Nuclear Matter at Extreme Densities and High Temperatures
September 17-23, 2023
Zakopane, Tatra Mountains, Poland

Kaonic atoms at the DAΦNE Collider in Italy: a strangeness Odyssey

Catalina Curceanu on behalf of the SIDDHARTA-2 Collaboration

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

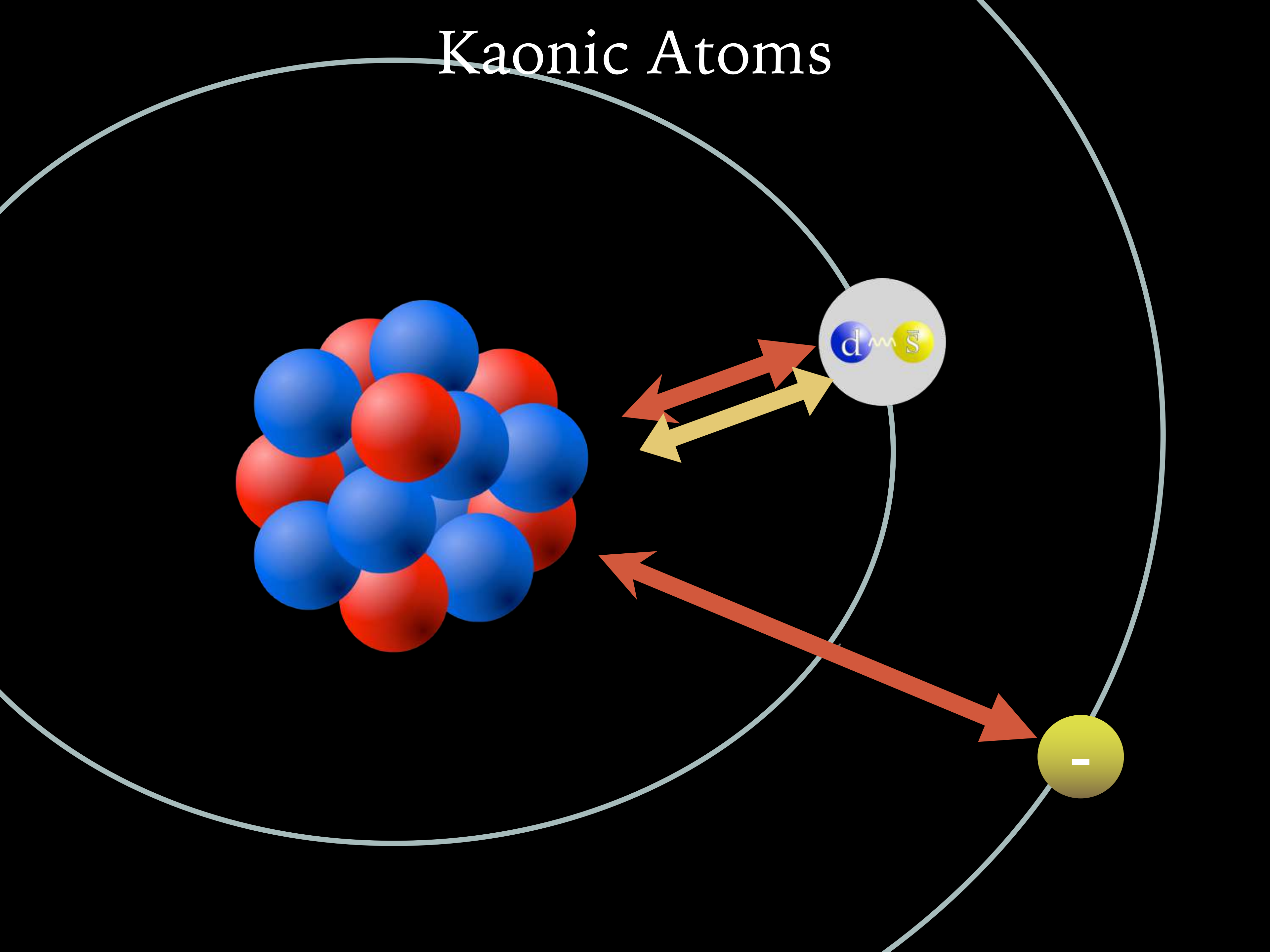
SIDDHARTA-2

SIlicon **D**rift **D**etector for **H**adronic **A**tom **R**esearch by **T**iming **A**pplications

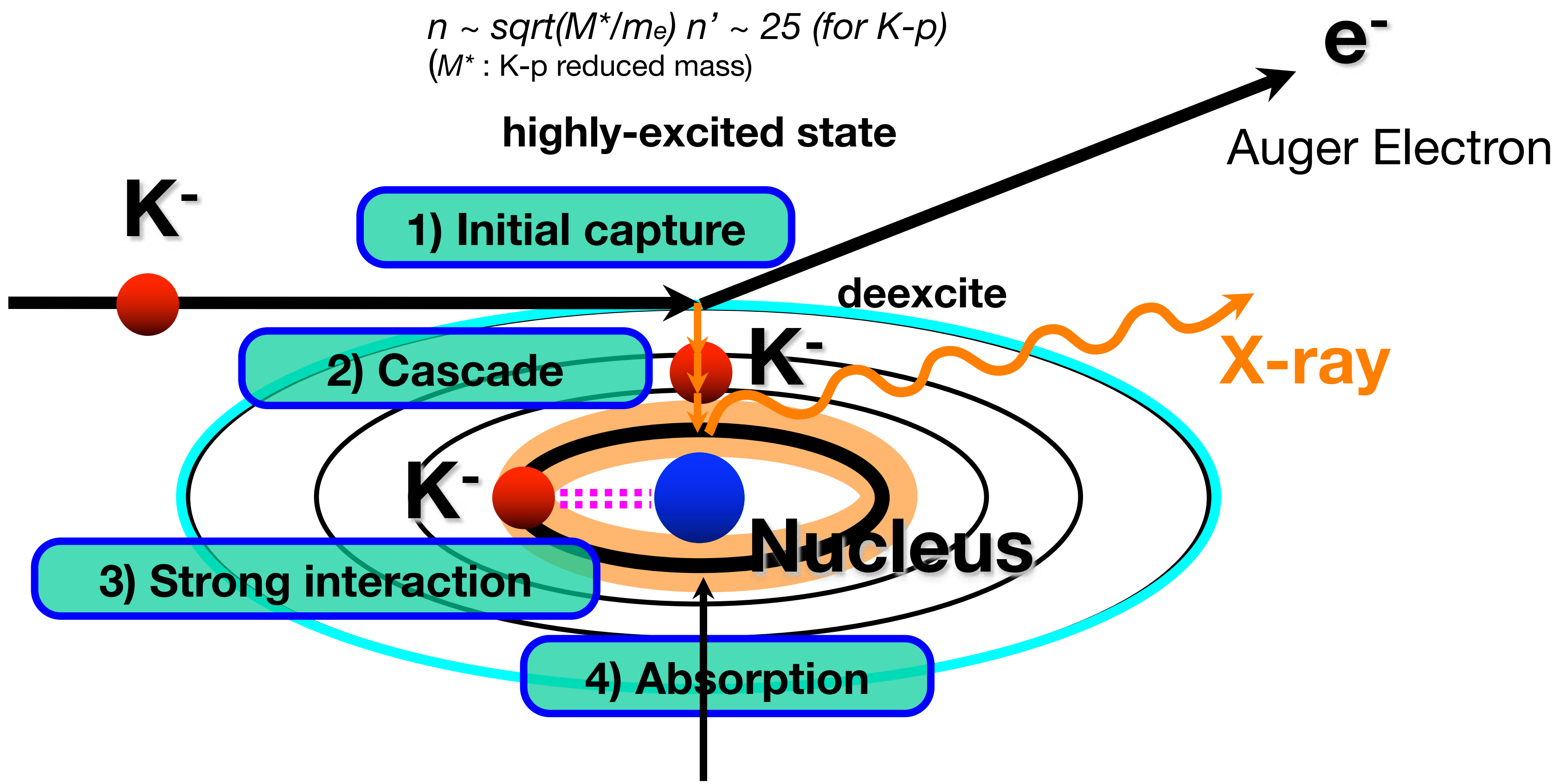
LNF-INFN, Frascati, Italy
SMI-ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN –HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
ELPH, Tohoku University
CERN, Switzerland

Part of the SIDDHARTA-2 collaboration

Kaonic Atoms



Kaonic atom formation

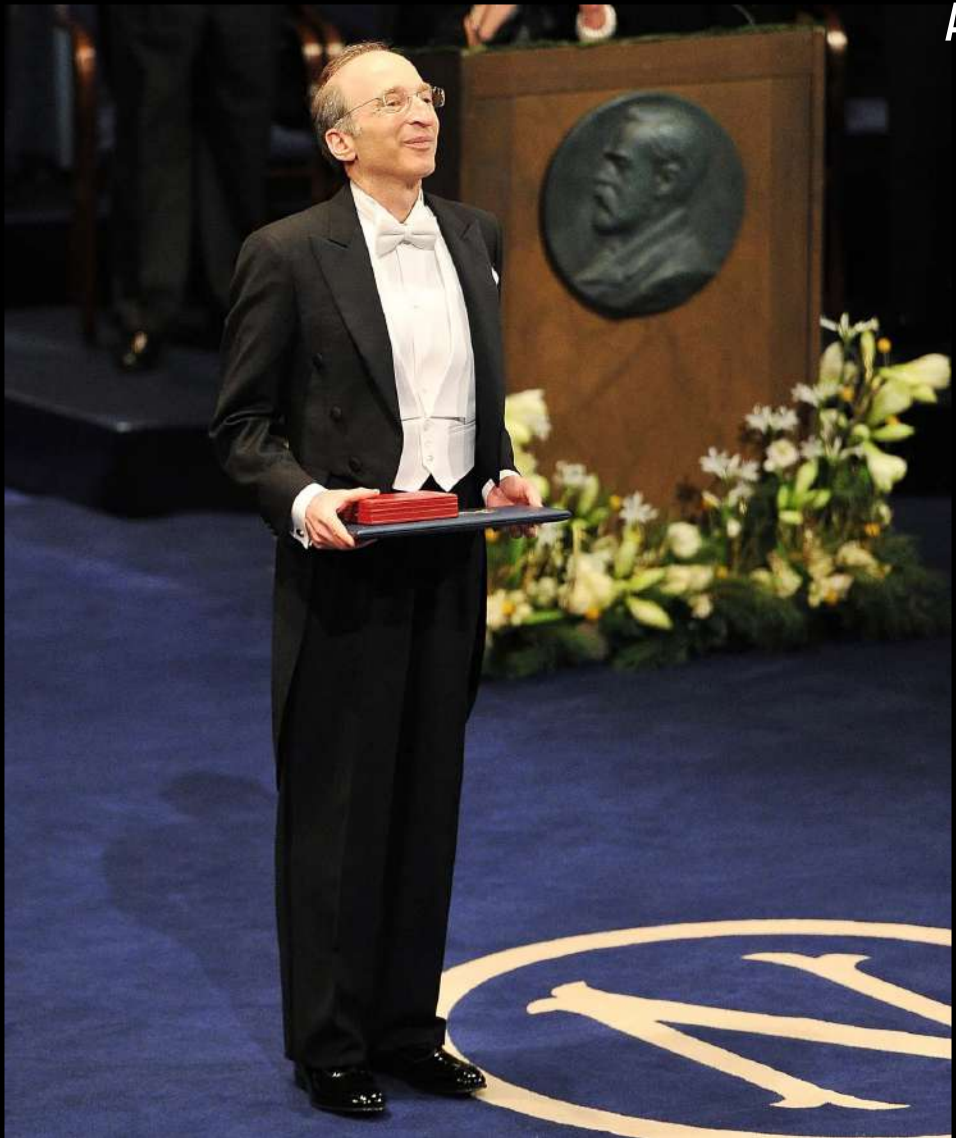


stopped in a target medium

Shift and Width
of last orbit

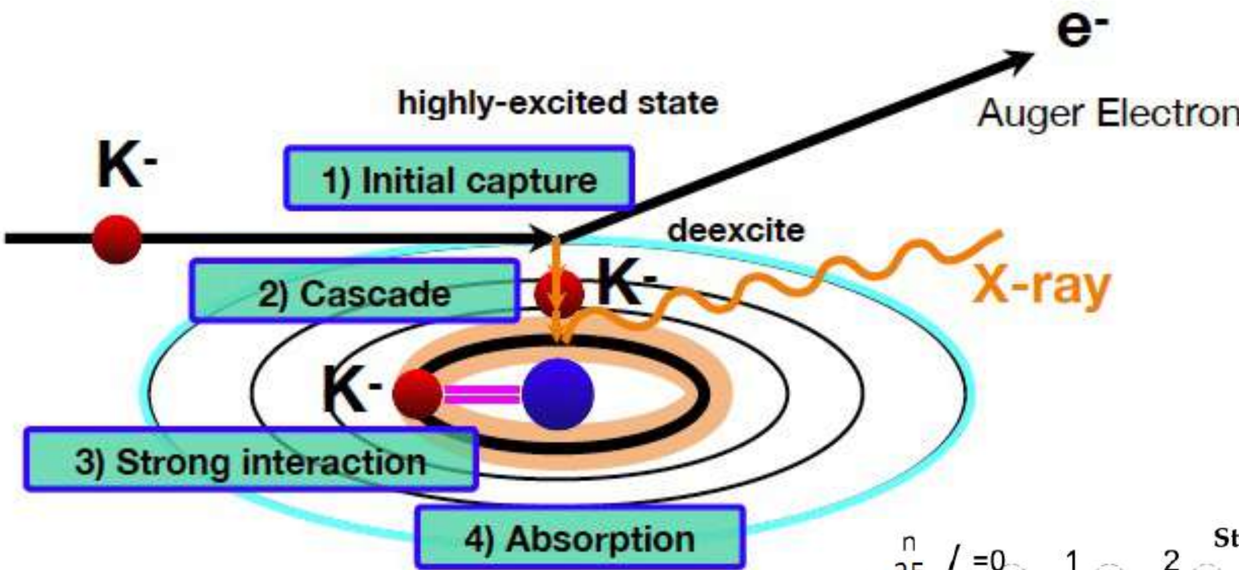
· 1s for K-p, K-d
· 2p for K-He

Saul Perlmutter, born 22 Sep 1959
Nobel 2011 for "the discovery of the accelerating expansion of the Universe through observations of distant supernovae."
– if this is the size of a normal atom…

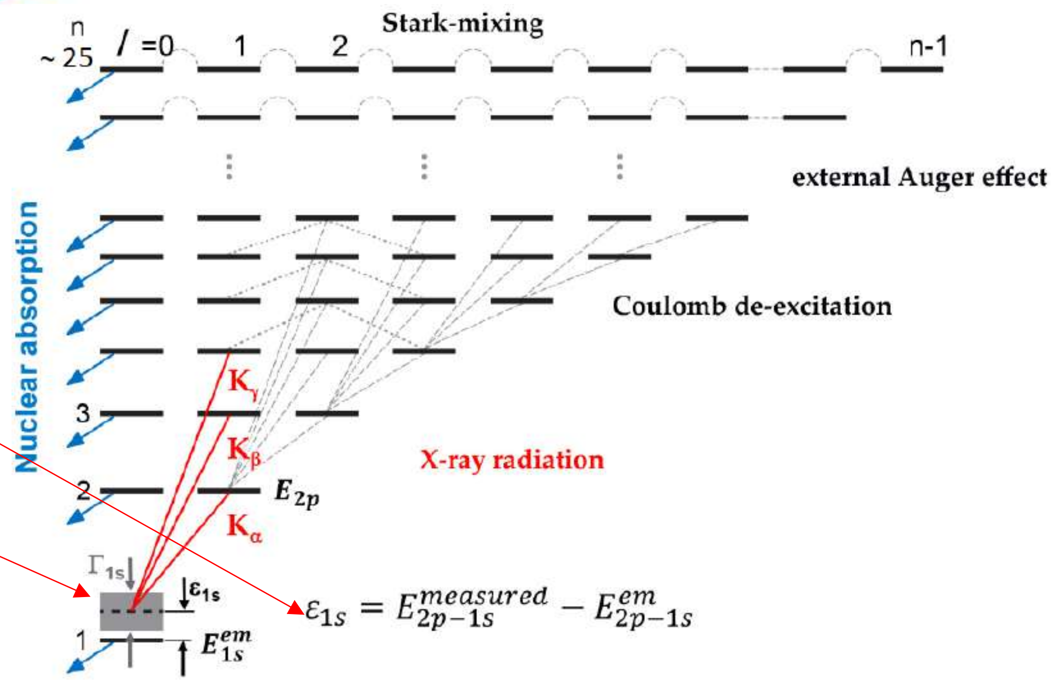


A bee – this is the relative size of a kaonic atom…

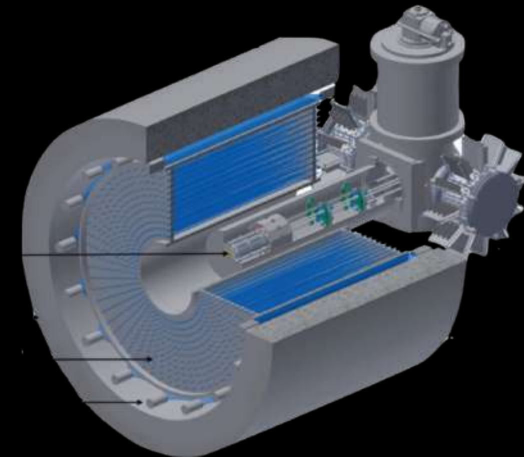
Kaonic atom Formation

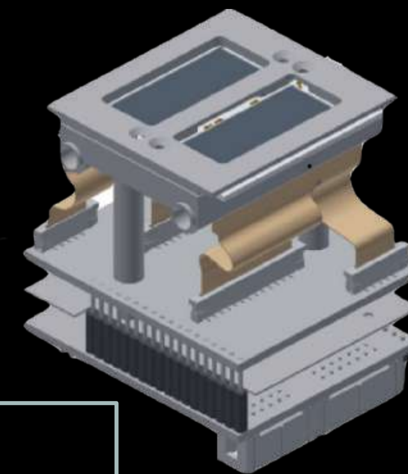


Width Γ and shift ε obtained by measuring the X-rays emitted



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

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

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)

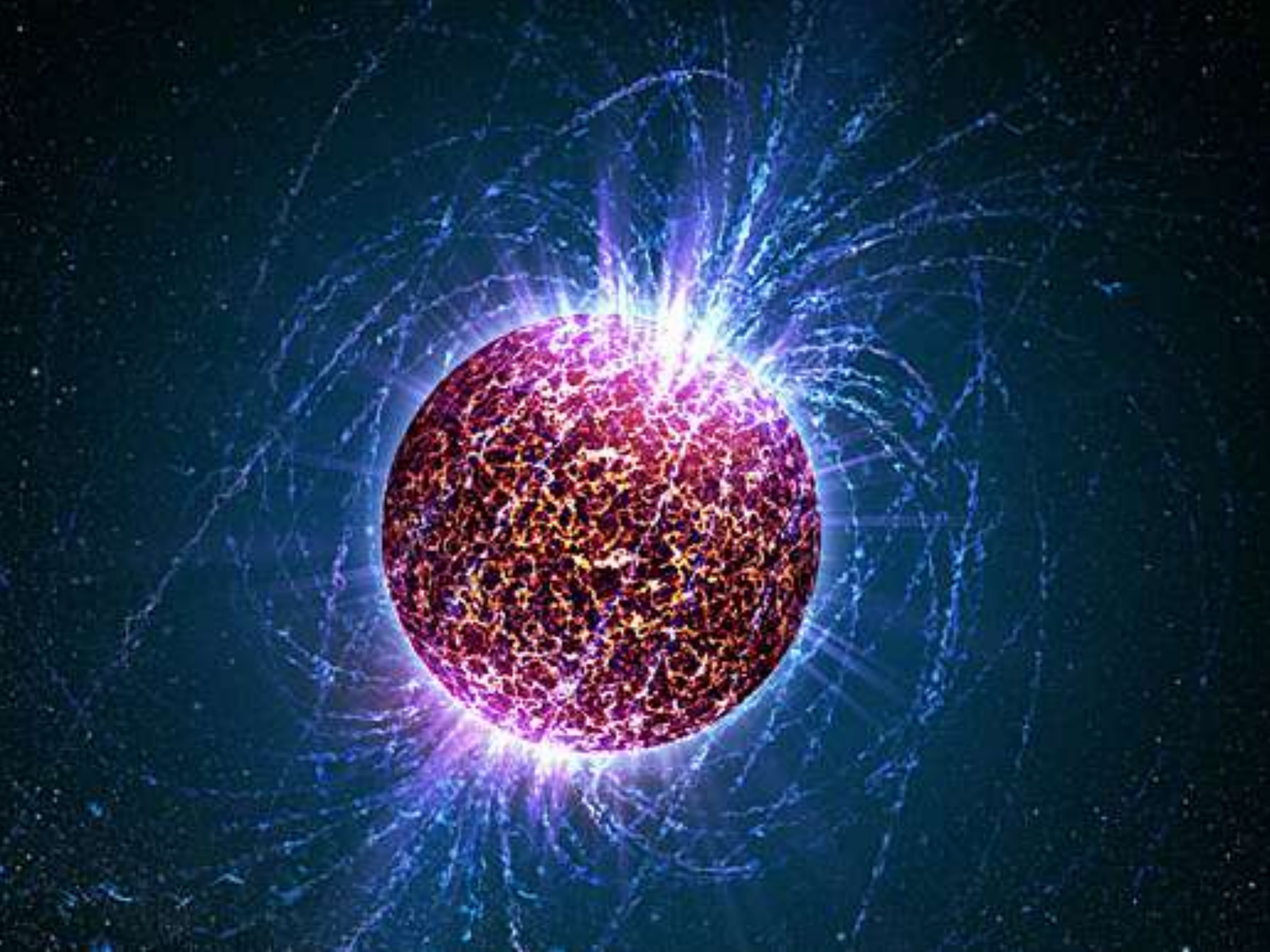
Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

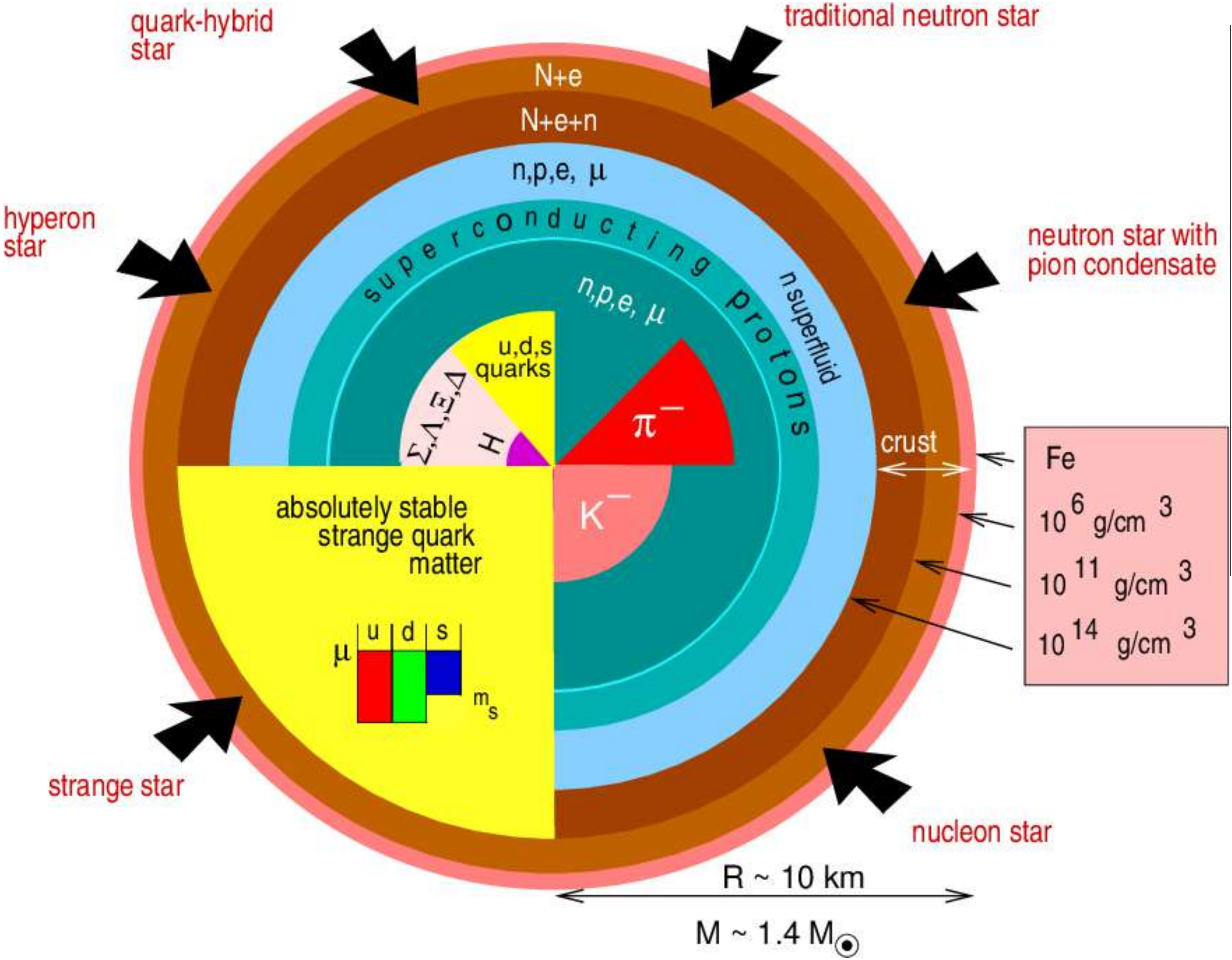
Merger of compact stars in the two-families scenario
Astrophys.J. 881 (2019) 2, 122

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



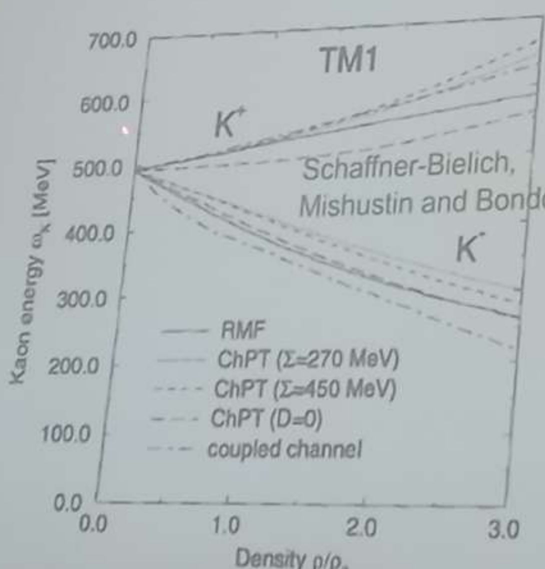

quark-hybrid star
traditional neutron star
N+e
N+e+n
n,p,e, μ
hyperon star
superconducting protons
n superfluid
neutron star with pion condensate
n,p,e, μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
crust
Fe
10 6 g/cm 3
10 11 g/cm 3
10 14 g/cm 3
K⁻
absolutely stable strange quark matter
μ
u
d
s
m s
strange star
nucleon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

Laura Tolos talk

Antikaons in matter

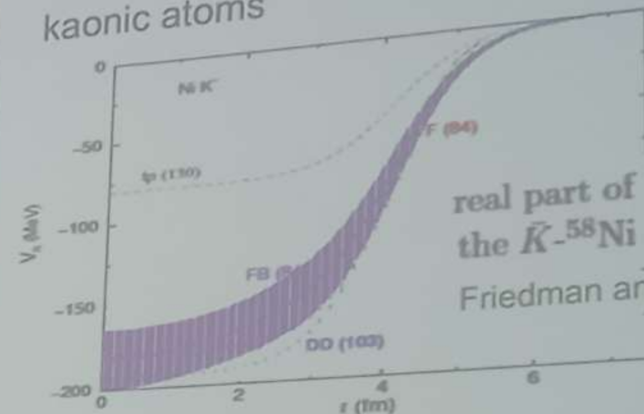
RMF schemes,
QMC models…

RMF: early works based on meson-exchange picture or the chiral approach for the $\overline{K}N$ interaction on the mean-field level and fit the parameters to the $\overline{K}N$ scattering length



Phenomenological models

density dependent potentials fitted to kaonic atoms



$U_{K^-}(\rho_0) \sim -100$ to -200 MeV

recent K^-N scattering amplitudes from χSU(3) EFT supplemented with phenomenological terms for K^- multinucleon interactions:
kaonic atoms test densities $\rho < \rho_0$

Friedman and Gal '17

Glendenning '85

Kaon condensation irrelevant as antikaons have to lower mass drastically

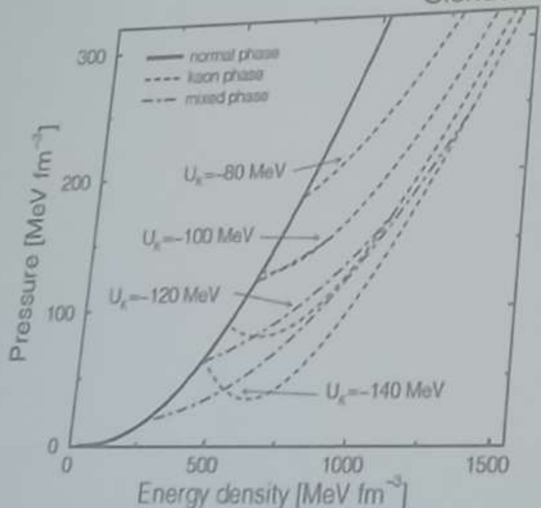
Kaplan and Nelson '86

Medium effects on antikaons important: kaon condensation is possible!

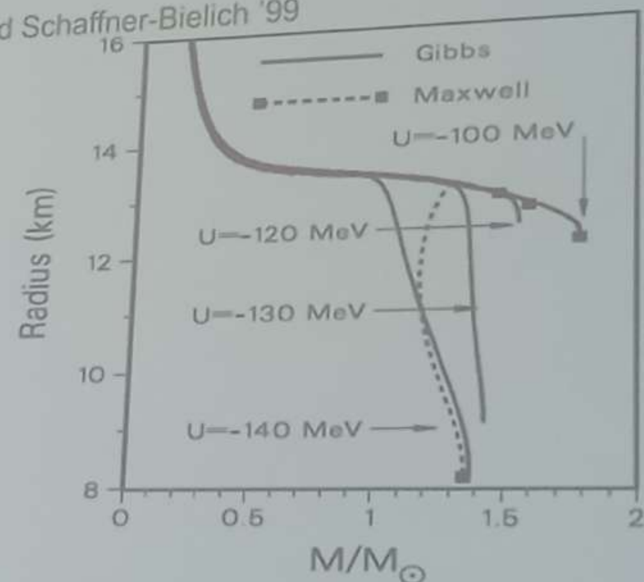
Brown, Kubodera, Rho and Thorsson'92; Thorsson, Prakash and Lattimer '94; Fujii, Maruyama, Muto and Tatsumi '96; Li, Lee and Brown '97; Knorren, Prakash and Ellis '95; Schaffner and Mishustin '96; Glendenning and Schaffner-Bielich '98 '99

Renewed interest on antikaon-nucleon interaction

Glendenning and Schaffner-Bielich '99



EoS is softened due to kaon condensation



The maximum mass is lowered with increasing attractive K⁻N potential

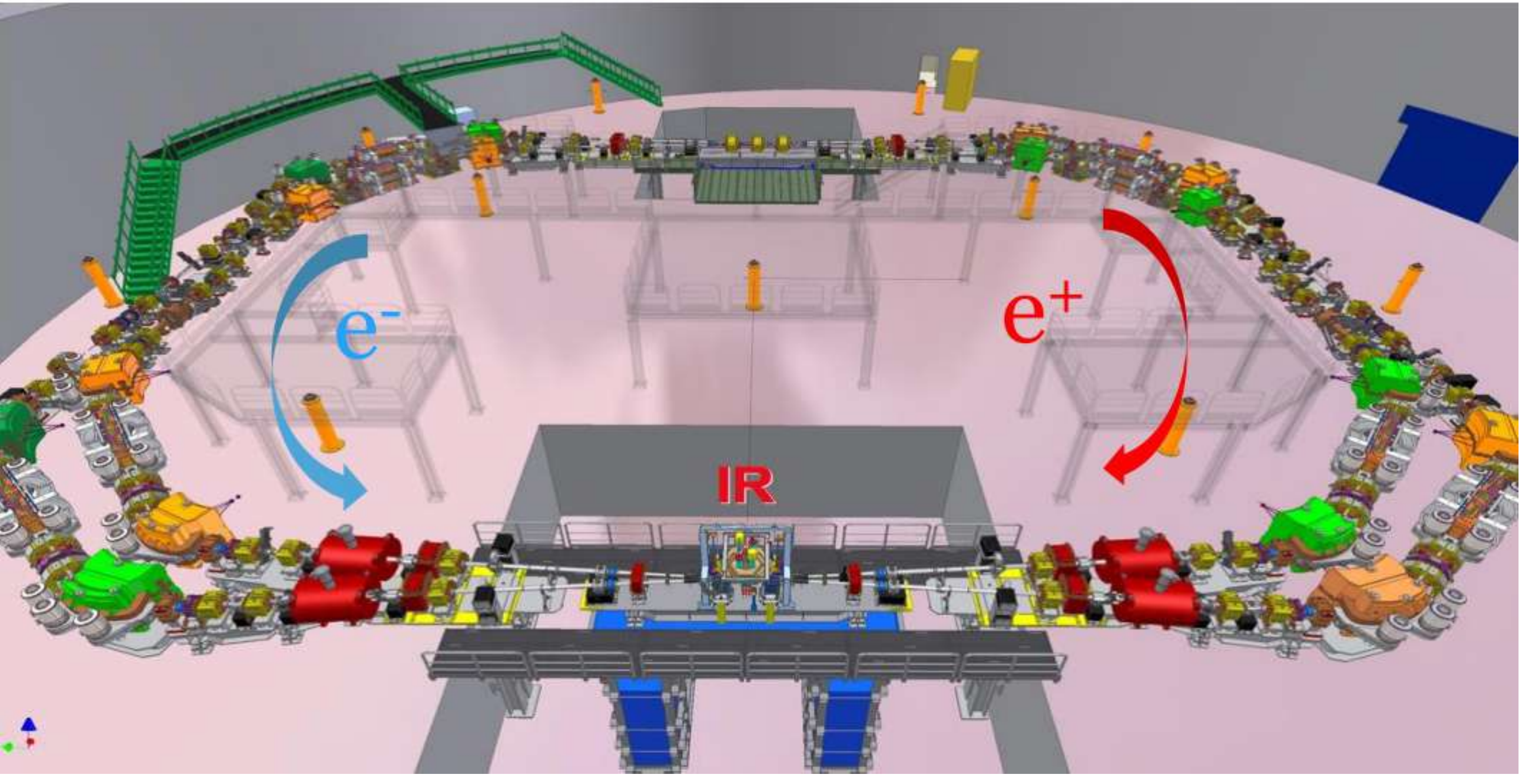
Laura Tolos talk

LNF - e^+e^- Accelerator Complex

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

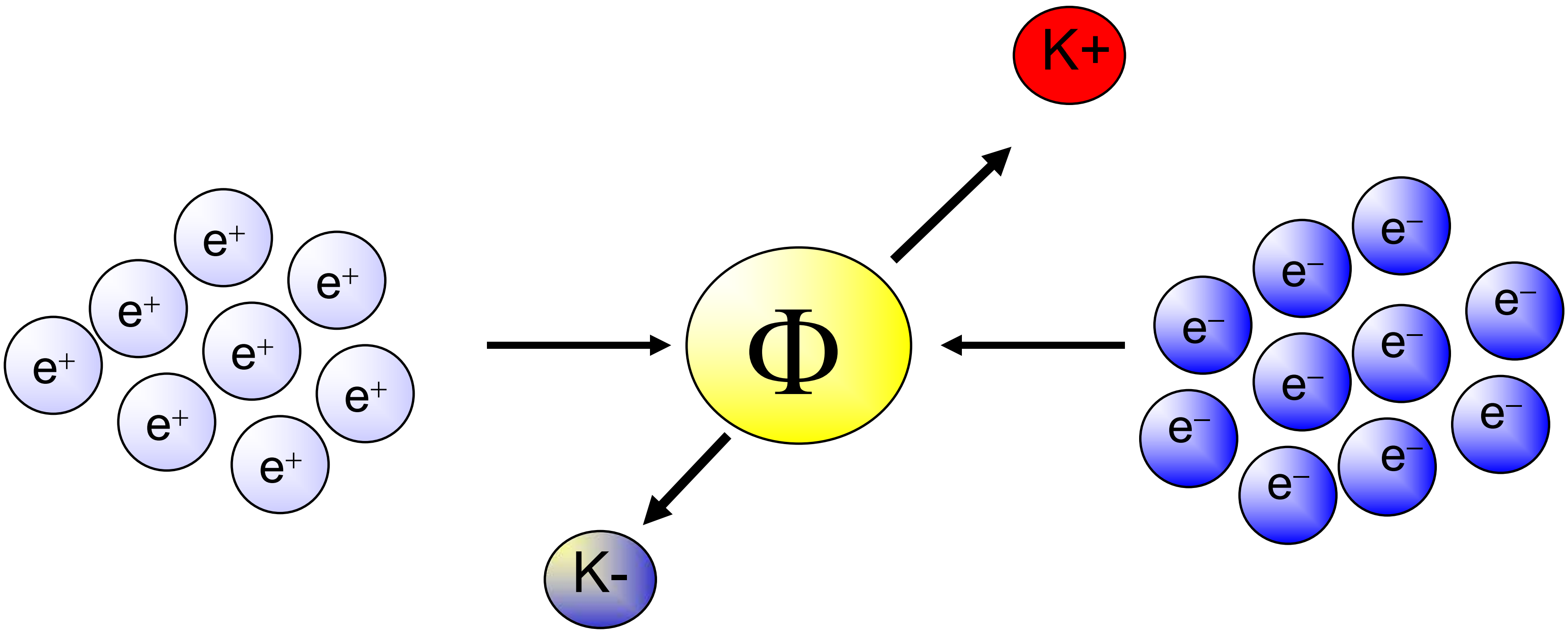
Laboratori Nazionali di Frascati (LNF-INFN)

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

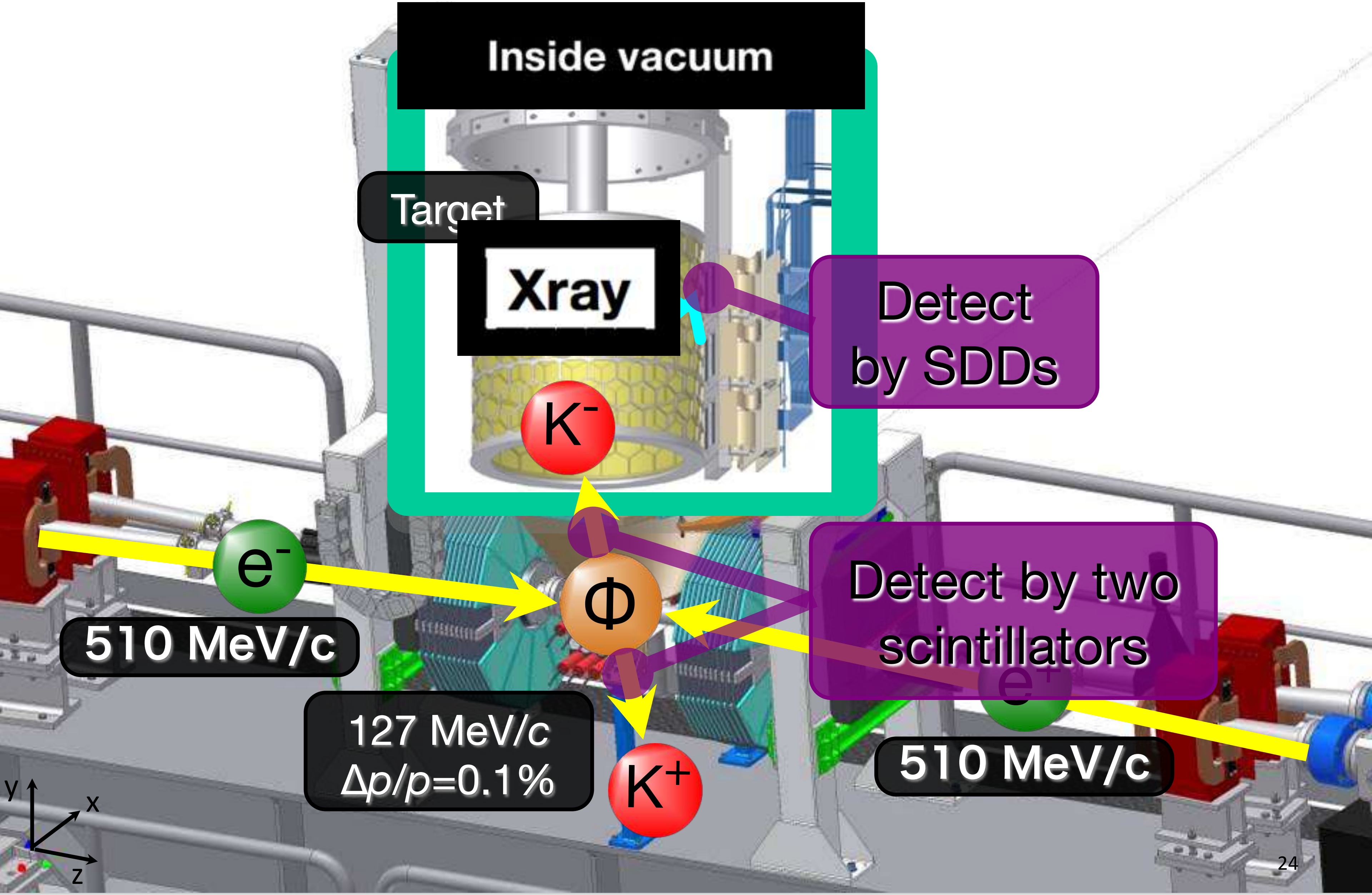
(compare to hadron beam line : e.g. KEK /JPARC)

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

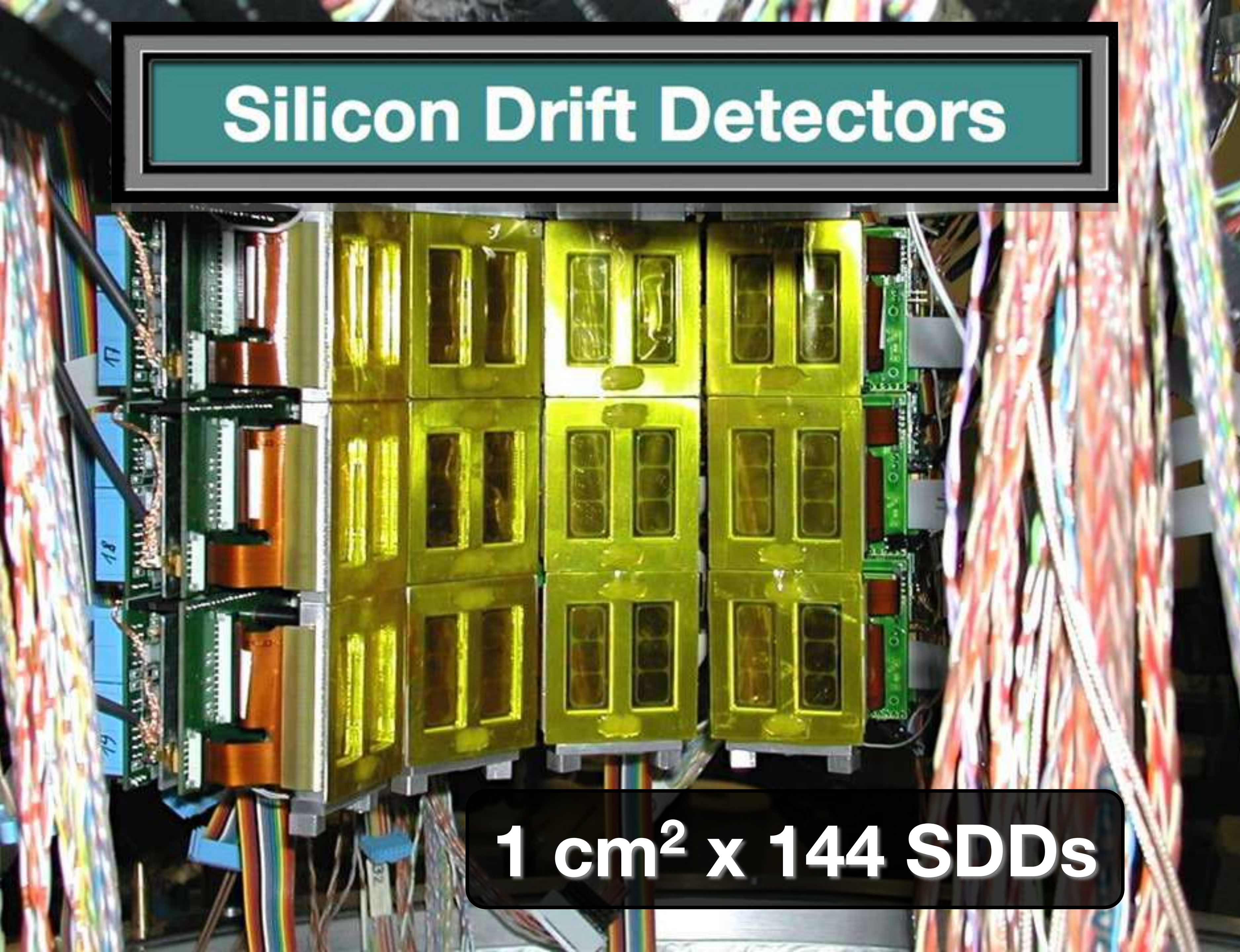
- LNF- INFN, Frascati, Italy
- SMI- ÖAW, Vienna, Austria
- IFIN – HH, Bucharest, Romania
- Politecnico, Milano, Italy
- MPE, Garching, Germany
- PNSensors, Munich, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada

EU Fundings: JRA10 – FP6 - I3H
FP7- I3HP2

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

The Cryogenic Target Cell

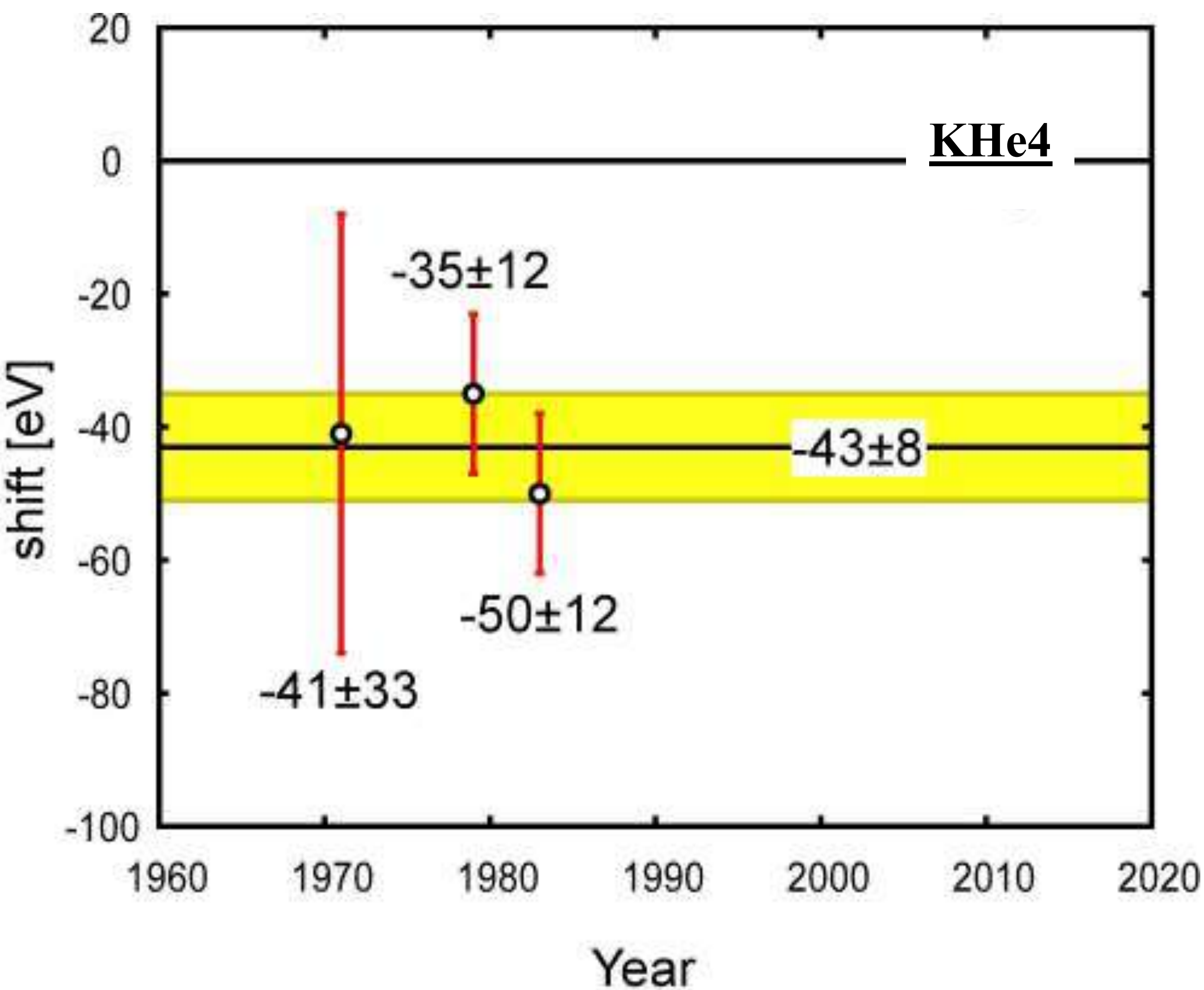
Silicon Drift Detectors



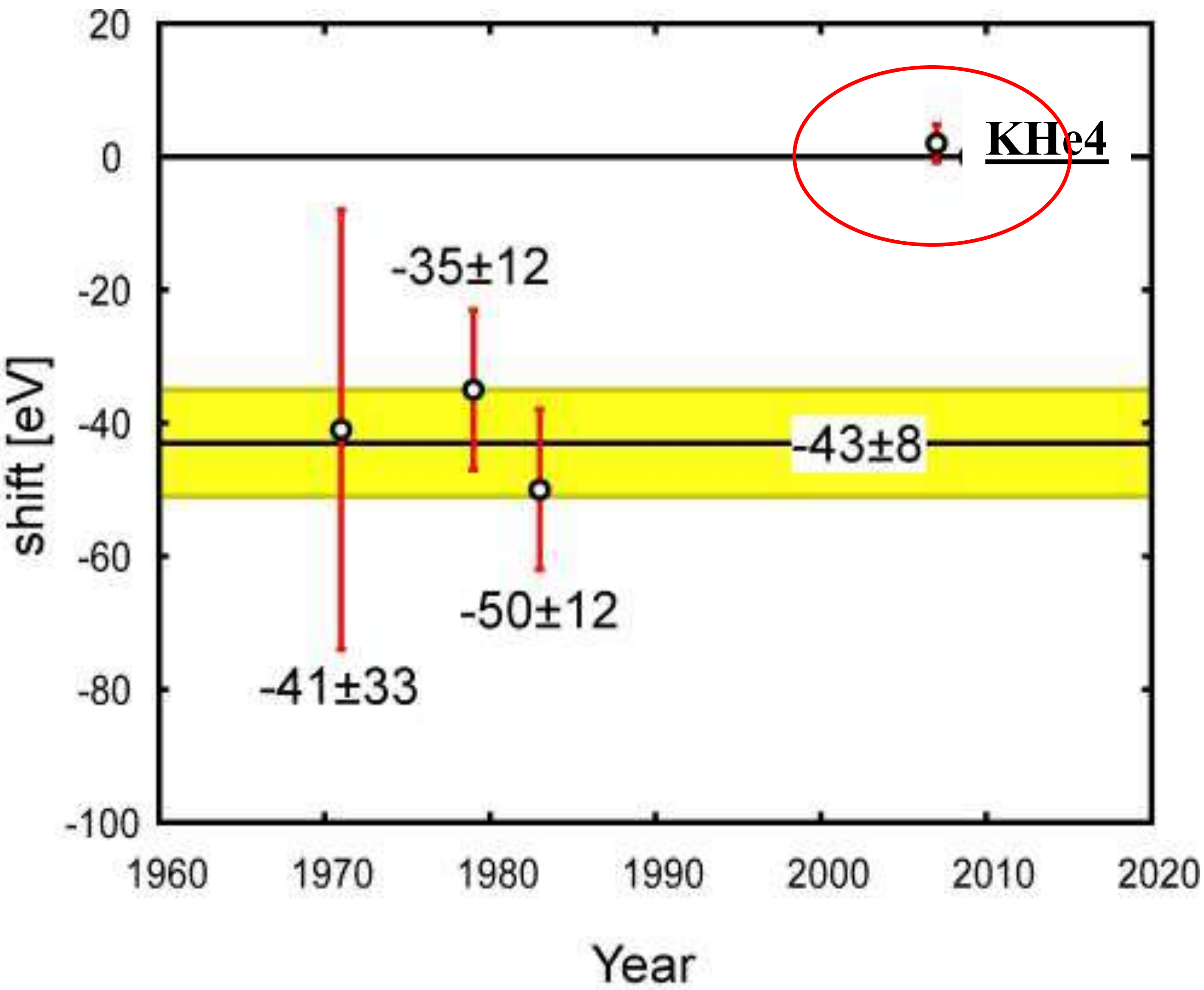
1 cm^2 x 144 SDDs

Kaonic helium (puzzle)

Kaonic 4 old data

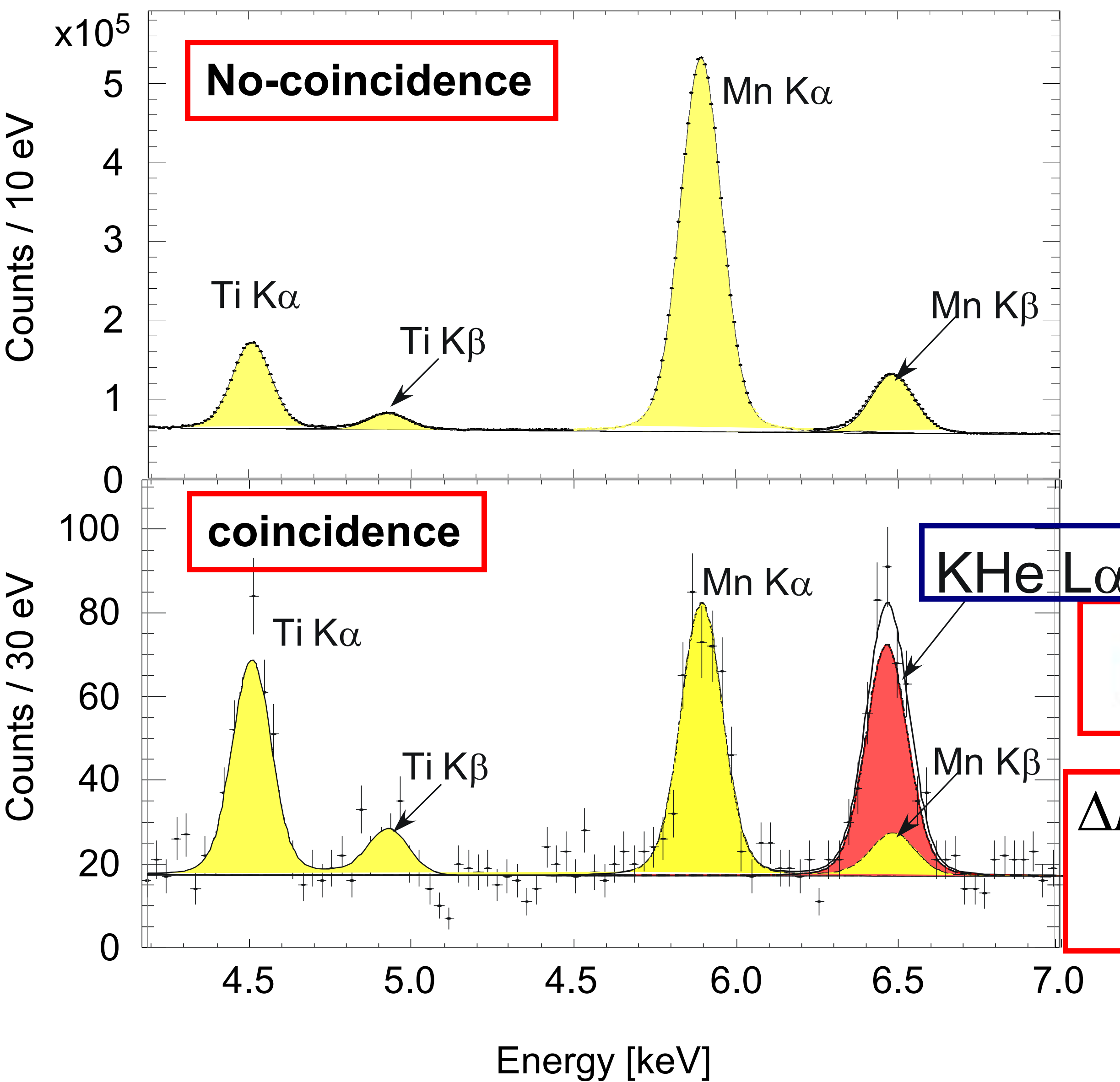


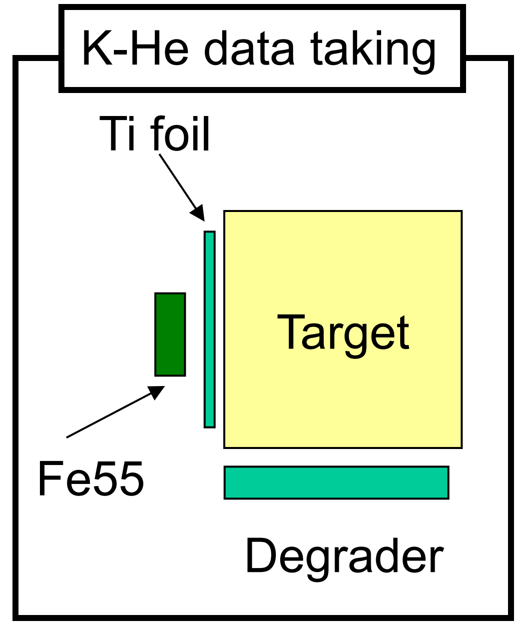
E570 solved the kaonic hydrogen puzzle



KHe-4 energy spectrum at SIDDHARTA

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

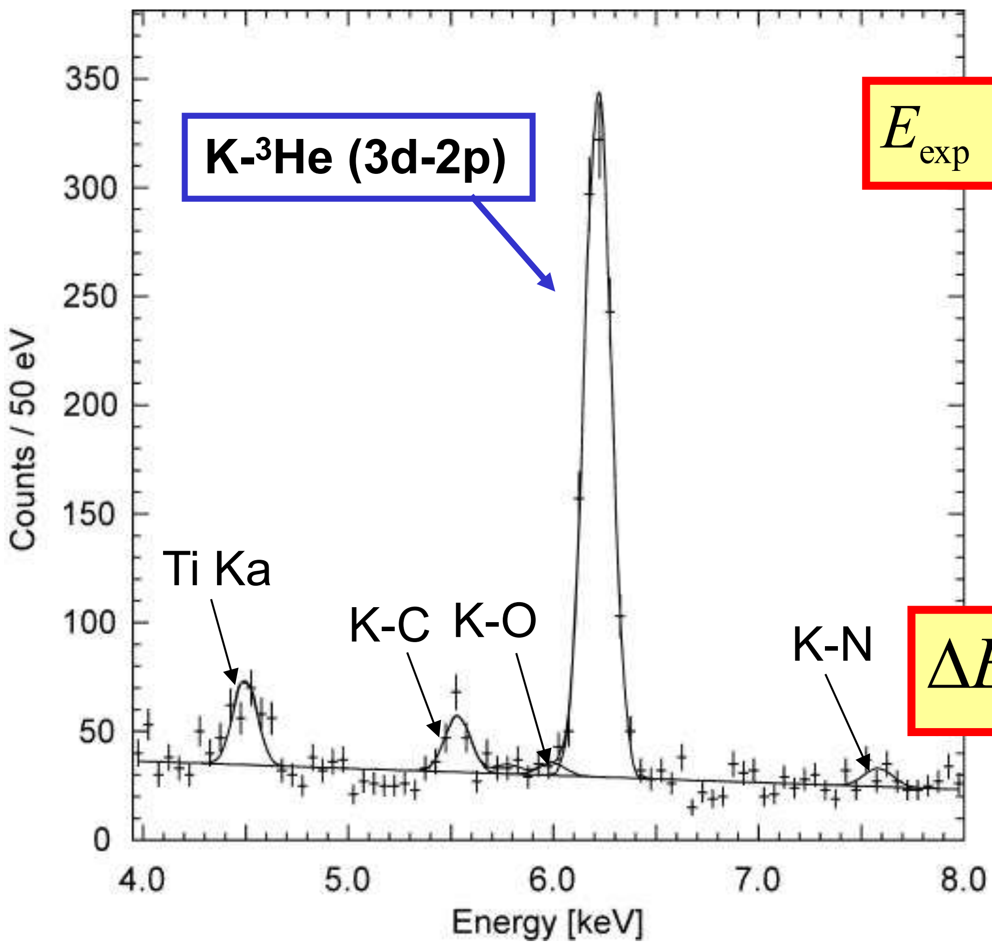




$$E_{\mathrm{exp}} = 6463.6 \pm 5.8 \text{ eV},$$

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

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

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

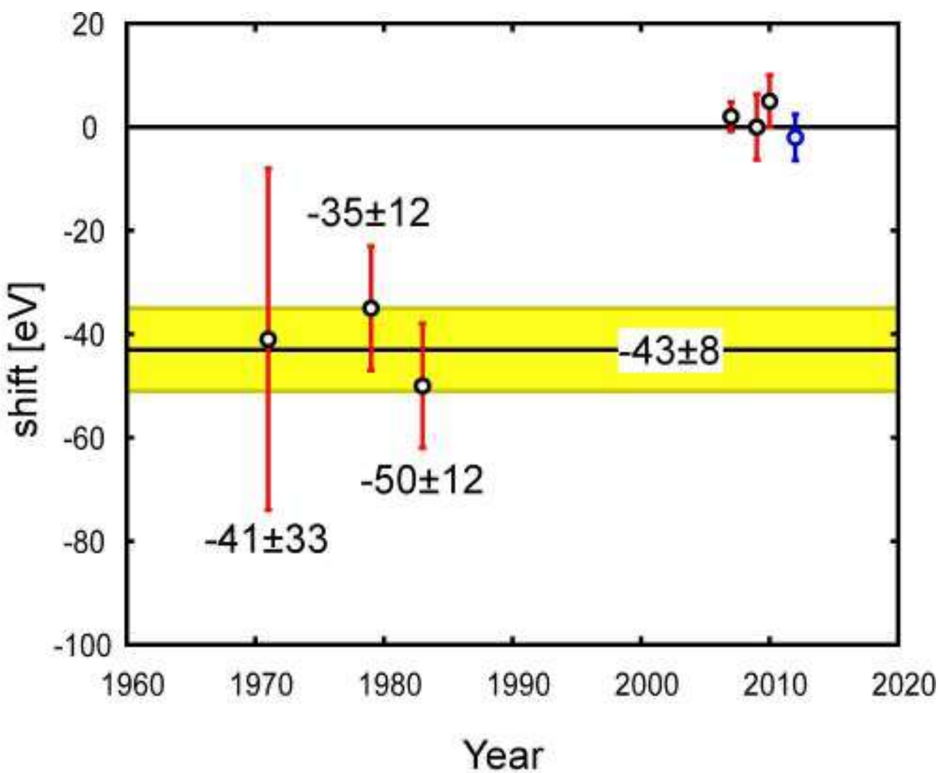
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

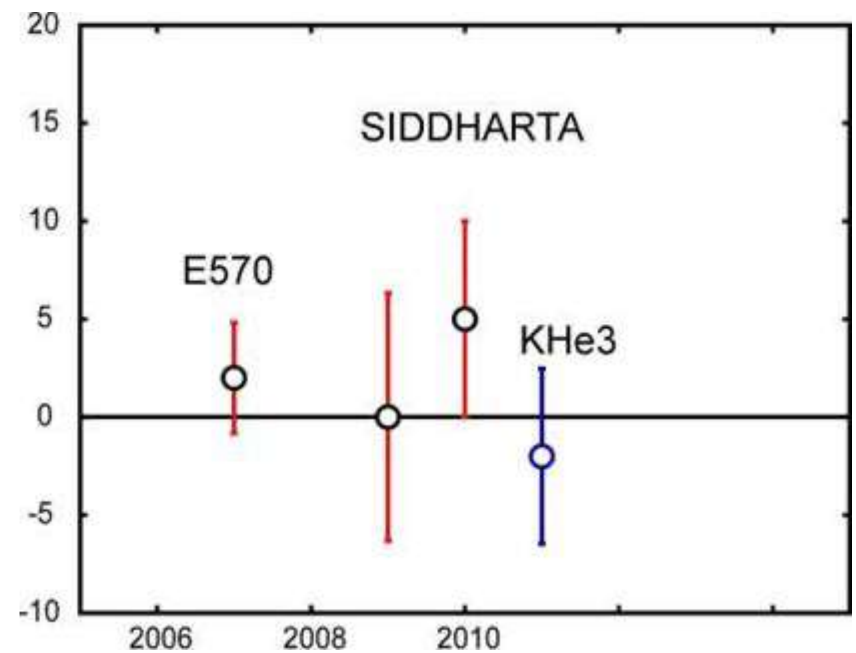
World First !
Observation of K-^{3}He X-rays
Determination of
strong-interaction shift

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

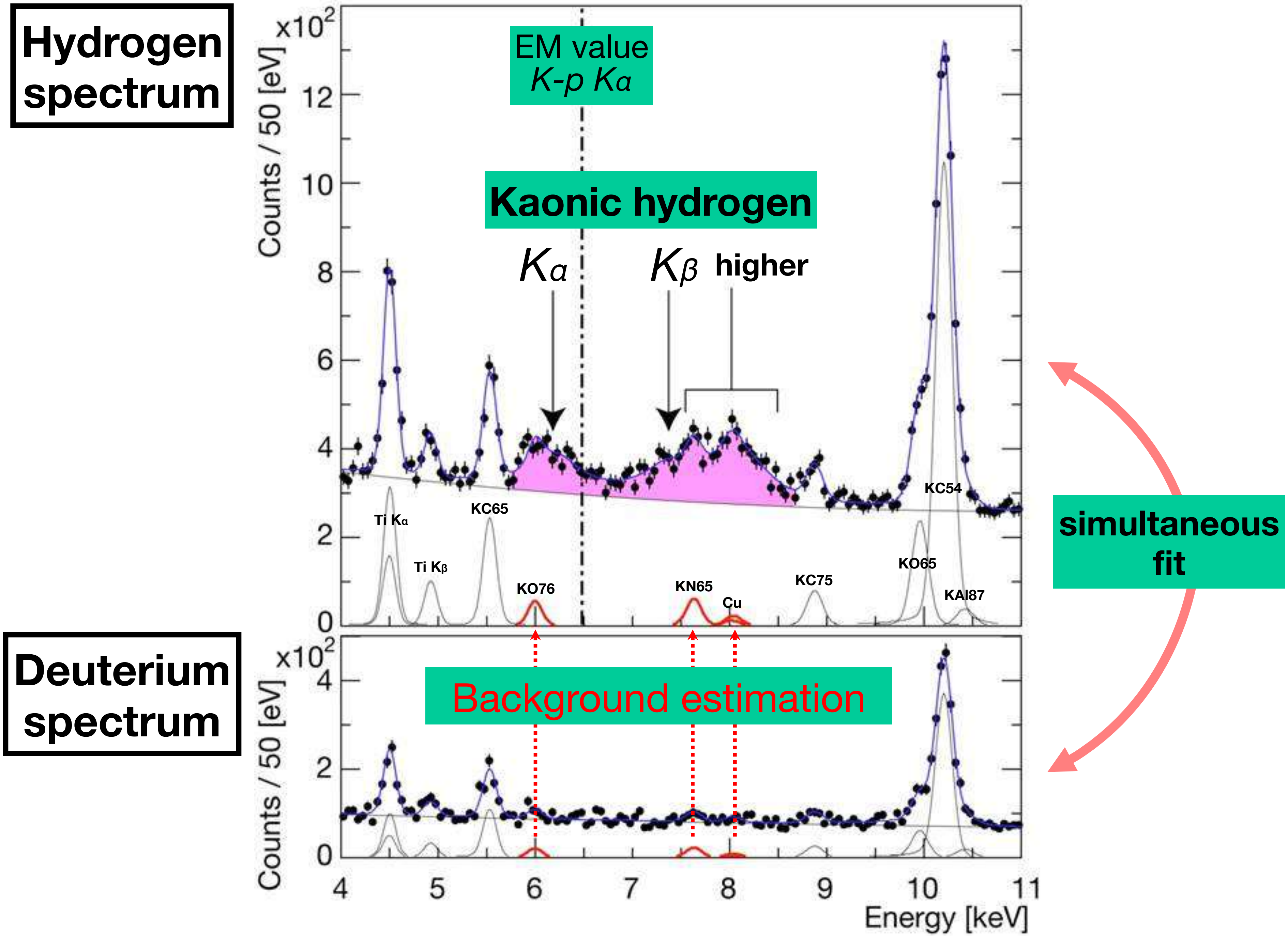
Comparison of results

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

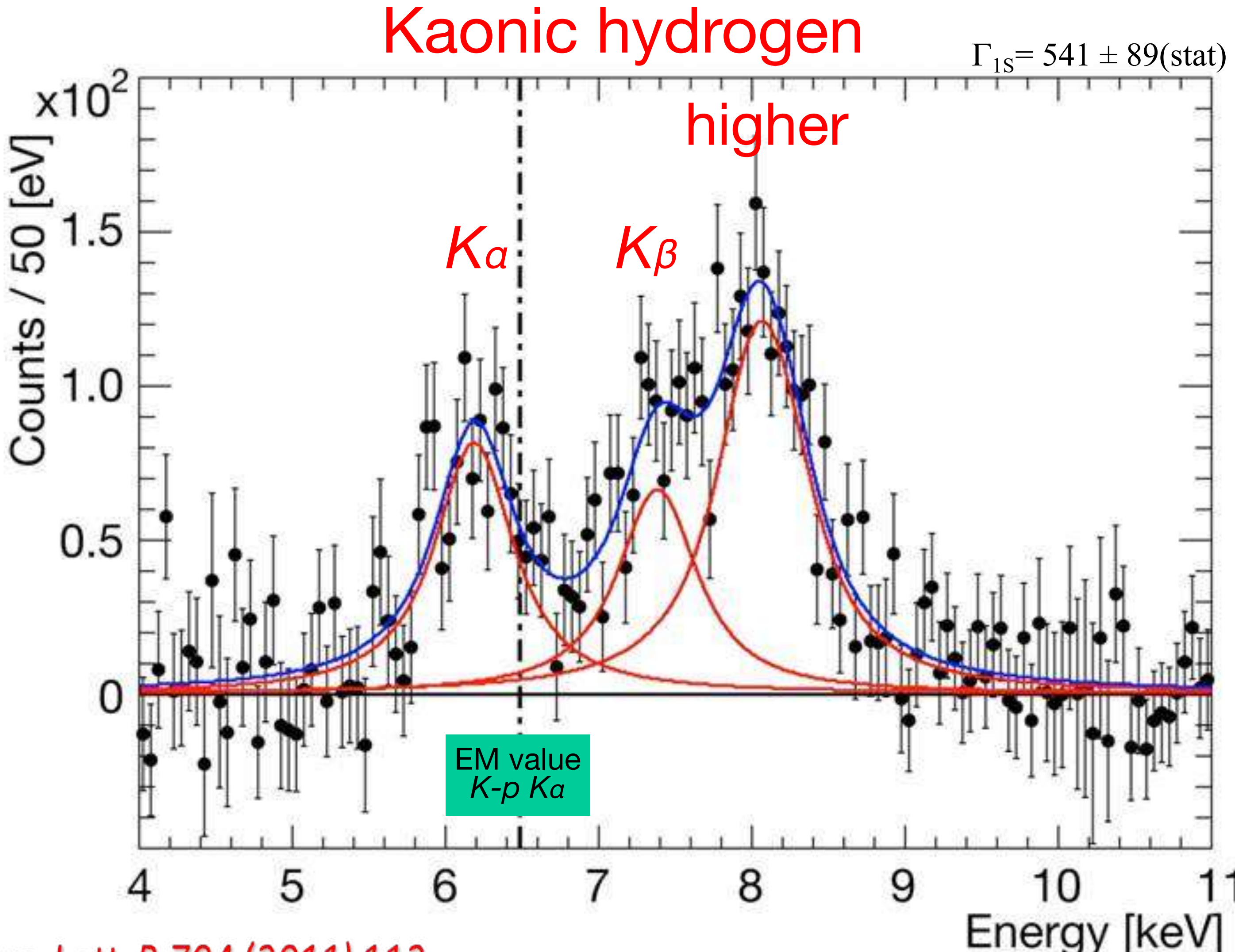


Hydrogen spectrum
Deuterium spectrum
x10²
Counts / 50 [eV]
EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ
higher
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87
simultaneous fit
Background estimation
Energy [keV]
0
2
4
6
8
10
12
5
7
9
11

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

SIDDHARTA-2 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

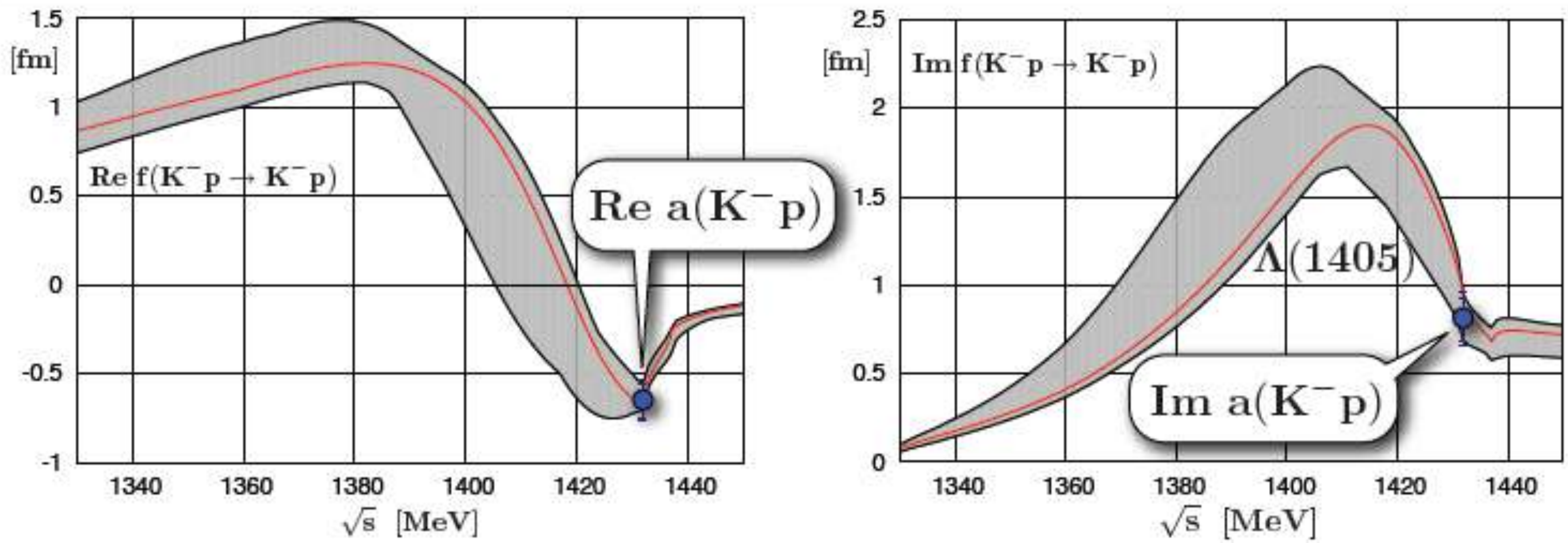
K^-p SCATTERING AMPLITUDE from CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

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

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

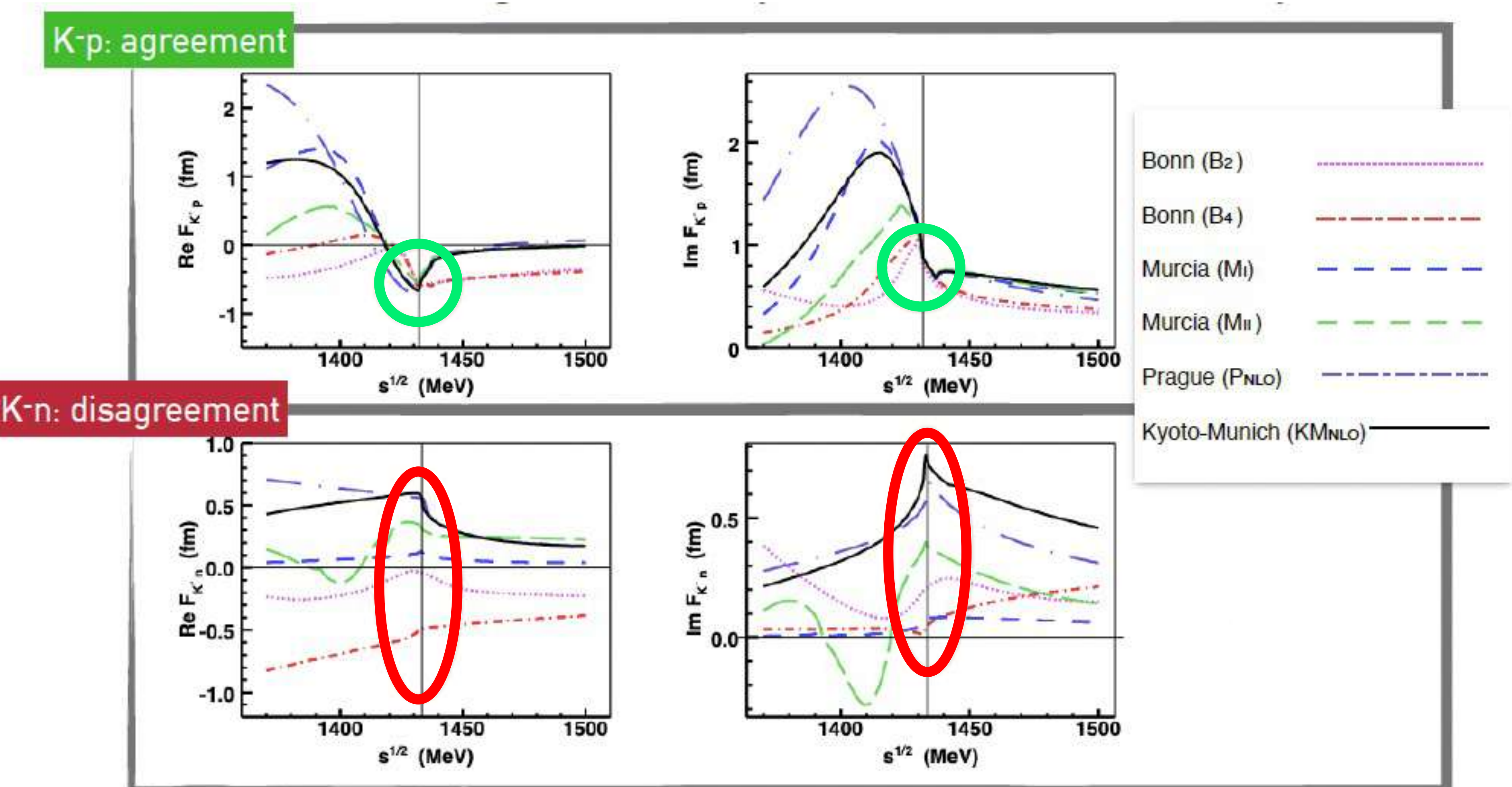


Complex scattering length (including Coulomb corrections)

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

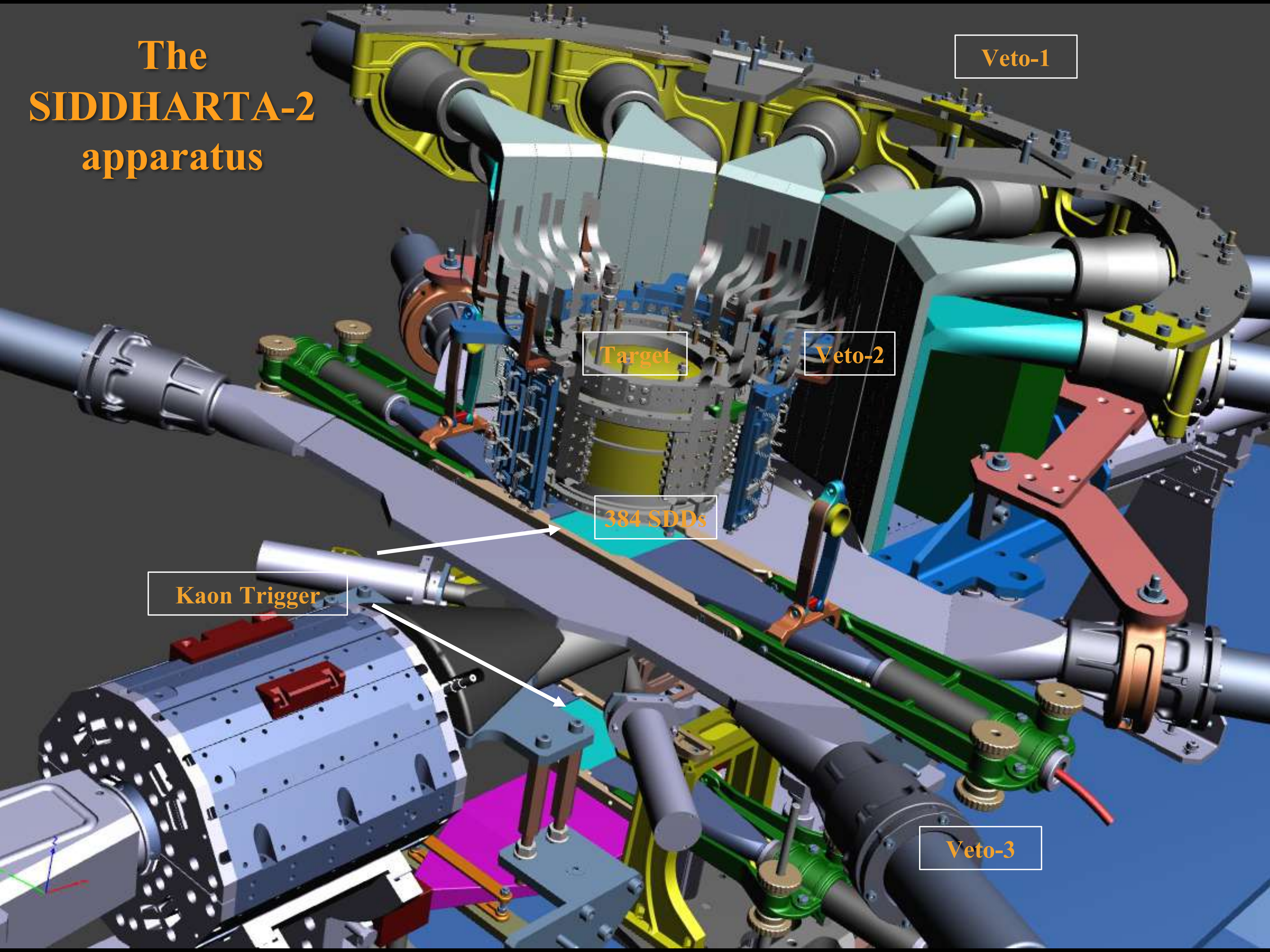
$$\mathrm{Im}\, a(K^-p) = 0.81 \pm 0.15 \;\; \mathrm{fm}$$

Kaonic atoms – scattering amplitudes

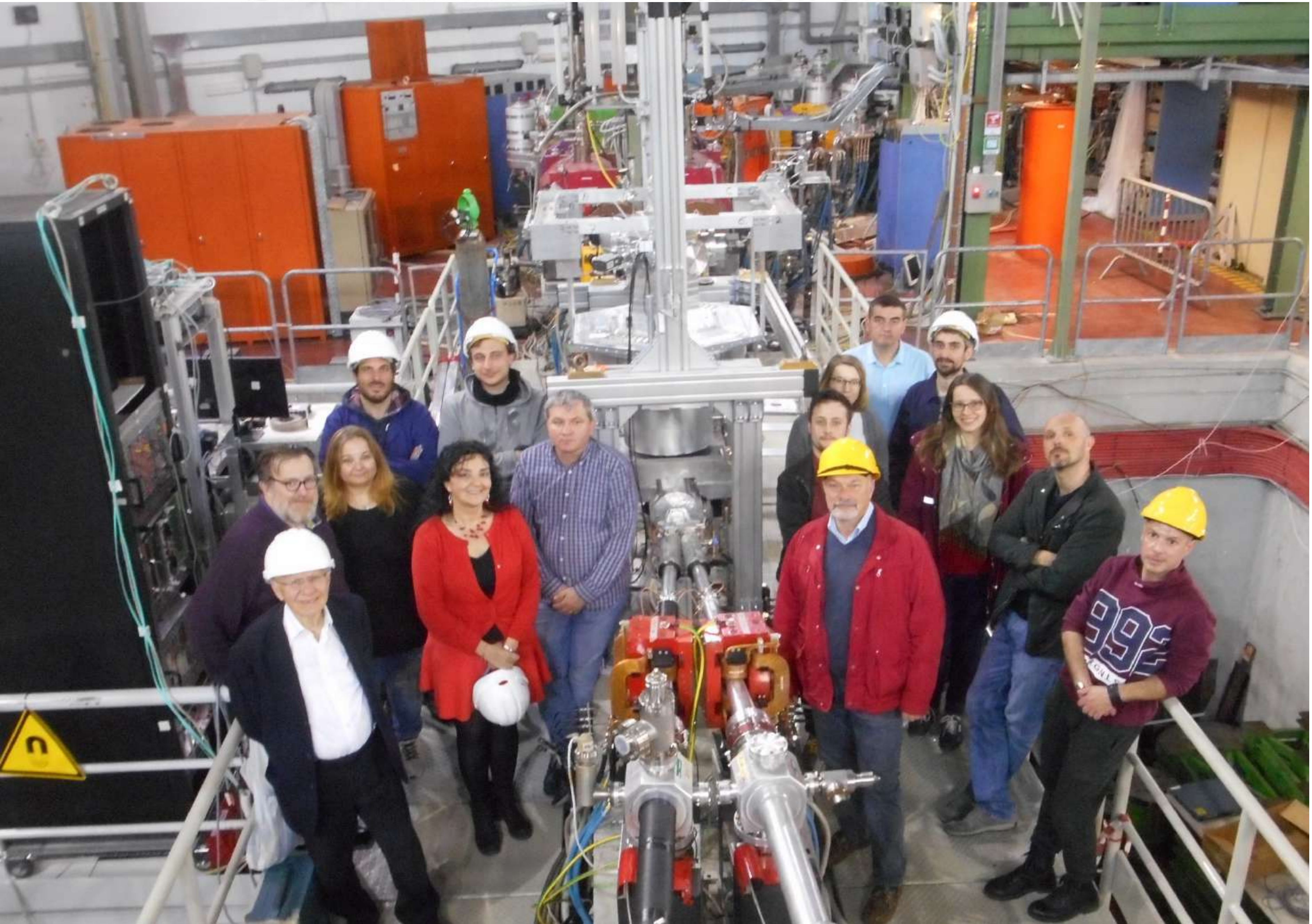


A. Ciepl$\acute{y}$, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

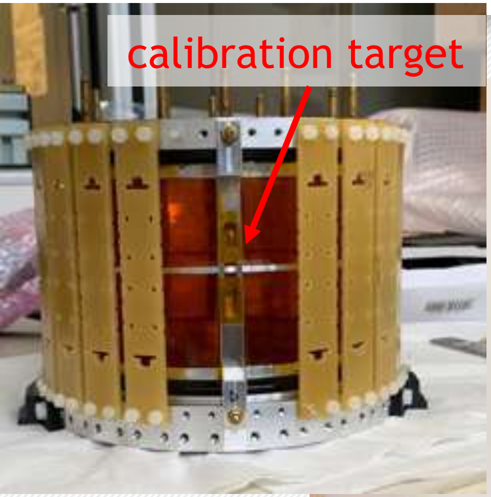
The SIDDHARTA-2 apparatus



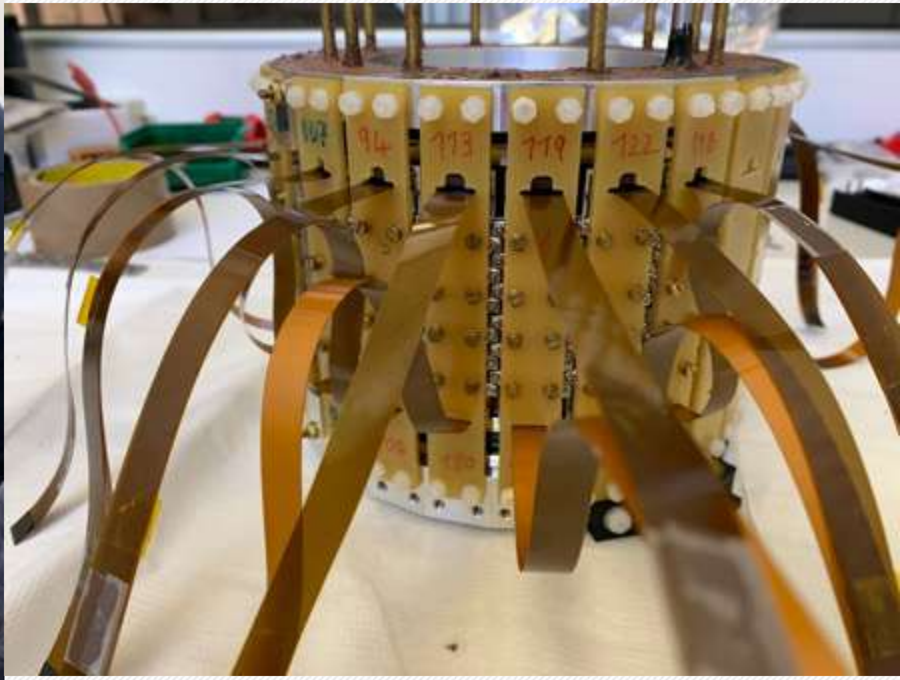
SIDDHARTA-2 installed on DAFNE

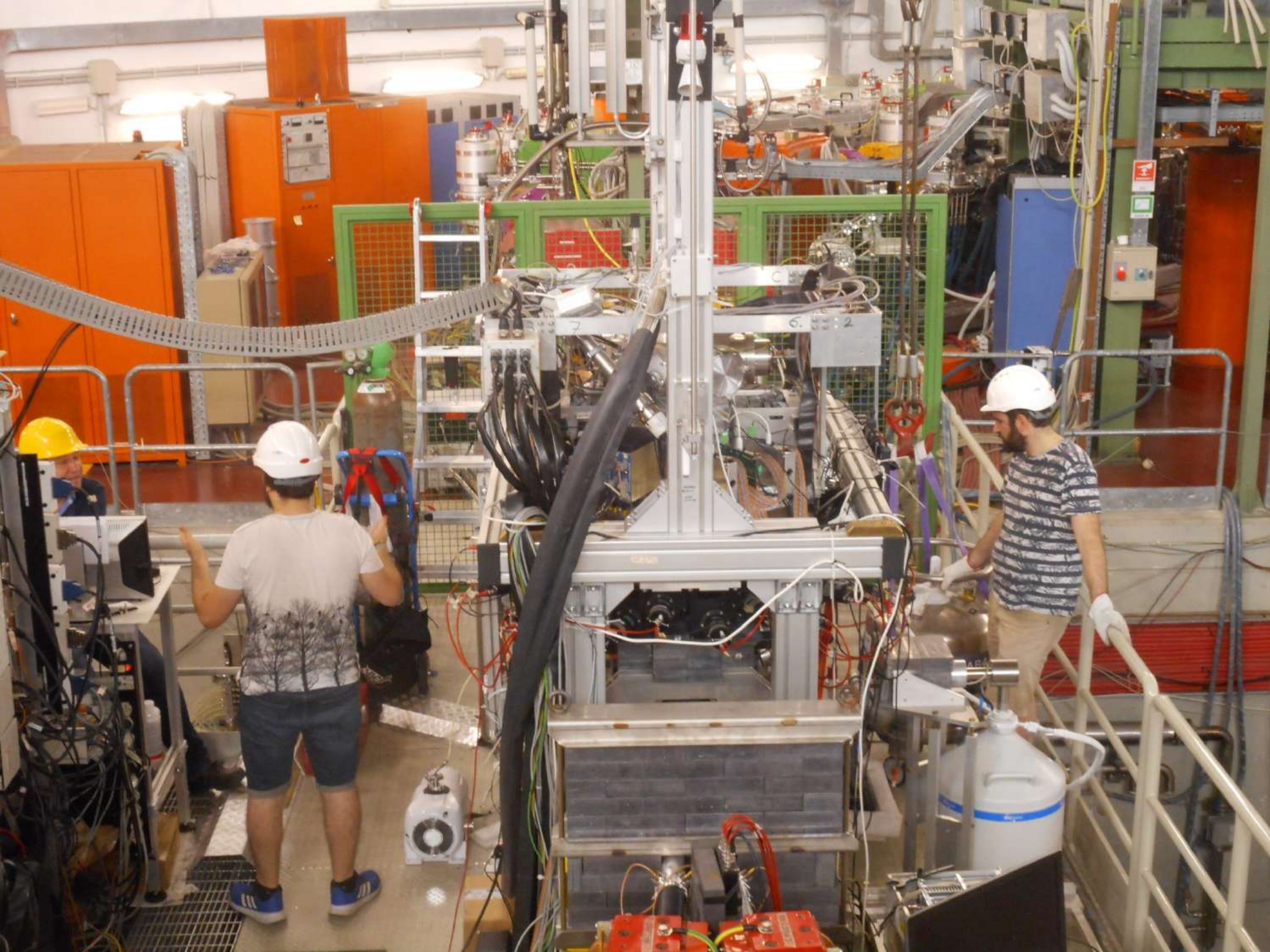


SDD installation



SDD installed around the target



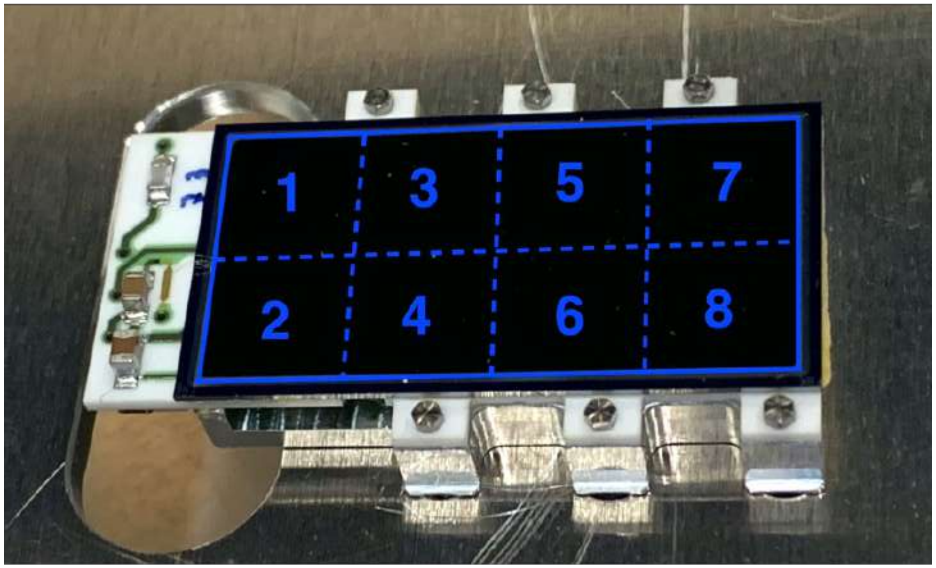


Silicon Drift Detectors

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

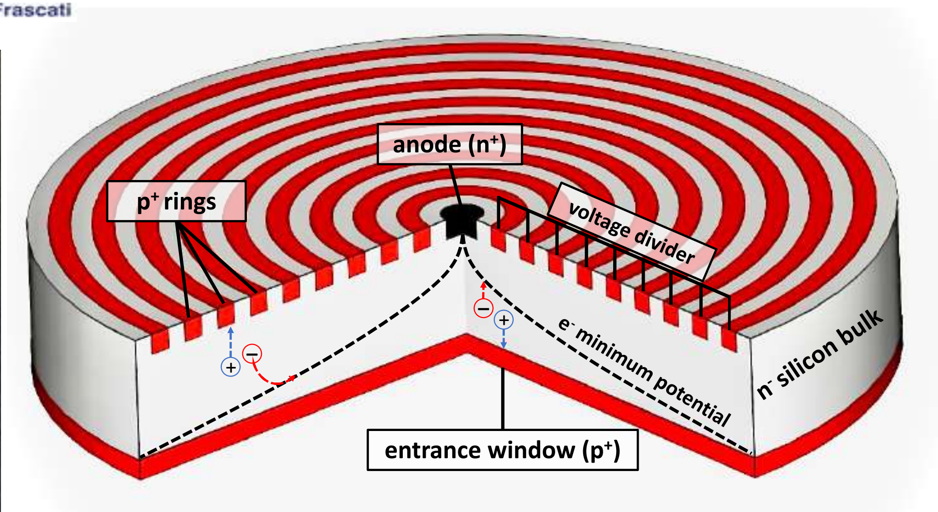
POLITECNICO MILANO 1863

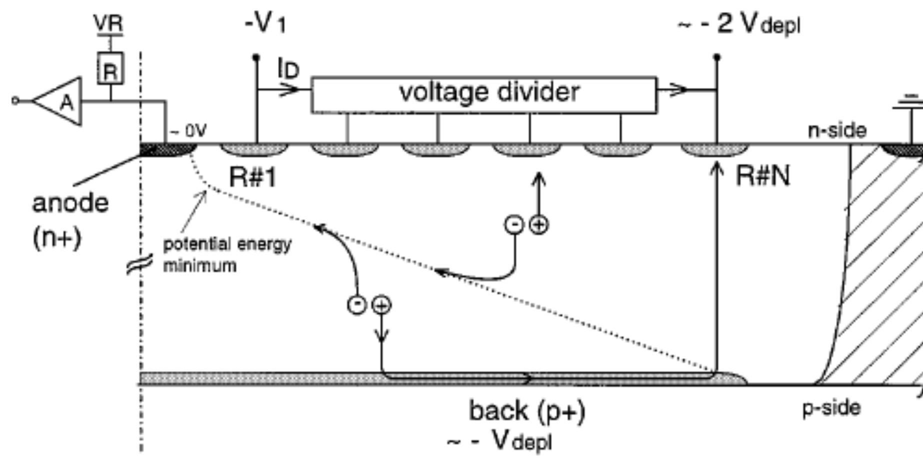
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



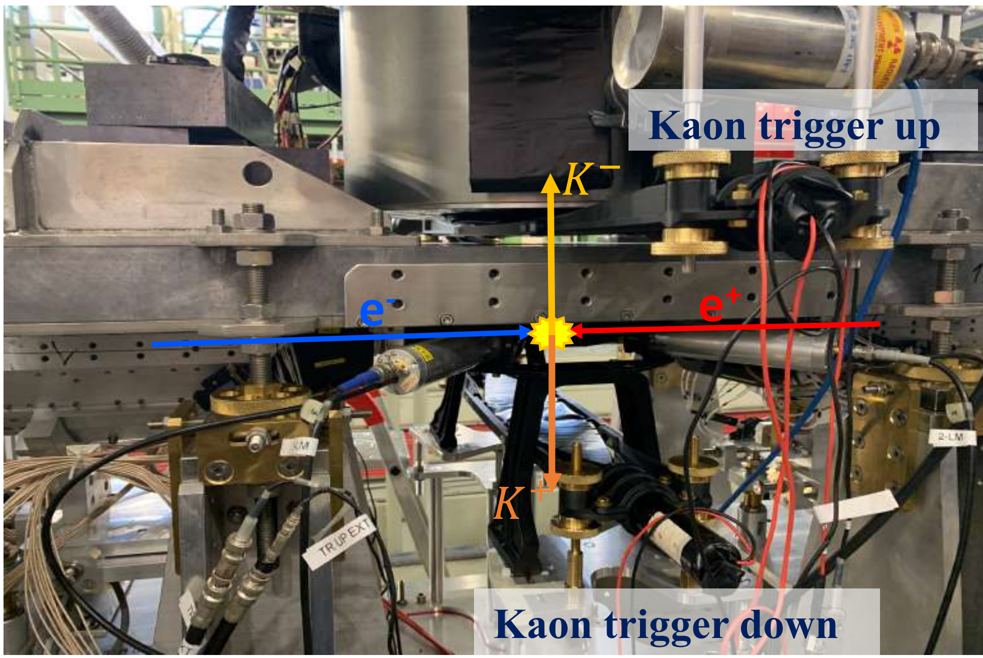
8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of 450 μm which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

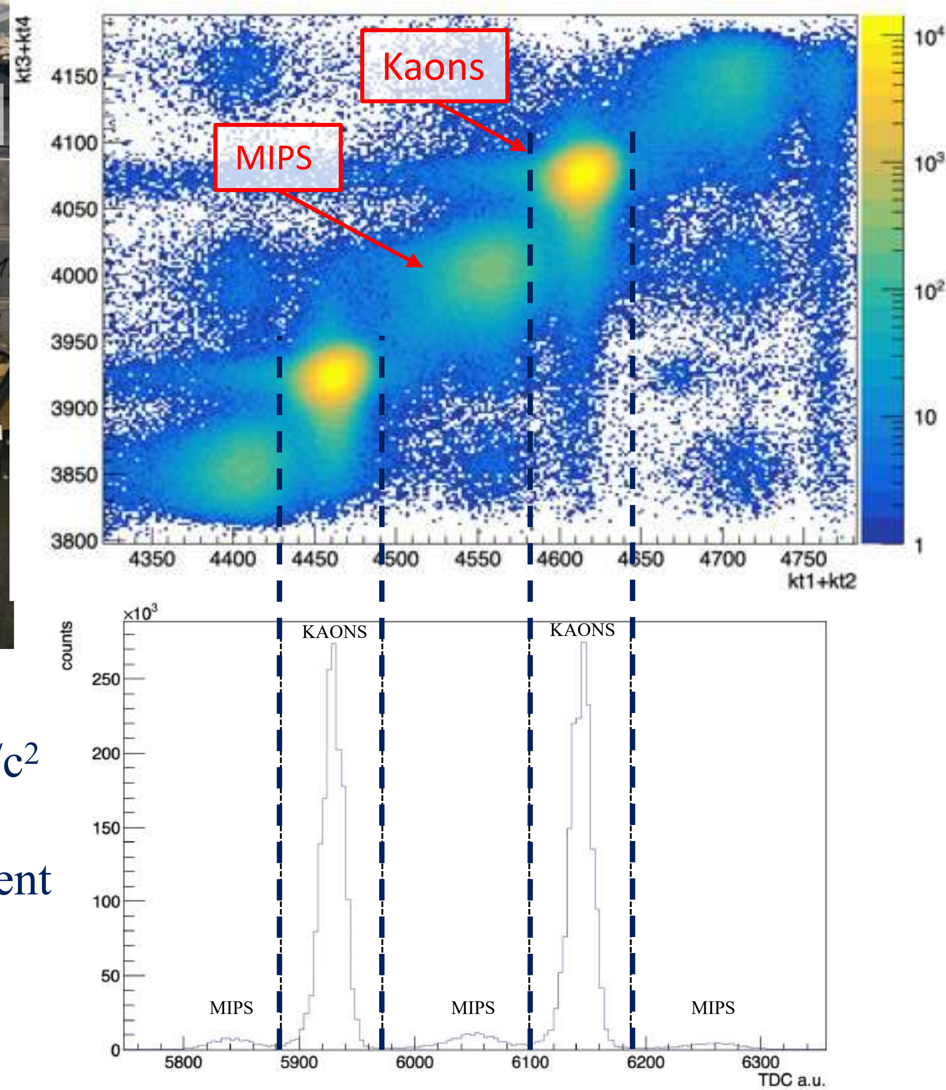
SDD cross section





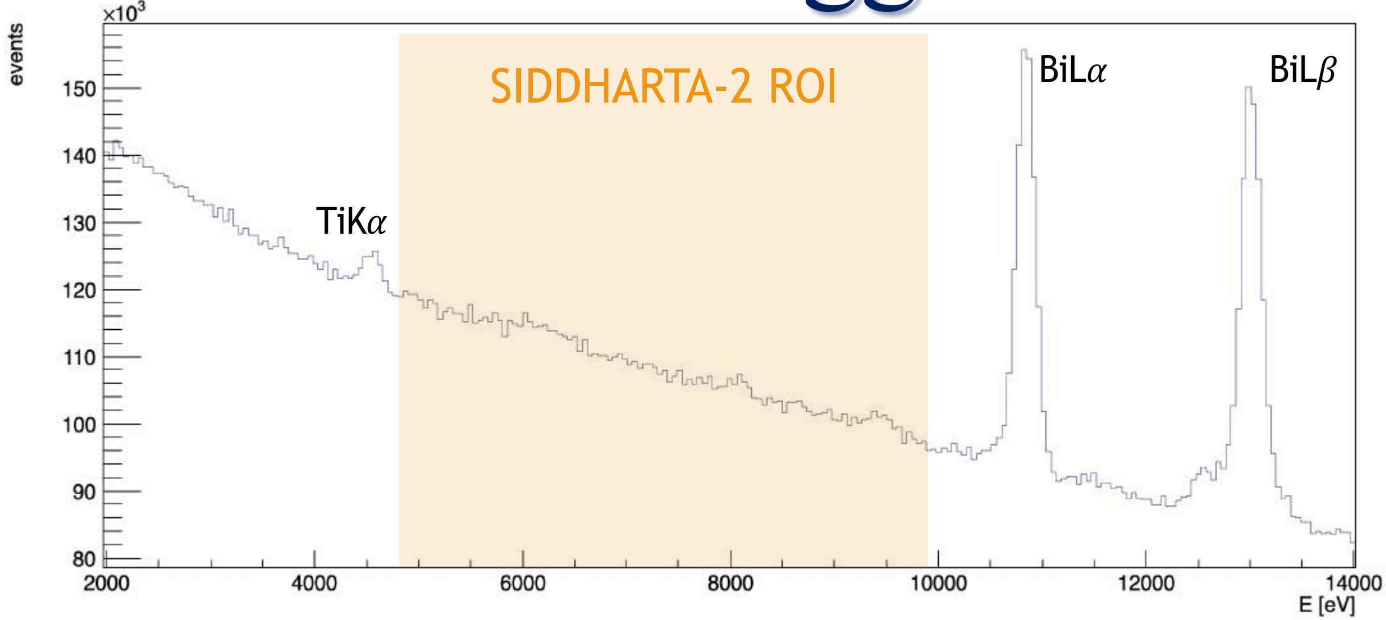
Kaon Trigger





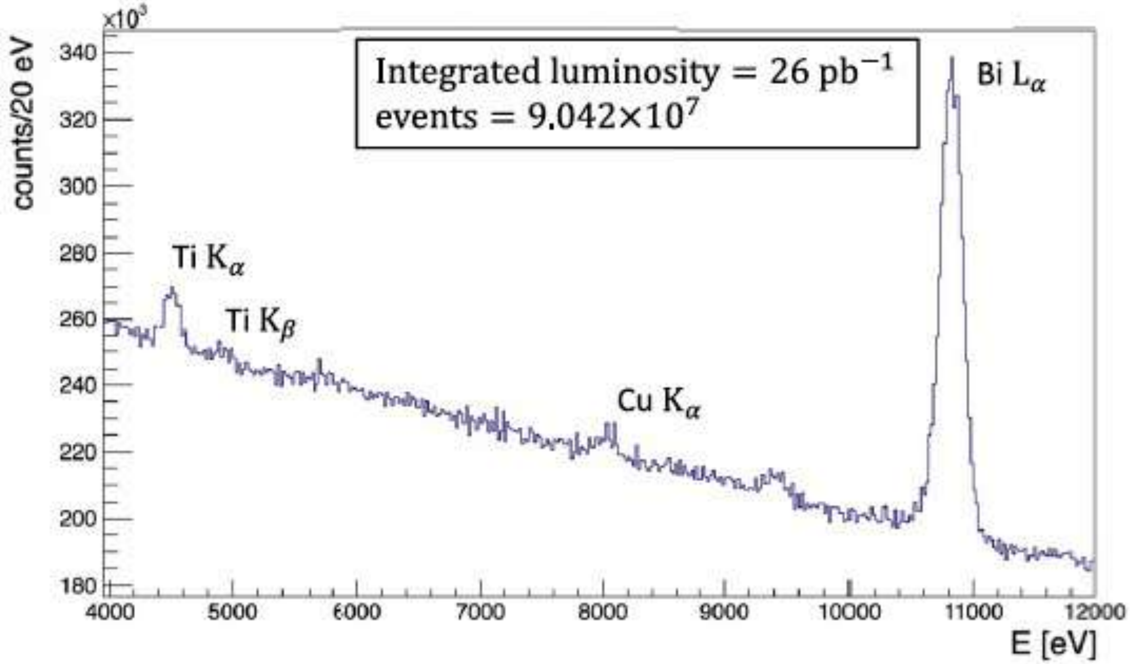
The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

Kaon Trigger

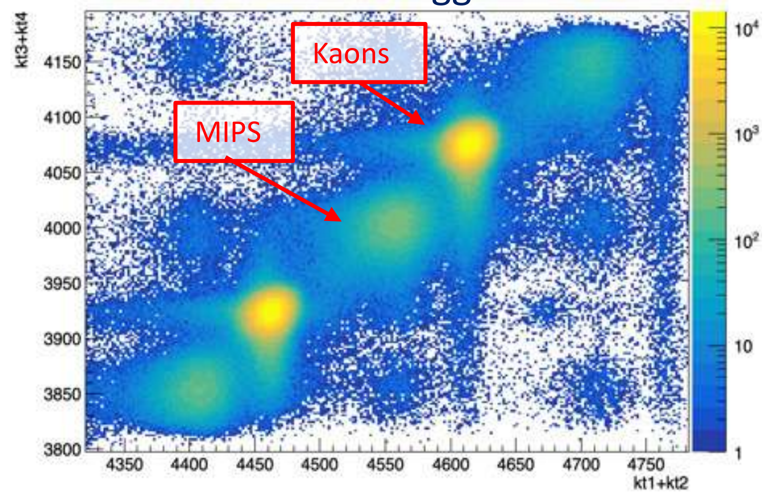


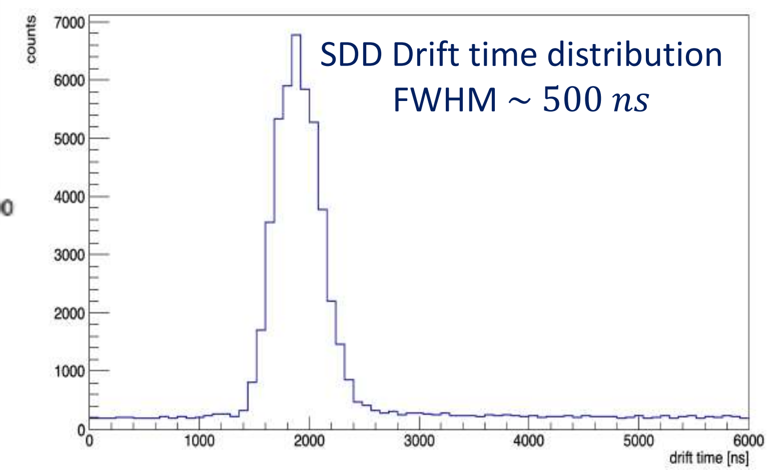
Kaonic ^{4}He 3d → 2p measurement

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

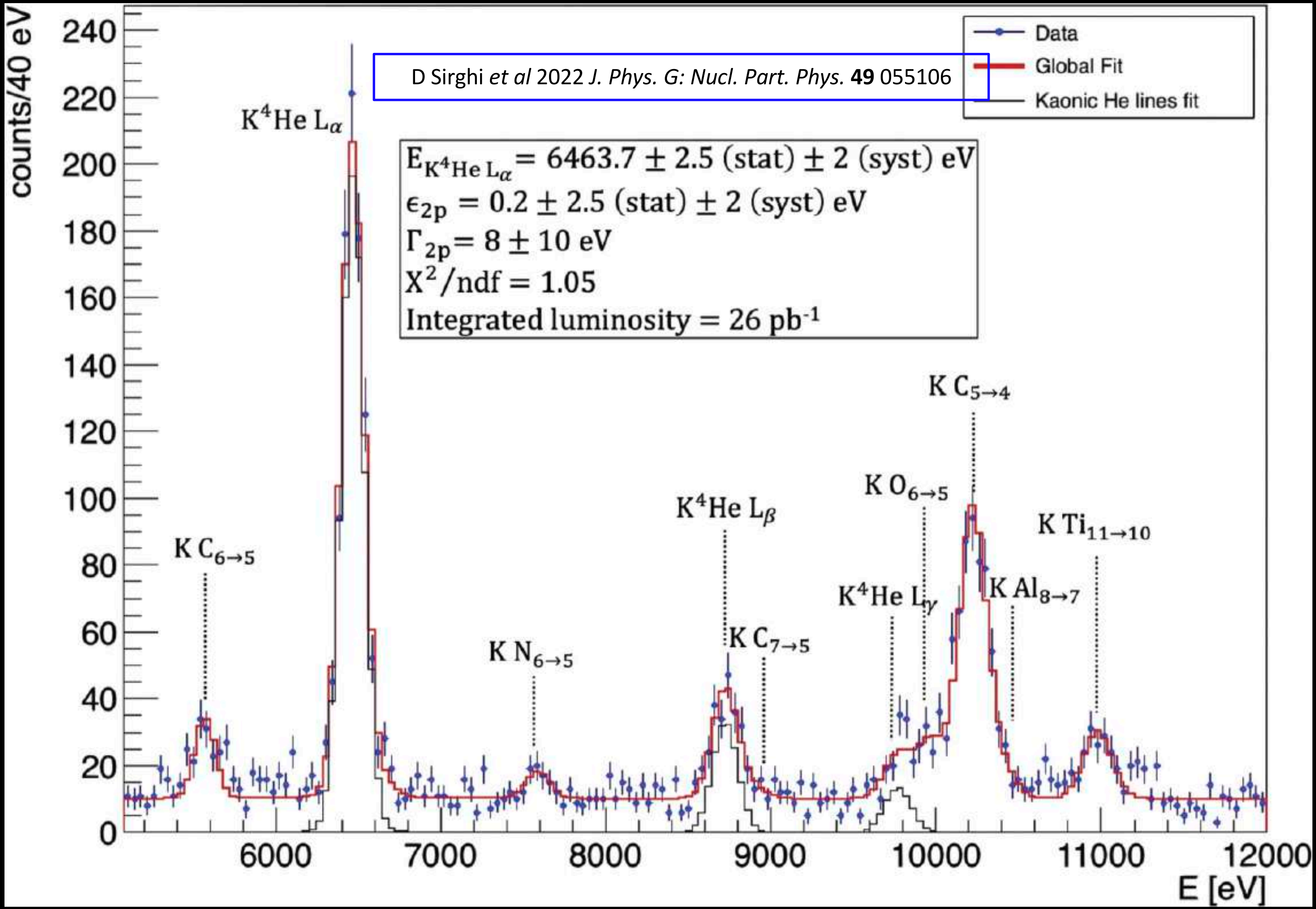


Kaon Trigger

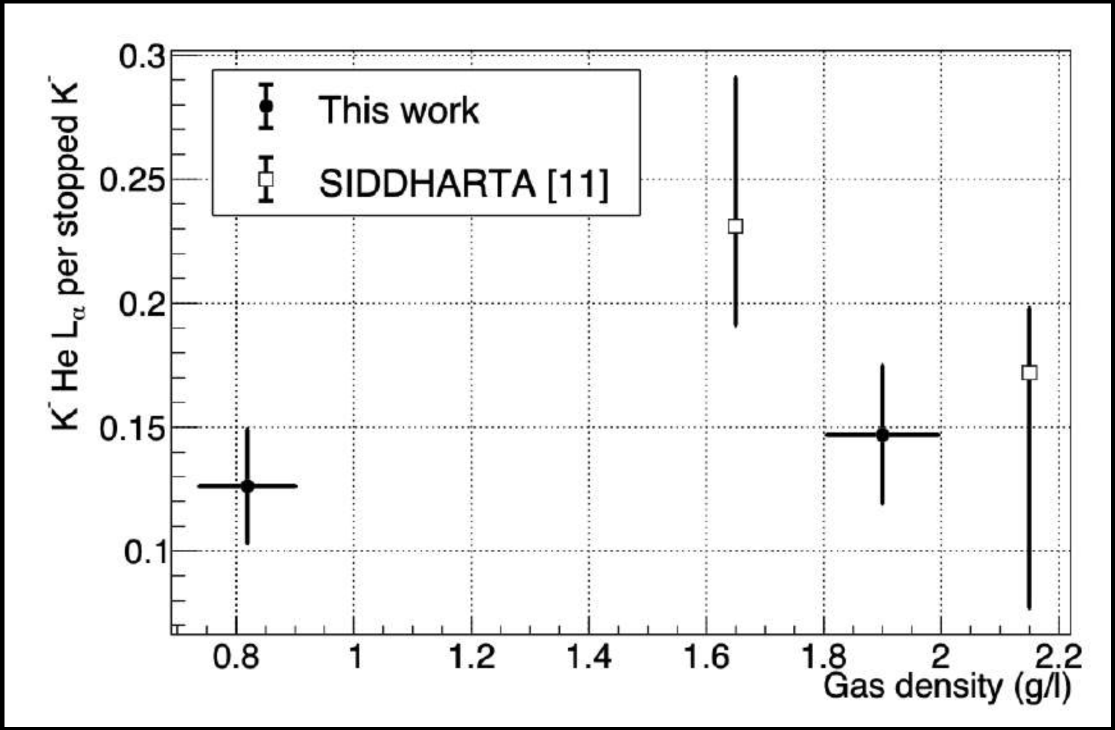




SIDDHARTINO (2021)



SIDDHARTINO (2021)



K-^{4}HE LOW DENSITY RUN: 0.75% LIQUID HELIUM DENSITY -> **YIELDS AT LOWEST MEASURED DENSITY**

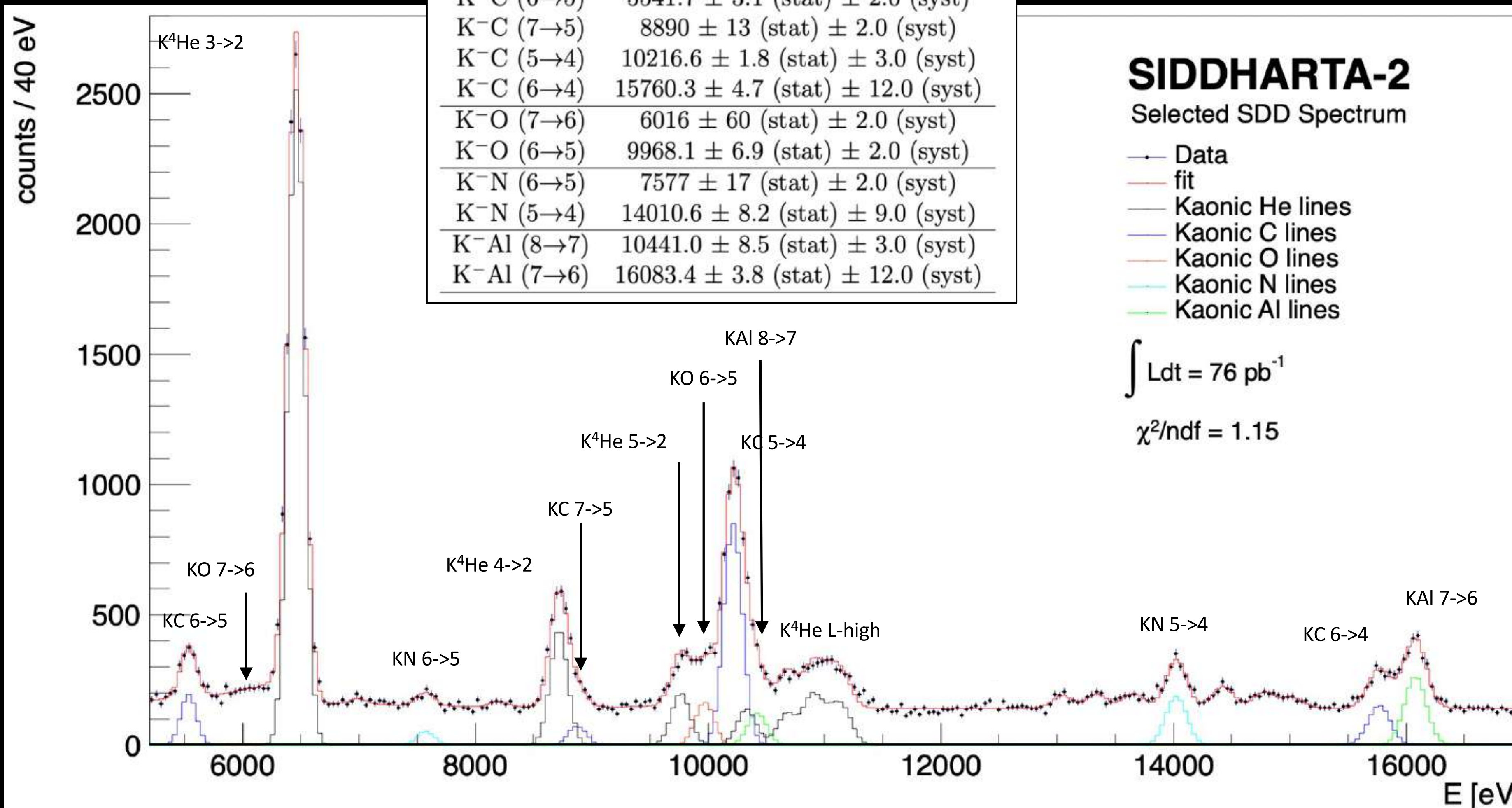
Density	1.90 g/l	0.82 g/l
L_α yield	0.148 ± 0.027	0.126 ± 0.023
L_β/L_α	0.193 ± 0.042	0.133 ± 0.037
L_γ/L_α	0.035 ± 0.015	not detected

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

SIDDHARTA-2 (2022)

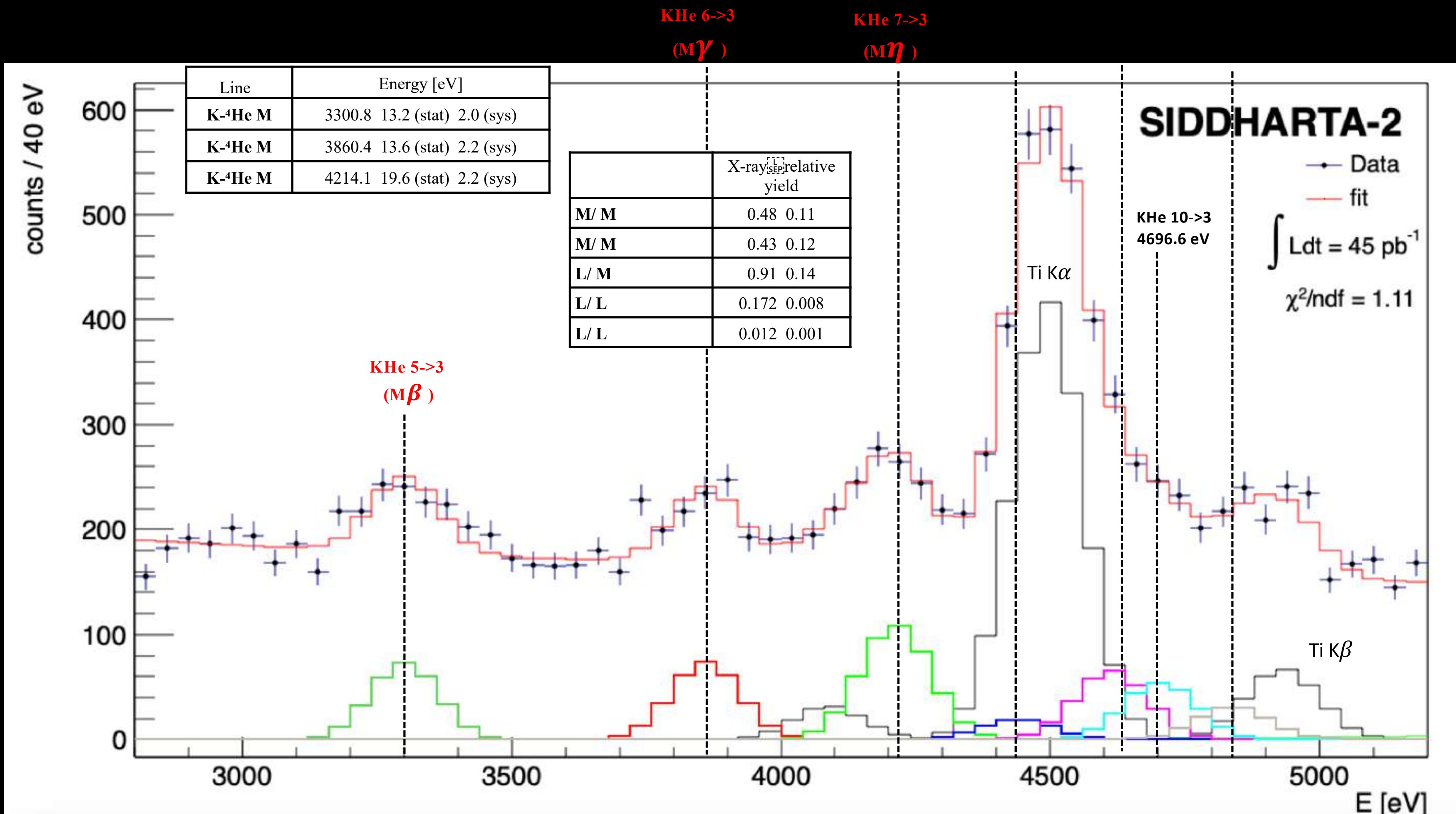
Measurements of high-n transitions in intermediate mass kaonic atoms

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)



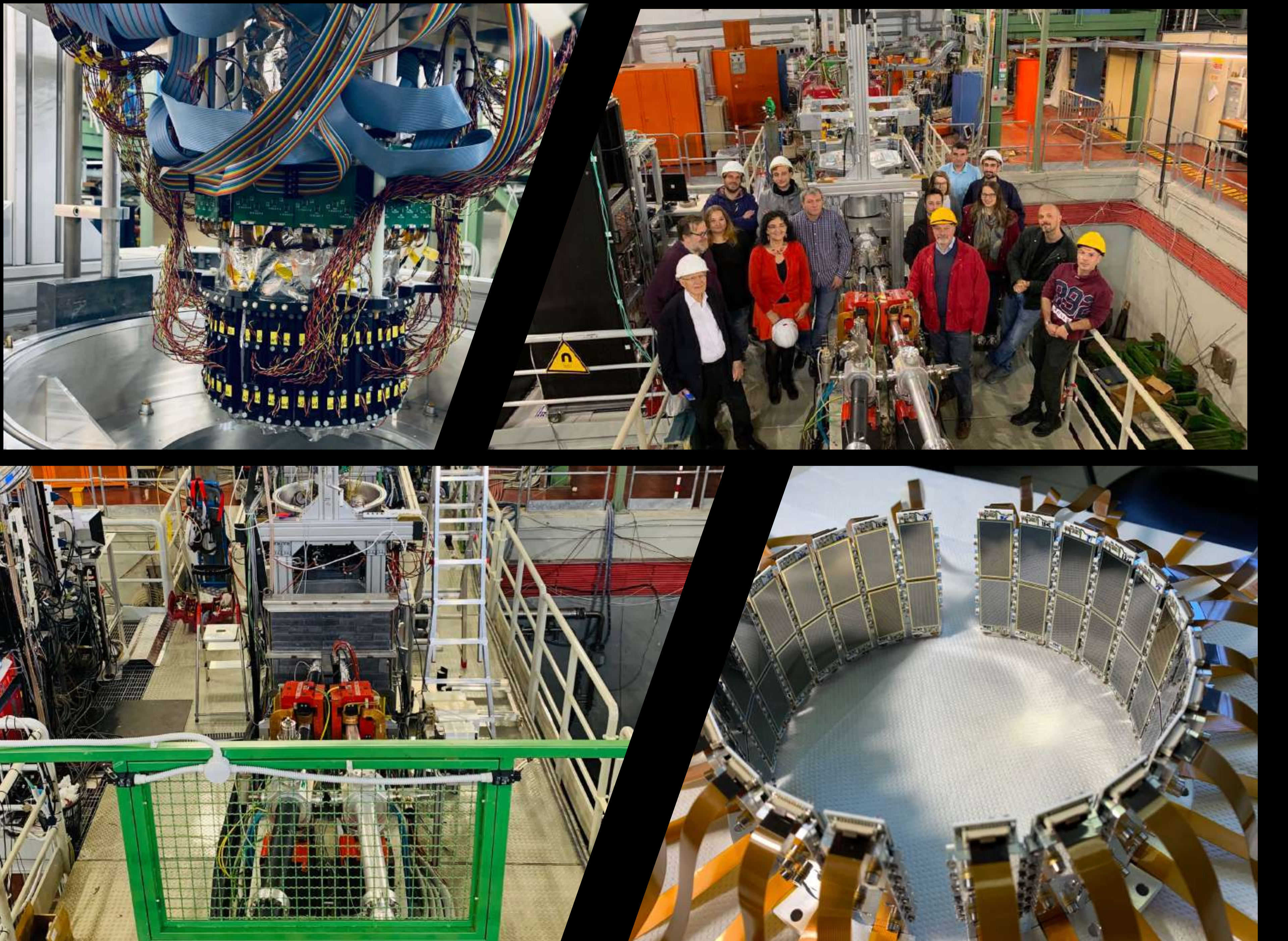
Sgaramella, F., *al. Eur. Phys. J. A* **59**, 56 (2023)

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

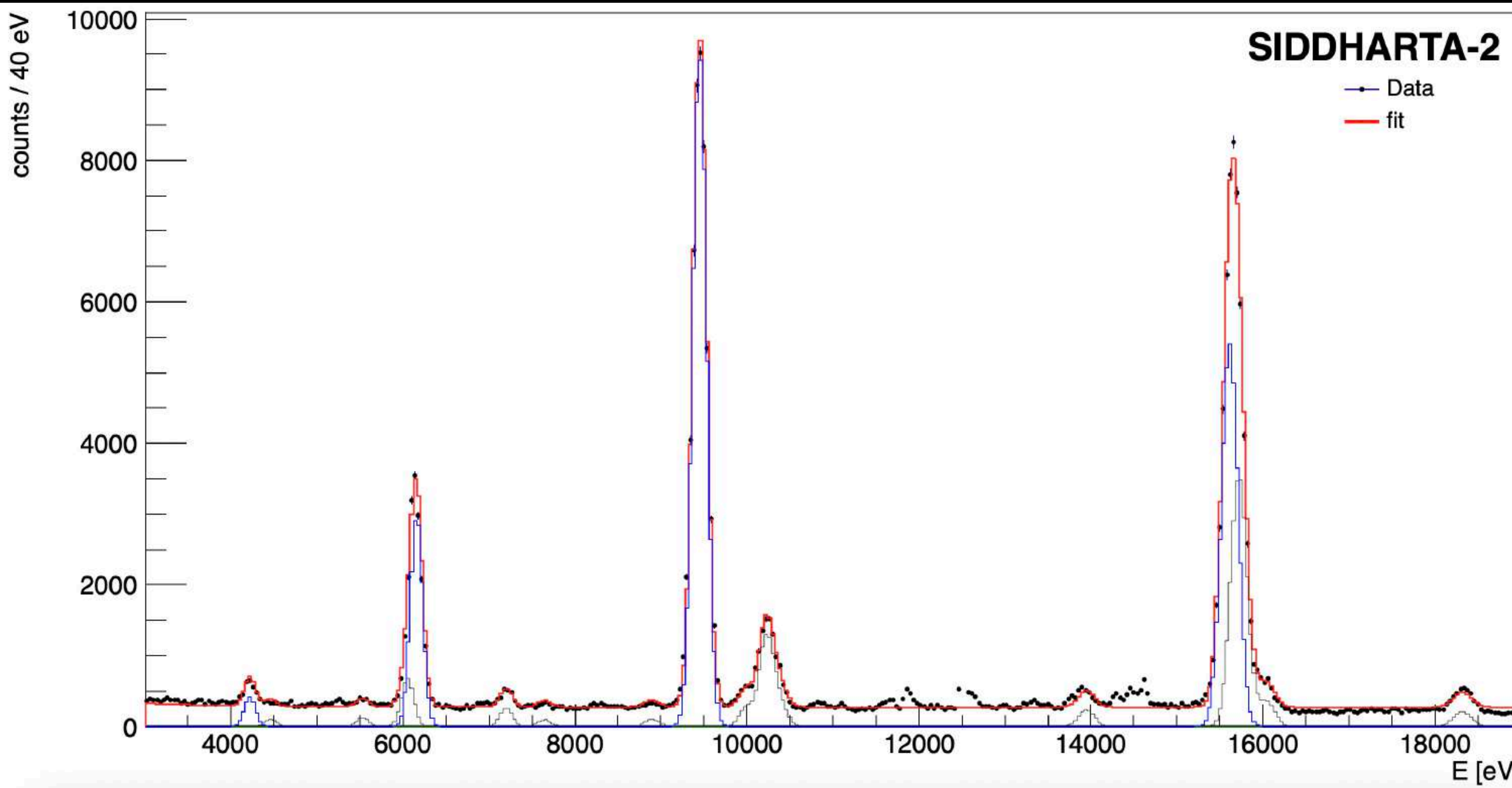


Line	Energy [eV]
K-⁴He M	3300.8 13.2 (stat) 2.0 (sys)
K-⁴He M	3860.4 13.6 (stat) 2.2 (sys)
K-⁴He M	4214.1 19.6 (stat) 2.2 (sys)

	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

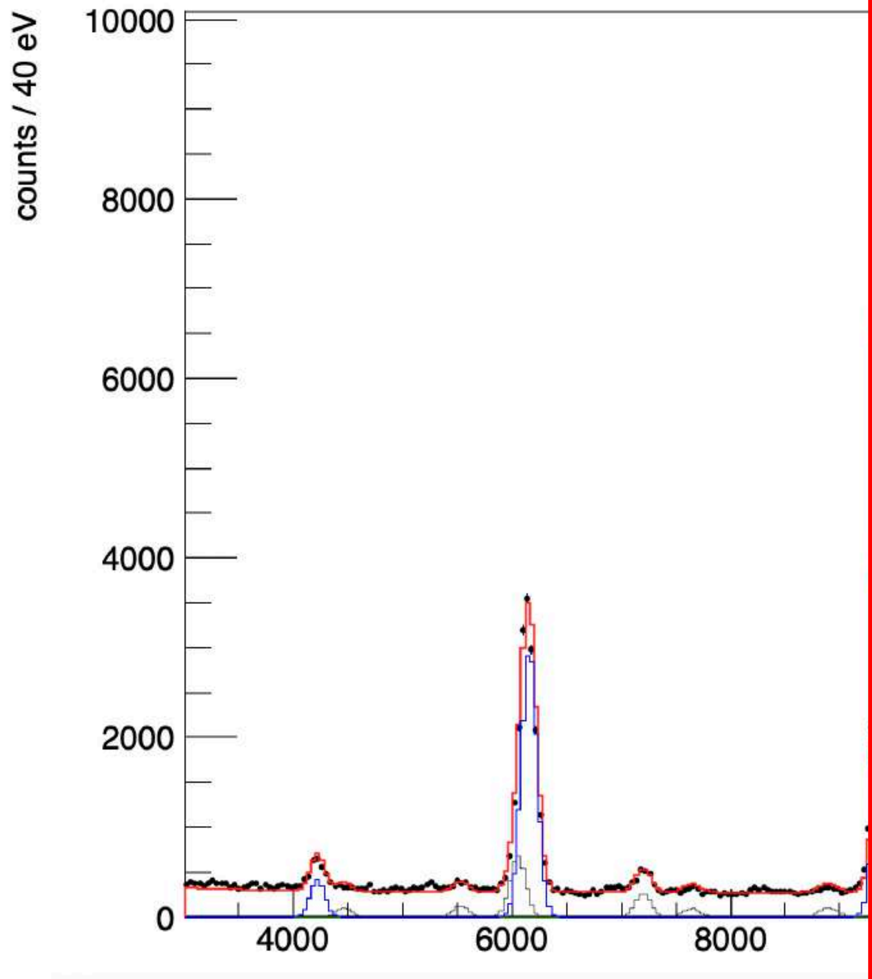


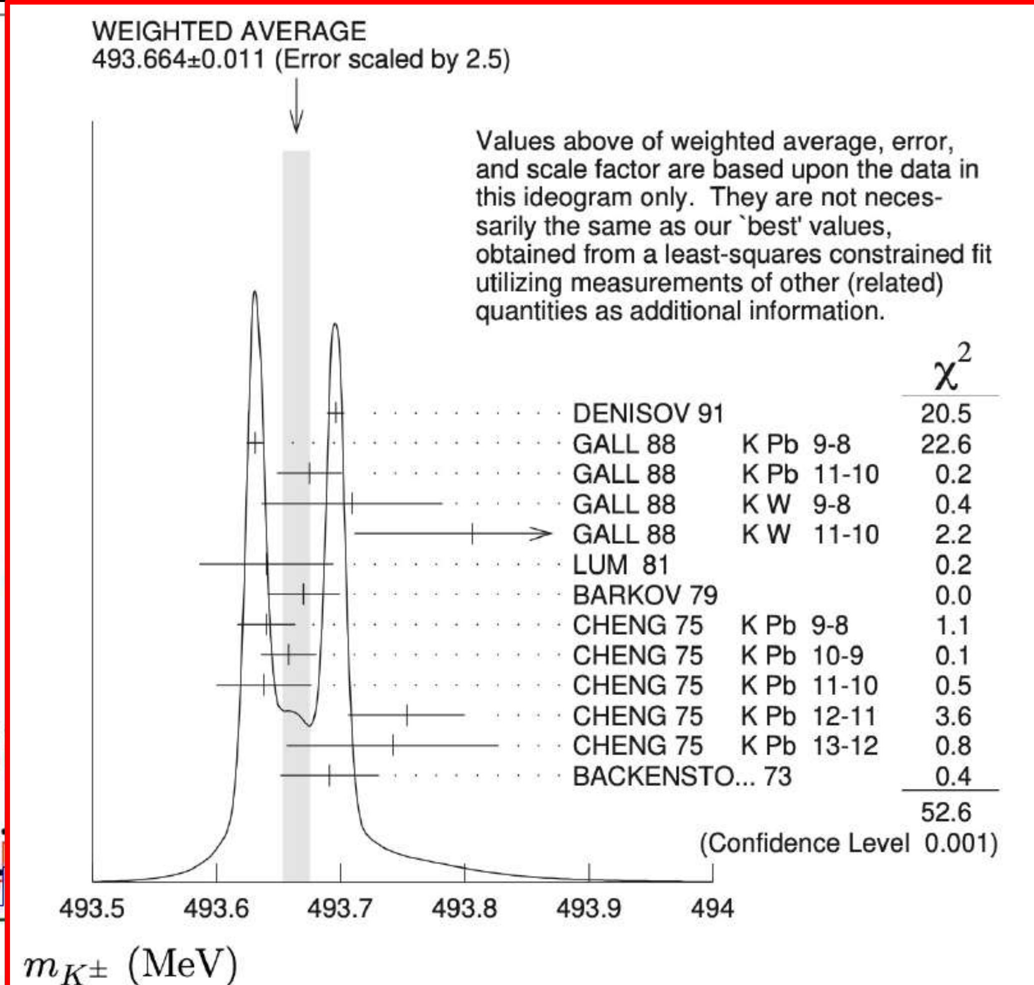
SIDDHARTA-2 (2023) Kaonic Neon



First K-Ne measurements – possible implications on K- multinucleon interaction and kaon mass

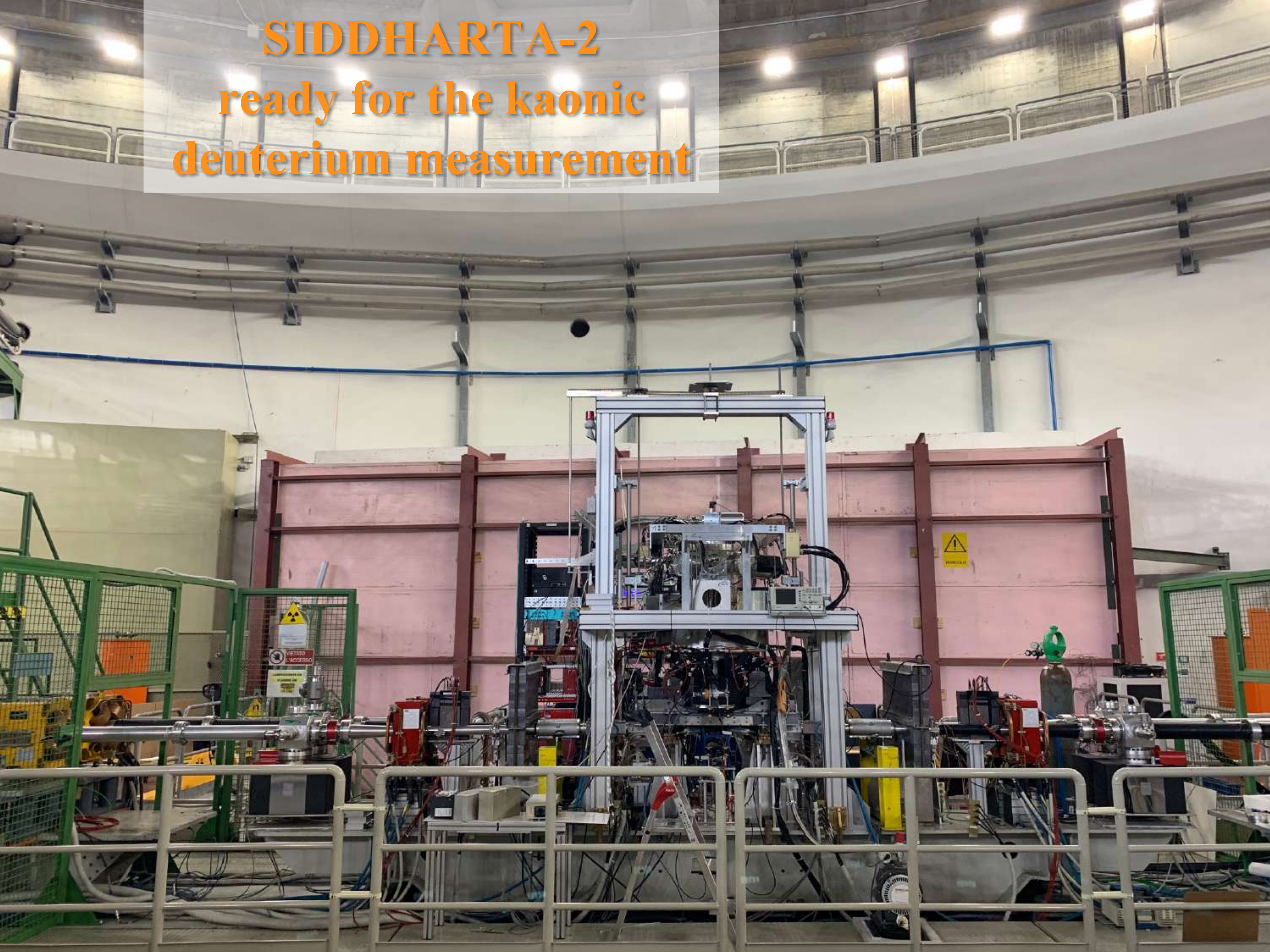
SIDDHARTA-2 (2023) Kaonic Neon





First K-Ne measurements – possible implications on K- multinucleon interaction and kaon mass

SIDDHARTA-2 ready for the kaonic deuterium measurement



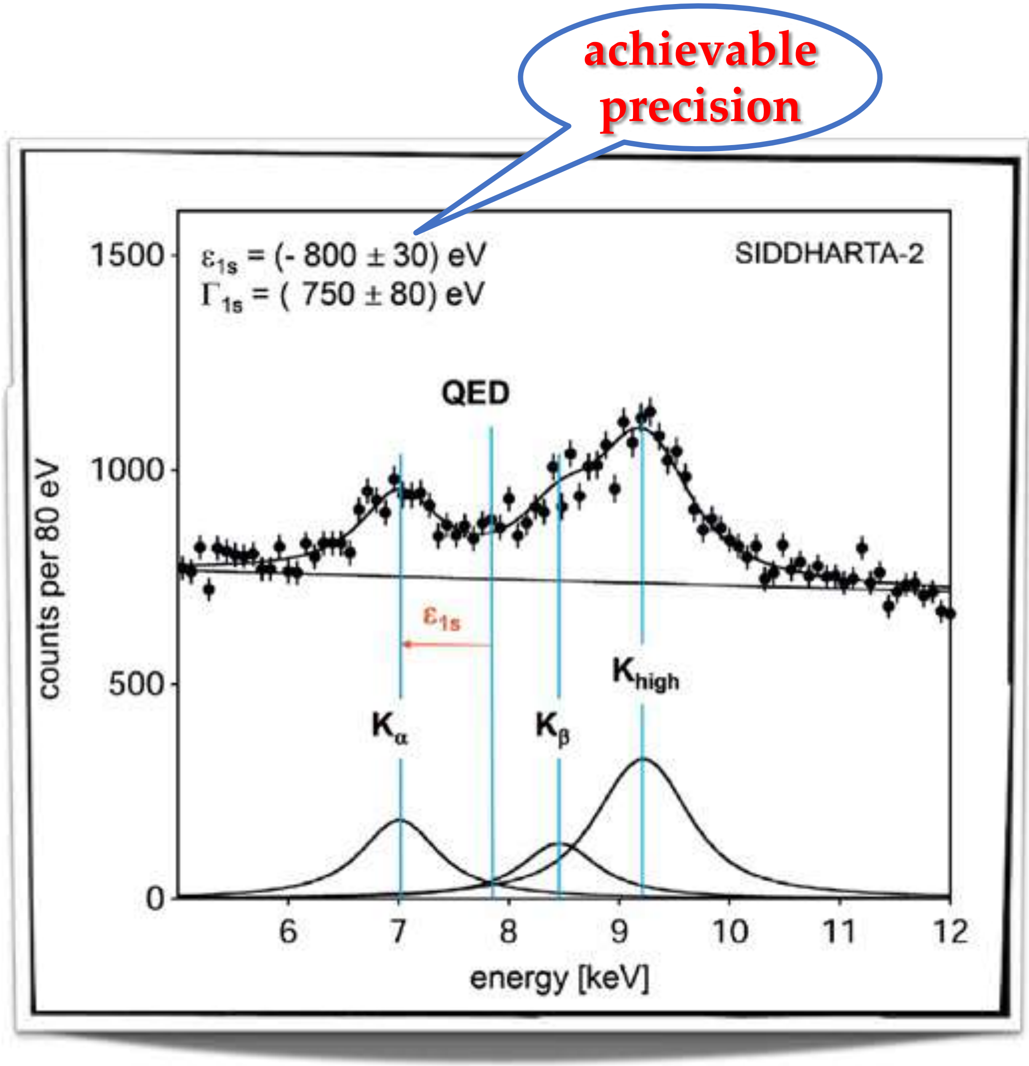
SIDDHARTA-2 K-d measurement

Kaonic deuterium run in (all)

2023/4

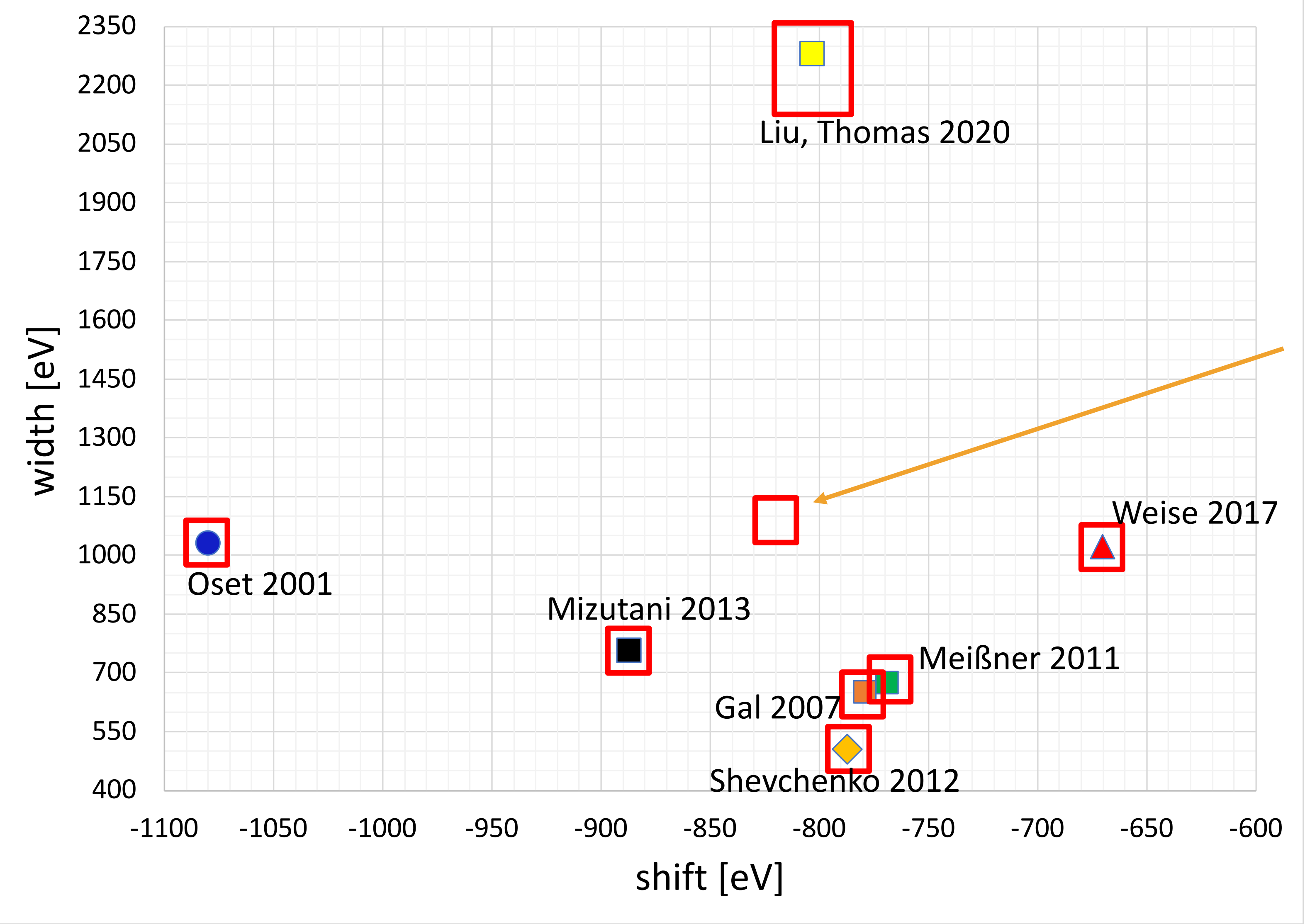
Monte Carlo for an integrated luminosity of 800 pb^{-1}

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

Kaonic deuterium measurement



achievable precision

Beyond SIDDHARTA-2: EXCALIBUR

- **<u>Feasibility studies in parallel with Siddharta-2</u>**

- **<u>Various setups in preparation:</u>**
  - *HPGe*
  - *Crystal spectrometers (VOXES)*
  - *CdZnTe detectors*
  - *SDD 1mm for kaonic atoms measurement*

- **<u>Proposal for Extension of the Scientific Program at DAFNE:</u>**
  - *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 – $\Lambda(1405)$ study*
  - *Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen)*

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**

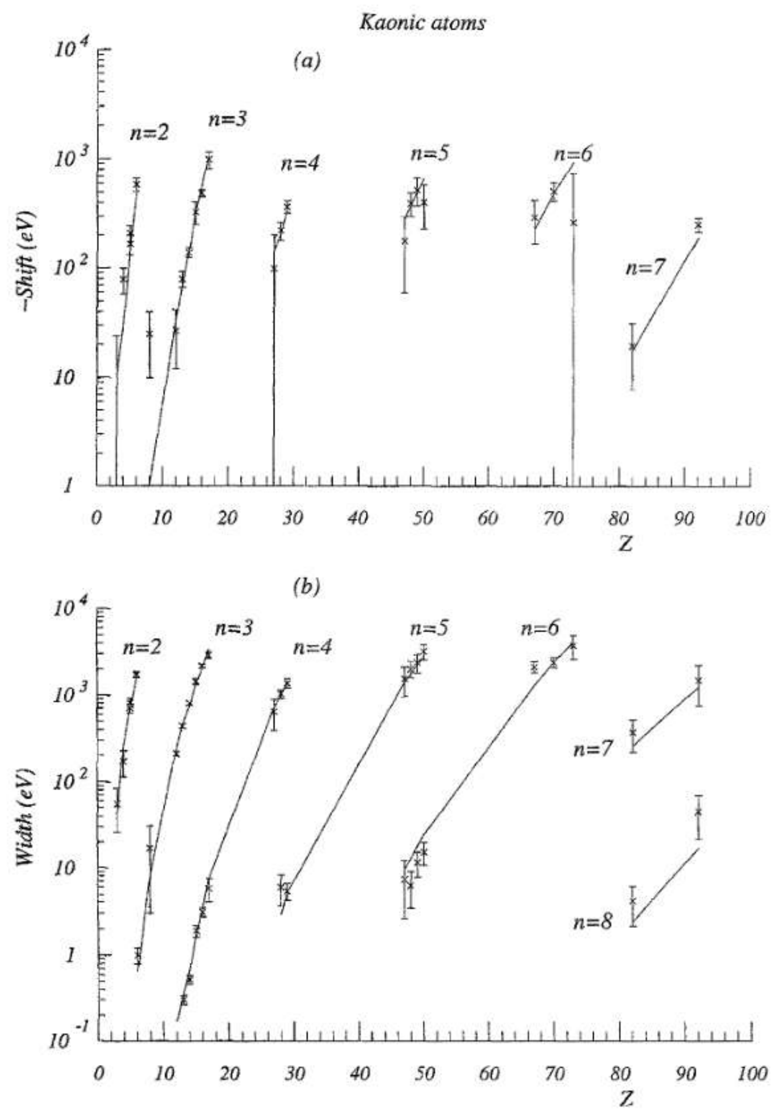
Present status: old and very old measurements with low precisison (some even wrong: kaonic helium puzzle)

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

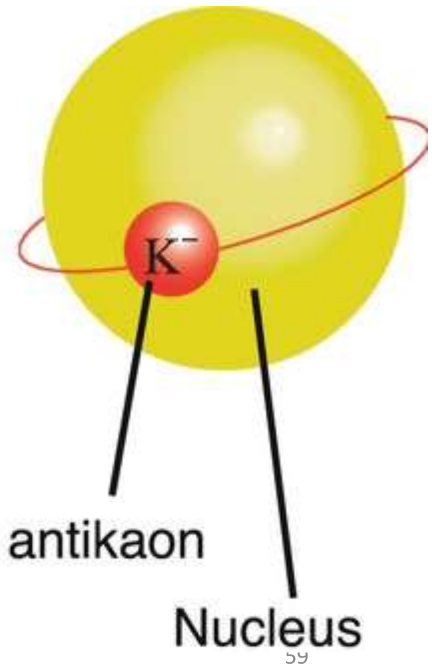
charting the periodic table

C.J. Batty et al. / Physics Reports 287 (1997) 385–445



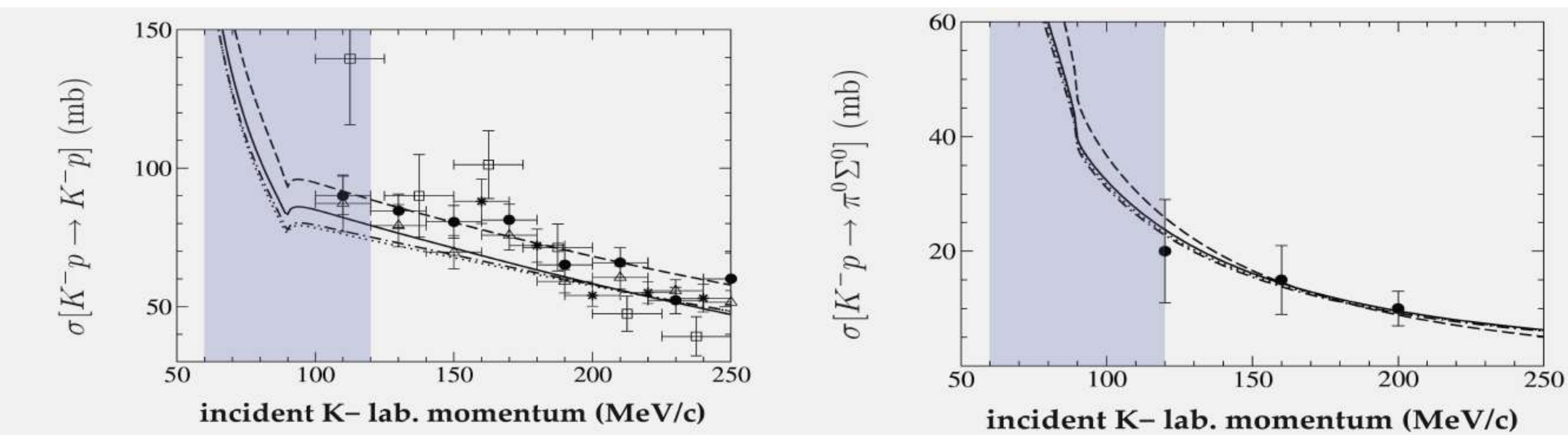
EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

EXKALIBUR



Knscat and int: KAON-NUCLEI SCATTERING and INTERACTION

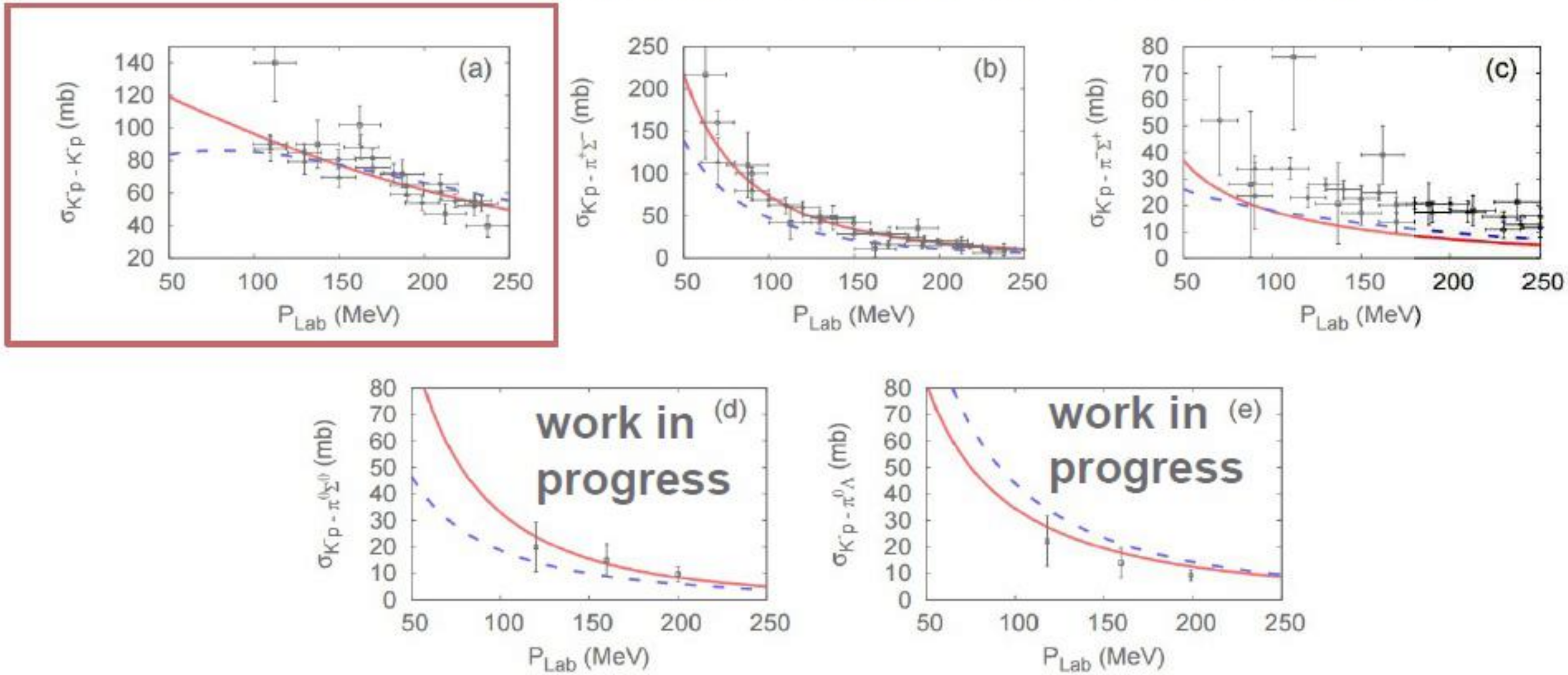
- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited.
- Below 150 MeV/c there is a "desert" - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.
- **Kaon-nucleon scattering/interaction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



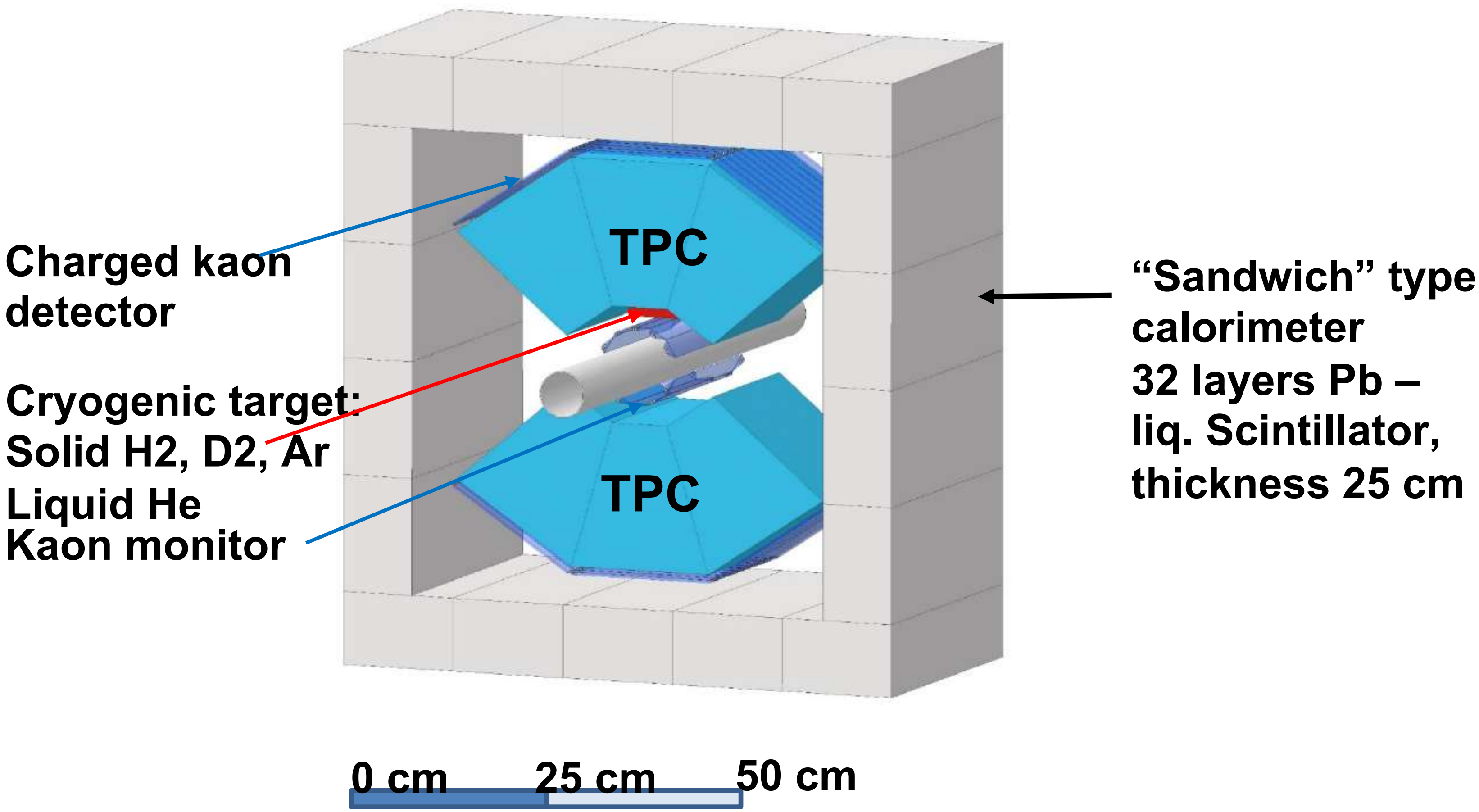
$K^{-}N$ elastic and inelastic scatterings for p_K < 100 MeV/c

The parameters of the models are constrained by the existing scattering data

Phen. [Y. Ikeda and T. Sato, Phys. Rev. C76, 035203 (2007)]
Chiral [S. Ohnishi, Y. Ikeda, T. Hyodo, W. Weise, Phys.Rev. C93 (2016) no.2, 025207]



KN2 – inelastic scattering, layout



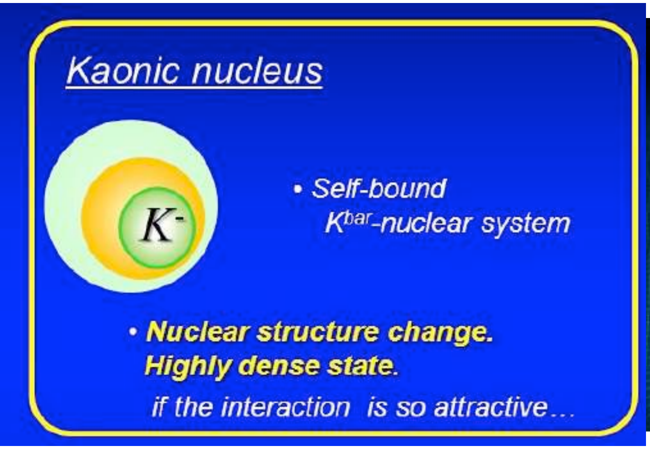
Fundamental Physics at the strangeness frontier at DAFNE:

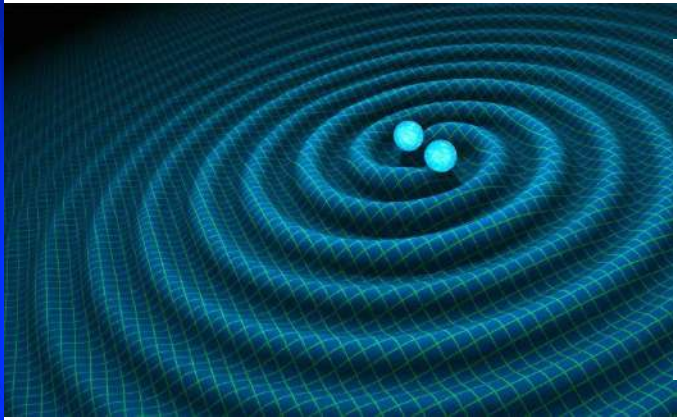
We have a very rich and broad scientific case for unique measurements of kaonic atoms and kaon-nuclei interactions processes at DAFNE contributing to understand physics going from chiral symmetry breaking to neutron stars EOS setting LNF in forefront of these studied – 5 years after SIDDHARTA-2 (modular)

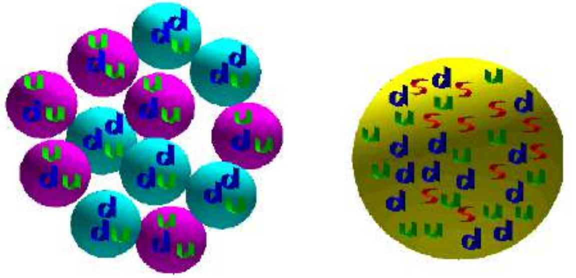
The proposed measurements have the potential to guide the developments of physics at the strangeness frontier in the coming decade, being fundamental not only for a better understanding of the strong interaction (QCD), but also in astrophysics and particle physics.

The Modern Era of precision measurements of hadronic (kaonic) atoms fosteres a deeper understanding of the antikaon-nuclei interactions at threshold, which is fundamental to unveil the mechanisms at work on non-perturbative strangeness QCD.

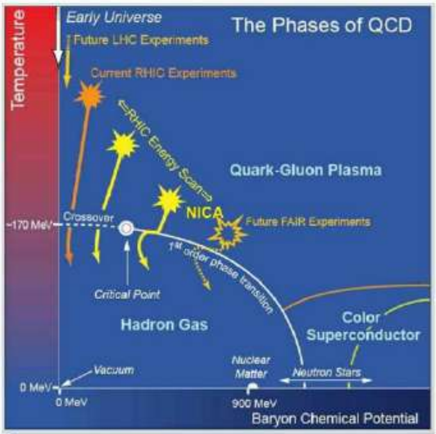
Implications going from particle and nuclear physics to astrophysics.



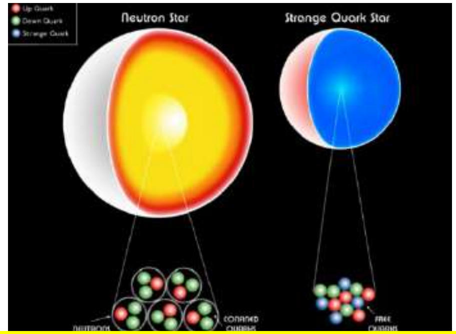




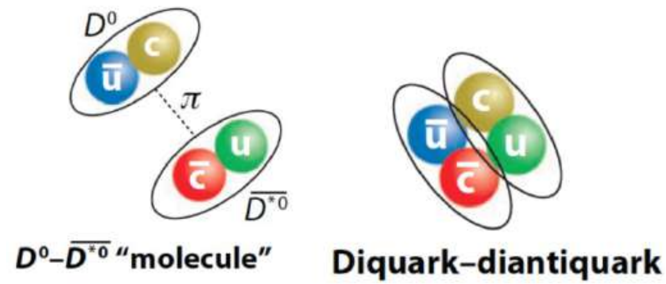
Strangeness Fundamental Physics



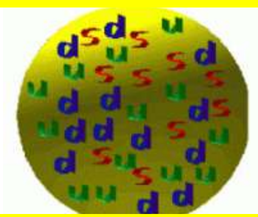
Cold Dense matter



Neutron star EOS

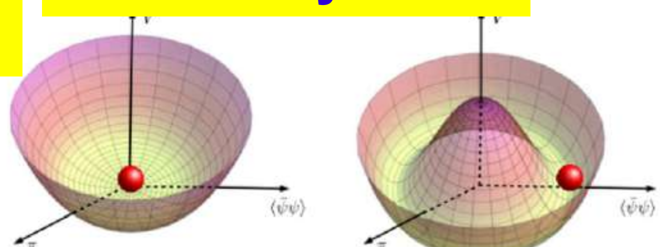


Particles structure

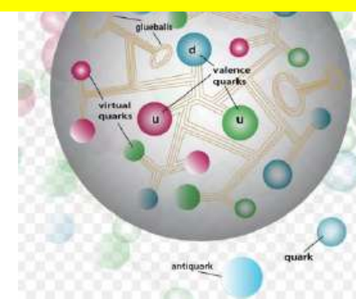


Strangelets & Dark Matter

QCD Chiral symm.



Mass generation, visible Universe



ThanK You

"Each man delights in the work that suits him best." — Homer, The Odyssey