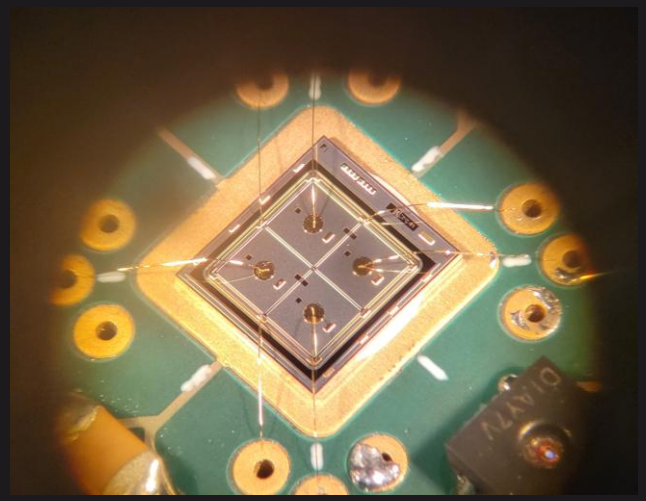
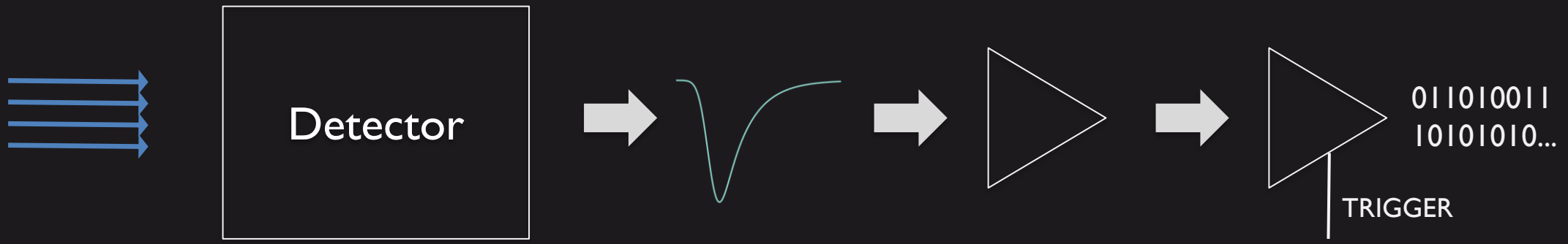
Detectores semicondutores



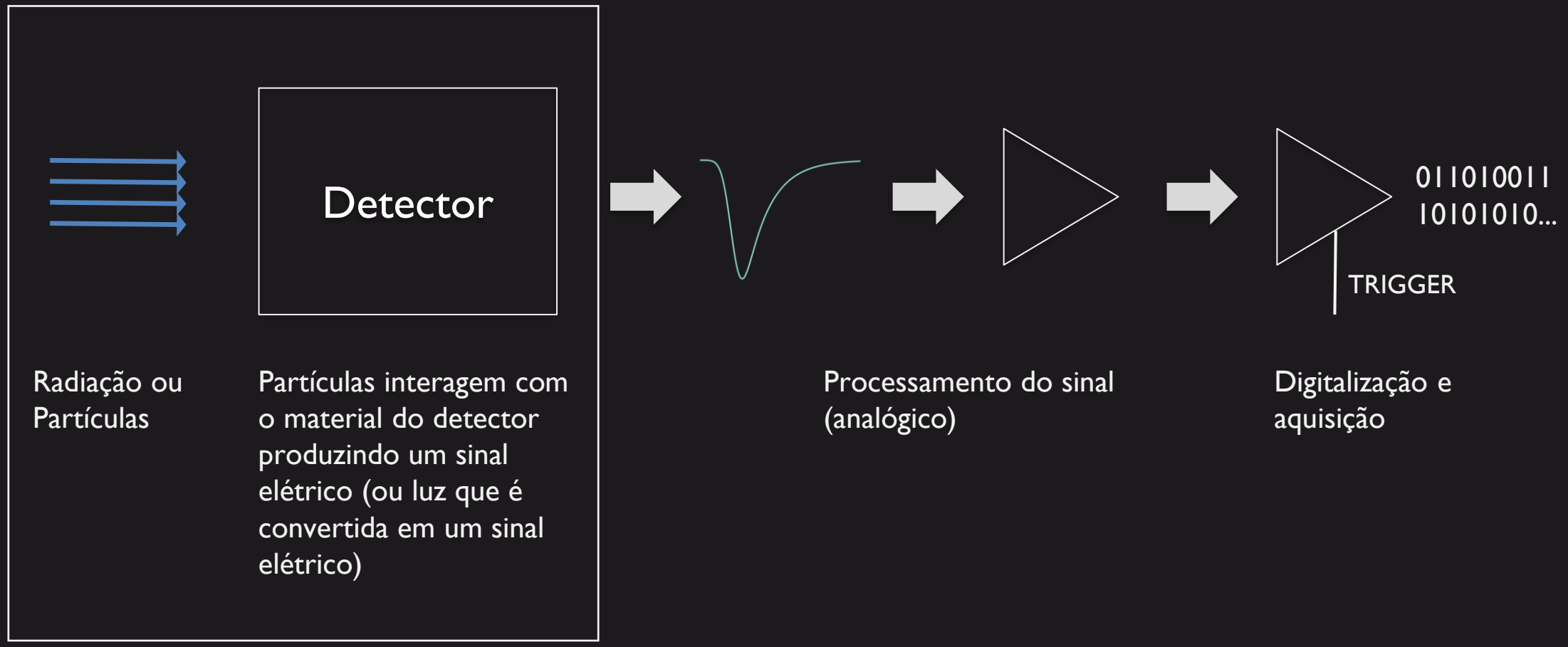


Radiação ou Partículas

Partículas interagem com o material do detector produzindo um sinal elétrico (ou luz que é convertida em um sinal elétrico)

Processamento do sinal (analógico)

Digitalização e aquisição



Radiação ou Partículas

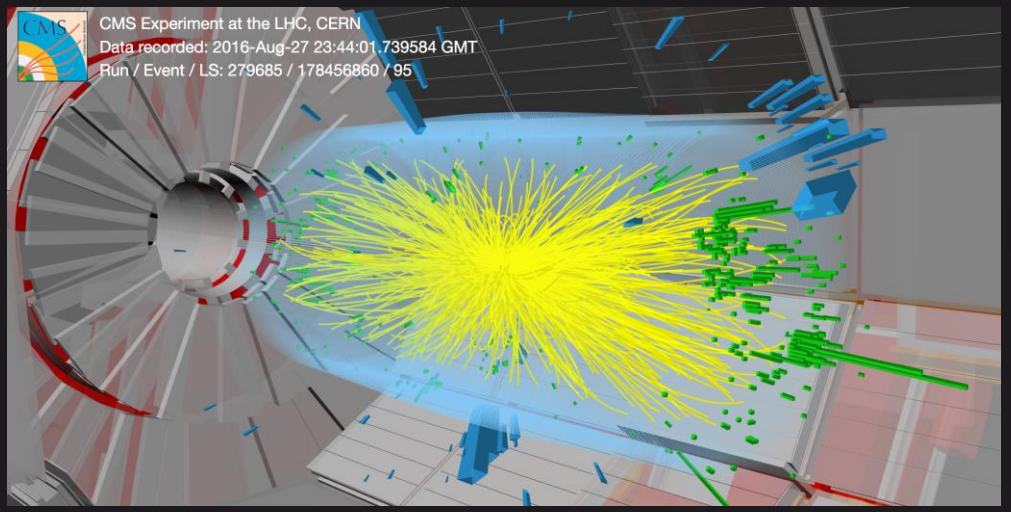
Partículas interagem com o material do detector produzindo um sinal elétrico (ou luz que é convertida em um sinal elétrico)

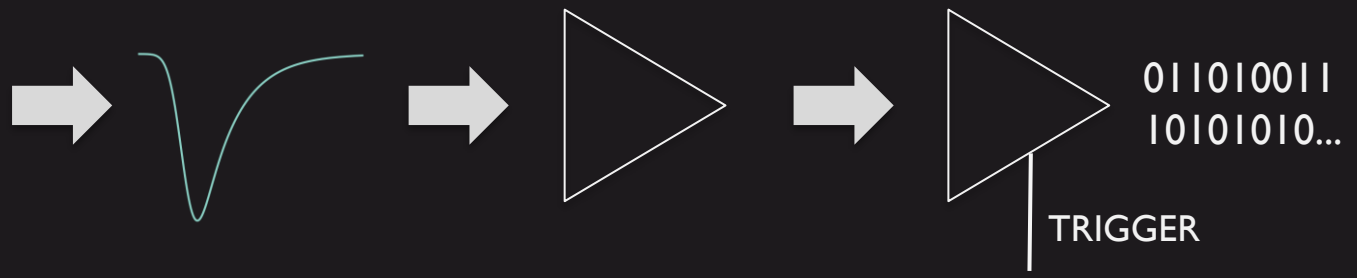
Processamento do sinal (analógico)

Digitalização e aquisição

Muito alta densidade de partículas perto do ponto de colisão

40 milhões de colisões por segundo





Processamento do sinal (analógico)

Digitalização e aquisição

Semicondutores

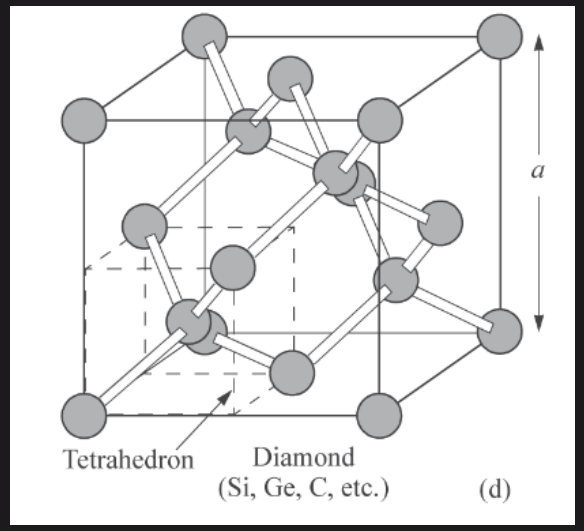
IA													IIIA	IVA	VA	VIA	VIIA	Noble
Hydrogen H $1s^1$ 1.0079	IIA																	Helium He $1s^2$ 4.0026
Lithium Li $1s^2 2s^1$ 6.941	Beryllium Be $1s^2 2s^2$ 9.0122												Boron B $1s^2 2s^2 2p$ 10.81	Carbon C $1s^2 2s^2 2p^2$ 12.01	Nitrogen N $1s^2 2s^2 2p^3$ 14.007	Oxygen O $1s^2 2s^2 2p^4$ 15.999	Fluorine F $1s^2 2s^2 2p^5$ 18.998	Neon Ne $1s^2 2s^2 2p^6$ 20.18
Sodium Na [Ne] $3s^1$ 22.9898	Magnesium Mg [Ne] $3s^2$ 24.305	IIIB	IVB	VB	VIB	VIIB	← VIII →		IB	IIB	Aluminum Al [Ne] $3s^2 3p^1$ 26.982	Silicon Si [Ne] $3s^2 3p^2$ 28.086	Phosphorous P [Ne] $3s^2 3p^3$ 30.974	Sulfur S [Ne] $3s^2 3p^4$ 32.064	Chlorine Cl [Ne] $3s^2 3p^5$ 35.453	Argon Ar [Ne] $3s^2 3p^6$ 39.948
Potassium K [Ar] $4s^1$ 39.09	Calcium Ca [Ar] $4s^2$ 40.08	Scandium Sc [Ar] $3d^1 4s^2$ 44.956	Titanium Ti [Ar] $3d^2 4s^2$ 47.90	Vanadium V [Ar] $3d^3 4s^2$ 50.942	Chromium Cr [Ar] $3d^5 4s^1$ 52.00	Manganese Mn [Ar] $3d^5 4s^2$ 54.938	Iron Fe [Ar] $3d^6 4s^2$ 55.85	Cobalt Co [Ar] $3d^7 4s^2$ 58.93	Nickel Ni [Ar] $3d^8 4s^2$ 58.71	Copper Cu [Ar] $3d^{10} 4s^1$ 63.55	Zinc Zn [Ar] $3d^{10} 4s^2$ 65.38	Gallium Ga [Ar] $3d^{10} 4s^2 4p^1$ 69.72	Germanium Ge [Ar] $3d^{10} 4s^2 4p^2$ 72.59	Arsenic As [Ar] $3d^{10} 4s^2 4p^3$ 74.922	Selenium Se [Ar] $3d^{10} 4s^2 4p^4$ 78.96	Bromine Br [Ar] $3d^{10} 4s^2 4p^5$ 79.91	Krypton Kr [Ar] $3d^{10} 4s^2 4p^6$ 83.80
Rubidium Rb [Kr] $5s^1$ 85.47	Strontium Sr [Kr] $5s^2$ 87.62	Yttrium Y [Kr] $4d^1 5s^2$ 88.91	Zirconium Zr [Kr] $4d^2 5s^2$ 91.22	Niobium Nb [Kr] $4d^4 5s^1$ 92.91	Molybdenum Mo [Kr] $4d^5 5s^1$ 95.94	Technetium Tc [Kr] $4d^5 5s^2$ 98.91	Ruthenium Ru [Kr] $4d^7 5s^1$ 101.07	Rhodium Rh [Kr] $4d^8 5s^1$ 102.90	Palladium Pd [Kr] $4d^{10} 5s^0$ 106.40	Silver Ag [Kr] $4d^{10} 5s^1$ 107.87	Cadmium Cd [Kr] $4d^{10} 5s^2$ 112.40	Indium In [Kr] $4d^{10} 5s^2 5p^1$ 114.82	Tin Sn [Kr] $4d^{10} 5s^2 5p^2$ 118.69	Antimony Sb [Kr] $4d^{10} 5s^2 5p^3$ 121.75	Tellurium Te [Kr] $4d^{10} 5s^2 5p^4$ 127.60	Iodine I [Kr] $4d^{10} 5s^2 5p^5$ 126.90	Xenon Xe [Kr] $4d^{10} 5s^2 5p^6$ 131.30
Cesium Cs [Xe] $6s^1$ 132.91	Barium Ba [Xe] $6s^2$ 137.34	Lanthanum La [Xe] $5d^1 6s^2$ 138.91	Hafnium Hf [Xe] $4f^{14} 5d^2 6s^2$ 178.49	Tantalum Ta [Xe] $4f^{14} 5d^3 6s^2$ 180.95	Tungsten W [Xe] $4f^{14} 5d^4 6s^2$ 183.85	Rhenium Re [Xe] $4f^{14} 5d^5 6s^2$ 186.2	Osmium Os [Xe] $4f^{14} 5d^6 6s^2$ 190.20	Iridium Ir [Xe] $4f^{14} 5d^7 6s^2$ 192.22	Platinum Pt [Xe] $4f^{14} 5d^{10} 6s^0$ 195.09	Gold Au [Xe] $4f^{14} 5d^{10} 6s^1$ 196.97	Mercury Hg [Xe] $4f^{14} 5d^{10} 6s^2$ 200.59	Thallium Tl [Xe] $4f^{14} 5d^{10} 6s^2 6p^1$ 204.37	Lead Pb [Xe] $4f^{14} 5d^{10} 6s^2 6p^2$ 207.19	Bismuth Bi [Xe] $4f^{14} 5d^{10} 6s^2 6p^3$ 208.98	Polonium Po [Xe] $4f^{14} 5d^{10} 6s^2 6p^4$ 210	Astatine At [Xe] $4f^{14} 5d^{10} 6s^2 6p^5$ 210	Radon Rn [Xe] $4f^{14} 5d^{10} 6s^2 6p^6$ 222
Francium Fr [Rn] $7s^1$ 223	Radium Ra [Rn] $7s^2$ 226	Actinium Ac [Rn] $6d^1 7s^2$ 227																

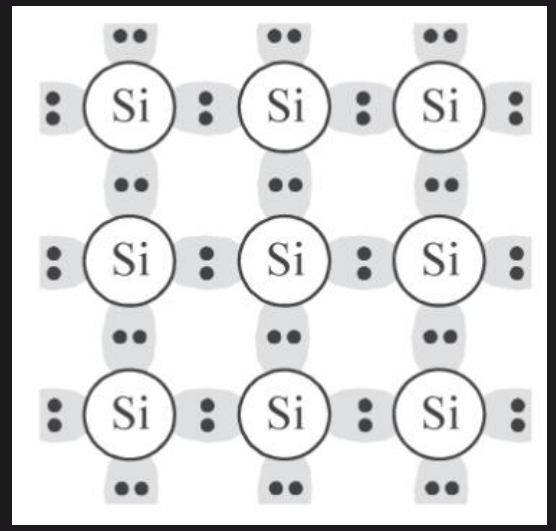
Rare earths

Lanthanides	Cerium Ce [Xe] $4f^2 5d^0 6s^2$ 140.12	Praseodymium Pr [Xe] $4f^3 5d^0 6s^2$ 140.91	Neodymium Nd [Xe] $4f^4 5d^0 6s^2$ 144.24	Promethium Pm [Xe] $4f^5 5d^0 6s^2$ 145	Samarium Sm [Xe] $4f^6 5d^0 6s^2$ 150.35	Europium Eu [Xe] $4f^7 5d^0 6s^2$ 151.96	Gadolinium Gd [Xe] $4f^7 5d^1 6s^2$ 157.25	Terbium Tb [Xe] $4f^9 5d^0 6s^2$ 158.92	Dysprosium Dy [Xe] $4f^{10} 5d^0 6s^2$ 162.50	Holmium Ho [Xe] $4f^{11} 5d^0 6s^2$ 164.93	Erbium Er [Xe] $4f^{12} 5d^0 6s^2$ 167.26	Thulium Tm [Xe] $4f^{13} 5d^0 6s^2$ 168.93	Ytterbium Yb [Xe] $4f^{14} 5d^0 6s^2$ 173.04	Lutetium Lu [Xe] $4f^{14} 5d^1 6s^2$ 174.97
Actinides	Thorium Th [Rn] $6d^2 7s^2$ 232.04	Protactinium Pa [Rn] $5f^2 6d^1 7s^2$ 231	Uranium U [Rn] $5f^3 6d^1 7s^2$ 238.03	Neptunium Np [Rn] $5f^5 6d^0 7s^2$ 237.05	Plutonium Pu [Rn] $5f^6 6d^0 7s^2$ 244	Americium Am [Rn] $5f^7 6d^0 7s^2$ 243	Curium Cm [Rn] $5f^7 6d^1 7s^2$ 247	Berkelium Bk [Rn] $5f^7 6d^2 7s^2$ 247	Californium Cf [Rn] $5f^9 6d^1 7s^2$ 251	Einsteinium Es	Fermium Fm	Mendelevium Md	Nobelium No	Lawrencium Lw

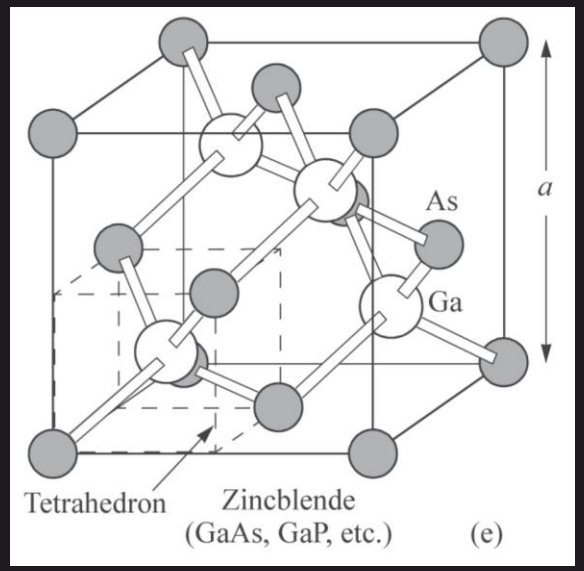
Semicondutores

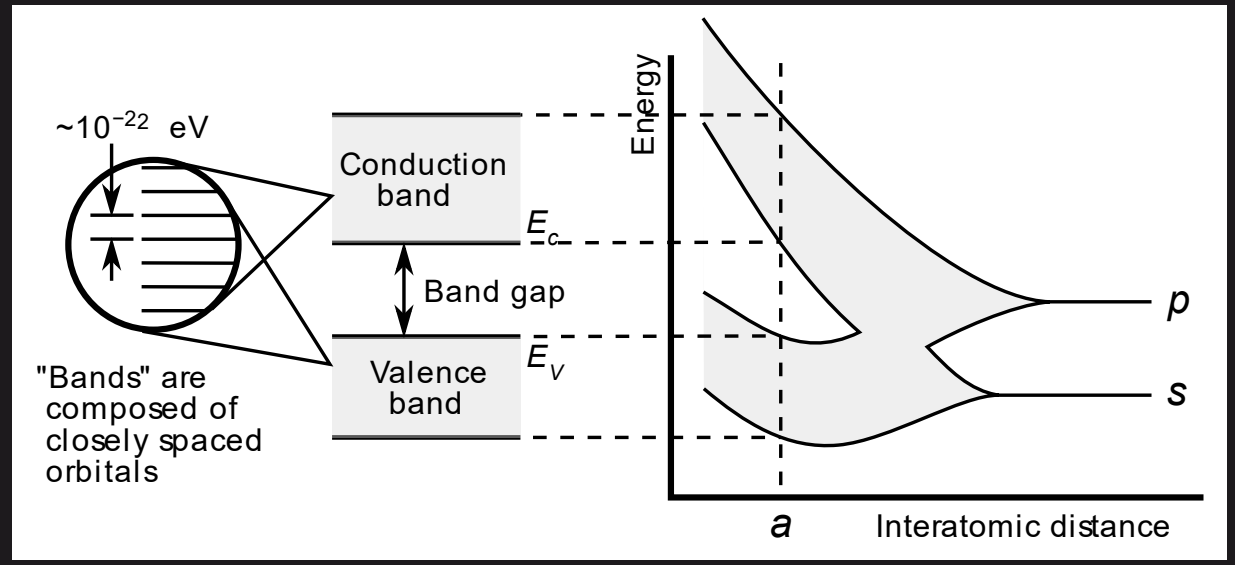
IIIA	IVA	VA
Boron B $1s^2 2s^2 2p$ 10.81	Carbon C $1s^2 2s^2 2p^2$ 12.01	Nitrogen N $1s^2 2s^2 2p^3$ 14.007
Aluminum Al $[Ne]\ 3s^2 3p^1$ 26.982	Silicon Si $[Ne]\ 3s^2 3p^2$ 28.086	Phosphorous P $[Ne]\ 3s^2 3p^3$ 30.974
Gallium Ga $[Ar]\ 3d^{10} 4s^2 4p^1$ 69.72	Germanium Ge $[Ar]\ 3d^{10} 4s^2 4p^2$ 72.59	Arsenic As $[Ar]\ 3d^{10} 4s^2 4p^3$ 74.922
Indium In $[Kr]\ 4d^{10} 5s^2 5p^1$ 114.82	Tin Sn $[Kr]\ 4d^{10} 5s^2 5p^2$ 118.69	Antimony Sb $[Kr]\ 4d^{10} 5s^2 5p^3$ 121.75
Thallium Tl $[Xe]\ 4f^{14} 5d^{10} 6s^2 6p^1$ 204.37	Lead Pb $[Xe]\ 4f^{14} 5d^{10} 6s^2 6p^2$ 207.19	Bismuth Bi $[Xe]\ 4f^{14} 5d^{10} 6s^2 6p^3$ 208.98





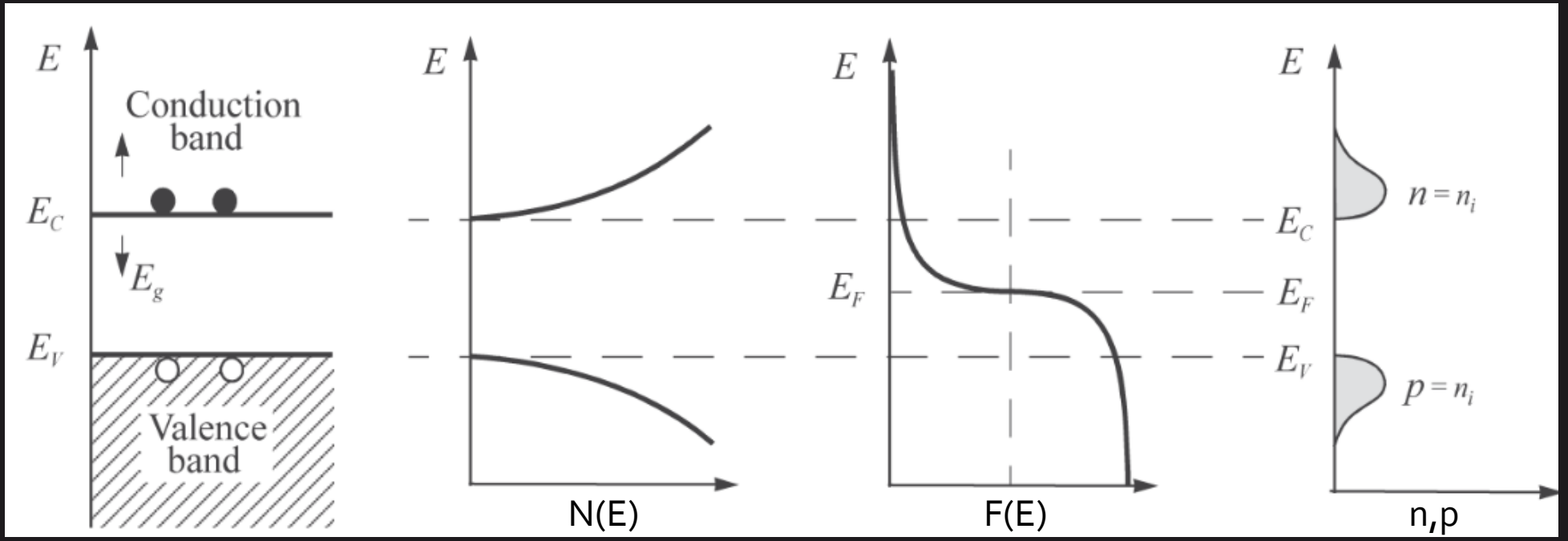
Si:
$E_g = 1.12$ eV
$E(\text{par e+h}) \sim 3.6$ eV
~ 100 pares e+h / μm (MIP)

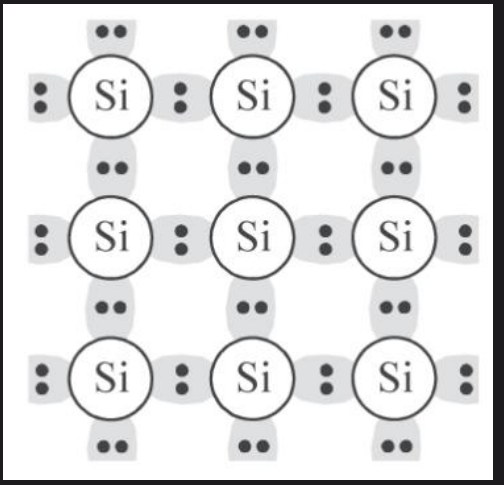




https://commons.wikimedia.org/w/index.php?curid=56983339

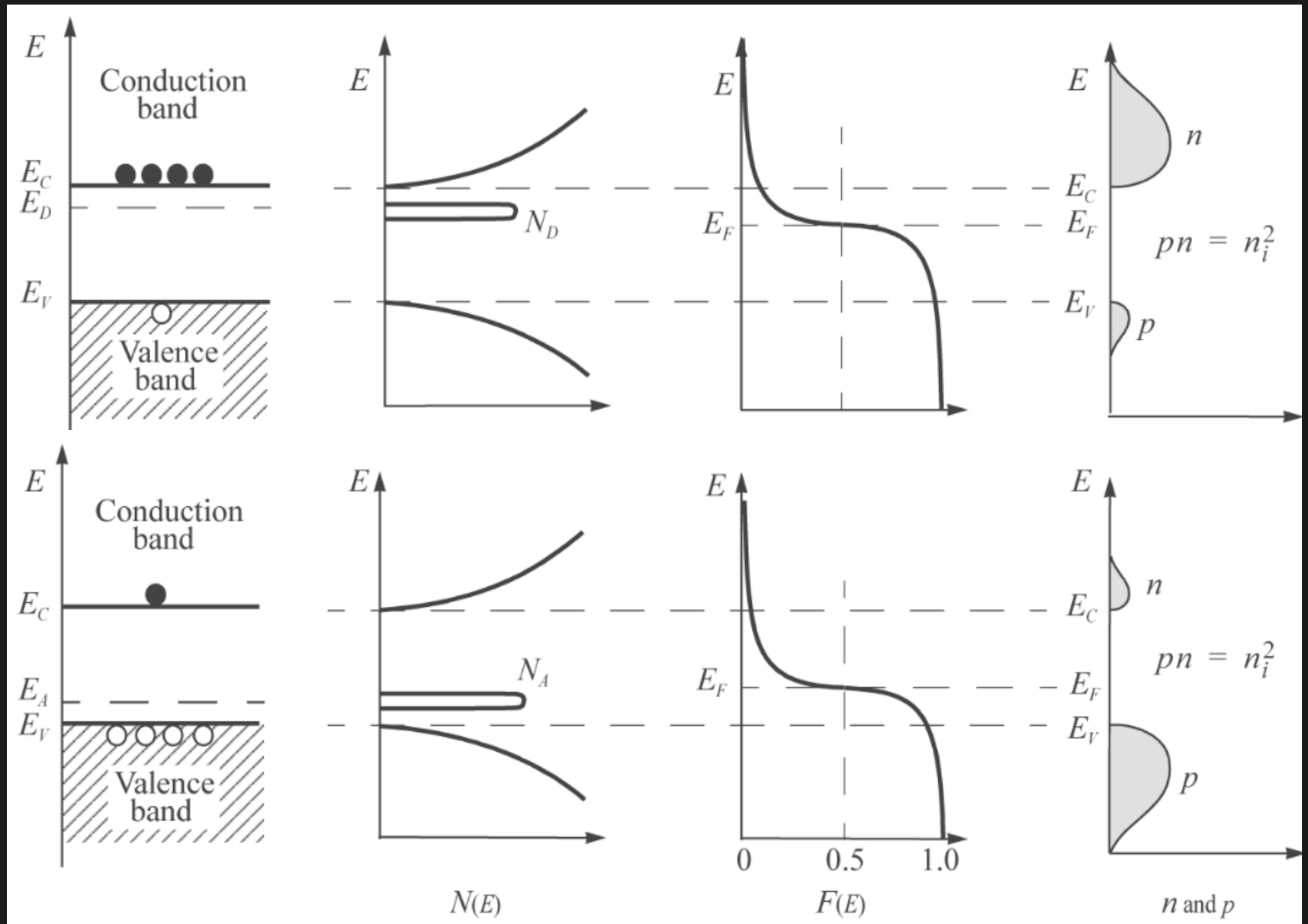
Semicondutores (intrínsecos)



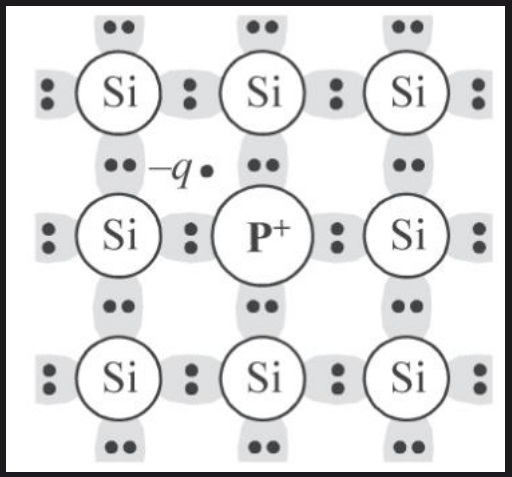


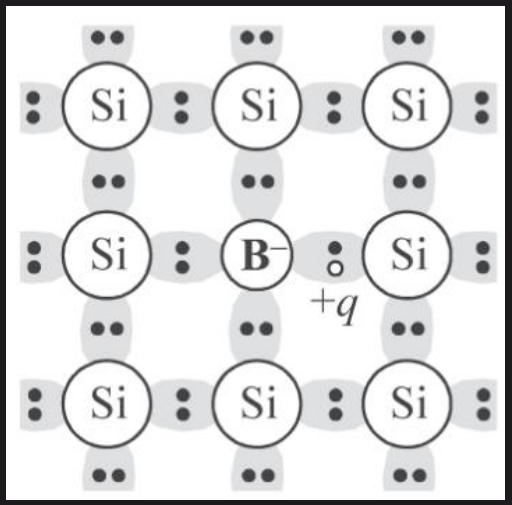
Portadores de carga negativa (elétrons) e positiva (buracos) com alta *mobilidade* na rede cristalina.

Semicondutores (extrínsecos)



tipo-n, excesso de portadores de carga negativa (elétrons)

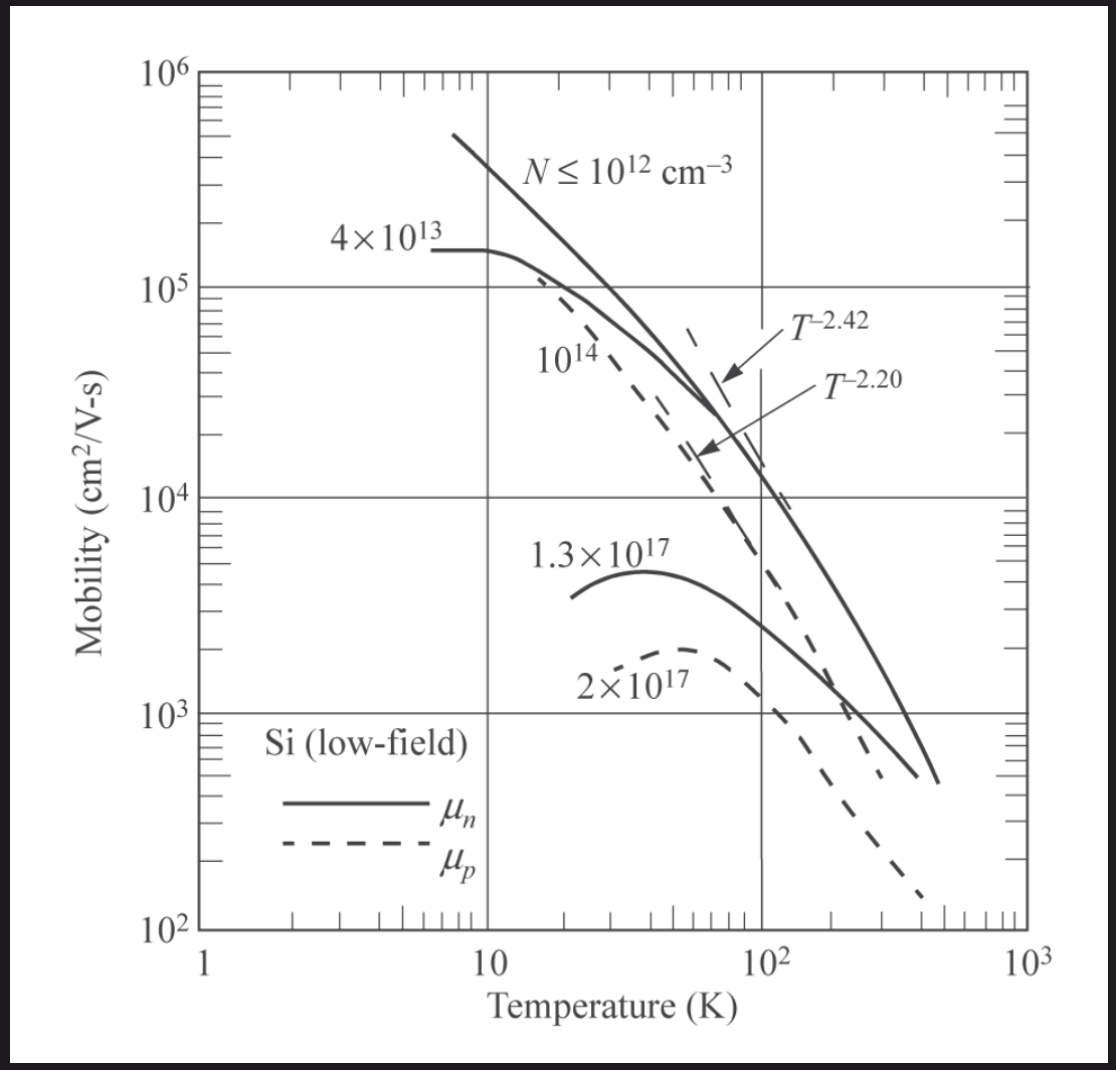




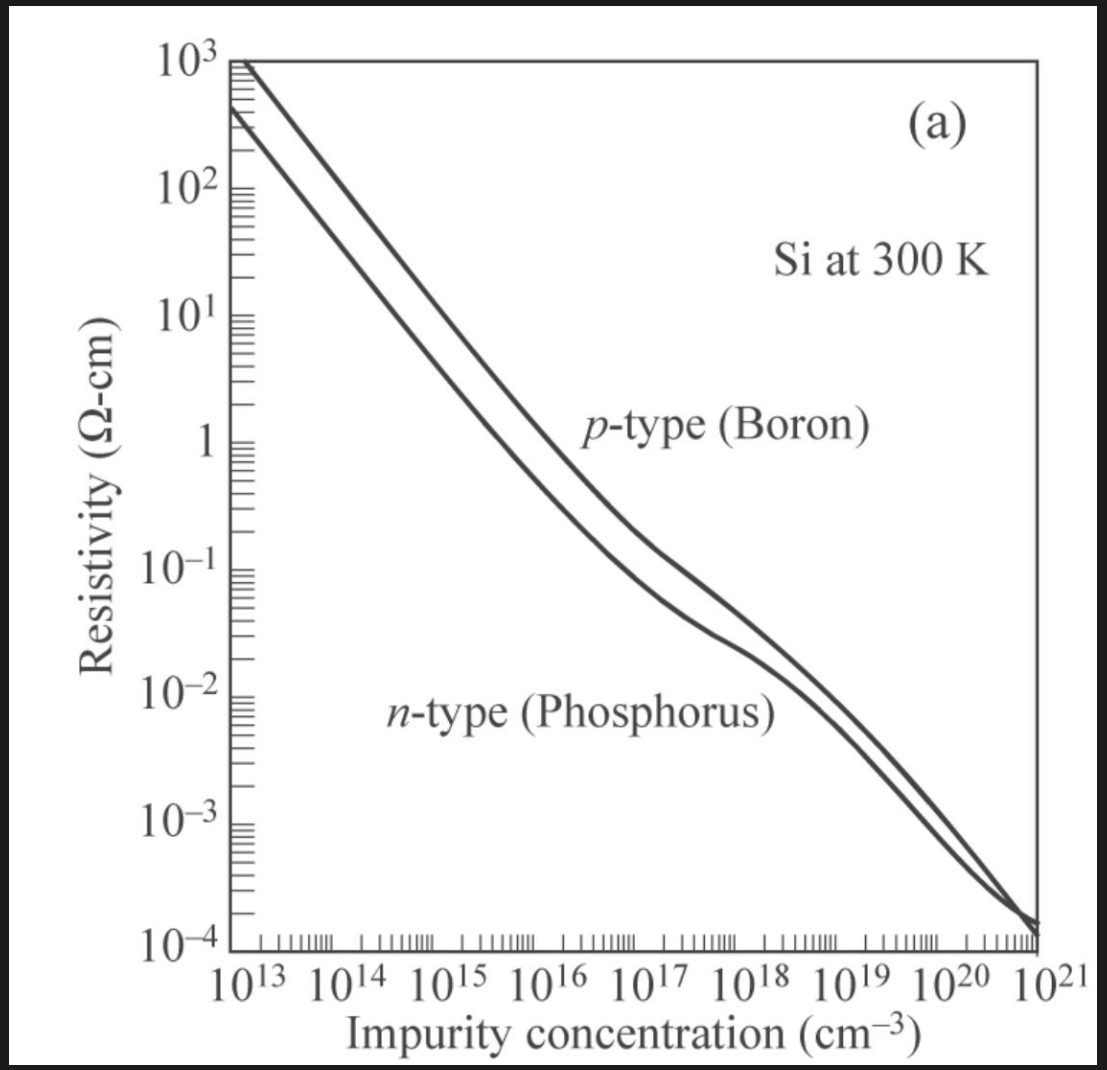
tipo-p, excesso de portadores de carga positiva (buracos)

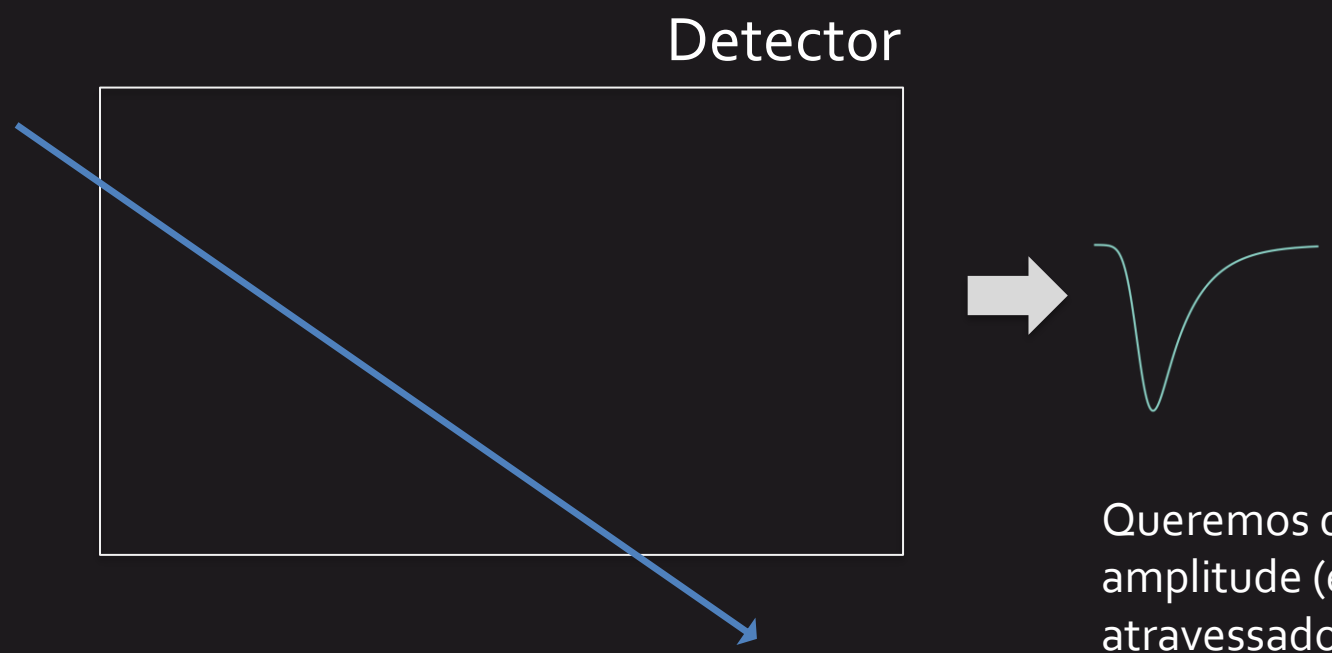
Semicondutores (extrínsecos)

Mobilidade $(v_d = \mu\,\mathcal{E})$



Resistividade



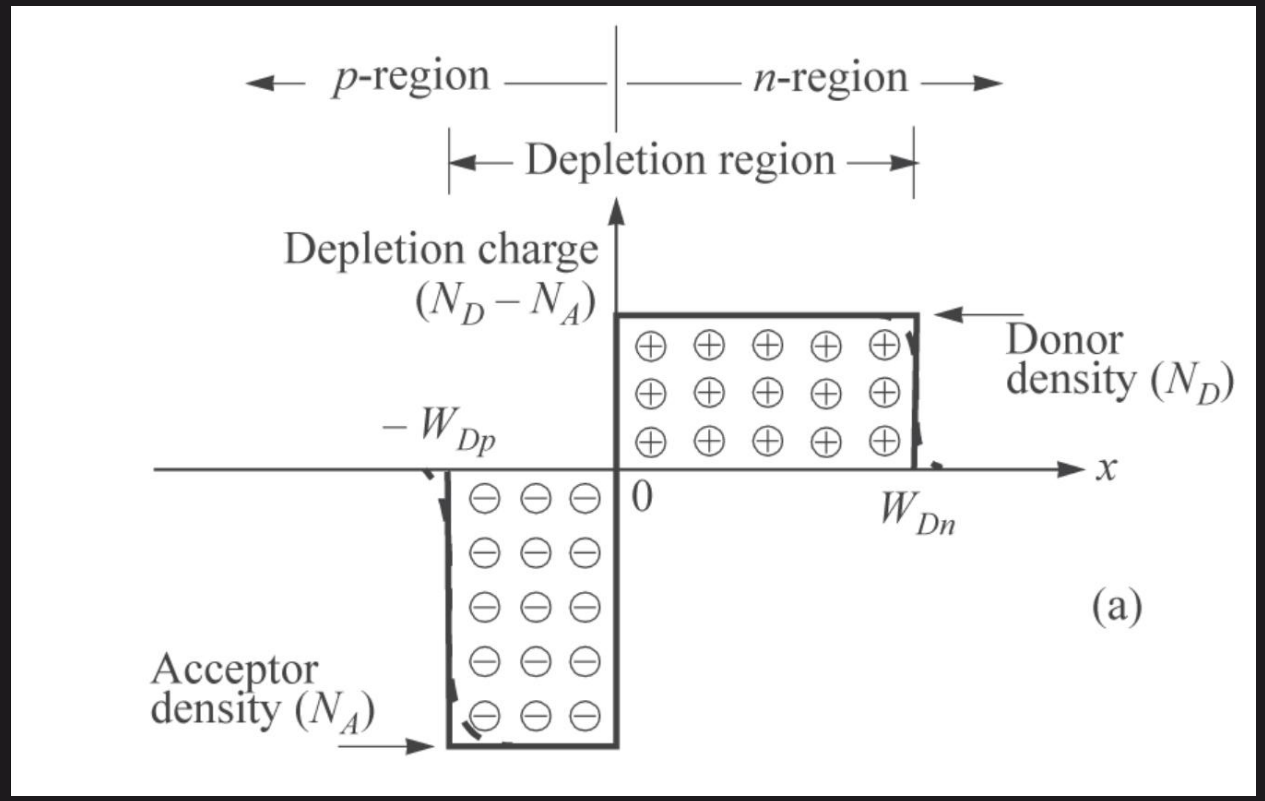


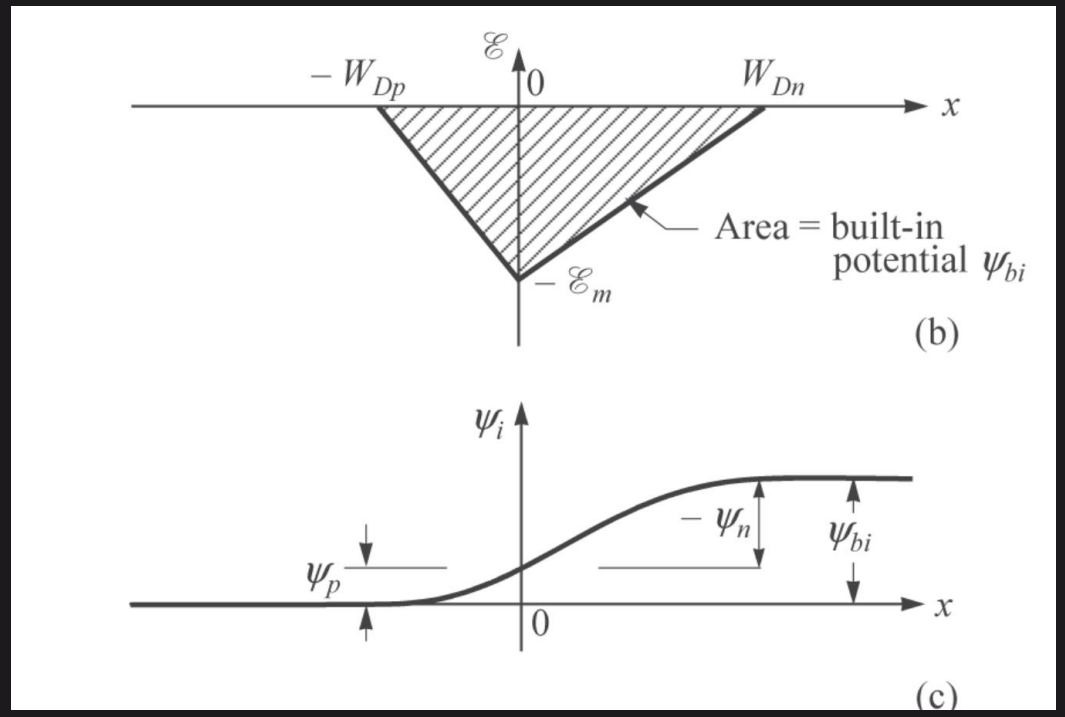
Queremos dispositivos que apresentem sinal com alta amplitude (e idealmente rápidos) ao serem atravessados por partículas incidentes, e baixo sinal na ausência de radiação incidente (ruído/fundo).

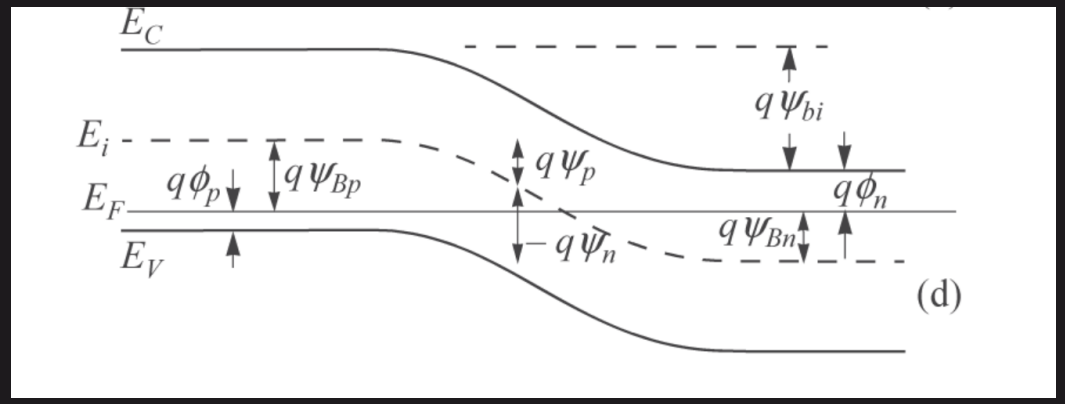
Energia entre bandas de semicondutores na faixa de poucos eV.

→ Junção p-n reversamente polarizada.

Junção p-n

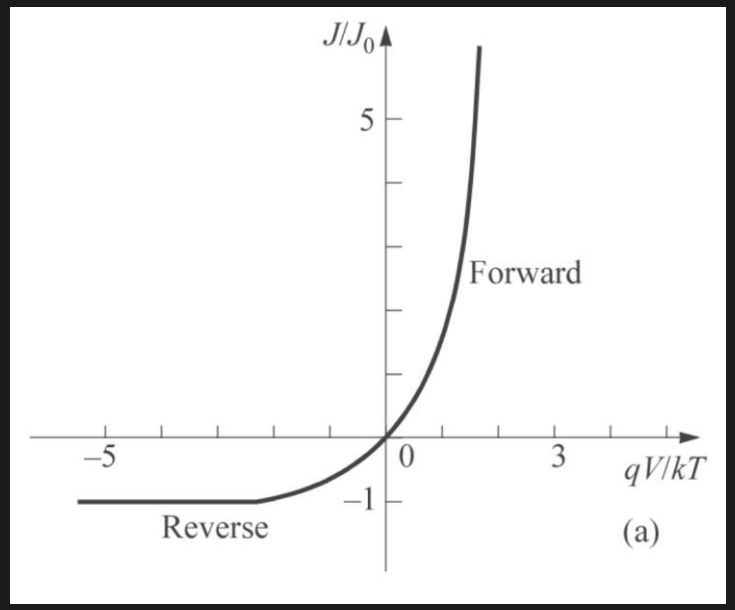


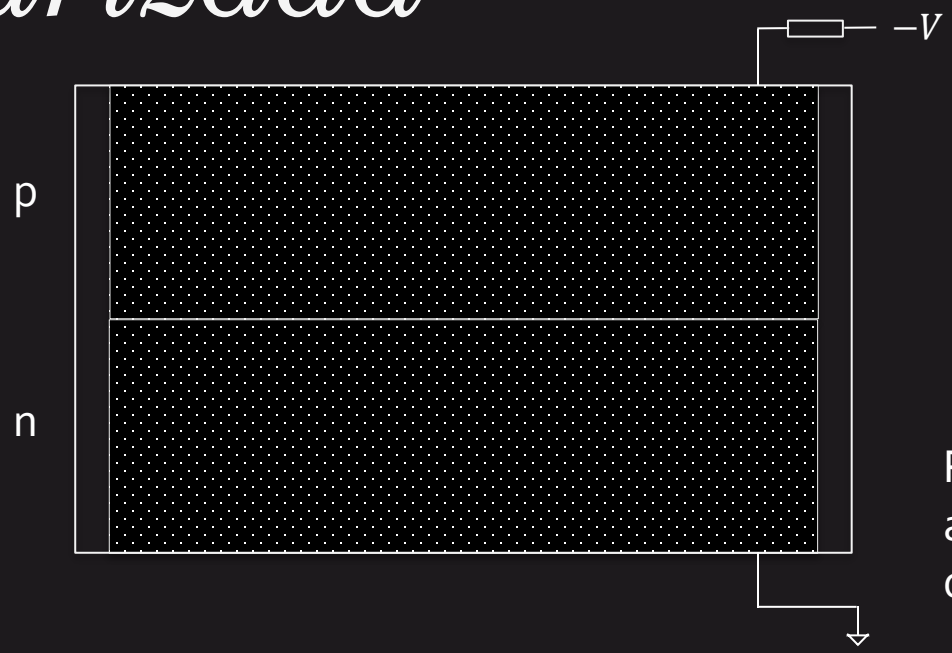




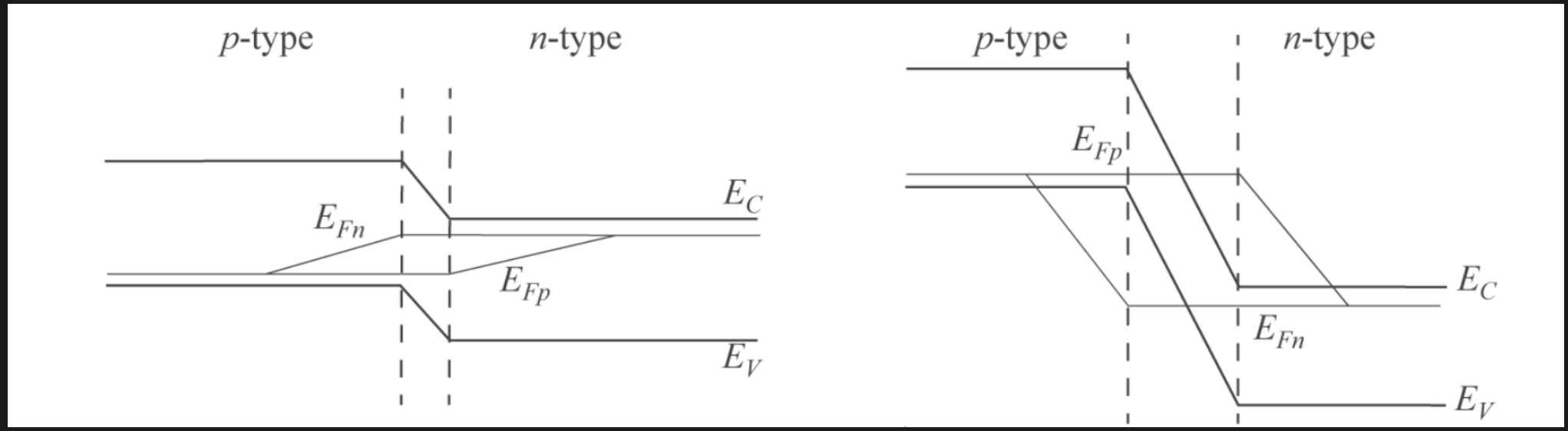
Junção p-n cria *região de depleção* que suprime movimento de cargas.

Junção p-n polarizada





Polarização reversa aumenta região de depleção

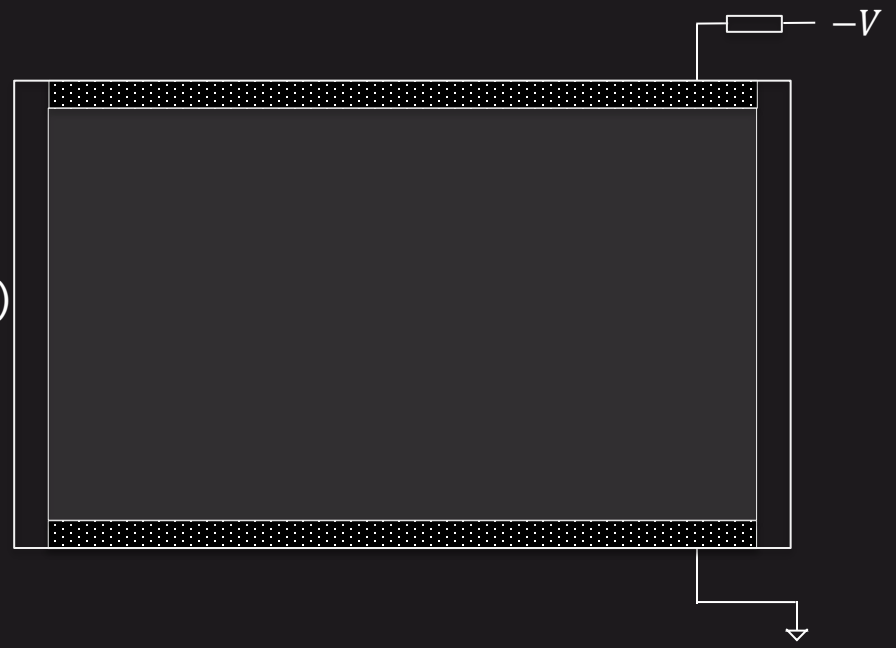


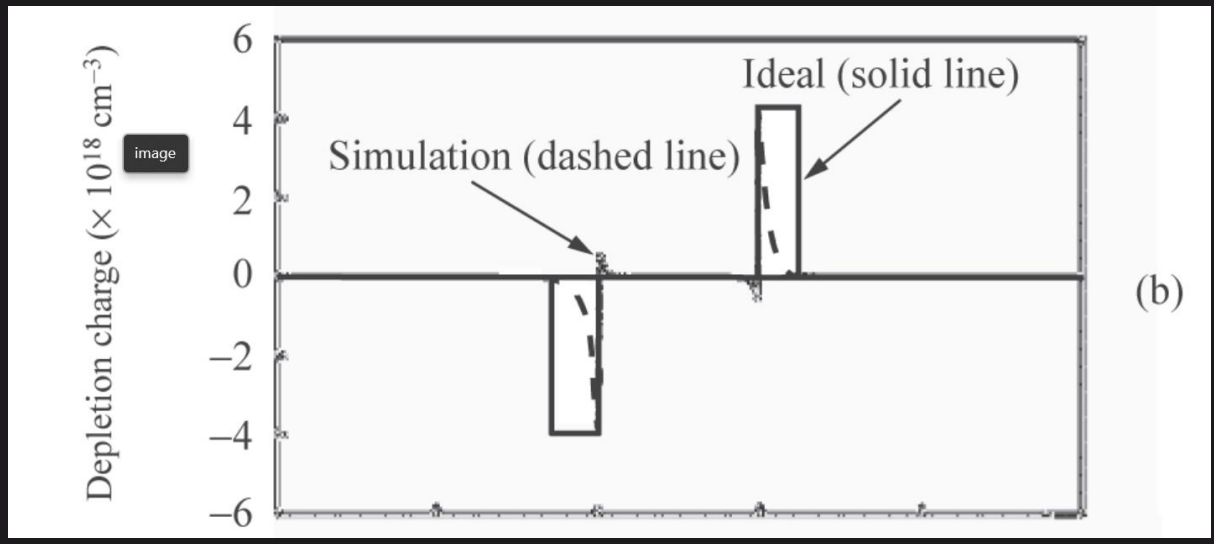
p-i-n

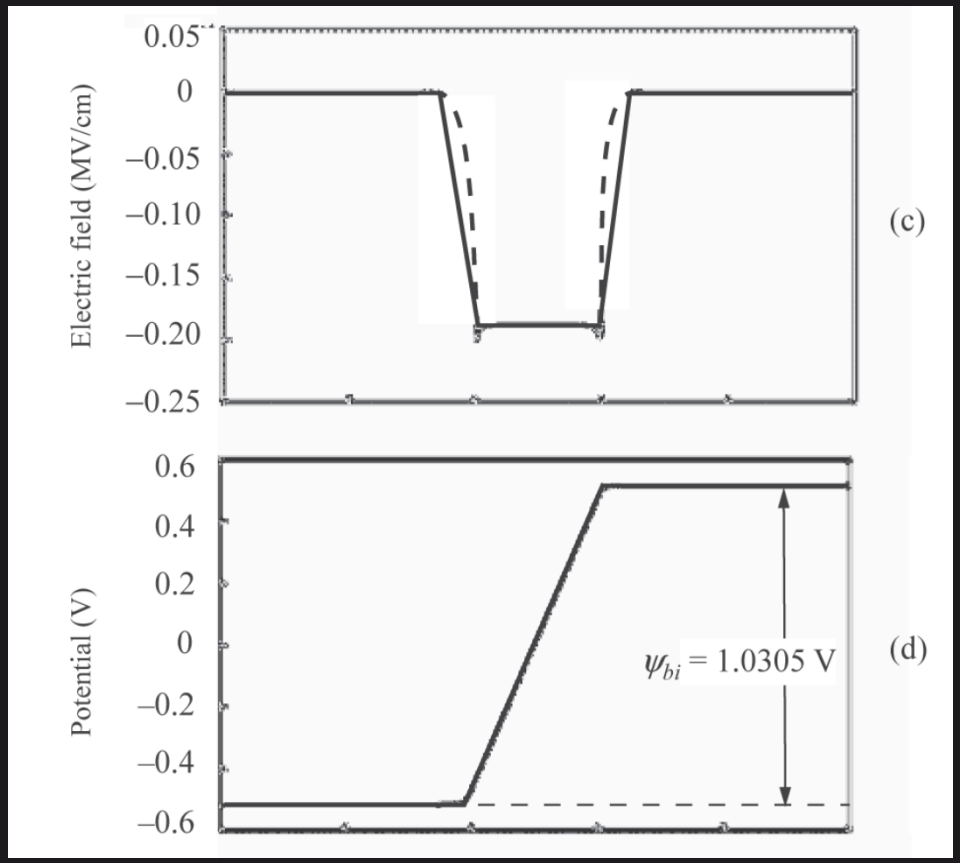
alta concentração p p+

intrínseco (i) ou baixa concentração n ou p i(n,p)

alta concentração n n+

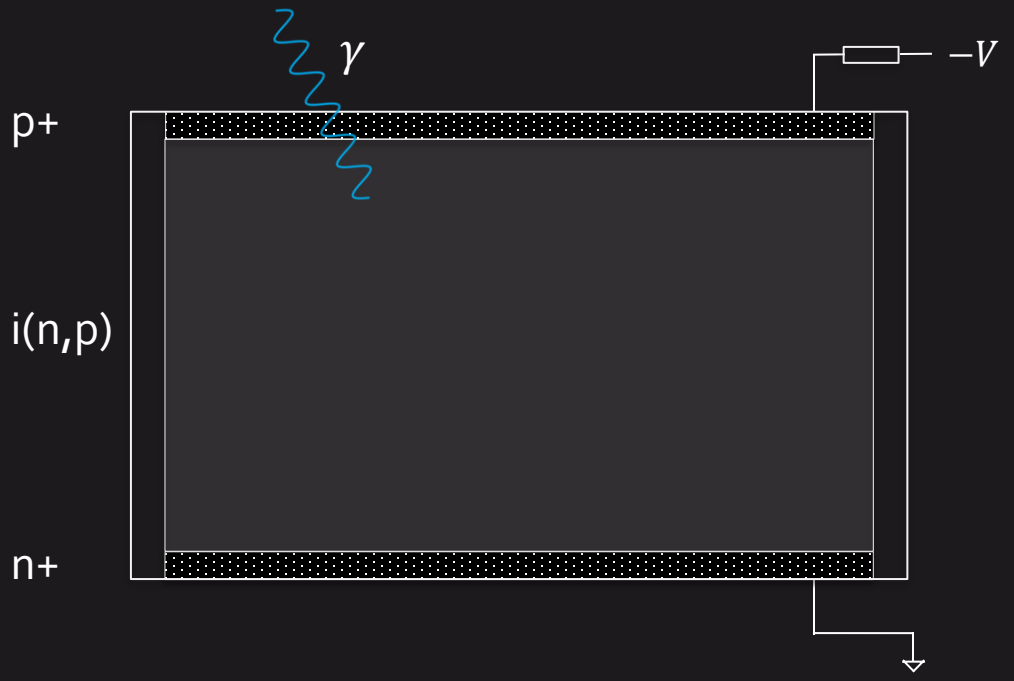


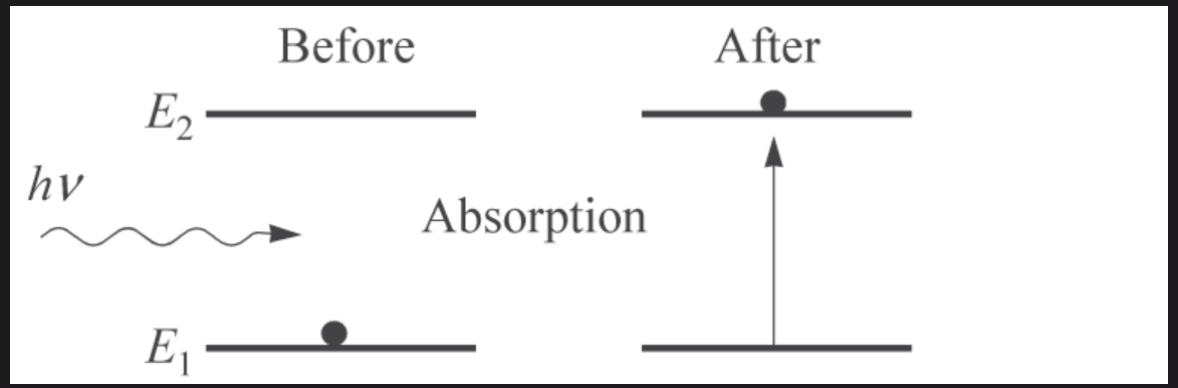




Semicondutores – Fososensores

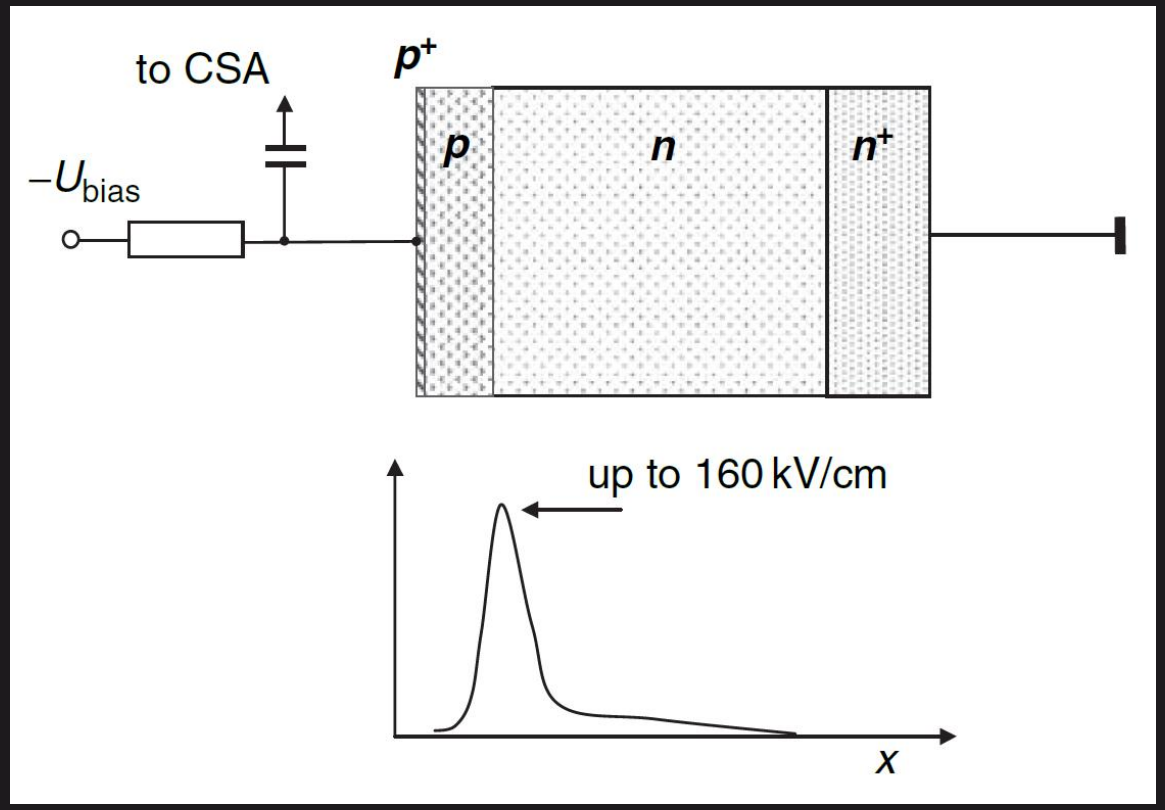
Fotodiodos

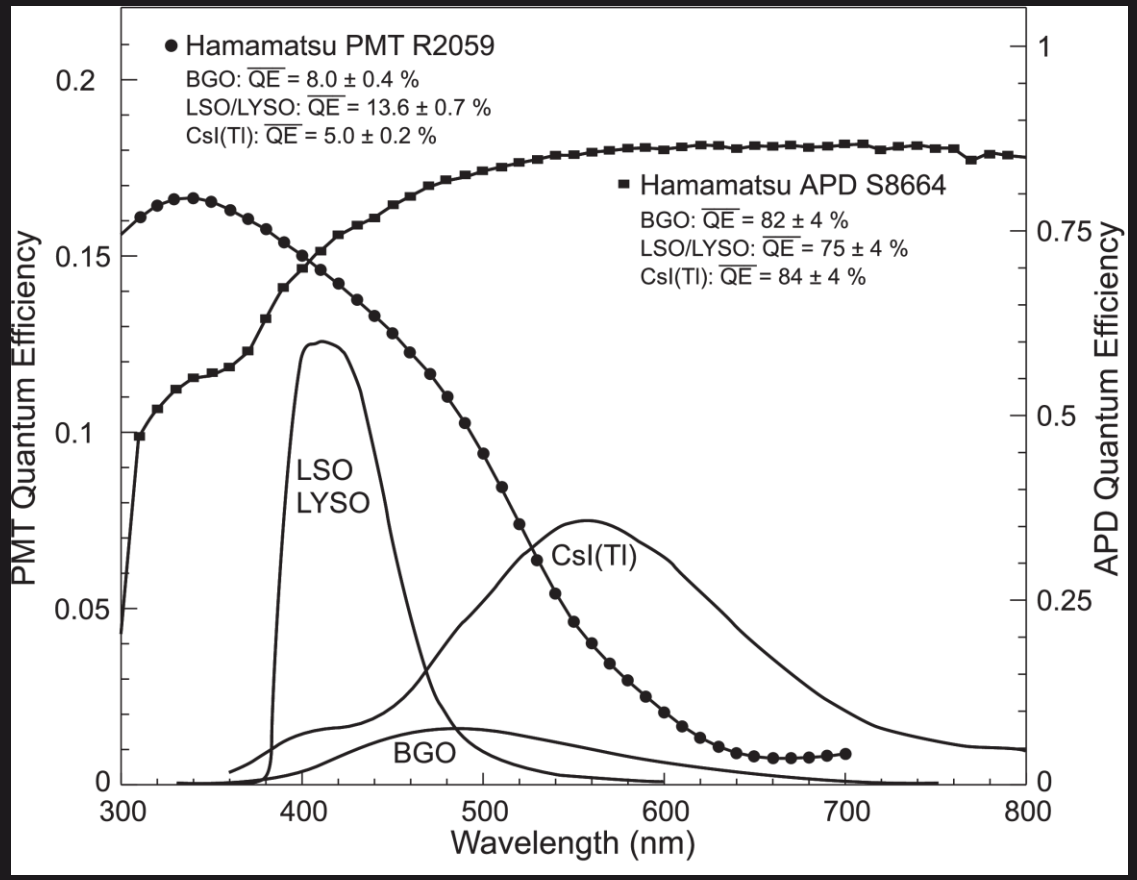




APDs e SiPMs

Avalanche Photodiode (APD)

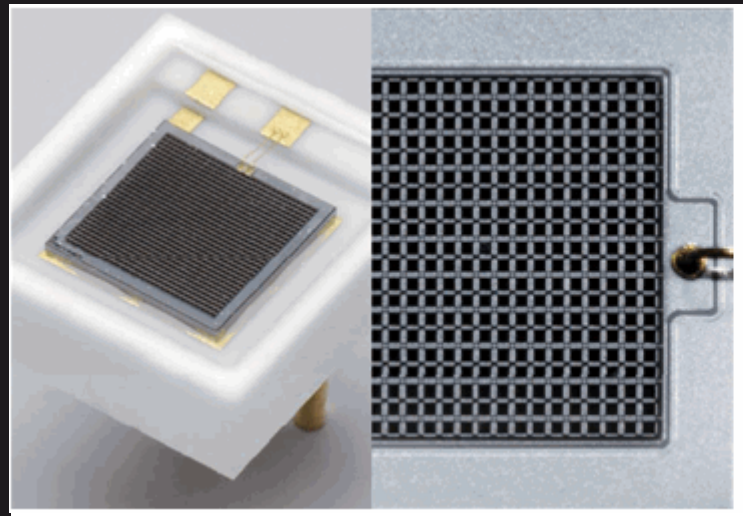


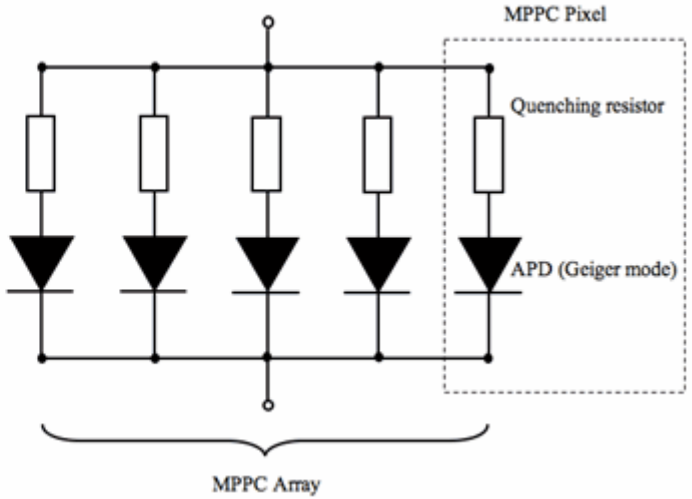


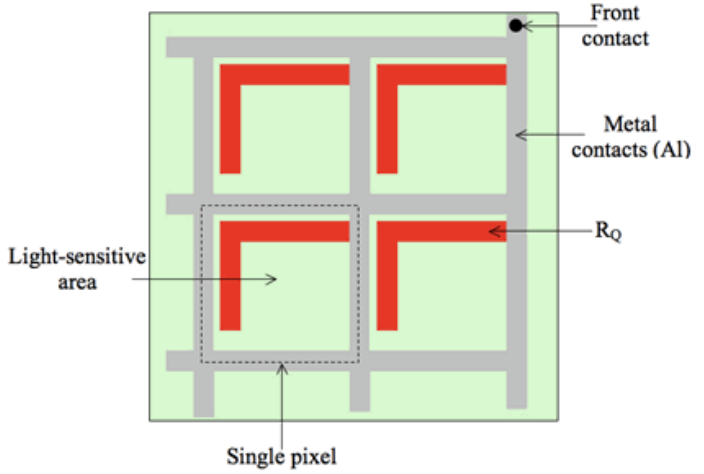
Possível operar APD em modo *breakdown*

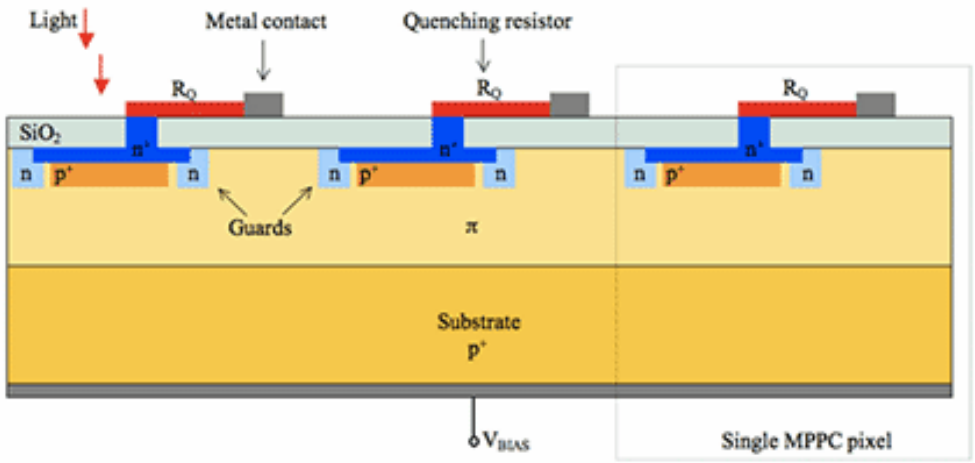
Multi-Pixel Photon Counter – SiPM

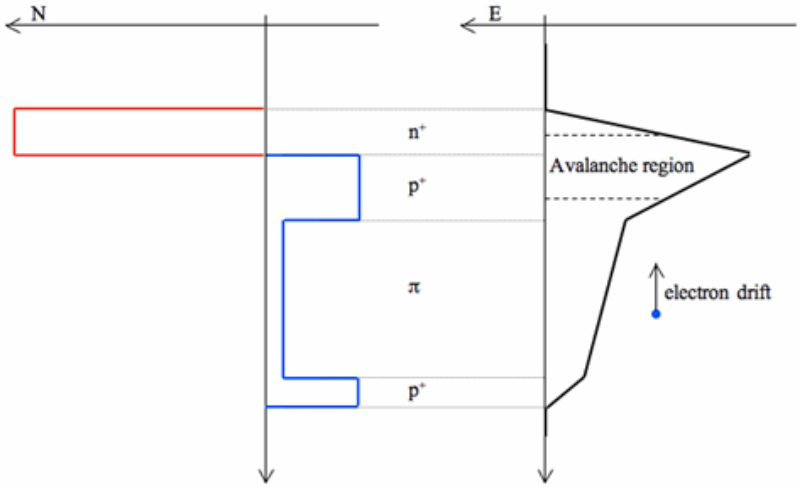
Operação em sobretensão à tensão de breakdown da APD



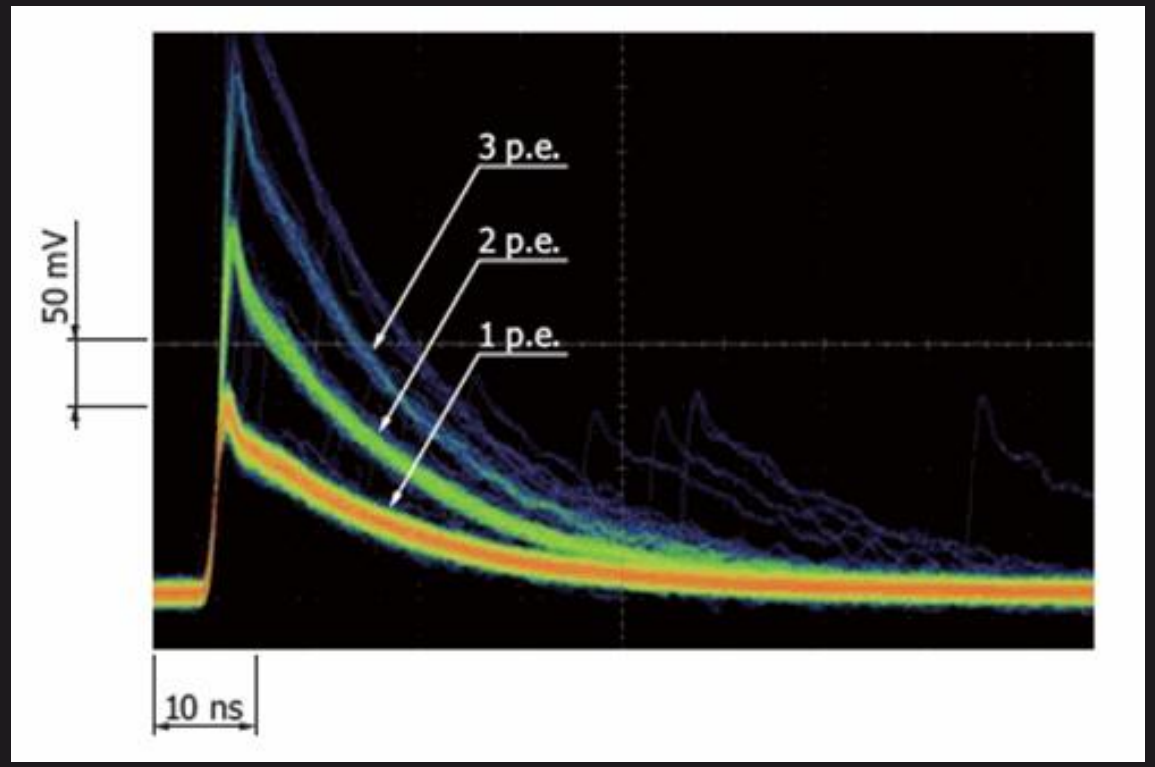


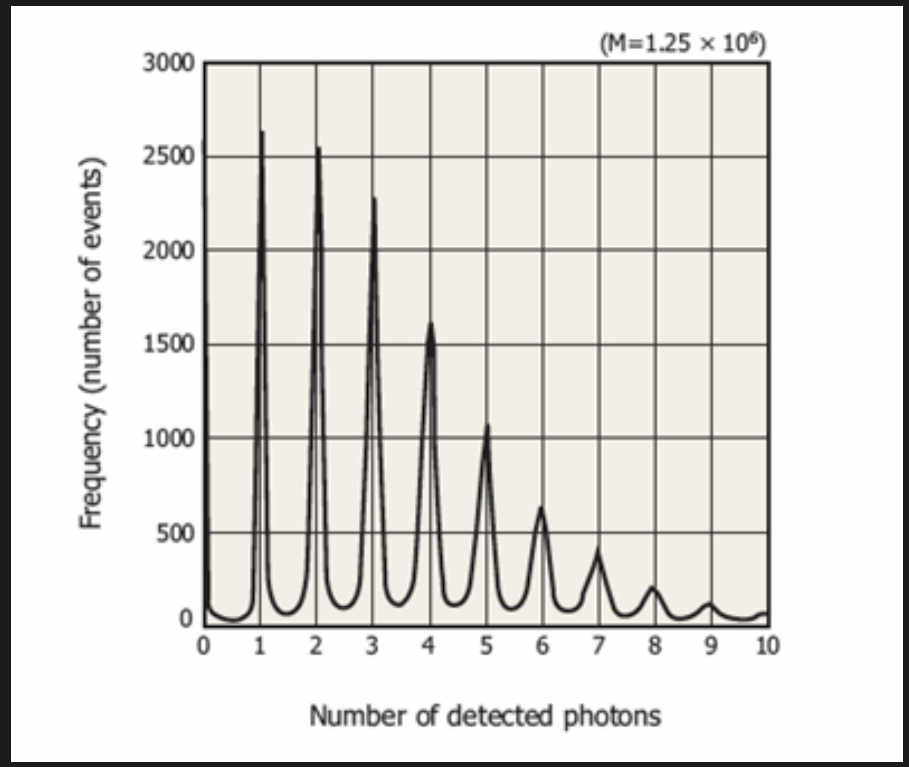




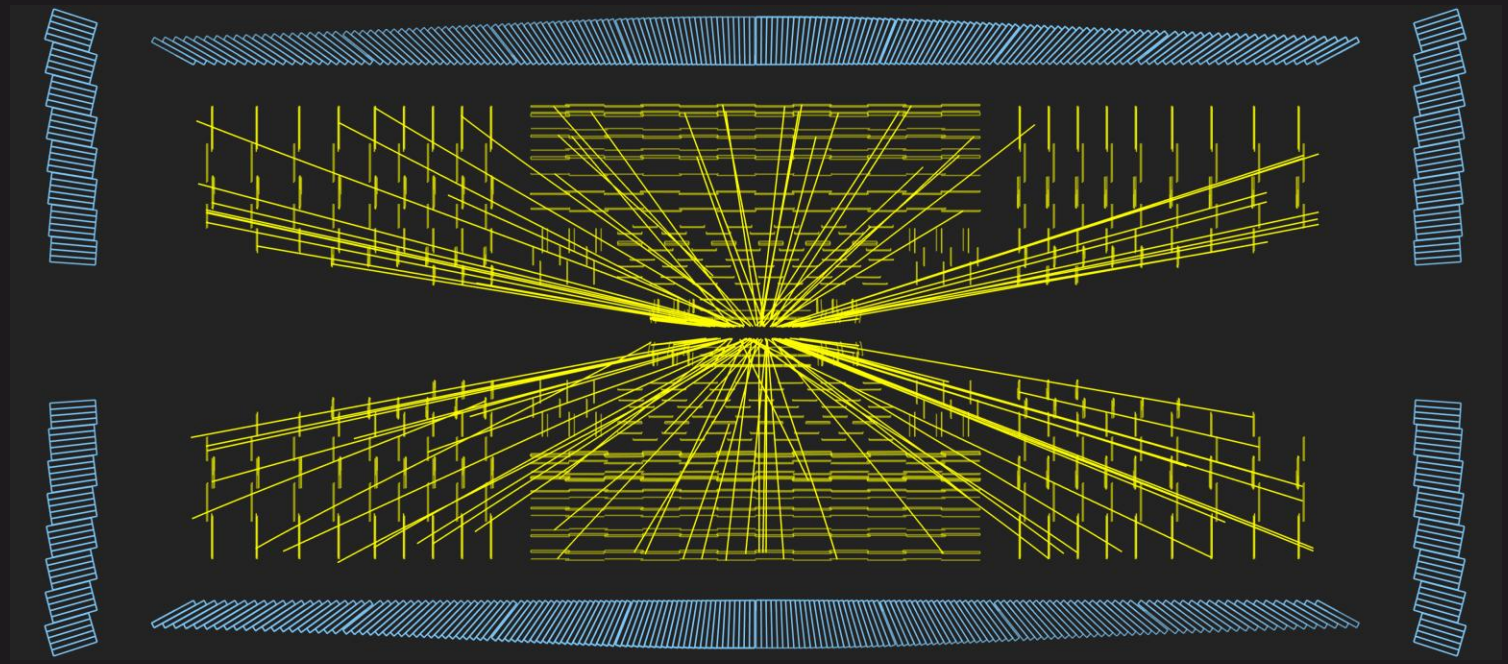


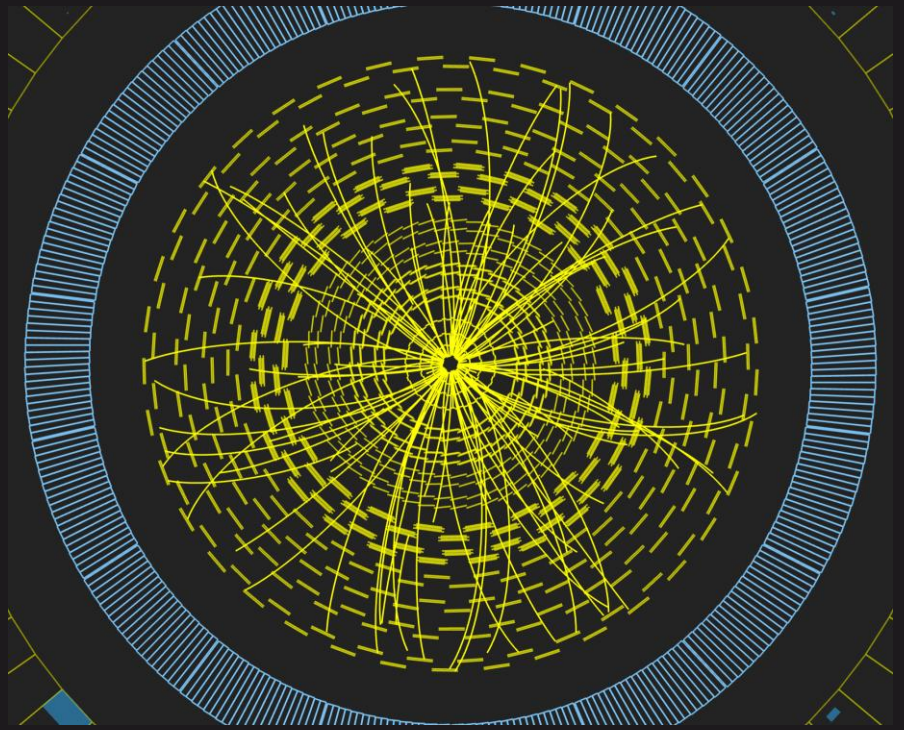
Multi-Pixel Photon Counter – SiPM



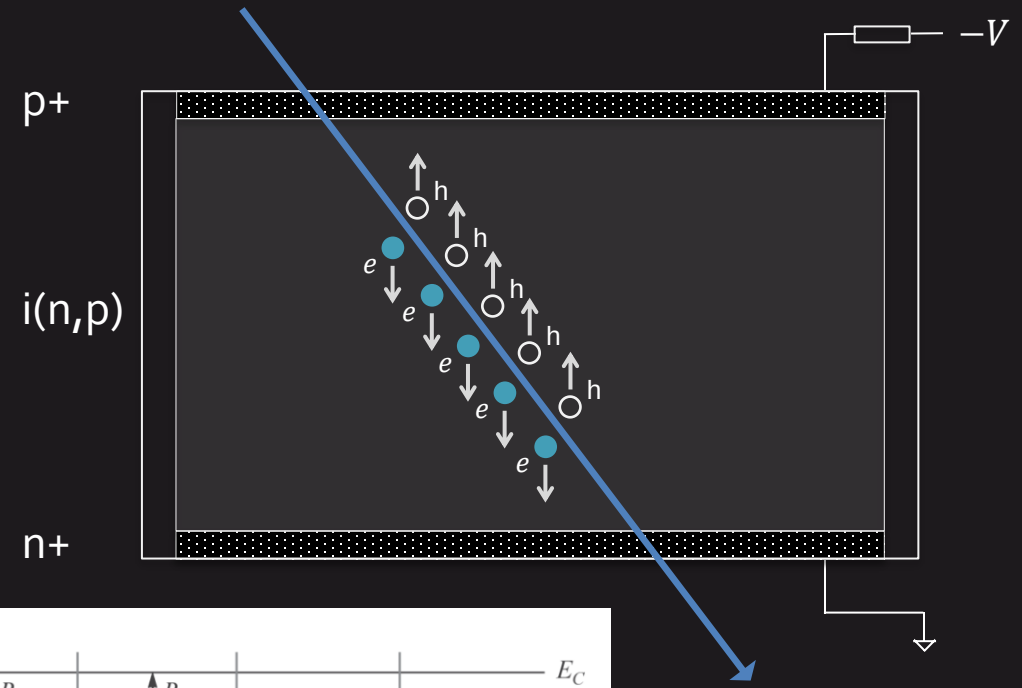


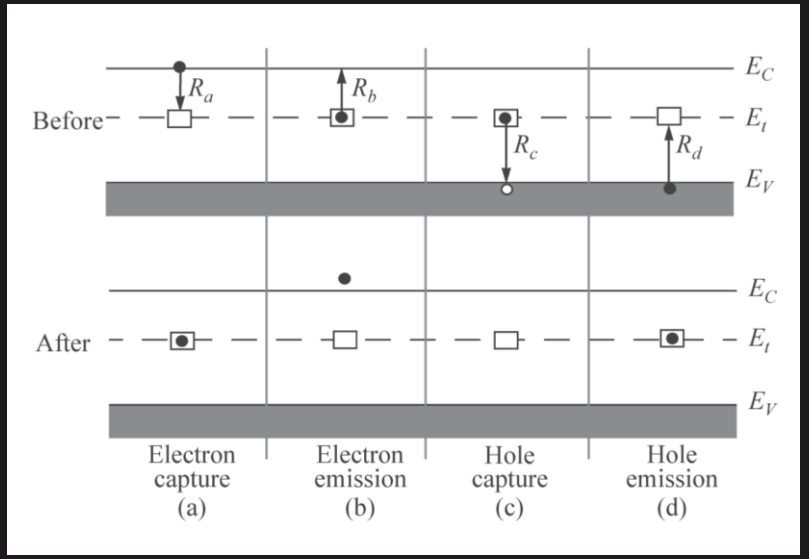
Detectores de traços (tracker)

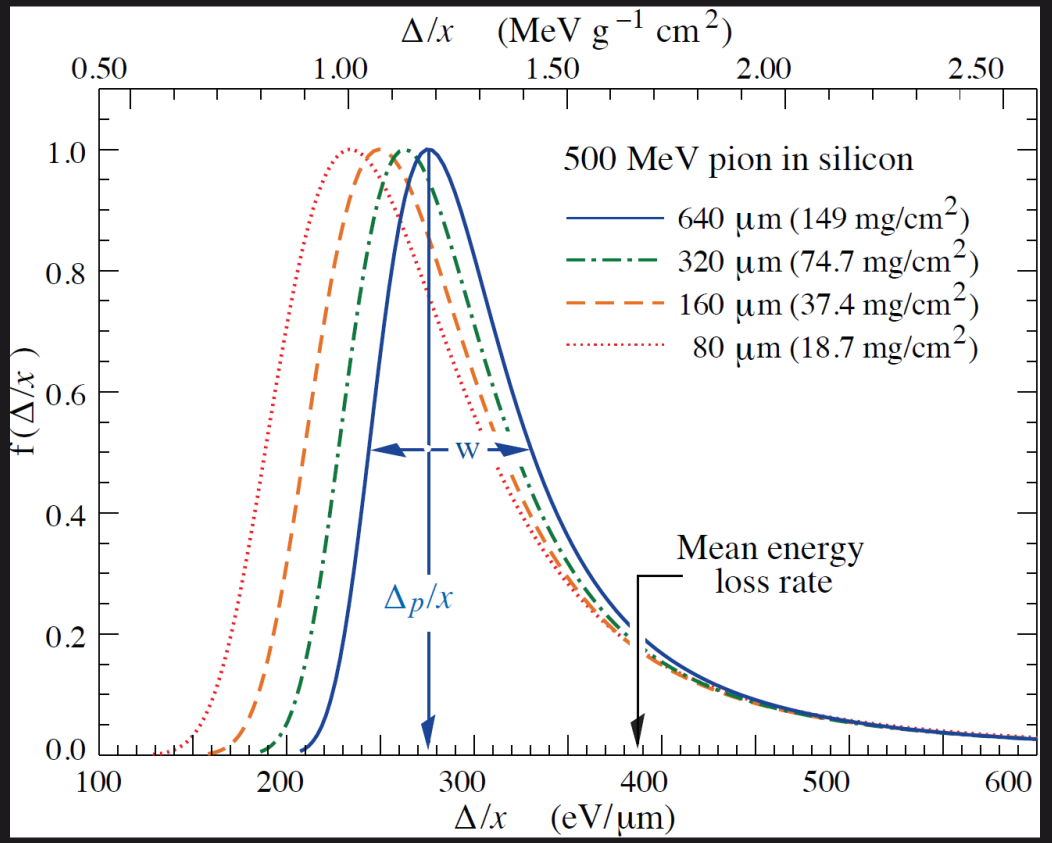




Geração de cargas – dE/dx

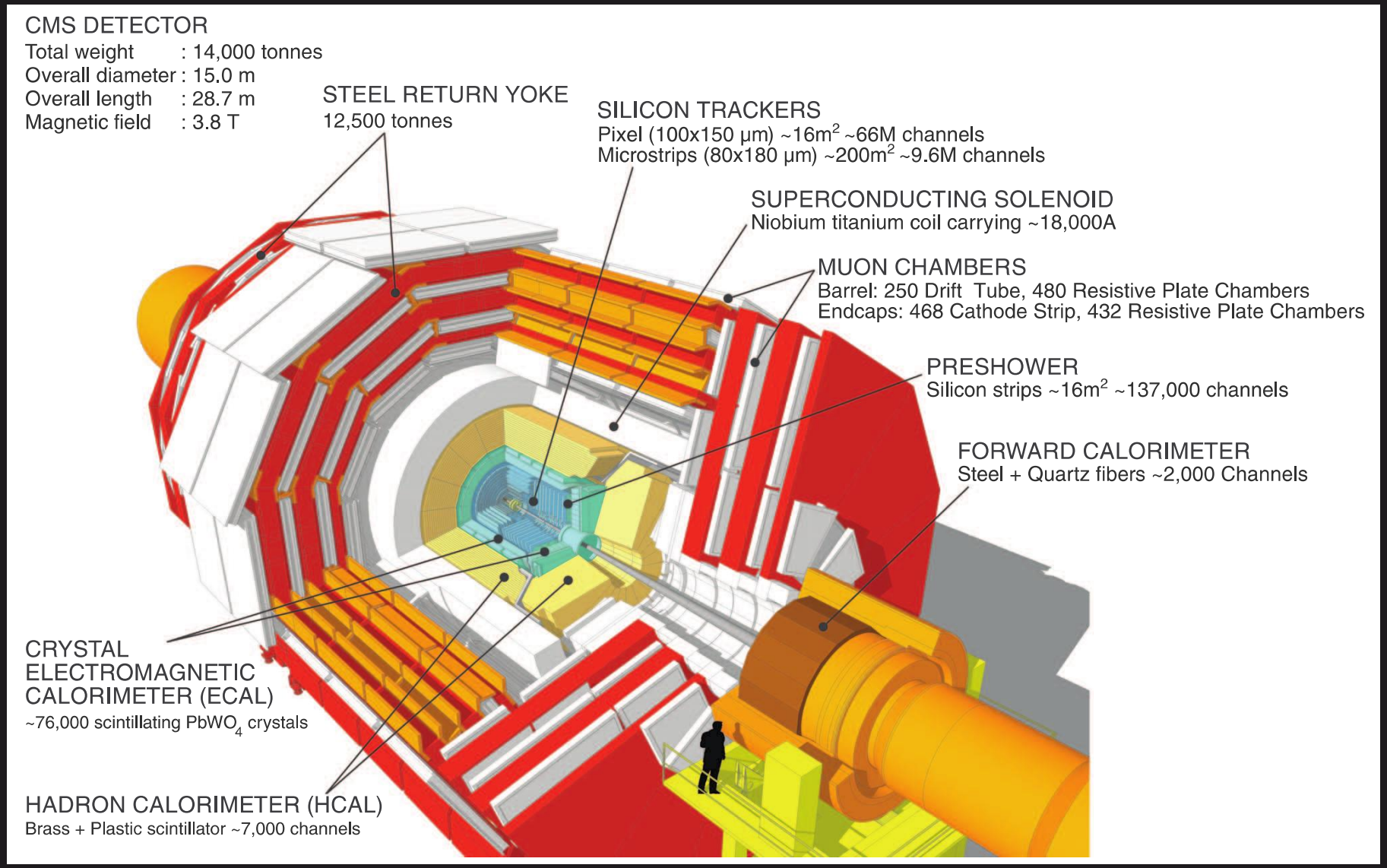




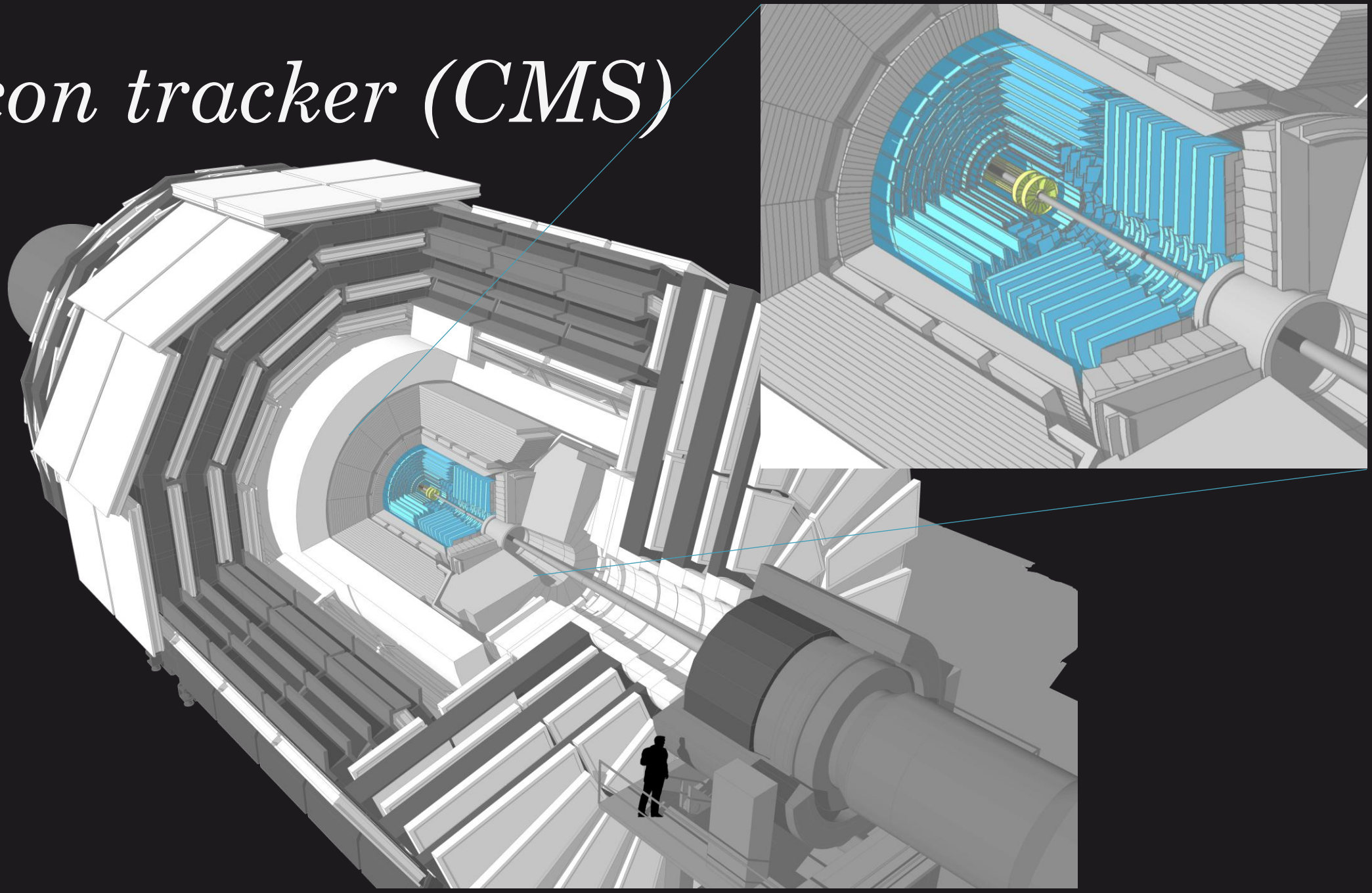


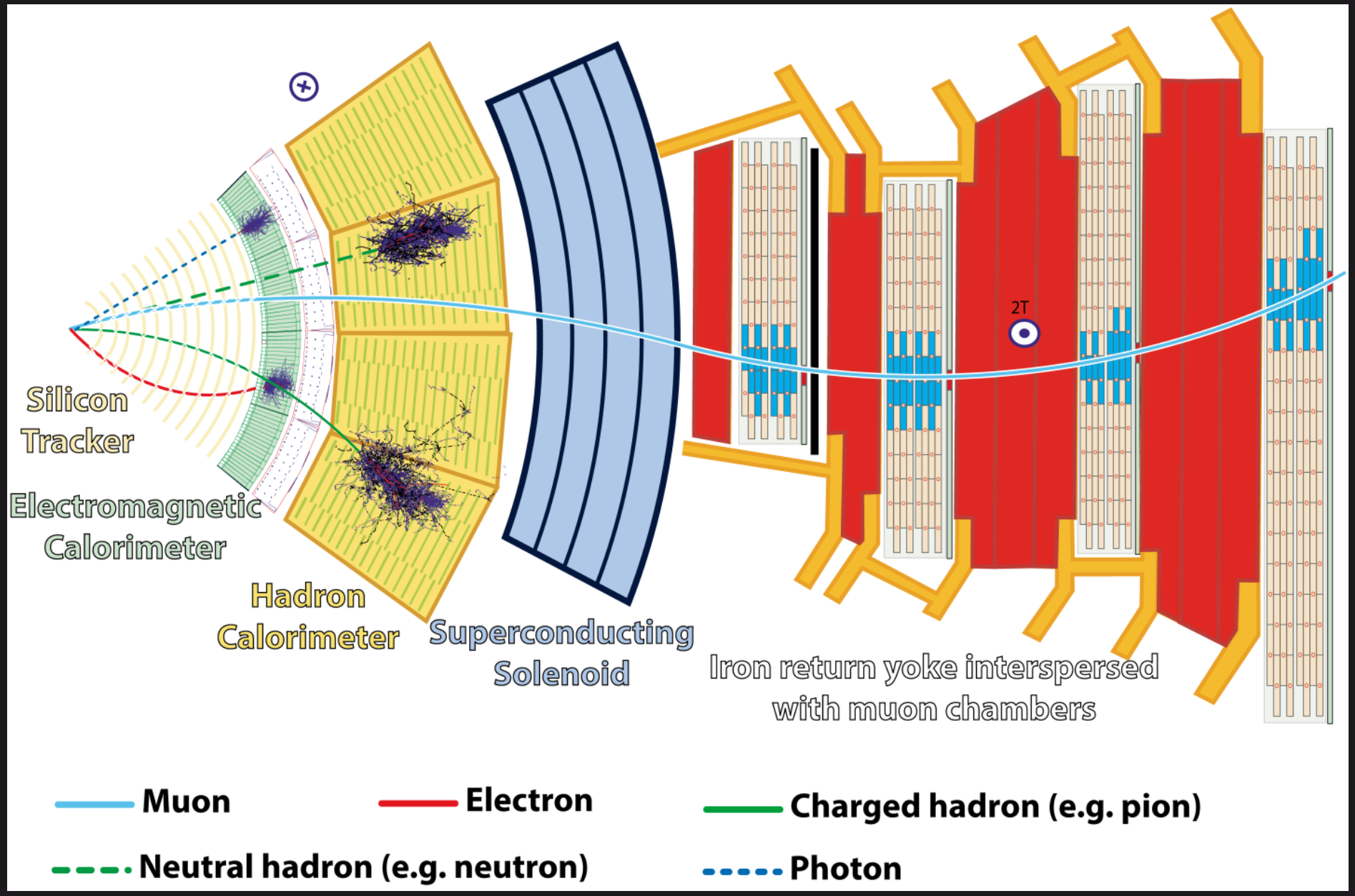
PDG

Silicon tracker (CMS)

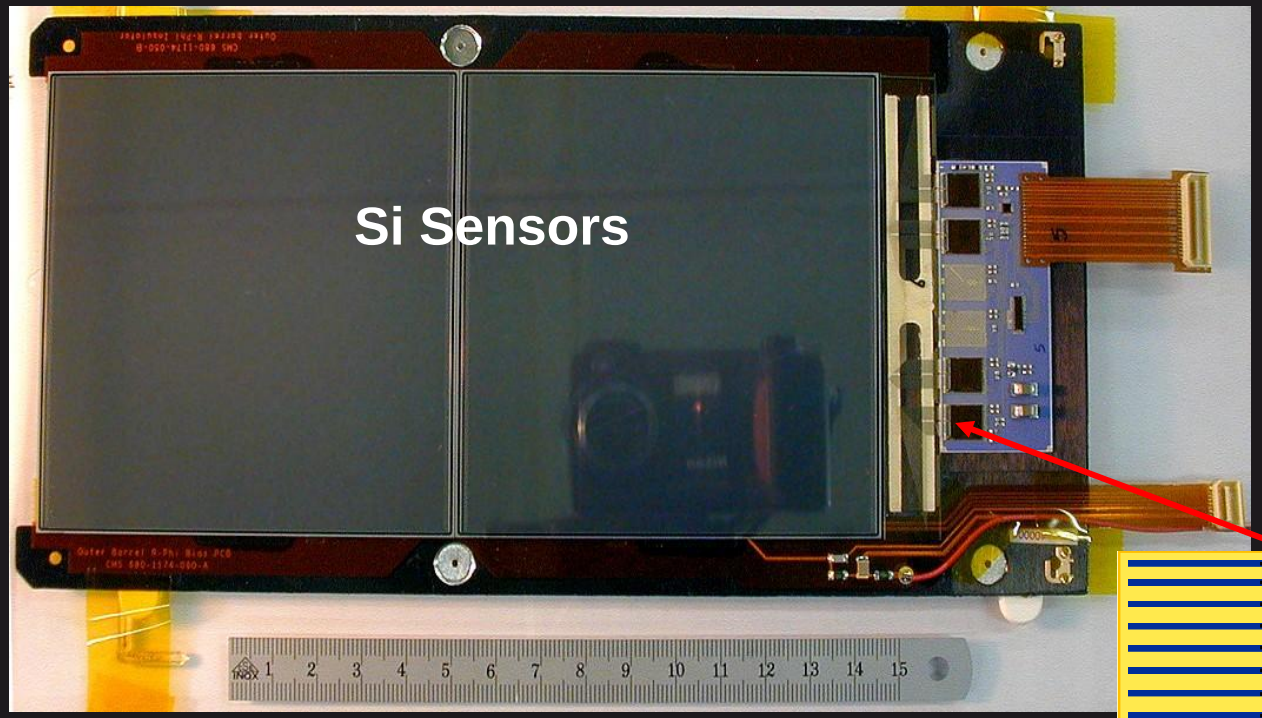


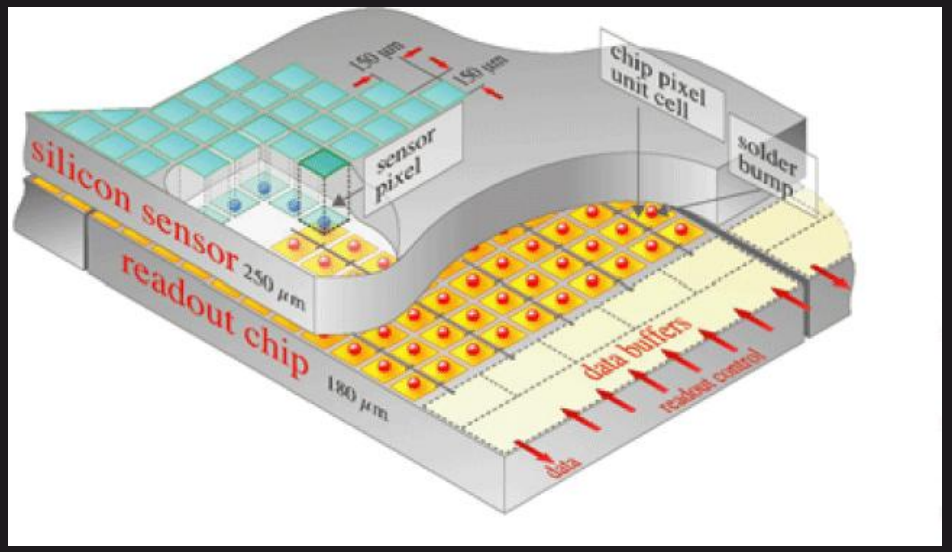
Silicon tracker (CMS)

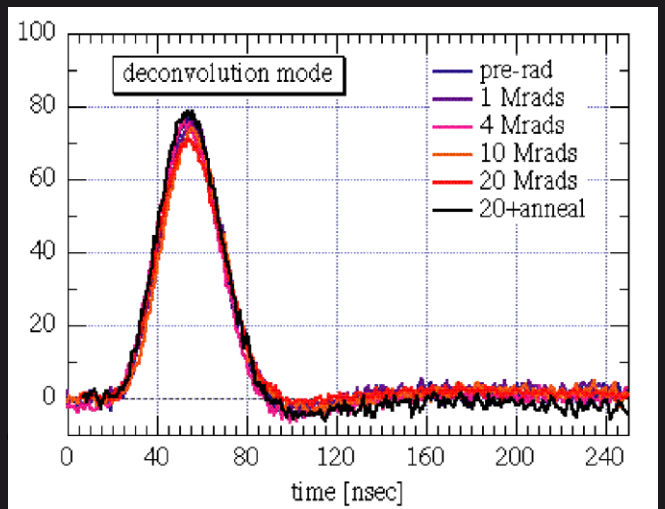


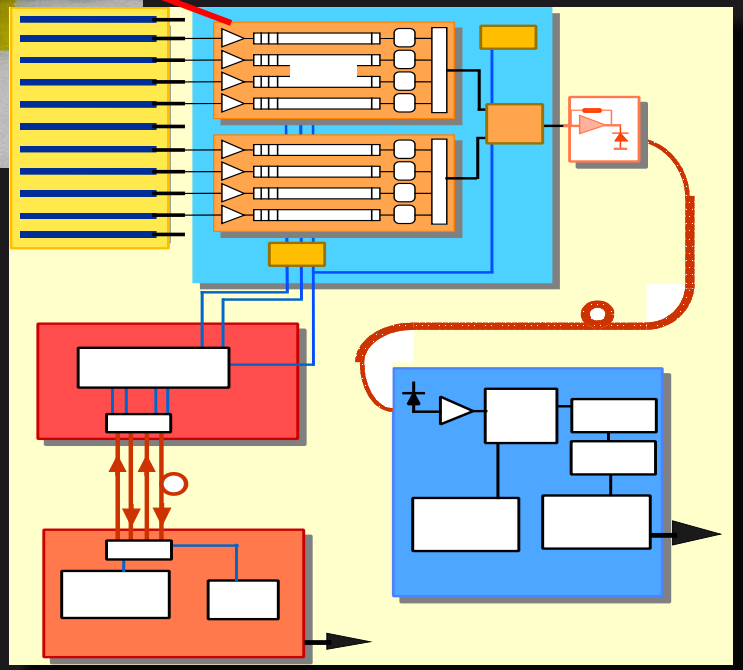

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with muon chambers
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

Si Modules and Electronics Chain



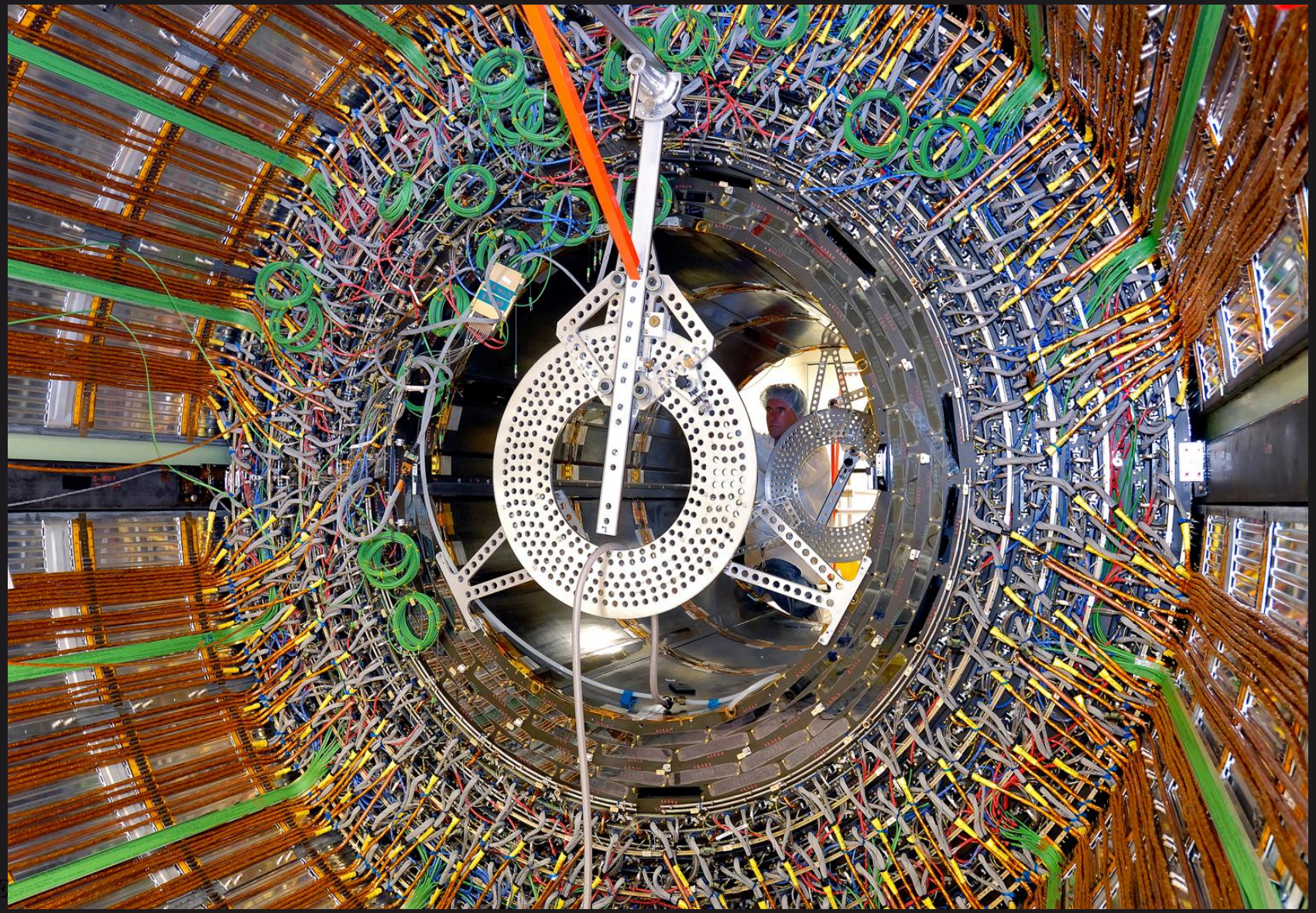




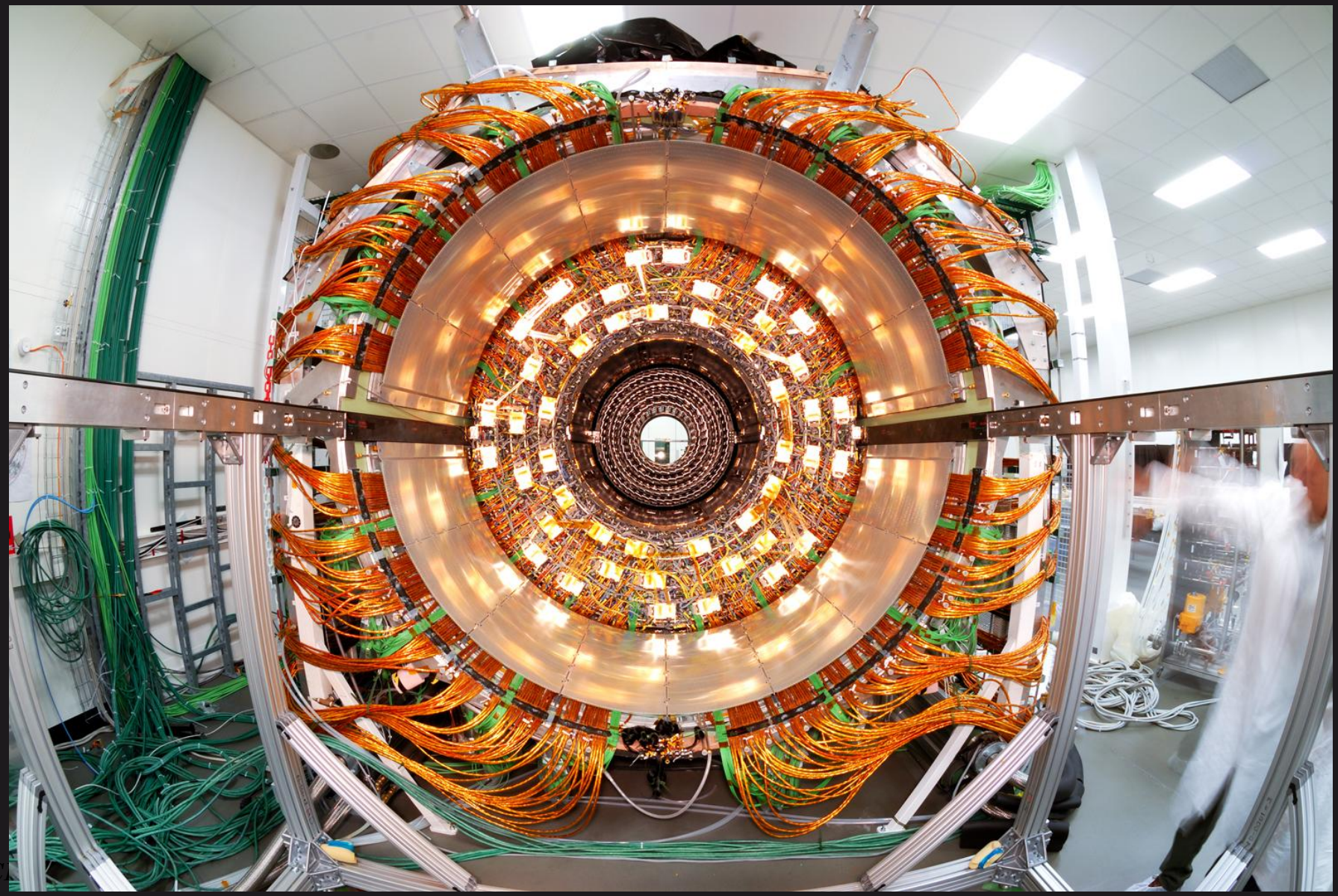


75k chips using
0.25μm technology

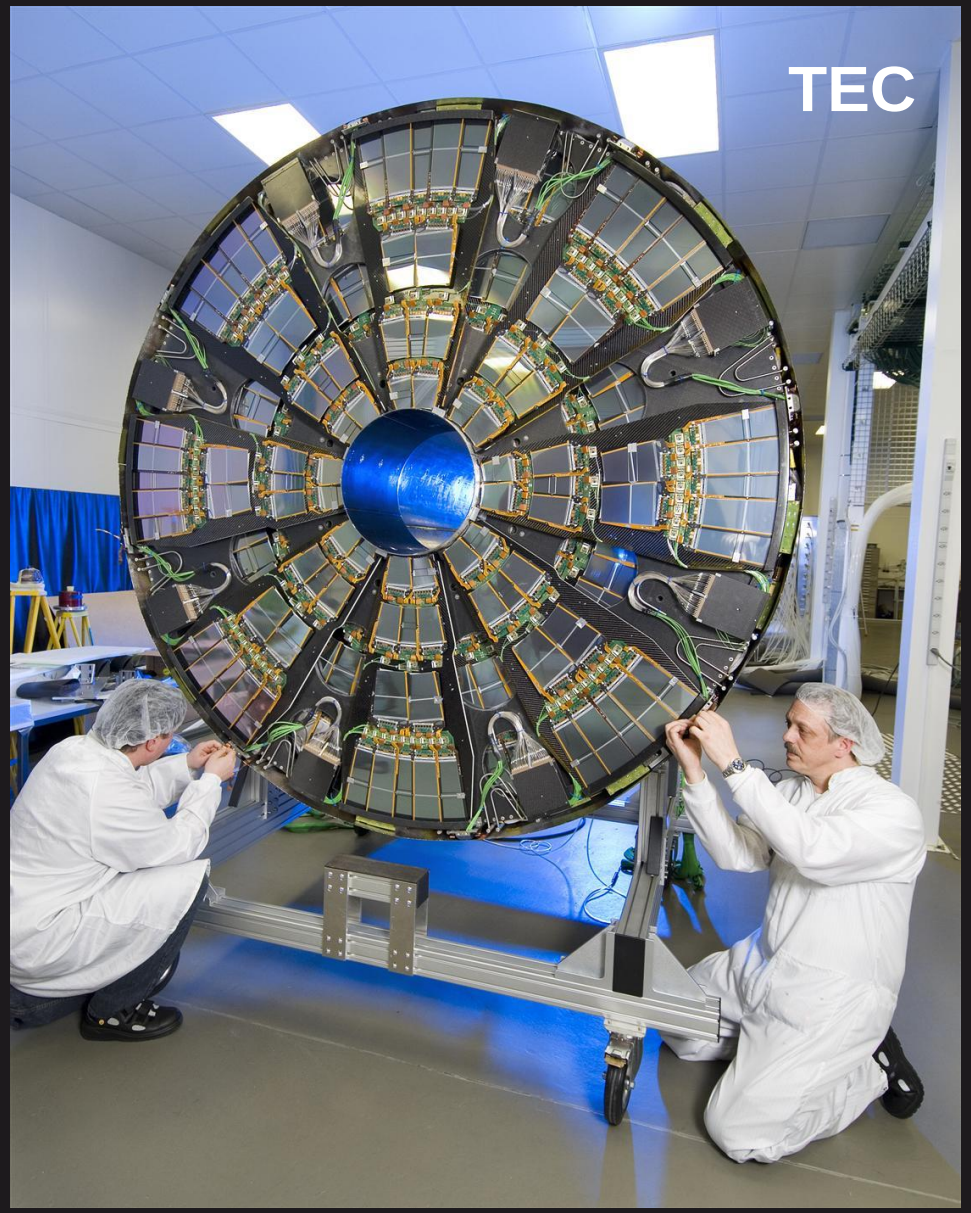
Si Tracker



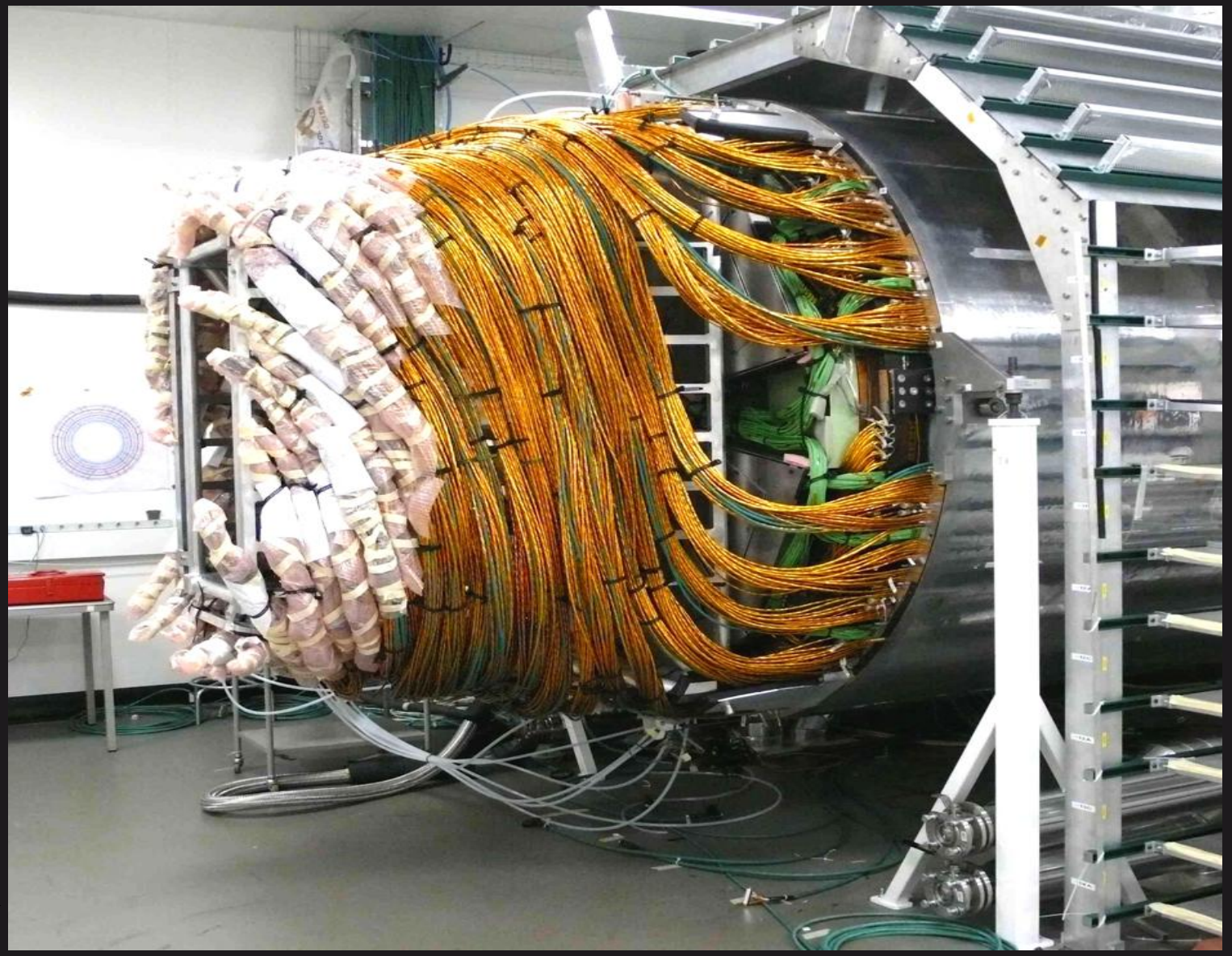
Si Tracker



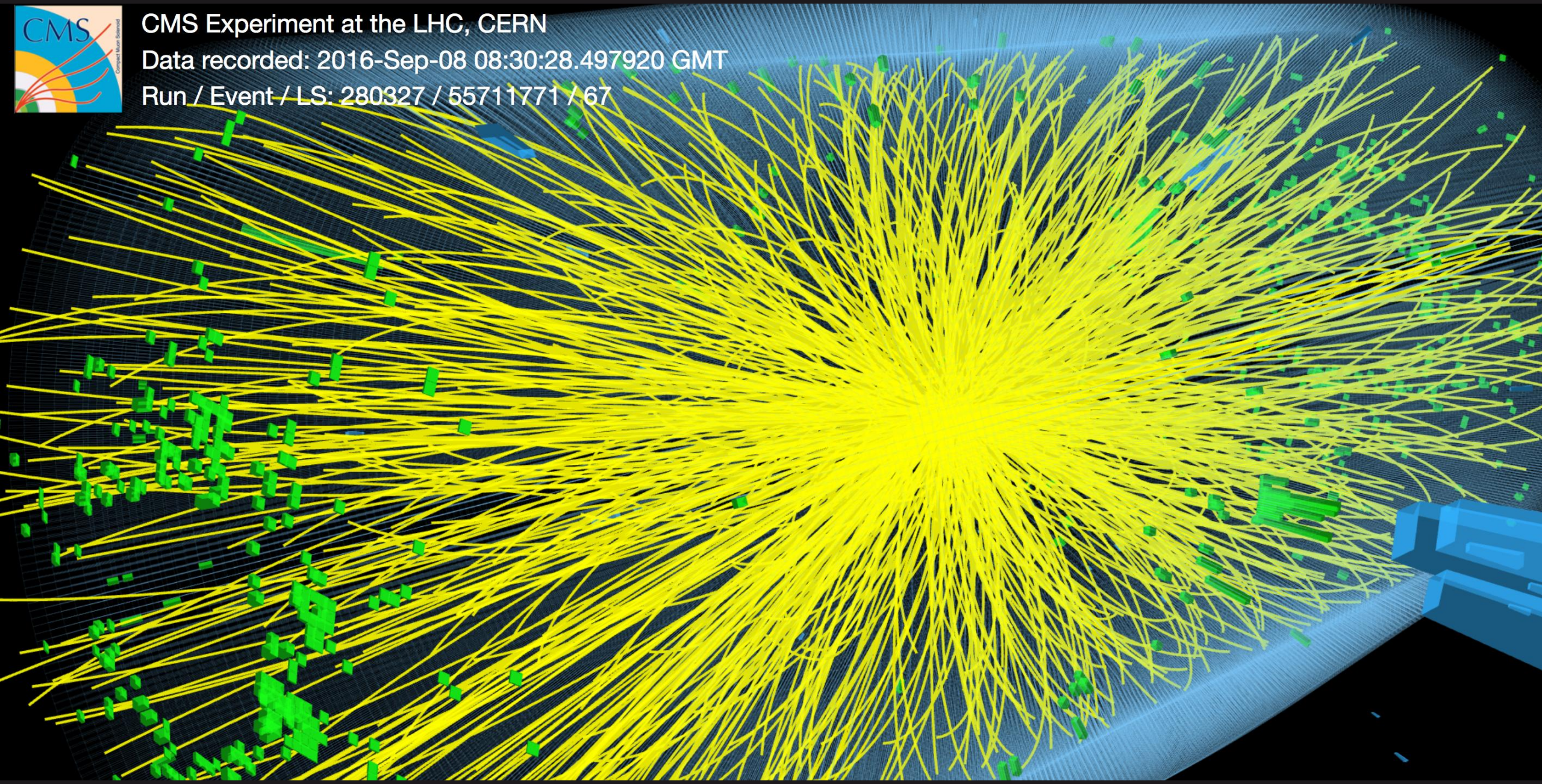
Si Tracker



Tracker Readied for Installation



CERN

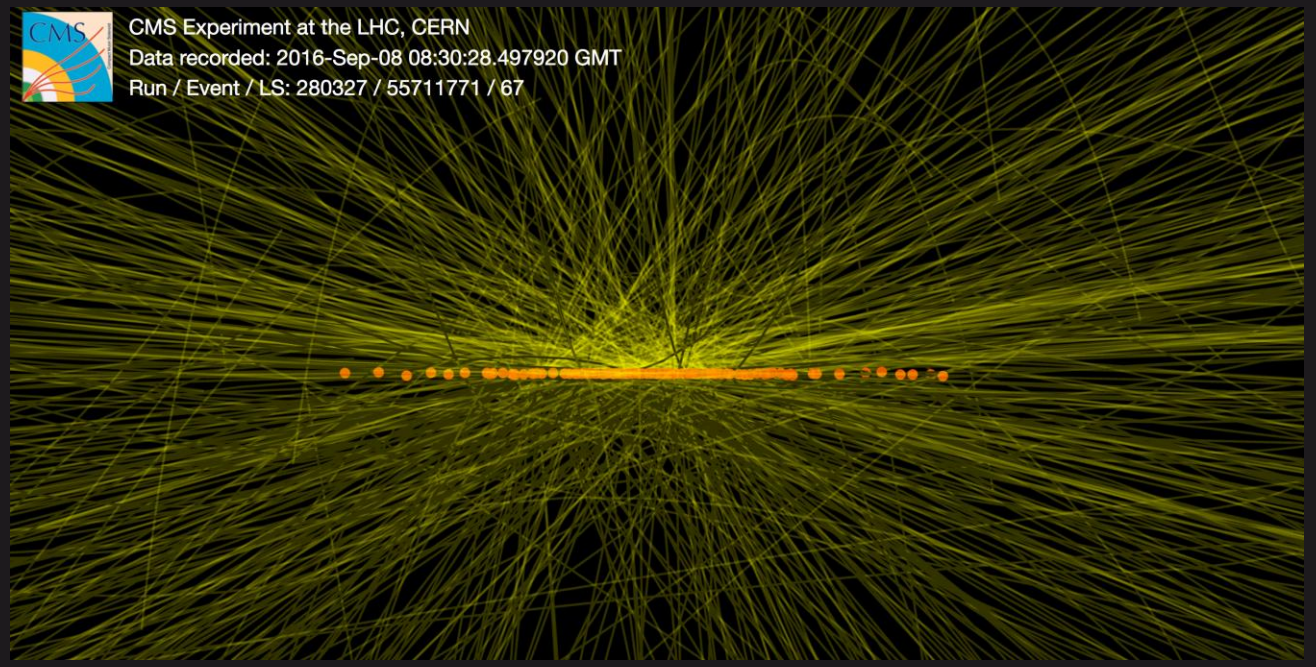

CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-08 08:30:28.497920 GMT
Run / Event / LS: 280327 / 55711771 / 67

Detectores em "4 dimensões"

Em colisores de alta luminosidade, múltiplas colisões cada vez que pacotes das partículas do feixe se cruzam nos pontos de colisão (*pileup* – empilhamento).

→ Medição do tempo de voo das partículas permite associá-las à colisão de interesse.

→ Muito alta resolução temporal necessária – $\mathcal{O}(10\ \mathrm{ps})$



Low Gain Avalanche Diode (LGAD)