Few fundamentals on detectors for X and γ rays

What is the task of a detector?

it converts the energy releases by a photon in the material of the detector in an electric signal.

The electric signal is processed by a suitable electronics for the purpose to determine the energy of the photon, the interaction point (to the determine the origin of the emission) and, if required, the time instant in which the interaction has taken place. **TIMING** => This is important for PET! It's based on timing! (not for the others)

Detector: 1) has to **stop the radiation**. That's why we have seen interaction with matter of rays. 2) **convert** energy **to electrical signal**. So the signal is then processed. Final information: energy of the photon (nuclear medicine), (not actually true for radiography you integrate xrays whatever the energy).

*E' L'ENERGIA CHE VARIA CON L'ASSORBIMENTO, comunque riuscendo a misurare l'energia, di fatto fai una spettrografia, nel senso che finisci DI FATTO a contare/integrare nel tempo, cioè hai una valutazione anche dell'intensità

2 CLASS OF DETECTORS

Detectors with direct conversion:

the energy of the photon is converted in a given quantity of electric charge directly on the detector material. This charge is collected at an output electrode of the detector.

--> they may be NOT very efficient to stop the radiation!!! <--
a det. NEEDS to be efficient in STOPPING the radiation!! (e.g. Si: problem, not efficient stop)

Detectors with indirect conversion:

the energy of the photon is converted in another physical quantity (e.g. visible photons) and a secondary detector (a photodetector, in the example) is necessary to convert the second physical quantity in an electrical signal.

We split the problem into 2 step, we choose a nice material like scintillator to privilege stopping power :). We can grow as big as we like without worring. They are passive. Very nice stopping power. Then served by a PHOTODETECTOR.

advantage: the material for the conversion of X/γ can be chosen different from the material which creates the electric signal

disadvantage: the cascade of two processes, instead of one, worsens the resolution on the overall conversion

Absorb energy => release el. charge. Can be done in 2 ways.
1) Energy to directly electrical charge, then the charge is trasfered to an output electrode of the det. This is very challenging, in med. imaging is not the most common case.

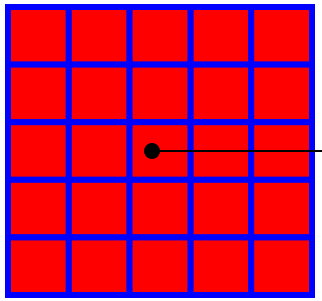
2) 2 STEP DETECTOR (most common). First step: conversion in another physical quantity which is not charge, then this second to el signal. e.g.: **SCINTILLATORS**: tipically crystals, the grays interact with the mat. and produces a 'cloud' of optical photons, which are then converted. Another eg.: thermal detector (en->heat)

2 type of detector

Imaging detectors

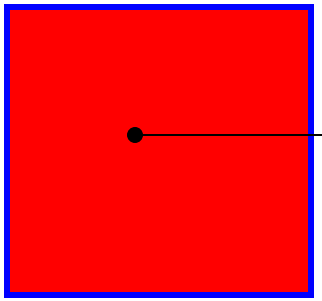
like phonecamera

pixel detector



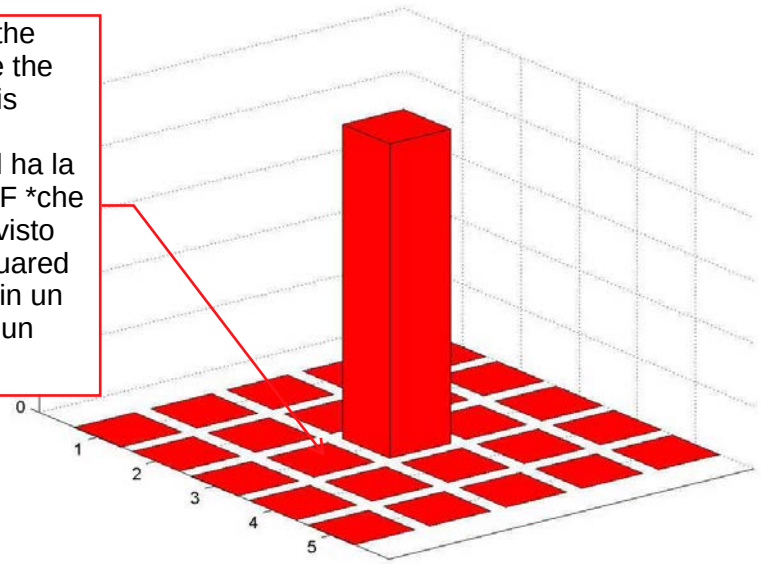
the resolution in the image is given by the dimensions of the pixel

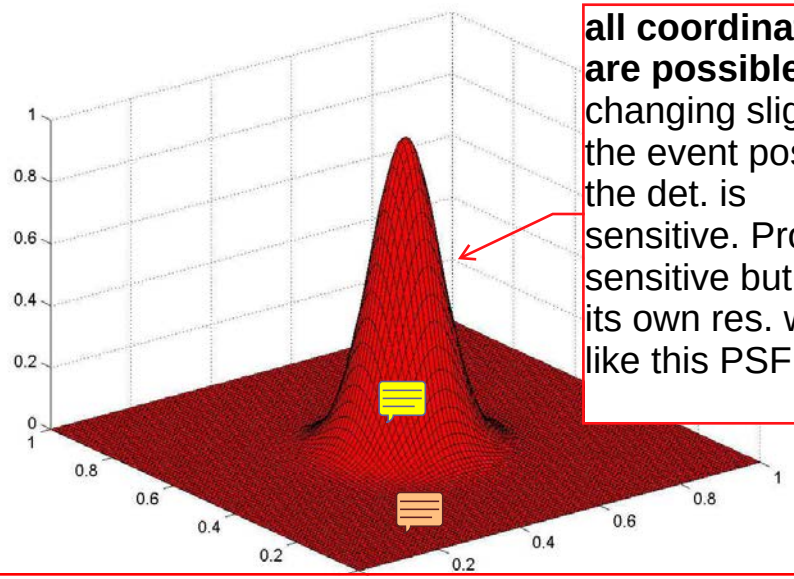
‘continuous’ detector



the coord. x,y of the determined point changes with continuity (e.g. with a Gaussian shape)

changing the coordinate the response is identical
*ogni pixel ha la stessa PSF *che avevamo visto essere squared *se arriva in un pixel crea un segnale lì!

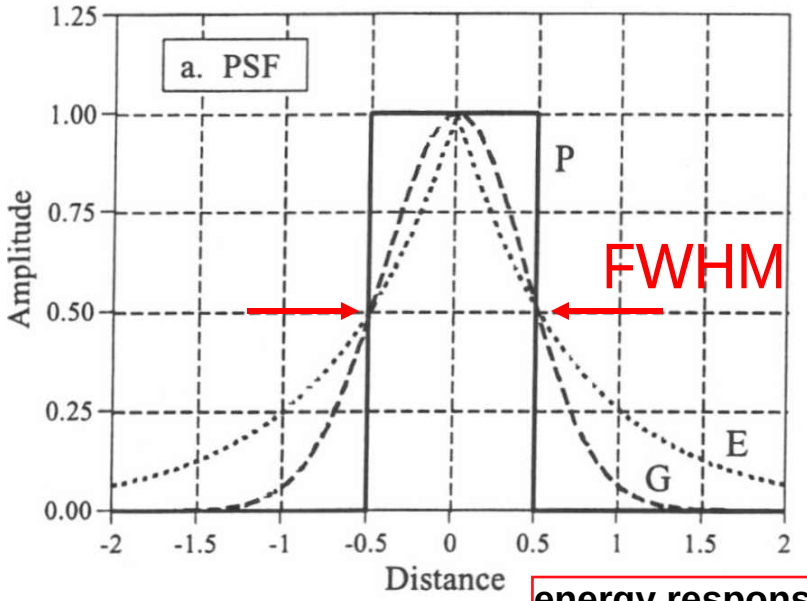




all coordinates are possible, changing slightly the event position the det. is sensitive. Problem: sensitive but with its own res. with like this PSF

coordinate del pixel detector:
sempre nel pixel
coordinate del continous: seguono una **probabilità,** dato un delta impulso arrivante in una posizione

Spatial resolution:
precision to determine the position of interaction



Energy resolution:
precision to determine the photon energy

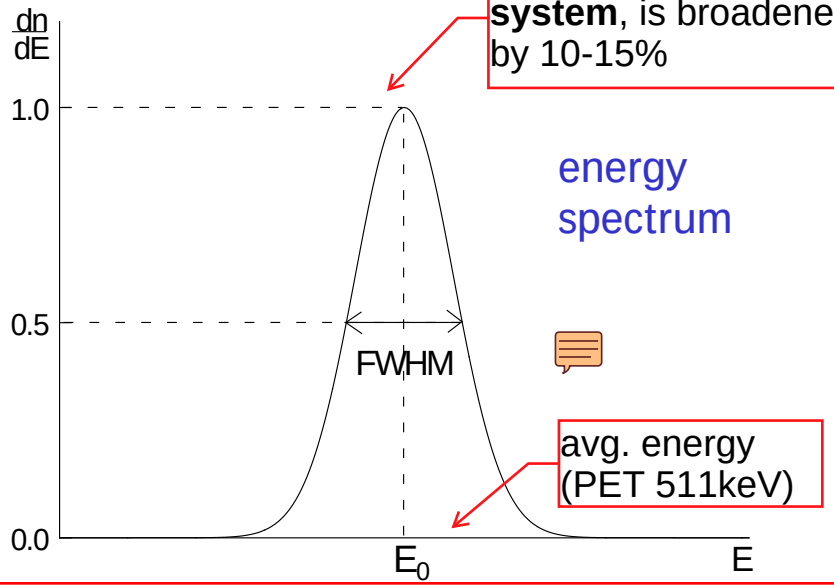
fitted like a guassian

$$G(E) = \frac{N_0}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right)$$

given usually in %

$$\mathrm{FWHM} = 2.35\,\sigma$$

$$R = \Delta E_{FWHM}/E_0$$



energy response of the system, is broadened by 10-15%

energy spectrum

avg. energy (PET 511keV)

Not only where, but also the reconstruct energy, important for scatter rejection. We want to know if the energy we are collecting is E0, indeed if we have compton it means we have a wrong coordinate. So we look at the energy (b/c compton changes it) and we reject the g-ray. Problem: eg. is 470 a bad measurmenet according to my res, or due to scattering? en. res. influences the capability of rejecting, because the broad it is we simply dont know

DETECTION => CAPABILITY TO STOP THE RAY, IT'S IMPORTANT! (not only generating photons)

Detection efficiency

for a given source activity (photon flux), how many (valid) events are generated in the detector?

Detection efficiency = number of detected events/number of events generated by the source [0-1]

3 contributions

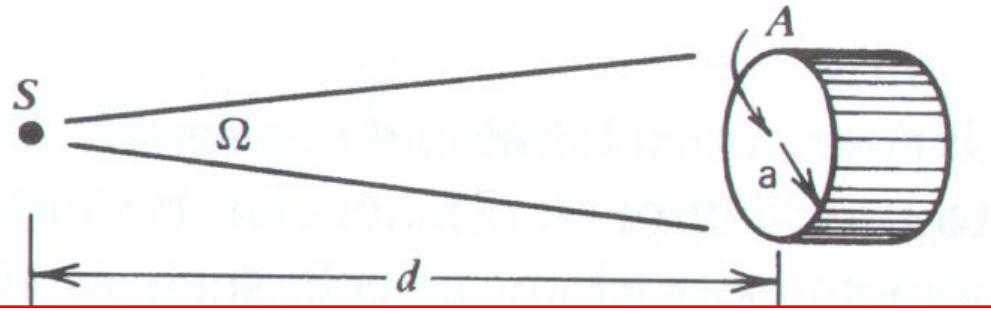
Detection efficiency =
Geometrical efficiency (**intersect**) × Absorption efficiency (**stop**) × 'Photopeak' efficiency (**delivery**)

Geometrical efficiency:

Geometrical coverage: ratio b/w solid angle & 4pi (overall solid angle).
Sphere => g.e. = 1 [è normalizzato]

fraction of photons emitted by the source that enters in the detector

most important contrib.



$\eta_G = \Omega/4\pi$

as large and close as possible

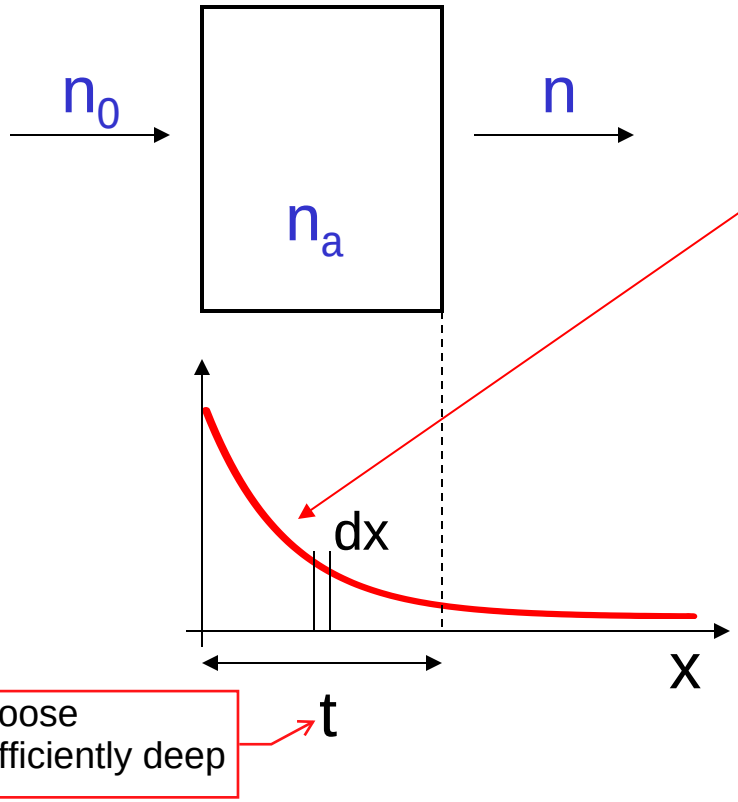
Ω: solid angle under which the detector intercepts the photons = A/d^2

Valid! (eg. no compton, that wont contribute to efficiency).
1) the detector has to **INTERSECT** the gamma-r. geometrical coverage.
2) Absorption: given that it has intersected geometrically, how many are **stopped** by the detect? (eg. paper wont stop them).
3) are the one stopped **delivering** full energy? instead of releasing total en. in the sensor, part is escaping

given the photons entered into the surface A, are they **stopped?** => **thickness+mat. type**

Absorption efficiency:

fraction of the photons entering the detector which is actually absorbed



choose sufficiently deep

probability a photon is stopped

$$p(x)dx = \mu \exp(-\mu x)dx$$

probability that a photon entering into the detector is absorbed in the thickness dx at x

$\Rightarrow$ probability that a photon entering into the detector is absorbed in the thickness t:

$$\int_0^t p(x)\,dx = 1 - \exp(-\mu t) = \eta_{abs.}$$

as seen, number of photons passing thorugh

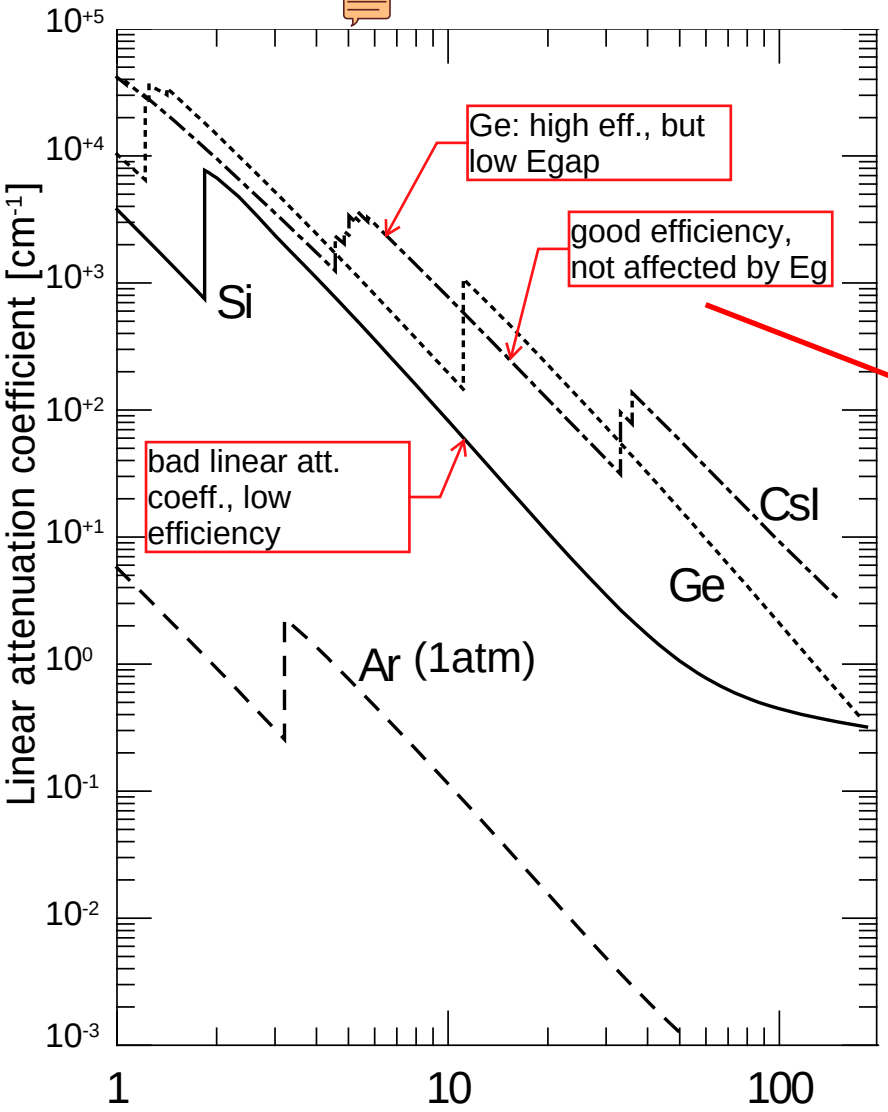
"entering" photons

choose material with larger Z

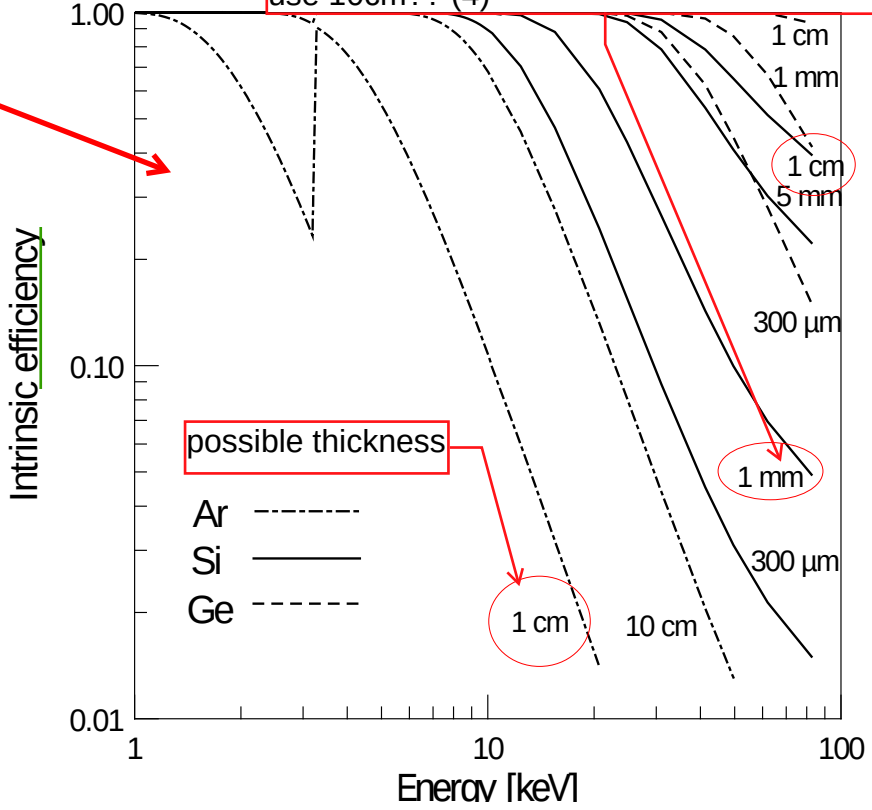
IN MEDICAL THIS IS CLOSE TO 80% OR 90%! We have to tune this to reach at least 80%, it's unacceptable to give activity to the patient and then simply transimt photons away from the det.

Come scegliere lo stopping material

linear attenuation coefficient (μ) for different materials used for detectors



1mm of Si is efficient up to 10keV. Then it stops to be eff. anyway increasing the thickness like 1cm you get to 100keV, so for mammography it can be used.. why dont we use 10cm?? (4)



$\eta_{abs.}$ for different thickness

Gasses are bad. adv: we can make it very thick. **Si** is not efficient mat (it's nice b/c it's a direct conversion). **Germanium**: direct conv. and efficient in linear att. PROBLEM: SMALL ENERGY GAP! the step may be done by charges just due to **thermal energy**. elctrons in valance band may have sufficient energy to jump over the EnGap to Conduction band.. they just mix up with the signal electrons generated by electrons!! :(bad! measured by putting it in dark.. but we'd subtract an avarage! we have a variation on top of the noise. EnGap in semiconductor to use in medical images is a KEY number. The larger the more likely we can use it in room temp.

DELIVERY OF ENERGY *histogramma dell'energia ricevuta dal detector, picco a E0

'Photopeak' Efficiency

• fraction of photons that have interact in the detector and that have released completely their energy (and therefore provide a peak in the energy spectrum in correspondence of the energy of the incoming photon)

• photons absorbed by photoelectric effect release completely their energy in the detector (with the exception of those interactions in which the fluorescence photon of the material escapes from the detector: *escape* peak)

most probable in PET w/t 511keV

• the interactions occurring by Compton effect imply a partial absorption of the energy of the primary photon in case the secondary photon leaves the detector without further interactions

*invece che secondary.. lo puoi pensare come l'originale rallentato. Se alla fine viene assorbito è ok, se riesce a fuggire è una riduzione della efficiency

⇒ to increase the efficiency it is necessary to size suitably the detector in order to maximize the probability that also the Compton photon is also absorbed in the material by photoelectric effect or by a second Compton interaction (note: Compton photons always have less energy than the primary photon)

Photopeak: when a g-ray interacts with a det. material, wich is now granted by the "previous" 2 efficiencies; if gamma-ray has an energy E0, is desirable that the full en. E0 is deposited into the material. ITS NOT GRANTED THAT IF YOU HAVE AN INTERACTION WITH THE MATERIAL THE FULL ENERGY IS RELEASED IN THE MATERIAL: photoelectric effect, compton effect.. etc. One thing is interaction, another is release of the fullenergy. Name comes from: if the total en. is released and you make an histogram of the en we have a peak on E0 broadened by the en. res. of the detector.

...provided that the det. has absorbed en E0 (cascade of 3 steps) => how much charge is created? (output electrode)

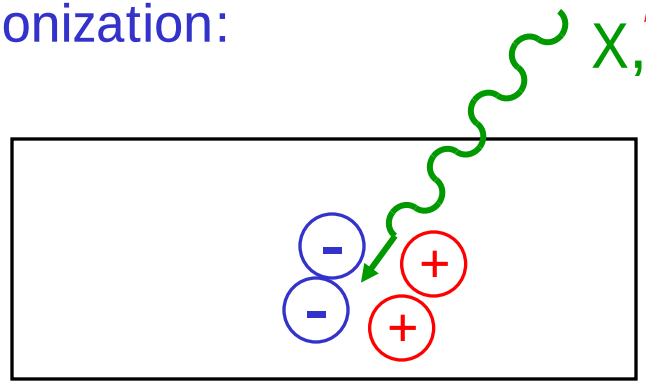
Conversion *energy → electrical charge*

CASO: DIRECT CONVERSRION

for a given energy released by a detected photon, how much charge is created in the detector?

mechanism of generation of carriers by ionization:

se non fosse direct allora sarebbe un fotone visibile



- electrons

+ ions (in gas)
holes (semiconductors)

Following the photon absorption in the material by one of the possible mechanisms (photoelectric, Compton, e-/e+ generation), the energy absorbed by the material causes the creation of electron-ion (hole) pairs. The creation of couples is related to a chain mechanism of further ionizations started by the first electron to which the energy has been released. The ionizations are due also to the re-absorption of possible fluorescence or Compton photons.

Direct conv. det.: energy released by g-rays create ions(gas) or el-holes pairs. NOT LISTED INDIRECT CONV. DET.
For one gamma-ray we dont have the creation of one el/hole pair for eg., but a generation of multiple cloud of charges. This is possible b/c the initial electron ejected in photoelectric-effect, it's very energetic[en gamma ray is not all absorbed for the ejection, but the surplus is transfered to the electron *Ekinetic] and it goes around the cristal creating multiple couples of el/holes.

".. it's always better to have a larger signal" b/c when we have a signal there's always an intrinsic fluctuation :) [AUDIOOOO] [S/N => sigma= sqrt(N) => n/sqrt(n)] **spiegazione:** signal dictated by poisson statistics => the fluctuation of the signal is sqrt(N), so if I calculate SNR = N / sqrt(N). So it's ALWAYS better to have a laerge signal!!! (*N è la media?)

The generated charge si proportional to the photon energy:

$$Q = qE/\varepsilon$$

conv. factor, we want it smaller

energy E

(q: e- charge)

the conversion factor ε is with good approx. independent from the energy and from the mechanism which has provided the absorption
(generated charge amount proportional only to the energy released to the electrons responsible for the ionization)

the conversion factor ε determines the sensitivity of the detector and depends strongly on the type of material used

physically speaking: the cost the conversion to generate an el/hole pair. [NOT RELATED TO EN TO PASS FROM V->C, IT'S MUCH MORE COMPLEX AND FIGURE OF MERIT OF MANY THINGS!!]

few examples:

Argon	$\varepsilon \sim 26$ eV for e-/ion pair
Silicon	$\varepsilon \sim 3.6$ eV for e-/h pair
Se-amorphous	$\varepsilon \sim 20$ eV for e-/h pair
CsI+PMT	$\varepsilon \sim 25$ eV for e-/h pair (scintillator+photodiode: indirect conversion)

small in semiconductor, b/c the eg is small

bad in terms of signal gen :(large en. cost

IMPORTANT: **independently that the energy released in material has been released by compton/photoel/pair, they count the same. Epsilon is not depneding from these, is just depeding on the material.** Once the en. released in the material, we dont pay attention anymore about the mechanism that has released it, and we have a production of charge according to this factor.

Few notes on detector materials:

detto prima:

• Silicon is an optimum material but is efficient only up to 10 –30 keV because of limited thickness that can be depleted in practice

• Germanium has a worse technology and has to be cooled to reduce the dark current

• gas detectors are intrinsecally low efficient but they can be still used for X rays because they can be fabricated of large dimensions (even few tens of cm)

• scintillator materials, like CsI (see later), are not able to create charge by ionization but they are also used (indirect conversion) thanks to their optimal efficiency

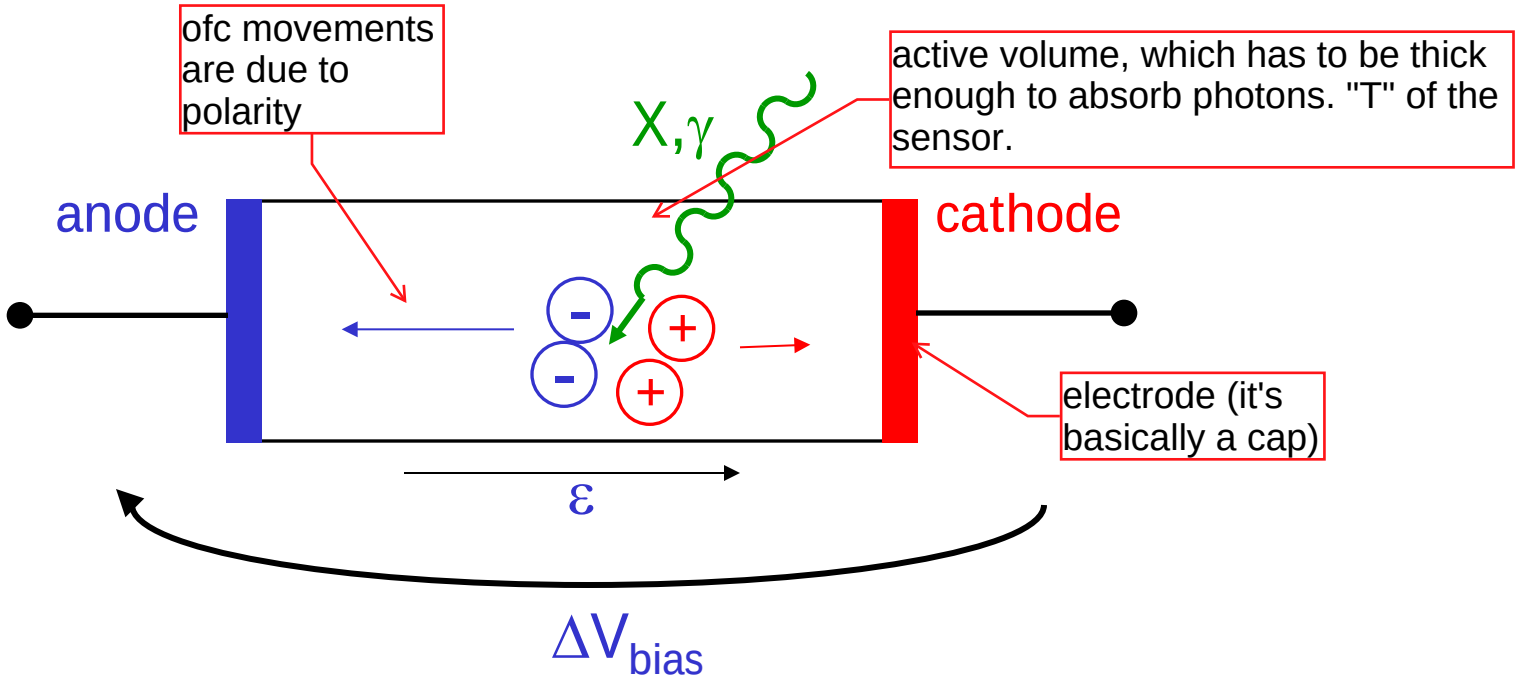
this was not told yet:

• there are semiconductor materials with high Z more efficient than Si (CdTe, HgI_2, ...) but with problems of charge trapping. Moreover, the fabrication technology is still in the development phase

problem: a lot of impurities => trapping effect

ONLY FOR DIRECT

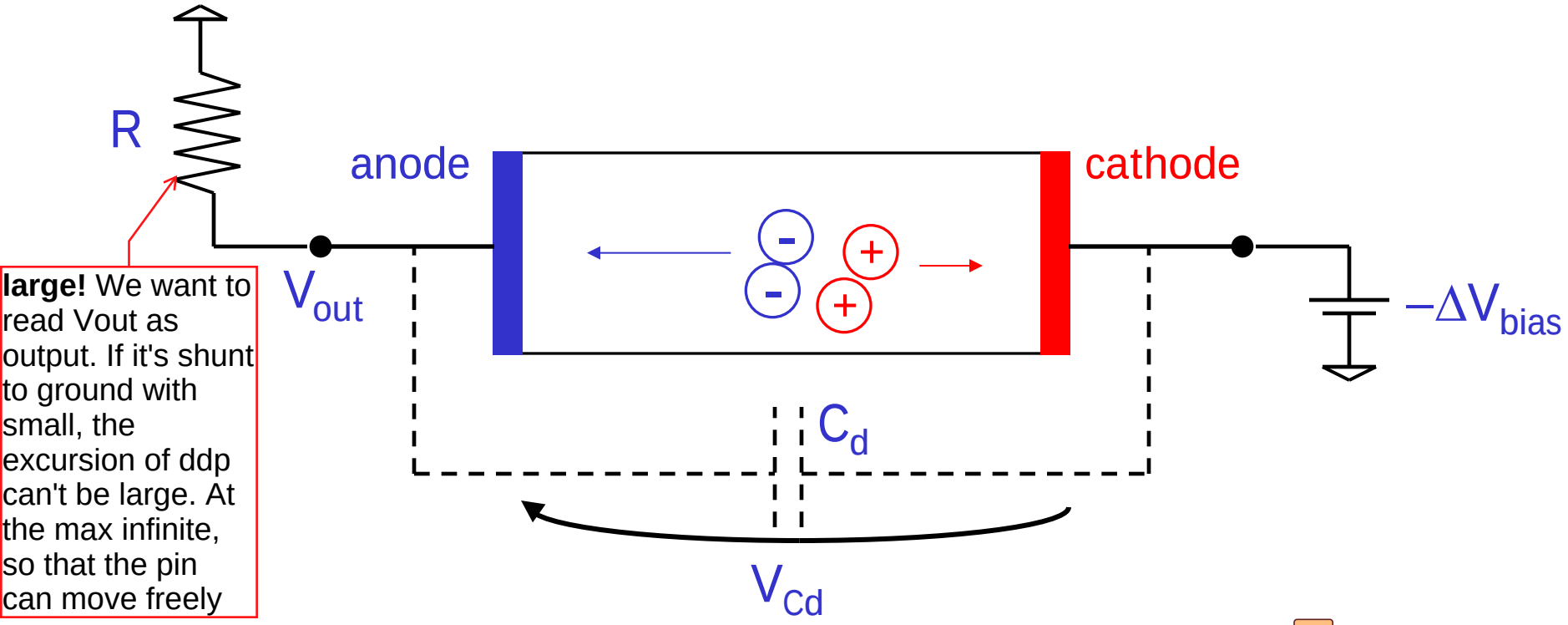
Principle of a basic ionizing detector



the electric field ε generated by the application of the potential difference is responsible for the separation of the e- from the positive charges (ions or holes) and it makes the e- drift toward the anode and the positive charges toward the cathode

IONIZING det: the en. of photon is absorbed, and we have creation of couples of pos/neg charges. problem: they have to be separed and collected. Principle: not only material that creates charges pairs, but apply an elect. field which causes separation of charges. The charge separate -> induce signal in the two electrodes. At the end we have add a potential difference across the two plates. This is valid for many material. It can be a gas for example. **Gas** container + electrodes. In case of gas the positive charges are IONS (neg is electrons). **Semiconductor:** pn junction (reversly biased), positive charges: holes, volume must be depleted by mobile charges.

HOW TO READ THE SIGNAL



large! We want to read Vout as output. If it's shunt to ground with small, the excursion of ddp can't be large. At the max infinite, so that the pin can move freely

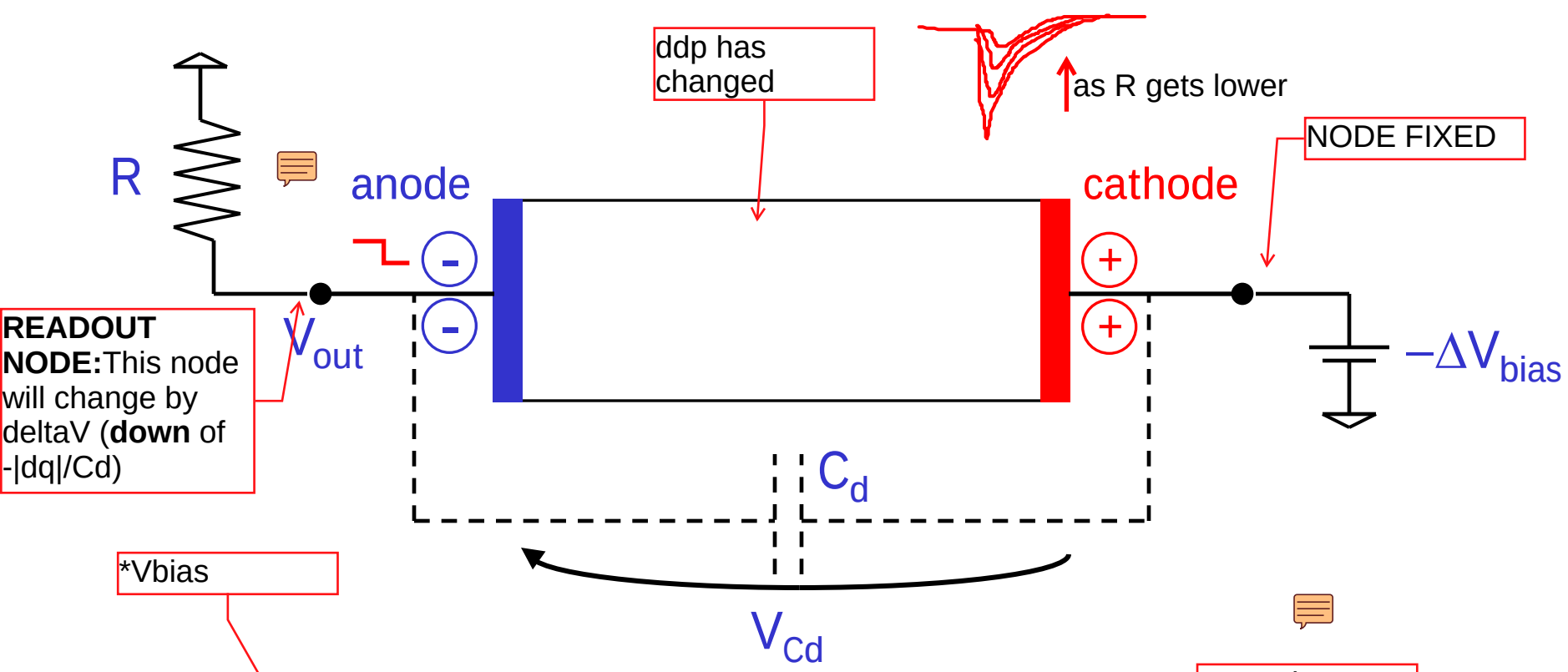
hypothesis: 1) R very large (at the limit ∞)

2) transient of charge of Cd to ΔV_{bias} ended $\Rightarrow V_{out}=0$

$\Rightarrow$ the charge induced on the electrodes by the motion of the charges acts to modify the voltage across C_d. V_{Cd} (initially equal to ΔV_{bias}) decreases and V_{out} becomes negative

(one supposes that the charge induced on the anode does not discharge to ground by means of R)

network RC classico, con C che inizia a caricarsi se all'inizio è scarico, con flowing di current su R. Una volta che è carico a deltaVbias, Vout = 0V. (serie di R, C, batteria). e la corrente diventa 0. [il componente è considerato C]. quindi l'inizio è un transiente di un RC. Questo Vbias è il nostro electric field che volevamo per separare le charges.



when the charges have reached the electrodes:

extra charge

(as the charge $-\Delta Q$ has modified the total amount of charge present on the electrodes of C_d)

$$V_{Cd} = V_{Cd\ initial} + \Delta V_{Cd} \qquad \Delta V_{Cd} = -|\Delta Q|/C_d$$

$$\Delta V_{out} = \Delta V_{Cd} = -|\Delta Q|/C_d$$

like to have small both.

$$|\Delta Q| = qE/\varepsilon \longrightarrow \Rightarrow \Delta V_{out} = -qE/(C_d\varepsilon)$$

We have an EXTRA voltage across the capacitor! contribution. "extra" deltaV. drawn with the same sign as bias voltage, ofc it's negative. by the eq of cap we obtain the extraV. I connect Vout to an non inverting amplifier, for example (we need high impedance!!). if R is very large, the charge accomulated, we have a step and nothing happens. Otherwise, if R is low, the charge accomulated will flow in R.

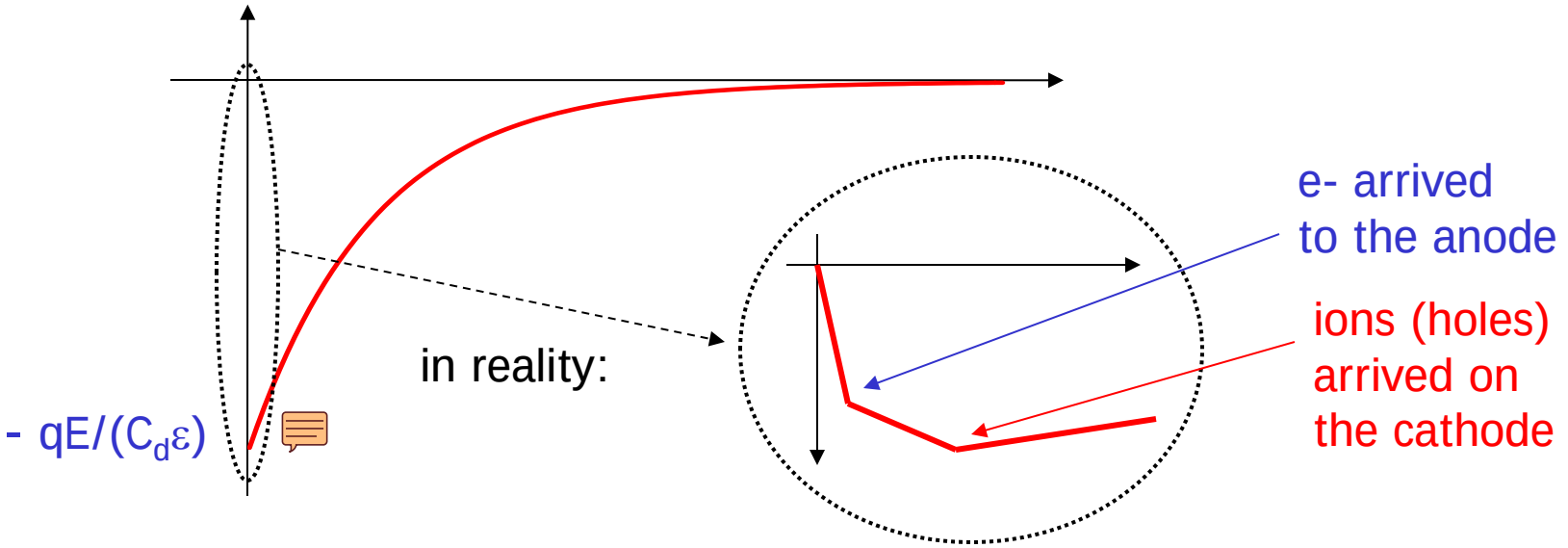
Effect of R: discharging C

R discharge the charge accumulated on the capacitance and restores V_{out} to 0

lo step di prima

con solita decadenza

$$\Delta V_{out}(t) = - qE/(C_d\varepsilon) \exp(-t/\tau) \qquad \tau = RC_d$$



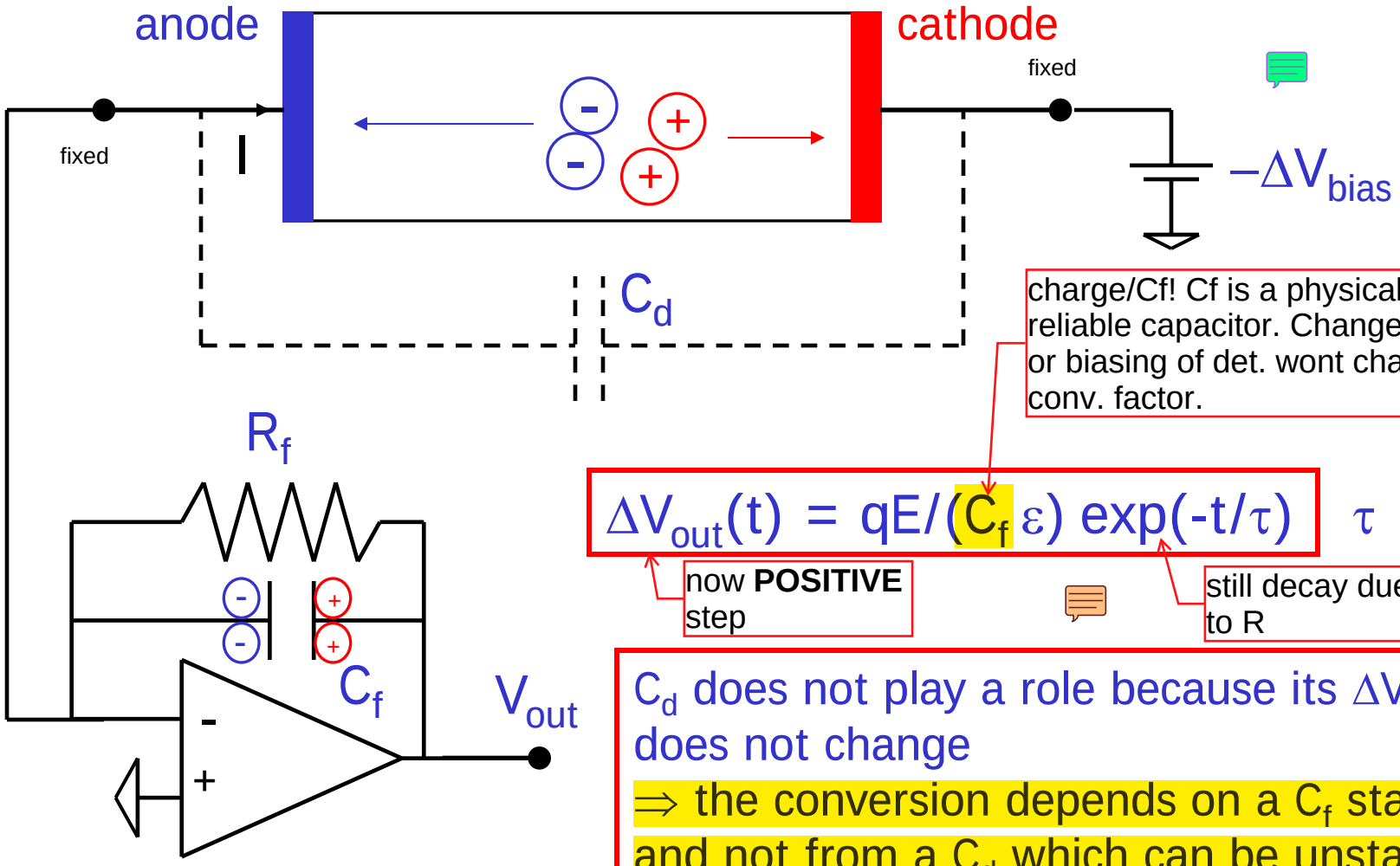
- the discharge is needed to restore the detector to the equilibrium conditions, ready to receive a new pulse

- further amplification and filtering of the signal has to use the signal front where the amplitude is the highest

R large: the larger the larger the step. **DRAWBACKS**: **pileup of pulses**:**The events arrives randomly distributed in time (characteristics of g/xrays)** distributed with poisson statistics. If we have a pulse, and a very large R, the tail of the amplitude of one pulse is "sitting" on the tail of a previous pulse.with a digitalizer we can subtract knowning a priory the shape (described indeed by the formula) and recontstruct correctly; or use small R

Very Robust

Alternative configuration: the charge preamplifier



charge/Cf! Cf is a physical and reliable capacitor. Changes in temp or biasing of det. wont change the conv. factor.

$$\Delta V_{out}(t) = qE/(C_f \varepsilon) \exp(-t/\tau) \qquad \tau = R_f C_f$$

now **POSITIVE** step

still decay due to R

C_d does not play a role because its ΔV does not change

$\Rightarrow$ the conversion depends on a C_f stable and not from a C_d which can be unstable because of changes of Temp., ΔV_{bias}, ...

we dont integrate the charge across the det. itself, it's no more collected to R the anode, it's connected to virtual ground of an integrator. So now the ddp across Cd cannot change anymore. One is biased, the other to virtualGND. The signal is no more generated as variation of ddp, but the electrons do not change the anode voltage, they flow into the Cf!!(they cant go into -) THE CONVERSION IS MADE ON CF, TOTALLY FREE TO MOVE!