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FORSCHUNGSZENTRUM

Particle Detectors

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Content

- Introduction (why? where? how?)
- Working Principle of Detectors
- Scintillating detectors (organic & inorganic)
- Some Examples

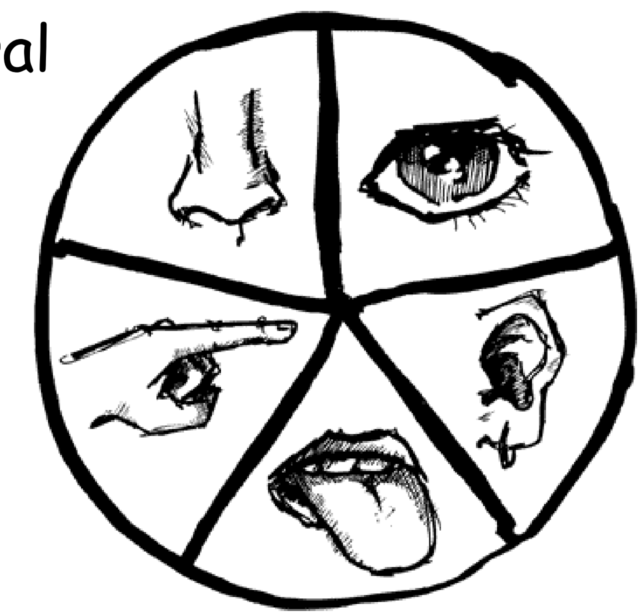
Why?

Why Detectors?

Particles cannot be measured <u>directly</u>!

Charged & Neutral

Smaller than the visible photons



Too Small for the nerves

This we always do :)

Smaller than molecules

Scientific Method

Understanding detectors & its artifacts

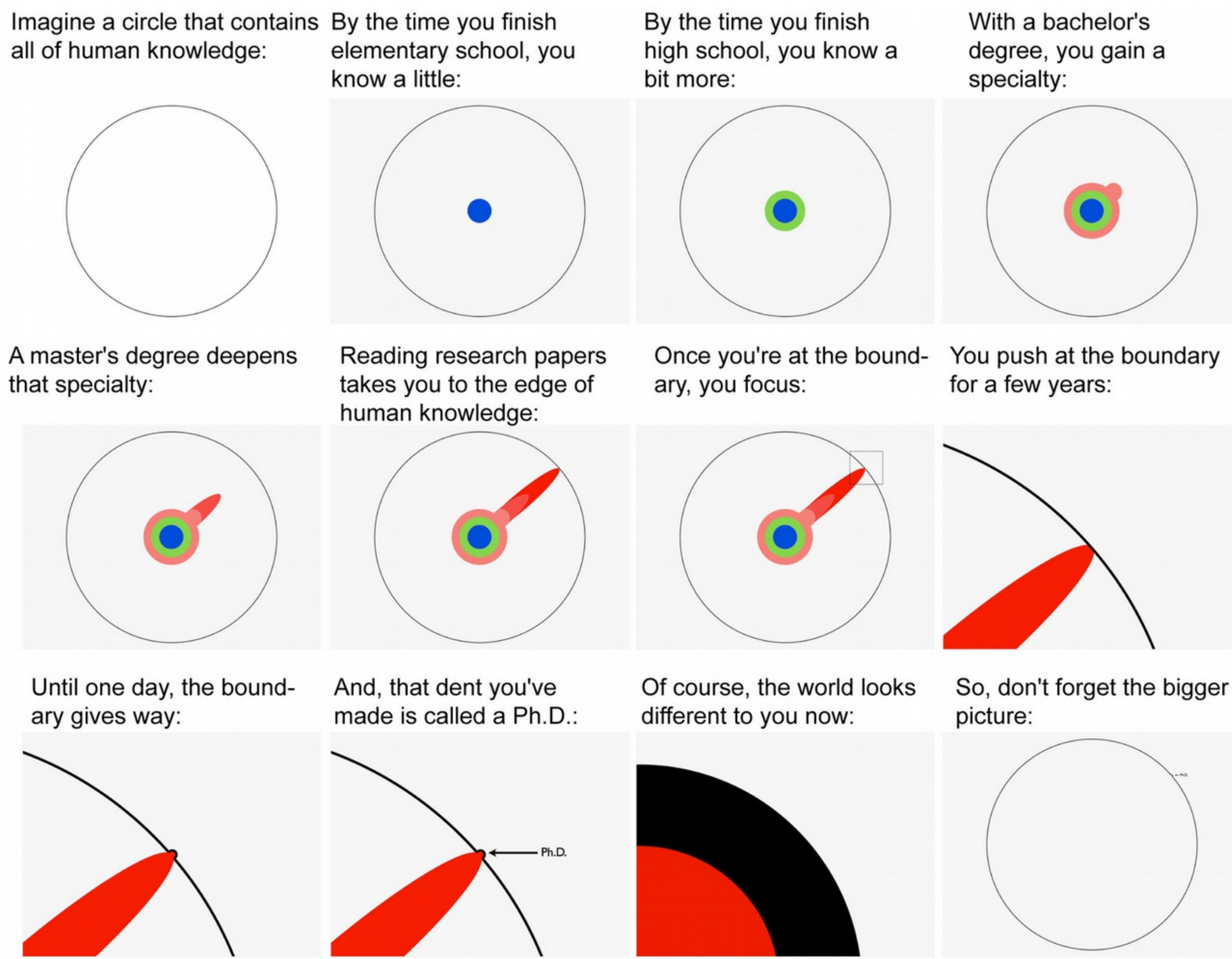
Build new detector

Ph.D. Thesis, Scientific publications

You need a detector

The software. In fact, a part of the detector

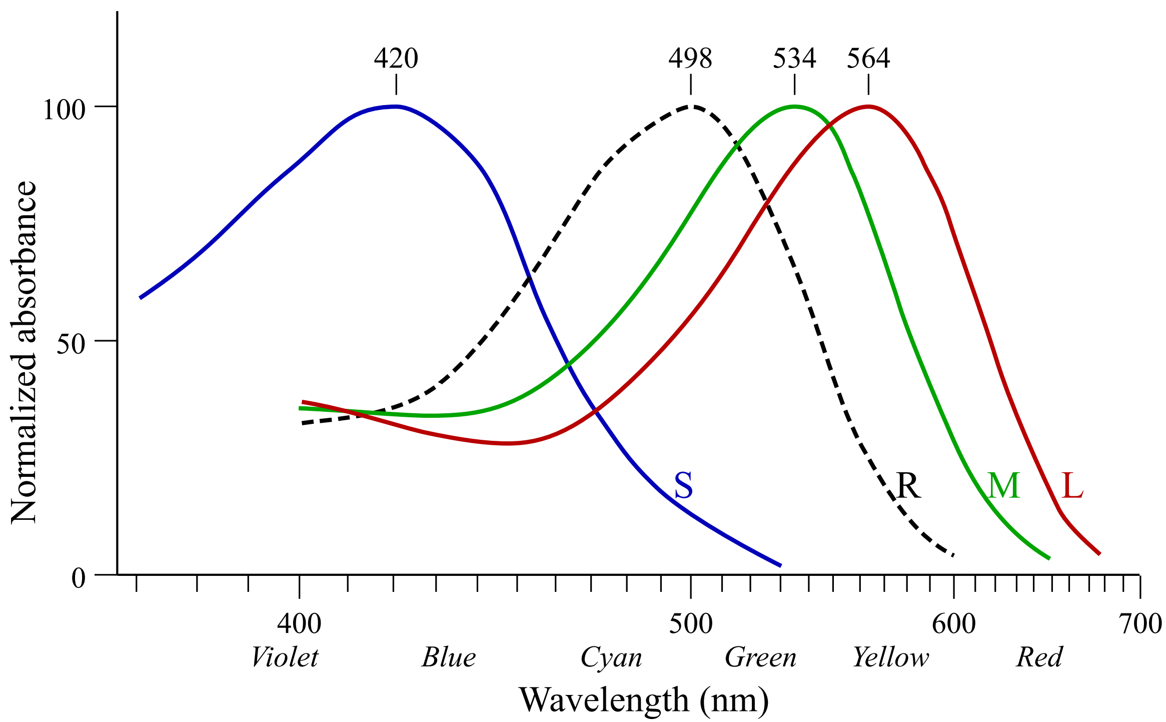
Keep Pushing Boundaries!

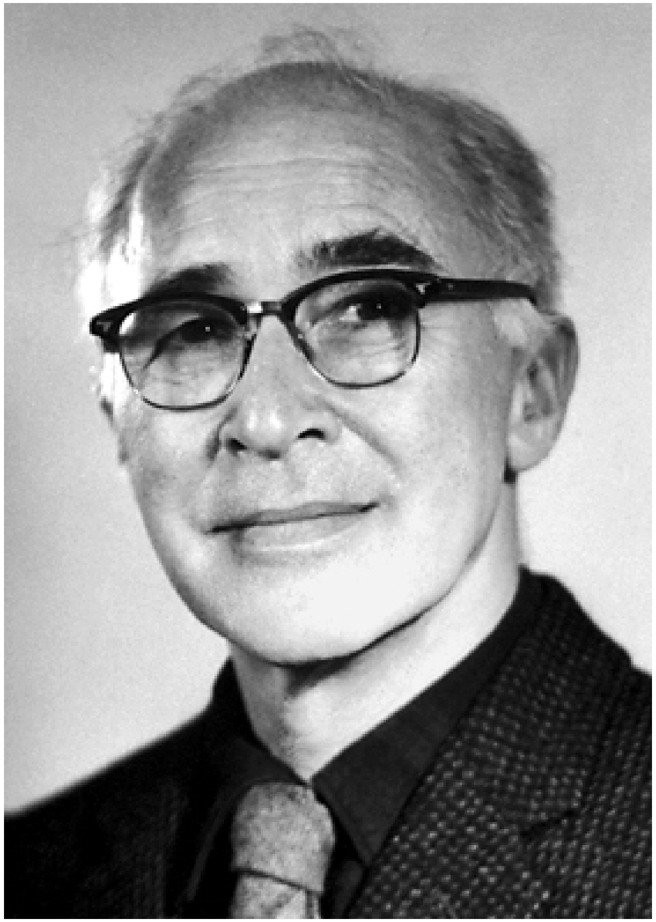


"A physicist is an atom's way of knowing about atoms."

George Wald, Neurobiologist

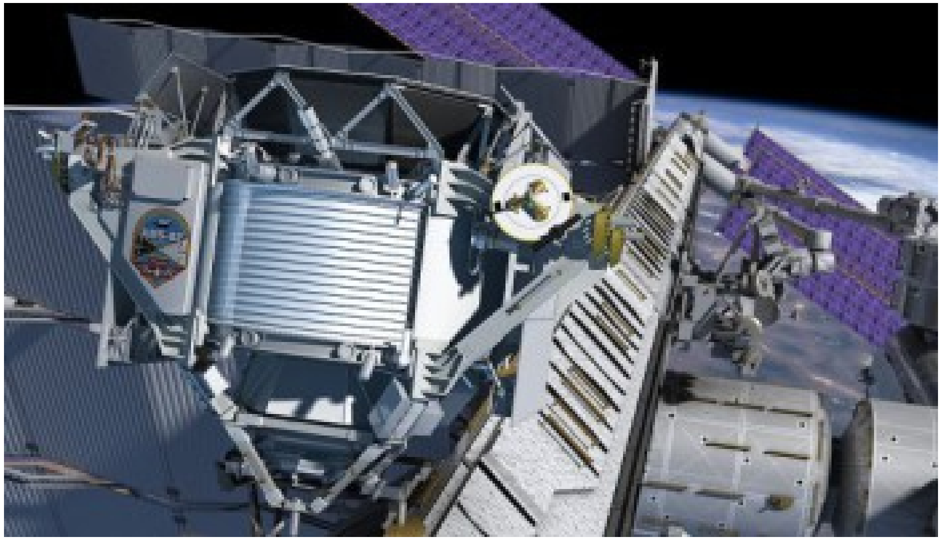
1967 Nobel Prize

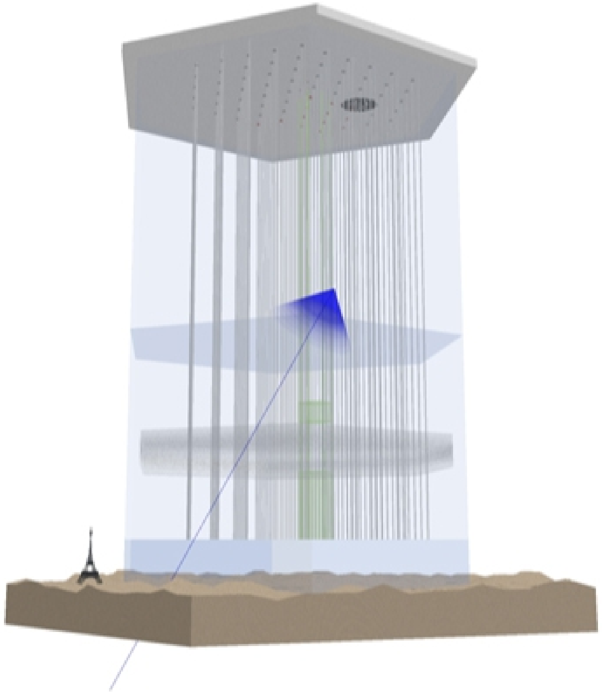


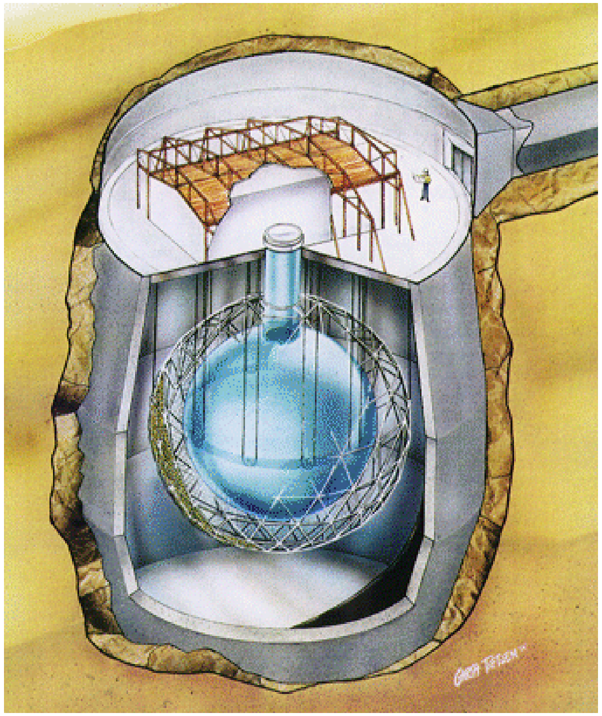


Where?

Where are Detectors on Earth?



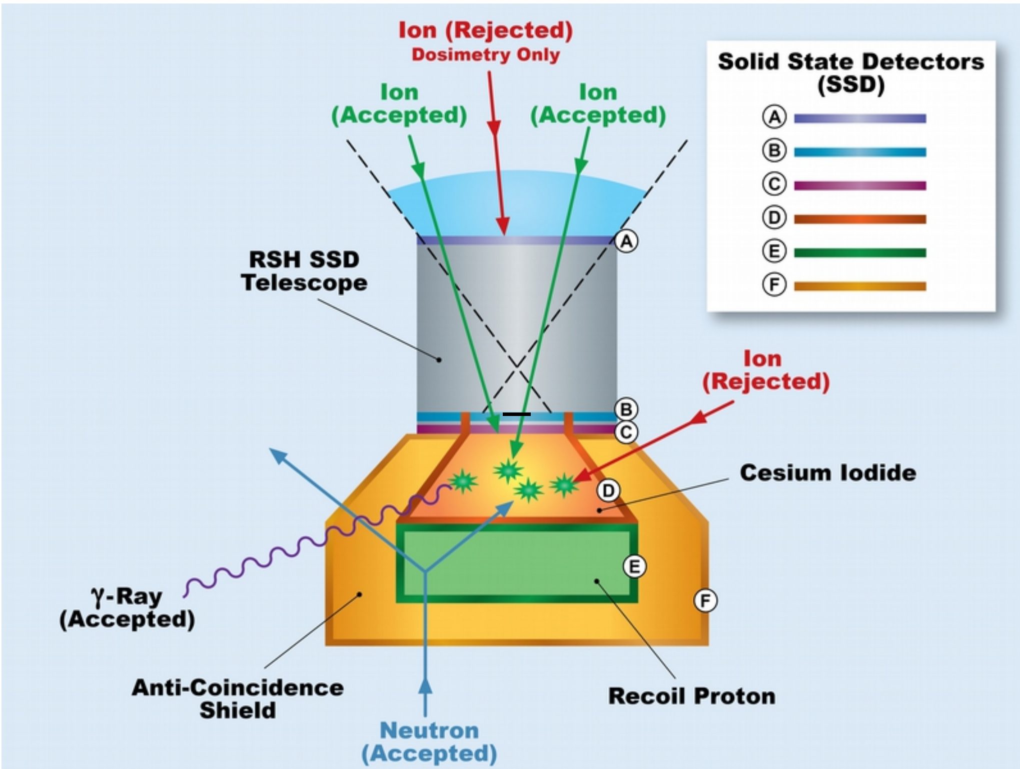


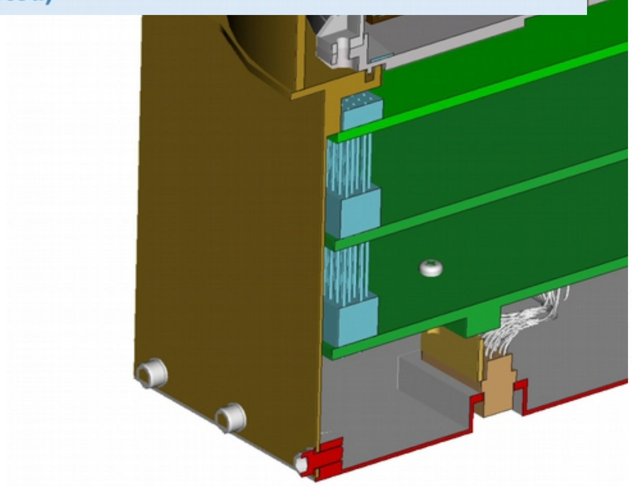


The Radiation Assessment Detector, or RAD

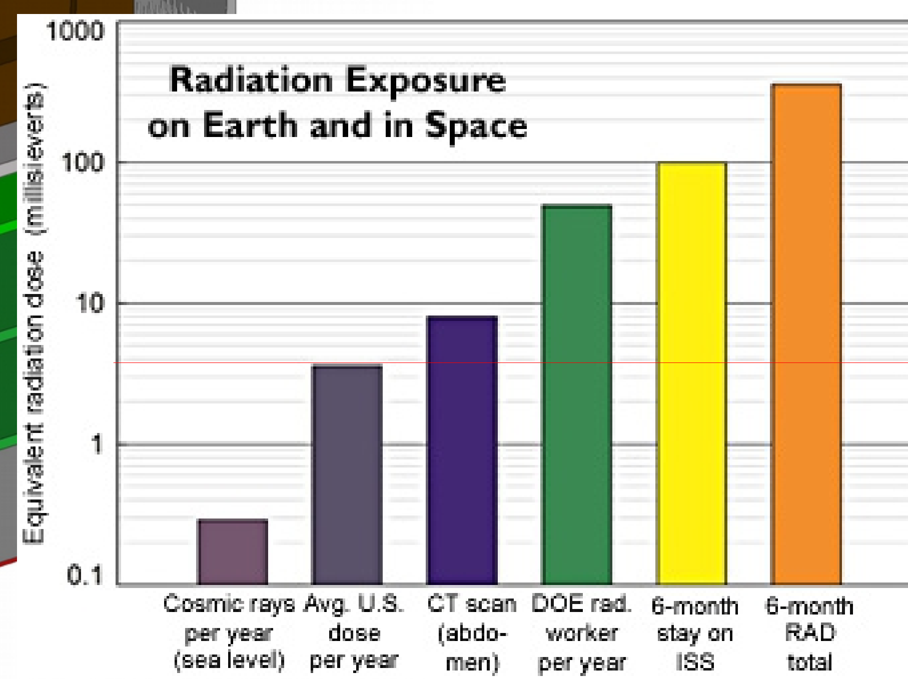
will monitor naturally occurring radiation that can be unhealthful if absorbed by living organisms. It will do so on the surface of Mars, where there has never before been such an instrument, as well as during the trip between Mars and Earth.

Curiosity's Radiation Assessment Detector



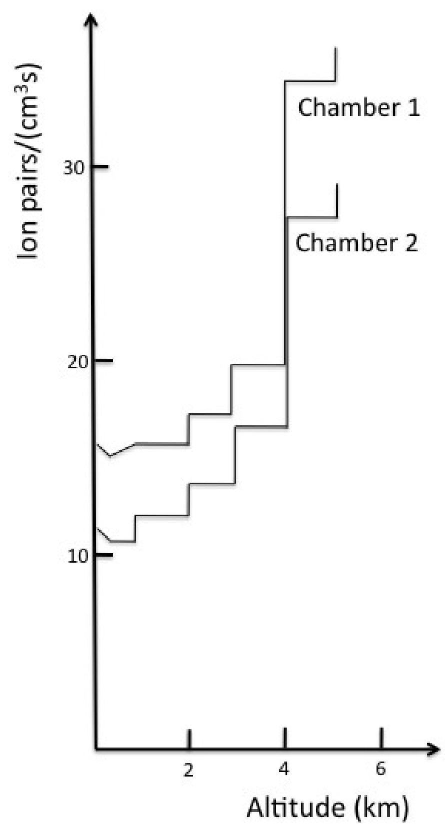


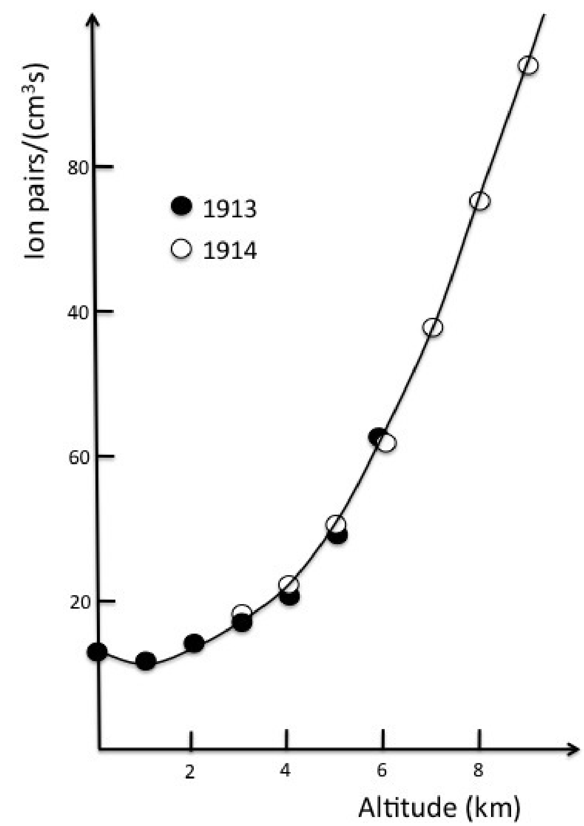
NASA scientists reported that a possible manned mission to Mars may involve a greater radiation risk than previously believed



Exactly 100 Years ago :)

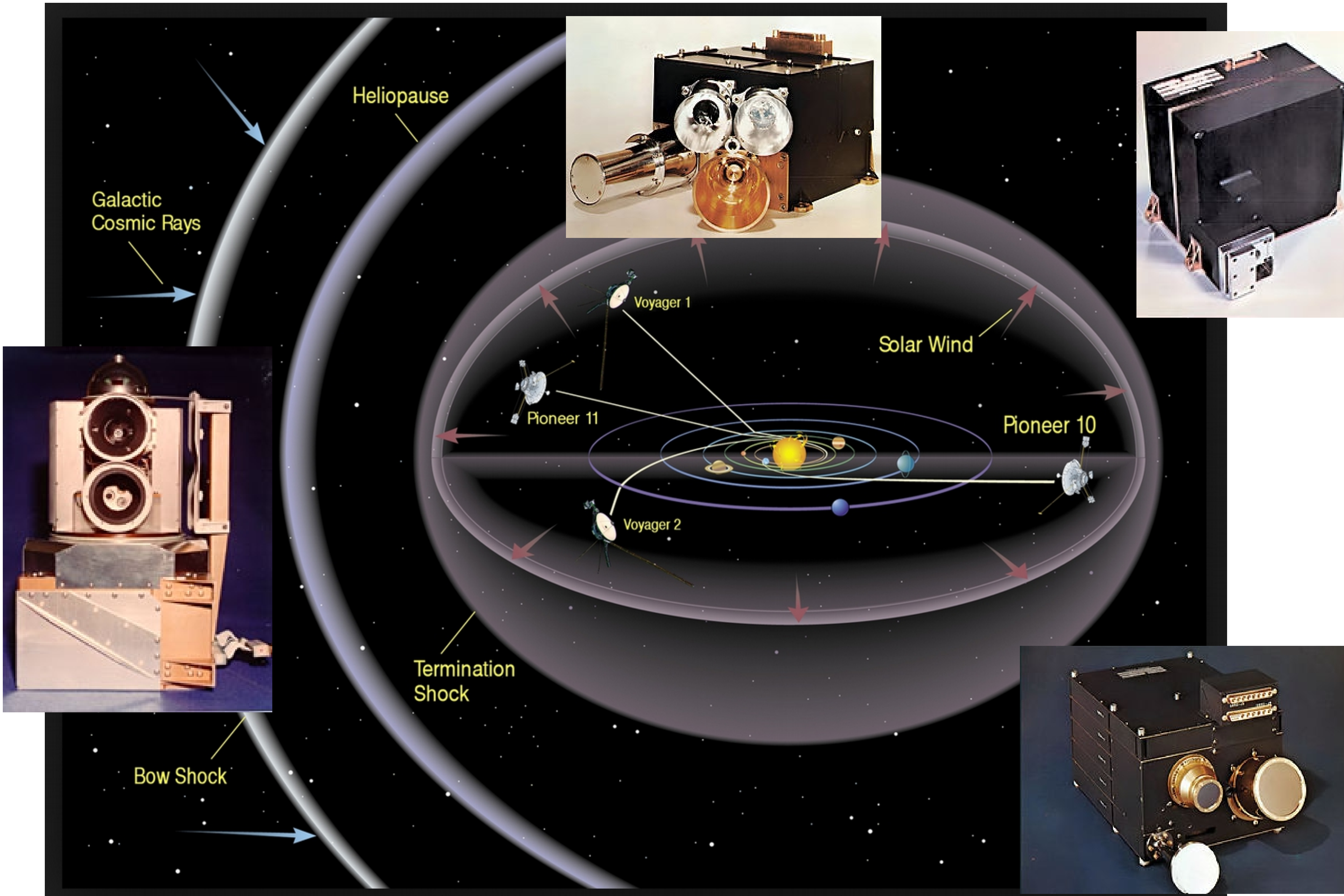
The Hess balloon flight took place on 7 August 1912. By sheer coincidence, exactly 100 years later on 7 August 2012, the Mars Science Laboratory rover used its RAD instrument to begin measuring the radiation levels on another planet for the first time.





Victor Hess received the Nobel Prize in Physics in 1936 for his discovery

Voyager + Pioneer



How & What?

Interaction with Matter

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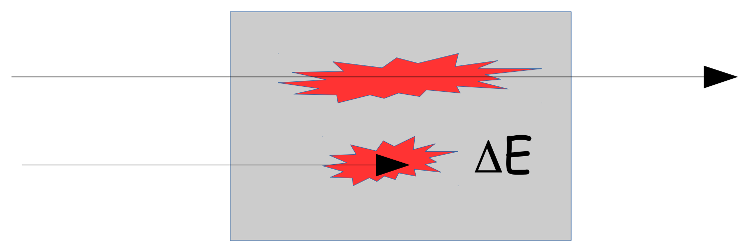
Only the result of an interaction with matter will be observed



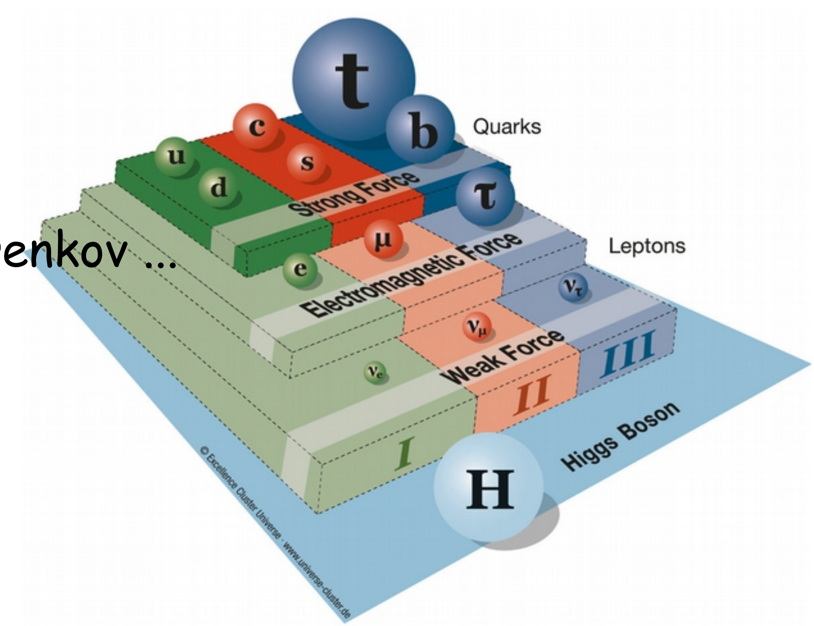
The detection of particles happens

via their ΔE in the material it traverses ...

Charged particles: Ionization, Bremsstrahlung, Cherenkov ...

Photons: EM $\rightarrow$ Photo, Compton, pair production

Hadrons: Strong, EM, Weak interactions



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HEAVY CHARGED PARTICLES - STOPPING POWER II

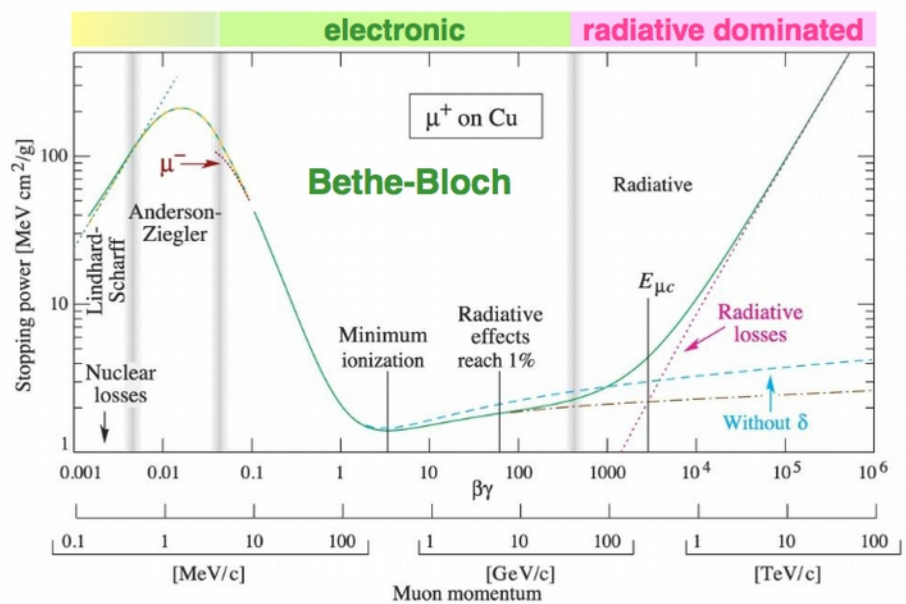
Bethe-Bloch range

$\alpha < \beta < 0.1$: $\beta_{electron}$ neglected

stopping power

$$S = \left(-\frac{dE}{dx}\right) \cdot \frac{1}{\rho}$$

[MeV· cm²/g]



C_0 shell corrections for low energies

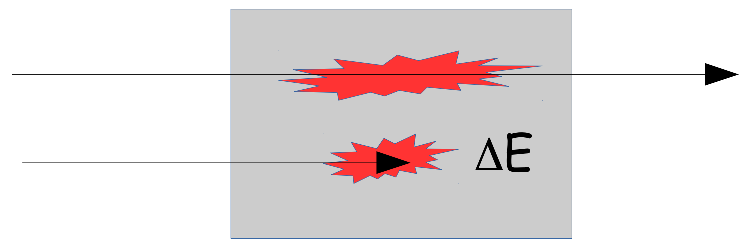
$$S = 4\pi N_A r_e^2 m_e c^2 \frac{Z_{target}}{A} \cdot \frac{z^2_{projectile}}{\beta^2} \cdot \left[\frac{1}{2} ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_e^{max}}{I^2}\right) - \beta^2 - \frac{C_0(\beta^2)}{Z_{target}} - \frac{\delta(\beta\gamma)}{2}\right]$$

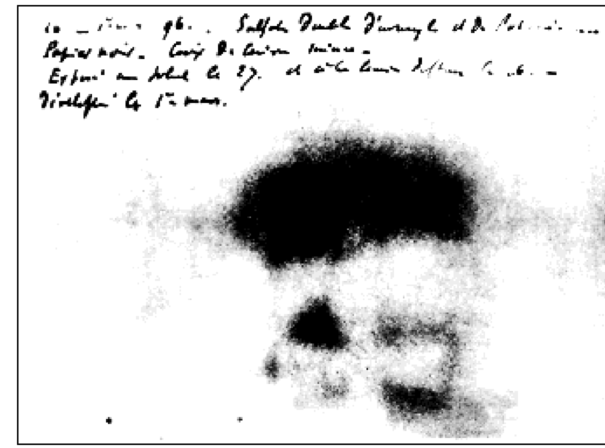
Folie 31

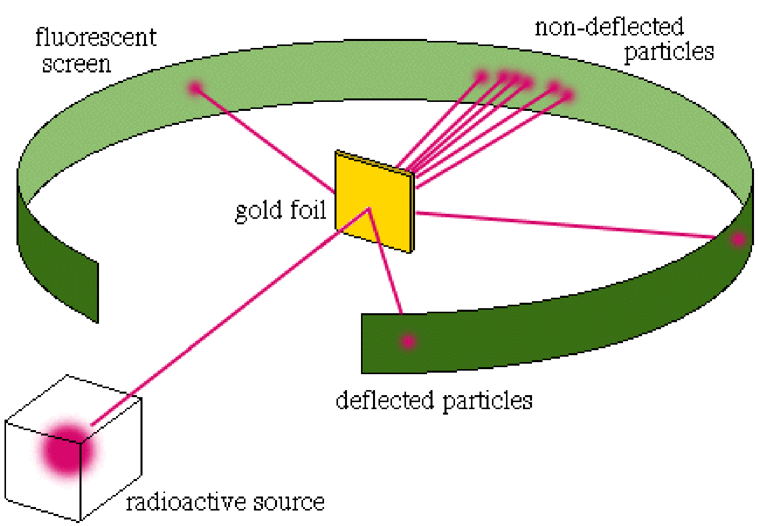
Detection Principle

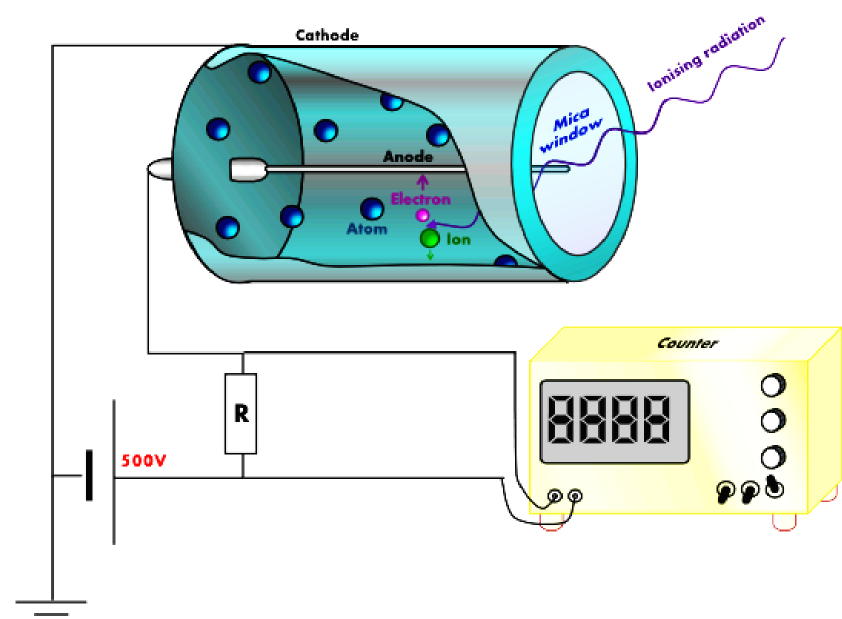
In the end, everything is converted to:

- Optical pictures
  - Visible flush → electric signals
    - Electric signals





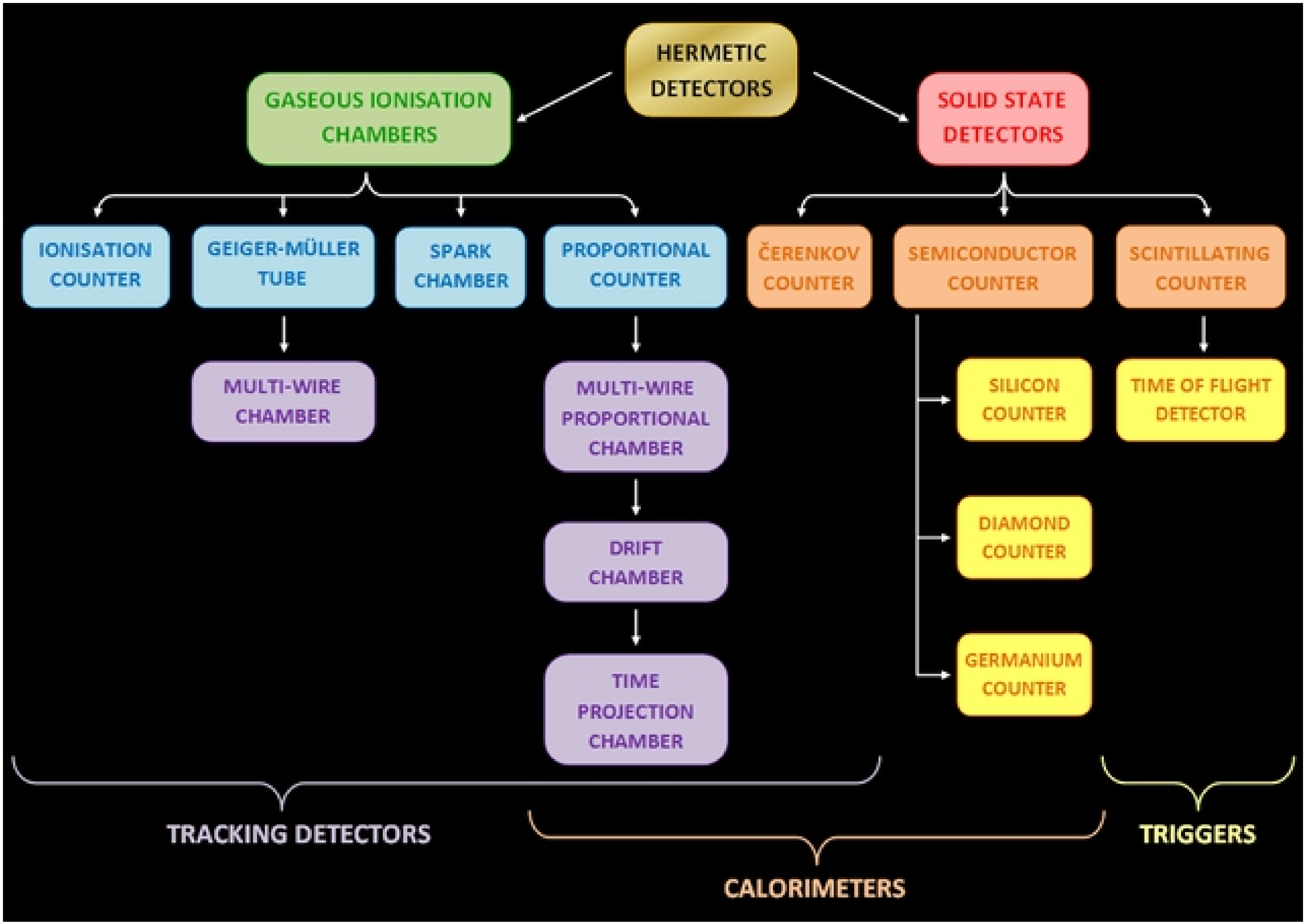




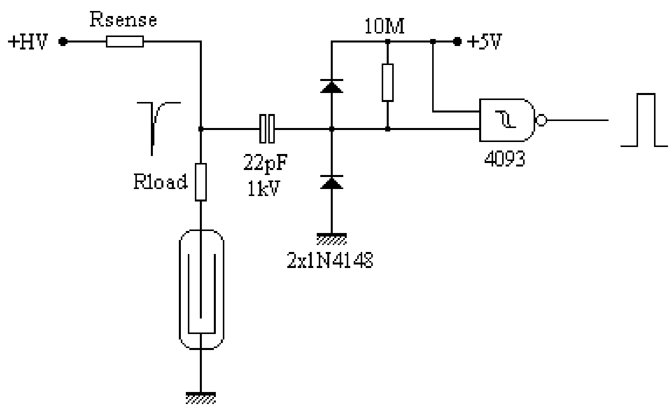
Different Types of Detectors

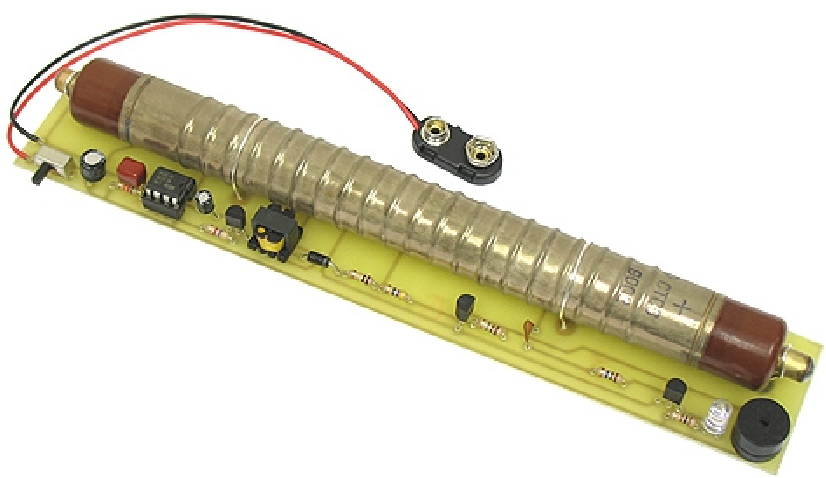
- Ionizing (Gaseous & Semiconductor)
- Scintillating (Organic & Inorganic)
- Cherenkov (VETO, RICH & DIRC)

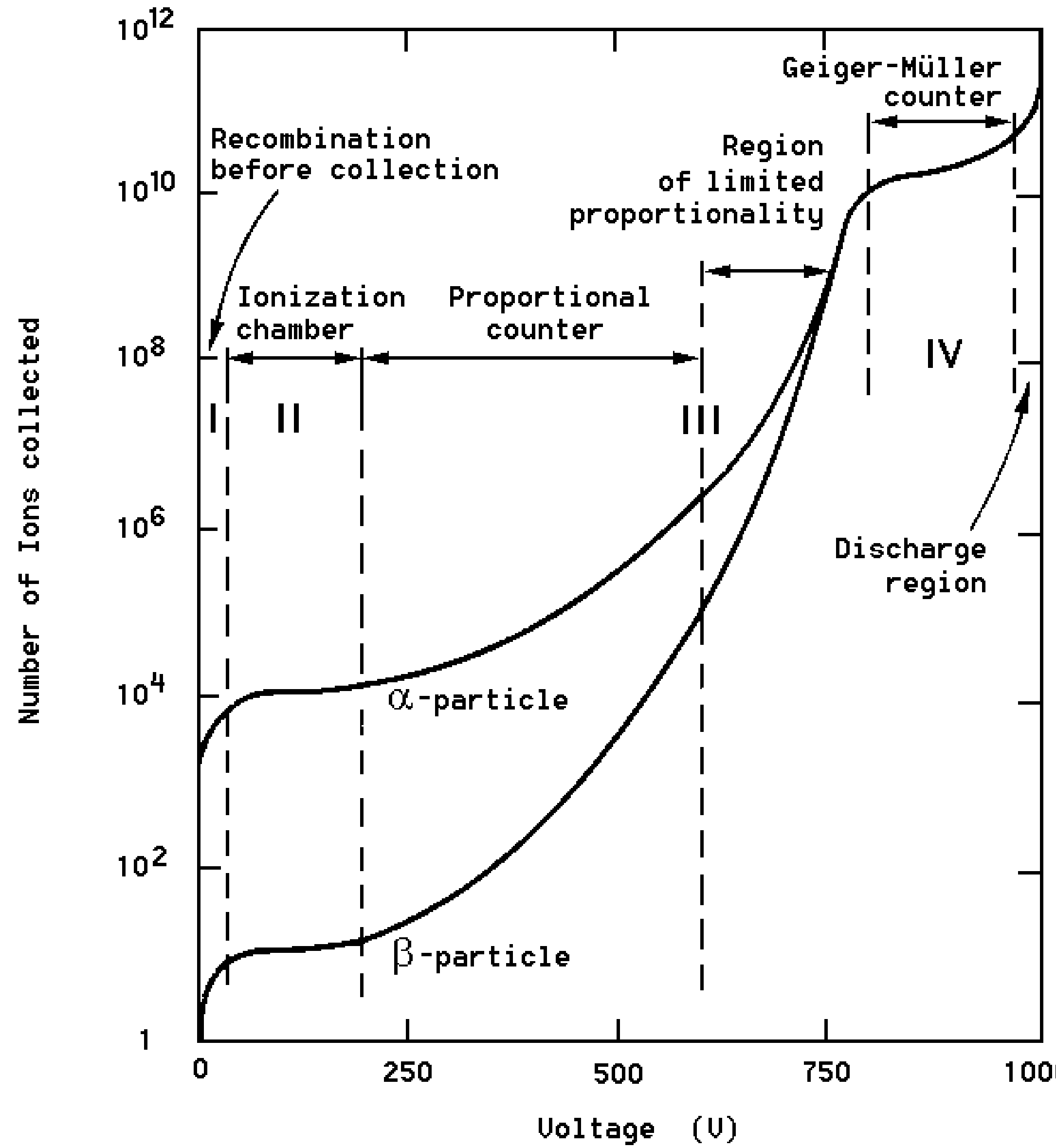
Detector Types



Gaseous

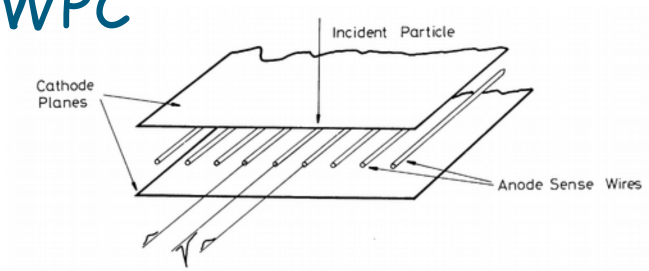

+HV
Rsense
10M
+5V
4093
22pF
1kV
Rload
2x1N4148

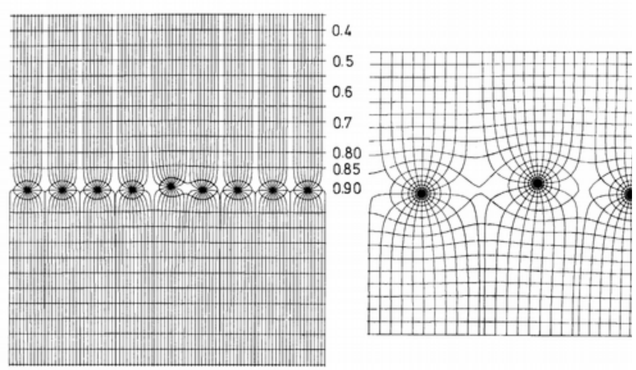


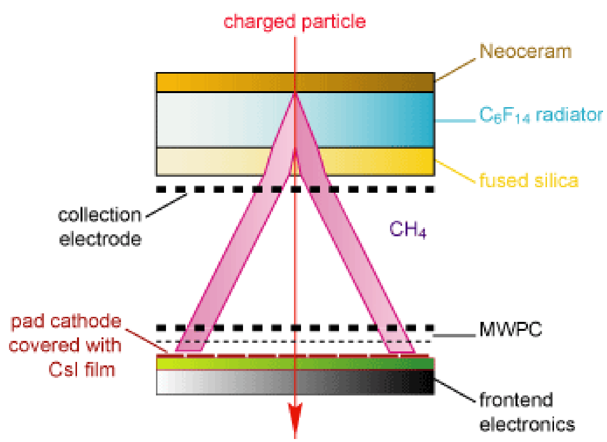

Number of Ions collected
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
0
250
500
750
1000
Voltage (V)
Geiger-Müller
counter
Recombination
before collection
Region
of limited
proportionality
Ionization
chamber
Proportional
counter
I
II
III
IV
Discharge
region
α-particle
β-particle

Wire Chambers

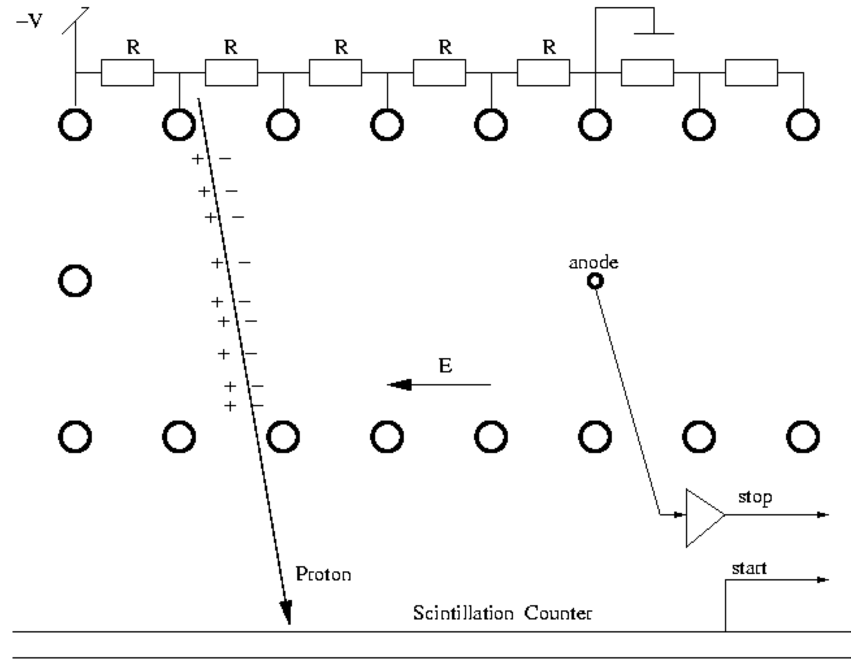
MWPC

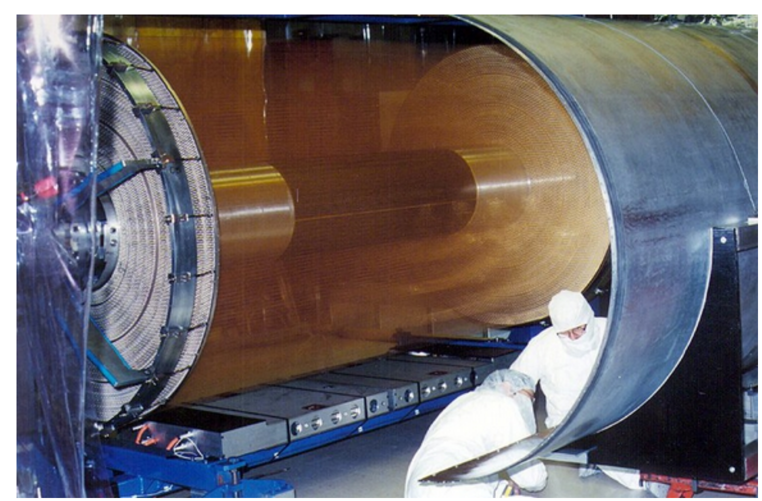




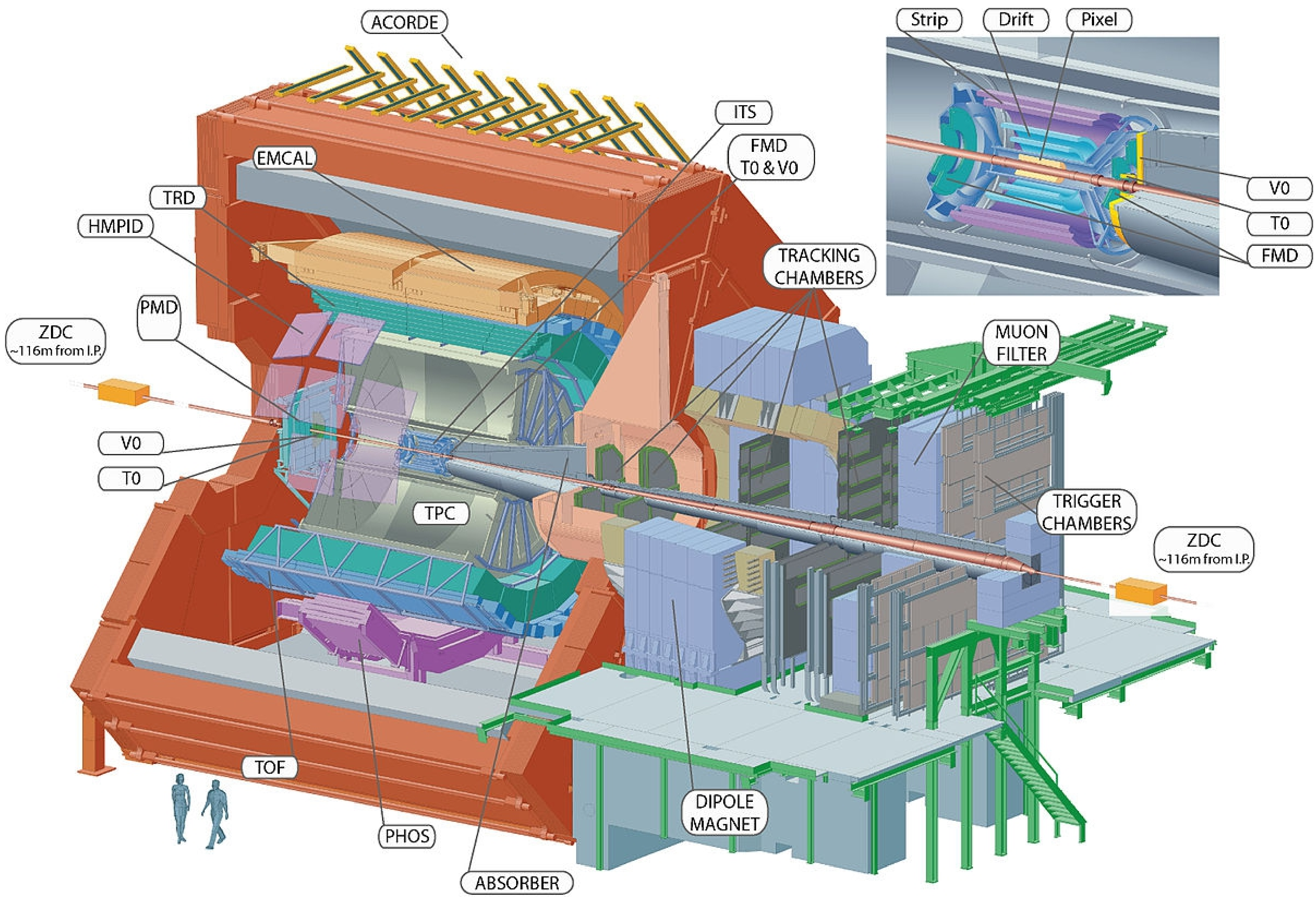


MDC



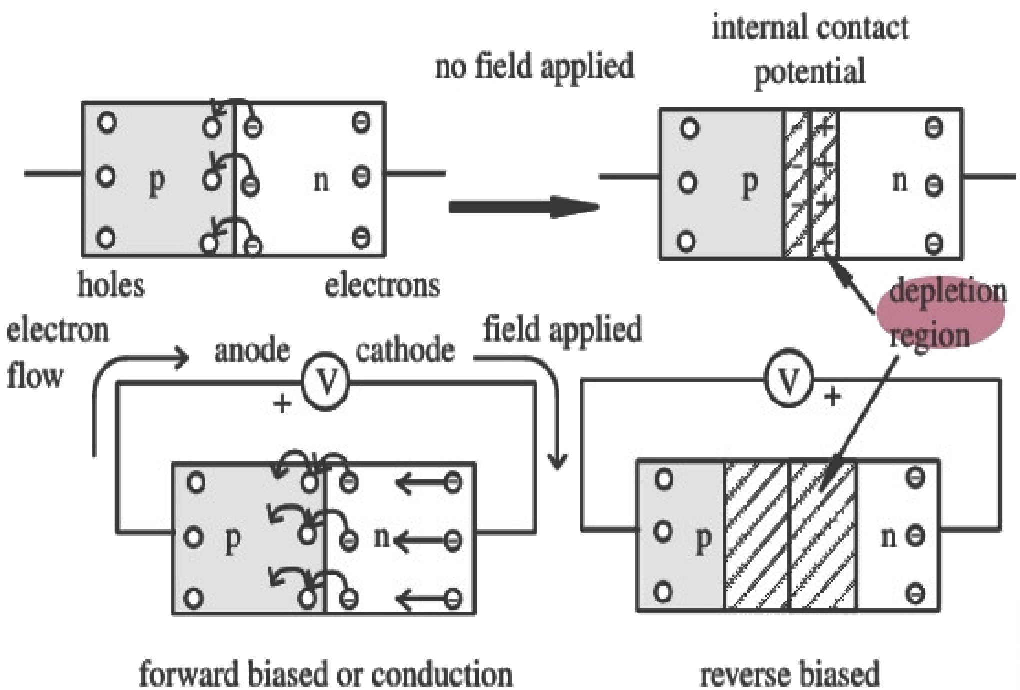


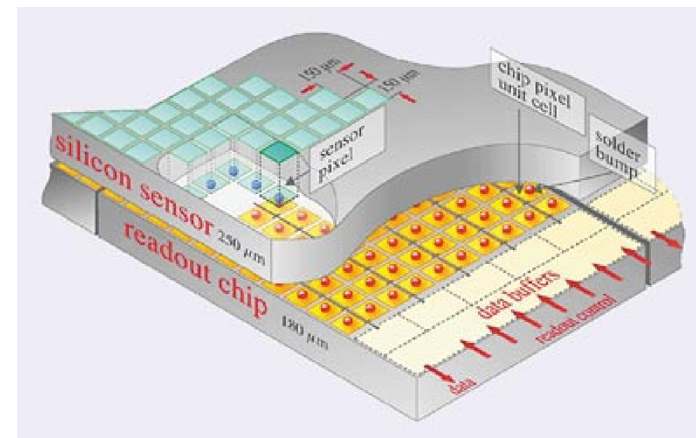
ALICE – TPC (MWPC)

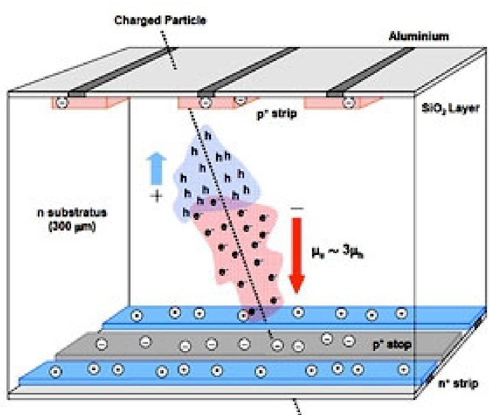


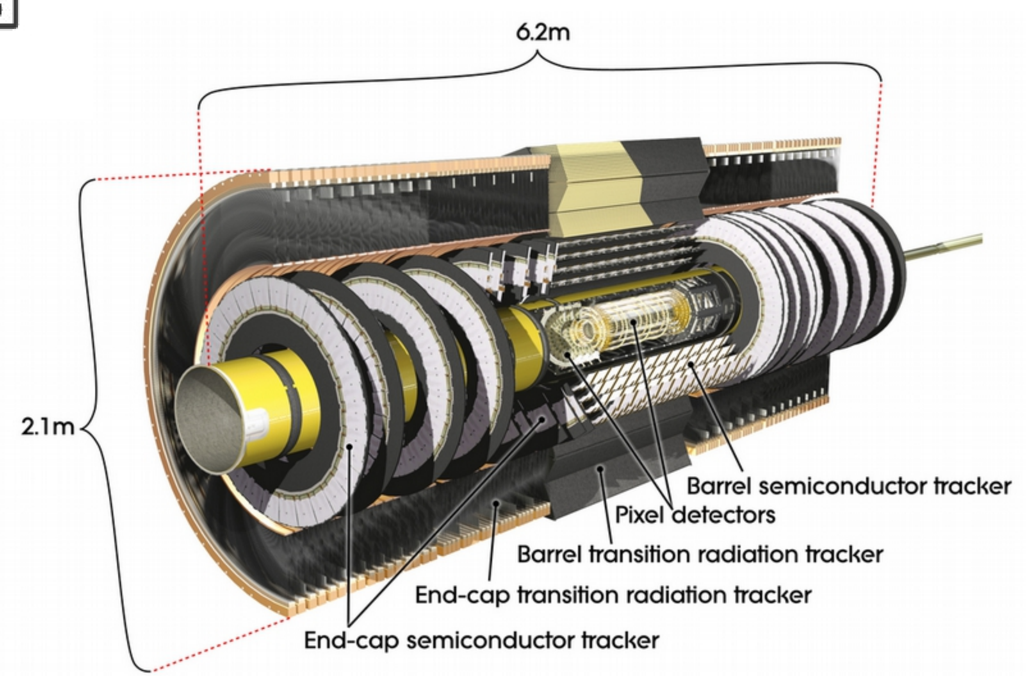
Semiconductors

Working Principle

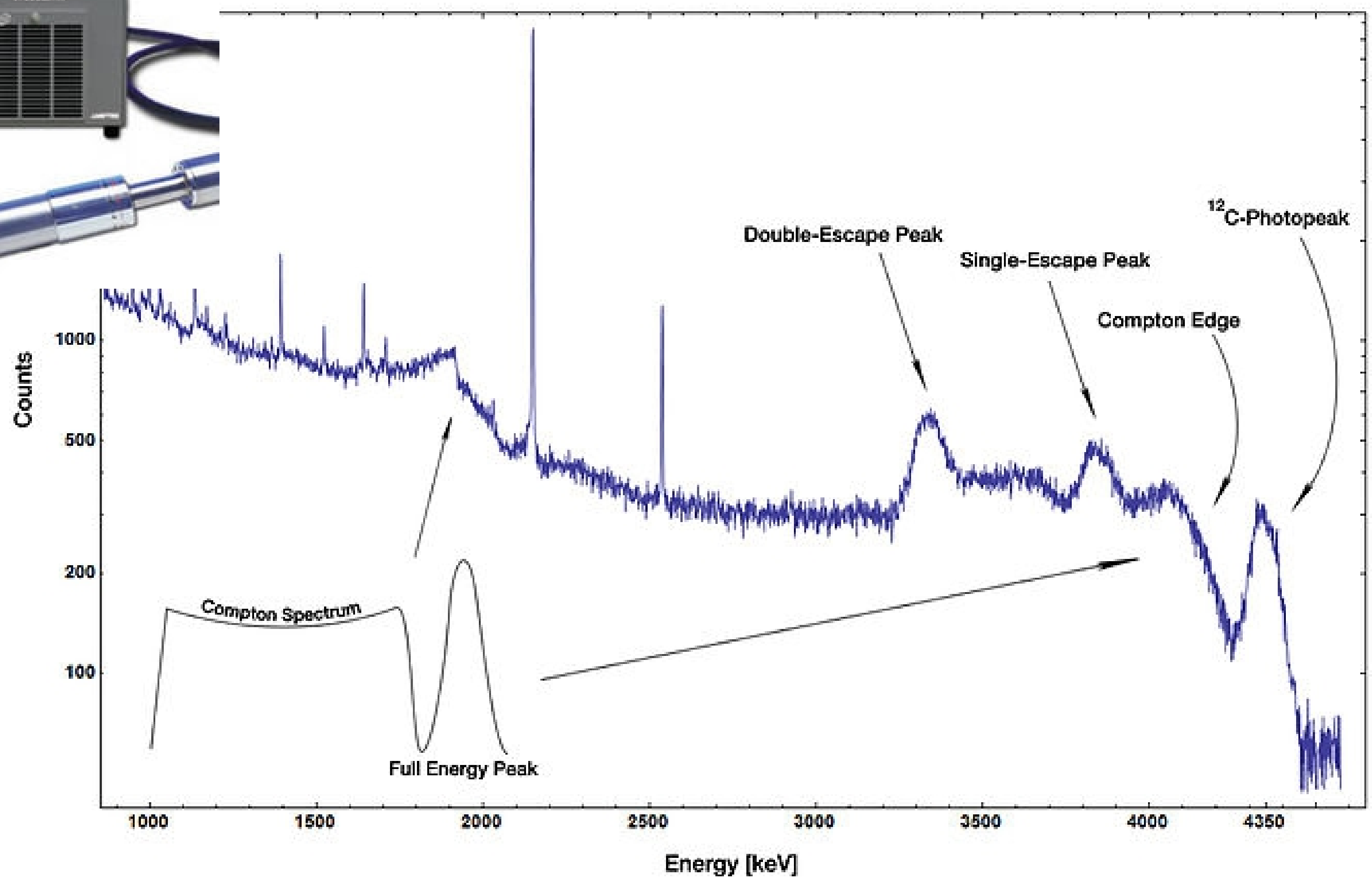








How to Interpret the Spectrum



Member of the Helmholtz-Association

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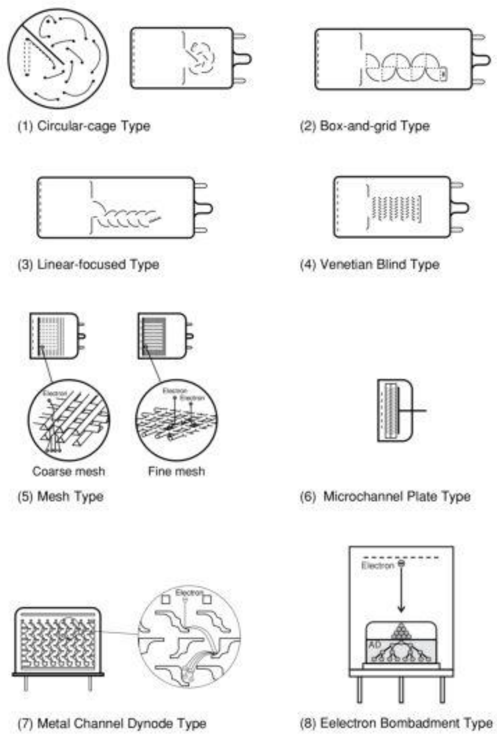
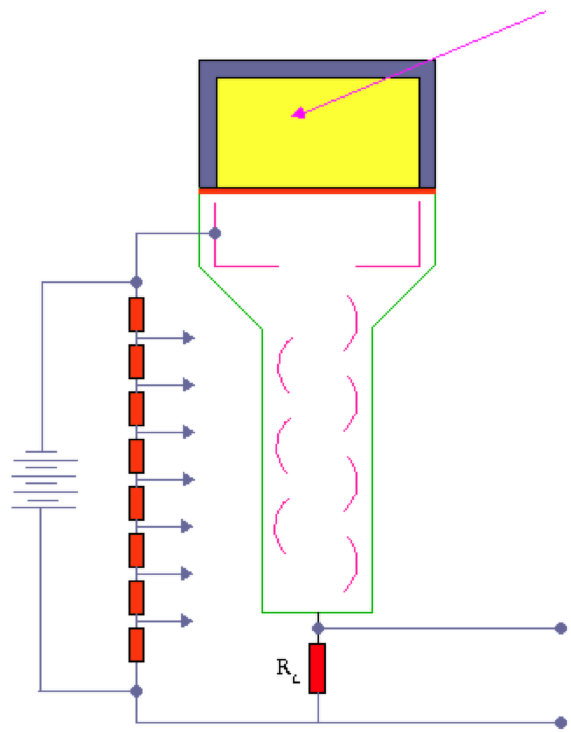
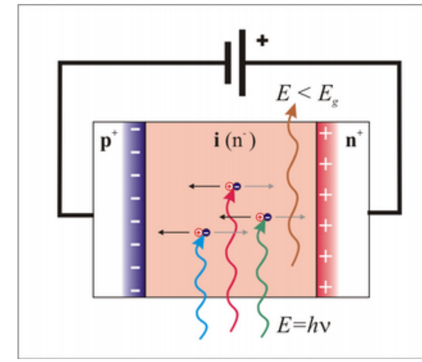
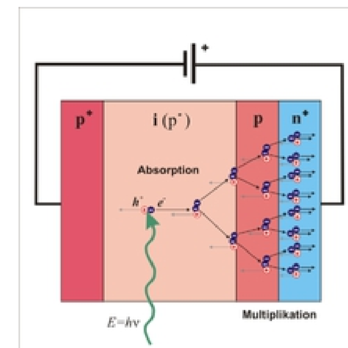
Scintillators

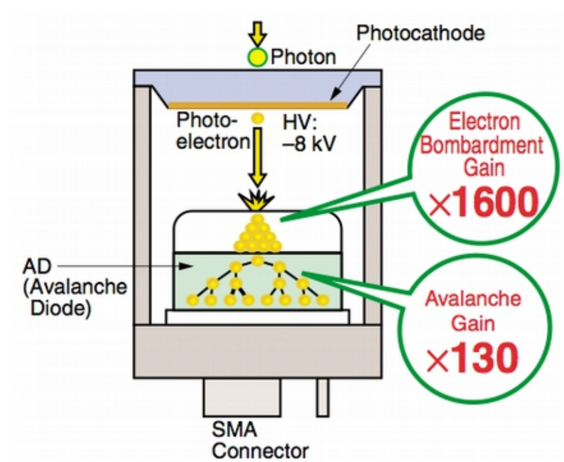
Photosensors

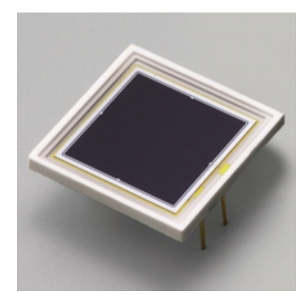


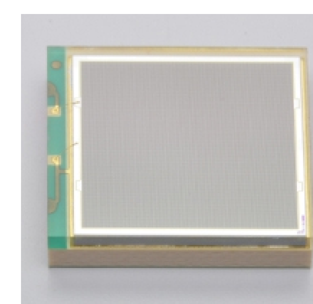






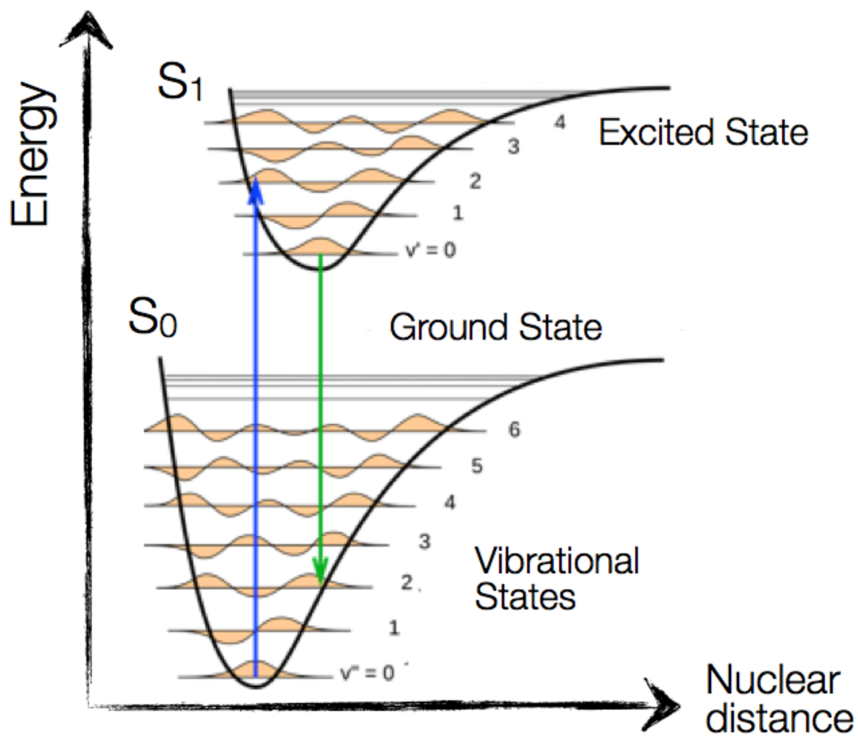


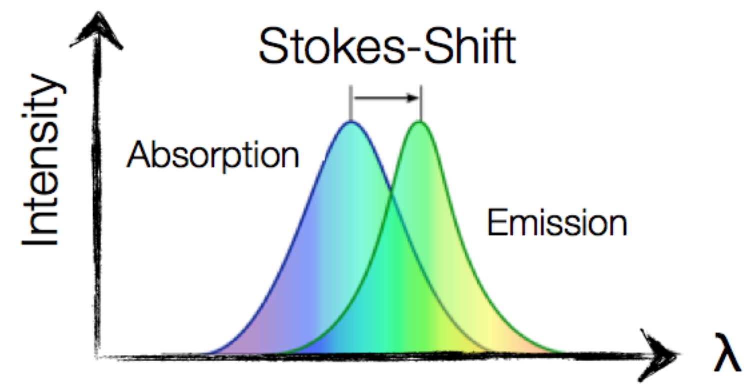




Scintillation Process

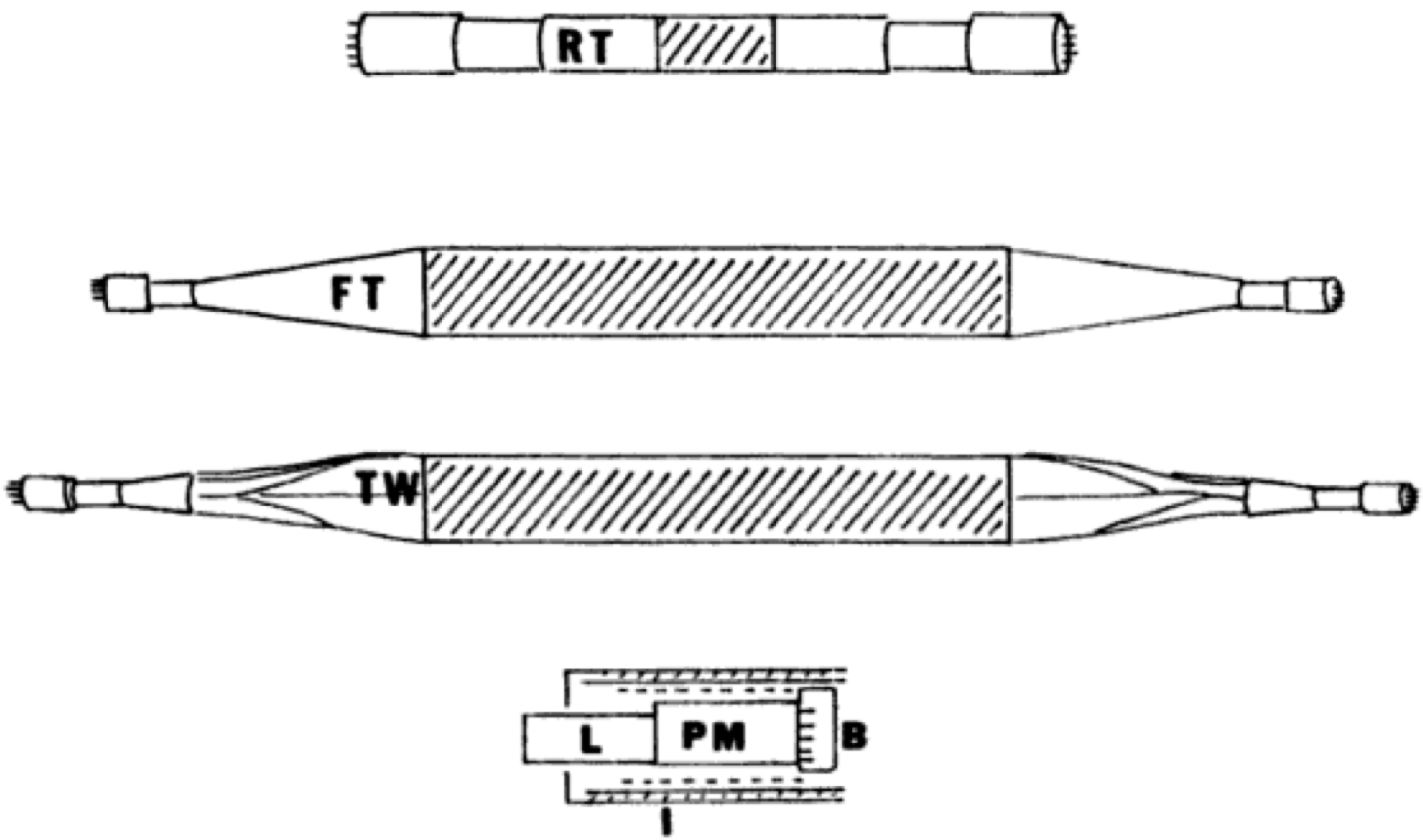
The light emission is governed by the electronic transitions in the molecule. The electronic levels have a typical energy spacing of ~4 eV. The vibrational levels of the molecule (dE ~ 0.2 eV) also play a role. Electrons in high levels typically deexcite to the lowest excited state without emission of radiation.





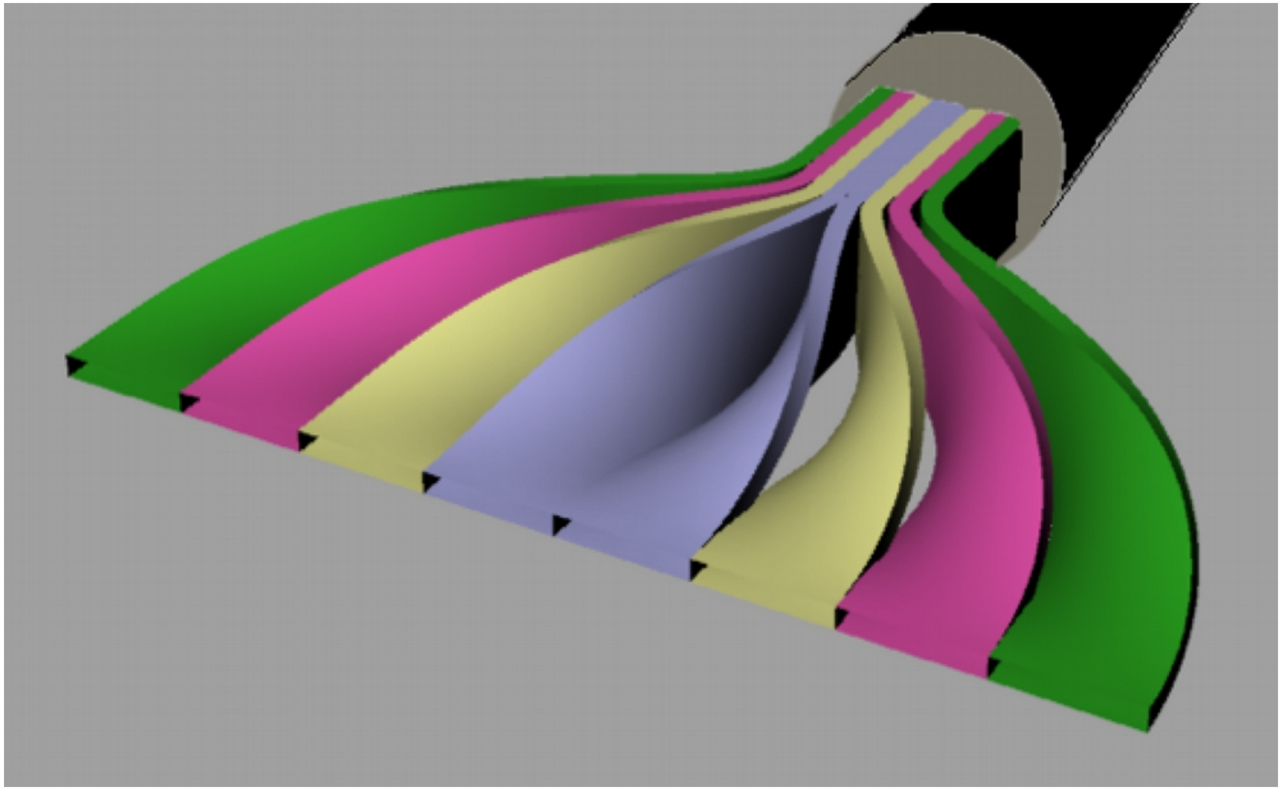
Light Guides

Types: (RT) rectangular, (FT) "fish tail," (TW) two twisted strips,
The bottom figure shows a photomultiplier tube assembly (PM) with base (B), standard coupling piece of light guide (L), mu metal shield (dotted lines), and soft iron shield (I).
(After G. D'Agostini et al., Nuc. Instr. Meth, 185: 49, 1981.)



Liouville's Theorem

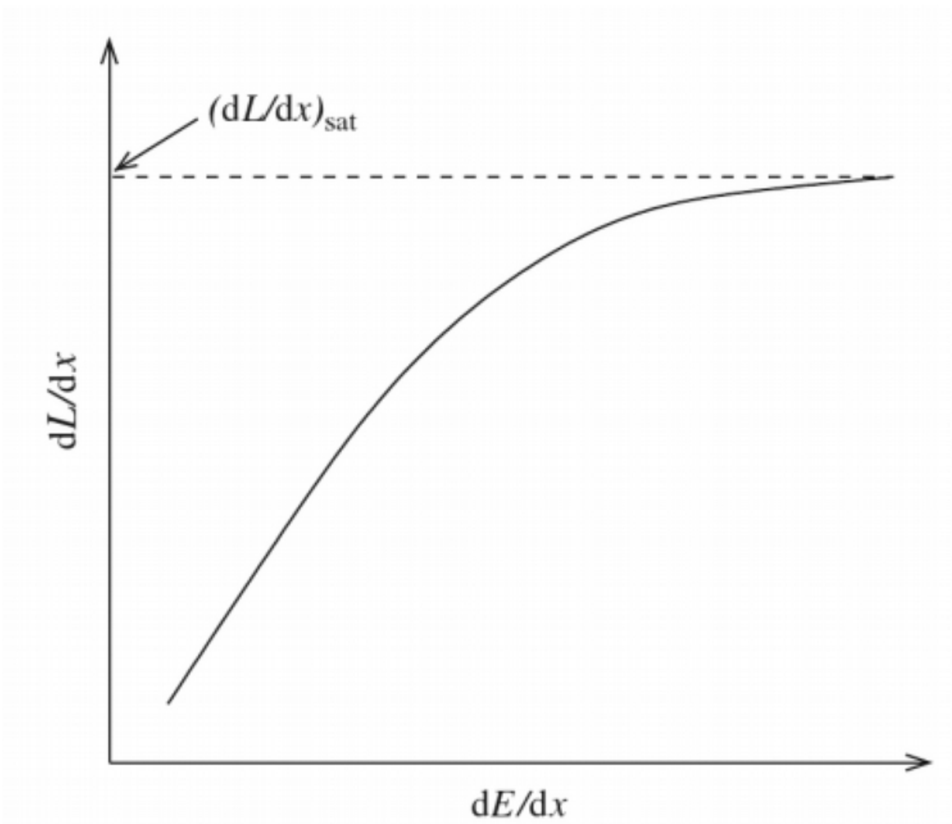
- presents a fundamental limitation on the transmission of light through the pipe. The theorem requires that the light flux per unit solid angle not increase while propagating in the pipe. This has the consequence that the maximum fraction of light that can be transmitted is Apm/Asc, where Apm (Asc) is the area of the PMT face (scintillator edge) and Apm < Asc.



Birk's Law

The amount of light produced for a given energy loss is not constant but depends on the production of quenching centers. These are activated molecules raised to excited vibrational levels. The number of produced photons roughly follows the equation

$$dL/dX = \frac{A \cdot dE/dX}{1 + B \cdot dE/dX}$$



where A and B are constants and dE/dx is the ionization energy loss. The parameter B is sometimes referred to as the a to b ratio. Note that the light output saturates for large energy losses.

Light Collection via Total Internal Reflection

The fraction of the emitted light transmitted via total internal reflection in one direction along the slab is

$$f=\frac{1}{4\pi}\int_{0}^{\theta} 2\pi\cdot\sin\theta\, d\theta=\frac{1}{2}\left(1-\frac{1}{n}\sqrt{n^{2}-1}\right)$$

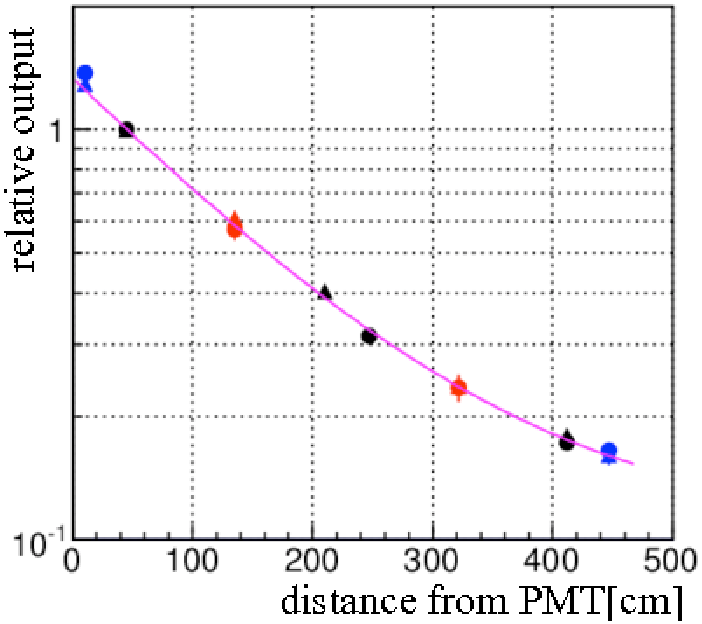
Note that this result is independent of the slab dimensions. For typical plastic scintillator with n = 1.58, Eq. gives f = 0.113.

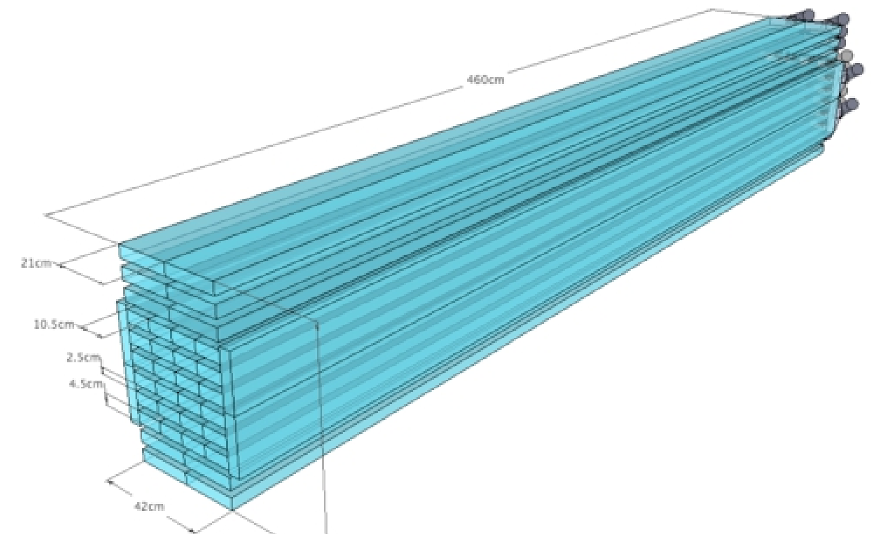
An improvement in light transmission in small counters can be achieved by using a reflector on the end of the scintillator opposite to the collection direction.

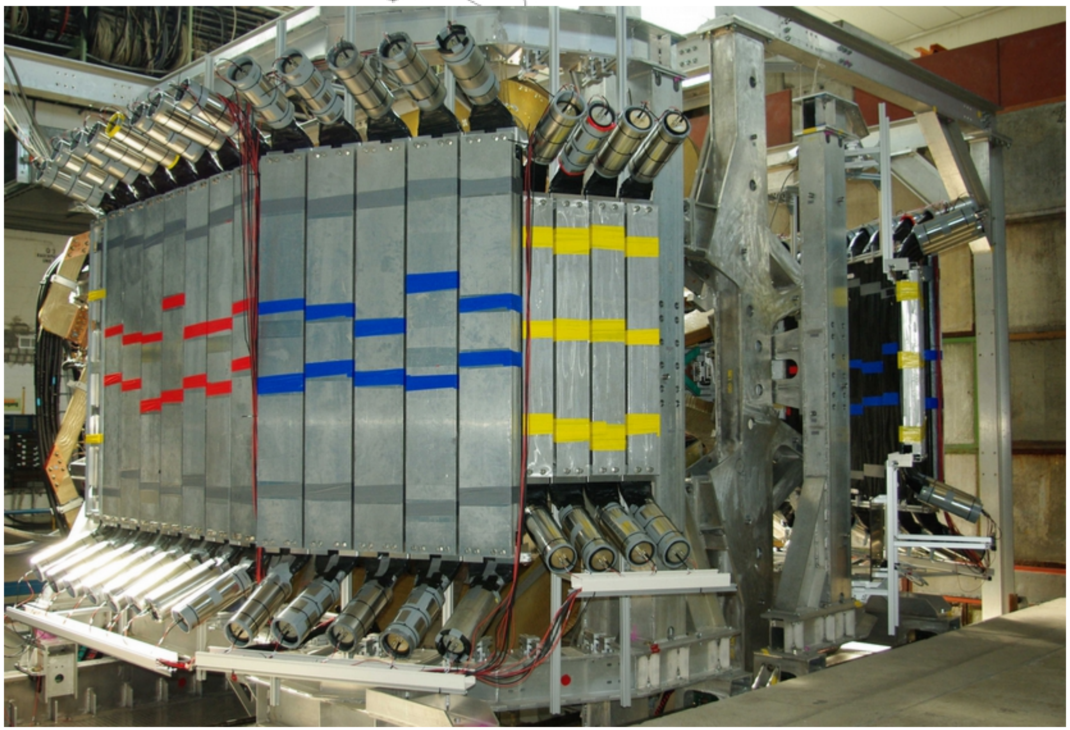
The reflectors may be either specular or diffuse and may be in direct contact with the medium or separated by a small air gap. Reflectors on the other four sides of the slab will in general have a much smaller influence on the collection efficiency.

Attenuation Length

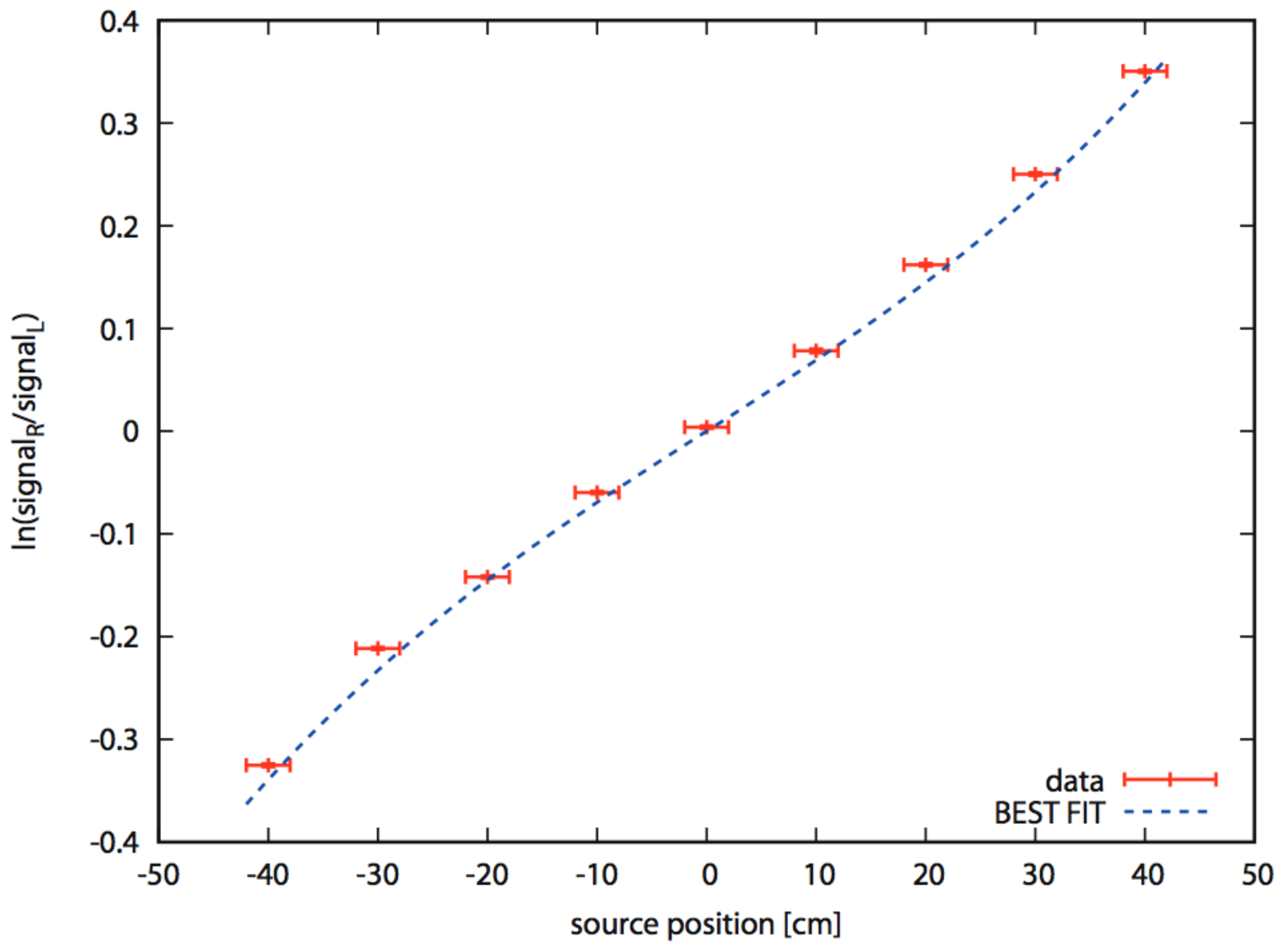
$$Y = Y_0 \cdot e^{\frac{-l}{\lambda}}$$



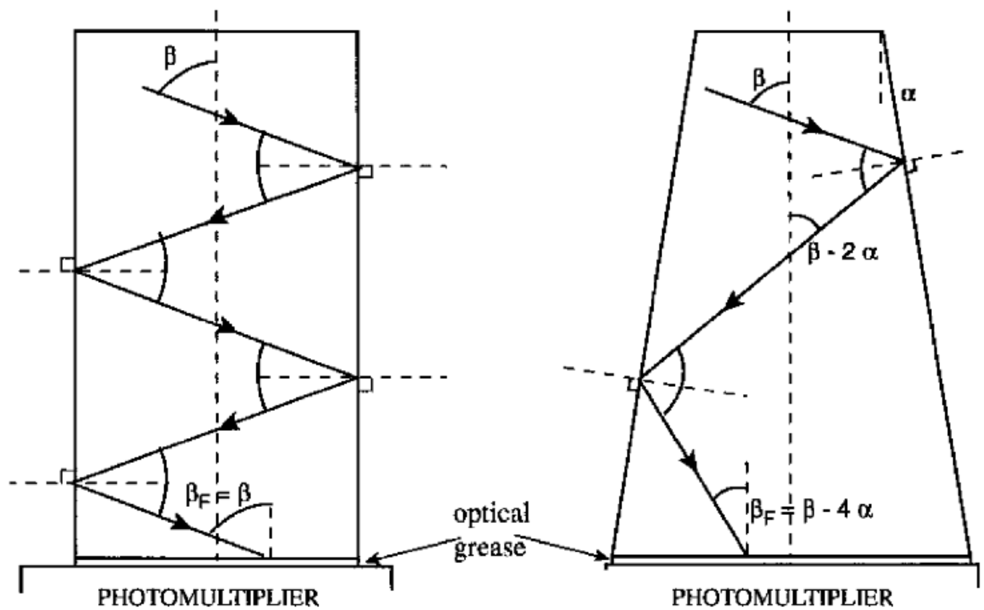




Source Position



Focusing Effect



Example

Rough design values

Energy loss in plastic = 2 MeV/cm

Scintillation efficiency = 1 photon/100 eV

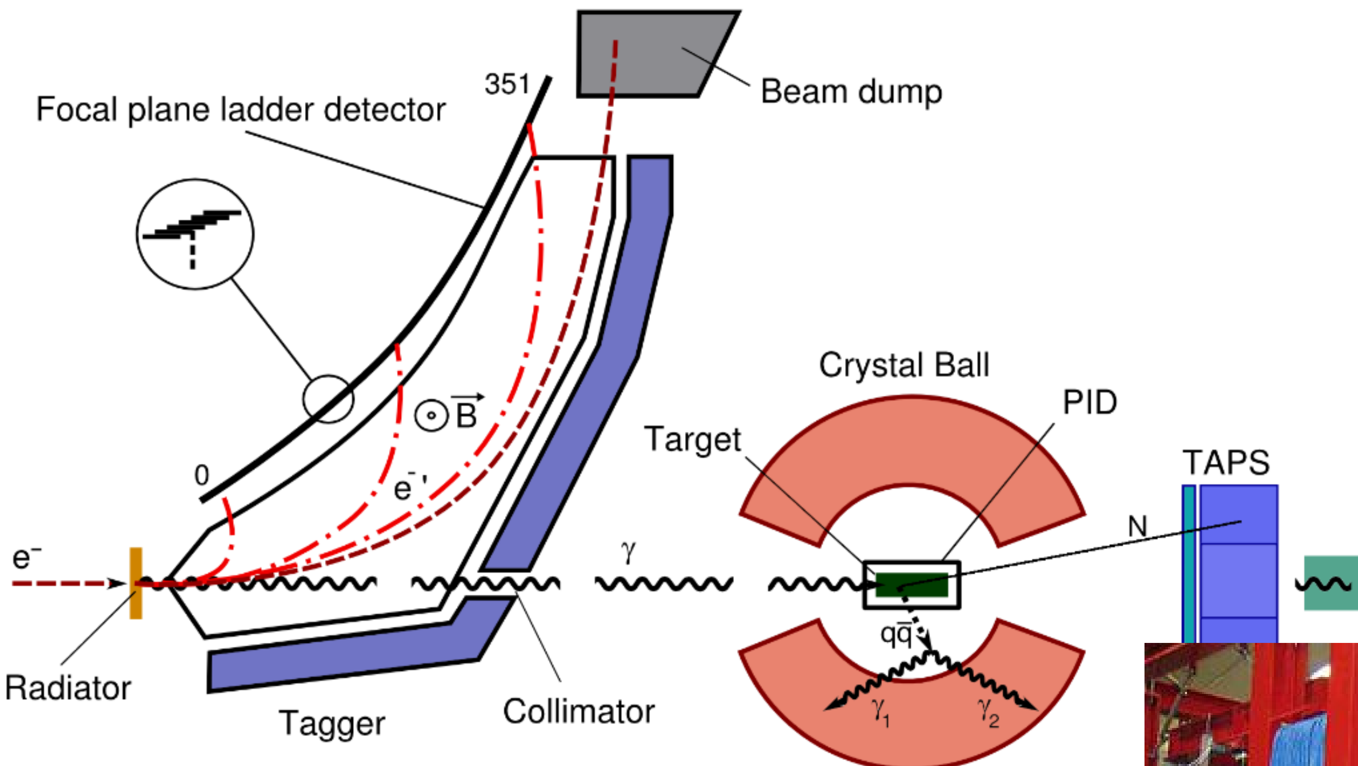
Collection efficiency = 0.10% (large counter)

Quantum efficiency = 0.25%

$$Y = Y_{lab} \cdot (1 - a) \cdot \epsilon_{cov} \cdot \epsilon_{PMT} = 10^4 / MeV \cdot 0.42 \cdot 0.75 \cdot 0.25 = 1100 / MeV$$

$$\Delta E / E = \Delta Y / Y \approx \sqrt{Y} / Y \approx 0.03$$

Crystal Ball-TAPS

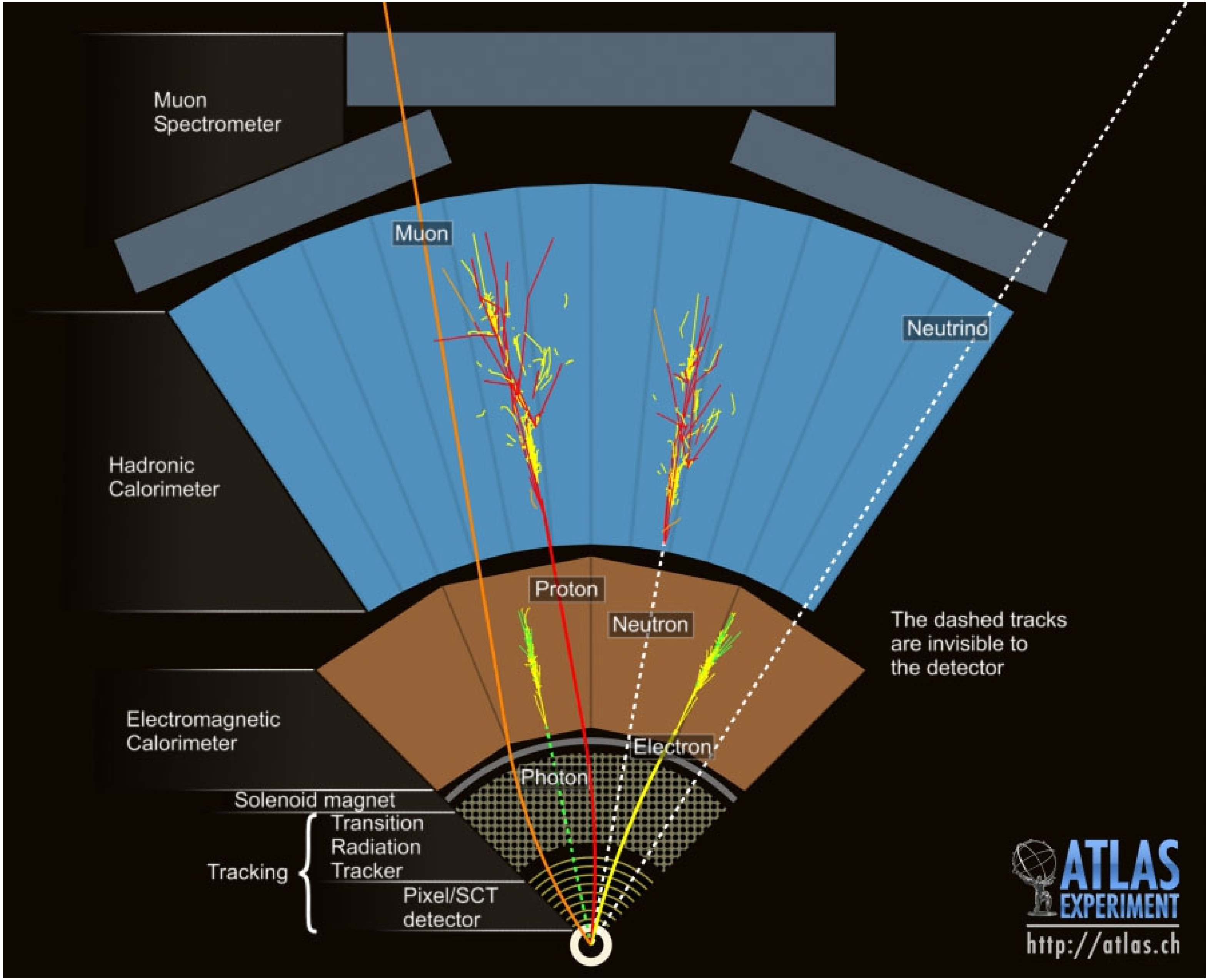


Commonly Used Inorganic Scintillators

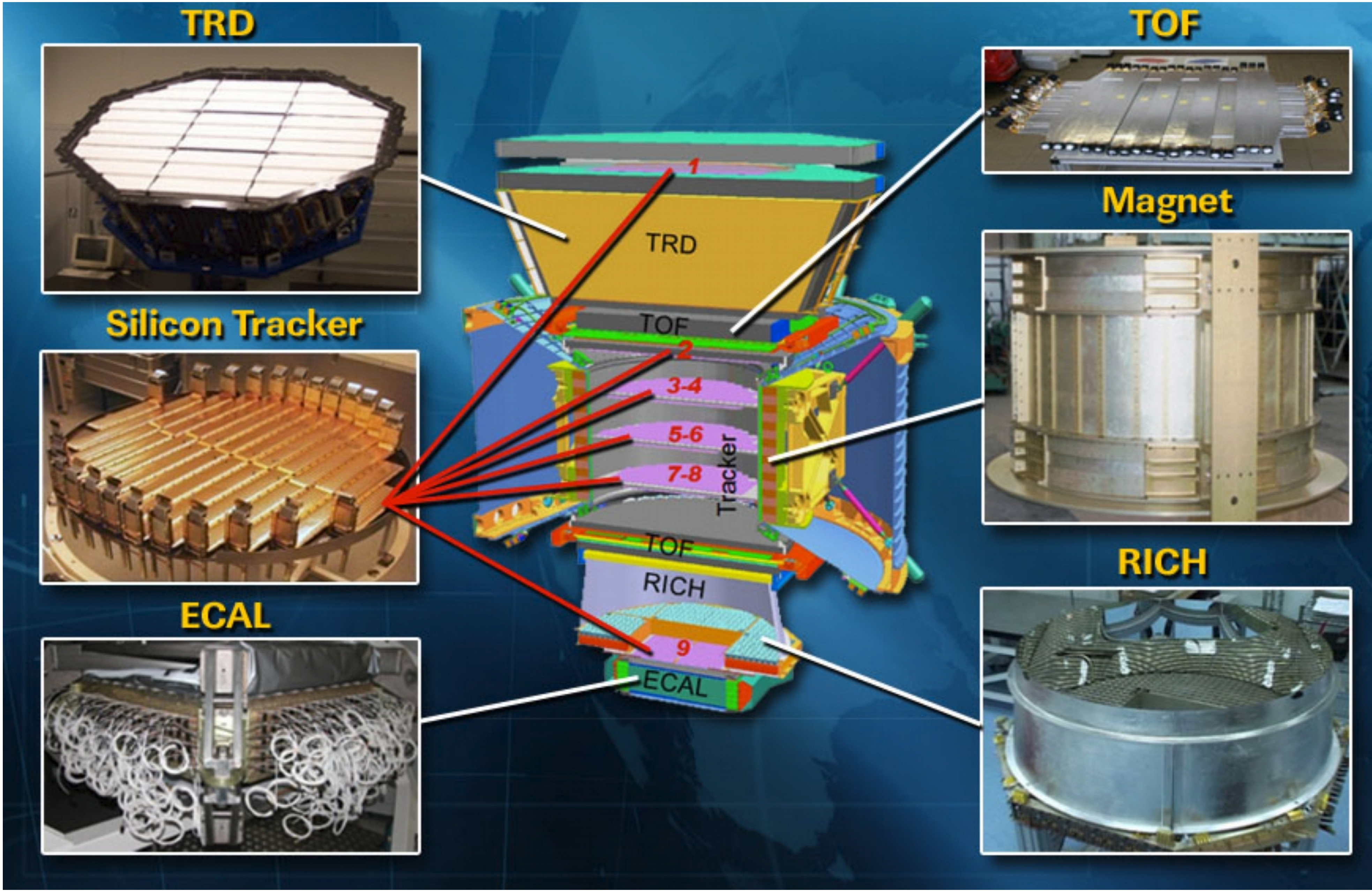
Scintillator	Light yield (photons/keV)	Light ouput (%) of NaI(Tl) bialkali pmt	Temperature coefficient of light output (%/C) 25°C to 50°C	1/e Decay time (ns) (10^{-3} μs)	Wavelength of maximum emission γ_m (nm)	Refractive index at γ_m	Thickness to stop 50% of 662 keV photons (cm)	Thermal expansion (°/C) x 10^{-6}	Hardness (Mho)	Density g/cm^3	Hygroscopic	Comments
BrilLanCe™380 $LaBr_3$(Ce)	63	165	0	16	380	~1.9	1.8	8		5.08	yes	General purpose, best energy resolution, rate of change of light output w/ temperature is small
NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	2	3.67	yes	General purpose, good energy resolution
Polyscin®NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	2	3.67	yes	Polycrystalline NaI(Tl), for extra strength
BrilLanCe™350 $LaCl_3$(Ce)	49	70 - 90	0.7	28	350	~1.9	2.3	11		3.85	yes	General purpose, excellent energy resolution
CsI(Na)	41	85	-0.05	630	420	1.84	2	54	2	4.51	yes	High Z, rugged
PreLude™420 $Lu_{1.8}Y_{.2}SiO_5$(Ce)	32	75	-0.28	41	420	1.81	1.1	--		7.1	no	Bright, high Z, fast, dense, background from ^{176}Lu activity
$CdWO_4$	12 - 15	30 - 50	-0.1	14000	475	~2.3	1	10.2	4 - 4.5	7.9	no	High Z, low afterglow, for use with photodioides
CaF_2(Eu)	19	50	-0.33	940	435	1.47	2.9	19.5	4	3.18	no	Low Z, α & β detection
CsI(Tl)	54	45	0.01	1000	550	1.79	2	54	2	4.51	slightly	High Z, rugged, good match to photodiodes
BGO	8 - 10	20	-1.2	300	480	2.15	1	7	5	7.13	no	High Z, compact detector, low afterglow
YAG(Ce) $Y_3Al_5O_{12}$(Ce)	8	15	--	70	550	1.82	2	~80	8.5	4.55	no	β-ray, X-ray counting, electron microscopy
CsI(pure)	2	4 - 6	-0.3	16	315	1.95	2	54	2	4.51	slightly	High Z, fast emission
BaF_2	1.8	3	0	0.6 - 0.8	220 (195)	1.54	1.9	18.4	3	4.88	slightly	Fast component (subnanosecond)
	10	16	-1.1	630	310	1.50	1.9	18.4	3	4.88	slightly	Slow component
ZnS(Ag)	~50	130	-0.6	110	450	2.36	--	--	--	4.09	no	Multicrystal, 15μ stops 5.5 MeV α (n detection with ^6Li)

The data presented are believed to be correct but are not guaranteed to be so.

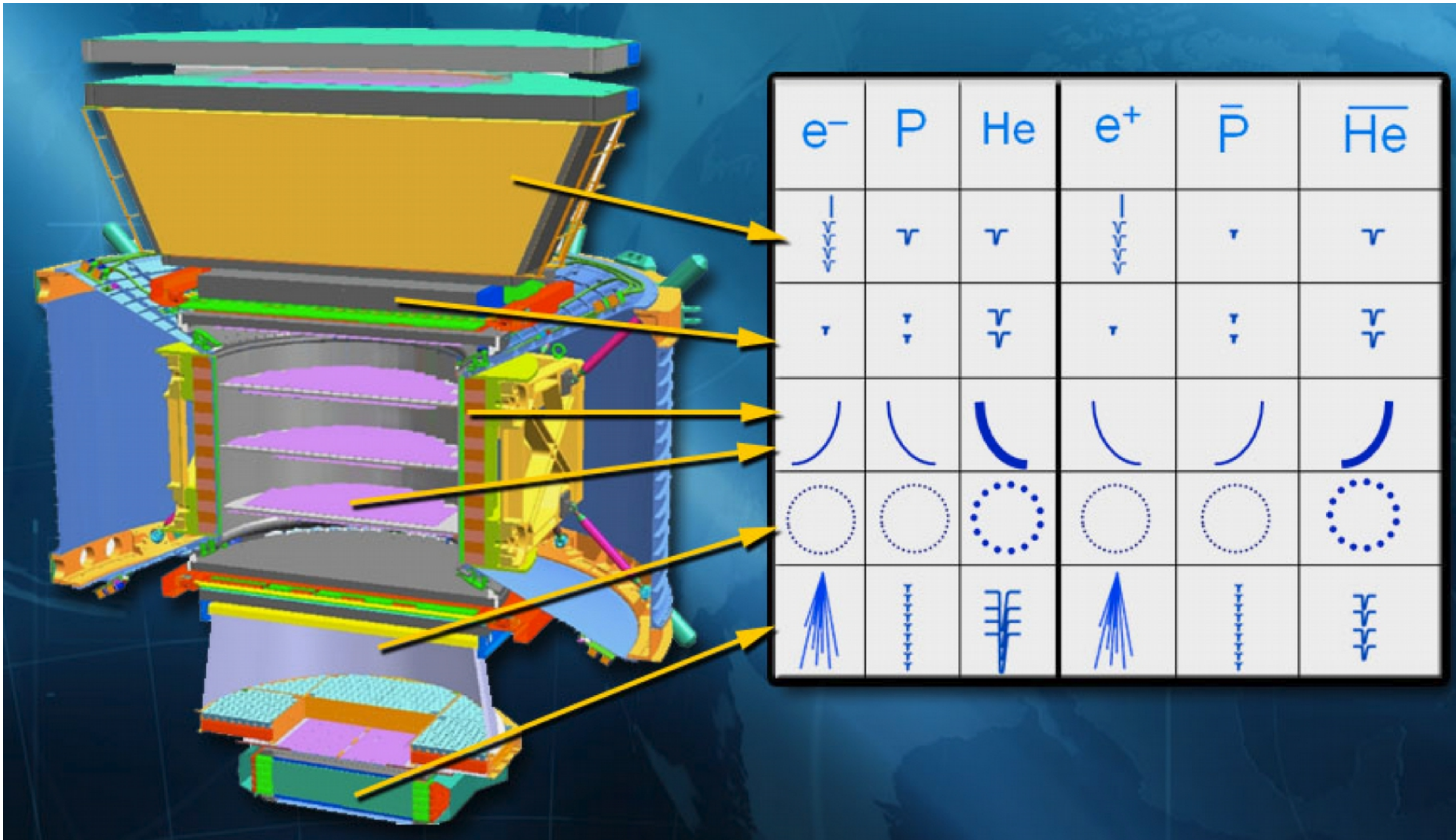
Modern Particle Detector



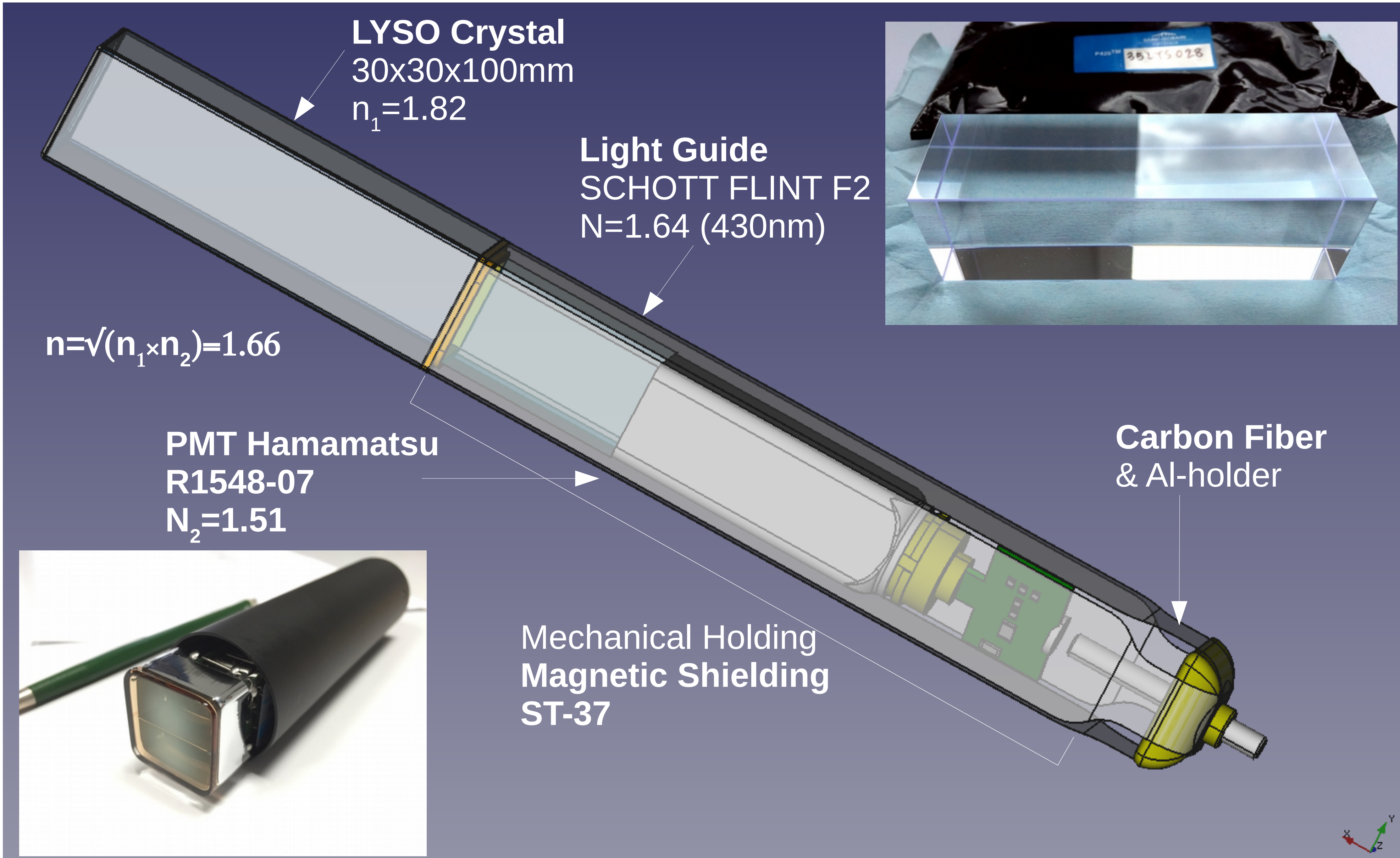
AMS-2


TRD
TOF
Magnet
Silicon Tracker
RICH
ECAL
1
TRD
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL

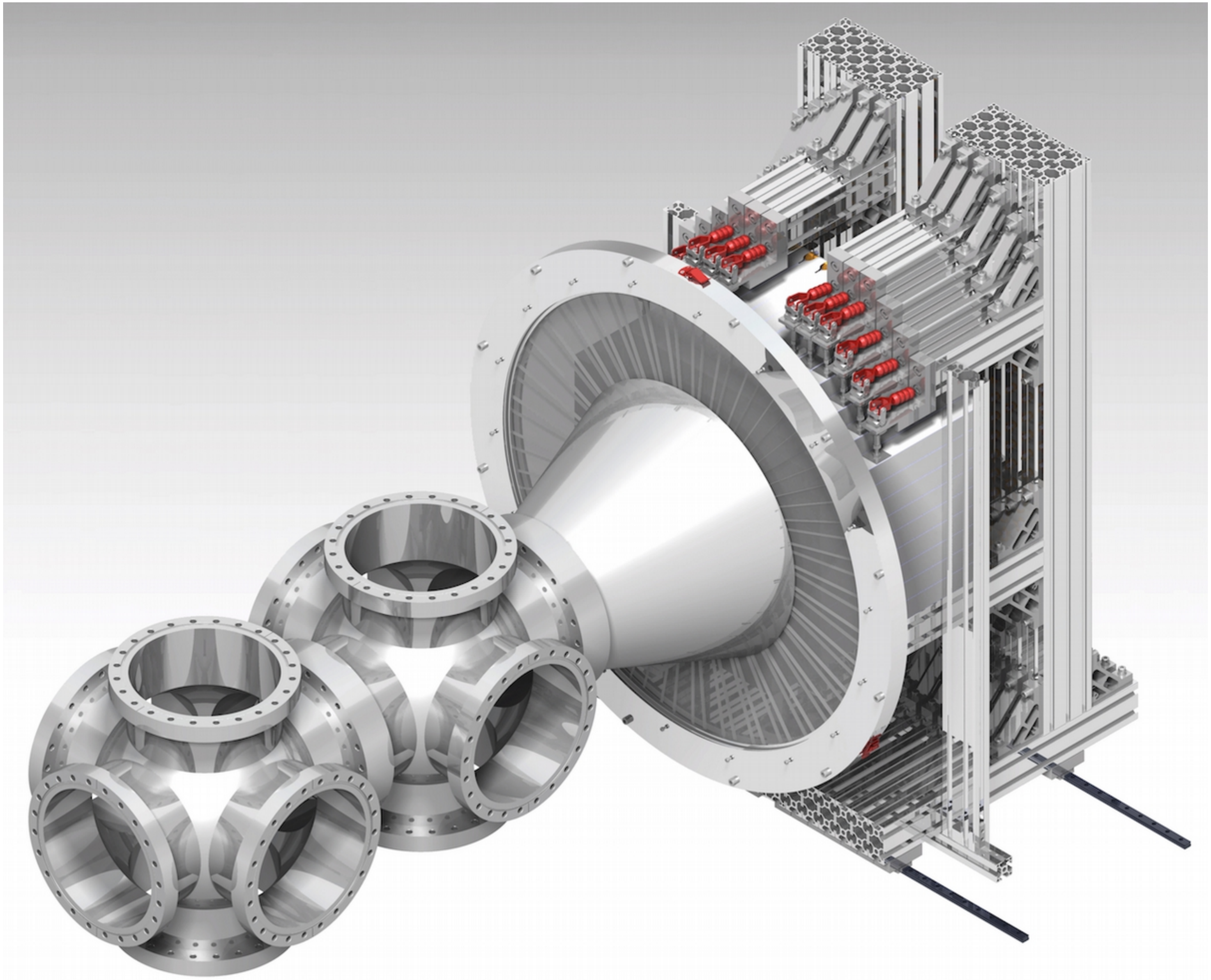
AMS-2



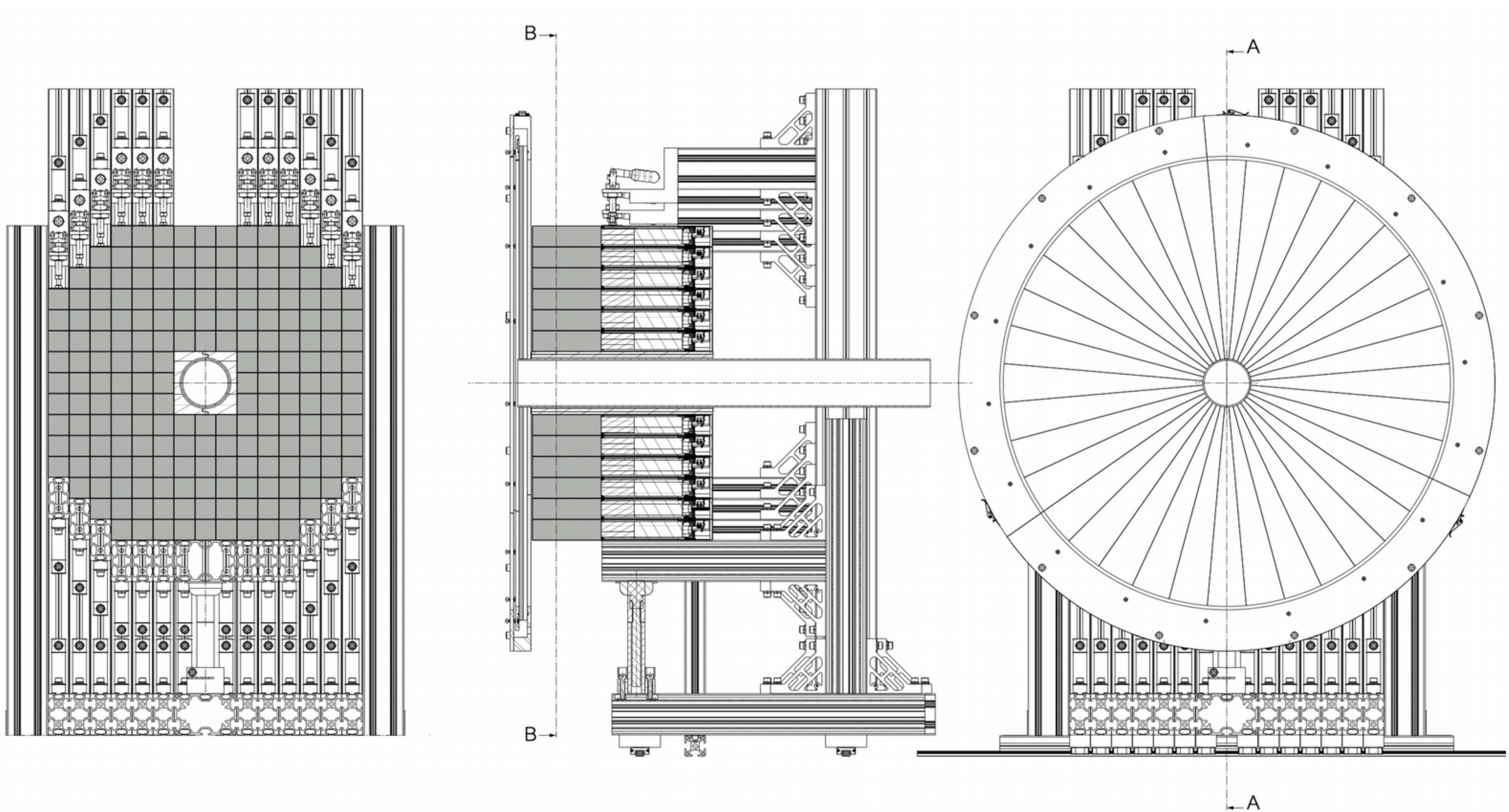
Polarimeter Module



JEDI Polarimeter



2D Drawings



Summary

- Purpose of the Detectors
- Working Principle of the Detectors
- How to choose the Detector Types/Materials
- Some Examples