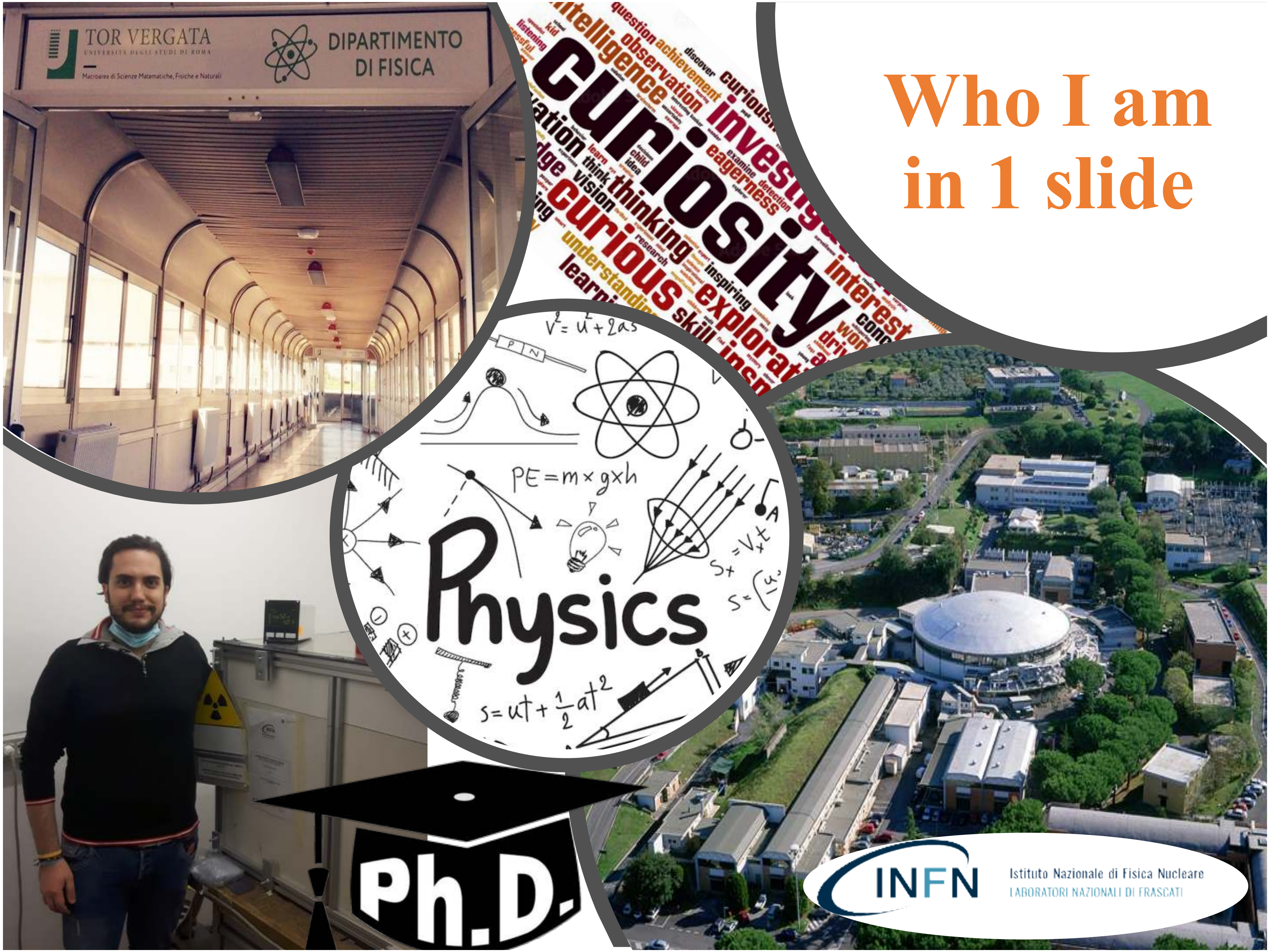
Unravelling the Secrets of the Strong Force: The SIDDHARTA-2 Experiment at the DAΦNE Collider

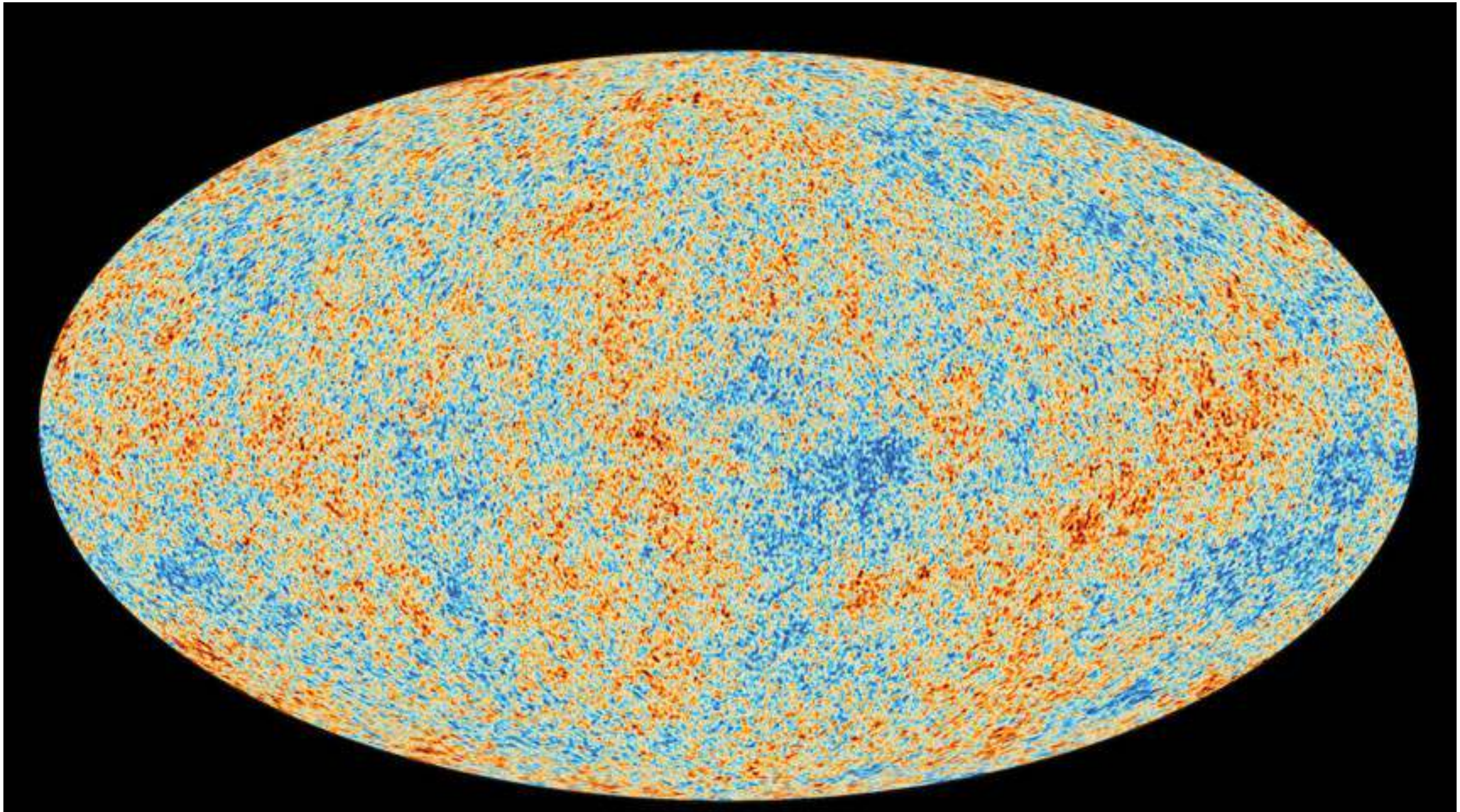
Francesco Sgaramella

INSPYRE, March 27-31, 2023

Who I am in 1 slide



The Universe



Plank telescope, the cosmic microwave background

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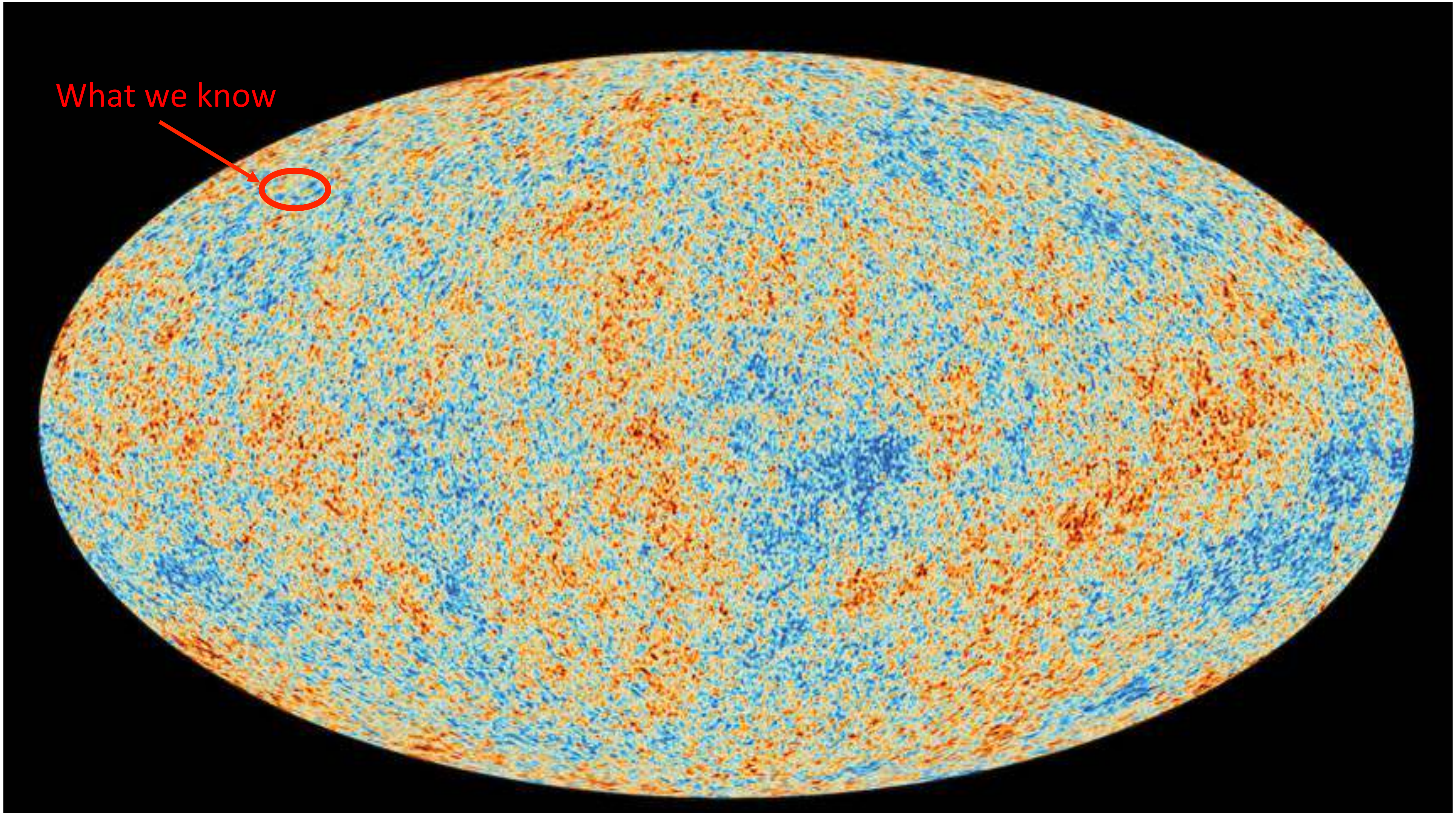

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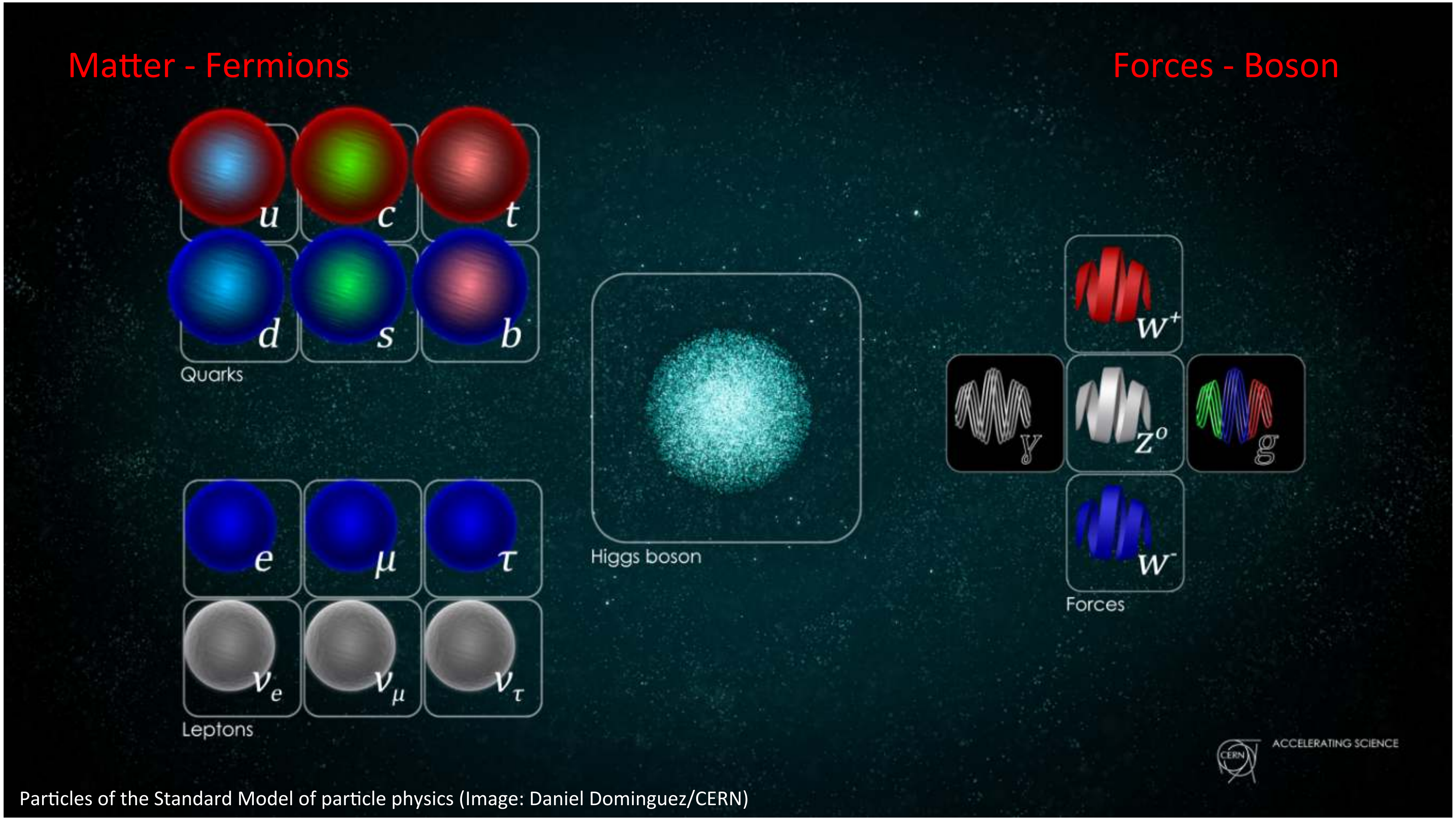
The Standard Model

"the Standard Model is currently the best description there is of the subatomic world, but it does not explain the complete picture"



Particles of the Standard Model of particle physics (Image: Daniel Dominguez/CERN)

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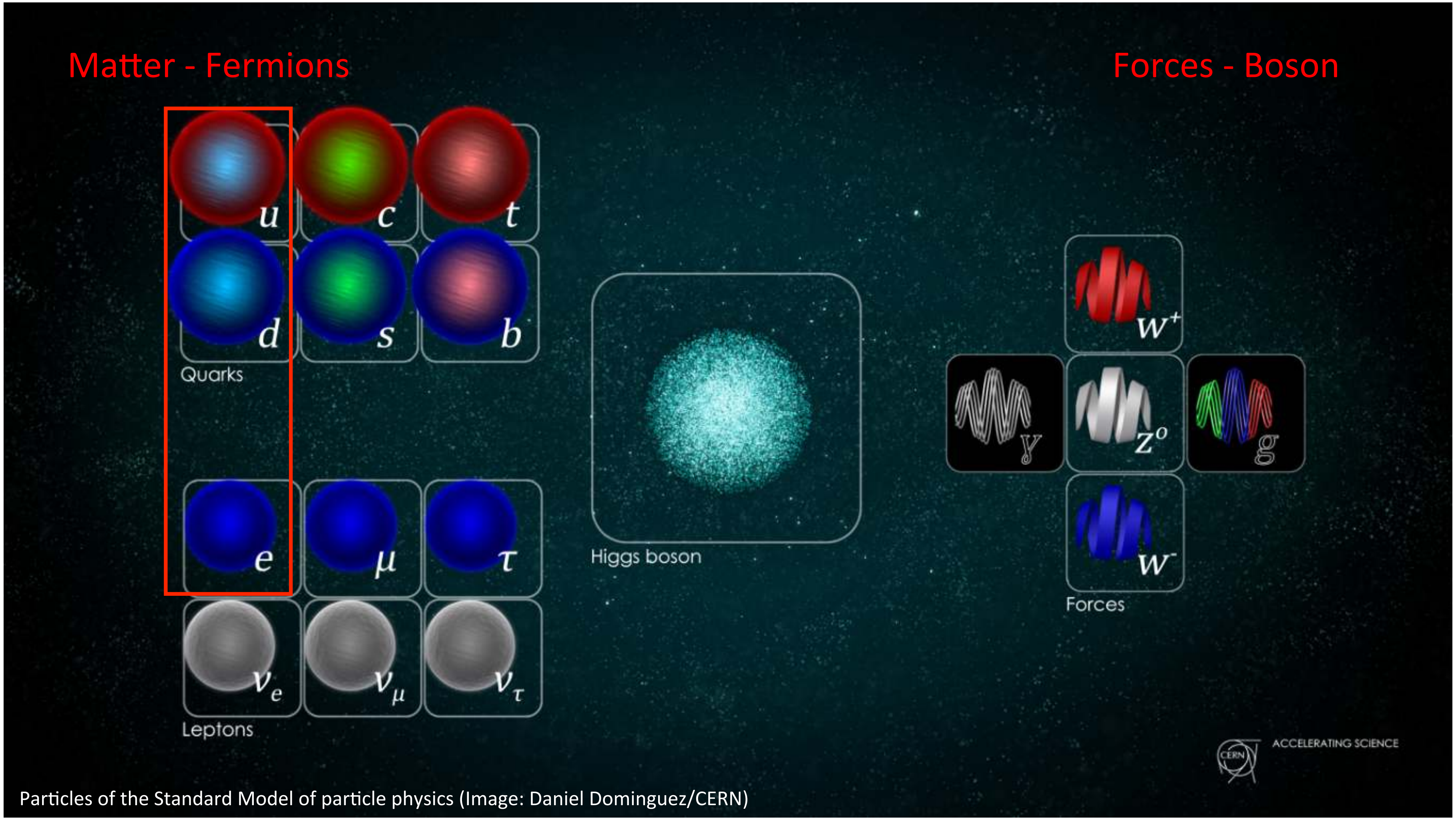

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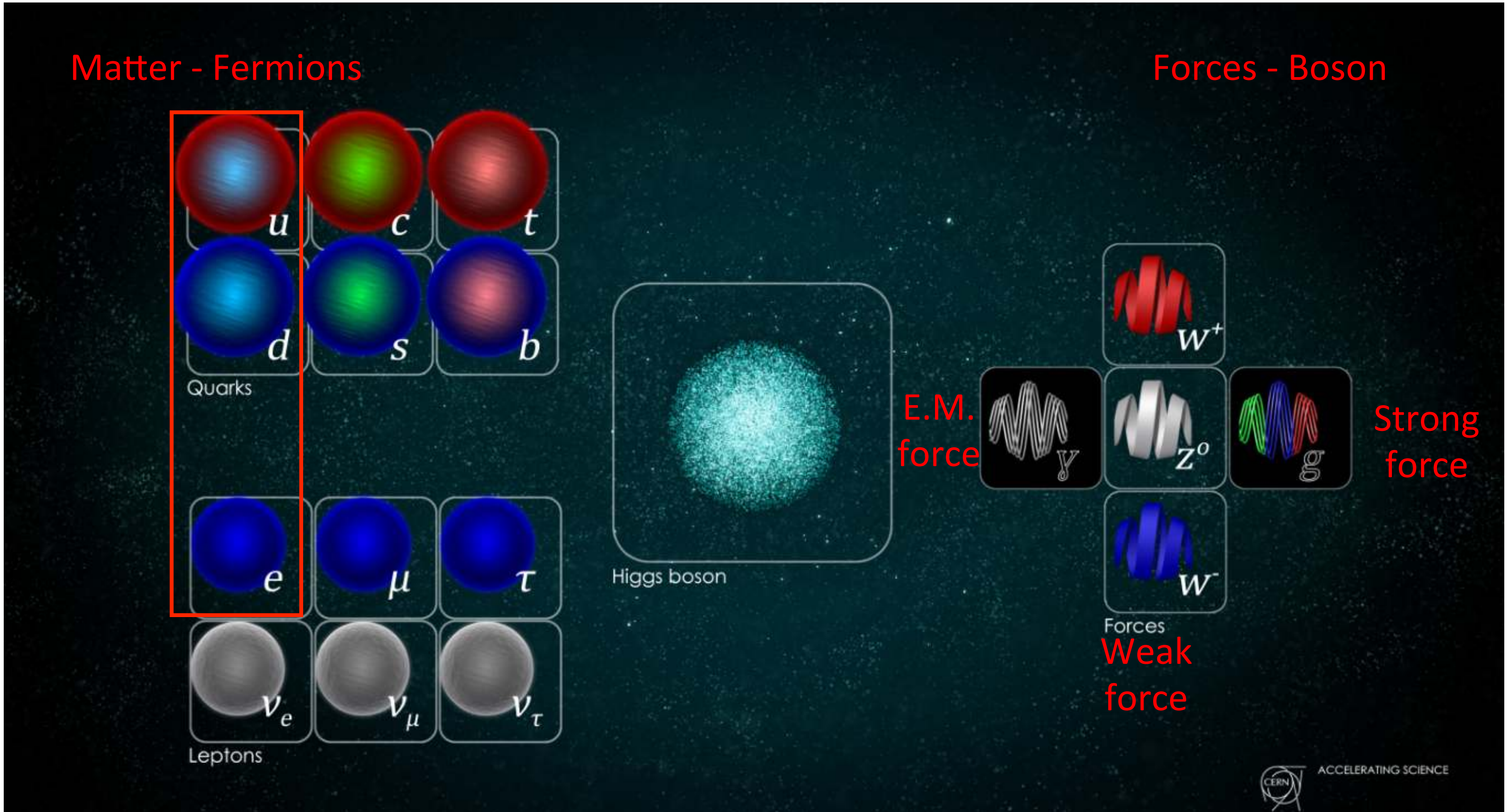
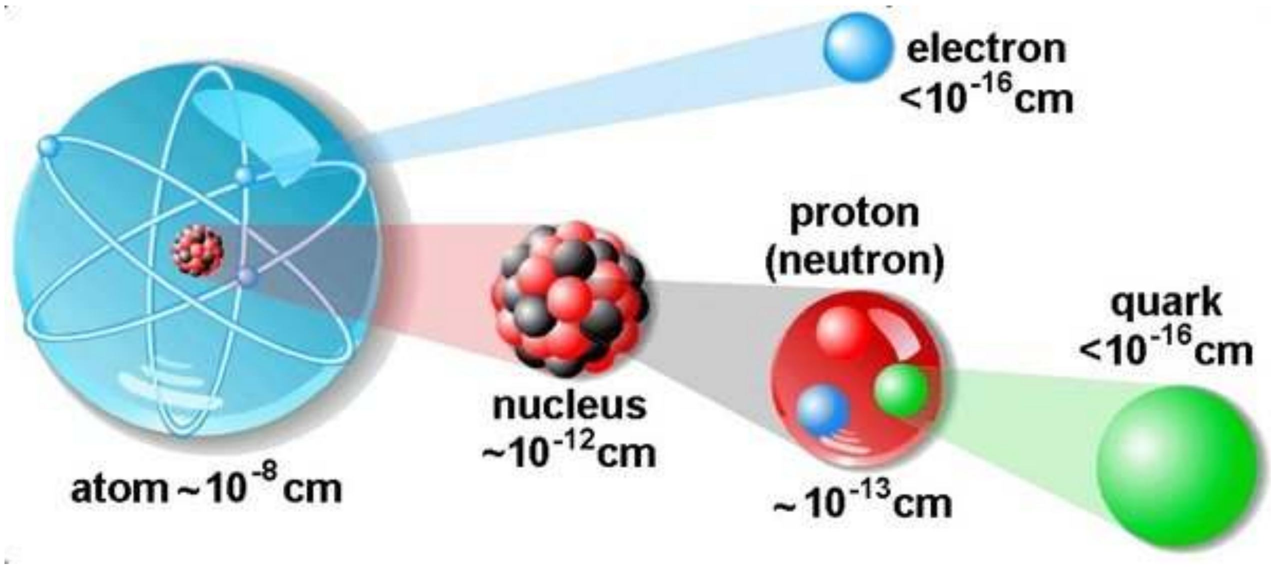


Particles of the Standard Model of particle physics (Image: Daniel Dominguez/CERN)

Why do protons and neutrons bind together in the nucleus?



- **Electromagnetic repulsion**: no force on neutron, but protons should repel each other violently
- **Gravity** weaker than electromagnetic force

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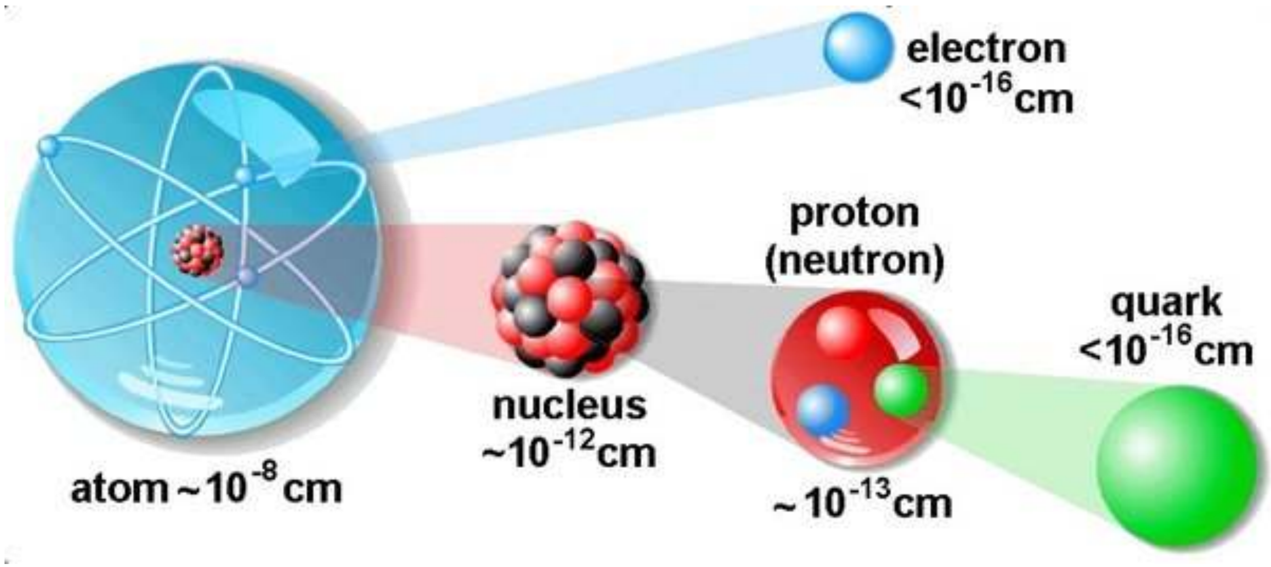

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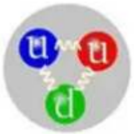
Need of a force stronger than E.M repulsion

The Strong Force

The Strong Force

Hadrons

Baryons are composed of three quarks



Baryons

Mesons are composed of one quark and one antiquark

Mesons

Nucleons

Particle	Mass (MeV/c^2)	τ (sec)
p	938.2	$>10^{11}$
n	939.5	10^3

Hyperons

Particle	Mass (MeV/c^2)	τ (sec)
Λ	1115	2.6×10^{-10}
Σ^+	1189	0.8×10^{-10}
Σ^0	1192	10^{-14}
Σ^-	1197	1.6×10^{-10}
Ξ^0	1314	3×10^{-10}
Ξ^-	1321	1.8×10^{-10}
Ω^-	1675	1.3×10^{-10}

Pions

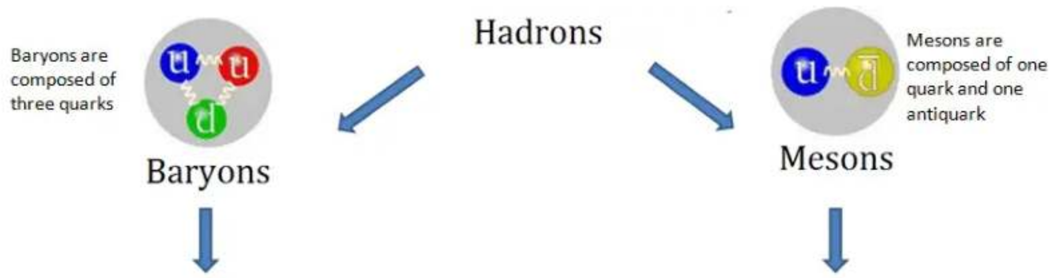
Particle	Mass (MeV/c^2)	τ (sec)
π^-, π^+	139	2.5×10^{-8}
π^0	135	1.8×10^{-16}

Kaons

Particle	Mass (MeV/c^2)	τ (sec)
K^-, K^+	494	1.2×10^{-8}
K^0	498	
η	550	10^{-18}

- The strong force acts **directly between quarks**. This force **holds quarks together** to form protons, neutrons, and other hadron particles.
- **The Strong Force** is a very short range (less than about 0.8 fm, the radius of a nucleon)
- the strong interaction is a very complicated interaction because it significantly varies with distance. At distances comparable to the diameter of a proton, the strong force is 100 times as strong as the electromagnetic force. However, **at smaller distances**, the strong force between quarks becomes **weaker**, this is known as **asymptotic freedom**.

The Strong Force



Nucleons

Particle	Mass (MeV/c^2)	τ (sec)

Pions

Particle	Mass (MeV/c^2)	τ (sec)

- The strong force acts **directly between quarks**. This force **holds quarks together** to form protons, neutrons, and other hadron particles.

- **Fundamental Strong Force** is a very

How can we study the strong interaction?

Hyperons

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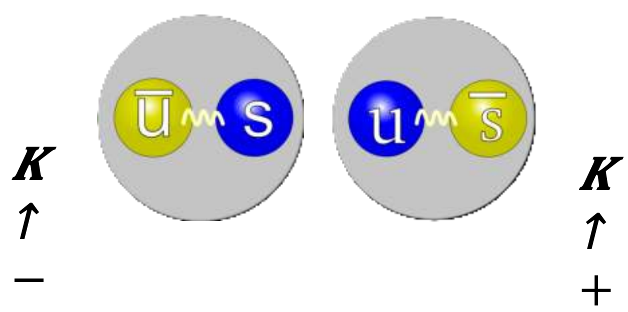

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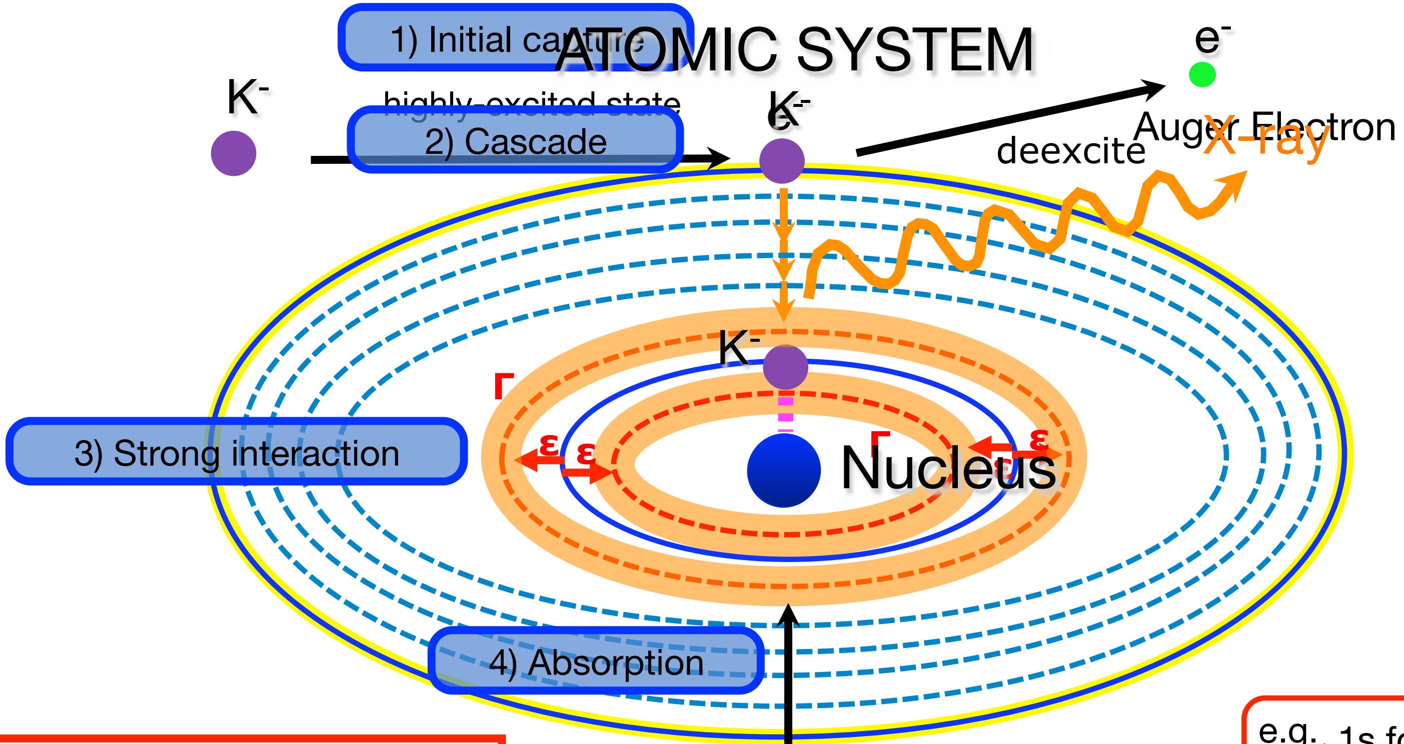
Kaonic atom

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

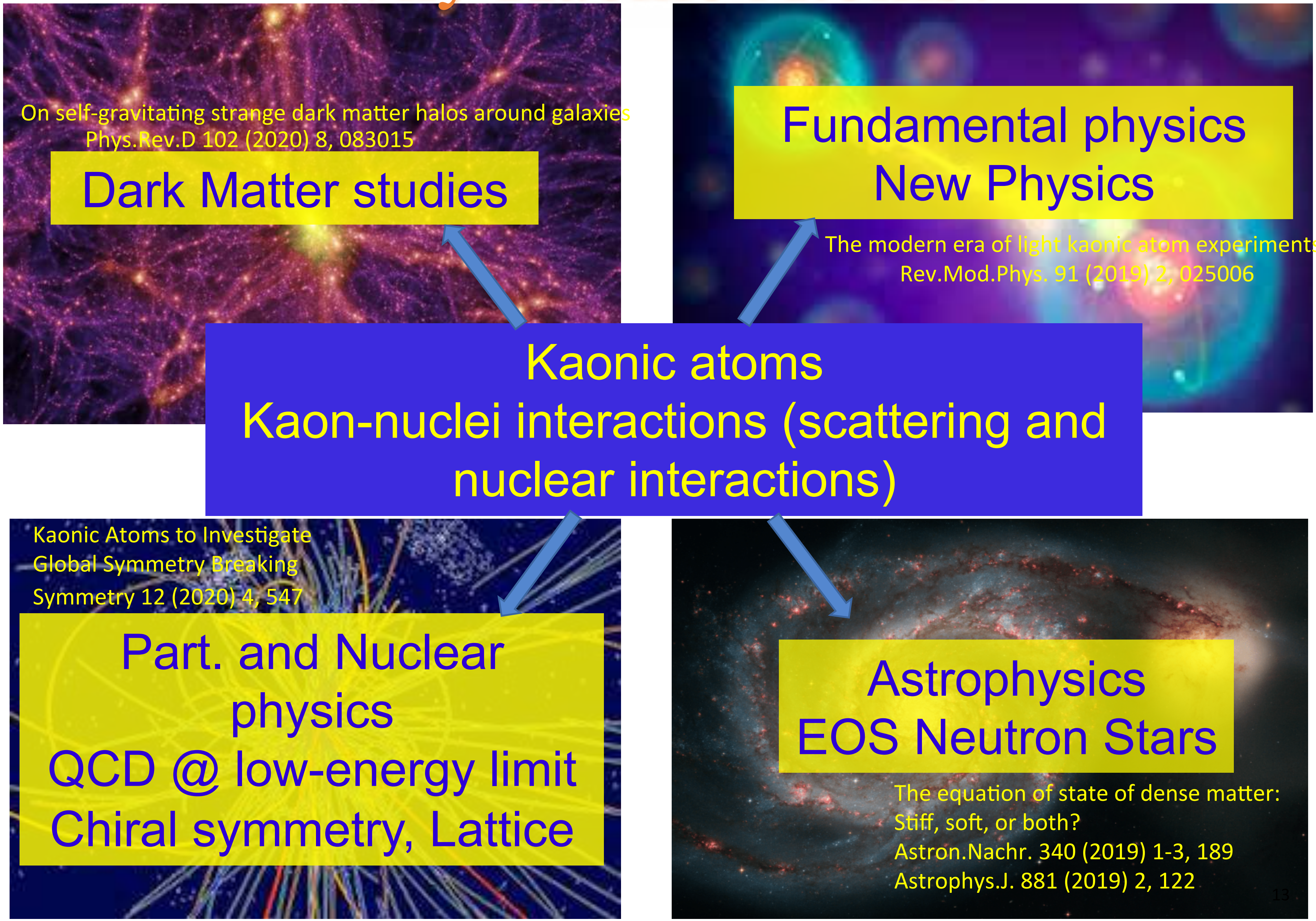


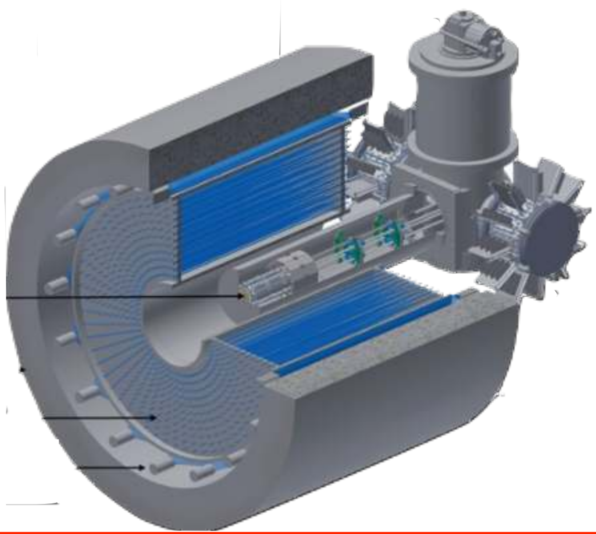
$n \sim sqrt(M^*/m_e)$ $n' \sim 25$ (for K-p)
(M^* : K-p reduced mass)

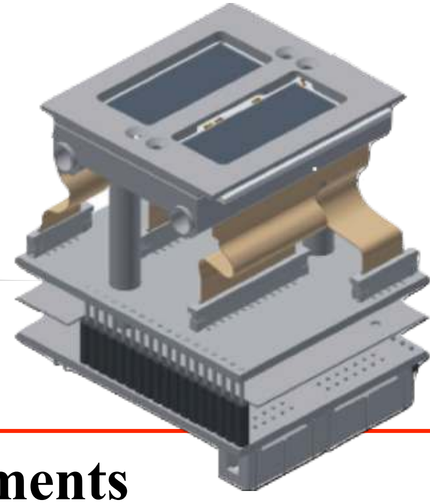
Shift (ε) and width (Γ) of the last orbit

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

Why Kaonic Atoms?



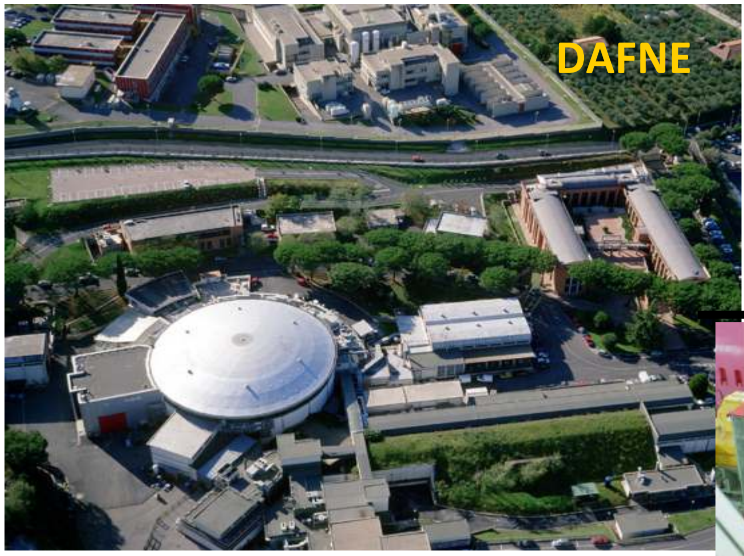




The modern era of light kaonic atom experiments

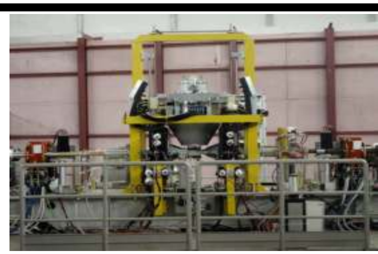
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

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



DEAR 2002

SIDDHARTA 2009



SIDDHARTA-2 2022

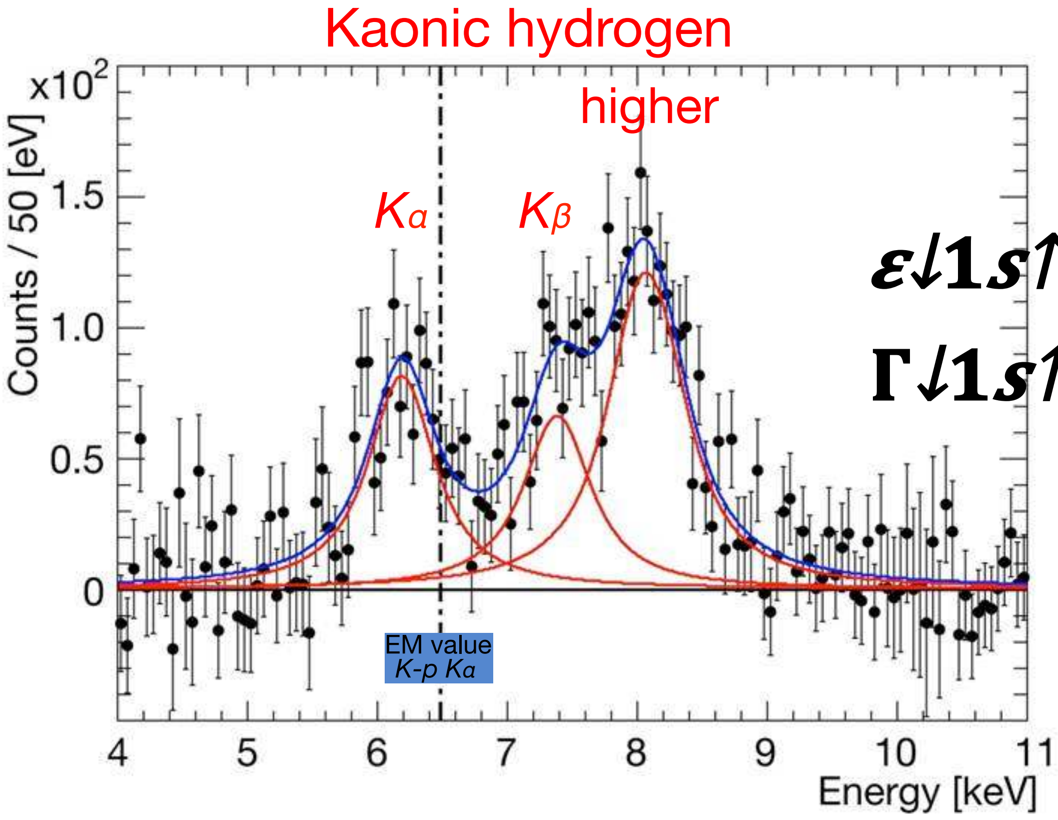
SIDDHARTA-2 Collaboration

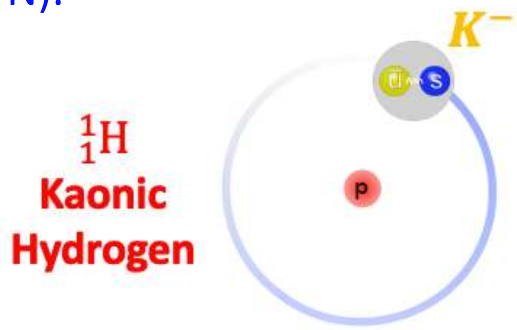
Silicon **D**rift **D**etectors for **H**adronic **A**tom
Research by **T**iming **A**pplication

- 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
- Univ. Jagiellonian Krakow, Poland
- ELPH, Tohoku University

The SIDDHARTA experiment

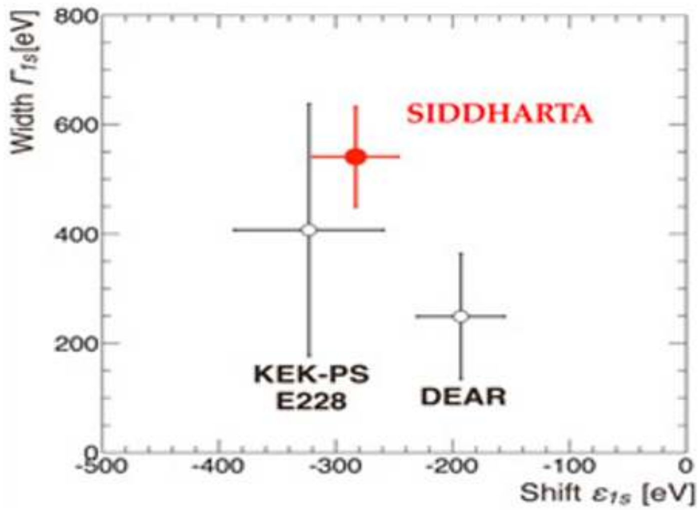
The SIDDHARTA experiment performed the first measurements of kaonic hydrogen in 2011 at National Laboratories of Frascati (LNF-INFN).





$\varepsilon\downarrow 1s\uparrow H = -283 \pm 36 (stat) \pm 6 (s$

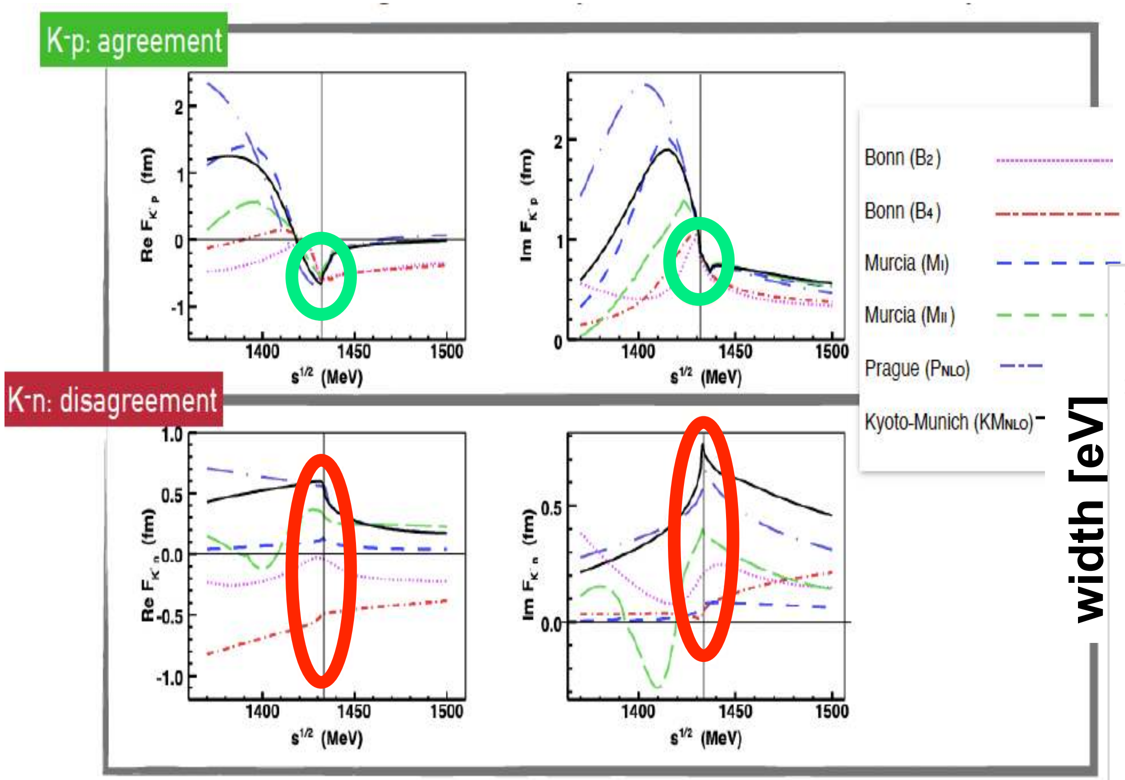
$\Gamma\downarrow 1s\uparrow H = 541 \pm 89 (stat) \pm 22 (s$



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

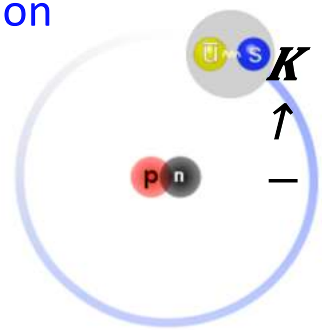
The SIDDHARTA-2 scientific goal

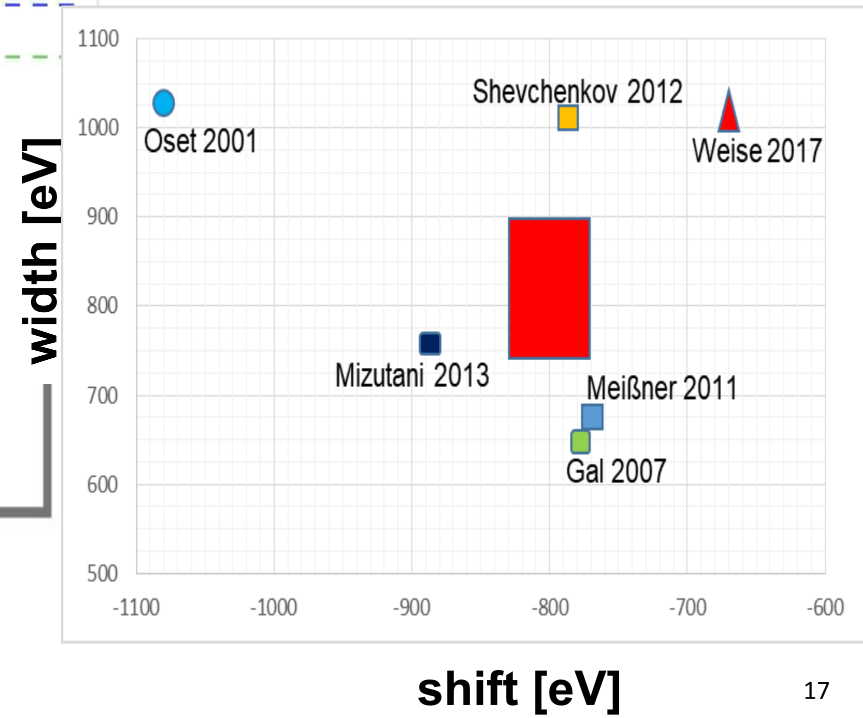
The SIDDHARTA-2 experiment aims to perform the *first measurement ever of kaonic deuterium X-ray* transition to the ground state (1s-level) such as to determine its shift and width induced by the presence of the strong interaction



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

^1↑2↓H
Kaonic Deuterium

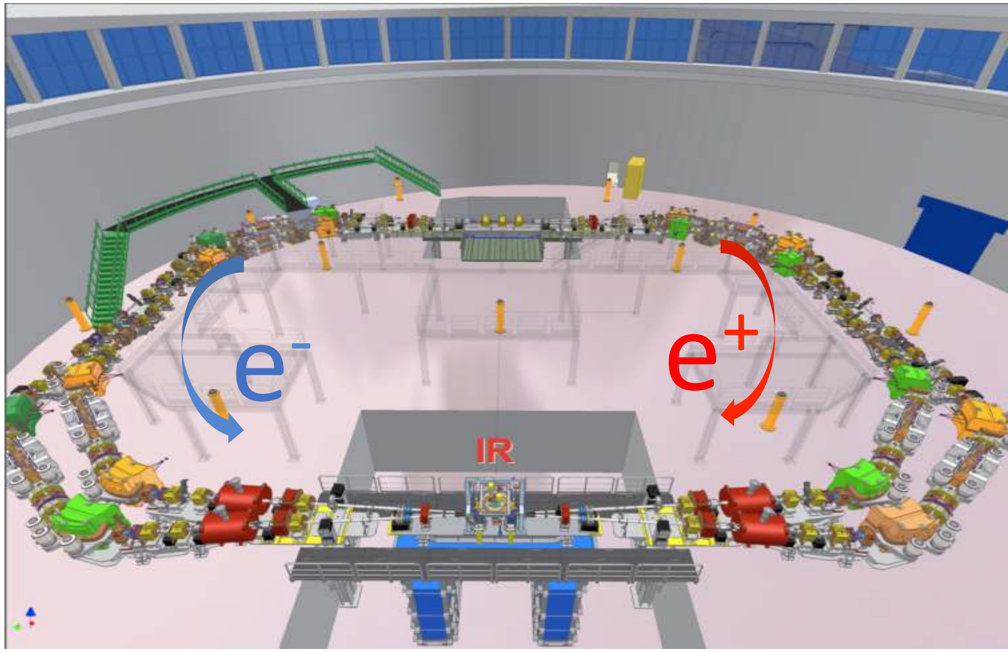


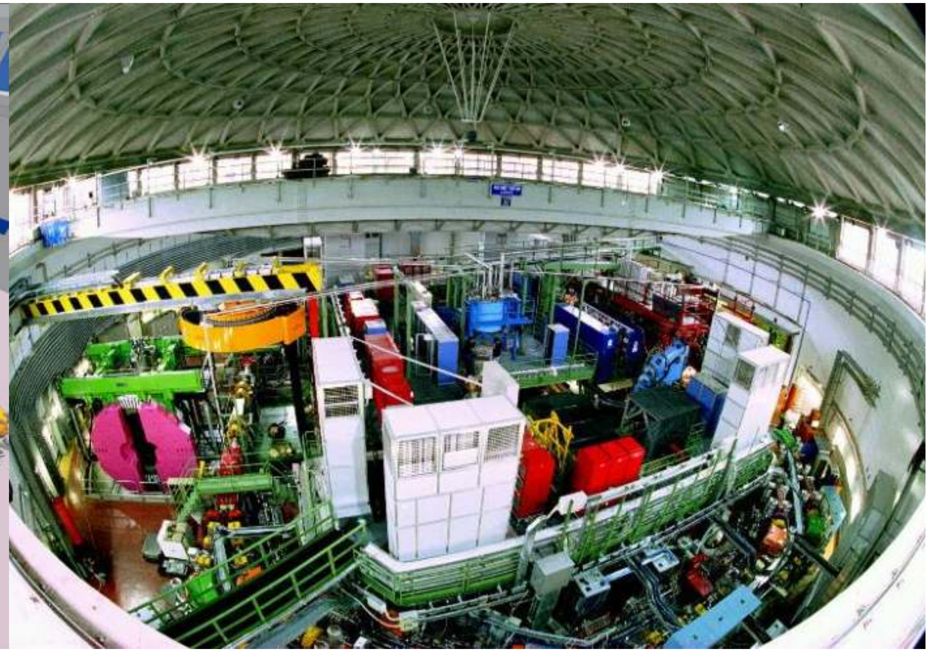


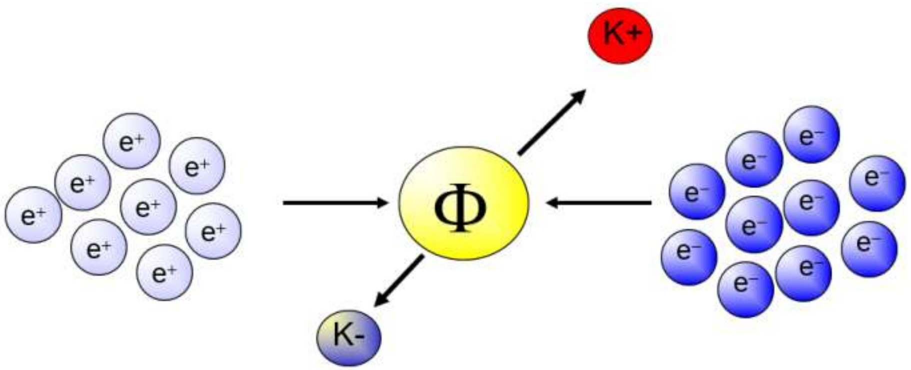
How to study kaonic atoms?

INFN-LNF
$e^+ e^-$ Accelerator Complex

The DAΦNE Collider

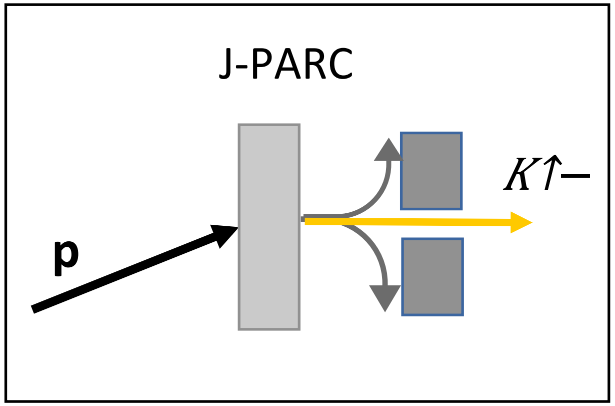






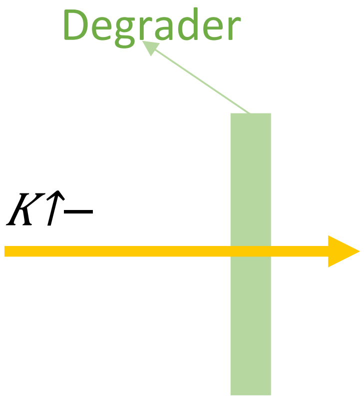
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p = 0.1\%$)
- **$\sim 360\times10^{6}$ collisions per second**
- **Flux of produced Φ: ~360/second**

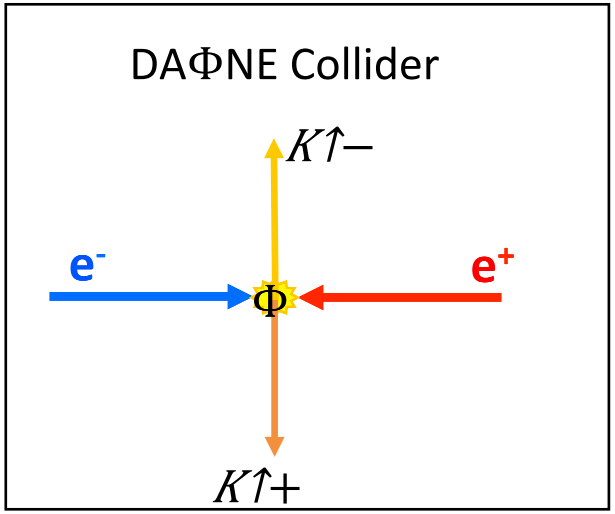
Experimental Principle



High intensity

High background



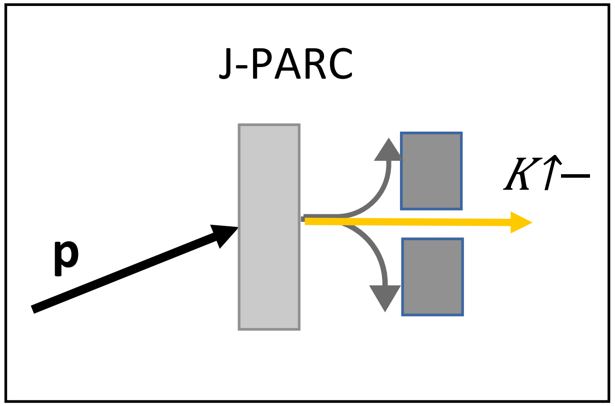


Monochromatic

Low energy kaons

Solid angle

Experimental Principle



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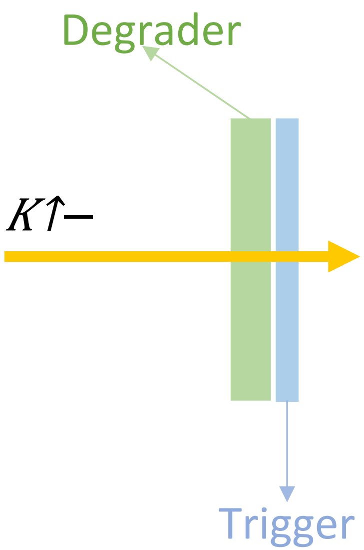

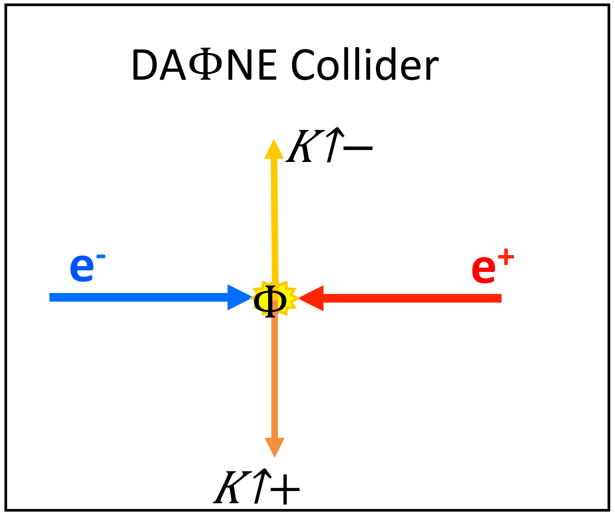

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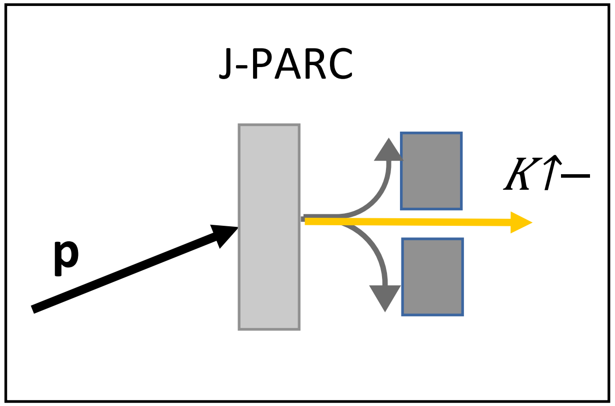

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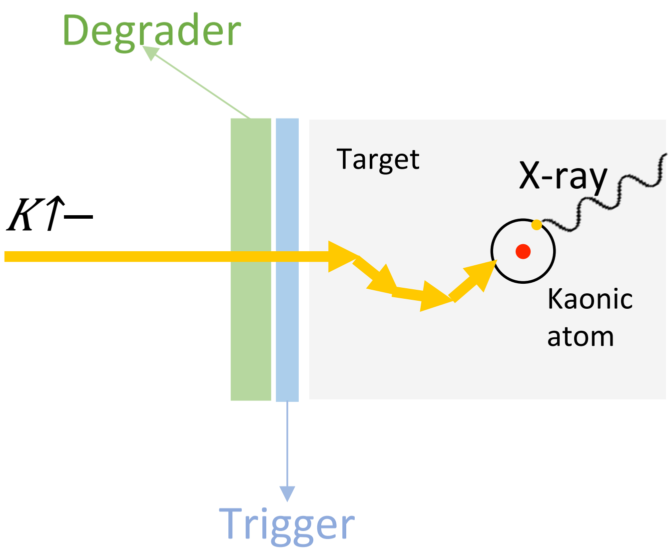

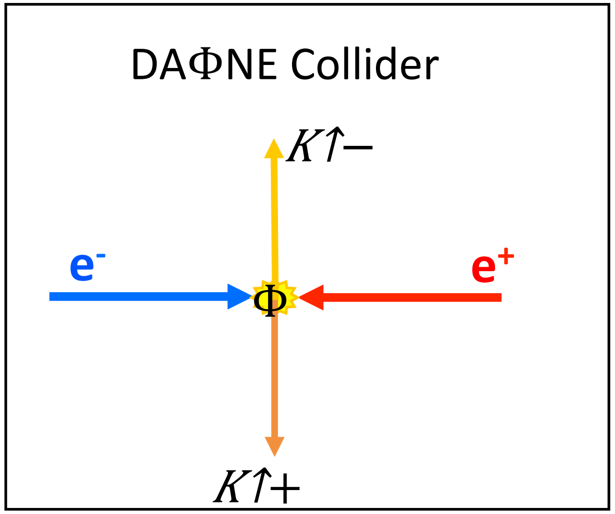

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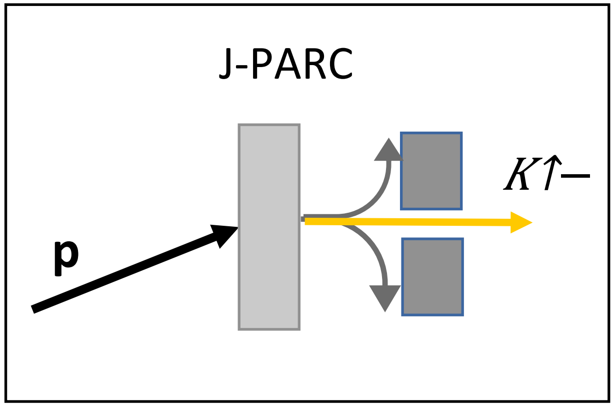

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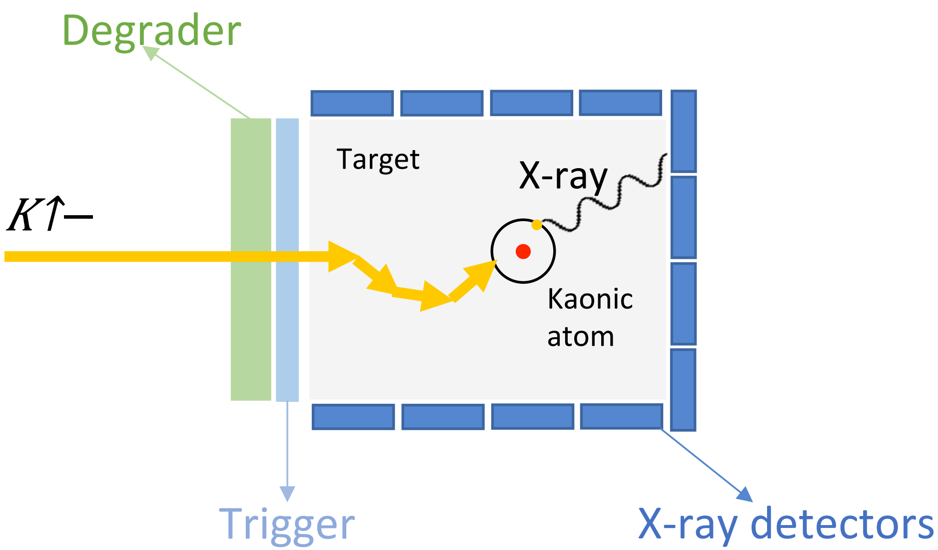

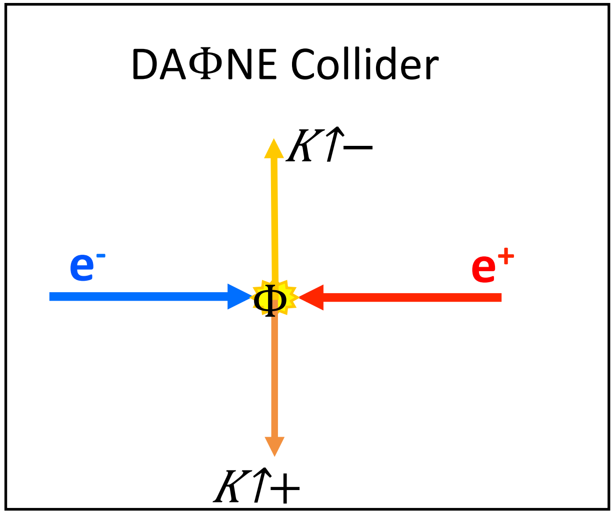

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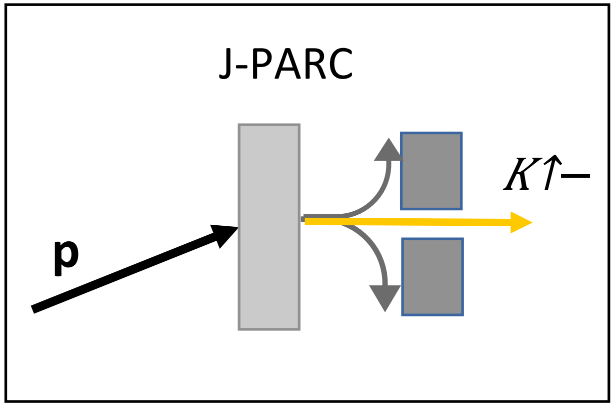

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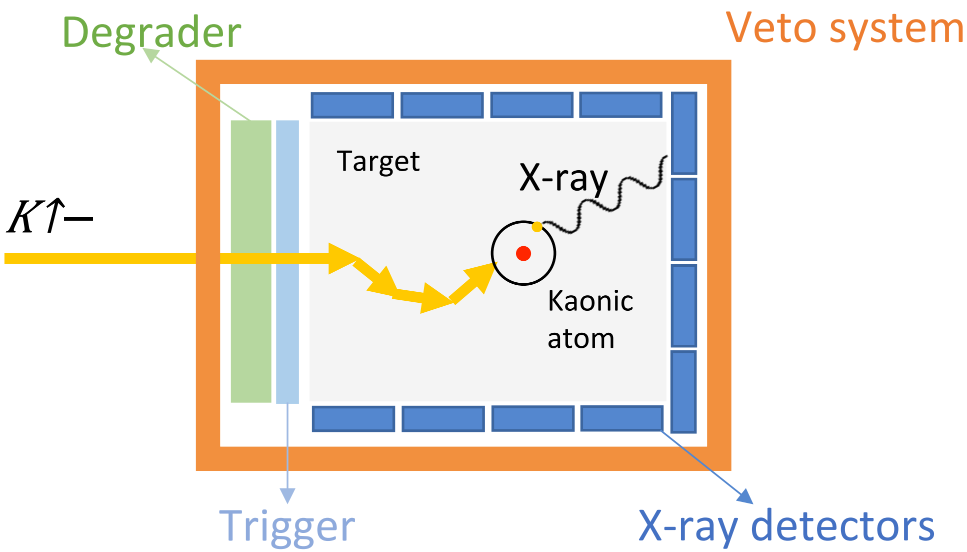

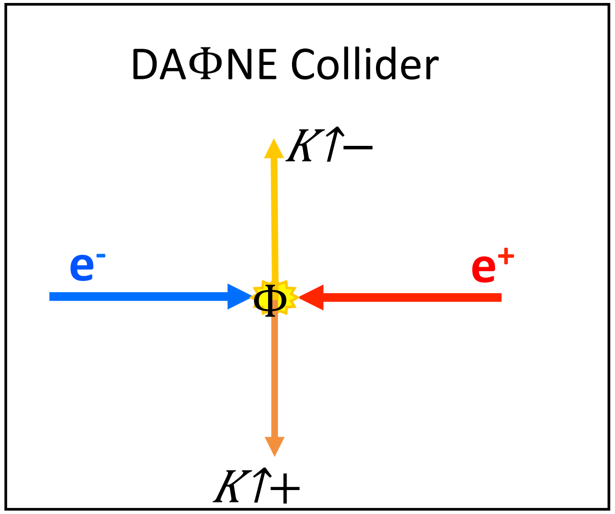

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Low energy kaons

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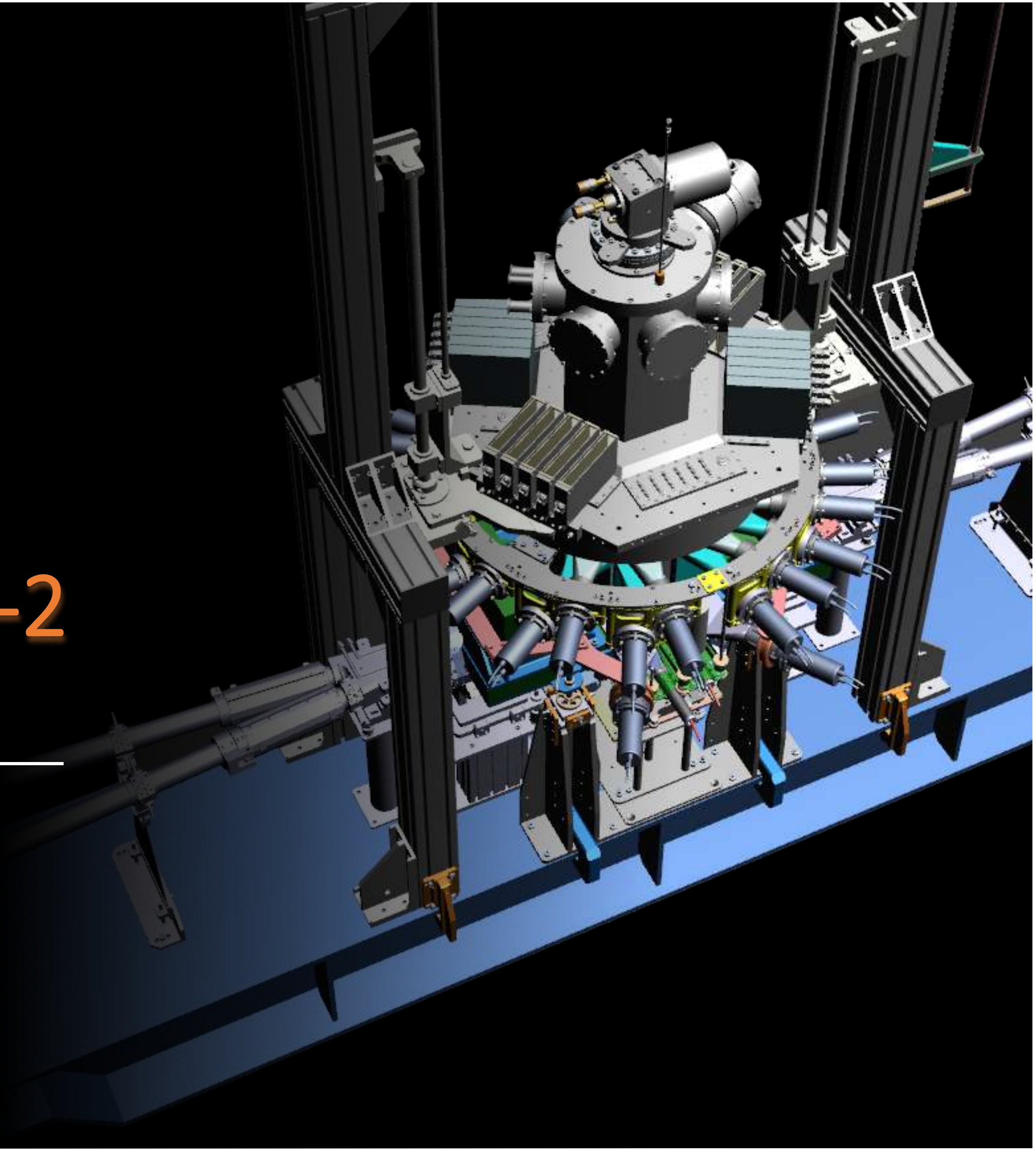
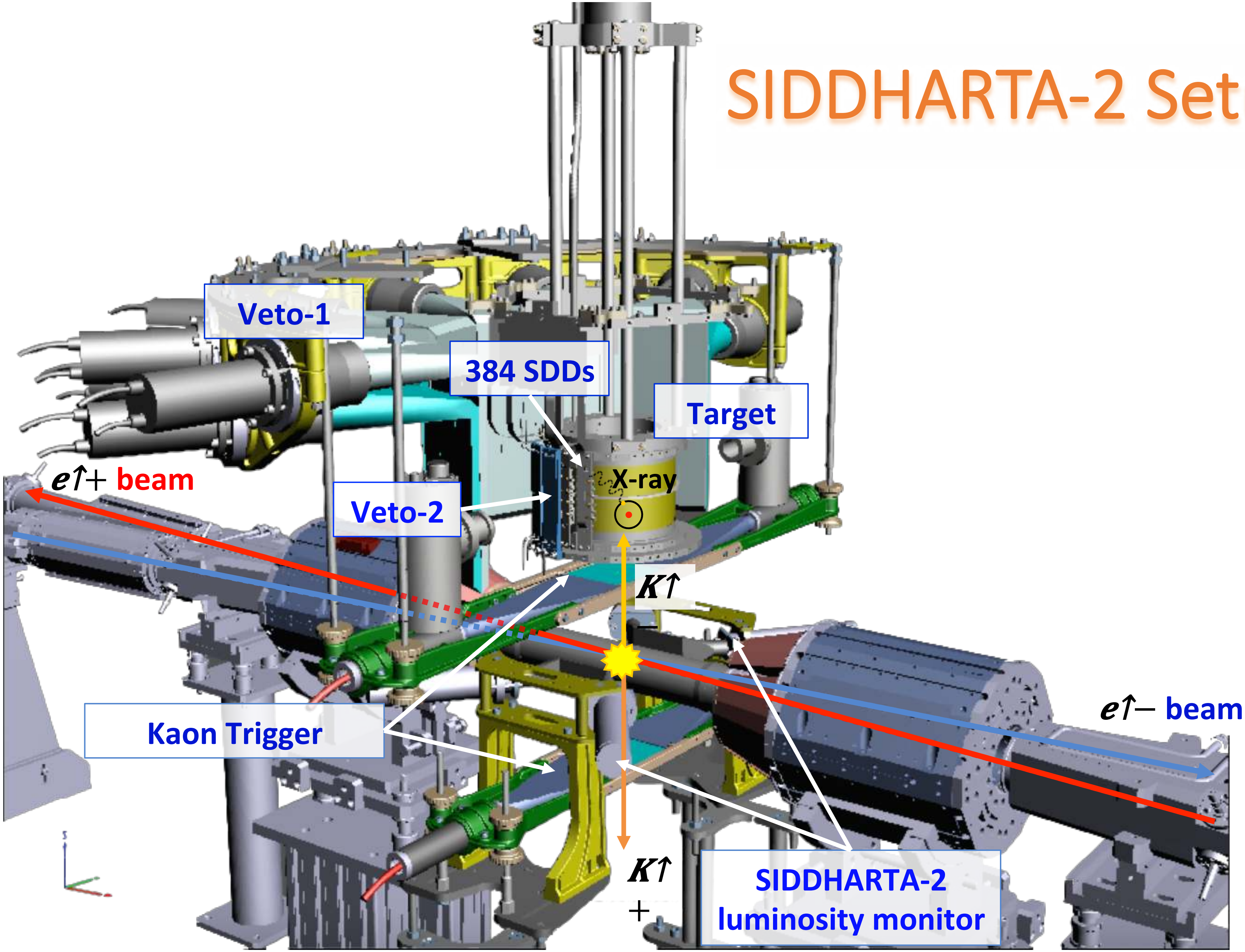
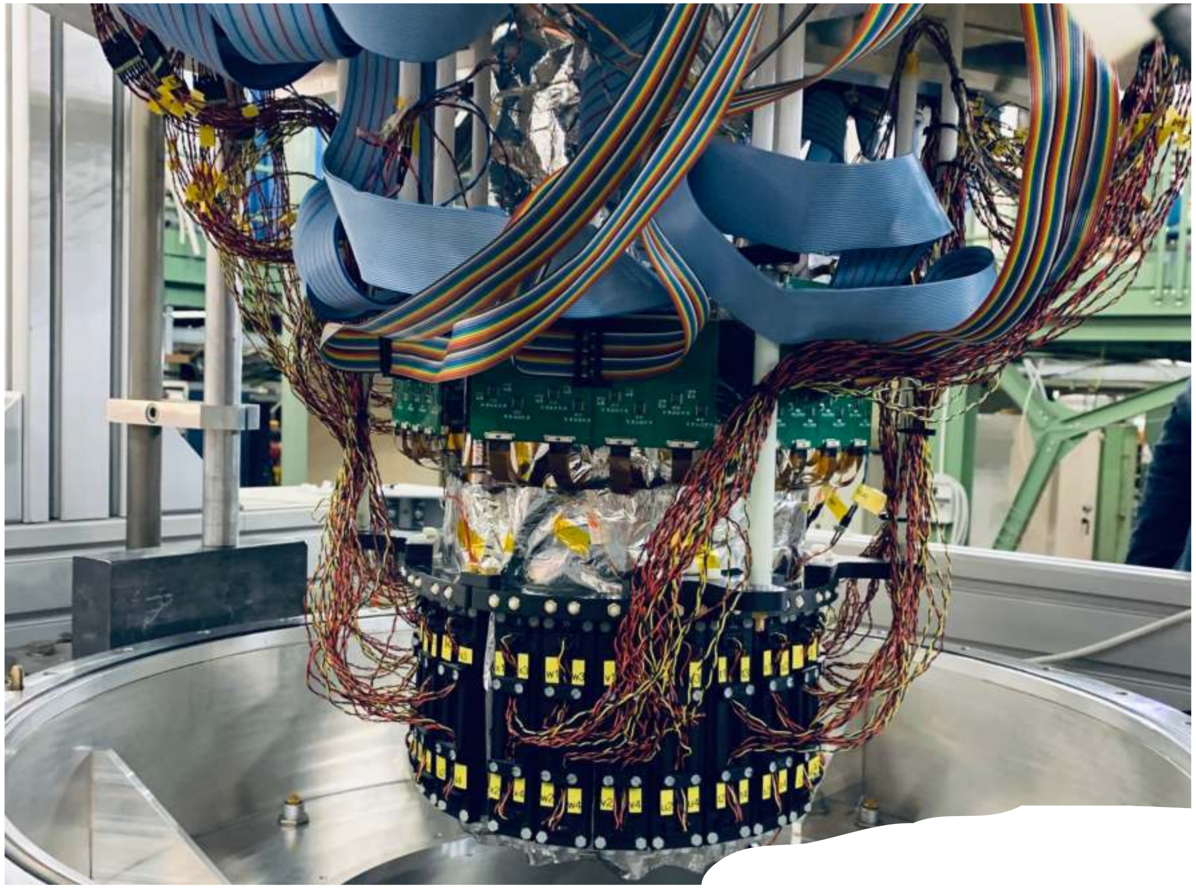
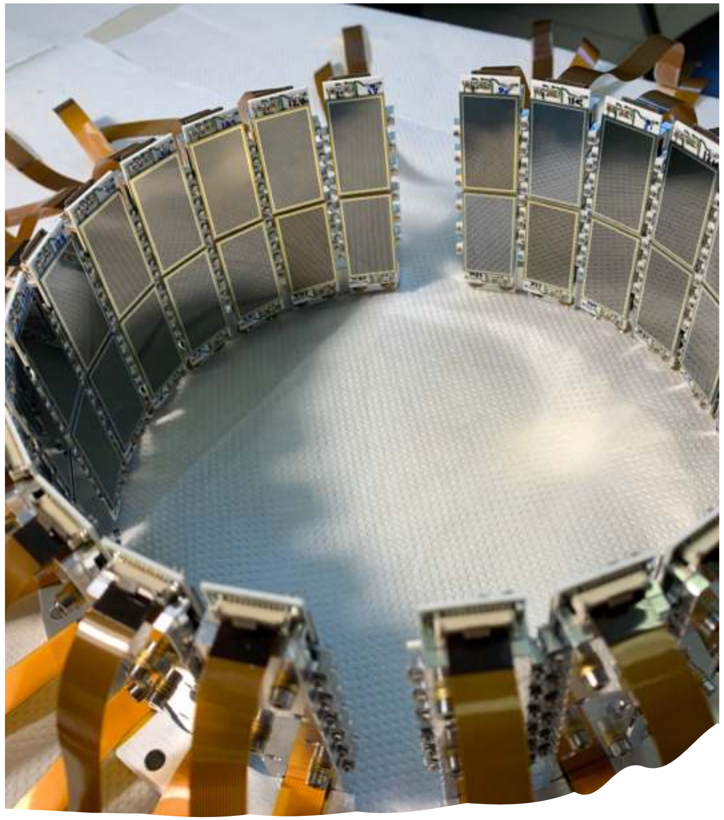
SIDDHARTA-2 experiment



SIDDHARTA-2 Setup

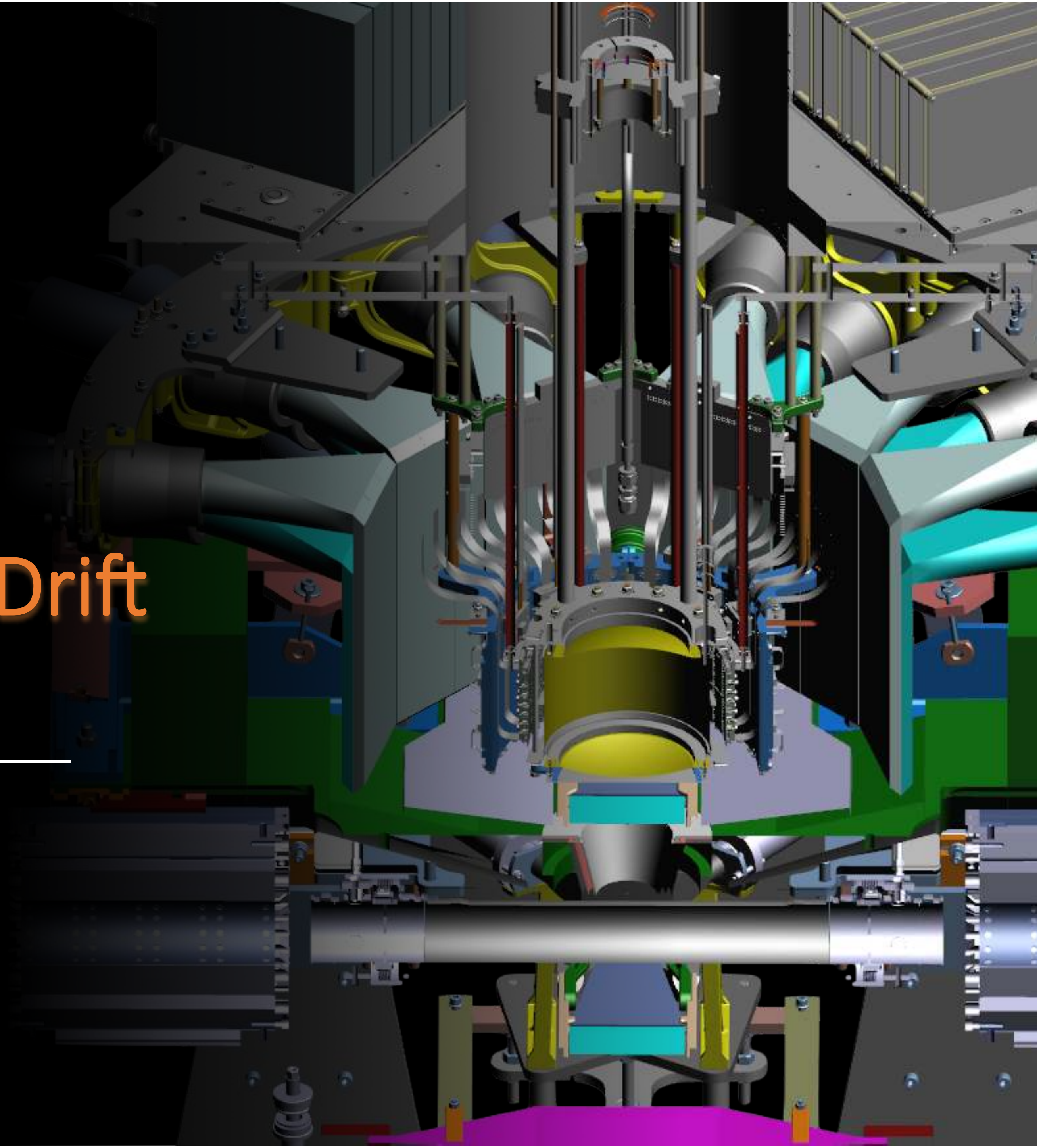






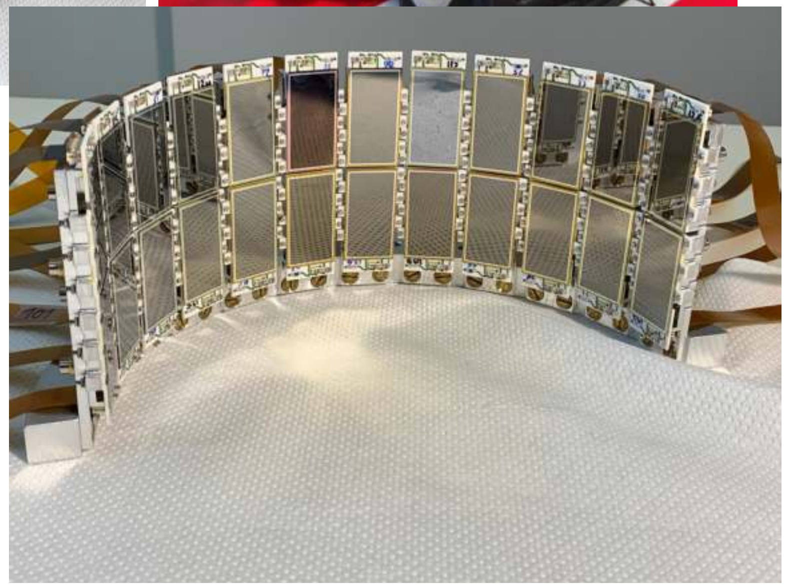
SIDDHARTA-2 Setup

The Silicon Drift Detectors



The SIDDHARTA-2 target

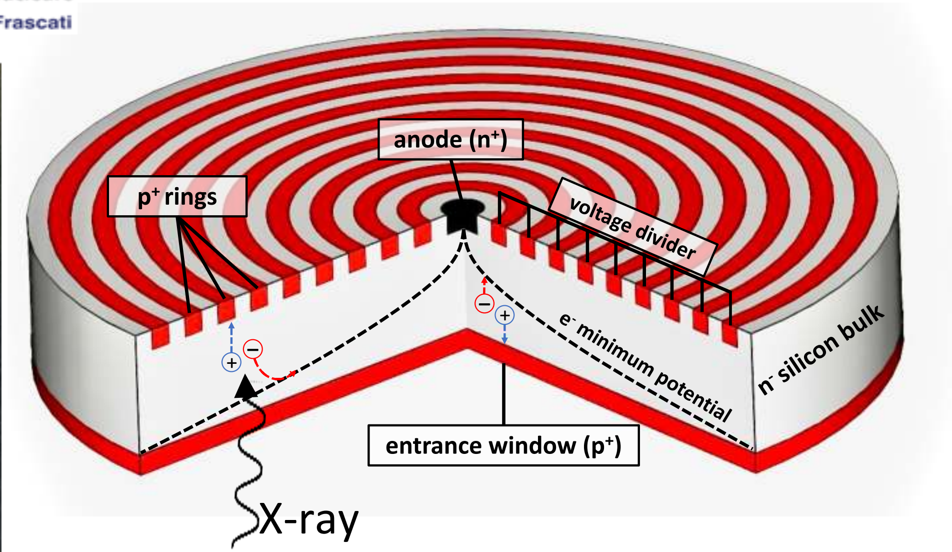
Cryogenic Cylindrical target cell made of high purity aluminium frame and 150 thick Kapton walls

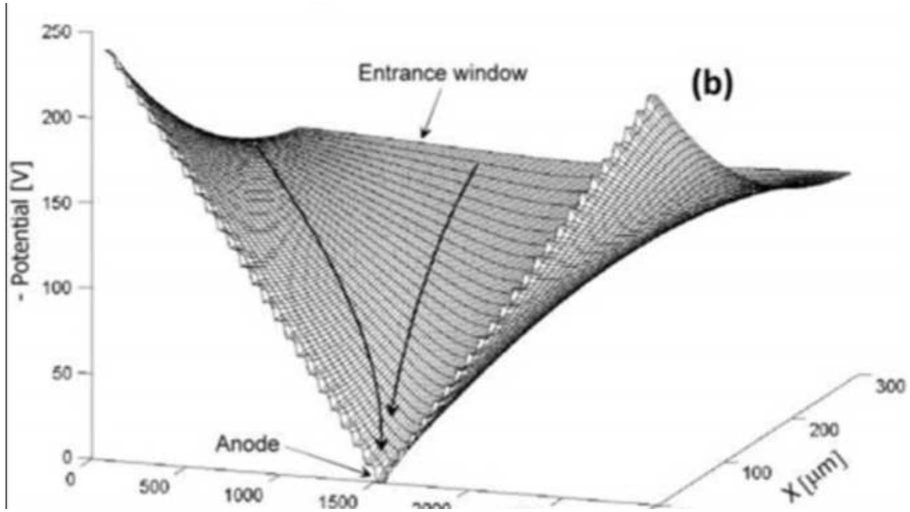


384 Silicon Drift Detectors (SDDs) are mounted on aluminium finger support for cooling (-150°C)

Silicon Drift Detectors

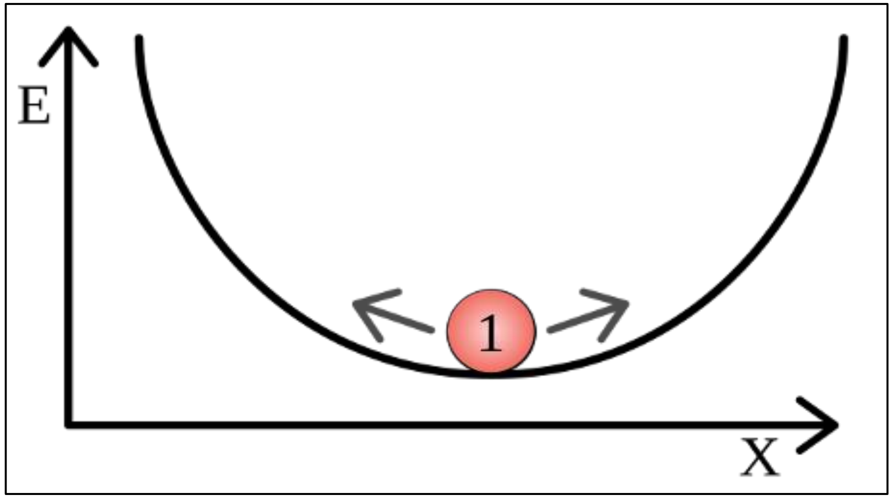
SDD cross section

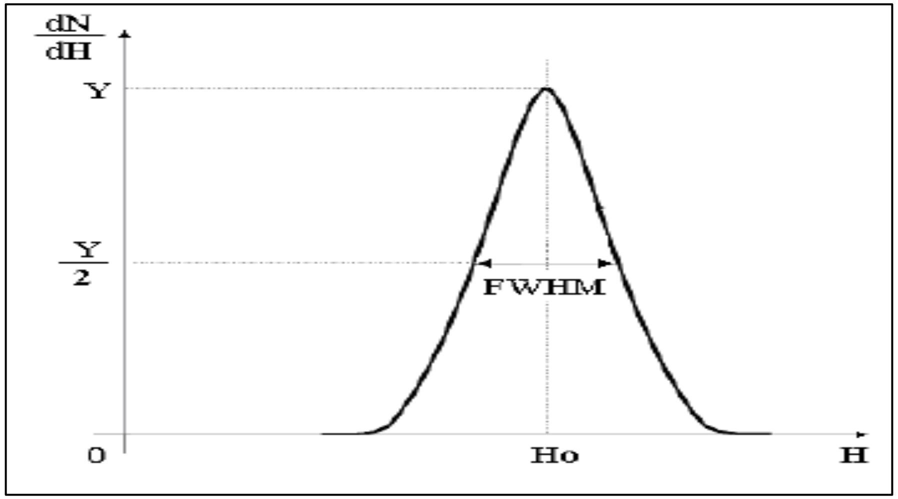




8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of 450 μm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

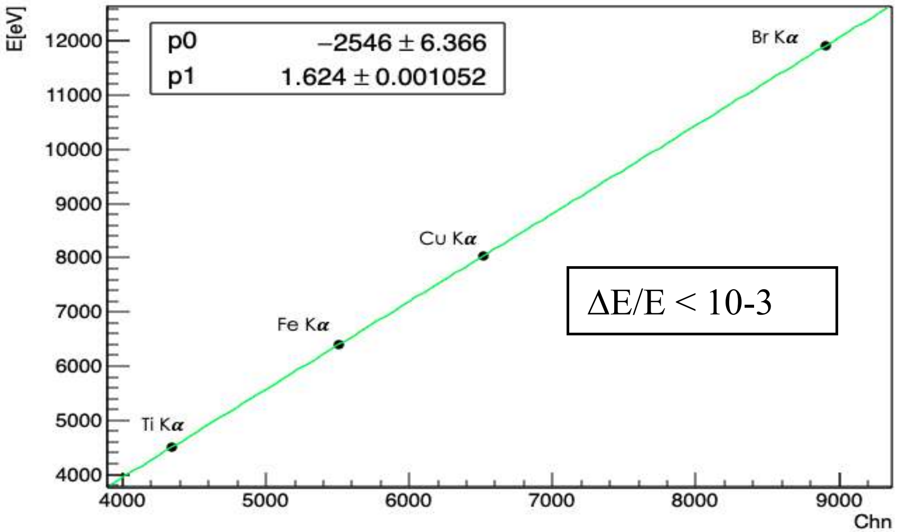
Silicon Drift Detectors
Energy response

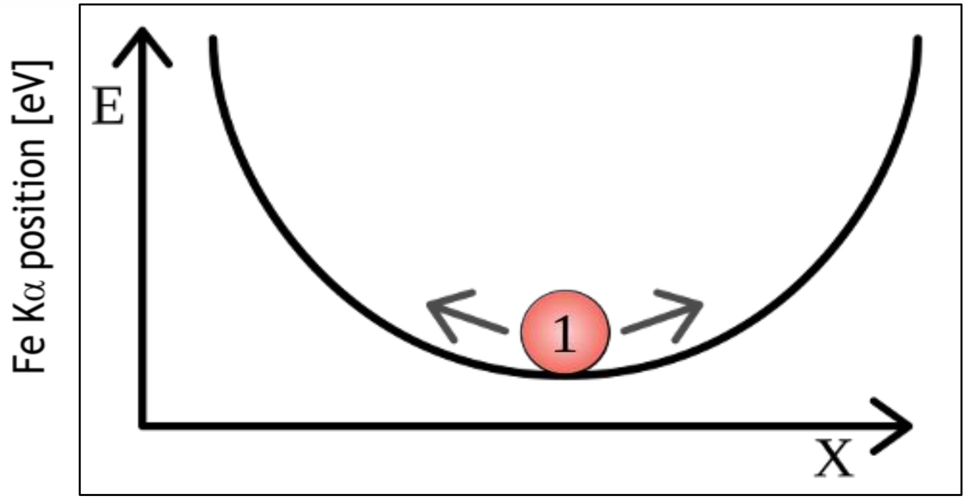


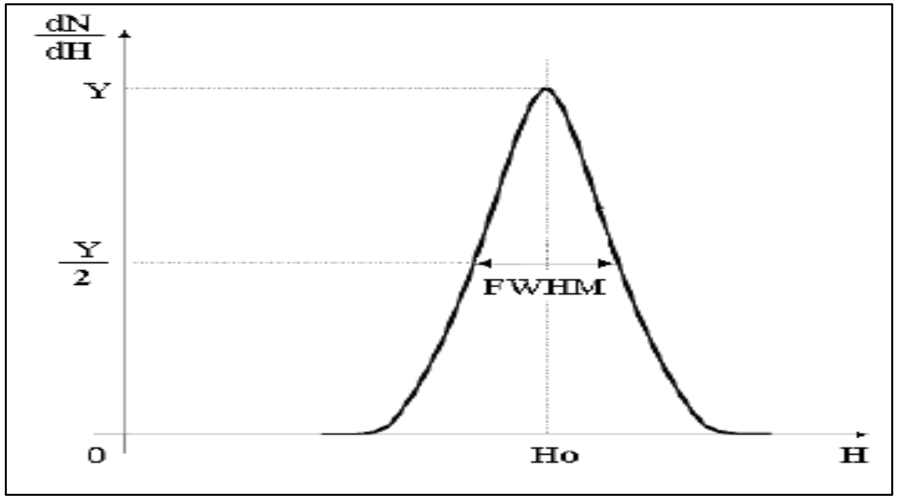


Silicon Drift Detectors
Energy response

Linearity







Silicon Drift Detectors
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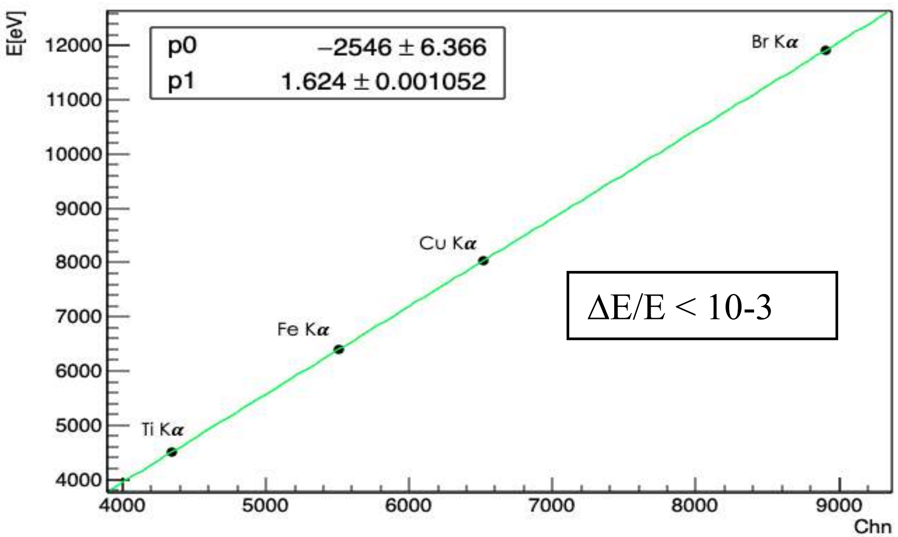
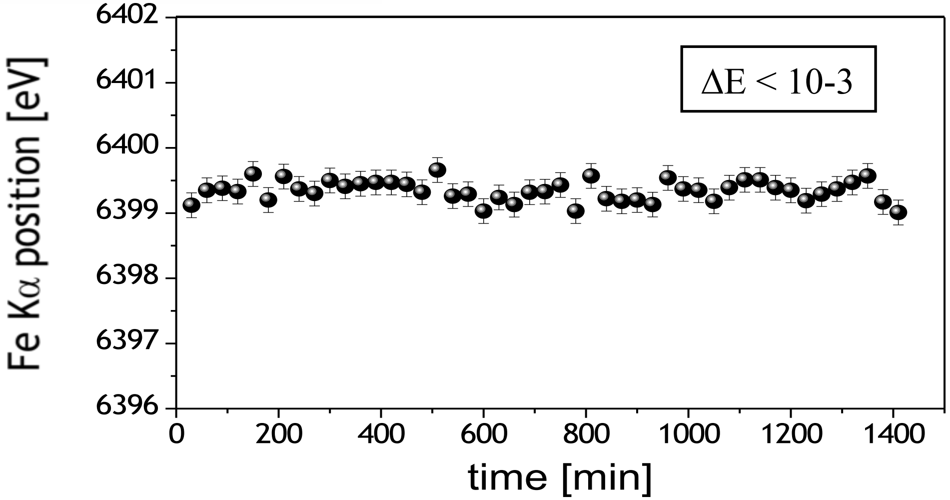
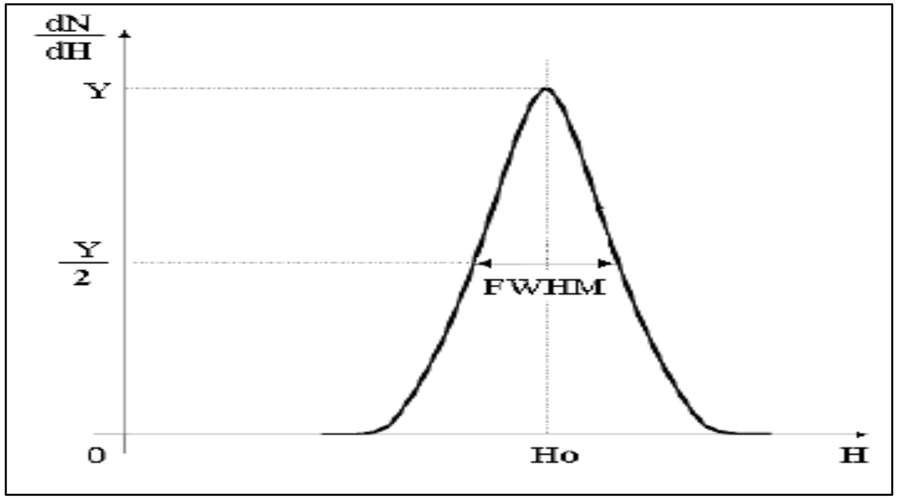


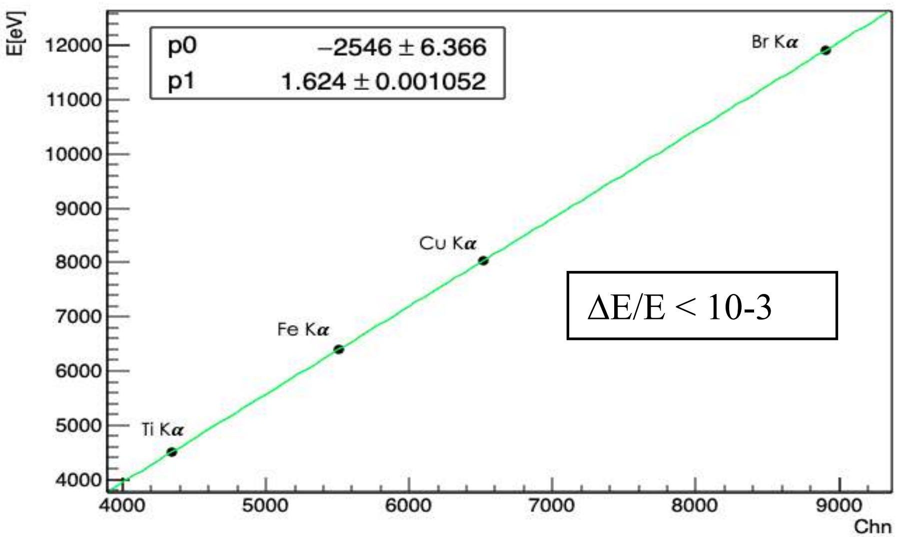
Stability





Silicon Drift Detectors
Energy response

Linearity



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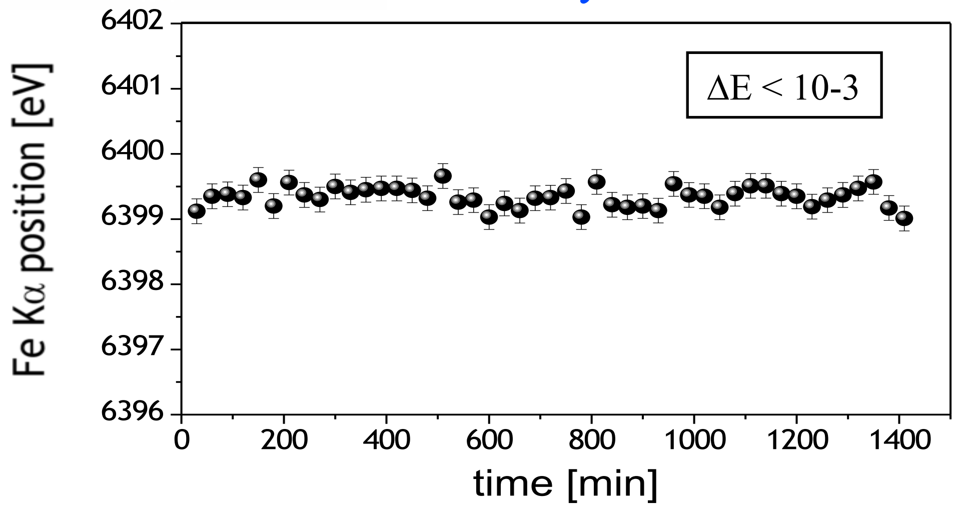
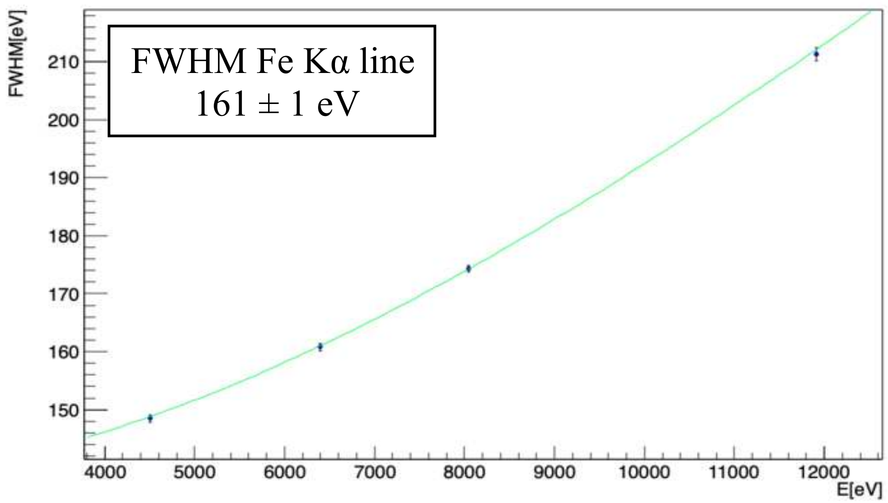
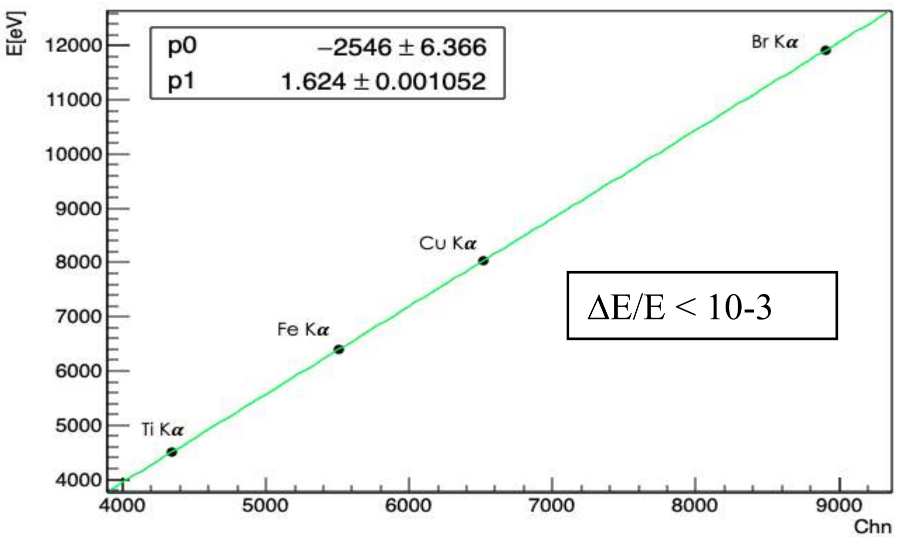


Energy Resolution

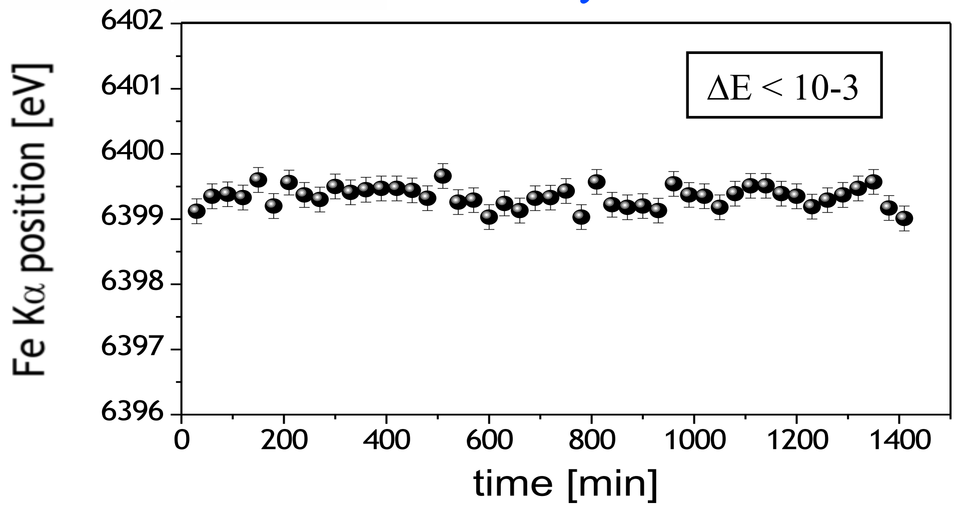


Silicon Drift Detectors
Energy response

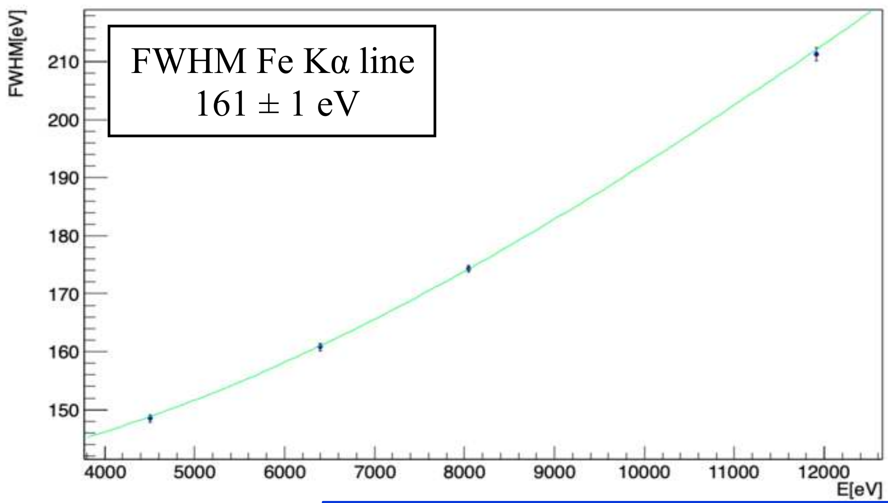
Linearity



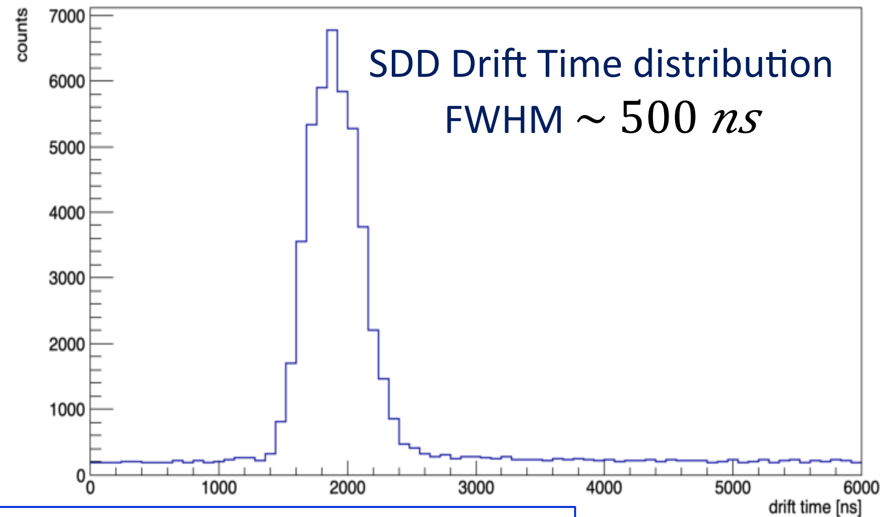
Stability



Energy Resolution



Time Resolution



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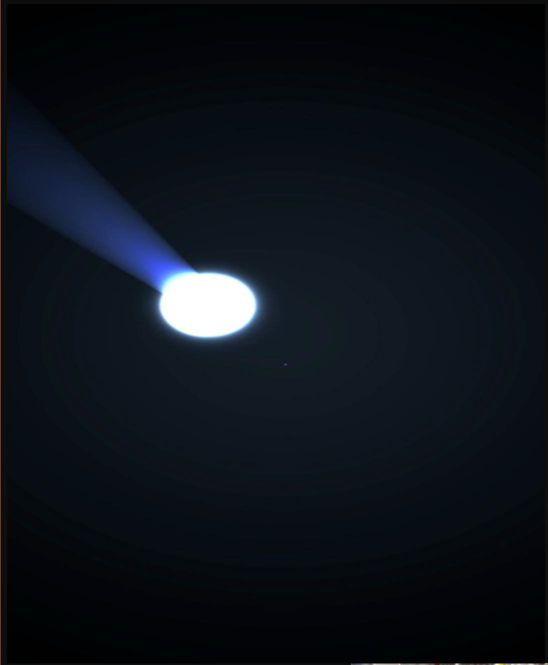
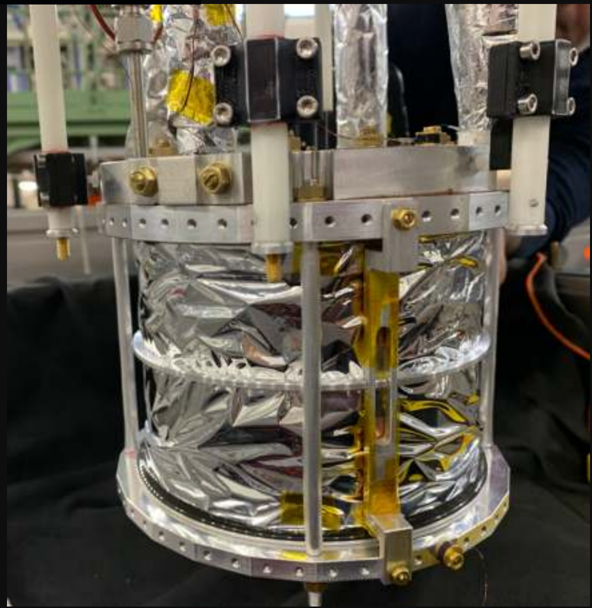
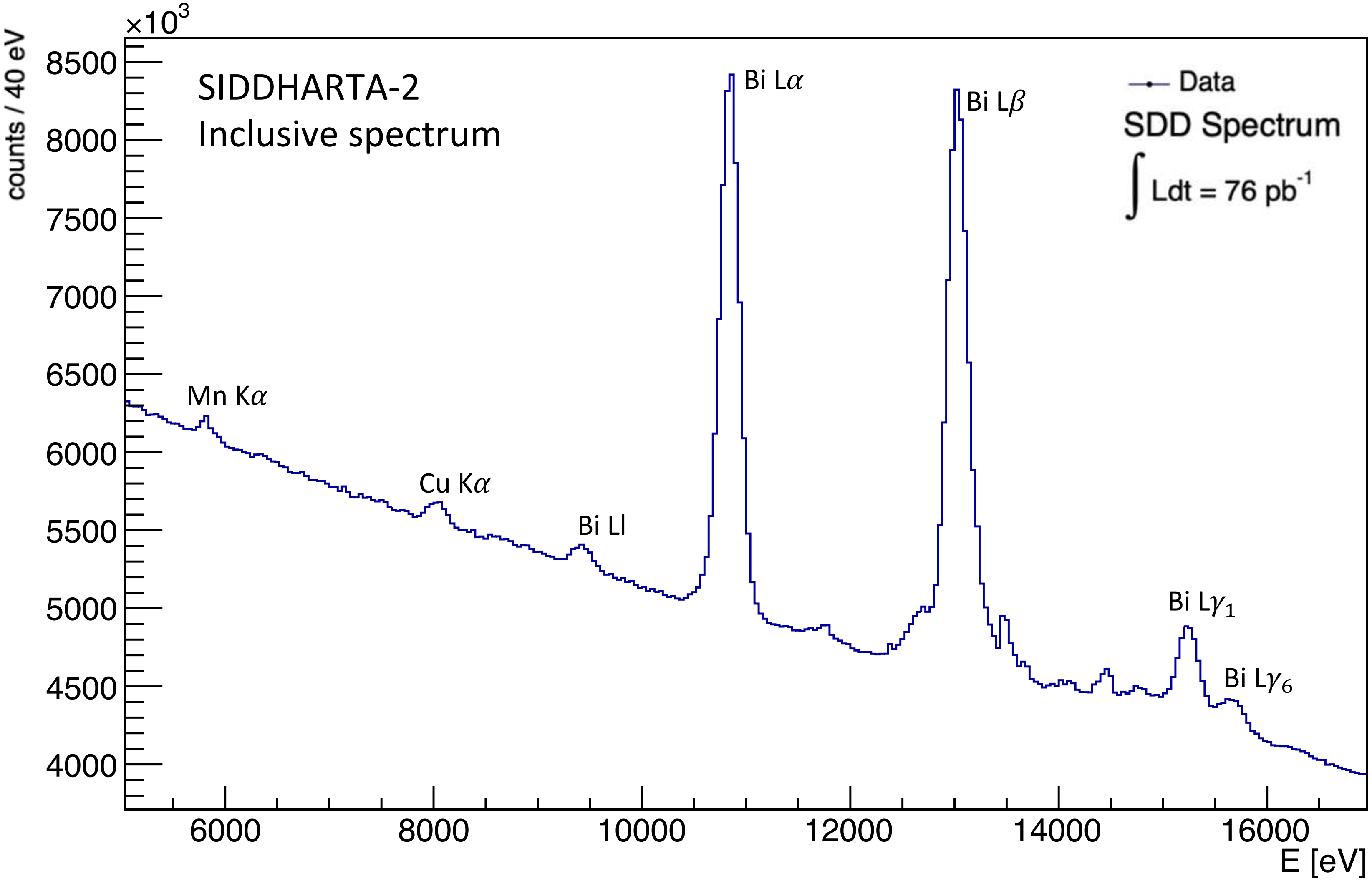
Kaonic Helium Run



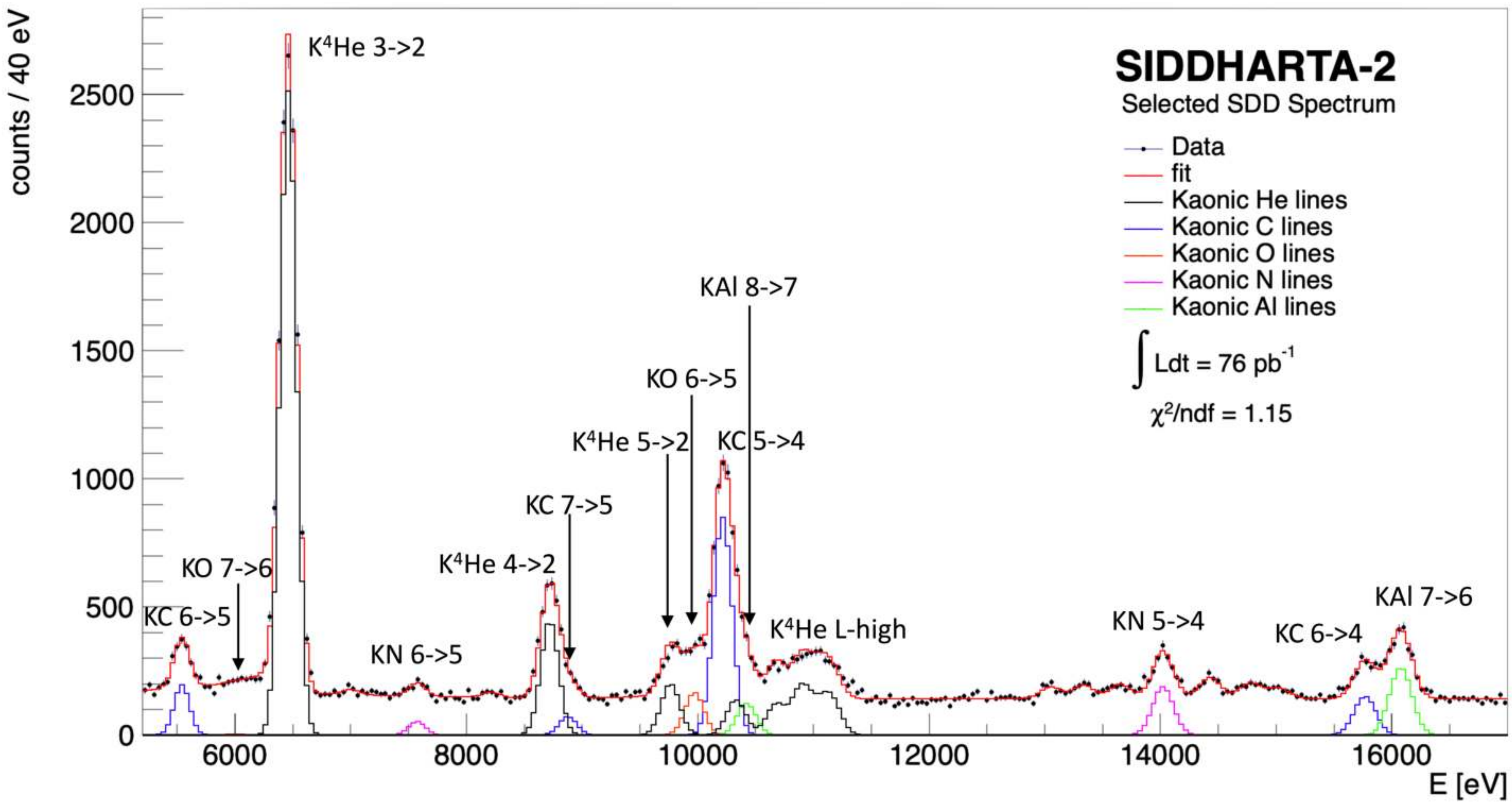


SIDDHARTA-2 Kaonic ^{4}He



Data Analysis

SIDDHARTA-2 Kaonic ^{4}He



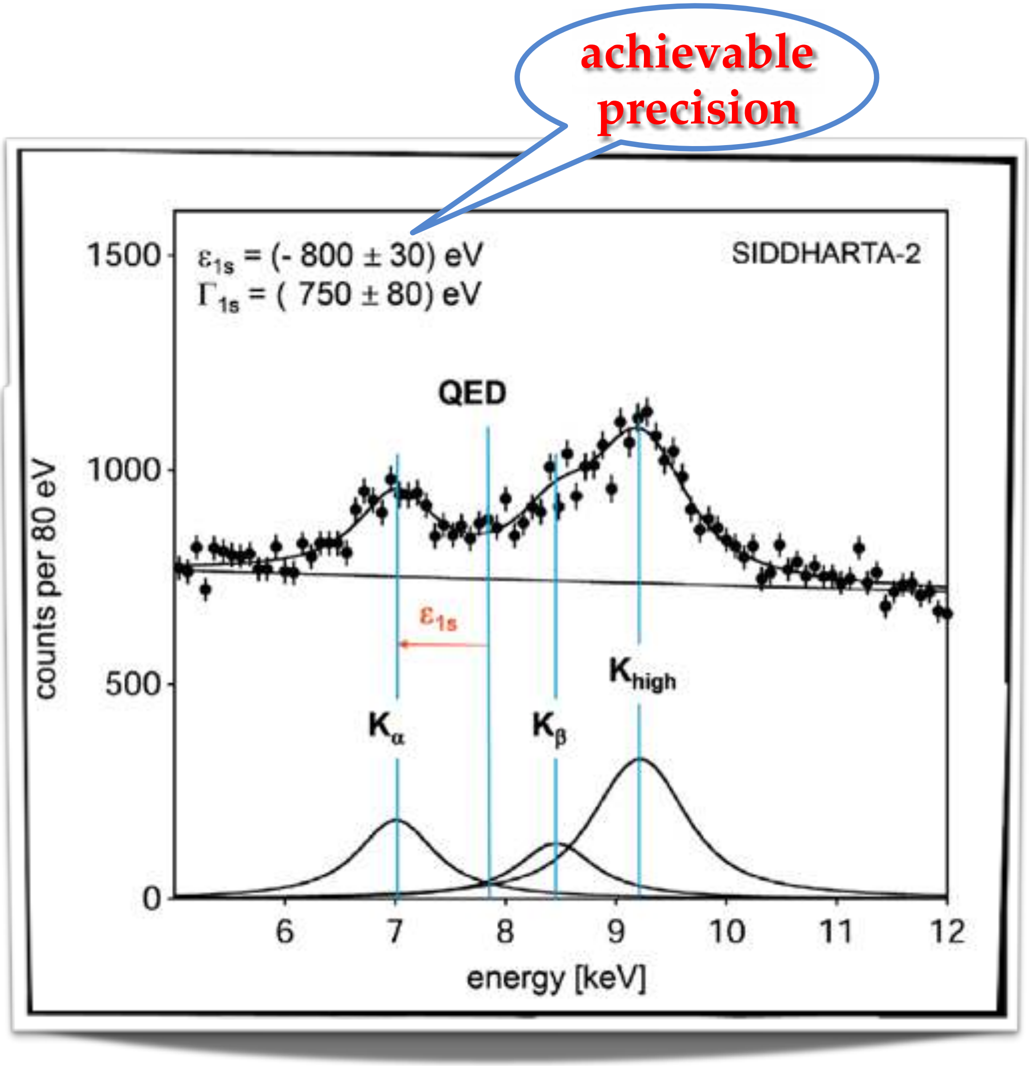
*F Sgaramella et al. Measurement of high-n transition in intermediate mass kaonic atom by SIDDHARTA-e at DAΦNE Eur. Phys. J. A **59**, 56*

SIDDHARTA-2 K-d measurement

Kaonic deuterium run on going

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

Thank You