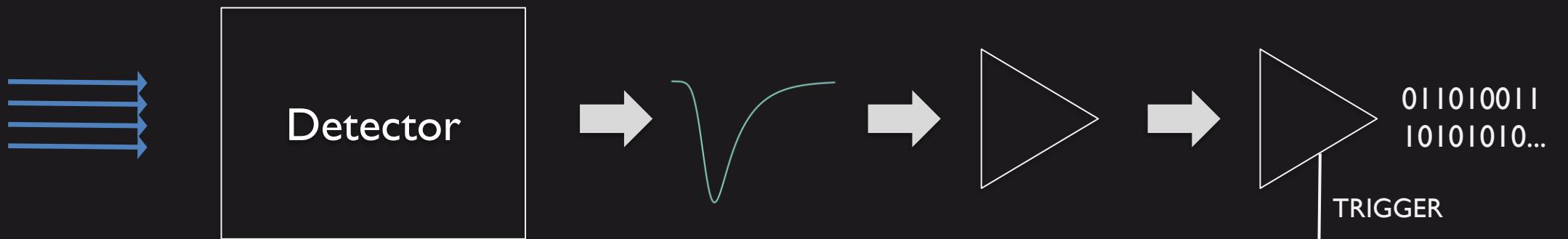
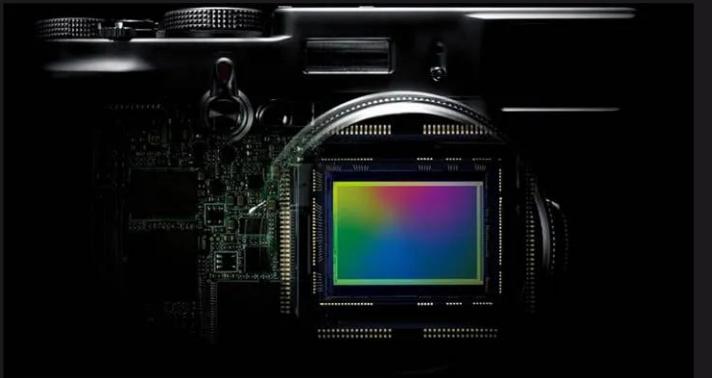


# *Detectores semicondutores*

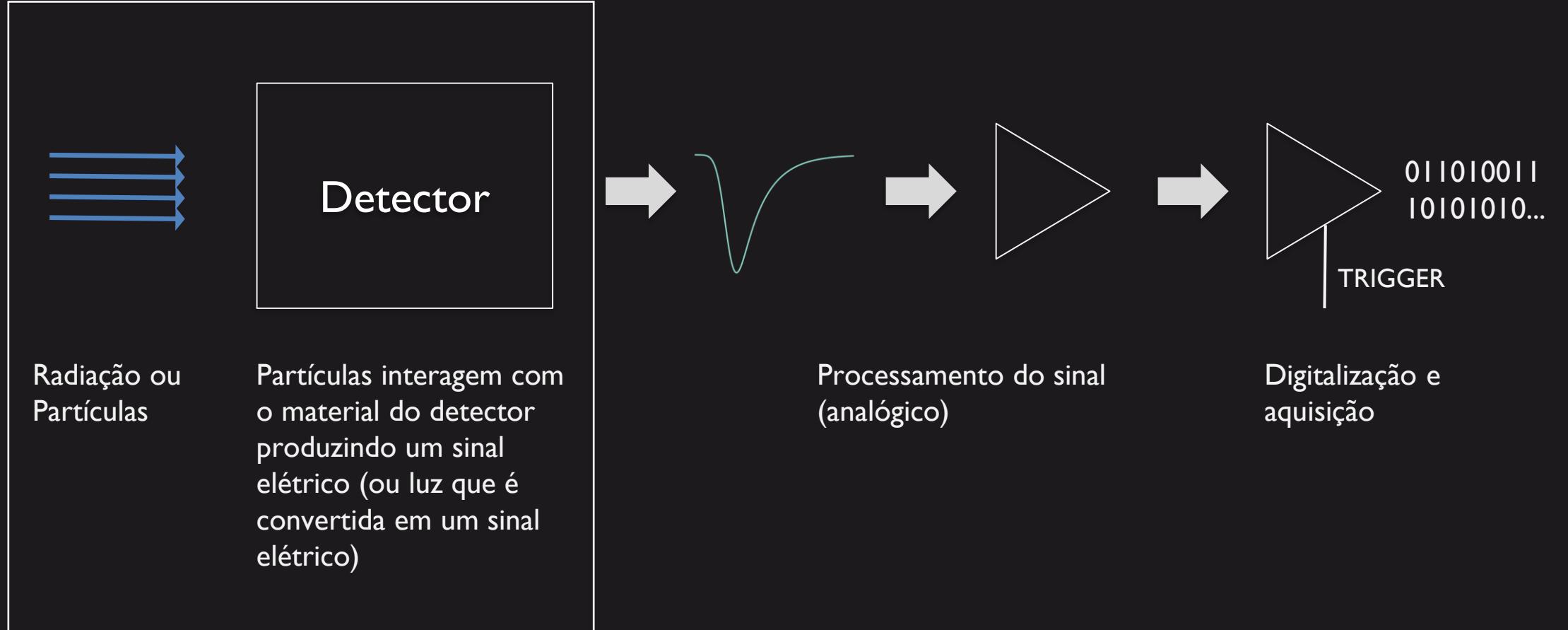


Radiação ou  
Partículas

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

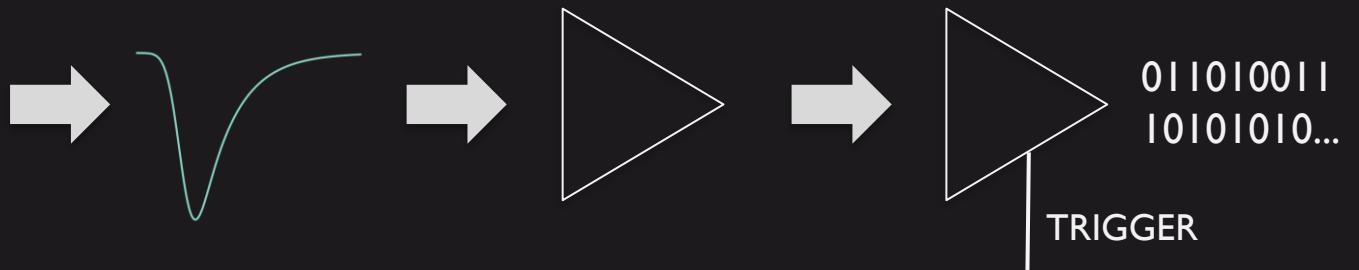
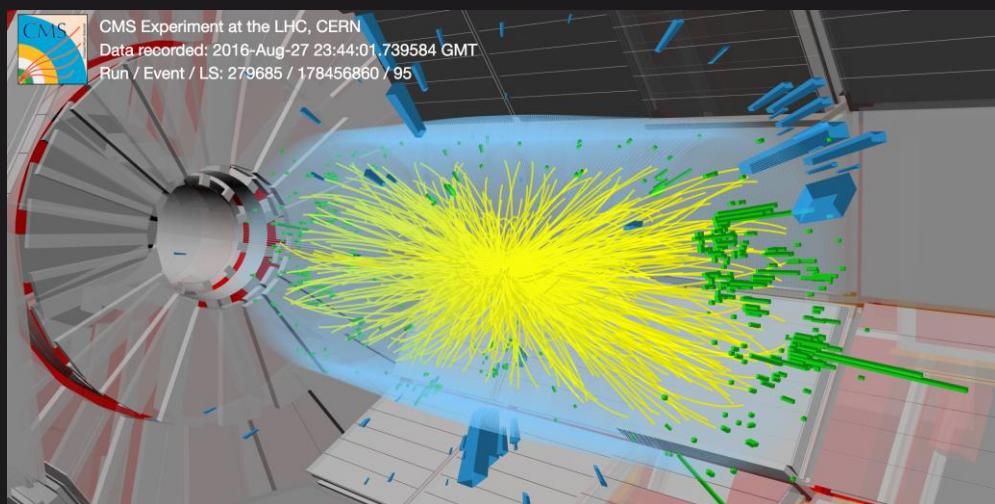
Processamento do sinal  
(análogo)

Digitalização e  
aquisição



Muito alta densidade de partículas perto do ponto de colisão

40 milhões de colisões por segundo



Processamento do sinal  
(análogo)

Digitalização e  
aquisição

# *Semicondutores*

IA

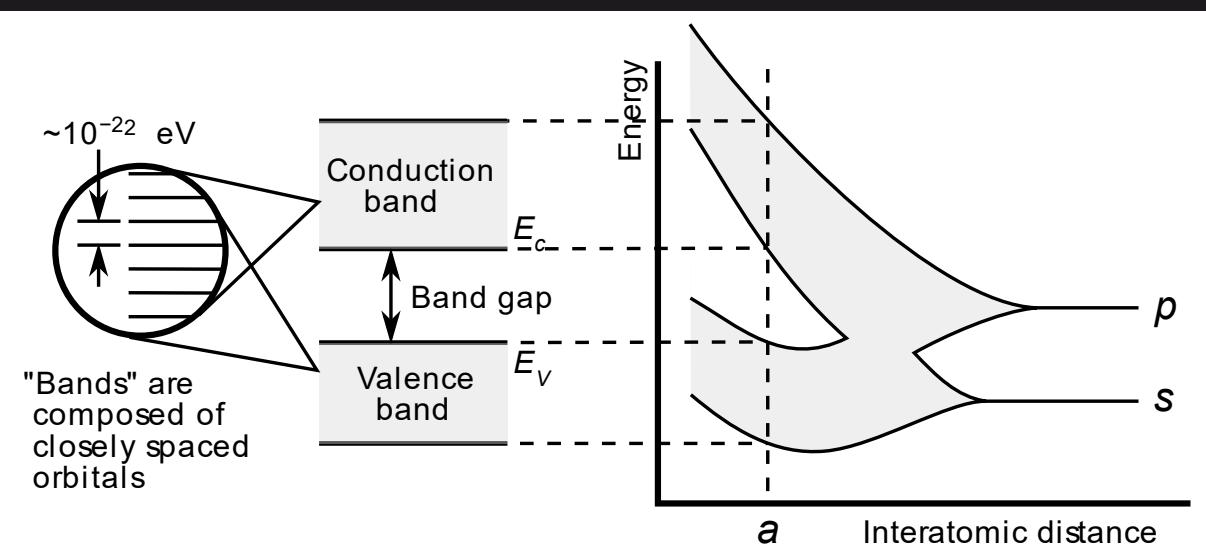
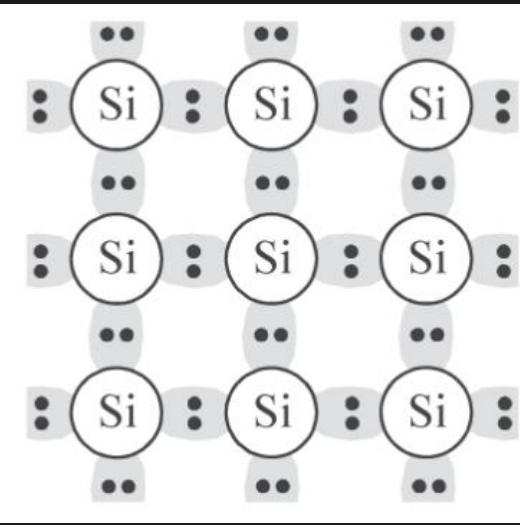
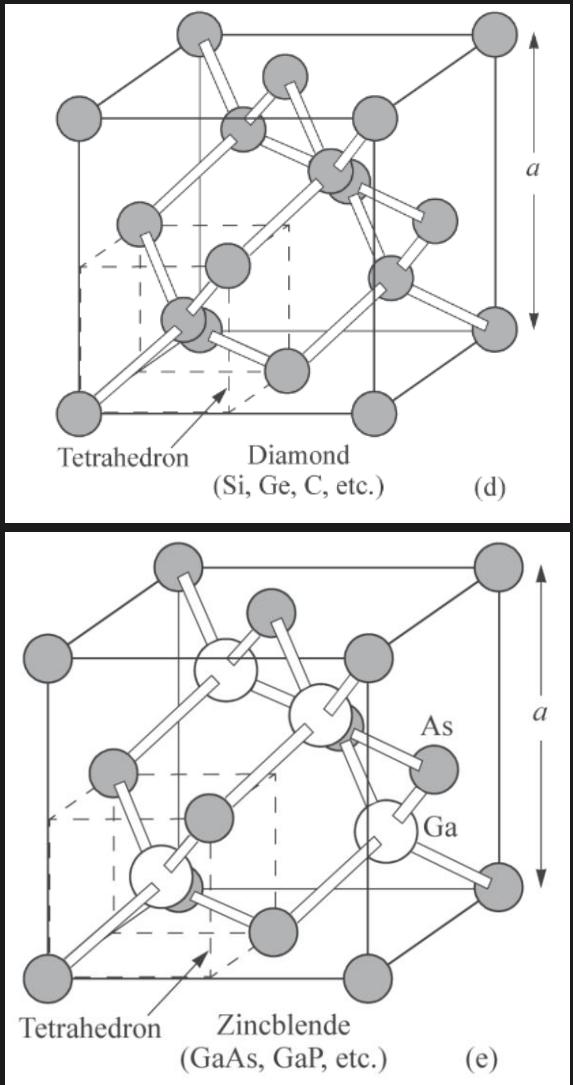
Noble

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

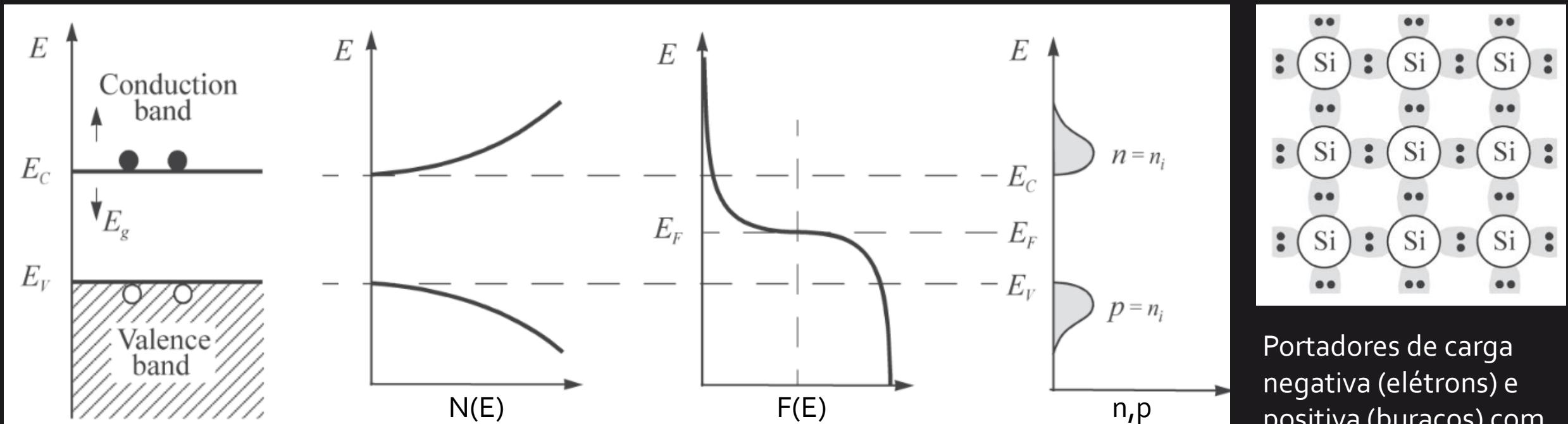
Lanthanides		Cerium Ce [Xe] 4f <sup>2</sup> 5d <sup>0</sup> 6s <sup>2</sup> 140.12	Praseodymium Pr [Xe] 4f <sup>3</sup> 5d <sup>0</sup> 6s <sup>2</sup> 140.91	Neodymium Nd [Xe] 4f <sup>4</sup> 5d <sup>0</sup> 6s <sup>2</sup> 144.24	Promethium Pm [Xe] 4f <sup>5</sup> 5d <sup>0</sup> 6s <sup>2</sup> 145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

# Semicondutores

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

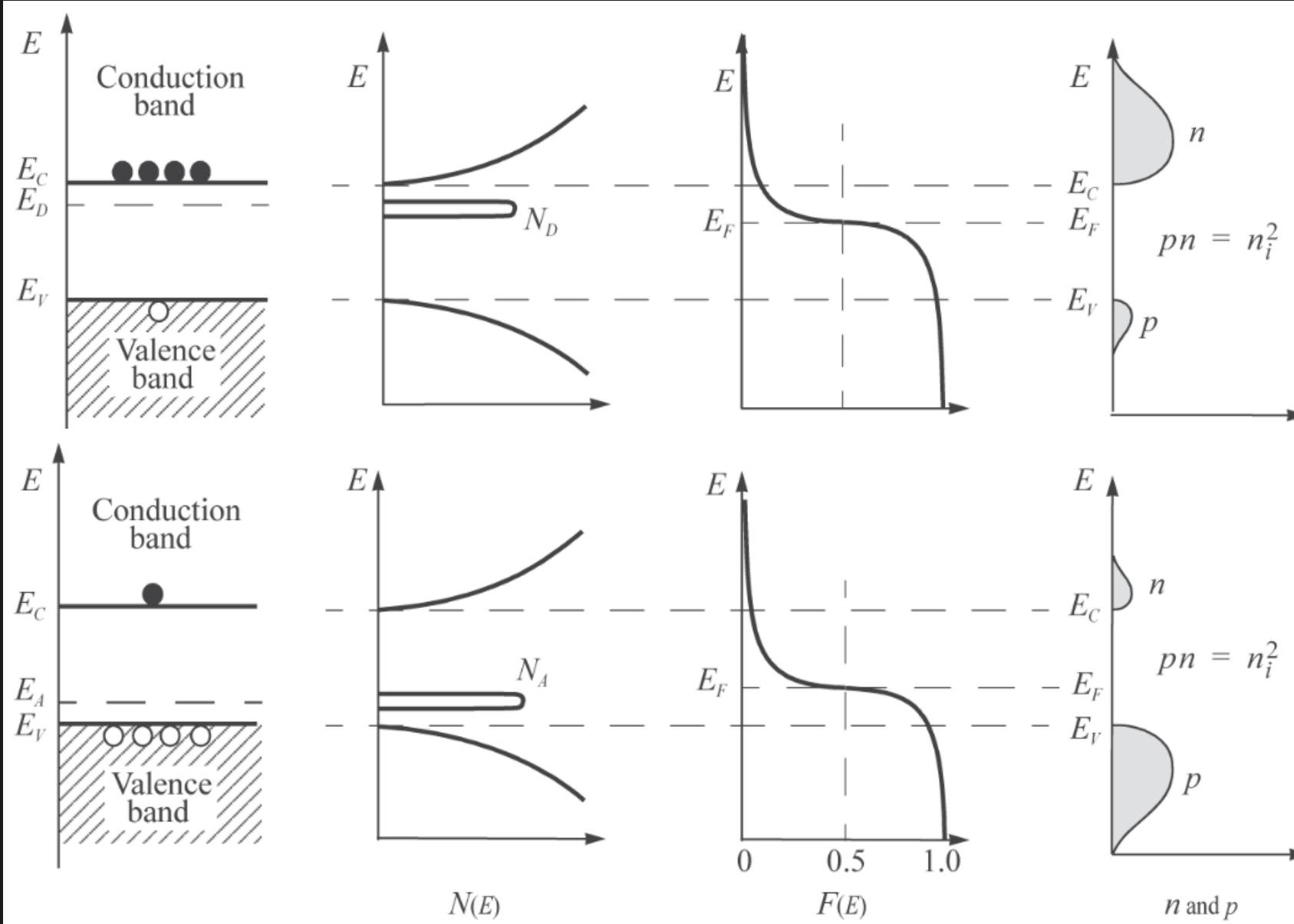


# Semicondutores (intrínsecos)

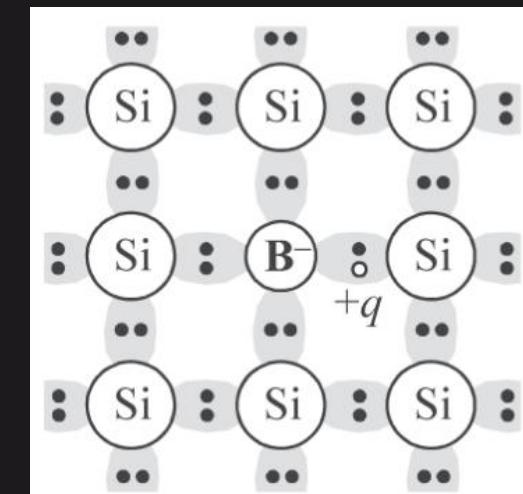
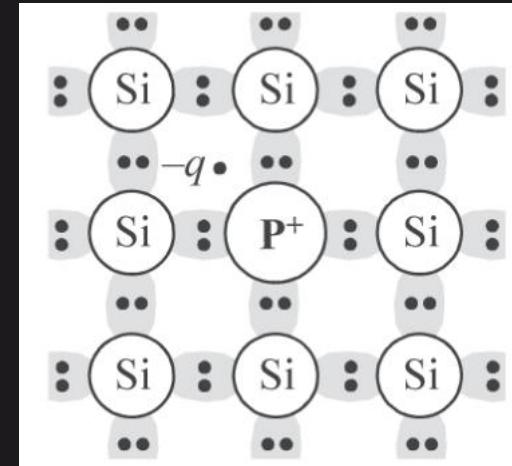


Portadores de carga negativa (elétrons) e positiva (buracos) com alta *mobilidade* na rede cristalina.

# Semicondutores (extrínsecos)



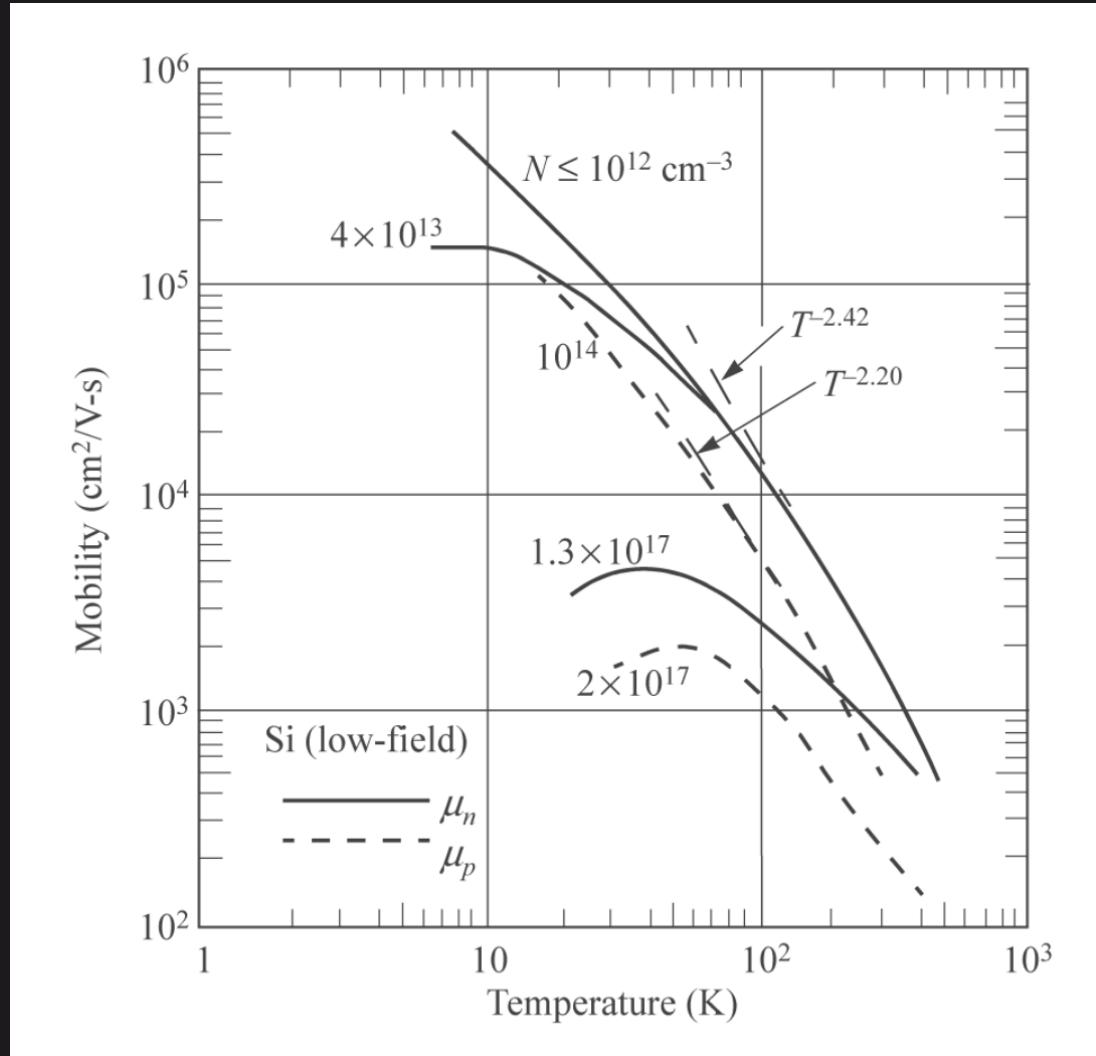
tipo-n, excesso de portadores de carga negativa (elétrons)



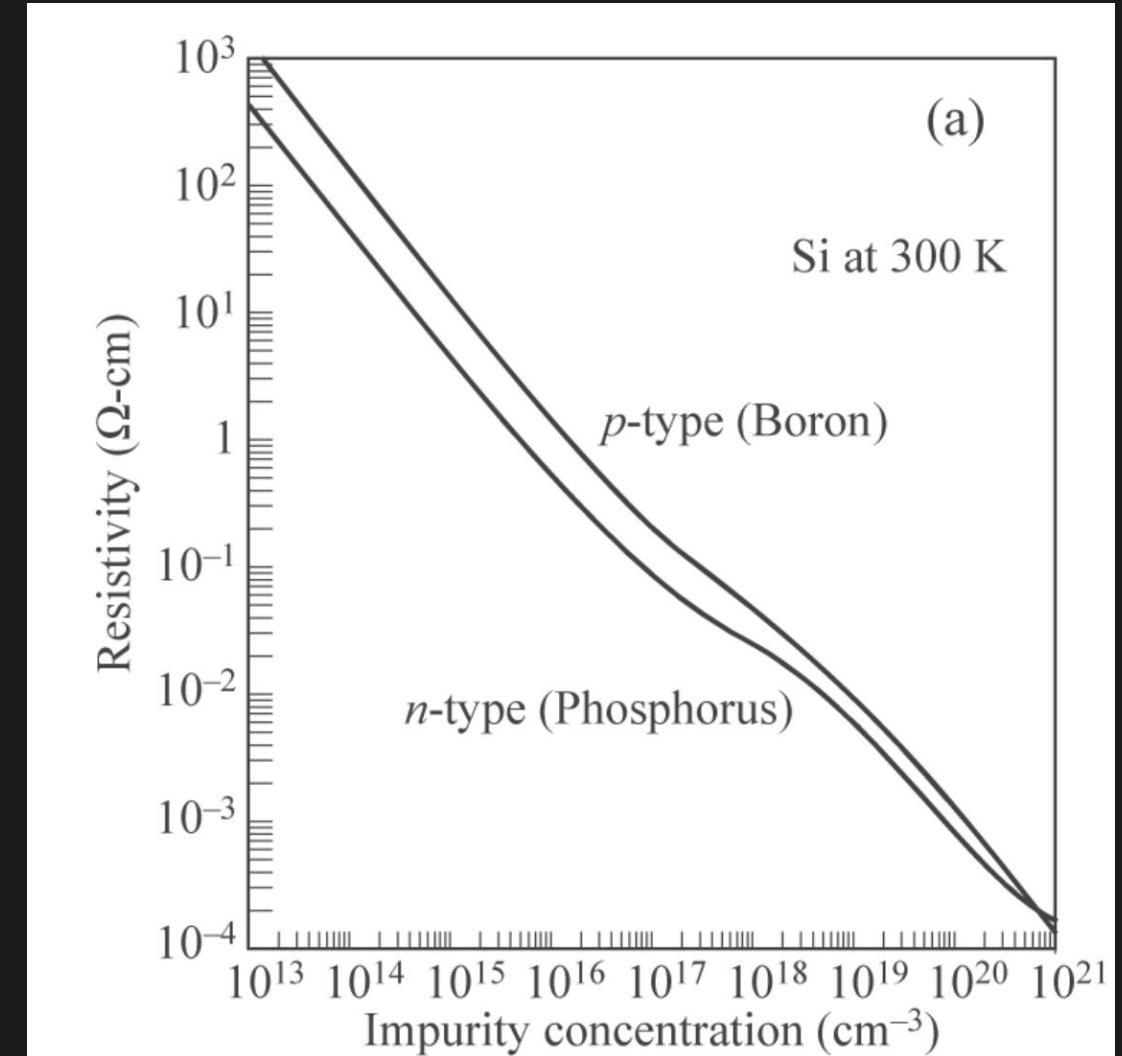
tipo-p, excesso de portadores de carga positiva (buracos)

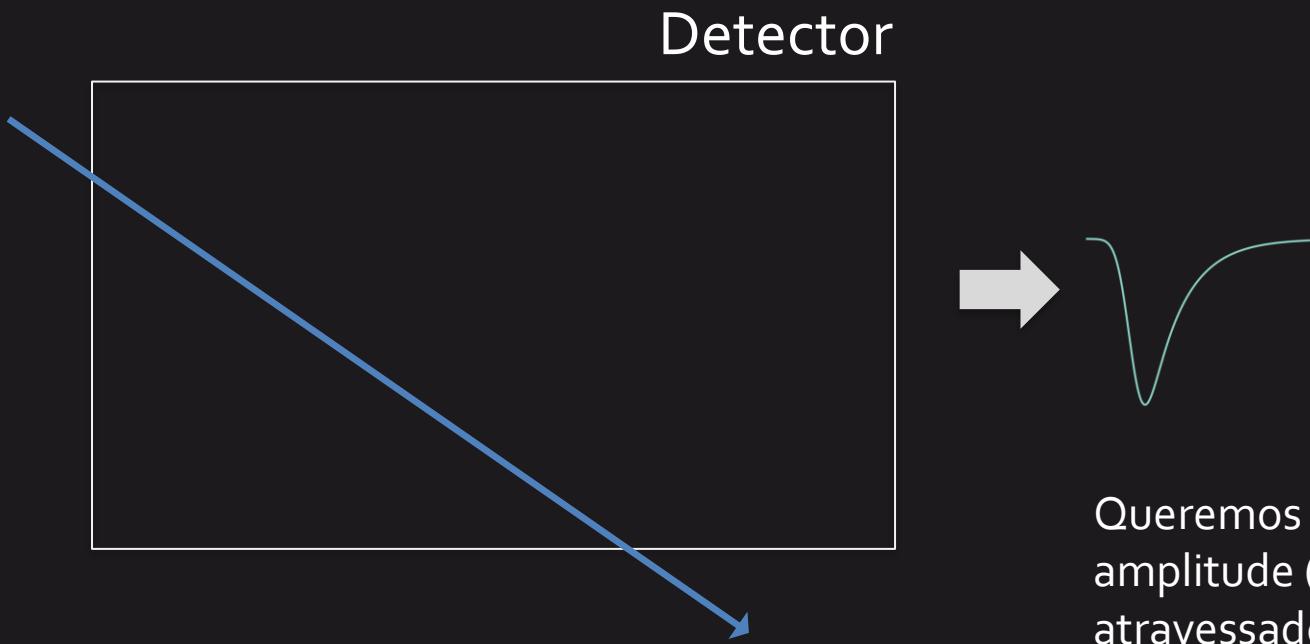
# Semicondutores (extrínsecos)

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



Resistividade



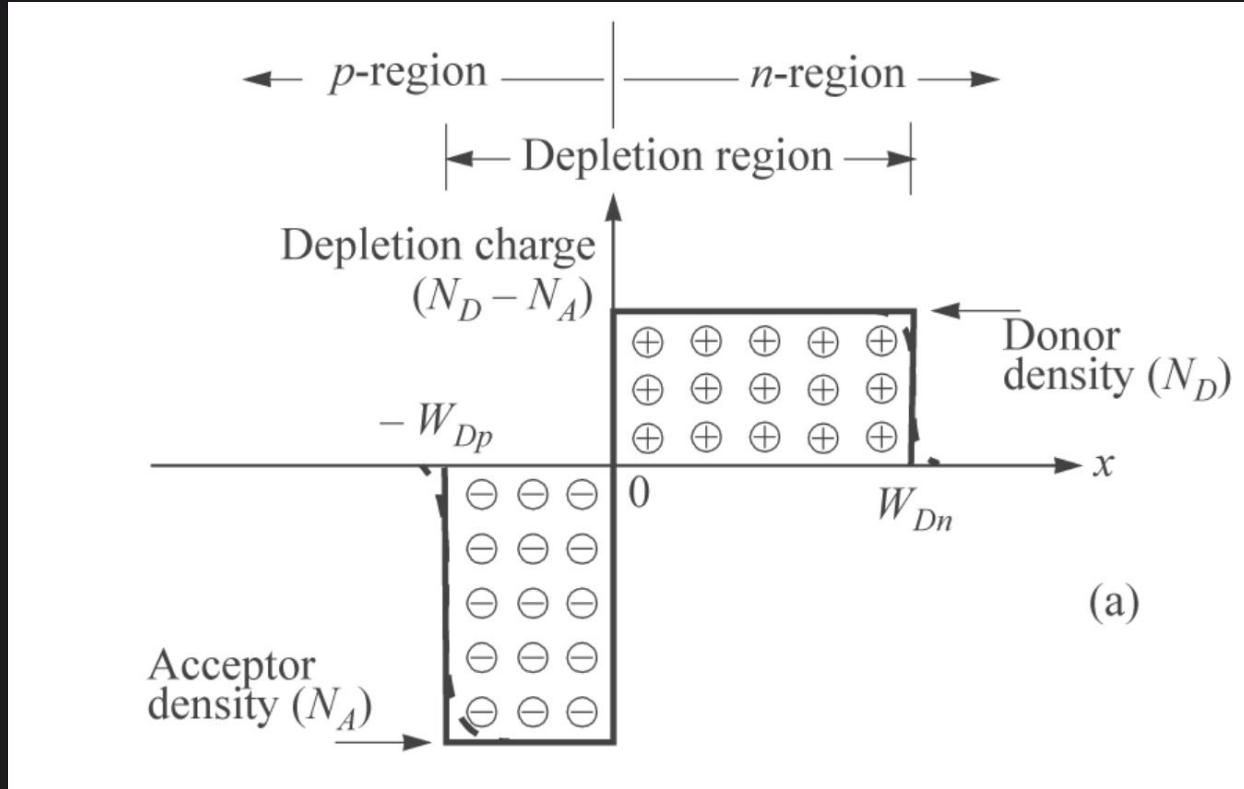


Queremos dispositivos que apresentem sinal com alta amplitude (e idealmente rápidos) ao serem atravessados por partículas incidentes, e baixo sinal na ausência de radiação incidente (ruído/fundo).

Energia entre bandas de semicondutores na faixa de poucos eV.

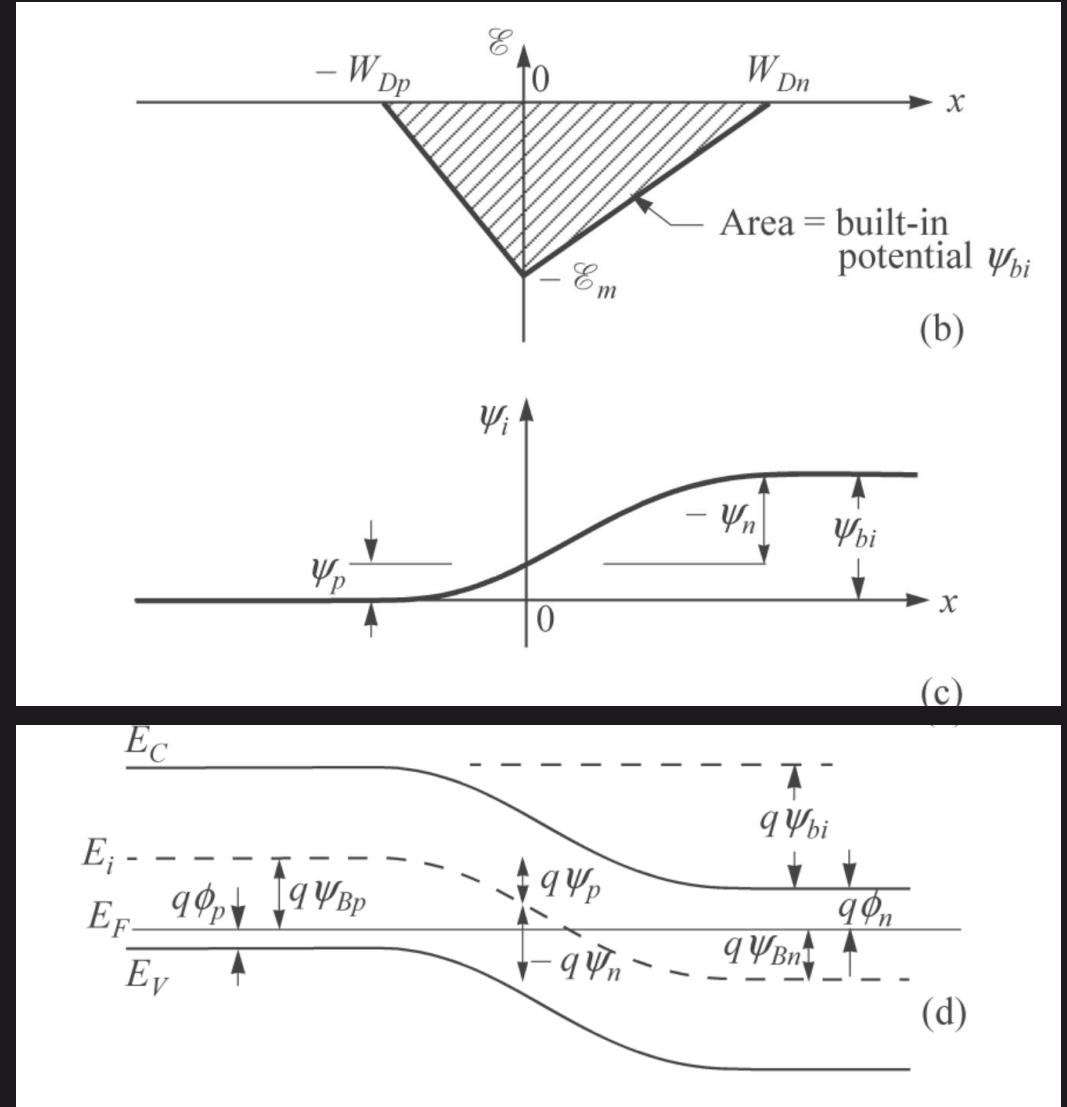
→ Junção p-n reversamente polarizada.

# *Junção p-n*



(a)

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

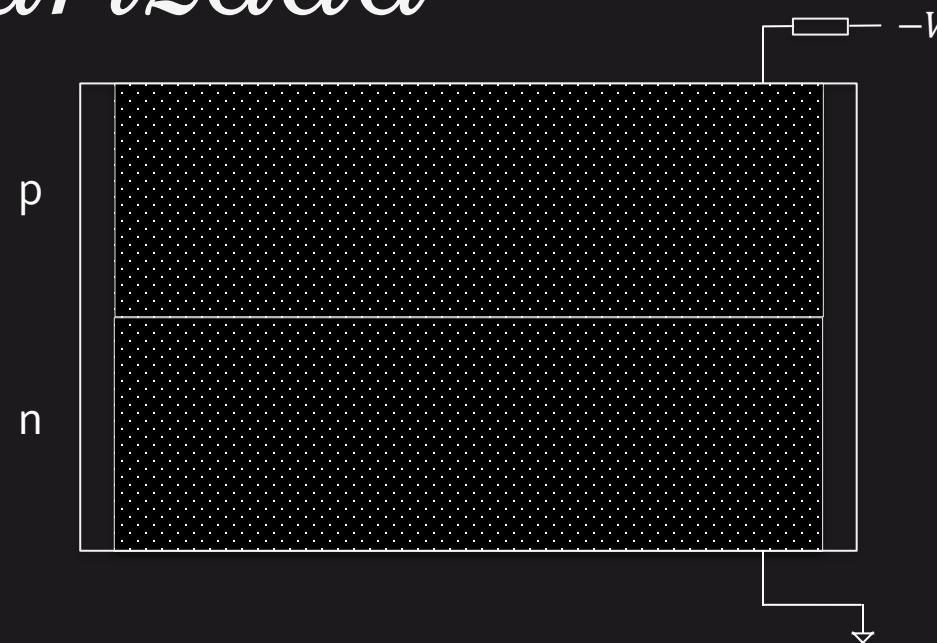
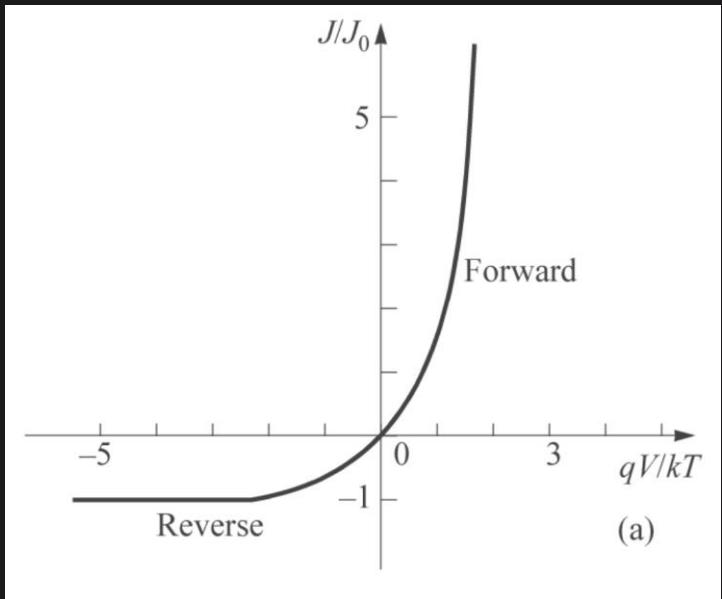


(b)

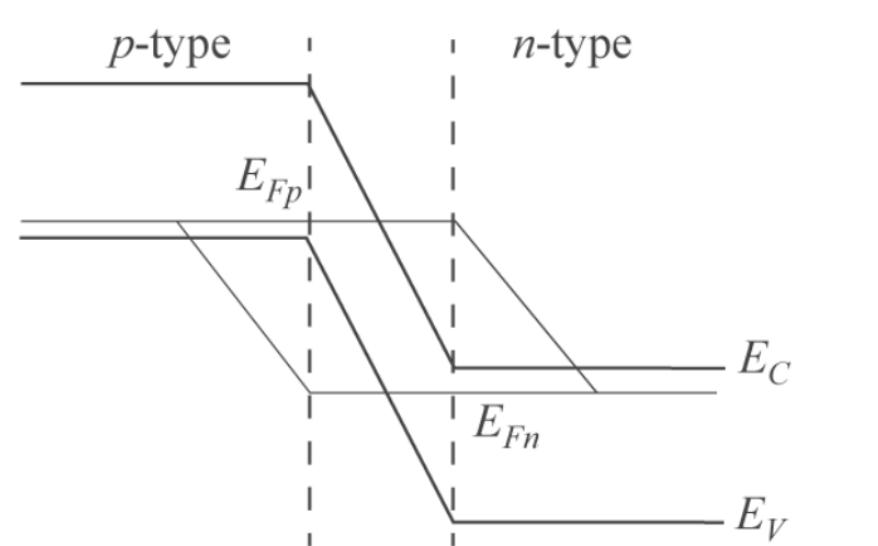
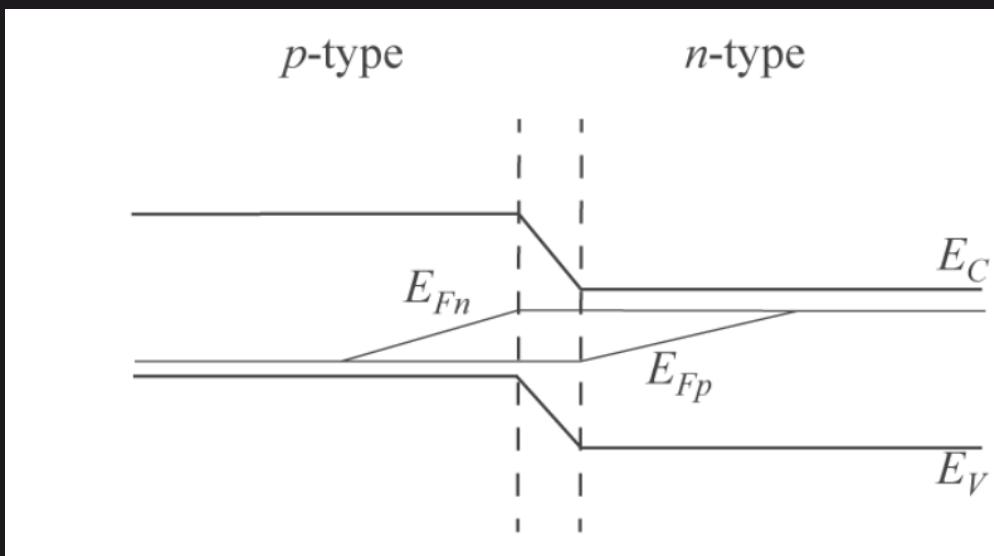
(c)

(d)

# *Junção p-n polarizada*



Polarização reversa  
aumenta região de  
depleção

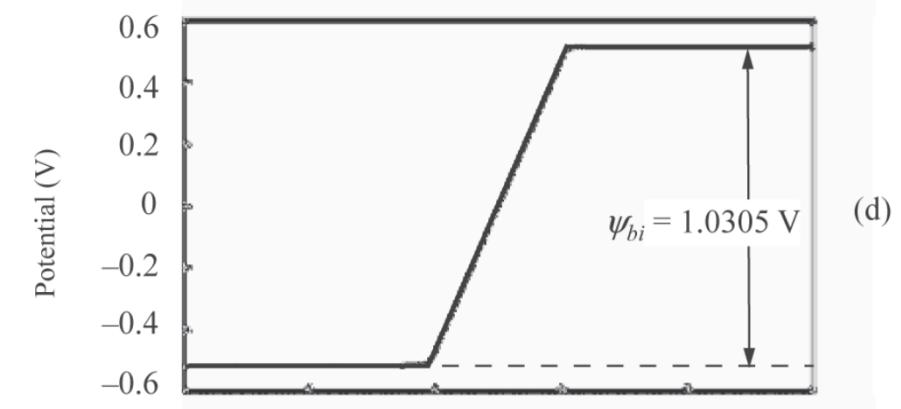
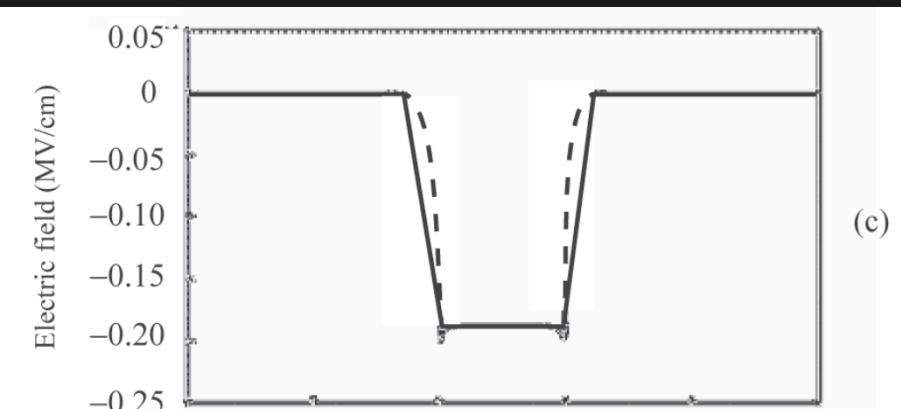
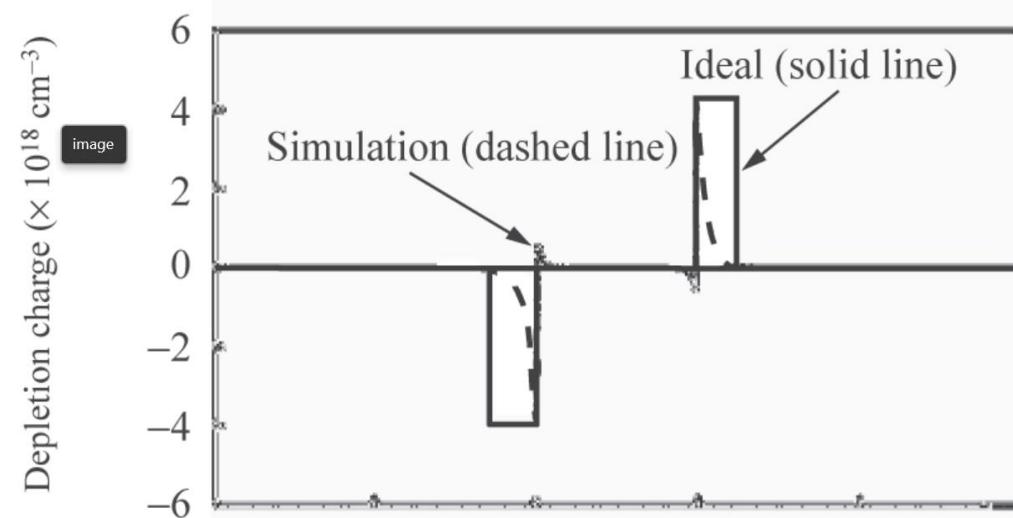


*p-i-n*

alta concentração p    p+

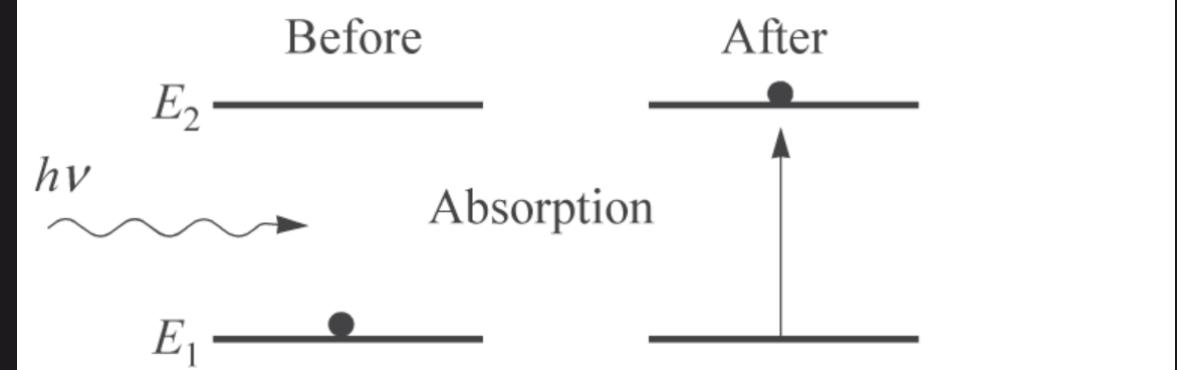
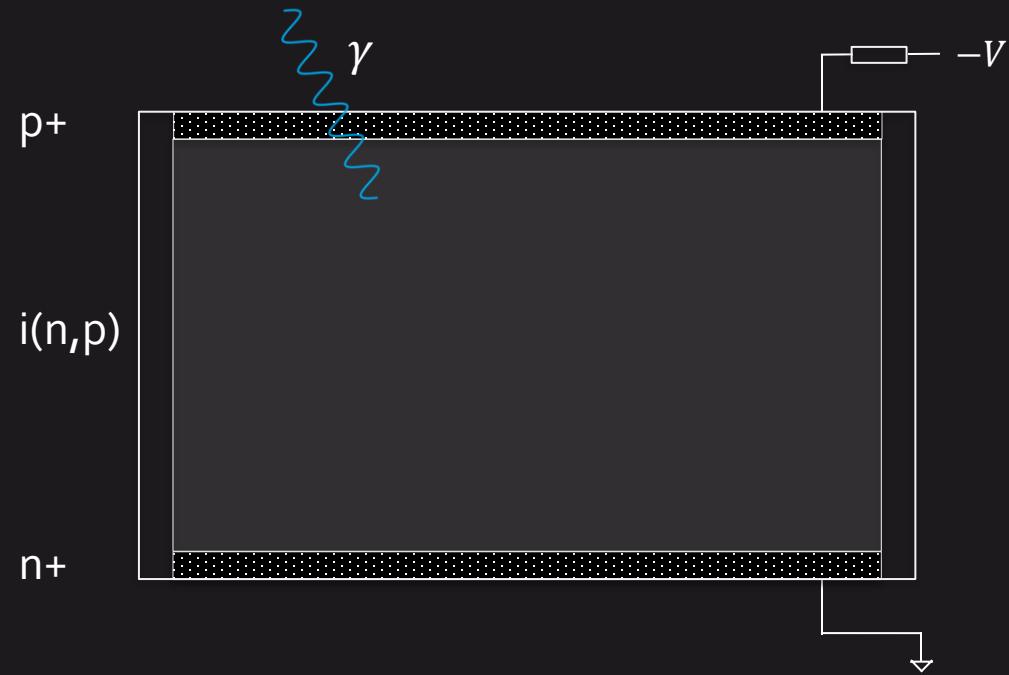
intrínseco (i) ou baixa i(n,p)  
concentração n ou p

alta concentração n    n+



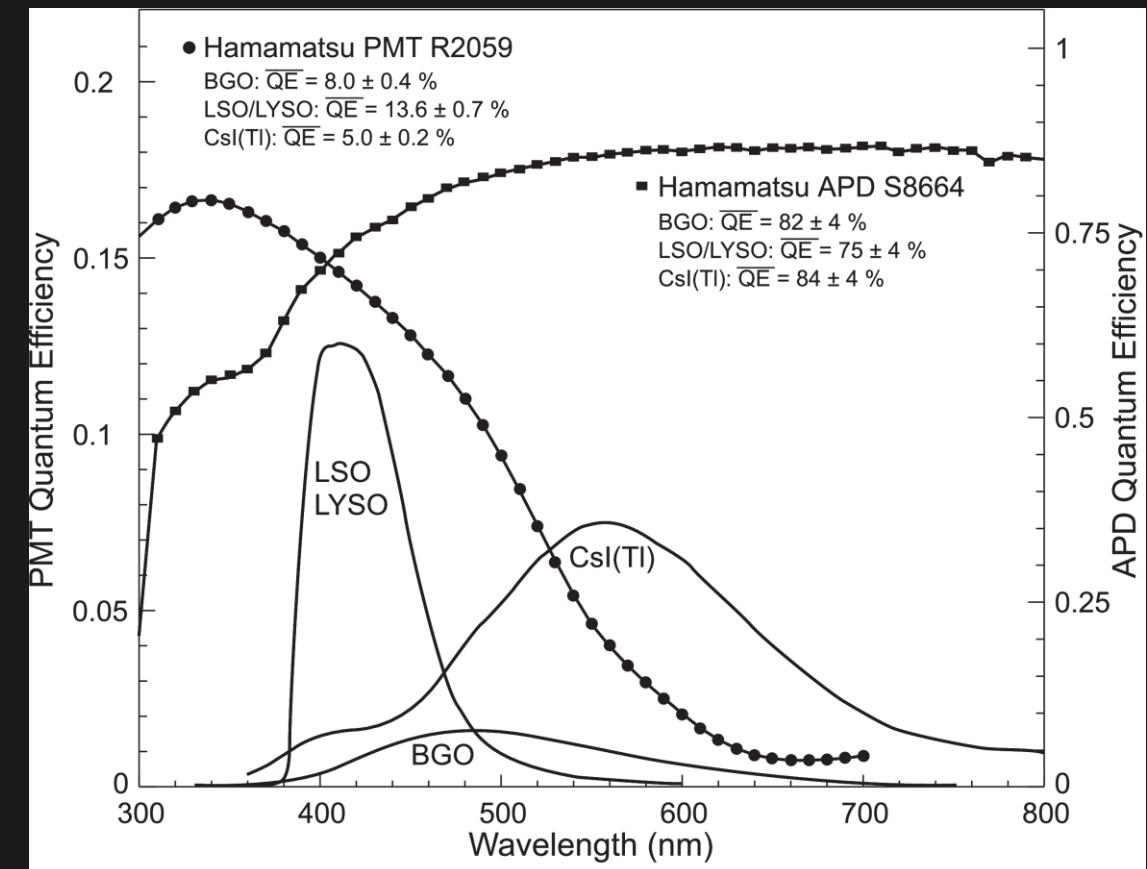
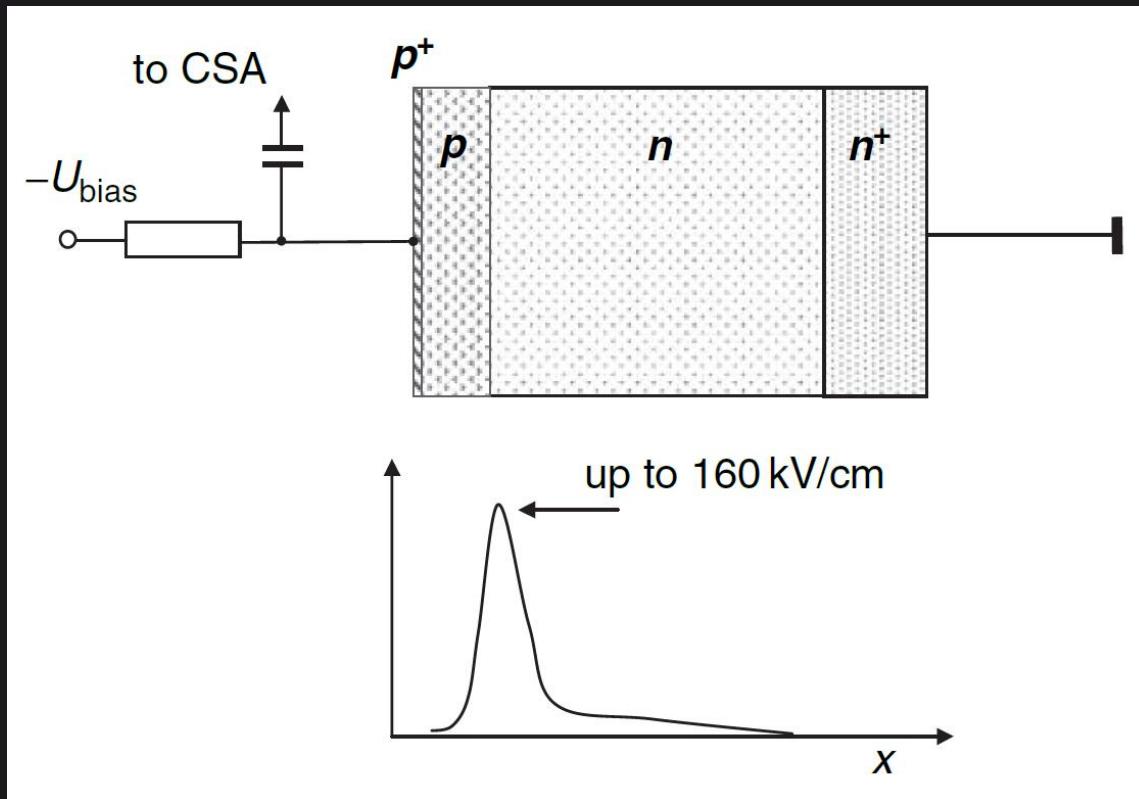
# *Semicondutores – Fososensores*

# Fotodiodos



# *APDs e SiPMs*

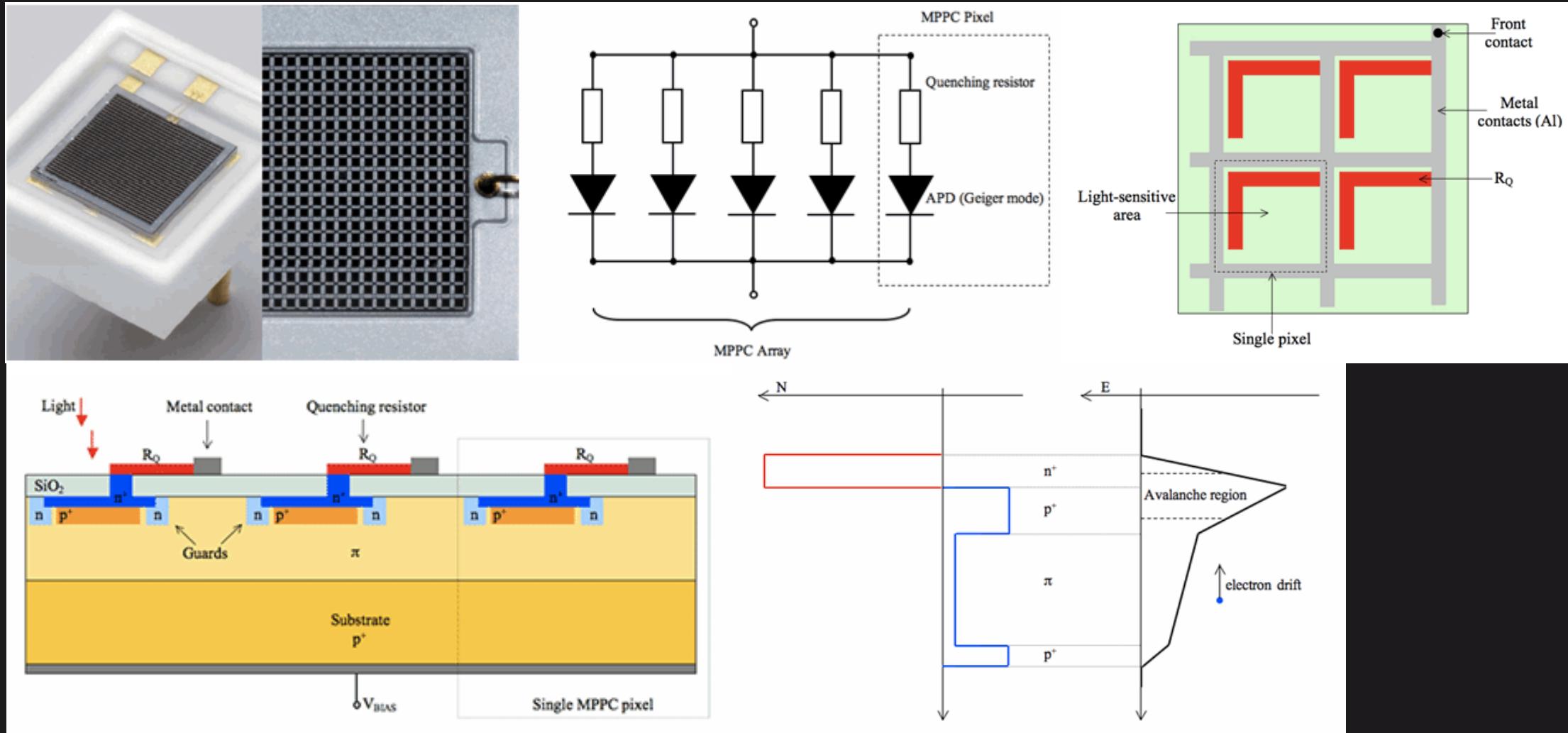
## Avalanche Photodiode (APD)



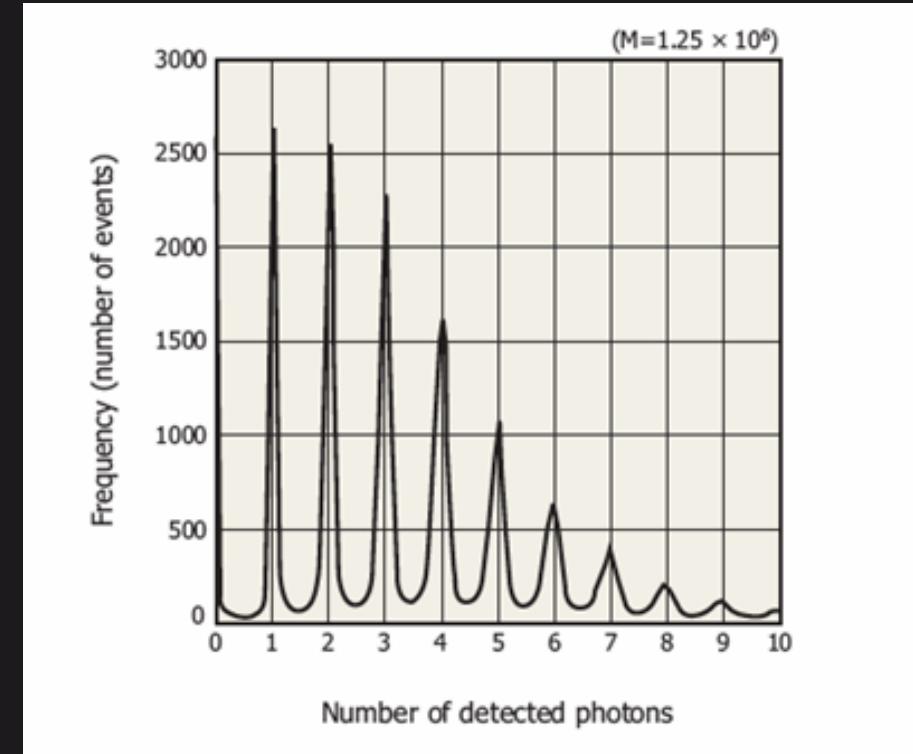
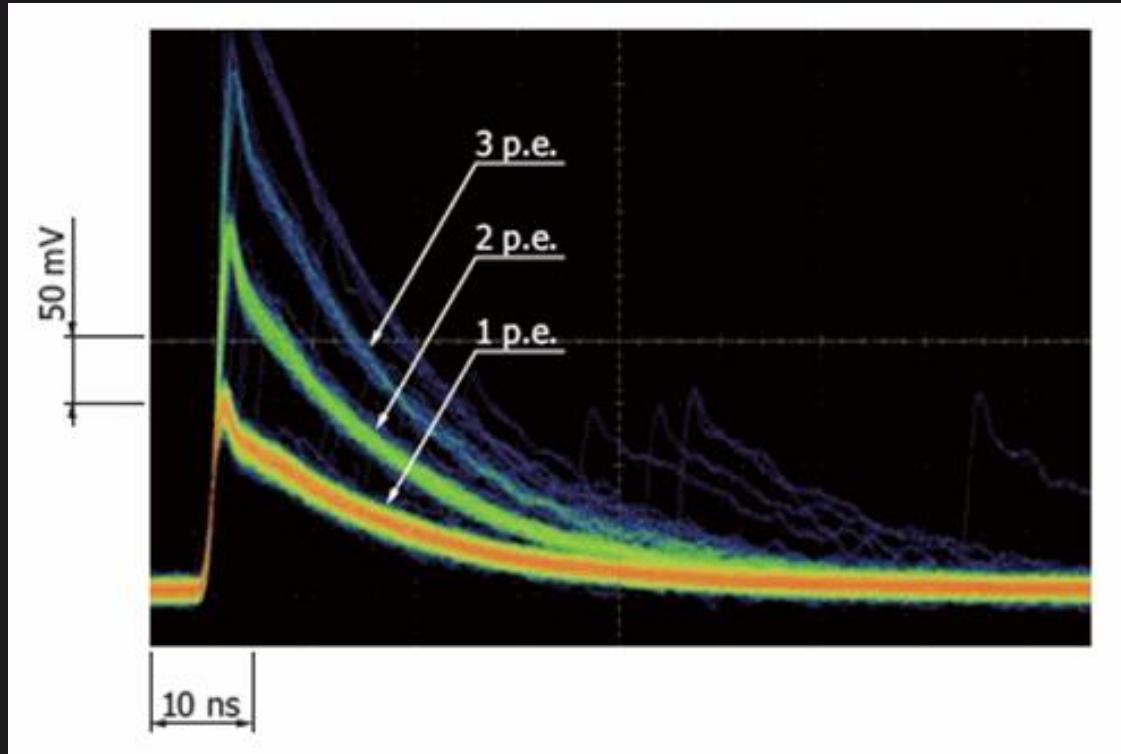
Possível operar APD em modo *breakdown*

# Multi-Pixel Photon Counter – SiPM

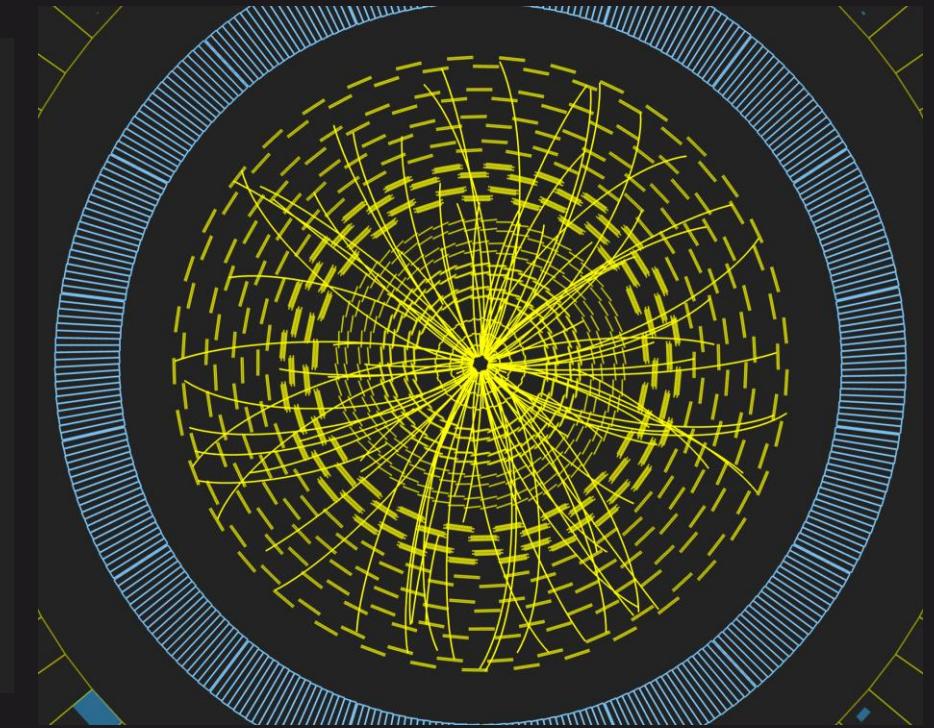
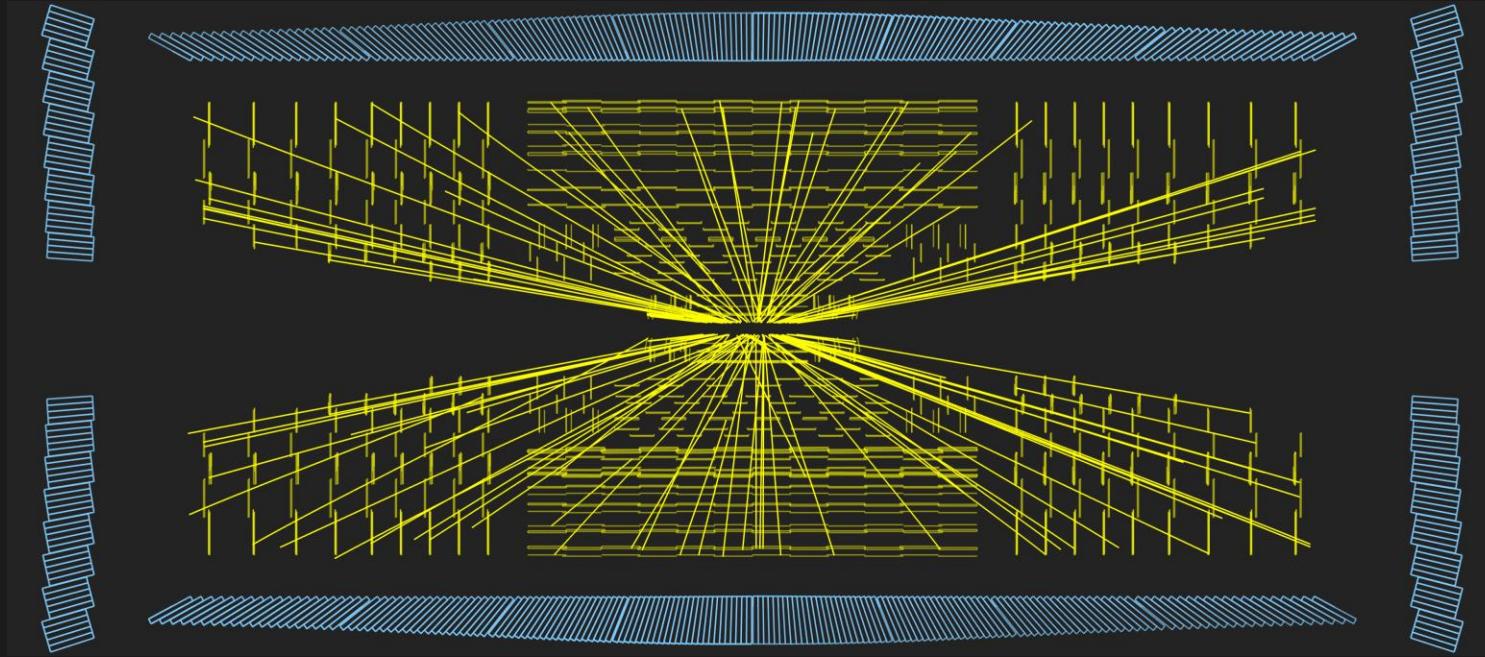
Operação em sobretensão à tensão de breakdown da APD



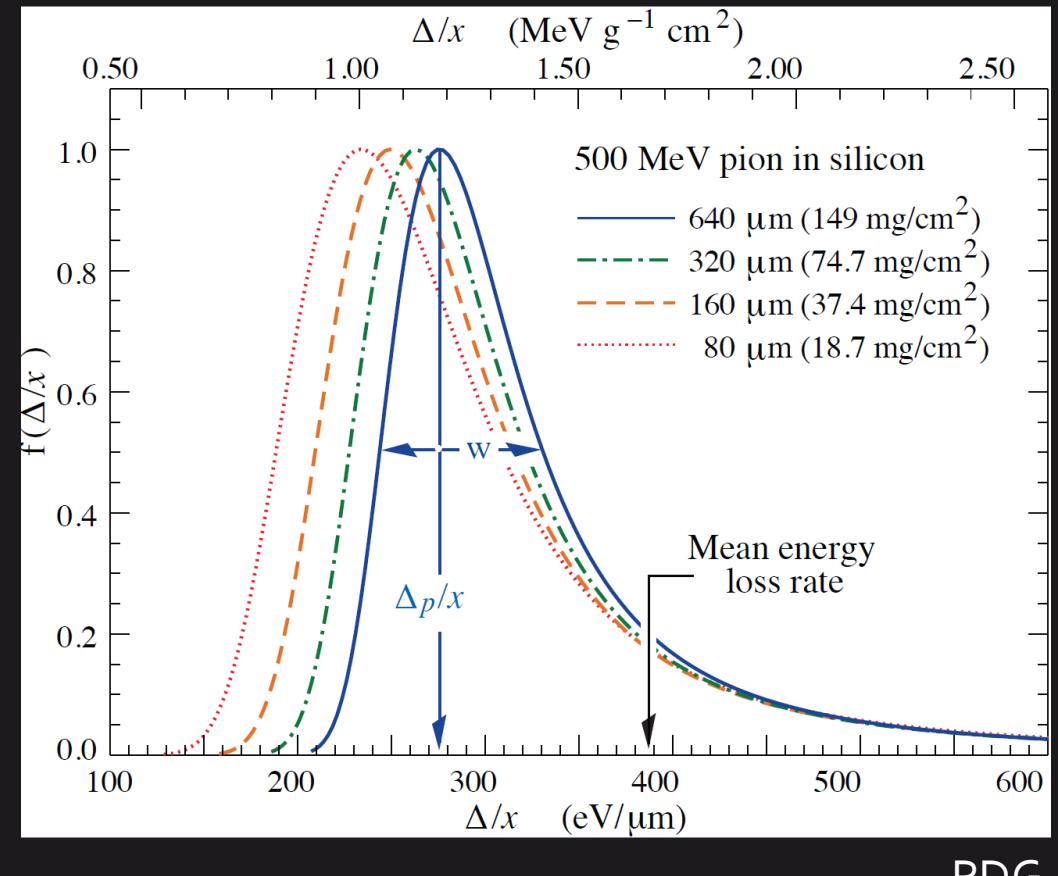
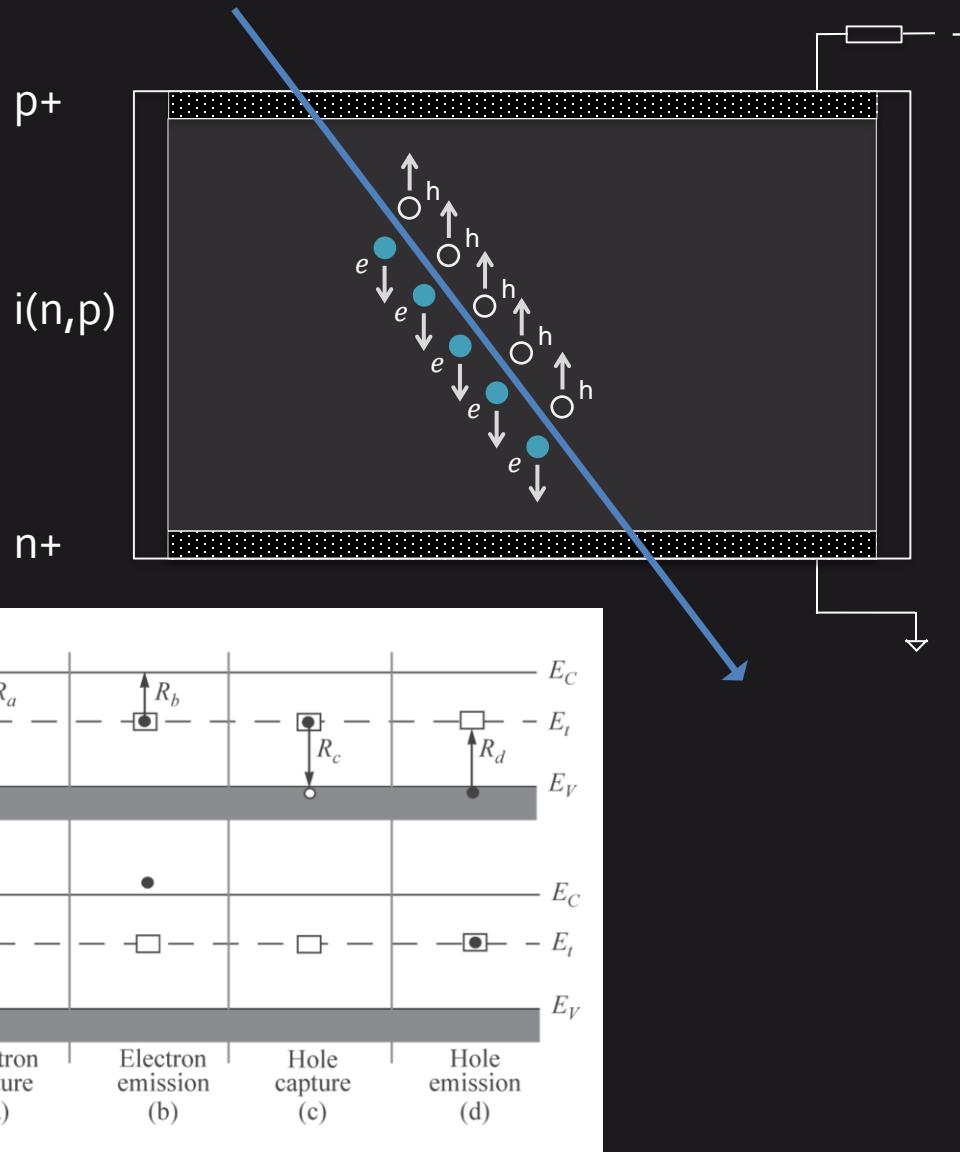
# *Multi-Pixel Photon Counter – SiPM*



# *Detectores de traços (tracker)*

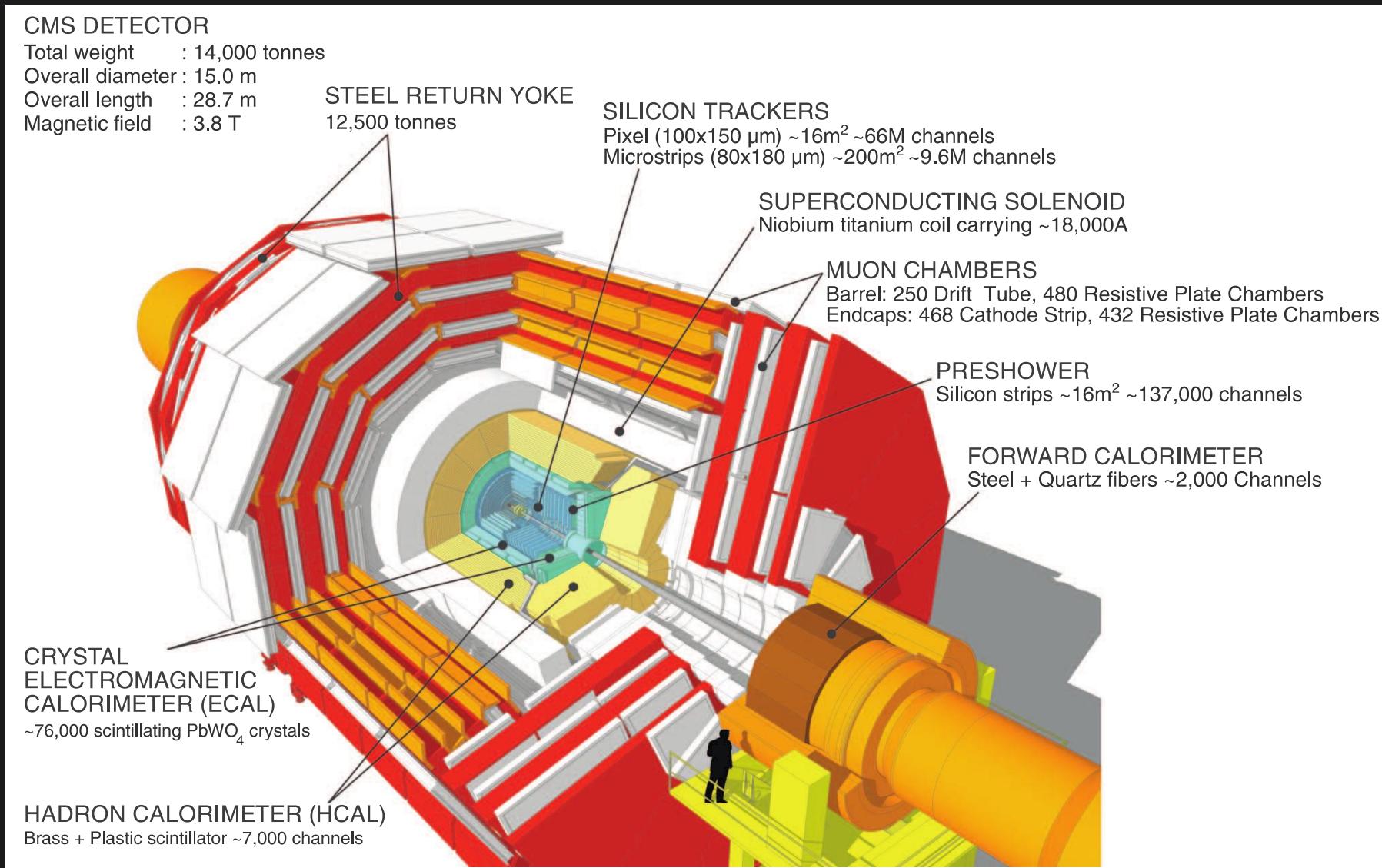


# Geração de cargas – $dE/dx$

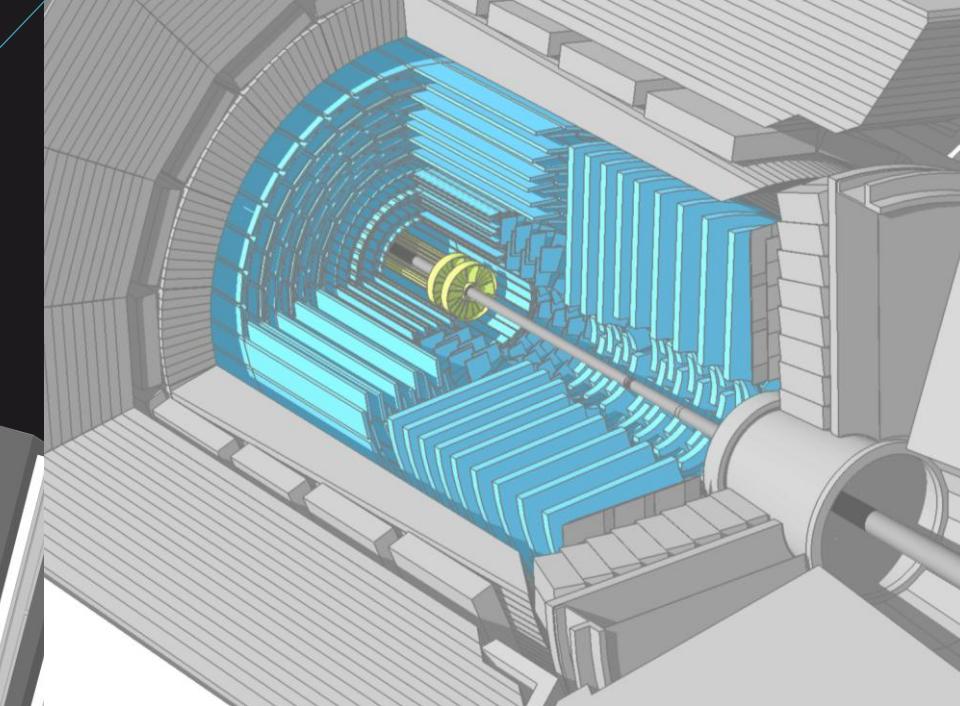
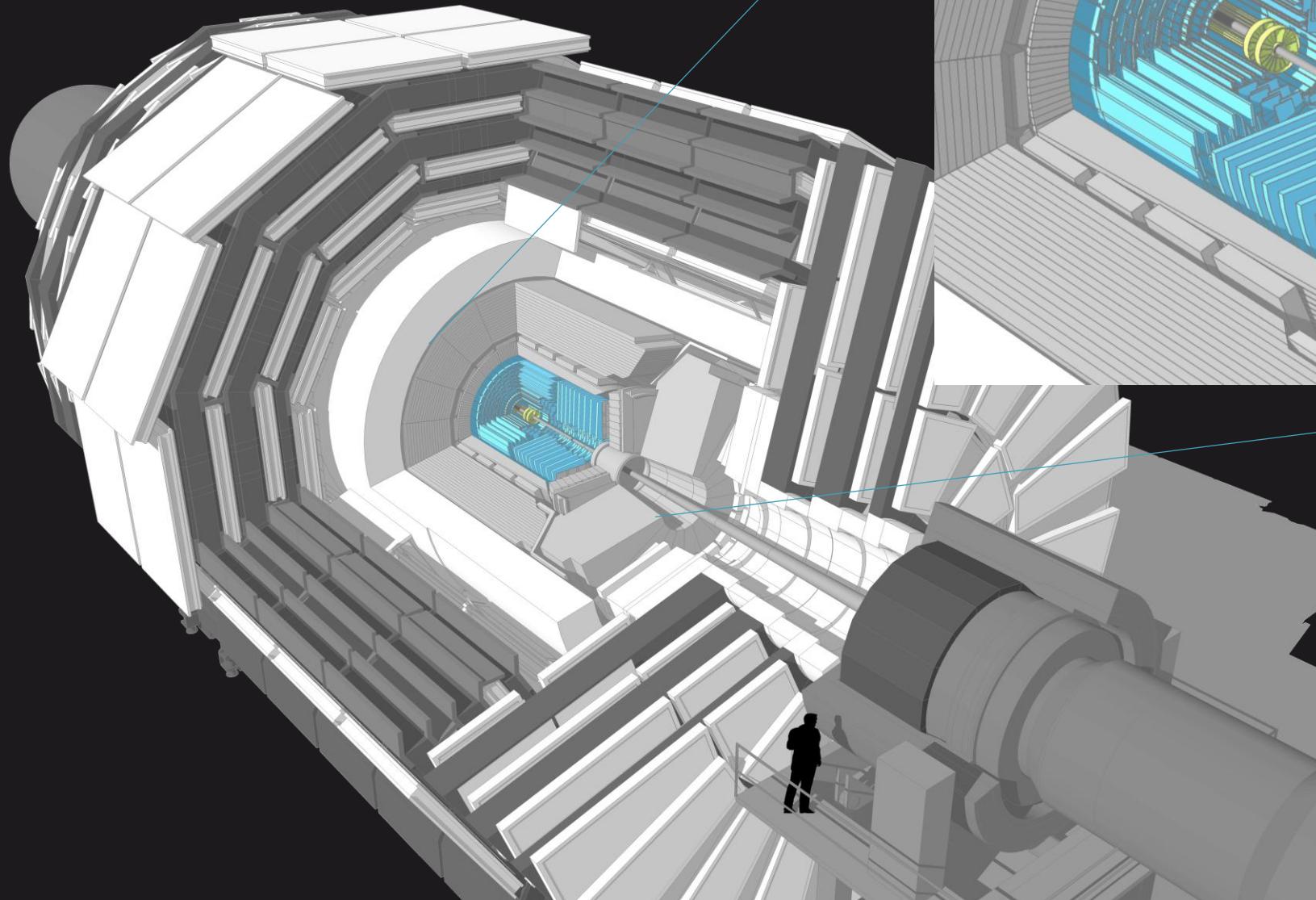


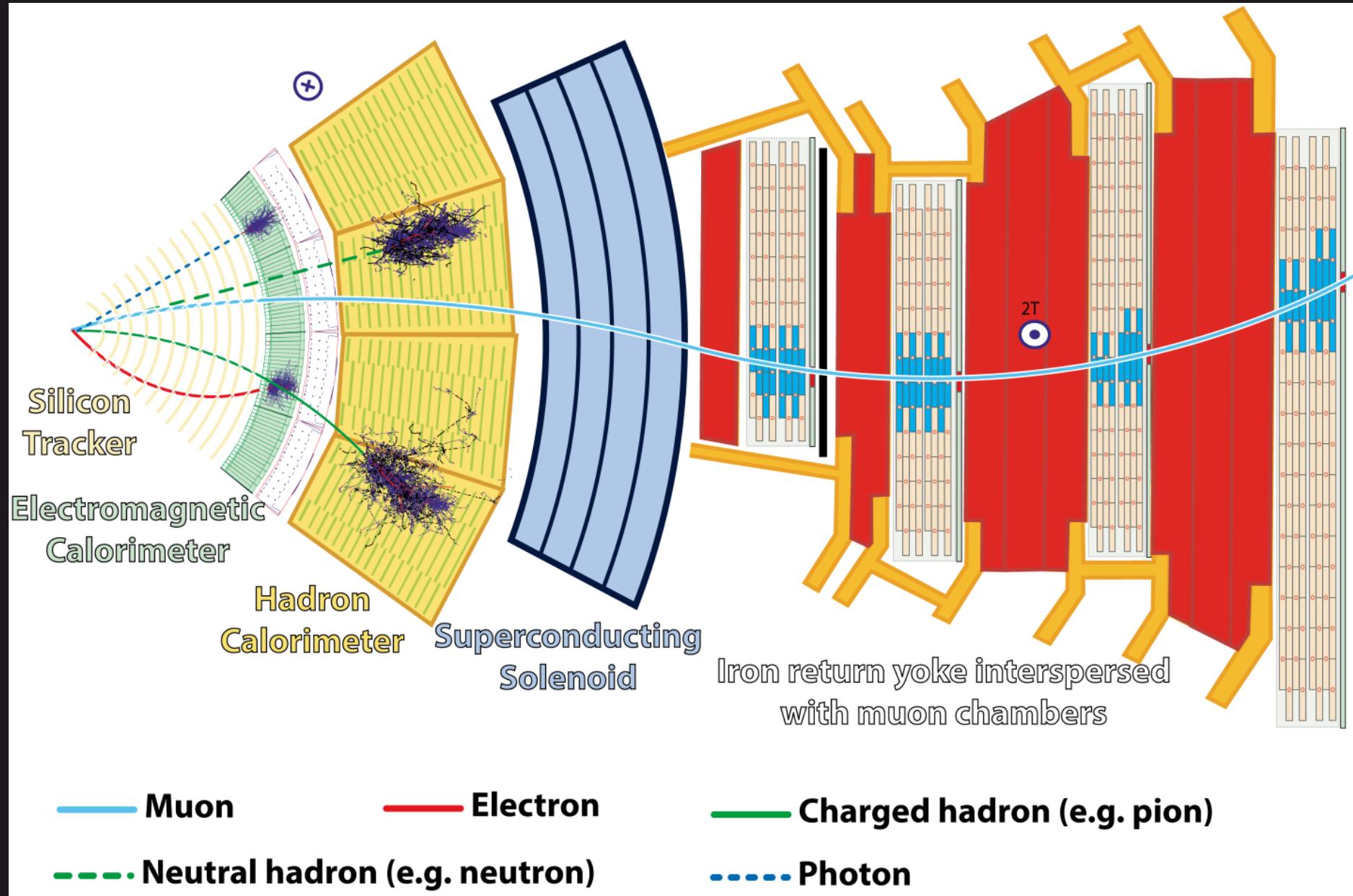
PDG

# Silicon tracker (CMS)

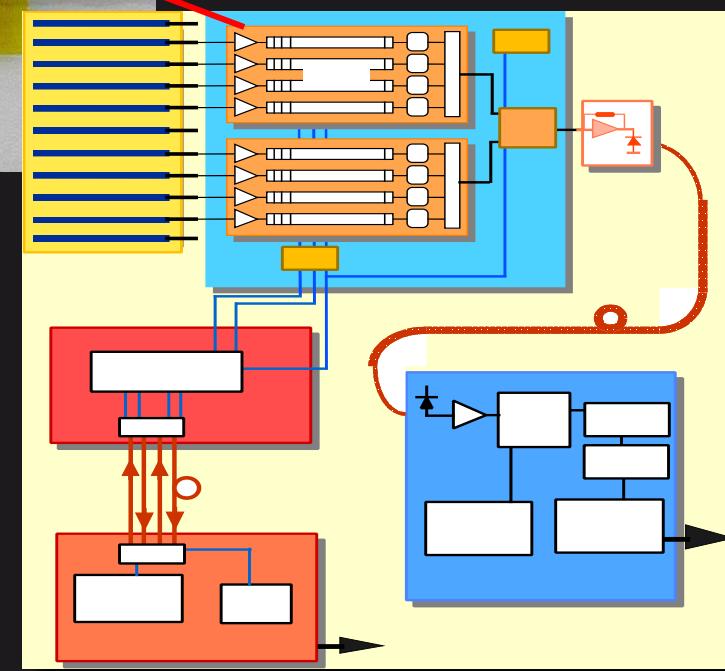
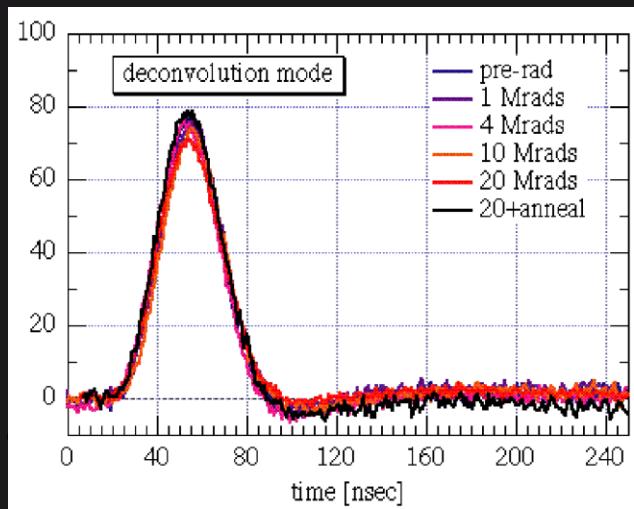
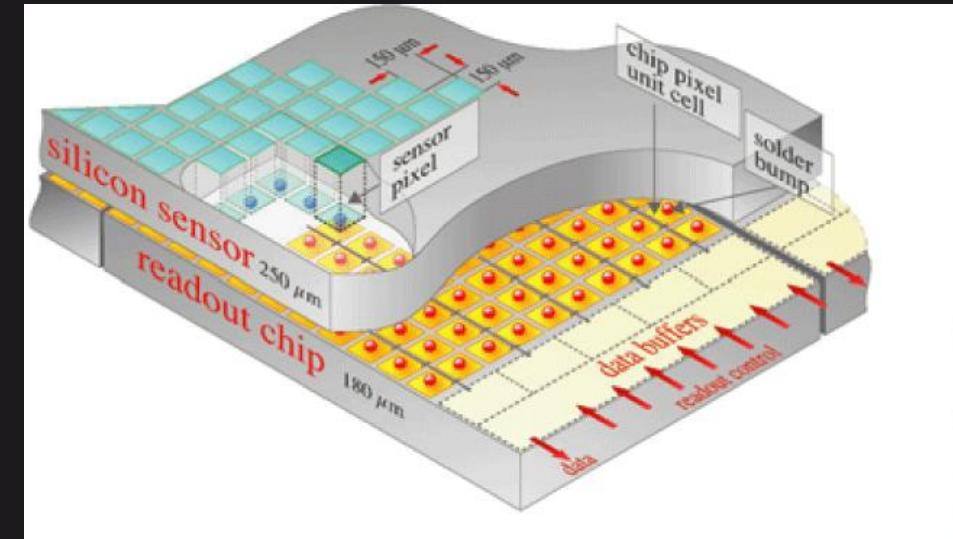
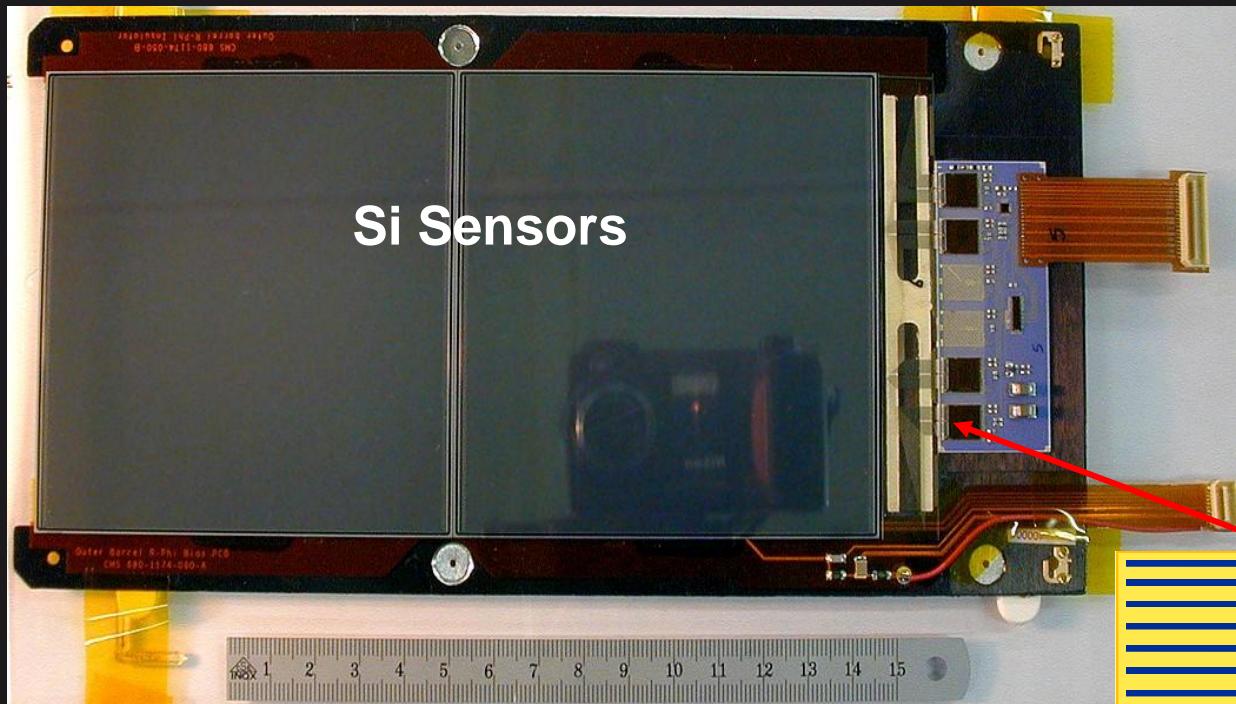


# *Silicon tracker (CMS)*



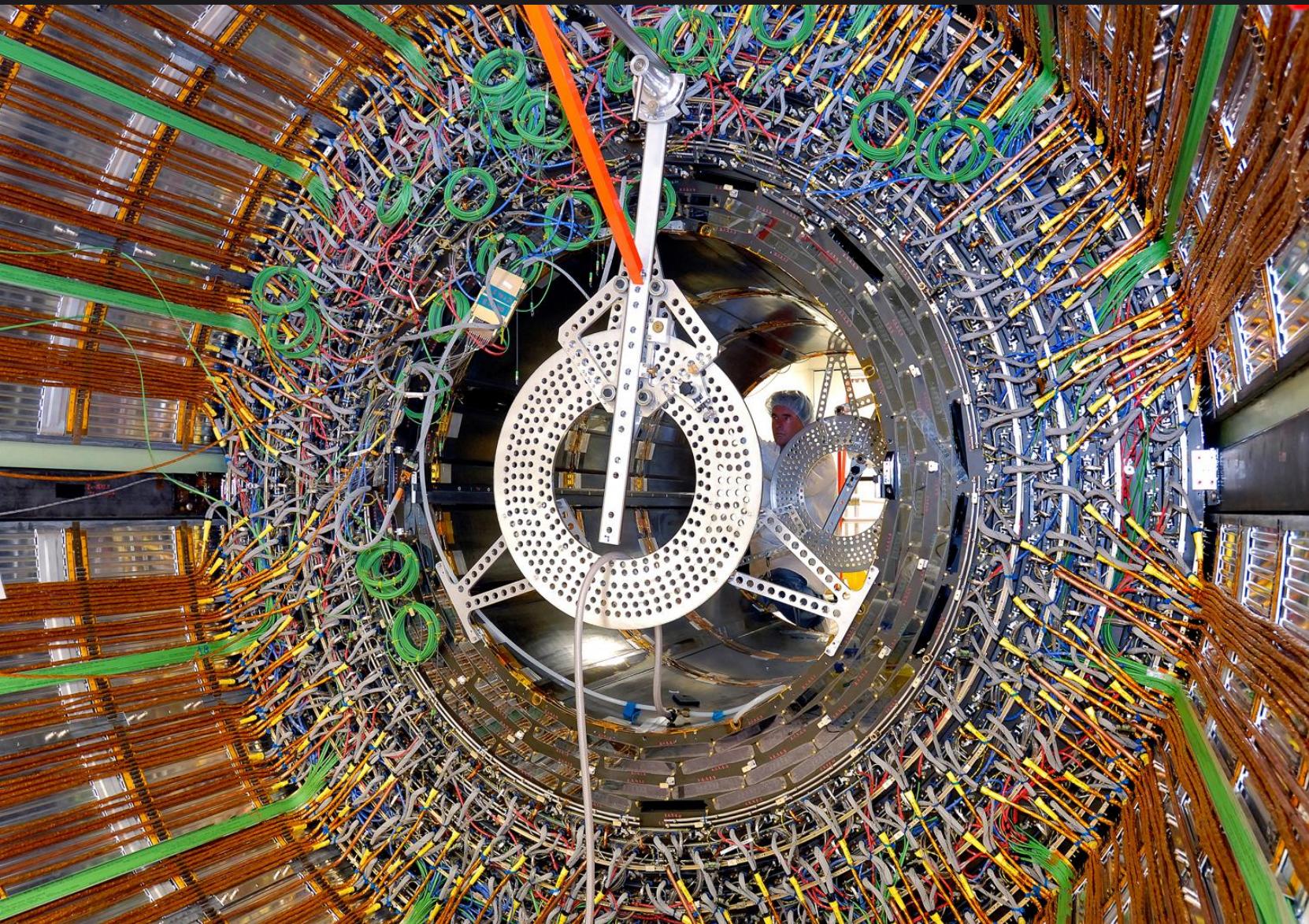


# *Si Modules and Electronics Chain*



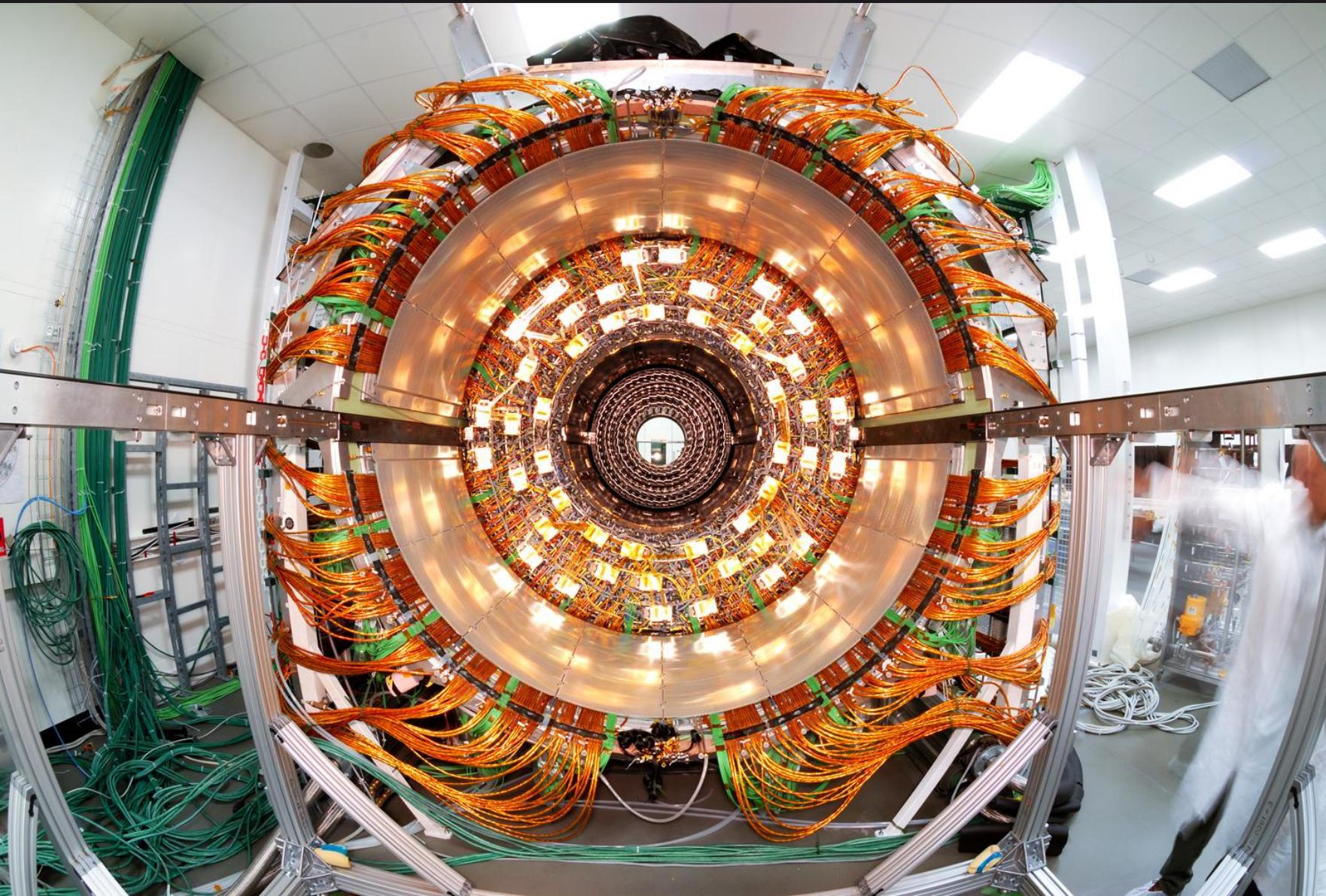
75k chips using  
 $0.25\mu\text{m}$  technology

# *Si Tracker*

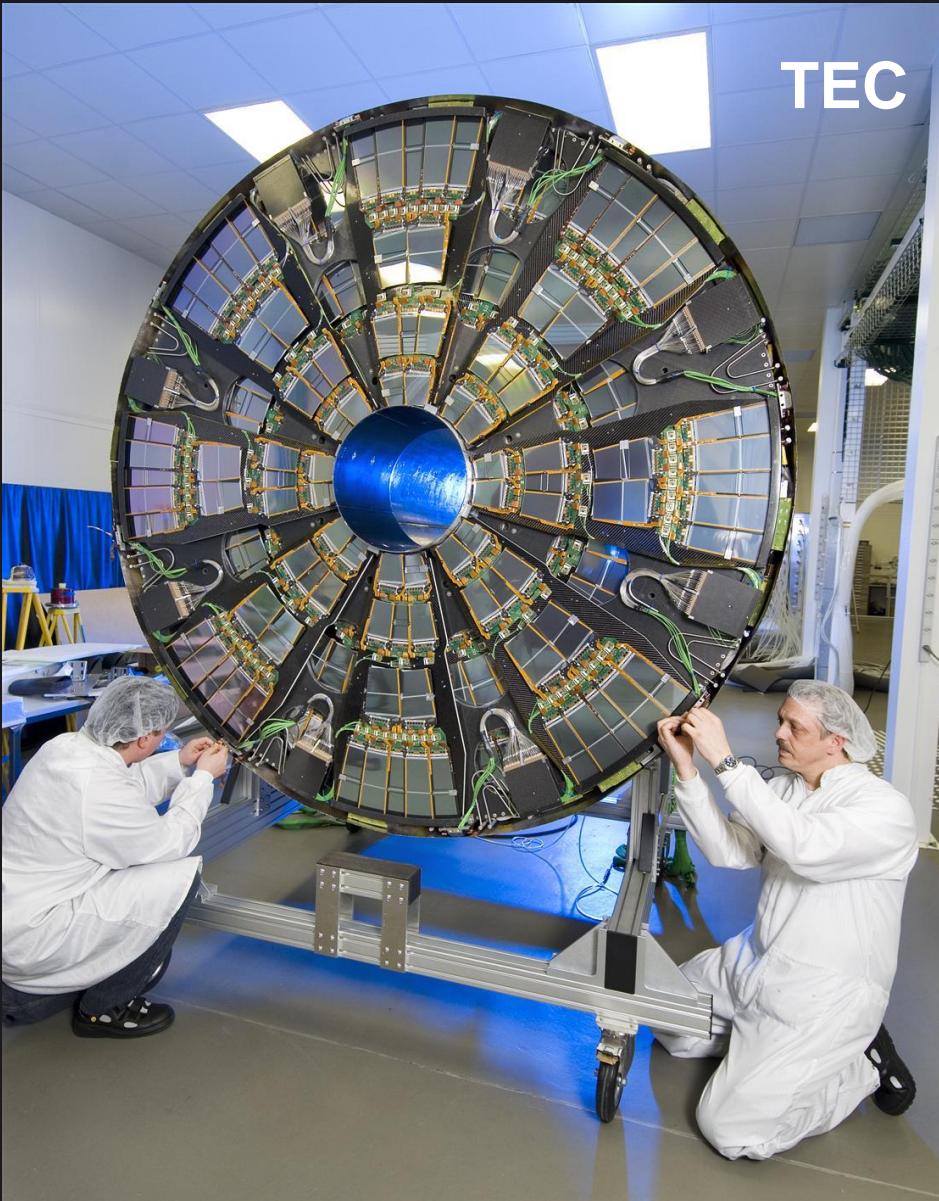
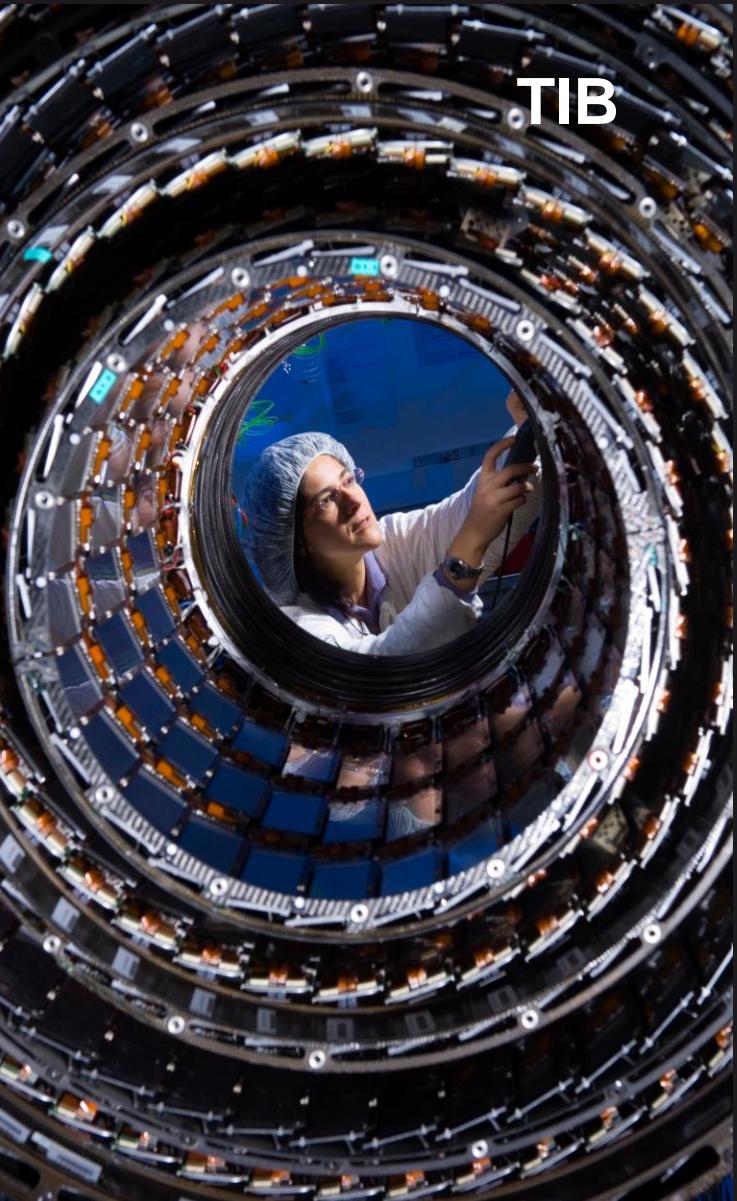


CE

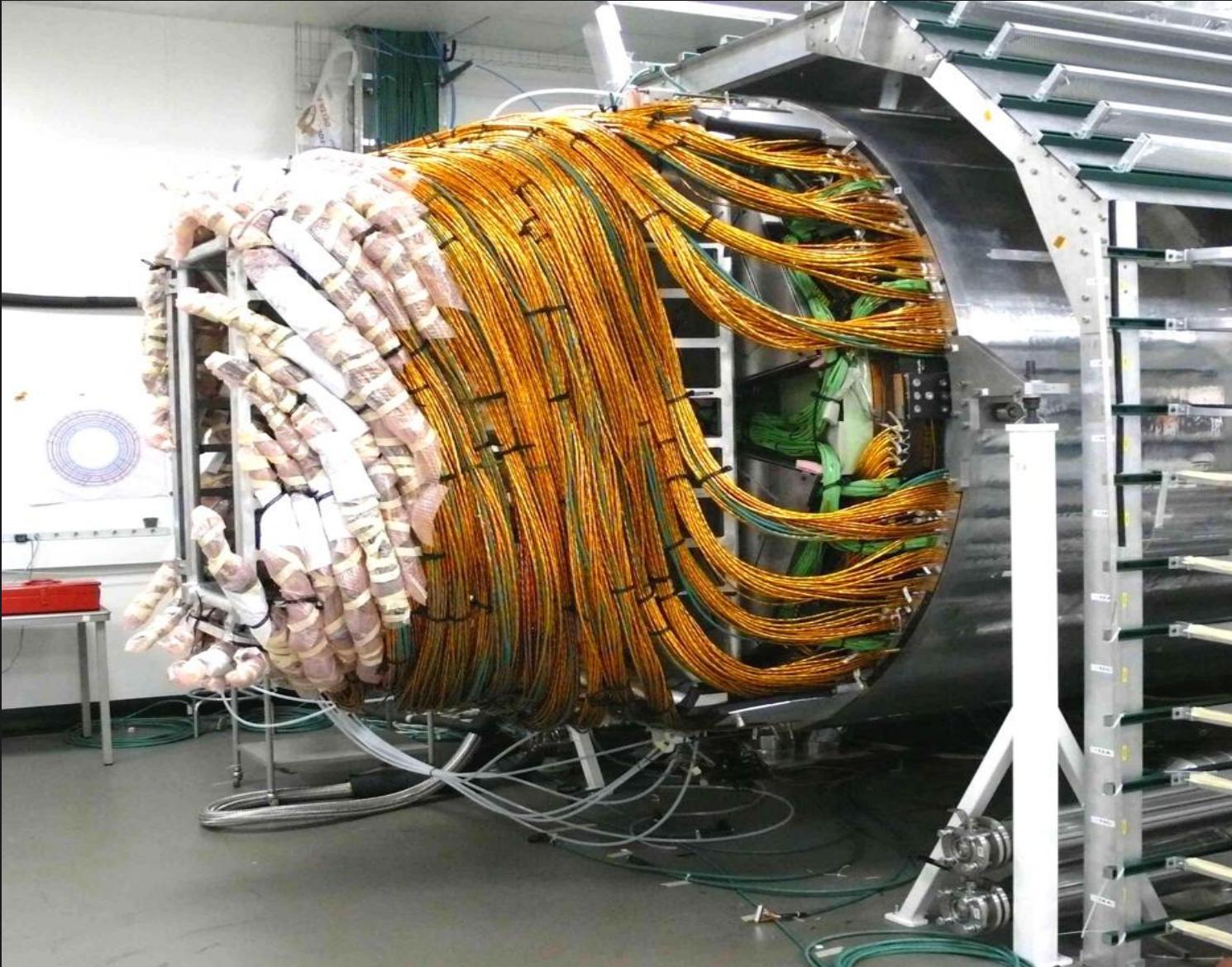
# *Si Tracker*



# *Si Tracker*



# *Tracker Readied for Installation*



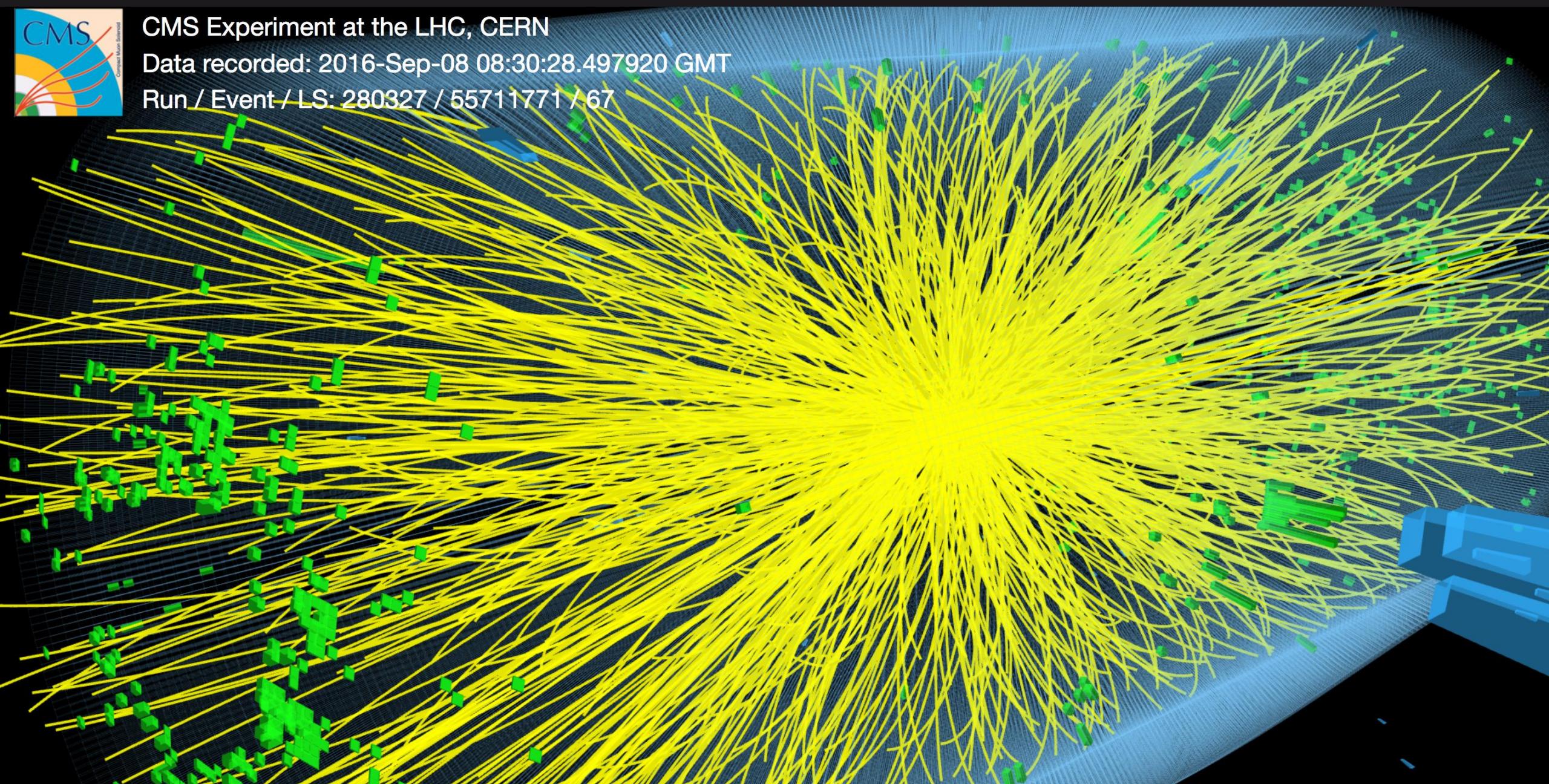
CERN



CMS Experiment at the LHC, CERN

Data recorded: 2016-Sep-08 08:30:28.497920 GMT

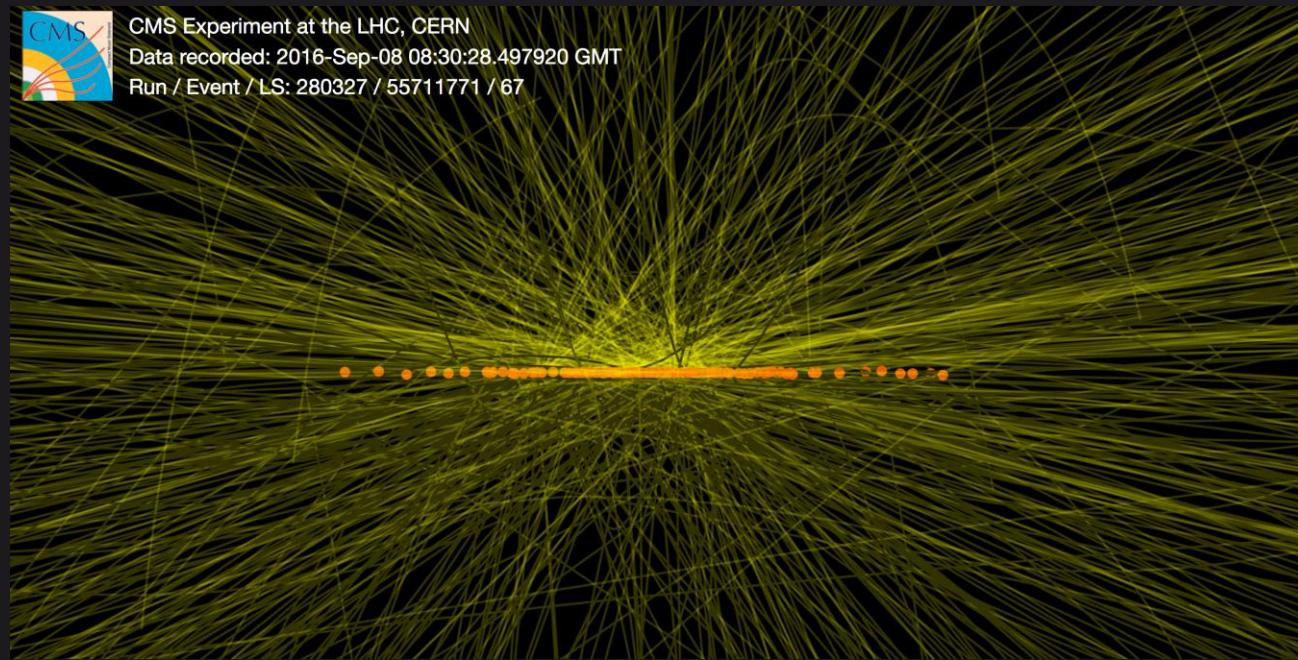
Run / Event / LS: 280327 / 55711771 / 67



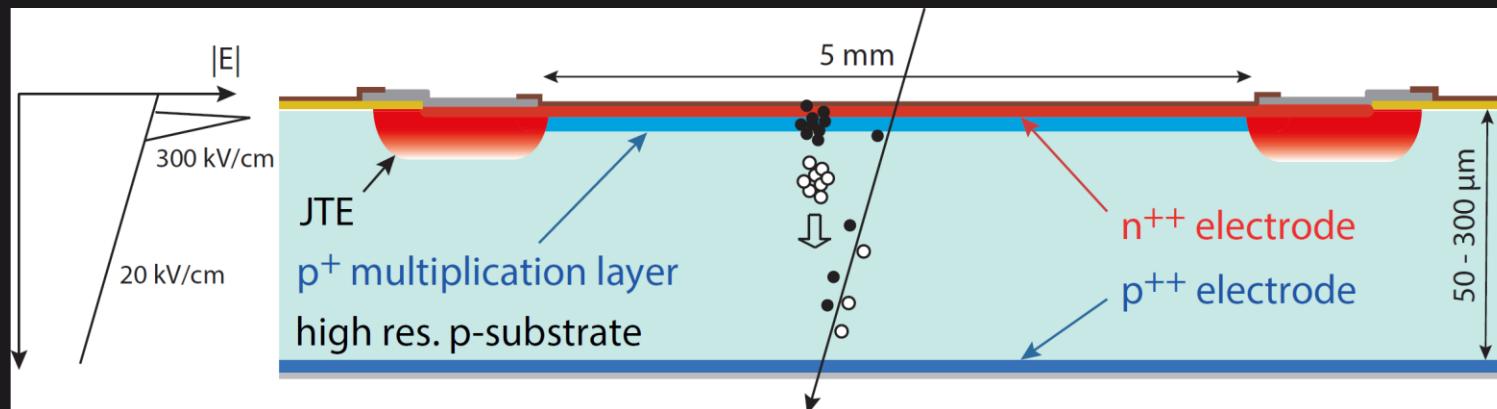
# *Detectores em “4 dimensões”*

Em colisões 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 –  $\mathcal{O}(10 \text{ ps})$



Low Gain Avalanche Diode (LGAD)



# *Testes com detector de silício (Lab.)*

- ✓ *Ponto de operação (curva I-V)*
- ✓ *Aquisição de sinal com fonte radioativa (Sr-90)*
- ✓ *Sinal com LASER IR*
- ✓ *Resolução temporal*

