Strangeness studies on DAFNE collider to unlock secrets of neutron stars

Catalina Curceanu and Kristian Piscicchia

Strangeness, gravitational waves and neutron stars
LNF-INFN, 1oth June 2016

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

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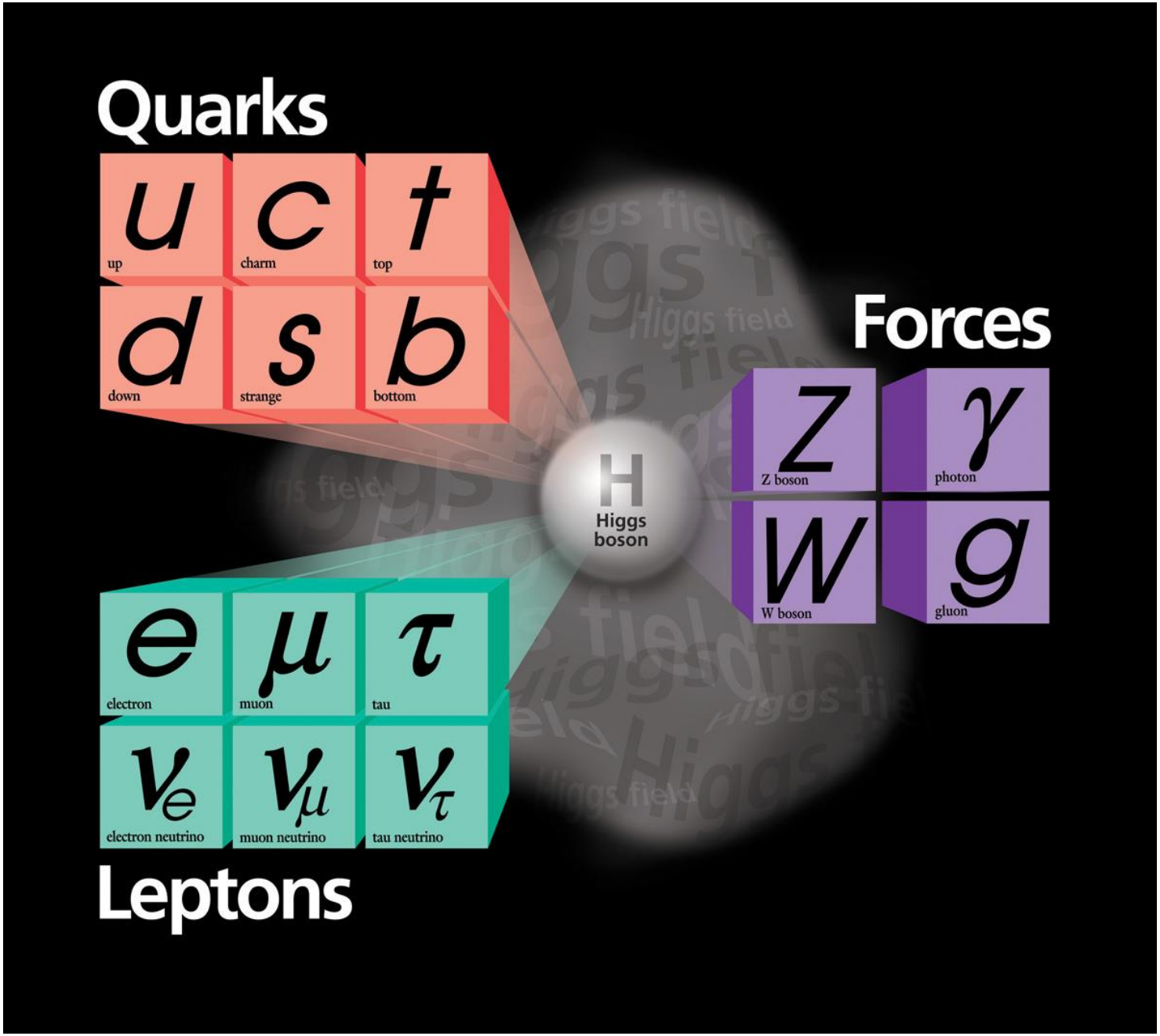
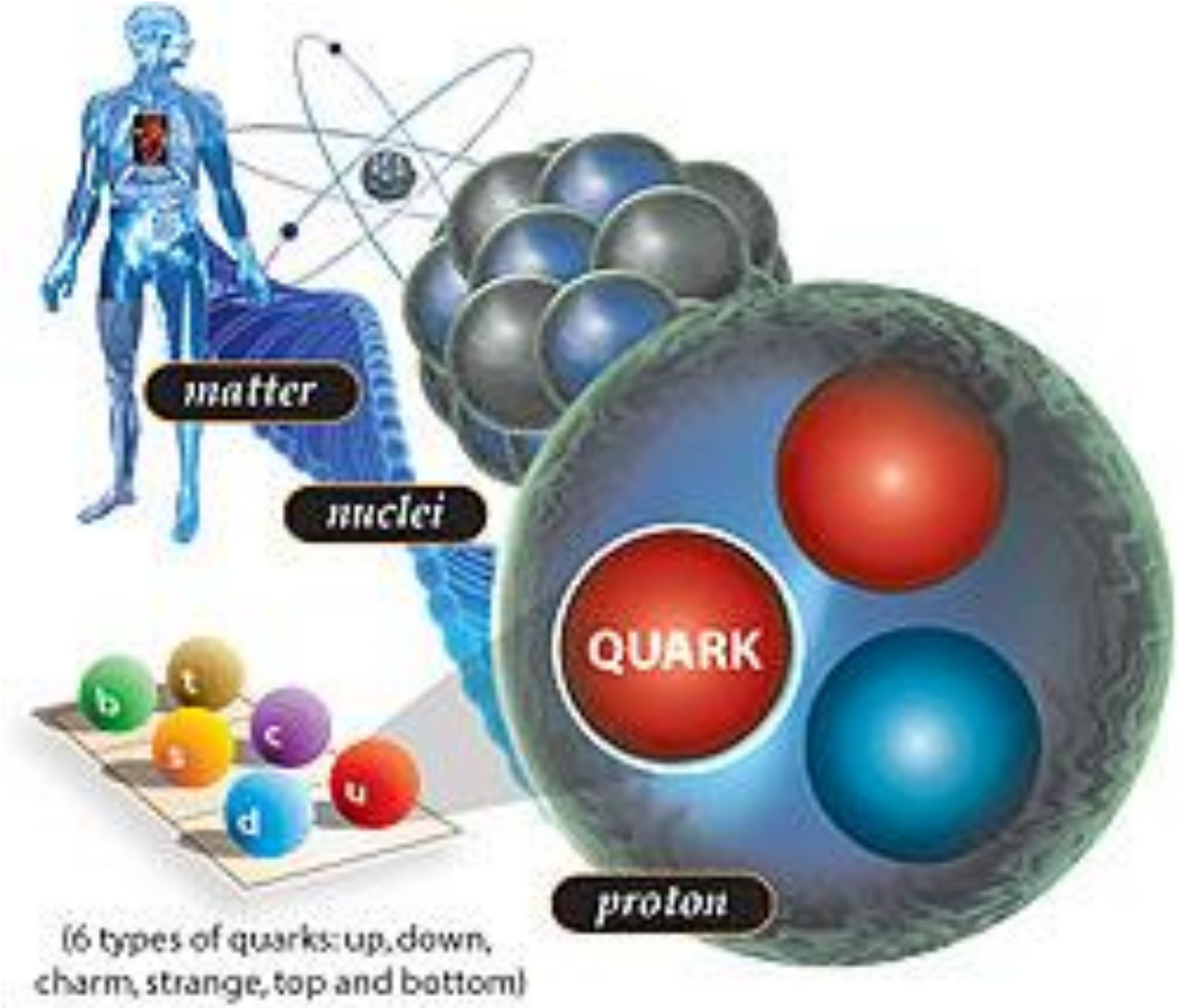
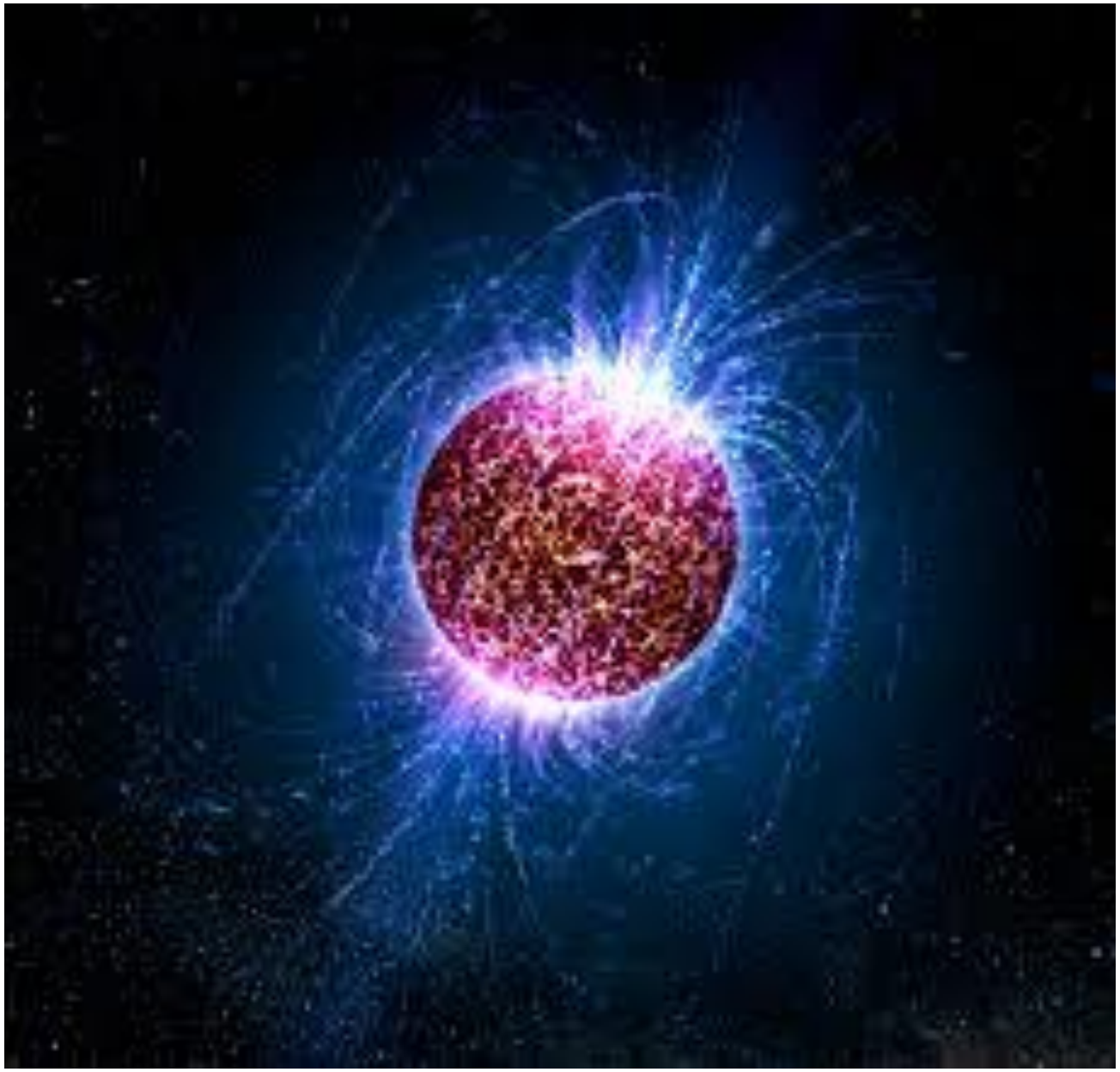
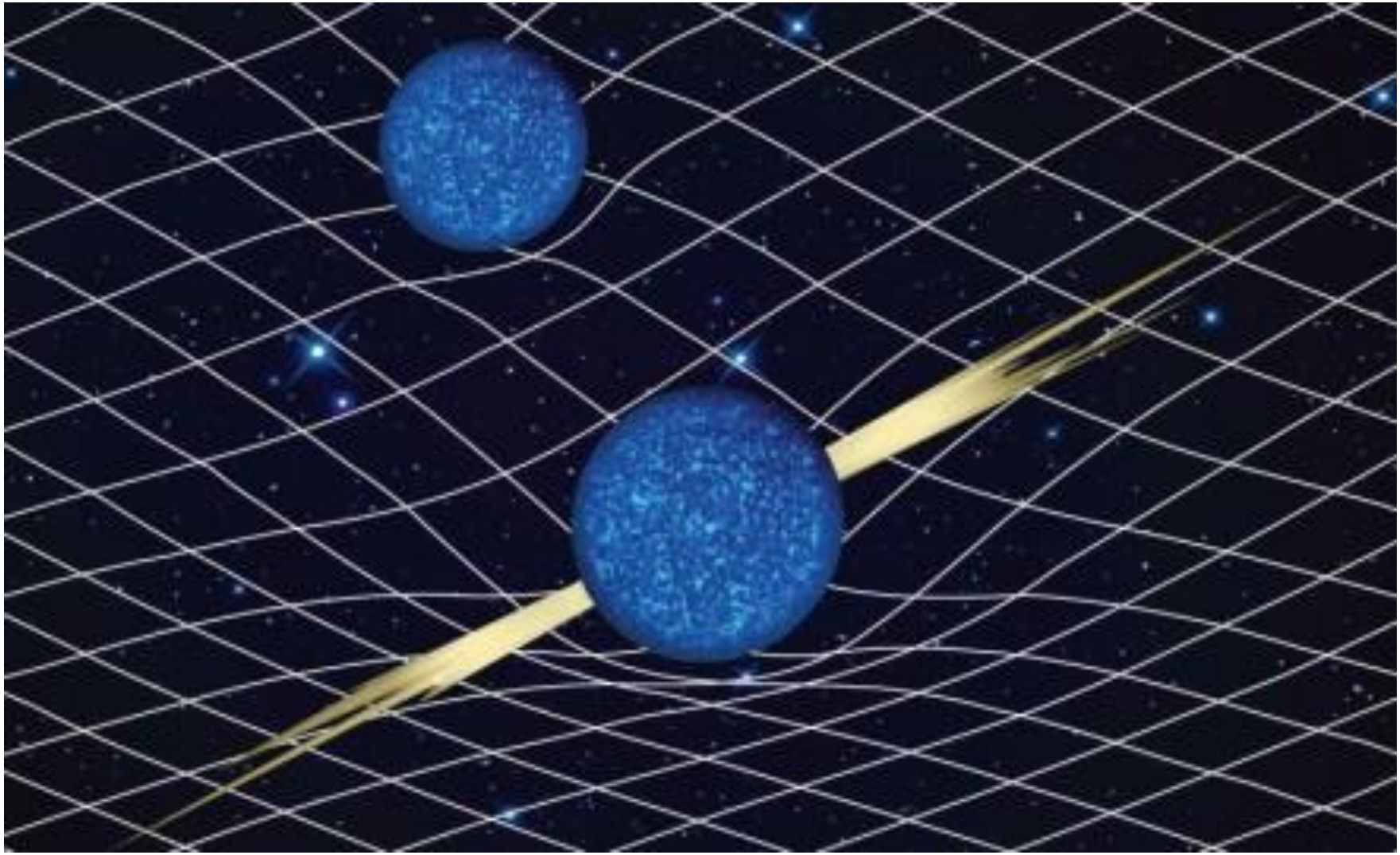
The Standard Model

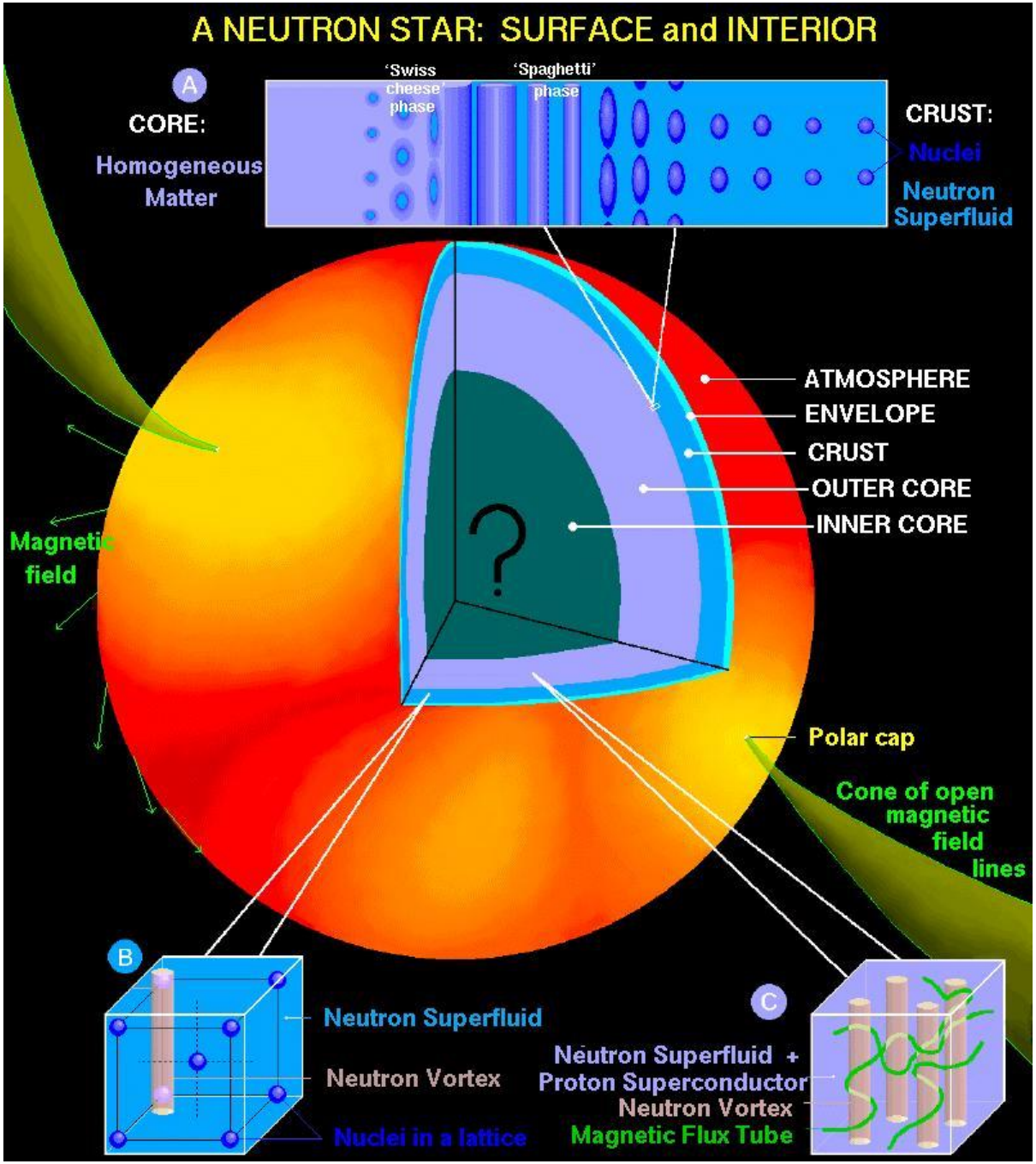


The Standard Model



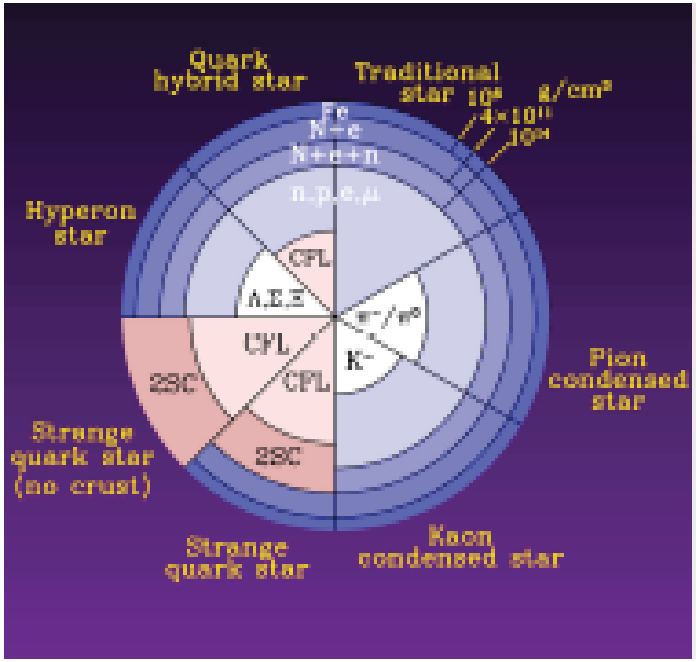




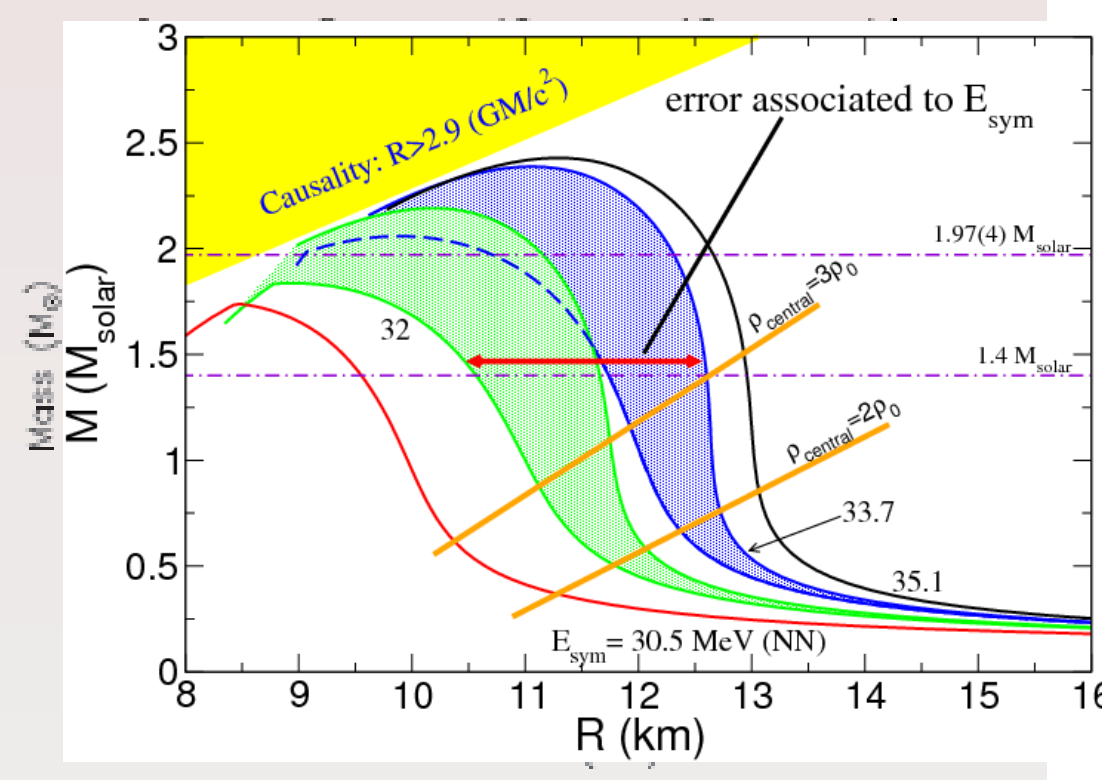

A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER

J. Lattimer, M. Prakash: Astrophys. J. 550 (2001) 426



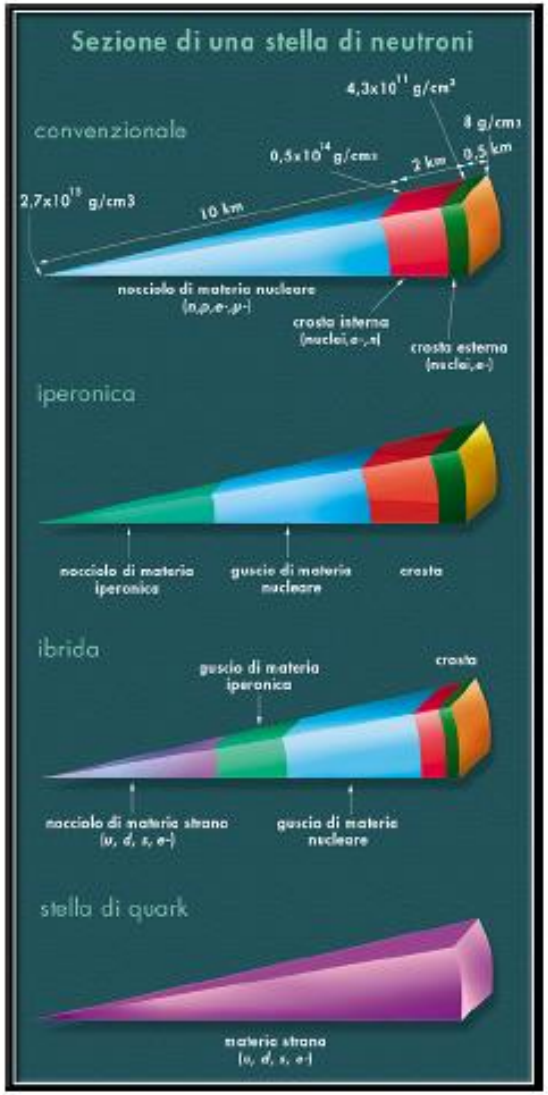
- **Mass-Radius Relation**



- **Neutron Star Scenarios**

$$\frac{dP}{dr} = -\frac{G}{c^2}\frac{(M + 4\pi P r^3)(\mathcal{E} + P)}{r(r - GM/c^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \frac{\mathcal{E}}{c^2}$$



Two families of Compact Stars

Hadron Stars (HS)

- Nucleonic Stars
- Hyperonic Stars

Quark Stars (QS)

- Hybrid Stars
- Strange Stars

Isaac Vidana

How strong is the interaction of kaons (strangeness) with nuclear matter?

How strong is the interaction of kaons (strangeness) with nuclear matter?

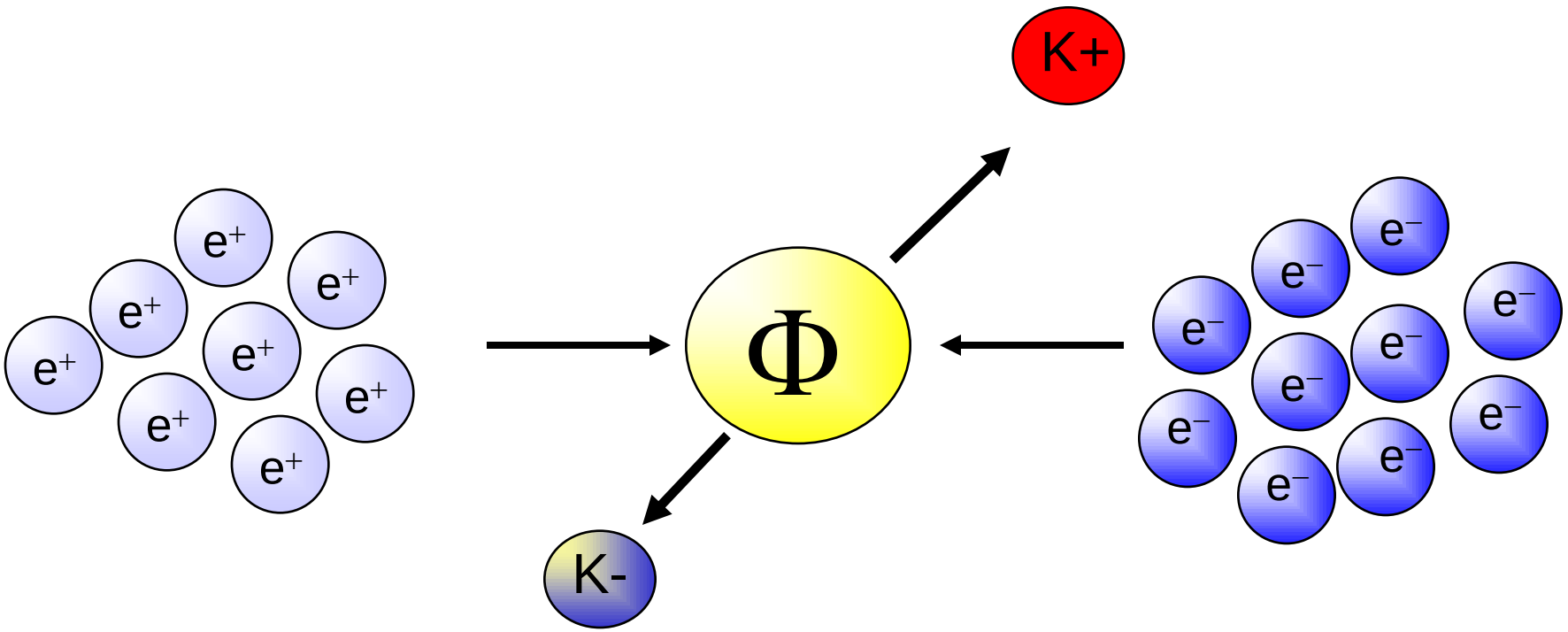
The low-energy kaon-nucleon/nuclei interaction studies are fundamental for understanding QCD in non-perturbative regime:

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

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

The DAFNE collider or the best possible beam of low energy kaons

The DAFNE principle



Flux of produced kaons: about 1000/second

DAΦNE, since 1998

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(-2)

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
- TUM, Munchen, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada
- Zagreb Univ.

The scientific aim

the determination of the ***isospin dependent KN scattering lengths*** through a

~ precision measurement of the shift
and *of the width*

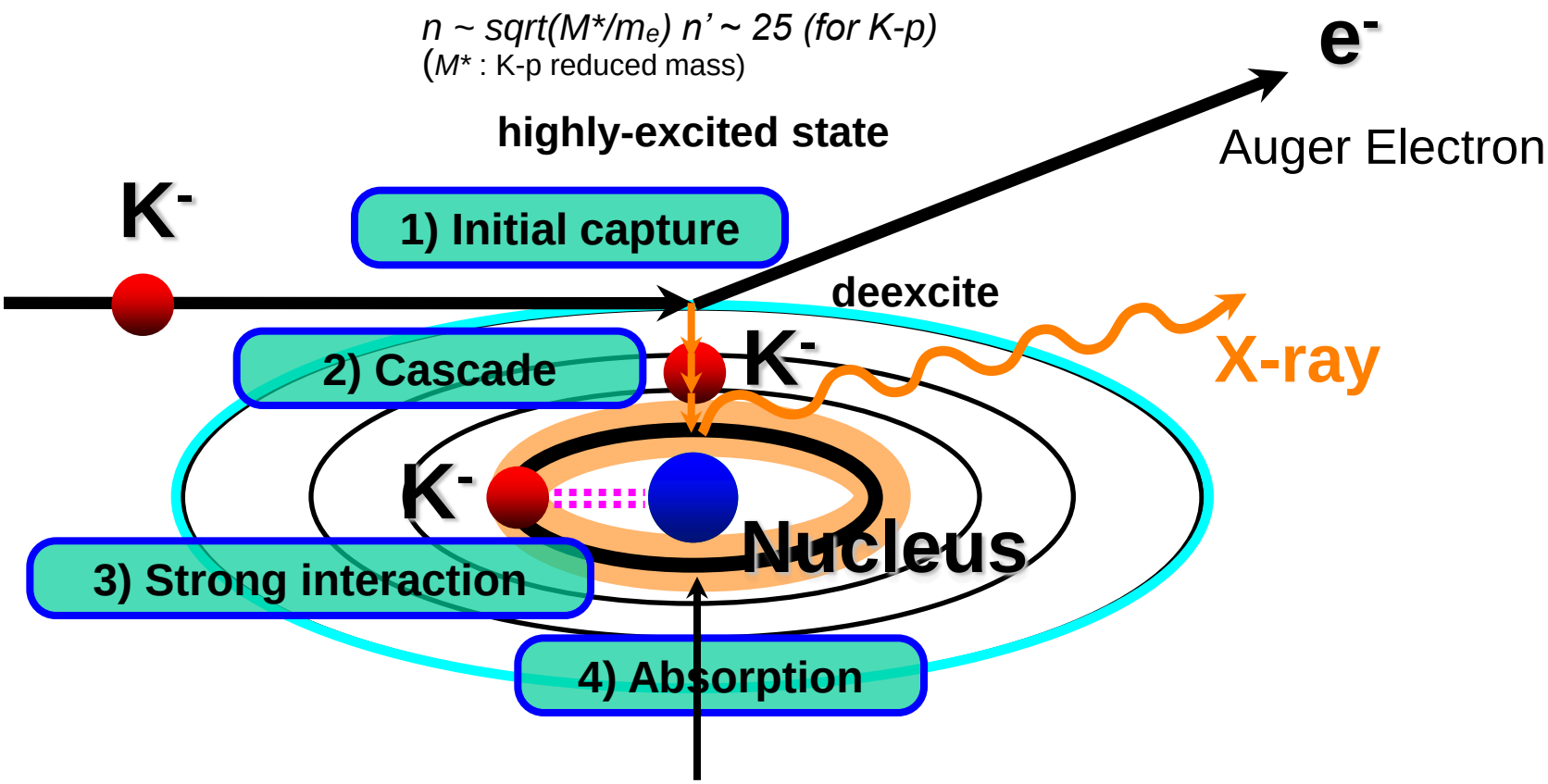
of the K_α line of **kaonic hydrogen**

and

the *first measurement* of **kaonic deuterium**

Measurements of kaonic Helium 3 and 4 as well (2p level)

Kaonic atom formation

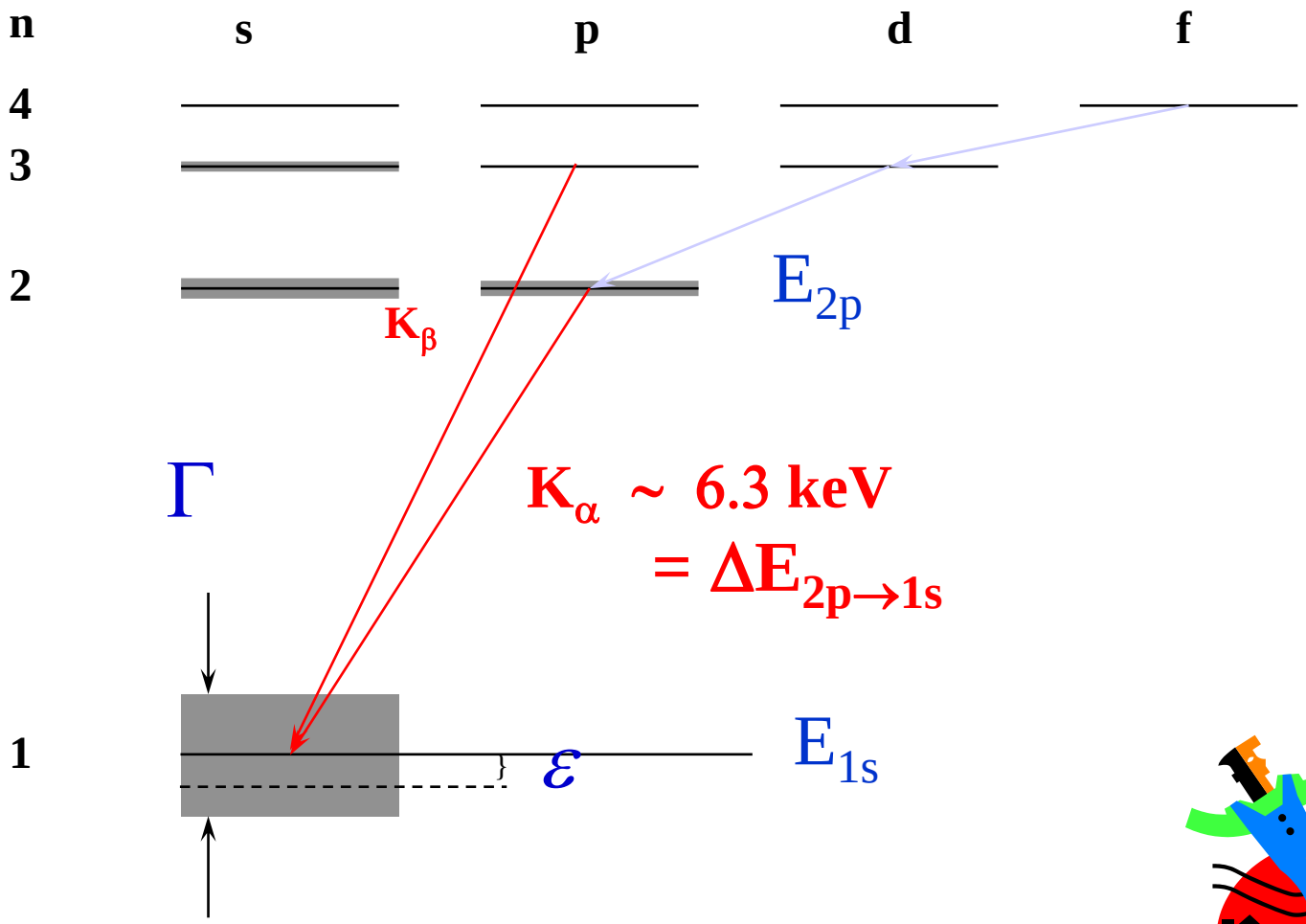


Shift and Width of last orbit

The strong interaction stopped in a target medium, width

- **1s** for K-p, K-d
- **2p** for K-He

Kaonic cascade and the strong interaction



Antikaon-nucleon scattering lengths

Once the shift and width of the 1s level for kaonic hydrogen and deuterium are measured -) scattering lengths

(isospin breaking corrections):

$$\varepsilon + i\,\Gamma/2 \Rightarrow a_{K^-p}\ \mathrm{eV\ fm^{-1}}$$

$$\varepsilon + i\,\Gamma/2 \Rightarrow a_{K^-d}\ \mathrm{eV\ fm^{-1}}$$

one can obtain the isospin dependent antikaon-nucleon scattering lengths

$$a_{K^-p} = (a_0 + a_1)/2$$

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

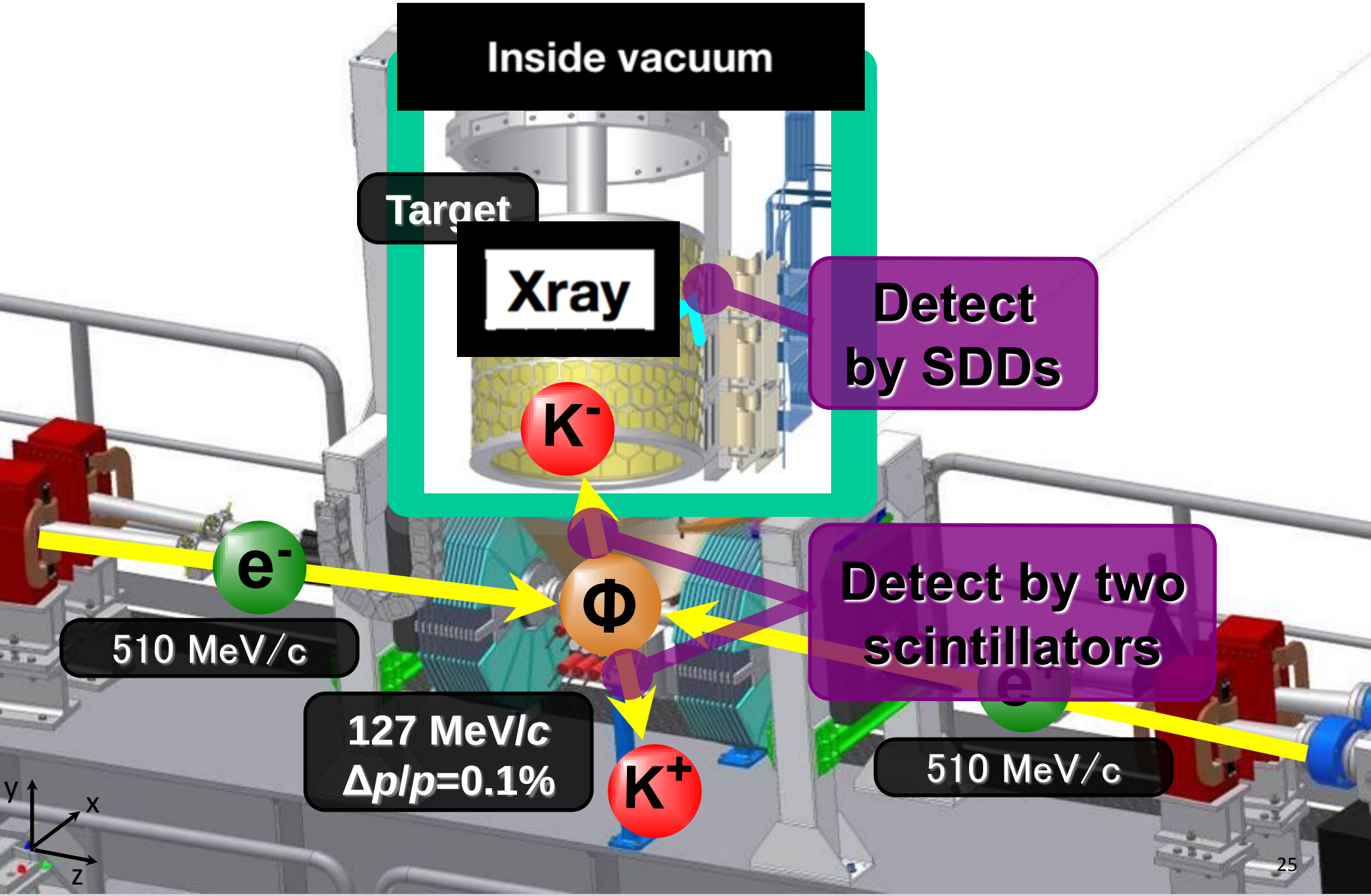
SIDDHARTA Scientific program

Measuring the $\bar{K}N$ scattering lengths with the precision of a few percent will drastically change the present status of low-energy $K\bar{N}$ phenomenology and also provide a clear assessment of the SU(3) chiral effective Lagrangian approach to low energy hadron interactions.

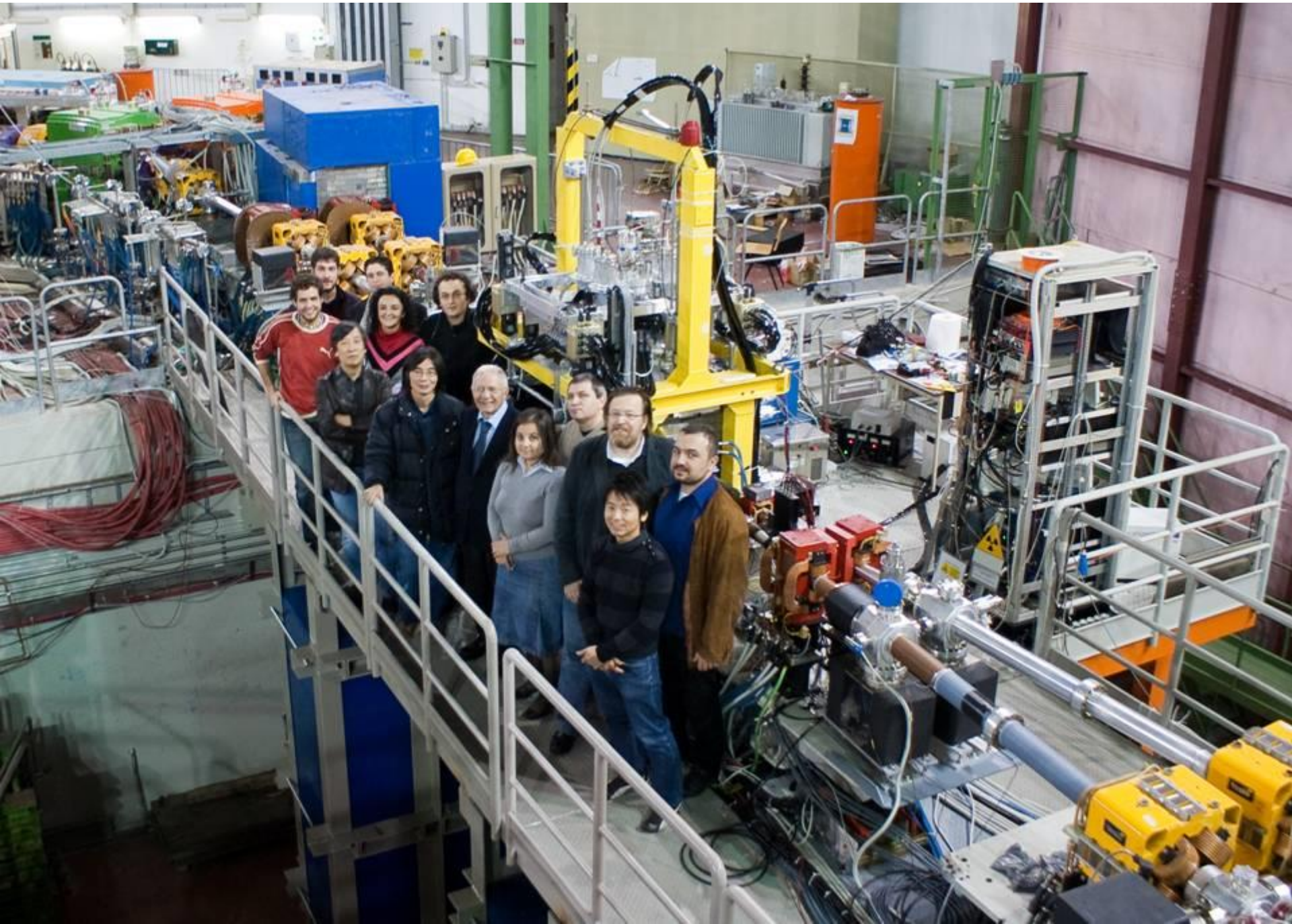
1. **Breakthrough in the *low-energy $\bar{K}N$ phenomenology*;**
2. **Threshold amplitude in QCD**
3. **Information on Λ(1405)**
4. **Contribute to the determination of the *KN sigma terms*, which give the degree of chiral symmetry breaking;**
5. **4 related alado with the determination of the *strangeness content of the nucleon* from the KN sigma terms**

SIDDHARTA

SIDDHARTA overview



SIDDHARTA setup



SIDDHARTA results:

- Kaonic Hydrogen: 400pb^{-1}, most precise measurement ever,Phys. Lett. B 704 (2011) 113, Nucl. Phys. A881 (2012) 88; Ph D

- Kaonic deuterium: 100 pb^{-1}, as an exploratory first measurement ever, Nucl. Phys. A907 (2013) 69; Ph D

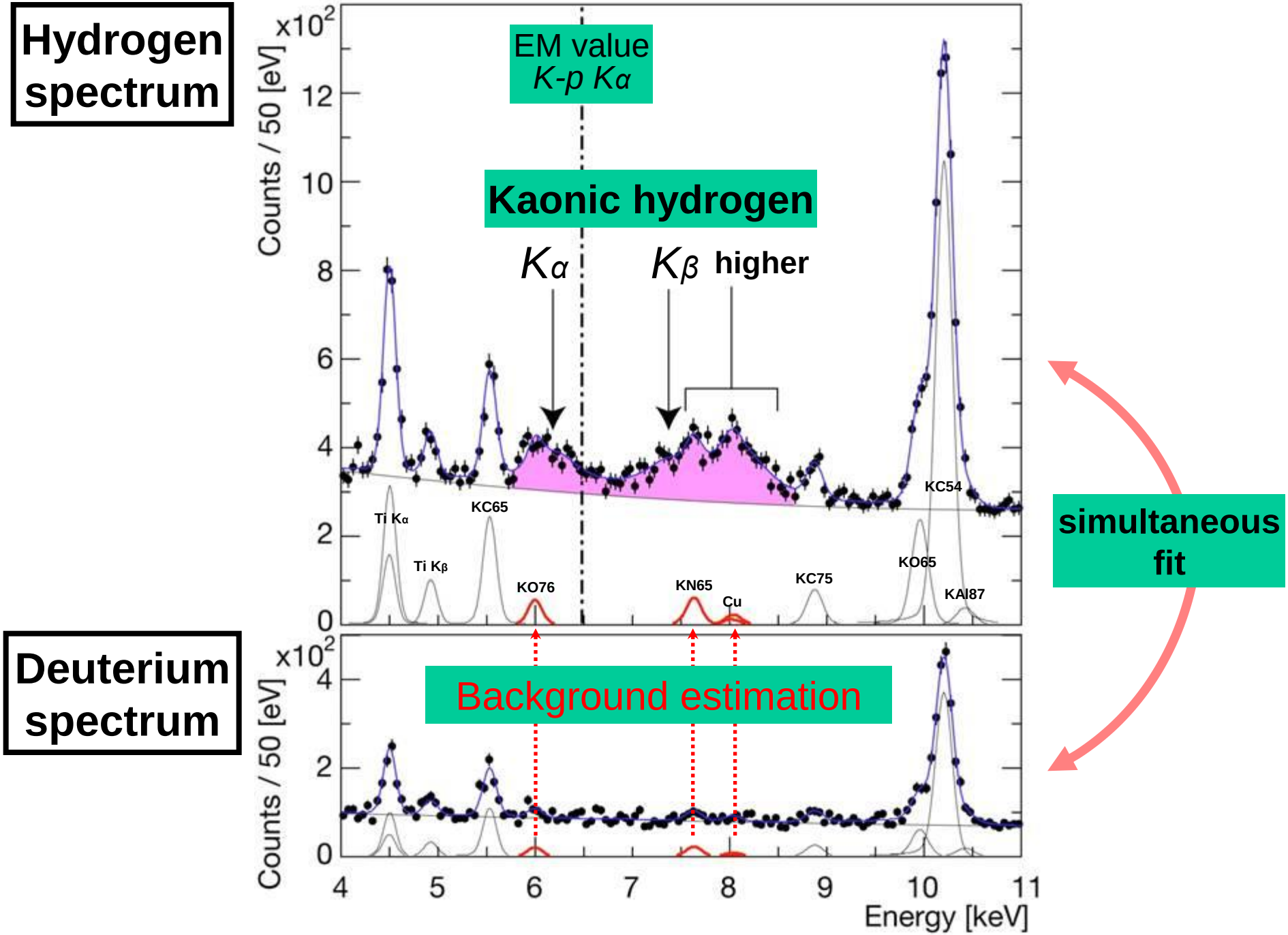
- Kaonic helium 4 – first measurement ever in gaseous target; published in Phys. Lett. B 681 (2009) 310; NIM A628 (2011) 264 and Phys. Lett. B 697 (2011);; PhD

- Kaonic helium 3 – 10 pb^{-1}, first measurement in the world, published in Phys. Lett. B 697 (2011) 199; Ph D

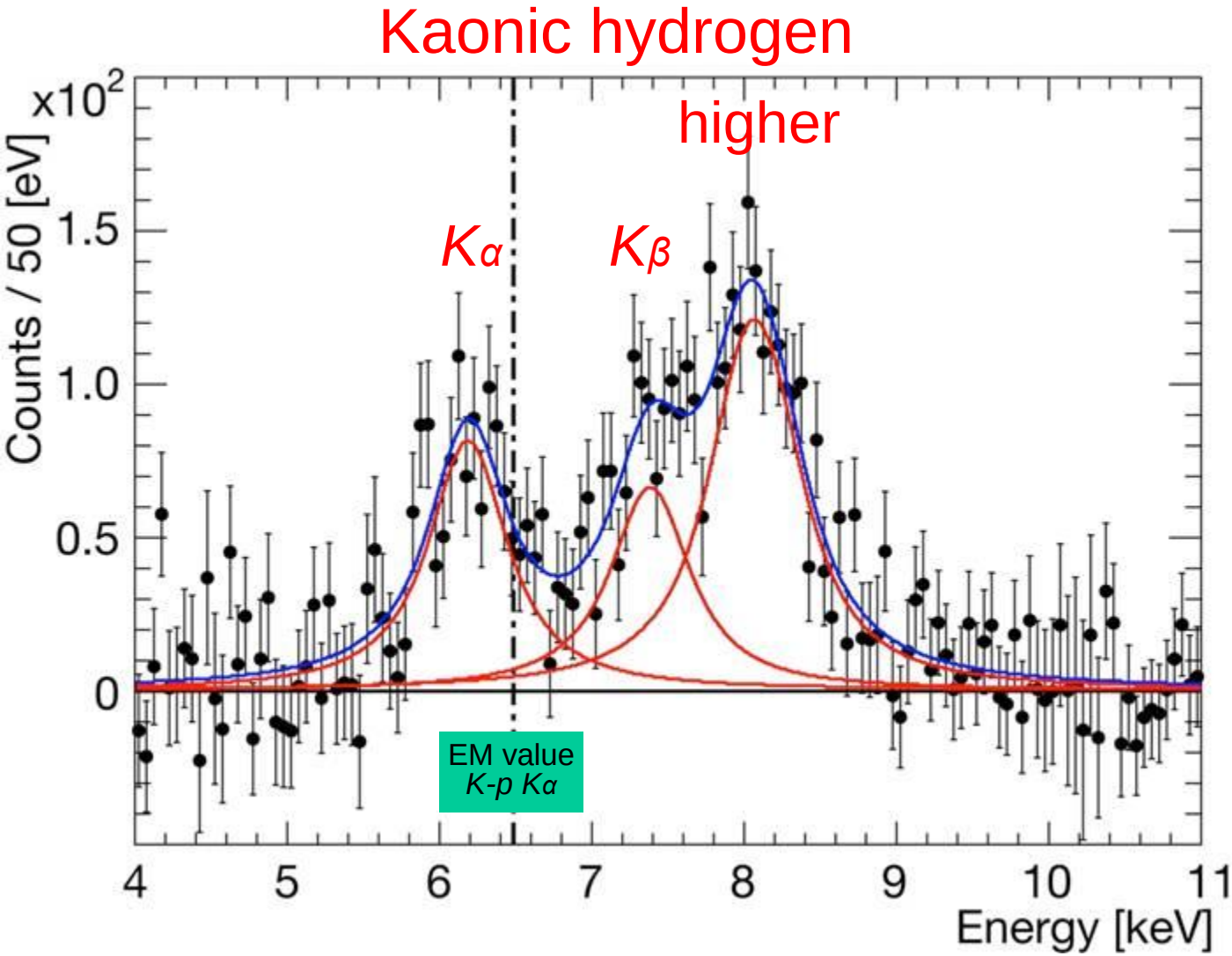
- Widths and yields of KHe3 and KHe4 - Phys. Lett. B714 (2012) 40; ongoing: KH yields; kaonic kapton yields -> draft for publications

SIDDHARTA – important TRAINING for young researchers

Kaonic Hydrogen


Hydrogen spectrum
Deuterium spectrum
EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ higher
Background estimation
simultaneous fit
Counts / 50 [eV]
x10^2
Energy [keV]
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87

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



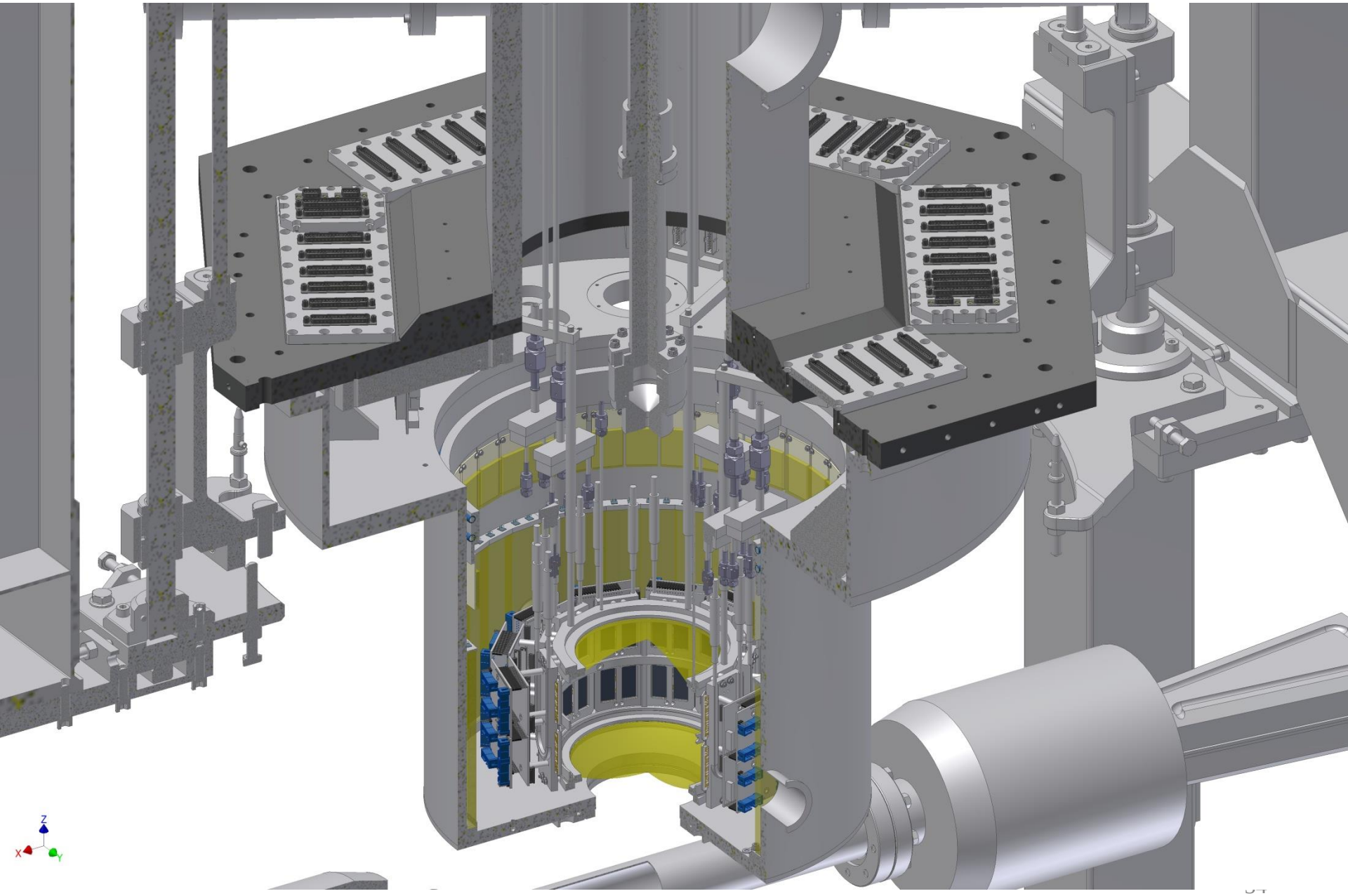
KAONIC HYDROGEN results

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

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

SIDDHARTA–2

SIDDHARTA-2 setup



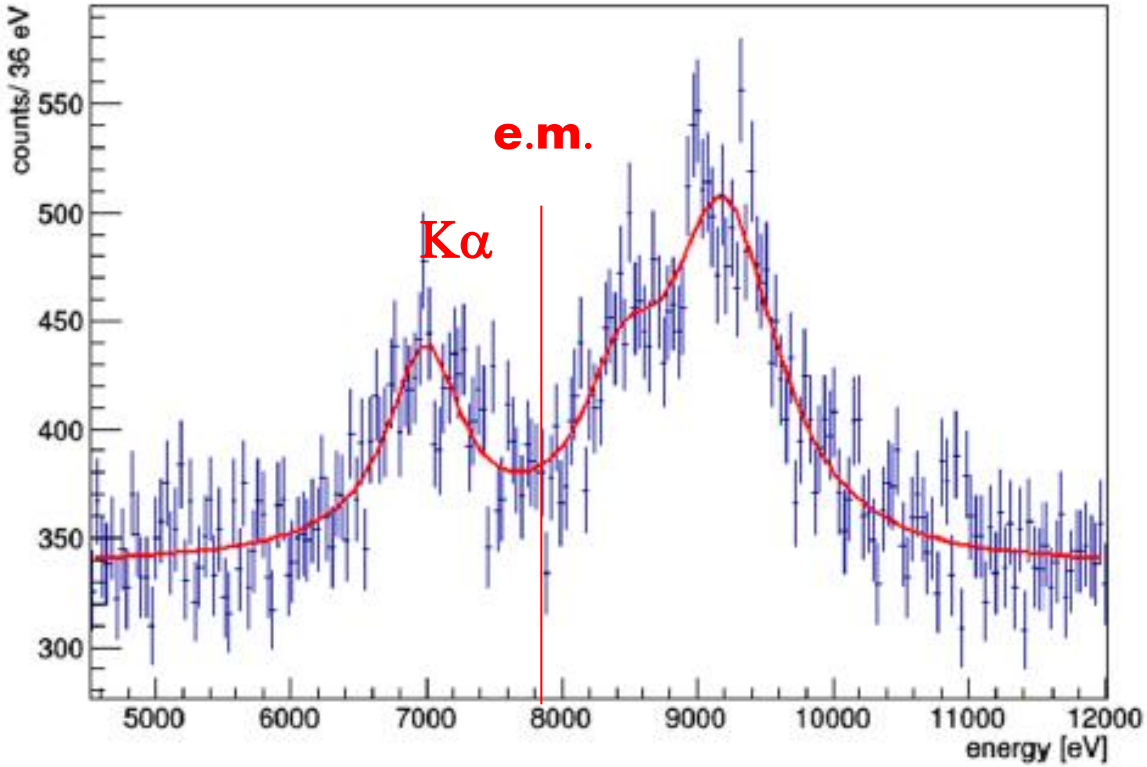


Figure 21: The simulated spectrum of K⁻d for SIDDHARTA-2 for 800 pb⁻¹ (the Kα line is at 7 keV, while from 8 to 10 keV there is the K-complex)

$\Delta\varepsilon(1s) = 30$ eV and $\Delta\Gamma(1s) = 70$ eV

SIDDHARTA2 future perspectives

1) Kaonic deuterium measurement - 1st measurement: and R&D for other measurements

2) Kaonic helium transitions to the 1s level – 2nd measurement, R&D

3) Other light kaonic atoms (KO, KC,…) -> HPGe

4) Heavier kaonic atoms measurement (Si, Pb…) -> HPGe

5) Kaon radiative capture – Λ(1405) study

6) Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)

7) Kaon mass precision measurement at the level of <7 keV (kaon mass puzzle) – TES, VOXES

Antikaonic Matter At DAΦNE: an Experiment Unraveling Spectroscopy