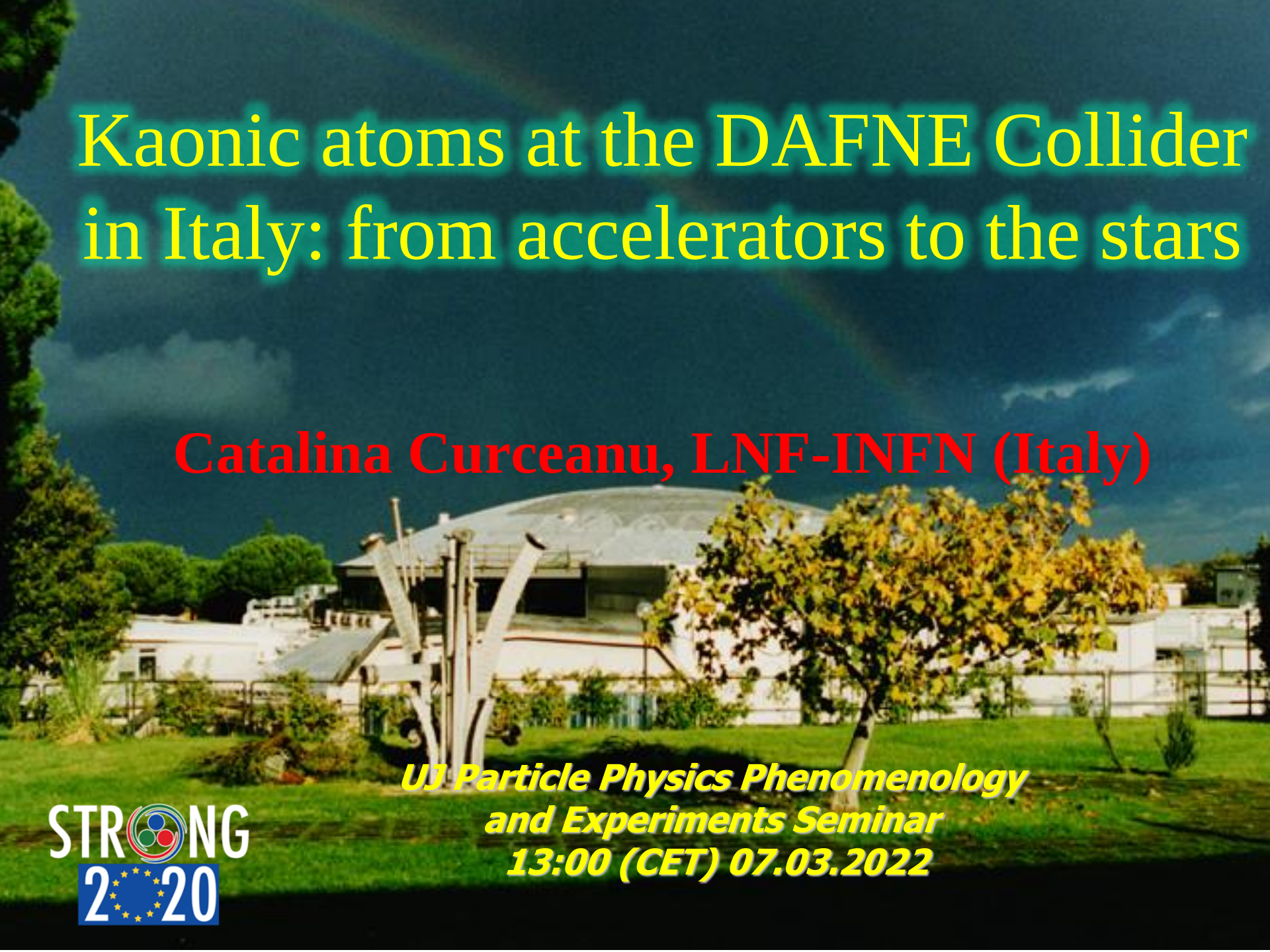


Kaonic atoms at the DAFNE Collider in Italy: from accelerators to the stars

Catalina Curceanu, LNF-INFN (Italy)

UJ Particle Physics Phenomenology and Experiments Seminar
13:00 (CET) 07.03.2022

STRONG 2020

Dedicated to Ukraine colleagues and population – my heart is with them! Science for peace!

STOP WAR AND AGGRESSION!

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

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

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

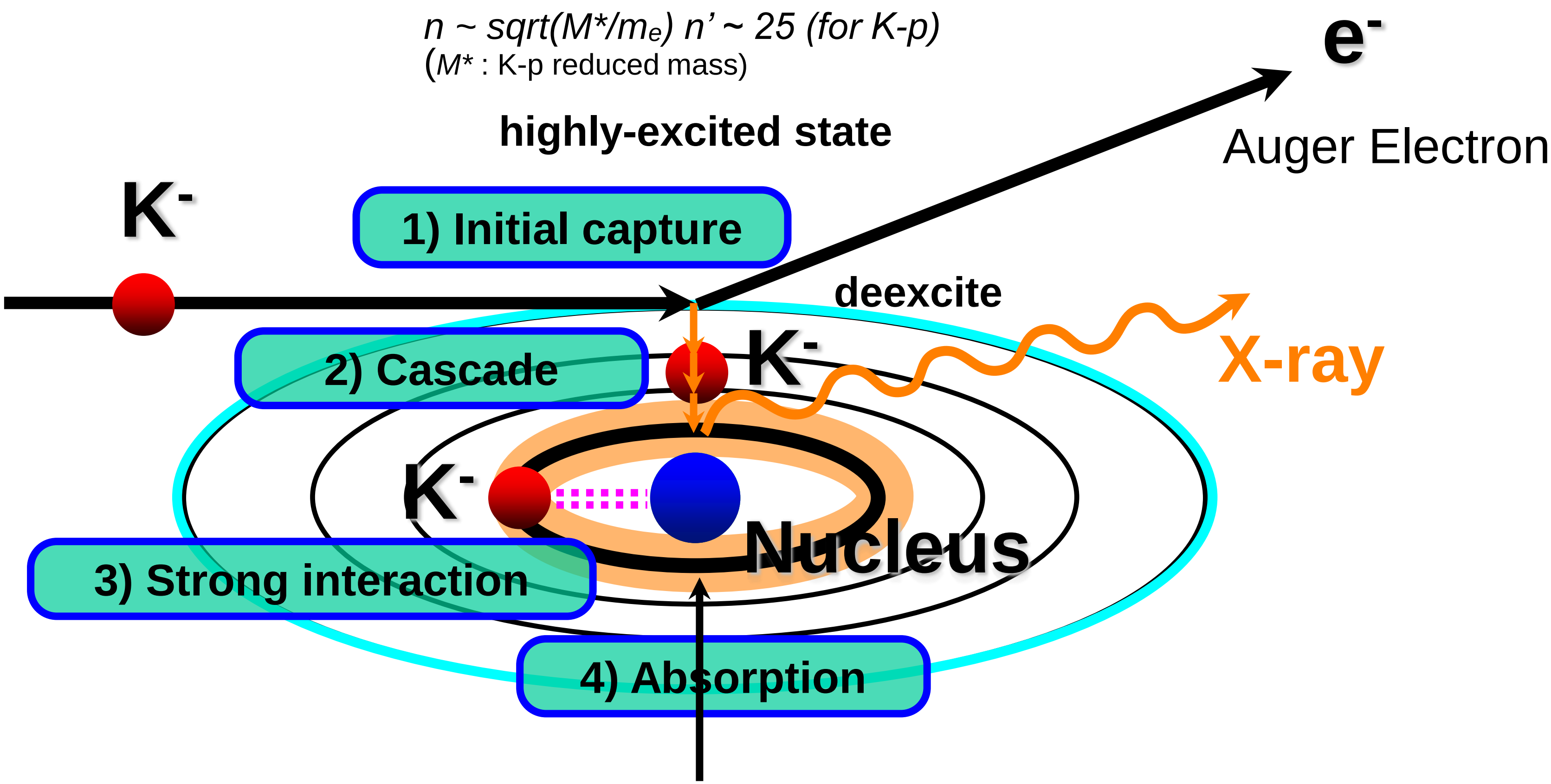
Astrophysics
EOS Neutron Stars

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


Kaonic atoms spectroscopy:
at DAFNE

Kaonis atoms: brief introduction

Kaonic atom formation

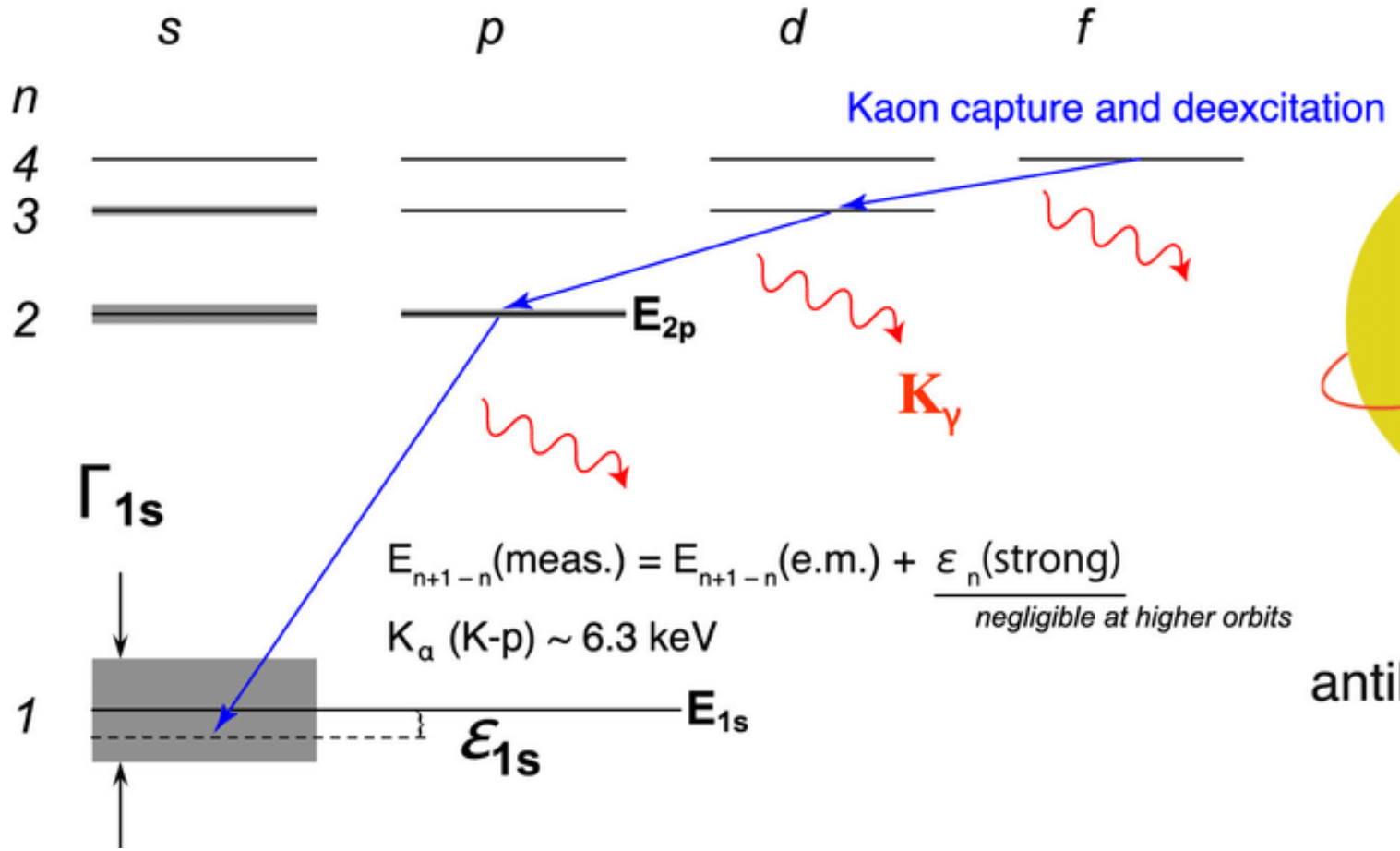


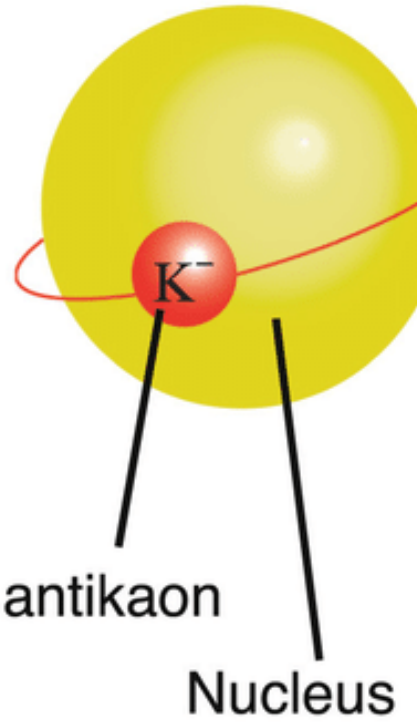
stopped in a target medium

Shift and Width
of last orbit

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

Kaonic atoms





The (main) 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

of **kaonic deuterium**

Measurements of kaonic Helium 3 and 4 as well (2p level)
And other types of exotic atoms

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):

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

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

one can obtain the isospin dependent antikaon-nucleon scattering lengths

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

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

SCATTERING LENGTHS

Deser-type relation connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of $a_{K\text{-}p}$

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

(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

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

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

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

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

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

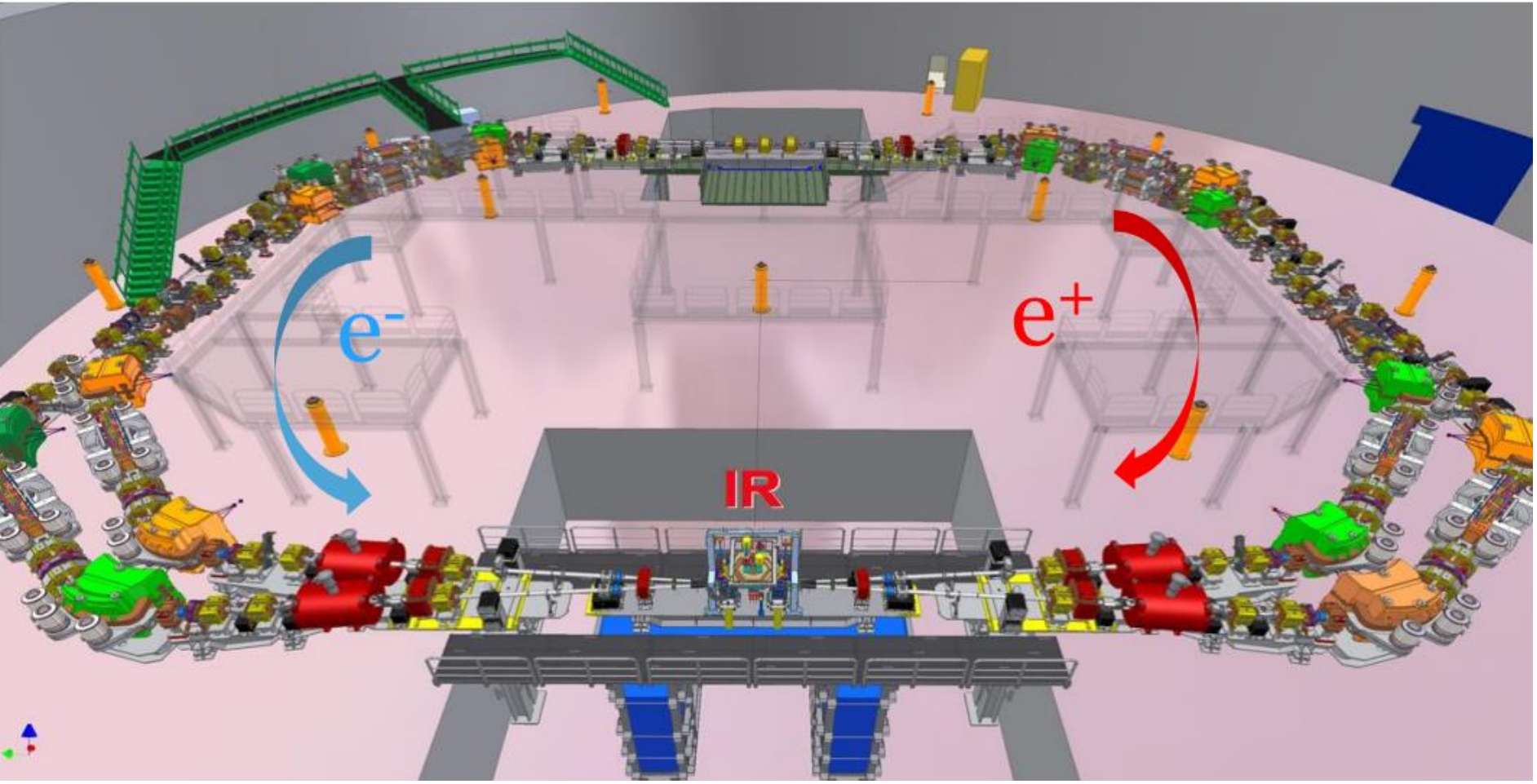
- **Explicit and spontaneous chiral symmetry breaking (mass of nucleons)**
- **Dense baryonic matter ->**
- **Neutron (strange?) stars EOS**

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

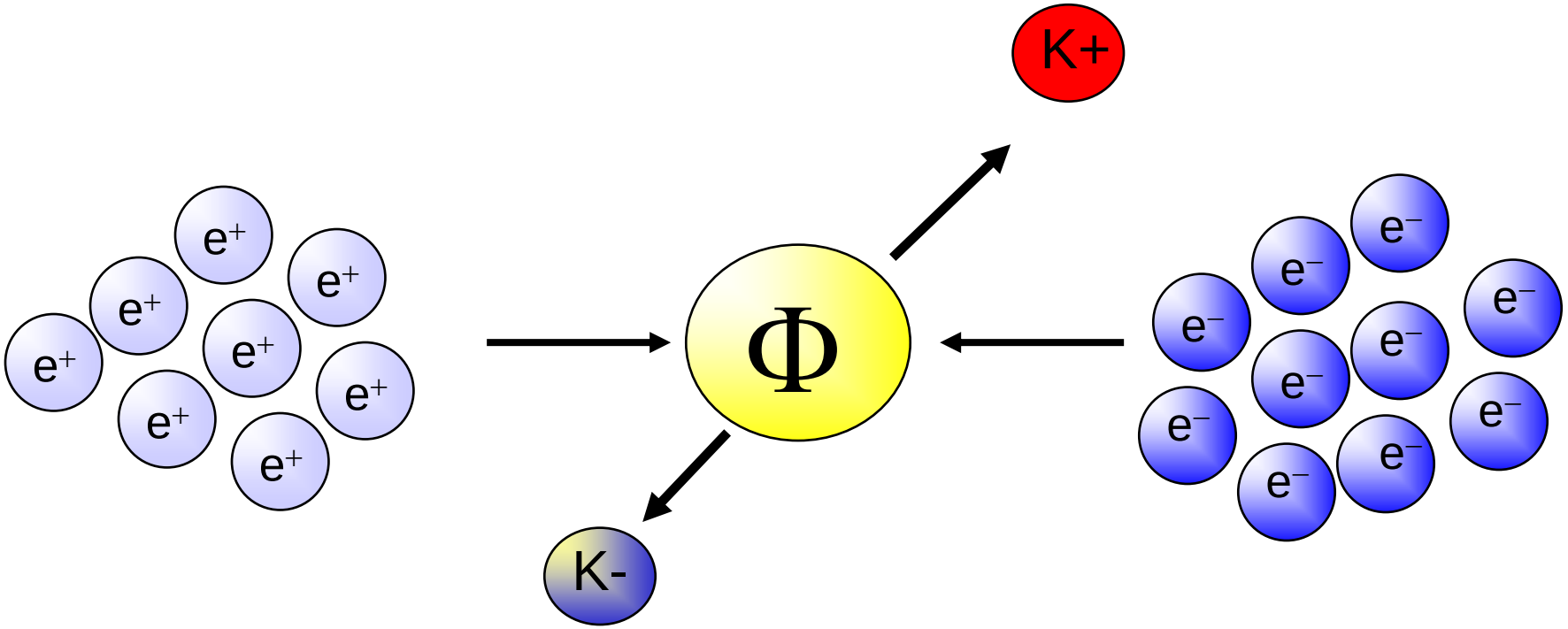
DAΦNE

Laboratori Nazionali di Frascati (LNF-INFN)

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



The DAFNE principle



Flux of produced kaons: about 1000/second

DAFNE

$e^- e^+$ collider

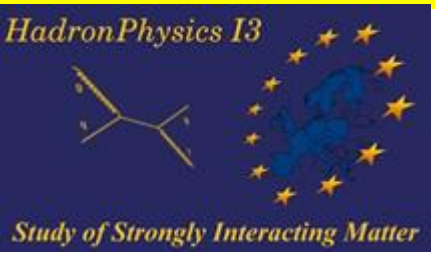
- **$\Phi \rightarrow K^- K^+$** (49.1%)
- **Monochromatic low-energy K^-** (~127MeV/c)
- **Less hadronic background due to the beam**

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

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

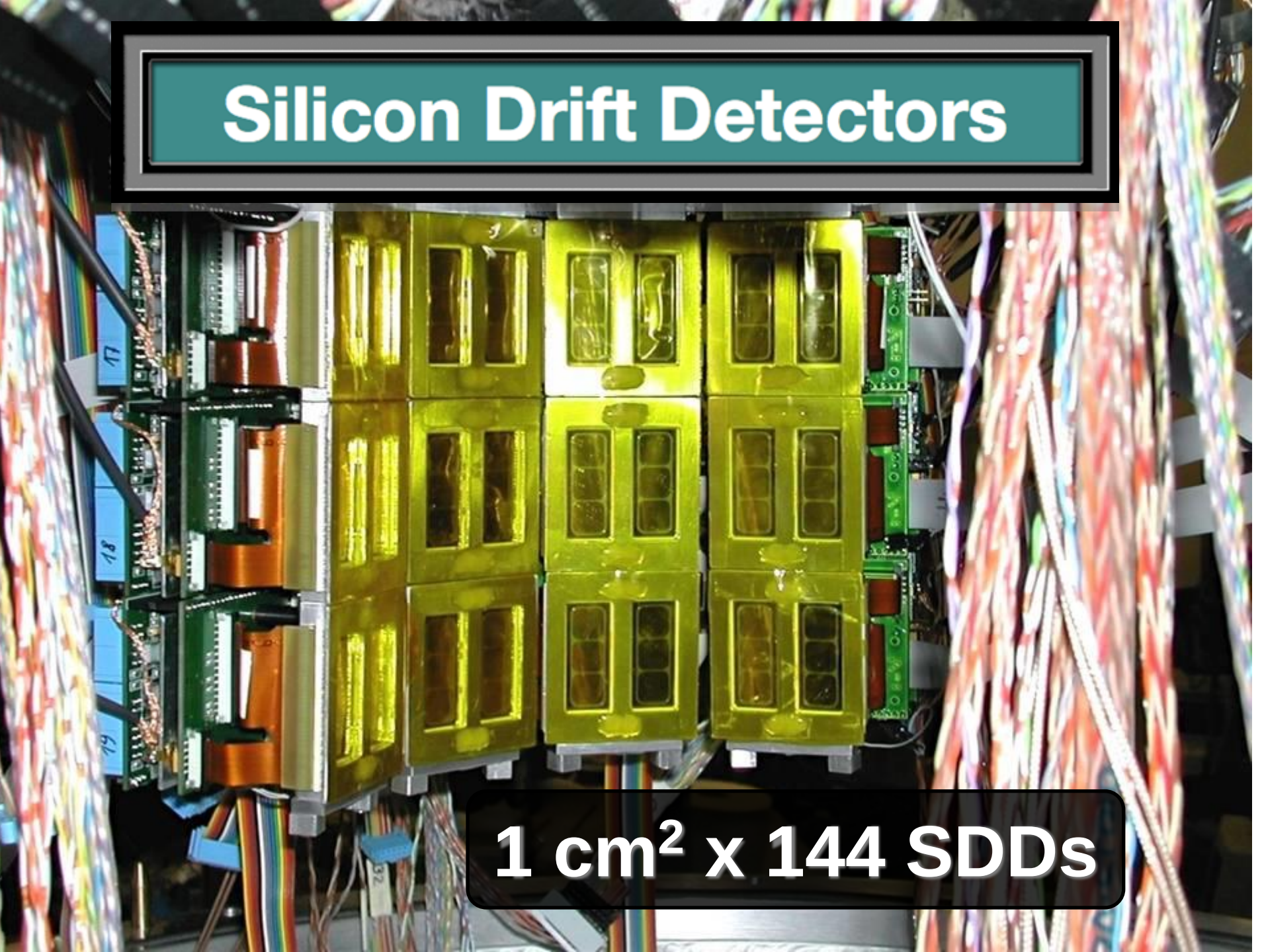
SIDDHARTA

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

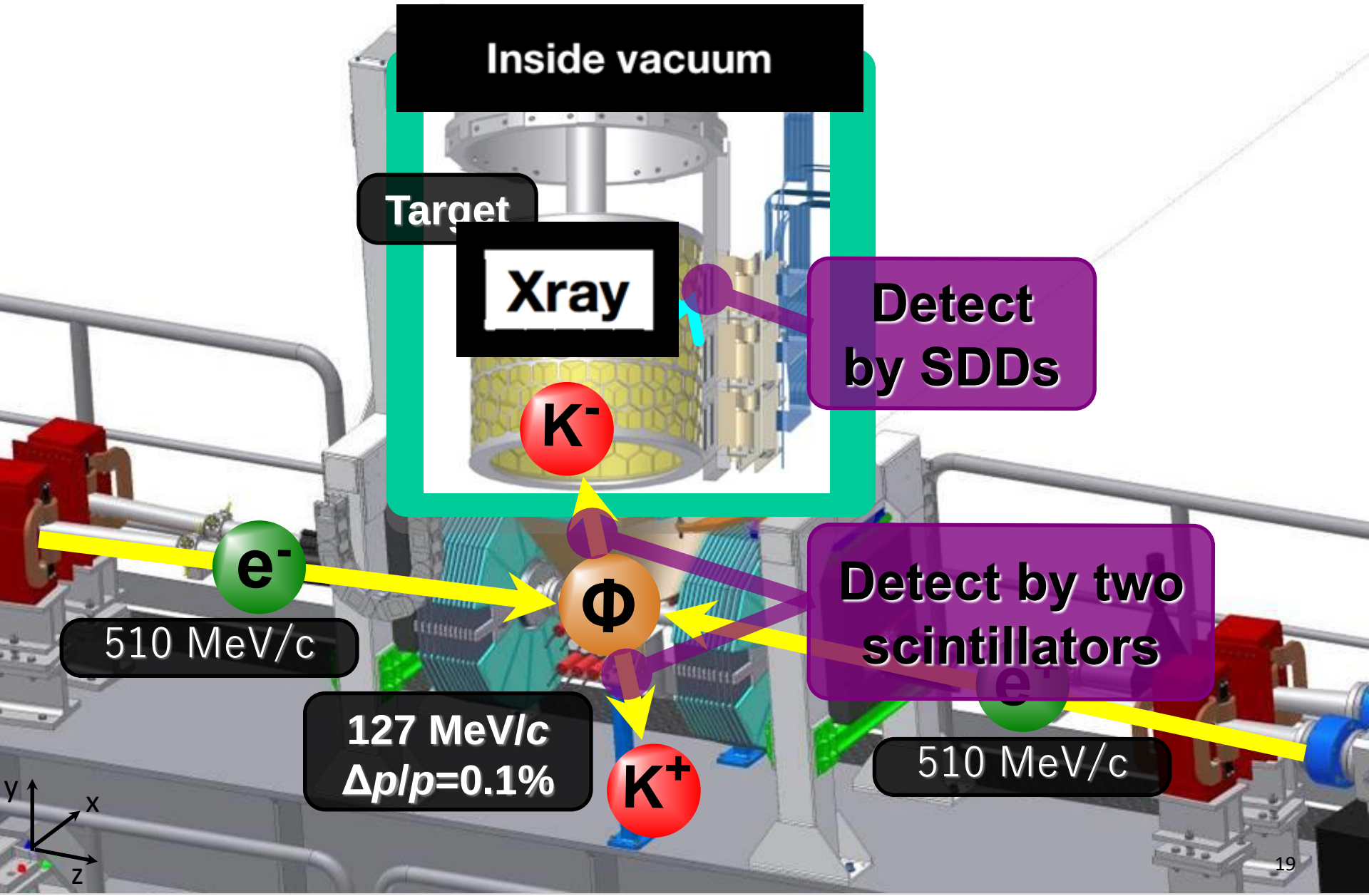


- LNF- INFN, Frascati, Italy
- SMI- ÖAW, Vienna, Austria
- IFIN – HH, Bucharest, Romania
- Politecnico, Milano, Italy
- MPE, Garching, Germany
- PNSensors, Munich, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada

EU Fundings: JRA10 – FP6 - I3H
FP7- I3HP2

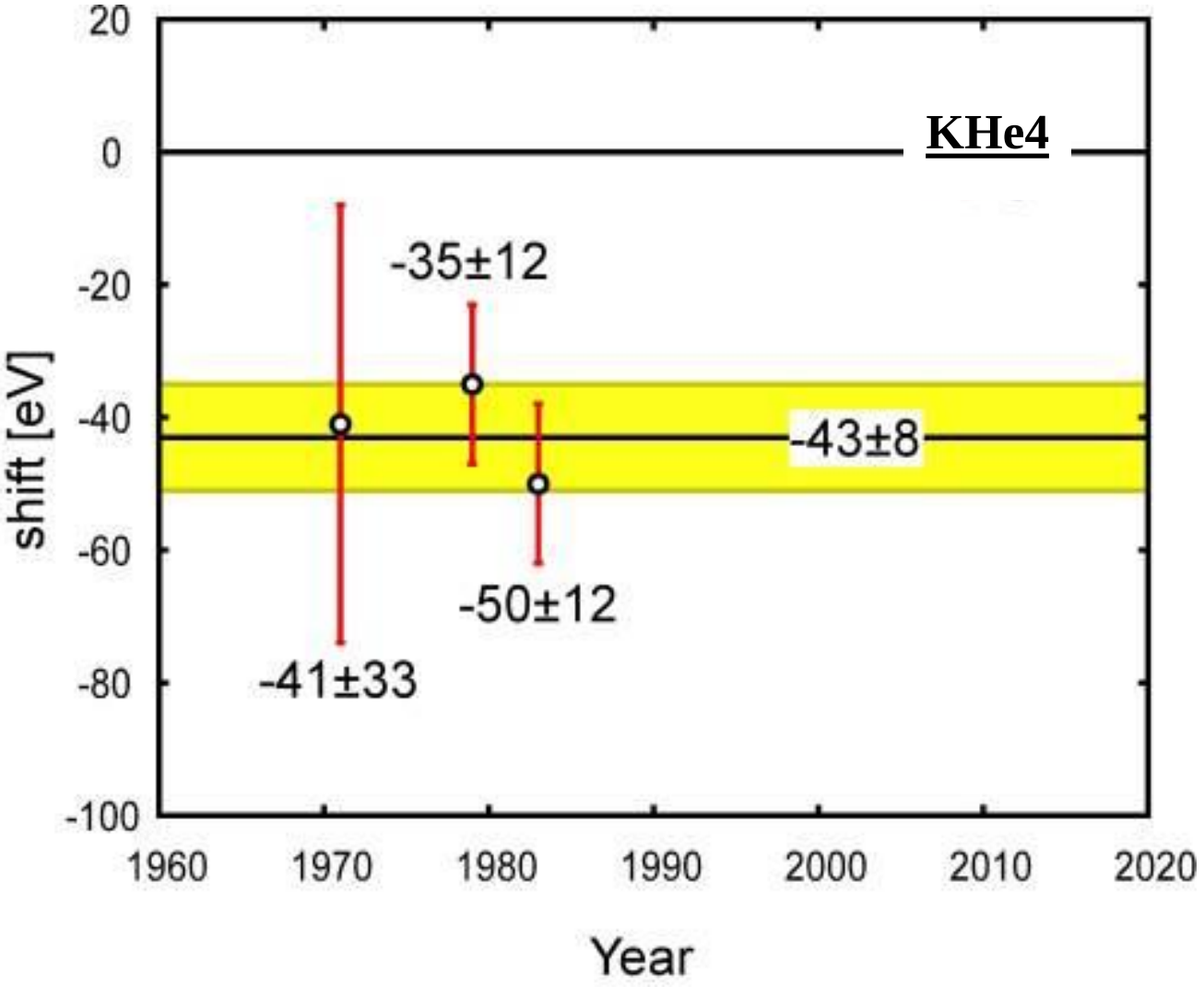

Silicon Drift Detectors
1 cm² x 144 SDDs

SIDDHARTA overview

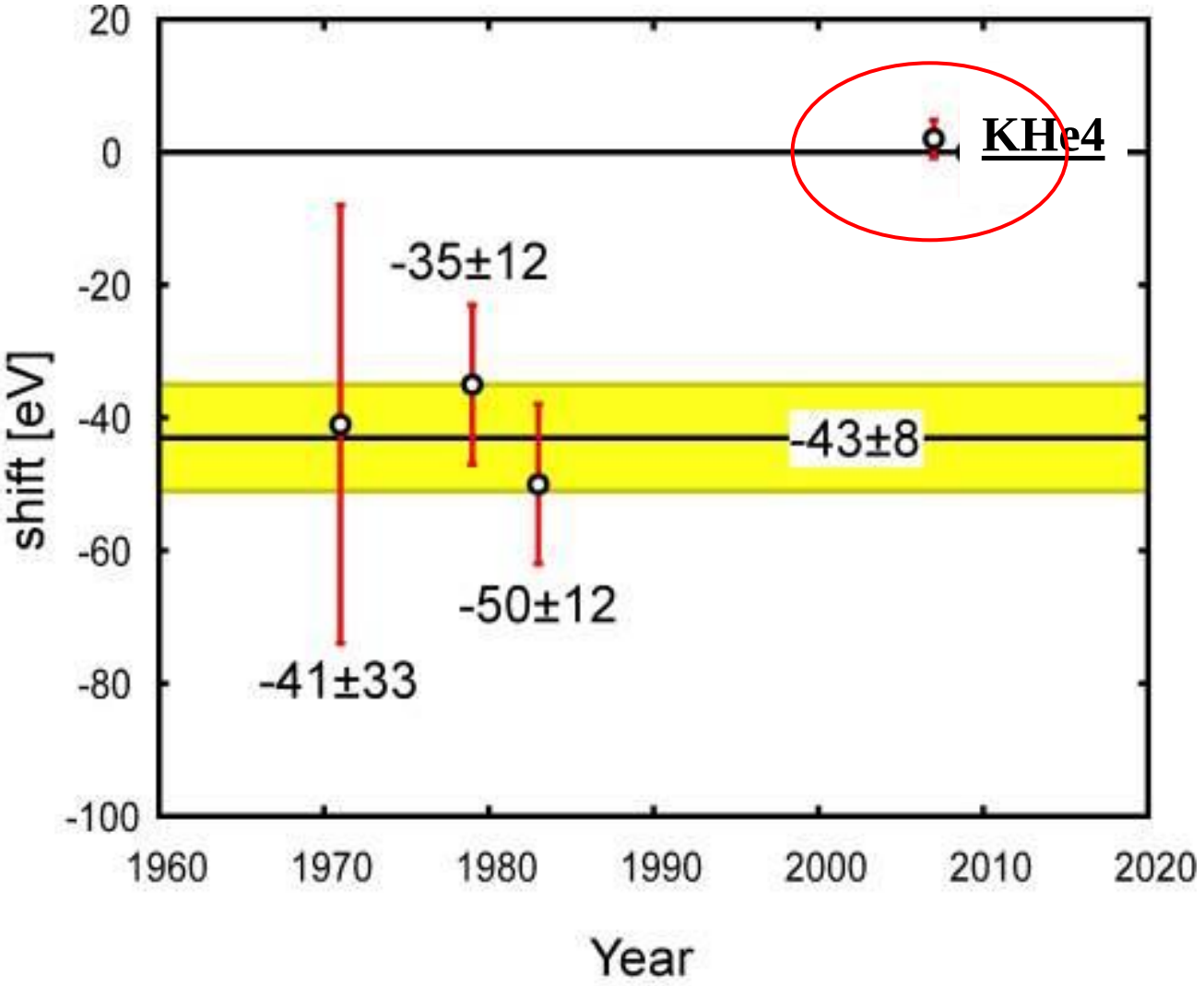


Kaonic helium (puzzle)

Kaonic 4 old data

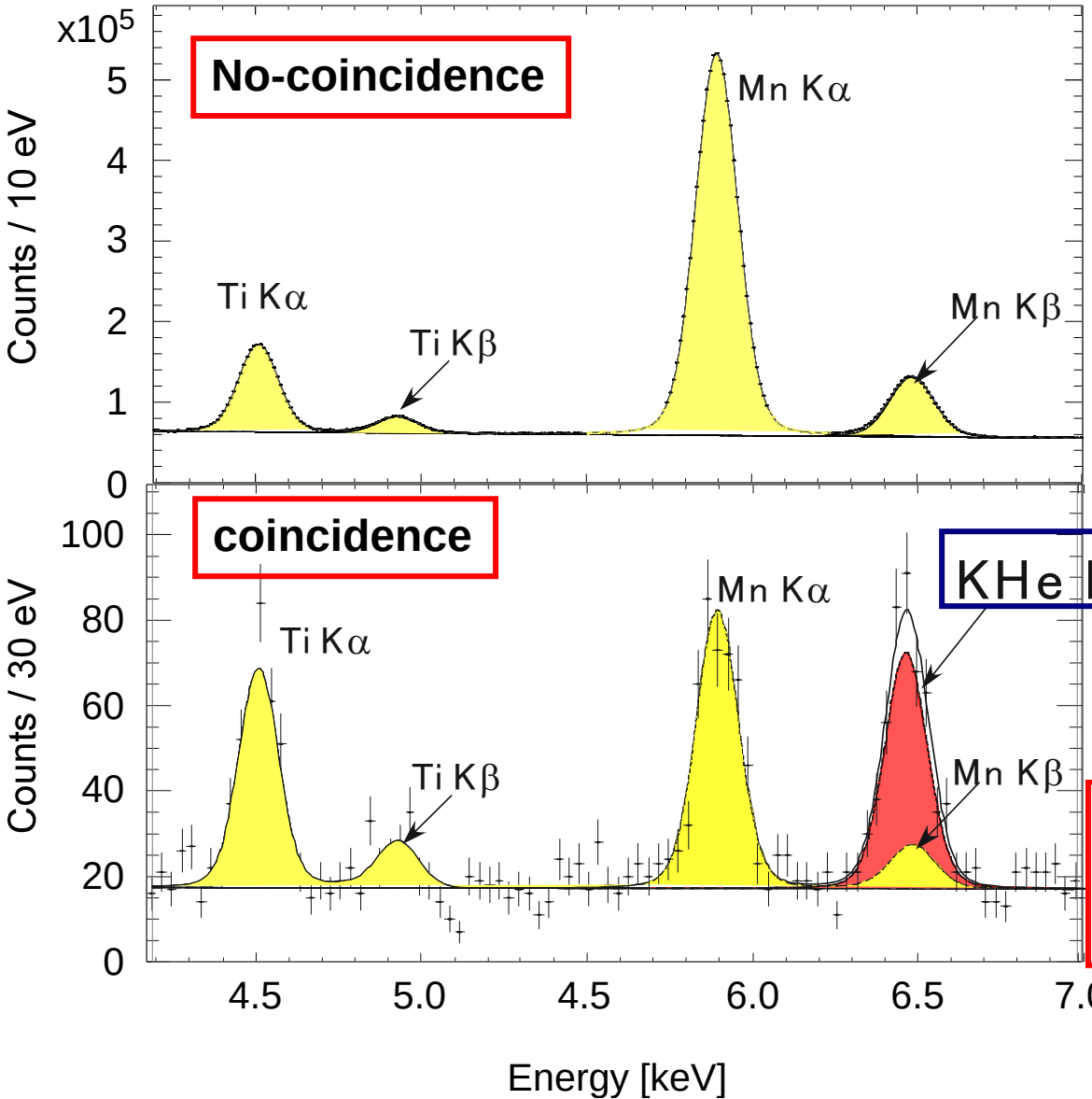


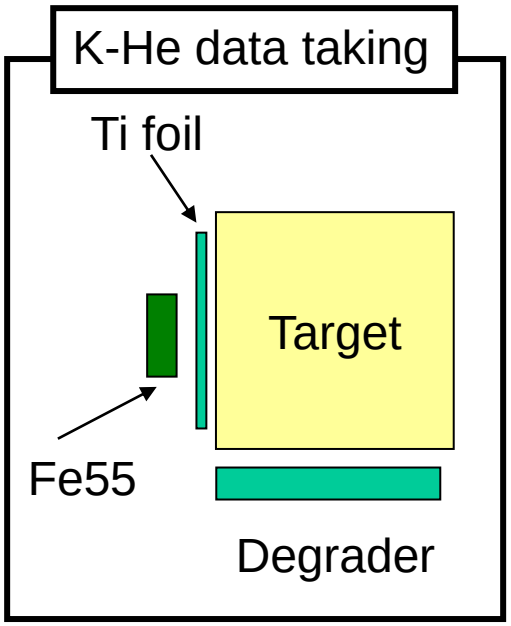
E570 solved the kaonic hydrogen puzzle



KHe-4 energy spectrum at SIDDHARTA

PLB681(2009)310; NIM A 628(2011)264

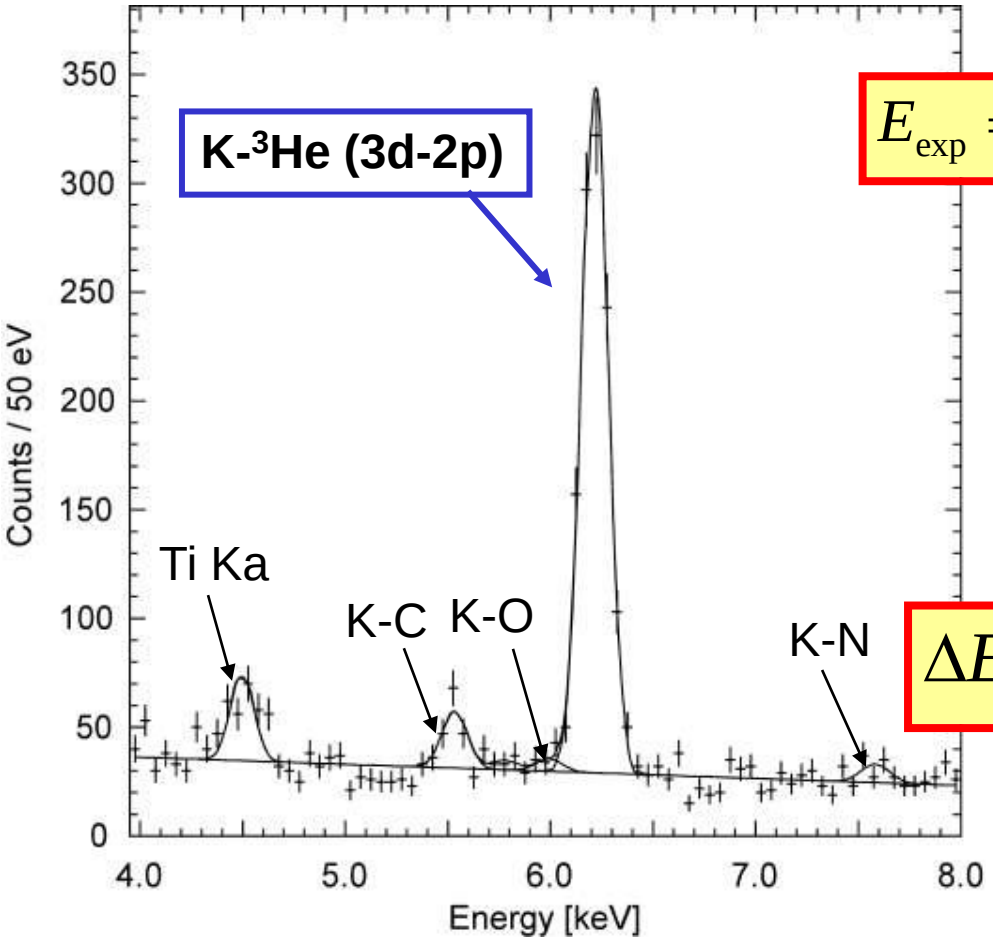




$$E_{\exp} = 6463.6 \pm 5.8 \text{ eV},$$

$$\Delta E = E_{\exp} - E_{e.m.}$$
$$= 0 \pm 6(\text{stat}) \pm 2(\text{syst}) \text{ eV}$$

Kaonic Helium-3 energy spectrum



X-ray energy of K-3He 3d-2p

$$E_{\exp} = 6223.0 \pm 2.4(sta) \pm 3.5(sys)\ \text{eV}$$

QED value: $E_{e.m.} = 6224.6\ \text{eV}$

$$\Delta E_{2p} = E_{\exp} - E_{e.m.}$$

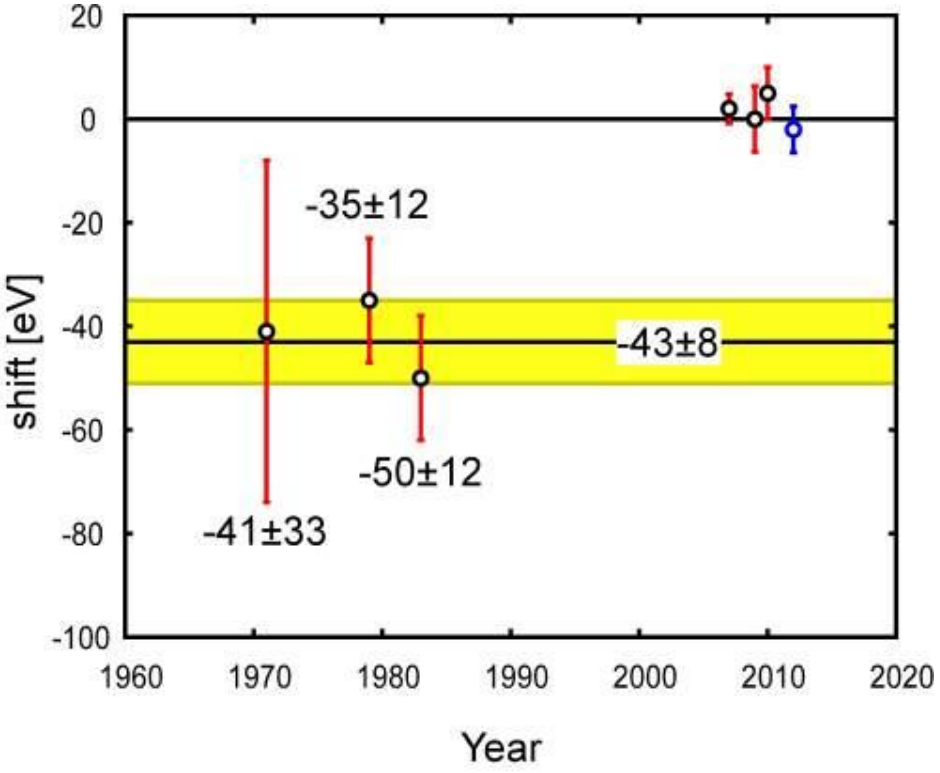
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

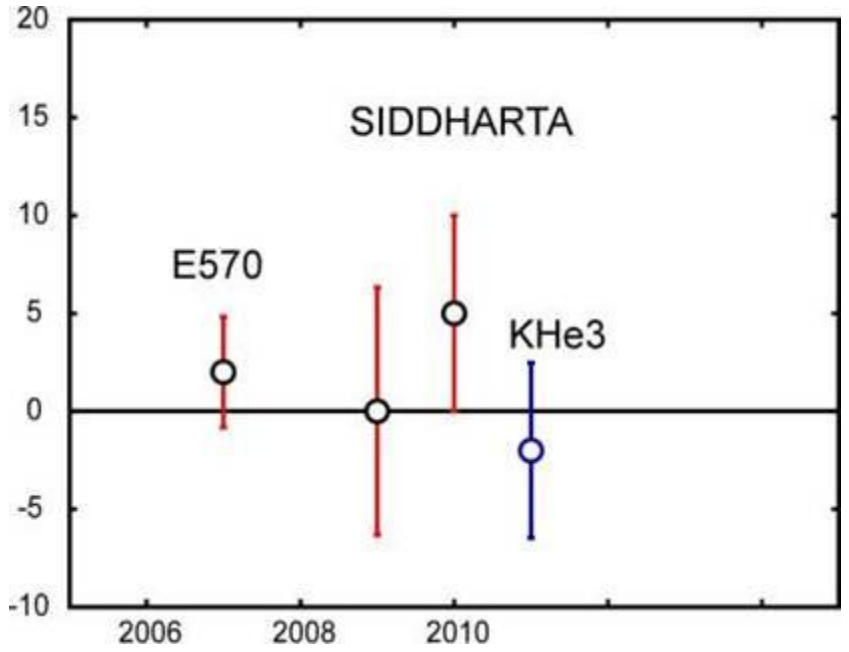
World First !
Observation of K-^{3}He X-rays
Determination of
strong-interaction shift

arXiv:1010.4631v1 [nucl-ex], PLB697(2011)199

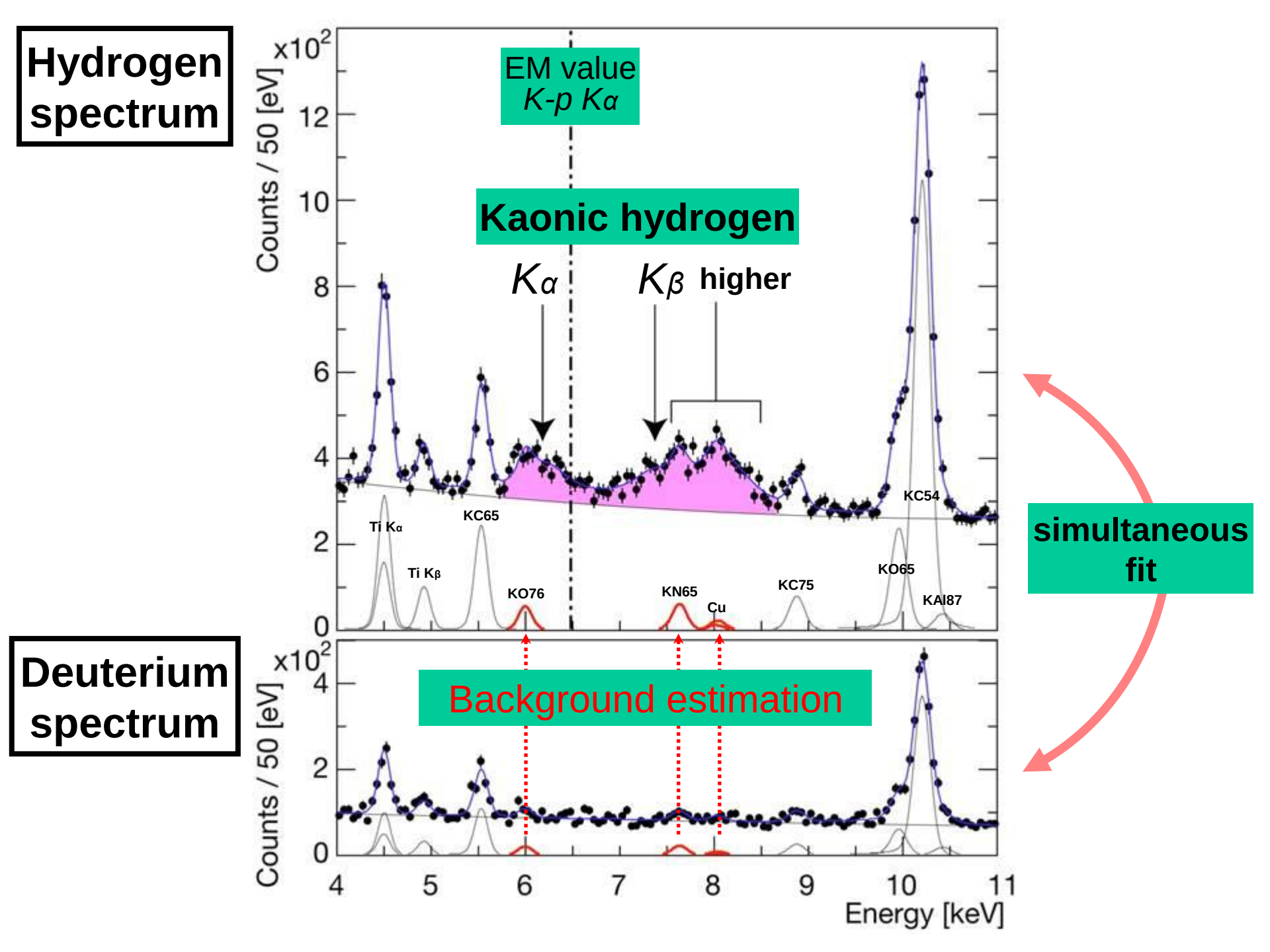
Comparison of results

	Shift [eV]	Reference
KEK E570	**+2±2±2**	**PLB653(07)387**
SIDDHARTA (He4 with 55Fe)	**+0±6±2**	**PLB681(2009)310**
SIDDHARTA (He4)	**+5±3±4**	**arXiv:1010.4631, PLB697(2011)199**
SIDDHARTA (He3)	**-2±2±4**	

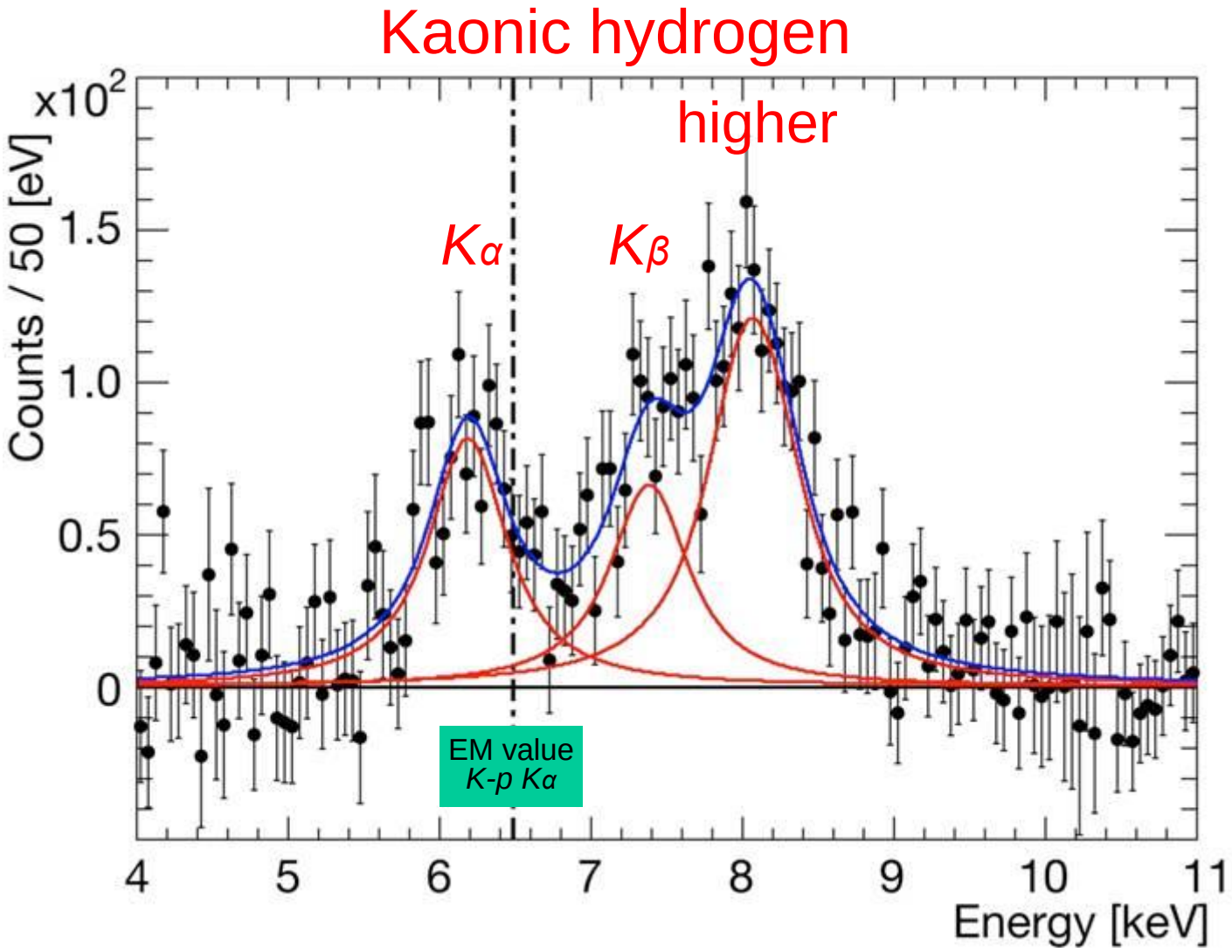




***error bar** $= \pm\sqrt{(stat)^2 + (syst)^2}$


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
Background estimation
simultaneous fit
Counts / 50 [eV]
x10²
Energy [keV]

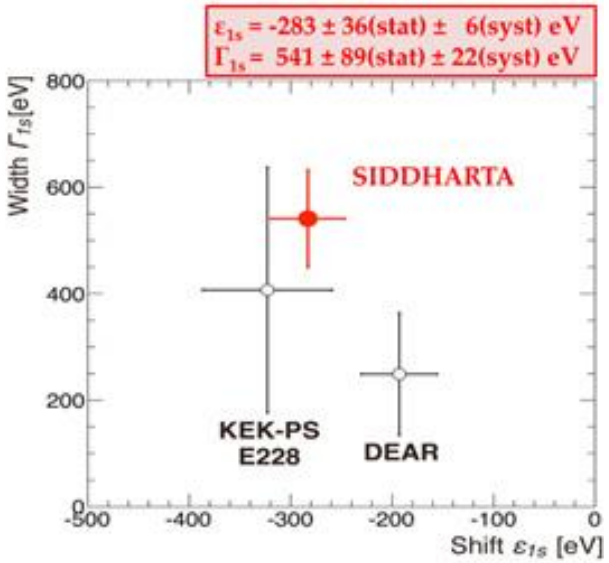
Residuals of K-p x-ray spectrum after subtraction of fitted background



KAONIC HYDROGEN results

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

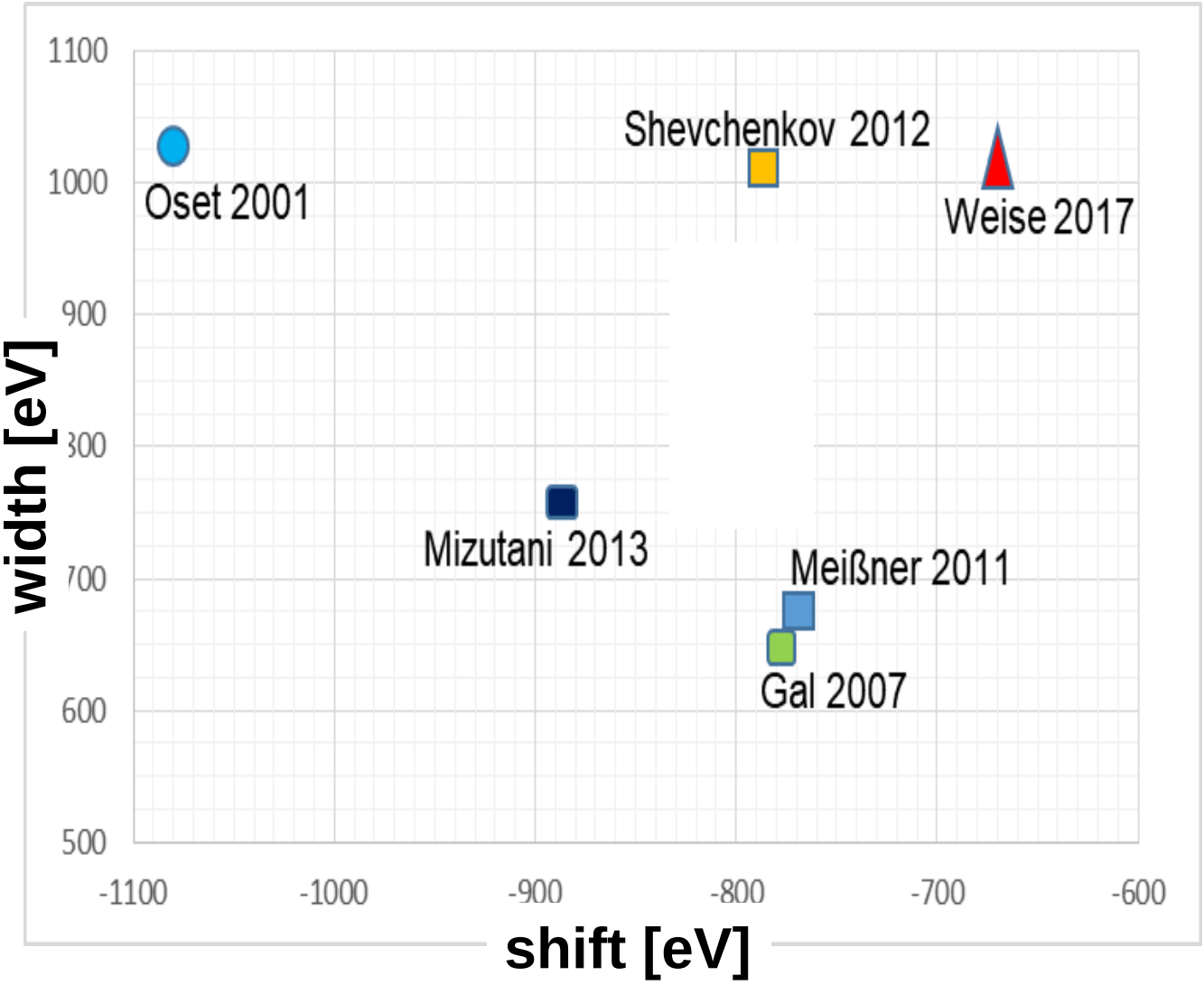
$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})$ eV



Phys. Lett. B 704 (2011) 113

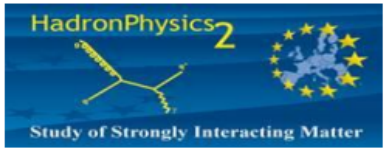
SIDDHARTA-2
Kaonic Deuterium

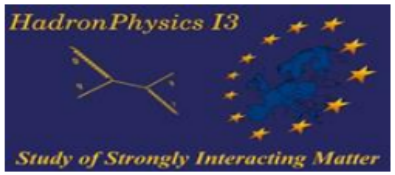
Theory for kaonic deuterium



SIDDHARTA-2

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications





FWF Der Wissenschaftsfonds.

Farnesina
Ministero degli Affari Esteri
e della Cooperazione Internazionale

LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN – HH, Bucharest, Romania
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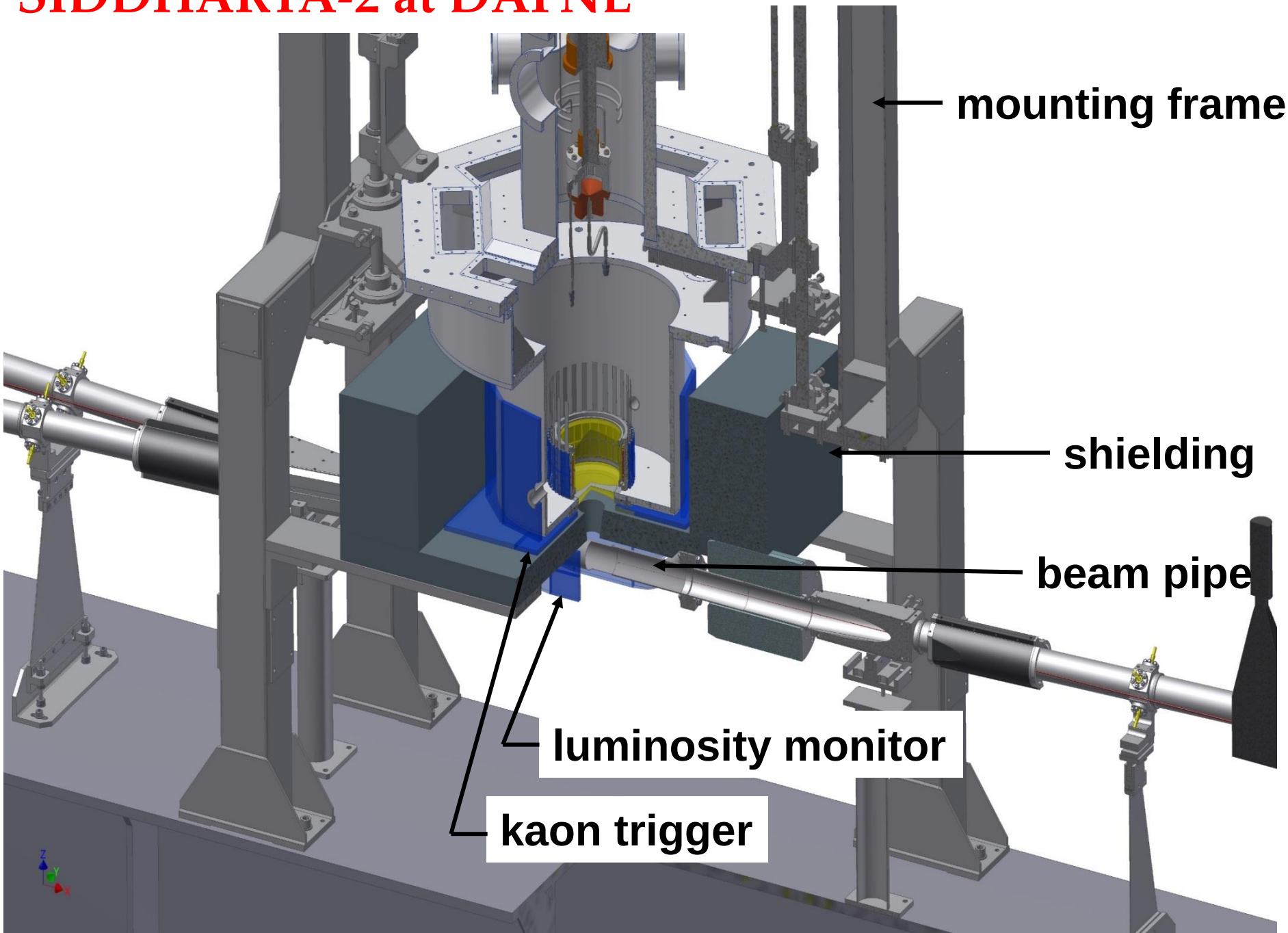
Univ. Jagiellonian Krakow, Poland
Research Center for Electron Photon Science (ELPH), Tohoku University
CERN, Switzerland

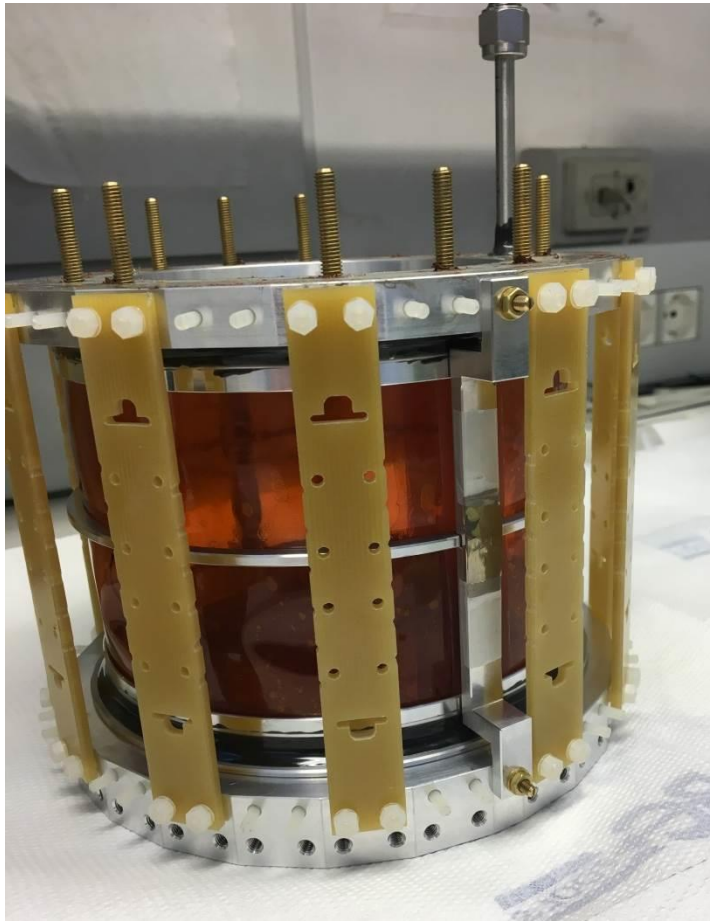
STRONG-2020

Croatian Science Foundation, research project 8570

SIDDHARTA-2 at DAFNE



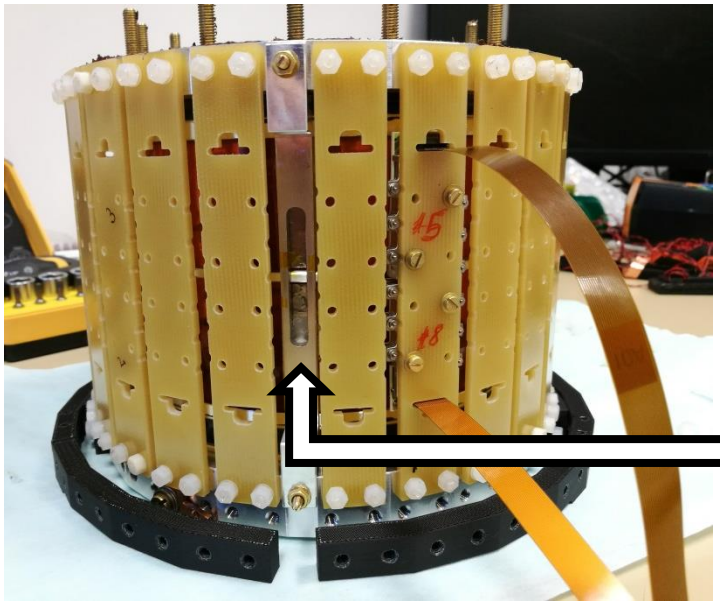
Light target and Silicon Drift Detector assembly



increase the target stopping power

almost double gas density with respect to SIDDHARTA (3% LHD)

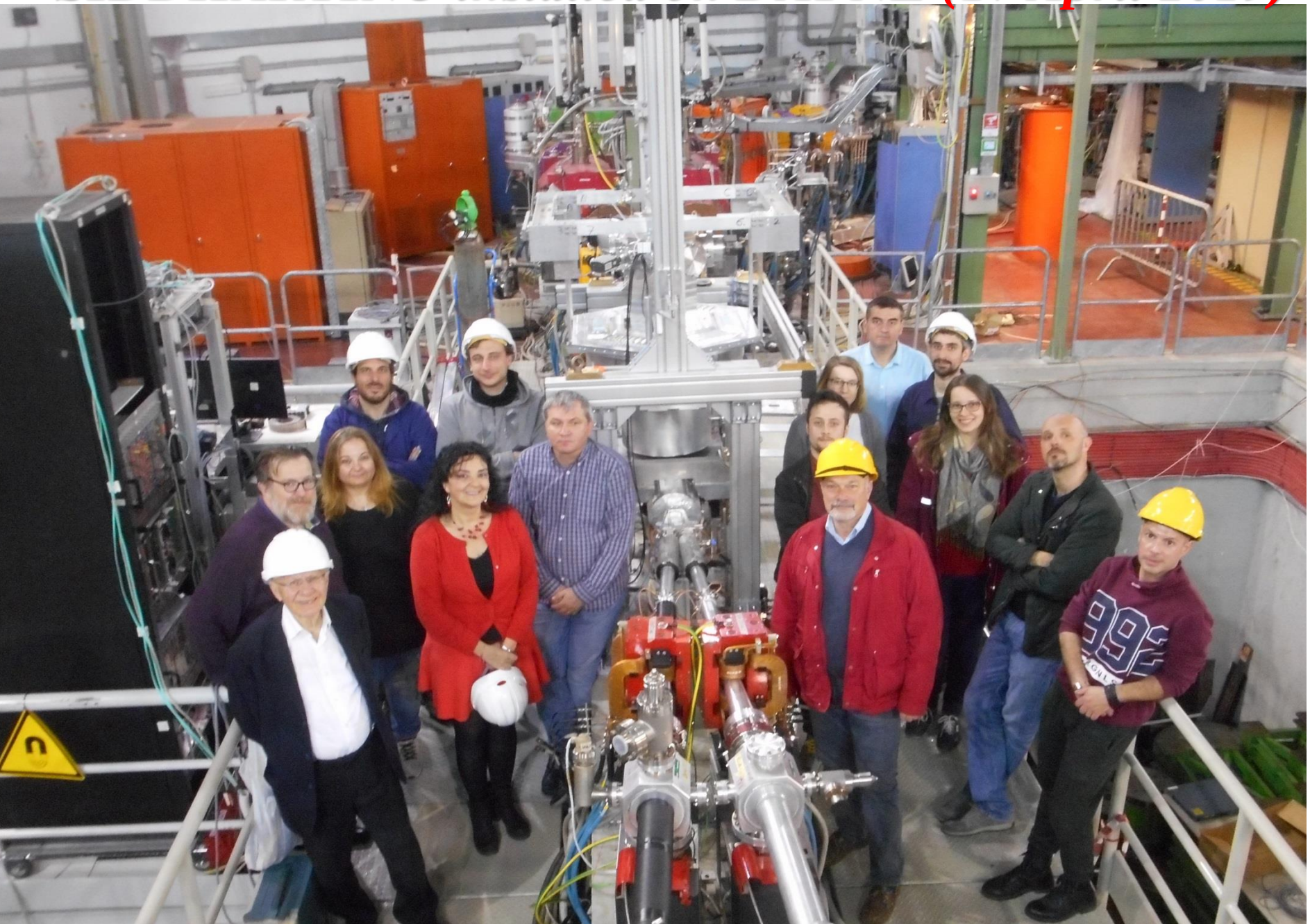
SDDs placed 5 mm from the target wall



Target cell wall is made of a 2-Kapton layer structure (75 μm + 75 μm + Araldit)

calibration foils inserted near to the SDD are activated by the X-ray tubes

SIDDHARTINO installed on DAFNE (17 April 2019)



Jinst

Published by IOP Publishing for Sissa Medialab

Received: *August 12, 2020*
Accepted: *September 22, 2020*
Published: *October 14, 2020*

Characterization of the SIDDHARTA-2 luminosity monitor

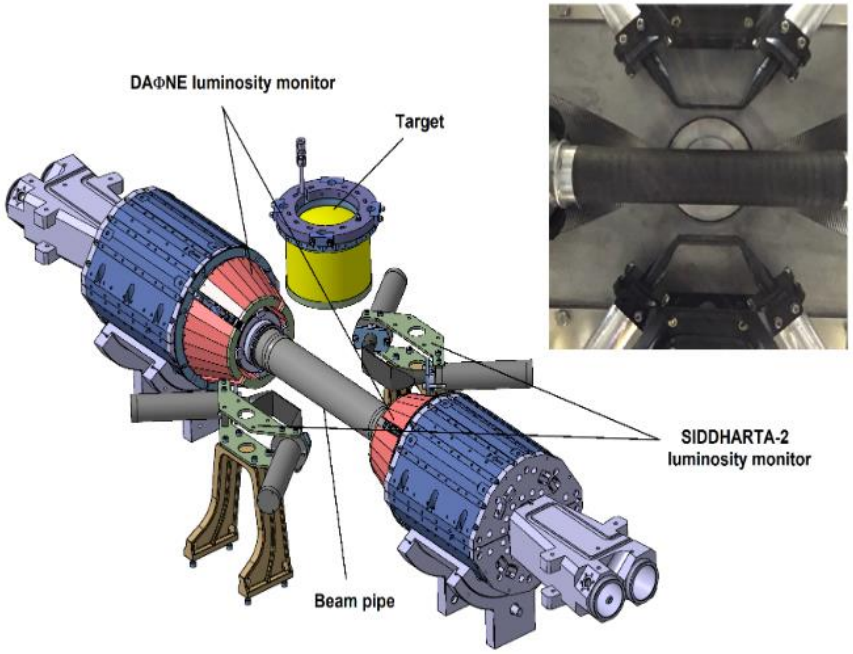


Figure 2. Schematic representation of the SIDDHARTA-2 setup with implemented luminosity monitor and the top view picture of the two installed modules (right upper corner).

Jinst

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *August 12, 2020*
ACCEPTED: *September 22, 2020*
PUBLISHED: *October 14, 2020*

Characterization of the SIDDHARTA-2 luminosity monitor

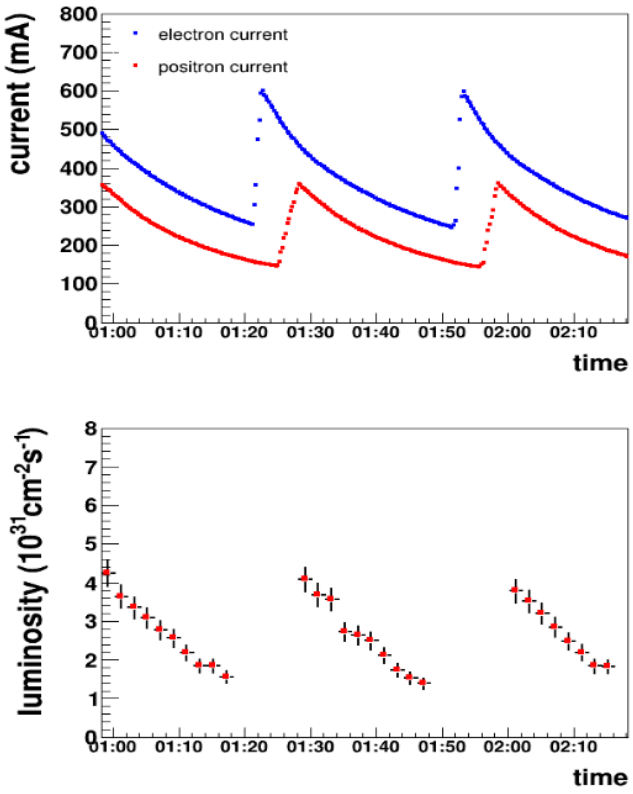


Figure 10. (upper) DAΦNE currents: electron (blue) and positron (red); (lower) measured luminosity — each point corresponds to 2 min of data taking.

Silicon Drift Detectors system for high precision light kaonic atoms spectroscopy

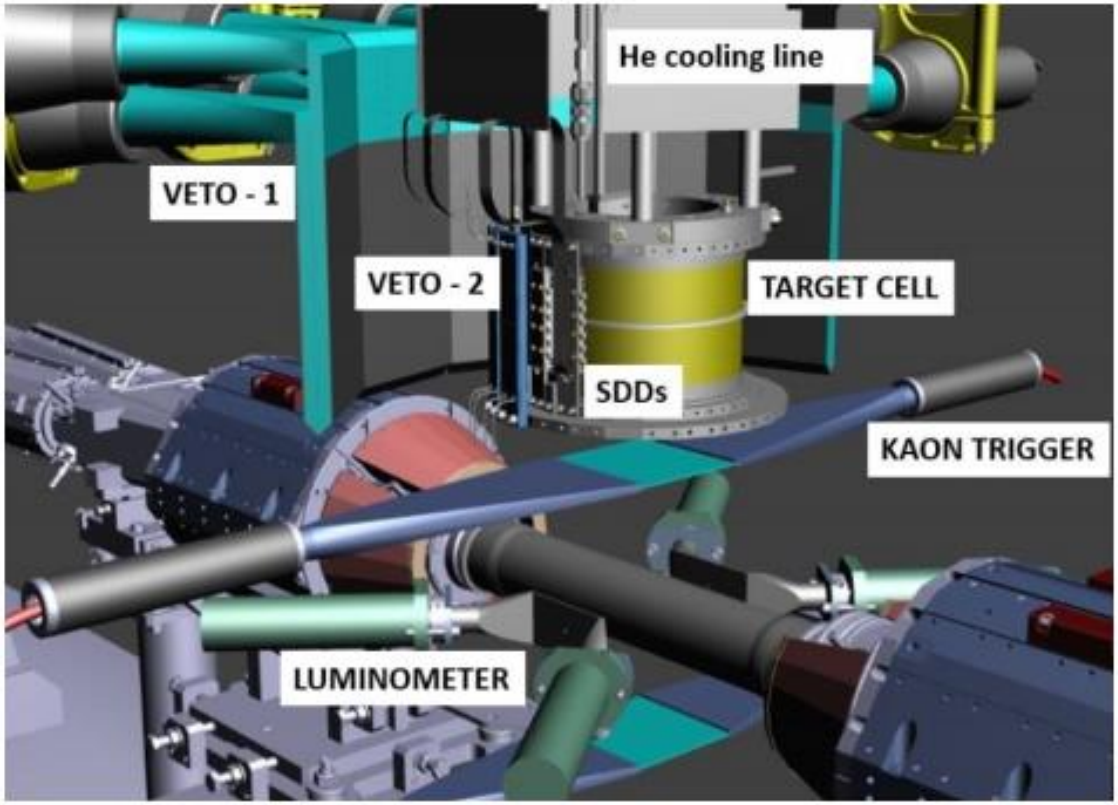
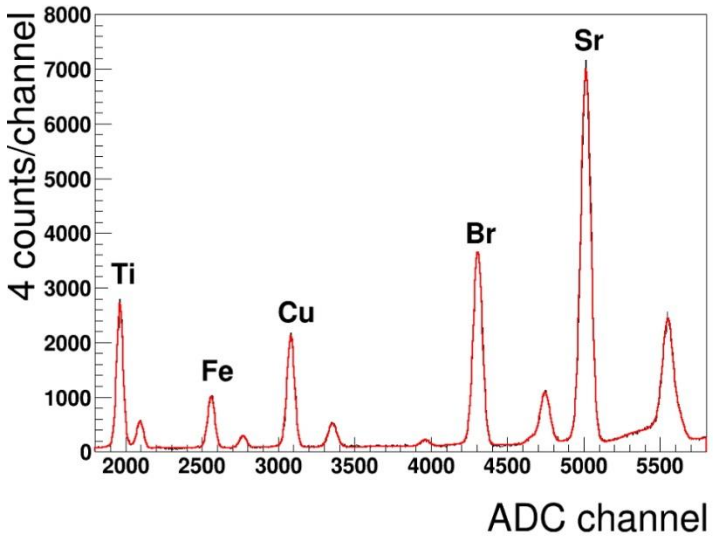
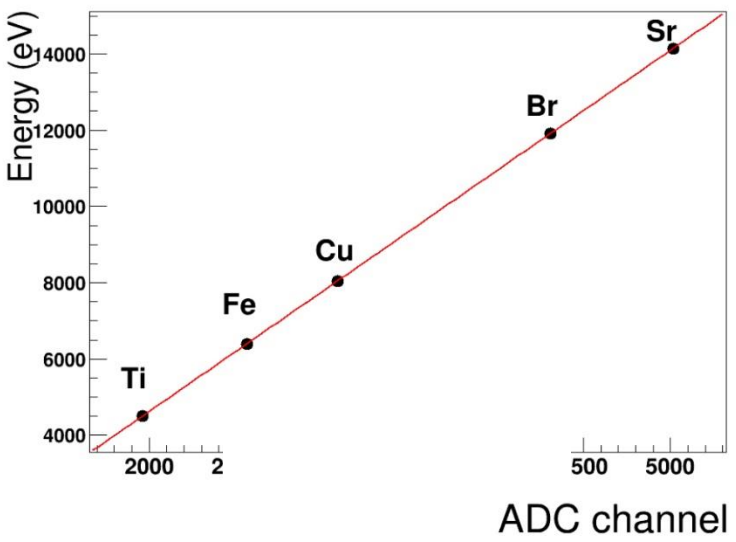
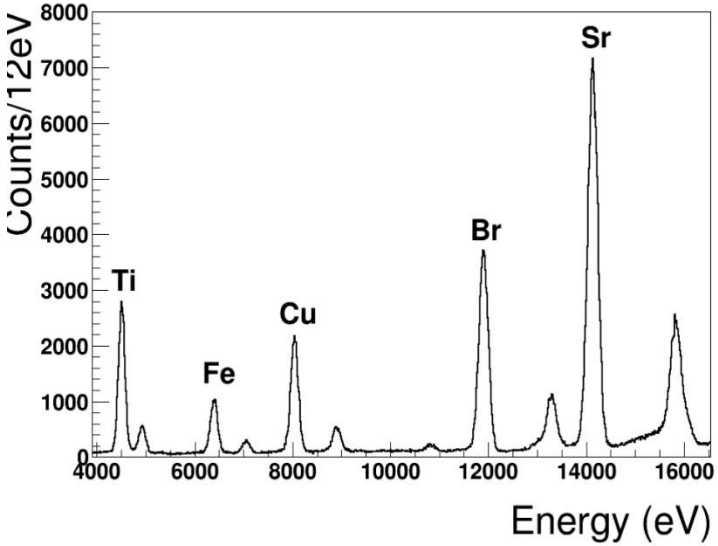


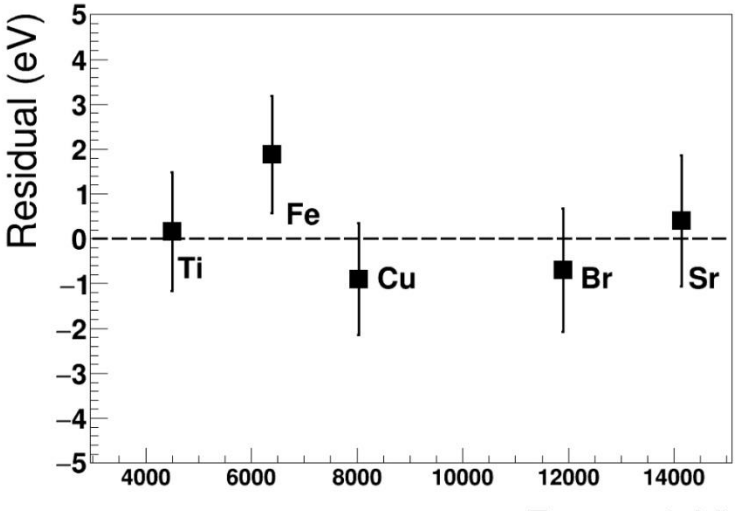
Figure 1: Schematic drawing of the SIDDHARTA-2 experiment.

Silicon Drift Detectors system for high precision light kaonic atoms spectroscopy



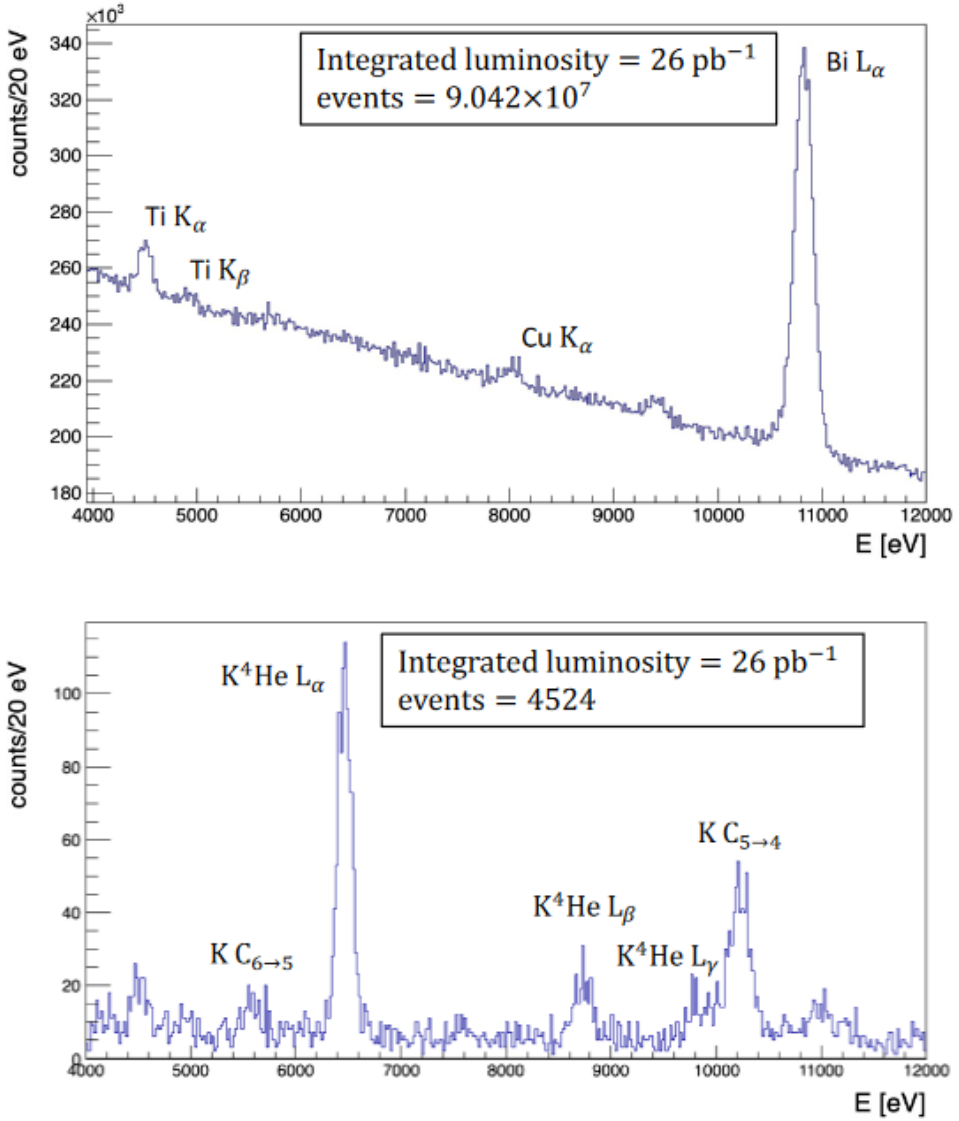






Paper draft ready (Marco Miliucci, Diana Sirghi, Alessandro Scordo)

A new kaonic helium measurement in gas by SIDDHARTINO at the DAΦNE collider



$$\varepsilon_{2p} = E_{exp} - E_{e.m} = 0.2 \pm 2.5(stat) \pm 2(syst)\ eV$$
$$\Gamma_{2p} = 8 \pm 10\ eV\ (stat)$$

Figure 4: Spectra without (top) and with (bottom) KT selections, from which the $\simeq 10^5$ rejection factor can be obtained (bottom). See text for details.


SIDDHARTA-2 setup
Ready for Run

SIDDHARTA-2 strategy and requests

Phase 2
SIDDHARTA-2

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

Action plan for Kd measurement:

- **First run with SIDDHARTA-2 setup as planned (about 300 pb^{-1} integrated)**
- **Second run with optimized shielding, readout electronics and other necessary optimizations; (for other 500 pb^{-1} integrated)**

Test runs for other kaonic atoms measurements (HPGE…)

Phase-2: SIDDHARTA-2 K-d measurement

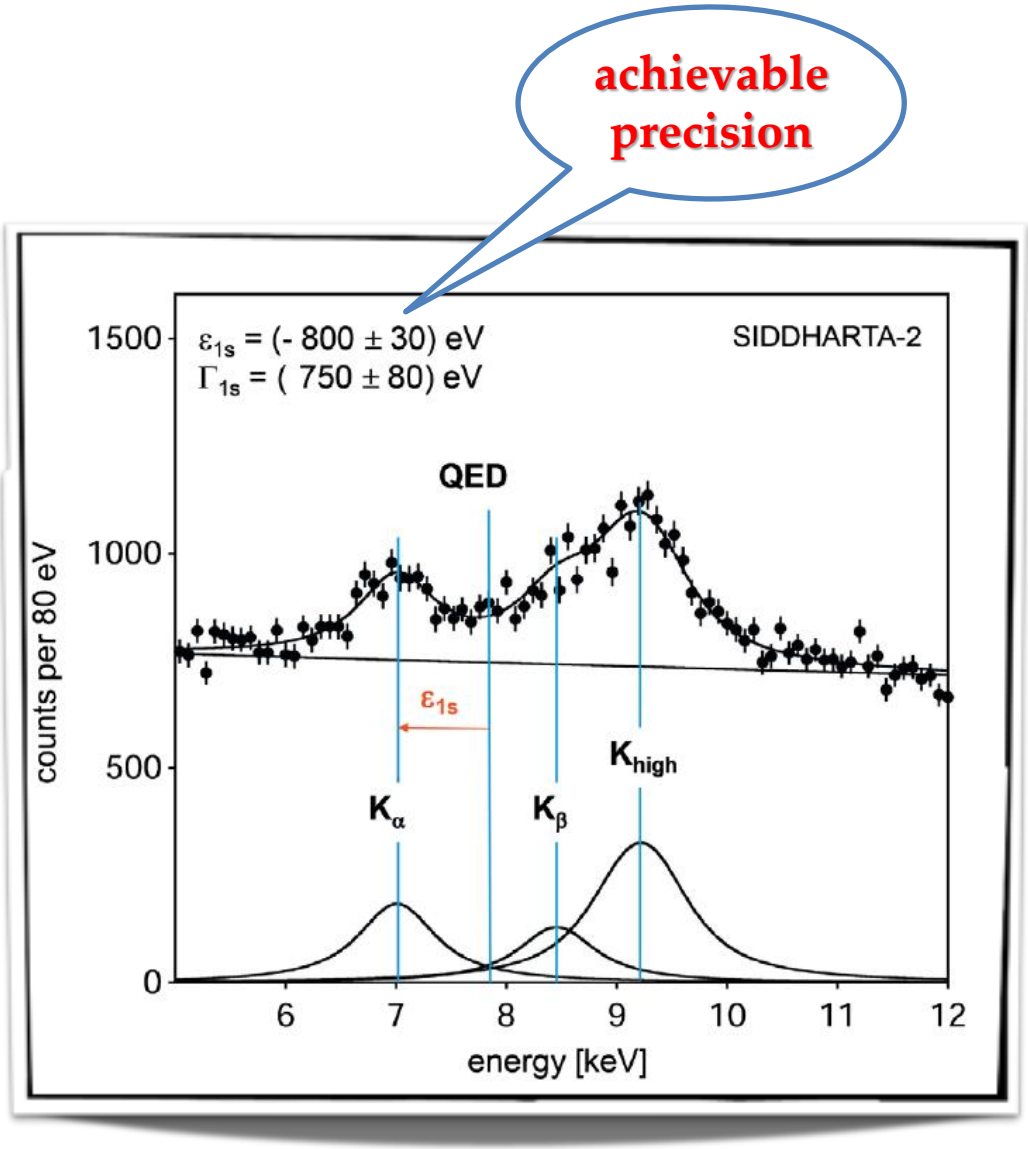
Kaonic deuterium run in (all)

2021

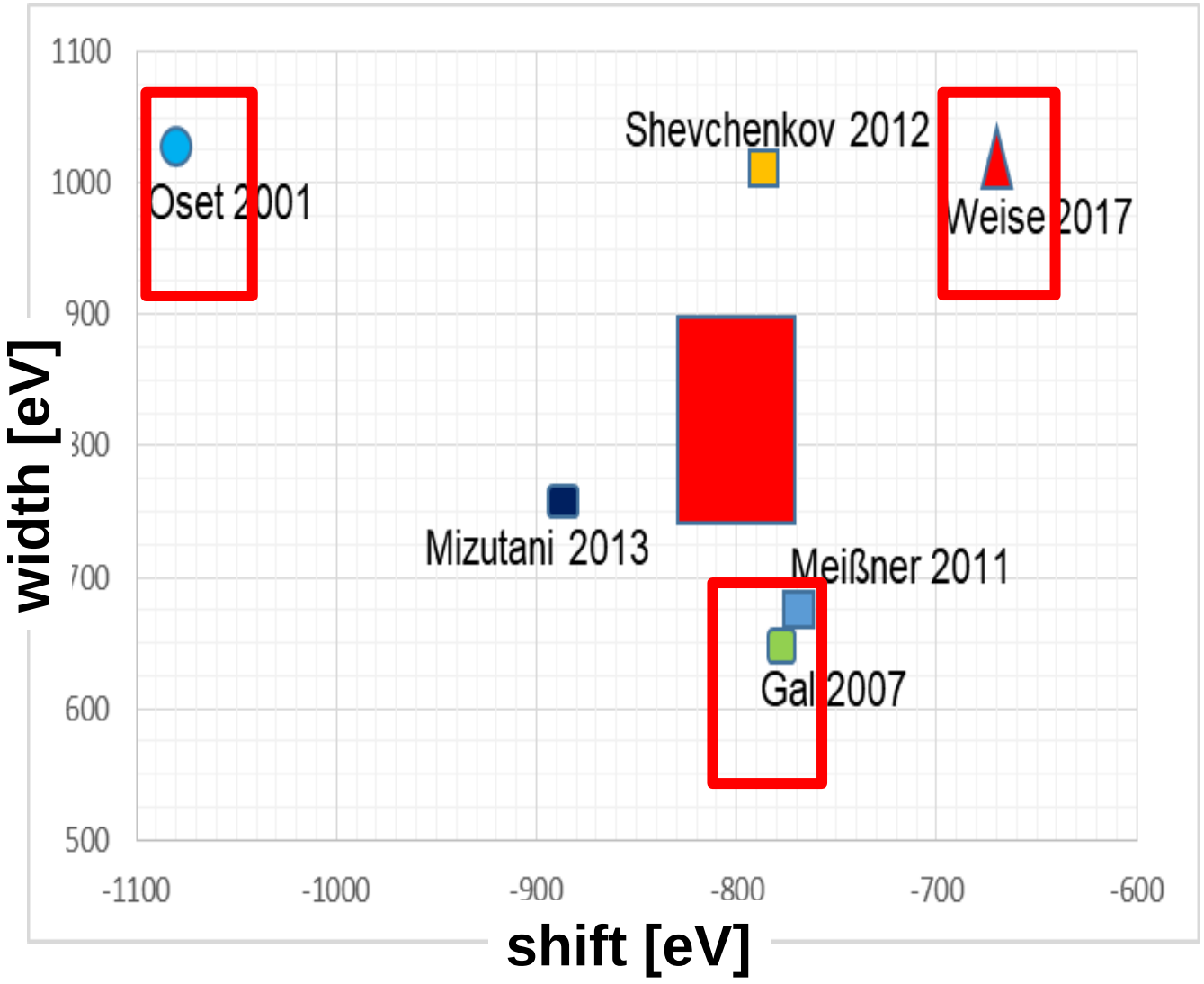
for S/B as 1/3:

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) !



SIDDHARTA-2 kaonic deuterium at DAFNE



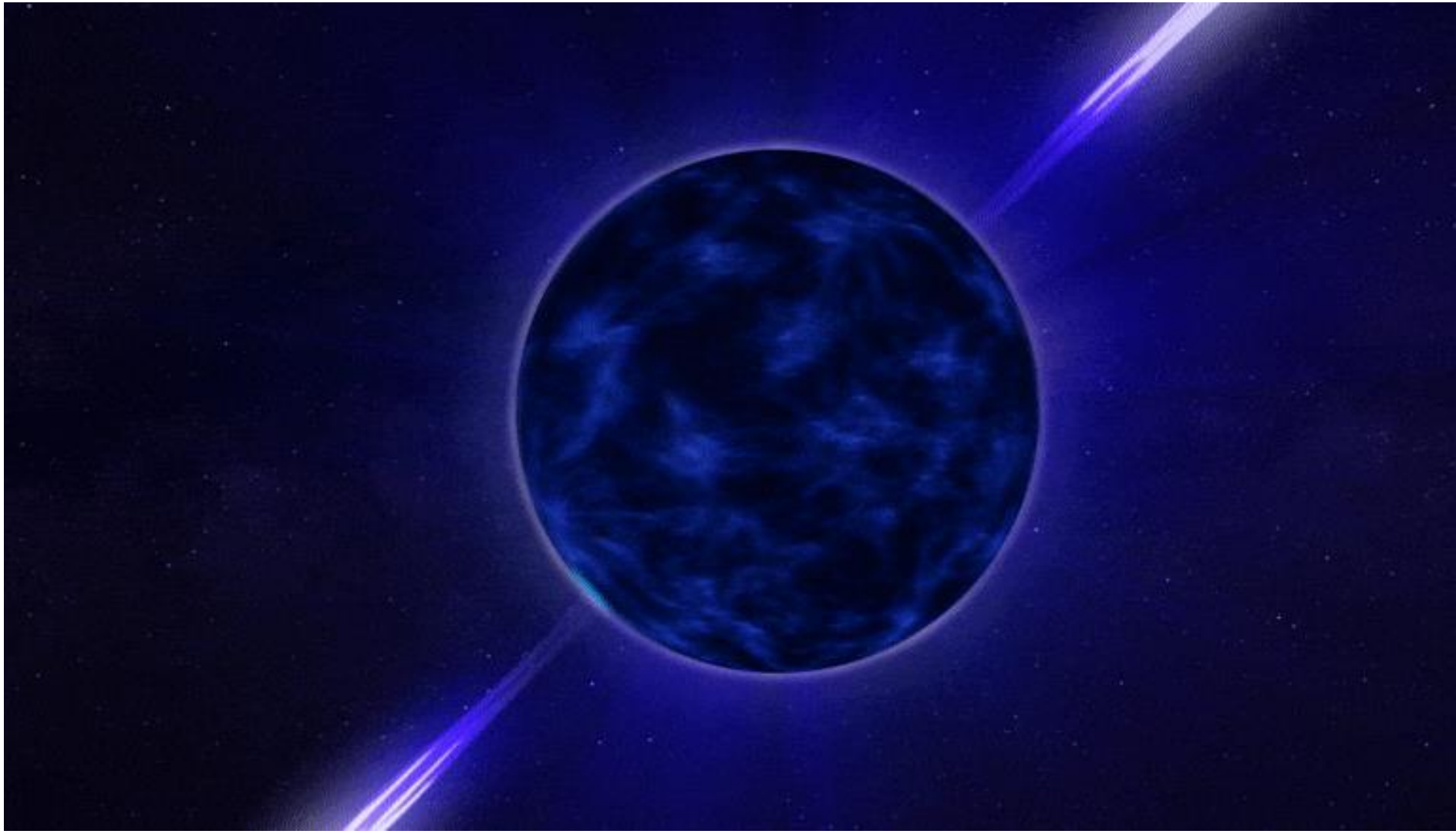
New insights into the strong interaction with strange exotic atoms

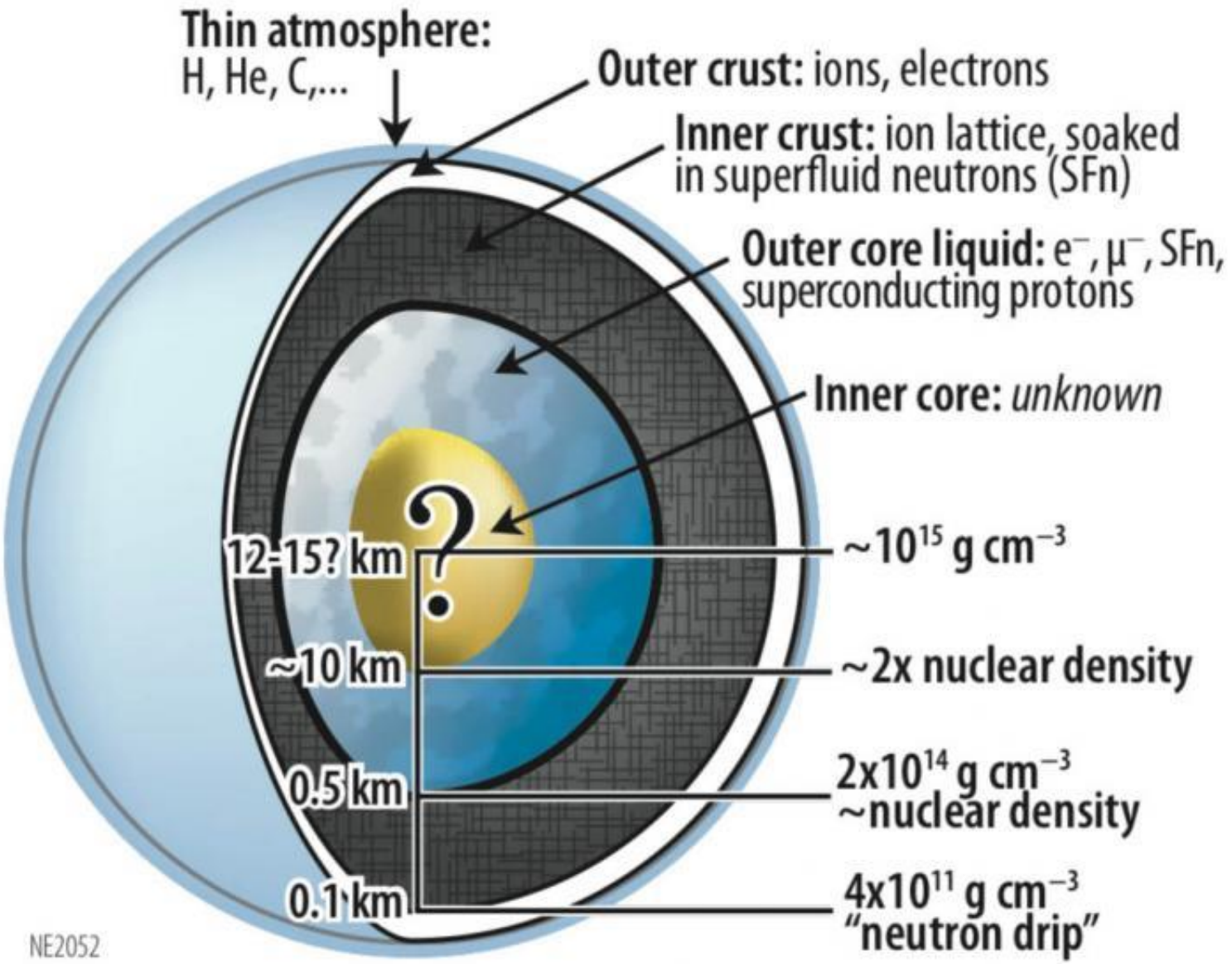
The strong interaction plays a fundamental role in our universe. The difficulty of performing precision measurements has limited our understanding of this interaction. Dr Catalina Curceanu at the National Institute for Nuclear Physics (INFN) in Frascati-Rome is leading ambitious new efforts to study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

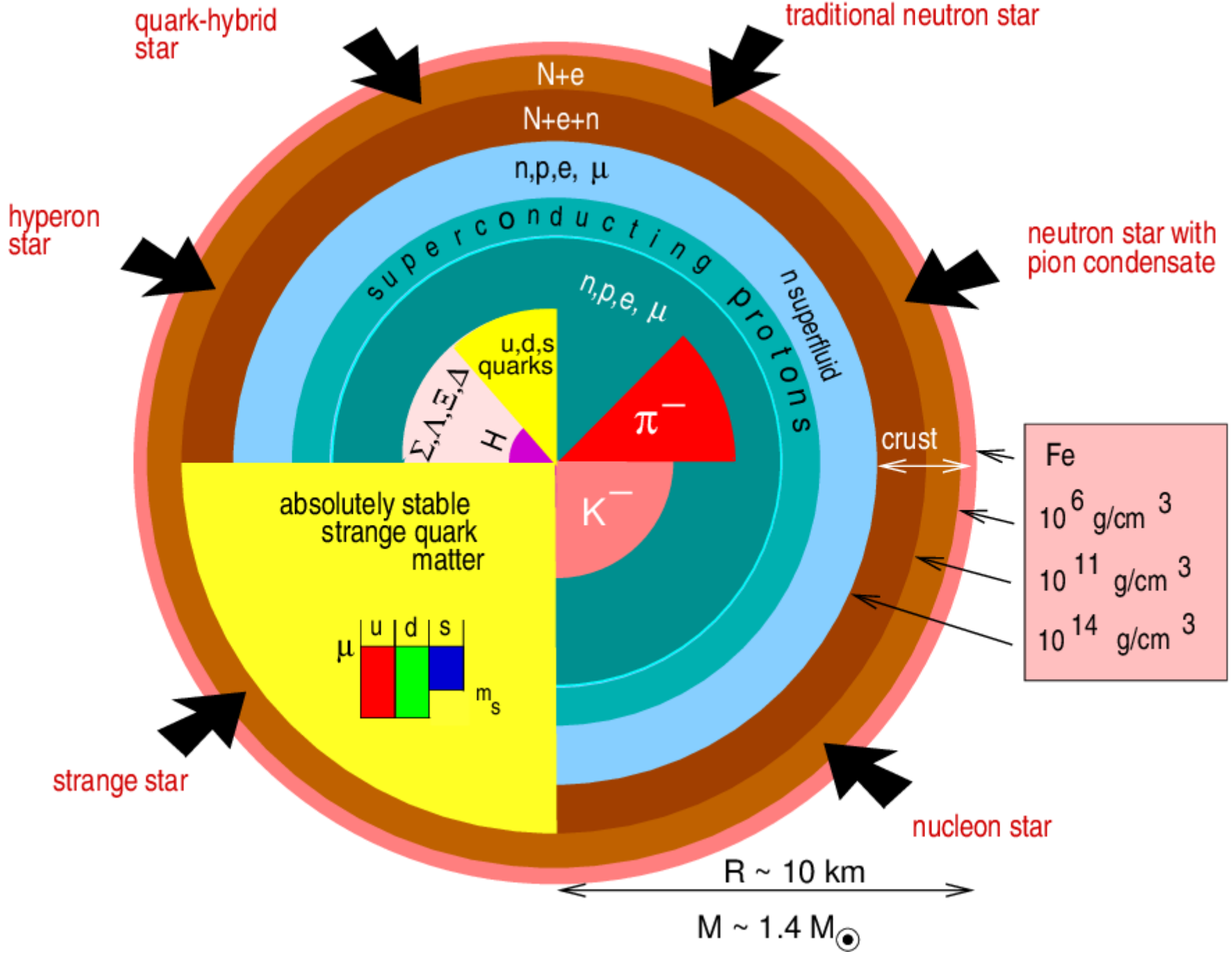
Download this Article

Article References

• Curceanu, C., Guaraldo, C., Sirghi, D., Amirkhani, A., Baniahmad, A., Bazzi, M., Bellotti, G., Bosnar, D., Bragadireanu, M., Cargnelli, M., Carminati, M. (2020). Kaonic Atoms to




Thin atmosphere:
H, He, C,...
Outer crust: ions, electrons
Inner crust: ion lattice, soaked in superfluid neutrons (SFn)
Outer core liquid: e⁻, μ⁻, SFn, superconducting protons
Inner core: unknown
?
12-15? km
~10 km
0.5 km
0.1 km
~10^15 g cm^-3
~2x nuclear density
2x10^14 g cm^-3
~nuclear density
4x10^11 g cm^-3
"neutron drip"
NE2052


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

Future programme and perspectives:

- **Feasibility studies in parallel with Siddharta-2 (Ge and VOXES crystal spectrometer)**
- **1mm SDDs**
- **Proposal for Extension of the Scientific Program at DAFNE**

- **Kaon mass - precision measurement at a level < 7 keV**
- **Kaonic helium transitions to the 1s level**

- **Other light kaonic atoms (K^-Bi, Li, B,, K^-C,…)**
- **Heavier kaonic atoms (K^-Si, K^-Pb…)**

- **Radiative kaon capture – Λ(1405) study**
- **Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)**

For future:

Physics at the strangeness frontier at DAΦNE studies:

High Precision Kaonic Atoms Measurements on DAΦNE:

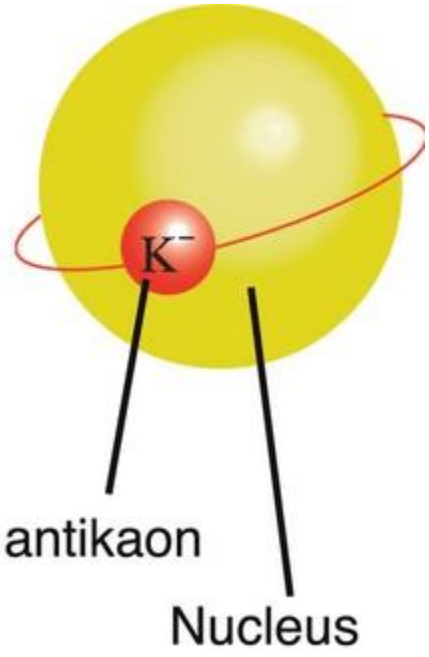
The strangeness Mendeleev table

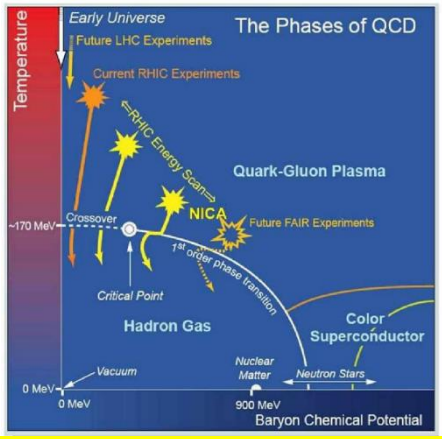
We presented a program for performing unique measurements of kaonic atoms along the periodic table to contributing to understand physics going from the strong interaction (symmetry breaking) to neutron stars, and from Dark Matter to Physics Beyond Standard Model, setting LNF in forefront of these studied.

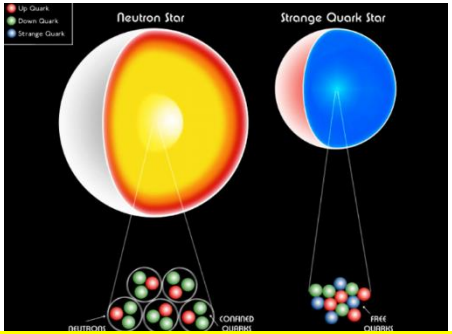
A strong international community is putting forward this realistic and feasible programme in particular in terms of the required integrated , that can be delivered within the upcoming 3-5 years, with support from National and European projects.

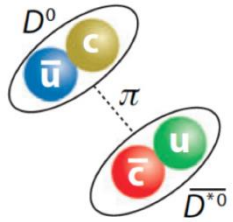
EXtensive Kaonic Atoms research: *from LIthium and Beryllium to Uranium*

EXKALIBUR









D^0–$\overline{D^{*0}}$ "molecule"

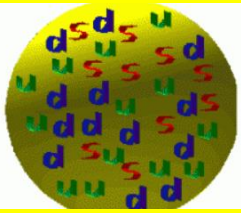
Diquark–diantiquark

Neutron star EOS

Particles structure

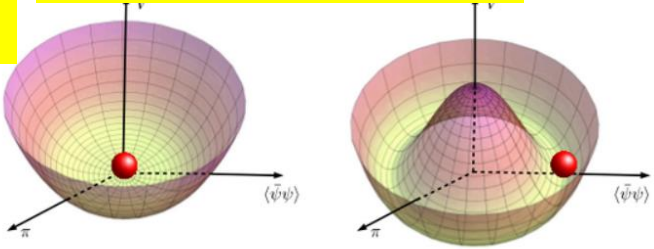
Cold Dense matter

Strangeness Fundamental Physics

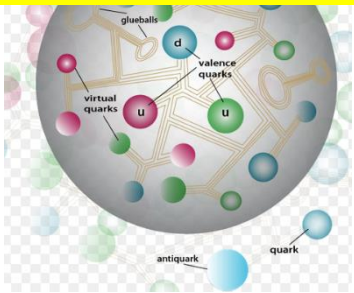


Strangelets & Dark Matter

QCD Chiral symm.



Mass generation, visible Universe



Conclusions

- **Kaonic atoms precision studies: SIDDHARTA-2 and perspectives (ongoing)**
- **Various setups in preparation: HPGe; crystal spectrometers; CdZnTe, SDD 1mm for kaonic atoms measurememys**

-> does strangeness play a role in the Universe?

- **Solid FUTURE PLANS ->**

-> WE INVITE YOU TO JOIN OUR COLLABORATION

NEW IDEAS???


Thank you!