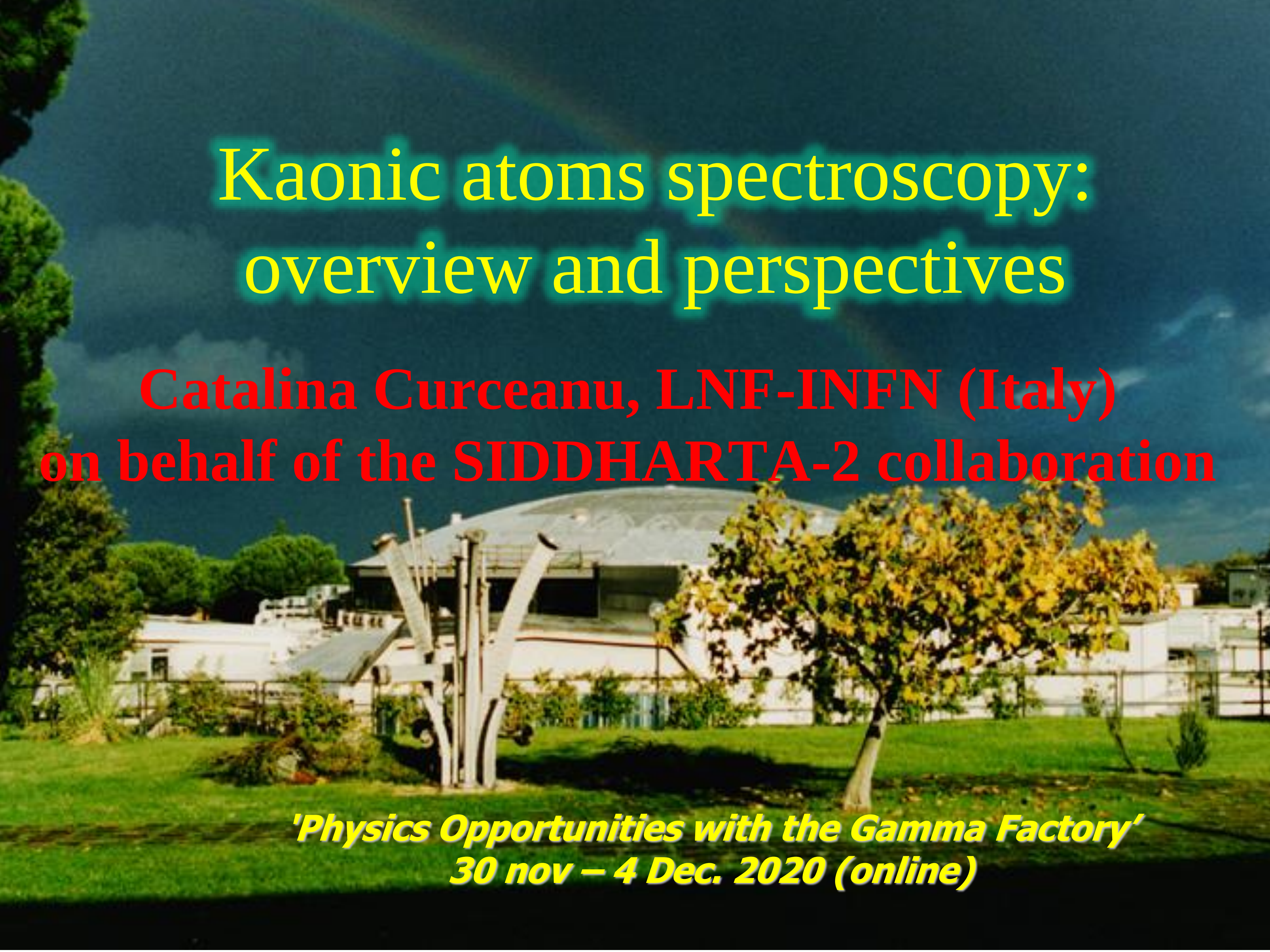


Kaonic atoms spectroscopy: overview and perspectives

Catalina Curceanu, LNF-INFN (Italy)
on behalf of the SIDDHARTA-2 collaboration

'Physics Opportunities with the Gamma Factory'
30 nov – 4 Dec. 2020 (online)

Connected with the proposal:

Resonance photoproduction of pionic and kaonic atoms at the Gamma Factory

Victor V. Flambaum
School of Physics, University of New South Wales, Sydney 2052, Australia
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany and
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany

Junlan Jin
Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

Dmitry Budker
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany and
Department of Physics, University of California, Berkeley, California 94720, USA
(Dated: October 29, 2020)

We present a possibility of direct resonance production of pionic atoms (Coulomb bound states of a negative pion and a nucleus) with a rate of up to $\sim 10^{10}$ per second using the gamma-ray beams from the Gamma Factory. We also estimate the rate of kaonic atoms production.

Phys.Rev.D 102 (2020) 8, 083015

On self-gravitating strange dark matter halos around galaxies

Dark Matter studies

Rev.Mod.Phys. 91 (2019) 2, 025006

The modern era of light kaonic atom experiments

Fundamental physics
New Physics

Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry

Kaonic Atoms to Investigate Global Symmetry Breaking

Symmetry 12 (2020) 4, 547

Astrophysics
EOS Neutron Stars

Astrophys.J. 881 (2019) 2, 122

Merger of compact stars in the two-families scenario width of the 1s level as

$$\Gamma_{tot}(Z, n=1) \approx \frac{20Z^4}{Z^3 - 9Z^2 + 100Z - 60}\,\text{keV}. \qquad (16)$$

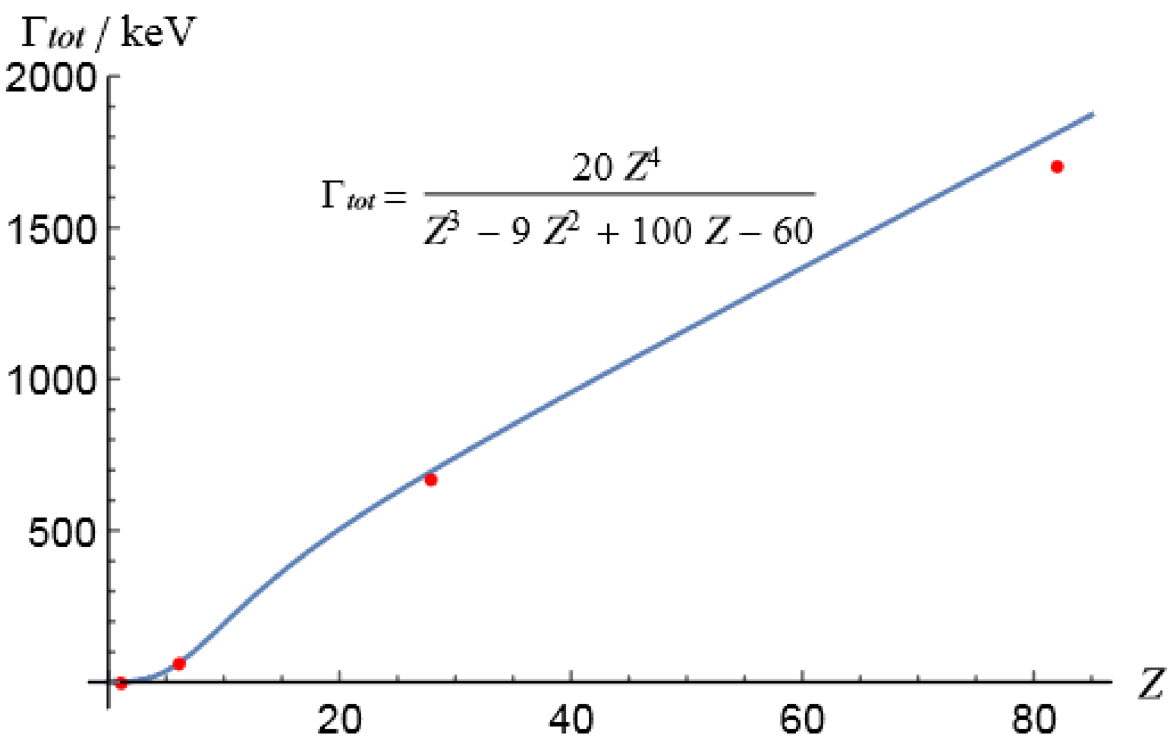


FIG. 3. Fitting of 1s width data (red dots on the graph) for kaonic atoms. The width data for carbon, nickel and lead are from Refs. [22, 23]; the 1s width of kaonic deuterium is from Ref. [6].

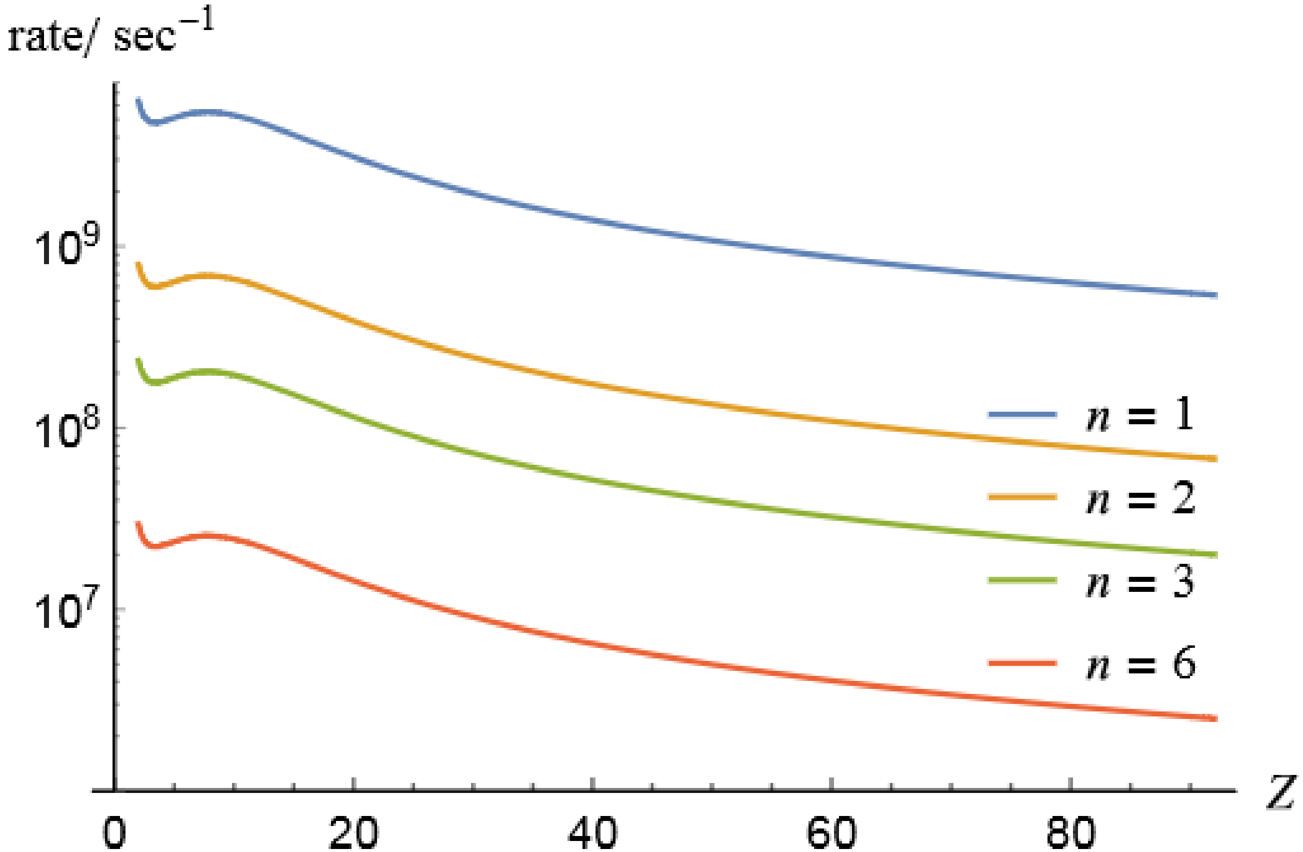
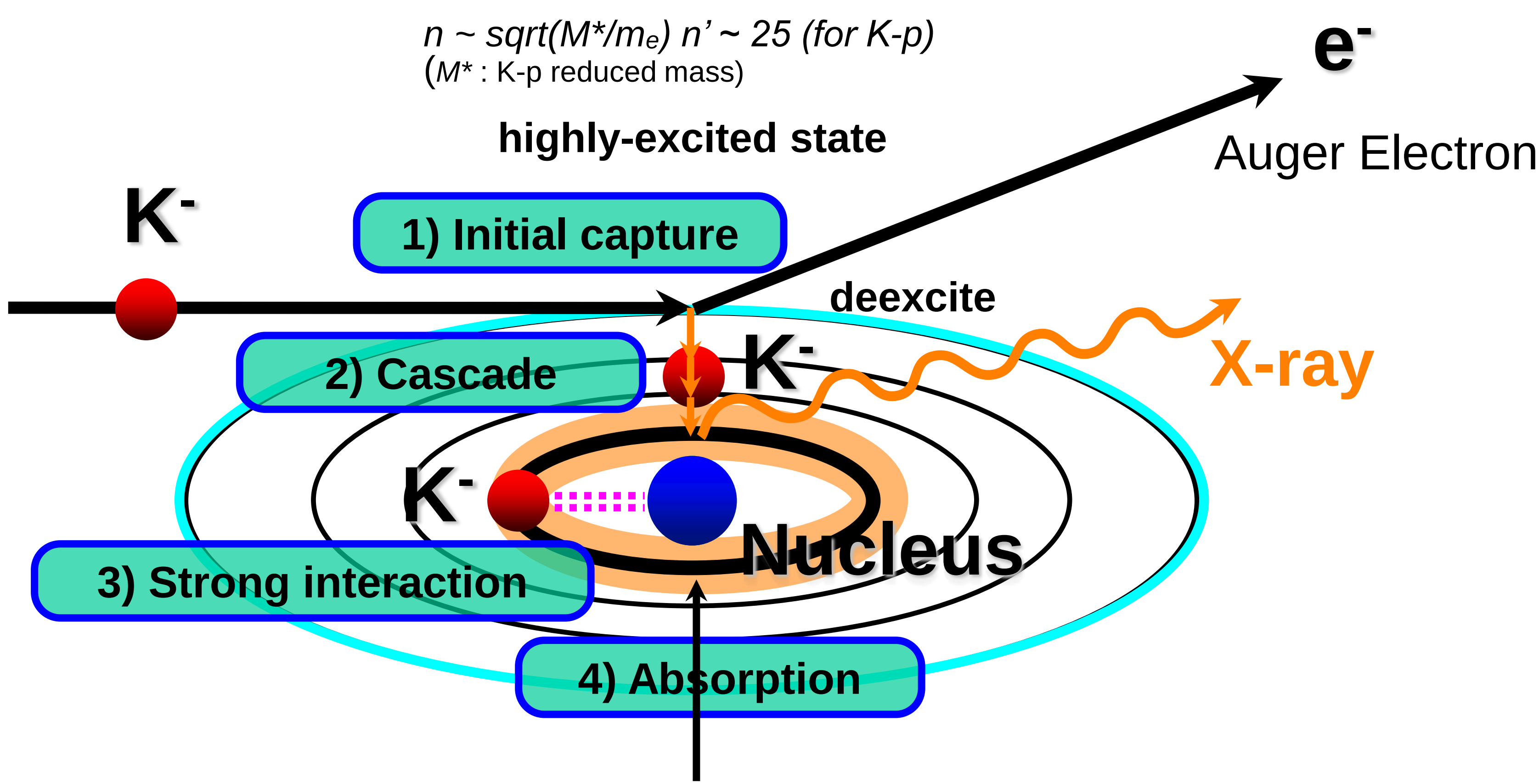


FIG. 4. Estimate of the maximal production rate of kaonic atoms in the $1s$, $2s$, $3s$ and $6s$ states utilizing photons from the GF.


Kaonic atoms spectroscopy:
at DAFNE

Kaonis atoms: brief introduction

Kaonic atom formation



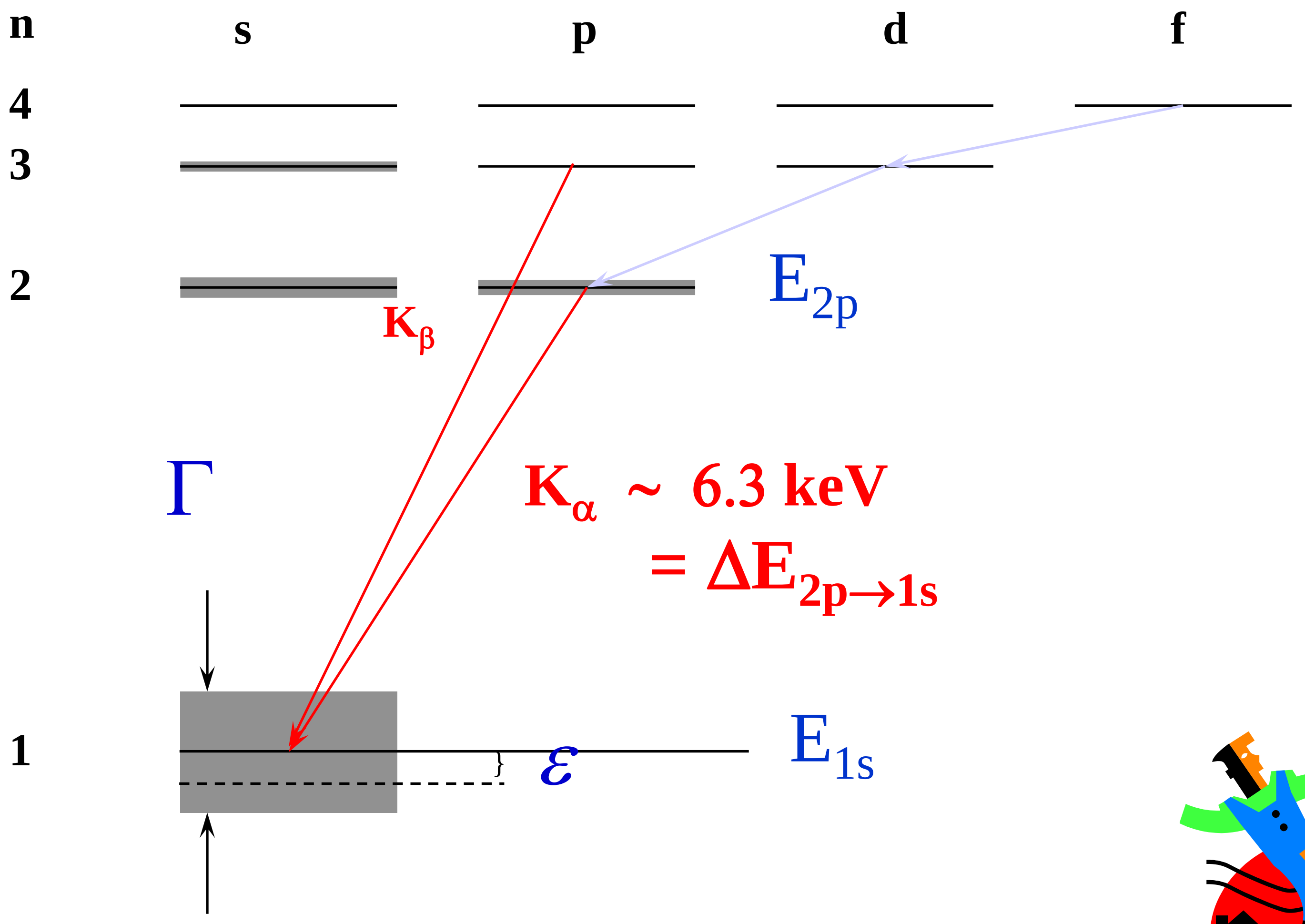
stopped in a target medium

Shift and Width of last orbit

The strong int. width > Radiative ... width

· **1s** for K-p, K-d
· **2p** for K-He

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):

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

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

one can obtain the isospin dependent antikaon-nucleon scattering lengths

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

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

Importance of the kaonic atoms studies

Measuring the $\bar{K}N$ scattering lengths with the precision of a few percent will drastically change the present status of low-energy $\bar{K}N$ phenomenology and also provide a clear assessment of the SU(3) chiral effective Lagrangian approach to low energy hadron interactions.

1. **Breakthrough in the *low-energy $\bar{K}N$ phenomenology*;**
2. **Threshold amplitude in QCD**
3. **Information on Λ(1405)**
4. **Contribute to the determination of the *KN sigma terms*, which give the degree of chiral symmetry breaking;**
5. **4 related alaso with the determination of the *strangeness content of the nucleon* from the KN sigma terms**

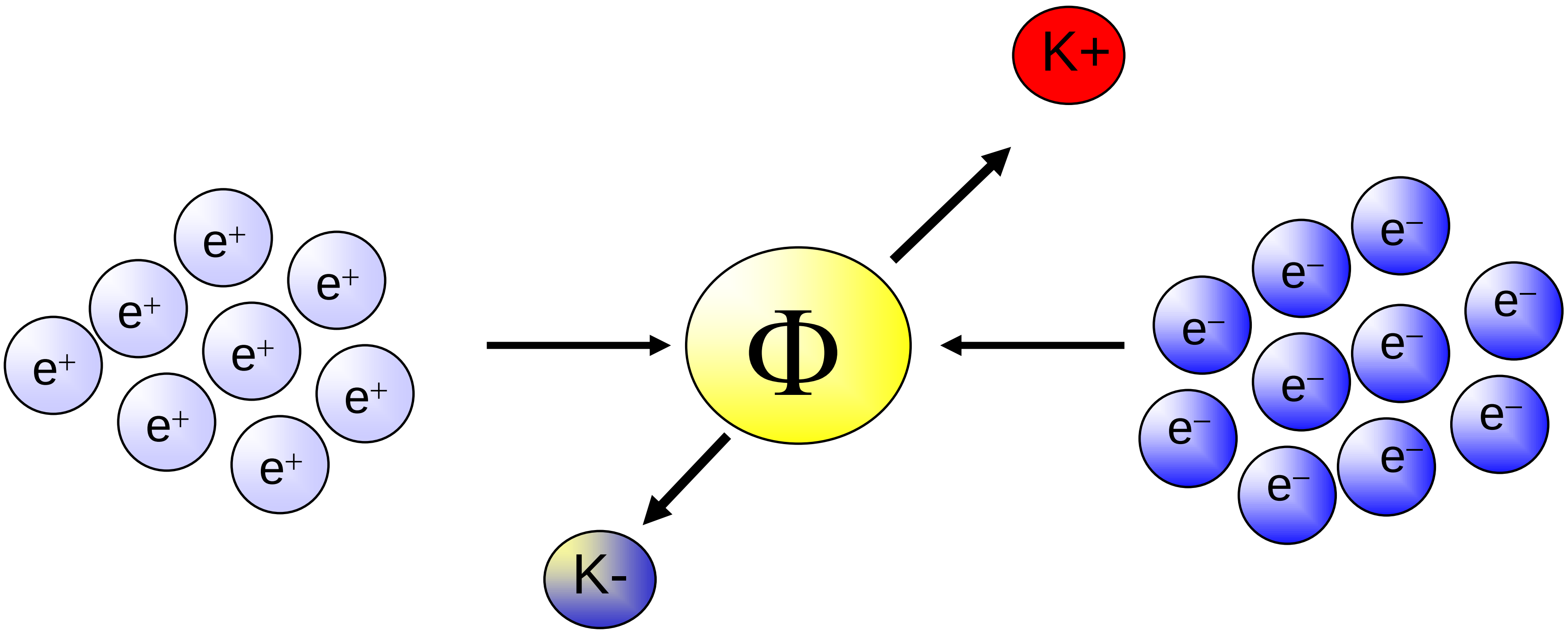
Kaonis atoms are fundamental tools for understanding QCD in non-perturbative regime:

- **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

DAΦNE

The DAFNE principle



Flux of produced kaons: about 1000/second

DAFNE

$e^- e^+$ collider

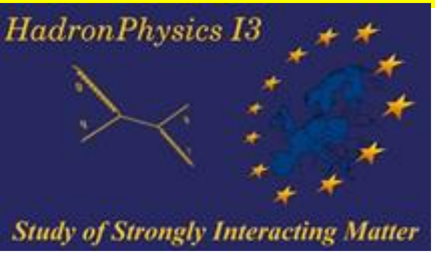
- **$\Phi \rightarrow K^- K^+$** (49.1%)
- **Monochromatic low-energy K^-** (~127MeV/c)
- **Less hadronic background due to the beam**

(compare to hadron beam line : e.g. KEK /JPARC)

Suitable for low-energy kaon physics:
kaonic atoms
Kaon-nucleons/nuclei interaction studies

SIDDHARTA

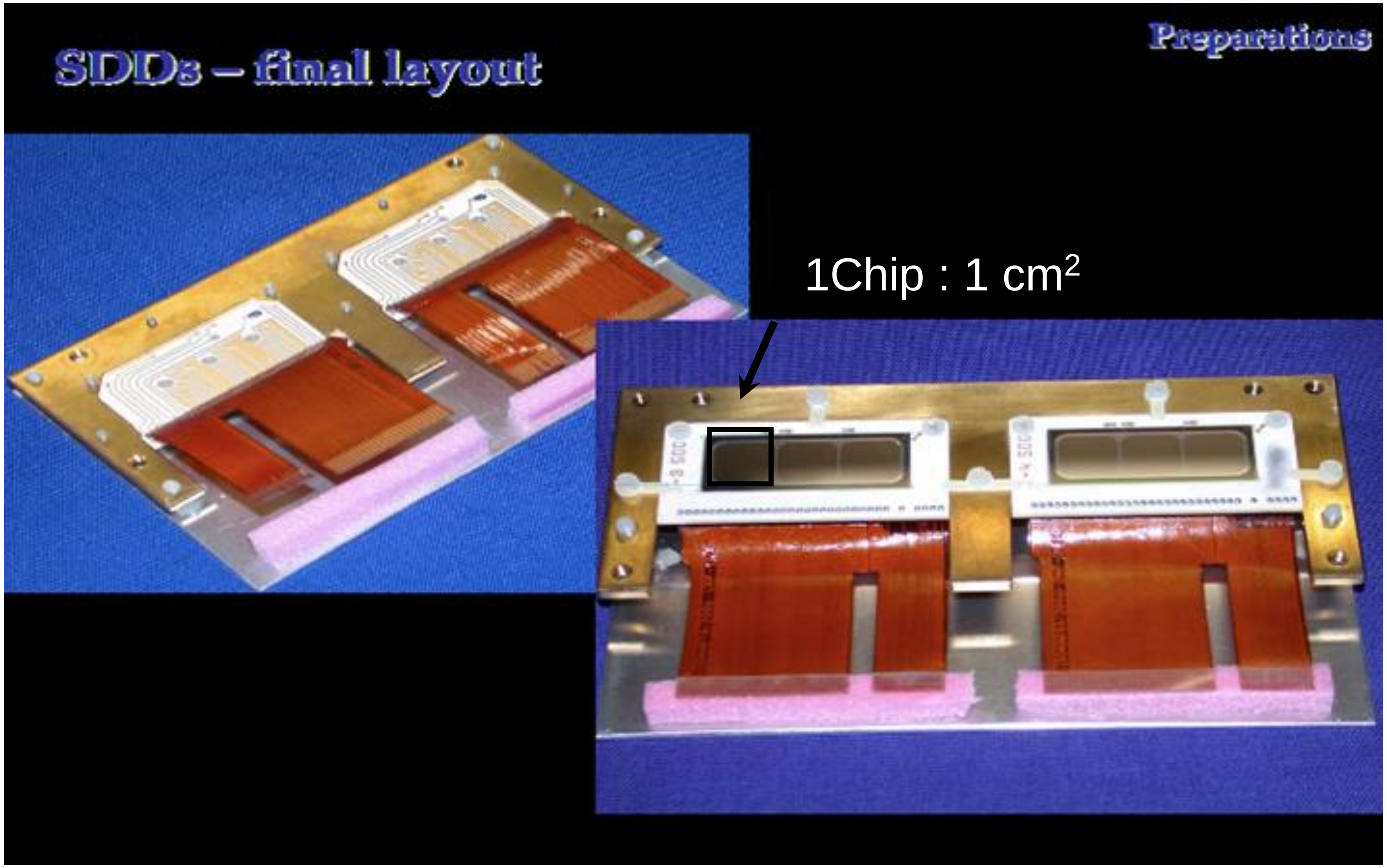
SIlicon Drift Detector for Hadronic Atom Research by Timing Applications



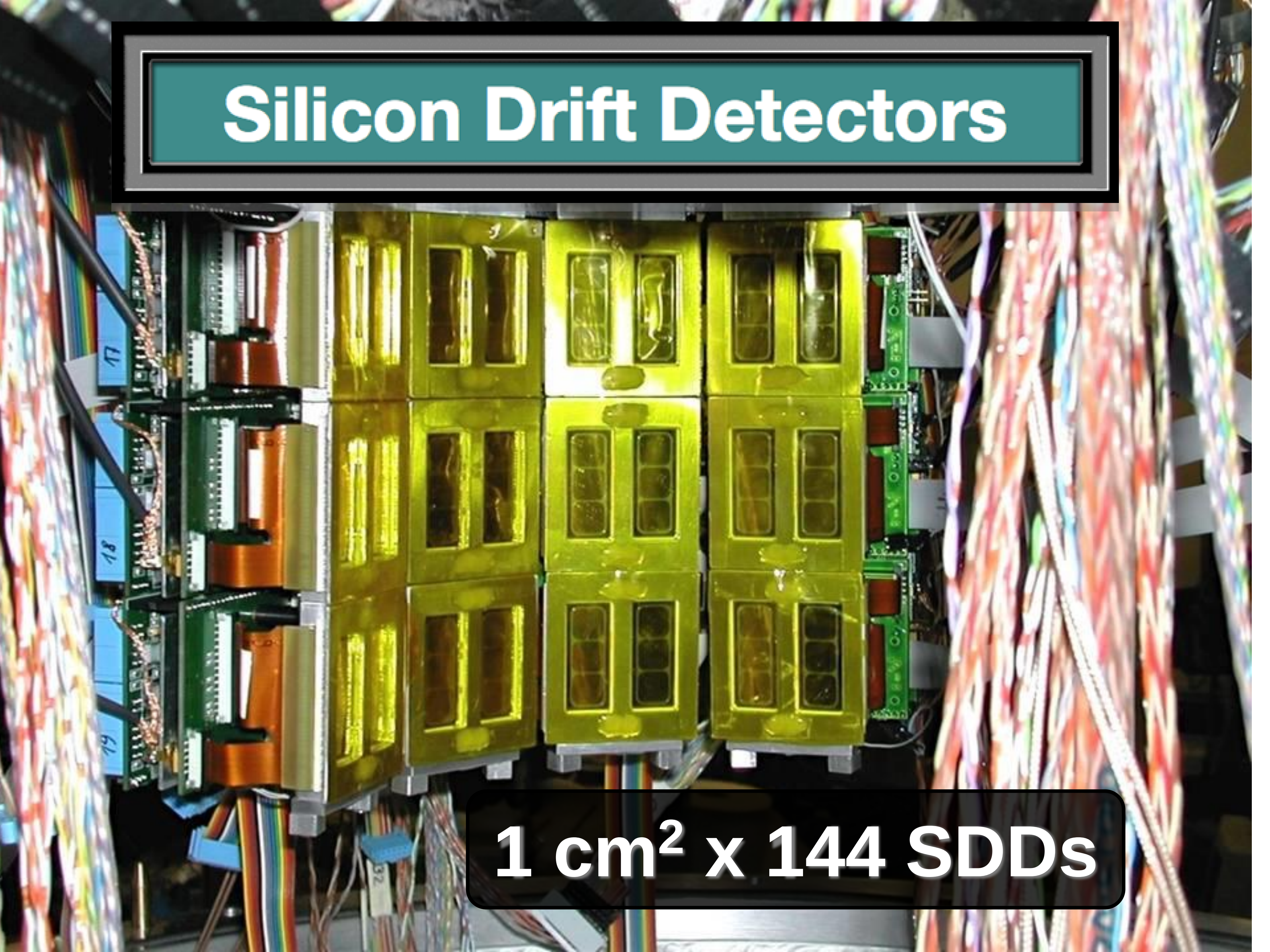
- LNF- INFN, Frascati, Italy
- SMI- ÖAW, Vienna, Austria
- IFIN – HH, Bucharest, Romania
- Politecnico, Milano, Italy
- MPE, Garching, Germany
- PNSensors, Munich, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada

EU Fundings: JRA10 – FP6 - I3H
FP7- I3HP2

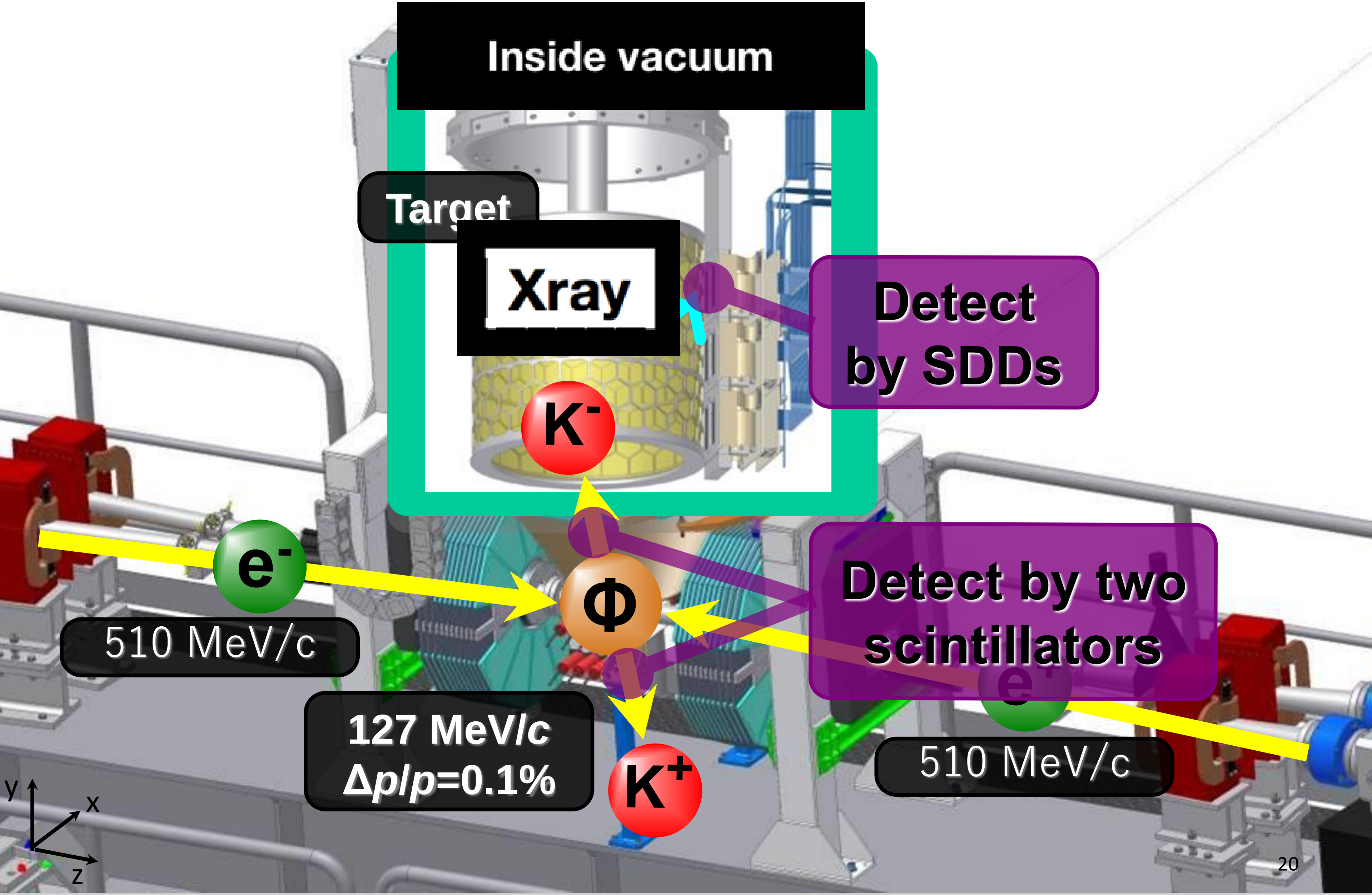
Silicon Drift Detector - SDD



Silicon Drift Detectors

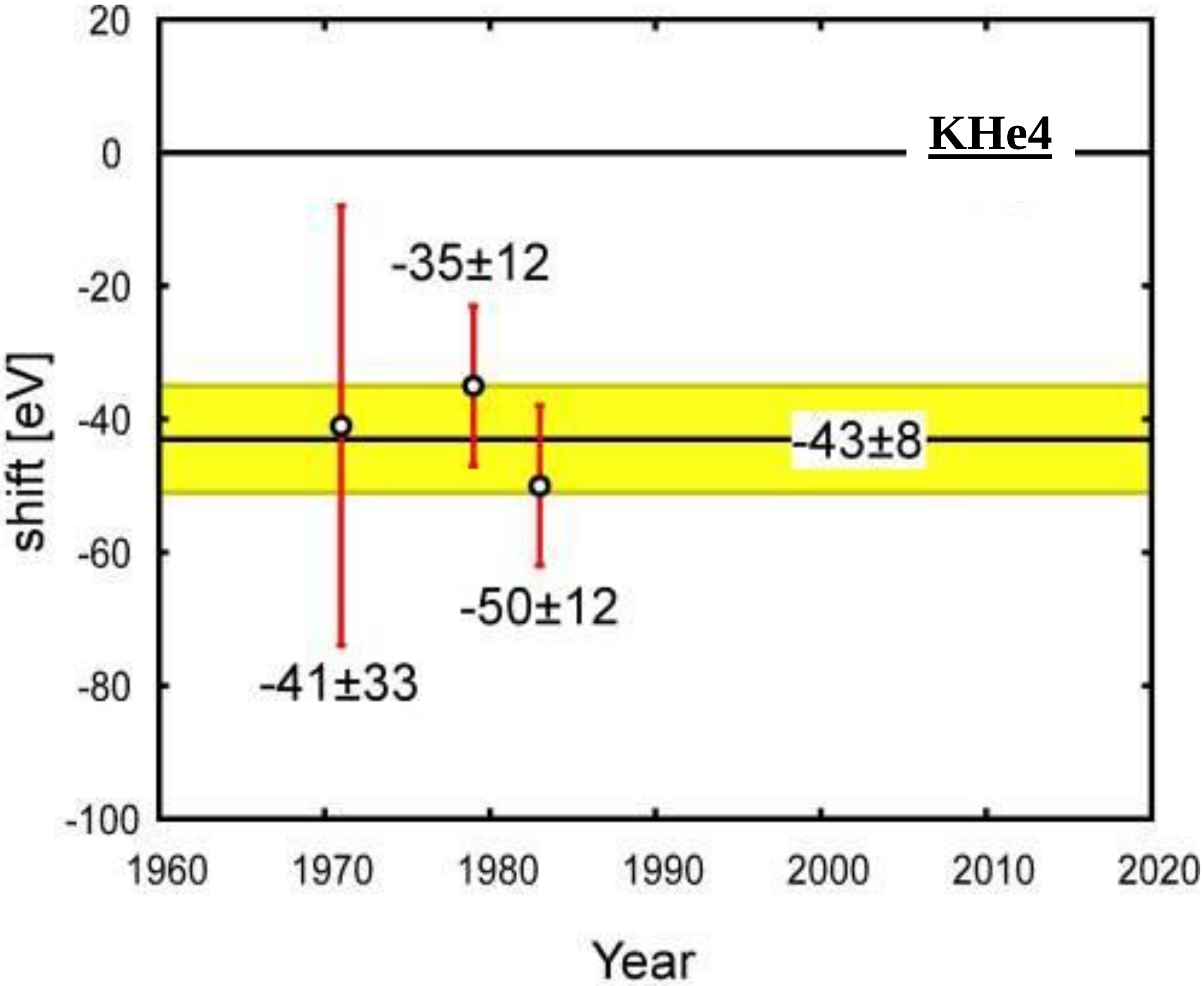


SIDDHARTA overview

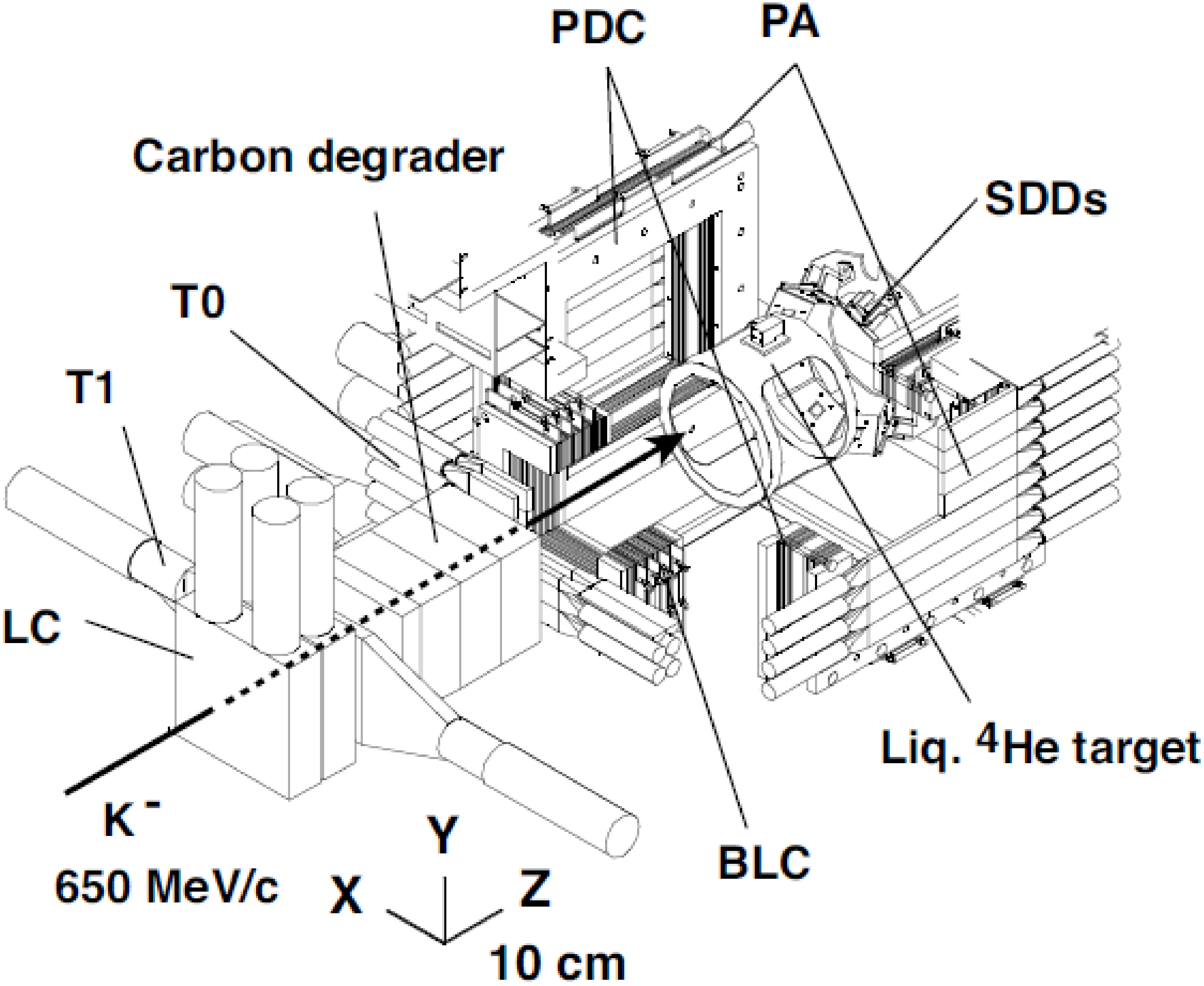


Kaonic helium (puzzle)

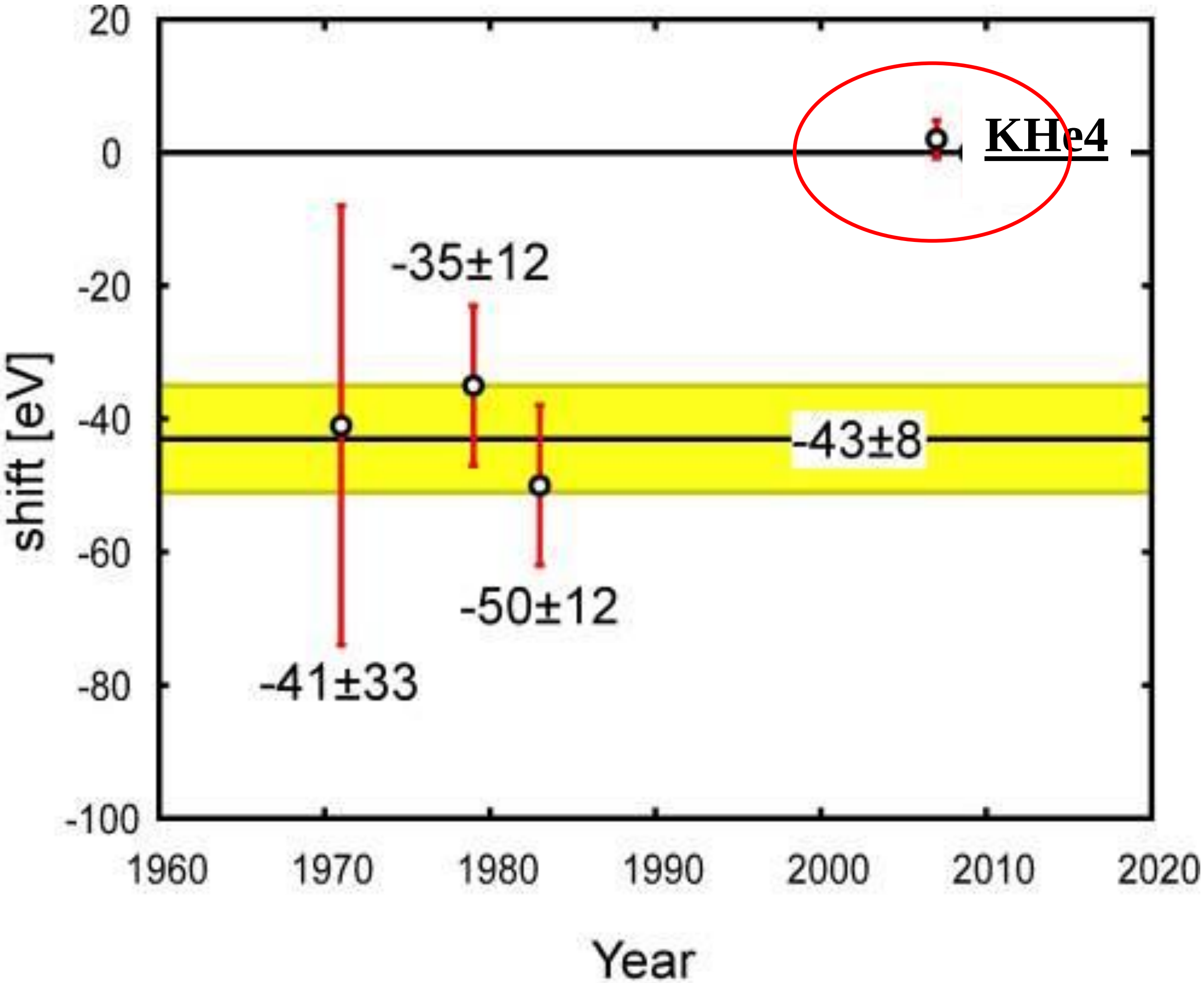
Kaonic 4 old data



E570 KEK

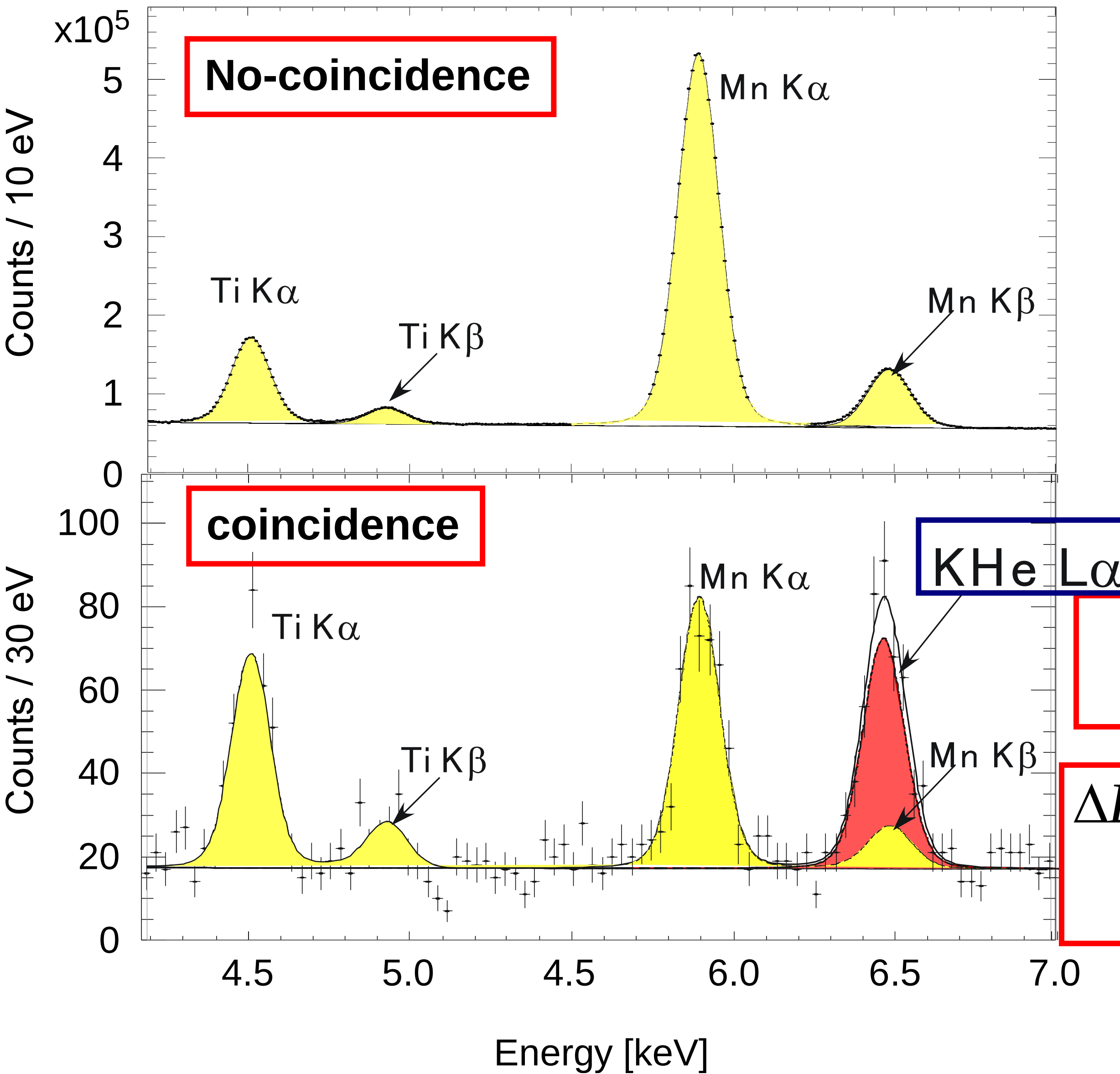

PDC
PA
Carbon degrader
SDDs
T0
T1
LC
K⁻
650 MeV/c
Y
X
Z
10 cm
BLC
Liq. ⁴He target

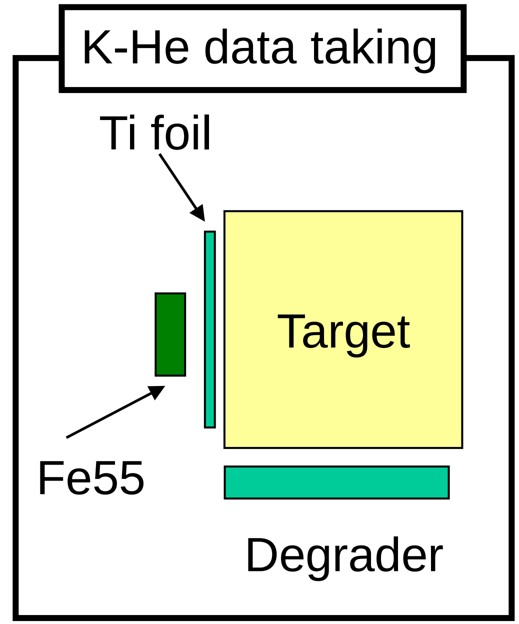
E570 solved the kaonic hydrogen puzzle



KHe-4 energy spectrum at SIDDHARTA

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

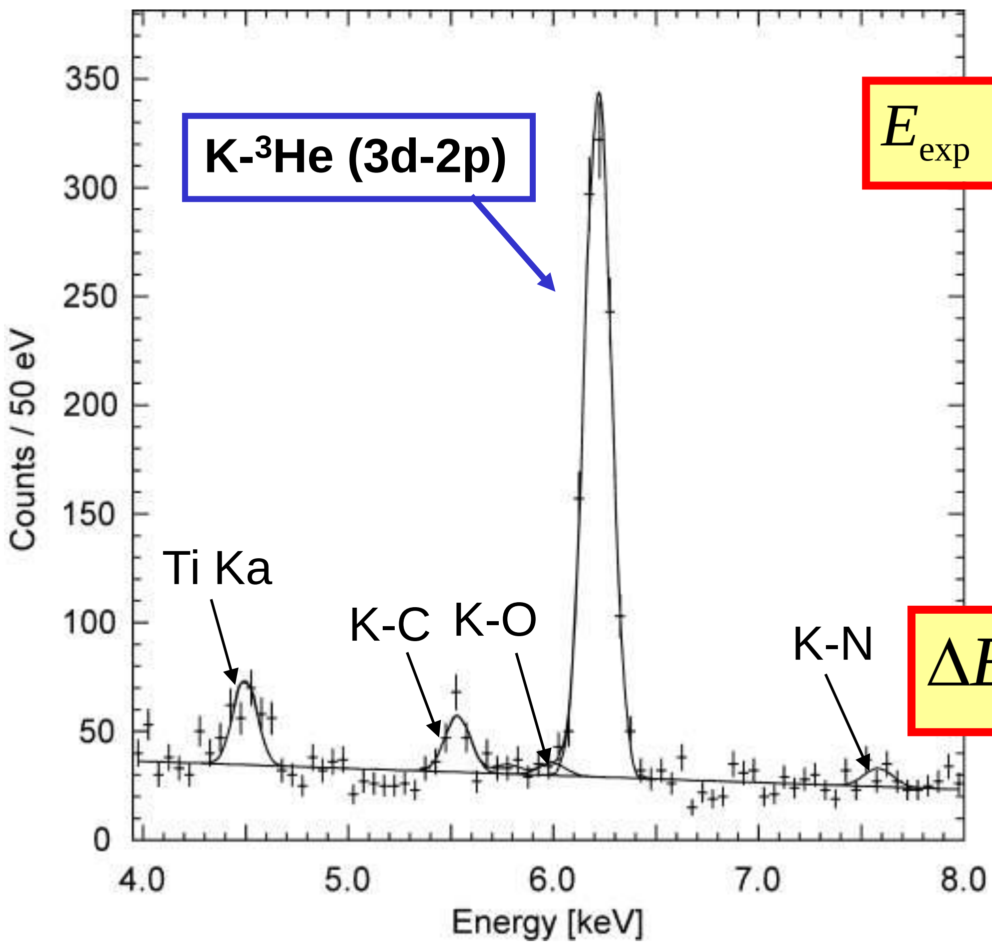




$$E_{\mathrm{exp}} = 6463.6 \pm 5.8 \text{ eV},$$

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

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

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

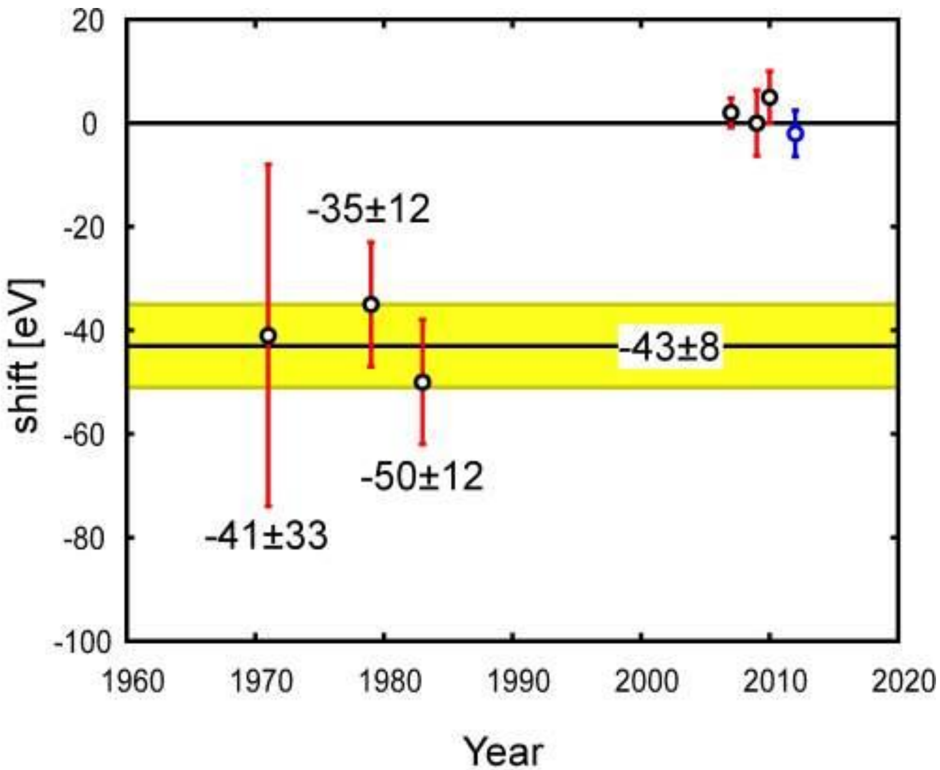
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

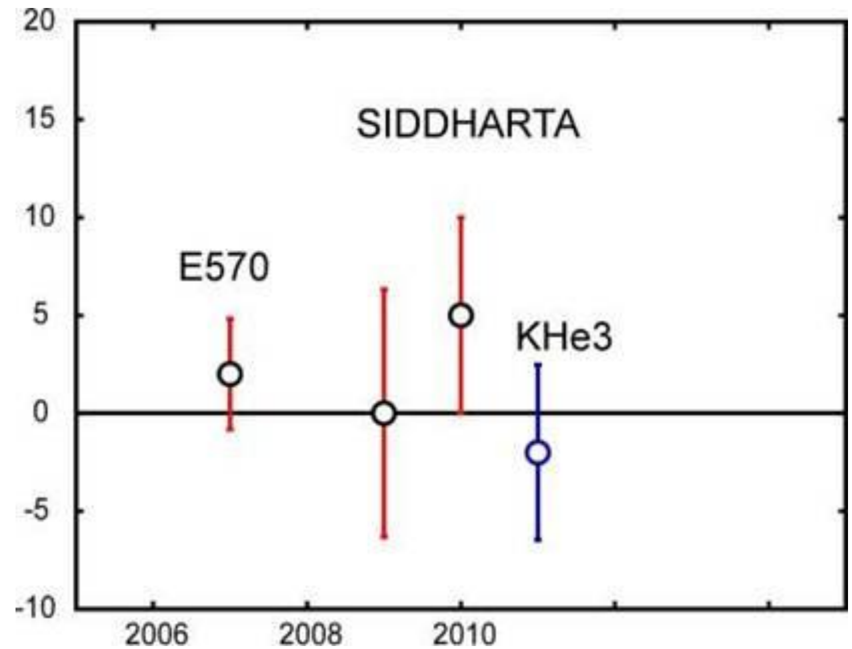
arXiv:1010.4631v1 [nucl-ex], PLB697(2011)199

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

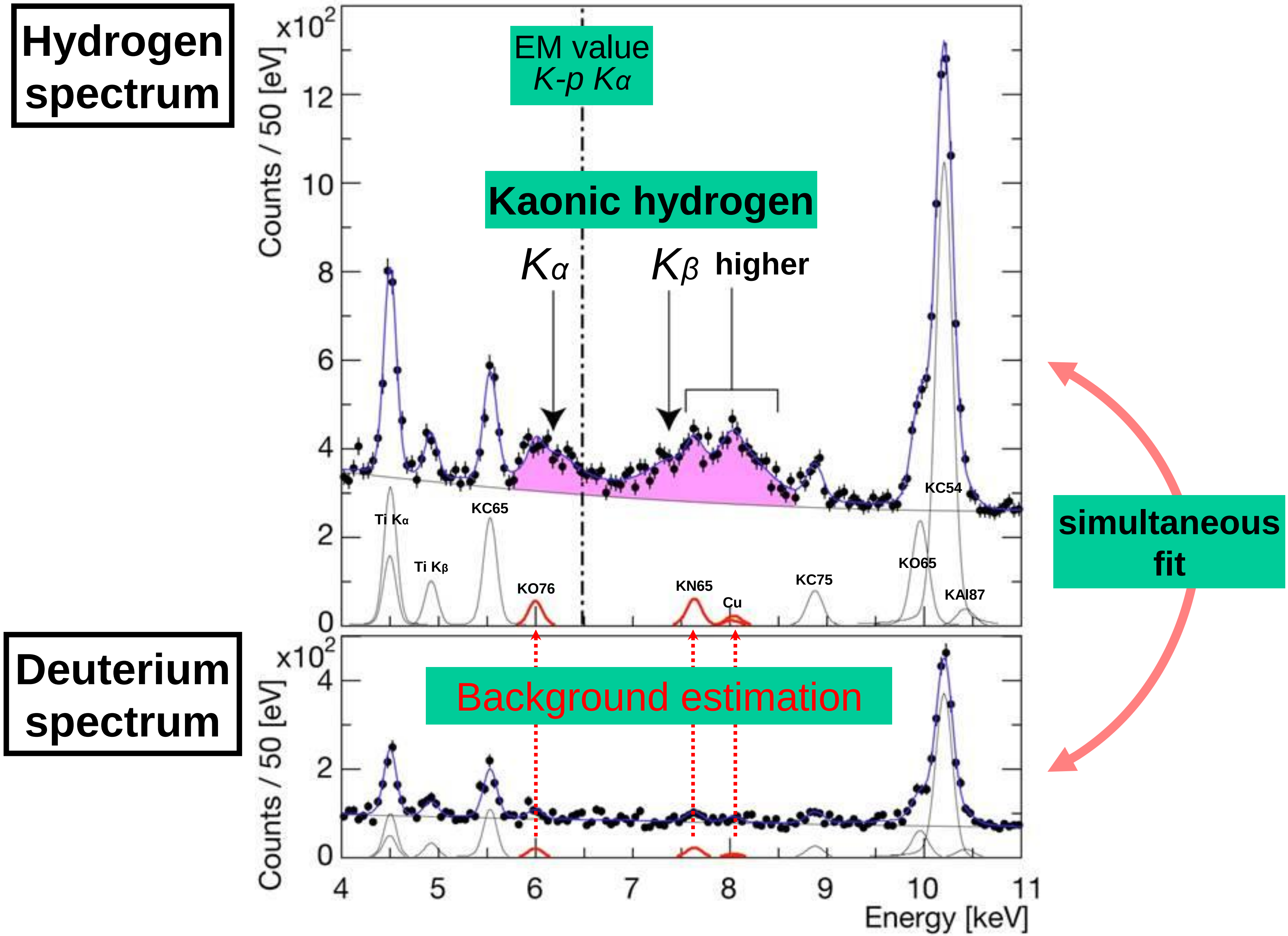
Comparison of results

	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	



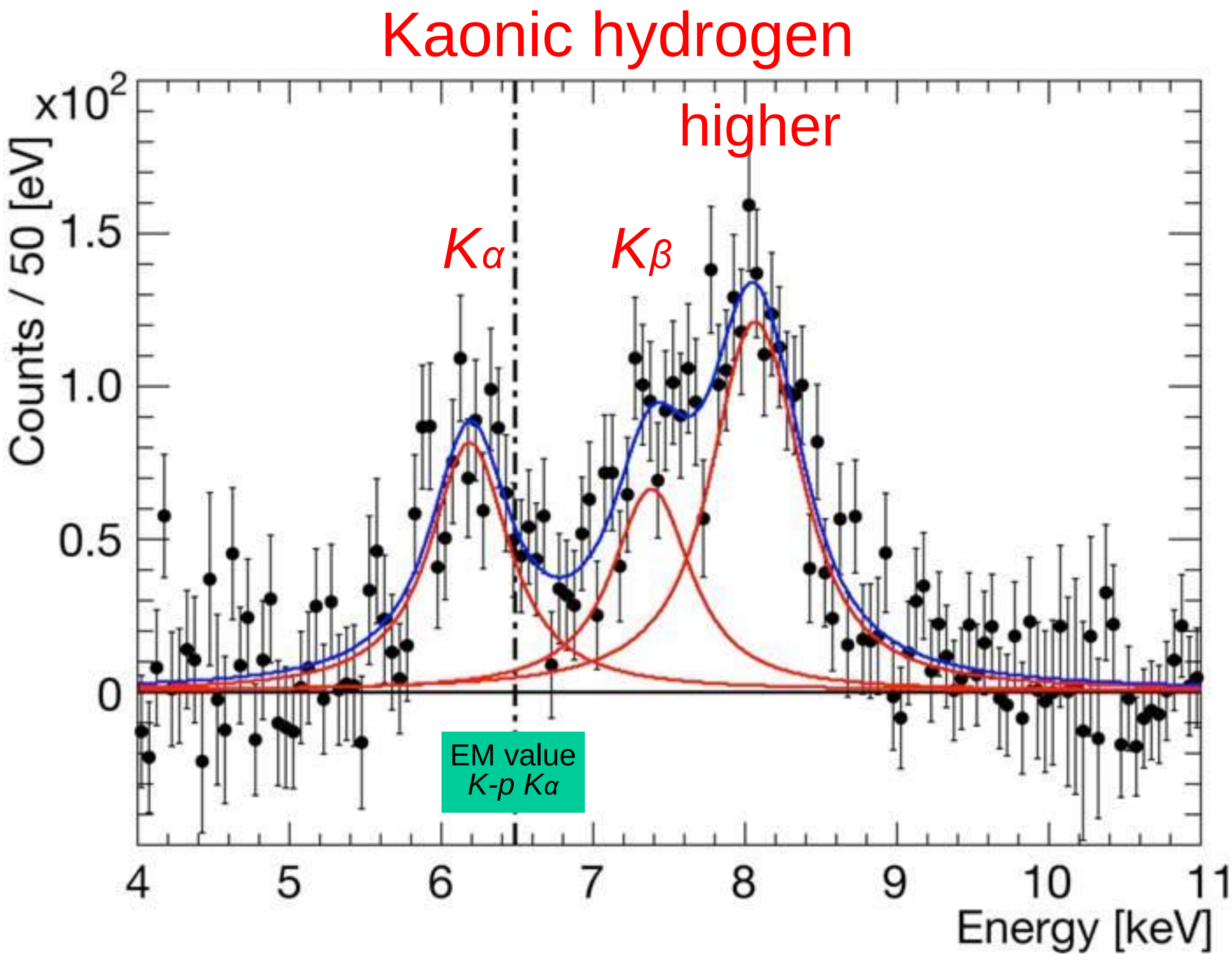


***error bar** $= \pm\sqrt{(stat)^2 + (syst)^2}$



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
Background estimation
simultaneous fit
Counts / 50 [eV]
x10²
Energy [keV]

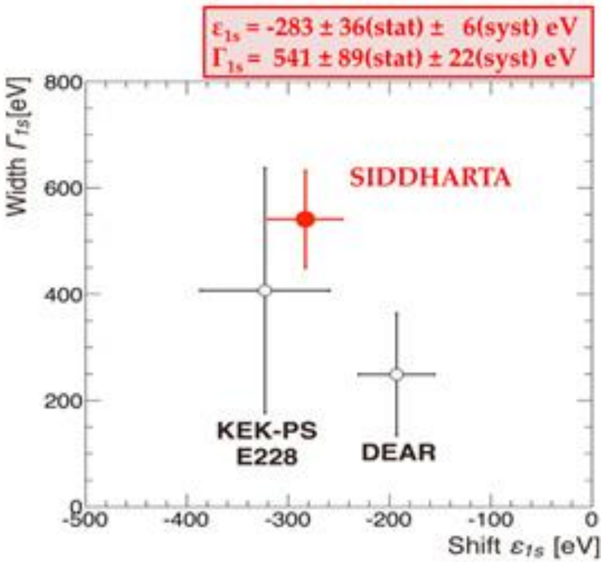
Residuals of K-p x-ray spectrum after subtraction of fitted background



KAONIC HYDROGEN results

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

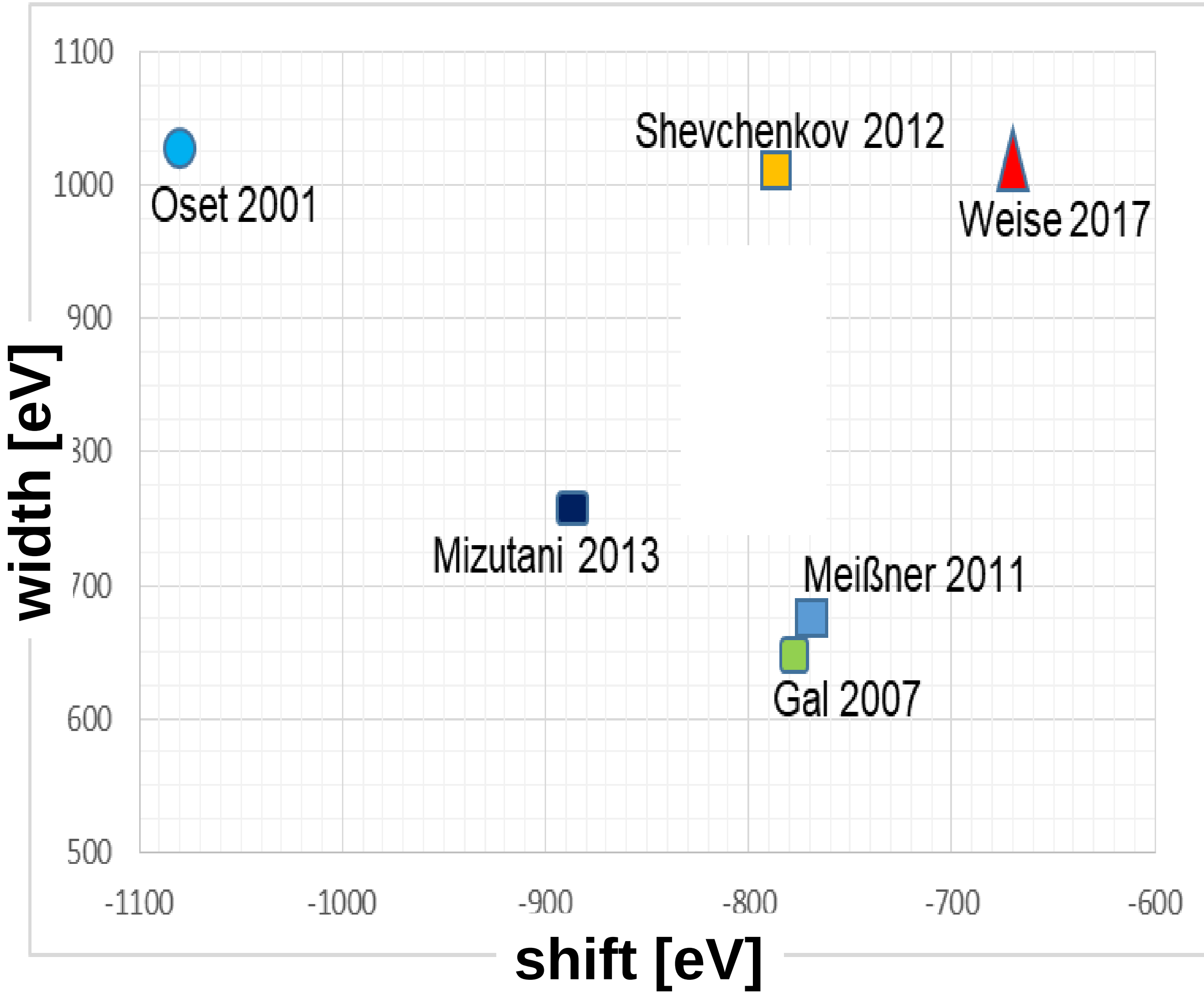
$$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV}$$



Phys. Lett. B 704 (2011) 113

SIDDHARTA-2
Kaonic Deuterium

Theory for kaonic deuterium



SIDDHARTA-2

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

HadronPhysics2 – Study of Strongly Interacting Matter

HadronPhysics I3 – Study of Strongly Interacting Matter

FWF Der Wissenschaftsfonds.

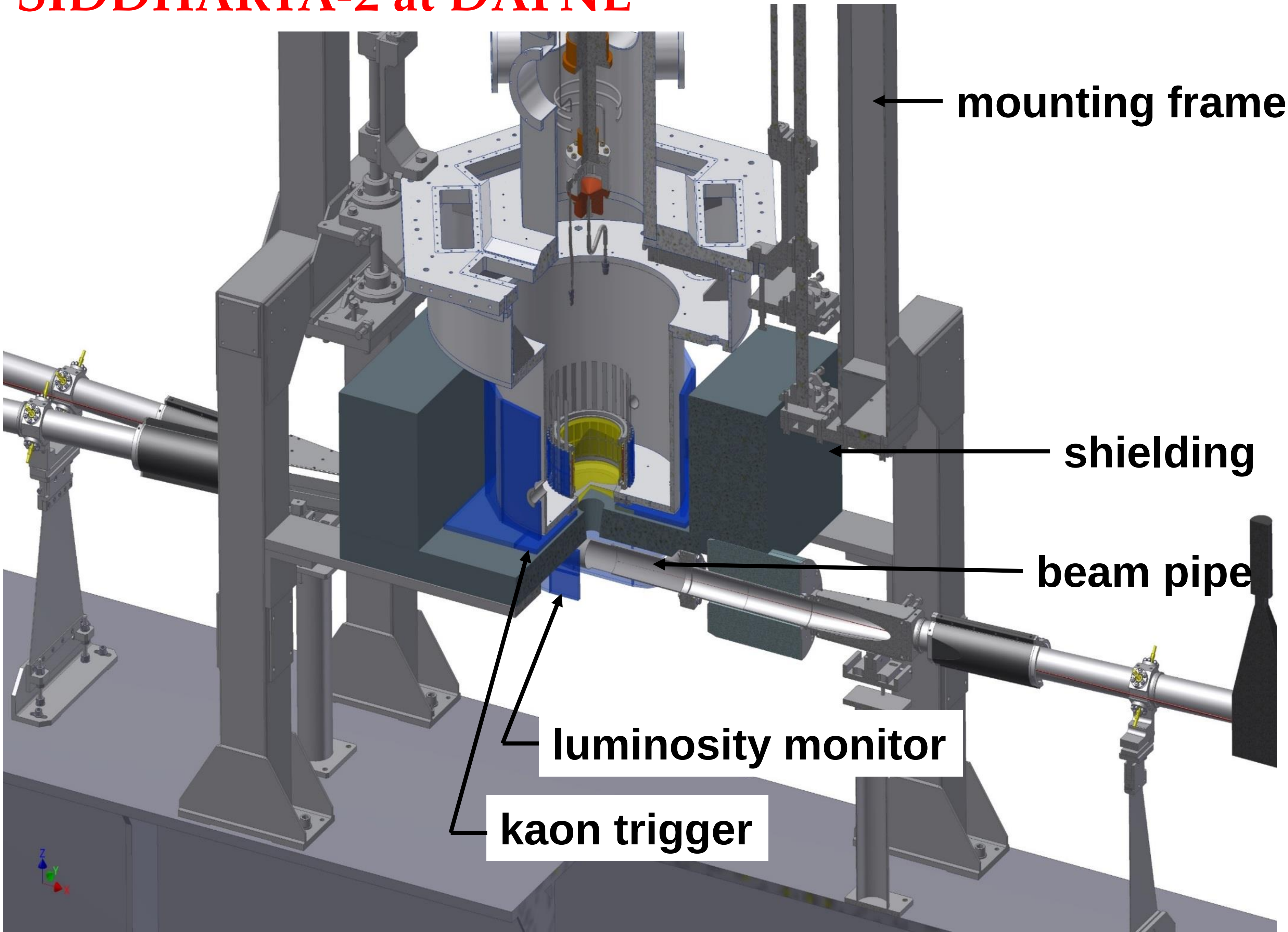
Farnesina – Ministero degli Affari Esteri e della Cooperazione Internazionale

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
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
Research Center for Electron Photon Science (ELPH), Tohoku University
CERN, Switzerland

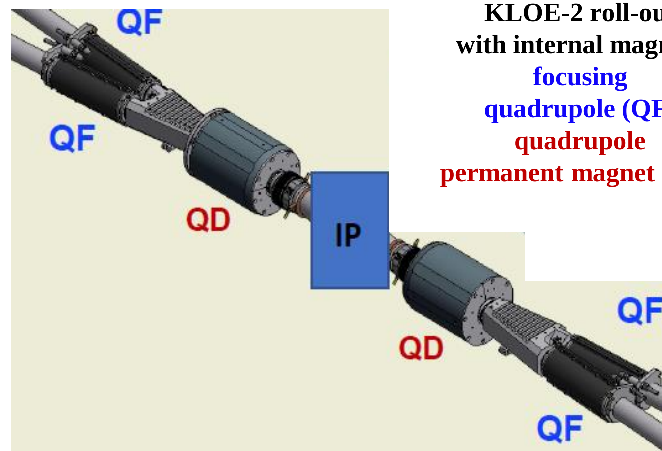
STRONG-2020

Croatian Science Foundation, research project 8570

SIDDHARTA-2 at DAFNE

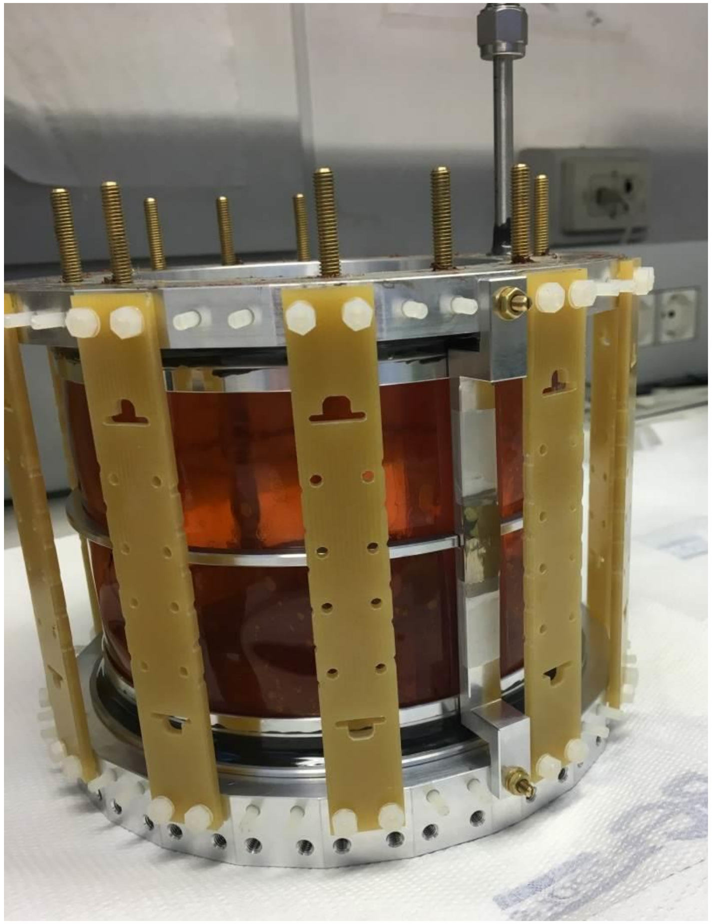


New platform near to interaction region



KLOE-2 roll-out
with internal magnets
focusing
quadrupole (QF)
quadrupole
permanent magnet (QD)

Light target and Silicon Drift Detector assembly

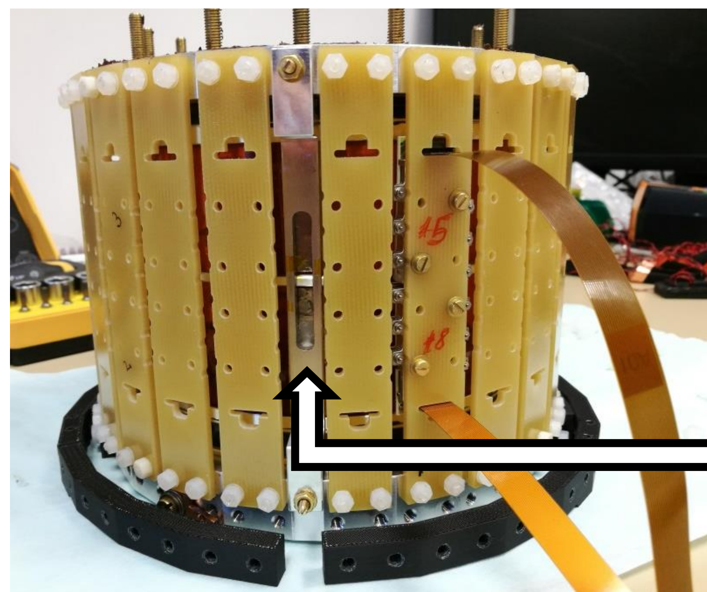


increase the target stopping power

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

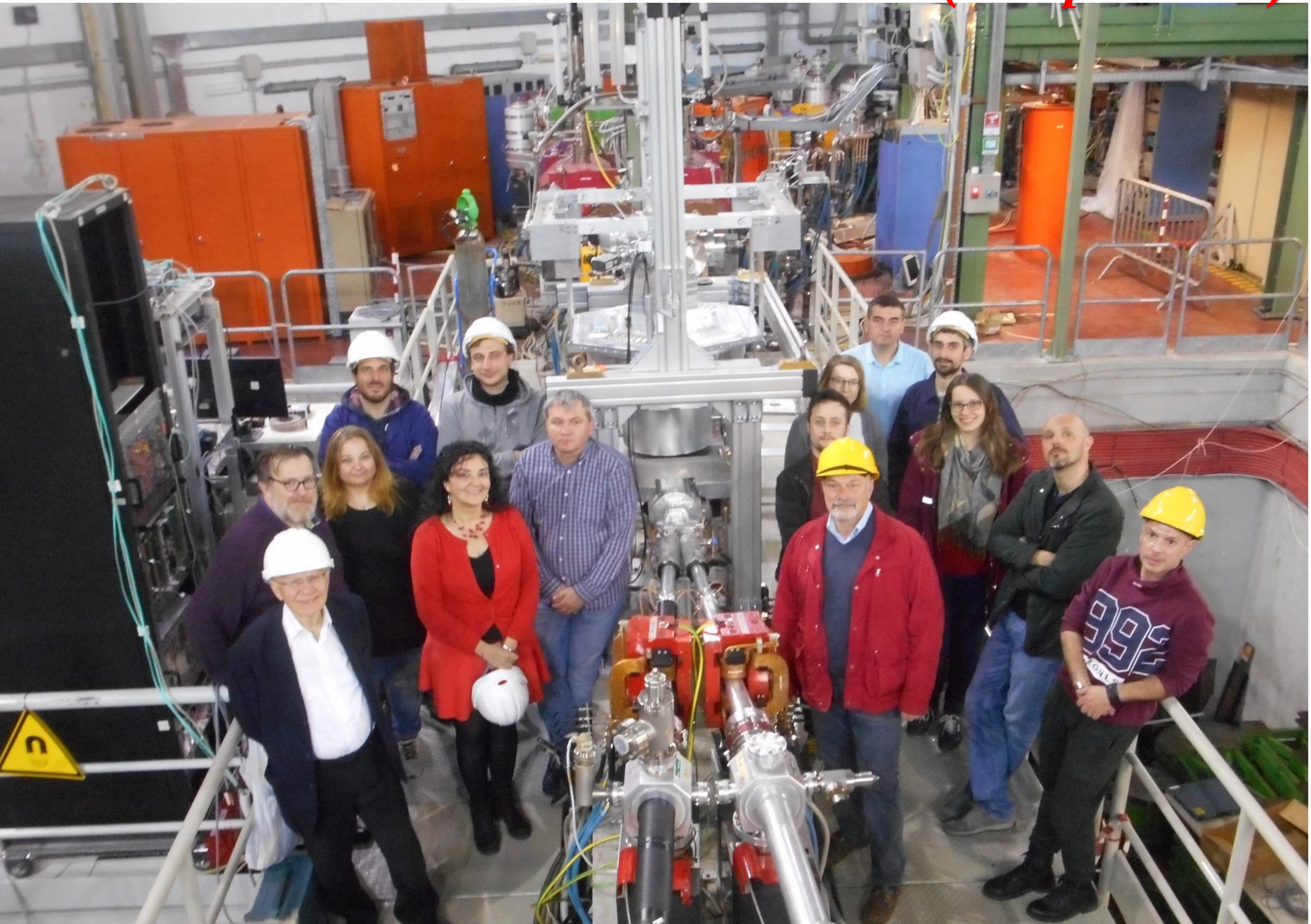
SDDs placed 5 mm from the target wall

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



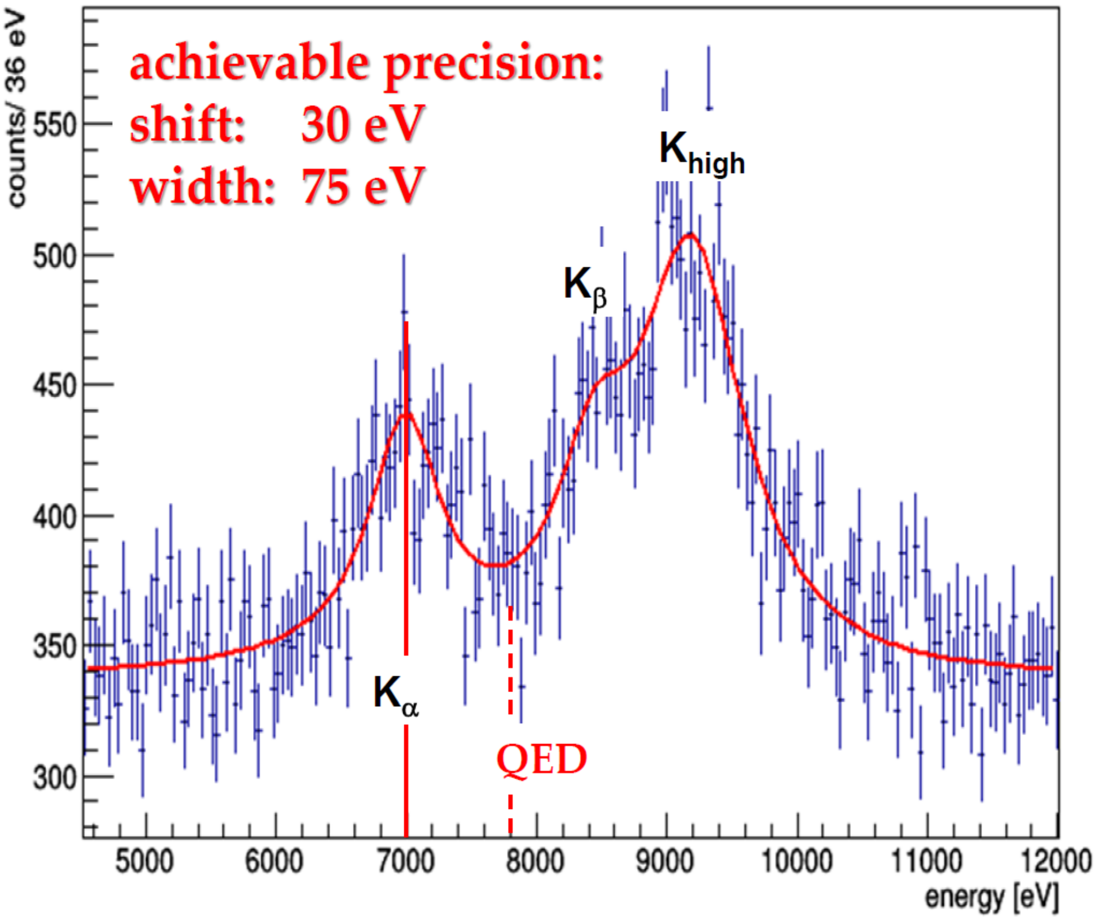
calibration foils inserted near to the SDD are activated by the X-ray tubes

SIDDHARTINO installed on DAFNE (17 April 2019)



SDDHARTA-2 expected result (2021)

Geant4 simulated $K^{-}d$ X-ray spectrum for 800 pb^{-1}

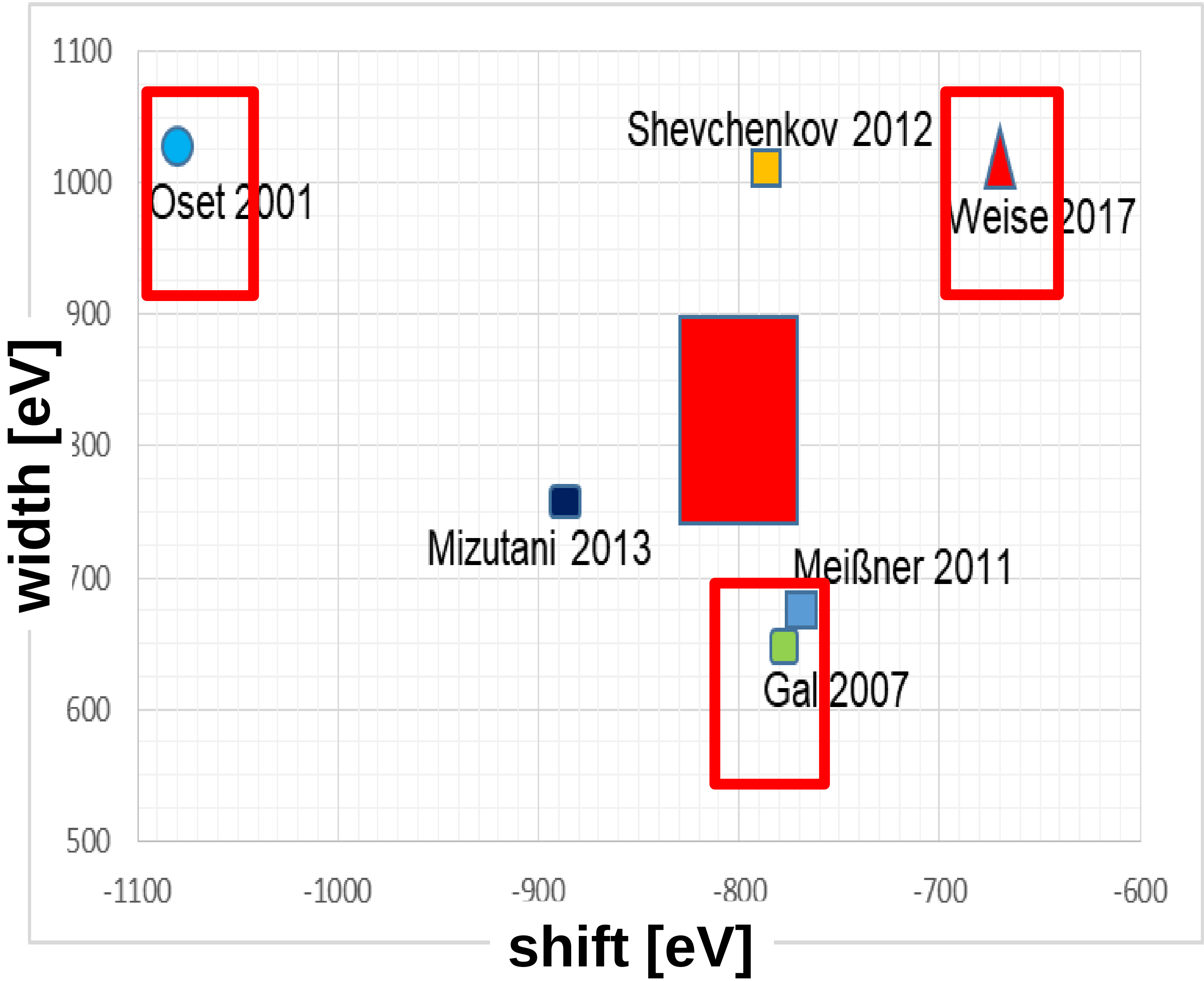


signal: shift - 800 eV
width 800 eV
density: 3% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
yield ratio as in $K^{-}p$
S/B ~ 1 : 3

- charged particle veto
- asynchronous BG

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

- **Other light kaonic atoms ($K^- O$, $K^- C$,…)**
- **Heavier kaonic atoms ($K^- Si$, $K^- Pb$…)**
- **Radiative kaon capture – Λ(1405) study**
- **Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)**

- ***Gamma Factory? Access kaonic atom states which cannot be accessed at DAFNE/JPARC***

Kaonic atoms have been less studied than pionic atoms, so this problem may be especially interesting. The rest energy of negative kaons is $m_{K^-}c^2 = 494\,\mathrm{MeV}$, so we need much higher photon energies than those for pionic atoms. This may, in principle, be achieved with higher-energy laser photons. At the GF, the energy of secondary photons is $\approx 4\gamma^2$ times larger than that of primary photons with γ up to 3000. When $\gamma = 3000$, primary photons should have energies of 13.7 eV to get 494 MeV secondary photons.

tween the pion or kaon with nucleons, nuclear structure and nuclear forces forming the structure, including, for example, the neutron skin problem related to the prediction of the neutron-star equation of state and maximal neutron-star mass. Understanding the kaon-nucleus interaction is important for testing the hypothesis of a possible K-condensation in neutron stars (see, for example, Ref. [25]). This study of the strong interaction effects is, in fact, the main aim of the pion- and kaon-atom production. Production of $1s$ states in heavy elements, so

Needs further work and understanding – how to detect? More on physics insight

We are moving ☺

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Accepted Paper

The modern era of light kaonic atom experiments

Rev. Mod. Phys.

Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

Accepted 8 March 2019

ABSTRACT

ABSTRACT

This review article covers the modern era of experimental kaonic atoms studies, encompassing twenty years of activity, defined by breakthroughs in technological developments which allowed performing a series of long-awaited precision measurements. Kaonic atoms are atomic systems where an electron is replaced by a negatively charged kaon, containing the strange quark, which interacts in the lowest orbits with the nucleus also by the strong interaction. As a result, their study offers the unique opportunity to perform experiments equivalent to scattering at vanishing relative energy. This allows to study the strong interaction between the antikaon and the nucleon or the nucleus "at threshold", namely at zero relative energy, without the need of {} extrapolation to zero energy, as in scattering experiments. The fast progress achieved in performing precision light kaonic atoms experiments, which also solved

Published 20th June 2019 <u>**Rev. Mod. Phys. 91, 025006**</u>

Future measurements planned at DAFNE promise to boost even farther our comprehension in "strangeness physics" and help having a better understanding of the role of strangeness in the Universe and of how Nature works.

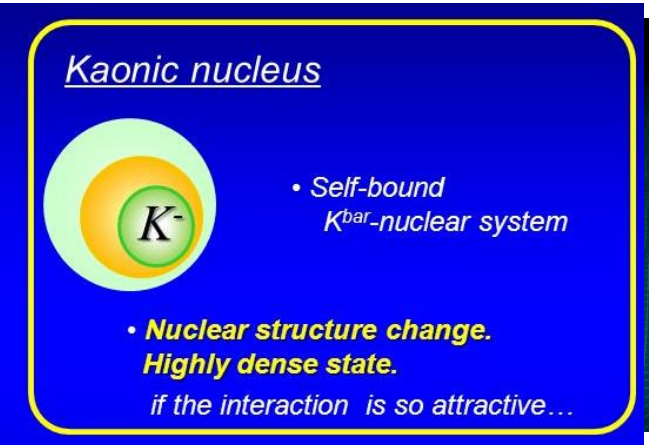
There is no exquisite
beauty without
some STRANGENESS
in the proportion.

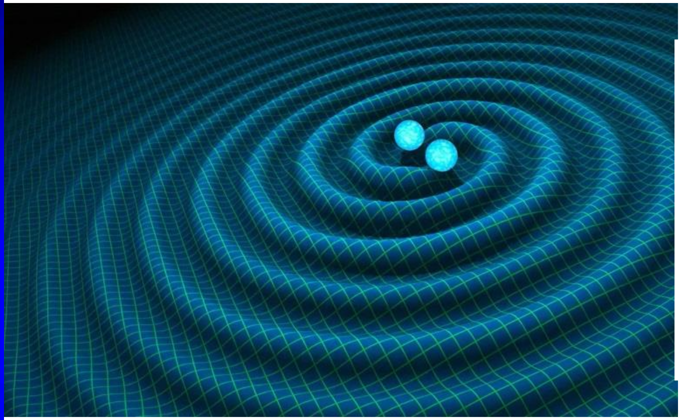
Edgar Allan Poe

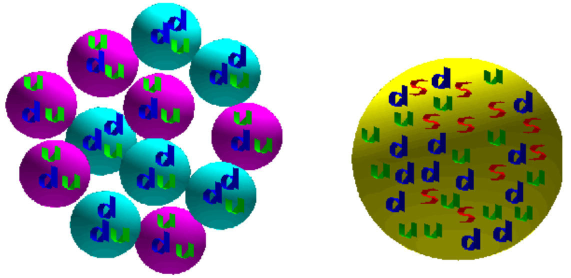
Thank you!

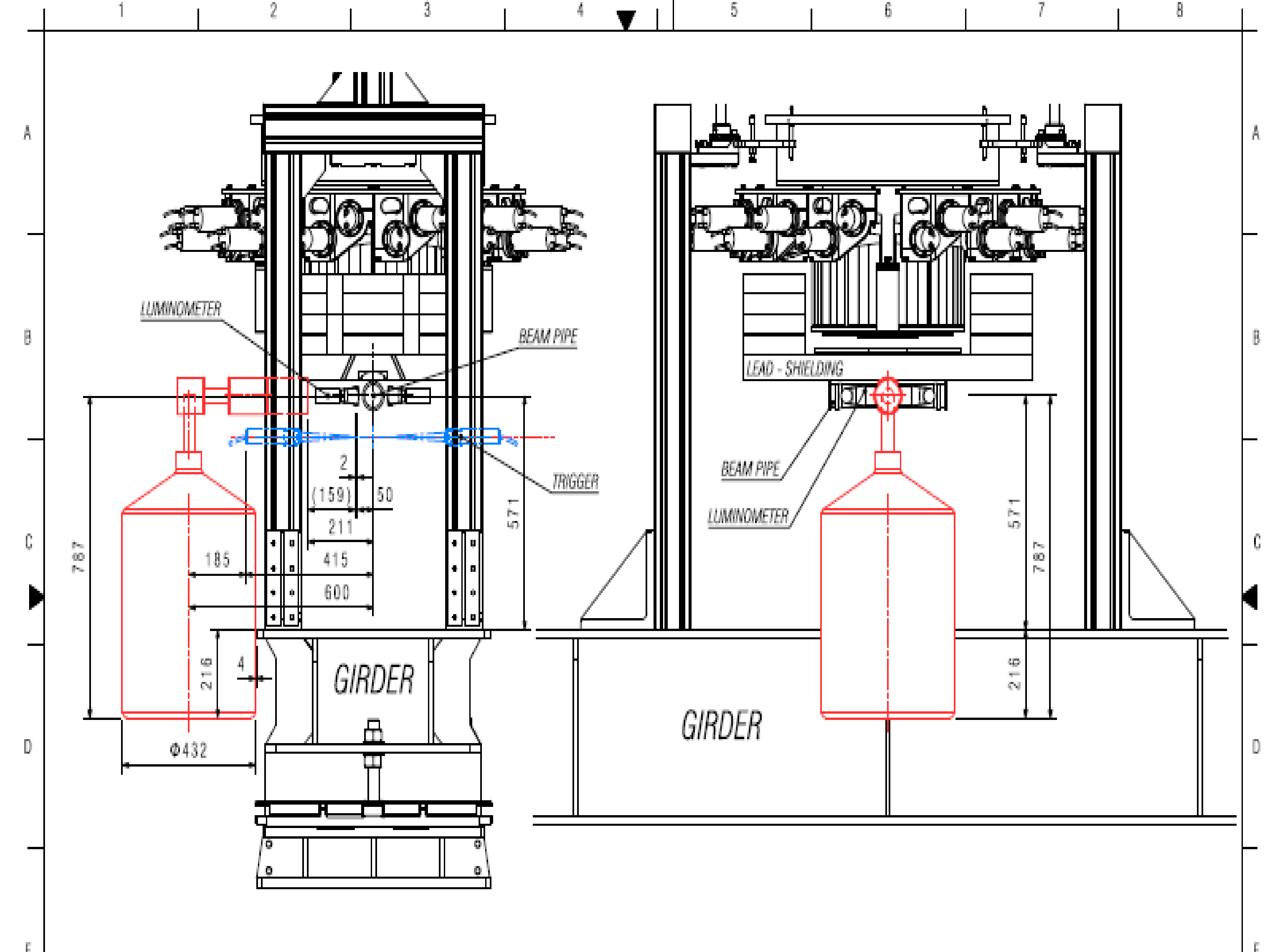
The Modern Era of precision measurements of hadronic (kaonic) atoms fosters a deeper understanding of the antikaon-nuclei interactions at threshold, which is fundamental to unveil the mechanisms at work on non-perturbative strangeness QCD.

Implications going from particle and nuclear physics to astrophysics.









LUMINOMETER
BEAM PIPE
TRIGGER
2
(159)
50
211
185
415
600
787
571
216
4
Φ432
GIRDER
LEAD - SHIELDING
BEAM PIPE
LUMINOMETER
571
787
216
GIRDER

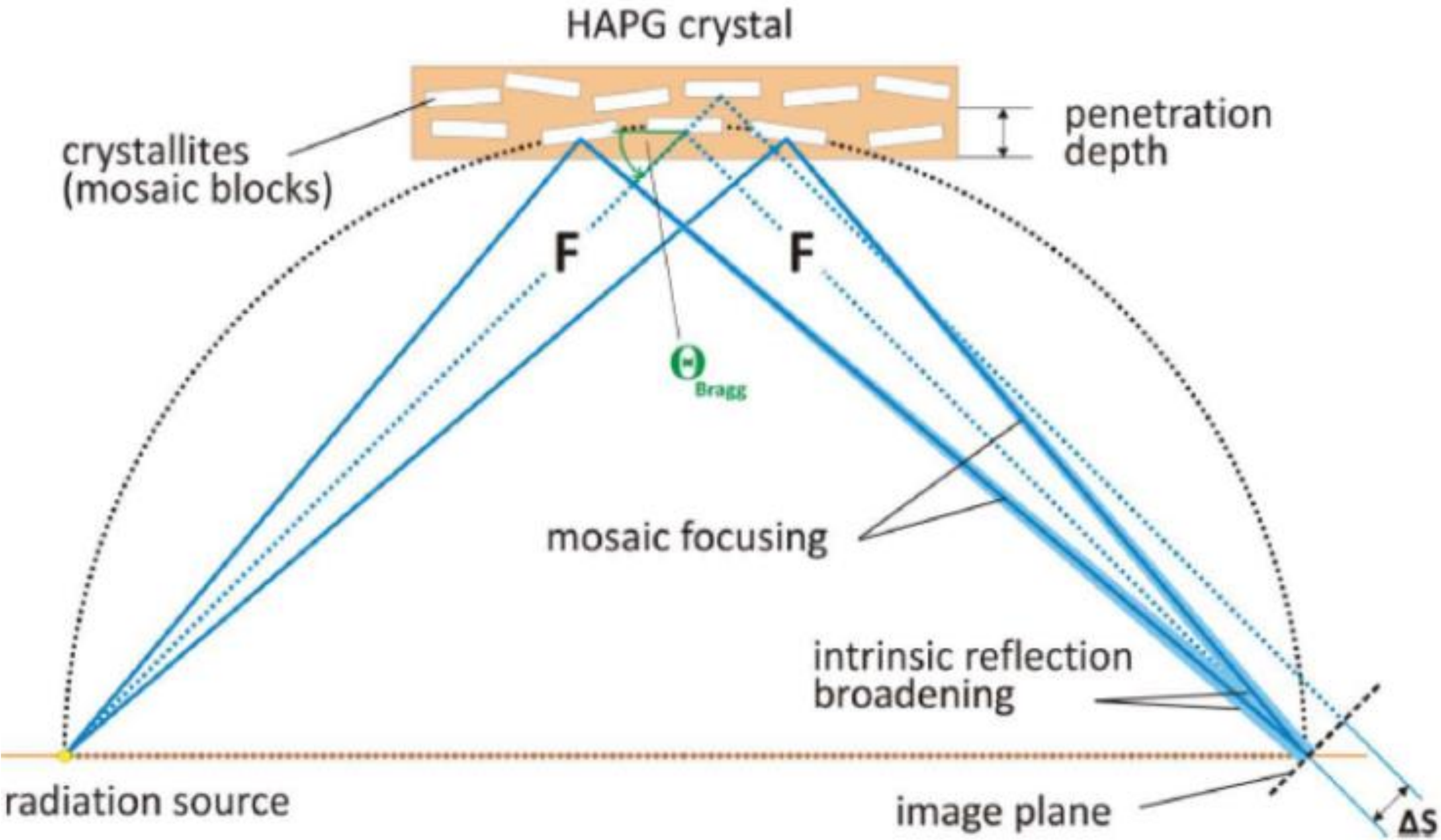
VOn hamos X-ray spectrometer for Extended Sources: VOXES

INFN-CSN5

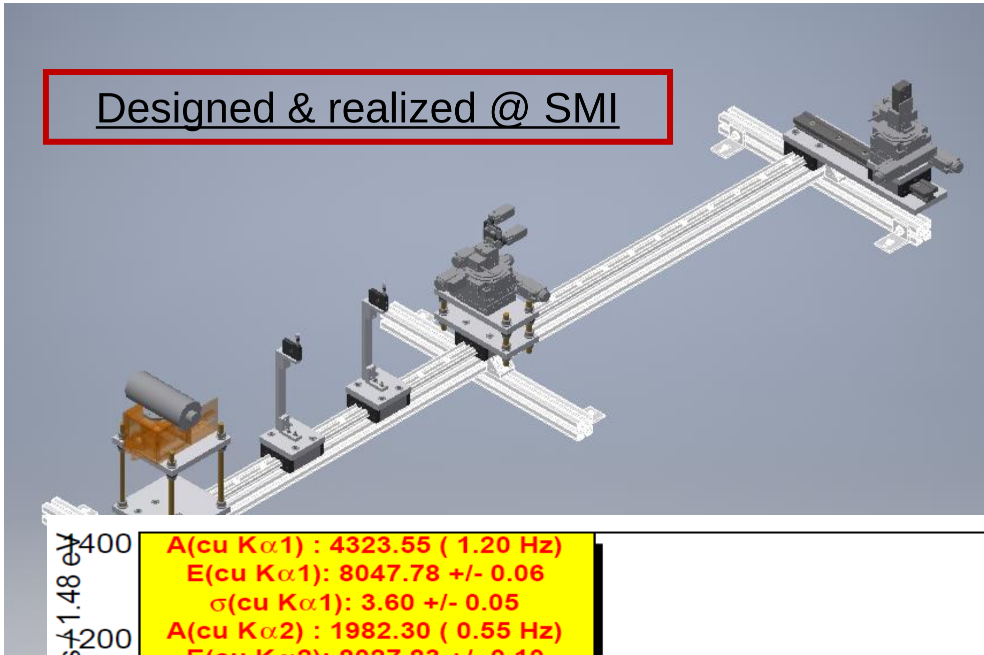
Young Researcher Grant 2015, n. 17367/2015.

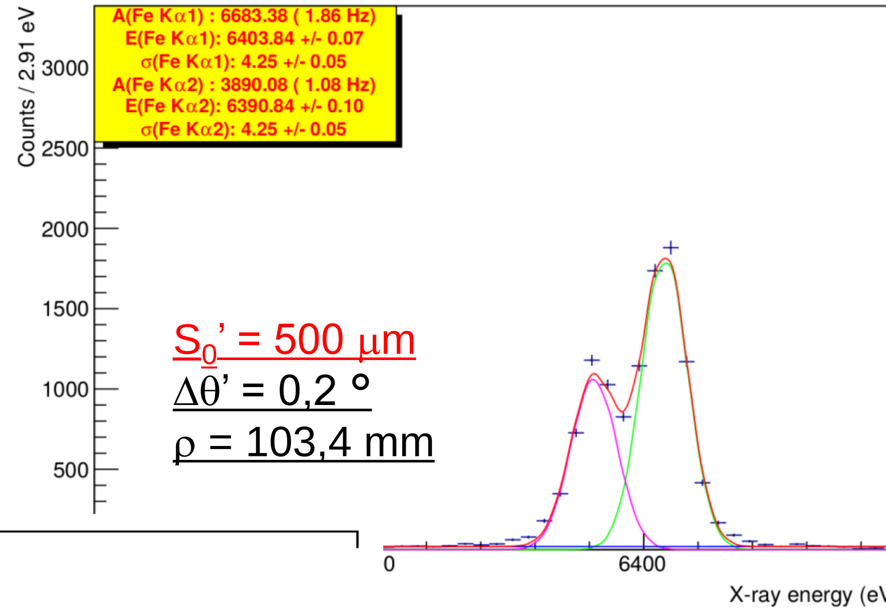
Alessandro Scordo (PI)
Laboratori Nazionali di Frascati, INFN

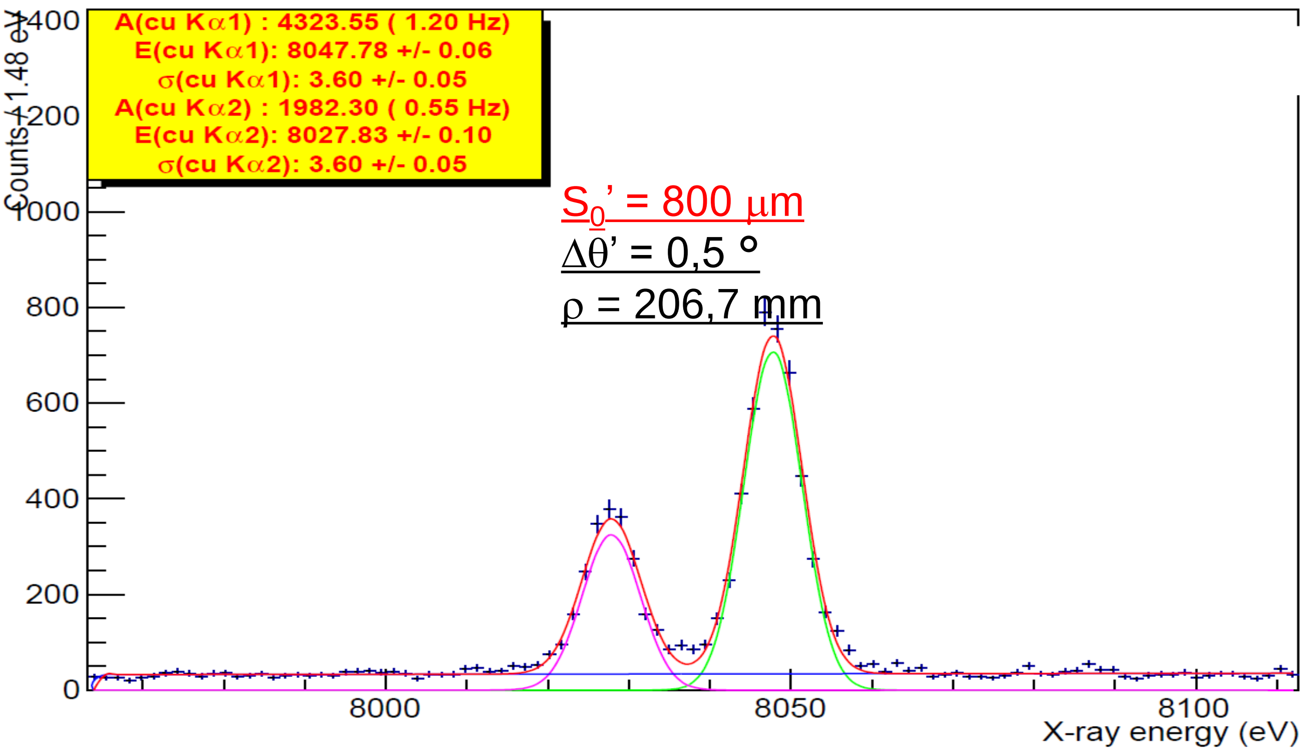
VOXES (Scordo @ LNF)



Multi line setup and complete characterization



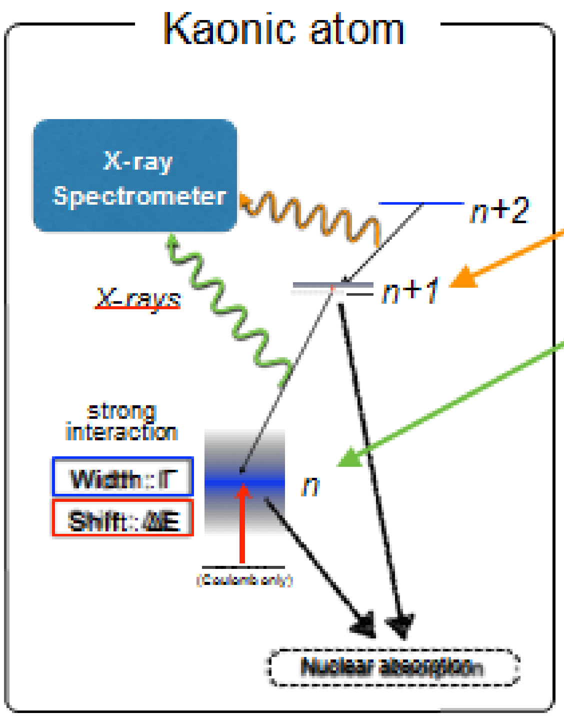




Feasibility tests for future measurements – (II)

WIKAMP proposal presented at DAFNE as ICFA, LNF December 17, 2018

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



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.

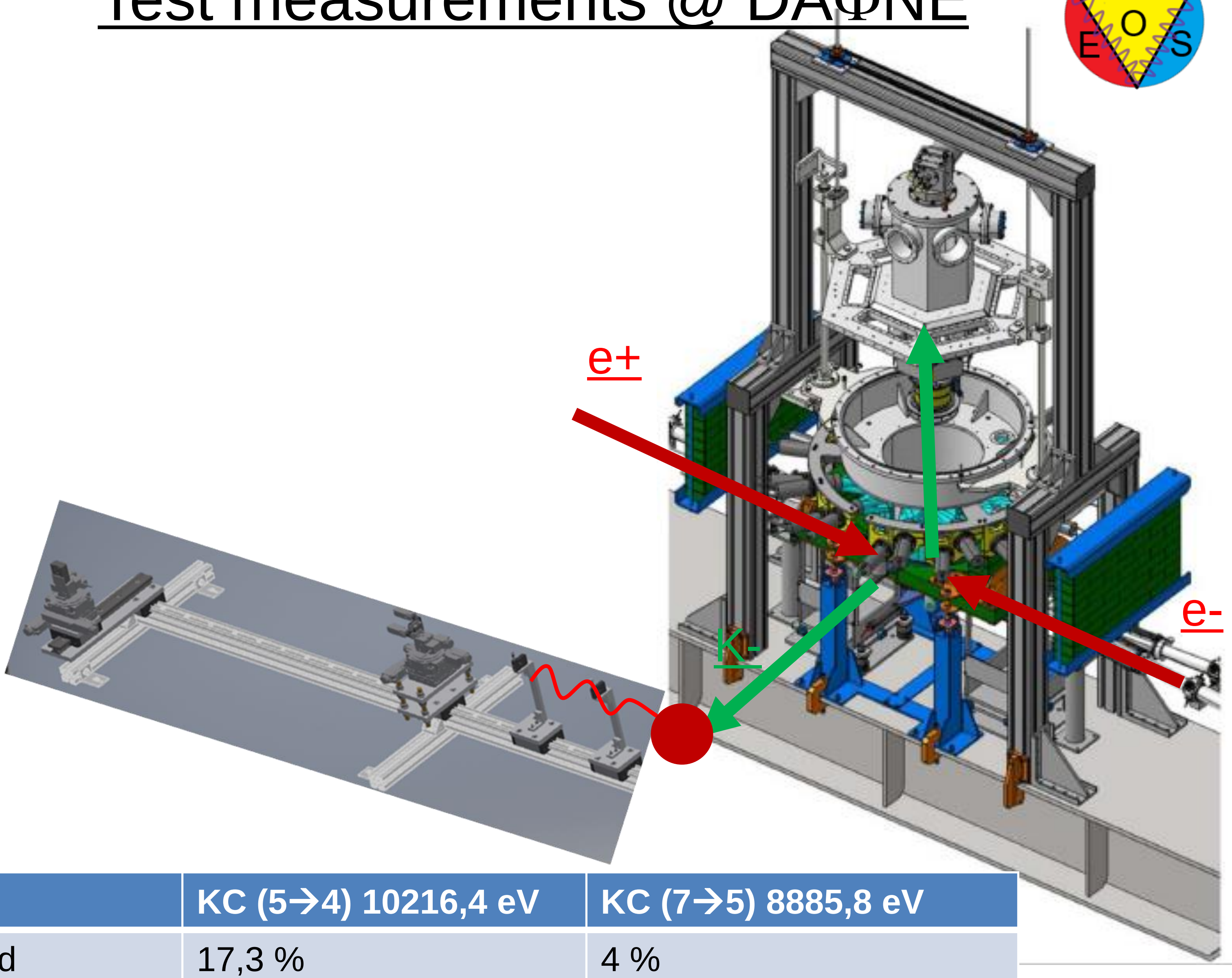
	r_m	Re(full)	Re(1N)	Re(mN)	Im(full)	Im(1N)	Im(mN)
Ni	3.72	3.34	3.82	2.86	3.73	4.46	3.12
Pb	5.56	5.21	5.71	4.78	5.46	6.23	5.00
			1N	mN		1N	mN

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

DAFNE-TF workshop - Dec. 17, 2018 15

- ❖kaon single-and multi-nucleon processes **using VOXES / TES**
- ❖determination of the charged kaon mass (K-) **using VOXES / TES**

Test measurements @ DAΦNE



	KC (5→4) 10216,4 eV	KC (7→5) 8885,8 eV
Yield	17,3 %	4 %
ev / 200 gg	95	16
δE (200 gg)	(<=) 0,7 eV	(≈) 1,6 eV