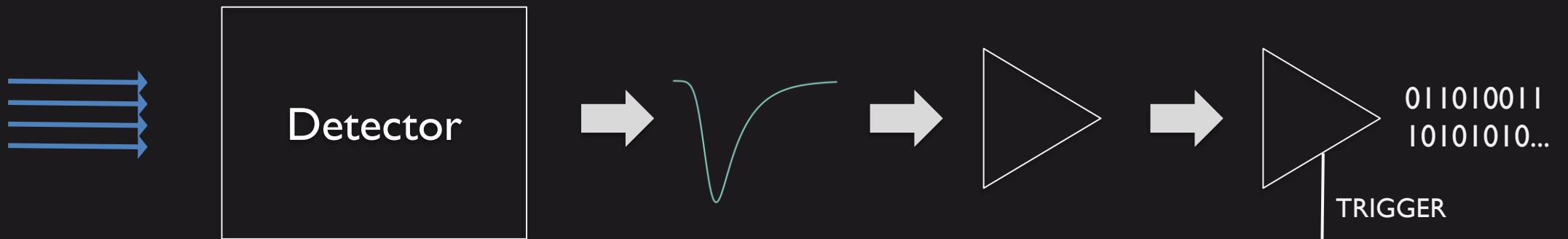


Detectores semicondutores

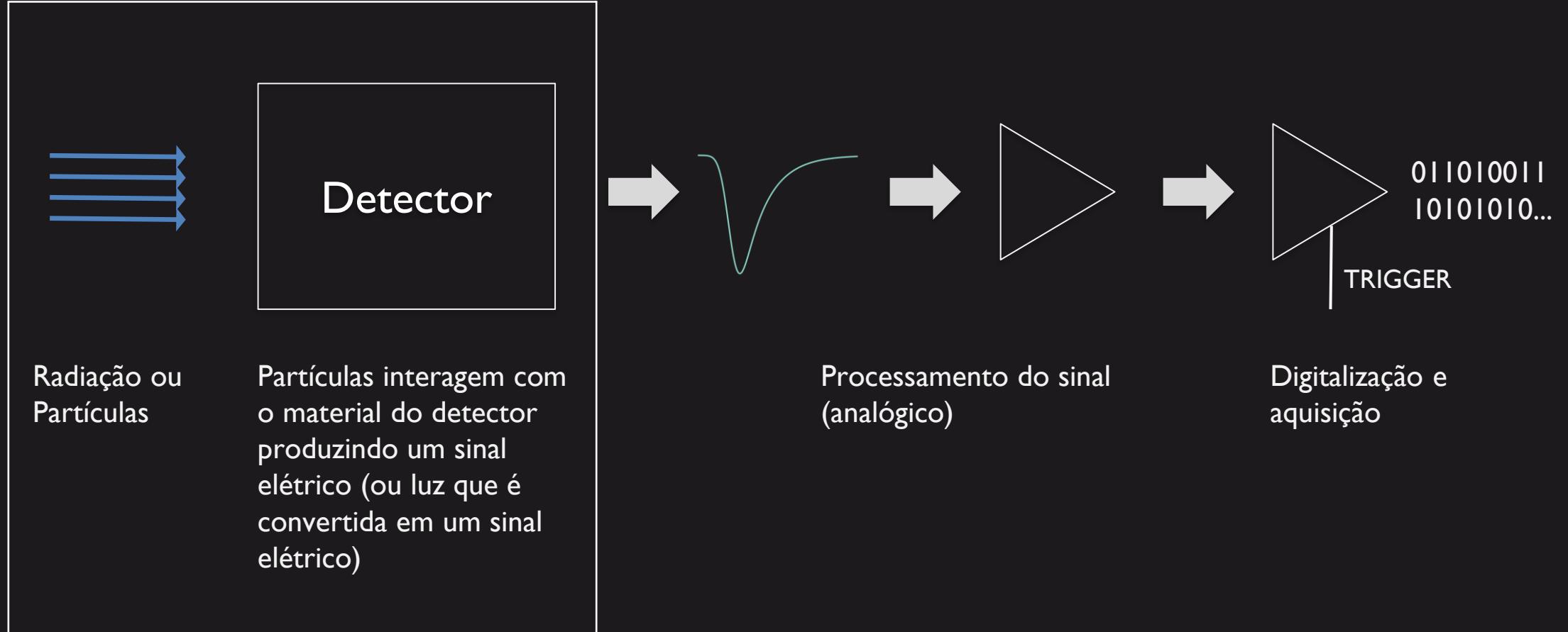


Radiação ou
Partículas

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

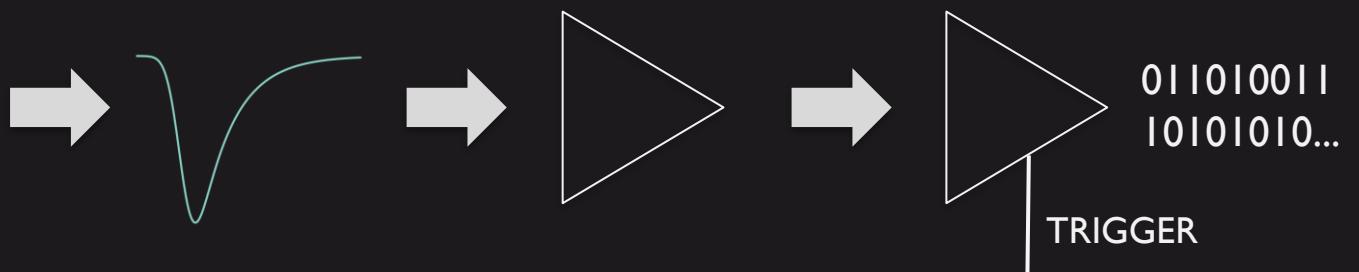
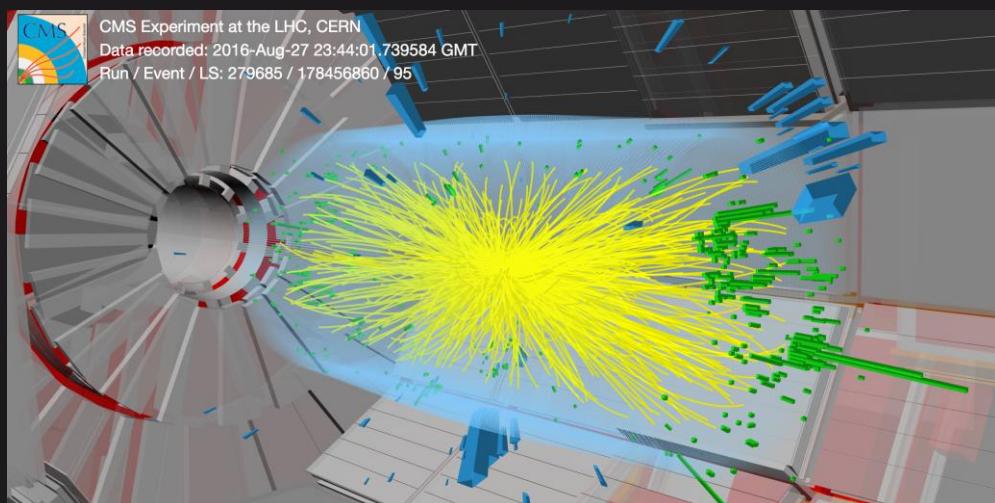
Processamento do sinal
(análogo)

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

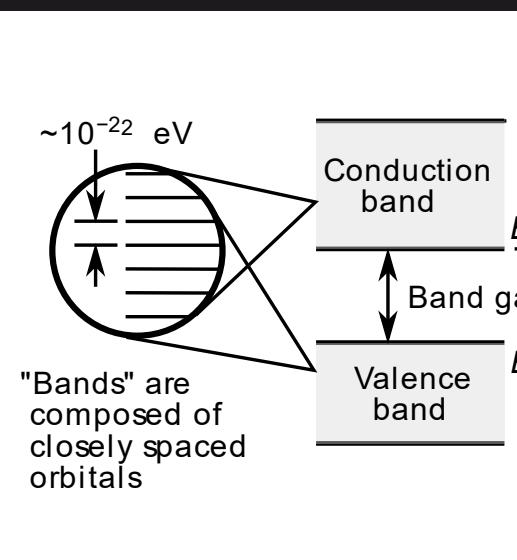
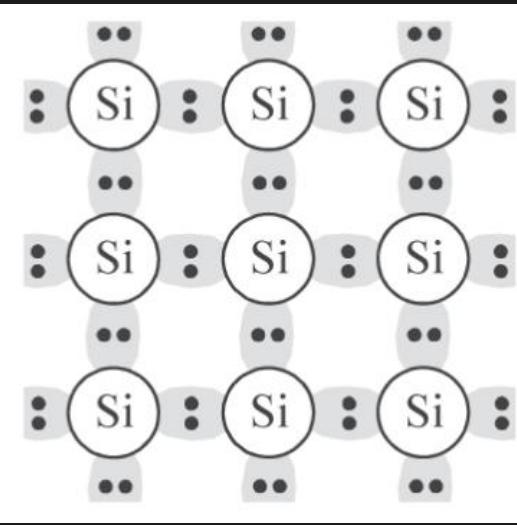
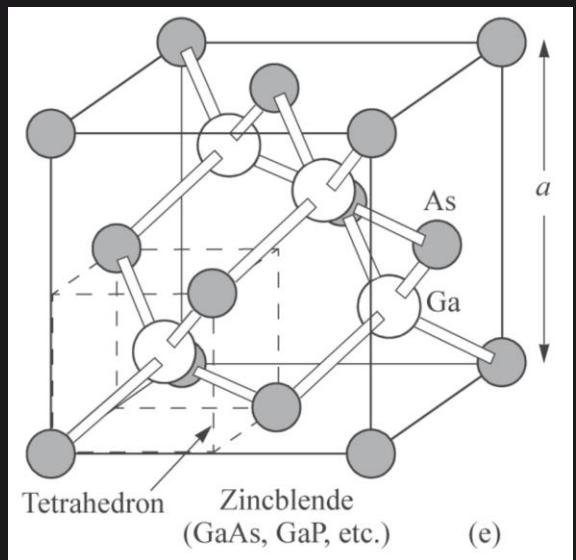
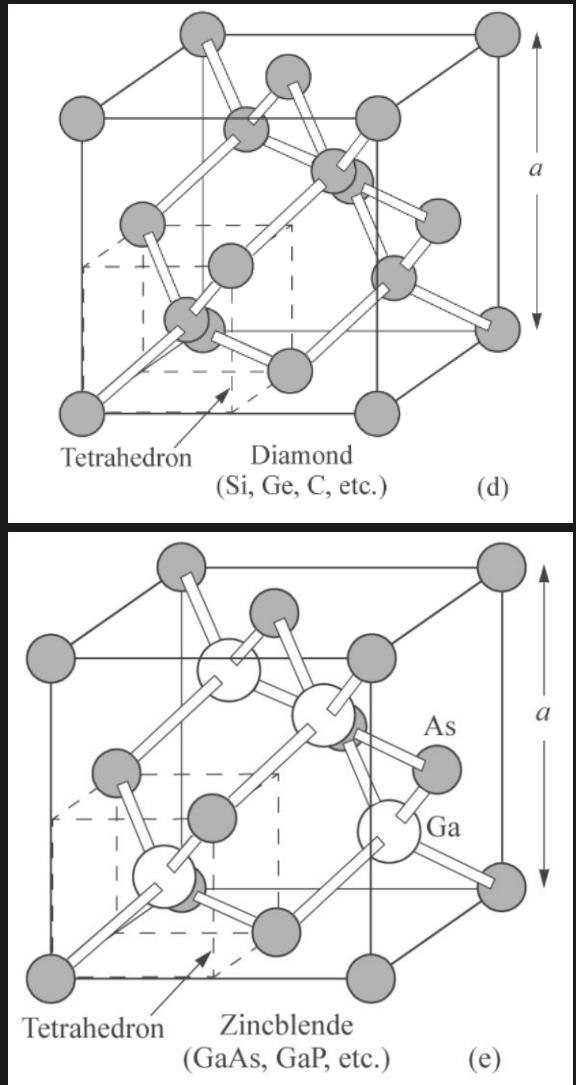
Noble

Hydrogen H 1s ¹ 1.0079	IIA Beryllium Be 1s ² s ² 9.0122							III A Boron B 1s ² 2s ² p 10.81	IV A Carbon C 1s ² 2s ² p ² 12.01	VA Nitrogen N 1s ² 2s ² p ³ 14.007	VIA Oxygen O 1s ² 2s ² p ⁴ 15.999	VIIA Fluorine F 1s ² 2s ² p ⁵ 18.998	Helium He 1s ² 4.0026							
Sodium Na [Ne] 3s ¹ 22.9898	Magnesium Mg [Ne] 3s ² 24.305	IIIB Lithium Li 1s ² s ¹ 6.941	IVB Scandium Sc [Ar] 3d ¹ 4s ² 44.956	VB Titanium Ti [Ar] 3d ² 4s ² 47.90	VIB Vanadium V [Ar] 3d ³ 4s ² 50.942	VIIIB 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	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	Neon Ne 1s ² 2s ² p ⁶ 20.18		
Potassium K [Ar] 4s ¹ 39.09	Calcium Ca [Ar] 4s ² 40.08	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 ⁵ s ¹ 92.91	Molybdenum Mo [Kr] 4d ⁵ s ¹ 95.94	Technetium Tc [Kr] 4d ⁵ s 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	Bromine Br [Ar] 3d ¹⁰ 4s ² 4p ⁶ 83.80	Krypton Kr [Ar] 3d ¹⁰ 4s ² 4p ⁶ 83.80
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 ⁵ 6s ² 183.85	Rhenium Re [Xe] 4f ¹⁴ 5d ⁶ 6s ² 186.2	Osmium Os [Xe] 4f ¹⁴ 5d ⁷ 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 [Rn] 5f ⁹ 6d ² 7s ² 251	Fermium Fm [Rn] 5f ¹⁰ 6s ² 251	Mendelevium Md [Rn] 5f ¹⁰ 6s ² 251	Nobelium No [Rn] 5f ¹⁰ 6s ² 251	Lawrencium Lw [Rn] 5f ¹⁰ 6s ² 251

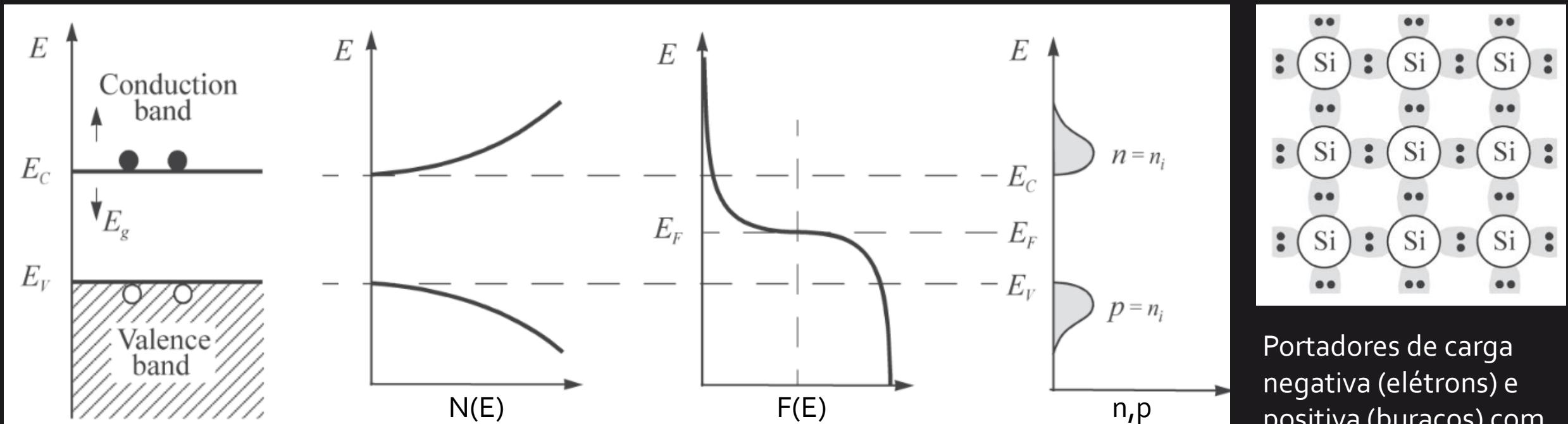
Semicondutores

IIIA	IVA	VA
Boron B 1s ² 2s ² 2p ¹ 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



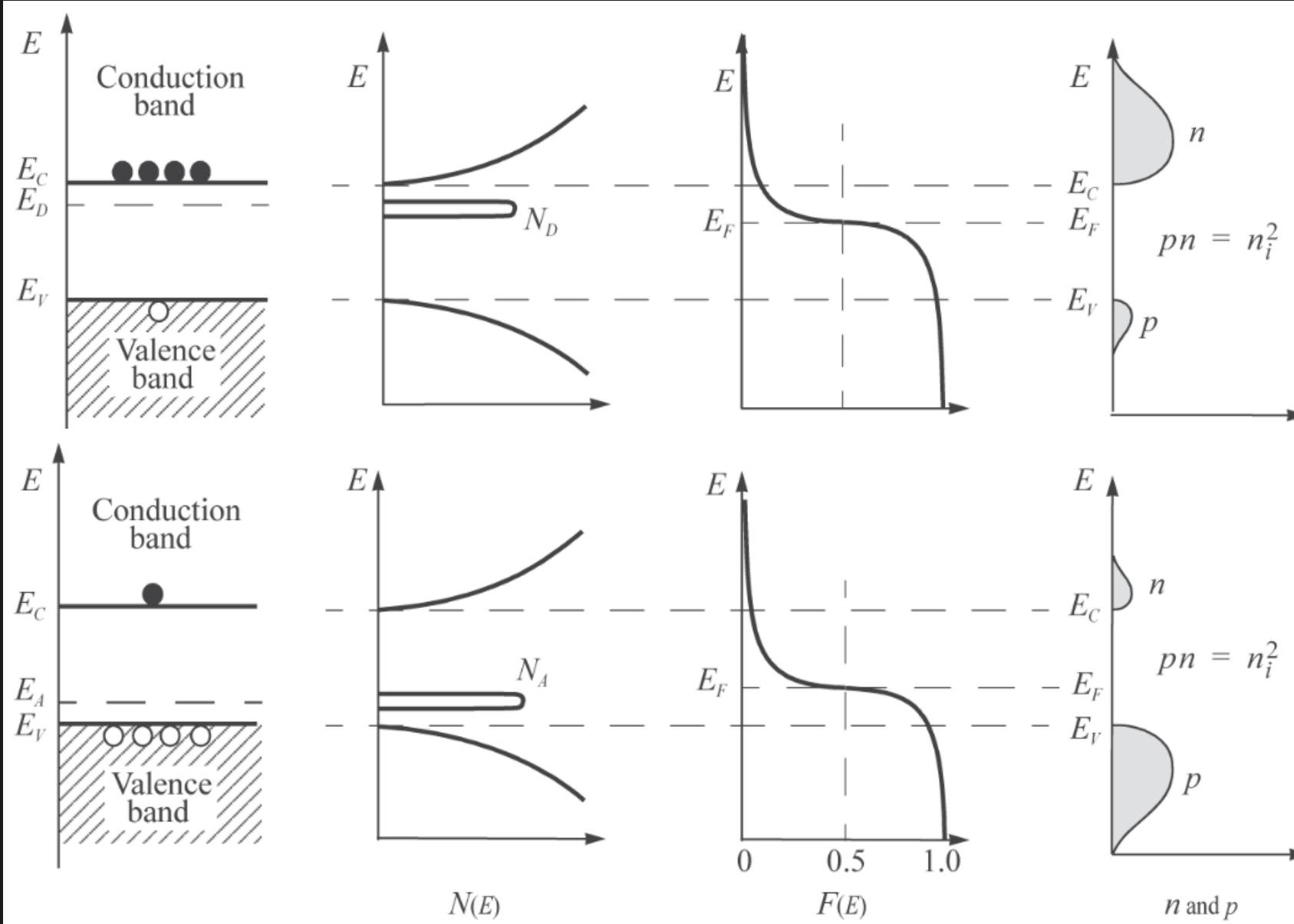
Si:
 $E_g = 1.12$ eV
 $E(\text{par e+h}) \sim 3.6$ eV
 ~ 100 pares e+h / μm (MIP)

Semicondutores (intrínsecos)

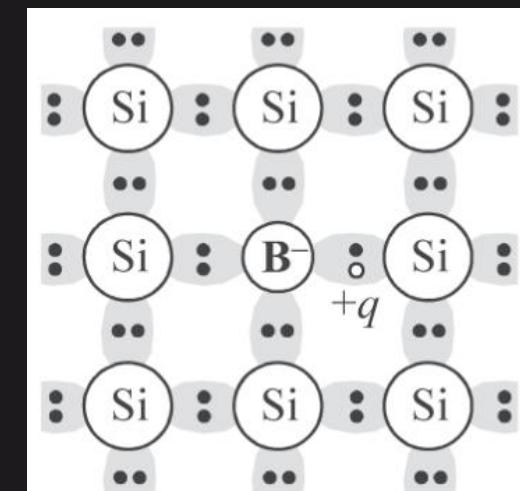
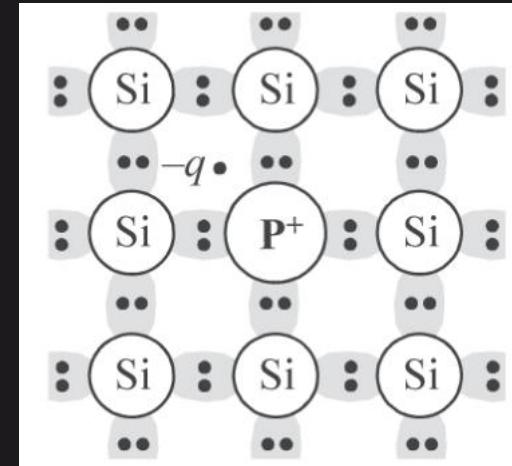


Portadores de carga negativa (elétrons) e positiva (buracos) com alta *mobilidade* na rede cristalina.

Semicondutores (extrínsecos)



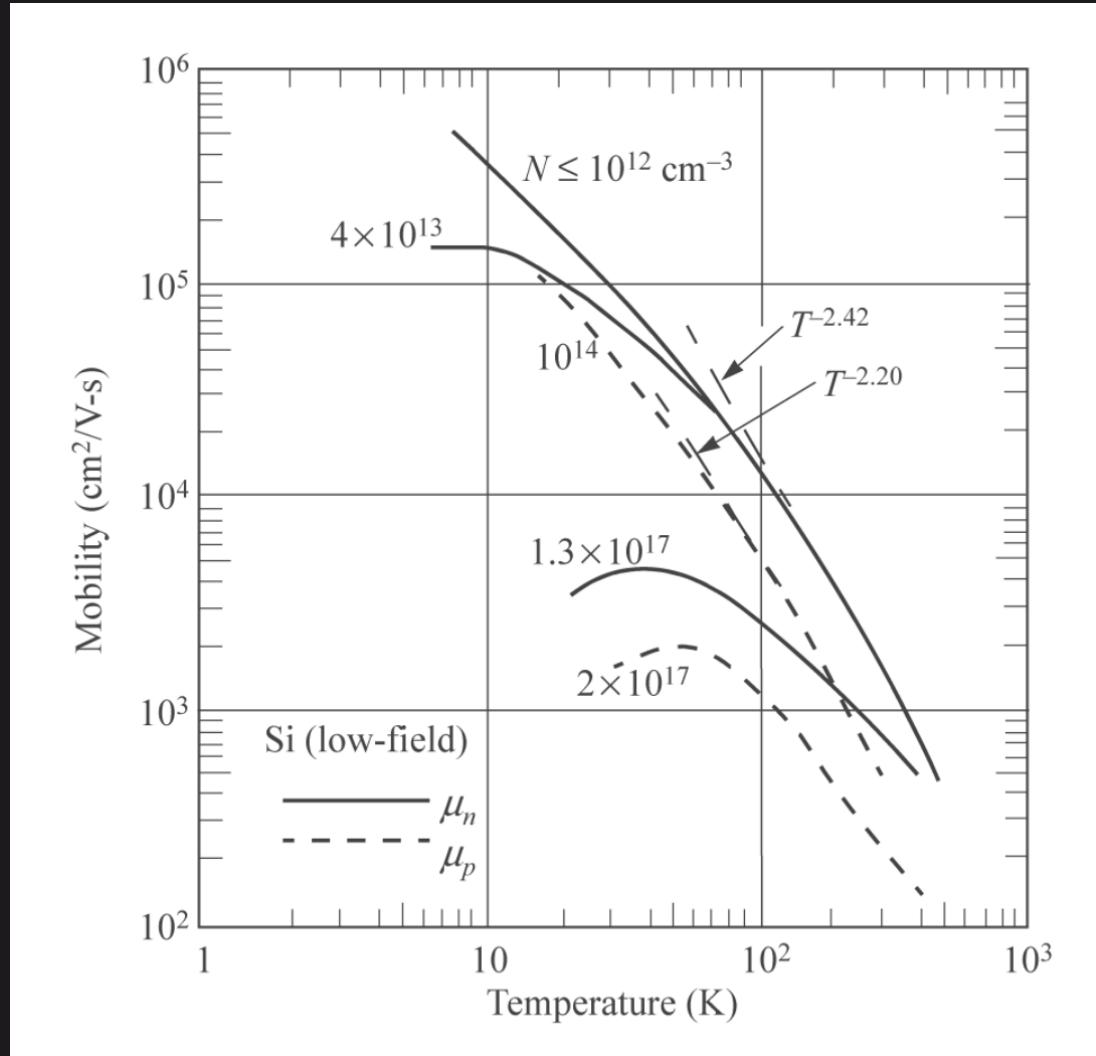
tipo-n, excesso de portadores de carga negativa (elétrons)



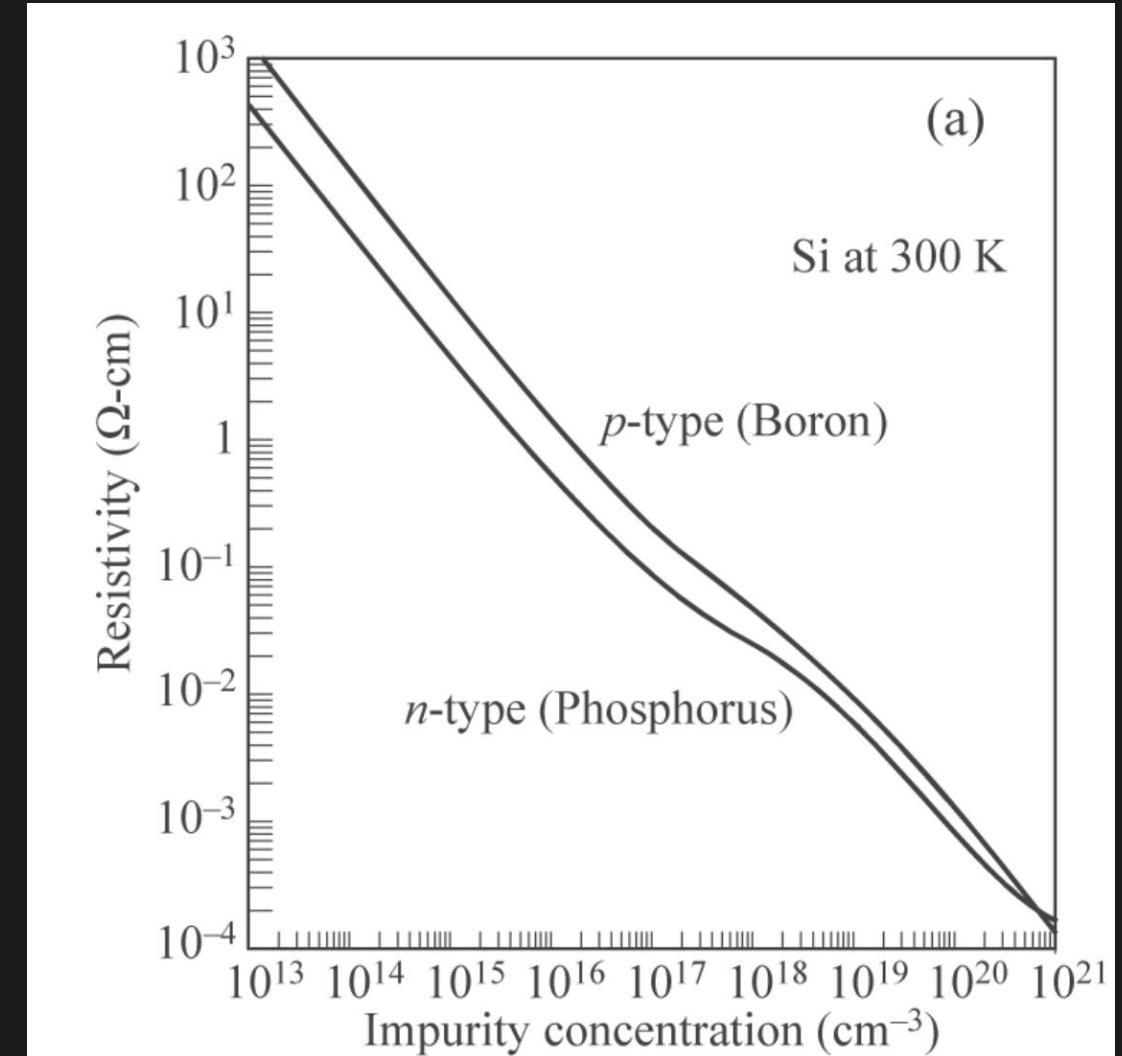
tipo-p, excesso de portadores de carga positiva (buracos)

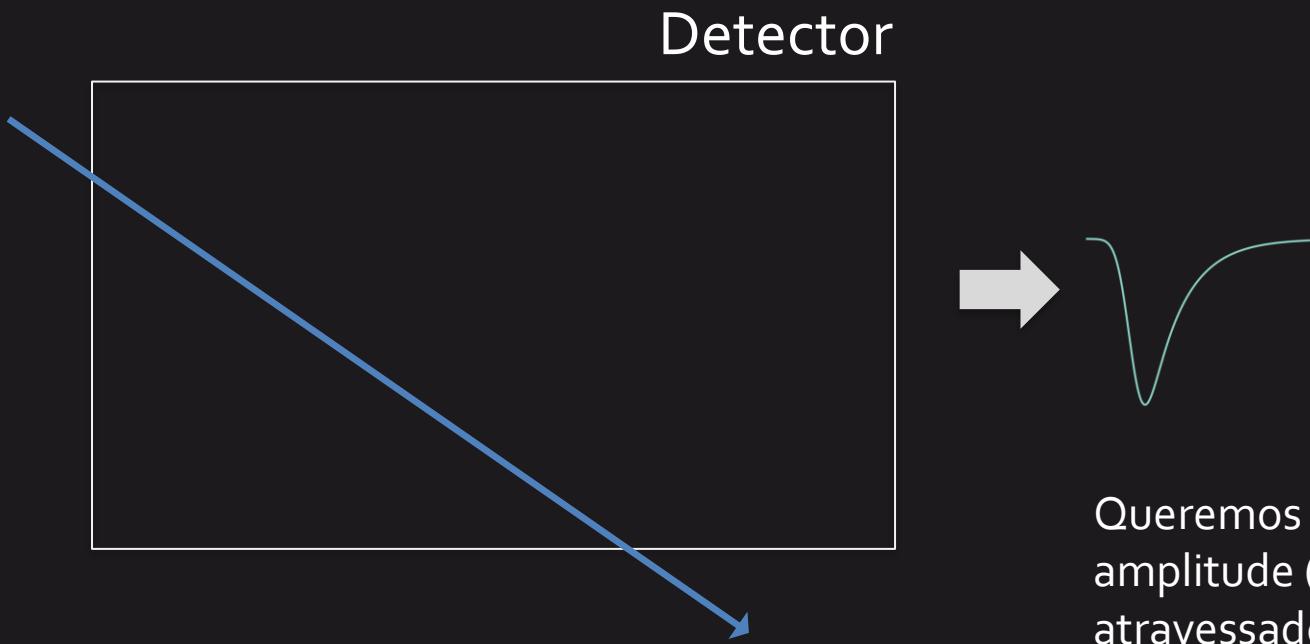
Semicondutores (extrínsecos)

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



Resistividade



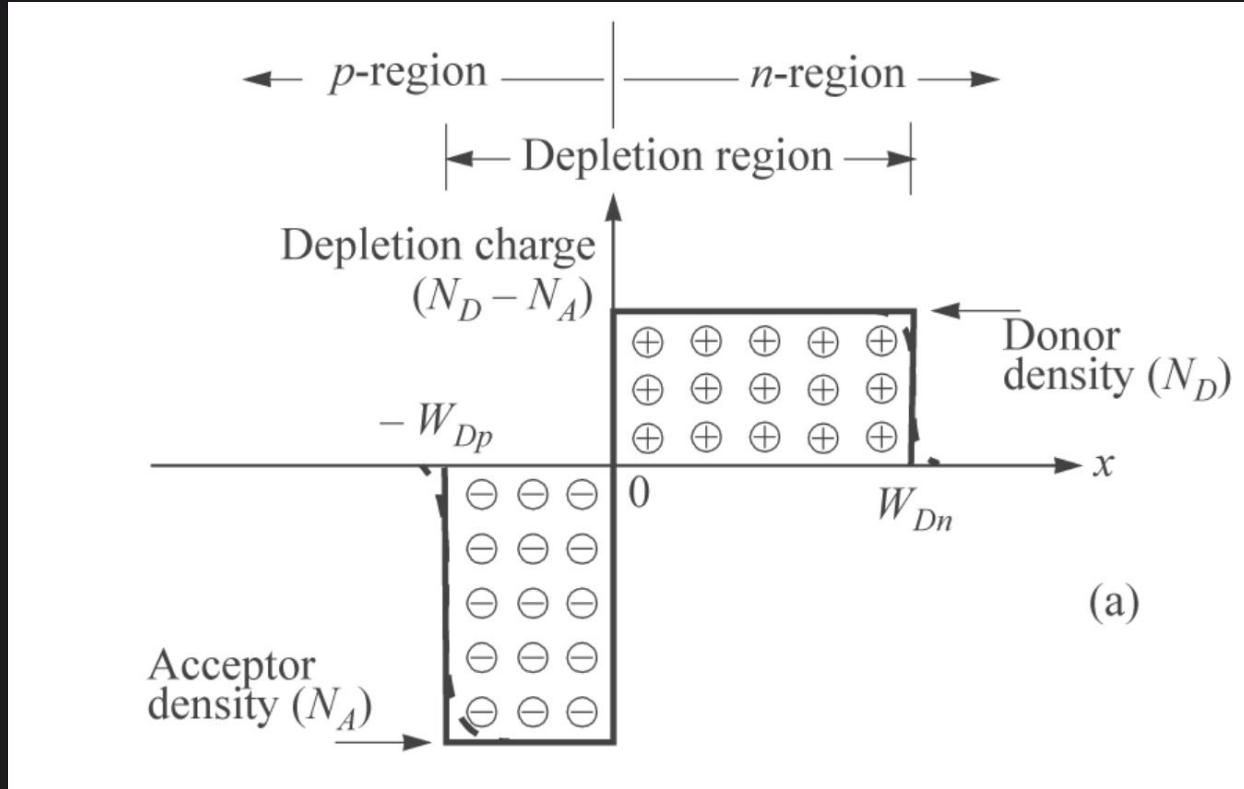


Queremos dispositivos que apresentem sinal com alta amplitude (e idealmente rápidos) ao serem atravessados por partículas incidentes, e baixo sinal na ausência de radiação incidente (ruído/fundo).

Energia entre bandas de semicondutores na faixa de poucos eV.

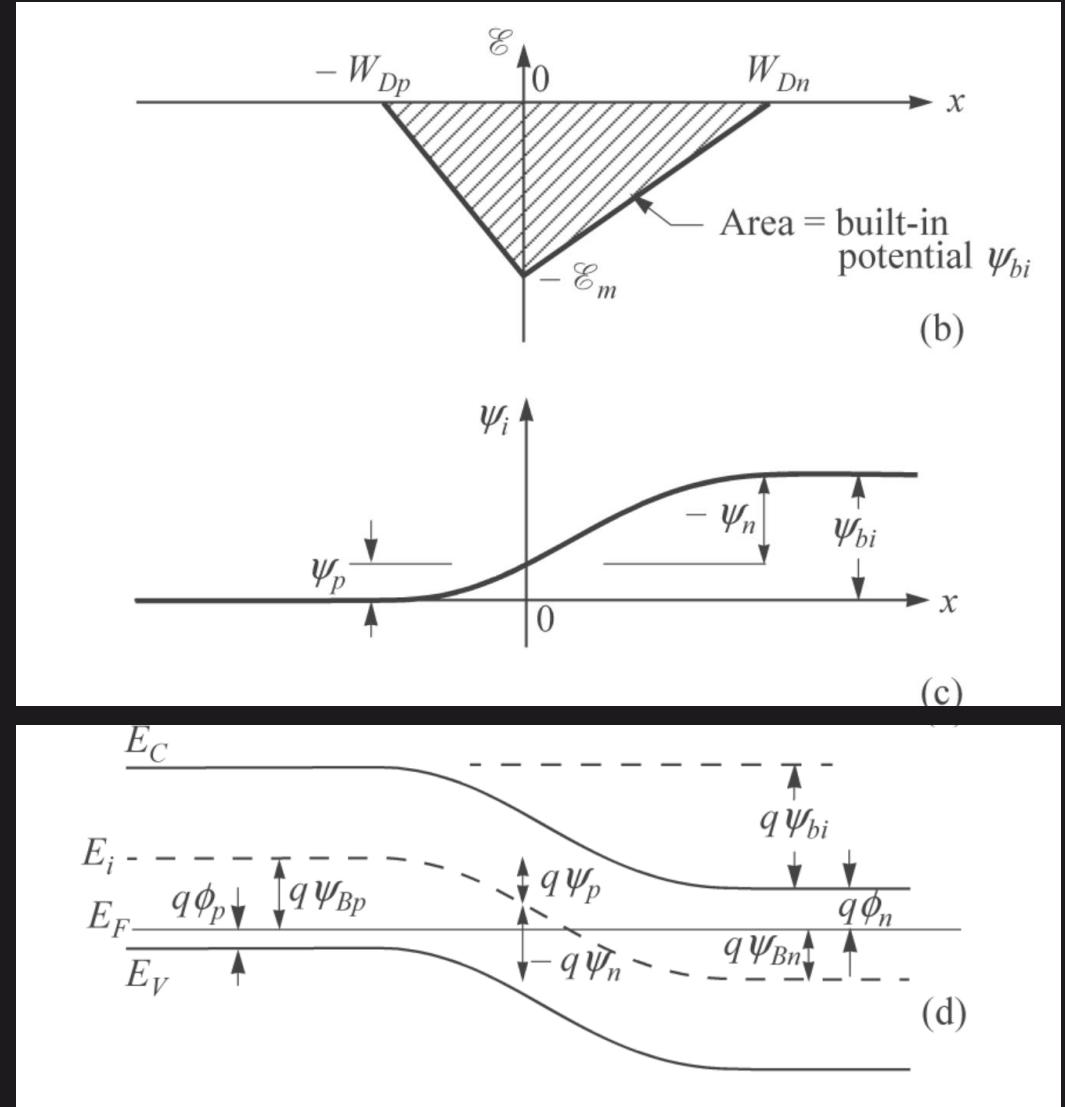
→ Junção p-n reversamente polarizada.

Junção p-n



(a)

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

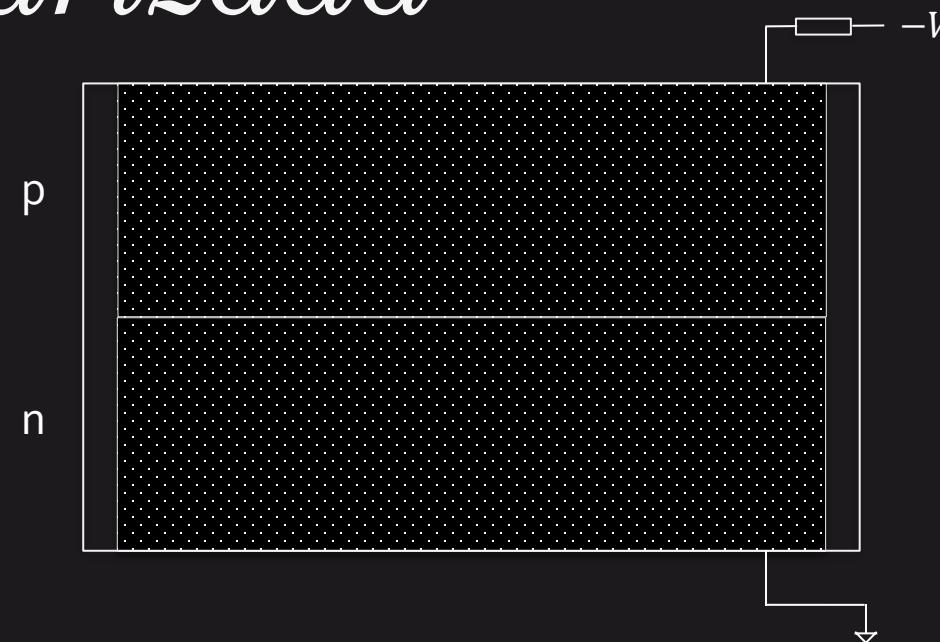
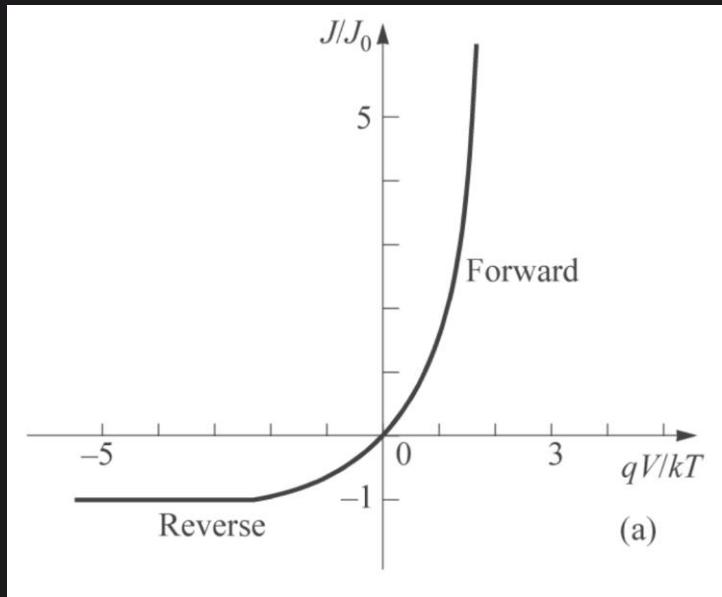


(b)

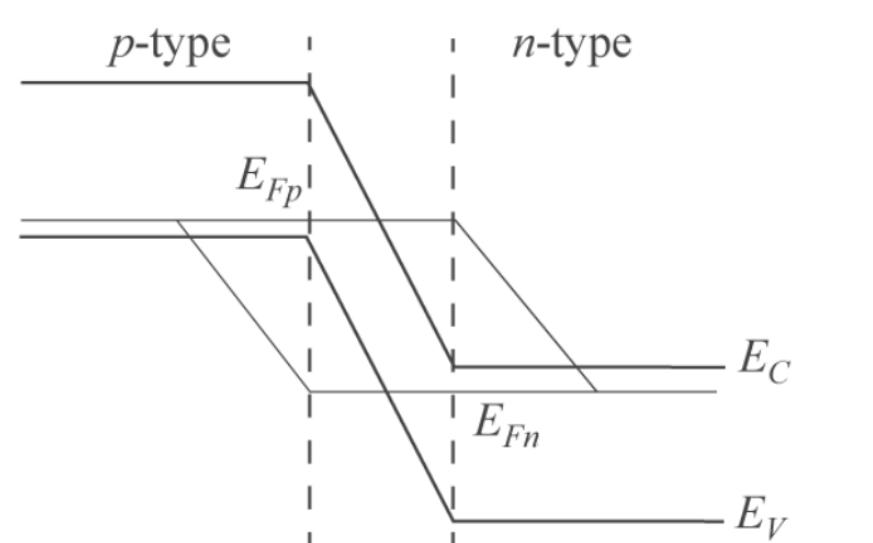
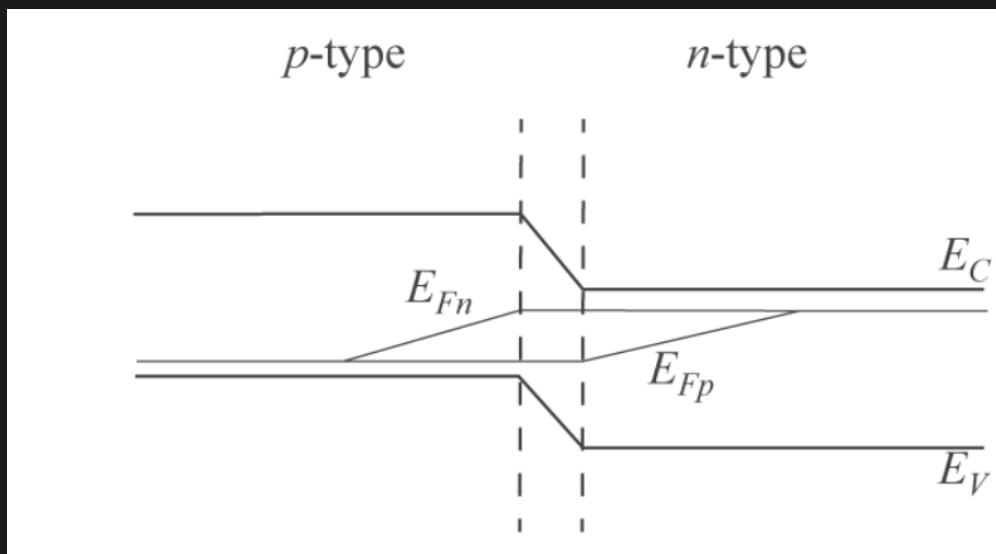
(c)

(d)

Junção p-n polarizada



Polarização reversa
aumenta região de
depleção

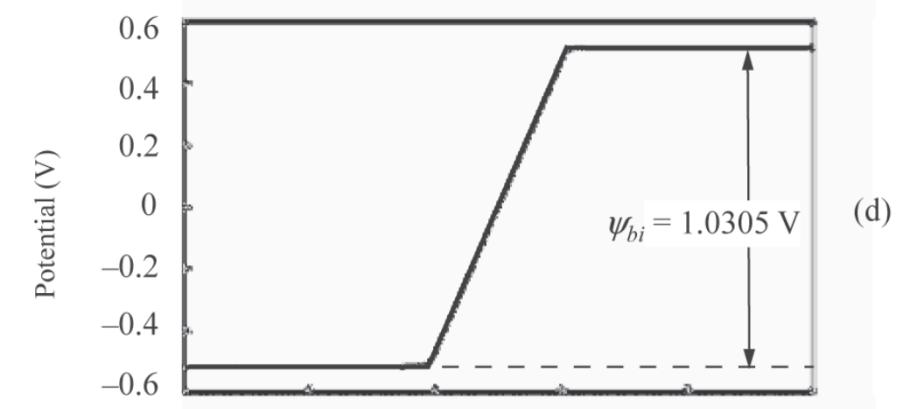
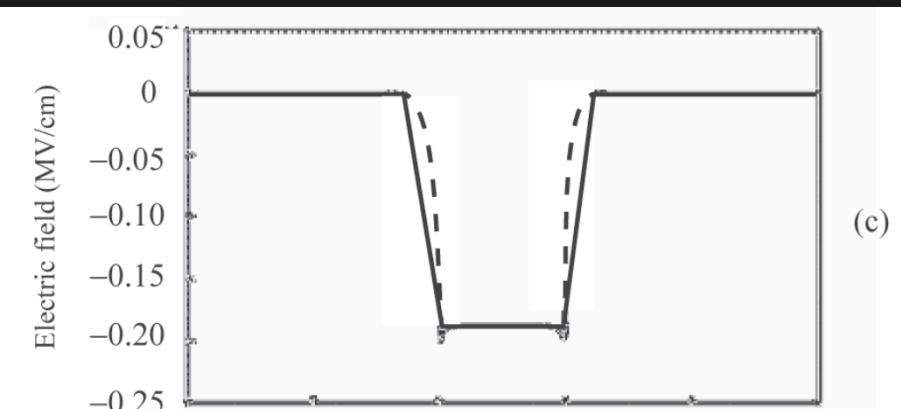
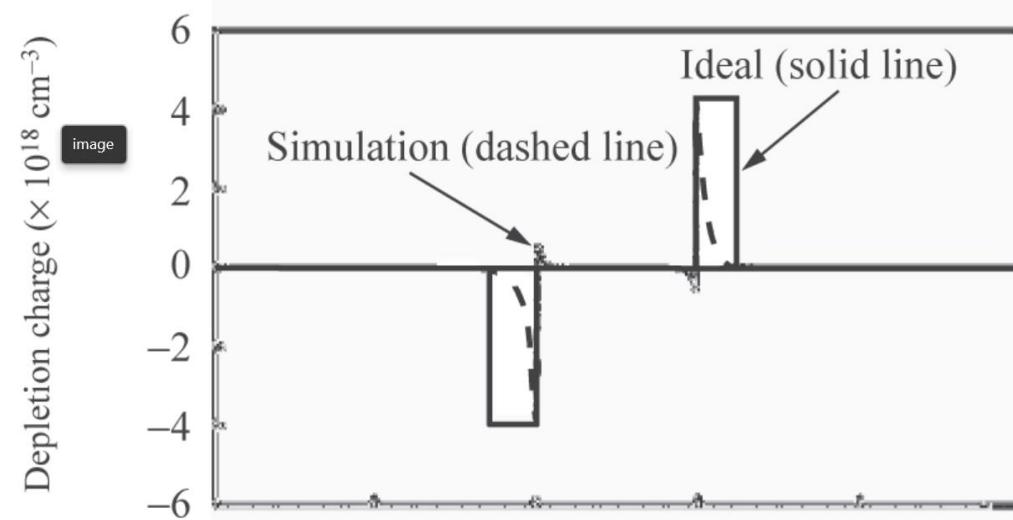
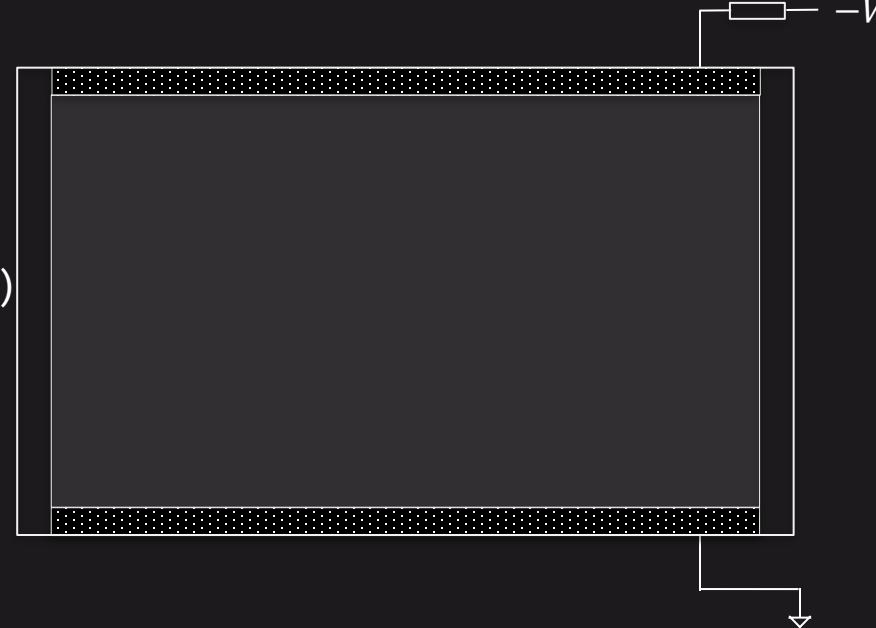


p-i-n

alta concentração p p+

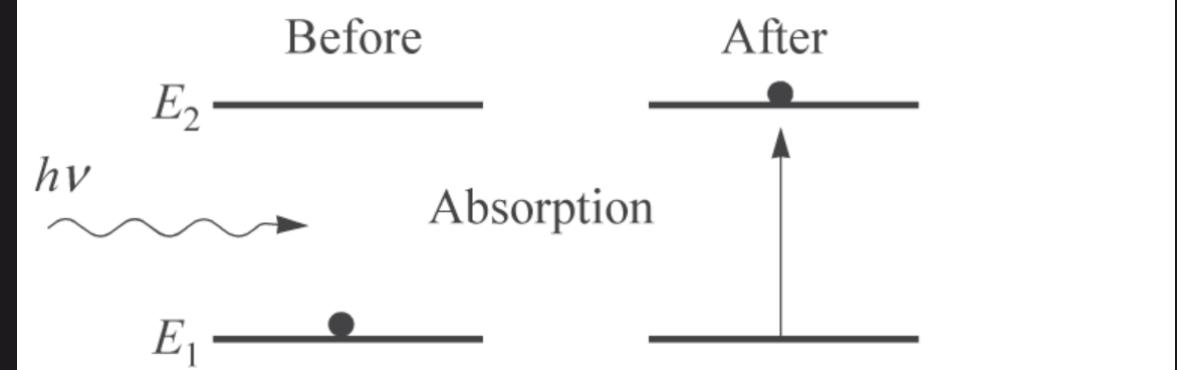
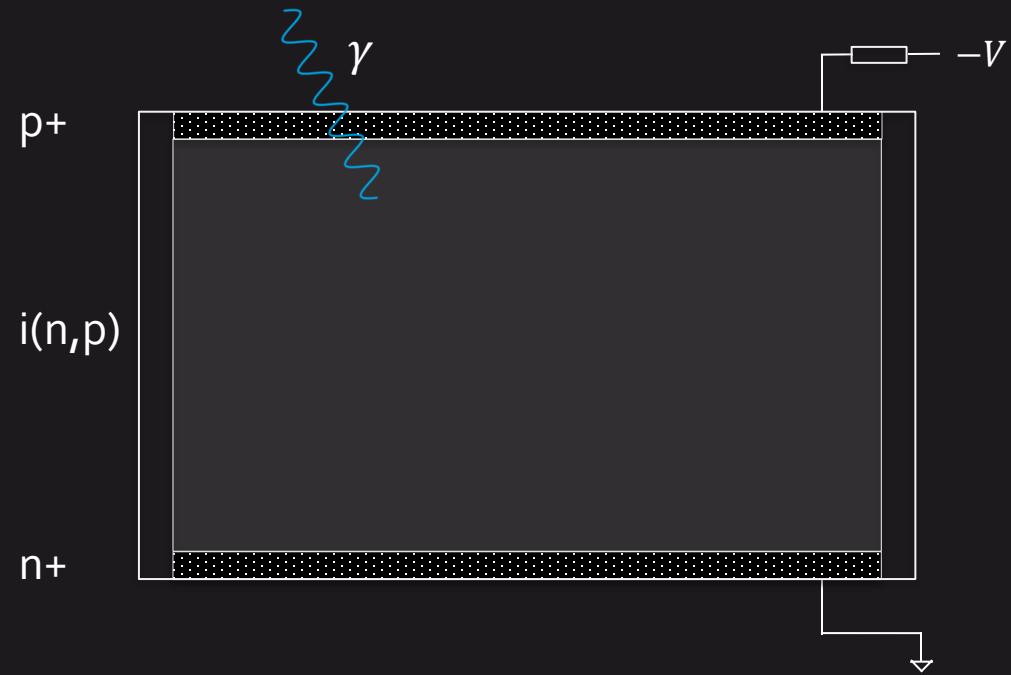
intrínseco (i) ou baixa i(n,p)
concentração n ou p

alta concentração n n+



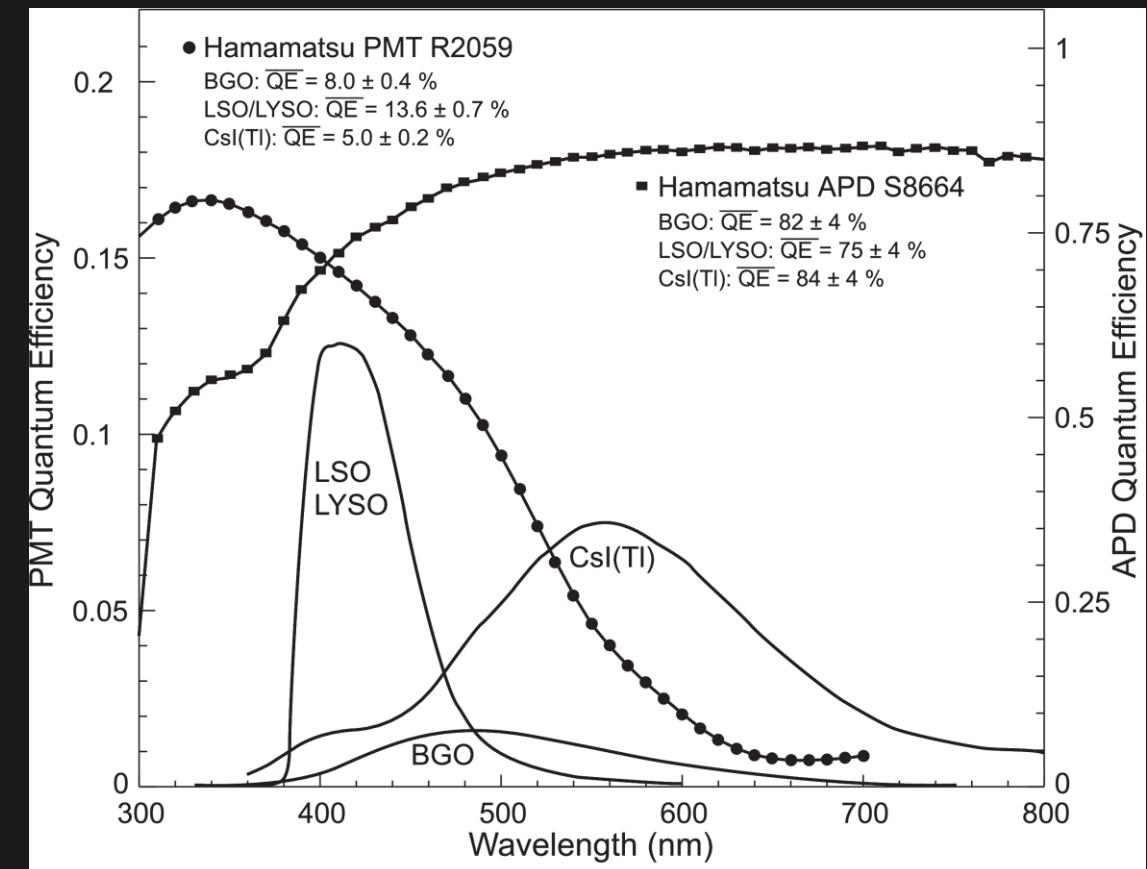
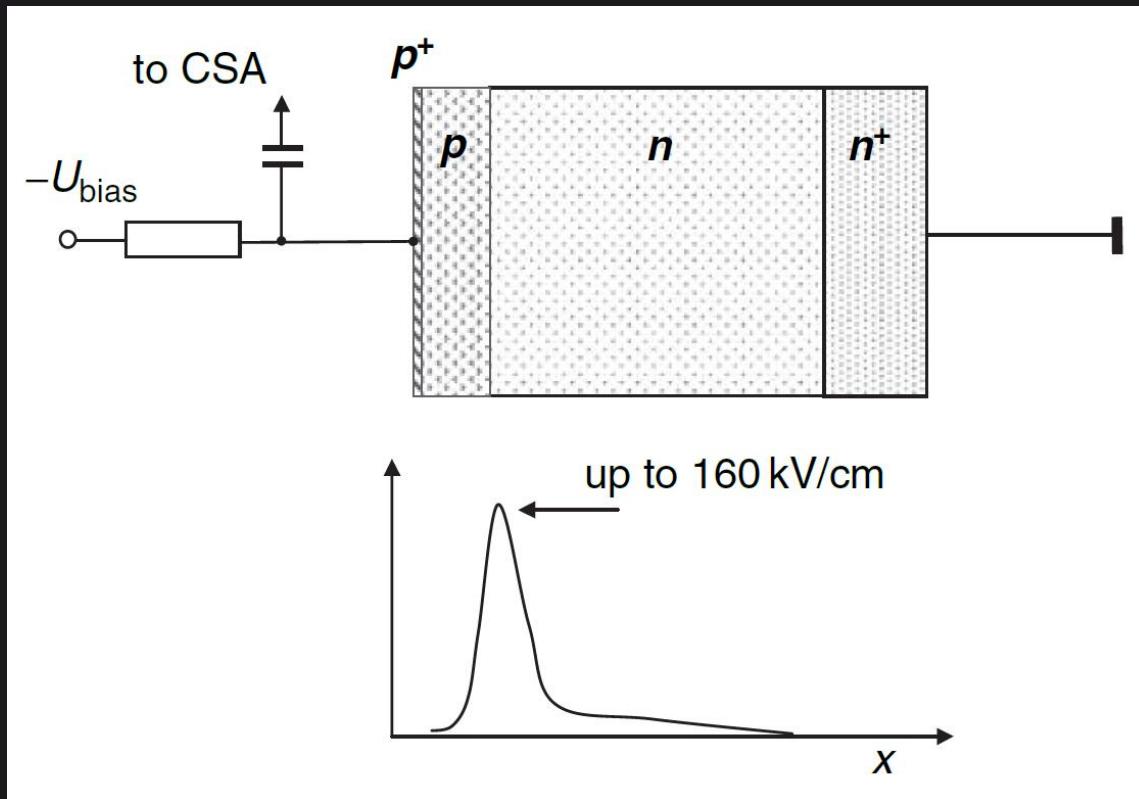
Semicondutores – Fososensores

Fotodiodos



APDs e SiPMs

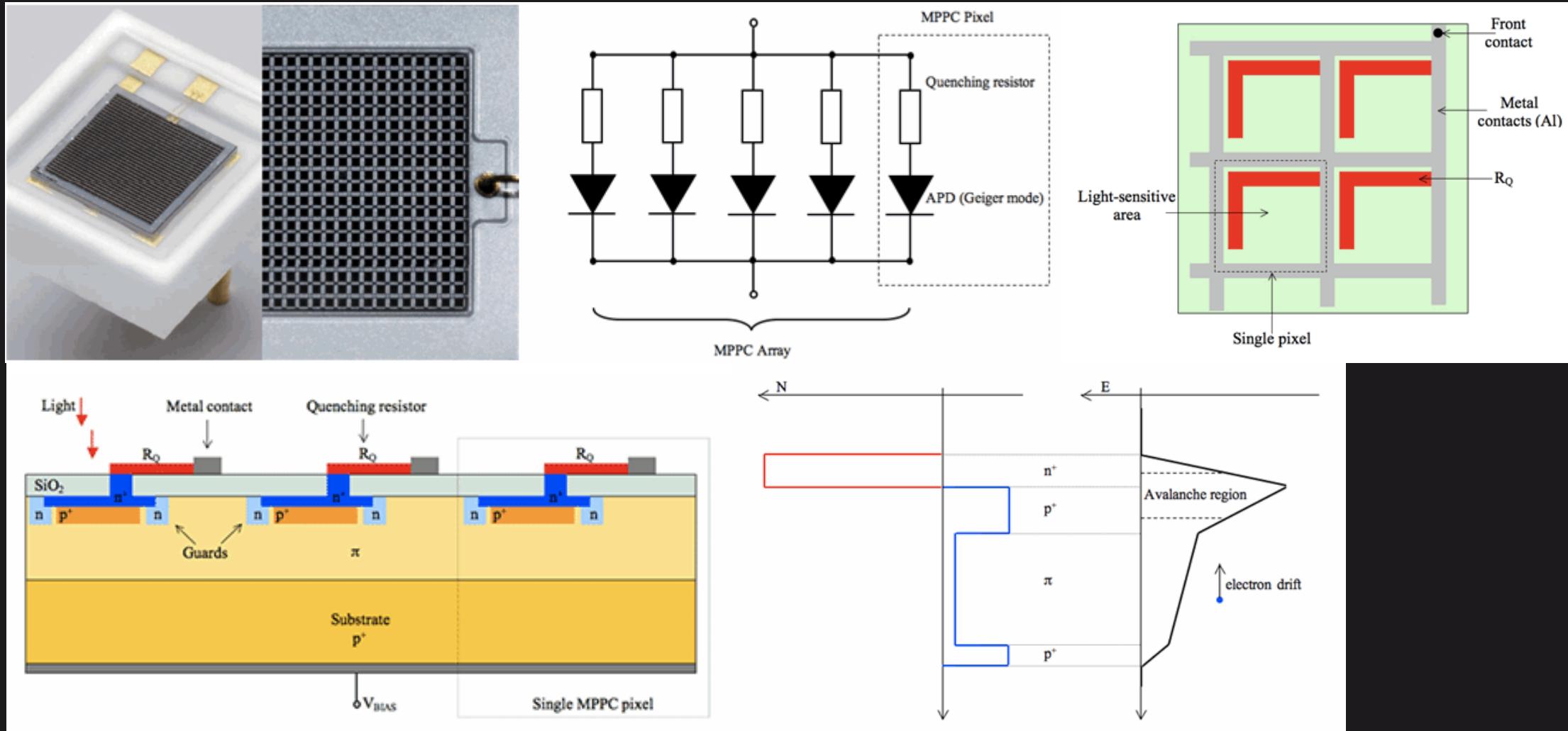
Avalanche Photodiode (APD)



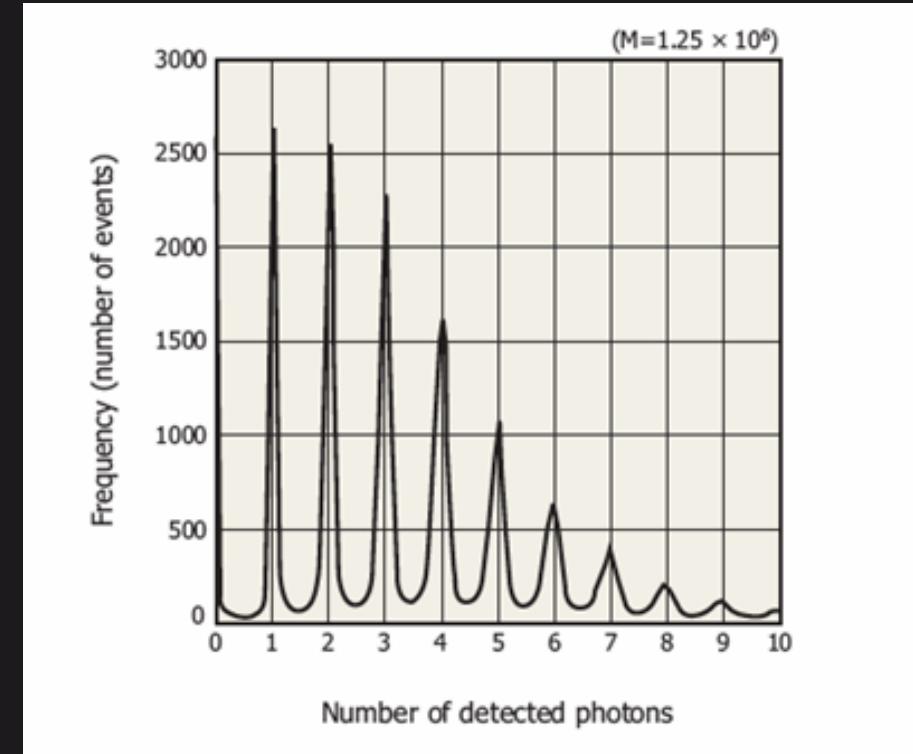
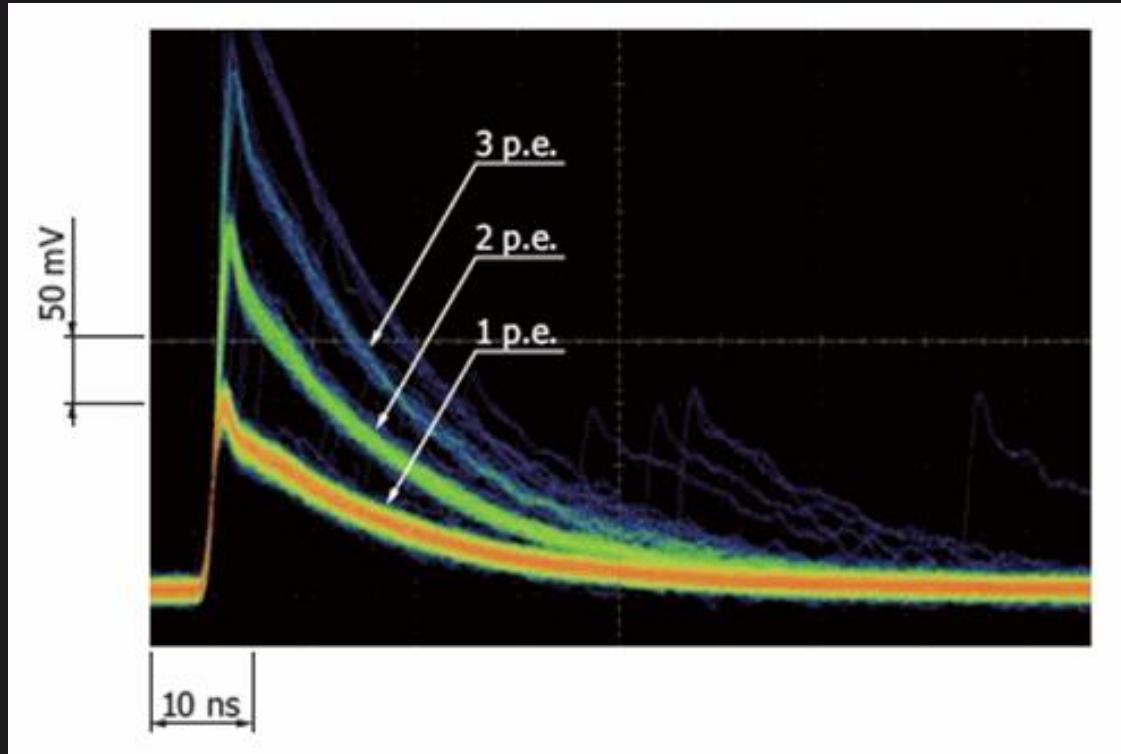
Possível operar APD em modo *breakdown*

Multi-Pixel Photon Counter – SiPM

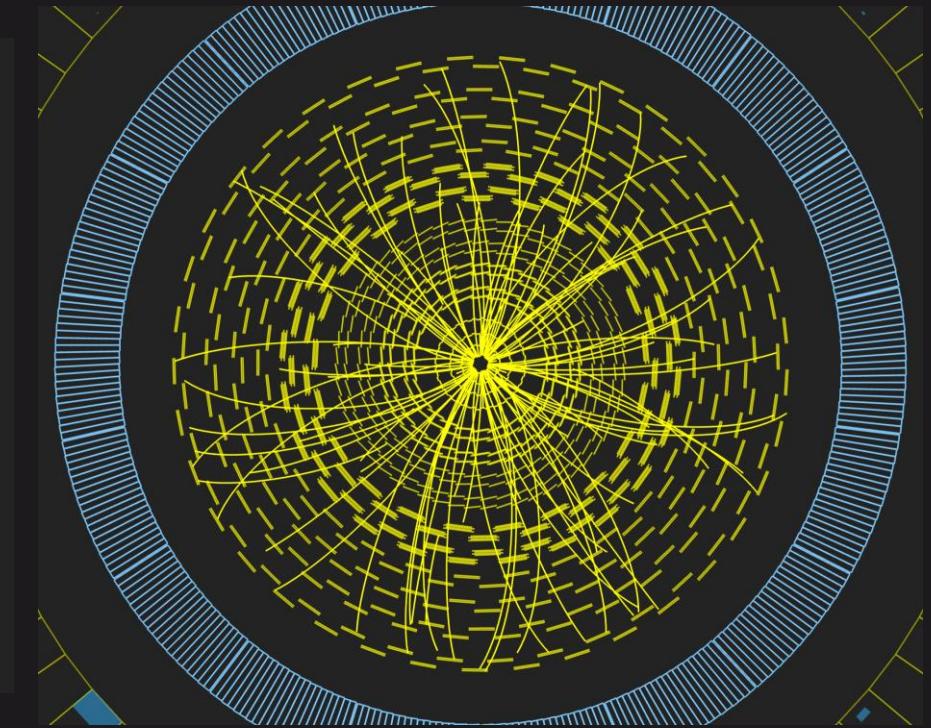
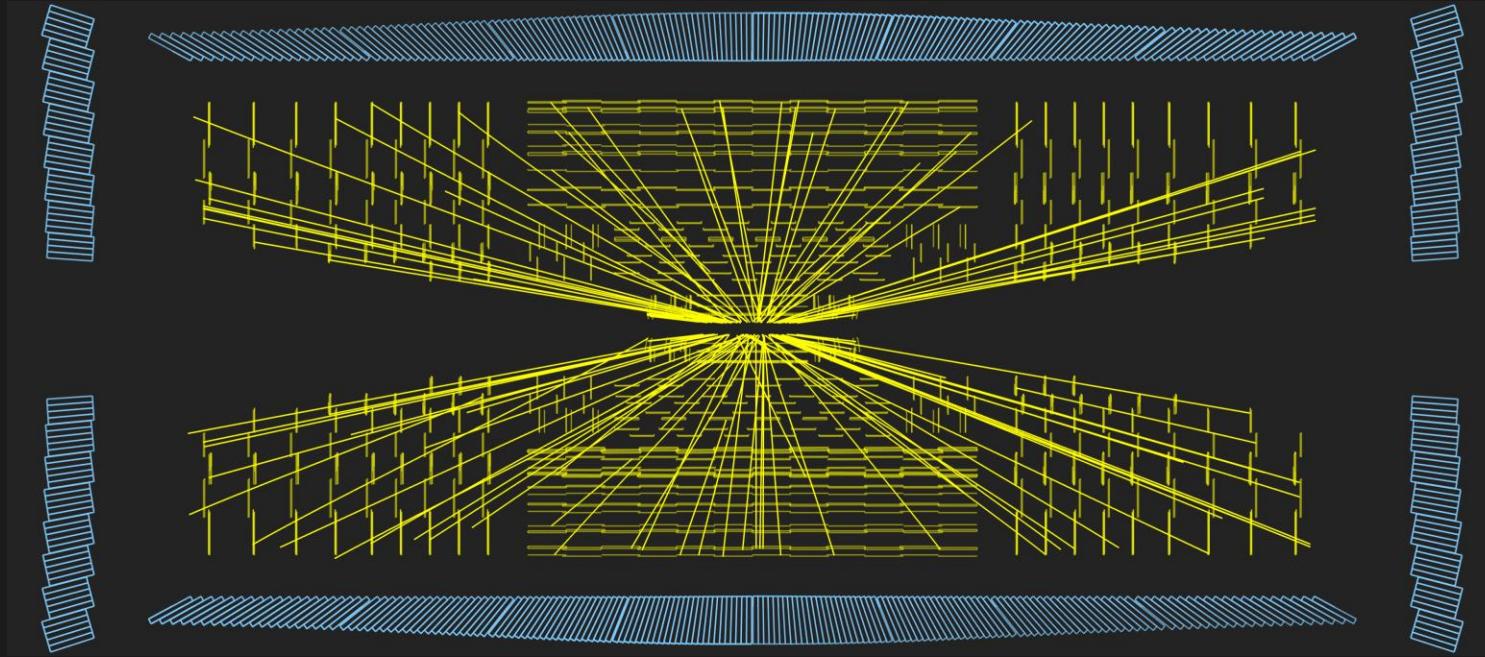
Operação em sobretensão à tensão de breakdown da APD



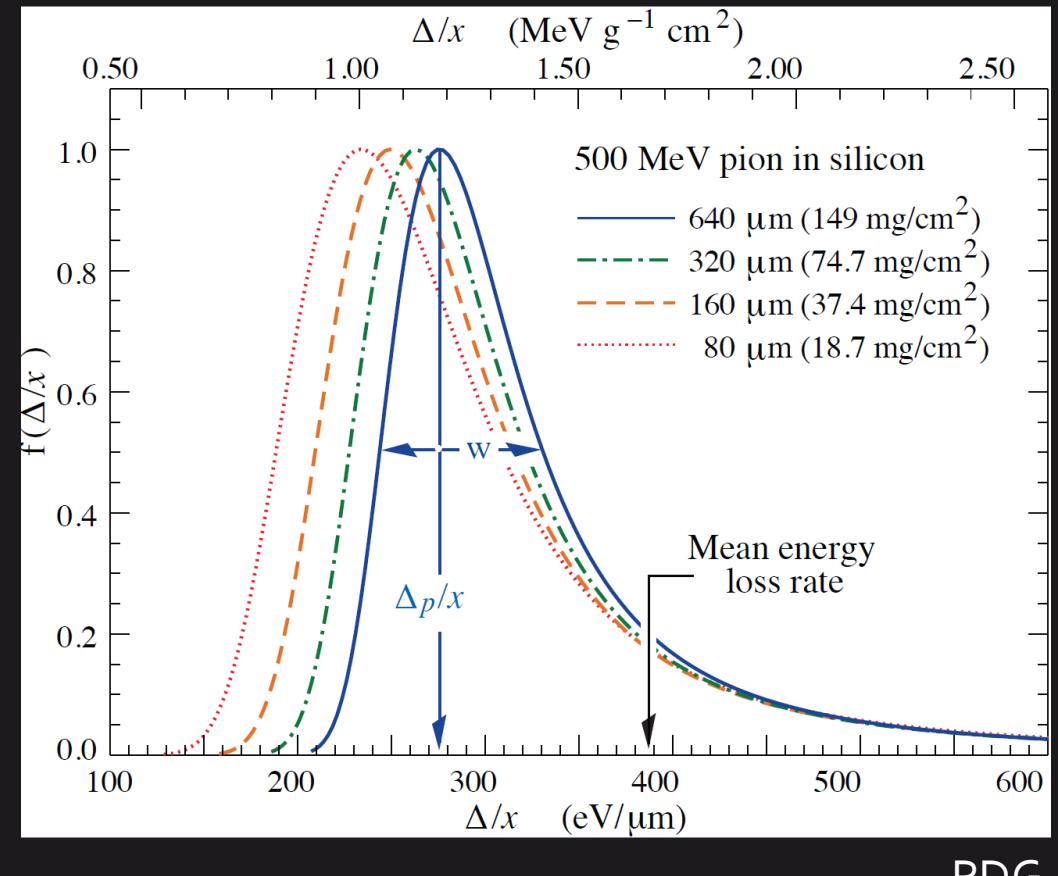
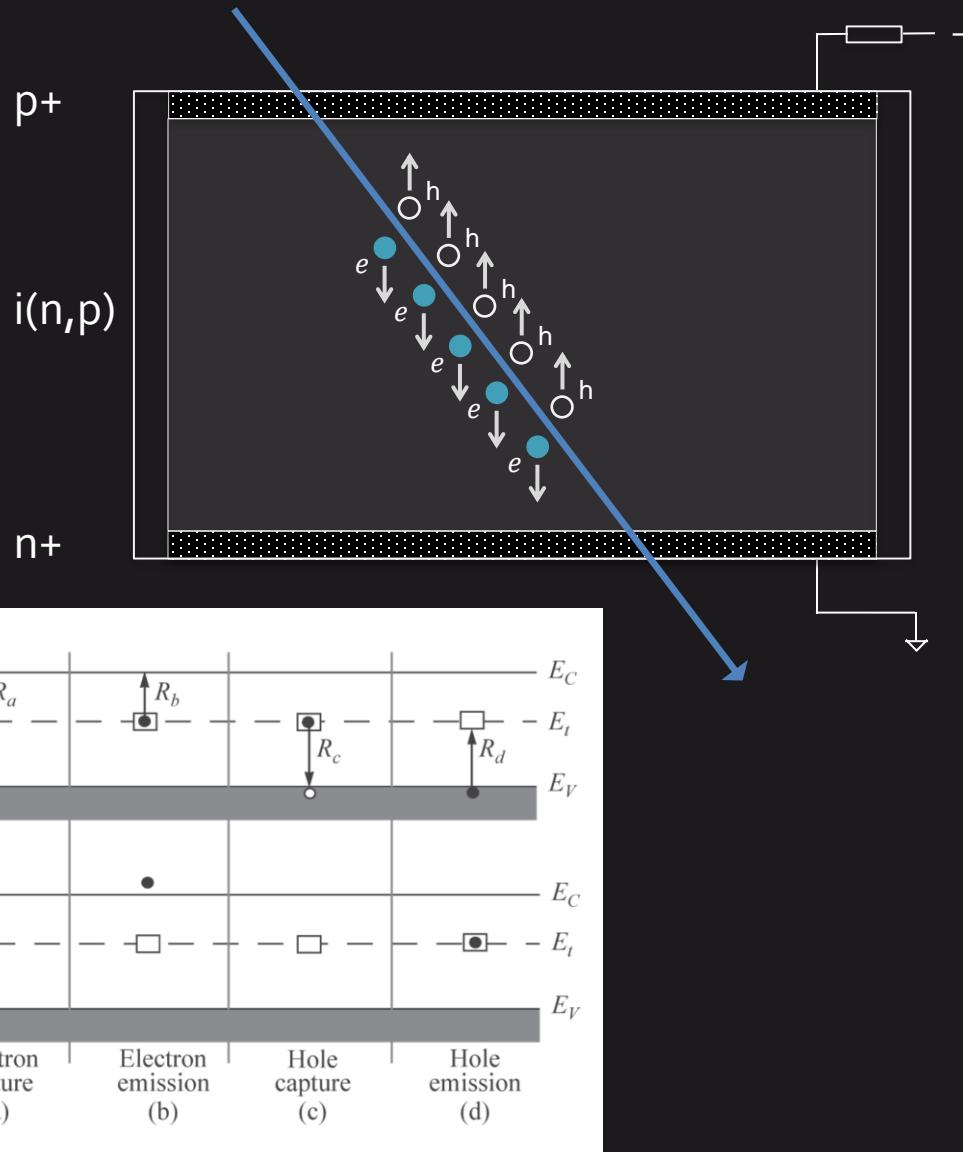
Multi-Pixel Photon Counter – SiPM



Detectores de traços (tracker)

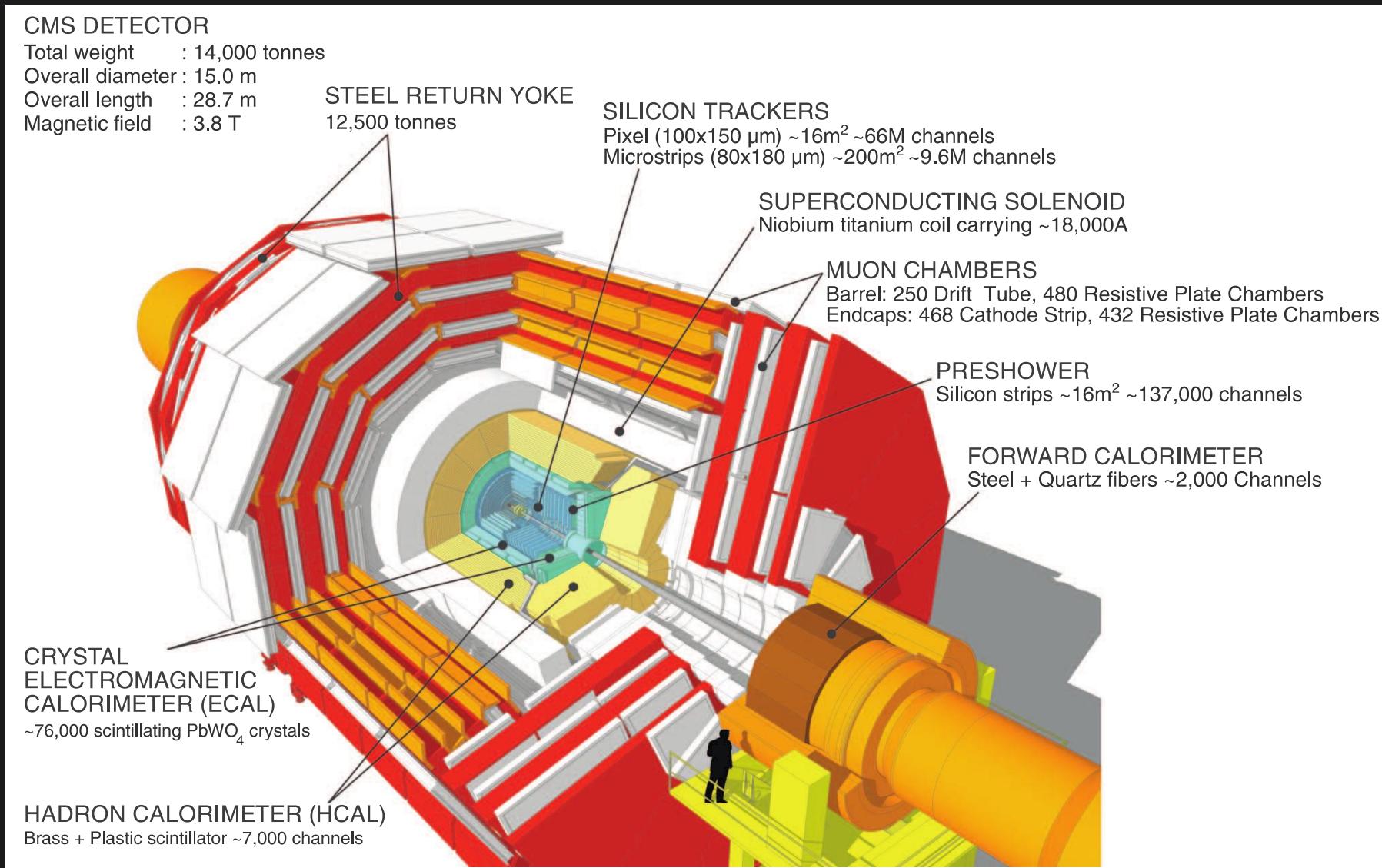


Geração de cargas – dE/dx

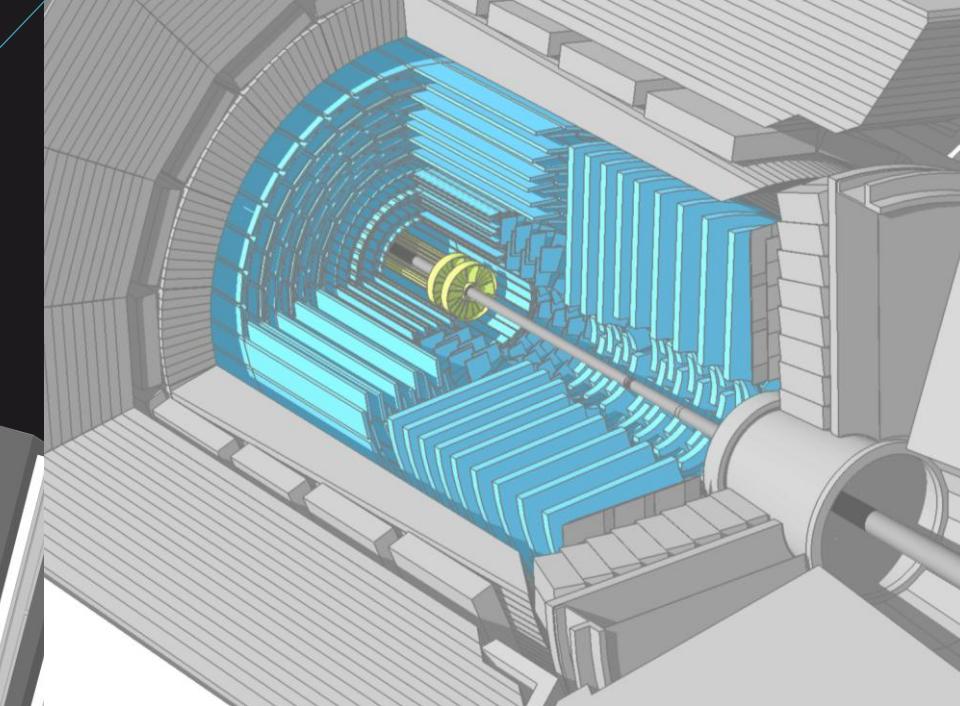
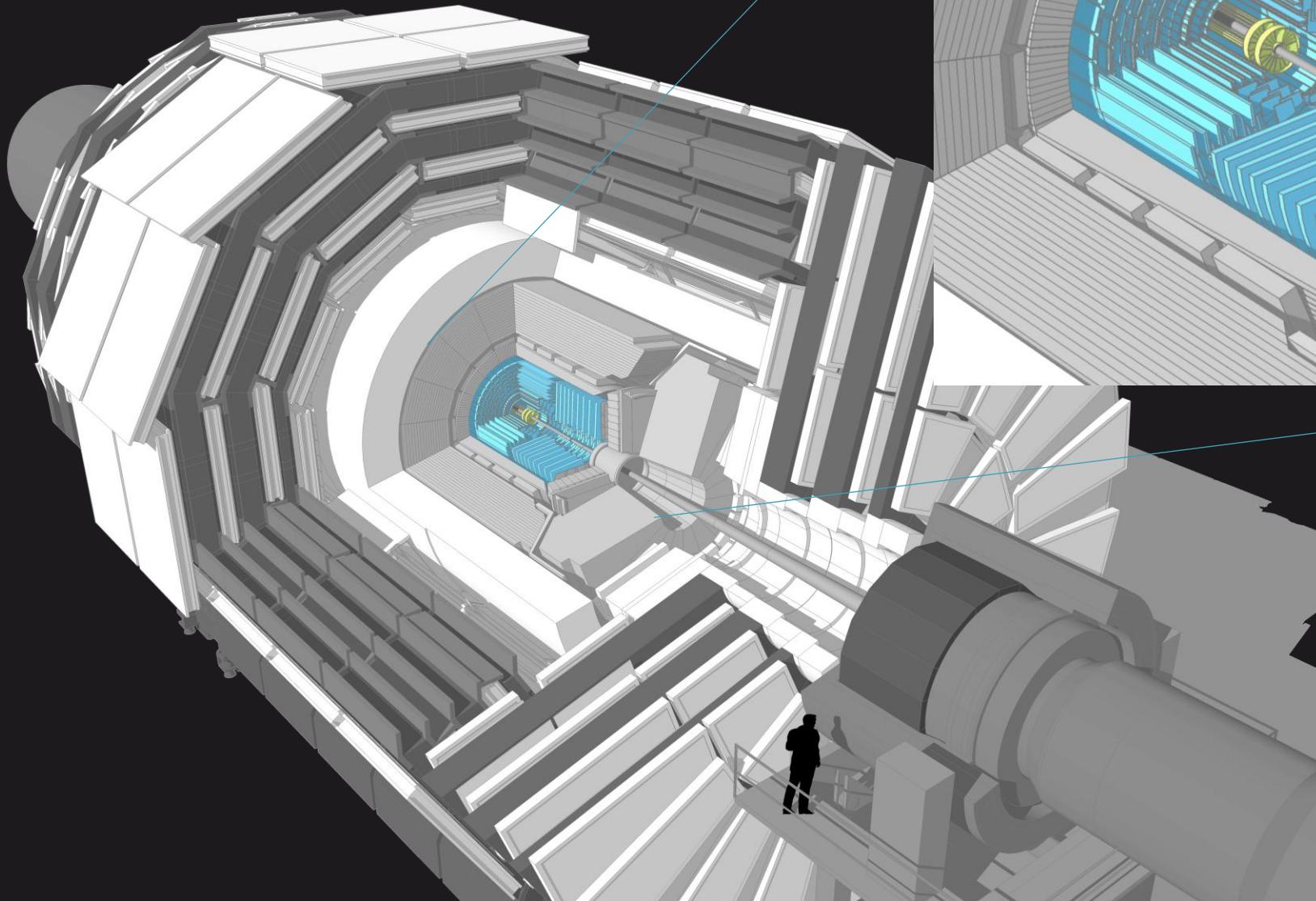


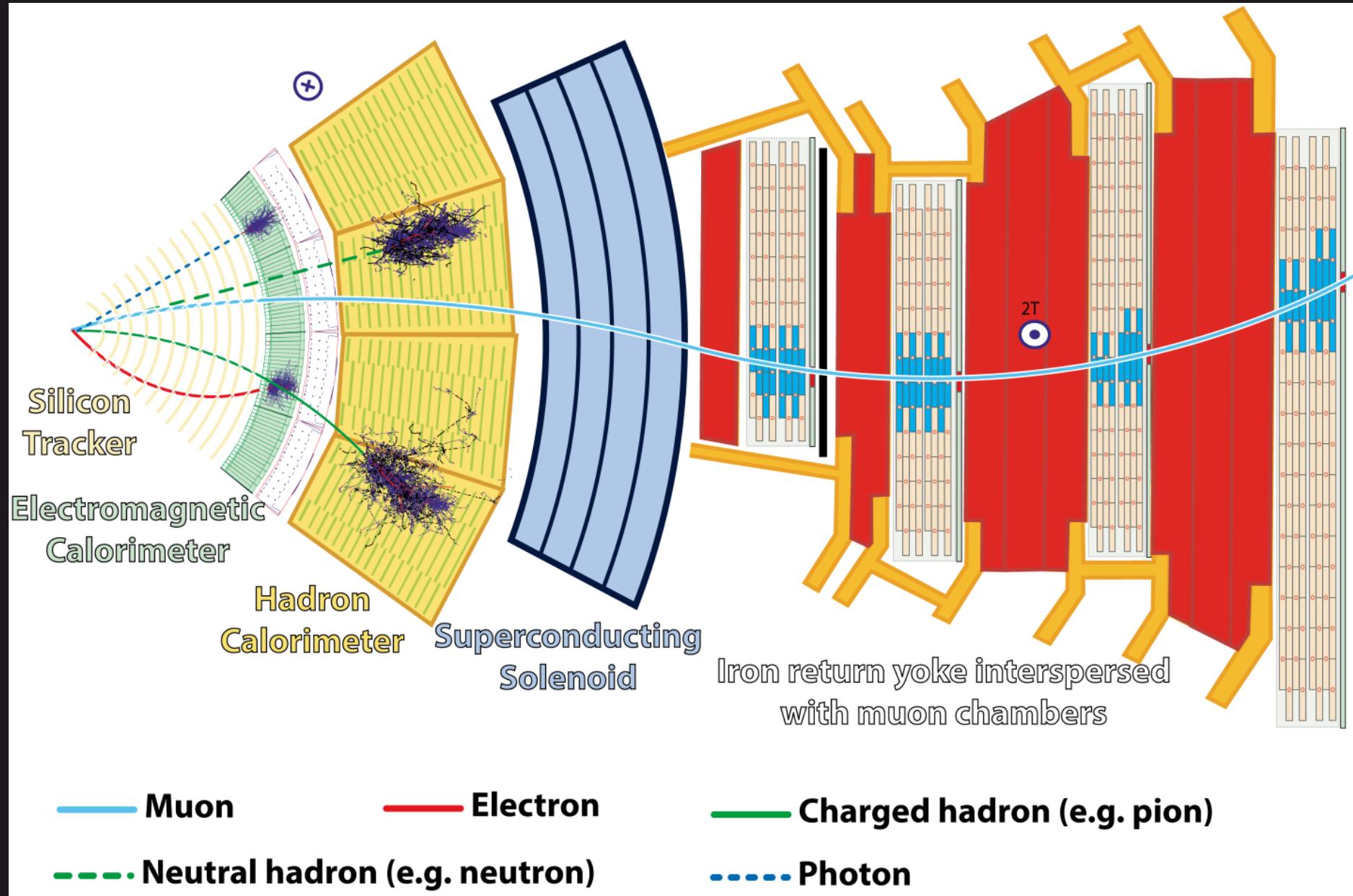
PDG

Silicon tracker (CMS)

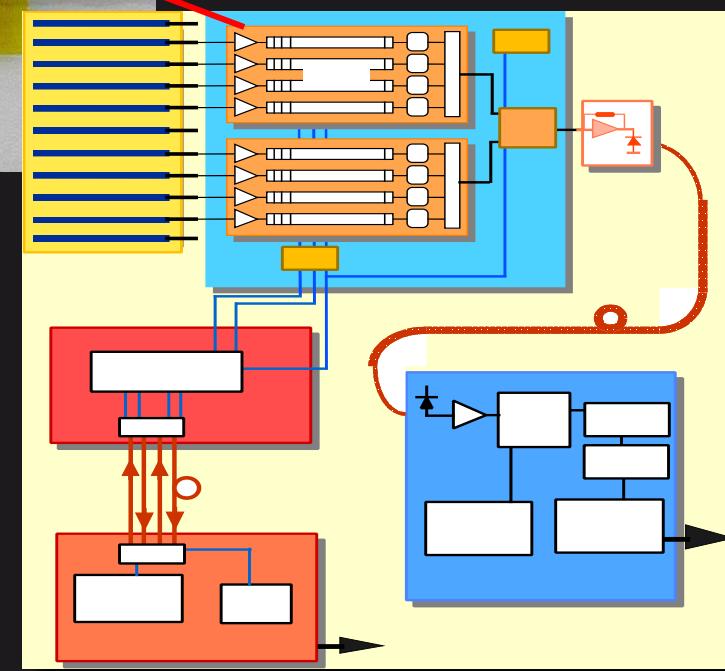
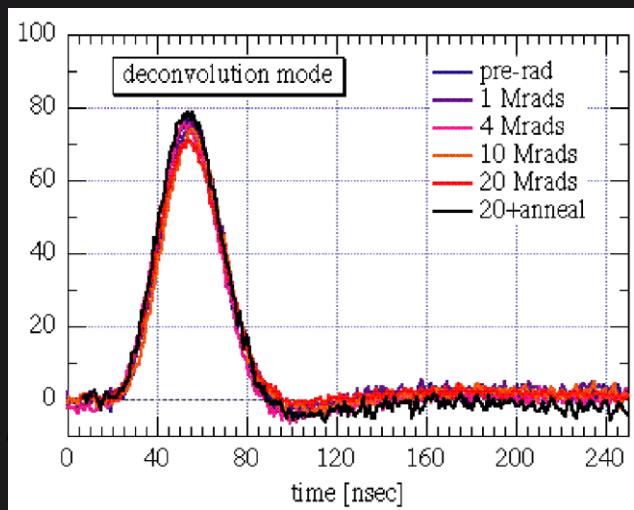
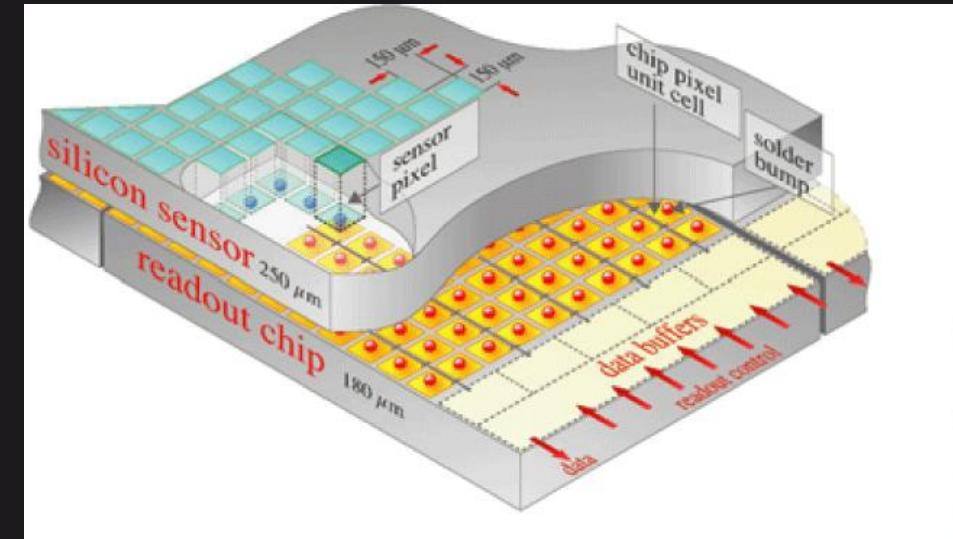
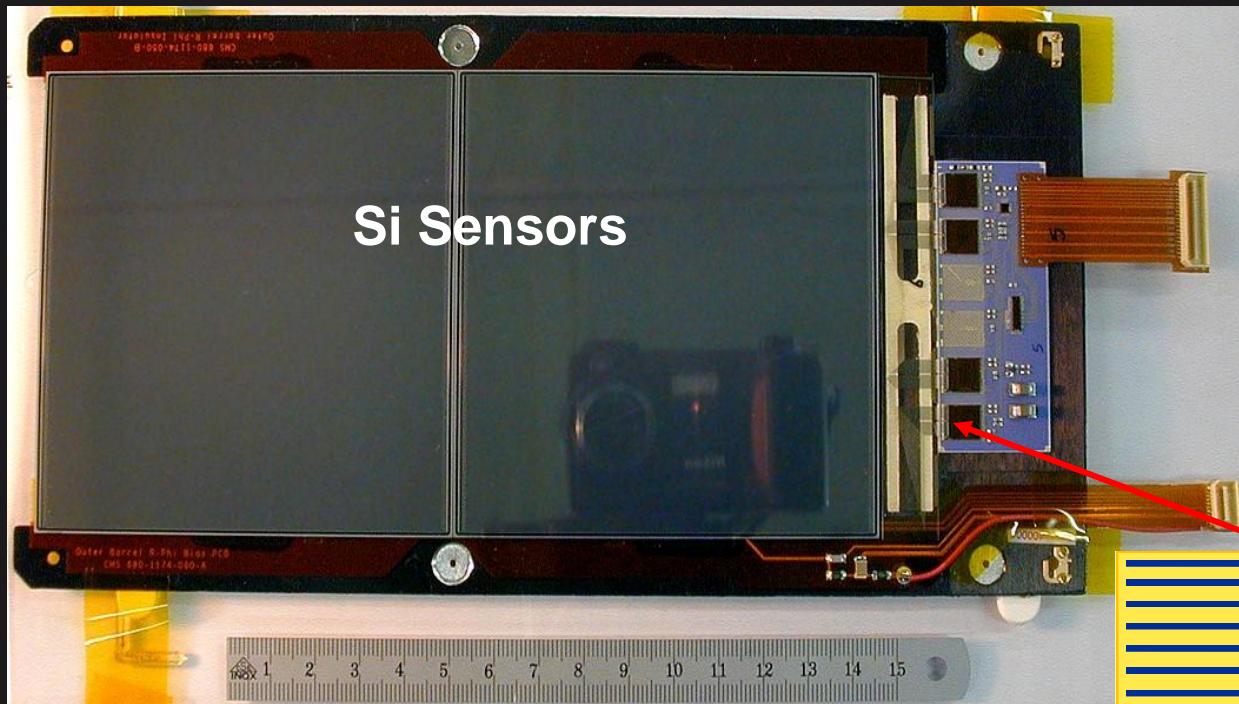


Silicon tracker (CMS)



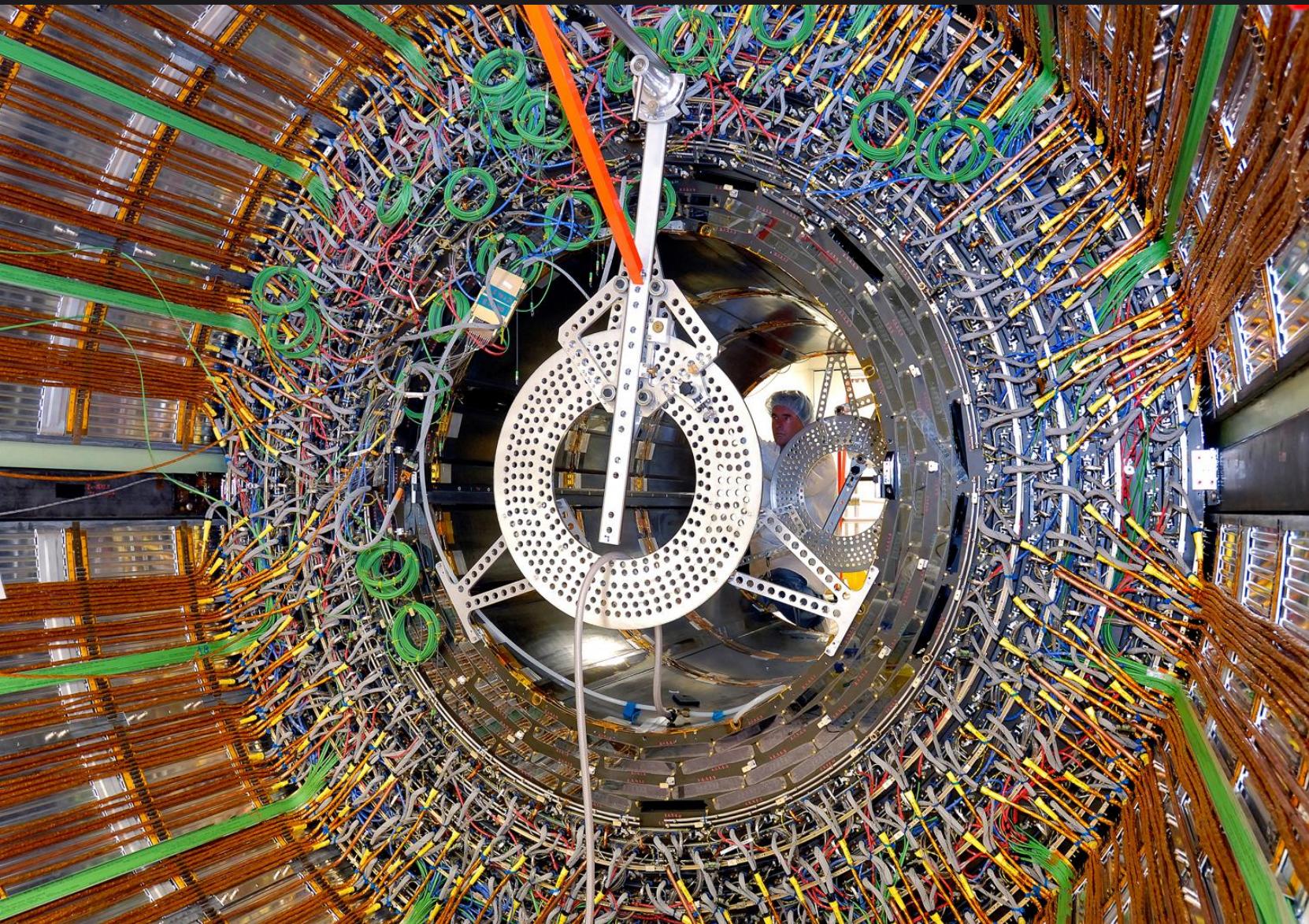


Si Modules and Electronics Chain



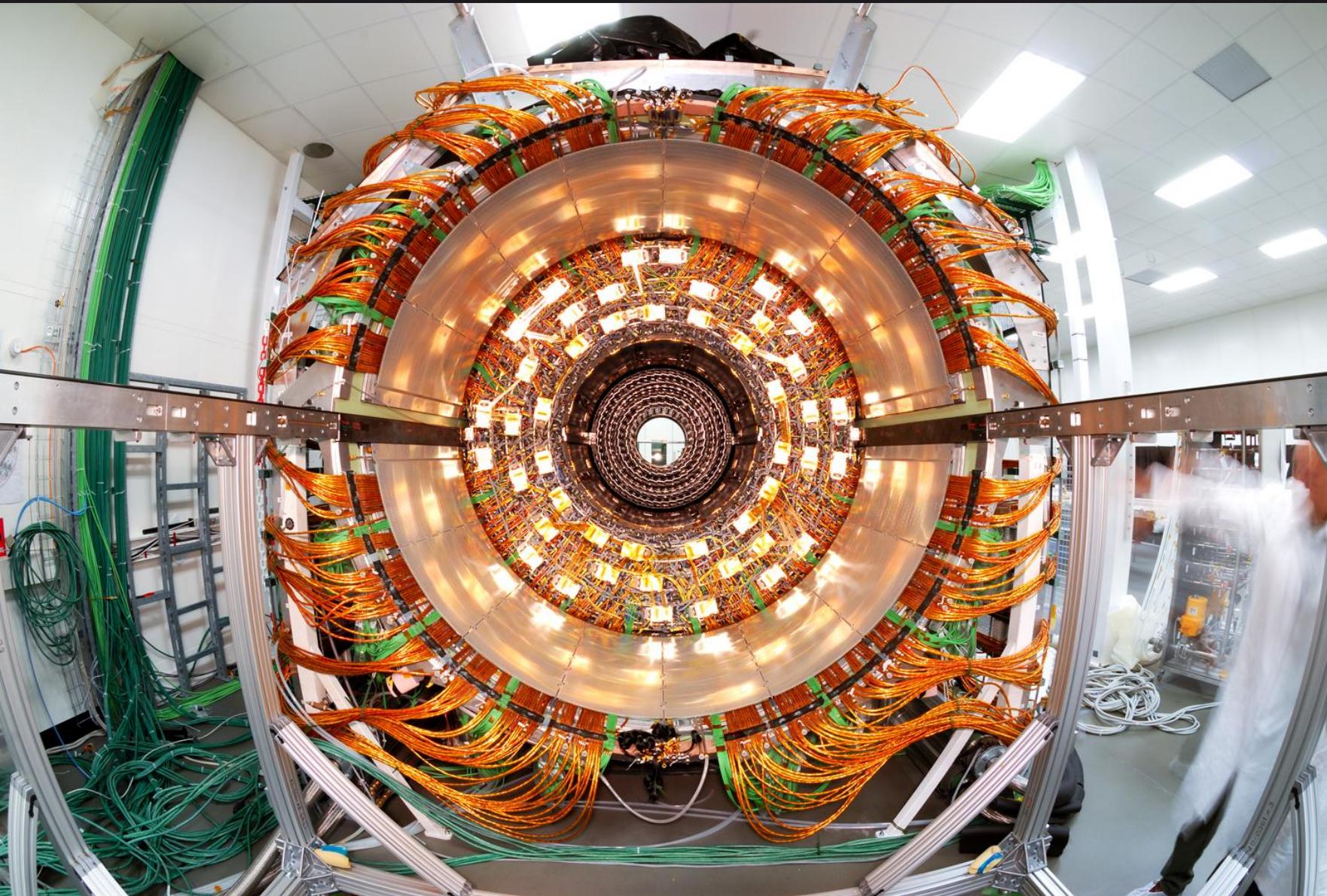
75k chips using
 $0.25\mu\text{m}$ technology

Si Tracker

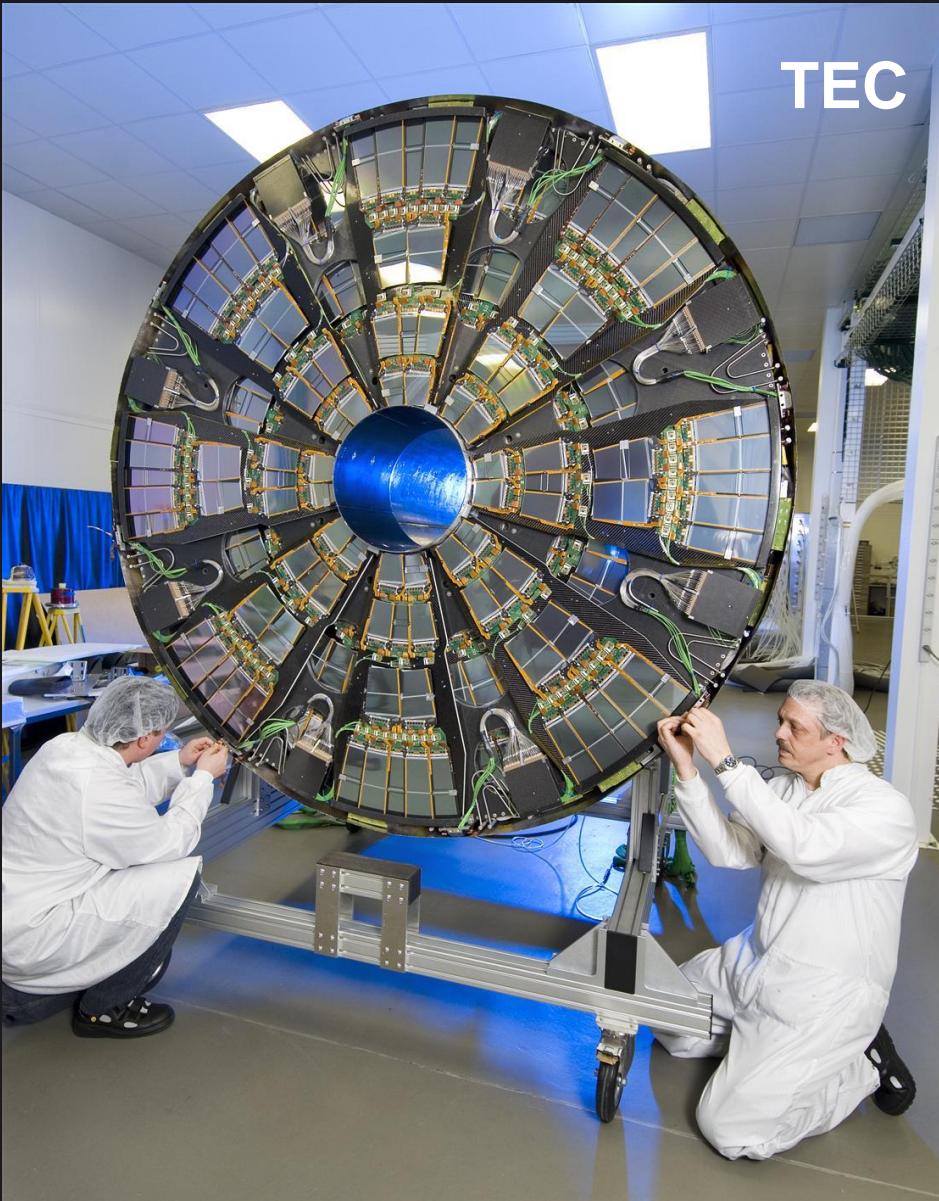


CE

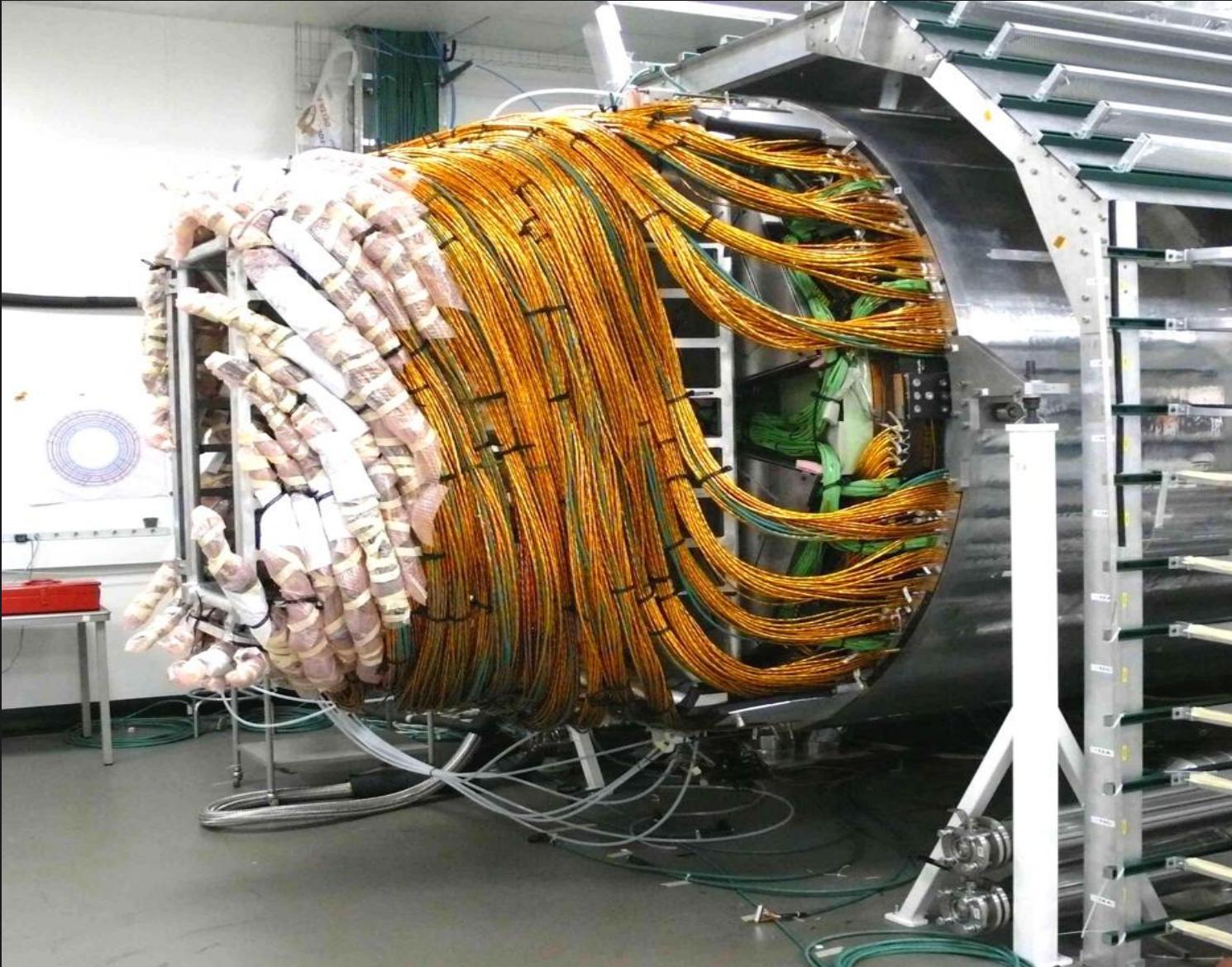
Si Tracker



Si Tracker



Tracker Readied for Installation



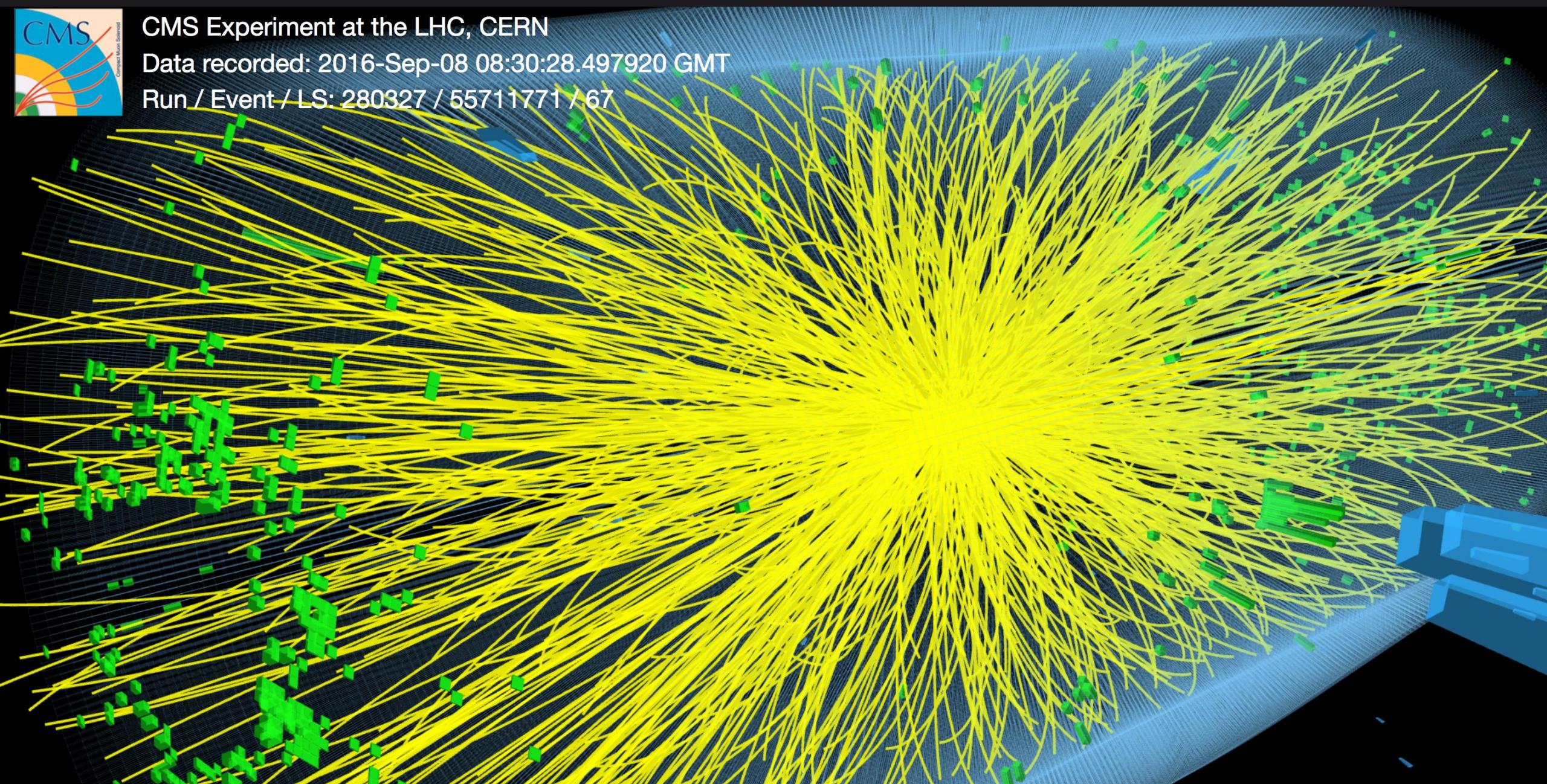
CERN



CMS Experiment at the LHC, CERN

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

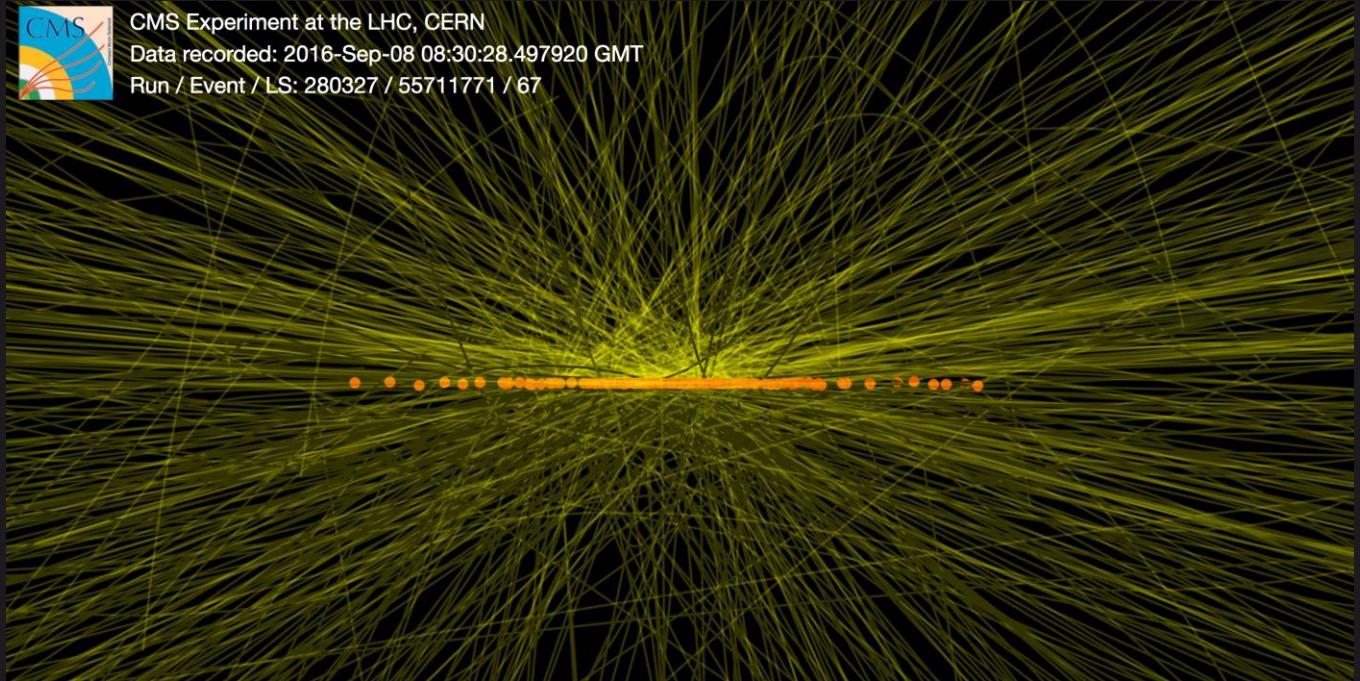
Run / Event / LS: 280327 / 55711771 / 67



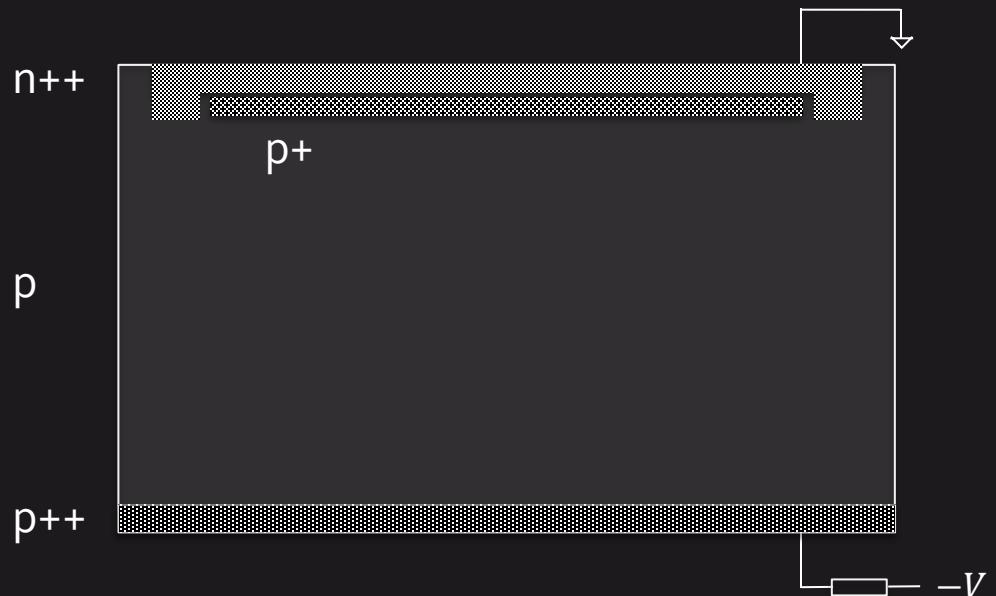
Detectores em “4 dimensões”

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

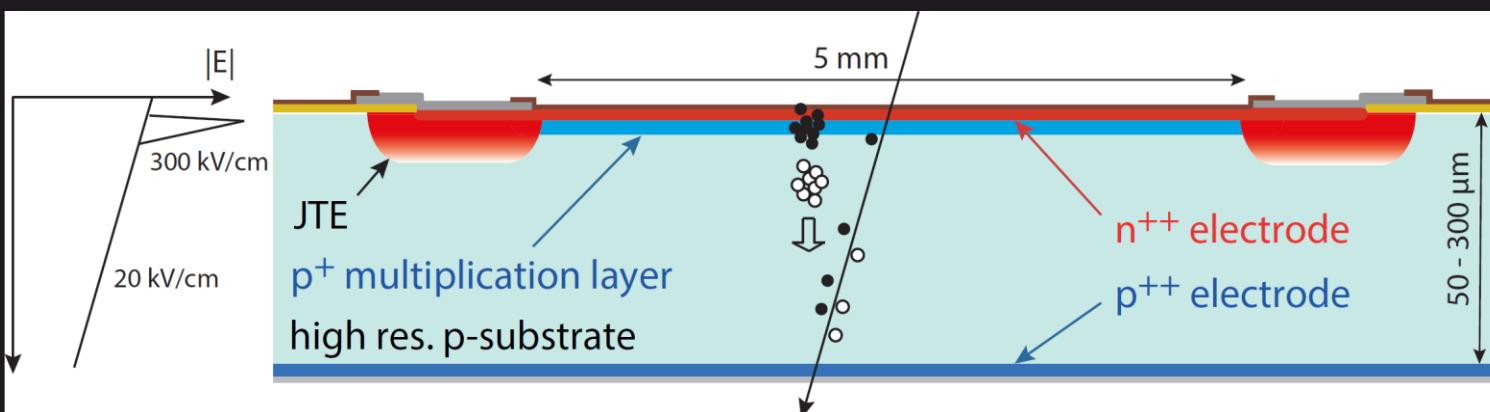
- Medição do tempo de voo das partículas permite associá-las à colisão de interesse.
- Muito alta resolução temporal necessária – $\mathcal{O}(10 \text{ ps})$



Sensores com amplificação



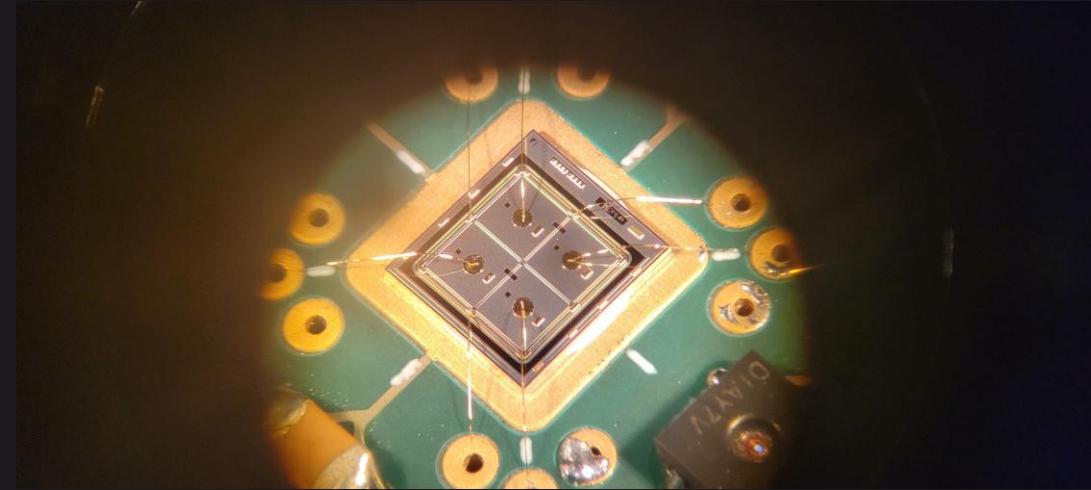
Low Gain Avalanche Diode (LGAD)



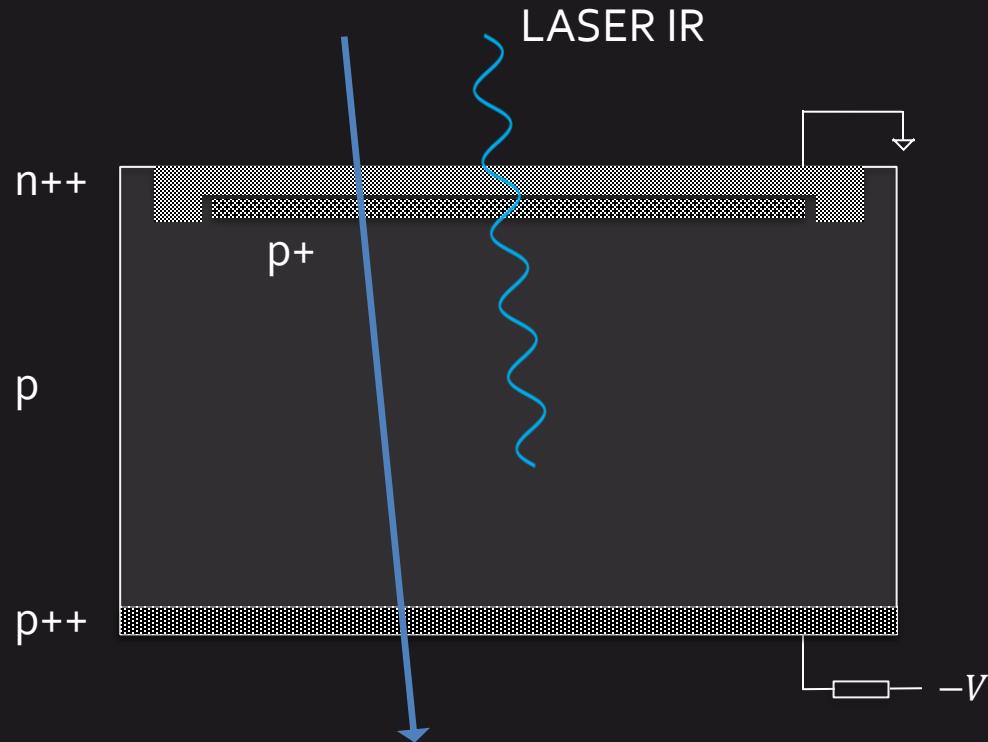
- Implantação de camada fina p+ abaixo do eletrodo n++ cria alto campo elétrico que provoca multiplicação de cargas.
- Relativo baixo ganho (*low gain*) relativo a APDs. Sensor não opera em modo *breakdown*.
- Pulso de maior amplitude e mais rápido tempo de subida. Aplicações com alta resolução temporal.
- Atualmente, desenvolvimento de sensores LGAD (alta resolução temporal) com pixels de pequena dimensão (alta resolução espacial) → Detectores em “4 dimensões”.

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*



Testes com detector de silício (Lab.)



LASER Infravermelho (IR) penetra no sensor de silício gerando cargas de forma análoga a uma partícula carregada.

LASER proporciona medição controlada com referência espacial e de tempo com alta precisão.