Advanced Kaonic Atom Measurements at DAΦNE collider:

The SIDDHARTA-2 experiment and beyond

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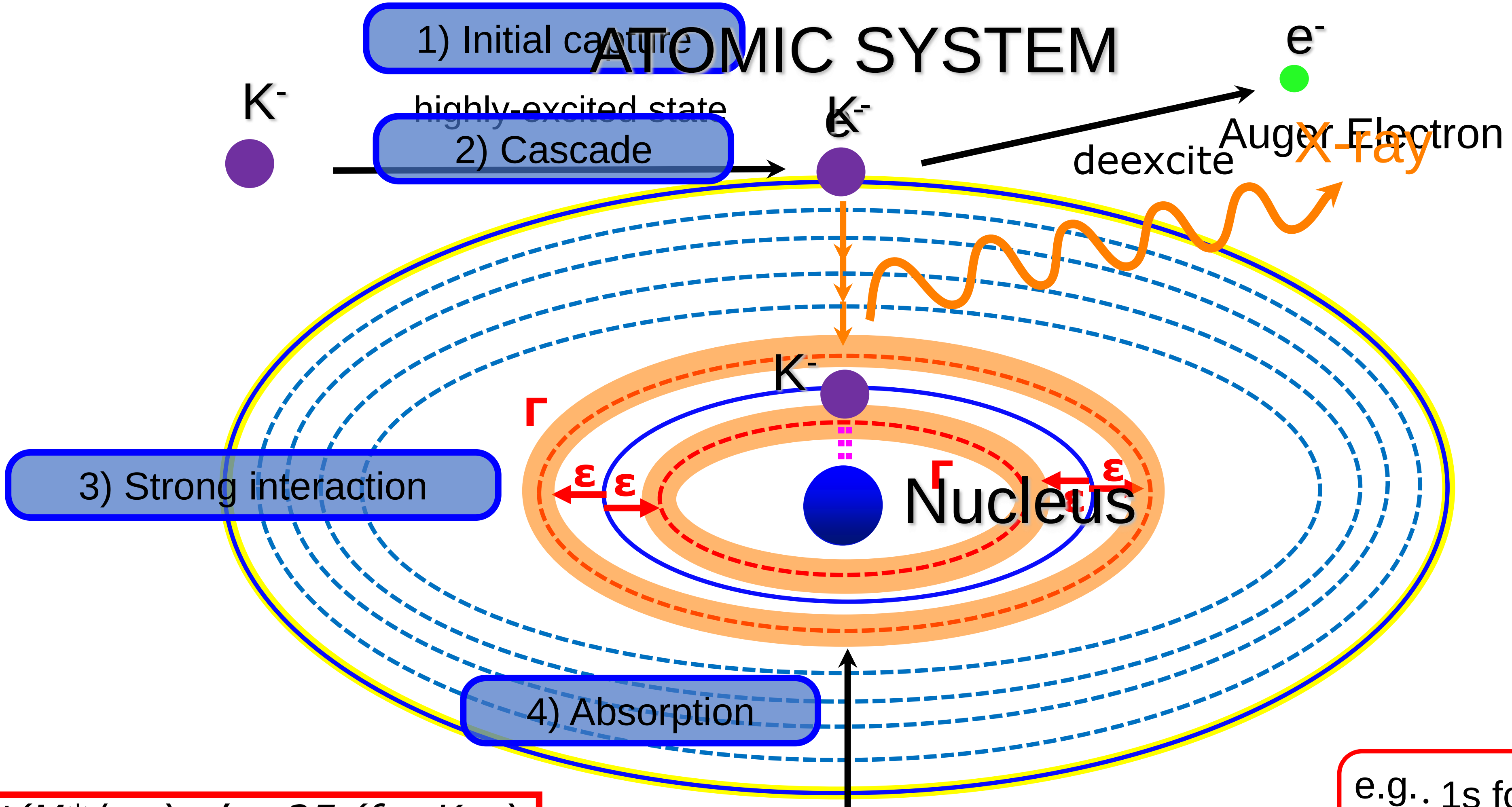
on behalf of the SIDDHARTA-2 collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

XII International Conference on New Frontiers in Physics, 10-23 July 2023, Kolymbari

Kaonic atoms formation

Kaonic atoms are formed by stopping a negatively charged kaon in a target medium



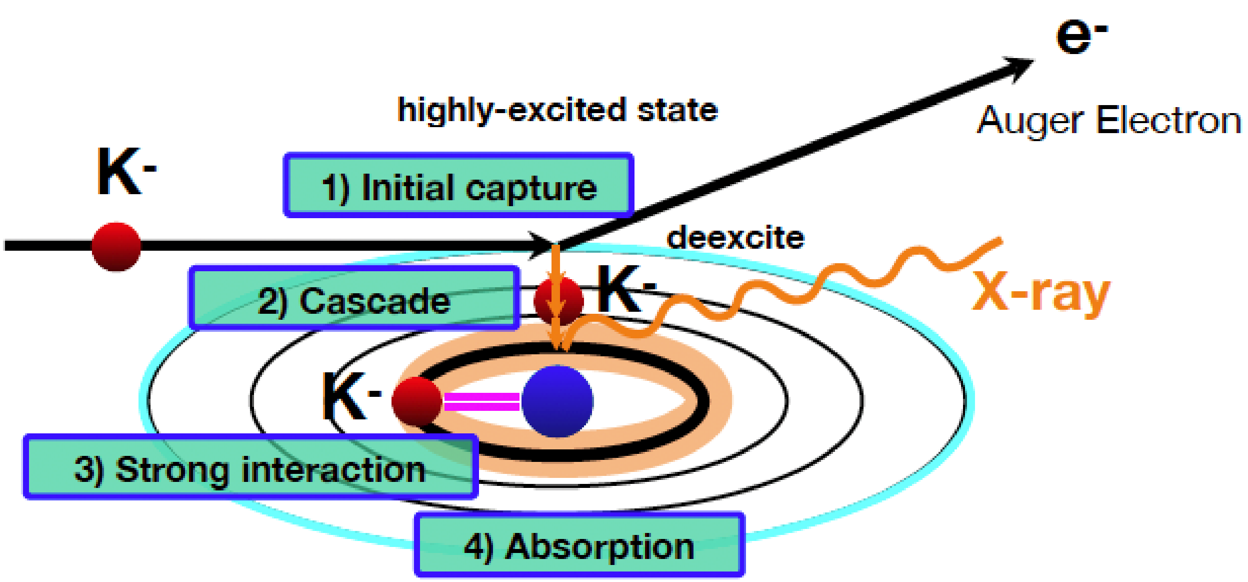
$n \sim sqrt(M^*/m_e)$ $n' \sim 25$ (for K-p)
(M^* : K-p reduced mass)

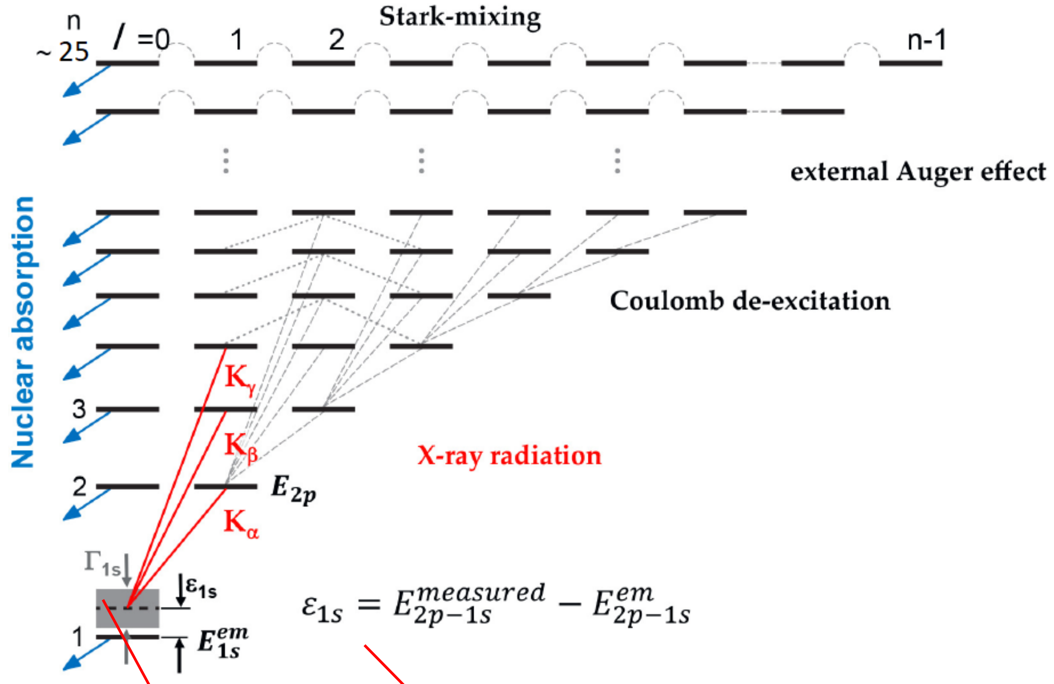
Shift (ε) and width (Γ) of the last orbit

e.g.. 1s for K-p, K-d
. 2p for K-He

Kaonic atoms formation

In kaonic atoms, part of the shift (ε) and width (Γ) of the innermost atomic levels is due to the strong kaon-nucleus interaction, thus allowing the study of the strong interaction at low energy (keV) in the *strange* sector.





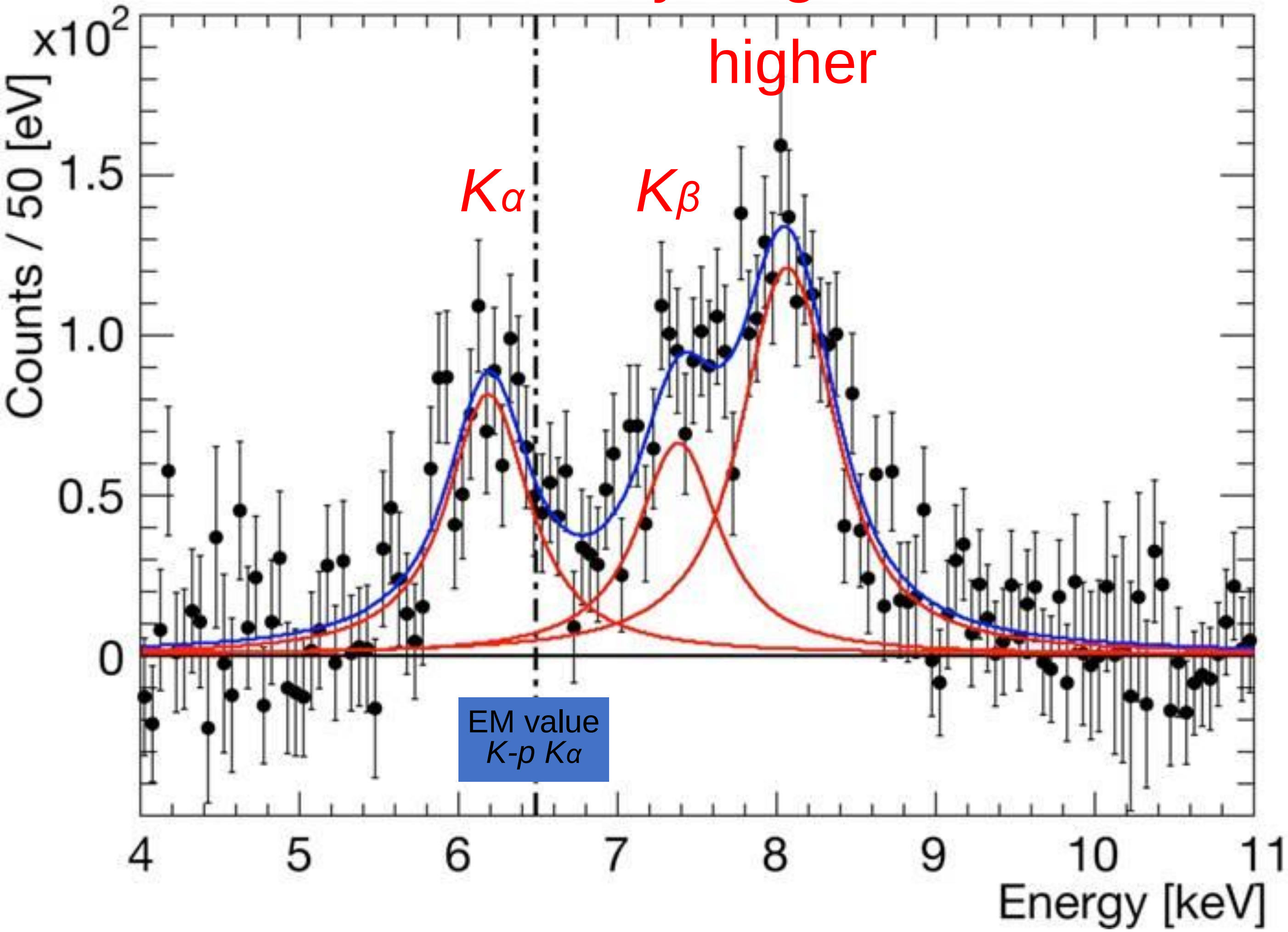
The measurement of shift and width of the 1S orbital in **Kaonic Hydrogen** and **Kaonic Deuterium** allow the first experimental determination of Isospin-dependent K-N scattering lengths.

Width Γ and shift ε obtained by measuring the X-rays emitted

The SIDDHARTA experiment

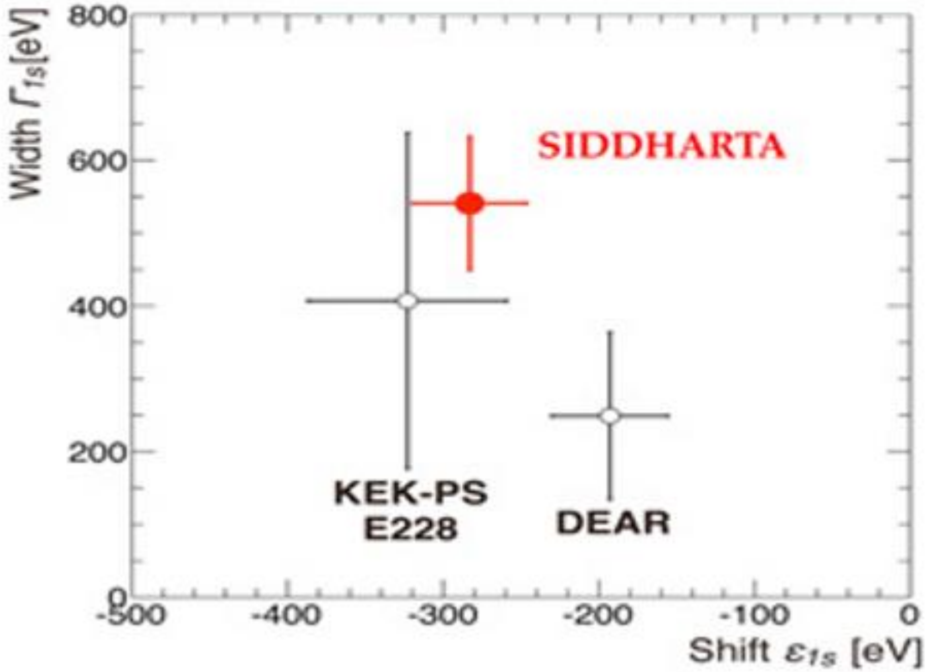
The SIDDHARTA experiment performed the first measurements of shift and width of kaonic hydrogen in 2011 at National Laboratories of Frascati (LNF-INFN).

Kaonic hydrogen



$$\varepsilon_{1s}^{H} = -283 \pm 36(stat) \pm 6(syst)eV$$

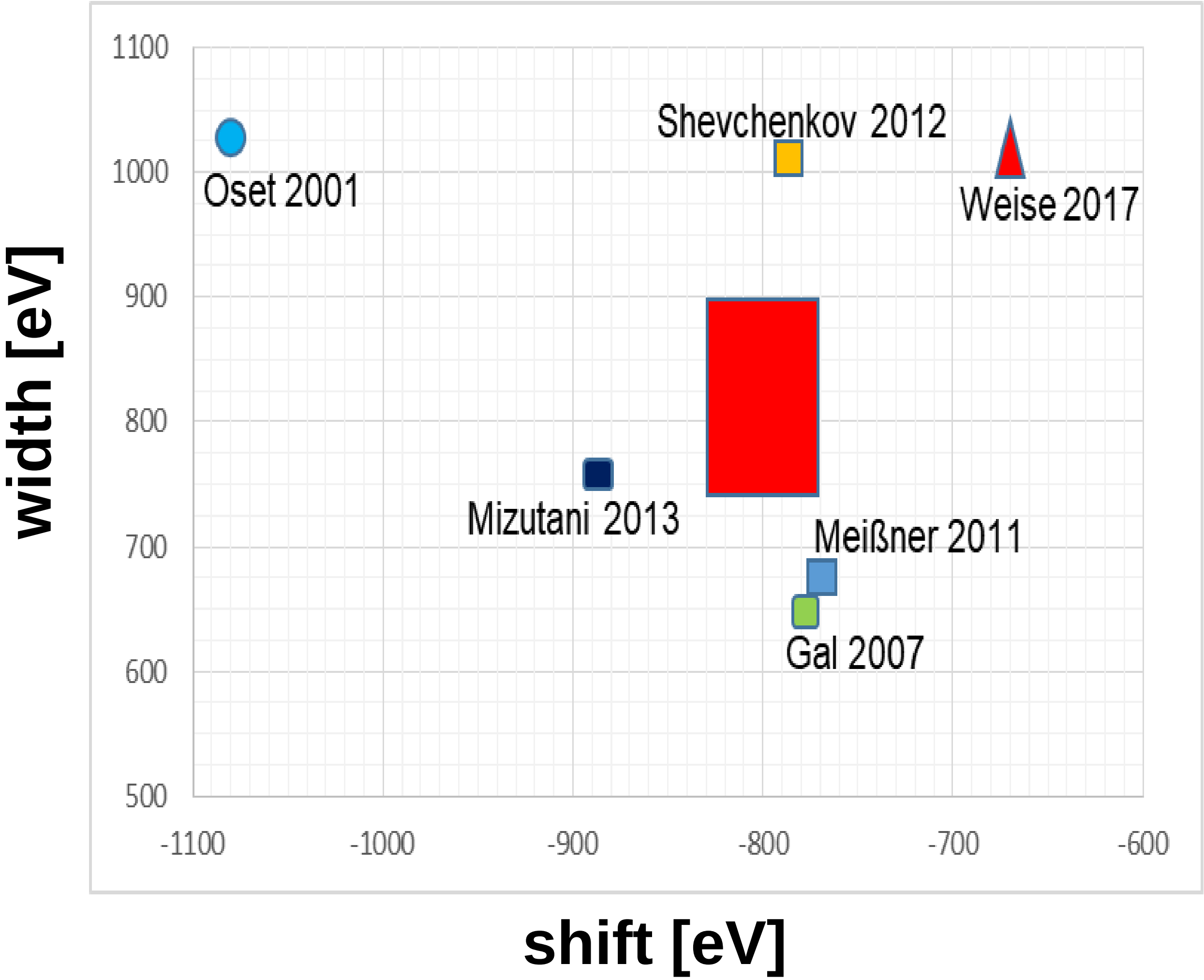
$$\Gamma_{1s}^{H} = 541 \pm 89(stat) \pm 22(syst)eV$$



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

The SIDDHARTA-2 scientific goal

The SIDDHARTA-2 experiment aims to perform the first measurement of shift and width of kaonic deuterium at the DAΦNNE e+e- collider at LNF-INFN.



ISOSPIN-DEPENDENT K-N SCATTERING LENGTHS WILL BE EXPERIMENTALLY DETERMINED

SIDDHARTA-2

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

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

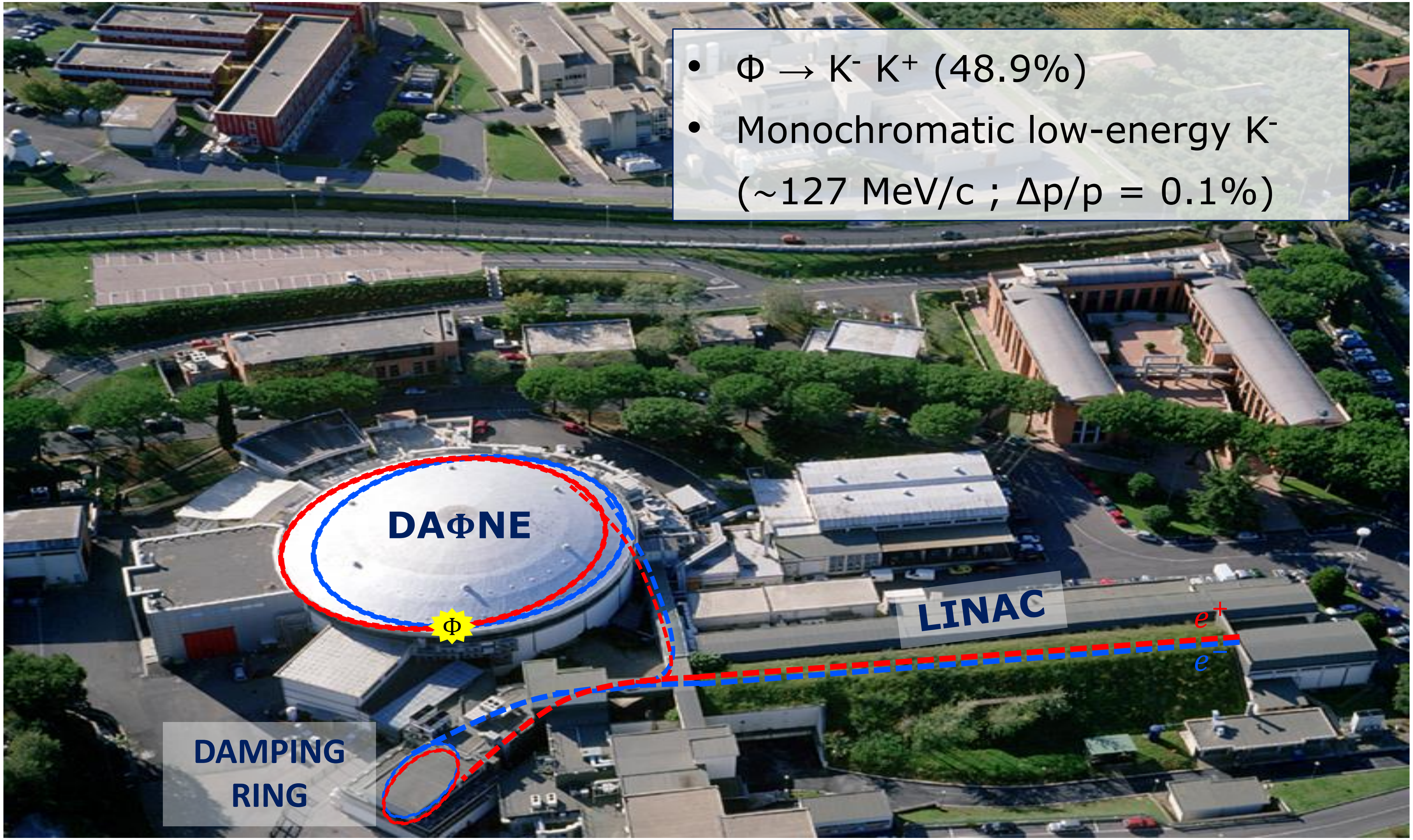
Univ. Jagiellonian Krakow, Poland

ELPH, Tohoku University

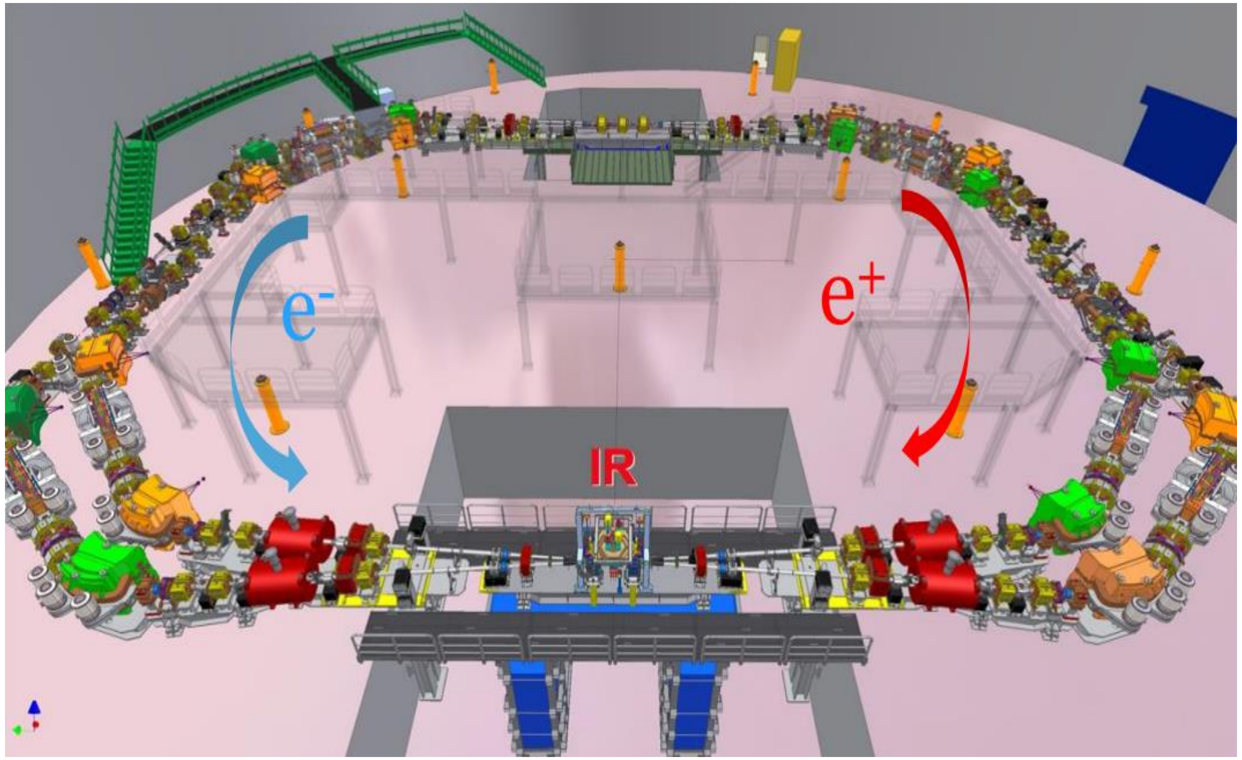
CERN, Switzerland

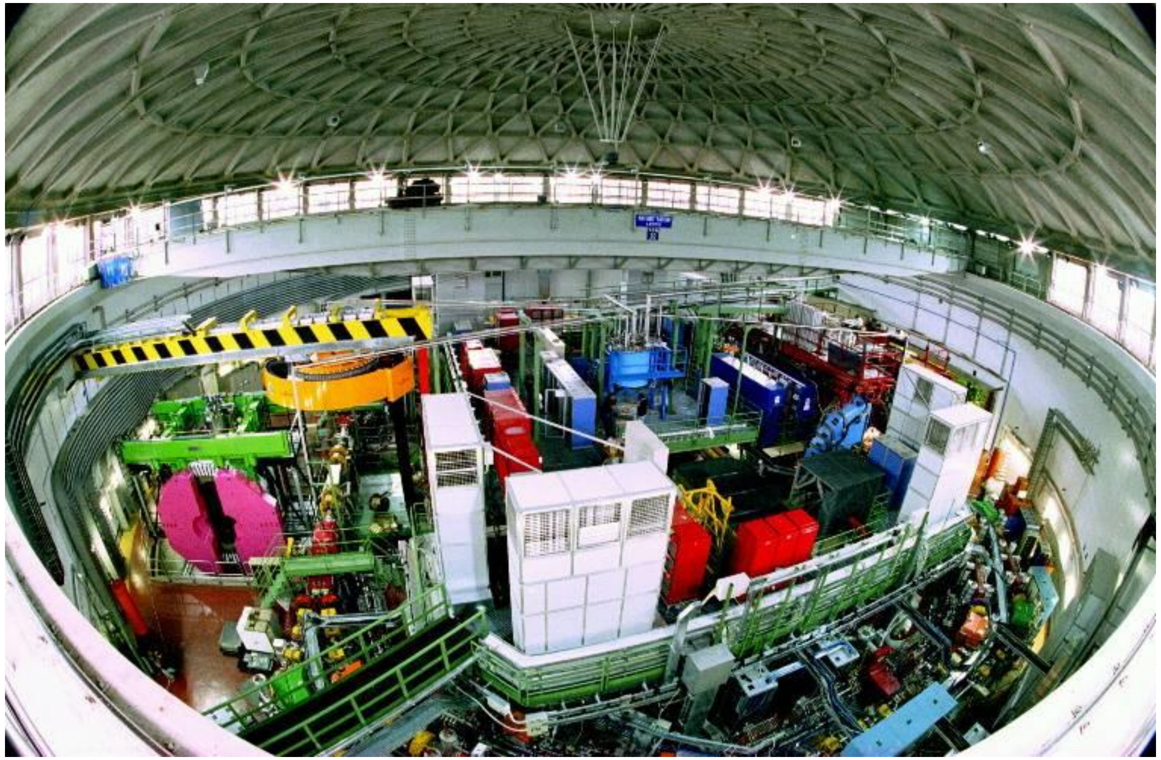
HadronPhysics2 Study of Strongly Interacting Matter
HadronPhysics I3 Study of Strongly Interacting Matter
FWF Der Wissenschaftsfonds.
STRONG-2020
HrZZ Croatian Science Foundation
Farnesina Ministero degli Affari Esteri e della Cooperazione Internazionale

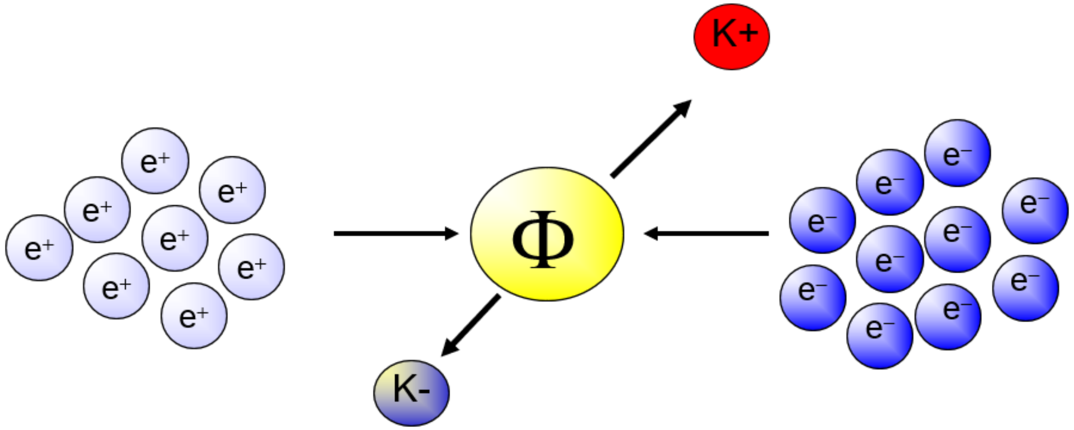
LNF e^+e^- Accelerators complex



The DAΦNE e^+e^- Collider



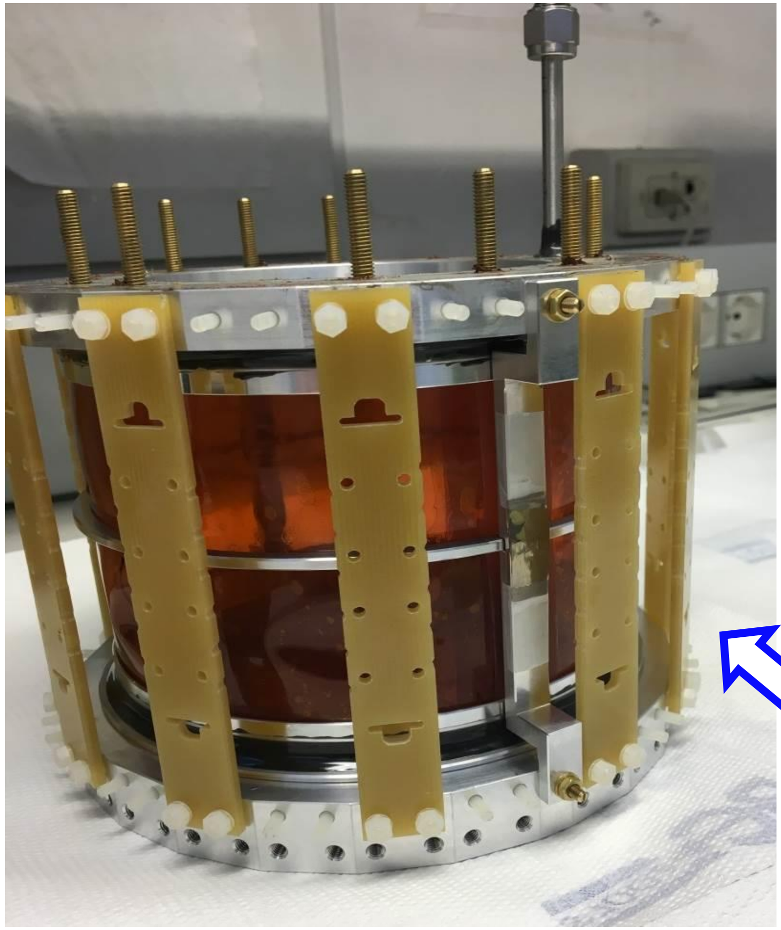


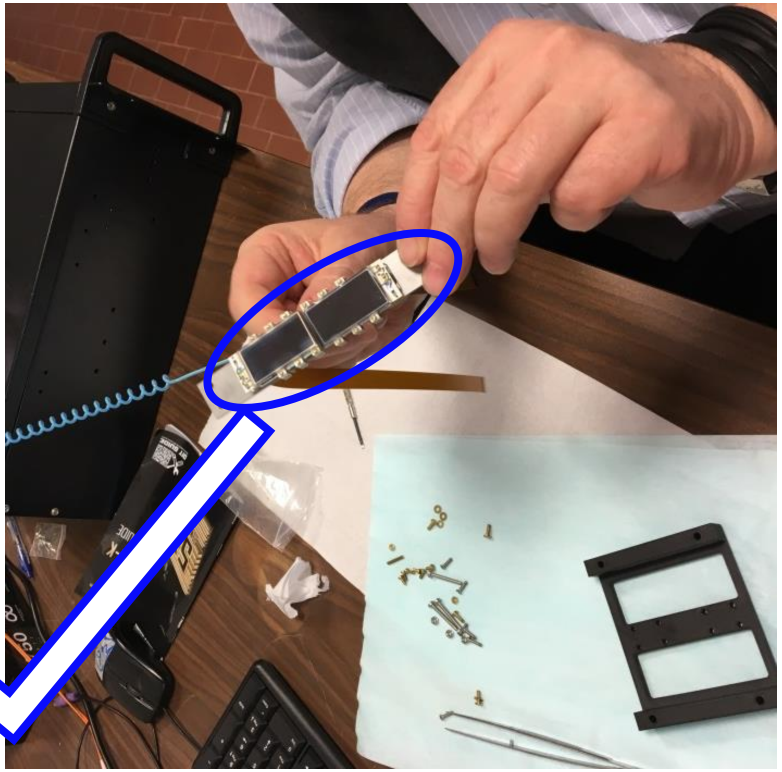


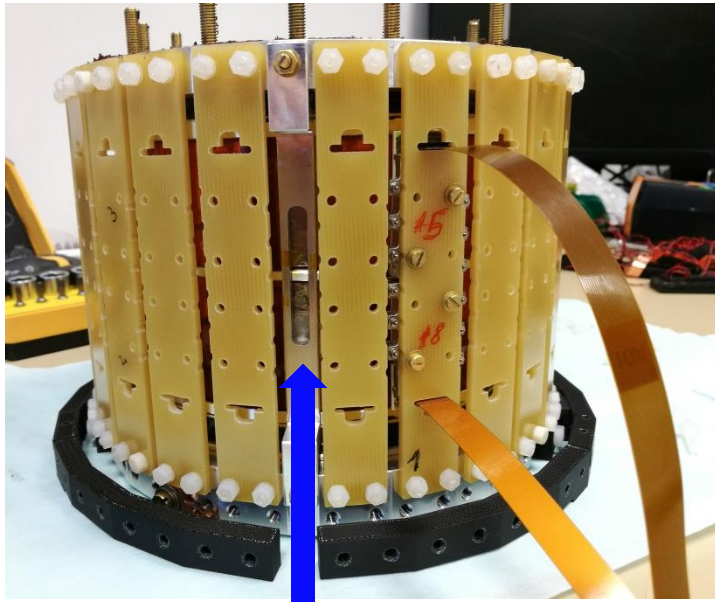
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)
- **Flux of produced kaons: about 1000/second**

The SIDDHARTA-2 target

The cylindric target cell consists of a wall made of a 2-Kapton layer structure (75 μm + 75 μm + Araldit), placed on aluminum support.







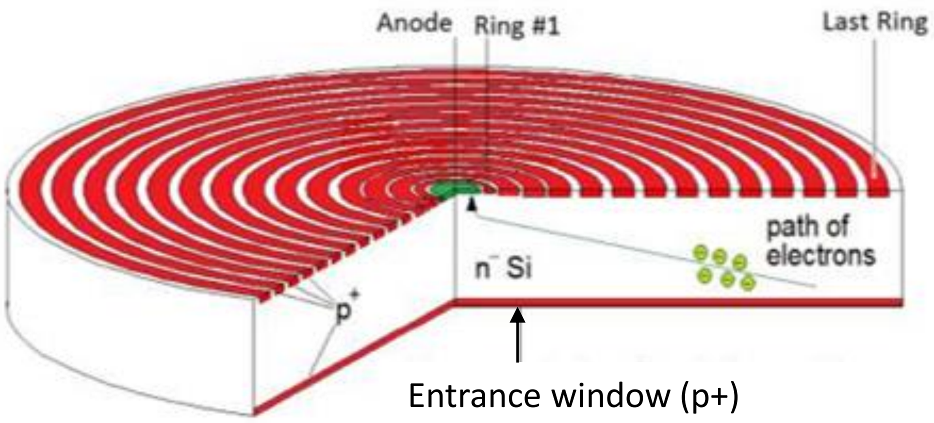
calibration foils inserted near to the SDD are activated by the X-ray tubes

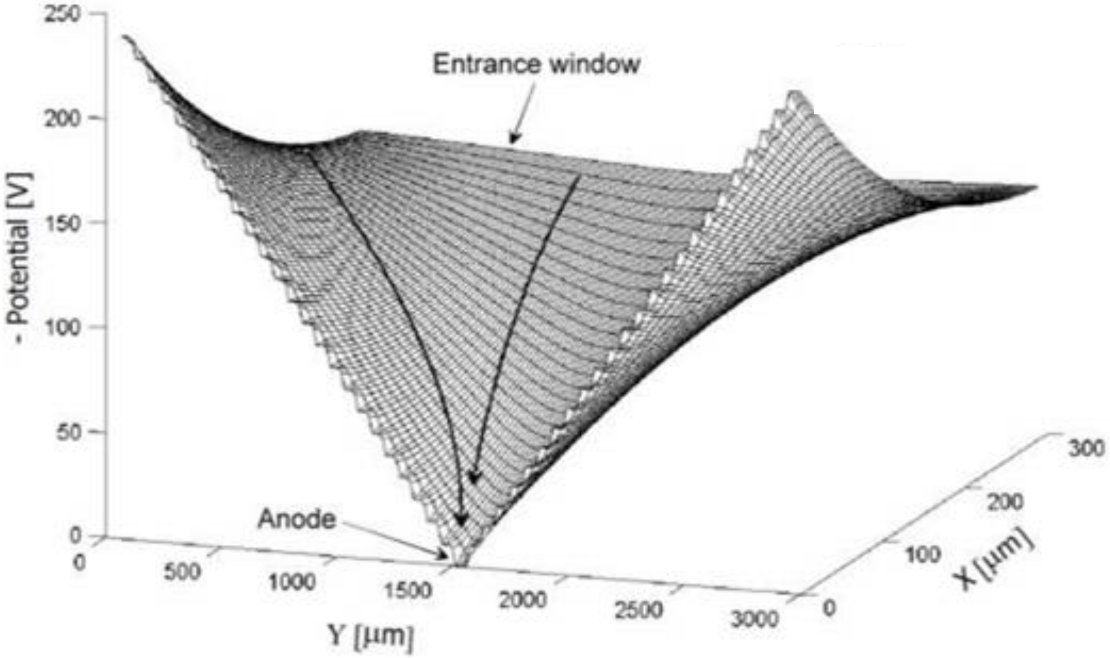
Silicon Drift Detectors (SDDs) are placed 5 mm from the target wall for the x-ray spectroscopy

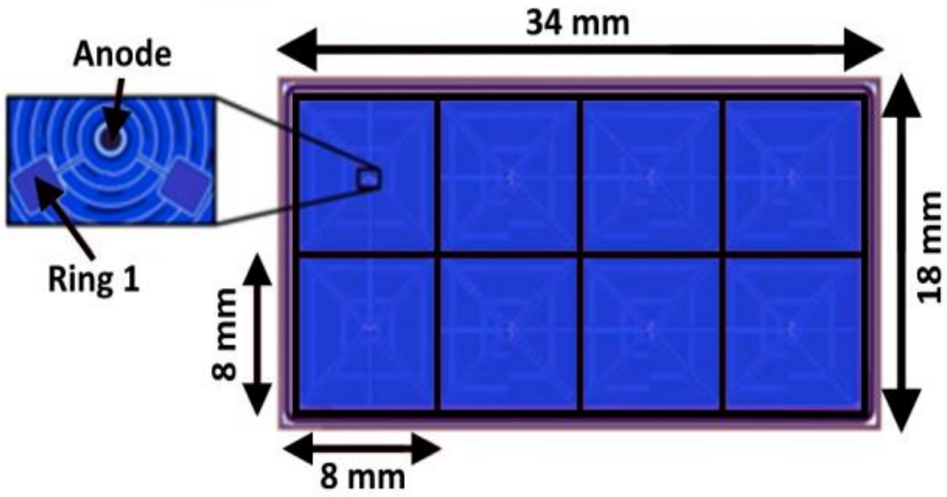
GASEOUS DEUTERIUM IS FLUXED WITHIN THE TARGET CELL

The Silicon Drift Detectors

SDD CELL CROSS SECTION



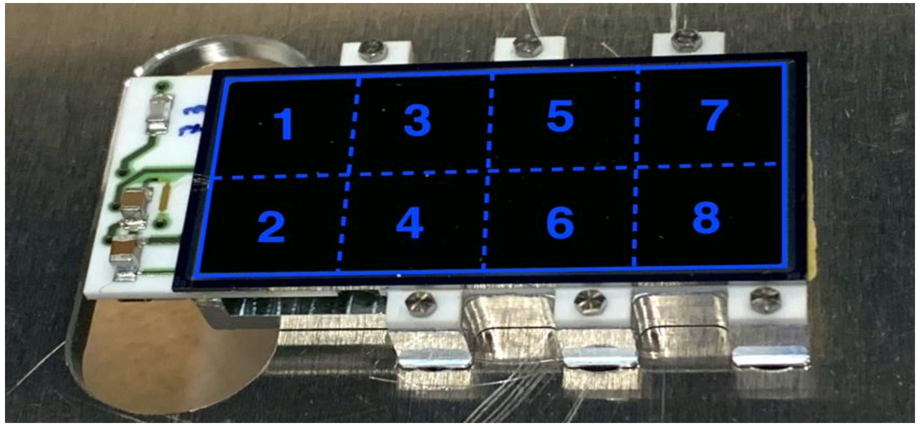




POLITECNICO MILANO 1863

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

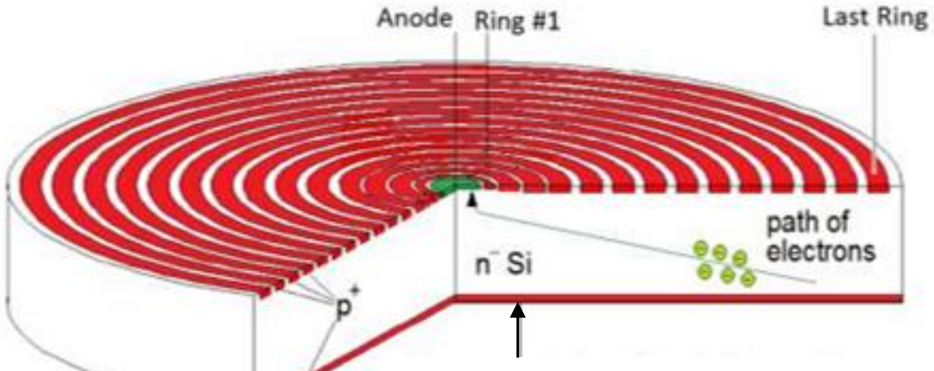
FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

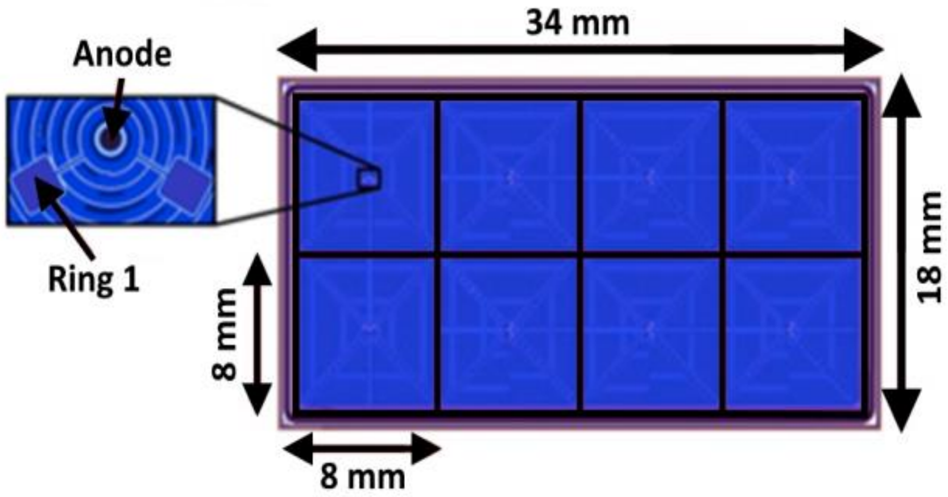


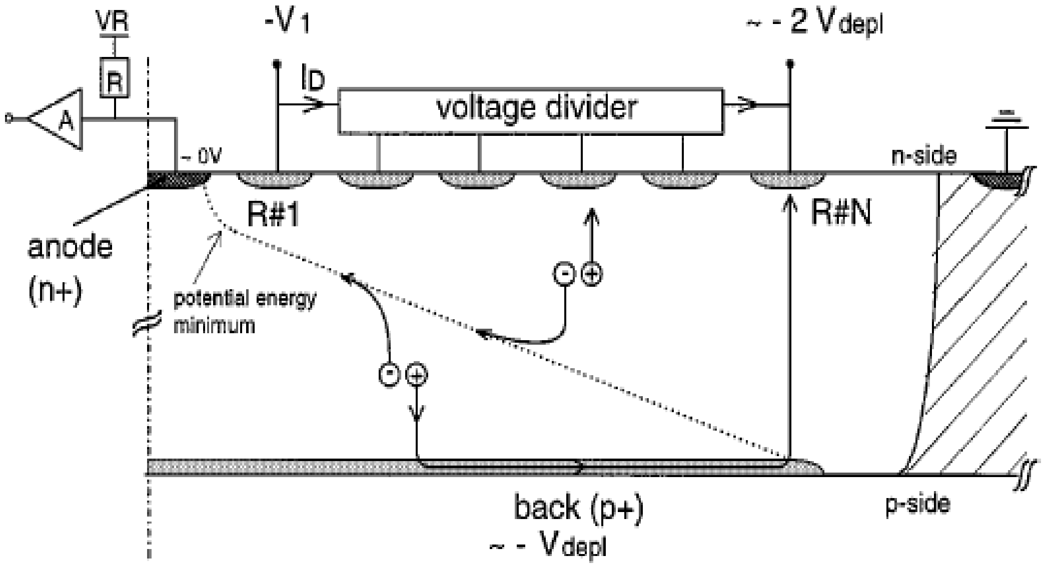
Each array consists of 8 SDD cells with 0.64 cm^2 of active area and 450 µm thickness each, which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

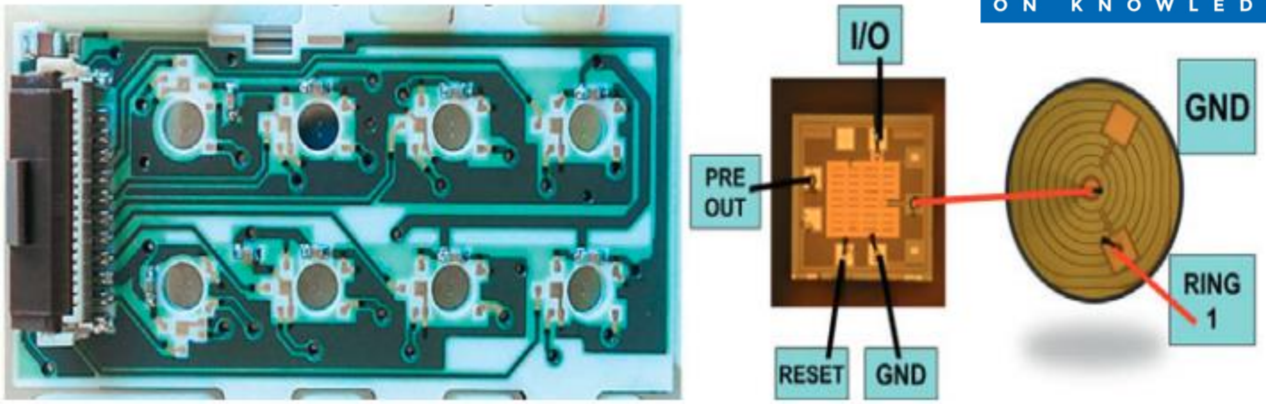
The Silicon Drift Detectors

SDD CELL CROSS SECTION





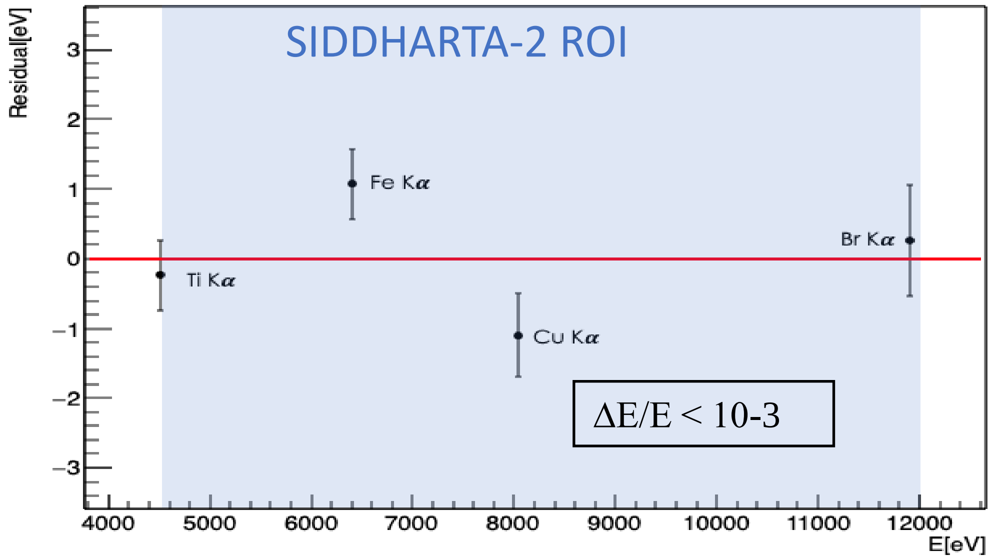




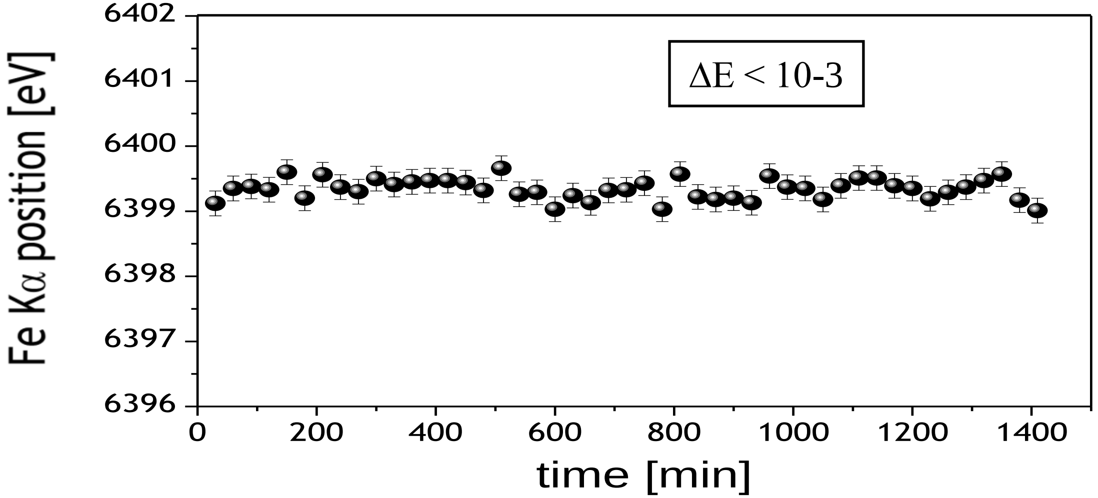
The SIDDHARTA-2 experiment equips 48 SDD arrays, for a total of 384 SDD cell detectors. Each SDD array has a total active area of 5.12 cm^2

The Silicon Drift Detectors

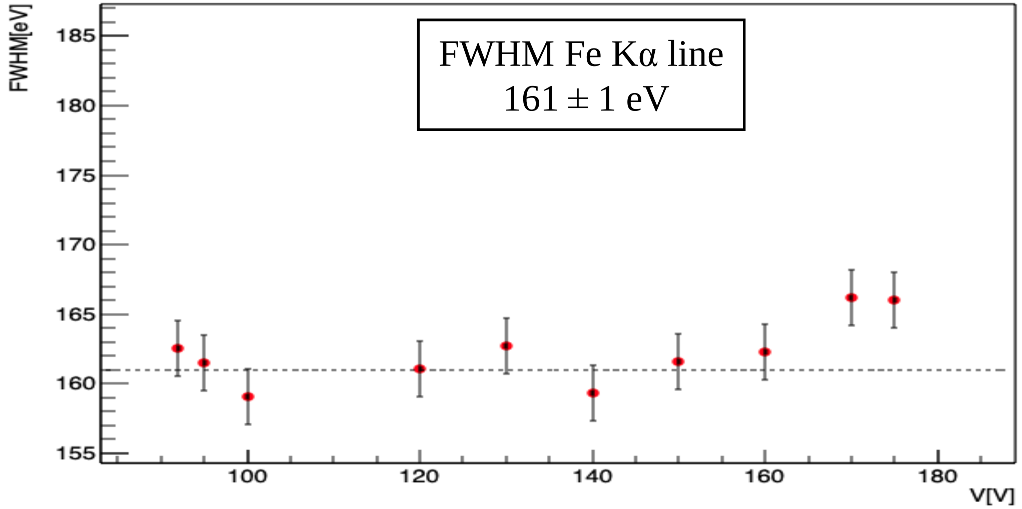
Linearity



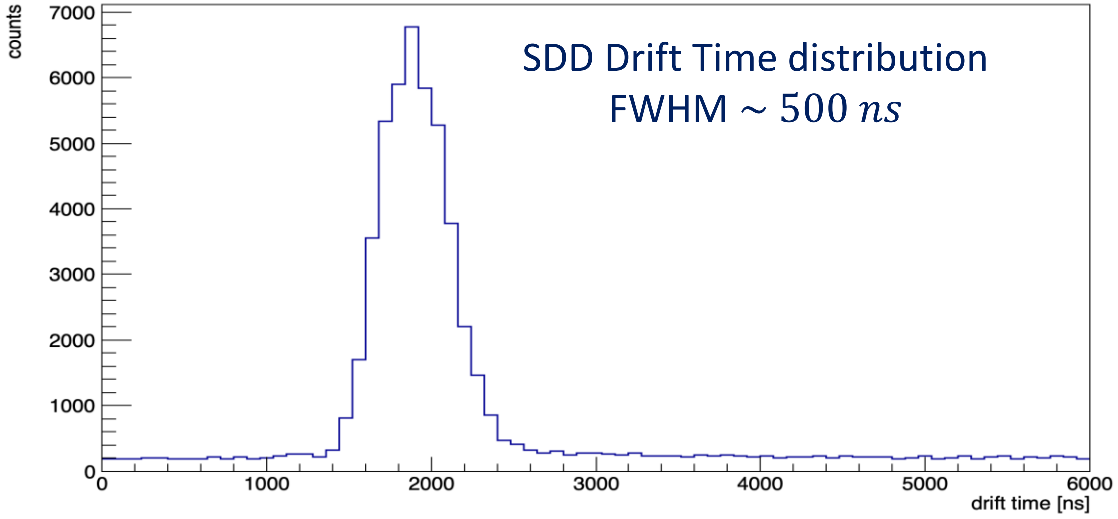
Stability



Energy Resolution

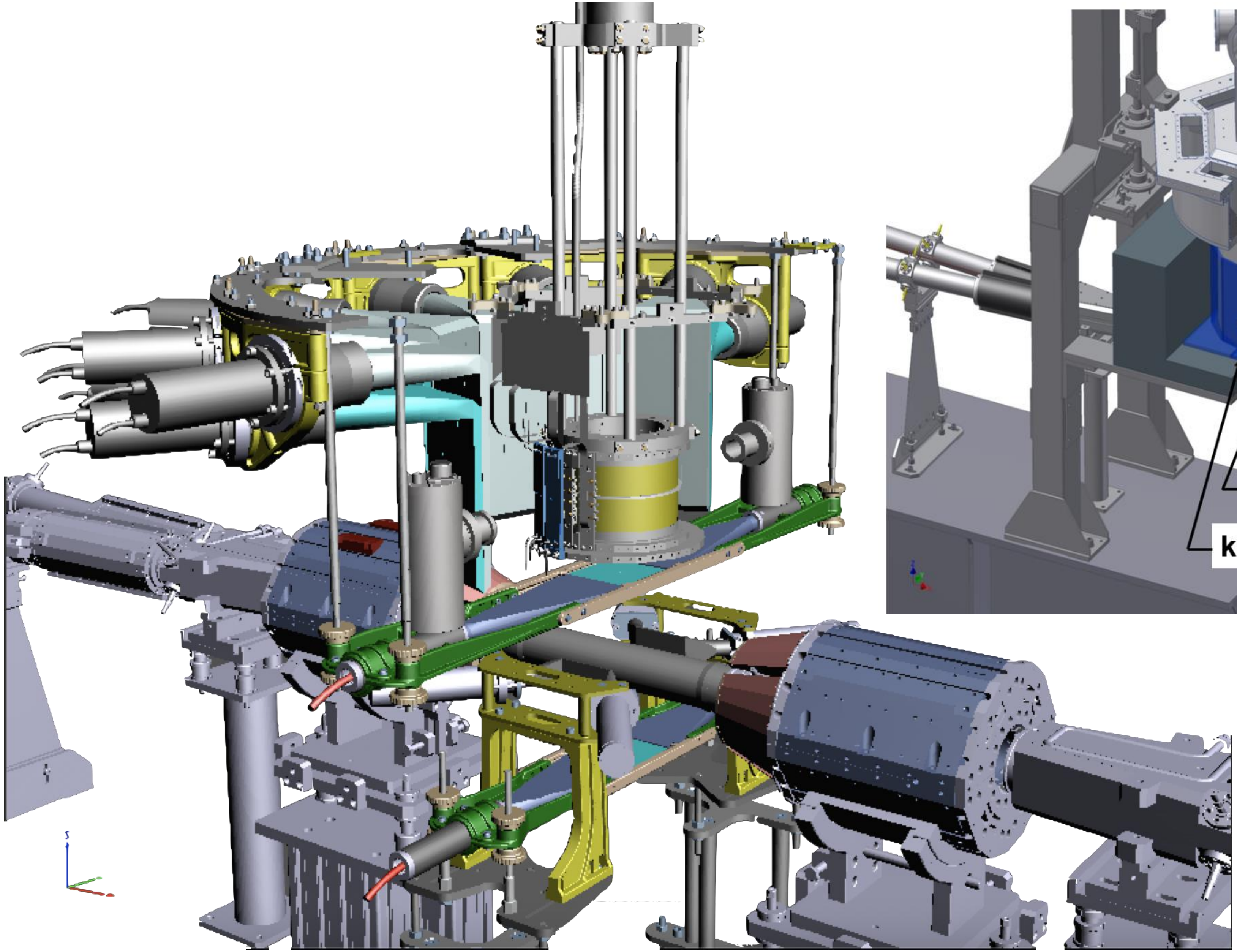


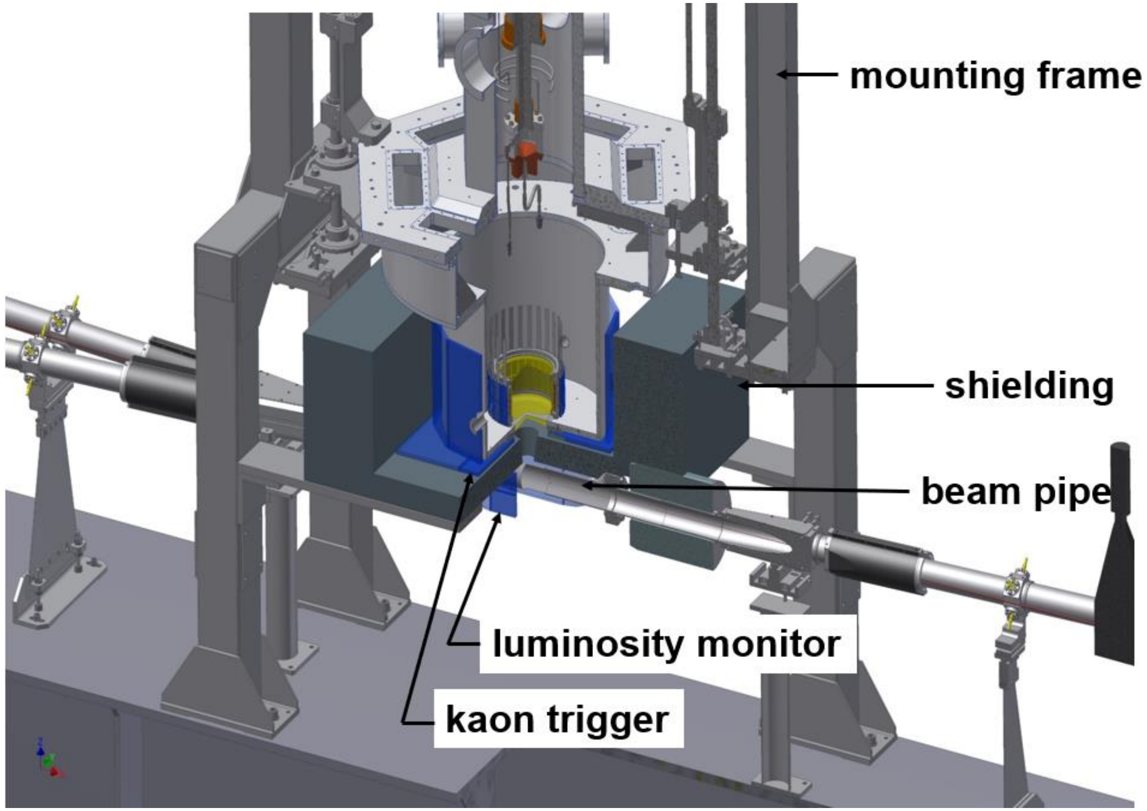
Timing Resolution



M Miliucci *et al* 2021 *Meas. Sci. Technol.* **32** 095501

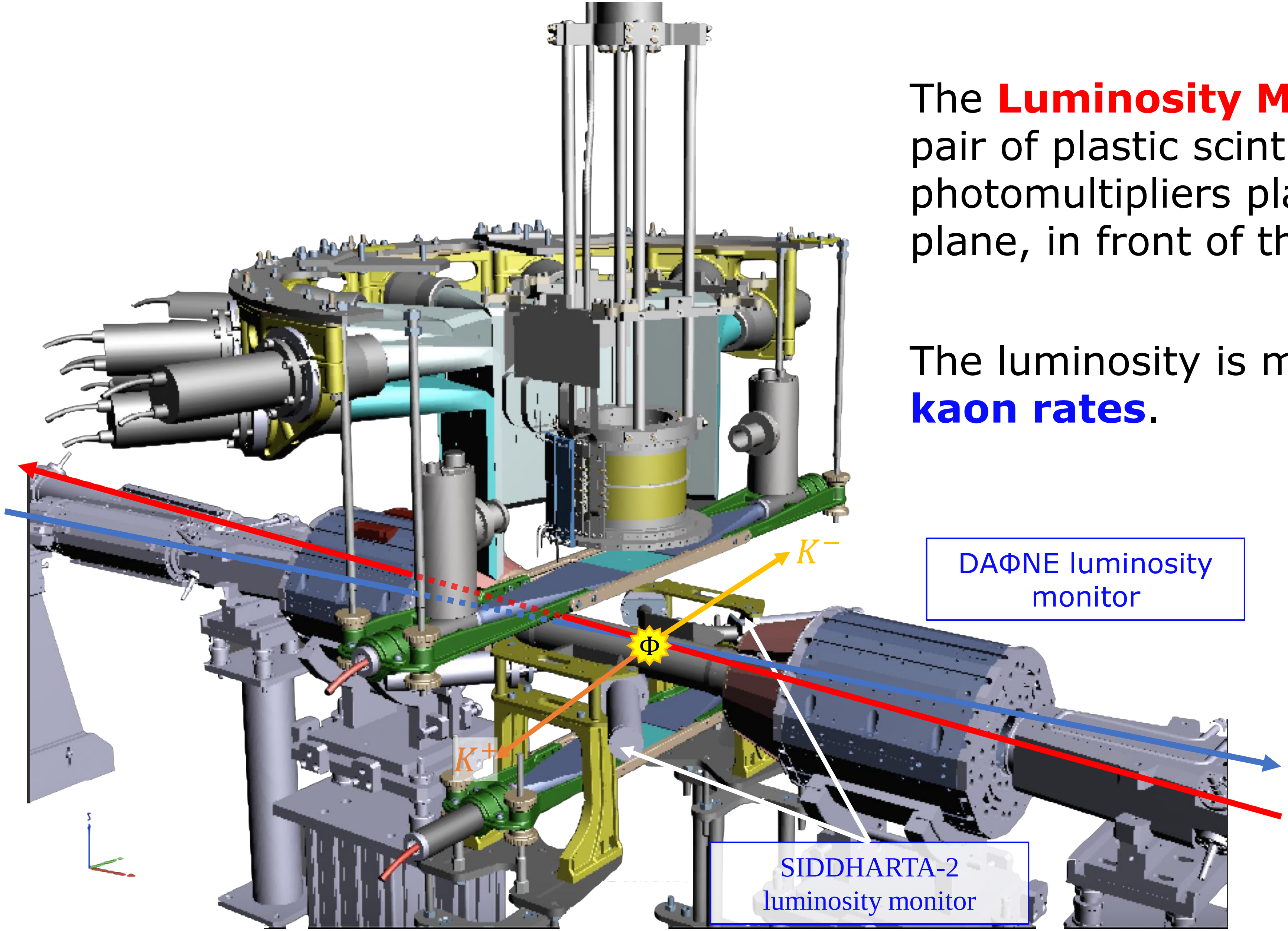
The SIDDHARTA-2 setup





The SIDDHARTA-2 experiment is actually installed in the DAΦNE collider at LNF.

The SIDDHARTA-2 setup

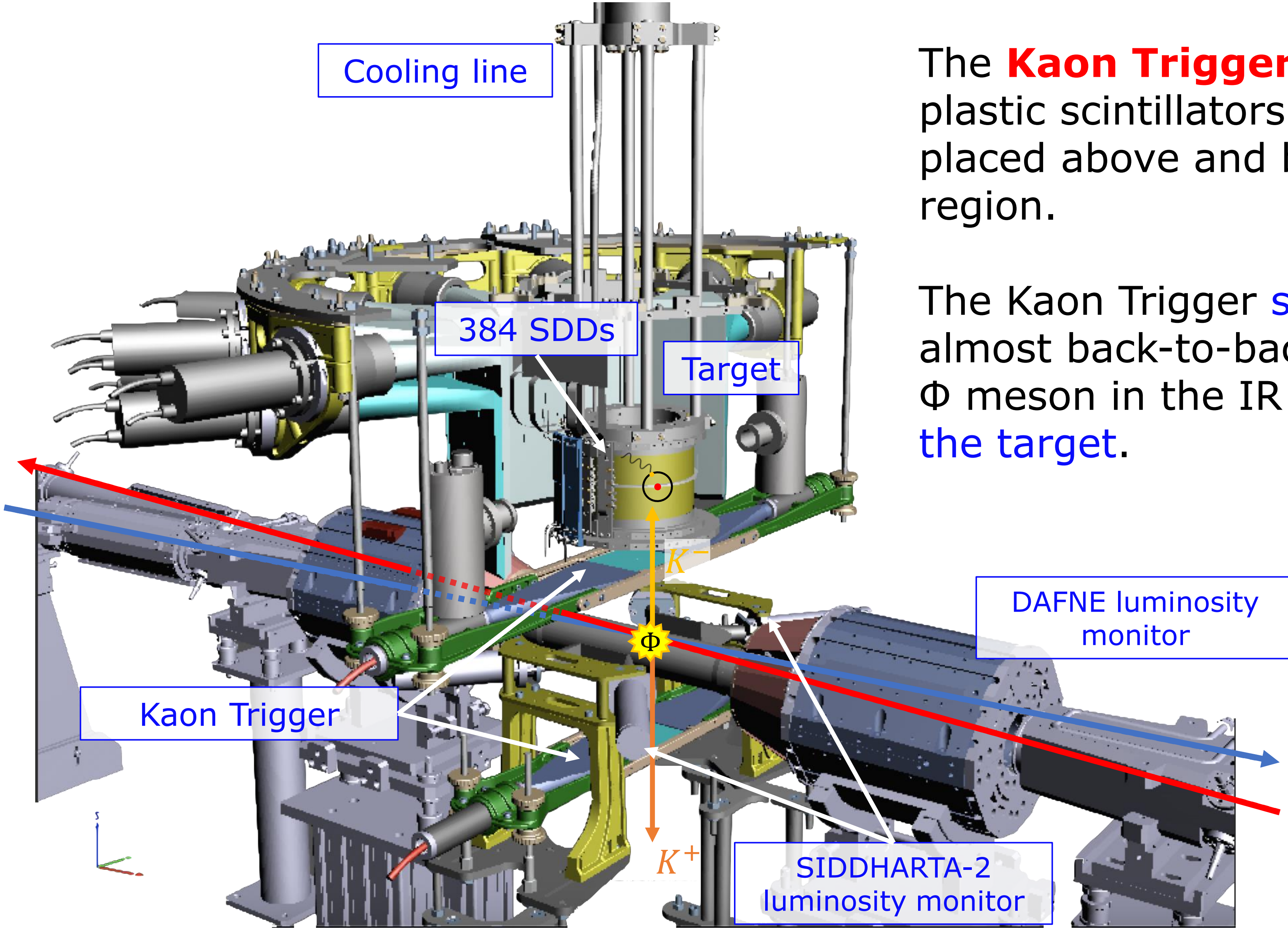


The **Luminosity Monitor** consists of a pair of plastic scintillators read by photomultipliers placed on the longitudinal plane, in front of the interaction region.

The luminosity is measured using the **kaon rates**.

The SIDDHARTA-2 luminosity monitor is complementary to the DAΦNE luminosity monitor, which use the Bhabha scattering $e^+e^- \rightarrow e^+e^-$

The SIDDHARTA-2 setup



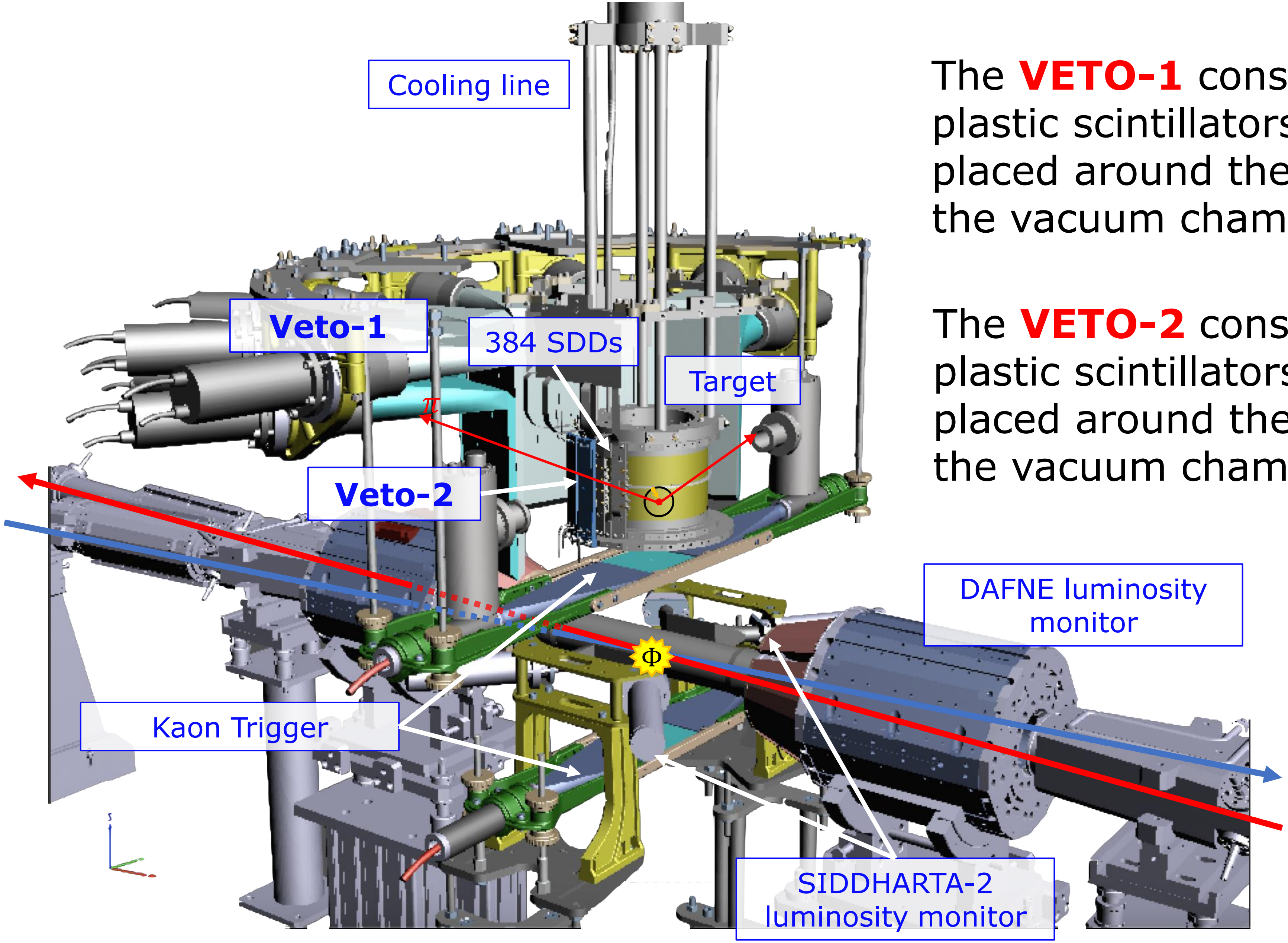
The **Kaon Trigger** consists of two pair of plastic scintillators read by photomultipliers placed above and below the Interaction region.

The Kaon Trigger selects kaons emitted almost back-to-back from the decay of the Φ meson in the IR and directed towards the target.

A cylindrical vacuum chamber is placed above the interaction point and contains target and SDDs.

SDDs are cooled to 170 K.

The SIDDHARTA-2 setup



The **VETO-1** consists of twelve pair of plastic scintillators read by photomultipliers placed around the cryogenic target, outside the vacuum chamber.

The **VETO-2** consists of smaller pair of plastic scintillators read by photomultipliers placed around the cryogenic target, inside the vacuum chamber.

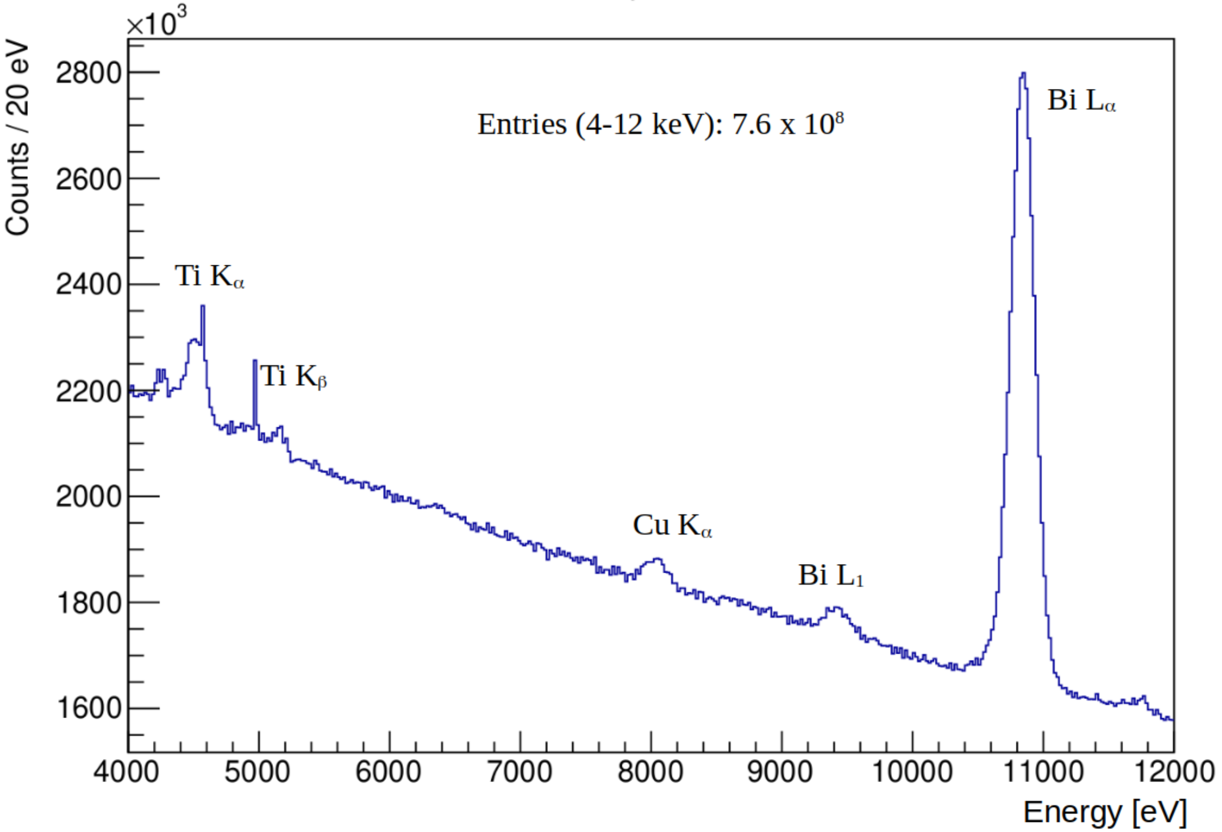
The Veto systems are used to suppress the synchronous and asynchronous background from the accelerator, and limit the fake signals due to minimum ionizing particles (MIPs)

SIDDHARTA-2 setup
Ready for Run

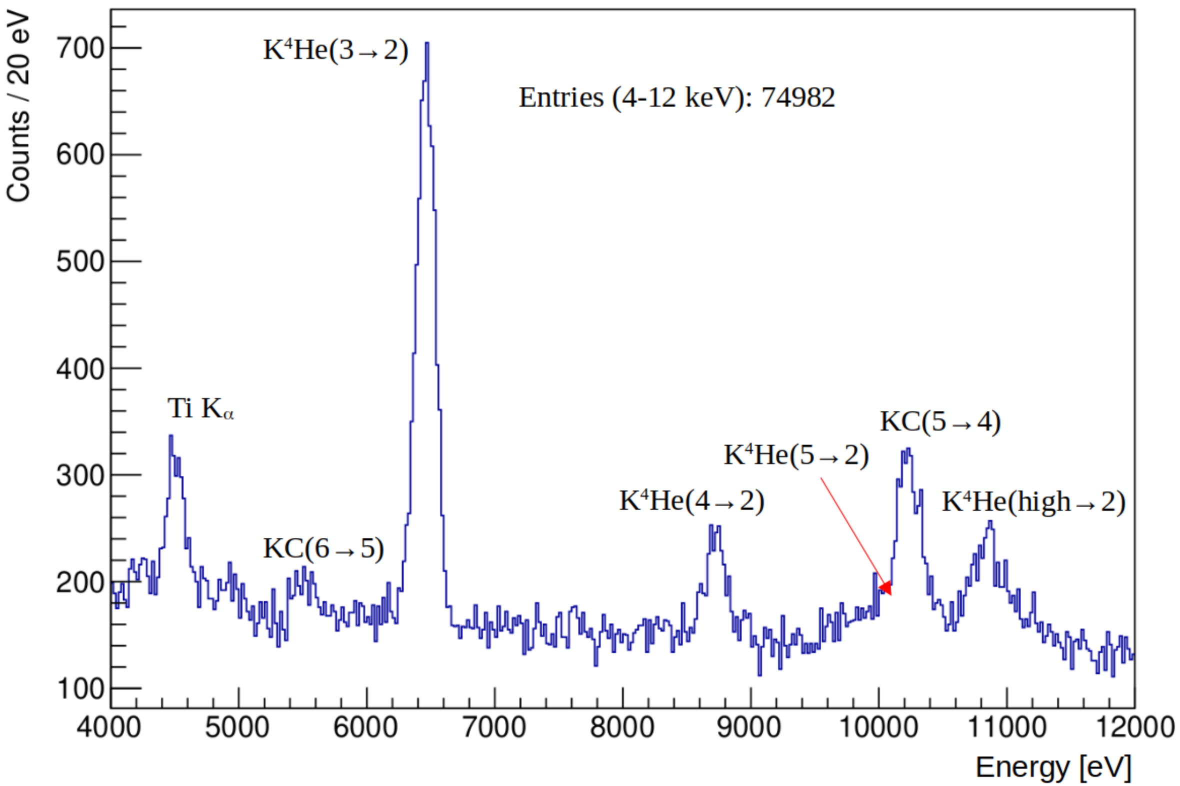
$K^{-}\,{}^{4}_{2}He$ measurement with SIDDHARTA2

The SIDDHARTA-2 installation was completed in the second half of 2021. In May 2022 a new measurement of $K^{-}\,{}^{4}_{2}He$ was performed to confirm the great performance shown by SIDDHARTINO, for the SIDDHARTA-2 apparatus.

COMPLETE SPECTRUM ACQUIRED BY SIDDHARTA-2

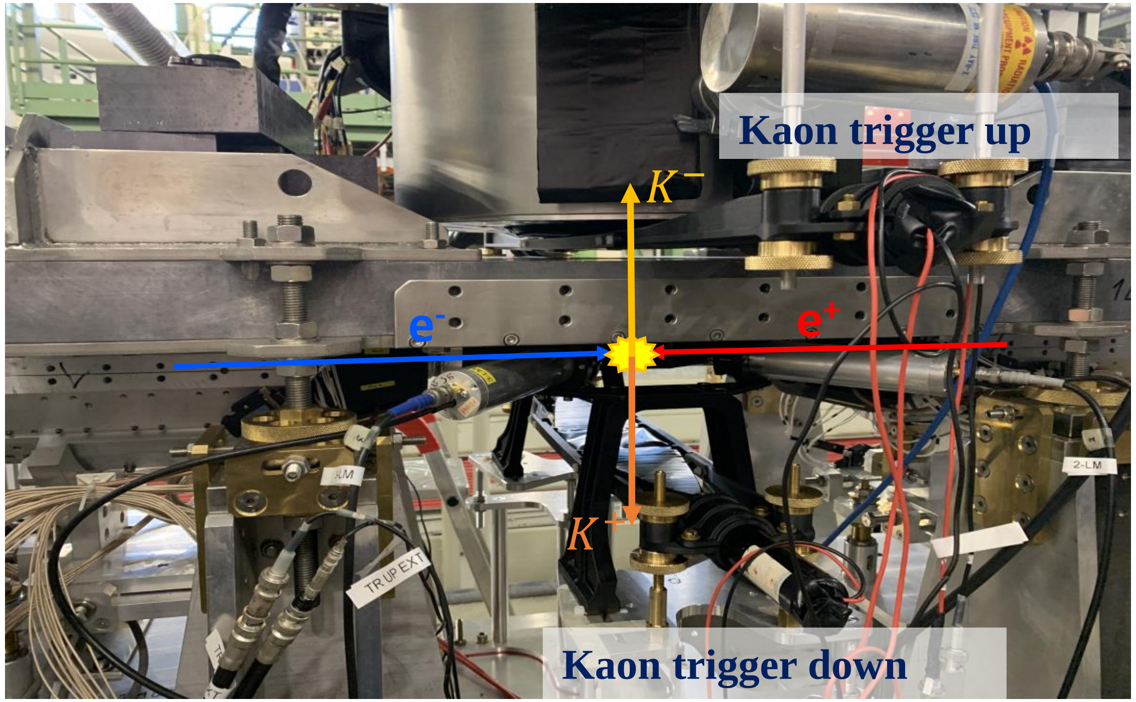


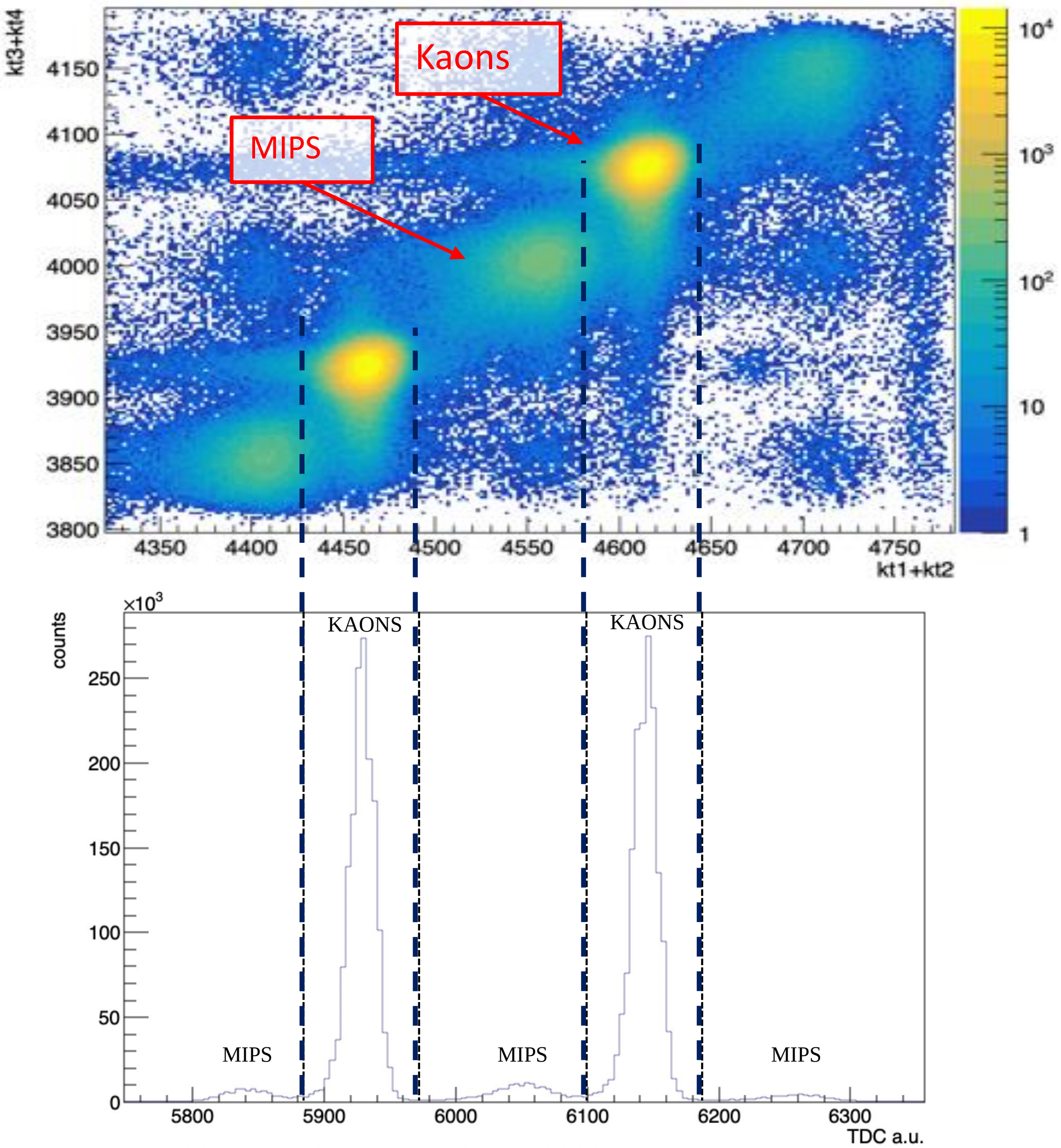
$K^{-}\,{}^{4}_{2}He$ SPECTRUM APPLYING KAON TRIGGER



Triggered rejection factor 3.15×10^{-5}

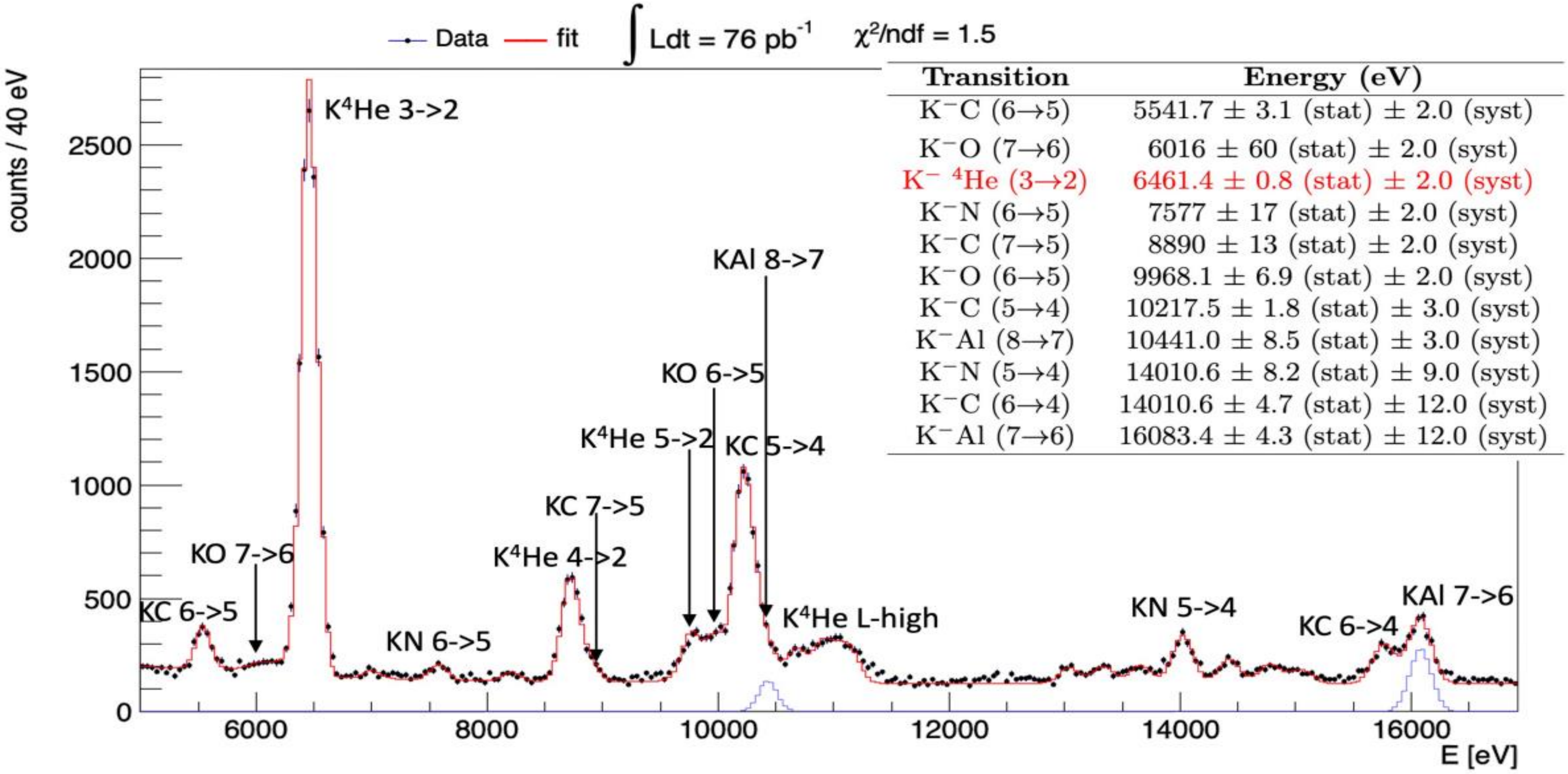
The Kaon Trigger





The Time of Flight (ToF) is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

$K^{-}\,{}^{4}_{2}He$ measurement SIDDHARTINO + SIDDHARTA-2



Transition	Energy (eV)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
$K^{-}\,{}^4He$ (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-C (5→4)	10217.5 ± 1.8 (stat) ± 3.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-C (6→4)	14010.6 ± 4.7 (stat) ± 12.0 (syst)
K^-Al (7→6)	16083.4 ± 4.3 (stat) ± 12.0 (syst)

READY TO START KAONIC DEUTERIUM MEASUREMENT!!!

Beyond SIDDHARTA-2: EXKALIBUR

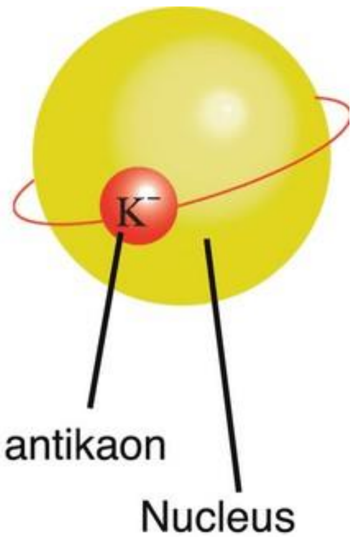
The SIDDHARTA-2 collaboration proposes fundamental physics measurements via kaonic atoms, at the strangeness frontier, to be performed at the DAΦNE collider for a 3-years period (beyond-SIDDHARTA-2).

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

- Kaonic Hydrogen: 200 pb^{-1} – with SIDDHARTA-2 setup – to get a precision < 10 eV (KH)
- Selected light kaonic atoms (LHKA)
- Selected intermediate and heavy kaonic atoms charting the periodic table (IMHKA)
- Ultra-High precision measurements of Kaonic Atoms (UHKA)

EXtensive
Kaonic
Atoms research:
from
LIthium and
Beryllium to
URanium

EXKALIBUR



Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements,
C. Curceanu et al., e-Print: 2104.06076

Beyond SIDDHARTA-2: EXKALIBUR

Except for the most recent measurements at DAFNE and JPARC on KHe and KH, the database on kaonic atoms dates back to 1970s and 1980s

These data are the experimental basis for all the developed theoretical models

These theoretical models are used to derive, for example:

- KN interaction at threshold
- KNN interaction at threshold
- Nuclear density distributions
- Possible existence of kaon condensates
- Kaon mass
- Kaonic atoms cascade models

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

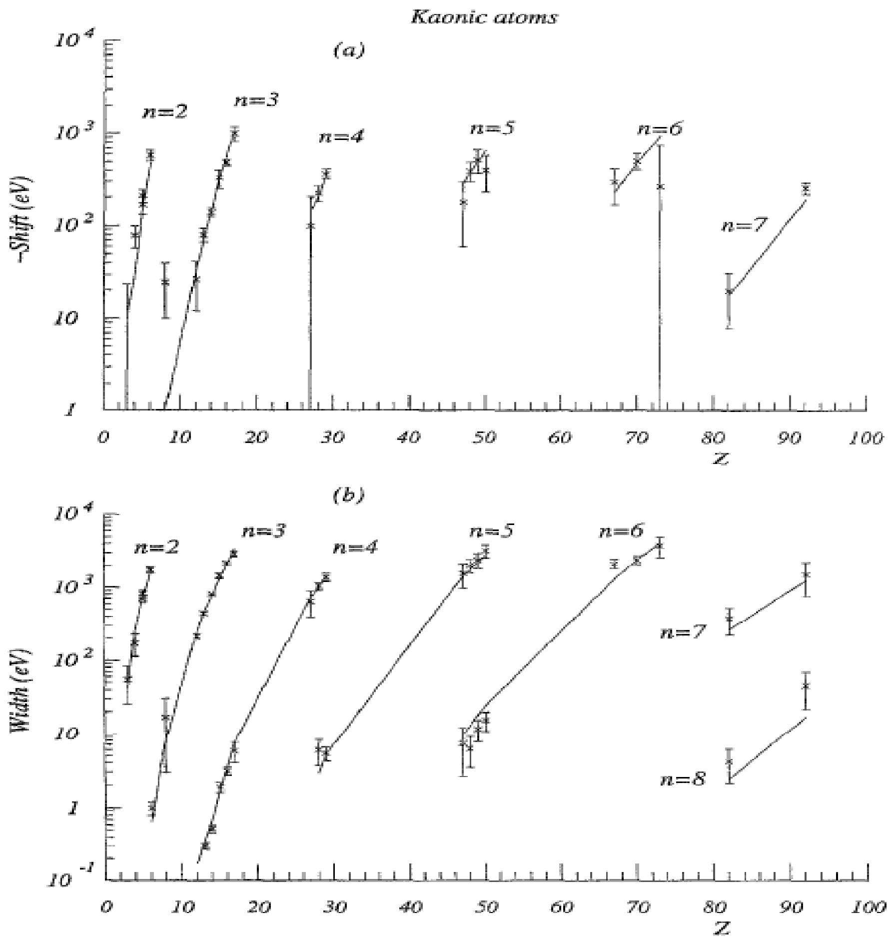


Fig. 7. Shift and width values for kaonic atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 4.2.

Beyond SIDDHARTA-2: EXKALIBUR

Kaonic atoms present database

1. The available data on "lower levels" have big uncertainties
2. Many of them are actually UNmeasured
3. Many of them are hardly compatible among each other
4. Relative yields with upper levels are not always measured
5. Absolute yields are basically unknown (except for few transitions)
6. The REmeasured ones have been proved WRONG

This situation would already be a proper justification for new measurements

Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	$3 \rightarrow 2$	-0.04 ± 0.03	–	–	–	[15]
		-0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	$3 \rightarrow 2$	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	$3 \rightarrow 2$	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	$3 \rightarrow 2$	-0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	$3 \rightarrow 2$	-0.167 ± 0.035	0.700 ± 0.080	–	–	[18]
C	$3 \rightarrow 2$	-0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20	[18]
O	$4 \rightarrow 3$	-0.025 ± 0.018	0.017 ± 0.014	–	–	[19]
Mg	$4 \rightarrow 3$	-0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03	[19]
Al	$4 \rightarrow 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–	[20]
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04	[19]
Si	$4 \rightarrow 3$	-0.240 ± 0.050	0.810 ± 0.120	–	–	[20]
		-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06	[19]
P	$4 \rightarrow 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30	[18]
S	$4 \rightarrow 3$	-0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36	[18]
		-0.43 ± 0.12	2.310 ± 0.170	–	–	[21]
		-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5	[19]
Cl	$4 \rightarrow 3$	-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7	[18]
		-0.94 ± 0.40	3.92 ± 0.99	–	–	[22]
		-1.08 ± 0.22	2.79 ± 0.25	–	–	[21]
Co	$5 \rightarrow 4$	-0.099 ± 0.106	0.64 ± 0.25	–	–	[19]
Ni	$5 \rightarrow 4$	-0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3	[20]
		-0.246 ± 0.052	1.23 ± 0.14	–	–	[19]
Cu	$5 \rightarrow 4$	-0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8	[20]
		-0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1	[19]
Ag	$6 \rightarrow 5$	-0.18 ± 0.12	1.54 ± 0.58	0.51 ± 0.16	7.3 ± 4.7	[19]
Cd	$6 \rightarrow 5$	-0.40 ± 0.10	2.01 ± 0.44	0.57 ± 0.11	6.2 ± 2.8	[19]
In	$6 \rightarrow 5$	-0.53 ± 0.15	2.38 ± 0.57	0.44 ± 0.08	11.4 ± 3.7	[19]
Sn	$6 \rightarrow 5$	-0.41 ± 0.18	3.18 ± 0.64	0.39 ± 0.07	15.1 ± 4.4	[19]
Ho	$7 \rightarrow 6$	-0.30 ± 0.13	2.14 ± 0.31	–	–	[23]
Yb	$7 \rightarrow 6$	-0.12 ± 0.10	2.39 ± 0.30	–	–	[23]
Ta	$7 \rightarrow 6$	-0.27 ± 0.50	3.76 ± 1.15	–	–	[23]
Pb	$8 \rightarrow 7$	–	0.37 ± 0.15	0.79 ± 0.08	4.1 ± 2.0	[24]
		-0.020 ± 0.012	–	–	–	[25]
U	$8 \rightarrow 7$	-0.26 ± 0.4	1.50 ± 0.75	0.35 ± 0.12	45 ± 24	[24]

E. Friedman et al. / Nuclear Physics A579 (1994) 518–538

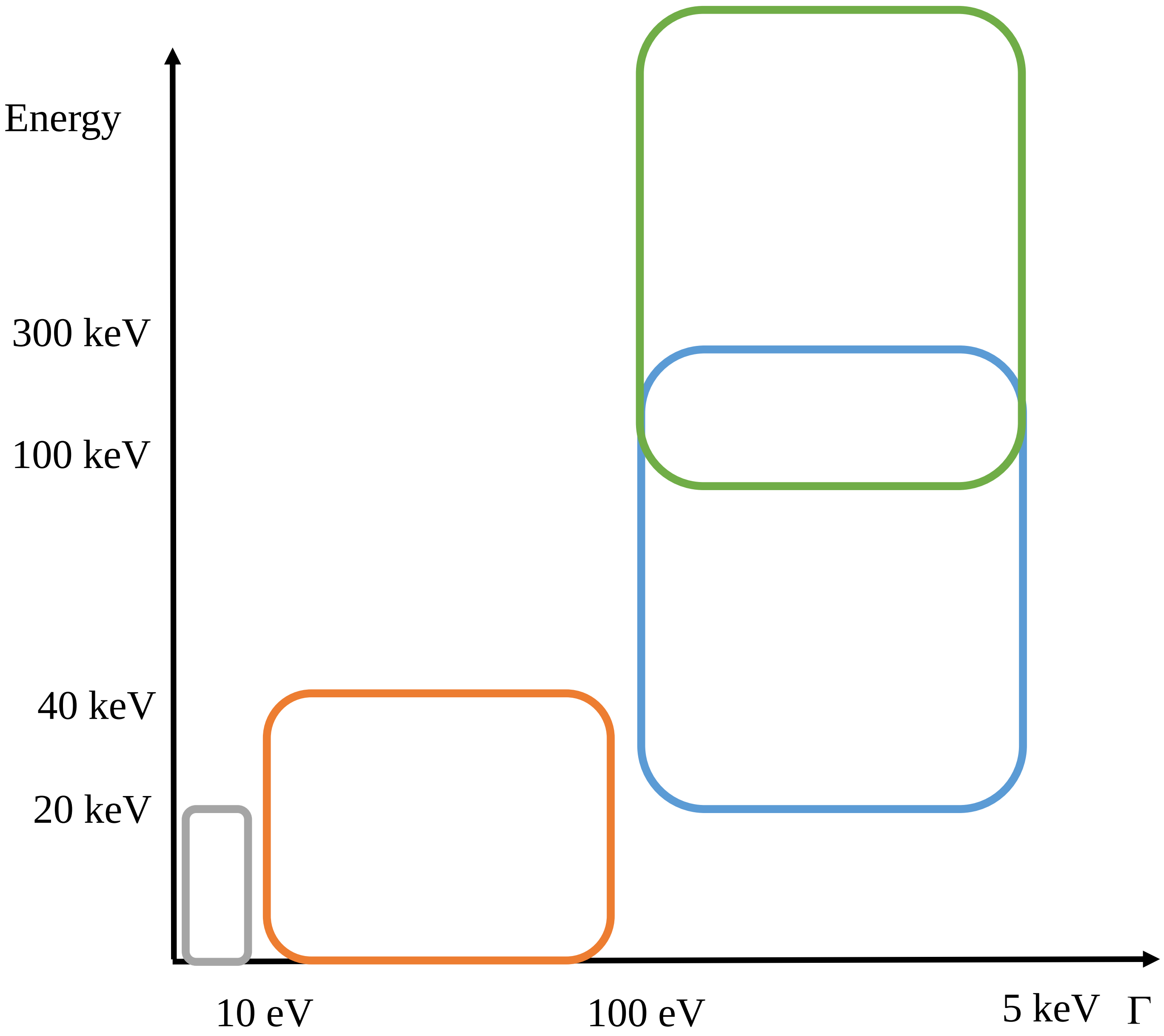
EXKALIBUR: which detector?

Crystal spectrometers (VOXES):
- High resolution
- Low efficiency
- 0-20 keV range

Silicon Drft Detectors (SDDs)
- 100 eV max resolution
- 4-40 keV range
- High efficiency

Cadmium-Zinc-Telluride (CdZnTe)
- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

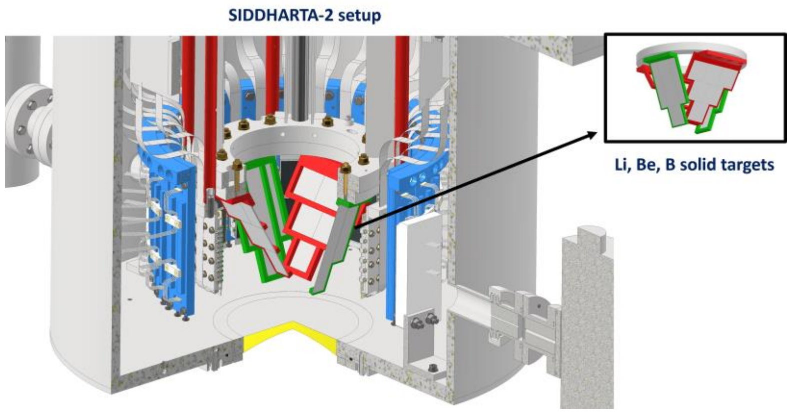
High Purity Germanium (HPGe)
- 100-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed

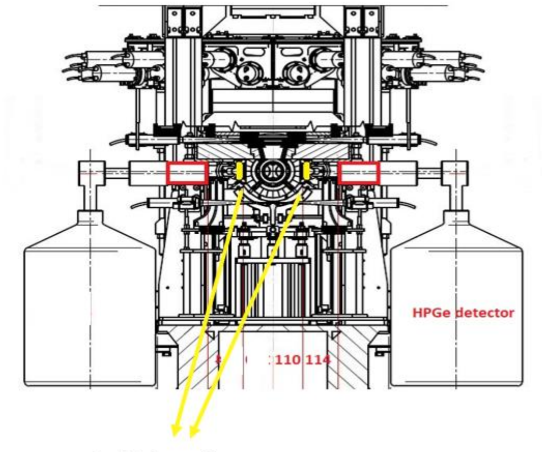


Beyond SIDDHARTA-2: EXKALIBUR

- **EXKALIBUR:** **a proposal for future kaonic atoms measurements at DAΦNE collider**
  - *Kaon mass - precision measurement at a level < 7 keV (actually it is 60 keV) with* ***HPGe***
  - *Kaonic helium transitions to the 1s level (never measured) with* ***SDD 1mm***
  - *Other light kaonic atoms (K^-Be, K^-Li, K^-B) with* ***SDD 1mm***
  - *Intermediare kaonic atoms (Kaonic Ti, S, Al, C, Ag, V, Zr) with* ***CdZnTe***
  - *Heavier kaonic atoms (Kaonic Pb, W, Co, Au, Pt) with* ***HPGe***
  - Ultra-High precision measurements of Kaonic Atoms with ***Crystal spectrometers (VOXES)***
  - *Measurement of Nuclear Resonance Effects in Kaonic Molybdenum Isotopes ($^{94}_{42}Mo, ^{96}_{42}Mo, ^{98}_{42}Mo, ^{100}_{42}Mo$) with investigation on nuclear pheriphery changement adding pair of neutrons from the lightest isotope (possible implication in* neutrinoless double beta ($0\nu\beta\beta$) decay) *with* ***HPGe***

- **Various setups in preparation:**
  - *HPGe*
  - *Crystal spectrometers (VOXES)*
  - *CdZnTe detectors*
  - *SIDDHARTA-2 like with SDD 1mm*






Thank you!