High precision measurements of kaonic atoms

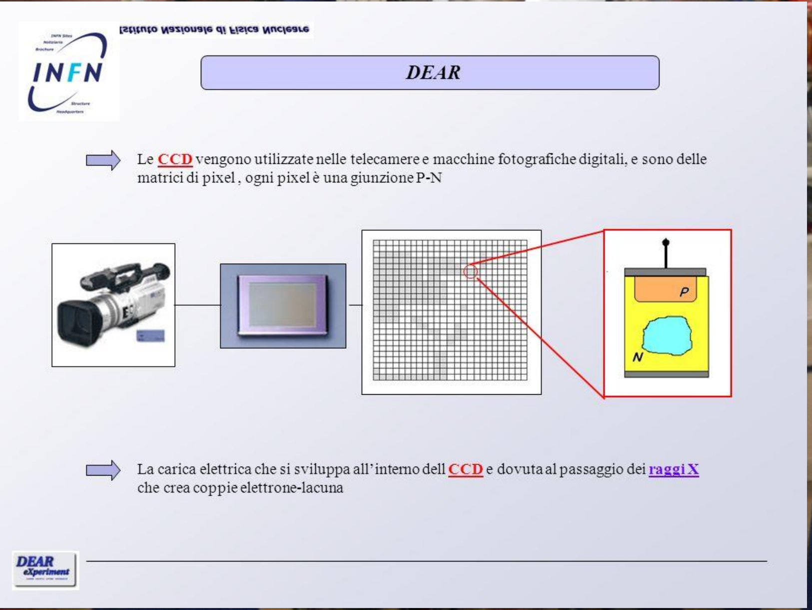
Catalina Curceanu, LNF-INFN (Italy)

STRONG 2020

High Precision measurements of kaonic atoms Symposium, 9th February 2022

Kaonic atoms spectroscopy: at DAFNE

A long story started in….last century…



PHYSICS LETTERS B

Physics Letters B 535 (2002) 52–58

www.elsevier.com/locate/npe

A new method to obtain a precise value of the mass of the charged kaon

G. Beer[b], A.M. Bragadireanu[c,e], W. Breunlich[a], M. Cargnelli[a], C. Curceanu (Petrascu)[c,e], J.-P. Egger[g], H. Fuhrmann[a], C. Guaraldo[c,*], M. Giersch[a], M. Iliescu[c,e], T. Ishiwatari[d], K. Itahashi[d], B. Lauss[h], V. Lucherini[c], L. Ludhova[f], J. Marton[a], F. Mulhauser[f], T. Ponta[e], A.C. Sanderson[b], L.A. Schaller[f], D.L. Sirghi[c,e], F. Sirghi[c], J. Zmeskal[a]

$(6\rightarrow5)$ transition: $M_{K^-} = 492.086 \pm 2.409$ MeV,

$(7\rightarrow6)$ transition: $M_{K^-} = 495.418 \pm 3.455$ MeV.

These two results are statistically compatible and can be averaged. The weighted average is $M_{K^-} = 493.176 \pm 1.976$ MeV.

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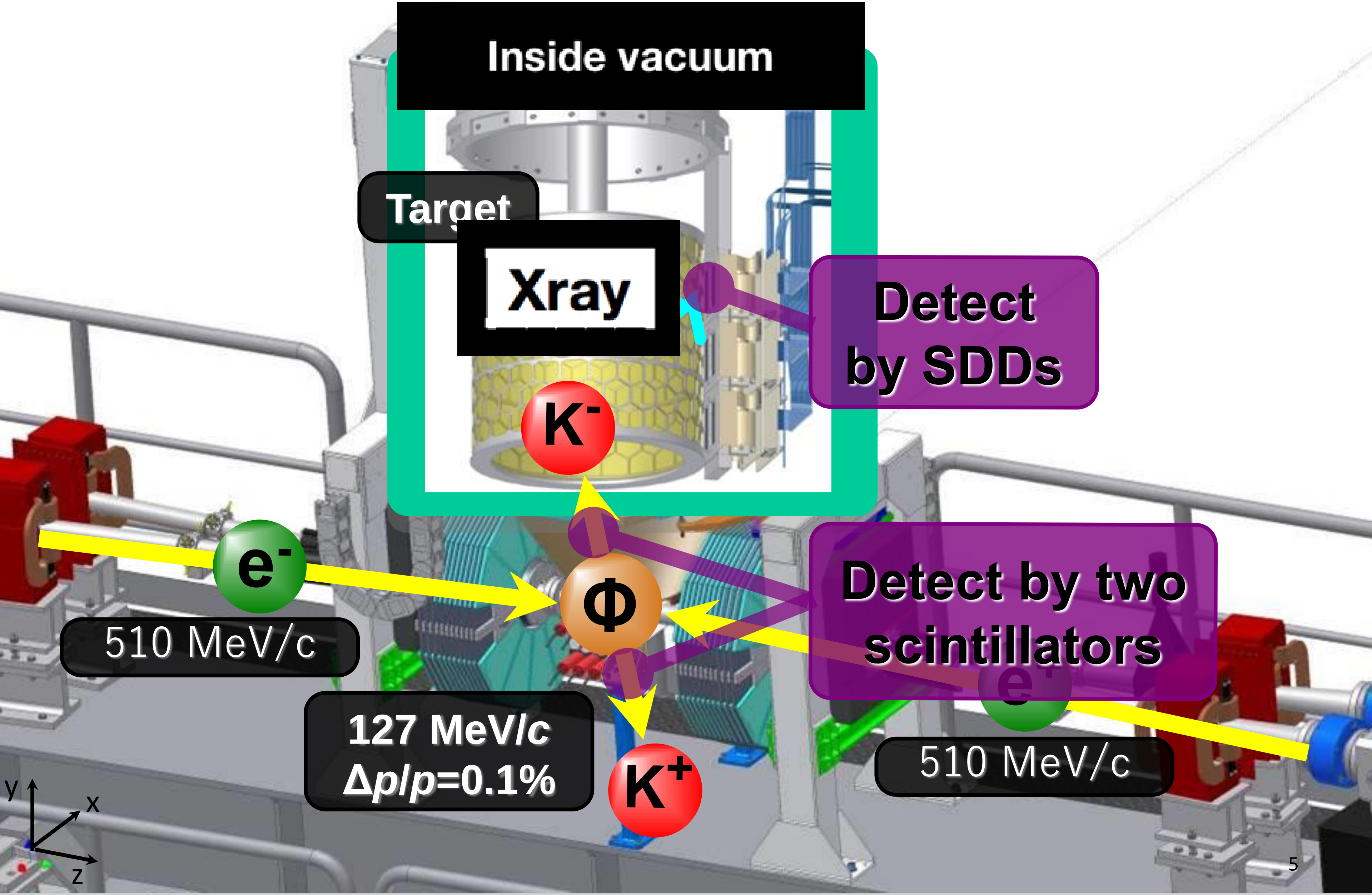
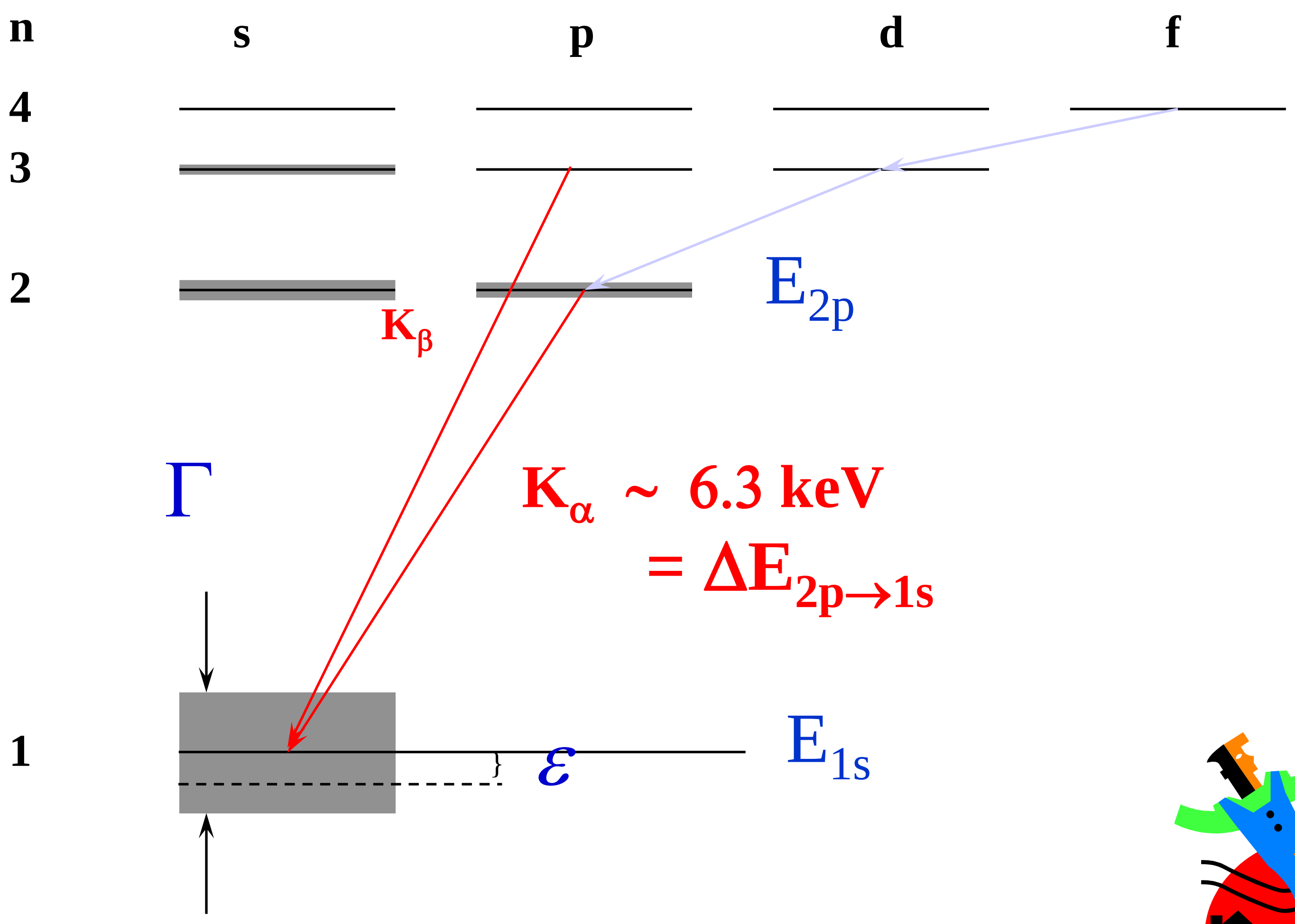
SIDDHARTA overview



Kaonic cascade and the strong interaction



The (main) scientific aim

the determination of the ***isospin dependent***
KN scattering lengths through a
–

~ precision measurement of the shift
and *of the width*

of the K_{α} line of **kaonic hydrogen**

and

of **kaonic deuterium**

Measurements of kaonic Helium 3 and 4 as well (2p level)
And other types of exotic atoms

Antikaon-nucleon scattering lengths

Once the shift and width of the 1s level for kaonic hydrogen and deuterium are measured -) scattering lengths

(isospin breaking corrections):

$$\varepsilon + i\,\Gamma/2 \Rightarrow a_{K^-p}\ \mathrm{eV\ fm^{-1}}$$

$$\varepsilon + i\,\Gamma/2 \Rightarrow a_{K^-d}\ \mathrm{eV\ fm^{-1}}$$

one can obtain the isospin dependent antikaon-nucleon scattering lengths

$$a_{K^-p} = (a_0 + a_1)/2$$

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

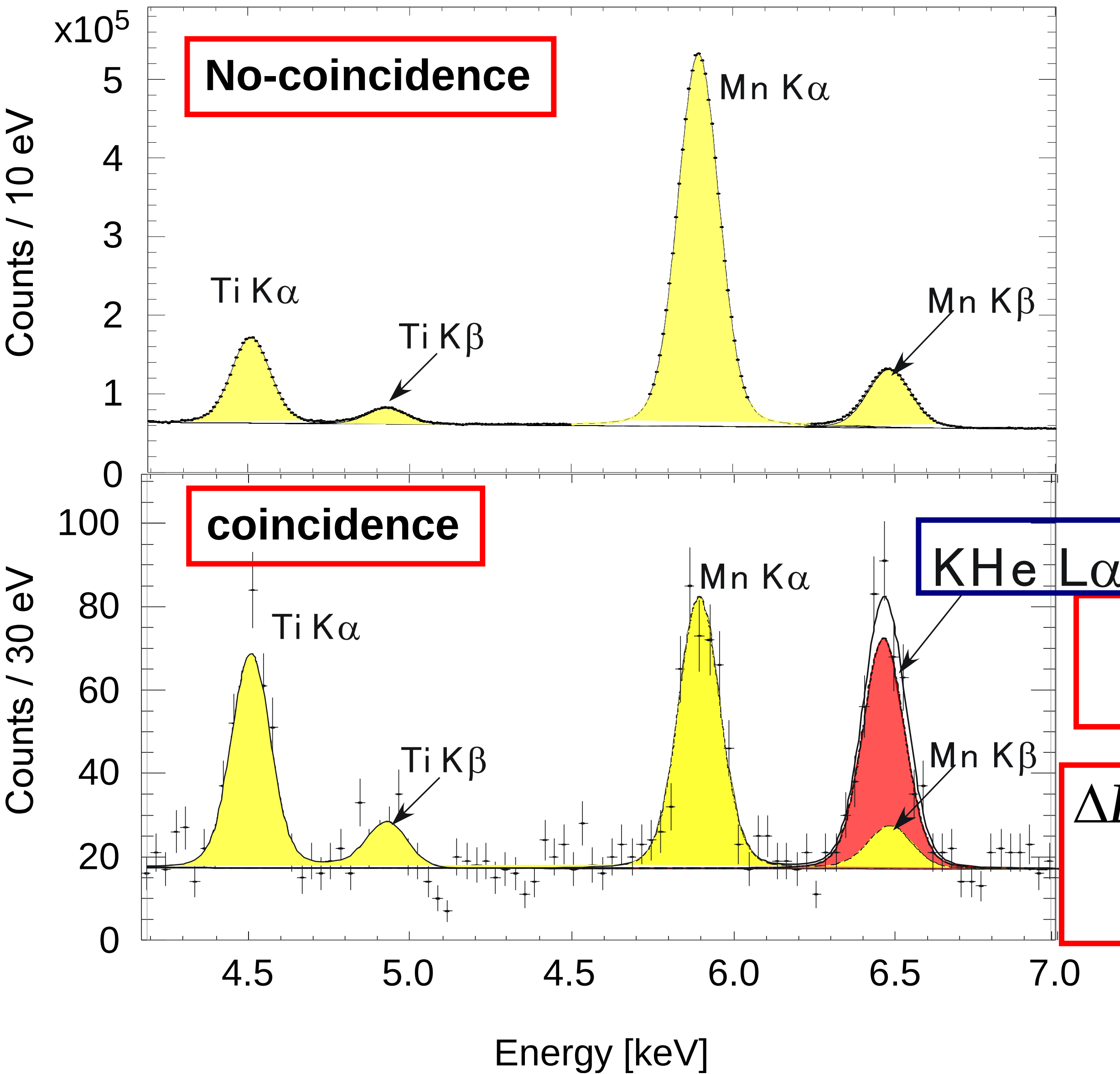
Kaonis atoms are fundamental tools for understanding QCD in non-perturbative regime:

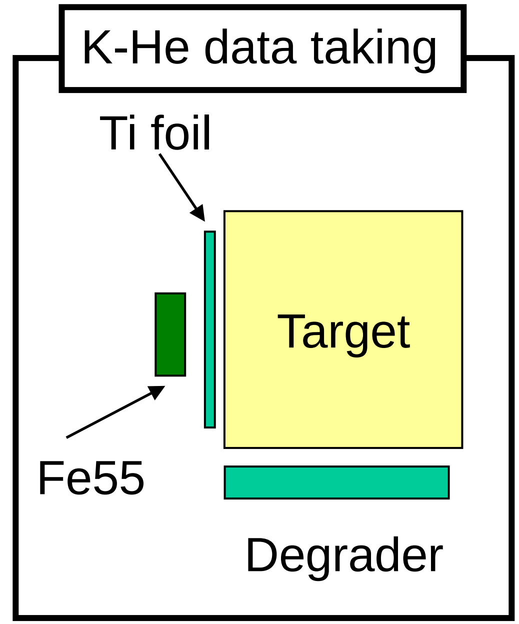
- **Explicit and spontaneous chiral symmetry breaking (mass of nucleons)**
- **Dense baryonic matter ->**
- **Neutron (strange?) stars EOS**

Role of Strangeness in the Universe from particle and nuclear physics to astrophysics

KHe-4 energy spectrum at SIDDHARTA

PLB681(2009)310; NIM A 628(2011)264

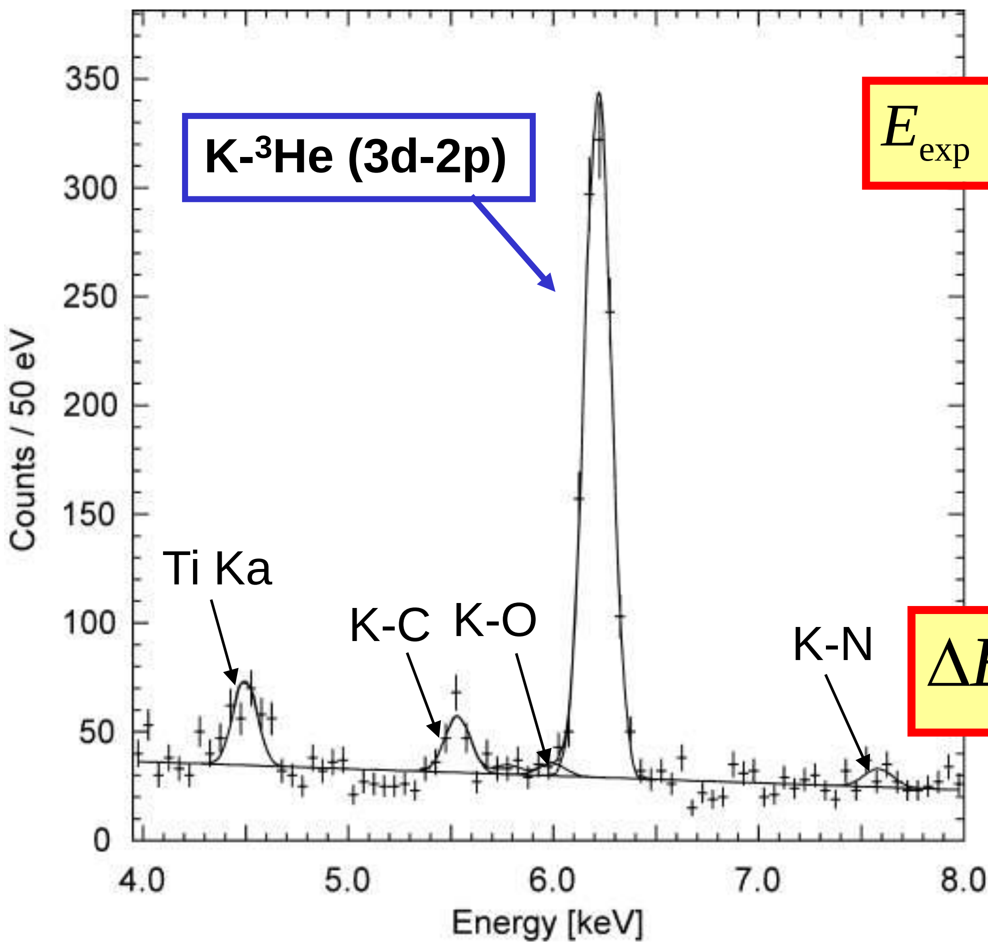




$$E_{\mathrm{exp}} = 6463.6 \pm 5.8 \text{ eV},$$

$$\Delta E = E_{\mathrm{exp}} - E_{e.m.}$$
$$= 0 \pm 6(\mathrm{stat}) \pm 2(\mathrm{syst})\,\mathrm{eV}$$

Kaonic Helium-3 energy spectrum



X-ray energy of K-3He 3d-2p

$$E_{exp} = 6223.0 \pm 2.4(sta) \pm 3.5(sys)\ \text{eV}$$

QED value: $E_{e.m.} = 6224.6\ \text{eV}$

$$\Delta E_{2p} = E_{exp} - E_{e.m.}$$

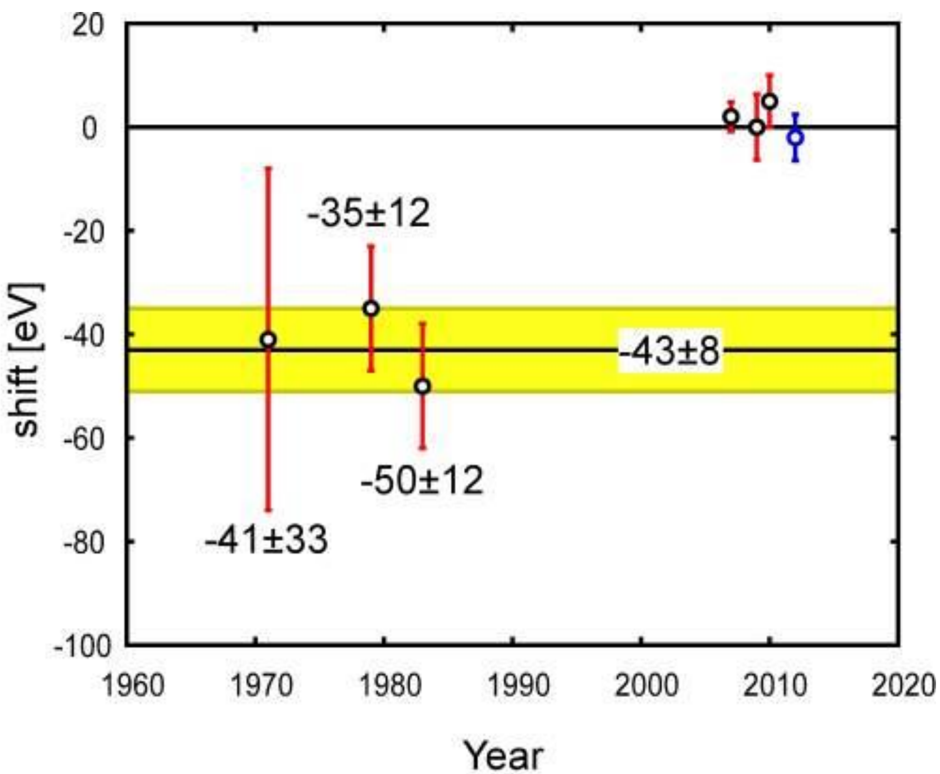
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

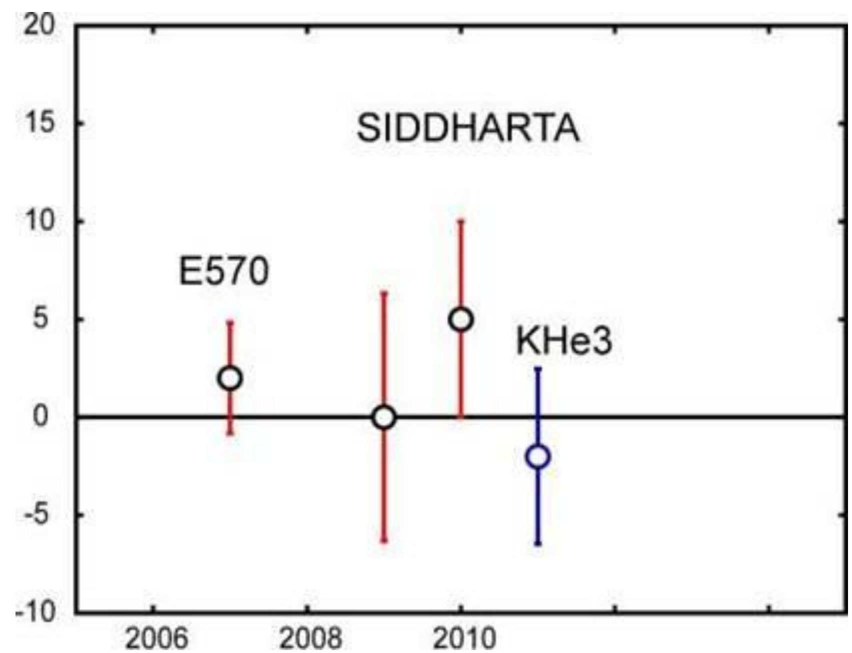
World First !
Observation of K-^{3}He X-rays
Determination of
strong-interaction shift

arXiv:1010.4631v1 [nucl-ex], PLB697(2011)199

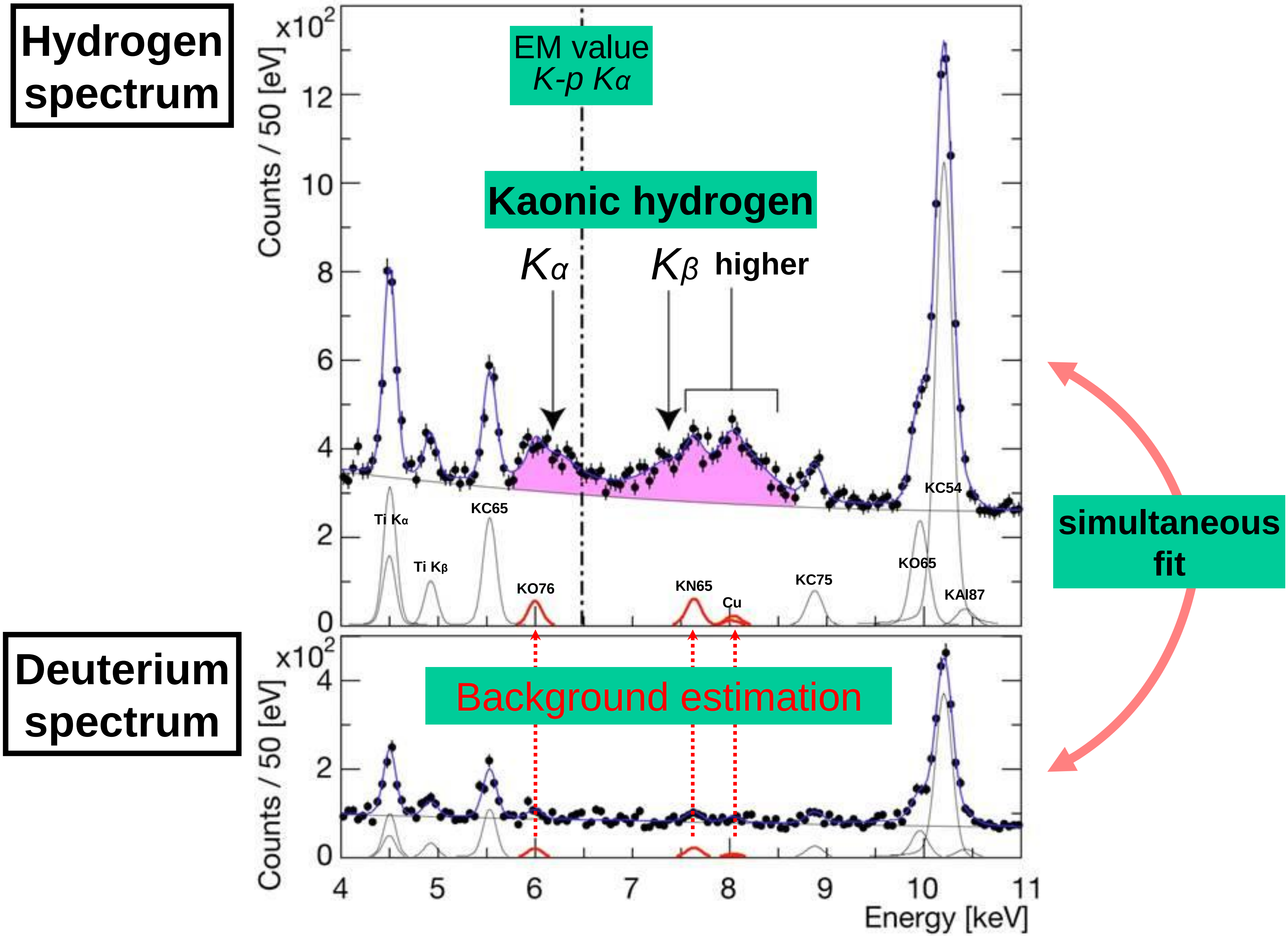
Comparison of results

	Shift [eV]	Reference
KEK E570	+2±2±2	PLB653(07)387
SIDDHARTA (He4 with 55Fe)	+0±6±2	PLB681(2009)310
SIDDHARTA (He4)	+5±3±4	arXiv:1010.4631, PLB697(2011)199
SIDDHARTA (He3)	-2±2±4	





***error bar** $= \pm\sqrt{(stat)^2 + (syst)^2}$

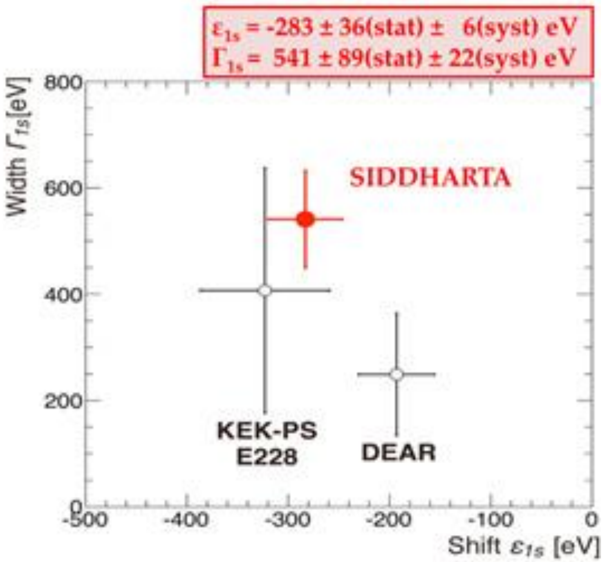


Hydrogen spectrum
Deuterium spectrum
EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ
higher
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87
simultaneous fit
Background estimation
Counts / 50 [eV]
x10²
Energy [keV]

KAONIC HYDROGEN results

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

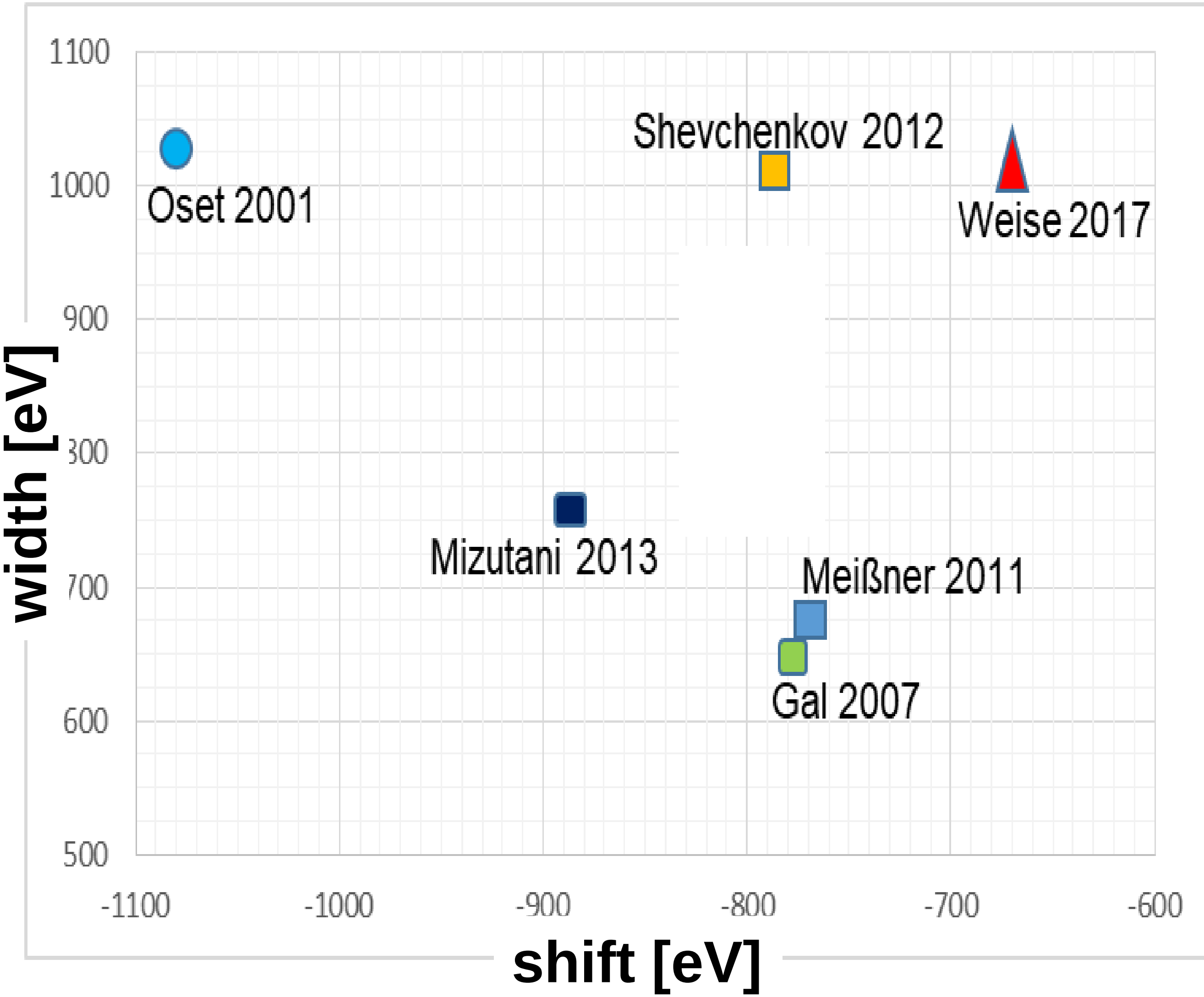
$$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV}$$



Phys. Lett. B 704 (2011) 113

SIDDHARTA-2
Kaonic Deuterium

Theory for kaonic deuterium

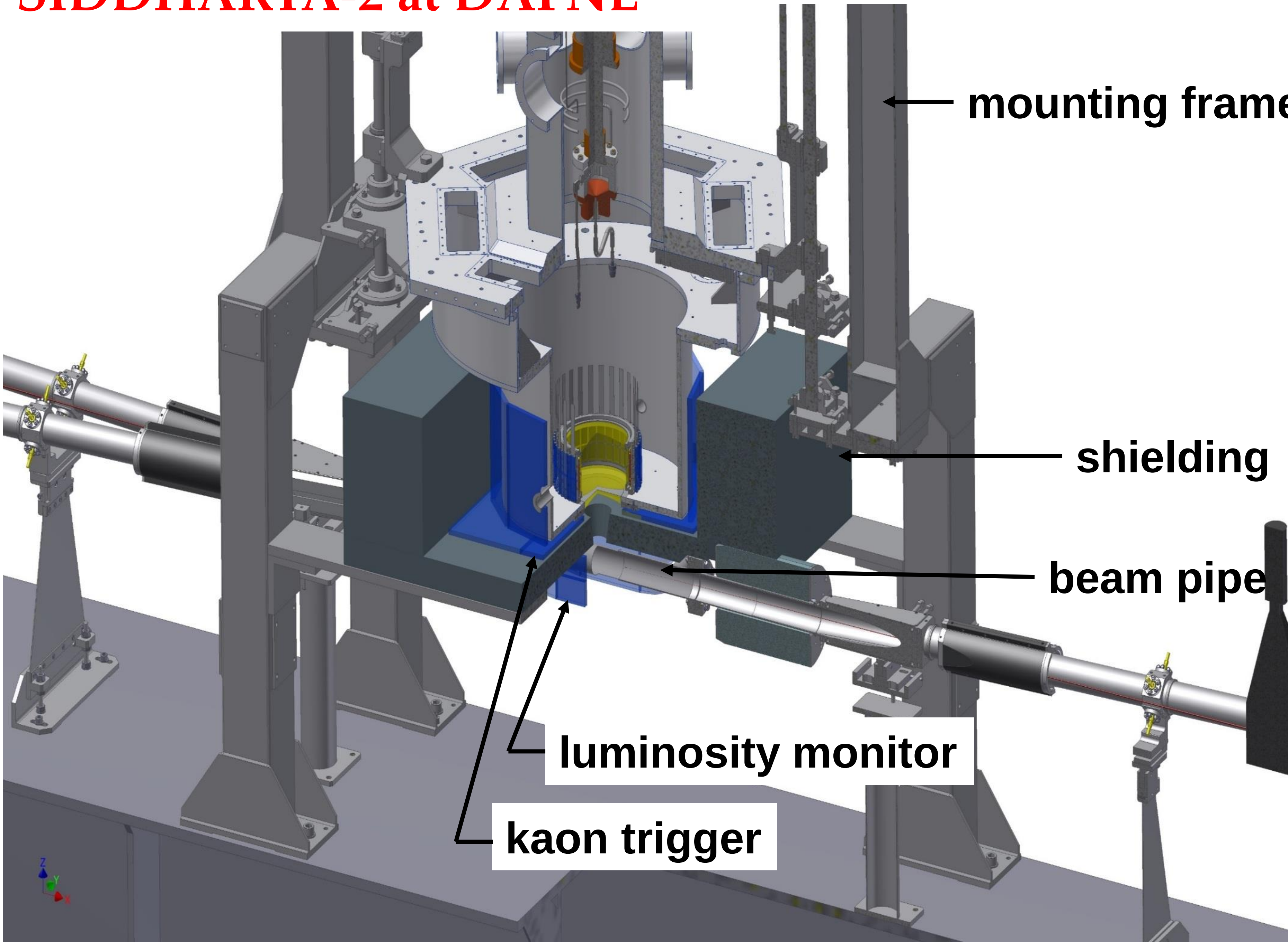


SIDDHARTA-2 Collaboration

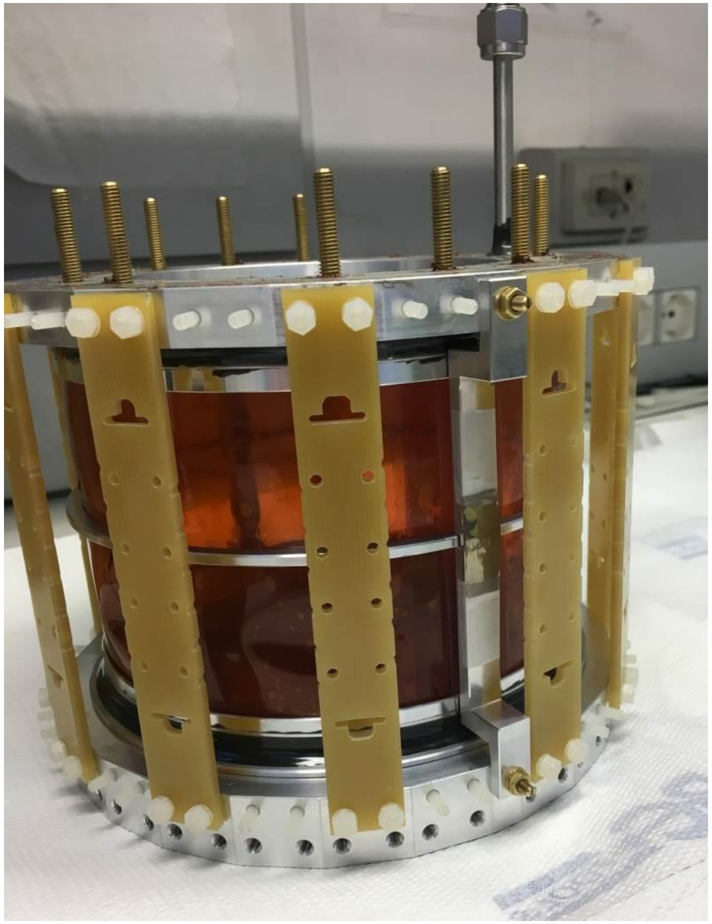
Silicon **D**rift **D**etectors for **H**adronic **A**tom **R**esearch by **T**iming **A**pplication

- LNF-INFN, Frascati, Italy
- SMI-ÖAW, Vienna, Austria
- Politecnico di Milano, Italy
- IFIN -HH, Bucharest, Romania
- TUM, Munich, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada
- Univ. Zagreb, Croatia
- Univ. Jagiellonian Krakow, Poland
- ELPH, Tohoku University

SIDDHARTA-2 at DAFNE



Light target and Silicon Drift Detector assembly

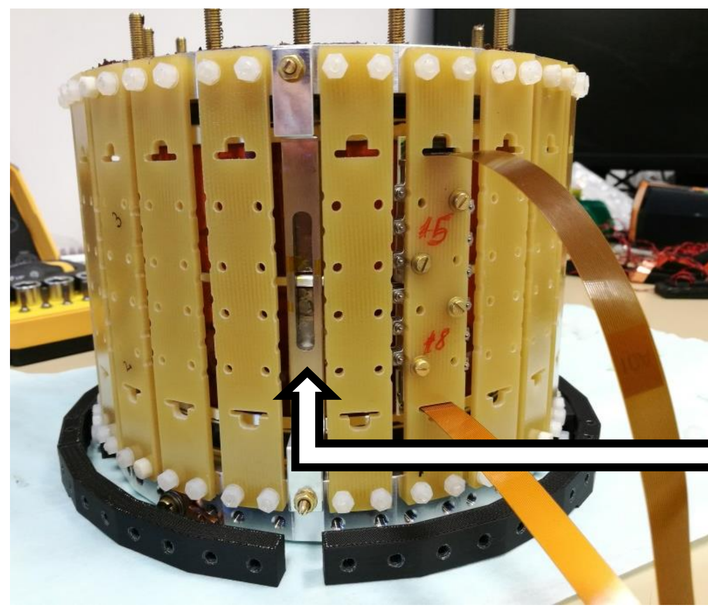


increase the target stopping power

almost double gas density with respect to SIDDHARTA (3% LHD)

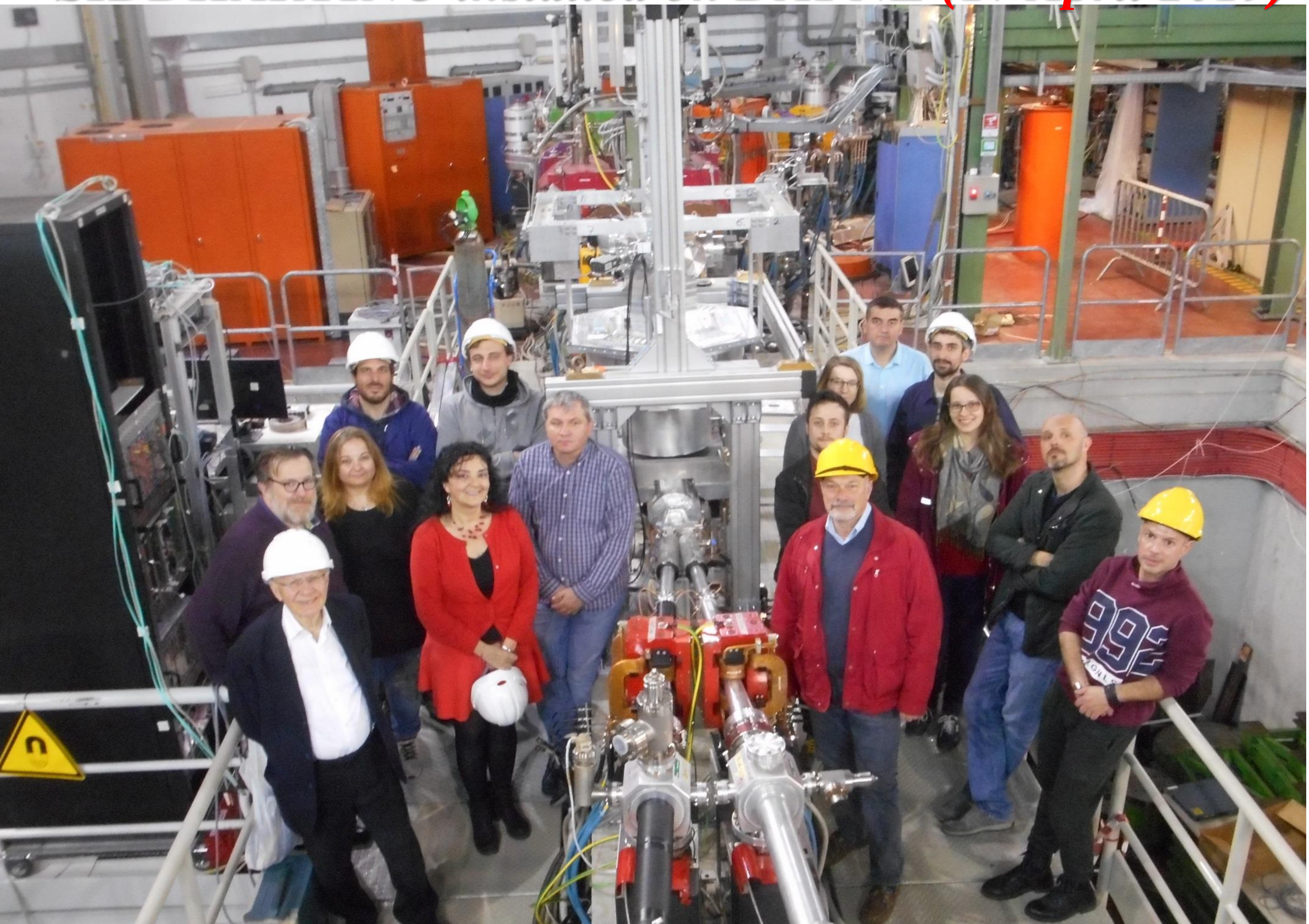
SDDs placed 5 mm from the target wall

Target cell wall is made of a 2-Kapton layer structure (75 µm + 75 µm + Araldit)

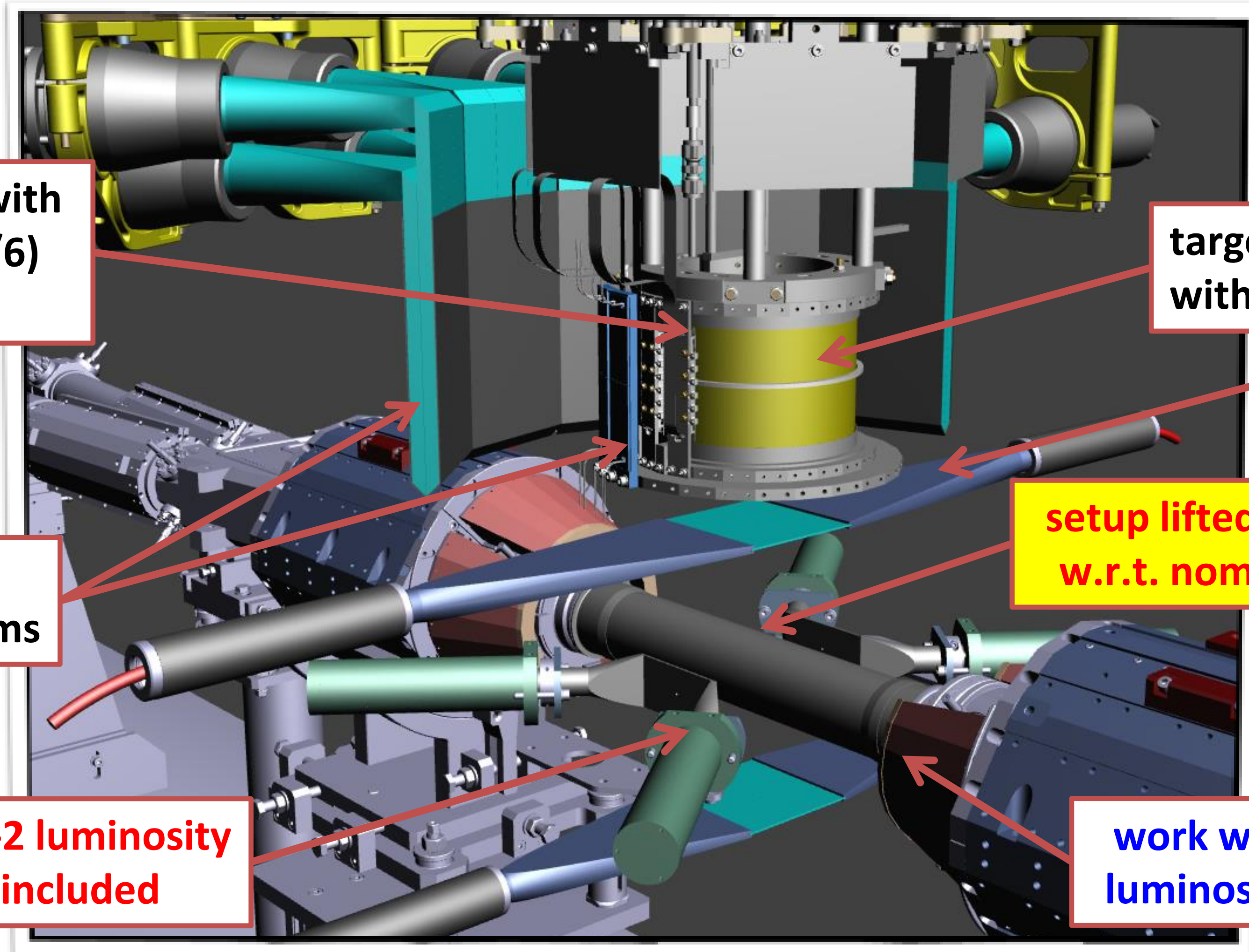


calibration foils inserted near to the SDD are activated by the X-ray tubes

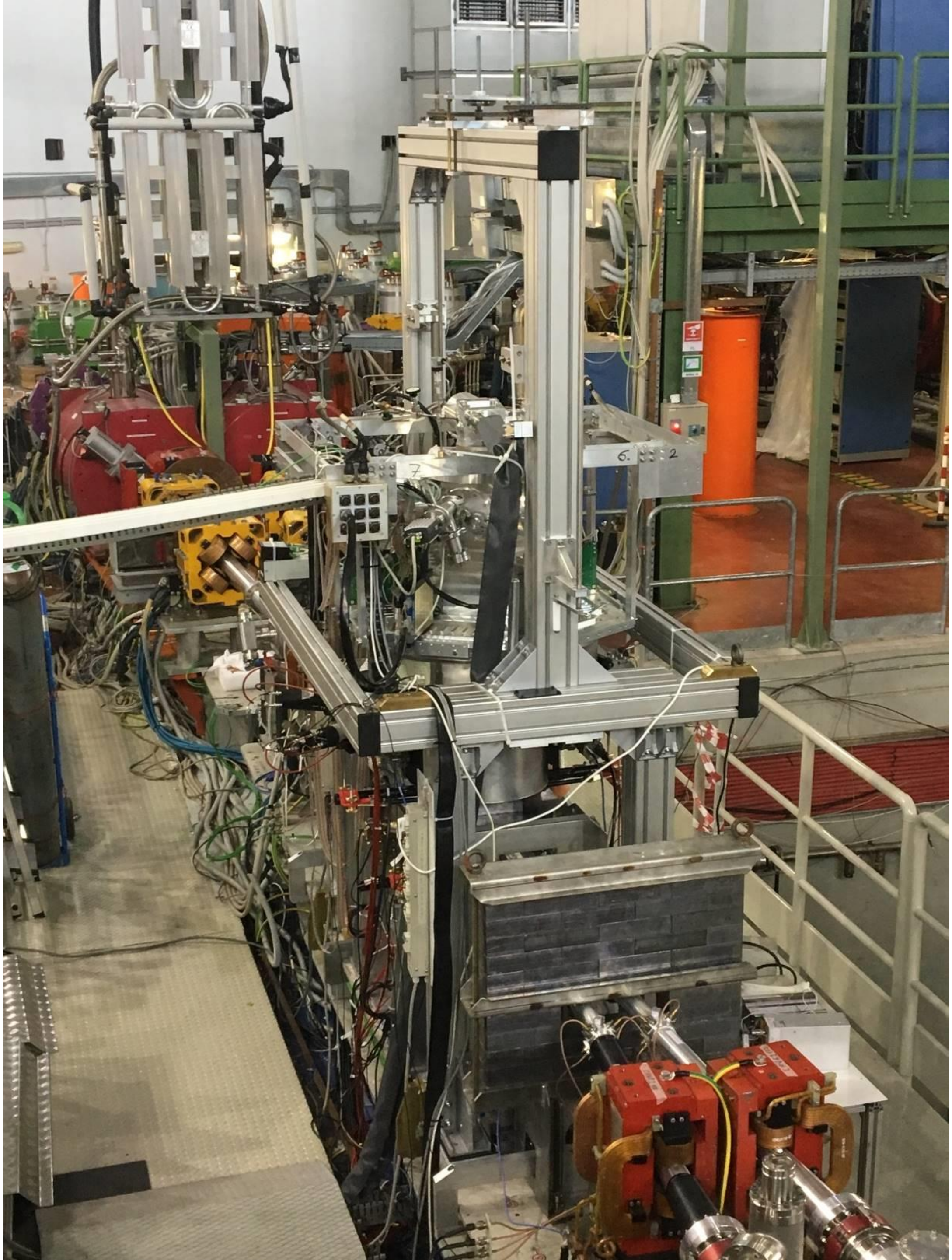
SIDDHARTINO installed on DAFNE (17 April 2019)



SIDDHARTINO apparatus and constraints



Aim: confirm when DAΦNE background conditions are similar to those in SIDDHARTA 2009



SIDDHARTA-2 timeline

Machine restart
Detectors working point...

Restart SIDDHARTINO (after 1 year stop)

Early 2021

Software and hardware optimization back. reduction

SIDDHARTINO optimization run

2021, till June

Optimization of degrader thickness and 2 different gas densities

SIDDHARTINO

K-^{4}He run

2021, 24 June – 18 July

Analysis of the SIDDHARTINO data.
Start SIDDHARTA-2 Installation

Start SIDDHARTA-2 installation: mechanics

2021, August

Installation of SDD, veto and electronics.
Update of the DAQ....

SIDDHARTA-2 Installation continued

September 2021 –January - 2022

Ready for run

March 2022

arXiv:2201.09735v1 [nucl-ex] 24 Jan 2022

A new kaonic helium measurement in gas by SIDDHARTINO at the DAΦNE collider

D Sirghi[1], F Sirghi[1], F Sgaramella[1*], M Bazzi[1], D Bosnar[2], M Bragadireanu[3], M Carminati[4], M Cargnelli[5], A Clozza[1], G Deda[4], L De Paolis[1], R Del Grande[1,6], L Fabbietti[6], C Fiorini[4], C Guaraldo[1], M Iliescu[1], M Iwasaki[7], P Levi Sandri[1], J Marton[5], M Miliucci[1], P Moskal[8], F Napolitano[1], S Niedźwiecki[8], K Piscicchia[9,1], A Scordo[1], H Shi[5], M Skurzok[8], M Silarski[8], A Spallone[1], M Tüchler[5], O Vazquez Doce[1], J Zmeskal[5] and C Curceanu[1]**

[1] Laboratori Nazionali di Frascati INFN, Via E. Fermi 54, 00044 Frascati, Italy
[2] Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia
[3] Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) Măgurele, Romania
[4] Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and INFN Sezione di Milano, Milano, Italy
[5] Stefan-Meyer-Institut für Subatomare Physik, Vienna, Austria
[6] Excellence Cluster Universe, Technische Universiät München Garching, Germany
[7] RIKEN, Tokyo, Japan
[8] Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland
[9] Centro Ricerche Enrico Fermi – Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Via Panisperna 89A 00184, Roma, Italy

E-mail: * `francesco.sgaramella@lnf.infn.it (Corresponding Author)`

E-mail: ** `alessandro.scordo@lnf.infn.it (Corresponding Author)`

January 2022

Submitted Journal of Phys G

Abstract.
The SIDDHARTINO experiment at the DAΦNE Collider of INFN-LNF, the pilot run for the SIDDHARTA-2 experiment which aims to perform the measurement of kaonic deuterium transitions to the fundamental level, has successfully been concluded. The paper reports the

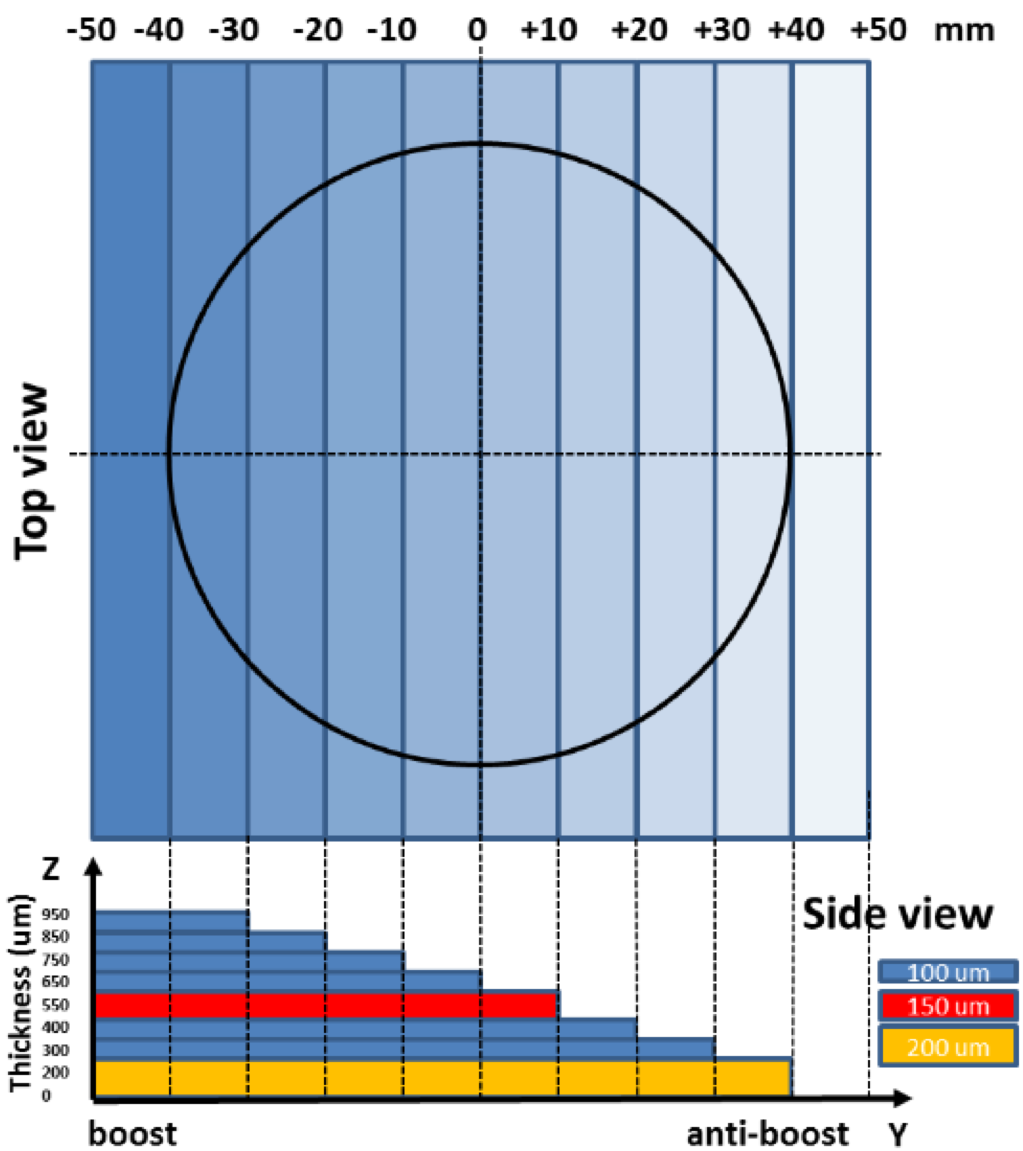


Figure 5: The final Mylar degrader configuration: the circle represents the size of the entrance window of the vacuum chamber; direction "Y" points to the outer side of the DAΦNE ring, corresponding to the anti-boost side for kaons. The degrader has eight steps to compensate for the boost effect, with thicknesses shown in the lower part of the figure.

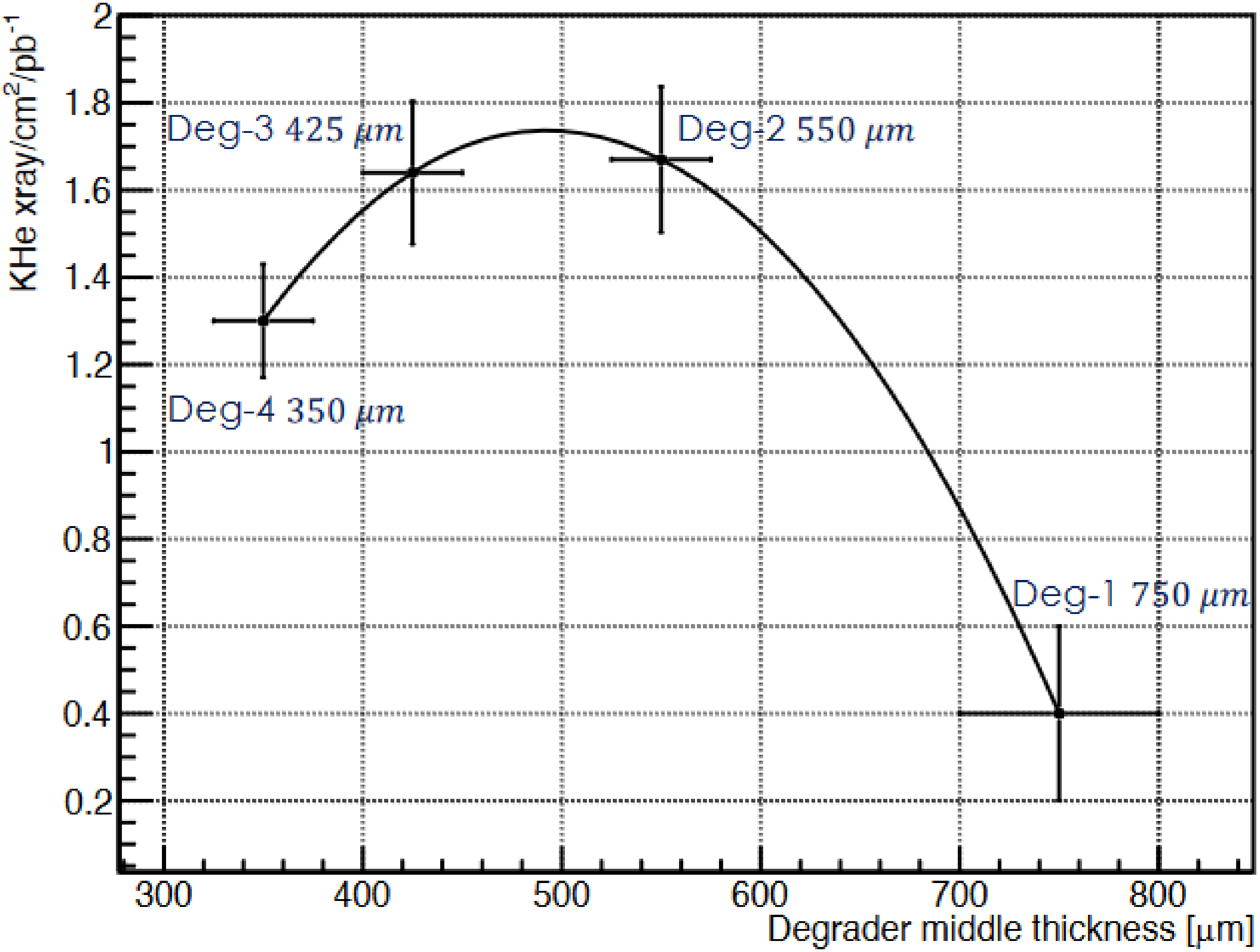


Figure 6: Degrader optimization curve: the horizontal axis is the central thickness and the vertical one the corresponding $K^4He(3d \rightarrow 2p)$ signal normalized by integrated luminosity and effective detection surface.

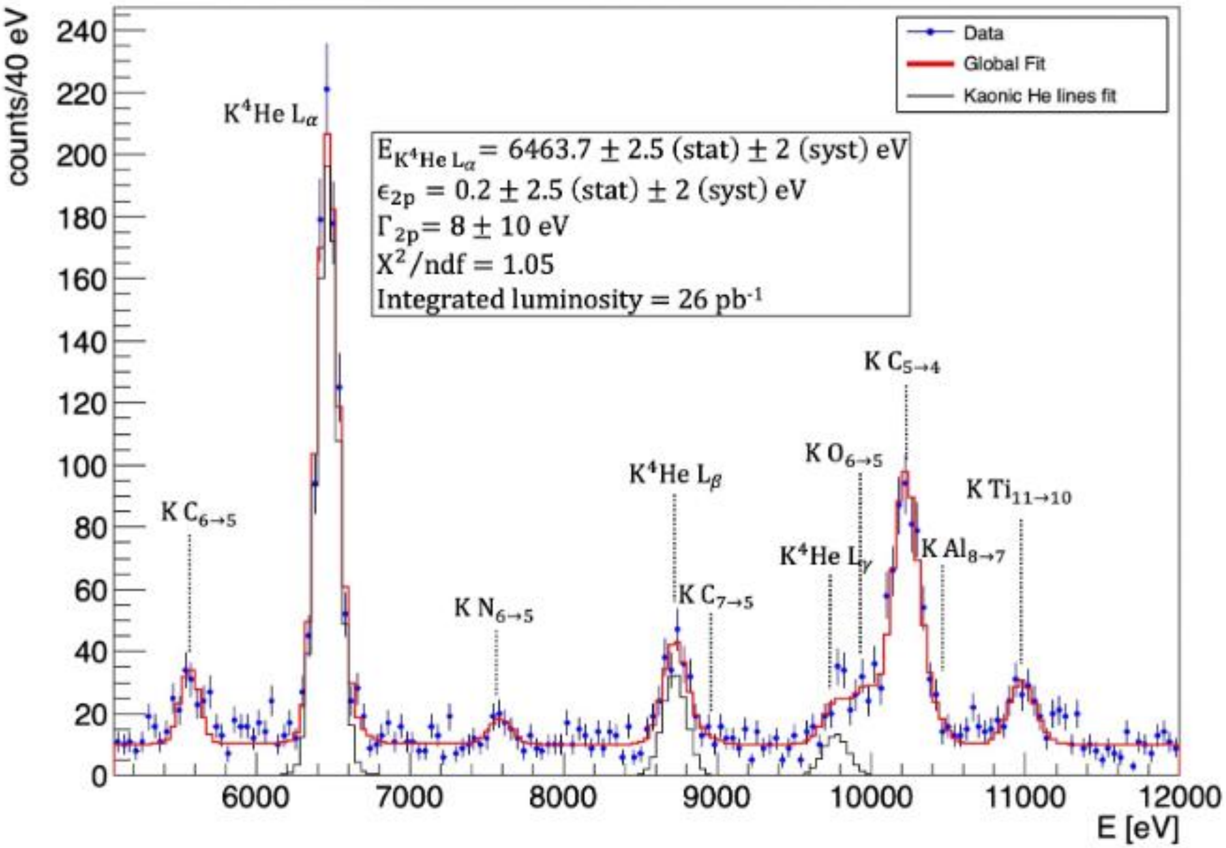


Figure 7: Fit (red line) of the K^4He energy spectrum. The Lα peak is seen together with the Lβ and Lγ ones (black lines). The peaks labeled as KN, KC, KAl, KTi (dotted lines) are the kaonic atoms lines produced by the kaons stopped in the Kapton ($C_{22}H_{10}O_5N_2$) walls of the target cell and in other parts of the setup (see text for details).

$$\varepsilon_{2p} = \mathrm{E}_{\mathrm{exp}} - \mathrm{E}_{\mathrm{e.m}} = 0.2 \pm 2.5(\mathrm{stat}) \pm 2(\mathrm{syst})\ \mathrm{eV}$$

$$\Gamma_{2p} = 8 \pm 10\ \mathrm{eV}\ (\mathrm{stat})$$

SIDDHARTA-2 strategy and requests

Phase 2
SIDDHARTA-2

Setup with all the SDDs (48 SDD arrays) **2022/2023**
and the *kaonic deuterium measurement* for a run of 800 pb^{-1}

Action plan for Kd measurement:

- **First run** with SIDDHARTA-2 setup as planned (about 300 pb^{-1} integrated)
- **Second run** with optimized shielding, readout electronics and other necessary optimizations; (for other 500 pb^{-1} integrated)

Test runs for other kaonic atoms measurements

Phase-2: SIDDHARTA-2 K-d measurement

Kaonic deuterium run in (all)

2022

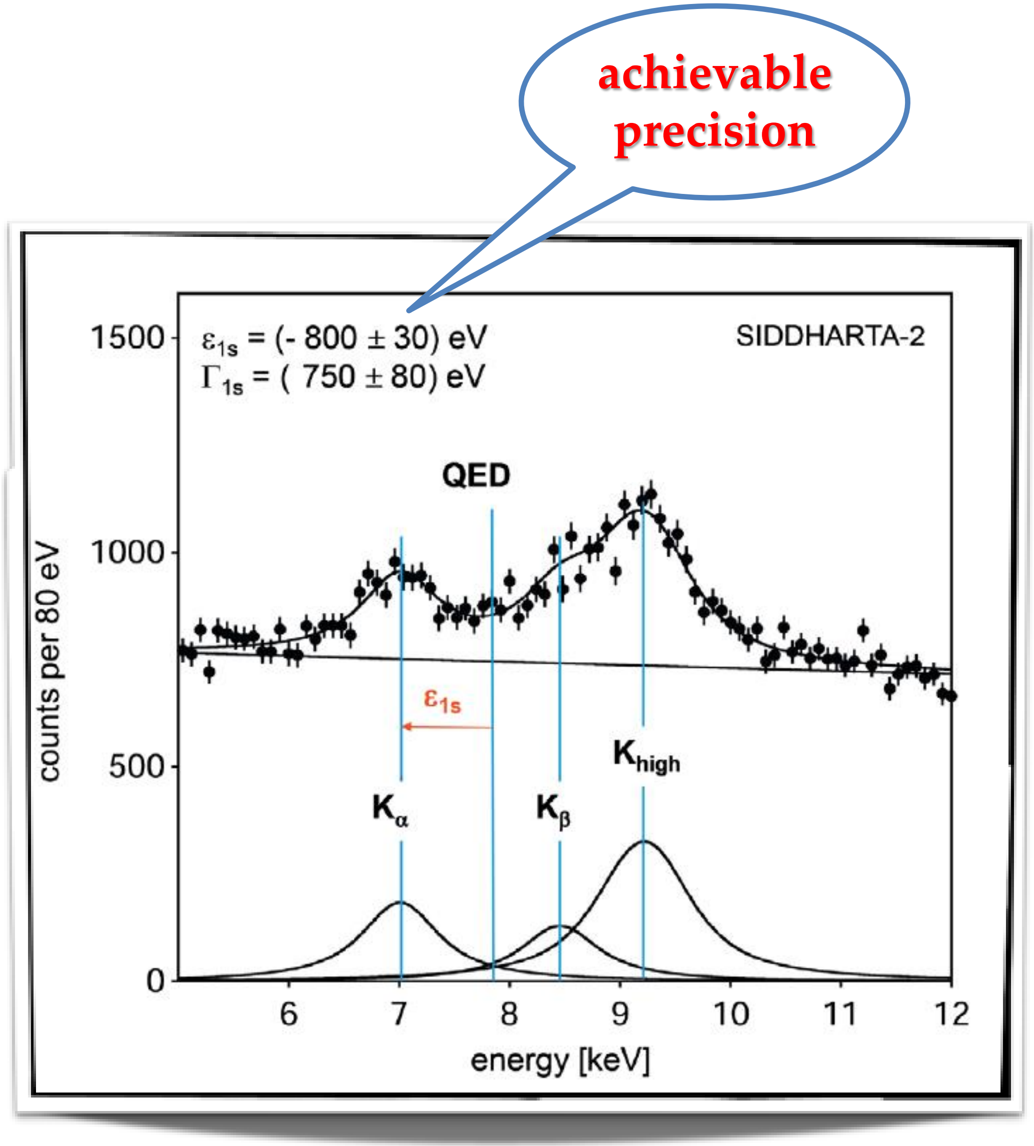
for S/B as 1/3:

for an integrated luminosity of 800 pb^{-1}

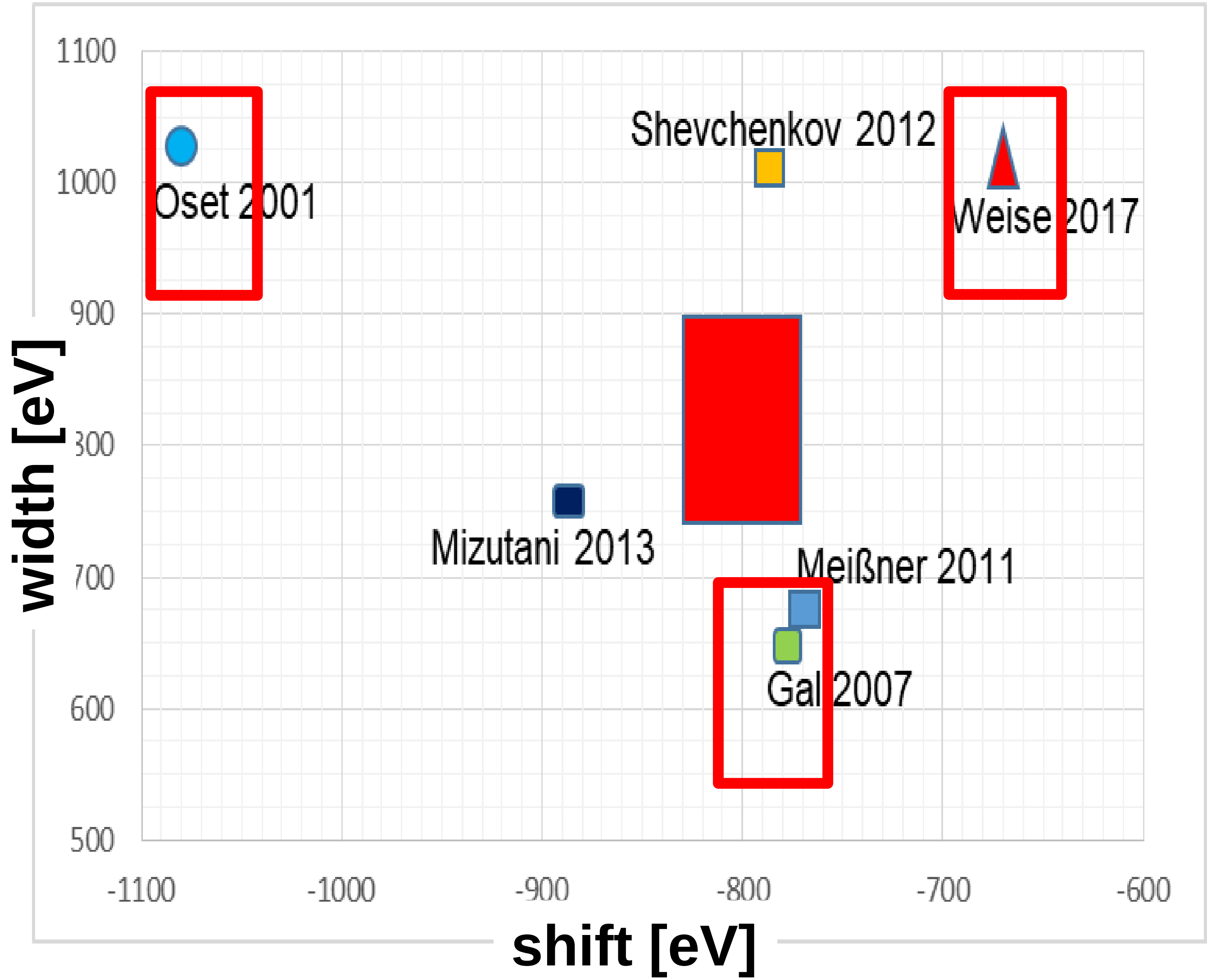
to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K^-p) !

Includes:

- **veto-2 second layer**
- **Optimizations SDD, veto1**
- **Shielding, trigger….**



SIDDHARTA-2 kaonic deuterium at DAFNE



Future programme and perspectives:

- Feasibility studies in parallel with Siddharta-2 (Ge and VOXES crystal spectrometer)

- Proposal for Extension of the Scientific Program at DAFNE

- **Kaon mass - precision measurement at a level < 7 keV (VOXES); kaon radius?**

RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Access to the Kaon Radius with Kaonic Atoms

*Niklas Michel and Natalia S. Oreshkina**

- **Kaonic helium transitions to the 1s level**

- **Other light kaonic atoms (K^-Bi, Li, B,, K^-C,…): 1mm SDDs, Cd(Zn)Te**
- **Heavier kaonic atoms (K^-Si, K^-Pb…): HPGe**

- **Radiative kaon capture – Λ(1405) study**
- **Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)**

Based on: https://arxiv.org/pdf/2104.06076.pdf

SELECTED PROPOSED MEASUREMENTS:
scientific interest, feasibility, community...

arXiv:2104.06076v1 [nucl-ex] 13 Apr 2021

Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements.

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C. Amsler, J. Zmeskal

Stefan Meyer Institute of the Austrian Academy of Sciences (SMI), Wien, Austria

D. Bosnar

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S. Eidelman

Budker Institute of Nuclear Physics (SB RAS), Novosibirsk and Lebedev Physical Institute (RAS), Moscow, Russia

H. Ohnishi, Y. Sada

Research Center for Electron Photon Science, Tohoku University, Sendai, Japan

The DAΦNE collider at INFN-LNF is a unique source of low-energy kaons, which was used by the DEAR, SIDDHARTA and AMADEUS collaborations for unique measurements of kaonic atoms and kaon-nuclei interactions. Presently, the SIDDHARTA-2 collaboration is underway to measure the kaonic deuterium exotic atom. With this document we outline a proposal for fundamental physics at the strangeness frontier for future measurements of kaonic atoms and kaon-nuclei interactions at DAΦNE, which is intended to stimulate discussions within the broad scientific community performing research directly or indirectly related to this field.

SciCom:

The proponents of the kaonic physics proposal are invited to elaborate an updated scheme with a reduced but realistic scope, in particular in terms of the required integrated luminosity that can realistically be delivered within the upcoming 3-5 years.

Part. and Nuclear physics
QCD @ low-energy (Ph1)

Astrophysics
EOS Neutron Stars (Ph2)

Kaonic atoms high precision measurements

Dark Matter studies (Ph3)

Fundamental physics
New Physics (Ph4)

Theoreticians support from (but not only):

(Ph1) (Ph2) STRONG-2020 EU, i.e. THEIA WP Strange Hadrons and the Equation-of-State of Compact Stars; ISNEUMAT-INFN,…

(Ph3) Merafina, Yamazaki, Akaishi…

(Ph4) Pospelov; Pohl, Indelicato…

Strangeness precision frontier at DAΦNE: a unique opportunity for measurements of kaonic atoms along the periodic table: **will represent a reference in physics with strangeness**

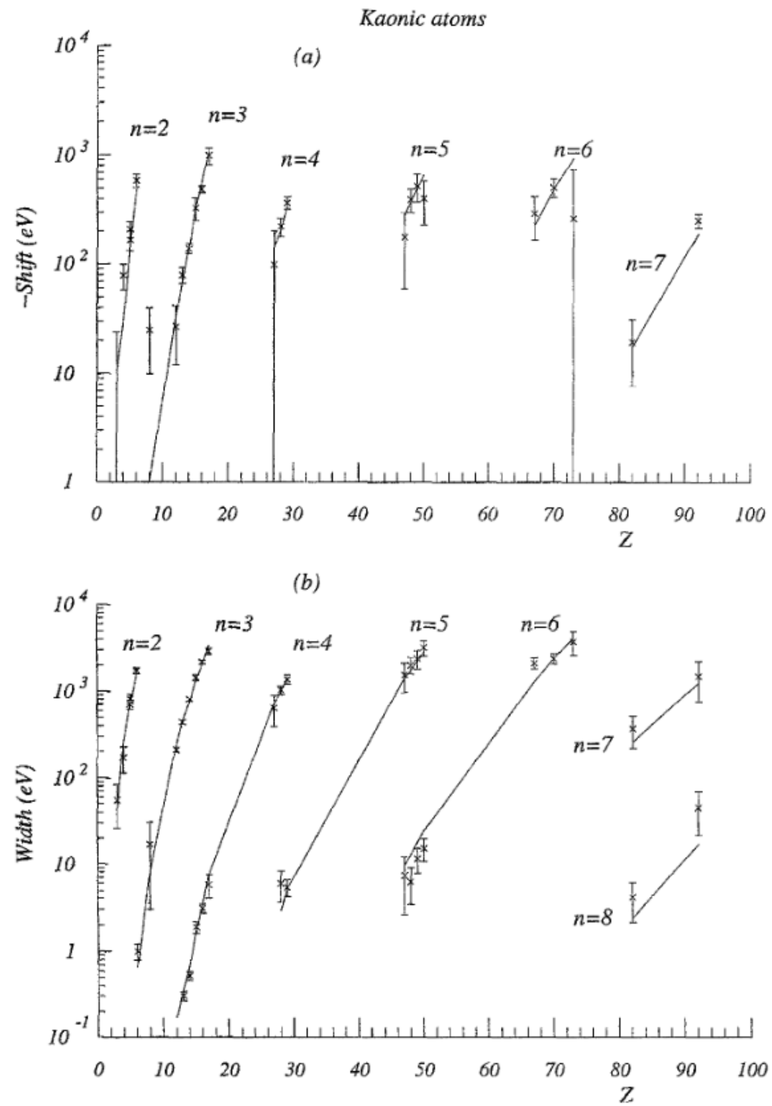
Present status: old and very old measurements with low precisison (some even wrong: kaonic helium puzzle)

We propose to do precision measurements along the periodic table at DAΦNE for:

- Selected light kaonic atoms
- Selected intermediate mass kaonic atoms
- Selected heavy kaonic atoms

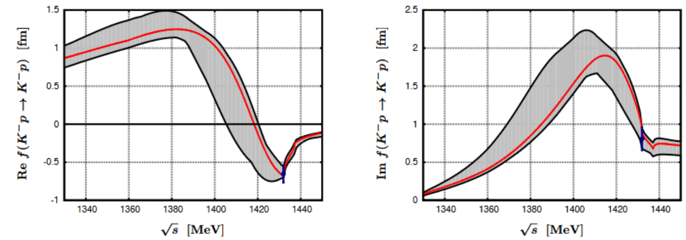
charting the periodic table

C.J. Batty et al. / Physics Reports 287 (1997) 385–445

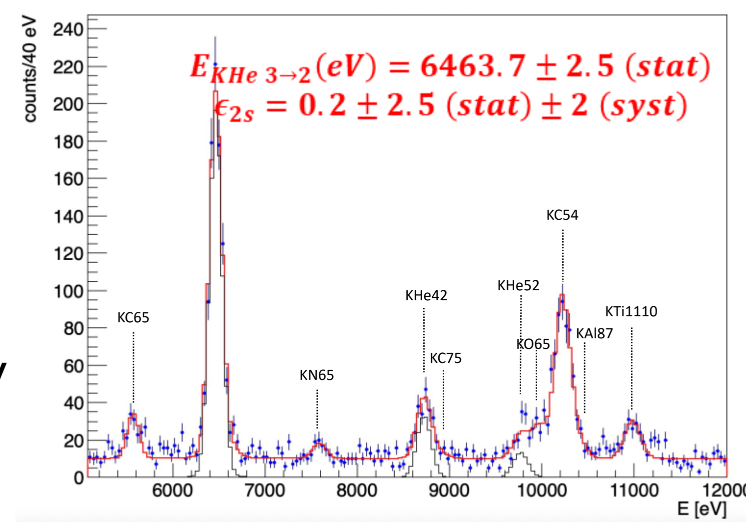


Light and Heavy Kaonic Atoms measurements: LHKA

1) **KH** *Kaonic Hydrogen*: **200 pb^{-1}** – with SIDDHARTA-2 setup – to get a precision < 10 eV (present precision about 40 eV shift and 90 eV width) very important for theory (QCD at threshold with strangeness – physic below threshold) – as soon as possible! (Weise, Nucl Phya A 2021)
Ph1, Ph2



2) Setup with 1 mm SDD detectors:
Kaonic Li; Be; B; He in the energy region 10-40 keV– precision < 2-3 eV
<u>SDDs are financed and ordered (FBK)</u>
Ph1, Ph2, Ph4
Will be ready within 2022!

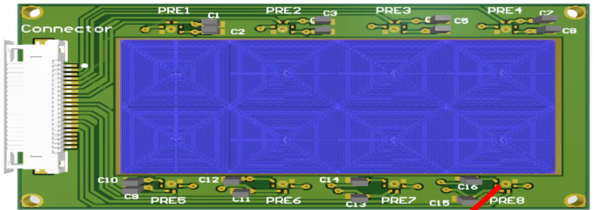


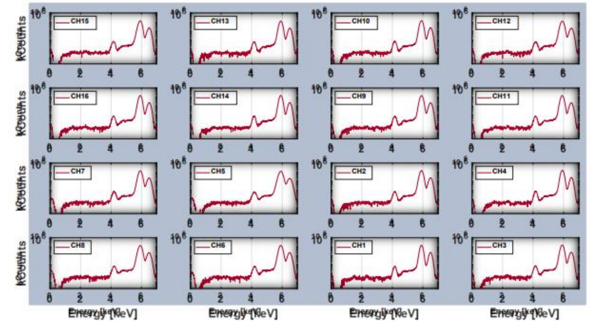
2) **Setup with 2 HPGe detectors**
Heavy kaonic atoms: transitions above 70 keV
Kaonic Pb, W – precision at the level of 3-10 eV
Ph2, Ph4
<u>HPGe available (Zagreb) and ready for use</u>

Total required integrated luminosity: 200 + 400 (200) pb^{-1}

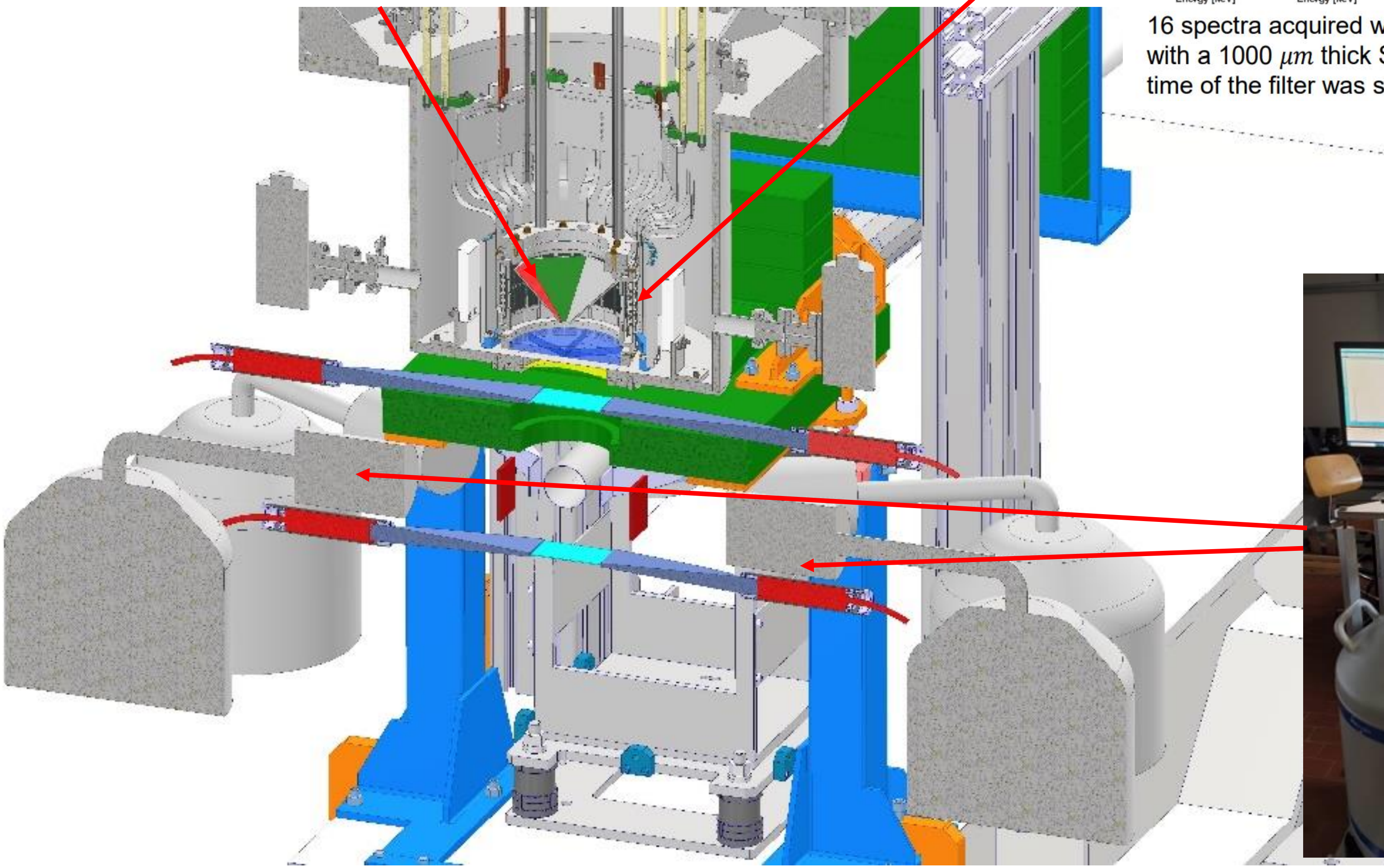
Light and heavy kaonic atoms measurements: LHKA setup

Li, Be, B targets

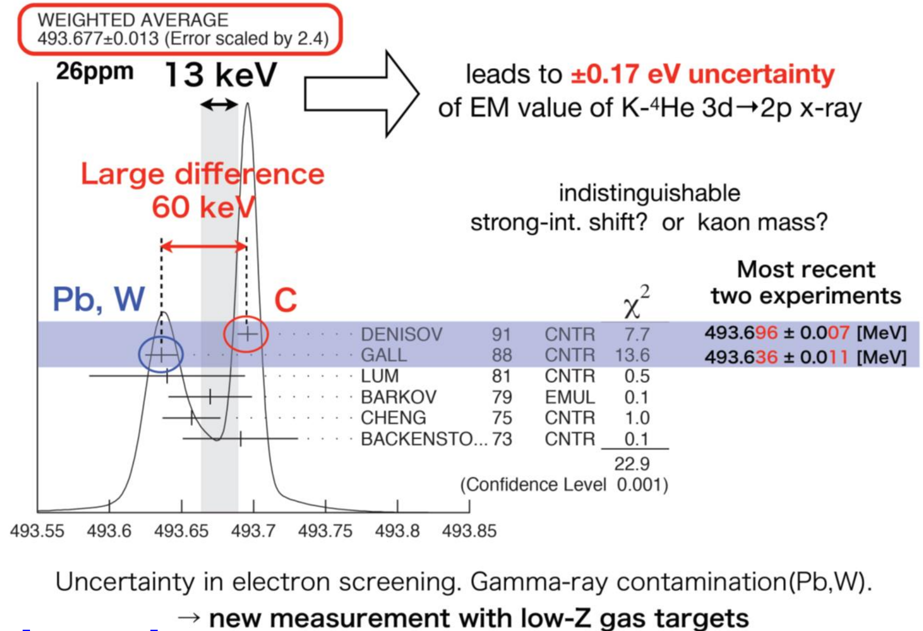




16 spectra acquired with an ^{55}Fe source with a 1000 μm thick SDD array (peaking time of the filter was set to 3 μs)



Intermediate and Heavy Kaonic Atoms measurements IHKA



1) Setup with CdZnTe detectors:

Kaonic Ti, V, Zr, Ag, between 40 and 200 keV keV – precision 3-5 eV

CdZnTe are developed within ASTRA STRONG-2020 project

Will be ready within 2023

Ph1, Ph2, Ph3

3) **Setup with 2 HPGe detectors continued**

Heavy kaonic atoms: transitions above 70/100 keV

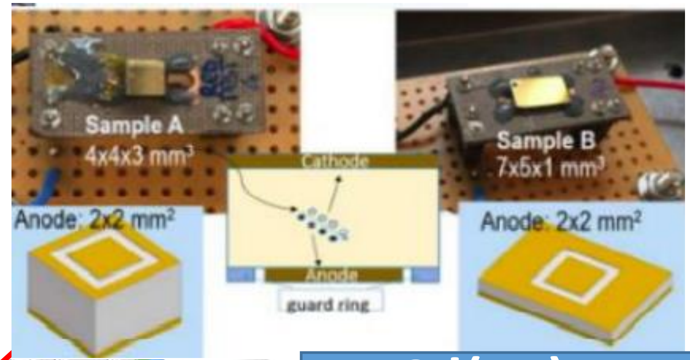
Kaonic Co, Au, Pt – precision at the level of 5-10 eV (depending on energy of transition)

HPGe available and ready for use (Zagreb Univ. plus Mainz – additional HPGe)

Ph1, Ph2, Ph3

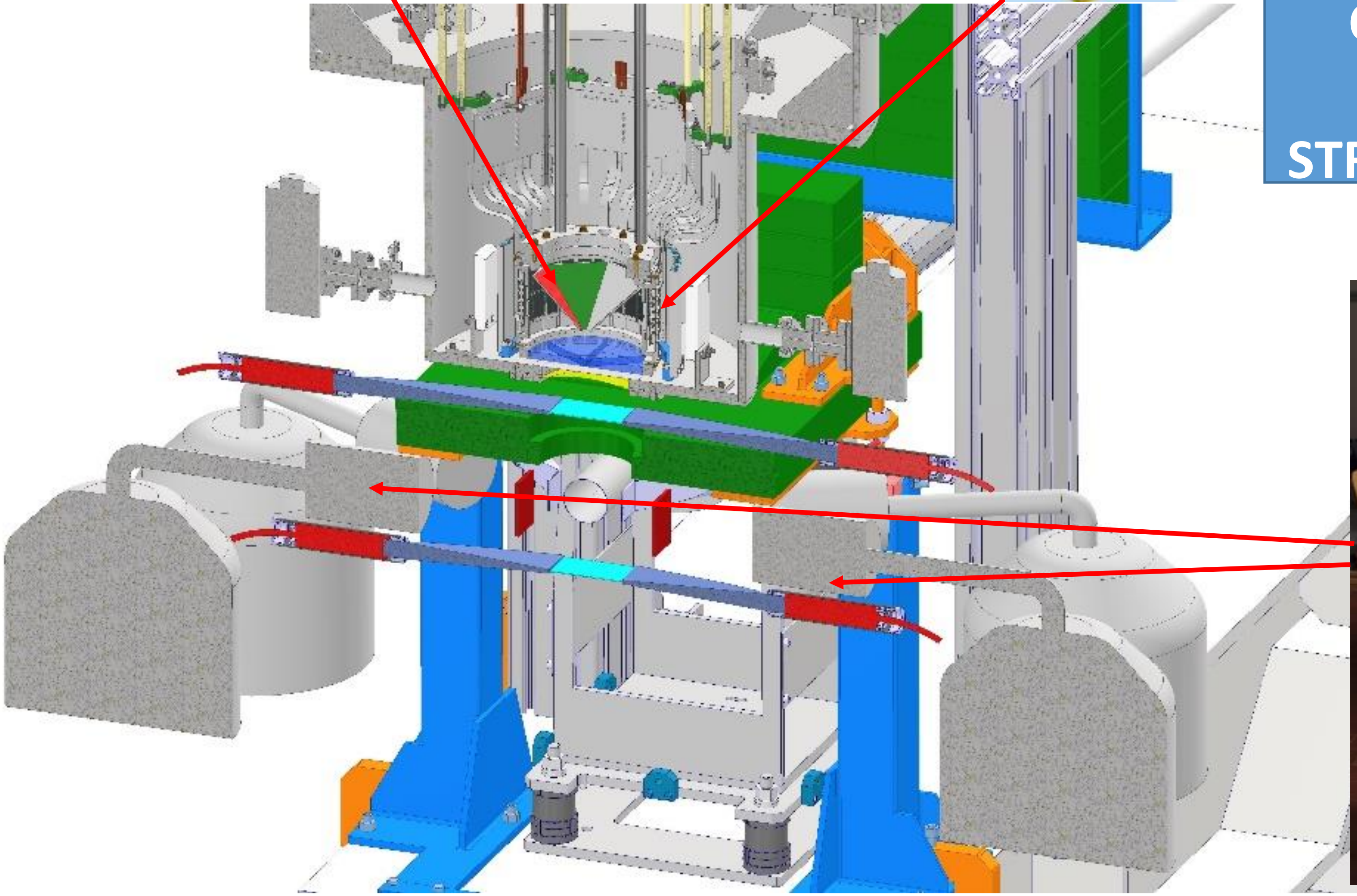
Total required integrated luminosity: 400 (200) pb^{-1}

Intermediate and heavy kaonic atoms measurements: IHKA



Ti, V, Zr, Ag targets

Cd(Zn)Te ASTRA STRONG-2020



Ultra-High precision measurements of Kaonic Atoms
UHKA

1) Setup with 8 VOXES lines (crystal HAPG spectrometer):

Kaonic C, N, He: **precision < 0.5 eV**

VOXES detector developed; financing for building 8 lines required (possibility of external funding)

Will be ready within early 2025

Ph4, Ph1, Ph3, Ph2

PHYSICAL REVIEW LETTERS **126**, 173001 (2021)

Testing Quantum Electrodynamics with Exotic Atoms

Nancy Paul,[1,*] Guojie Bian,[1,2,†] Toshiyuki Azuma,[3,‡] Shinji Okada,[4,§] and Paul Indelicato[1,‖]

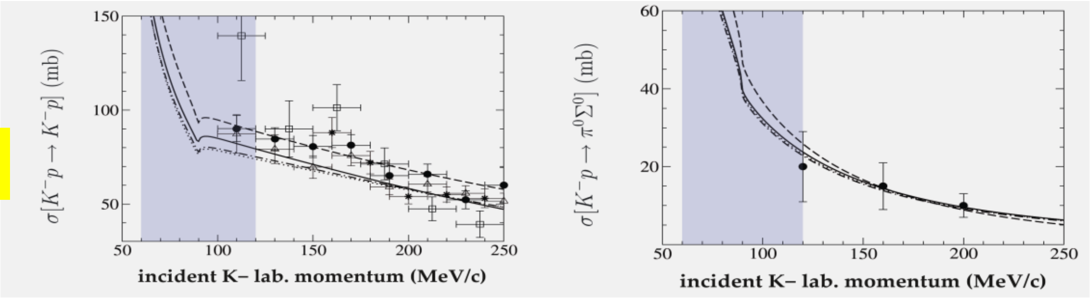
2) Feasibility test (measurements) for kaon-nuclei scattering exp.

With TPG detector

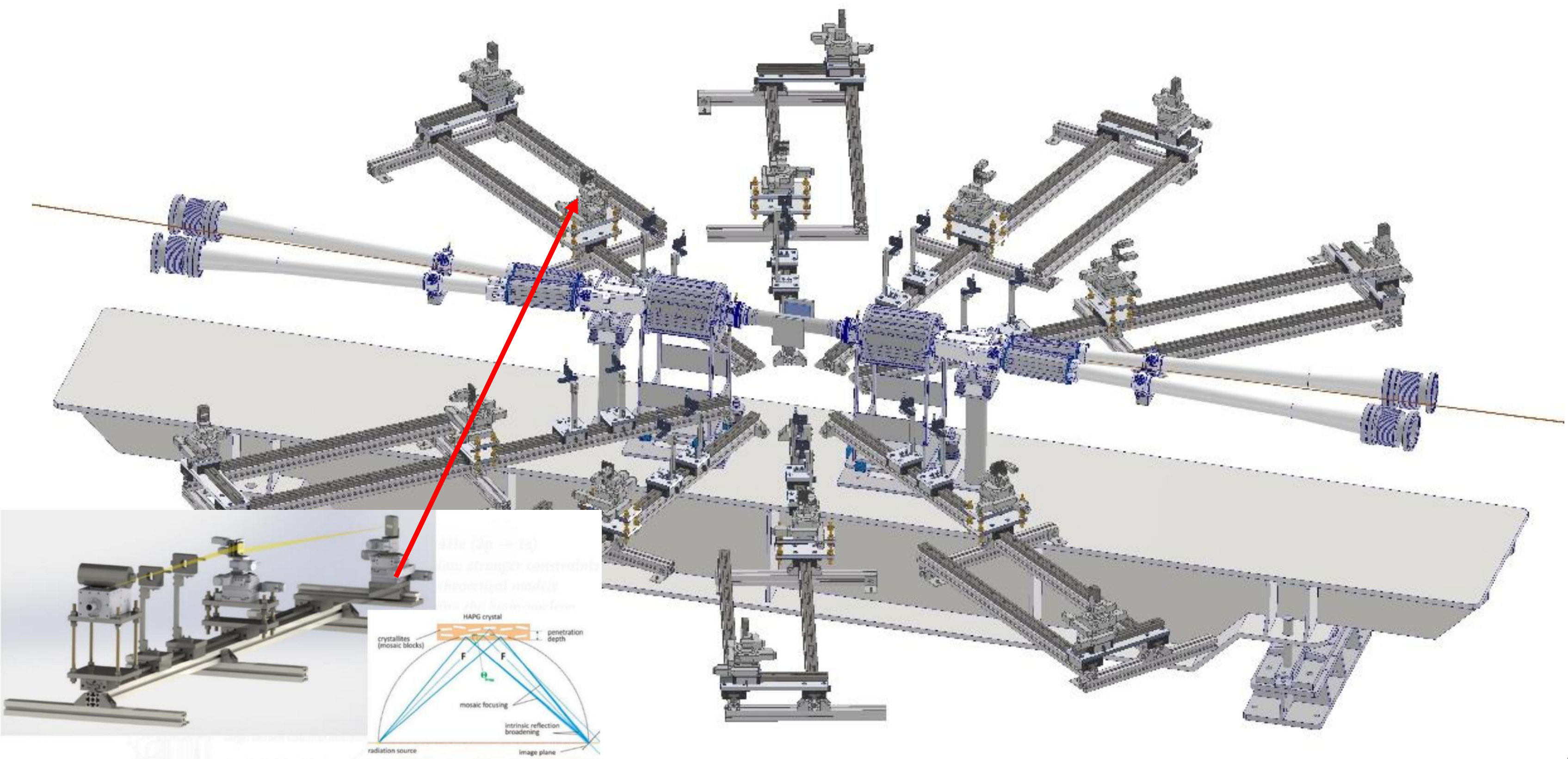
TPC developed by Sendai ELPH Japan, SMI-Vienna and LNF-INFN (HP2, HP3 EU)

KP nuclear scattering – feasibility for FUTURE MEASUREMETS (2 years after KA)

Total required integrated luminosity: 400 pb^{-1}



Ultra-high precision measurements of kaonic atoms
UHKA



HAPG mosaic crystals in Von Hamos configuration:
- Higher intrinsic reflectivity wrt standard crystals
- VH configuration to exploit sagittal focusing
- Optical optimisation to work with millimetric/centimetric sources

***JINST* 13 (2018) 04, C04002** **CSN5 Young Research (Scordo)**

We proposed to perform fundamental Physics at the strangeness frontier at DAΦNE studies:

High Precision Kaonic Atoms Measurements on DAΦNE:

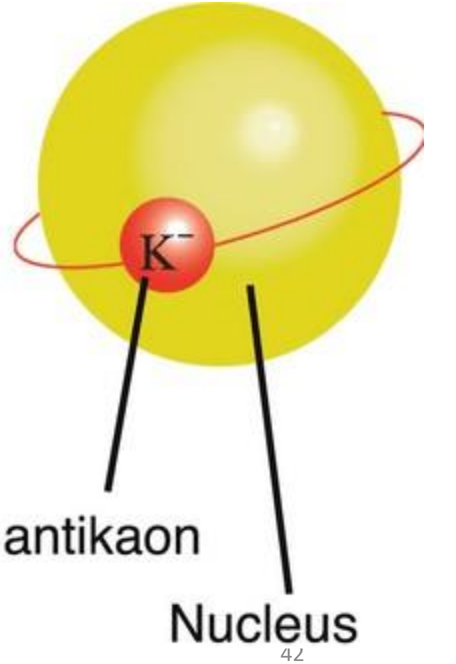
The strangeness Mendeleev table

We presented a program for performing unique measurements of kaonic atoms along the periodic table to contributing to understand physics going from the strong interaction (symmetry breaking) to neutron stars, and from Dark Matter to Physics Beyond Standard Model, setting LNF in forefront of these studied.

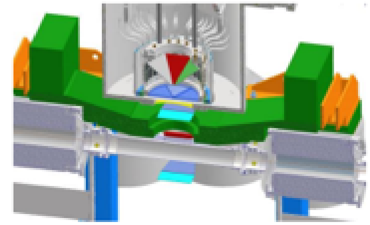
Cascade calculations are FUNDAMETAL

EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

EXKALIBUR



We anticipate the request for an extension of run with same setup with solid targets

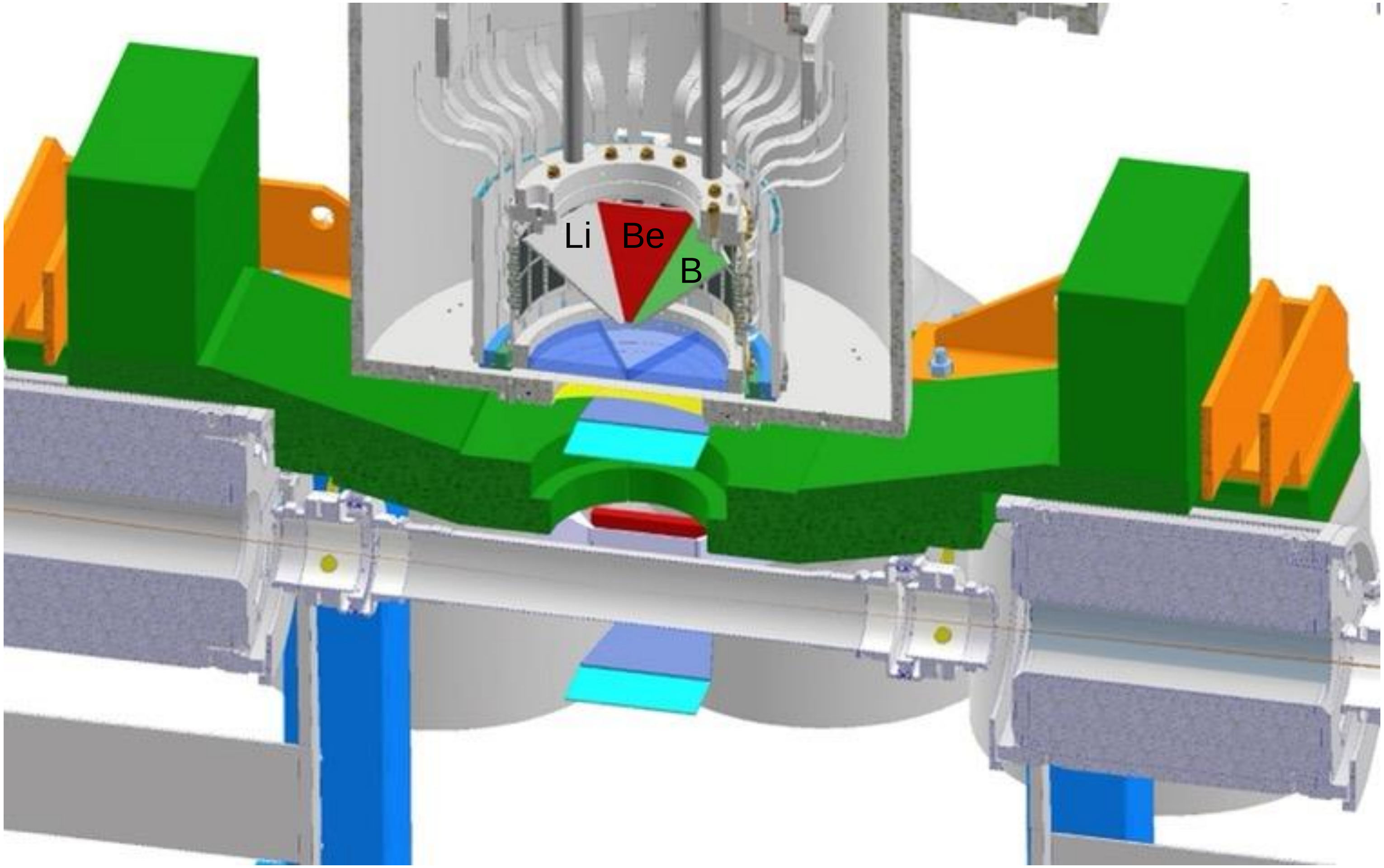


Light Kaonic Atoms Measurements with SIDDHARTA-2 after Kd run

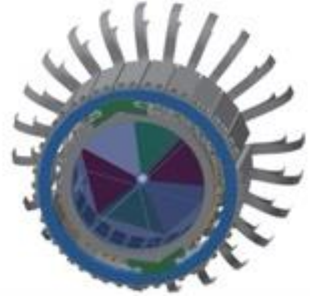
July 2021

The SIDDHARTA-2 Collaboration

Use of present SDDs: Solid target system for light kaonic atoms: e.g. **Li – Be - B financed by INFN Nuclear physics (gr 3) as first step towards Future (see Curceanu talk)**

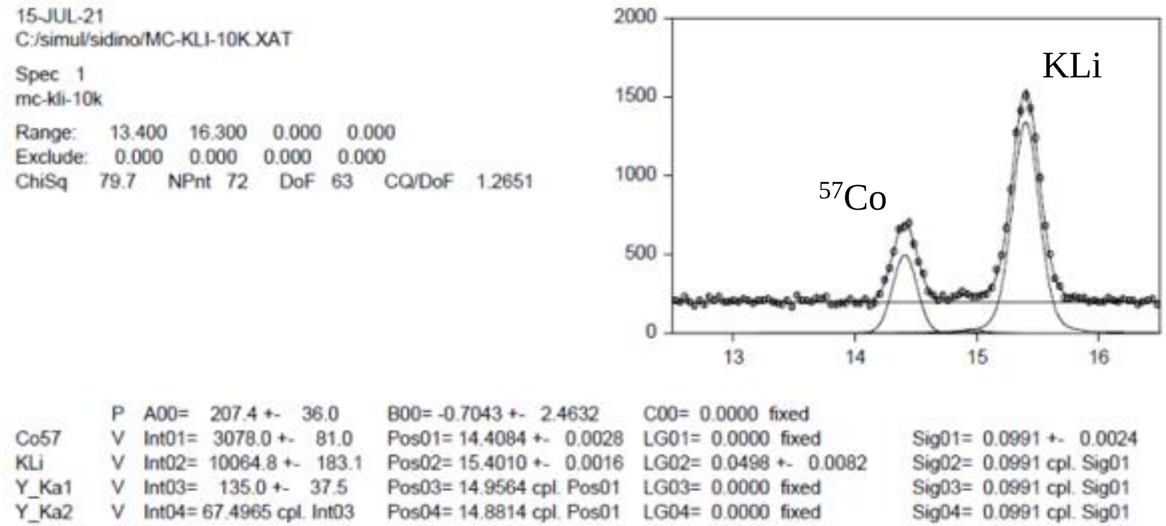


Solid target system for light kaonic atoms: e.g. Li – Be – B



kaonic Li-transitions

3-2	**~15 keV**
4-2	~21 keV
5-2	~23 keV
4-3	**~ 5 keV**
5-3	**~ 8 keV**
6-3	**~ 9 keV**
5-4	**~2.5 keV**
6-4	**~ 4 keV**



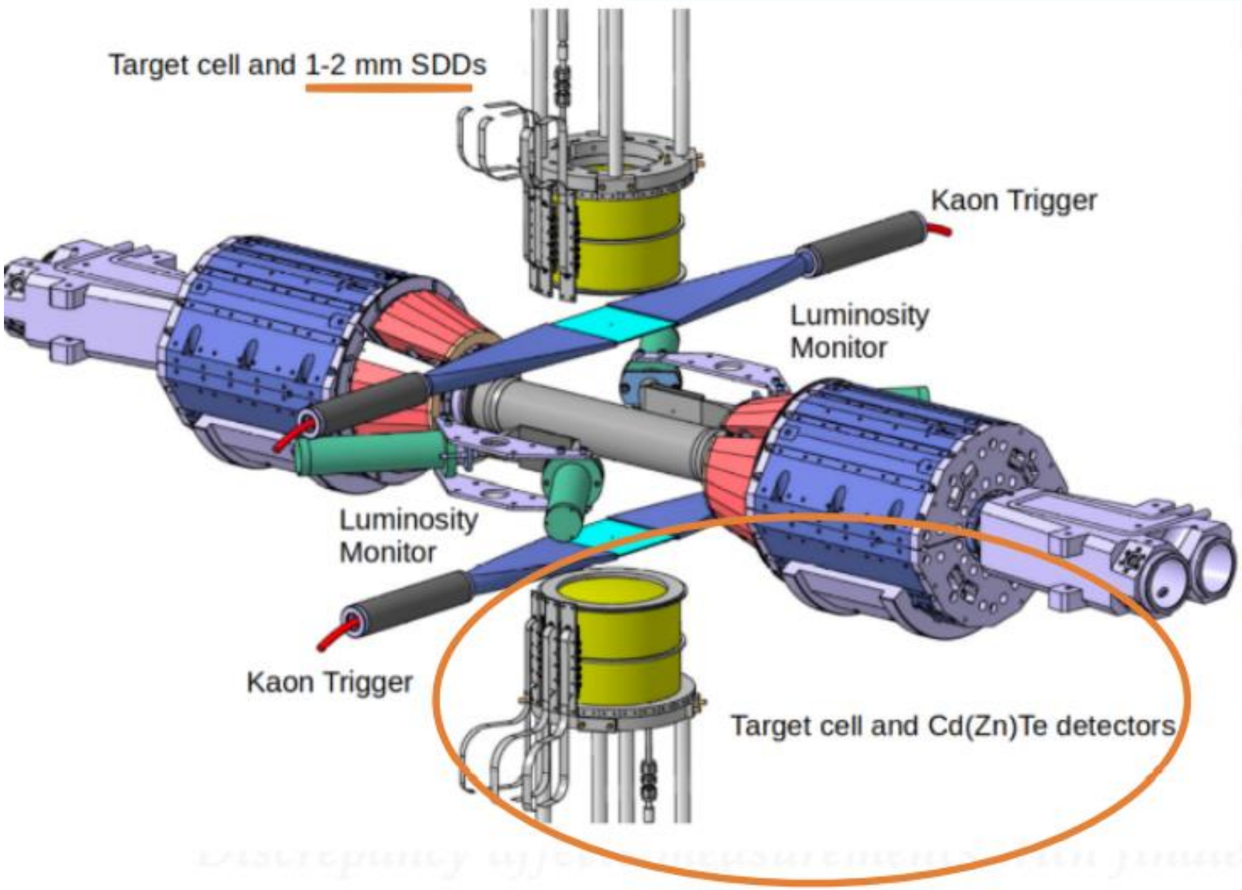
The energy spectra of light kaonic atom transitions for Li, Be and B targets below 17 keV can achieve a precision below 2-3 eV, for an integrated luminosity of **about 150 pb^{-1}** (including calibrations and test).

We anticipate the request of this additional run post-SIDDHARTA-2

Future Plans

Light Kaonic atoms measurements

Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{10,11}B



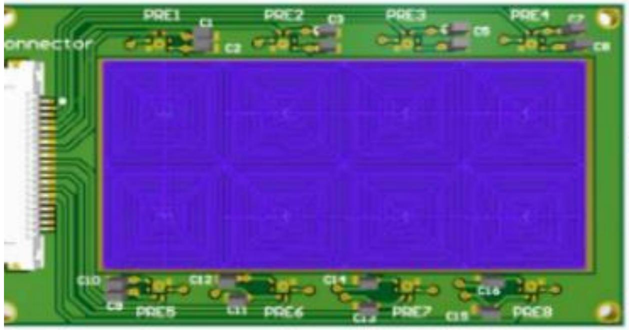
- *3He,4He ($2p \rightarrow 1s$) transition: stronger constraints on the theoretical models describing the kaon-nucleon interaction in systems with more than two nucleons*

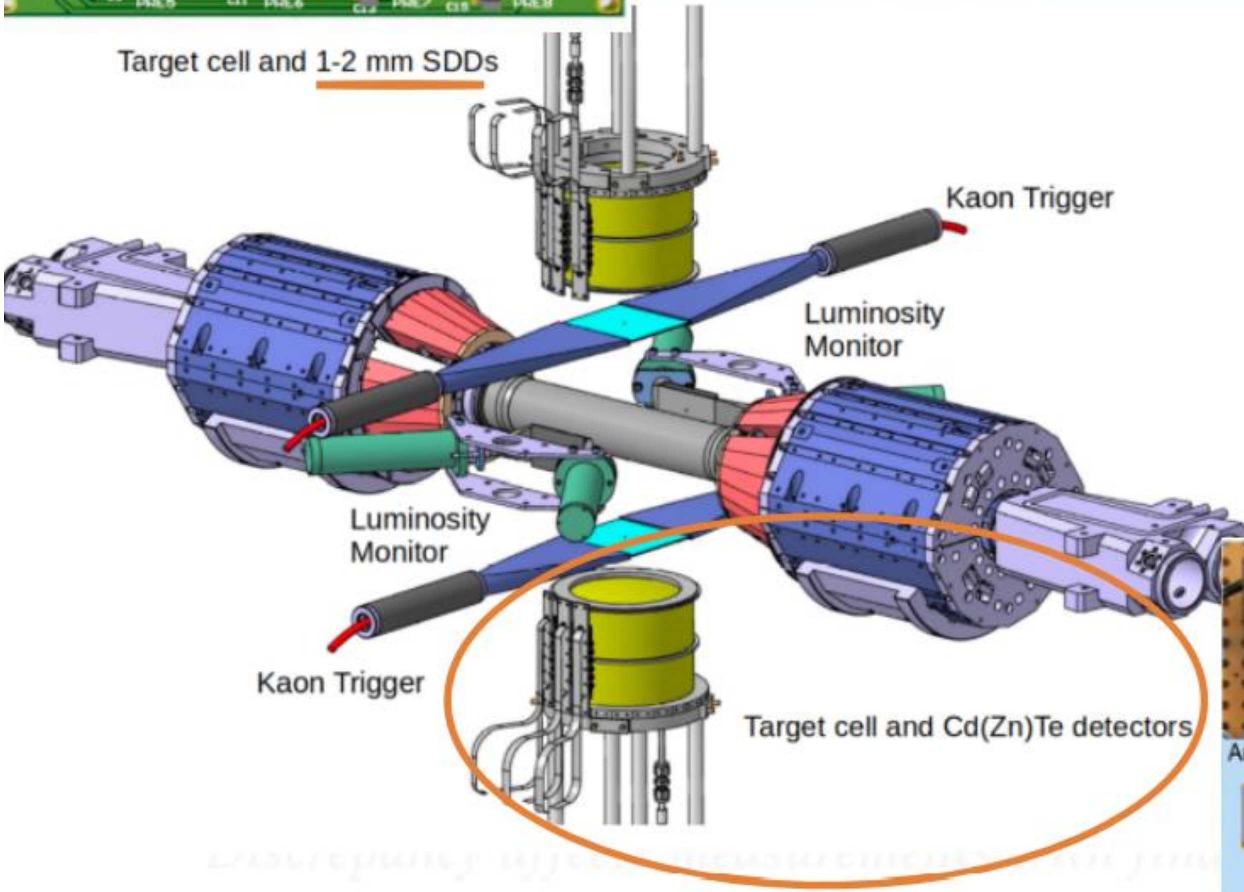
- *Information on the nature of the $\Lambda(1405)$ state can be obtained from the upper-level transitions of light kaonic atoms*

Future Plans

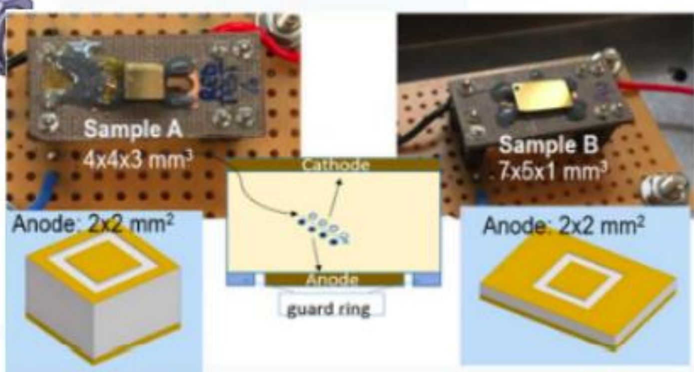
ght Kaonic atoms measurements

Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{10,11}B





- *3He,4He (2p → 1s) transition: stronger constraints on the theoretical models describing the kaon-nucleon interaction in systems with more than two nucleons*

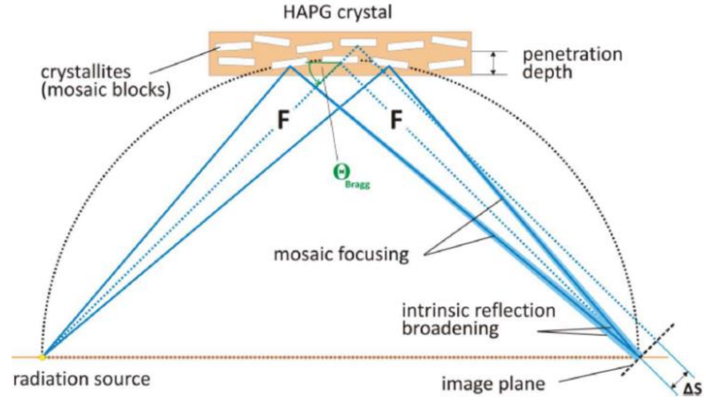


VOXES SPECTROMETER

HAPG mosaic crystals: improving efficiency

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

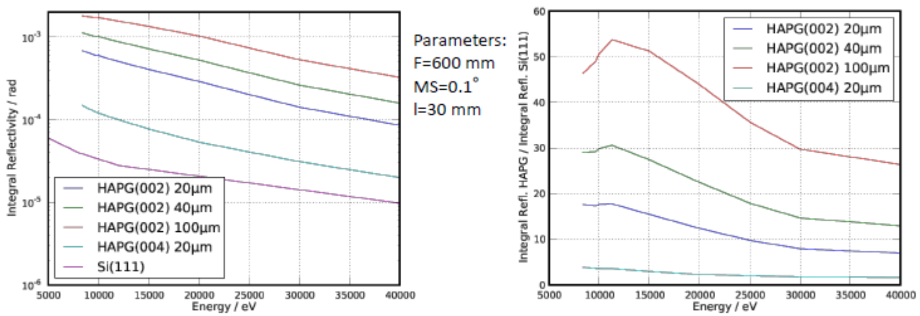
Loss in resolution

Pyrolitic Graphite mosaic crystals (d = 3.354 Å):

- 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

Integral reflectivity

- Measured integral reflectivities (synchrotron measurements)



→ The integral reflectivity can be more than 50 times higher compared to Si(111) reflection.

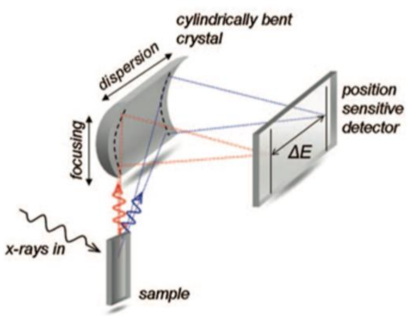
→ The use of the von Hamos geometry can increase the overall efficiency even more.

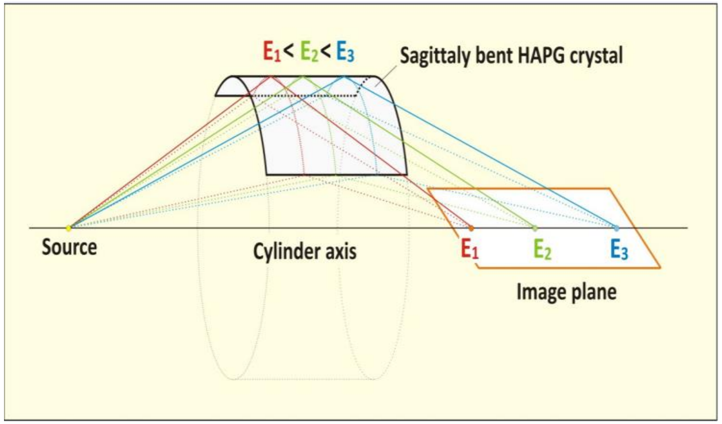
Characterization of HAPG mosaic crystals using synchrotron radiation

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: improving solid angle

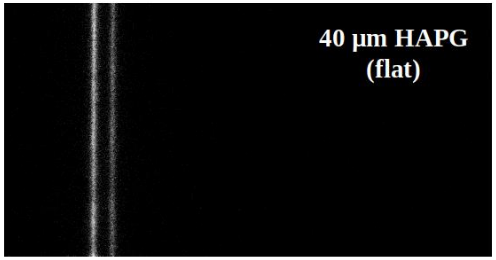


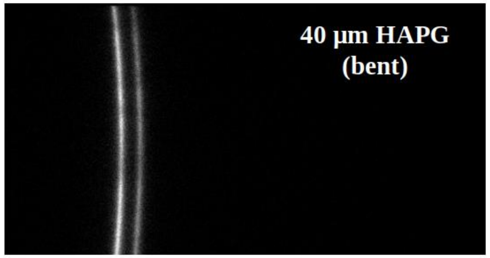


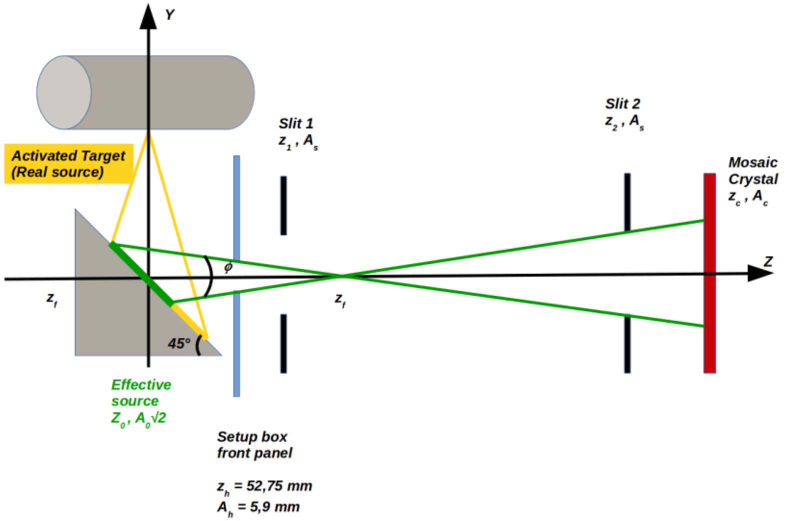
VH configuration can further improve the signal collection efficiency.

In this configuration, also the vertical dimension of the X-ray source can be exploited

distance: F = 400 mm in (004)-reflexion @ 8 keV (Cu K_a)



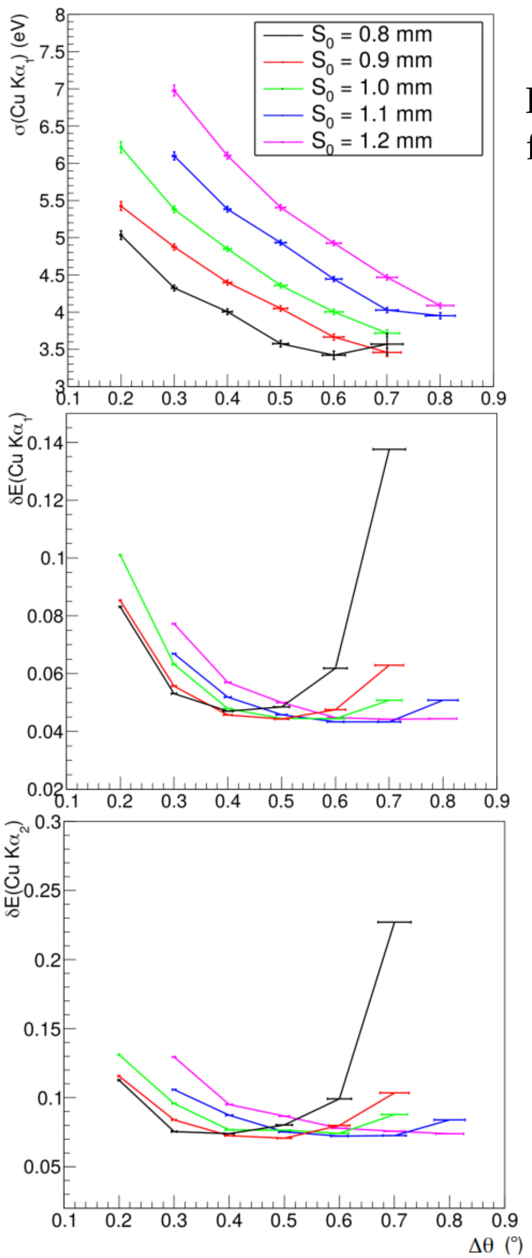




Spectral resolution of bent HAPG/HOPG crystal is comparable to the flat one !

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

VOXES: results



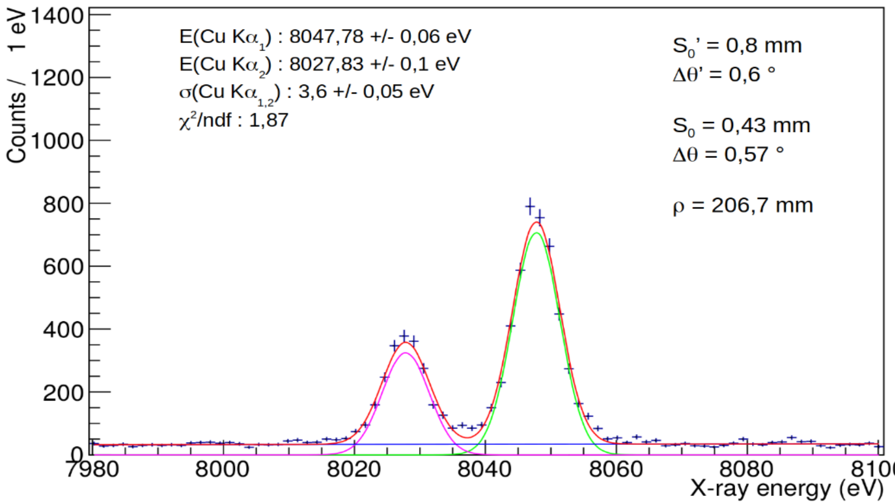
In the limit of a background free pure gaussian peak, the precision is related to the resolution via:

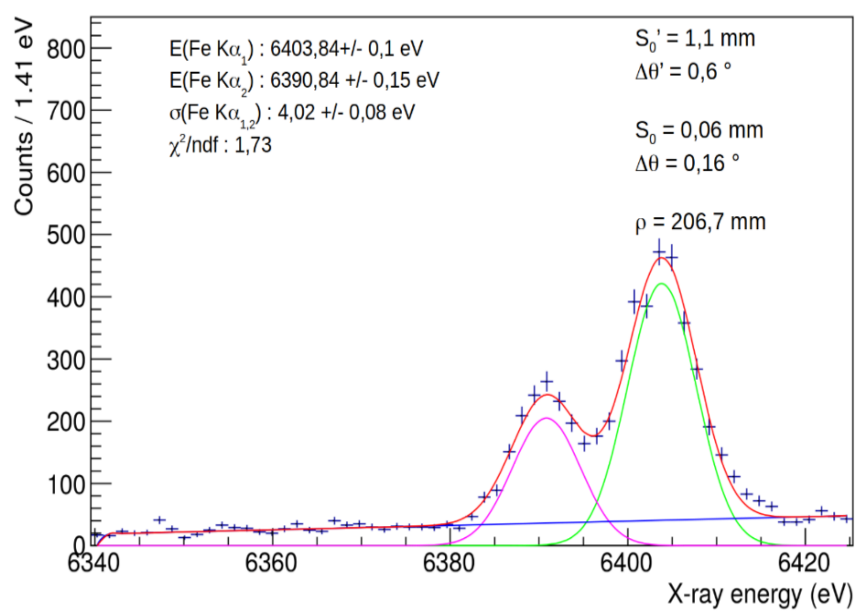
$$\delta E = \frac{\sigma E}{\sqrt{N}}$$

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

Given the energy and ρ_c it is alwasy possible to find the optimal configuration to obtain the best peak position precision

Valid for all energies (tested for 6-20 keV)





VOXES: ray tracing simulations

Possible kaonic transitions to be measured with HAPG crystal spectrometer:

$K^3He(3\to2)$: 6.2 keV
$K^3He(4\to2)$: 8.4 keV
$K^3He(5\to2)$: 9.4 keV
$K^3He(6\to2)$: 9.9 keV
$K^3He(7\to2)$: 10.2 keV

$K^4He(3\to2)$: 6.4 keV
$K^4He(4\to2)$: 8.7 keV
$K^4He(5\to2)$: 9.7 keV
$K^4He(6\to2)$: 10.3 keV
$K^4He(7\to2)$: 10.7 keV

$KN(6\to5)$: 7.6 keV
$KN(7\to5)$: 12.1 keV
$KN(8\to5)$: 15.1 keV
$KN(7\to6)$: 4.6 keV
$KN(8\to6)$: 7.5 keV
$KN(9\to6)$: 9.6 keV
$KN(10\to6)$: 11 keV
$KN(11\to6)$: 12.1 keV
$KN(10\to7)$: 6.5 keV
$KN(11\to7)$: 7.5 keV
$KN(12\to7)$: 8.3 keV

Expected Impact:

- **Kaon mass measurements** from different lines in parallel
- **Cascade processes**
- Impact on dark matter search driven experiments using exotic atoms in space (accurate cascade models calculations)
- Upper level measurments with very small Γ
- Proton radius puzzle (???)

Manifestatation of interest from international institution and research centers (PSI, …)

Feasibility:

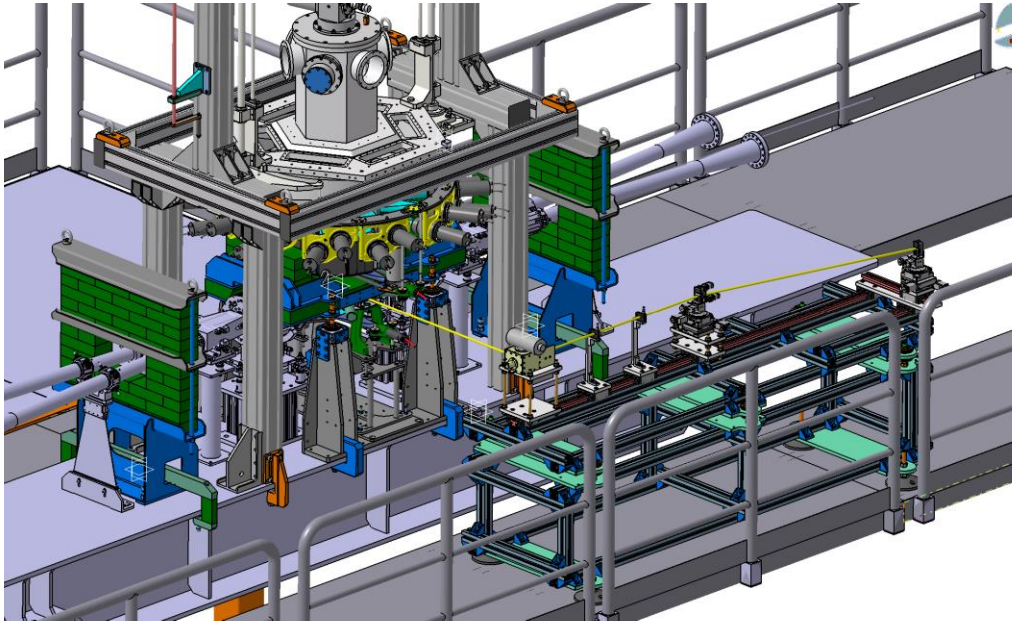
- Working principle tested in laboratory
- Dependence from HAPG parameters well investigated and published (thickness, mosaicity, …)
- Consistent Ray Tracing simulations available
- Few eV resolutions confirmed for solid sources with millimetric dimensions

VOXES: a possible preliminary run

First run with KC for a feasibility test and background evaluation

Available:

1) Multi - Crystal support structure
2) Target (Solid or Liquid/Gas)
3) Optics
4) Alignement support
5) Target box
6) Detector
7) DAQ (integ. KM)



Future implementations:

- Shielding around Detector
- Solid support structure

Possible run in parallel with SIDDHARTA-2 @ LNF in spring 2022

X-ray detectors:

- ***Silicon Drift Detectors (0.5, 1 mm)***
- ***Cd(Zn)Te***
- ***HPGe***
- ***VOXES***

We are also doing tests on quantum mechanics (VIP experiment) – if interested ask me ☺

There are a plethora of other applications (food quality, medicine, industrial) – IDEAS?