



**Strangeness in the Universe?
Low-energy kaon-nuclei interaction studies
by AMADEUS at the DAFNE Collider**

Catalina Curceanu

(On behalf of the AMADEUS collaboration)

LNF – INFN, Frascati

KLOE2 Workshop on e^+e^- collision at 1 GeV, LNF-INFN, 26-28 Oct. 2016

The Standard Model

Quarks

<i>u</i>	<i>c</i>	<i>t</i>
up	charm	top

<i>d</i>	<i>s</i>	<i>b</i>
down	strange	bottom

Forces

Z	γ
Z boson	photon

W	g
W boson	gluon

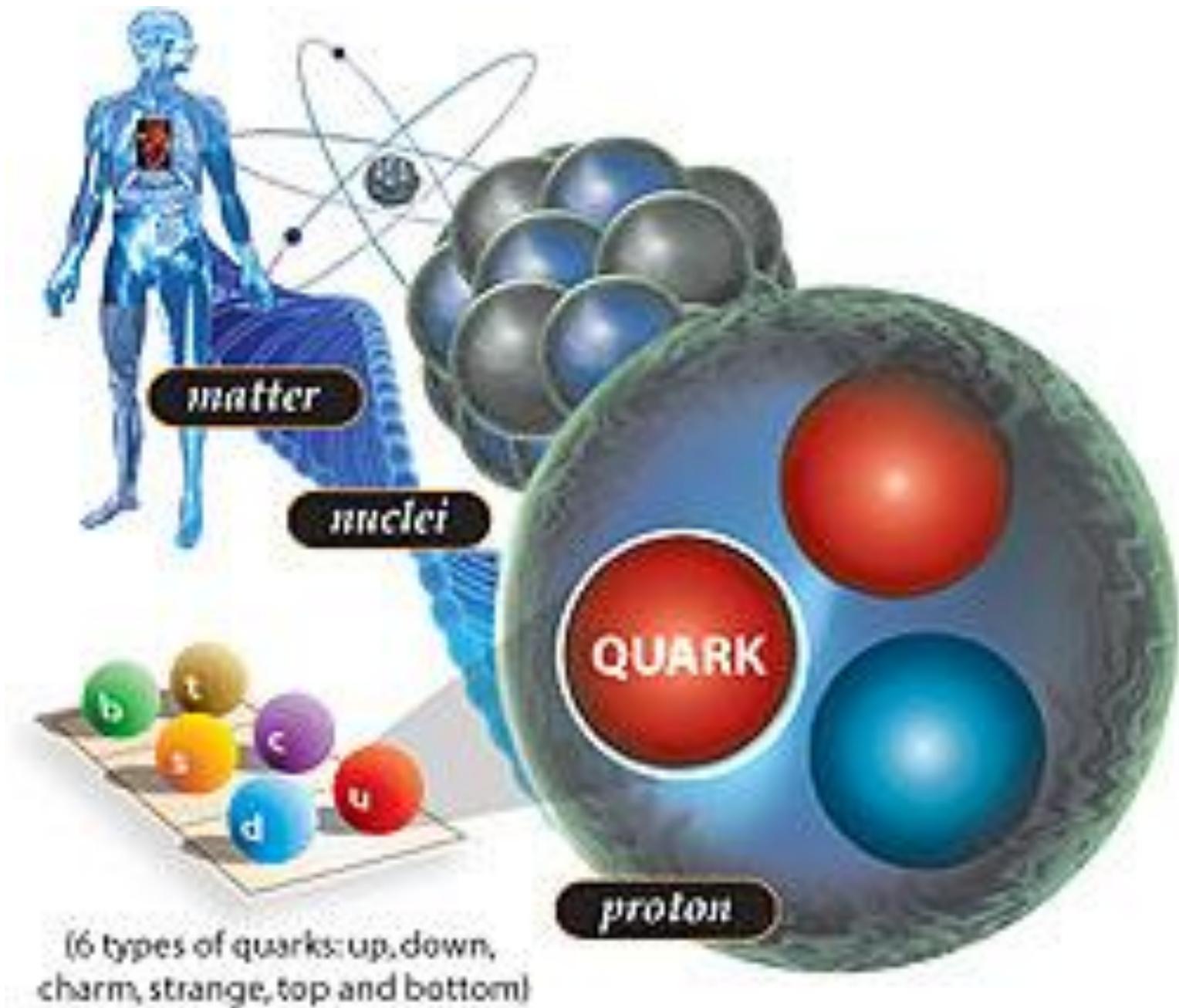
e	μ	τ
electron	muon	tau

ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

Leptons



The Standard Model



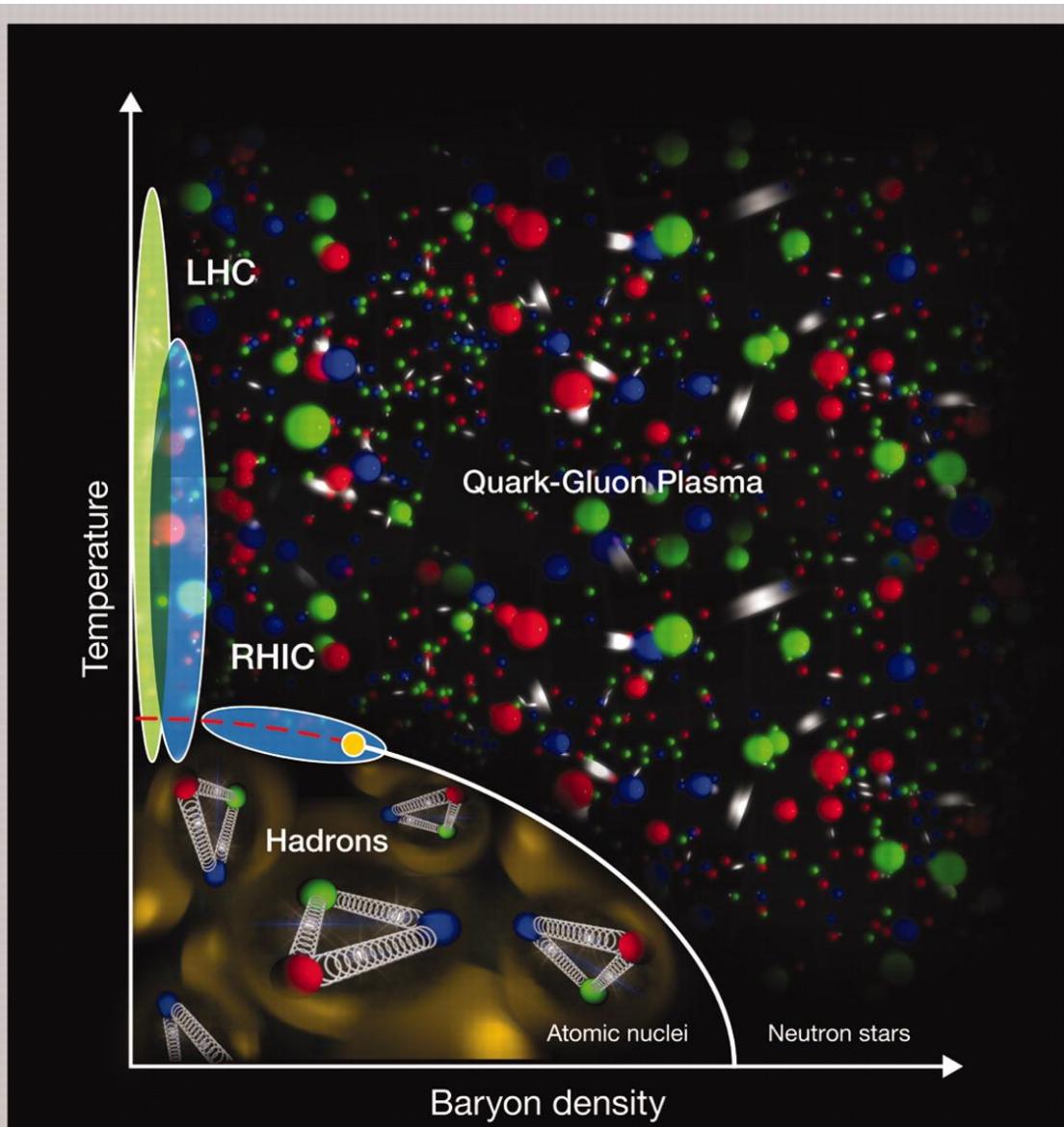
The low-energy kaon-nucleon/nuclei interaction studies are fundamental for understanding QCD in non-perturbative regime:

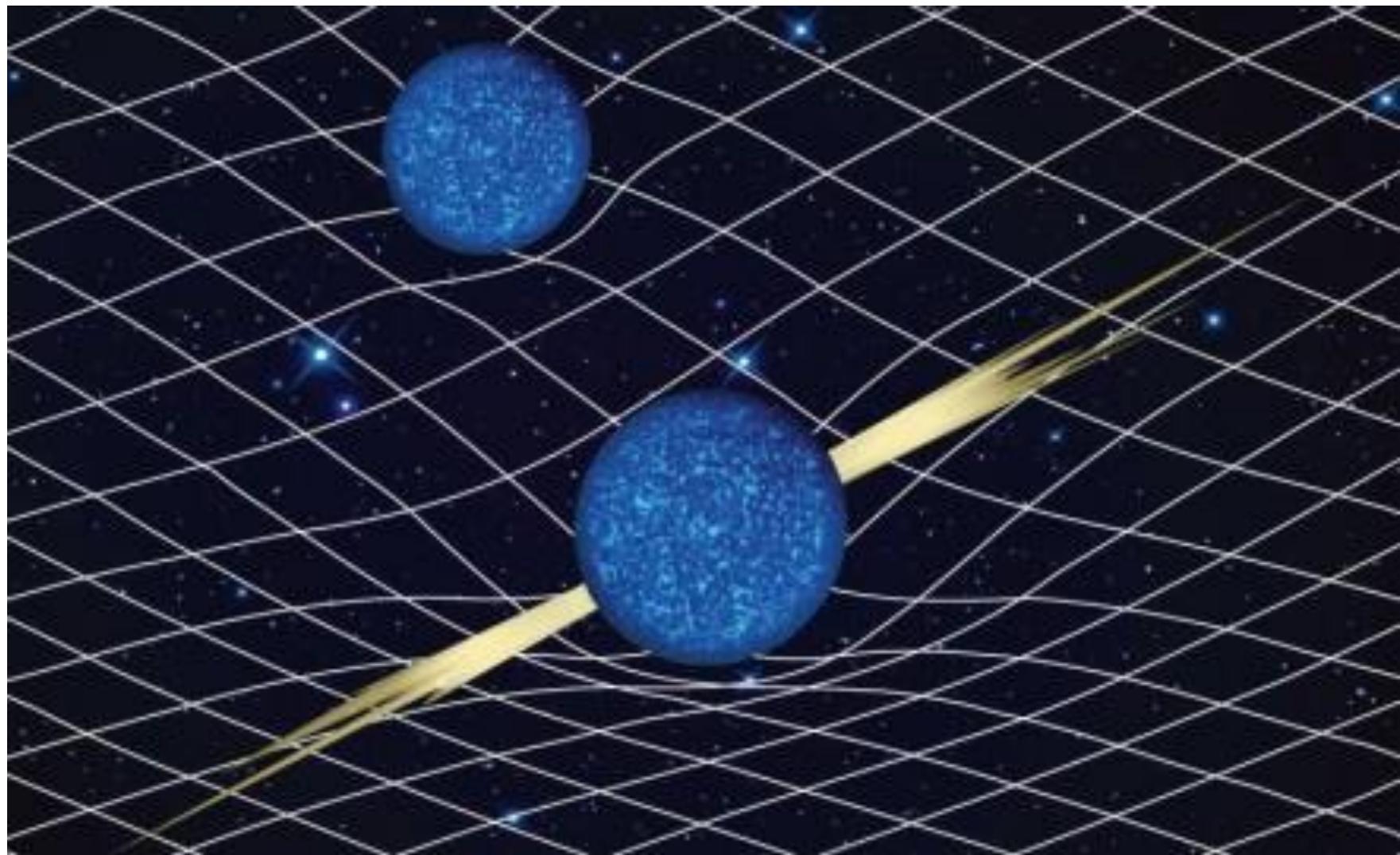
- **Explicit and spontaneous chiral symmetry breaking (mass of nucleons)**
- **Dense baryonic matter ->**
- **Neutron (strange?) stars EOS**
- **Dark matter with strangeness?**

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



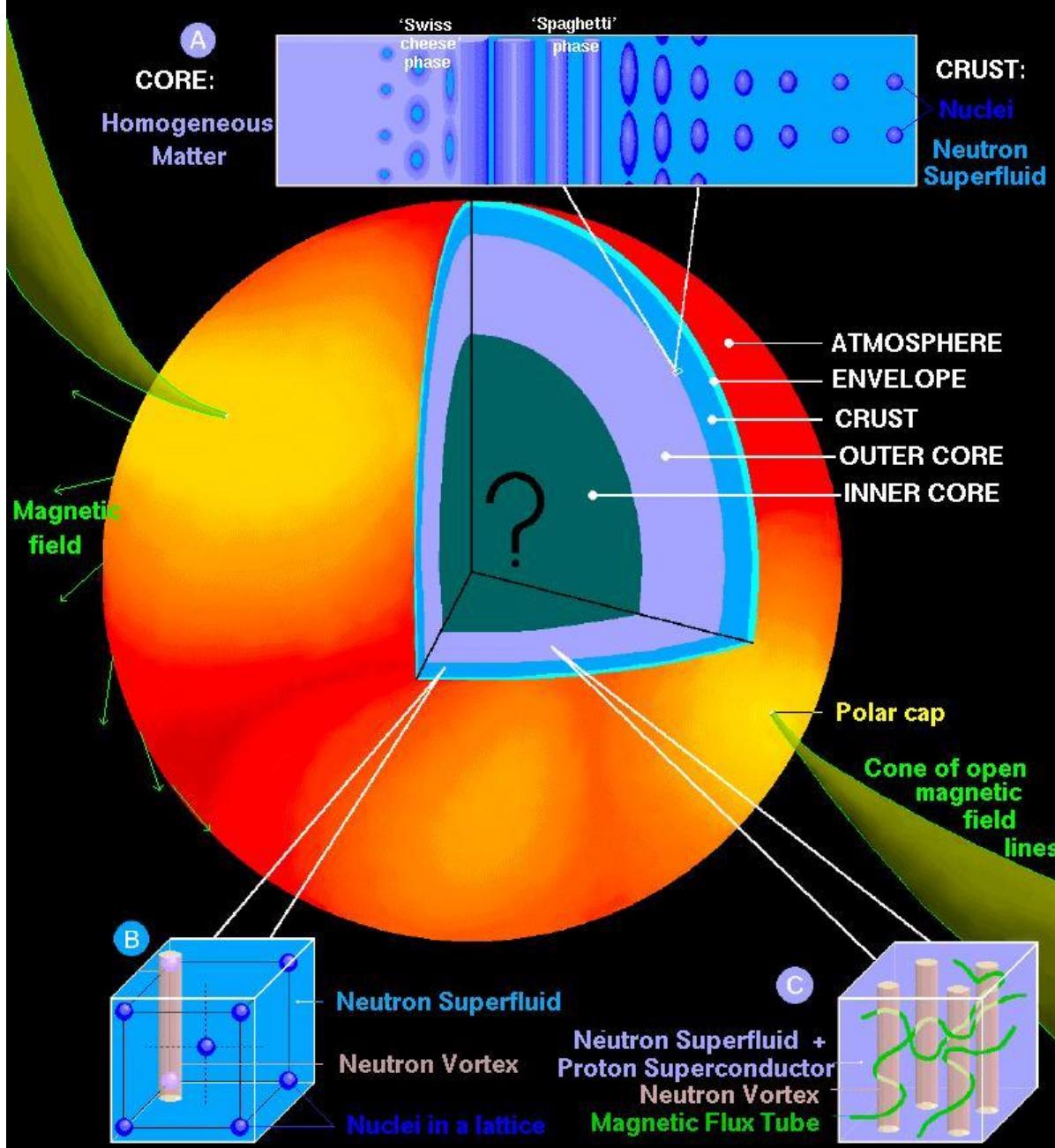
Low-energy kaon-nuclei Interactions studies



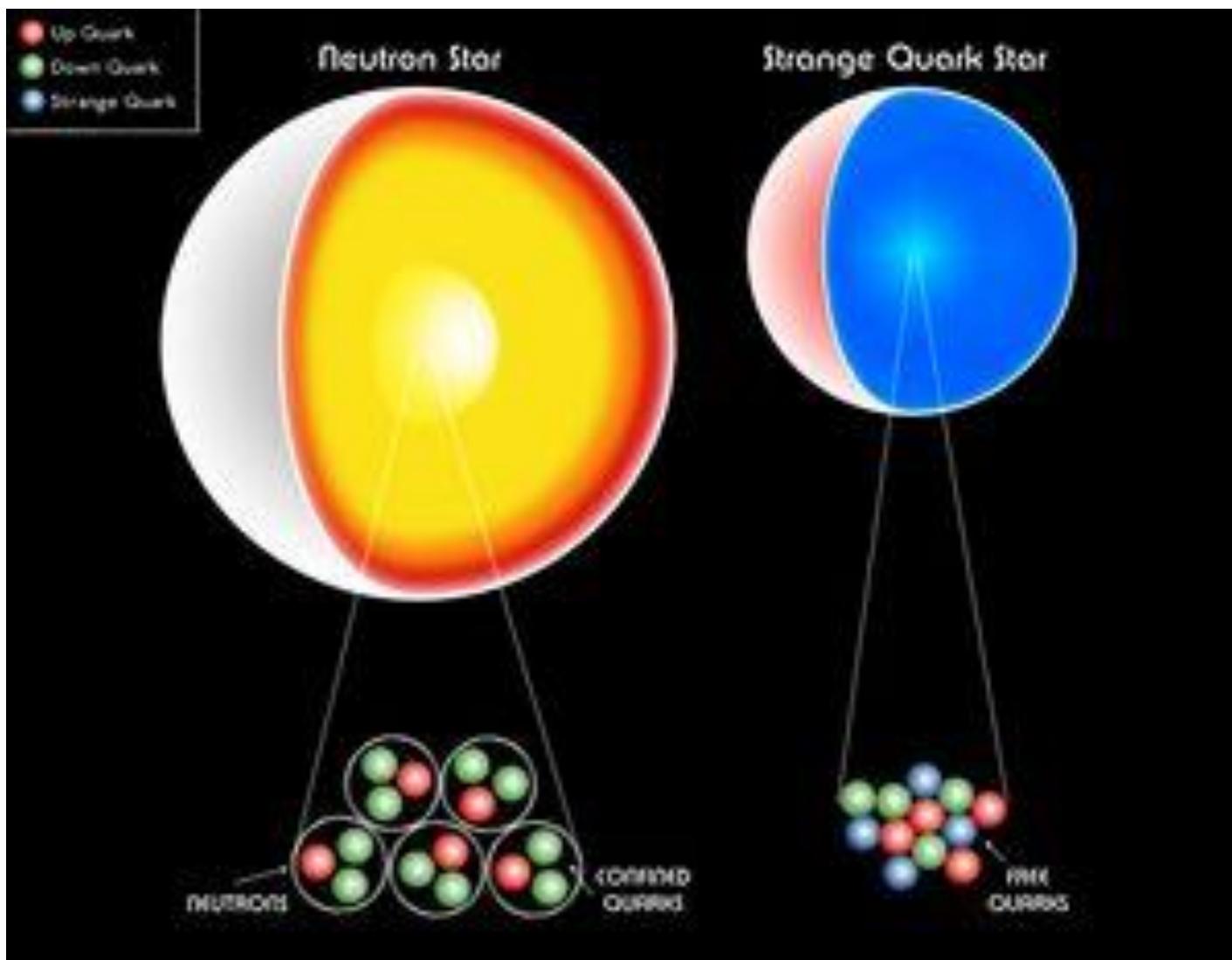


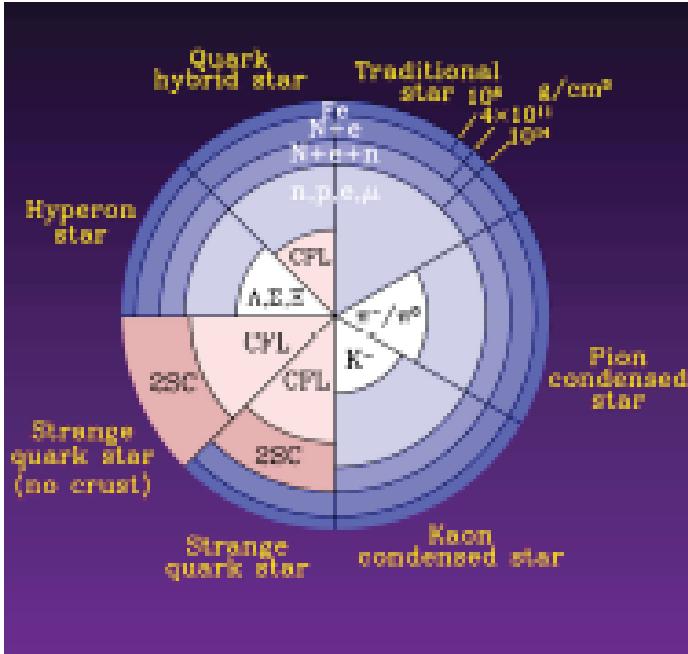


A NEUTRON STAR: SURFACE and INTERIOR



Could strangeness play a role in neutron stars?





Neutron Star Scenarios

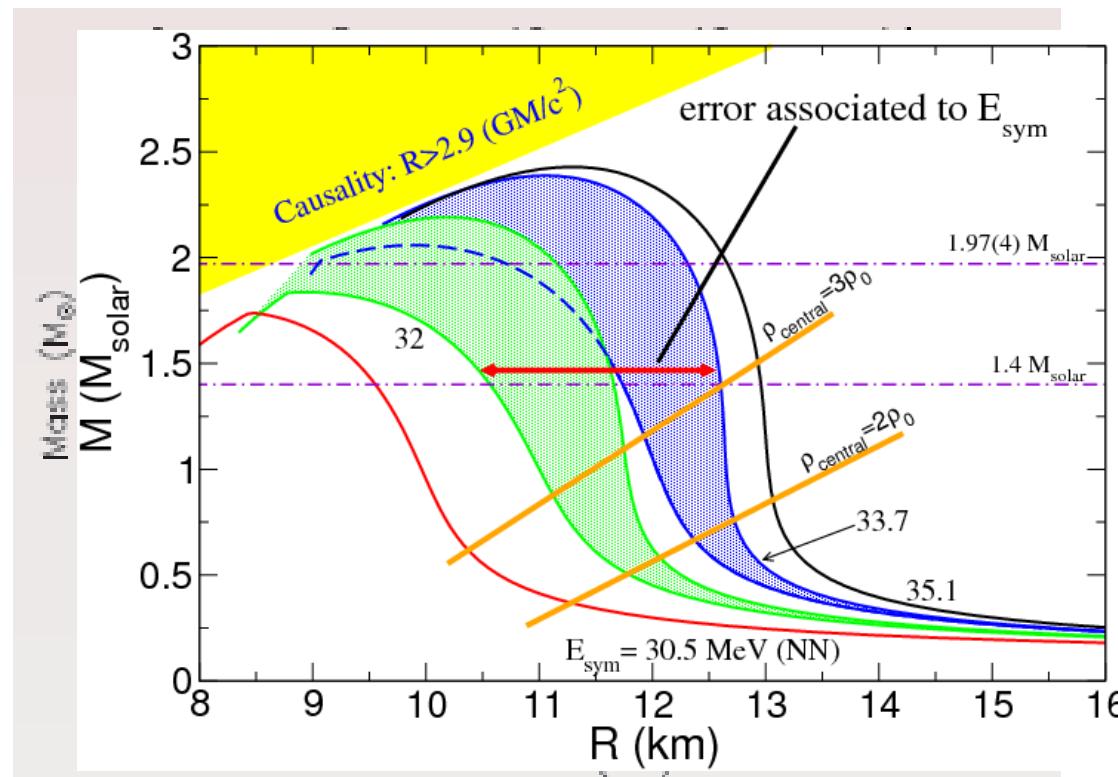
$$\frac{dP}{dr} = -\frac{G}{c^2} \frac{(M + 4\pi r^3 P)(\epsilon + P)}{r(r - GM/c^2)}$$

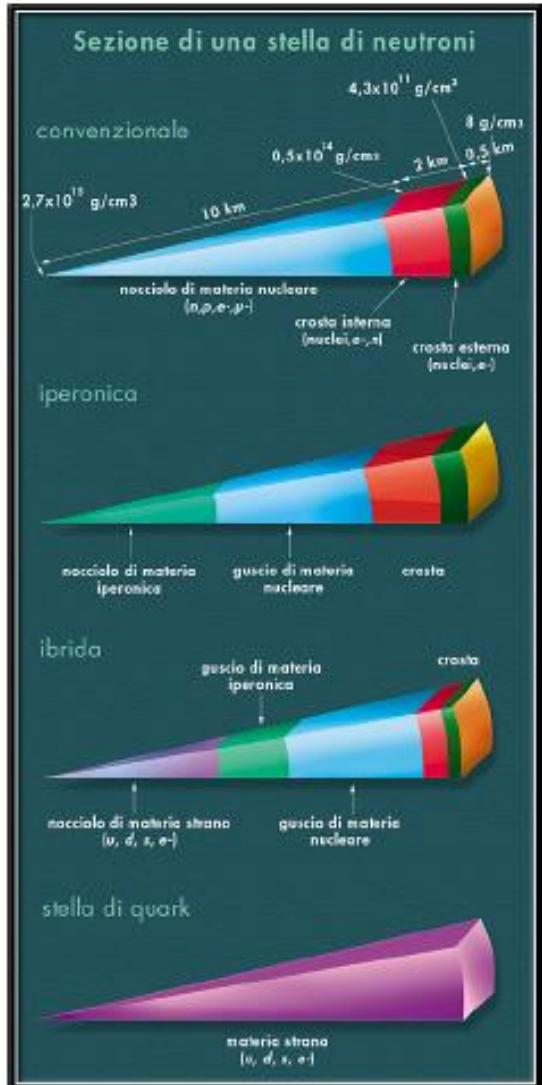
$$\frac{dM}{dr} = 4\pi r^2 \frac{\epsilon}{c^2}$$

NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER

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

Mass-Radius Relation





Two families of Compact Stars

Hadron Stars (HS)

- Nucleonic Stars
- Hyperonic Stars

Quark Stars (QS)

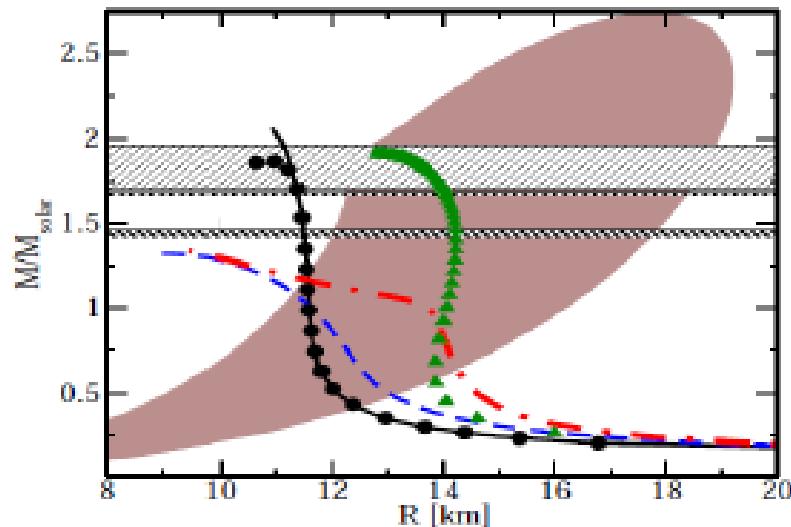
- Hybrid Stars
- Strange Stars

Isaac Vidana

Signature in the gravitational wave signal of the two-families scenario: the merger of two neutron stars

Alessandro Drago - Ferrara

Hybrid stars or quark stars?



Kurkela et al PRD81(2010)105021

pQCD calculations: "... equations of state including quark matter lead to hybrid star masses up to $2M_s$, in agreement with current observations.

For strange stars, we find **maximal masses of $2.75M_s$** and conclude that confirmed observations of compact stars with $M > 2M_s$ would strongly favor the existence of stable strange quark matter"

Before the discoveries of the $2M_s$ stars!!

The two families scenario

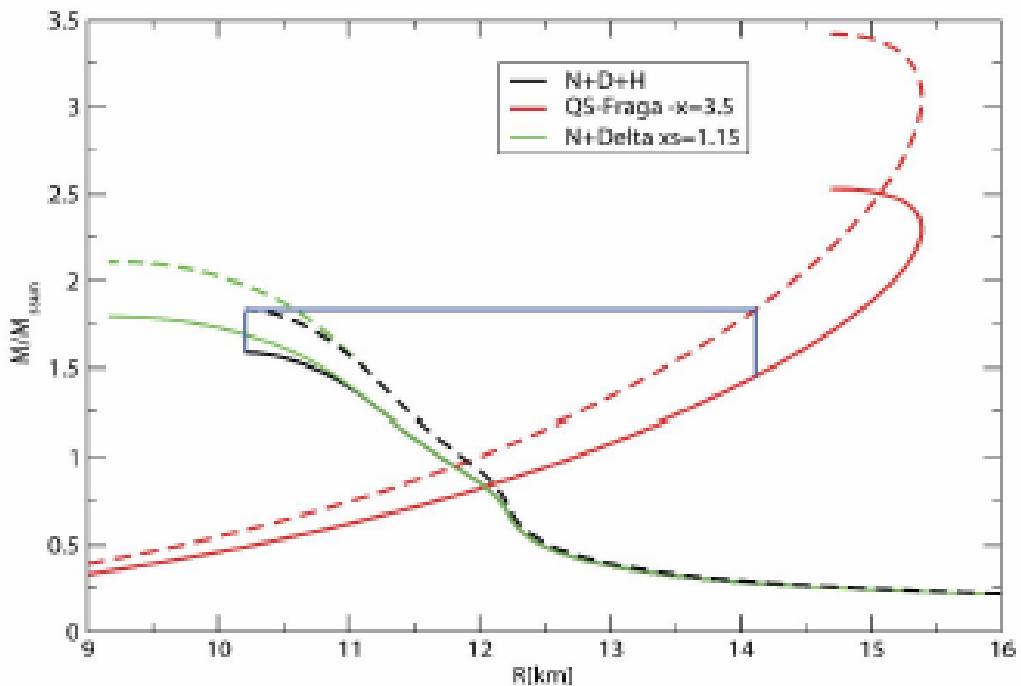
Why conversion should then occur?

Quark stars are more bound:
at a fixed total baryon number
they have a smaller gravitational
mass wrt hadronic stars.

The hadronic stars are stable
till when some strangeness
component (e.g. hyperons)
starts appearing in the core.

Only at that point quark matter
nucleation can start.

Finite size effects (surface tension)
can further delay the formation
of the first droplet of strange matter



The maximum mass of a quark star can be as large as
 $2.75 M_s \geq 2 \times (1.3 \div 1.4) M_s$. (Dynamically stable up to almost 1.3+1.3)

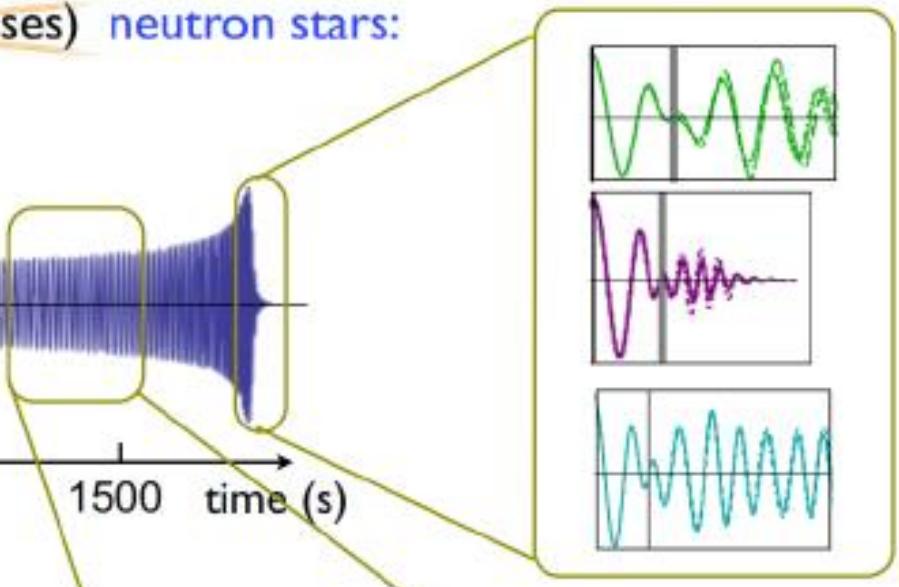
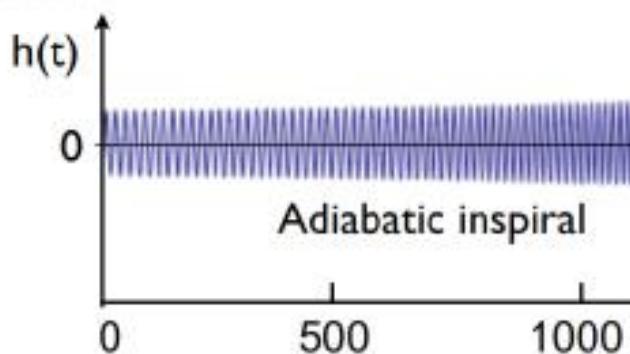
Therefore it is possible to have a ultra-massive quark star produced
by the merging of two normal-mass neutron stars.

The post-merging e.m. signal of the associated short GRB could show a
quasi-plateau emission, similar to the one observed in many long GRBs.

Gravitational wave signal from coalescing binaries

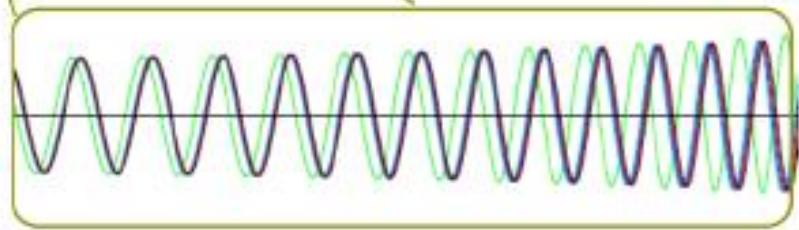
- expect to observe ~ tens of NS binary inspirals per year [0.4-400]
- signal from black holes (point masses) neutron stars:

waveform



precise shape of “chirp” depends
on parameters of the binary
(masses, spins, equation of state ..)

$$M_{\text{chirp}} = (M_1 M_2)^{3/5} (M_1 + M_2)^{-1/5}$$



Strangeness, Gravitational Waves and Neutron Stars

Frascati, June 12, 2016

**Quark Deconfinement in
Neutron Stars
and
Astrophysical implications**

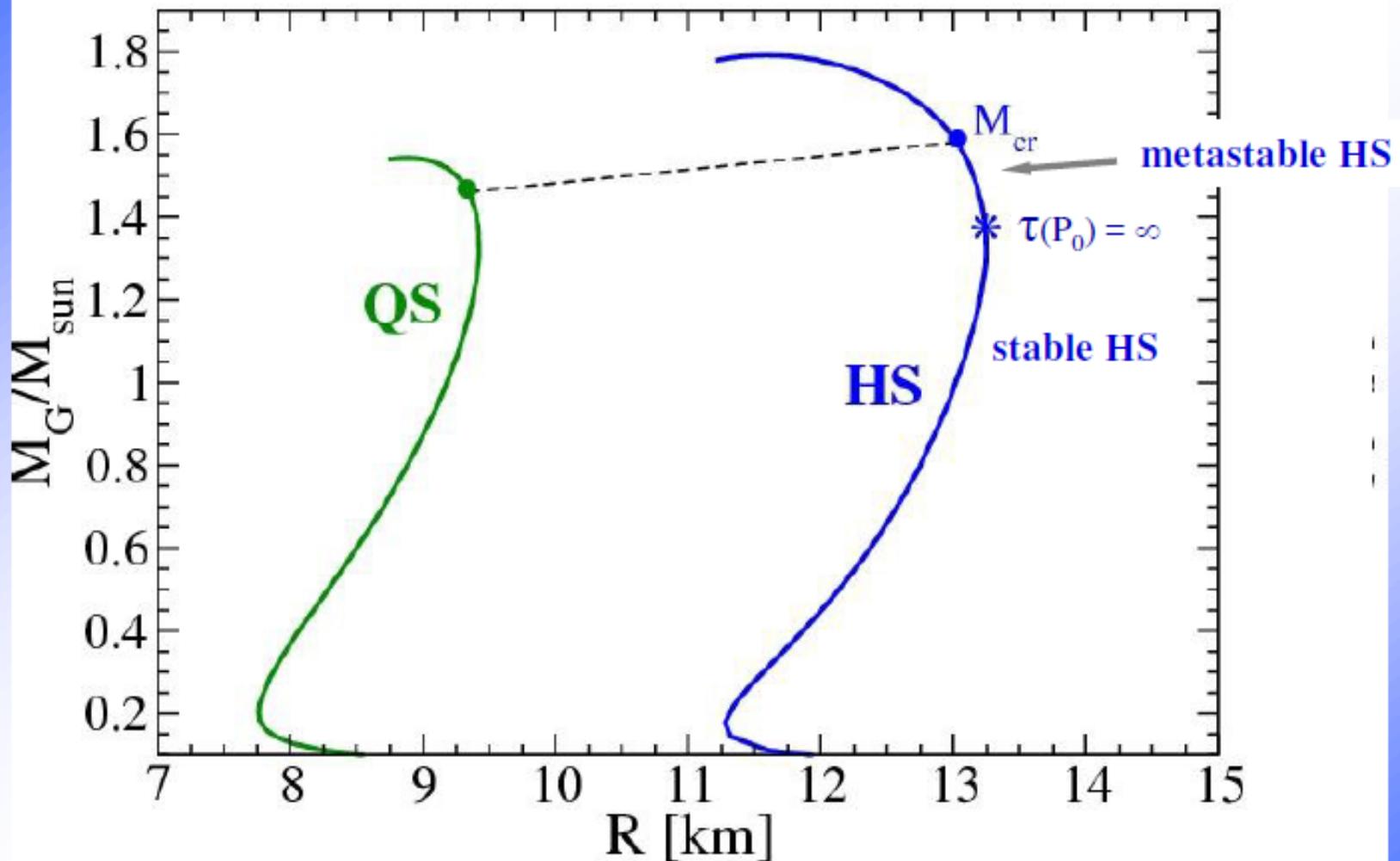
Ignazio Bombaci

Dipartimento di Fisica “E. Fermi”, Università di Pisa

Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa

European Gravitational Observatory (EGO), Cascina

The two families of Compact Stars



GM1($X\sigma = 0.6$) + MIT bag model ($B=85 \text{ MeV/fm}^3$, $m_s=150 \text{ MeV}$)

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



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





DAΦNE, since 1998



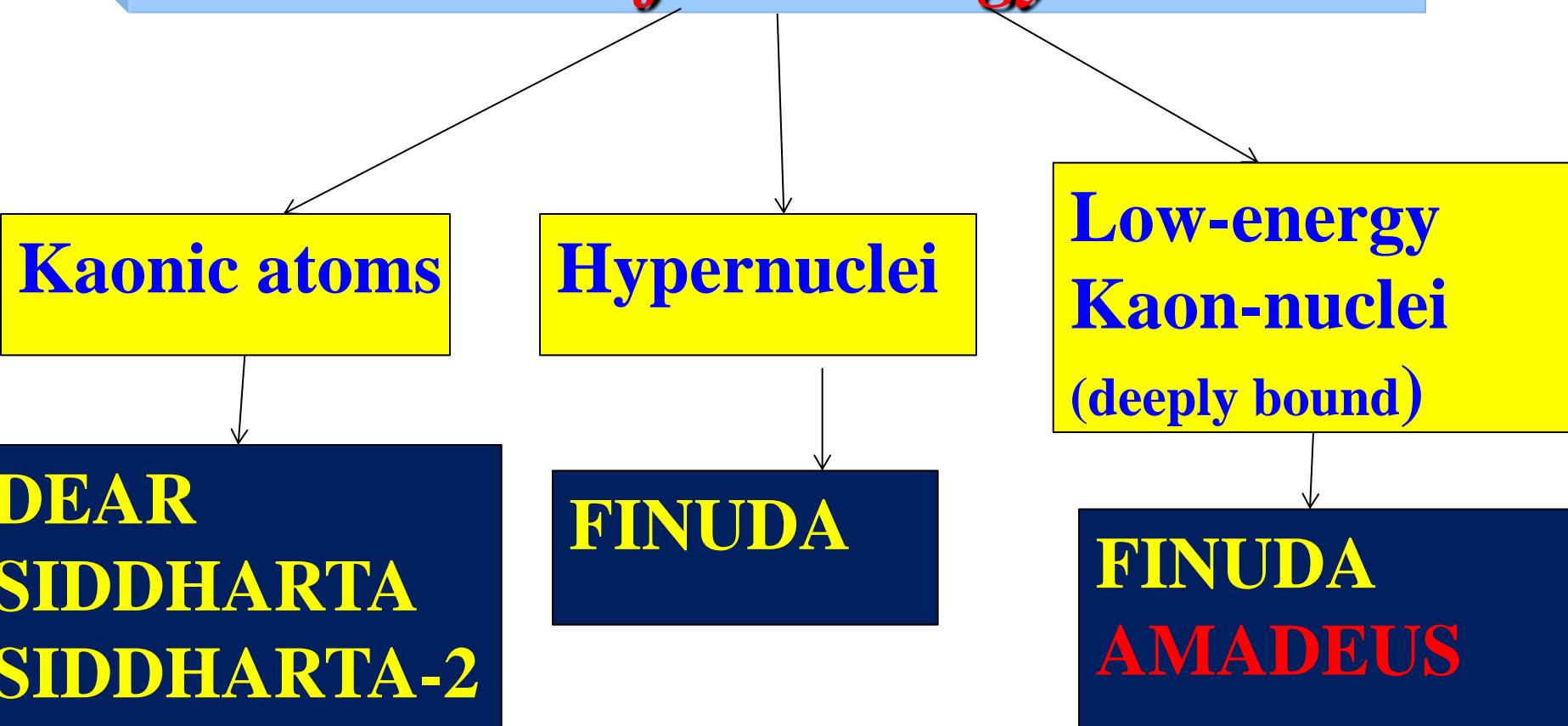
DAFNE

e⁻ e⁺ collider

- $\Phi \rightarrow K^- K^+ (49.1\%)$
- Monochromatic low-energy K⁻ ($\sim 127 \text{ MeV}/c$)
- Less hadronic background due to the beam
(compare to hadron beam line : e.g. KEK /JPARC)

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

The DAFNE collider the best possible beam of low energy kaons



AMADEUS proposal

Antikaon Matter At DAΦNE: Experiments with Unraveling Spectroscopy

AMADEUS collaboration

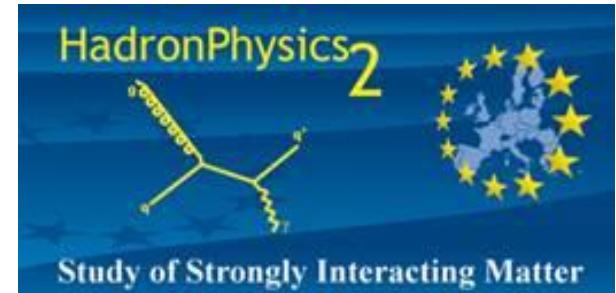
116 scientists from 14 Countries and 34 Institutes

lnf.infn.it/esperimenti/siddharta
and

LNF-07/24(IR) Report on lnf.infn.it web-page (Library)

AMADEUS started in 2005 and
was presented and discussed in all the LNF Scientific
Committees

EU Fundings FP7 – I3HP2:
Network WP9 – LEANNIS;
WP24 (SiPM JRA);
WP28 (GEM JRA)



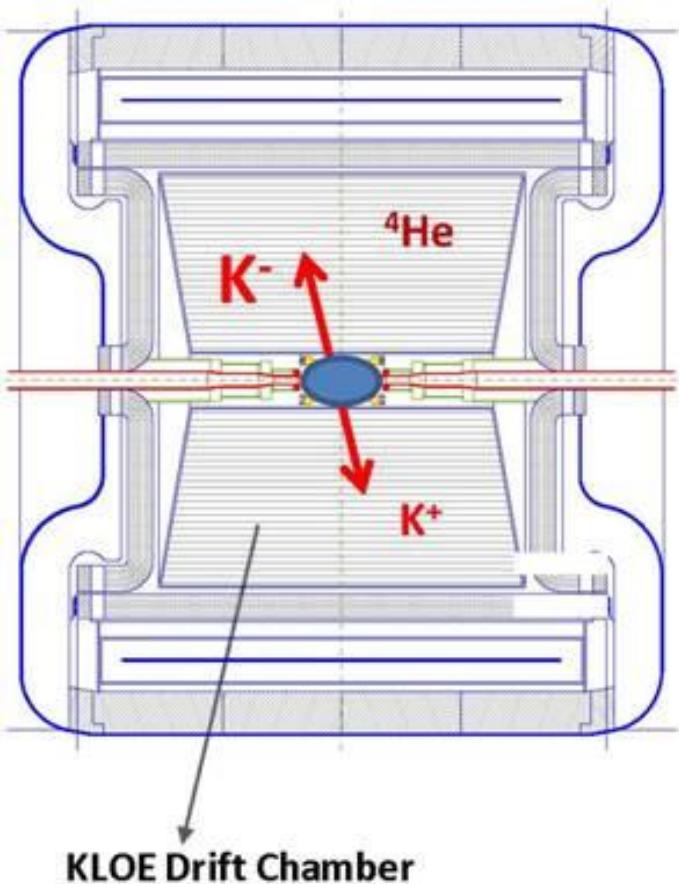
AMADEUS experimental program

Unprecedented studies of the low-energy charged kaons interaction in nuclear matter in order to obtain unique quality information about:

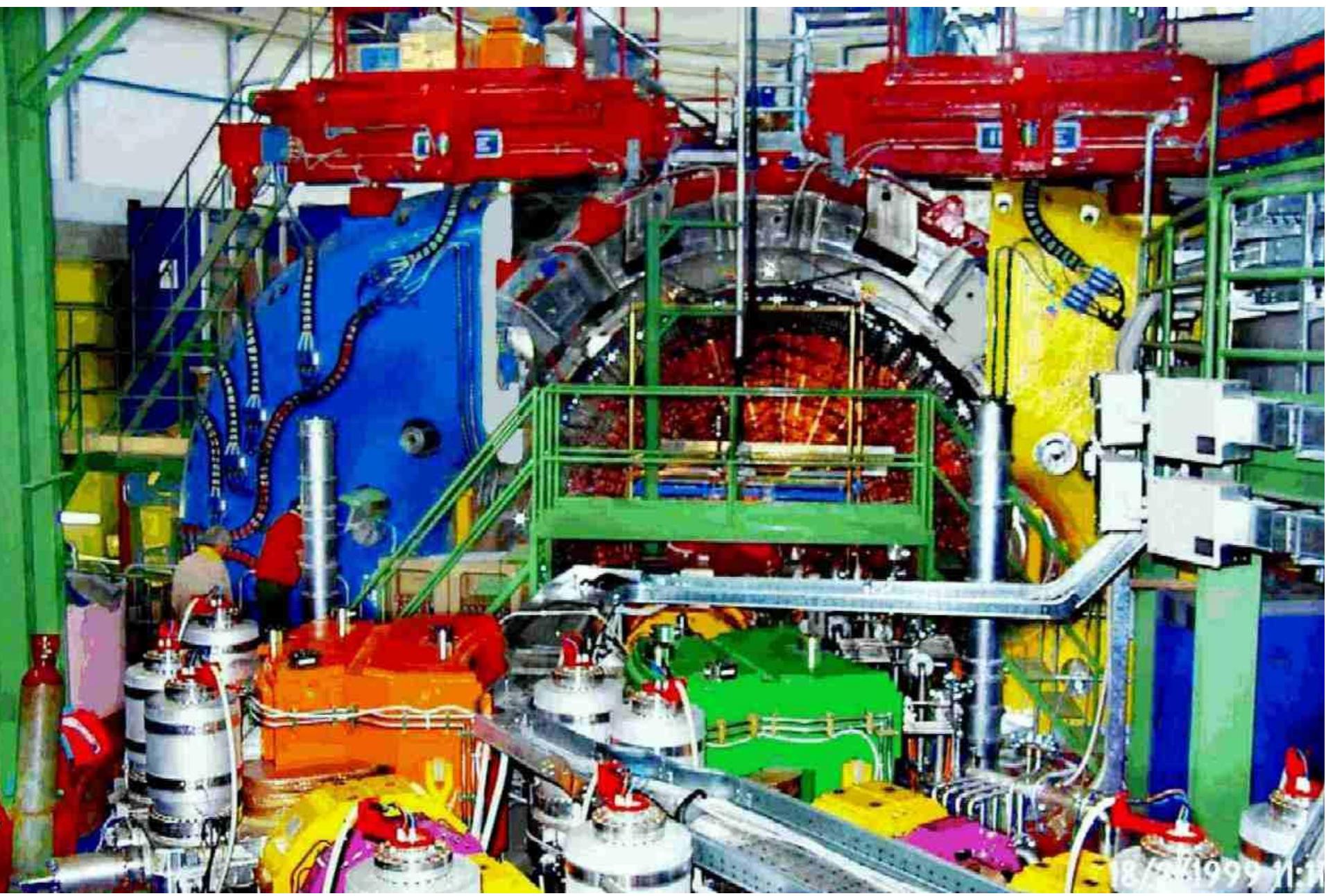
- investigation of the $\Lambda(1405)$ properties,
- extraction of hyperon-nucleon two and three body interactions
YN (NN) → strong impact on the EOS of neutron stars
- $K^{-/+}$ N elastic and inelastic scattering cross section below 100 MeV/c
- search for kaonic nuclear clusters (deeply bound kaonic nuclei)
- study of neutron rich hypernuclei
- Many other processes of interest

Hadronic interactions of K⁻ in KLOE

- *AMADEUS – step 0 – feasibility studies*



- The Drift Chambers of KLOE contain mainly ${}^4\text{He}$
- From analysis of KLOE data and Monte Carlo:
0.1 % of K⁻ from daΦne should stop in the DC volume
- This would lead to hundreds of possible kaonic clusters produced in the 2 fb^{-1} of KLOE data.

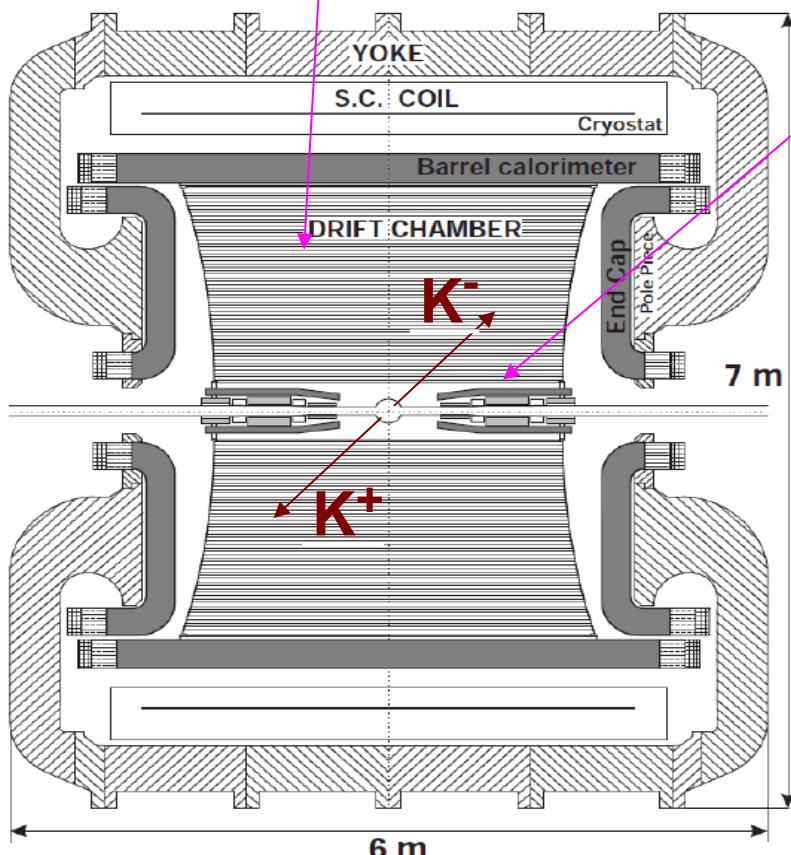


18/5/99

K⁻ absorption on light nuclei

from the materials of the KLOE detector

DC gas (90% He, 10% C₄H₁₀) & DC wall (C + H)
AT-REST (K⁻ absorbed from atomic orbit) or **IN-FLIGHT**
(p_K~100MeV)



Advantage:
excellent resolution ..

$$\sigma_{p\Lambda} = 0.49 \pm 0.01 \text{ MeV/c in DC gas}$$
$$\sigma_{m\gamma\gamma} = 18.3 \pm 0.6 \text{ MeV/c}^2$$

Disadvantage:

Not dedicated target → different nuclei
contamination → complex interpretation .. but
→ new features .. K⁻ in flight absorption.

AMADEUS status

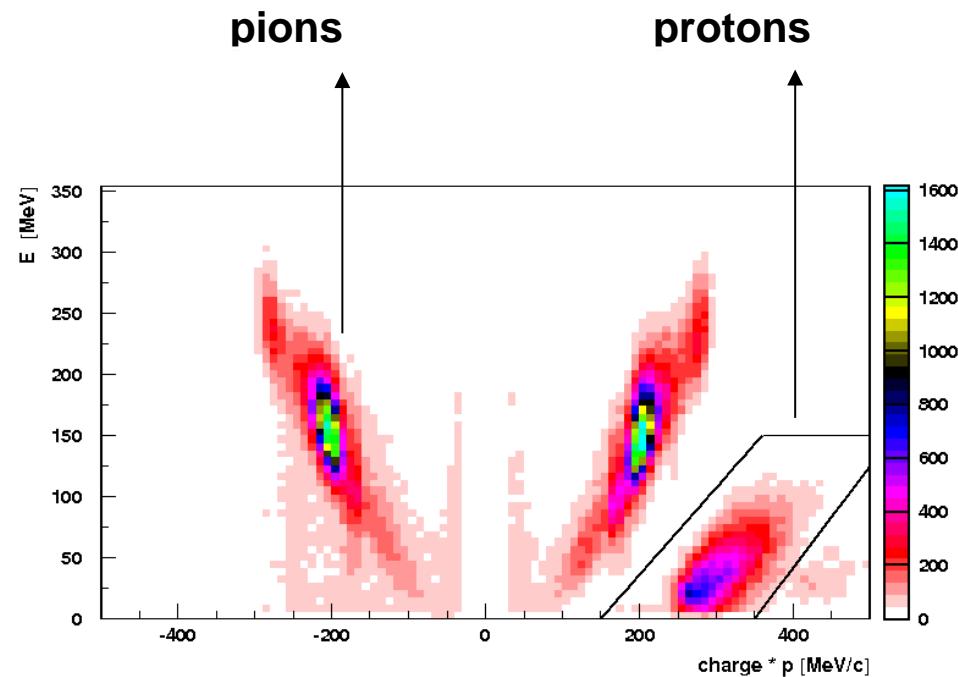
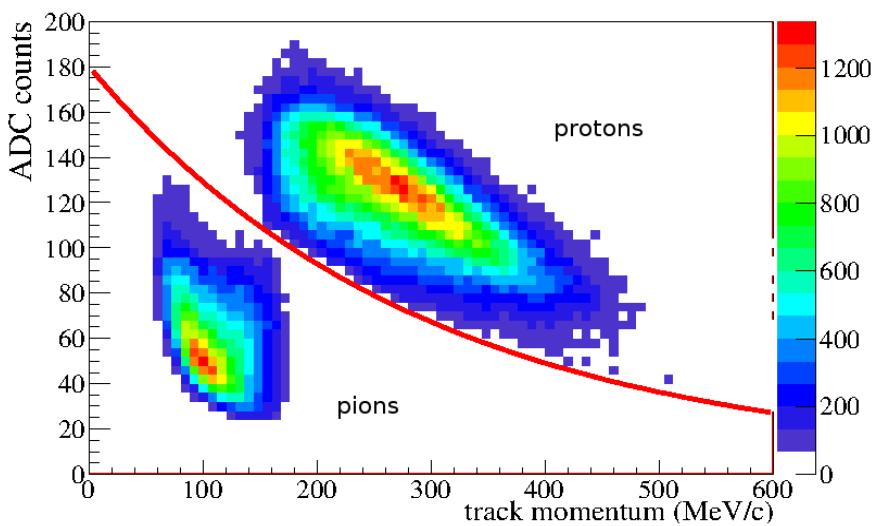
- Analyses of the **2002-2005 KLOE data**:
- Dedicated **2012 run with pure Carbon target** inside KLOE
 - Λp from 1NA or 2NA (single or multi-nucleon absorption)
 - Λd and Λt channels
 - $\Lambda(1405) \rightarrow \Sigma^0 \pi^0$
 - $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$
 - $\Sigma N/\Lambda N$ internal conversion rates
- R&D for more refined setup
- Future possible scenario

event selection

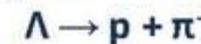
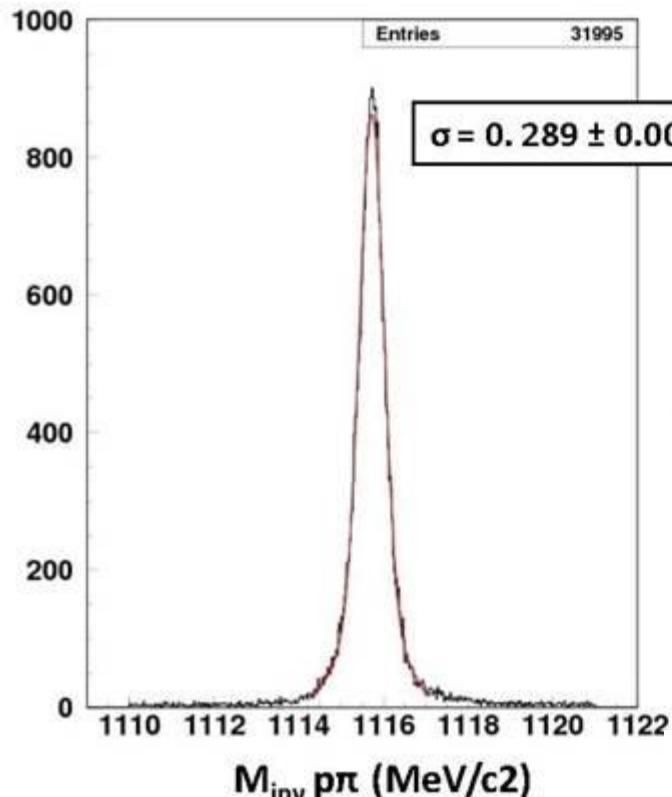
1st step : $\Lambda \rightarrow p + \pi^-$ identification
(BR = 63.8%)

- p - π^- identification via:**
- dE/dx information
 - E deposited in the EMC

- dE/dx



Lambda invariant mass



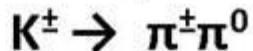
- Dedicated event selection to avoid **Energy loss in the DC wall**
- Best χ^2 tracks and vertices

PRELIMINARY

$$M_{\text{inv}} = 1115,723 \pm 0.003 \text{ stat} \quad (\text{MeV}/c^2)$$

PDG: $M_\Lambda = 1115,683 \pm 0.006 \text{ stat} \pm 0.006 \text{ syst } (\text{MeV}/c^2)$

- Sistematics dependent of momentum calibration
- Preliminary evaluation with 2-body decay



- Pure carbon target inserted in KLOE end of August 2012 ; data taking till December 2012

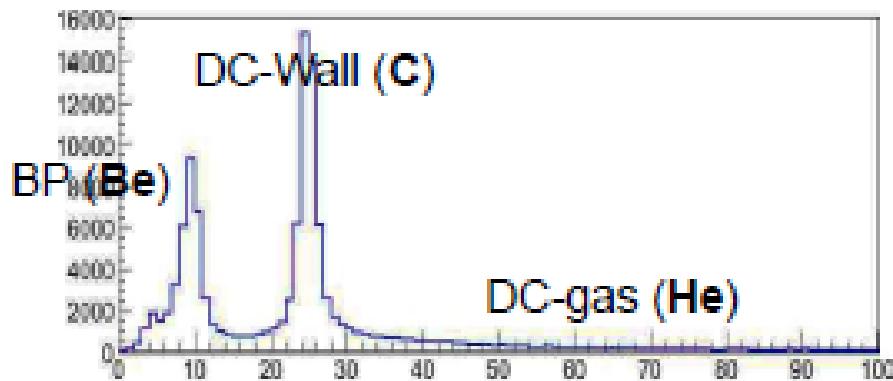


KLOE data on K⁻ nuclear absorption

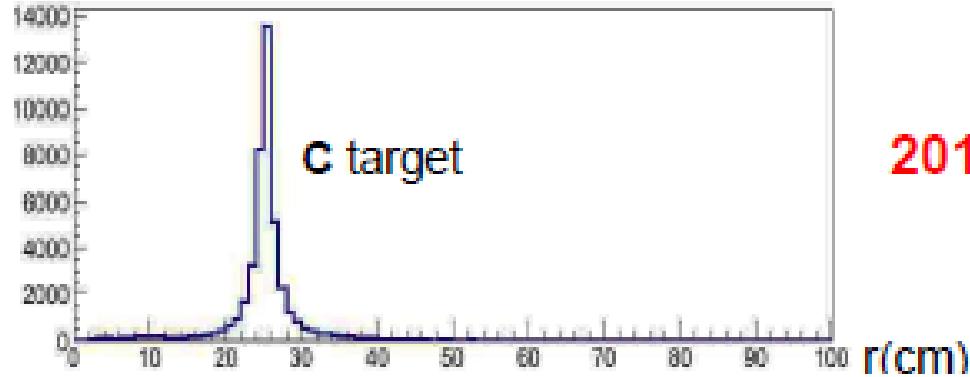
Use of two different data samples:

- KLOE data from 2004/2005 (2.2 fb^{-1} total, 1.5 fb^{-1} analyzed)
- Dedicated run in november/december 2012 with a **Carbon target** of 4/6 mm of thickness ($\sim 90 \text{ pb}^{-1}$; analyzed 37 pb^{-1} , x1.5 statistics)

Position of the K⁻ hadronic interaction inside KLOE:



2005 data



2012 with Carbon target



K^-

2/3/4 NA yields

from

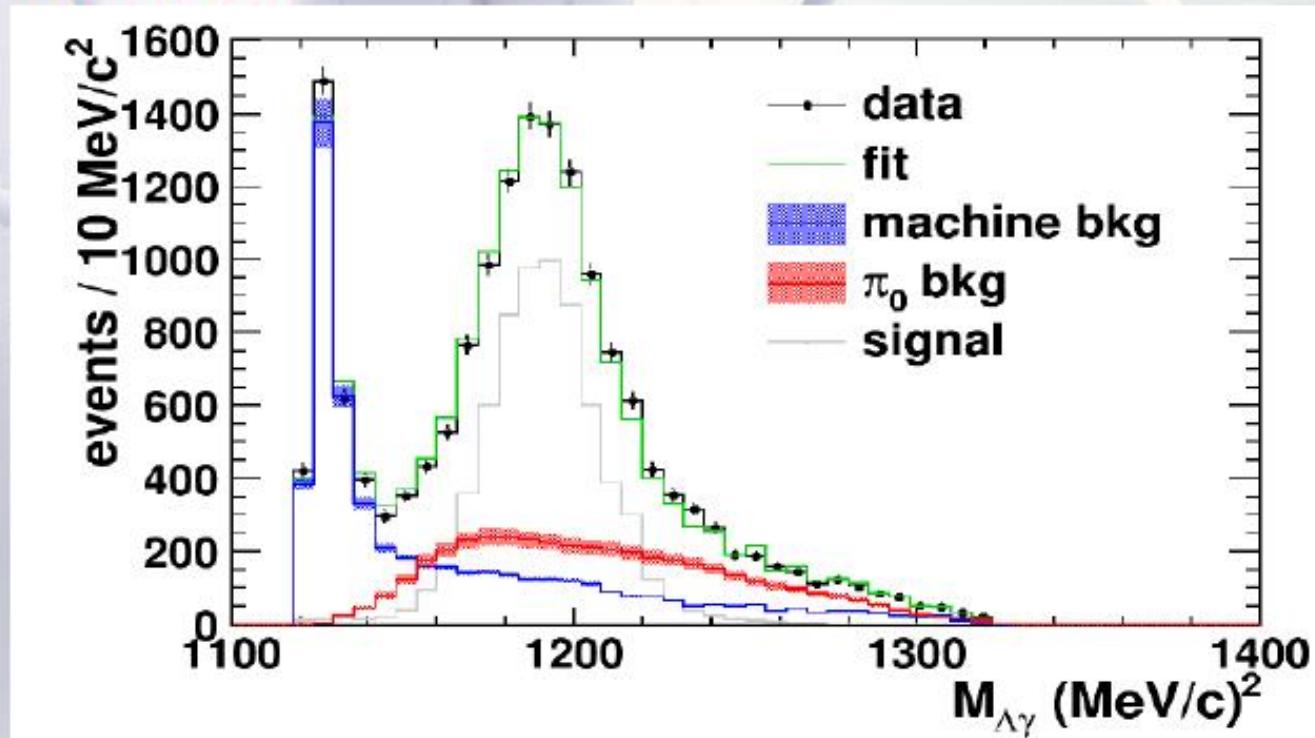
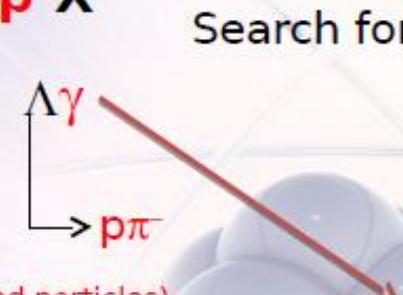
$\Sigma^0 p / \Lambda t$ channels

$\Sigma^0 p$ correlation study .. PART 2b



$\Sigma^0 p$ correlation study

K^-



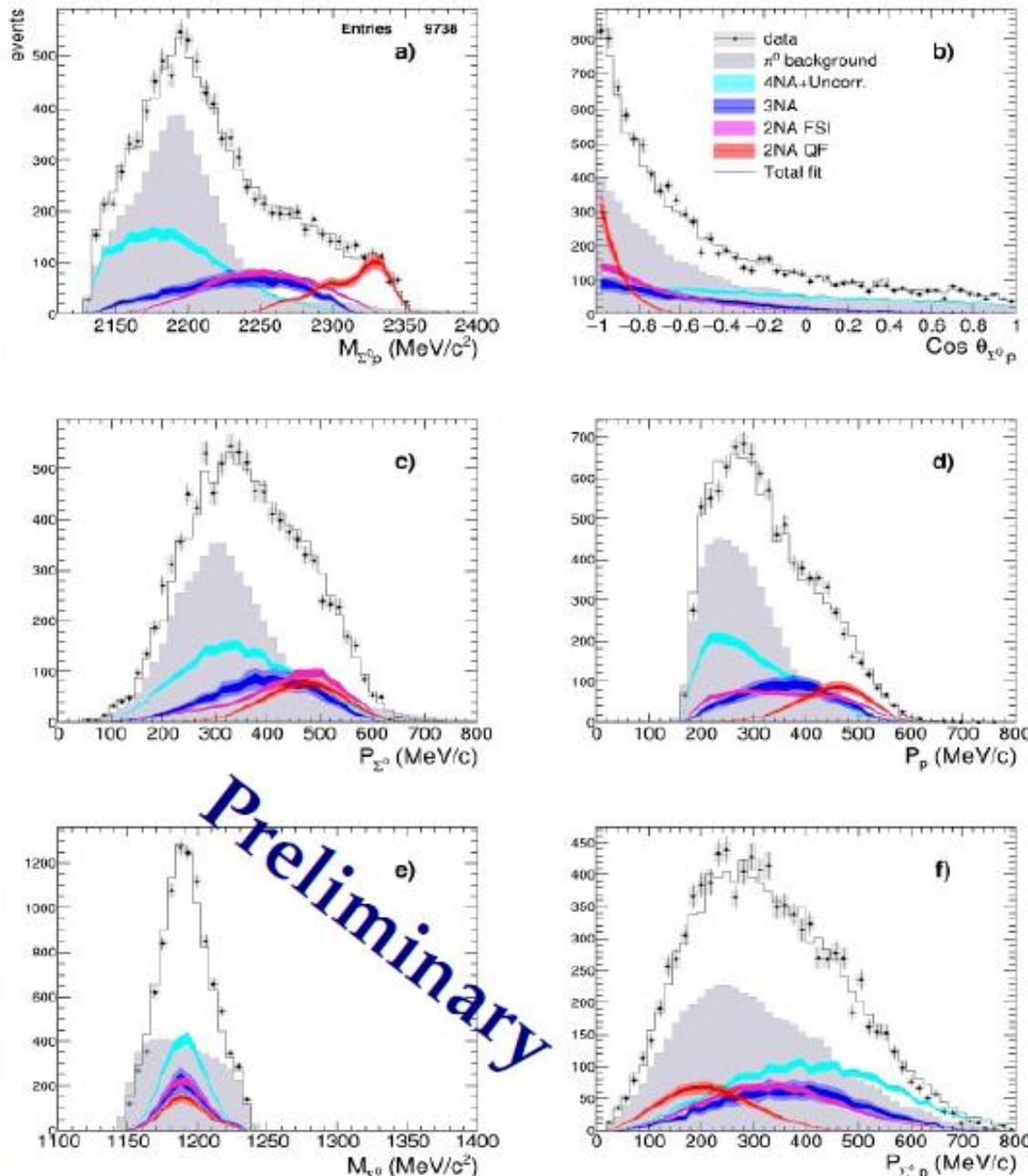
K^-

$\Sigma^0 p$ the fit

Simultaneous fit to the machine bkg subtracted spectra with simulated distributions for all the relevant physical quantities:

Momentum of proton
momentum of Σ^0
 Σ^0 -p invariant mass
angle $\Sigma^0 p$

$$\chi^2 / (\text{ndf} - \text{np}) = 0.85$$



Extracted yields

	yield / K _{stop} ⁻ · 10 ⁻²	$\sigma_{stat} \cdot 10^{-2}$	$\sigma_{syst} \cdot 10^{-2}$
2NA-QF	0.124	± 0.019	+0.004 -0.008
2NA-FSI	0.265	± 0.027	+0.021 -0.022
Tot 2NA	0.366	± 0.032	+0.022 -0.031
3NA	0.267	± 0.067	+0.043 -0.020
Tot 3body	0.532	± 0.072	+0.047 -0.032
4NA + Uncorr. bkg.	0.753	± 0.052	+0.024 -0.074

Table 1. Production probability of the $\Sigma^0 p$ final state for different intermediate processes normalized to the number of stopped K^- in the DC wall. The statistical and systematic errors are shown as well.

Upper limit for K-pp bound state production

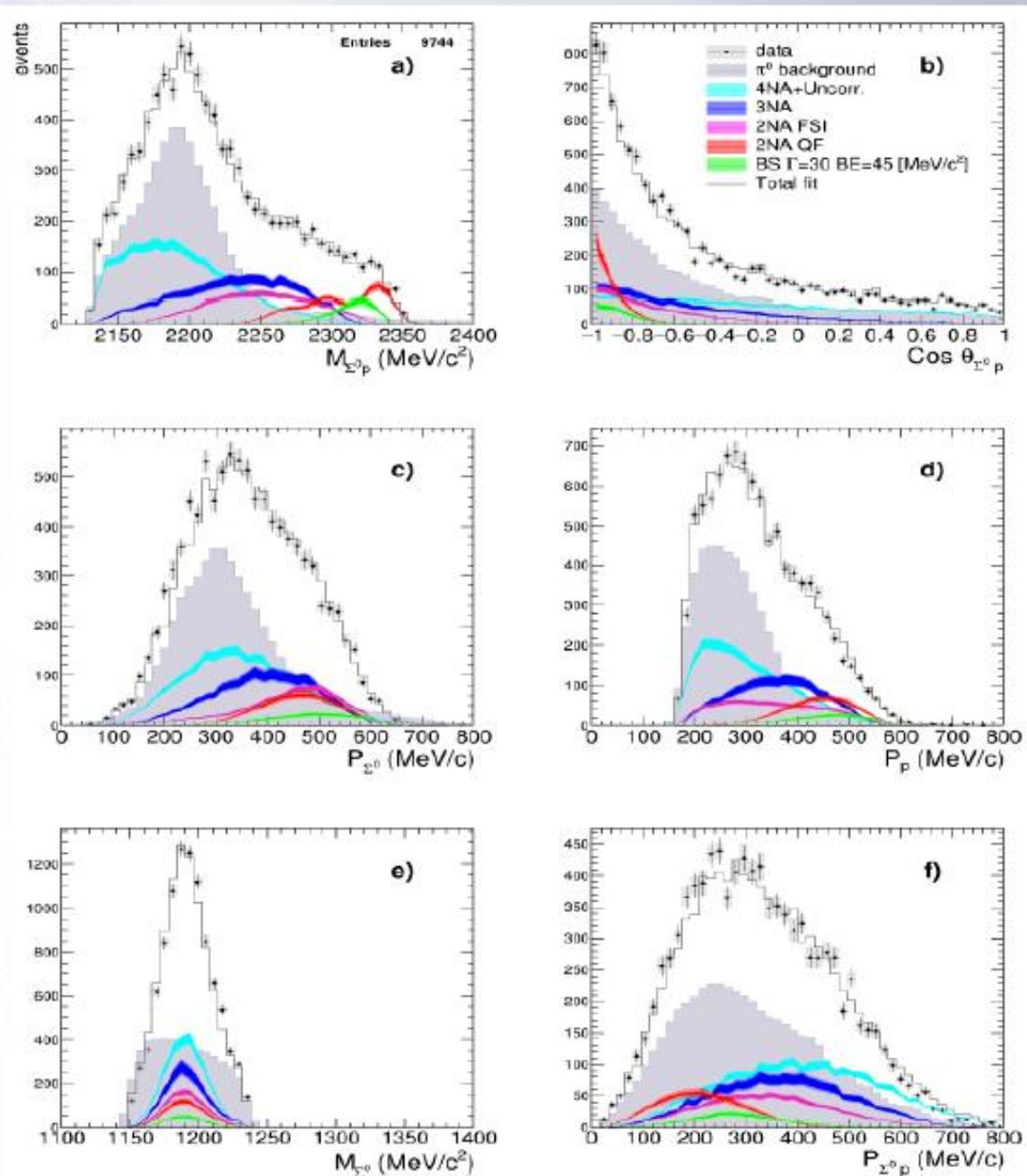
BE = 45 MeV

Width = 30 MeV

$$Yield/K_{stop}^- = (0.043 \pm 0.009 \text{stat}^{+0.004}_{-0.005} \text{syst}) \cdot 10^{-2}$$

statistical
significance = 1σ

Phys.Lett. B758
(2016) 134-139



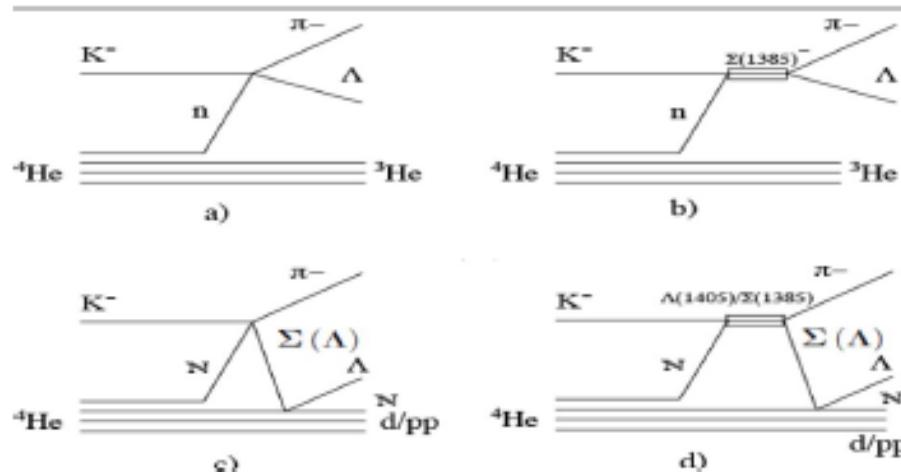
- Highest statistics ever in the Λt channel
- **4NA process** clearly seen for the first time
- **4NA Cross section & 100 MeV
and upper limit on branching ratio extracted**

$$\text{BR}(\text{K}^4\text{He}(4\text{NA}) \rightarrow \Lambda t) < 1.1 \times 10^{-4} / K_{\text{stop}}$$

$$\begin{aligned}\sigma(100 \text{ MeV/c}) (\text{K}^4\text{He}(4\text{NA}) \rightarrow \Lambda t) = \\ (0.41 \pm 0.13 \text{ (stat)} + 0.01 - 0.02 \text{ (sys)}) \text{ mb}\end{aligned}$$

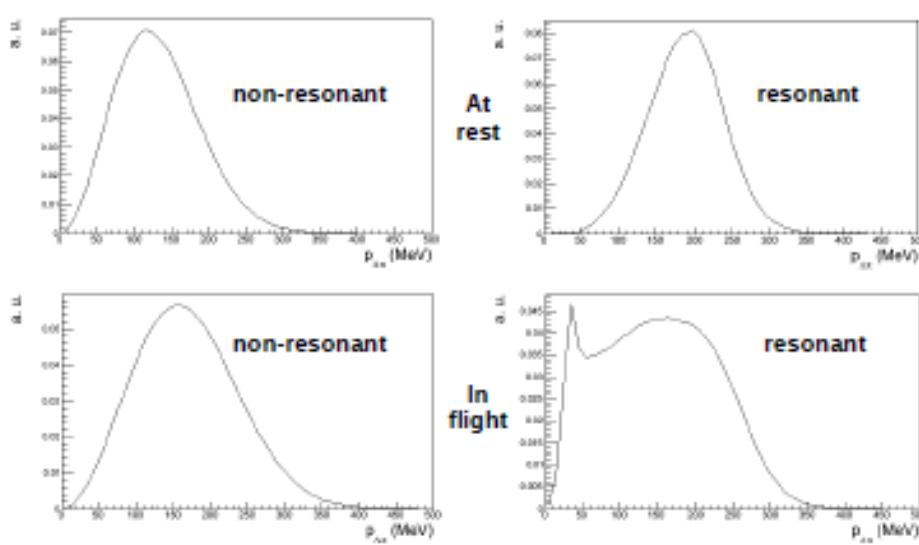
→ paper in preparation

On the K^- - ${}^4He \rightarrow \Lambda p$ - 3He resonant and non-resonant processes (K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A954 (2016) 75-93)



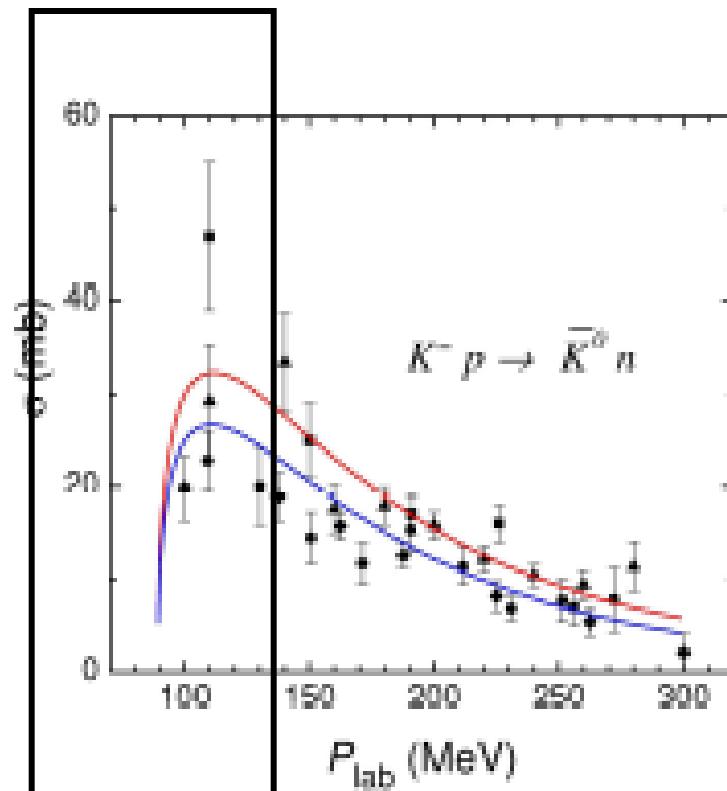
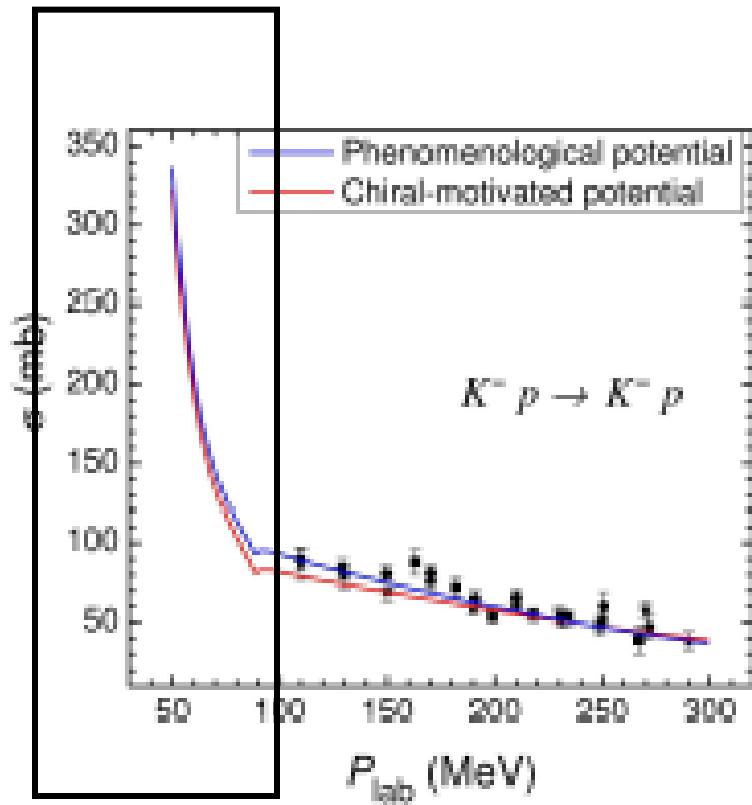
Total $\Lambda\pi^-$ momentum spectra for the resonant (Σ^*) and non-resonant ($I = 1$) processes were calculated, for both S-state and P-state K^- capture at-rest and in-flight. Corrections to the amplitudes due to Λ/π final state interactions were estimated.

The determination of the $K^- N \rightarrow Y\pi$ non-resonant transition amplitude below threshold (about 33 MeV in 4He) is essential to pin-down the $\Lambda(1405)$ resonant shape in absorption experiments.

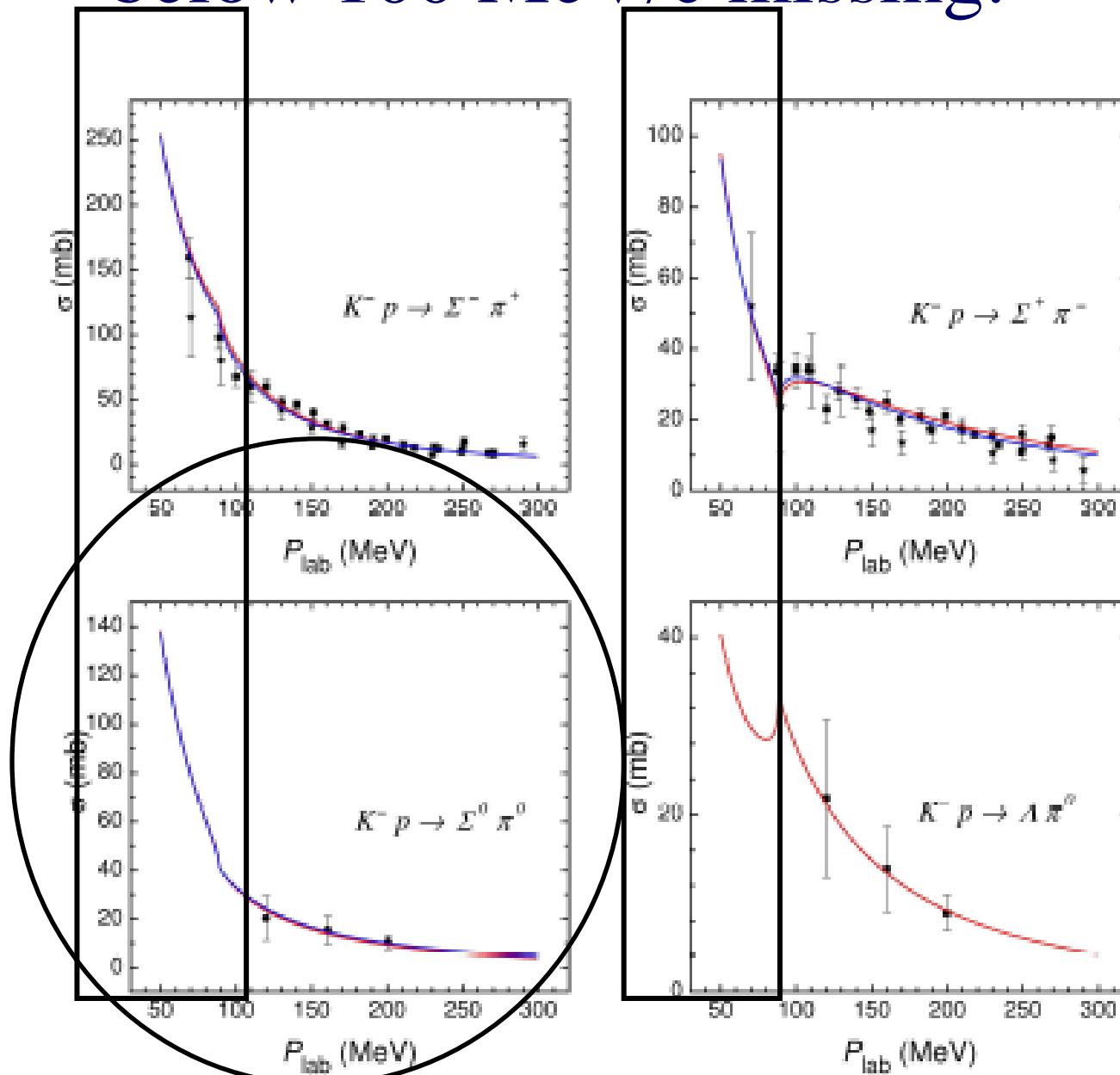


These will be used by the AMADEUS collaboration to fit the $Y\pi$ measured spectra and extract, for the first time, the non-resonant transition amplitude ($|f_{N-R}^{N-R} \Lambda\pi^- (I=1)|$ and $|f_{N-R}^{N-R} \Sigma\pi^- (I=0)|$) fundamental to determine the $\Lambda(1405)$ properties.

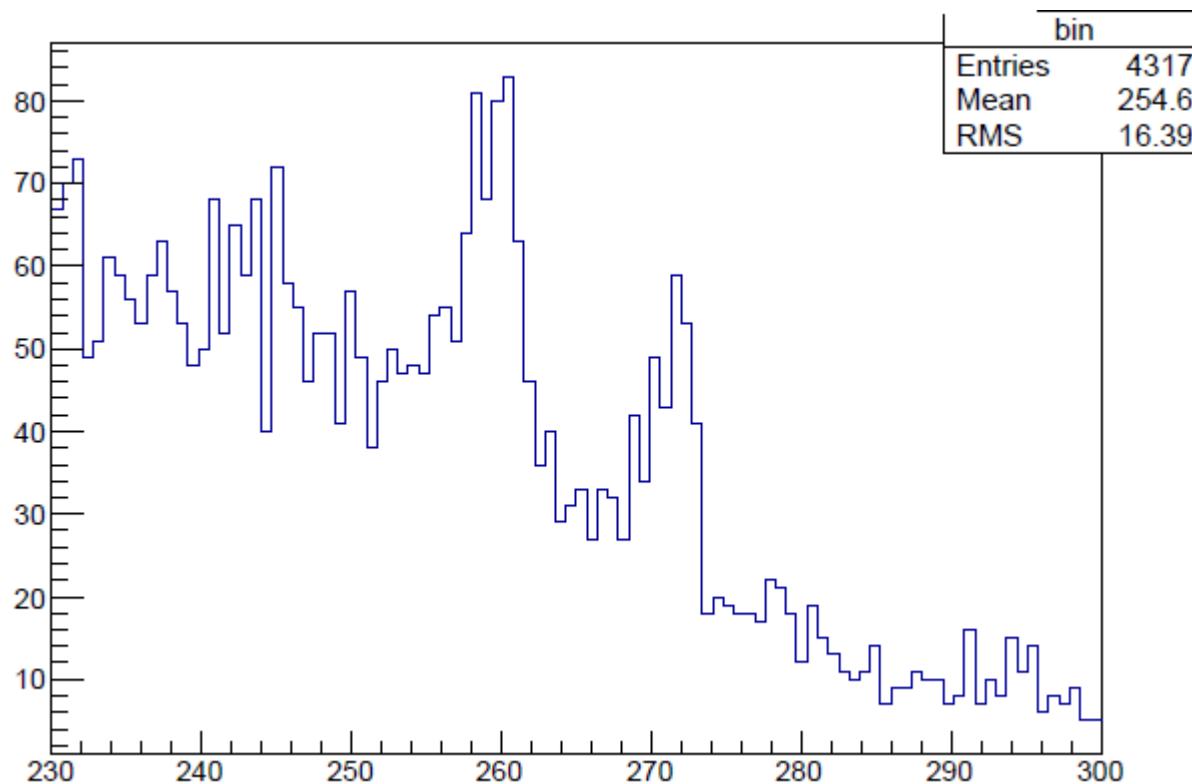
Low-energy kaon scattering below 100 MeV/c missing:



Low-energy kaon processes below 100 MeV/c missing:



Carbon hypernuclei signals (carbon) – very preliminary

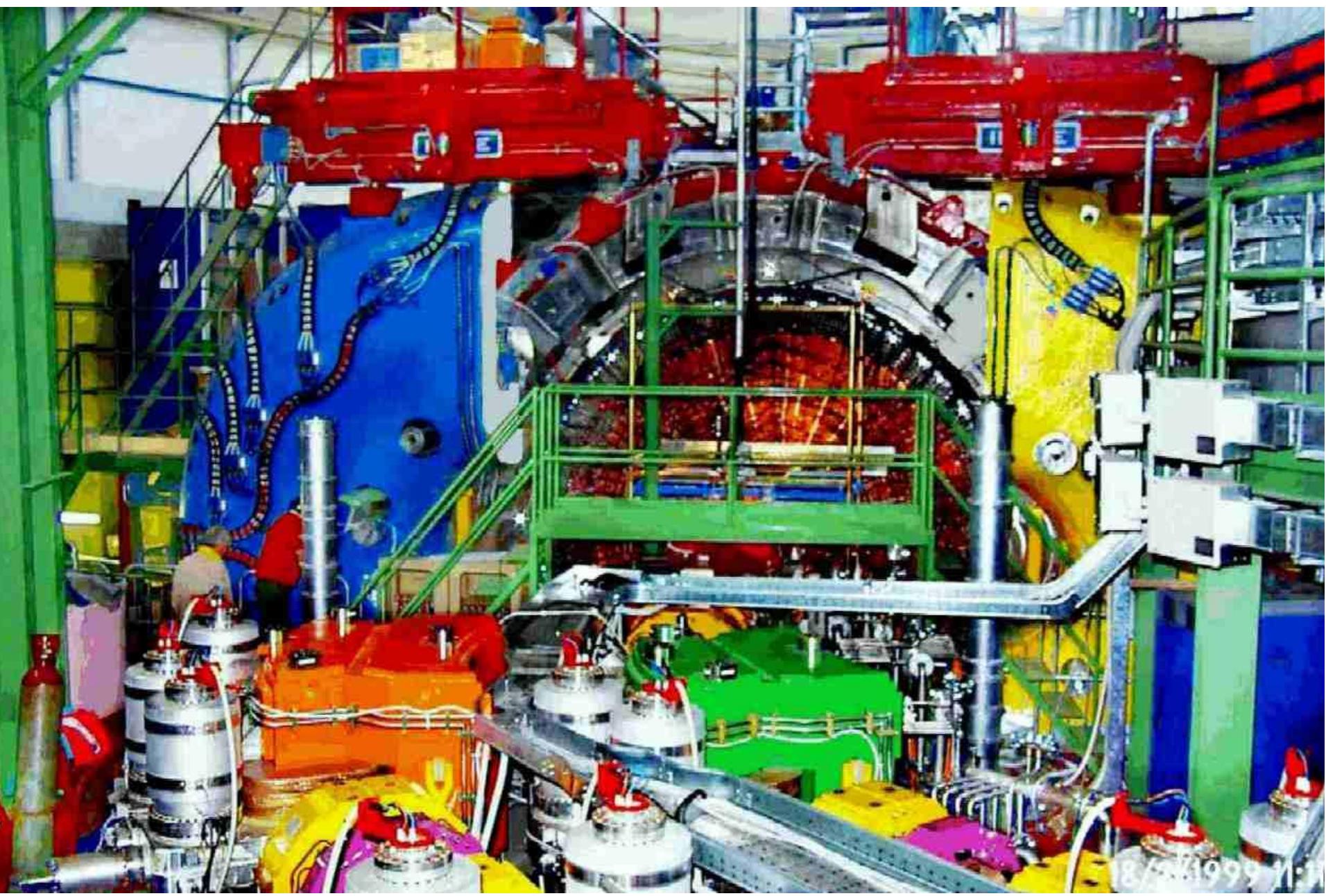


What about the future?

- AMADEUS scientific case -> extract GOLDEN channels
- AMADEUS dedicated setup

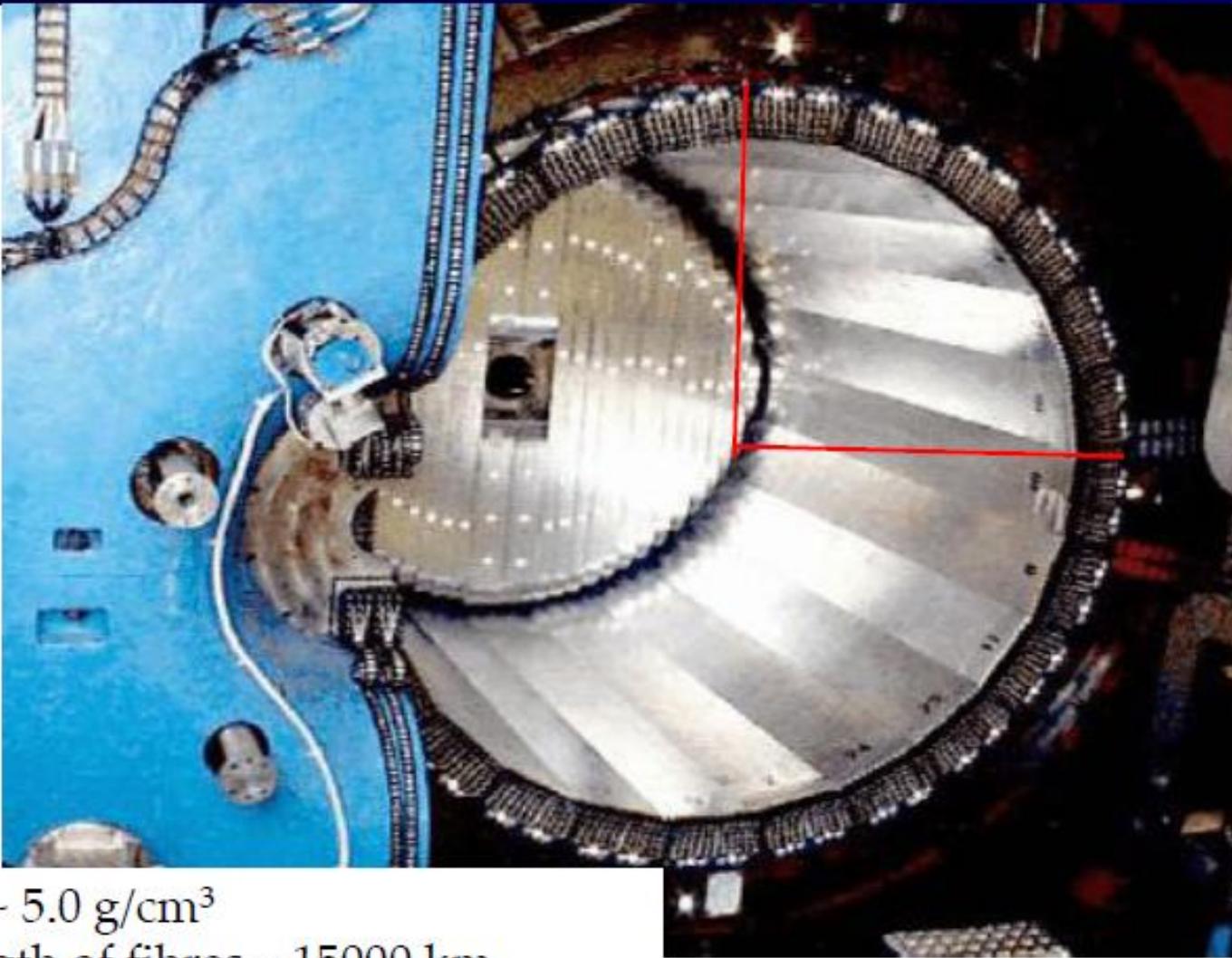
- **AMADEUS scientific case**
 - Lambda(1405)
 - Deeply bound states
 - Hyperon-nucleon interaction(s)
 - Hypernuclear physics
 - Scattering
 -

- **AMADEUS dedicated setup**



18/5/99 11:11

KLOE electromagnetic calorimeter



density $\sim 5.0 \text{ g/cm}^3$

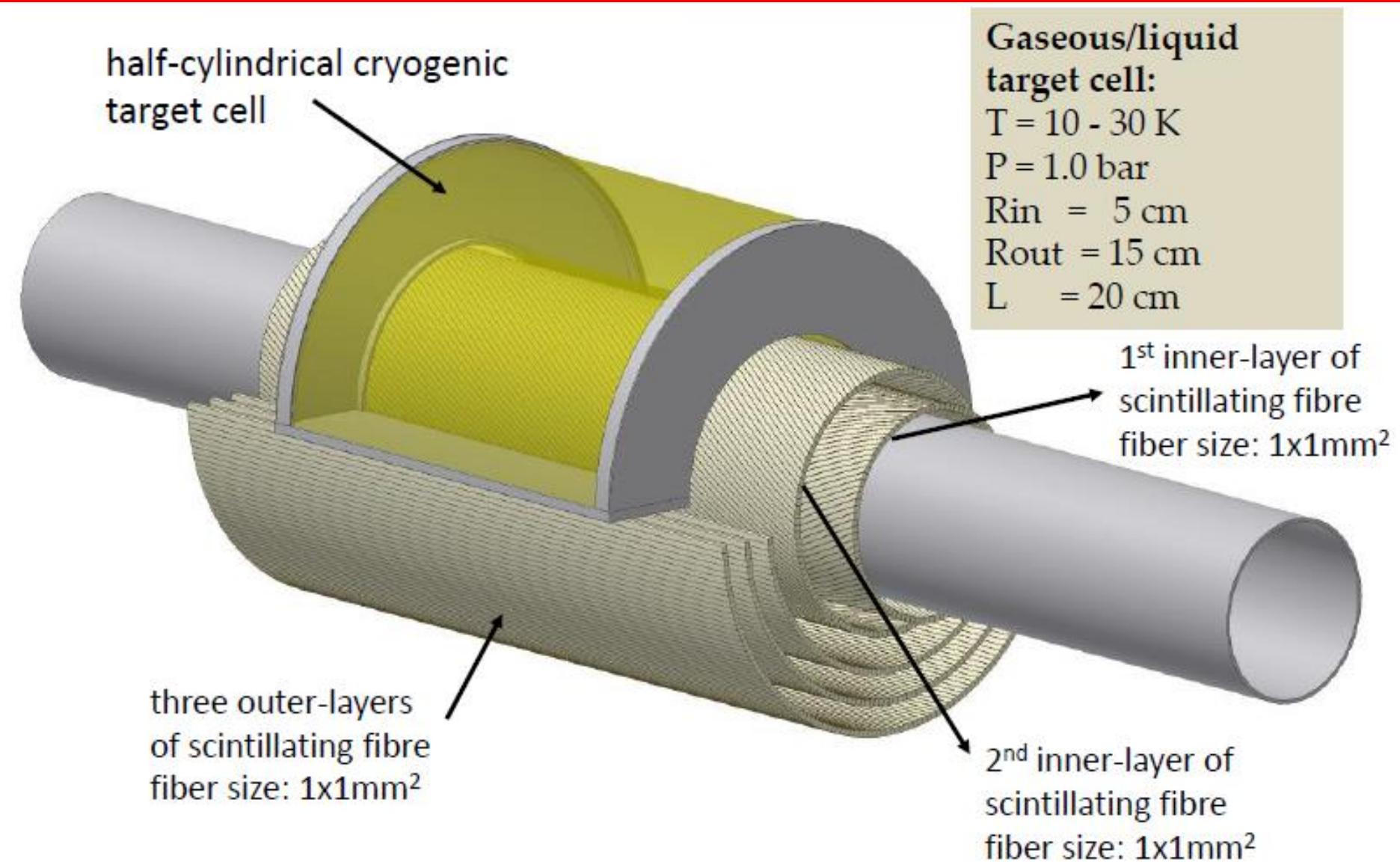
total length of fibres $\sim 15000 \text{ km}$

read out by ~ 5000 mesh PM

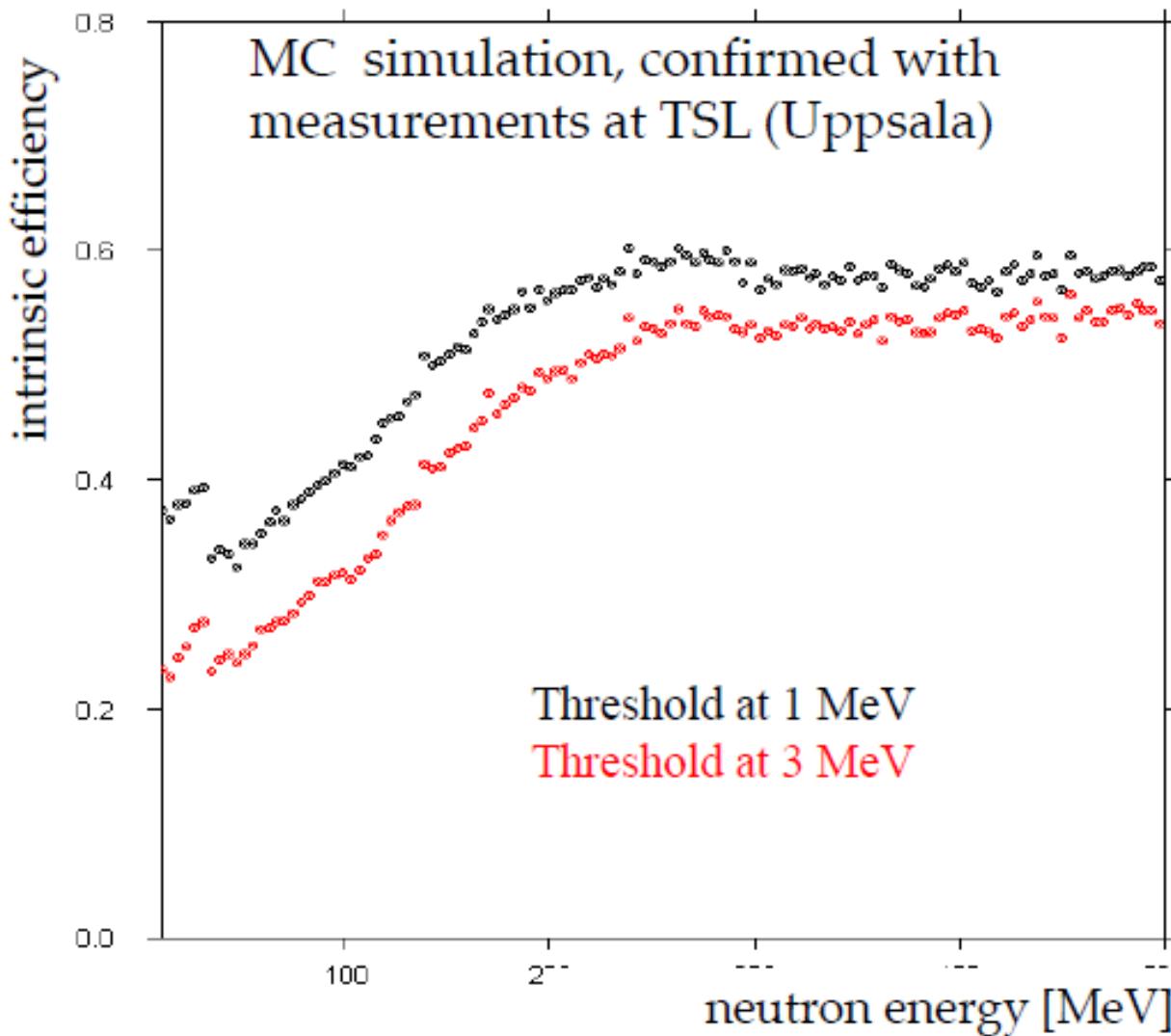
Possible scenario

- Use KLOE calorimeter only:
 - Inside set detector systems (tracker, active target....)
- Use KLOE calorimeter and DC
- Other possible ideas?

AMADEUS dedicated setup

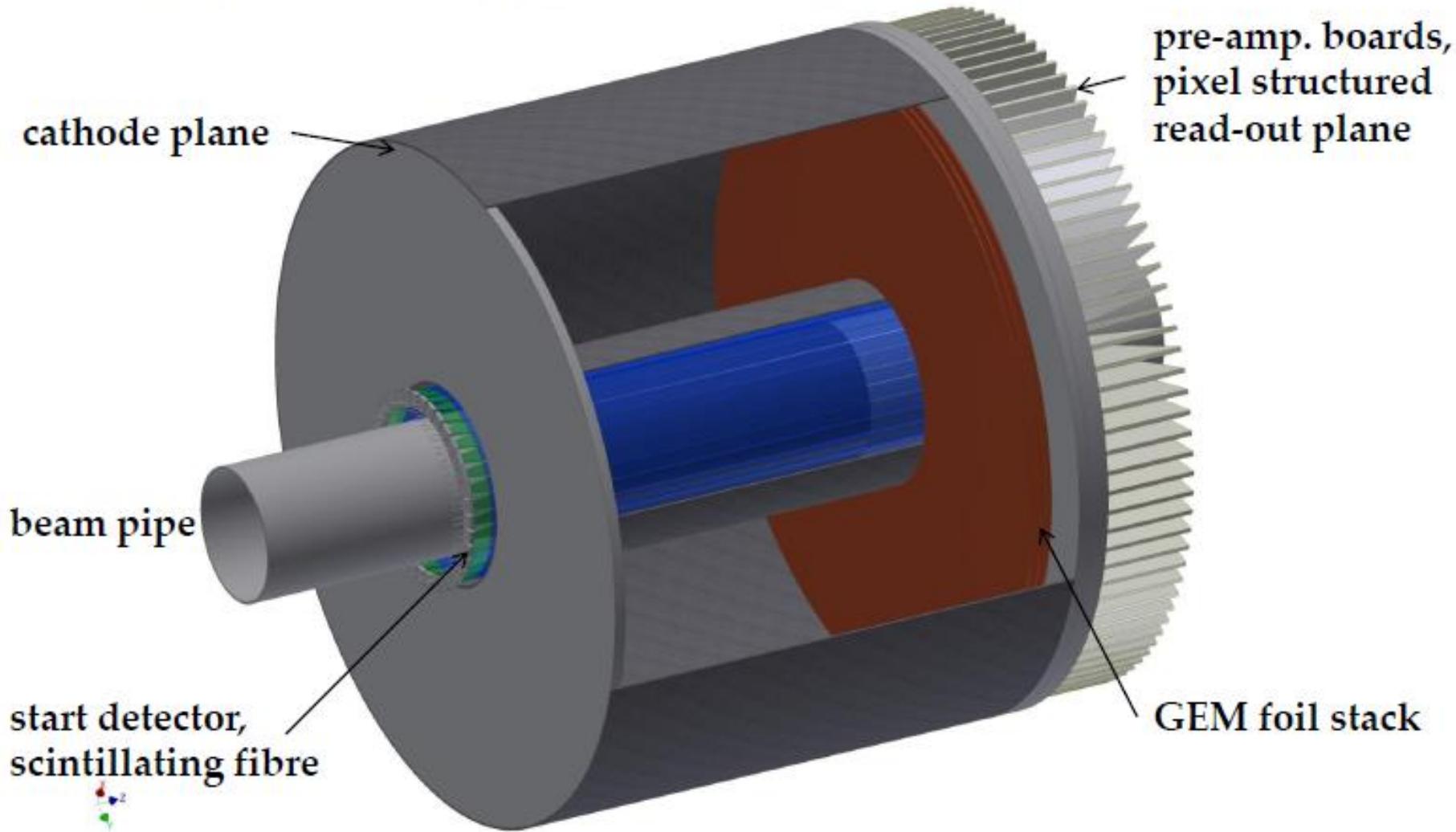


Neutron detection efficiency



R&D – advanced setup

- active target TPC with GEM technology, with 6000 pads
 - R&D work within EU-FP7 HadronPhysics3

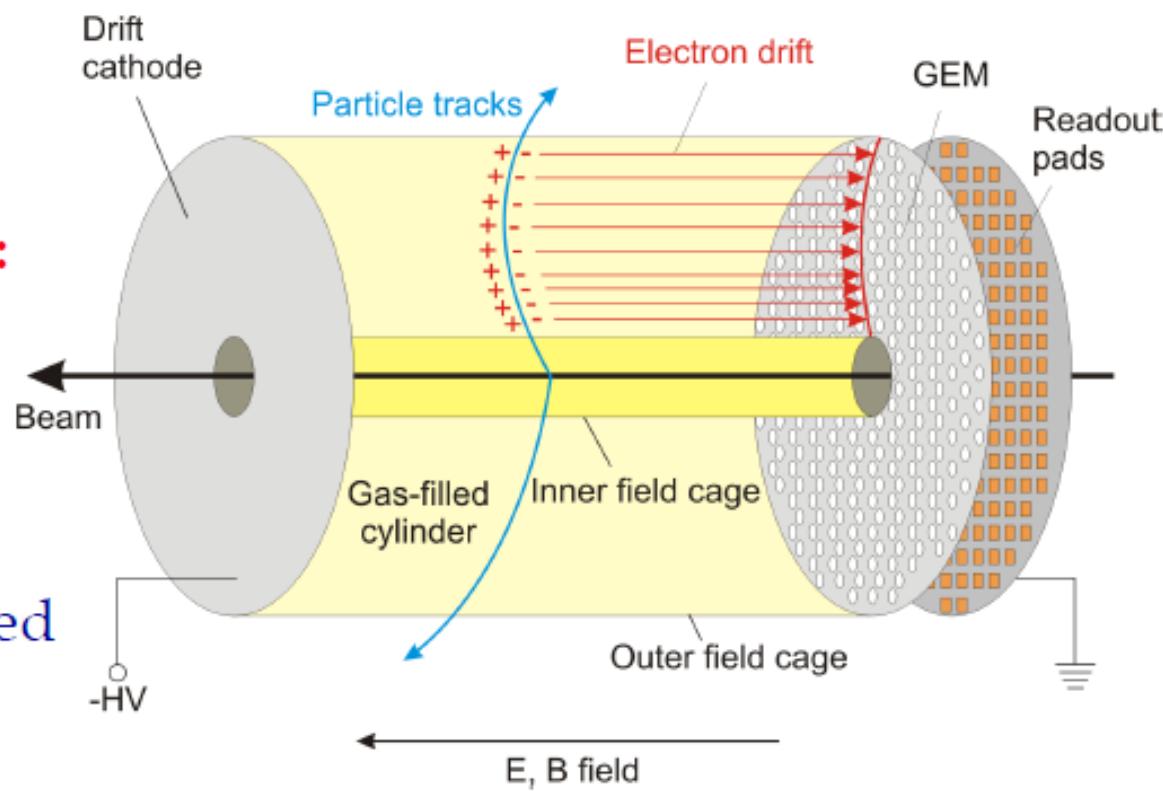


TPC with GEM Readout

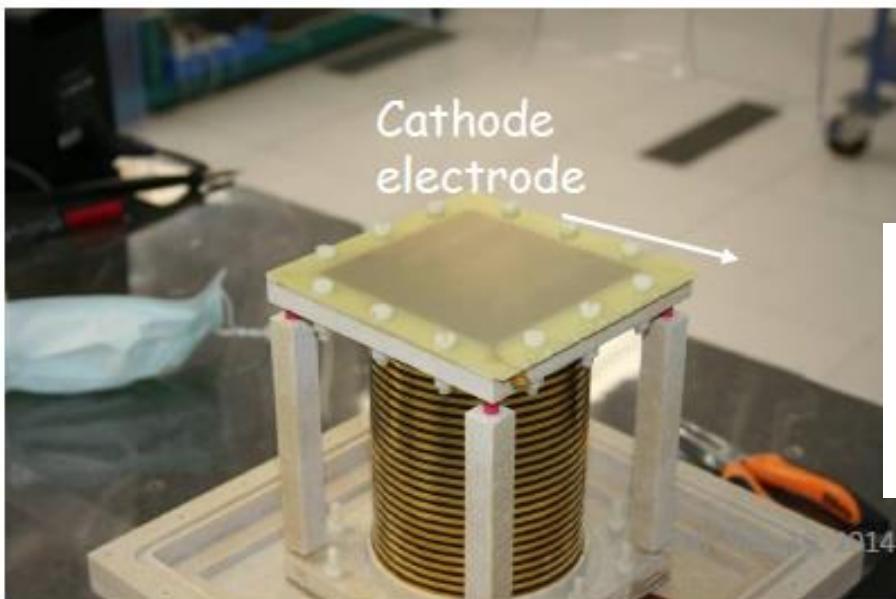
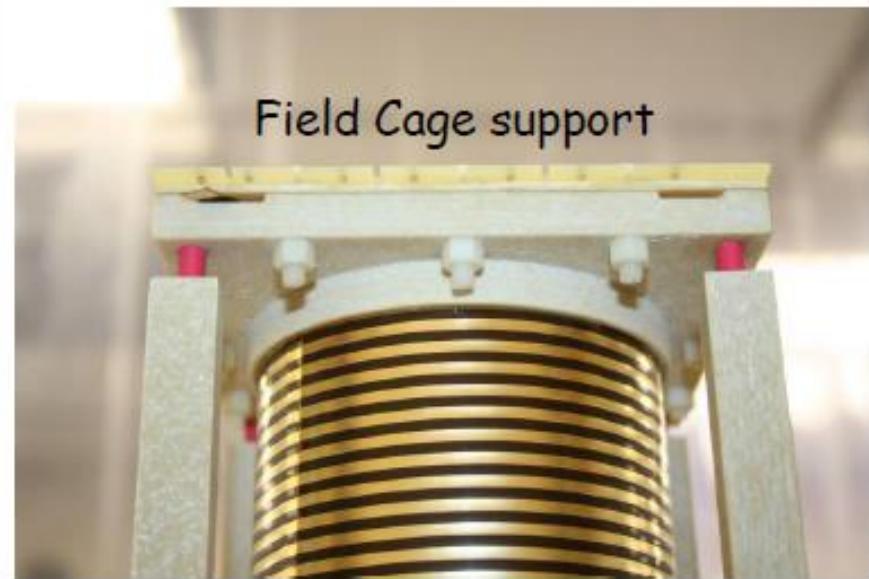
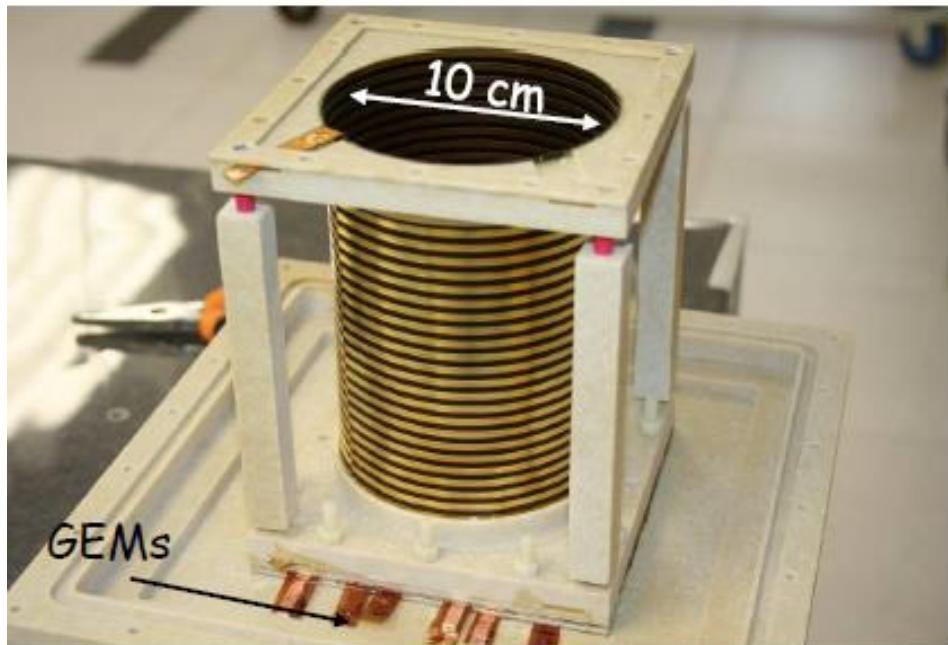
- EU-FP7 HadronPhysics2 WP24: JointGEM
→ large TPC prototype
- EU-FP7 HadronPhysics3 WP24: JointGEM
→ active TPC

TPC with GEM readout:

- High granularity
- Fast signal
- Multi-track resolution
- Ion feedback suppressed



“active” TPC-GEM test setup at LNF



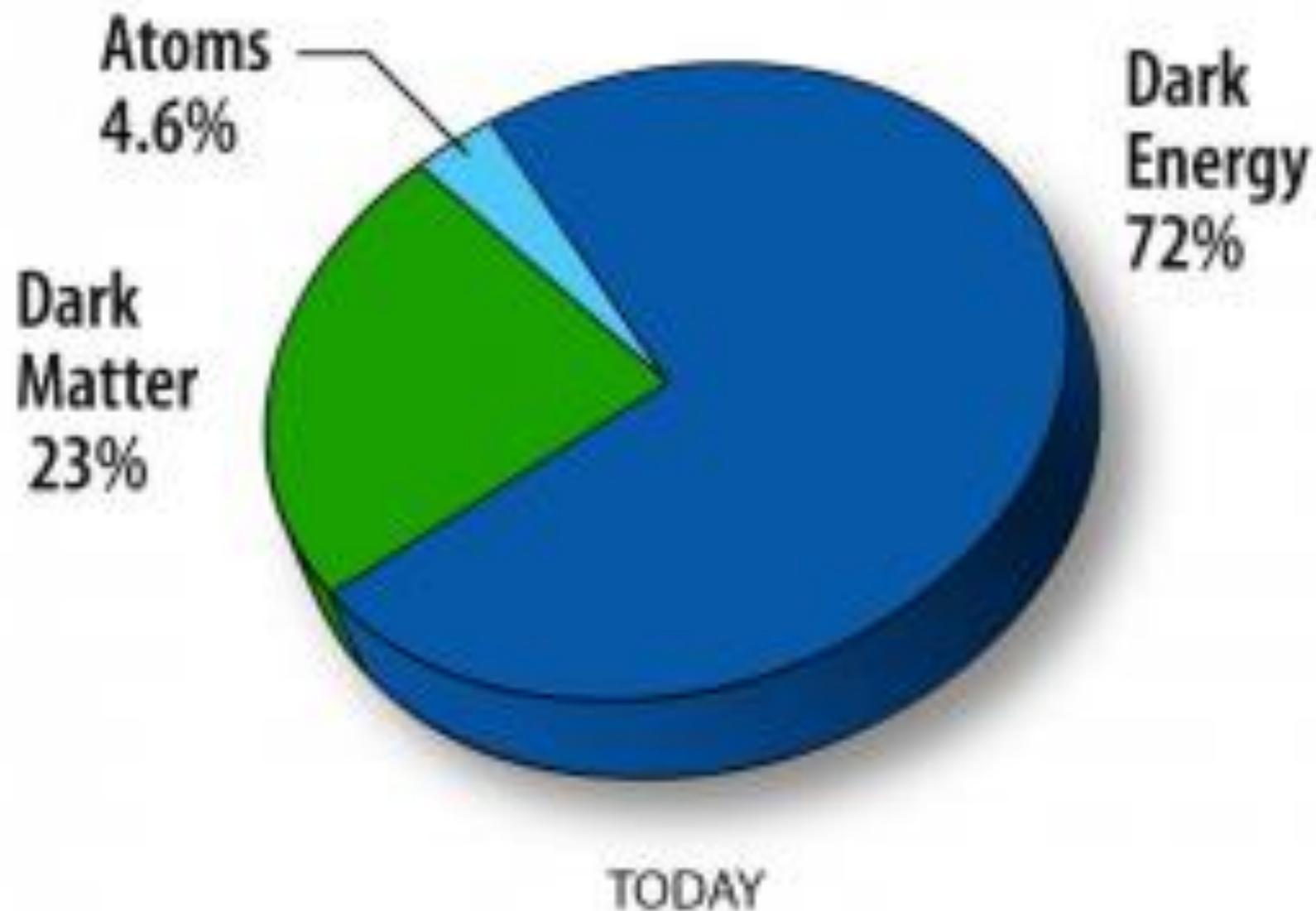
Tests at PSI

Modern Instrumentation, 2015, 4, 32-41
Published Online July 2015 in SciRes. <http://www.scirp.org/journals/mi>
<http://dx.doi.org/10.4236/mi.201543004>

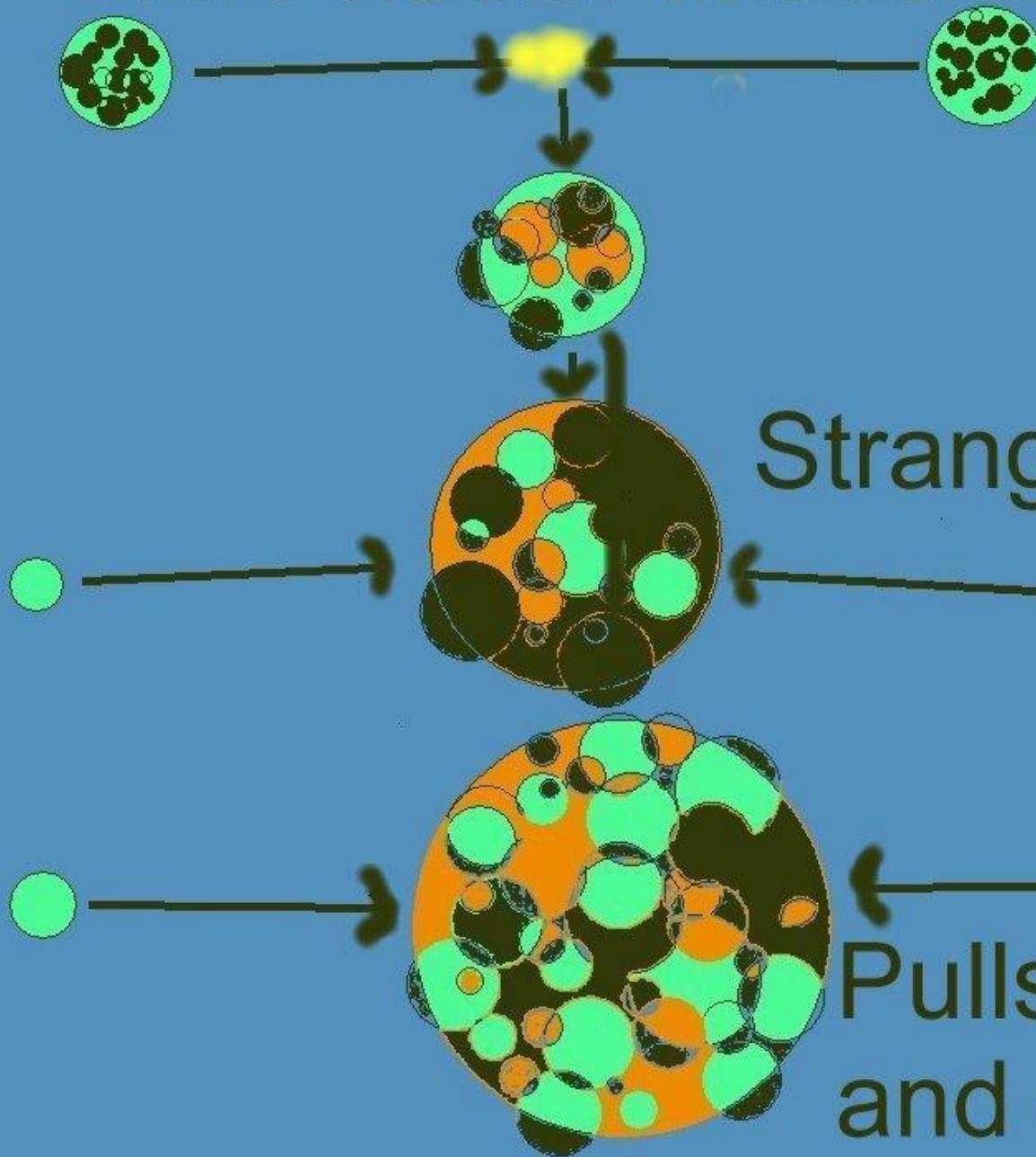


Performances of an Active Target GEM-Based
TPC for the AMADEUS Experiment

M.Poli Lener



Two nuclei collide



Strangelet

Pulls in atoms
and grows

Conclusions

- AMADEUS has an enormous potential to perform complete measurements of low-energy kaon-nuclei interactions in various targets
-> does strangeness play a role in the Universe?
- Data analyses ongoing -> papers coming soon
- For future: AMADEUS dedicated setup with new active targets (gas and solid)
- Which setup? Which golden channels?

There is no exquisite
beauty without
some **STRANGENESS**
in the proportion.

Edgar Allan Poe