Exotic multi-quark states and baryon spectroscopy workshop
25-27 June2024,
Bonn, Germany

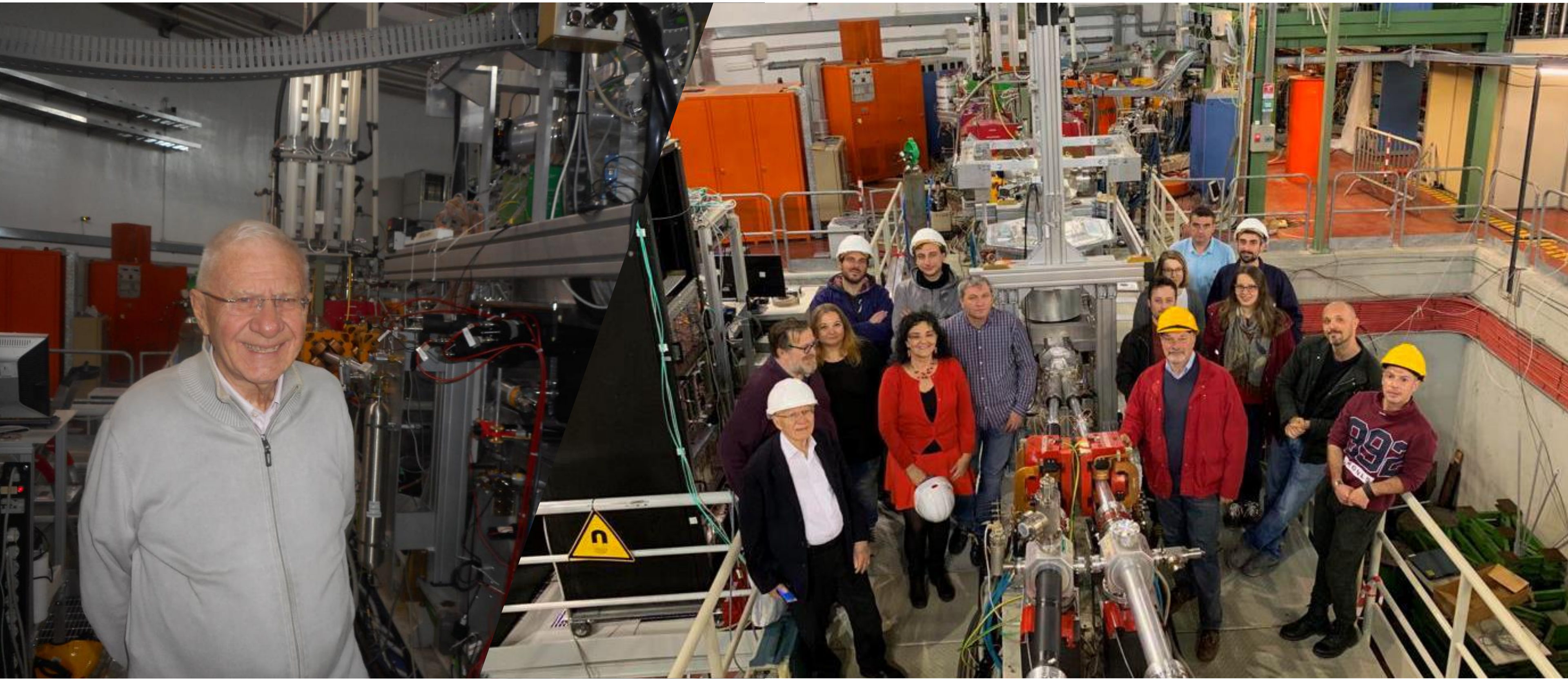
Low-energy kaon-nuclei interaction studies at the DAFNE collider: a strangeness Odyssey

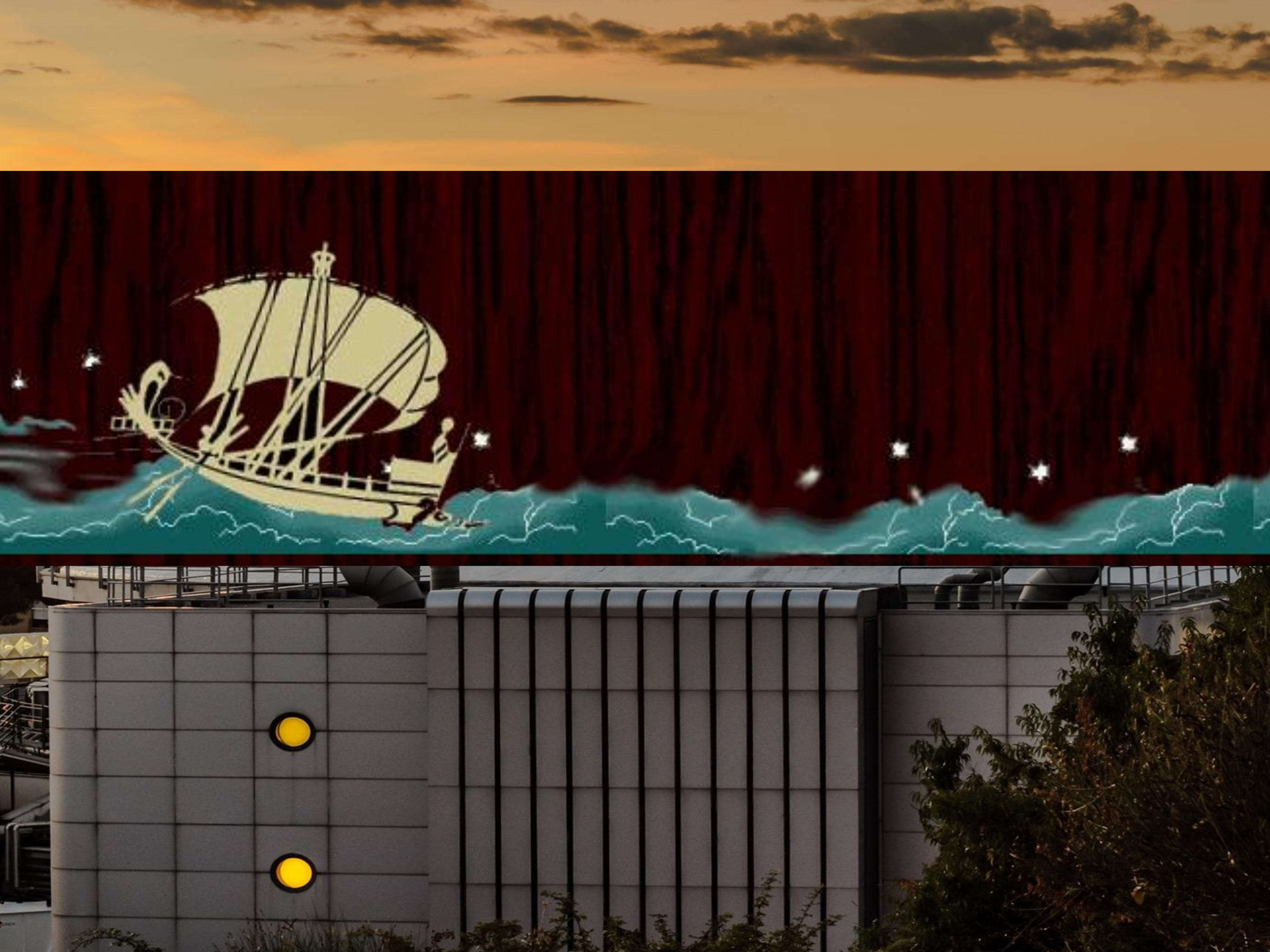
Catalina Curceanu on behalf of the SIDDHARTA-2 Collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

We dedicated our results to our dear colleague and friend Prof **Carlo Guaraldo**
you'll be very much missed!



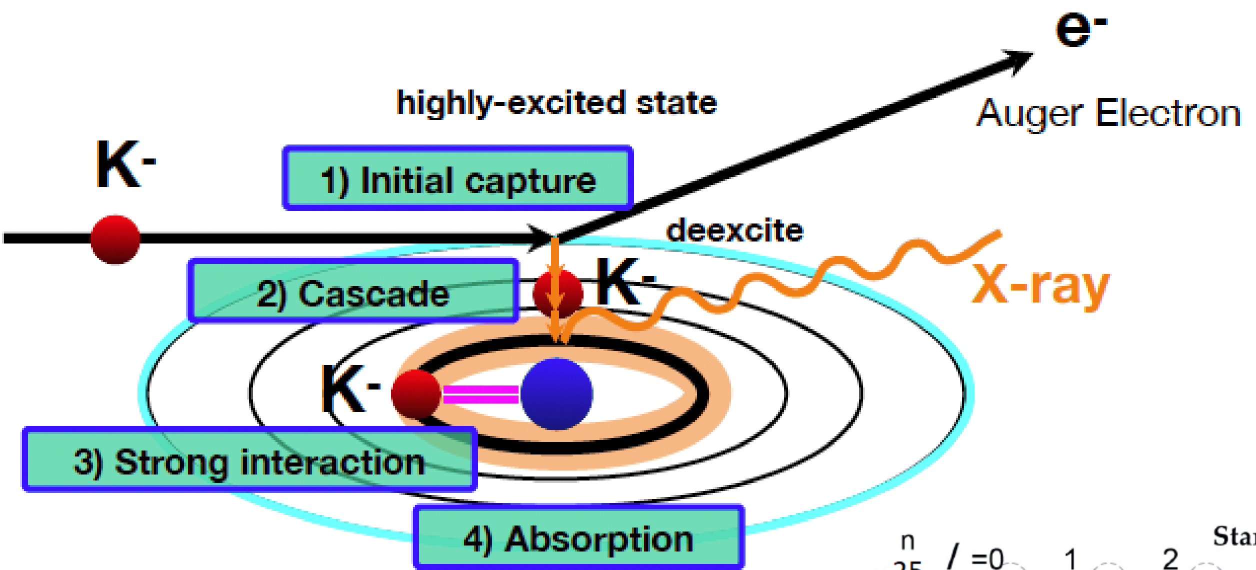


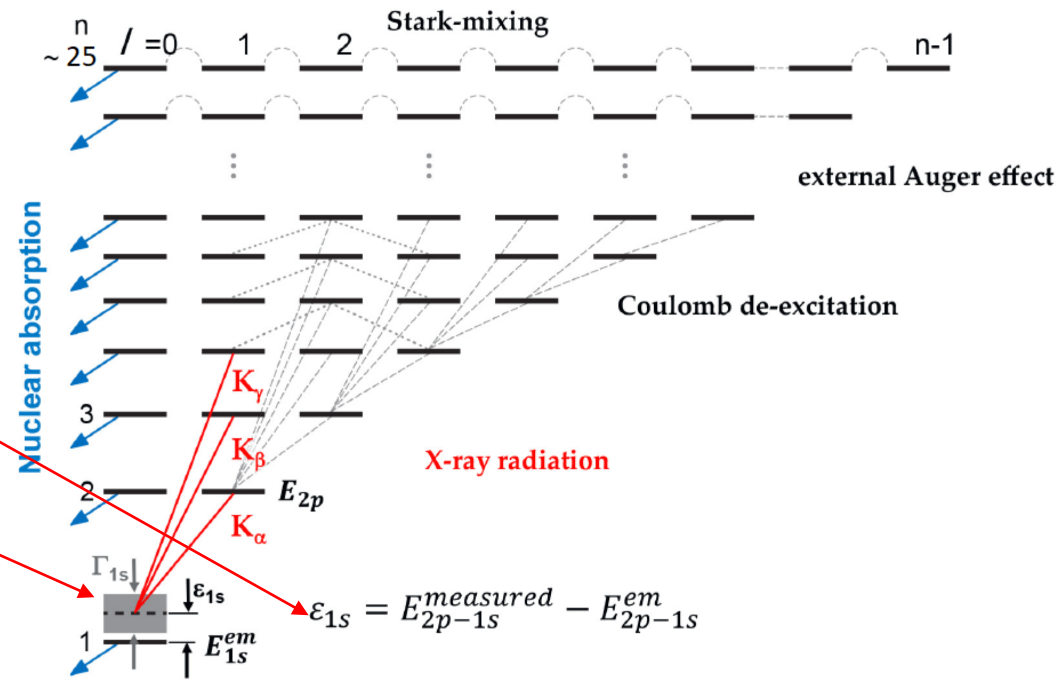
SIDDHARTA-2

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

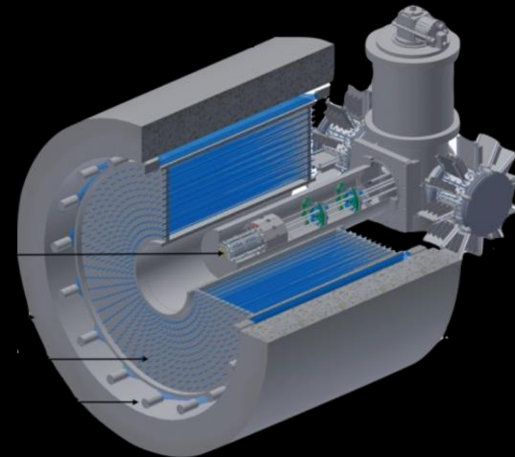
Kaonic atom Formation

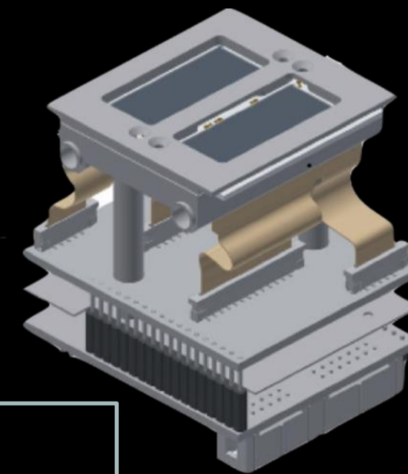




Width Γ and shift ε obtained by measuring the X-rays emitted

A long journey





The modern era of light kaonic atom experiments

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

Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

DEAR 2002

SIDDHARTA 2009

SIDDHARTA-2 2022

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)

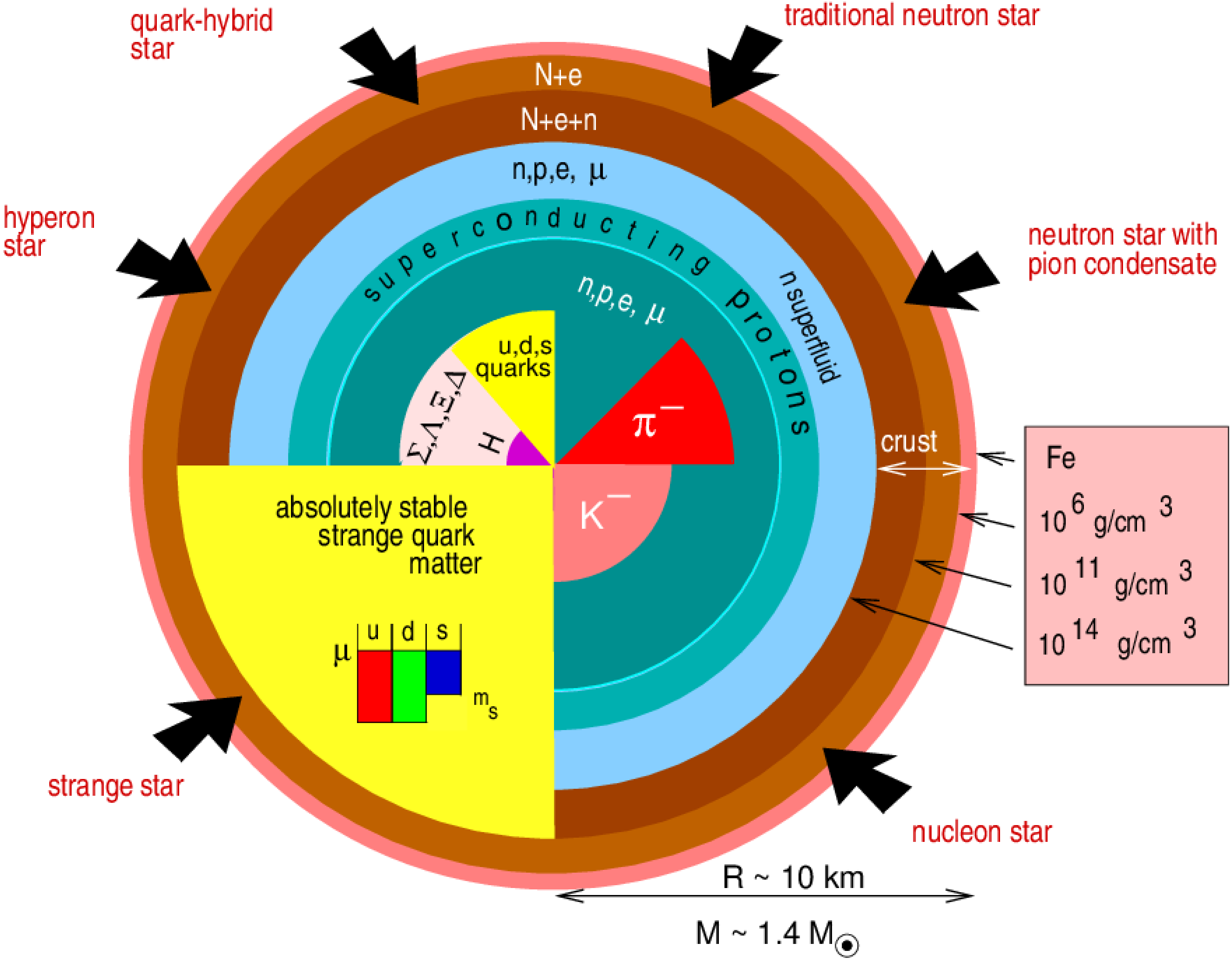
Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

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



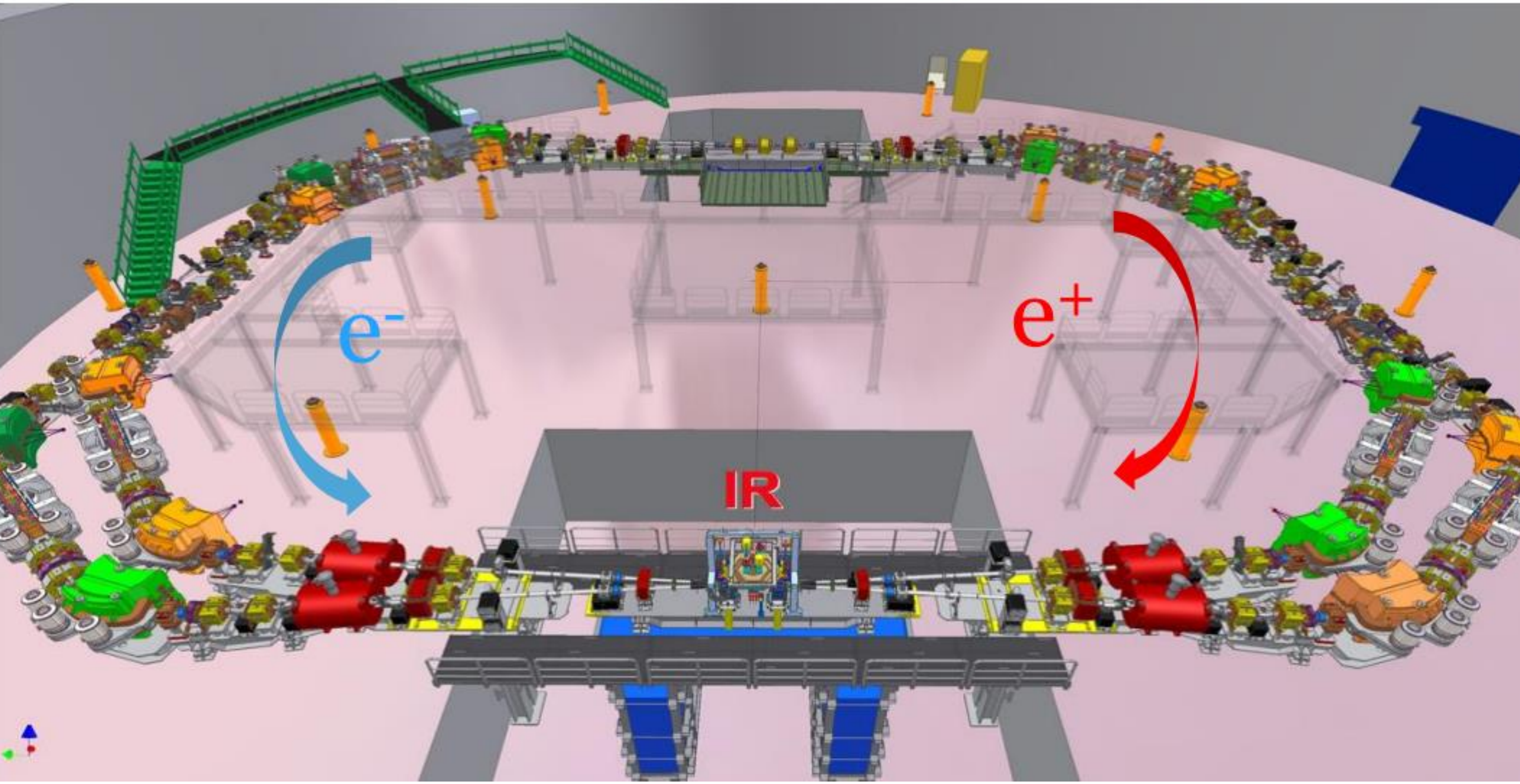
quark-hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e, μ
superconducting protons
n superfluid
n,p,e, μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
crust
absolutely stable strange quark matter
μ
u
d
s
m_s
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14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

LNF - e^+e^- Accelerator Complex

- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p = 0.1\%$)

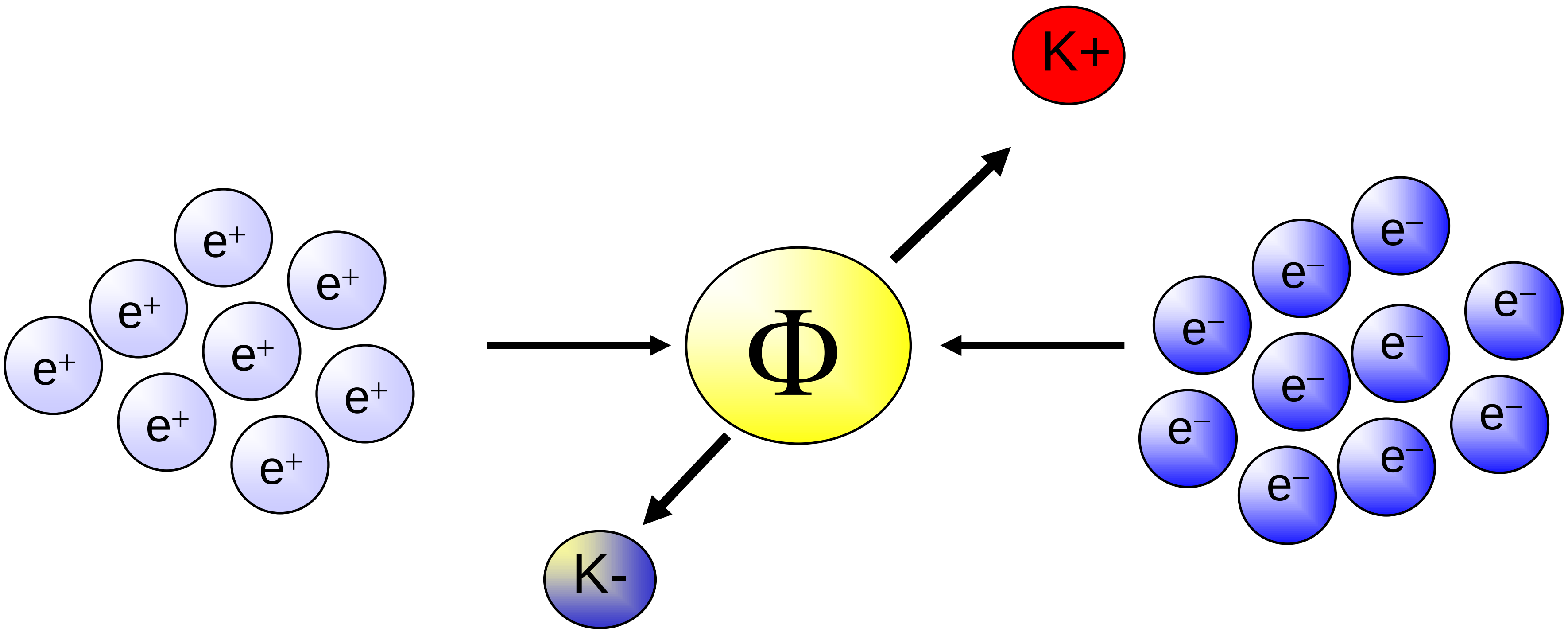
Laboratori Nazionali di Frascati (LNF-INFN)

- $\Phi \rightarrow K^- K^+$ (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**

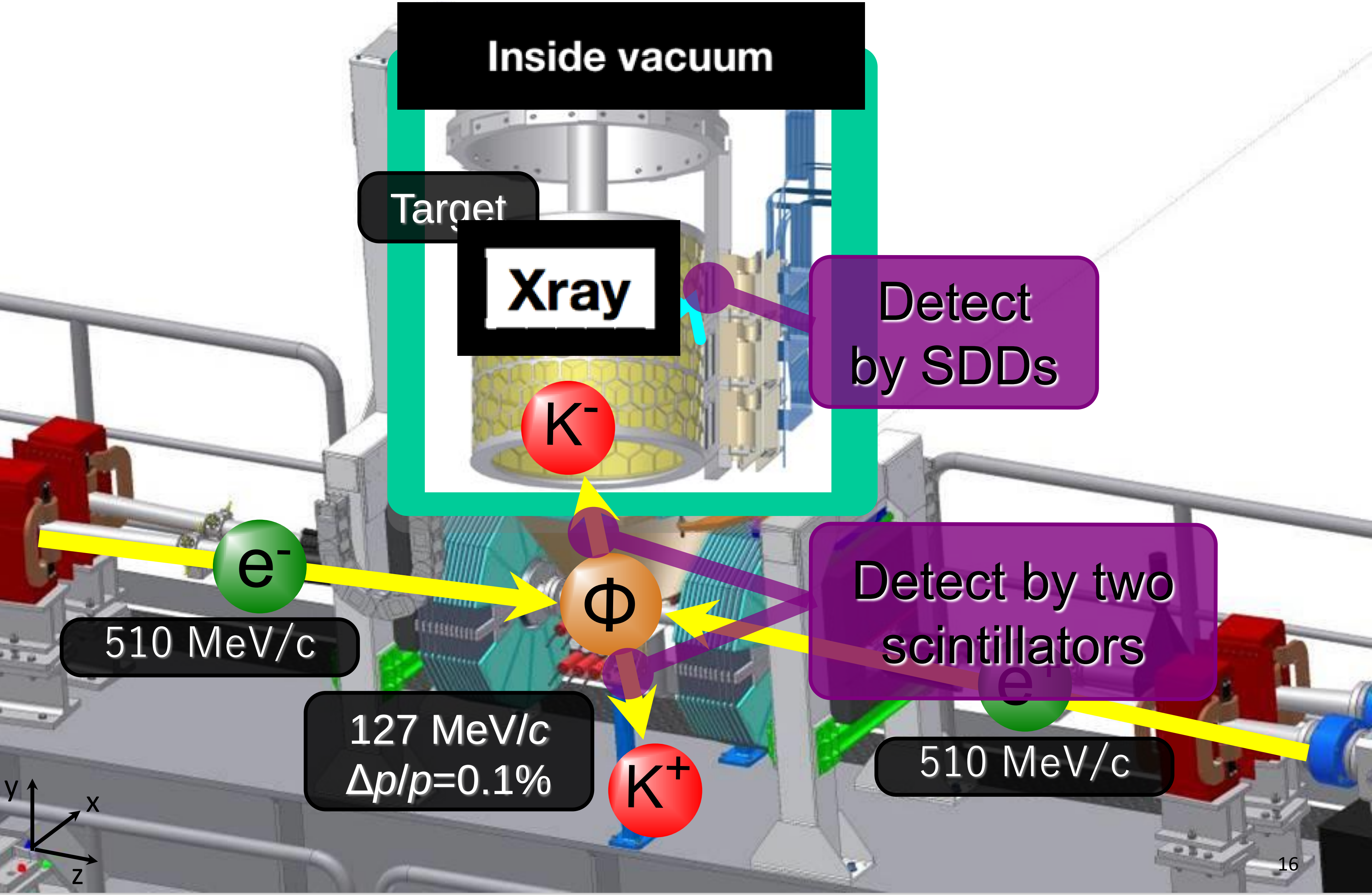
(compare to hadron beam line : e.g. KEK /JPARC)

Suitable for low-energy kaon physics:

kaonic atoms

Kaon-nucleons/nuclei interaction studies

SIDDHARTA overview



SIDDHARTA - 2009

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

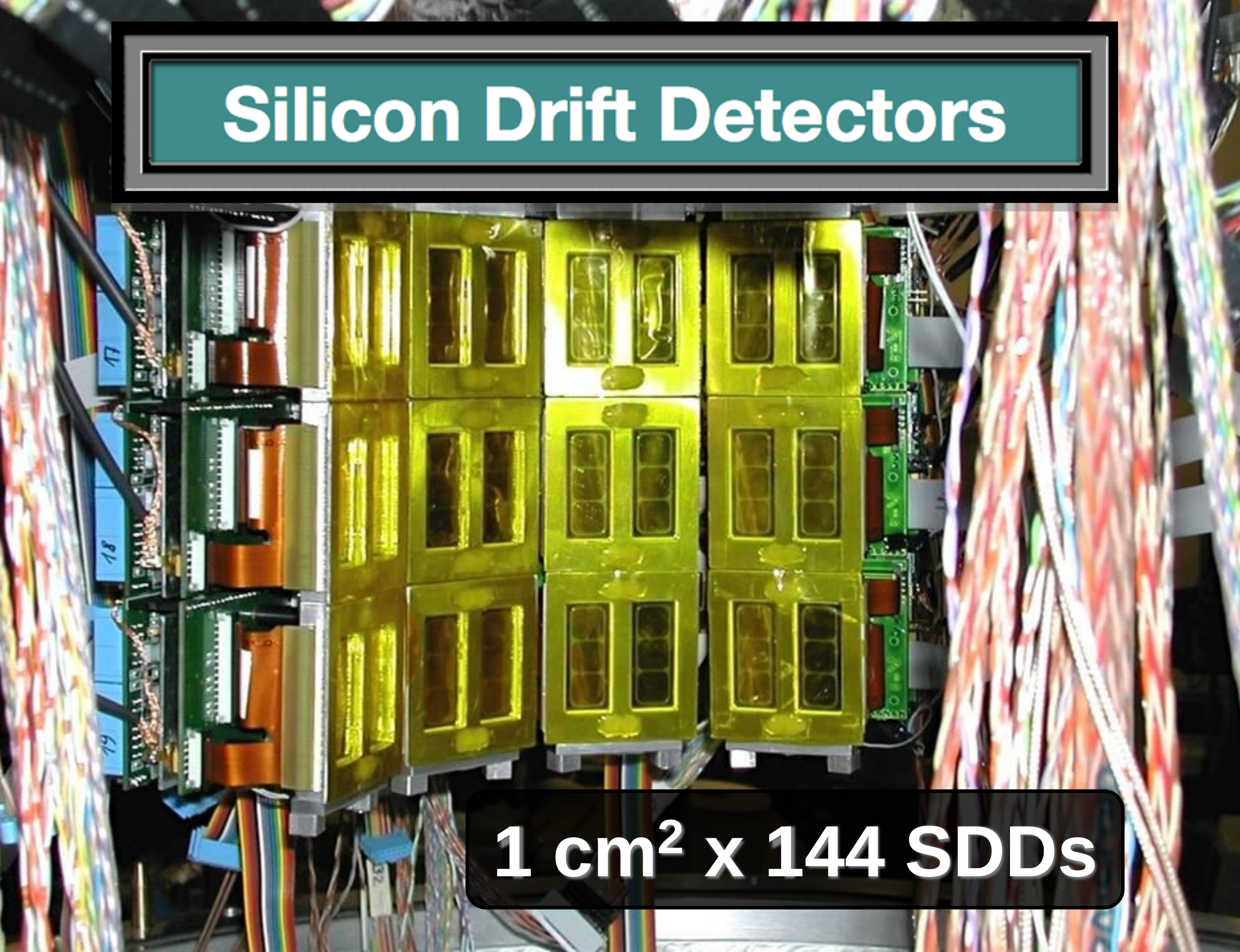
- **LNF- INFN, Frascati, Italy**
- **SMI- ÖAW, Vienna, Austria**
- **IFIN – HH, Bucharest, Romania**
- **Politecnico, Milano, Italy**
- **MPE, Garching, Germany**
- **PNSensors, Munich, Germany**
- **RIKEN, Japan**
- **Univ. Tokyo, Japan**
- **Victoria Univ., Canada**

EU Fundings: JRA10 – FP6 - I3H
FP7- I3HP2

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

The Cryogenic Target Cell

Silicon Drift Detectors



SIDDHARTA 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 (but also other kaonic atoms).

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

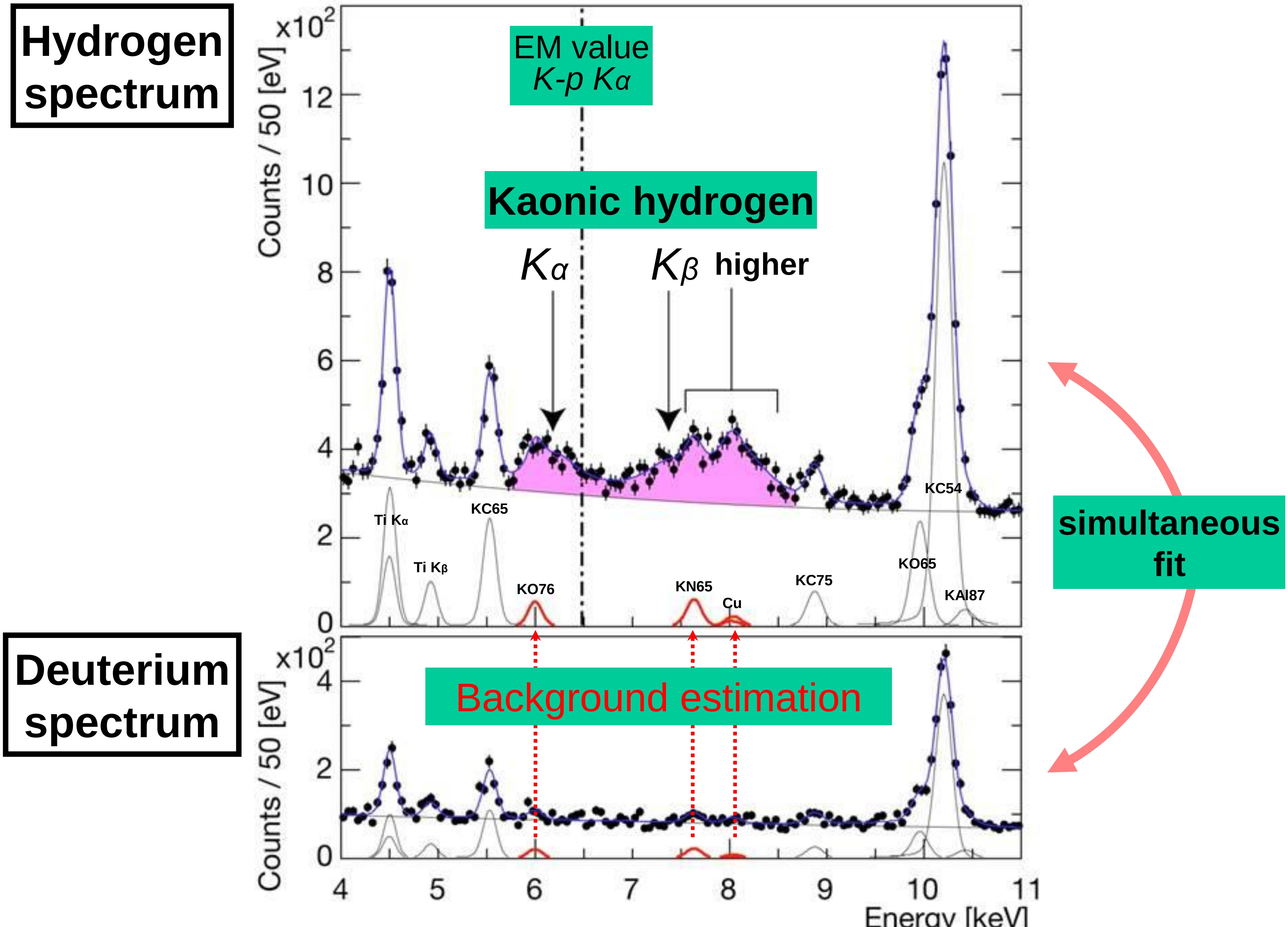
$$a_{K^-p} = \frac{1}{2}\left[a_0 + a_1\right]$$

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

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

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

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

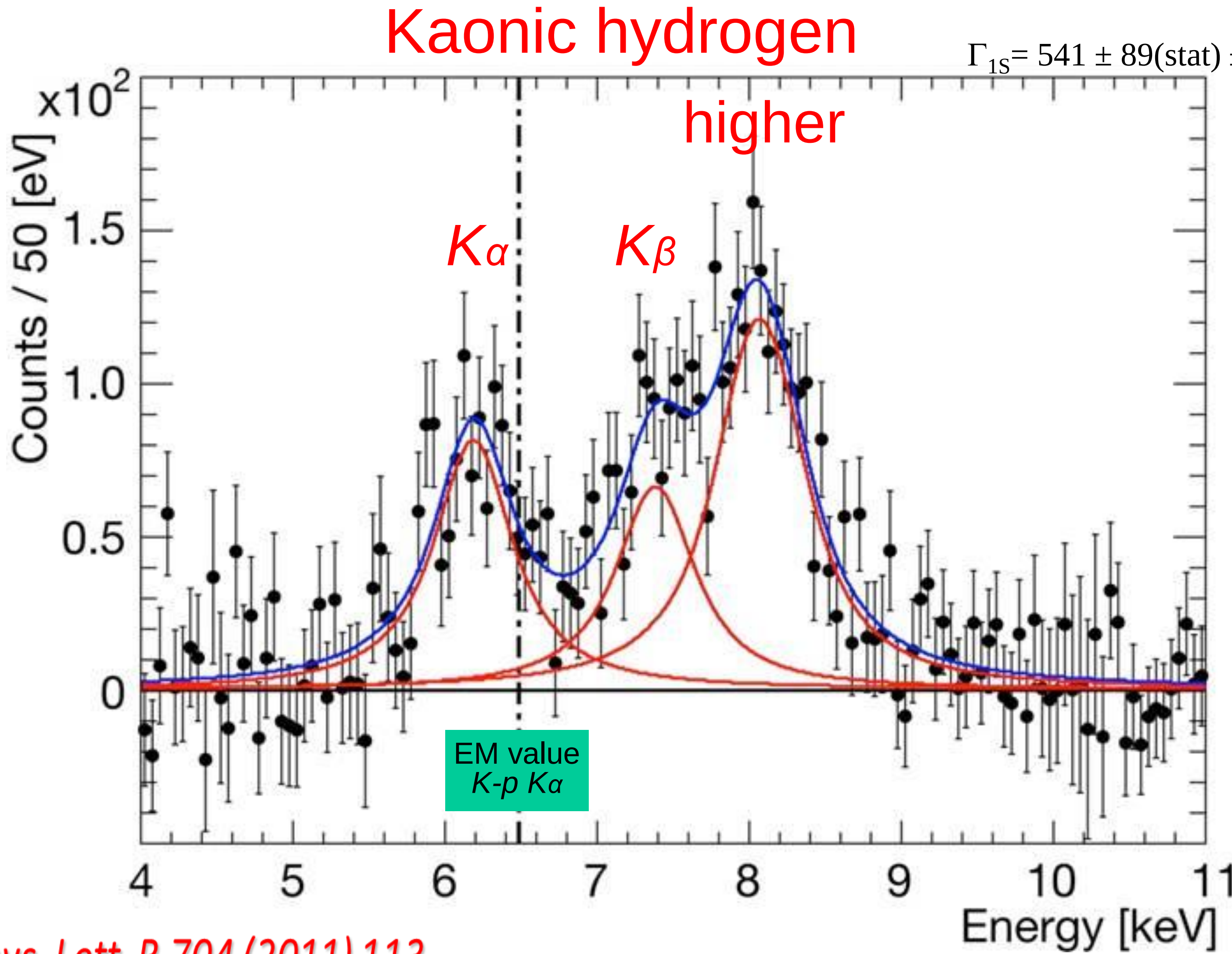


Hydrogen spectrum
Deuterium spectrum
EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ
higher
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87
simultaneous fit
Background estimation
Counts / 50 [eV]
x10²
Energy [keV]

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

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

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



Phys. Lett. B 704 (2011) 113

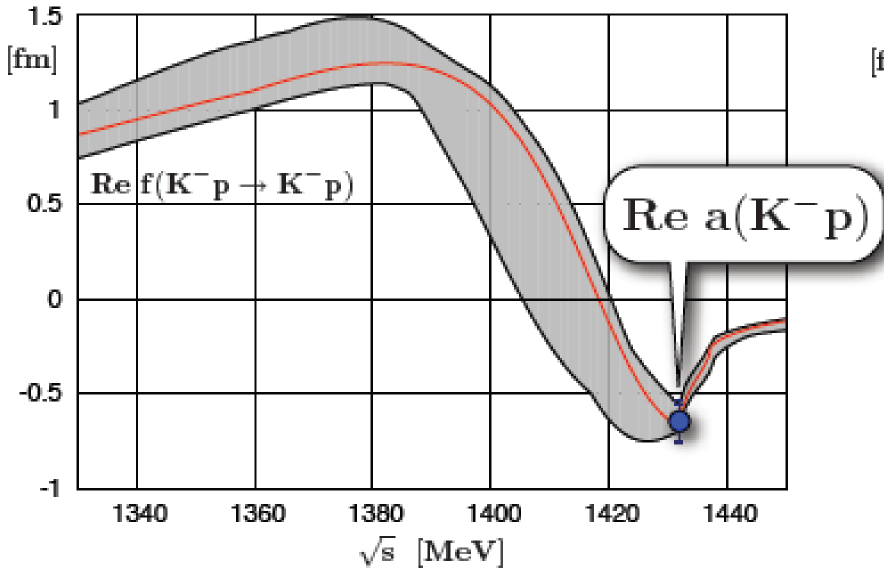
K^-p SCATTERING AMPLITUDE from CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

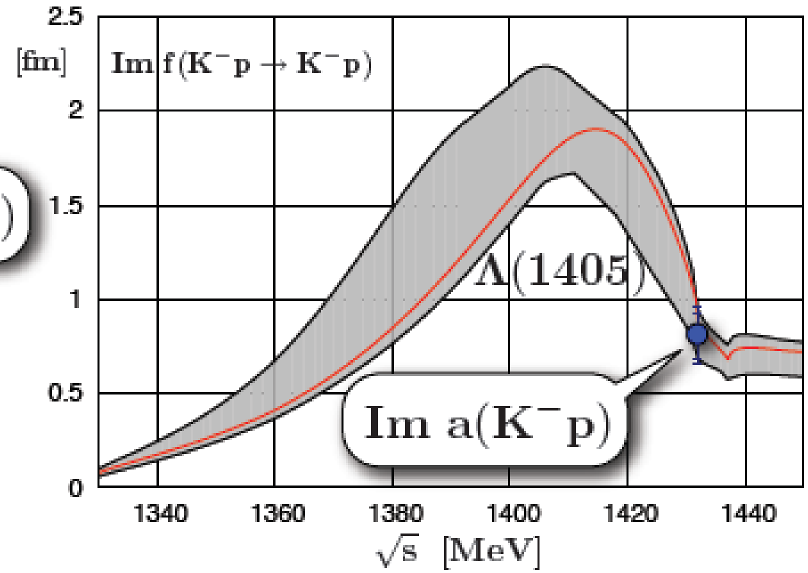
$$f(K^-p) = \frac{1}{2}\left[f_{\bar{K}N}(I=0) + f_{\bar{K}N}(I=1)\right]$$

Y. Ikeda, T. Hyodo, W.W.
PLB 706 (2011) 63
NPA881 (2012) 98

$\Lambda(1405)$: $\bar{K}N$ $(I=0)$ **quasibound state** embedded in the $\pi\Sigma$ continuum

Prototype example for emergence of **resonant structure** close to a threshold



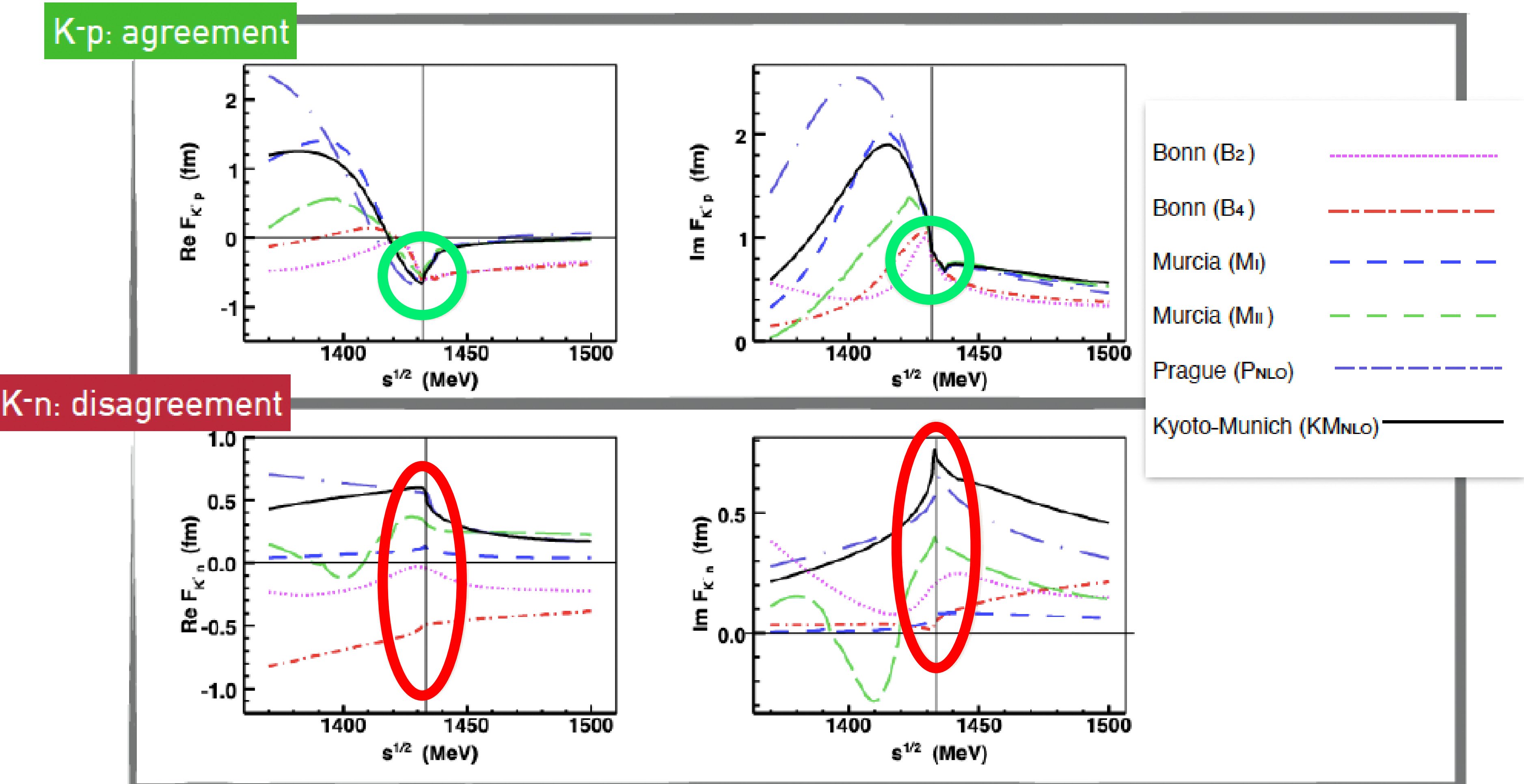


Complex scattering length (including Coulomb corrections)

$$\mathrm{Re}\, a(K^-p) = -0.65 \pm 0.10 \quad \mathrm{fm}$$

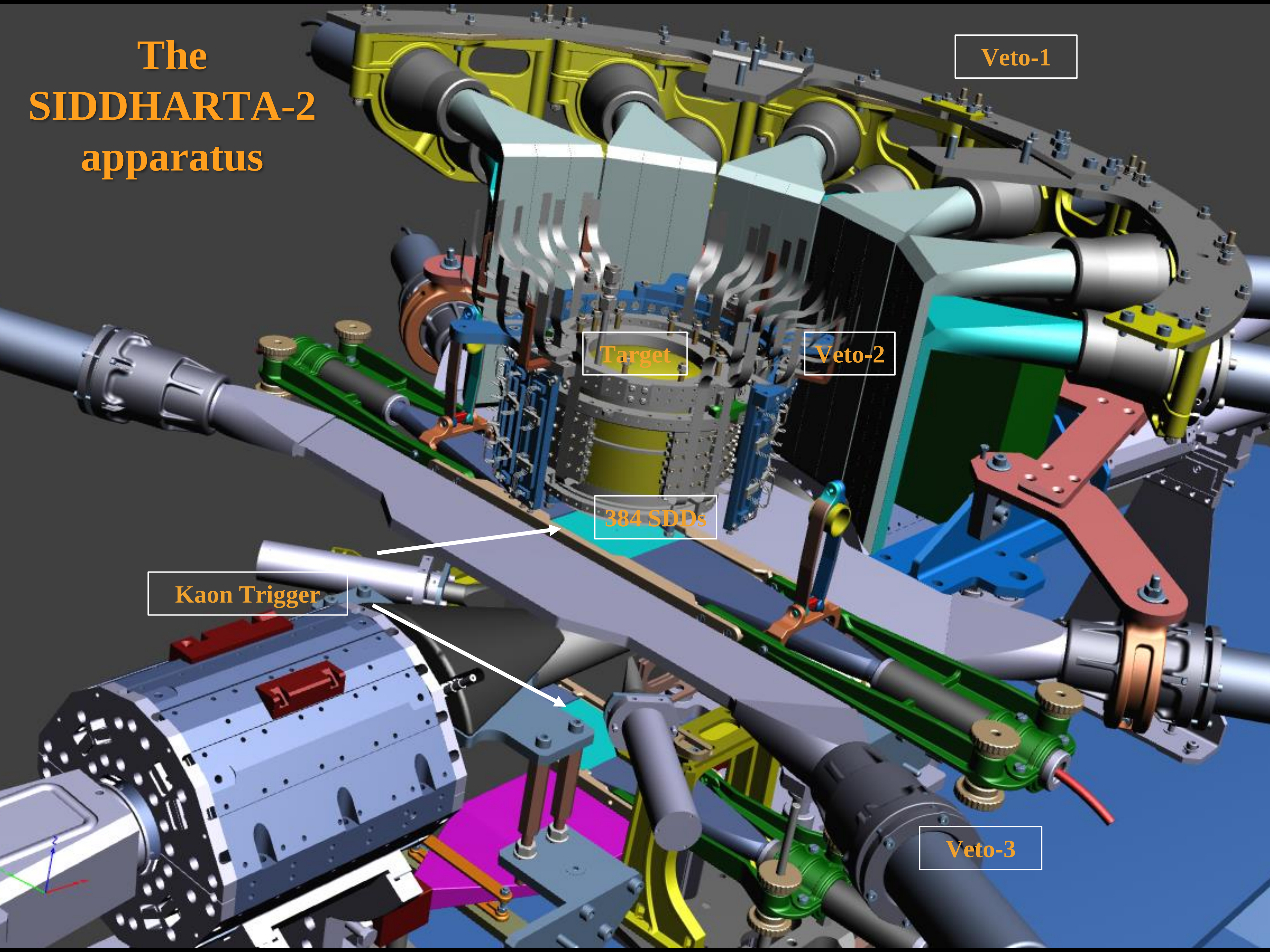
$$\mathrm{Im}\, a(K^-p) = 0.81 \pm 0.15 \quad \mathrm{fm}$$

Kaonic atoms – scattering amplitudes



A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

The SIDDHARTA-2 apparatus



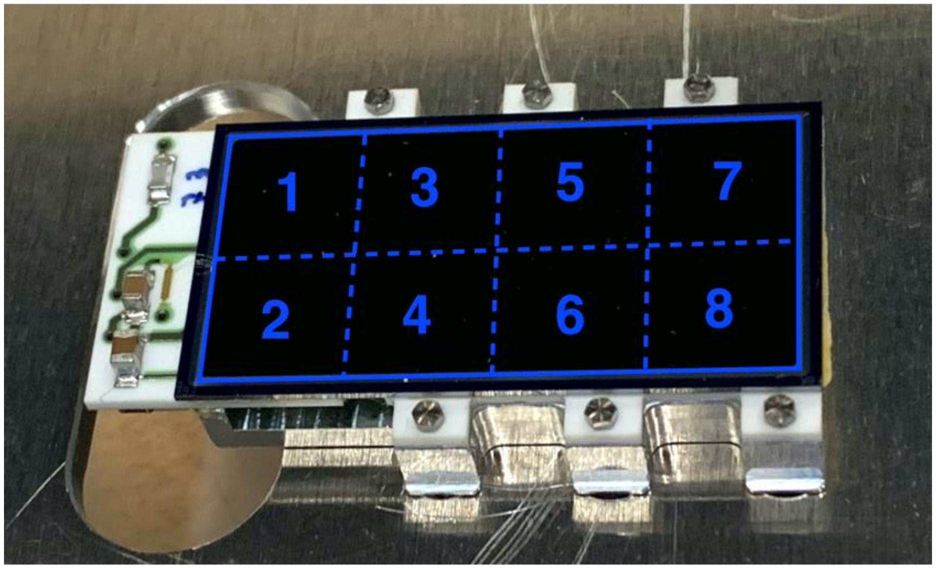
SIDDHARTA-2 installed on DAFNE

Silicon Drift Detectors

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

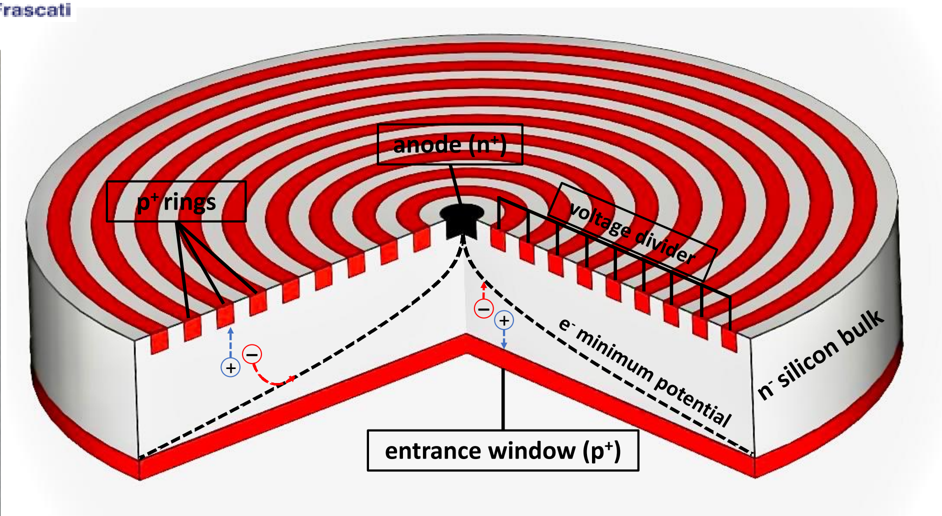
POLITECNICO MILANO 1863

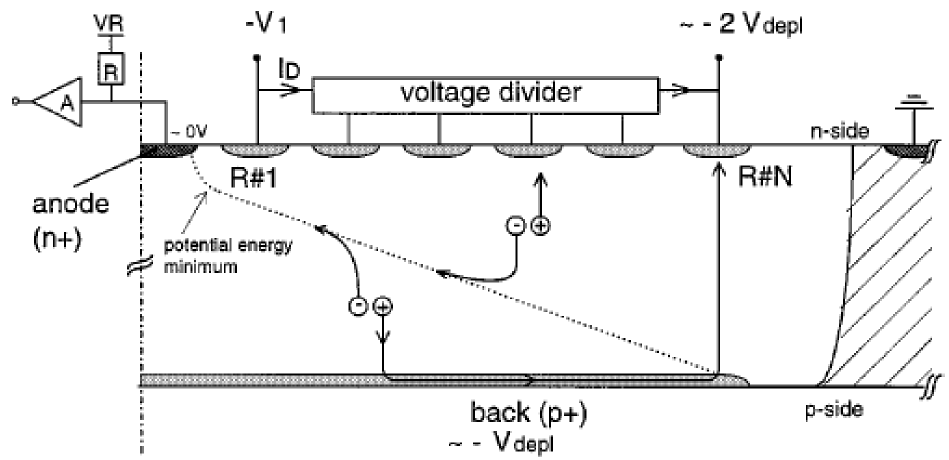
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



8 SDD units (0.64 cm²)
for a total active area of 5.12 cm²
Thickness of 450 µm which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

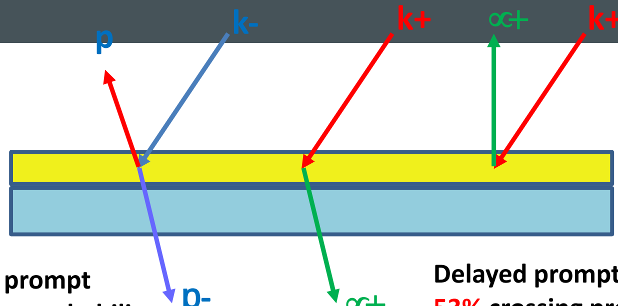
SDD cross section





The Kaon charge detector Done in Sendai!

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

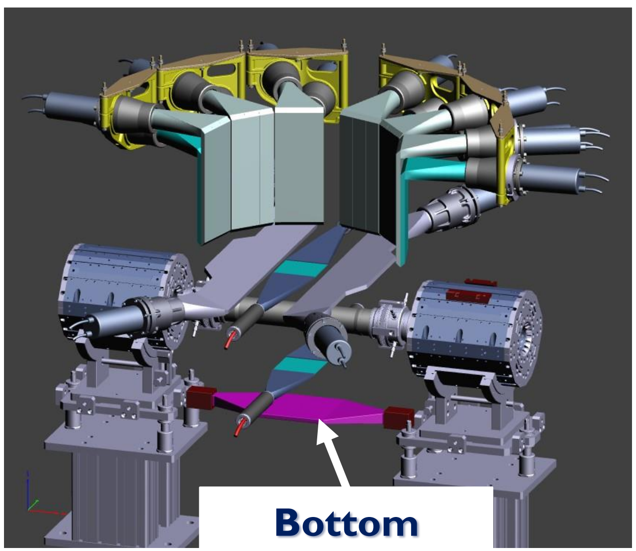


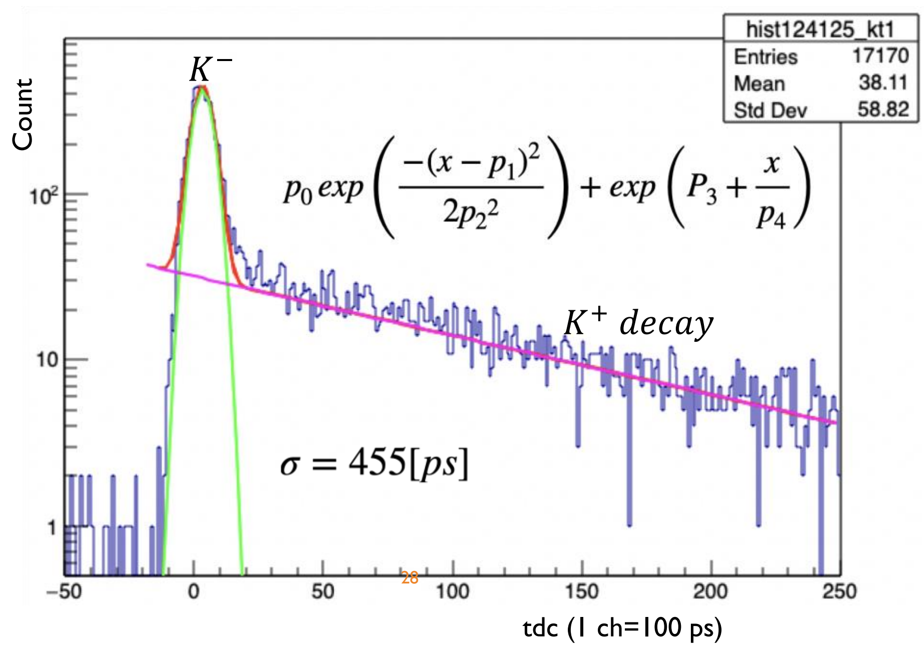
2 mm teflon

5-10 mm thick scintillator

Immediate prompt
83% crossing probability

Delayed prompt
53% crossing probability

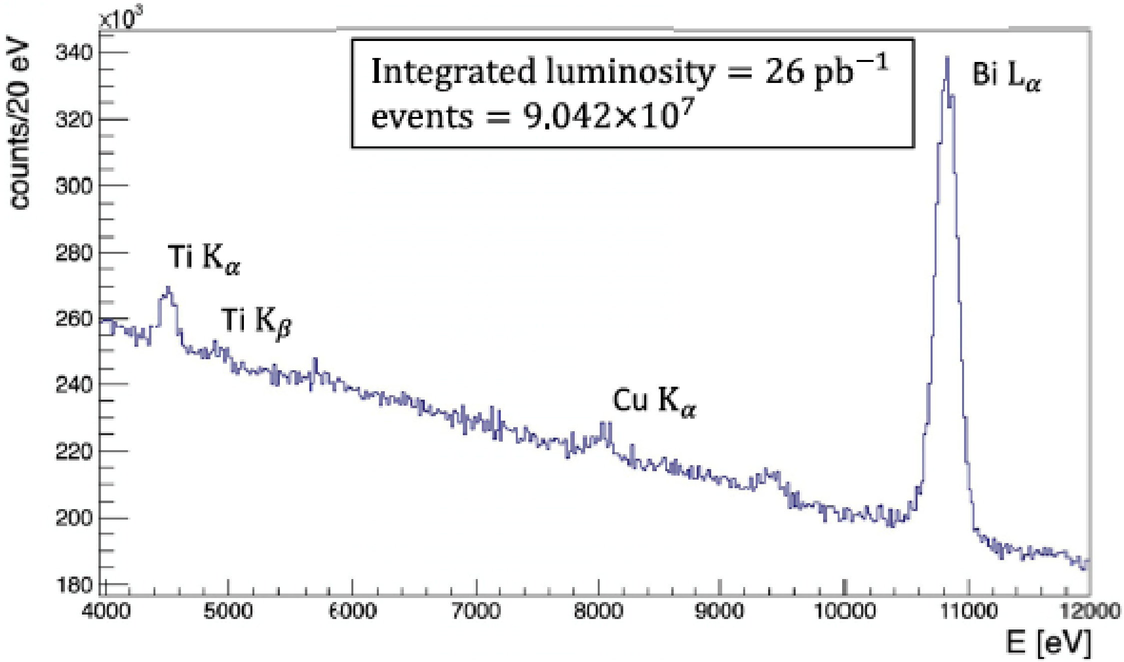




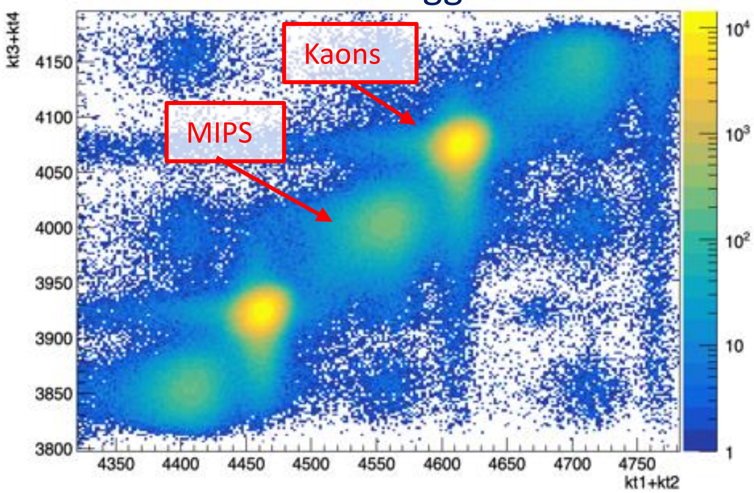
TOHOKU UNIVERSITY

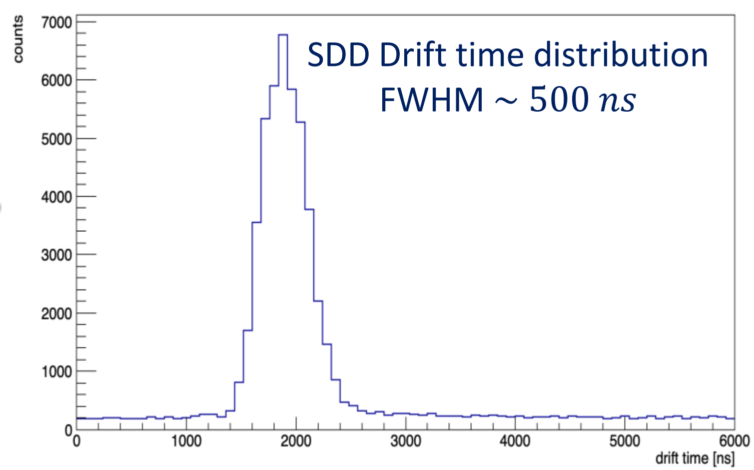
Kaonic ^{4}He 3d → 2p measurement

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

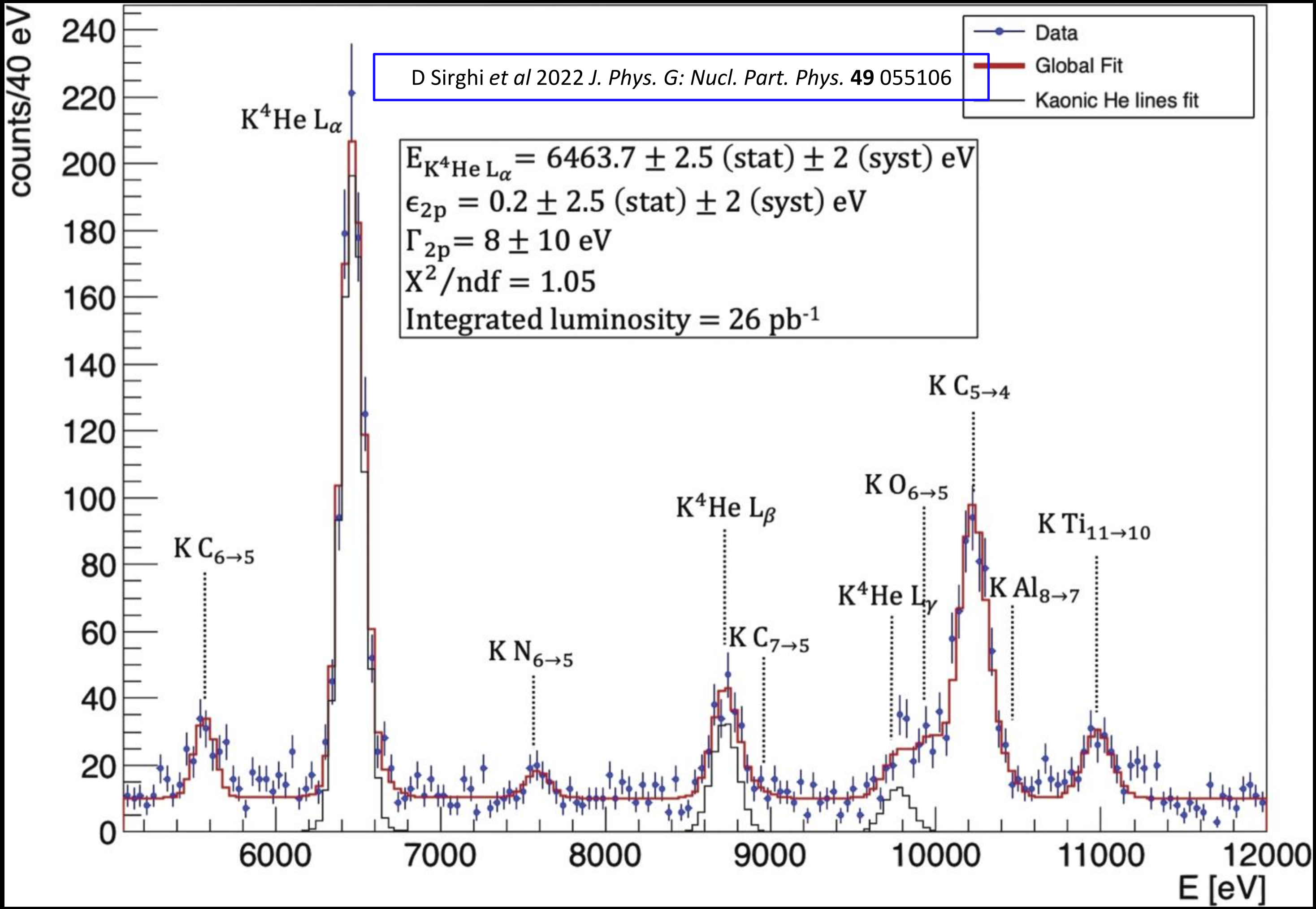


Kaon Trigger

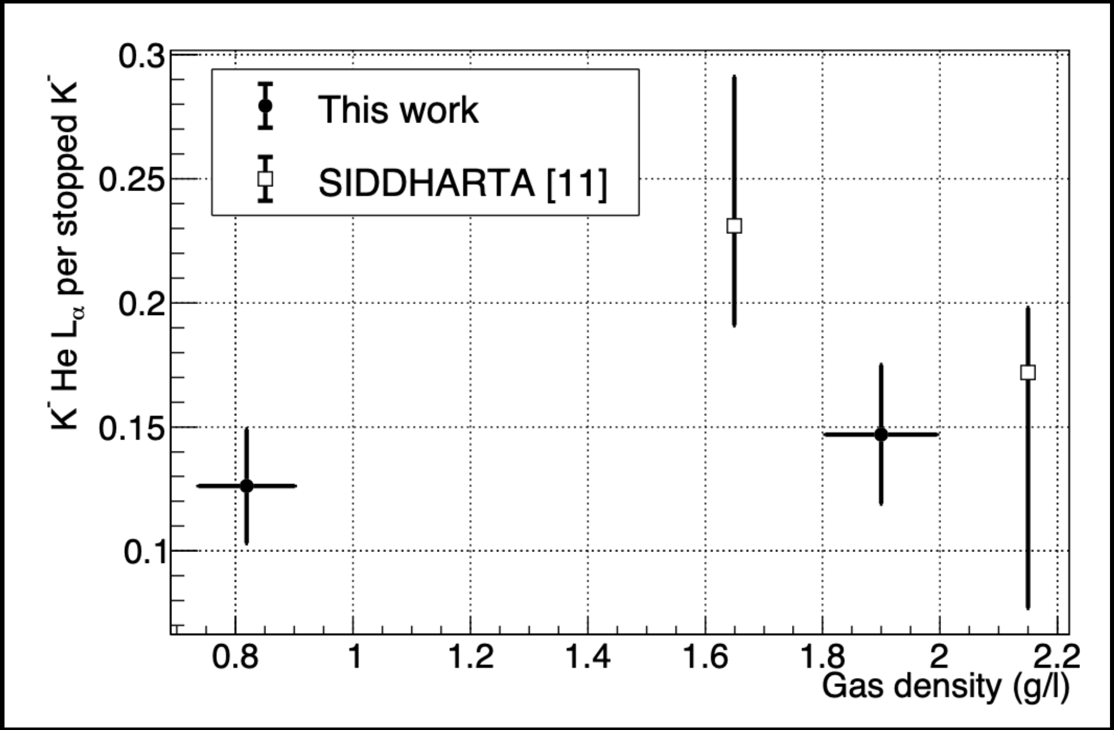




SIDDHARTINO (2021)



SIDDHARTINO (2021)



K-[4]HE LOW DENSITY RUN: 0.75% LIQUID HELIUM DENSITY -> **YIELDS AT LOWEST MEASURED DENSITY**

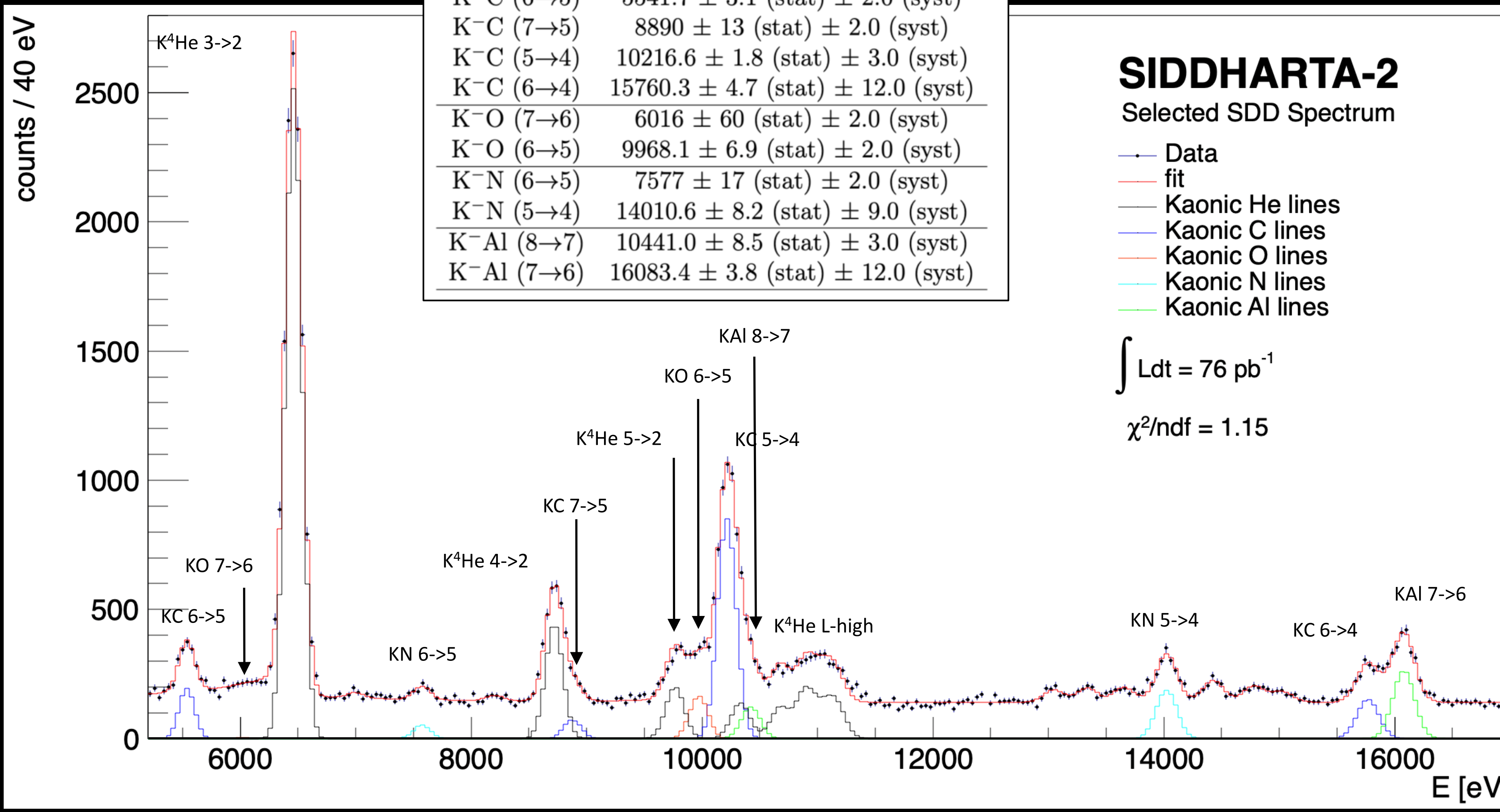
Density	1.90 g/l	0.82 g/l
L_α yield	0.148 ± 0.027	0.126 ± 0.023
L_β/L_α	0.193 ± 0.042	0.133 ± 0.037
L_γ/L_α	0.035 ± 0.015	not detected

D.L. Sirghi, et al. Nuclear Physics A 1029 (2023) 122567

SIDDHARTA-2 (2022)

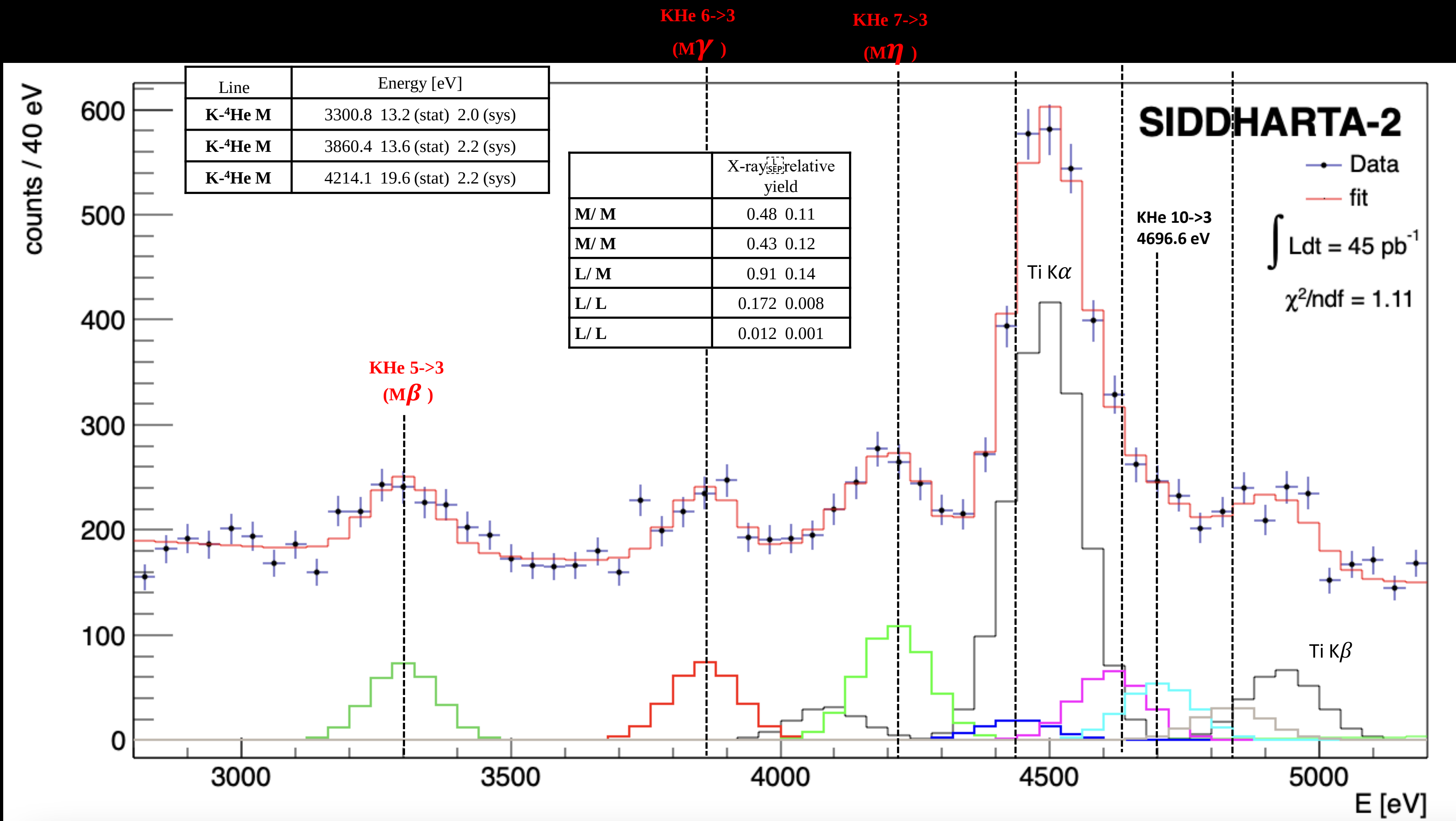
Measurements of high-n transitions in intermediate mass kaonic atoms

Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)



Sgaramella, F., *al. Eur. Phys. J. A* **59**, 56 (2023)

SIDDHARTA-2 Kaonic ^{4}He – M-type transitions



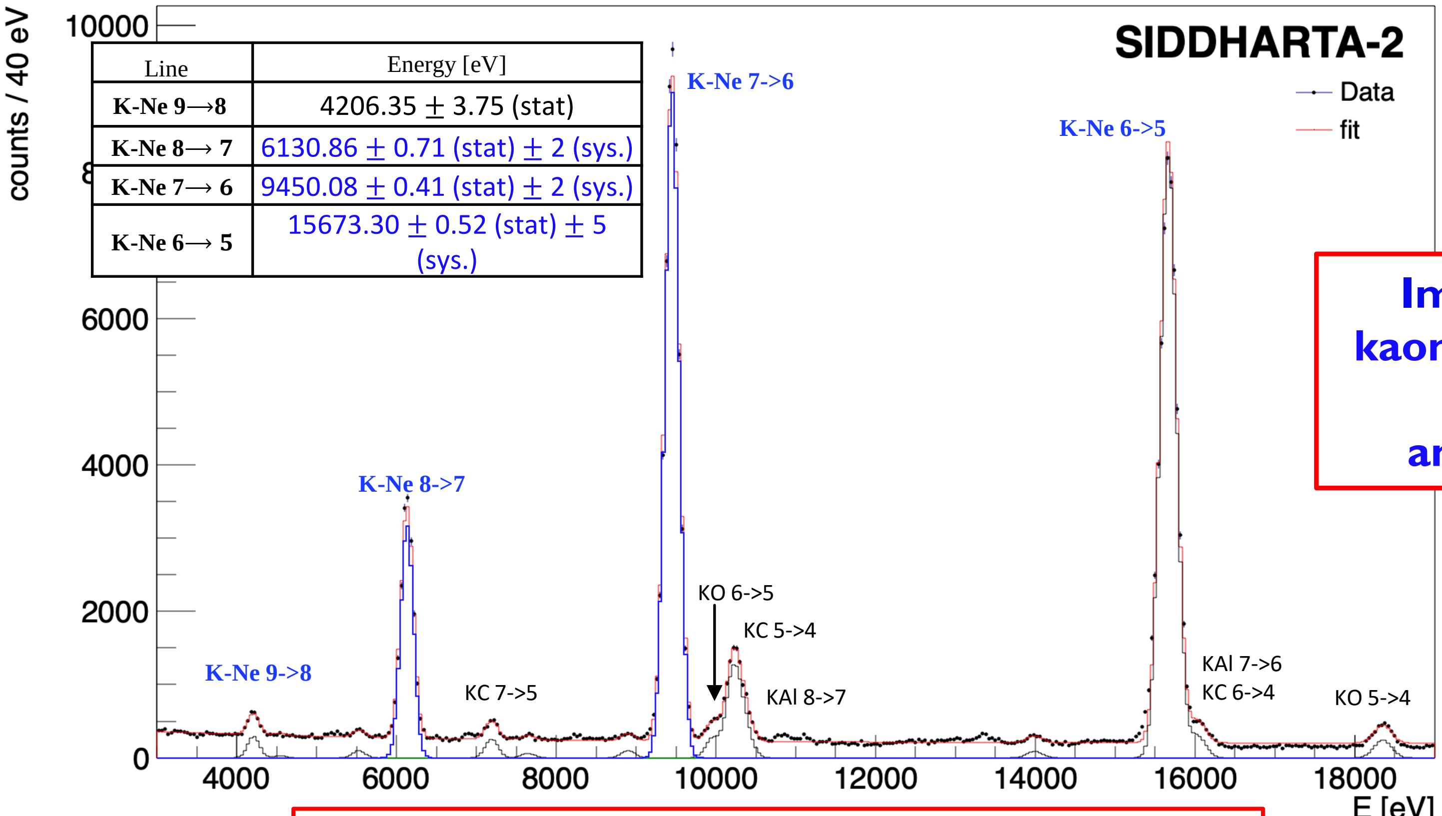
Line	Energy [eV]
K-^{4}He M	3300.8 13.2 (stat) 2.0 (sys)
K-^{4}He M	3860.4 13.6 (stat) 2.2 (sys)
K-^{4}He M	4214.1 19.6 (stat) 2.2 (sys)

	X-ray relative yield
M/ M	0.48 0.11
M/ M	0.43 0.12
L/ M	0.91 0.14
L/ L	0.172 0.008
L/ L	0.012 0.001

KAONIC NEON

The Kaonic Neon measurement (2023)

First measurement of kaonic neon X-ray transitions (record of precision < 1 eV)



Line	Energy [eV]
K-Ne 9⟶8	4206.35 ± 3.75 (stat)
K-Ne 8⟶ 7	6130.86 ± 0.71 (stat) ± 2 (sys.)
K-Ne 7⟶ 6	9450.08 ± 0.41 (stat) ± 2 (sys.)
K-Ne 6⟶ 5	15673.30 ± 0.52 (stat) ± 5 (sys.)

Implications on kaon - multinucleon interaction and kaon mass

Kaonic Neon Yield analysis on going ⟶ paper in preparation

The (charged) Kaon mass puzzle and kaonic Neon

Kaon mass (K-Ne 8 ⟶ 7and K-Ne 7 ⟶ 6) = 493.671 ± 0.021 (stat) MeV

Feasibility test in view of a dedicated measure

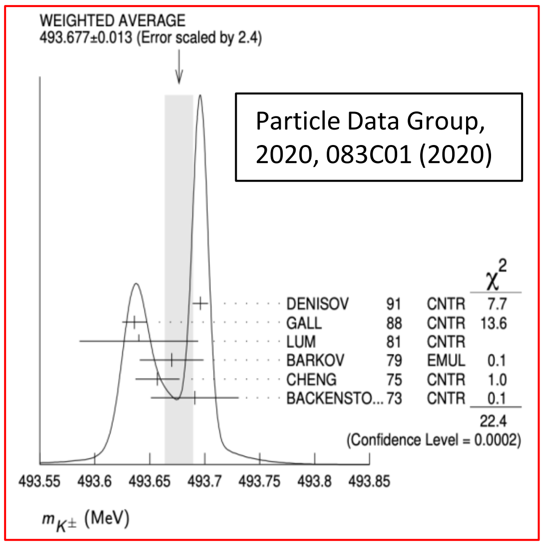
Kaon mass discrepancy

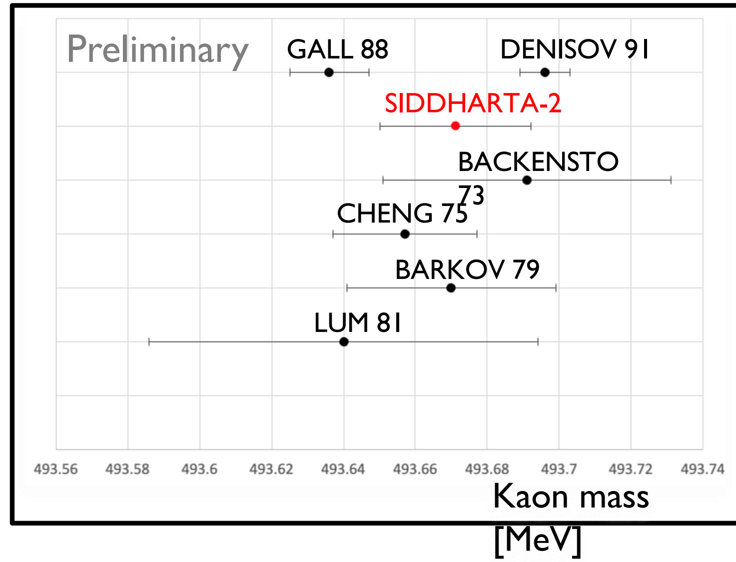
The kaonic Neon measurement to determine the K^- (K^+) mass

Less systematic uncertainty with respect to DENISOV 91 and GALL 88 measurements, thanks to the use of a low Z gas (Ne) target

A dedicated kaonic Ne run could solve the kaon mass discrepancy issue

Impact on the charmonium spectrum and on all processes in which charged kaons are involved



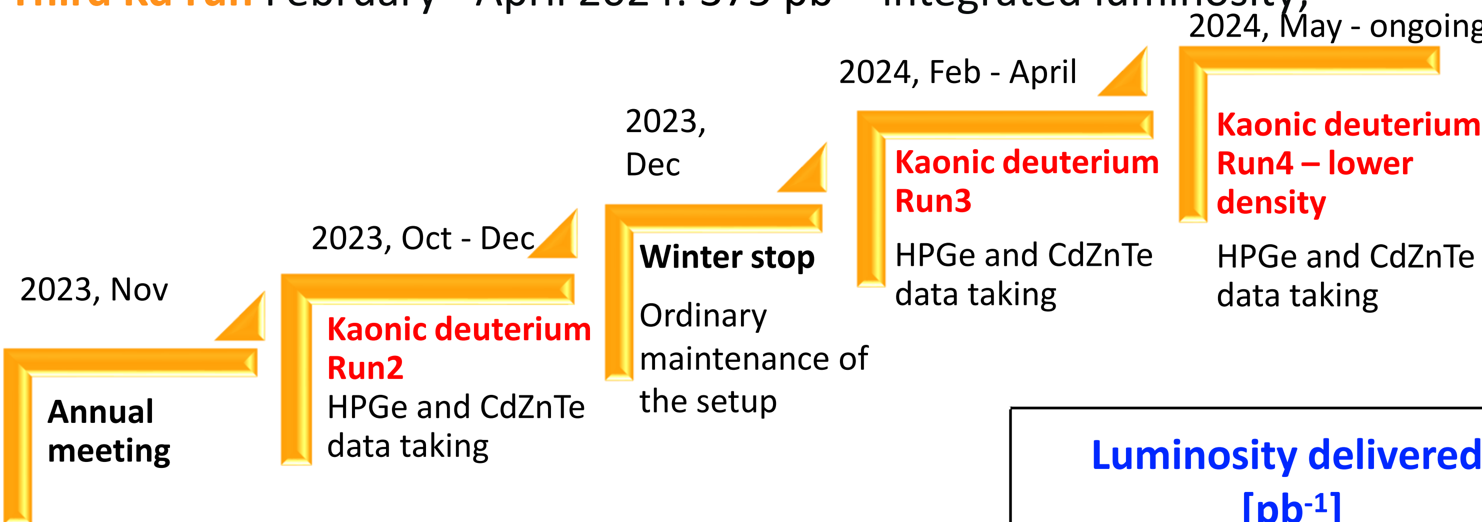


VALUE (MeV)		*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
493.677±0.016 OUR FIT		Error includes scale factor of 2.8.				
493.677±0.013 OUR AVERAGE		Error includes scale factor of 2.4. See the ideogram below.				
493.696±0.007	1	DENISOV	91	CNTR	–	Kaonic atoms
493.636±0.011	2	GALL	88	CNTR	–	Kaonic atoms
493.640±0.054		LUM	81	CNTR	–	Kaonic atoms
493.670±0.029		BARKOV	79	EMUL	±	$e^+e^- \to K^+K^-$
493.657±0.020	2	CHENG	75	CNTR	–	Kaonic atoms
493.691±0.040		BACKENSTO...	73	CNTR	–	Kaonic atoms

SIDDHARTA-2 preliminary: kaonic deuterium measurement

The Kaonic Deuterium Measurement - Timeline

- **First Kd run** May - July 2023**:** 164 pb^{-1} integrated luminosity;
- **Second Kd run** October **-** December 2023: 276 pb^{-1} integrated luminosity;
- **Third Kd run** February - April 2024: 375 pb^{-1} integrated luminosity;

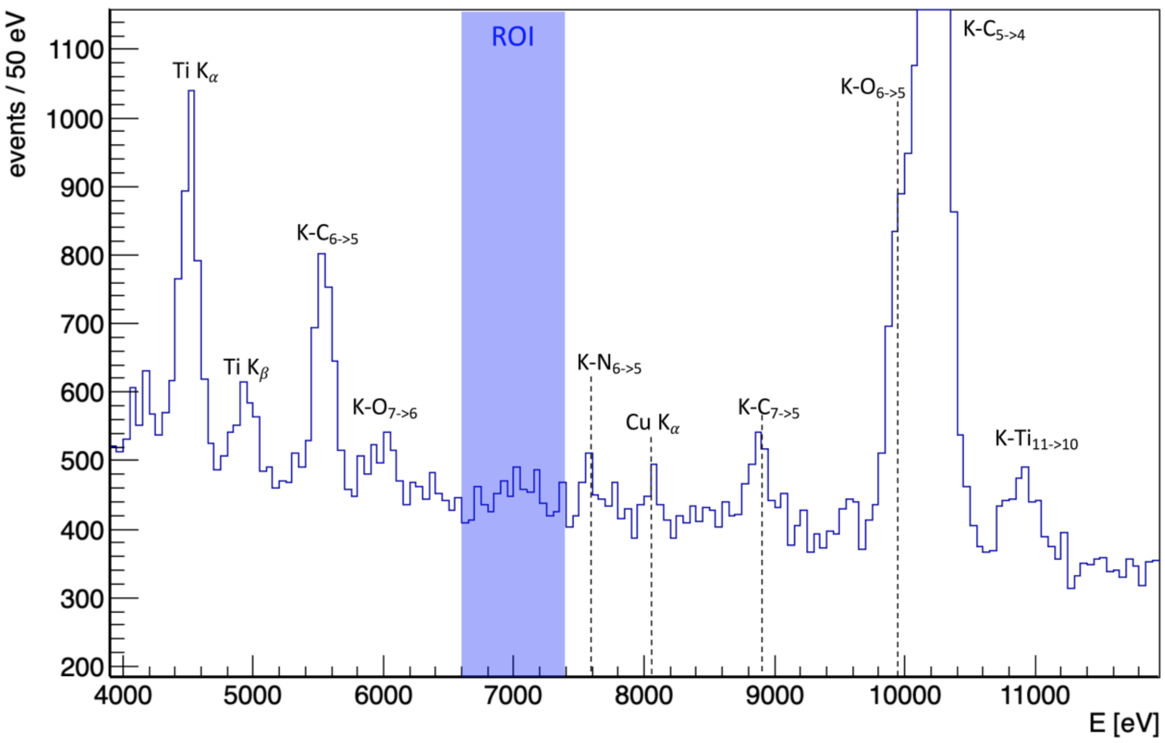


...with the aim of <u>collecting 800-900 pb-1 in total –</u> goal achieved! Thanks to excellent DAΦNE working conditions.

	Luminosity delivered [pb^{-1}]
Run1	196
Run2	344
Run3	435
Total	**975**

Kaonic Deuterium Run1: data analysis

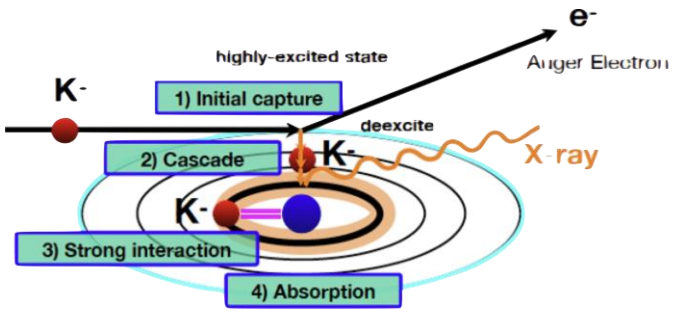
Preliminary energy spectrum after asynchronous (electromagnetic) background rejection

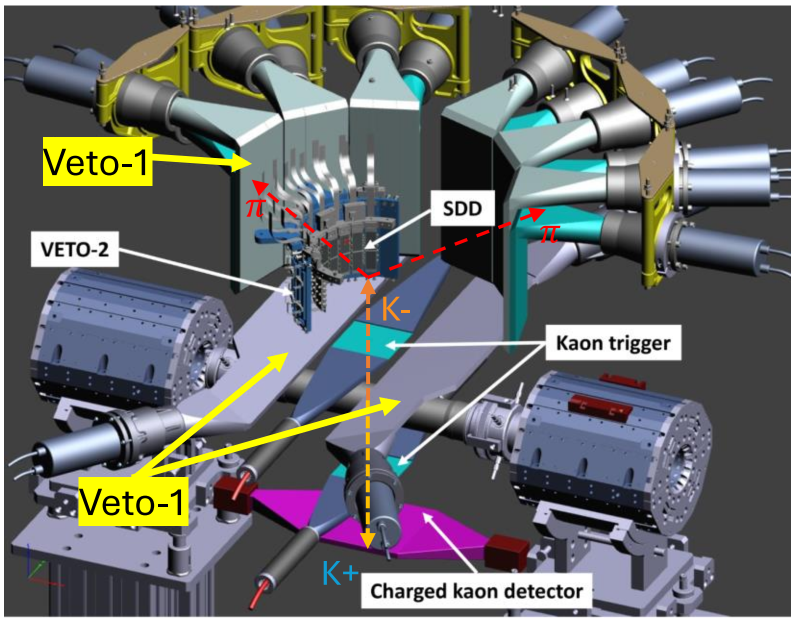


- ✓ Refined calibration
- ✓ Analysis of all veto systems data
  - ➢ Veto-1 system
  - ➢ Veto-2 system
  - ➢ Charged kaon system
- ✓ Hadronic background rejection
- ✓ Preliminary fit of the energy spectrum

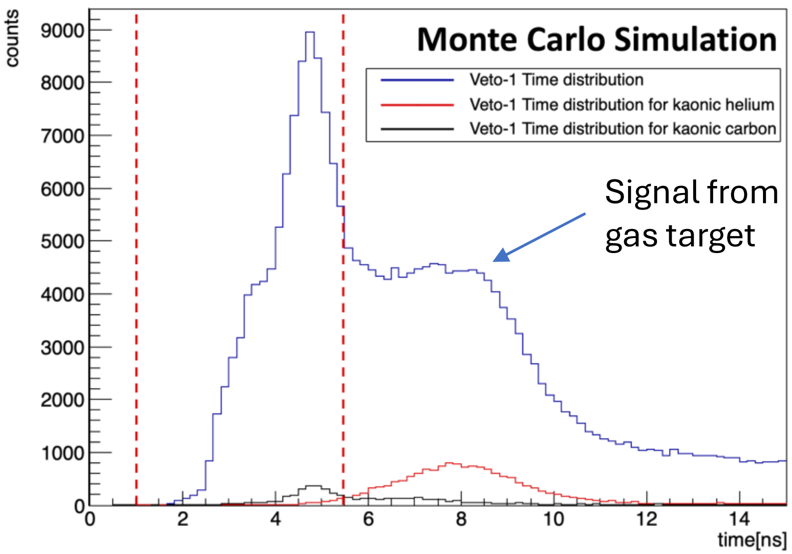
Kaonic Deuterium Run1: veto-1 system analysis

Veto-1 for synchronous background reduction:
measure the arrival time of the charged particles emitted by the kaon-nucleus absorption



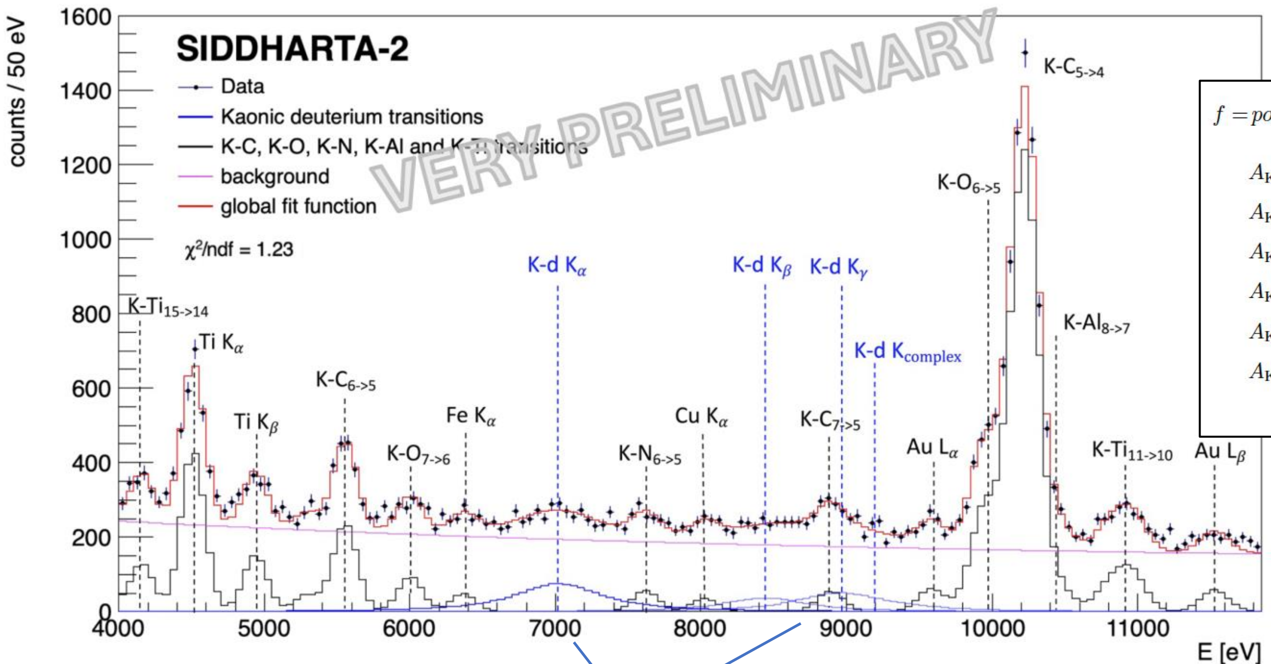


Veto-1: 14 plastic scintillators placed around and below the vacuum chamber



Kaonic Deuterium Run1: preliminary result (F. Sgaramella Ph.D. thesis)

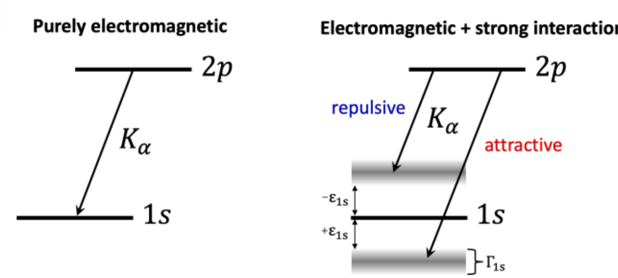
Preliminary fit of the kaonic deuterium energy spectrum



$$f = pol_1(E) + \exp(E) + \sum_i \text{Gauss}(A_{Gi}, E_i, \sigma) + \text{Tail}(A_{Ti}, E_i, \beta, \sigma) +$$
$$A_{\text{Kd}_{2\to1}} \cdot \text{Voigt}(E_{2\to1}, \sigma, \Gamma_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{3\to1}} \cdot \text{Voigt}(E^{e.m.}_{3\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot \text{Voigt}(E^{e.m.}_{4\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{5\to1}} \cdot \text{Voigt}(E^{e.m.}_{5\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{6\to1}} \cdot \text{Voigt}(E^{e.m.}_{6\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{7\to1}} \cdot \text{Voigt}(E^{e.m.}_{7\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s})$$

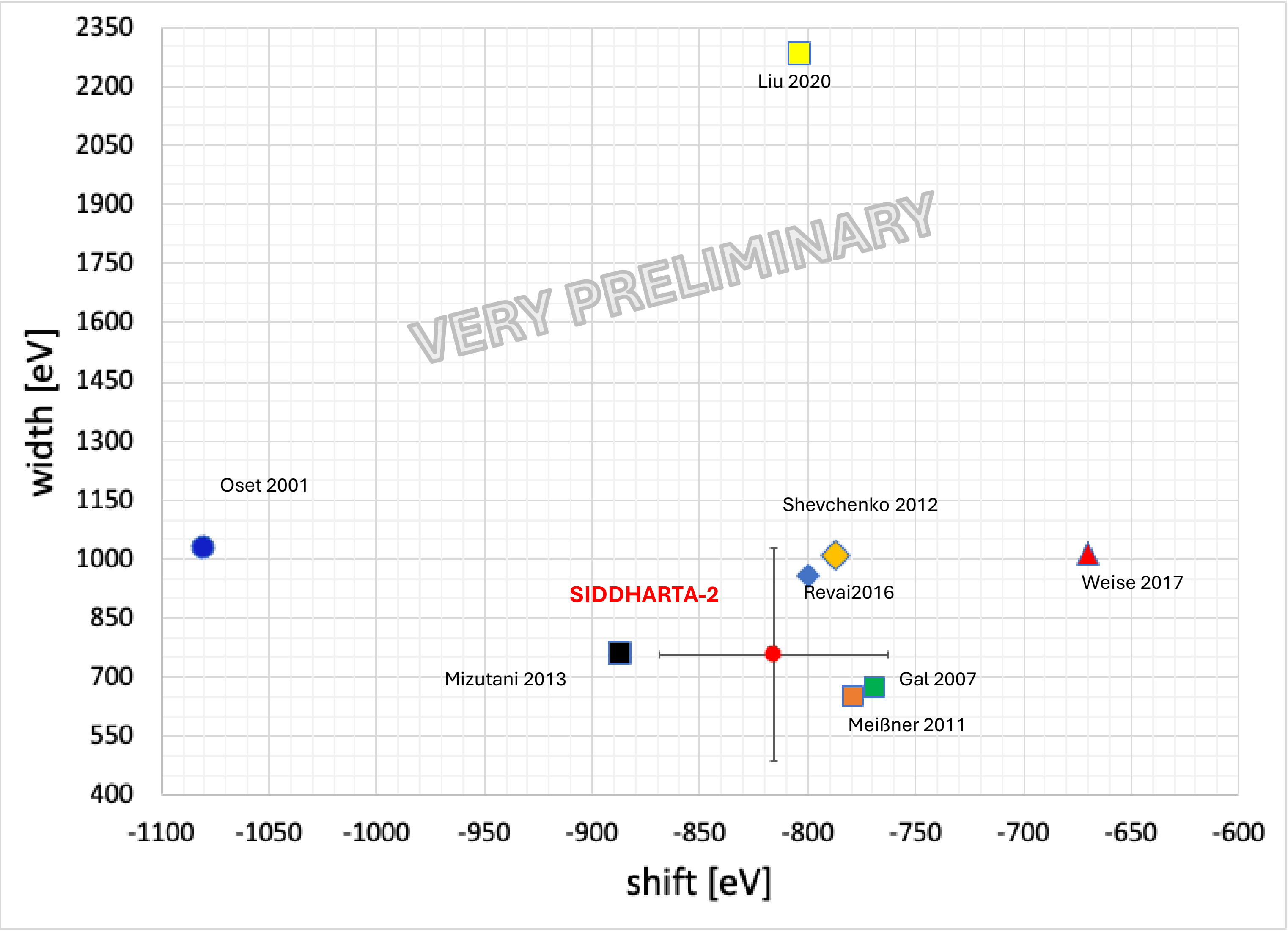
$$\varepsilon_{1s} = -816 \pm 53\ (\text{stat}) \pm 2\ (\text{syst})\ \text{eV}$$

$$\Gamma_{1s} = 756 \pm 271\ (\text{stat})\ \text{eV}$$



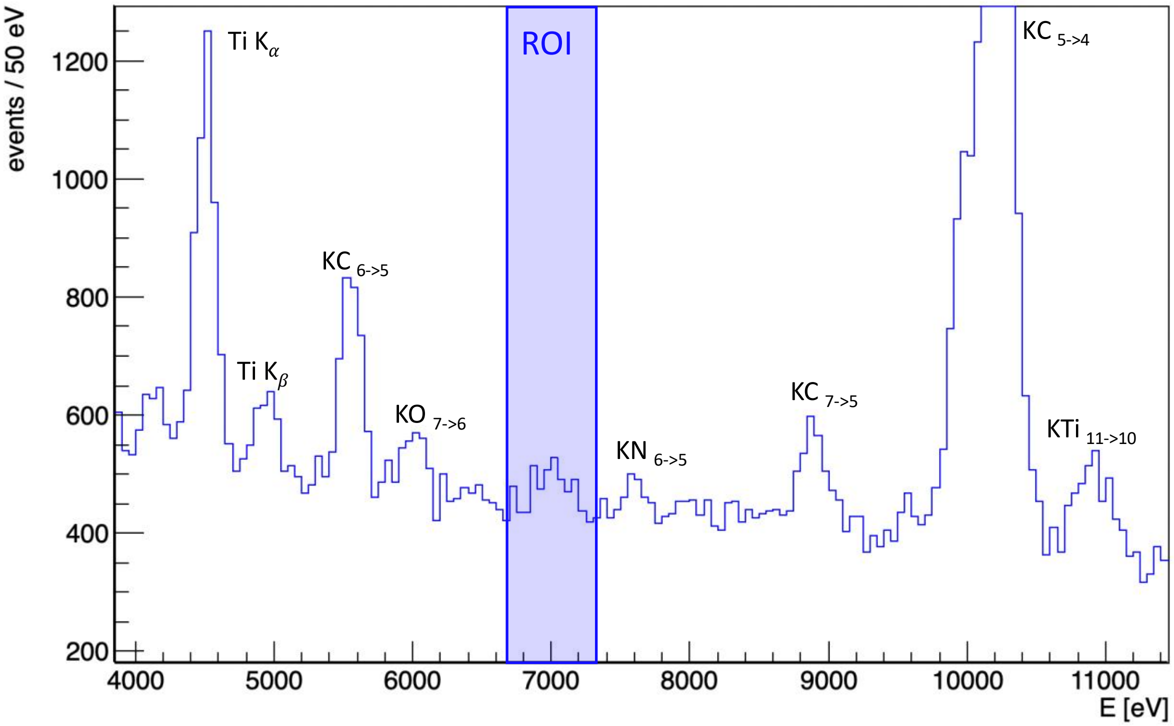
Kaonic Deuterium Run1: preliminary result

Preliminary comparison between SIDDHARTA-2 Run1 result and the theoretical model



Kaonic Deuterium Run2 and Run3: analysis ongoing

Preliminary energy spectrum from run2 + run3 (partial statistics ~300 pb^{-1})



Next Step of the analysis:

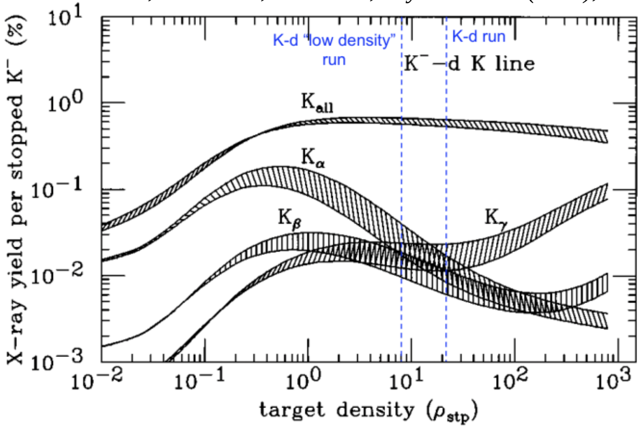
- Refined calibration of Run3 data (ongoing)
- Veto-1 analysis (similar to run1 data)
- Define a proper fit function
- Fit of the energy spectrum (full dataset)

The analysis of the full dataset can potentially improve the statistical accuracy by a factor 2

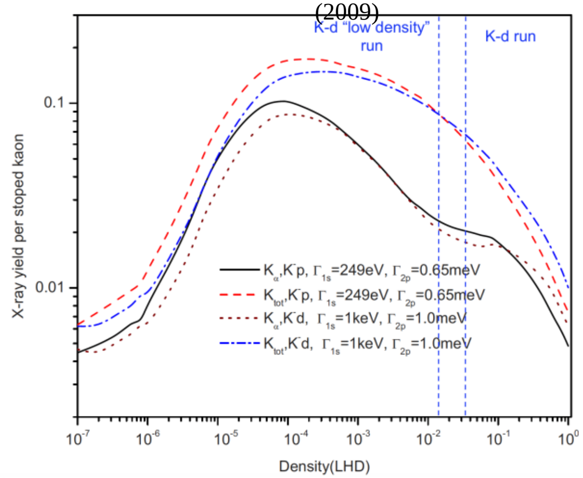
(precision similar to kaonic hydrogen measurement)

Kaonic Deuterium yield puzzle– low density run

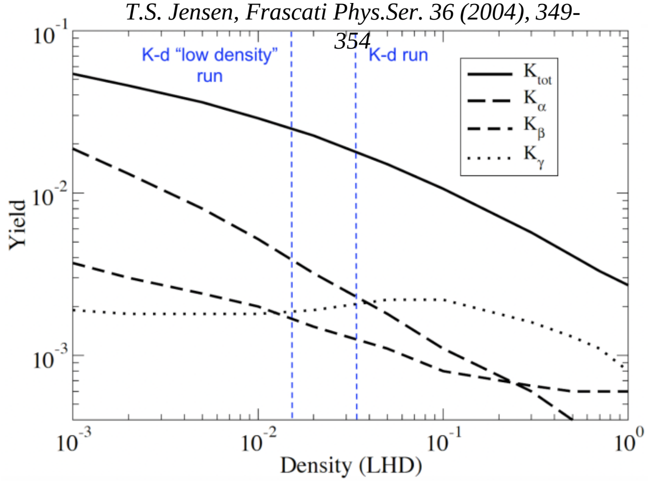
T. Koike, T. Harada, Y. Akaishi, Phys.Rev.C 53 (1996), 79-87



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



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



Several cascade model predict **completely different kaonic deuterium X-ray yields** (absolute and relative) and different trends as function of the density

Low density kaonic deuterium measurement

(60% lower compared to the previous run)

Providing unique data to investigate the de-excitation mechanism in kaonic atoms (cascade model)

The combined analysis of the kaonic deuterium measurement performed at 1.4% LDD and the ongoing measurement at 0.8% LDD **can help to disentangle between the various theoretical cascade models**

SIDDHARTA-2 Kd run – Future plan

- **First Kd run** May - July 2023: 164 pb^{-1} integrated luminosity;
- **Second Kd run** October - December 2023: 276 pb^{-1} integrated luminosity;
- **Third Kd run** February - April 2024: 375 pb^{-1} integrated luminosity;
- **Calibration run** with hydrogen 150 pb^{-1};
- **Kd low density run** – goal 200 pb^{-1}

We aim to collect 200 pb^{-1} (similar statistics to Kd run1)

12th April 2024
End of Kaonic deuterium Run3

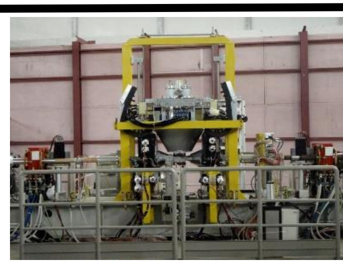
15th Apr – 6th May (3 weeks)
Calibration run with kaonic hydrogen

6th -12th May
DAΦNE maintenance: refill of the target cell with deuterium (low density)

24th May – End of June - first week of July
Kaonic deuterium "low density" run

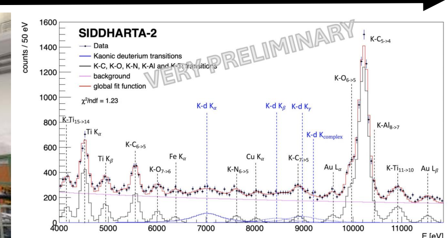
DEAR

SIDDHARTA



SIDDHARTA-2

First measurement ever of Kd



Kaonic Lead Measurement at DAΦNE with HPGe

HPGe provided by Zagreb University (Croatian Science Foundation project 8570)
to perform the kaonic lead measurement
in parallel with the SIDDHARTA-2 kaonic deuterium measurement

- BSI HPGe detector with transistor reset preamplifier (TRP).
- DAQ based on CAEN DT5781 digitizer
- Coincidence between:
  - -> ch0 Luminometer
  - -> ch1 HPGe signal
  - -> ch2 TAC signal
- Data acquired:
  - -> June-July 2023: 109.38 pb^{-1}
  - -> September-now 2023: 117.67 pb^{-1}

The Kaonic Lead Measurement

(Zagreb Uni; Krakow, Jagiellonian Uni – Lumi)

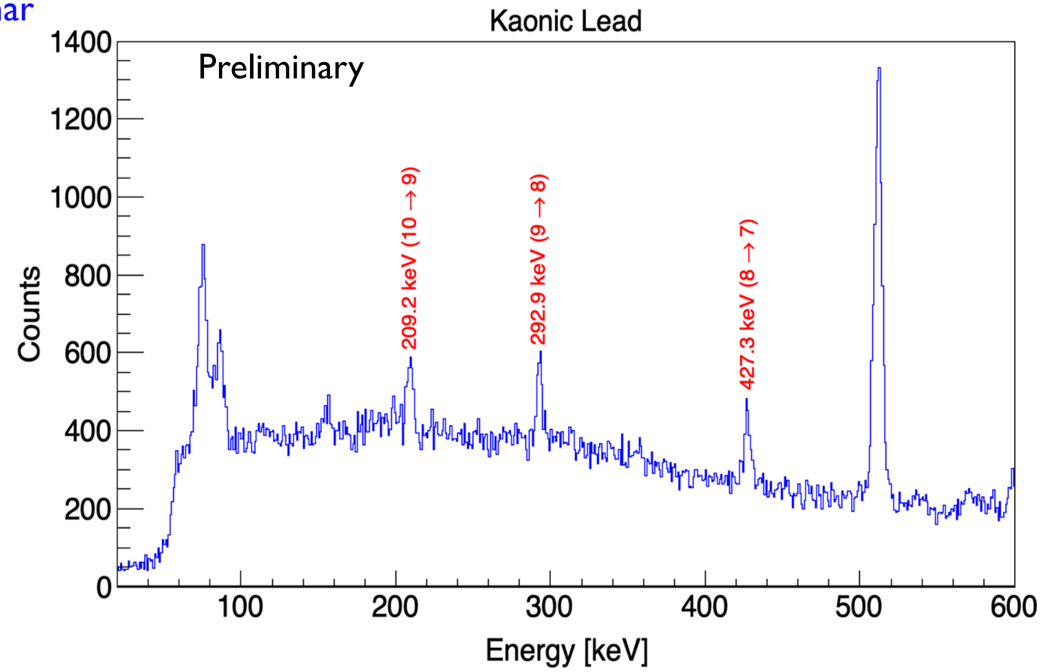
Integrated luminosity: 109.38 pb^{-1} (June – July 2023)

Preliminary analysis of June-July 2023 data (D.. Bosnar and I. Friščić) :

Gaus+linear function was fitted for each peak:

- (10 -> 9) : 906 events in peak,
  position 209.191 ± 0.171 keV
- (9 -> 8) : 947 events in peak,
  position 292.939 ± 0.134 keV
- (8 -> 7) : 943 events in peak,
  position 427.200 ± 0.152 keV

Optimization and detailed analysis is in progress-> towards a publication

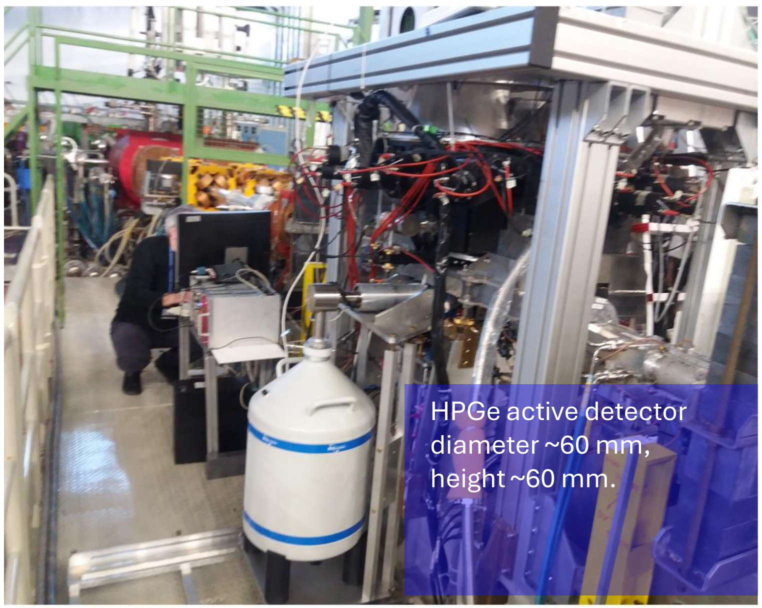


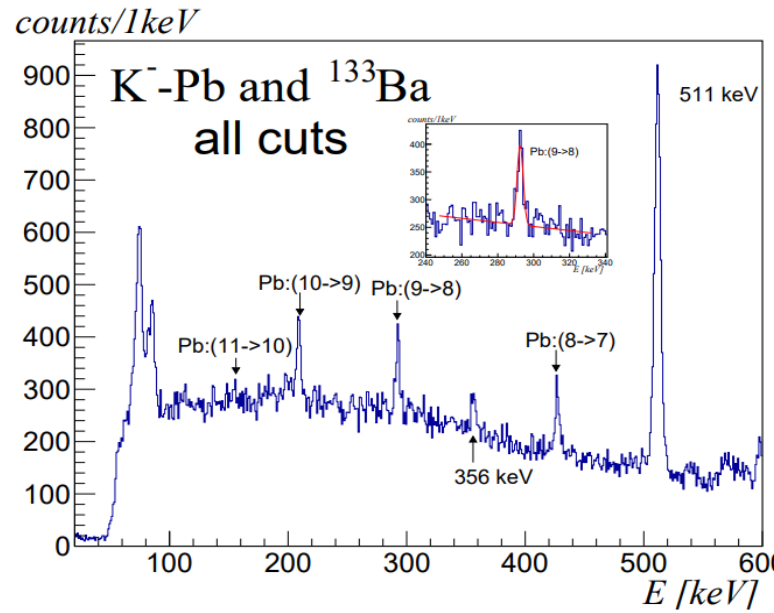
Kaonic Lead Measurement at DAΦNE with HPGe

(Zagreb Uni; Krakow, Jagiellonian Uni – Lumi)

deuterium measurement

Integrated luminosity: 109.38 pb^{-1}: subset of 40 pb^{-1} already analysed

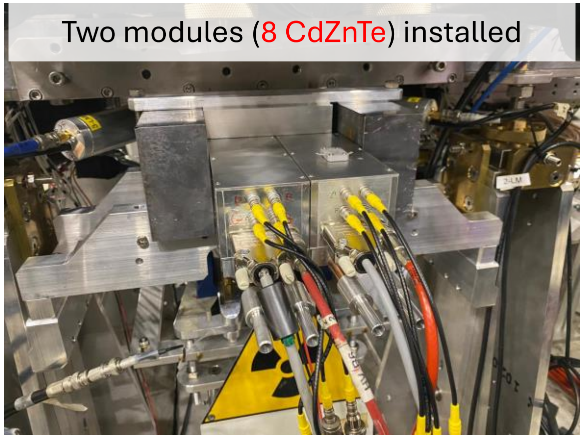


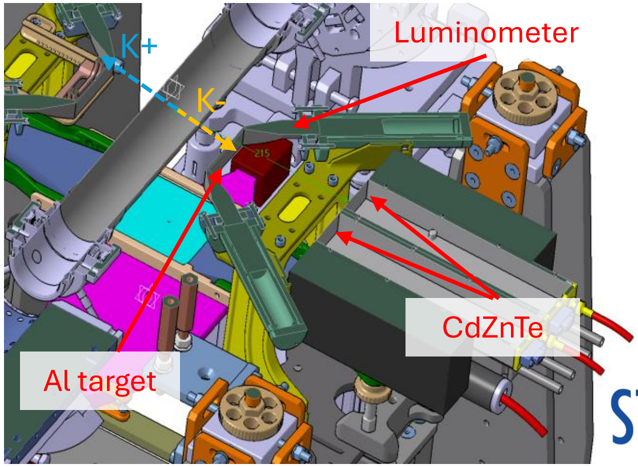


K^--Pb transition	Peak position (keV)	Resolution (FWHM) (keV)	Number of events
$10 \to 9$	208.92 ± 0.17	3.68 ± 0.42	584 ± 30
$9 \to 8$	292.47 ± 0.17	3.97 ± 0.49	770 ± 65
$8 \to 7$	427.07 ± 0.24	4.37 ± 0.54	457 ± 45

Article submitted to Nuclear Instruments and Methods A preprint: arXiv:2405.12942

CdZnTe detectors: test run with 8 detectors

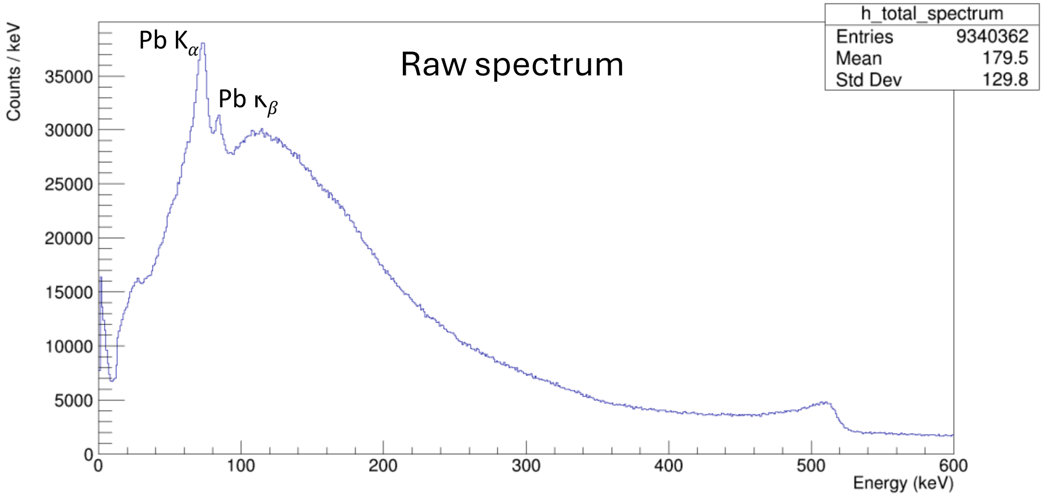




8 cm^2 CdZnTe detectors to perform X-ray spectroscopy of kaonic aluminium in parallel with SIDDHARTA-2 kaonic deuterium run (L. Abbene, A. Buttacavoli, F. Principato, A. Scordo)

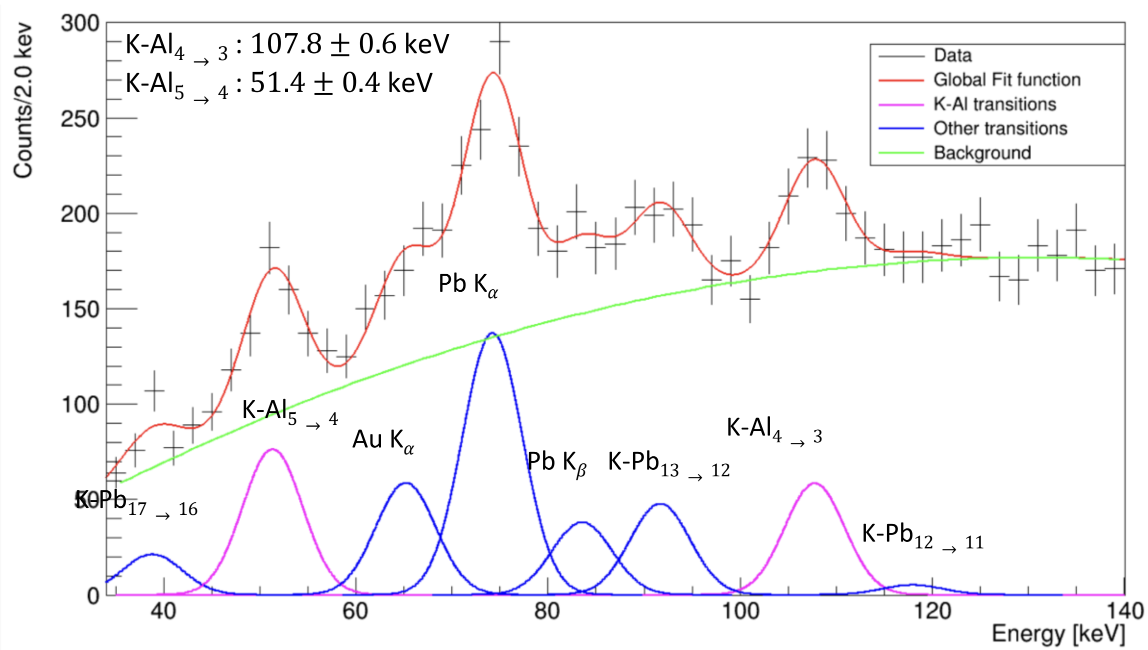
Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy : ASTRA

~ 60 pb^{-1} of data with a 2,2 mm Al target



CdZnTe detectors: test run with 8 detectors

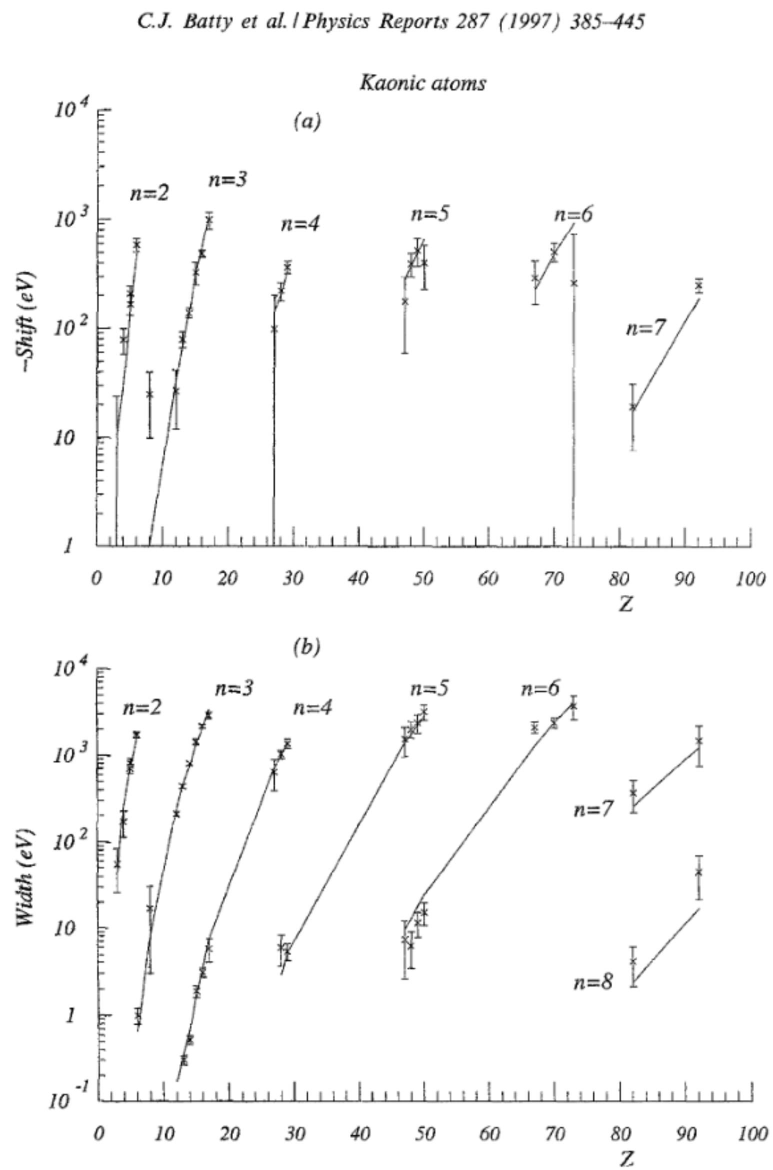
Preliminary result from the kaonic aluminium analysis (~60 pb^{-1})



- First kaonic atoms' spectrum measured with CZT detectors
- CZT proved to be the **perfect technology for intermediate mass kaonic atoms**, with very good "in-beam" performances during preliminary tests
- CdZnTe detectors can be easily used in parallel with already existing experiments, requiring very small space and not invasive electronics.

An article is in preparation

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)

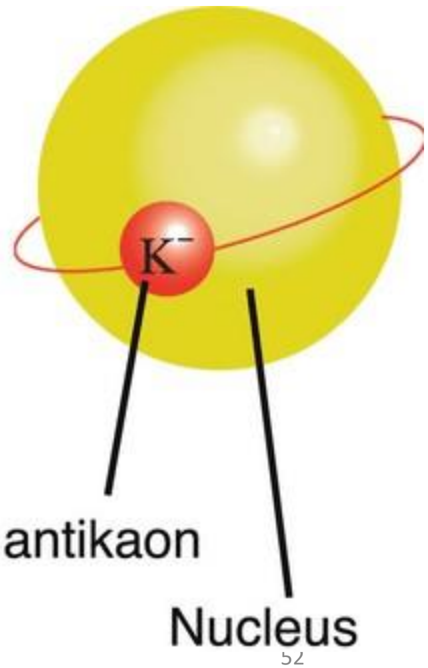
We propose to do precision measurements along the periodic table at DAΦNE for:

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

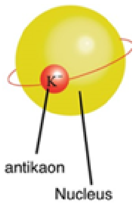
charting the periodic table

EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

EXKALIBUR



First Module of Kaonic Atoms Measurements within the EXKALIBUR scientific program



20th May 2024

By SIDDHARTA2-/EXKALIBUR Collaboration

EXtensive Kaonic Atoms research: from LIthium and Beryllium to URanium

Built up on our world-recognized expertise:

- Kaonic Hydrogen
- Kaonic Nitrogen
- Kaonic Helium
- Kaonic Neon
- Kaonic deuterium
- + more

The measurement for the **first EXKALIBUR module** were selected based on two criteria:

Feasibility with **minimal modifications/addings** of the already existent SIDDHARTA-2 setup and within a reduced timescale

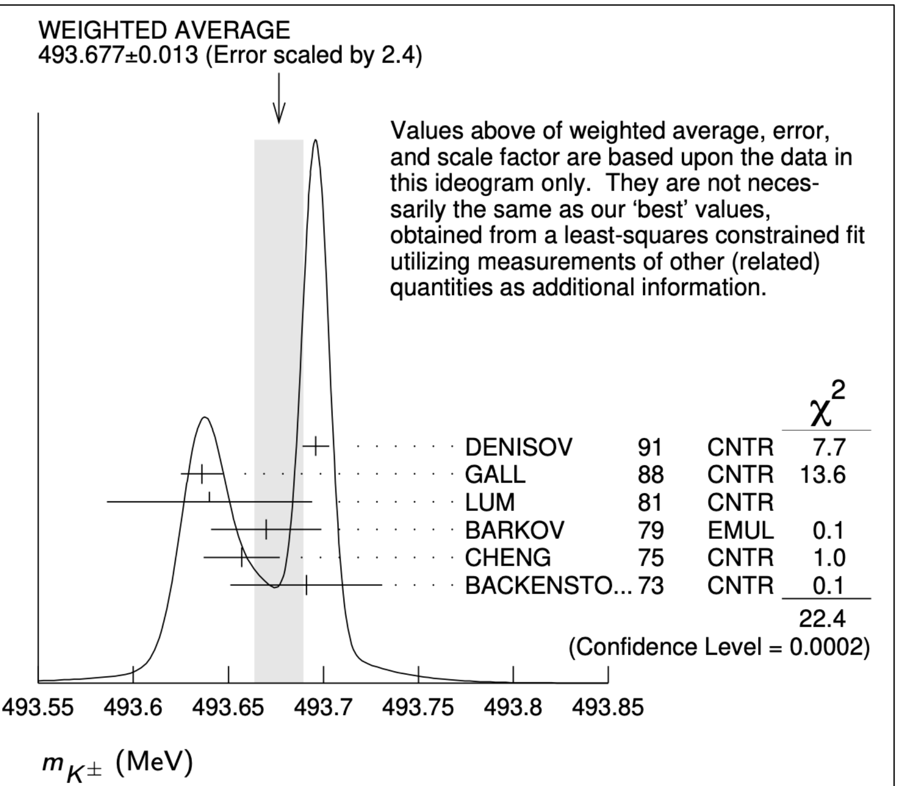
Impact: i.e. the **maximal scientific outcome:**

Kaonic Neon -> kaon mass

Light kaonic atoms (KLi; Be; B)

In parallel intermediate mass kaonic atoms

Kaonic neon for the charged kaon mass

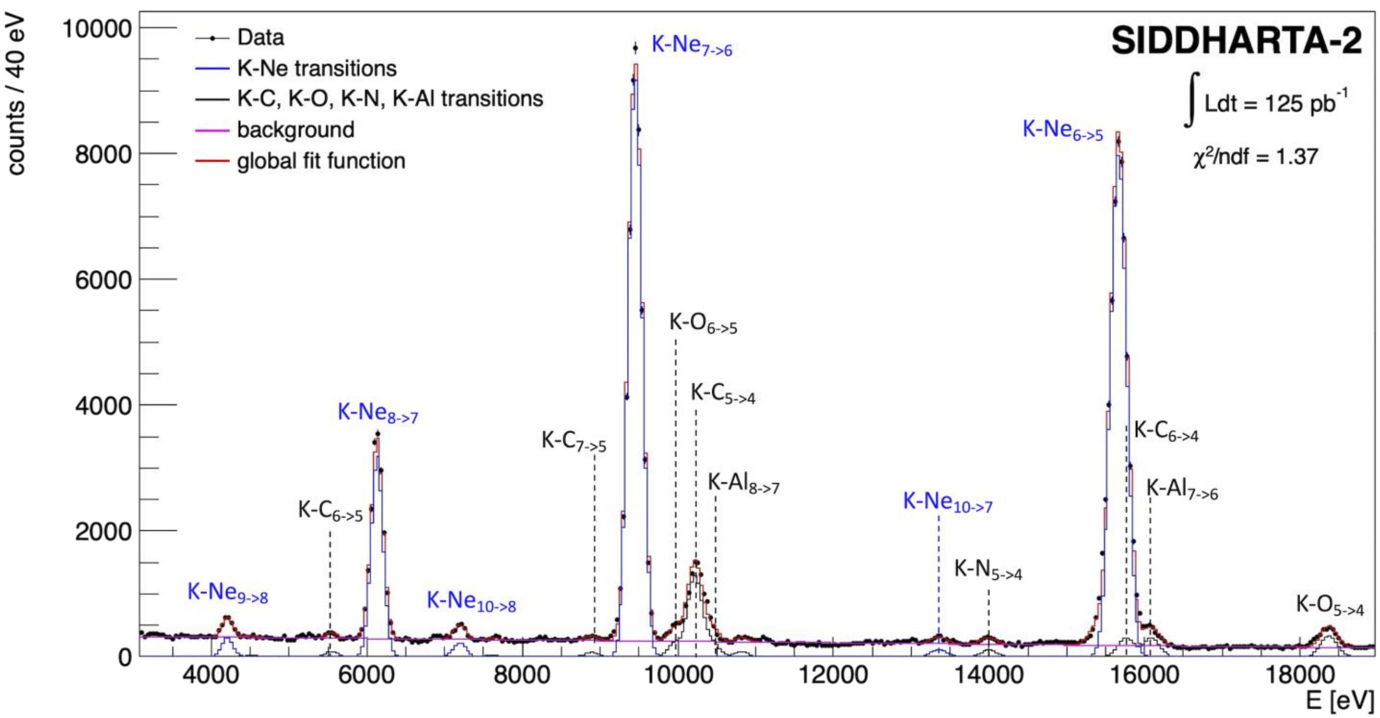


- The first measurement we plan doing is the kaon neon high-n levels transition with precisions below 1 eV, **to extract the charged kaon mass**.

- By using a **gaseous target**, we can resolve the ambiguity in the charged kaon mass de-termination, providing **a new precise value through the measurement of kaonic neon high-n transitions**. Moreover, the measurement also provides **a precision test of QED in atomic systems with strangeness** (Rydberg constant, as example).

Our own Kaonic Neon measurement (2023)

Transition	Energy [eV]
K-Ne (9 → 8)	4206.35 ± 3.75 (stat) ±2.00 (syst) eV
K-Ne (8 → 7)	**6130.86 ± 0.71 (stat) ±1.50 (syst) eV**
K-Ne (10 → 8)	7191.21 ± 4.91 (stat) ±2.00 (syst) eV
K-Ne (7 → 6)	**9450.08 ± 0.41 (stat) ±1.50 (syst) eV**
K-Ne (10 → 7)	11428.30 ± 8.37 (stat) ±3.00 (syst) eV
K-Ne (6 → 5)	**15673.30 ± 0.52 (stat) ±9.00 (syst) eV**



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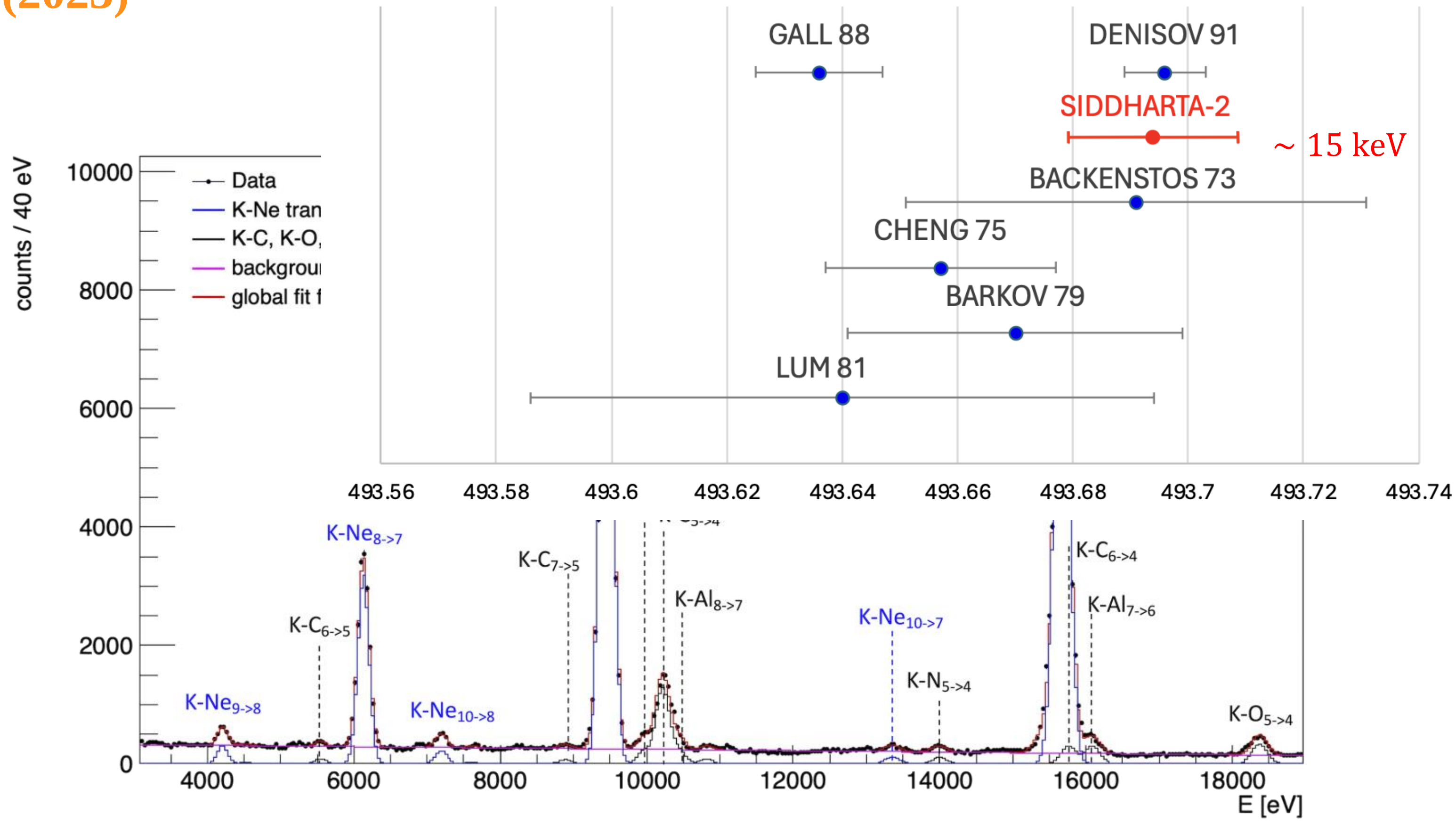
[illegible]	[illegible] 0 (syst) eV
[illegible]	[illegible] **(syst) eV**
[illegible]	[illegible] 00 (syst) eV
[illegible]	[illegible] **0 (syst) eV**



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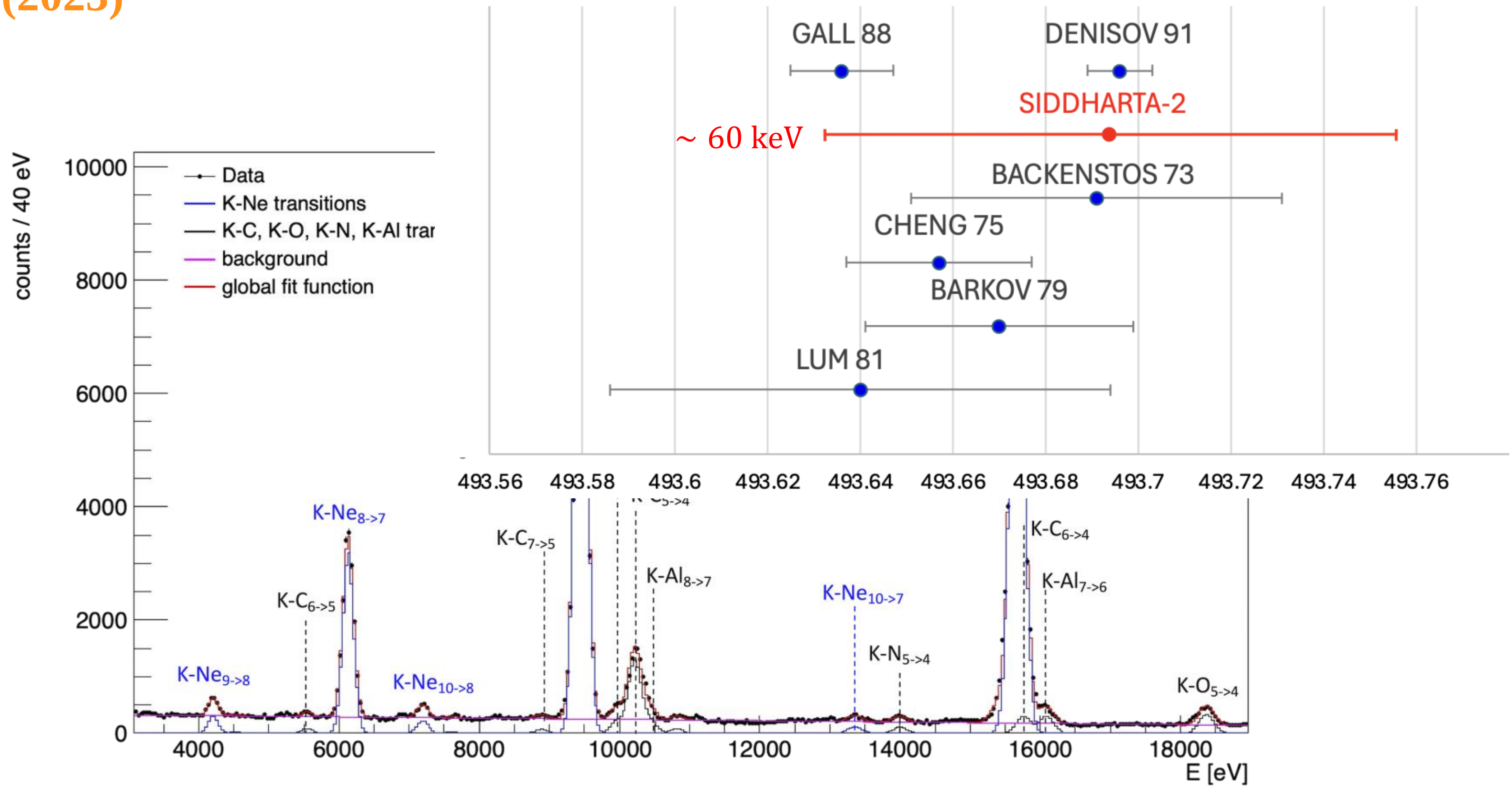
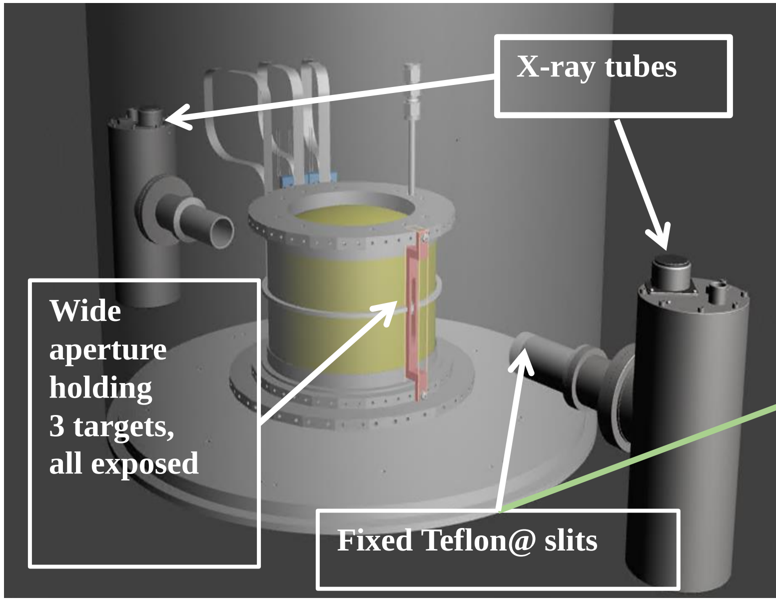
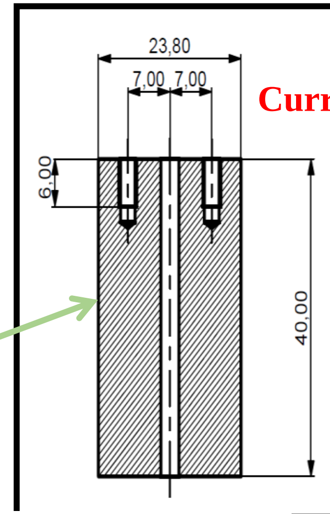
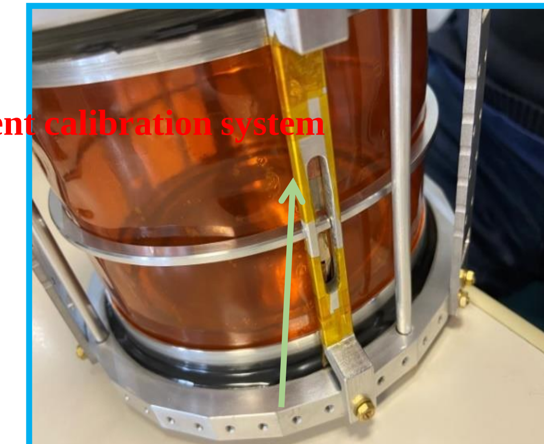


Refined calibration system : 7 (8) movable fluorescent foils



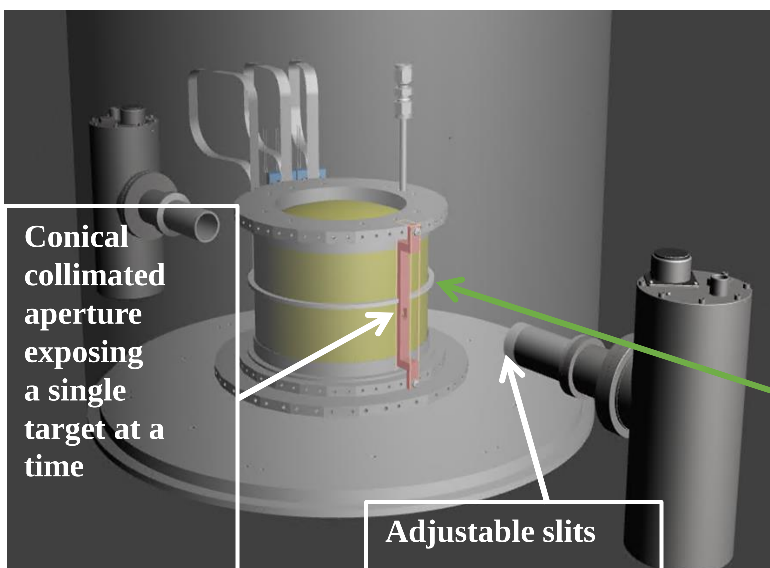


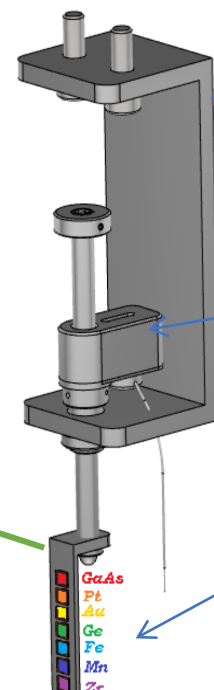
Current calibration system



Ti, Cu, Zr calibration foils holder

Upgraded calibration system



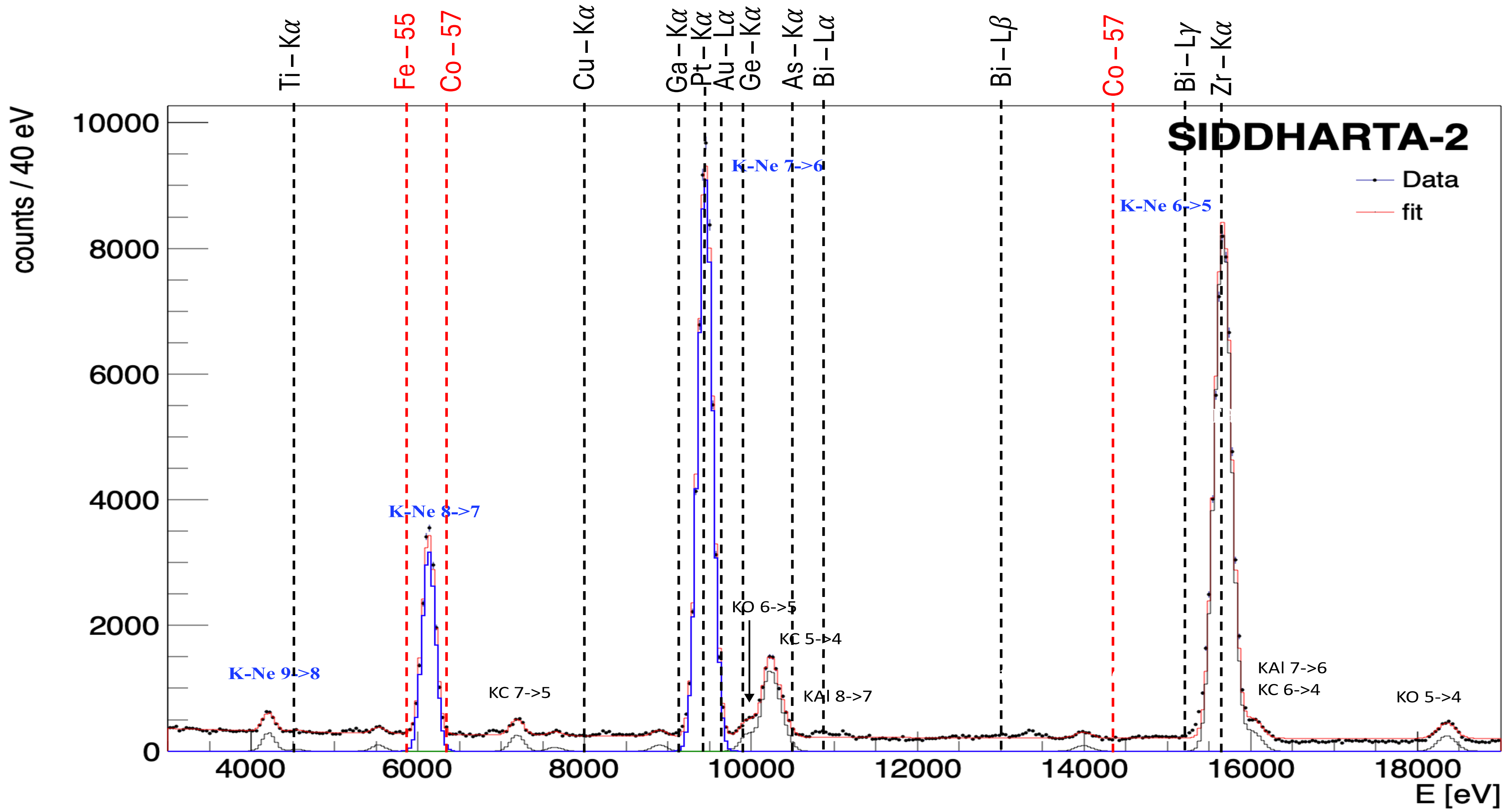


Holding structure

Actuator motor and gear box

Movable targets arm inserted behind the collimator.
Selected materials:
GaAs, Pt, Au, Ge, Fe, Mn, Zr

New calibration system for a systematic error of 0.2 eV or better



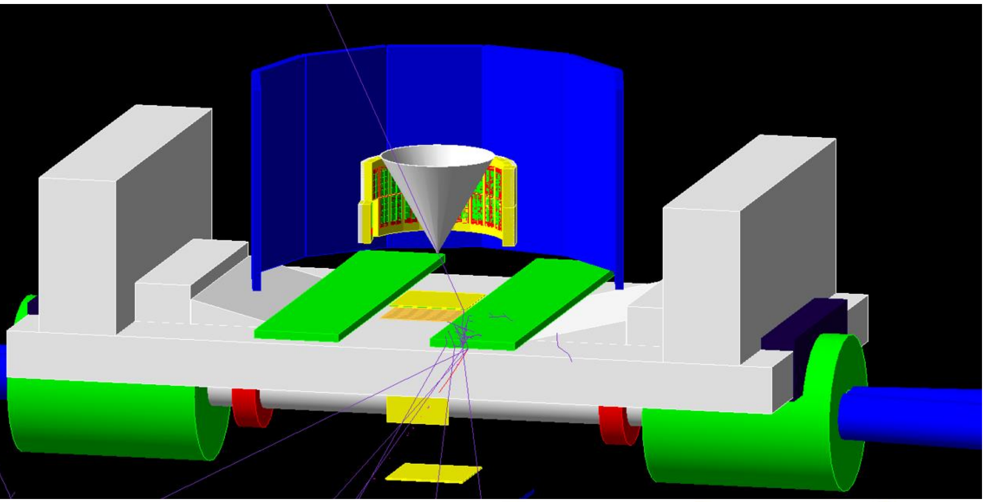
Light Mass (low-Z) Kaonic Atoms

- The second module of measurement are **light mass (Li, Be, B)** kaonic atoms, **to study in detail the strong interaction between kaon and few nucleons (many body).**

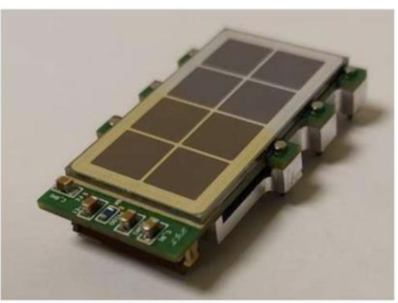
- Now precise measurements for these kaonic atoms of the shifts, widths and yields will result in a **significative improvement on the knowledge of the interactions of kaons in matter**, with a great impact on the **low energy QCD and astrophysics** (equation of state for neutron stars) .

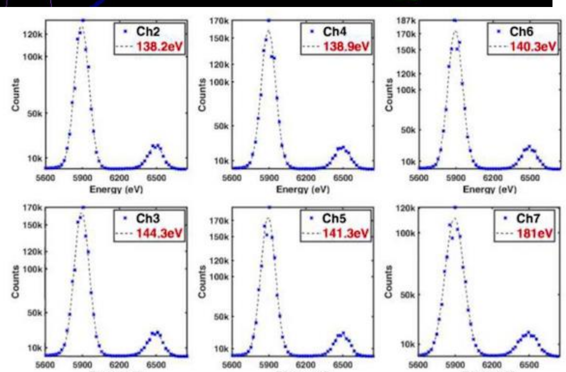
Lithium-6		Lithium-7		Beryllium-9		Boron-10		Boron-11	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
$3 \to 2$	**15.085**	**$3 \to 2$**	**15.261**	**$3 \to 2$**	**27.560**	**$4 \to 3$**	**15.156**	**$4 \to 3$**	**15.225**
$4 \to 2$	**20.365**	**$4 \to 2$**	**20.603**	**$4 \to 3$**	**9.646**	**$5 \to 3$**	**22.171**	**$5 \to 3$**	**22.273**
$5 \to 2$	**22.809**	**$5 \to 2$**	**23.075**	**$5 \to 3$**	**14.111**	$5 \to 4$	7.015	$5 \to 4$	7.047
$4 \to 3$	5.280	$4 \to 3$	5.341	$5 \to 4$	4.465	$6 \to 4$	10.826	$6 \to 4$	10.875
$5 \to 3$	7.724	$5 \to 3$	7.814	$6 \to 4$	6.890	$6 \to 5$	3.811	$6 \to 5$	3.828
$5 \to 4$	2.444	$5 \to 4$	2.472	$6 \to 5$	2.425				
$6 \to 4$	3.771	$6 \to 4$	3.815						

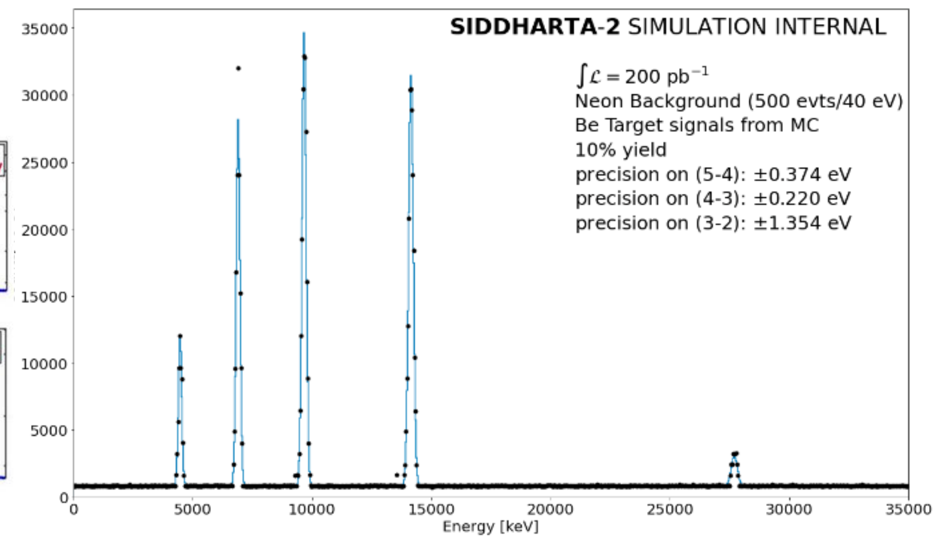
Solid targets replacing the gaseous one and possible use of 1/2 buses of 1 mm SDDs (>20 keV)



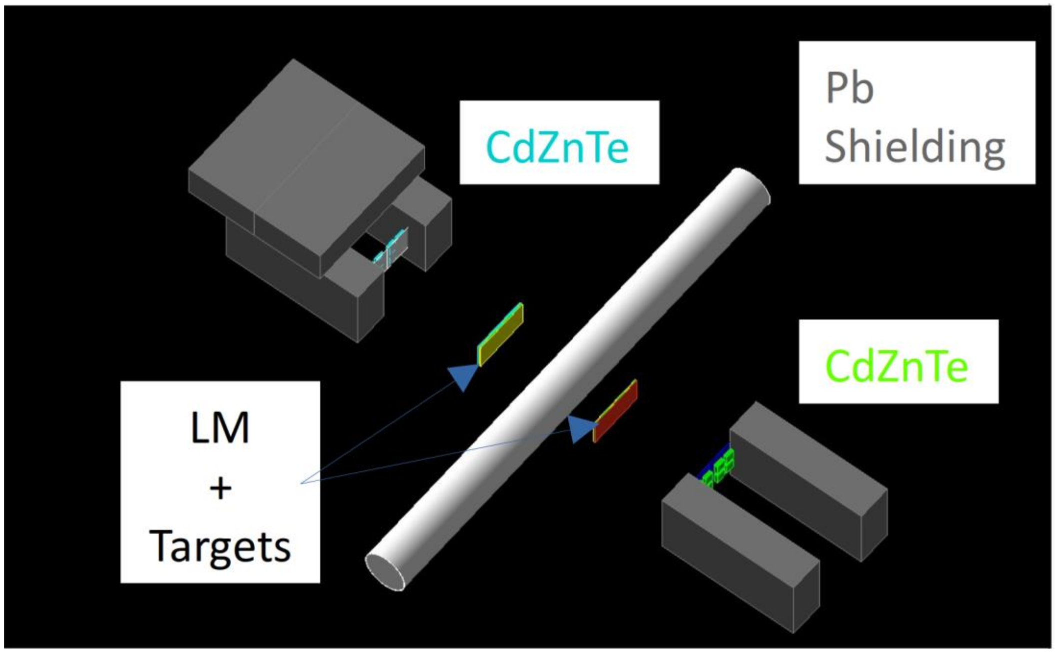
Precision measurements:
Precision below (around) eV







As a bonus: intermediate-mass kaonic atoms measurements with CdZnTe setups (same beam)



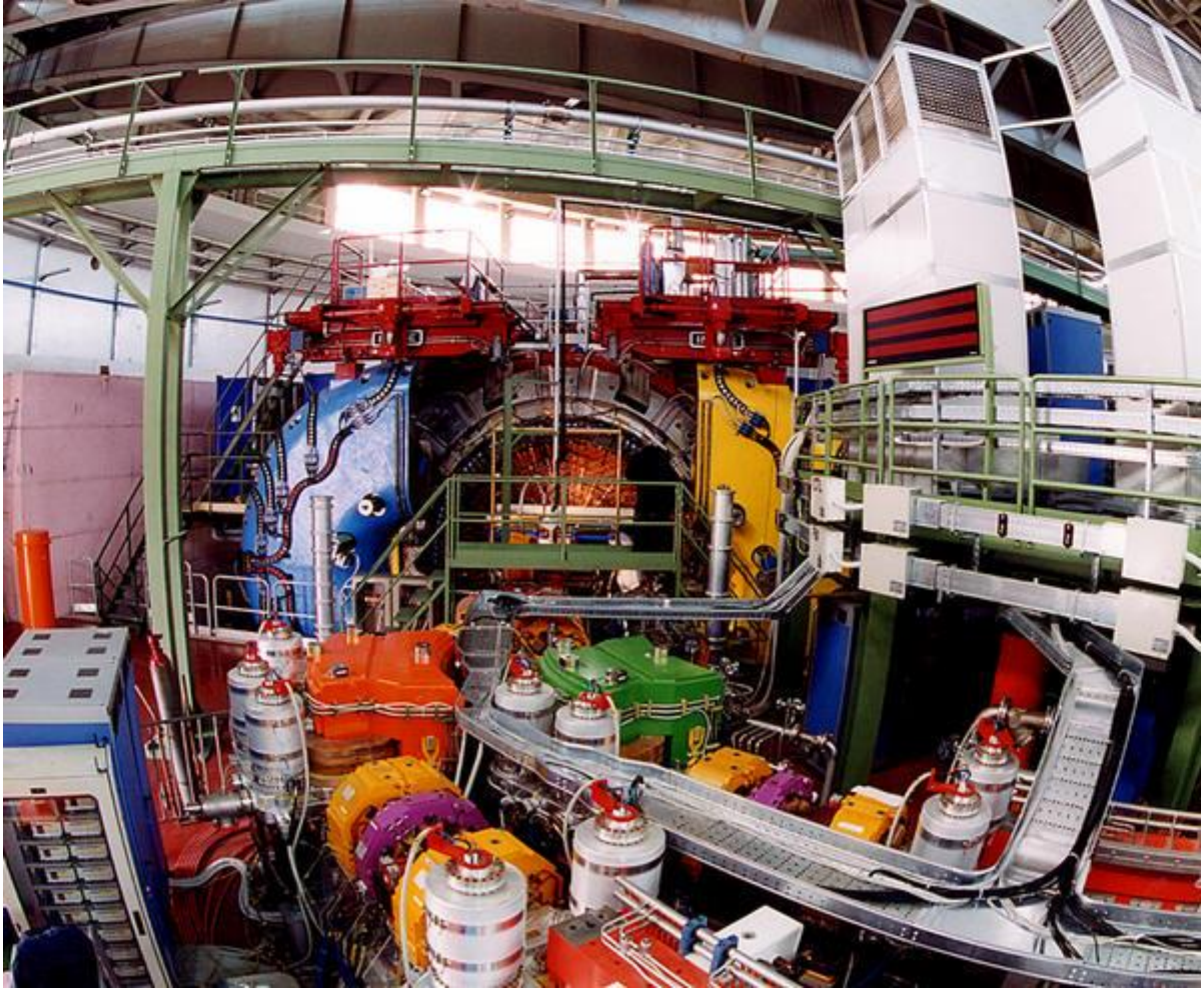
- **Kaonic Oxygen**: key role in the description of the nuclear-matter density distribution which enters in the formula for the density-dependent optical potentials
- **Kaonic Aluminium**; 3->2 QCD – never measured; 4->3 the inconsistent measurements **Kaonic Sulphur**:

S	4 → 3	−0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36	[18]
		−0.43 ± 0.12	2.310 ± 0.170	–	–	[21]
		−0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5	[19]

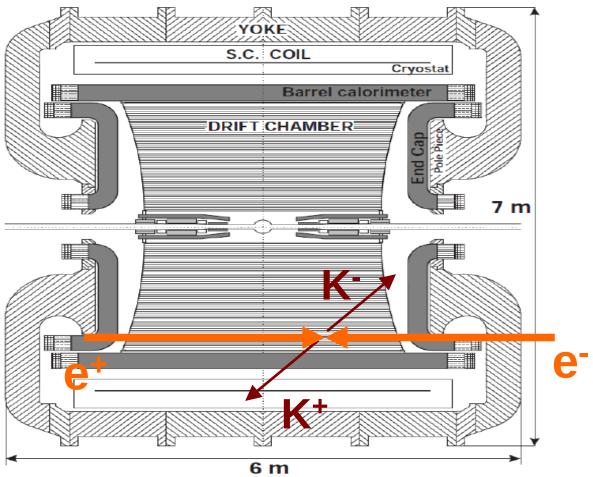
AMADEUS scientific case (with KLOE data)

AMADEUS (**A**ntikaonic **M**atter **A**t **D**AΦNE: an **E**xperiment with **U**nravelling **S**pectroscopy) investigates **low-energy K^- absorption in nuclei** with the aim to extract information on

- K^-N interaction above and below threshold
  - Λ(1405) nature
  - K^-N scattering amplitudes and cross sections
- K^-NN, K^-NNN, K^-NNNN (multi-nucleon) interactions
  - K^--multi nucleon cross sections
  - essential for the determination of K^--nuclei optical potential
  - kaonic bound states
- Hyperon-nucleon/(multi-nucleons) interaction cross sections



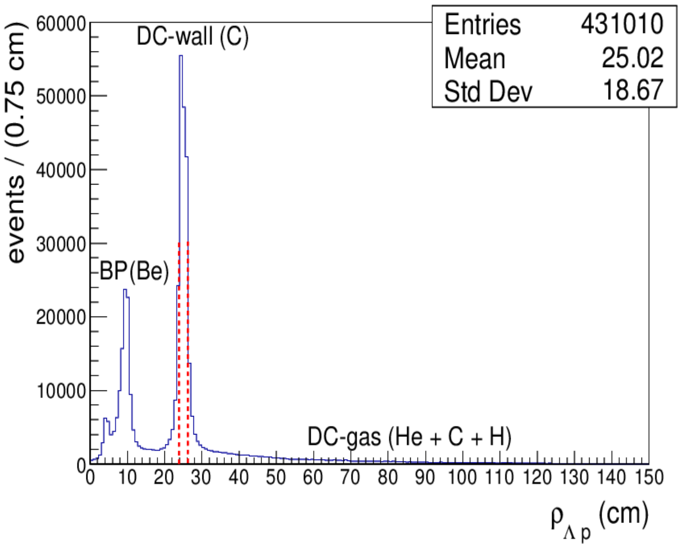
The KLOE detector



Cylindrical drift chamber with a **4π geometry** and electromagnetic calorimeter, **96% acceptance**

- optimized in the energy range of all **charged particles** involved
- **good performance** in detecting **photons and neutrons** checked by kloNe group

[M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)]



KLOE used as an active target

- DC wall (750 μm C foil , 150 μm Al foil);
- DC gas (90% He, 10% C_4H_{10}).

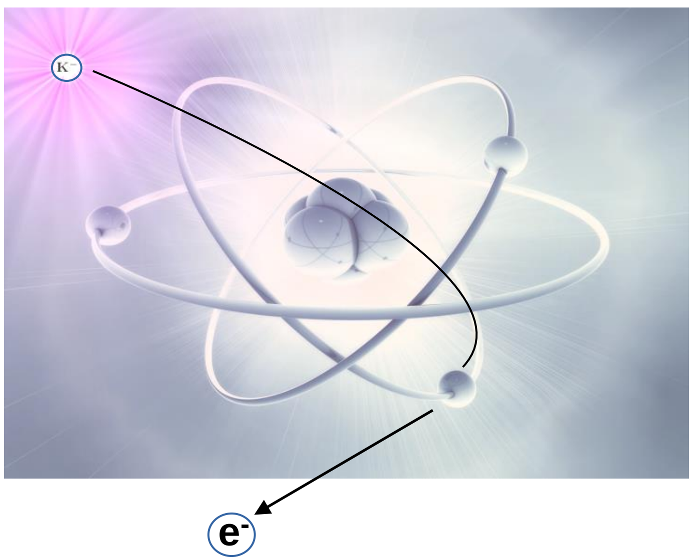
  \+

  pure sample of K^- ^{12}C absorptions at-rest

K^- absorptions at-rest and in-flight

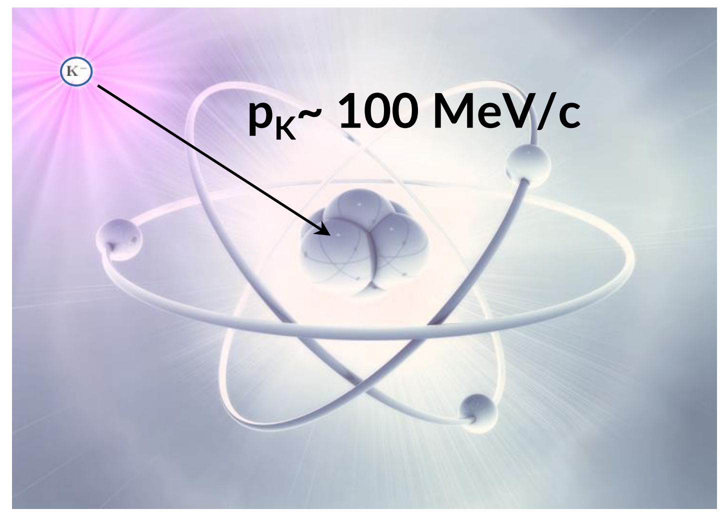
AT-REST

K^- absorbed from atomic orbitals
(p_K ~ 0 MeV/c)



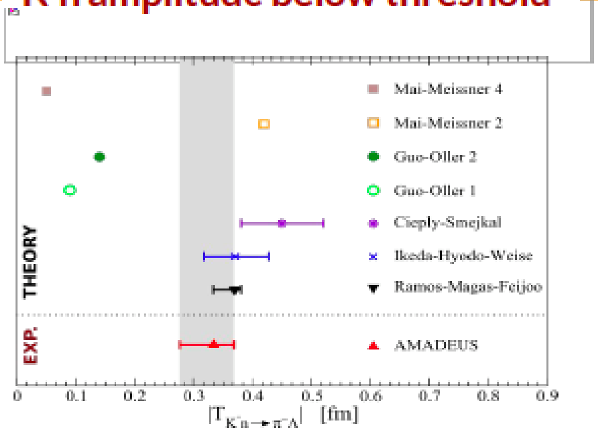
IN-FLIGHT

(p_K~ 100 MeV/c)



Highlights of AMADEUS results

$K^- n$ amplitude below threshold



Λ p channel: 2NA, 3NA and 4NA BRs and σ

Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) $\pm$ 6 (syst.)	@	128 ± 29
2NA-QF Σ^0p	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)	3.9 ± 1.0 (stat.) $^{+1.4}_{-0.7}$ (syst.)	@	128 ± 29
2NA-FSI Σ^0p	7.2 ± 2.2(stat.) $^{+4.2}_{-5.4}$(syst.)	80 ± 25 (stat.) $^{+46}_{-60}$ (syst.)	@	128 ± 29
2NA-CONV Σ/Λ	2.1 ± 1.2(stat.) $^{+0.9}_{-0.5}$(syst.)	-		
3NA Λpn	1.4 ± 0.2(stat.) $^{+0.1}_{-0.2}$(syst.)	15 ± 2 (stat.) $\pm$ 2 (syst.)	@	117 ± 23
3NA Σ^0pn	3.7 ± 0.4(stat.) $^{+0.2}_{-0.4}$(syst.)	41 ± 4 (stat.) $^{+2}_{-5}$ (syst.)	@	117 ± 23
4NA Λpnn	0.13 ± 0.09(stat.) $^{+0.08}_{-0.07}$(syst.)	-		
Global $\Lambda(\Sigma^0)$p	21 ± 3(stat.) $^{+5}_{-6}$(syst.)	-		

The ratio between the branching ratios of the 2NA-QF in the Λp channel and in the Σ^0p is measured to be:

$$\mathcal{R} = \frac{BR(K^-pp \to \Lambda p)}{BR(K^-pp \to \Sigma^0 p)} = 0.7 \pm 0.2(stat.)^{+0.2}_{-0.3}(syst.)$$

$$\mathrm{BR}(K^-2NA \to YN) = (21.6 \pm 2.9(stat.)^{+4.4}_{-5.6}(syst.))\%$$

K- p -> $(\Sigma^0/\Lambda)\ \pi^0$

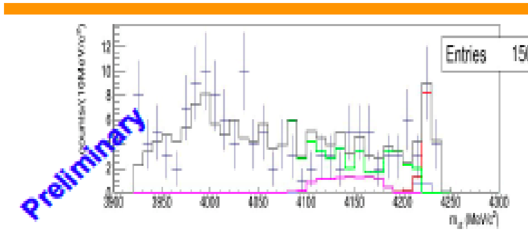
cross section at p_{K^-} = 98 ± 10 MeV/c :

- $\sigma_{K^-p\to\Sigma^0\pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)$ mb
- $\sigma_{K^-p\to\Lambda\pi^0} = 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)$ mb,

Λ t channel: 4NA BRs and σ

$BR(K^-\,{}^4He(4NA) \to \Lambda t) < 2.0 \times 10^{-4}/K_{stop}$ (95% c. l.)

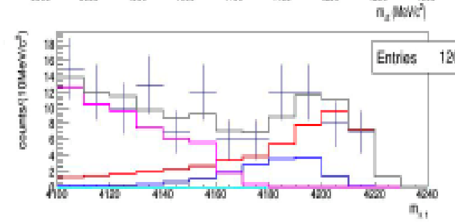
$\sigma(100 \pm 19$ MeV/c$)$ $(K^-\,{}^4He(4NA) \to \Lambda t) = (0.81 \pm 0.21$ (stat) $^{+0.03}_{-0.04}$ (syst)) mb



$BR(K^-\,{}^{12}C(4NA) \to \Lambda t\,{}^8Be) = 1.5 \pm 0.5 \times 10^{-4}$ (stat) $/K_{stop}$

$\sigma(K^-\,{}^{12}C\,(4NA) \to \Lambda t\,{}^8Be) = 0.58 \pm 0.11$ (stat) mb

$\sigma(K^-\,{}^{12}C\,(4NA) \to \Sigma^0 t\,{}^8Be) = 1.88 \pm 0.35$ (stat) mb



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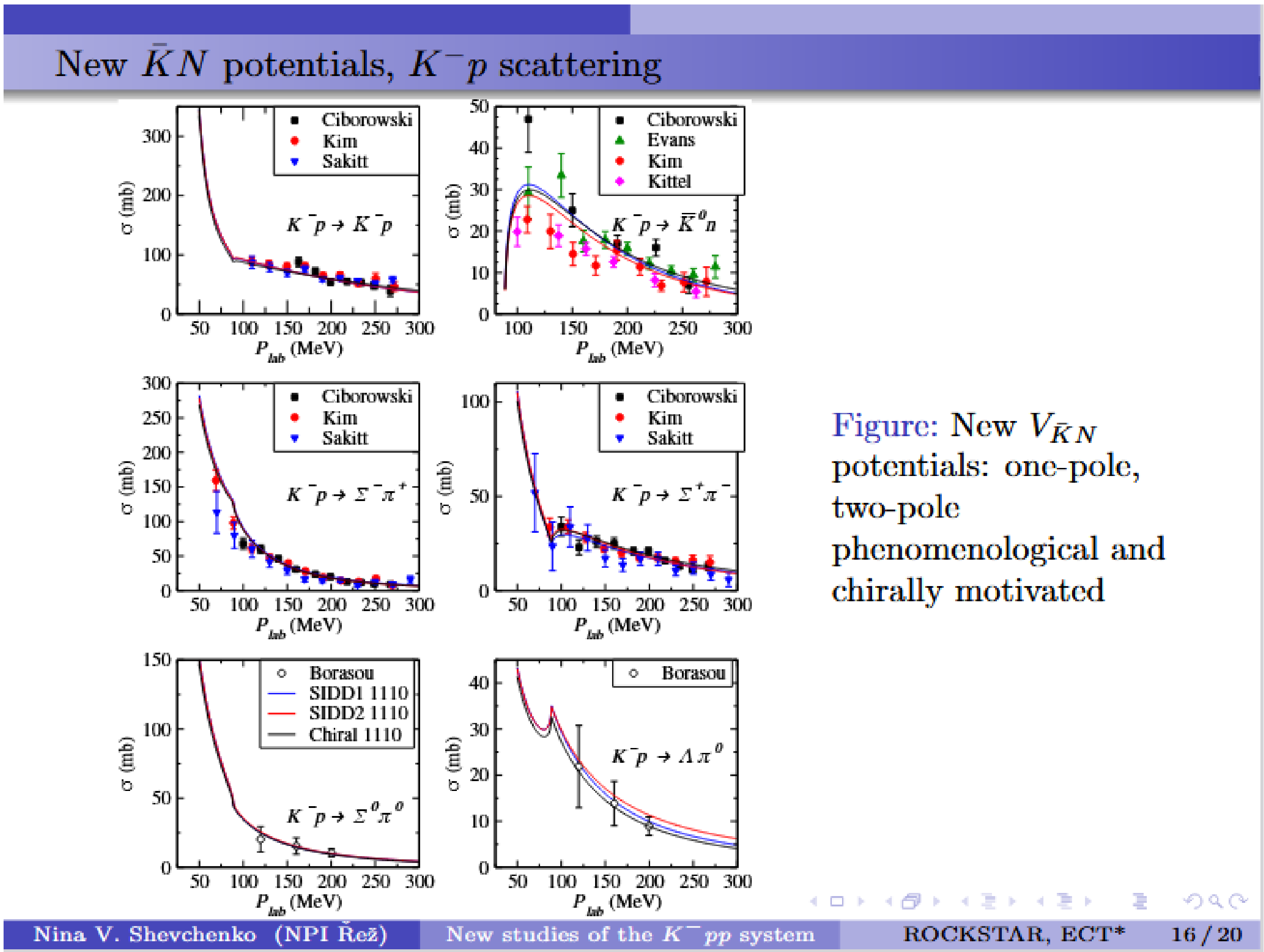
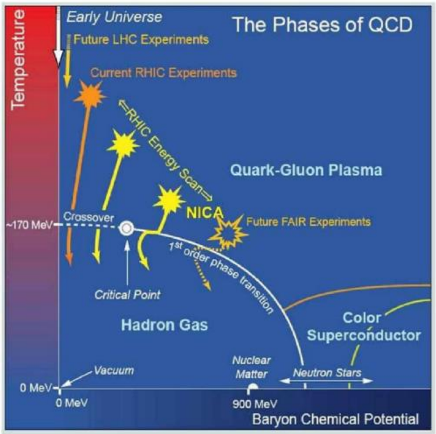
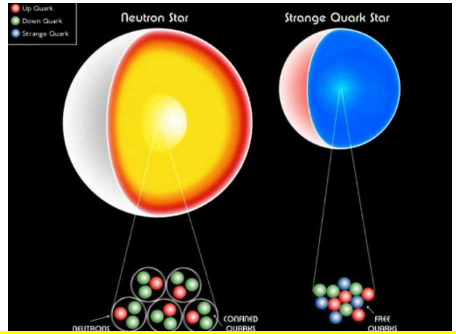
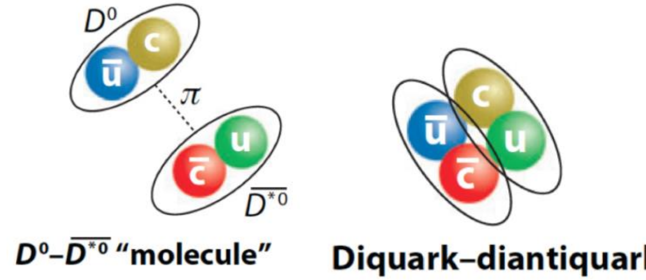
Future perspectives

- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited: below 150 MeV/c there is a “desert” - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.
- **Kaon-nucleon scattering/interaction data are fundamental to validate theories: chiral symmetries; lattice calculations; potential models etc.**





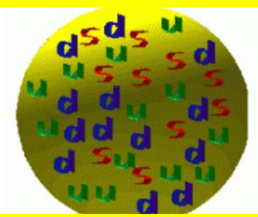




Neutron star EOS

Particles structure

Cold Dense matter

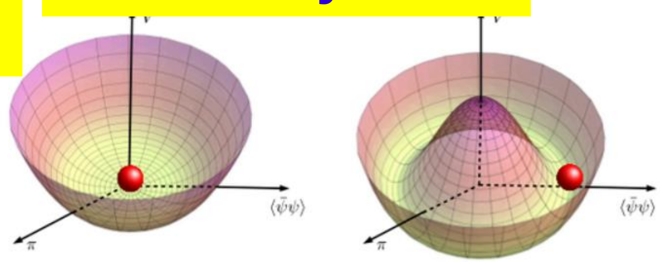


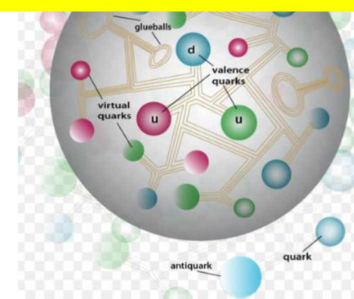
Strangeness Fundamental Physics

Mass generation, visible Universe

QCD
Chiral symm.

Strangelets & Dark Matter





ThanK You

Immortals are never alien to one another.

— Homer, The Odyssey

Grazie Carlo!

Kaonic deuterium data analysis – Run1

First run

200 pb^{-1}