Workshop on Standard Model and Beyond
Corfu, 28 August – 8 September 2022

Kaonic atoms at the DAFNE Collider: strangeness from accelerators to the stars

Catalina Curceanu on behalf of the SIDDHARTA-2 Collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

On self-gravitating strange dark matter halos around galaxies
Phys.Rev.D 102 (2020) 8, 083015

Dark Matter studies

Fundamental physics
New Physics

The modern era of light kaonic atom experiment
Rev.Mod.Phys. 91 (2019) 2, 025006

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

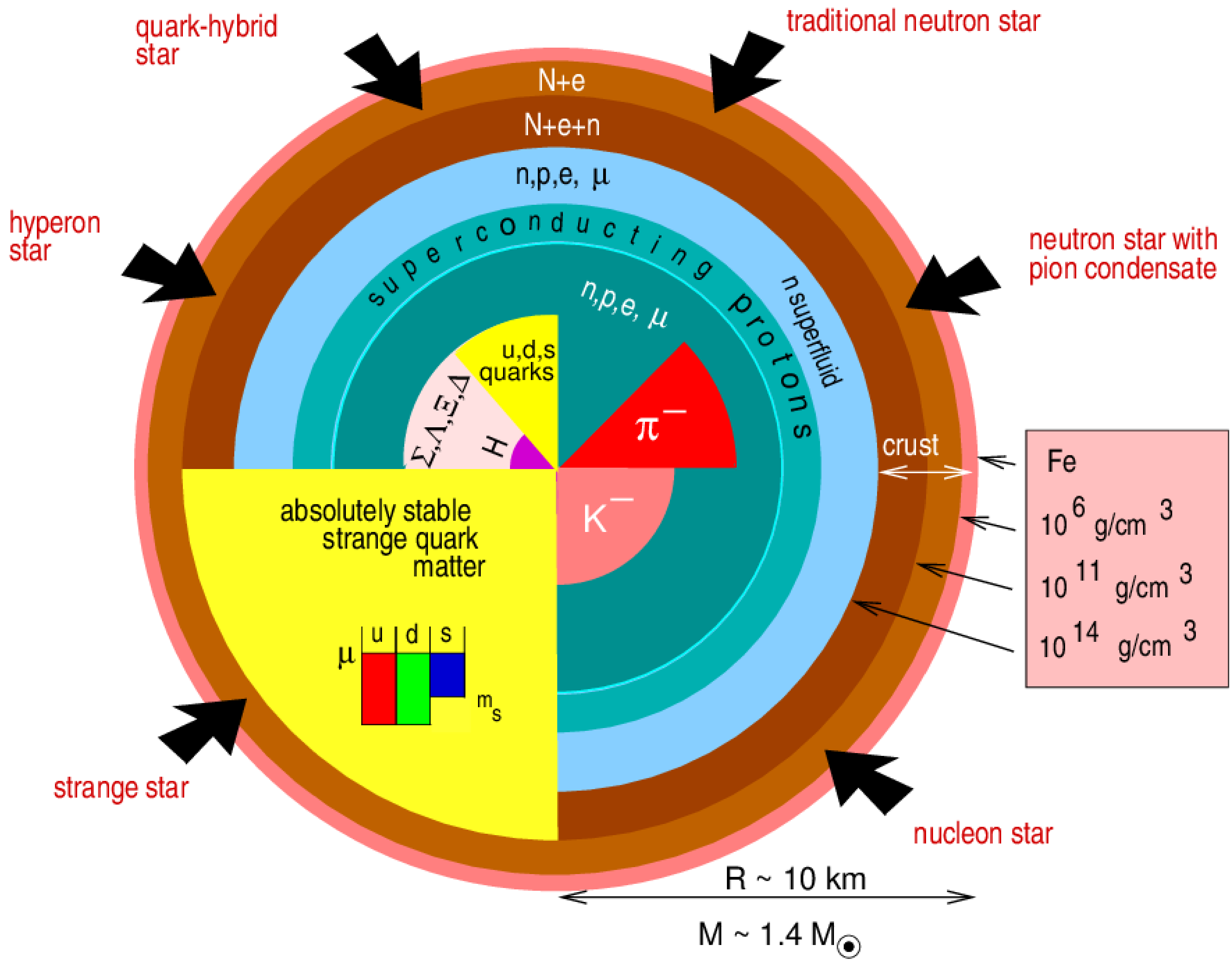
Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

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

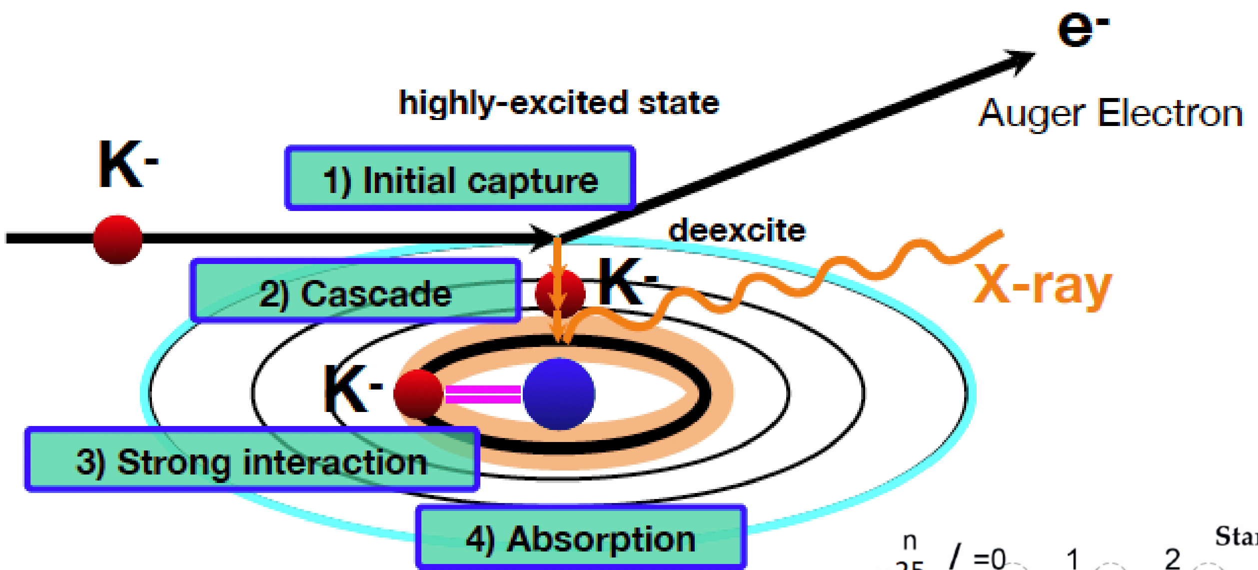
Merger of compact stars in the two-families scenario
Astrophys.J. 881 (2019) 2, 122

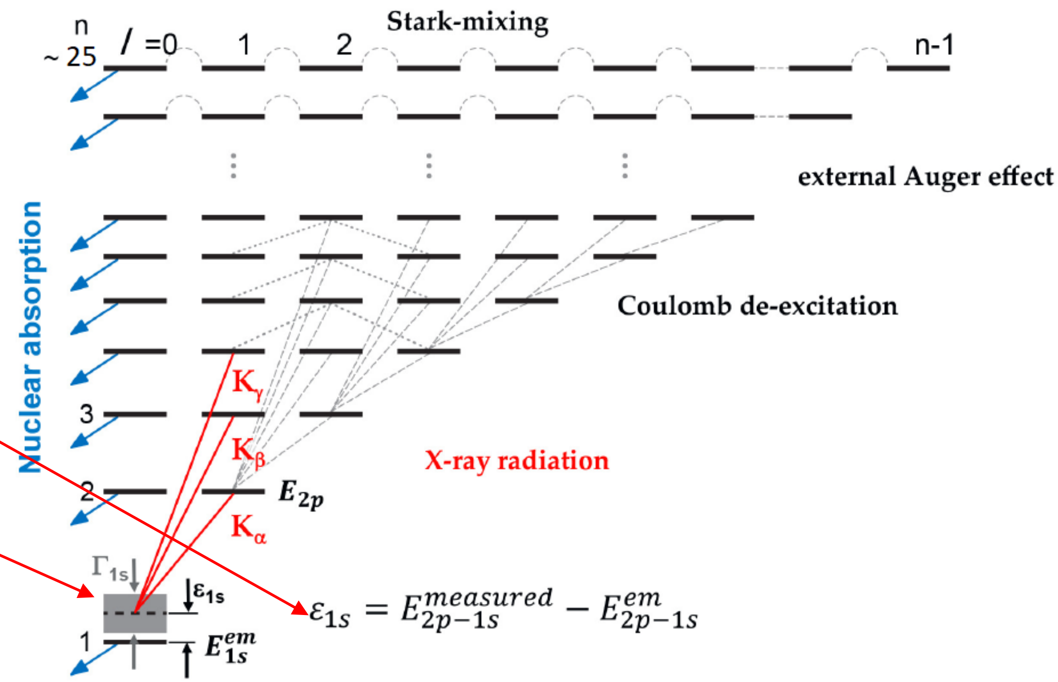
Astrophysics
EOS Neutron Stars

The equation of state of dense matter: Stiff, soft, or both?
Astron.Nachr. 340 (2019) 1-3, 189


quark-hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e, μ
superconducting protons
n superfluid
n,p,e, μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
crust
absolutely stable strange quark matter
μ
u
d
s
m_s
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
R ~ 10 km
M ~ 1.4 M_⊙

Kaonic atom Formation





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

SIDDHARTA-2

SIlicon **D**rift **D**etector for **H**adronic **A**tom **R**esearch by **T**iming **A**pplications

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

STRONG-2020

HadronPhysics I3
Study of Strongly Interacting Matter

HRZZ
Croatian Science Foundation

FWF Der Wissenschaftsfonds.

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

SIDDHARTA-2 Scientific Goal

To perform the *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.

⬇

Analysis of the combined measurements of kaonic deuterium and kaonic hydrogen

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3 \mu_c^2 a_{K^-p}\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}\right)$$

(μ_c reduced mass of the K⁻p system, α fine-structure constant)

U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

$$a_{K^-p} = \frac{1}{2}[a_0 + a_1] \qquad a_{K^-n} = a_1$$

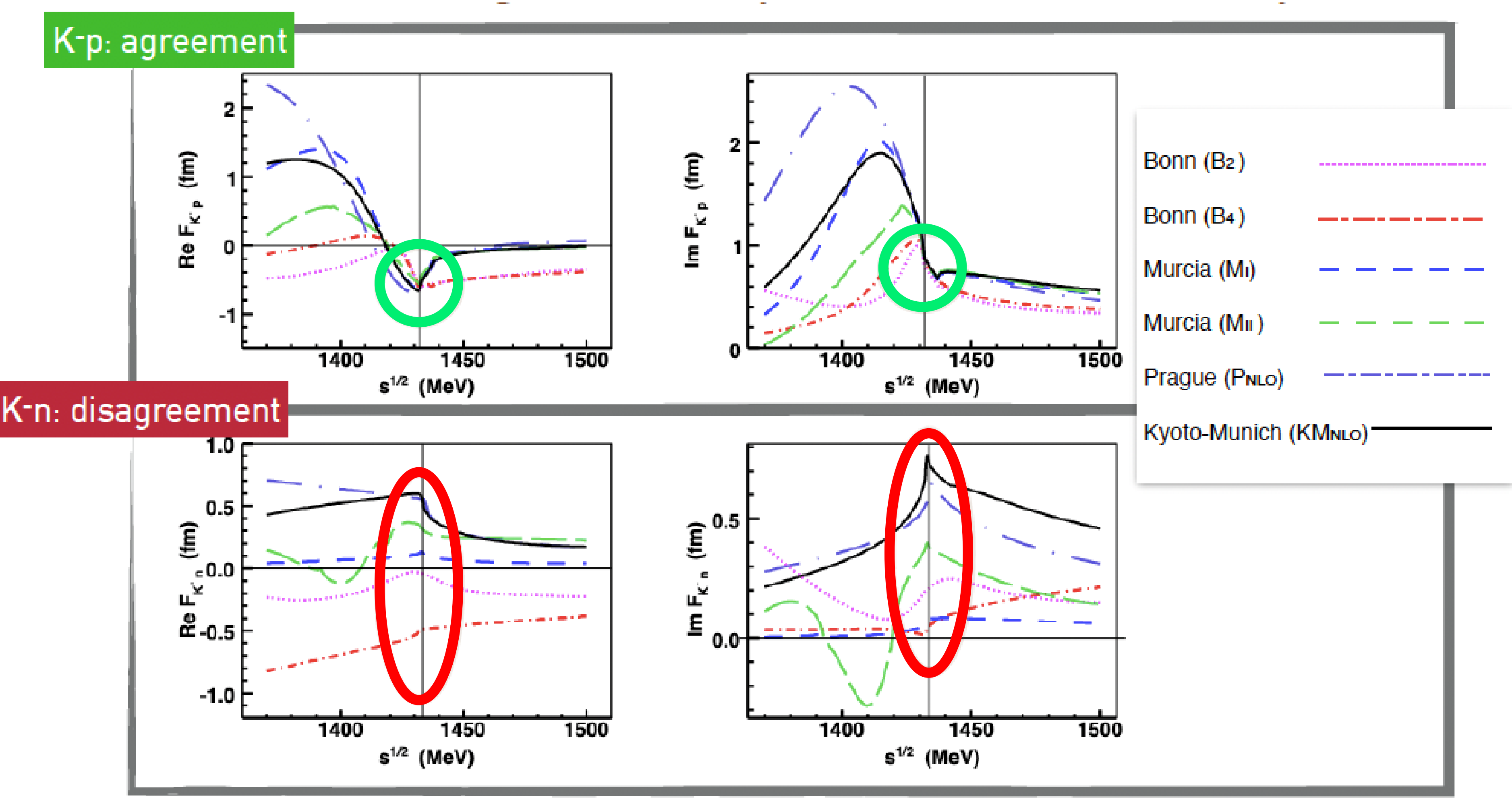
⬅

$$a_{K^-d} = \frac{k}{2}\left[a_{K^-p} + a_{K^-n}\right] + C = \frac{k}{4}[a_0 + 3a_1] + C$$

$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

Experimental determination of the isospin-dependent K-N scattering length

Kaonic atoms – scattering amplitudes



A. Ciepl$\acute{y}$, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

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

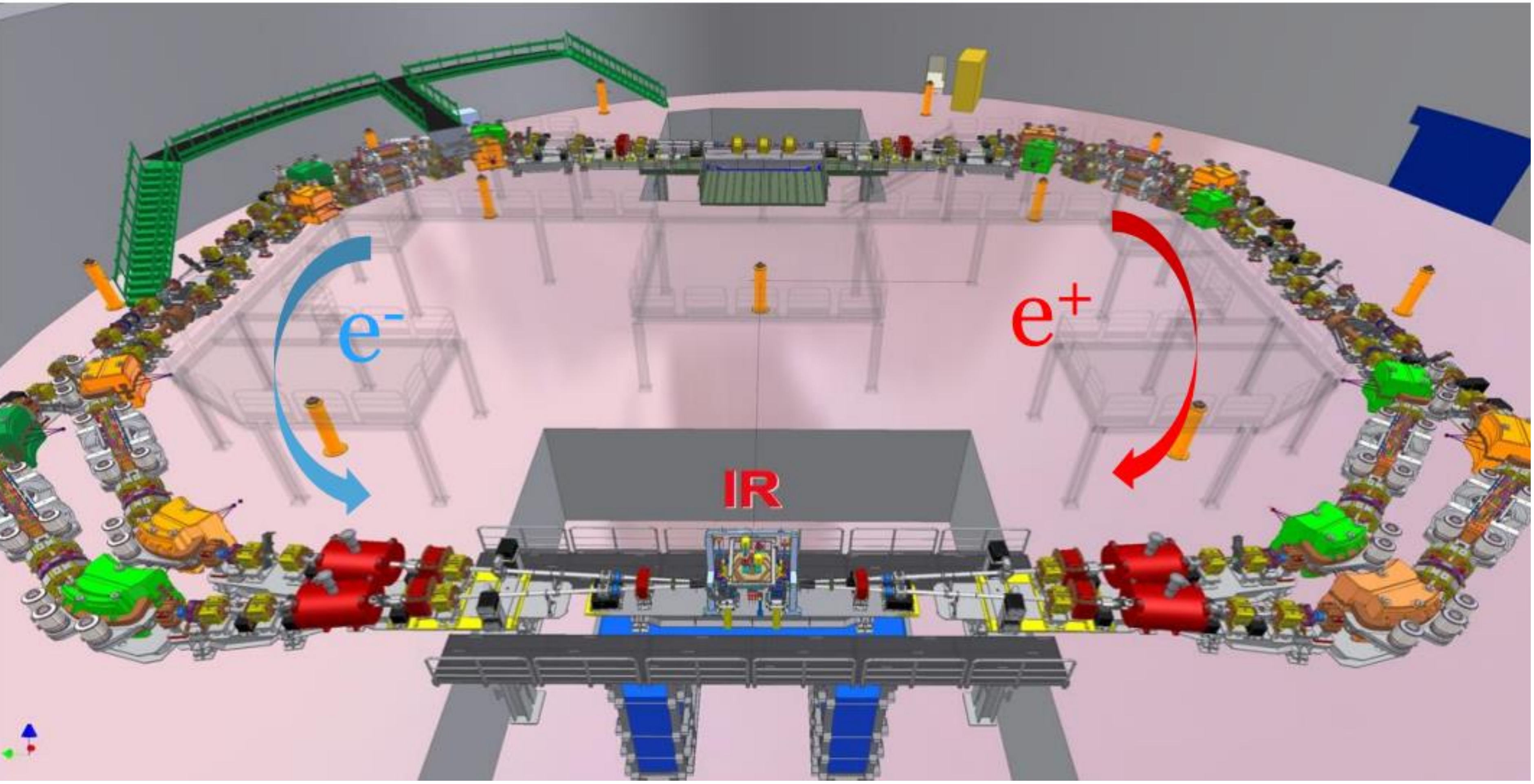
- **Explicit and spontaneous chiral symmetry breaking (mass of nucleons)**
- **Dense baryonic matter ->**
- **Neutron (strange?) stars EOS**

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

LNF - e^+e^- Accelerator Complex

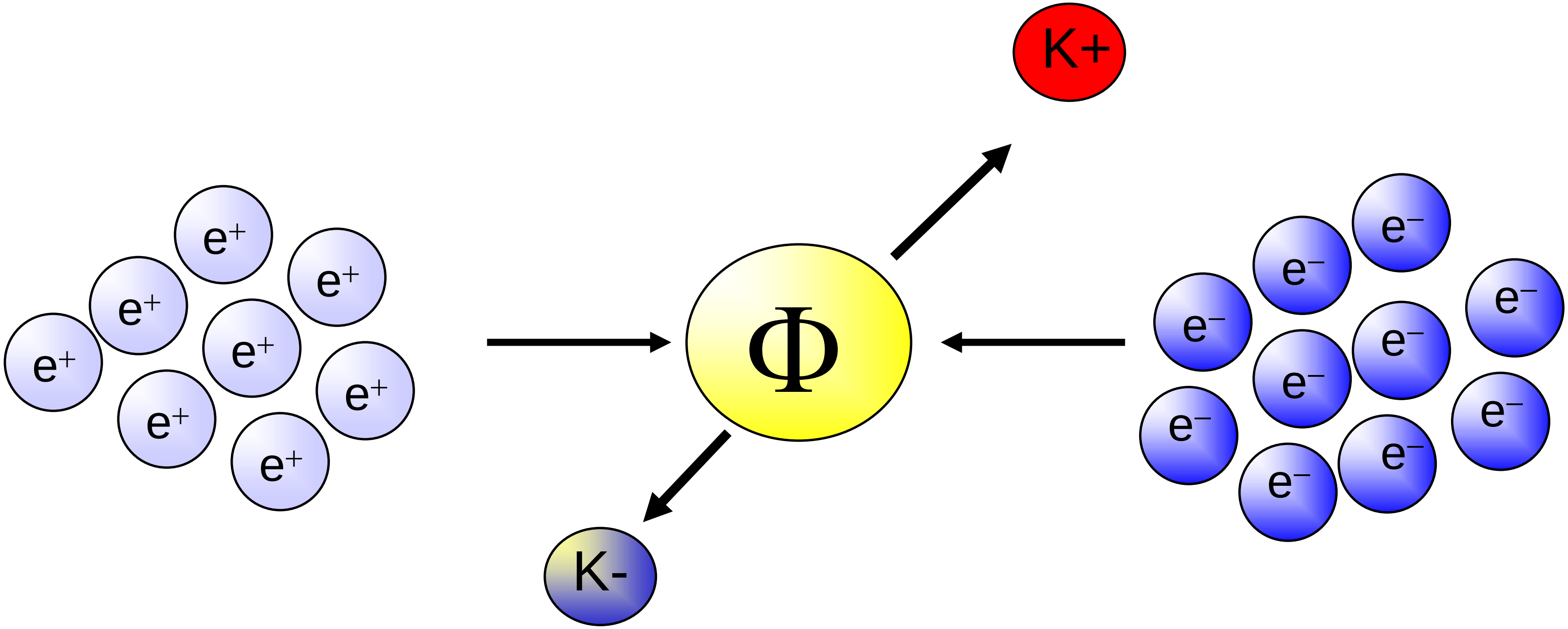
Laboratori Nazionali di Frascati (LNF-INFN)

- $\Phi \rightarrow K^- K^+$ (49.1%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)



DAΦNE

The DAFNE principle



Flux of produced kaons: about 1000/second

DAFNE

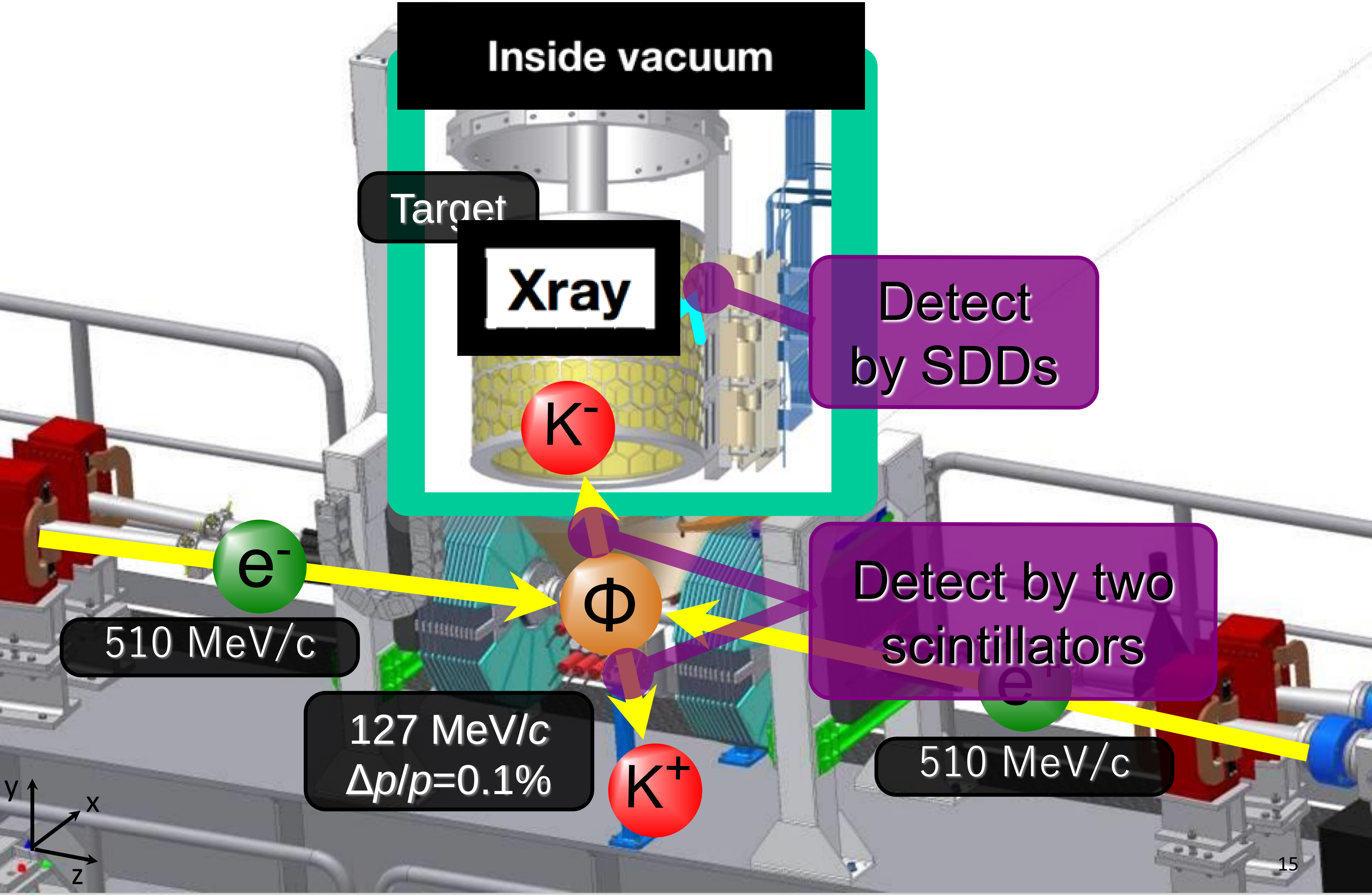
$e^{-}e^{+}$ collider

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

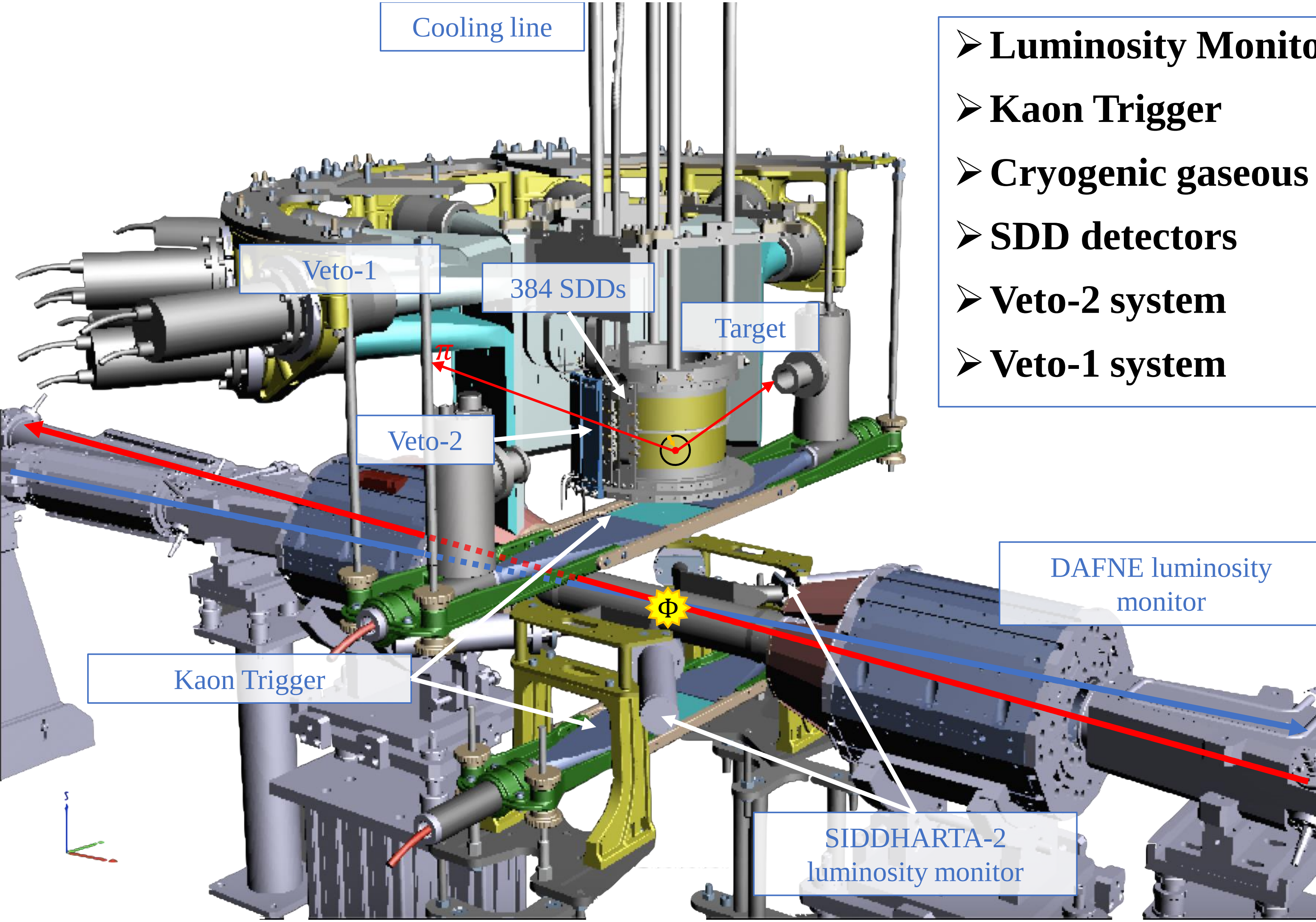
(compare to hadron beam line : e.g. KEK /JPARC)

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

SIDDHARTA overview

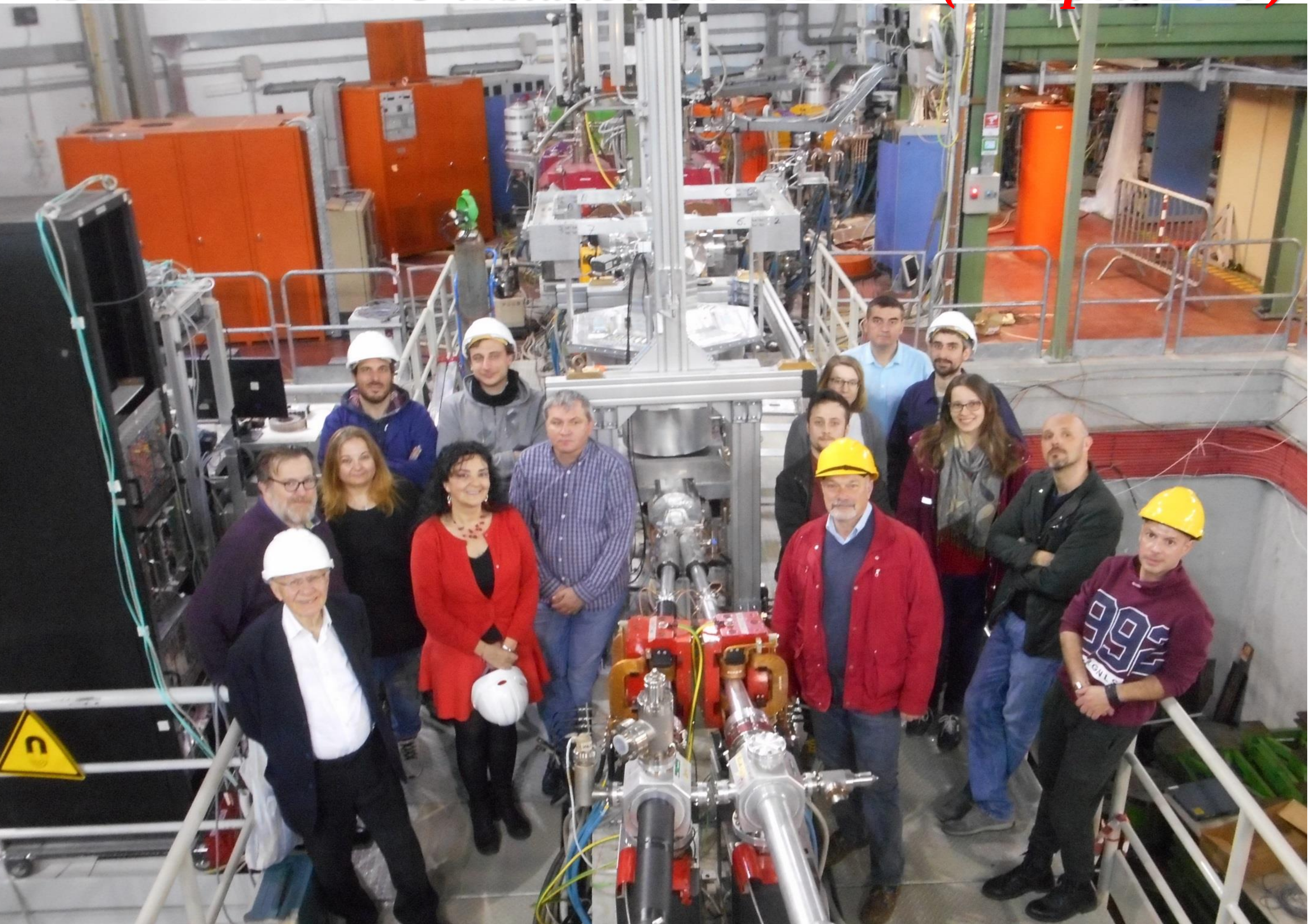


SIDDHARTA-2 setup

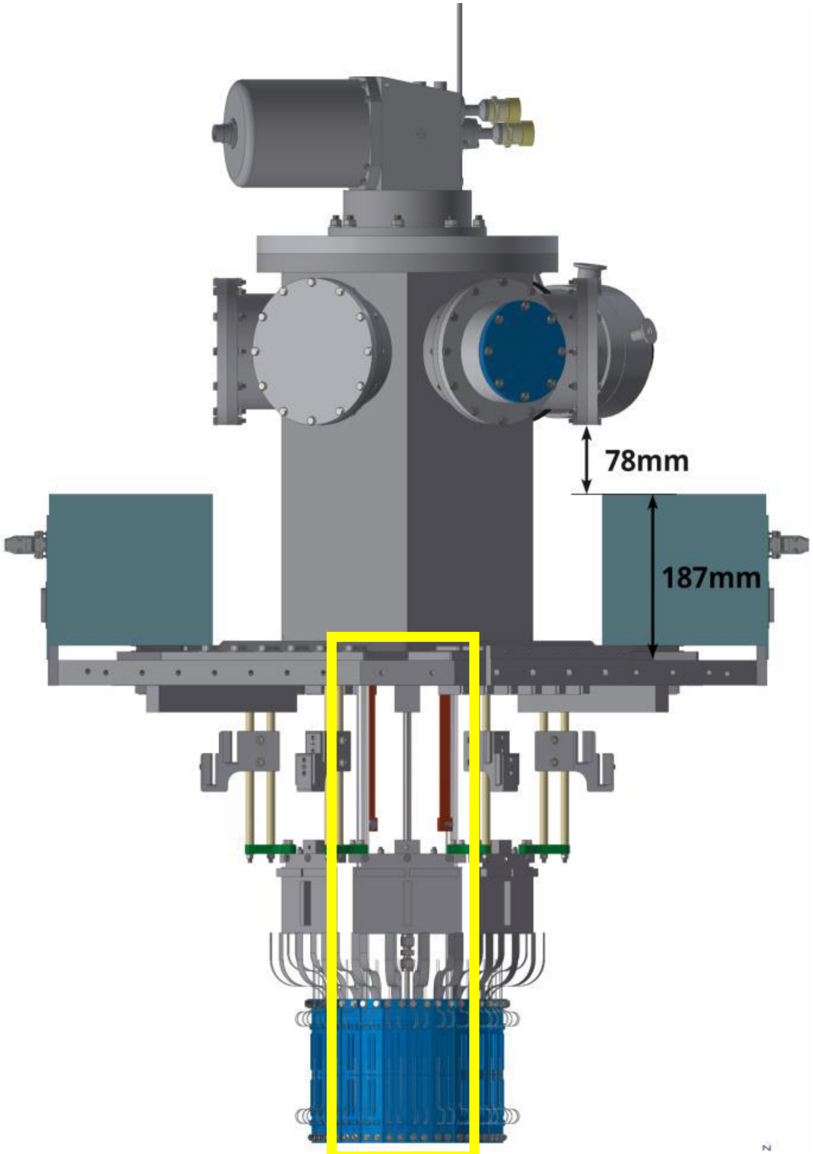


- **Luminosity Monitor**
- **Kaon Trigger**
- **Cryogenic gaseous target**
- **SDD detectors**
- **Veto-2 system**
- **Veto-1 system**

SIDDHARTINO installed on DAFNE (17 April 2019)



SIDDHARTINO



SIDDHARTINO: phase 1 of SIDDHARTA-2
1/6 of SIDDHARTA-2

Evaluation of the machine background during the DAΦNE beams commissioning phase in preparation for the K-d run through the **measurement of K-^{4}He 3d->2p transition**

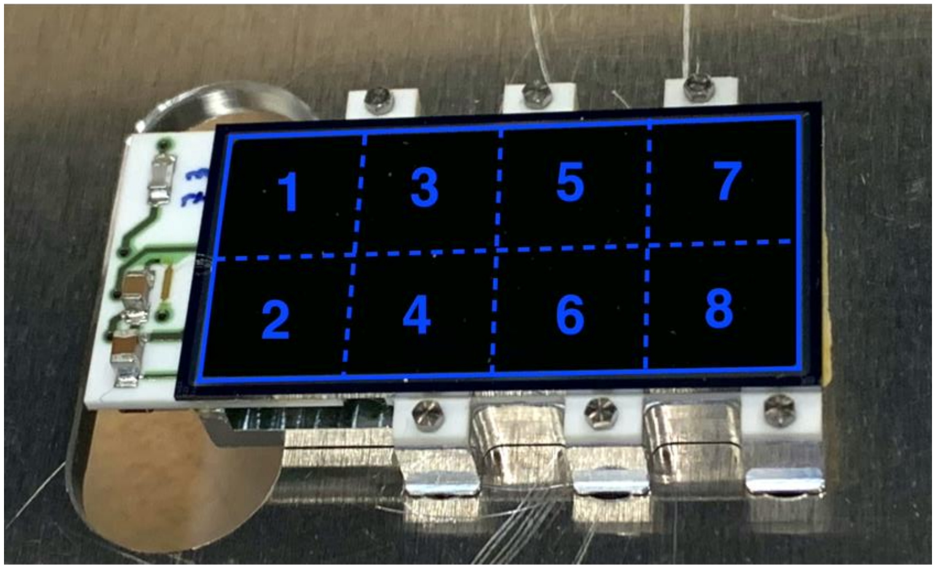
- **Detector tuning for SIDDHARTA-2:**
  - **SDDs**
  - **Kaon Trigger**
- **Concluded in July 2021**

Silicon Drift Detectors

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

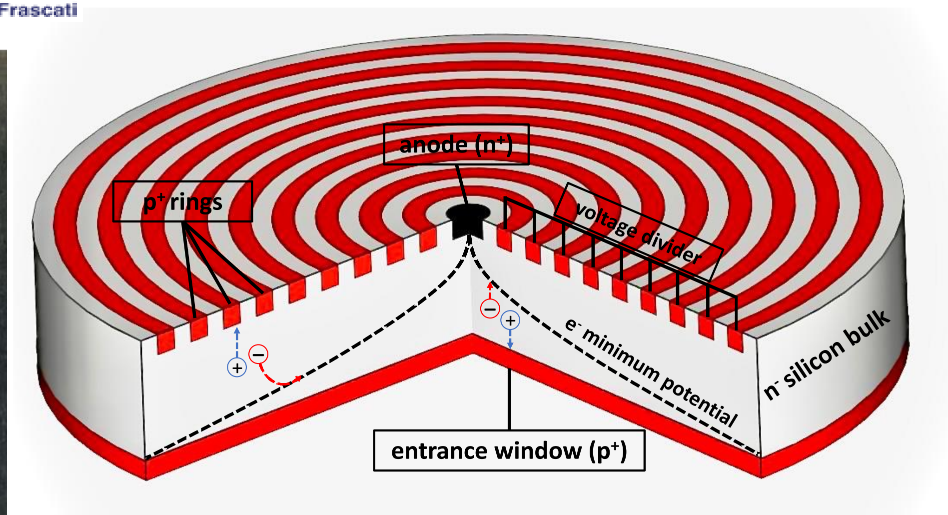
POLITECNICO MILANO 1863

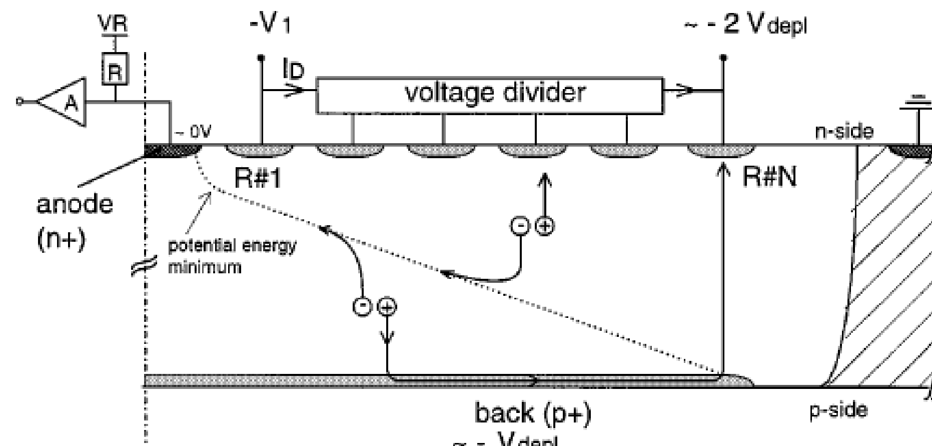
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



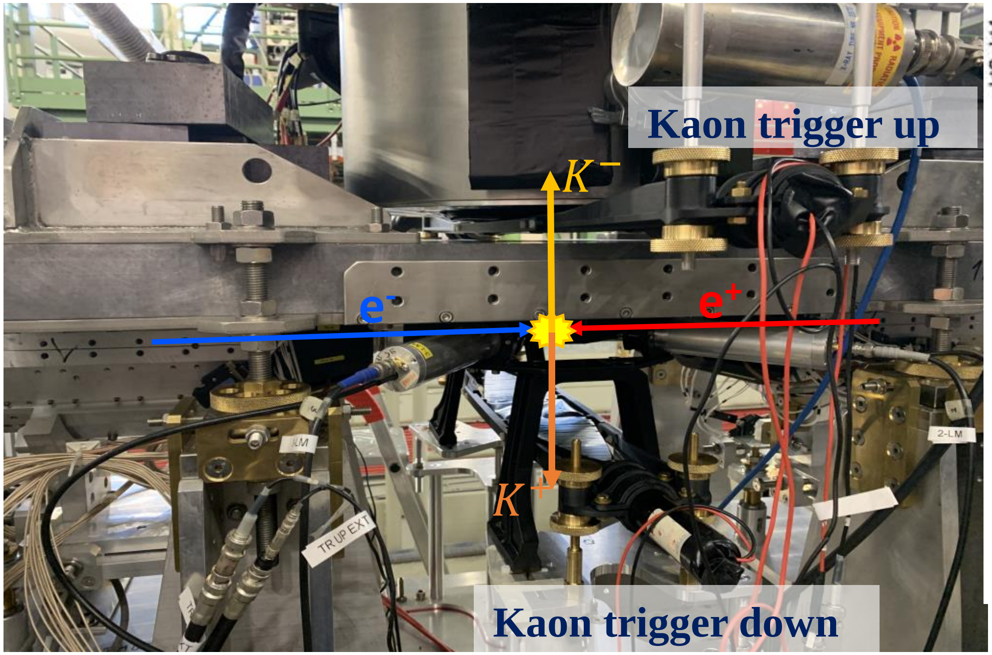
8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of 450 μm which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

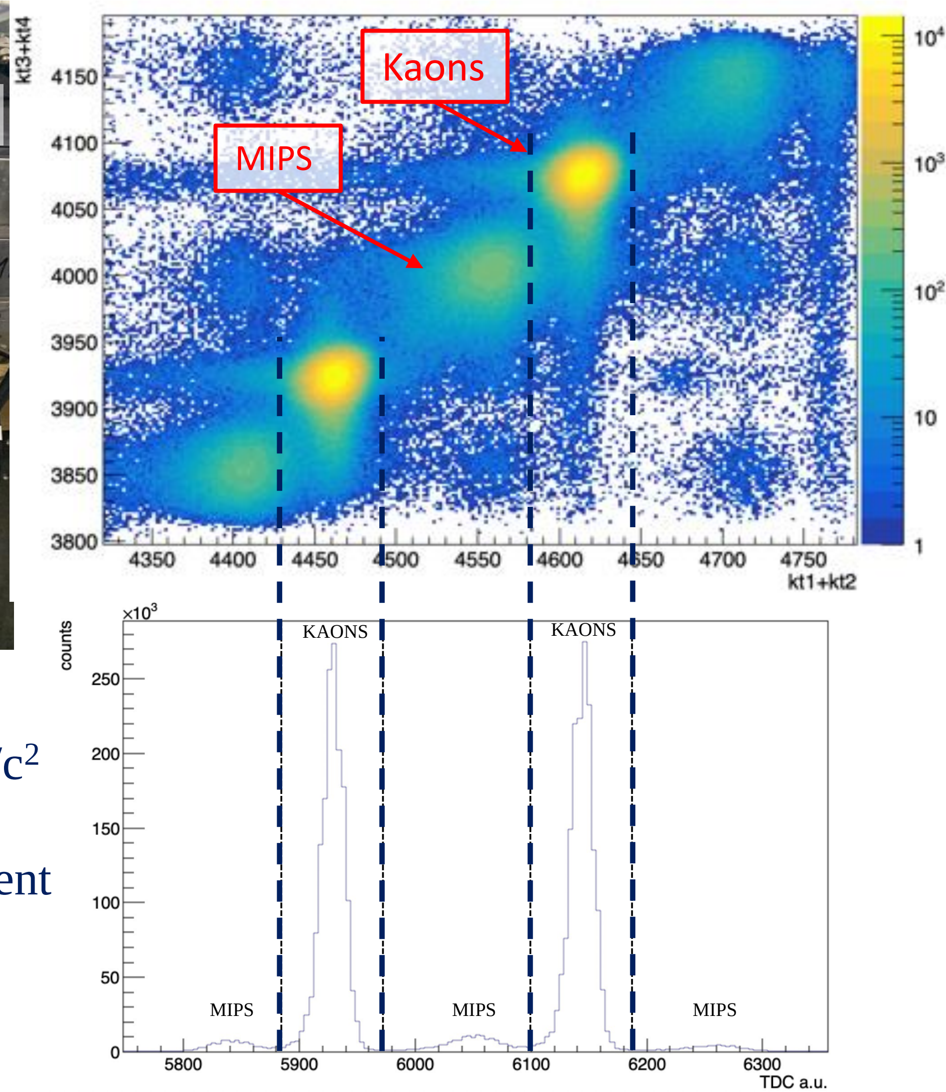
SDD cross section





Kaon Trigger

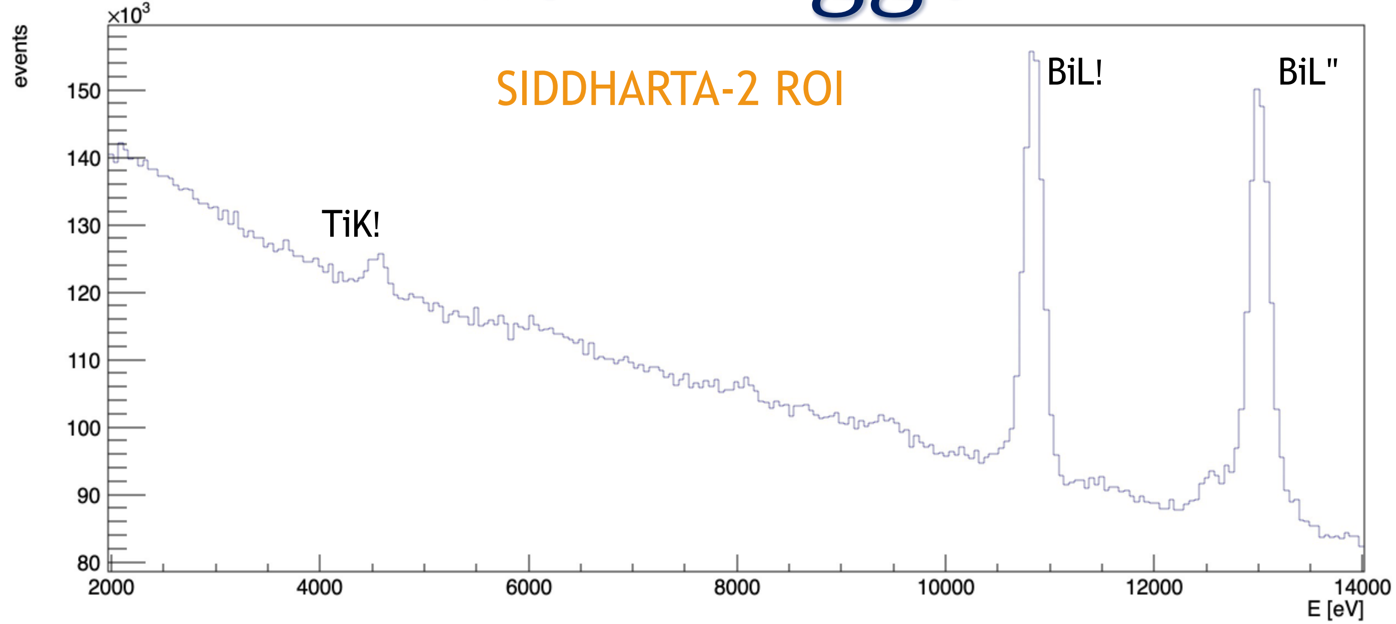




The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

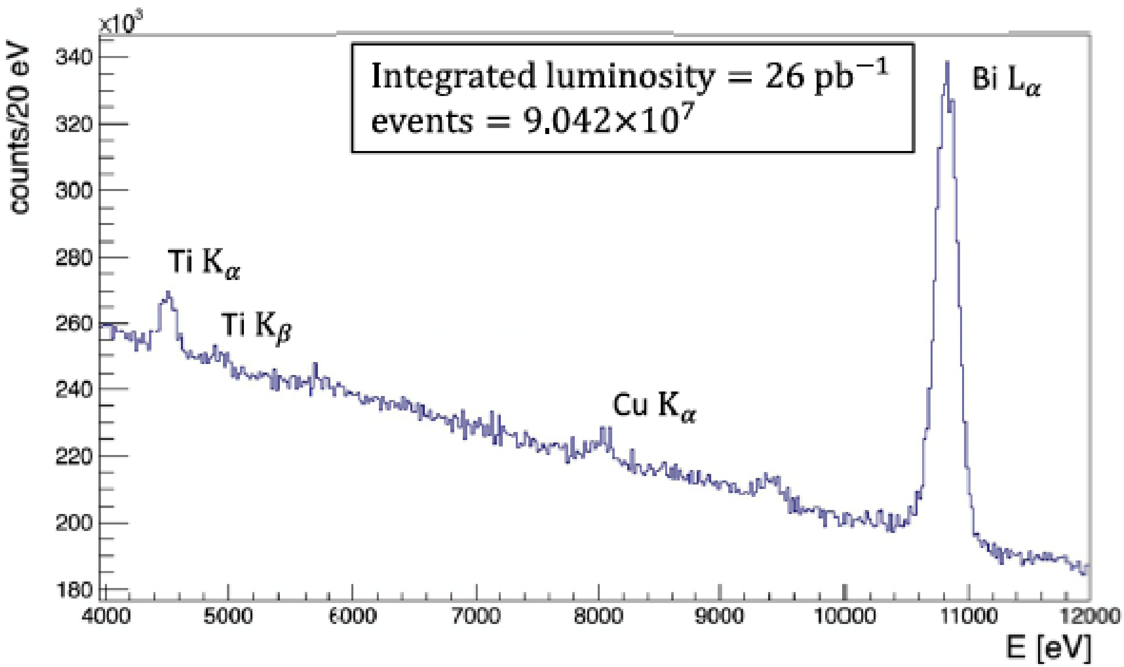
Can efficiently discriminate by ToF Kaons and MIPs!

Kaon Trigger

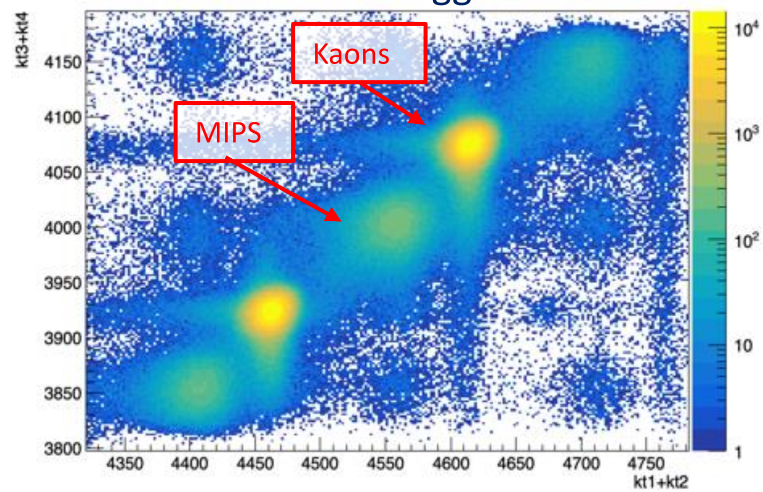


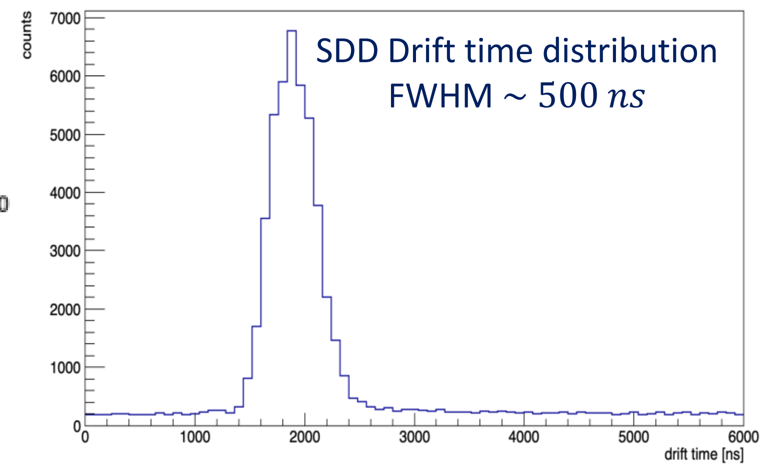
Kaonic ^{4}He 3d → 2p measurement

SIDDHARTINO spectrum before applying the **kaon trigger** and the **drift time rejection**



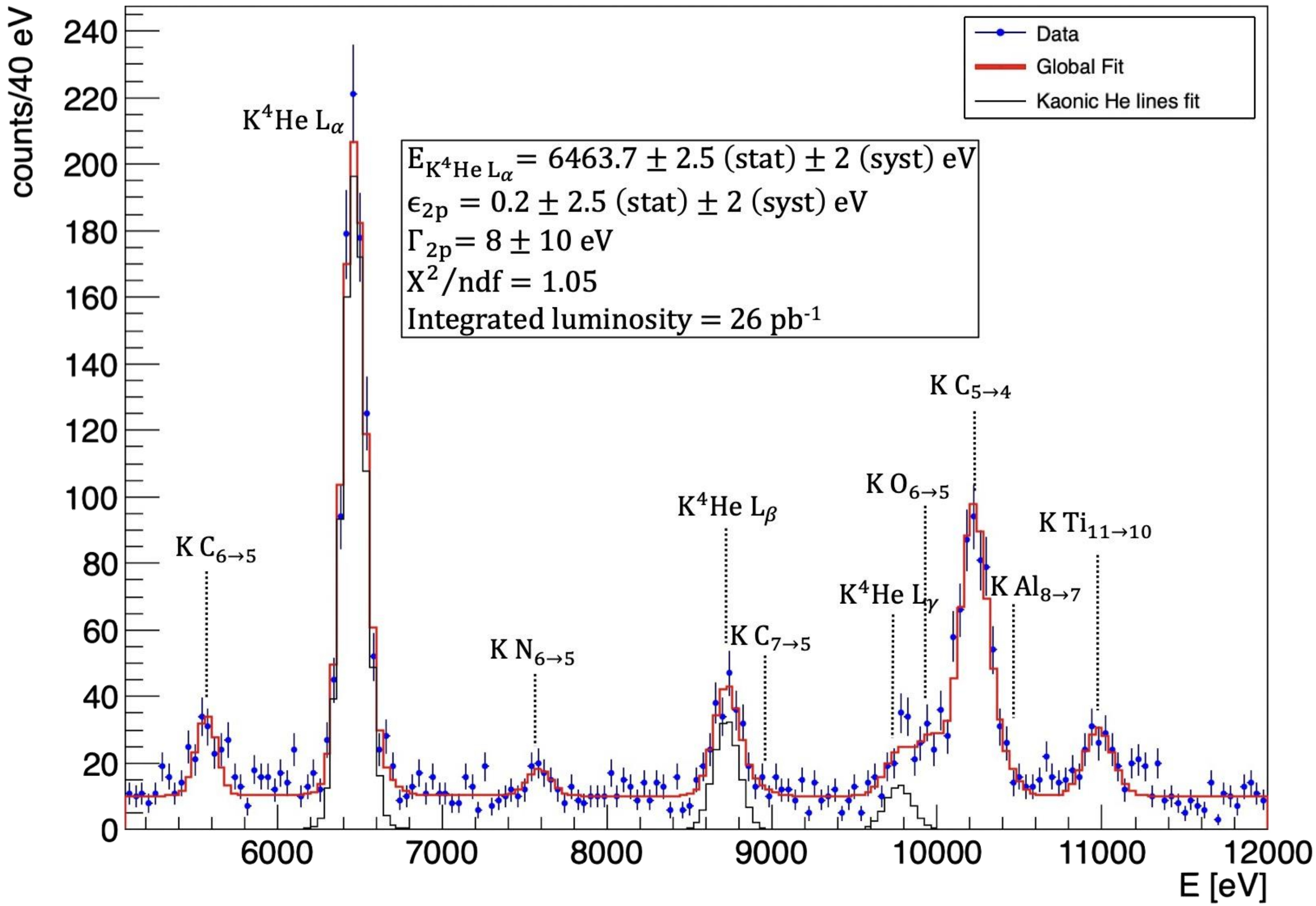
Kaon Trigger





More details in Aleksander Khreptak's poster: *Calibration of Silicon Drift Detectors for the SIDDHARTA-2 Experiment*

Kaonic ^{4}He 3d $\rightarrow$ 2p measurement

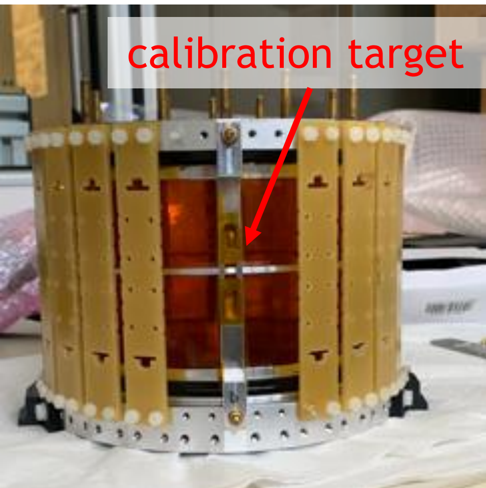


Sirghi *et al* 2022 *J. Phys. G: Nucl. Part. Phys.*

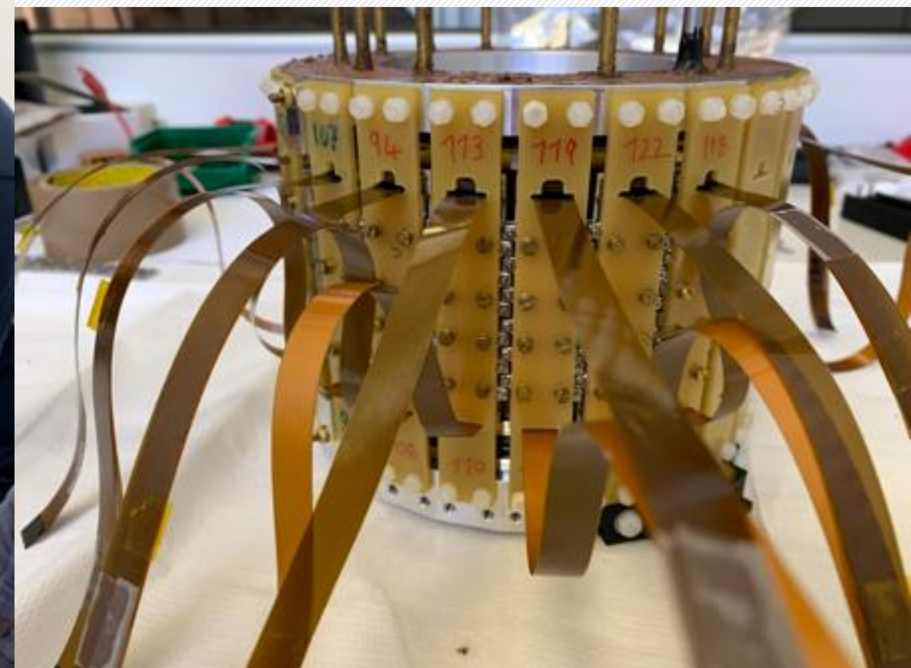
SIDDHARTA-2 setup
Installed on DAFNE autumn 2021

Run: KHe and Kd
7 April – 11 July 2022

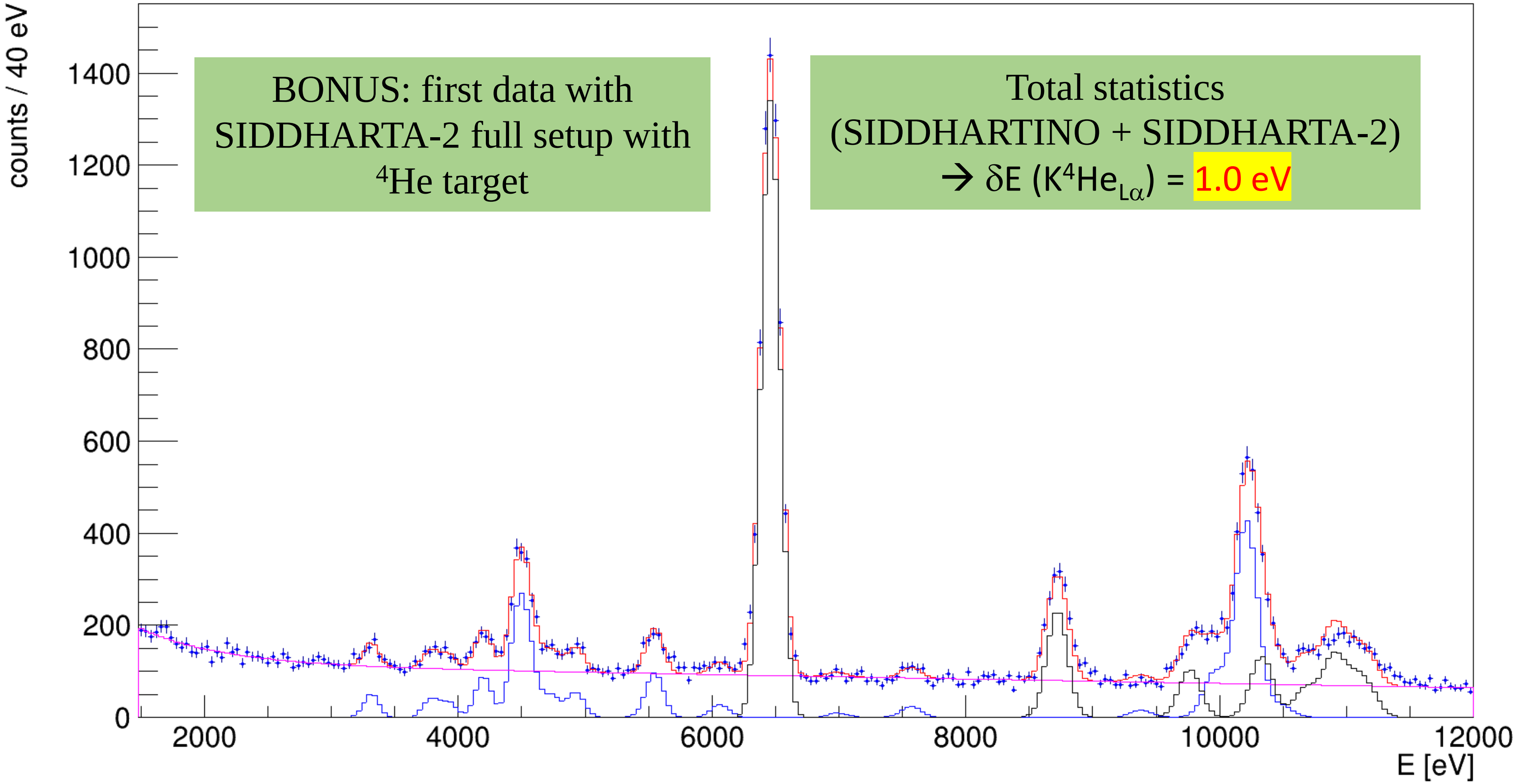
SDD installation



SDD installed around the target



Kaonic ^{4}He 3d → 2p measurement



Very preliminary

SIDDHARTA-2 K-d measurement

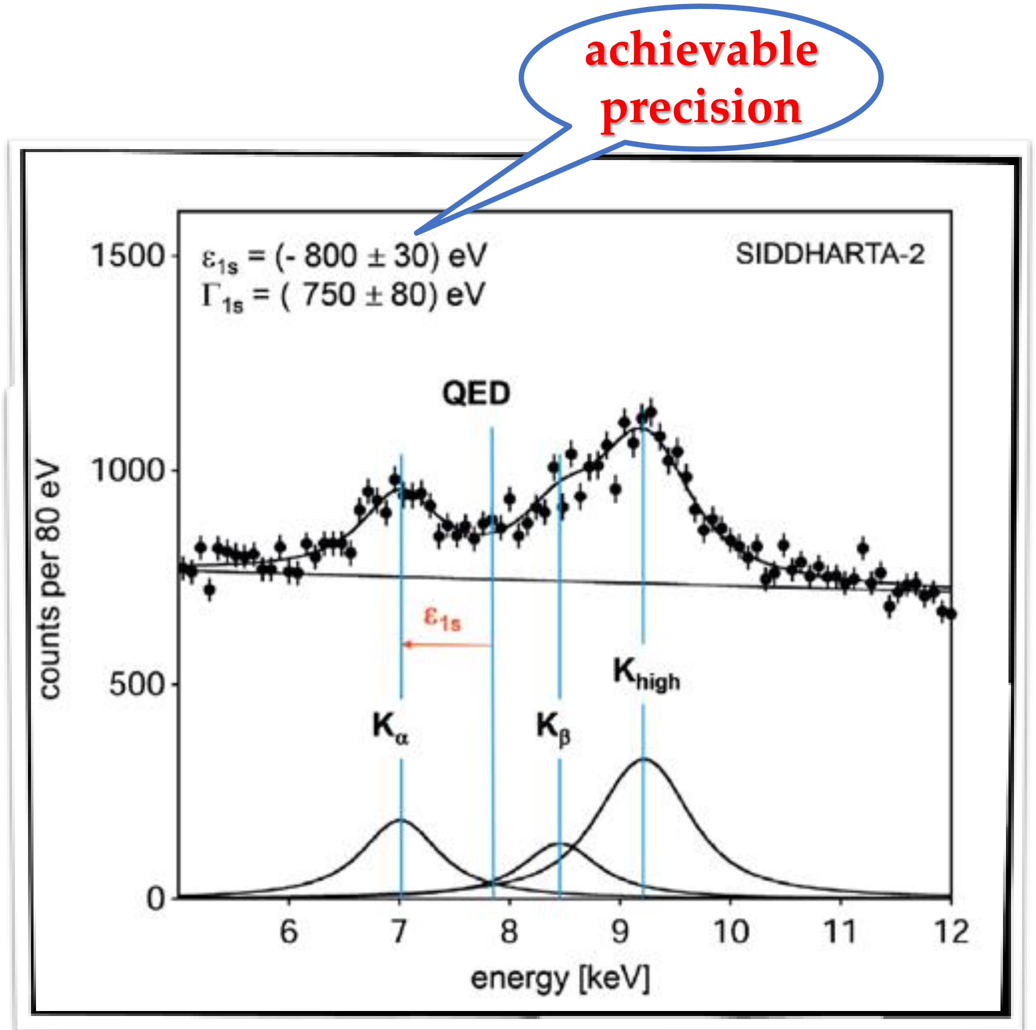
Kaonic deuterium run in (all)

2022

Monte Carlo for an integrated luminosity

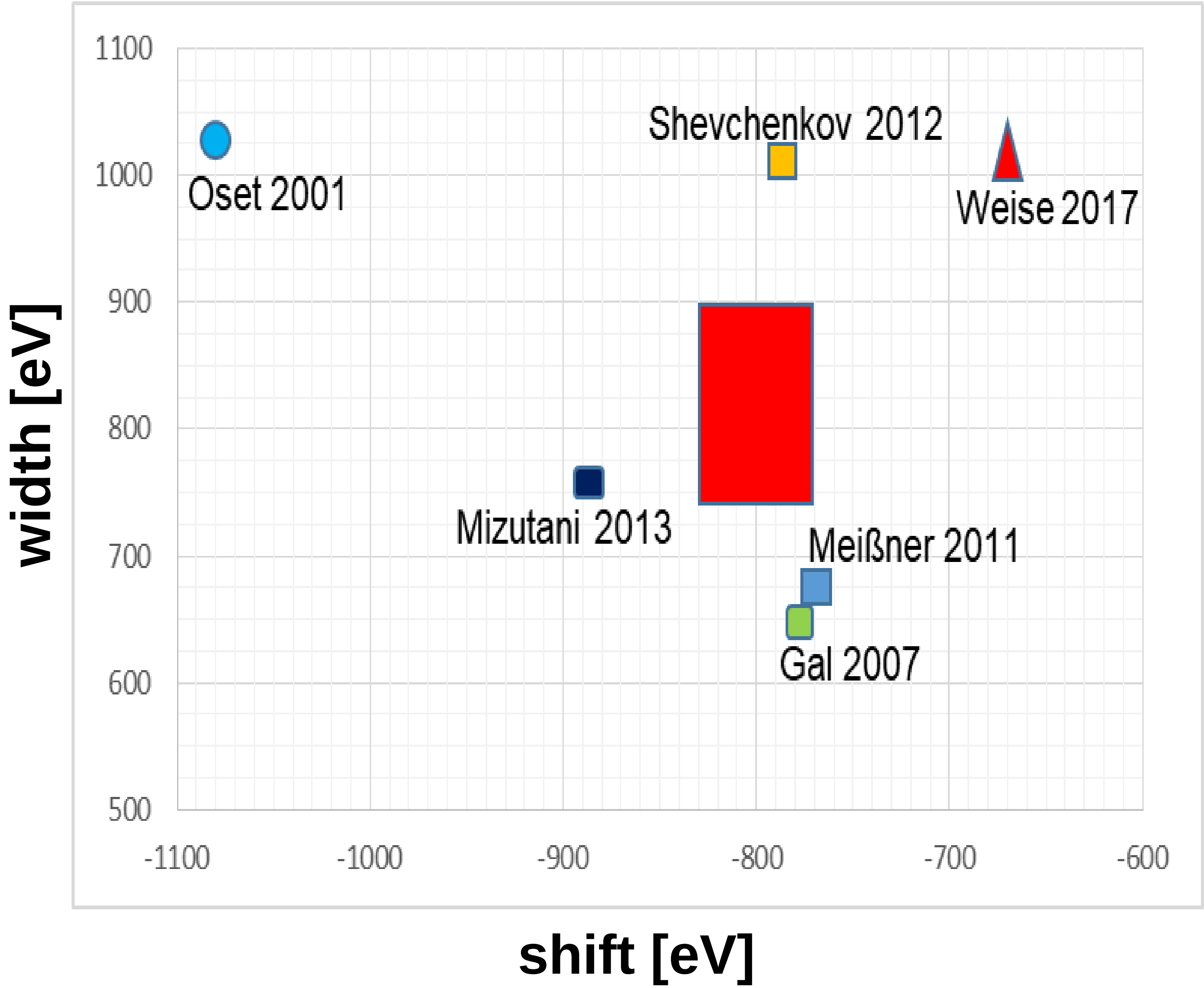
of 800 pb^{-1}

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



Significant impact in the theory of strong interaction with strangeness

SIDDHARTA-2 K-d measurement

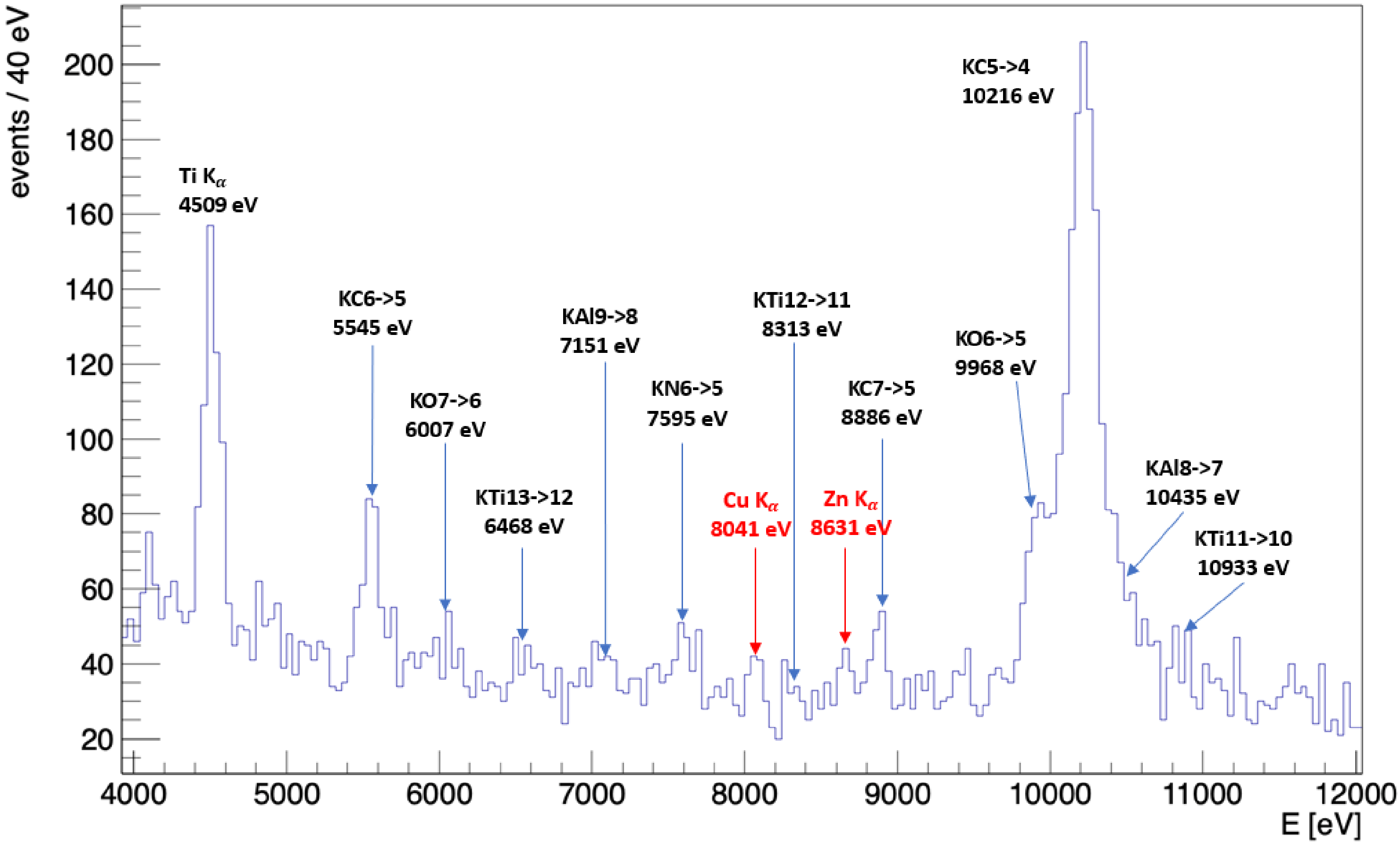


SIDDHARTA-2 K-d measurement

SIDDHARTA-2 KD 1.1%

Date: 03/06/2022 to 24/06/2022 (run from ID 166 to ID 305)
Degrader: deg_rot1_475um
N° SDDs: 98 (bus1 + bus4)
L (lumi) = 30.248 pb^{-1}

Very preliminary
First spectrum with deuterium target



SIDDHARTA-2 strategy and requests

Phase 2

SIDDHARTA-2

Setup with all the SDDs (48 SDD arrays) 2022/3 and the *kaonic deuterium measurement* for a run of 800 pb^{-1}

Action plan for Kd measurement:

- **First run of test with SIDDHARTA-2 setup as planned (about 50 pb^{-1} integrated) - 2022**
- **Second run with optimized shielding, readout electronics and other necessary optimizations; (for other 750 pb^{-1} integrated) - 2023**

Test runs for other kaonic atoms measurements (HPGE…)

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

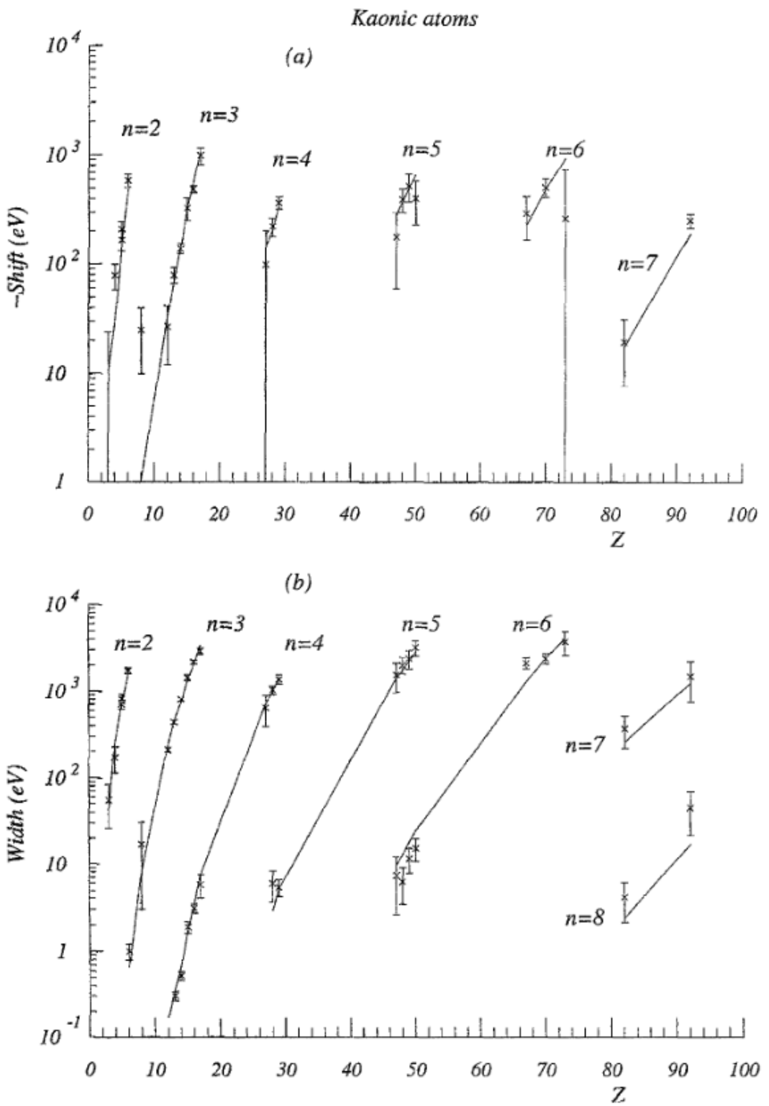
Present status: old and very old measurements with low precisison (some even wrong: kaonic helium puzzle)

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

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

charting the periodic table

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



For future:

Physics at the strangeness frontier at DAΦNE studies:

High Precision Kaonic Atoms Measurements on DAΦNE:

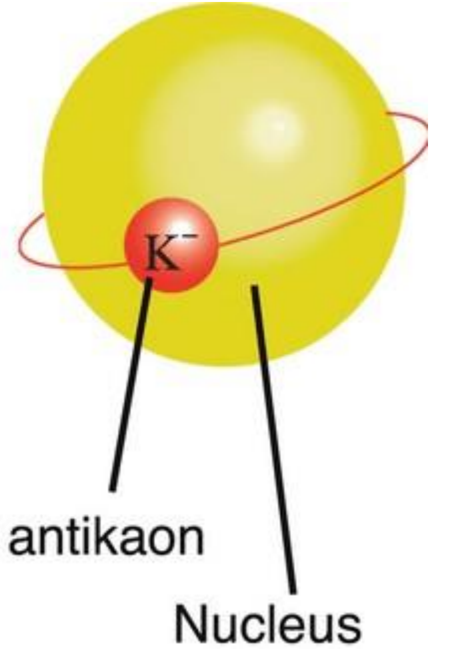
The strangeness Mendeleev table

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

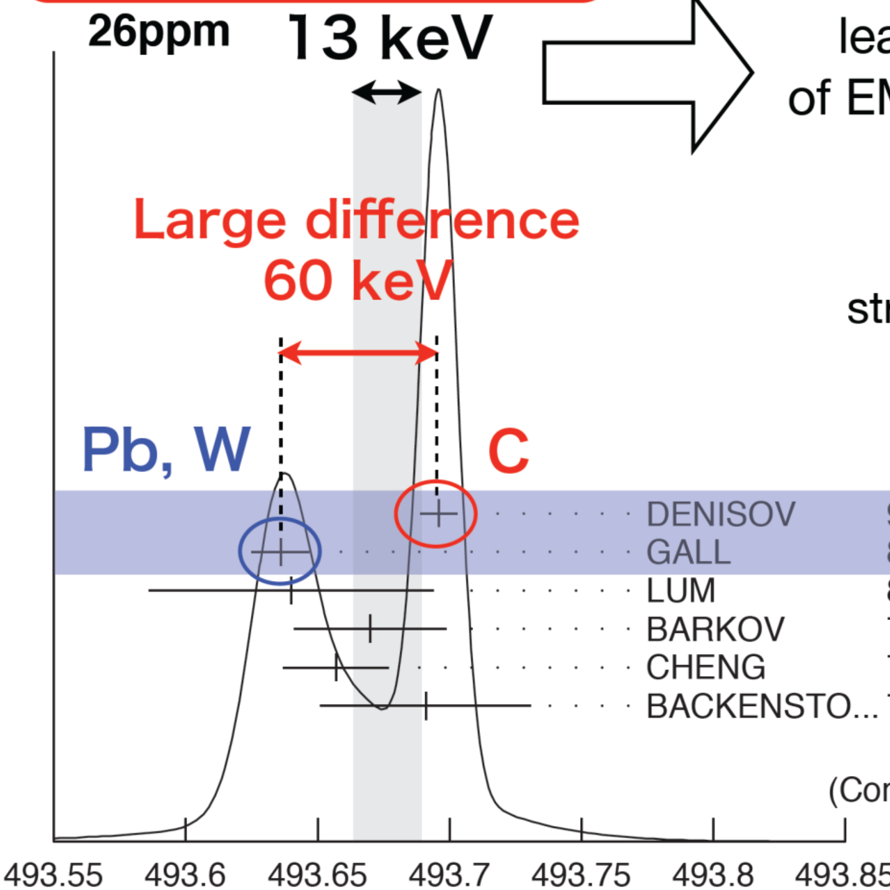
A strong international community is putting forward this realistic and feasible programme in particular in terms of the required integrated , that can be delivered within the upcoming 3-5 years, with support from National and European projects.

EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

EXKALIBUR



WEIGHTED AVERAGE
493.677±0.013 (Error scaled by 2.4)



leads to **±0.17 eV uncertainty**
of EM value of K-^{4}He 3d→2p x-ray

indistinguishable
strong-int. shift? or kaon mass?

			χ^2
DENISOV	91	CNTR	7.7
GALL	88	CNTR	13.6
LUM	81	CNTR	0.5
BARKOV	79	EMUL	0.1
CHENG	75	CNTR	1.0
BACKENSTO...	73	CNTR	0.1
			22.9

(Confidence Level 0.001)

Most recent two experiments

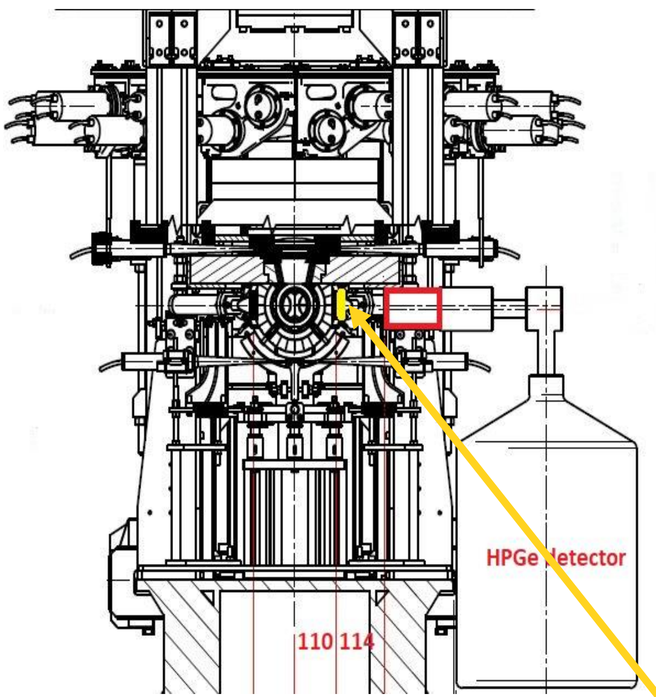
493.696 ± 0.007 [MeV]
493.636 ± 0.011 [MeV]

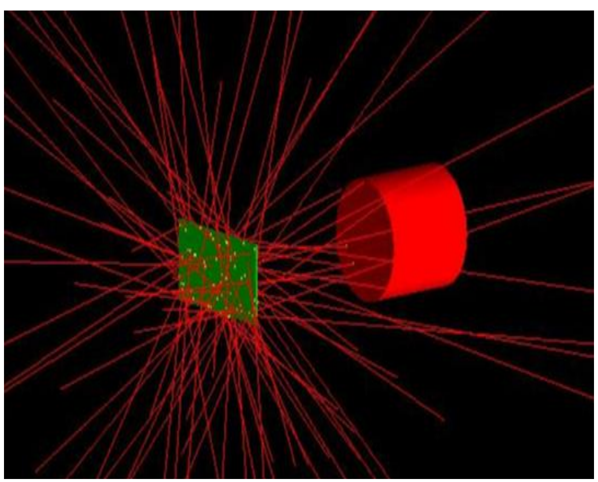
Uncertainty in electron screening. Gamma-ray contamination(Pb,W).

→ **new measurement with low-Z gas targets**

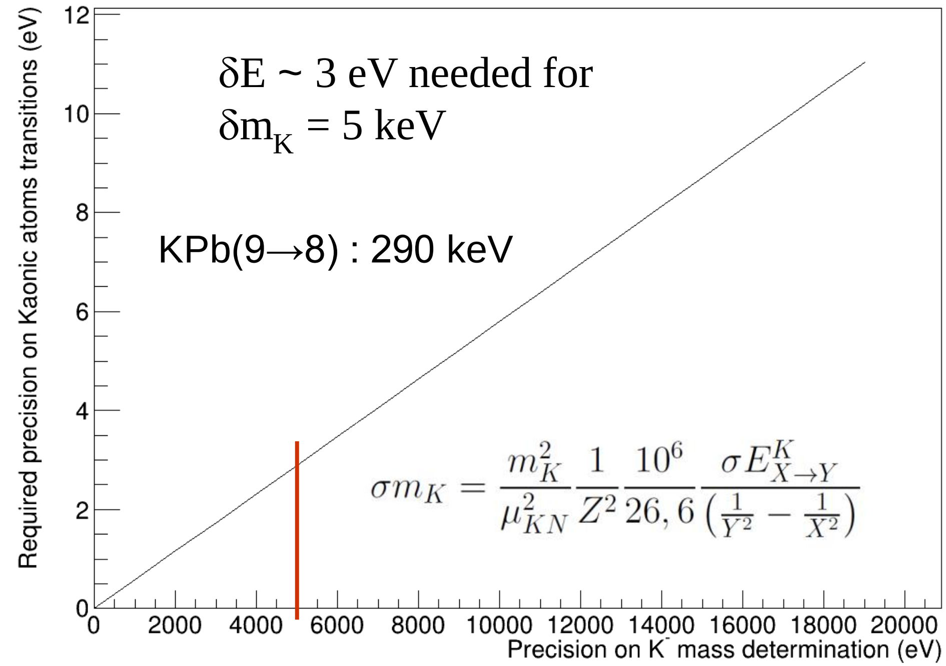
New Kaon Mass measurement with HPGe

Parallel run with SIDDHARTA-2: (already installed)





Pb target just behind the SIDDHARTA-2 luminometer, which is used as trigger

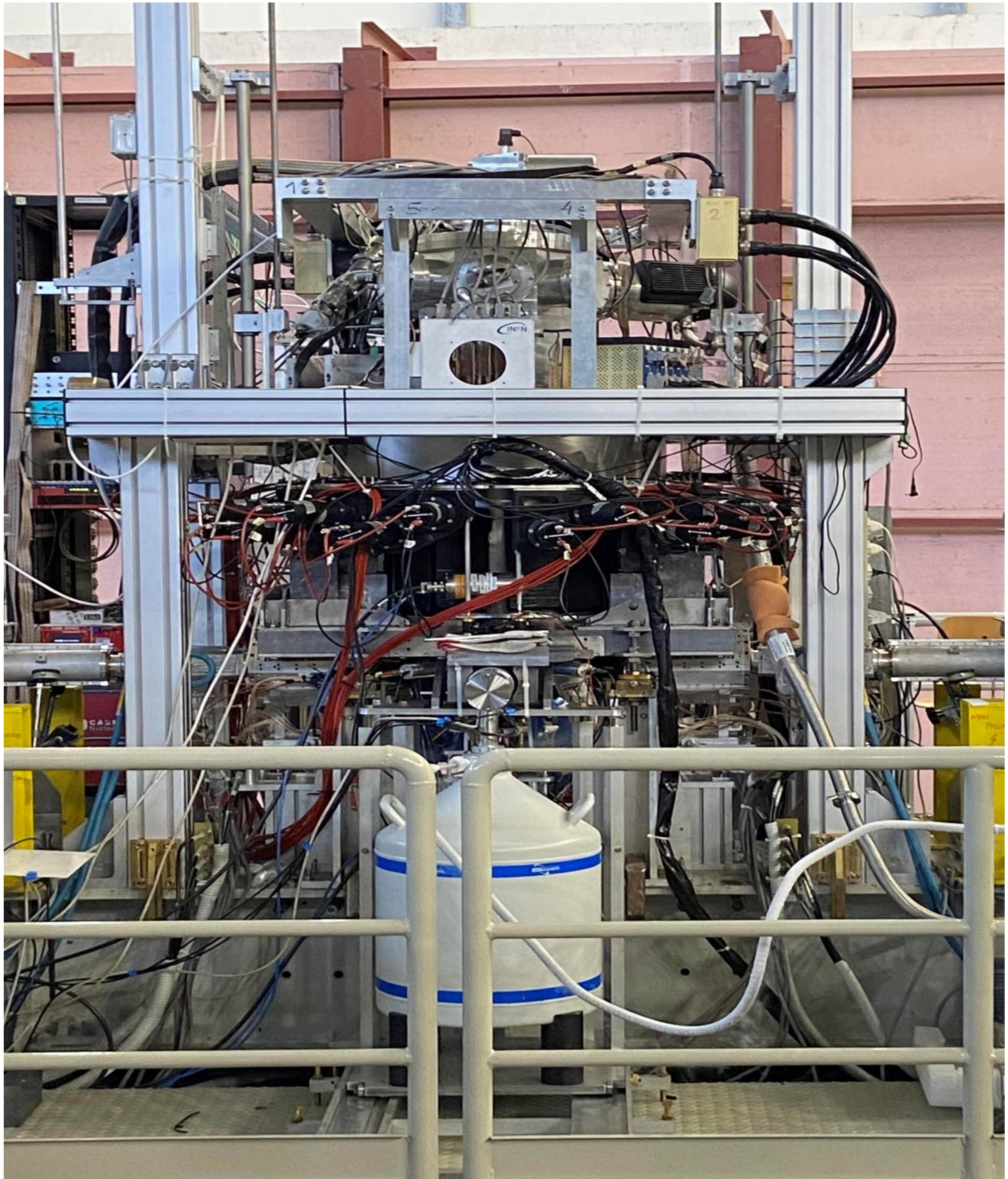


Resolutions (FWHM)
obtained with ^{60}Co, ^{133}Ba sources :

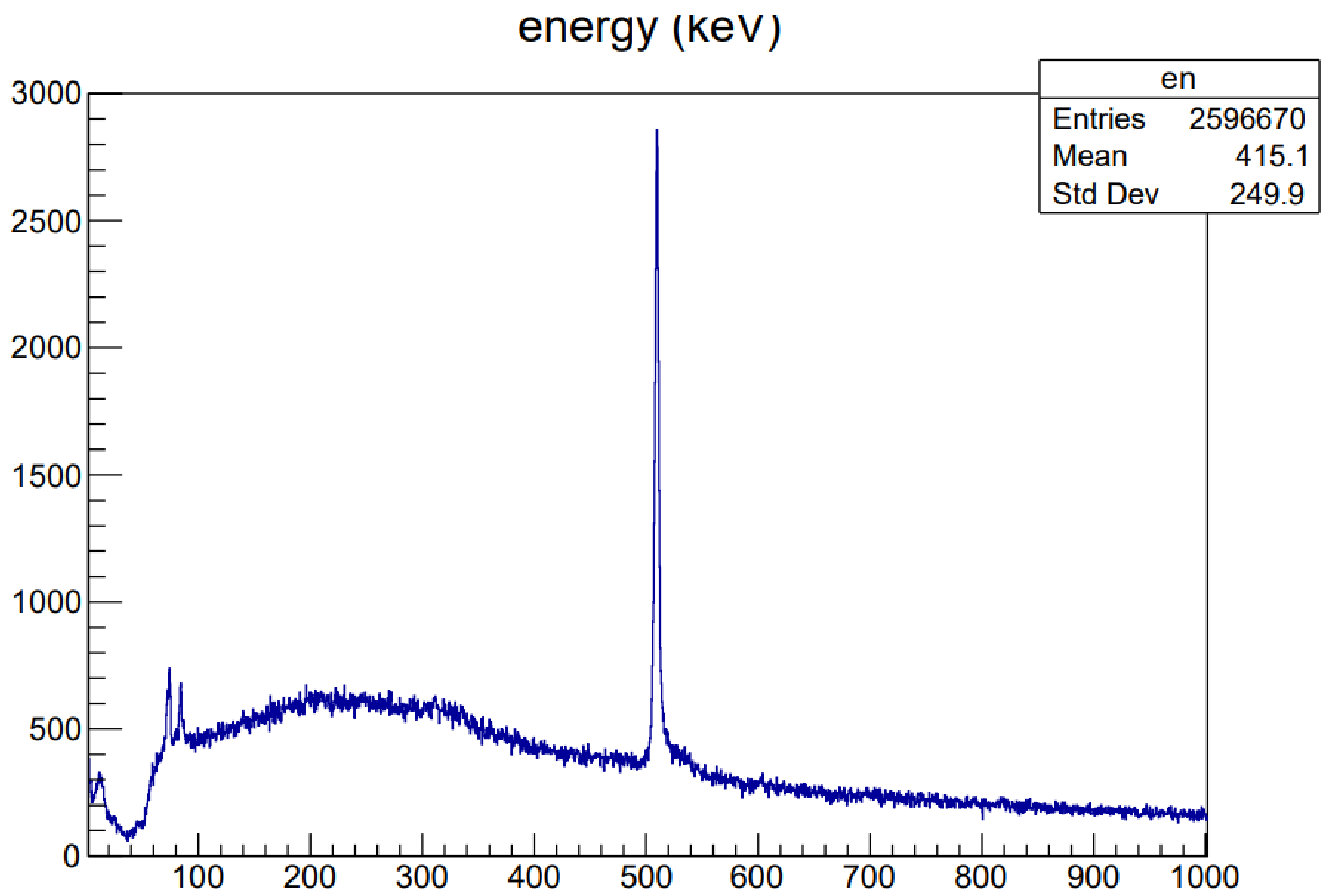
0.870 keV @ 81 keV
1.106 keV @ 302.9 keV
1.143 keV @ 356 keV
1.167 keV @ 1330 keV

HPGe detector available,
Croatian Science Foundation project 8570

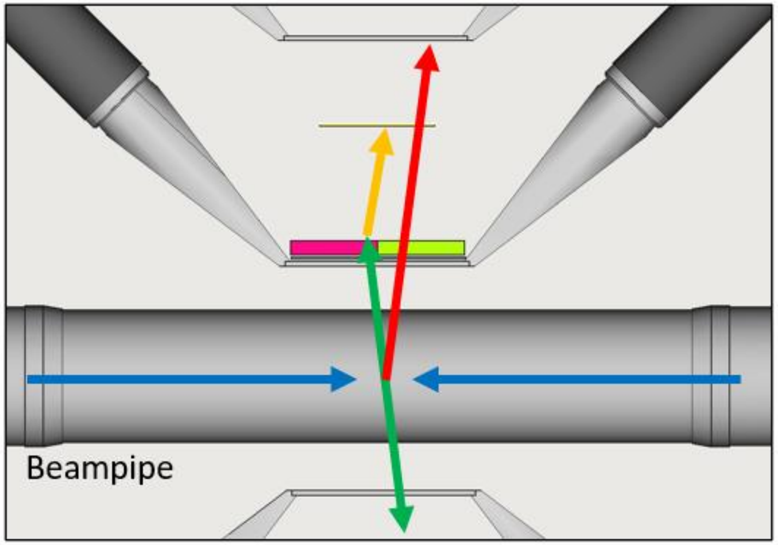
Present
status

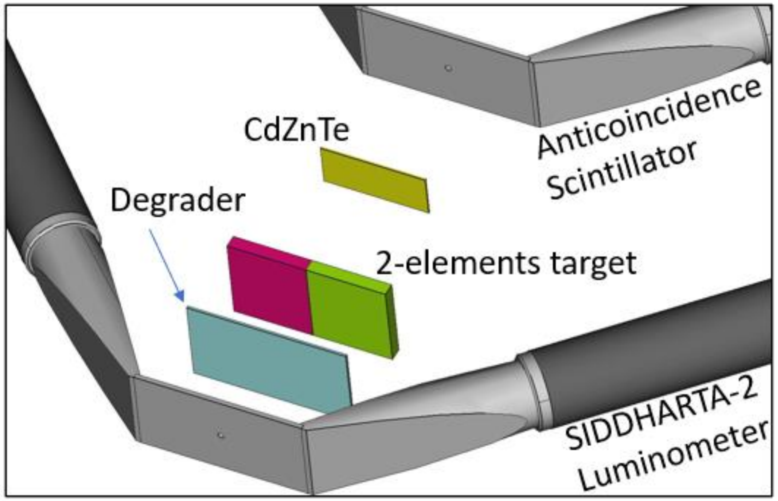


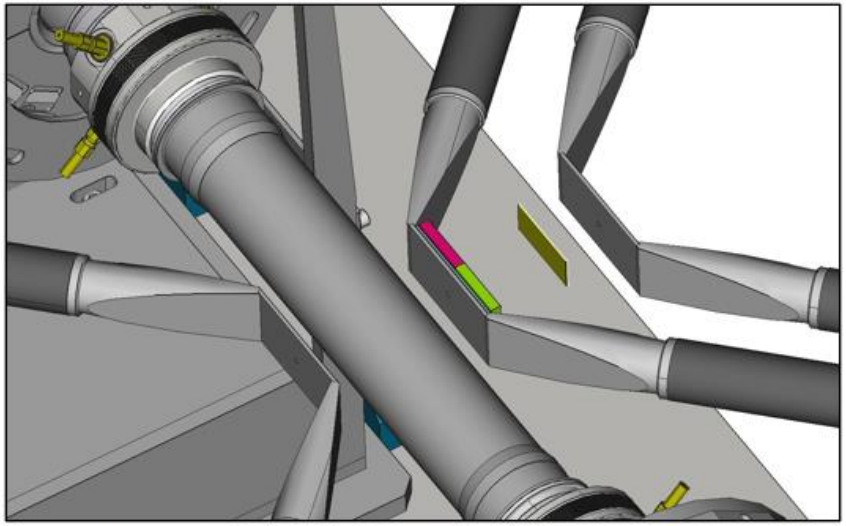
First HPGe spectrum (we plan a technical paper)

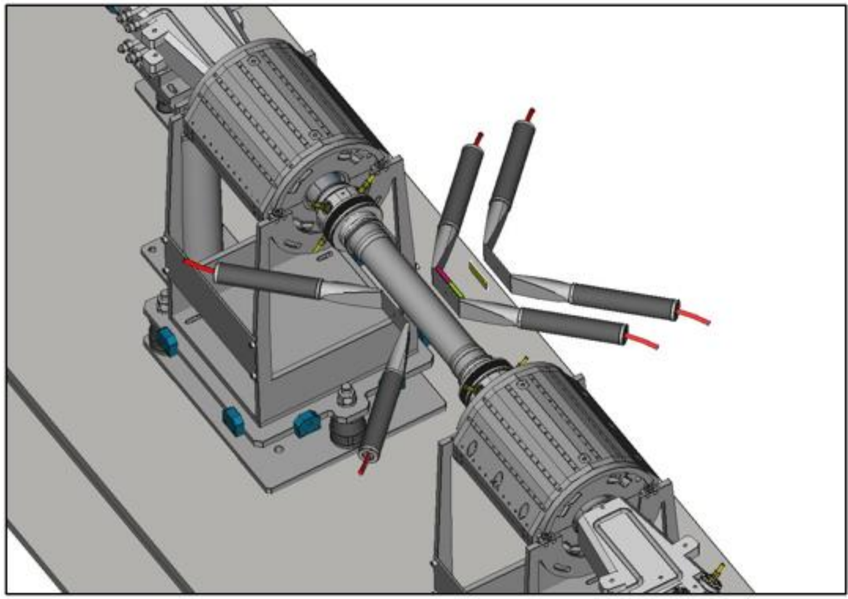


CZT: proposal for new measurements at DAFNE



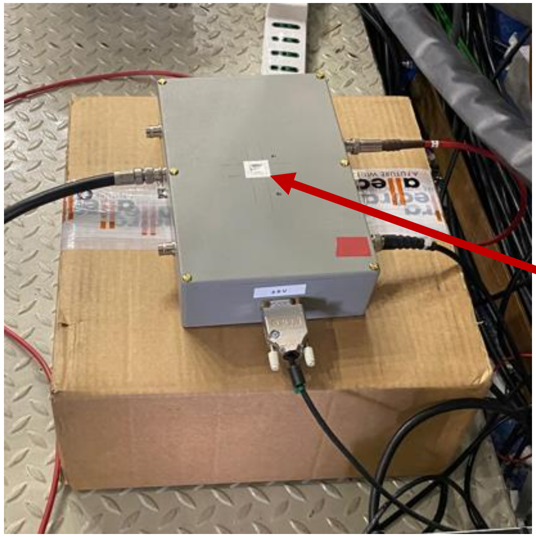






CZT: test prototype mounted in DAFNE (22/06/2022)

1 mm^2 5mm thick CZT detector produced by IMEM-Parma

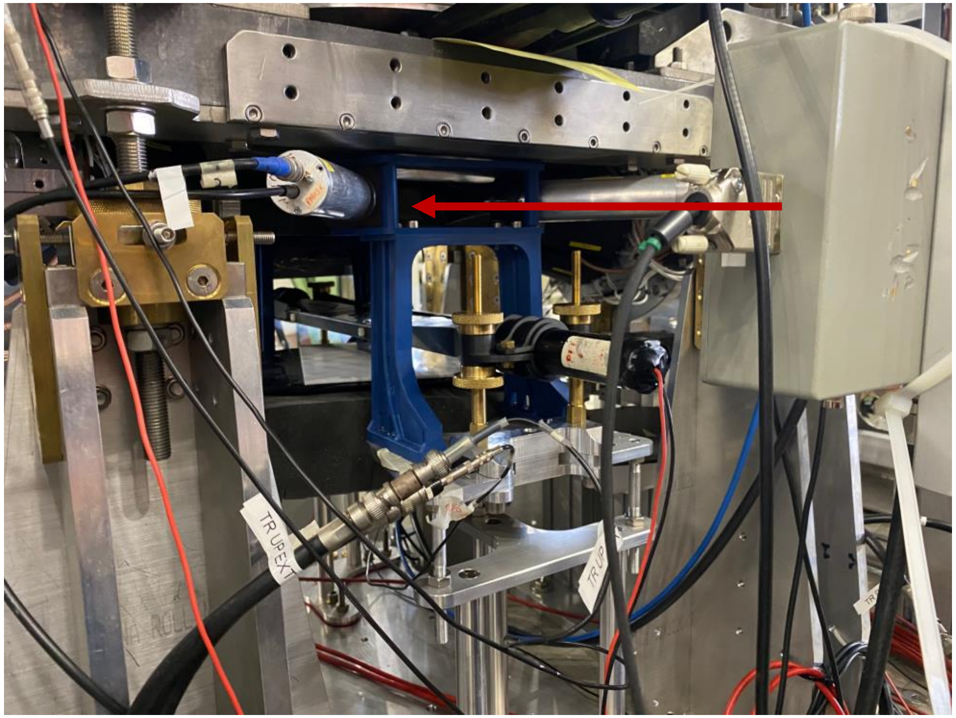


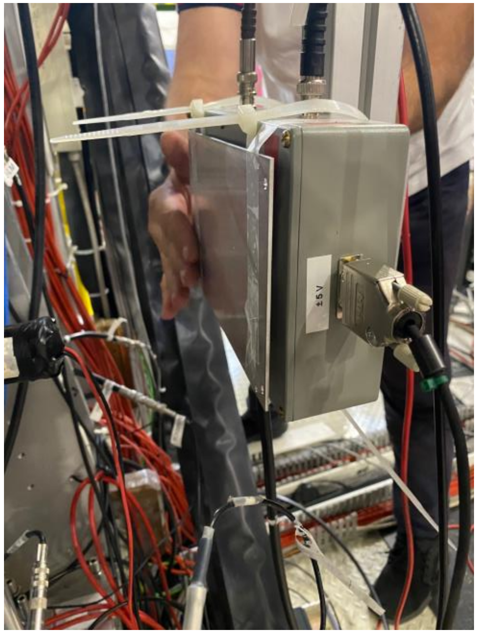
Light-tight box with Electronics (UniPa)

Entrance window

Goal: background and resolution assessment in machine environment (first time)

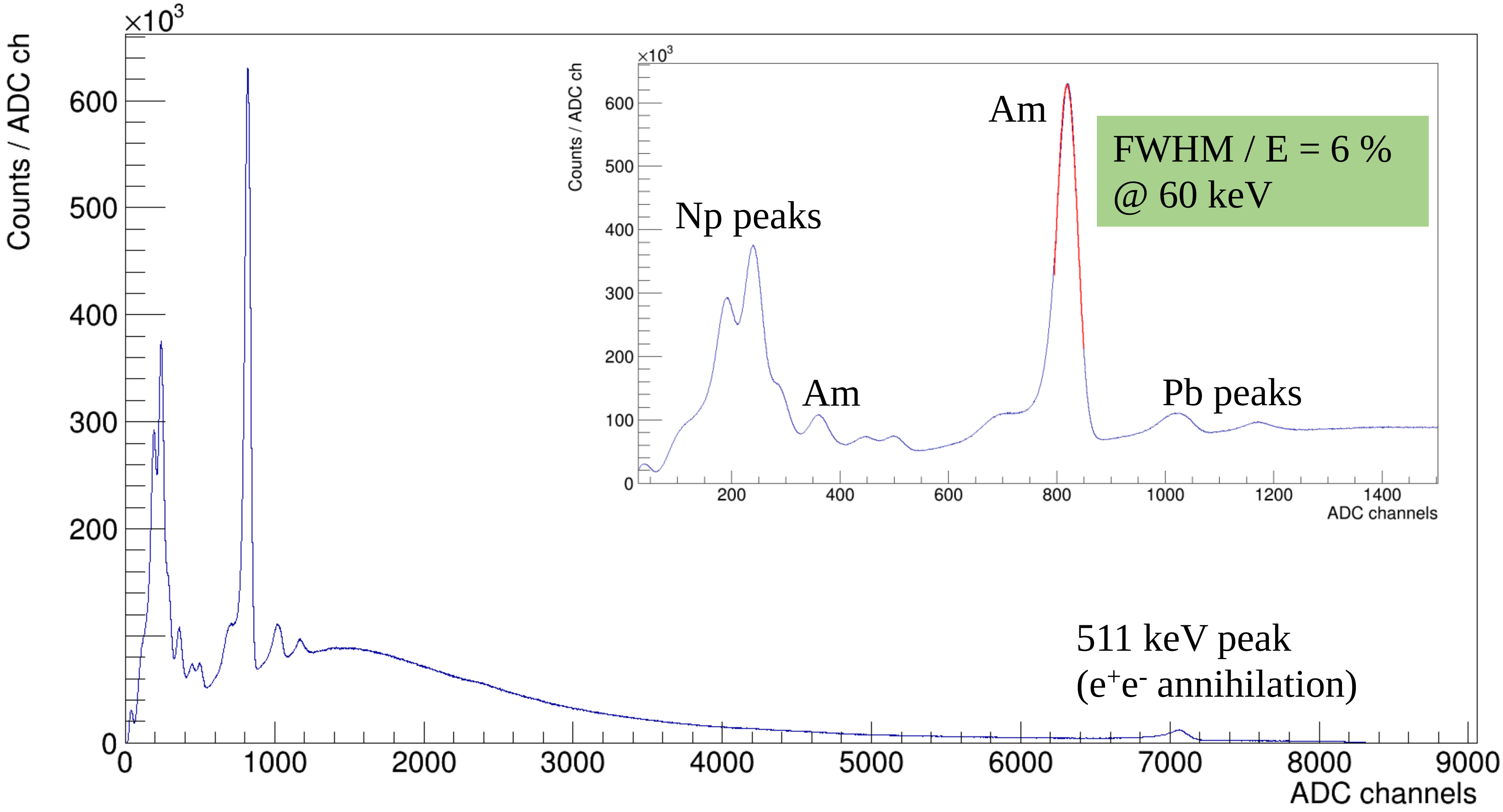
Aligned with SIDDHARTA-2 luminometer





Al plate (thickness not optimized) + ^{241}Am source for calibration

CZT: test prototype mounted in DAFNE (22/06/2022)



Conclusions

- **Kaonic Atoms measure the kaon-nucleon/nuclei interaction at threshold (no other way to perform direct measurements!)**
  - *Tool to directly probe low-energy QCD*
  - *With implications from nuclear and particle physics to astrophysics and cosmology*

- **Phase1: SIDDHARTINO concluded**
  - *SDDs and Kaon Trigger tuned*
  - *Evaluation of the machine background*
  - ***Performed the most precise K-^{4}He $3d \rightarrow 2p$ measurement in gas***

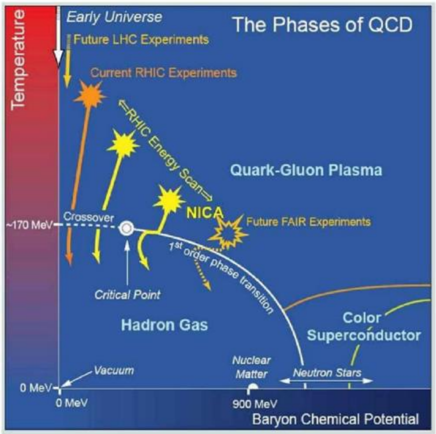
- **SIDDHARTA-2 presently on DAFNE**
  - *Installation of the full SIDDHARTA-2 setup: autumn 2021*
  - *First technical kaonic deuterium run performed in 2022; run to be continued in 2023 (800 pb)*

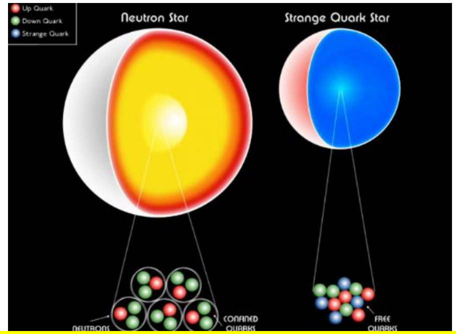
Beyond SIDDHARTA-2: EXCALIBUR
JOIN US!

- **Feasibility studies in parallel with Siddharta-2**

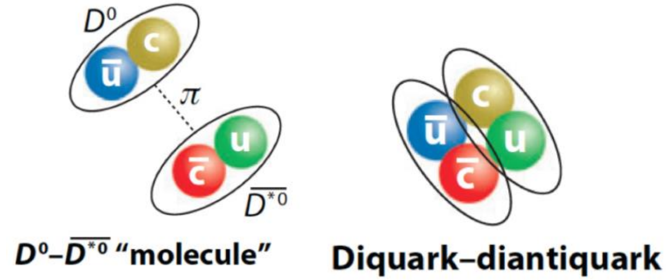
- **Various setups in preparation:**
  - *HPGe*
  - *Crystal spectrometers (VOXES)*
  - *CdZnTe detectors*
  - *SDD 1mm for kaonic atoms measurement*

- **Proposal for Extension of the Scientific Program at DAFNE:**
  - *Kaon mass - precision measurement at a level < 7 keV*
  - *Kaonic helium transitions to the 1s level*
  - *Other light kaonic atoms (K^-Bi, Li, B,, K^-C, ...)*
  - *Heavier kaonic atoms (K^-Si, K^-Pb ...)*
  - *Radiative kaon capture – $\Lambda(1405)$ study*
  - *Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen)*



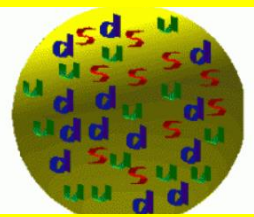


Neutron star EOS



Particles structure

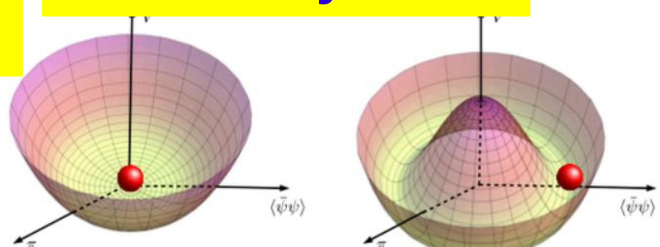
Cold Dense matter



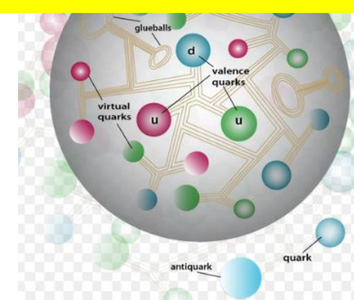
Strangeness Fundamental Physics

Strangelets & Dark Matter

QCD
Chiral symm.



Mass generation, visible Universe



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New insights into the strong interaction with strange exotic atoms

The strong interaction plays a fundamental role in our universe. The difficulty of performing precision measurements has limited our understanding of this interaction. Dr Catalina Curceanu at the National Institute for Nuclear Physics (INFN) in Frascati-Rome is leading ambitious new efforts to study and measure the strong interaction in her lab. Her team's work is centred around an intriguing form of matter in which the electrons of regular atoms are replaced by exotic strange particles named 'kaons,' and could help to explain mysteries ranging from the composition of neutron stars, to the origin of mass itself.

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Article References

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