetfeld → Helix-Bahn
Ortsinformation (Bahnkurve) → Krümmungsradius ρ

→ Impuls $p = 0.3\,B\,\rho$
(Einheiten: p in GeV/c, B in Tesla und ρ in m)





•Energie:

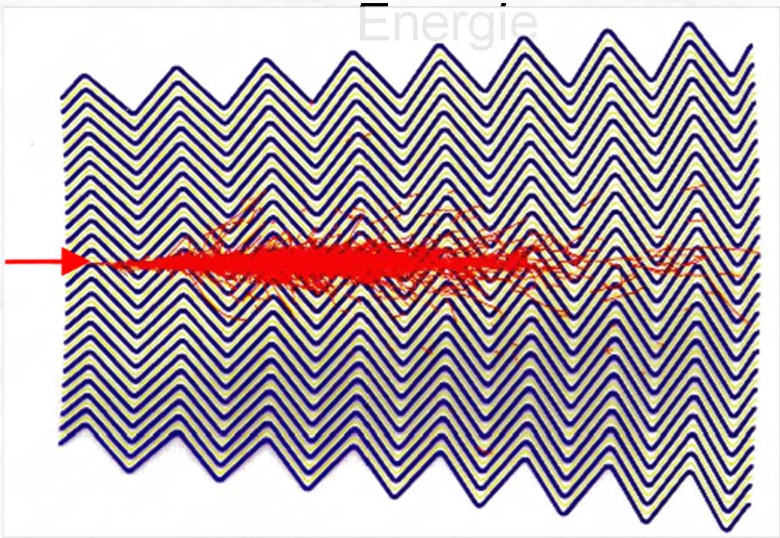
Deposition der totalen Energie in einem sensitiven (Detektormedium)

z.B. Szintillator, Halbleiter (Ge), flüssiges Argon, ...

Energie → Wechselwirkung des Teilchens mit
dem Medium (vollständige Absorption des Teilchens)
Anregungsenergie eines Mediums → messbares Signal

Physikalischer Prozess → z.B. Licht,
(Ionisation u. Anregung, ..) Ionisationsladung

Energie ~ $\text{Signal}_{\text{Detektor}}$



•Identität der Teilchen

Die Identität der Teilchen ist durch ihre Masse (und Ladung) eindeutig bestimmt

In der Elementarteilchenphysik müssen aufgrund der hohen Impulse / Energien relativistische Energie-Impulsbeziehungen benutzt werden:
(h = c = 1)

$$\Rightarrow m = \sqrt{E^2 - p^2}$$

$$\beta = \frac{v}{c} = \frac{p}{E} = \frac{1}{\sqrt{1 + m^2/p^2}}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{m} = \sqrt{1 + p^2/m^2}$$

$$\Rightarrow m = \sqrt{E^2 - p^2}$$

$$\beta = \frac{v}{c} = \frac{p}{E} = \frac{1}{\sqrt{1 + m^2/p^2}}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{m} = \sqrt{1 + p^2/m^2}$$

Identifizierung / Massenbestimmung ist möglich durch:
-Messung zweier Größen, z.B. Impuls und Geschwindigkeit β
Impuls und γ-Faktor

Benötigt werden physikalische Prozesse, die sensitiv auf β und γ sind und Detektoren, die diese Signaturen nachweisen können.
(Flugzeitmessung, Cherenkov- und Übergangsstrahlungssignatur)

-Kombination der Signaturen aus verschiedenen Detektoren
→ komplexe Detektorsysteme (z.B. Spurdetektor und Kalorimeter)

- Zeitmessung:

Für viele Physikalische Prozesse ist eine direkte Zeitmessung erforderlich

Zeitauflösungen: ns → ps

Schnelle Signale (Szintillatoren, Halbleiterzähler) und schnelle Elektronik erforderlich !

- Lebensdauer von Teilchen

Hauptanwendung:

- Messung der Lebensdauer von Hadronen mit schweren Quarks z.B. B-Hadronen; Typische B-Meson Lebensdauer $\tau \sim 1.5$ ps

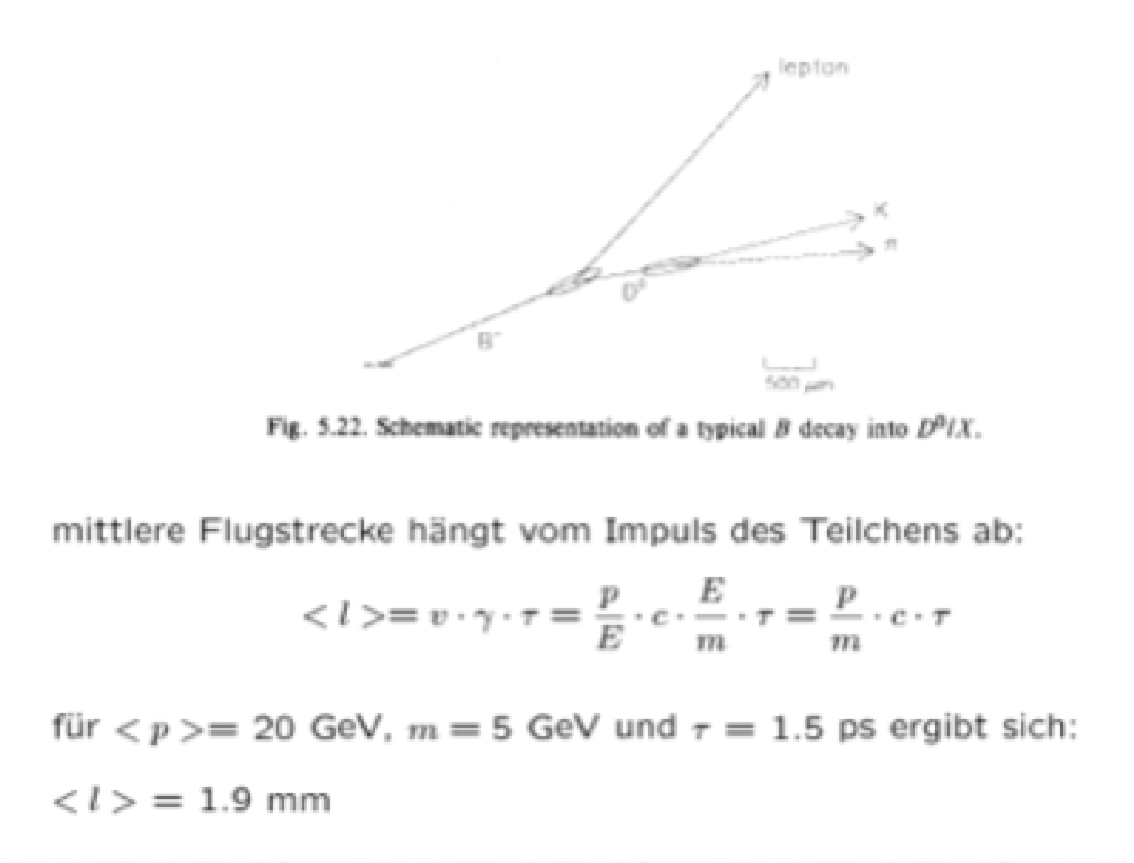


Fig. 5.22. Schematic representation of a typical B decay into $D^0 l X$.

mittlere Flugstrecke hängt vom Impuls des Teilchens ab:

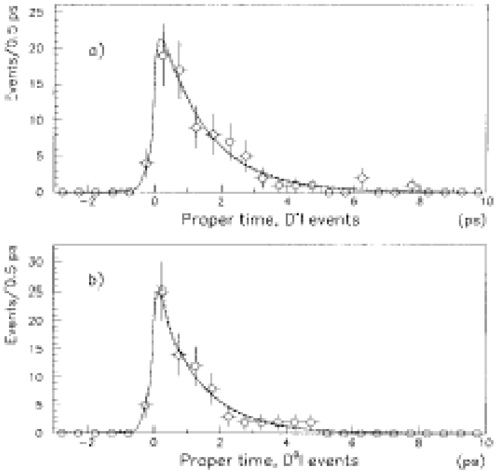
$$< l >= v \cdot \gamma \cdot \tau = \frac{p}{E} \cdot c \cdot \frac{E}{m} \cdot \tau = \frac{p}{m} \cdot c \cdot \tau$$

für $< p >= 20$ GeV, $m = 5$ GeV und $\tau = 1.5$ ps ergibt sich:

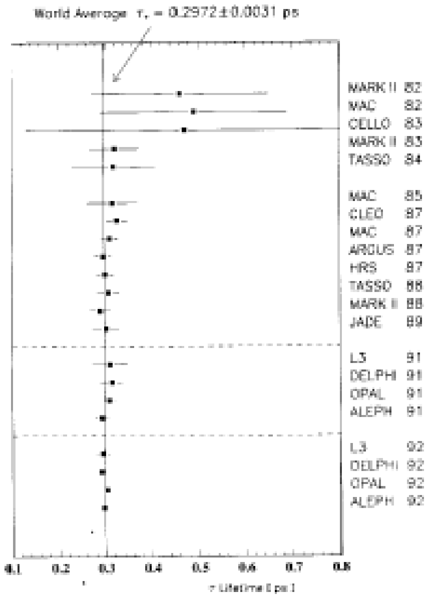
$< l > = 1.9$ mm

→ Einsatz von Silizium Streifen- und Pixeldetetoren erforderlich

a) gemessene Lebensdauerverteilung in $D - l$ Ereignissen (ALEPH Kollaboration)



b)Messungen der τ-Lepton Lebensdauer



Signifikante Verbesserung durch neue Detektortechnologie (Siliziumstreifen-Vertexdetektoren)

1.4: α and β Sources (with applications in detector physics)

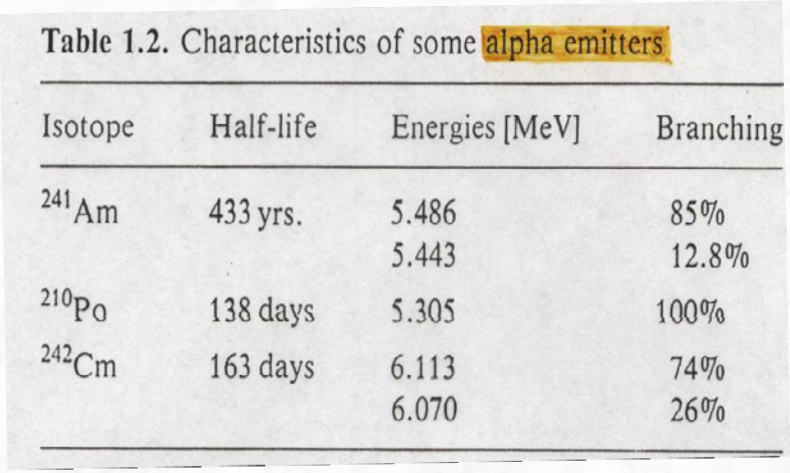


Table 1.2. Characteristics of some alpha emitters

Isotope	Half-life	Energies [MeV]	Branching
^{241}Am	433 yrs.	5.486	85%
		5.443	12.8%
^{210}Po	138 days	5.305	100%
^{242}Cm	163 days	6.113	74%
		6.070	26%

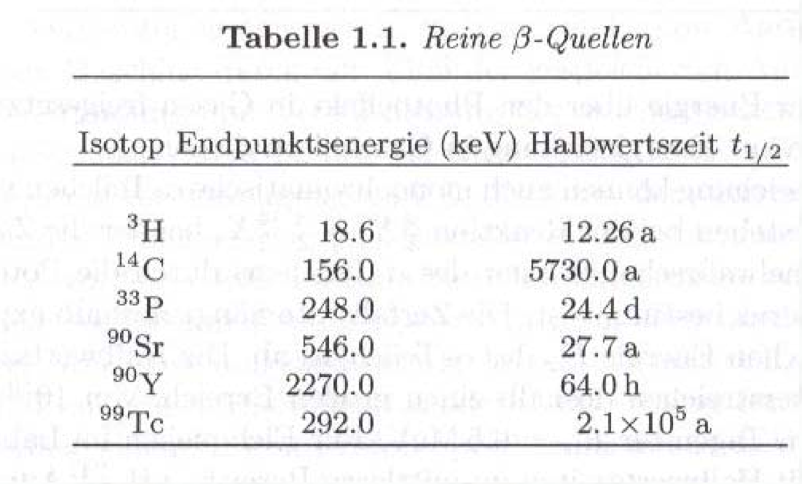
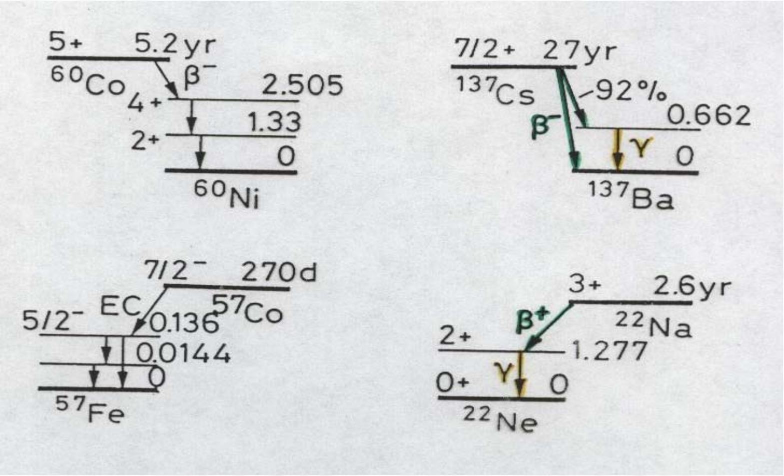


Tabelle 1.1. *Reine β-Quellen*

Isotop	Endpunktsenergie (keV)	Halbwertszeit $t_{1/2}$
^{3}H	18.6	12.26 a
^{14}C	156.0	5730.0 a
^{33}P	248.0	24.4 d
^{90}Sr	546.0	27.7 a
^{90}Y	2270.0	64.0 h
^{99}Tc	292.0	2.1×10^5 a



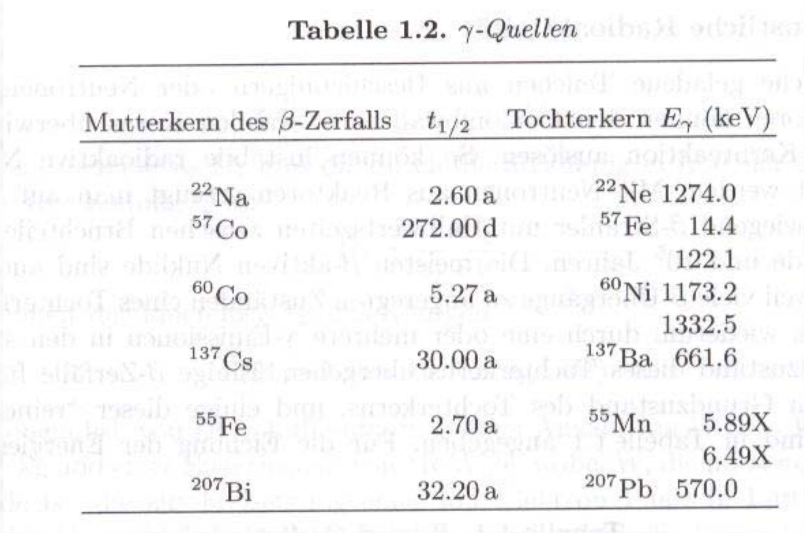
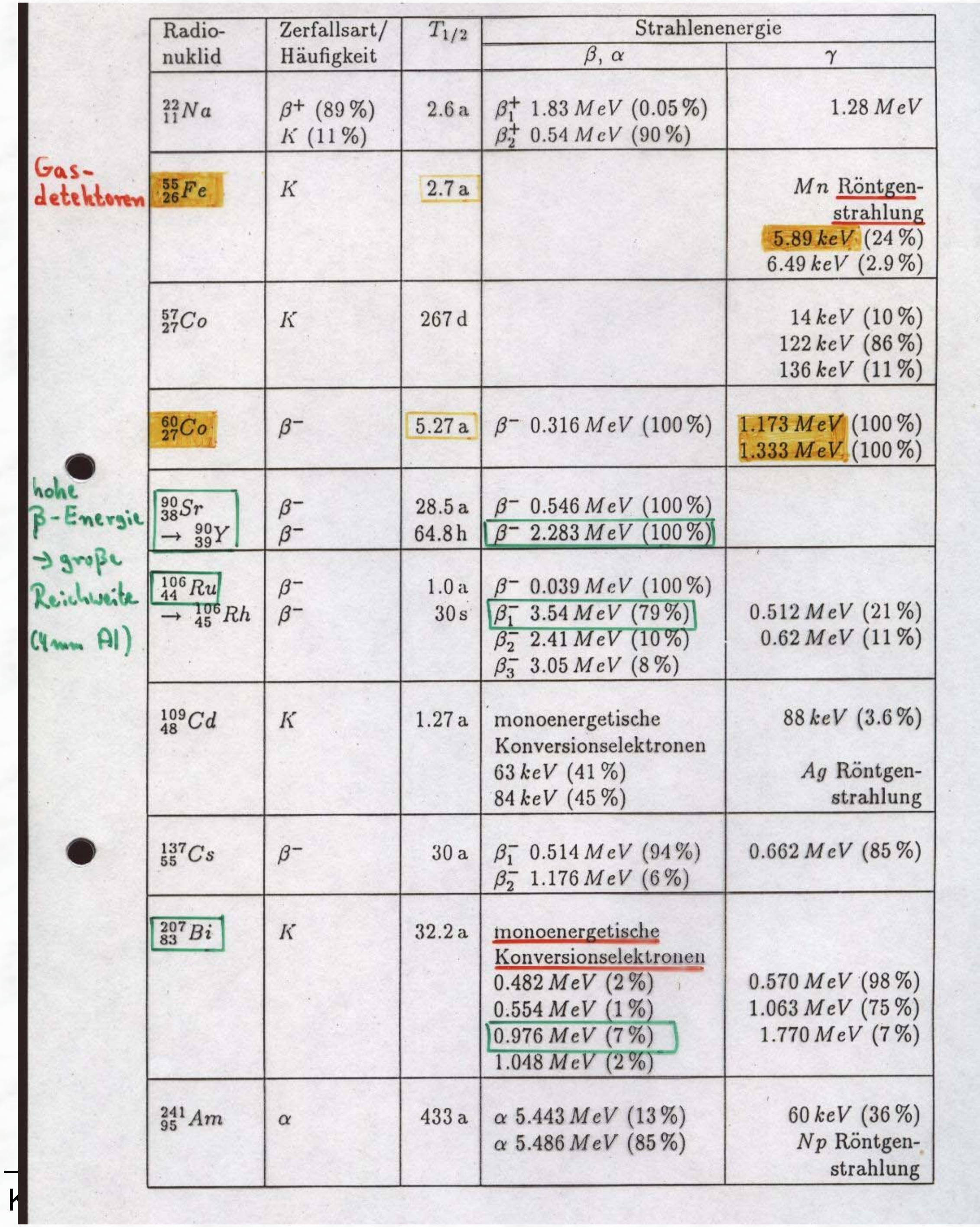


Tabelle 1.2. *γ-Quellen*

Mutterkern des β-Zerfalls	$t_{1/2}$	Tochterkern	E_γ (keV)
^{22}Na	2.60 a	^{22}Ne	1274.0
^{57}Co	272.00 d	^{57}Fe	14.4 122.1
^{60}Co	5.27 a	^{60}Ni	1173.2 1332.5
^{137}Cs	30.00 a	^{137}Ba	661.6
^{55}Fe	2.70 a	^{55}Mn	5.89X 6.49X
^{207}Bi	32.20 a	^{207}Pb	570.0

Commonly used isotopes for tests of particle detectors



Radio-nuklid	Zerfallsart/Häufigkeit	$T_{1/2}$	Strahlenenergie	
			β, α	γ
$^{22}_{11}Na$	β^+ (89 %) K (11 %)	2.6 a	β_1^+ 1.83 MeV (0.05 %) β_2^+ 0.54 MeV (90 %)	1.28 MeV
$^{55}_{26}Fe$	K	2.7 a		Mn Röntgenstrahlung 5.89 keV (24 %) 6.49 keV (2.9 %)
$^{57}_{27}Co$	K	267 d		14 keV (10 %) 122 keV (86 %) 136 keV (11 %)
$^{60}_{27}Co$	β^-	5.27 a	β^- 0.316 MeV (100 %)	1.173 MeV (100 %) 1.333 MeV (100 %)
$^{90}_{38}Sr$ $\rightarrow$ $^{90}_{39}Y$	β^- β^-	28.5 a 64.8 h	β^- 0.546 MeV (100 %) β^- 2.283 MeV (100 %)	
$^{106}_{44}Ru$ $\rightarrow$ $^{106}_{45}Rh$	β^- β^-	1.0 a 30 s	β^- 0.039 MeV (100 %) β_1^- 3.54 MeV (79 %) β_2^- 2.41 MeV (10 %) β_3^- 3.05 MeV (8 %)	0.512 MeV (21 %) 0.62 MeV (11 %)
$^{109}_{48}Cd$	K	1.27 a	monoenergetische Konversionselektronen 63 keV (41 %) 84 keV (45 %)	88 keV (3.6 %) Ag Röntgenstrahlung
$^{137}_{55}Cs$	β^-	30 a	β_1^- 0.514 MeV (94 %) β_2^- 1.176 MeV (6 %)	0.662 MeV (85 %)
$^{207}_{83}Bi$	K	32.2 a	monoenergetische Konversionselektronen 0.482 MeV (2 %) 0.554 MeV (1 %) 0.976 MeV (7 %) 1.048 MeV (2 %)	0.570 MeV (98 %) 1.063 MeV (75 %) 1.770 MeV (7 %)
$^{241}_{95}Am$	α	433 a	α 5.443 MeV (13 %) α 5.486 MeV (85 %)	60 keV (36 %) Np Röntgenstrahlung

Gas-detektoren

hohe β-Energie
→ große Reichweite
(4mm Al)

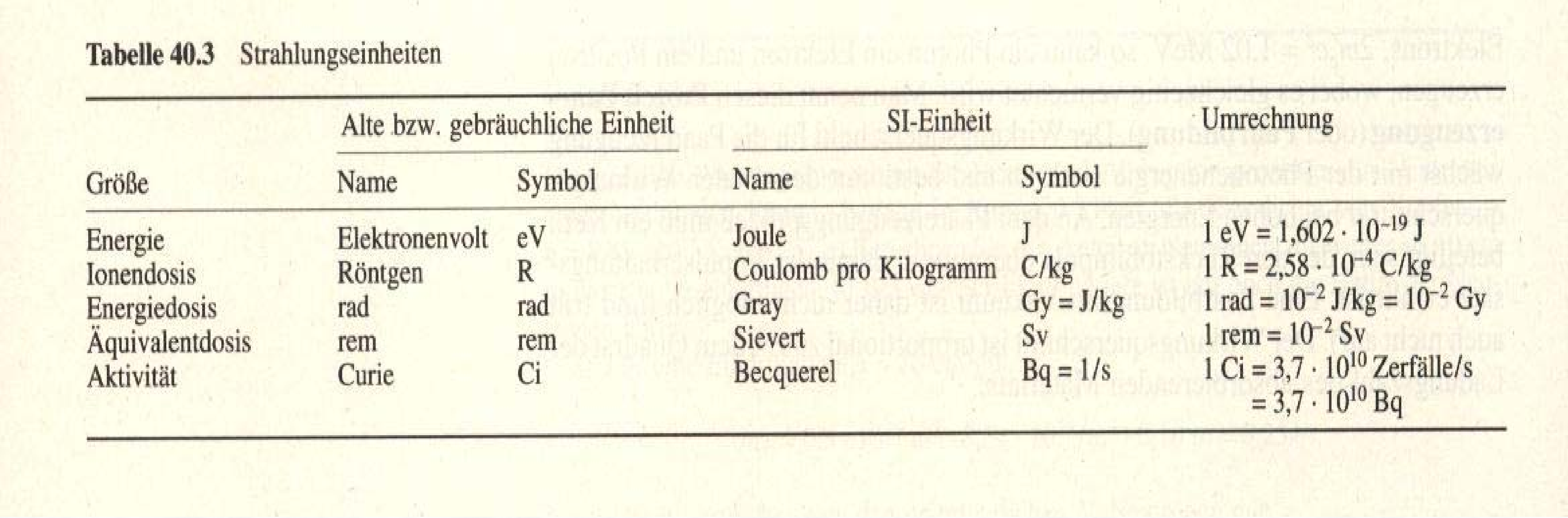
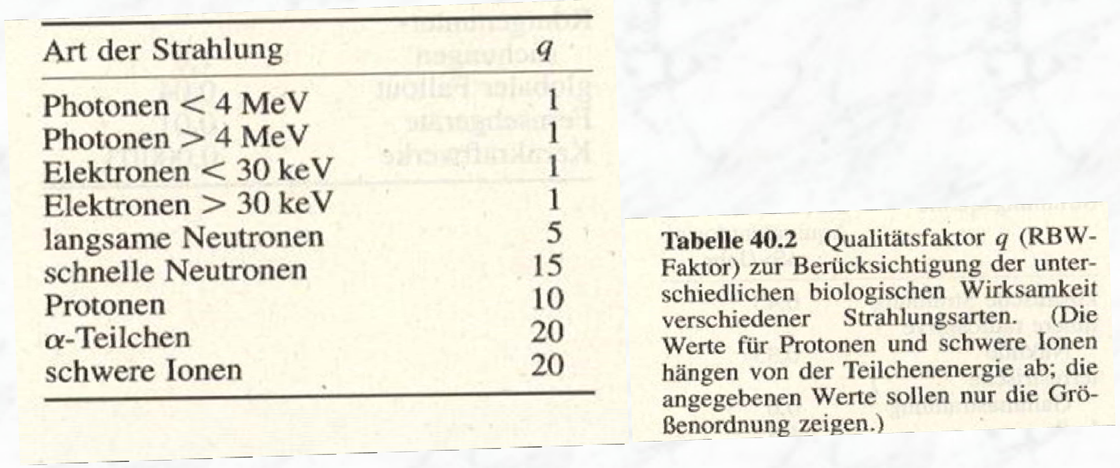


Tabelle 40.3 Strahlungseinheiten

	Alte bzw. gebräuchliche Einheit		SI-Einheit		Umrechnung
Größe	Name	Symbol	Name	Symbol	
Energie	Elektronenvolt	eV	Joule	J	$1\ \mathrm{eV} = 1{,}602 \cdot 10^{-19}\ \mathrm{J}$
Ionendosis	Röntgen	R	Coulomb pro Kilogramm	C/kg	$1\ \mathrm{R} = 2{,}58 \cdot 10^{-4}\ \mathrm{C/kg}$
Energiedosis	rad	rad	Gray	Gy = J/kg	$1\ \mathrm{rad} = 10^{-2}\ \mathrm{J/kg} = 10^{-2}\ \mathrm{Gy}$
Äquivalentdosis	rem	rem	Sievert	Sv	$1\ \mathrm{rem} = 10^{-2}\ \mathrm{Sv}$
Aktivität	Curie	Ci	Becquerel	Bq = 1/s	$1\ \mathrm{Ci} = 3{,}7 \cdot 10^{10}$ Zerfälle/s $= 3{,}7 \cdot 10^{10}\ \mathrm{Bq}$



Art der Strahlung	q
Photonen < 4 MeV	1
Photonen > 4 MeV	1
Elektronen < 30 keV	1
Elektronen > 30 keV	1
langsame Neutronen	5
schnelle Neutronen	15
Protonen	10
α-Teilchen	20
schwere Ionen	20

Tabelle 40.2 Qualitätsfaktor q (RBW-Faktor) zur Berücksichtigung der unterschiedlichen biologischen Wirksamkeit verschiedener Strahlungsarten. (Die Werte für Protonen und schwere Ionen hängen von der Teilchenenergie ab; die angegebenen Werte sollen nur die Größenordnung zeigen.)