

# X-ray detectors and measurements at LNF for nuclear and fundamental physics, Quantum Gravity, and agrifood applications



“Channeling 2023”

*A. Scordo, Riccione, 08/06/2023*

# X-ray detectors at Laboratori Nazionali di Frascati of INFN (LNF)

Crystal spectrometers:

- High resolution
- Low efficiency
- 0-20 keV range

SDDs

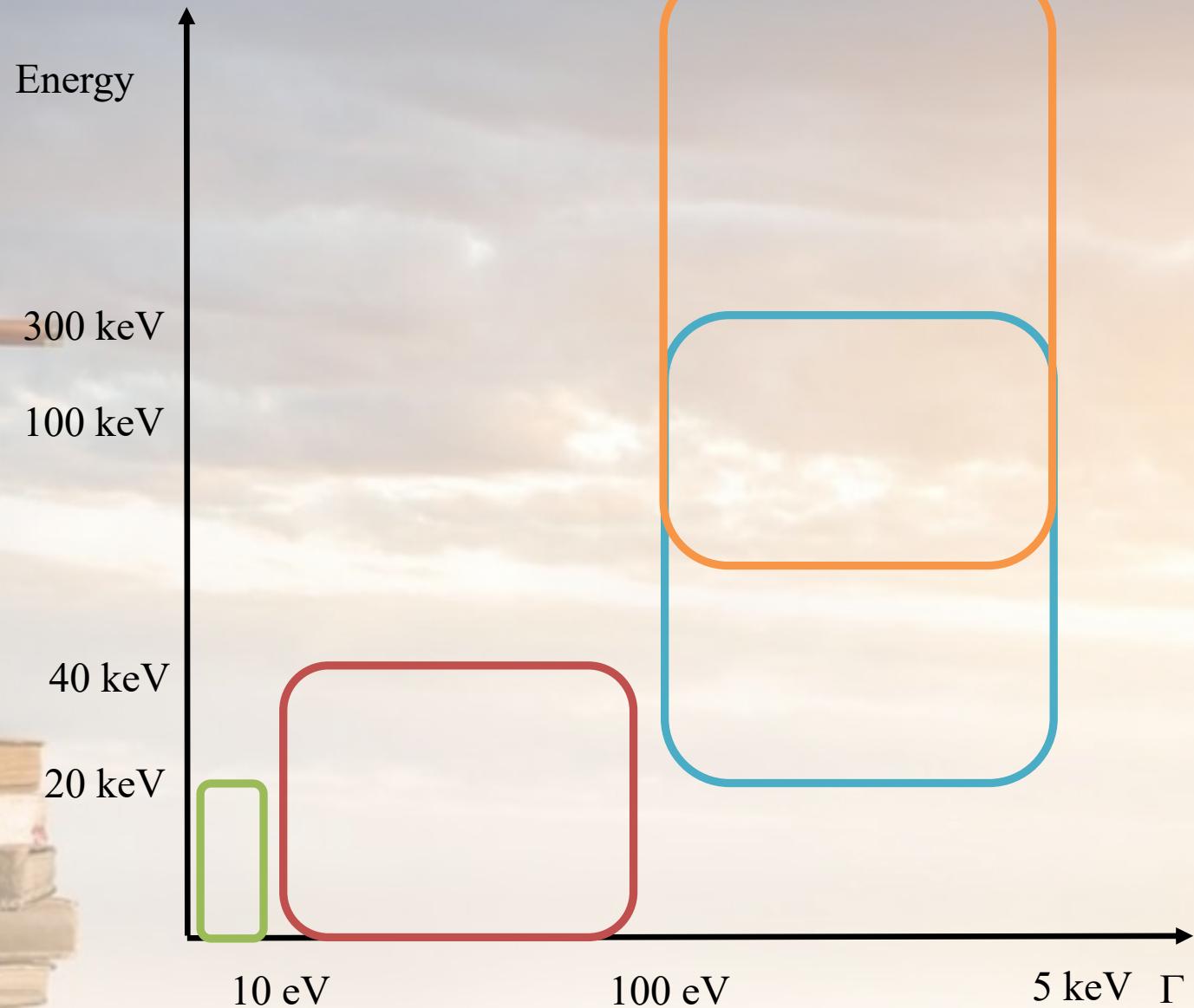
- 120 eV max resolution
- 4-40 keV range
- High efficiency

Cd(Zn)Te

- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

HPGe

- 50-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed



# X-ray detectors at LNF

Crystal spectrometers:

- High resolution
- Low efficiency
- 0-20 keV range

SDDs

- 120 eV max resolution
- 4-40 keV range
- High efficiency

Cd(Zn)Te

- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

HPGe

- 50-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed

(Strangeness)  
Nuclear Physics  
with exotic atoms

Tests of foundations  
of physics

Tests of Quantum  
Gravity

Agrifood: metals'  
oxidation in liquids

# X-ray detectors at LNF

Crystal spectrometers:

- High resolution
- Low efficiency
- 0-20 keV range

SDDs

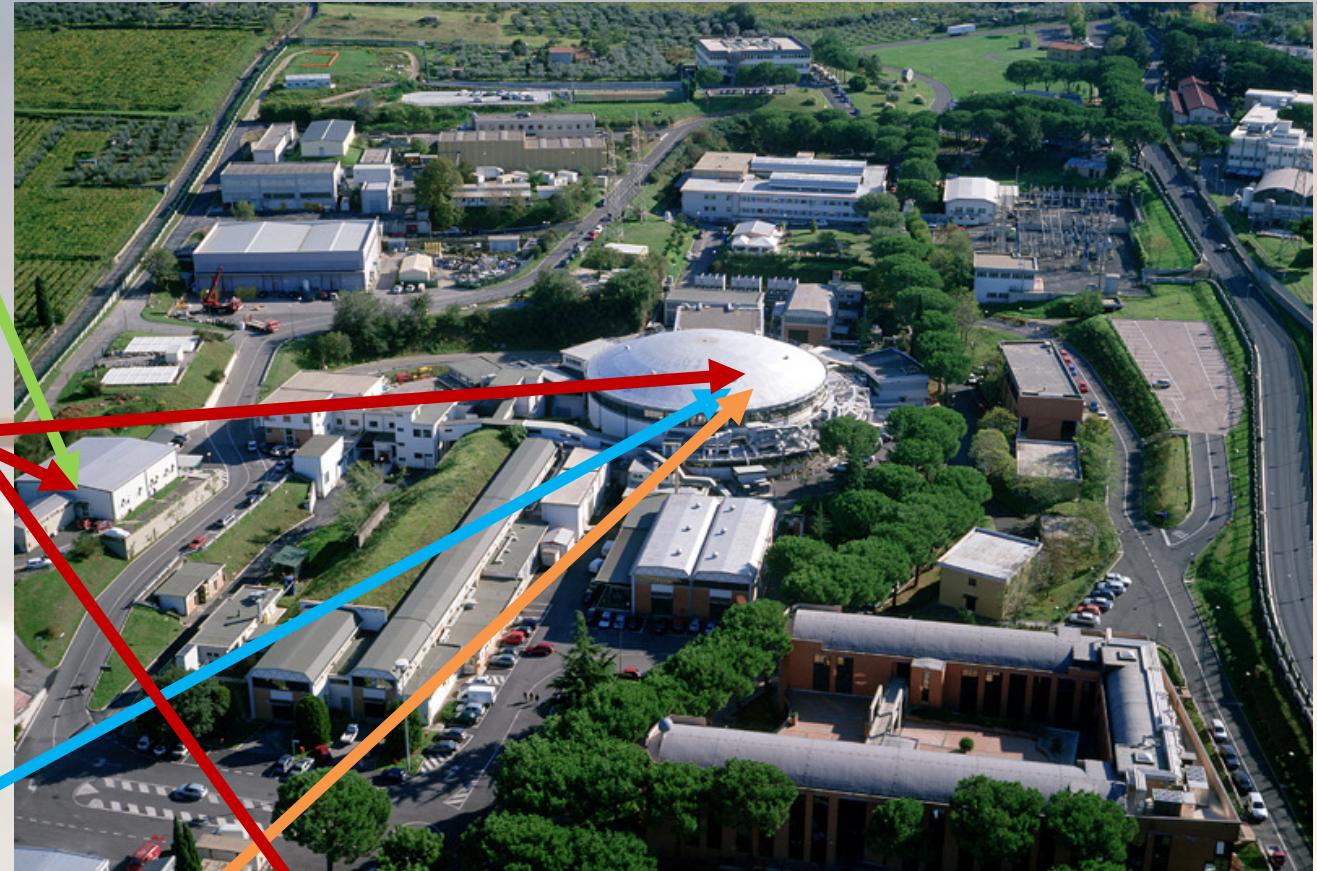
- 120 eV max resolution
- 4-40 keV range
- High efficiency

Cd(Zn)Te

- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

HPGe

- 50-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed

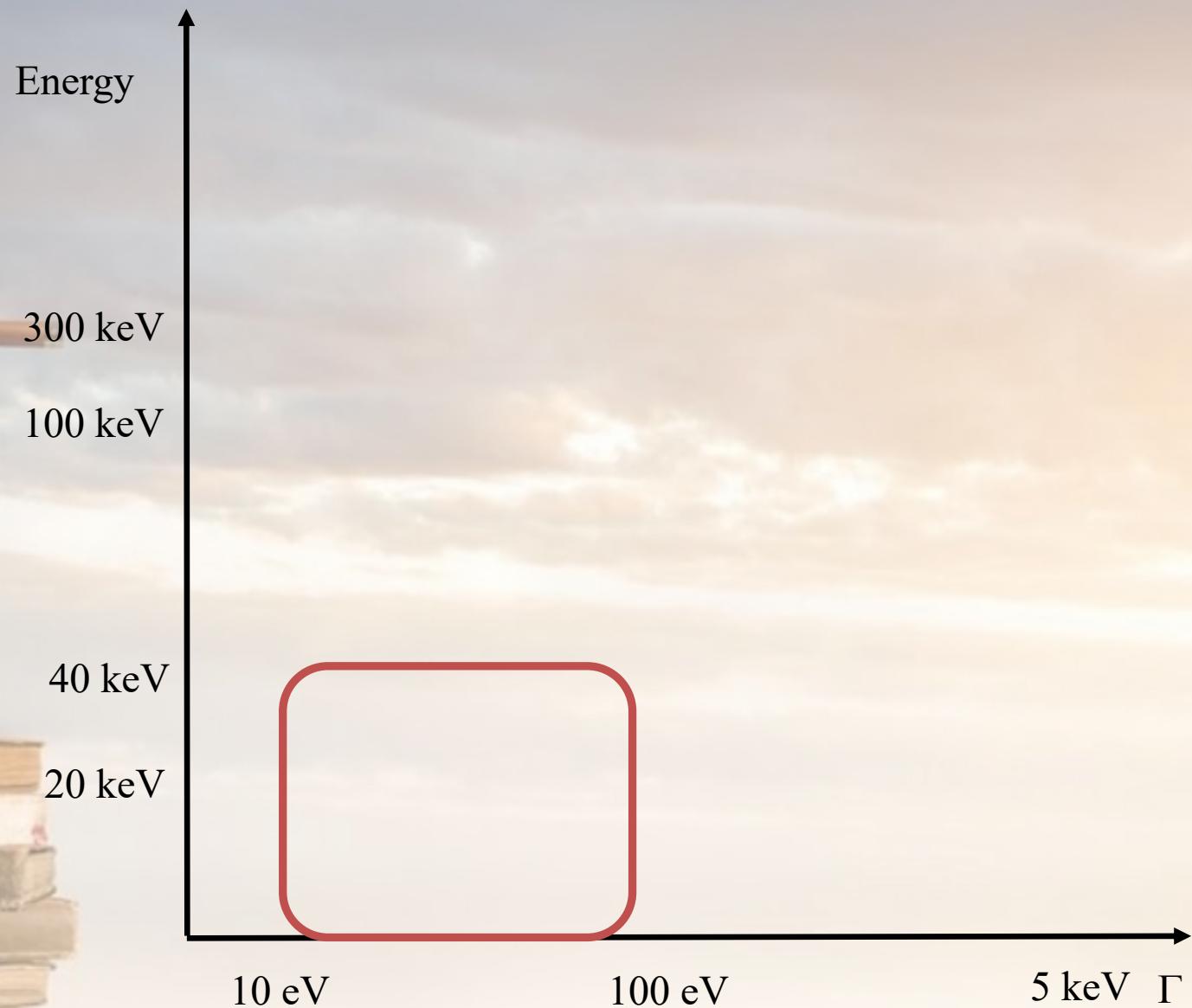
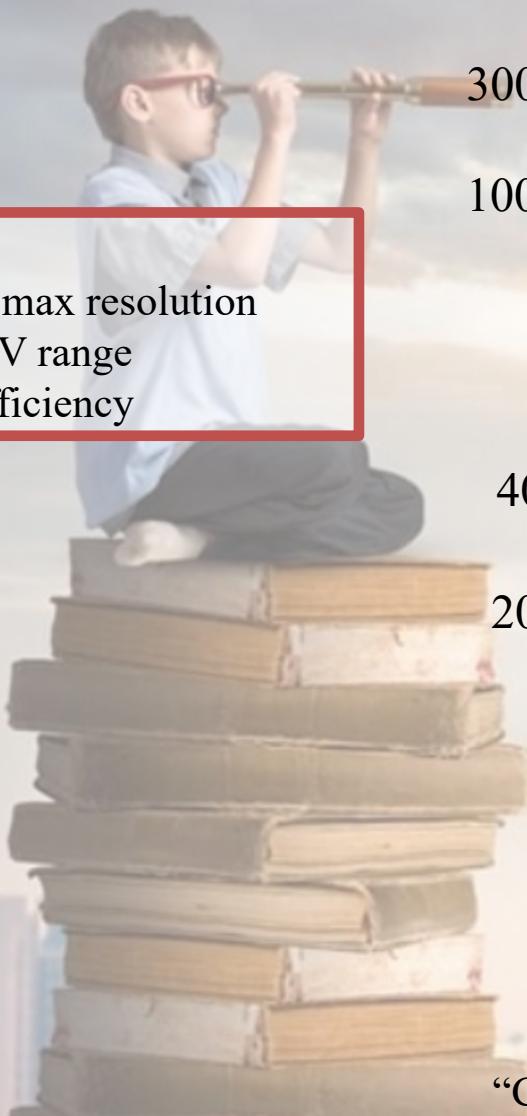


Underground Laboratories of Gran Sasso (LNGS)

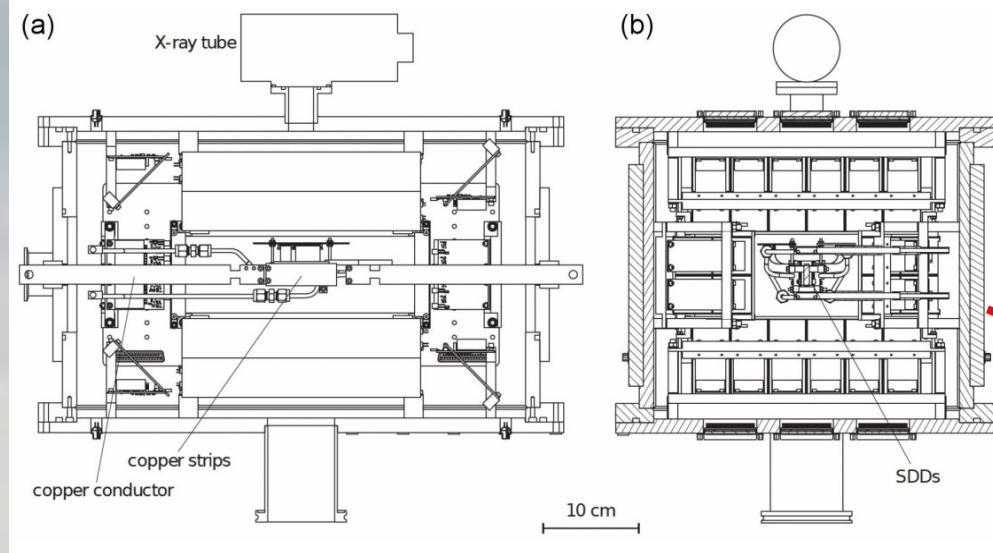
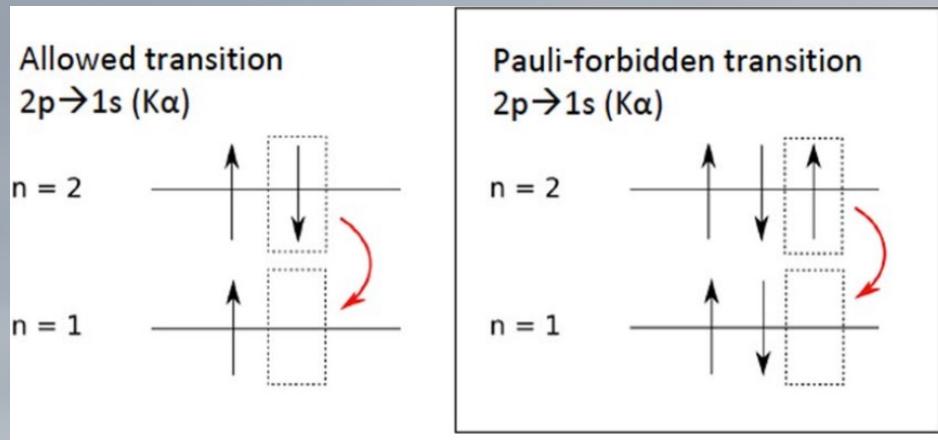
# X-ray detectors at LNF

## SDDs

- 120 eV max resolution
- 4-40 keV range
- High efficiency



# Tests of foundations of physics: the VIP-2 experiment



$$\beta^2/2 \leq 6.8 \times 10^{-43} \quad (\text{Bayesian}),$$

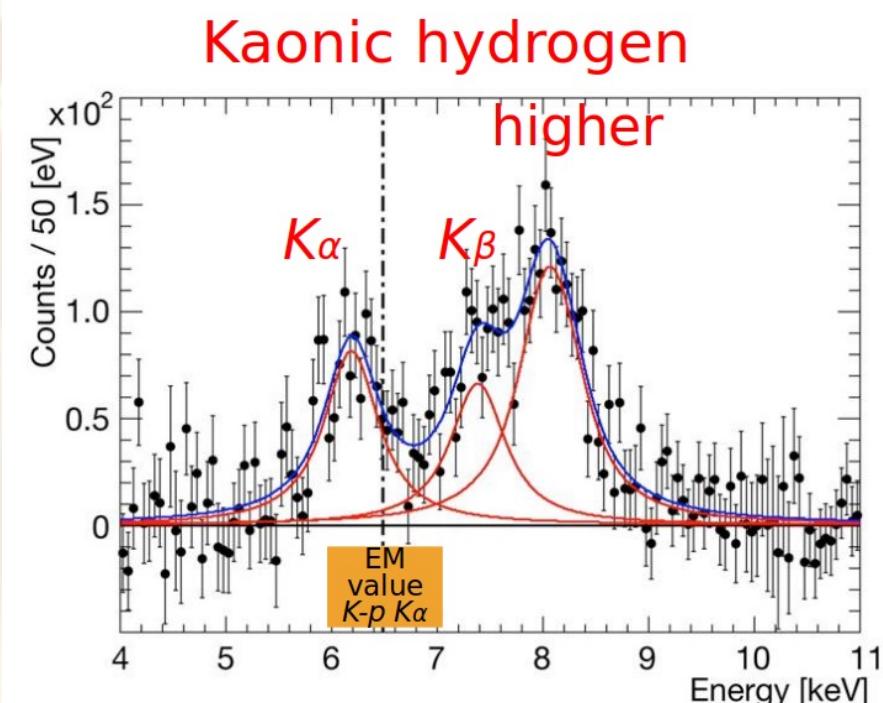
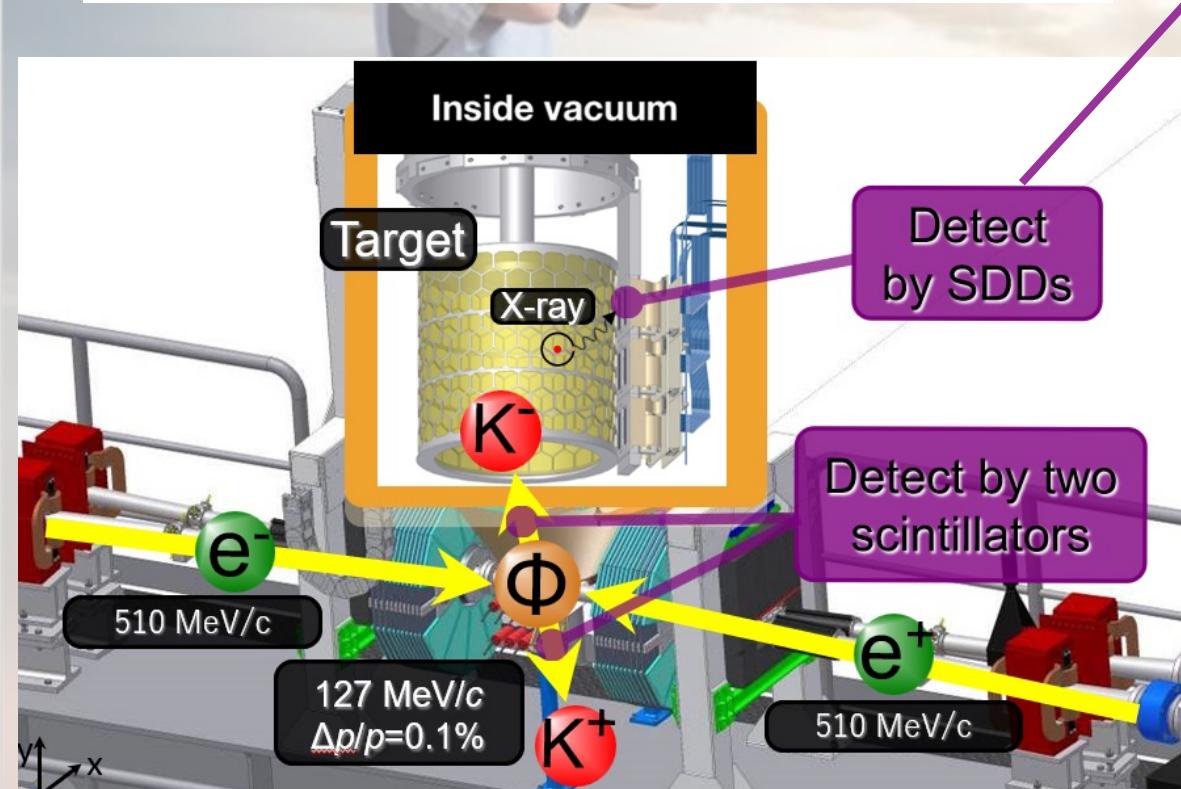
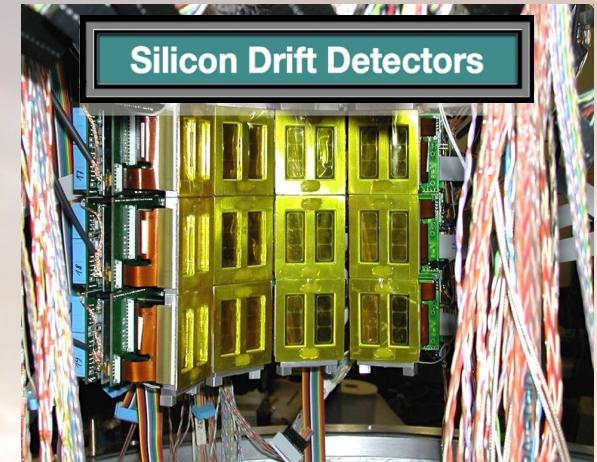
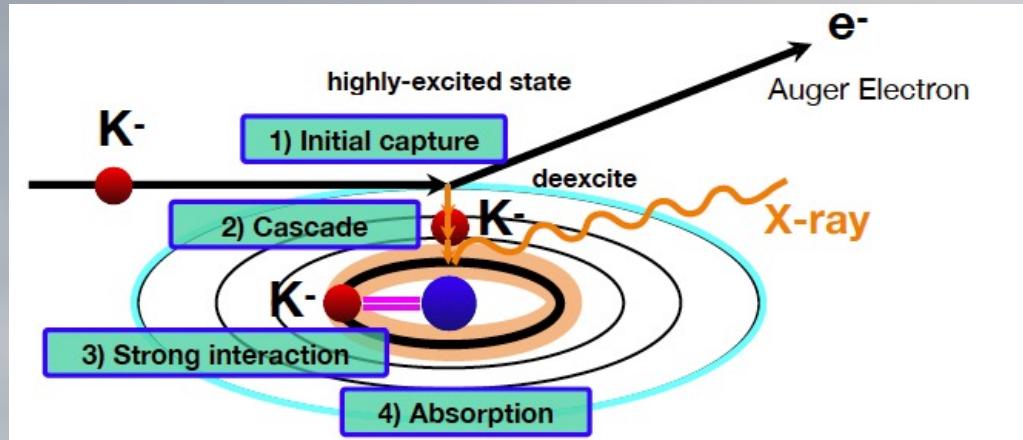
$$\beta^2/2 \leq 7.1 \times 10^{-43} \quad (\text{CL}).$$

Symmetry 2022, 14(5), 893;  
<https://doi.org/10.3390/sym14050893>

Cu Transitions	Standard E[eV]	PEP-Forbidden E[eV]
$\text{K}\alpha 1 (2p_{1/2} \rightarrow 1s_{1/2})$	8047.78	7746.73
$\text{K}\alpha 2 (2p_{3/2} \rightarrow 1s_{1/2})$	8027.83	7728.92



# Strangeness nuclear physics with exotic atoms: the SIDDHARTA experiment at LNF



C. Curceanu et al., Phys. Lett. B **704** (2011) 113

# From SIDDHARTA to SIDDHARTA-2: the quest for kaonic deuterium

Analysis of the combined measurements of kaonic deuterium and kaonic hydrogen

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3 \mu_c^2 a_{K^-p} (1 - 2\alpha \mu_c (\ln \alpha - 1) a_{K^-p})$$

( $\mu_c$  reduced mass of the  $K^-p$  system,  $\alpha$  fine-structure constant)

U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349  
next-to-leading order, including isospin breaking

$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$

$$a_{K^-n} = a_1$$

$$a_{K^-d} = \frac{k}{2}[a_{K^-p} + a_{K^-n}] + C = \frac{k}{4}[a_0 + 3a_1] + C$$

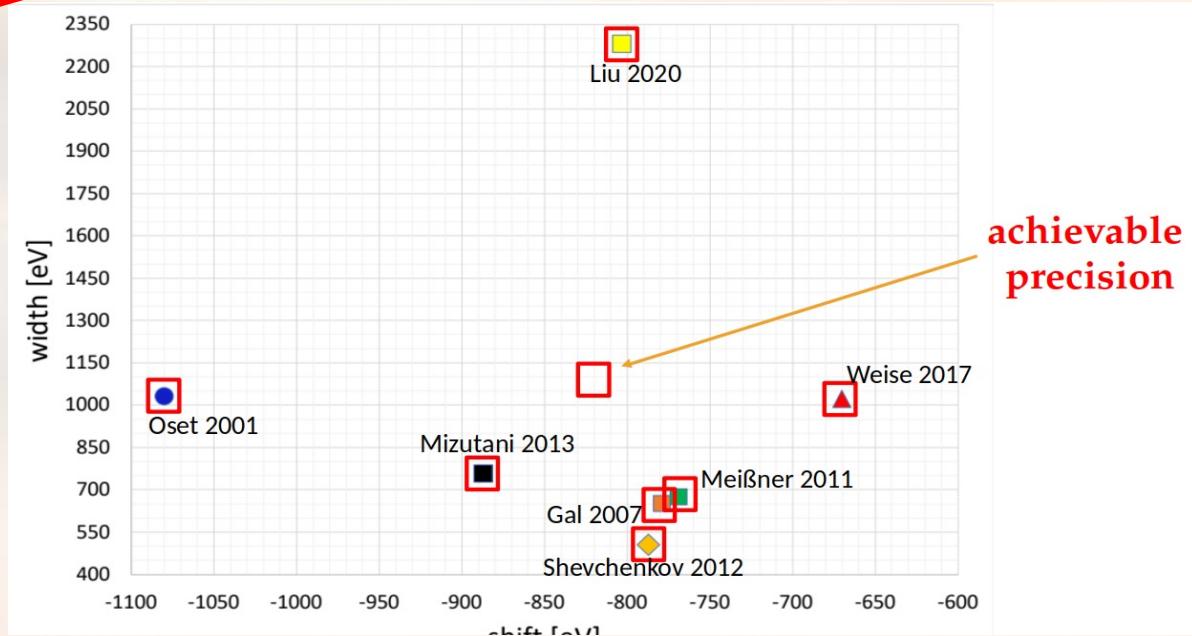
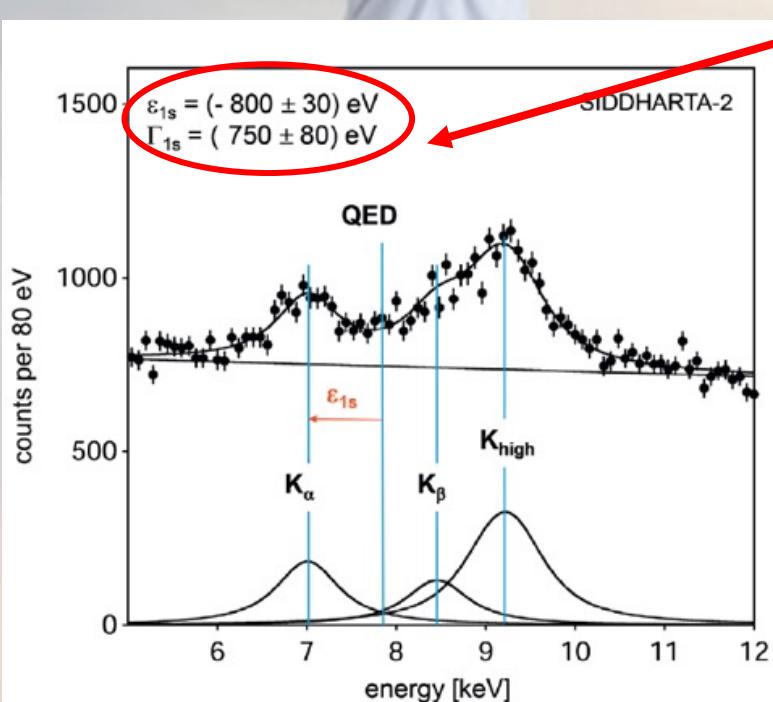
$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

Difficult technological challenges

Crucial background reduction

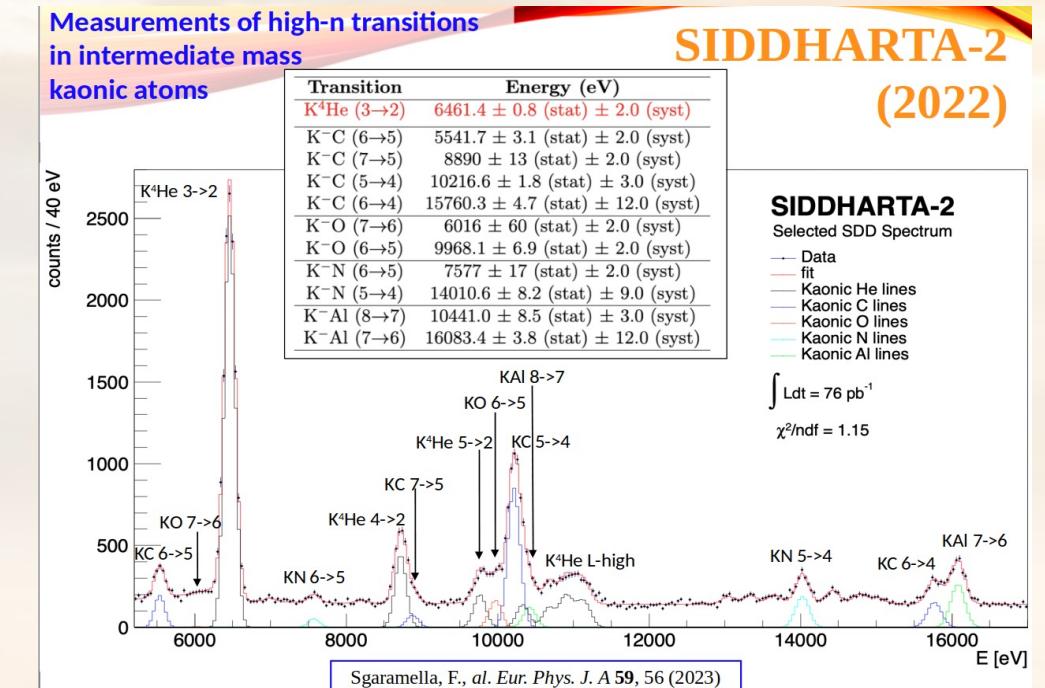
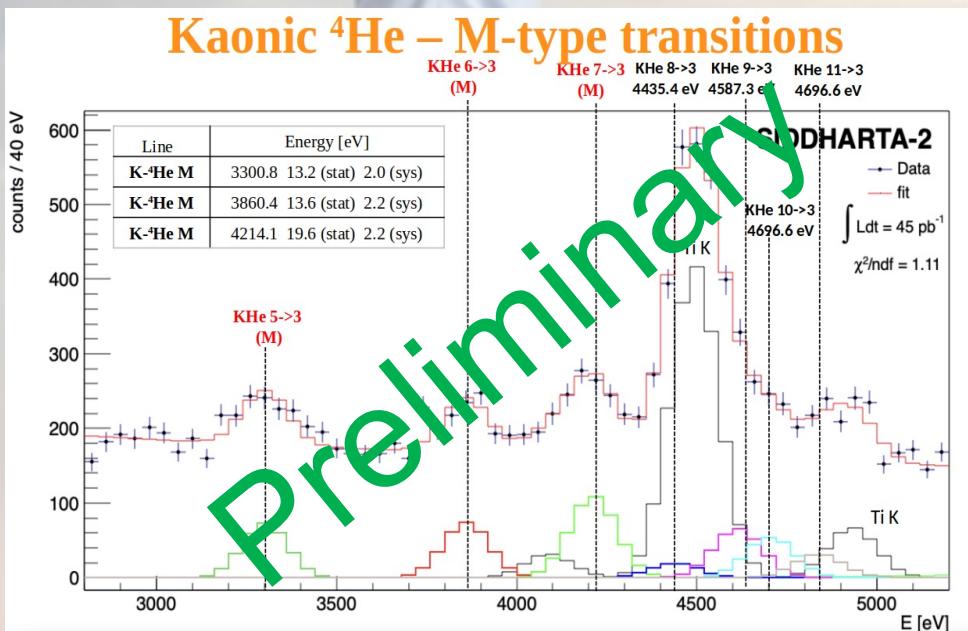
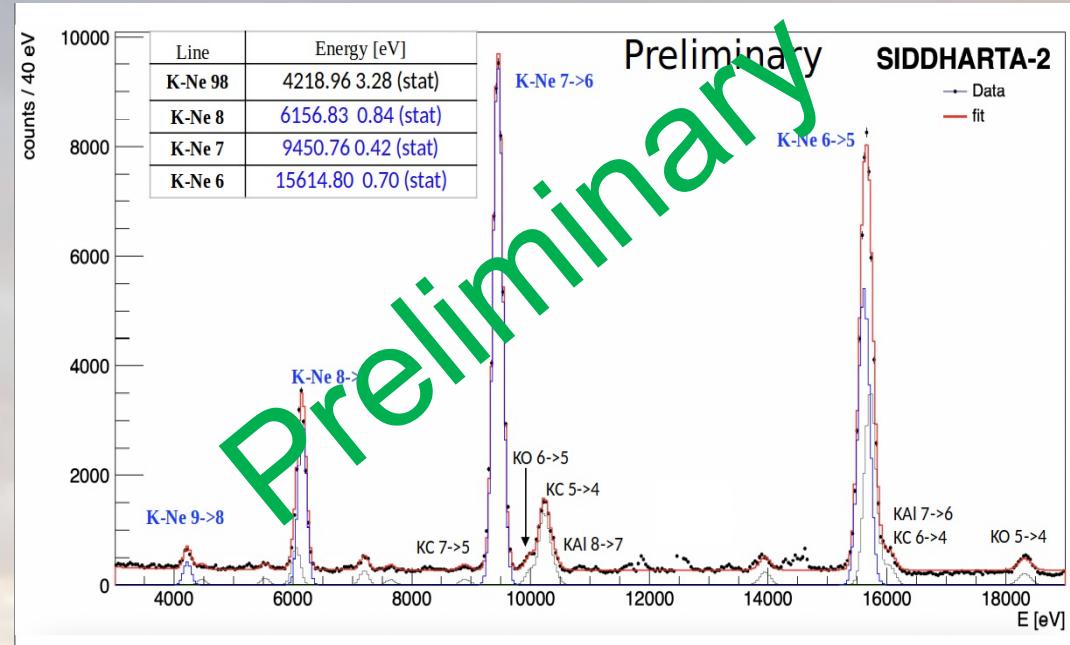
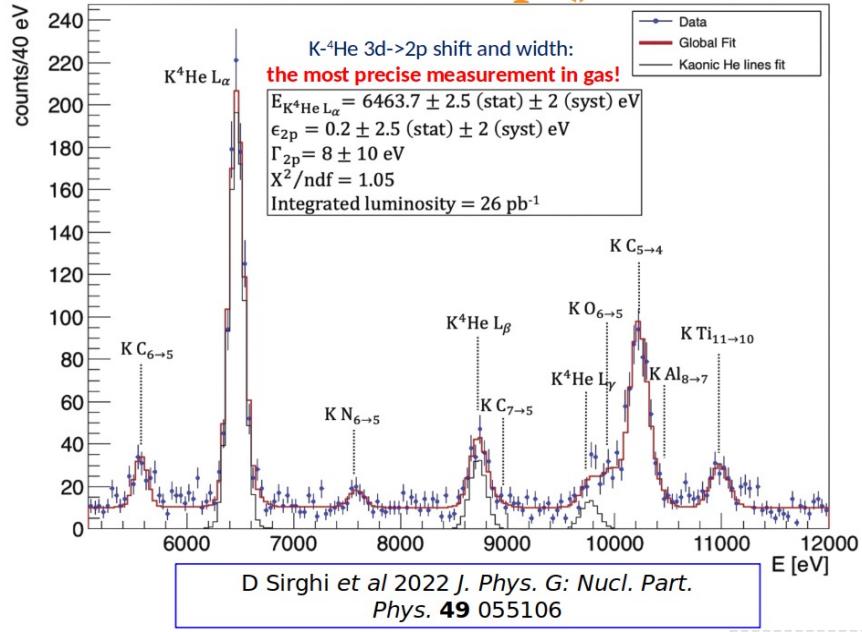
Several improvements (2009 → 2019)

With 800 pb<sup>-1</sup> of integrated luminosity, important results are expected



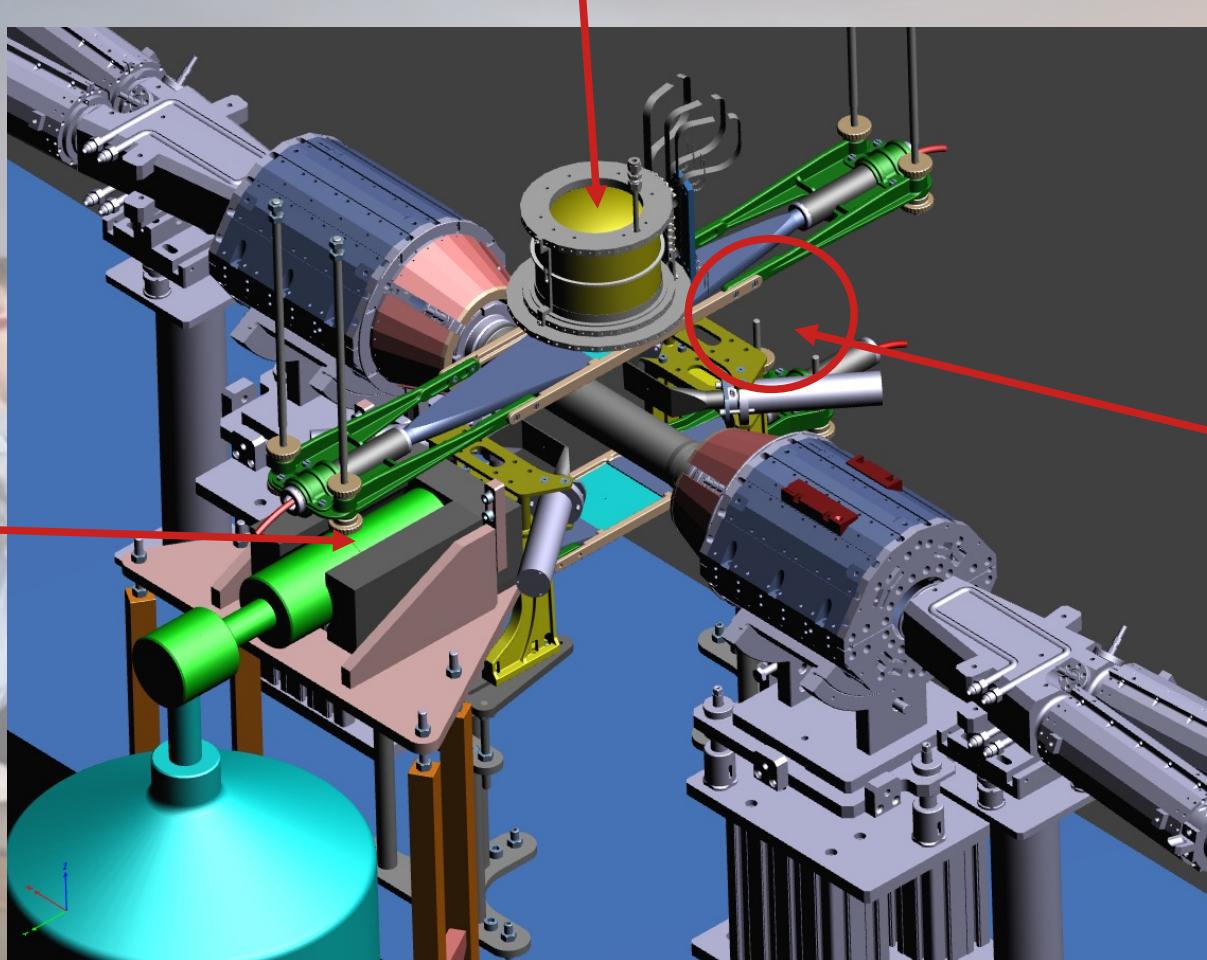
# First SIDDHARTA-2 results

## The kaonic ${}^4\text{He}$ 3d->2p () measurement



# Exploiting DAΦNE

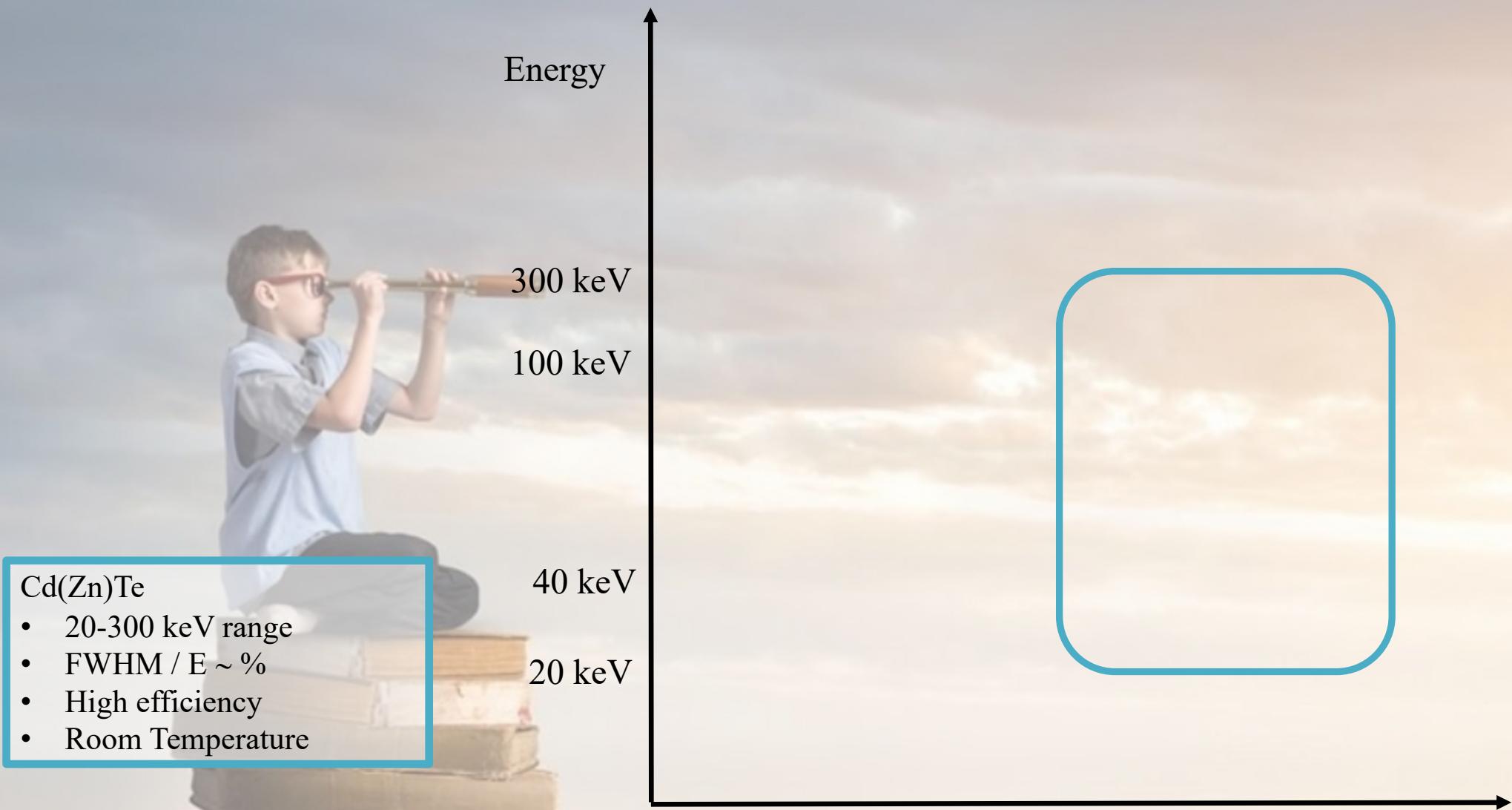
SDDs (4-15 keV) - Light Kaonic Atoms



DAΦNE delivers almost  $4\pi K^-$

We want to exploit this unique beam as much as possible to perform important physics measurements

# X-ray detectors at LNF



# Advanced ultra-fast solid State detectors for high precision RAdiation spectroscopy : ASTRA

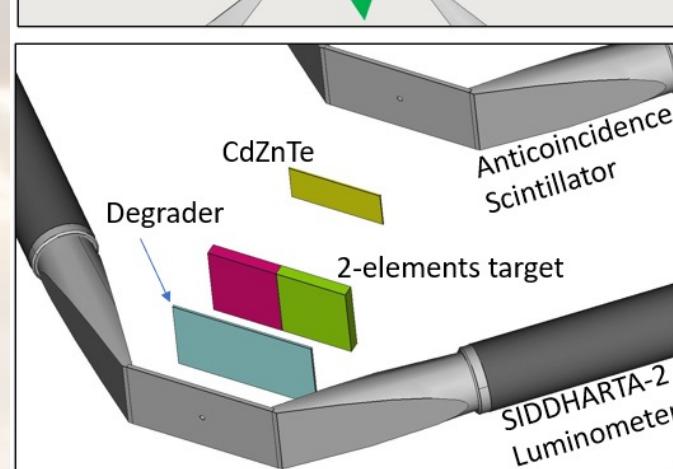
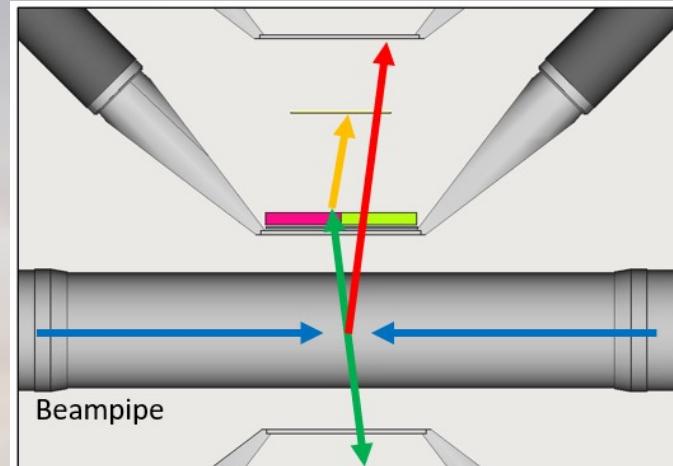
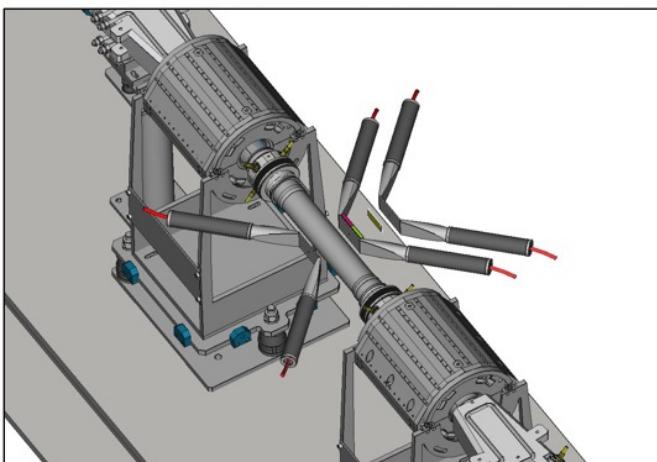
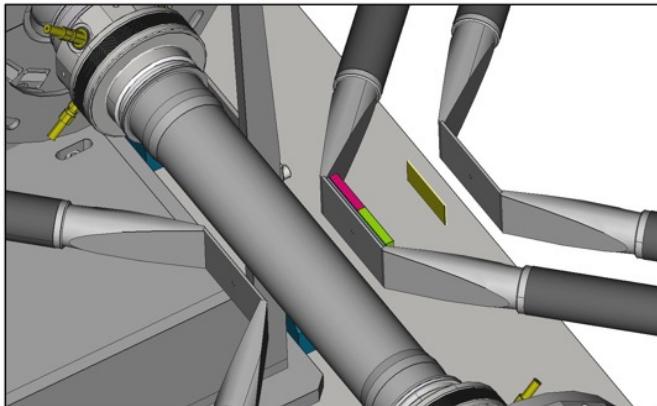
Organization legal name	Short name	Activity leader
Austrian Academy of Sciences, Stefan Meyer Institute, Austria	OEAW	J. Zmeskal
Istituto Materiali per Elettronica e Magnetismo, CNR, Parma, Italy	CNR	A. Zappettini
Jagiellonian University, Krakow, Poland	UJ	P. Moskal
Laboratori Nazionali di Frascati (LNF) – INFN, Italy	INFN	A. Scordo
Politecnico Milano, Dipartimento di Elettronica, Italy	POLIMI	C. Fiorini
University of Zagreb, Croatia	UNIZG	D. Bosnar

The main objective of the **ASTRA** project is to develop beyond state-of-art ultra-fast CdZnTe/CdTe radiation detector systems for high-precision measurements of gamma- and X-ray events in a broad energy range, few keV to MeV.

# CZT: proposal for new measurements at DAΦNE

## Detector Key Points:

- High efficiency in the 20-100 keV region
- Reasonable efficiencies up to 300 keV
- Good resolution ( $\text{FWHM}/\text{E} \sim \%$ )
- Fast response and time resolution (< 50 ns)
- No need for cooling
- Compact readout and installation package



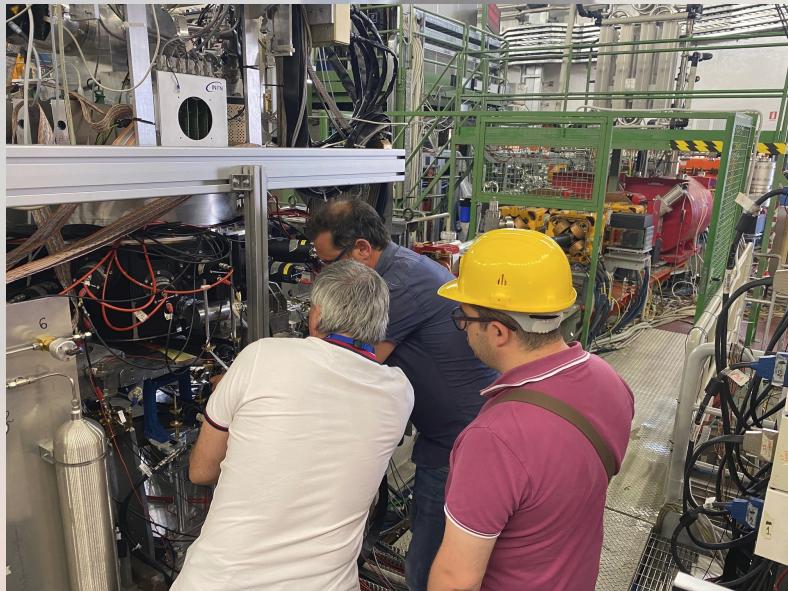
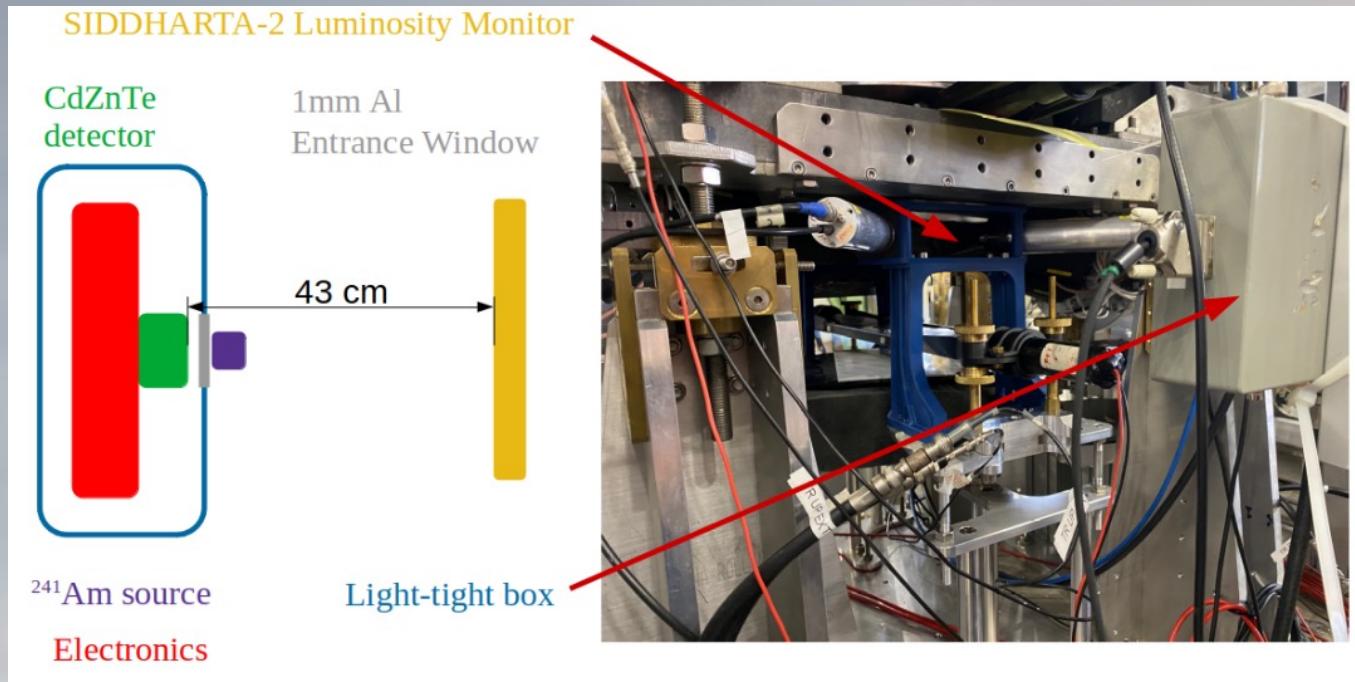
## Feasibility:

CdTe (and also CdZnTe) detectors developed in the JRA8-ASTRA (STRONG-2020) project

Further prototypes will be available by June 2023

# CZT: first tests @ DAΦNE

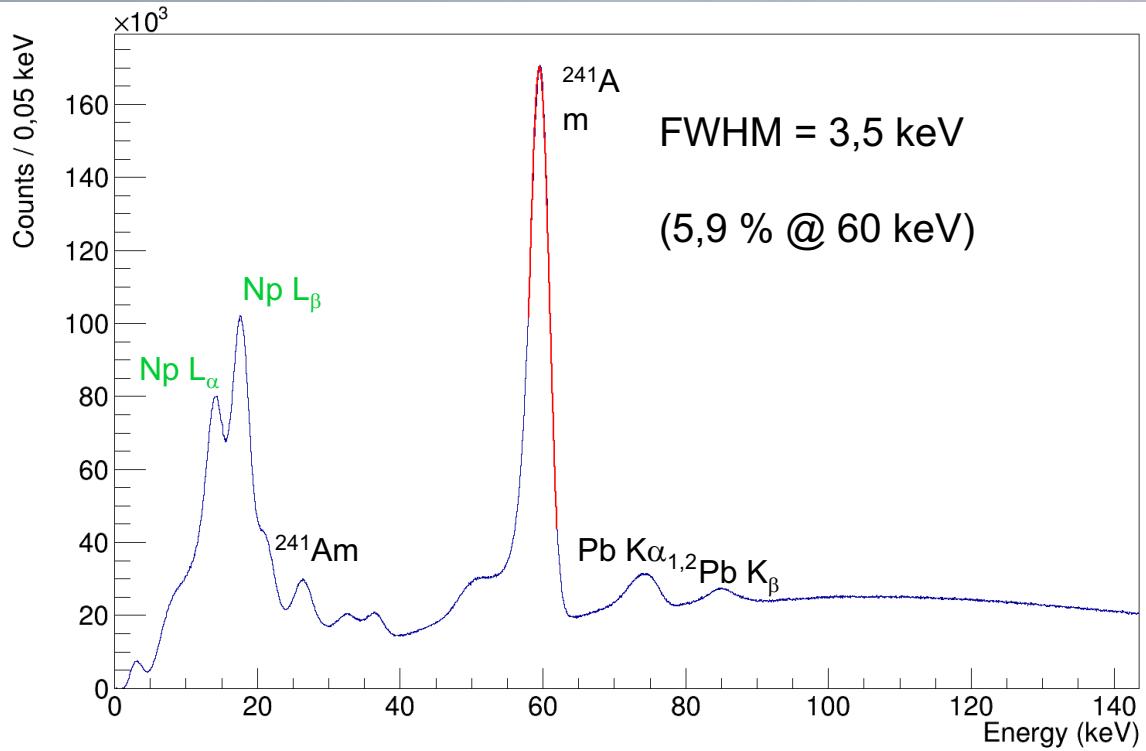
Goal: background and resolution assessment in machine environment (first time)



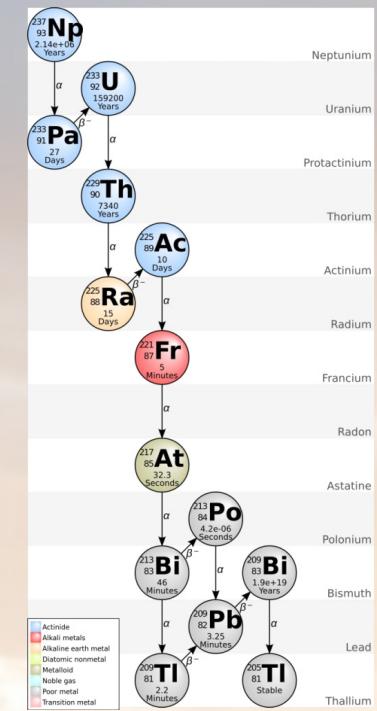
22/06/2022:  
First prototype installed  
in DAΦNE to check  
“on beam” response  
and possible issues



# CZT: first tests @ DAΦNE



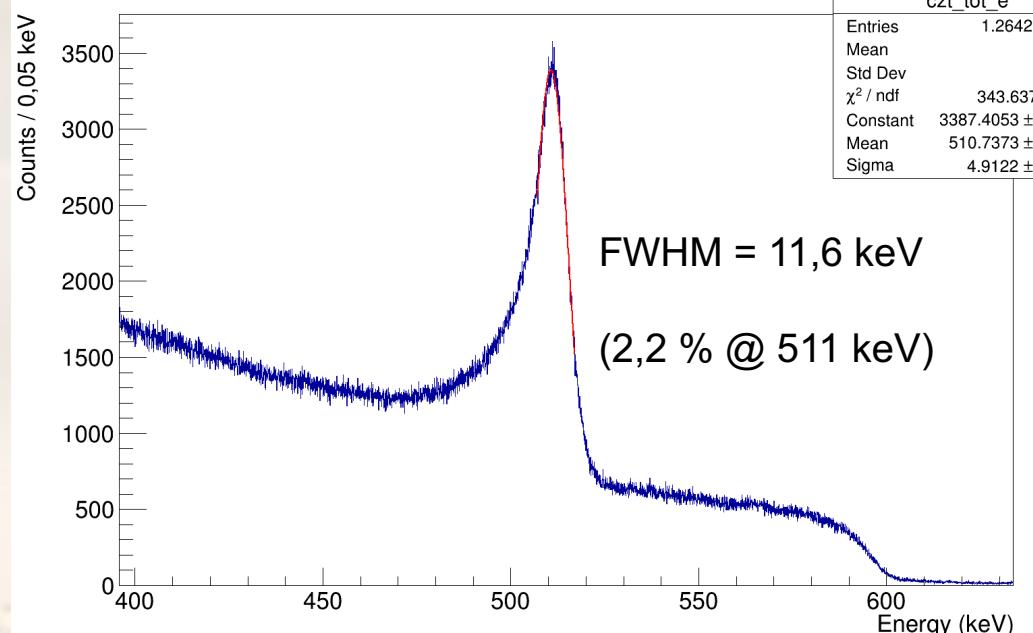
Np peaks  
(X-rays)  
from decay of  
 $^{241}\text{Am}$



Good energy  
resolution  
confirmed “on  
beam”

Also linearity “on beam” is preserved

Element	K-shell absorption energy (keV)	Fluorescent lines	Energy of fluorescent lines (keV)	$\lambda_{\text{CdZnTe}}$ ( $\mu\text{m}$ )
Cd	26.7	$K\alpha_1$	23.17	116
		$K\beta_1$	26.10	161
Zn	9.7	$K\alpha_1$	8.54	8.4
		$K\beta_1$	9.57	11.4
Te	31.8	$K\alpha_1$	27.47	69
		$K\beta_1$	31.00	95



Abbene, L., Bettelli, M., Buttacavoli, A. et al.  
New opportunities for kaonic atoms measurements from CdZnTe detectors.

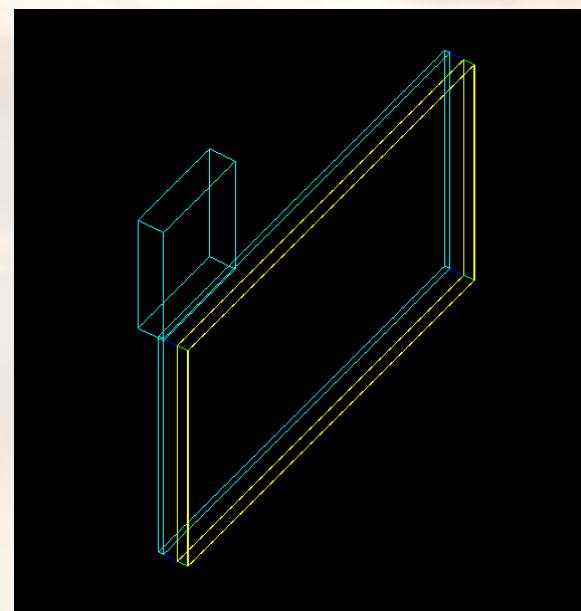
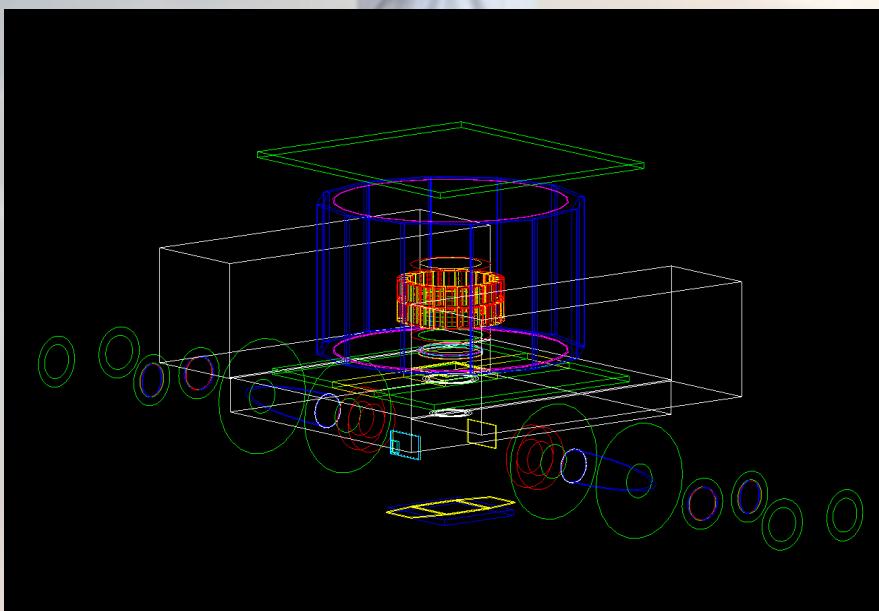
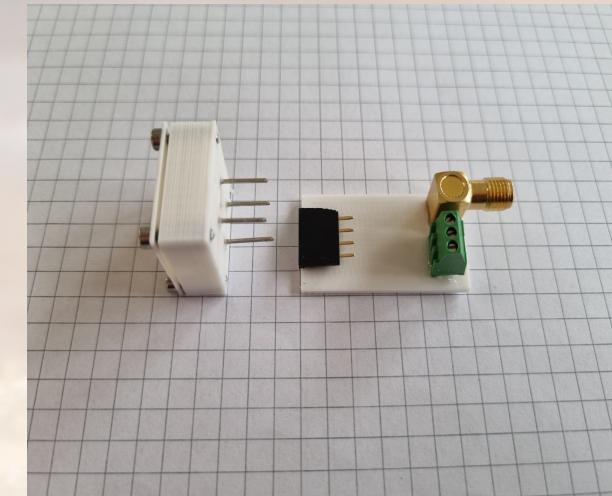
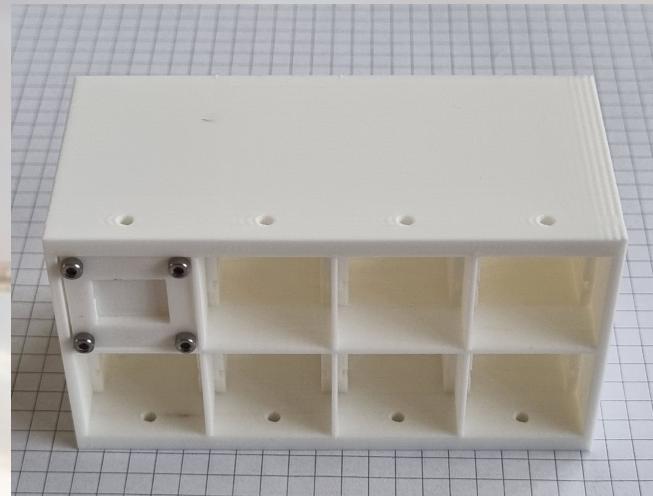
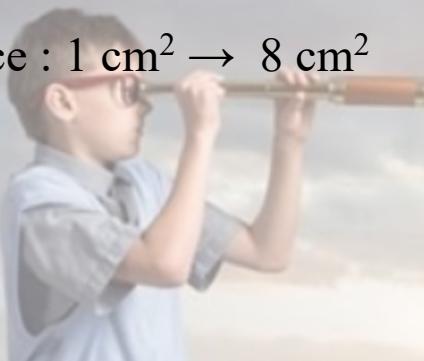
Eur. Phys. J. Spec. Top. (2023).

<https://doi.org/10.1140/epjs/s11734-023-00881-x>

# Intermediate-mass kaonic atoms' spectroscopy with CZT detectors: Preliminary MC simulations

A new run is foreseen in 2023

Detecting surface :  $1 \text{ cm}^2 \rightarrow 8 \text{ cm}^2$



Target:  $1 \times 20 \times 40 \text{ mm Al}$

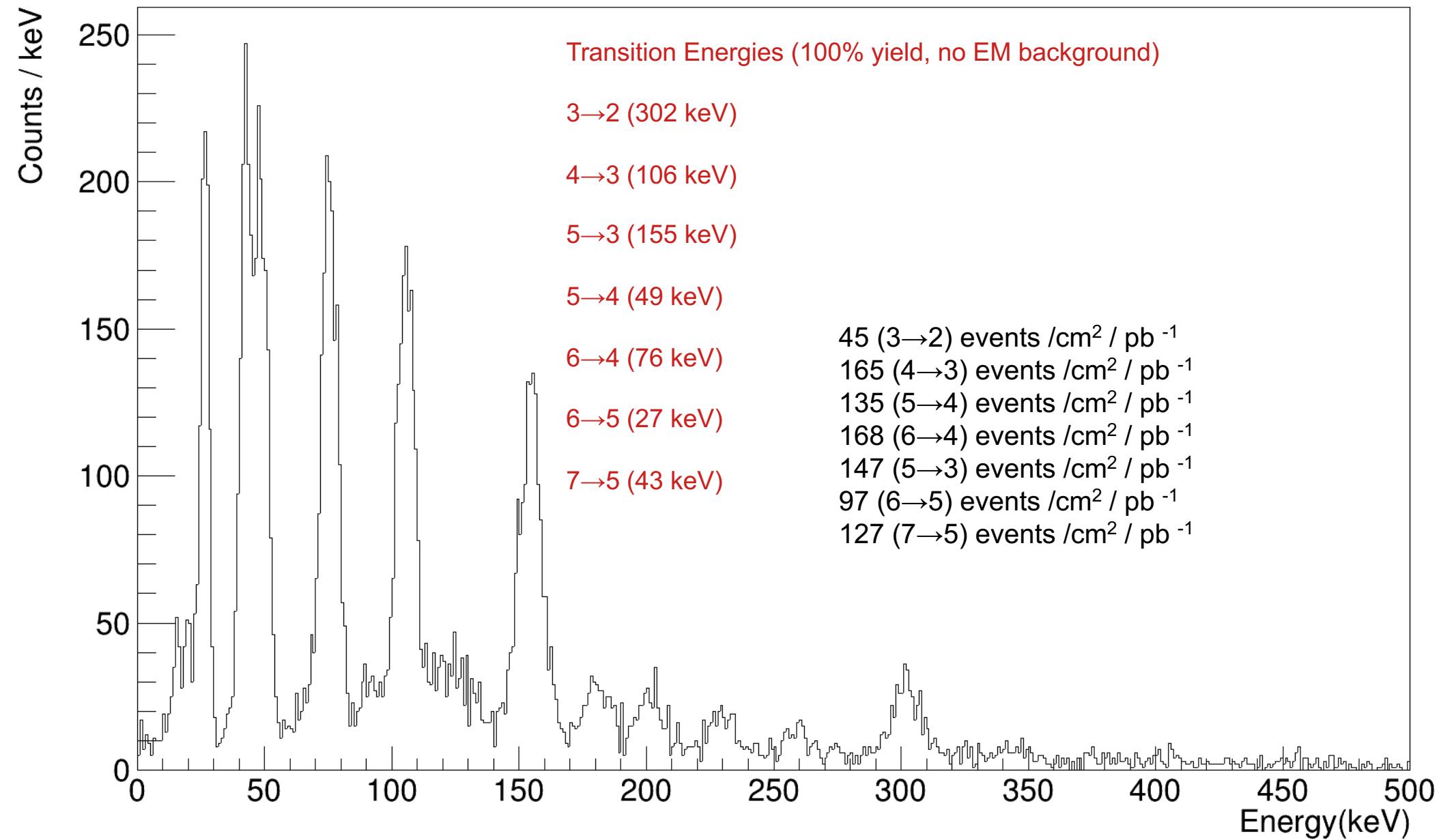
CZT:  $5 \times 20 \times 40 \text{ mm CdZnTe}$

LM - Target distance = 10 mm

Target - CZT distance = 20 mm

Target - IP distance = 95 mm

# Intermediate-mass kaonic atoms' spectroscopy with CZT detectors: Preliminary MC simulations



EM background is not (yet) included

# X-ray detectors at LNF



# New Kaon Mass measurement with HPGe

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

$$m_K = 493.696 \pm 0.007 \text{ MeV}$$

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

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

$$m_K = 493.636 \pm 0.011 \text{ MeV}$$

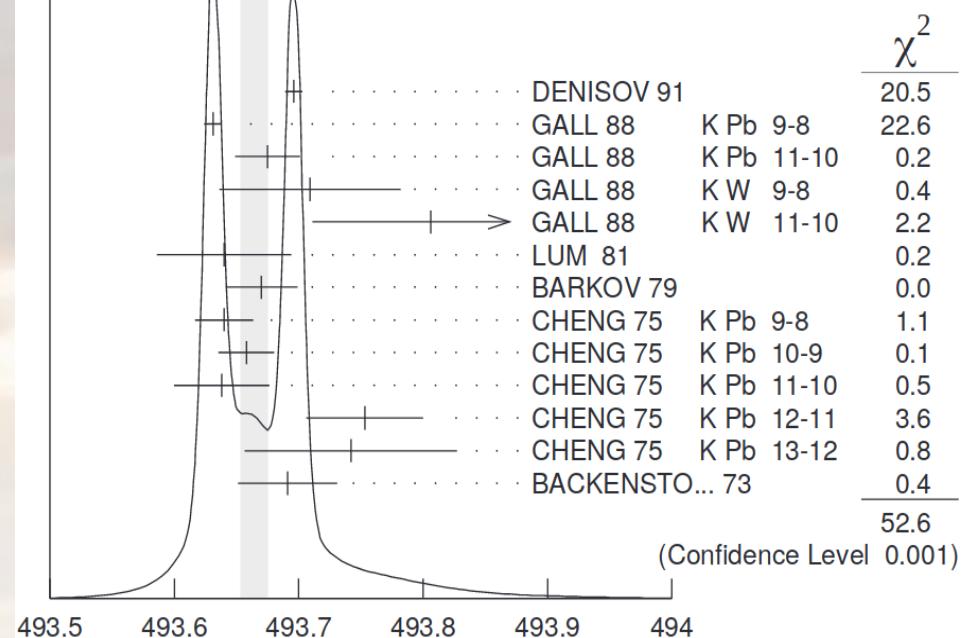
K.P. Gall et al.  
Phys. Rev. Lett. 60 (1988) 186

$K^-$ -Pb,  $K^-$ -W; HPGe detector, **K-Pb (9 → 8),**  
 **$K^-$ -Pb (11 → 10),  $K^-$ -W (9 → 8),  $K^-$ -W (11 → 10)**

WEIGHTED AVERAGE  
493.664 ± 0.011 (Error scaled by 2.5)

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

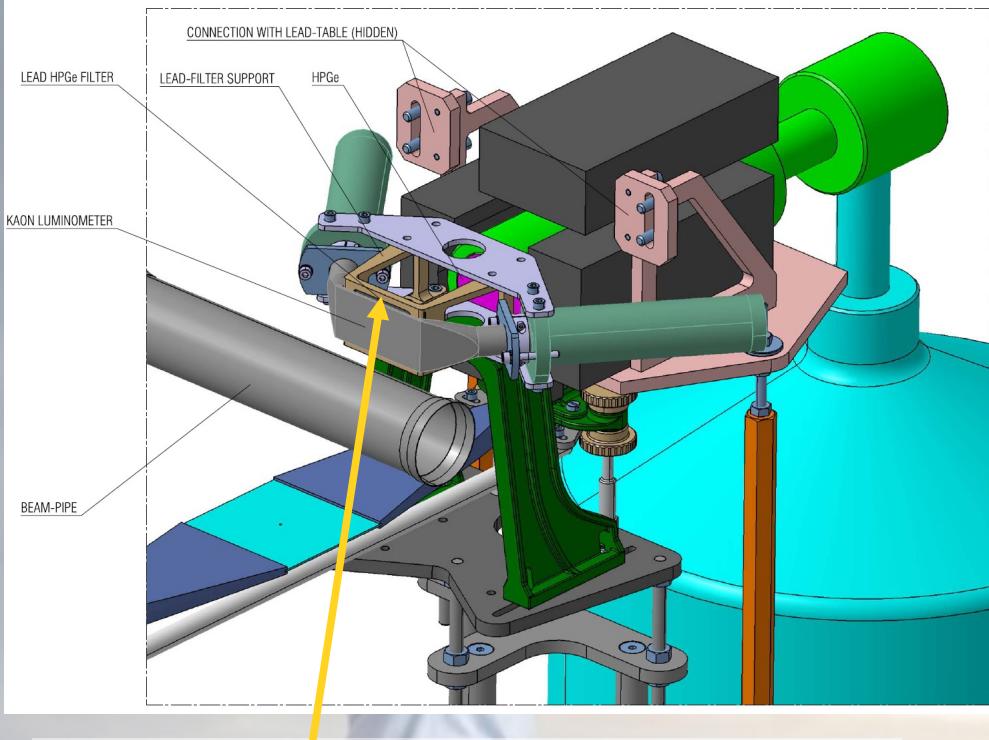
Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.



This puzzle could be addressed, together with the renewal of the kaonic atoms database, again with the recent advancements in radiation detectors.

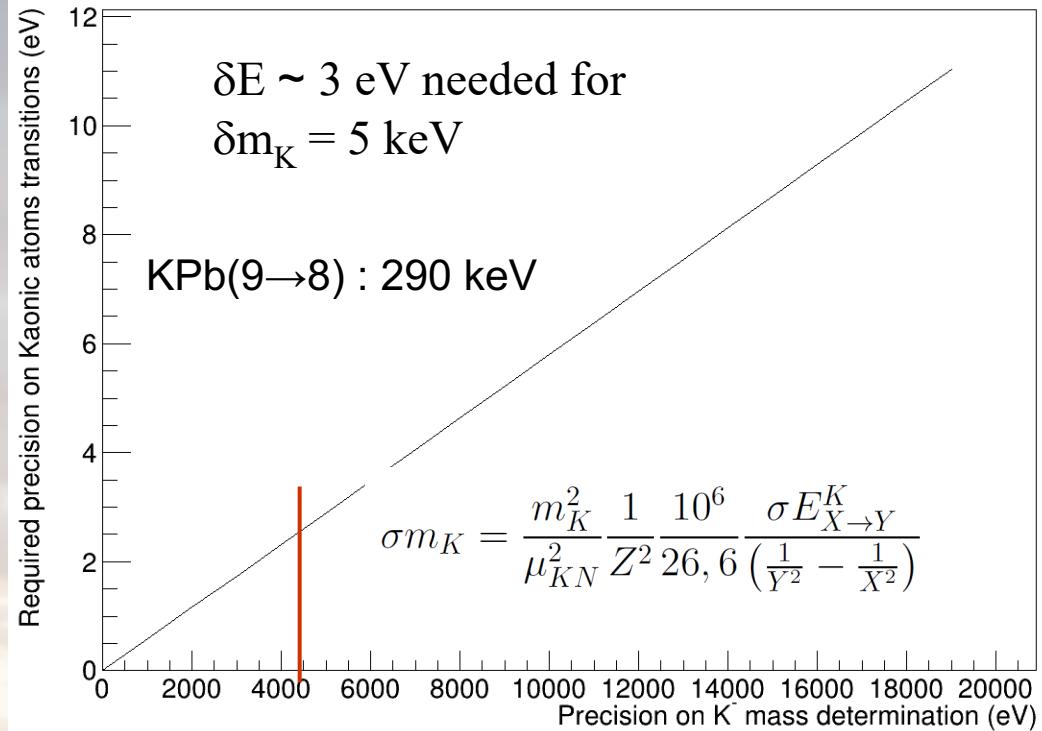
In particular, K-Pb (9→8) transition measurement could be performed again with HPGe

# New Kaon Mass measurement with HPGe



Pb target just behind  
the SIDDHARTA-2 luminometer,  
which is used as trigger

HPGe detector provided by the group of the  
University of Zagreb (Croatian Science  
Foundation project 8570)

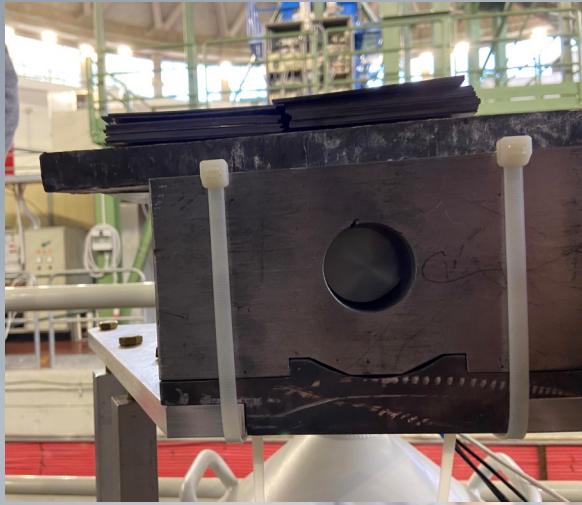


Resolutions (FWHM)  
obtained with  $^{60}\text{Co}$ ,  $^{133}\text{Ba}$  sources :

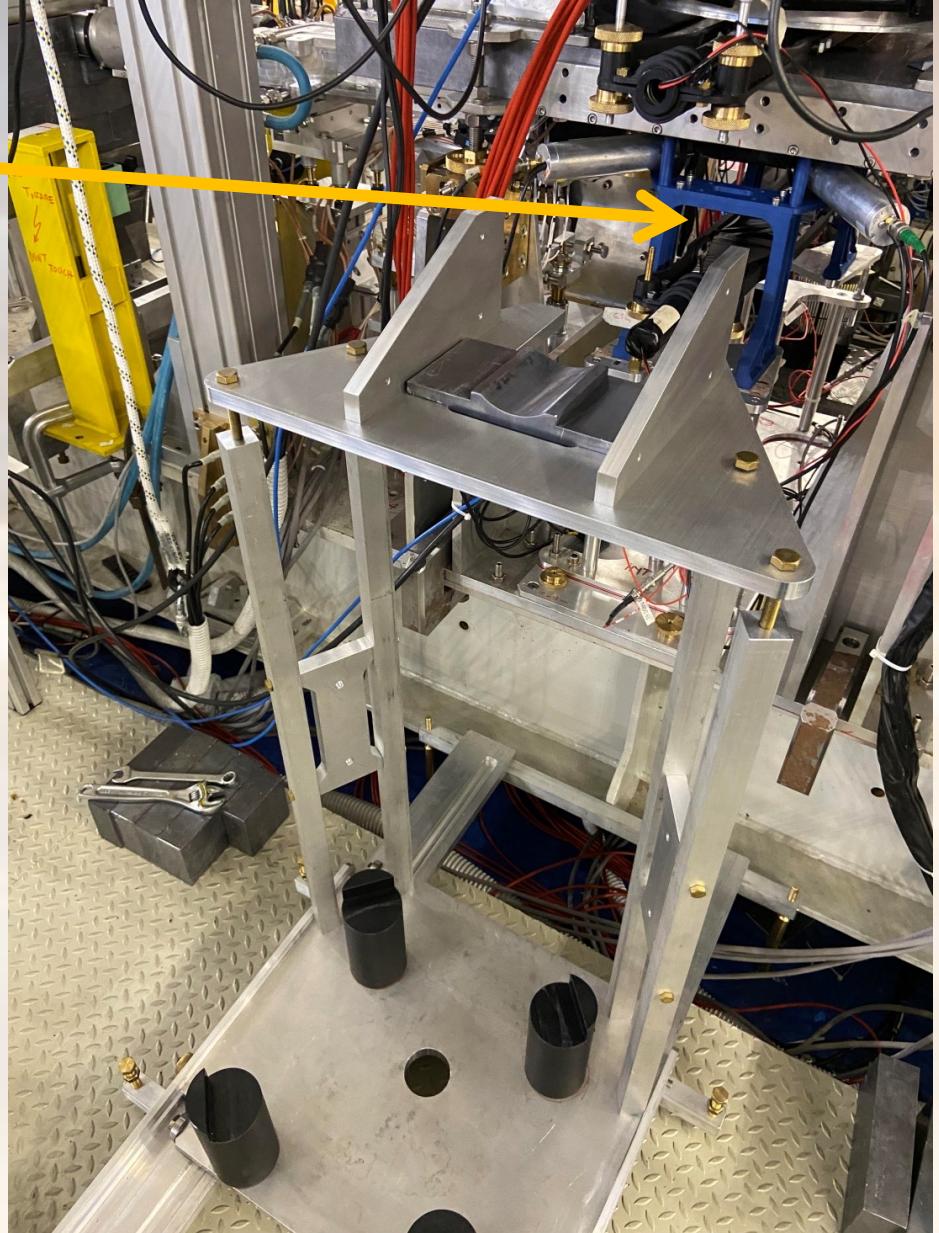
0.870 keV @ 81 keV  
1.106 keV @ 302.9 keV  
1.143 keV @ 356 keV  
1.167 keV @ 1330 keV

# New Kaon Mass measurement with HPGe

Installation of HPGe structures and preliminary shielding



Pb target support  
behind luminometer



Installed and ready  
to take data



# Testing Quantum Gravity with HPGe: the VIP-Lead experiment

Quantum gravity models can embed PEP violating transitions!

PEP is a consequence of the spin statistics theorem based on: Lorentz/Poincaré and CPT symmetries; locality; unitarity and causality. Deeply related to the very same nature of space and time



most effective theories of QG foresee the non-commutativity of the space-time quantum operators (e.g.  $k$ -Poincarè,  $\theta$ -Poincarè)



non-commutativity induces a deformation of the Lorentz symmetry and of the locality → naturally encodes the violation of PEP

S. Majid, Hopf algebras for physics at the Planck scale, *Class. Quantum Grav.* 5 (1988) 1587.

S. Majid and H. Ruegg, Bicrossproduct structure of Kappa Poincarè group and noncommutative geometry, *Phys. Lett. B* 334 (1994) 348, [hep-th/9405107](#).

M. Arzano and A. Marciano, *Phys. Rev. D* 76, 125005 (2007) [[arXiv:0707.1329](#)].

G. Amelino-Camelia, G. Gubitosi, A. Marciano, P. Martinetti and F. Mercati, *Phys. Lett. B* 671, 298 (2009) [[arXiv:0707.1863](#)].

A. Addazi, A. Marcianò [International Journal of Modern Physics A](#) Vol. 35, No. 32, 2042003 (2020)



PEP violation is suppressed with  $(E/\Lambda)^n$ ,  $n$  depends on the specific model,  $E$  is the energy of the PEP violating transition,  $\Lambda$  is the scale of the space-time non-commutativity emergence.

Theoretical prediction *Int.J.Mod.Phys.A* 35 (2020) 32, 2042003

specific calculation of atomic levels transitions probabilities for  $\theta$ -Poincarè

$$W_\theta = W_0 \cdot \phi_{\text{PEPV}}$$

$$\phi_{\text{PEPV}} = \delta^2 \simeq \frac{D}{2} \frac{E_N}{\Lambda} \frac{\Delta E}{\Lambda} \quad \phi_{\text{PEPV}} = \delta^2 \simeq \frac{C}{2} \frac{\bar{E}_1}{\Lambda} \frac{\bar{E}_2}{\Lambda}$$
$$\theta_{0i} \neq 0 \quad \theta_{0i} = 0$$

for non-vanishing (vanishing) electric like components of the  $\theta^{\mu\nu}$  tensor.

The  $Q$ -Poincarè tensor can be explicitly related to the energy scale

$$\theta_{\mu\nu} = \tilde{\theta}_{\mu\nu}/\Lambda^2$$

PEP forbidden transitions are now included with a suppression factor

$$\text{suppression } \delta^2 = (E/\Lambda)^2$$

Limits on the PEP violation probability can validate NCQG models

# Testing Quantum Gravity with HPGe: the VIP-Lead experiment

## High purity Ge detector measurement:

- high purity co-axial p-type germanium detector (HPGe), diameter of 8.0 cm, length of 8.0 cm, surrounded by an inactive layer of lithium-doped germanium of 0.075 mm.
- The target material is composed of three cylindrical sections of radio-pure Roman lead, completely surrounding the detector.

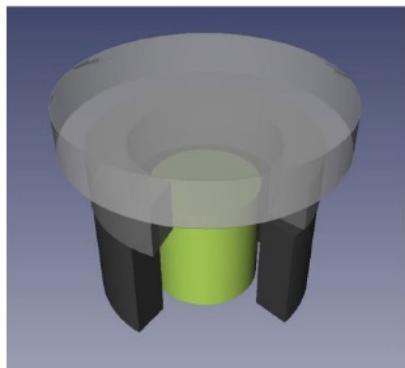


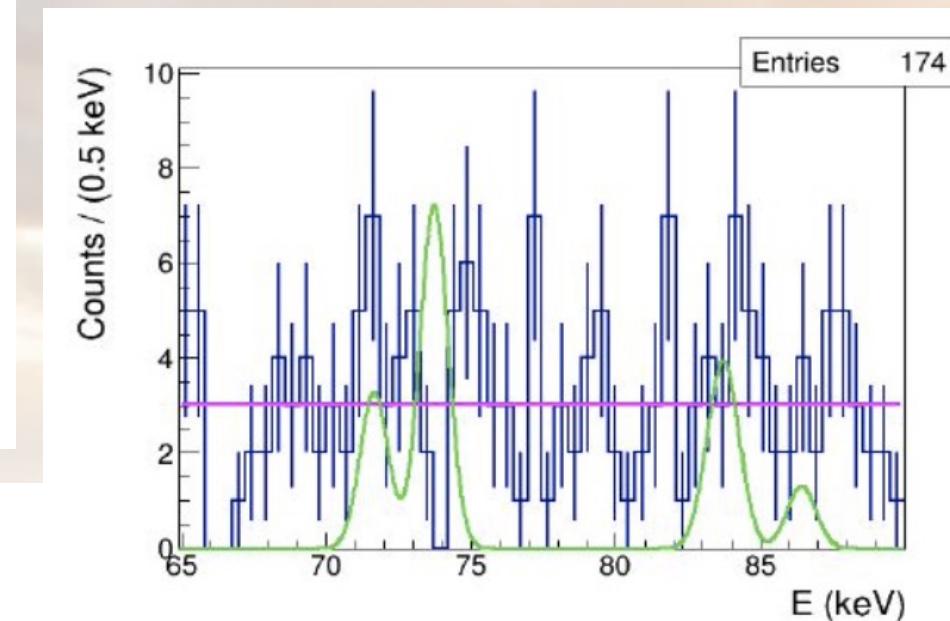
Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

From which an upper limit on the non-commutativity scale is obtained (90% Probability):

$\theta_{0i}$	$\bar{S}$	lower limit on $\Lambda$ (Planck scales)
$\theta_{0i} = 0$	13.2990	$6.9 \cdot 10^{-2}$
$\theta_{0i} \neq 0$	18.1515	$2.6 \cdot 10^2$

PHYSICAL REVIEW D 107, 026002 (2023)  
PHYSICAL REVIEW LETTERS 129, 131301 (2022)

Transitions in Pb	allow. (keV)	forb. (keV)
1s – 2p <sub>3/2</sub> K <sub>α1</sub>	74.961	73.713
1s – 2p <sub>1/2</sub> K <sub>α2</sub>	72.798	71.652
1s – 3p <sub>3/2</sub> K <sub>β1</sub>	84.939	83.856
1s – 4p <sub>1/2(3/2)</sub> K <sub>β2</sub>	87.320	86.418
1s – 3p <sub>1/2</sub> K <sub>β3</sub>	84.450	83.385



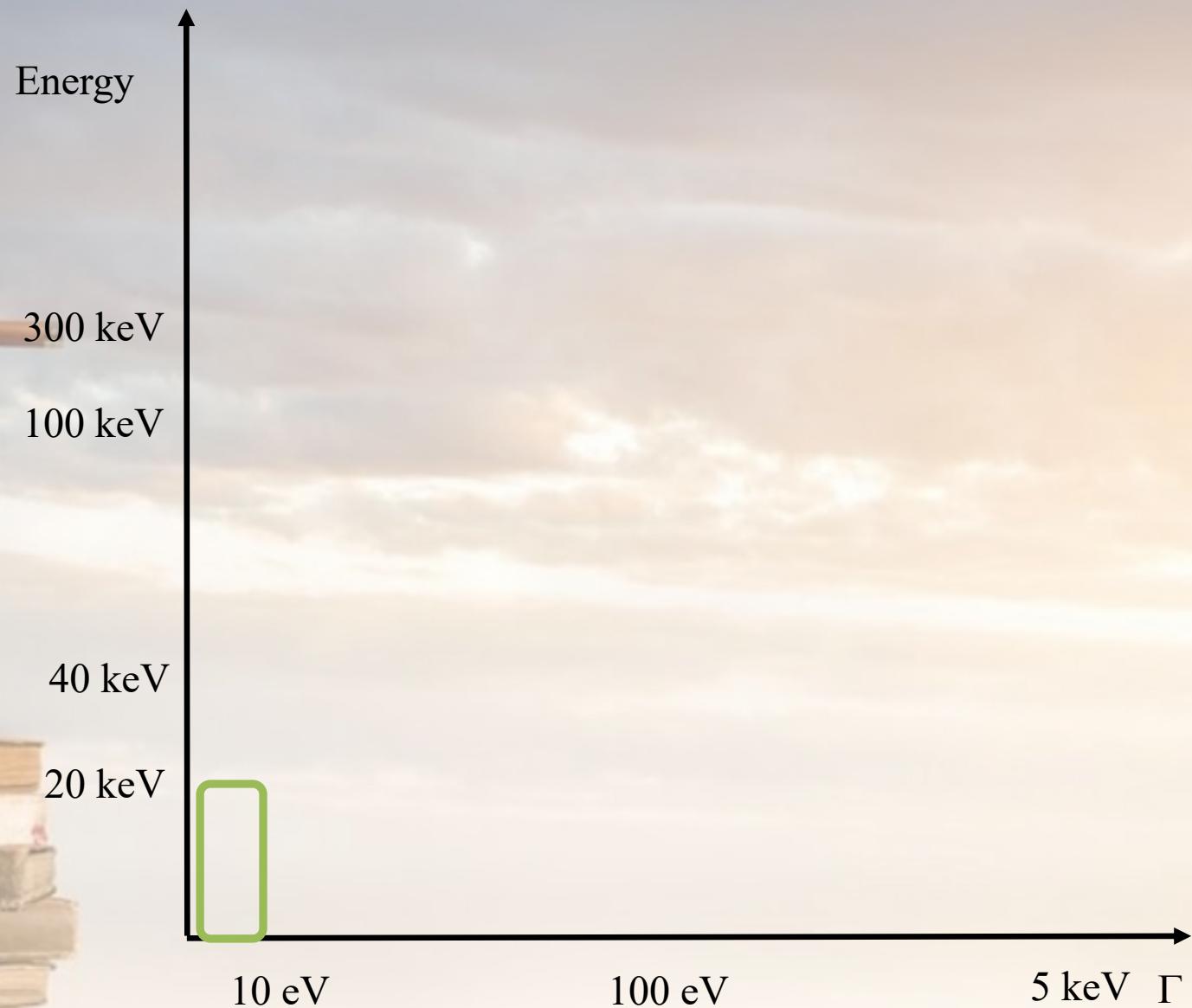
Background

Signal from violating  
Transitions in Lead

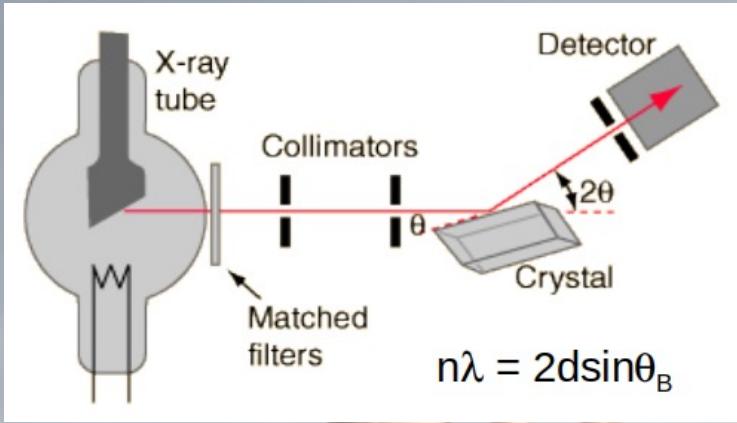
# X-ray detectors at LNF

Crystal spectrometers:

- High resolution
- Low efficiency
- 0-20 keV range



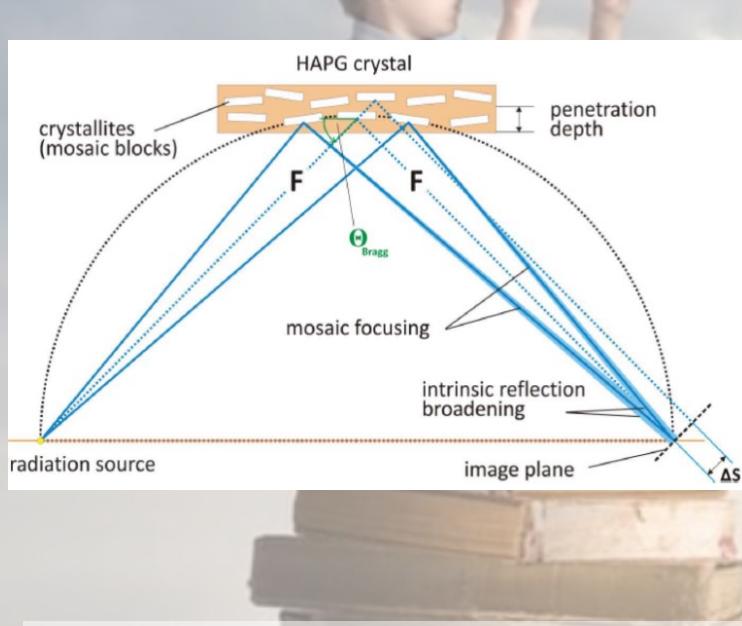
# Bragg spectrometers



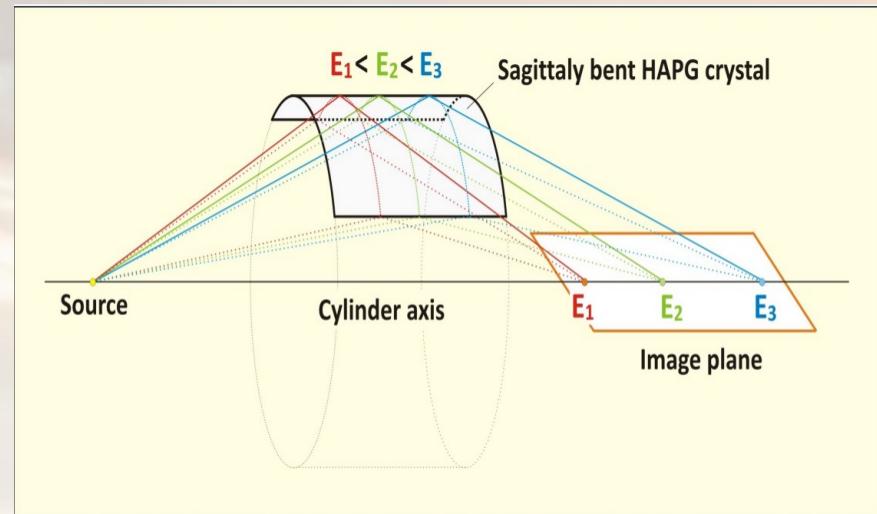
Photons of different energies are reflected in different positions

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



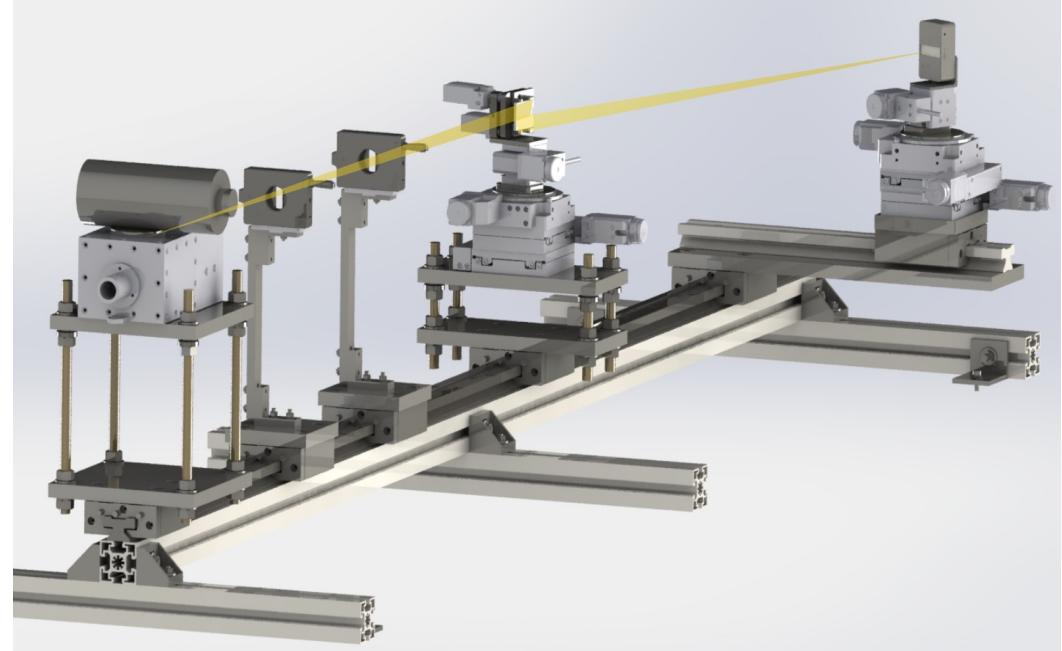
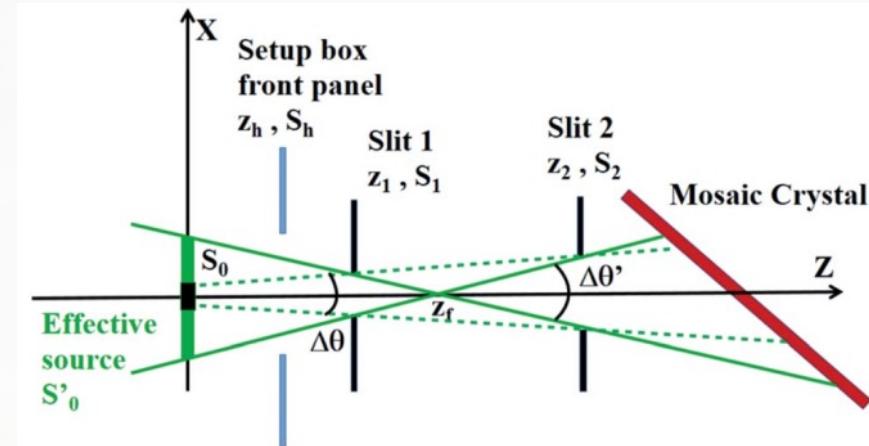
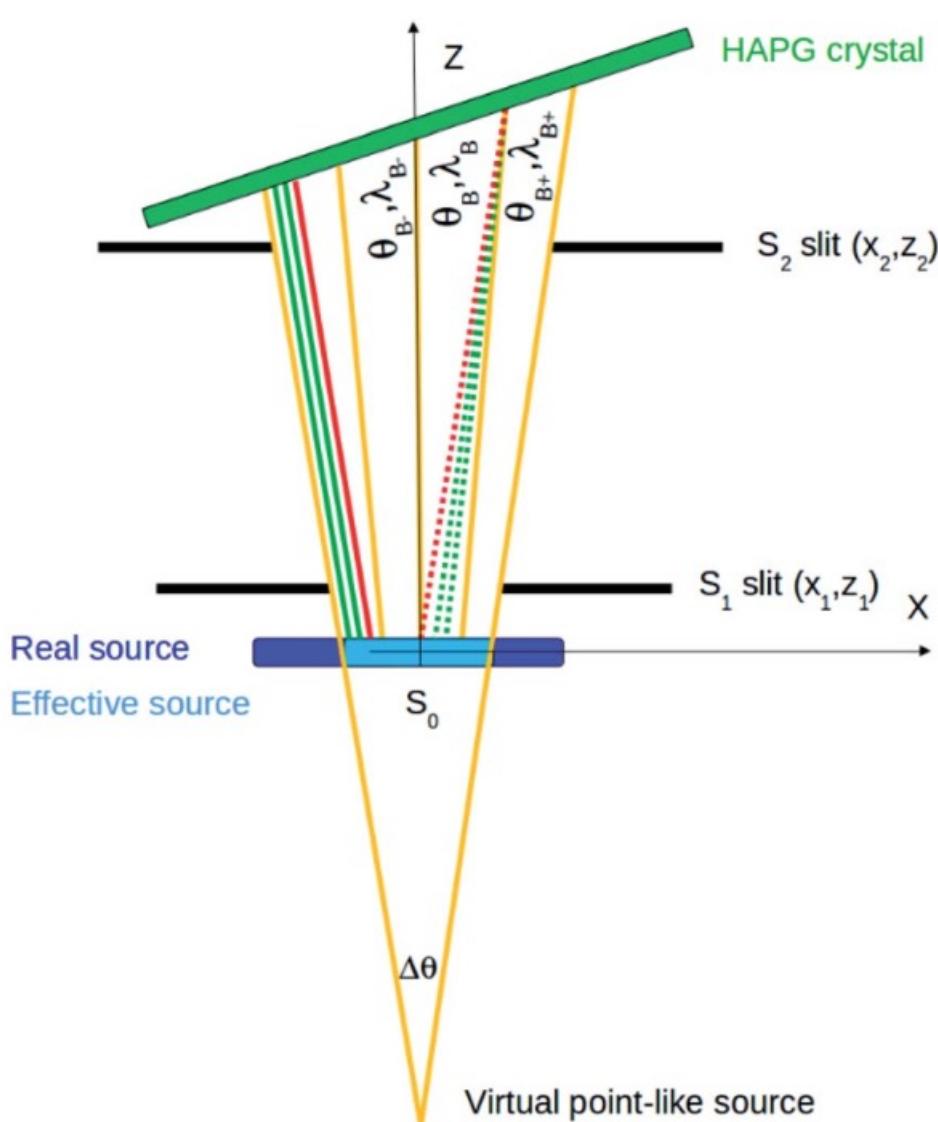
FWHM of few eV with NO COOLING

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)



# Bragg spectrometers: VOXES

**Table 3** Best achieved resolutions and precisions summary.

Element	$\rho_c$ (mm)	Parameter	value (eV)	$S'_0/\Delta\theta'$ (mm,°)
Fe	77,5	$\sigma(K\alpha_{1,2})$	$4,17 \pm 0,16$	0,3 / 0,24
		$\delta(K\alpha_1)$	0,11	0,6 / 0,44
		$\delta(K\alpha_2)$	0,18	0,6 / 0,44
Fe	103,4	$\sigma(K\alpha_{1,2})$	$4,05 \pm 0,13$	0,3 / 0,18
		$\delta(K\alpha_1)$	0,09	0,7 / 0,34
		$\delta(K\alpha_2)$	0,13	0,7 / 0,34
Cu	206,7	$\sigma(K\alpha_{1,2})$	$4,02 \pm 0,08$	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	$\sigma(K\alpha_{1,2})$	$6,8 \pm 0,07$	0,3 / 0,16
		$\delta(K\alpha_1)$	0,07	0,6 / 0,32
		$\delta(K\alpha_2)$	0,1	0,6 / 0,32
Cu	103,4	$\sigma(K\alpha_{1,2})$	$4,77 \pm 0,05$	0,3 / 0,16
		$\delta(K\alpha_1)$	0,04	0,7 / 0,32
		$\delta(K\alpha_2)$	0,07	0,7 / 0,32
Zn	206,7	$\sigma(K\alpha_{1,2})$	$3,60 \pm 0,05$	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	$\sigma(K\alpha_{1,2})$	$5,15 \pm 0,13$	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	$\sigma(K\beta)$	$6,02 \pm 0,24$	0,5 / 0,27
		$\delta(K\beta)$	0,13	0,6 / 0,22
Zn	103,4	$\sigma(K\alpha_{1,2})$	$6,20 \pm 0,34$	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	$\sigma(K\alpha_{1,2})$	$21,1 \pm 0,8$	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	$\sigma(K\beta)$	$36,9 \pm 1,3$	1,6 / 0,80
		$\delta(K\beta)$	1,3	1,6 / 0,80

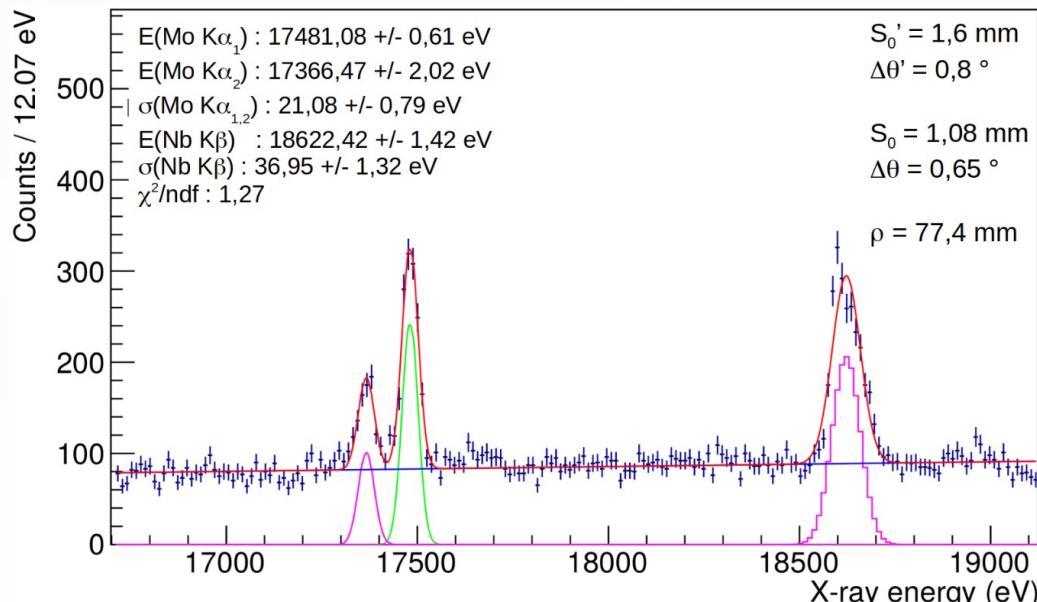
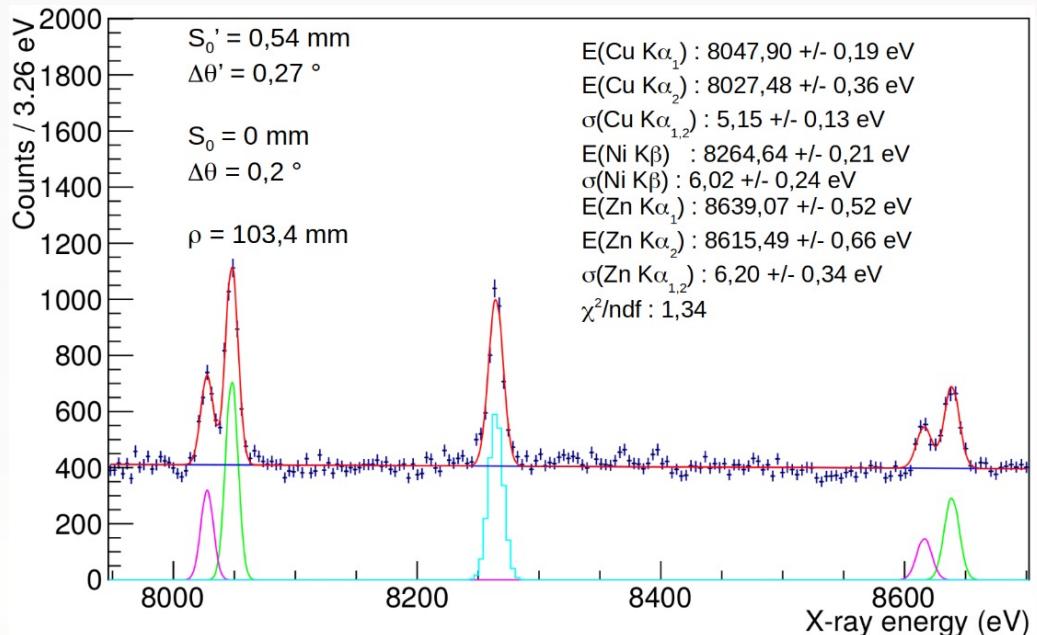
Condens. Matter 2019, 4(2), 38

J. Anal. At. Spectrom., 2020, 35, 155-168

J. Anal. At. Spectrom., 2021, 36, 2485-2491

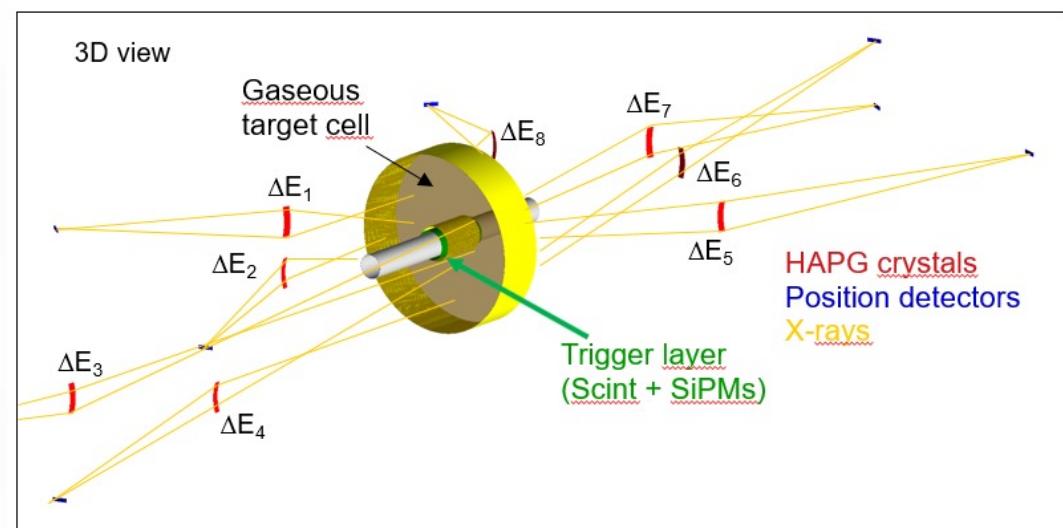
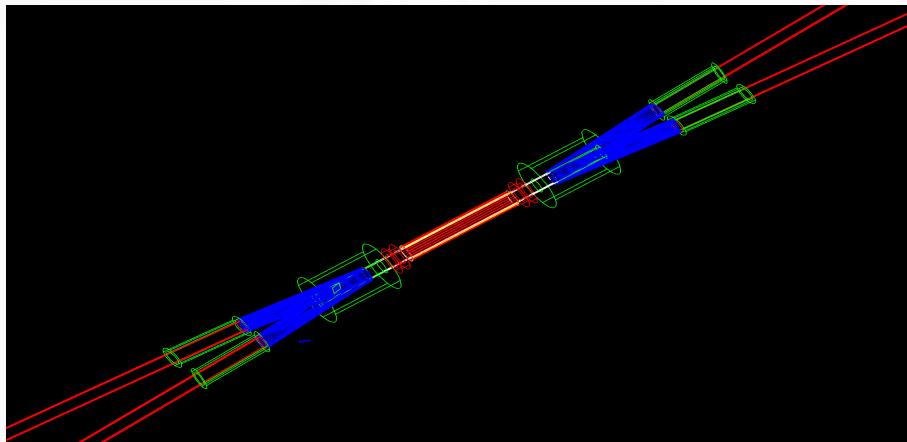
Condens. Matter 2022, 7(1), 1

## High precision measurements with VOXES in LNF Lab



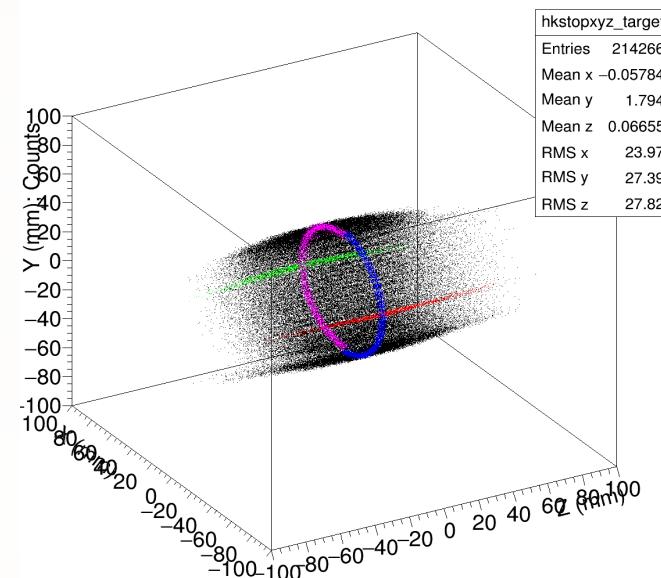
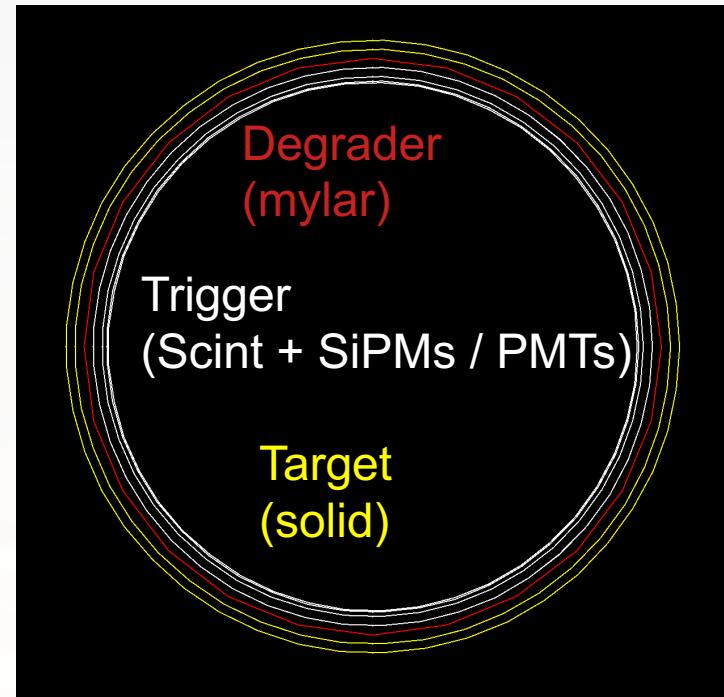
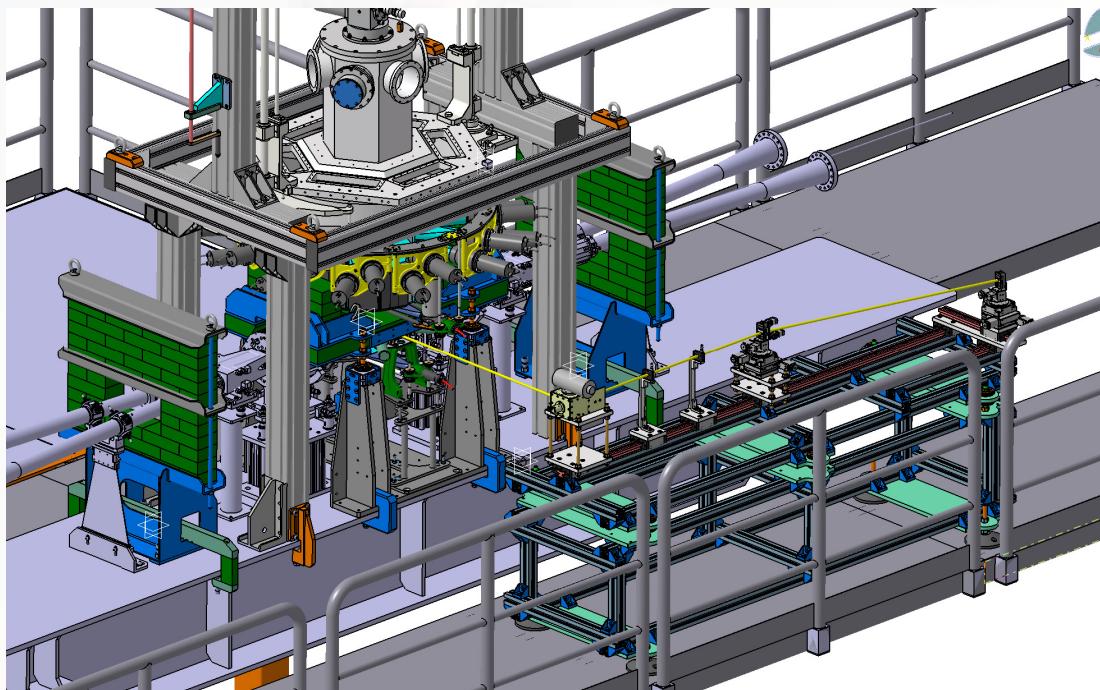
# VOXES: (possible) applications in DAΦNE

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



# VOXES: (possible) 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

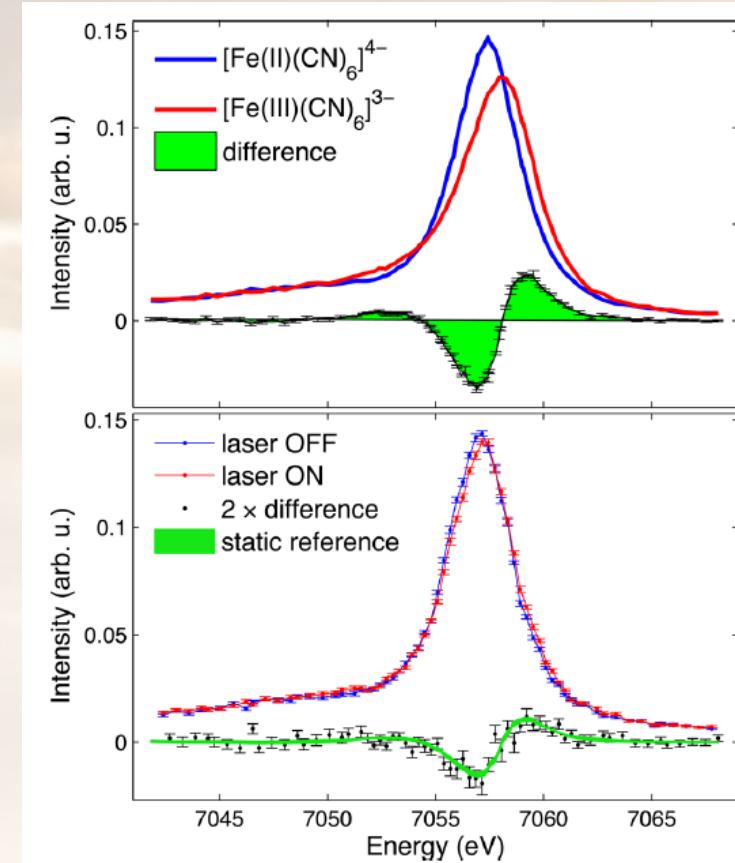
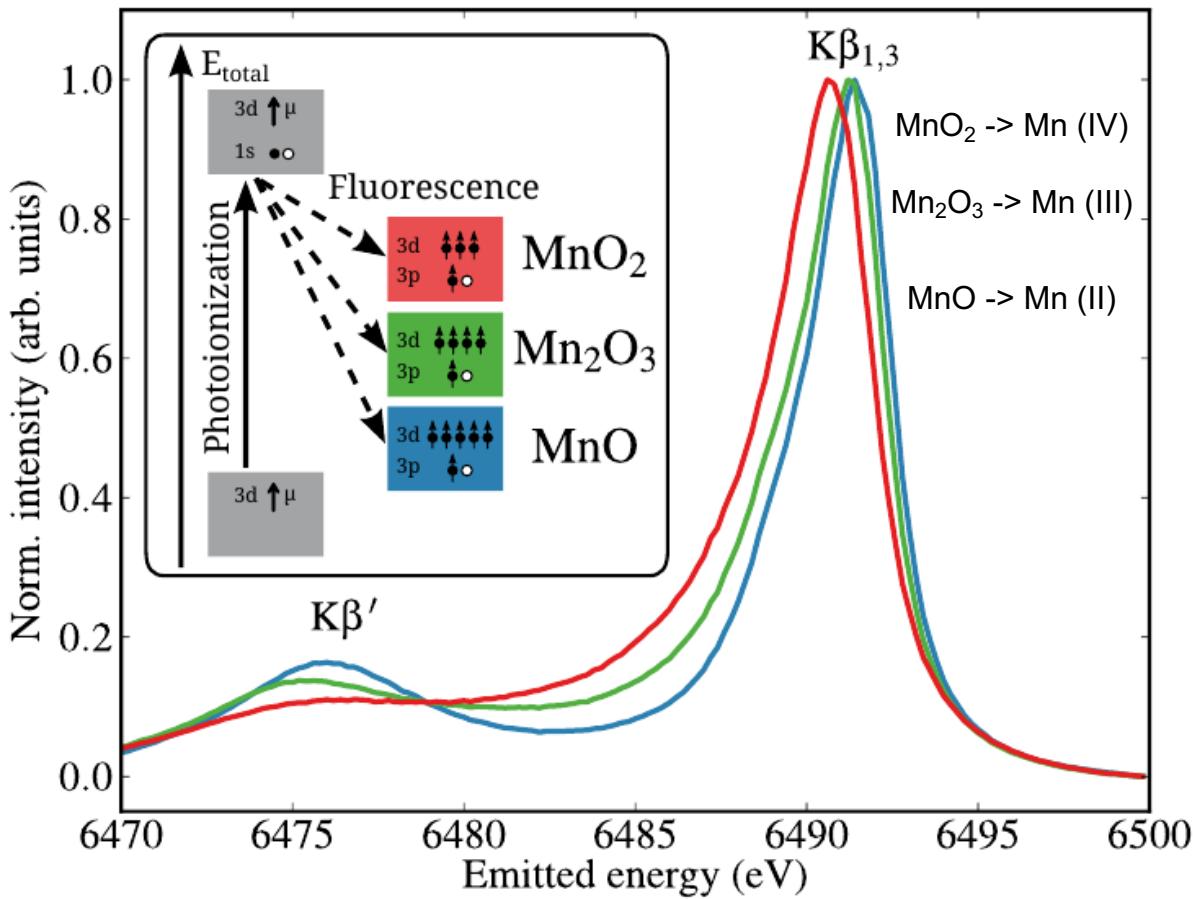


# Testing food and liquids with VOXES: the MITIQO project

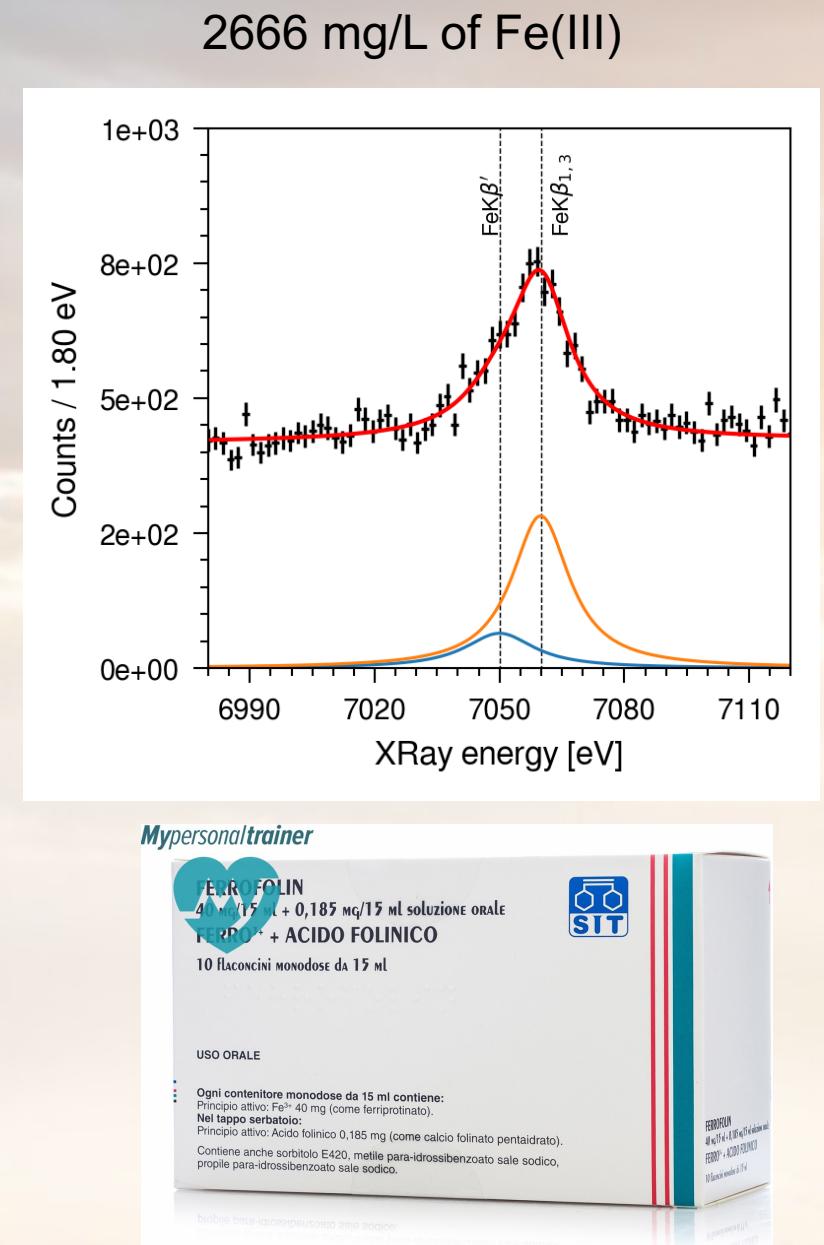
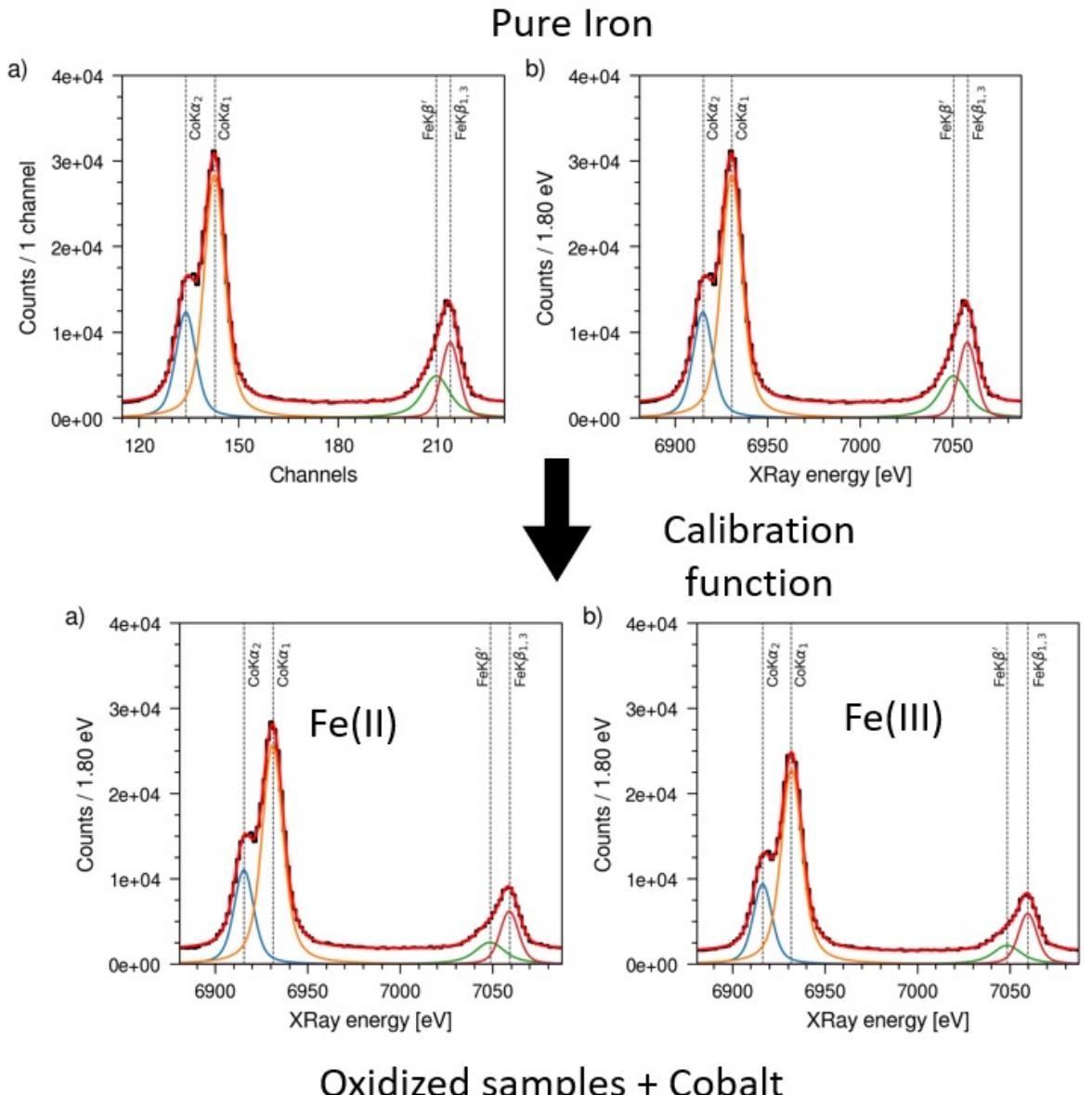
M | T | Q | O

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

Oxidation affects:  
 $\Delta E = E_{1,3} - E'$   
Ratio =  $I' / I_{1,3}$

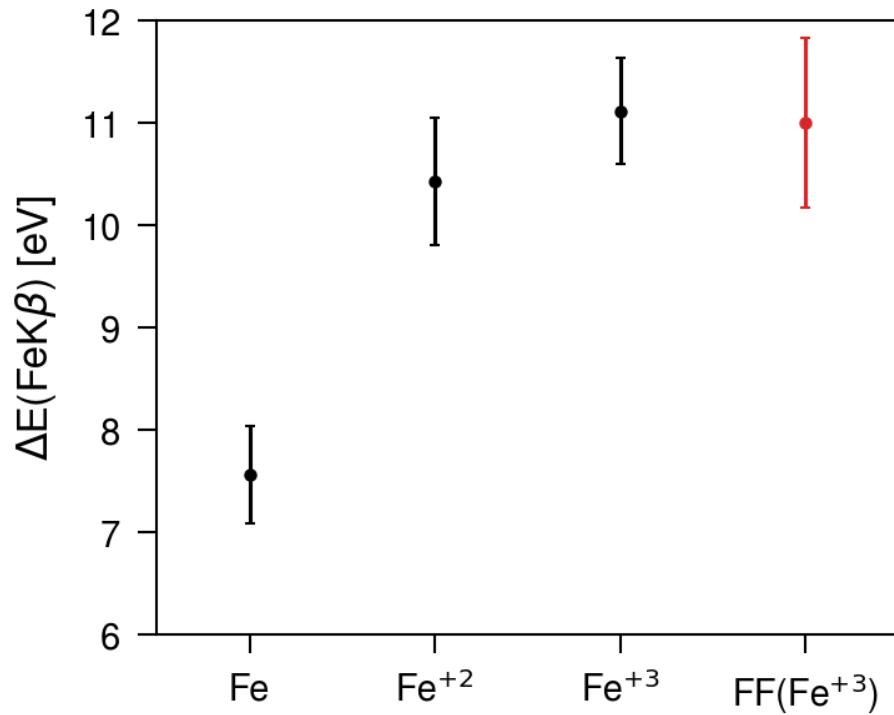


# Testing food and liquids with VOXES: the MITIQO project

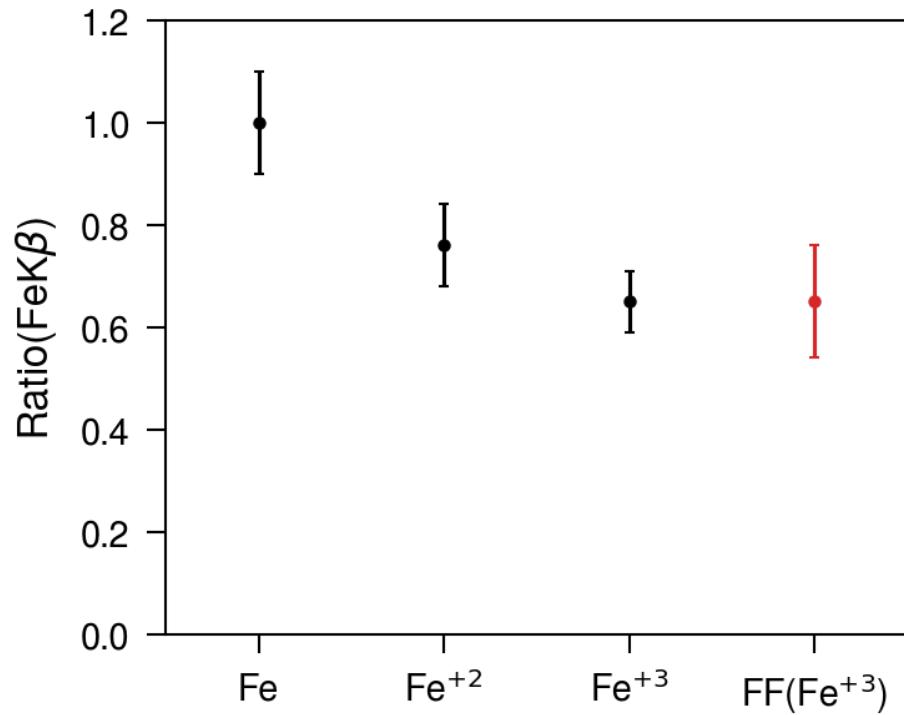


# Testing food and liquids with VOXES: the MITIQO project

a)



b)



First evidence of Fe oxidation  
identification in a liquid sample

To be improved to distinguish between II and III

# CONCLUSIONS

- The SIDDHARTA / VIP / VOXES group at LNF is very active in the X-ray spectroscopy community
- We use several X-ray detectors to perform high-quality measurements in nuclear physics, foundations, quantum gravity and agrifood applications
- SDDs, CdZnTe, HPGe detectors are presently used for our main research activity on kaonic atoms, while Bragg spectrometer are still being tested
- SDDs and HPGe detectors are very successfully used by the VIP/VIP-2/VIP-Lead collaboration to perform measurements on foundations and quantum gravity at LNGS
- The VOXES spectrometer developed at LNF allows for ultra-high resolution (and precision) X-ray spectroscopy also from extended sources
- We are involved both in detector R&D and in physics measurements, and we welcome new ideas and collaborations