

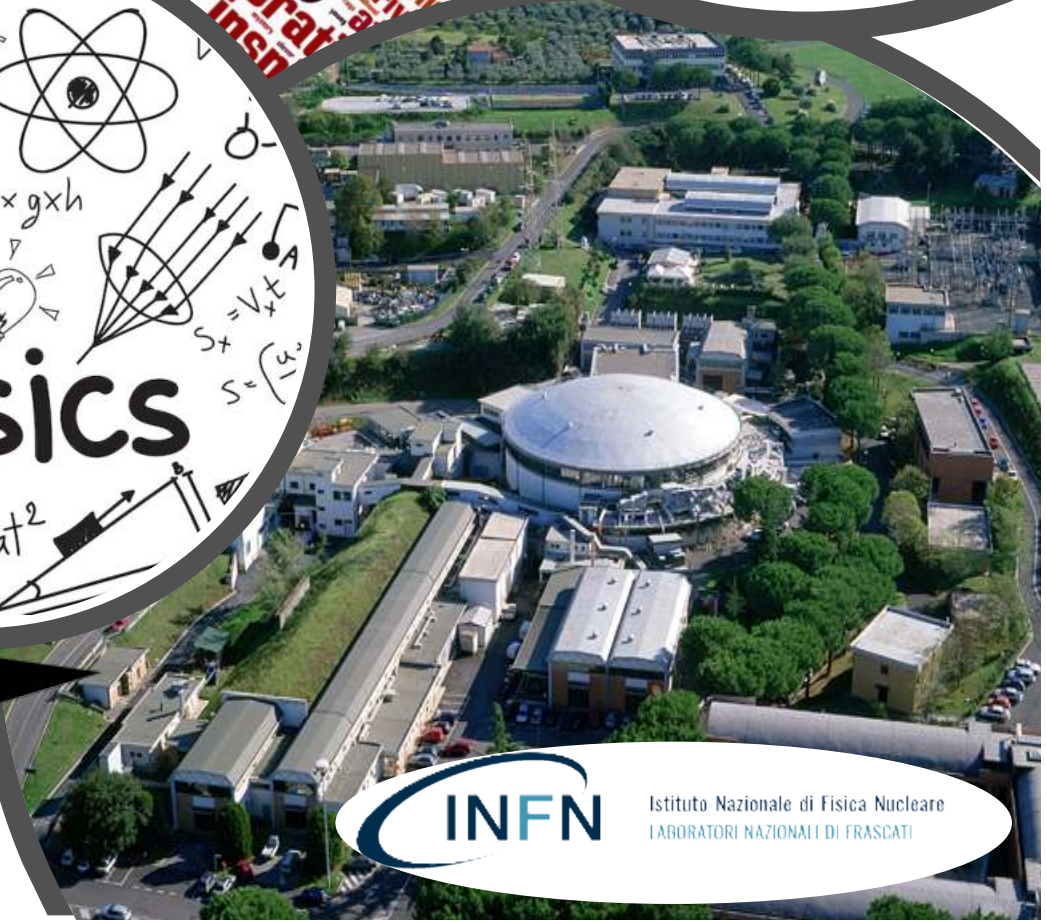
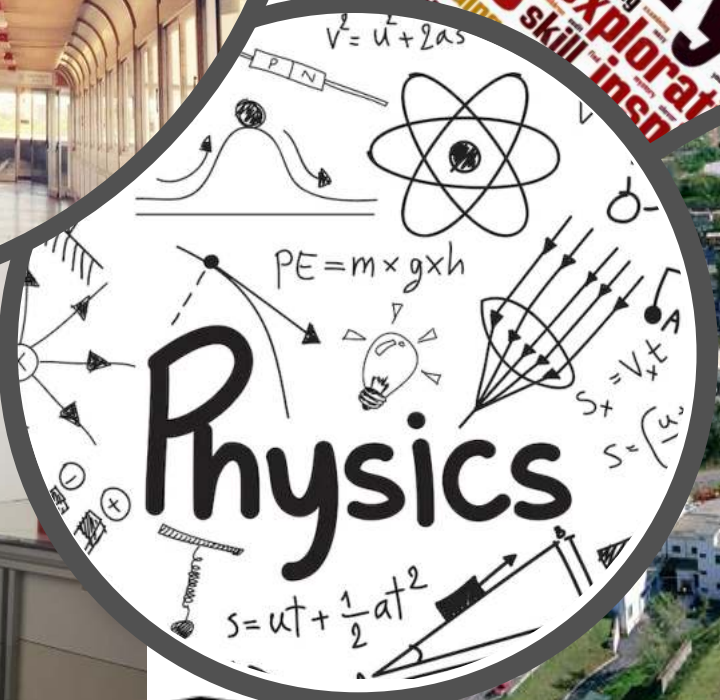
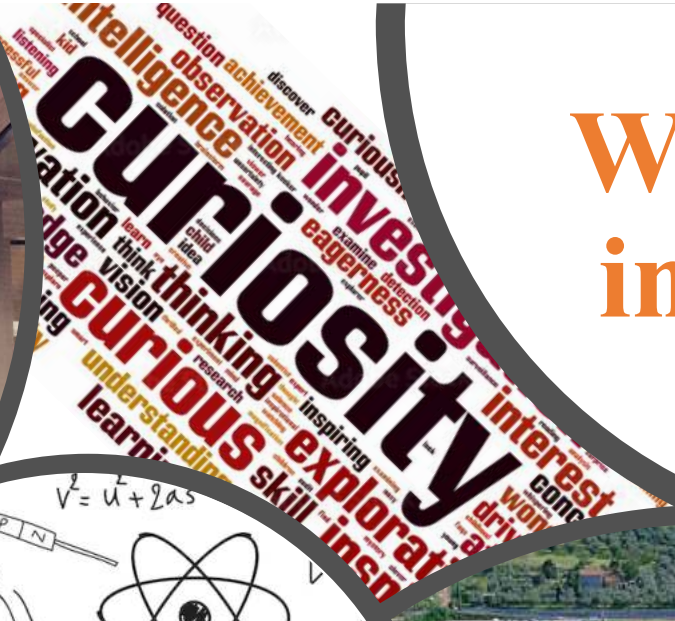
Unravelling the Secrets of the Strong Force: The SIDDHARTA-2 Experiment at the DAΦNE Collider

Francesco Sgaramella

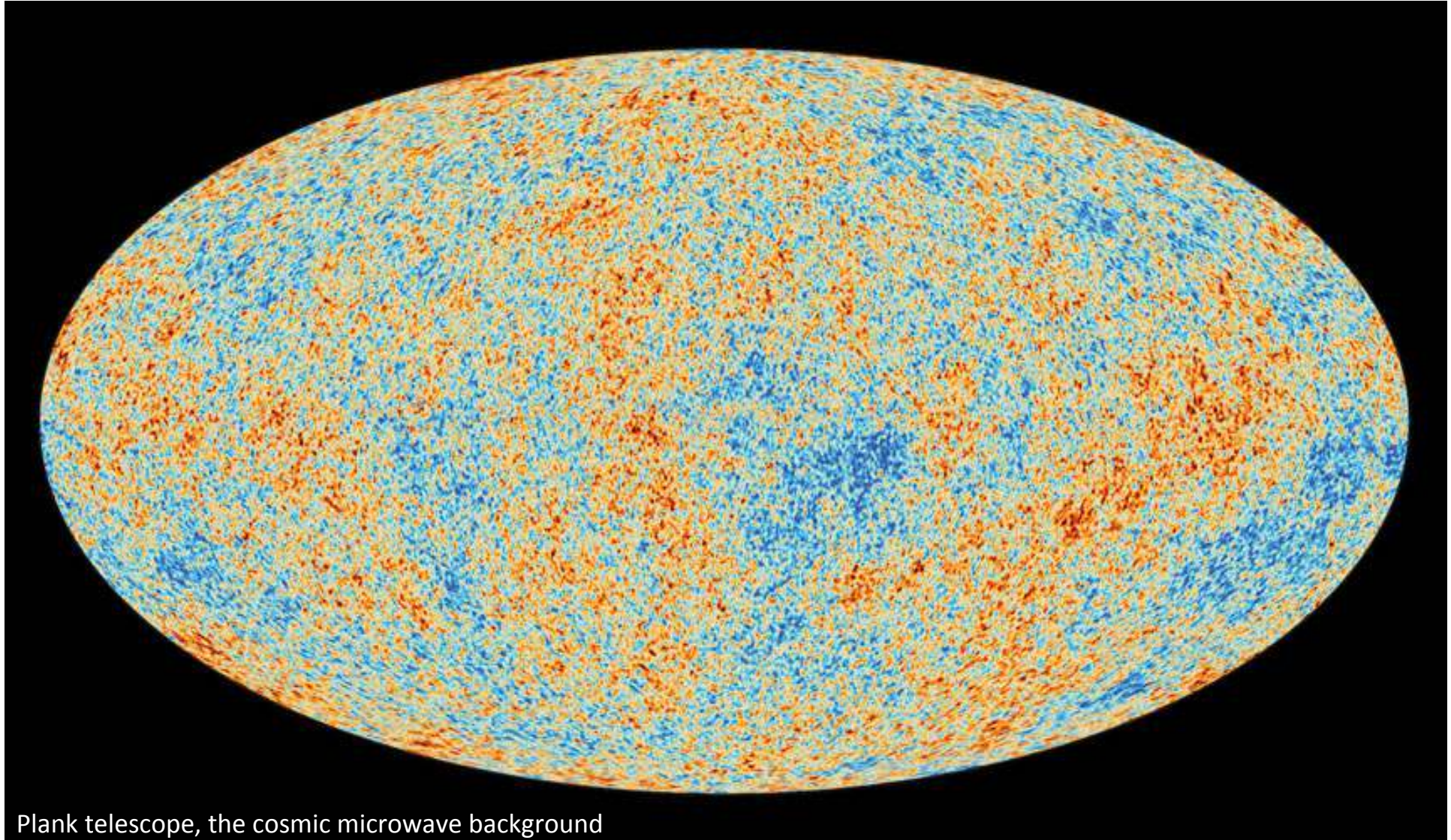


INSPIRE, March 27-31, 2023

Who I am in 1 slide

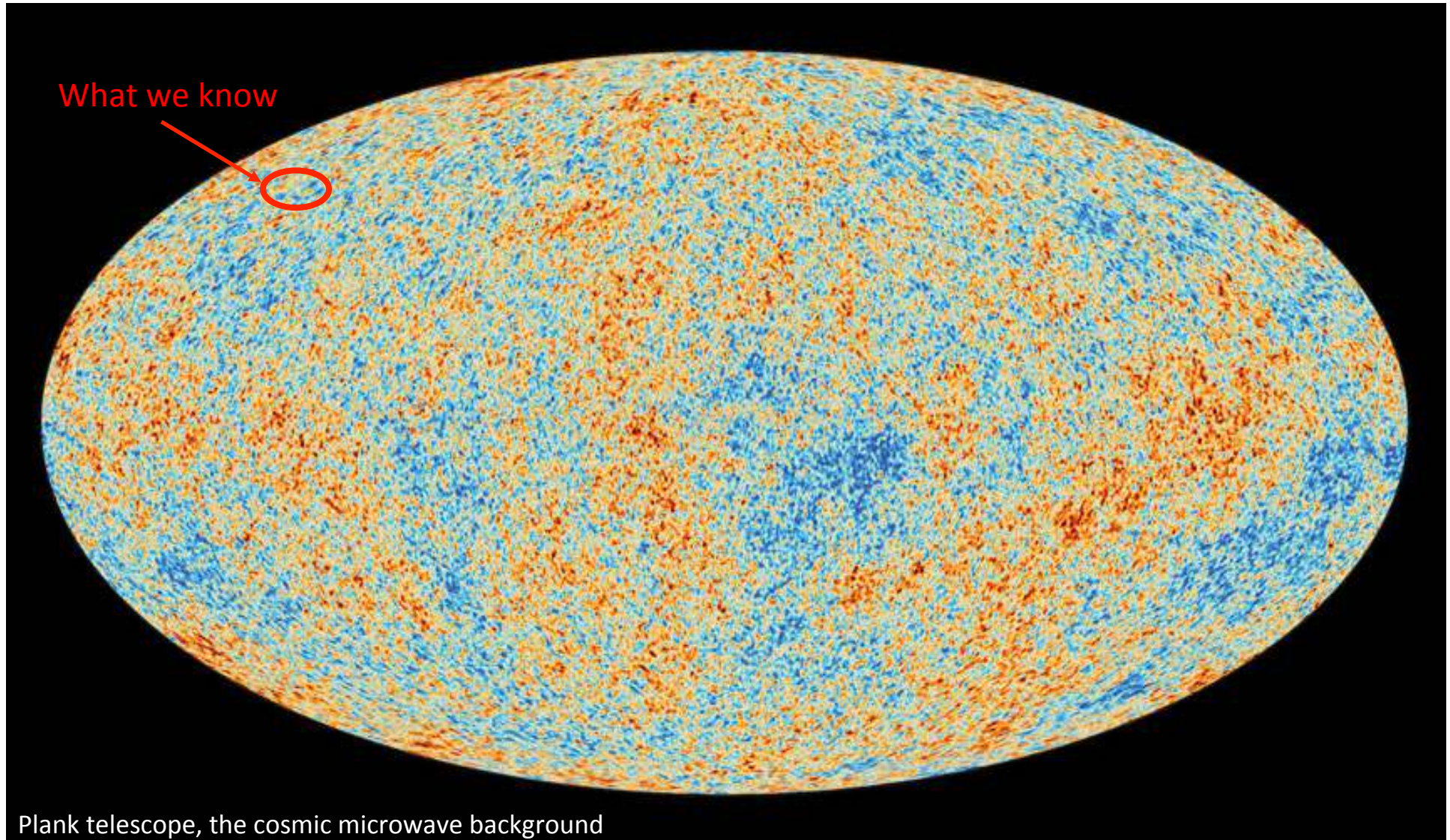


The Universe



Plank telescope, the cosmic microwave background

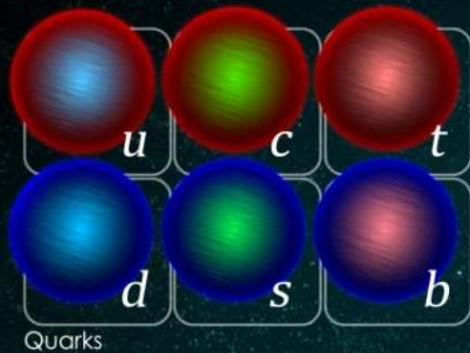
The Universe



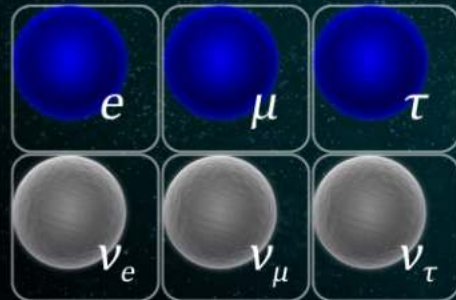
The Standard Model

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

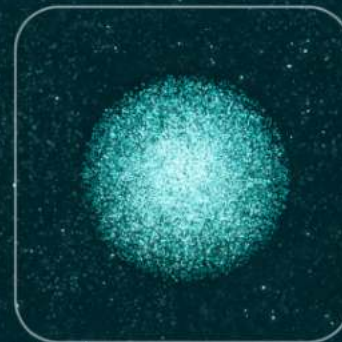
Matter - Fermions



Quarks



Leptons



Higgs boson

Forces - Boson

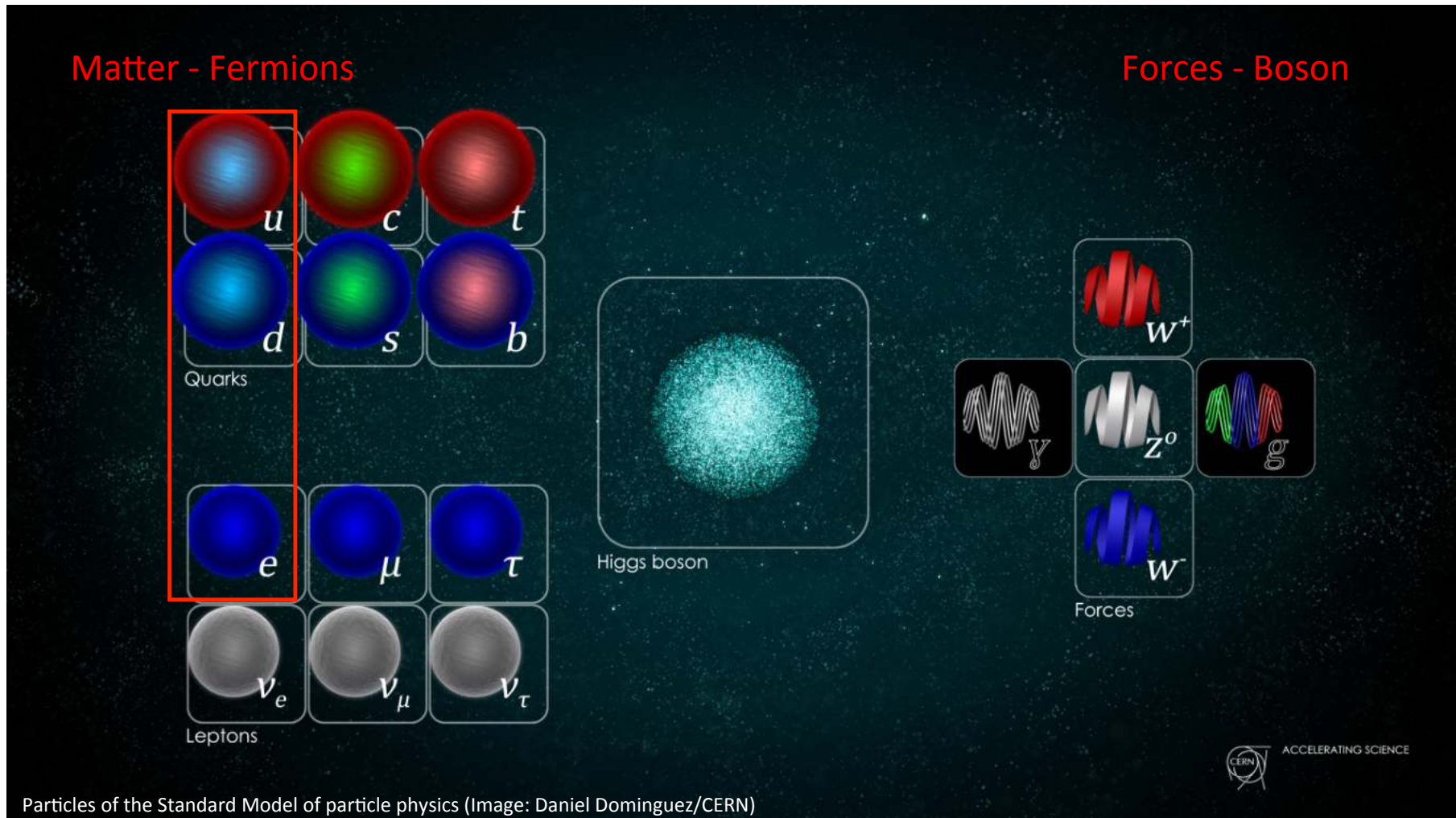


Forces

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

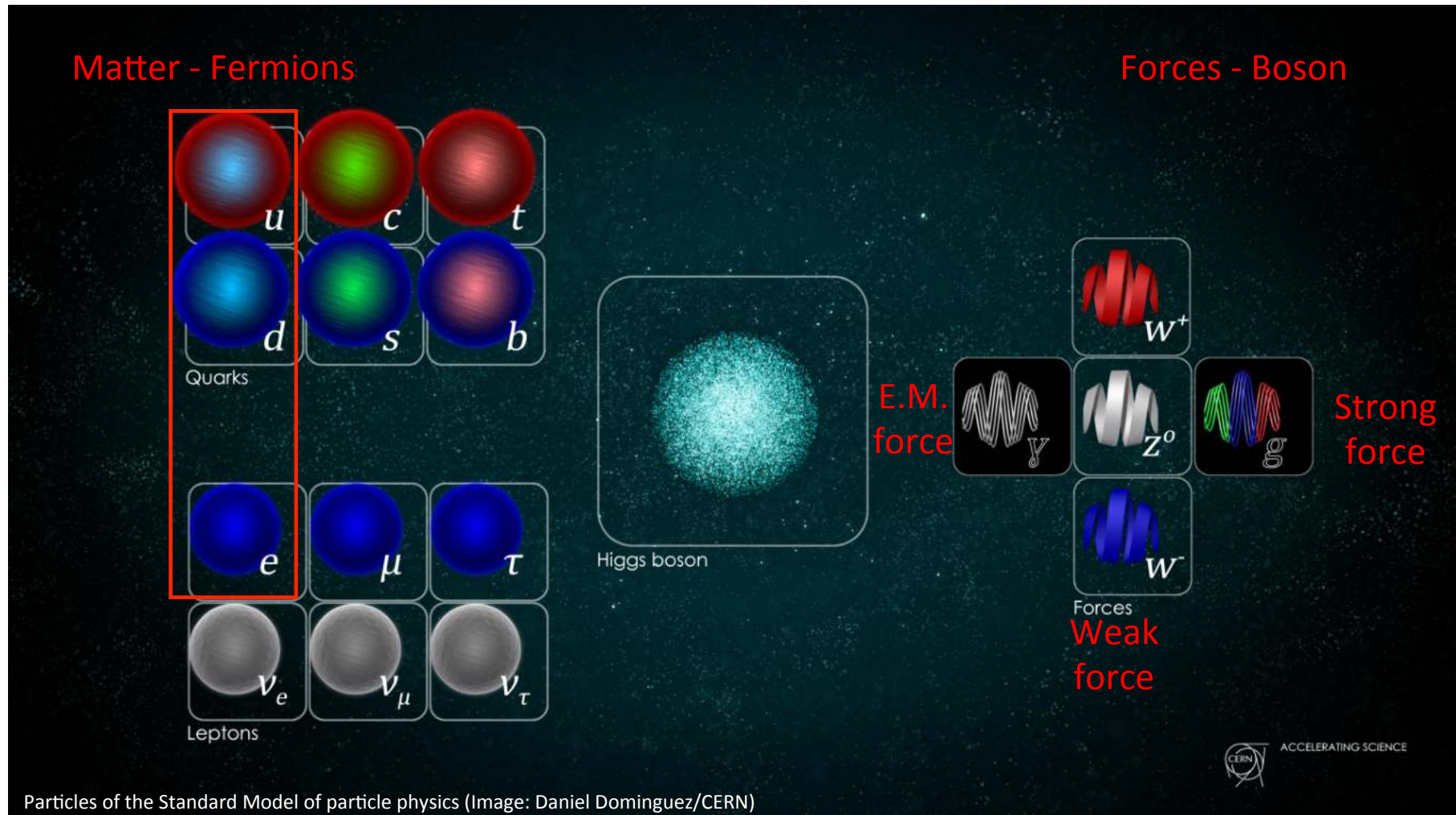
The Standard Model

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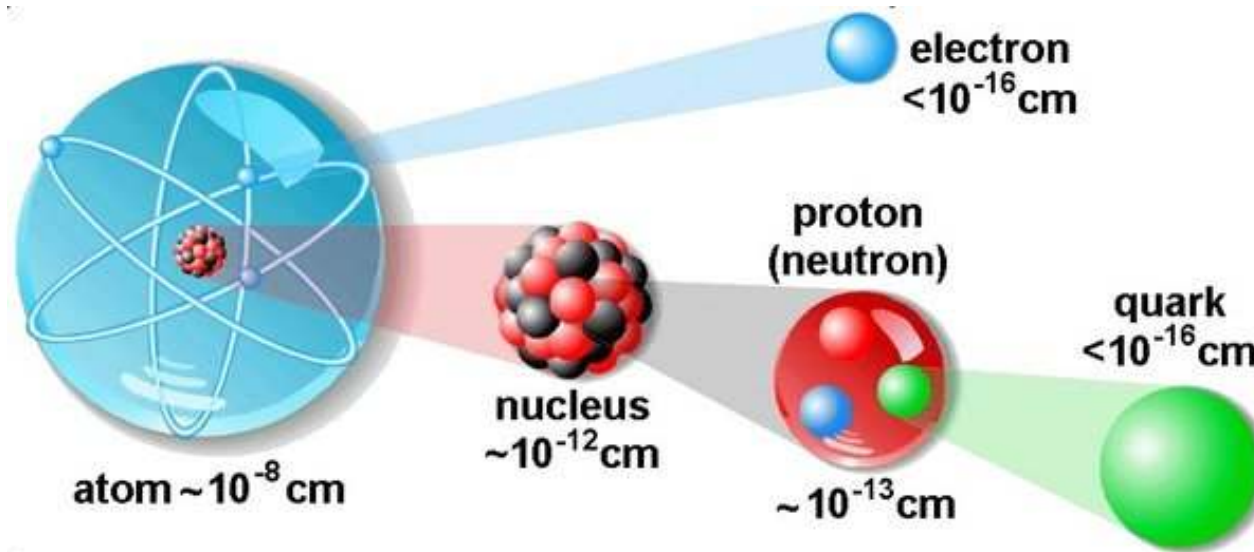


The Standard Model

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

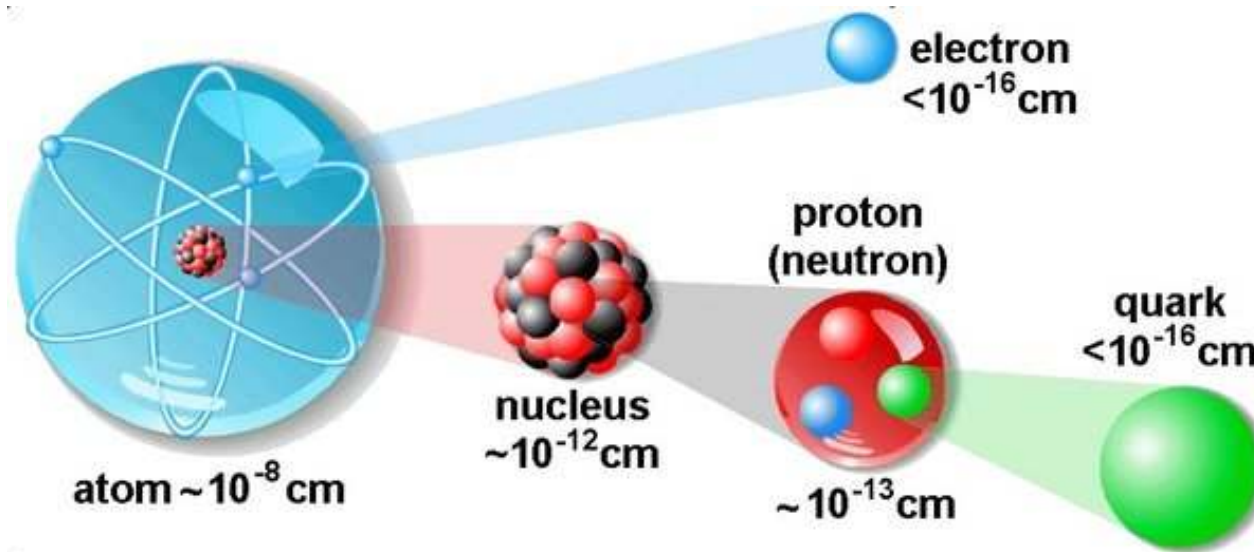


Why do protons and neutrons bind together in the nucleus?



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

Why do protons and neutrons bind together in the nucleus?

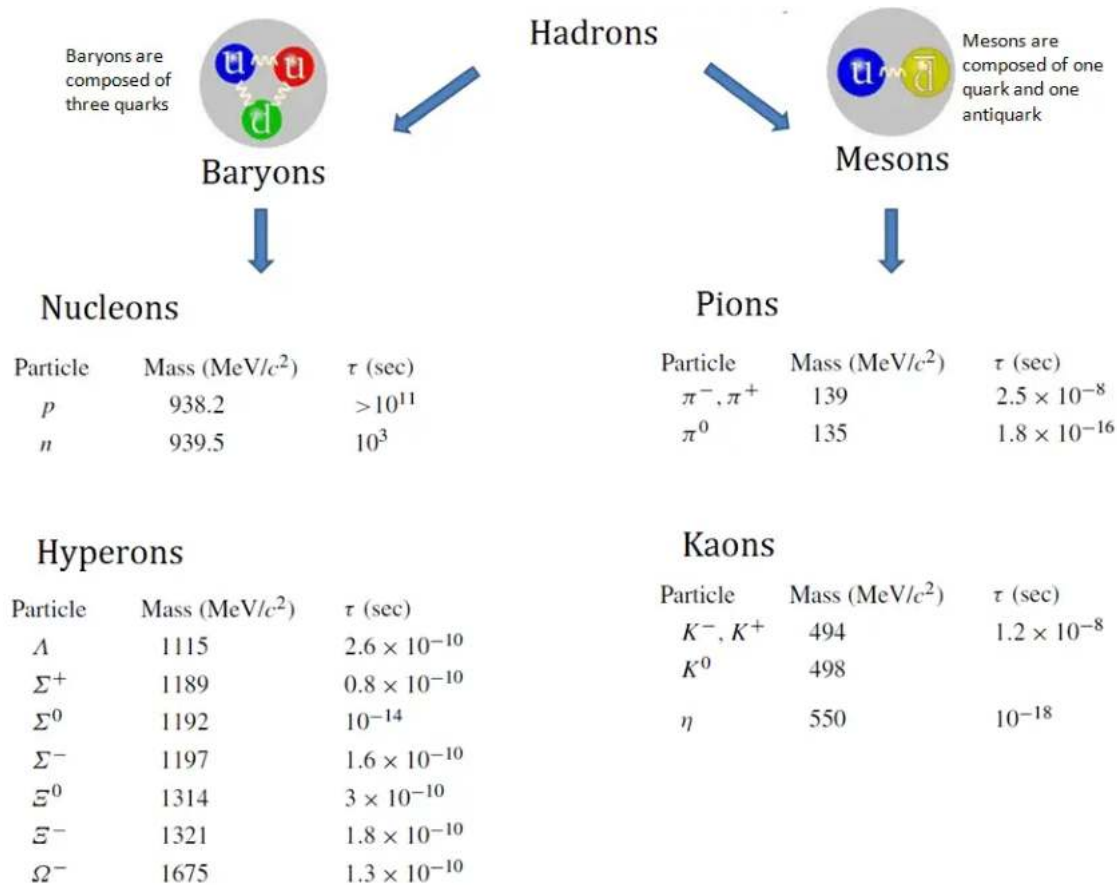


- **Electromagnetic repulsion:** no force on neutron, but protons should repel each other violently
 - **Gravity** weaker than electromagnetic force

Need of a force stronger than E.M repulsion

The Strong Force

The Strong Force

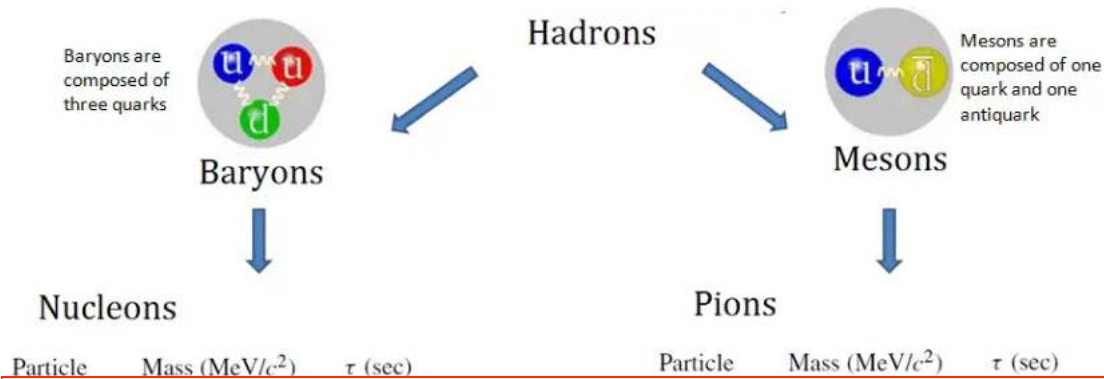


- The strong force acts **directly between quarks**. This force **holds quarks together** to form protons, neutrons, and other hadron particles.

- 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



- 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

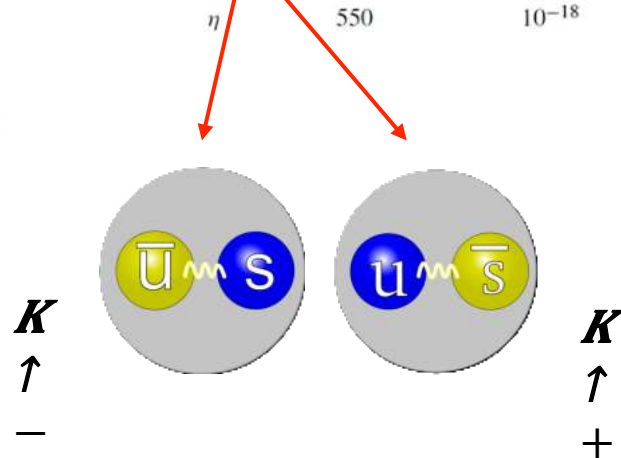
How can we study the strong interaction?

Hyperons

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}

Kaons

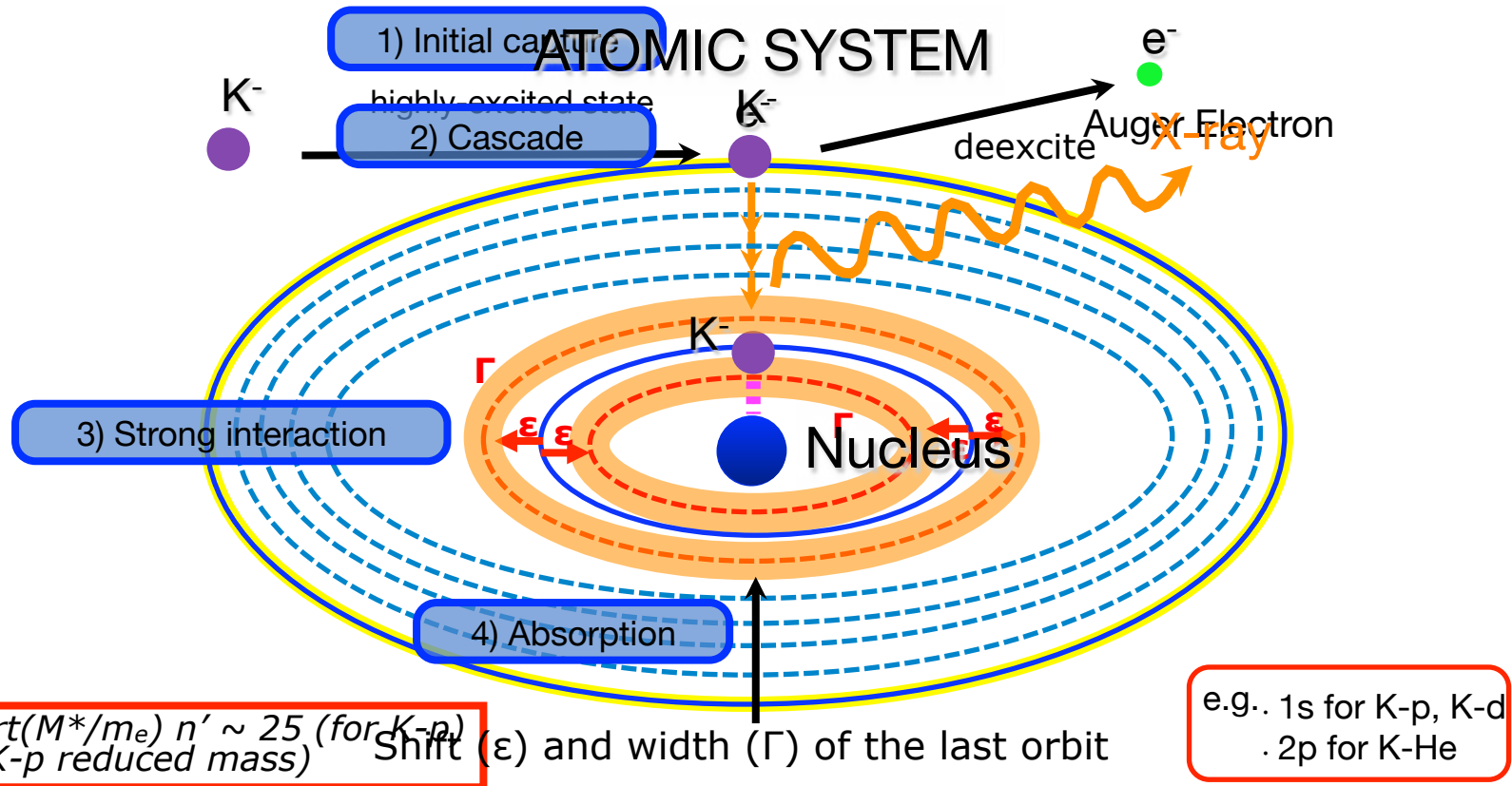
Particle	Mass (MeV/c ²)	τ (sec)
K^-, K^+	494	1.2×10^{-8}
K^0	498	
η	550	10^{-18}



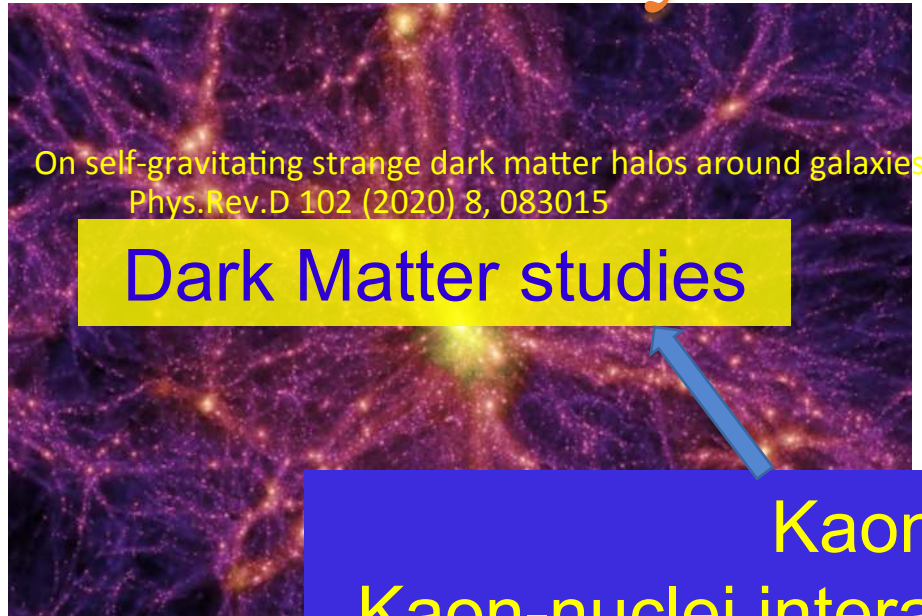
- the strong interaction is a very complicated interaction because it significantly varies with distance. At distances comparable to the diameter of a proton, the strong force is 100 times as strong as the electromagnetic force. However, **at smaller distances**, the strong force between quarks becomes **weaker**, this is known as **asymptotic freedom**.

Kaonic atom

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

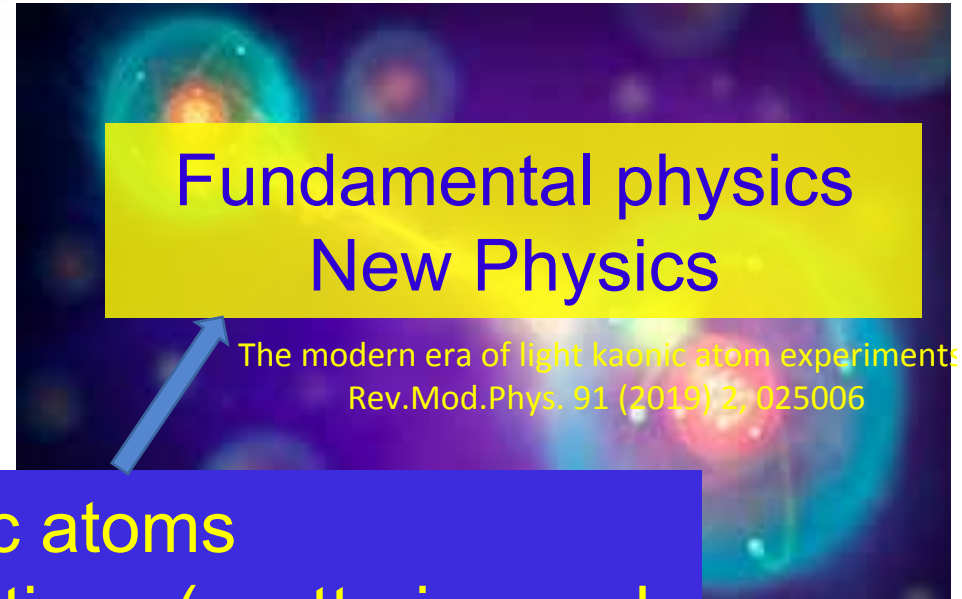


Why Kaonic Atoms?



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

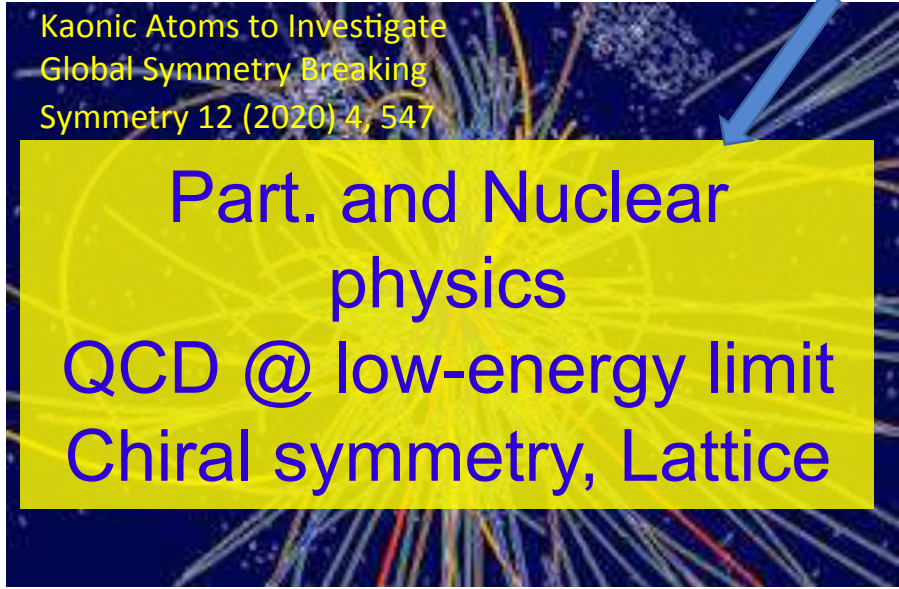
Dark Matter studies



**Fundamental physics
New Physics**

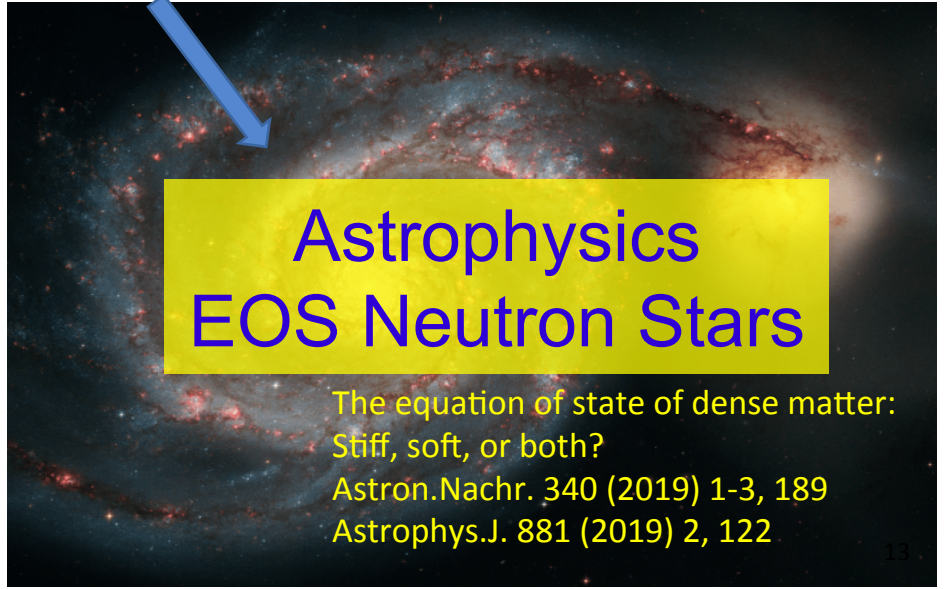
The modern era of light kaonic atom experiments
Rev.Mod.Phys. 91 (2019) 2, 025006

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



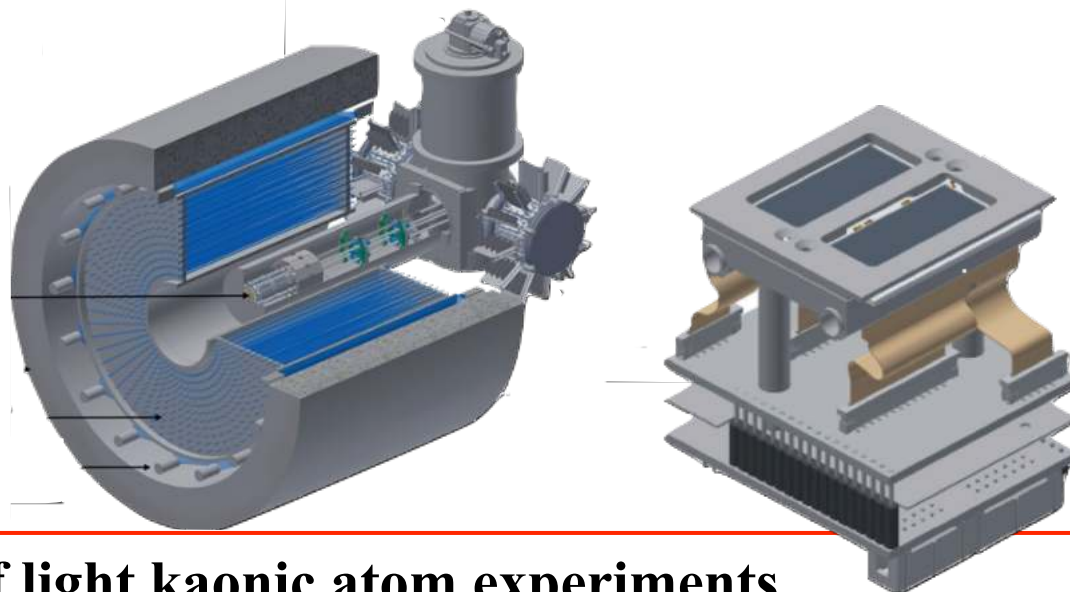
Kaonic Atoms to Investigate
Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

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



**Astrophysics
EOS Neutron Stars**

The equation of state of dense matter:
Stiff, soft, or both?
Astron.Nachr. 340 (2019) 1-3, 189
Astrophys.J. 881 (2019) 2, 122



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 Drift Detectors for Hadronic Atom
Research by Timing Application

LNF-INFN, Frascati, Italy

SMI-ÖAW, Vienna, Austria

Politecnico di Milano, Italy

IFIN –HH, Bucharest, Romania

TUM, Munich, Germany

RIKEN, Japan

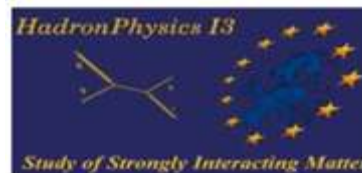
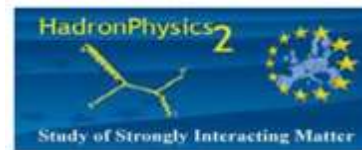
Univ. Tokyo, Japan

Victoria Univ., Canada

Univ. Zagreb, Croatia

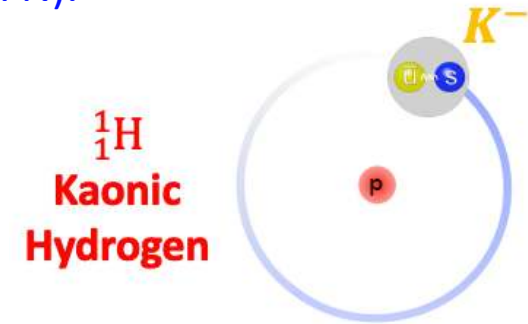
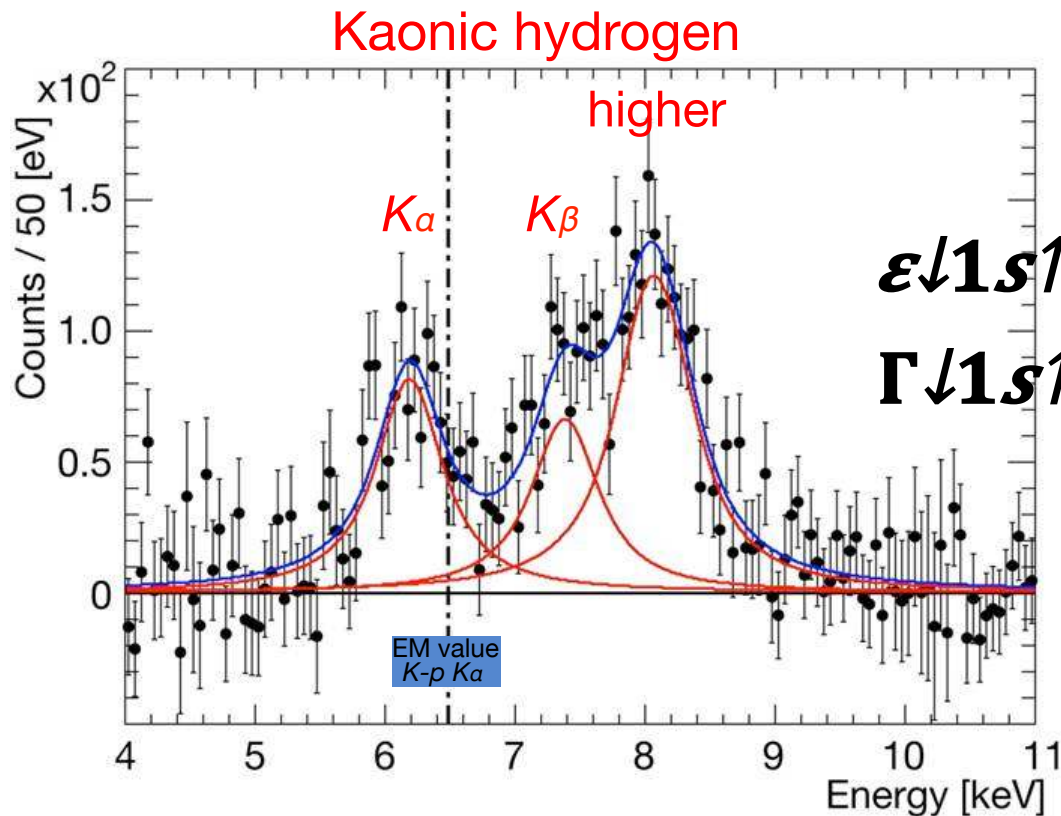
Univ. Jagiellonian Krakow, Poland

ELPH, Tohoku University



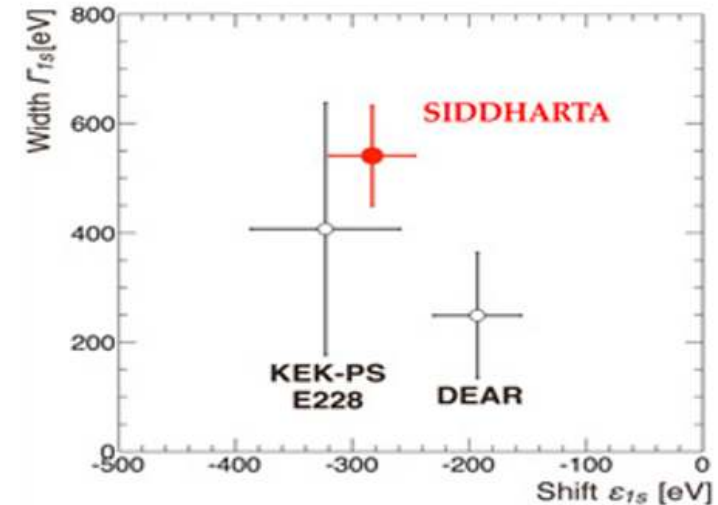
The SIDDHARTA experiment

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



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

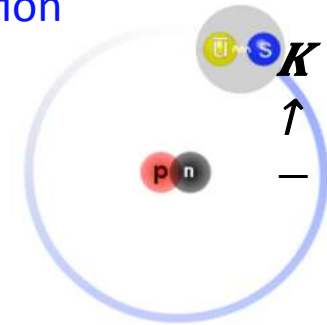
$$\Gamma \downarrow 1s \uparrow H = 541 + 89 (stat) + ?? (s)$$



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

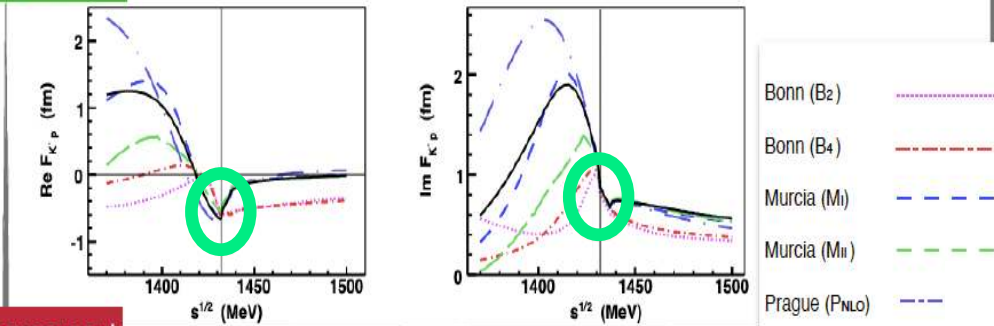
The SIDDHARTA-2 scientific goal

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

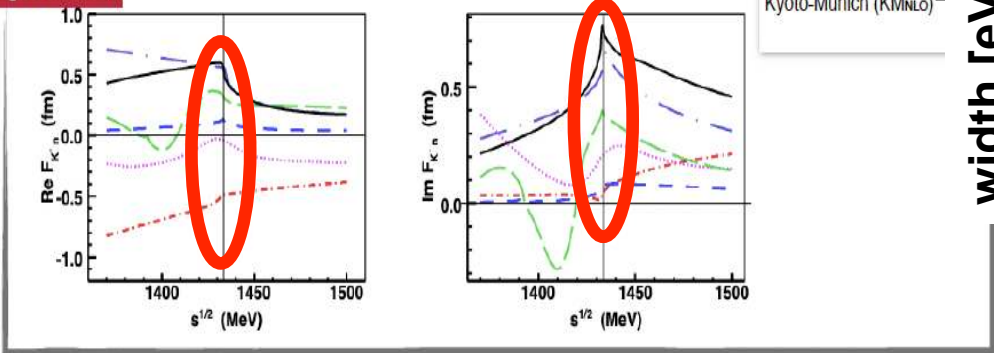


$^1 1 \bar{2} J H$
**Kaonic
 Deuterium**

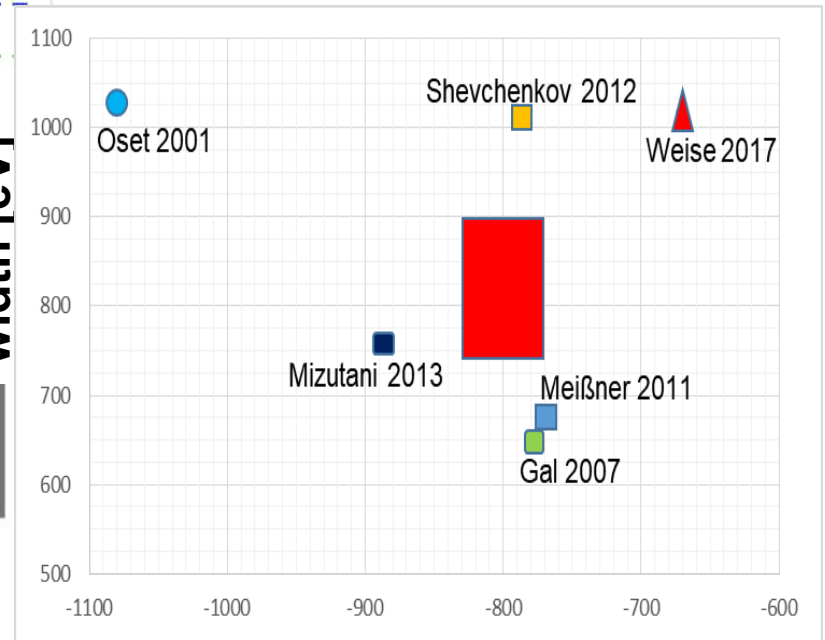
K-p: agreement



K-n: disagreement



width [eV]



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

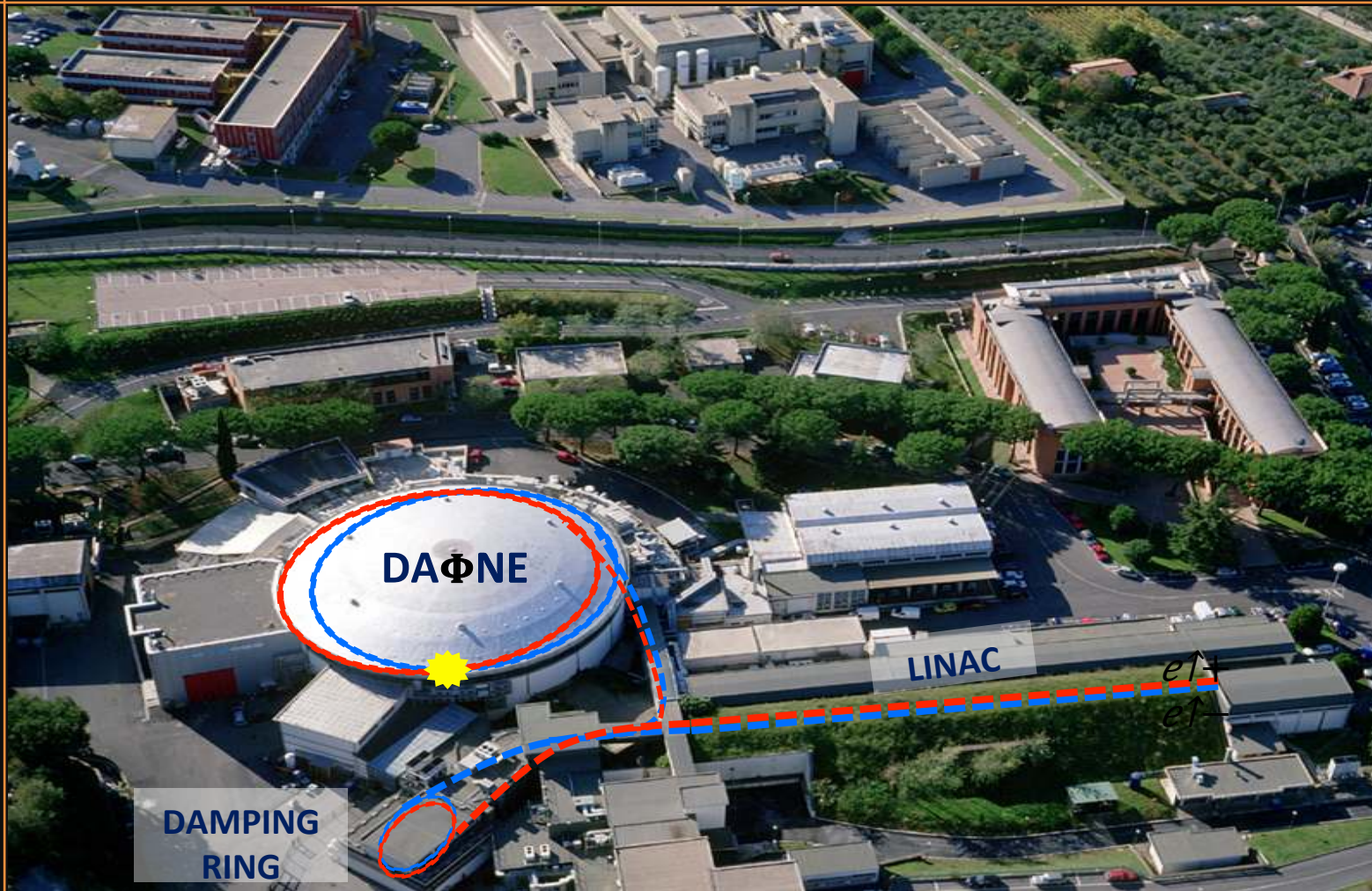
shift [eV]

How to study kaonic atoms?

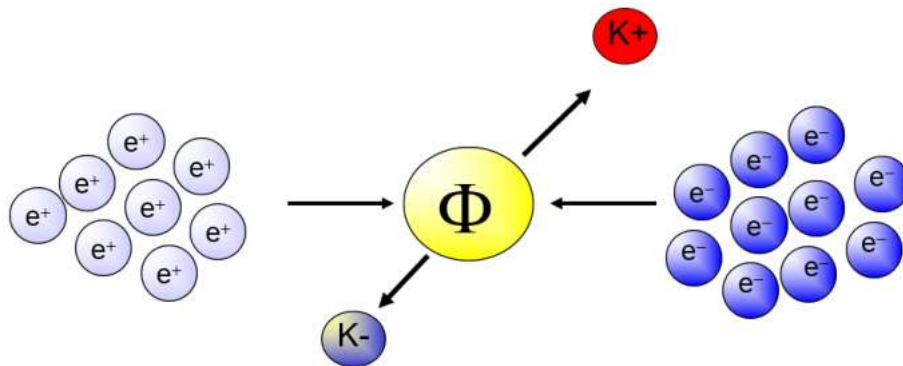
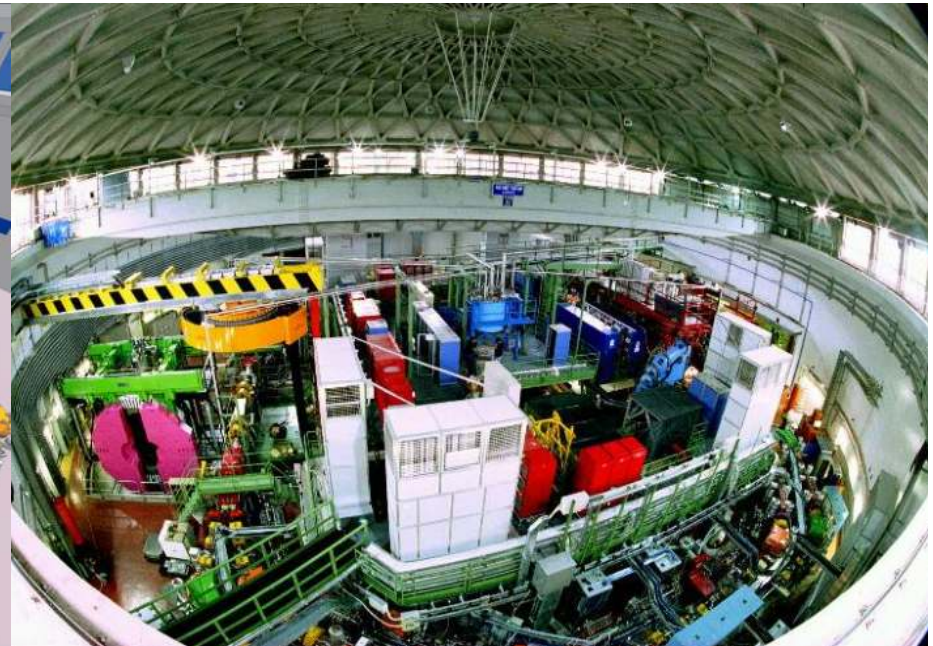
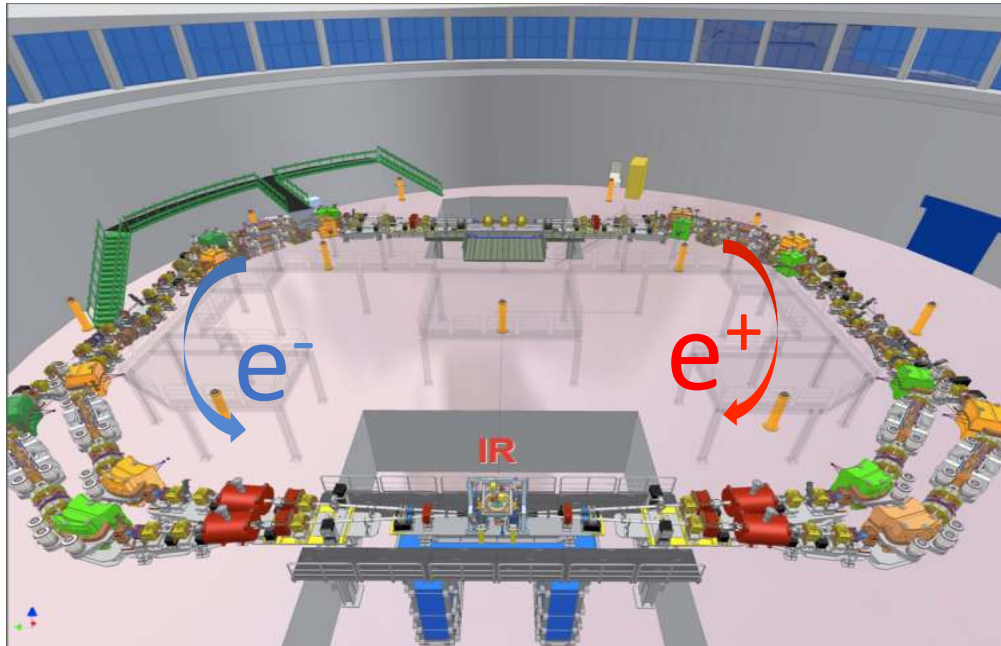


INFN-LNF

e^+e^- Accelerator Complex

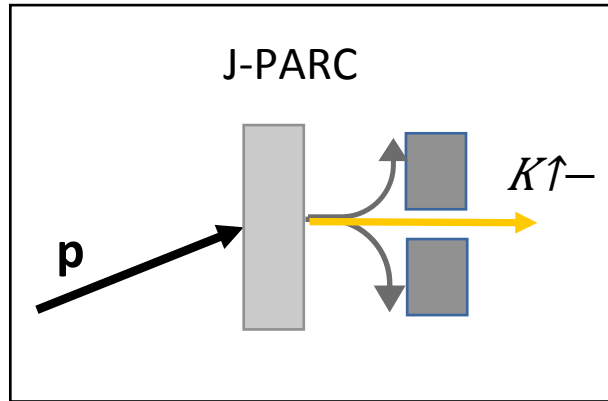


The DAΦNE Collider



- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~ 127 MeV/c ; $\Delta p/p = 0.1\%$)
- $\sim 360 \times 10^{16}$ collisions per second
- Flux of produced Φ : ~ 360 /second

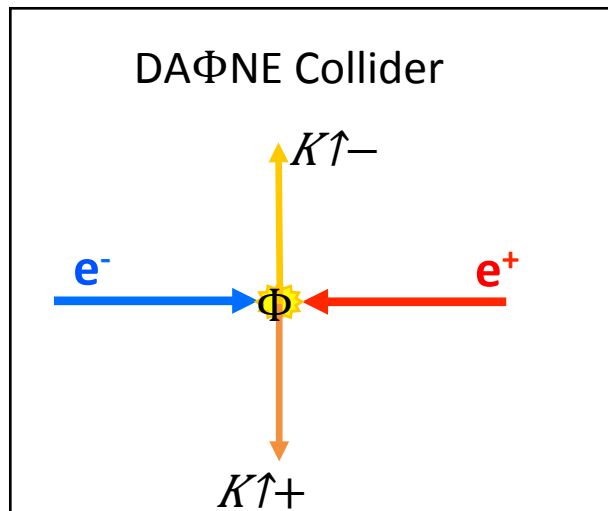
Experimental Principle



High intensity

High background

Degrader

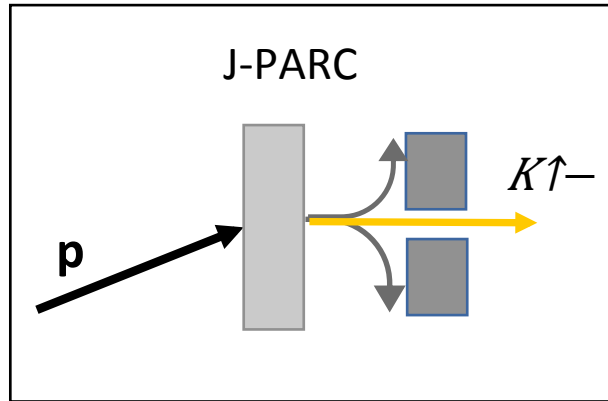


Monochromatic

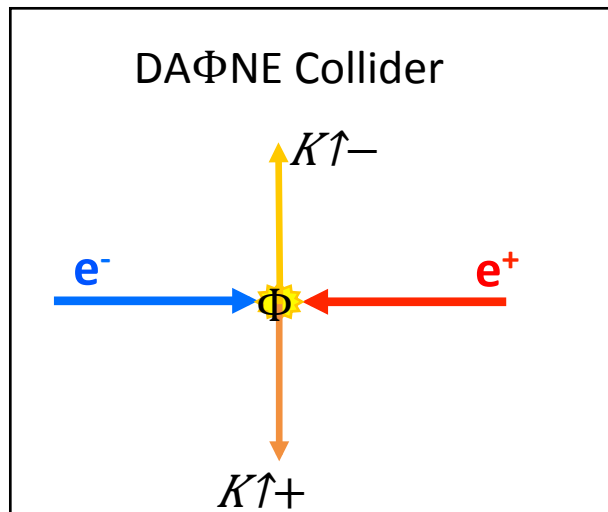
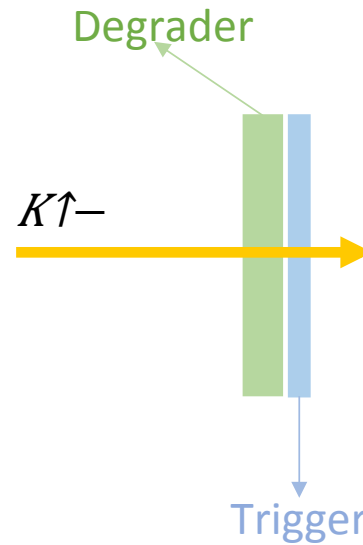
Low energy kaons

Solid angle

Experimental Principle

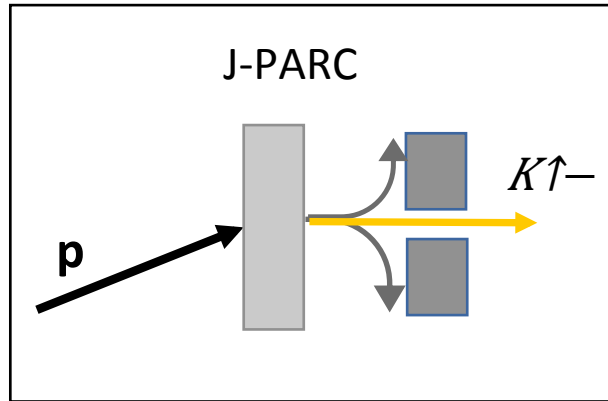


High intensity
High background



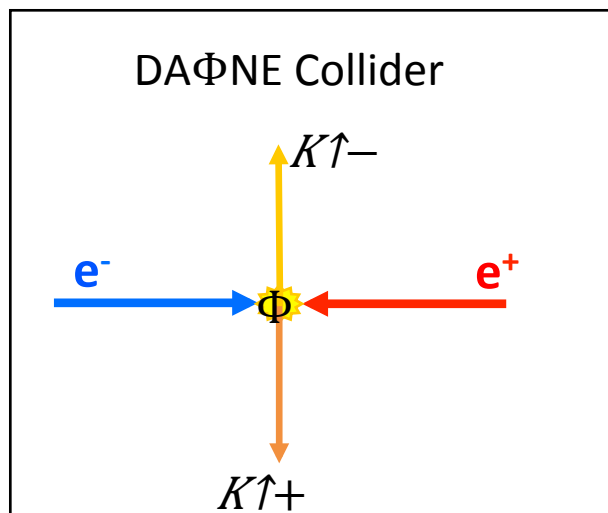
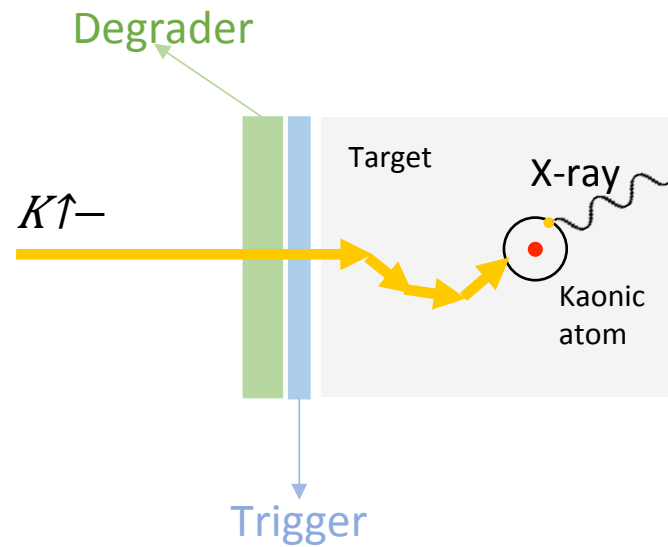
Monochromatic
Low energy kaons
Solid angle

Experimental Principle



High intensity

High background

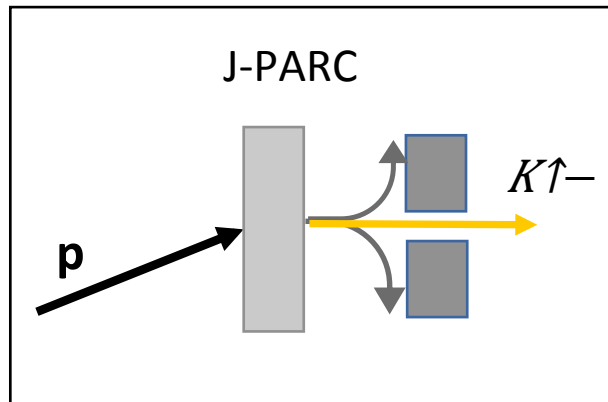


Monochromatic

Low energy kaons

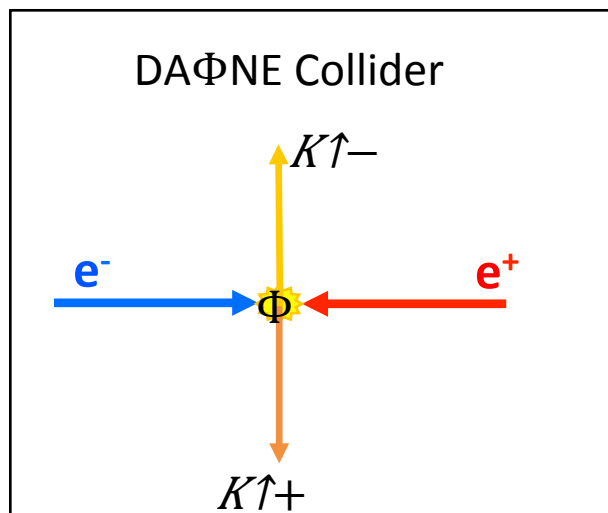
Solid angle

Experimental Principle



High intensity

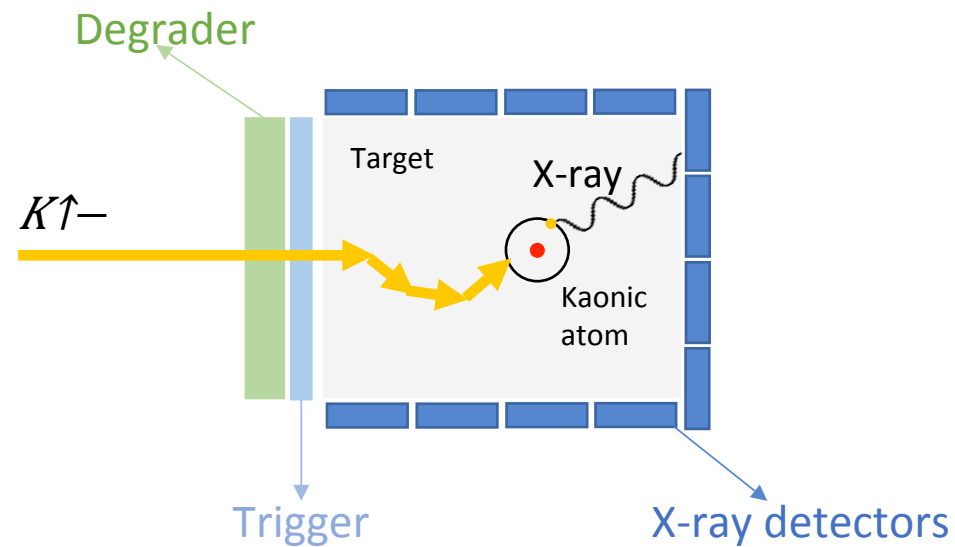
High background



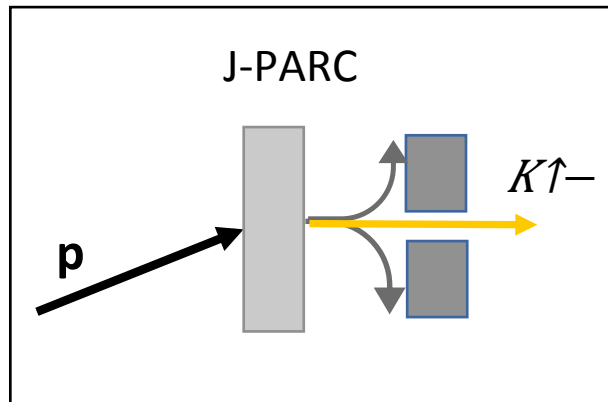
Monochromatic

Low energy kaons

Solid angle

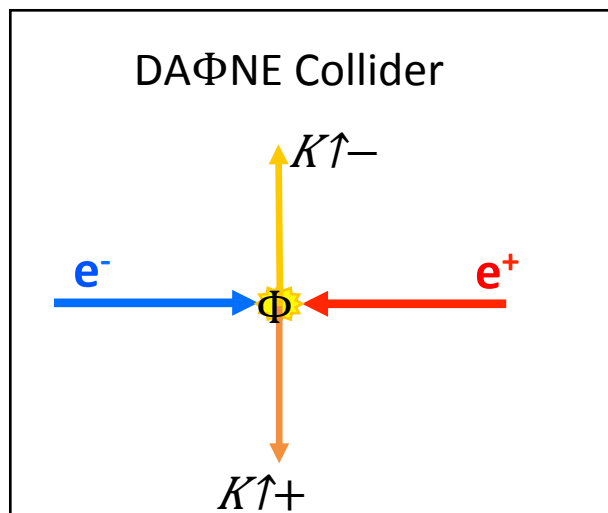


Experimental Principle



High intensity

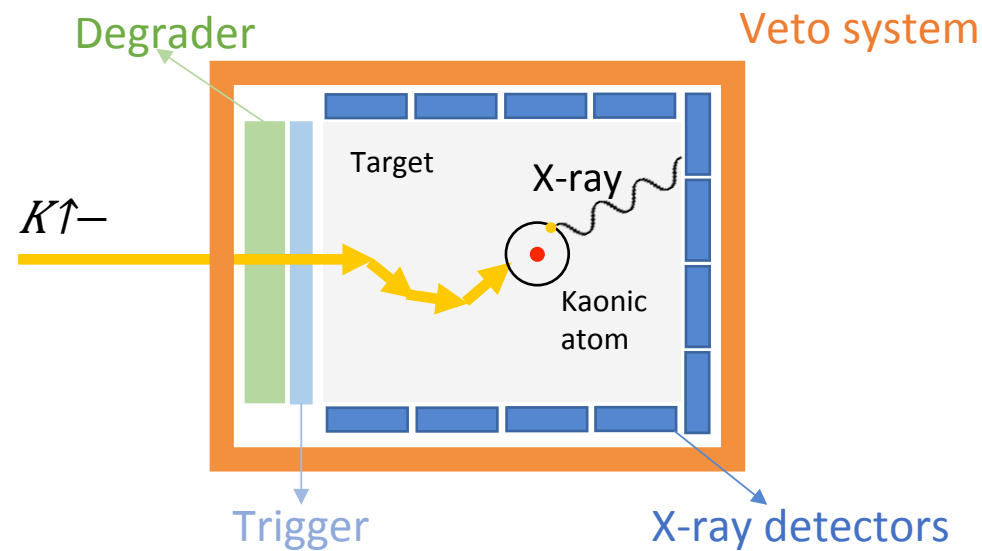
High background



Monochromatic

Low energy kaons

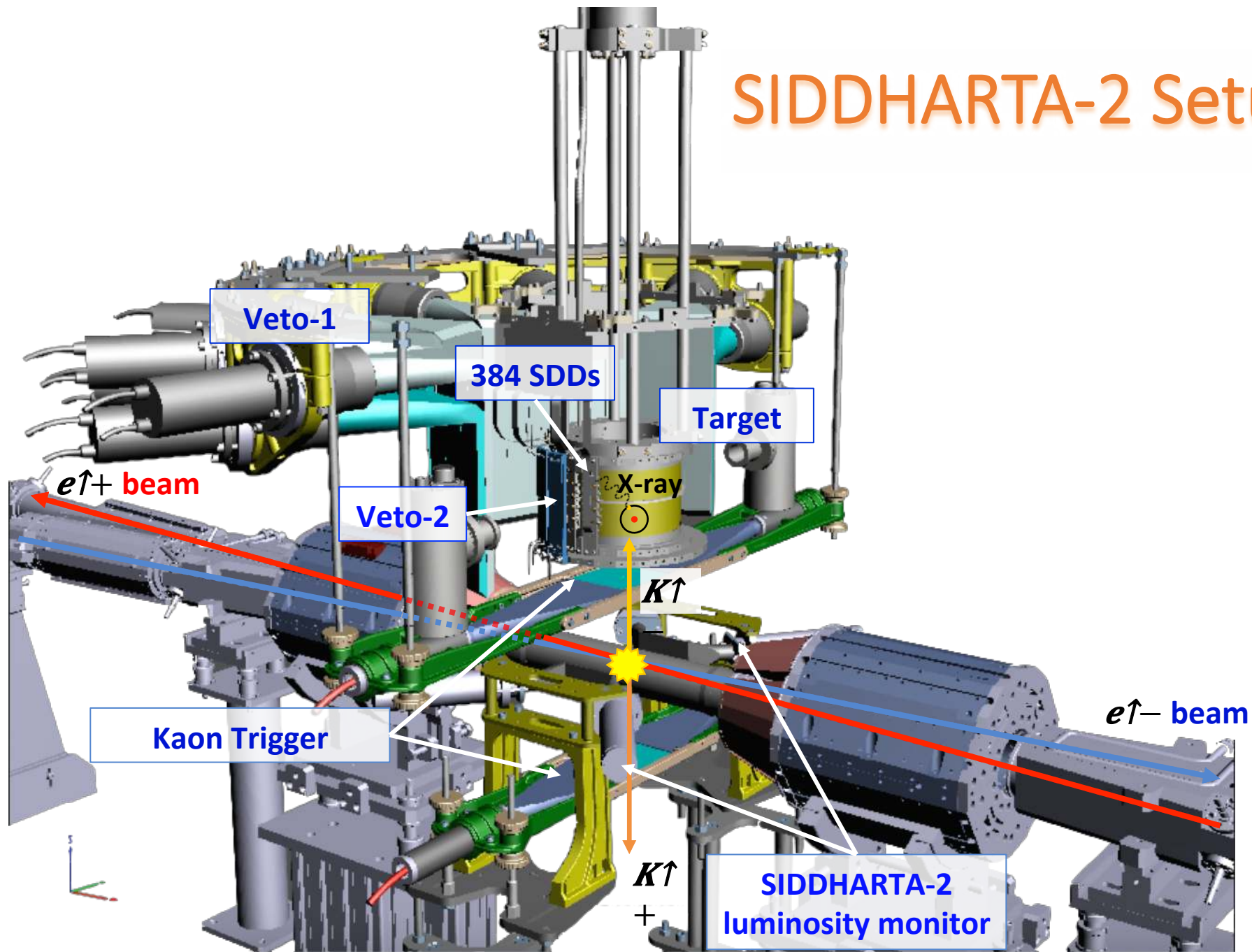
Solid angle

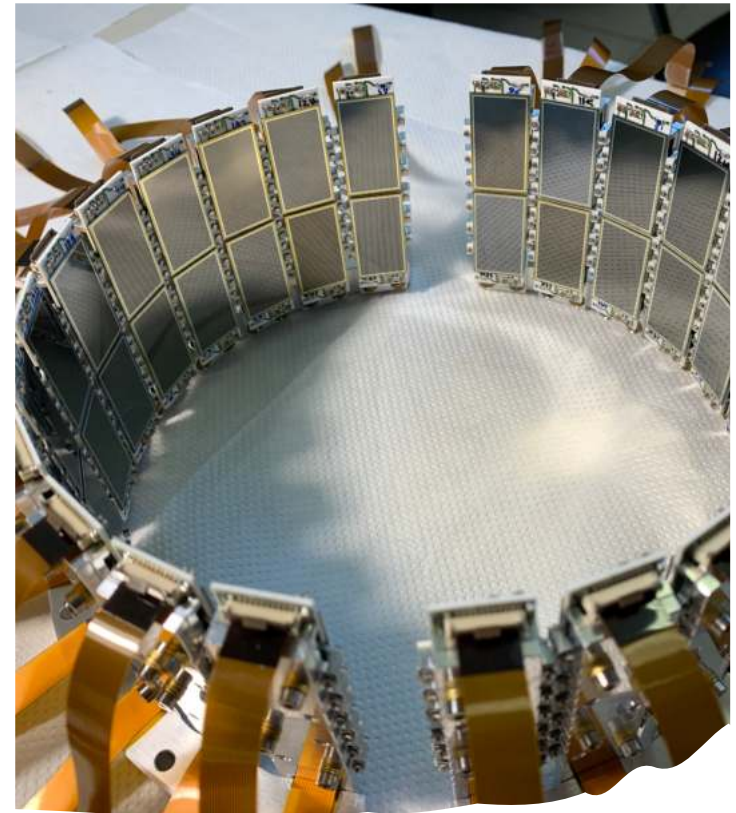
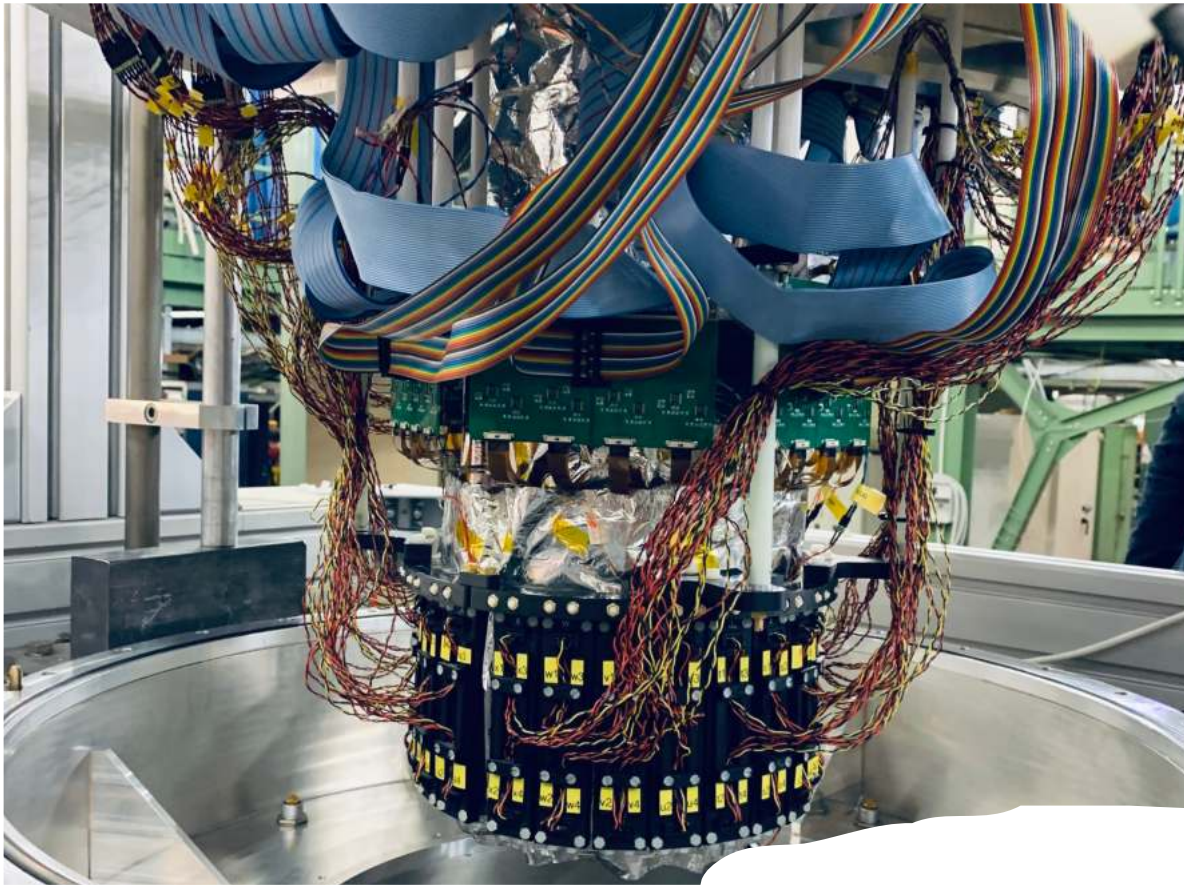


A detailed 3D CAD model of the Siddharta-2 experiment apparatus. The model shows a central cylindrical component with various ports and sensors, mounted on a complex mechanical structure. The structure includes a base with several legs, a central platform, and various support arms and brackets. The model is rendered in a dark blue color, with some components highlighted in orange and yellow. The background is black.

SIDDHARTA-2
experiment

SIDDHARTA-2 Setup





SIDDHARTA-2 Setup

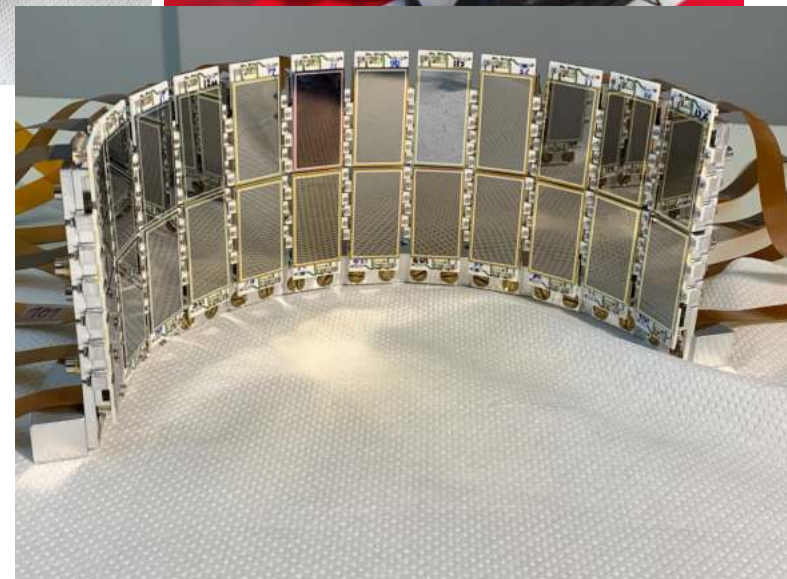


A detailed 3D cutaway diagram of a complex particle detector assembly. The central component is a cylindrical silicon drift detector, highlighted in yellow. It is surrounded by various support structures, including a large grey cylindrical component and several smaller blue and green parts. The assembly is mounted on a base with various mechanical components and wiring. The background is dark, emphasizing the intricate details of the detector's internal structure.

The Silicon Drift Detectors

The SIDDHARTA-2 target

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

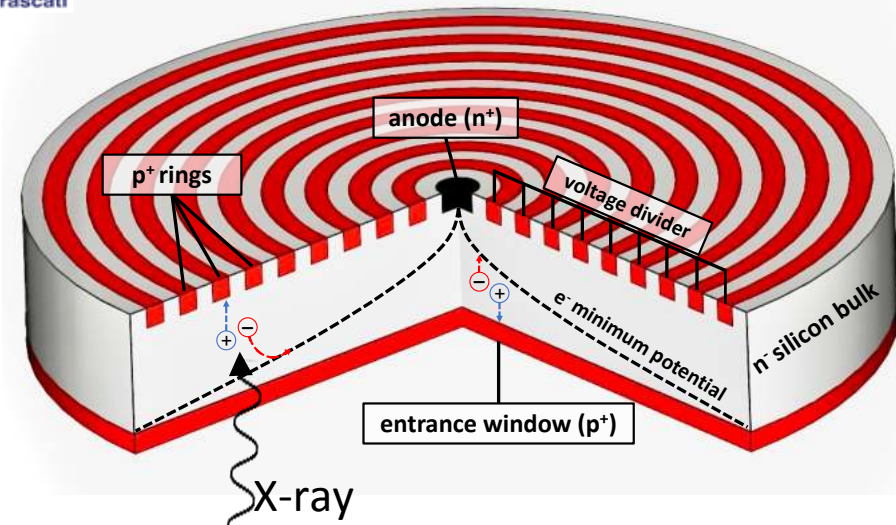
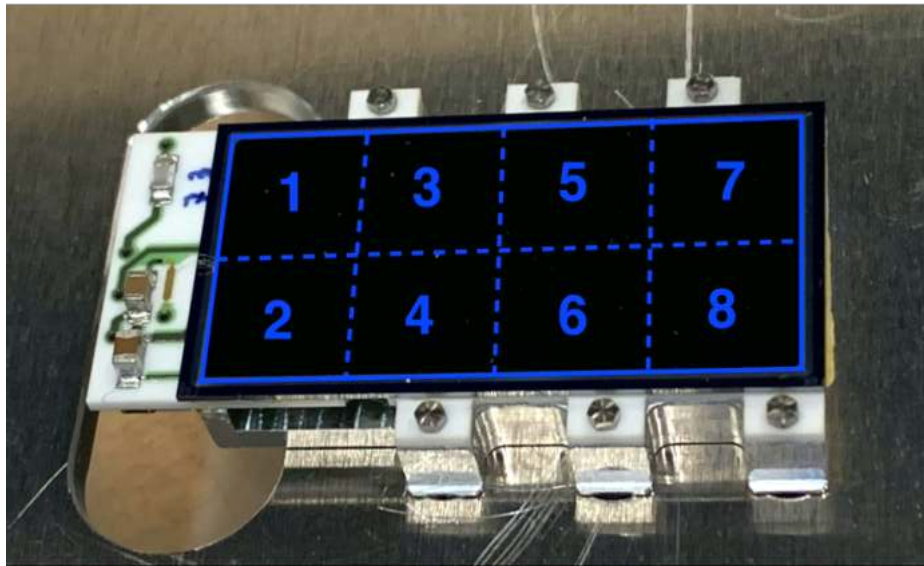


384 Silicon Drift Detectors (SDDs) are mounted on aluminium finger support for cooling (-150°C)

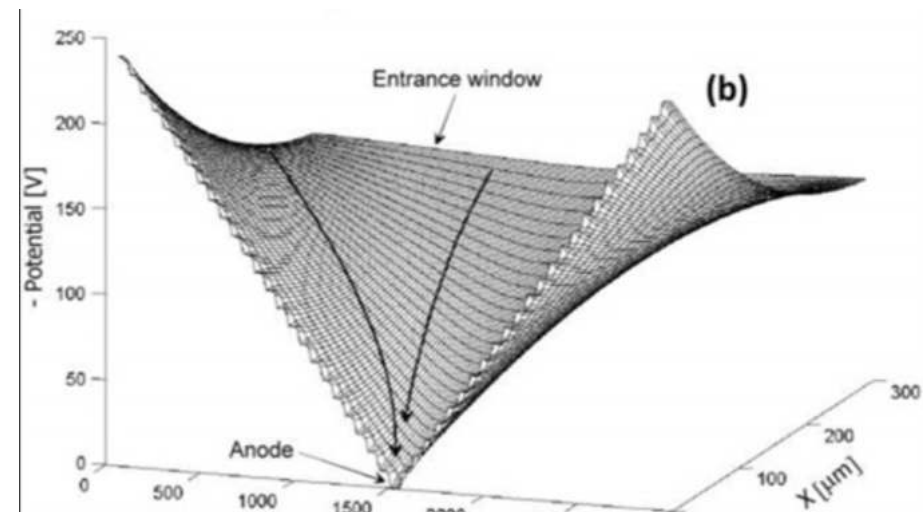
Silicon Drift Detectors



SDD cross section

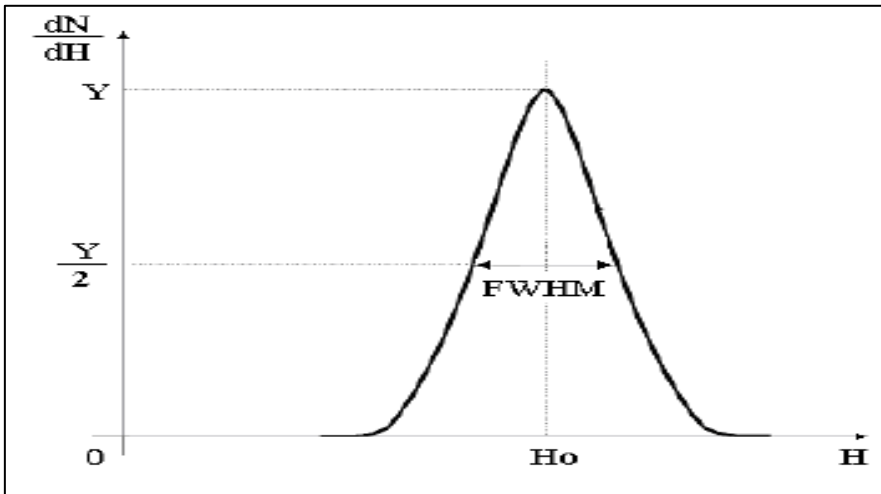
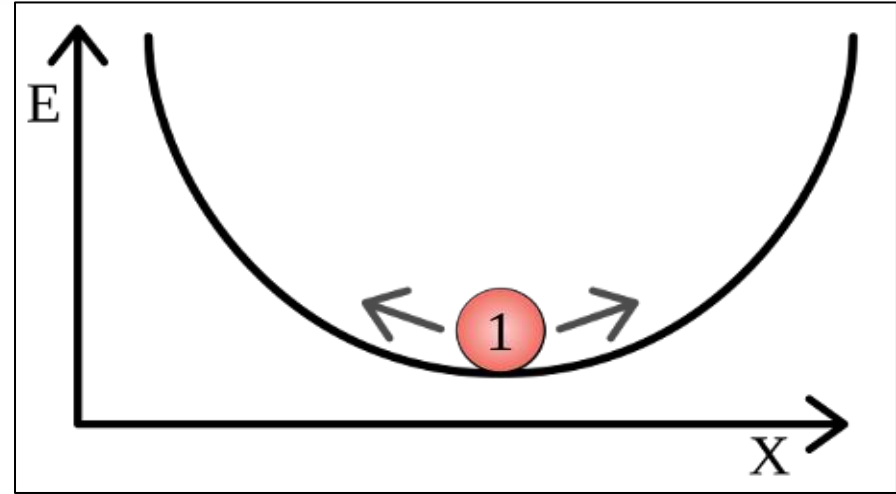


8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of $450 \mu\text{m}$ ensures a high
collection efficiency for X-rays of energy
between 5 keV and 12 keV



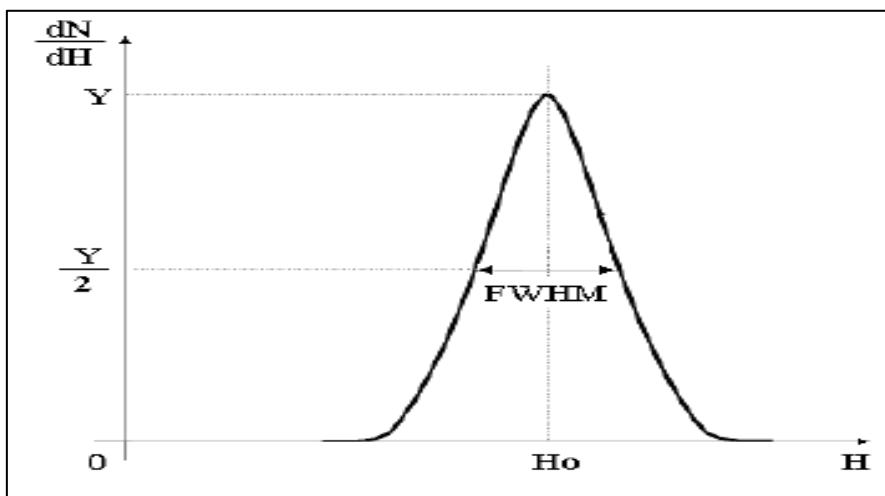
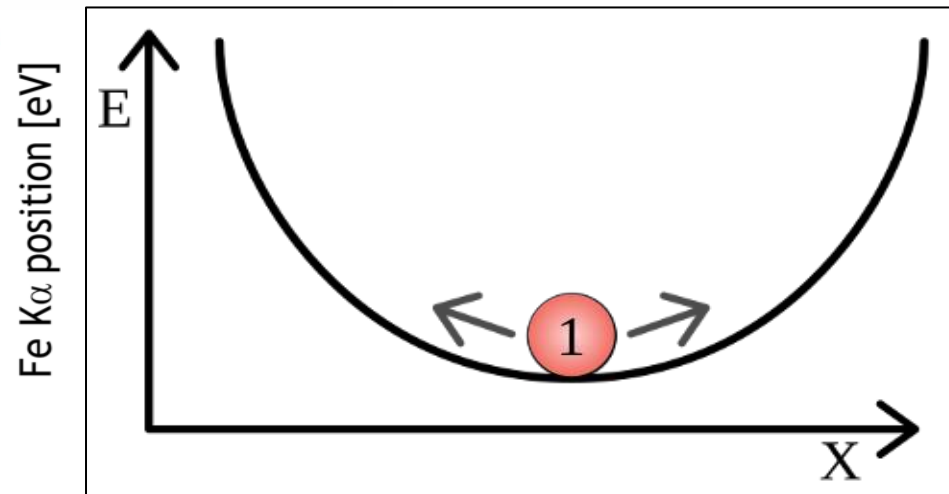
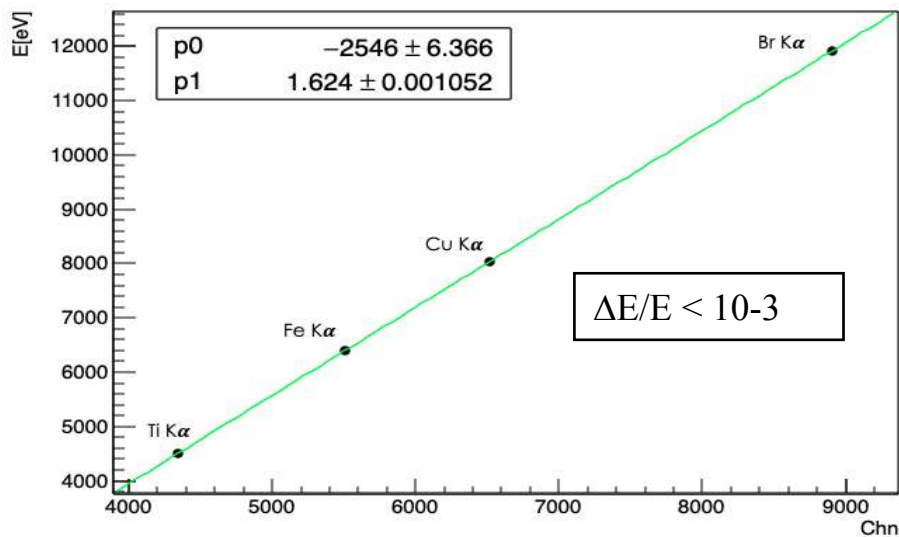
Silicon Drift Detectors

Energy response



Silicon Drift Detectors

Linearity Energy response

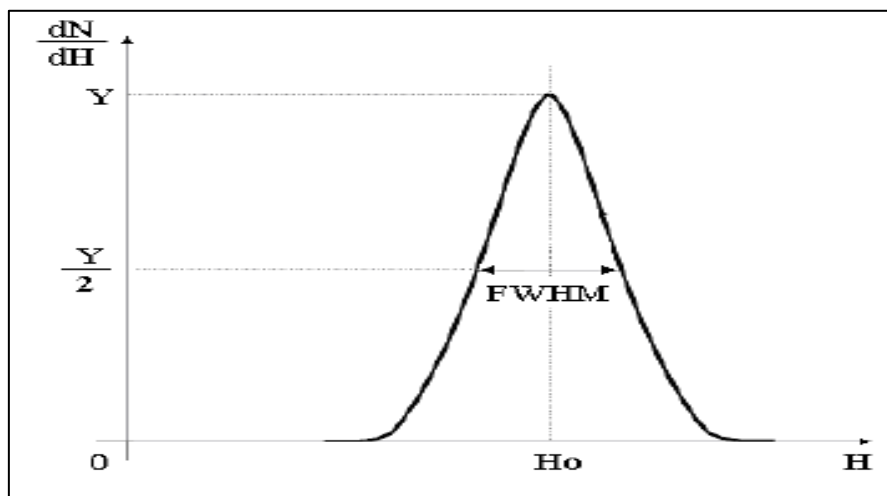
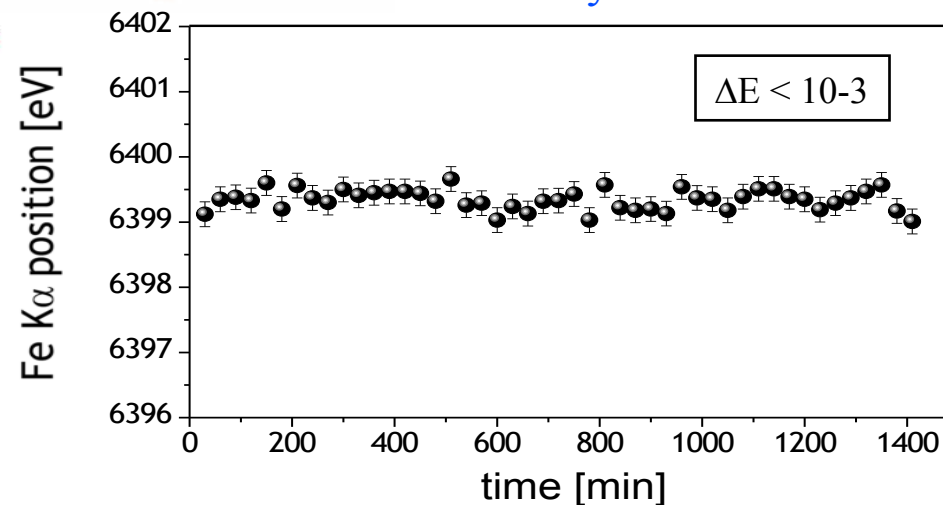
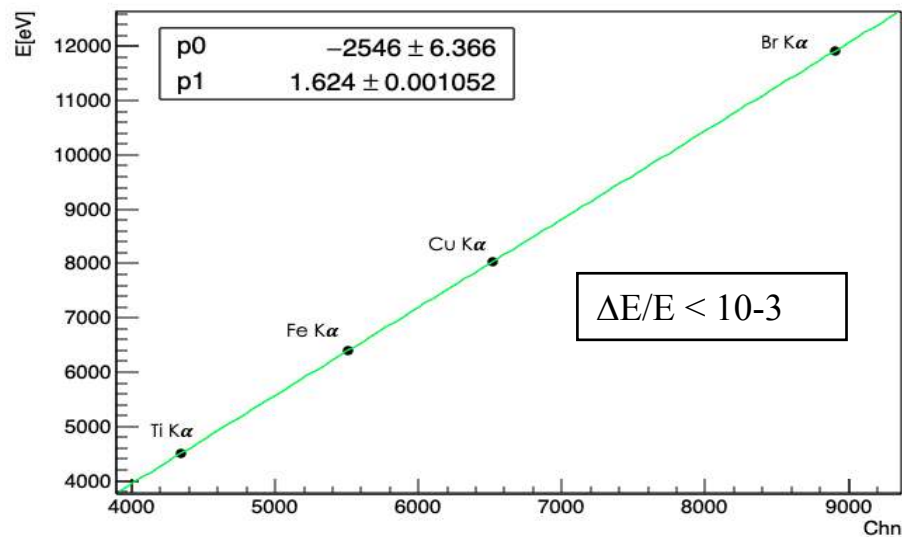


Silicon Drift Detectors

Energy response

Linearity

Stability

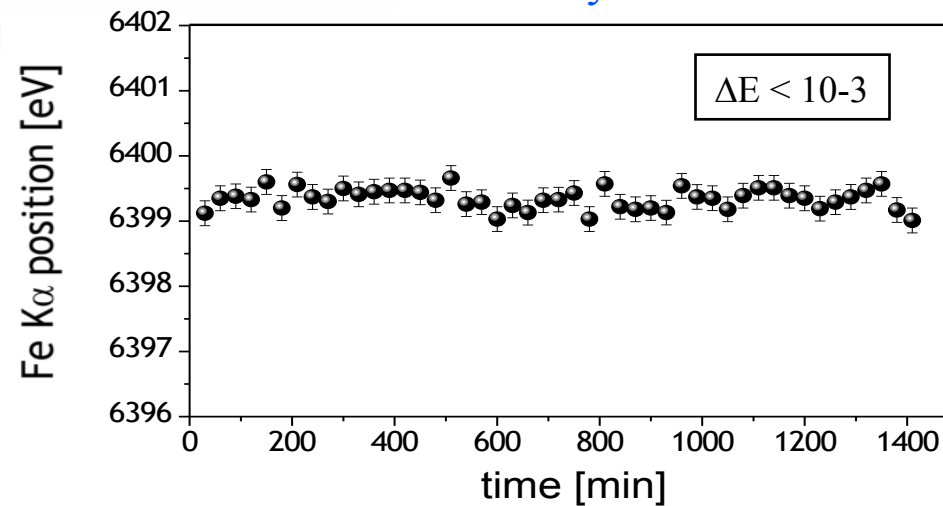
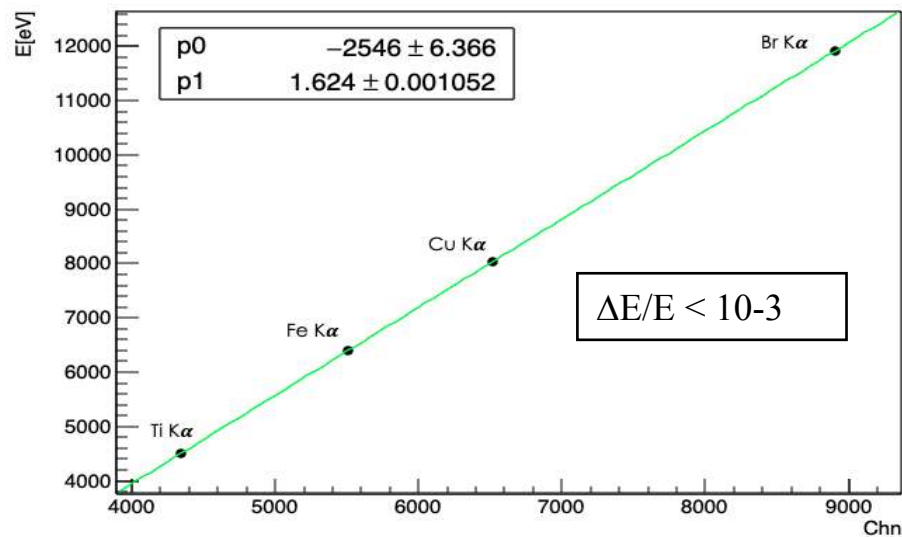


Silicon Drift Detectors

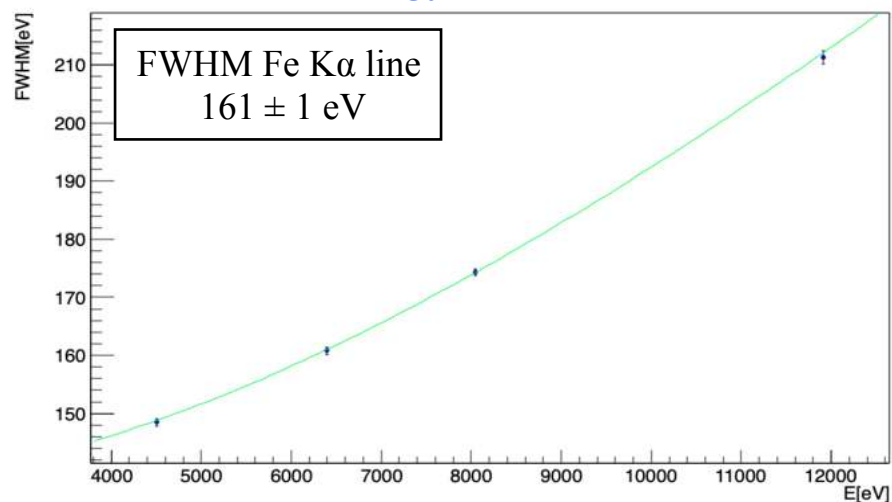
Energy response

Linearity

Stability



Energy Resolution

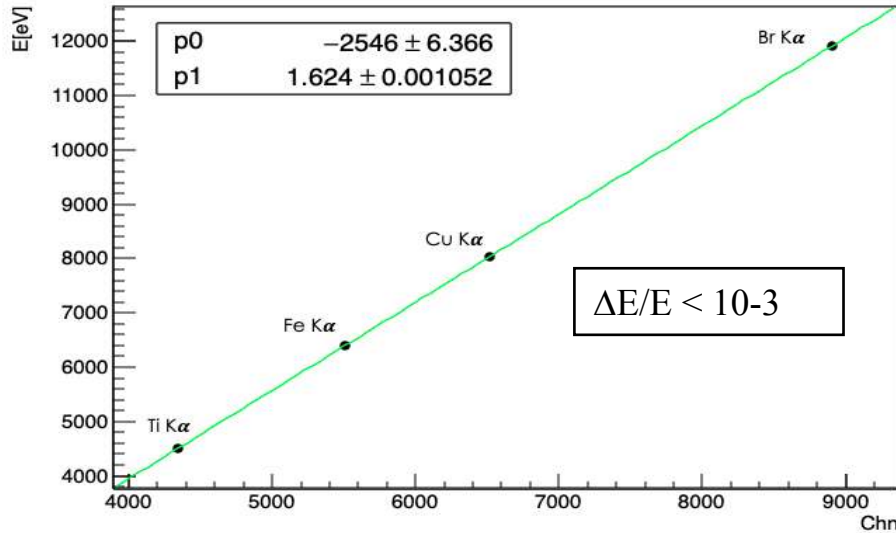


Silicon Drift Detectors

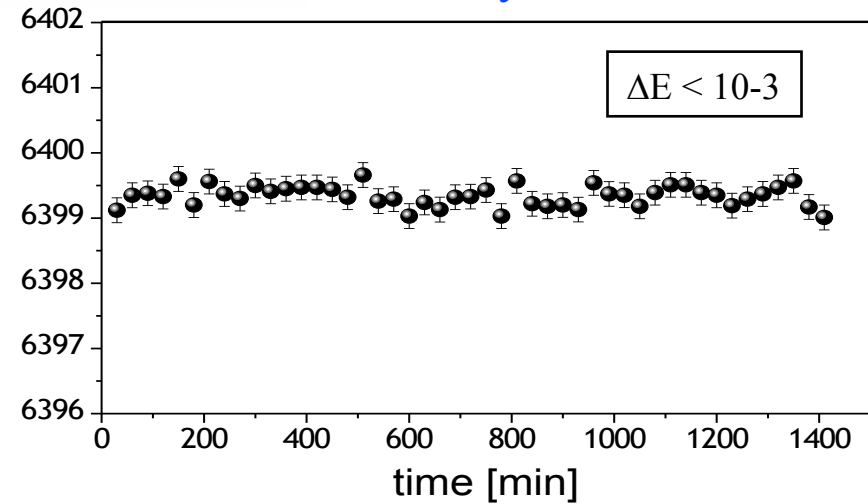
Energy response

Linearity

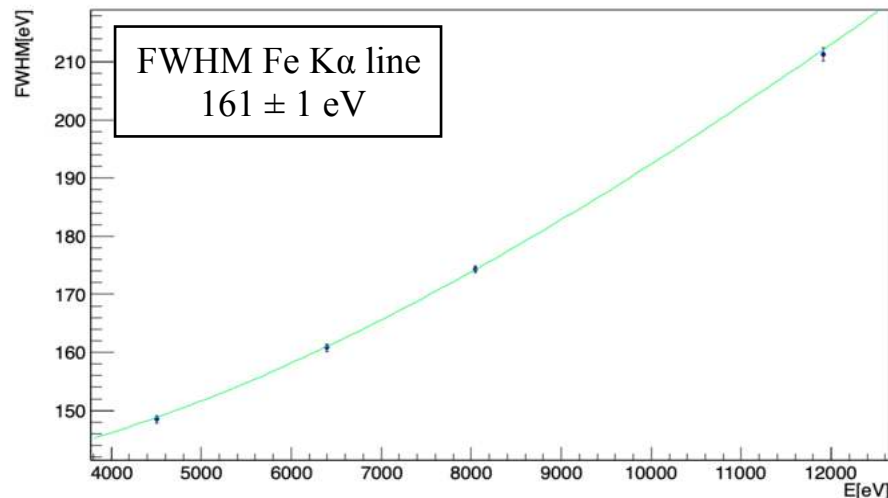
Stability



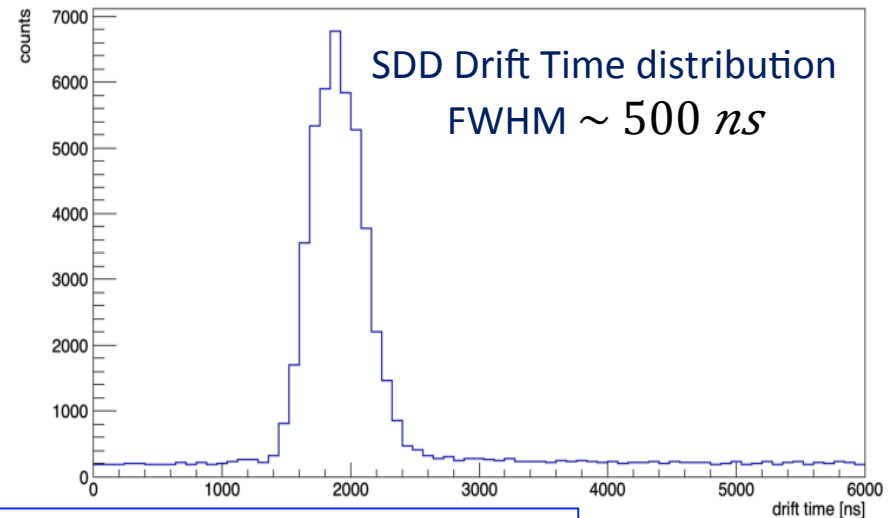
Fe K α position [eV]



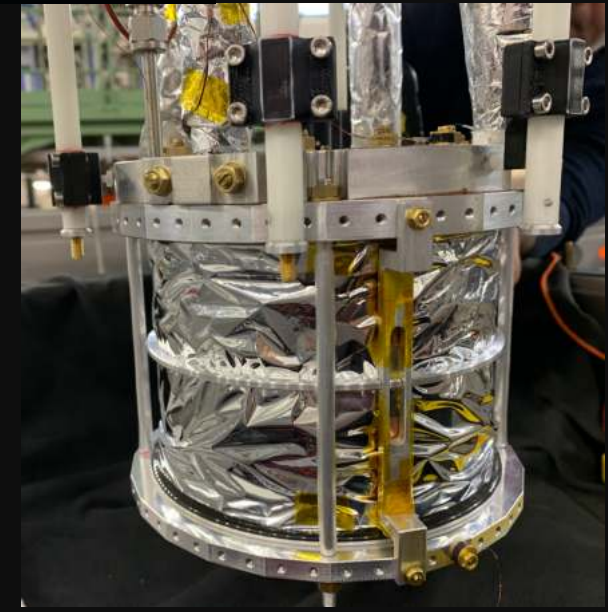
Energy Resolution



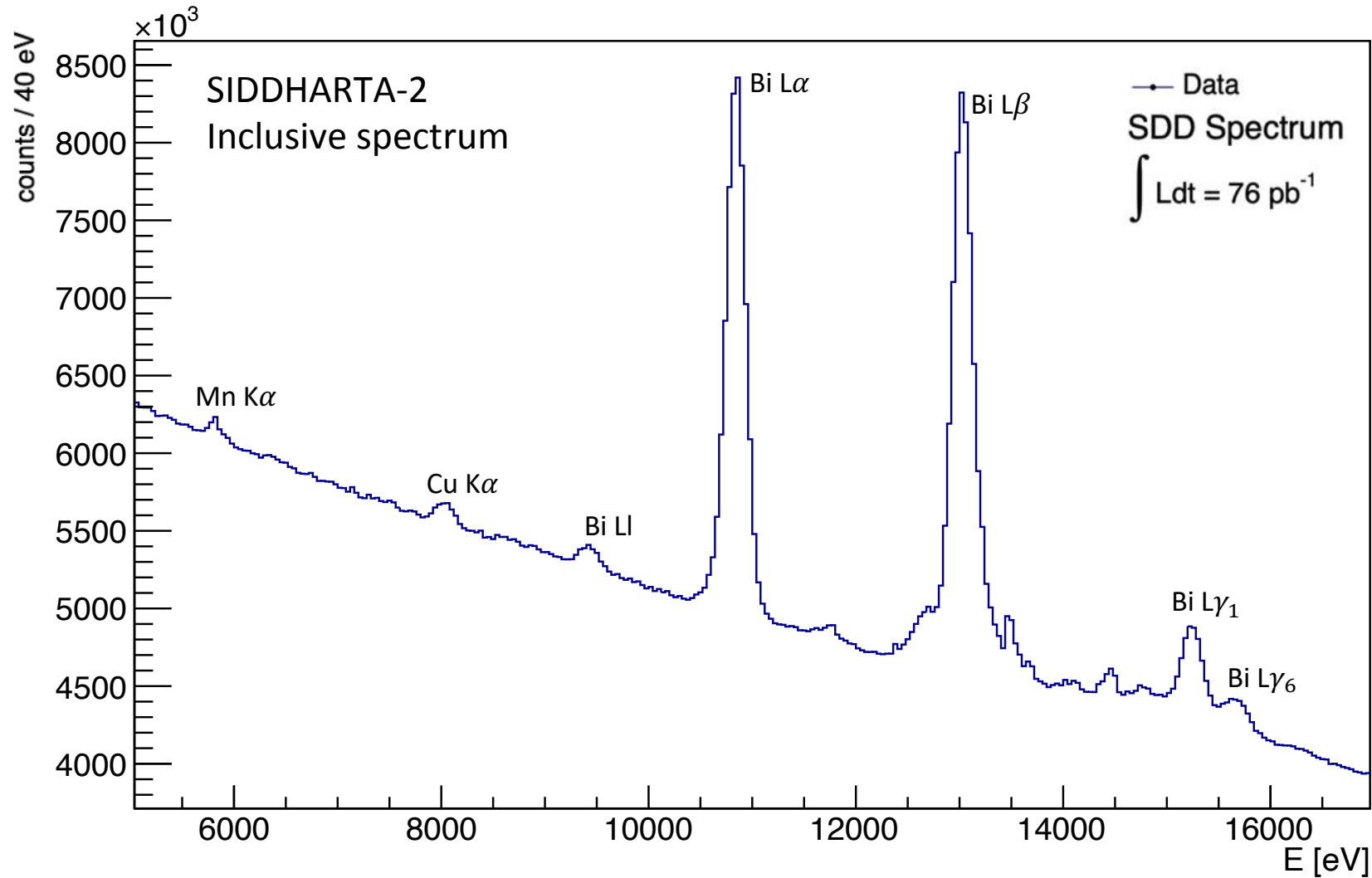
Time Resolution



Kaonic Helium Run



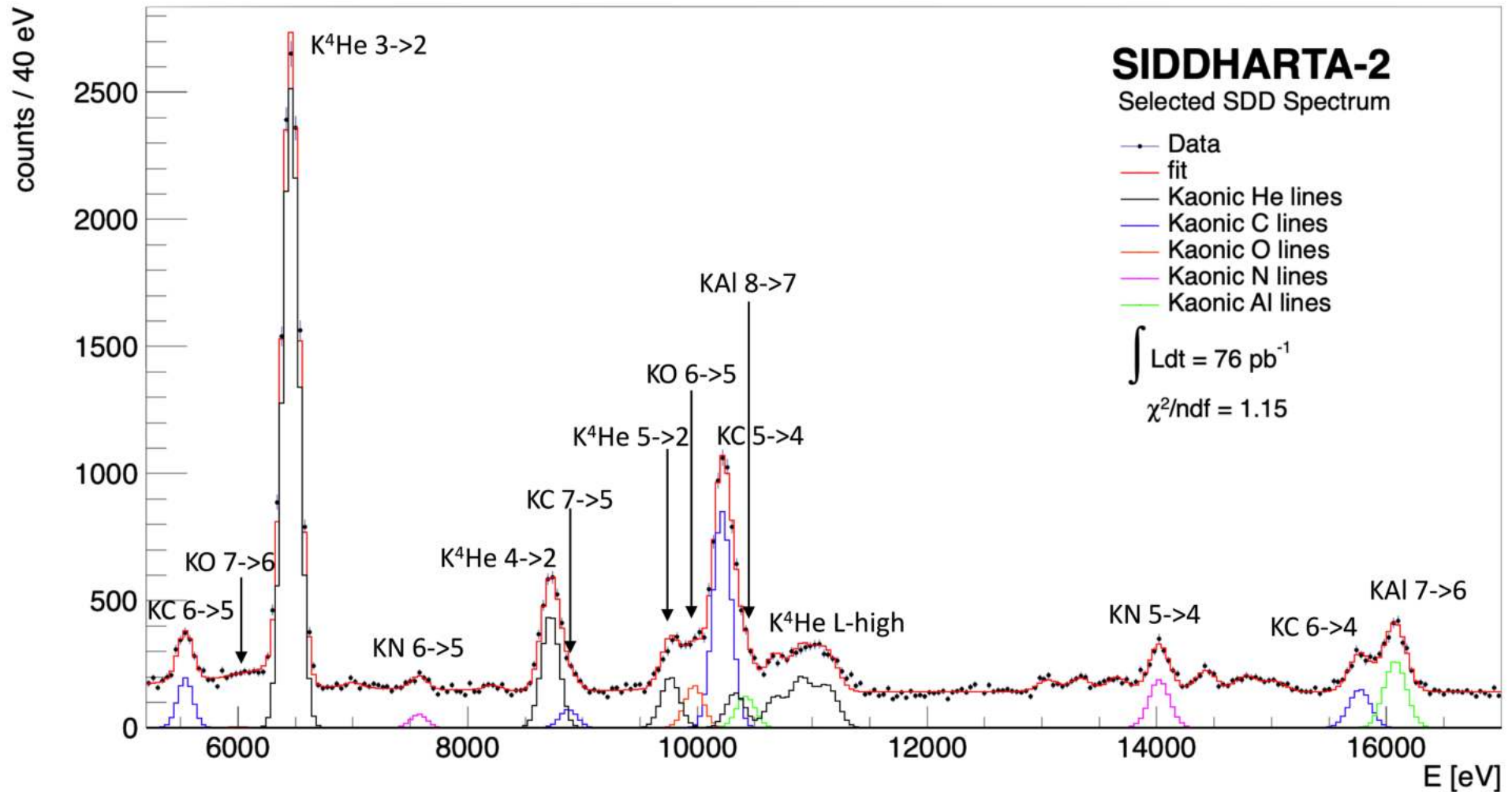
SIDDHARTA-2 Kaonic ^4He





Data Analysis

SIDDHARTA-2 Kaonic ^4He



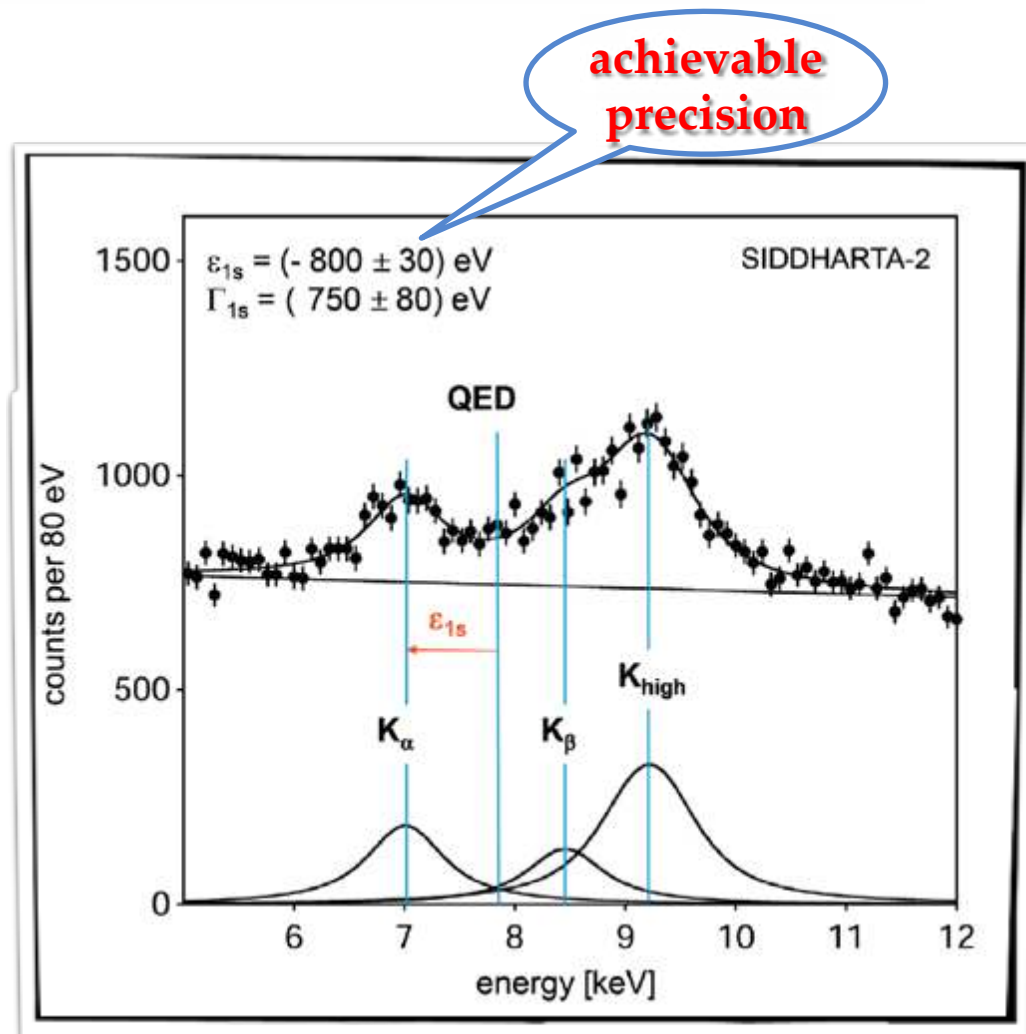
*F Sgaramella et al. Measurement of high-n transition in intermediate mass kaonic atom by SIDDHARTA-e at DAΦNE Eur. Phys. J. A **59**, 56*

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

