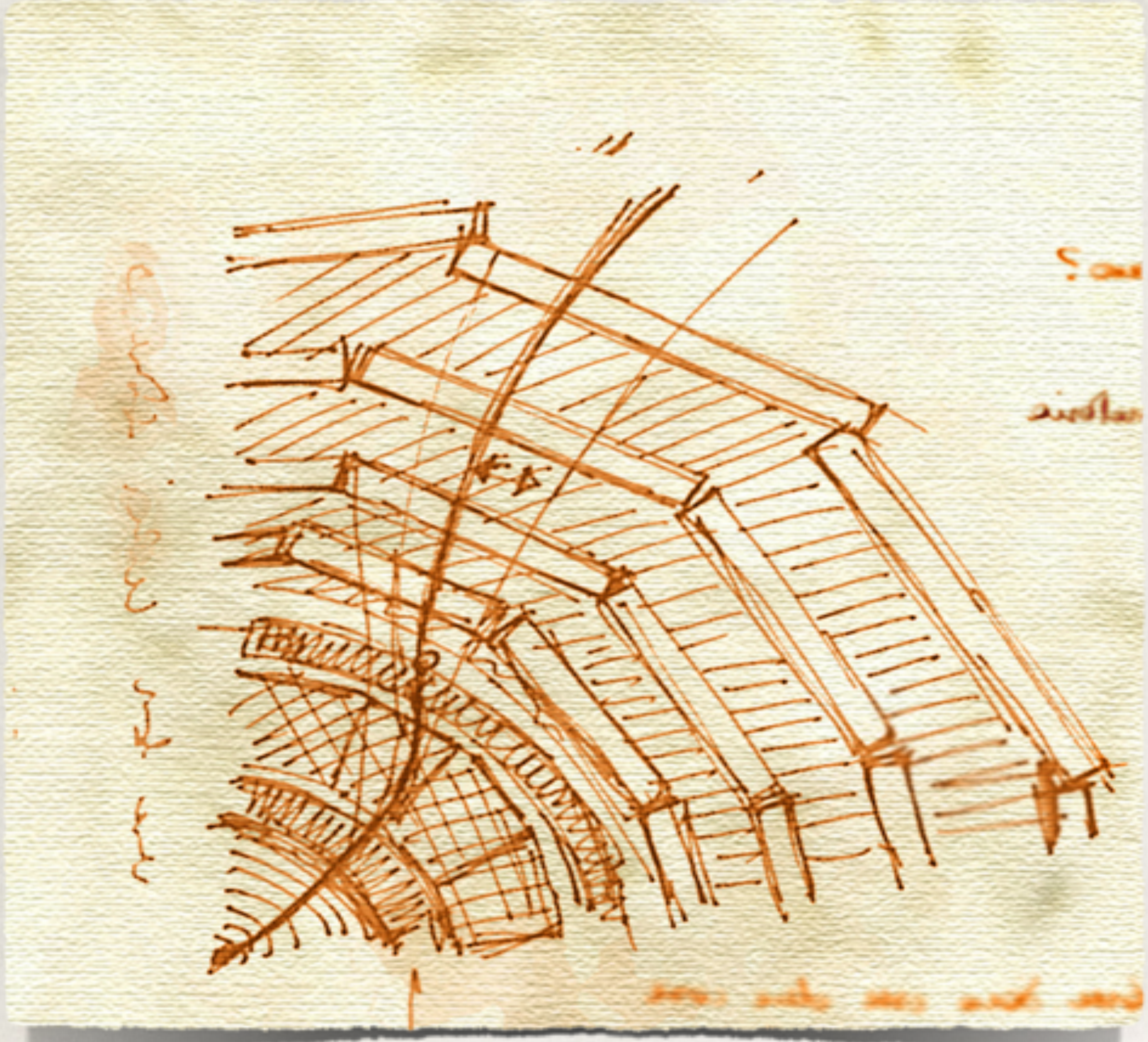

XI Escola do CBPF

Curso de Pós-Graduação

Notas de Aula

A Física dos Detectores de Partículas

Dr Arthur M. Moraes - CBPF (web-page: http://cern.ch/amoraes)

24 de Julho de 2017

CBPF
Centro Brasileiro de Pesquisas Físicas

Introdução

Programa do Curso:

Aula 1: De Rutherford ao LHC: Desenvolvimento dos detectores ao longo da história da física das partículas elementares. (2ªf. 17/07)

Aula 2: Interações das partículas com a matéria. (3ªf. 18/07)

Aula 3: Detectando partículas carregadas & neutras. (5ªf. 20/07)

Aula 4: Cintiladores: detectando partículas via luminescência. (6ªf. 21/07)

Aula 5: Detectores de semicondutores: medidas de alta precisão. (2ªf. 24/07)

Aula 6: Detectores de gás: medindo partículas em grandes volumes. (3ªf. 25/07)

Aula 7: Calorímetros: eletromagnéticos & hadrônicos. (5ªf. 27/07)

Aula 8: Exemplos de aplicações dos detectores em várias áreas. (6ªf. 28/07)

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Aula 5

Cintiladores e detectores de semicondutores

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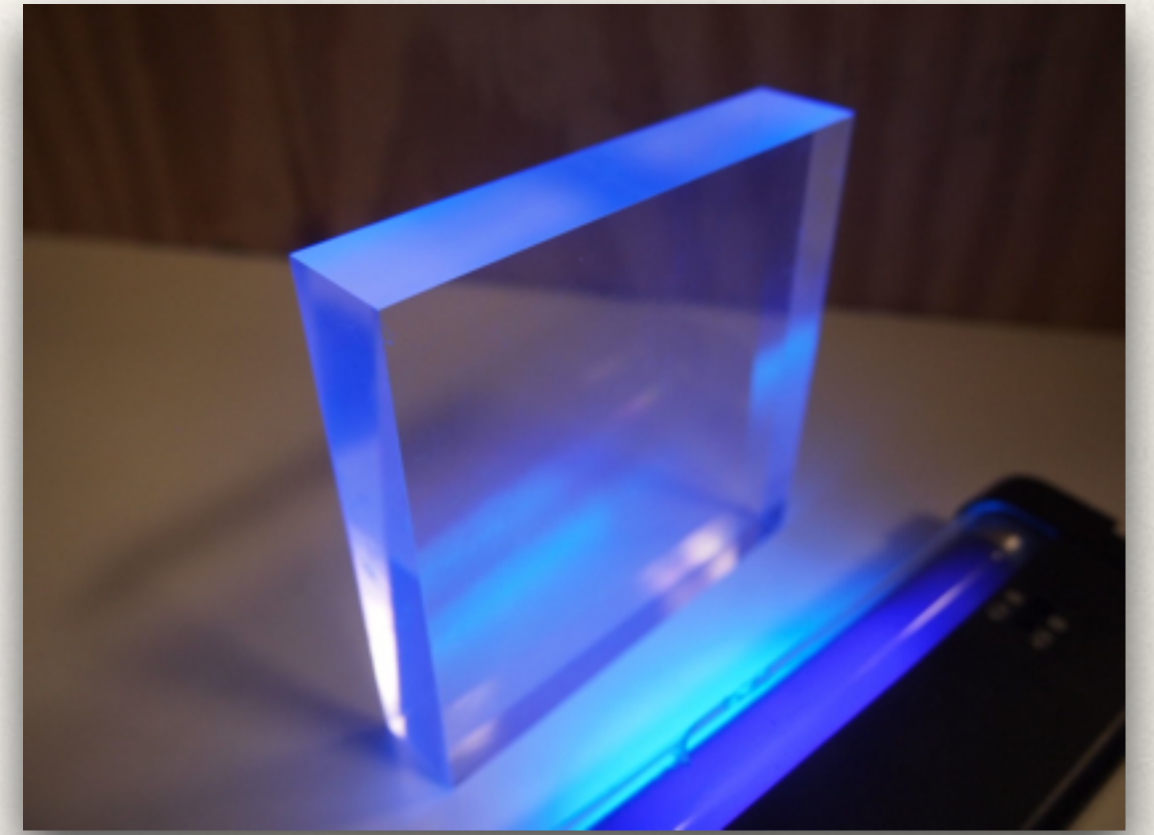
Cintiladores



Princípio:

- dE/dx é convertida em luz visível

- *detecção feita com foto-sensor*

(fotomultiplicadora, olho humano)

Características principais:

- *sensitividade à energia*
- *rápida resposta* *(curto tempo de resposta)*
- *perfil de pulso bem característico*

Requisitos:

- *alta-eficiência para conversão de energia de excitação em radiação fluorescente*
- *transparência à radiação fluorescente para permitir transmissão da luz*
- *emissão da luz na região do espectro detectável por fotossensores*
- *curto tempo de decaimento permitindo resposta rápida*

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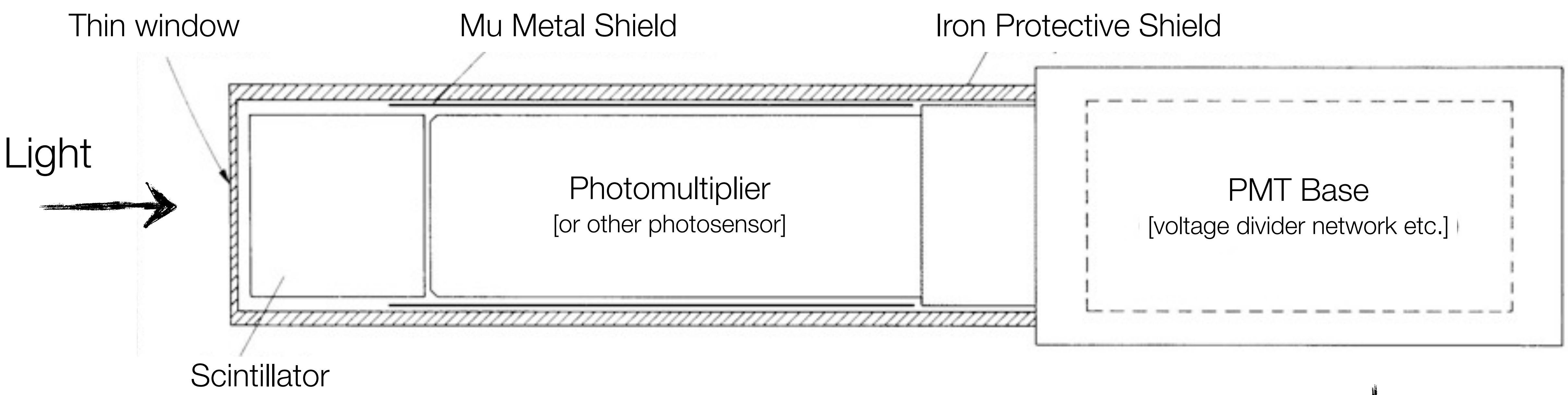
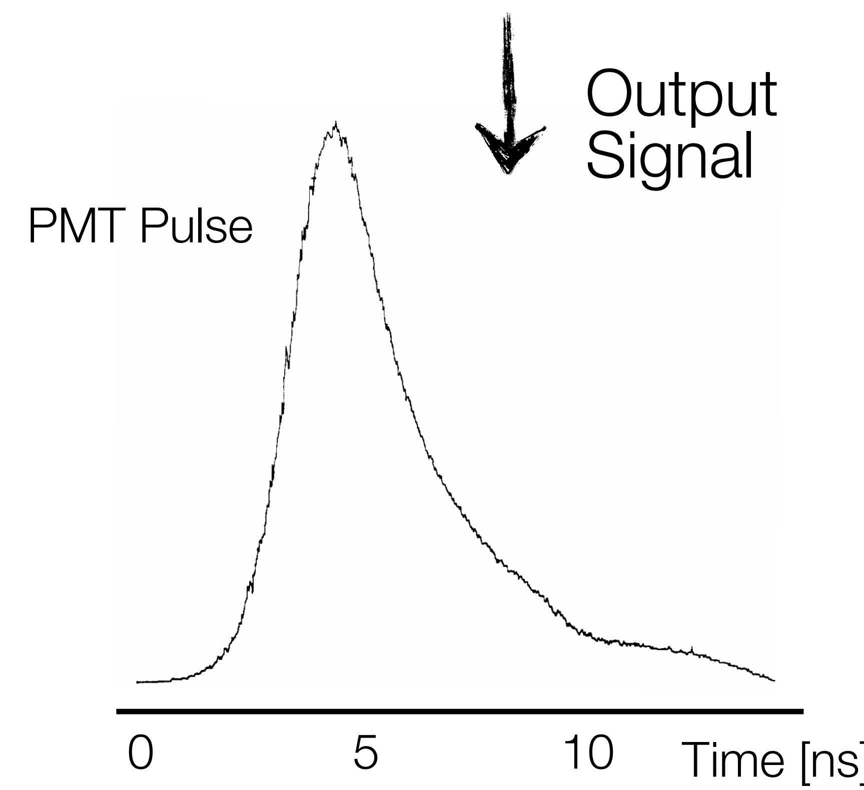
Cintiladores





Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

Photosensors

Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photomultipliers

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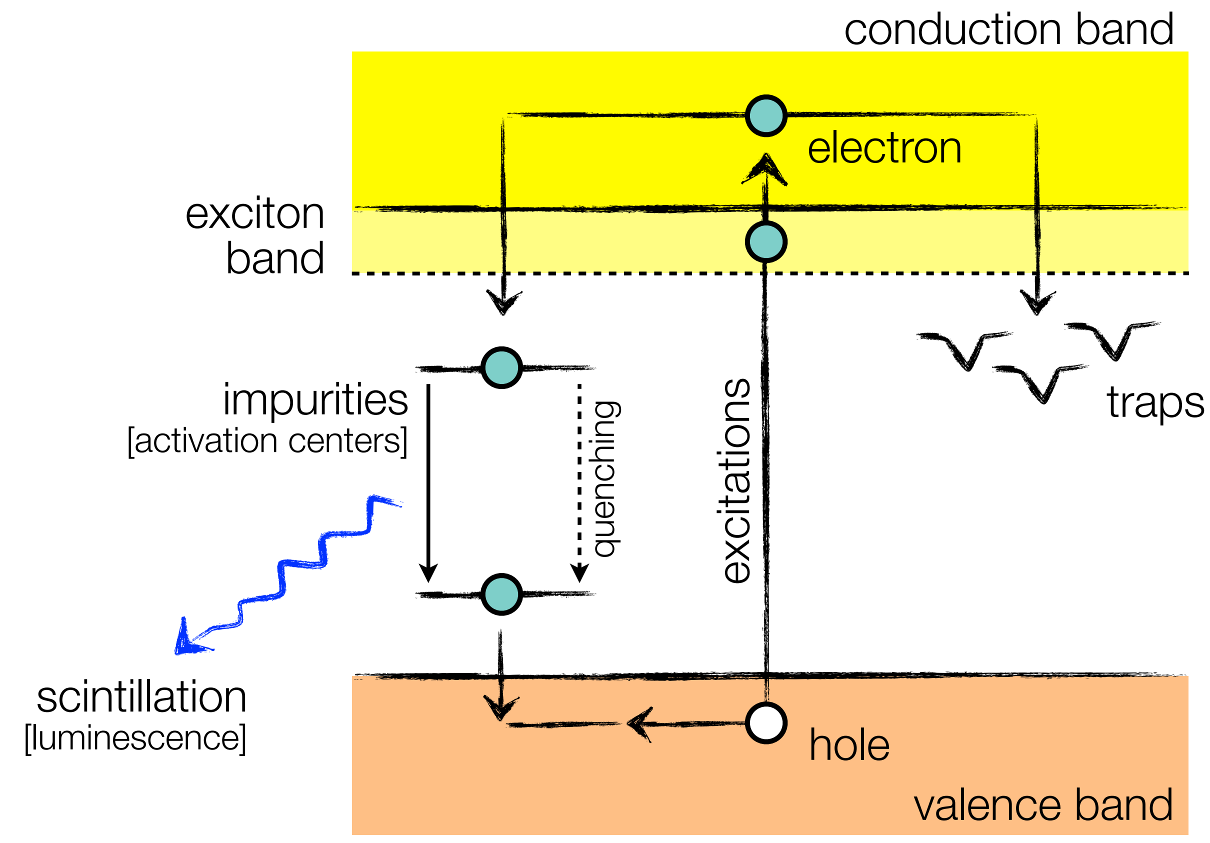
Cintiladores: cristais inorgânicos

Materiais:

- *Iodeto de sódio (NaI)*
- *Iodeto de césio (CsI)*
- *Floreto de bário (BaF_2)*
- *….*

Mecanismo:

- *Deposição de energia por ionização*
- *Transferência de energia à impurezas*
- *Radiação por cintilação de fótons*



Energy bands in impurity activated crystal
showing excitation, luminescence, quenching and trapping

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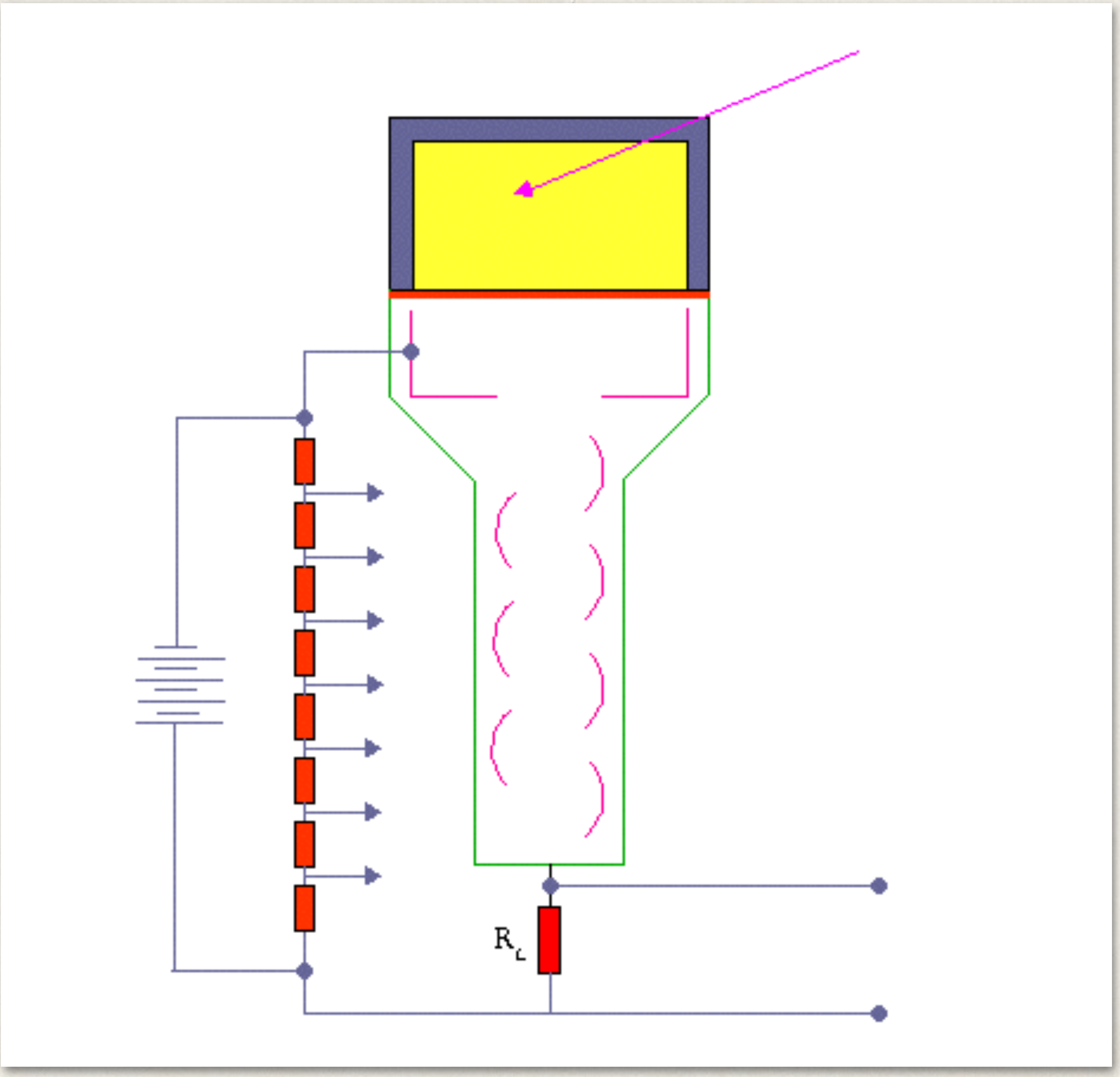
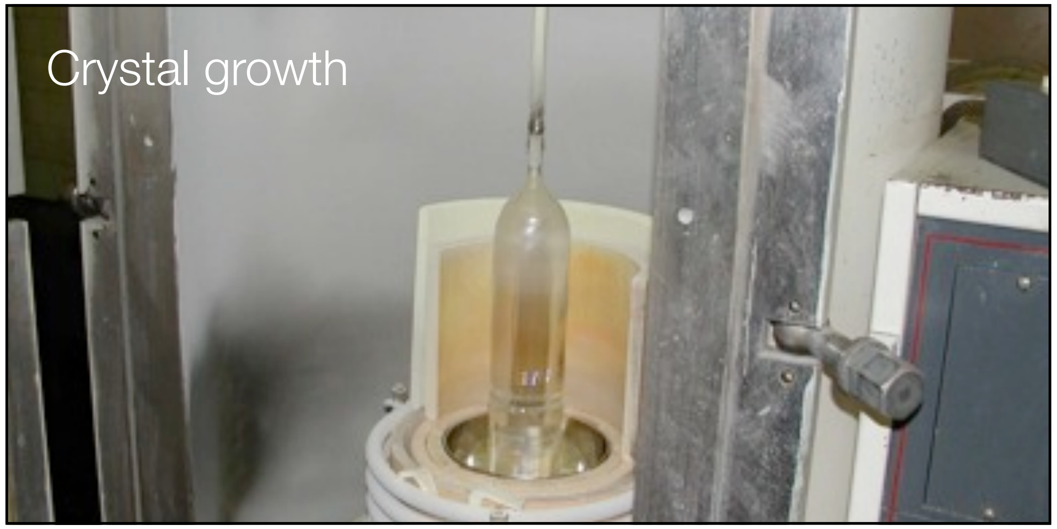
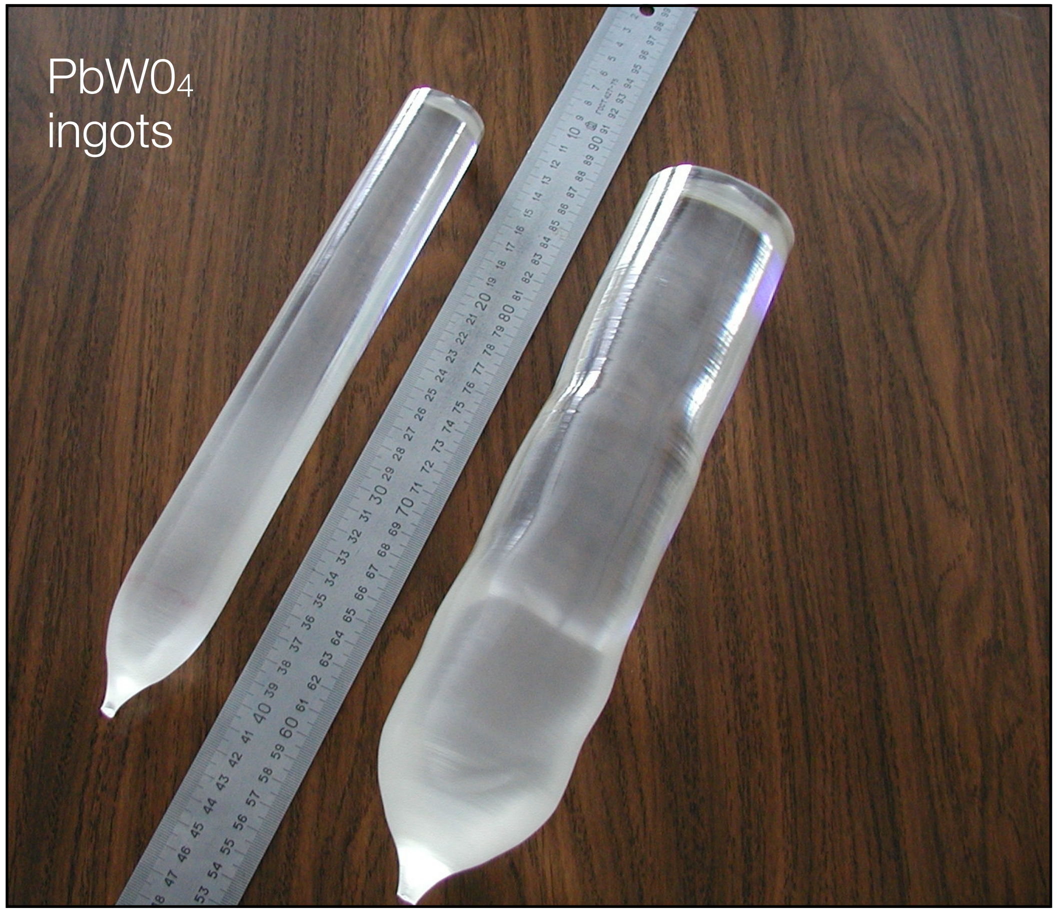
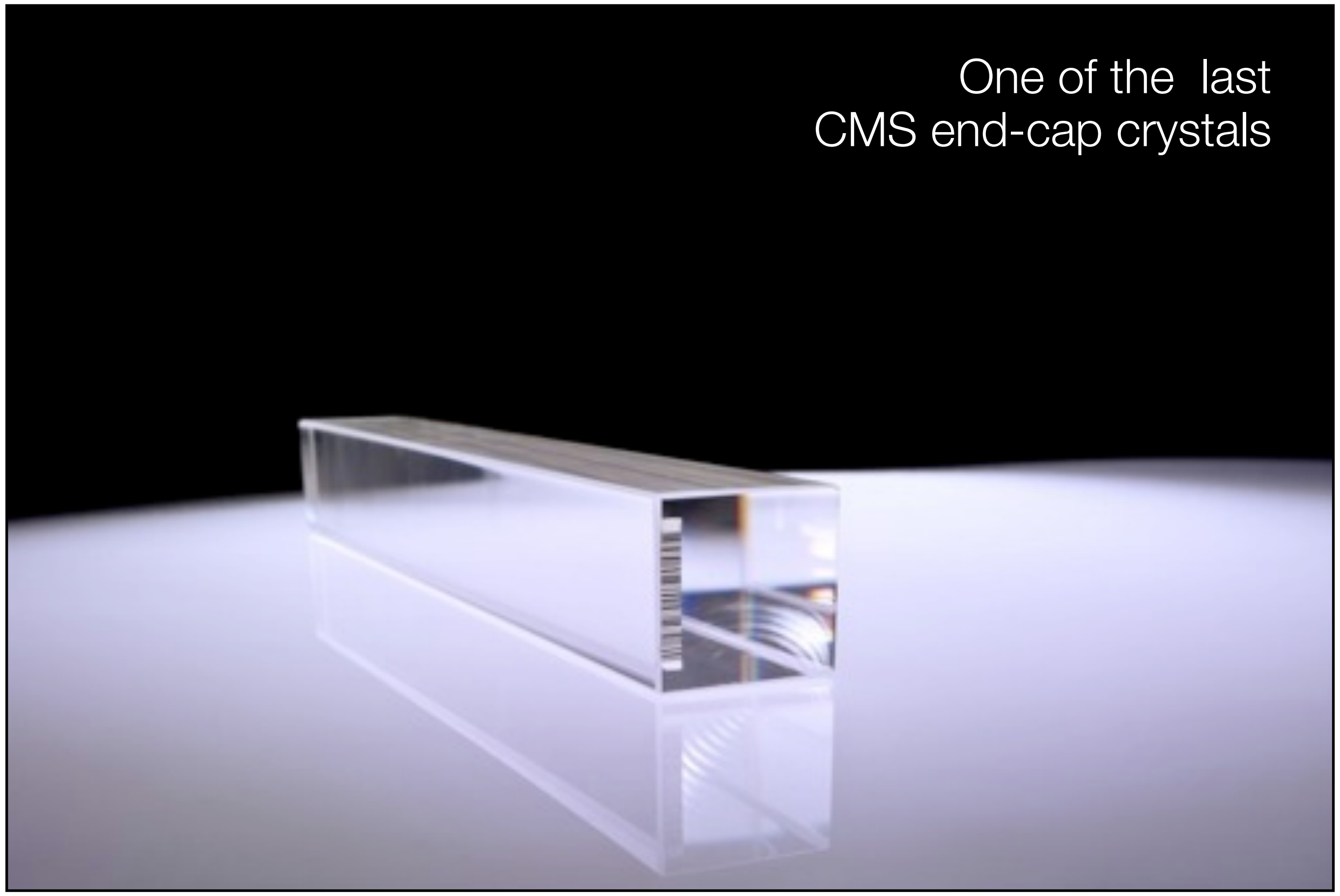

R_L

Cintiladores: cristais inorgânicos



Example CMS
Electromagnetic Calorimeter





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Cintiladores: cristais inorgânicos

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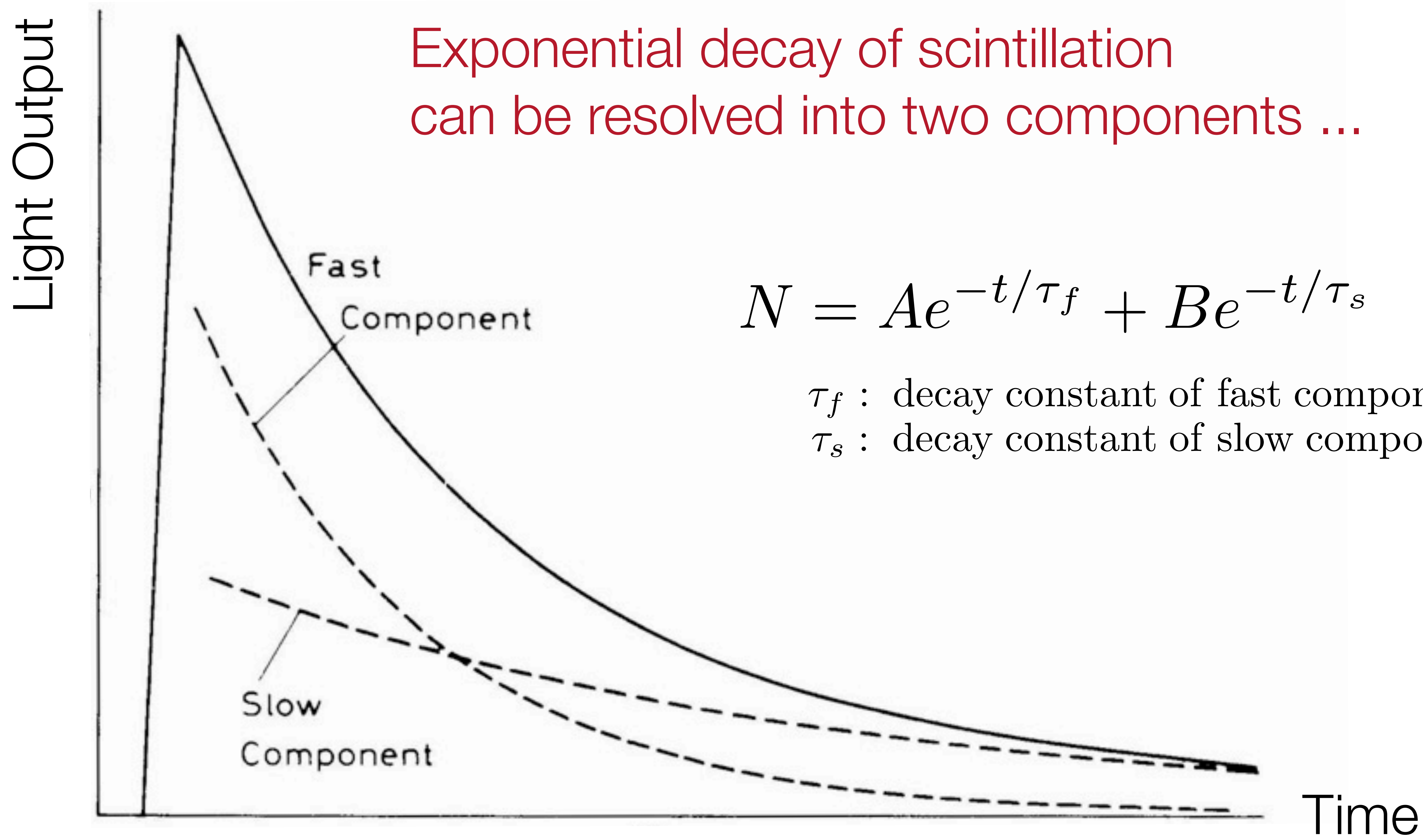
Cristais inorgânicos: constante de tempo



Exponential decay of scintillation
can be resolved into two components ...

$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

τ_f : decay constant of fast component
τ_s : decay constant of slow component

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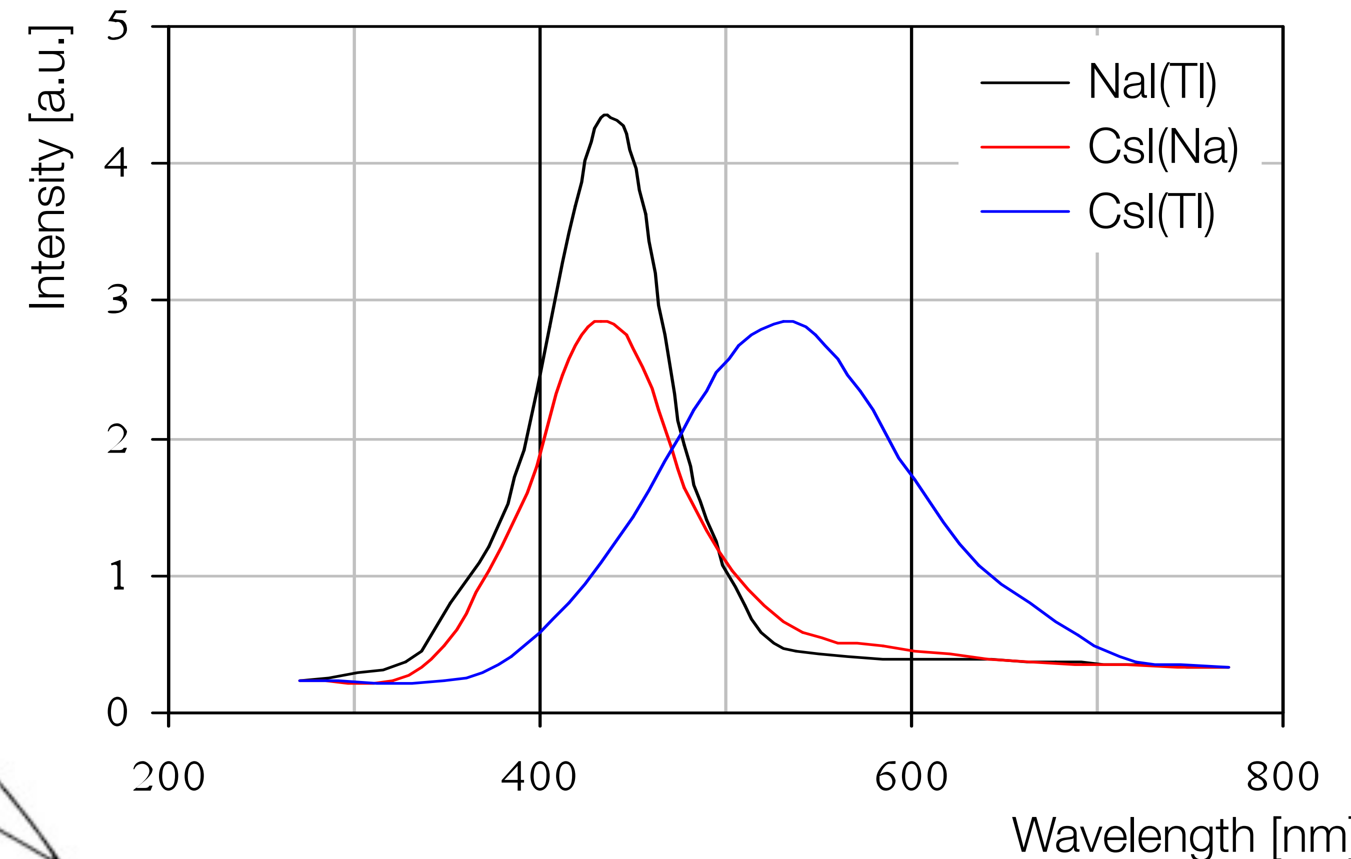
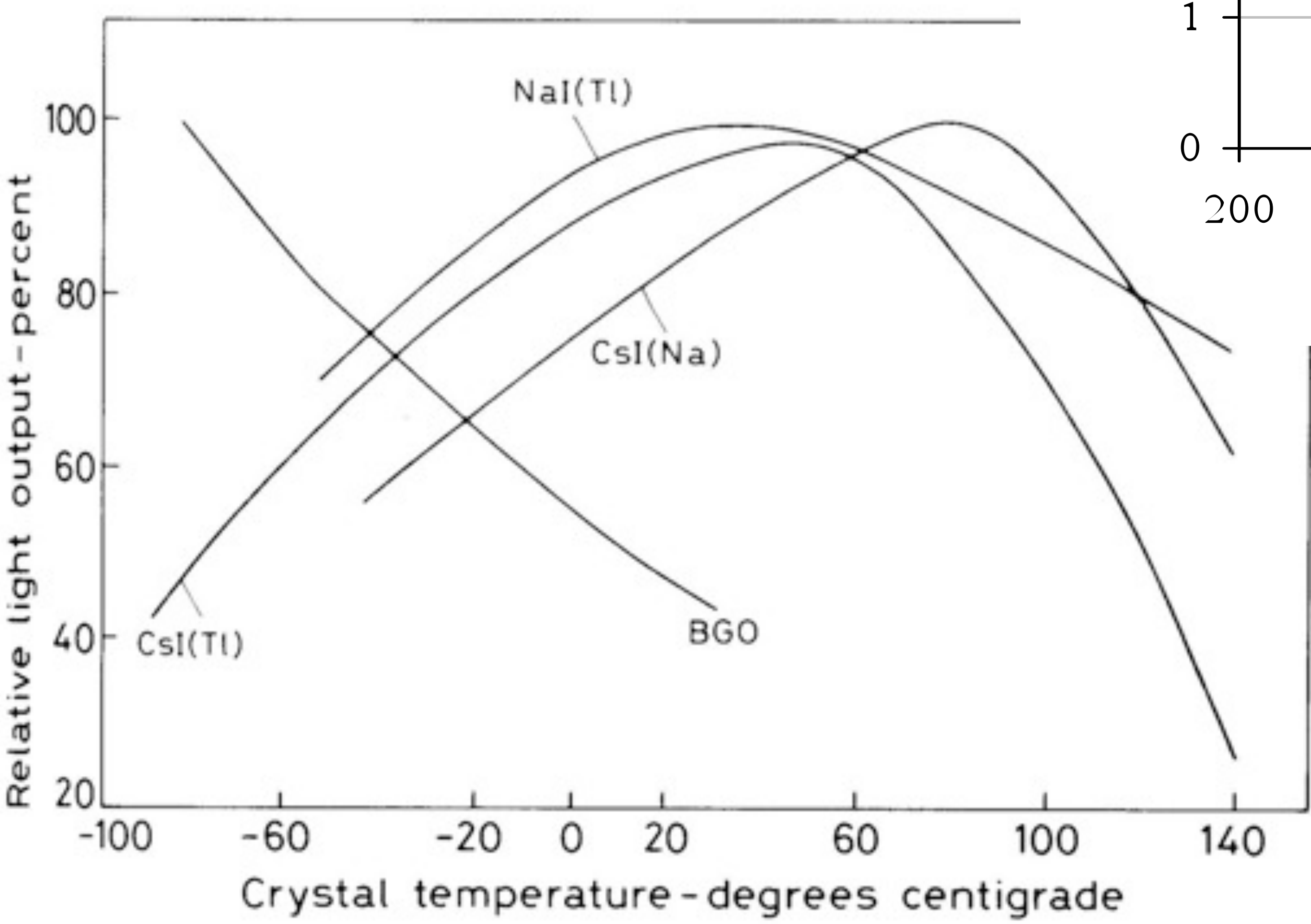
Cristais inorgânicos: luz de saída

Scintillation Spectrum
for NaI and CsI





Strong
Temperature Dependence
[in contrast to organic scintillators]

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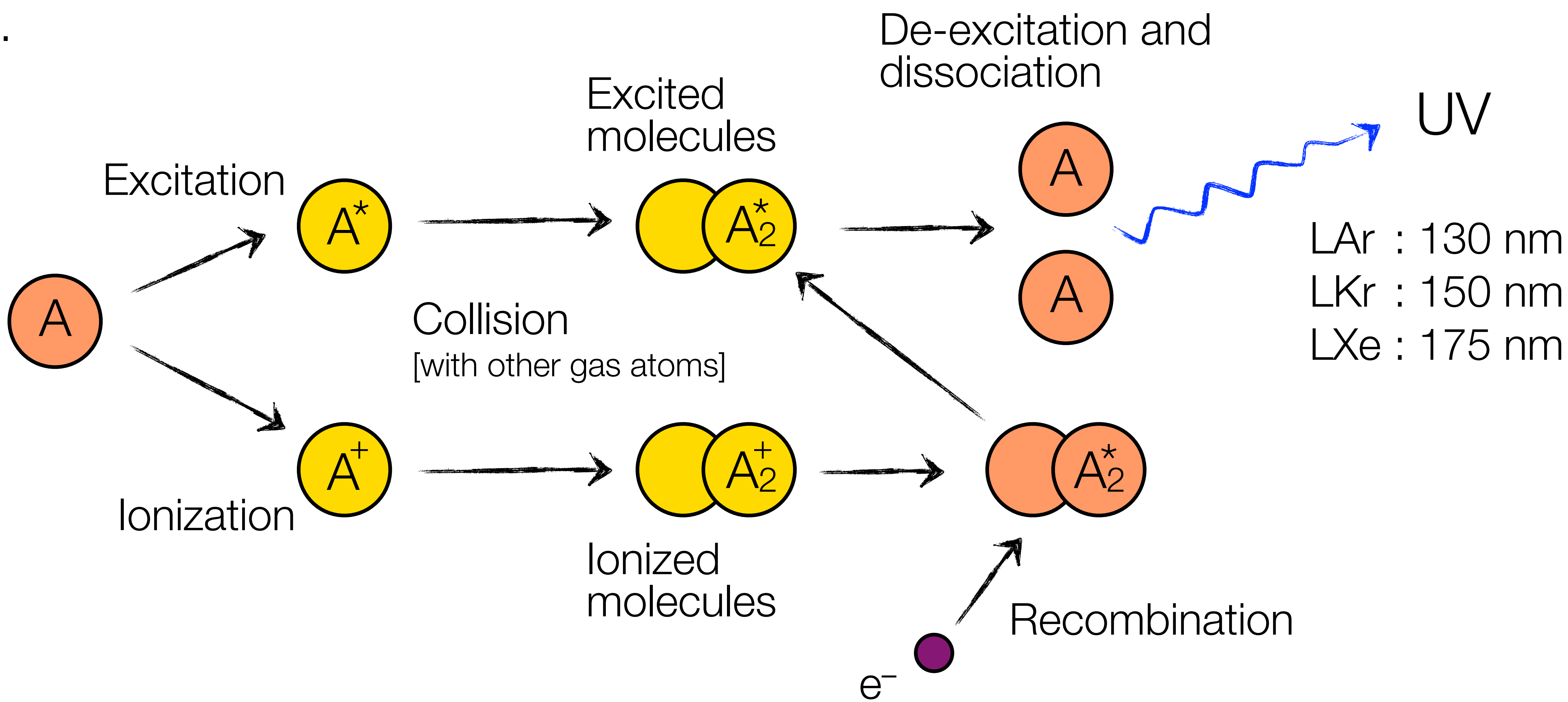
Cintiladores: gases nobres líquidos

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)
...

Decay time constants:

Helium : τ_1 = .02 μs, τ_2 = 3 μs
Argon : $\tau_1 \leq$ .02 μs



Cintiladores: propriedades

Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [µs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8\cdot10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4\cdot10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1\cdot10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8\cdot10^3$
CsF	4.1	1.48	390	0.003	$2\cdot10^3$
LSO	7.4	1.82	420	0.04	$1.4\cdot10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2\cdot10^2$
LHe	0.1	1.02	390	0.01/1.6	$2\cdot10^2$
LAr	1.4	1.29 *	150	0.005/0.86	$4\cdot10^4$
LXe	3.1	1.60 *	150	0.003/0.02	$4\cdot10^4$

* at 170 nm

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Cintiladores: propriedades

Numerical examples:

NaI(Tl) λ_{max} = 410 nm; hν = 3 eV
photons/MeV = 40000
τ = 250 ns

$PBWO_4$ λ_{max} = 420 nm; hν = 3 eV
photons/MeV = 200
τ = 6 ns

Scintillator quality:

Light yield – ε_{sc} ≡ fraction of energy loss going into photons

e.g. NaI(Tl) : 40000 photons; 3 eV/photon ➛ $\varepsilon_{sc} = 4 \cdot 10^4 \cdot 3$ eV/10^6 eV = 11.3%
$PBWO_4$: 200 photons; 3 eV/photon ➛ $\varepsilon_{sc} = 2 \cdot 10^2 \cdot 3$ eV/10^6 eV = 0.06%
[for 1 MeV particle]

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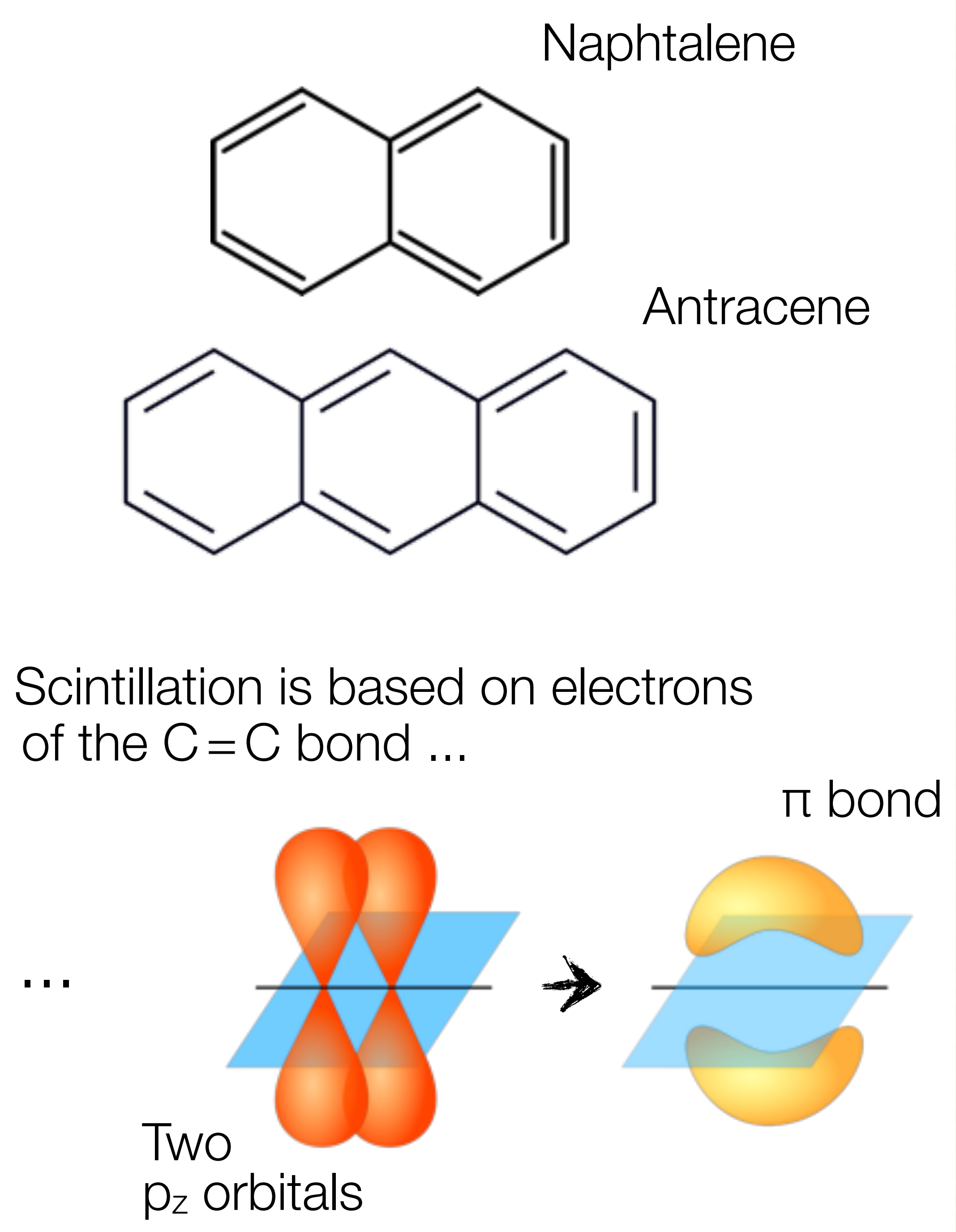
Cintiladores orgânicos

Compostos hidrocarbonetos aromáticos:

- *Naftaleno ($C_{10}H_8$)*
- *Antraceno ($C_{14}H_{10}$)*
- *….*

Mecanismo:

- *Tempo de resposta muito rápido (~ns)!*
- *Transição de elétrons livres nos orbitais*
- *Luz de cintilação surge dos elétrons nos orbitais-π*



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Cintiladores orgânicos

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

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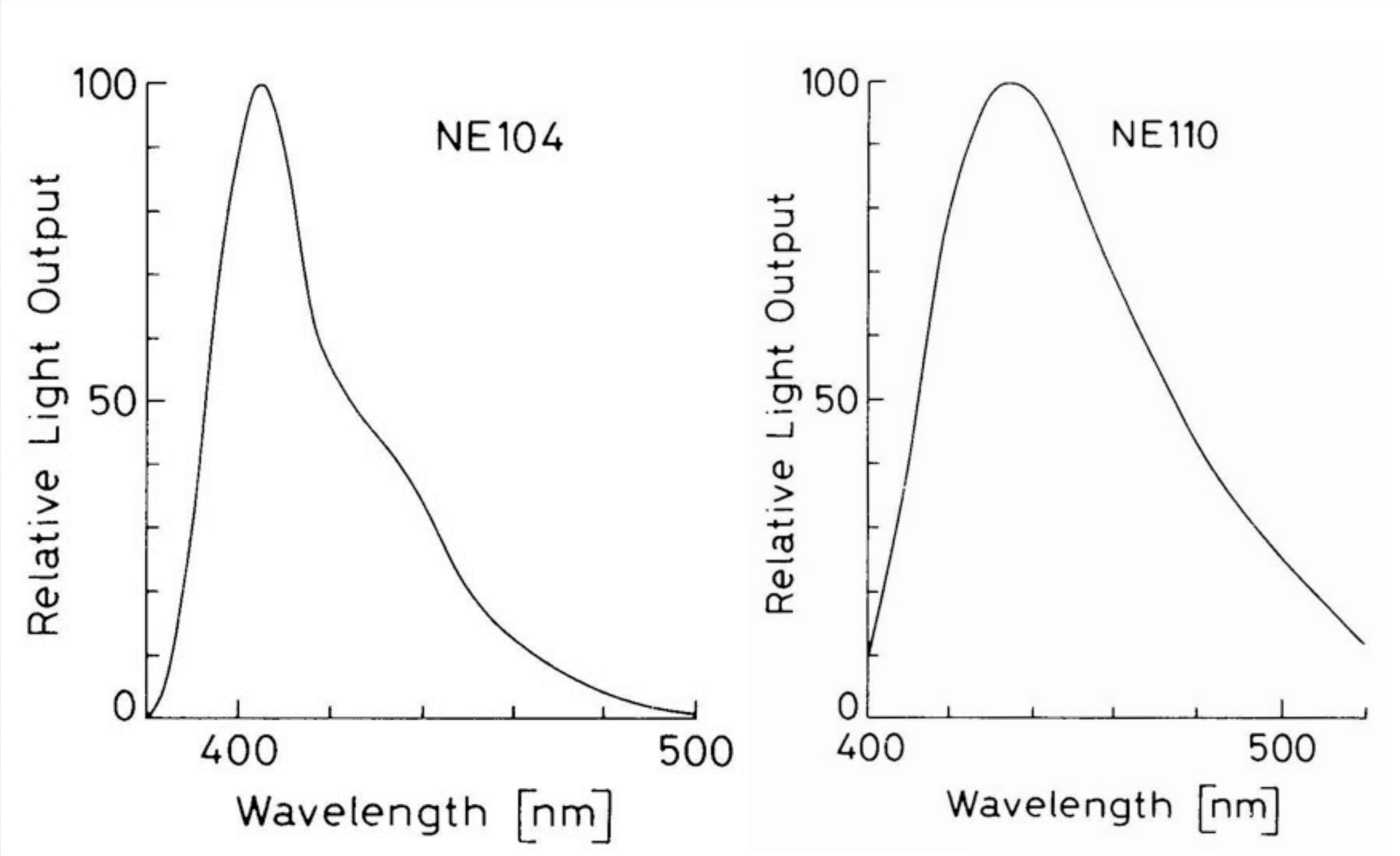
Cintiladores orgânicos



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Cintiladores: comparação

Inorganic Scintillators

Advantages	high light yield [typical; $\varepsilon_{SC} \approx 0.13$] high density [e.g. $PBWO_4$: 8.3 g/cm^3] good energy resolution	
Disadvantages	complicated crystal growth large temperature dependence	Expensive

Organic Scintillators

Advantages	very fast easily shaped small temperature dependence pulse shape discrimination possible	
Disadvantages	lower light yield [typical; $\varepsilon_{SC} \approx 0.03$] radiation damage	Cheap

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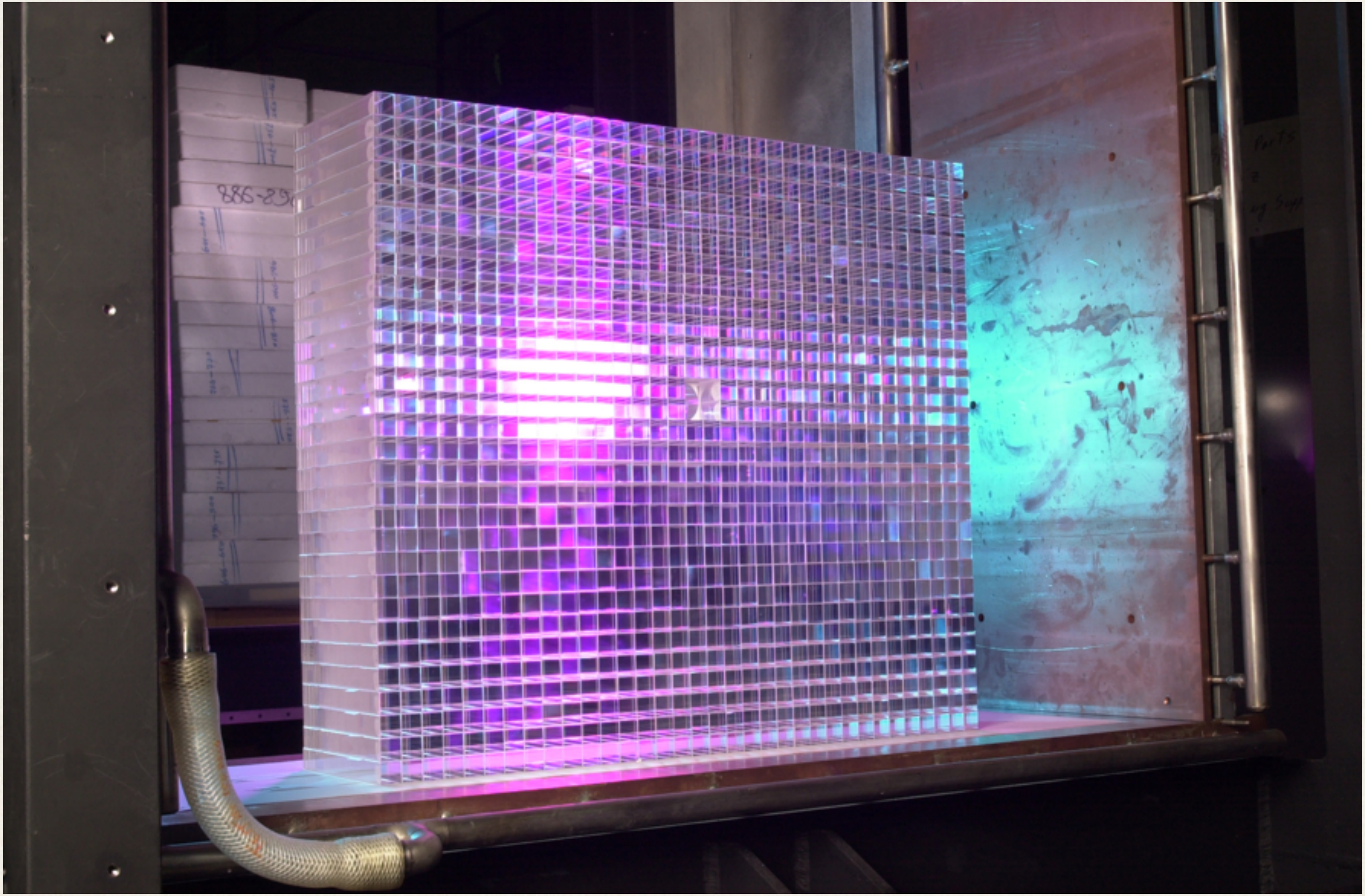

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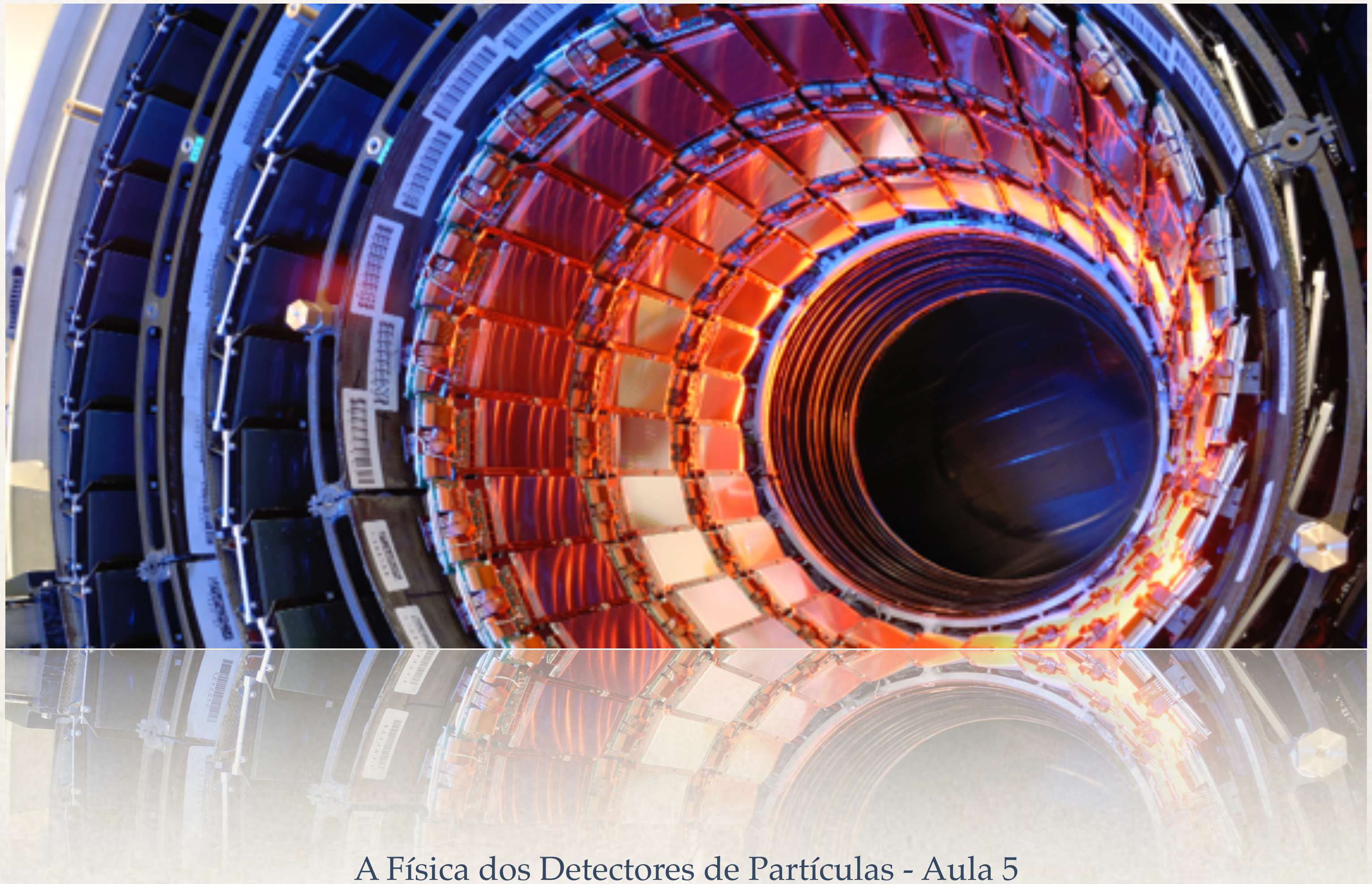
Detectores de semicondutores



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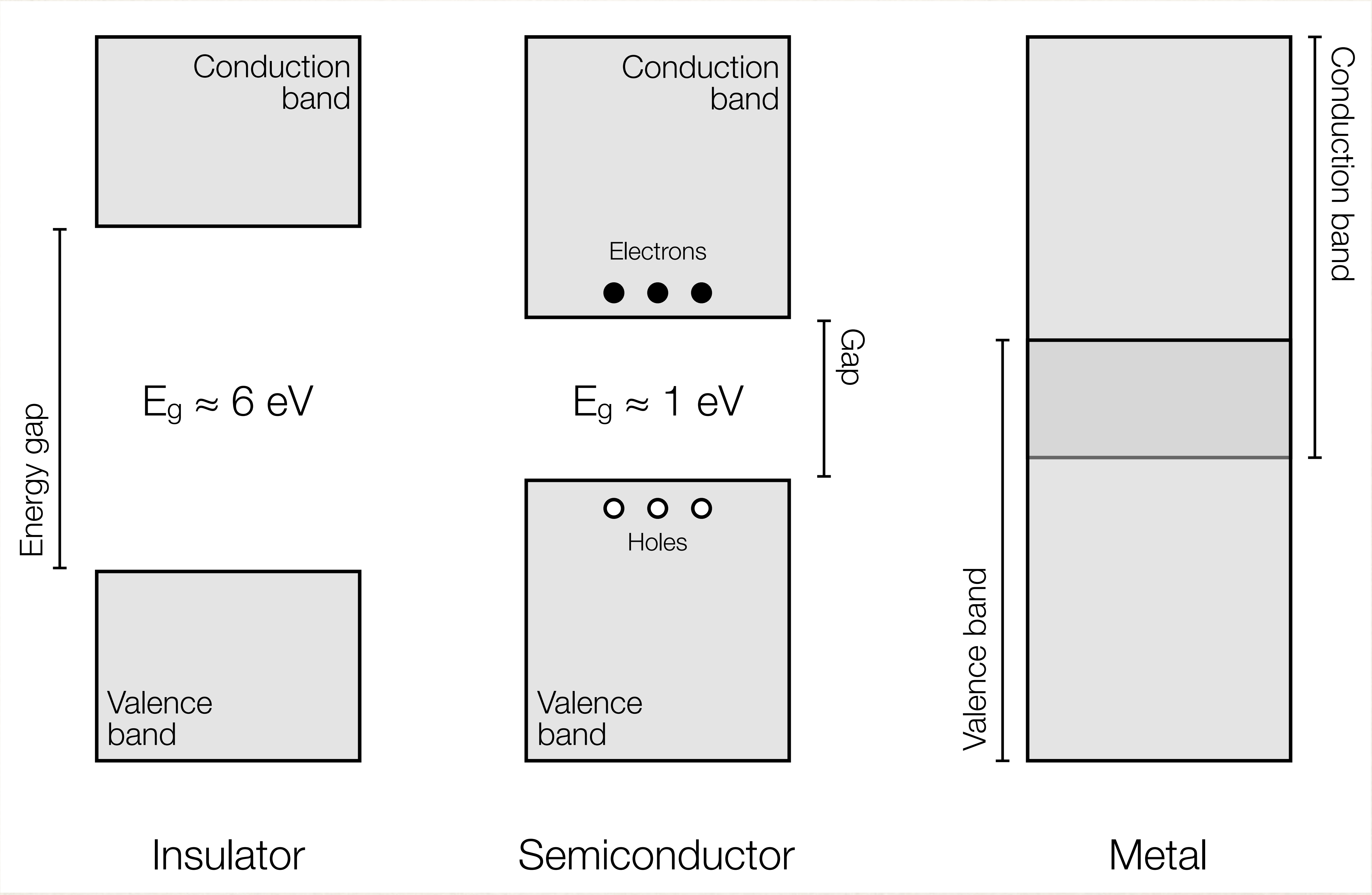
Propriedades básicas de semicondutores



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Propriedades básicas de semicondutores

Intrinsic semiconductor:

Very pure material; charge carriers are created by thermal, optical or other excitations of electron-hole pairs; $N_{electrons} = N_{holes}$ holds ...

Commonly used: Silicon (Si) or Germanium (Ge); four valence electrons ...

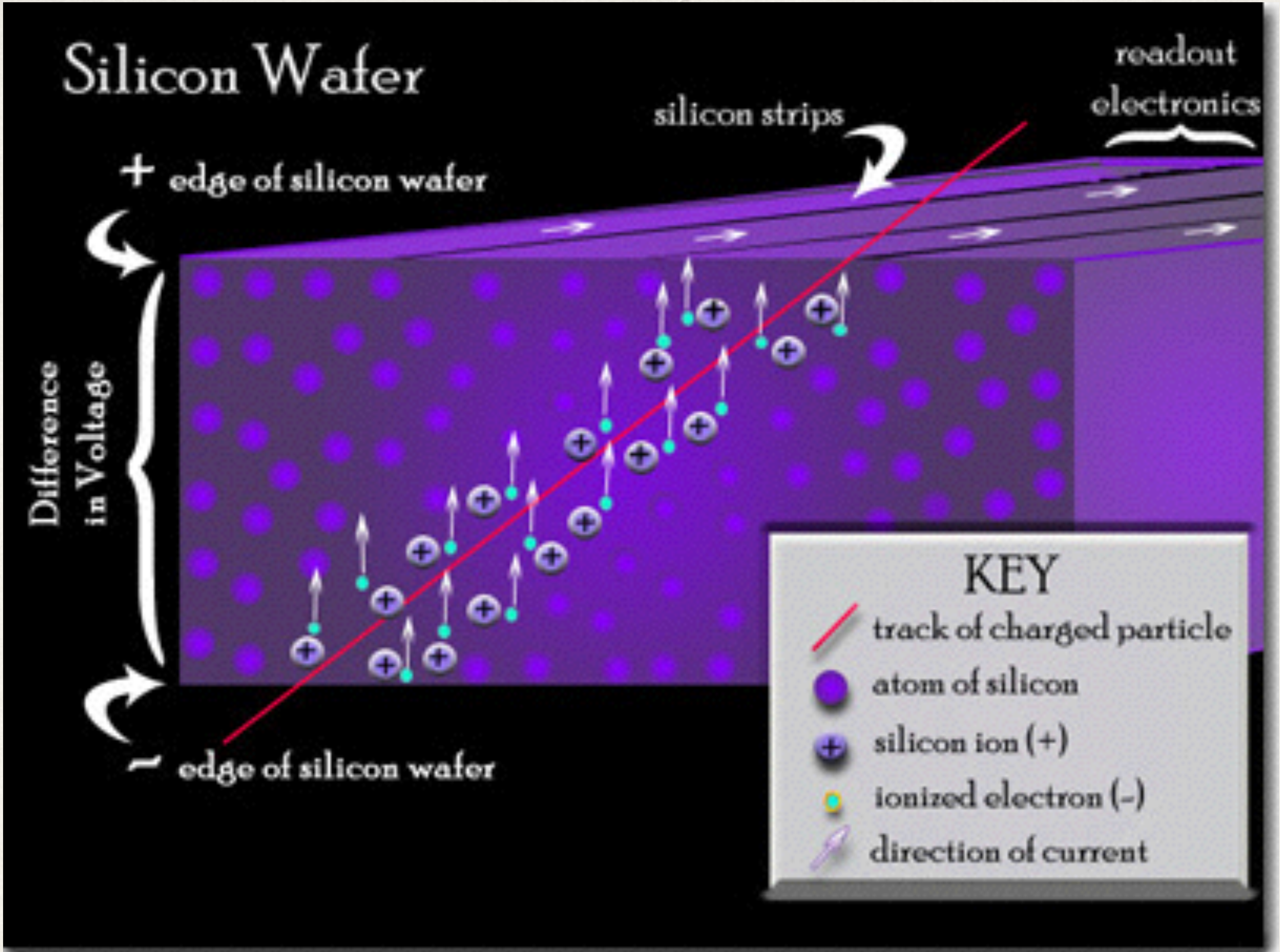
Doped or extrinsic semiconductor:

Majority of charge carriers provided by donors (impurities; doping)

n-type : majority carriers are electrons (pentavalent dopants)
p-type : majority carriers are positive holes (trivalent dopants)

Pentavalent dopants (electron donors): P, As, Sb, ...
[5th electron only weakly bound; easily excited into conduction band]

Trivalent dopants (electron acceptors): Al, B, Ga, In, ...
[One unsaturated binding; easily excepts valence electron leaving hole]



http://www-cdf.fnal.gov/virtualtour/video_ionizationanimation.html

Propriedades básicas de semicondutores

Carrier concentration in conduction and valence band:

$N_{C,V}$ ~ $(m^*T)^{3/2}$
T dependent

$$n = N_C \cdot e^{-(E_C-\mu)/k_BT}$$

N_C: effective density
of electrons at edge of conduction band

$$p = N_V \cdot e^{-(\mu-E_V)/k_BT}$$

N_V: effective density
of holes at edge of valence band

Pure semiconductors: carrier concentration depends on separation of conduction/valence band from chemical potential or Fermi level ...

Location of Fermi level determines n and p ...
But, product is independent of location of Fermi level ...

$$np = N_C N_V e^{(E_V-E_C)/k_BT} \quad \propto (m_e^* m_h^*)^{\frac{3}{2}}$$

Law of mass action
[holds more generally]

At given temperature characterized by effective mass and band gap.

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Propriedades básicas de semicondutores

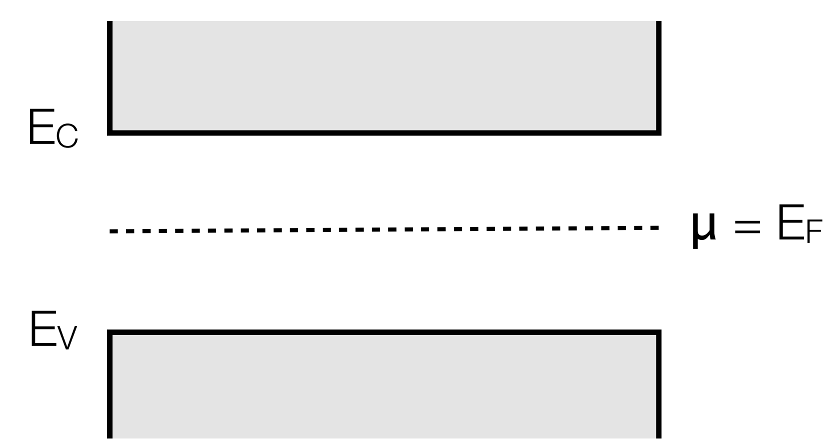
Intrinsic semiconductors; no impurities ➛ number of electrons in conduction band is equal to number of holes in valence band.

$$n = p \qquad \left[\text{or } n_i = p_i \text{ to characterize that this holds for intrinsic semiconductors only}\right]$$

The expressions for n,p then yield:

$$\mu = \frac{E_C + E_V}{2} - \frac{k_B T}{2} \ln\left(\frac{N_C}{N_V}\right) = \frac{E_C + E_V}{2} - \frac{3}{4} k_B T \ln\left(\frac{m_e^*}{m_h^*}\right)$$

At T = 0:
Fermi-level ($E_F = \mu$) lies in the middle between valence and conduction band ...



At T > 0:
In case the effective masses of electrons and holes are non-equal, i.e. $N_C \neq N_V$ the Fermi-level changes with temperature ...

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Propriedades básicas de semicondutores

Some properties of intrinsic semiconductors

	Si	Ge	GaAs [III-V Semiconductor]
E_{gap} [eV]	1.11	0.67	1.43
n_i @ 150 K [m^{-3}]	$4.1 \cdot 10^{6}$	—	$1.8 \cdot 10^{0}$
n_i @ 300 K [m^{-3}]	$1.5 \cdot 10^{16}$	$2.4 \cdot 10^{19}$	$5.0 \cdot 10^{13}$
m_e^*/m_e	0.43	0.60	0.065
m_h^*/m_e	0.54	0.28	0.50
Energy/e-hole-pair [eV]	$3.7^{\dagger}$	$3.0^{\dagger}$	—

† at 77 K

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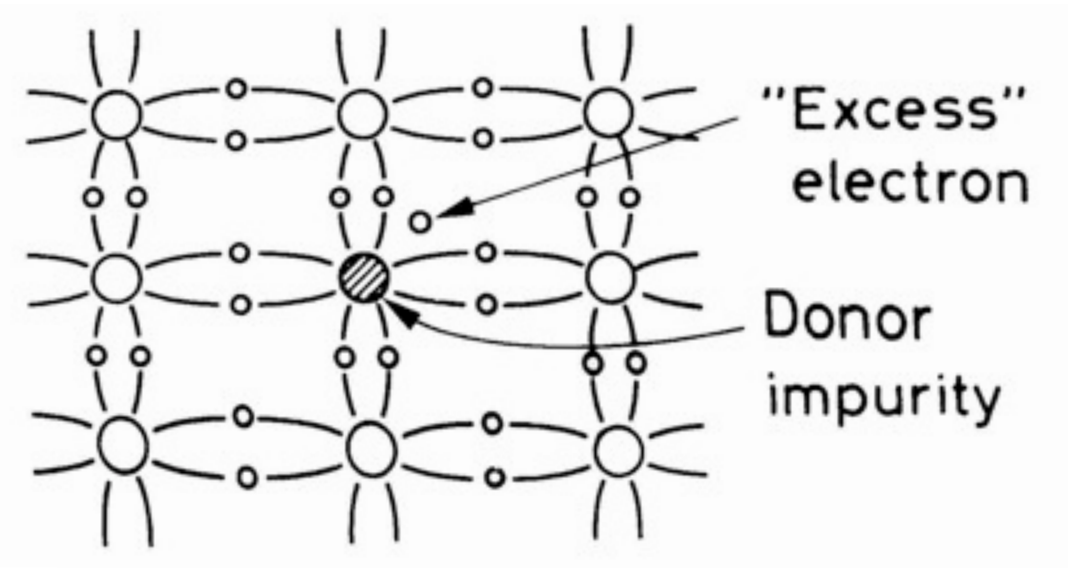
Propriedades básicas de semicondutores

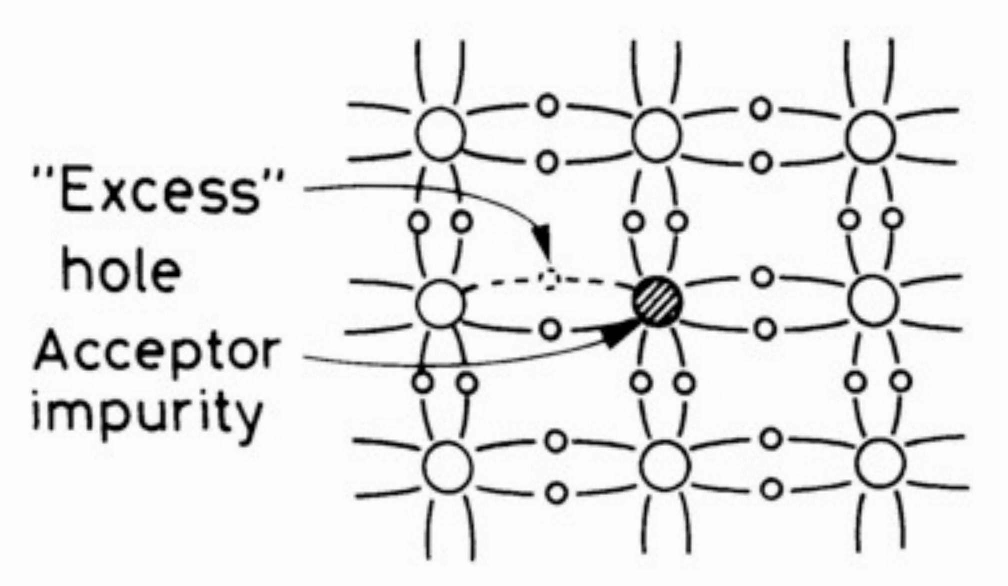
Introducing impurities (doping) ➛ balance between holes and electrons in conduction band can be changed; yields higher carrier concentrations.

n-doping: extra electron resides in discrete energy level close to conduction band ...

p-doping: additional state close to the valence band can accept electrons ...

n-doping





p-doping

n-doping:	majority carriers = electrons [holes don't contribute much; minority carriers]
p-doping:	majority carriers = holes [electrons are minority carriers]
n-doping:	Sb, P, As ...
p-doping:	B, Al, Ga ...

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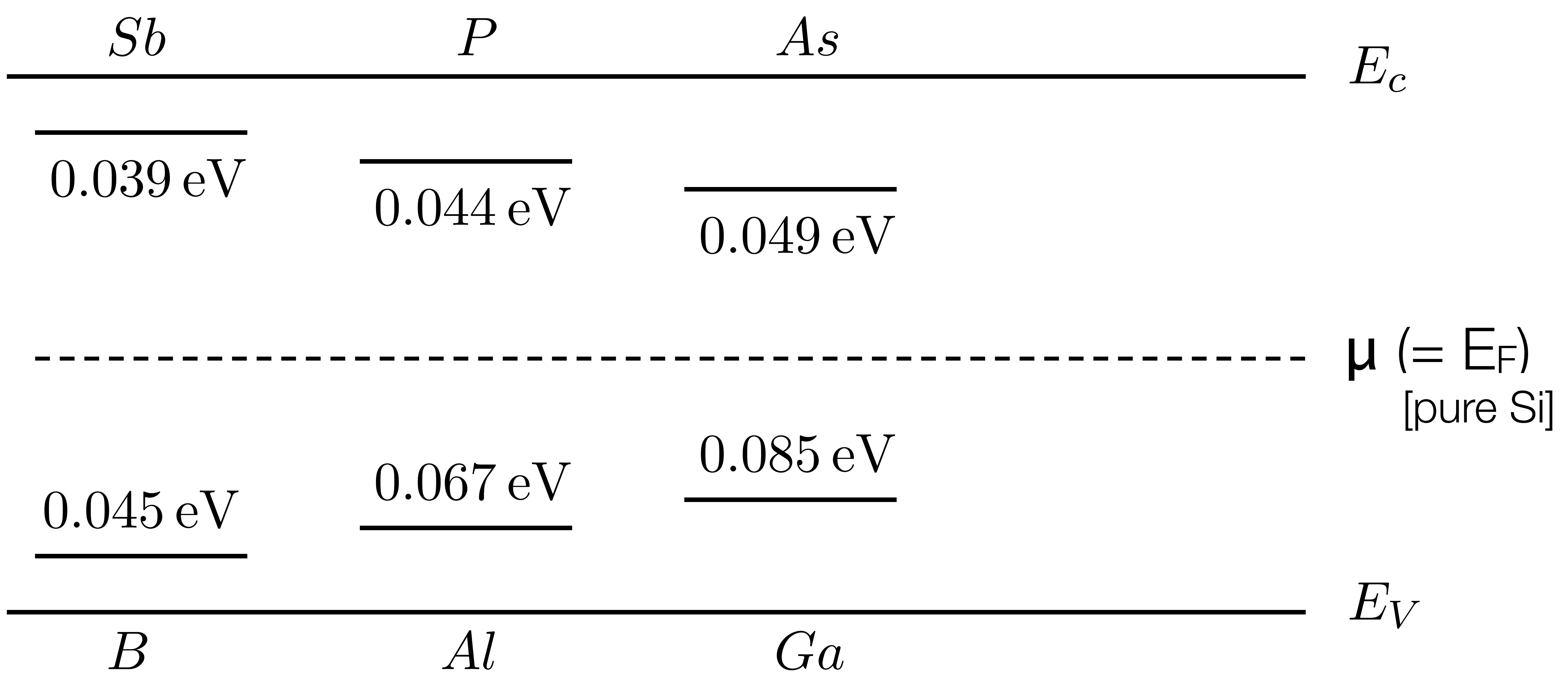
Propriedades básicas de semicondutores



Energy levels for silicon with different dopants

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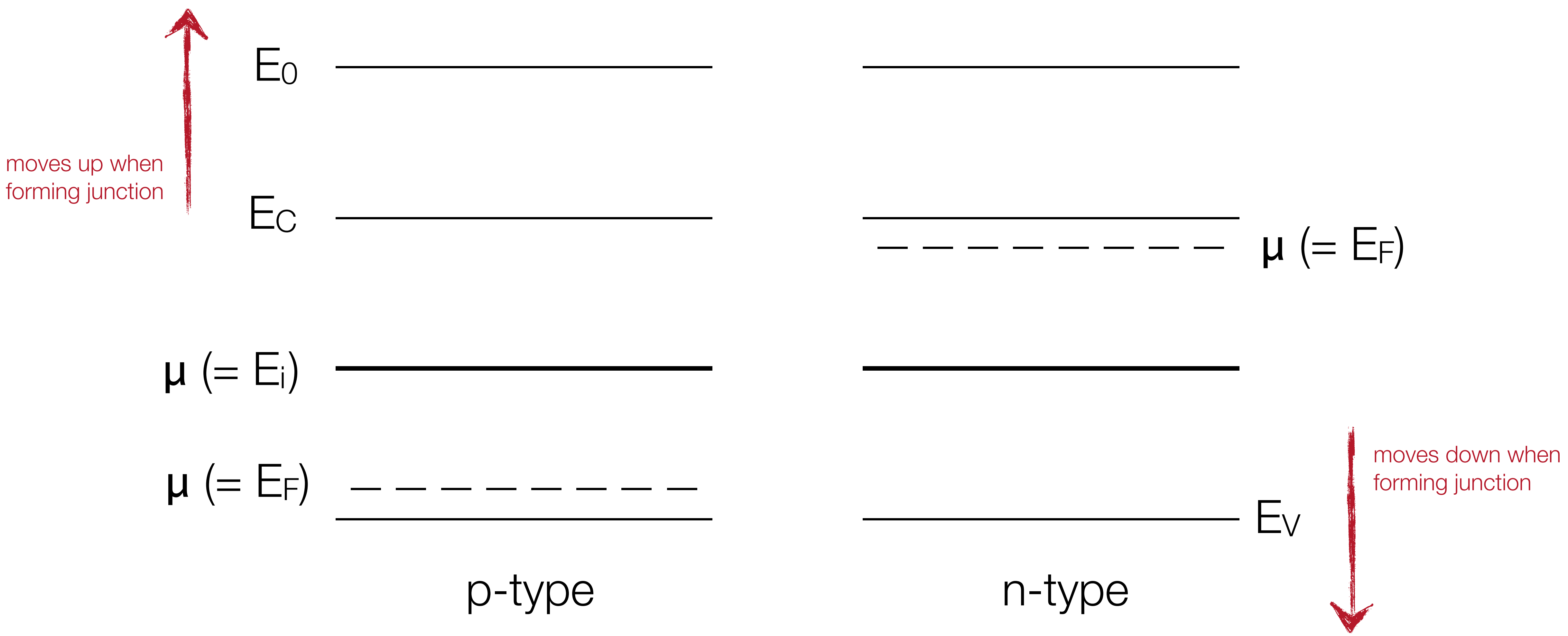
Propriedades de semicondutores: junção np

Function of semiconductor detectors depends
on formation of a junction between n- and p-type semiconductors ...

Thermodynamic equilibrium ➛ Fermi energies should become equal ...



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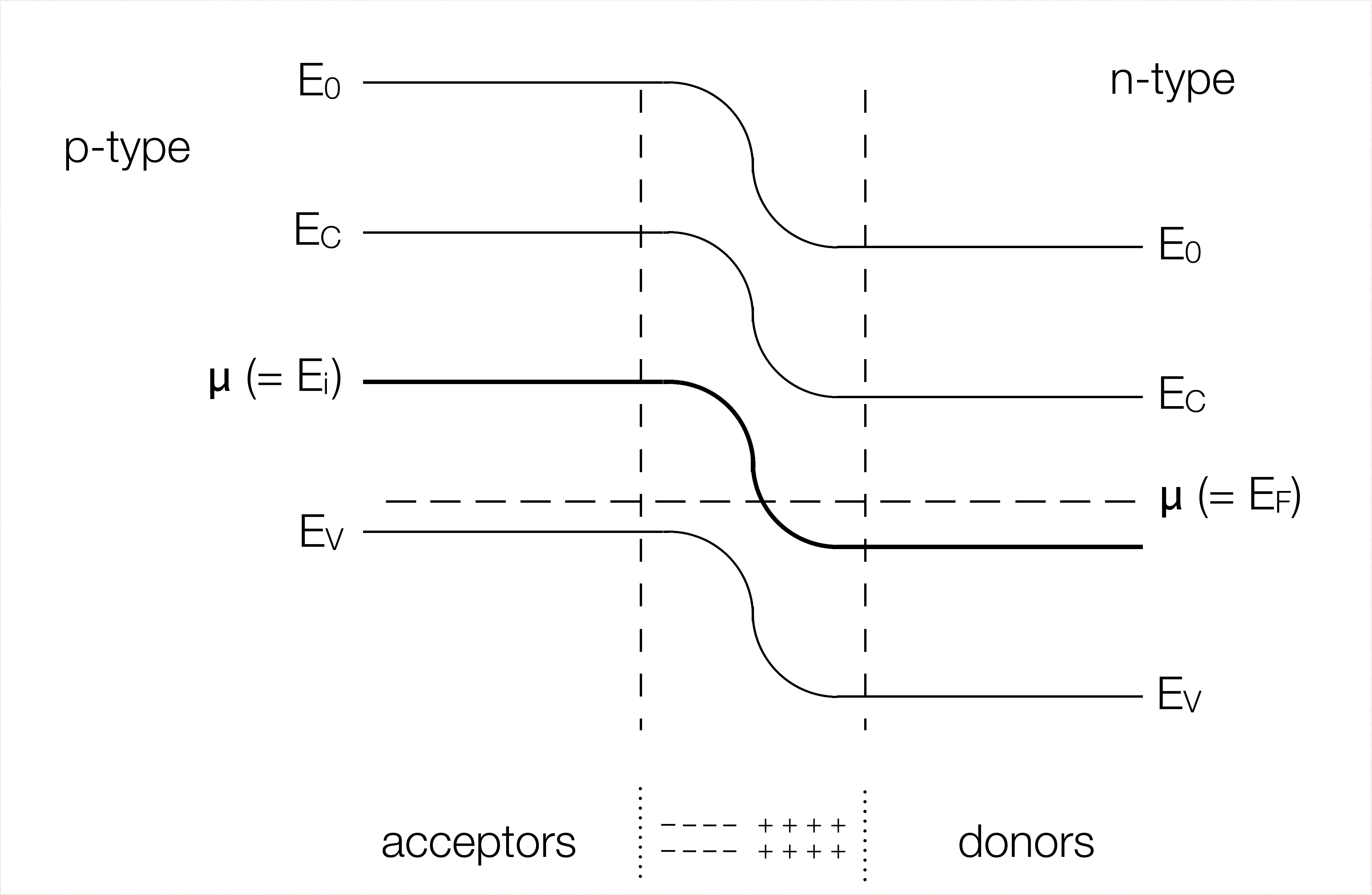
Junção np



Junção np

Equilibration process:

Electrons diffuse from n to p-type semiconductor and recombine ...

Holes diffuse from p to n-type semiconductor and recombine ...

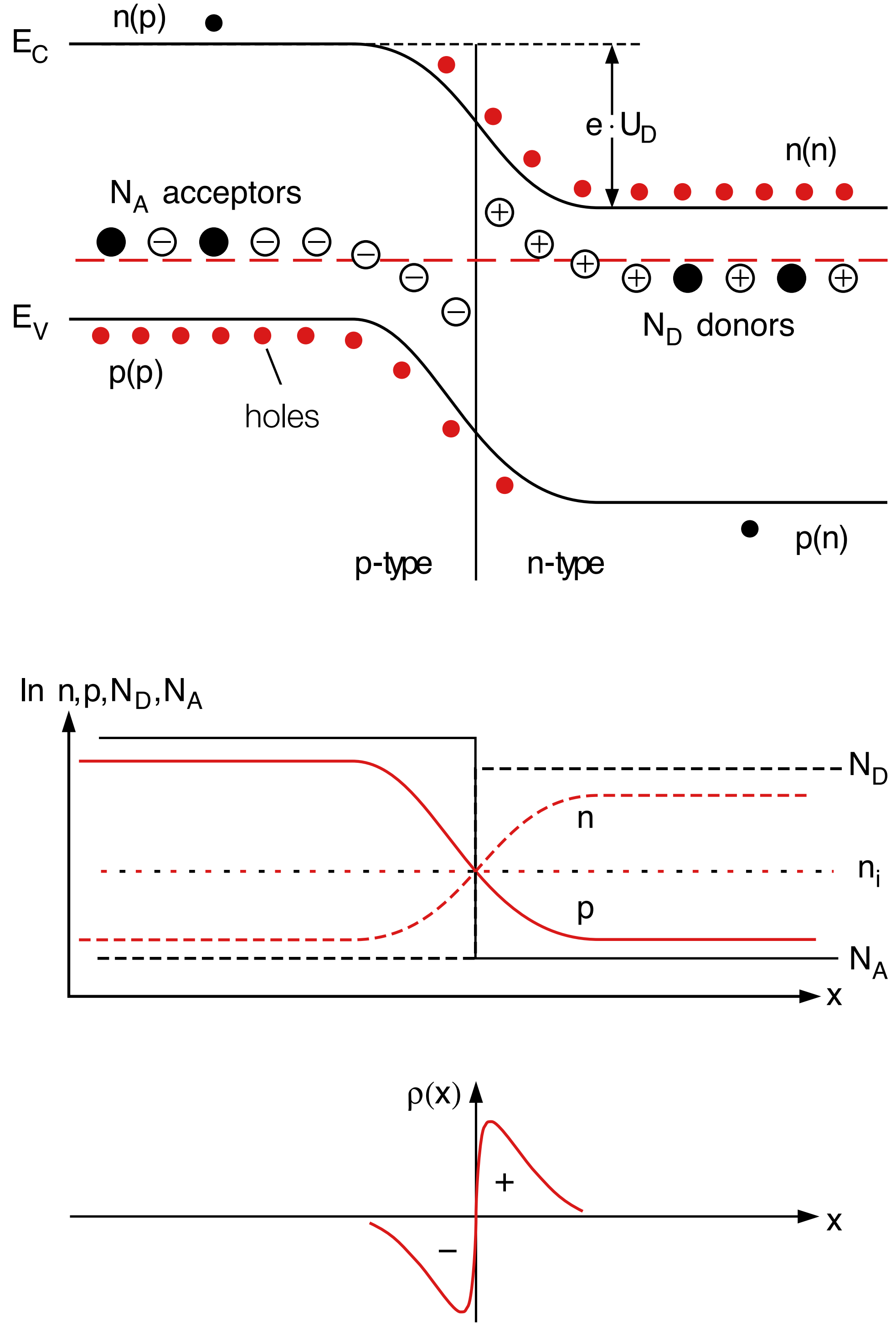
Resulting electric field counteracts and stops diffusion process ...

$$eU_D = \Delta E_{\text{pot}} = E_C^{(p)} - E_C^{(n)}$$

$$= k_B T \cdot \ln \frac{n_{\text{n-type}}}{n_{\text{p-type}}} = k_B T \cdot \ln \frac{N_D N_A}{n_i^2}$$

$$[\,\text{using } \; n = N_C \cdot e^{-(E_C - \mu)/k_B T}, \; p = \ldots\,]$$

At the boundary concentration of mobile carriers is depleted ... [depletion layer]



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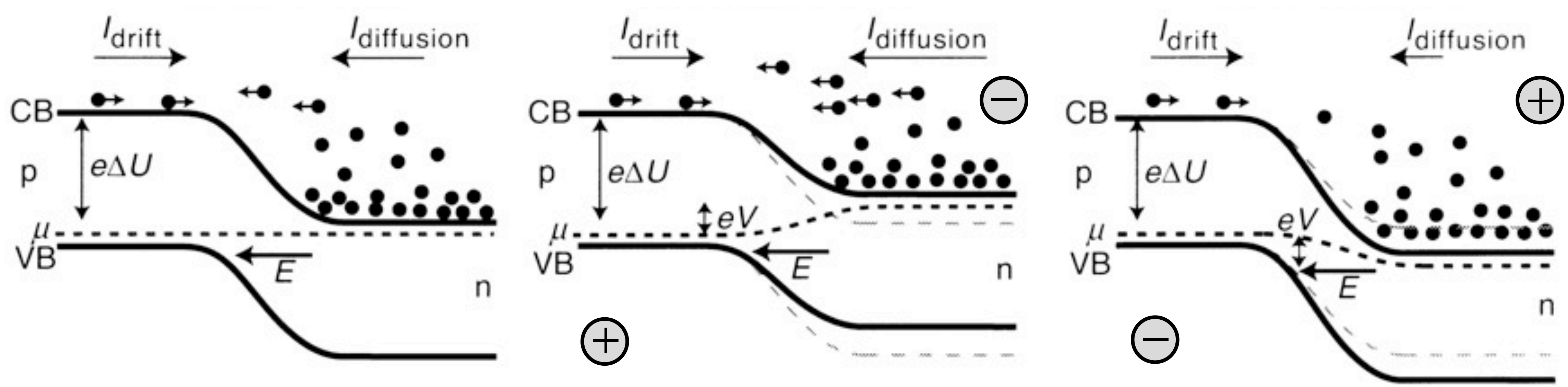
Junção np

Here: consider only electrons
[similar for holes]

Application of an external voltage:



No voltage	Forward bias	Reverse bias
Equilibrium: drift of minority electrons from p-side compensates diffusion current from n-side which have to move against E-field	Voltage drop over depletion zone; diffusion current higher due to shift of chemical potential; current increases exponentially with bias	Voltage drop over depletion zone; diffusion current smaller due to shift of chemical potential; widening of the depletion zone
	$I = I_0 (e^{eV/kT} - 1)$	$I = I_0 (e^{-eV/kT} - 1)$

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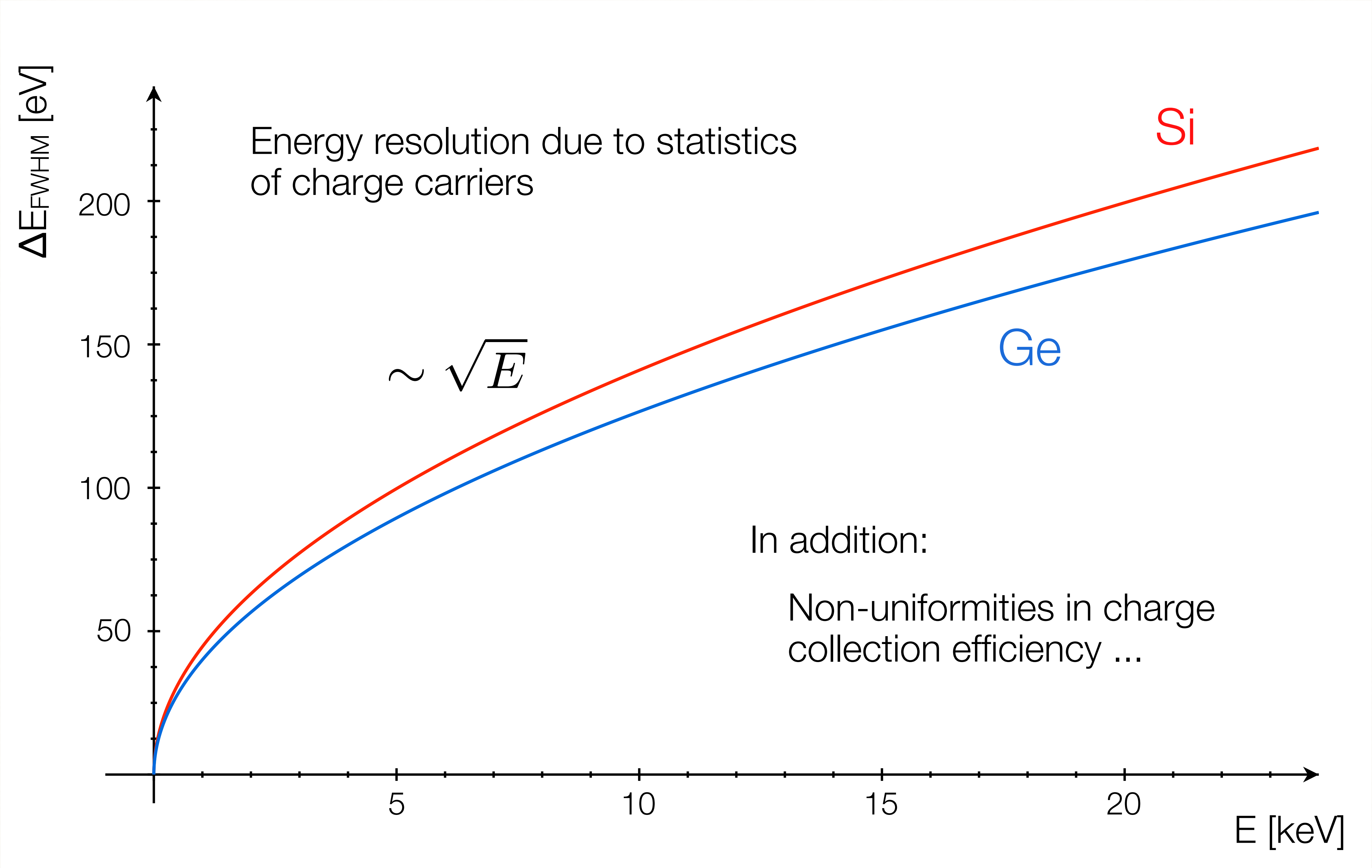
Propriedades básicas de semicondutores



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Propriedades básicas de semicondutores

Comparison
of energy resolutions ...

Scintillator [NaI(Tl)]: 1 MeV photon; $\sigma/E \approx 2\%$; $\Delta E/E \approx 5\%$
[N_i = 40000 photons/MeV x η x Q.E.; η =0.2, Q.E. = 0.25; $\sigma/E = 1/\sqrt{N_i}$]

Semiconductor [Si]: 1 MeV photon; $\sigma/E \approx 0.06\%$; $\Delta E/E \approx 0.15\%$
[N_i = 300000 e/h-pairs/MeV; $\eta \approx 1$, Q.E. ≈ 1; F = 0.1 $\sigma/E = \sqrt{F}/\sqrt{N_i}$]

Energy resolution of a semiconductor detector
can be better by a factor 25 to 30.

This is indeed observed:
[for E_γ = 1.33 MeV]

Ge(Li) Counter: Resolution of 0.15% possible (at ~ 1 MeV)
NaI(Tl) Detector: Resolution of about 6% (at ~ 1 MeV)

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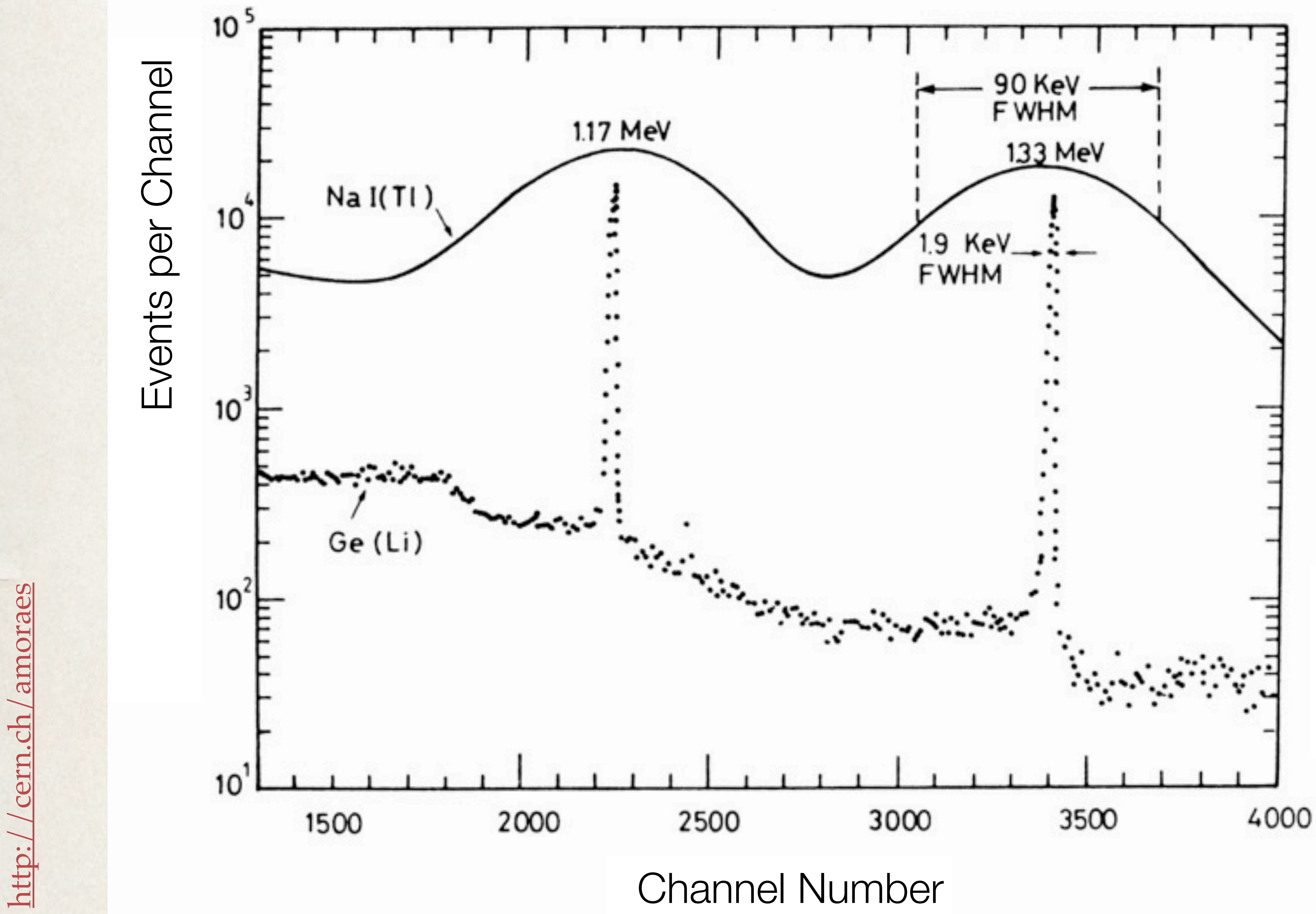
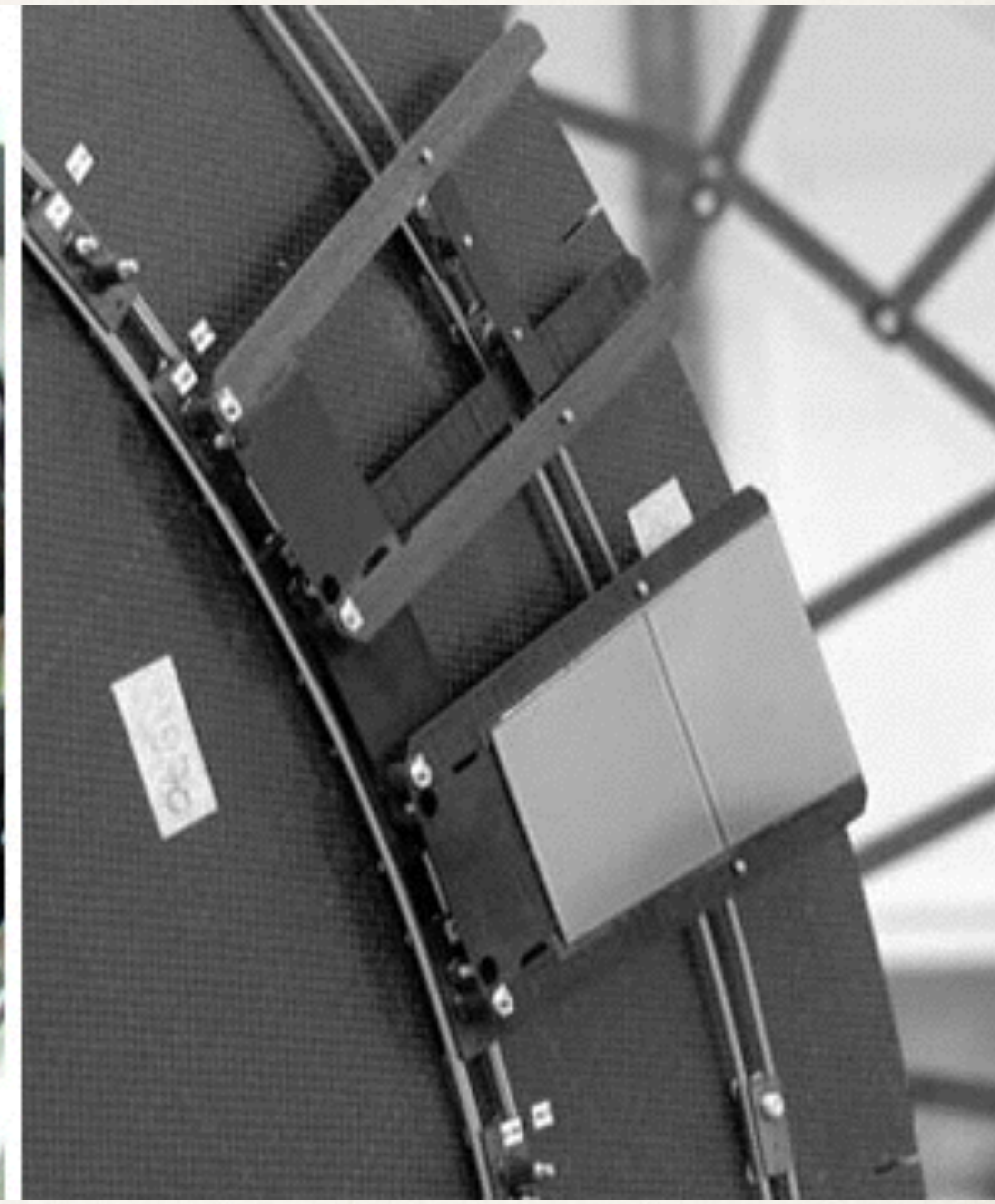
Propriedades básicas de semicondutores



Comparison
of two ^{60}Co γ-spectra
one measured with NaI(Tl)
and With Ge(Li) Detector

CMS Si-strip detector



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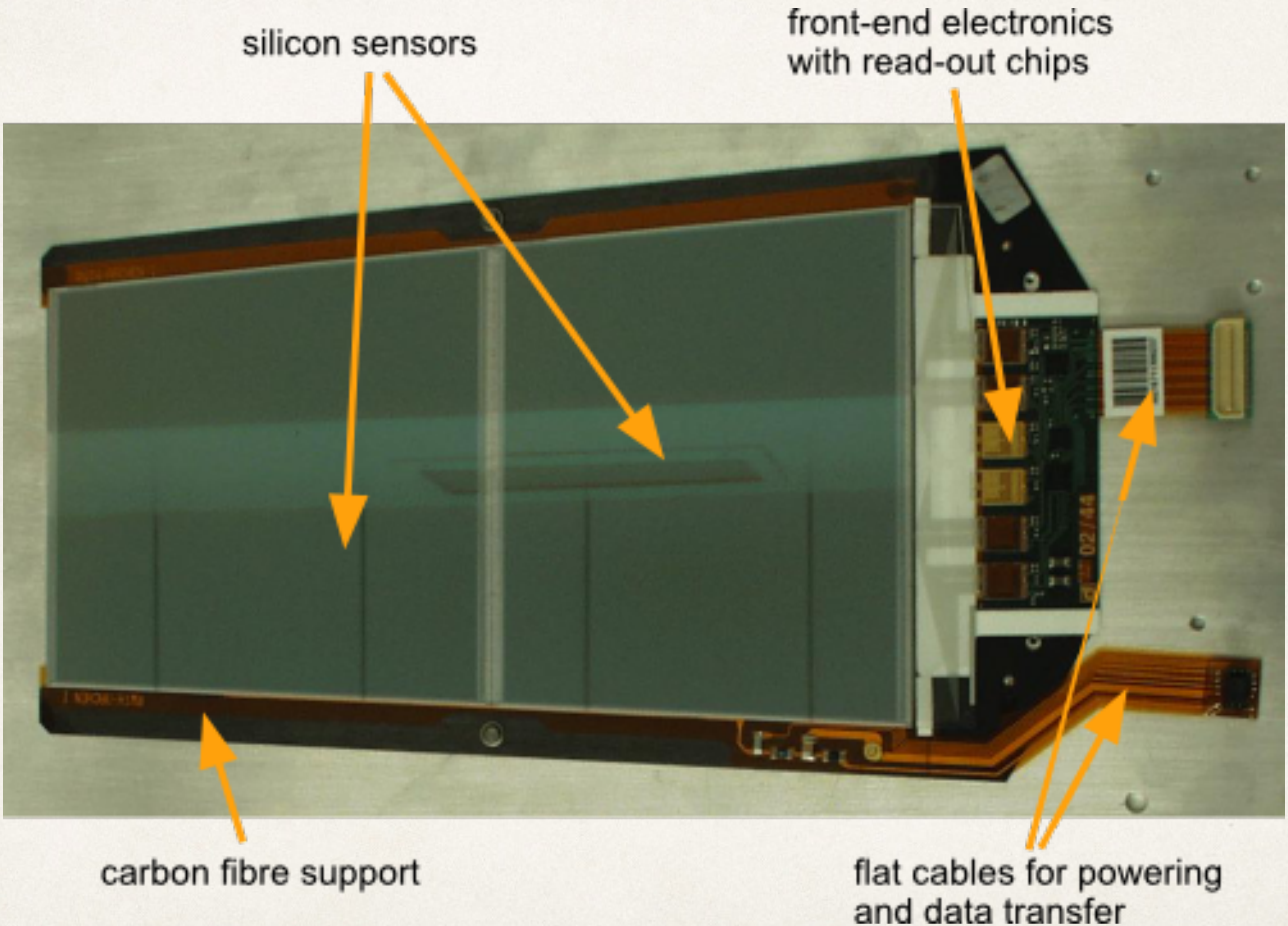
CMS Si-strip detector



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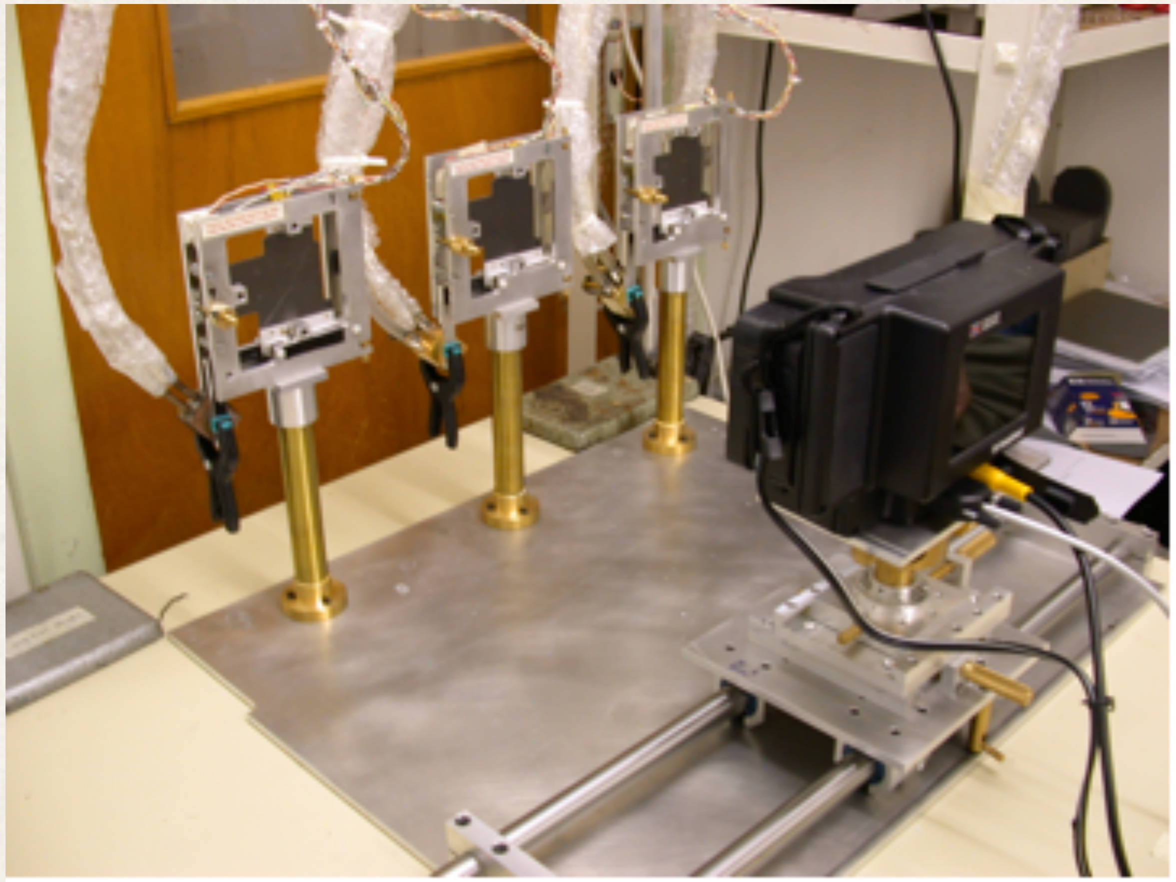
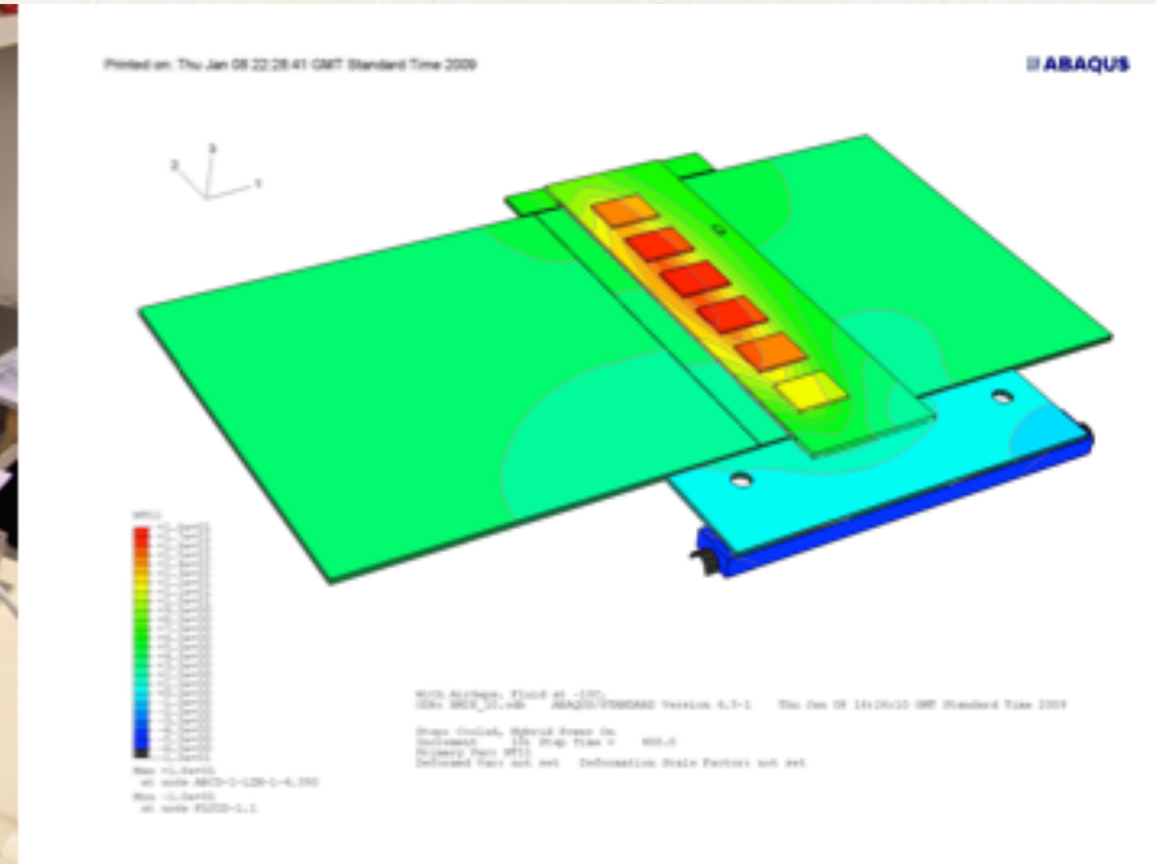
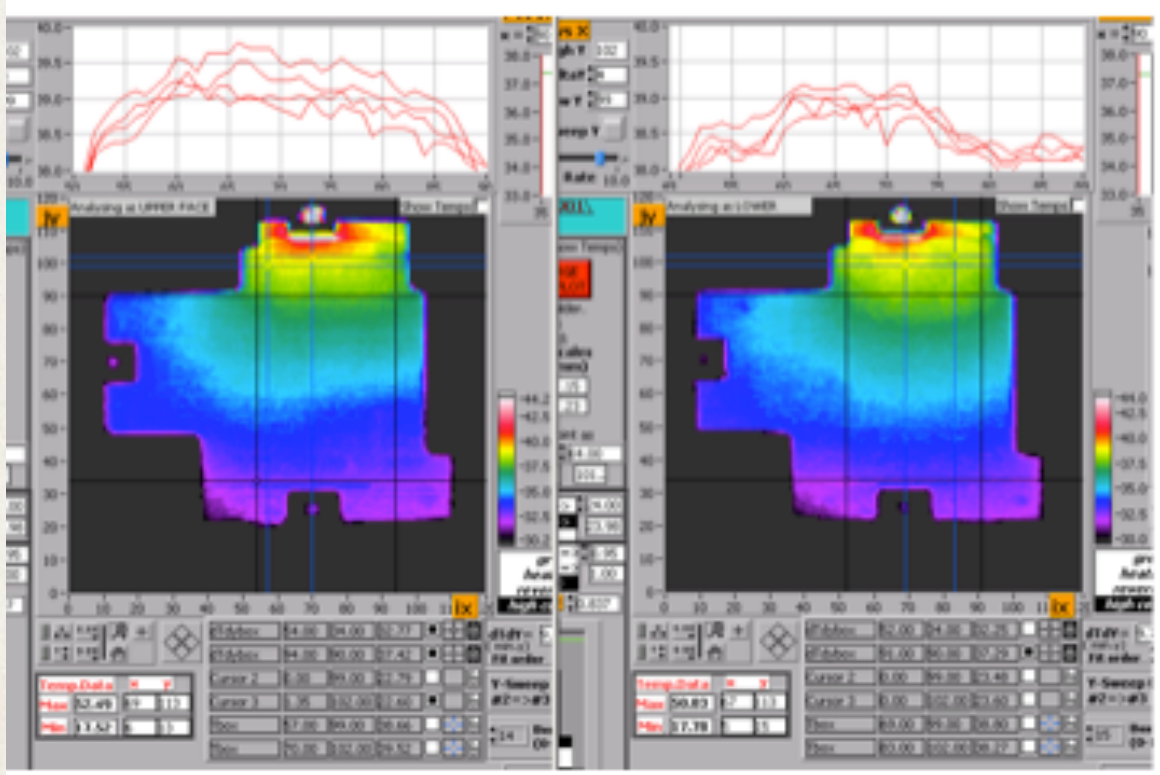
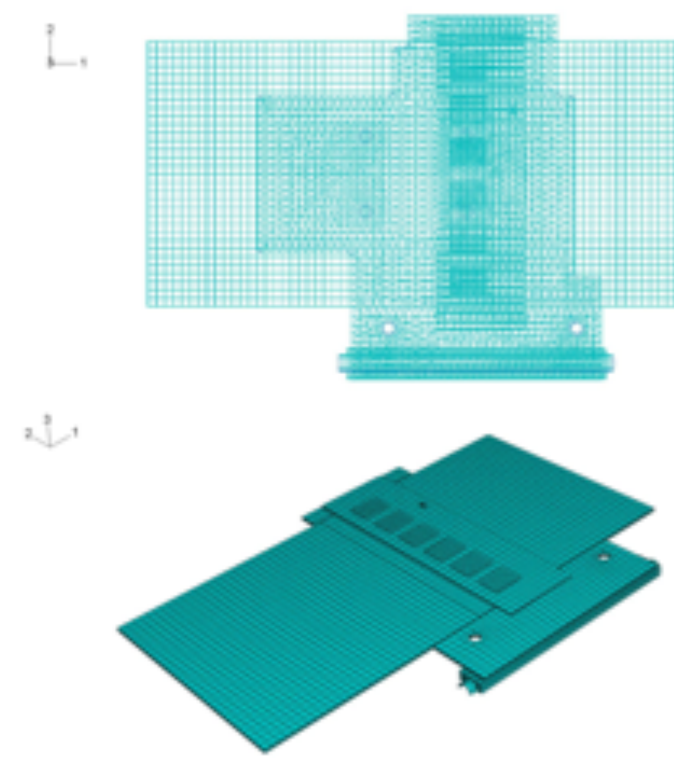
ATLAS SCT-strip detector









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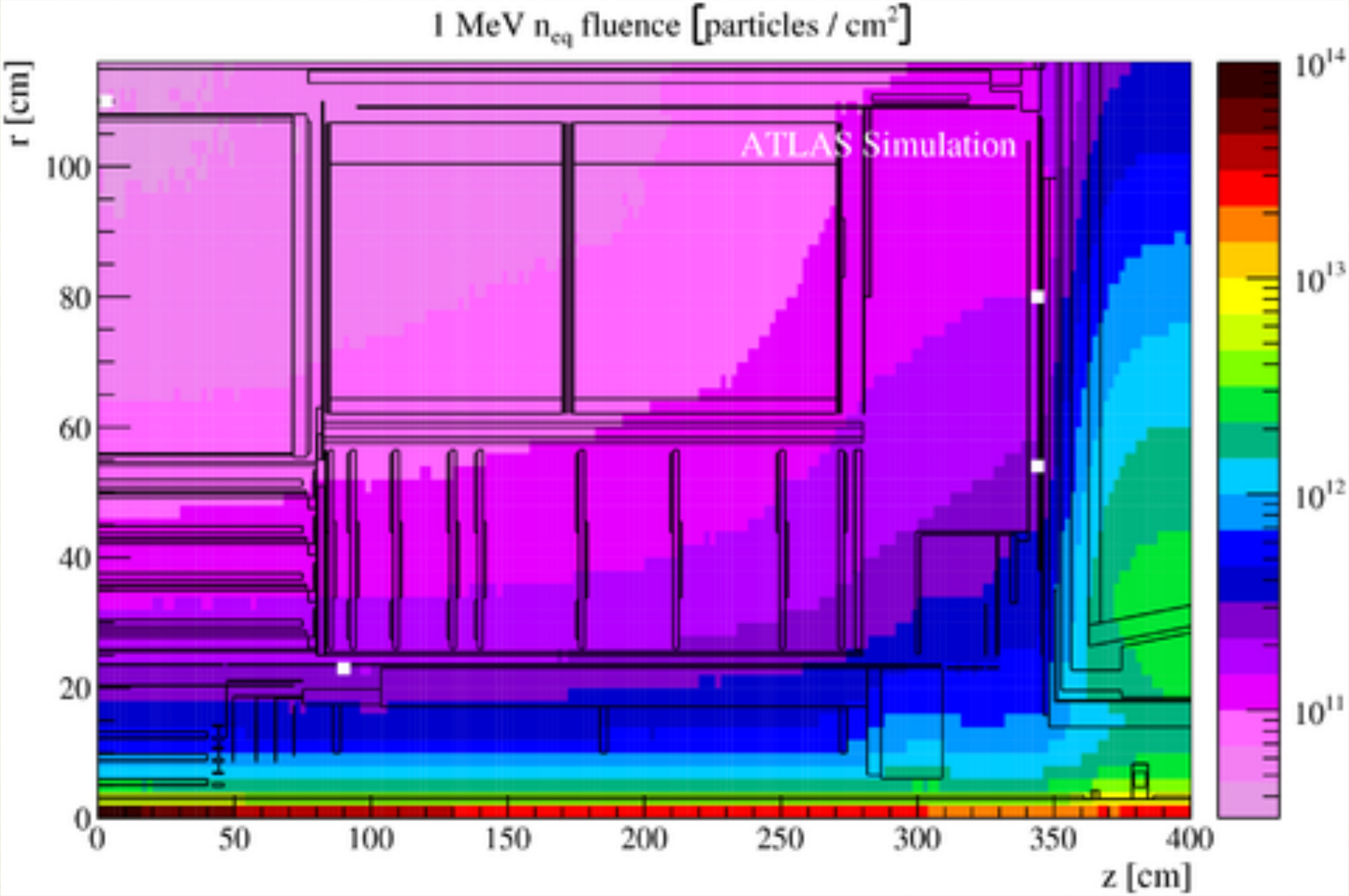
Radio-ativação nos detectores do ATLAS



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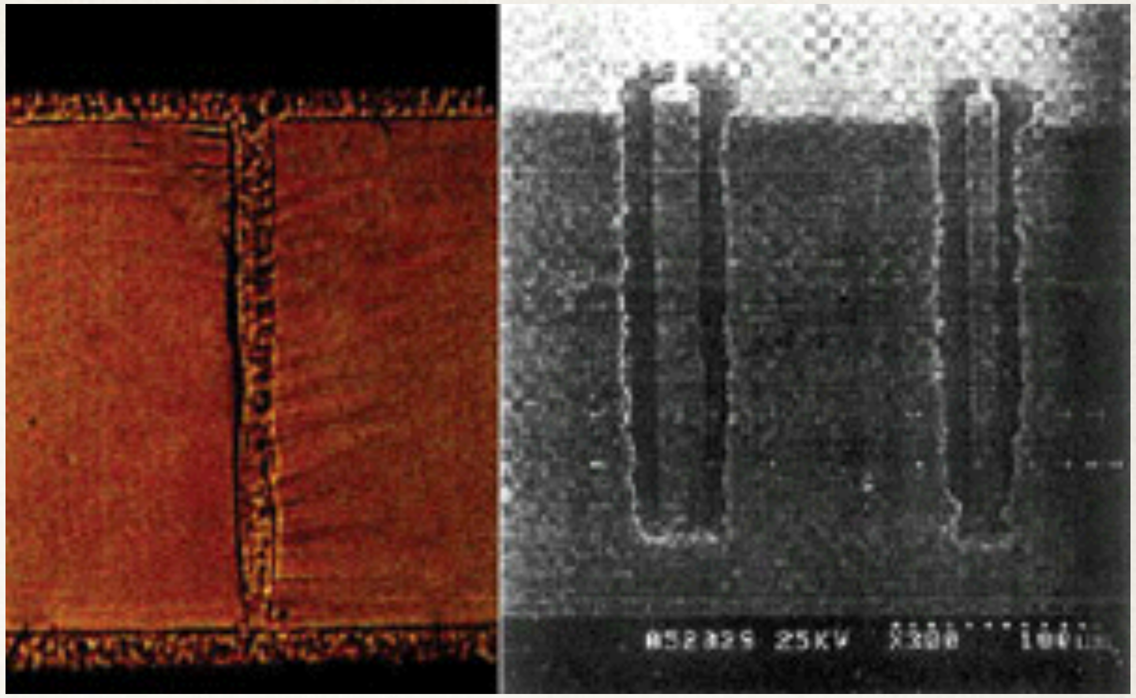
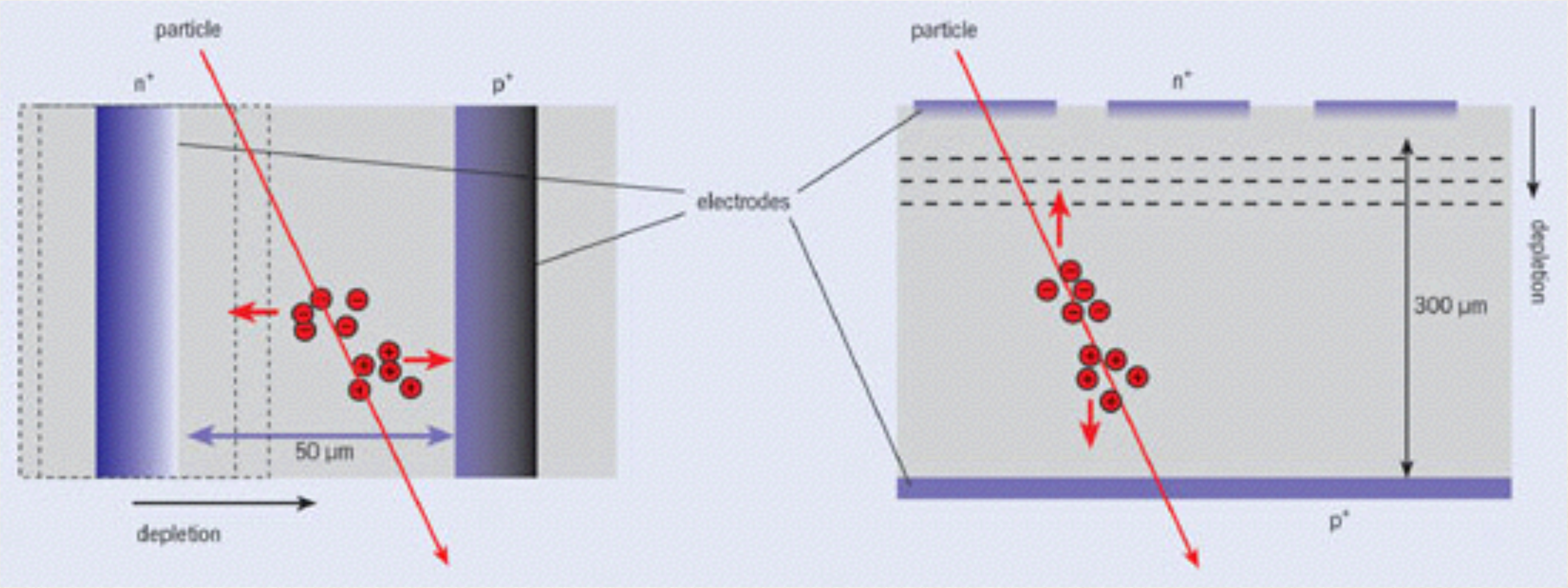
Detectores de semicondutor 3D





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