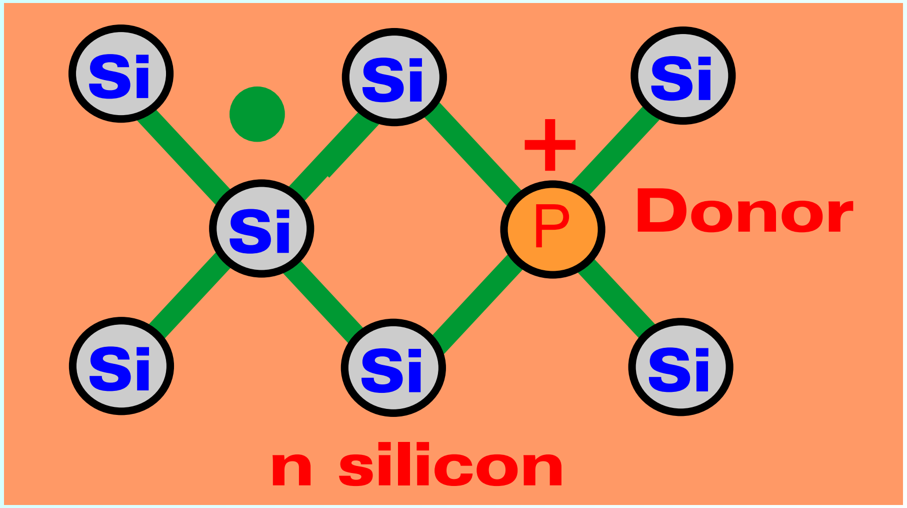
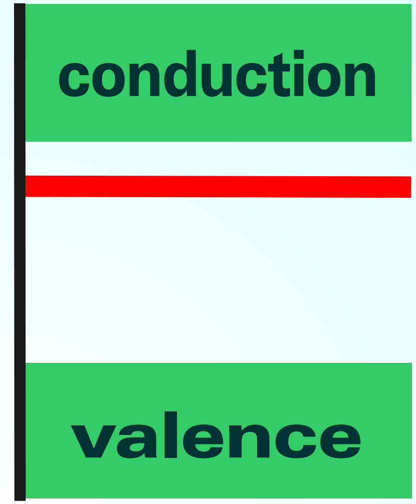
Germanium Detectors

- Germanium, a special material
- Detectors, big is beautiful
- Operational features
- Applications

The Material

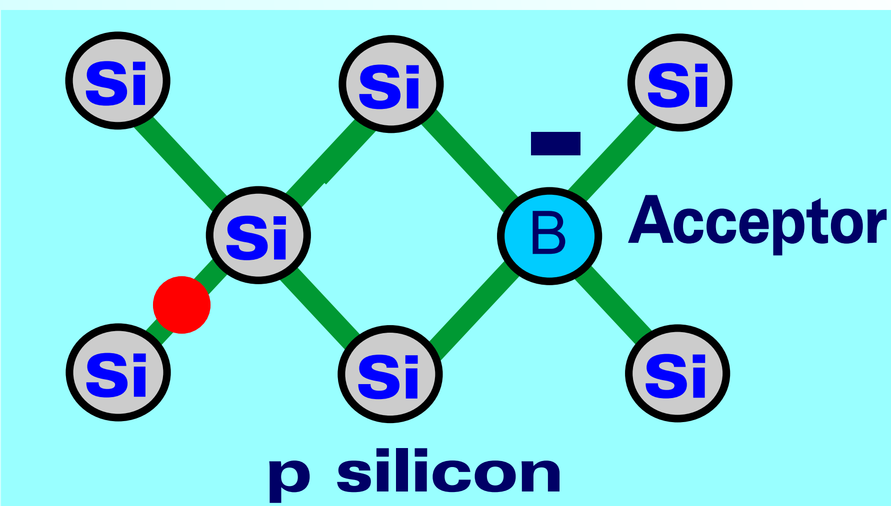


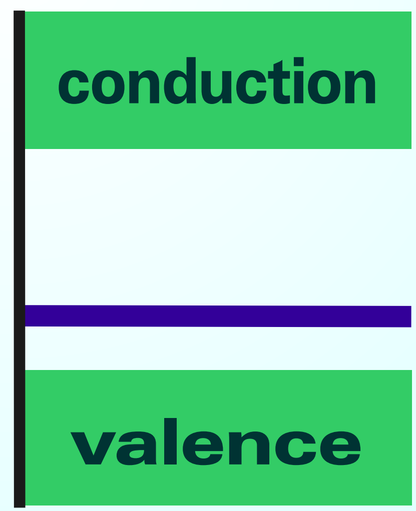


P → Li

Lithium is drifted, not implanted

Si → Ge





B → B

Boron is implanted

The Material

The properties of silicon and germanium are determined by the amount of impurities.

Silicon wafers with a certain resistivity are ordered, resulting in a particular full depletion voltage.

Germanium is not so well under control.
Crystal growing is done by very few people and it could be called alchemie of the 20th century.

Germanium crystals are incredibly pure!

The Material

	Silicon	Germanium
N/cm³	$5.0 \cdot 10^{22}$	$4.4 \cdot 10^{22}$
ε	11.9	16.0
bandgap	1.12	0.66
E/ e-h	3.62	2.85
e speed	3ns/100µm	1ns/100µm
h speed	8ns/100µm	2ns/100µm

$$\text{Full depletion voltage} = \frac{e N_D}{2\,\varepsilon} d^2$$

$N_D = 10^{12}$ d=300 µm : 66V

$N_D = 10^{10}$ d=300 µm : 0.5V

The Material

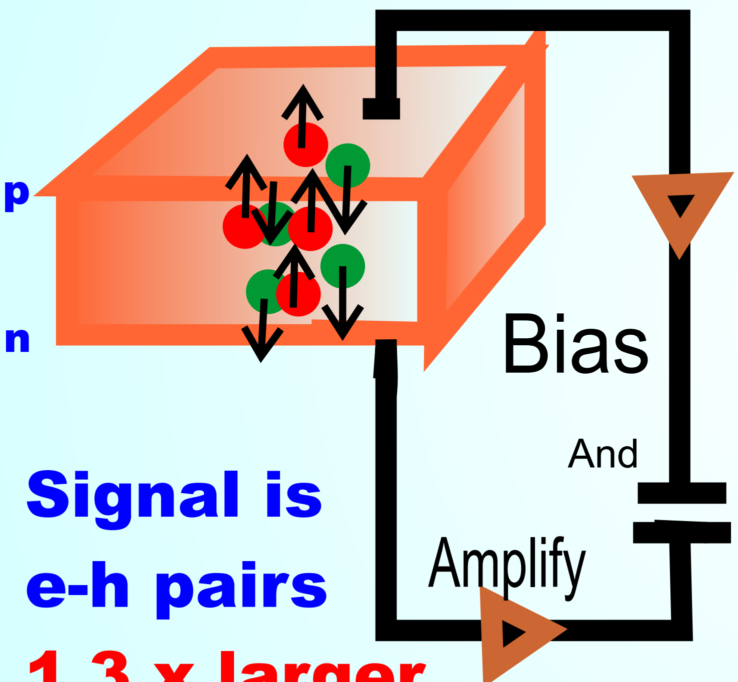
Electrically active impurities: 0.5 10^{10}/cm^3

compare to 4.4 10^{22} Ge/cm^3

13N material

Bias voltage
0.3V for a 300µm
standard wafer

Why don't we
use germanium
everywhere ?

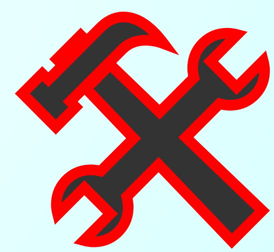


Signal is
e-h pairs
1.3 x larger
in Ge than in Si

Germanium Detectors

Germanium does not work at room temperature.

This makes integrating germanium detectors into anything cumbersome.

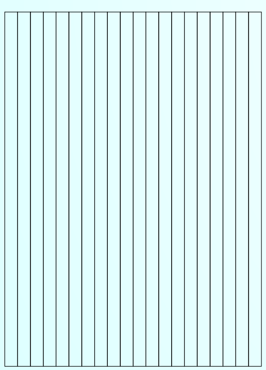


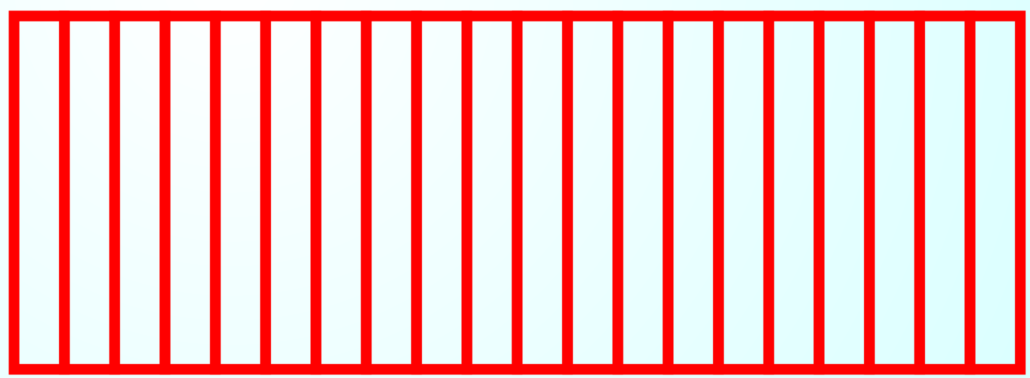
Germanium Detectors

Silicon is everywhere and germanium not.

Types p and n:

- **p-side: boron implants still work**
- **n-side: phosphor implants do not**
  - **lithium is drifted**





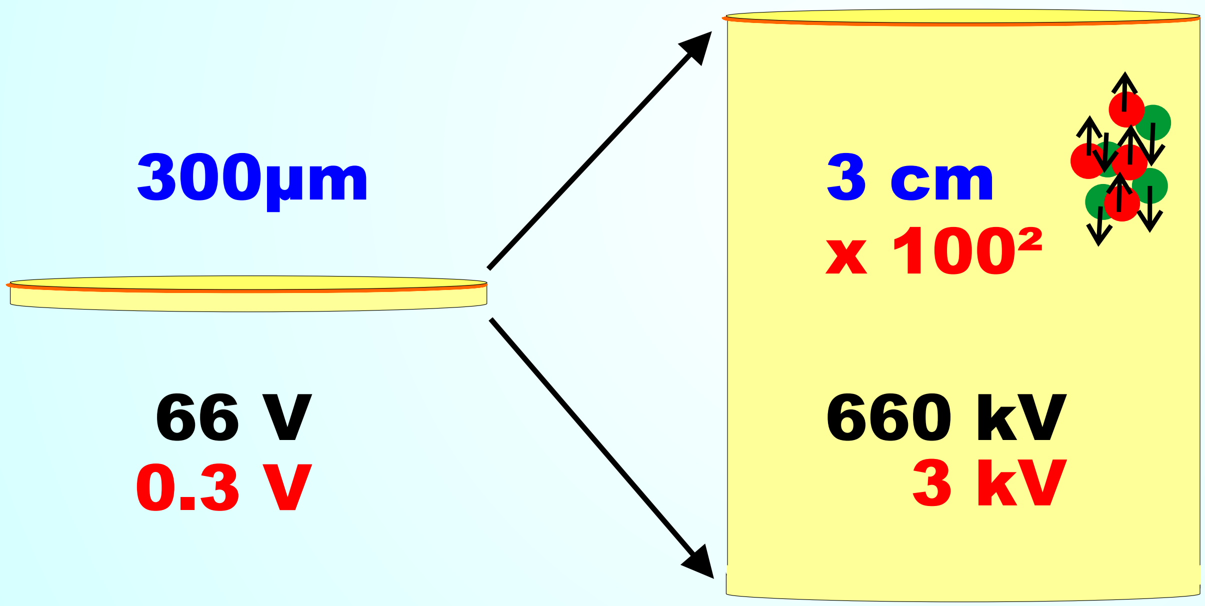
10 μm   **10 mm scale**

Segmentation is not so well developed.

Germanium Detectors

cannot compete with silicon vertex detectors.

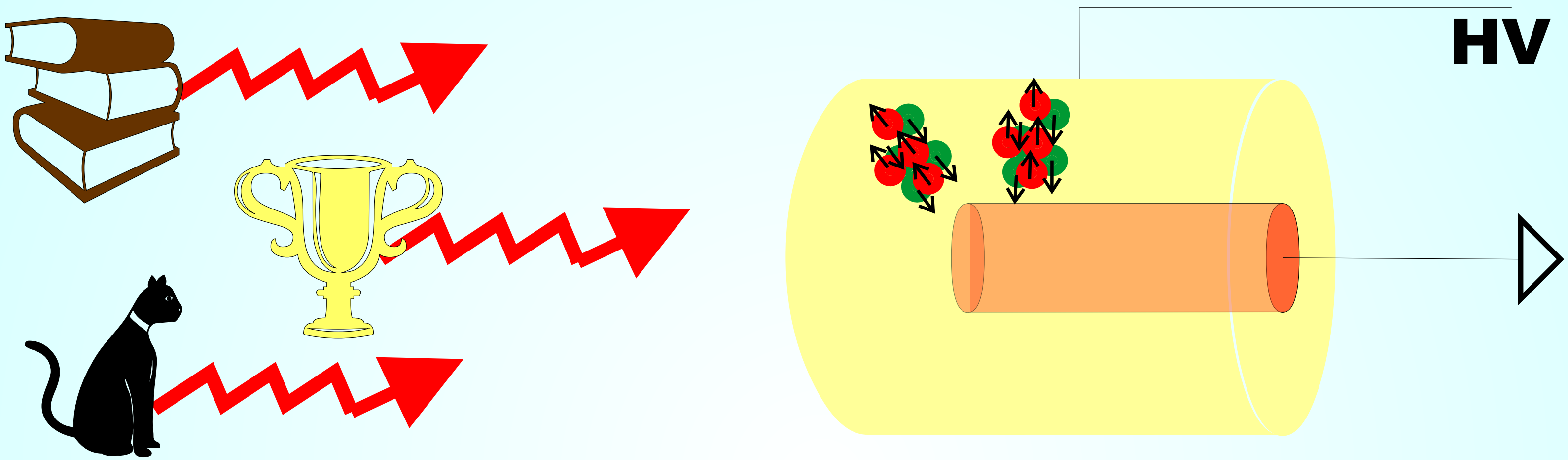
But we can make them big.



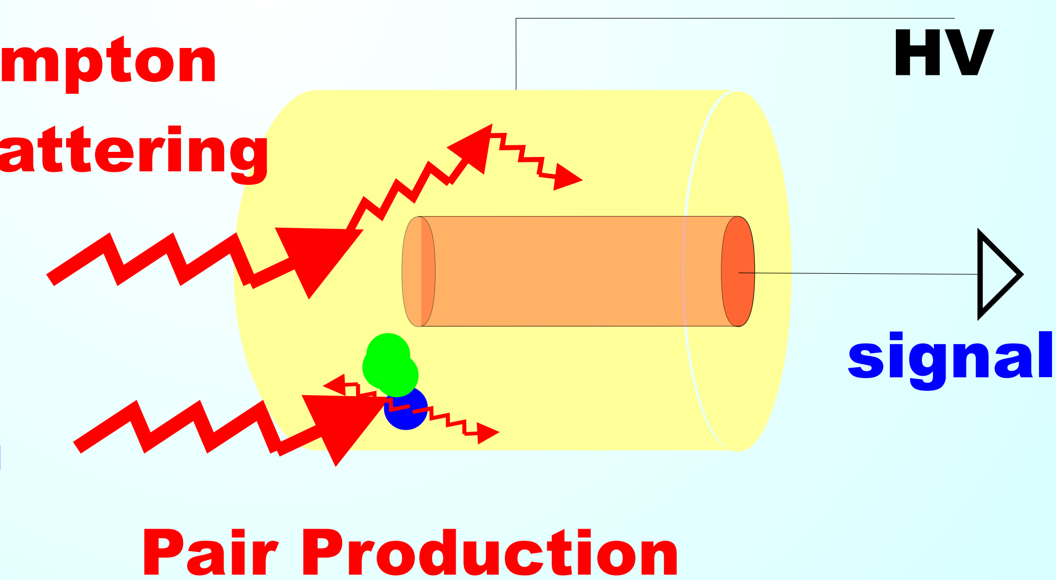
This is not what is most commonly done.

Big detectors are good for spectroscopy.

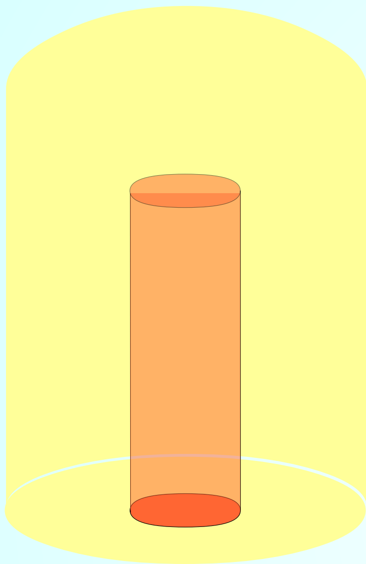
Germanium Detectors



See all the energy with high resolution



Standard Detectors

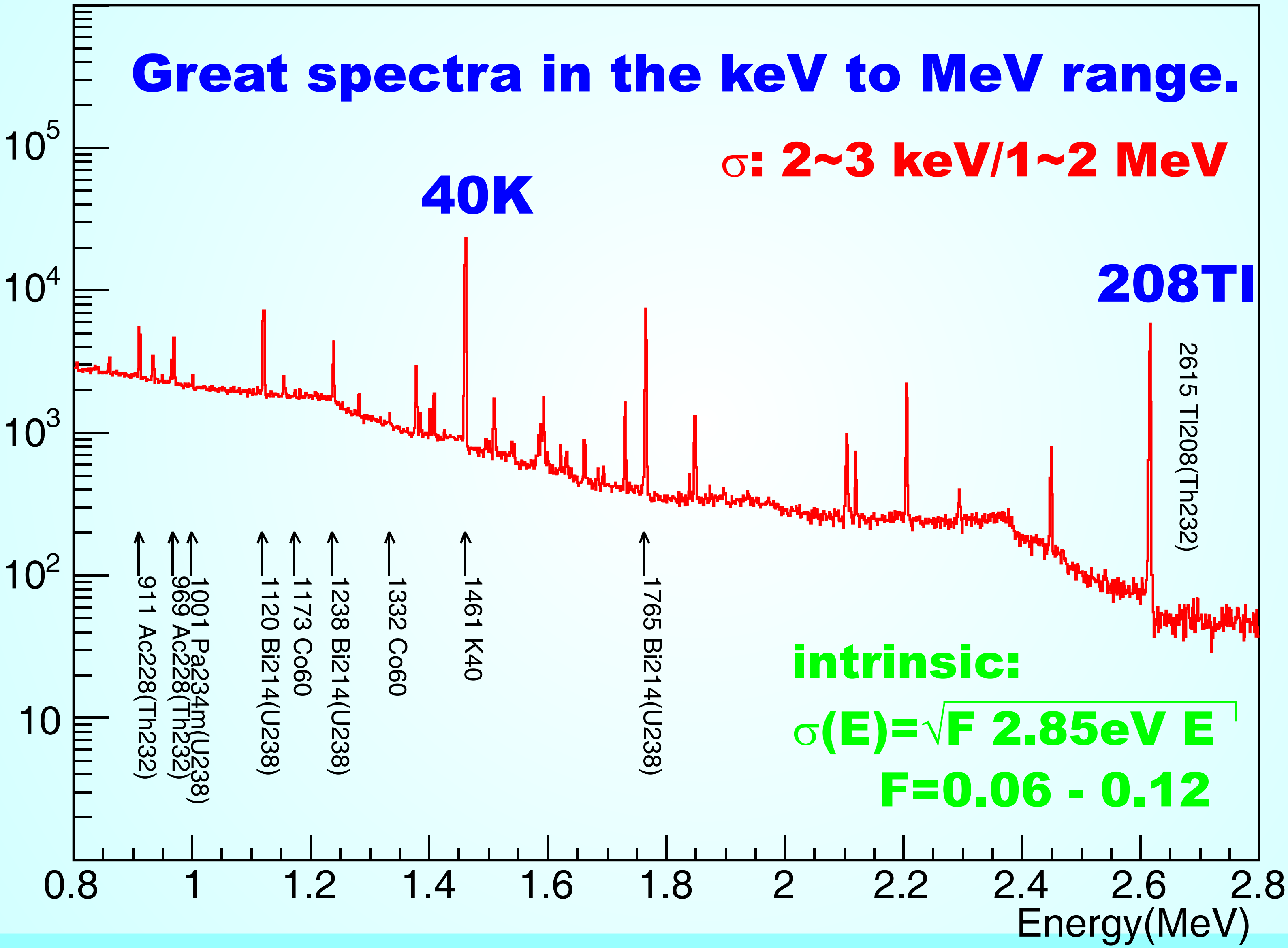


Cap
geometry
and
cryostat

Standard
n-type
germanium
detector
6 cm diameter
6 cm long

Mikesch
has a
special
vessel.

Germanium Detectors



Energy Resolution

Intrinsic, i.e. from charge carrier creation:

Naive expectation: σ^2 = #e-h pairs

But it is much better!

$$\sigma(E)=\sqrt{F\ 2.85\text{eV}\ E}$$

F=0.06 - 0.12

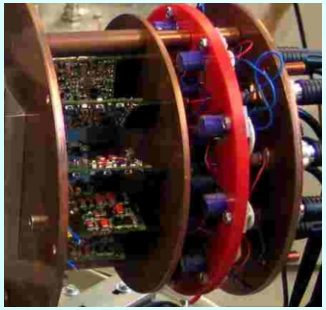
Fano factor

Charge carrier creation is not purely stochastical.

Reality

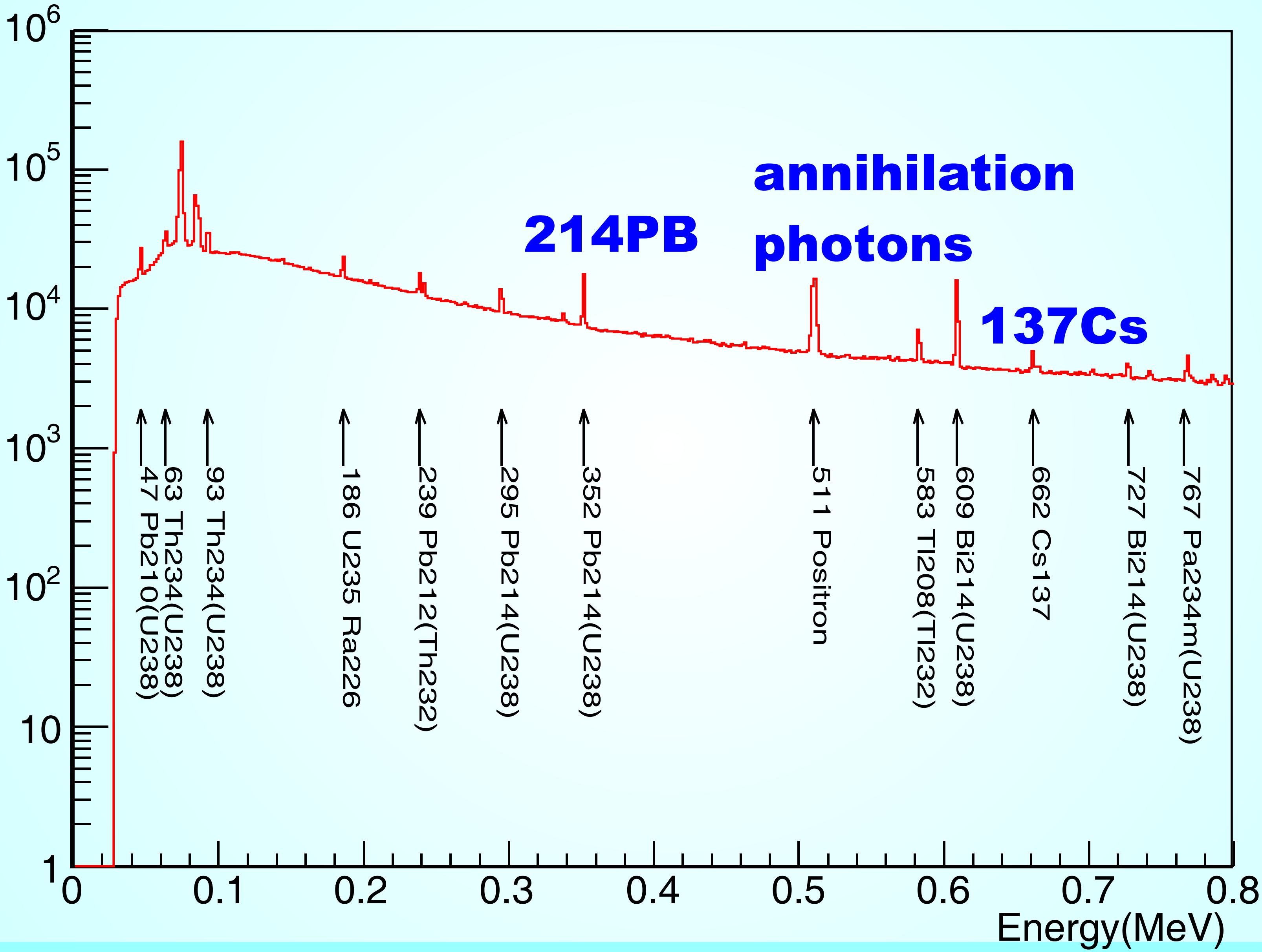
$$\sigma^2 = \alpha\ C^2_{in} / T_r + \beta\ I\ T_r + \delta\ C^2_{in}$$

white noise — **1/F**

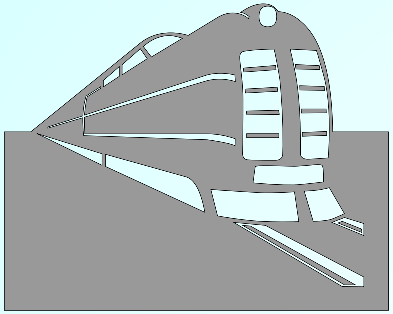


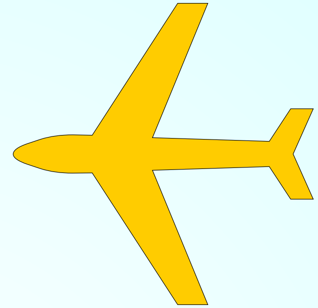
Electronics is what determines resolution!

Germanium Detectors



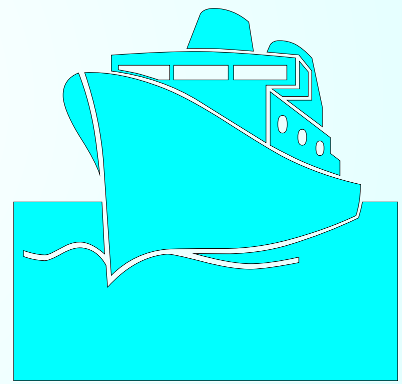
Applications

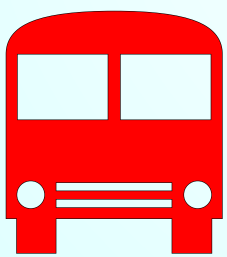




Homeland Security

Germanium Detectors against terrorism

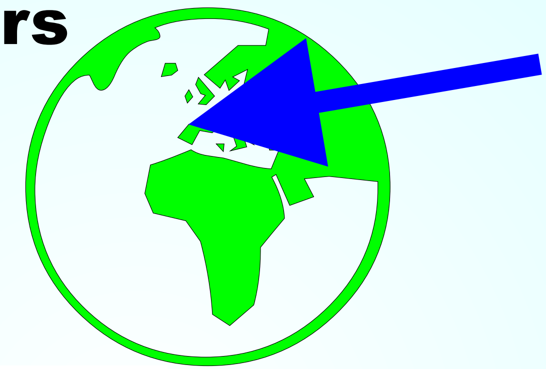


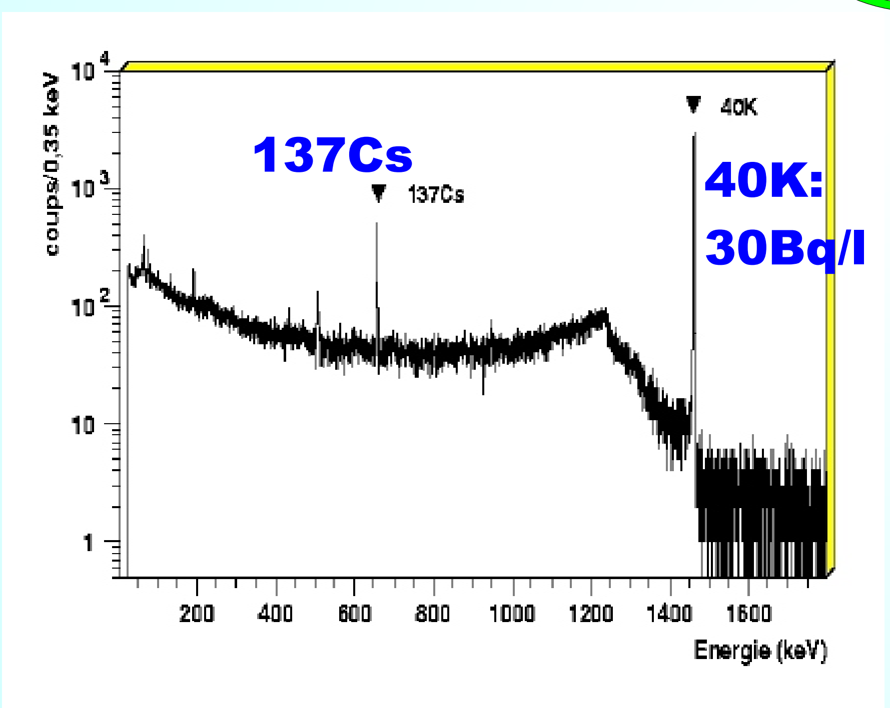


Should somebody tell them about lead shielding?

Applications

Germanium detectors against wine swindles



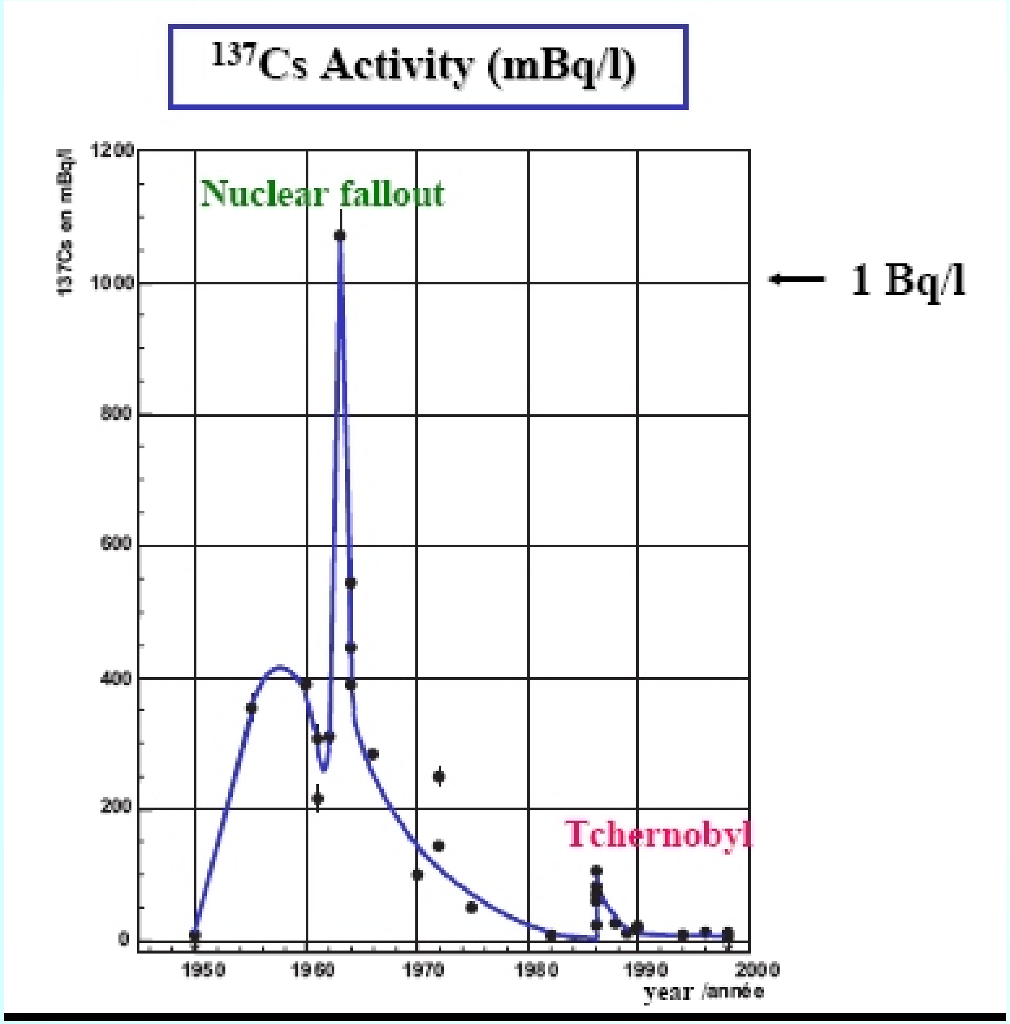


137 Cs is man-made

29 authentic wines as reference

If a wine is pre-nuclear-testing, there is no 137Cs.

Applications



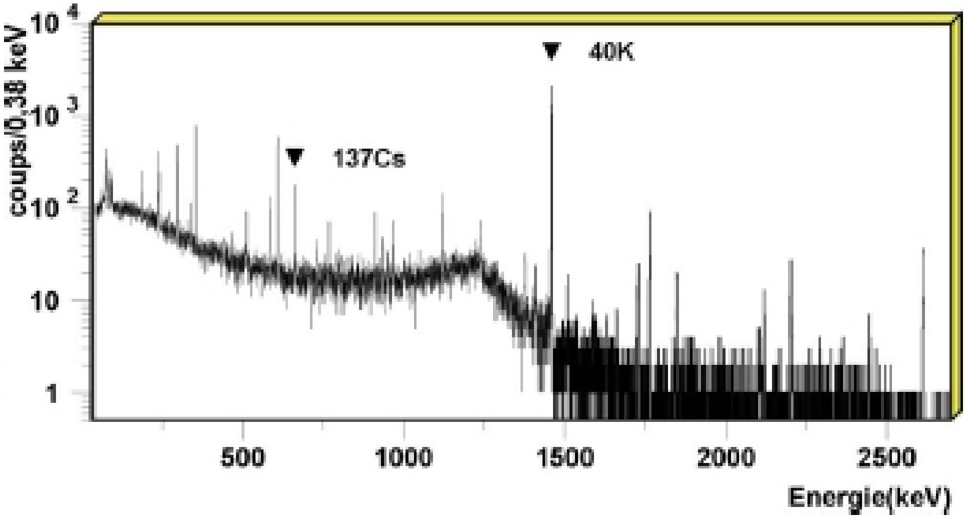
If somebody wants to sell you expensive vintage wine, have it checked.

Applications

Non destructive measurements

^{137}Cs → 661 keV gamma line

easily crossed through wine and glass



No ^{137}Cs in glass

Only trace of ^{137}Cs in corks

Applications

In year 2000 a series of Margaux 1900 and Lafite 1900 to be sold !

Price for 1 bottle around 3000 euros!

From justice: 6 bottles of Margaux and 6 bottles of Lafite

	^{137}Cs	^{14}C	
Margaux	1964±1	1961-1962	OK
Lafite	1963 ±1	1957	6 years difference?
# bottle	4	6	

Non destructive ^{137}Cs measurements of all bottles

All of them contain a ^{137}Cs activity, but different from 1 bottle to another one

⇓

Different mixings, different wines?

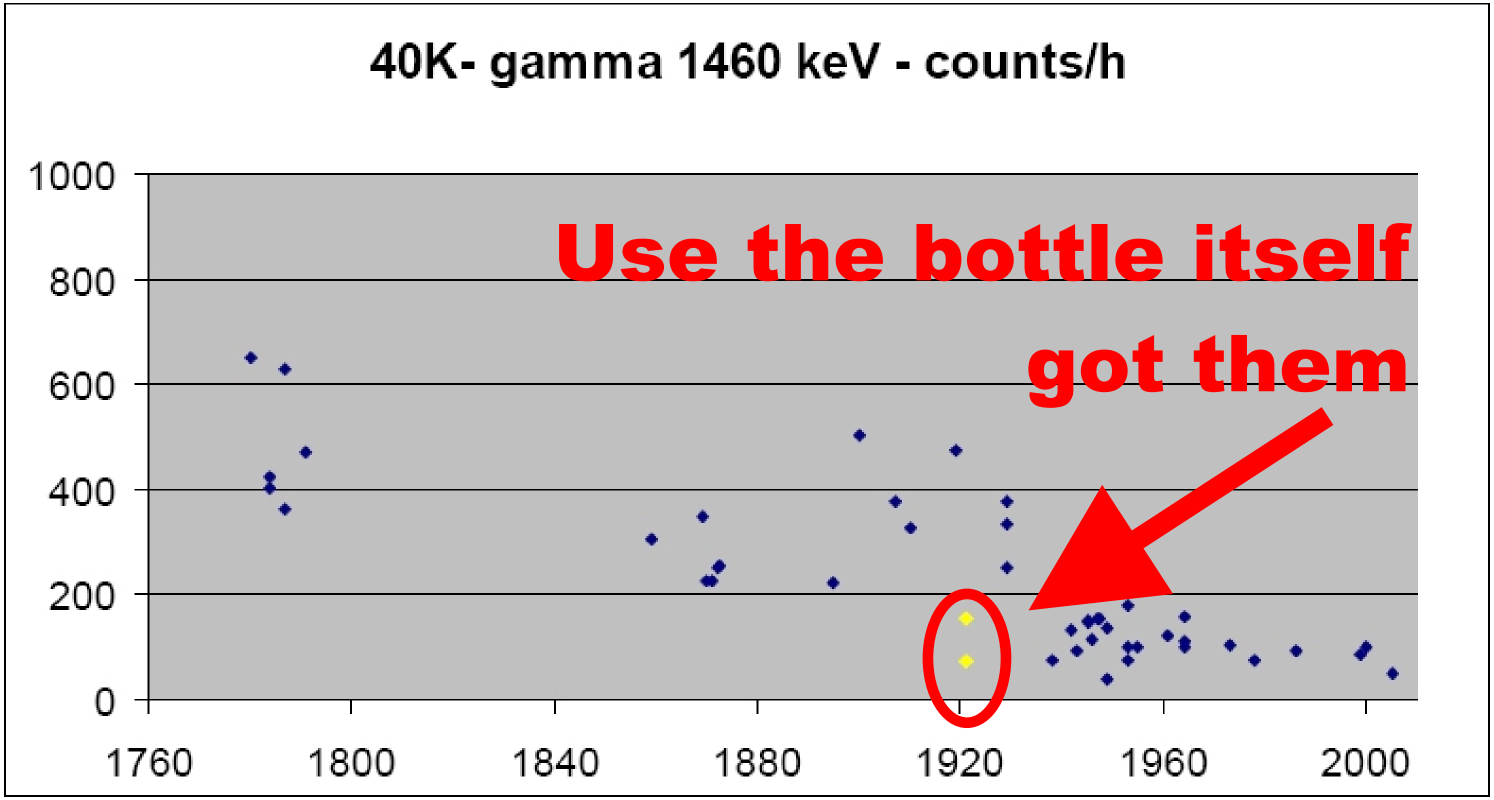
Applications

Château Pétrus "1921" (Magnum, ~15000 $)

$^{137}Cs < 22$ mBq/l ⟹ vintage < 1952

Applications

Activity in ^{40}K of the glass of the bottles versus age of the bottle

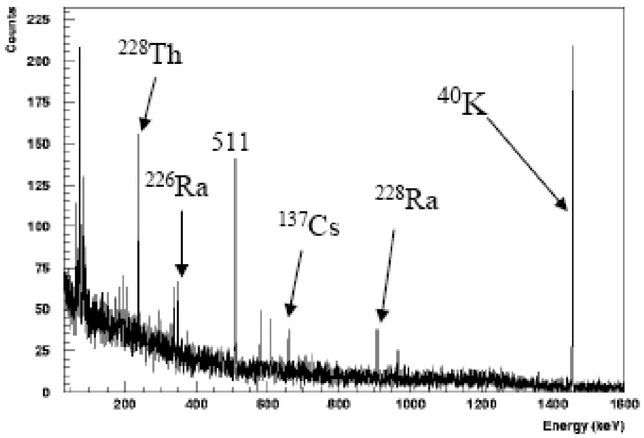


Points in yellow : Petrus “1921”

Applications

Gamma radioactivity in marine salts

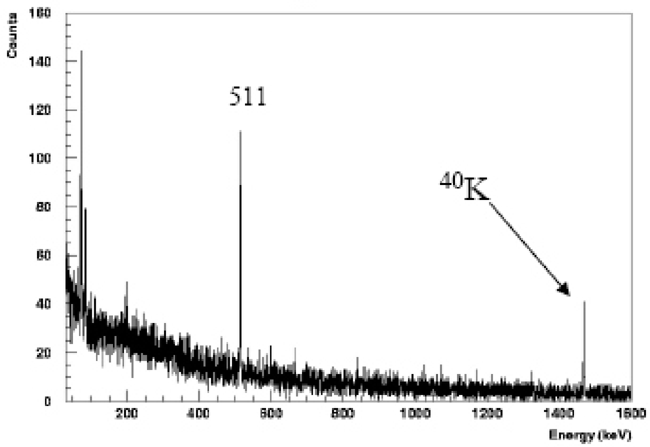
French atlantic salt from the island of Ré



- Typical mass sample: 80 g in a ϕ=7 cm, h=2 cm box
- Measure with the 100 cm^3 Ge detector
- Acquisition time: few days

In the french atlantic salt:
- ^{40}K activity: ~40 Bq/kg
- ^{226}Ra, ^{228}Ra, ^{228}Th: ~500 mBq/kg
- traces of ^{137}Cs: ~70 mBq/kg

Marine salt from Spain



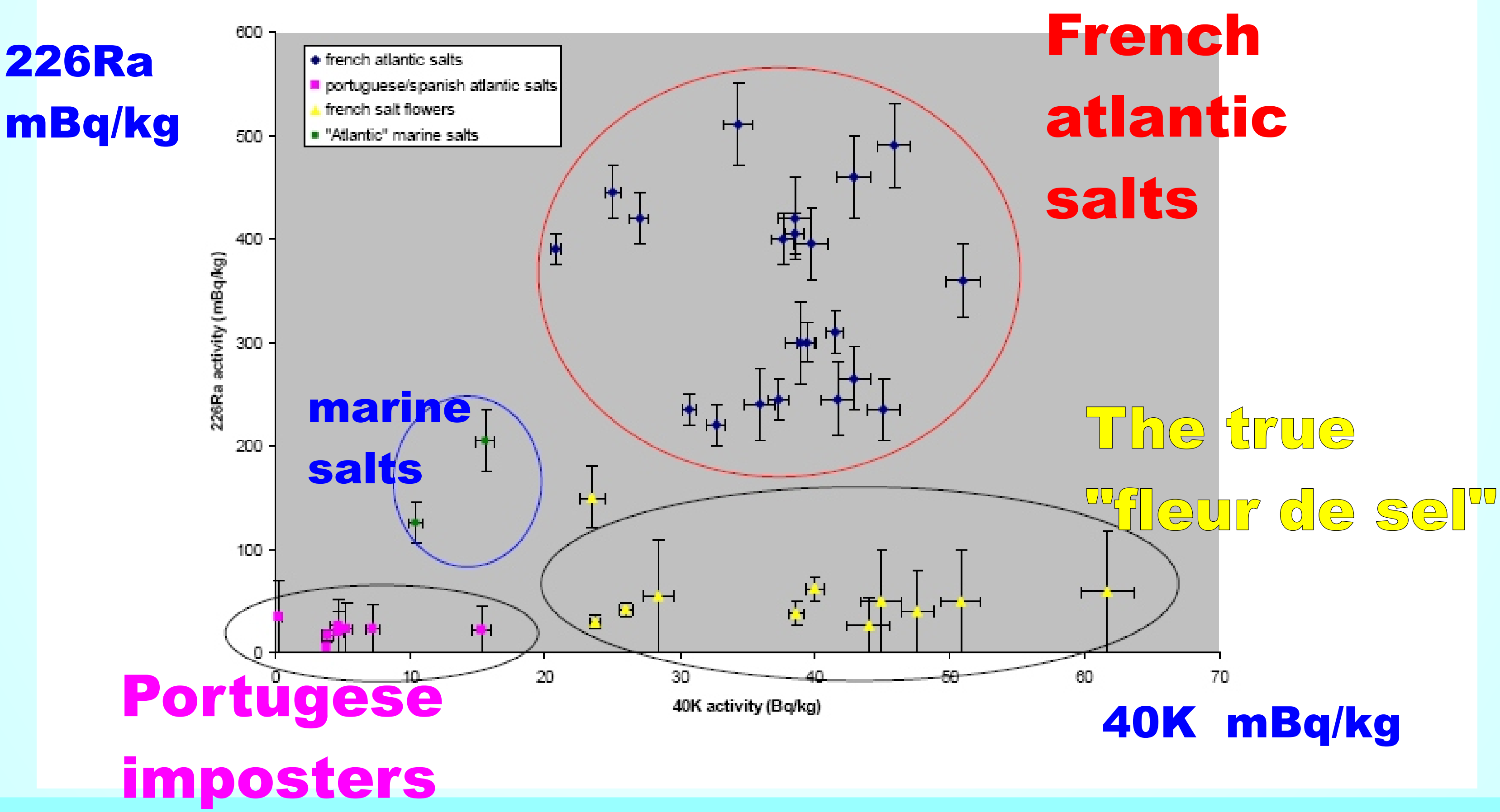
In the spanish atlantic salt:
- ^{40}K activity: ~5 Bq/kg
- only upper limits for ^{226}Ra, ^{228}Ra, ^{228}Th and ^{137}Cs

The French like their salt radioactive!

Applications

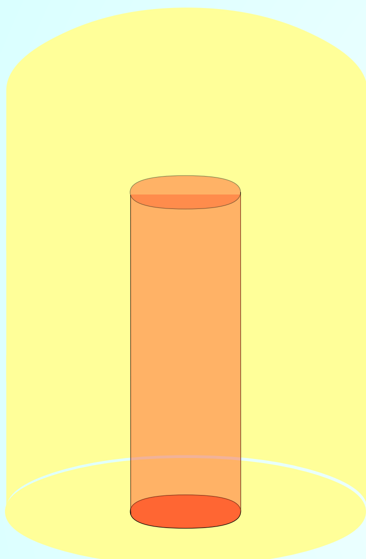
In marine salts: « salt flowers » are most expensive and better taste for cooking

This salt is collected at the surface of the salt-marine fields



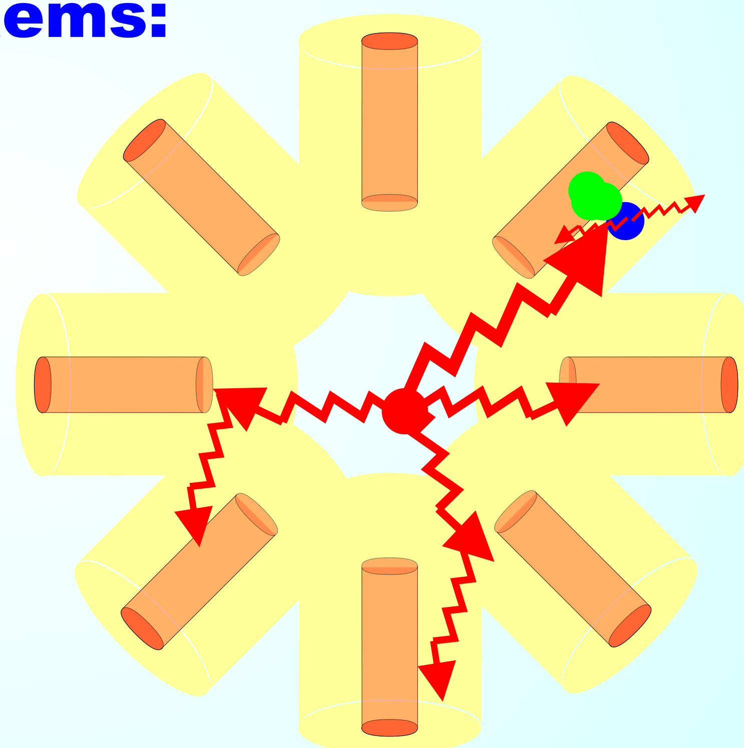
Detector Systems

Back to "normal" science: Nuclear Physics



These things can built into large systems:

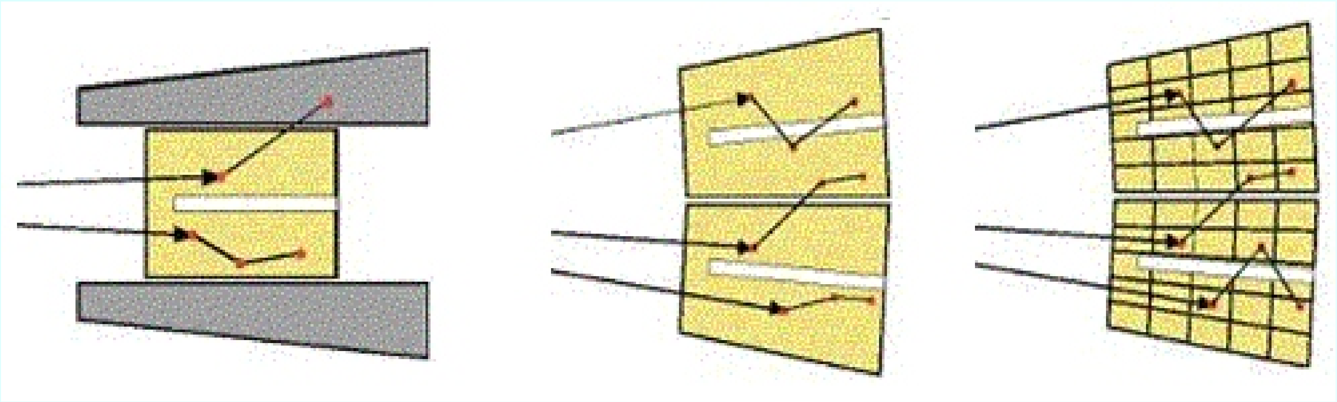
But:



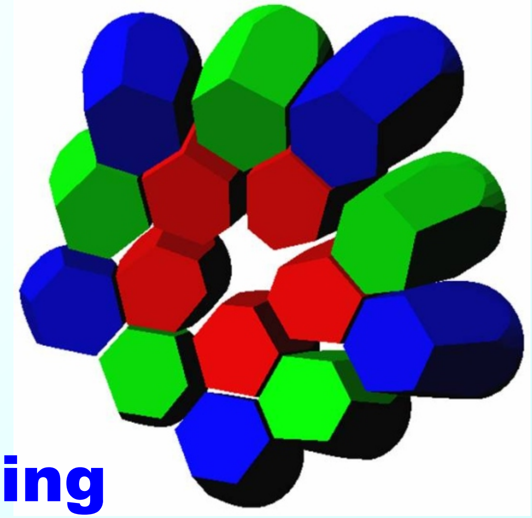
Obviously there are some geometrical problems......

Gamma Tracking

AGATA, the Advanced Gamma Tracking Array



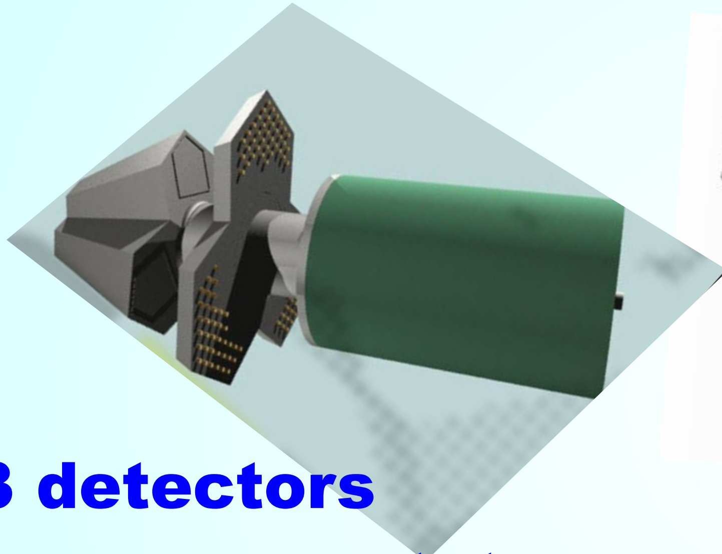
Cut crystals into shape needed and segment for tracking



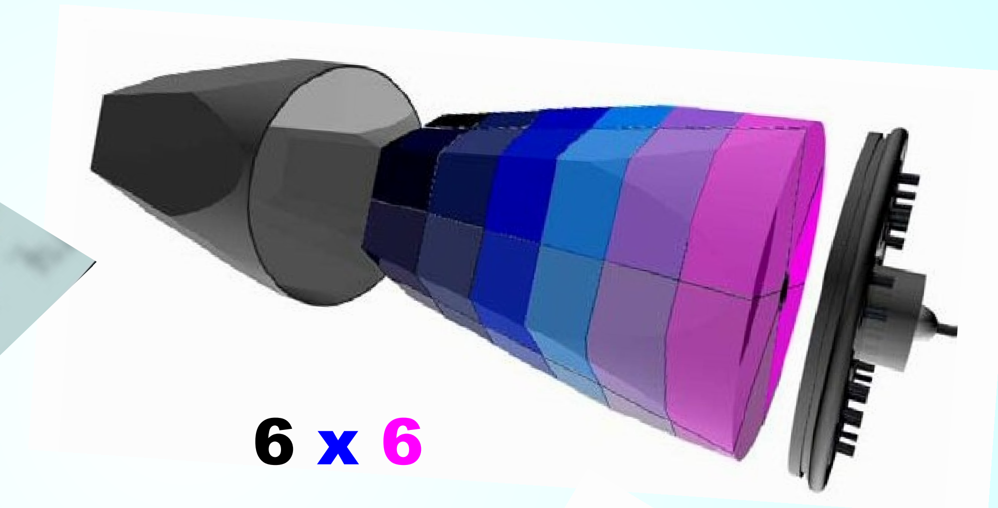
Form groups of three for packaging

Gamma Tracking

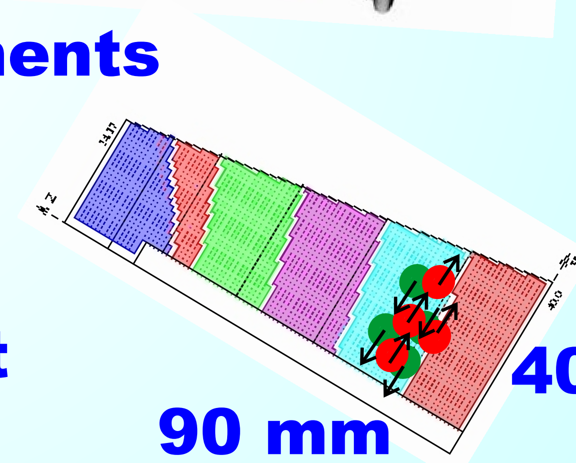
AGATA, the Advanced Gamma Tracking Array



3 detectors
in one cryostat



6 x 6
segments



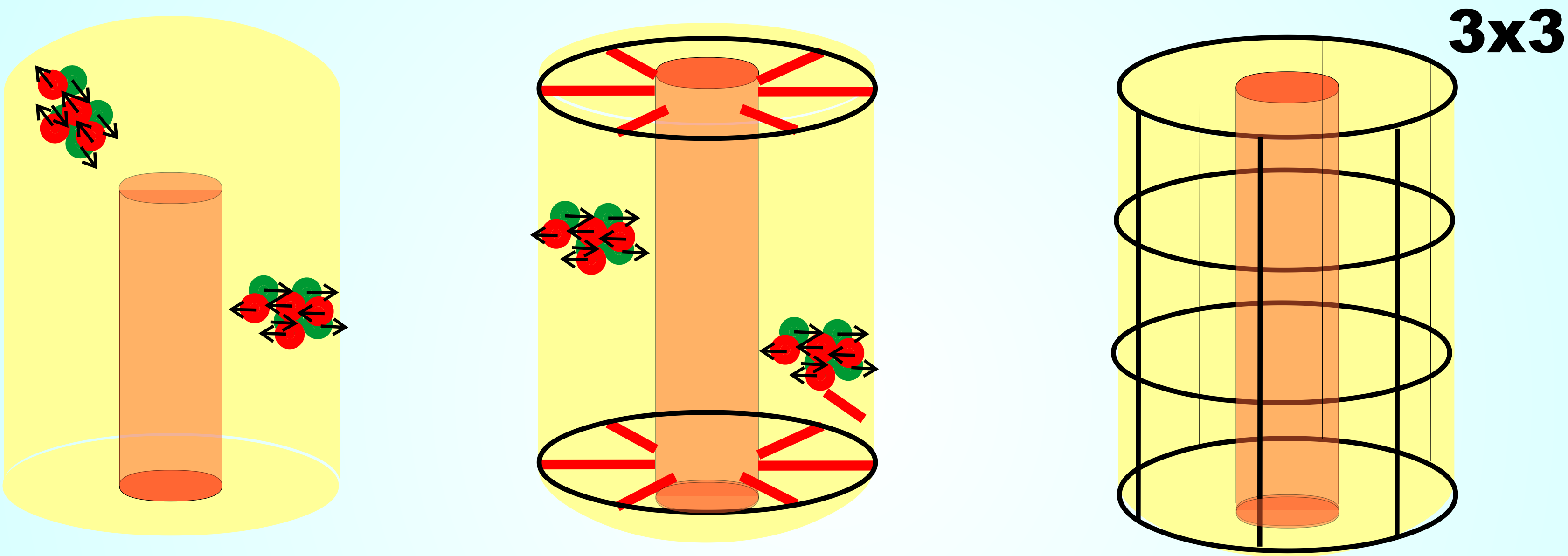
40mm

90 mm

Very special detectors
with extremely different
segments and pulses.

Germanium Detectors

Let us come back to detectors:



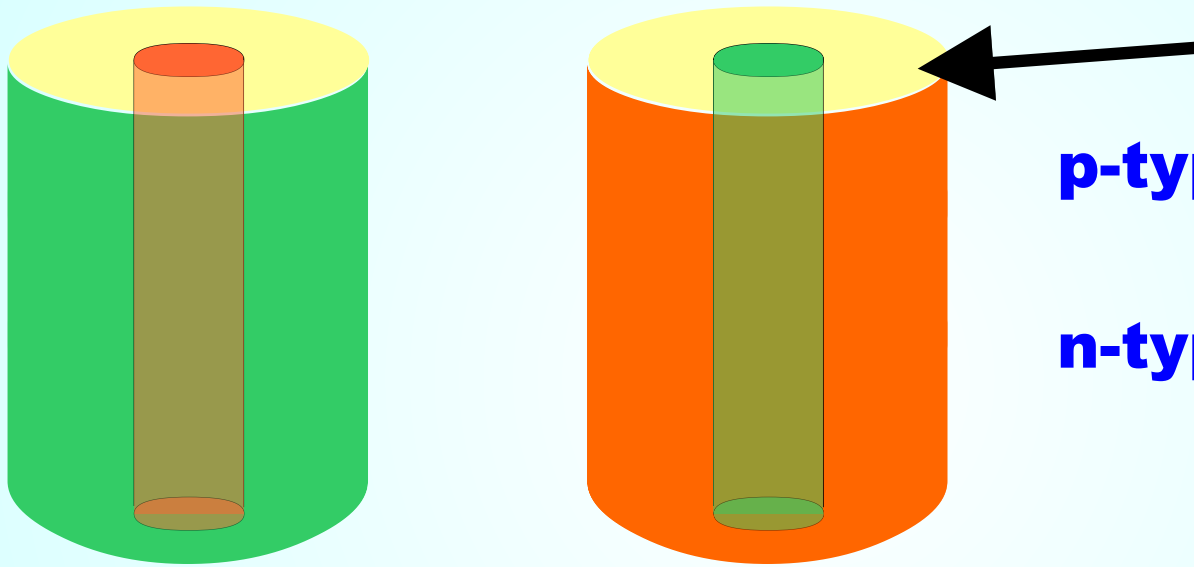
cap → true coax → segmented

homogenous electric field (true coax)

direct spatial information (segmented)

Detector Types

p-type | n-type



Passivation

p-type: holes

→ **centre**

n-type: holes

→ **mantle**

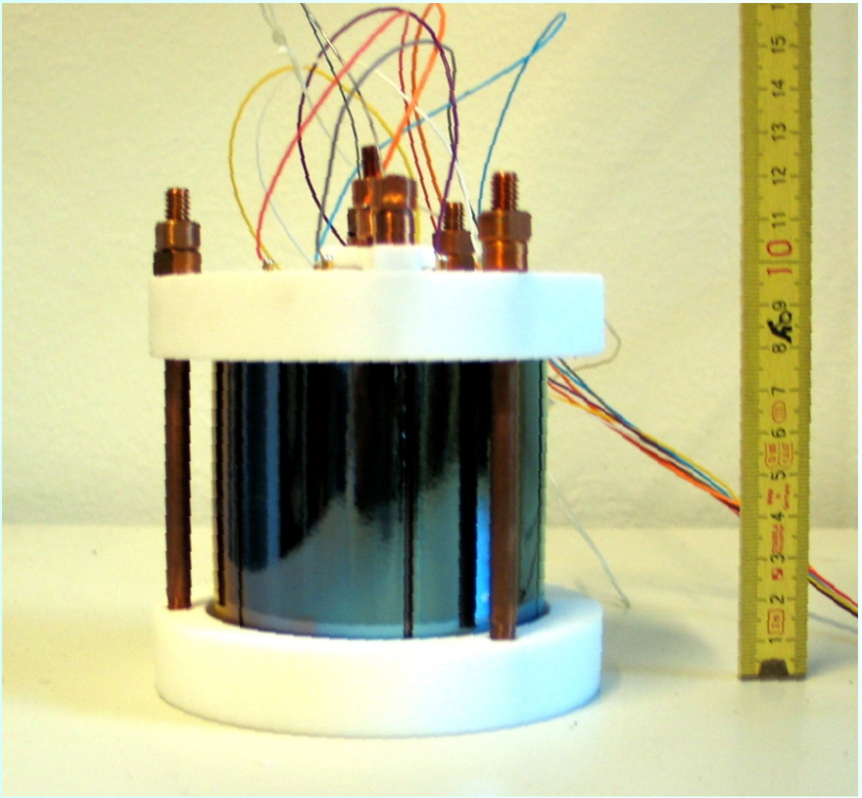
Lithium drift
≈ **500 µm**

Boron implant
≈ **500 nm**

primitive compared to silicon devices

Segmented Detectors

p-type cannot be segmented gracefully.



Have to cut deep into the crystal... not good for field or durability!

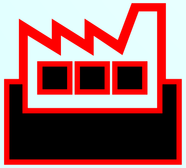
Segmented Detectors

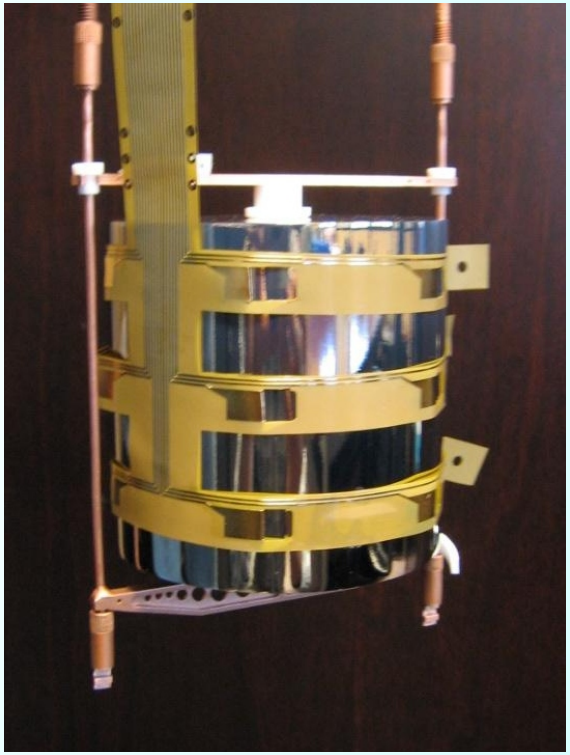
n-type detectors are segmented in the implantation step:

Planar detectors are like silicon detectors [without industrial support].

3d segmented boron implantation is possible.

[one supplier only]

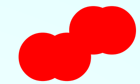




Siegfried

Design a Detectors

Goal: Observe $0\nu\ \beta\beta$ signal

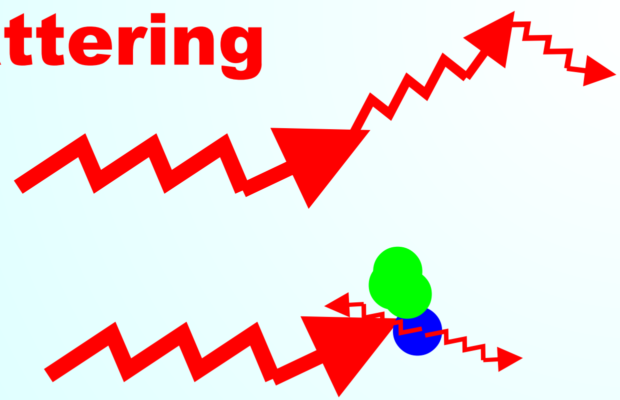


Signature: localized deposit   **Energy $\approx$ 2 MeV**

Background: normal radioactivity

Signature: multi-site deposit [Compton, pair prod.]

Compton Scattering

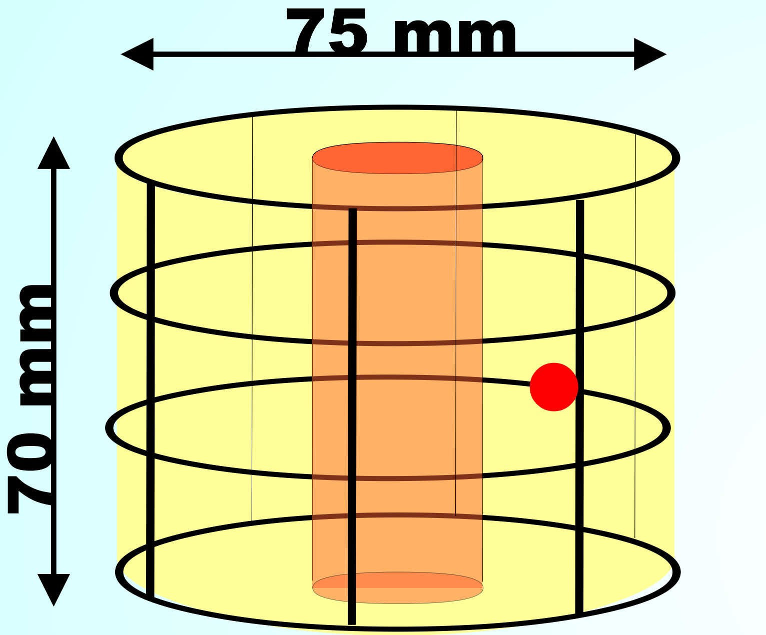


Pair Production

Need segments $\approx$ 2 cm scale

Need as large a crystal as possible to catch the photons

Design a Detectors



The size of the crystal is limited. In this case also because of limited availability of enriched material.

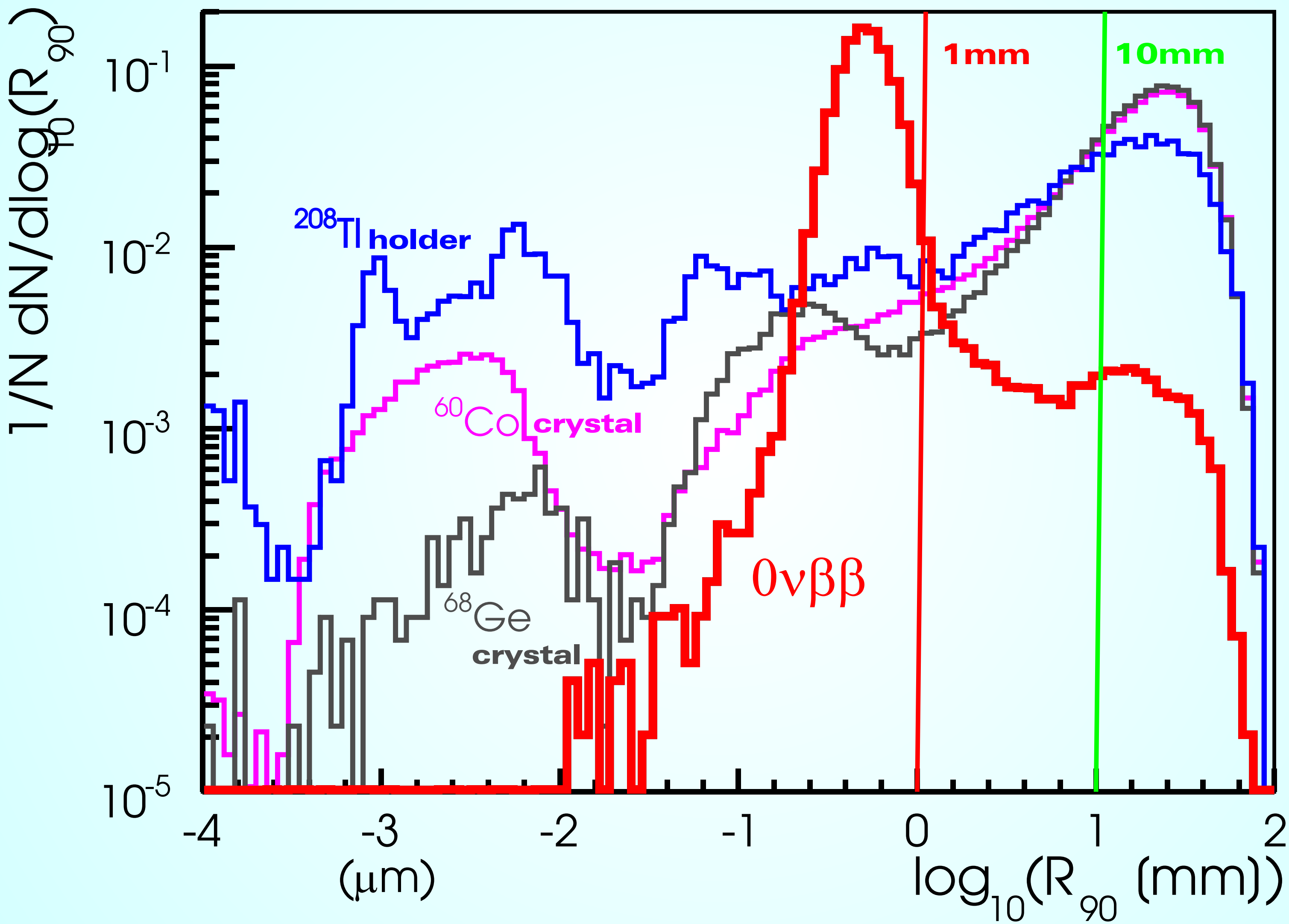
70 : 20 = 3 segments in z

200 : 20 = 6 segments in phi

Some people claim that MC is needed....

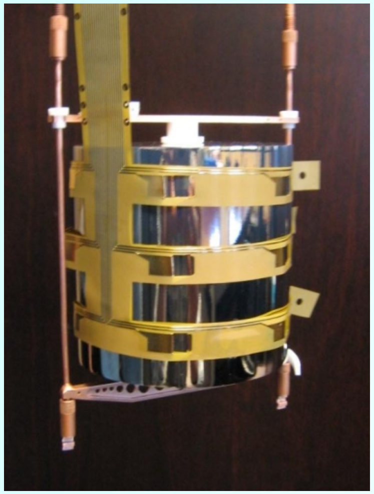
True coax: use pulse shapes for inside segment information

Size of energy deposits



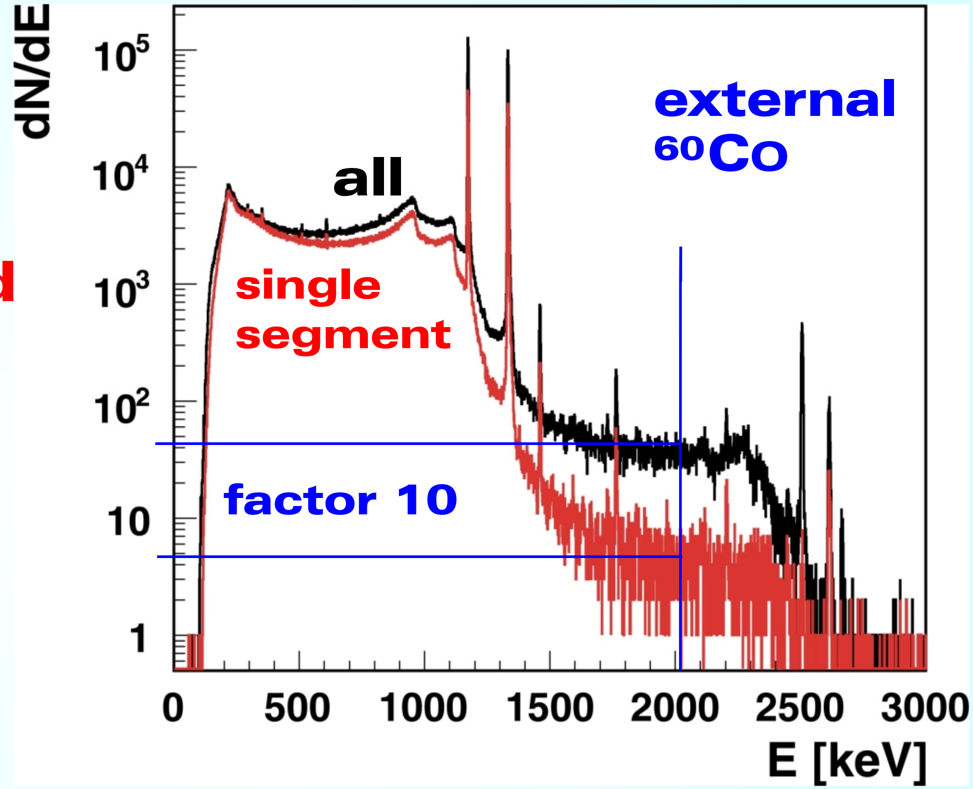
Back of the envelope works!

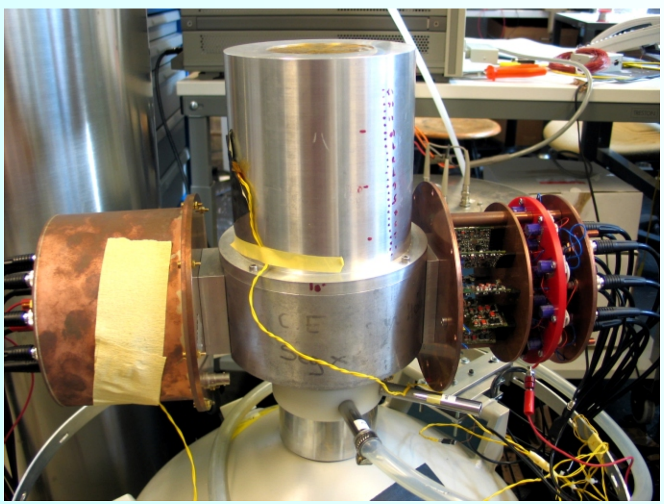
Test the Detector



n-type
z=70 mm
d=75 mm

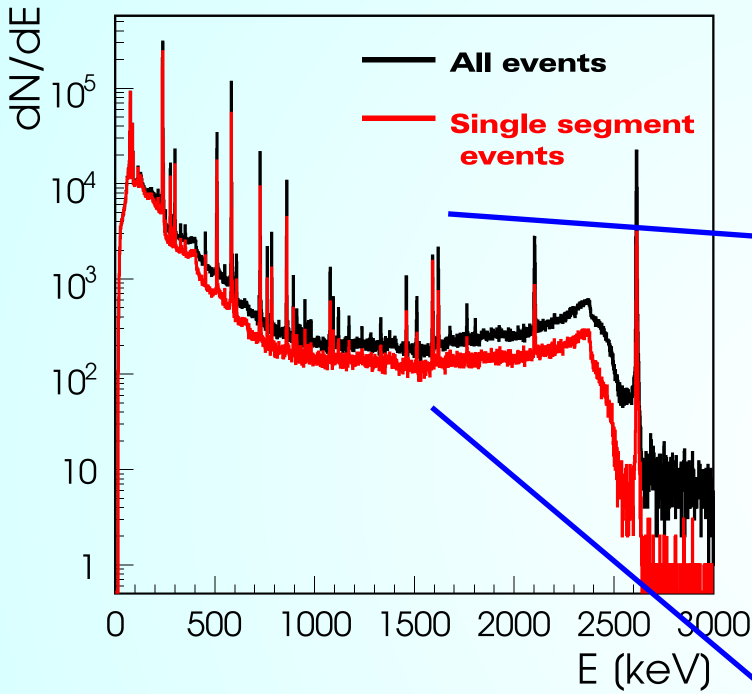
segmented
3 in z
6 in φ



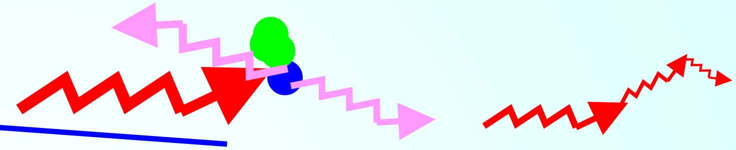


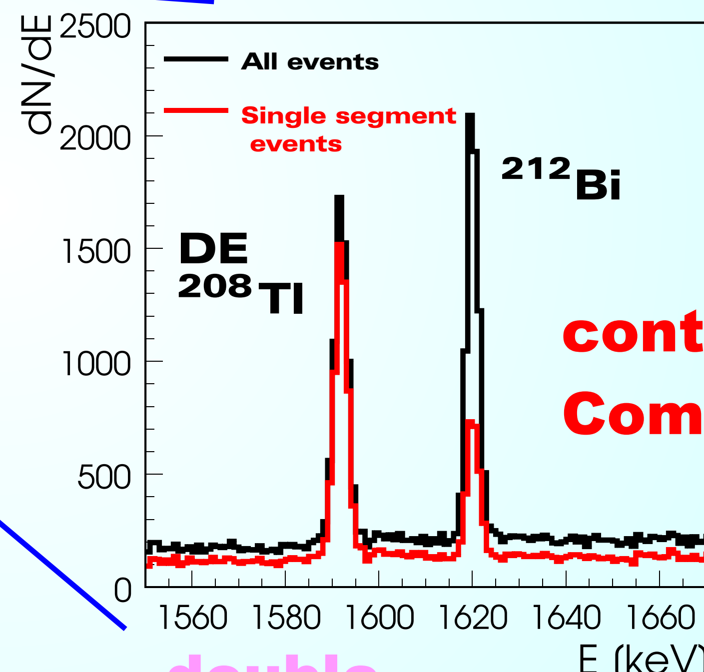
Operation in vacuum
test cryostat

Test the Detector



^{228} Thorium



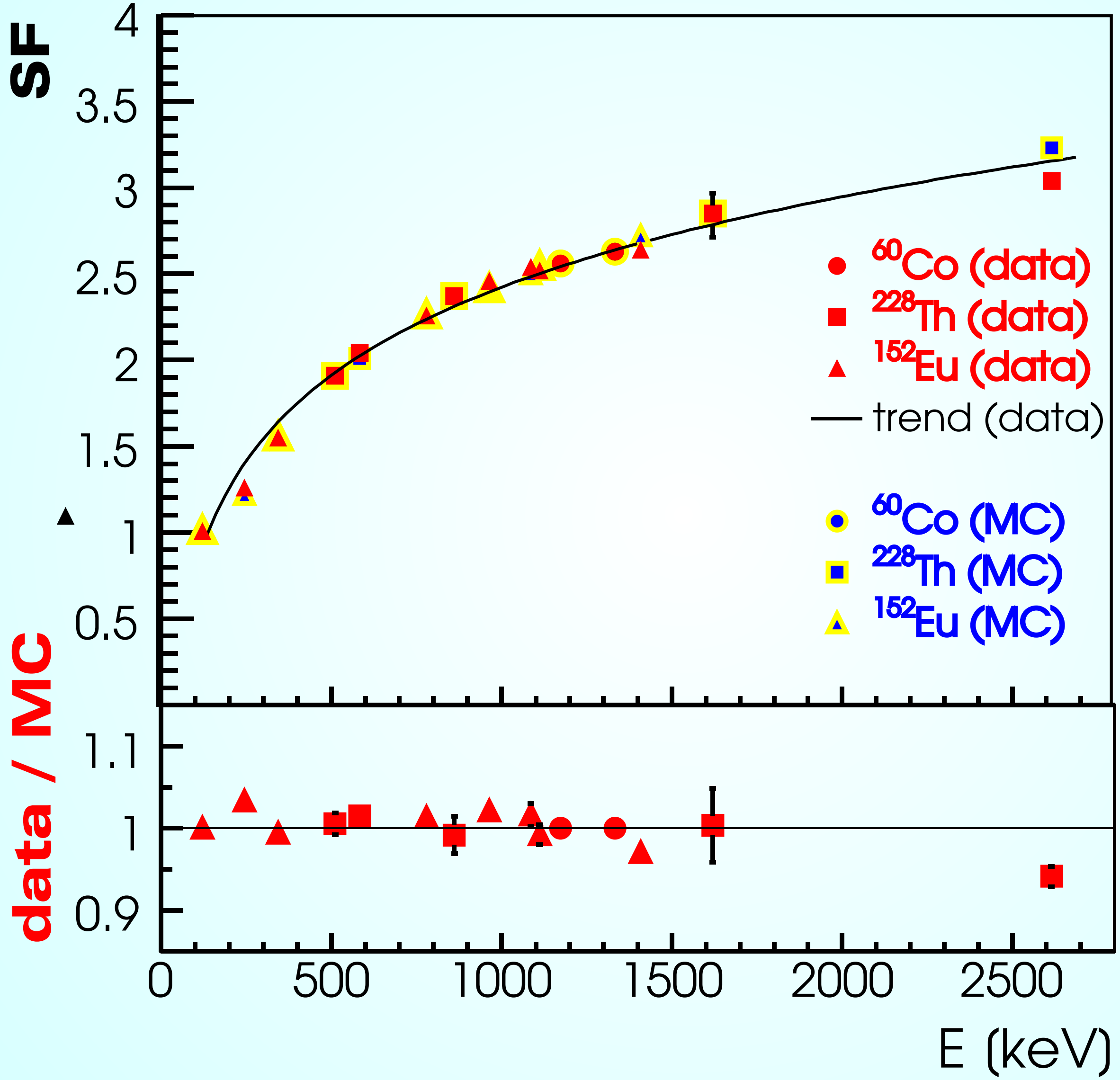


contained Compton

double escape

We get rid of what we try to get rid of...

Test the Detector



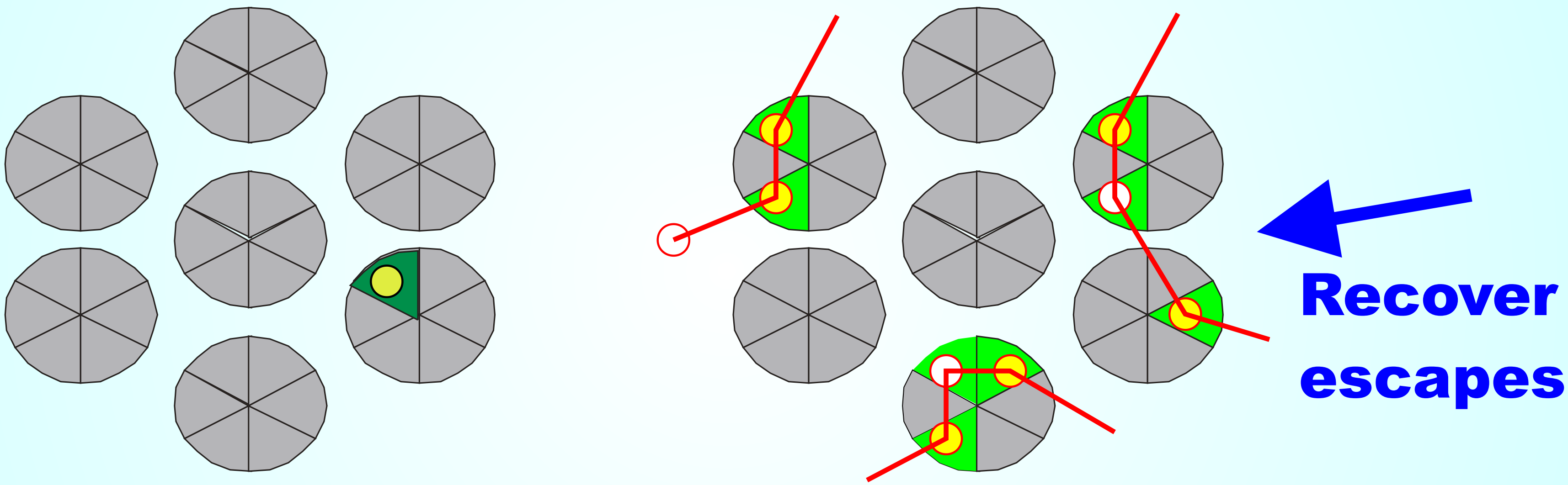
There is nothing like data!

Sometimes its nice, if one doesn't see the points.

Data confirms Monte Carlo

Detector Array

$0\nu\beta\beta$ γ or 2γ

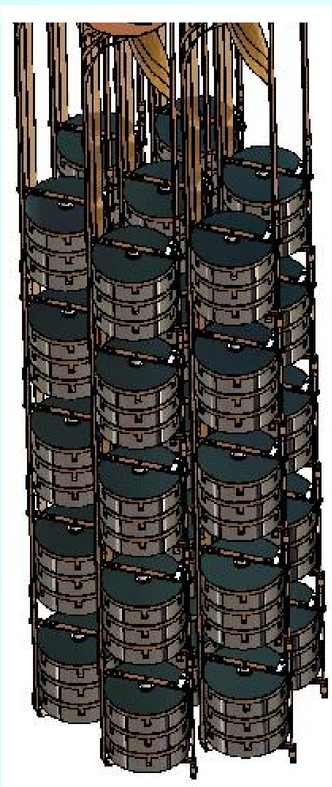


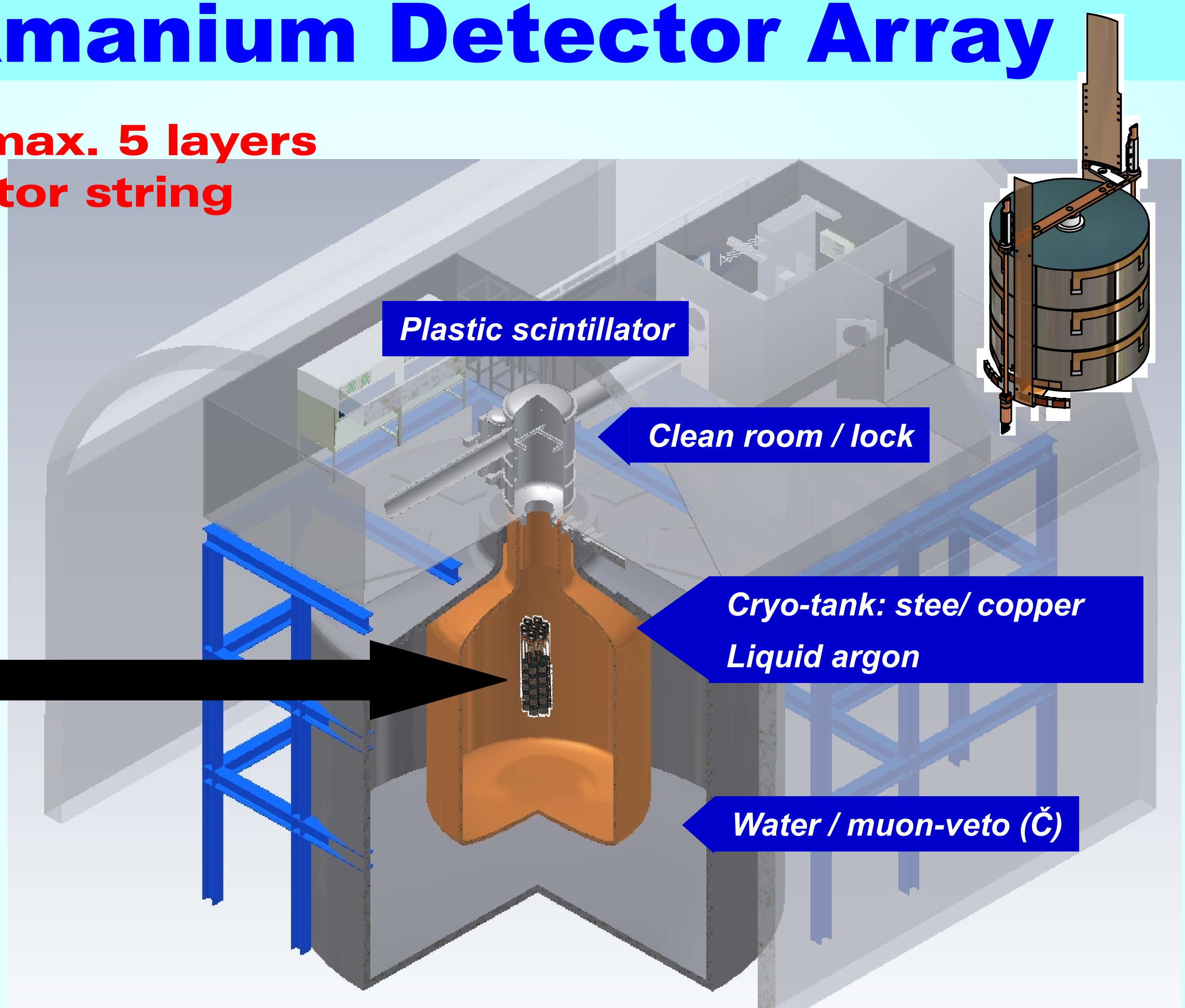
localized deposit
single site event

several deposits
multi site event

GERmanium Detector Array

Array with max. 5 layers and 7 detector string positions

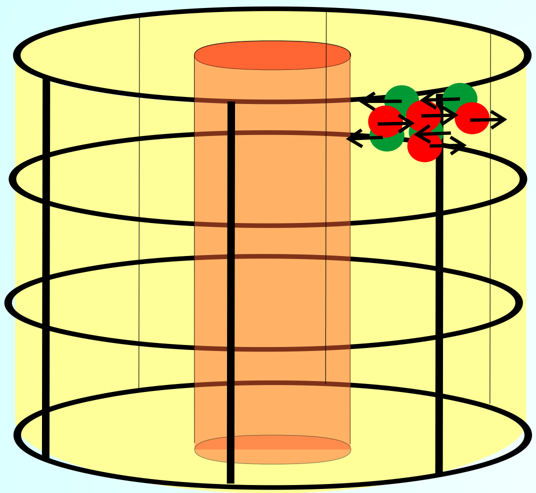




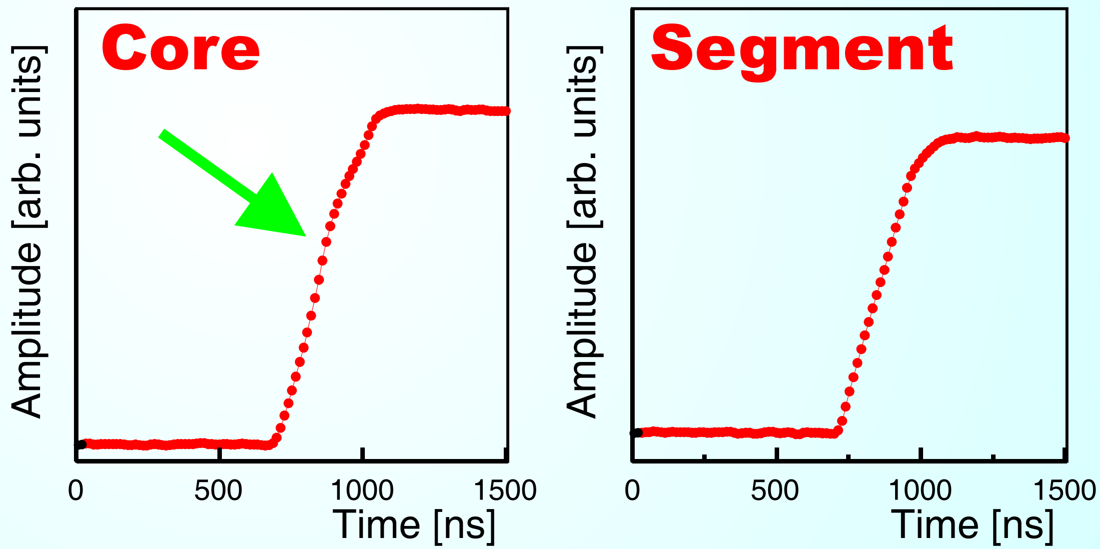
Nominal Phase II setup

Pulse Shapes

n-type



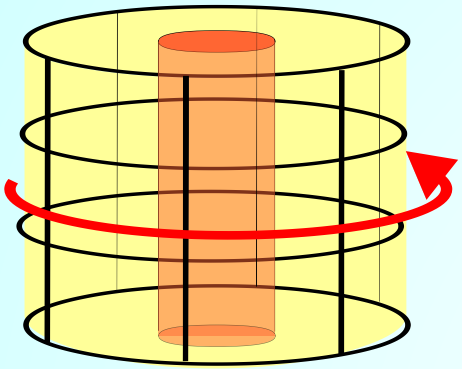
The electrical field pulls the electrons to the core and the holes to the mantle.



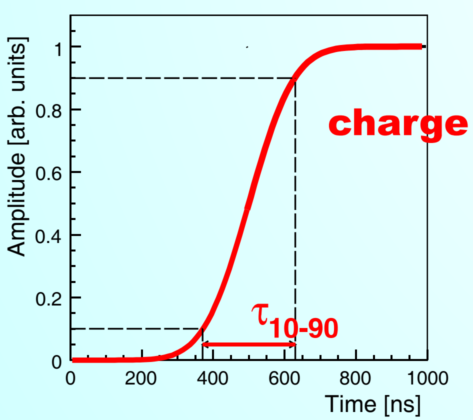
Get radial information from rise times.

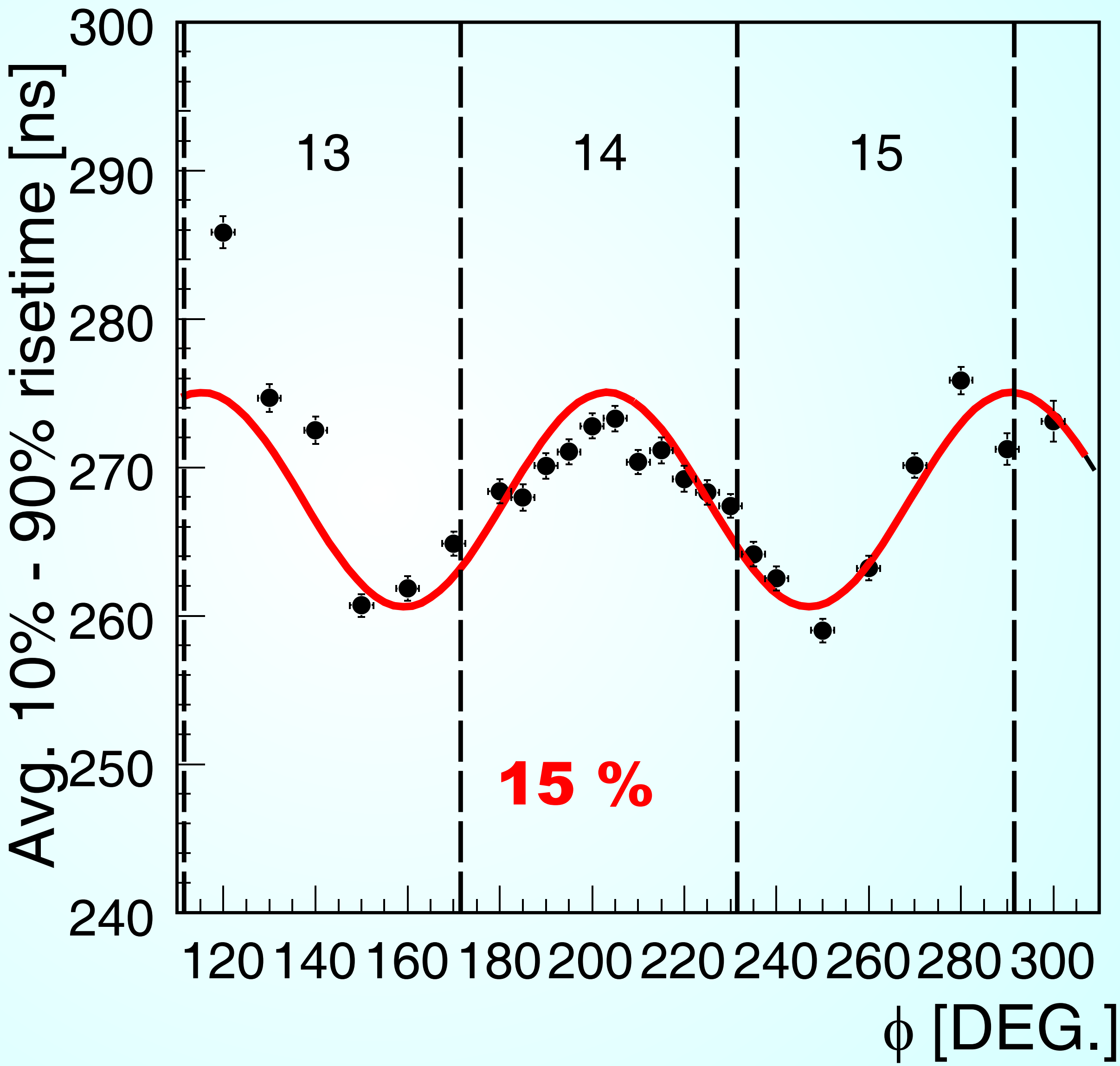
1~2 mm, but degenerate

Rise-time and Crystal Axis

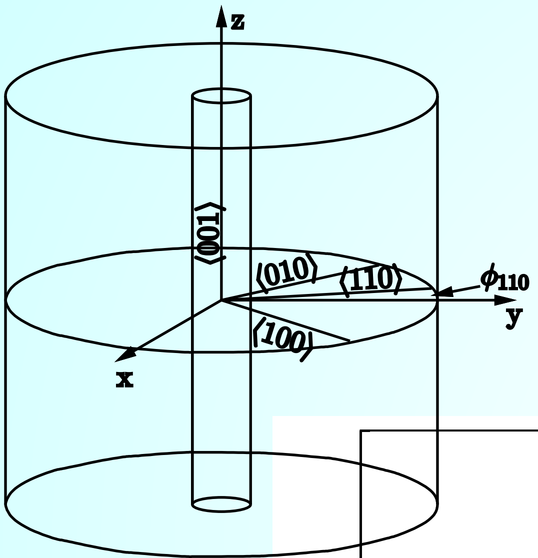


Scan with Europium Source

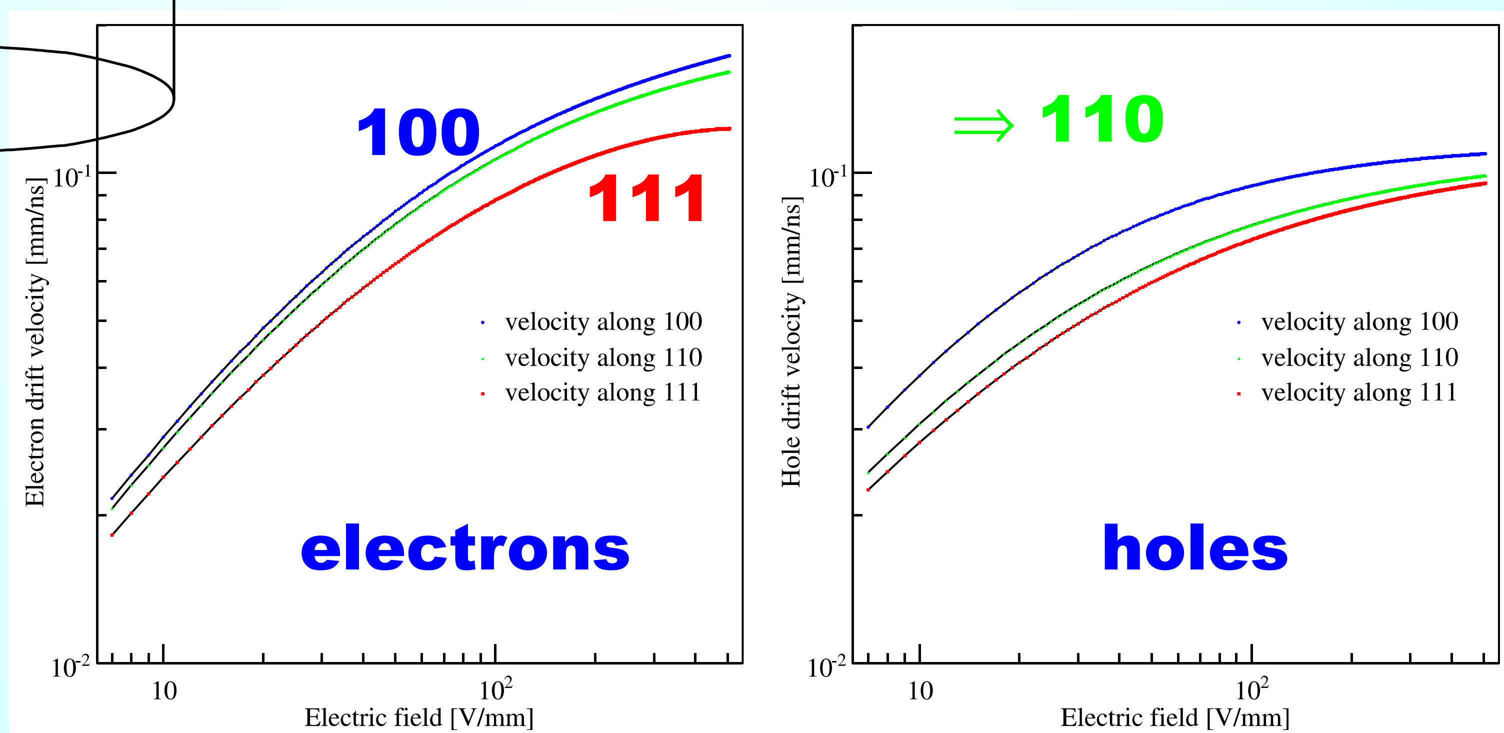




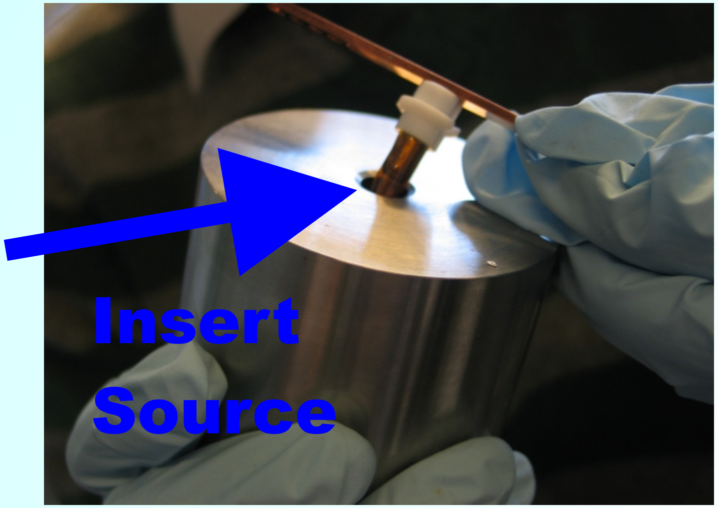
Speed and Crystal Axis



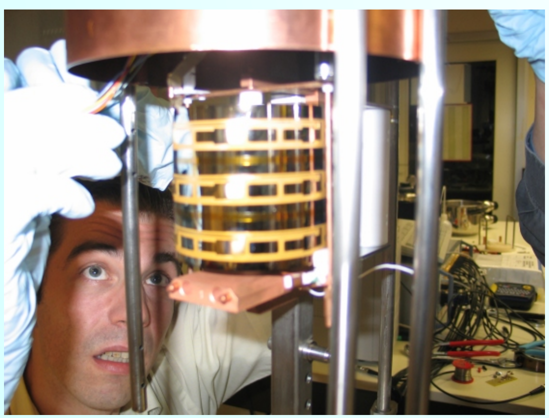
Speed ⇒ rise-time depend on angle between trajectory crystal axes

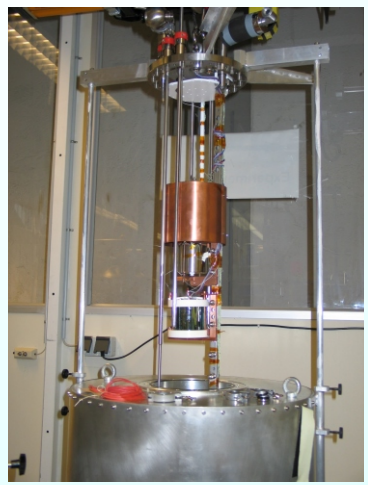


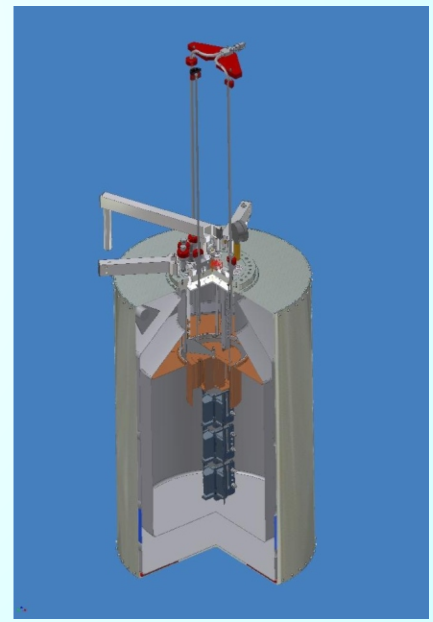
Hole Drift



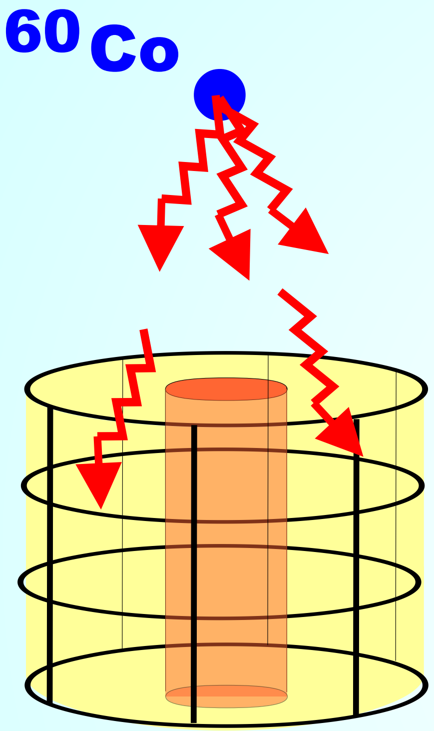
True coax detector operated "naked" in LN provides unique opportunity to measure hole drift.

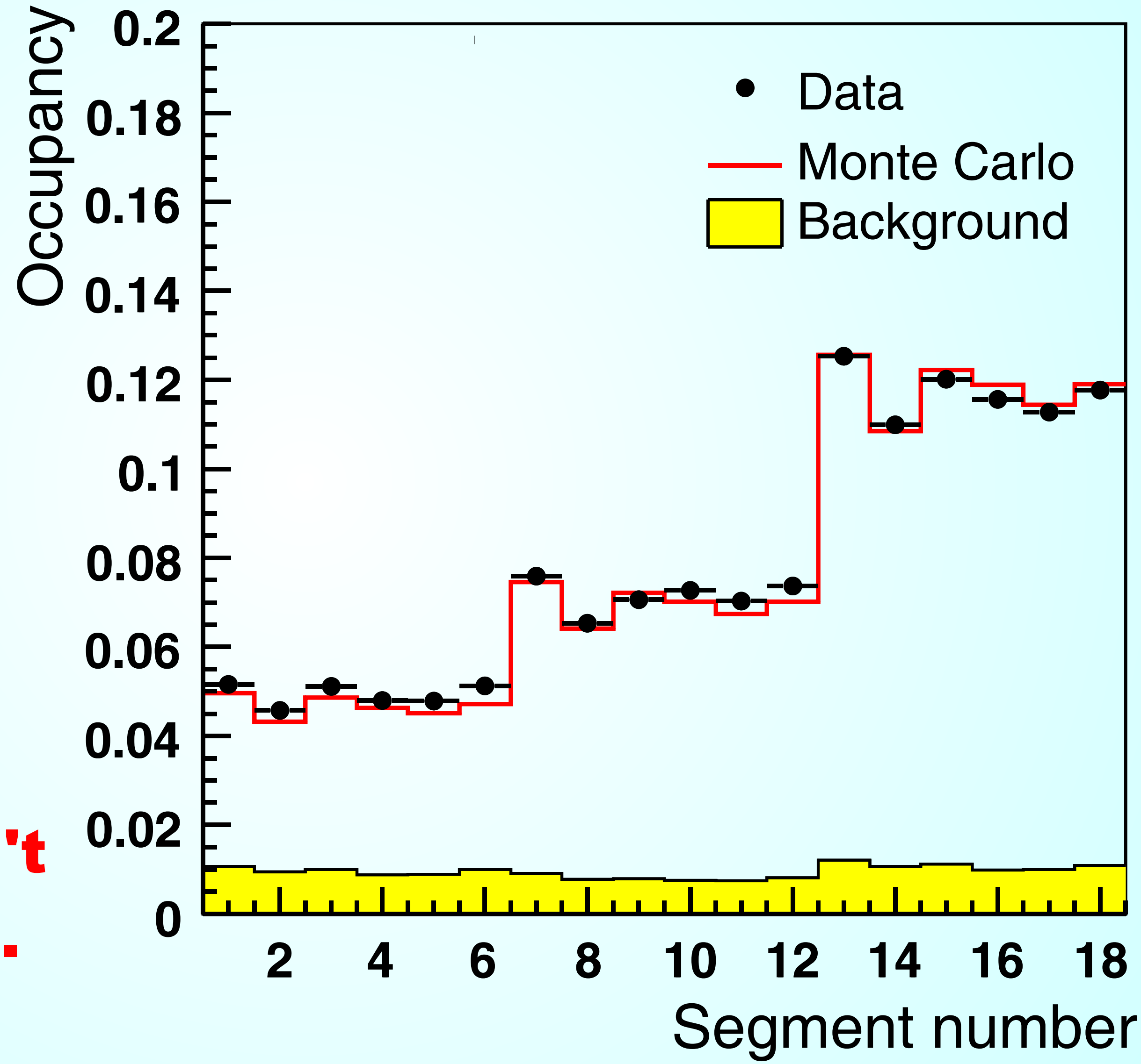






Occupancy and Crystal Axis

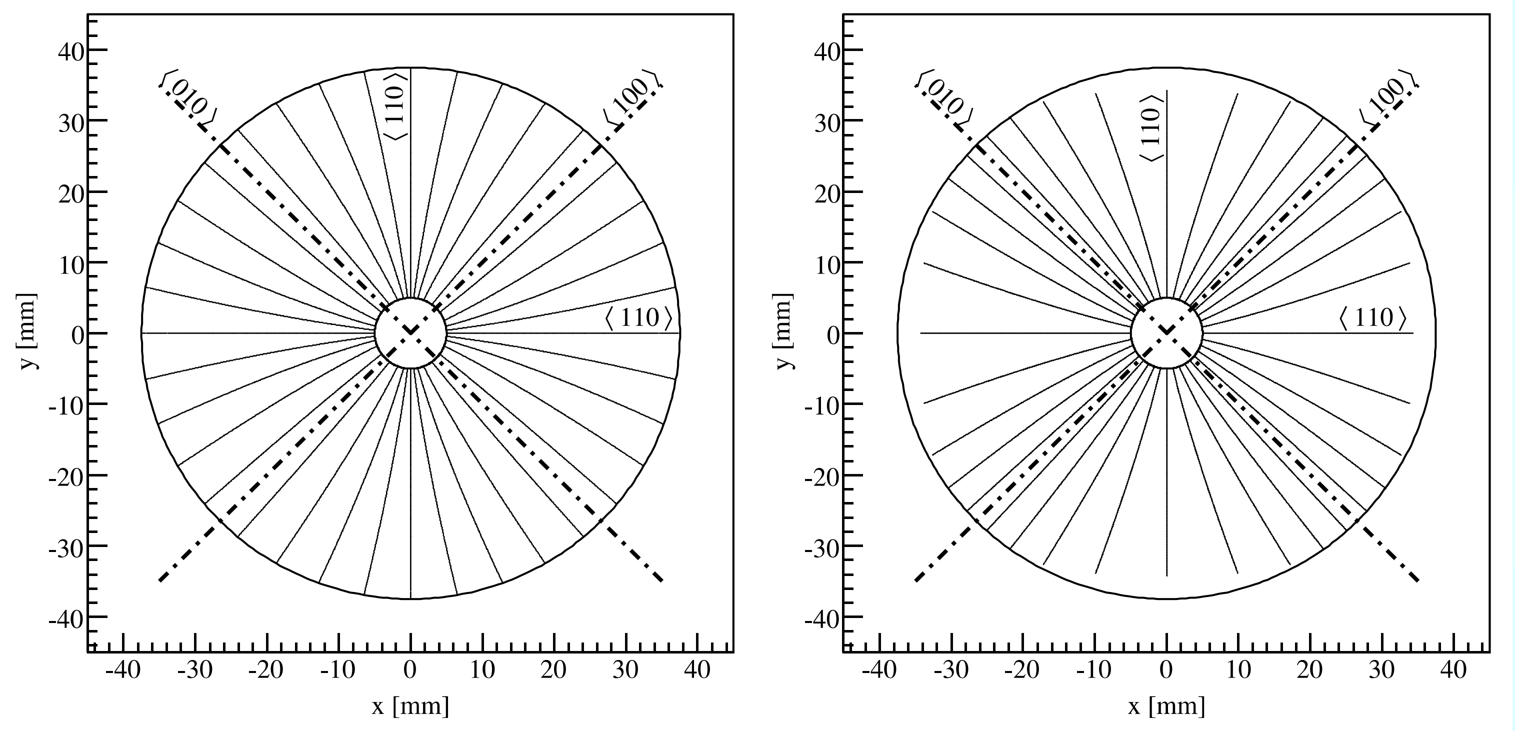




The charge carriers don't go straight...

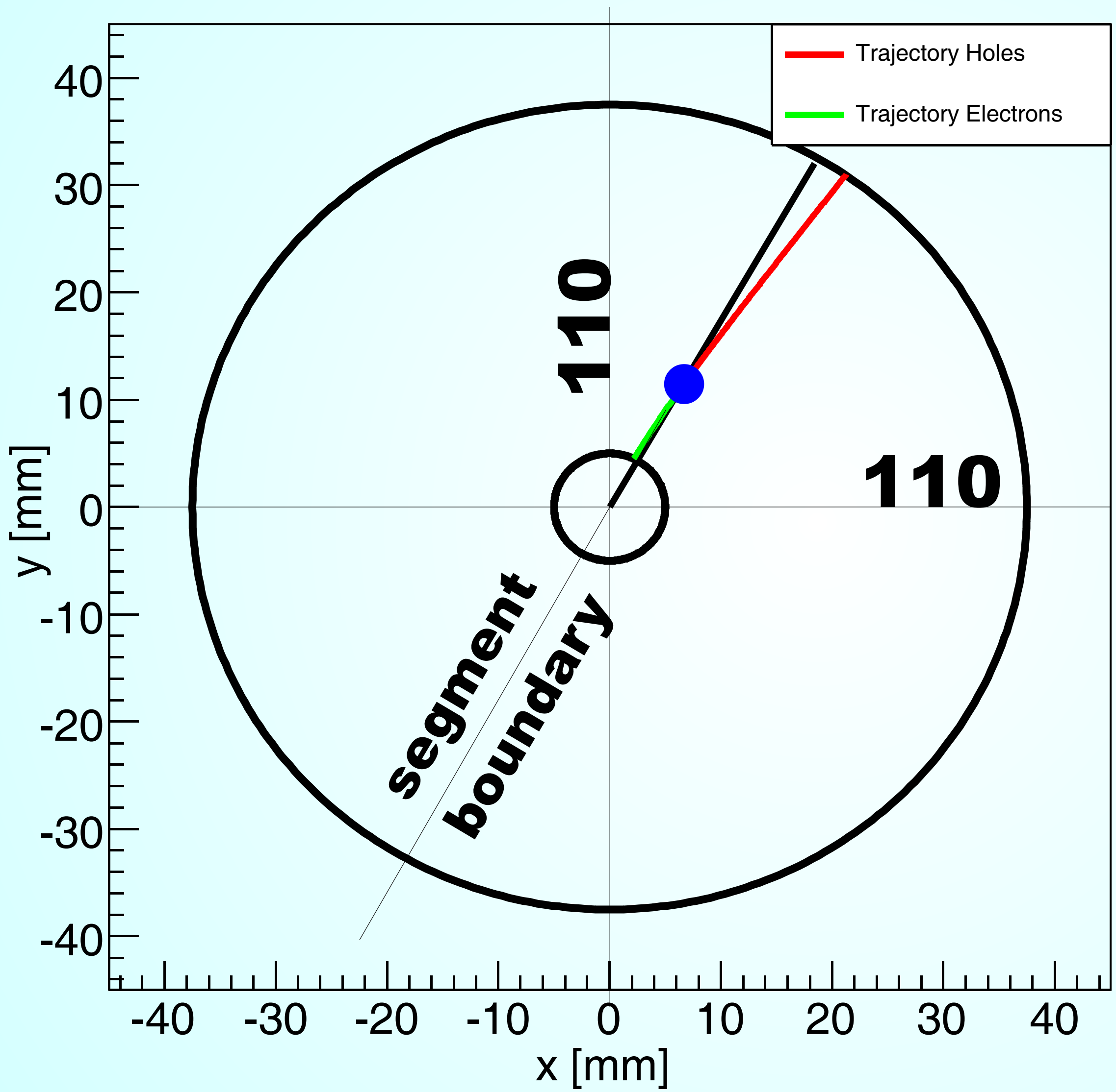
Trajectories

Different speeds ⇒ bent trajectories



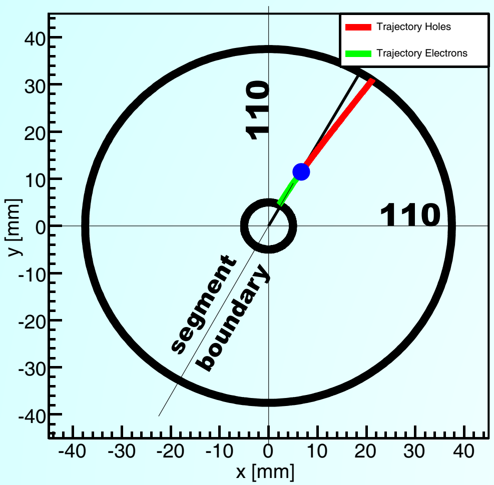
Electrons **Holes**

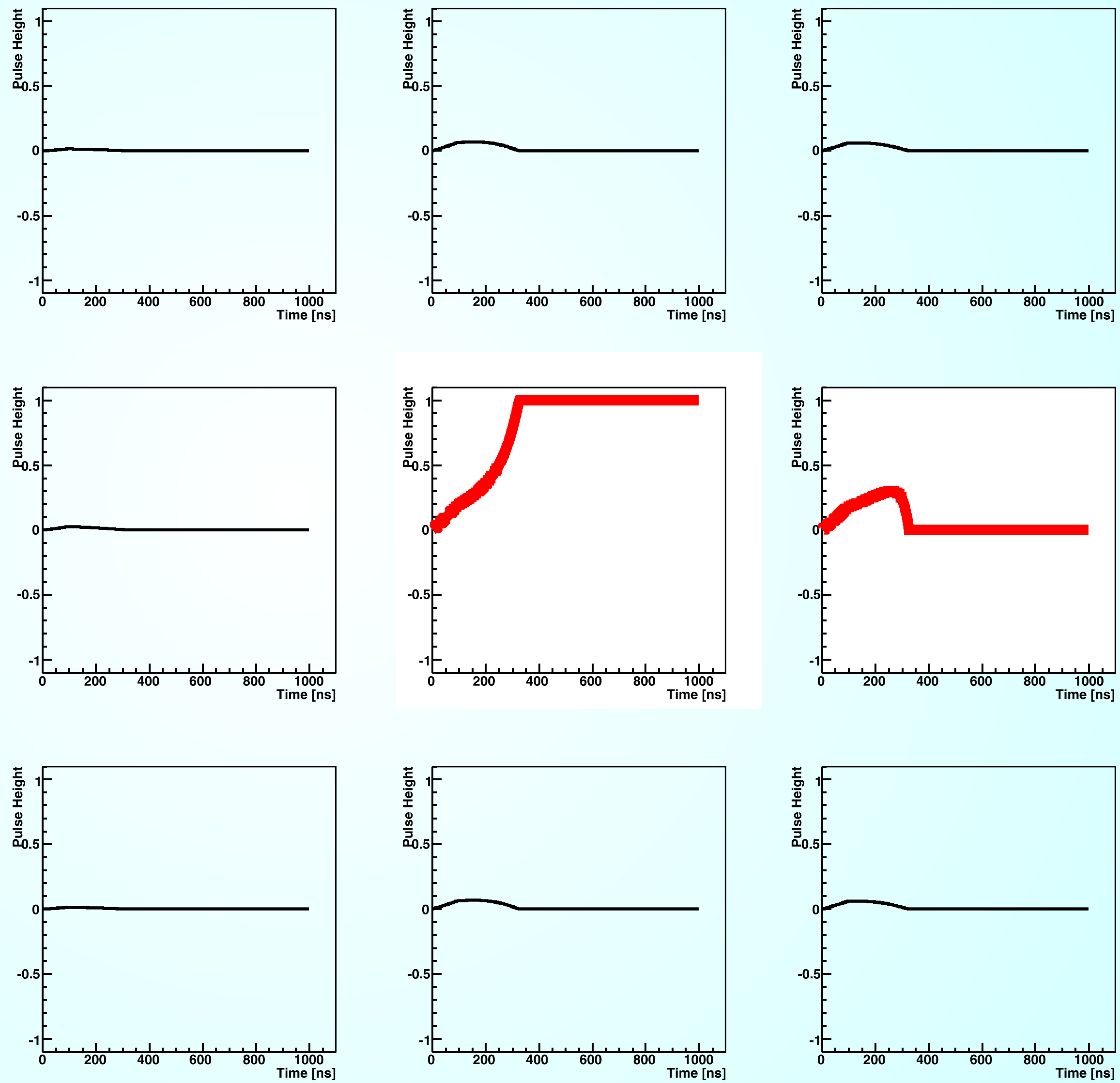
Trajectories



Depending on the relative orientation of crystal axes and segment boundaries different occupancy patterns are produced.

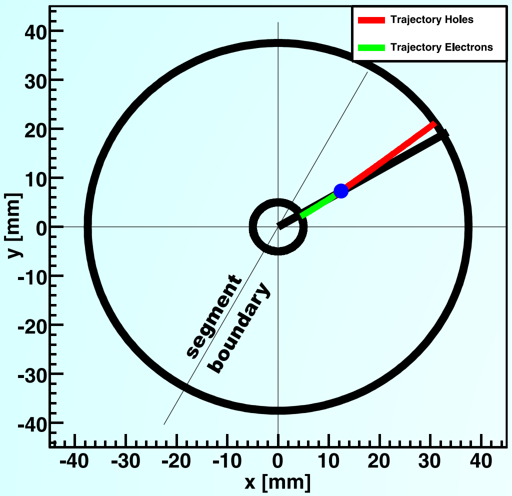
Pulse Shapes and Trajectories

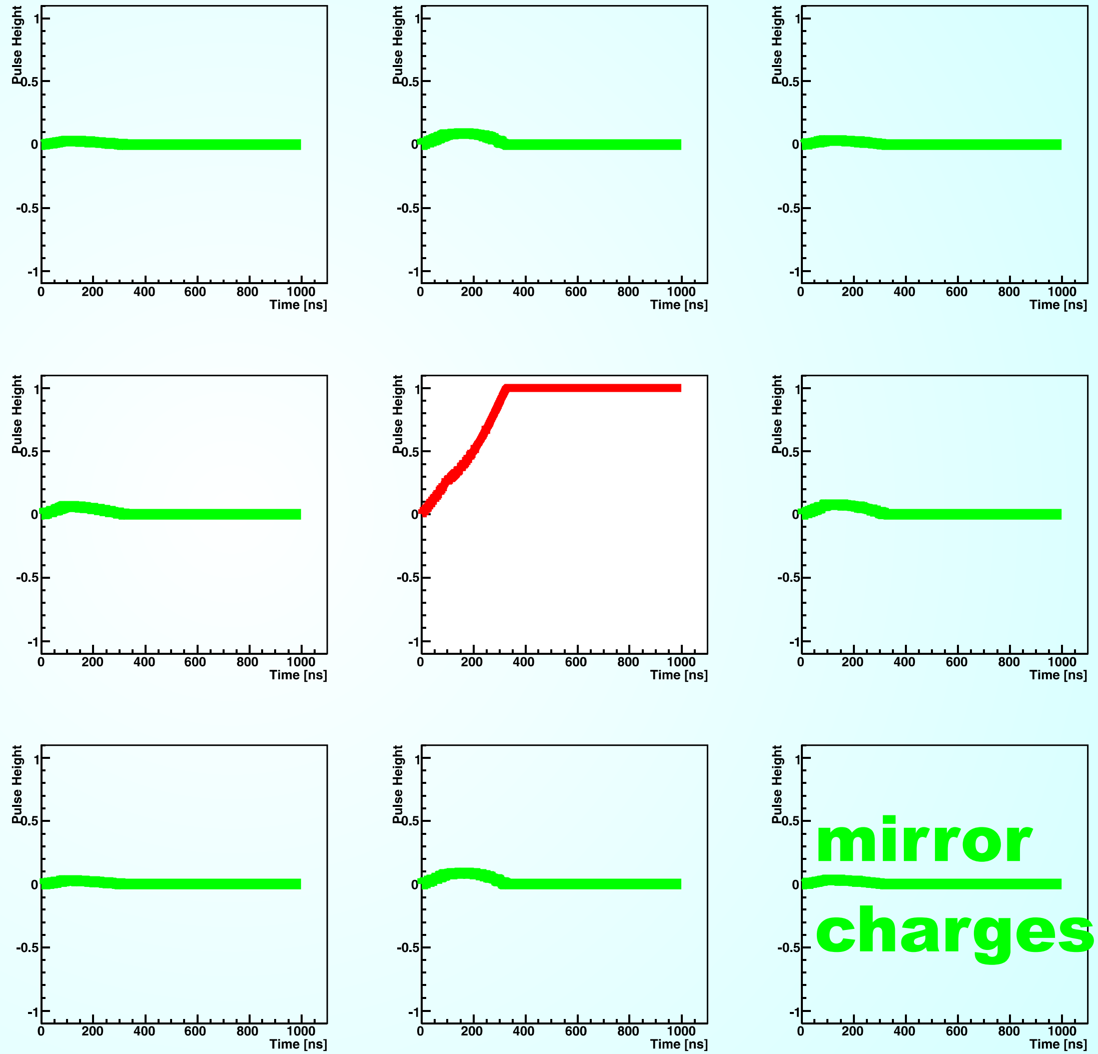




Start on a boundary, end nowhere near.....

Pulse Shapes and Trajectories

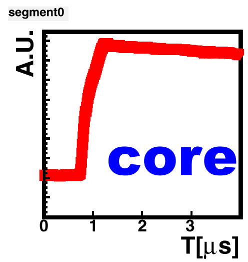




Start inside, stay inside....

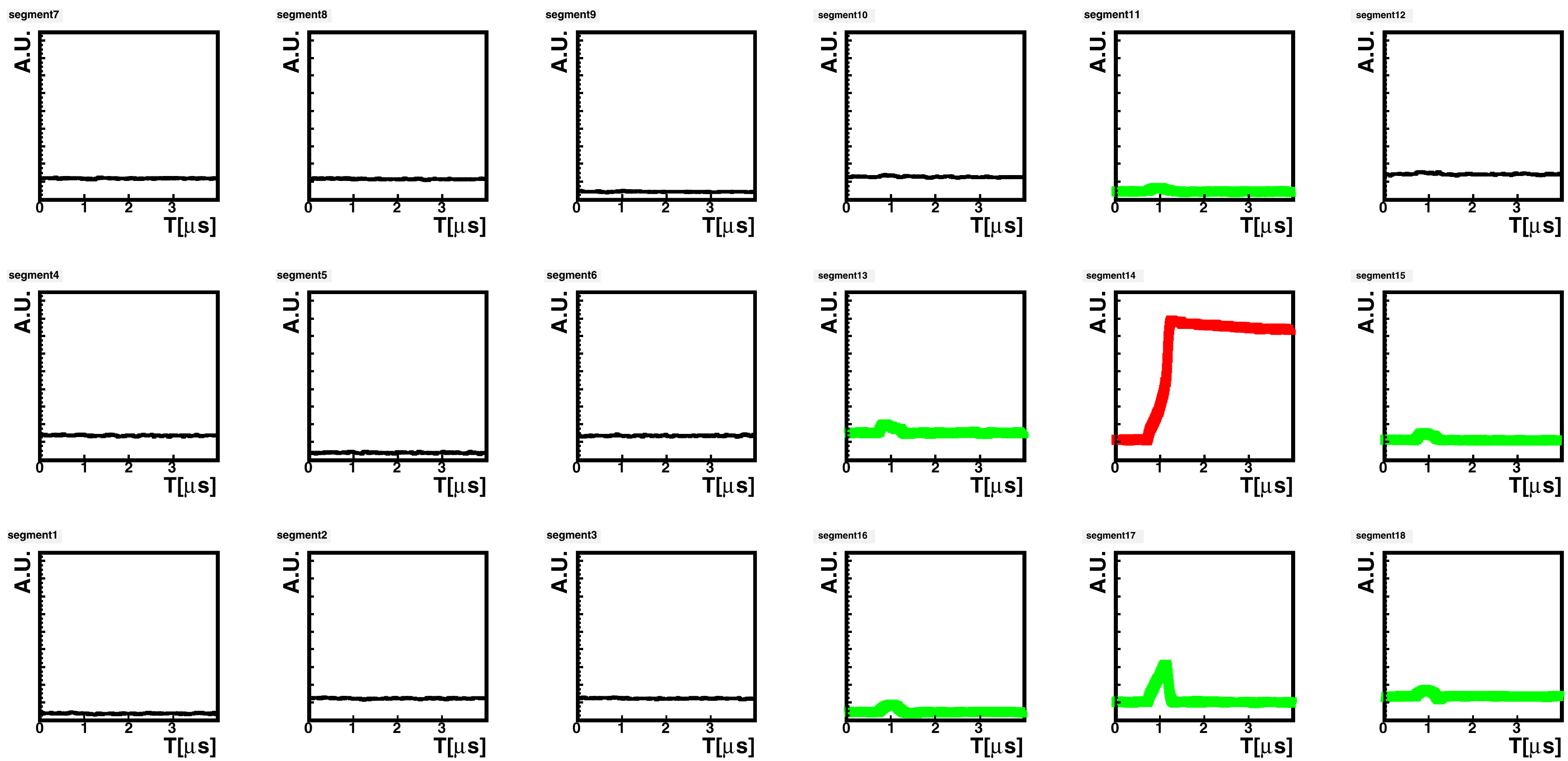
Reality has no single charges.

Event Complexity

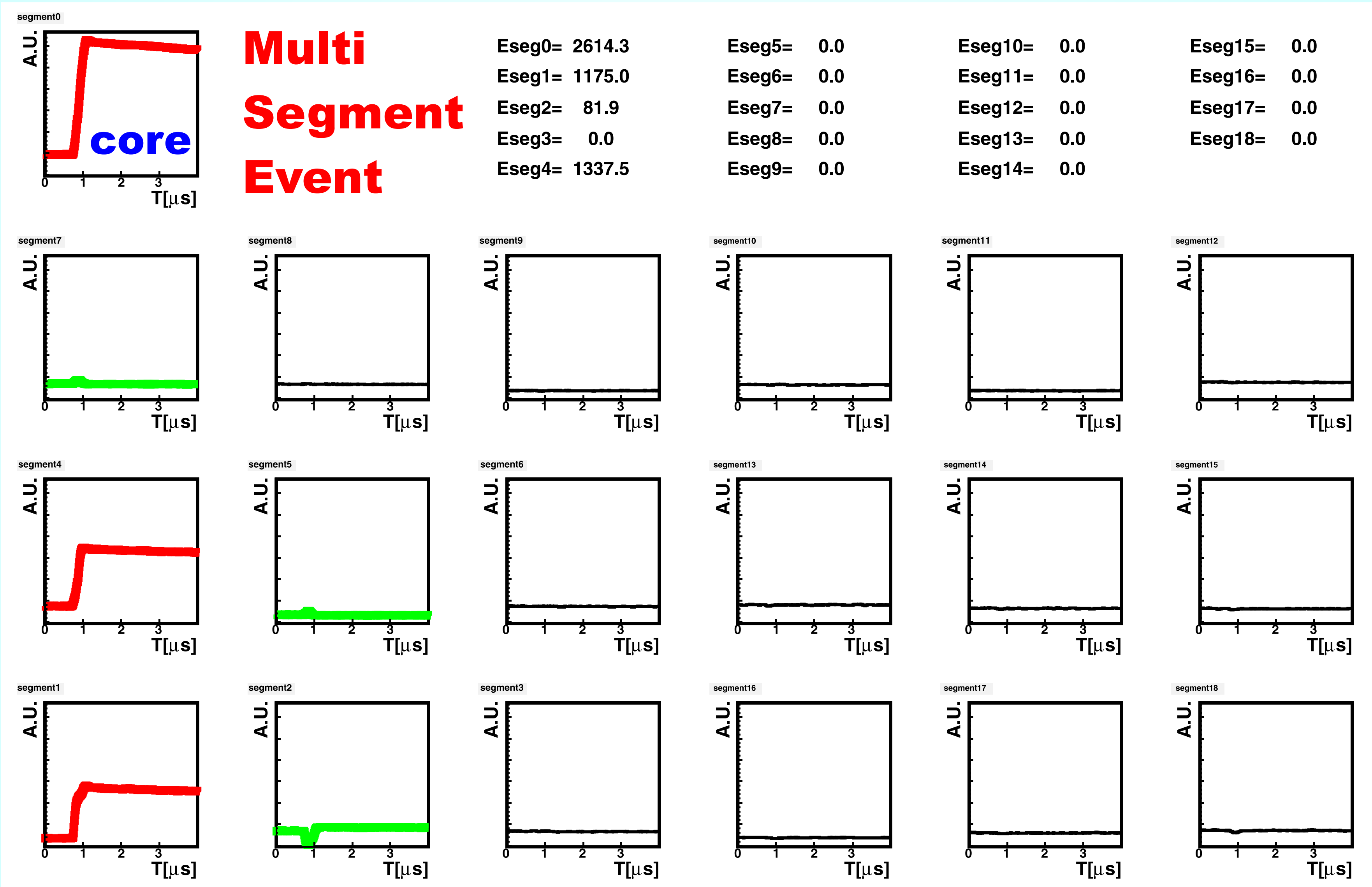


Single Segment Event

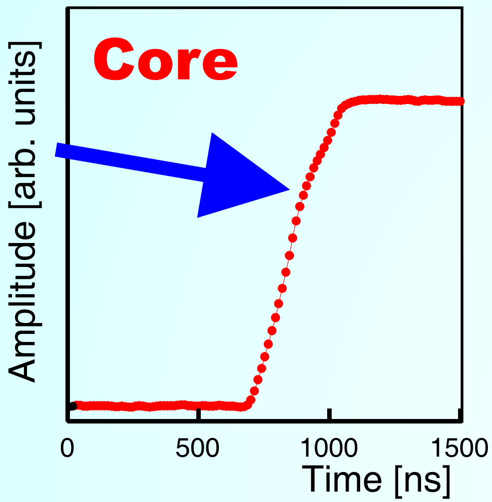
Eseg0= 1330.2	Eseg5= 0.0	Eseg10= 0.0	Eseg15= 0.0
Eseg1= 0.0	Eseg6= 0.0	Eseg11= 0.0	Eseg16= 0.0
Eseg2= 0.0	Eseg7= 0.0	Eseg12= 0.0	Eseg17= 1.1
Eseg3= 0.0	Eseg8= 0.0	Eseg13= 0.0	Eseg18= 0.4
Eseg4= 0.0	Eseg9= 0.0	Eseg14= 1327.6	



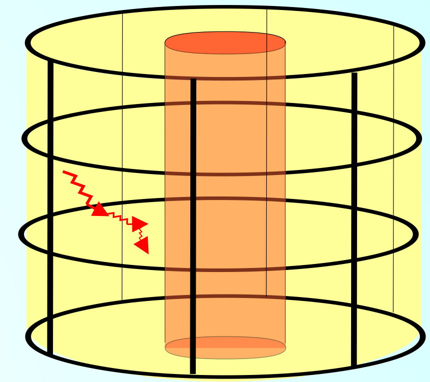
Event Complexity



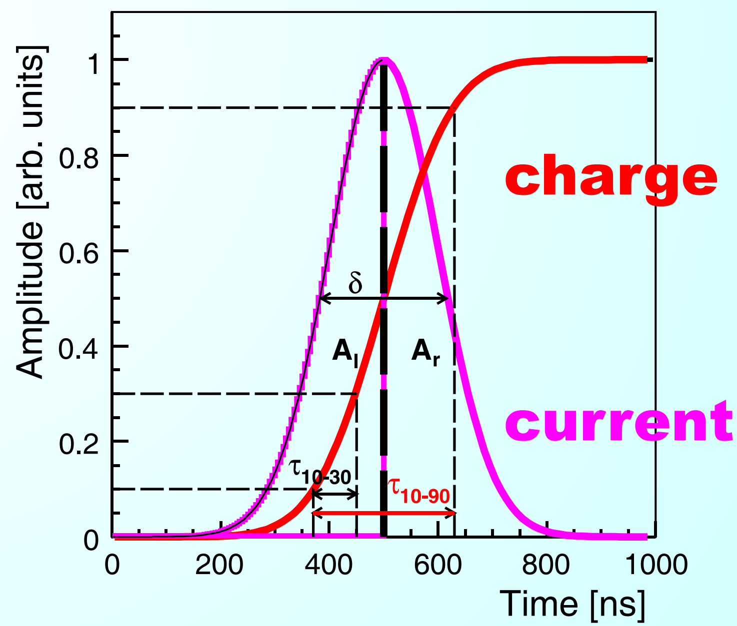
Pulse Shape Analysis



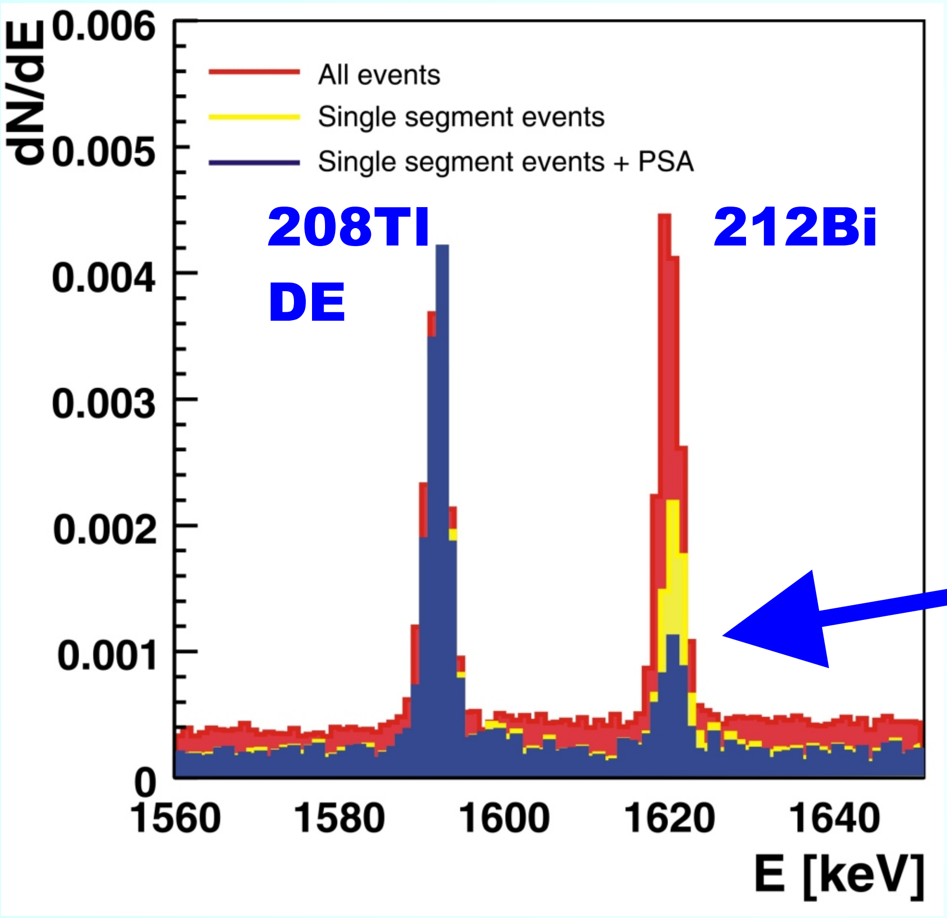
Use pulse shapes to identify multi-site events within one segment.



Counting kinks is not really easy → Calculate parameters of pulse and analyse them.



Pulse Shapes

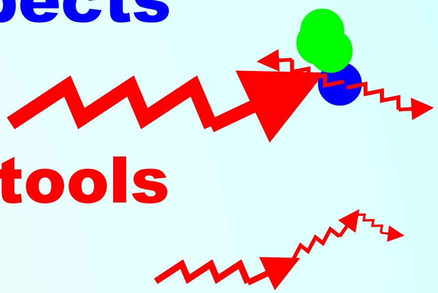


Pulse shapes can be used to identify multi-site events within one segment.

So far "core only"

Final Remarks

Germanium detectors are not as fashionable as silicon detectors and in some respects more archaic.



Germanium detectors are wonderful tools to understand radiation.

Germanium detectors offer a lot of opportunity to further investigate their properties:

charge transfer, charge trapping, surface effects,

.... .