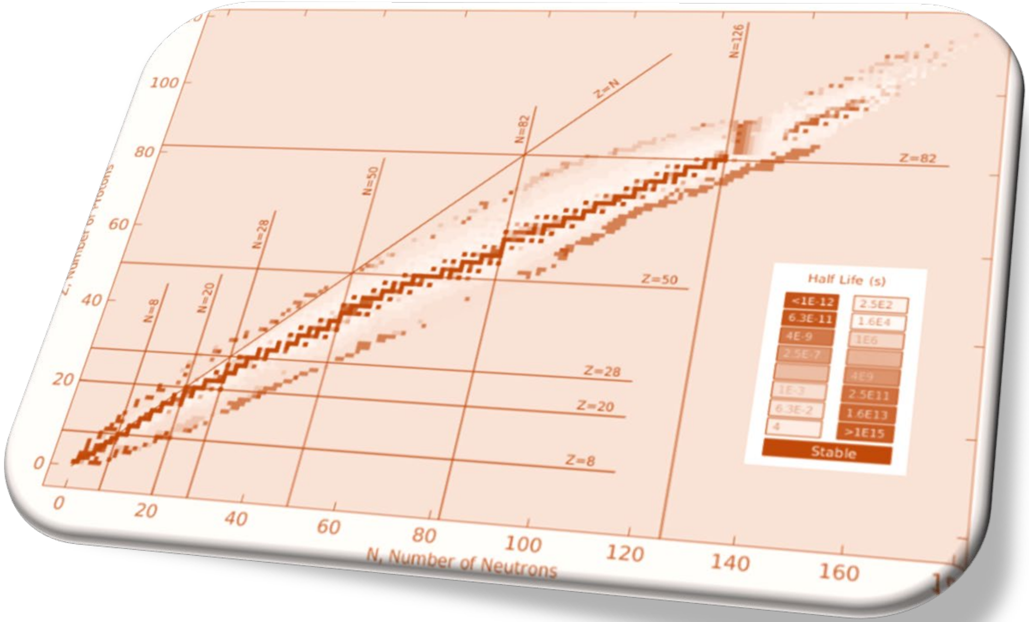
Review CSN3



R. Nania - 30th September 2024

Thanks to P. Giubellino, P. Antonioli, A. Dainese, N. Jacazio, L. Cosentino, D. Santonocito, L. Venturelli, S. Leoni, A. Nannini, M. La Cognata, C. Agodi

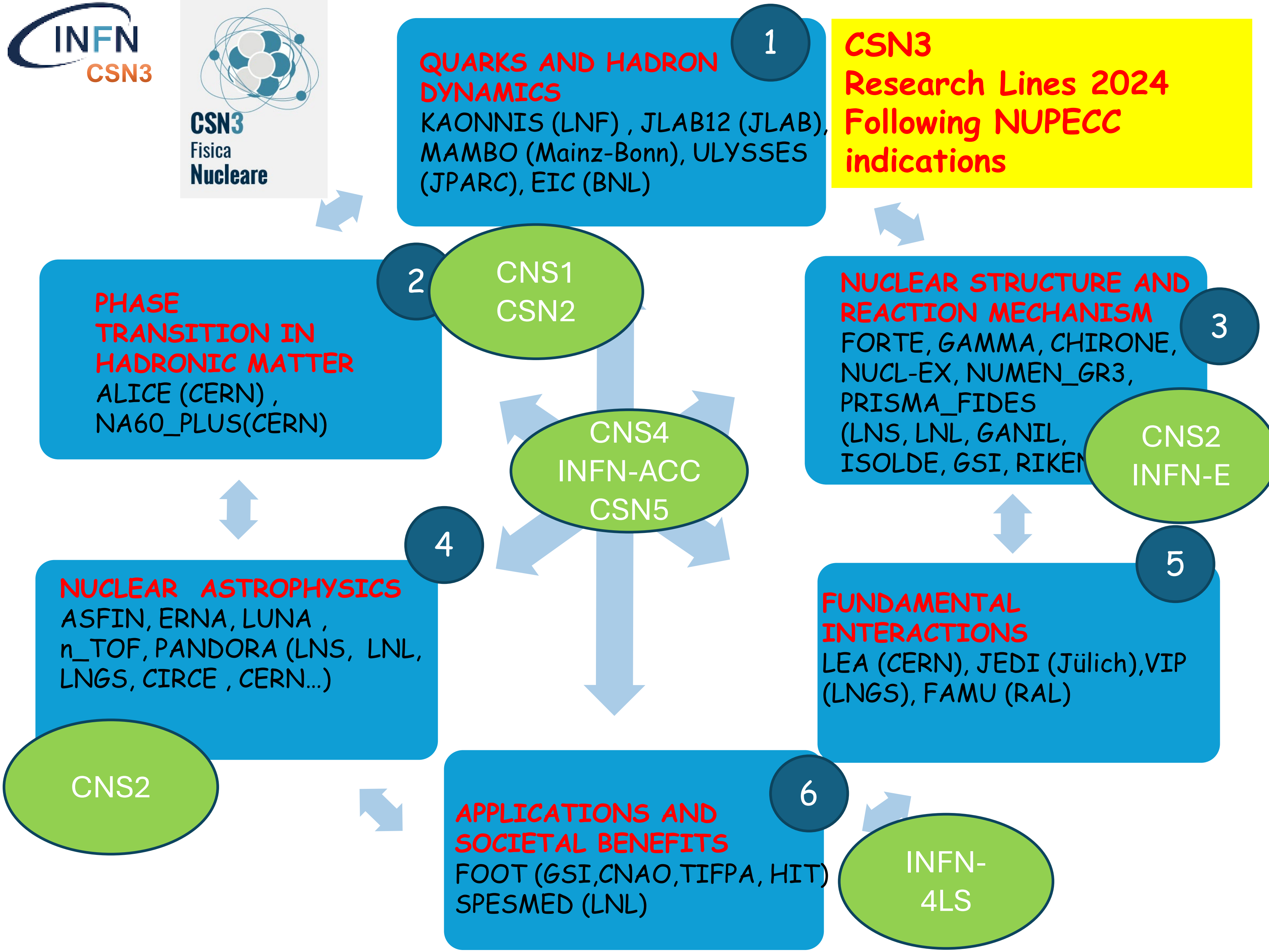
https://web.infn.it/csn3/index.php/it/

How nuclear physics can contribute to the European Strategy for Particle Physics (ESPP)

INFN CSN3

CSN3 Fisica Nucleare

CSN3 Research Lines 2024 Following NUPECC indications



1

QUARKS AND HADRON DYNAMICS

KAONNIS (LNF) , JLAB12 (JLAB), MAMBO (Mainz-Bonn), ULYSSES (JPARC), EIC (BNL)

CNS1
CSN2

2

PHASE TRANSITION IN HADRONIC MATTER

ALICE (CERN) , NA60_PLUS(CERN)

3

NUCLEAR STRUCTURE AND REACTION MECHANISM

FORTE, GAMMA, CHIRONE, NUCL-EX, NUMEN_GR3, PRISMA_FIDES (LNS, LNL, GANIL, ISOLDE, GSI, RIKEN

CNS2
INFN-E

CNS4
INFN-ACC
CSN5

4

NUCLEAR ASTROPHYSICS

ASFIN, ERNA, LUNA , n_TOF, PANDORA (LNS, LNL, LNGS, CIRCE , CERN…)

CNS2

5

FUNDAMENTAL INTERACTIONS

LEA (CERN), JEDI (Jülich),VIP (LNGS), FAMU (RAL)

6

APPLICATIONS AND SOCIETAL BENEFITS

FOOT (GSI,CNAO,TIFPA, HIT) SPESMED (LNL)

INFN-4LS

CSN3
Fisica
Nucleare

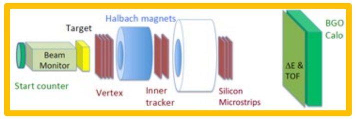
INFN Third Commission on Nuclear Physics

Huge energy interval covered. Many Laboratories involved around the world.

N_TOF, LUNA, ERNA

GAMMA/AGATA

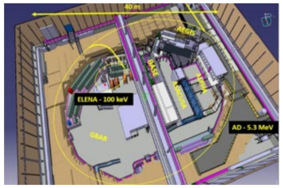
FOOT



JLAB

ALICE

Energy **keV** **MeV** **GeV** **TeV**

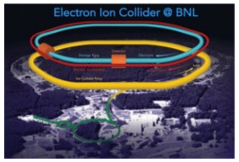


LEA

**NUMEN, ASFIN2,NUCLEX,
CHIRONE, FORTE**

SIDDHARTA

JEDI



EIC

INFN

70 1951 2021 infn

Nuclear Physics
Mid Term Plan in Italy

INFN Nuclear Physics
Mid-term Strategy Plan

2022-2027

Web site for 2022 workshops in INFN laboratories https://web.infn.it/nucphys-plan-italy/
Publications EPJ FOCUS site https://epjplus.epj.org/component/toc/?task=topic&id=1894

See also the review paper on PID techniques prepared mostly by young researchers
Trends in particle and nuclei identification techniques in nuclear physics experiments

ECFA guidelines for inputs from national HEP communities to the European Strategy for Particle Physics

2) The ESG's remit explicitly states that “The Strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive”.

It is imperative that the European HEP community should provide explicit feedback on both the preferred and alternative options for this “next collider at CERN”, which will be the Laboratory's next flagship project, and an explanation of any specific prioritisation.

ECFA guidelines for inputs from national HEP communities to the European Strategy for Particle Physics

4**)** **The remit given to the ESG also specifies that "The Strategy update should also** **indicate areas of priority for exploration complementary to colliders and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe."** **It would thus be most useful if the national inputs explicitly included the preferred prioritisation for non-collider projects. Specific questions to address:**

a) What other areas of physics should be pursued, and with what relative priority?
b) What are the most important elements in the response to 4a)? (The set of considerations in 3b should be used).
c) To what extent should CERN participate in nuclear physics, astroparticle physics or other areas of science, while keeping in mind and adhering to the CERN Convention? Please use the current level and form of activity as the baseline for comparisons.

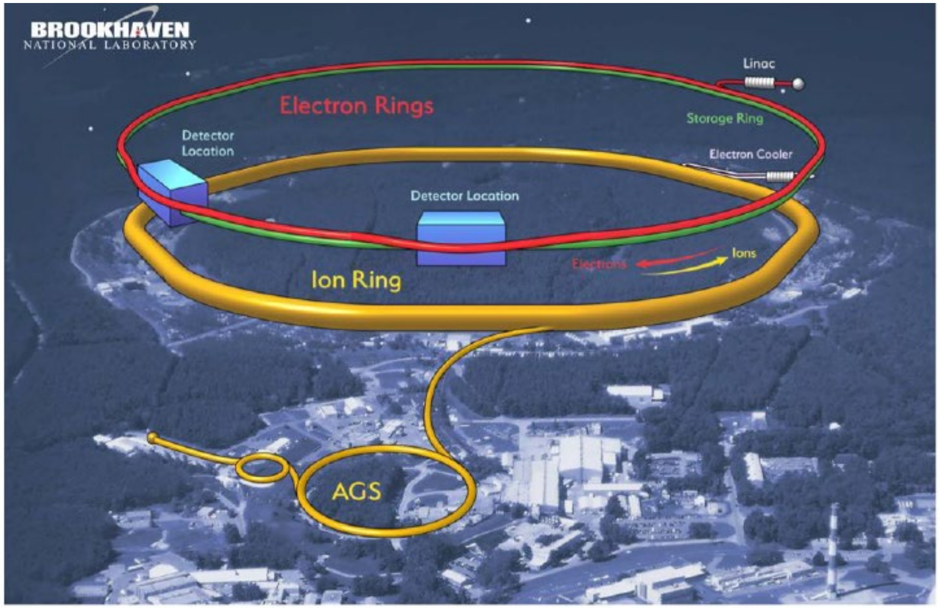
ELECTRON ION COLLIDER @ BNL.

p: 41 GeV, 100 to 275 GeV

p/A beam →

← e beam

e: 5 GeV to 18 GeV

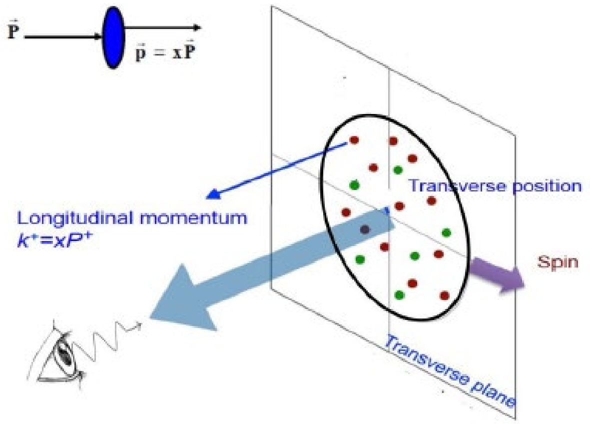


Project Design Goals

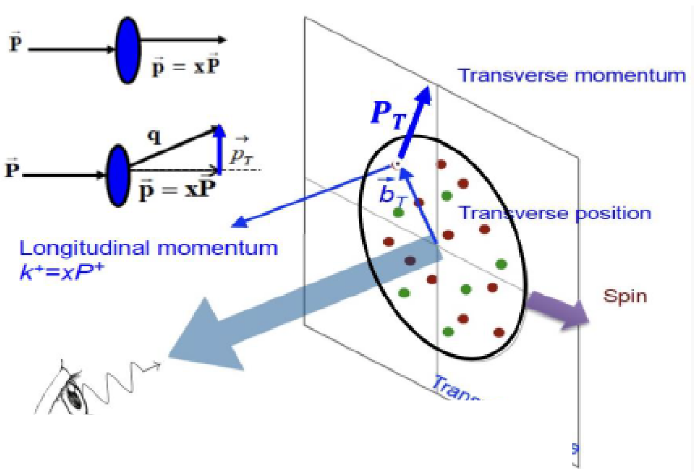
- High Luminosity: L= 10^{33} – 10^{34} cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- **Highly Polarized Beams: 70%**
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)
- **Start operation 2032-2033**

High Energy Frontier

From this vision

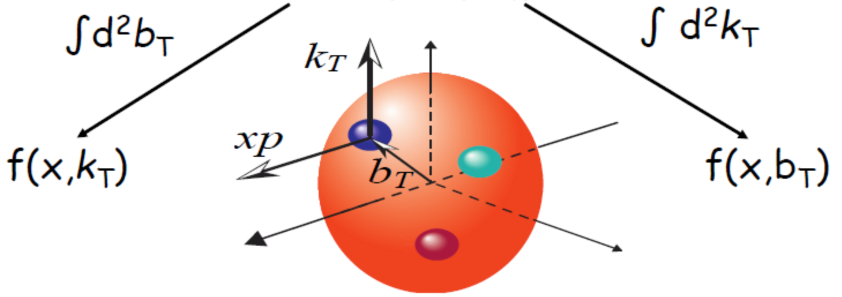


To this vision



Wigner functions

$W(x,b_T,k_T)$



Momentum space

$\int d^2b_T$

$f(x,k_T)$

$\int d^2k_T$

Coordinate space

$f(x,b_T)$

Spin-dependent 3D **momentum space** images from **semi-inclusive scattering** → **Transverse Momentum Distribution (TMDs)s**

Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from **exclusive scattering** → **Generalized Parton Distributions (GPDs)**

Program already started by JLAB at lower energies

ePIC design (barrel)

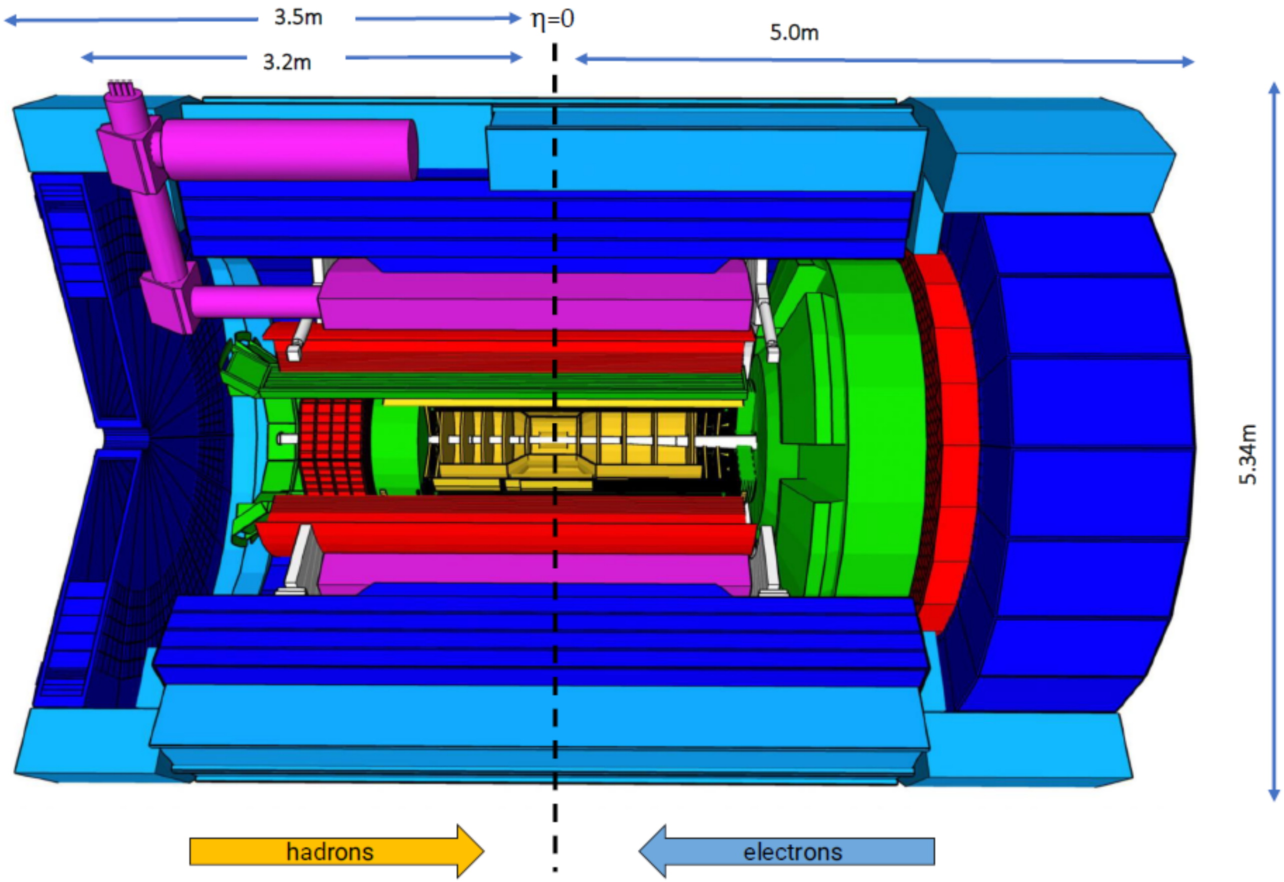
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (µRWELL, MMG) cylindrical and planar

PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



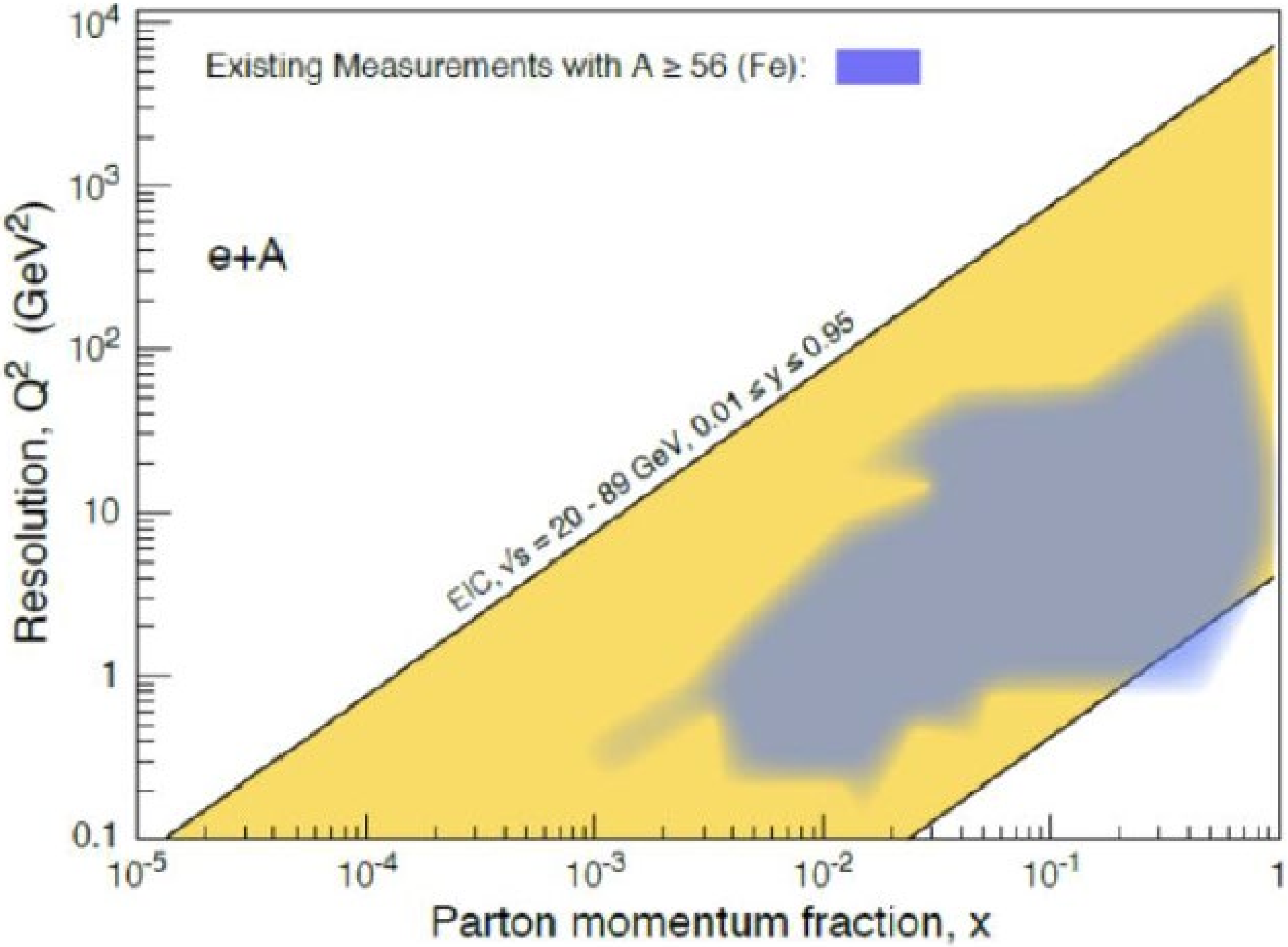
(extended instrumentation in far forward/backward regions)

Large collaboration with LHC and FCC groups for detector developments (CERN Detector Road MAP)

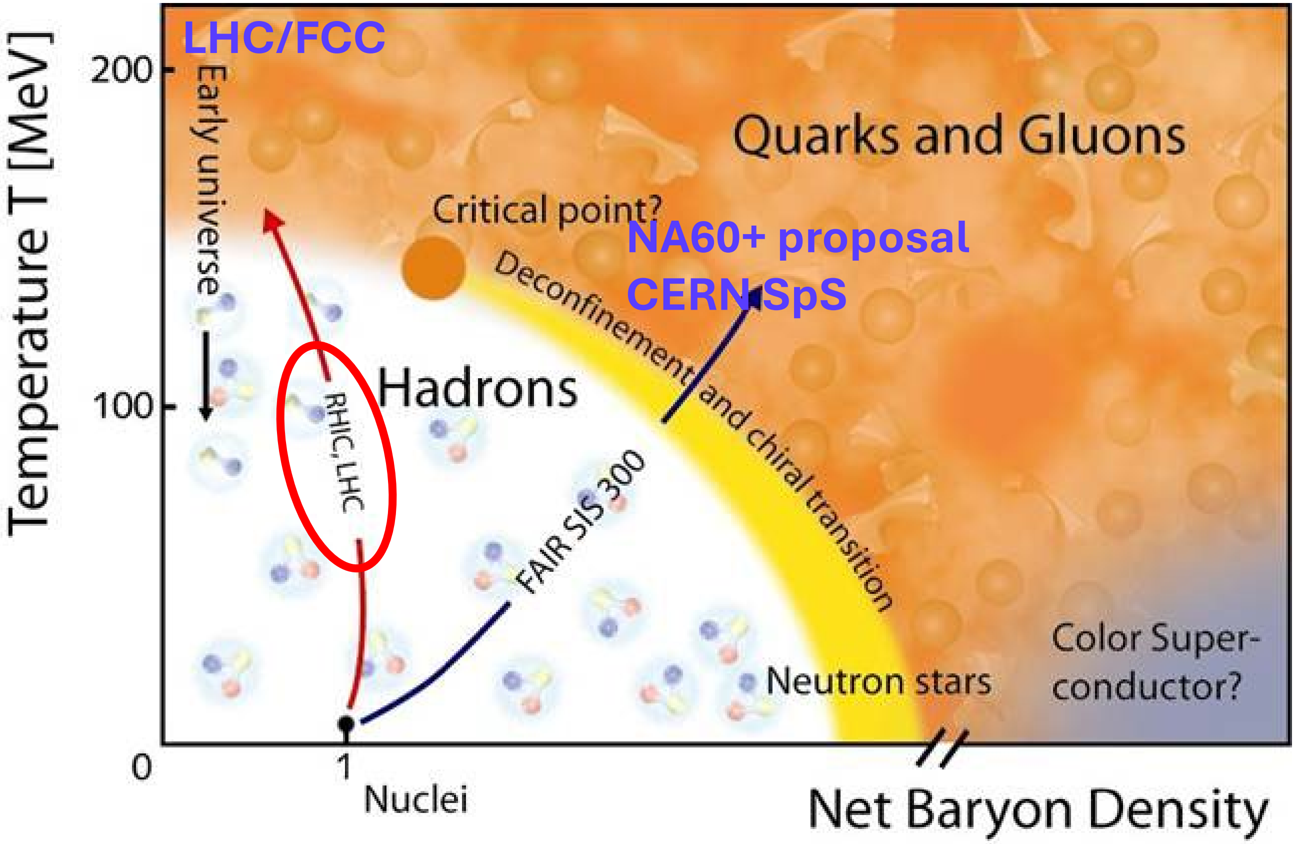
DGLAP and saturation models offer different prediction (Q^2 , A, x dependence)

- channels → di-hadron angular correlations, diffractive particle production in eA
- strategy→ large Q^2 span at fixed x performing A scan!

$$(Q_s^A)^2 \sim cQ_o^2\left(\frac{A}{x}\right)^{1/3}$$

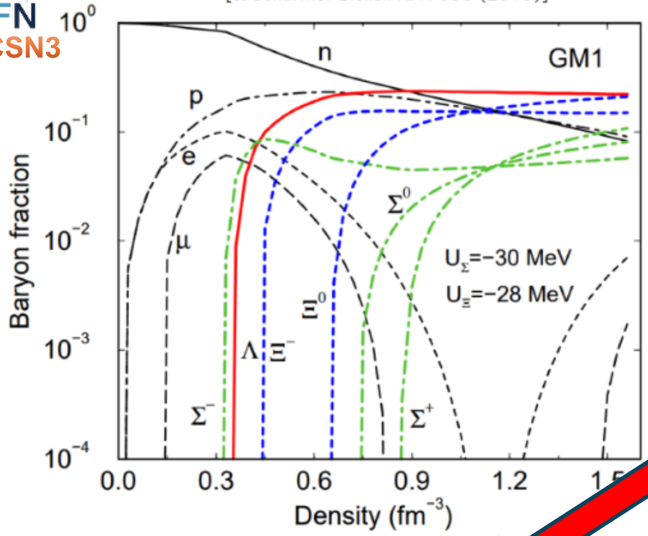


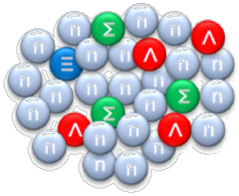
THE EXPLORATION OF THE PHASE DIAGRAM OF STRONGLY INTERACTING MATTER



Strong LHC program with all experiments involved and long range plans already under discussion

[J. Schaffner-Bielich NPA 835 (2010)]

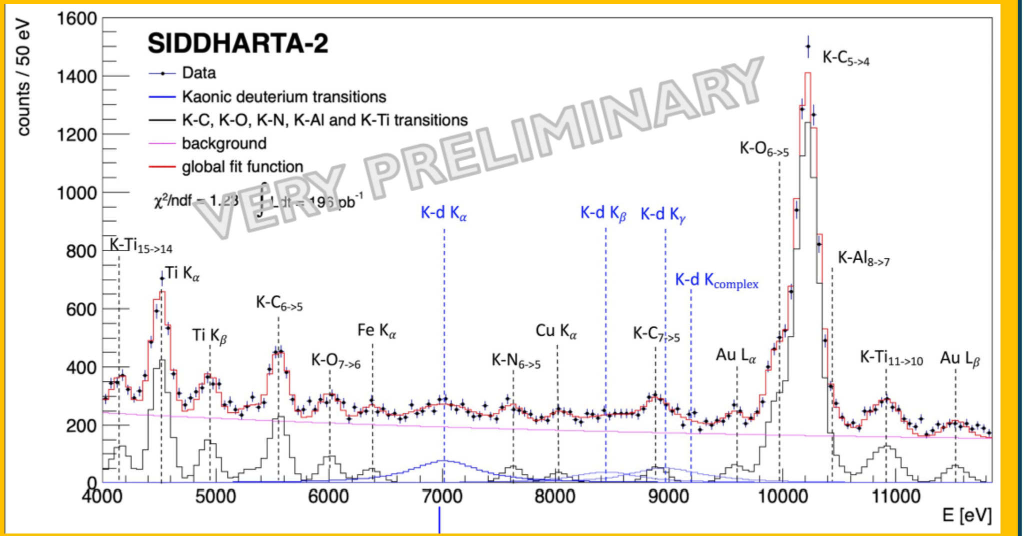




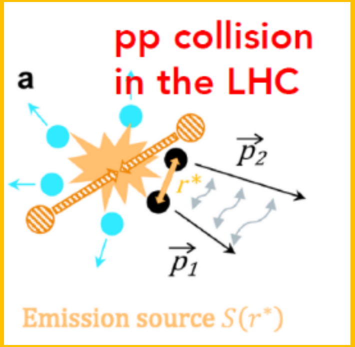
How to study interactions among quarks in stars ?

Via Kaonic atoms

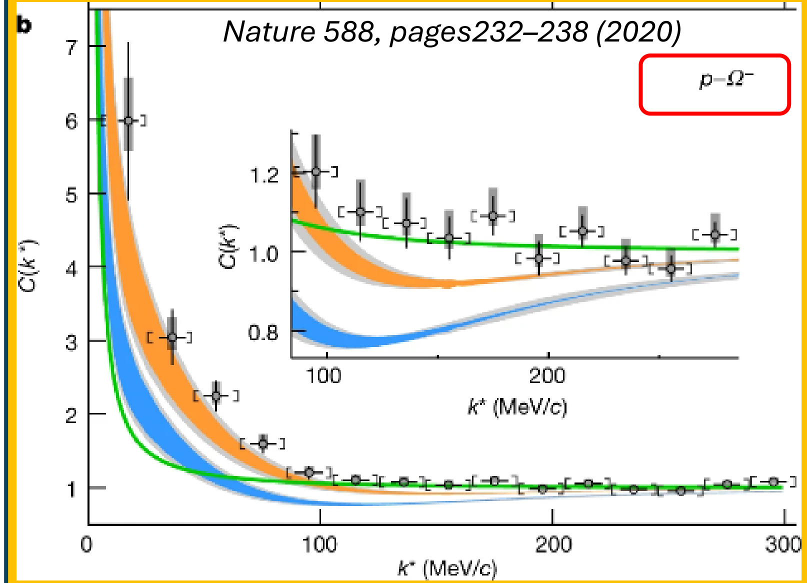
A more precise kaonic helium/deuterium measurement in gas by SIDDHARTA-2 at the DAΦNE



Via particle correlations at LHC



Nature 588, pages232–238 (2020)

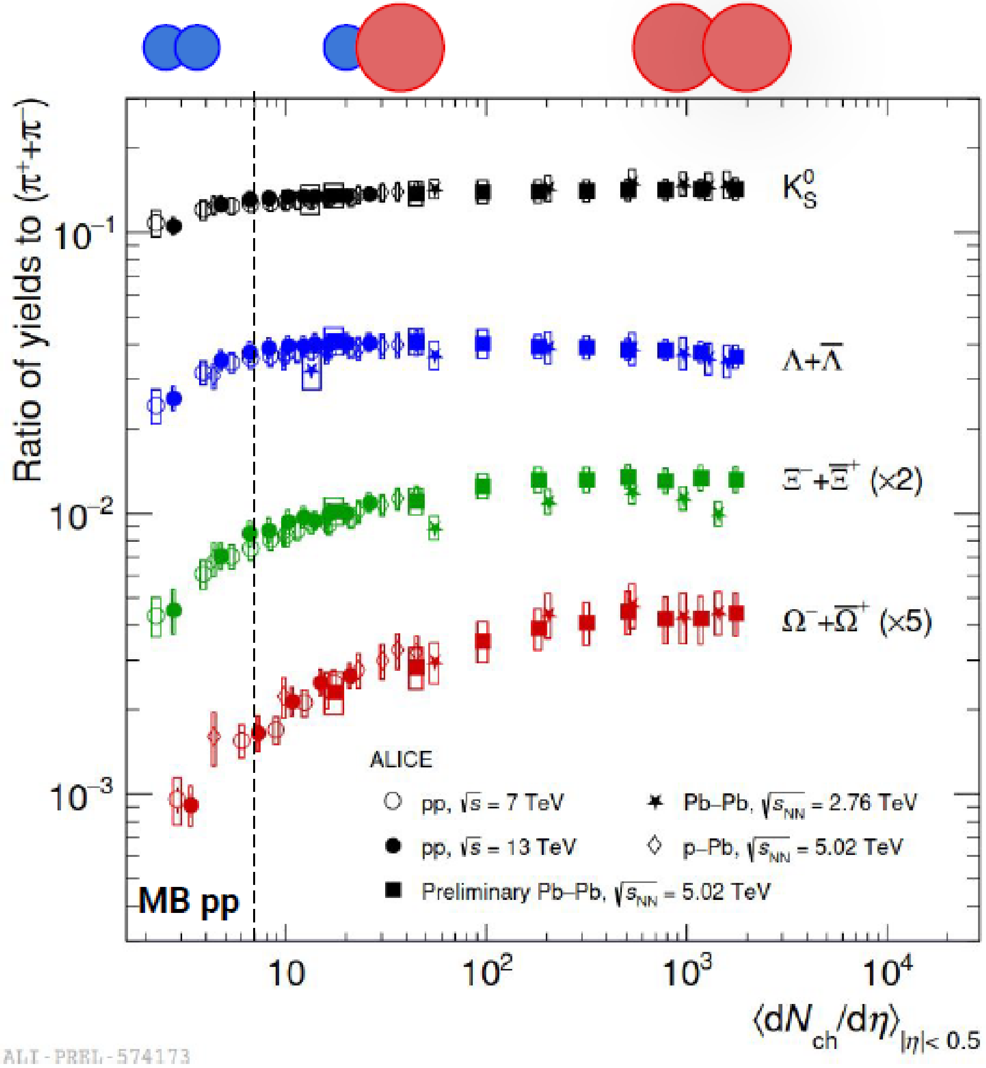


An example of strong interconnection among different size systems (pp,pPB and PbPb collisions) at LHC : the importance of particle multiplicity.

NB: LHC/RHIC important achievement marks the passage from a description purely thermodynamic to QCD based Monte Carlo approaches.

- Core-corona models → EPOS4
- Models of microscopic interactions of strings → Pythia 8.3

See [here]

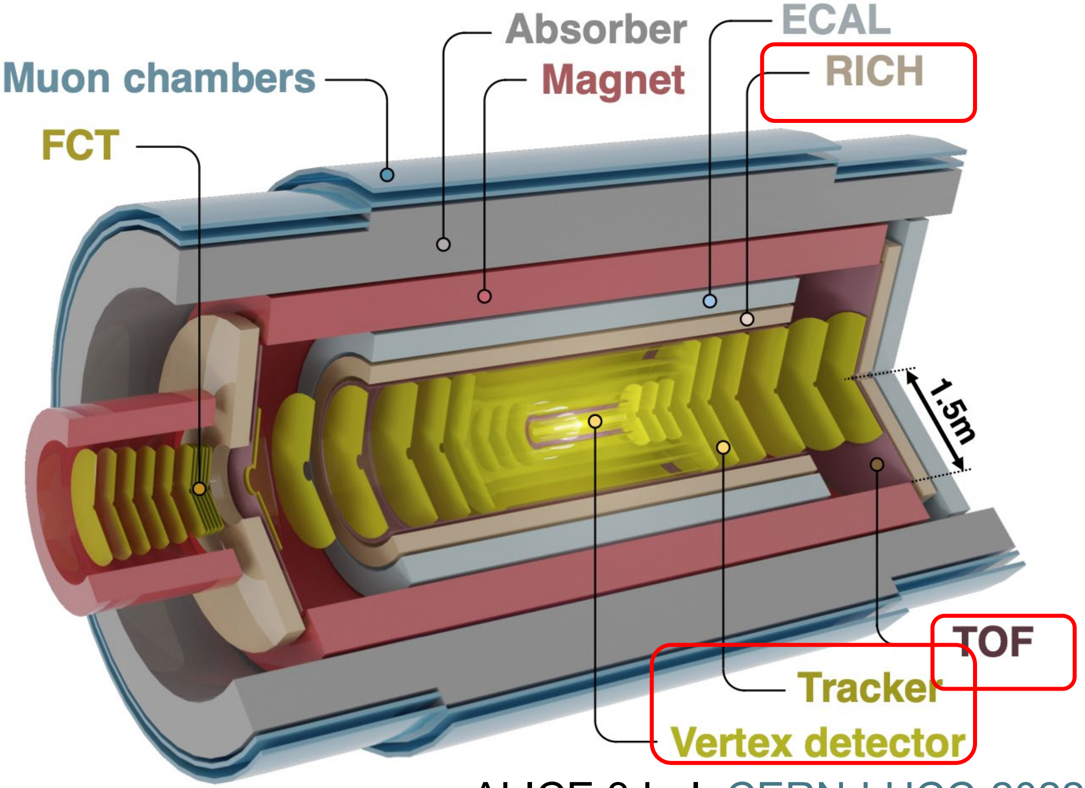


Question: is HI-LHC event comparable to what expected at FCC ?

ALICE 3 detector proposal for Runs 5-6 (> 2034)

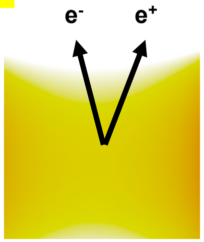
Novel and innovative detector concept

- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Extensive particle identification
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing



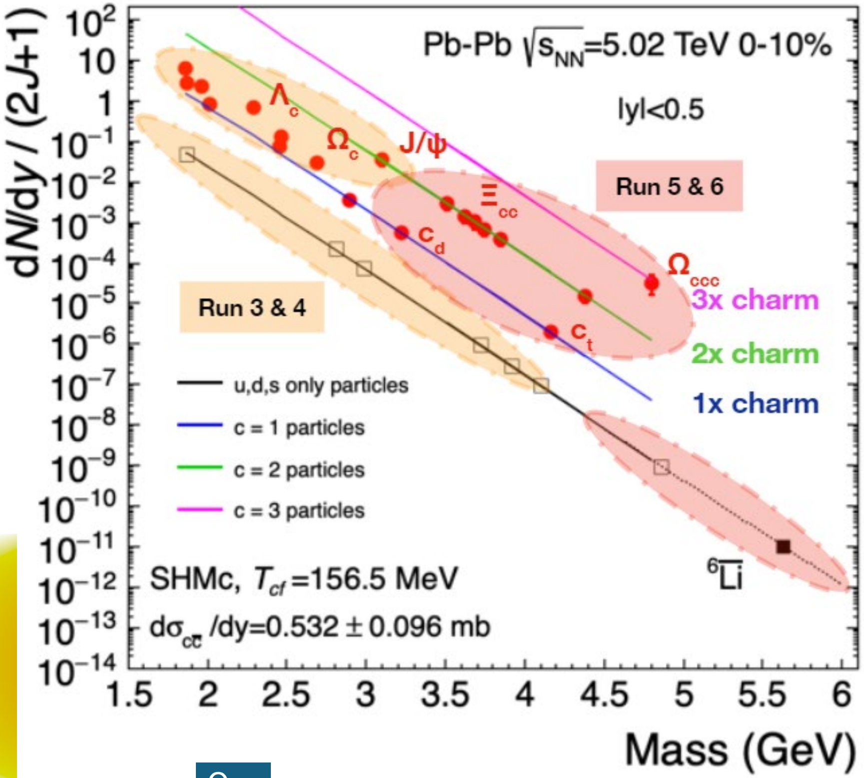
ALICE 3 LoI: CERN-LHCC-2022-009

ALICE 3 physics goals



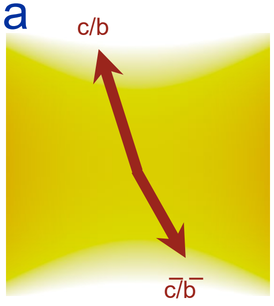
Precision measurements of dileptons

- ➟ evolution of the quark gluon plasma temperature
- ➟ mechanisms of chiral symmetry restoration in the quark-gluon plasma



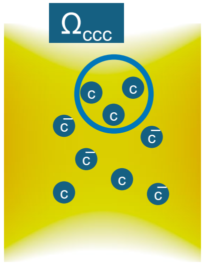
Systematic measurements of (multi-)heavy-flavoured hadrons

- ➟ transport properties in the quark-gluon plasma
- ➟ mechanisms of hadronisation from the quark-gluon plasma

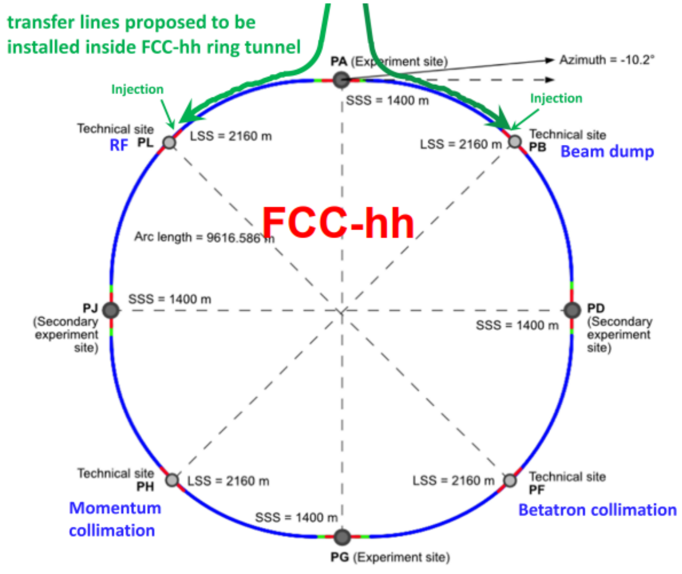


Hadron correlations

- ➟ hadron-hadron interaction potentials
- ➟ net-baryon and net-charm fluctuations

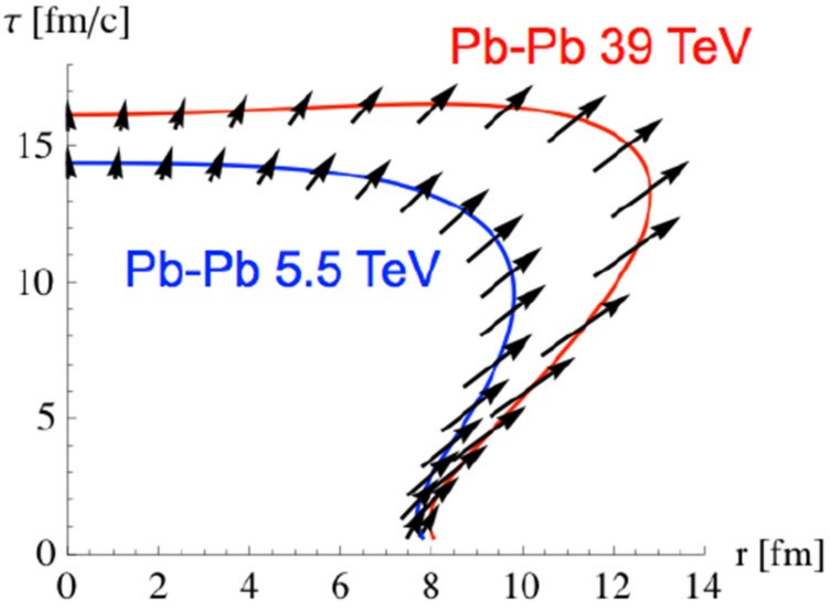


Heavy Ion Physics at FCC



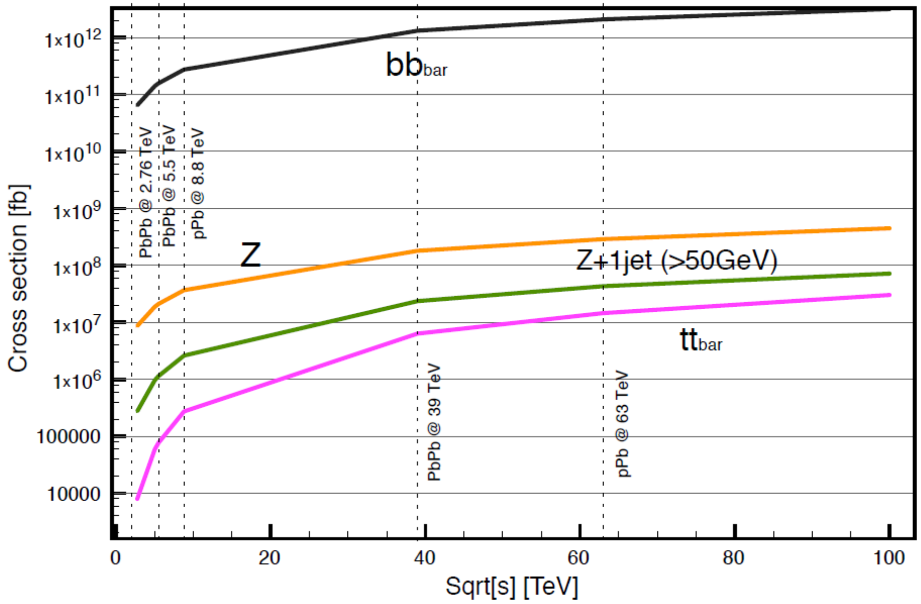
2070 - 2095

M.Benedikt 7



Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 GeV/fm^3	16–17 GeV/fm^3	35–40 GeV/fm^3

Pb-Pb at FCC: 39 TeV; L_{int} >100x LHC programme



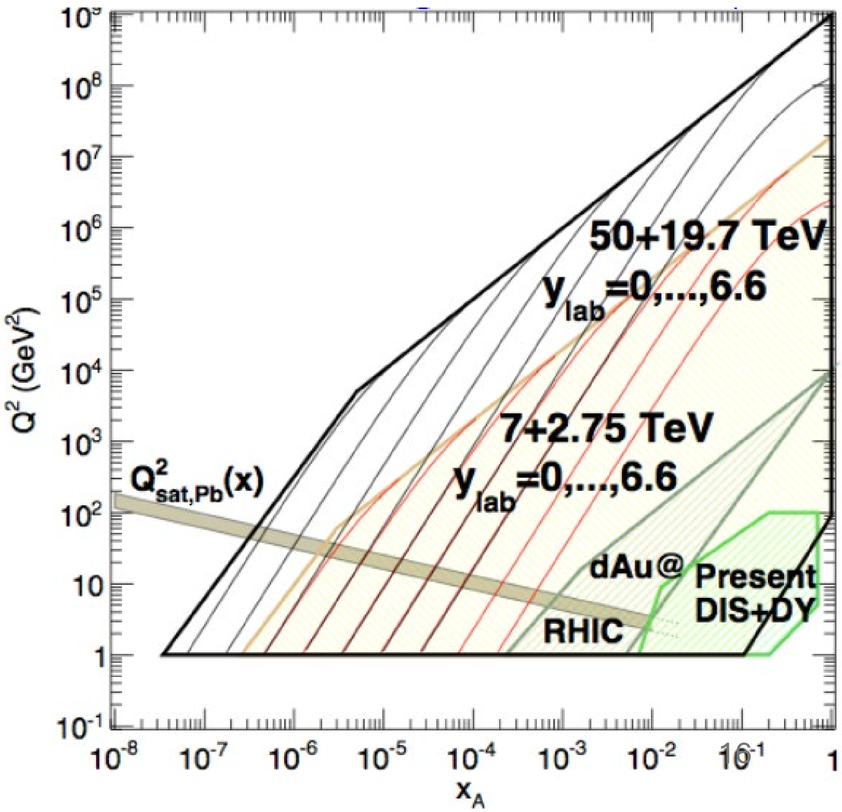
Unique studies of the Quark-Gluon Plasma

- Larger temperature → thermal production of charm, Y(1S) melting
- Larger √s and L_{int} → new hard observables, e.g. top, Higgs, to characterize the QGP

Unique studies of high-density initial state

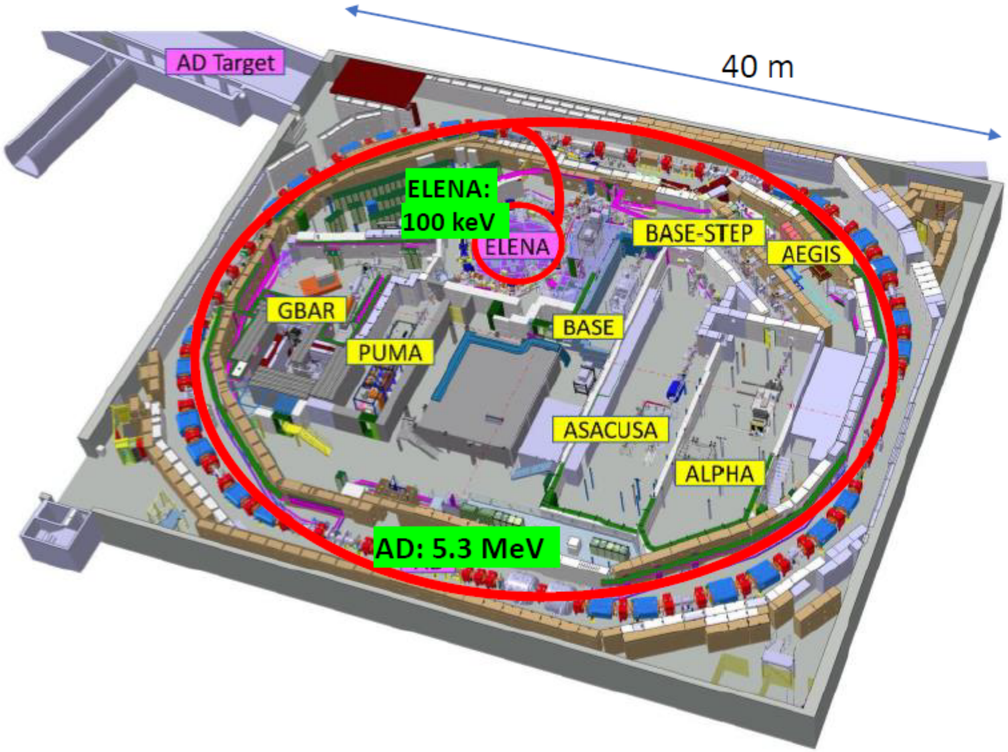
- *Access to saturation region (down to $x<10^{-6}$)*
- *Access to [small-x, large-Q2] region with top, W, Z*

See https://arxiv.org/abs/1605.01389v3



Other programs at CERN that ESPP cannot miss

The Antimatter Factory : AD/ELENA Facility @ CERN



The only low-energy $\bar{p}$ source

AD: 5.3 MeV

Pulsed beam: 3×10^7 $\bar{p}$ every ~ 100 s

ELENA: 5.3 MeV → 100 keV

- 6 collaborations
- 60 research institutes/universities
- 350 researchers

- Fundamental properties of $\bar{p}$ (BASE)
- Spectroscopy of antihydrogen (ASACUSA, ALPHA)
- Test free fall/equivalence principle with antihydrogen (ALPHA, AEgIS, GBAR)
- Antiprotonic helium spectroscopy (ASACUSA)
- Nuclear physics (PUMA, ASACUSA, AEgIS)

ELENA **from 2021 full operation**

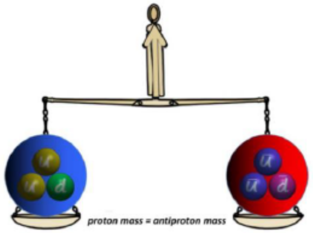
ADVANTAGES: ➢ x 10-100 $\bar{p}$s trapped per experiment ➢ 4 experiments run in parallel (24h/day)

Which studies with antimatter at low energy

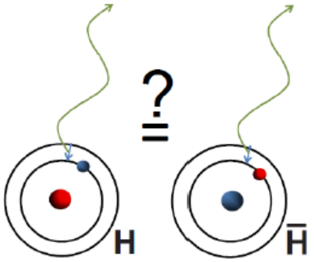
1) Precise matter/antimatter comparison

→ test of CPT symmetry

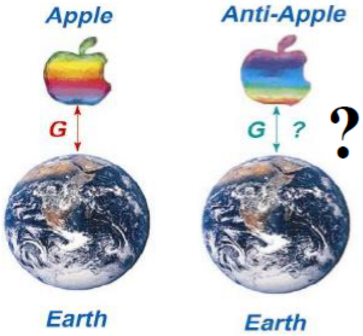
e.g. compare particle and antiparticle mass

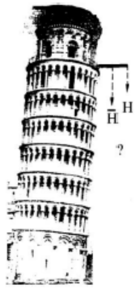


e.g. Spectroscopy of $\overline{\mathrm{H}}$



2) Measurement of the gravitational behaviour of antimatter → test of WEP





Possible only with neutral system → $\overline{\mathrm{H}}$ or Ps

Previous attempts with charged particles were unsuccessful due to the stray **E** and **B** fields:

- with positrons (1967, Fairbank and Witteborn)
- with (4 K)-antiprotons (1089, PS-200 @ CERN)

Consequences:

particle/antiparticle: equal mass, lifetime; equal and opposite charge and magnetic moment

atom/antiatom: identical energy levels

Consequences:

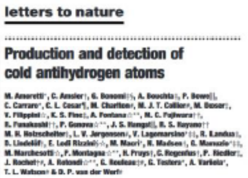
two bodies of different compositions and/or mass fall at the same rate in a gravitational field Newtonian version

NB: CPT invariance is inside the Standard Model.
No measurements of CPT violation exists

NB: From **General relativity no difference expected**
Quantum gravity **theories may allow differences**

Main achievements at AD

letters to nature



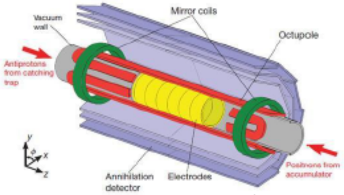
Production and detection of cold antihydrogen atoms

M. Amoretti, C. Amsler, G. Bonomi, A. Bouchta, P. Bowe, C. Carraro, C. L. Cesar, M. Charlton, M. J. T. Collier, M. Doser, V. Filippini, K. S. Fine, A. Fontana, M. C. Fujiwara, R. Funakoshi, P. Genova, J. S. Hangst, R. S. Hayano, M. H. Holzscheiter, L. V. Jørgensen, V. Lagomarsino, R. Landua, D. Lindelöf, E. Lodi Rizzini, M. Macrì, N. Madsen, G. Manuzio, M. Marchesotti, P. Montagna, H. Pruys, C. Regenfus, P. Riedler, J. Rochet, A. Rotondi, G. Rouleau, G. Testera, A. Variola, T. L. Watson & D. P. van der Werf

2002

ALPHA
ASACUSA

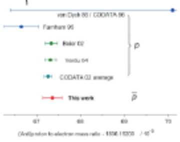
trapped antihydrogren



2010

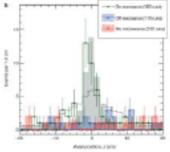
physicsworld TOP 10 BREAKTHROUGH 2010

2011



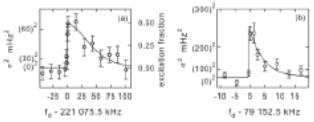
$m_{\bar{p}}/m_e$ at 1.5 ppb

2012



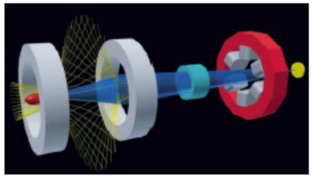
Resonant quantum transitions in Hbar

2013



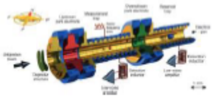
5ppm pbar moment

2014



Production of a beam of antihydrogen atoms

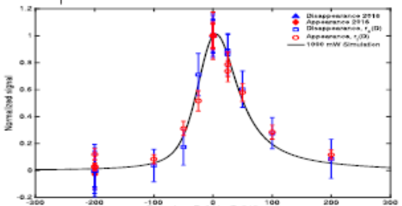
2015



69 p.p.t. proton/antiproton q/m comparison

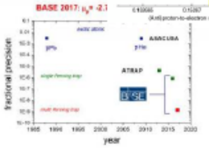
$$1+\frac{(q/m)_{\bar{p}}}{(q/m)_p}=1(69)\times10^{-12}$$

2017



2ppt antihydrogren 1S-2S spectroscopy

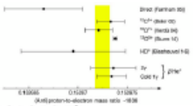
2018



1.5ppb pbar moment

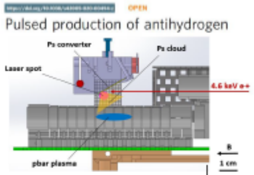
2019

$m_{\bar{p}}/m_e$ at 0.8ppb



2020

Pulsed production of antihydrogen



2021

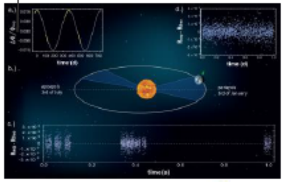
laser-cooled antihydrogren and sympathetically cooled protons

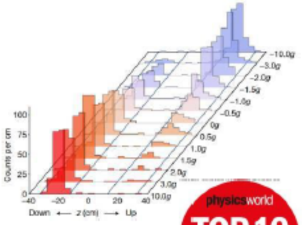
physicsworld TOP 10 BREAKTHROUGH 2021

ALPHA
BASE

2022

WEP test





physicsworld TOP 10 BREAKTHROUGH 2023

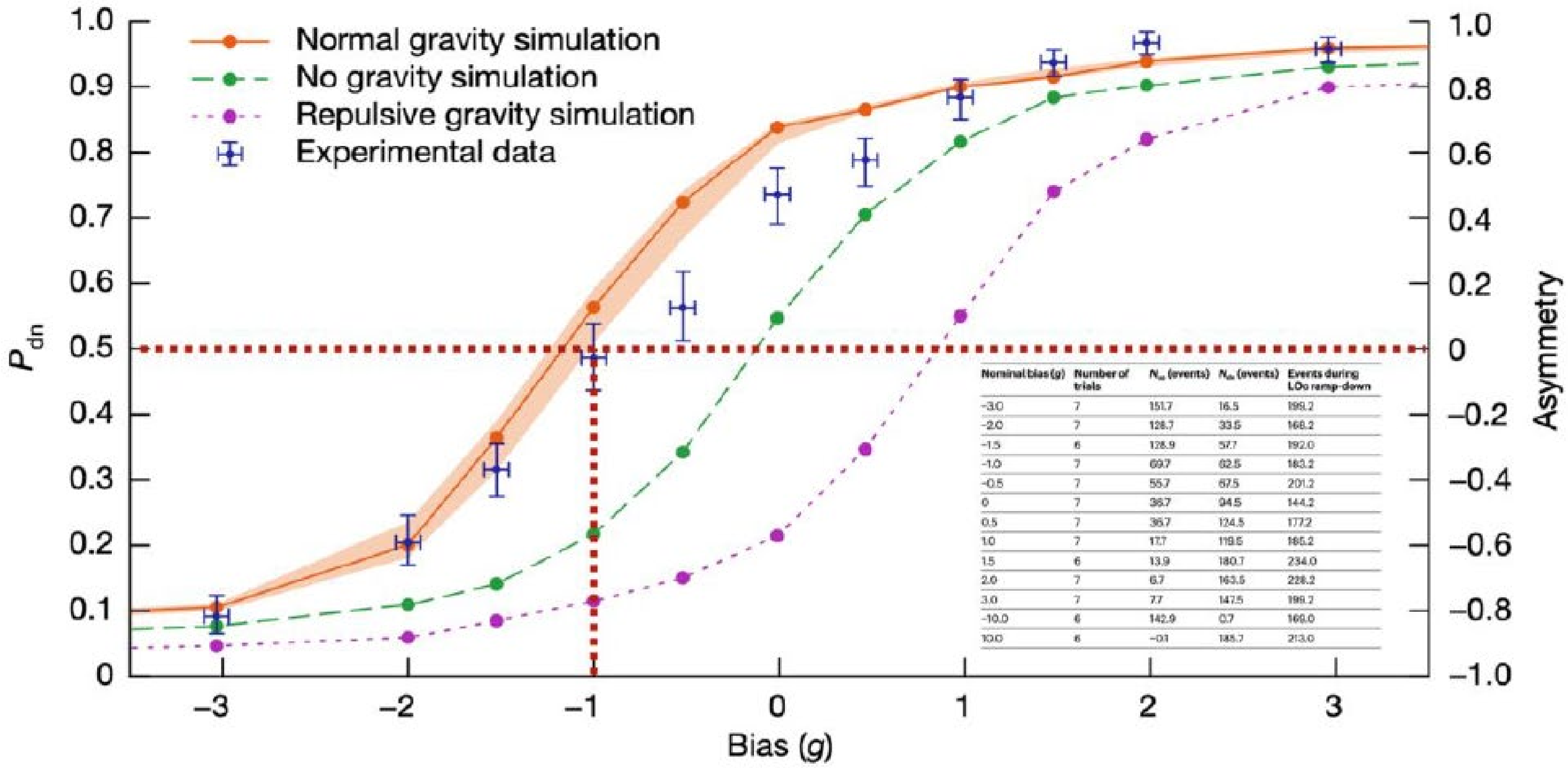
2024

Ps laser cooling

LEA - SIF 2024

First Experimental result on antimatter and gravitation (ALPHA Coll.) : motion of antihydrogen is due to a combination of magnetic-trap field and gravitational field

Asymmetry = $(N_{dn}-N_{up})/(N_{dn}+N_{up})$

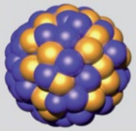


Nominal bias (g)	Number of trials	N_{up} (events)	N_{dn} (events)	Events during LOc ramp-down
−3.0	7	151.7	16.5	199.2
−2.0	7	128.7	33.5	168.2
−1.5	6	128.9	57.7	192.0
−1.0	7	69.7	62.5	183.2
−0.5	7	55.7	67.5	201.2
0	7	36.7	94.5	144.2
0.5	7	36.7	124.5	177.2
1.0	7	17.7	119.5	185.2
1.5	6	13.9	180.7	234.0
2.0	7	6.7	163.5	228.2
3.0	7	7.7	147.5	199.2
−10.0	6	142.9	0.7	169.0
10.0	6	−0.1	185.7	213.0

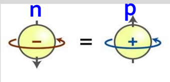
Nuclear Structure

OUR PLAYGROUND: the NUCLEAR Chart

ATOMIC NUCLEI

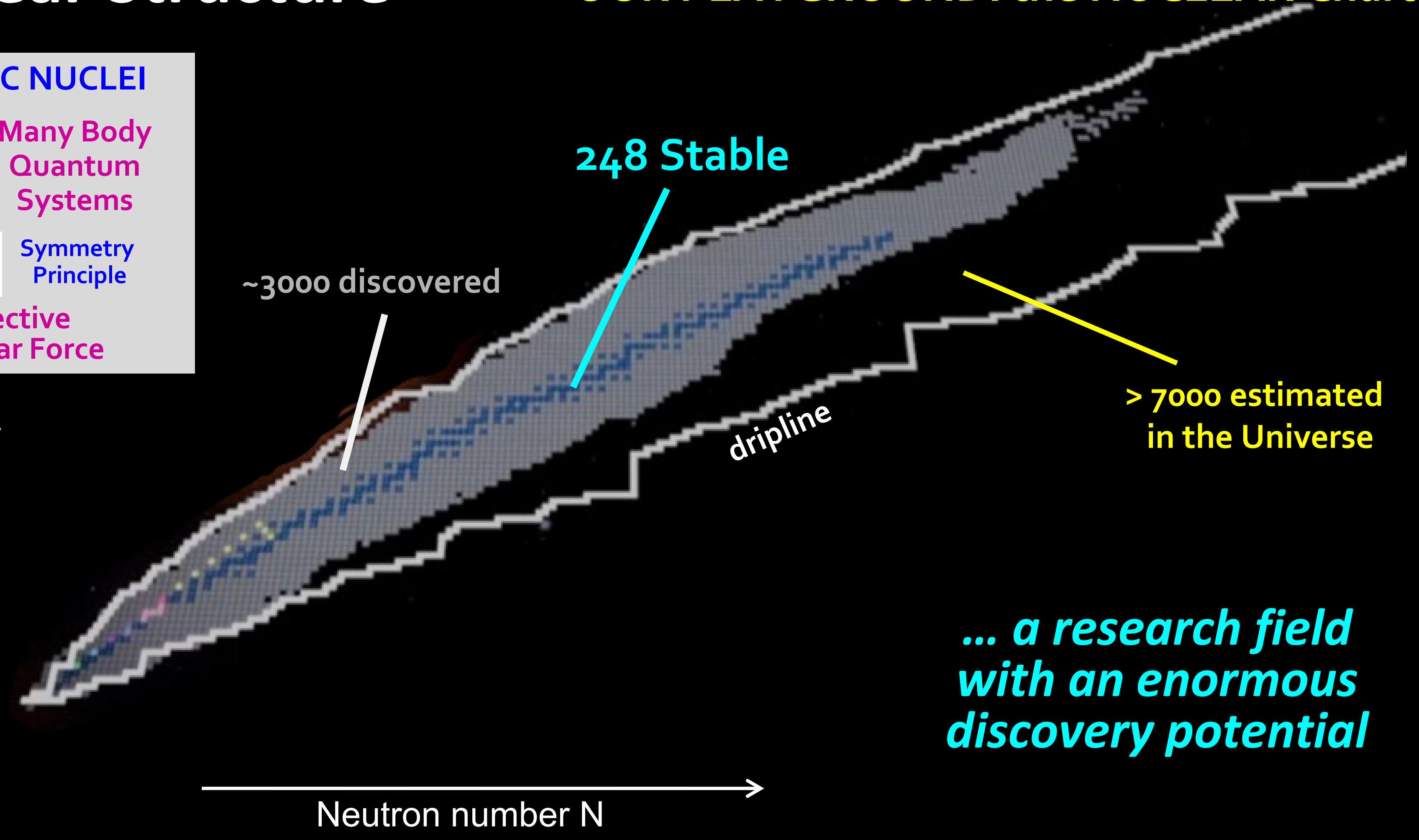


Many Body Quantum Systems



Symmetry Principle

Effective Nuclear Force



~3000 discovered

248 Stable

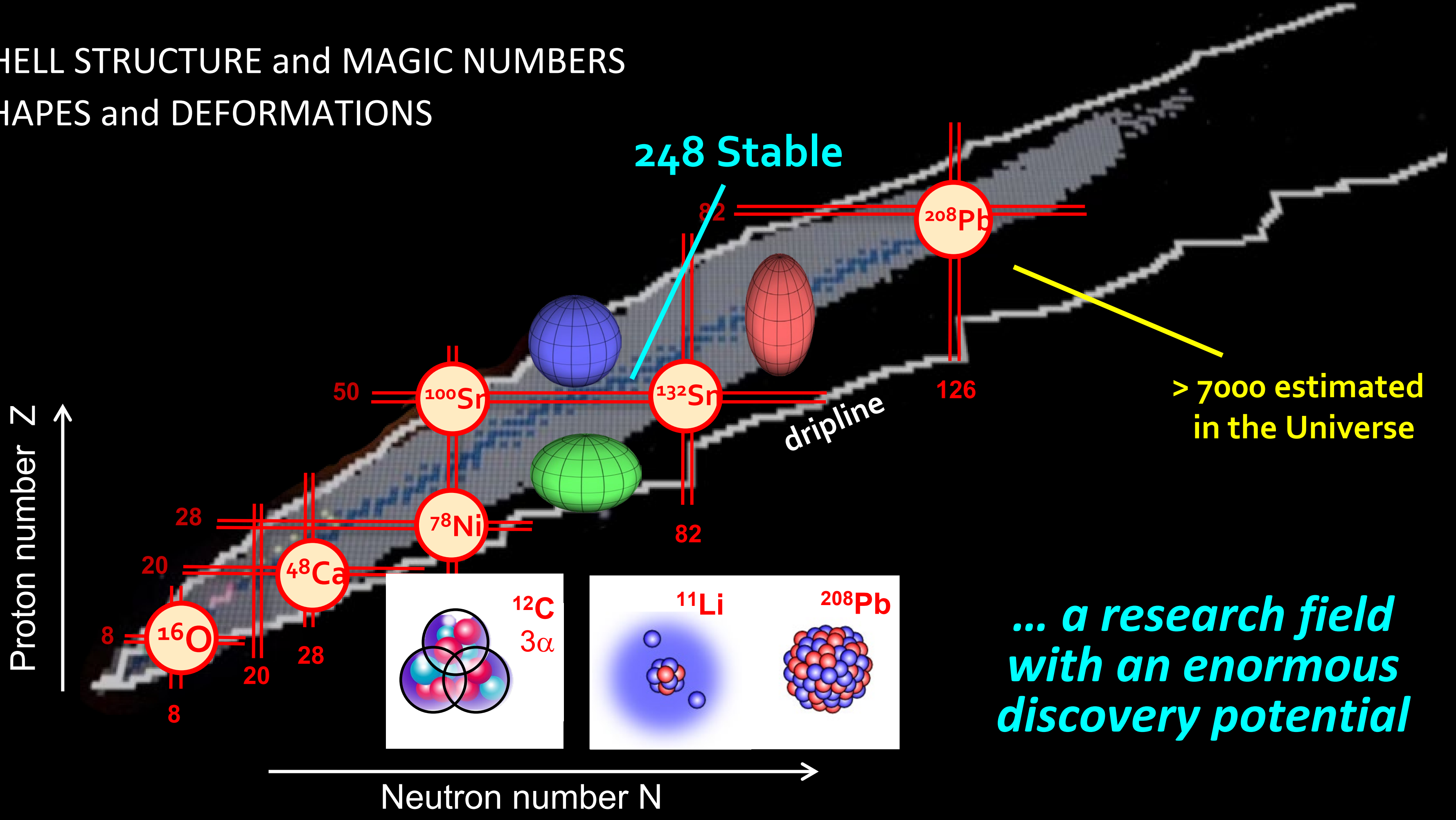
> 7000 estimated in the Universe

… a research field with an enormous discovery potential

A PUZZLE of INFORMATION

SHELL STRUCTURE and MAGIC NUMBERS

SHAPES and DEFORMATIONS



248 Stable

> 7000 estimated
in the Universe

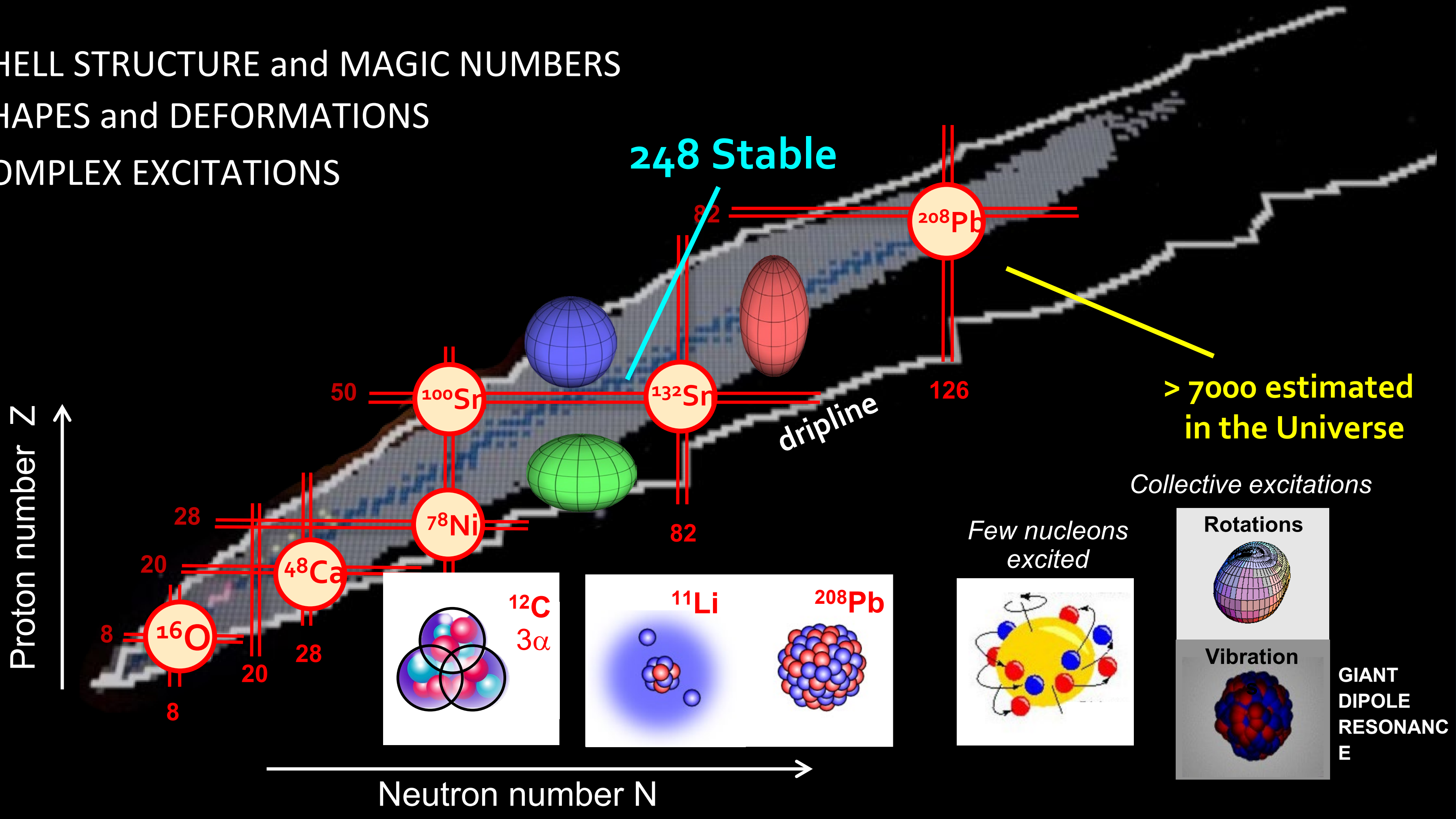
… a research field with an enormous discovery potential

A PUZZLE of INFORMATION

SHELL STRUCTURE and MAGIC NUMBERS

SHAPES and DEFORMATIONS

COMPLEX EXCITATIONS



248 Stable

> 7000 estimated
in the Universe

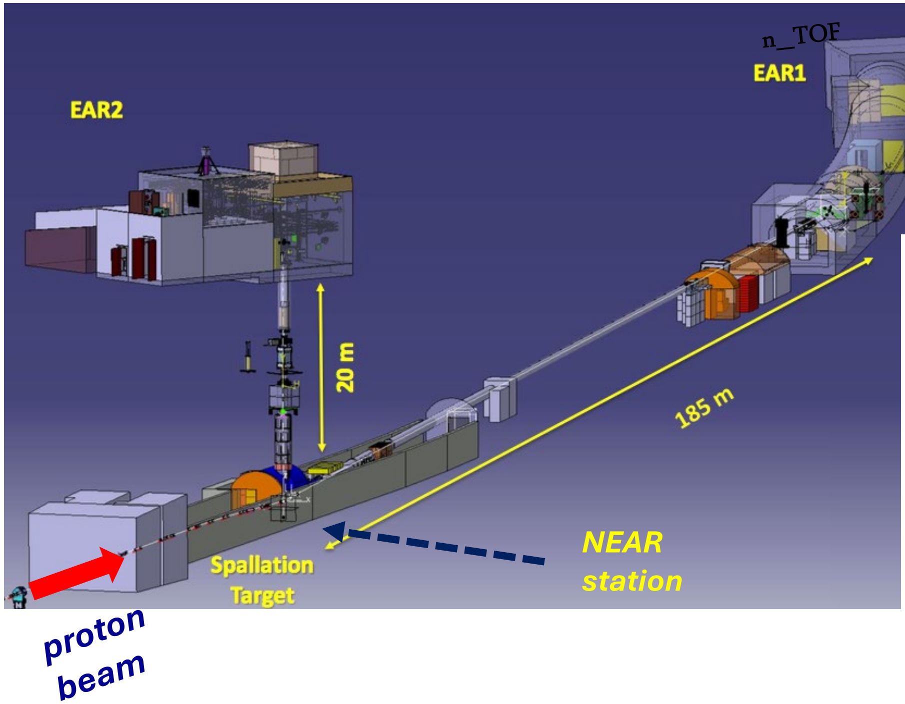
Few nucleons excited

Collective excitations

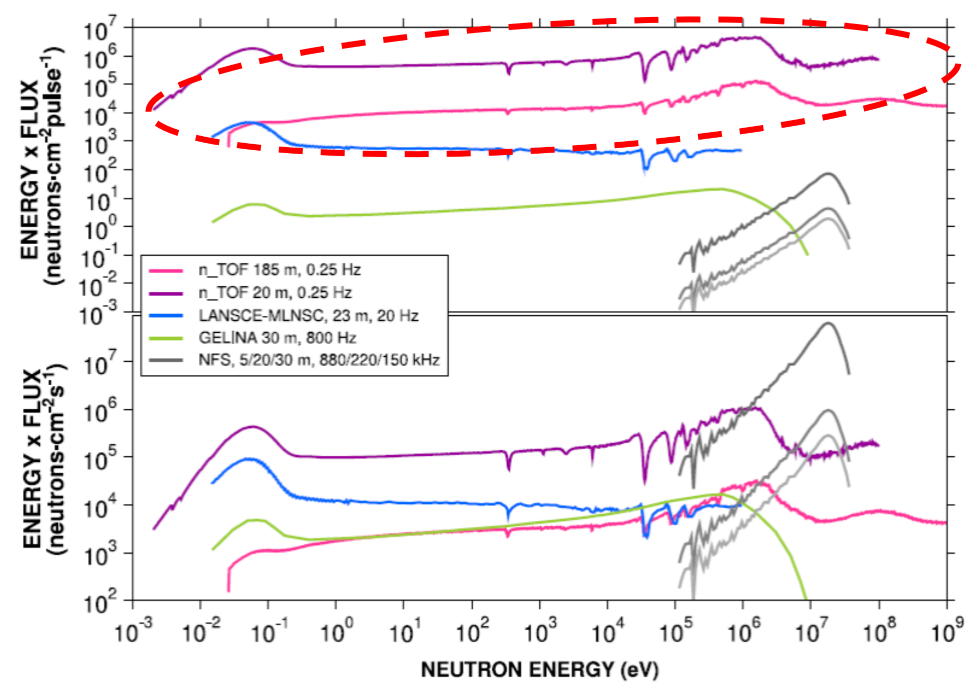
GIANT DIPOLE RESONANCE

https://www.youtube.com/watch?v=VZHpAwSGYZE https://www.youtube.com/watch?v=VZHpAwSGYZE

n_TOF facility at CERN



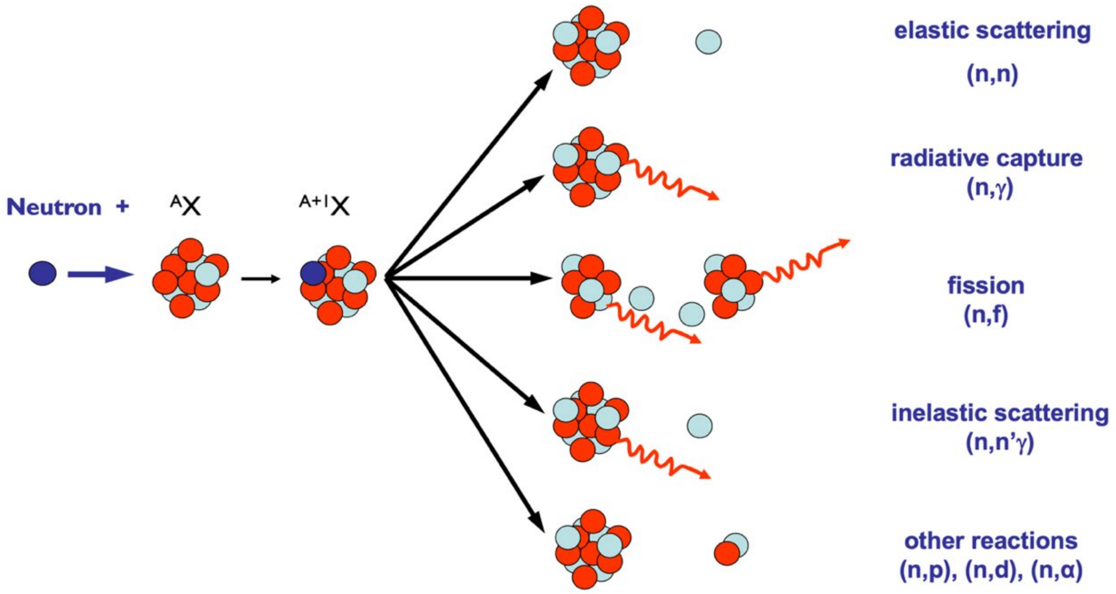
Comparison to other neutron beam facilities



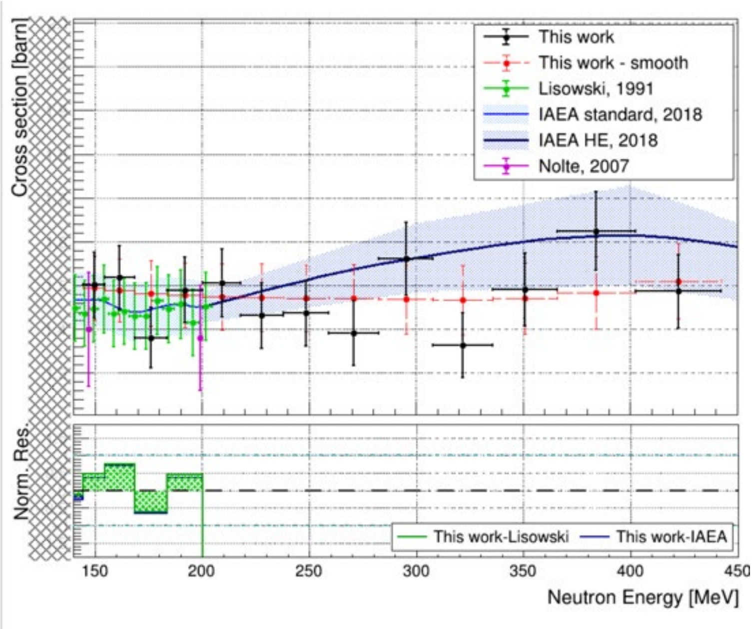
- n_TOF has the world-wide **highest instantaneous flux** (neutrons/pulse), while being competitive also in term of average flux (neutrons/second).
- EAR1 has the widest energy range available

Nuclear reactions at CERN

Neutron-induced reactions



- Big Bang and stellar nucleosynthesis
- Investigation of nuclear level densities
- Advanced nuclear technology
- Transmutation of nuclear waste
- Accelerator driven systems
- Nuclear fuel cycle investigations
- Medical Applications
- …



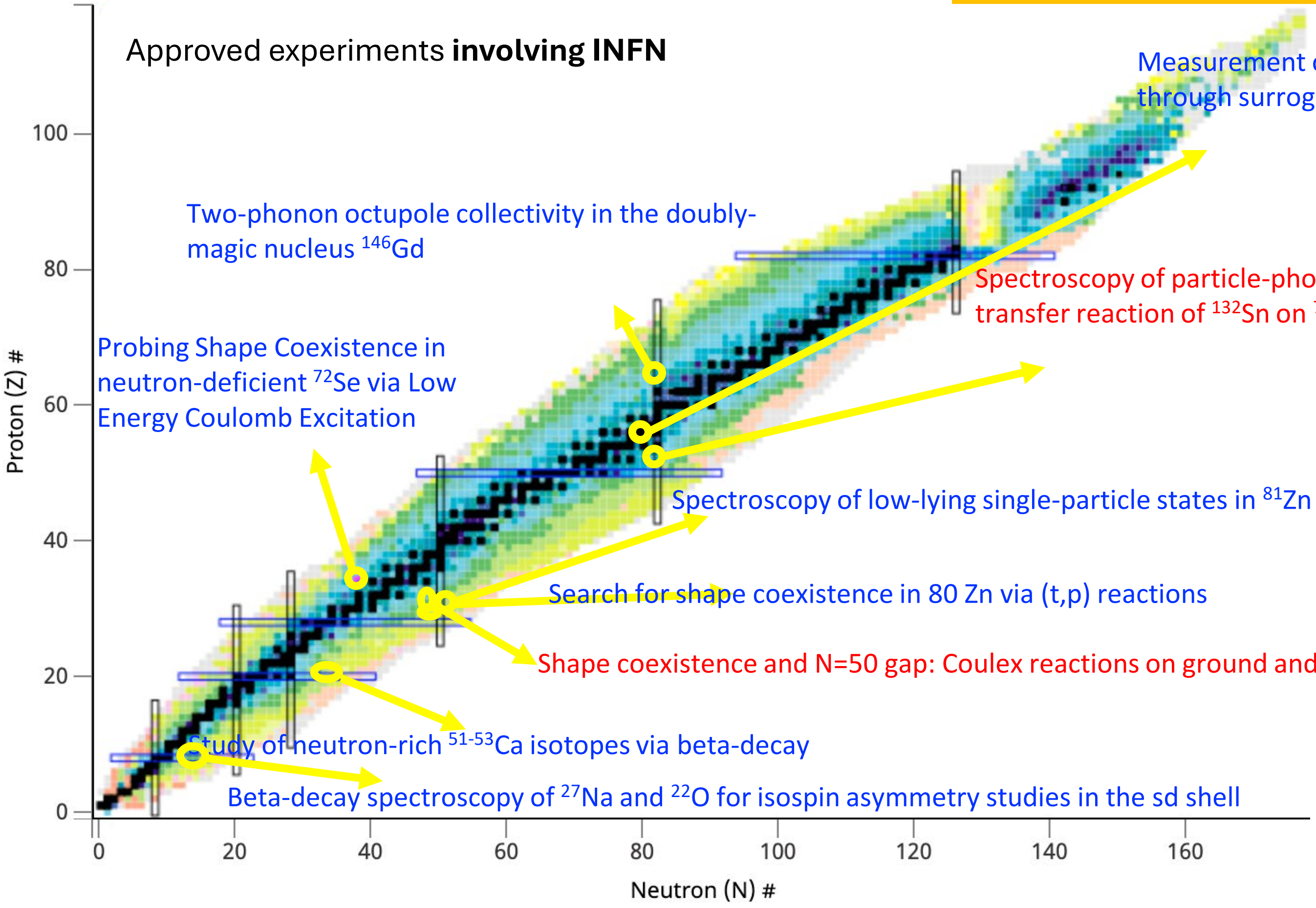
First ^{235}U(n,f) cross section data above 200MeV!!

The International Atomic Energy Agency (IAEA) strongly requests new data for up to 1GeV.

Nuclear reactions at CERN

@CERN

The Isotope mass Separator On-Line facility (ISOLDE) at CERN is a facility dedicated to the production of a large variety of radioactive ion beams: more than 700 different beams of isotopes from 70 chemical elements



Approved experiments **involving INFN**

Measurement of neutron capture cross section on ^{134}Cs through surrogate reaction (d,pγ) at ISS

Two-phonon octupole collectivity in the doubly-magic nucleus ^{146}Gd

Spectroscopy of particle-phonon coupled states in ^{133}Sb by the cluster transfer reaction of ^{132}Sn on ^{7}Li: an advanced test of nuclear interactions

Probing Shape Coexistence in neutron-deficient ^{72}Se via Low Energy Coulomb Excitation

Spectroscopy of low-lying single-particle states in ^{81}Zn populated in the ^{80}Zn(d,p) reaction

Search for shape coexistence in 80 Zn via (t,p) reactions

Shape coexistence and N=50 gap: Coulex reactions on ground and isomeric states in N=49 ^{79}Zn, ^{81}Ge isotones

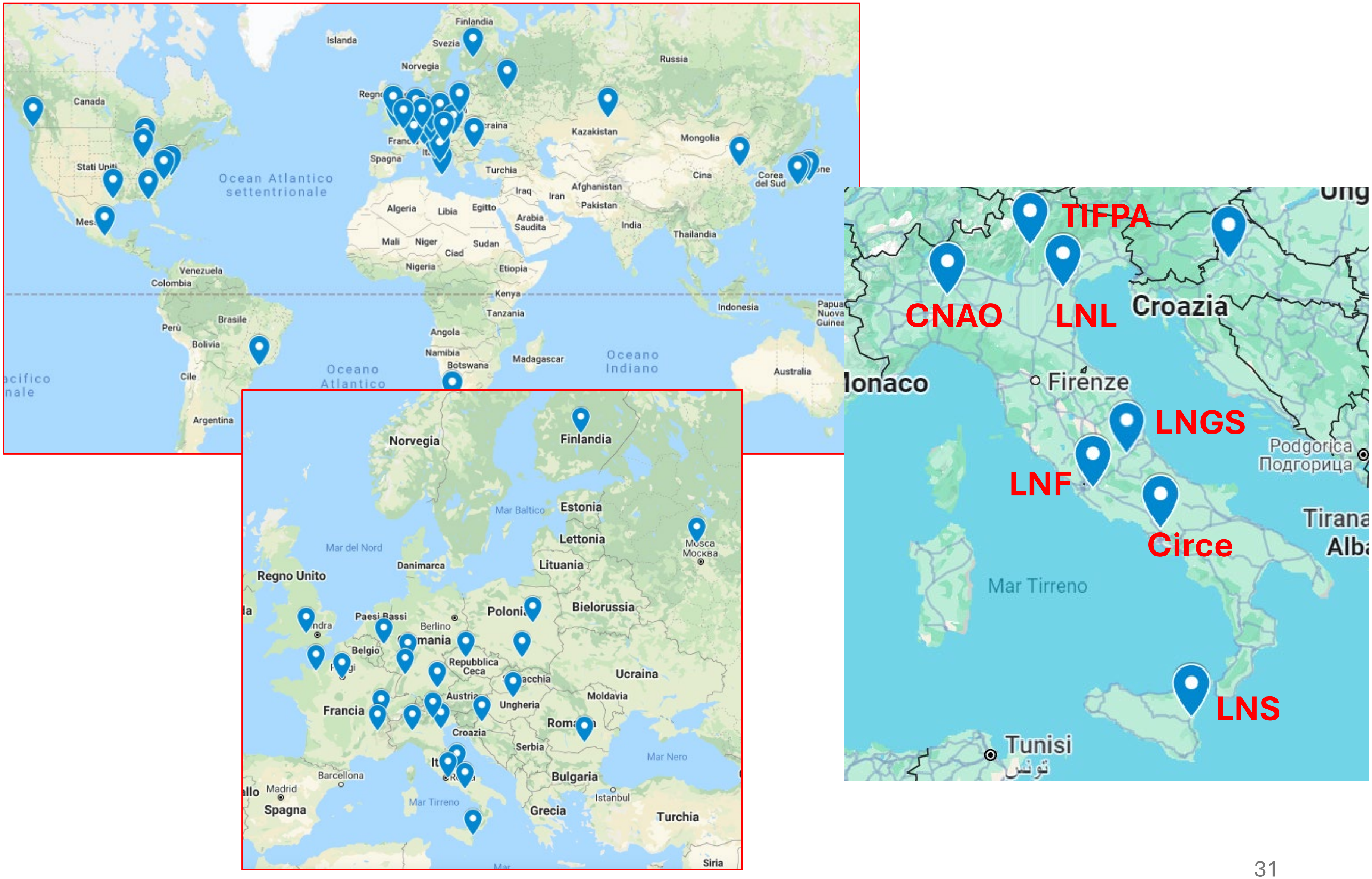
Study of neutron-rich $^{51-53}$Ca isotopes via beta-decay

Beta-decay spectroscopy of ^{27}Na and ^{22}O for isospin asymmetry studies in the sd shell

performed last year

Other INFN programs outside CERN that ESPP cannot miss and their connection with different CERN and international projects

National and International Laboratories for CSN3 experiments



Expected by 2025-2026

SPES at the LNL
https://web.infn.it/spes/

In operation

LUNA-MV accelerator of the Bellotti Ion Beam Facility at the LNGS
http://l.infn.it/lngs-accel.

Expected by 2026

POTLNS at the LNS
https://potlns.lns.infn.it/en/

Approved in design phase

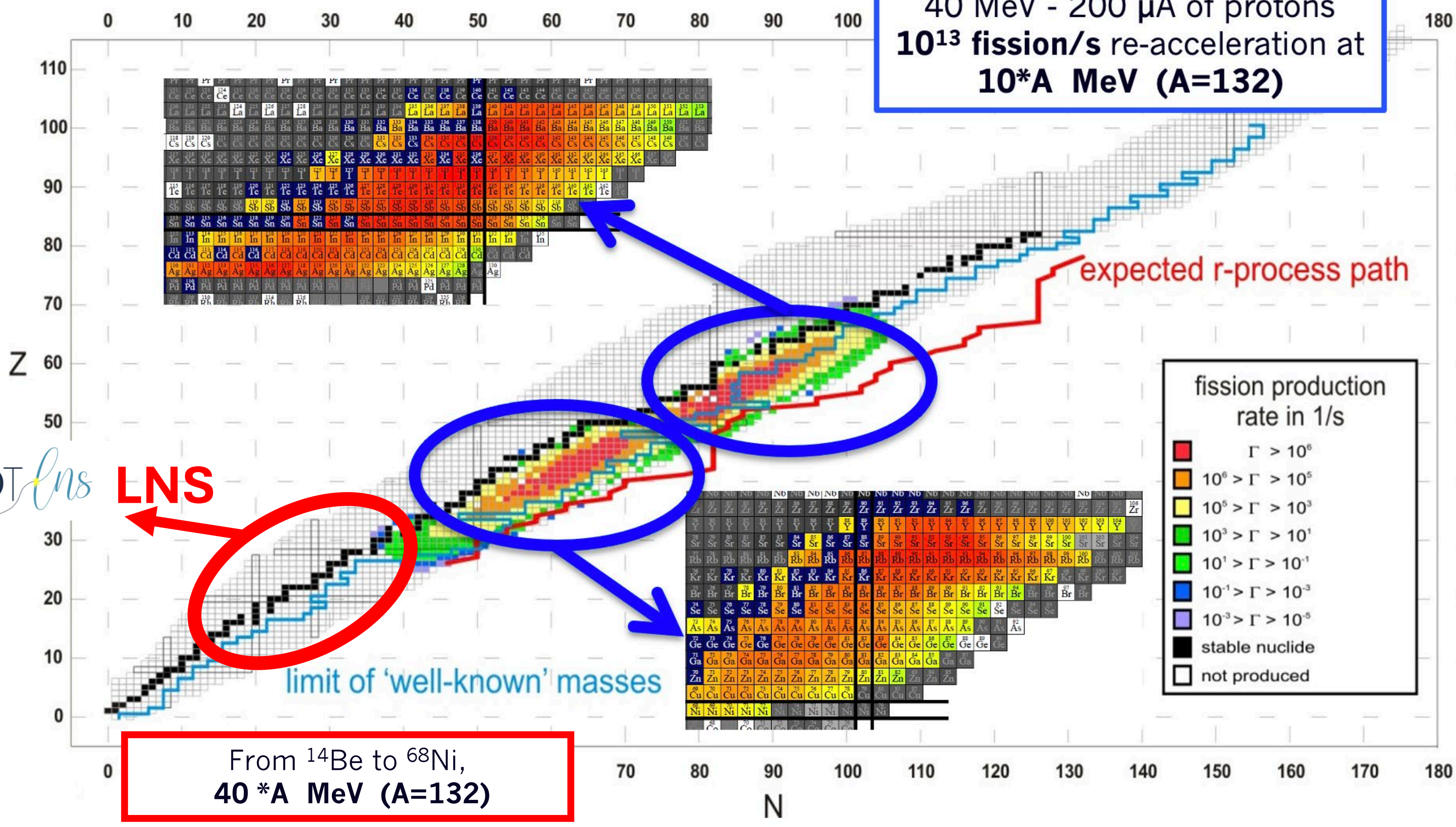
LNF and EuPRAXIA
https://www.eupraxia-project.eu

LNL-LNS complementarity

LNL

SPES

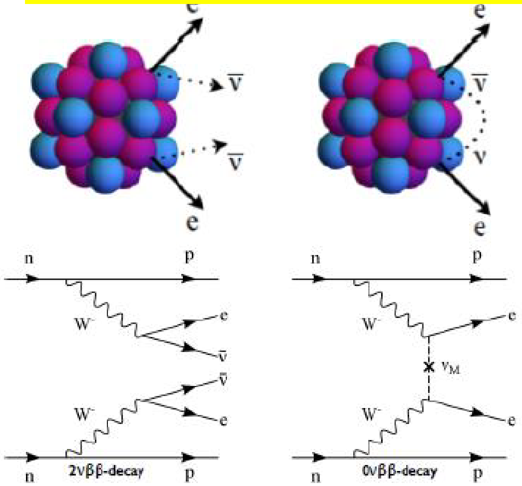
40 MeV - 200 μA of protons
10^{13} fission/s re-acceleration at
10*A MeV (A=132)

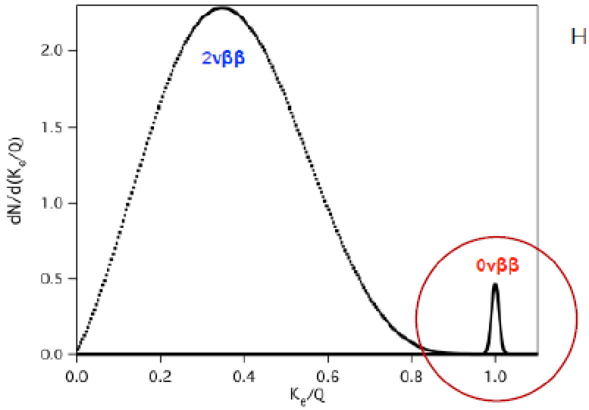


LNS

From ^{14}Be to ^{68}Ni,
40 *A MeV (A=132)

Neutrino-less double beta decay (NLDBD) – measurement of the Nuclear matrix element with NUMEN/MAGNEX @LNS





Half-life

Phase space factor

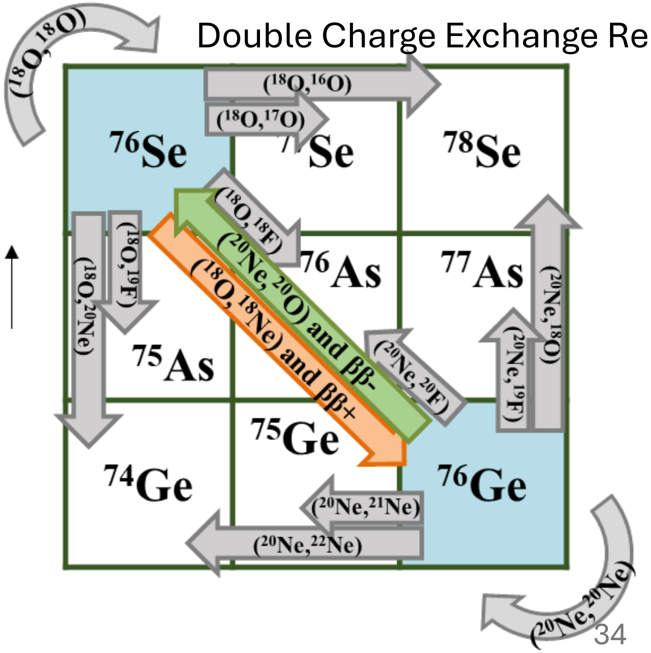
$$\boxed{\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2}$$

Nuclear matrix element

Effective Majorana neutrino mass:
(exact form depends on the lepton flavor violating mechanism!)

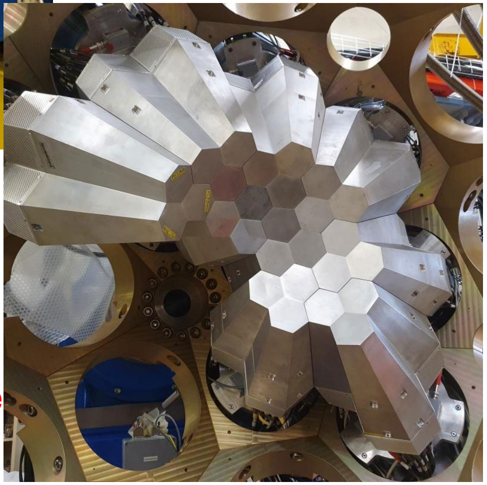
$$\boxed{m_{\beta\beta} \equiv \sum_{i=1}^{3} U_{ei}^2 m_i}$$

Double Charge Exchange Reaction



Reaction dynamics and nuclear structure @ LNL and LNS

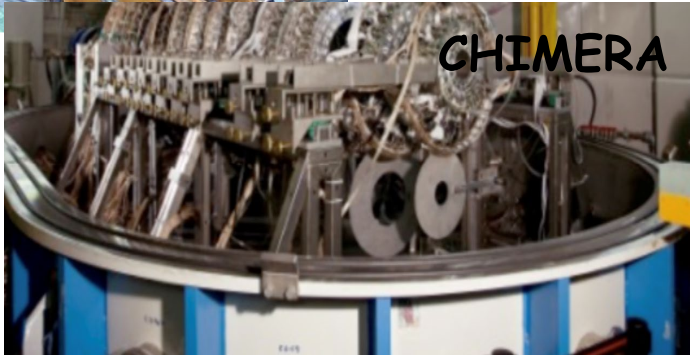
The complex TANDEM+ALPI+PIAVE **and SPES** @ LNL



AGATA: Advanced Gamma-ray Tracking Array

NB: Esperimento itinerante (GANIL, GSI , LNL....)

The complex TANDEM-NEW Cyclotron -FRAISE @ LNS

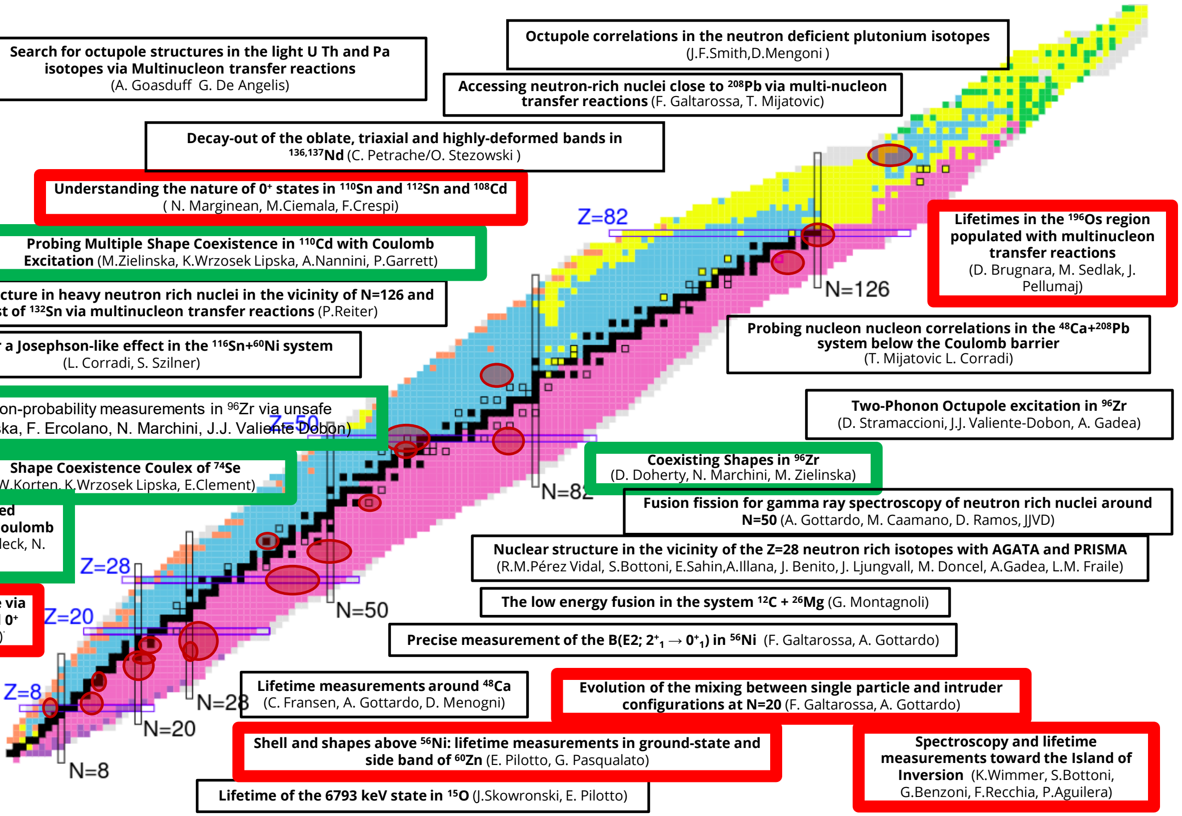


CHIMERA

The AGATA campaign at LNL (since 2022)

Coulomb excitation

Transfer reactions



Octupole correlations in the neutron deficient plutonium isotopes (J.F.Smith,D.Mengoni)

Search for octupole structures in the light U Th and Pa isotopes via Multinucleon transfer reactions (A. Goasduff G. De Angelis)

Accessing neutron-rich nuclei close to ^{208}Pb via multi-nucleon transfer reactions (F. Galtarossa, T. Mijatovic)

Decay-out of the oblate, triaxial and highly-deformed bands in ^{136,137}Nd (C. Petrache/O. Stezowski)

Understanding the nature of 0^{+} states in ^{110}Sn and ^{112}Sn and ^{108}Cd (N. Marginean, M.Ciemala, F.Crespi)

Lifetimes in the ^{196}Os region populated with multinucleon transfer reactions (D. Brugnara, M. Sedlak, J. Pellumaj)

Probing Multiple Shape Coexistence in ^{110}Cd with Coulomb Excitation (M.Zielinska, K.Wrzosek Lipska, A.Nannini, P.Garrett)

Pathway to nuclear structure in heavy neutron rich nuclei in the vicinity of N=126 and nuclei northwest of ^{132}Sn via multinucleon transfer reactions (P.Reiter)

Probing nucleon nucleon correlations in the ^{48}Ca+^{208}Pb system below the Coulomb barrier (T. Mijatovic L. Corradi)

Search for a Josephson-like effect in the ^{116}Sn+^{60}Ni system (L. Corradi, S. Szilner)

Combined lifetime and transition-probability measurements in ^{96}Zr via unsafe Coulomb excitation (M. Zielinska, F. Ercolano, N. Marchini, J.J. Valiente Dobon)

Two-Phonon Octupole excitation in ^{96}Zr (D. Stramaccioni, J.J. Valiente-Dobon, A. Gadea)

Shape Coexistence Coulex of ^{74}Se (W.Korten, K.Wrzosek Lipska, E.Clement)

Coexisting Shapes in ^{96}Zr (D. Doherty, N. Marchini, M. Zielinska)

The emergence of enhanced collectivity near magic nuclei: Coulomb excitation of ^{60}Ni (K. HadinskaKleck, N. Marchini, M. Rocchini,)

Fusion fission for gamma ray spectroscopy of neutron rich nuclei around N=50 (A. Gottardo, M. Caamano, D. Ramos, JJVD)

Nuclear structure in the vicinity of the Z=28 neutron rich isotopes with AGATA and PRISMA (R.M.Pérez Vidal, S.Bottoni, E.Sahin,A.Illana, J. Benito, J. Ljungvall, M. Doncel, A.Gadea, L.M. Fraile)

Study of shape coexistence in ^{60}Fe via lifetime measurement of excited 0^{+} states (G.Pasqualato/J.Ljungvall)

The low energy fusion in the system ^{12}C + ^{26}Mg (G. Montagnoli)

Precise measurement of the B(E2; $2^{+}_{1} \rightarrow 0^{+}_{1}$) in ^{56}Ni (F. Galtarossa, A. Gottardo)

Test of the CKM unitarity and the existence of Fierz interference through the measurement of superallowed beta decay of light nuclei (J.Ha/F.Recchia)

Lifetime measurements around ^{48}Ca (C. Fransen, A. Gottardo, D. Menogni)

Evolution of the mixing between single particle and intruder configurations at N=20 (F. Galtarossa, A. Gottardo)

Shell and shapes above ^{56}Ni: lifetime measurements in ground-state and side band of ^{60}Zn (E. Pilotto, G. Pasqualato)

Spectroscopy and lifetime measurements toward the Island of Inversion (K.Wimmer, S.Bottoni, G.Benzoni, F.Recchia, P.Aguilera)

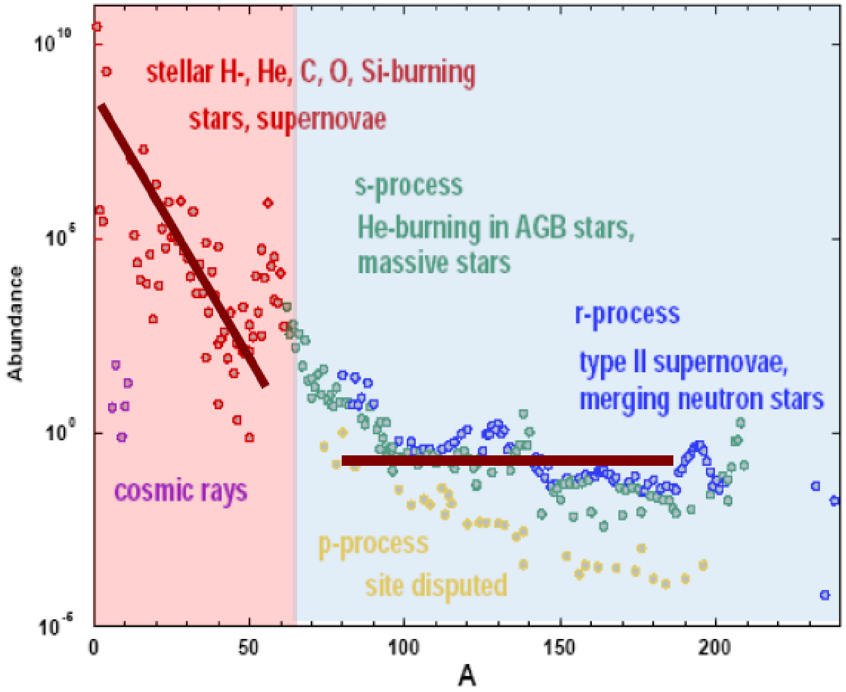
Lifetime of the 6793 keV state in ^{15}O (J.Skowronski, E. Pilotto)

Lifetime measurements intruder states towards the island of inversion along the N=20 shell closure (Z. Irene, D. Brugnara)

Stellar Nuclear Reactions in the Laboratory: Experimental Challenges at low energy

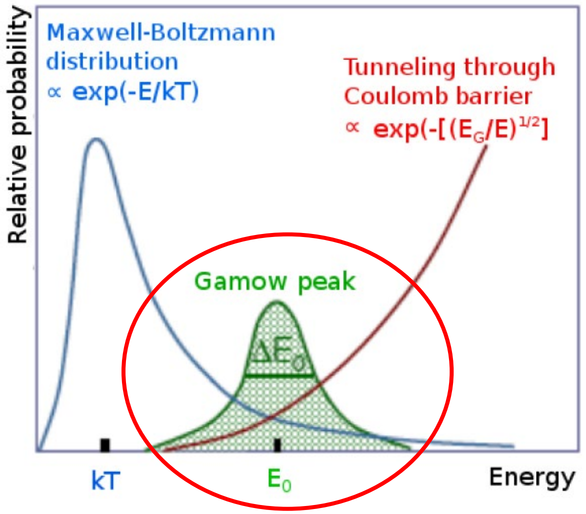
fusion of charged particles

mainly **stable nuclei**



neutron-capture reactions

mainly **unstable nuclei**



Different Experimental methods:

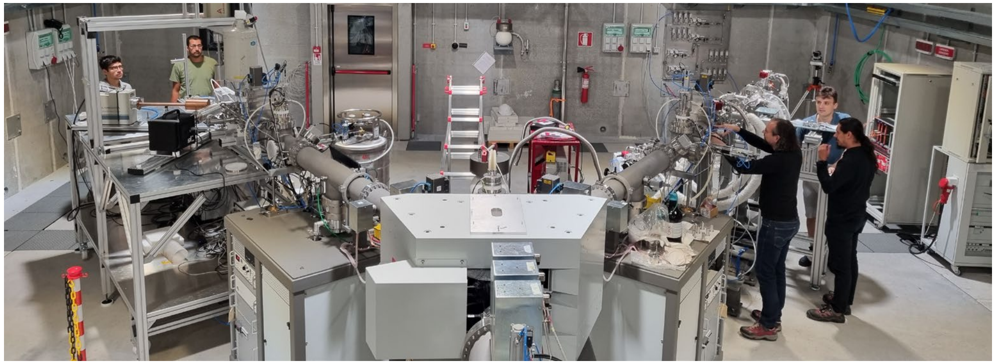
- Extrapolation from higher energies
- Direct Measurements (LUNA)
- Indirect Measurements (Trojan Horse Method)

Nuclear Astrophysics in laboratories

INFN
CSN3

Bellotti Ion Beam Facility @ LNGS

The 3.5 MV Accelerator Singletron “LUNA-MV” can provide Proton, Alpha and Carbon beams (Evolution in 30 years from LUNA 50 through LUNA 400)



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

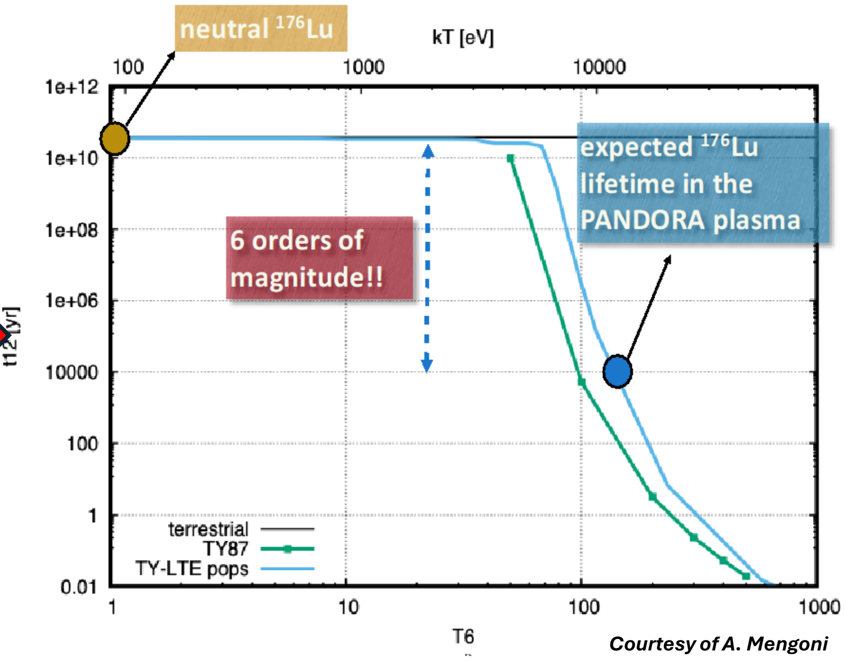
- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$
  $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(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**
  $^{13}C(\alpha,n)^{16}O$

…. However !

Stars are made of matter in plasma state where nuclei behaviour could be different

In future, nuclear astrophysics studies will require measurements in extreme conditions different from earth laboratories.

^{176}Lu: lifetime vs. T – theoretical predictions



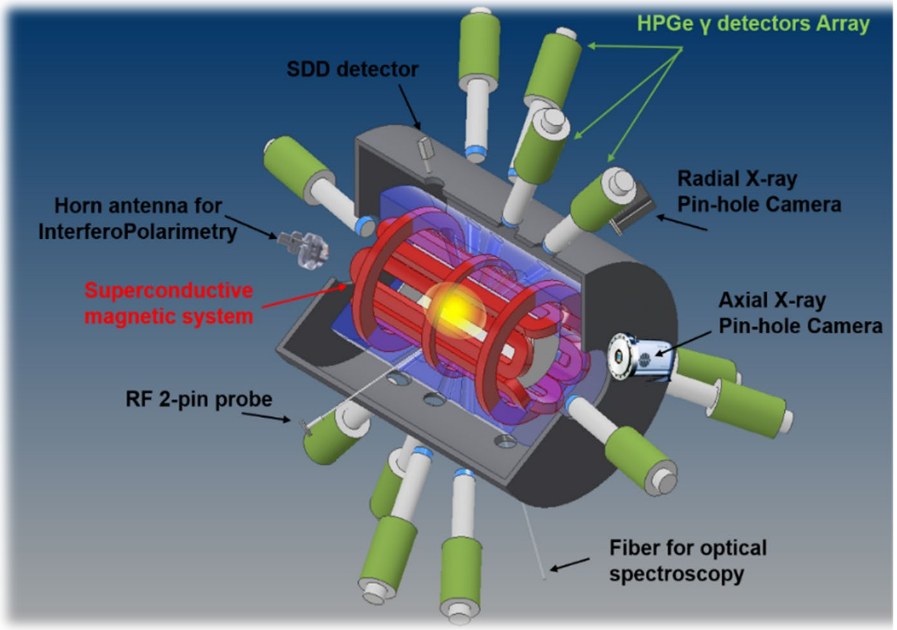
Courtesy of A. Mengoni

Takahashi et al. 1987, Phys Rev C 36, 1522

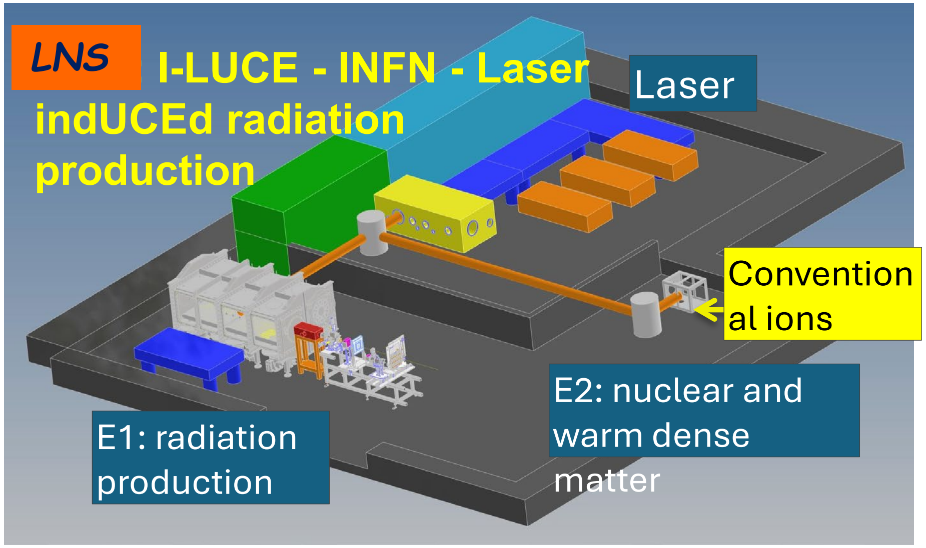
The PANDORA experiment (2025)

Build a **plasma trap** where ion species are confined in a magnetic field and a plasma is created with:

- Electron density: $10^{12} \div 10^{14}\ cm^{-3}$
- Electron temperature: 0.1 ÷ 100 keV
- Ion density: $10^{11}\ cm^{-3}$ → relies on the radiactive isotope concentration in plasma
- Ion temperature: ~ 1 eV → Ions are cold: no access to the excited states



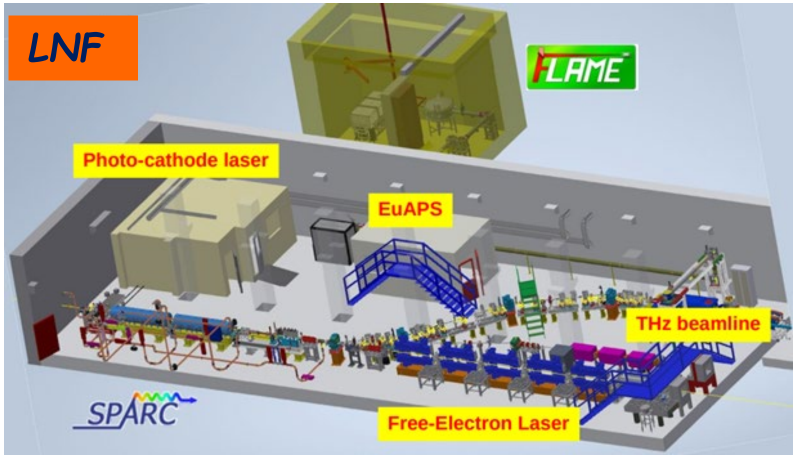
Laser induced plasma physics at LNS and LNF



Possible physics topics

- Stopping power in plasma
- Radioisotope production
- Hydrogen generation
- Positron, proton, electrons generation
- Nuclear reaction scheme

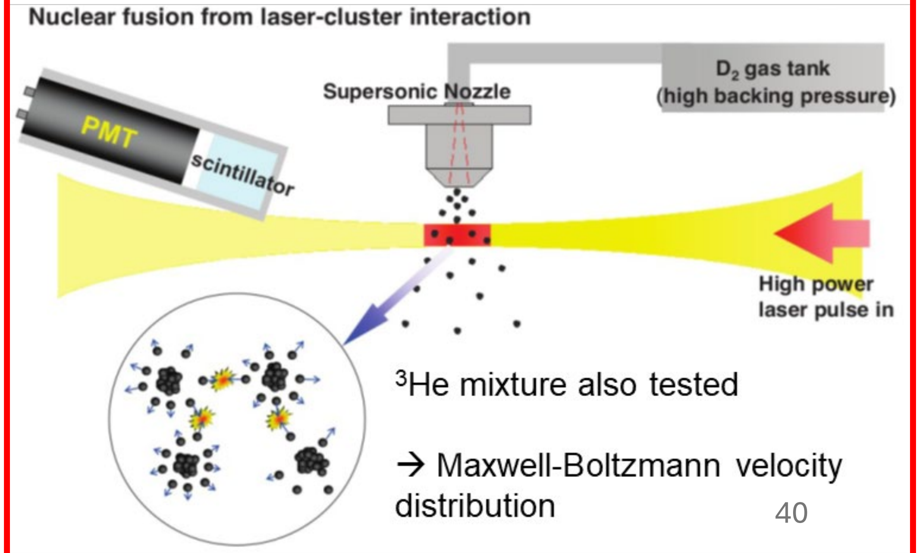
https://link.springer.com/article/10.1140/epjp/s13360-023-04358-7



LNF

EuPRAXIA

Coulomb Explosion technique



^{3}He mixture also tested

→ Maxwell-Boltzmann velocity distribution

INFN
CSN3

A comparison between magnetic and laser induced physics with plasma

Magnetic confinement (PANDORA)

PRO:

- **Long-living plasma** (order of weeks)
- Steady state dynamical equilibrium for density and temperature (by compensating ion losses)
- Hence, over days/weeks constant values for charge state distribution of in-plasma ions
- Online monitoring of plasma density, temperature, volume, at any energy domain in nLTE conditions

CONS:

- Low density/high temperature plasma: non local termal equilibrium (**nLTE conditions**)
- Difficult "plasmization" of solid/metallic isotopes
- **No access to nuclear excited state studies** (too low T)

Laser-induced plasma

PRO:

- **High density plasma, reaching local thermodynamical equilibrium (LTE)**
- Fully thermodynamical equilibrium allows, in principle, to **estimate the population of nuclear excited states**

CONS:

- **Difficult to implement diagnostics** following on-time the fast time-variation of plasma parameters
- **Short living plasma**, with duration much shorter than typical lifetimes of isotopes involved in stellar nucleosynthesis

Workshop@LNF 4-6 December 2024

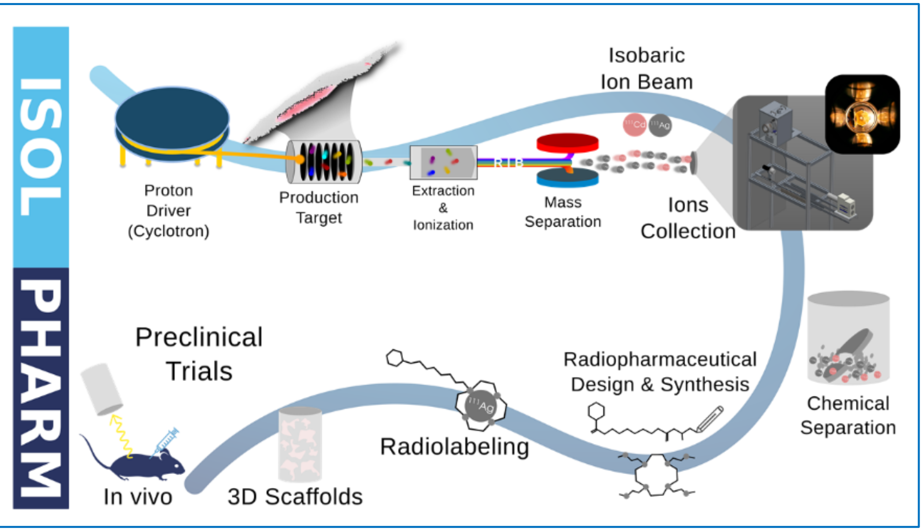
INFN CSN3

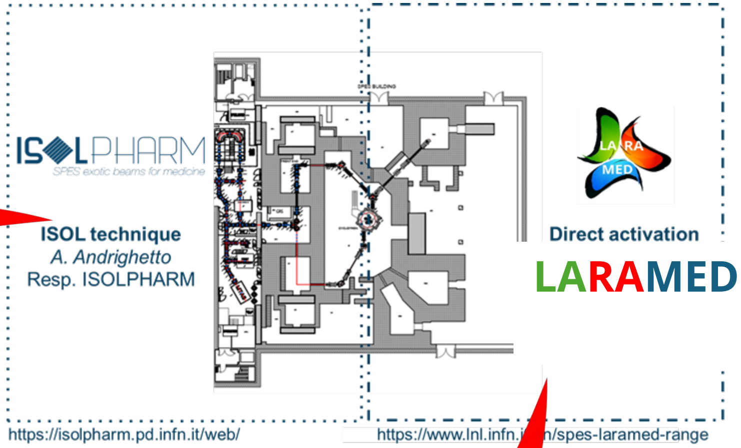
Medical radionuclides production with SPES-MED @ LNL

SPES-γ

PRISMAP Medical Radionuclides

https://www.prismap.eu/





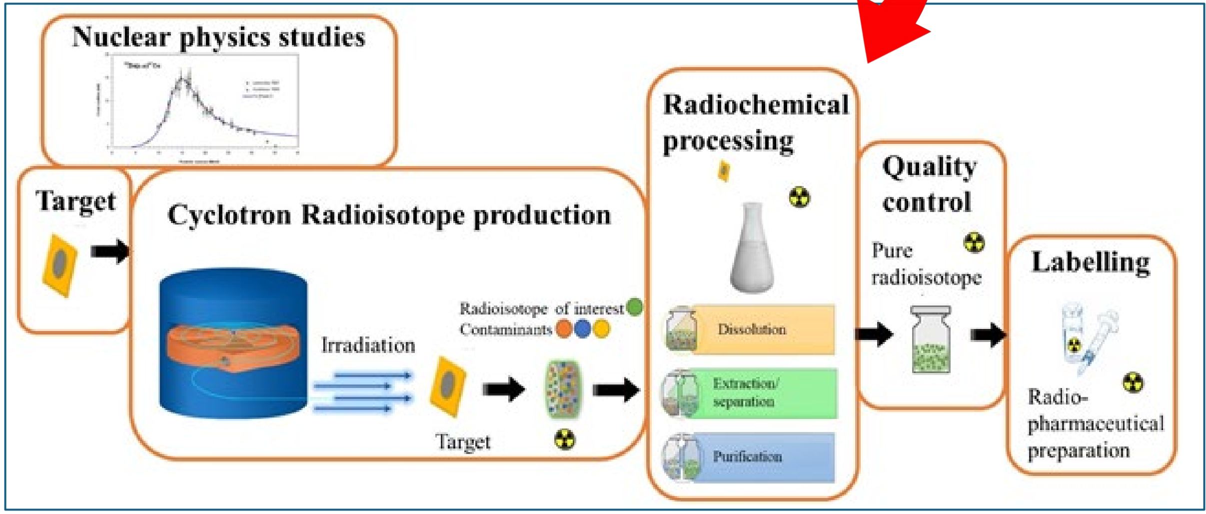
ISOL technique
A. Andrighetto
Resp. ISOLPHARM

Direct activation

LARAMED

https://isolpharm.pd.infn.it/web/

https://www.lnl.infn.it/en/spes-laramed-range



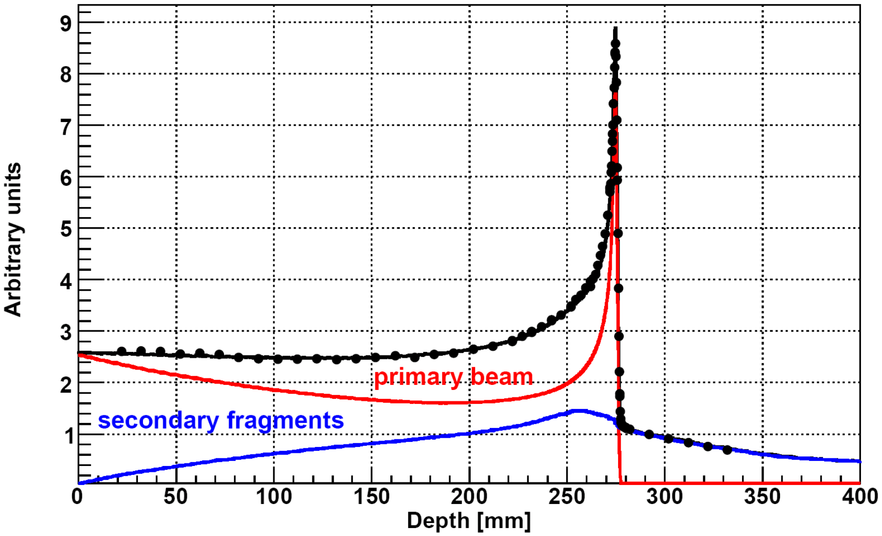
In this **multi-disciplinary** research activity **nuclear physics** plays a key role in the optimization of medical radionuclides production, exploiting innovative routes

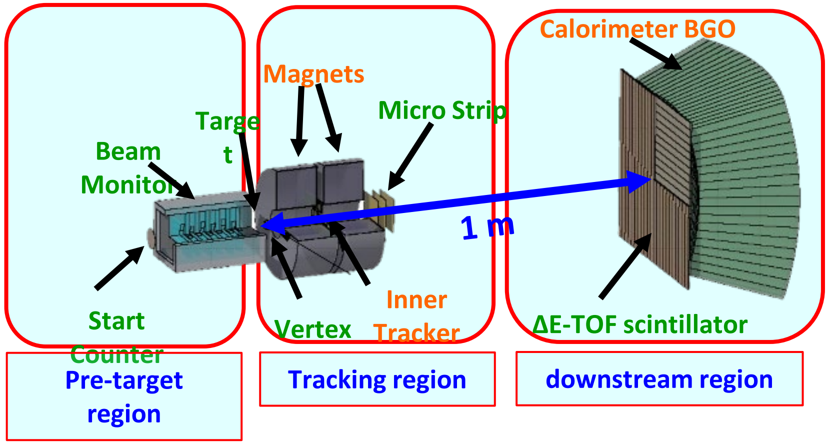
Strong collaboration also with LNS and CERN

INFN CSN3

FOOT: (FragmentatiOn Of Target)

Cross section measurements for hadro-therapy and for evaluation of possible dangers for astronauts. CNAO-GSI-Heidelberg




Calorimeter BGO

Magnets

Micro Strip

Targe t

Beam Monitor

1 m

Start Counter

Vertex

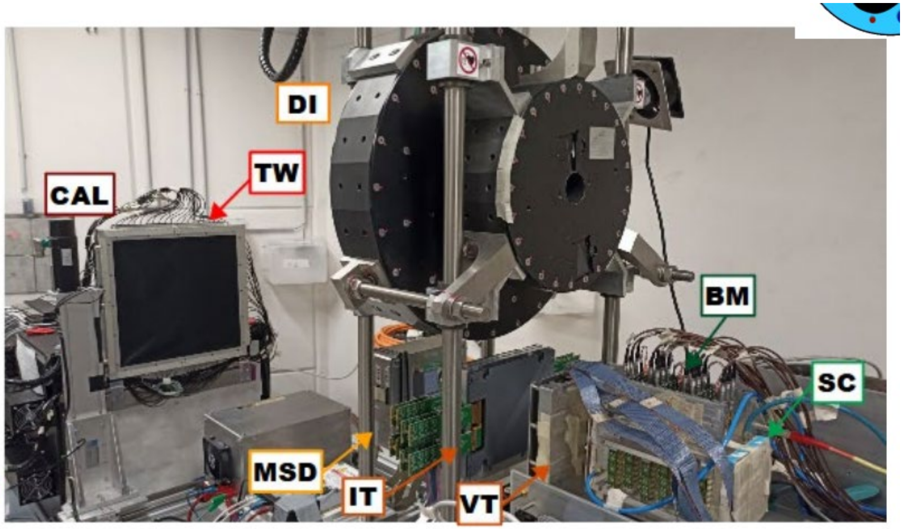
Inner Tracker

ΔE-TOF scintillator

Pre-target region

Tracking region

downstream region



INFN Nuclear Physics in ESPP

High energy frontier
Support to EIC, HL-LHC , FCC-hh

CERN complementary projects
Support to AD/ELENA , ISOLDE , n_TOF

Importance of connections with lower energies nuclear physics studies
Nuclear Matrix element for Neutrinoless double beta decay
Studies of the caracteristics (structure, shape, cross section, dynamics) of the elements of the nuclear chart

SPES-LNL, POT- LNS (with other national laboratories like RAL, GANIL, FAIR) complemetary to ISOLDE

Nuclear astrophysics reactions and connections with astrophysics measurement, star evolution and multimessanger studies
Particular attention to lower energies reactions.
LNGS, LNS, LNL, LNF, CIRCE (complementary to n_TOF)

Medical applications
Hadro-theraphy , Radionuclides production .
SPES-LNL, LNS, CNAO, TIFPA