Fundamental Physics with Exotic Atoms

Overview of Technological Challenges in Exotic Atom Precision Experiments

Florin Sirghi on behalf of

SIDDHARTA-2 Collaboration

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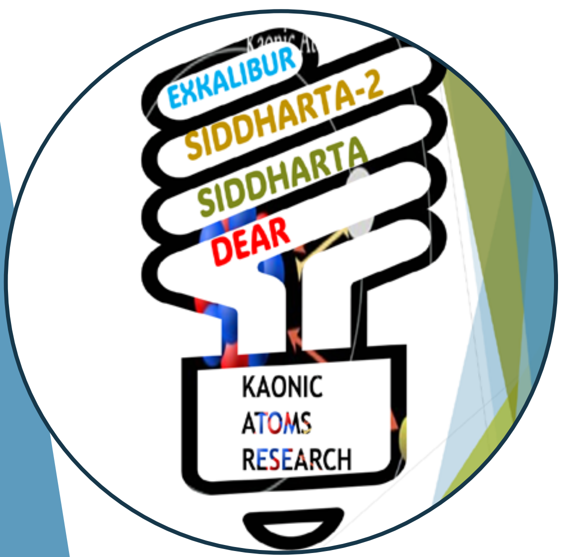
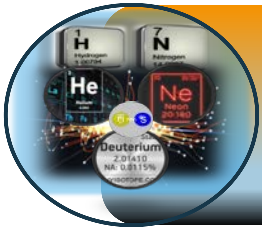
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

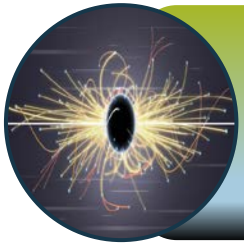
Precision experiments with exotic atoms offer unique insights into fundamental physics, from testing quantum electrodynamics (QED) to probing the strong interaction (QCD), high precision test of BSQED

Achieving the necessary precision is fraught with significant technological challenges. These challenges primarily stem from the nature of exotic atoms themselves: their short lifetimes, the weak signals they produce, and the demanding experimental conditions required for their creation and study.

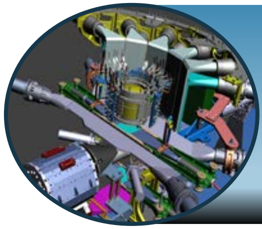




New IDEAS



Kaon beam/source



Target and Detector systems

The key technological challenges:

Weak Signals and Low Event Rates:

- **Low Production Yields:** Creating exotic atoms often involves complex processes
- **Short Lifetimes:** time available for them to form exotic atoms and undergo de-excitation
- **Dilute Targets:** To minimize unwanted interactions and effects like the Stark effect, increase the stopping power
- **Limited Beam Intensity:**

Background Interference:

- **High Background Radiation:** accelerator facilities where a multitude of other particles and radiation are present
- **Unwanted X-ray Emission:** environment (e.g., from conventional atomic transitions in target materials, cosmic rays, or facility-related radiation).
- **Charged Particle Contamination:** Charged particles from the beam or secondary interactions
- **Spurious Signals:** Detector noise, electronic interference, and other spurious signals

Limitations in Detector Technology:

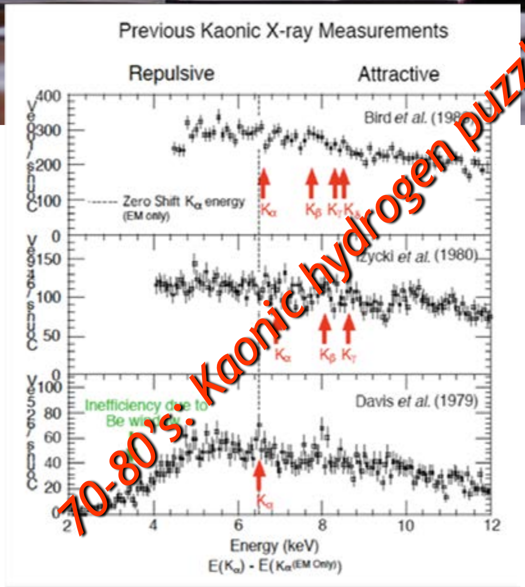
- **Energy Resolution:** detectors with high energy resolution are required.
- **Detection Efficiency:** detectors must have very high quantum efficiency
- **Timing Resolution:** Good timing resolution - fast trigger and veto capabilities
- **Background Rejection Capabilities:** pulse shape discrimination, spatial reconstruction, and coincidence measurements.
- **Radiation Hardness:** accelerator environments, detectors must withstand high levels of radiation
- **Cryogenic Requirements:** require extremely low operating temperatures (TES) (cryogenic conditions), adding complexity to the experimental setup and operation.
- **Area vs. Resolution Trade-off:** large active detection area (to maximize signal capture) and maintaining excellent energy resolution.

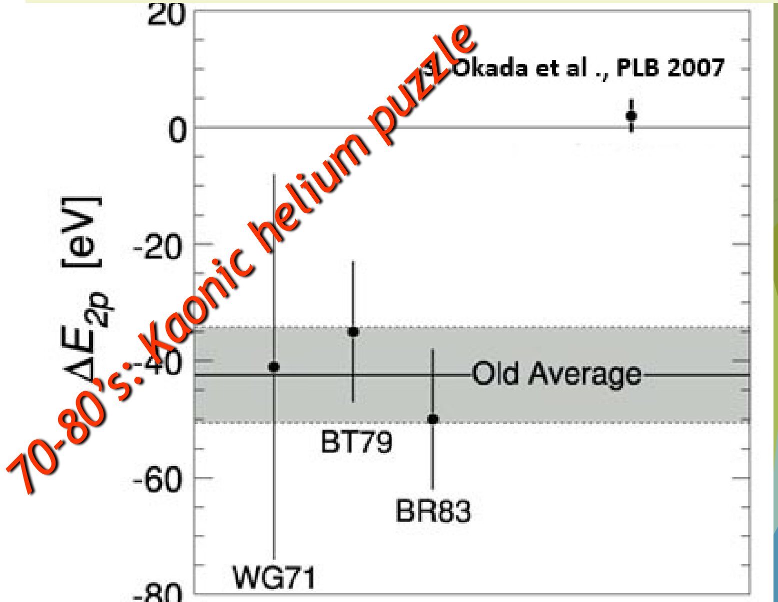
"The <u>most important experiment to be carried out in low energy K-meson physics today</u> is the **definitive determination of the energy level shifts in the K−p and K−d atoms**, because of their direct connection with the physics of $\bar{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

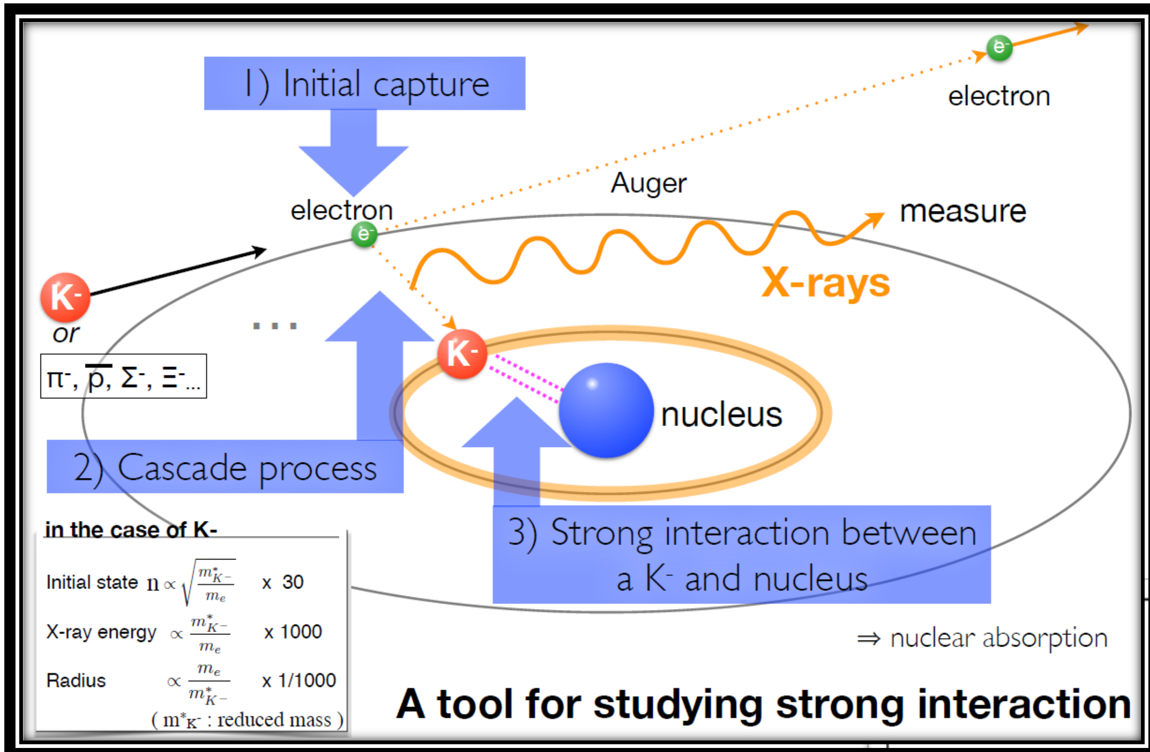
R.H. Dalitz (1982)

Carlo Guaraldo
Hannes Zmeskal

the key initiators and drivers of kaonic atoms studies at the DAΦNE, JPARC



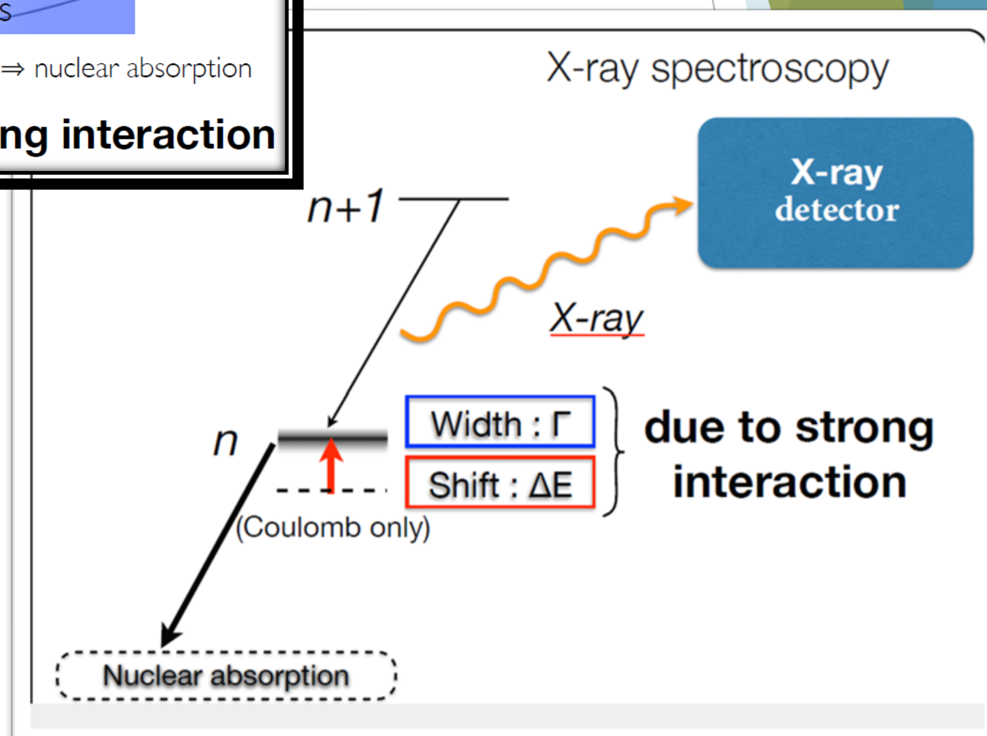


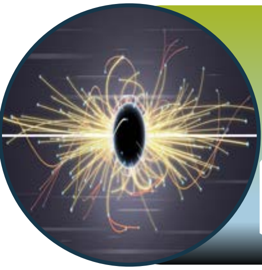


Exotic atoms
are formed
by stopping a
negatively charged hadron or
lepton (e.g., π^-, K^-, μ^-) in a
target medium

H, He, D, N, ...
Li, Be, C, Al, ...

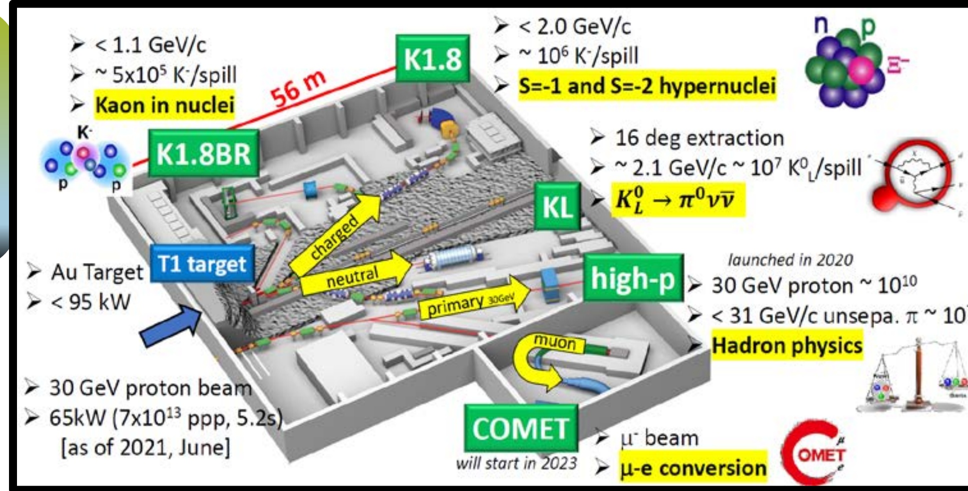
Strong interaction induced
width Γ and shift ε
obtained by measuring the
X-rays emitted



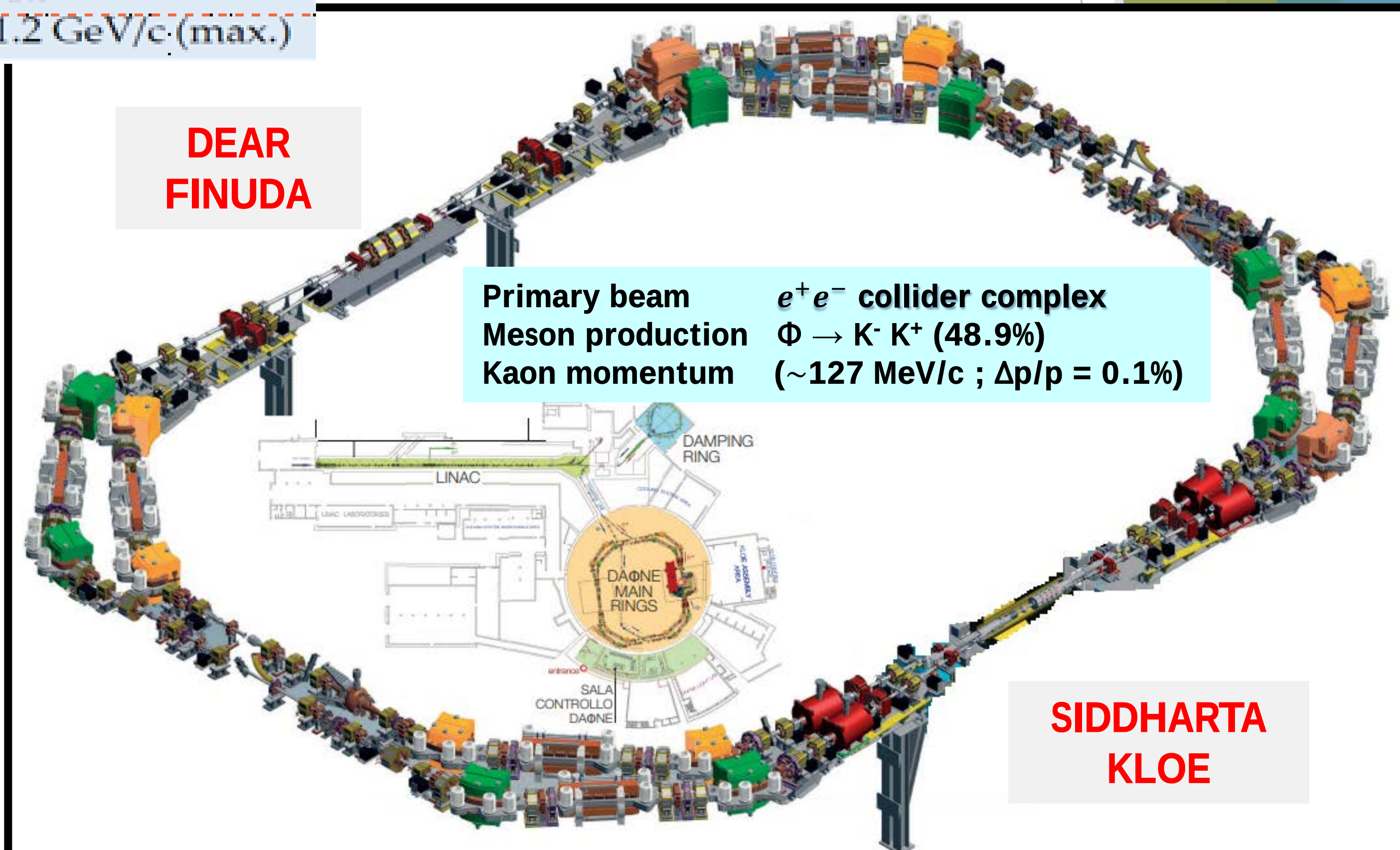


Kaon beam/source

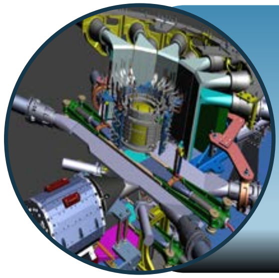
Primary beam:	30 GeV/c protons
Repetition cycle:	5 sec
Flat top:	3 sec
Production target:	Au
Kaon momentum:	1.2 GeV/c (max.)



activities using the unique kaon beams available at J-PARC and DAΦNE.



DAΦNE collider at LNF

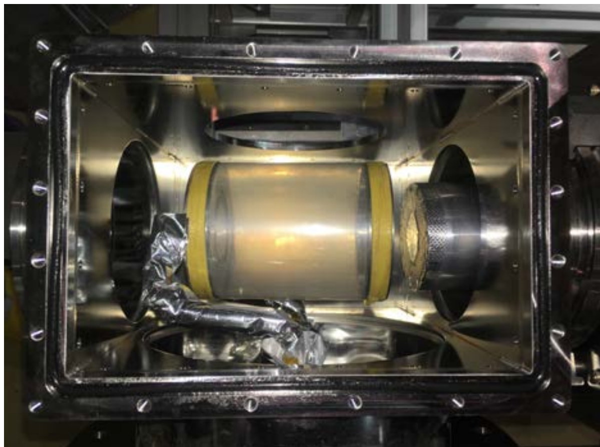


Targets

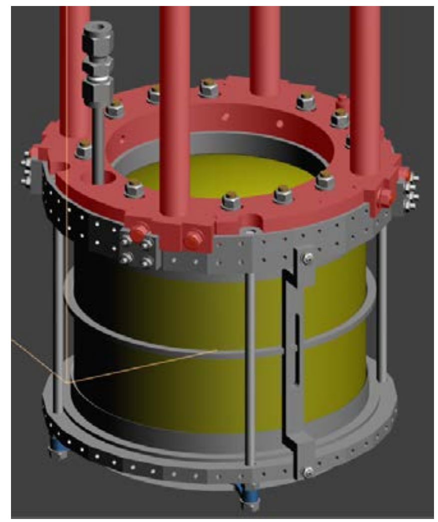
SIDDHARTA-2 setup: cryogenics

hydrogen density of 1.3×10^{-3} g/cm^3
Deuterium: ~1.5% of liquid deuterium density

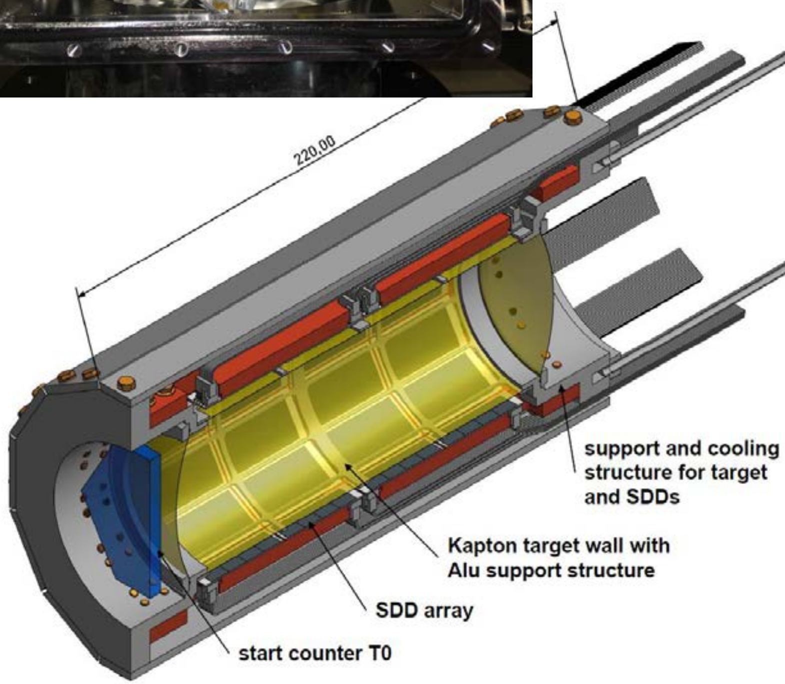
liquid $_4$He / liquid $_3$He at JPARC



Kapton polyimide ($C_{22}H_{10}N_2O_5$) foils, with a thickness of 75 µm



❖ Target + SDD cooling



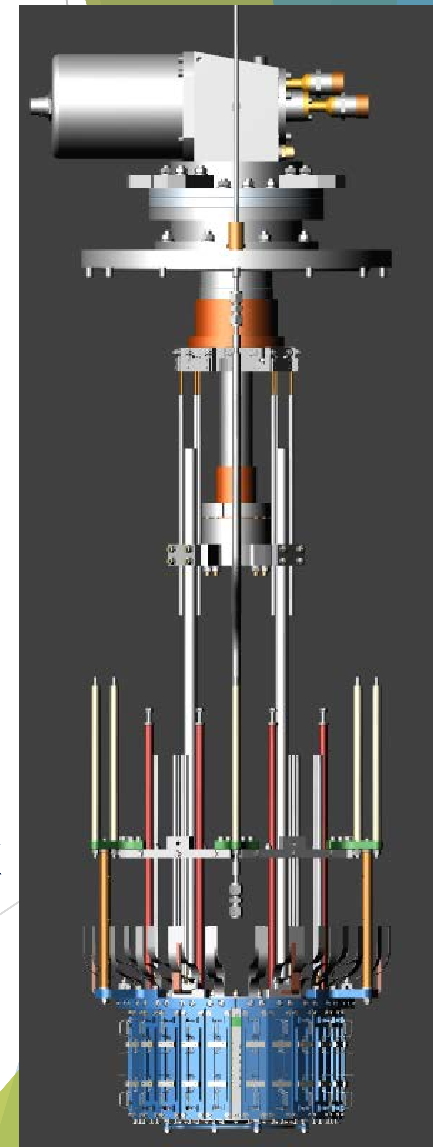
Leybold MD10 - 18 W @ 20 K

target cell and SDDs are cooled via ultra pure aluminum bars

T_{TC} = 20-30 K

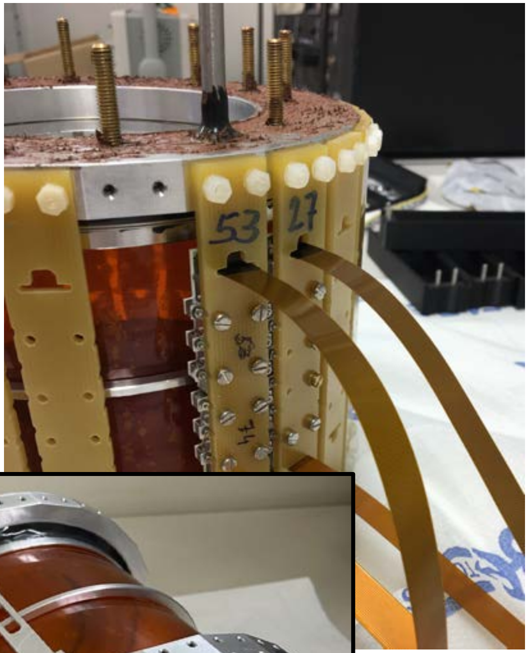
T_{SDD} ~ 130 K

P_{TC} =1.5 -2 bar

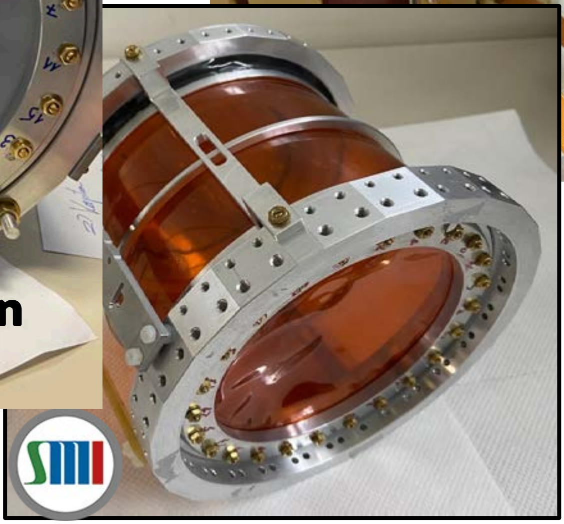
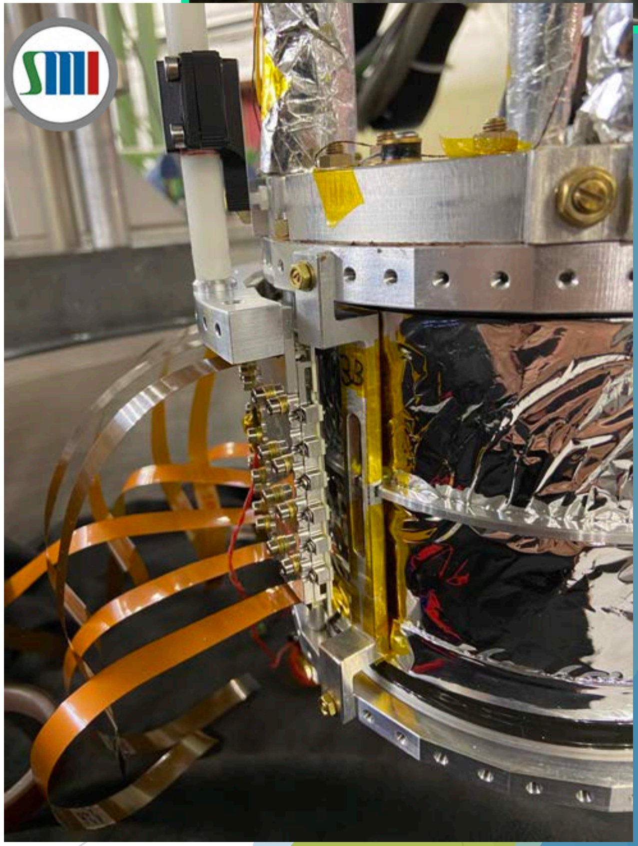


SIDDHARTA-2 setup: cryogenic targets

✓ **Selected materials in different configuration:**
  vacuum entrance windows
  target walls
  cooling supports

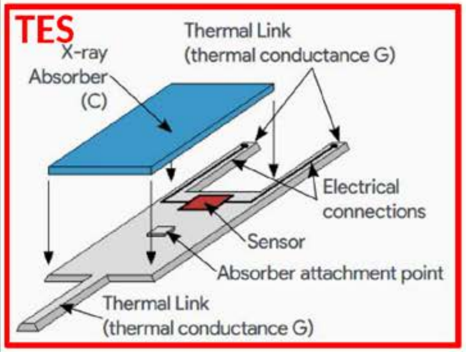

Nitrogen and Oxygen contamination

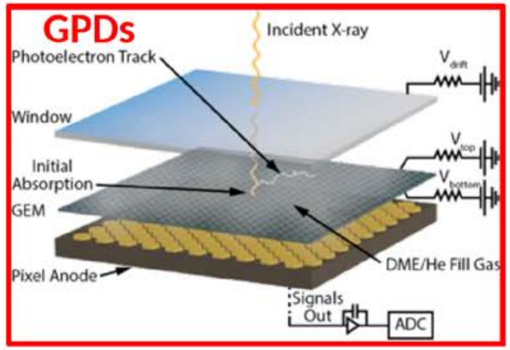



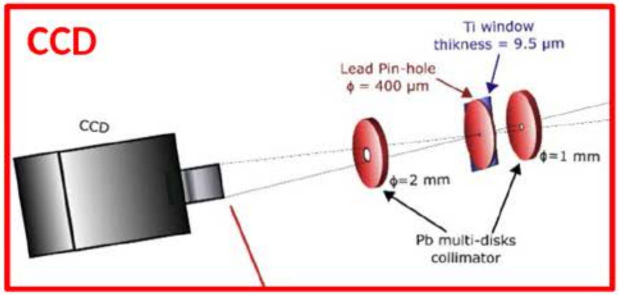
windowless designs to enhance low-energy X-ray transmission and detection efficiency.

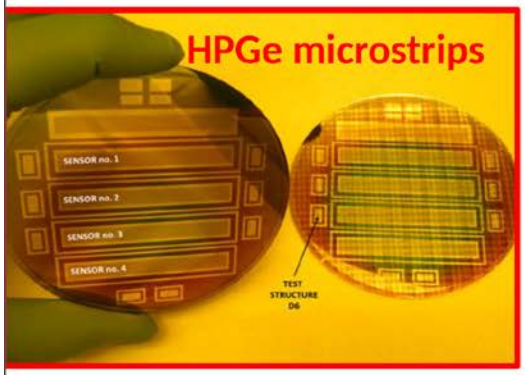
Detector System

Whole X-ray energy range
Different detection methods
Excellent features









Hybrid Detectors
Microstrips/ pixels

Characteristic	Charge Couple device (CCD)	Silicon Drift Detectors (SDDs)	Transition-Edge-Sensor (TES) Microcalorimeters	Cadmium-Zinc-Telluride (CdZnTe) Detectors
Energy Resolution (FWHM)	~140 eV at 6 keV ;	~150 eV at 6.4 keV ; <200 eV at 6 keV	< 10 eV at 6 keV Absolute calibration 0.04 eV uncertainty at 6.4 keV	Few % FWHM ; 6% at 60 keV; 2.2% at 511 keV
Timing Resolution	~30 sec Exposure time ~ 1 minutes	Below 1 μsec ; ~ 800 ns FWHM ; < 500 ns FWHM ;	fall times <100 μs rise times ~ tens μs	Few tens of ns
Material	Silicon (high purity)	Silicon (high purity)	Mo/Cu + Bi (absorber), Au 2um + Bi 4um, 20 mm^2	Cadmium-Zinc-Telluride (CdZnTe)
Quantum Efficiency	~ 80% up to 6 keV	> 95% efficiency in 1-10 keV ;	85% at 6 keV (NIST TES spectrometer)	> 98% theoretical absorption for 1.25 mm thick at 58.9 keV
Detector Area	22.5 x 22.5 um pixel size; 1242 x1152 pixels; 116 cm^2 total area	SIDDHARTA: 144 SDDs, 1 cm^2; SIDDHARTA-2: 384 SDDs, 246 cm^2; J-PARC E57: 300 cm^2 total	240 pixels, ~ 0.23 cm^2 total collecting area	1 cm^2 active surface (prototype)
Operating Temperature	~130 - 150 K ;	~170 K	~100 mK	Room temperature

Detector System

Charge Coupled Device (CCD)

Pixelated detectors
for a wide energy range

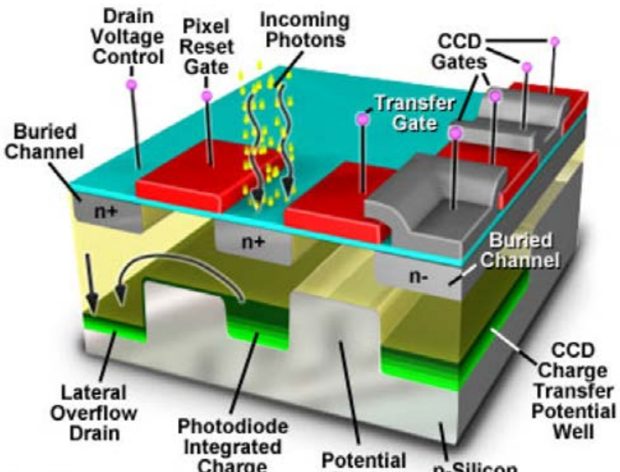
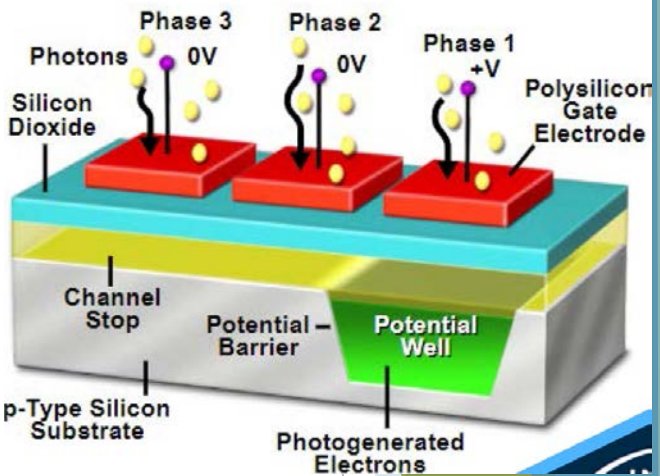
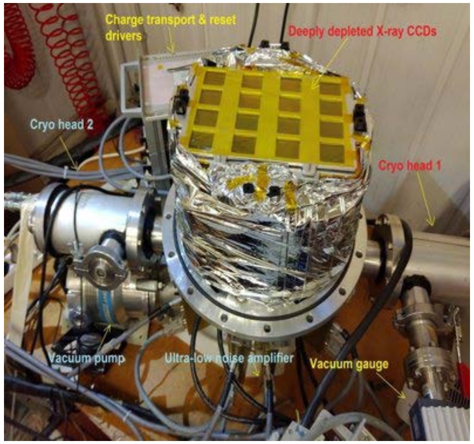
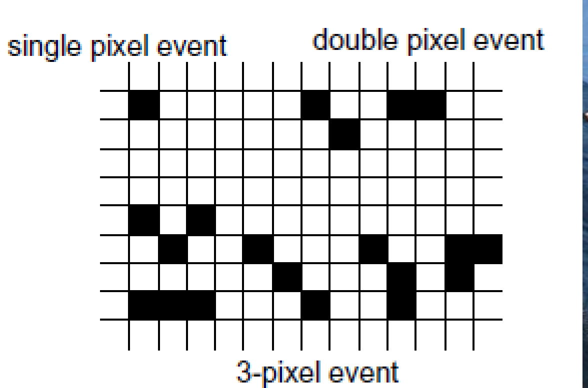


Figure 1

Characteristic	Value
Pixel Format/size	1152 (H) x 1242 (V) pixels 22.5 x 22.5µm
Active Area	7.24 cm²
Depletion Depth	~30 µm
Energy Resolution	~140 eV at 6 keV
Timing Capability	Non-triggerable; ~10 s readout time
Background Rejection Mechanism	Event Topology (Spatial Pattern Analysis)

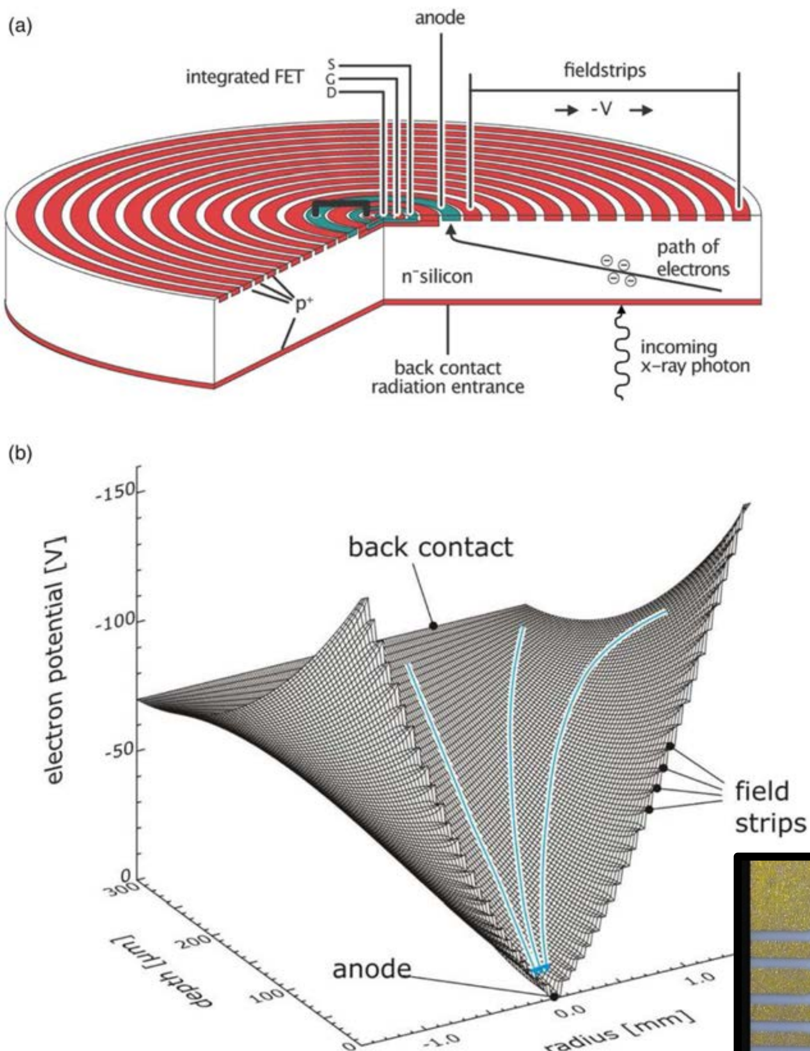






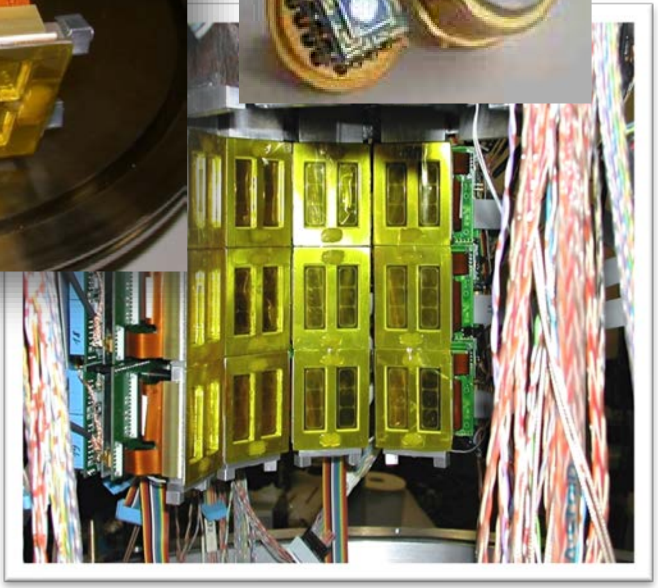
See talk of M. Iliescu - SPHINX project

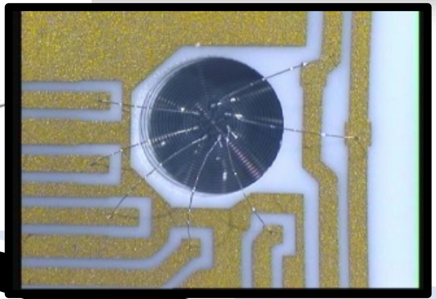
SIlicon Drift Detectors (first large area) with integrated JFET



New x-ray detectors specially designed
as well as readout electronics

energy range < 20 keV
energy resolution ~ 150 eV (FWHM) at 6 keV;
stability and linearity better than 10^{-4};
Fast detector - > trigger system at the level of 1µs;
Operating in high radiation environment;
Custom topology – large active area (~ cm^2 / channel)



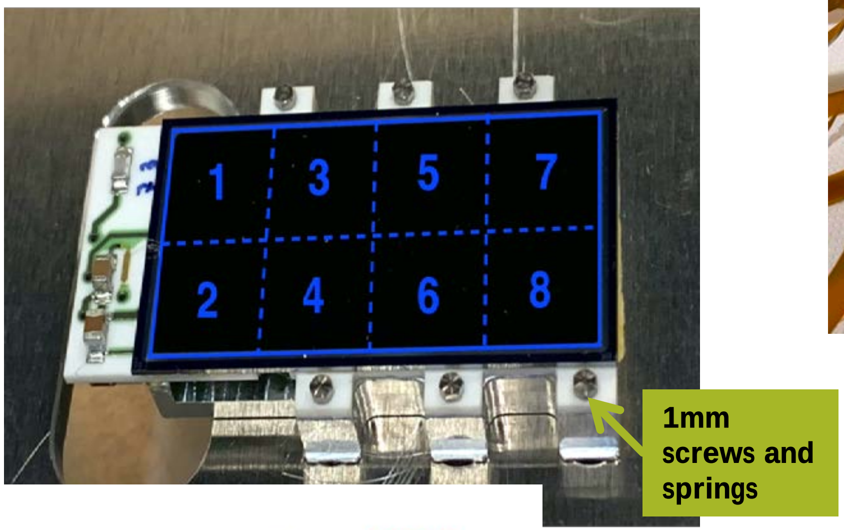


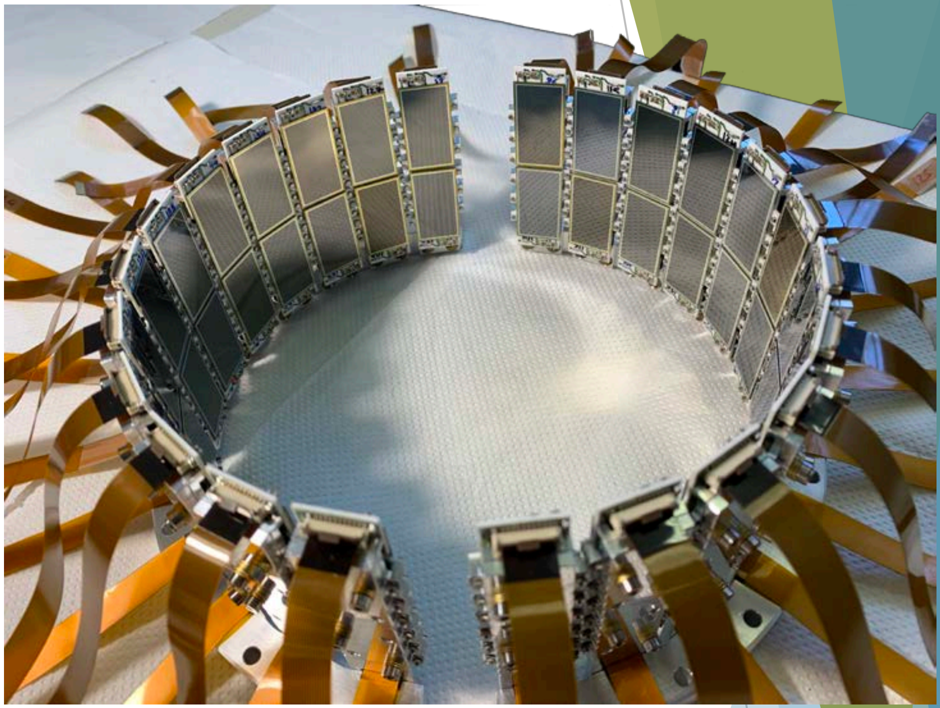
SDD with external CUBE preamplifier

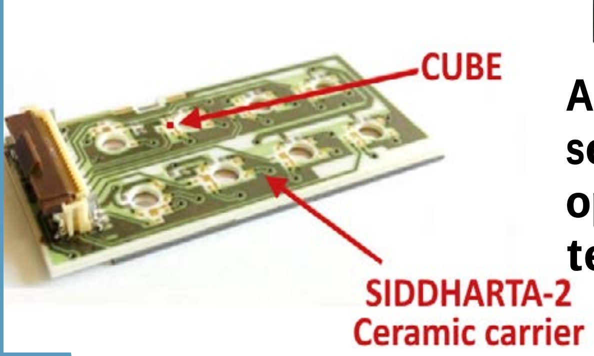
Monolithic SDDs arrays developed by Fondazione Bruno Kessler

new technology, lower production cost

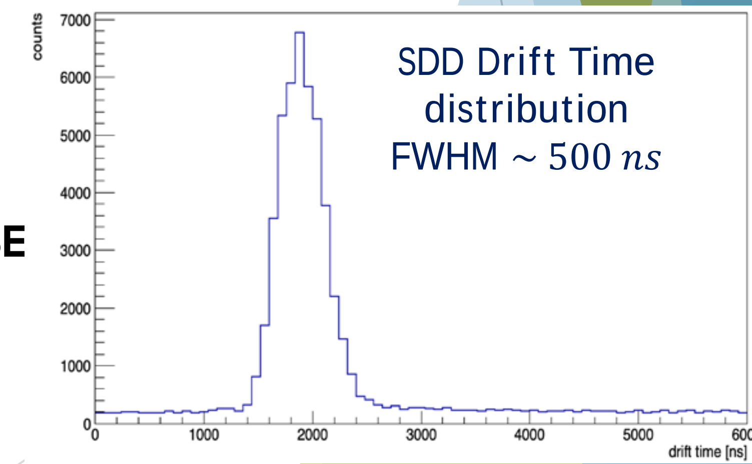
- **2x4 matrix SDD units (0.64 cm^2)**
- **active/total surface ratio of 0.75**



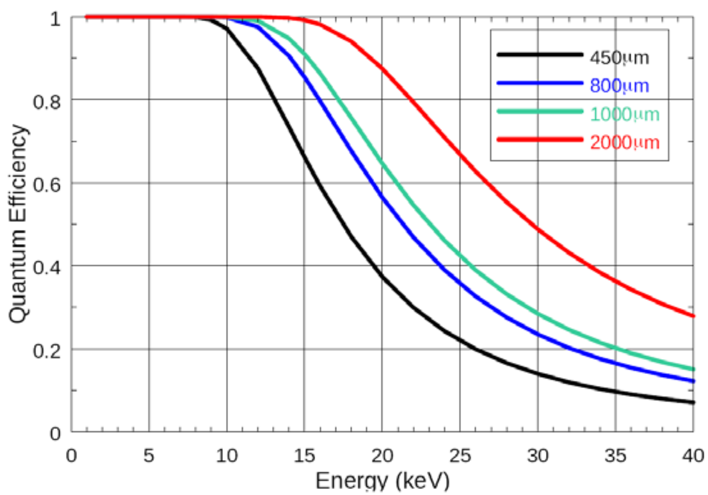




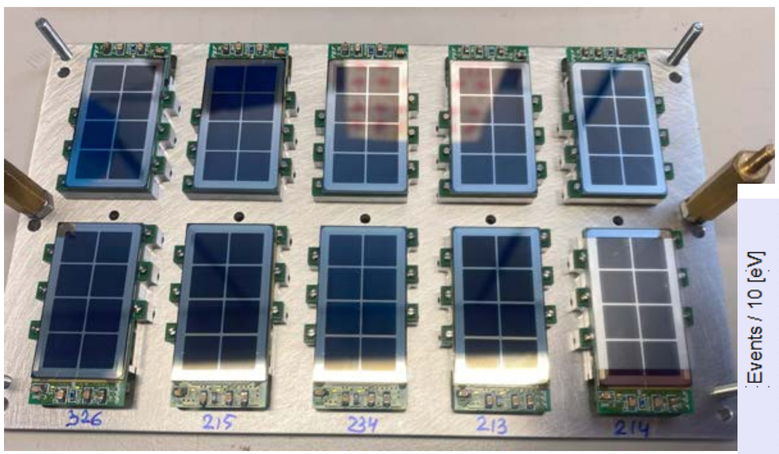
A CMOS low-noise charge sensitive preamplifier (CUBE operate at lower cryogenic temperature (up to 50k)

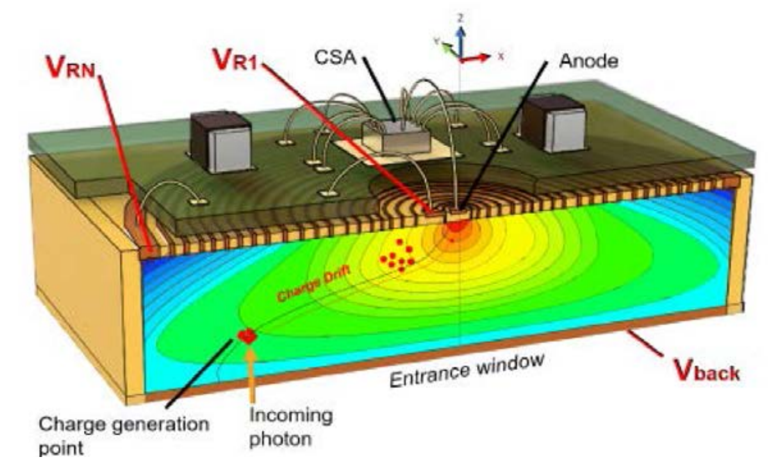


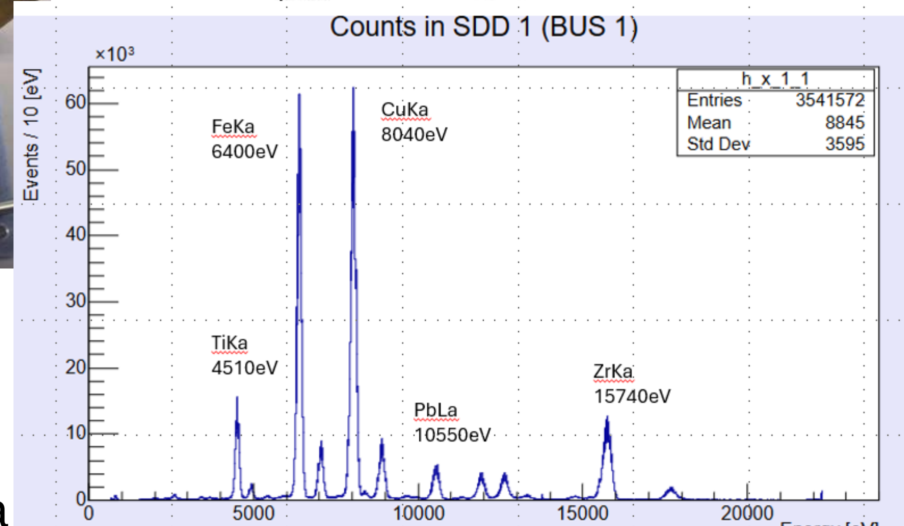
Thick SDD: extending the working range



X-ray Energy (keV)	Eff. (0.45 mm Si)	Eff. (1.0 mm Si)
10	~100 %	~100 %
15	~90 %	~90 %
20	~37 %	~65 %
25	~18 % (≈)	~45 %
30	~10 % (≈)	~28 %

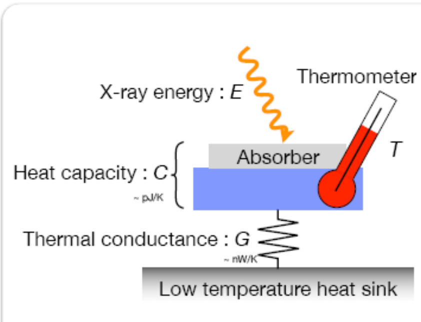


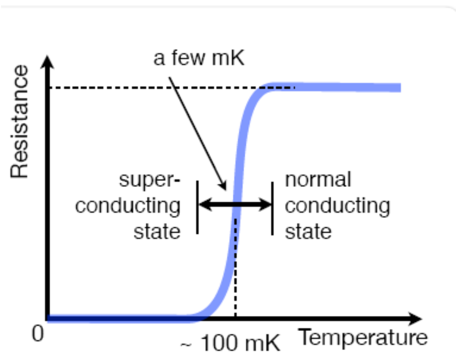




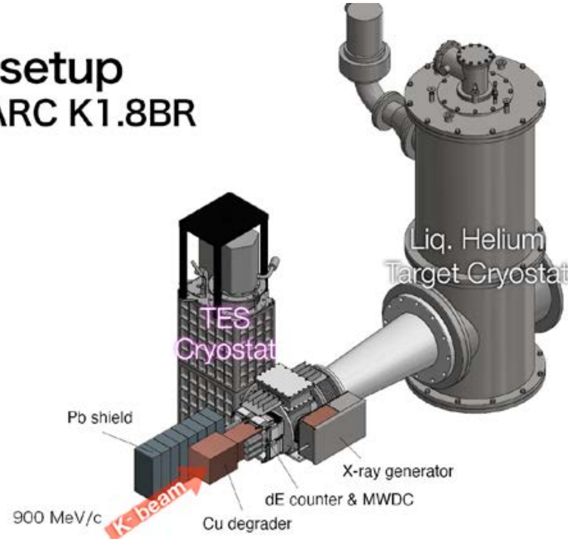
See talk of F. Cloza

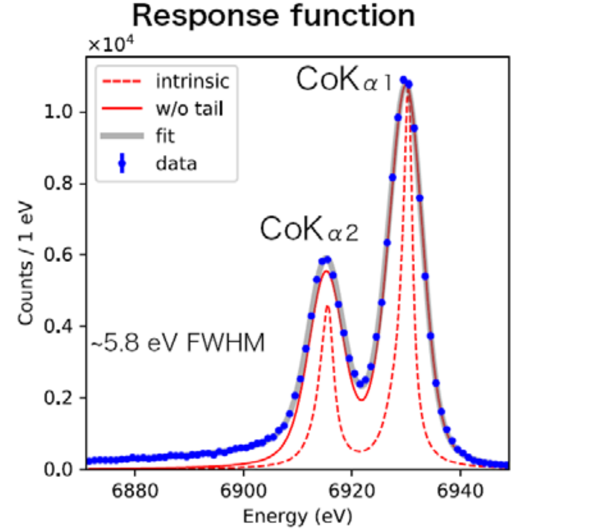
Transition Edge Sensors (TES)





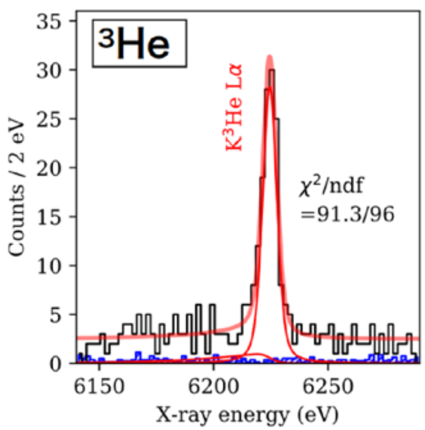
E62 setup
@J-PARC K1.8BR

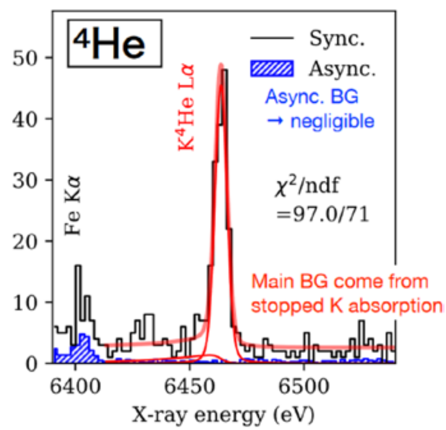




Detector response is well described by a gaussian and a low-energy exponential tail

Groundbreaking high-resolution measurement of $K_{3,4}$He isotopic shift on 2p level





$E^{K^{-3}He}_{3d\to 2p} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})$ eV

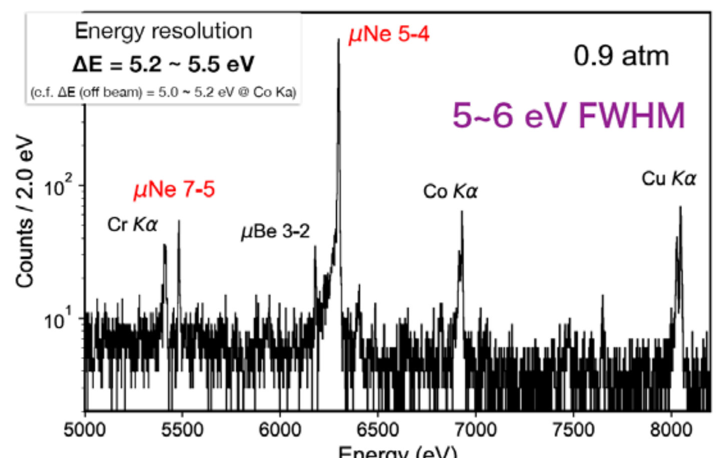
$\Gamma^{K^{-3}He}_{2p} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})$ eV

$E^{K^{-4}He}_{3d\to 2p} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})$ eV

$\Gamma^{K^{-4}He}_{2p} = 1.0 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})$ eV

Muonic Ne atom 5→4

Phys. Rev. Lett. 130, 173001 (2023)



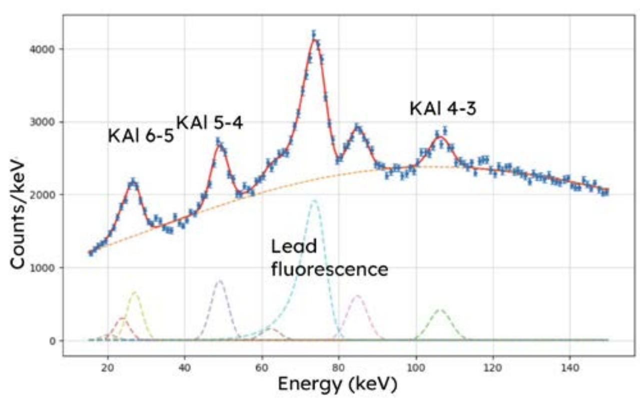
See talk of T. Hashimoto

Cadmium Zinc Telluride (CZT)

High atomic number
Good absorption efficiency
- 1mm thick detectors >98% at 60keV
- 10mm thick detectors >86% at 200keV

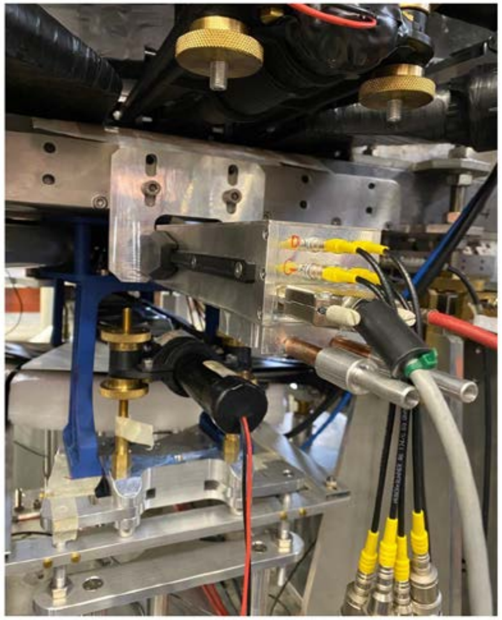
Optimal band gap
Room Temperature Operation
High energy resolution:
- 1.5 % at 50 keV
- 0.82 % at 660 keV
- Fast detector response: down to 50 ns

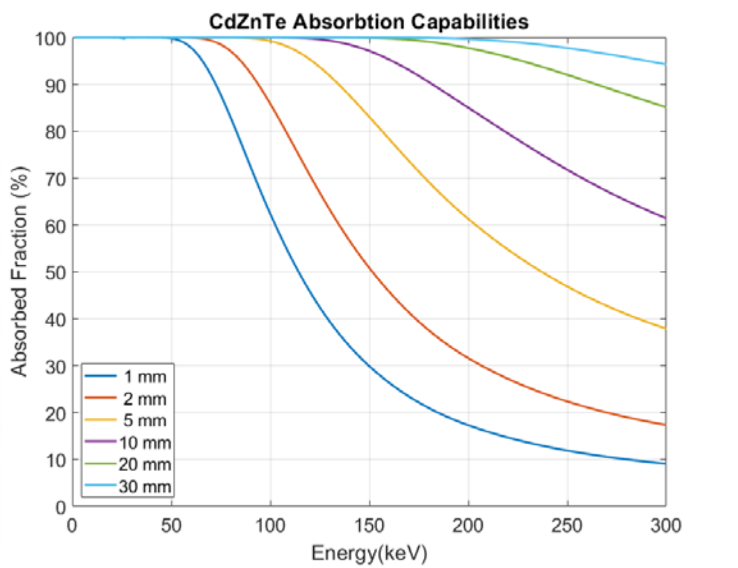
Compound	Si	Ge	GaAs	CZT	CdTe
Mean atomic number	14	32	32	**49.1**	50
Bandgap (eV)	1.12	0.66	1.42	**1.57**	1.5
electrons (cm^2/V)	2-5	5	10^{-4}	**10^{-2}**	10^{-3}
holes (cm^2/V)	1-2	2	10^{-5}	**$3\ 10^{-5}$**	$5\ 10^{-4}$
Resistivity (Ωcm)	$2.3\ 10^5$	47	10^8	**$5\ 10^{10}$**	10^8-10^9
Thickness to absorb 90% of 60keV incident radiation (cm)	130	2.6	2.6	**0.5**	0.5



See talk of F. Artibani

2 modules with four detectors
13mmx15mmx5mm

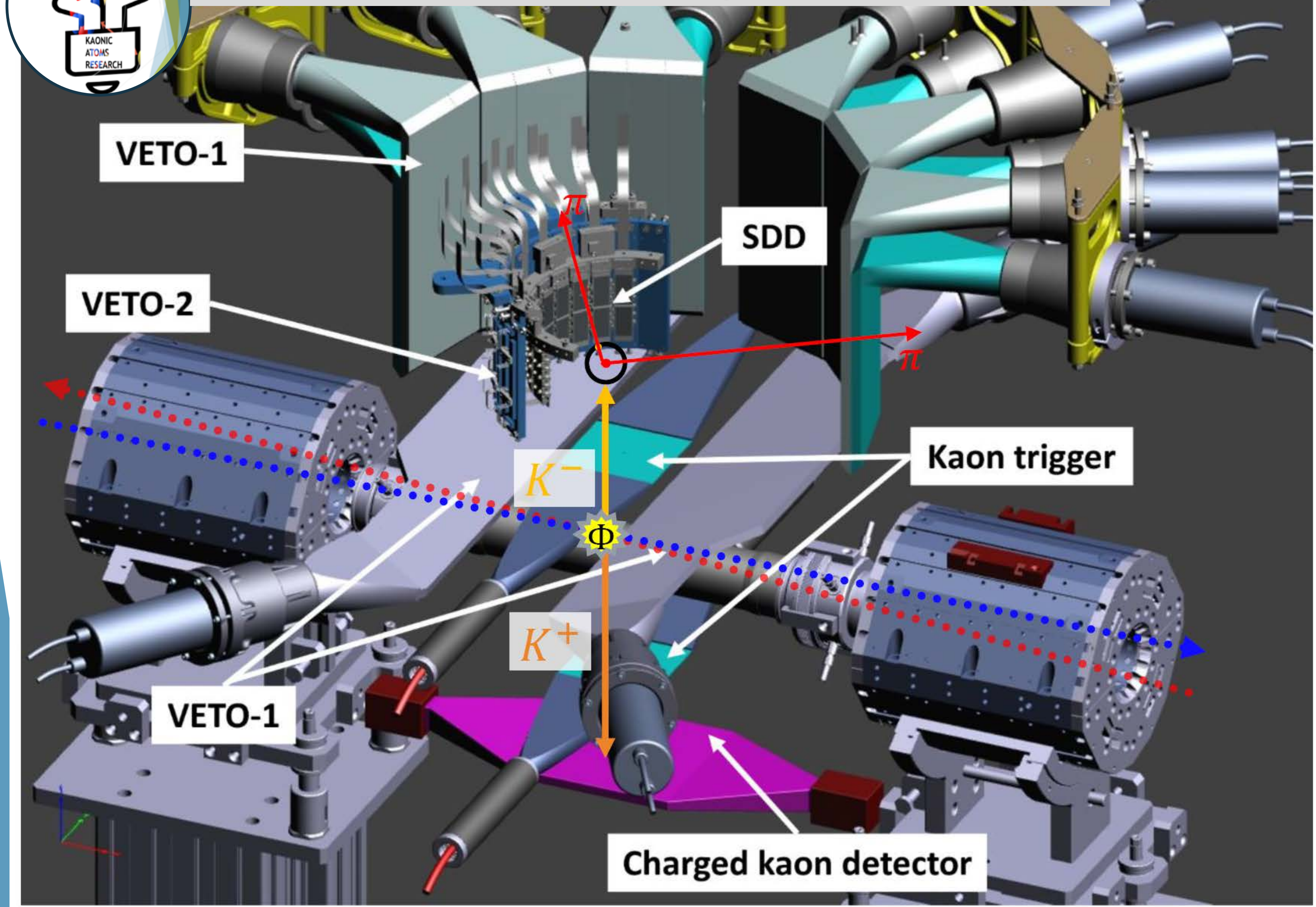




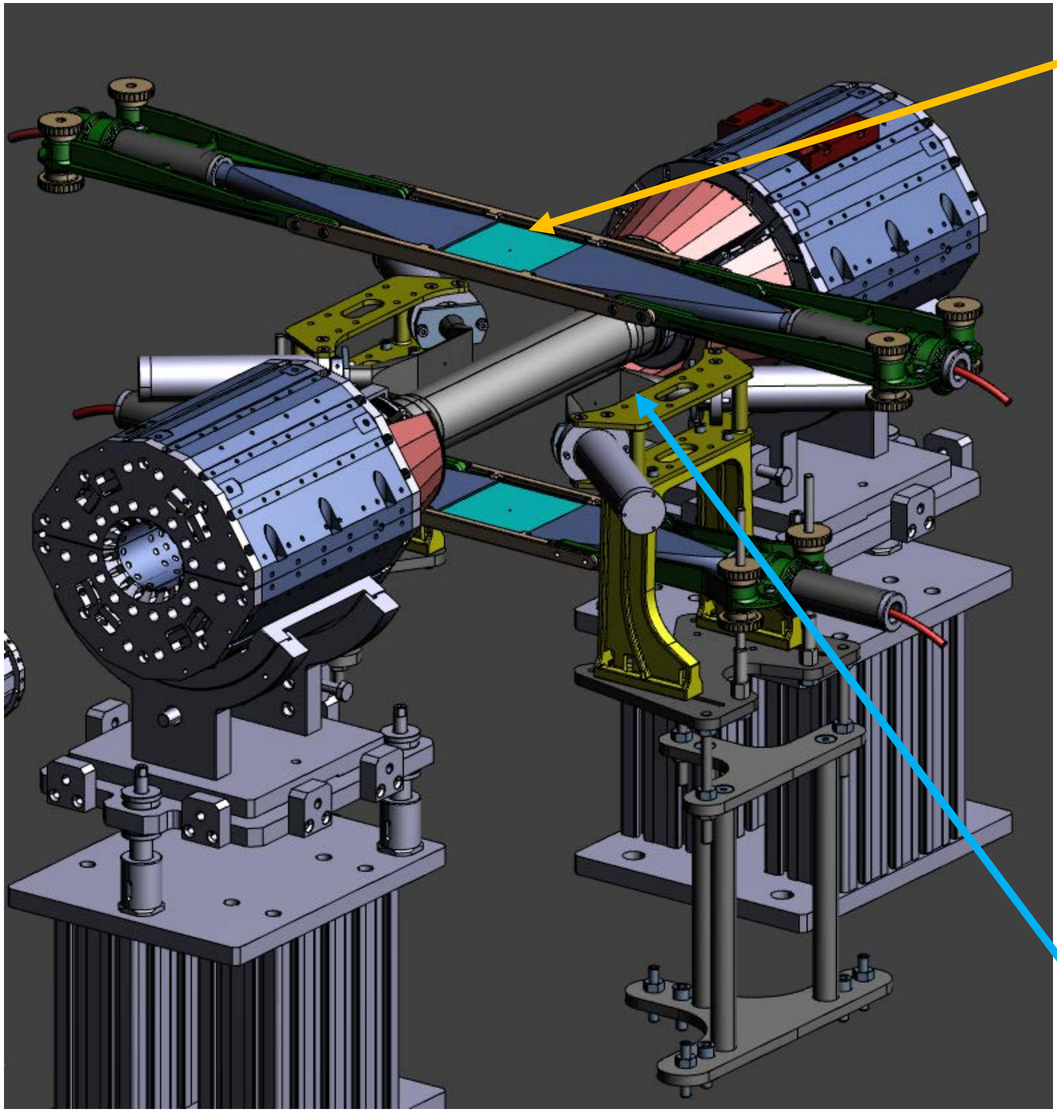
UniPa DiFC (Palermo)
IMEM-CNR (Parma)

CZT does not need complex cryogenic cooling systems, like those needed for high-purity germanium (HPGe)

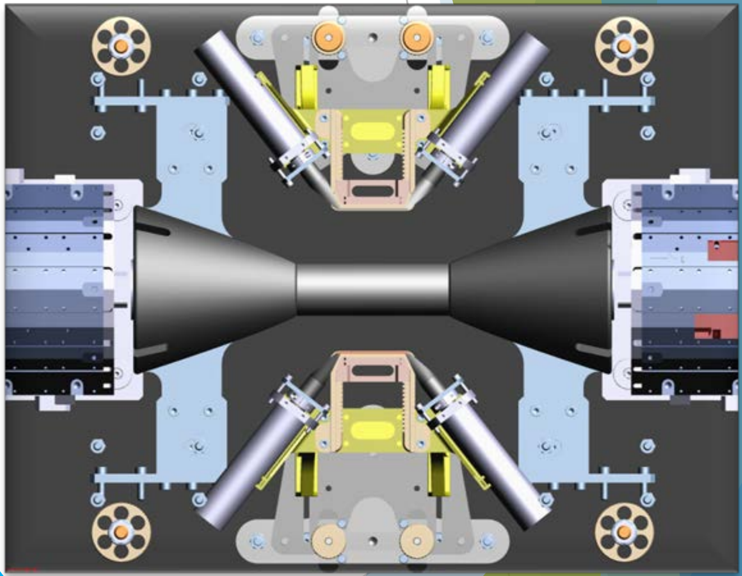
SIDDHARTA-2 (2019 -2024)



SIDDHARTA-2 setup: kaon trigger and luminosity monitor

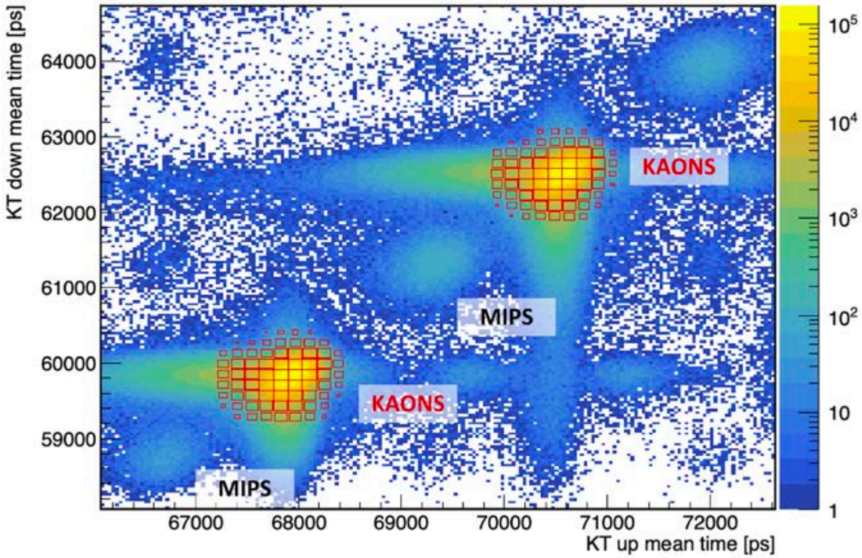


Kaon Trigger consists of two plastic scintillators read by PMT's placed above and below the IR.

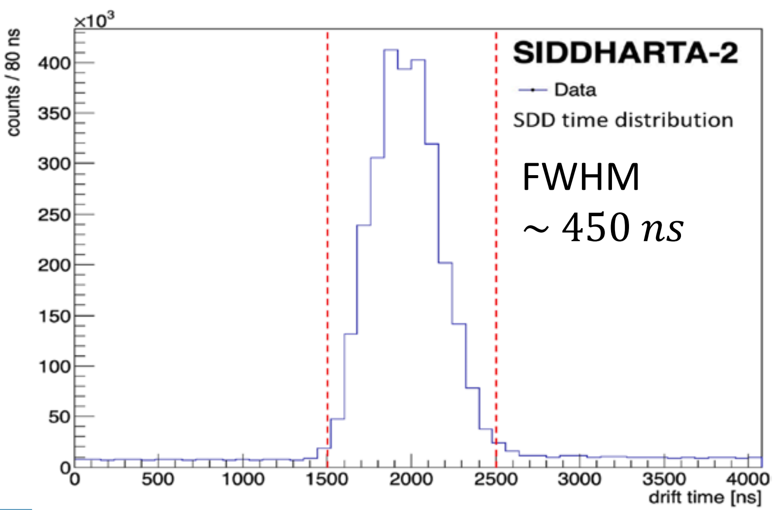


The **Luminosity monitor** consists of two plastic scintillators in the horizontal plane

Kaon Trigger



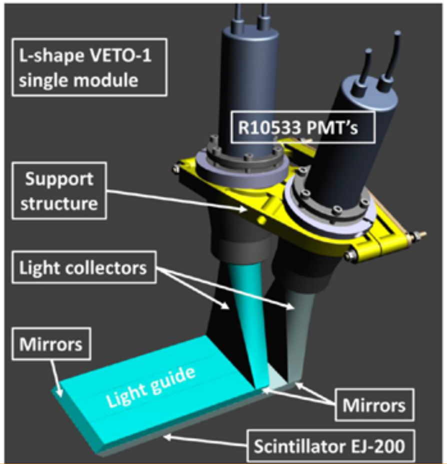
The combined used of Kaon Trigger and SDDs drift time allows to reduce the asynchronous background by a factor $\sim 2 \cdot 10^4$



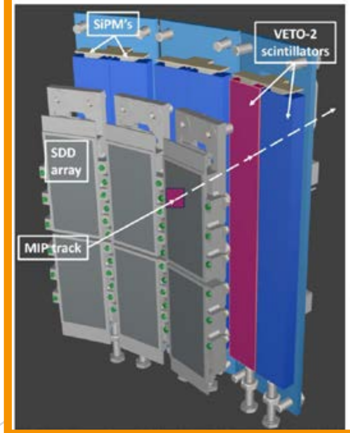
Synchronous background

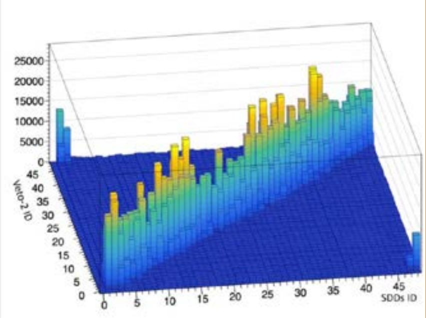
associated to kaon absorption on materials nuclei, or to other Φ decay channels.

Veto-1 14 plastic scintillator read by PMTs to select the events occurring in the gas target, rejecting the X-ray background corresponding to K- stopped in the solid elements of the setup



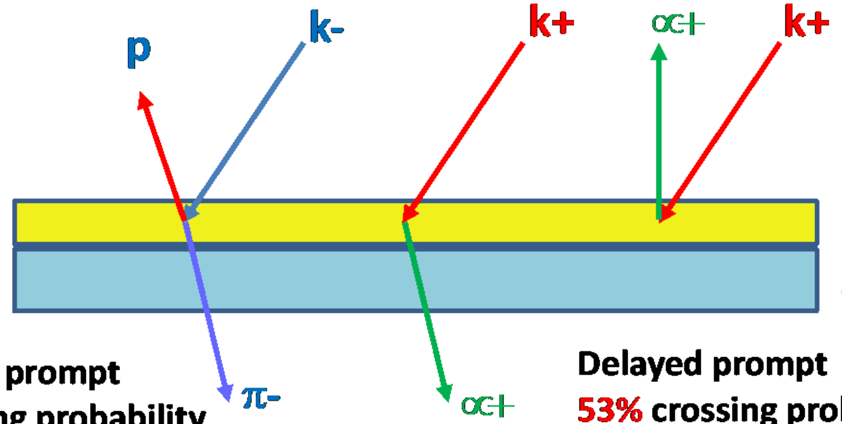
Veto-2 48 plastic scintillator read by SiPMs to suppress the background induce by particles produced by kaon absorption, passing through the SDDs.





SIDDHARTA-2 setup: Charge Kaon Detector

Stop both K^+ and K^- in a passive layer (Teflon) and detect secondaries in a scintillator

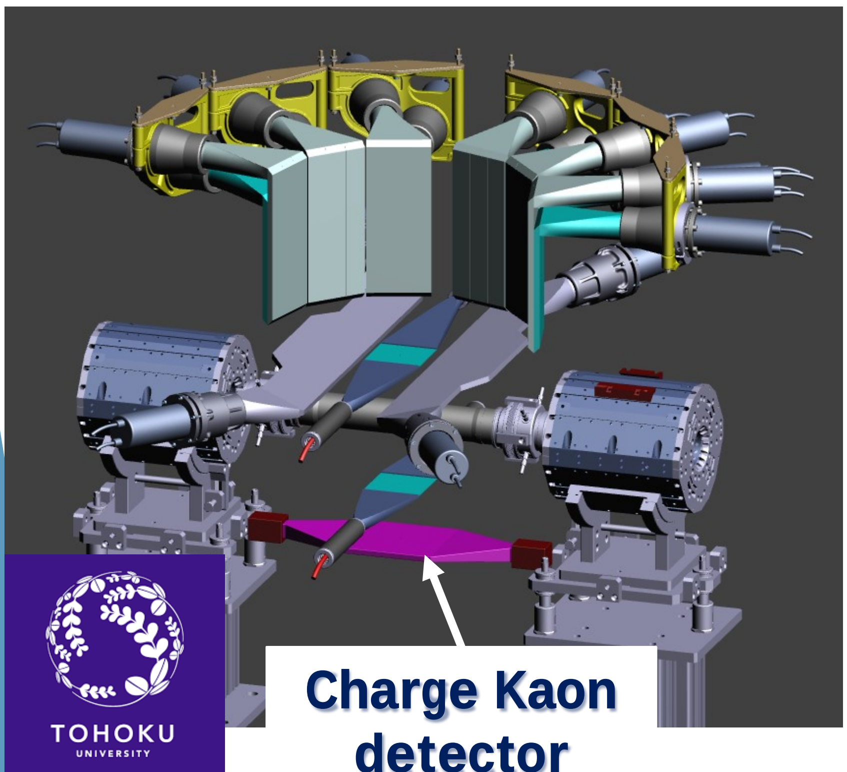


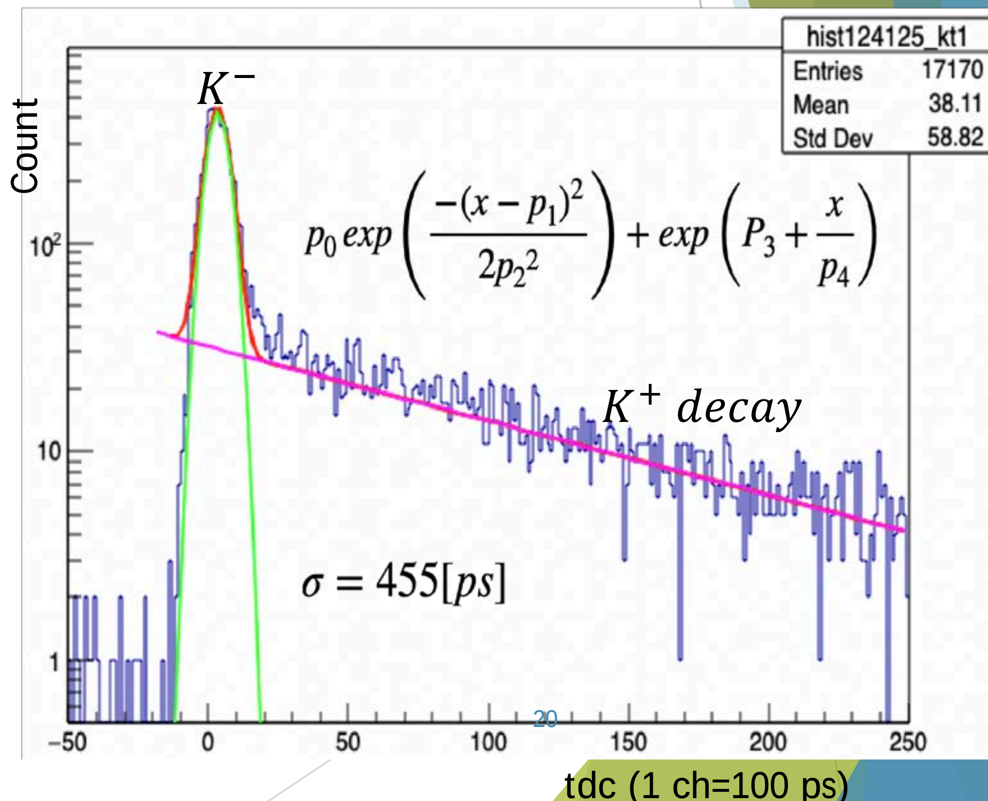
2 mm teflon

5-10 mm thick scintillator

Immediate prompt
83% crossing probability

Delayed prompt
53% crossing probability





Beyond SIDDHARTA-2 - EXKALIBUR

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

- *proposal to perform fundamental physics at the strangeness frontier at DAΦNE presented in varies Scientific Committee and INFN commissions*

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

Kaon mass by Kaonic neon measurement
- **Use the present setup**
- **Minimal modification**
- ***new calibration system***
- **300 pb-1 of integrated luminosity**

Light kaonic atoms (LHKA)
- **Use the present setup**
- ***solid target Li, Be, B***
- **Minimal modification target**
- ***integration 1mm SDD***
- **200 pb-1 of integrated luminosity**

Intermediate kaonic atoms (IMKA)

In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with different types of detectors:
CdZnTe detectors
- **200 -300 pb-1 of integrated luminosity**

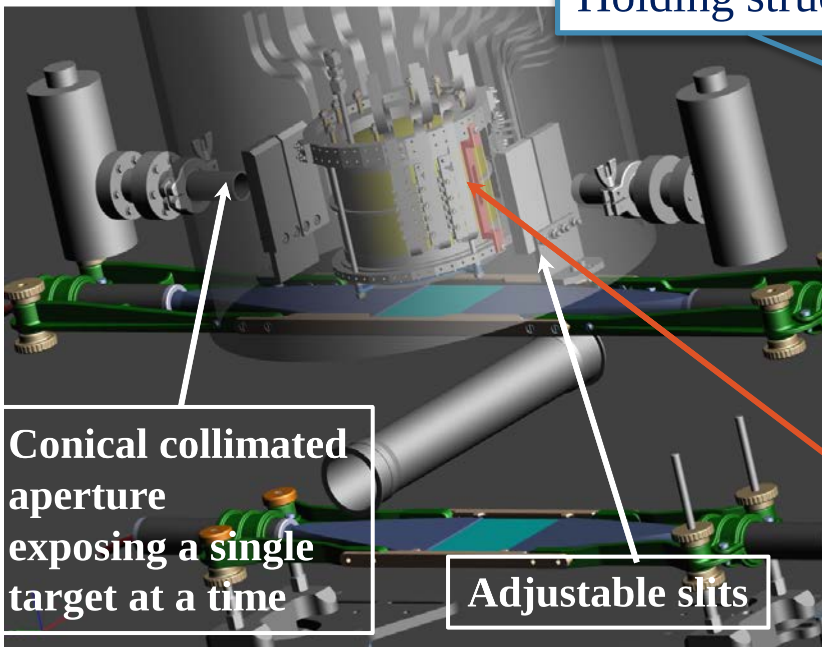
NEW SDD Calibration – High Precision

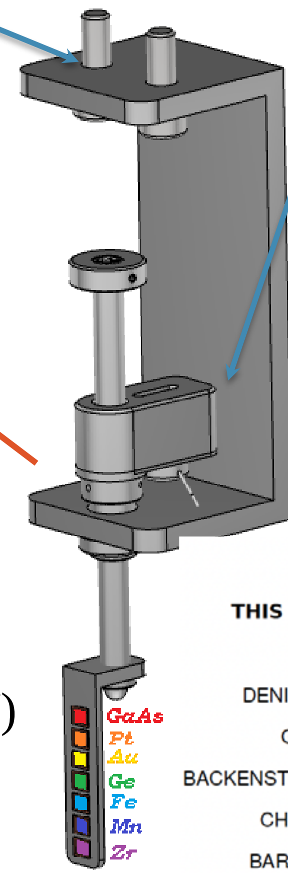
Modifying the calibration target system from 3 fixed to 7 movable fluorescent foils

Advanced calibration system

Goal: systematic uncertainty ~0.1 eV - 0.2 eV

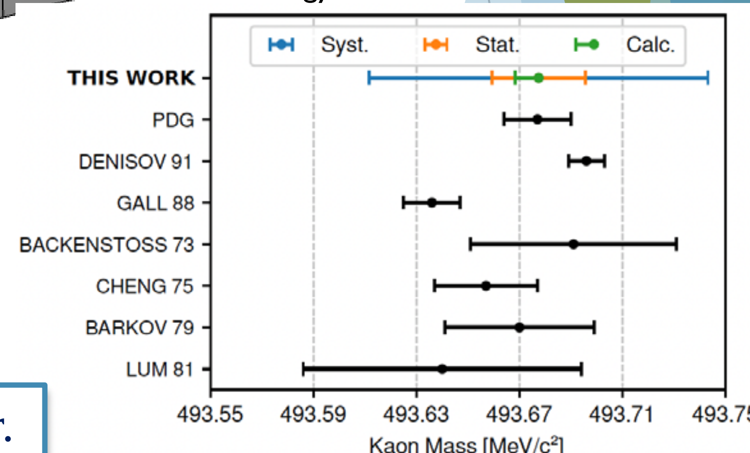
Holding structure





The 8303-V Vacuum Compatible Picomotor™ Actuator

Limited by systematic uncertainty on energy calibration



External Laser system for alignment
Fluke PLS 6G RBP SYS

Ga (Ka 9243 eV)
As (Ka 10532 eV)
Ge (Ka 9876 eV)
Au (La 9685 eV)
Pt (La 9416 eV)

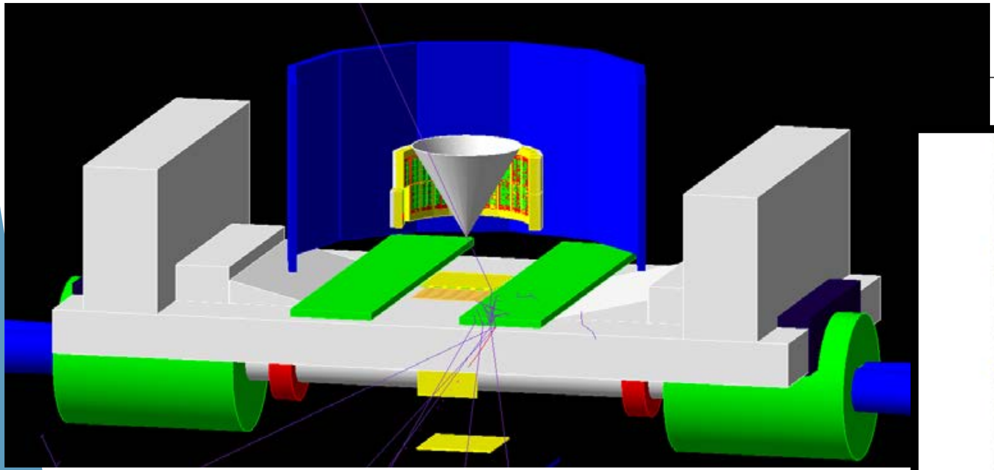
Movable targets arm inserted behind the collimator.

See talk of S. Manti

Light kaonic atoms (LHKA)

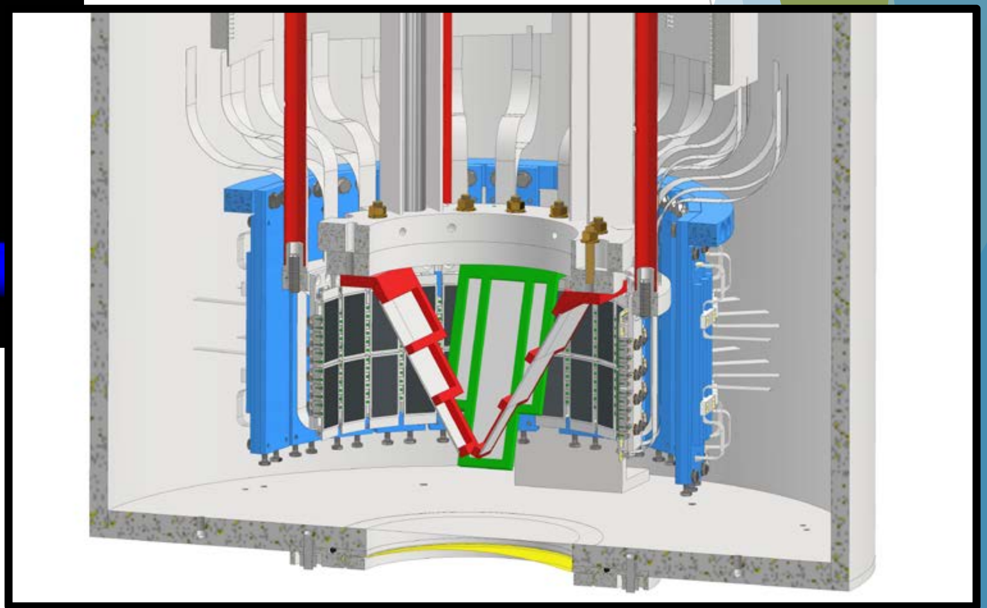
Integration of 1 mm SDD

Lithium-6		Lithium-7	Beryllium-9		Boron-10	Boron-11
Transition	Energy (keV)	Energy (keV)	Transition	Energy (keV)	Energy (keV)	Energy (keV)
$3 \to 2$	15.085	15.261	$3 \to 2$	27.560	43.568	43.768
$4 \to 2$	20.365	20.603	$4 \to 3$	9.646	15.156	15.225
$5 \to 2$	22.809	23.075	$5 \to 3$	14.111	22.171	22.273
$4 \to 3$	5.280	5.341	$5 \to 4$	4.465	7.015	7.047
$5 \to 3$	7.724	7.814	$6 \to 4$	6.890	10.826	10.875
$5 \to 4$	2.444	2.472	$6 \to 5$	2.425	3.811	3.828



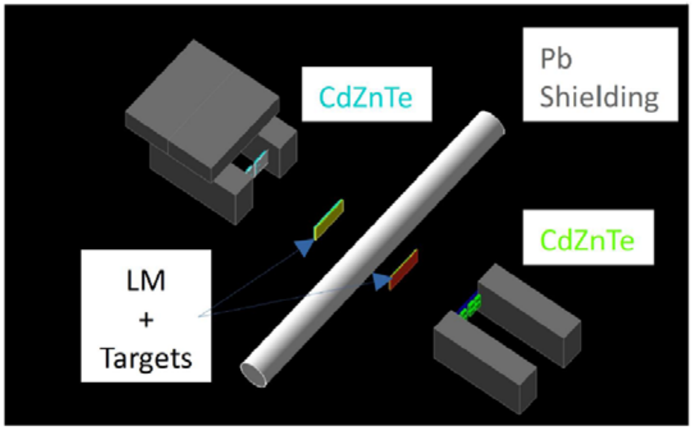
Solid target system

Kaonic boron test measurement successfully achieved
Construction of new support system
conical shape to maximize the solid angle
MC simulations ongoing



Intermediate kaonic atoms (IMKA)

In parallel we plan dedicated runs for kaonic atoms (*O*, *Al*, *S*) with different types of detectors:
CdZnTe detectors
- 200 -300 pb-1 of integrated luminosity

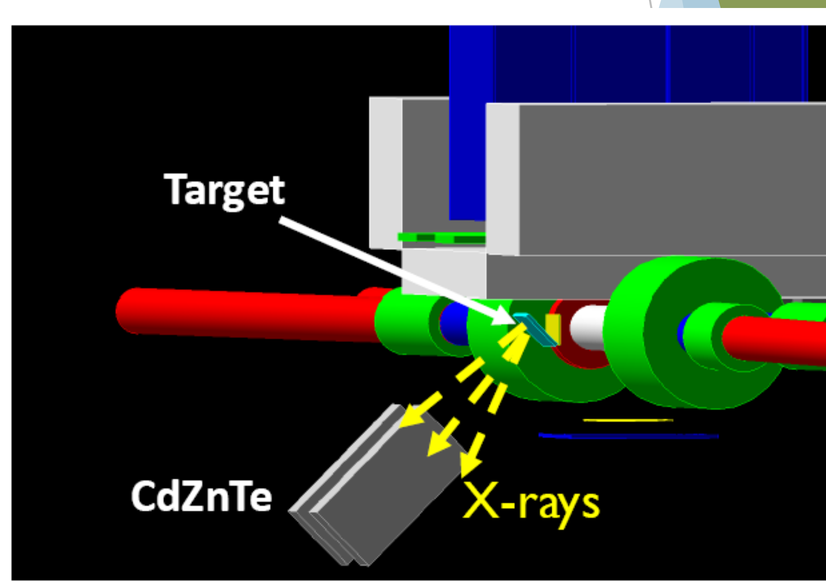


Kaonic Oxygen: key role in the description of the nuclear-matter density distribution which enters in the formula for the density-dependent optical potentials

- **Kaonic Aluminium**: 3->2 QCD – never measured;
- **Kaonic Sulphur**: 4->3 past measurements are inconsistent

We are developing an optimized CdZnTe based setup

Larger active area:
32 detectors instead of 8
Optimized geometry and shielding
to reduce the background



Kaonic Atoms measurements at DaΦne

DEAR 2002

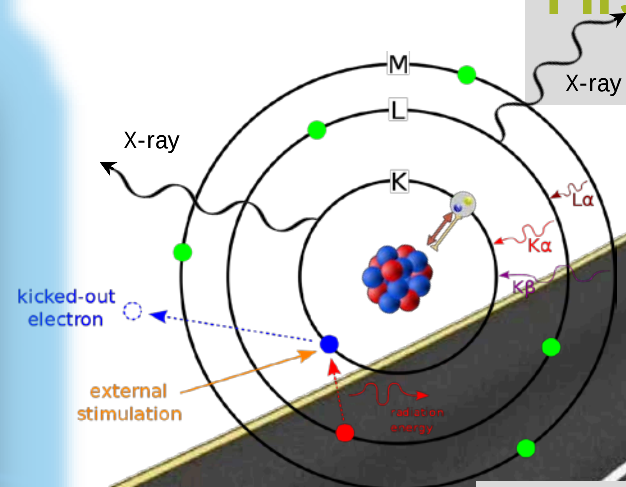
SIDDHARTA 2009

SIDDHARTA-2 2022

EXKALIBUR

Kaonic Neon (Kaon mass)

First kaonic deuterium (2023 -2024)



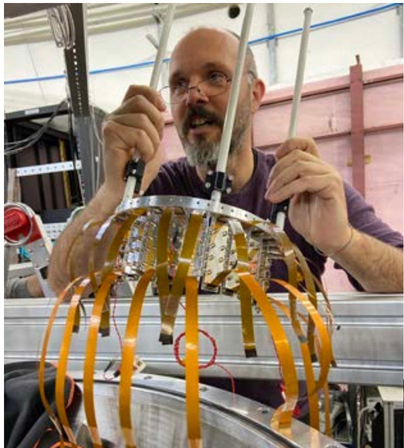
Kaonic Neon (2023)

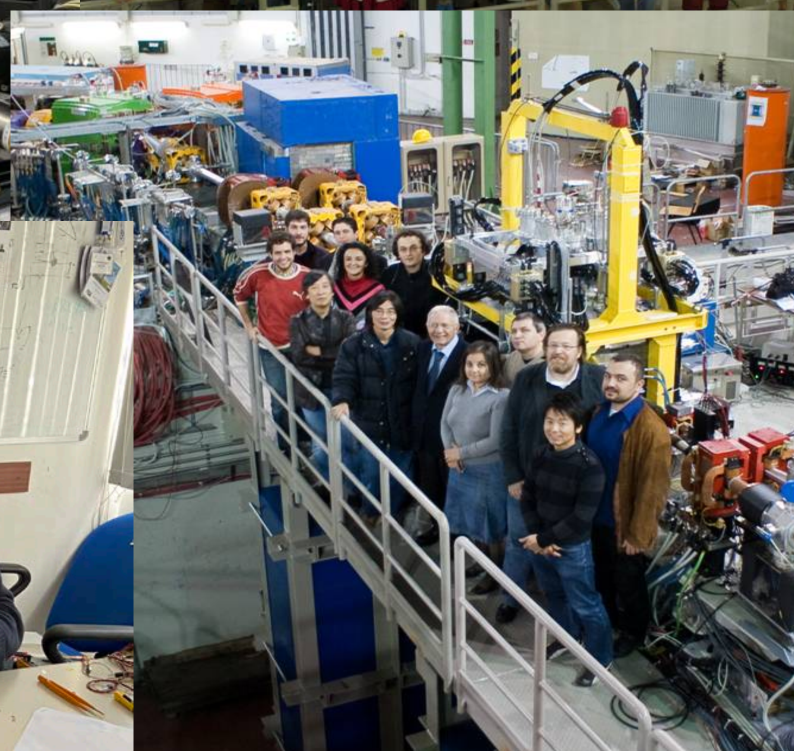
Kaonic Helium-4 (2022)

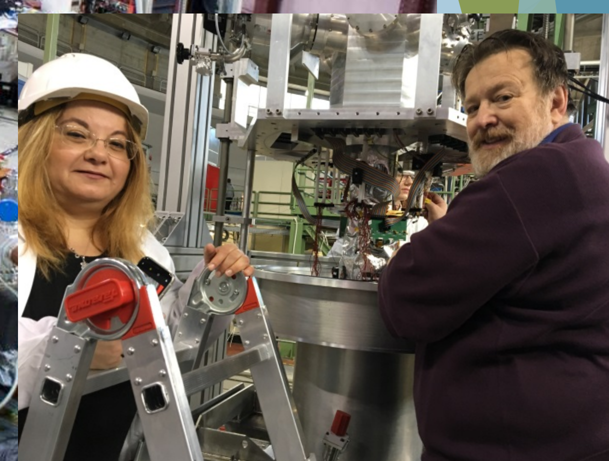
Kaonic Hydrogen (2011)

Kaonic Nitrogen (2002)

Thank you !



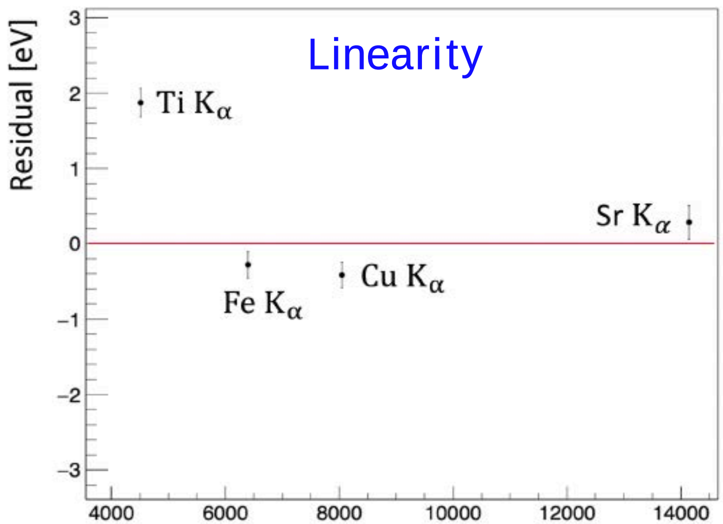


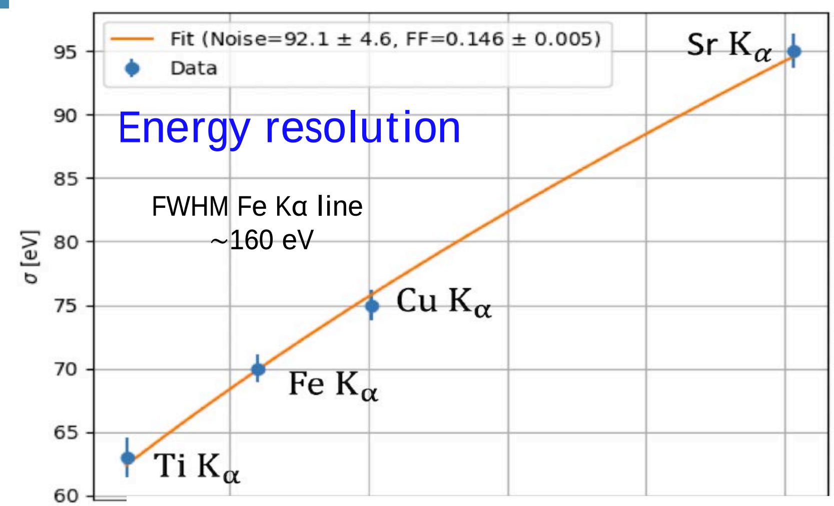


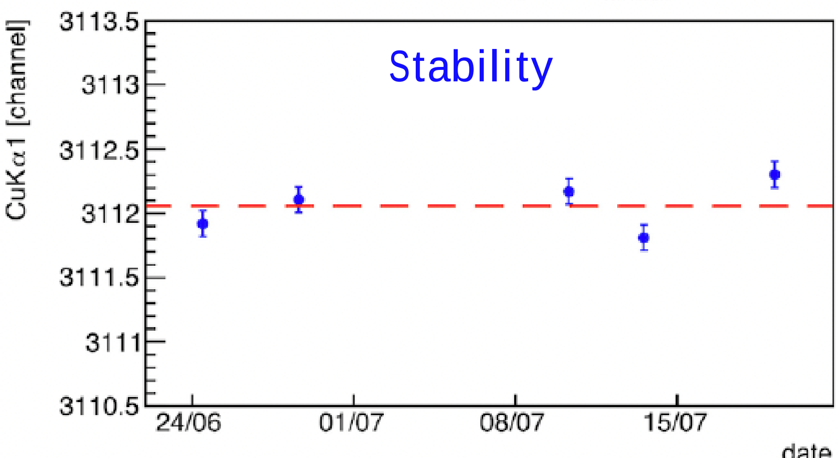
SPARE

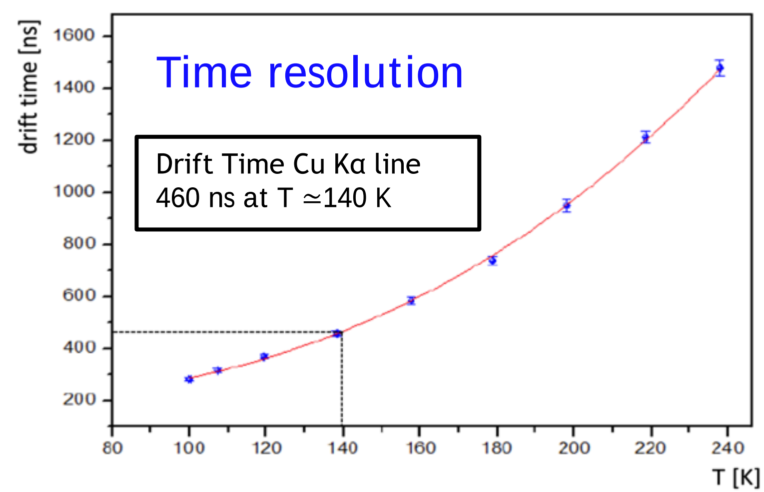
Silicon Drift Detectors spectroscopy response

The energy response is linear within few (<5 eV between 4 keV and 14 keV)
Excellent energy and time resolution @ 140 K









Miliucci M., Iliescu M**., Sgaramella F.,** et al., 2022,Meas. Sci. Technol., 33 (9) 95502