Proposal for Future measurements at DAΦNE

Fundamental Physics at the strangeness frontier

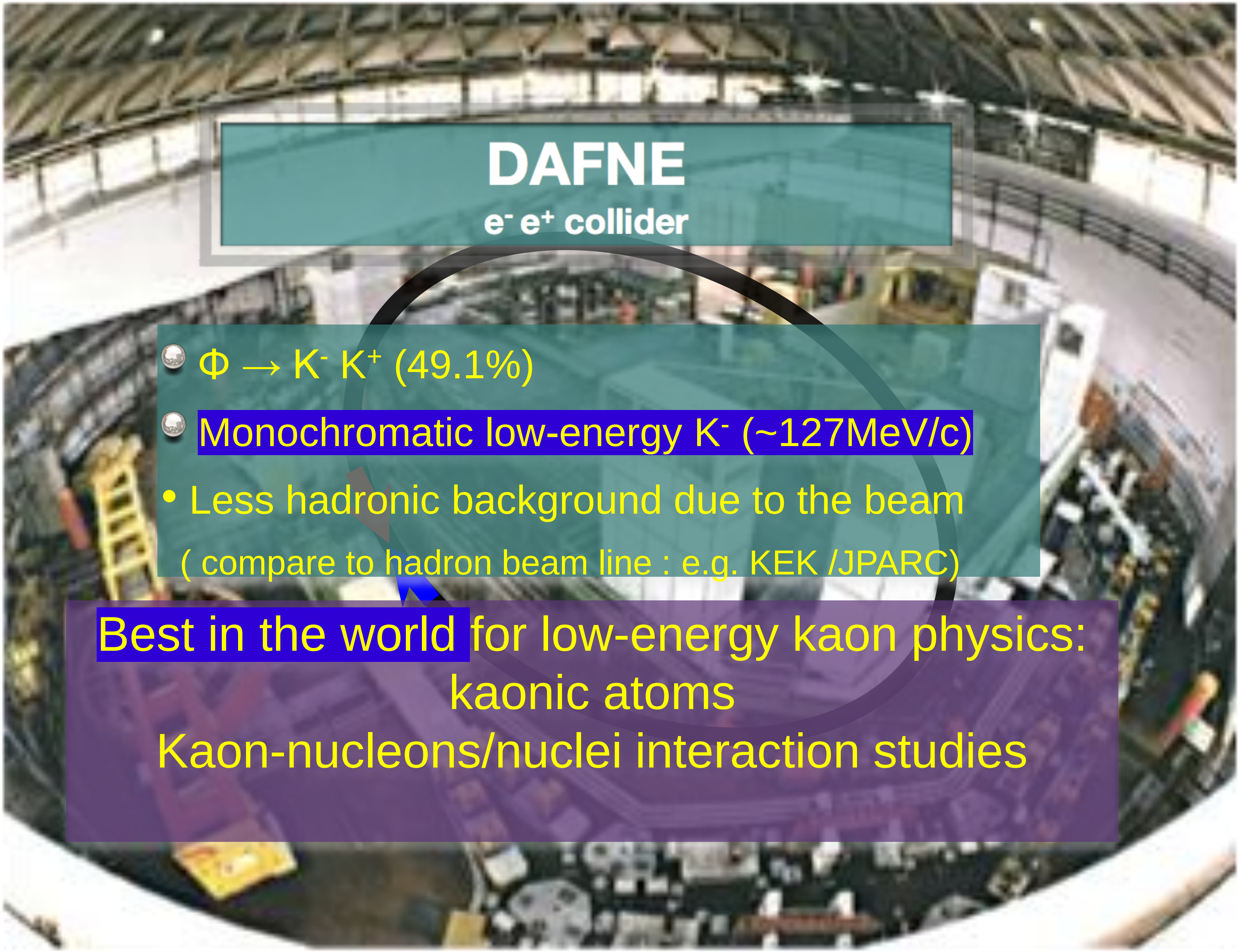
Kaonic atoms and kaon-nuclei interaction studies

Catalina Curceanu, on behalf of strangeness community

Sci. Com. 6th May 2021

WHY DAΦNE?

The DAΦNE Φ-factory at LNF is **the world leading facility** for
low-energy kaons, producing charge kaons in the
momentum range 115 – 140 MeV/c
and
is therefore **ideally suited for studying particle and nuclear physics
in the sector of low-energy QCD with strangeness**



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)

Best in the world for low-energy kaon physics:

kaonic atoms

Kaon-nucleons/nuclei interaction studies

A New Measurement of Kaonic Hydrogen X-rays
Phys.Lett.B 704 (2011) 113-117
312 citations

Measurement of the kaonic hydrogen X-ray spectrum
Phys.Rev.Lett. 94 (2005) 212302
225 citations

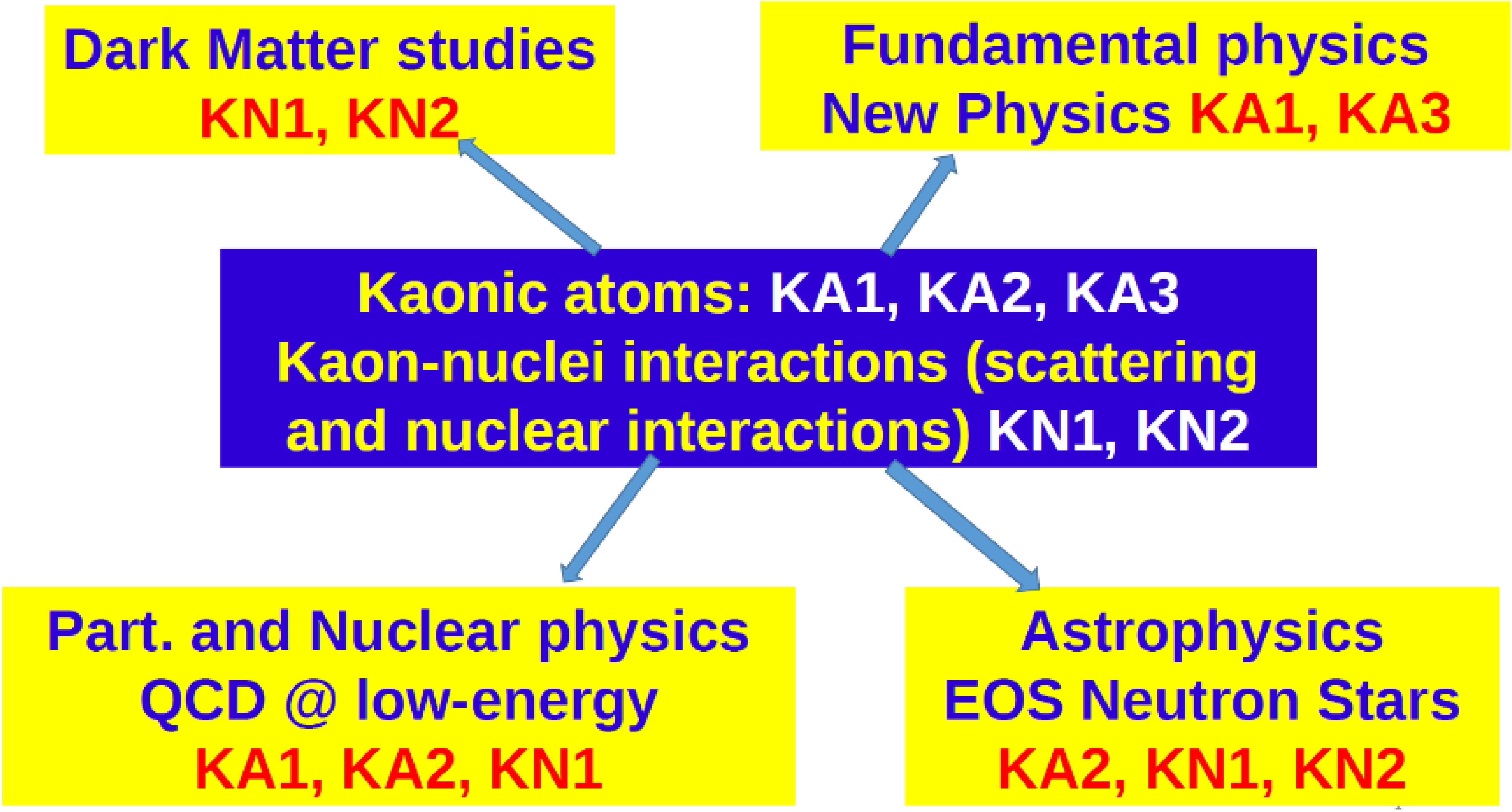
Kaonic helium-4 X-ray measurement in SIDDHARTA
Phys.Lett.B 681 (2009) 310-314
104 citations

https://agenda.infn.it/event/25725/overview

“Fundamental Physics at the strangeness frontier at DAΦNE“ Workshop

INFN-LNF - ONLINE, 25-26/02/2021


INFN
LNF
Istituto Nazionale di Fisica Nucleare
STRONG 2020



Dark Matter studies
KN1, KN2

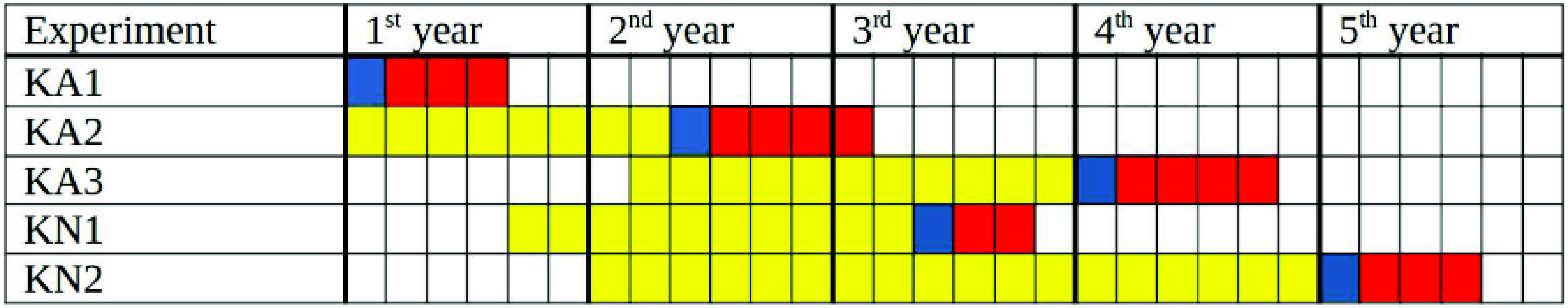
Fundamental physics
New Physics KA1, KA3

Kaonic atoms: KA1, KA2, KA3
Kaon-nuclei interactions (scattering and nuclear interactions) KN1, KN2

Part. and Nuclear physics
QCD @ low-energy
KA1, KA2, KN1

Astrophysics
EOS Neutron Stars
KA2, KN1, KN2

Priorities and readiness:



Experiment	1st year						2nd year						3rd year						4th year						5th year					
KA1	🟦	🟥	🟥	🟥																										
KA2	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟥	🟥	🟥	🟥																	
KA3								🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟥	🟥	🟥	🟥							
KN1					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟥	🟥													
KN2							🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟥	🟥	🟥		

Fig. 1. Schematic Gantt Chart for Fundamental physics at the Strangeness Frontier at the DAΦNE Proposal: KA1 (see Sec. 2.1), KA2 (see Sec. 2.2), KA3 (see Sec. 2.3), KN1 (see Sec. 3.2), KN2 (see Sec. 3.3). Yellow: preparation phase. Blue: installation phase. Red: data taking.

Support:

STRONG-2020, EU

THEIA Network

Theoreticians who provided input:

- **Ignazio Bombaci**
- **Alessandro Drago**
- **Isaac Vidana**
- **Wolfram Weise, TU Munich**
- **Avraham Gal, Jerusalem**
- **Eli Friedman, Jerusalem**
- **Jiri Mares. Prague**
- **Oset & Ramos, Spain**
- **Laura Tolos, Spain**
- **Ulf Meissner, Bonn & China**
- **Tony Thomas, Adelaide**
- **Tetsuo Hyodo, Japan**
- **Shota Ohnishi, Japan**
- **Maxim Pospelov, Randolf Pohl**
  -> new physics

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

Fundamental physics
New Physics

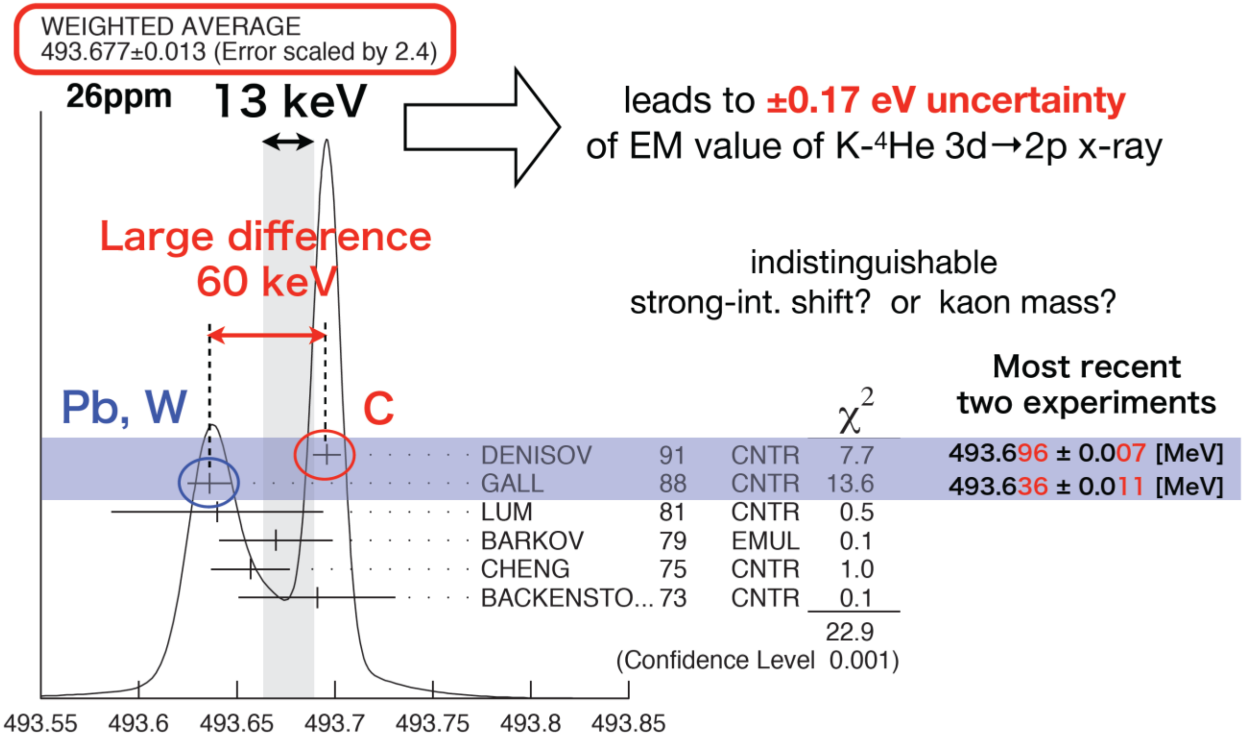
The modern era of light kaonic atom experiments

Kaonic atoms

Kaon mass discrepancy – impact on kaonic atoms; CPT, all physics where kaon mass is important such for charmed meson studies and searches beyond standard model

- a new measurement is strongly required – PDG…

The best D0 mass relies, and is limited by the K- mass (Claude Amsler; Simon Eydelman)



WEIGHTED AVERAGE
493.677±0.013 (Error scaled by 2.4)

leads to ±0.17 eV uncertainty of EM value of K-^{4}He 3d→2p x-ray

indistinguishable
strong-int. shift? or kaon mass?

			χ^2	Most recent two experiments
DENISOV	91	CNTR	7.7	493.696 ± 0.007 [MeV]
GALL	88	CNTR	13.6	493.636 ± 0.011 [MeV]
LUM	81	CNTR	0.5	
BARKOV	79	EMUL	0.1	
CHENG	75	CNTR	1.0	
BACKENSTO...	73	CNTR	0.1	
			22.9	

(Confidence Level 0.001)

Uncertainty in electron screening. Gamma-ray contamination(Pb,W).

→ **new measurement with low-Z gas targets**

Impact of the kaon mass uncertainty on the charm meson spectrum

Claude Amsler[1] and Simon Eidelman[2,3,4]

Contact Novosibirsk
Possible competitor:
J-PARC

The last measurements of the charged kaon mass are very old (at least 30 years).

There is a discrepancy of 60 keV between the two most accurate measurements, each measured with about 10 keV r.m.s resolution.

This leads to an error of 16 keV (σ) on the charged kaon mass and propagates to an error of 50 keV on the D^0 mass.

This uncertainty is propagated to the charmonium spectrum, in particular to precise values of charm-anticharm meson thresholds.

A particular case is that of $D^0\bar{D}^{*0}$ which lies within the measured width of the best known candidate for a di-hadron molecule, the X(3872).

An improved K-mass measurement would lead to a better interpretation of the X(3872) and a determination of its radius.

Reducing the error on the K-mass by a factor of 2 could lead to an improvement of 4-5 on the D^0 mass in the two-kaon decay mode (in an ideal experiment).

New physics?

In principle one could use precision measurements of K - atoms to set constraints on some sort of new physics.
The best sensitivity will be for masses of mediating particles in the ~ few MeV mass range.

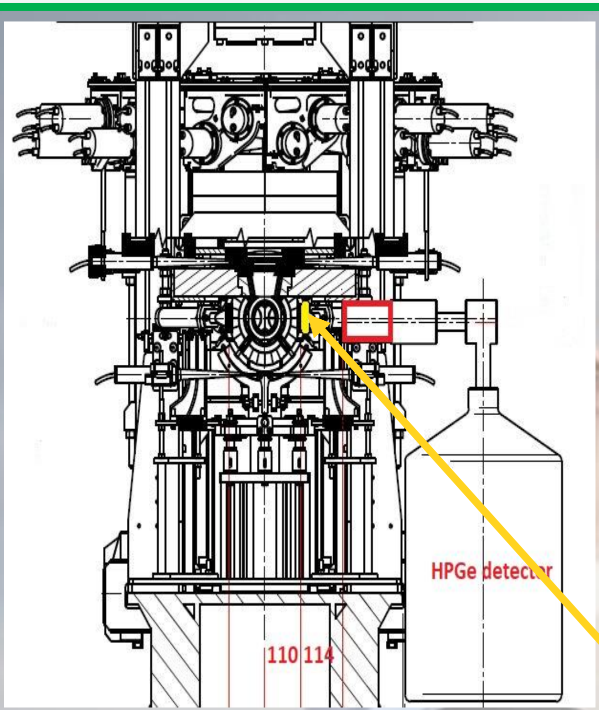
(Maxim Pospelov)

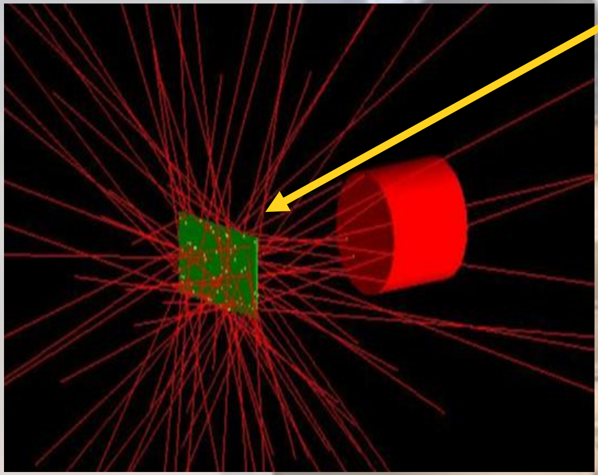
Randolf Pohl: similar to muonic atoms -> proton radius

We study feasibility!

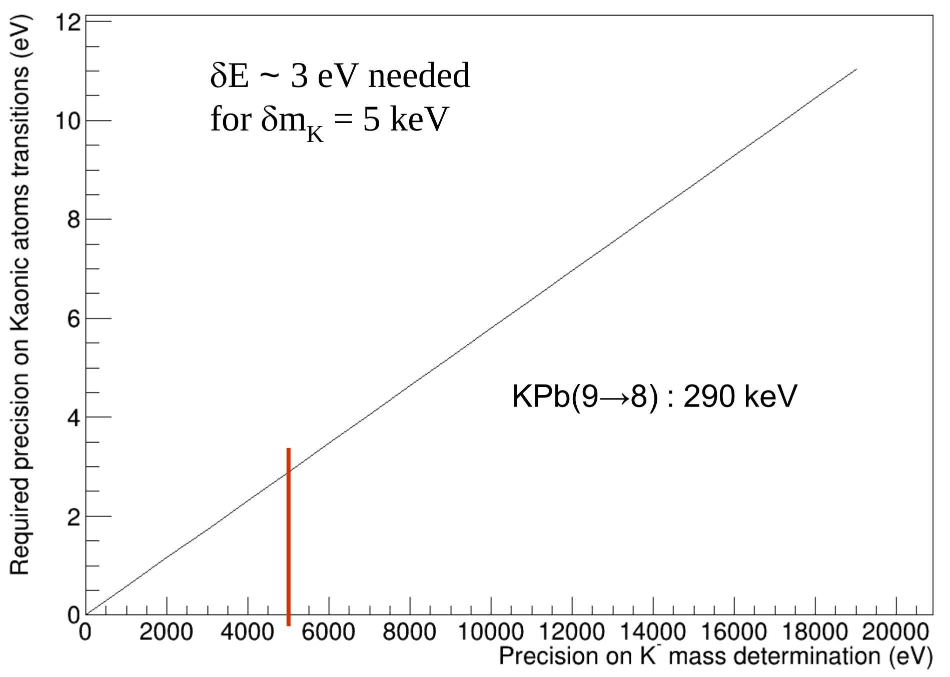
KA1: Kaon Mass and High Z kaonic atoms: **HPGE**

Feasibility test run during SIDDHARTA-2: KPb





Target just behind
the luminometer,
which is used as trigger



$$\sigma m_K = \frac{m_K^2}{\mu_{KN}^2}\frac{1}{Z^2}\frac{10^6}{26,6}\frac{\sigma E^K_{X\to Y}}{\left(\frac{1}{Y^2}-\frac{1}{X^2}\right)}$$

Dedicated measurements:

- Targets : Se, Zr, Ta, Pb

- New mechanics to reduce the distance from IP
- Optimised shielding according to MC and feasibility test

~ 360 pb-1 (~ 30 days) of beamtime requested

!!! Similar estimations for each target !!!

KNN
Chiral QCD
Potential models
Lattice QCD
C; Be; B…

Lambda(1405) QCD
He3,4; Be; Li

Kaonic atoms

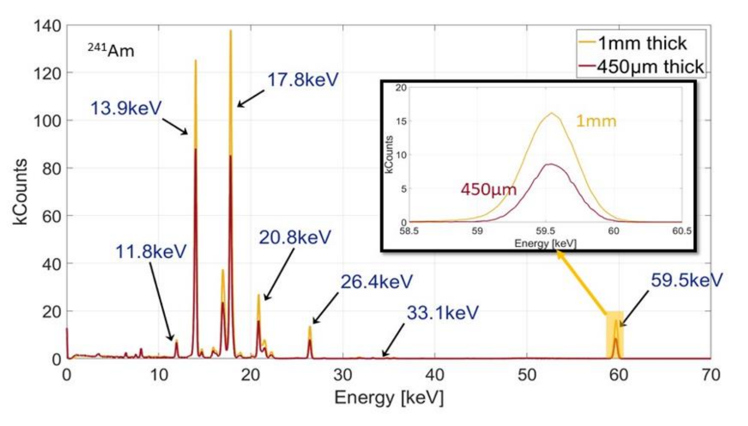
Kaonic Atoms to Investigate
Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

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

Complementarity:
ALICE – femtoscopy
J-PARC

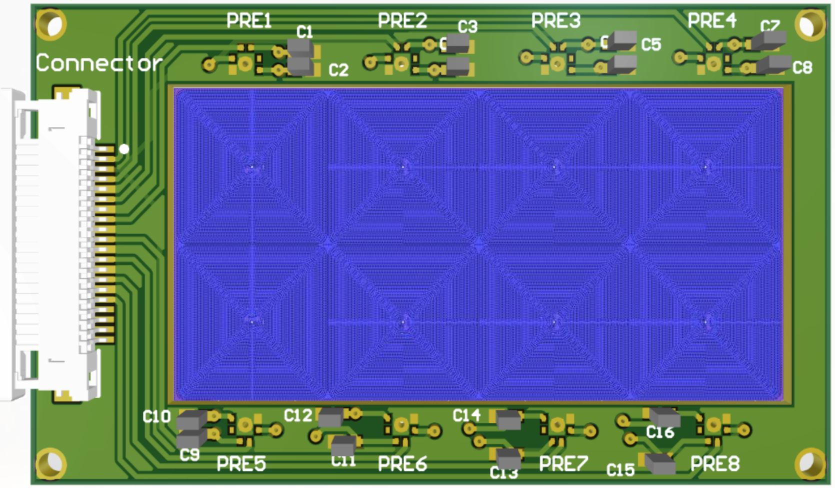
KA2: Light Kaonic Atoms Measurements: **SDD 1mm**

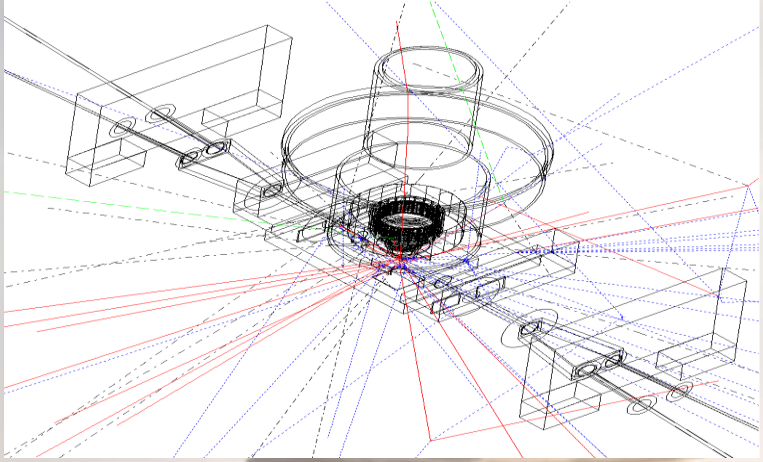
1mm SDDs – FBK – **FINANCED AND ORDERED**



First XRF tests with known targets show very promising results

Prototypes of electronics boards are already available





Proposed measurements:

- Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{10,11}B
- Second SIDDHARTA-2 like setup
- Optimised shielding according to feasibility test
- MC implementation (already started) with real DAΦNE conditions

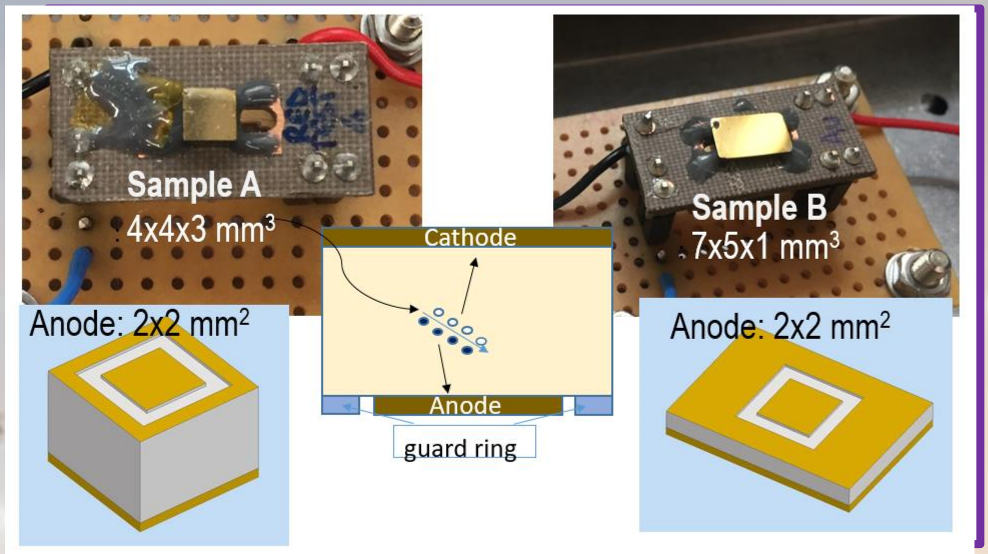
KA2: Light Kaonic Atoms Measurements: Cd(Zn)Te

Possible kaonic transitions to be measured with

CdTe detectors:

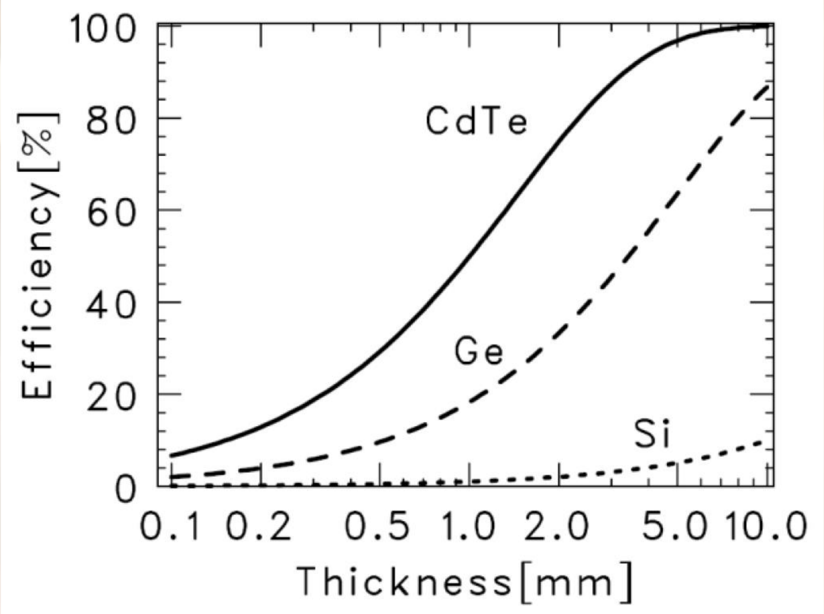
$K^{6}Li(2\rightarrow1)$: 81 keV
$K^{6}Li(3\rightarrow1)$: 97 keV
$K^{7}Li(2\rightarrow1)$: 82 keV
$K^{7}Li(3\rightarrow1)$: 98 keV
$K^{9,10}B(4\rightarrow2)$: 58 keV
$K^{9,10}B(5\rightarrow2)$: 65 keV
$K^{9,10}B(6\rightarrow2)$: 69 keV
$K^{9,10}B(7\rightarrow2)$: 71 keV
$K^{11}B(4\rightarrow2)$: 59 keV
$K^{11}B(5\rightarrow2)$: 66 keV
$K^{11}B(6\rightarrow2)$: 70 keV
$K^{11}B(7\rightarrow2)$: 72 keV

required 300 pb-1 for each target

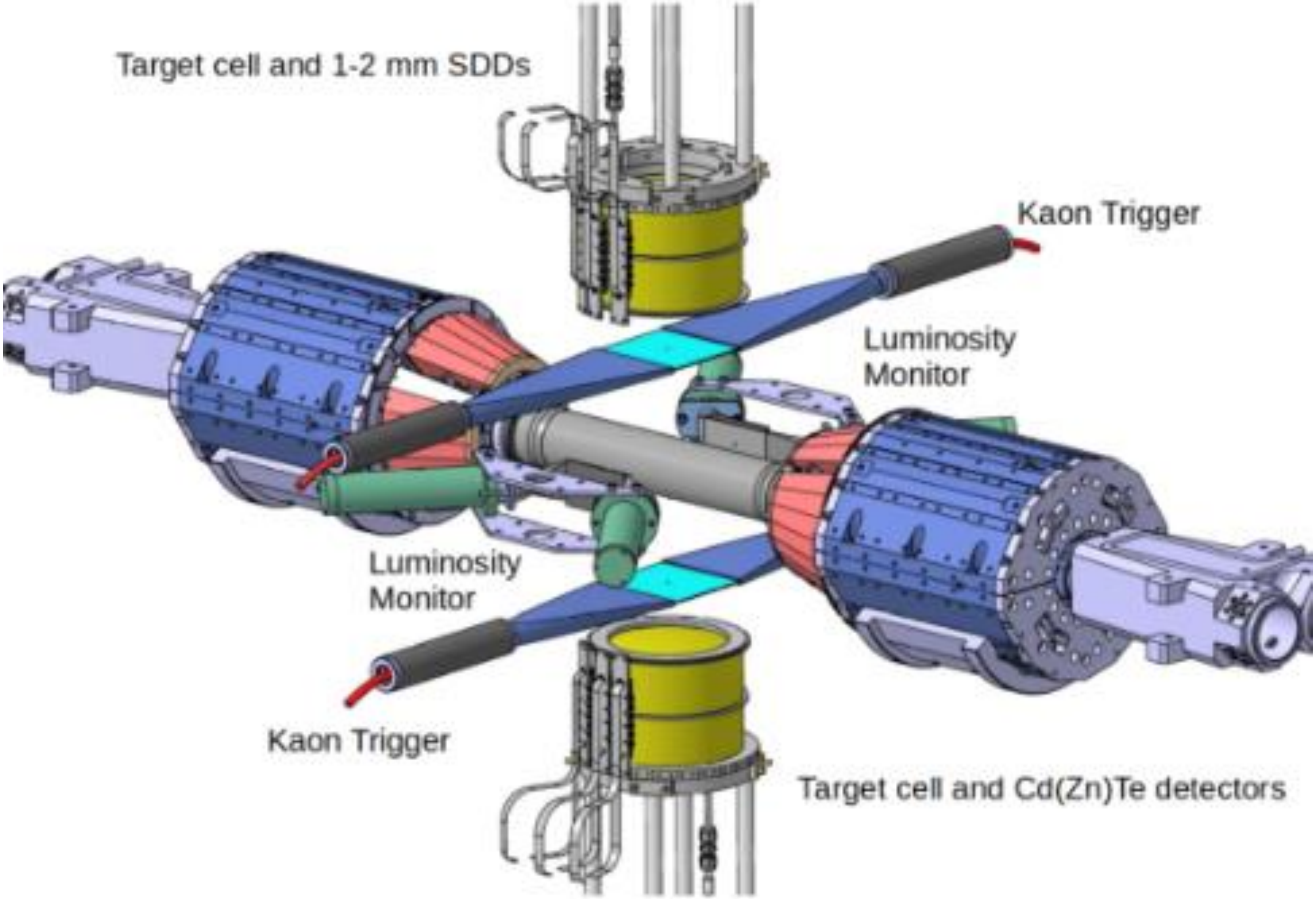


CdTe (and also CdZnTe) detectors will be developed in the STRONG2020-ASTRA project

First prototypes will be available by mid ‘22

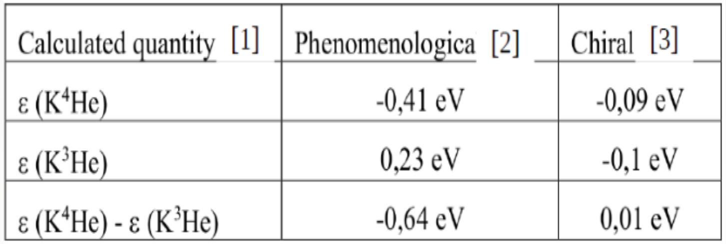


Setup: SDD1mm & CdTe



KA3: sub-eV precision Kaonic Atoms measurements: **VOXES**

There is only ONE possible solving measurment:
The $K^{3,4}He$ **isotopic shift measurement**



Calculated quantity [1]	Phenomenologica [2]	Chiral [3]
$\varepsilon\,(K^4He)$	-0,41 eV	-0,09 eV
$\varepsilon\,(K^3He)$	0,23 eV	-0,1 eV
$\varepsilon\,(K^4He) - \varepsilon\,(K^3He)$	-0,64 eV	0,01 eV

Kaon-Nucleon interaction:
Chiral vs Phenomenological models

Solve the kaonic helium isotopic shift problem

Precise determination of the K^- mass (2)

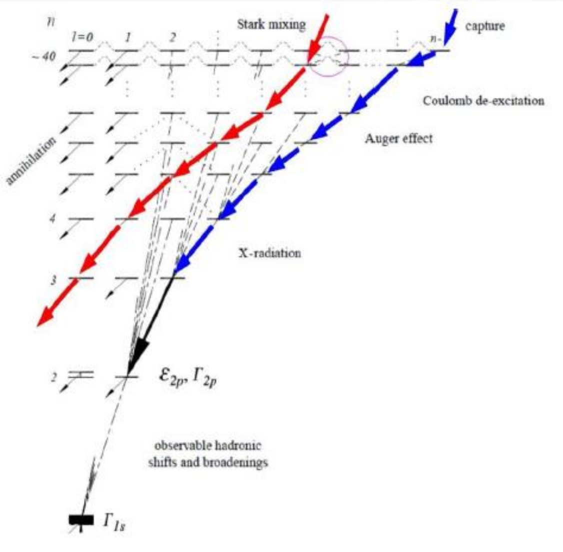
Stronger constraints for the EM cascade models for kaonic atoms

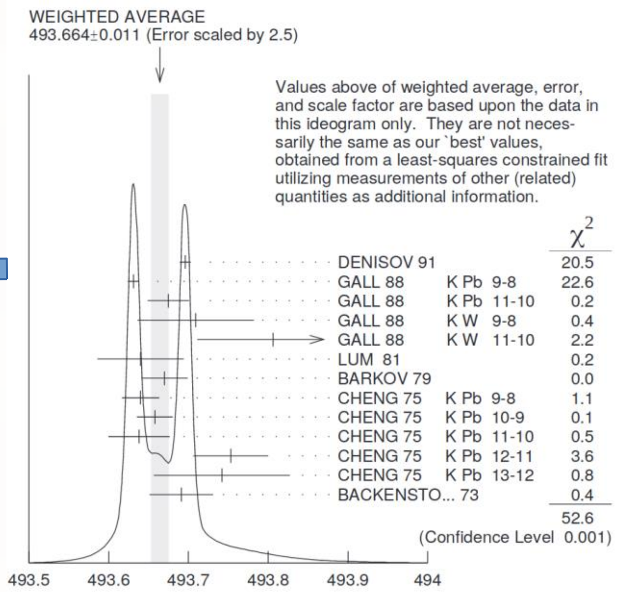
New Physics?

… ALL IN PARALLEL

But...EM calculated levels depend on the cascade processes...

But...levels and calculated shifts depend on the K^- mass value...





“Giornata di discussione sulle prospettive per la Fisica Fondamentale a Frascati (FFF)” , *A. Scordo*, Frascati (LNF), 13/01/2021

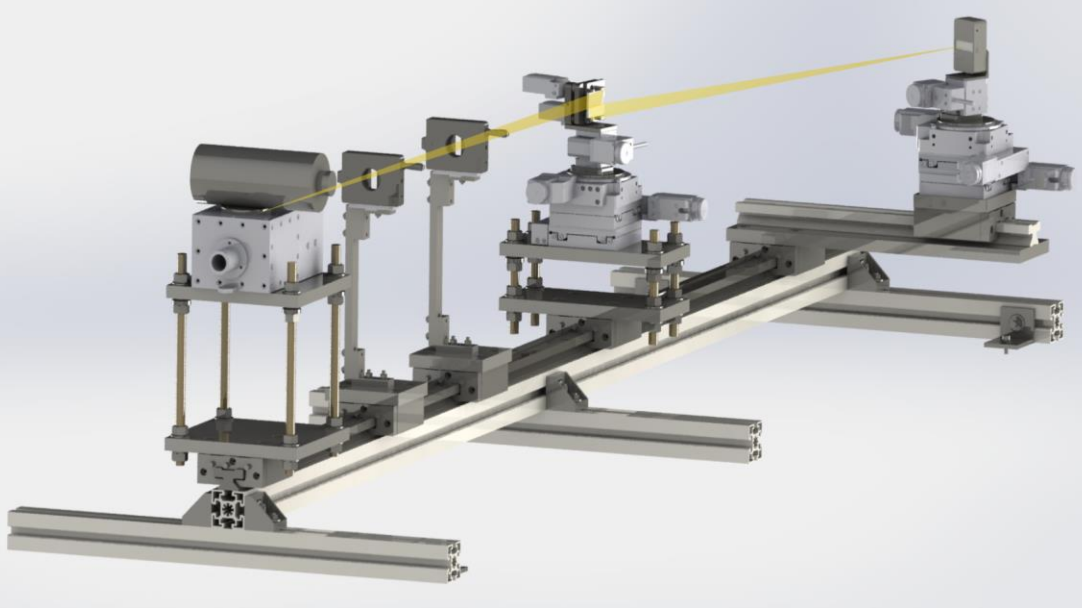
KA3: sub-eV precision Kaonic Atoms measurements

Possible kaonic transitions to be measured with HAPG crystal spectrometer:

$K^3He(3\to2)$: 6.2 keV
$K^3He(4\to2)$: 8.4 keV
$K^3He(5\to2)$: 9.4 keV
$K^3He(6\to2)$: 9.9 keV
$K^3He(7\to2)$: 10.2 keV

$K^4He(3\to2)$: 6.4 keV
$K^4He(4\to2)$: 8.7 keV
$K^4He(5\to2)$: 9.7 keV
$K^4He(6\to2)$: 10.3 keV
$K^4He(7\to2)$: 10.7 keV

$KN(6\to5)$: 7.6 keV
$KN(7\to5)$: 12.1 keV
$KN(8\to5)$: 15.1 keV
$KN(7\to6)$: 4.6 keV
$KN(8\to6)$: 7.5 keV
$KN(9\to6)$: 9.6 keV
$KN(10\to6)$: 11 keV
$KN(11\to6)$: 12.1 keV
$KN(10\to7)$: 6.5 keV
$KN(11\to7)$: 7.5 keV
$KN(12\to7)$: 8.3 keV



- Tunable energy range from 2-20 keV
- Extremely high resolutions of few eV
- Very low background after shielding

Feasibility:

- **Working principle tested in laboratory**
- **Dependence from HAPG parameters well investigated and published (thickness, mosaicity, …)**
- **Consistent Ray Tracing simulations available**
- **Few eV resolutions confirmed for solid sources with millimetric dimensions**

Spectrometer developed under CSN5 Young Researcher Grant (2016-2018)

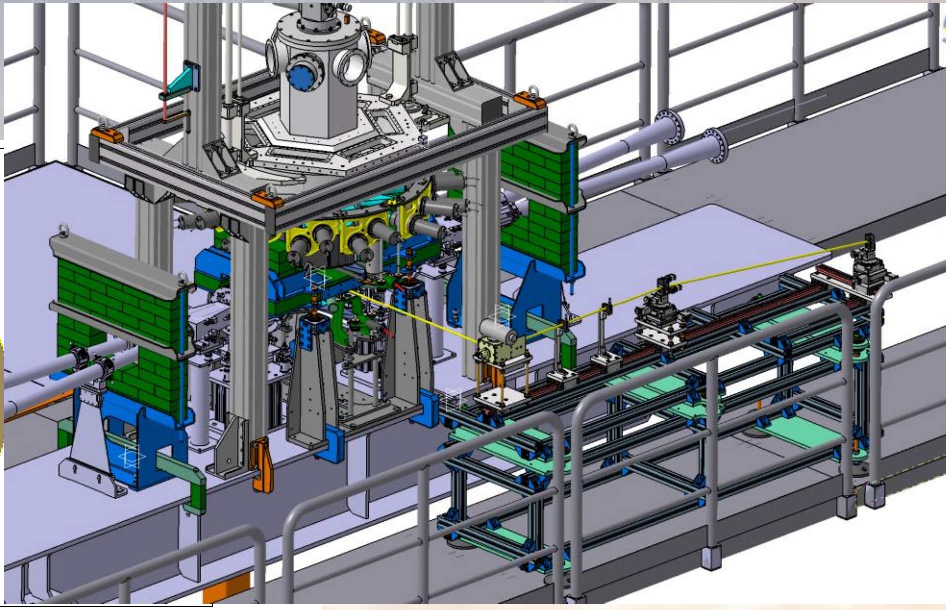
KA3: KC run with existing setup & future

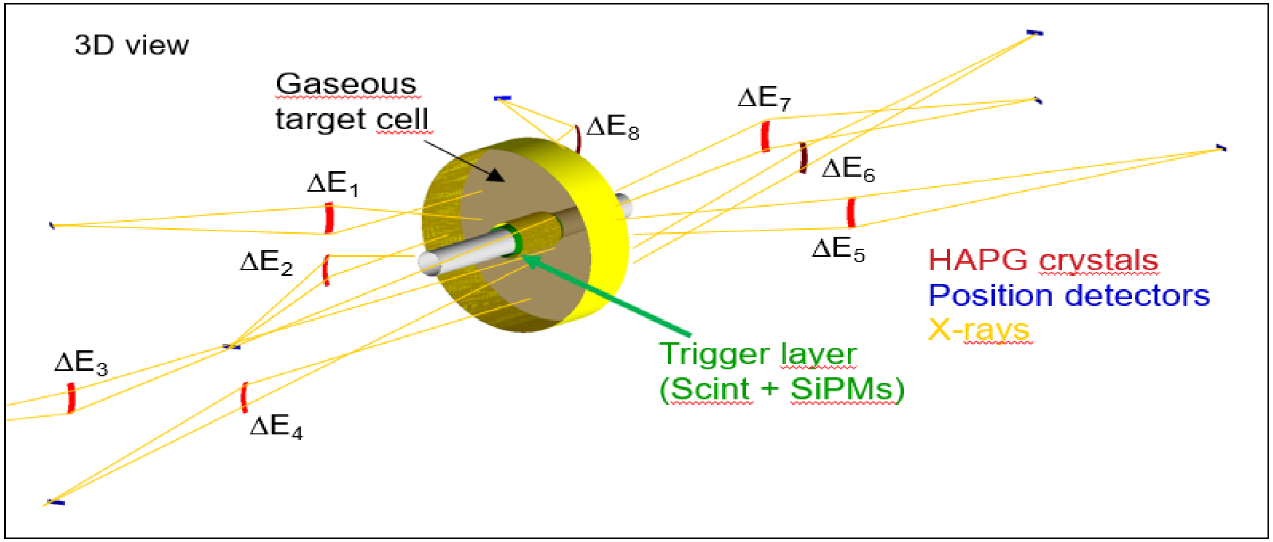
First run with KC for a K- mass measurement

From MC simulations,
assuming L = 1,4x10^{32} (~ 12 pb^{-1} / day):

- ~ 1,4 recorded signals / day
- Background ~ 0 (using shielding and kaon trigger)
- ~ 250 total events goal (δE ~ 0,2 – 0,3 eV)
- σ = 3,6 eV @ 8 keV (from Cu lab measurements)

- ~ 2000 pb^{-1} (~ 180 days) of beamtime (under study)





Phase 2: 8 arms spectrometer

Phys.Rev.D 102 (2020) 8, 083015

On self-gravitating strange dark matter halos around galaxies

Dark Matter studies

Complementary:
J-PARC
ALICE – femtoscopy
(O. **Vazquez Doce** – Fellini - Antikaon-deuteron femtoscopic correlations with ALICE: A new era of hadron-hadron interaction measurements – LNF)
…….

Kaon-nuclei interactions (scattering and nuclear interactions)

Merger of compact stars in the two-families scenario

Astrophys.J. 881 (2019) 2, 122

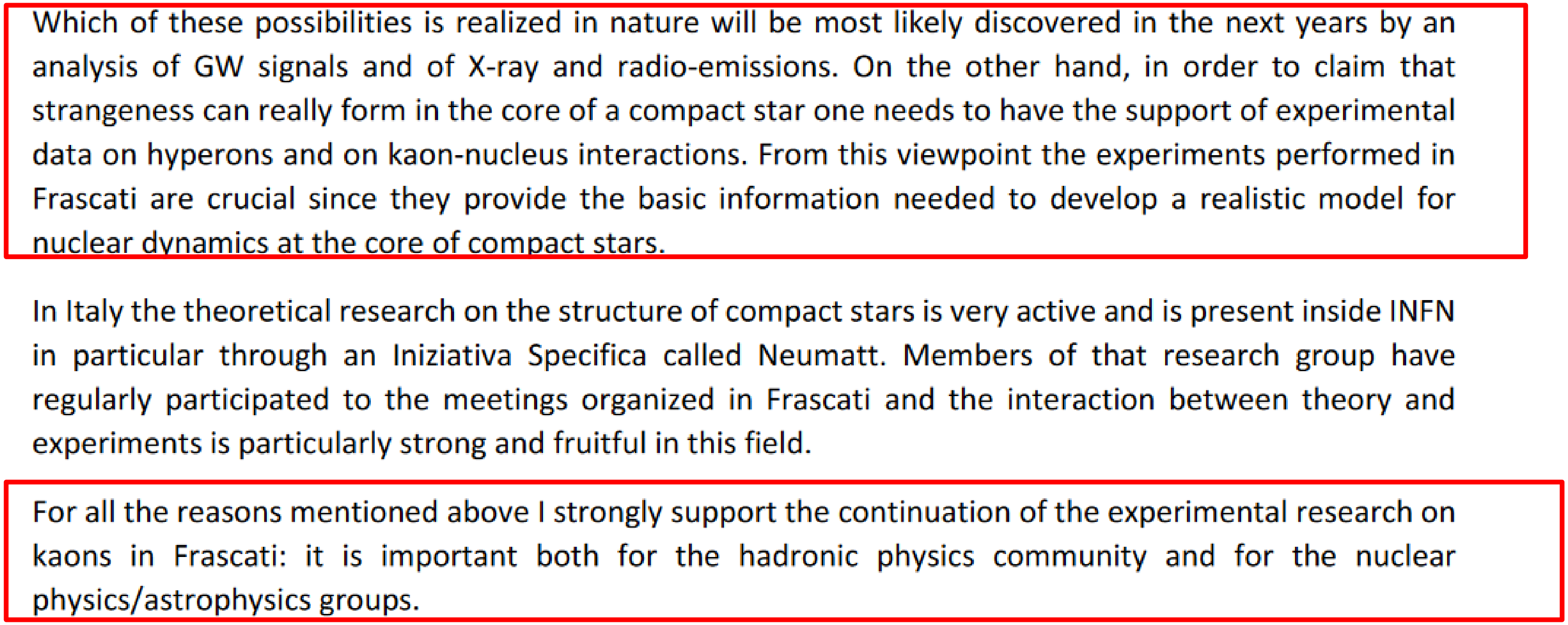
The equation of state of dense matter: Stiff, soft, or both?

Astron.Nachr. 340 (2019) 1-3, 189

Astrophysics
EOS Neutron Stars
MULTIMESSANGER

Obj: **In support of the research activity on kaonic atoms and on kaon-nucleus interaction**

The research on strangeness in general and on kaon-nucleus interaction (and on kaonic atoms) in particular, plays quite a crucial role in the understanding of the structure of compact stars. During the last years it has become more and more clear that the possible production of hyperons or the formation of a kaonic condensate at the center of compact stars have a deep impact on the structure of those stellar objects. The so-called hyperon-puzzle, namely the difficulty in reaching large masses if hyperons are produced and the similar problem in the case of kaon condensation have been solved by indicating that the crucial role is played by repulsive hyperonic three-body forces and by the anti-kaon optical potential. By tuning those interactions it is possible to reach and exceed 2 M_s while allowing the formation of strangeness in the star. A price has though to be paid: the radii of compact stars having a mass of about 1.4 M_s cannot be smaller than about 11.5 km. On the other hand there are indications, although based on model-dependent analysis, that objects with smaller radii can indeed exist. A solution has been proposed, based on the idea that strange quark matter can be produced once strangeness is already present in the star, either in the form of hyperons or of a kaon condensate. In that way the stiff quark matter phase can support large masses while the production of strangeness softens the equation of state at densities of the order of 2-3 times nuclear matter saturation, allowing to produce compact objects with small radii.



Which of these possibilities is realized in nature will be most likely discovered in the next years by an analysis of GW signals and of X-ray and radio-emissions. On the other hand, in order to claim that strangeness can really form in the core of a compact star one needs to have the support of experimental data on hyperons and on kaon-nucleus interactions. From this viewpoint the experiments performed in Frascati are crucial since they provide the basic information needed to develop a realistic model for nuclear dynamics at the core of compact stars.

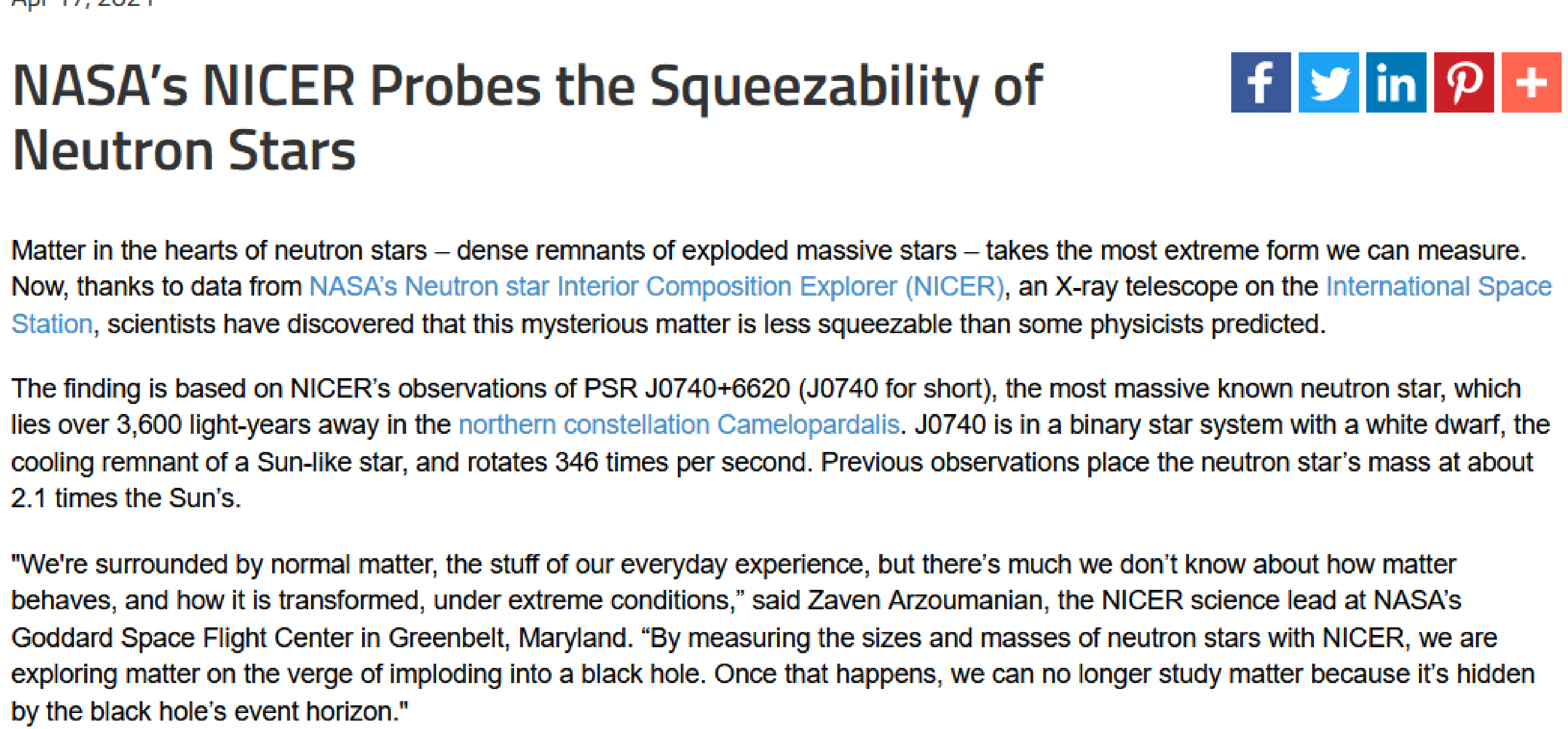
In Italy the theoretical research on the structure of compact stars is very active and is present inside INFN in particular through an Iniziativa Specifica called Neumatt. Members of that research group have regularly participated to the meetings organized in Frascati and the interaction between theory and experiments is particularly strong and fruitful in this field.

For all the reasons mentioned above I strongly support the continuation of the experimental research on kaons in Frascati: it is important both for the hadronic physics community and for the nuclear physics/astrophysics groups.

Prof. Alessandro Drago – Univ. Ferrara

National coordinator of the I.S. Neumatt of INFN

Similar letters from:
Ignazio Bombaci, Univ. and INFN Pisa
Isaac Vidaña, INFN Sezione di Catania
Member THEIA Network, STRONG2020



Apr 17, 2021

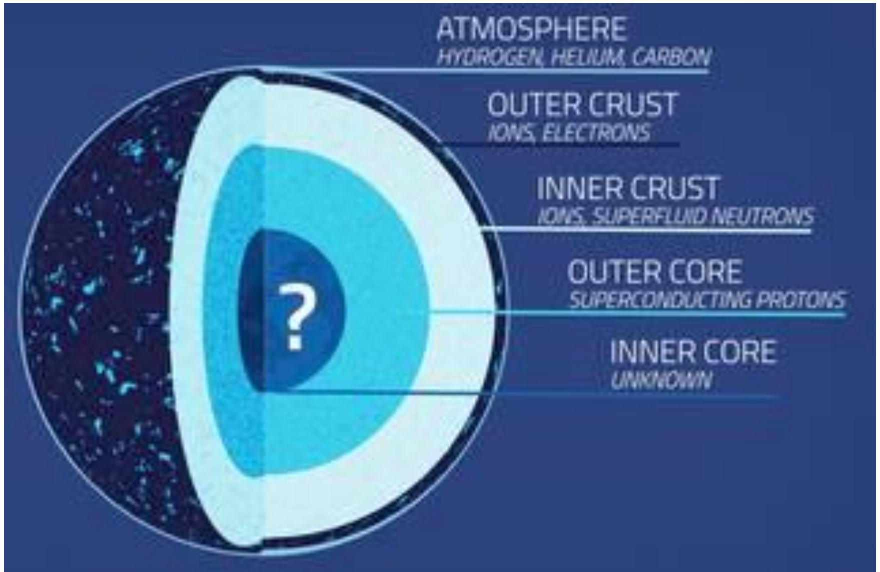
NASA's NICER Probes the Squeezability of Neutron Stars

Matter in the hearts of neutron stars – dense remnants of exploded massive stars – takes the most extreme form we can measure. Now, thanks to data from NASA's Neutron star Interior Composition Explorer (NICER), an X-ray telescope on the International Space Station, scientists have discovered that this mysterious matter is less squeezable than some physicists predicted.

The finding is based on NICER's observations of PSR J0740+6620 (J0740 for short), the most massive known neutron star, which lies over 3,600 light-years away in the northern constellation Camelopardalis. J0740 is in a binary star system with a white dwarf, the cooling remnant of a Sun-like star, and rotates 346 times per second. Previous observations place the neutron star's mass at about 2.1 times the Sun's.

"We're surrounded by normal matter, the stuff of our everyday experience, but there's much we don't know about how matter behaves, and how it is transformed, under extreme conditions," said Zaven Arzoumanian, the NICER science lead at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "By measuring the sizes and masses of neutron stars with NICER, we are exploring matter on the verge of imploding into a black hole. Once that happens, we can no longer study matter because it's hidden by the black hole's event horizon."

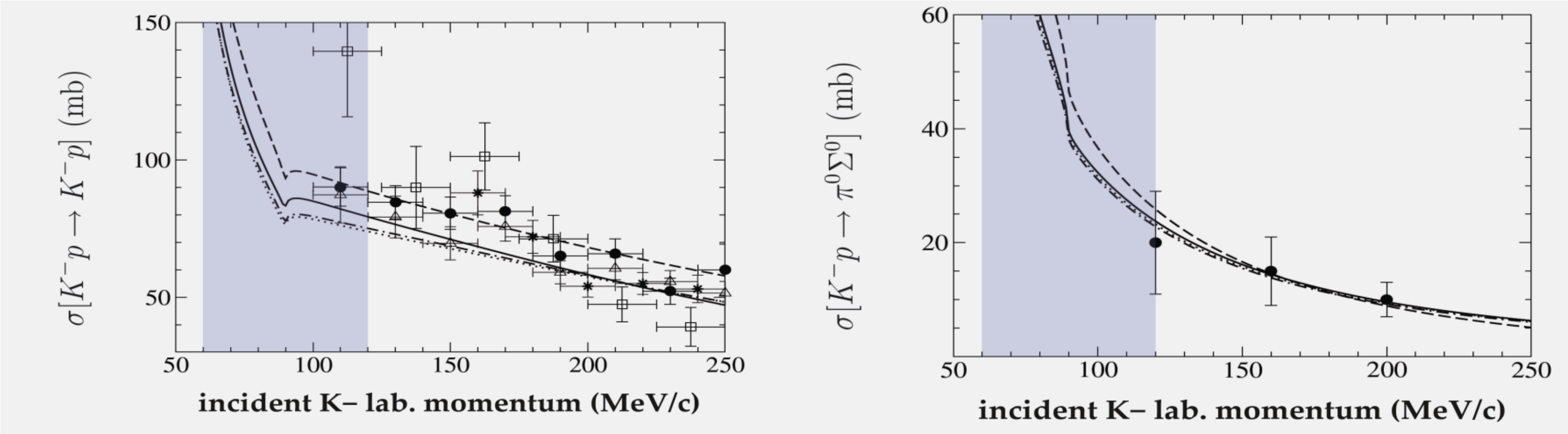
News NASA: NICER (ISS)
Pulsar – white dwarf
Neutron 2.1 Sollar mass
with radius: 12-15 km
the interior is just a sea of quarks…?



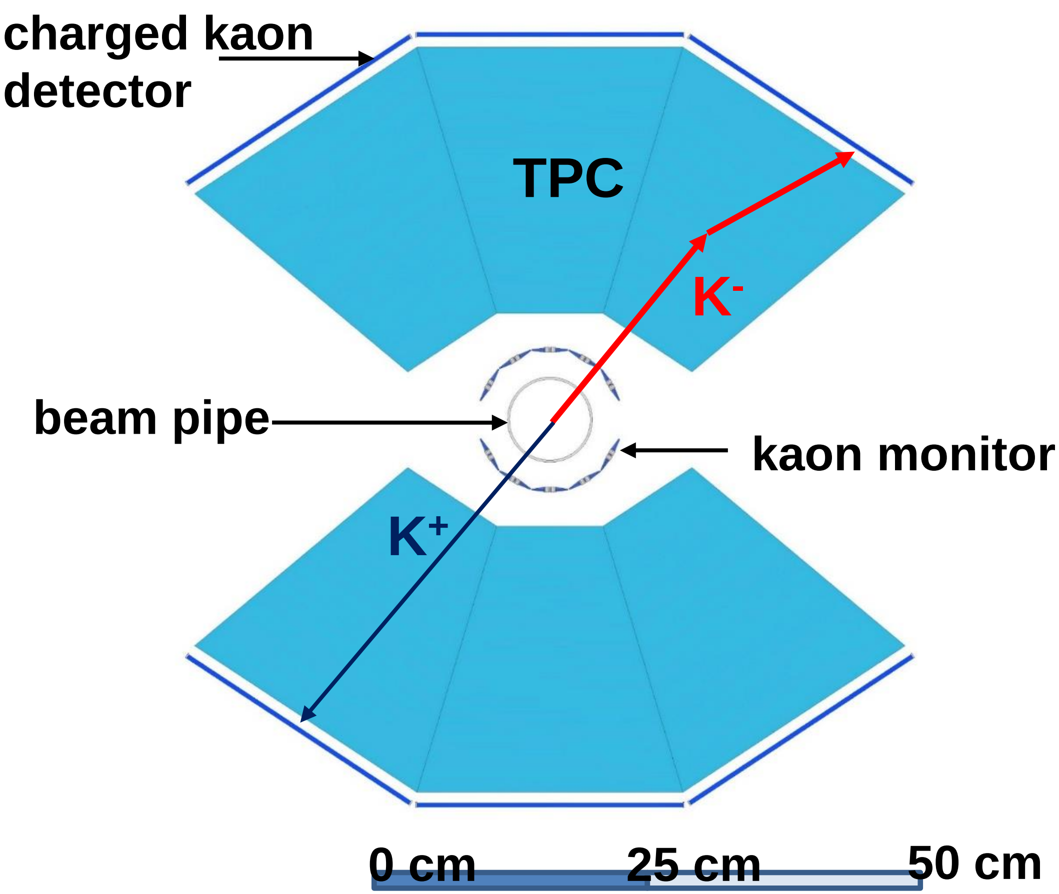
Knscat and int: KAON-NUCLEI SCATTERING and INTERACTION

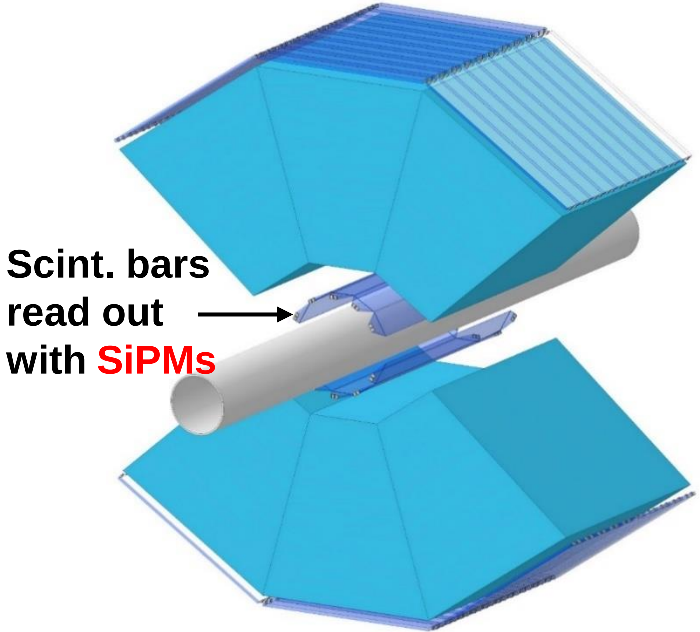
- The present knowledge of total and differential cross sections of low energy k nucleon reactions is very limited.
- Below 150 MeV/c there is a “desert” - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.

- **Studies of Hyperon-nucleon, Hyeron-multinucleaon (AMADEUS experience)**
- **Kaon-nucleon scattering/interaction data are fundamental to validate theories: chiral symmetries; lattice calculations; potential models etc.**

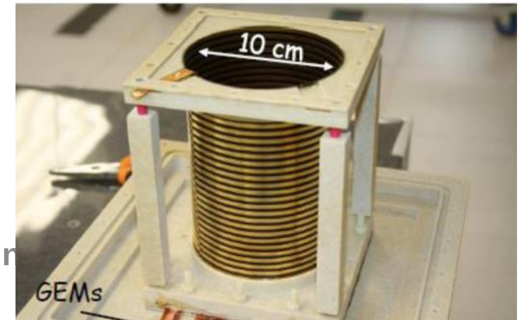


KN1: elastic scattering, layout

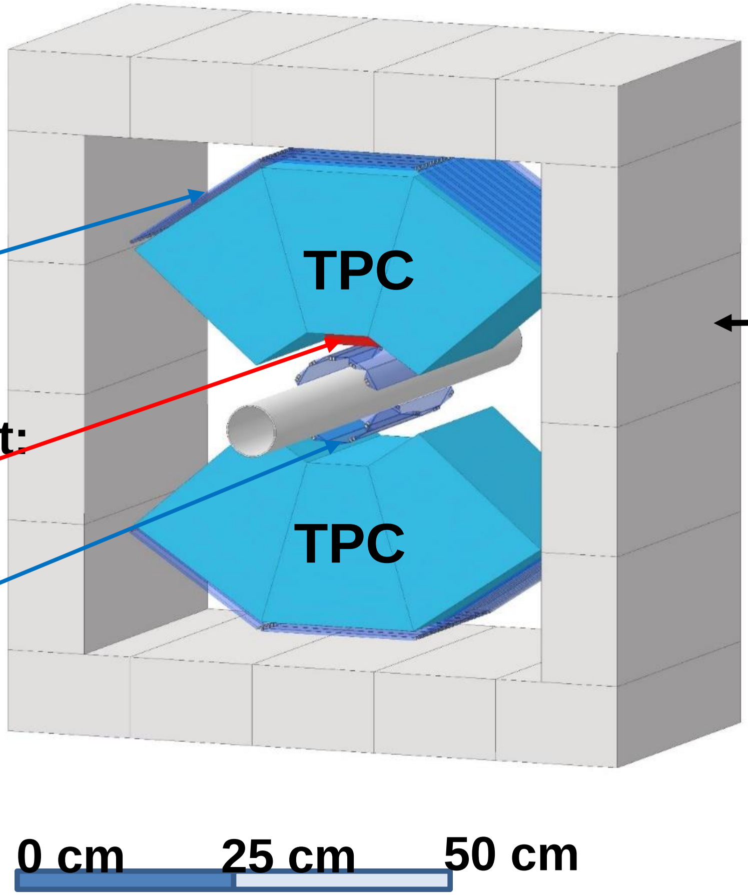




TPC prototyping ongoing at:
Sendai Univ., Japan
SMI, Austria (EU-STRONG2020)



KN2 – inelastic scattering, nuclear interaction…layout



Charged kaon detector

Cryogenic target:
Solid H2, D2, Ar
Liquid He

Kaon monitor

“Sandwich” type calorimeter
32 layers Pb – liq. Scintillator, thickness 25 cm

https://arxiv.org/pdf/2104.06076.pdf

Towards a LOI (authors: Editorial Board only)

Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements.

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K. Piscicchia

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Stefan Meyer Institute of the Austrian Academy of Sciences (SMI), Wien, Austria

D. Bosnar

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The DAΦNE collider at INFN-LNF is a unique source of low-energy kaons, which was used by the DEAR, SIDDHARTA and AMADEUS collaborations for unique measurements of kaonic atoms and kaon-nuclei interactions. Presently, the SIDDHARTA-2 collaboration is underway to measure the kaonic deuterium exotic atom. With this document we outline a proposal for fundamental physics at the strangeness frontier for future measurements of kaonic atoms and kaon-nuclei interactions at DAΦNE, which is intended to stimulate discussions within the broad scientific community performing research directly or indirectly related to this field.

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Very preliminary (sent one week ago) – 11 countries

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STRANU: HOT TOPICS IN STRANGENESS NUCLEAR AND ATOMIC PHYSICS

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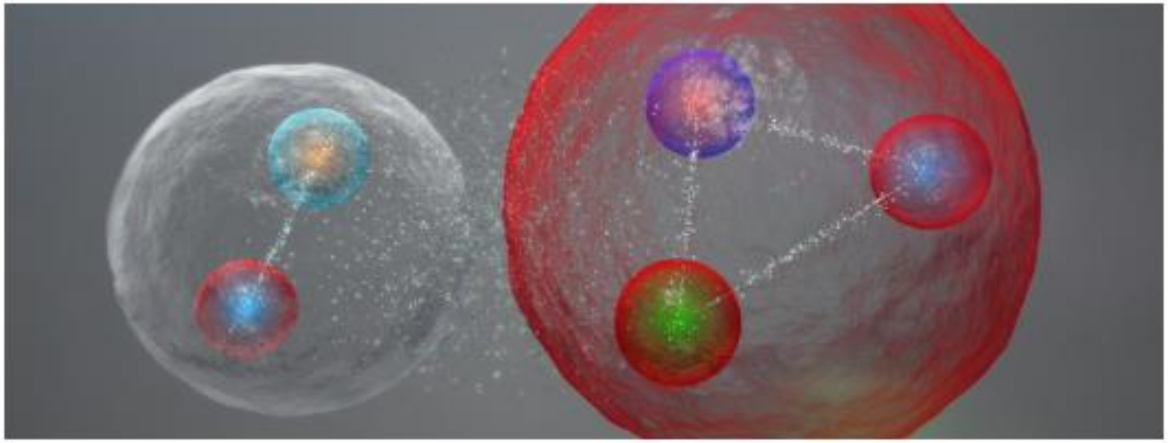
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS



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LOI in preparation

We strongly believe that this is an opportunity which cannot be missed, since we propose to measure fundamental interaction processes which could not be measured till now, and which will have <u>a huge and concrete impact, “now and here”, in particle and nuclear physics, astrophysics, cosmology and foundational Issues, supported by a strong international collaboration.</u>

Our proposed measurements have a huge potential of producing a consistent number of high-impact publications in high-impact factor journals, which will guide the developments of physics at strangeness frontier in the next 10-20 years, setting DAΦNE and LNF on the forefront of fundamental physics studies.

Thank you