# New perspectives for high precision X-ray detection experiments

INFN-CSN5

Young Researcher Grant 2015, n. 17367/2015.

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Laboratori Nazionali di Frascati, INFN

“Is Quantum Theory exact? From quantum foundations to quantum applications”

LNF, Frascati, 25/09/2019

# K- mass precision measurement @ DAΦNE

The main disagreement is between the two most recent and precise measurements (x-ray energies from kaonic atoms):

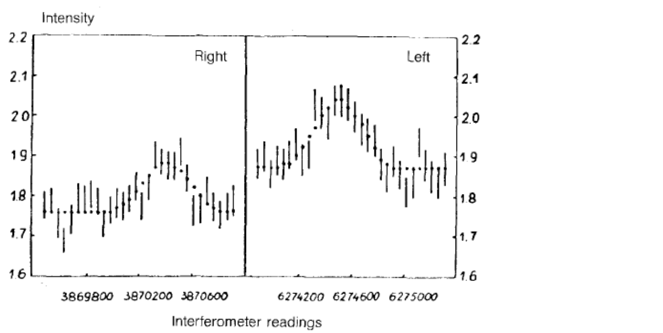



FIG. 1. Right and left reflections of the 4f–3d transition of the $K^-$–$^{12}C$ atom. The interferometer readings are plotted along the abscissa; the detector count rate per $10^{12}$ protons is plotted along the ordinate. The vertical lines are the experimental values with the corresponding error; the heavy points are the results of a fit.

**$m_K$=493.696±0.007 MeV**

A.S. Denisov et al.
JEPT Lett. 54 (1991)558

$K^{-}\,{}^{12}C$, crystal diffraction spectrometer
(6.3 eV at 22.1 keV), 4f-3d

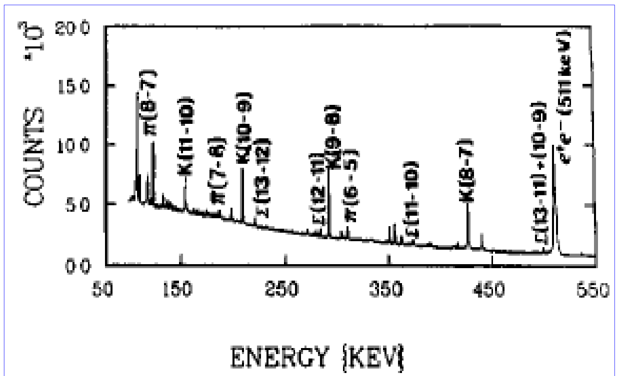
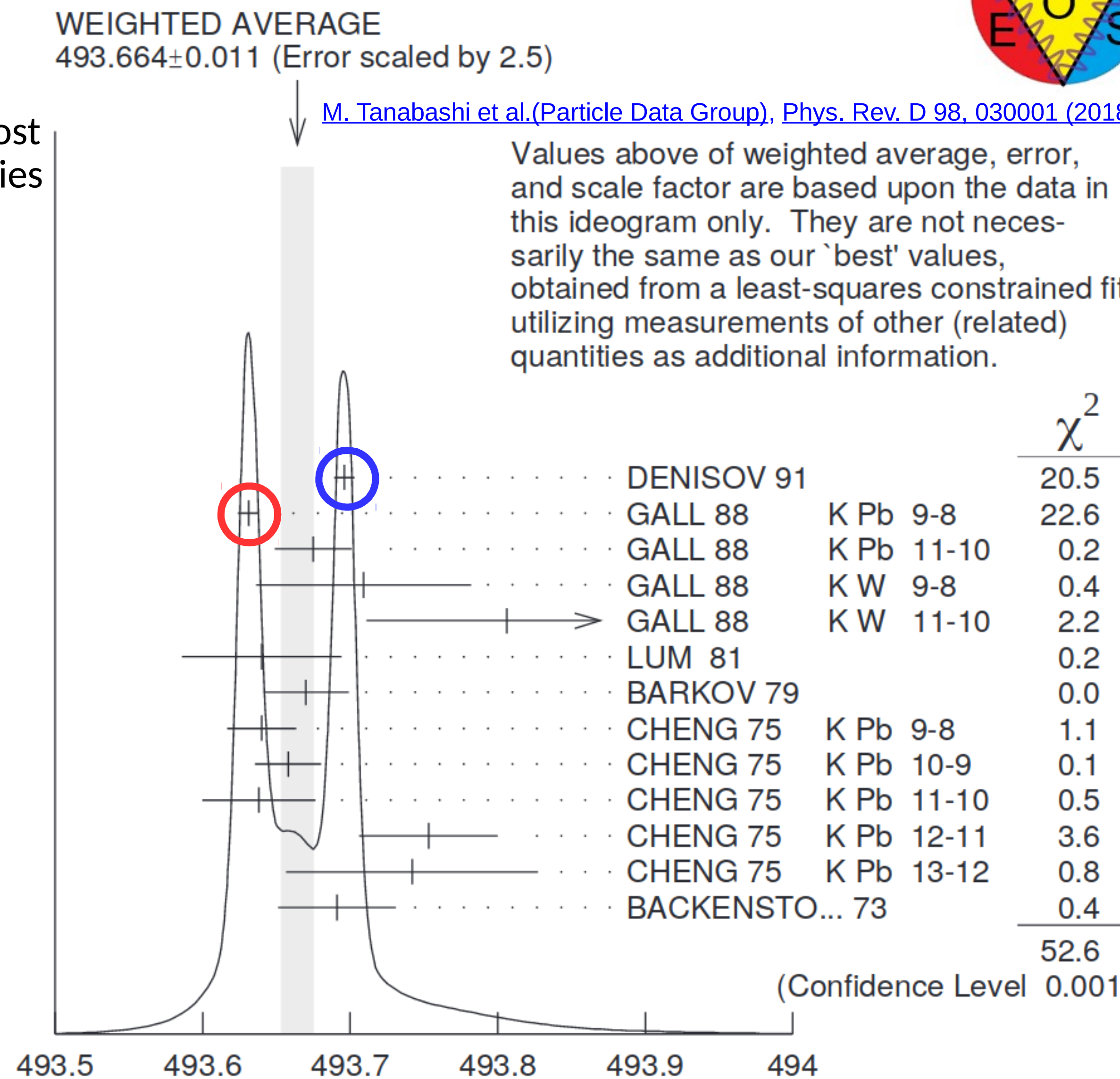



FIG. 1. Untagged Pb x-ray spectrum showing intense kaonic x-ray transitions.




M. Tanabashi et al.(Particle Data Group), Phys. Rev. D 98, 030001 (2018).

**$m_K$=493.636±0.011 MeV**

K.P. Gall et al.

Phys. Rev. Lett. 60 (1988)186

$K^-$Pb, $K^-$W; HPGe detector (1 keV), **$K^-$Pb (9 -> 8),**

$K^-$Pb (11 -> 10), $K^-$W (9 -> 8), $K^-$W (11 -> 10),

# Project's goal

- High resolution (few eV) measurements of the X rays (2-20 keV) emitted in various processes is strongly demanded in: particle and nuclear physics, fundamental science, astrophysics, biology, medical and industrial applications
- Additionally, for some applications (like exotic atoms measurements) X-ray detector systems have to be operated in high background environment.
- These X-rays not always are produced by a point-like source; it is mandatory to develop detectors working with 'extended' (diffused) sources.

**VOXES's goal**: to develop, test and qualify the first prototype of ultra-high resolution and high efficiency X-ray spectrometer in the range of energies 2 - 20 keV using HAPG bent crystals able to work with 'extended' sources

High resolution von-Hamos X-Ray spectrometer using HAPG for Extended Sources in a broad energy range

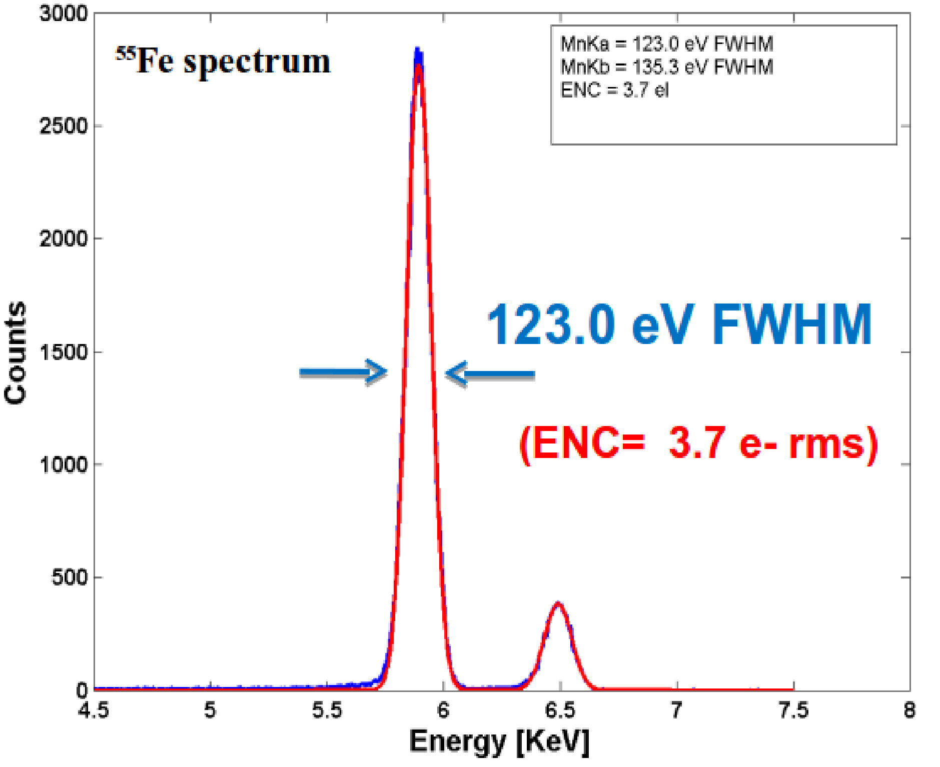
# State of art: high resolution X-ray detectors

Commonly used detectors for X-rays in the range 1-20 keV are the Solid State Detectors (CCD, SDD, etc…)

However…

The solid state detectors have intrinsic resolution (FWHM ~ 120 eV at 6 keV) given by the electronic noise and the Fano Factor

$$\sigma = \frac{FWHM}{2.35} = \omega\sqrt{W_N^2 + \frac{F \times E}{\omega}}$$

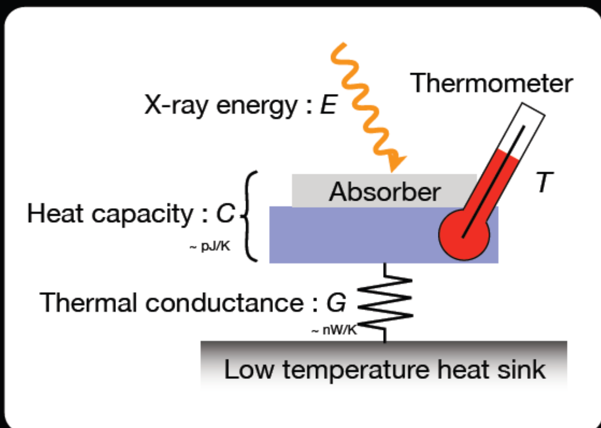



Presently, to achieve ~ eV resolution, two options are available:

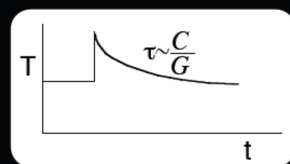
- Transition Edge Sensors (TES)
- Crystals and position detectors (Bragg spectrometers)

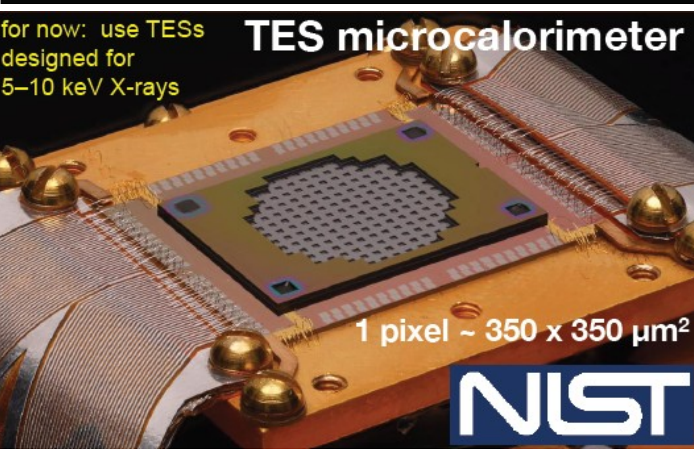
# TES microcalorimeter

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

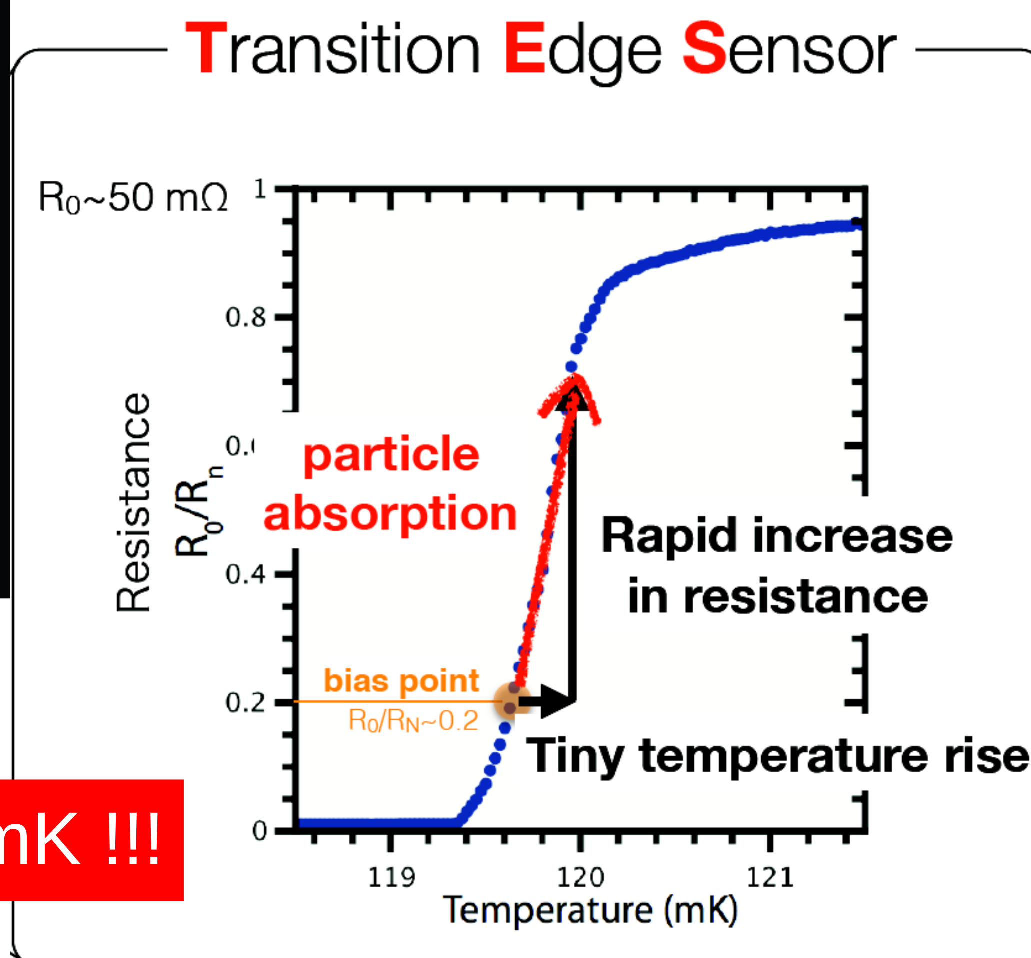



Decay time constant
= C / G ( ~ 500 μs )




$T_C$ ~ 50 mK !!!




**high energy resolution (ΔE / E ~ $10^{-3}$)**

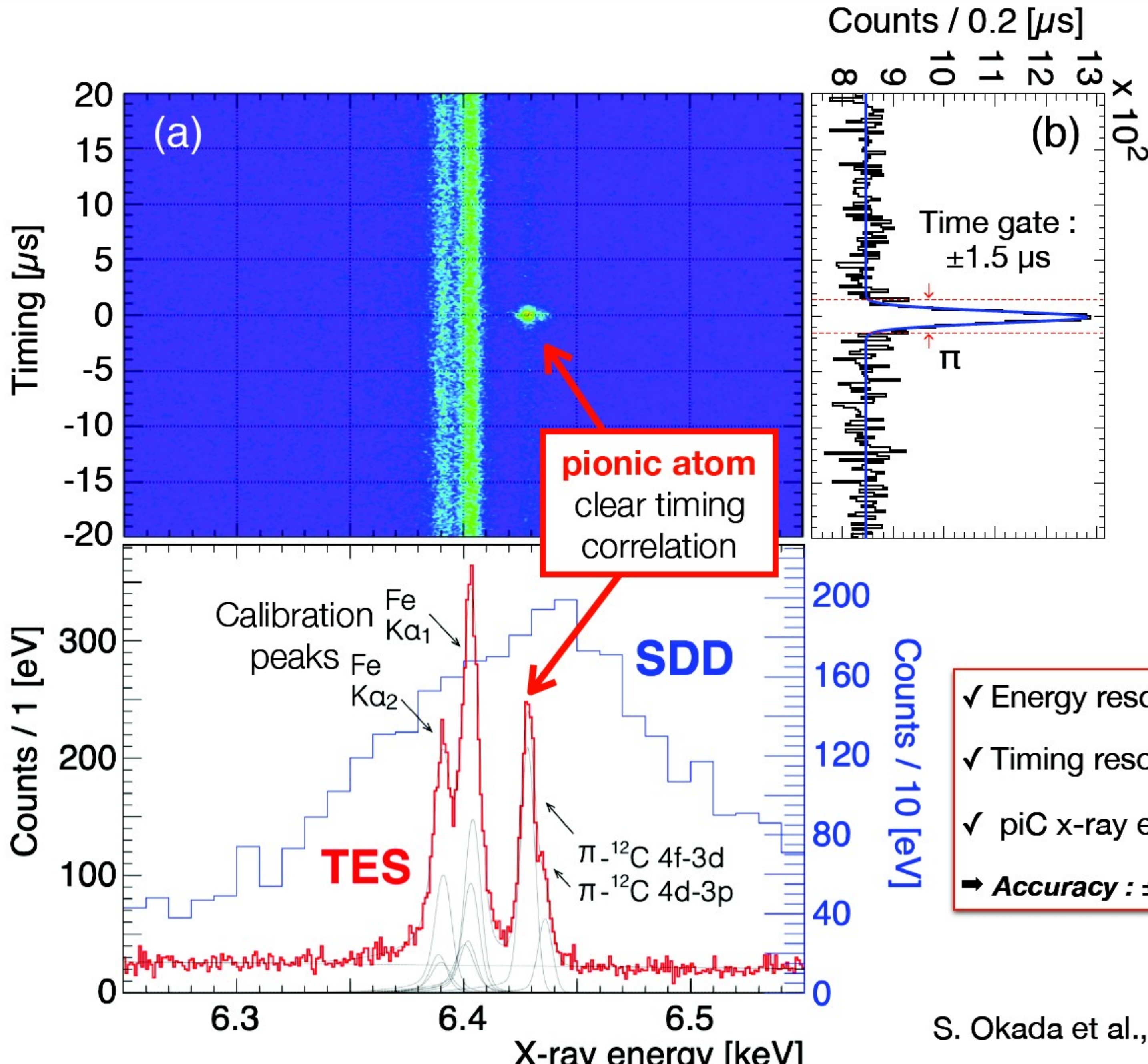
TES : ΔE (FWHM) ~ 5 eV @ 6 keV X-ray
(ref. SDD : ΔE (FWHM) ~ 150 eV @ 6 keV)

LIMITATIONS:

- not optimised for E < 5 keV
- very small active area
- prohibitively high costs
- complex cryogenic system needed
- complex calibration

Reference : Bennet et al., Rev. Sci. Instrum. 83, 093113 (2012)

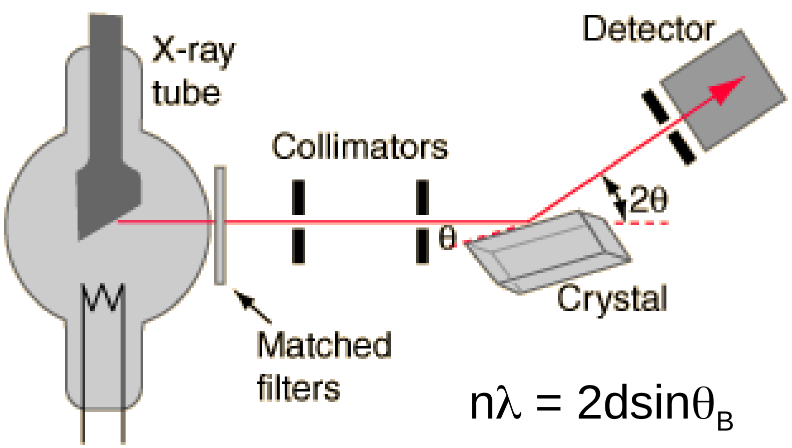
# Pionic atom with TES @ PSI




- ✓ Energy resolution : 6.8 eV @ 6 keV
- ✓ Timing resolution ~ 1.2 us FWHM
- ✓ piC x-ray energies agree with theo. val
- ➡ ***Accuracy : ±0.13 (stat.) ± 0.09 (syst.) eV***

S. Okada et al., PTEP 2016, 091D01 (2016)

# Crystal spectrometers limitations




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

High resolution can be achieved depending on the quality of the crystal and the dimensions of the detectors

Geometry of the detector determines also the energy range of the spectrometer

But….

Crystals response may not be uniform (shape, impurities, ecc.) → Lineshapes are difficult to be measured within few eV precision (surface scan)

In accelerator environments particles may hit the detector → Background reduction capability is mandatory

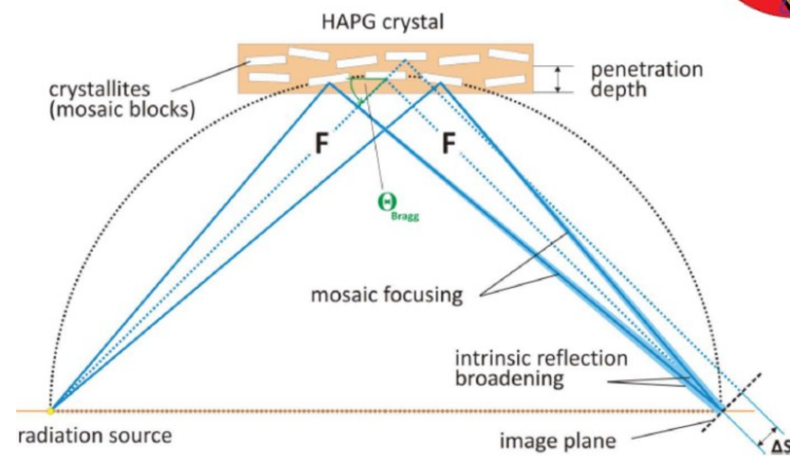
Typical d (Si) ≈ 5.5 Å → $\theta_B$ < 10° for E > 6 keV (forward & difficult)

**Limitation in efficiency**

# Mosaic crystals

Mosaic crystal consist in a large number of nearly perfect small crystallites.

Mosaicity makes it possible that even for a fixed incidence angle on the crystal surface, an energetic distribution of photons can be reflected



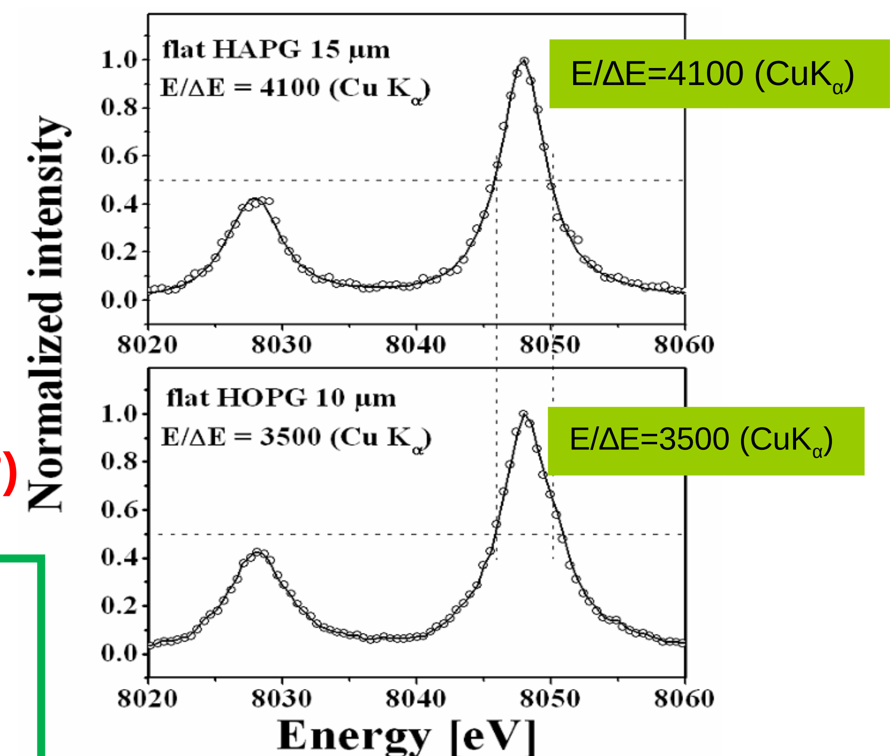

Increase of efficiency (focusing) ~ 50

Loss in resolution

Pyrolitic Graphite mosaic crystals (d = 3.354 Å):

Highly Oriented Pyroliltic Graphite (HOPG, Δθ≈1°)

**Highly Annealed Pyrolitic Graphite (HAPG, Δθ≈0.07°)**

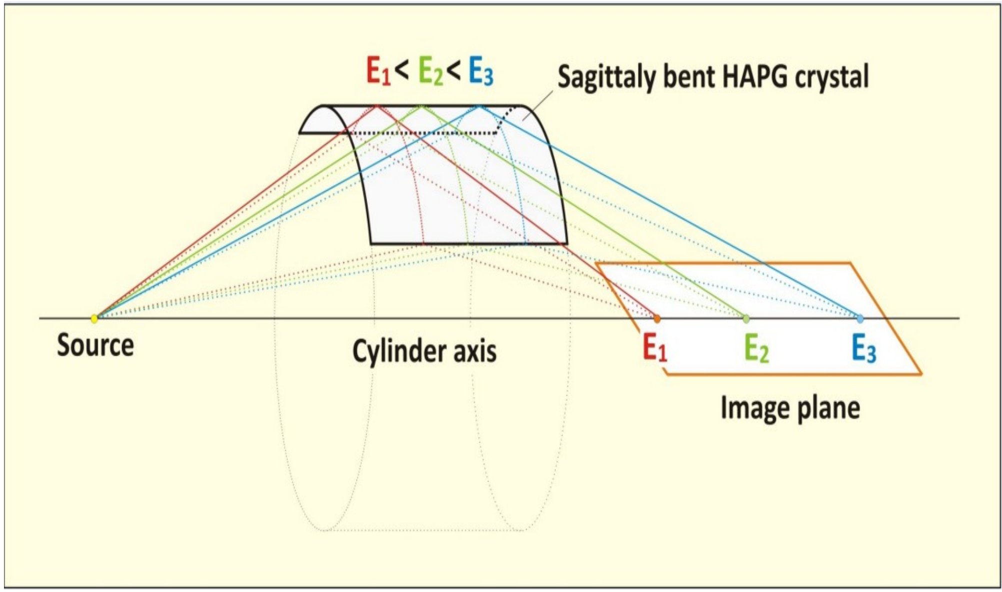



flexible HAPG has twice higher spectral resolution, while flexible HOPG – approximately twice higher reflectivity

H. Legall, H. Stiel, I. Grigorieva, A. Antonov et al., FEL Proc. 2006

# HAPG:
# High Annealed Pyrolitic Graphite

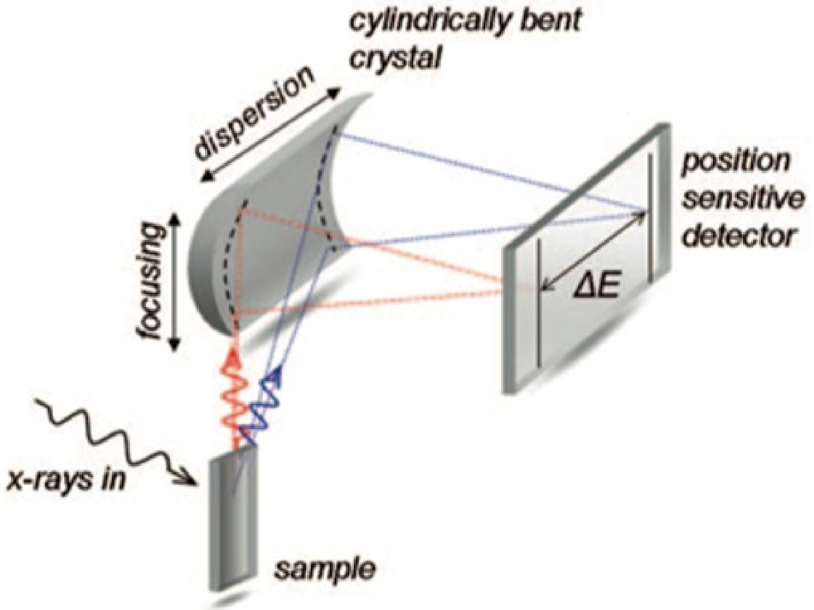
- Bending does not influence resolution and intensity
- Mosaic spread down to 0.05 degree
- Integral reflectivity ~ $10^2$ higher than for other crystals
- Variable thickness (efficiency)
- Excellent thermal and radiation stability



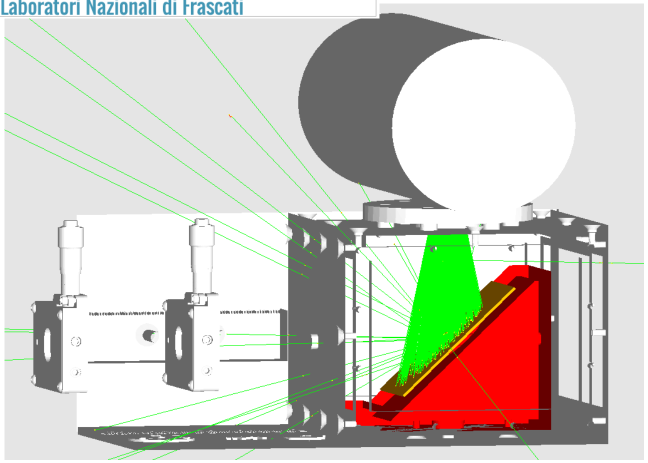

Characterization of HAPG mosaic crystals using synchrotron radiation

Martin Gerlach,[a] Lars Anklamm,[b] Alexander Antonov,[c] Inna Grigorieva,[c] Ina Holfelder,[a] Birgit Kanngießer,[b] Herbert Legall,[c] Wolfgang Malzer,[b] Christopher Schlesiger[b] and Burkhard Beckhoff[a*]

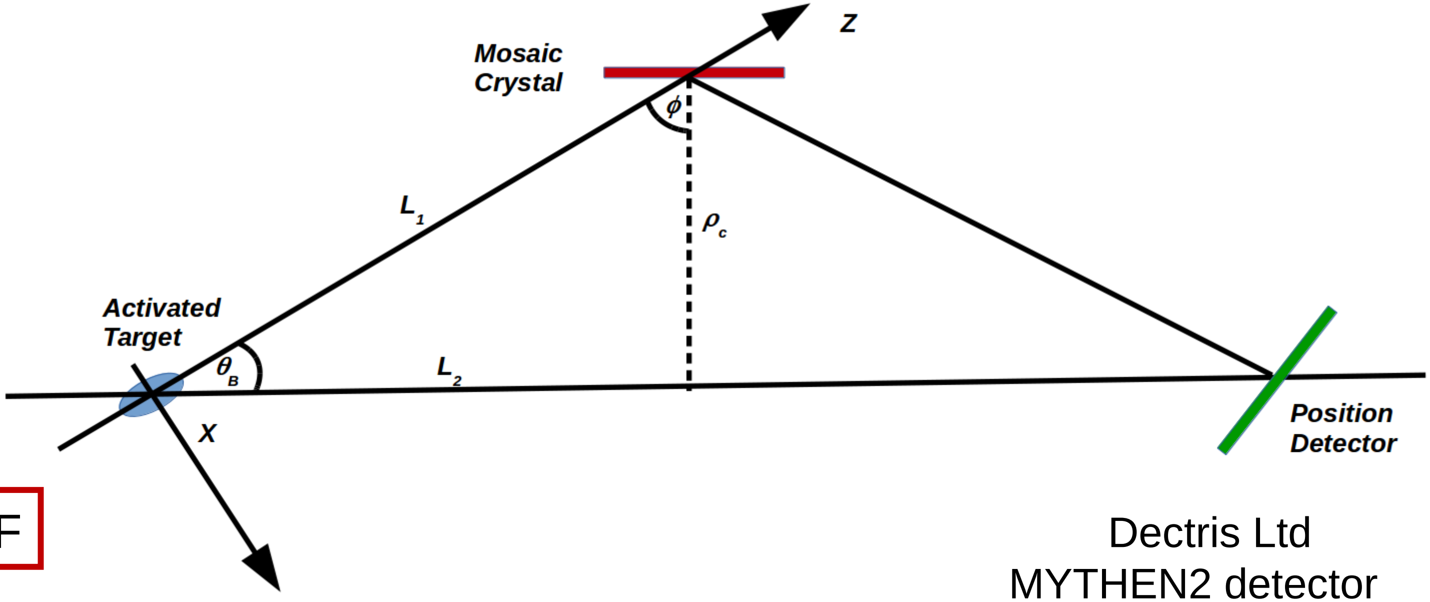
*J. Appl. Cryst.* (2015). **48**



# Von Hamos configuration



Designed & 3D-printed @ LNF



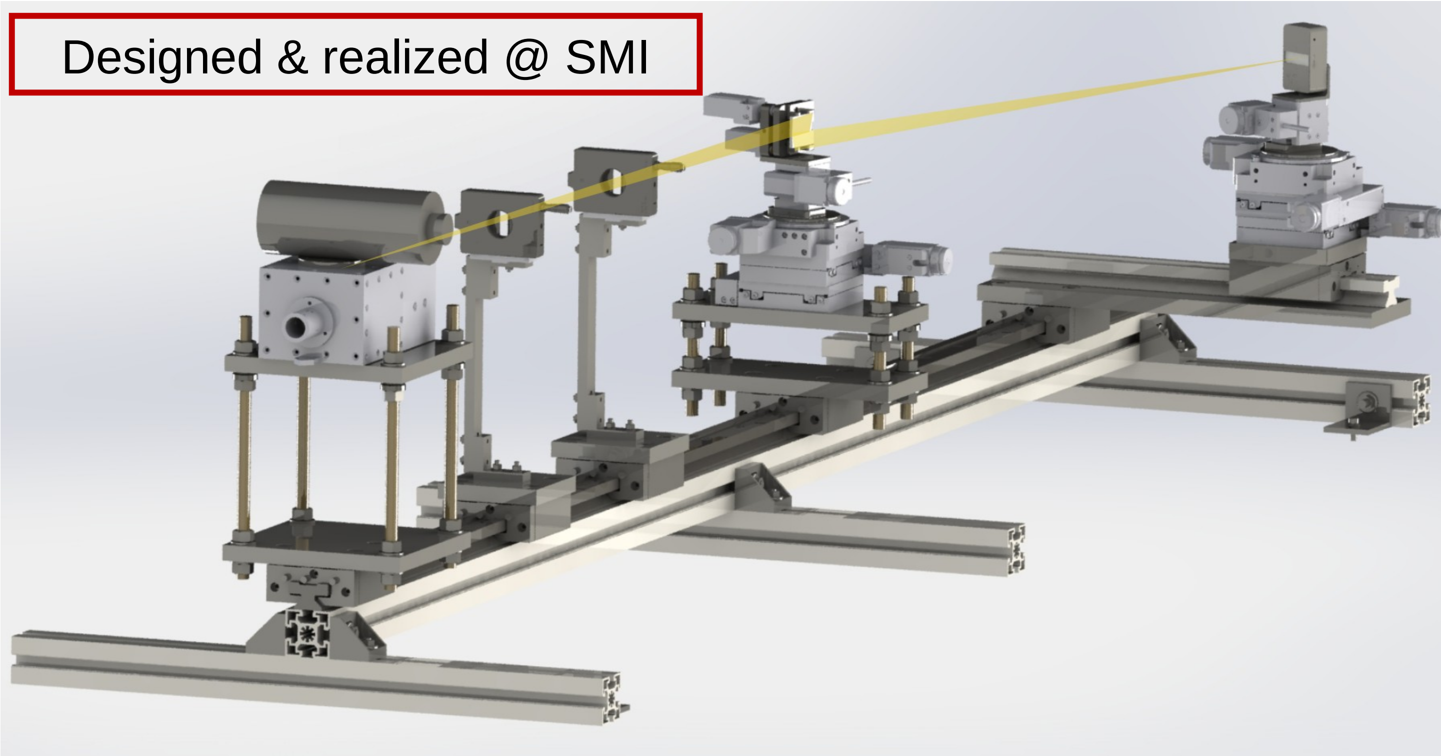

Dectris Ltd
MYTHEN2 detector

For a given X-ray energy the Bragg angle ($\theta_B$ ) and the curvature radius of the crystal ($\rho_c$ ) completely determine the position of the source, the crystal and the position detector

$$L_1 = \frac{\rho_c}{sin\theta_B}$$

$$L_2 = L_1 sin\phi$$

Designed & realized @ SMI



# The source size problem
# What has been done so far?

Bragg spectroscopy is usually exploited by XAS, XES, synchrotron light users, etc…

This means:
- Point-like sources
- High yields (no need to increase them)
- 1 eV (Si, Mica, etc) or 2-3 eV (HAPG) resolution is very easily achievable

The x-ray source, which was used for the measurements, is a low power microfocus x-ray tube (IfG) with a source diameter of about $50\ \mu m$. Measurements were performed with the Cu $K_\alpha$ emission of a Cu anode at 8 keV. The spec-

Laser-produced plasmas were created using the "Phoenix" Nd glass laser (the Lebedev Physical Institute) operated at a wavelength of 0.53 $\mu$m with pulse energy up to 10 J and 2 ns pulse duration. The laser beam was focused onto massive Mg, Al, Ti, or Fe targets (see Fig. 2). The focal spot diameter was about $\sim 15\ \mu m$

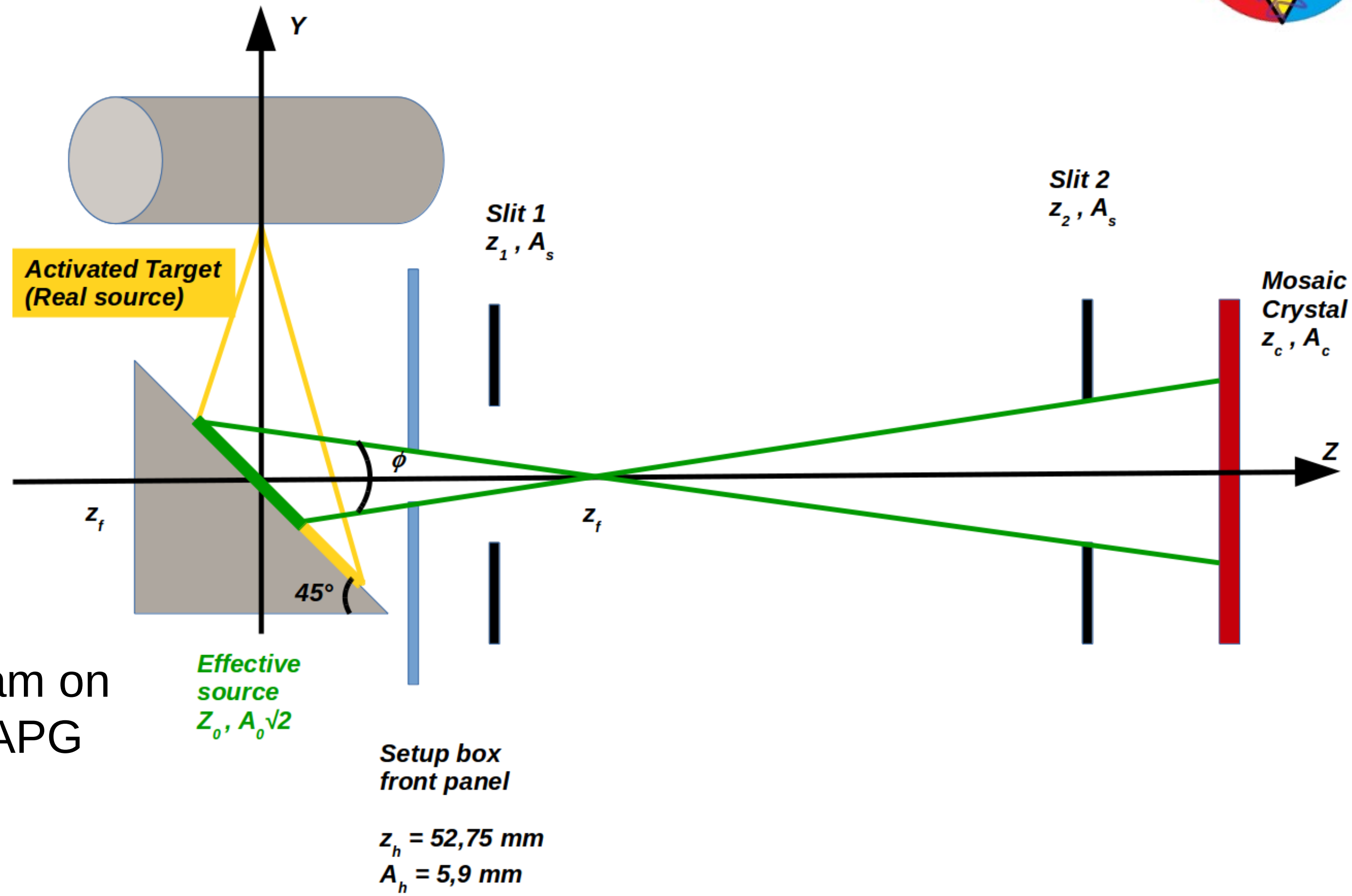
### III. SPECTROMETER SETUP

The spectrometer consists of three principal components: the X-ray source, the HAPG optic, and the position sensitive detector. As source a watercooled 100 W micro focus X-ray tube with a tungsten anode and a focus size of 50 $\mu$m is used. The emitted radiation is focused onto the sample by a polycapillary full lense with a spot size of 35 $\mu$m. The HAPG

But what if we really need wider sources for higher statistics?
Or what if our photons come from a diffused isotropic source?

# Vertical spread

The vertical spread of the X-ray beam is fixed by the slits positions ($z_1$,$z_2$) and their frame size ($A_s$), together with the hole in the front panel of the setup box ($z_h$,$A_h$).




The vertical spread of the beam on the target ($A_0$) and on the HAPG crystal ($A_c$) are then:

$$A_0 = 2z_f tg\phi$$

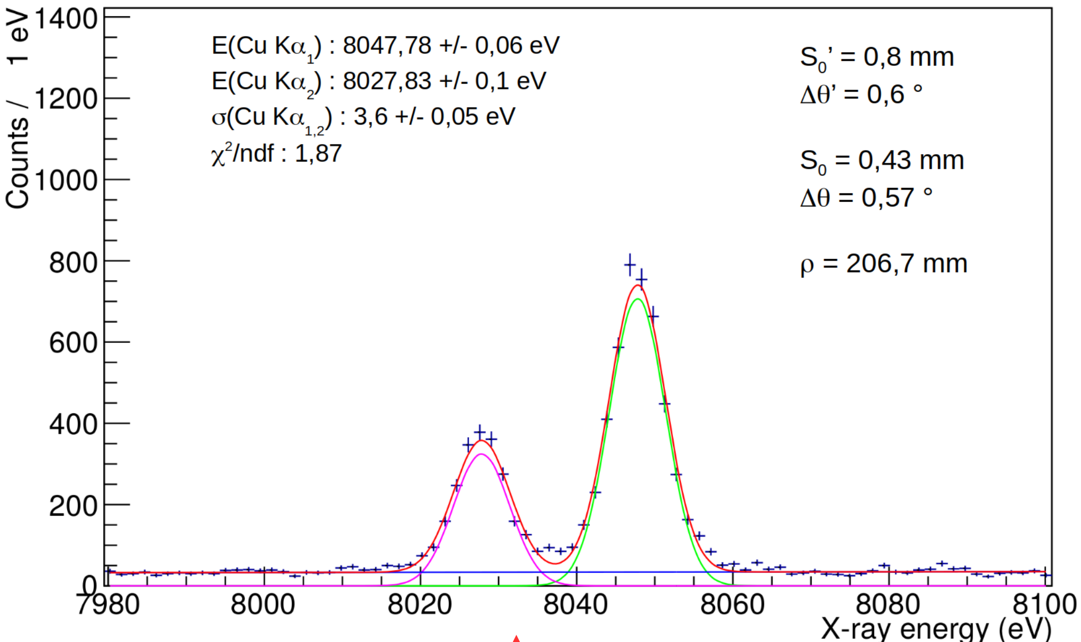
$$A_c = 2(z_c - z_f)tg\phi$$

We first define the position of the intersection point $z_f$ and the $\phi$ angle :

$$tg\phi = \frac{A_s + A_h}{2(z_2 - z_h)}$$

$$z_f = z_2 - \frac{A_s}{2tg\phi}$$

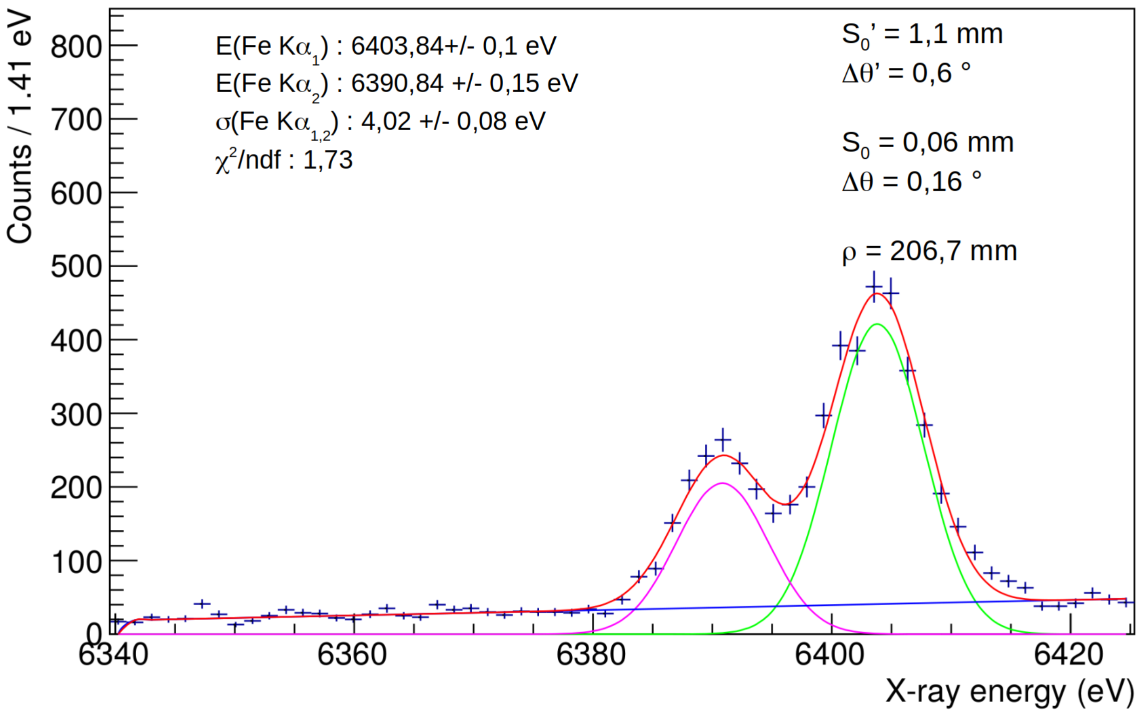
# Characterization @ 6-8 keV



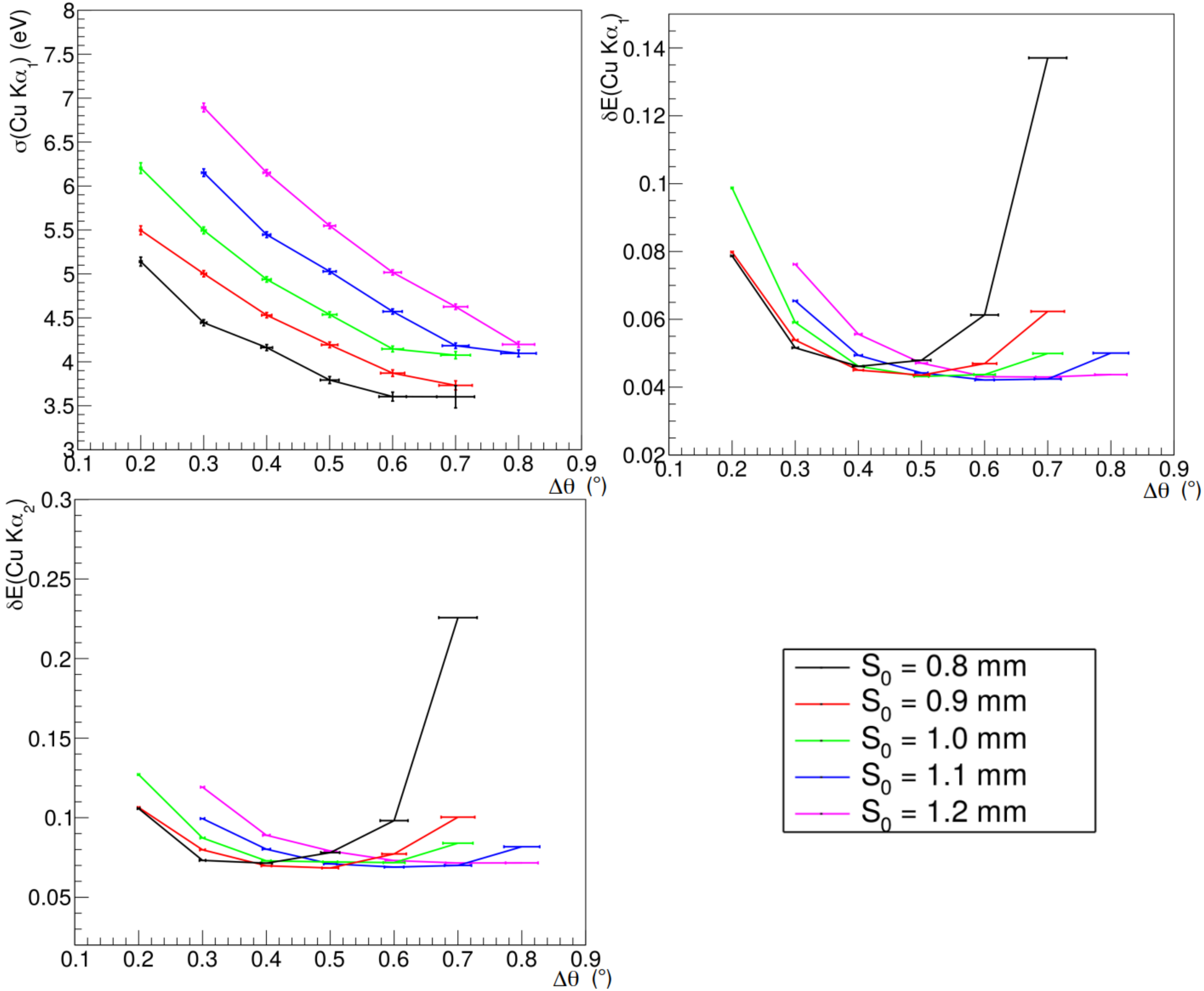

In the limit of a background free pure gaussian peak, the precision is related to the resolution via:

$$\delta E = \frac{\sigma E}{\sqrt{N}}$$

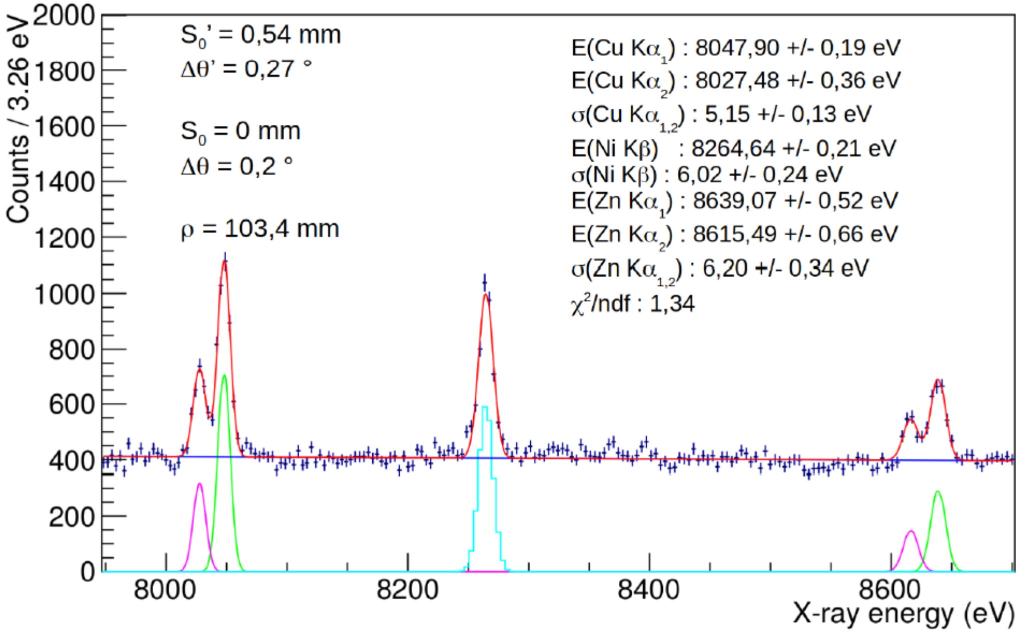
$$\frac{3,6}{\sqrt{4323}} = 0{,}0547\, eV$$

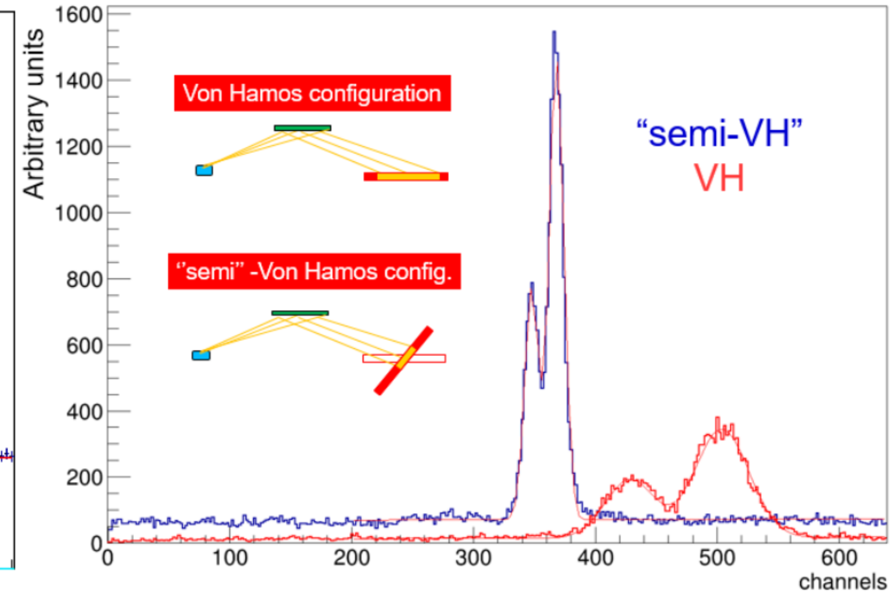


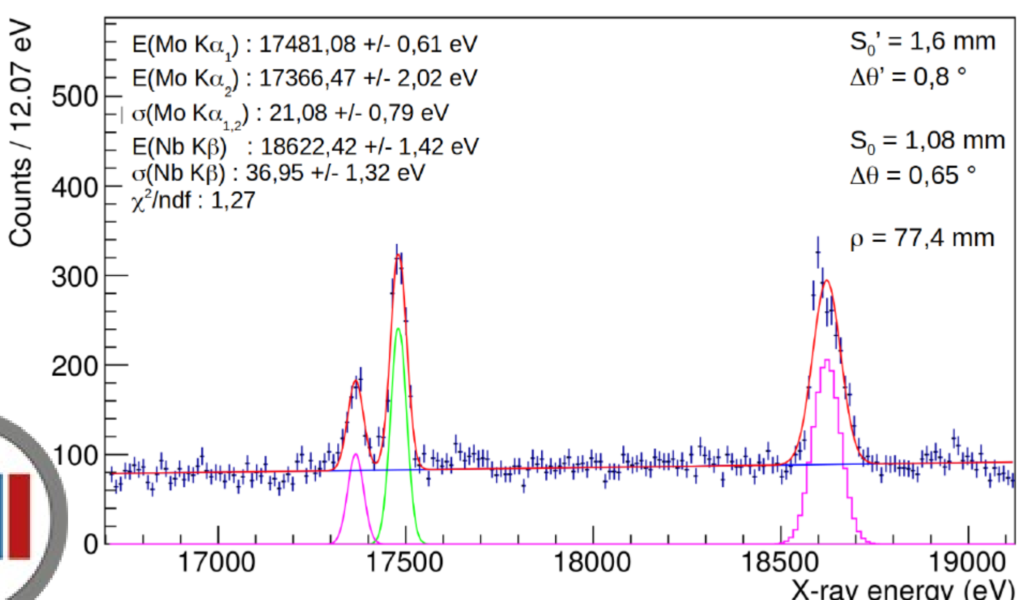
# Scan over Δθ’, $S_0$’ (Cu 206,7 mm ρ)

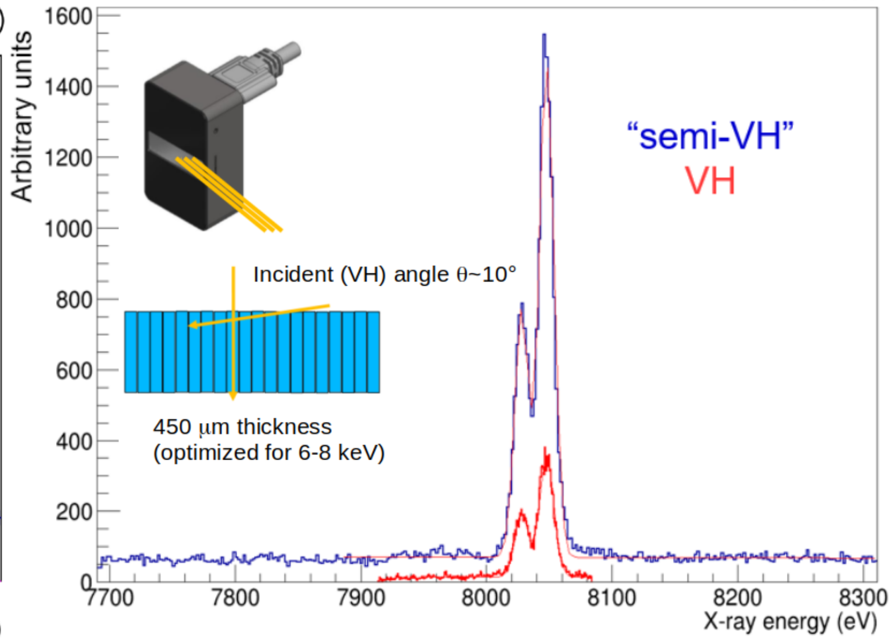


# Semi VH configuration: wider dynamic range



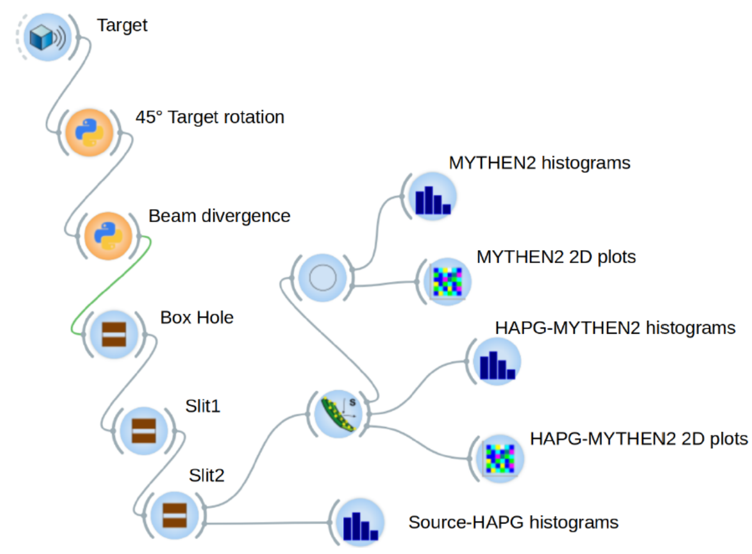



# Results summary

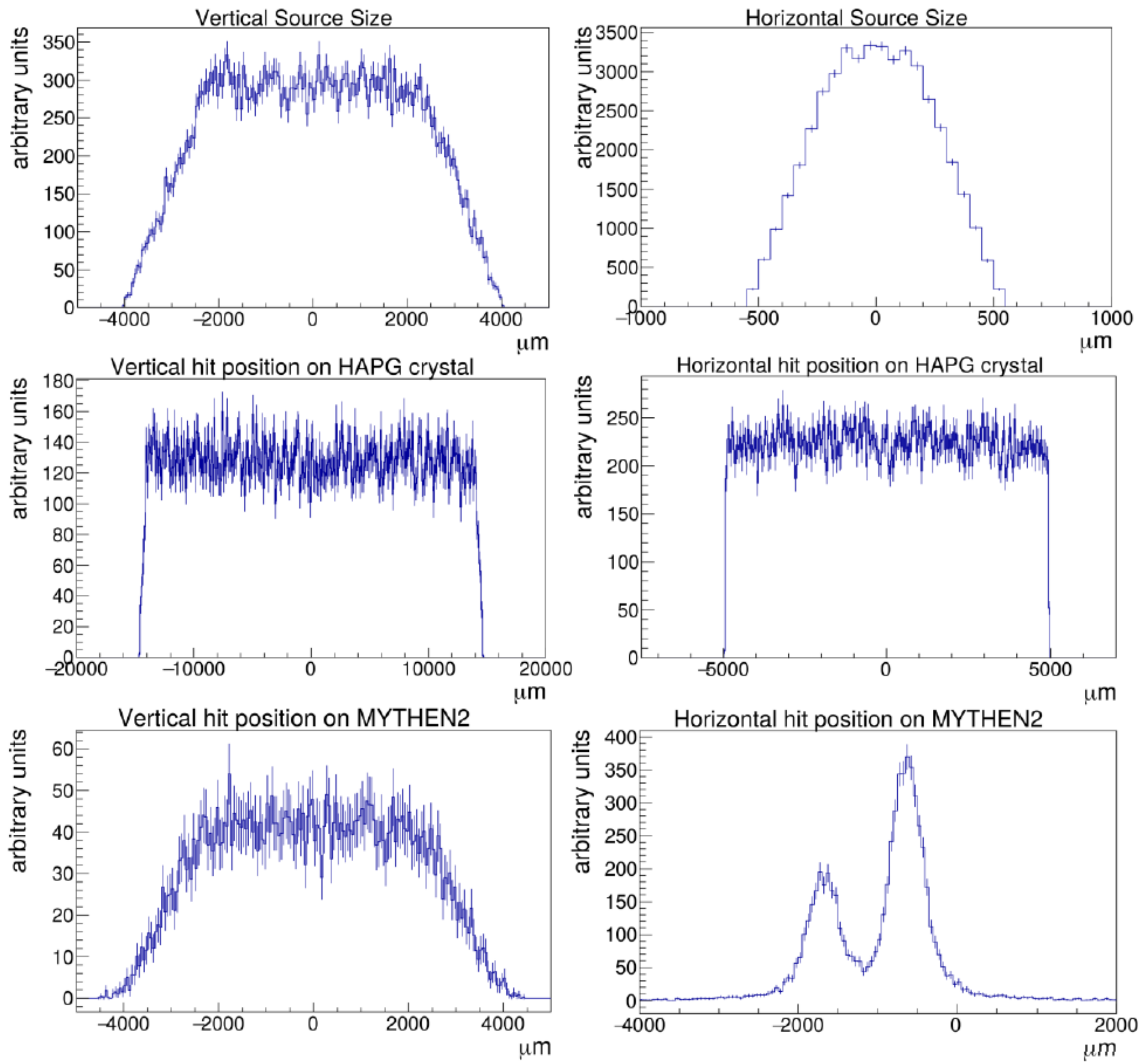
| Element | $\rho_c\,(mm)$ | Parameter | value (eV) | $S_0'/\Delta\theta'\,(mm,^\circ)$ |
|---|---|---|---|---|
| | | $\sigma(K\alpha_{1,2})$ | $4,17 \pm 0,16$ | $0,3/0,24$ |
| | 77,5 | $\delta(K\alpha_1)$ | $0,11$ | $0,6/0,44$ |
| | | $\delta(K\alpha_2)$ | $0,18$ | $0,6/0,44$ |
| | | $\sigma(K\alpha_{1,2})$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

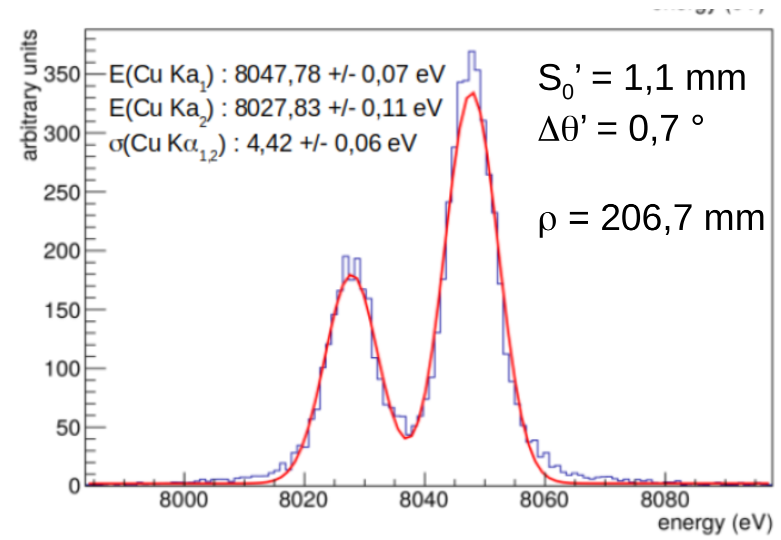


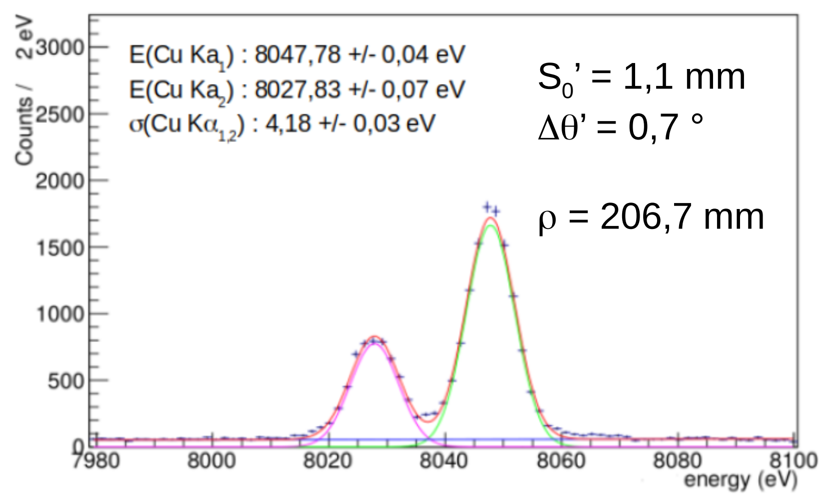

**To be checked with X-ray tracing simulations**

**Shadow and XOP software integrated in the OASYS environment.**

# Ray tracing simulations



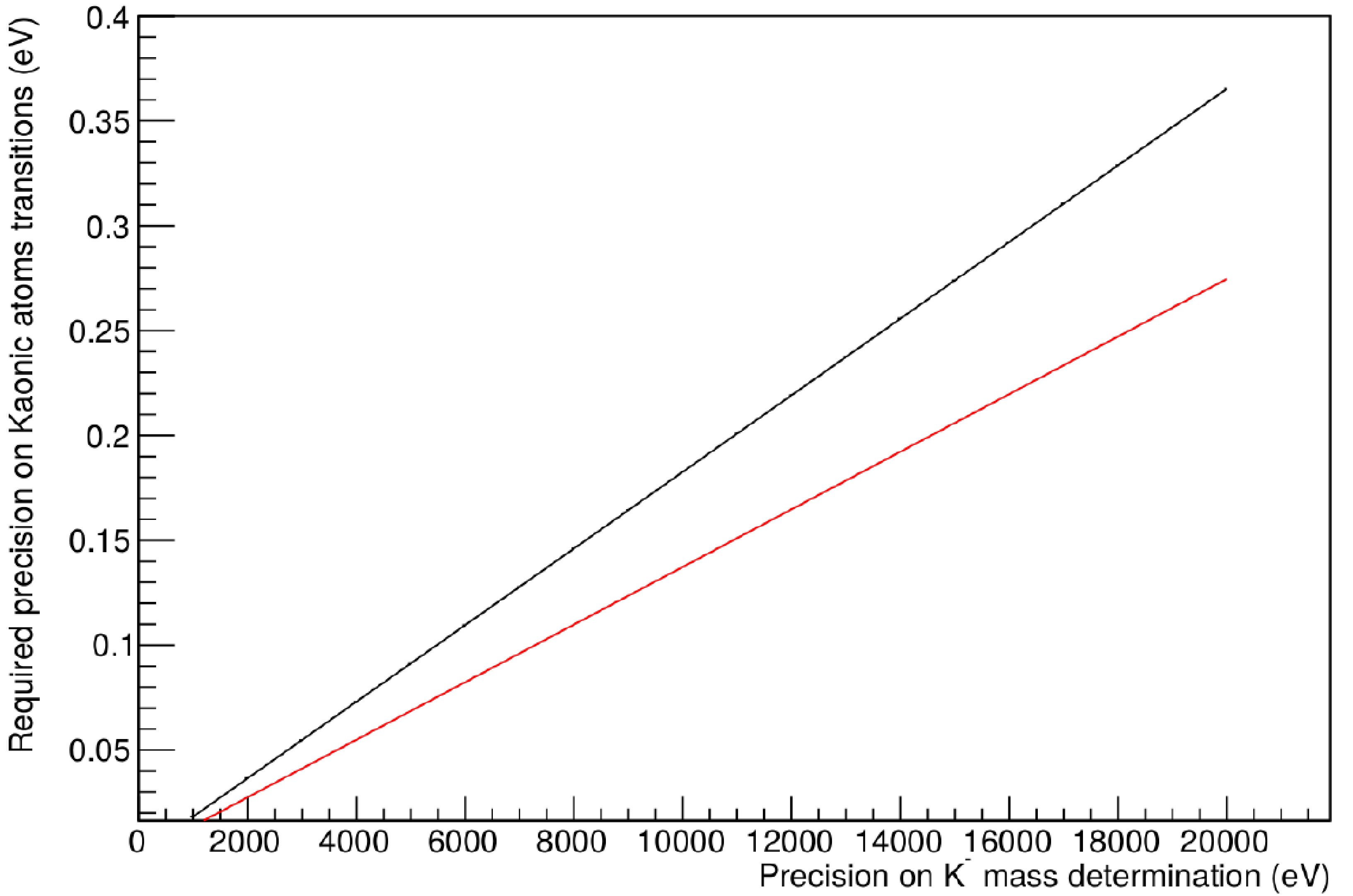
# K mass determination

$$E^K_{X\to Y} = \frac{Z^2 e^4 \mu_{KN}}{8h^2\varepsilon_0^2}\left(\frac{1}{Y^2} - \frac{1}{X^2}\right)$$

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

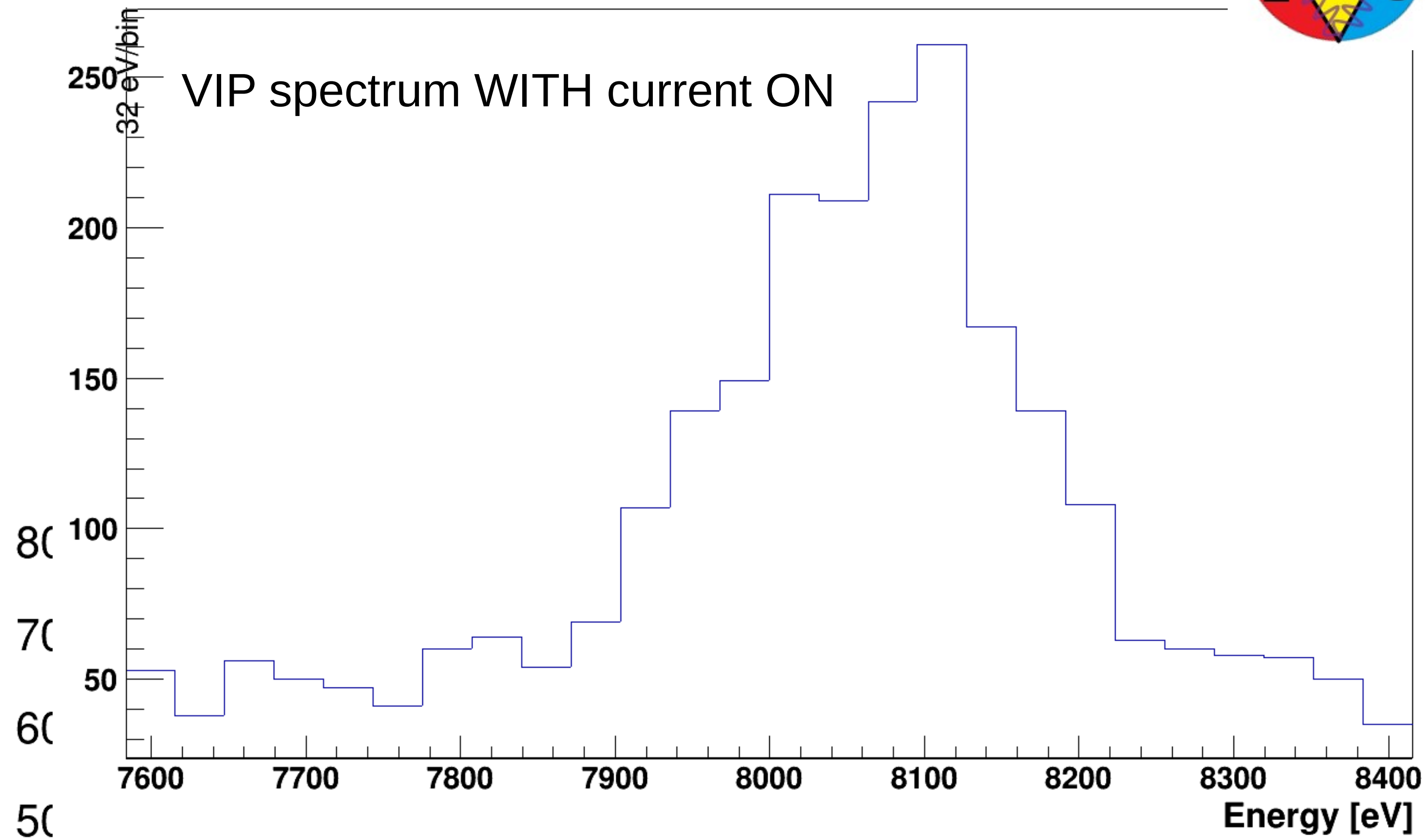
$$\mu_{KN} = \frac{m_K m_N}{m_k + m_N}$$

$$m_K = \frac{\mu_{KN} m_N}{m_N - \mu_{KN}}$$

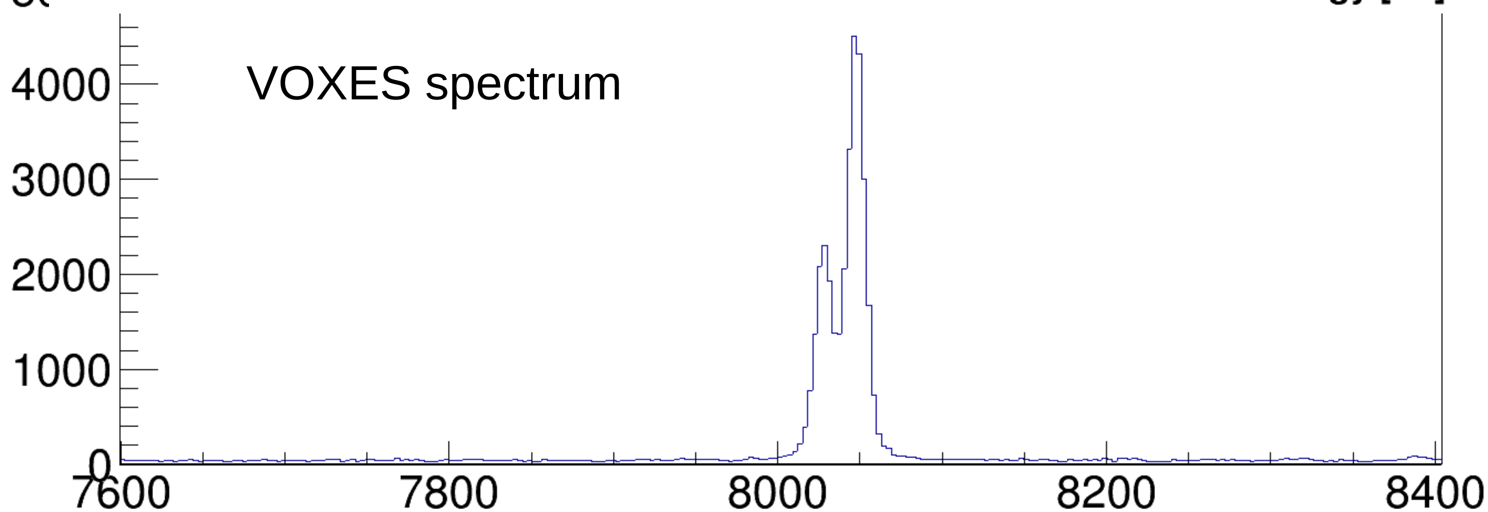


# What about the VIP Cu spectrum?

How much could one gain with a ≈ 100 times better resolution?




Estimations including efficiency and MC to optimize a possible setup are needed



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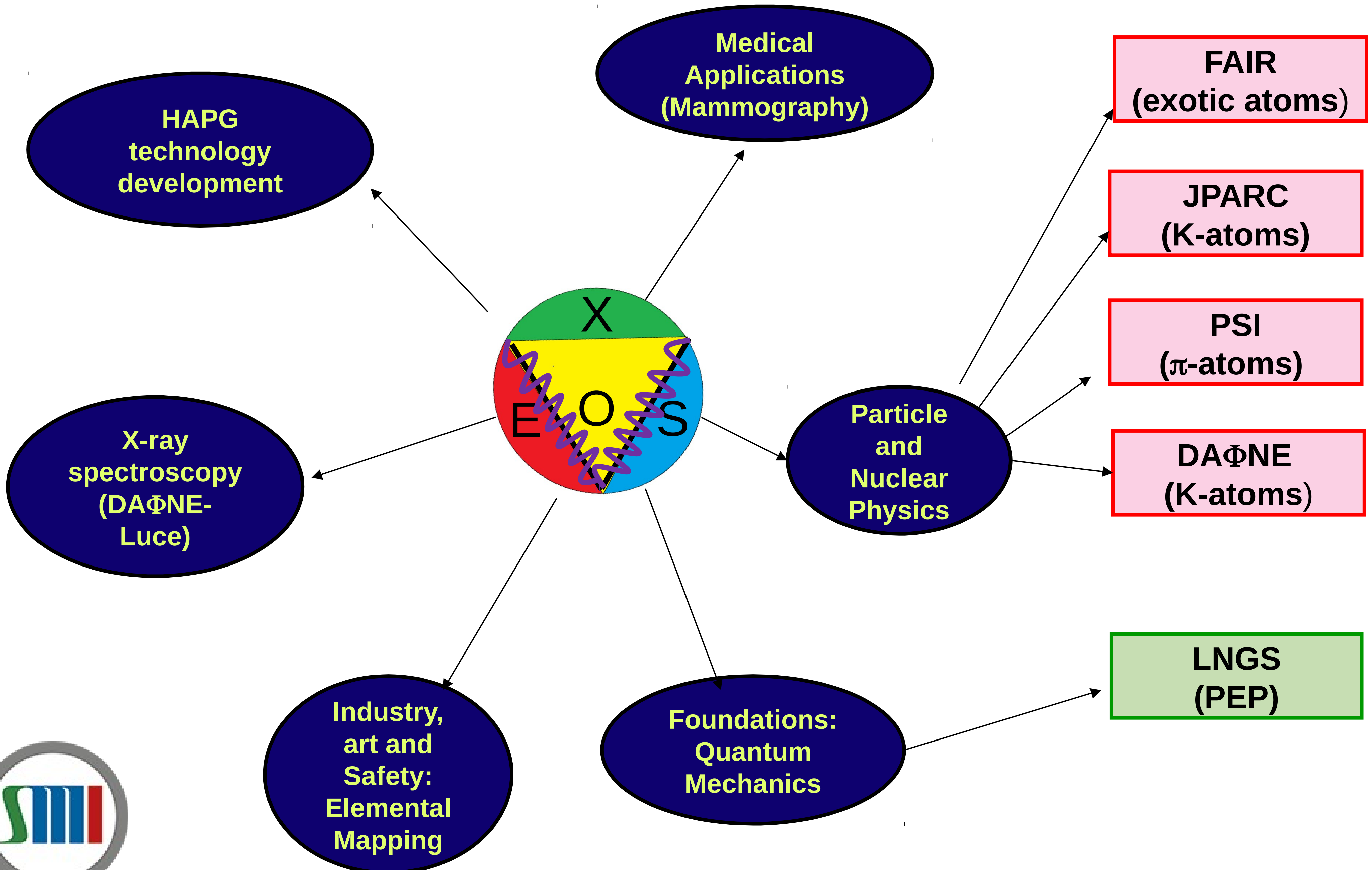
# Impact (scientific, technological, socioeconomic)



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# Impact
# (scientific, technological, socioeconomic)

**Transportable and Agile Spectrometer for metal Trace in Edible liquids : TASTE**

**INFN-CNTT commision**
**“Research 4 Innovation 2020” awarded**

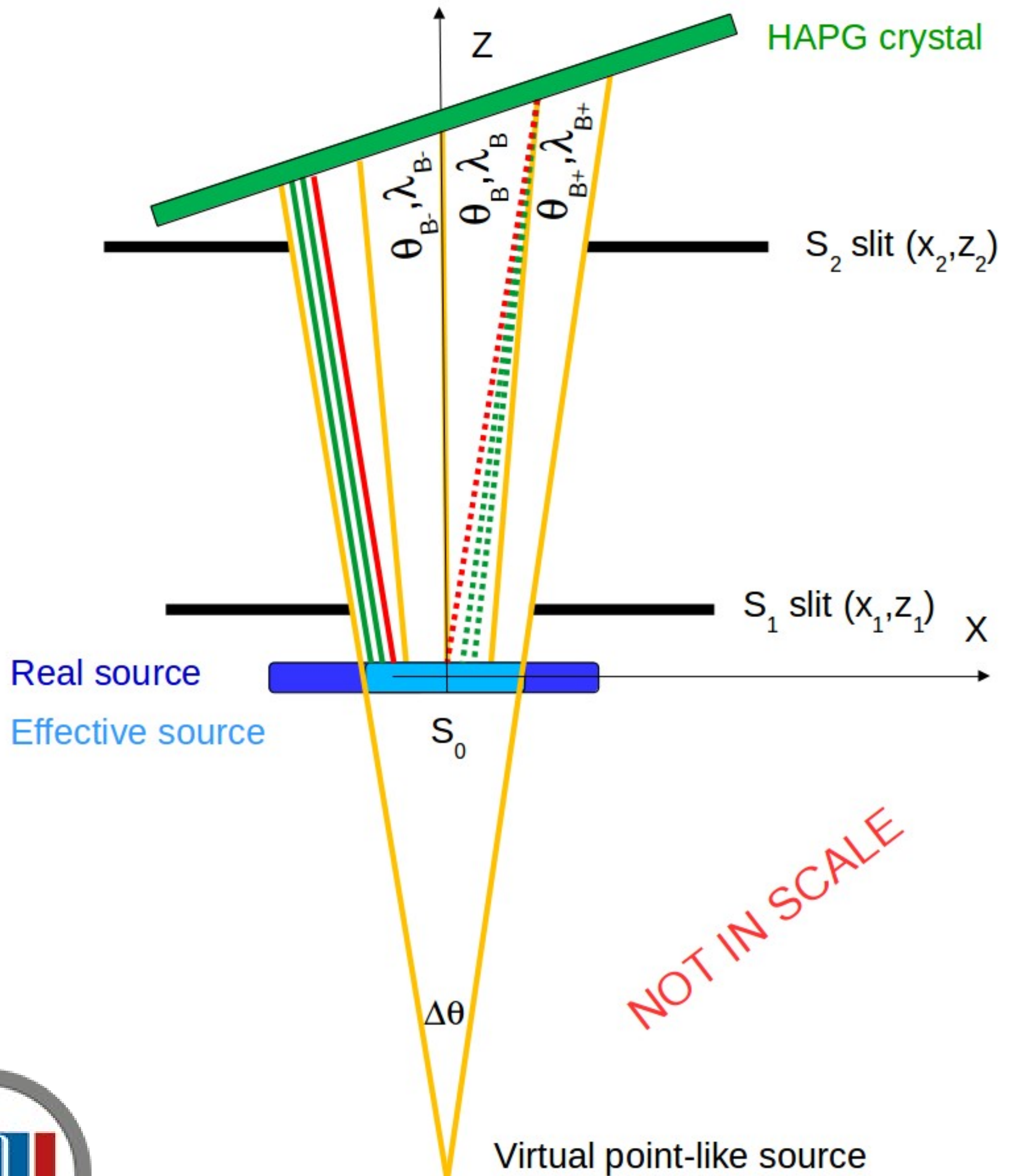
Istituto Nazionale di Fisica Nucleare
Trasferimento Tecnologico

**Hints for possible measurements???**

**We wait for your theory….to prove it!!!**

**Thanks for your attention**

# The source size problem

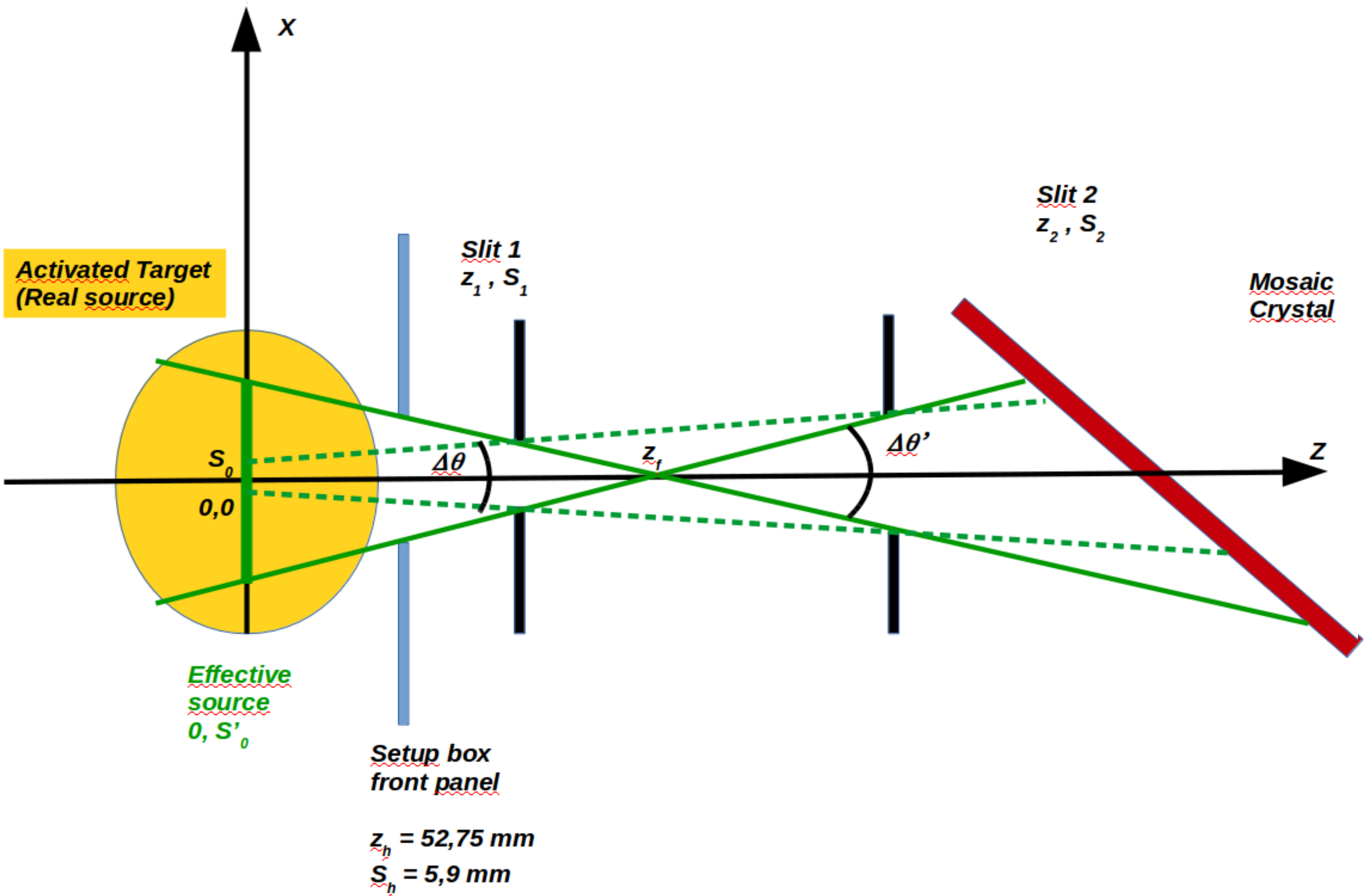



X ray source
Slits
HAPG
Signal photons
Background (?)

Is it all? Are the red lines really (only) background?

With this configuration you are limited to few tens of microns sources and very compact spectrometers….

# Horizontal spread




For each Δθ' , $S_0$' pair, the 2 values of the slits can be found; first, we define the position of the intersection point $z_f$ :

$$z_f = \frac{S_0'}{2} ctg\left(\frac{\Delta\theta'}{2}\right)$$

Then, the 2 slits aperture are defined by:

$$S_1 = \frac{z_f - z_1}{z_f} S_0'$$

$$S_2 = \frac{z_2 - z_f}{z_f} S_0'$$

and the vertical illuminated portion of the HAPG is

$$S_c = \frac{z_c - z_f}{z_f} S_0'$$