Overview and plans of the Italian German Collaboration in hadron and nuclear physics

Learning from the joint successful research in hadron and nuclear physics to design a bright future

Angela Bracco

Università degli Studi di Milano

and INFN

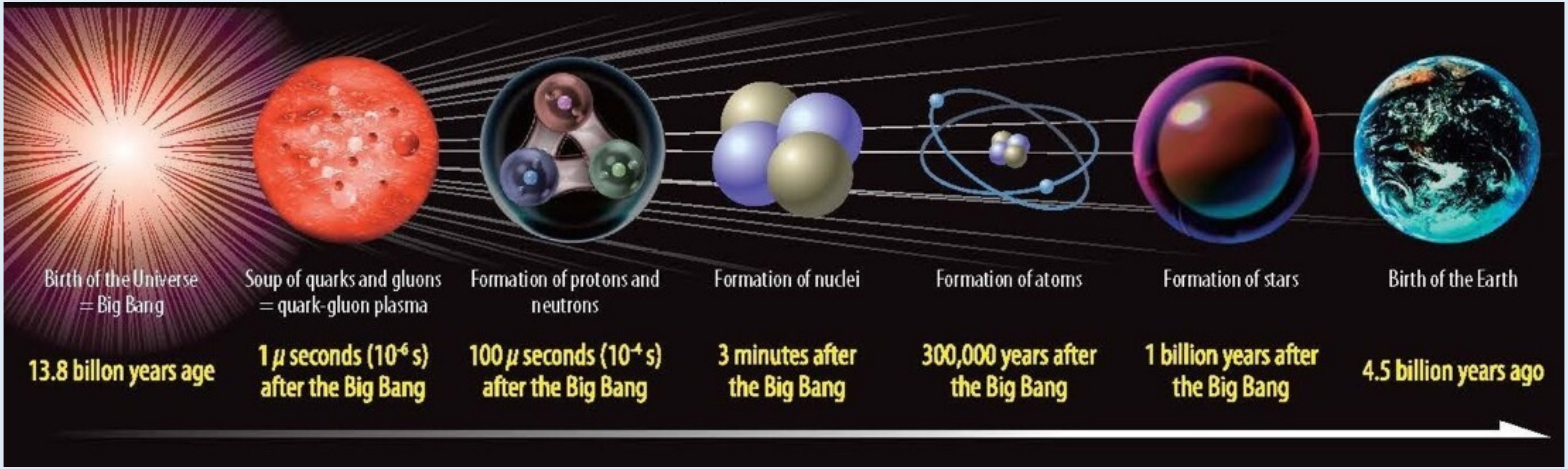
President of Italian Physical Society

Köln25

dpg-tagungen.de

Deutsche Physikalische Gesellschaft e.V.

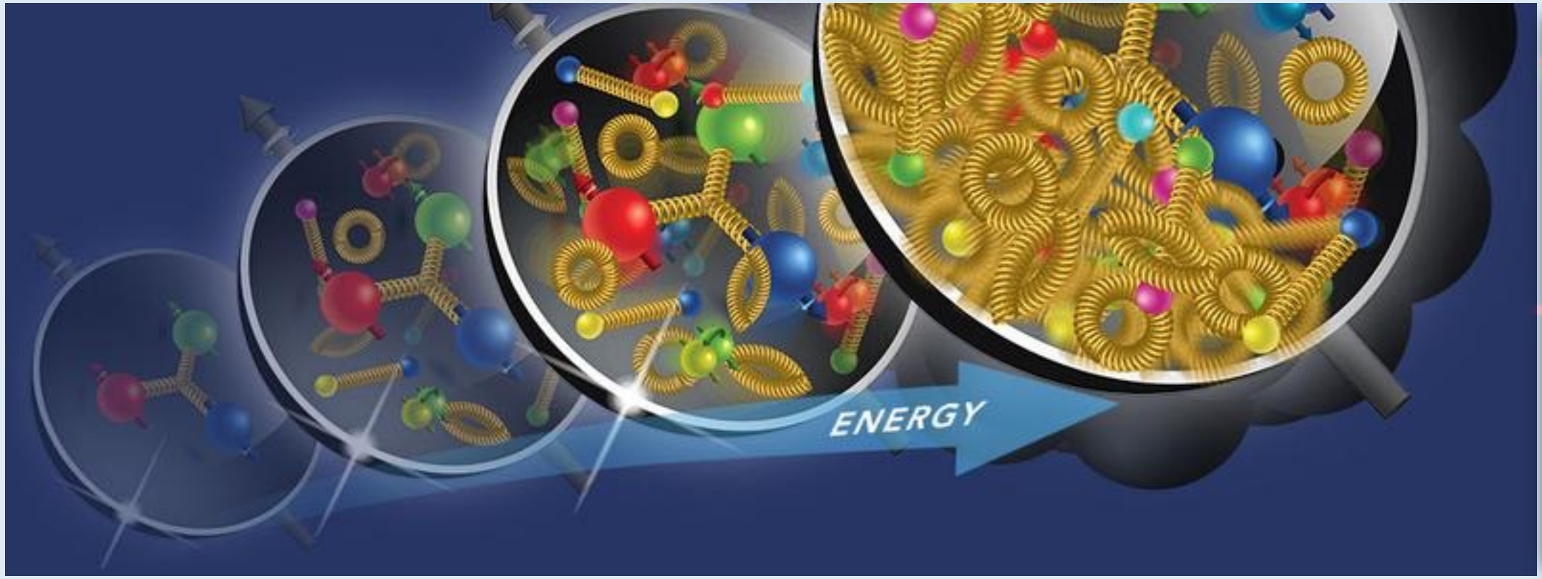
Collaboration to address physics questions related to the different steps of the evolution of the Universe

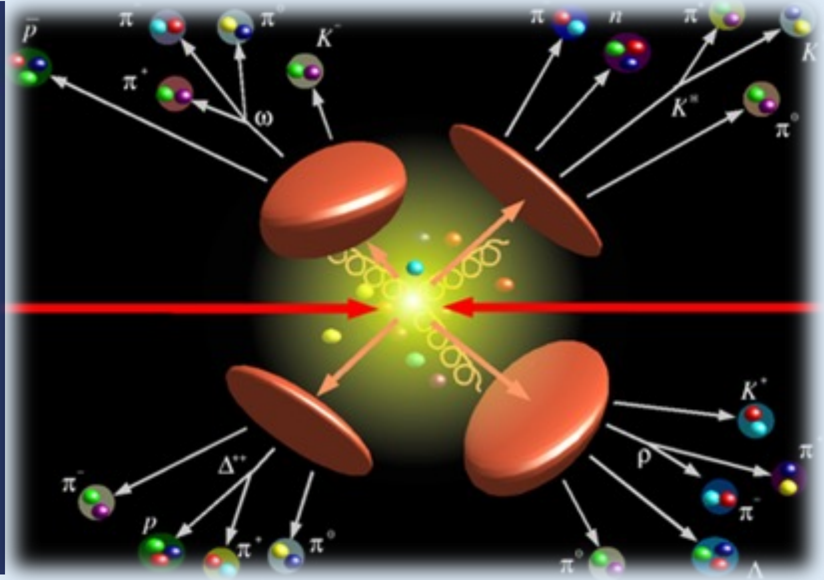


The collaboration with Italy concerns several research topics studied experimentally and theoretically mostly via particle collisions at low (a few tens of keV) and high (up to 14 TeV) energies.

During the years there were joint developments in state-of-the-art detectors/data-acquisition/beams/targets, and in theoretical (lattice, effective field, perturbative) calculations.

Hadrons: the structure and interactions of Baryons and Mesons



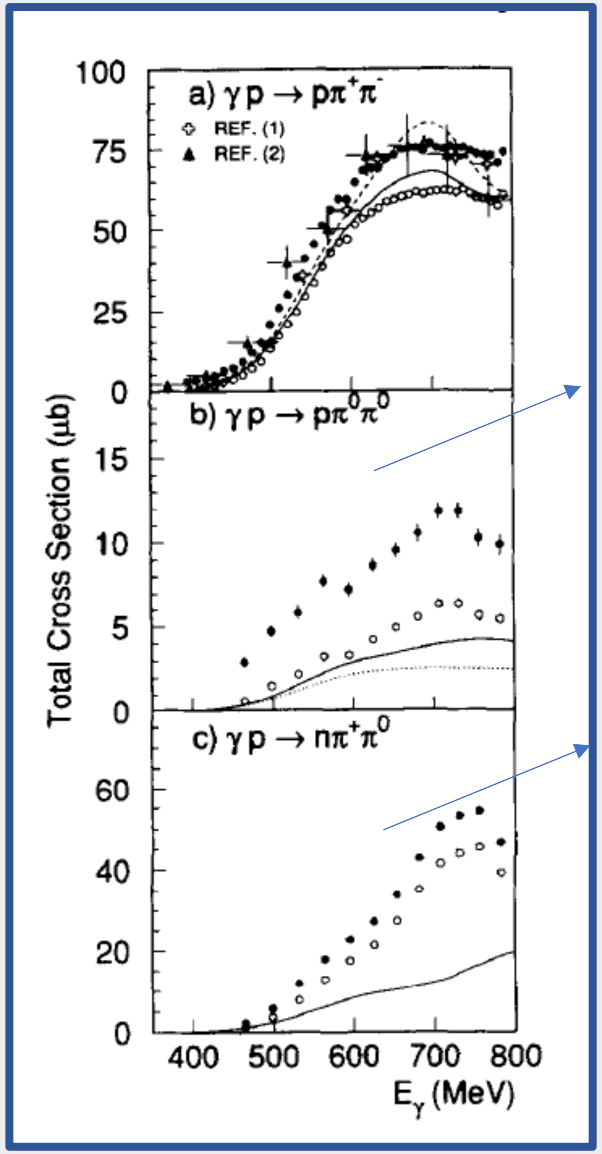


Extensive research to relate the observed degrees of freedom to QCD

Several fundamental open questions with the main focus on the full understanding of:

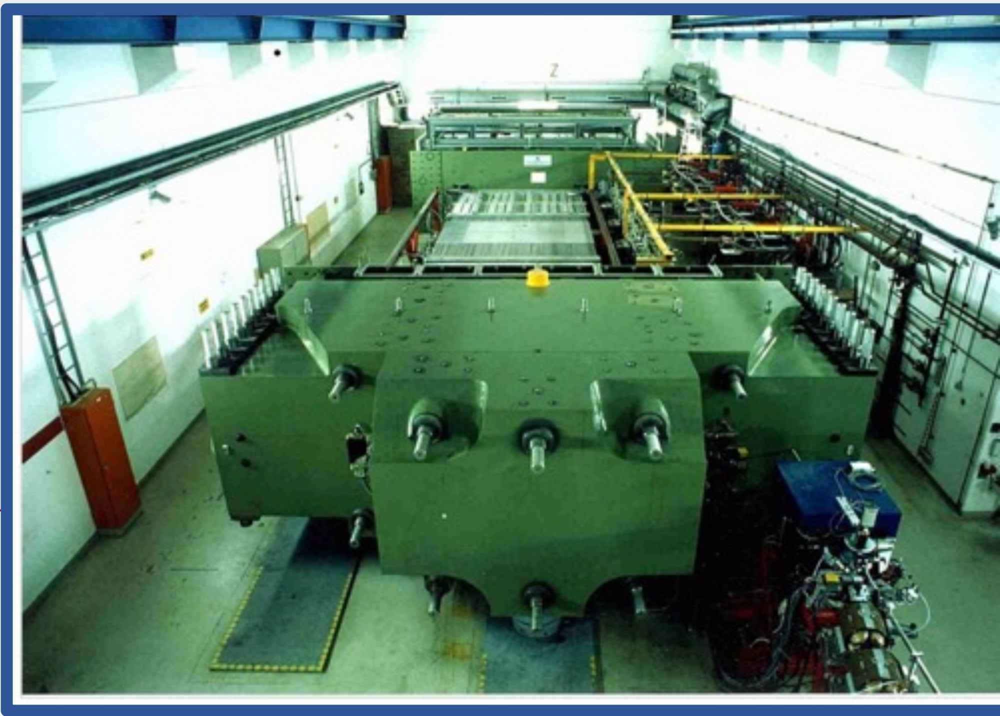
(i) the partonic structure of hadrons, (form factors, partonic distribution, TDM)
(ii) exotic hadronic states, properties (spectroscopy, formation and decays)
(iii) precision tests of the SM.

Gamma beams reactions ….some history for the Italian German collaboration



Selected results published in 1995 from MAMI experiments

Double pion production - Never Measured before



ELSEVIER

Physics Letters B 363 (1995) 46–50

Total cross section measurement for the three double pion photoproduction channels on the proton

A. Braghieri [a,b], L.Y. Murphy [b,c,1], J. Ahrens [e], G. Audit [b], N. d'Hose [b], V. Isbert [b], S. Kerhoas [b], M. Mac Cormick [b], P. Pedroni [a,2], T. Pinelli [a,d], G. Tamas [b], A. Zabrodin [b,f]

[a] *INFN-Sezione di Pavia, via Bassi 6, 27100 Pavia, Italy*
[b] *CEA DAPNIA-SPhN, C.E. Saclay, 91191 Gif sur Yvette, France*
[c] *Physics Department, Rensselaer Polytechnic Institute, Troy, NY 12180, USA*
[d] *Dipartimento di Fisica Nucleare e Teorica, Università degli Studi di Pavia, via Bassi 6, 27100 Pavia, Italy*
[e] *Institut für Kernphysik, Universität Mainz, 55099 Mainz, Germany*
[f] *INR, Russian Academy of Sciences, Moscow, Russia*

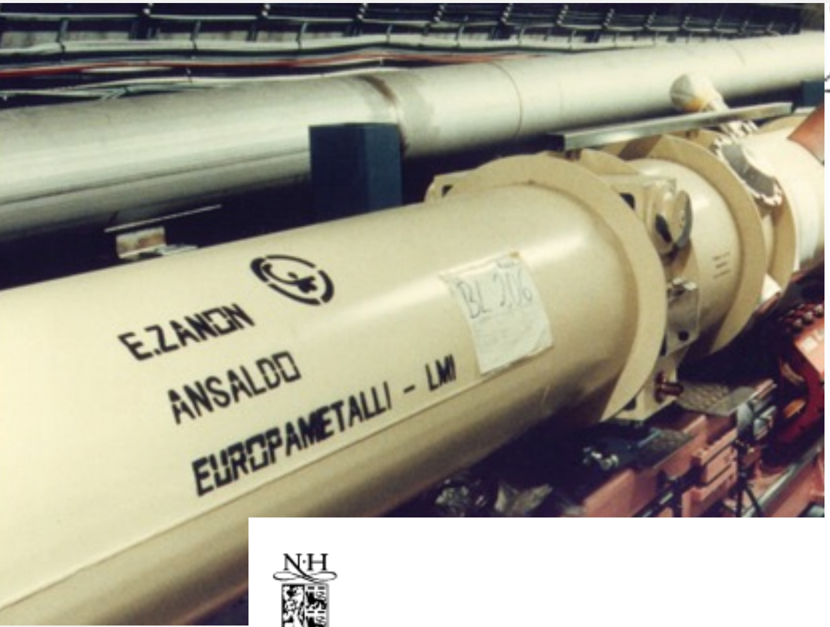
Received 3 October 1994; revised manuscript received 14 September 1995
Editor: J.P. Schiffer

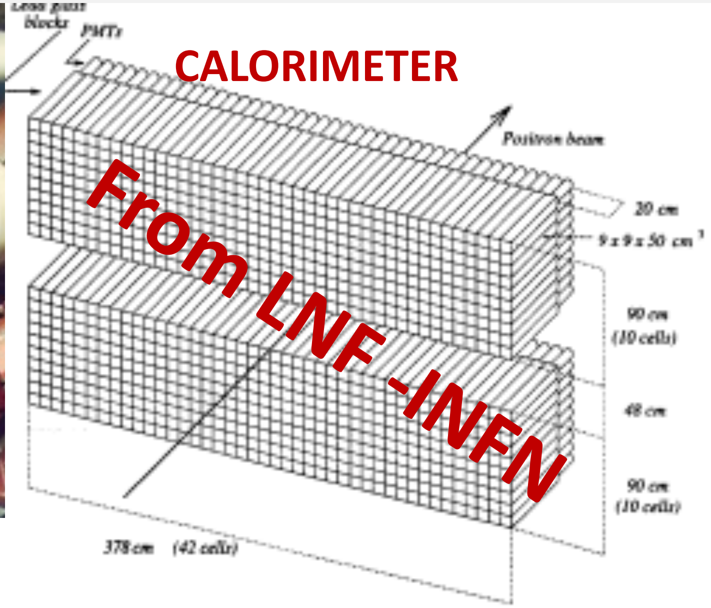
The HERMES Experiment at HERA (27.5 GeV polarized e⁻)

Successfully explored the spin structure of the nucleon.

Fixed sophisticated polarized target of hydrogen or deuterium. This target, has been a key to the experiment's success.

INFN large contribution





ELSEVIER
Nuclear Instruments and Methods in Physics Research A 417 (1998) 69–78
IN PHYSICS RESEARCH Section A

1998

Performance of the electromagnetic calorimeter of the HERMES experiment

H. Avakian[a], N. Bianchi[a], G.P. Capitani[a], E. De Sanctis[a], P. Di Nezza[a], A. Fantoni[a,*], V. Giourdjian[a], R. Mozzetti[a], V. Muccifora[a], M. Nupieri[a], A.R. Reolon[a], P. Rossi[a], J.F.J. van den Brand[b,c], M. Doets[c], T. Henkes[c], M. Kolstein[c], A. Airapetian[d], N. Akopov[d], M. Amarian[d], R. Avakian[d], A. Avetissian[d], V. Garibian[d], S. Taroian[d]

[a] LNF-INFN, C.P.13, Via E. Fermi 40, I-00044 Frascati Roma, Italy
[b] Vrije Universiteit Amsterdam, de Boelelaan 1081 1083 HV Amsterdam, The Netherlands
[c] NIKHEF, Kruislaan 411, 1098 SJ Amsterdam, The Netherlands
[d] YPI, Alikhanian Brothers St. 2, Yerevan AM-375036, Armenia

Received 10 March 1998

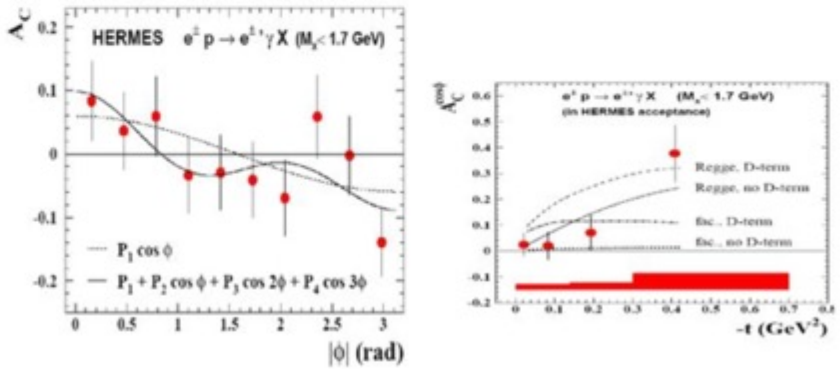
Start of HERMES 1995

only at HERA $e^{+/-}\,p \rightarrow e'p'\gamma$

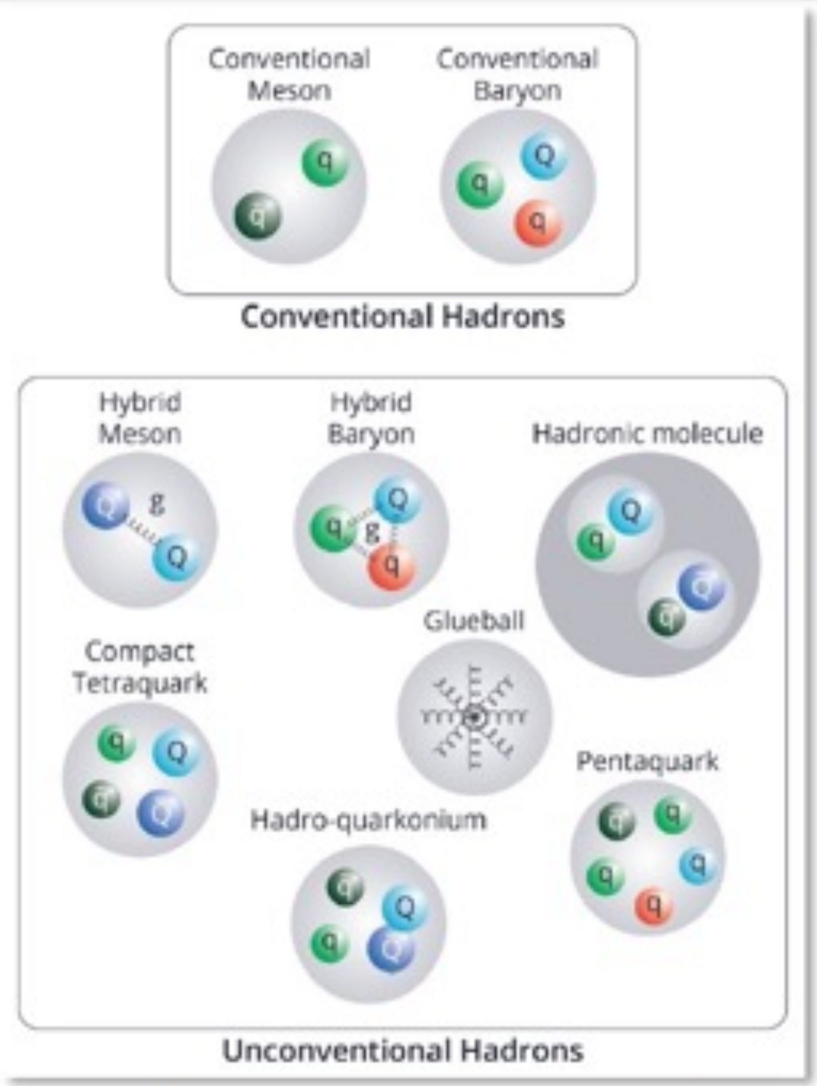
Beam Charge Asymmetry

$\sigma \propto \cos\phi \times \ldots$

[PRD 75 (2007)]



experiments at MAMI and ELSA



Valence content of conventional and exotic hadrons

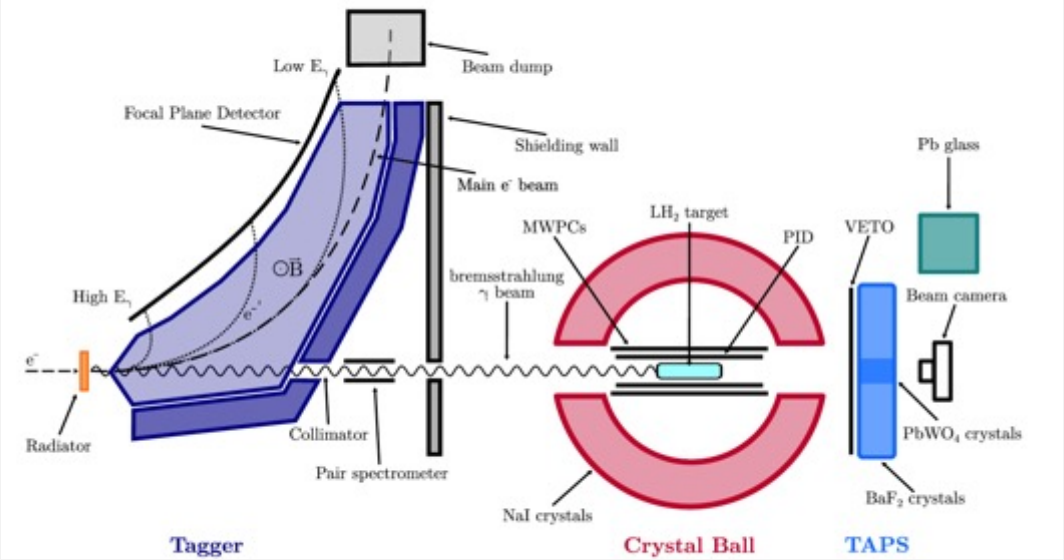
Are there exotic structures in the light quark sector?

Exotic, multi-quark states beyond (3-quarks and quark-antiquark) systems are now unambiguously realised in the heavy, charmed quark sector.

Many of these states, are close to open charm thresholds, *indicative of molecular-like structure*.

Equivalent structures may also be evidenced in the light, *uds* sector,

A2 experiment at MAMI

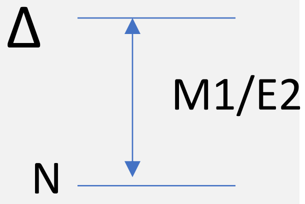


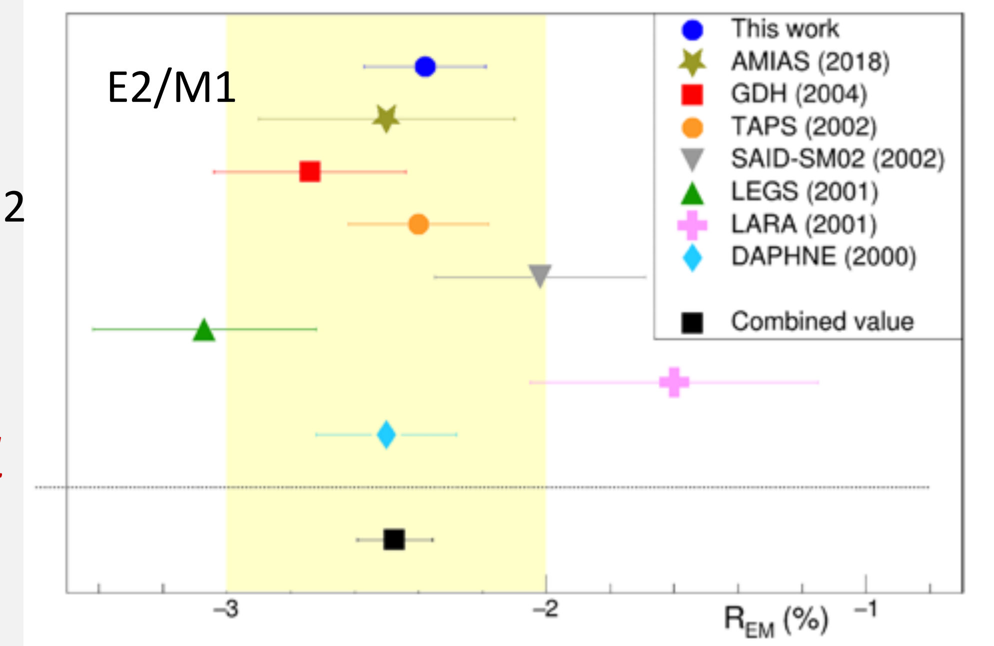
Several interesting measurements e.g.:

- First Measurement Using Elliptically Polarized Photons of the Double-Polarization for pion photoproduction
- Neutron polarization in deuteron photodisintegration

Investigation of fundamental states of hadrons : complex quark-gluon and meson cloud dynamics in nonperturbative QCD

N → Δ (1232) electromagnetic transition



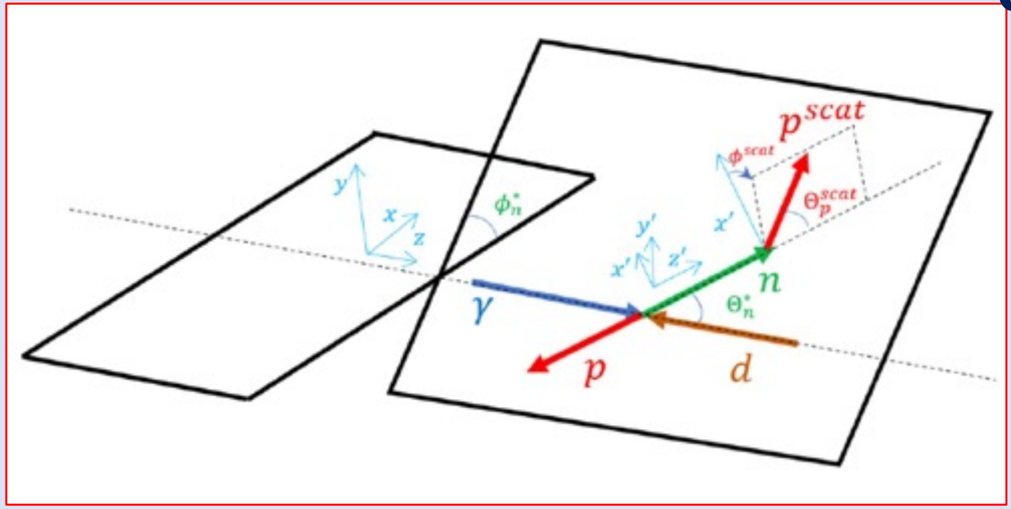


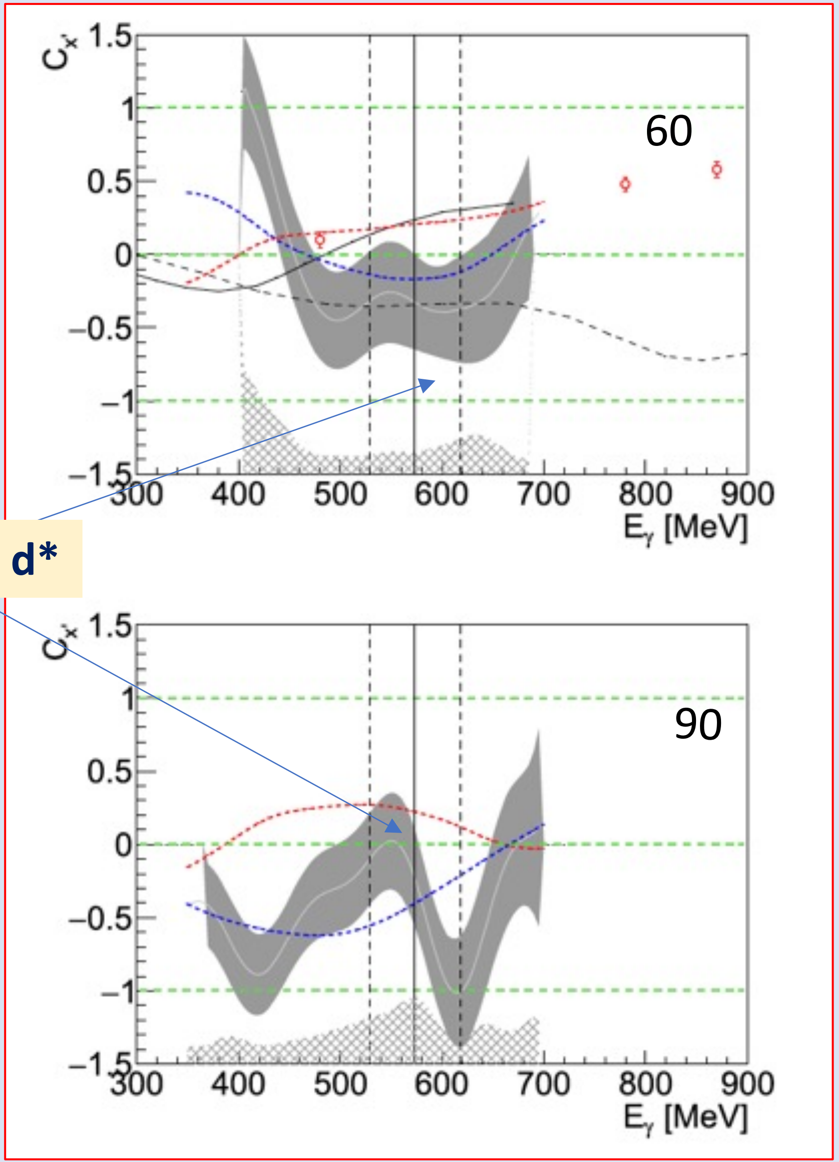
Mainly M1 spin flip in s wave

any d-wave mixture (non spherical) in the nucleon and/or in the Δ (1232) allows for E2.

A2 exp at MAMI

The neutron spin-transfer coefficient *Cnx* in deuteron photo-disintegration at different angles



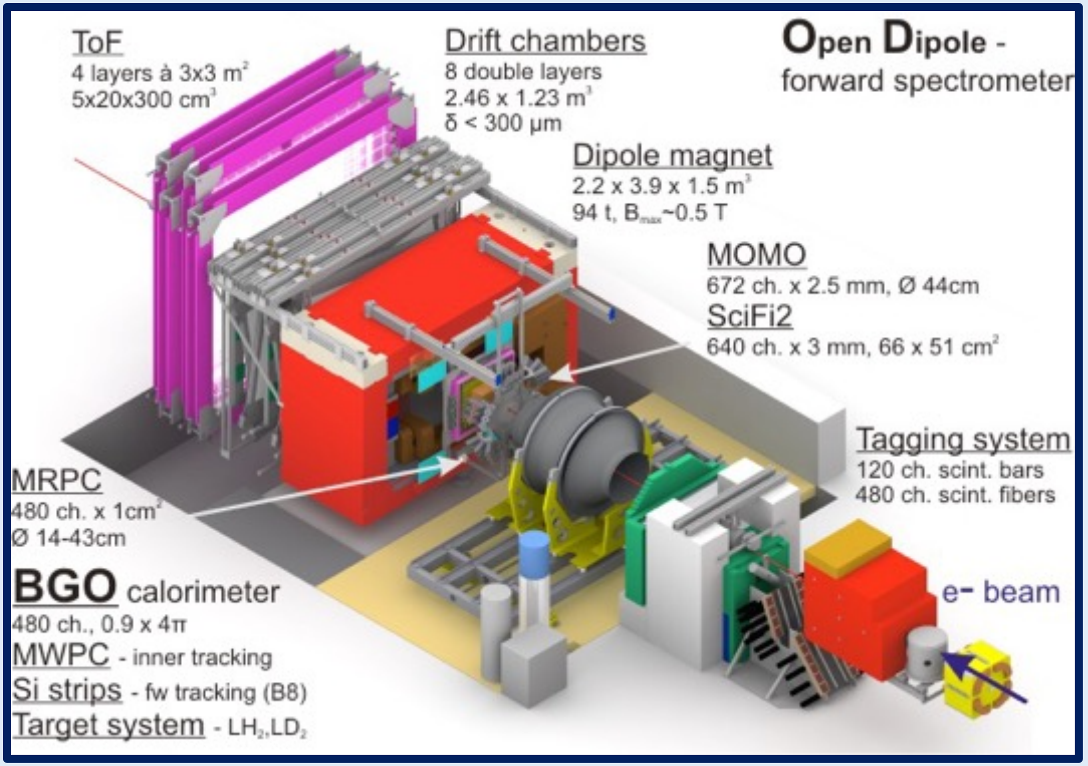


Models with known resonances do not reproduce the data

Indication of the need to include the ***exaquark state d∗(2380)*** as an explicit degree of freedom

Destabilization of high-mass neutron stars by the emergence of d-hexaquarks

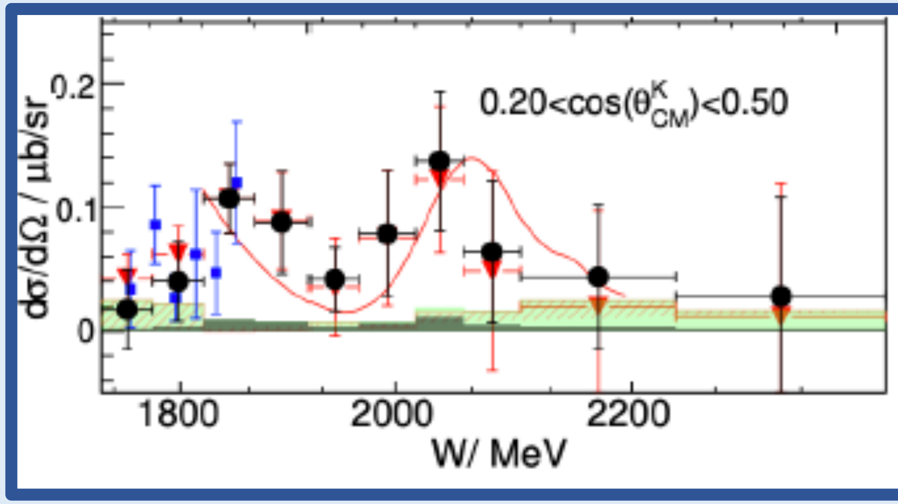
BGO experiment at ELSA (Bonn)



3 GeV e beams

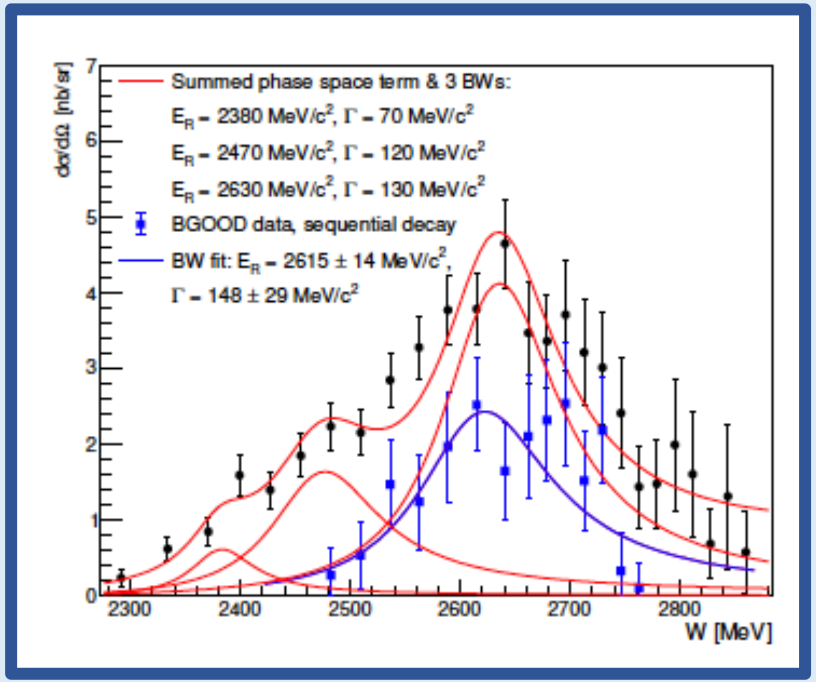
Strangeness photoproduction at low momentum transfer

$\gamma n \to K^0 \Sigma^0$ differential cross section



Coherent photoproduction of the deuteron

The search for dibaryon d(2380)* in the isoscalar (I = 0) channel



Cooler synchrotron (COSY) storage ring at Forschungszentrum Jülich

JEDI collaboration : *to investigate systematic effects in the search for the electric dipole moment of charged particles in storage rings*

Spin decoherence and off-resonance behavior of radio-frequency-driven spin rotations in storage rings

N. N. Nikolaev,[1] F. Rathmann,[2,*] J. Slim,[3,†] A. Andres,[2,3] V. Hejny,[2] A. Nass,[2] A. Kacharava,[2] P. Lenisa,[4] J. Pretz,[2,3] A. Saleev,[4,‡] V. Shmakova,[4,§] H. Soltner,[5] F. Abusaif,[2,3,‖] A. Aggarwal,[6] A. Aksentev,[7] B. Alberdi,[2,3,¶] L. Barion,[4] I. Bekman,[2,**] M. Beyß,[2,3] C. Böhme,[2] B. Breitkreutz,[2,‡] N. Canale,[4] G. Ciullo,[4] S. Dymov,[4] N.-O. Fröhlich,[2,†] R. Gebel,[2] M. Gaisser,[3] K. Grigoryev,[2,‡] D. Grzonka,[2] J. Hetzel,[2] O. Javakhishvili,[8] V. Kamerdzhiev,[2,‡] S. Karanth,[6] I. Keshelashvili,[2,‡] A. Kononov,[4] K. Laihem,[3,‡] A. Lehrach,[2,3] N. Lomidze,[9] B. Lorentz,[10] G. Macharashvili,[9] A. Magiera,[6] D. Mchedlishvili,[9] A. Melnikov,[7] F. Müller,[2,3] A. Pesce,[2] V. Poncza,[2] D. Prasuhn,[2] D. Shergelashvili,[9] N. Shurkhno,[2,‡] S. Siddique,[2,3,‡] A. Silenko,[11] S. Stassen,[2] E. J. Stephenson,[12] H. Ströher,[2] M. Tabidze,[9] G. Tagliente,[13] Y. Valdau,[2,‡] M. Vitz,[2,3] T. Wagner,[2,3,‡] A. Wirzba,[2,14] A. Wrońska,[6] P. Wüstner,[5] and M. Żurek[2,††]

(JEDI Collaboration)

[1]L.D. Landau Institute for Theoretical Physics, 142432 Chernogolovka, Russia
[2]Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[3]III. Physikalisches Institut B, RWTH Aachen University, 52056 Aachen, Germany
[4]University of Ferrara and Istituto Nazionale di Fisica Nucleare, 44100 Ferrara, Italy

University of Ferrara and INFN

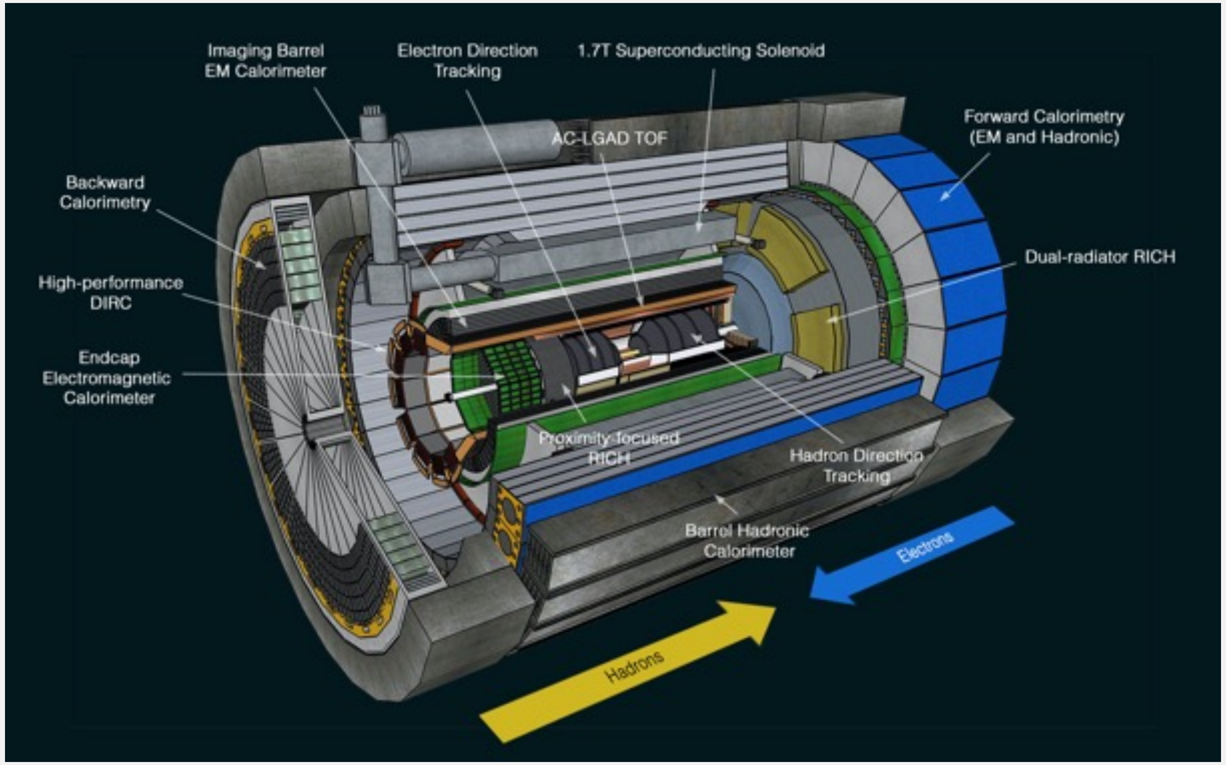
PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 111002 (**2024**)

A permanent electric dipole moment violates both parity (P) and time reversal symmetry (T)

Near Future plans at MAMI and ELSA for the Italian collaboration

- Runs with polarized deuteron to study d*(2380)
- Runs for scattering Compton on polarized protons
- A new TPC in the set up

Longer term future : participation at EIC EPIC detectors

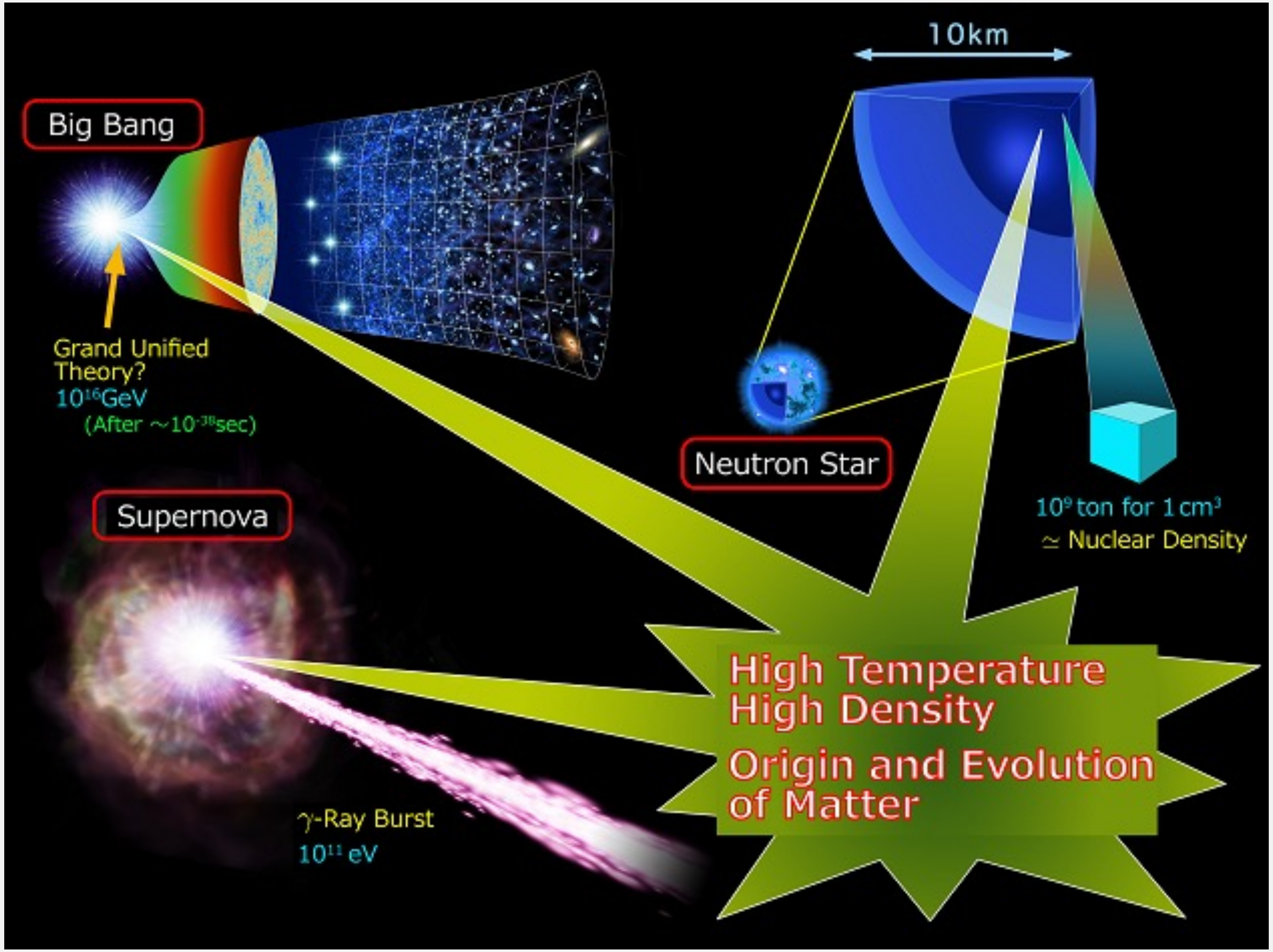


Heavy ion Physics

- Phase transitions in nuclei and in nuclear matter

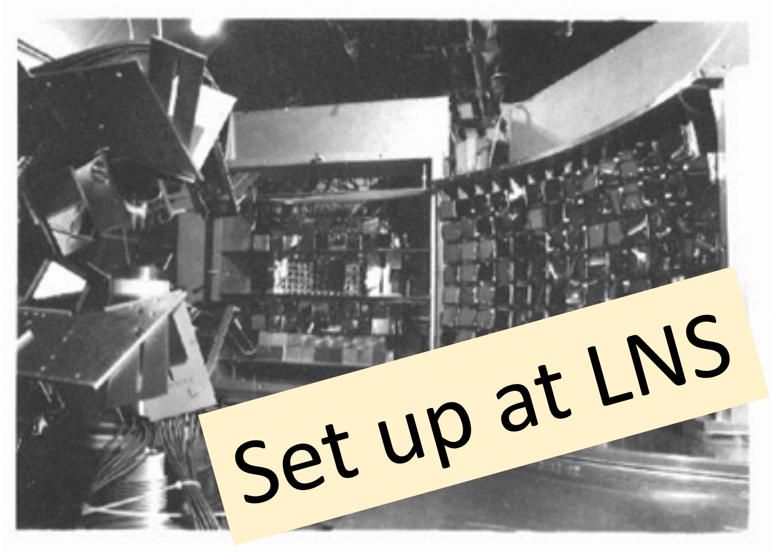
- dense nuclear matter
- dense quark matter
- hot and dense quark-gluon plasma

Equation of state for neutron stars

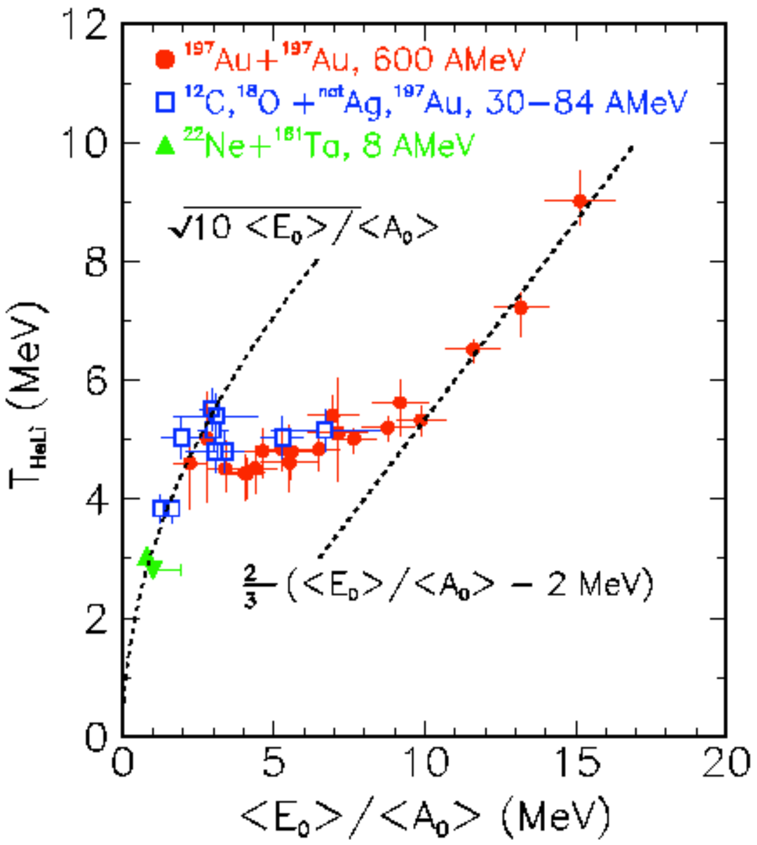


Heavy ion reactions….some history for the Italian German collaboration

multifragmentation reactions



Study of the nuclear caloric curve

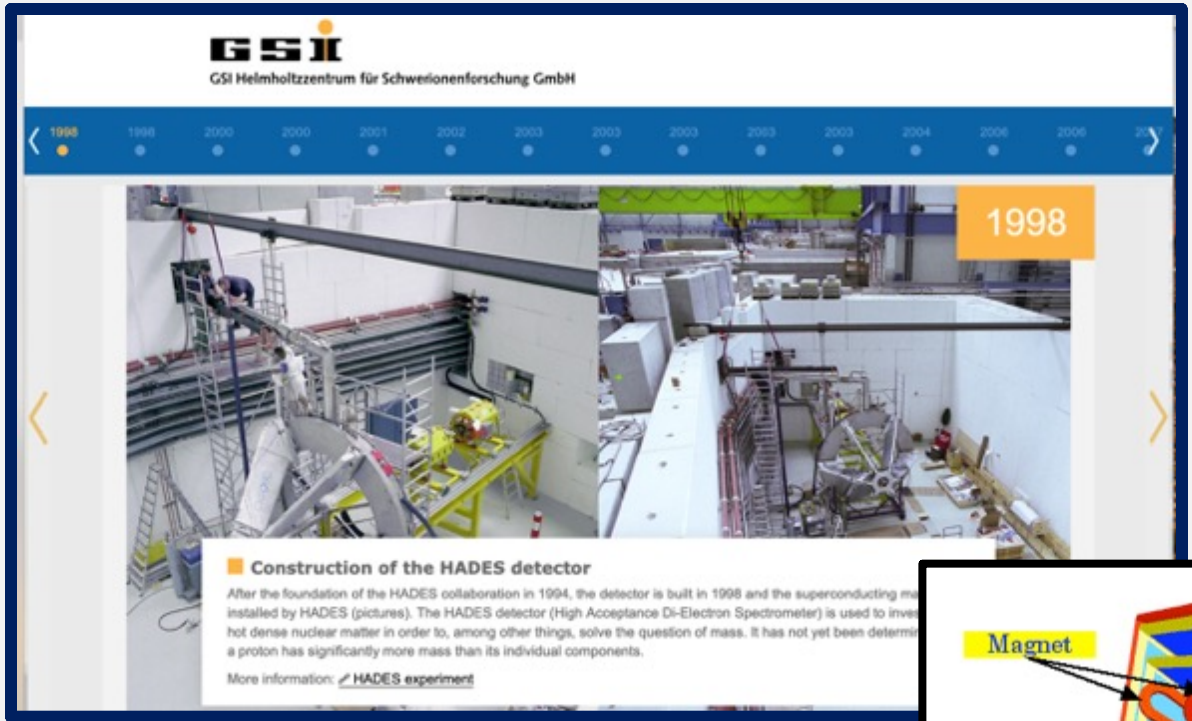


Liquid Gas Transition in nuclei

Measurements at GSI and LNS

LNS and Univ. di -Catania,
Universita di Milano and INFN,
GSI
Michigan State University
MPI Heidelberg
Dresden
Soltan Institute - Warsaw,

Heavy ion reactions….some history for the Italian German collaboration

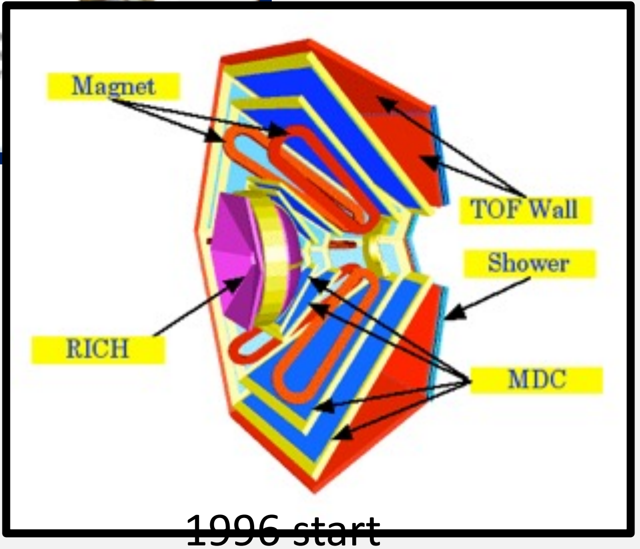


The aim was to study the in-medium properties of nuclear matter and mesons at of 1-2A GeV, via the e^+e^- decay channel.

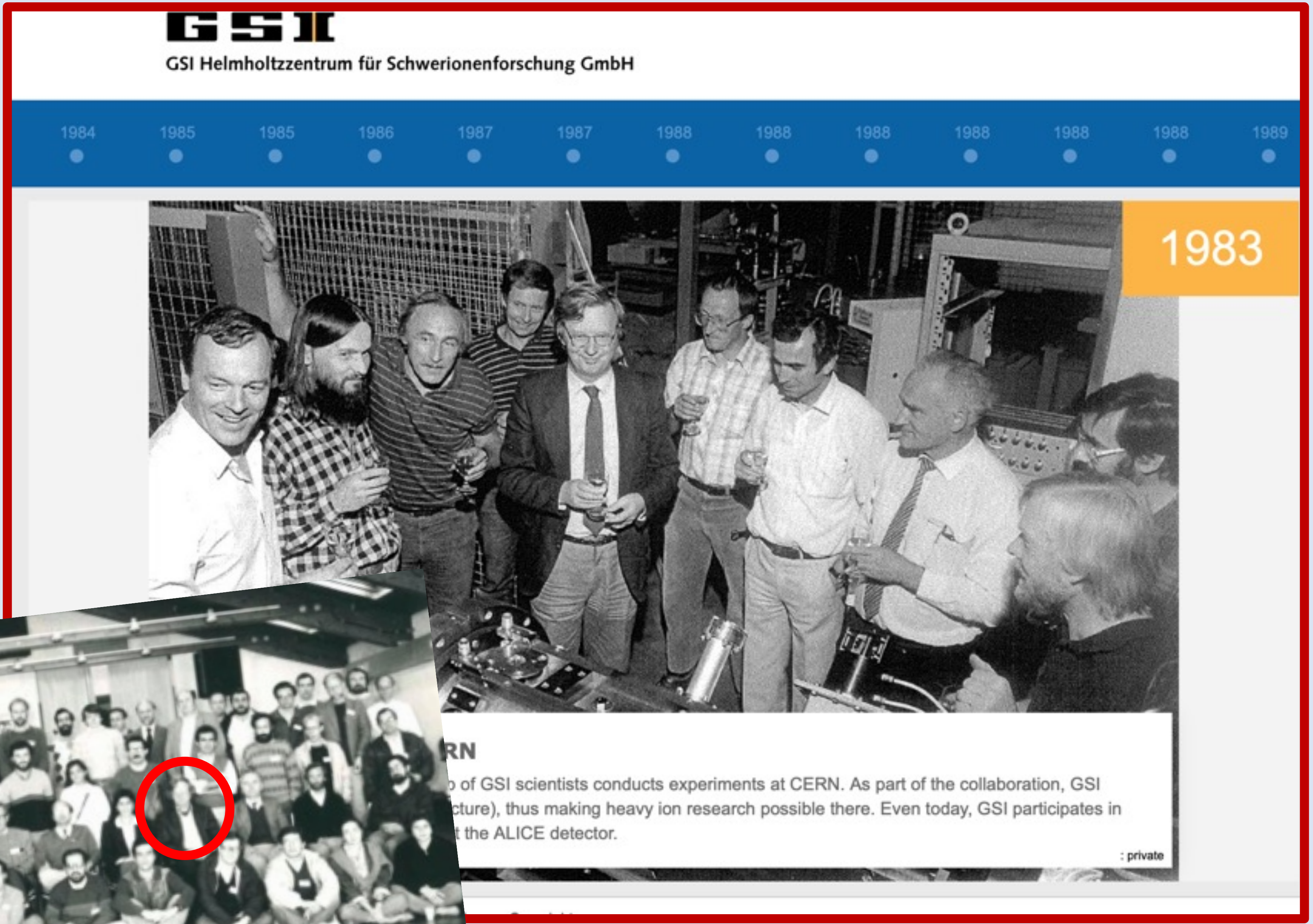
The HADES time-of-flight wall

Under the responsibility of INFN

INFN, LNS, Università di Milano and INFN
Università di Catania
Bratislava, Slovakia
GSI
Nuclear Physics Institute, Řež, Czech Republic



1996 start
Construction TOF



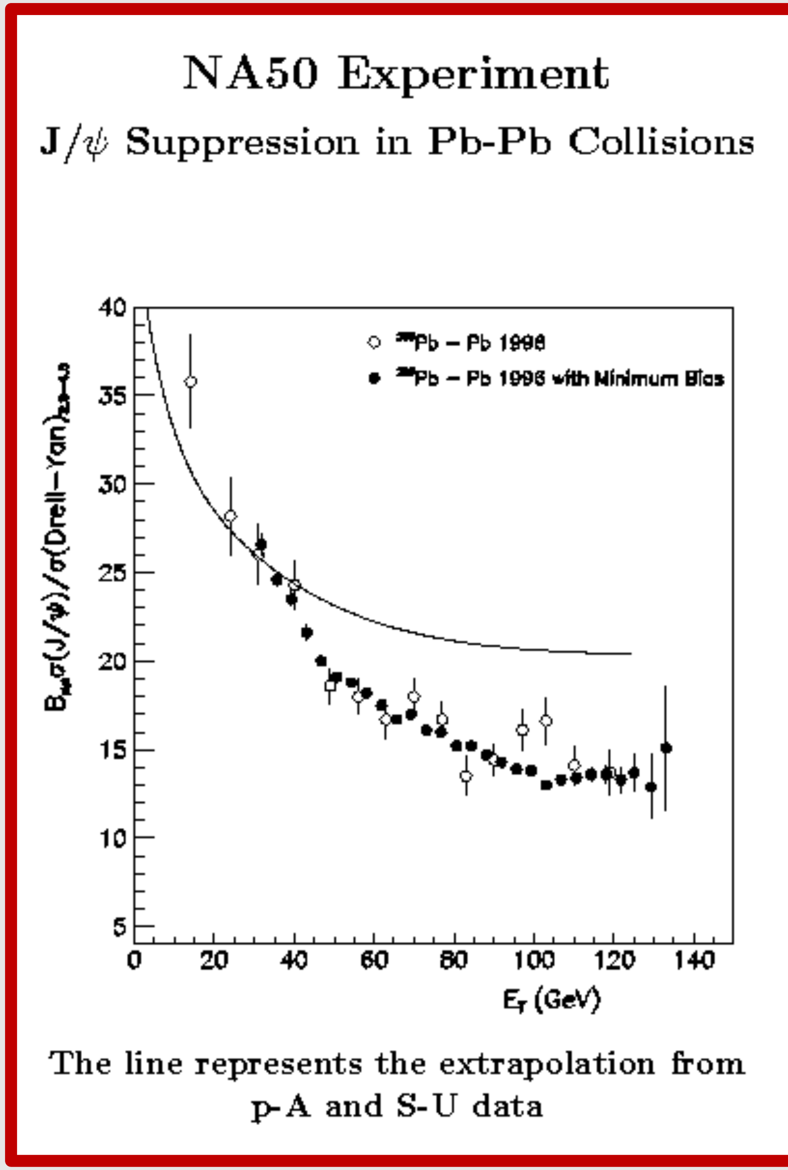
GSI built an ion source for Heavy Ions Research at CERN

GSI director Paul Kienle – ERICE school on heavy ion physics 1986 – Director School
(Today directors are Michael Buballa and Christian Fischer)

Heavy ion reactions….some history for the Italian German collaboration

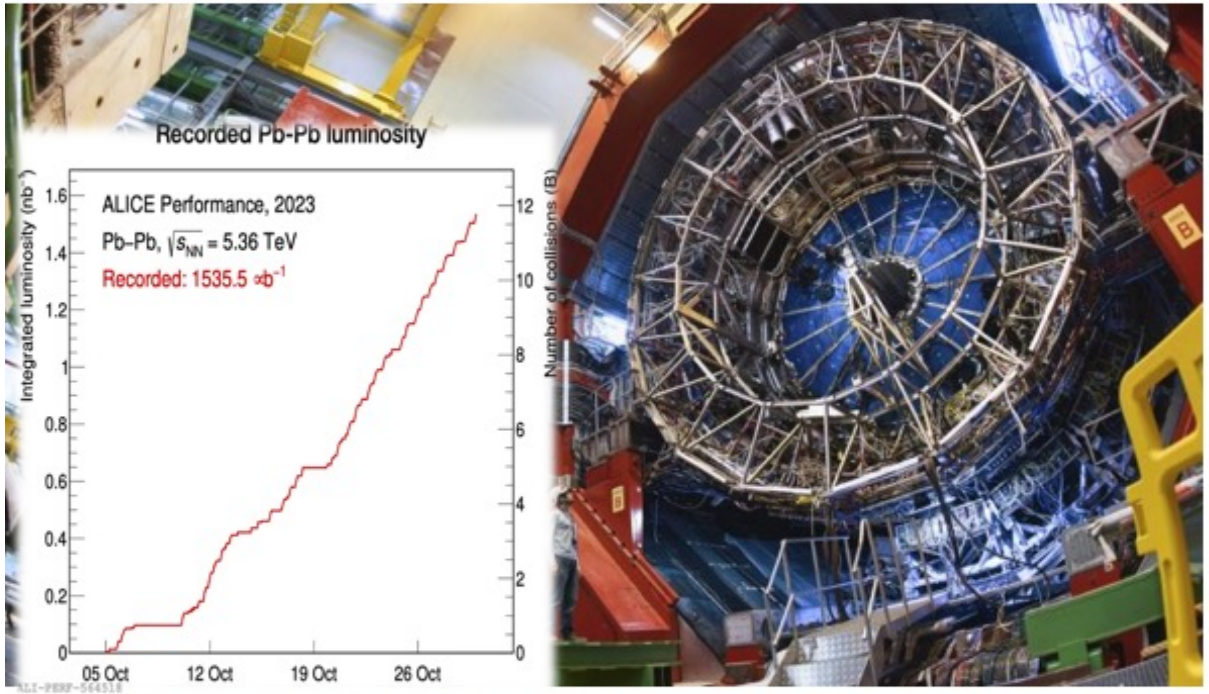
The SPS heavy-ion programme was to investigate :

- properties of dense quark matter
- of hot and dense quark-gluon plasma
- transition from hadronic matter to a *plasma of* ***deconfined quarks*** and gluons will occur (in opposite direction, at 10−5 s after the Big Bang).



A signal of phase transition?

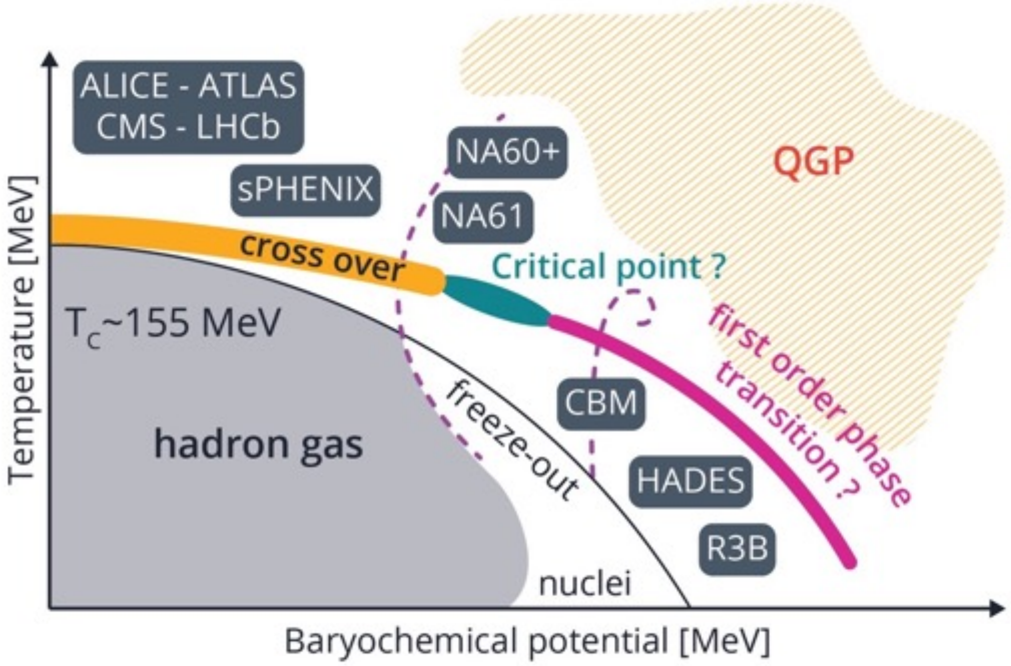
INFN Torino, Cagliari and others



ALICE@CERN

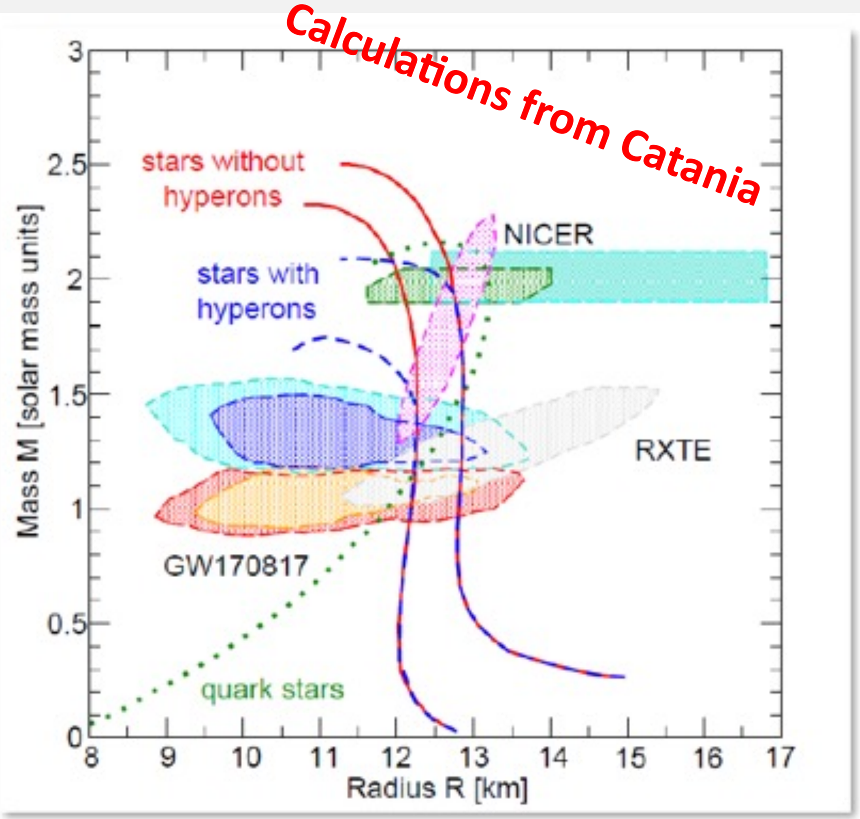
- Goal is to investigate the properties of the quark-gluon plasma, namely the qualitatively novel state of nuclear matter at extreme conditions of temperature and density

- Discover in microscopic detail the material properties of the Quark Gluon Plasma at the highest temperature reached at the LHC at CERN



Italian Collaboration is about 20% of the total

Neutron stars and hyperons



The blobs represent the mass and radius constraints from the gravitational wave detectors LIGO and Virgo, as well as NASA's Neutron star Interior ExploreR (NICER), while the dashed and solid lines represent the predictions obtained with various EoS models, with and without hyperons. Picture credit I. Vidana (Universita di Catania).

24

VIDANA

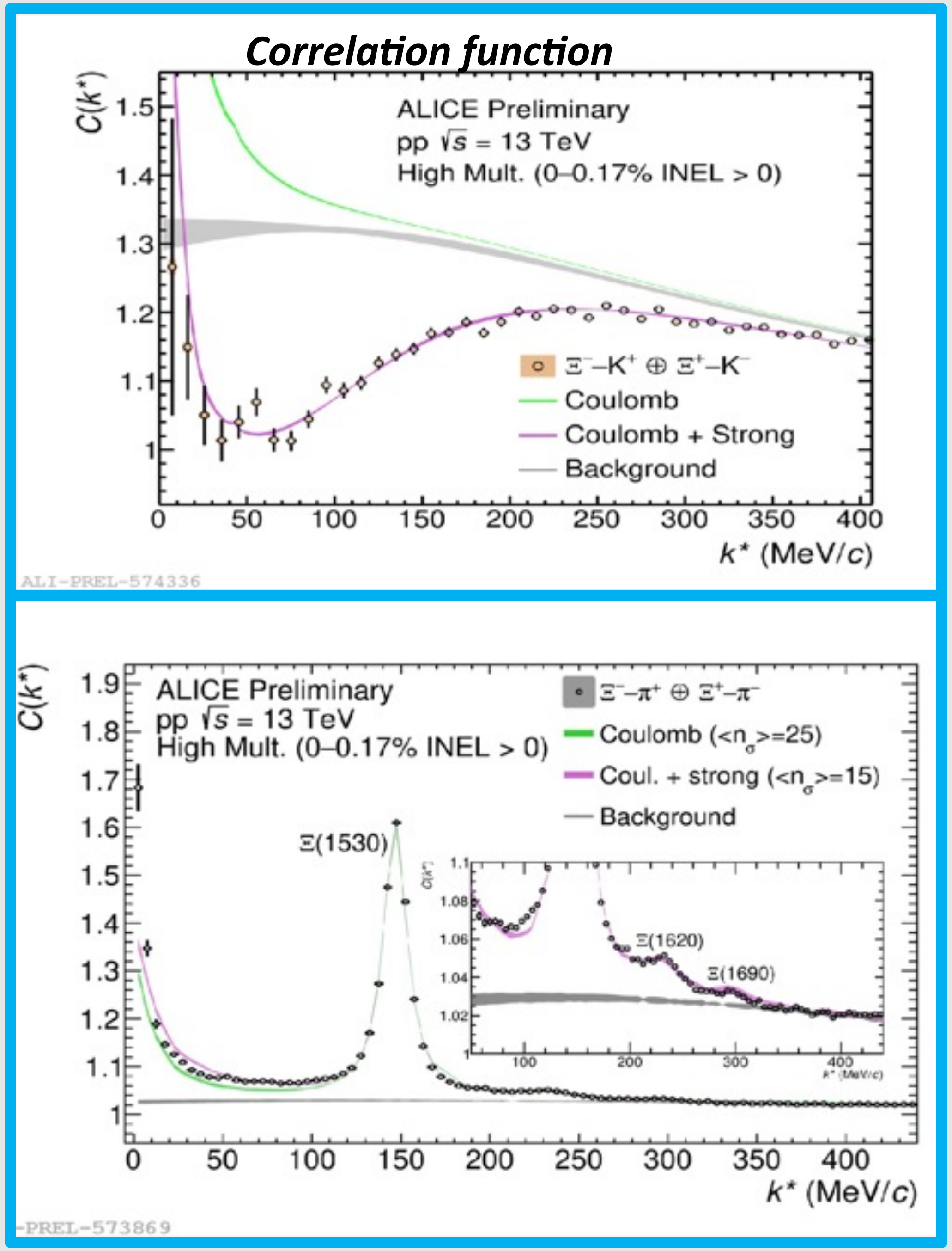
Strangeness

Some history : KaoS experiment with the Kaon spectrometer at GSI

Particles (Kaons) change their mass in dense nuclear matter crucial for the understanding of stars

Importance of better knowledge of hyperons properties and their interaction

high-precision constraints meson- baryon interactions are needed



Preliminary data presented at SQM2024

ΞK and Ξπ femtoscopy in pp collisions in ALICE

to be added to the other meson-baryon systems $K^{-}p$, $K^{0}\Lambda$ already studied

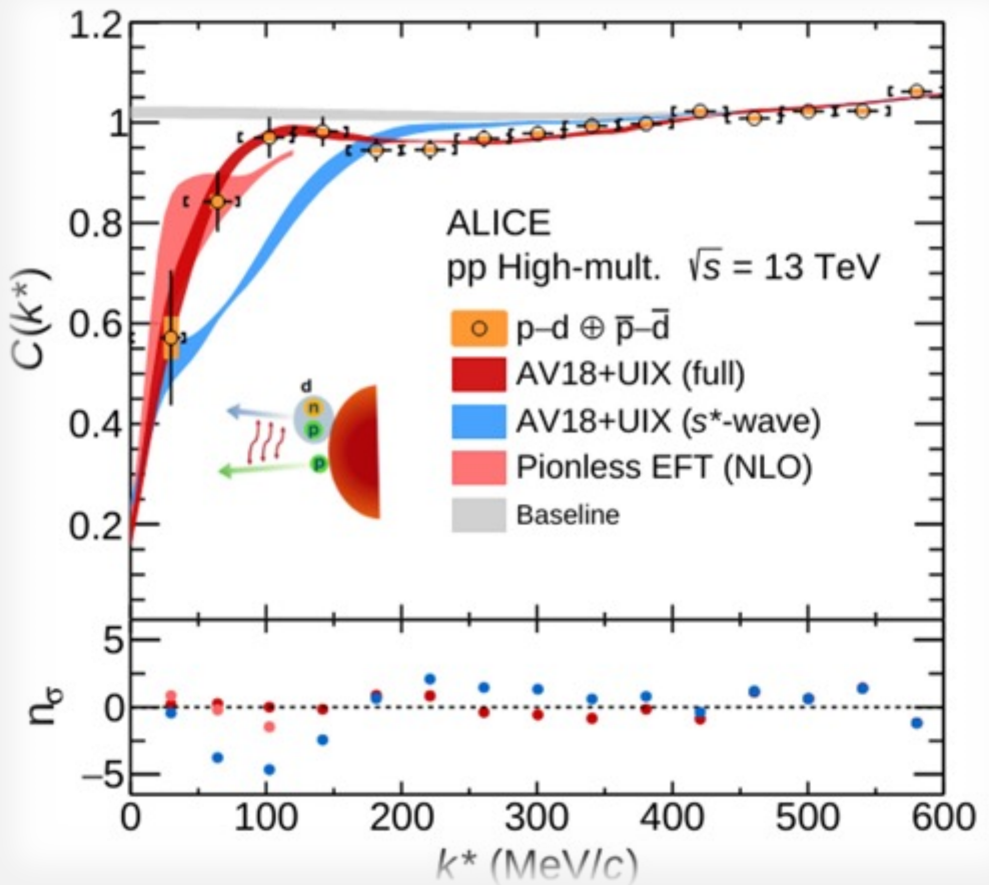
novel high-precision constraints on S=-1 and S=-2 meson- baryon interactions

Contribution from the INFN (LNF)

Exploring the strong interaction of three-body systems at the LHC

ALICE results show that for the p-d data (formation and interaction) are understood only via full three-body calculations *considering the internal structure of the deuteron*

Two-body femtoscopy at ALICE gives access to the dynamics and effects of the strong interaction in three-body systems.



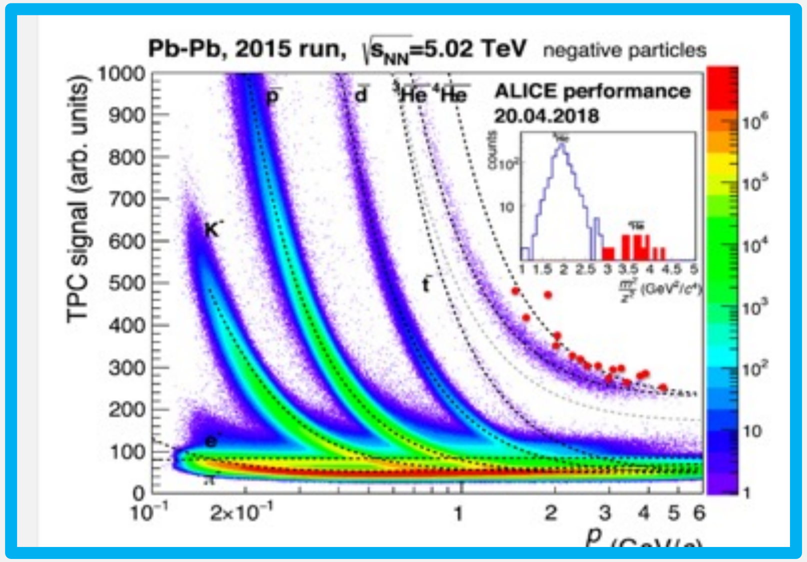
Expectation to be sensible to 3-body forces with ALICE Run-3 data!

Calculations (red) *Phys.Rev.C 108 (2023) 6, 064002*,

«Role of three-body dynamics in nucleon-deuteron correlation functions»

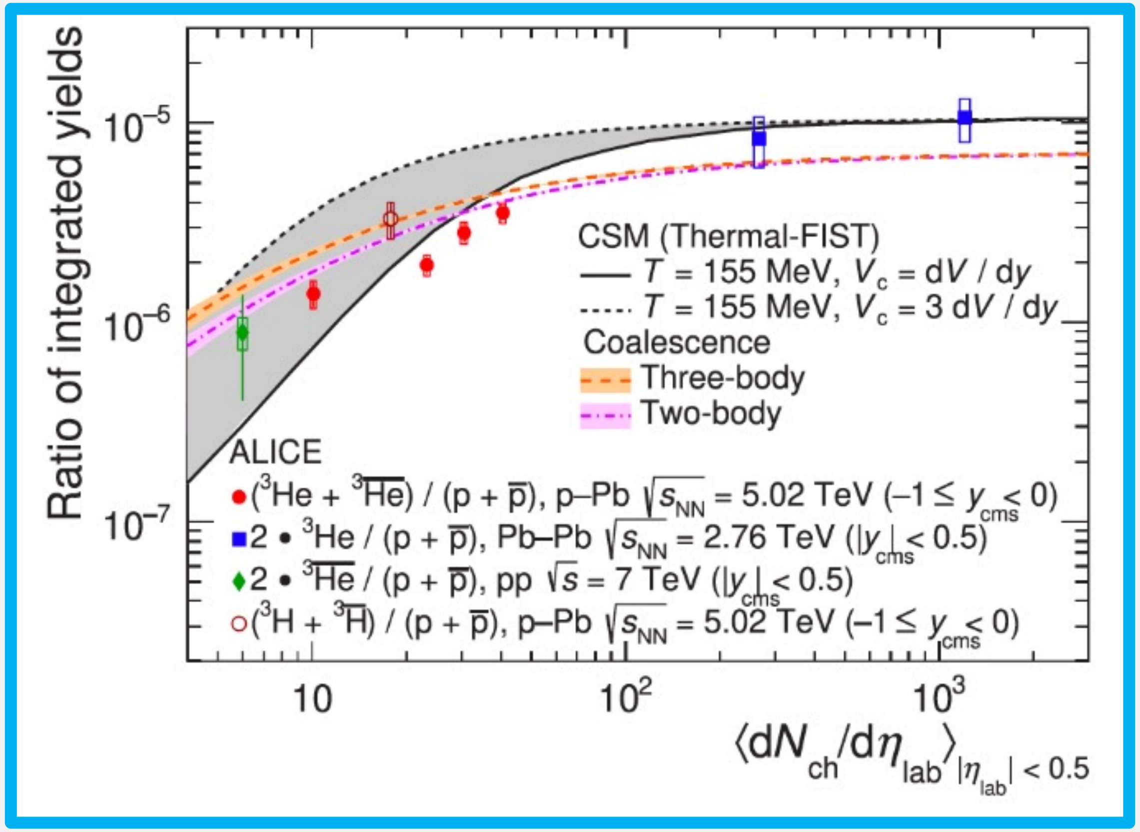
Published in arXiv:2308.16120 [nucl-ex]. *Physical Review X*

Anti-nuclei in ALICE
………and connections with experiments in the space



Production of (anti)triton and (anti)helium relative to the(anti)proton-

It evolves with the number of produced charge particles



Data favor the coalescence models (colored bands) statistical hadronization (black and gray bands).

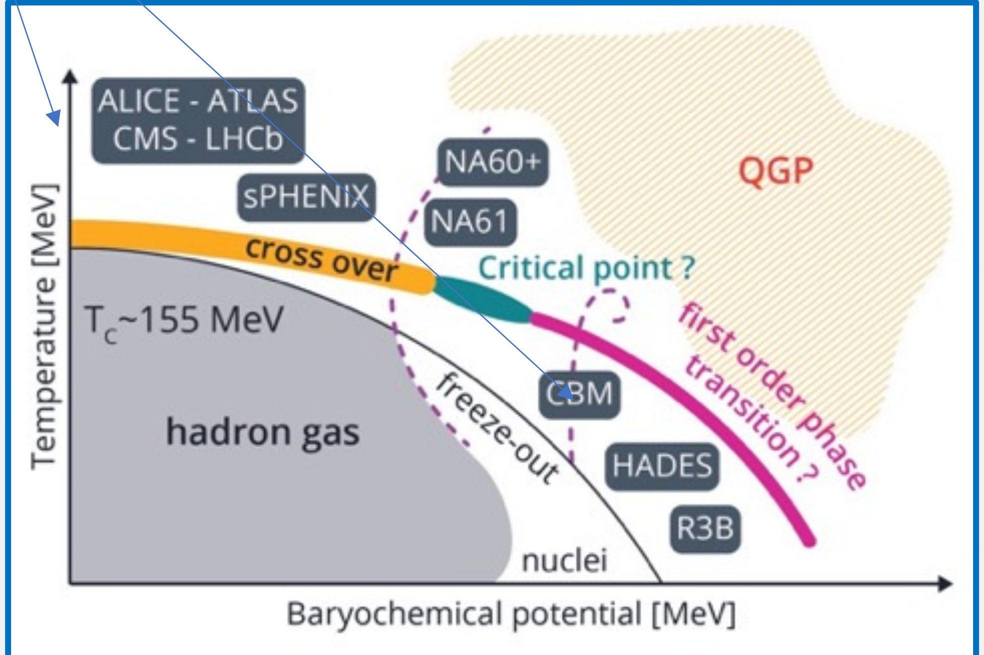
- synergy with the astrophysical domain
- *antihelium measurements constrain cosmic antinuclei fluxes (AMS in space) and indirectly dark matter (prerequisite)*

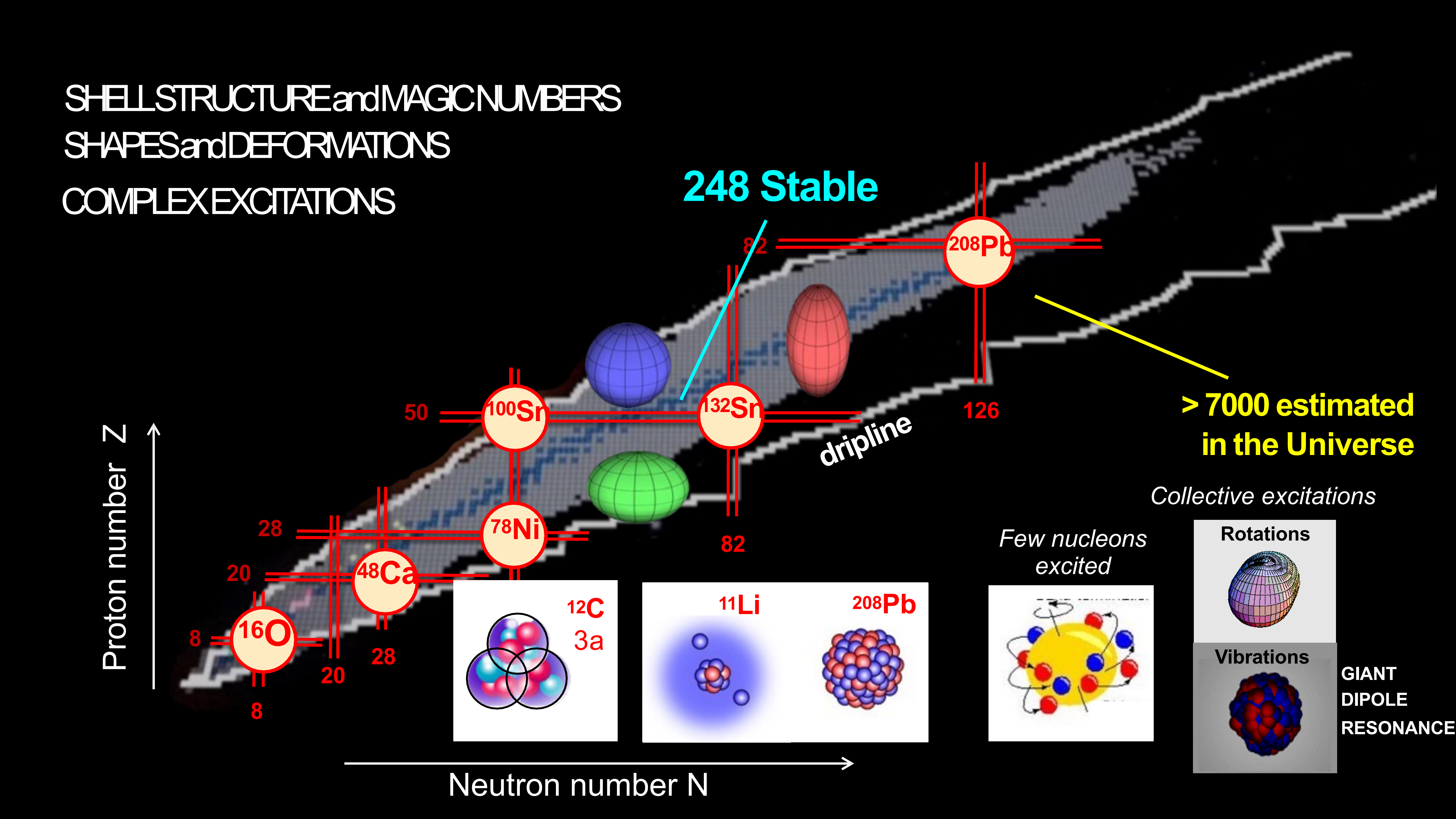
Future perspectives on QGP studies

The collaboration is and will be engaged in

- the construction of **ALICE 3 (Run 5)** as part of the **HL-LHC** plans
- It will be very importart to investigate nuclear matter at high baryonic density, when the completion of SIS-100 at FAIR and the completion of the CBM experiment are realized.

Efforts will continue in R&D activities for tracking devices.



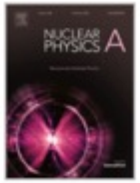

SHELL STRUCTURE and MAGIC NUMBERS
SHAPES and DEFORMATIONS
COMPLEX EXCITATIONS
248 Stable
> 7000 estimated in the Universe
Proton number Z
Neutron number N
dripline
82
50
28
20
8
126
82
28
20
8
16O
48Ca
78Ni
100Sn
132Sn
208Pb
12C
3a
11Li
208Pb
Few nucleons excited
Collective excitations
Rotations
Vibrations
GIANT DIPOLE RESONANCE

Nuclear structure ….some history for the Italian German collaboration

ELSEVIER

Nuclear Physics A

Volume 531, Issue 2, 2 September 1991, Pages 383-403



Levels in ^{130}Cs and the IBFFM

1990

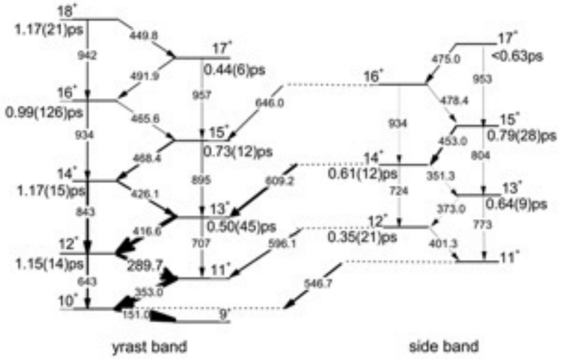
P.R. Sala, N. Blasi, G. Lo Bianco, A. Mazzoleni

Dipartimento di Fisica dell'Università, and INFN, Sezione di Milano, I-20133 Milano, Italy

R. Reinhardt, K. Schiffer, K.P. Schmittgen, G. Siems, P. Von Brentano

Institut für Kernphysik der Universität Köln, D-5000 Köln, Germany

Spontaneous symmetry breaking in odd-odd triaxial nuclei implies chiral bands

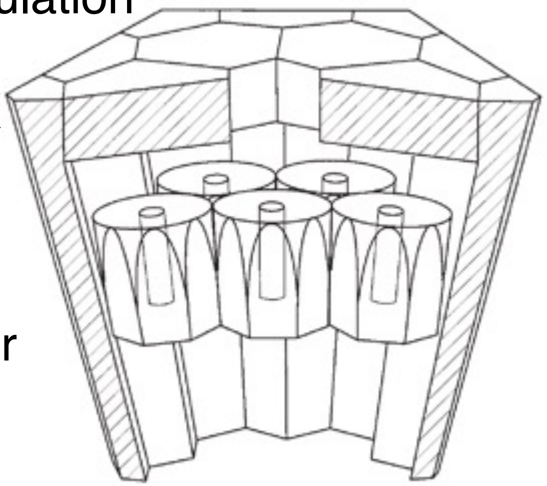


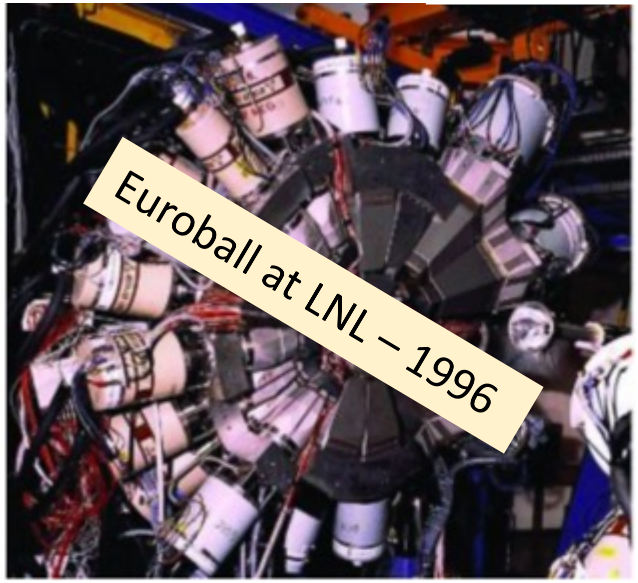
Nuclear structure ….some history

Important milestones with the important developments made at Cologne

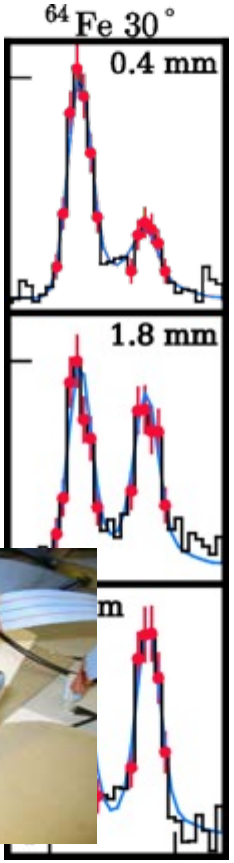
Hermetical encapsulation of Ge detectors developed by U.oK and the company Eurisys

Larger efficiency for Photopeak

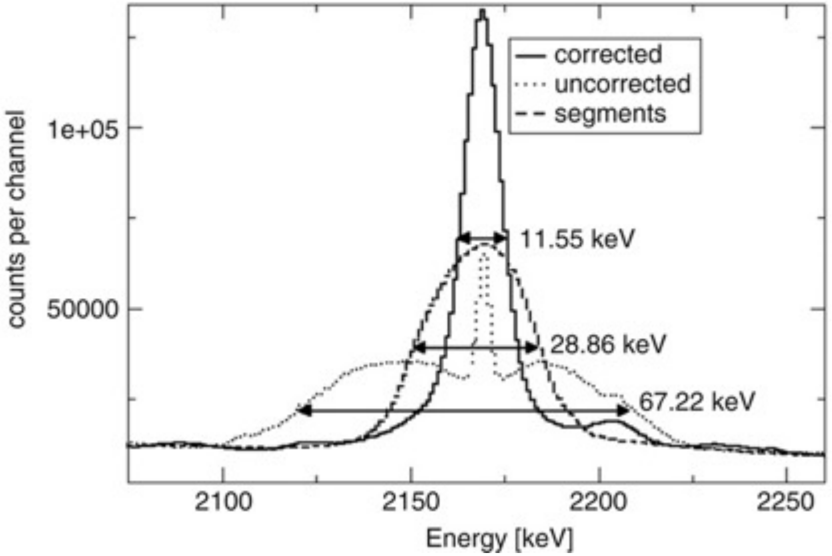




Plunger for lifetimes

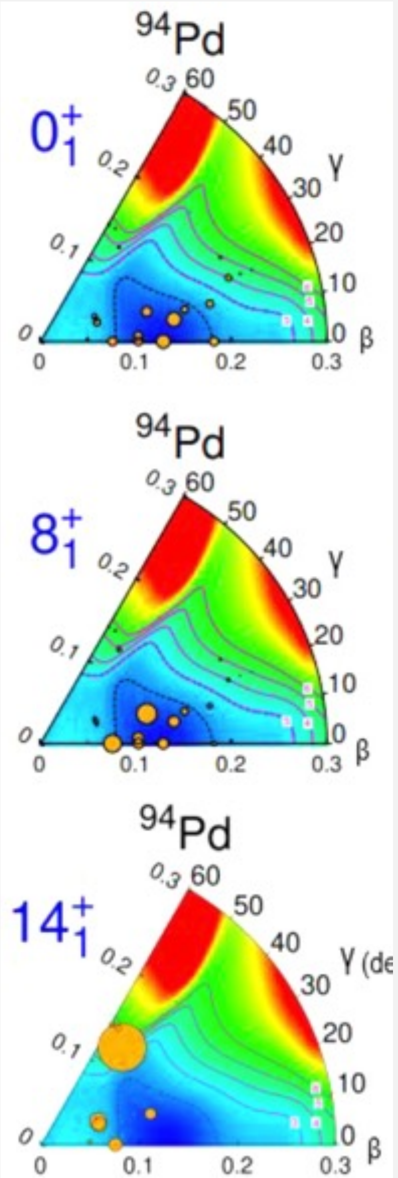


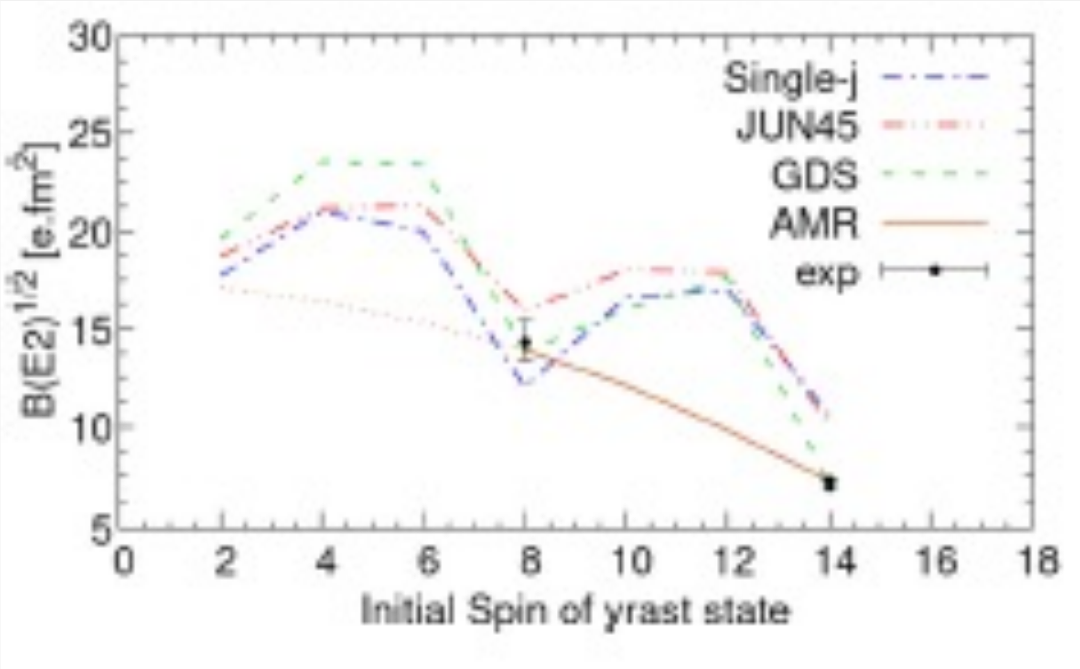
To AGATA cryostat and mounting and tests at UoC



*With **RISING** the first gamma spectroscopy for nuclear structure with radioactive beams at Relativistic Energy Measurements around ^{100}Sn*

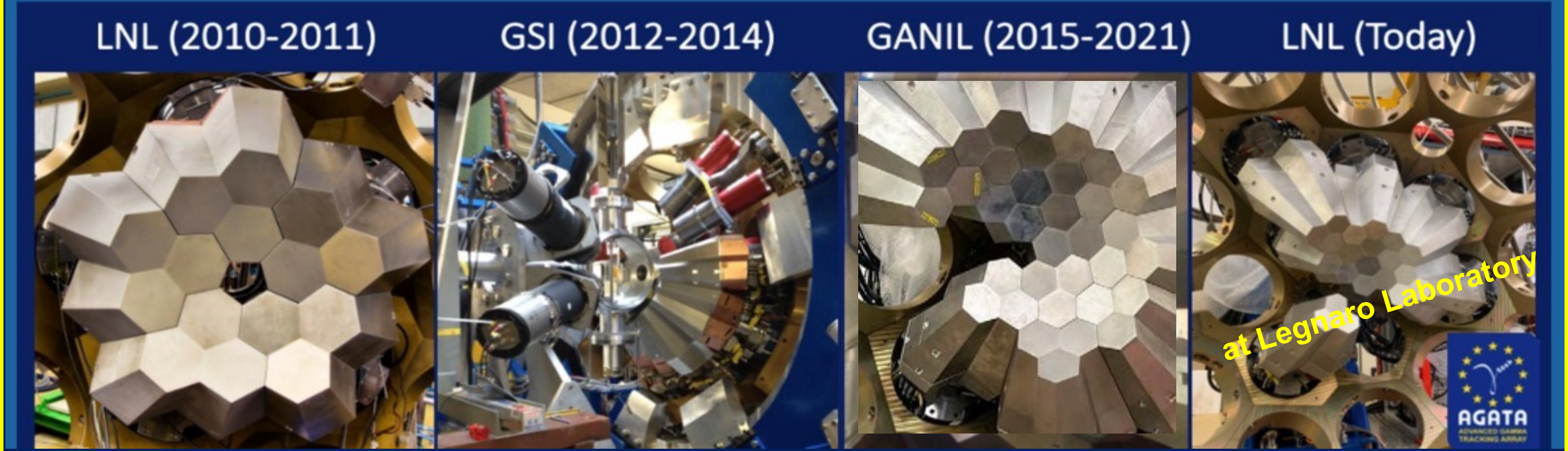
Nuclear shapes and proton neutron interaction in nuclei



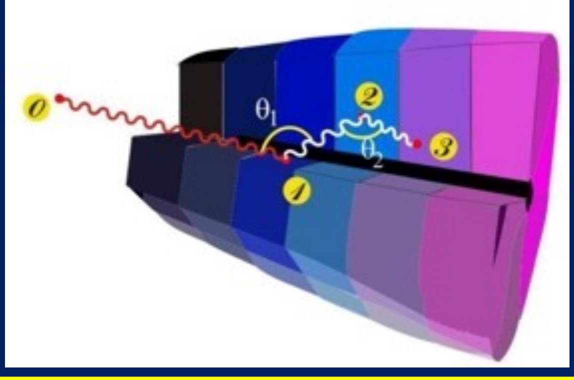


Decay of the isomeric, yrast $I\pi$ = 14+ produced via the projectile fragmentation of a ^{124}Xe beam at 982 MeV/u from the SIS18 synchrotron at GSI

Transition probability in the Tz =+1 nucleus $^{94}Pd_{46}$



AGATA STATE-of-the-ART Ge ARRAY



Gamma spectroscopy with AGATA coupled with different devices

AGATA web page: https://www.agata.org

Nuclear Structure Selected Highlights

Light Nuclei (A~20)

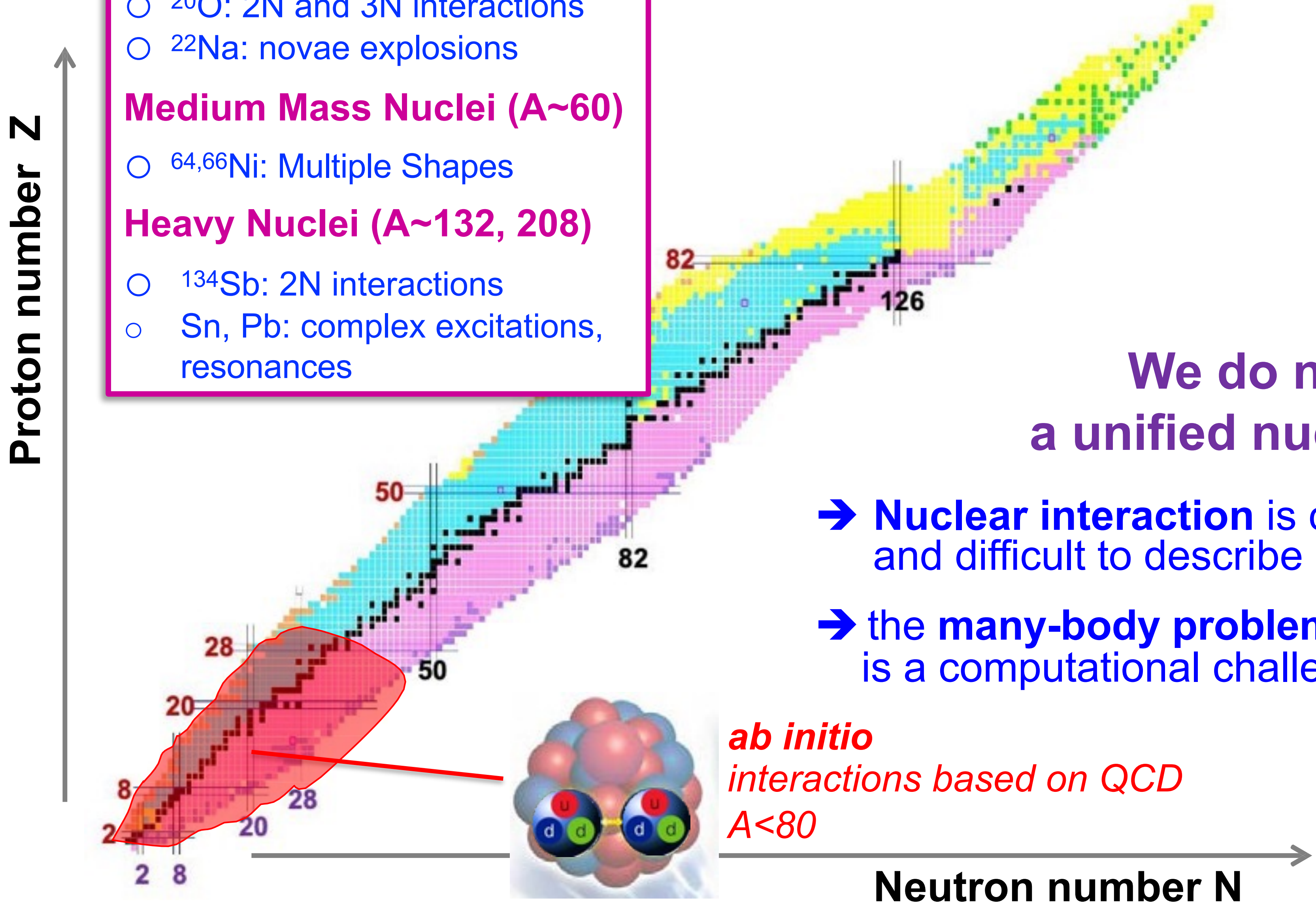
- ^{20}O: 2N and 3N interactions
- ^{22}Na: novae explosions

Medium Mass Nuclei (A~60)

- $^{64,66}Ni$: Multiple Shapes

Heavy Nuclei (A~132, 208)

- ^{134}Sb: 2N interactions
- Sn, Pb: complex excitations, resonances



ab initio
interactions based on QCD
A<80

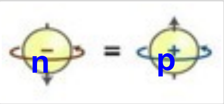
We do not have a unified nuclear theory

➔ **Nuclear interaction** is complex and difficult to describe

➔ the **many-body problem** (2<A<300) is a computational challenge

ATOMIC NUCLEI

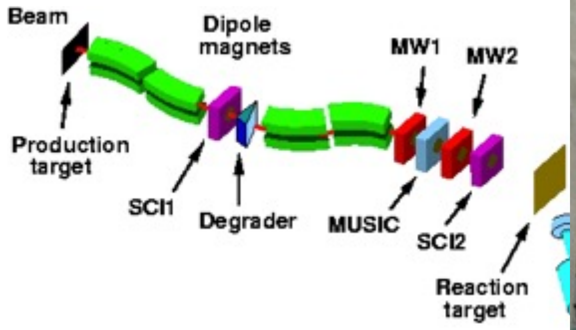
Many Body Quantum Systems

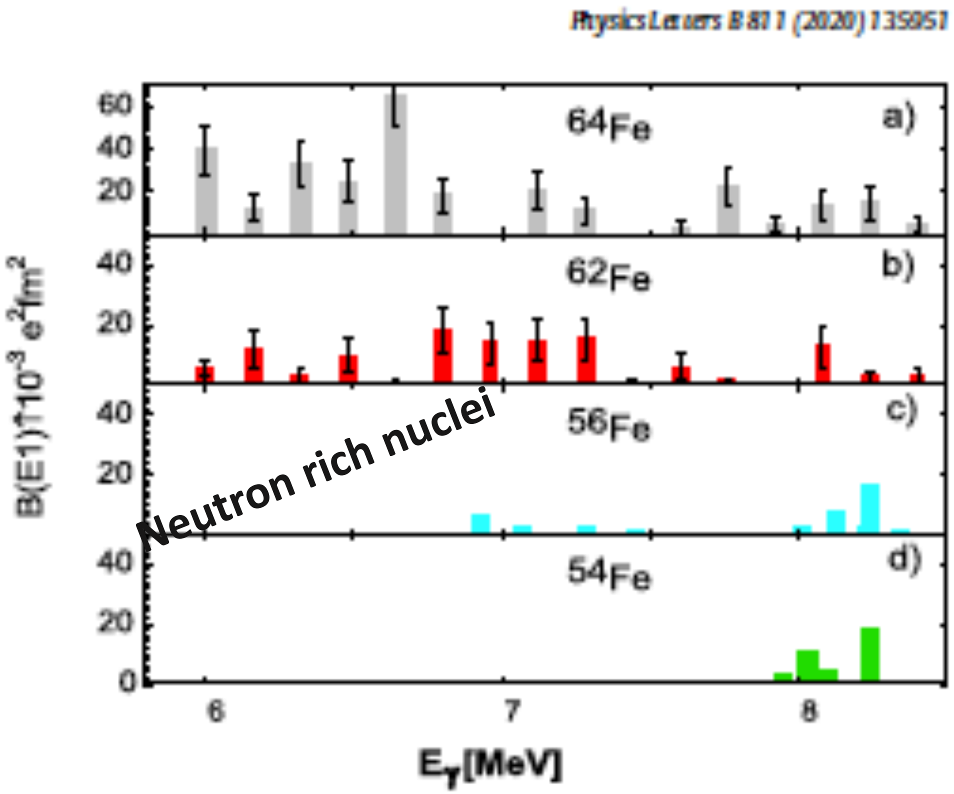


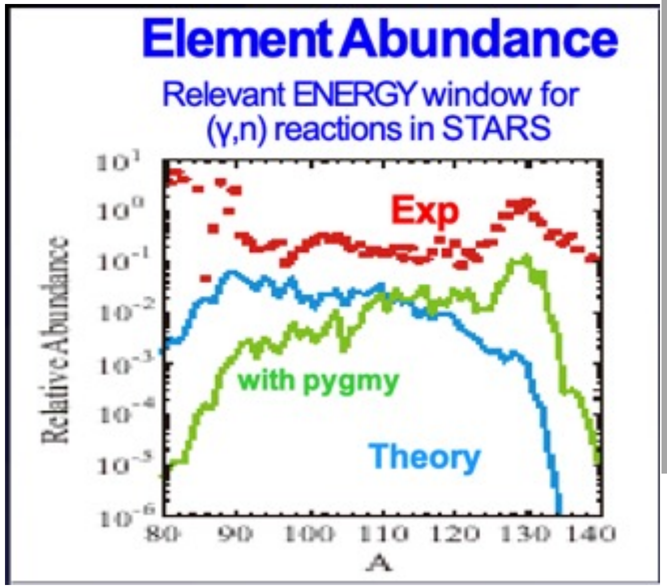
Symmetry Principle

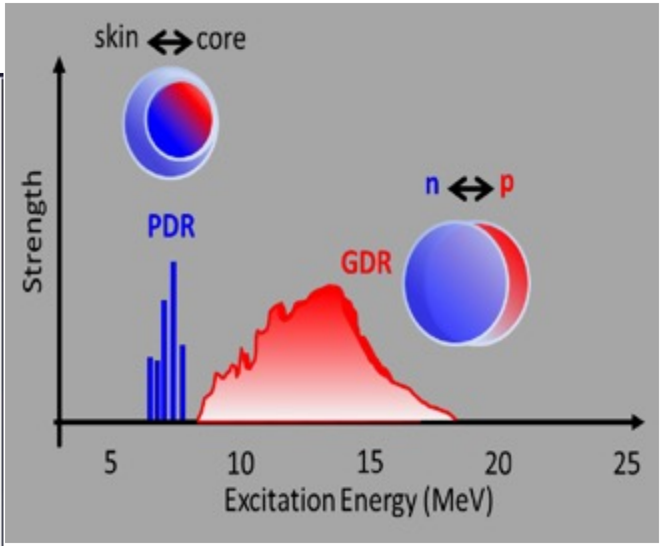
Effective Nuclear Force

Electric Dipole resonances in nuclei :
nuclear structure information for r-process and neutron stars





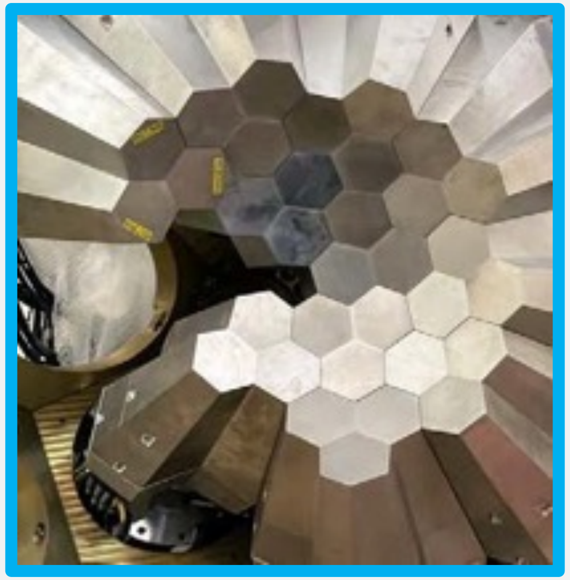




In Cologne and Darmstadt important research and results during the years on this problem

AGATA

Spectroscopy with different types of heavy ion induced reactions at low energy



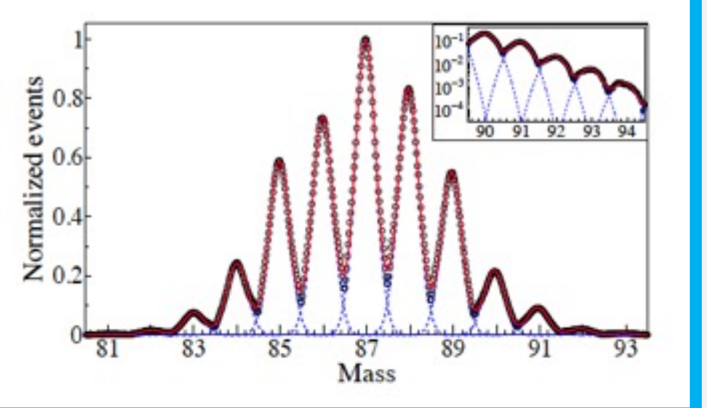
With AGATA plus magnetic spectrometer, charge particle and neutron detectors

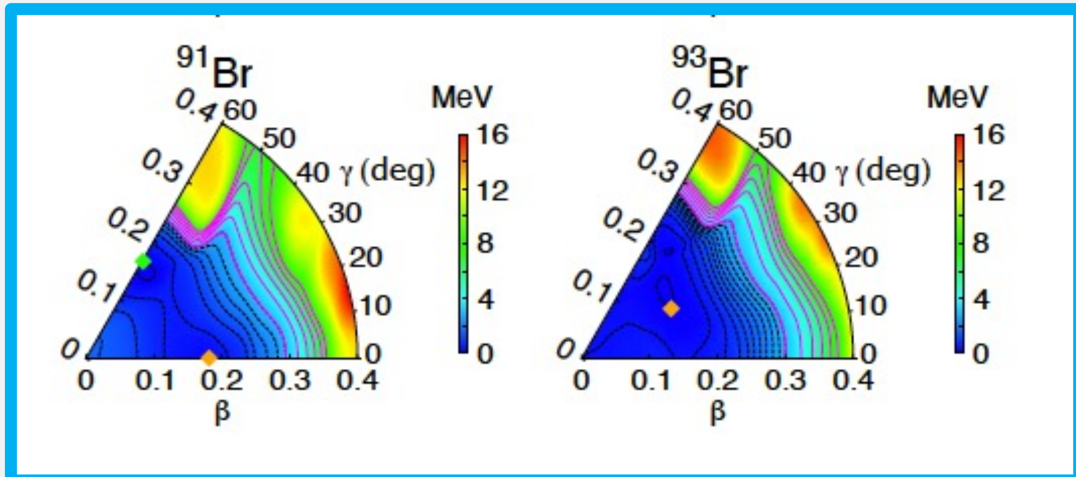
fusion evaporation, multi particle transfer

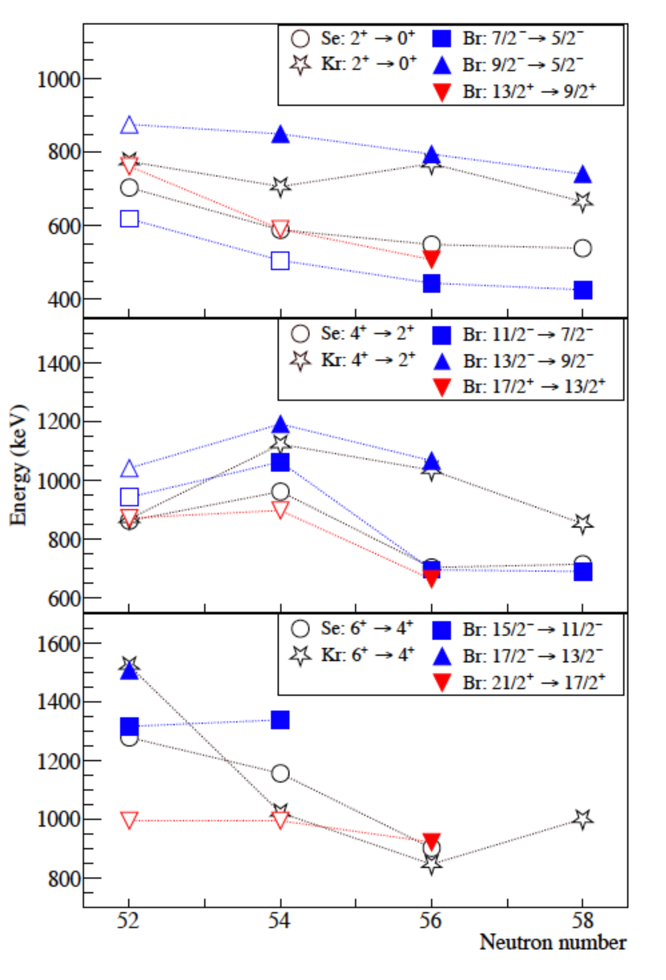
Fission to populate neutron rich nuclei

High-resolution spectroscopy of neutron-rich Br isotopes and signatures for a prolate-to-oblate shape transition at N=56

Mass of fission products







- **The NUCLEAR STRUCTURE community studies**

  the most fundamental aspects of Atomic Nuclei by particle and gamma spectroscopy

  SHELL structure
  Shapes and deformations
  Resonances

- **A Major Challenge for THEORY – Effective Interactions, ...**
- **Strong Interdiciplinarity – Astrophyiscs**
- **FACILITIES for Radioactive Beams: SPES (ISOL), FAIR (fragmentation), …**
- **State of the Art SETUP: AGATA, charged-particle det., magnetic spectrometers, ...**

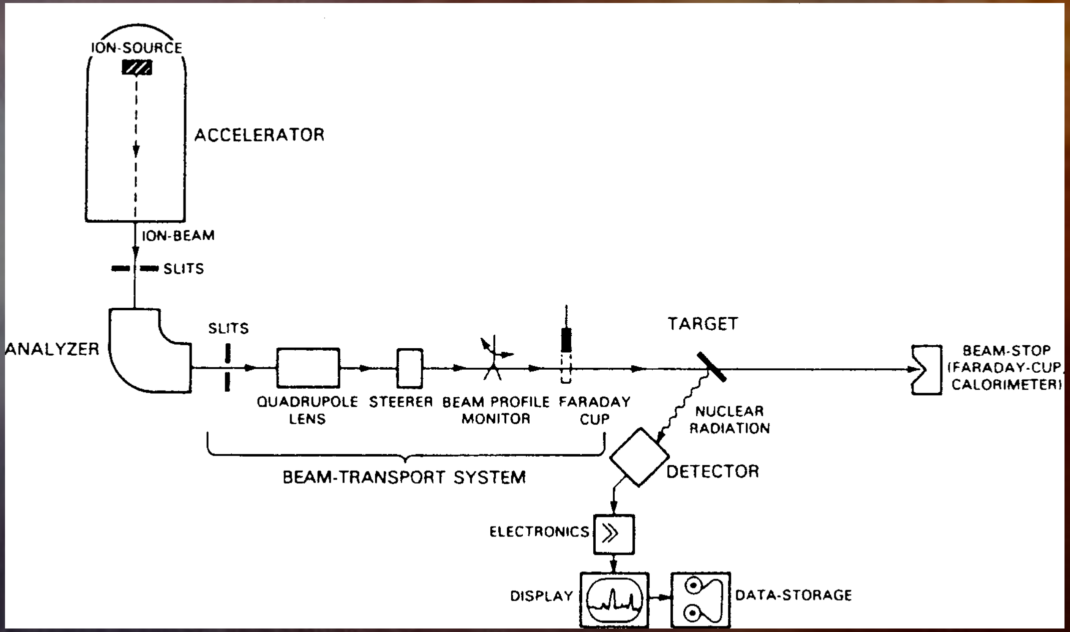
… We are moving into Precision Physics of EXOTIC

Nuclear Astrophysics

stellar evolutionary codes

nucleosynthesis calculations

Thermonuclear Reactions in the Laboratory: Experimental Challenges



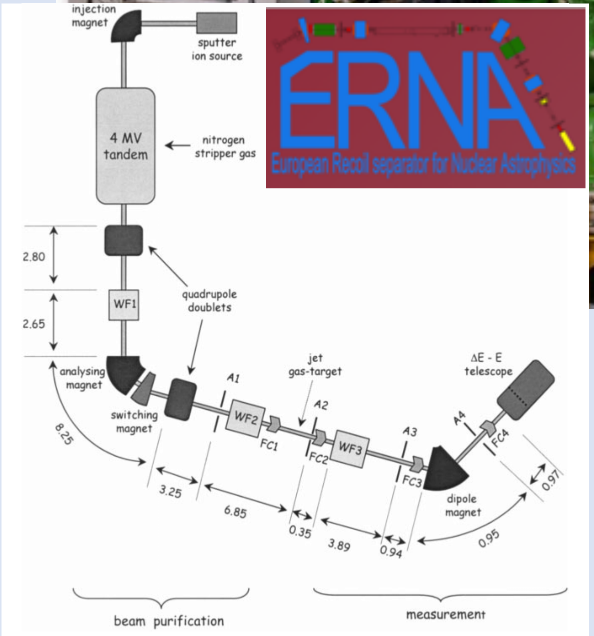
Low energy reactions

Very small cross sections

Up to 10^{-15} barn

Nuclear astrophysics ....some history for the Italian German collaboration

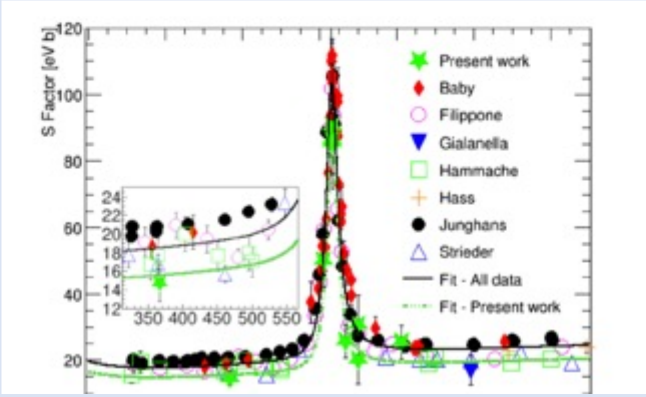
From Bochum



European Recoil Separator for Nuclear Astrophysics

to Caserta

^{7}Be(p, γ)^{8}B at CIRCE

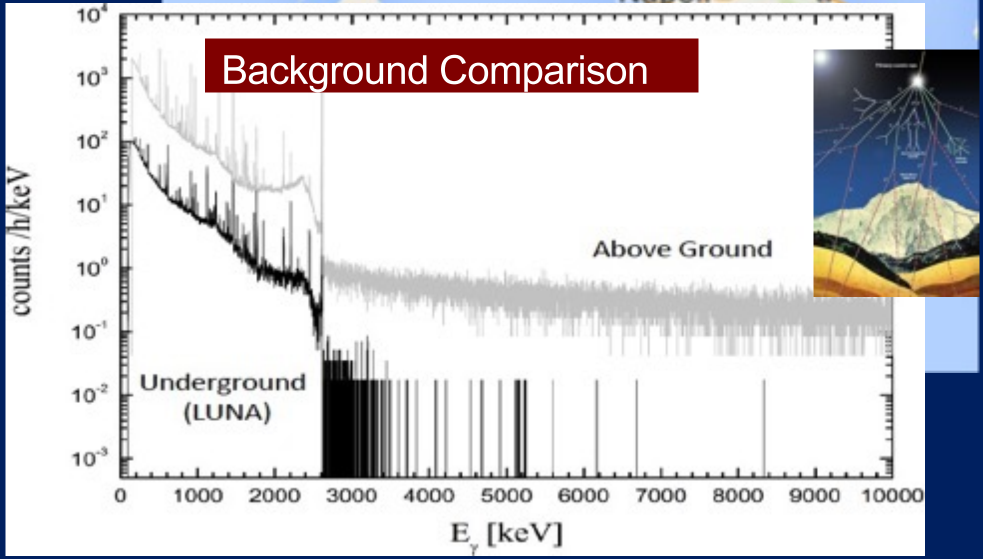


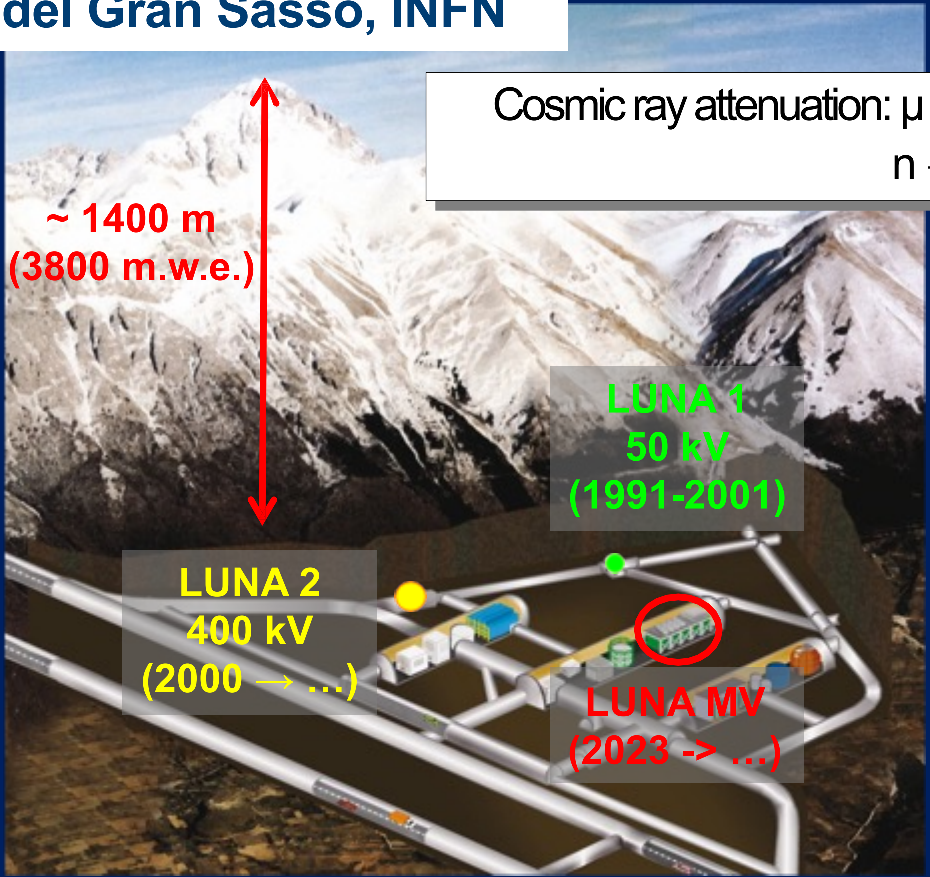
Physics Letters B 824 (2022) 136819

The reaction ^{7}Be(p, γ)^{8}B plays an important role in the Sun, where it determines the high energy component of the solar neutrino spectrum.

LUNA at LNGS

Laboratori Nazionali del Gran Sasso, INFN





Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$

$n \rightarrow 10^{-3}$

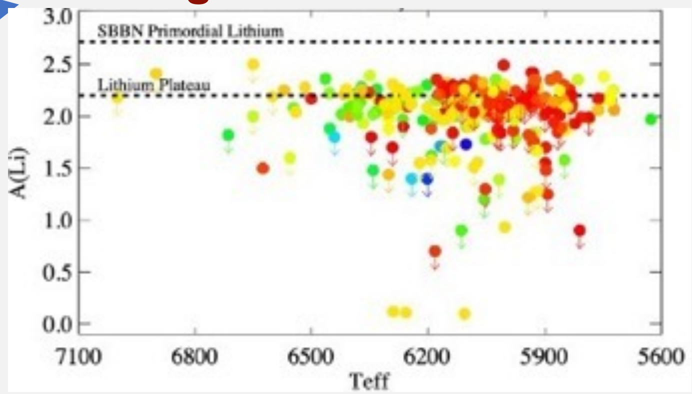
30 years of Nuclear Astrophysics at LUNA (LNGS, INFN)

- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$
  $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(explosive) hydrogen burning in novae and AGB stars**
  $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ $^{18}O(p,\alpha)^{15}N$
- **Big Bang nucleosynthesis**
  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ $^{6}Li(p,\gamma)^{7}Be$
- **neutron capture nucleosynthesis**
  $^{13}C(\alpha,n)^{16}O$

some of the lowest cross sections ever measured (few counts/month)

24 reactions in 30 years: ~15 months data taking per reaction!

Cosmological Lithium Problem

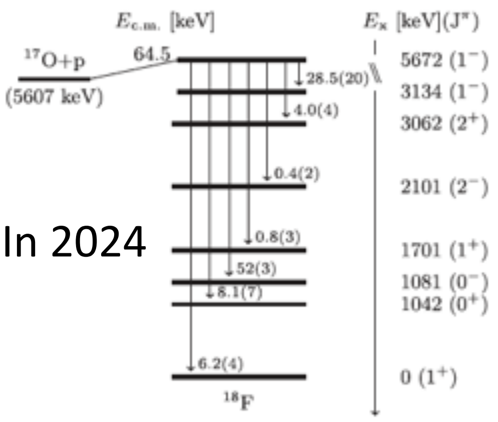


[K]

factor of 3 discrepancy between observed and predicted Li abundance

Standard Model of Particle Physics + Cosmology

^{17}O(p,y)^{18}F reaction in novae



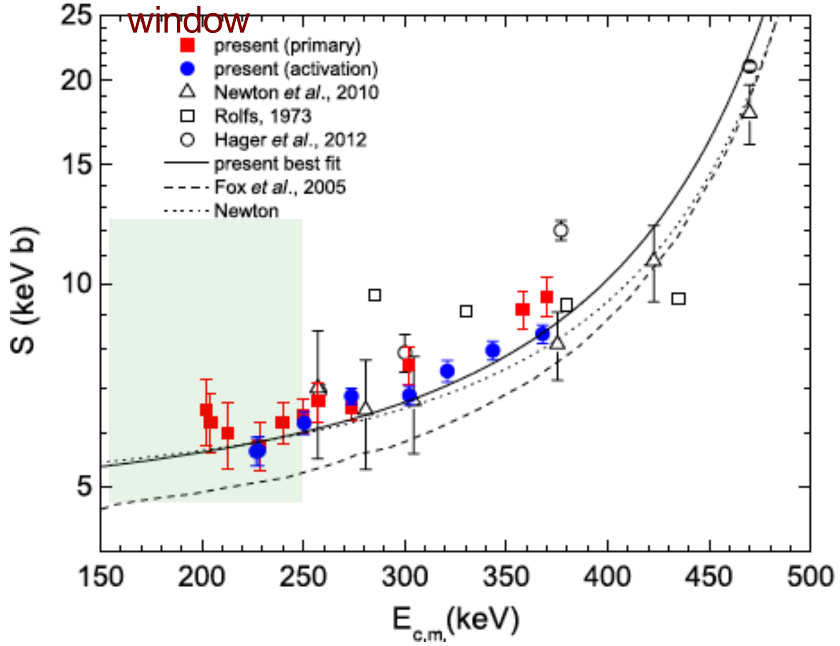
In 2024

- *first direct measurements of the 64.5 keV resonance strength* and the direct capture contribution at 142 keV (9.8 pb). ***The resonance strength is 2 times higher than previous values***

- The calculated proton width in agreement with previous LUNA data

Better understanding of the ^{16}O/^{17}O ratio measured in redgiant stars and in O-reach presolar grains

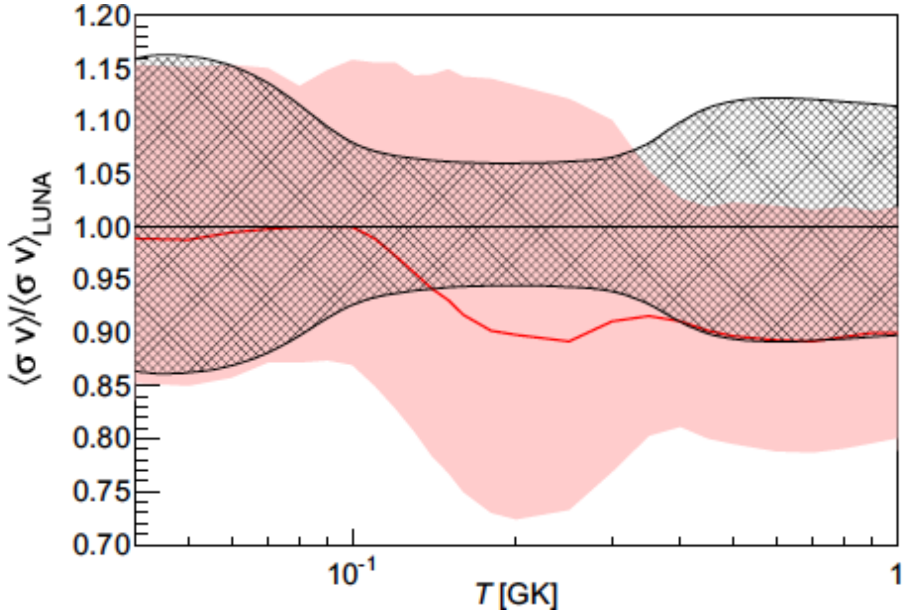
first measurement within Gamow window



firmer constraints on amount of ^{18}F produced in novae

new limits to satellite detection of 511keV y rays

reaction rate: factor of 4 reduction



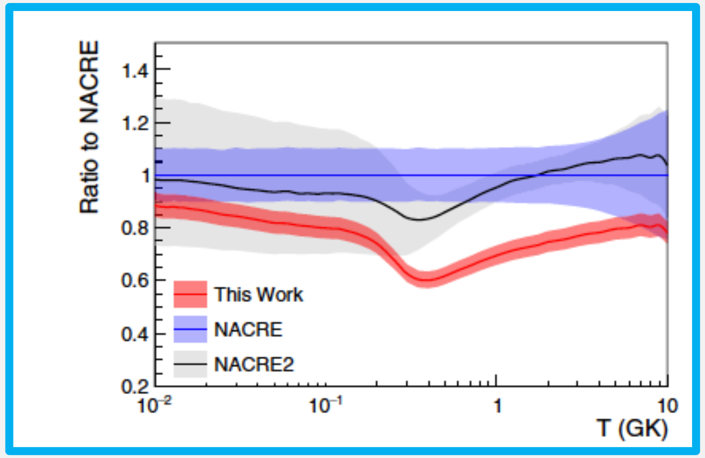
At the 5MV Pelletron accelerator of Felsenkeller Laboratory Dresden

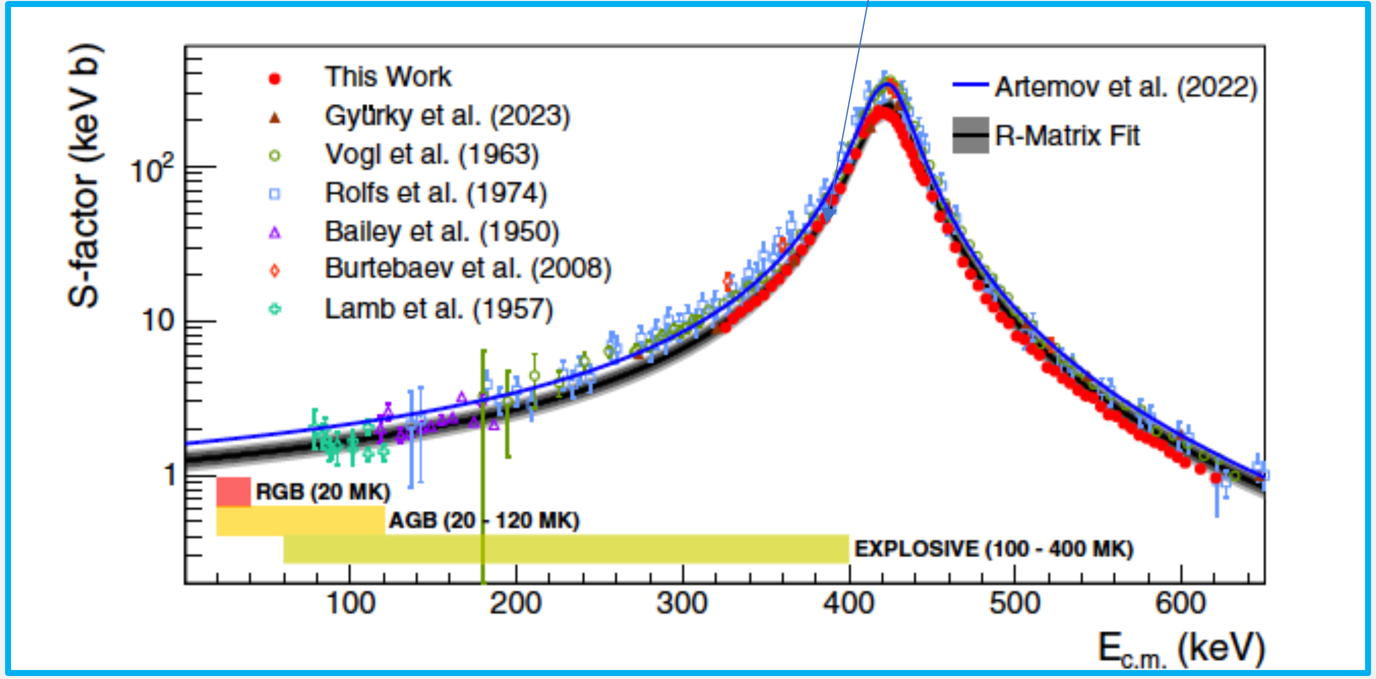
5MV Pelletron accelerator Dresden

- Measurement of the **$^{12}C(p, \gamma)^{13}N$ reaction** (part of H burning in the CNO cycle).
- Important role in the abundance of ^{12}C

- In asymptotic giant and giant branches stars (AGB and RGB) the $^{12}C/^{13}C$ is used to trace stellar nucleosynthesis and the galactic evolution

Improved astrophysical S factor at E = 320–620 keV and the 422 keV resonance

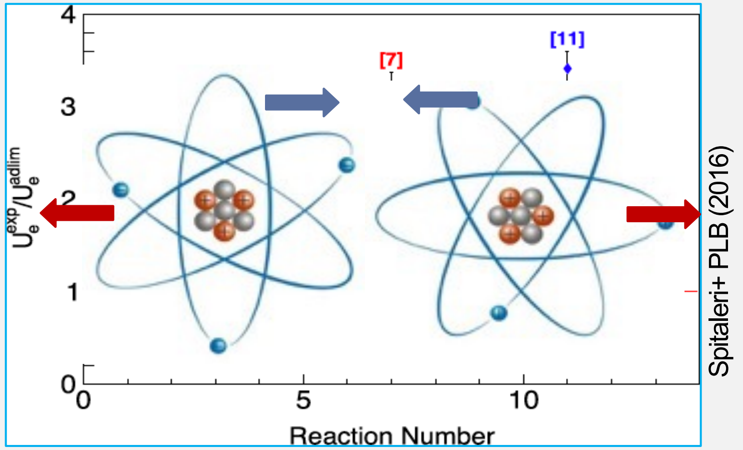




Puzzling Facts and Open Questions Still Remain

- Cosmological Li problem(s)
- Nucleosynthesis and Evolution of First Stars
- Core metallicity of the Sun
- Fate of massive stars
- The origin of heavy elements
- …

Electron Screening Puzzle

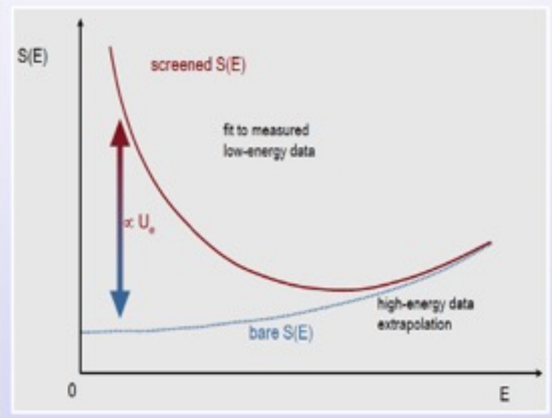


discrepancy between experiment and theory remains unexplained

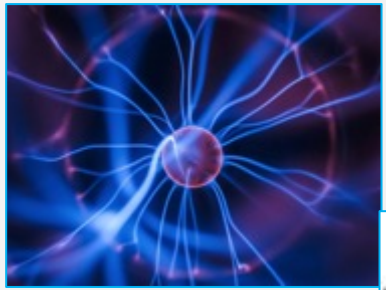
Reactions in Plasmas

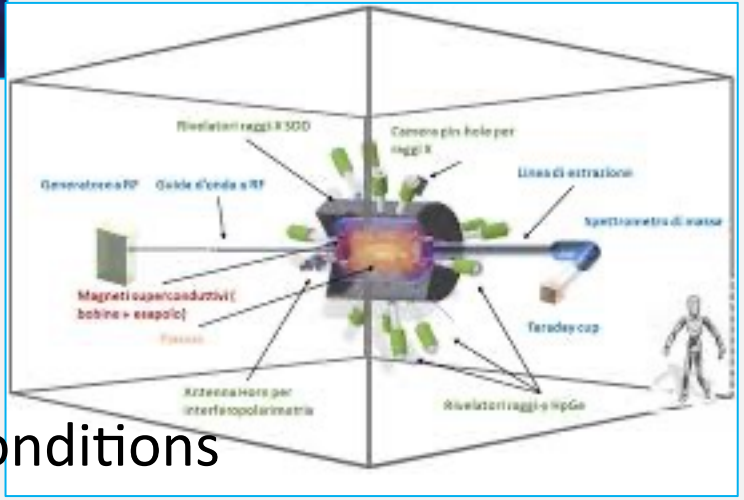
Fusion-driven Energy Generation

$$\sigma(E) = 1/E \ \exp(-2\pi\eta) \ S(E)$$



Nuclear Physics and Astrophysics in PlasmaTraps

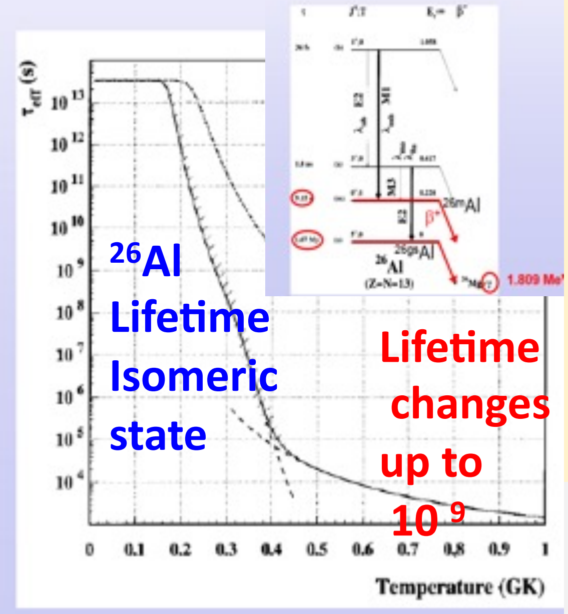




major difference between laboratory and stellar conditions

- accurate knowledge of neutron capture and β-decay in a stellar environment and study of mechanism affecting isotope times of life.

- temperatures and densities give different values (over several orders of magnitude) in the different nucleosynthesis environments.



INFN LNS experiment PANDORA

(under construction)

Built on the ECRIS developments

Carried out in the past at GSI

To be noted : a program of reactions in plasma within ELI-NP

Concerning theory a central role European Centre for Theoretical Studies (ECT*),Trento,

- the only European centre dedicated to theoretical nuclear physics in the broadest sense.
- It constitutes a platform for a wealth of workshops and training schools and is complementary in scope and activities to research facilities

NUCLEAR APPLICATIONS

The hadron therapy with ^{12}C beams

The facility at GSI a model and a drive for the realization of the CNAO center in Pavia

Research to improve the hadron therapy

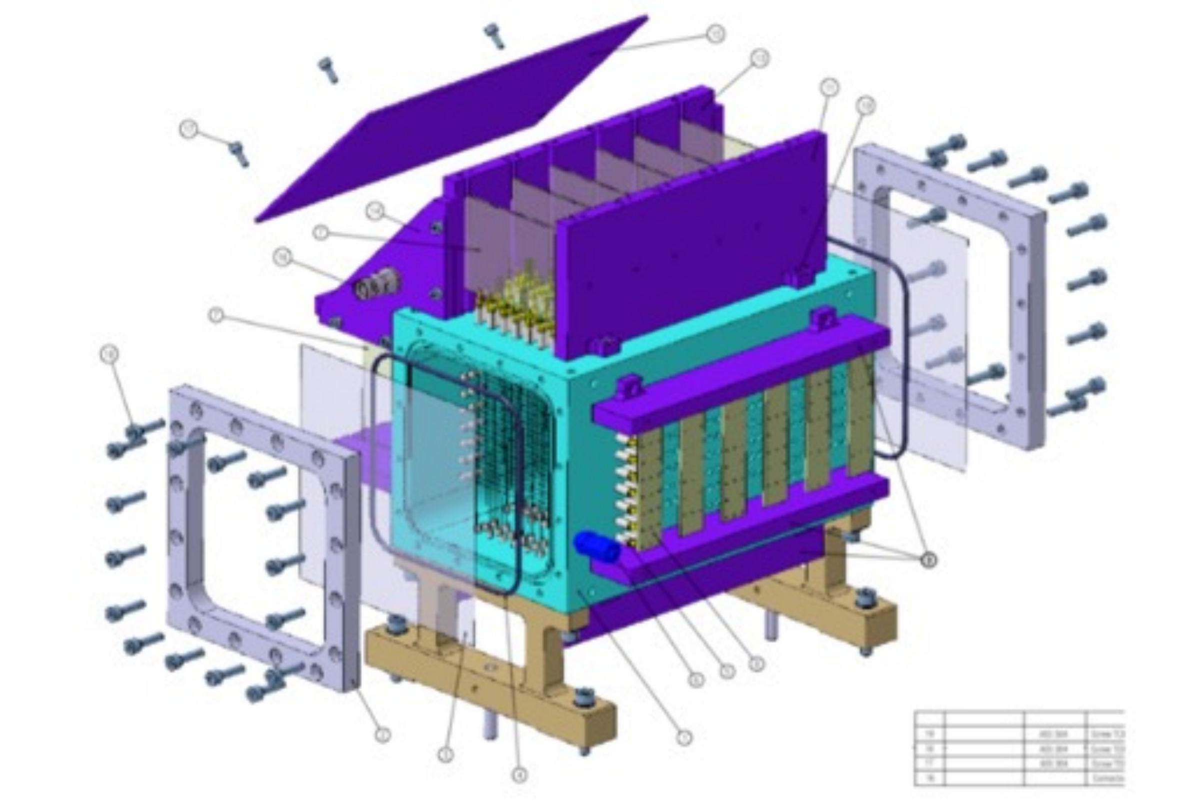
There are several research projects to improve the beam position in real time.

Developments for

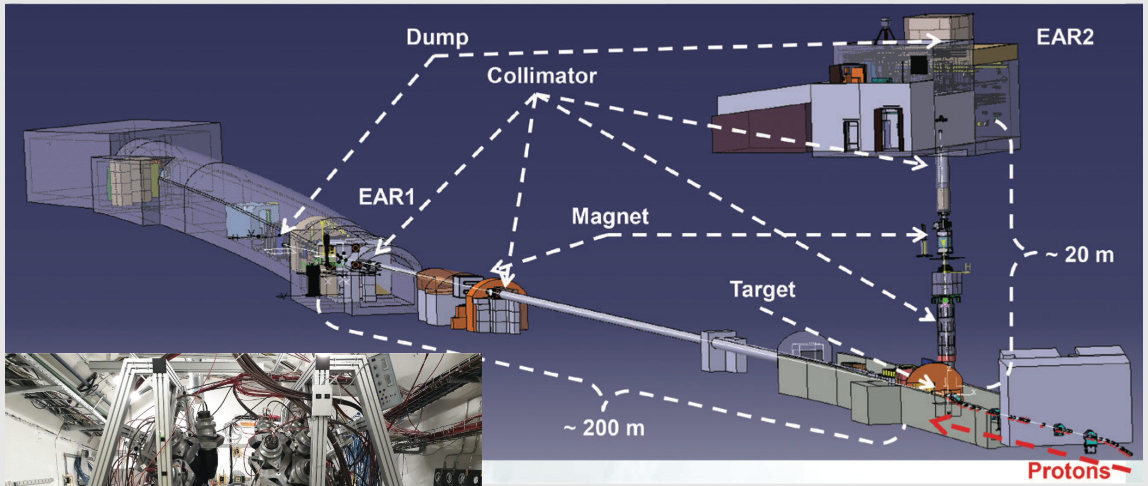
- Drift chamber acting as beam monitor to measure the direction and the position of the impinging beam on the target

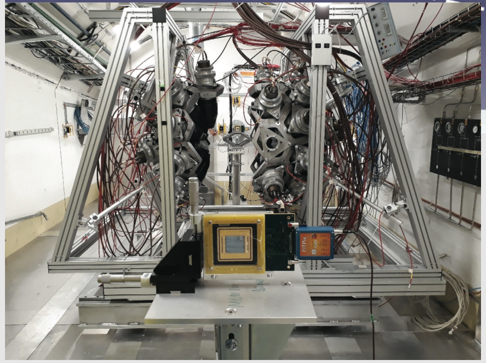
- to look for fragmented primaries

Developments for flash therapy



n_TOF at CERN





n_TOF covers the production of accurate nuclear data for innovations in advanced nuclear technologies

+ nuclear astrophysics

The core participants:

Karlsruhe Inst. Technology, INFN,

CIEMAT , IFIC ,CEA, IN2P3,NTUA , LIP,CERN

Table 1. Examples of n_TOF experiments.

Reaction	Energy	Research area
^{204}Tl(n,γ)	<1 MeV	stellar nucleosynthesis
^{171}Tm(n,γ)	<1 MeV	stellar nucleosynthesis
^{7}Be(n,p) ^{7}Be(n,α)	<1 MeV	big bang nucleosynthesis
^{63}Ni(n,γ)	<1 MeV	stellar nucleosynthesis
^{151}Sm(n,γ)	<1 MeV	stellar nucleosynthesis
^{232}Th(n,f), ^{233}U(n,f)	<1 GeV	advanced fuel cycles
^{235}U(n,f)	<1 MeV	cross-section standard
^{238}U(n,f)/^{235}U(n,f)	1 MeV–1 GeV	cross-section standard
^{232}Th(n,γ)	<1 MeV	advanced fuel cycles
^{245}Cm(n,f)	<1 MeV	transmutation of minor actinides

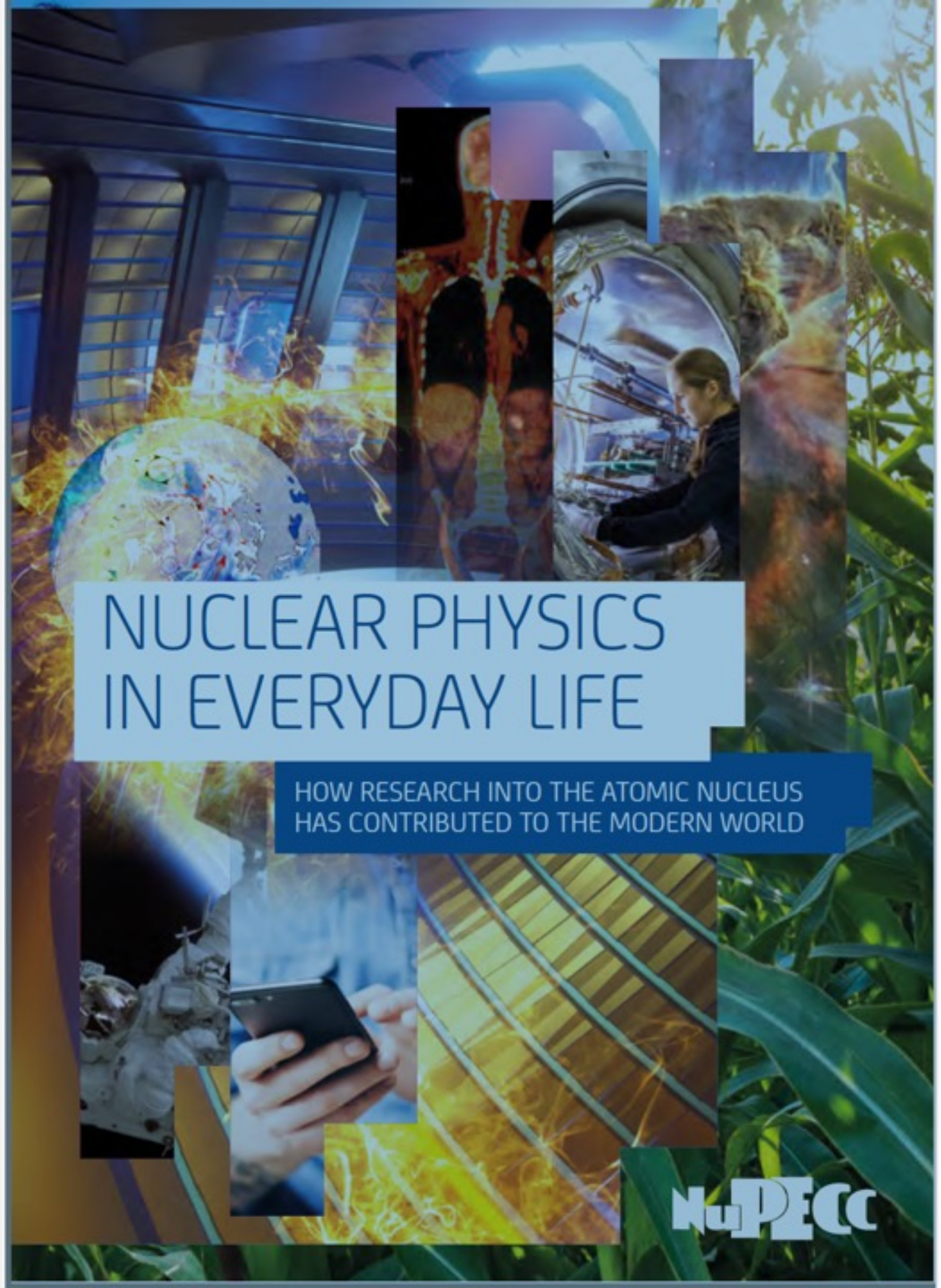
Neutron-induced fission, capture, charged-particle emission investigated with unprecedented accuracy

Nuclear waste imaging
and spent fuel verification by muon tomography

international collaboration among

- INFN; Italy,
- Jülich Research Center (FZJ;Germany),
- BGZ Company for Interim Storage (BGZ; Germany))
- (EURATOM).

A technology developed from muon detection and in total safety is the task of the MuTomCa (MUon TOmography for shielded CAsks) project. In Europe, there are currently around 1500 casks to which this technology could be applied.



- **CLIMATE AND ENVIRONMENT**
- **ENERGY**
- **Radioactivity**
- **HEALTH**
- **PRODUCTS AND FOOD**
- **FORENSICS AND HERITAGE**
- **SPACE**

Conclusions

Historical comments

privilege to have collaborated with colleagues that have driven nuclear and hadron physics at top level
and had built a solid ground and ispiration for today research

Several experiments and also technical developments for accelerators (see e.g. those from INFN for the magnets for FAIR and the linac of XFEL). Collaborations in other CERN experiments as e.g. COMPASS very prolific

Important and impactful results from the collaboration during the years

Ready to make the collaboration stronger as the future is bright with appealing and challenging questions to be answered