Strangeness precision frontier:
A unique opportunity for measurements from kaonic atoms to kaon-nuclei interactions

Johann Zmeskal

ICFA Mini-Workshop on
DAFNE as Open Accelerator Test Facility
LNF December 17, 2018

Strangeness precision frontier: A unique opportunity for measurements from kaonic atoms to kaon-nuclei interactions

Includes the following submitted proposals:

GeKA: Precision measurement of X and gamma-ray transitions in selected Kaonic Atoms with High Purity Germanium detectors (C. Curceanu)

KNscat: Low-energy kaon-nucleon scattering (J. Zmeskal)

WiKAMP: Investigation of single- and multi-nucleon processes of antikaons in nuclei by simultaneous measurements of upper and lower levels transition widths of kaonic atoms with ultra-high energy resolution detectors (A. Scordo)

KAHEL: QCD with strangeness: the first measurement of the 1s state of kaonic helium isotopes (F. Sirghi)

Strangeness precision frontier: A unique opportunity for measurements from kaonic atoms to kaon-nuclei interactions

Participating Institutes

• LNF – INFN	Italy
• SMI – OeAW	Austria
• Univ. Zagreb	Croatia
• Jagiellonian Univ.	Poland
• TUM Munich	Germany
• IFIN-HH, Bucharest	Romania
• INFN and Politecnico di Milano	Italy
• IMEM CNR Parma	Italy
• RIKEN, Wako-shi	Japan
• JAEA, Tokai	Japan
• Univ. Mainz	Germany

WHY EXPERIMENTS WITH STRANGE QUARKS ?

Strange quarks are intermediate between "light" and "heavy" quarks, ideal to study the

- interplay between **spontaneous and explicit chiral symmetry breaking** in low-energy QCD

Hadron mass problem -> related to chiral symmetry breaking mechanism

Nature and structure of $\Lambda(1405)$ B=1; S=-1, $J^P = 1/2^-$ (important in astrophysics)

- "molecular" meson-baryon state
- two pole structure

Quest for bound antikaon-NN systems

Role of strangeness in dense baryonic matter

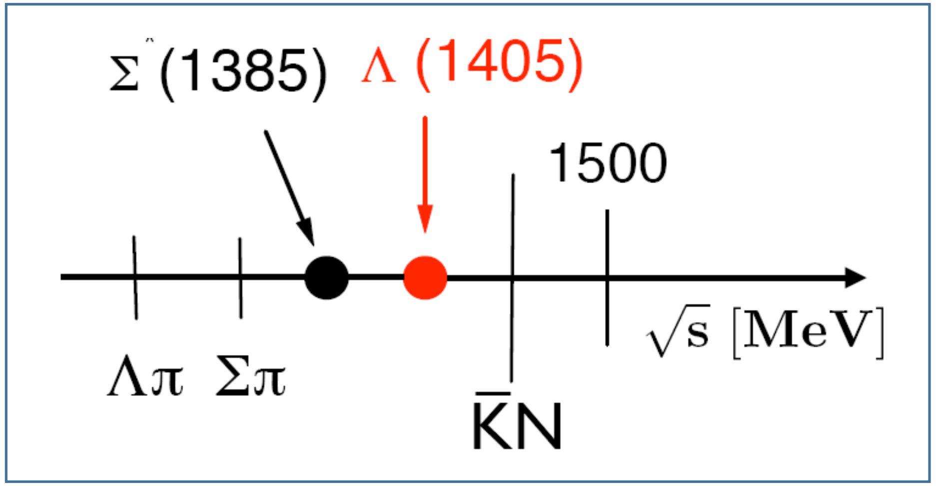
- hyperons in **neutron stars**, kaon condensation

New ongoing studies: kaonic atoms as laboratory for gravity at femtometer scale

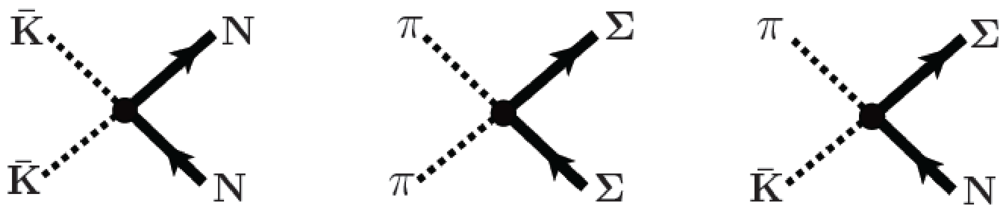
MOTIVATION

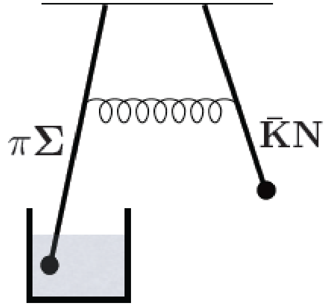
The low-energy antikaon nucleon system is of special interest in particle and nuclear physics, as well as in astrophysics, since the rather large mass of the strange quark allows testing chiral SU(3) symmetry in QCD.

Chiral perturbation theory developed for πp, ππ **not** applicable for $\bar{K}N$ systems



non-perturbative coupled channels approach based on **chiral SU(3) dynamics**



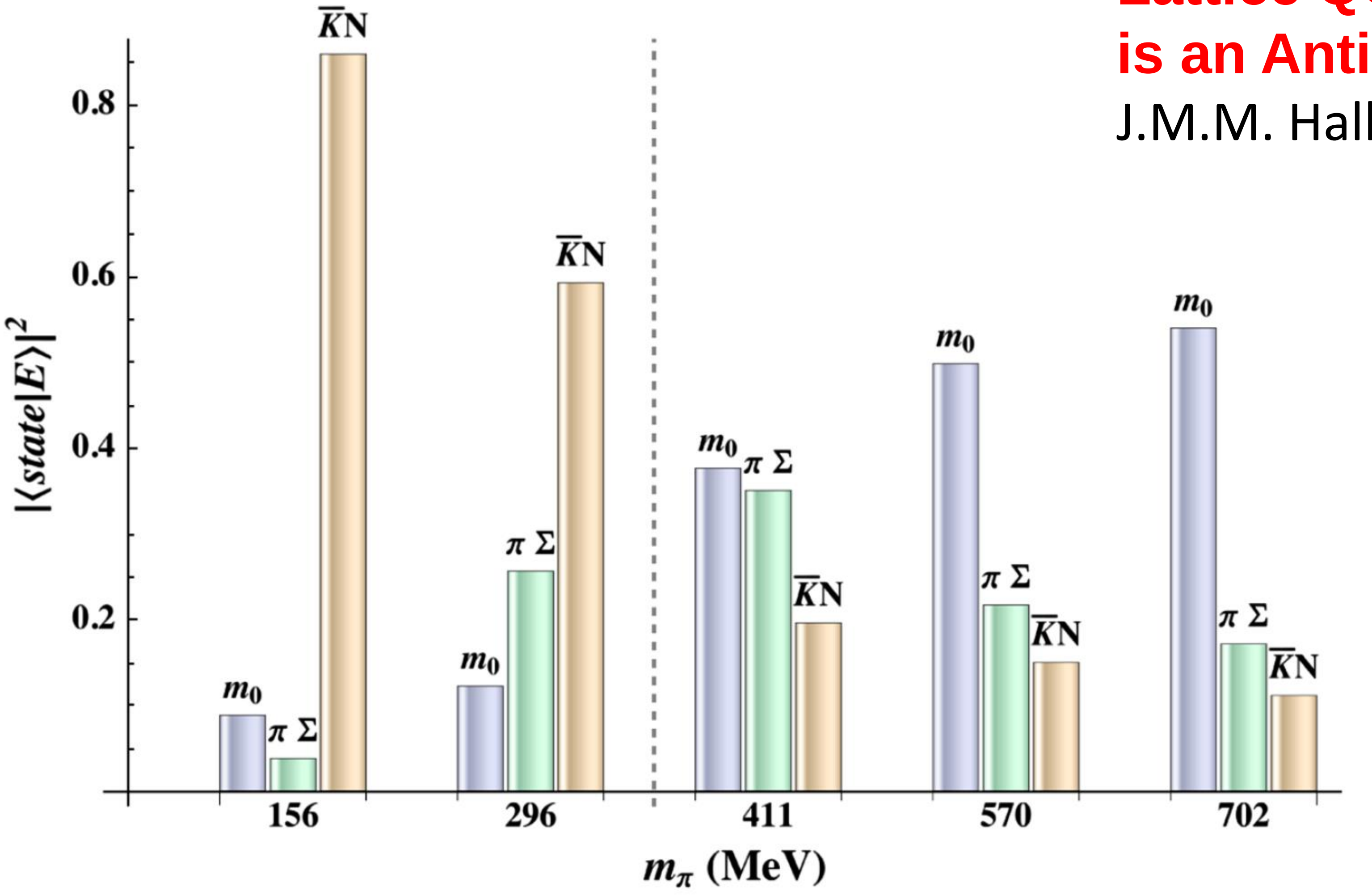


channel coupling

Review:
T. Hyodo, D. Jido
Prog. Part. Nucl. Phys. 67 (2012) 55

Λ(1405) IN LATTICE-QCD

~ real world (m_π = 140 MeV/c^2)

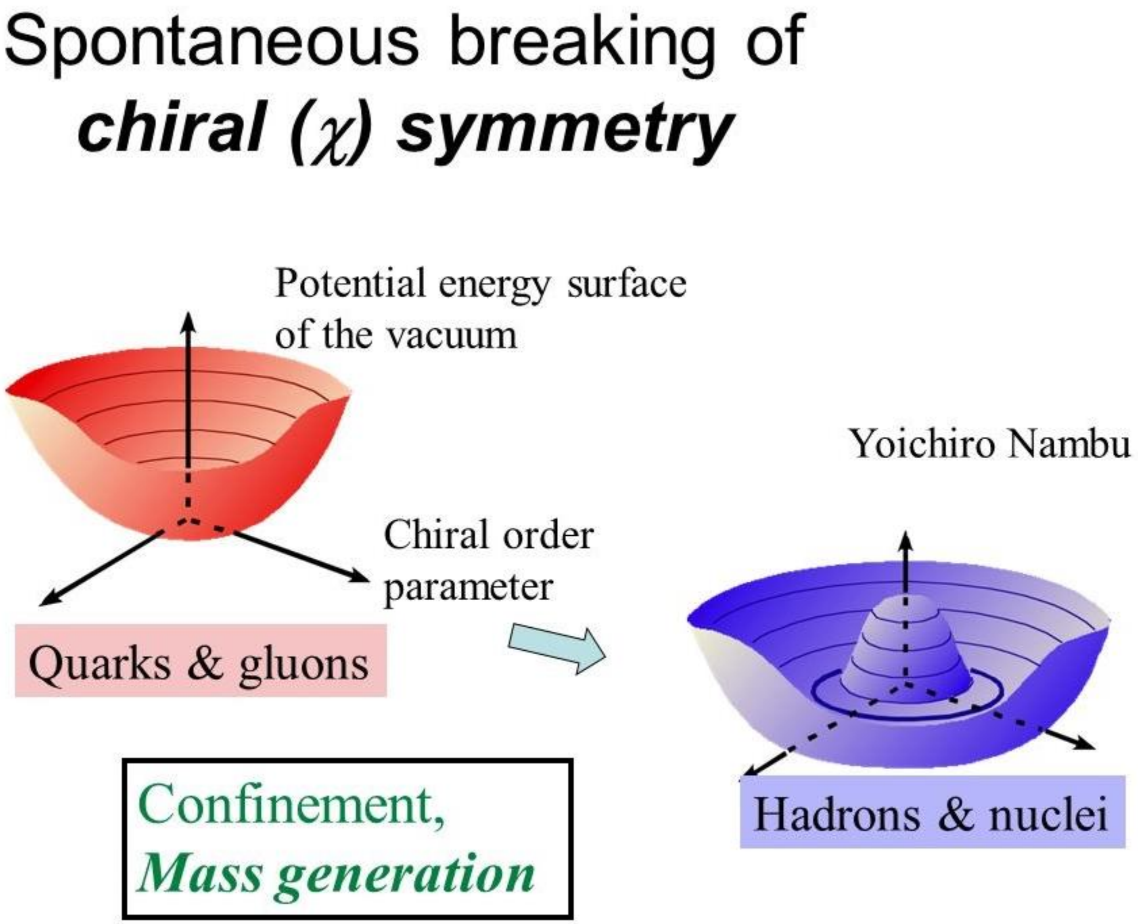


Lattice QCD Evidence that Λ(1405) is an Antikaon-Nucleon Molecule

J.M.M. Hall et al., PRL 114 (2015) 132002

Needs further studies, because there is still a pending debate of its structure

IMPACT OF THE STRANGENESS PRECISION FRONTIER STUDIES GOES FROM:



WHY DAΦNE?

The DAΦNE Φ-factory at LNF is the world leading facility for low-energy kaons, producing charge kaons in the momentum range 115 – 140 MeV/c

and

is therefore ideally suited for studying particle and nuclear physics in the sector of low-energy QCD with strangeness

Strategy and programme - strangeness precision frontier

Abstract: GEKA - Precision measurement of X and gamma-ray transitions in selected Kaonic Atoms with High Purity Germanium detectors (C. Curceanu)

- measurement of kaonic atoms on selected solid targets (C, Se, Zr, Ta and Pb) using **HPGe** (Croatian Science Foundation Project 8570)
  - 100 pb^{-1} per data points
- radiative kaon capture on the proton with direct formation of $\Lambda(1405)$ using **HPGe**
  - 100 pb^{-1}

Abstract: WIKAMP - Investigation of single- and multi-nucleon processes of antikaons in nuclei by simultaneous measurements of upper and lower levels transition widths of selected kaonic atoms with ultra-high energy resolution detectors (A.Scordo)

- kaon single- and multi-nucleon processes **using VOXES / TES**
  - 300 pb^{-1} for 3 data points
- determination of the charged kaon mass (K^-) **using VOXES / TES**
  - 300 pb^{-1} per data point

Strategy and programme - strangeness precision frontier

Abstract: KNScat - Low-energy kaon-nucleon scattering (J. Zmeskal)

- measurement of low-energy kaon scattering and interactions on hydrogen and helium

  development of an **"active TPC"** within EU-programme STRONG2020

  - 200 pb^{-1} for hydrogen + deuterium
  - 200 pb^{-1} for ^{4}He + ^{3}He

Abstract: KAHEL - QCD with strangeness - the first measurement of the 1s state of kaonic helium isotopes (F. Sirghi)

- determination of the 1s state of kaonic helium

  development of **CdZnTe detectors** within EU-programme STRONG2020

  - 100 pb^{-1} + 500 pb^{-1}

GEKA: MEASUREMENT OF KAONIC ATOMS ON SELECTED SOLID TARGETS (C, Se, Zr, Ta and Pb)

- Measurement of X-ray transitions in a series of selected kaonic atoms in order to deliver fundamental experimental information on the potential problem of the interaction of kaons with nuclear matter and its dependency on density.

- ➢ Input to the development of chiral theories by experimental studying the interaction strength of kaons with nuclei.

GEKA: RADIATIVE KAON CAPTURE ON THE PROTON WITH DIRECT FORMATION OF $\Lambda(1405)$

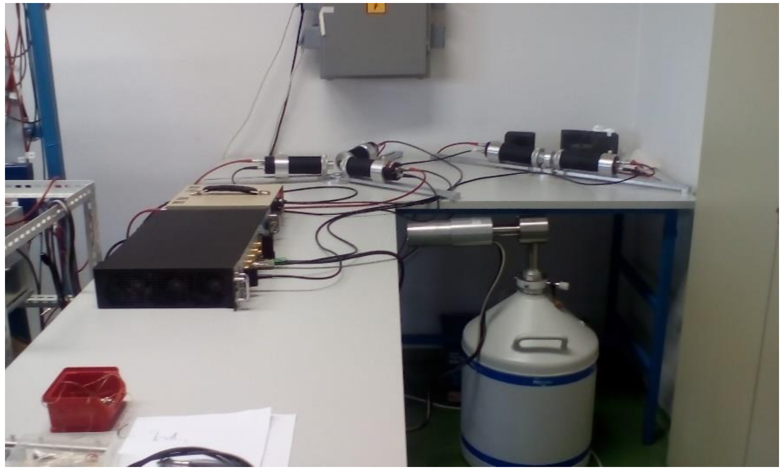
- A measurement of $\Lambda(1405)$ of the radiative transition from the hydrogen atomic 2p level to the $\Lambda(1405)$ state will provide important information on the structure of $\Lambda(1405)$ – molecular state / dipole structure.

  If the kaon is absorbed from a p-level with a certain probability a gamma will be emitted with the energy equal to the binding energy of $\Lambda(1405)$ as a kaon-proton bound state, which could be between 5 and 27 MeV, depending on theoretical model.

  S. Wycech Int.J.Mod.Phys. A26 (2011) 402-407
  DOI: 10.1142/S0217751X11051731

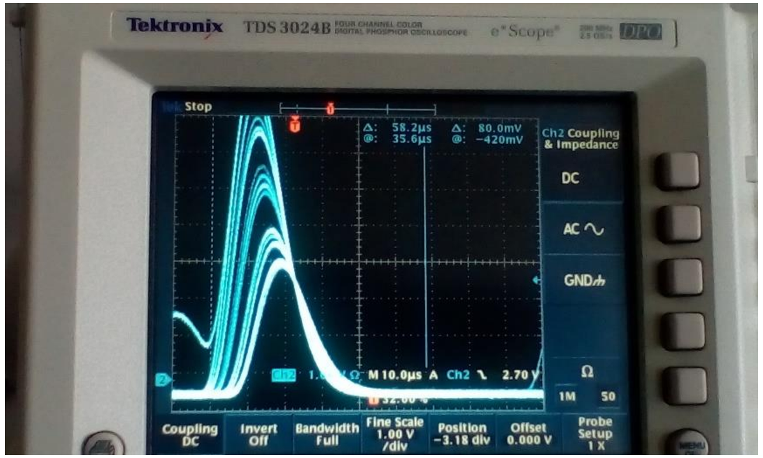
HPGe LABORATORY TESTS & ANALOGUE ELECTRONICS

Croatian Science Foundation Project 8570



CAEN spectroscopy amplifier N968,
Canberra Multiport II,
Canberra Genius DAQ + analysis

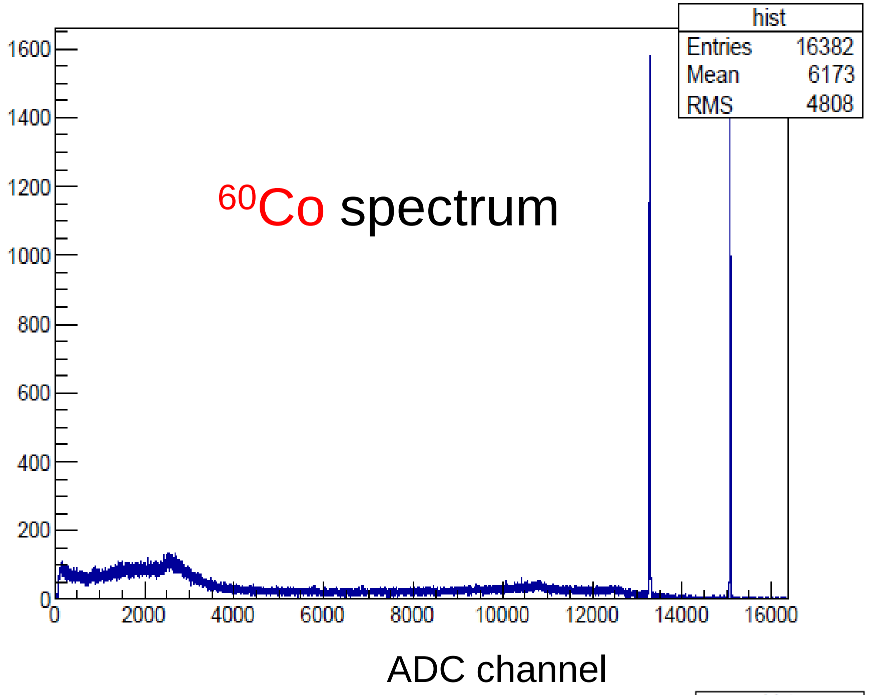
Signal from spectroscopy amplifier

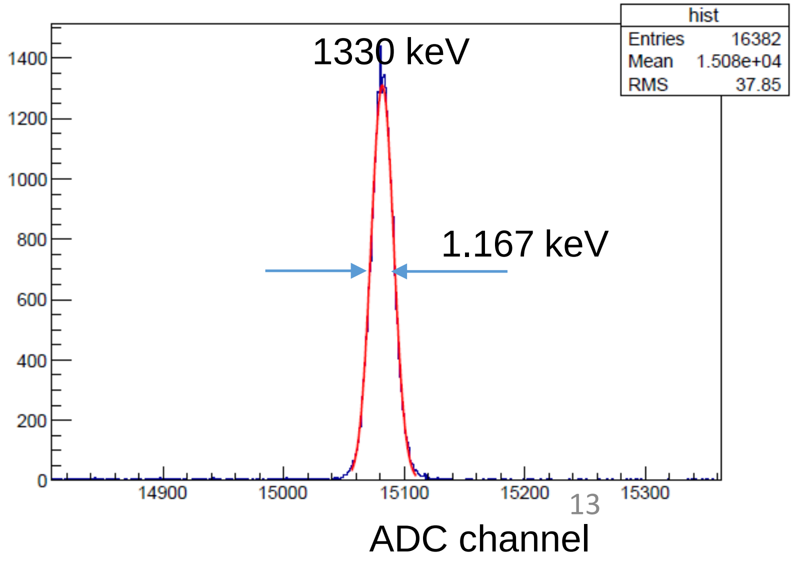


^{133}Ba and ^{60}Co spectra,
Resolutions with fast readout:

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

Setup ready for measurements!





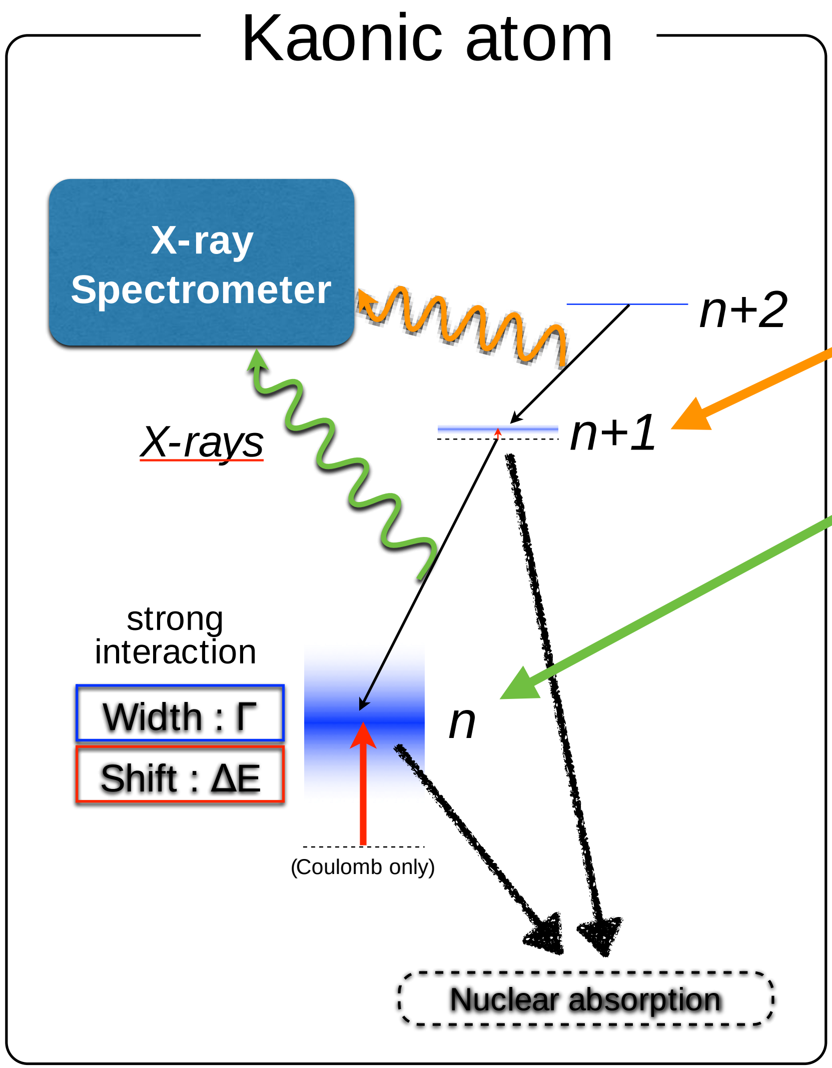
WIKAM: KAON SINGLE- AND MULTINUCLEON PROCESSES

- The simultaneous measurement of the widths of the radiative transitions occurring from upper and lower levels from the same element, will provide fundamental information on the antikaon-nucleon potential (light atoms) and on the single- and multinucleon processes of antikaons in nuclei (medium and heavy atoms), which is fundamental to understand the non-perturbative QCD with strangeness.

- Such measurements, in particular for the transitions at higher n-levels are very challenging due to the relatively small influence of the strong interaction, which leads to small widths of these states of only a few eV.

- Therefore, the capability to detect X-rays with ultra-high resolution is mandatory. Different detector systems are under evaluation:
  - New high resolution X-ray spectrometer setup based on Pyrolitic Graphite mosaic crystals (HAPG or HOPG)
  - Detector system based on Transition Edge Sensors

KAON SINGLE- AND MULTINUCLEON PROCESSES



Simultaneous measurement of the widths of the radiative transitions occurring from **upper** and **lower** levels from the same element

common density distribution
-> removing the density uncertainties

providing fundamental information on **single-** and **multi-nucleon** processes of anti-K in nuclei

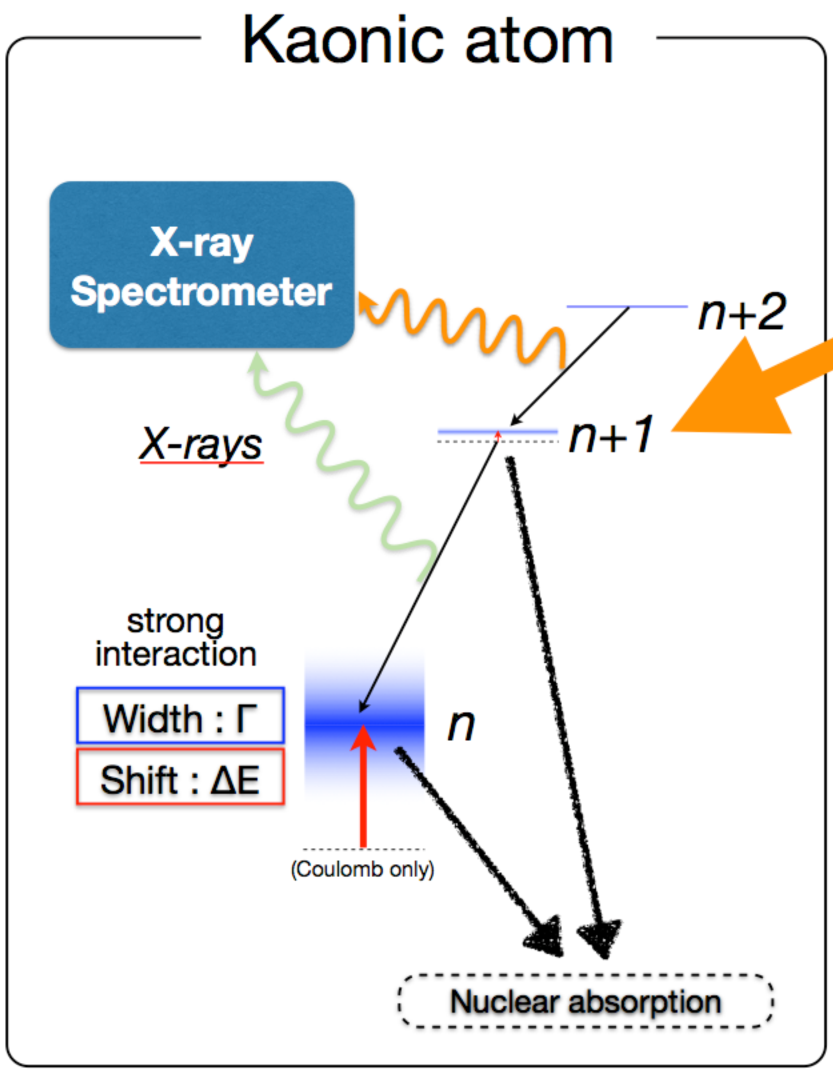
Very different radial dependences of the 1N and 2N terms

rms radii of various terms of the K^-–nucleus potential (in fm). r_m is the rms radius of the nucleus.

	r_m	Re(full)	Re(1N)	Re(mN)	Im(full)	Im(1N)	Im(mN)
Ni	3.72	3.34	3.82	2.86	3.73	4.46	3.12
Pb	5.56	5.21	5.71	4.78	5.46	6.23	5.00
			1N	mN		1N	mN

E. Friedman, S. Okada, Nucl. Phys. A915 (2013) 170-178

CHALLENGE WITH NEW X-RAY DETECTORS



determined so far only with indirect measurement (with relative yields of the upper to lower level transitions)

No direct measurement due to quite small strong-interaction widths

Breakthrough with ultra-high resolution

X-ray spectrometers :

(1) Superconducting Transition Edge Sensor Microcalorimeters

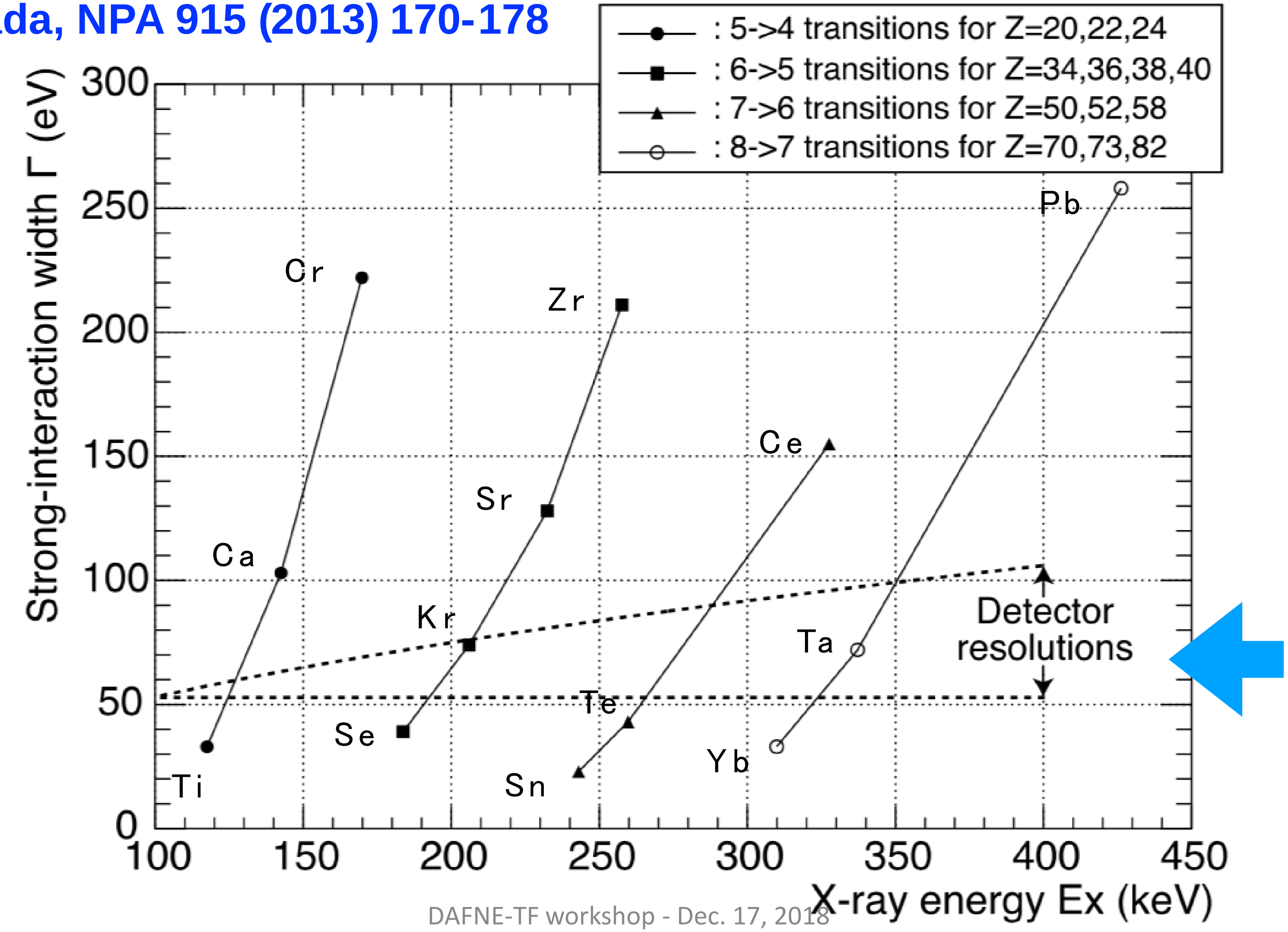
(2) Pyrolitic Graphite mosaic crystals (HAPG or HOPG)

FEASIBILITY GUIDELINE FOR KAONIC-ATOM EXPERIMENTS

with ultra-high-resolution X-ray spectrometry

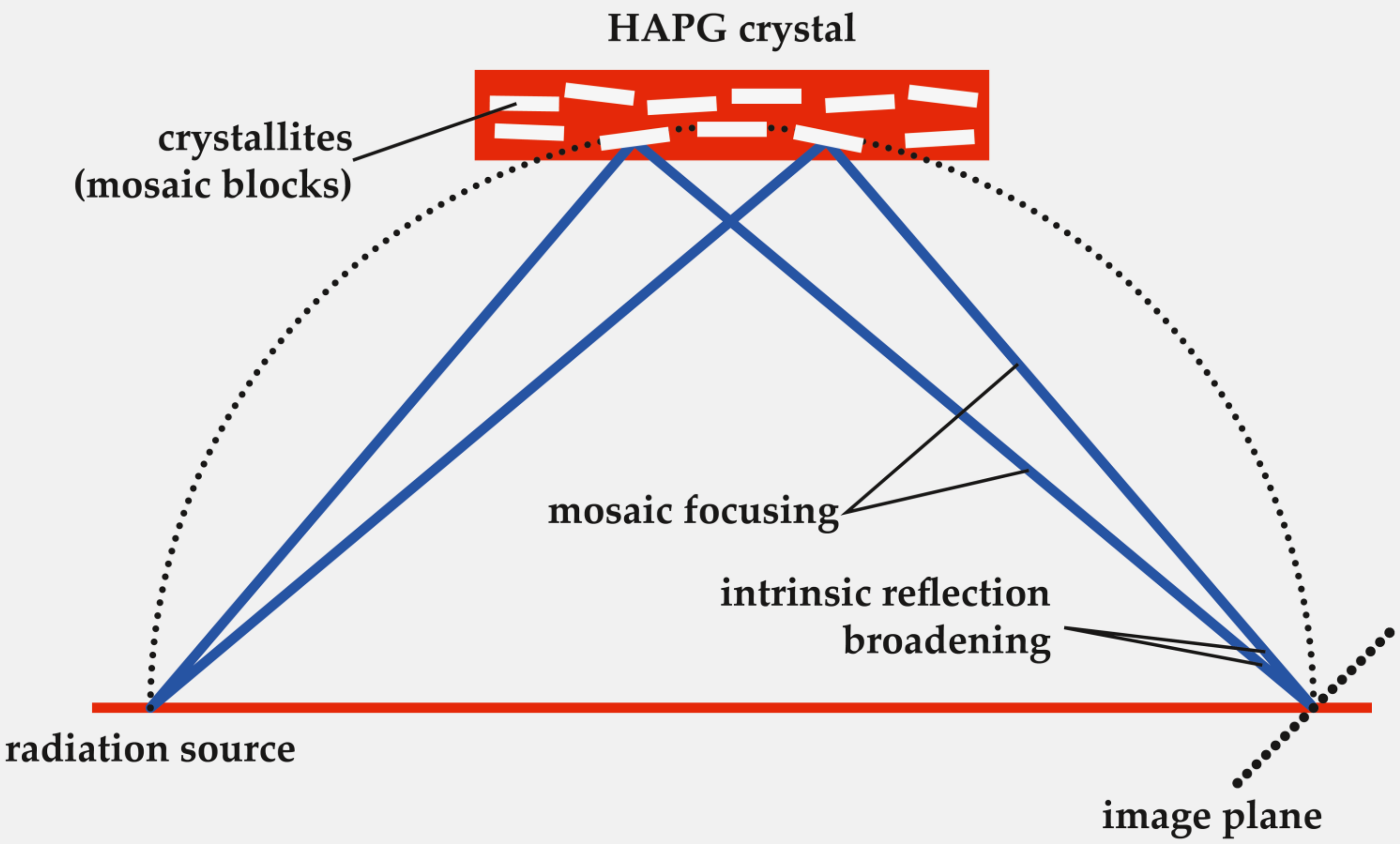
E. Friedman, S. Okada, NPA 915 (2013) 170-178

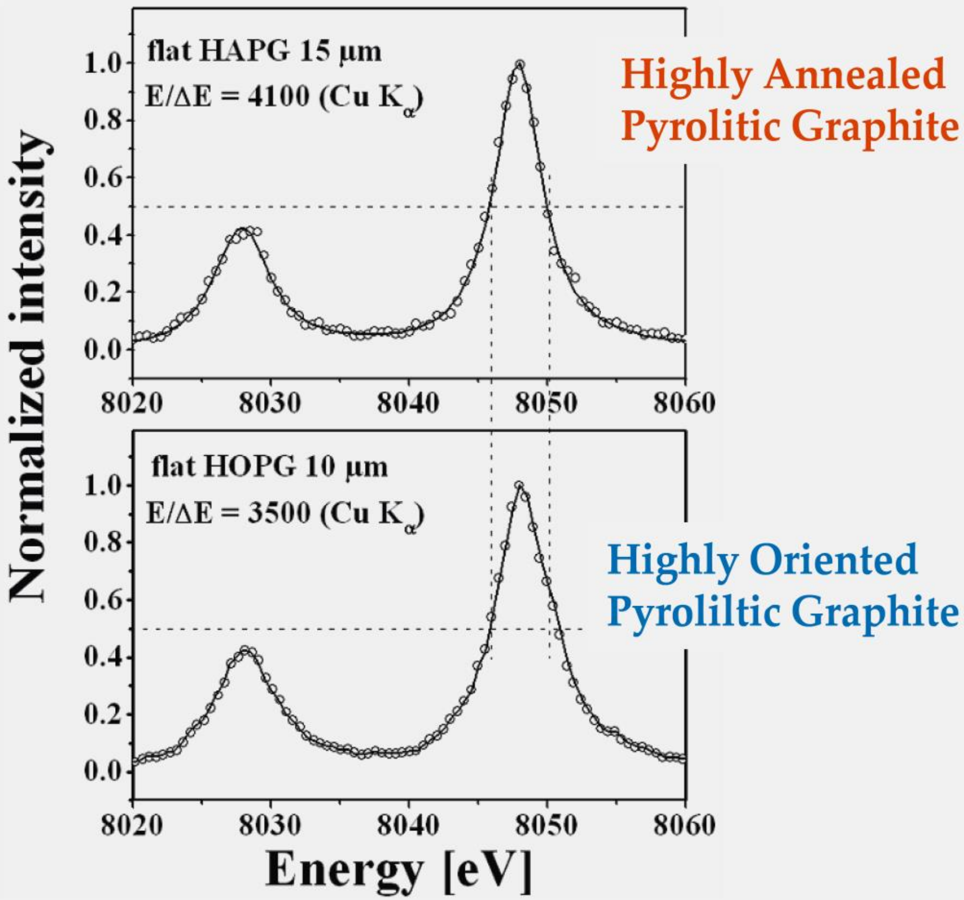
Width of upper levels



TES detector resolution

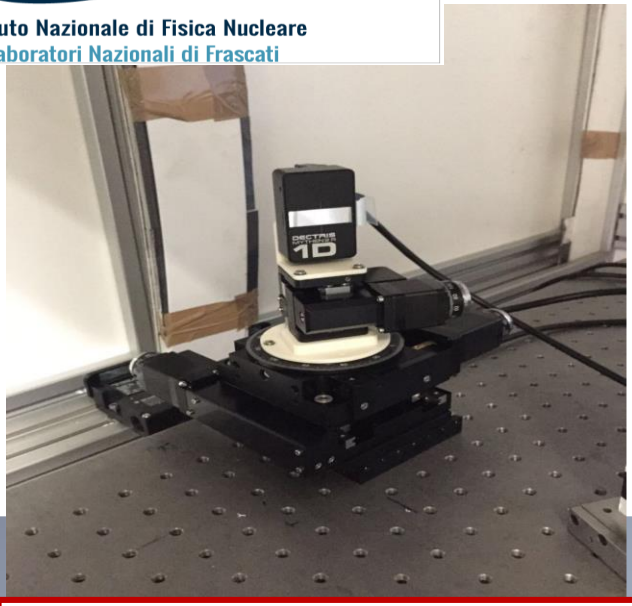
High resolution **VO**n-Hamos **X**-Ray spectrometer using HAPG for **E**xtended **S**ources in a broad energy range - **VOXES**





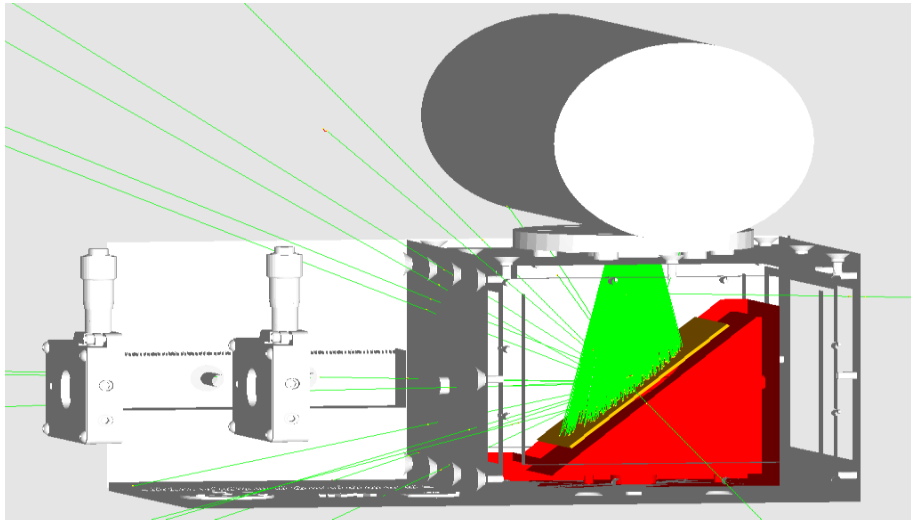
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

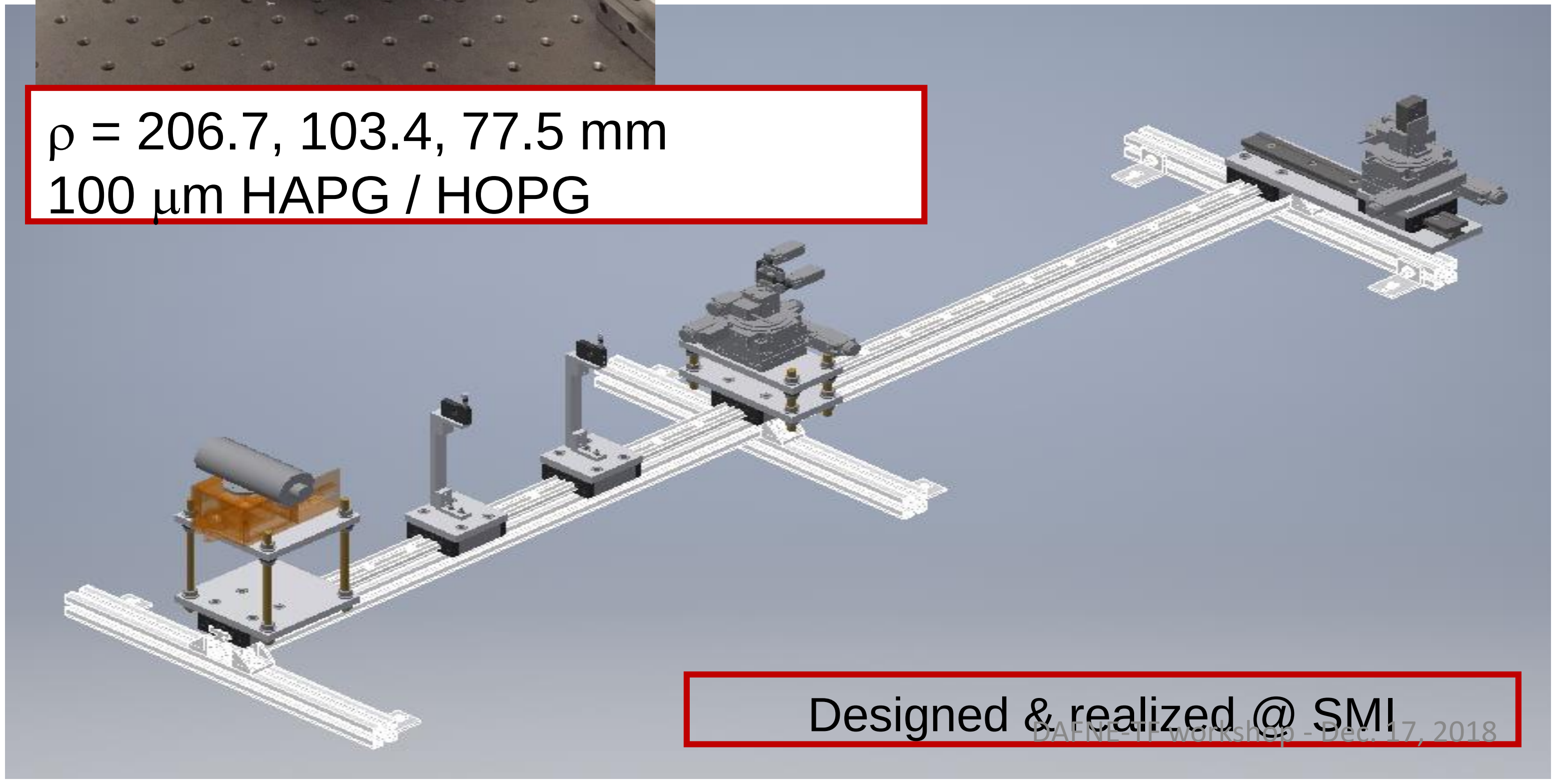
VOXES: Setup tested in laboratory



MYTHEN2 detector:
32 x 8 mm surface
640 channels → 50 μm resolution
4-40 keV range
working @ room temperature

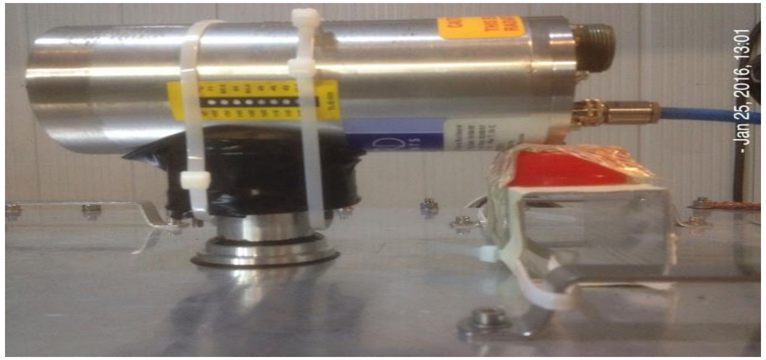
Designed & 3D-printed @ LNF





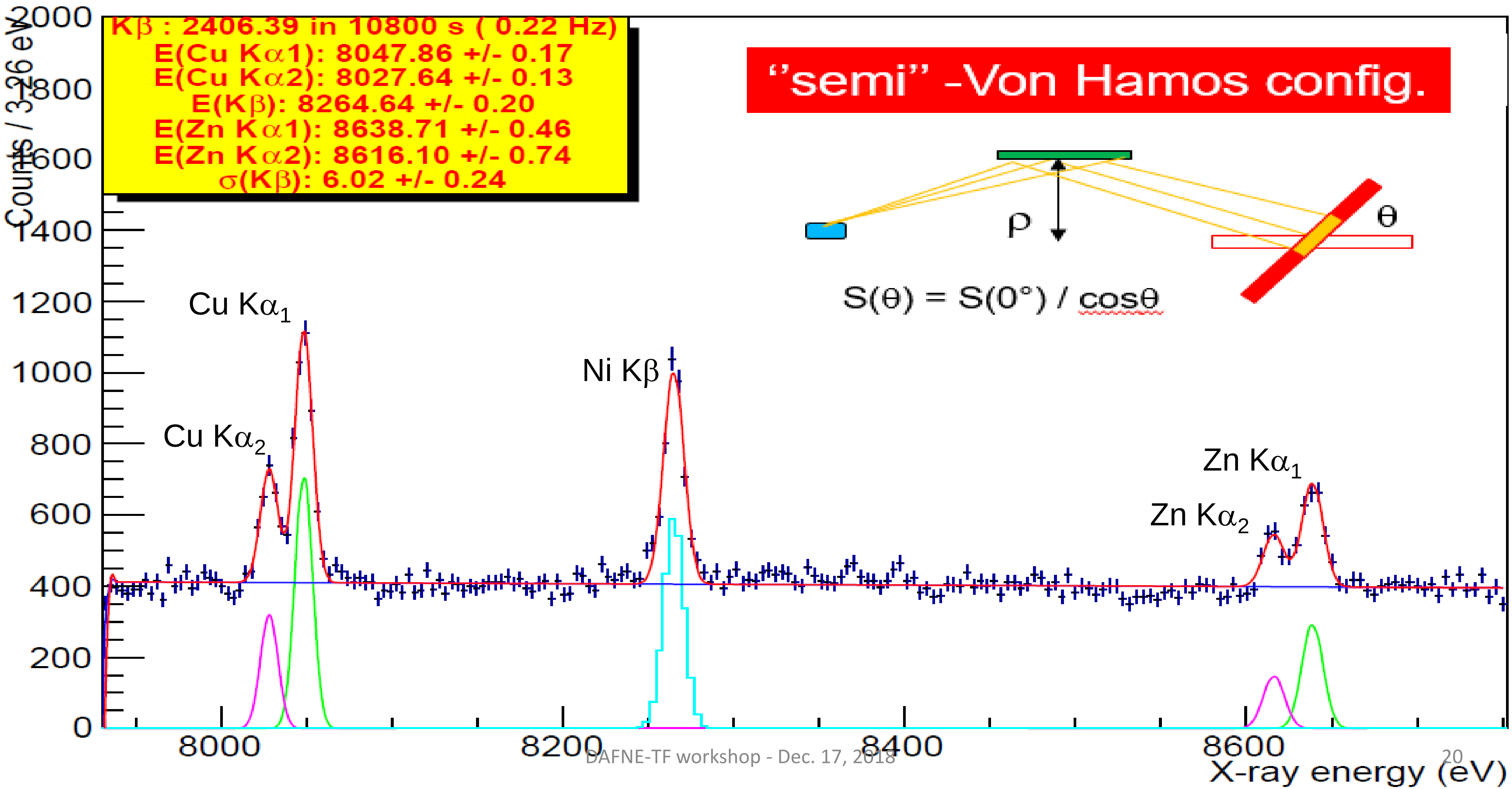
ρ = 206.7, 103.4, 77.5 mm
100 μm HAPG / HOPG

Designed & realized @ SMI

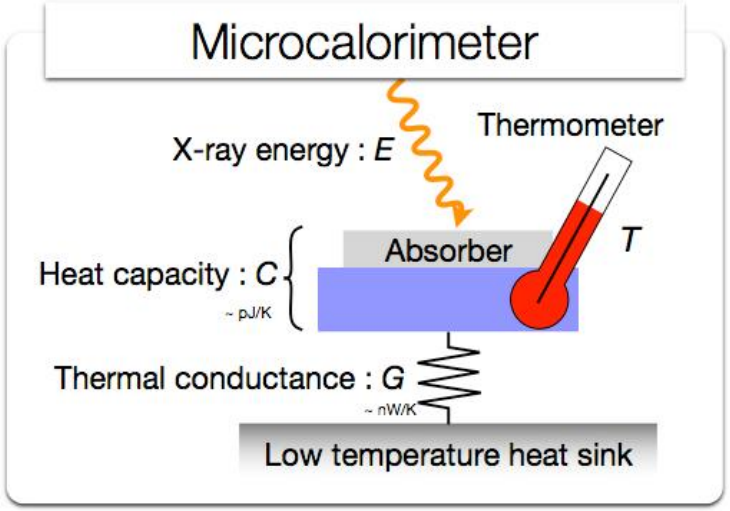


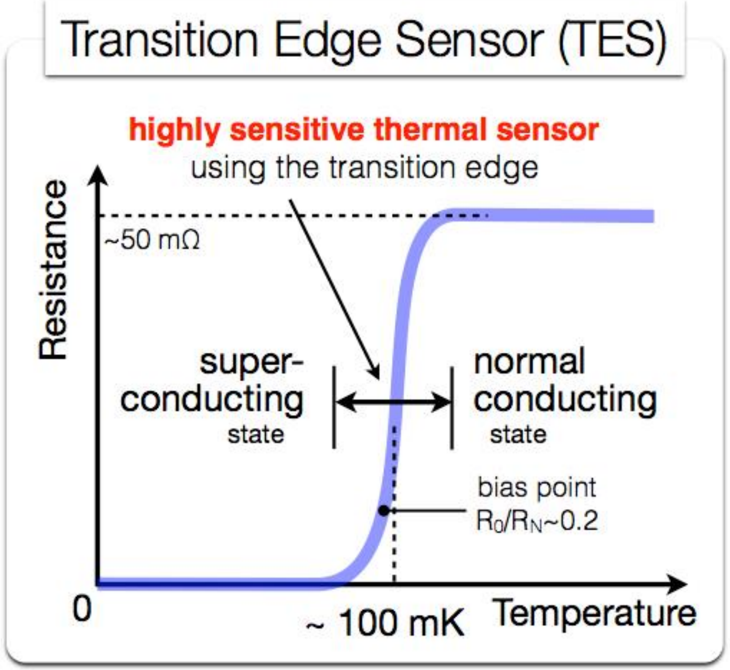
Oxford Instruments
XRF-5011
Tungsten (W) X-ray tube

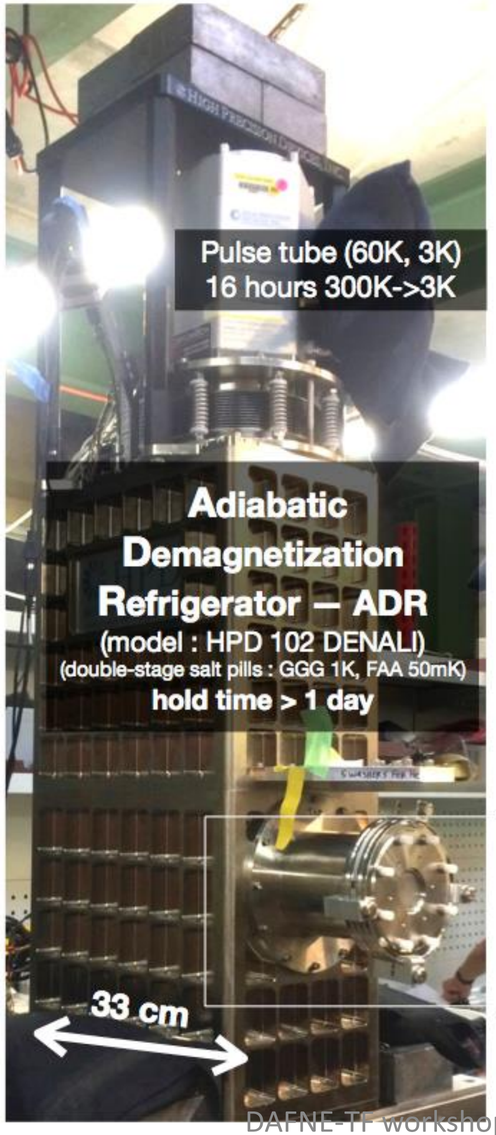
WIDE DYNAMIC RANGE



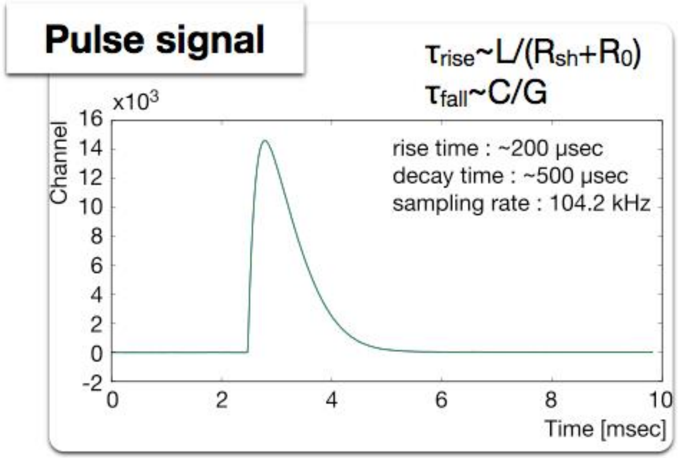
TRANSITION-EDGE-SENSOR (TES) MICROCALORIMETER

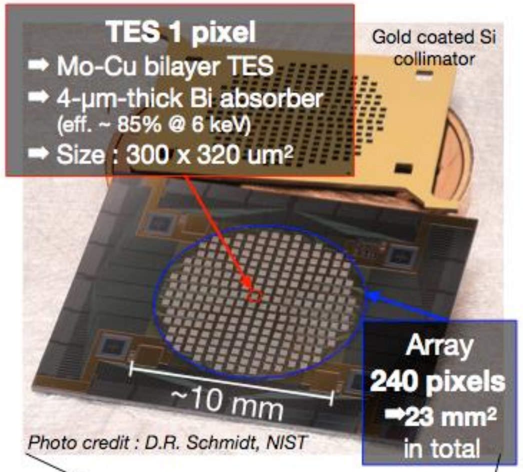


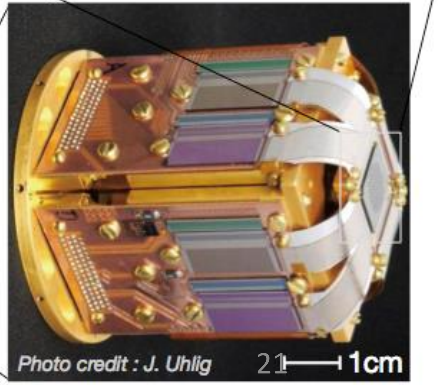




- ✓ High energy resolution : ΔE ~ 5 eV FWHM @ 6 keV
- ✓ Wide dynamic range
- ✓ Large effective area w/multiplexing tech.



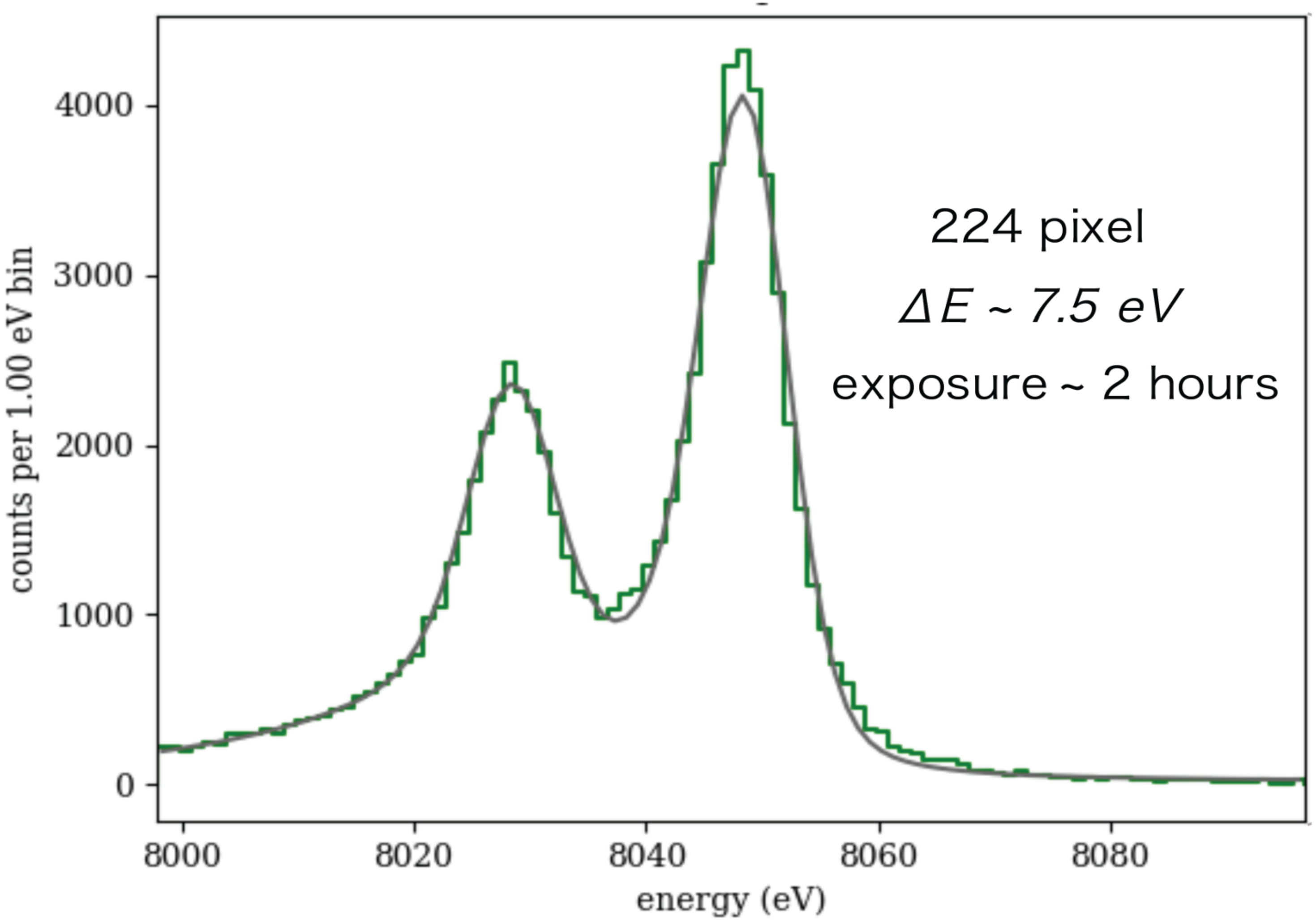




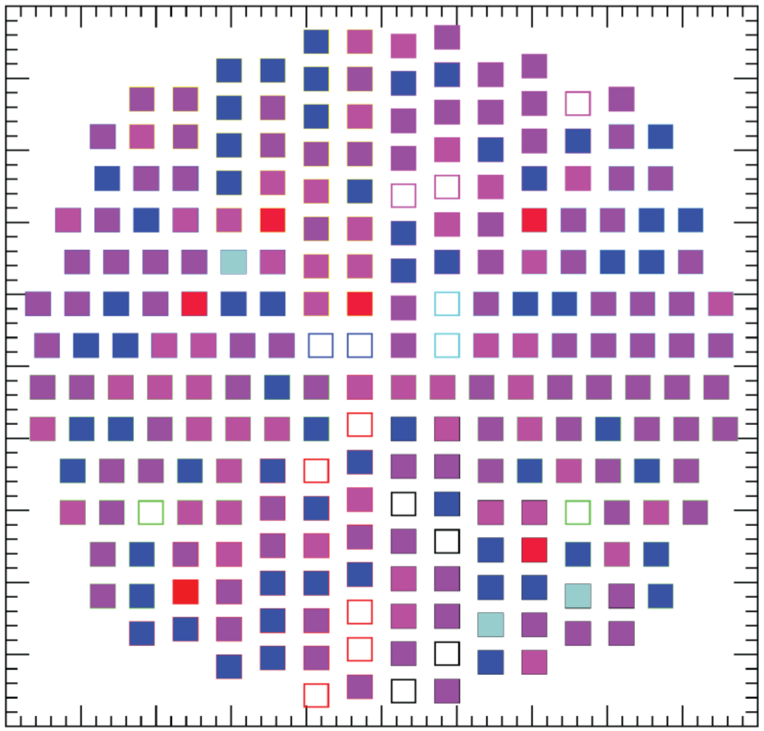
X-RAY ENERGY SPECTRA IN BEAM CONDITION

with X-ray tube

~200 cps/array in total, 10~20 cps/array without x-ray tube



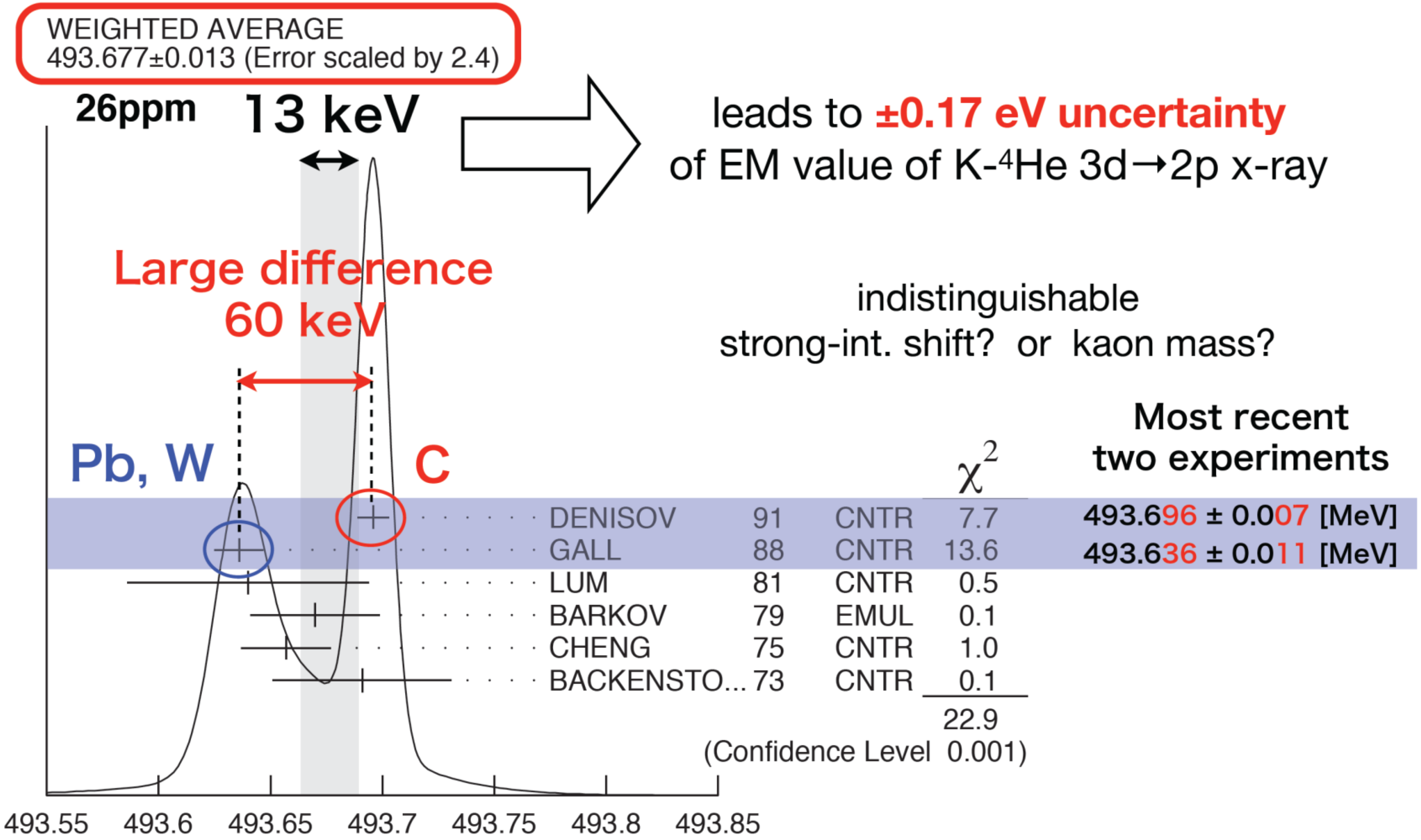
pixel map



no color : doesn't work
(the colors show their resolutions)

Kaon mass discrepancy – impact on kaonic atoms; CPT, all physics where kaon mass is important (searches beyond standard model)

➢ a new measurement is required

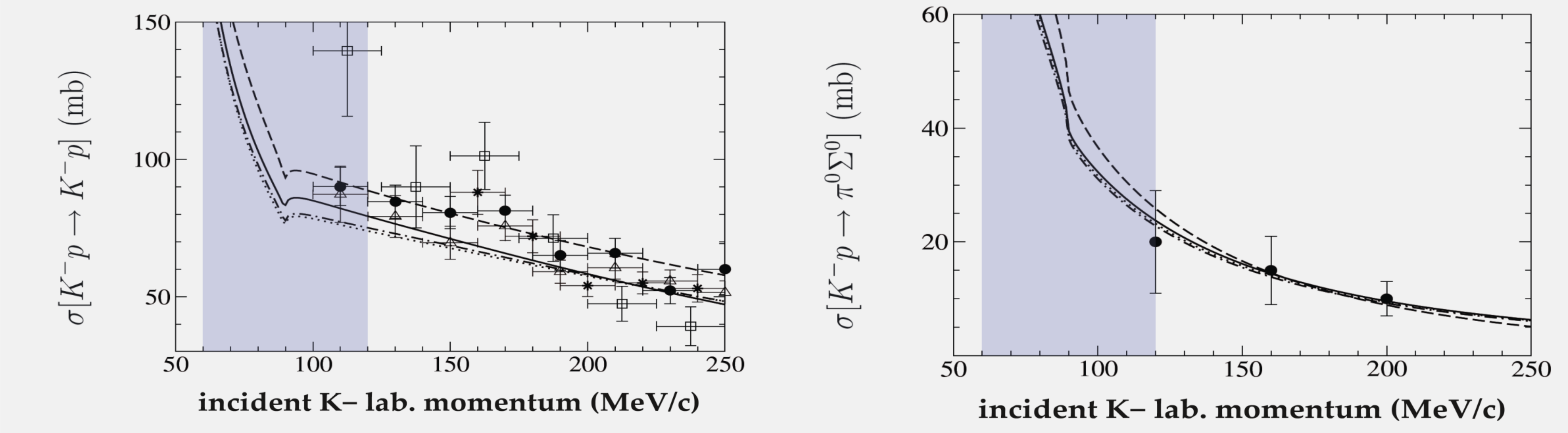


Uncertainty in electron screening. Gamma-ray contamination(Pb,W).

→ **new measurement with low-Z gas targets**

KNScat: KAON-NUCLEON SCATTERING

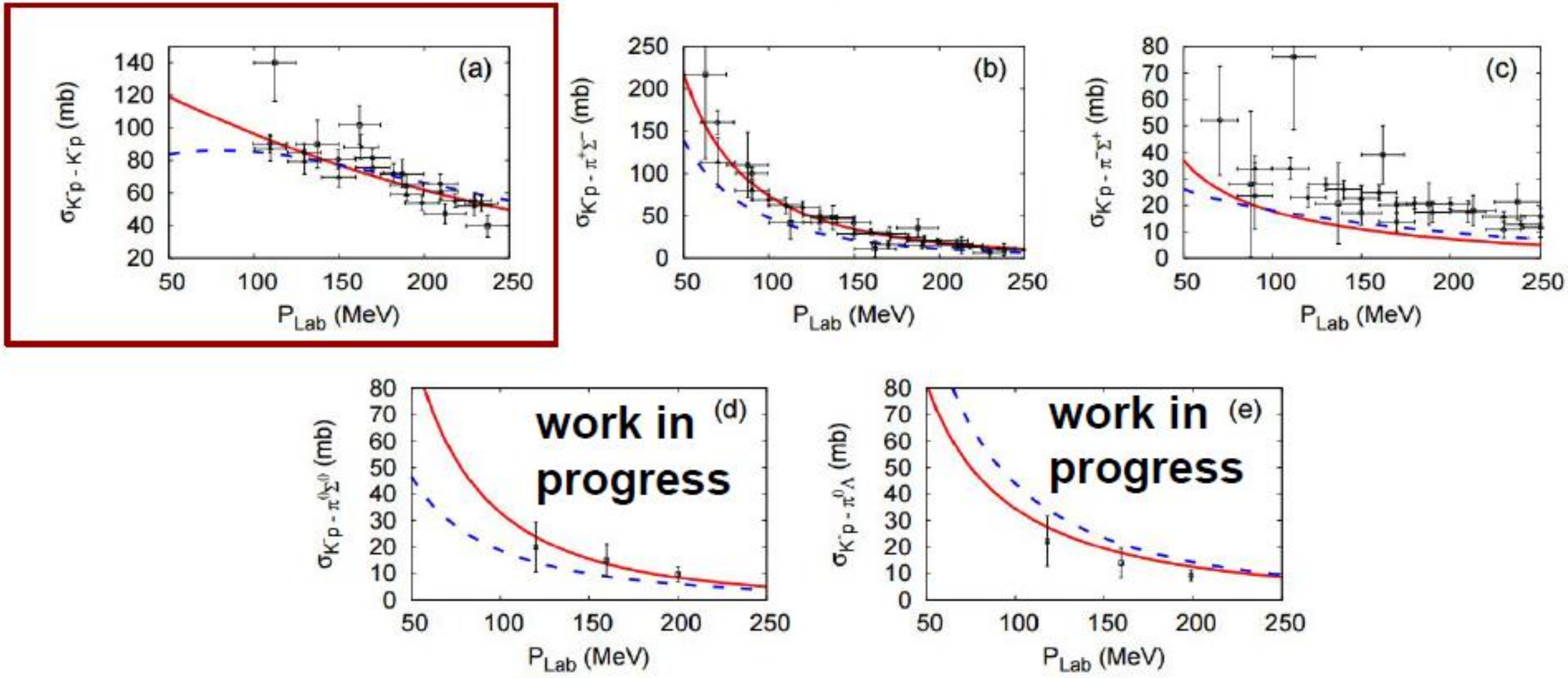
- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited.
- Below 150 MeV/c there is a “desert” - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.
- Kaon-nucleon scattering data are fundamental to validate theories: chiral symmetries; lattice calculations; potential models etc.



$K^{-}N$ elastic and inelastic scatterings for p_K < 100 MeV/c

The parameters of the models are constrained by the existing scattering data

- - - - **Phen.** [Y. Ikeda and T. Sato, Phys. Rev. C76, 035203 (2007)]
—— **Chiral** [S. Ohnishi, Y. Ikeda, T. Hyodo, W. Weise, Phys.Rev. C93 (2016) no.2, 025207]



KAON-NUCLEON SCATTERING

GOAL

Measuring the particle resulting from the scattering processes on various targets (starting with hydrogen, deuterium, helium-3 and helium-4) with low momenta.

DETECTOR

Measuring scattering processes at low energy represents a big experimental challenge. Therefore, we will develop in the framework of the

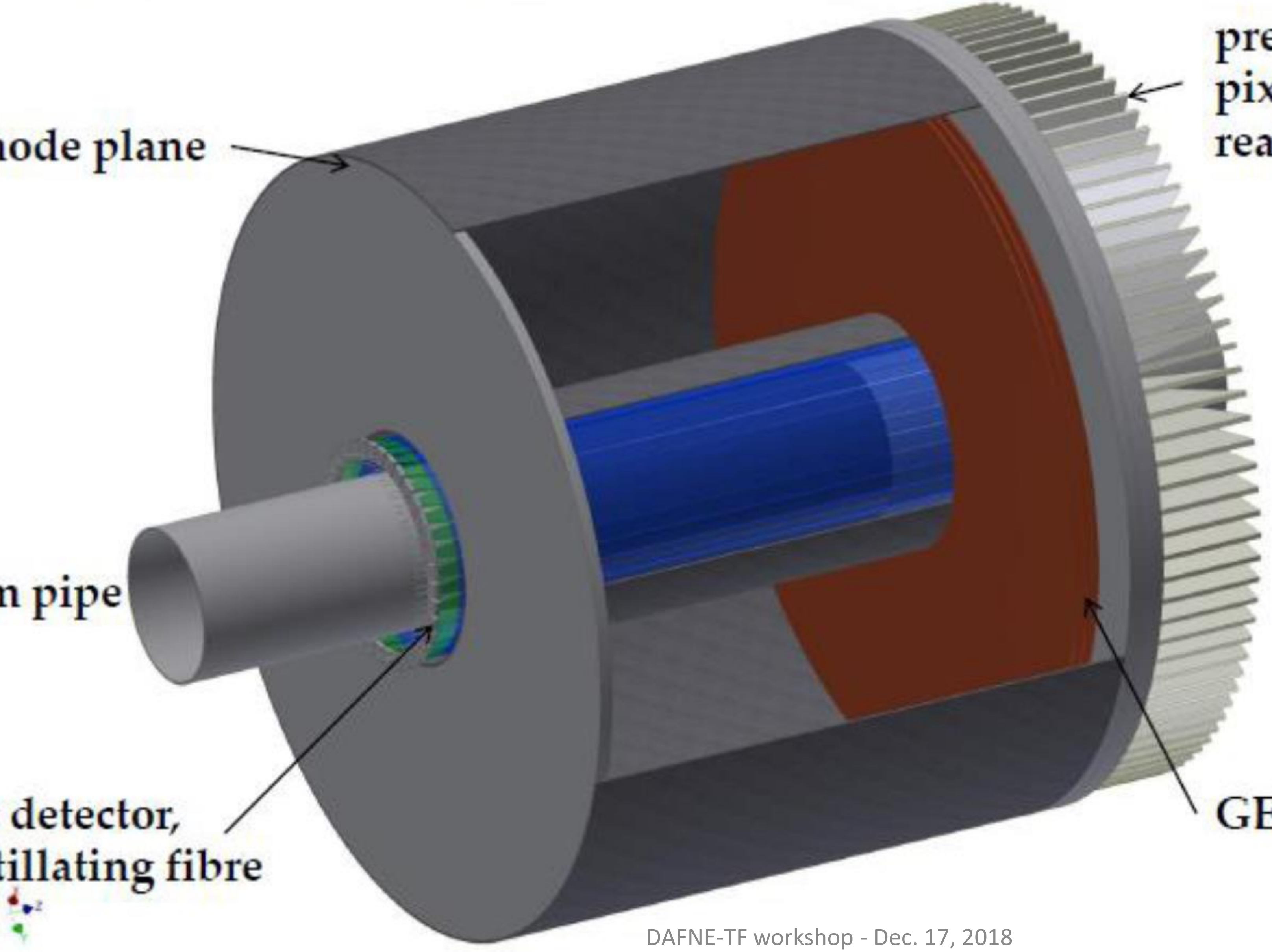
EU programme Horizon 2020, project STRONG2020,

an active Time Projection Chamber (TPC), which will allow to study the kaon interaction directly in the TPC, without additional material.

Scintillator tiles will surround the TPC for charged particle tracking.

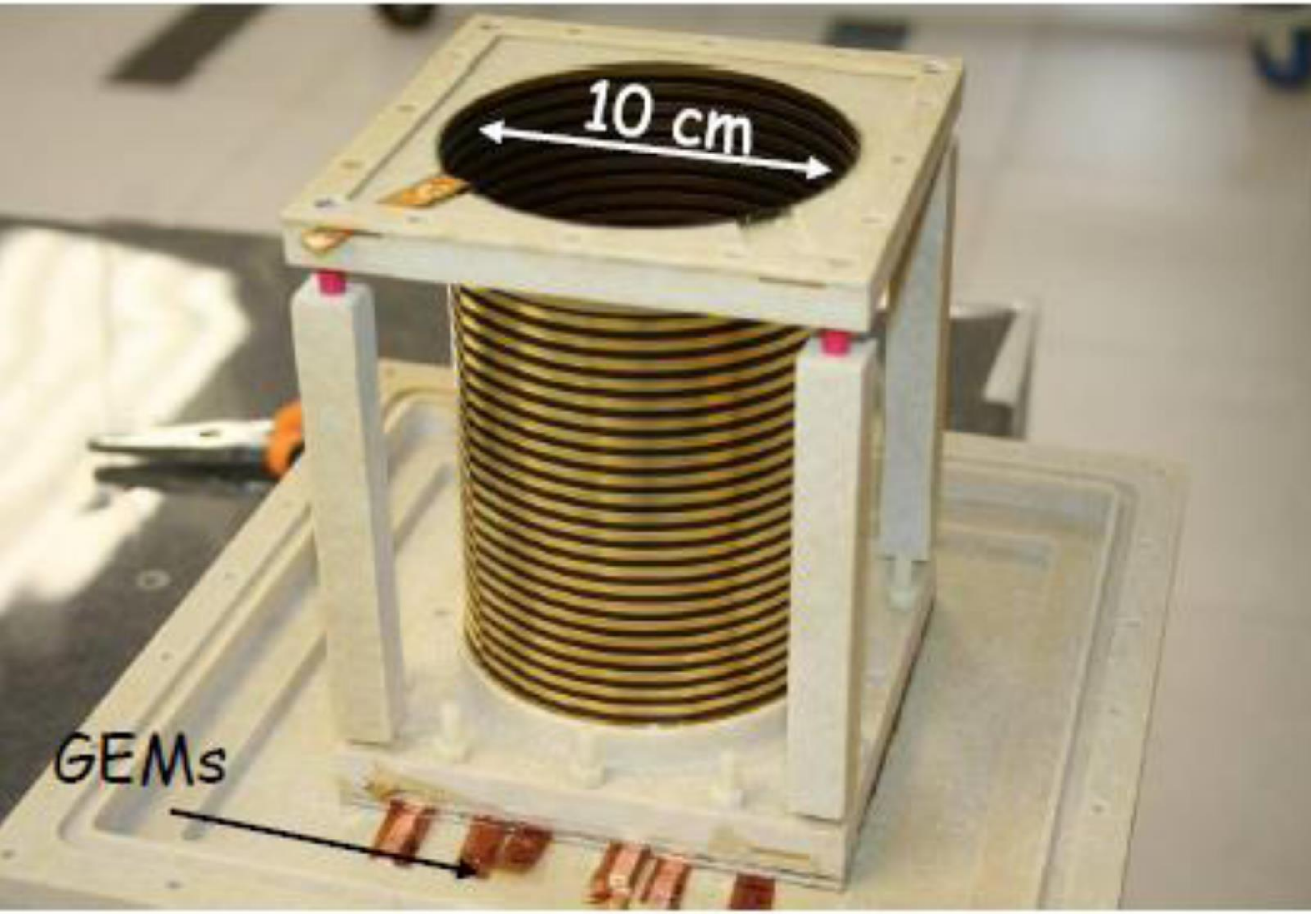
To study inelastic channels it is necessary to the detect neutrons as well as gammas; a new detector concept is under study.

- **active target TPC with GEM technology, with 6000 pads**
  - R&D work within EU-FP7 HadronPhysics3



ACTIVE TPC PROTOTYPE DEVELOPED AT LNF

within EU-FP7 HadronPhysics3



Performances of an Active Target GEM-Based TPC for the AMADEUS Experiment

Modern Instrumentation 4 (2015) 32-41

KAHEL: KAONIC HELIUM 1S TRANSITION

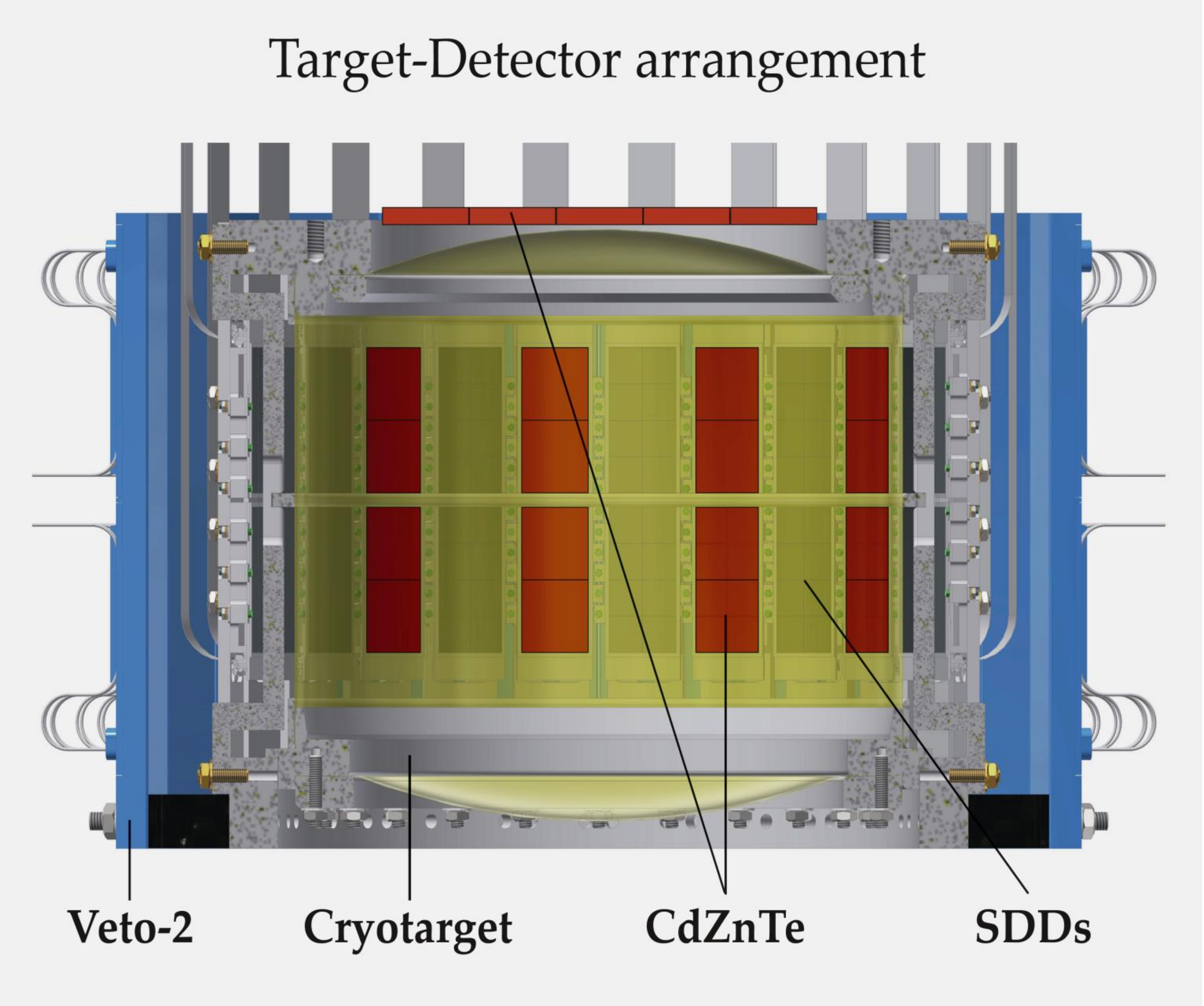
- Understanding of the antikaon-nucleon interaction has been substantially deepened by the most recent kaonic-hydrogen atom measurement, however, the depth of kaon-nucleus potential remains still unknown because of insufficient kaonic-atom data for Z > 1. Up to now, measurements of ^{3}He and ^{4}He transitions were performed only to the 2p state.

- A measurement of the 1s state of kaonic helium has to deal with the much stronger influence of the strong interaction as compared to measurements of the 2p state: the X-ray transition yield is expected to be more than 100 times smaller, while the width is about 1000 times larger.

KAONIC HELIUM 1S TRANSITION

Such a demanding experiment needs an improved detector system made of CdTe/CdZnTe-detectors with high X-ray efficiency at 30 keV.

CdTe/CdZnTe will be developed within a JRA, called ASTRA in the EU project STRONG2020.



Advanced ultra-fast solid **ST**atedetectors for high precision **Ra**diation spectroscopy - **ASTRA**

EU Project - STRONG2020

CdZnTe / CdTe detectors

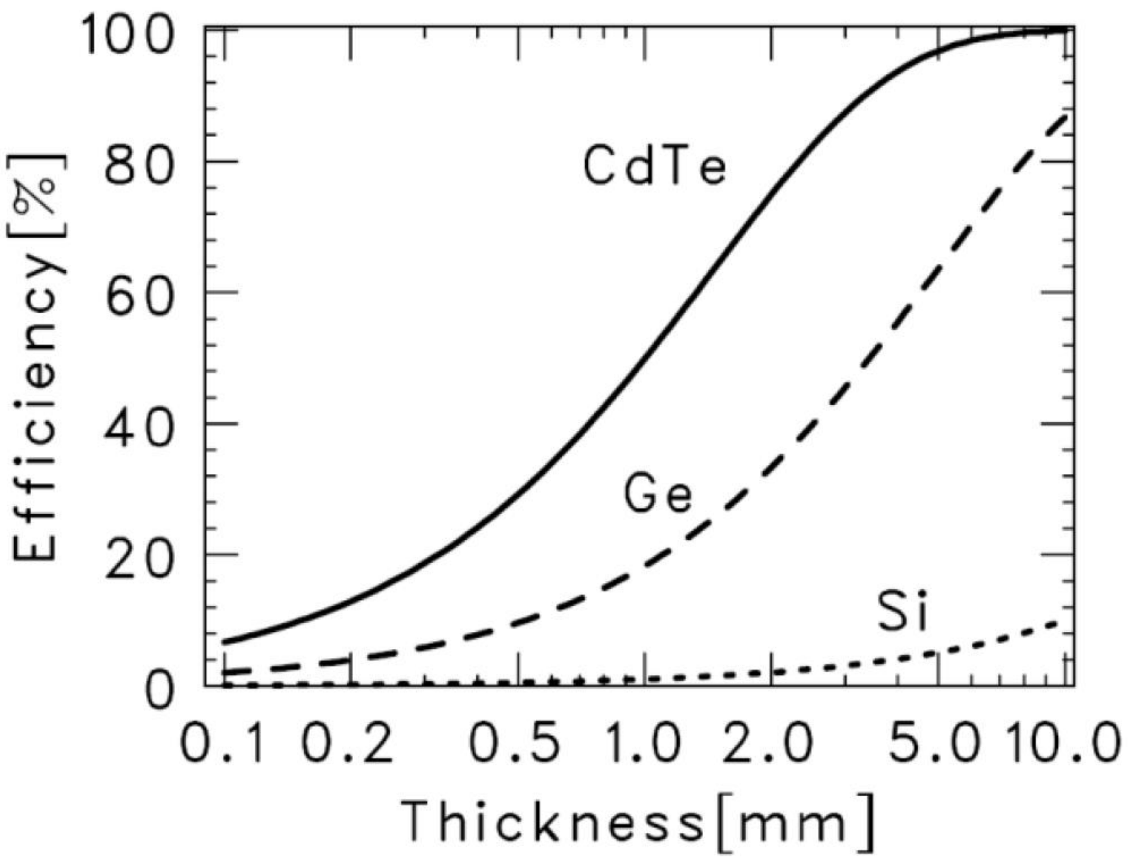
- efficient, compact due to their high density
- broad photon energy range (few keV - MeV)
- do not require cooling (RT operation)

GOAL to develop CdZnTe/CdTe detectors for high precision photon measurements, with customised read-out electronics

CdTe energy range up to 50 keV, resolution 500 eV (FWHM) @ 20 keV

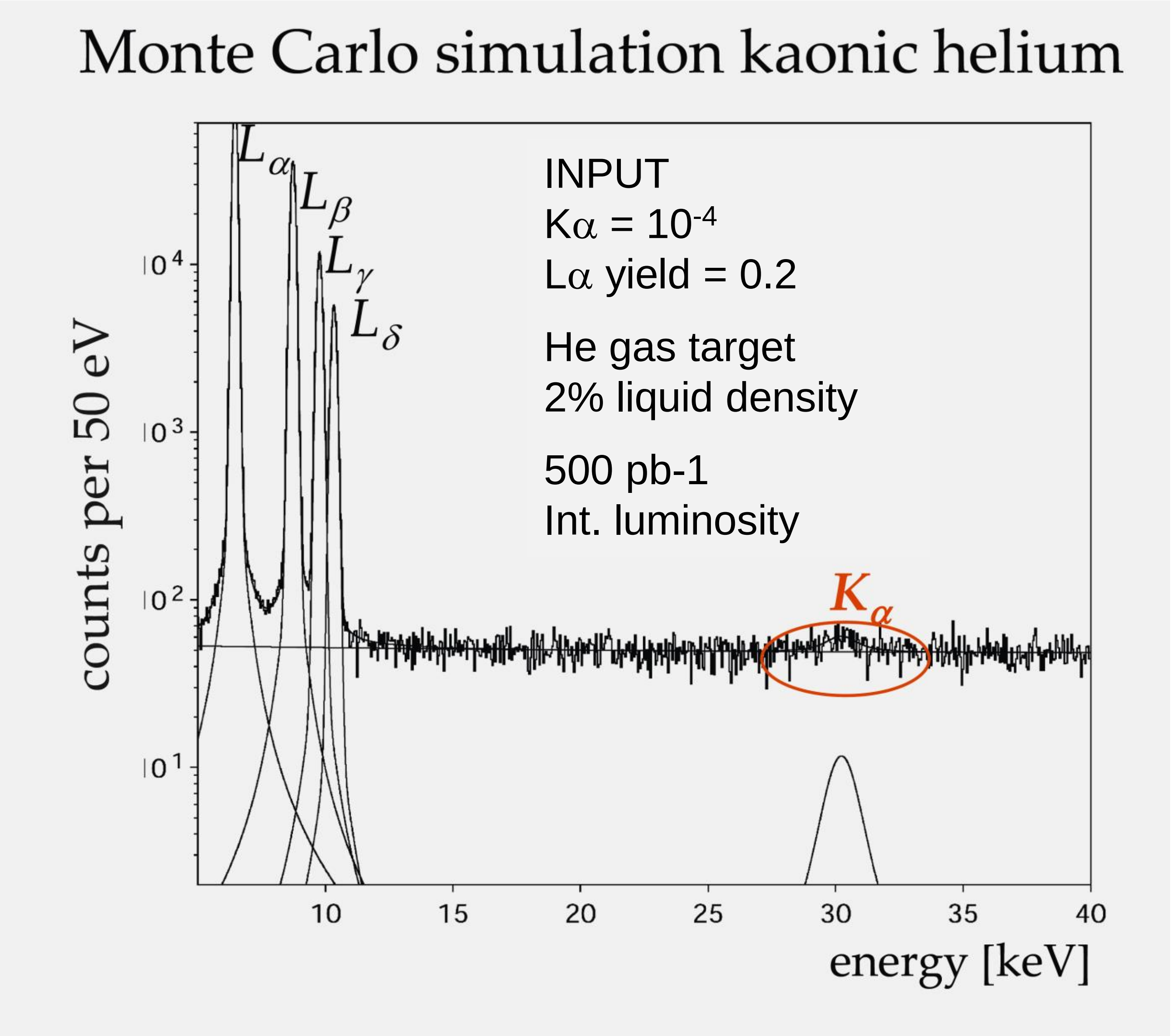
CdZnTe energy range 0.05 –1 MeV, resolution 1 keV (FWHM) @ 200 keV

Detection efficiency for 100 keV photons



KAONIC HELIUM 1S TRANSITION –

Monte Carlo simulation for the sketched setup were carried out and have shown that with the assumption on X-ray
Kα yield = 10^{-4}
Kα width =1000 eV
precision in determination of
shift ~ 100 eV
width ~ 300 eV



CONCLUSION

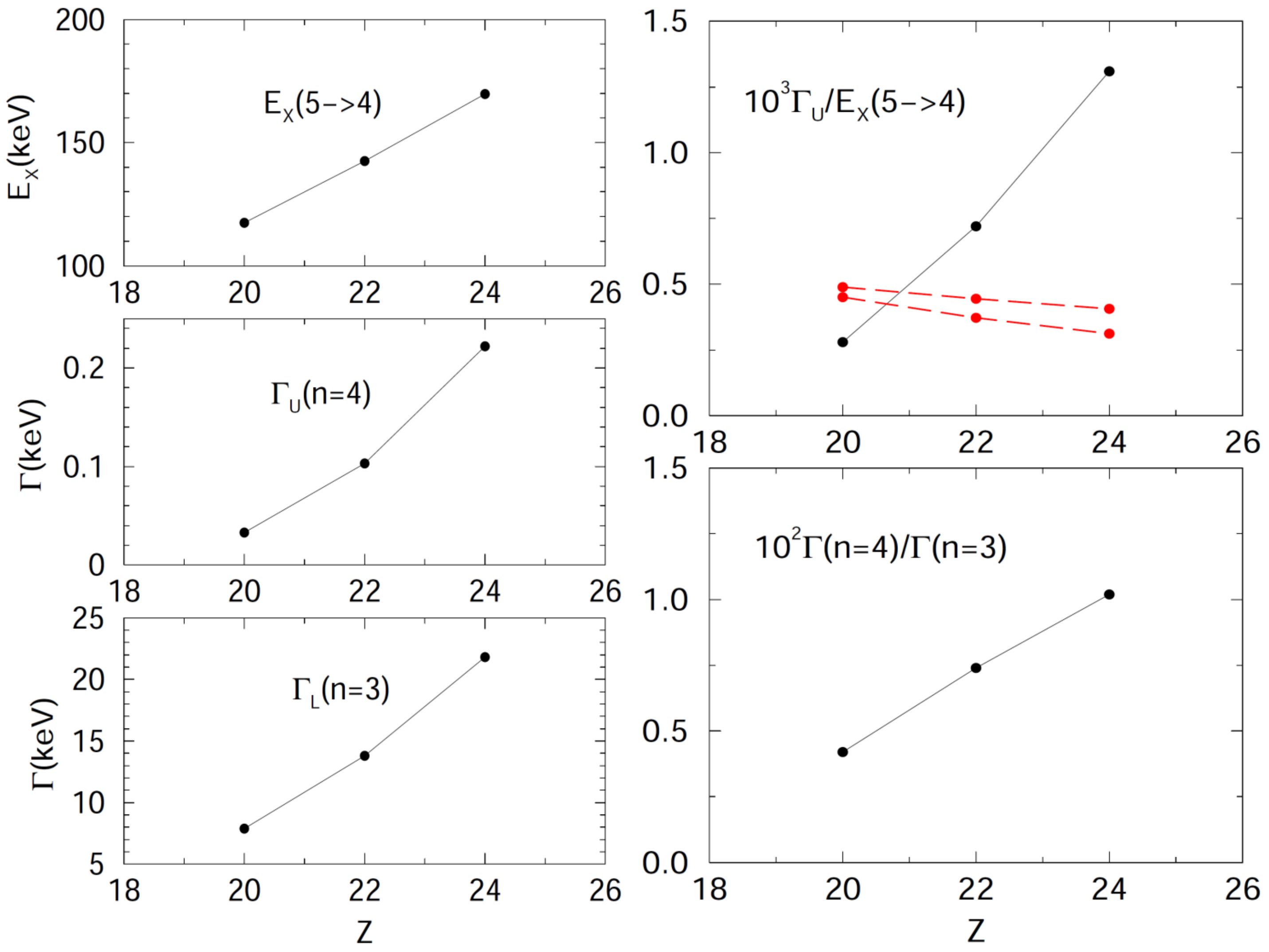
Strangeness precision frontier offers a unique opportunity for measurements from kaonic atoms to kaon-nuclei interactions at DAFNE-TF

- with the goal to understand processes going from chiral symmetry breaking to neutron stars EOS which cannot be obtained otherwise

A strong international community is putting forward a programme to perform these experiments, with support from National and European projects


HAPPY 80th BIRTHDAY
DEAR CARLO,
THANK YOU VERY MUCH FOR HAVING INITIATED THIS
RESEARCH AT DAFNE, FOR ALL YOUR
CONTINUOUS EFFORT, SUPPORT
AND
THE MANY INSPIRING
DISCUSSIONS AND ADVICES!
WE WISH YOU ALL THE BEST AND LOOK FORWARD TO AN
EXCITING AND FRUITFUL TIME TOGETHER!

KAON SINGLE- AND MULTINUCLEON PROCESSES



X-ray energy of the transition feeding into the upper level.

Calculated strong-interaction widths of lower (3d) and upper (4f) levels

Ratios of the upper level width to the energy of the transition into that level (x10^3).

Ratios of upper to lower level widths (x10^2).