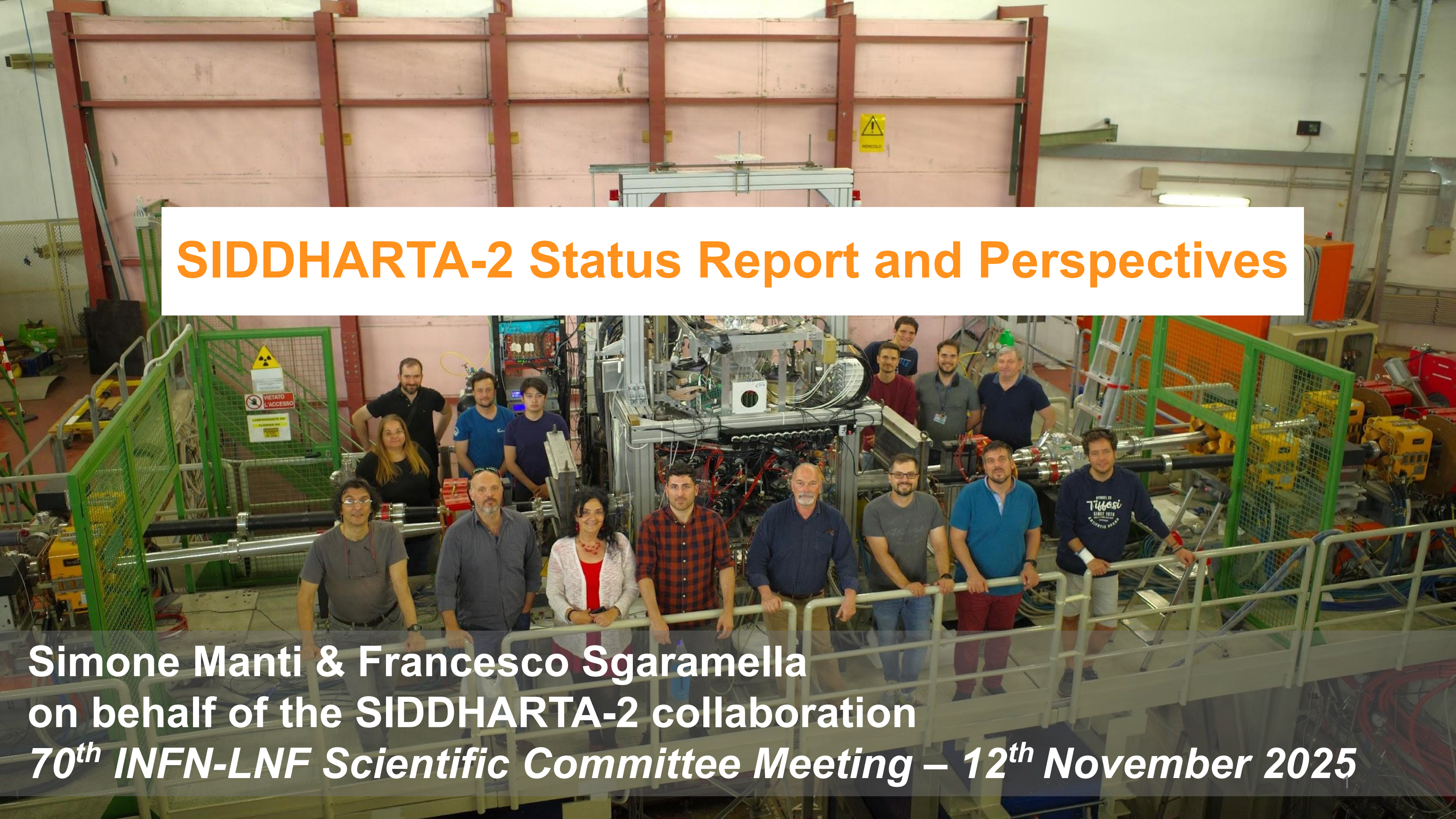
SIDDHARTA-2 Status Report and Perspectives



Simone Manti & Francesco Sgaramella
on behalf of the SIDDHARTA-2 collaboration

70th INFN-LNF Scientific Committee Meeting – 12th November 2025

Contents

- SIDDHARTA-2: Scientific Case Reminder
  - Kd Report and Other Results
  - Theoretical Insight KNe, KF
- EXKALIBUR: Update Program
- X-ray Detectors Development: SDDs and CdZnTe

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

HadronPhysics2
Study of Strongly Interacting Matter

HadronPhysics I3
Study of Strongly Interacting Matter

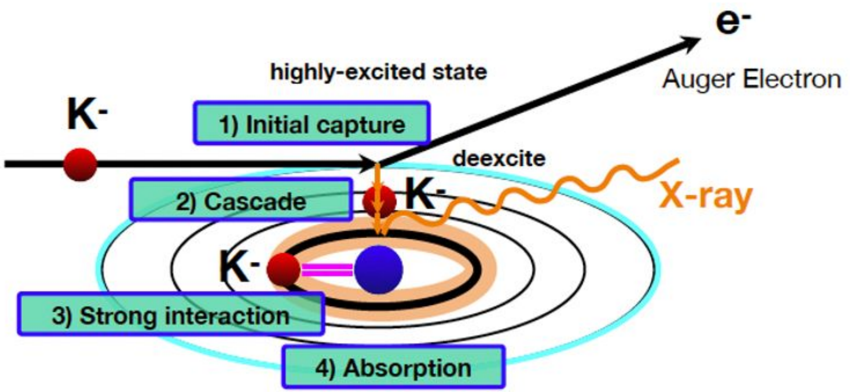
FWF Der Wissenschaftsfonds.

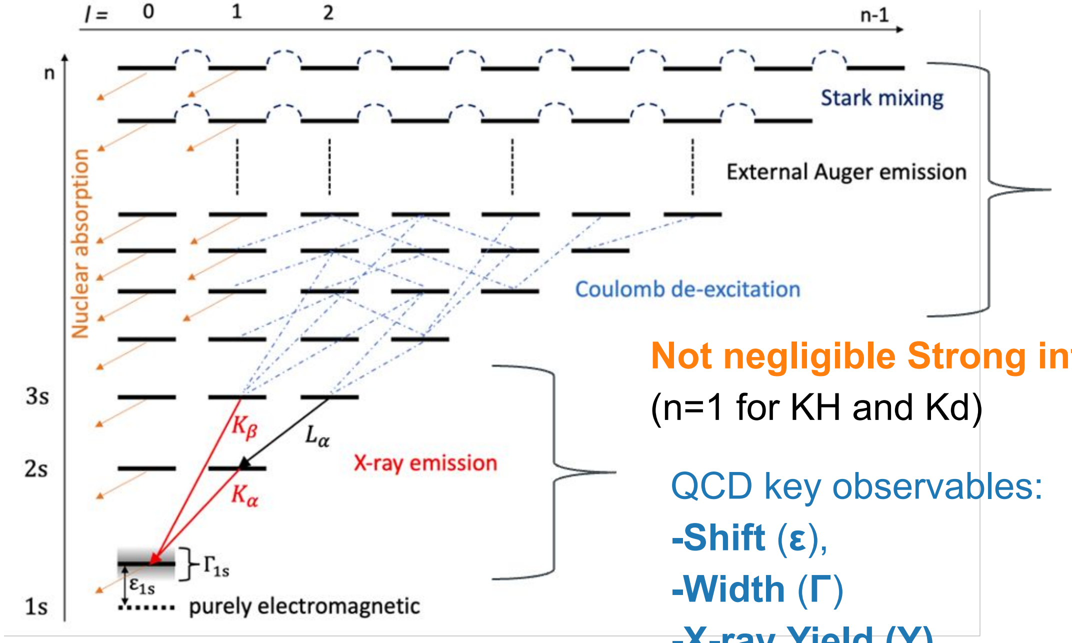
STRONG-2020

HRZZ
Croatian Science Foundation

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

Kaonic Atoms X-ray Spectroscopy (Reminder)





Pure Bound State QED transition

QED key observables: **Energy** and **X-ray Yield**

-Precision test of QED in Bound-State systems

Not negligible Strong interaction effect

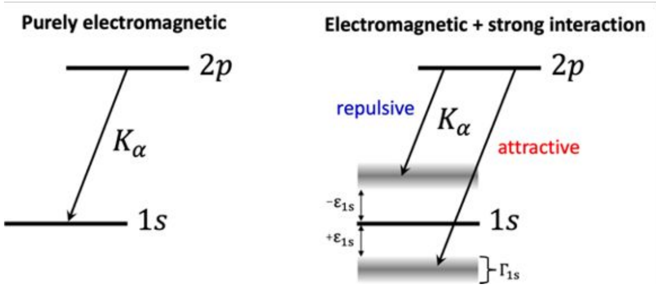
(n=1 for KH and Kd)

QCD key observables:

-Shift (**ε**),

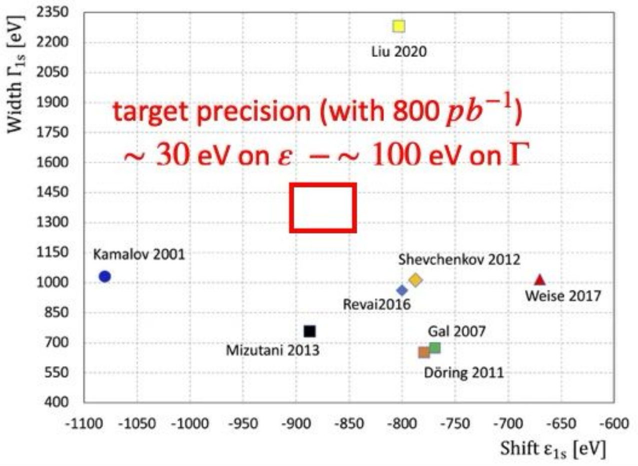
-Width (**Γ**)

-X-ray Yield (Y)



The SIDDHARTA-2 Experiment Main Aim (Reminder)

Main scientific goal: **First measurement ever of kaonic deuterium X-ray transition** to the ground state (1s-level) such as to determine its shift and width induced by the presence of the strong interaction, providing unique data to investigate the QCD in the non-perturbative regime with strangeness.

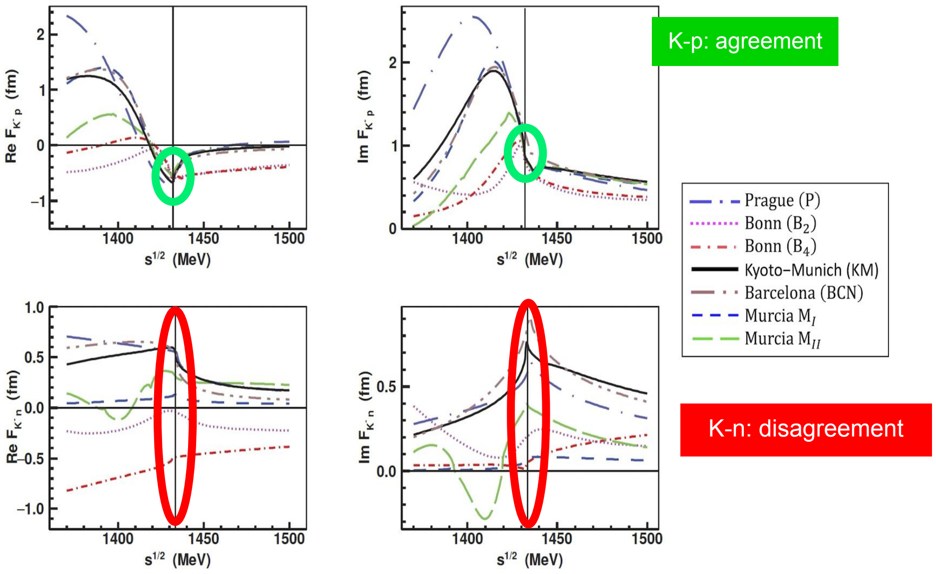


Determine the kaonic deuterium scattering length through the"summed up" Deser-Truman formula

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-d} / [1 + 2\alpha\mu(\ln\alpha - 1)a_{K-d}]$$

Shevchenko, N. V. Few Body Syst. 63, 22 (2022).

Combined analysis of the kaonic deuterium and kaonic hydrogen measurements to determine theisospin-dependet scattering lengths



Ciepl y, A. et al. AIP Conf. Proc. 2249, 030014 (2020).

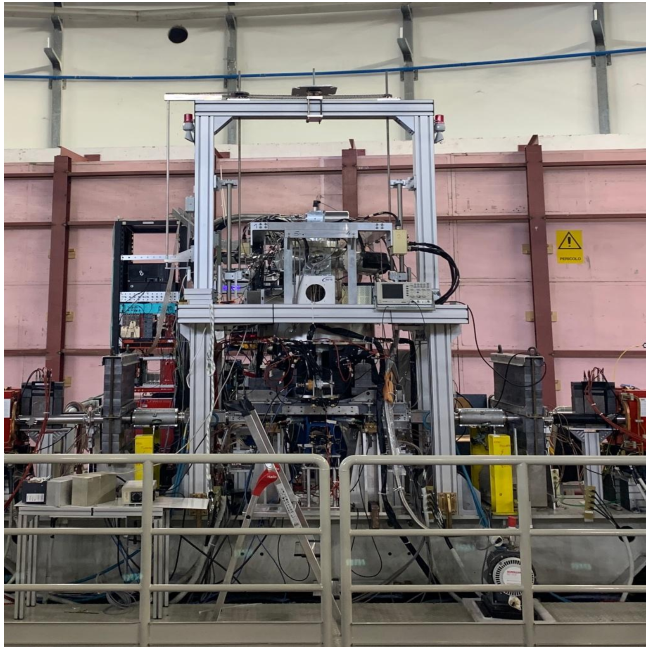
Data Taking Summary

- ***Kaonic Neon***: initial calibration and optimization of the setup, int. lumi 125 pb^{-1} (April 2023)
- ***K-d Run-1: int. luminosity 164 pb^{-1}*** *(May – July 2023)*
- ***Kaonic Helium-4***: final calibration of the setup , int. lumi 40 pb^{-1} (July 2023)

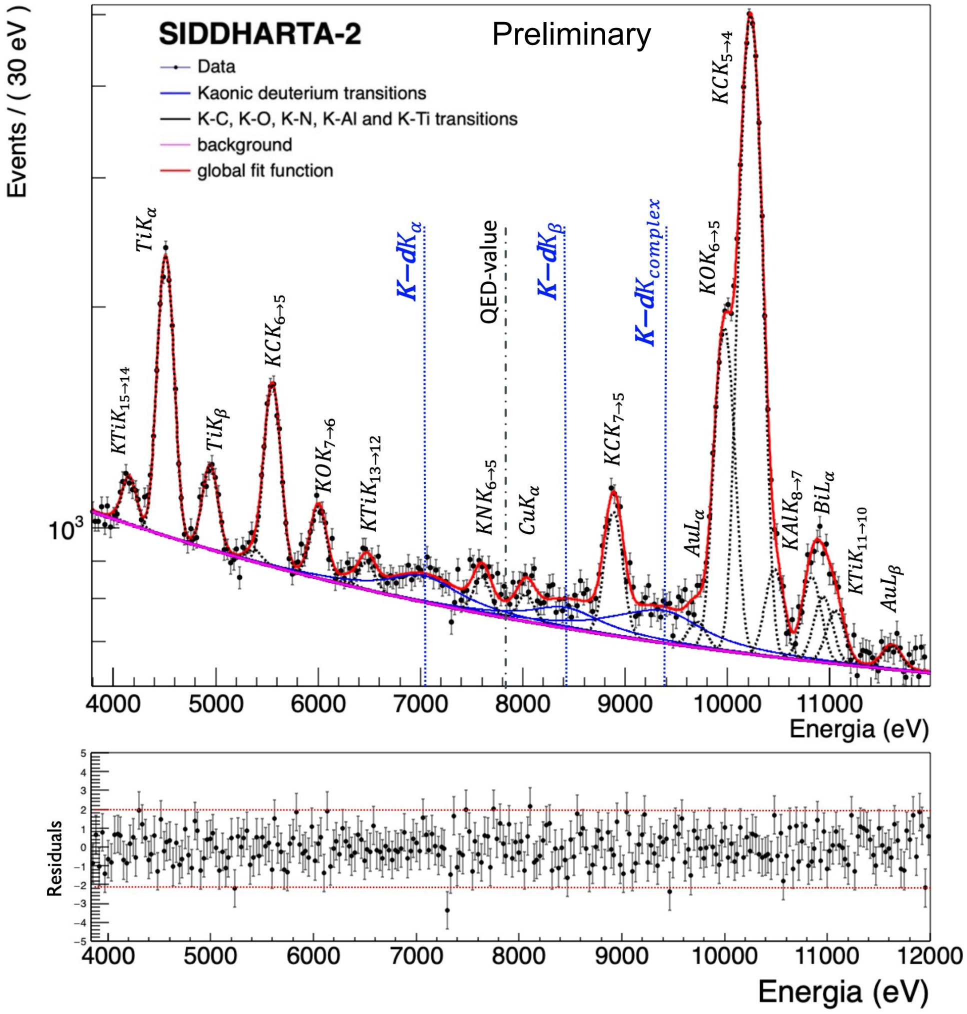
- ***Kaonic Neon***: initial calibration of the setup, int. lumi 36 pb^{-1} (Sept 2023)
- ***K-d Run-2: int. luminosity 276 pb^{-1}*** *(October – December 2023)*
- ***Kaonic Hydrogen***: final calibration of the setup , int. lumi 26 pb^{-1} (Dec 2023)

- ***Kaonic Hydrogen***: initial calibration of the setup, int. lumi 70 pb^{-1} (Jan 2024)
- ***K-d Run-3: int. luminosity 375 pb^{-1}*** *(February – April 2024)*
- ***Kaonic Hydrogen***: final calibration of the setup , int. lumi 150 pb^{-1} (April 2024)

- ***Low density run: int. luminosity 185 pb^{-1}*** (May – July 2024)
- ***Post Kd calibration run*** (July 2024) – 20 pb^{-1} *with solid targets (B and F)*



Total 1467 pb^{-1} of good data (April 2023 - July 2024; about 13 months)
K-d total integrated luminosity good for physics : 1000 pb^{-1}
Other Elements (H,He,B,F,Ne): 467 pb^{-1}

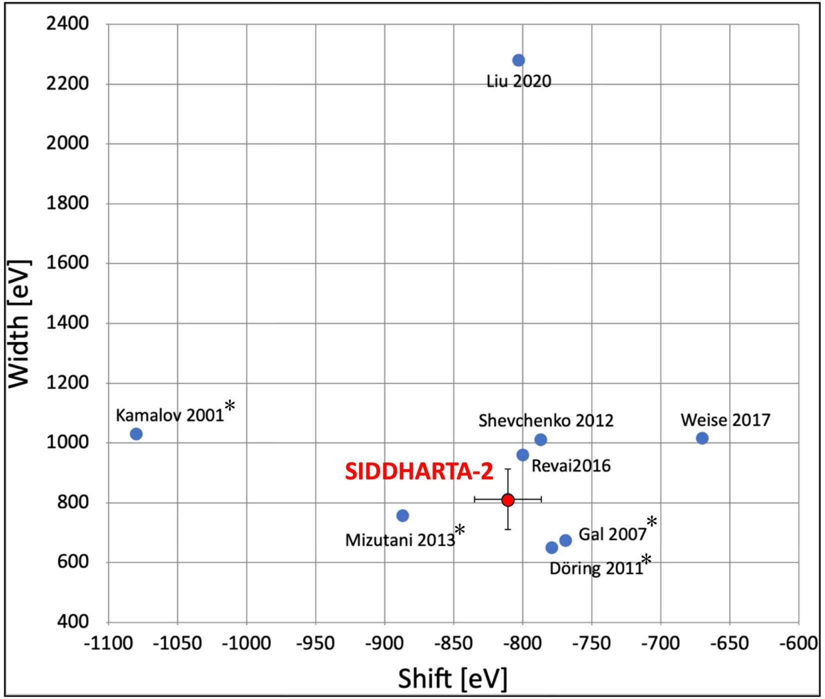


Kaonic Deuterium Results

$$\varepsilon_{1s} = -810.9 \pm 24.5(\text{stat}) \pm 2.1(\text{syst})\ \text{eV}$$

$$\Gamma_{1s} = 812 \pm 97(\text{stat}) \pm 33(\text{syst})\ \text{eV}$$

Targeted precision achieved!



*The energy shift and width are extracted from scattering length using the Deser-Trueman formula

Recommendation from the 69th Scientific Committee

"The Scientific Committee compliments the members of the collaboration on their scientific results, publications, and training and dissemination activities. The SC reiterates its recommendation to aspire to a ***high-impact physics journal*** *for the publication of their final result on the* ***Kd 1s energy shift and width****, as well as for the* ***expected yield determinations*** *and* ***derived results****."*

- Preliminary **Kd Spectrum** in **PPNP** article on kaonic atoms [(IF17.9)]
- **Kd 1s Energy Shift and Width** to **Nature Physics (tbc)** [(IF18.4)]
- $Y_{K_\alpha} = (6.01 \pm 0.14) \times 10^{-4}$ with ~ 22.9% **Relative Error.**
- Several **Cascade Models** predict different **Yields and Density trends**.
- Combining the **1.4%** and **0.8%** **LDD Kaonic Deuterium measurements** can help discriminate between cascade models.

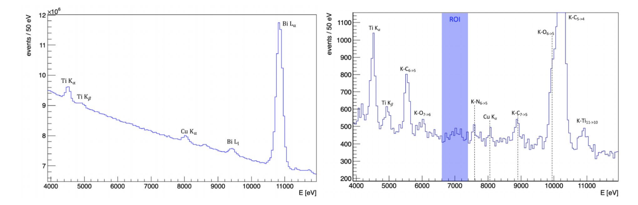


Figure 4.11: Left: SIDDHARTA-2 run-1 inclusive energy spectrum. Right: Preliminary SIDDHARTA-2 energy spectrum from run-1 data, after background subtraction. The region of interest (ROI) for the kaonic deuterium Kα line is highlighted.

- Extracting K^-d **Scattering Length**:

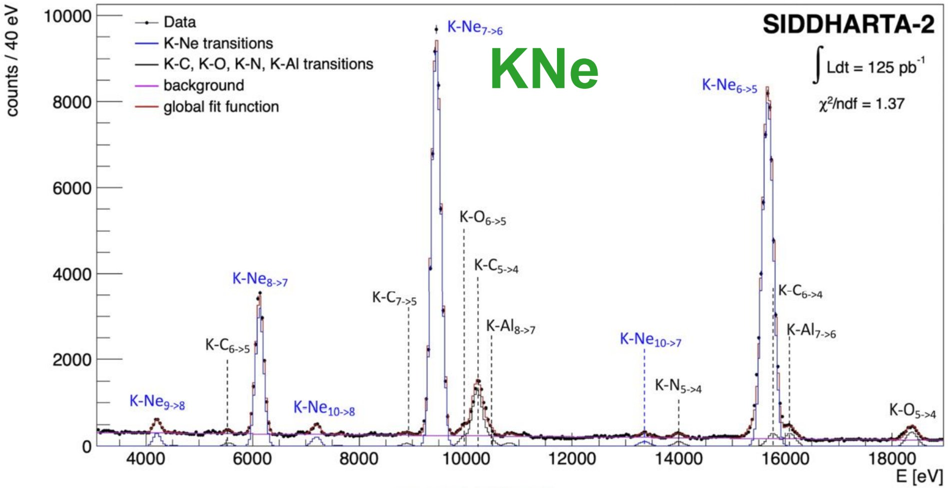
$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-d} / [1 + 2\alpha\mu(\ln\alpha - 1)a_{K-d}]$$

$$\mathrm{Re}(a_{K_D}) = -1.57 \pm 0.07\ (\mathrm{exp.}) \pm 0.01\ (\mathrm{th.})\ \mathrm{fm},$$
$$\mathrm{Im}(a_{K_D}) = \quad 1.11 \pm 0.13\ (\mathrm{exp.}) \pm 0.04\ (\mathrm{th.})\ \mathrm{fm}.$$

Shevchenko, N.V. Light Kaonic Atoms: From "Corrected" to "Summed Up" Deser Formula. *Few-Body Syst* 63, 22 (2022)
V. Baru, E. Epelbaum, A. Rusetsky, The role of nucleon recoil in low-energy antikaon-deuteron scattering. Eur. Phys. J. A 42, 111 (2009)

Light Kaonic Atoms: KNe, KB, KF

Accepted to PRA (S.Manti)



Phys. Lett. B 865 (2025) 139492

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

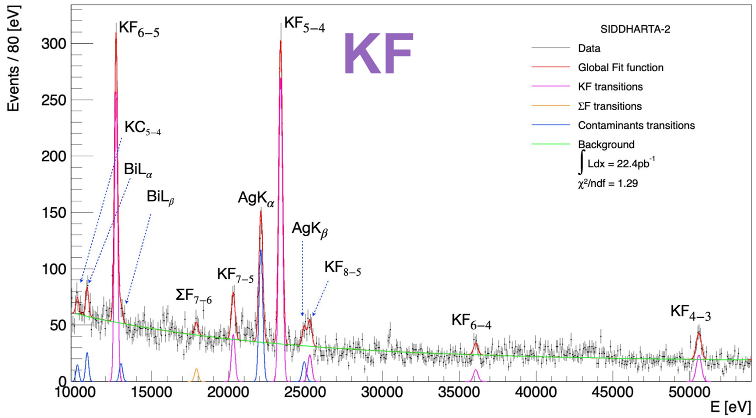
Letter

High precision X-ray spectroscopy of kaonic neon ☆

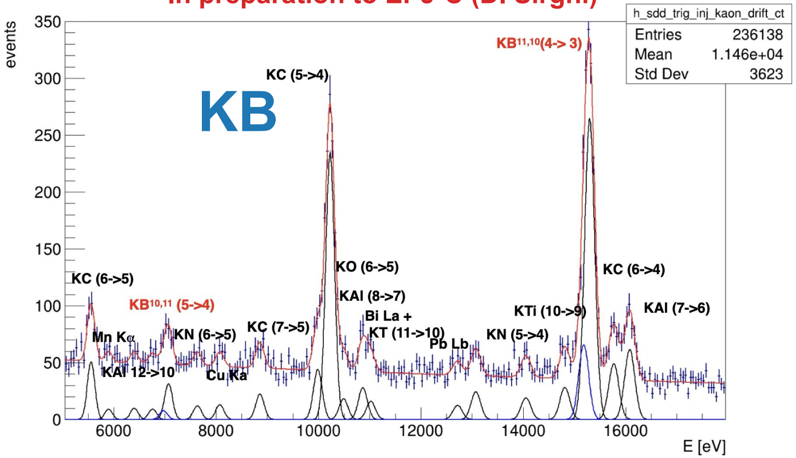
F. Sgaramella [a,*], D. Sirghi [b,a,c,**], K. Toho [d], F. Clozza [a], L. Abbene [e], C. Amsler [f], F. Artibani [a,g], M. Bazzi [a], G. Borghi [h,i], D. Bosnar [j], M. Bragadireanu [c], A. Buttacavoli [e], M. Cargnelli [f], M. Carminati [h,i], A. Clozza [a], R. Del Grande [k,a], L. De Paolis [a], K. Dulski [a,l,m], L. Fabbietti [k], C. Fiorini [h,i], I. Friščić [j], C. Guaraldo [a,l], M. Iliescu [a], M. Iwasaki [n], A. Khreptak [l,m], S. Manti [a], J. Marton [f], P. Moskal [l,m], F. Napolitano [a], S. Niedźwiecki [l,m], H. Ohnishi [d], K. Piscicchia [b,a], F. Principato [e], A. Scordo [a], M. Silarski [l], F. Sirghi [a,c], M. Skurzok [l,m], A. Spallone [a], L.G. Toscano [h,i], M. Tüchler [f], O. Vazquez Doce [a], E. Widmann [f], J. Zmeskal [f,l], C. Curceanu [a]

F Sgaramella, et al., Physics Letters B, 139492

In preparation to PRL (F. Clozza)



In preparation to EPJ-C (D. Sirghi)

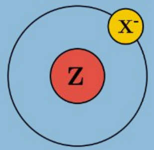


New Theoretical Developments - Ab initio Calculations

Recommendation from 69th Scientific Committee

*“The SC welcomes the enrichment of the **scientific program of the first EXKALIBUR module** with **BSQED** and **strong electric field dynamics studies**. It is therefore recommended that specific goals or targets be identified for these new objectives.”*

Ab Initio Input



- **Ab Initio Approach:** based only on **Physical Laws** and **Fundamental Constants.**
- Supports **Normal, Exotic,** or **Mixed Atomic Systems.**
- Supported **Exotic Particles:**
  - K^- : Kaons
  - μ^- : Muons
  - π^- : Pions
  - Σ^- : Sigmas
  - $\bar{p}^-$: Antiprotons
  - X^- : Test Particles

MCDF Framework

Basis Wavefunctions:

- Dirac Equation (spin-½ particles)

$$\left[c\boldsymbol{\alpha}\cdot\mathbf{p} + \beta mc^2 + V(\mathbf{r})\right]\psi_i(\mathbf{r}) = \varepsilon_i\psi_i(\mathbf{r})$$

- Klein-Gordon Equation (spin-0 particles)

$$\left[-\hbar^2c^2\nabla^2 + m^2c^4\right]\phi(\mathbf{r}) = \left[E - V(\mathbf{r})\right]^2\phi(\mathbf{r})$$

Multi-Configuration Dirac-Fock:

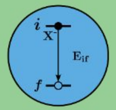
$$\Psi = \sum_{v=1}^{NCF} W_v\phi^v(1,2,...,N;J,J_z)$$

$$\mathrm{E_{tot}} = \sum_{\nu\mu} W_\nu W_\mu \langle\phi^\nu|H|\phi^\mu\rangle / \sum_\nu W_\nu^2$$

Total Energies Contributions:

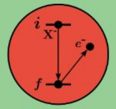
- QED (All-Orders)
- Breit Interaction
- Recoil Effect
- Nuclear Finite Size
- Screening Effect

Output Quantities

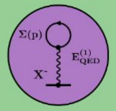


Energy Levels & Transitions

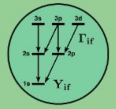
Radiative Transition Probabilities



Auger Decay Rates

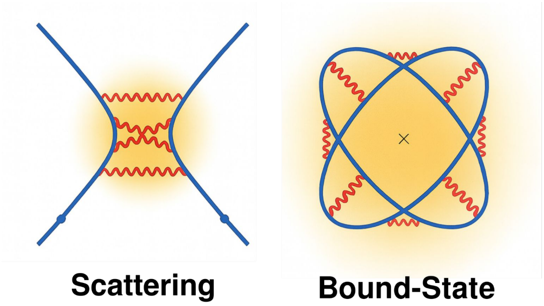


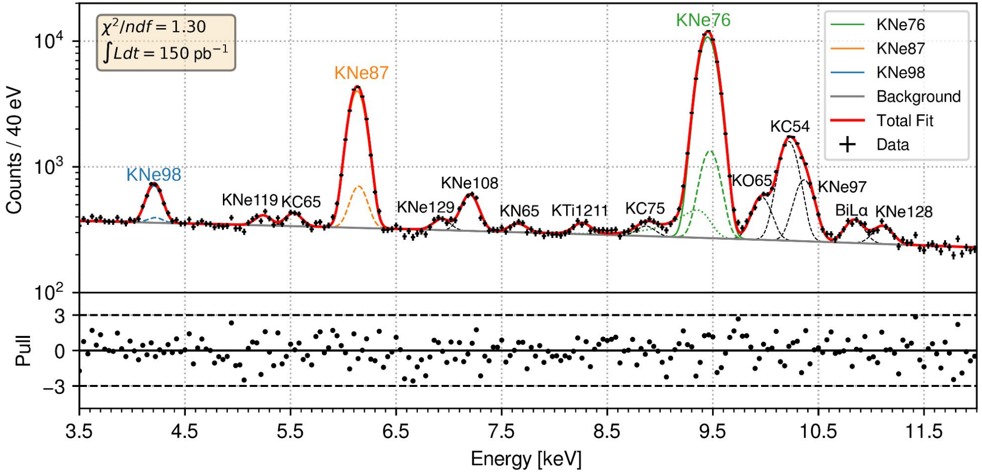
QED Self-Energy & Vacuum Polarization



Parameters for Atomic Cascade

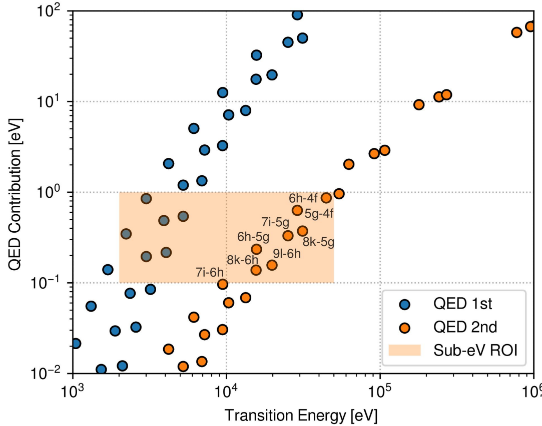
Testing Bound State QED with Kaonic Atoms?





- **Dirac-Fock vs Data** in KNe show **Negligible Nuclear Effects** (FNS, Recoil, QCD Shifts).
- **BSQED Contributions** exceed experimental uncertainties **(~8σ for the 7i-6h)**
- For KNe many transitions **2nd Order QED contributions** lie in the **sub-eV ROI**, enabling **Precision BSQED Tests**.

Transition	$E_{if}^{(\mathrm{exp.})}$	$\delta E_{if}^{(\mathrm{stat.})}$	$\delta E_{if}^{(\mathrm{sys.})}$	$E_{if}^{(\mathrm{calc.})}$	$E_{if}^{(\mathrm{QED})}$	$E_{if}^{(\mathrm{QED1})}$	$E_{if}^{(\mathrm{QED2})}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02
8k-7i	6130.57	0.65	1.50	6130.31	5.09	5.05	0.04
7i-6h	9450.23	0.37	1.50	9450.28	12.66	12.56	0.10
6h-5g[a]	15673.30	0.52	9.00	15685.39	32.75	32.51	0.24

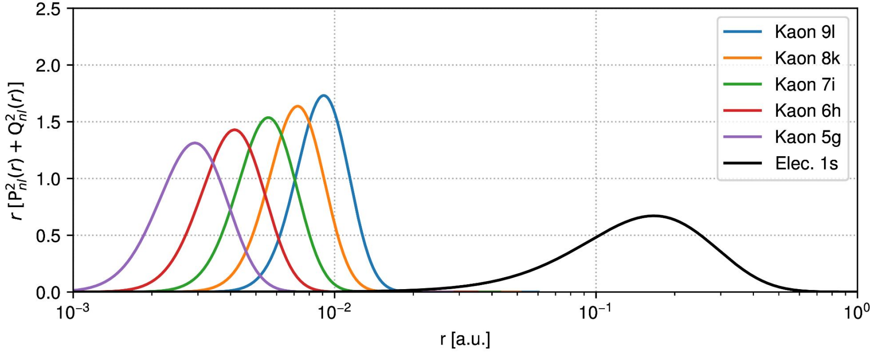


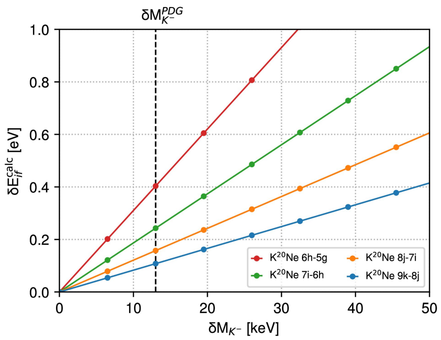
Testing Bound State QED with Kaonic Atoms? YES!

- Evaluation of **Electronic Screening** effects and **Uncertainty on the Kaon Mass (~13 keV)** on the observed lines in comparison to the size of QED contributions
- **Both Effects are Small (< 0.5 eV)** relative to the QED contributions and, moreover, electronic screening is negligible for the considered transitions.

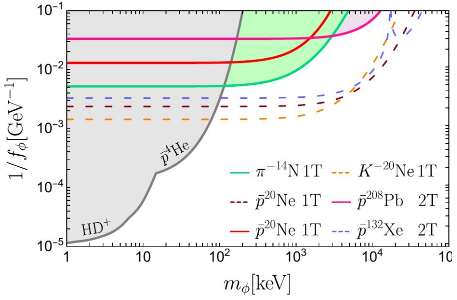
Transition	$E_{if}^{(\mathrm{exp.})}$	$\delta E_{if}^{(\mathrm{stat.})}$	$\delta E_{if}^{(\mathrm{sys.})}$	$E_{if}^{(\mathrm{calc.})}$	$E_{if}^{(\mathrm{QED})}$	$E_{if}^{(\mathrm{QED1})}$	$E_{if}^{(\mathrm{QED2})}$	$\Delta E_{if}^{(\mathrm{isot.})}$	$\Delta E_{if}^{(\mathrm{screen.})}$	$\Delta E_{if}^{(\mathrm{PDG})}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02	9.90	-0.38	0.11
8k-7i	6130.57	0.65	1.50	6130.31	5.09	5.05	0.04	14.45	-0.27	0.16
7i-6h	9450.23	0.37	1.50	9450.28	12.66	12.56	0.10	22.28	-0.18	0.24
6h-5g[a]	15673.30	0.52	9.00	15685.39	32.75	32.51	0.24	37.01	-0.11	0.40

Kaon WFs are well inside the 1s electron orbit -> **Neon Fully Ionized!**





Exotic atoms constrain uds-scalar
[Phys. Rev. Lett. **135**, 131803 (2025)]



Article Accepted by PRA! (arXiv:2508.08161)

Kaonic Atoms for Strong Fields QED: Schwinger Limit

- Interest in Studying **QED in Strong Fields with Exotic Atoms** (e.g., **Antiprotons** with **PAX@CERN**, **Muons** at **J-PARC**)

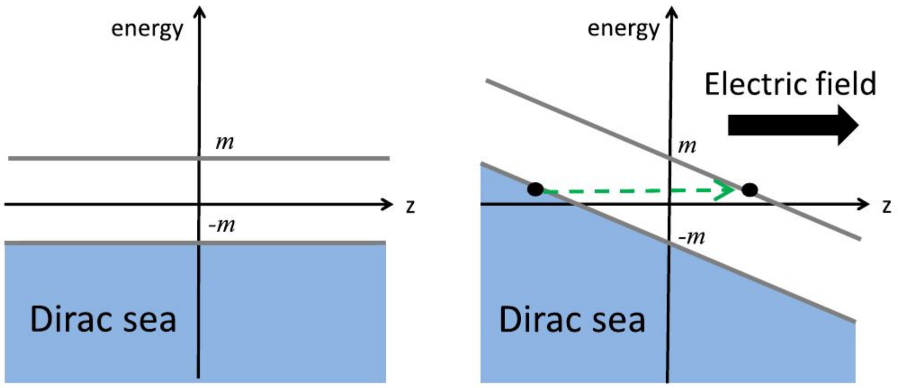
$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18} V/m$$

- Search for Transitions where the **Electric Field** experienced by the Exotic Particle Exceeds the **Schwinger Limit** E_C

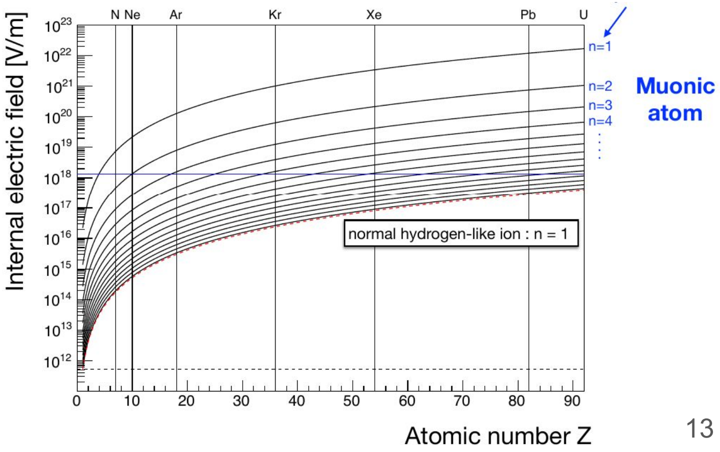
$$P \sim \exp\left(-\frac{E_c}{E}\pi\right)$$

- Limit defined where the **Spontaneous e^+- e^- Pair Production** occurs below threshold

Hattori, Koichi, et al. *Progress in Particle and Nuclear Physics* 133 (2023): 104068.



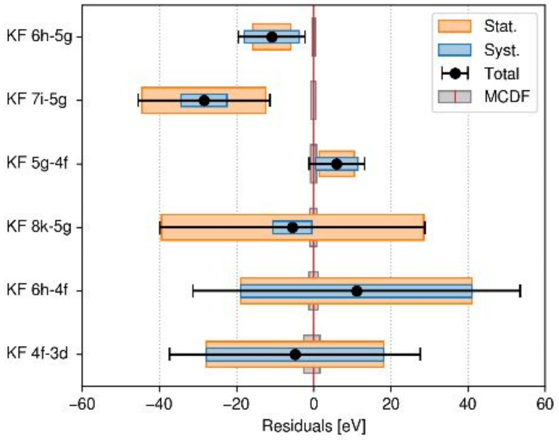
Above E_c ~ Dielectric Breakdown

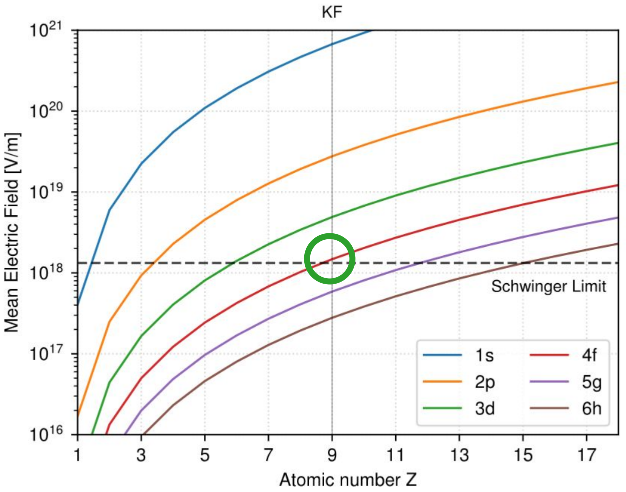


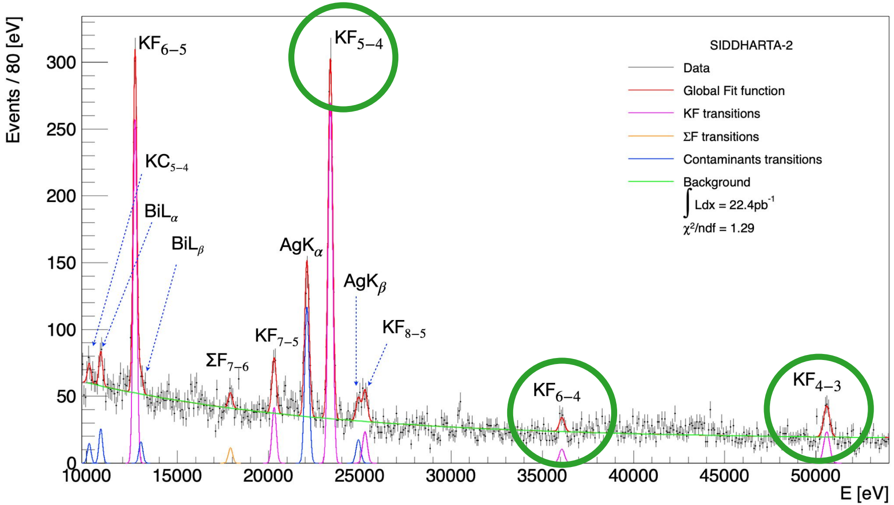
Kaonic Atoms for Strong Fields QED: Schwinger Limit for KF!

- For KF, the **5g-4f, 6h-4f** and **4f→3d** the **Average Orbital Electric Field** approaches the **Schwinger limit** (**a First in Exotic Atoms!**)

- **Significant BSQED contribution** due to the Nonlinear Dependence of **VP Diagrams** on the Electric Field Strength **(~9σ for 5g-4f with only 22.4 pb^{-1} ~ 2 days)**







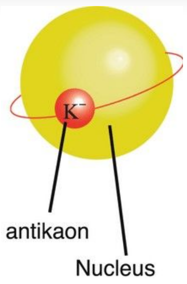
A Paper in Preparation to PRL!

Contents

- **SIDDHARTA-2: Scientific Case Reminder**
  - **Kd Report and Other Results**
  - **Theoretical Insight KNe, KF**
- **EXKALIBUR: Update Program**
- **X-ray Detectors Development: SDDs and CdZnTe**

1.1 - High Precision Kaonic Neon Measurement
To extract the negatively charged kaon mass with a precision < 10 keV

1.2 - Light kaonic atoms (LHKA)
– solid target Li, Be, B
– integration of 1mm SDD



EXKALIBUR

C. Curceanu et al., Front.in Phys. 11 (2023) 1240250

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

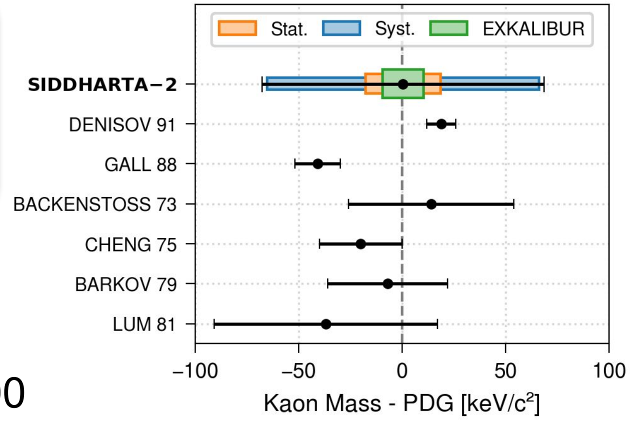
Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

- **Feasibility** with **minimal modifications/addings** of the already existent SIDDHARTA-2
  - ➢ New calibration system (0.2 eV accuracy)
  - ➢ New 1mm thick SDDs
  - ➢ New and improved CZT setup
- **Impact**: i.e. the **maximal scientific outcome**

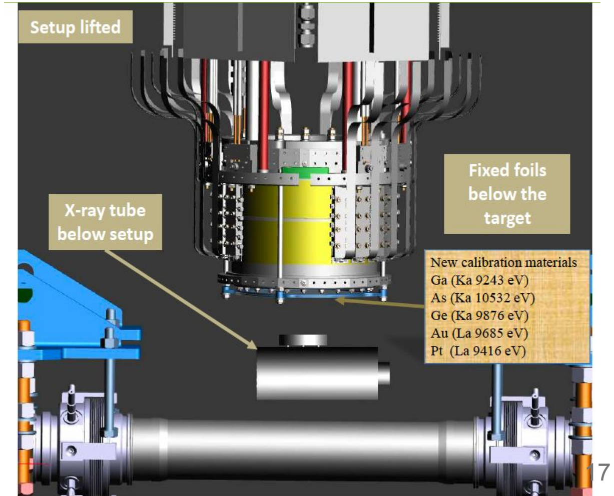
EXKALIBUR 1.1 - High Precision Kaonic Neon Measurement

Recommendation from 69th Scientific Committee

*"The SC welcomes the enrichment of the **scientific program of the first EXKALIBUR module** with **BSQED** and **strong electric field dynamics studies**. It is therefore recommended that specific goals or targets be identified for these new objectives."*



- **A KNe Dedicated Optimized Run can reach < 10 keV** via:
  - **×2** improvement by **Doubling Luminosity** (150 $pb^{-1} \rightarrow 300\ pb^{-1}$)
  - **×2** improvement by **Optimized Neon Gas Target Design**
    - **Efficiency~Lower Statistical**
    - **Calibration~Systematic→0.2 eV**



- **Uncertainty ~ 0.2 eV** will match 2nd order BSQED Contribution useful for recent **All-Order Wichmann and Kroll Contribution** studies ([Paul Indelicato et al. arXiv:2509.08763](arXiv:2509.08763))

EXKALIBUR 1.2 - Light Kaonic Atoms (LHKA) - Solid Targets

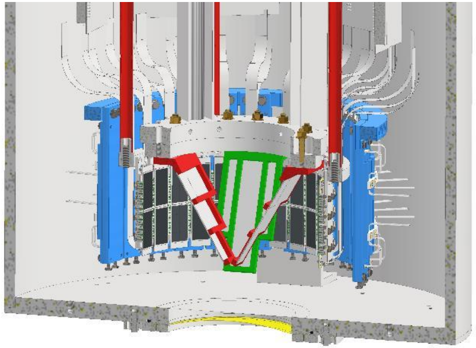
Recommendation from the 69th Scientific Committee

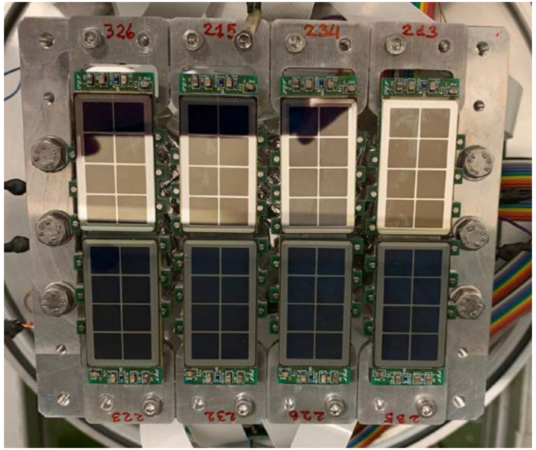
*"The SC welcomes the enrichment of the **scientific program of the first EXKALIBUR module** with **BSQED** and **strong electric field dynamics studies**. It is therefore recommended that specific goals or targets be identified for these new objectives."*

- **Kaonic Boron test** measurement successfully achieved!
- Construction of **new support system for Solid Targets** (Li,Be,B) conical shape to maximise the solid angle **MC simulations ongoing**
- **1mm thick SDDs** with **Enhanced Efficiency** above **15 keV**
- **QED in Strong Fields ($E>E_c$):** Kaonic Fluorine 5g-4f line Precision to ~ 0.5 eV with ~200 pb^{-1} using the same Solid-Target Setup
- In parallel **CZT measurement** of **(O, Al, S)**

Lithium-6		Lithium-7		Beryllium-9	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
$3 \to 2$	**15.085**	**$3 \to 2$**	**15.261**	**$3 \to 2$**	**27.560**
$4 \to 2$	**20.365**	**$4 \to 2$**	**20.603**	**$4 \to 3$**	**9.646**
$5 \to 2$	**22.809**	**$5 \to 2$**	**23.075**	**$5 \to 3$**	**14.111**
$4 \to 3$	5.280	$4 \to 3$	5.341	$5 \to 4$	4.465
$5 \to 3$	7.724	$5 \to 3$	7.814	$6 \to 4$	6.890
$5 \to 4$	2.444	$5 \to 4$	2.472	$6 \to 5$	2.425
$6 \to 4$	3.771	$6 \to 4$	3.815		

Solid targets system





Realising a (Strange) Periodic Table of Kaonic Atoms

- **Awarded 500,000 Core-Hours** on the **Helios Supercomputer** (PLGrid, Krakow ~36 PFlops) to build a **Kaonic Atoms Database (KaonDB)**

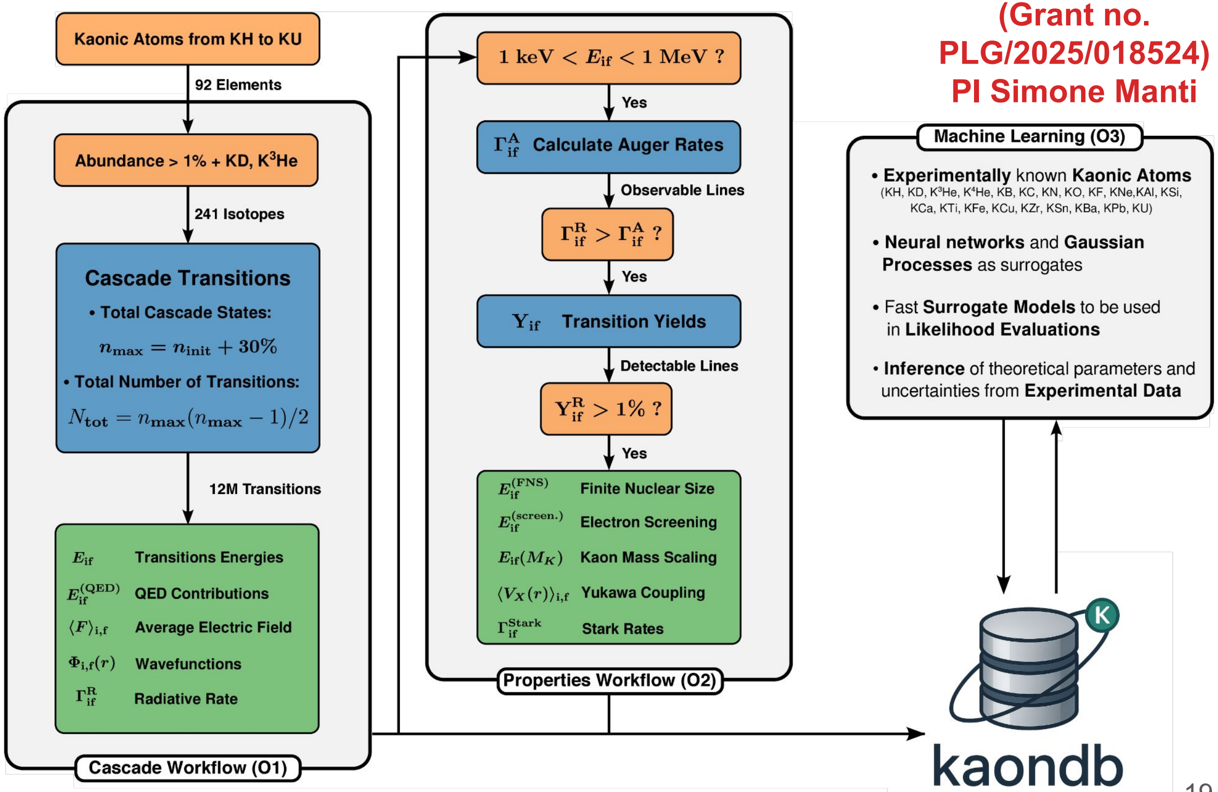
- **Cascade Workflow O1:** Calculating **Cascades** (KH–KU, ~12M transitions)

- **Properties Workflow O2:** Screening for **Observable** and **Detectable Lines** (BSQED, QCD, BSM)

- **Machine Learning O3:** Inferring **Parameters & Uncertainties** from Exp. with Surrogate Models

- Deliver an **Online-Accessible Database (FAIR principles)**

(Grant no. PLG/2025/018524) PI Simone Manti



[arXiv:2510.21519: EXKALIBUR: Towards a Kaonic Atoms Periodic Table to test Fundamental Interactions]

Contents

- SIDDHARTA-2: Scientific Case Reminder
  - Kd Report and Other Results
  - Theoretical Insight KNe, KF
- EXKALIBUR: Update Program
- X-ray Detectors Development: SDDs and CdZnTe

Recommendation from the 69th Scientific Committee

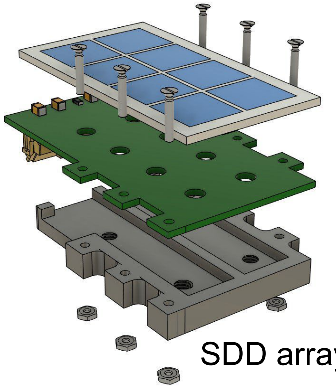
"The group is encouraged to continue their good work ***developing and testing X-ray detectors for EXKALIBUR****, yet to* ***explore also how these developments can be used in other experimental setups*** *in particular if DAΦNE will not further operate in collider mode."*

New 1mm thick Silicon Drift Detectors

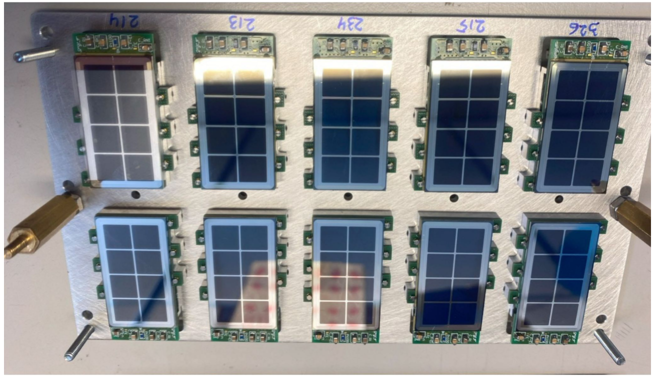
- **Innovative monolith large area (~5 cm^2) 1 mm thick SDD arrays:**
  - **New multilayer PCB and bias lines** better signal integrity
  - **higher efficiency** compared to SIDDHARTA-2 SDDs

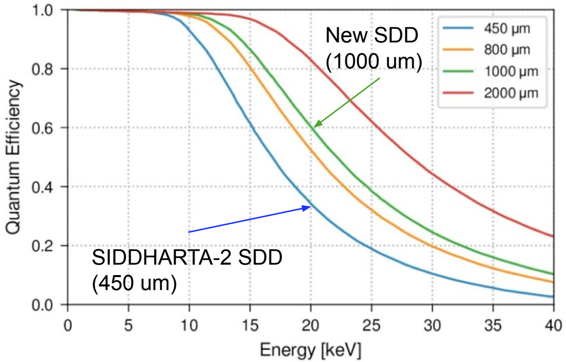
- **The first 12 arrays of SDD 1mm arrived in May 2025** to be characterized
  very successful test done in laboratory at LNF (technical article in preparation)

- **"Mass" production** of the SDD modules (~80 arrays) on going:
  - The SDD assembly will be done at **FBK**
  - **Cryogenic tests and spectroscopic optimization, and bus assembly at LNF**



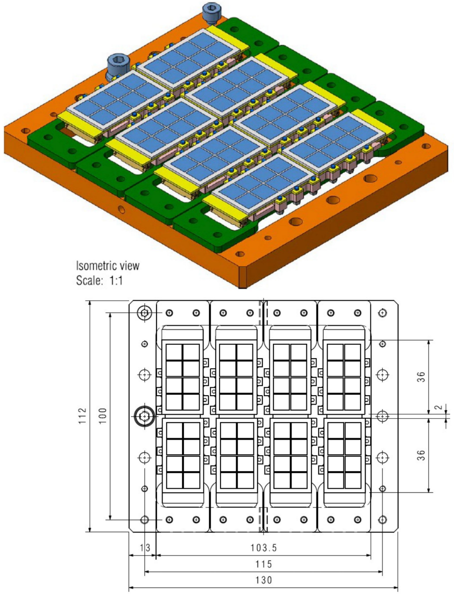
SDD array

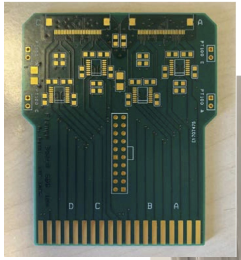


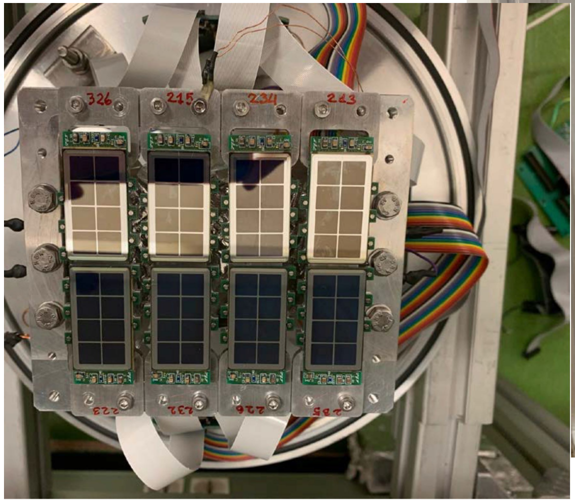


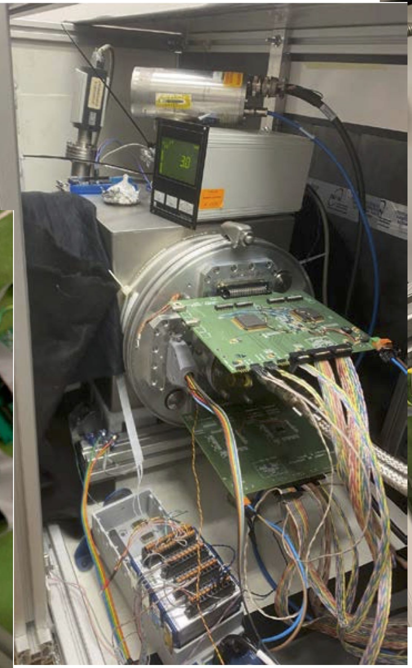
New 1mm thick Silicon Drift Detectors

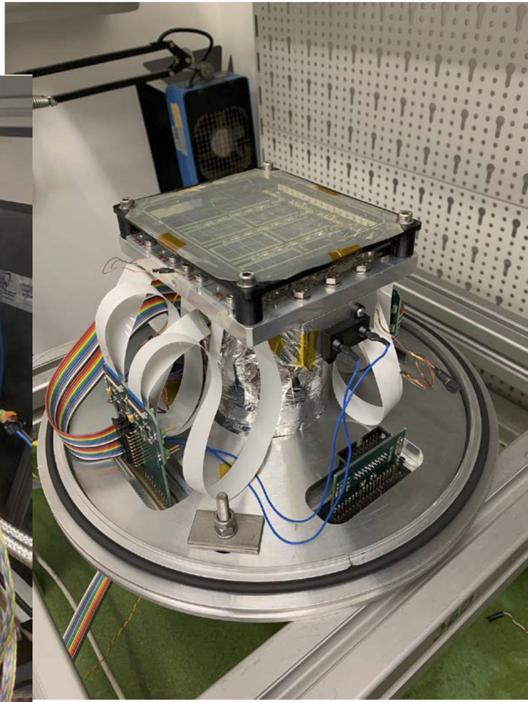
- **First BUS of the new SDD 1mm (64 SDDs) successfully installed and characterized in laboratory:**
    - New support holders
    - New Front-end and buffer board
    - New feedthroughs connectors for high voltage and signals









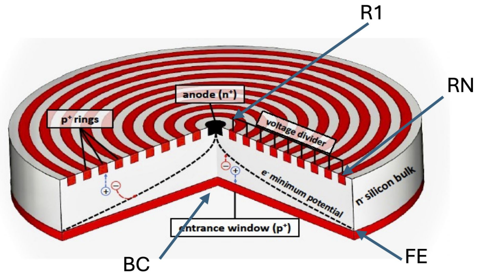


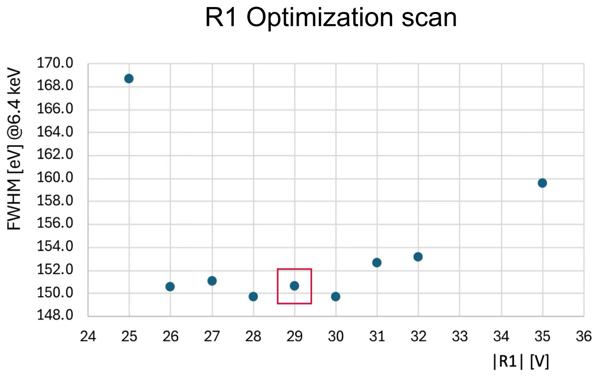
Courtesy of M. Bazzi, F. Sirghi

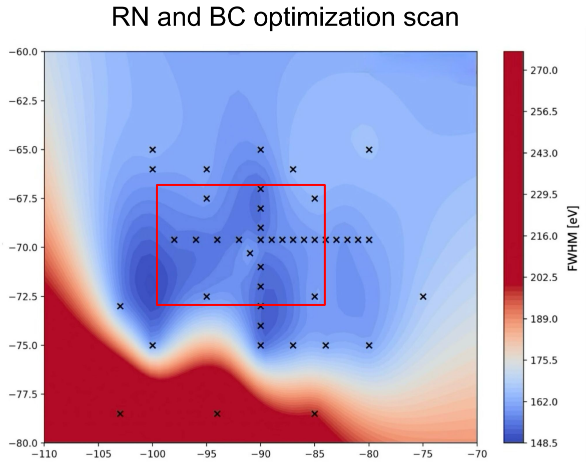
Test and optimization of the energy response

Fine-tuning 4 bias voltages for optimal spectroscopic response:

- **BC (Back Contact):** Depletes silicon bulk → improves charge transport
- **R1 & RN: Bias concentric rings** → create gutter like potential toward an
- **FE (Focusing Electrode): Enhances charge collection** → better signal integrity and energy resolution



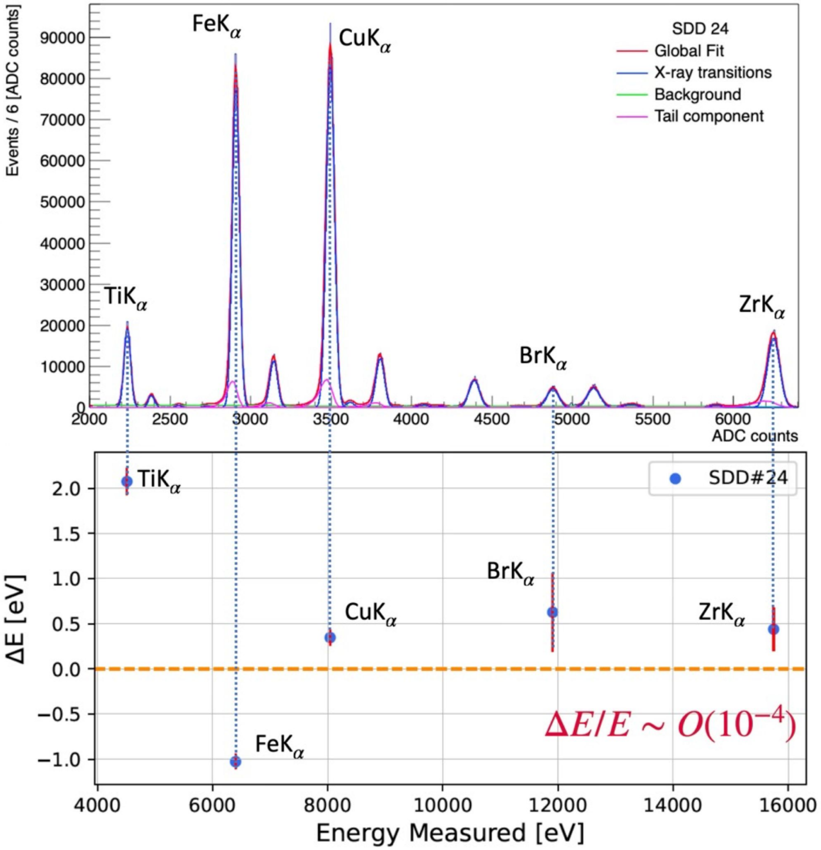




Optimized Energy Response

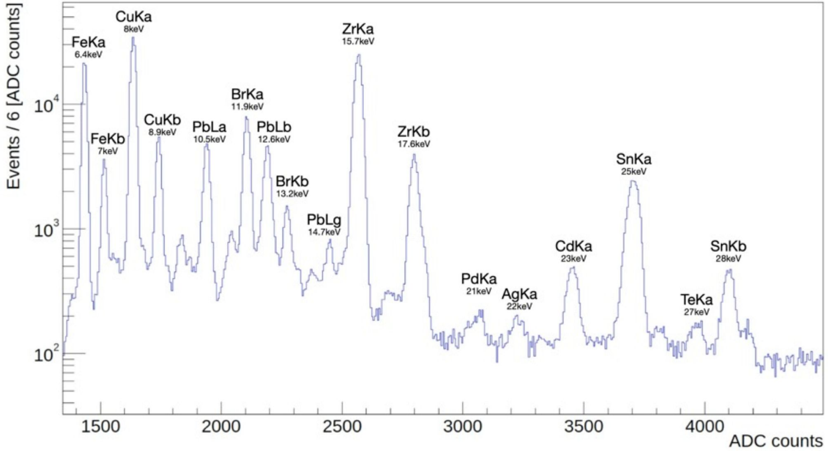
- **Ideal working point identified** → minimum energy resolution
- Typical energy resolution: **~ 150 eV FWHM@6.4 keV**
- **Stable performance** (variation within a few eV)

Test and optimization of the energy response



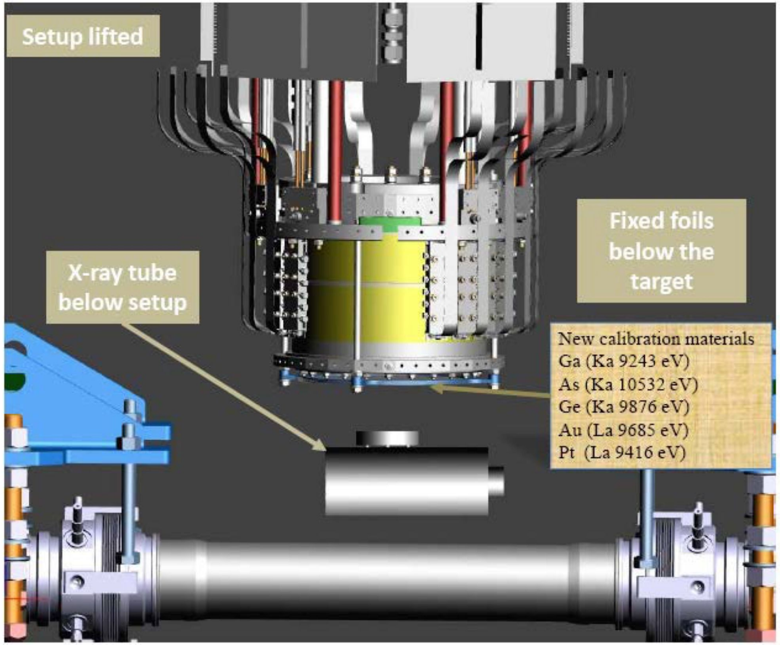
- **Energy response characterization** completed up to **16 keV**, showing **excellent linearity** **(< 2 eV deviation)**
- **Extension to 30 keV successfully achieved** data analysis in progress
- **Next step:** extend the range and evaluate **performance up to 50 keV**

Paper in preparation



New calibration system for SDD

- Upgraded calibration system for SDD calibration to achieve a 0.2 eV accuracy
  (to be applied to KNe existent measurements)
- Currently under construction – to be installed in DAFNE by end 2025
- **Measurement and test (DAFNE off) to begin in 2026**



New Calibration System – Activities

Completed:

- Setup modification completed
- Lifted the setup for easier access
- Entrance window modified
- Calibration materials ordered

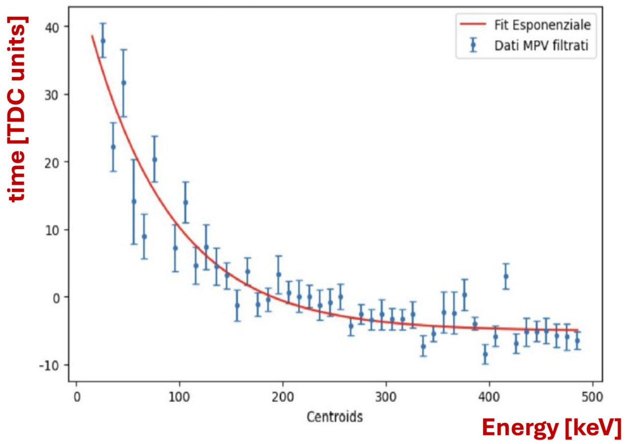
To be done:

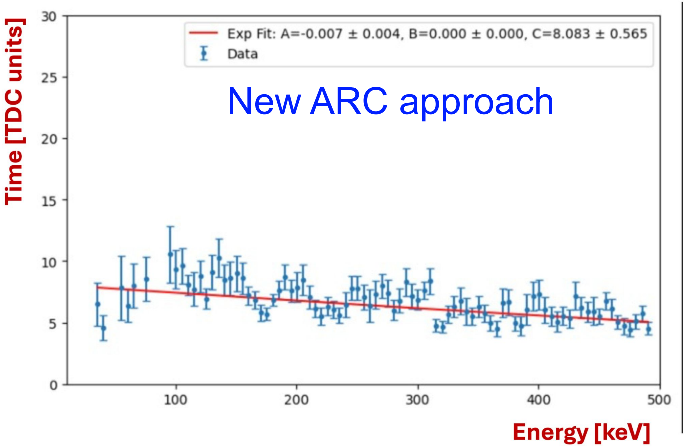
- Installation of calibration materials
- Alignment and verification of the setup

CdZnTe detectors for energy and time spectroscopy

Development of new pulse processing techniques to improve the timing resolution in CZT hemispherical detectors. Exciting results from simulation and measurements (Completed).

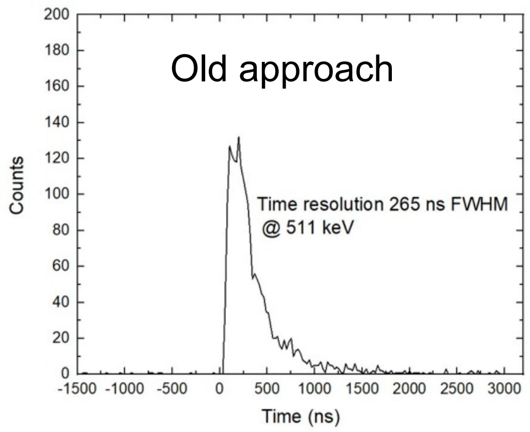
- Events interacting at different depths → different amplitudes (energy) and different shapes (rise time)
- By performing the classical leading-edge detection the arrival time strongly depends by the energy
- **Solution: Amplitude and Rise Time compensated (ARC)** timing based on a digital constant fraction discrimination → timing is independent by the energy

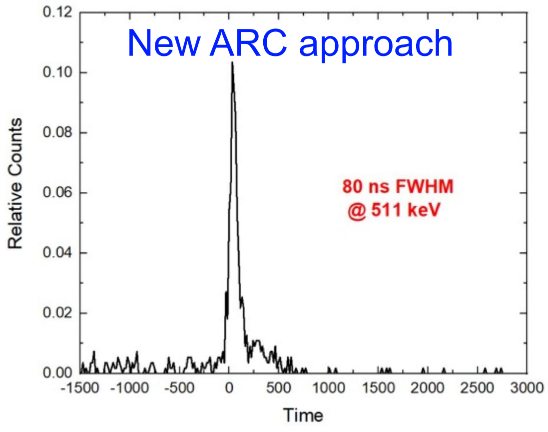




CdZnTe detectors for energy and time spectroscopy

- New pulse processing technique for improved time resolution **tested with a ^{22}Na (511 keV) source**
- **Time resolution (FWHM) improved by more than a factor 3**



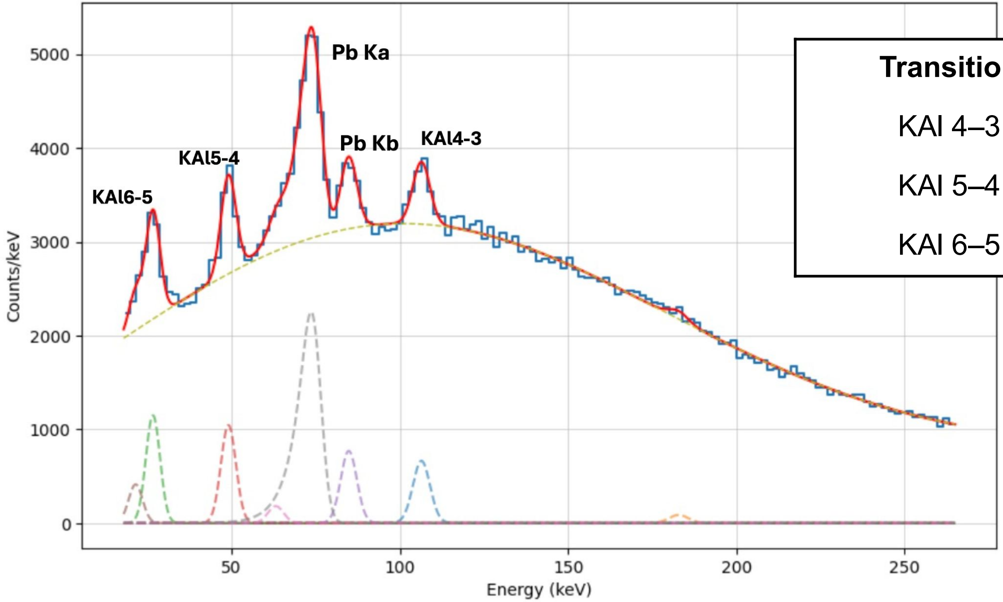


Timing performance of CdZnTe detectors studied for the first time
→ crucial for background reduction in accelerator environments
(**Technical article submitted to Meas. Scie. and Tech. (IOP)** (arXiv:2511.0267))

Courtesy of A. Scordo, F. Artibani, L. Abbene

Kaonic Aluminium measurement with CdZnTe detectors

A **25-30% improvement in the precision of K–Al** transition measurements was achieved with the new ARC analysis



Transition	Energy (keV)
KAl 4–3	106.46 ± 0.20 (stat) ± 0.20 (syst)
KAl 5–4	49.13 ± 0.10 (stat) ± 0.10 (syst)
KAl 6–5	26.70 ± 0.14 (stat) ± 0.10 (syst)

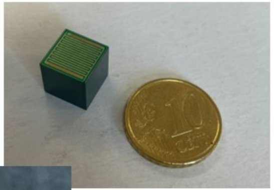
Scientific paper in preparation

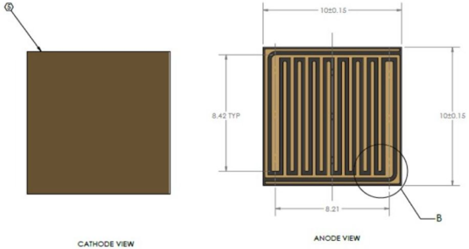
Courtesy of A. Scordo, F. Artibani

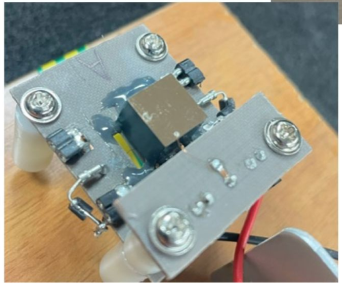
CdZnTe detectors for energy and time spectroscopy

Investigation (simulation and measurements) on new electrode design in CZT-based detectors for <u>energy and timing resolution</u> improvements (Ongoing).

Electrode Configurations: Coplanar Design







- **Detectors were wire bonded on a custom board to test with new preamplifiers**

Prototype ready to be tested at the BTF

- **Energy response** and **energy resolution** characterization
- **Timing performance measurement**
- **Evaluate the spectroscopic response in a high-background environment** a key step toward application in particle accelerator environment

Courtesy of A. Scordo, L. Abbene

Possible applications beyond EXKALIBUR

Quantum Foundation

- **VIP-3 (LNGS)**: Test of the Pauli Exclusion Principle and physics beyond Standard Model

Fundamental Interactions

- **J-PARC-E57**: Kaonic atoms → study low-energy QCD
- **CERN-PAX**: Antiprotonic atoms → test bound-state QED in strong fields
- **PSI:** Muonic/pionic atoms

Astrophysics

- **FIREBALL (LNF-BTF)** → e^-e^+ – plasma interaction

Applied Research

- Non-destructive high-resolution material characterization e.g. batteries - **RCLIB**

Future Possibility

- Beam diagnostic at X-ray facilities: **EuPRAXIA–EuAPS**

Publication since last SciCom - May 2025

- S. Manti, et al., "Precision Test of Bound-State QED at Intermediate-Z with Kaonic Neon", accepted by Phys. Rev. A

- C. Curceanu, et al., "Light kaonic atoms as probes of fundamental interactions in strange systems", accepted by Progress in Particle and Nuclear Physics (PPNP)

- F. Artibani, et al., "Time-based Selection of Kaonic Atom X-ray Events with Quasi-Hemispherical CZT Detectors at the DAΦNE collider" submitted to Meas. Scie. and Tech. (IOP)

- F. Clozza, et al., "Characterization of the X-ray spectroscopy SIDDHARTA-2 Silicon Drift Detectors' energy response up to 50 keV" submitted to Meas. Scie. and Tech. (IOP)

- F. Artibani, et al., "Low-Energy Kaon-Nuclei Interaction studies at the DAΦNE Collider: a Strangeness Odyssey", PoS(QCHSC24) 266

❖ **Scientific papers in preparation:**
Kaonic Deuterium, Kaonic Fluorine, Kaonic Boron, Kaonic Aluminium

Workshops and Conferences

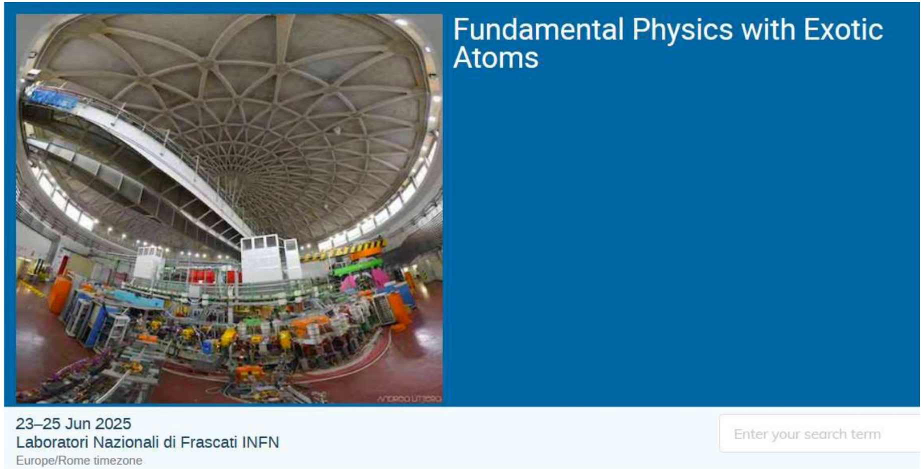
List of conferences and workshop we organized at LNF:

High Precision X-ray Measurement

80 participants and more than 50 talks

we presented the new 1 mm-thick SDDs, along with recent advances in CZT timing performance and application at particle colliders

https://agenda.infn.it/event/43727/



Fundamental Physics with Exotic Atoms

46 participants and 24 talks

we presented the results of the kaonic deuterium measurement, along with recent findings on kaonic neon, boron, and fluorine for BSQED studies

https://agenda.infn.it/event/46674/

Good news about SIDDHARTA folks

- **Riccardo Gasbarrini** - bachelor degree student at Univ. Tor Vergata
  completed his stage within SIDDHARTA-2
- **Michaela Lizardou - erasmus student from Greece starting in January**
- **Francesco Clozza** - Ph.D. student - **2nd best talk at HPXM 2025**

- **Simone Manti** - **Awarded 500,000 Core-Hours** on the **Helios Supercomputer**
  (PLGrid, Krakow ~36 PFlops) **(Grant no. PLG/2025/018524)**

- **Francesco Sgaramella, Francesco Artibani, Francesco Clozza – PROM Program Grant**
  (FERS.01.05-IP.08-0218/723): Short-term academic exchange on radiation detectors at Krakow University
-

  Alessandro Scordo: Chair of Cost Action ENRICH
  European Network for research and innovation in Radiation-based applications to address Increasing societal CHallenges

- **Leonardo Abbene: PI of DRESS - HADRON 2030 proposal:**
  Digital high REsolutionposition-sensitive room temperature Semiconductor detectors for high precision radiation Spectroscopy in hadron physics and related areas
  (WP5 TA5: Next-generation Instrumentation and target technologies)

- **Raffaele Del Grande - ERC starting Grant:** "Hunting three-body forces (HUNTING-3BFs)"

Summary

- **SIDDHARTA-2 data taking**

  Kd:shift and width of the 1s level determined

  Yield evaluation and scattering length determination ongoing

  Other kaonic atoms: K-Ne, K-F, K-B, K-Al, K-Cu

$$\varepsilon_{1s} = -810.9 \pm 24.5(\text{stat}) \pm 2.1(\text{syst})\ \text{eV}$$

$$\Gamma_{1s} = 812 \pm 97(\text{stat}) \pm 33(\text{syst})\ \text{eV}$$

- **New Opportunities in Kaonic Atom Spectroscopy**

  High-precision tests of **Bound-State QED (BSQED)** - **Physics beyond the Standard Model**

- **EXKALIBUR Scientific Modular Program**

  Kaon–multi-nucleon interaction (low-energy QCD):

  kaonic boron, beryllium, lithium with 1 mm SDD

  kaonic Oxygen, Sulfur with CdZnTe

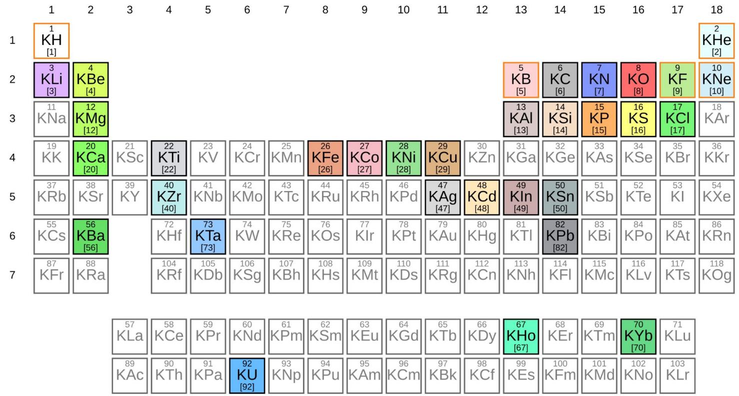
  High-precision BSQED & extreme-field physics:

  kaonic neon, fluorine (sub-eV precision)

  Kaon mass measurement:

  via kaonic neon transitions

➔ Ready to start as soon as possible

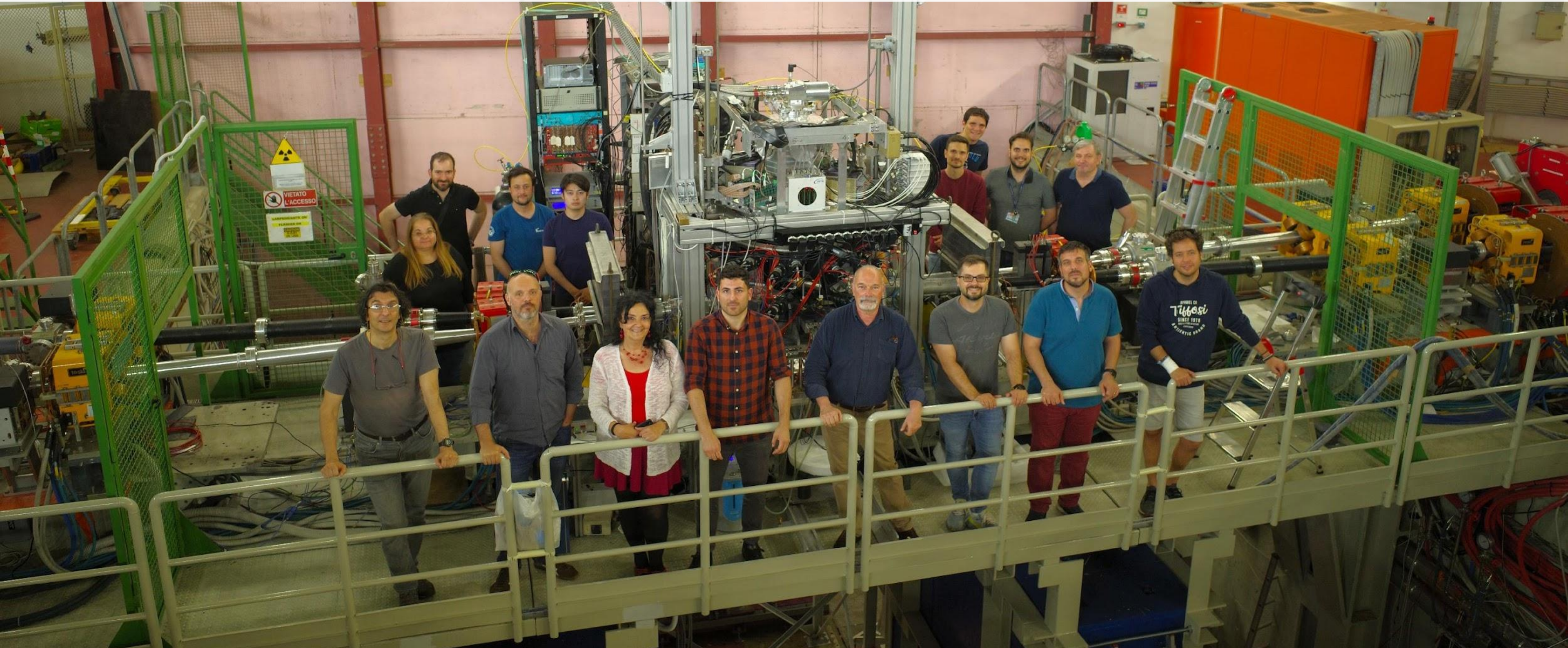


- **Technological Developments - Application Beyond EXKALIBUR**

  First 1 mm-thick SDD bus successfully tested: EXKALIBUR, VIP3, and FIREBALL

  CdZnTe detectors: time response characterization and **new prototype to be tested at BTF**

Special thanks to the accelerator, research and technical divisions, to the DAΦNE staff, in particular to Catia Milardi, the LNF Director, to the Gruppo 3-INFN and to all those who made this possible!



SPARE

Recommendation the from 69th Scientific Committee

*“The Scientific Committee compliments the members of the collaboration on their scientific results, publications, and training and dissemination activities. The SC reiterates its recommendation to aspire to a **high-impact physics journal** for the publication of their final result on the **Kd 1s energy shift and width**, as well as for the **expected yield determinations** and **derived results**.”*

- Preliminary **Kd Spectrum** in **PPNP** article on kaonic atoms (IF17.9)
- **Kd 1s Energy Shift and Width** to **Nature Physics (tbc)** (IF18.4)
- $Y_{K_\alpha} = (6.01 \pm 0.14) \times 10^{-4}$ with ~ 22.9% **Relative Error.**
- Several **Cascade Models** predict different **Yields and Density trends**.
- Combining the **1.4%** and **0.8%** **LDD Kaonic Deuterium measurements** can help discriminate between cascade models.

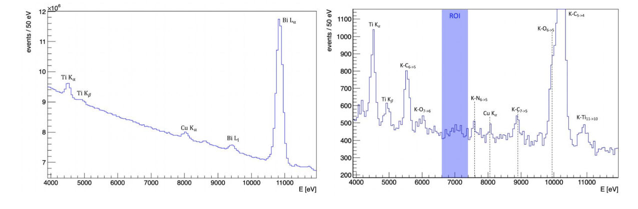
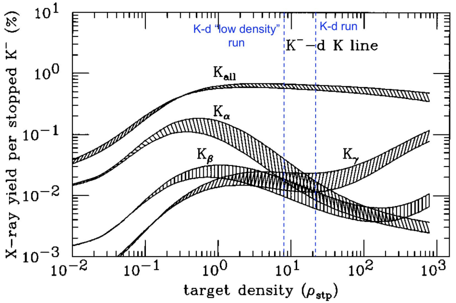
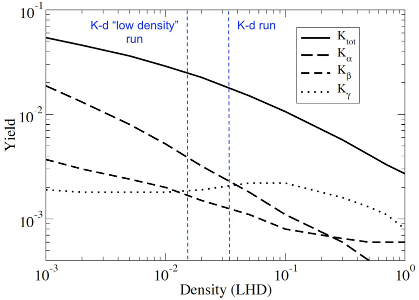


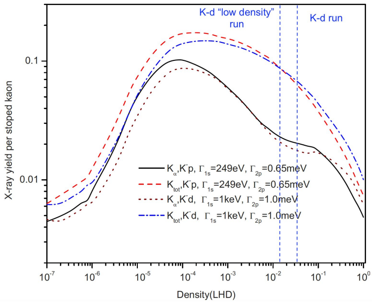
Figure 4.11: Left: SIDDHARTA-2 run-1 inclusive energy spectrum. Right: Preliminary SIDDHARTA-2 energy spectrum from run-1 data, after background subtraction. The region of interest (ROI) for the kaonic deuterium Kα line is highlighted.



T. Koike, T. Harada, Y. Akaishi, Phys.Rev.C 53 (1996), 79-87



T.S. Jensen, Frascati Phys.Ser. 36 (2004), 349-354

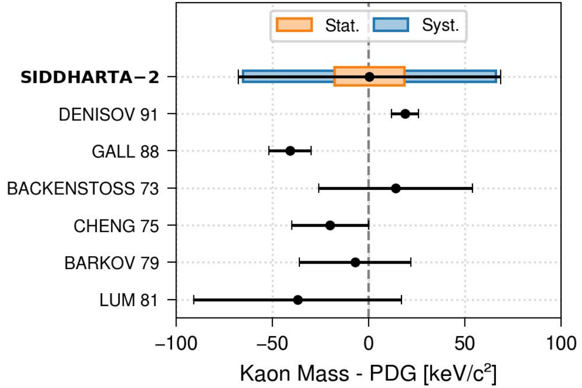


M Raeisi, S. Z. Kalantari, Phys.Rev.A 79, 012510 (2009)

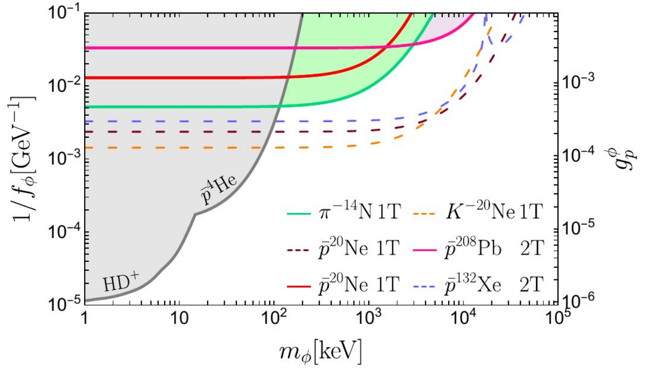
Fundamental Physics with KNe: Kaon Mass & BSM Physics

- Transitions with **Sub-eV Statistical Precision (~30 ppm)** already provide a **Statistical Uncertainty of ~18 keV** on the Kaon Mass combining the 7i-6h + 8k-7i

Transition	M_{K^-} [MeV]	$\delta M_{K^-}^{\text{stat.}}$ [keV]	$\delta M_{K^-}^{\text{syst.}}$ [keV]
7i-6h	493.674	19	78
8k-7i	493.699	52	121
7i-6h + 8k-7i	493.677	18	66



- **Transition Energies Residuals** useful for **Exclusion Limits Plots** for hypothetical particles with **Yukawa-Type Couplings**



Exotic atoms constrain uds-scalar [Phys. Rev. Lett. **135**, 131803]

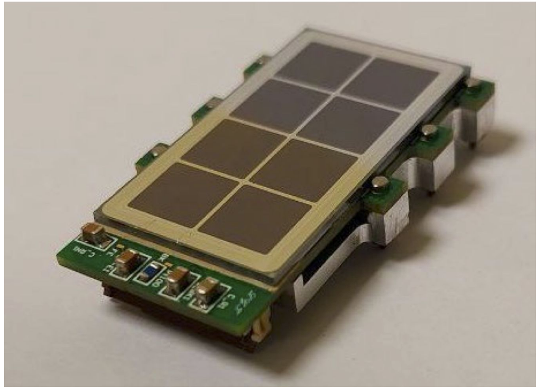
High-Throughput Search of Kaonic Atom Transitions

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 KH [1]																	2 KHe [2]
2	3 KLi [3]	4 KBe [4]											5 KB [5]	6 KC [6]	7 KN [7]	8 KO [8]	9 KF [9]	10 KNe [10]
3	11 KNa	12 KMg [12]											13 KAl [13]	14 KSi [14]	15 KP [15]	16 KS [16]	17 KCl [17]	18 KAr
4	19 KK	20 KCa [20]	21 KSc	22 KTi [22]	23 KV	24 KCr	25 KMn	26 KFe [26]	27 KCo [27]	28 KNi [28]	29 KCu [29]	30 KZn	31 KGa	32 KGe	33 KAs	34 KSe	35 KBr	36 KKr
5	37 KRb	38 KSr	39 KY	40 KZr [40]	41 KNb	42 KMo	43 KTc	44 KRu	45 KRh	46 KPd	47 KAg [47]	48 KCd [48]	49 KIn [49]	50 KSn [50]	51 KSb	52 KTe	53 KI	54 KXe
6	55 KCs	56 KBa [56]		72 KHf	73 KTa [73]	74 KW	75 KRe	76 KOs	77 KIr	78 KPt	79 KAu	80 KHg	81 KTl	82 KPb [82]	83 KBi	84 KPo	85 KAt	86 KRn
7	87 KFr	88 KRa		104 KRf	105 KDb	106 KSg	107 KBh	108 KHs	109 KMt	110 KDs	111 KRg	112 KCn	113 KNh	114 KFl	115 KMc	116 KLv	117 KTs	118 KOg
			57 KLa	58 KCe	59 KPr	60 KNd	61 KPm	62 KSm	63 KEu	64 KGd	65 KTb	66 KDy	67 KHo [67]	68 KEr	69 KTm	70 KYb [70]	71 KLu	
			89 KAc	90 KTh	91 KPa	92 KU [92]	93 KNp	94 KPu	95 KAm	96 KCm	97 KBk	98 KCf	99 KEs	100 KFm	101 KMd	102 KNo	103 KLr	

*measured by SIDDHARTA-2

arXiv:2510.21519: EXKALIBUR: Towards a Kaonic Atoms Periodic Table to test Fundamental Interactions

New 1mm thick Silicon Drift Detectors



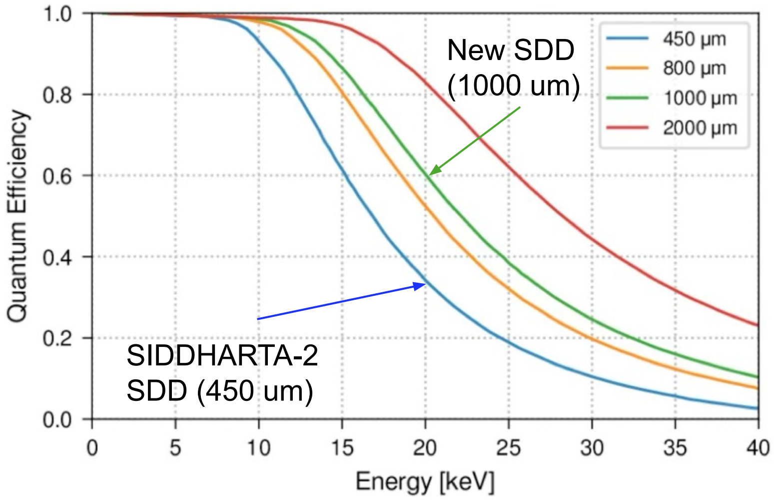
- Pixel dimensions: 7.9 mm X 7.9 mm
  N. pixels per array: 2 X 4

- **1mm thick silicon bulk** will allow for a **better efficiency at high energy**

- **Very good Leakage** Current Density @ 24°C:
  1-mm-thick SDDs: ~ 0.5-2 nA/cm2

- **Good production yield: 93 arrays**

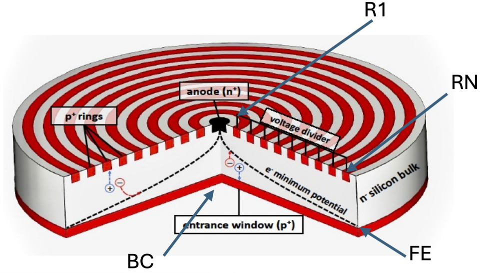
- **New multilayer PCB and bias lines**
  introduced to
  reduce noise and signal integrity

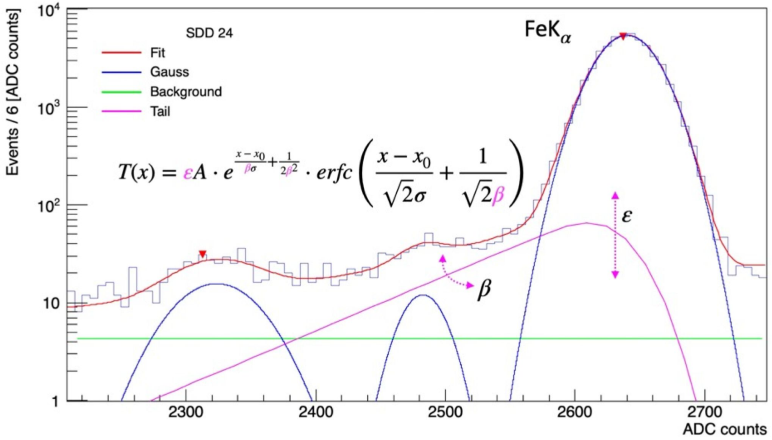


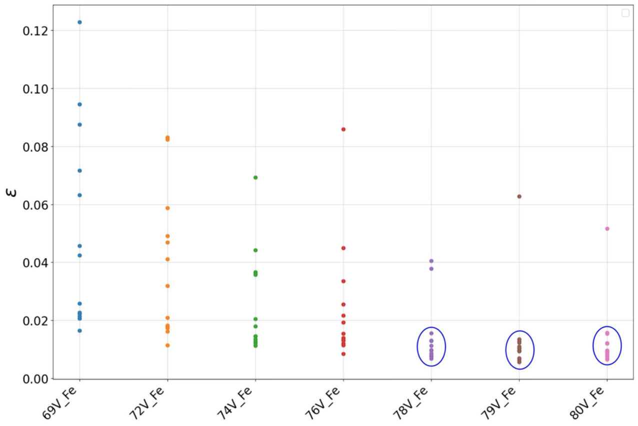
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
POLITECNICO MILANO 1863
FONDAZIONE BRUNO KESSLER

Test and optimization of the energy response

- **FE (Focusing Electrode) bias voltage tuning to enhances the signal integrity** reducing the exponential tail component of the response function (due to incomplete charge collection and e-h recombination)





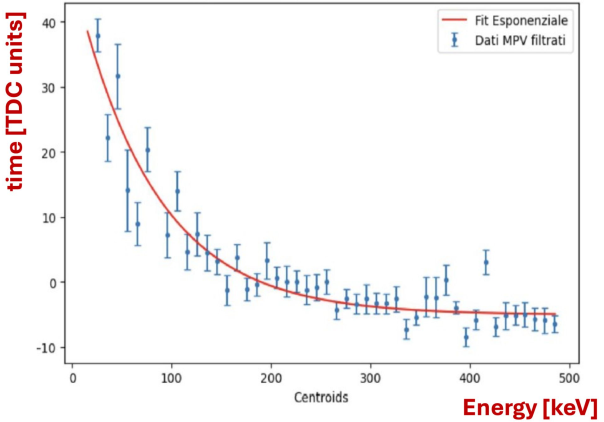


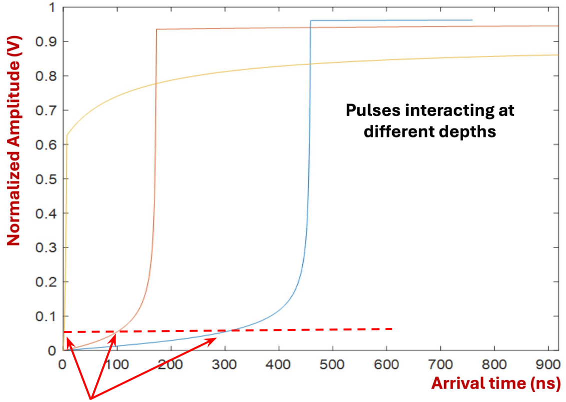
Smaller tail contribution and **more uniform energy response** of the SDDs at higher FE (Focusing Electrode) bias voltages

CdZnTe detectors for energy and time spectroscopy

Development of new pulse processing techniques to improve the timing resolution in CZT hemispherical detectors. Exciting results from simulation and measurements (Completed).

- Events interacting at different depths → different amplitudes (energy) and different shapes (rise time)
- By performing the classical leading-edge detection the arrival time strongly depends by the amplitude
- **Solution: Amplitude and Rise Time compensated (ARC)** timing based on a digital constant fraction discrimination → timing is independent by the amplitude



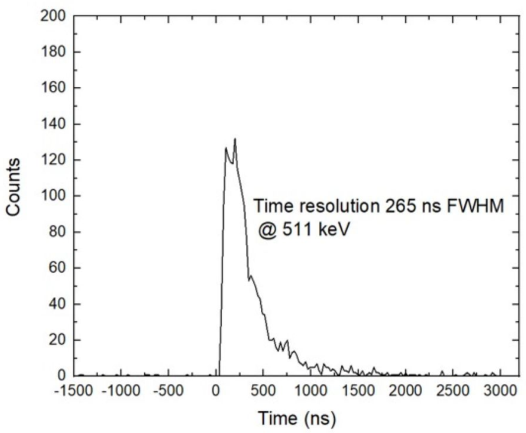


Different timing measurements
(true arrival time t=0)

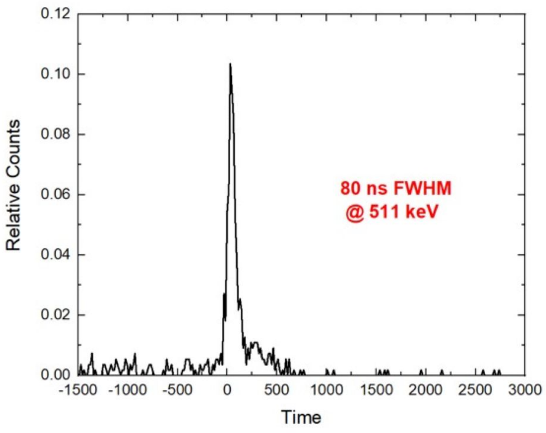
CdZnTe detectors for energy and time spectroscopy

Development of new pulse processing techniques to improve the timing resolution in CZT hemispherical detectors. Exciting results from simulation and measurements (Completed).

- New pulse processing technique for improved time resolution **tested with a ^{22}Na (511 keV) source**
- **Time resolution (FWHM) improved by more than a factor 3**



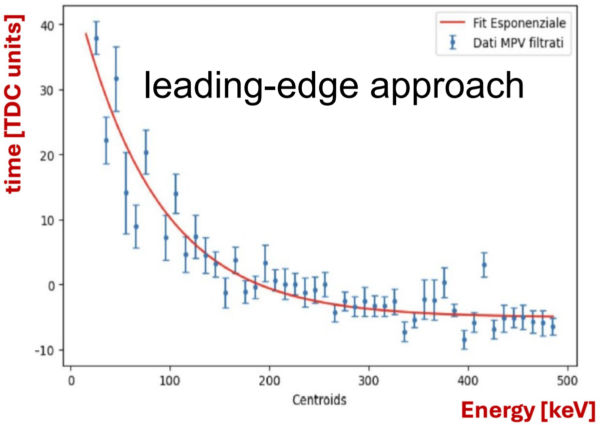
Old approach

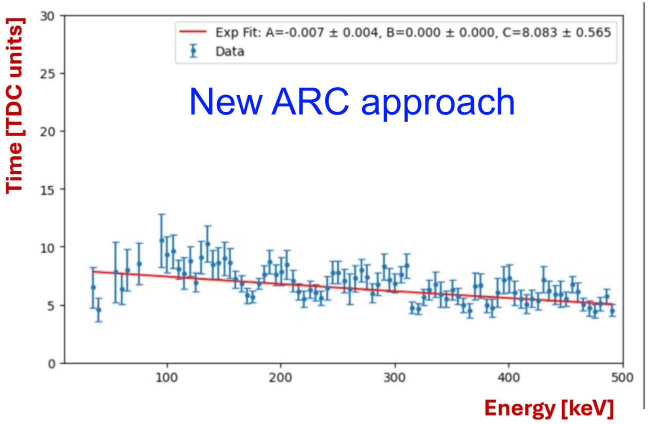


New ARC approach

CdZnTe detectors for energy and time spectroscopy

New ARC approach applied to data acquired in DAFNE → Energy dependence removed



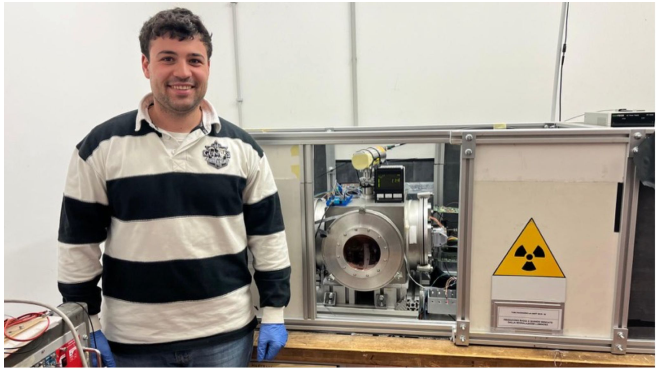


- ➢ **Timing performance of CdZnTe detectors studied for the first time** → crucial for background reduction in accelerator environments
(**Technical article submitted to Meas. Scie. and Technology (IOP)** (arXiv:2511.0267))

- ➢ A **25-30% improvement in the precision of K–Al** transition measurements was achieved with the new ARC analysis

Good news about SIDDHARTA folks

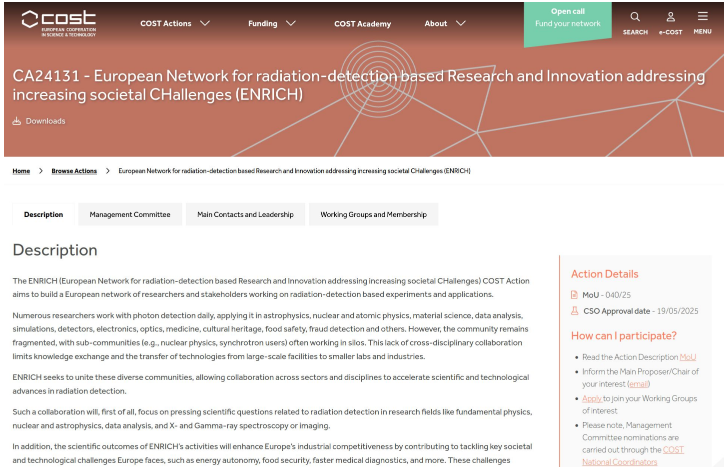
- **Riccardo Gasbarrini -** bachelor degree student at Univ. Tor Vergata **completed his stage within SIDDHARTA-2**
- **Michaela Lizardou - summer student from Greece starting in January**
- **Francesco Clozza** - Ph.D. student - **2nd best talk at HPXM 2025**
- **Simone Manti** - **Awarded 500,000 Core-Hours** on the **Helios Supercomputer** (PLGrid, Krakow ~36 PFlops) **(Grant no. PLG/2025/018524)**
- **Francesco Sgaramella, Francesco Artibani, Francesco Clozza – PROM Program Grant** (FERS.01.05-IP.08-0218/723): Short-term academic exchange to perform research on detector development at Jagiellonian University (J-PET Group), Krakow



Good news about SIDDHARTA folks

- **Alessandro Scordo: Chair of Cost Action ENRICH**
  European Network for research and innovation in Radiation-based applications to address Increasing societal CHallenges

- **Leonardo Abbene: PI of DRESS - HADRON 2030 proposal:**
  Digital high REsolutionposition-sensitive room temperature Semiconductor detectors for high precision radiation Spectroscopy in hadron physics and related areas
  (WP5 TA5: Next-generation Instrumentation and target technologies)



cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY | COST Actions | Funding | COST Academy | About | Open call Fund your network | SEARCH | e-COST | MENU

CA24131 - European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges (ENRICH)

Downloads

Home > Browse Actions > European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges (ENRICH)

Description | Management Committee | Main Contacts and Leadership | Working Groups and Membership

Description

The ENRICH (European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges) COST Action aims to build a European network of researchers and stakeholders working on radiation-detection based experiments and applications.

Numerous researchers work with photon detection daily, applying it in astrophysics, nuclear and atomic physics, material science, data analysis, simulations, detectors, electronics, optics, medicine, cultural heritage, food safety, fraud detection and others. However, the community remains fragmented, with sub-communities (e.g., nuclear physics, synchrotron users) often working in silos. This lack of cross-disciplinary collaboration limits knowledge exchange and the transfer of technologies from large-scale facilities to smaller labs and industries.

ENRICH seeks to unite these diverse communities, allowing collaboration across sectors and disciplines to accelerate scientific and technological advances in radiation detection.

Such a collaboration will, first of all, focus on pressing scientific questions related to radiation detection in research fields like fundamental physics, nuclear and astrophysics, data analysis, and X- and Gamma-ray spectroscopy or imaging.

In addition, the scientific outcomes of ENRICH's activities will enhance Europe's industrial competitiveness by contributing to tackling key societal and technological challenges Europe faces, such as energy autonomy, food security, faster medical diagnostics, and more. These challenges

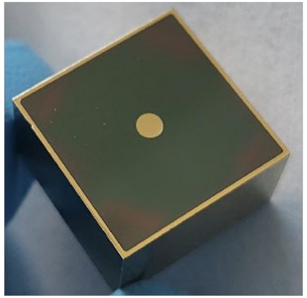
Action Details

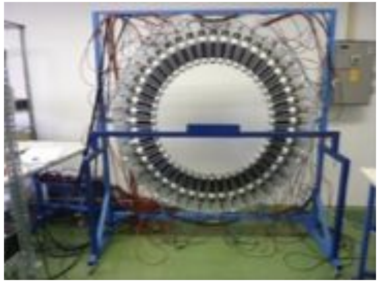
MoU - 040/25

CSO Approval date - 19/05/2025

How can I participate?

- Read the Action Description MoU
- Inform the Main Proposer/Chair of your interest (email)
- Apply to join your Working Groups of interest
- Please note, Management Committee nominations are carried out through the COST National Coordinators





ENRICH

European Network for research and innovation in Radiation-based applications to address Increasing societal CHallenges

Alessandro Scordo: Action Chair of ENRICH

COST Actions | Funding | COST Academy | About | Open call Fund your network | SEARCH | e-COST | MENU

CA24131 - European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges (ENRICH)

Downloads

Home > Browse Actions > European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges (ENRICH)

Description | Management Committee | Main Contacts and Leadership | Working Groups and Membership

Description

The ENRICH (European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges) COST Action aims to build a European network of researchers and stakeholders working on radiation-detection based experiments and applications.

Numerous researchers work with photon detection daily, applying it in astrophysics, nuclear and atomic physics, material science, data analysis, simulations, detectors, electronics, optics, medicine, cultural heritage, food safety, fraud detection and others. However, the community remains fragmented, with sub-communities (e.g., nuclear physics, synchrotron users) often working in silos. This lack of cross-disciplinary collaboration limits knowledge exchange and the transfer of technologies from large-scale facilities to smaller labs and industries.

ENRICH seeks to unite these diverse communities, allowing collaboration across sectors and disciplines to accelerate scientific and technological advances in radiation detection.

Such a collaboration will, first of all, focus on pressing scientific questions related to radiation detection in research fields like fundamental physics, nuclear and astrophysics, data analysis, and X- and Gamma-ray spectroscopy or imaging.

In addition, the scientific outcomes of ENRICH's activities will enhance Europe's industrial competitiveness by contributing to tackling key societal and technological challenges Europe faces, such as energy autonomy, food security, faster medical diagnostics, and more. These challenges

Action Details

- MoU - 040/25
- CSO Approval date - 19/05/2025

How can I participate?

- Read the Action Description MoU
- Inform the Main Proposer/Chair of your interest (email)
- Apply to join your Working Groups of interest
- Please note, Management Committee nominations are carried out through the COST National Coordinators

DRESS

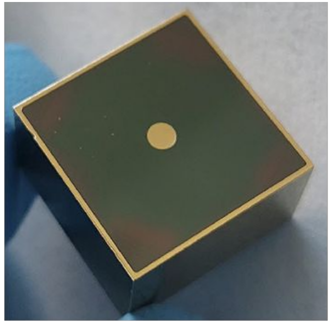
Digital high REsolutionposition-sensitive room temperature Semiconductor detectors for high precision radiation Spectroscopy in hadron physics and related areas

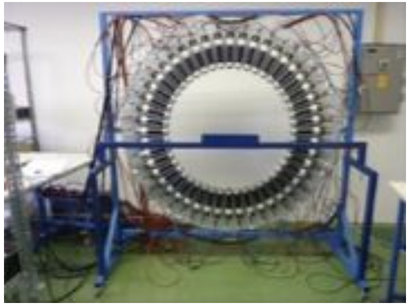
Leonardo Abbene:
PI of DRESS

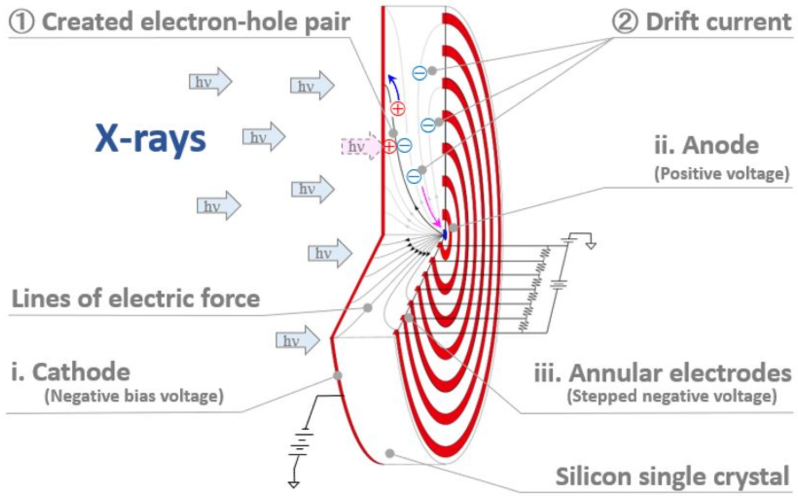
HADRON 2030 proposal:

WP5 TA5: Next-generation Instrumentation and target technologies

DRESS: to push the performance limit of of X- and gamma-rays detection







Silicon-drift detector