Recent advancements in radiation detectors for precision experiments

(and what do we use them for)

“The Hitchhiker's Advanced Guide to Quantum Collapse Models
and their impact in science, philosophy, technology and biology”
A. Scordo, LNF, Frascati, 03/10/2022

Suitable detector(s) for each radiation

Transition Edge Sensors (TES): Microcalorimetry

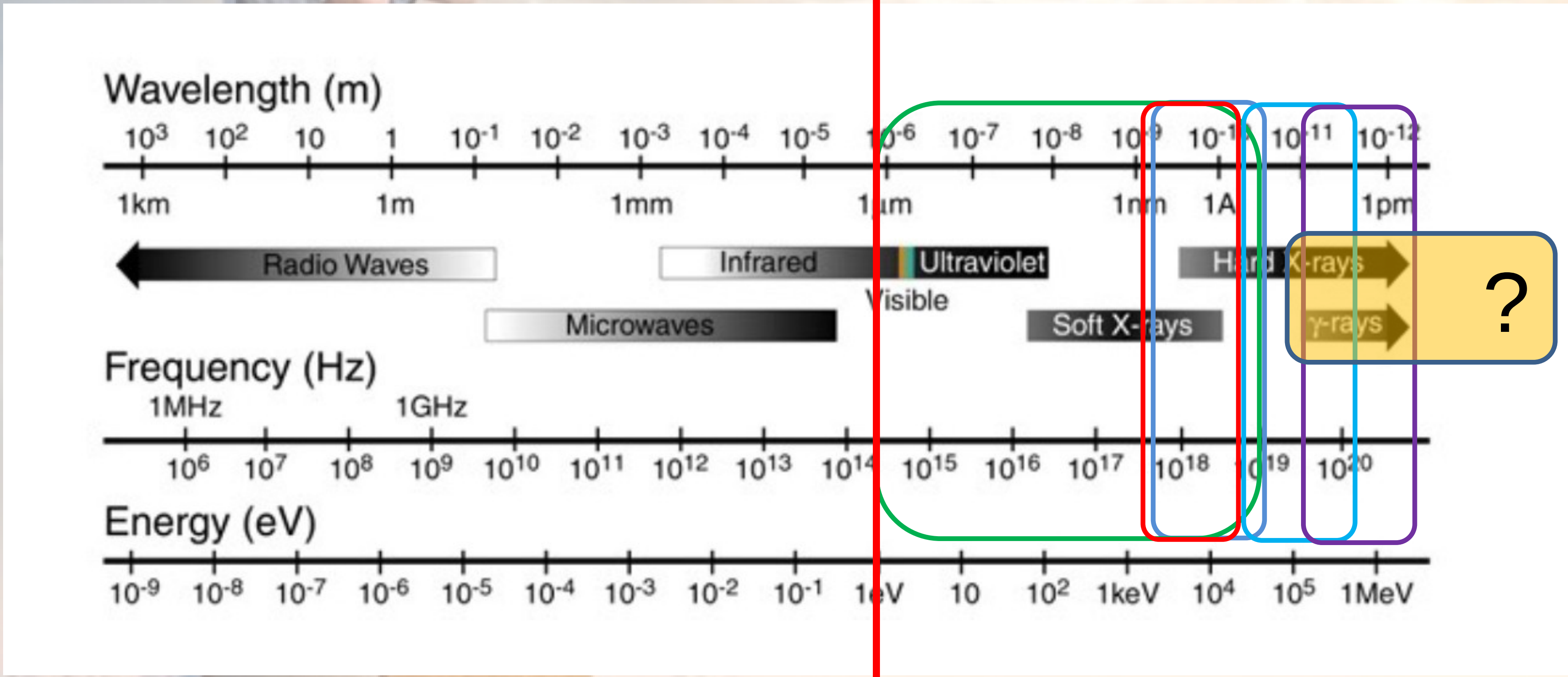
Bragg Spectrometers

Silicon Detectors

CdZnTe Detectors

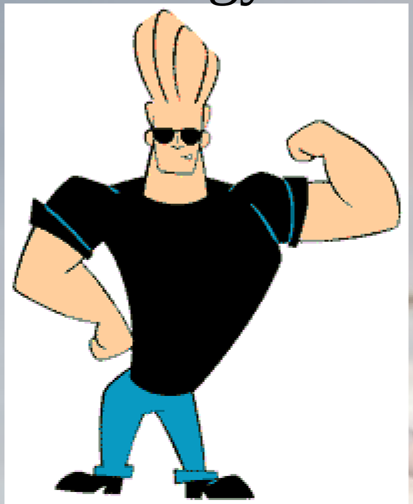
Ge Detectors

} Semiconductors

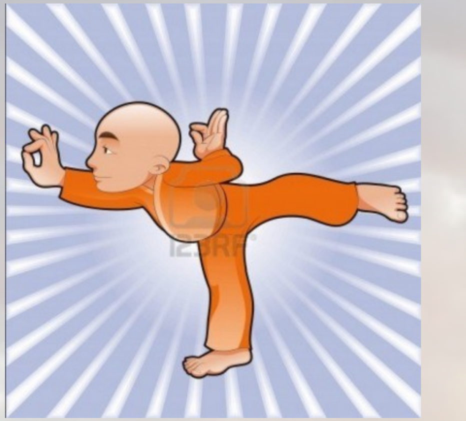


What do we want (could) measure...

Energy



Position

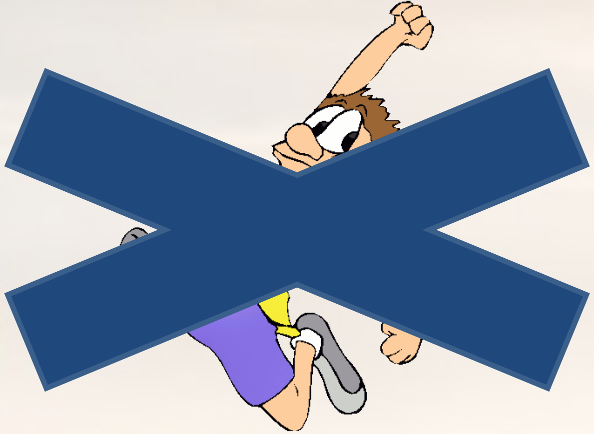


Multiplicity

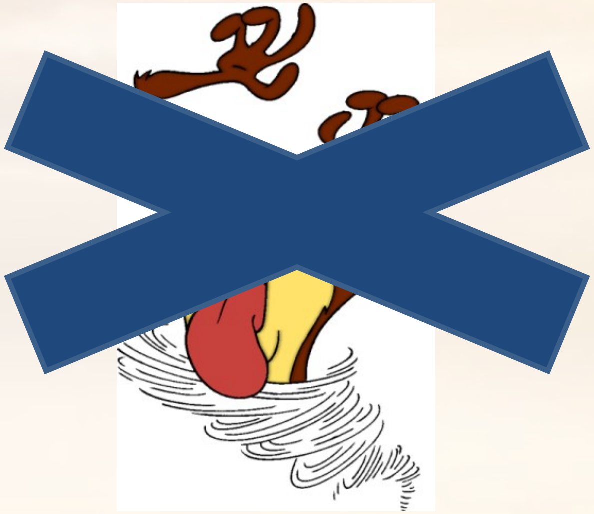
u

Direction

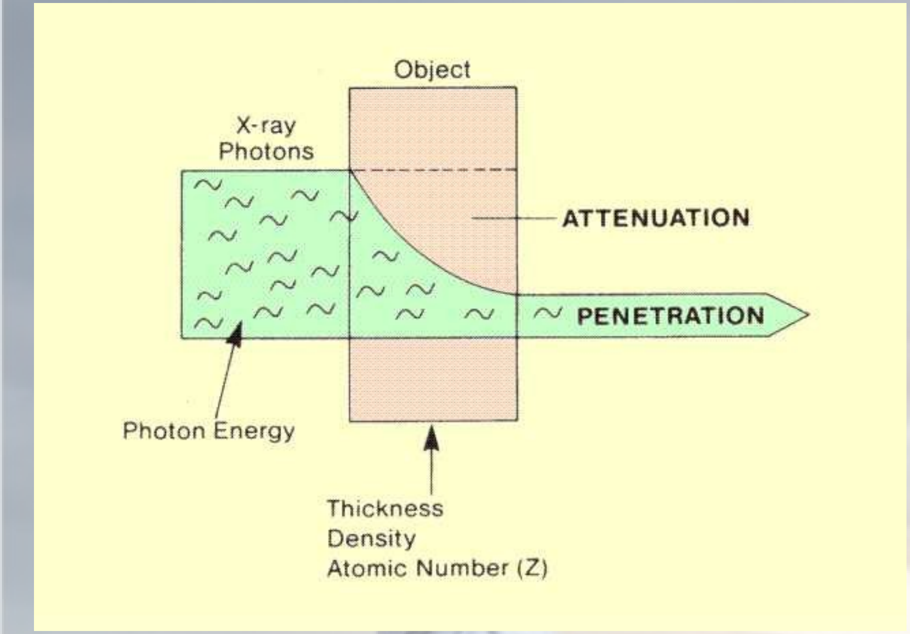
Time



Rates



… and how



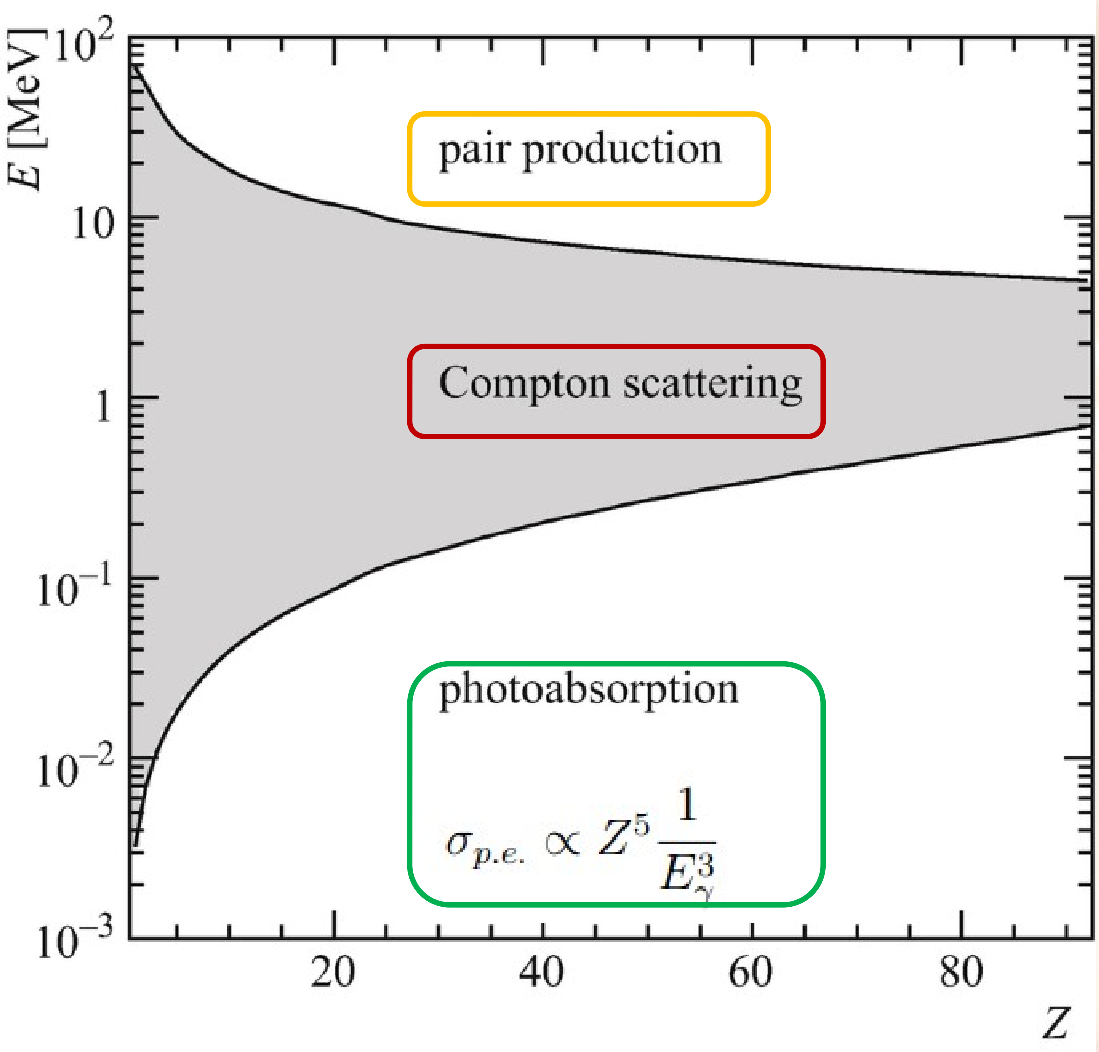
Photon absorption is a binary process

No energy loss like for charged particles

Photoelectric effect: main effect for visible, X and gamma radiation
TO BE MAXIMIZED

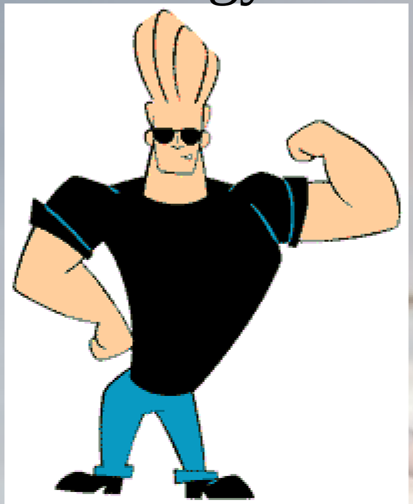
Compton effect: unwanted, source of background and loss in resolution
TO BE MINIMIZED

Pair generation: main effect for HEP experiments
NOT INTERESTING FOR OUR RANGES

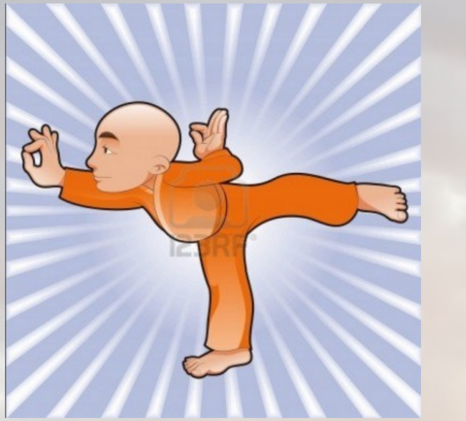


What do we want (could) measure...

Energy



Position

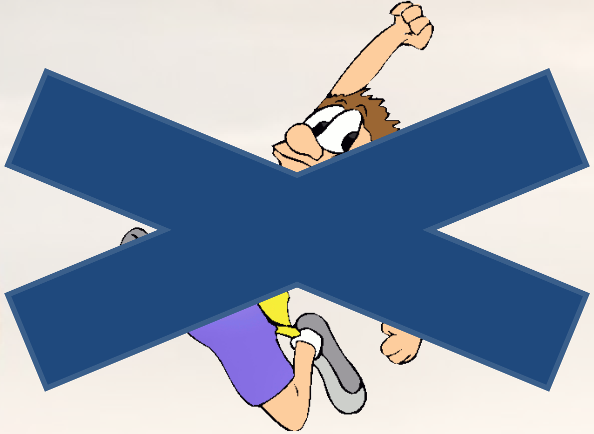


Multiplicity

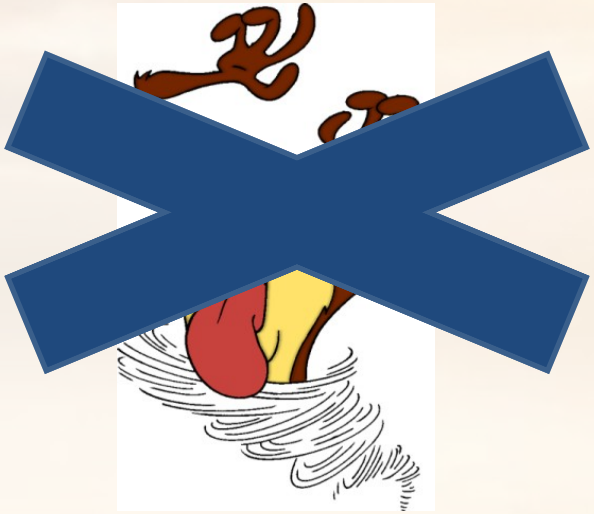
u

Polarization

Time



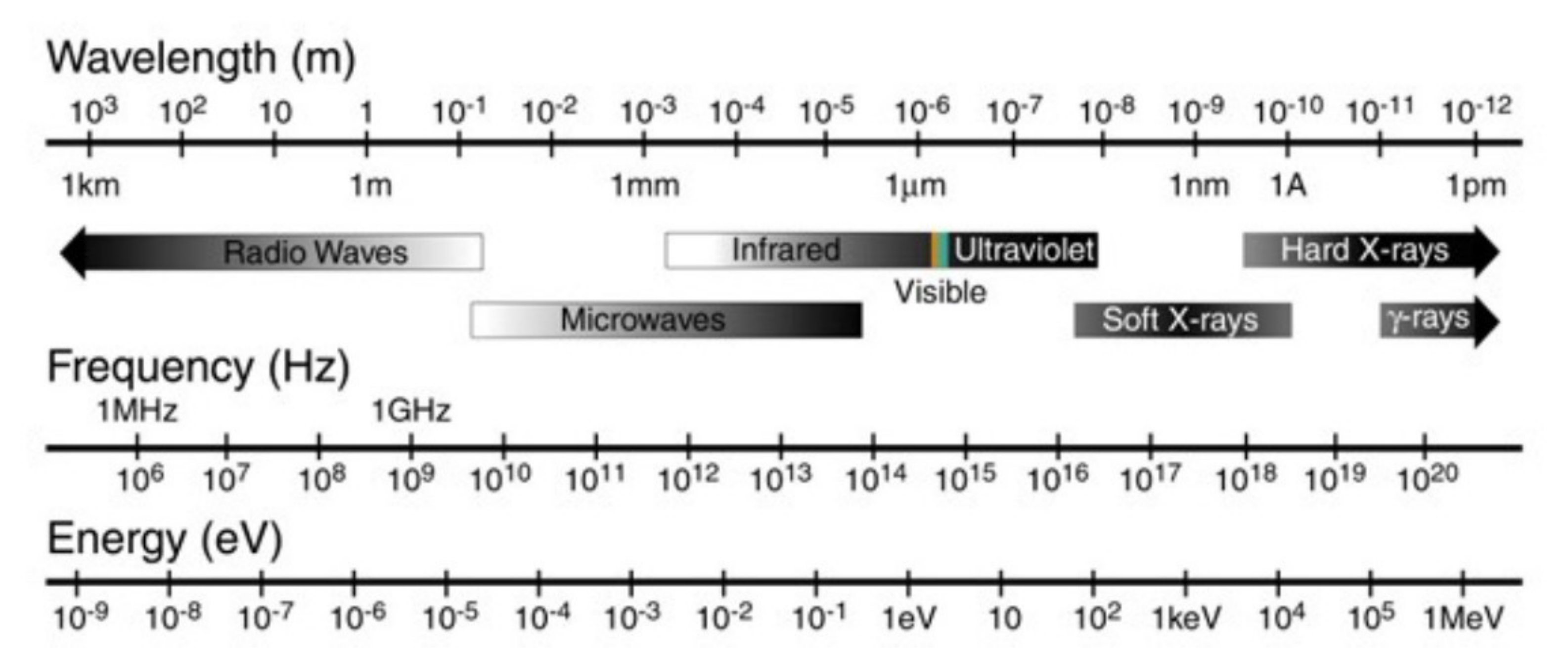
Rates



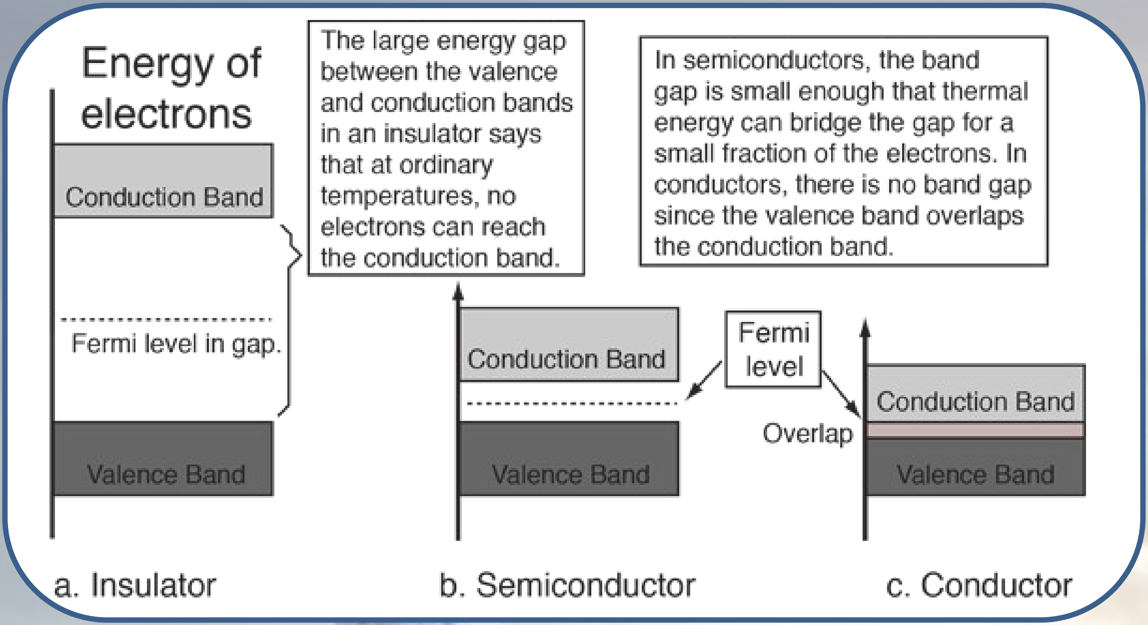
Suitable detector(s) for each radiation

- Silicon Detectors
- CdZnTe Detectors
- Ge Detectors

Semiconductors



Semiconductor detectors



The large energy gap between the valence and conduction bands in an insulator says that at ordinary temperatures, no electrons can reach the conduction band.

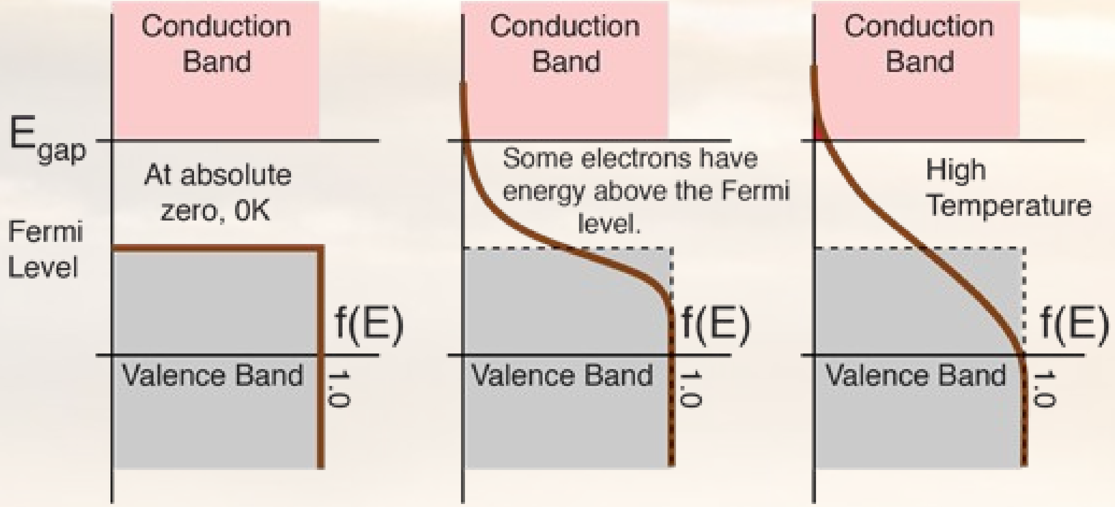
In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

probability that a given available electron energy state will be occupied at a given temperature

$k_BT \sim 0.025$ eV @ 300 K

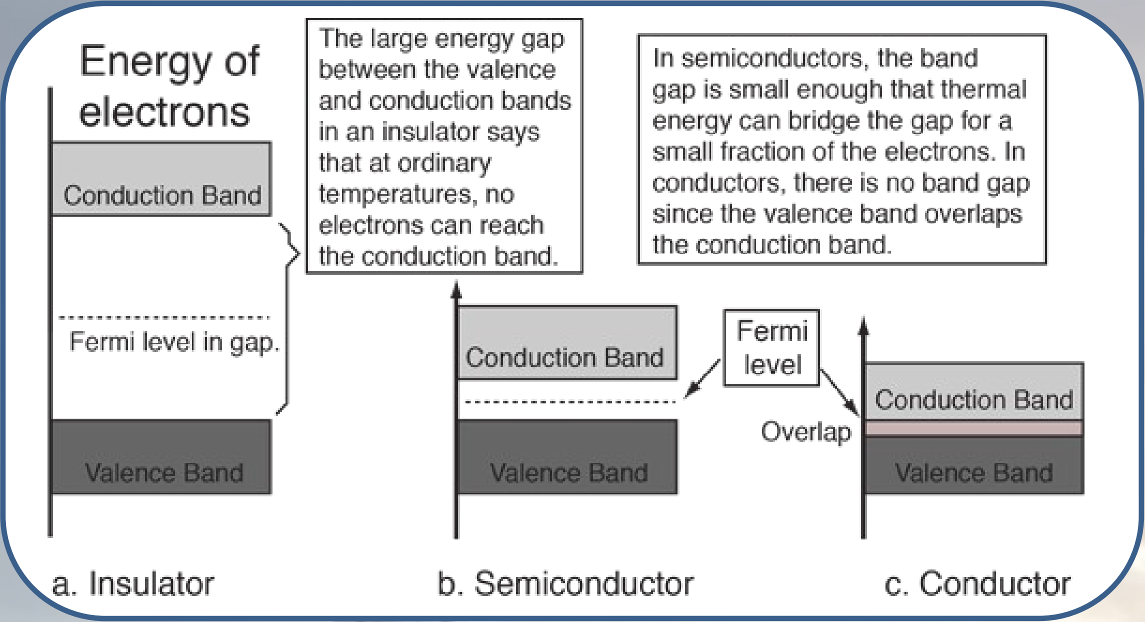
Playing with Temperature allows moving the Fermi Level



No electrons can be above the Fermi level at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

Semiconductor detectors



The large energy gap between the valence and conduction bands in an insulator says that at ordinary temperatures, no electrons can reach the conduction band.

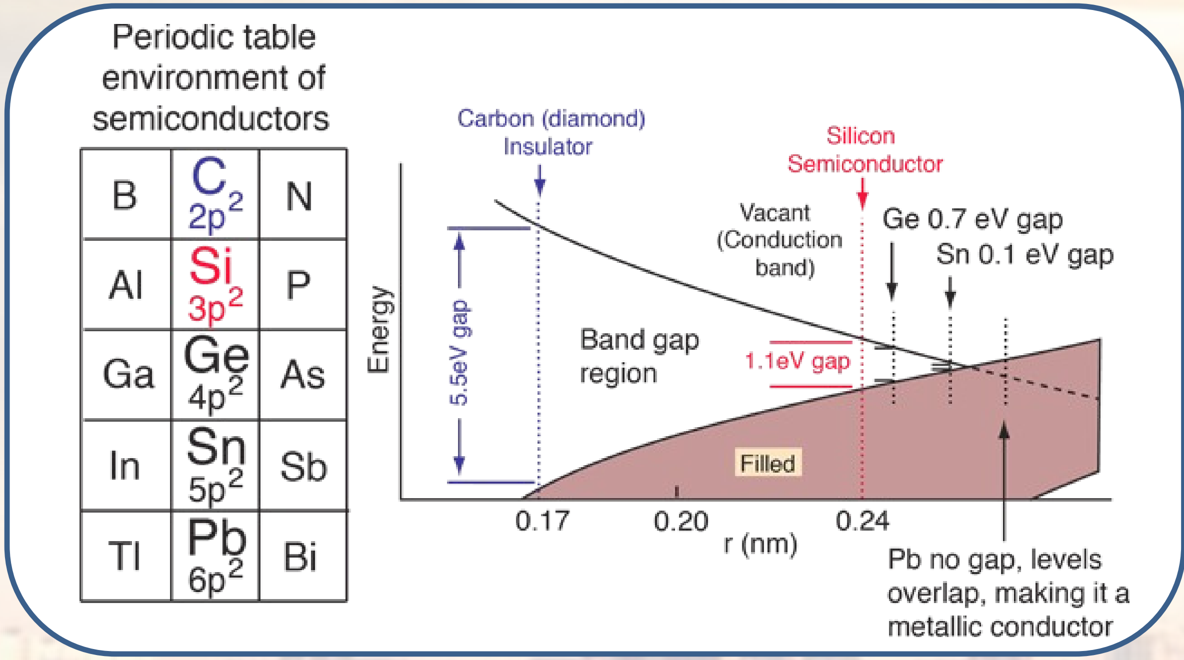
In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.

$$P(T) = C\,T^{3/2} e^{-E_g/2k_BT}$$

Probability to thermally promote an electron in the conduction band

$k_BT \sim 0.025$ eV @ 300 K

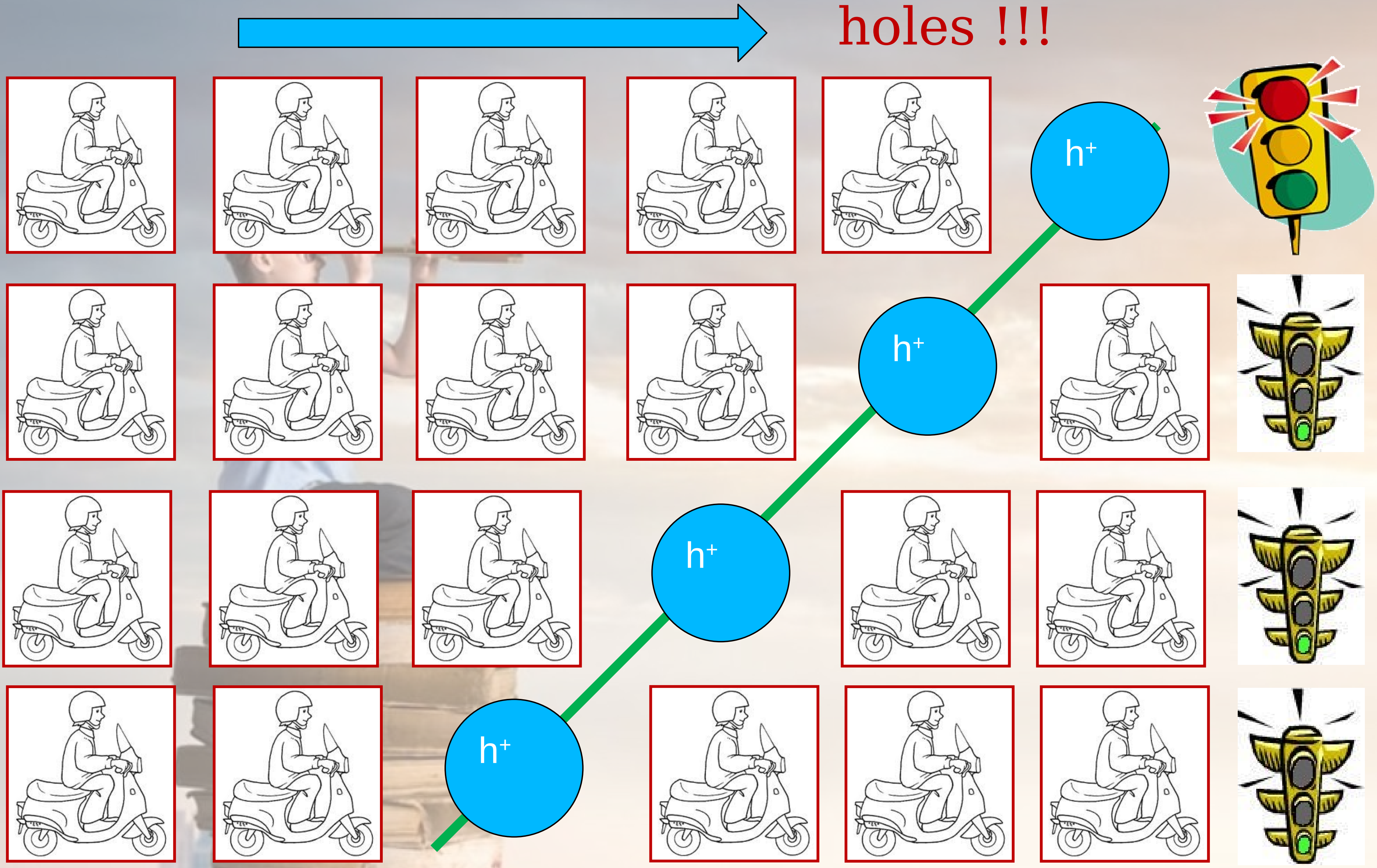
This is why Silicon and, most of all, Germanium detectors need to be cooled down


Periodic table environment of semiconductors

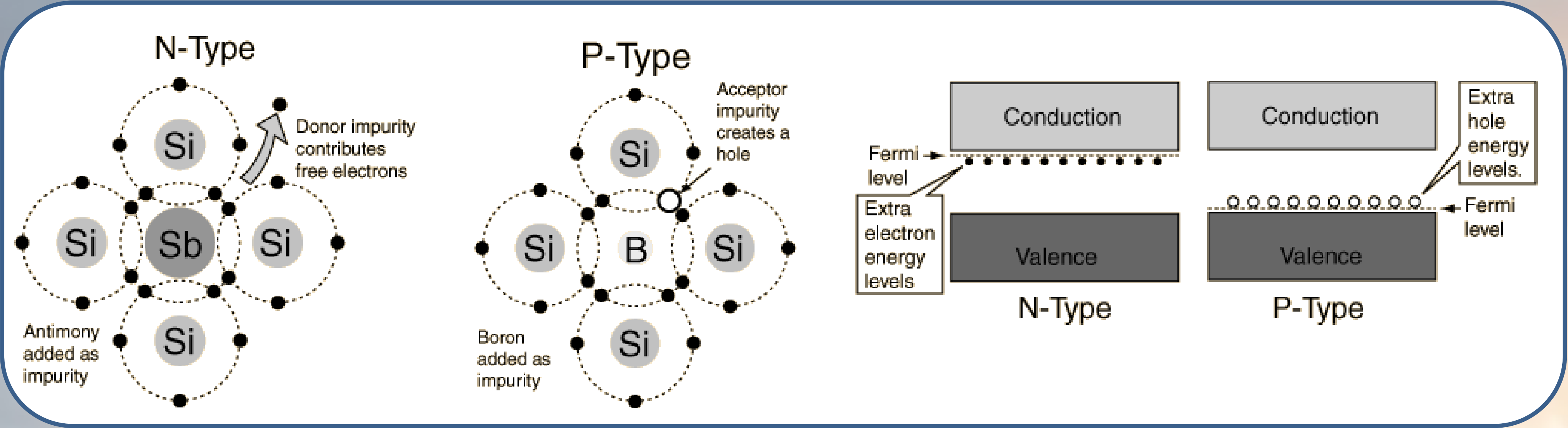
B	C $2p^2$	N
Al	Si $3p^2$	P
Ga	Ge $4p^2$	As
In	Sn $5p^2$	Sb
Tl	Pb $6p^2$	Bi

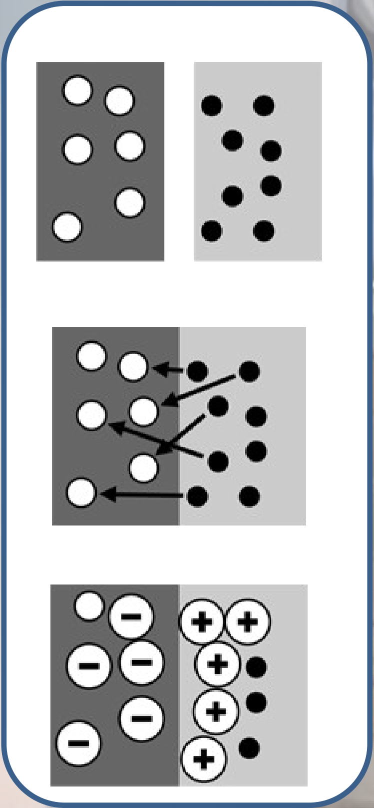
Physicists must be smart and clever….

holes !!!



..and use drugs!!!



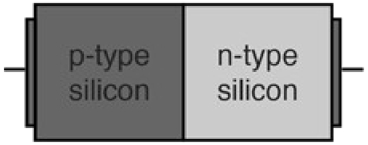


● Electron ○ Hole ⊖ Negative ion from filling of p-type vacancy. ⊕ Positive ion from removal of electron from n-type impurity.

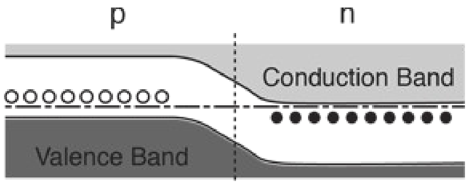
Near a junction, electrons diffuse across to combine with holes, creating a "depletion region" which inhibits any further electron transfer unless it is helped by putting a forward bias on the junction.

Semiconductor detectors

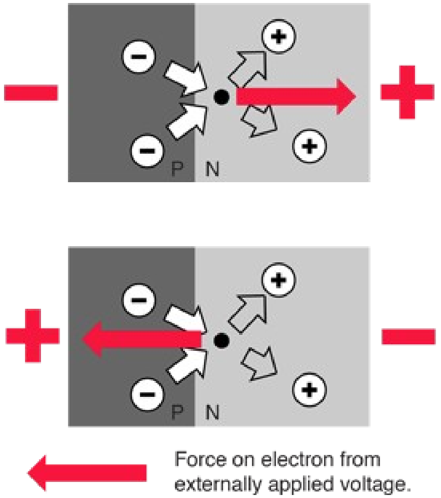
Situation at equilibrium



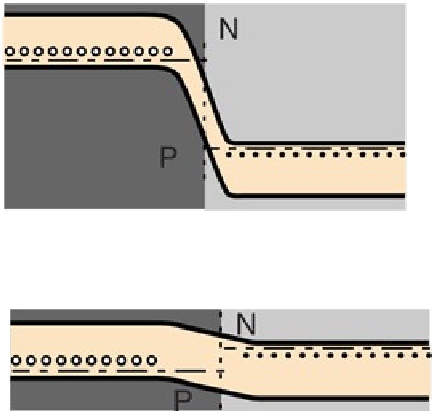
p-n junction

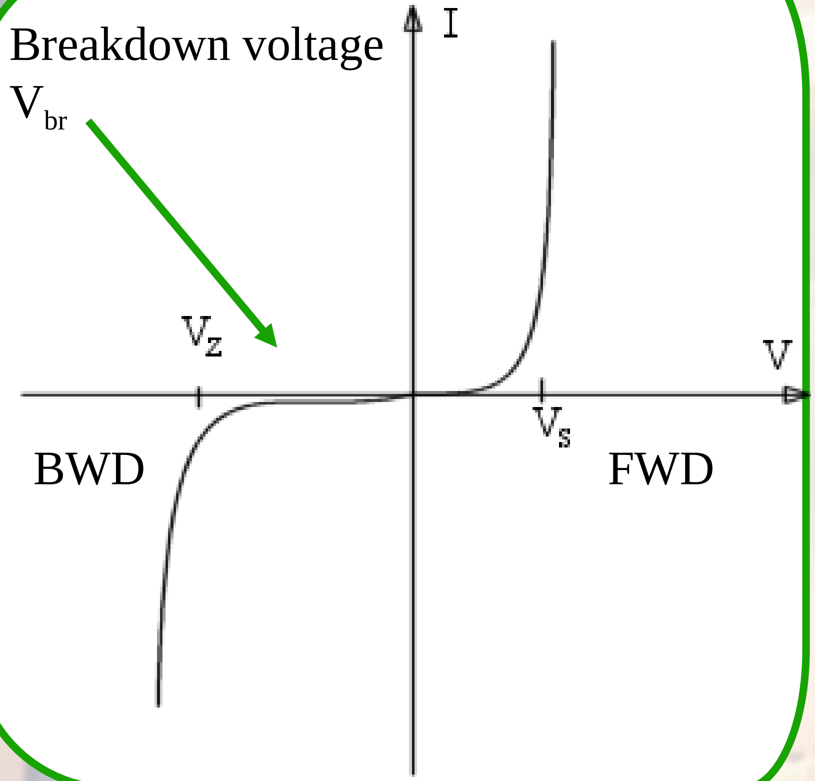


Energy bands at equilibrium



Force on electron from externally applied voltage.





PN junction is the elemental brick for all semiconductor devices

Silicon Drift Detectors

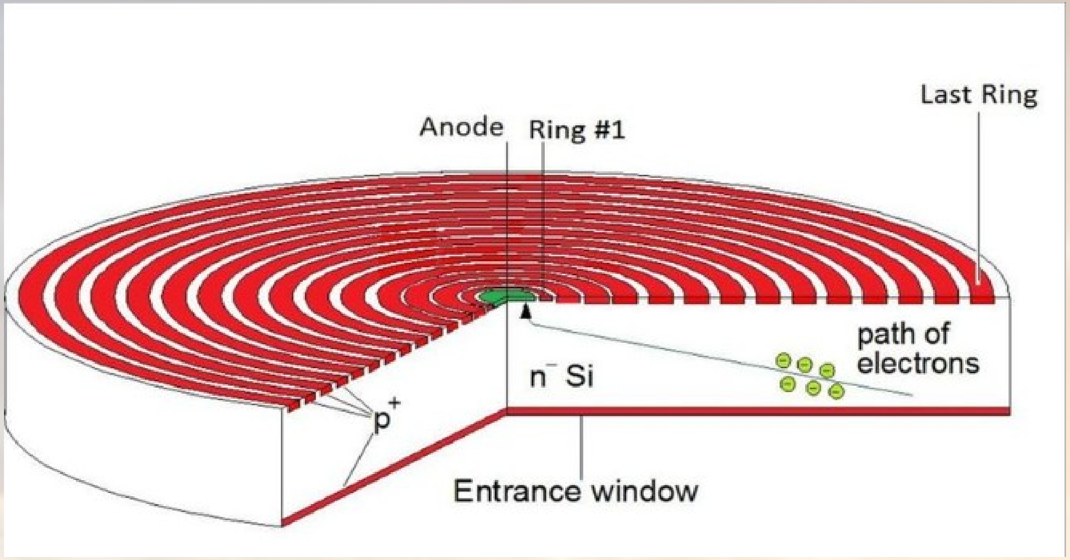
Perfect linearity and easy calibration

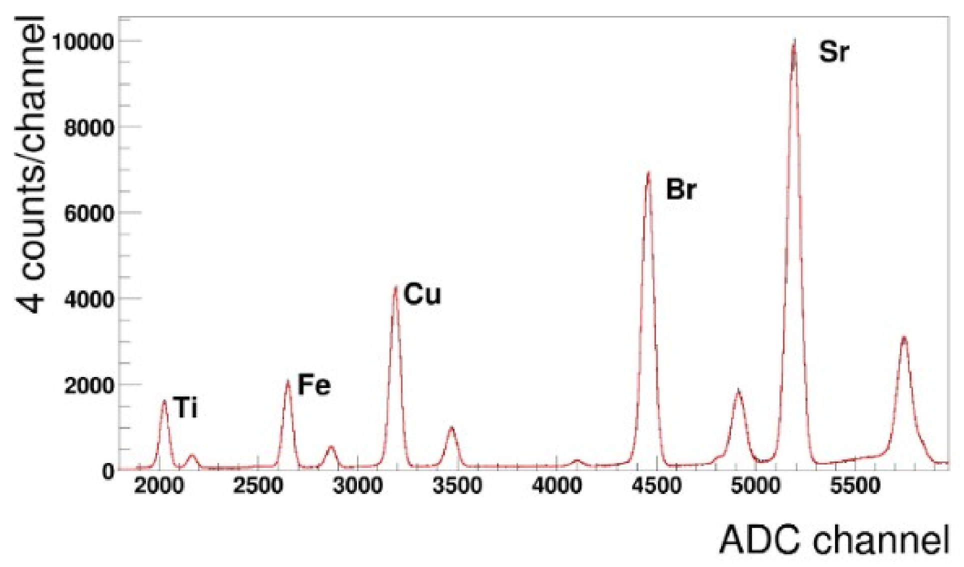
Large area and geometrical efficiency

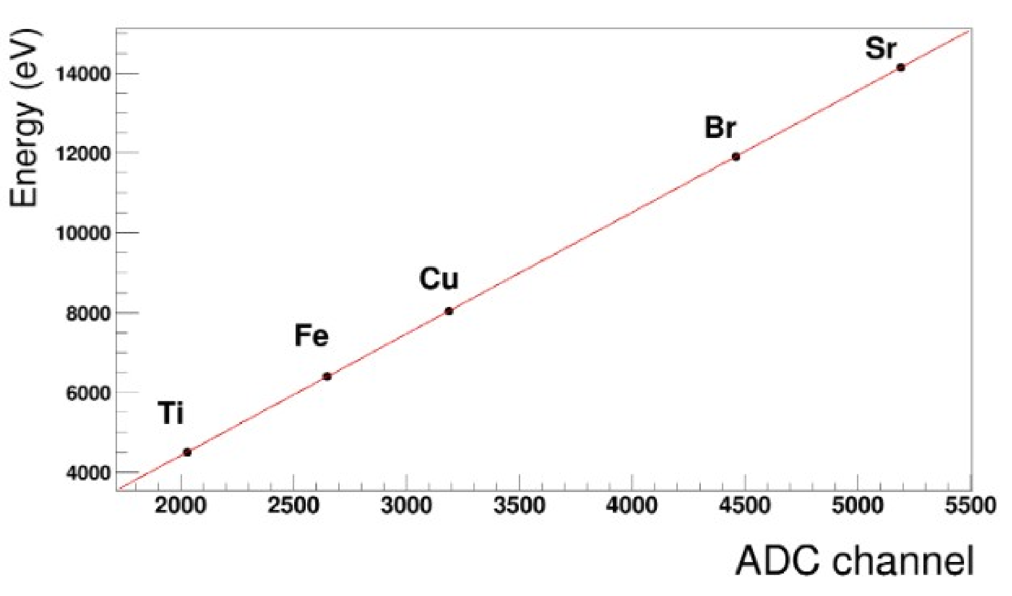
Fast readout for triggering

Suitable for 4-20 keV
(450 μm thickness)

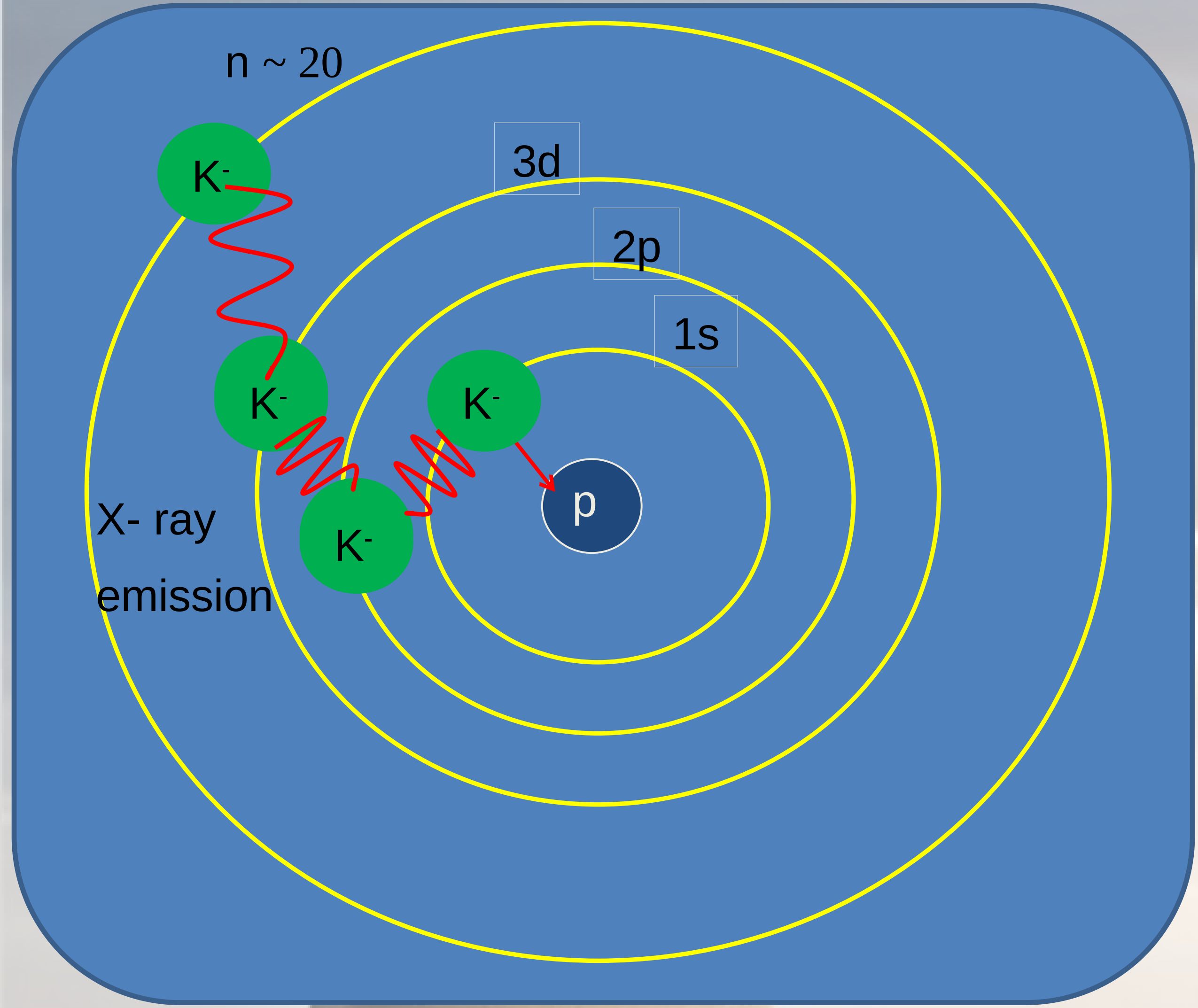
Resolution limited to ~120 eV





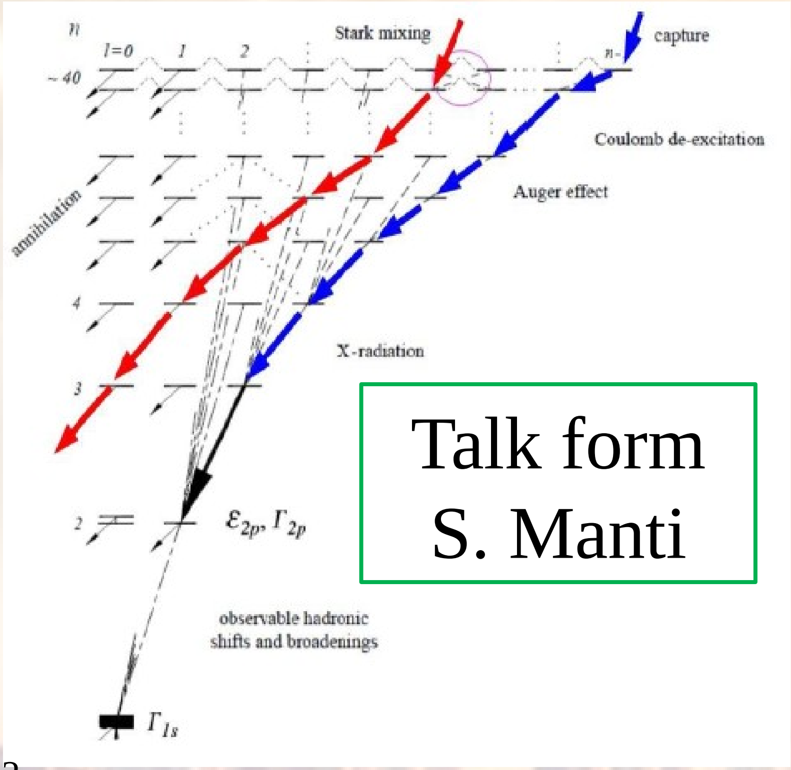


Silicon Drift Detectors for kaonic atoms



$$E_{1s} \simeq m_{red} c^2 \frac{\alpha^2 Z^2}{2}$$

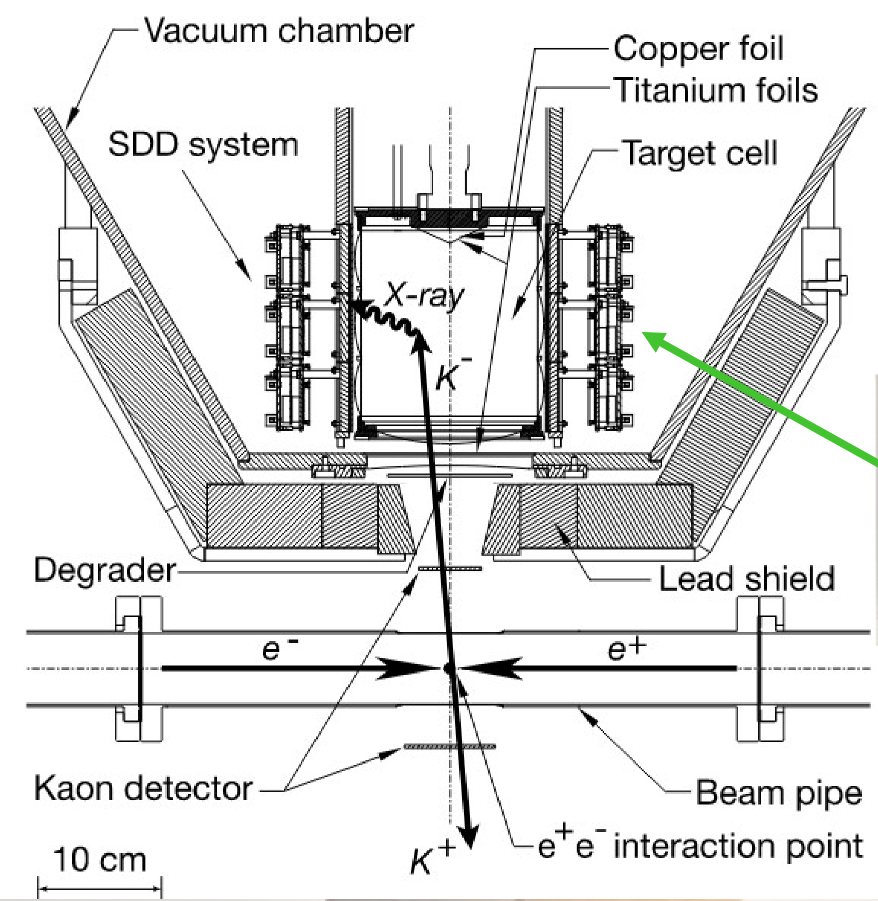
$$n \simeq \sqrt{\frac{m_{red}}{m_e}} n_e$$

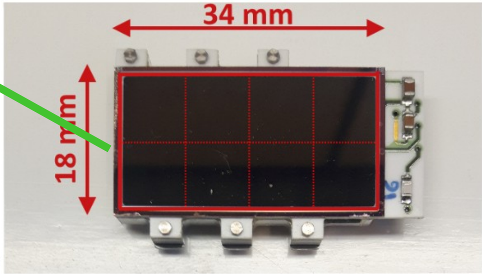


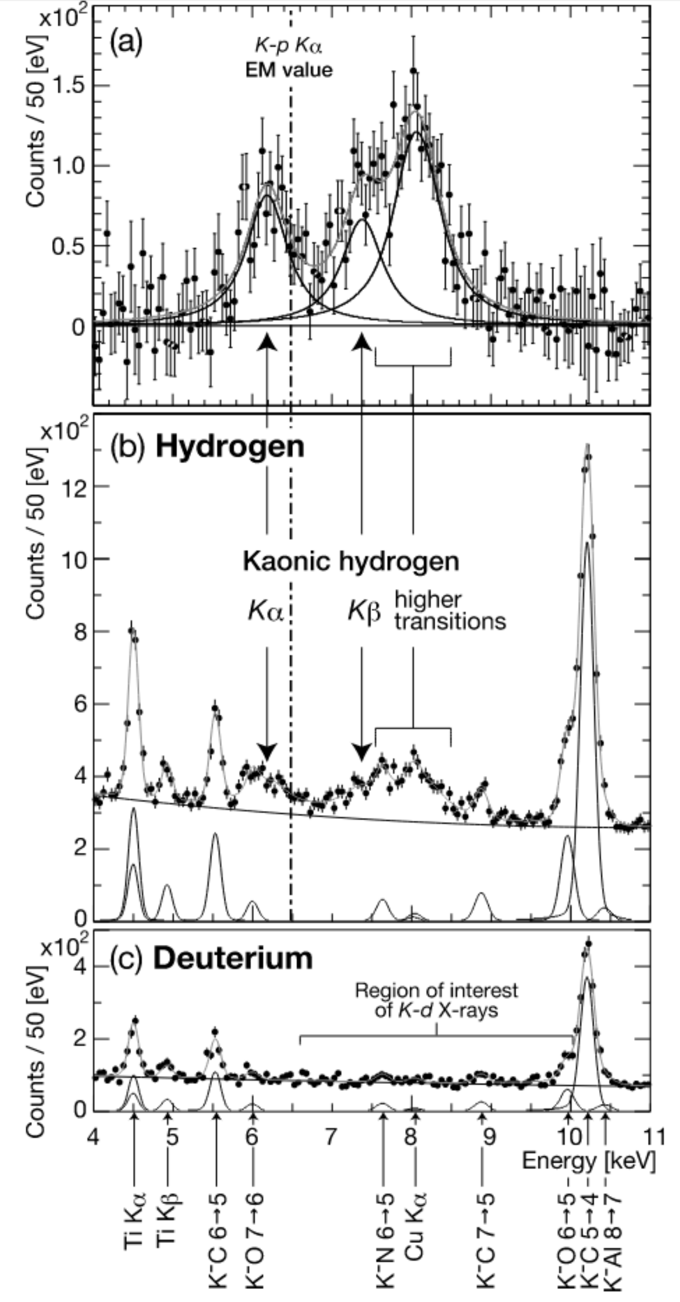
Talk form
S. Manti

Shifts and widths with respect to pure electromagnetic calculations provide information on the strong interaction

Silicon Drift Detectors







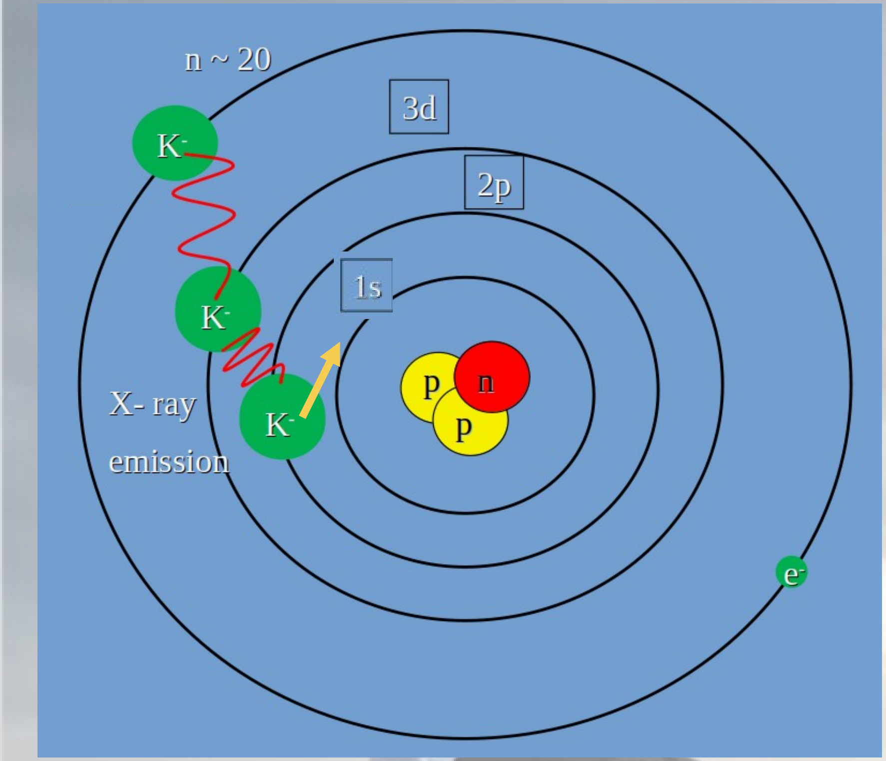
$$\epsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$

and $\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV},$

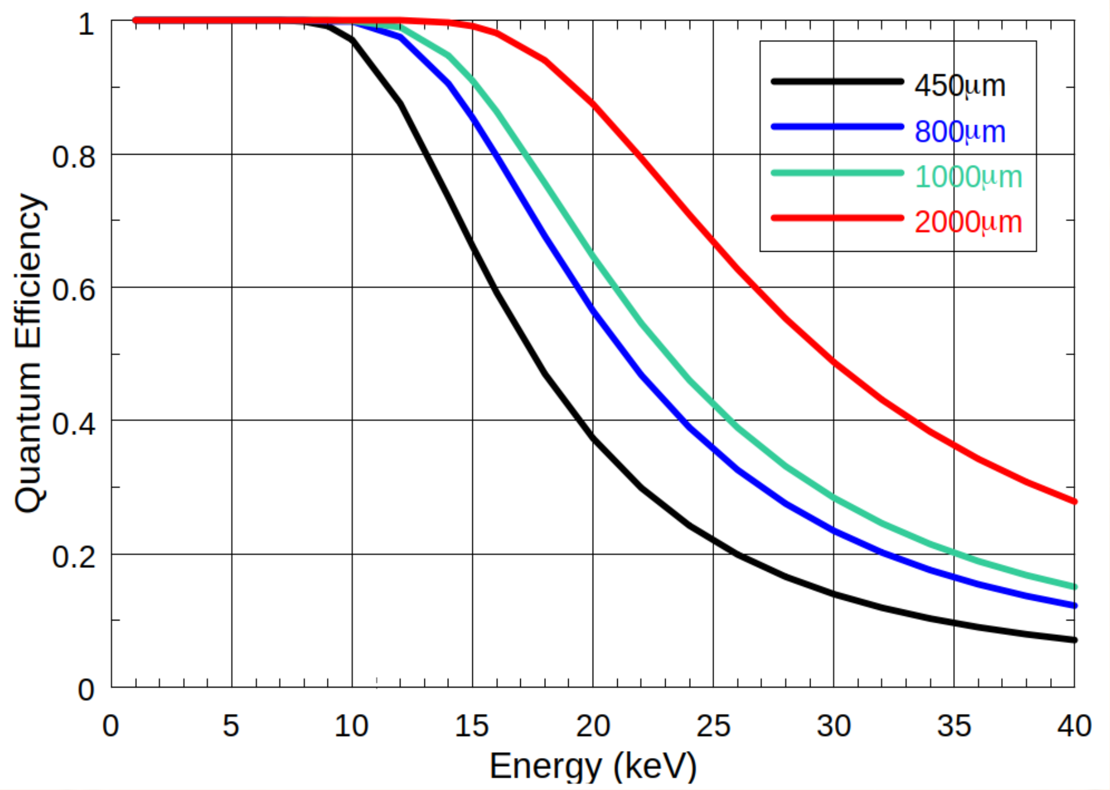
Most precise measurement of 1s level shift and width in KH

SIDDHARTA Collaboration / Physics Letters B 704 (2011) 113–117

Silicon Drift Detectors



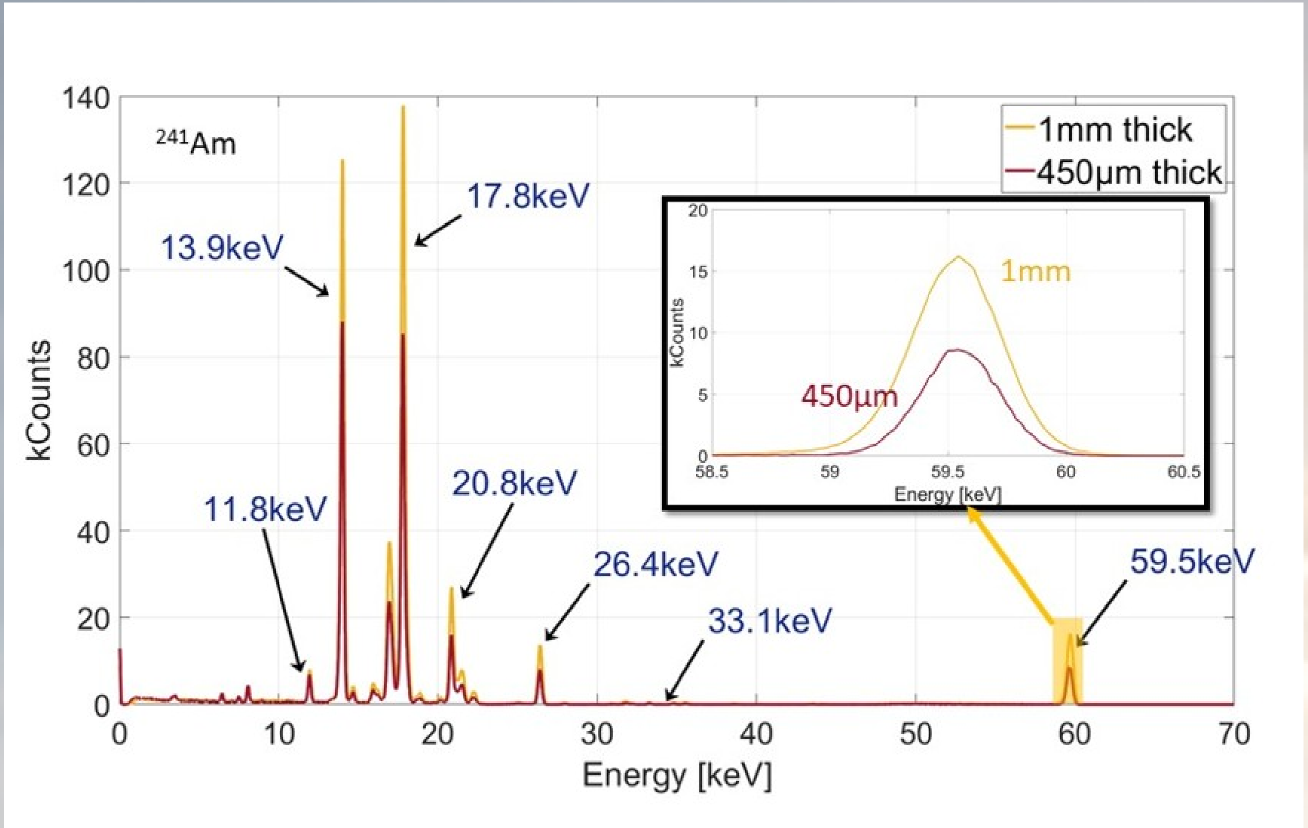
Measurement of 1s level shift and width of KHe is one of the most wanted measurement in our community but the transition is expected at ~30 keV



Thicker SDDs could be used to extend the working range

This is not trivial and there are technological limitations to overcome

Silicon Drift Detectors



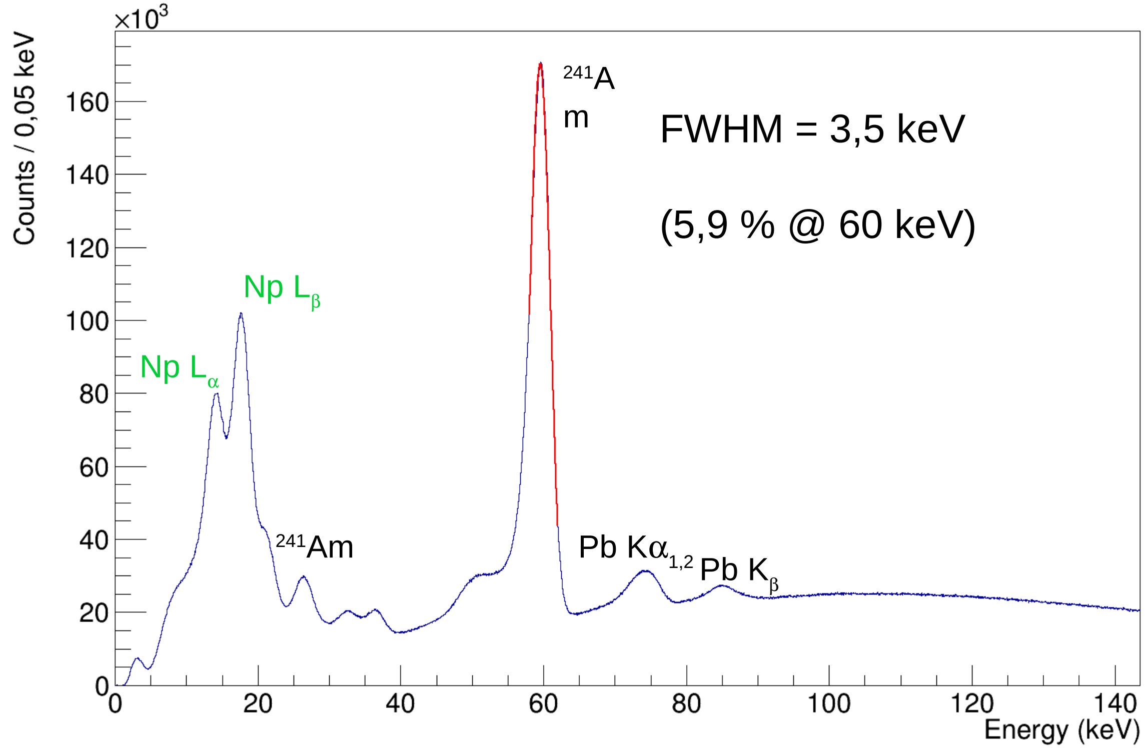
First XRF tests with known targets show very promising results

Efficiency @ 60 keV is increased of 100%

1-2 mm SDDs already financed by INFN CSN3

800μm and 1mm SDDs prototypes already produced by FBK for ARDESIA (INFN)

CdZnTe detectors

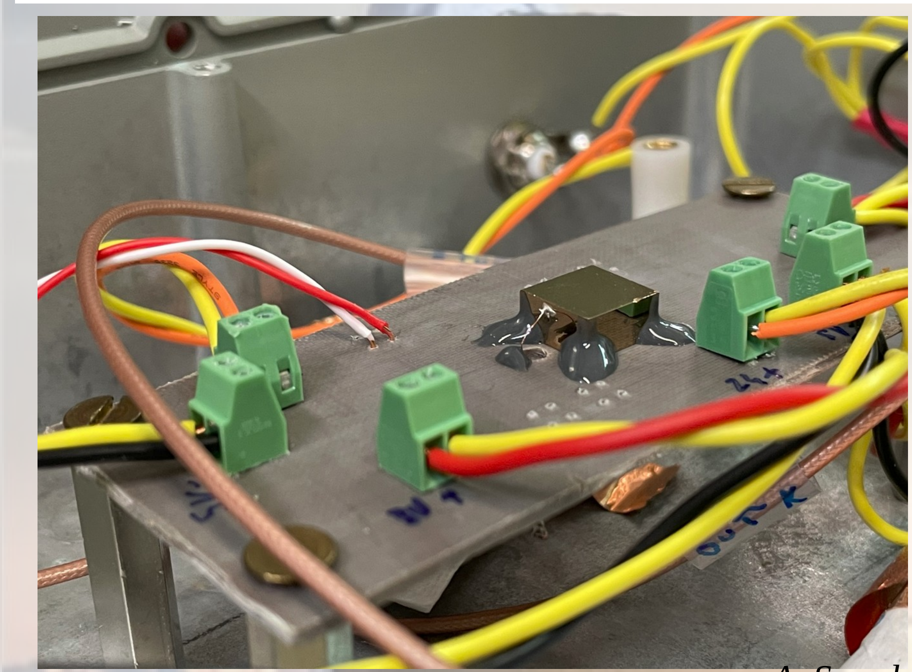


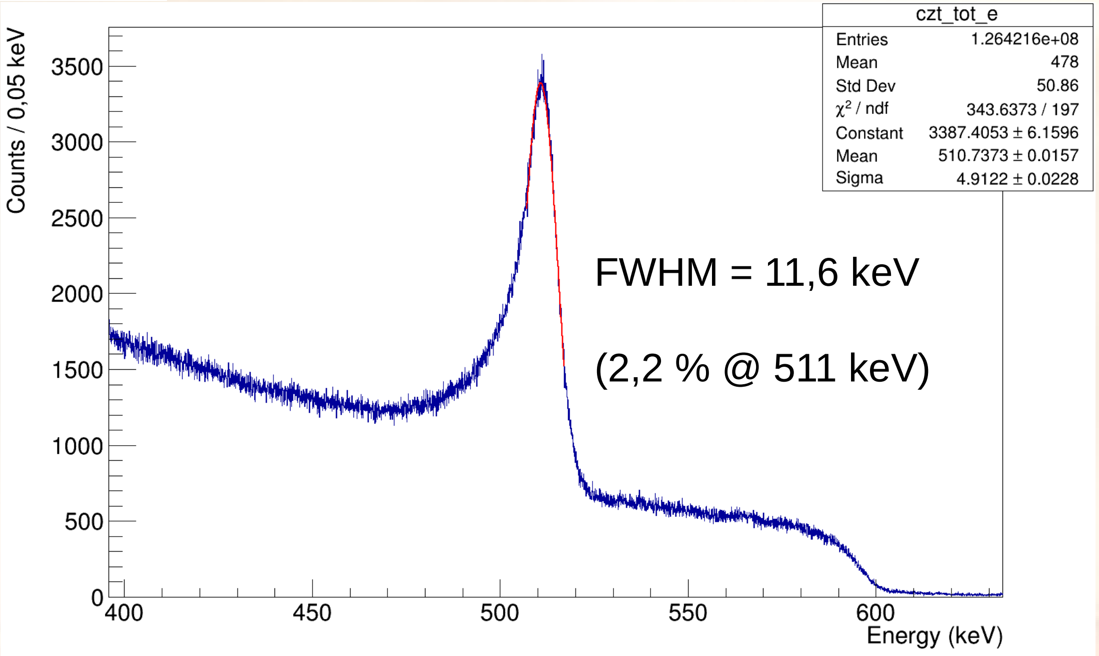
High efficiency and linearity in a broad energy range (optimizable between 20-30 keV and 1-2 MeV)

Good energy resolutions with no need for cooling

Fast readout for triggering

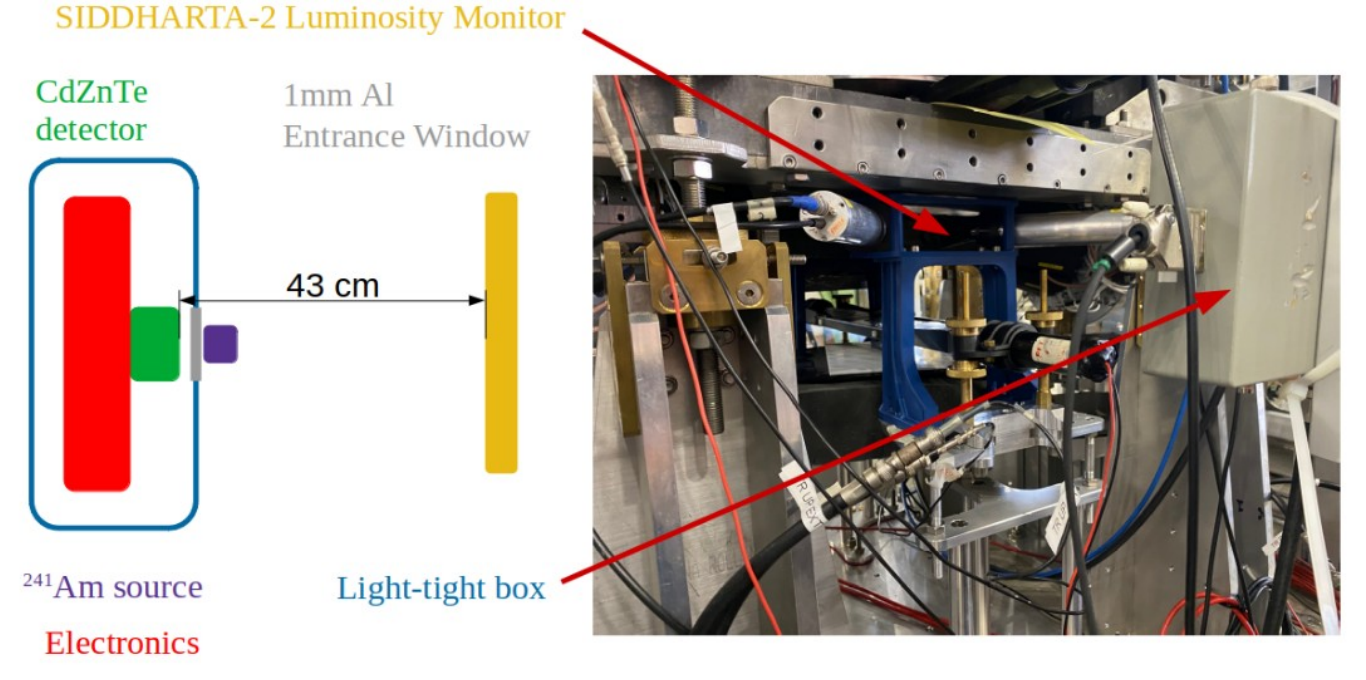
More recent technology, not “commercial” yet





CZT: first tests @ DAΦNE

Goal: background and resolution assessment in machine environment (first time)

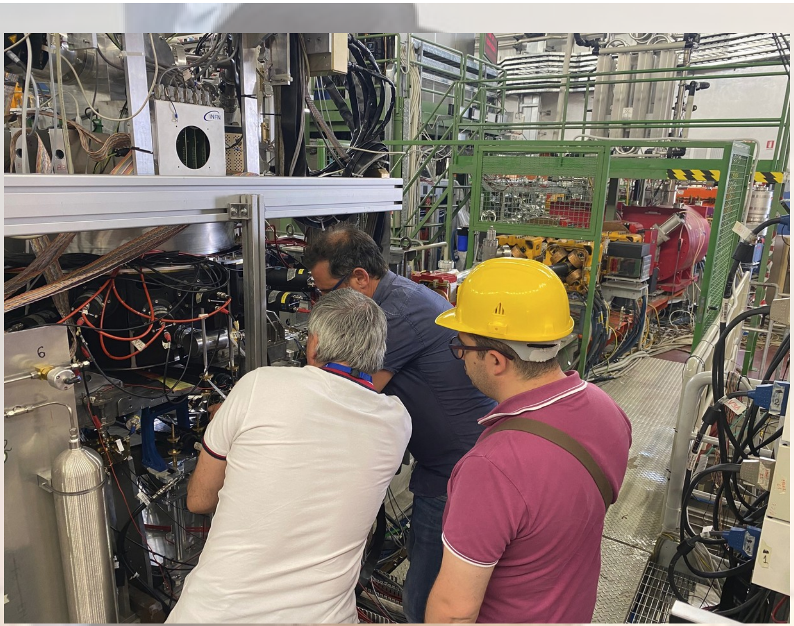


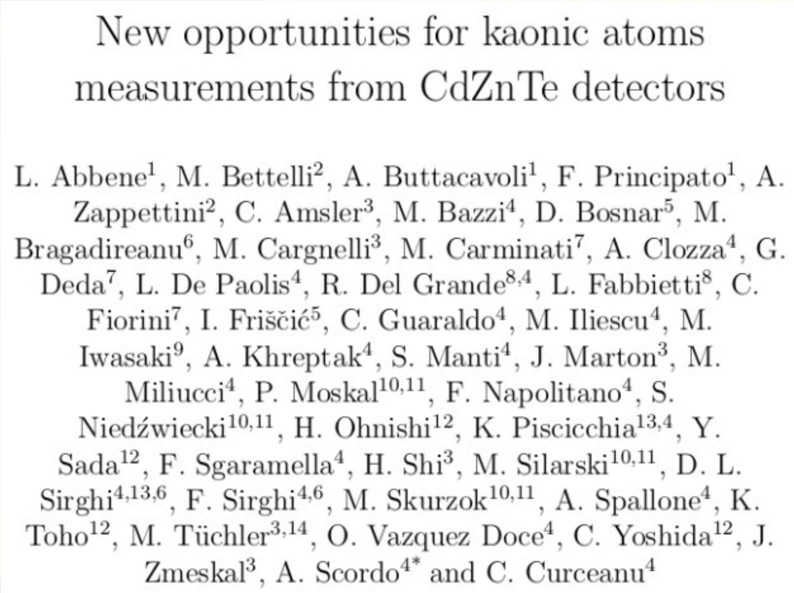
22/06/2022:

First prototype installed in DAΦNE

Promising results obtained ON BEAM

First technical paper submitted

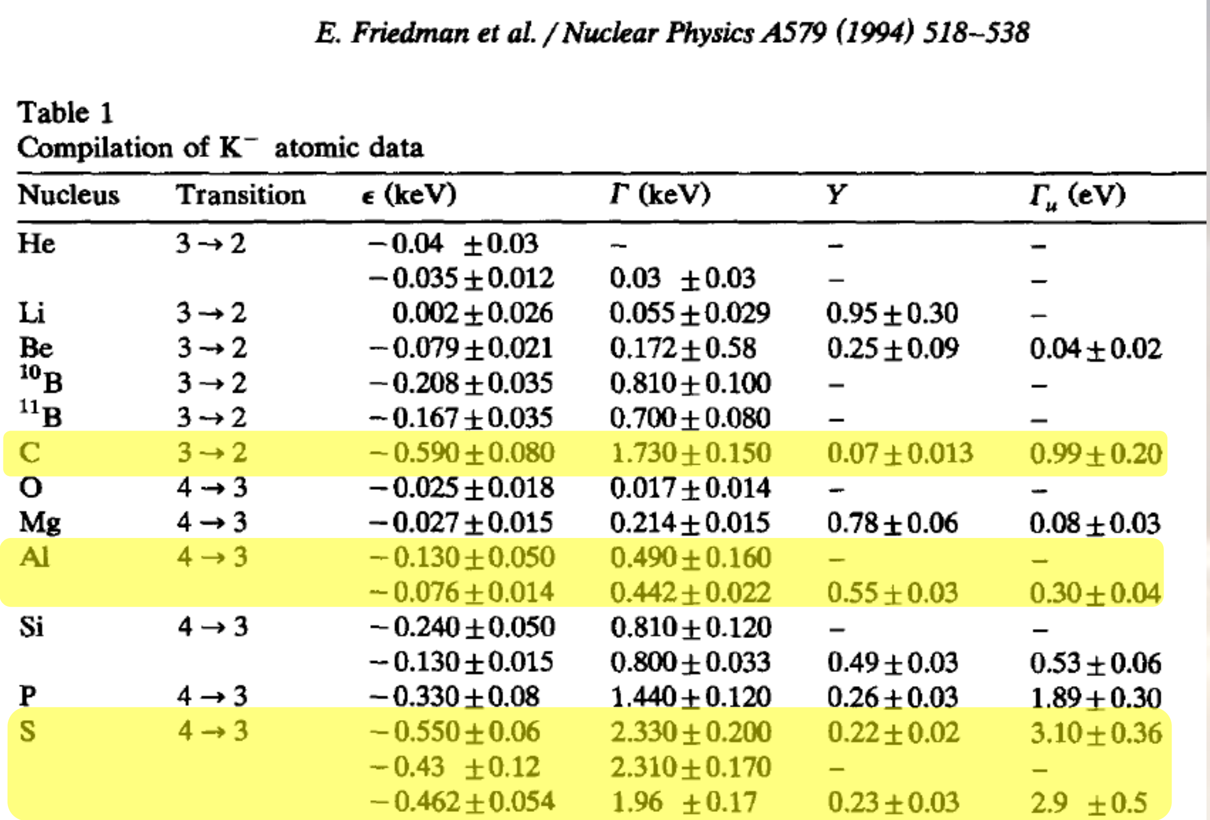




New opportunities for kaonic atoms measurements from CdZnTe detectors

L. Abbene[1], M. Bettelli[2], A. Buttacavoli[1], F. Principato[1], A. Zappettini[2], C. Amsler[3], M. Bazzi[4], D. Bosnar[5], M. Bragadireanu[6], M. Cargnelli[3], M. Carminati[7], A. Clozza[4], G. Deda[7], L. De Paolis[4], R. Del Grande[8,4], L. Fabbietti[8], C. Fiorini[7], I. Friščić[5], C. Guaraldo[4], M. Iliescu[4], M. Iwasaki[9], A. Khreptak[4], S. Manti[4], J. Marton[3], M. Miliucci[4], P. Moskal[10,11], F. Napolitano[4], S. Niedźwiecki[10,11], H. Ohnishi[12], K. Piscicchia[13,4], Y. Sada[12], F. Sgaramella[4], H. Shi[3], M. Silarski[10,11], D. L. Sirghi[4,13,6], F. Sirghi[4,6], M. Skurzok[10,11], A. Spallone[4], K. Toho[12], M. Tüchler[3,14], O. Vazquez Doce[4], C. Yoshida[12], J. Zmeskal[3], A. Scordo[4*] and C. Curceanu[4]

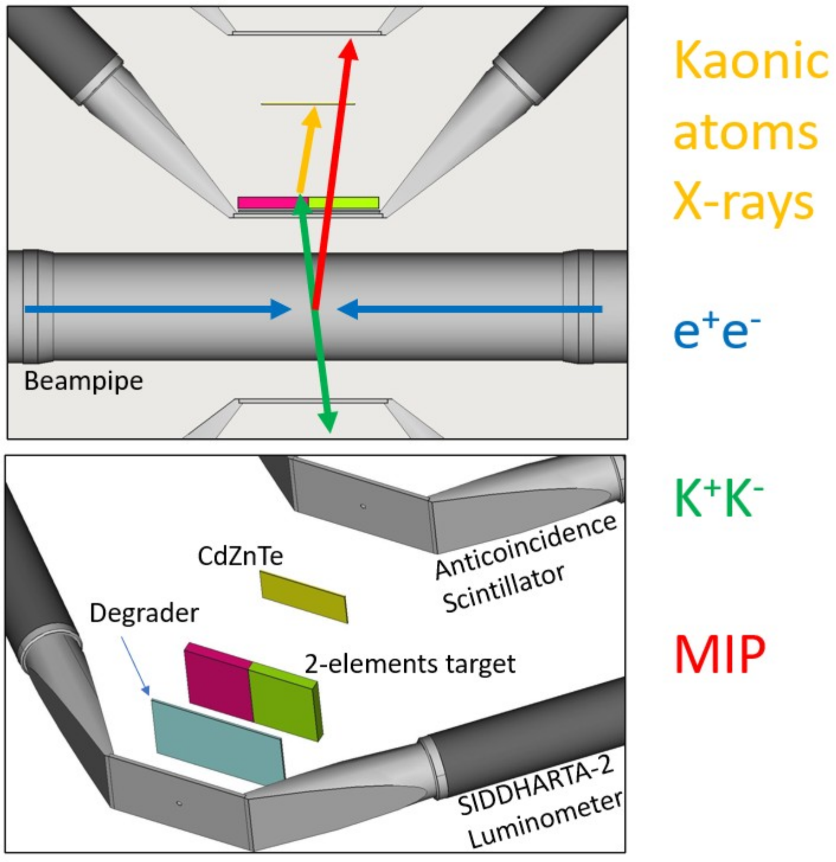
CZT: proposal for new measurements at DAΦNE



E. Friedman et al. / Nuclear Physics A579 (1994) 518–538

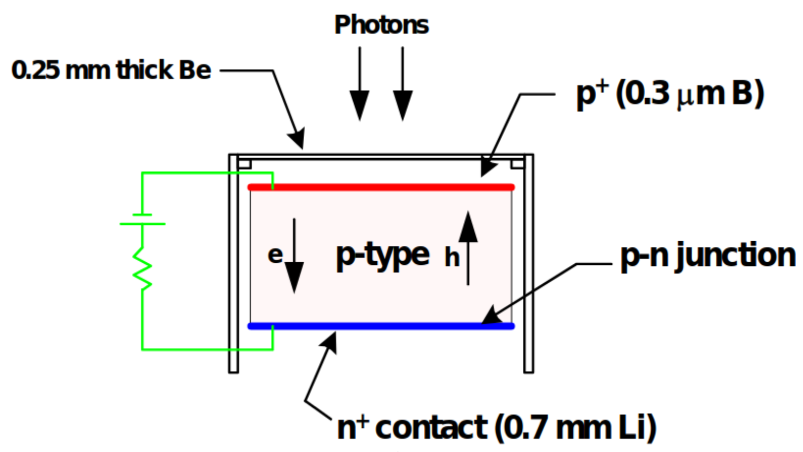
Table 1
Compilation of K^- atomic data

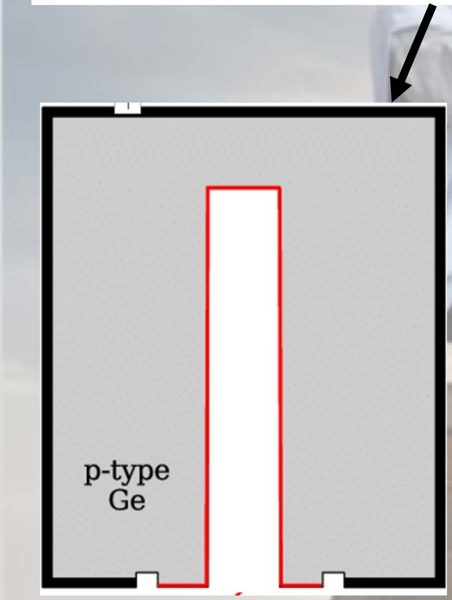
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
He	3 → 2	−0.04 ± 0.03	–	–	–
		−0.035 ± 0.012	0.03 ± 0.03	–	–
Li	3 → 2	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–
Be	3 → 2	−0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02
^{10}B	3 → 2	−0.208 ± 0.035	0.810 ± 0.100	–	–
^{11}B	3 → 2	−0.167 ± 0.035	0.700 ± 0.080	–	–
C	3 → 2	−0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20
O	4 → 3	−0.025 ± 0.018	0.017 ± 0.014	–	–
Mg	4 → 3	−0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03
Al	4 → 3	−0.130 ± 0.050	0.490 ± 0.160	–	–
		−0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04
Si	4 → 3	−0.240 ± 0.050	0.810 ± 0.120	–	–
		−0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06
P	4 → 3	−0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30
S	4 → 3	−0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36
		−0.43 ± 0.12	2.310 ± 0.170	–	–
		−0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5



With CdZnTe detectors the present database on kaonic atoms can be updated and renewed, and new important measurements can be done as well

HPGe detectors





High resolutions in a very wide energy range

Cryogenic cooling is needed

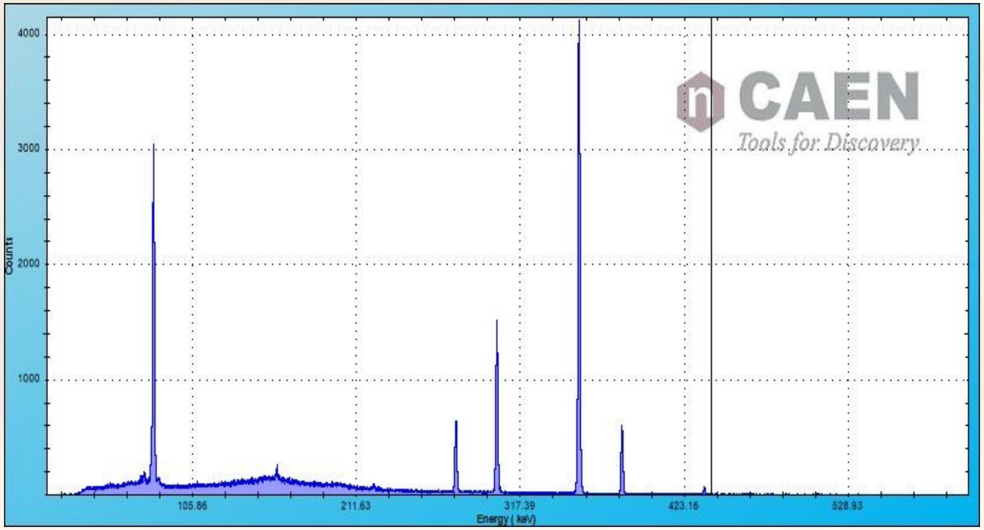
Subject to radiation damage

The maximum depletion depth for the planar detectors is limited to 1-2 cm.

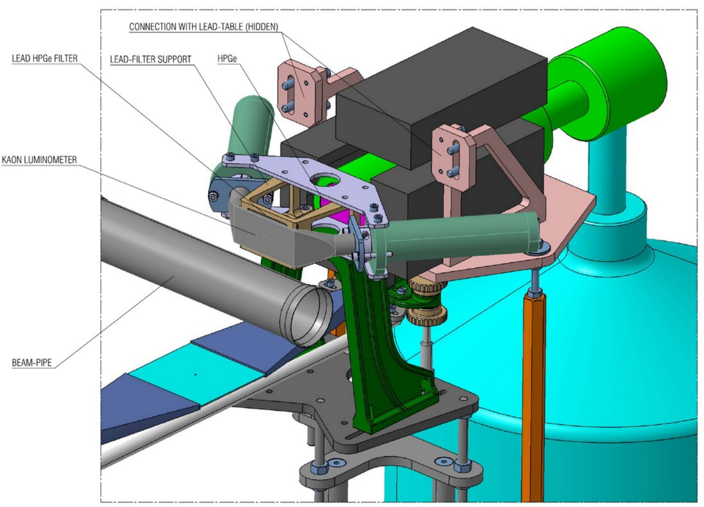
5 cm is required for efficient detection of MeV photons.

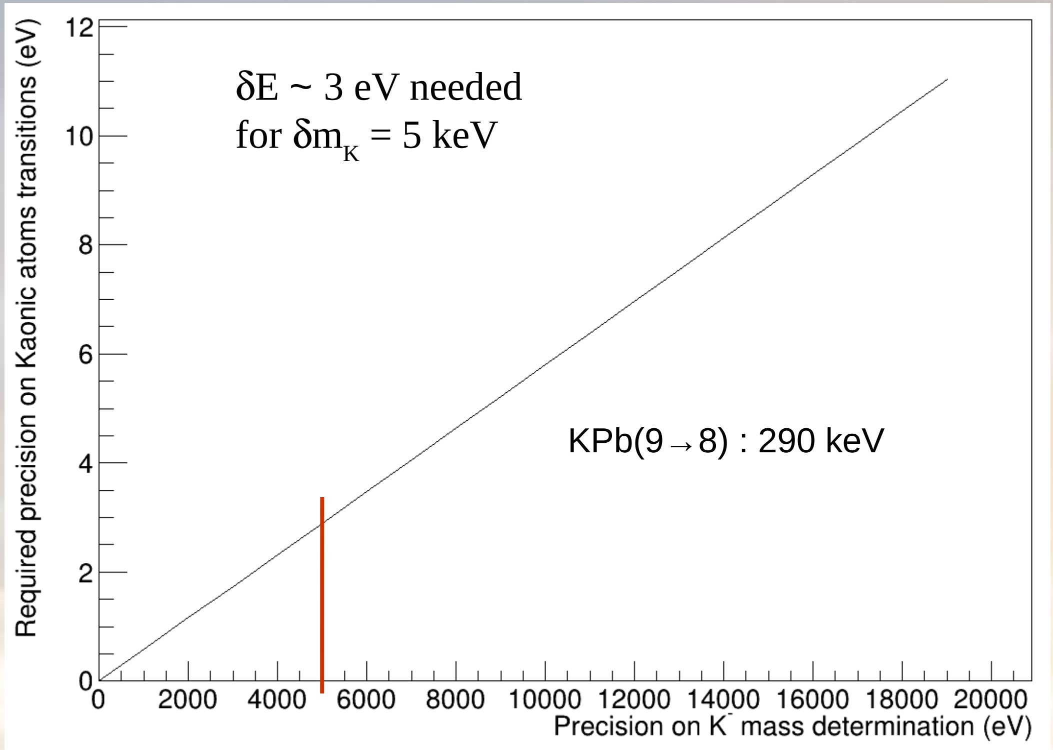
Resolutions (FWHM) obtained with ^{60}Co, ^{133}Ba

0.870 keV	@	81 keV
1.106 keV	@	302.9 keV
1.143 keV	@	356 keV
1.167 keV	@	1330 keV



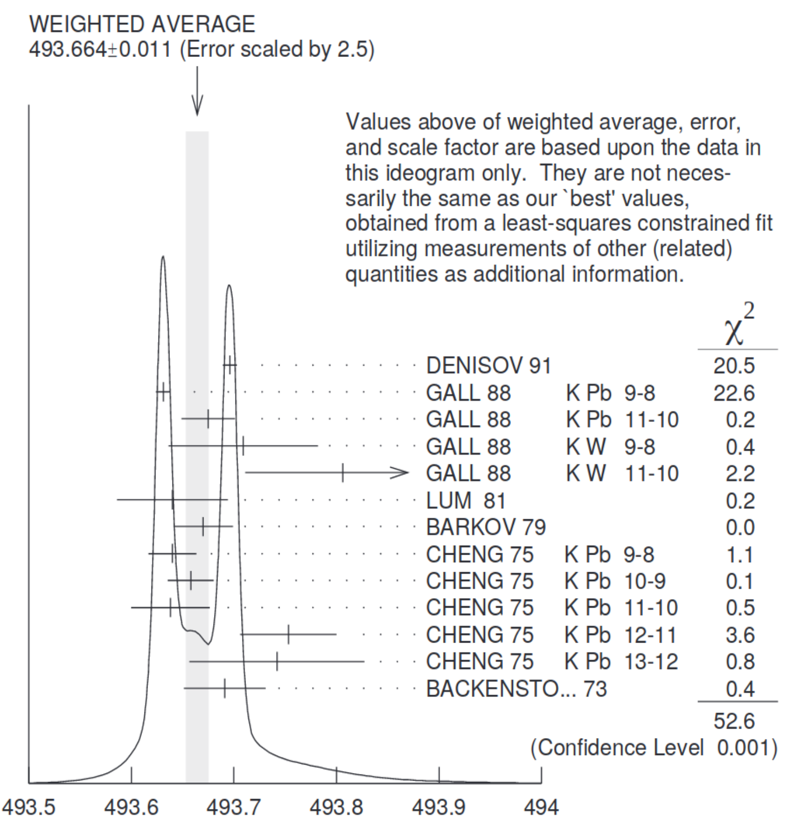
HPGe detectors





δE ~ 3 eV needed
for δm_K = 5 keV

$$\sigma m_K = \frac{m_K^2}{\mu_{KN}^2}\frac{1}{Z^2}\frac{10^6}{26,6}\frac{\sigma E^K_{X\to Y}}{\left(\frac{1}{Y^2}-\frac{1}{X^2}\right)}$$



WEIGHTED AVERAGE
493.664±0.011 (Error scaled by 2.5)

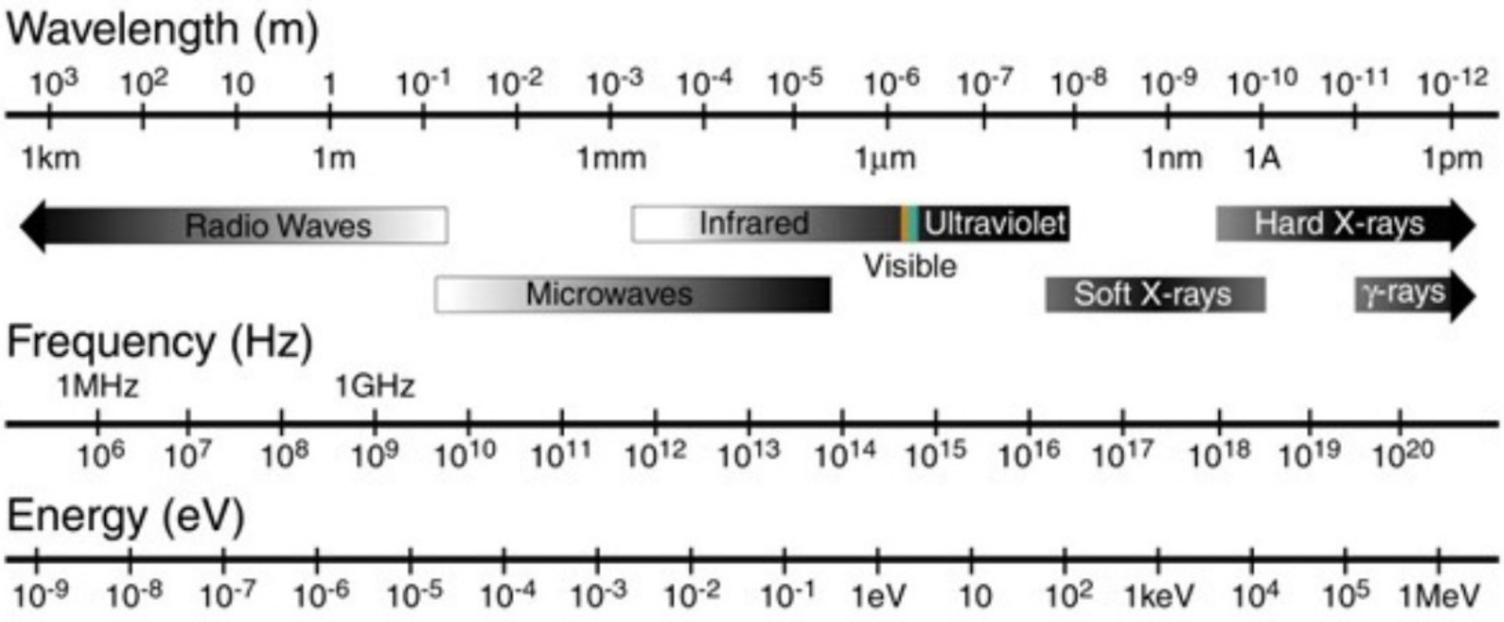
Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our `best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

			χ^2
DENISOV 91			20.5
GALL 88	K Pb	9-8	22.6
GALL 88	K Pb	11-10	0.2
GALL 88	K W	9-8	0.4
GALL 88	K W	11-10	2.2
LUM 81			0.2
BARKOV 79			0.0
CHENG 75	K Pb	9-8	1.1
CHENG 75	K Pb	10-9	0.1
CHENG 75	K Pb	11-10	0.5
CHENG 75	K Pb	12-11	3.6
CHENG 75	K Pb	13-12	0.8
BACKENSTO... 73			0.4
			52.6
		(Confidence Level	0.001)

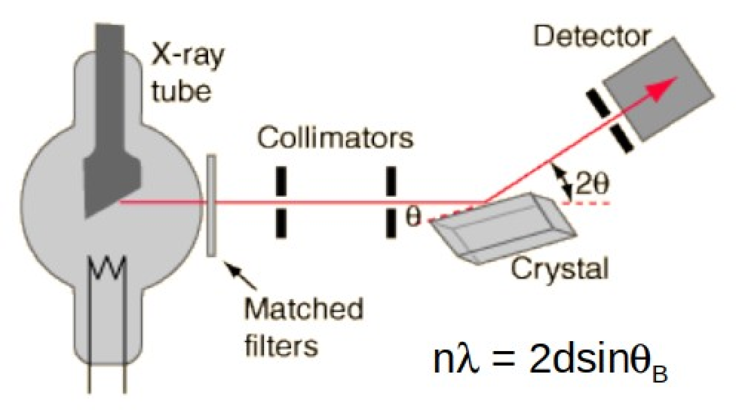
HPGe detector is used in DAΦNE to perform a new precise measurement of the K⁻ mass

Suitable detector(s) for each radiation

Bragg Spectrometers



Bragg spectrometers



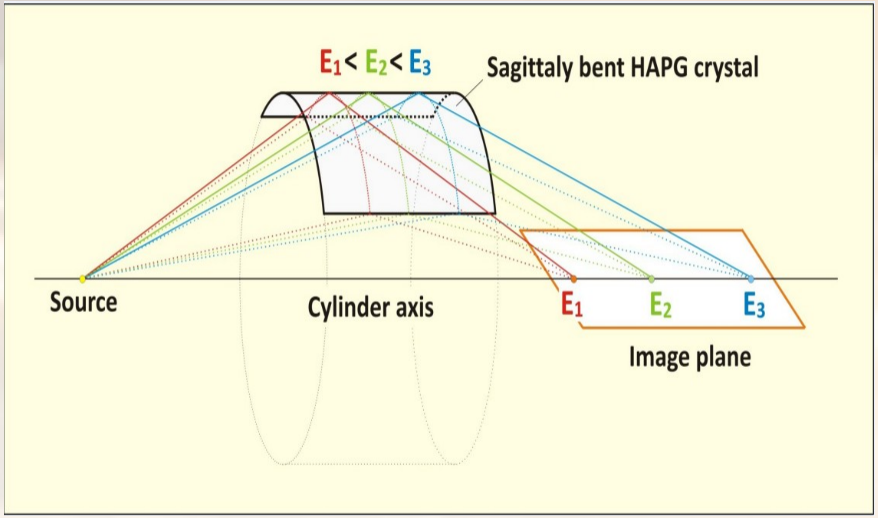
$n\lambda = 2d\sin\theta_B$

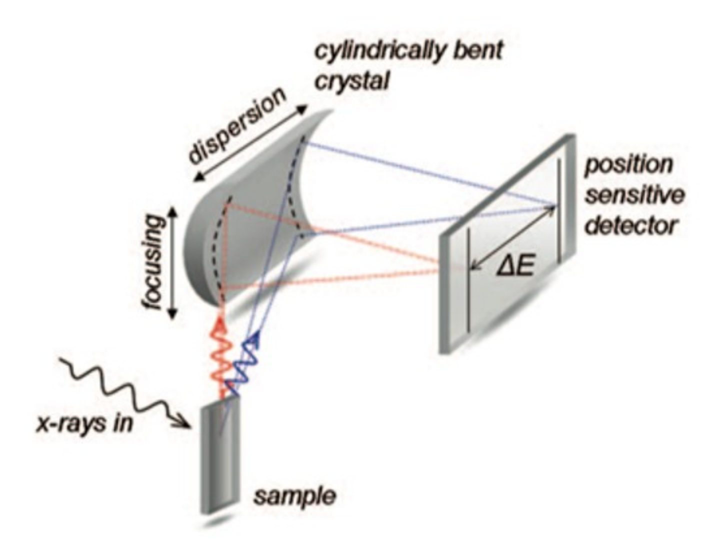
Photons of different energies are reflected in different positions

With a crystal and a position detector, energy spectra with ultra-high resolution can be obtained

For monochromatic sources, also directionality could be tested

Von Hamos geometry and mosaic crystals can improve collection efficiency





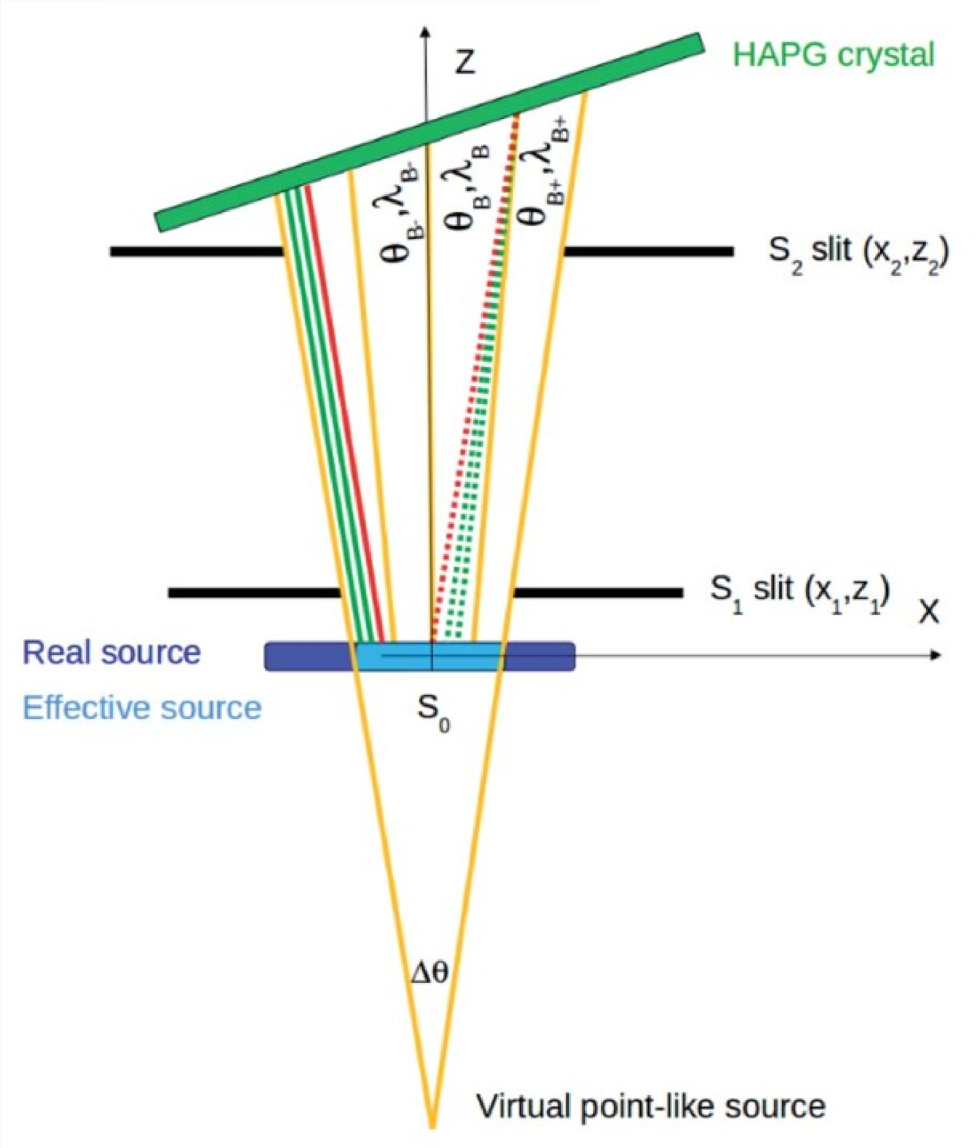
FWHM of few eV with NO COOLING

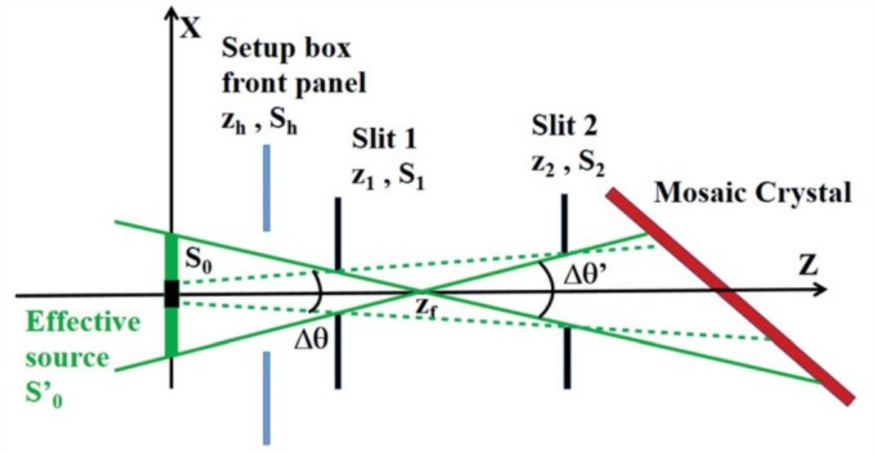
Energy range between 1-20 keV (n=1, depending on the crystal)

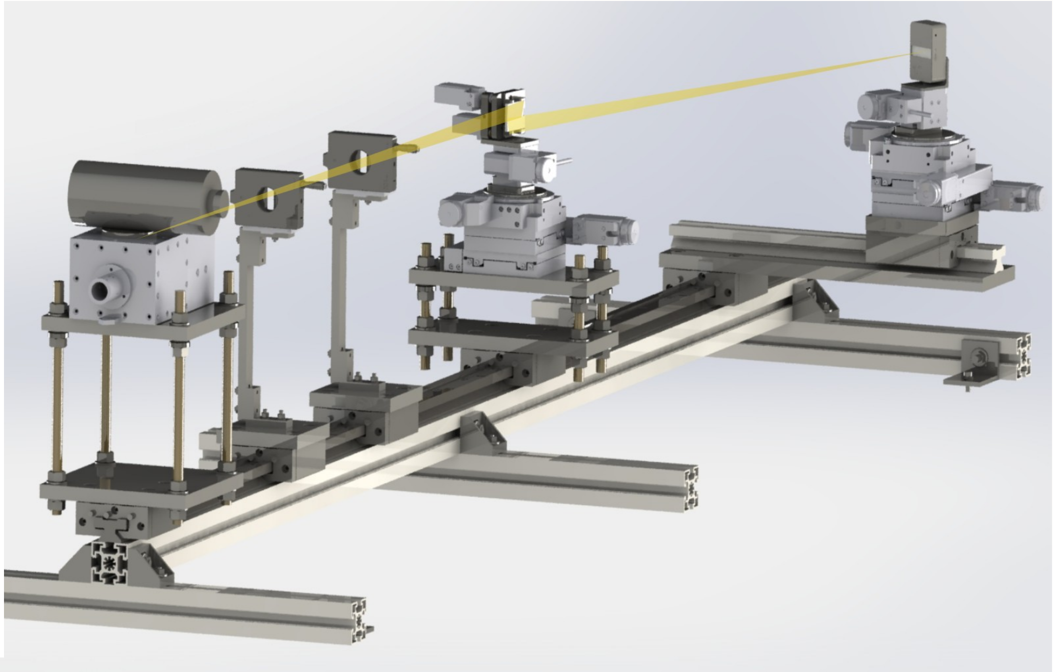
Extremely low efficiencies (solid angle)

Bragg spectrometers: VOXES

Spectrometer developed under CSN5 Young Researcher Grant (2016-2018)







Crystal spectrometers: VOXES

High precision measurements with VOXES in LNF Lab

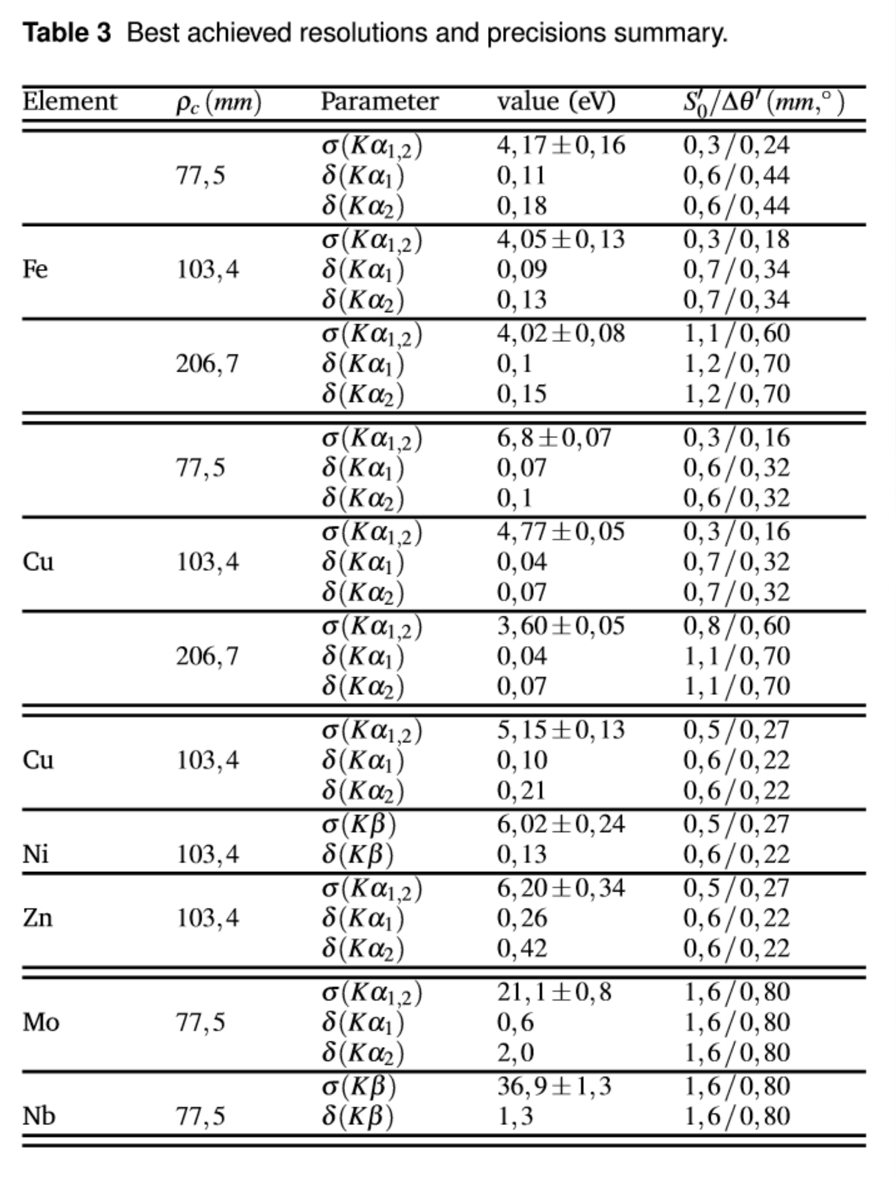
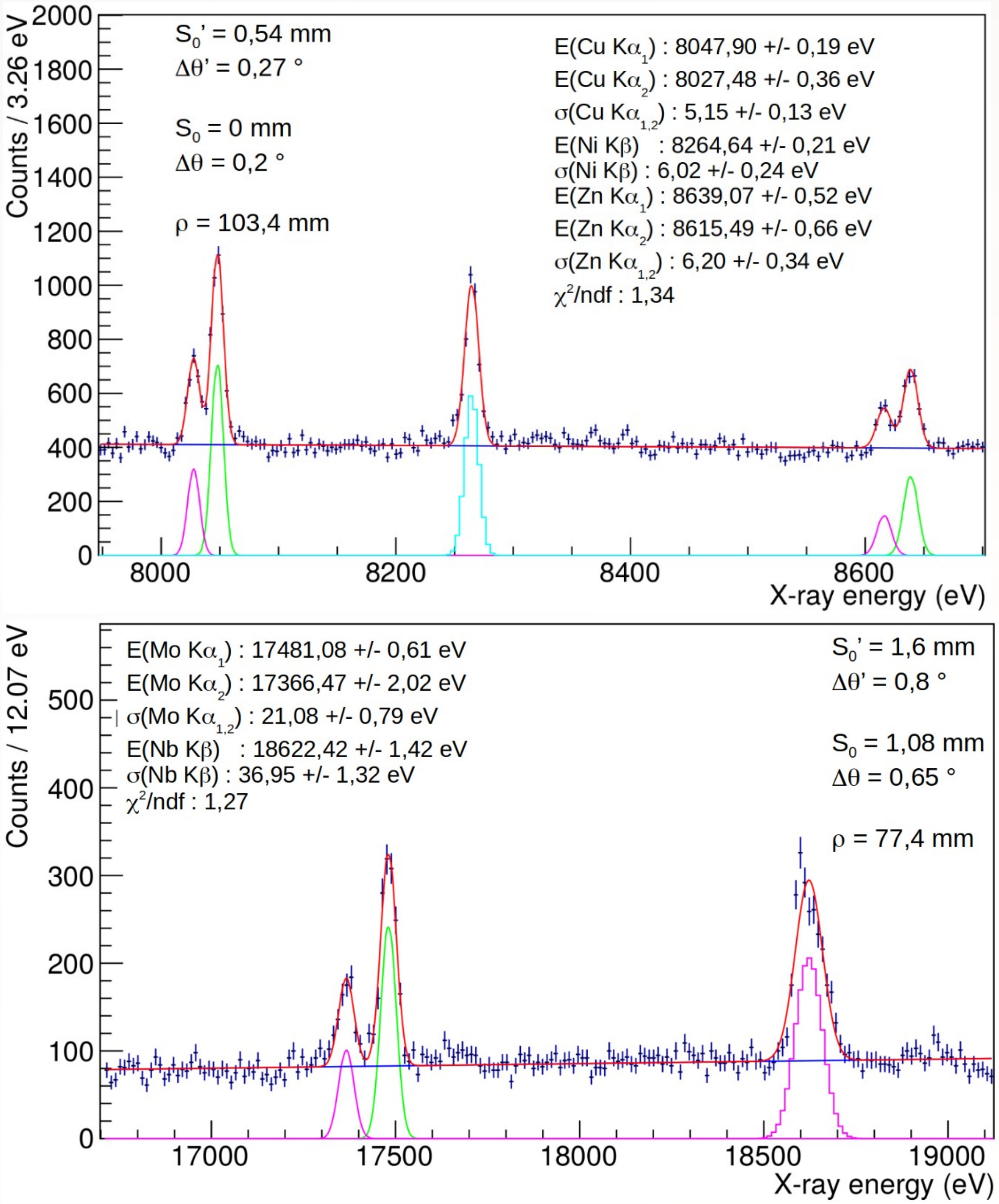


Table 3 Best achieved resolutions and precisions summary.

Element	$\rho_c\,(mm)$	Parameter	value (eV)	$S_0'/\Delta\theta'\,(mm,^\circ)$
Fe	77,5	$\sigma(K\alpha_{1,2})$	$4,17\pm0,16$	0,3/0,24
		$\delta(K\alpha_1)$	0,11	0,6/0,44
		$\delta(K\alpha_2)$	0,18	0,6/0,44
	103,4	$\sigma(K\alpha_{1,2})$	$4,05\pm0,13$	0,3/0,18
		$\delta(K\alpha_1)$	0,09	0,7/0,34
		$\delta(K\alpha_2)$	0,13	0,7/0,34
	206,7	$\sigma(K\alpha_{1,2})$	$4,02\pm0,08$	1,1/0,60
		$\delta(K\alpha_1)$	0,1	1,2/0,70
		$\delta(K\alpha_2)$	0,15	1,2/0,70
Cu	77,5	$\sigma(K\alpha_{1,2})$	$6,8\pm0,07$	0,3/0,16
		$\delta(K\alpha_1)$	0,07	0,6/0,32
		$\delta(K\alpha_2)$	0,1	0,6/0,32
	103,4	$\sigma(K\alpha_{1,2})$	$4,77\pm0,05$	0,3/0,16
		$\delta(K\alpha_1)$	0,04	0,7/0,32
		$\delta(K\alpha_2)$	0,07	0,7/0,32
	206,7	$\sigma(K\alpha_{1,2})$	$3,60\pm0,05$	0,8/0,60
		$\delta(K\alpha_1)$	0,04	1,1/0,70
		$\delta(K\alpha_2)$	0,07	1,1/0,70
Cu	103,4	$\sigma(K\alpha_{1,2})$	$5,15\pm0,13$	0,5/0,27
		$\delta(K\alpha_1)$	0,10	0,6/0,22
		$\delta(K\alpha_2)$	0,21	0,6/0,22
Ni	103,4	$\sigma(K\beta)$	$6,02\pm0,24$	0,5/0,27
		$\delta(K\beta)$	0,13	0,6/0,22
Zn	103,4	$\sigma(K\alpha_{1,2})$	$6,20\pm0,34$	0,5/0,27
		$\delta(K\alpha_1)$	0,26	0,6/0,22
		$\delta(K\alpha_2)$	0,42	0,6/0,22
Mo	77,5	$\sigma(K\alpha_{1,2})$	$21,1\pm0,8$	1,6/0,80
		$\delta(K\alpha_1)$	0,6	1,6/0,80
		$\delta(K\alpha_2)$	2,0	1,6/0,80
Nb	77,5	$\sigma(K\beta)$	$36,9\pm1,3$	1,6/0,80
		$\delta(K\beta)$	1,3	1,6/0,80

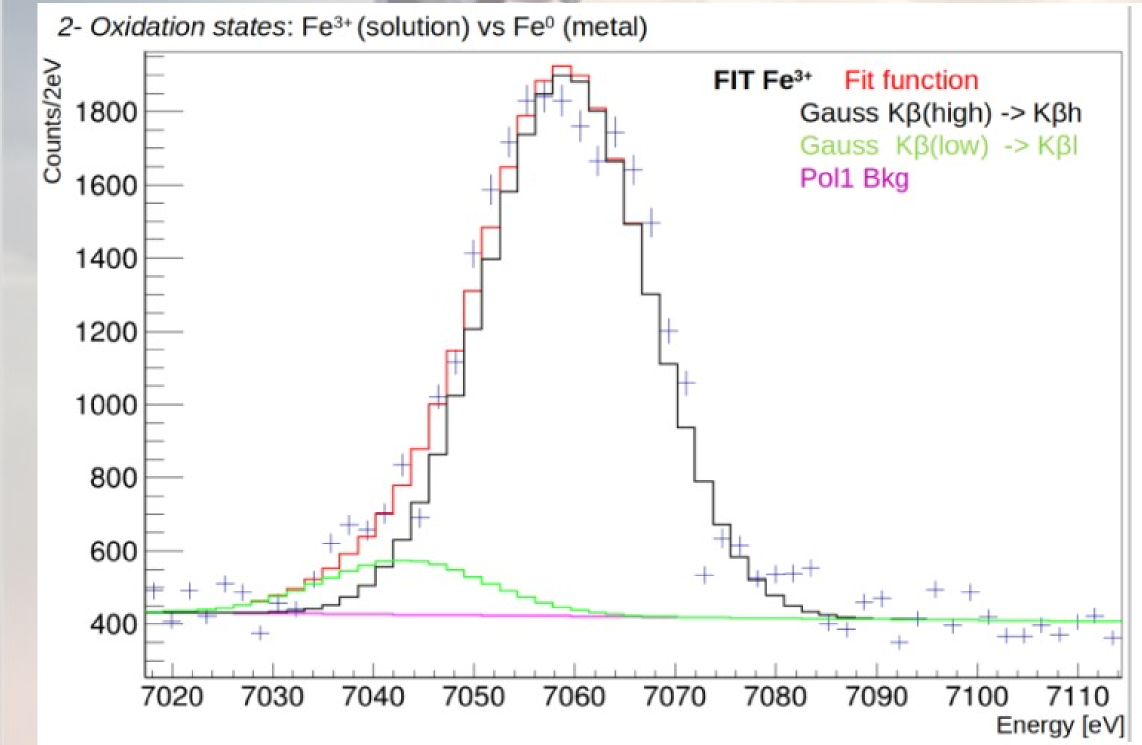


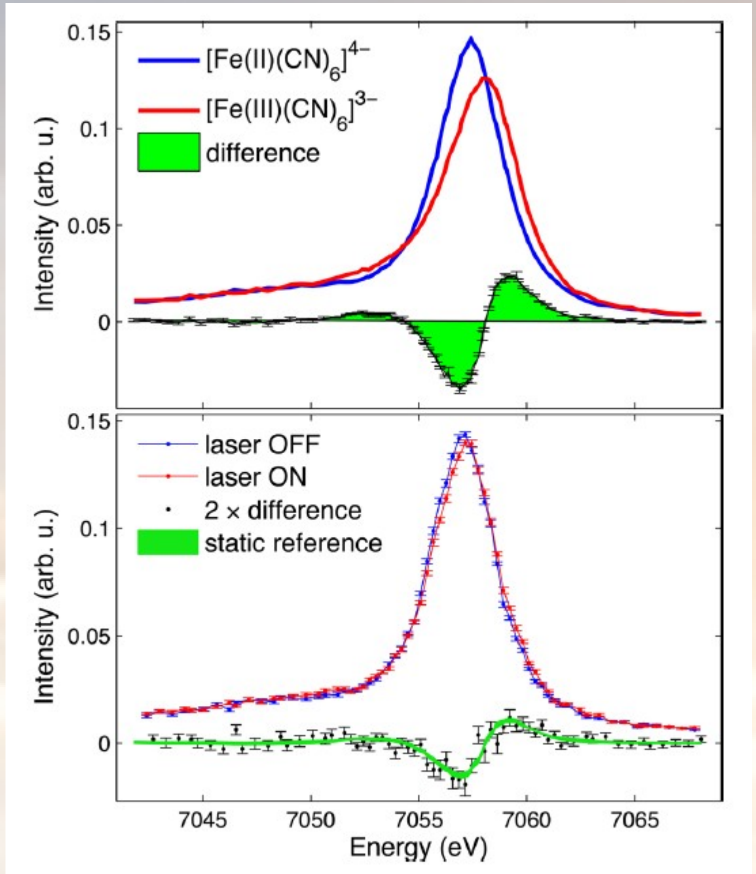
VOXES: applications

TRANSPORTABLE AND AGILE SPECTROMETER FOR METAL TRACE IN EDIBLE LIQUIDS : TASTE

MITIQO

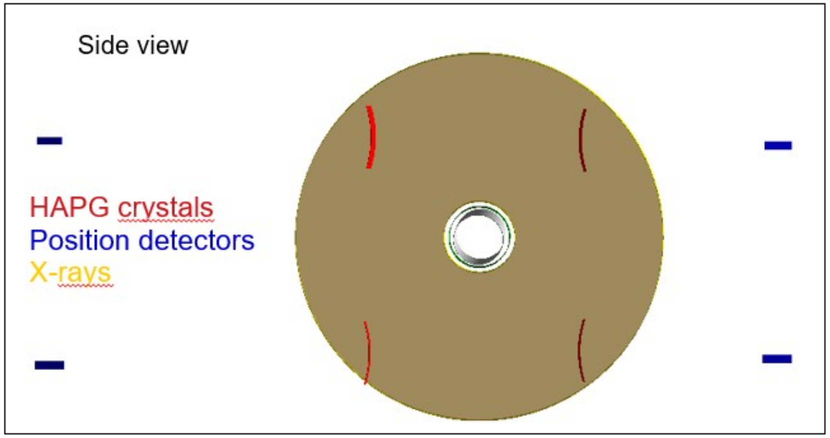
Monitoraggio In situ di Tossicità, Indicazione geografica e Qualità di Olio d'oliva, vino e altri liquidi edibili

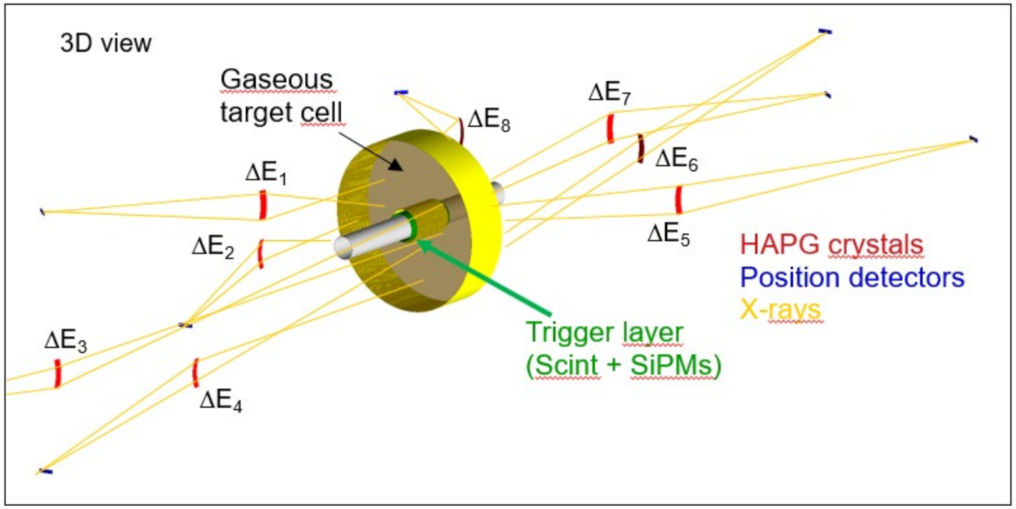


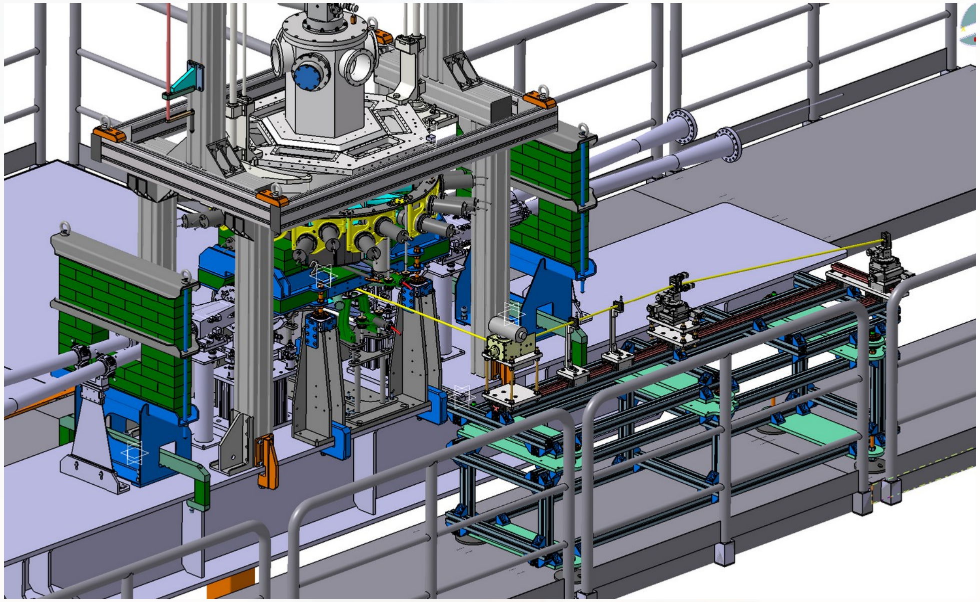


VOXES: applications in DAΦNE

A new setup including several spectrometer arms could allow for new and very precise measurements of kaonic atoms transitions both from solid and gaseous targets

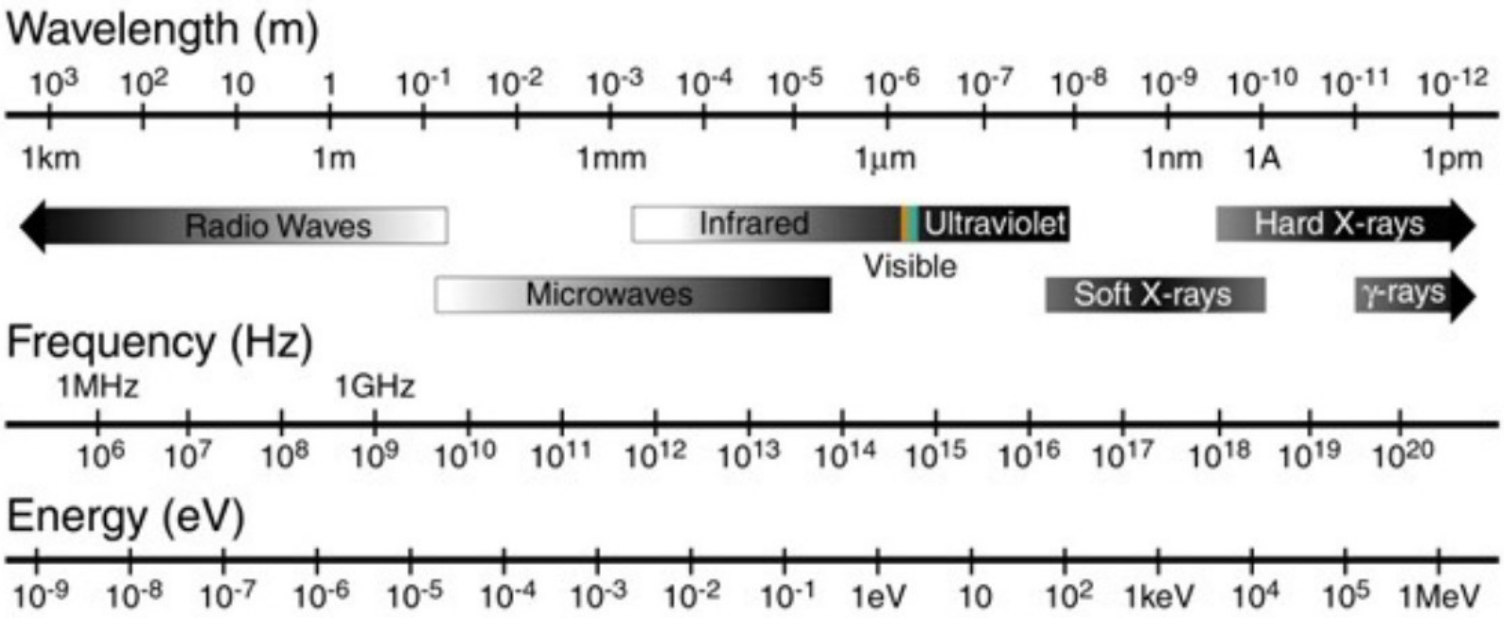






Suitable detector(s) for each radiation

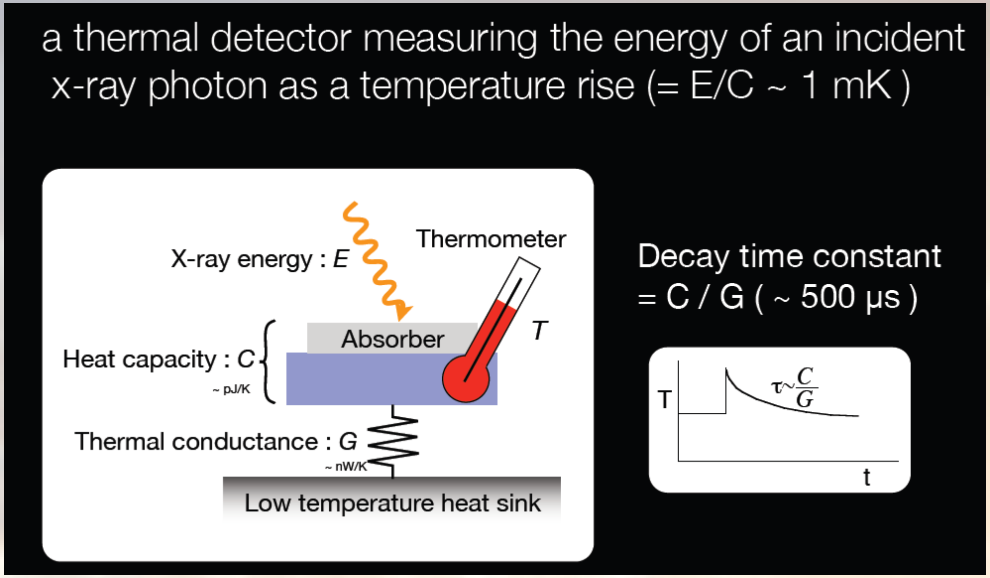
Transition Edge Sensors (TES): Microcalorimetry



Transition Edge Sensors

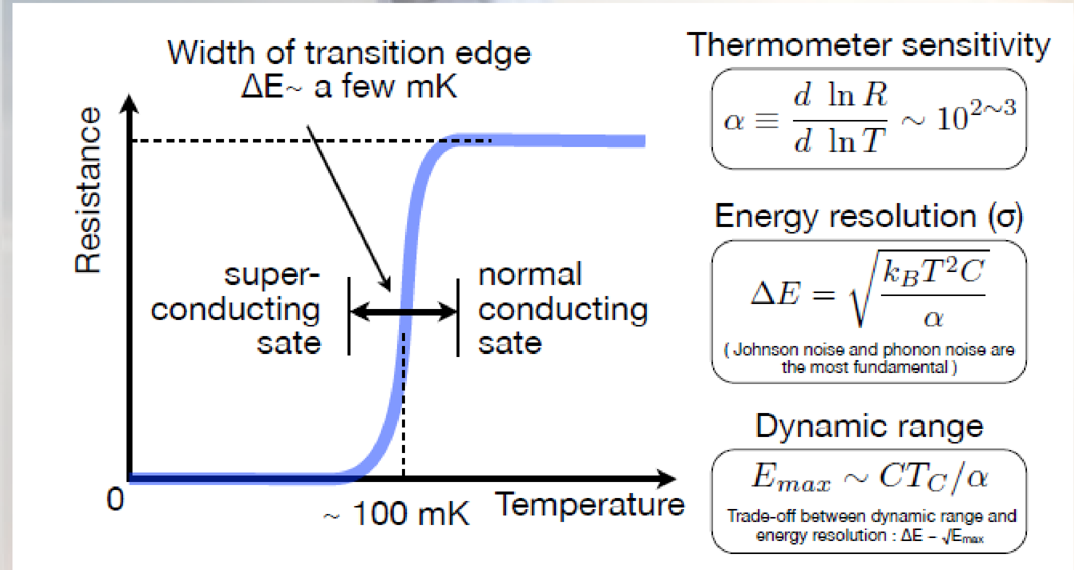
Photon absorption is used to rise the temperature of a thin film of superconducting material above the Tc

ΔT is proportional to the photon energy which can be derived with extremely high accuracy



a thermal detector measuring the energy of an incident x-ray photon as a temperature rise (= E/C ~ 1 mK)

Decay time constant = C / G (~ 500 μs)



Thermometer sensitivity

$$\alpha \equiv \frac{d\ \ln R}{d\ \ln T} \sim 10^{2\sim3}$$

Energy resolution (σ)

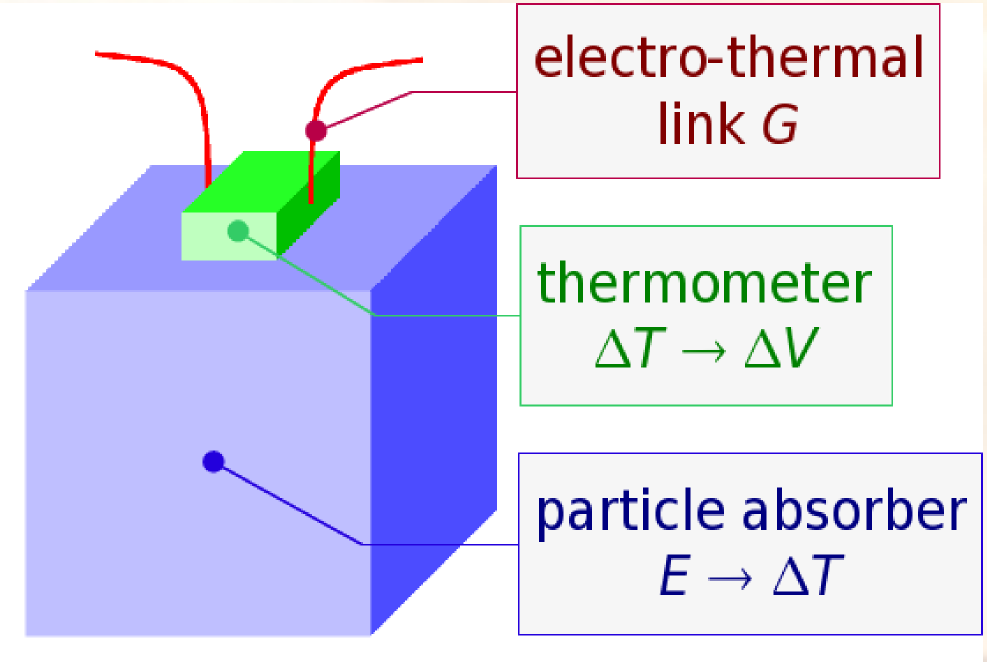
$$\Delta E = \sqrt{\frac{k_B T^2 C}{\alpha}}$$

(Johnson noise and phonon noise are the most fundamental)

Dynamic range

$$E_{max} \sim C T_C / \alpha$$

Trade-off between dynamic range and energy resolution : $\Delta E - \sqrt{E_{max}}$



electro-thermal link *G*

thermometer $\Delta T \rightarrow \Delta V$

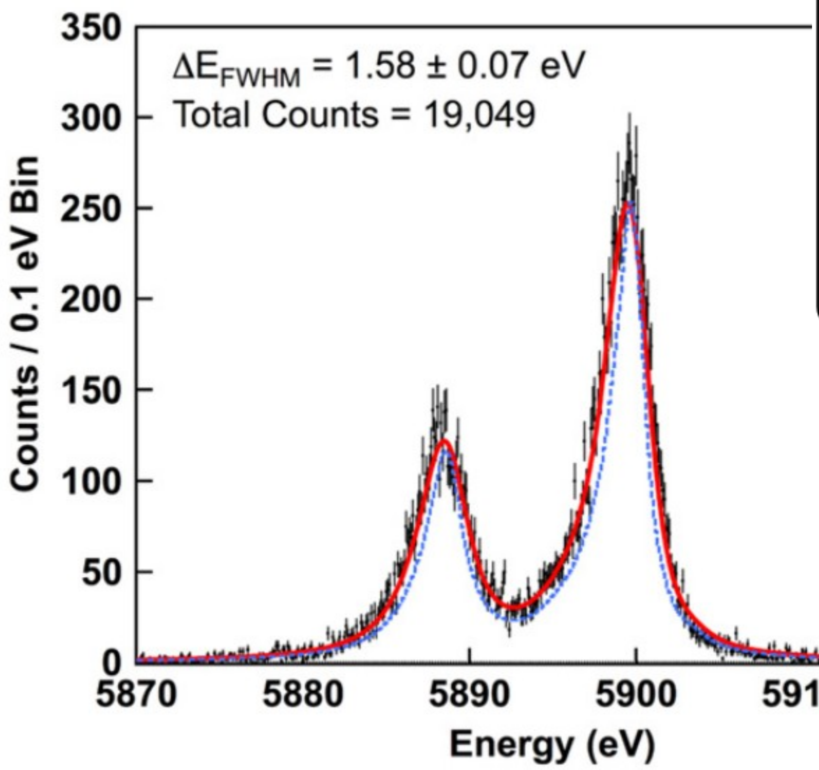
particle absorber $E \rightarrow \Delta T$

Transition Edge Sensors

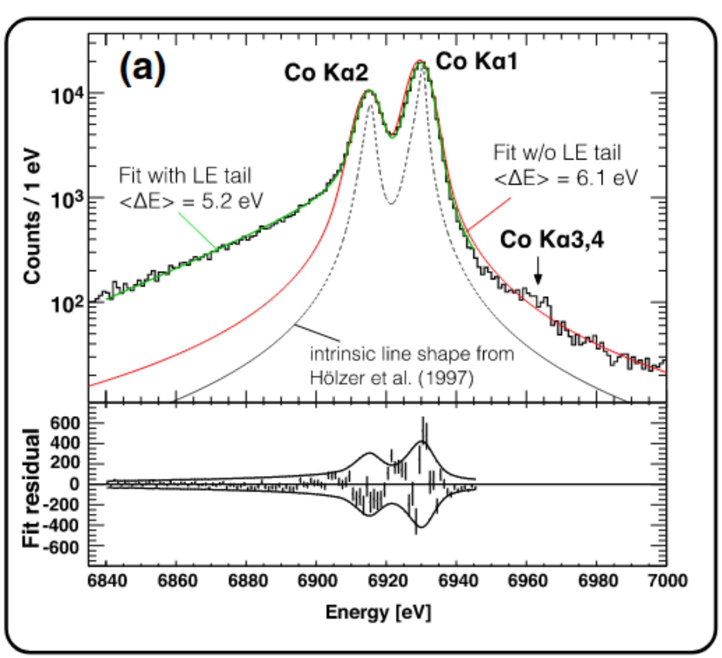
Ultra-High resolution
(FHWM ~0,03% @ 5900 eV)

Acceptable geometrical
efficiency (small active areas)

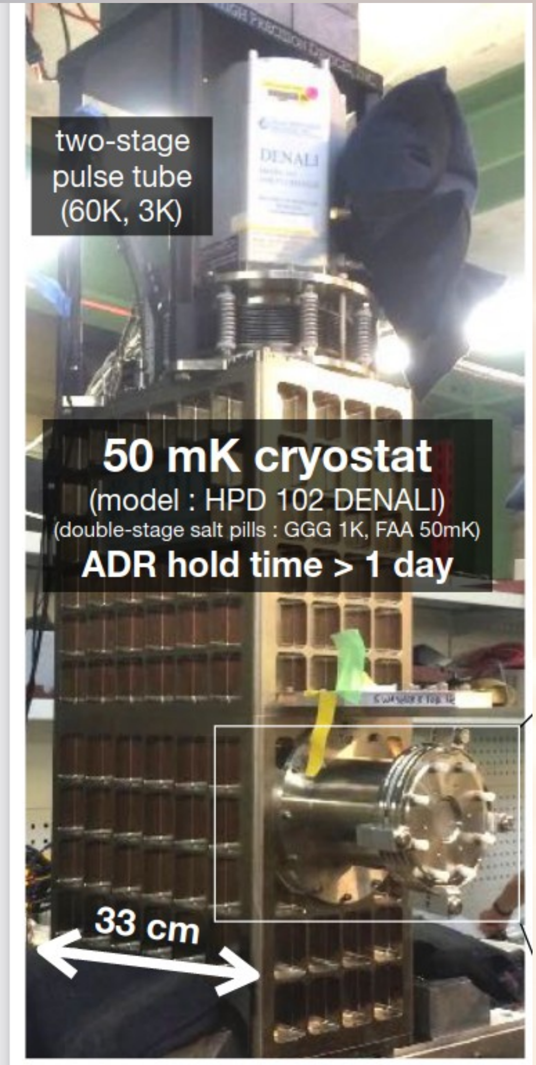
Extremely high costs
Non-trivial calibration



Supercond. Sci. Technol. **28** (2015) 084003



H. Tatsuno et al.,
J Low Temp Phys 184 (2016) 930-937

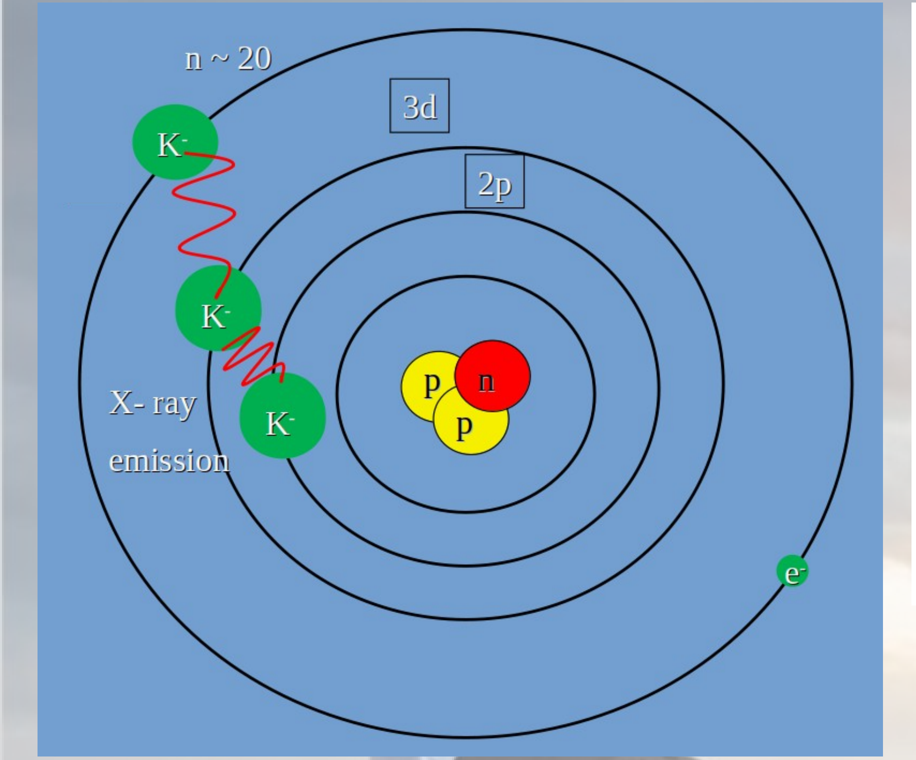


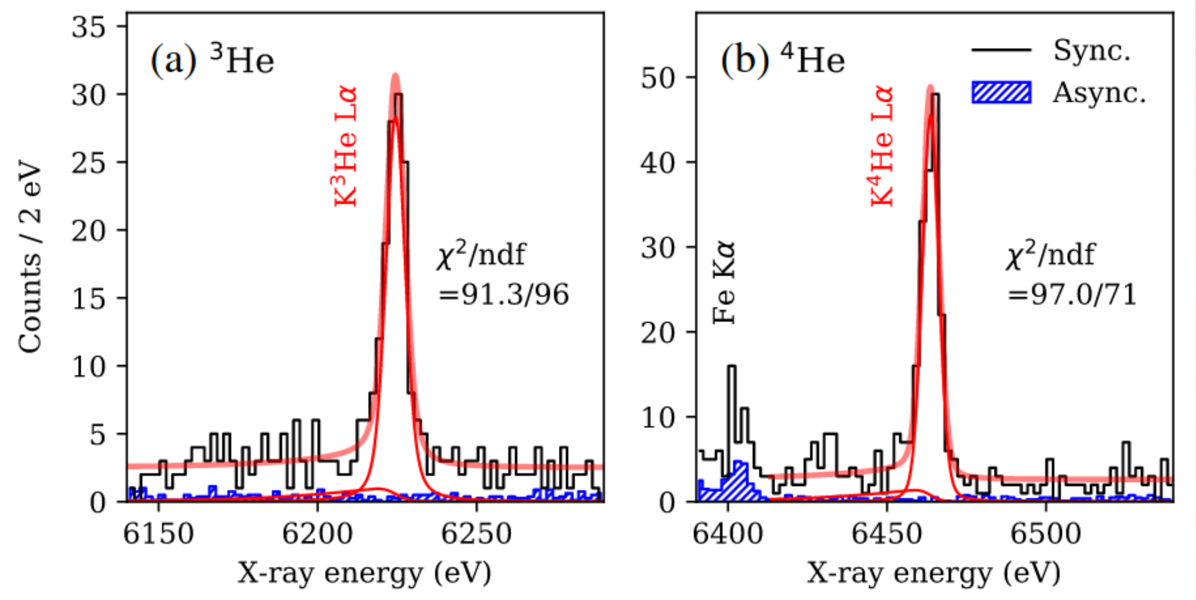
two-stage
pulse tube
(60K, 3K)

50 mK cryostat
(model : HPD 102 DENALI)
(double-stage salt pills : GGG 1K, FAA 50mK)
ADR hold time > 1 day

T_C ~ 50 mK !!!

Transition Edge Sensors





T. Hashimoto *et al.* (J-PARC E62 Collaboration)
Phys. Rev. Lett. **128**, 112503 – Published 18 March 2022

$$E_{3d\to 2p}^{K^- {}^3\mathrm{He}} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV},$$

$$E_{3d\to 2p}^{K^- {}^4\mathrm{He}} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV},$$

$$\Gamma_{2p}^{K^- {}^3\mathrm{He}} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV},$$

$$\Gamma_{2p}^{K^- {}^4\mathrm{He}} = 1.0 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV}.$$

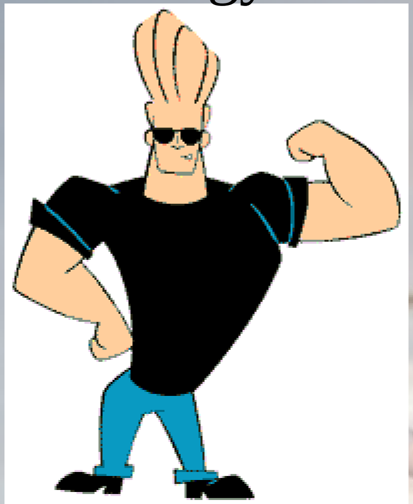
$$\Delta E_{2p}^{K^- {}^3\mathrm{He}} = -0.2 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV},$$

$$\Delta E_{2p}^{K^- {}^4\mathrm{He}} = 0.2 \pm 0.3(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}.$$

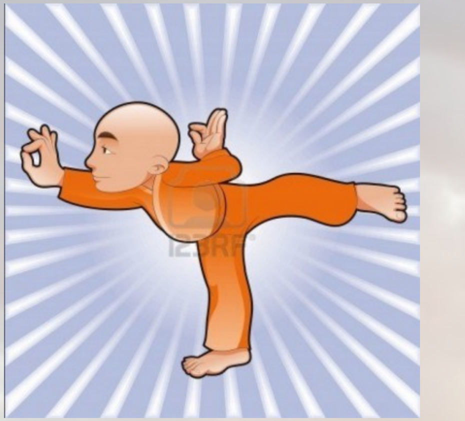
Sub-eV of 2d level shift and width in
Kaonic Helium

What do we want (could) measure...

Energy



Position

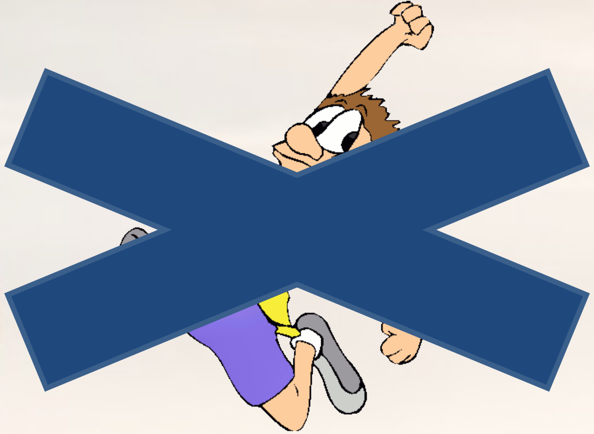


Multiplicity

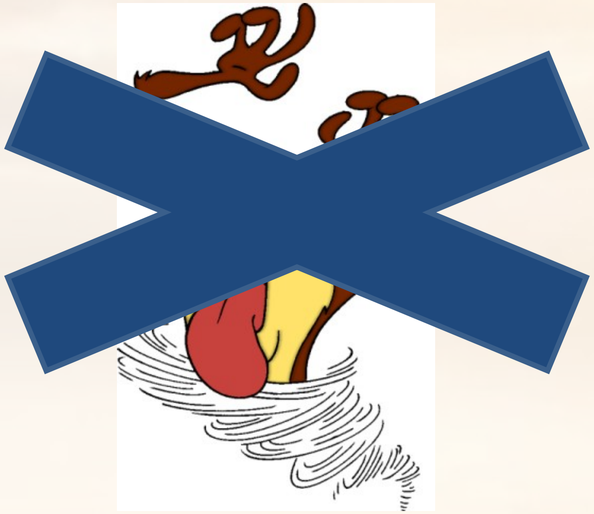
u

Polarization

Time



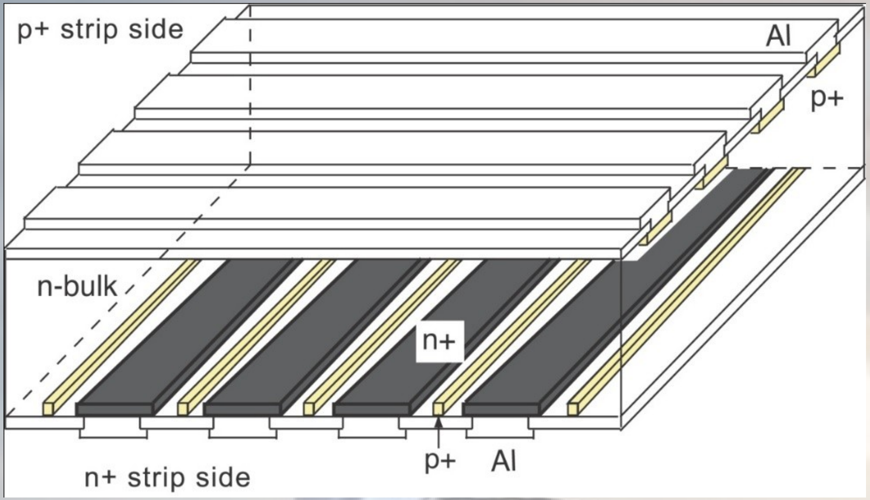
Rates

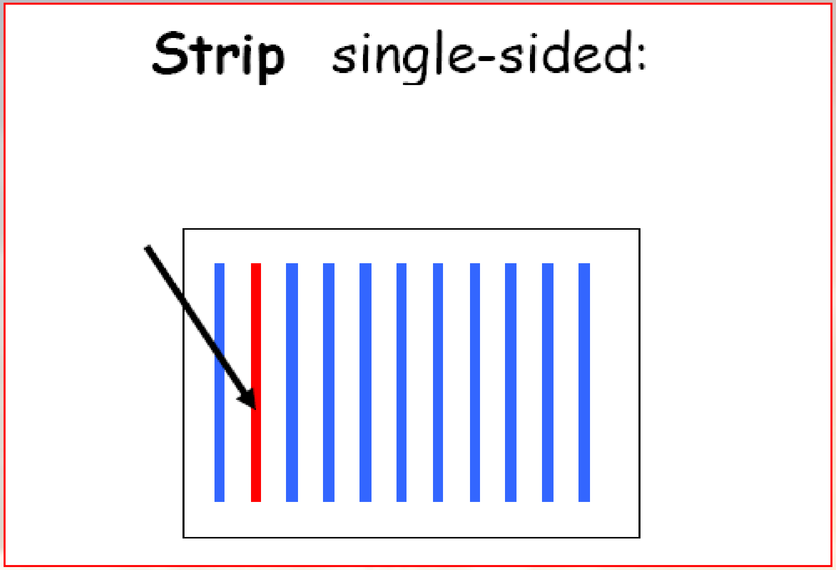


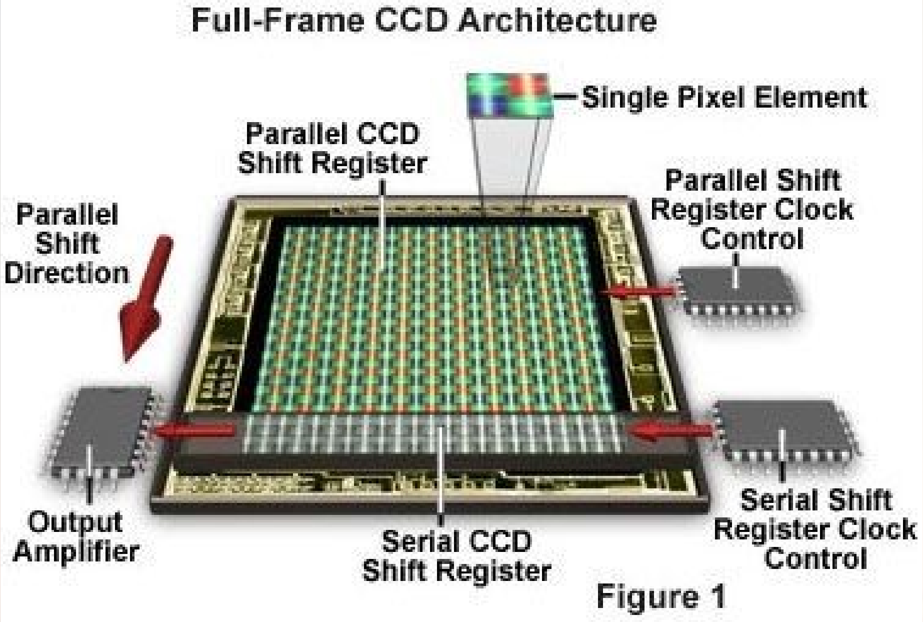
Strip & Pixel detectors

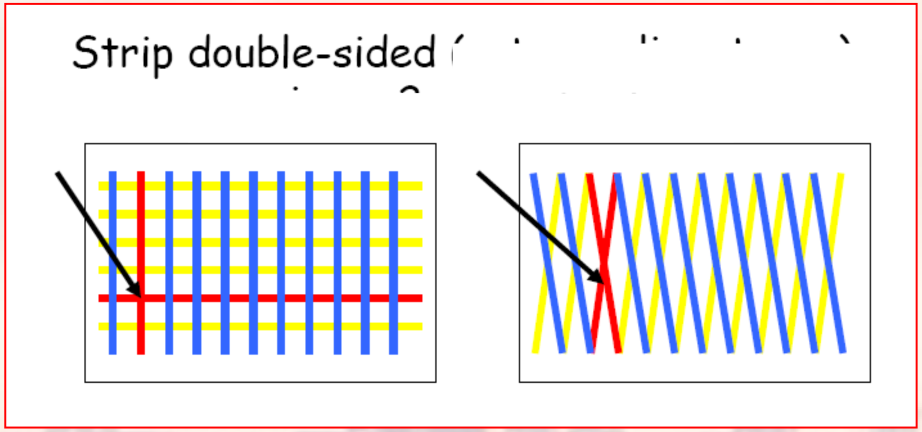
With strip detectors, 1D position spectra can be obtained

2D spectra are obtained from double sided strip detectors or Pixel Detectors (like CCD)



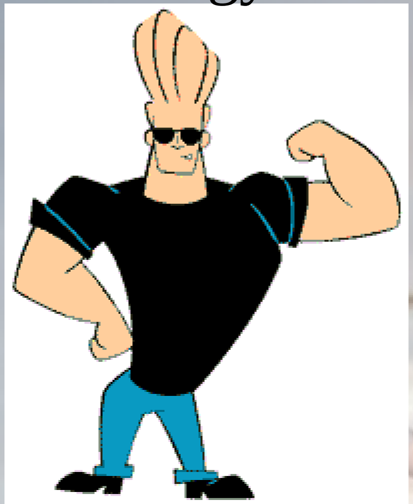




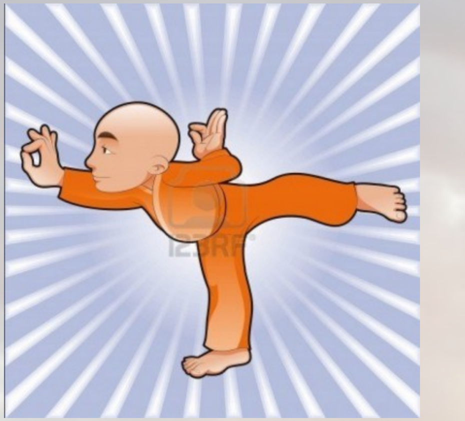


What do we want (could) measure...

Energy



Position

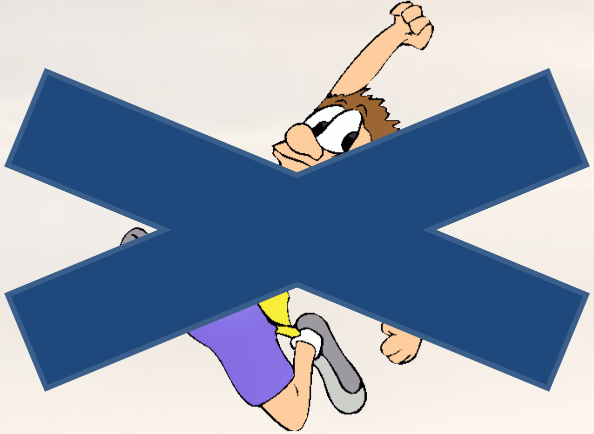


Multiplicity

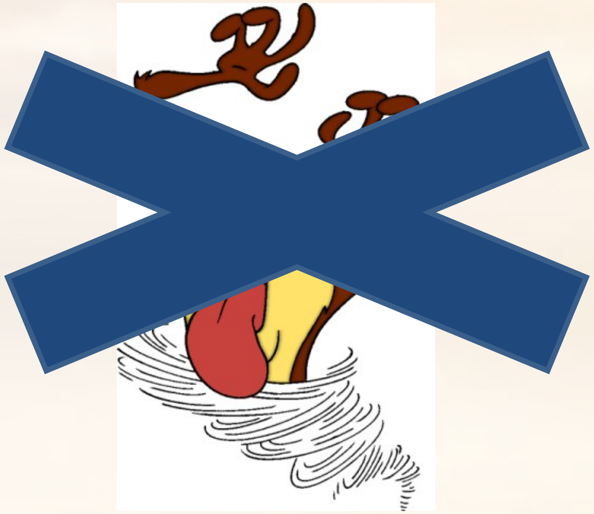
u

Polarization

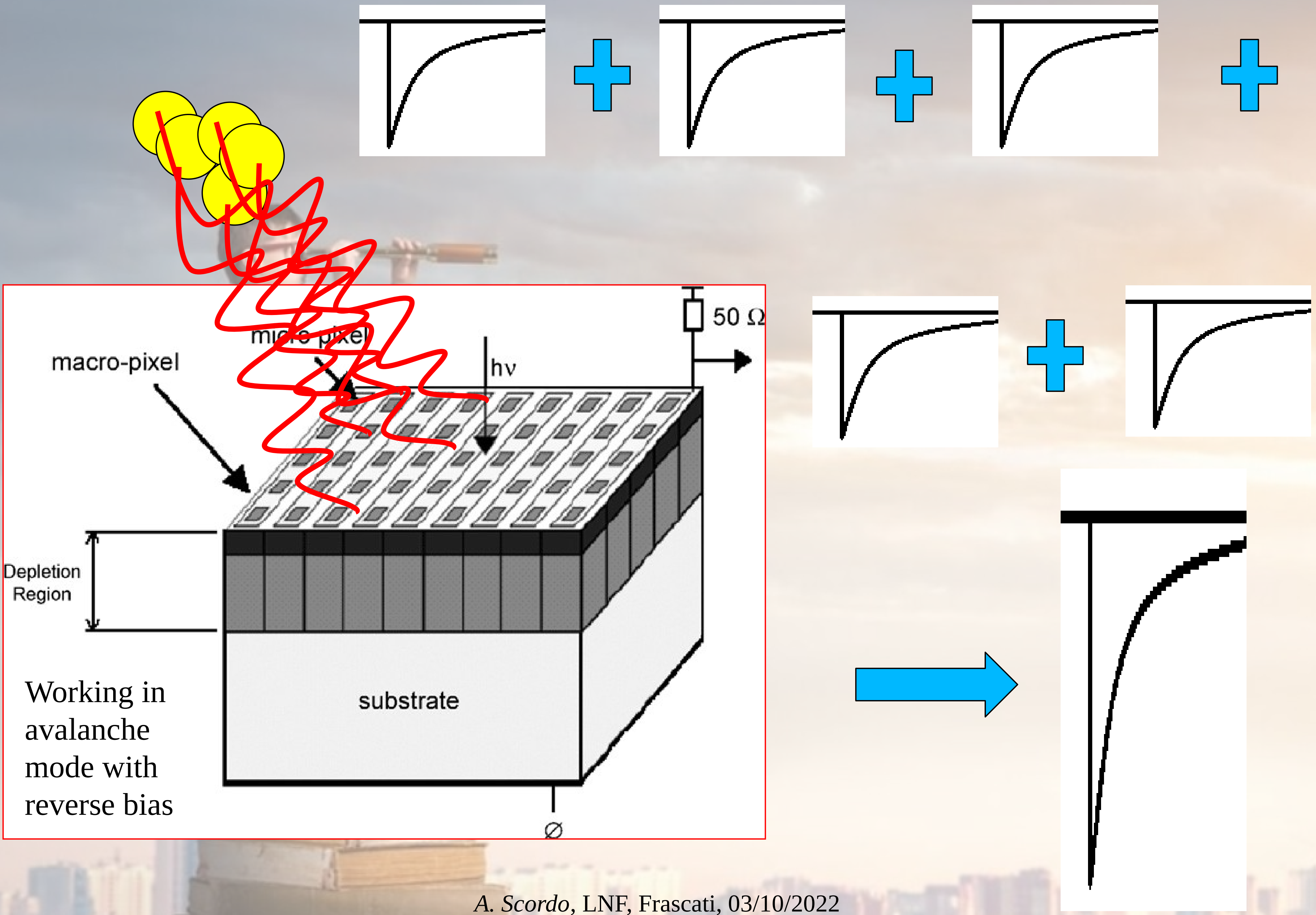
Time



Rates

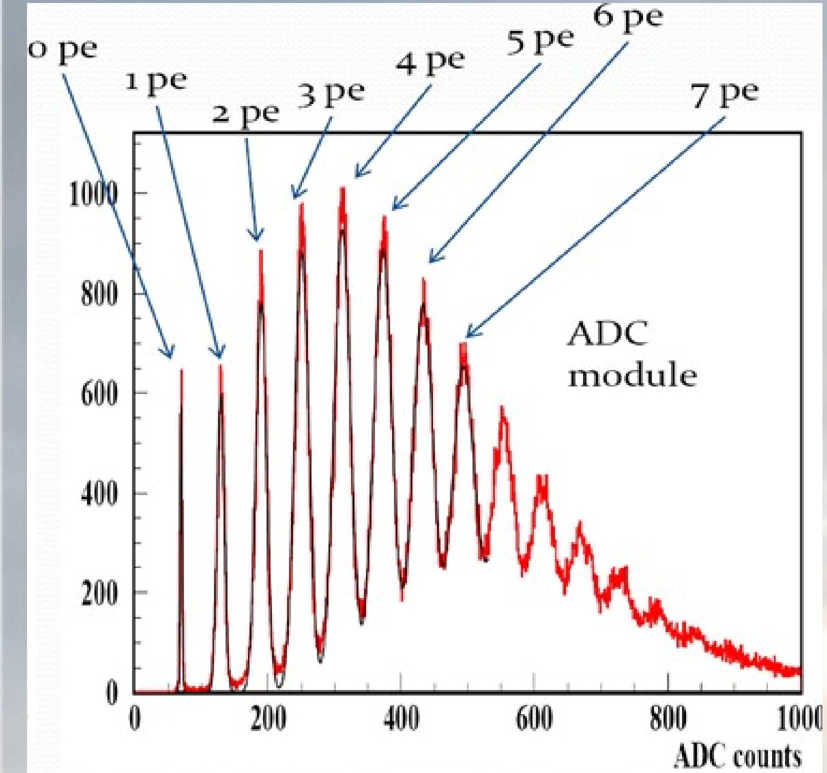


Multi Pixel Photon Counters

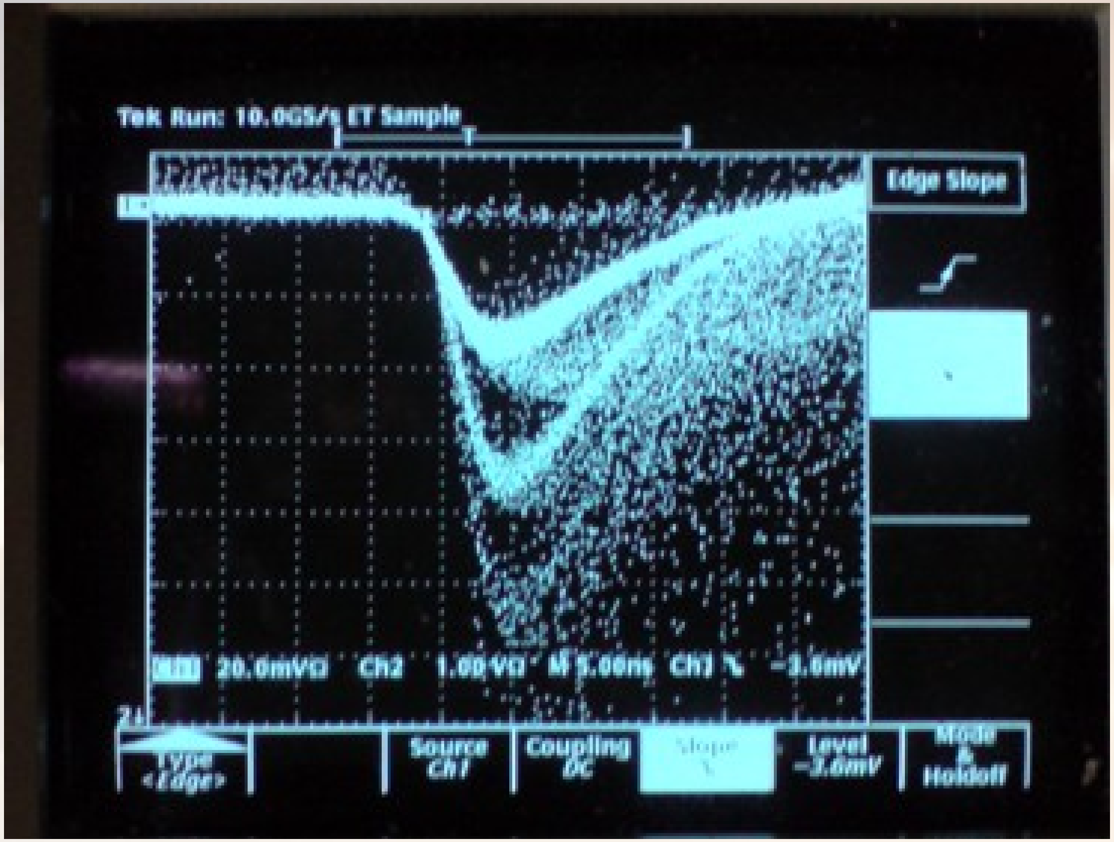


Working in avalanche mode with reverse bias

Multi Pixel Photon Counters



Signal "quantization" is even visible on an oscilloscope

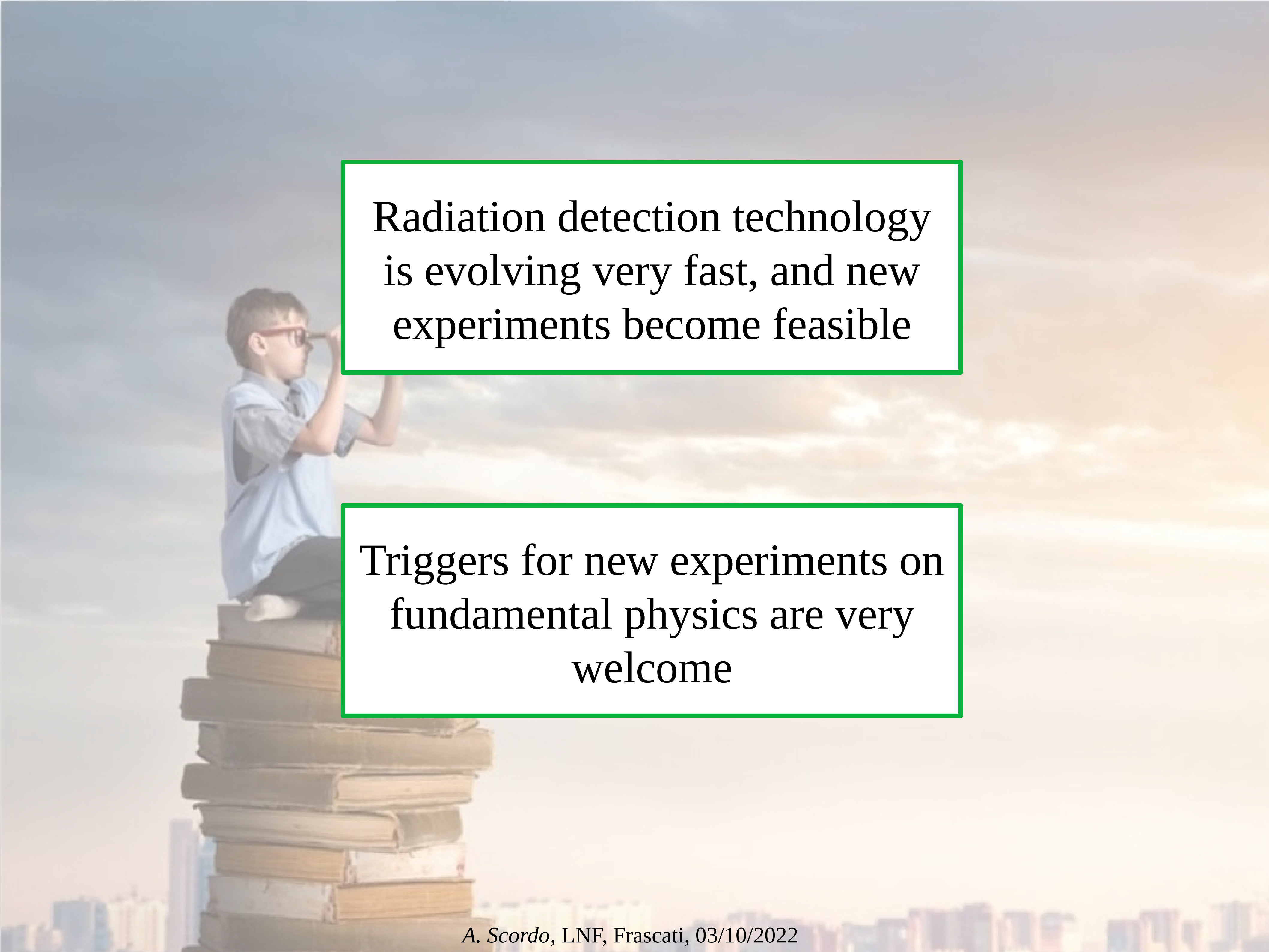


No Cooling
No radiation damage
Working within magnetic fields

Few photons can be measured
Visible photon range (some attempts with direct X-rays)

Saturation effects (non-linearity)

Electron charge can be measured (for students)



Radiation detection technology is evolving very fast, and new experiments become feasible

Triggers for new experiments on fundamental physics are very welcome