Advances in gamma-ray spectroscopy for nuclear Physics and Astrophysics

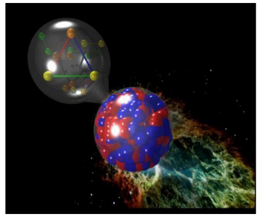
Daniele Mengoni

Dept. Phyisics e Astronomy, Università di Padova & INFN Padova

AGATA ADVANCED GAMMA TRACKING ARRAY

GRIT

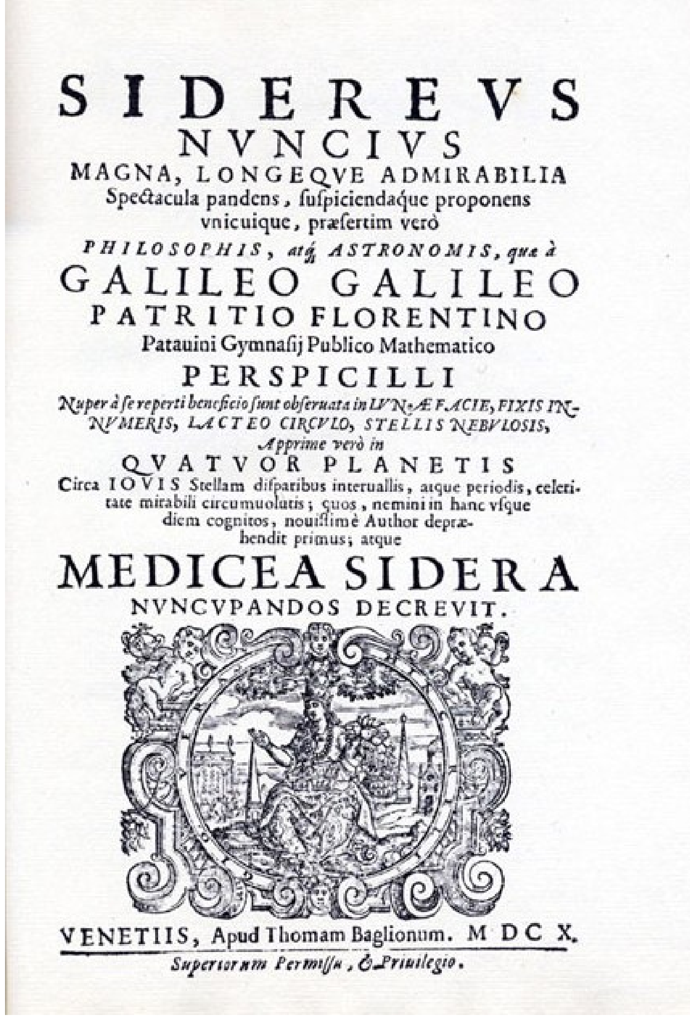
SPES exotic beams for science



UNIVERSITÀ DEGLI STUDI DI PADOVA 800 ANNI 1222-2022

INFN Istituto Nazionale di Fisica Nucleare

Camerino 7 Nov. 2022



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

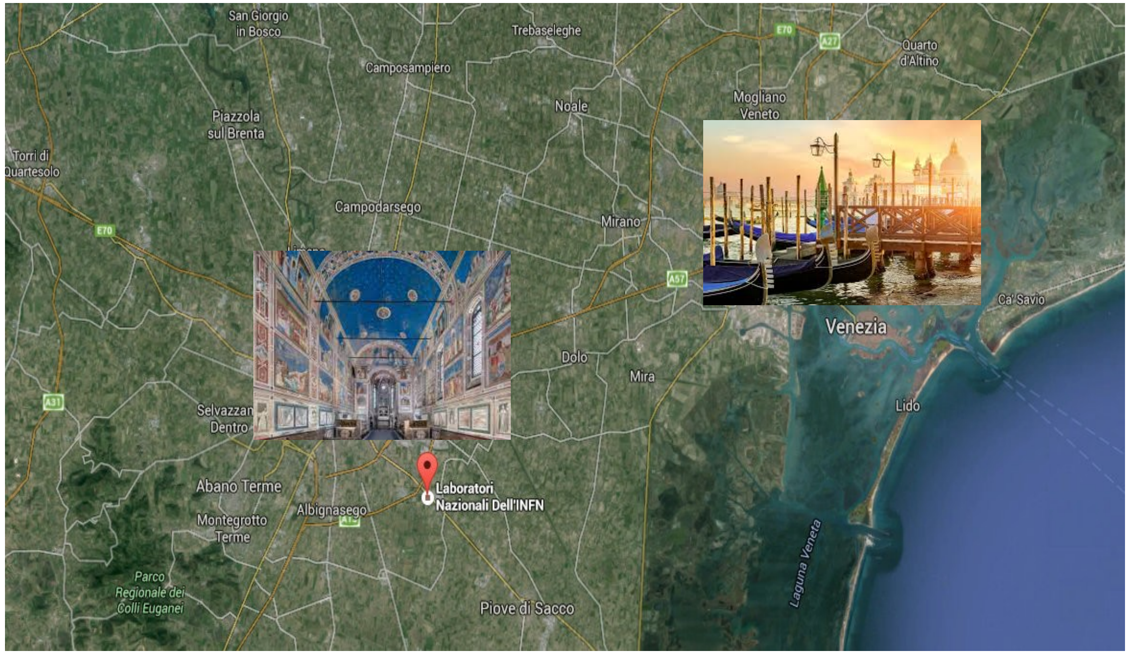
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

1222·2022 800 ANNI

UNIVERSITÀ DEGLI STUDI DI PADOVA

70 1951 2021 infn

15 ottobre 2021
Laboratori Nazionali di Legnaro
LNL
60 anni
tra fisica nucleare e innovazione

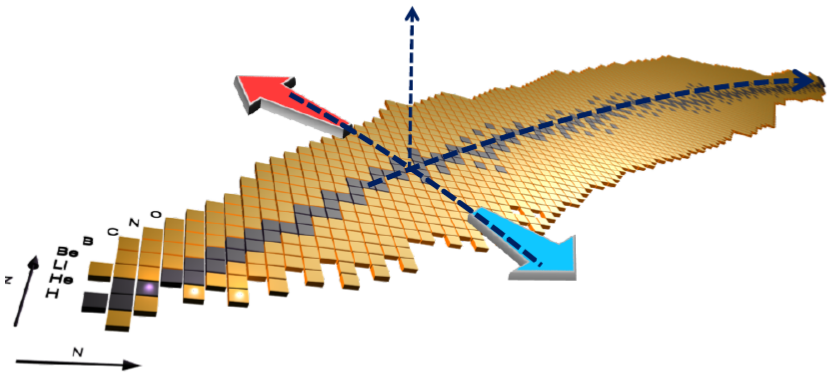


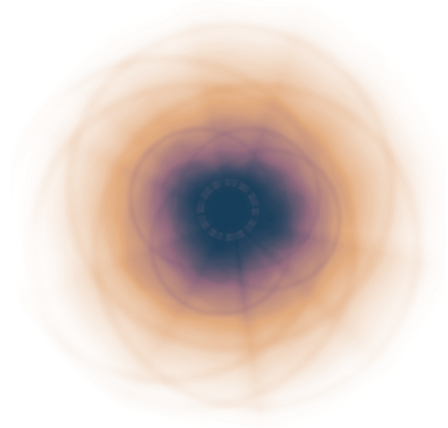
My youth: XIX “ciclo” PHD

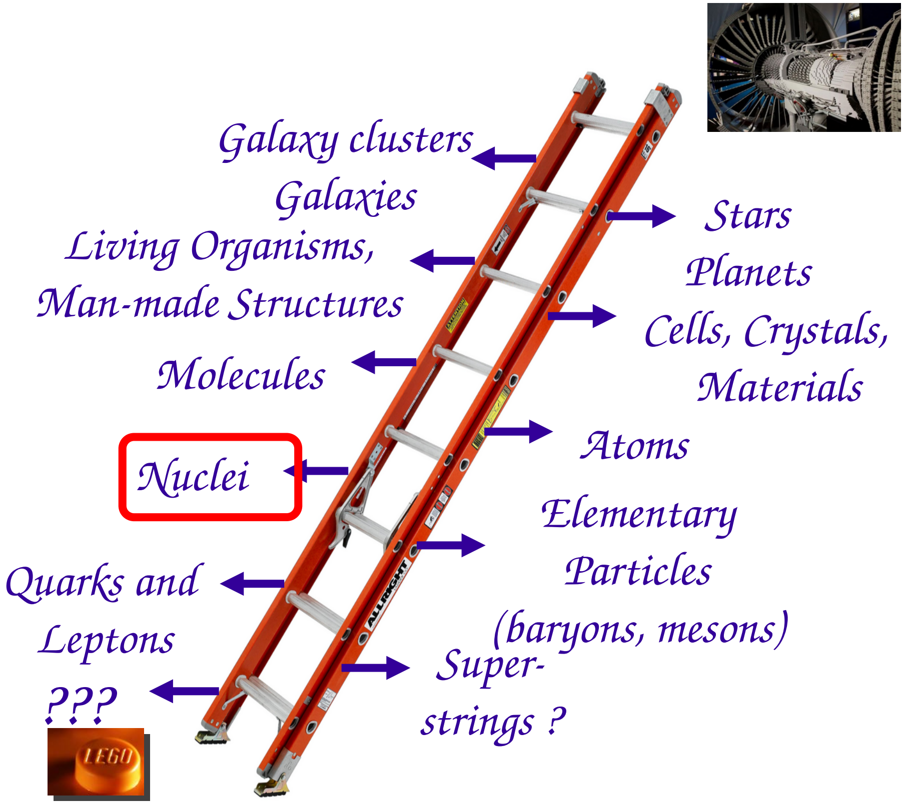
Outlook

- Why Nuclear Structure
- The leap
- Science campaign
- The future

Why NS?



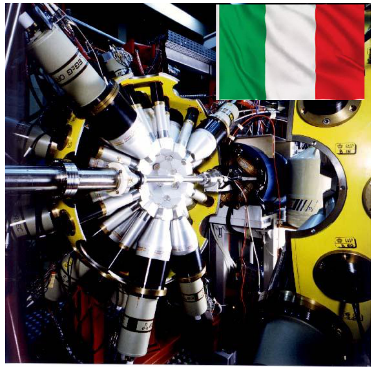




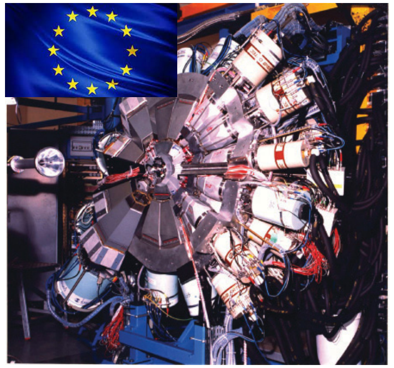
- Complex many-body quantal systems at mesoscopic scale
- Hamiltonian describes systems from few eV to GeV: 9 orders!!!
- Comprehensive theory starting from "first principles"

Credit W.Nazarewicz

Nuclear Structure (t)rail

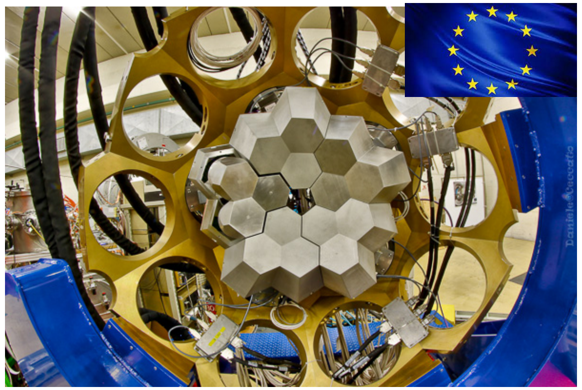


1990s



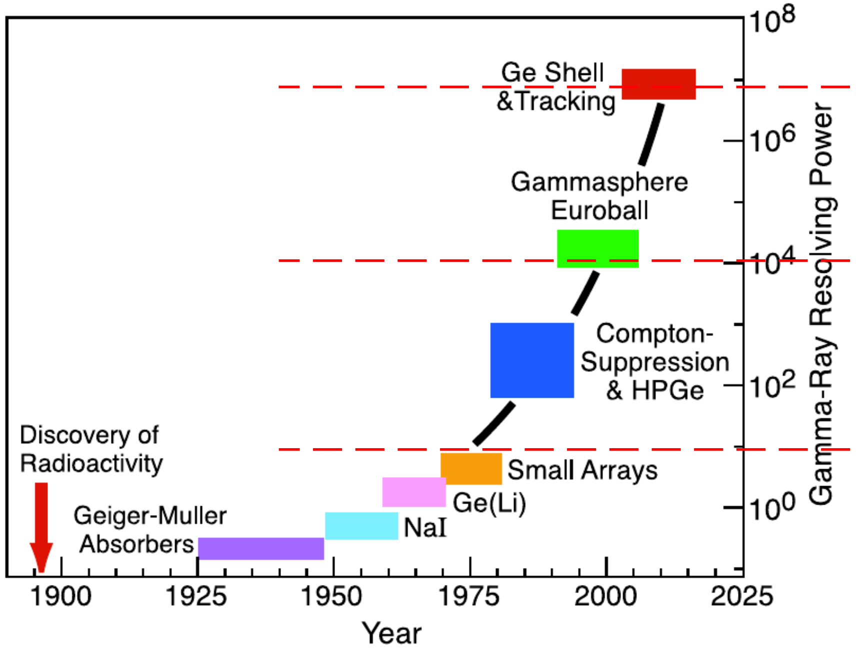
~2000

~2005



2010

Technological leap: γ-ray tracking

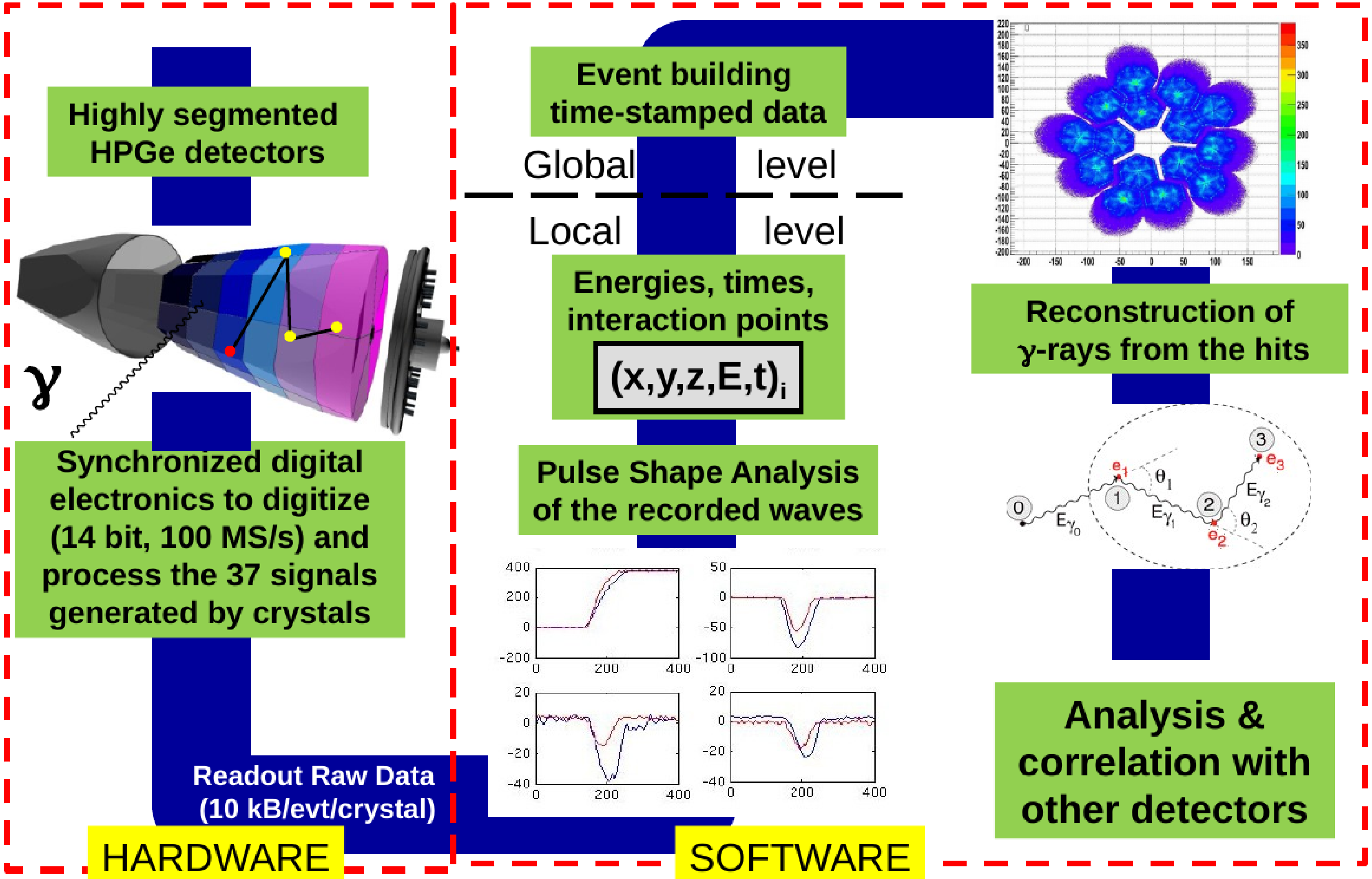


Resolving Power:

- Outstanding sensitivity for lifetime measurement (~Ψ)
- Reduced minimum detectable limit, cross section (~E)

$\Delta E_\gamma \Leftrightarrow \sim\sigma_\theta$ (fast moving ions)

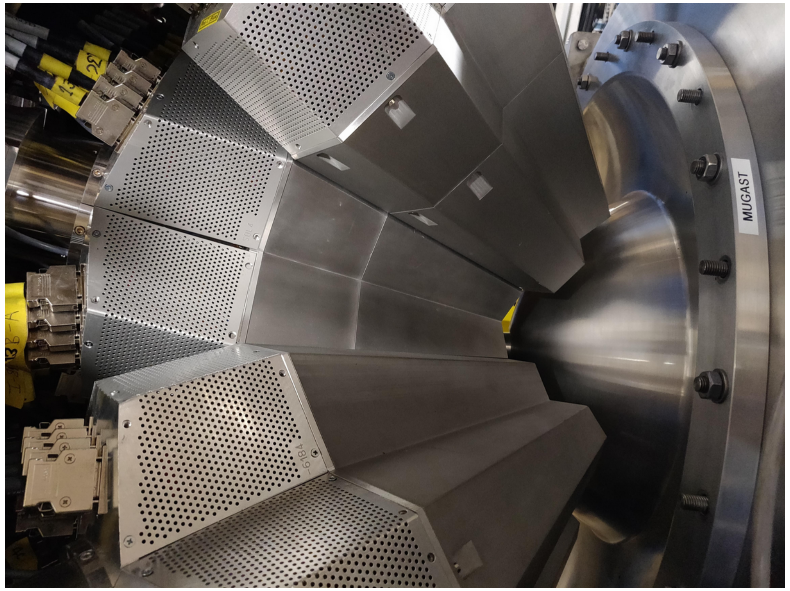
price to pay: complexity and cost

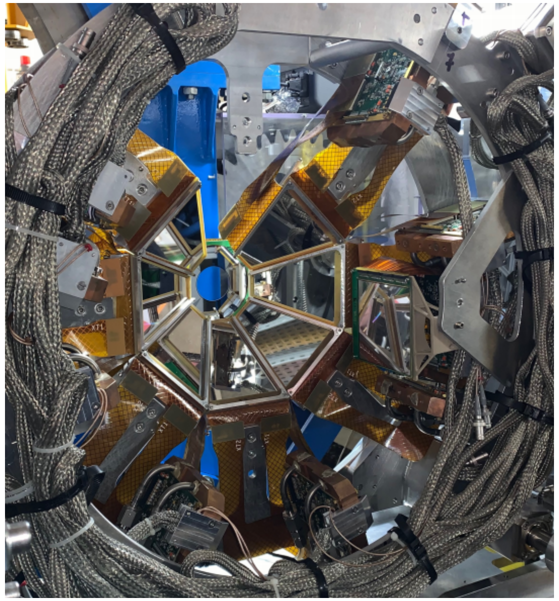


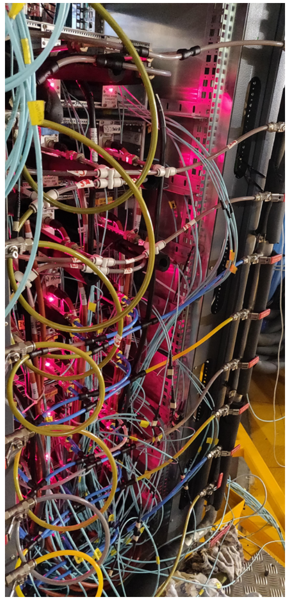
- 6660 high-resolution **digital electronics channels**
- High throughput DAQ / load **computational resources**
- Pulse Shape Analysis → position sensitive operation mode
- γ-ray tracking algorithms → maximum efficiency and P/T

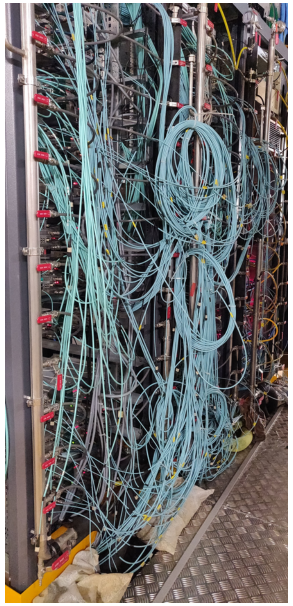
Scientific campaign

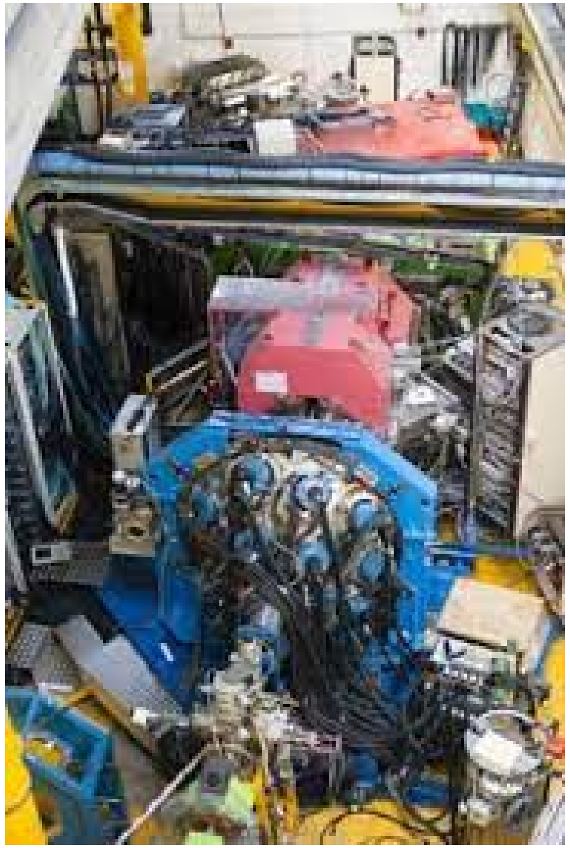
some evidence: highlights of the AGATA+MUGAST+VAMOS campaign









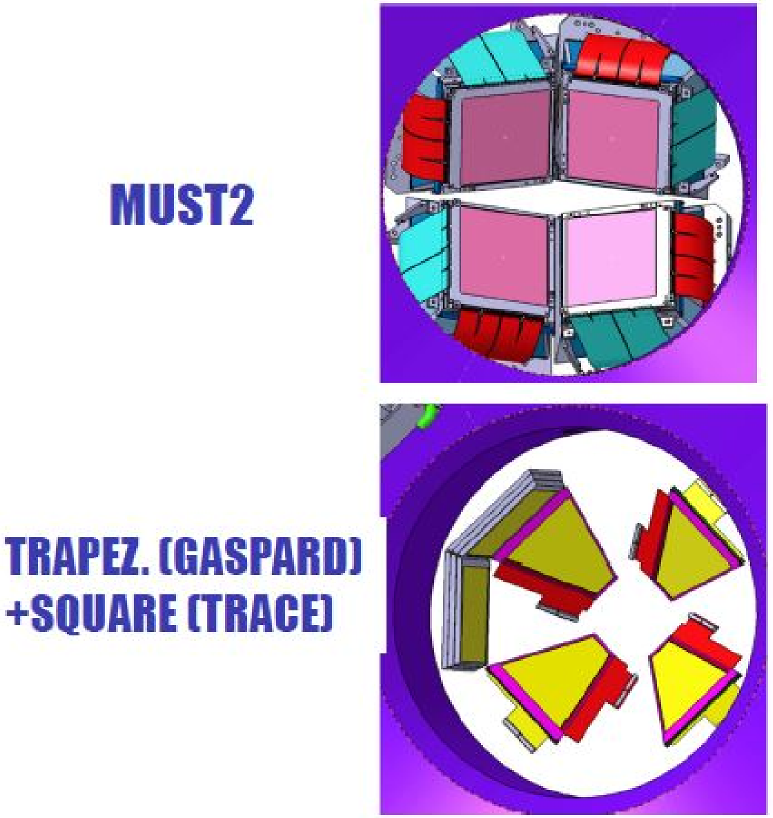


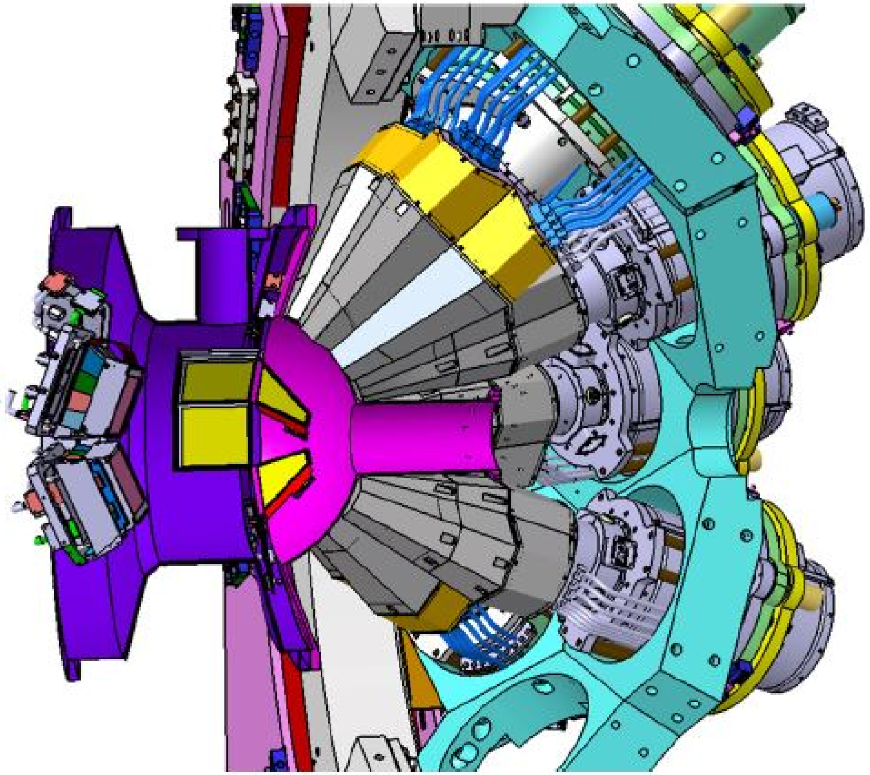
GANIL spiral2
laboratoire commun CEA/DRF CNRS/IN2P3

Once upon a time .... (2015)

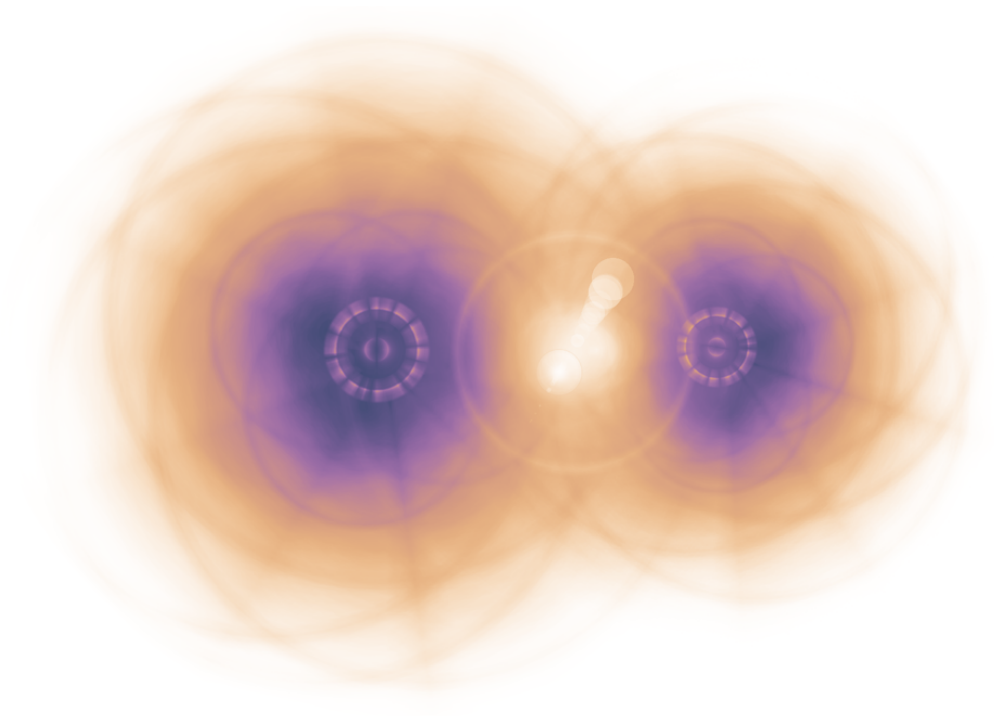
- **New Si DSSD for GASPARD-TRACE**
- **1π AGATA at VAMOS**
- **New spiral1 beams**
- **Cryo target**

First high-resolution direct reaction studies using AGATA and ISOL RIB beams (2019)





Direct reaction with ISOL beam



nuclei A + B at energy E:

- predict initial and all final states
- predict C.S. for each one

- Selectivity :

Memory of initial state: single particle, np-nh, cluster

- Sensitivity:

C.S. carries W.F. information

Specific state structure

Probe $\ll \Delta\Psi \gg$

Credit A.Matta

MUGAST–AGATA-VAMOS set-up @ GANIL with Spiral1 beams

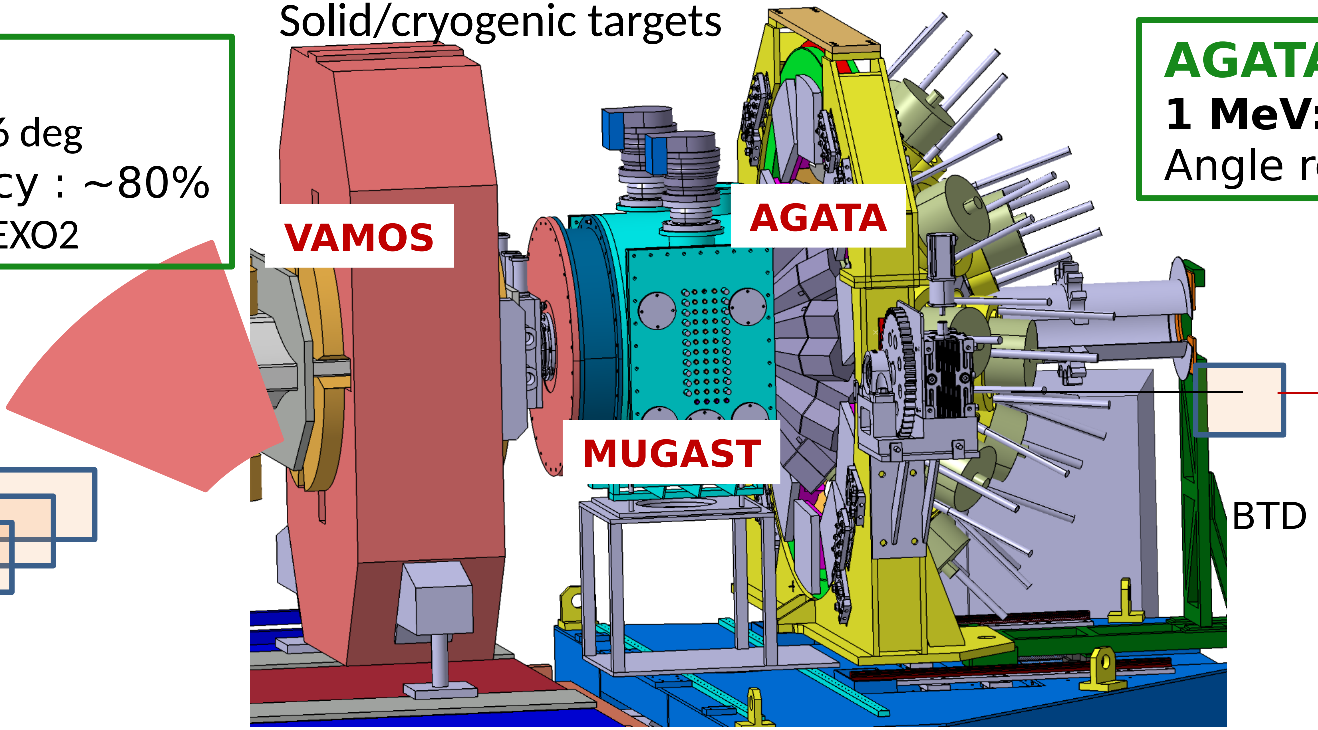
Unmatched worldwide performances and versatility for direct reactions

VAMOS

Acceptance of VAMOS : +/- 6 deg

VAMOS typical efficiency : ~80%

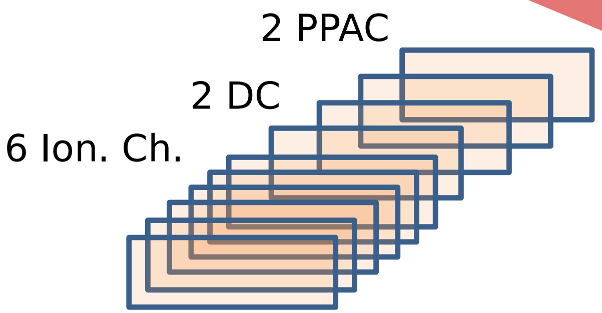
Numerical electronics NUMEXO2

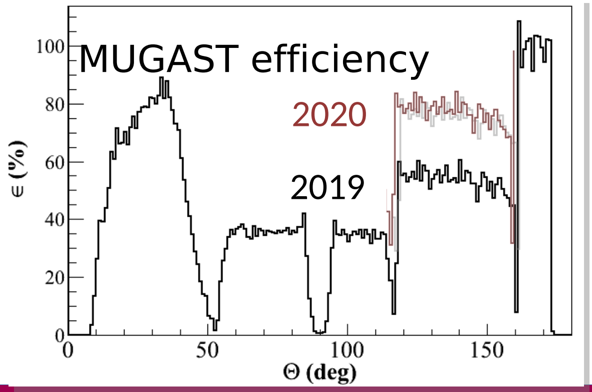


AGATA **efficiency (18cm) at 1 MeV:** 5.5% - ~8% (w add-back)

Angle resolution 1 deg

Spiral1 radioactive beams





MUGAST

Forward : 4 MUST2 (128X+128Y) DSSD 300um + CsI

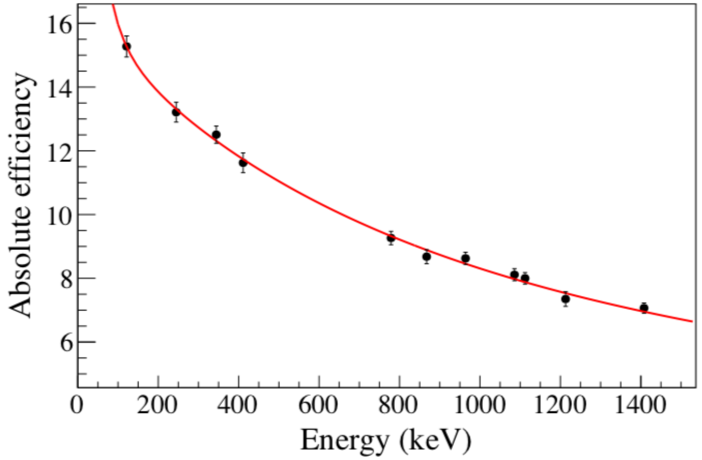
Backward : 5 in 2019 (7 in 2020) trapezoid (128X+128Y) DSSD 500um + Annular (S1)

90 deg : square (128X+128Y) DSSD 500um

Granularity : 0.4 deg

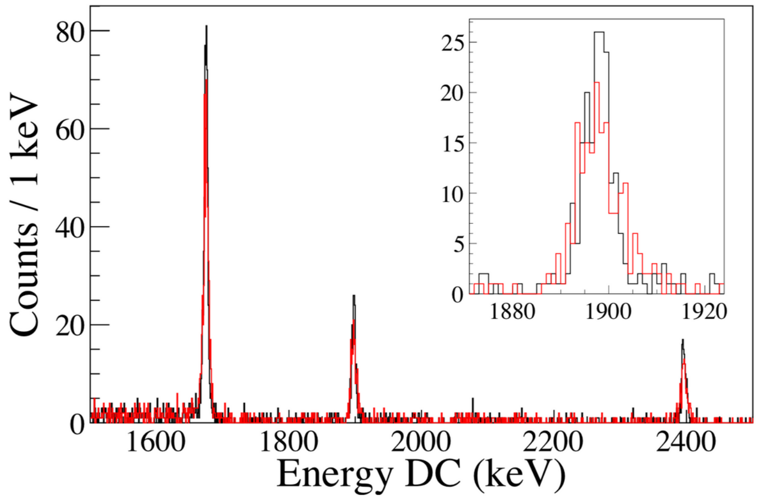
~ 3000 channels all read by MUST2 integrated electronics

Performance set-up



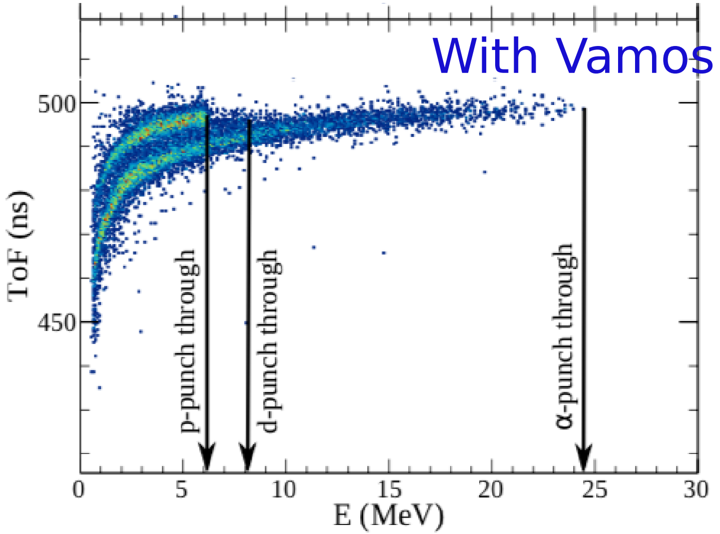
AGATA abs ε_{ph}

- **MUGAST at 18cm**
- **41 operational crystals**



Doppler correction using:

- β beam at mid-target(red, 10 keV FWHM)
- Using light particle info in MUGAST (black, 7 keV FWHM)



- Particle ID with MUGAST-VAMOS

M. Assié et al, NIMA (2021)

AGATA + MUGAST + VAMOS science campaign

2019

UNBOUND STATES
Above barrier narrow resonances in ^{15}F
PhD : V. Alcindor
I. Stefan (IJC lab), F. de Oliveira (GANIL)
$^{14}O(p,p')$ with few 10^5 pps

NUCLEAR ASTROPHYSICS.
Determining the α+^{15}O radiative capture rate
PhD : J. Sanchez Rojo
C. Diget (York), N De Séréville (IJC lab)
$^{15}O(^7Li,t\gamma)^{19}Ne$ with 4. 10^7 pps

SHELL STRUCTURE
Is there a problem with protons in N=28 nucleus ^{46}Ar ?
A. Gottardo INFN, M. Assié IJCLab, D.M. UniPd
PhD : D. Brugnara
$^{46}Ar(^3He,d\gamma)^{47}K$ with 4. 10^4 pps
HeCTOr Target

2020

SHELL STRUCTURE
Lifetime measurements of 2_2^+ and 3_1^+ of ^{20}O by direct nucleon transfer
PhD : I. Zanon
E. Clément (GANIL), A. Goasduf (INFN)
$^{18}O(d,p\gamma)$ + DSAM

SHELL STRUCTURE
Proton-neutron interactions across the N = 28 shell closure via $^{47}K(d,p)^{48}K$
W. Catford (Surrey), A. Matta (LPC)
$^{47}K(d,p\gamma)^{48}K$ neutron transfer

First time:
- α-transfer (stripping) at Ganil
- Lifetime measurement of states populated by transfer
- (^{3}He,d) reaction

With radioactive ion beams

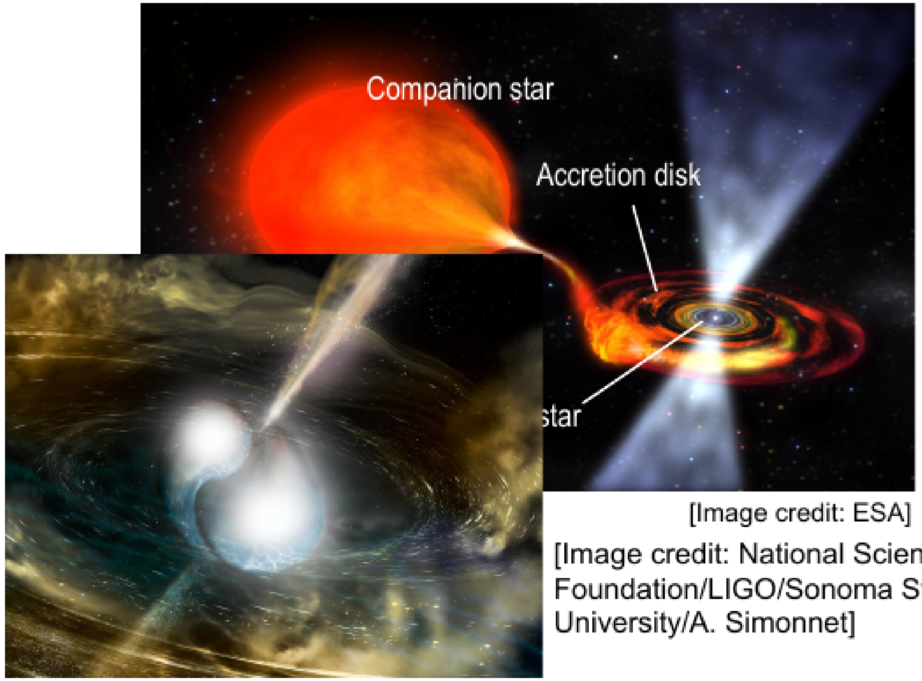
2021

SHELL STRUCTURE
Proton-neutron interactions across the N = 28 shell closure via $^{47}K(d,p)^{48}K$
W. Catford (Surrey), A. Matta (LPC)
$^{47}K(d,p\gamma)^{48}K$ neutron transfer

~~NUCLEAR ASTROPHYSICS~~
~~**Neutron capture at the 85Kr s-process branching**~~
~~*F. Recchia (INFN), S. Palmerini*~~
~~$^{85}Kr(d,p\gamma)^{86}Kr$ with 10^8 pps~~
Approved in 2019, backlog

MUGAST@LISE

Accreting neutron stars & X-ray bursts



[Image credit: ESA]

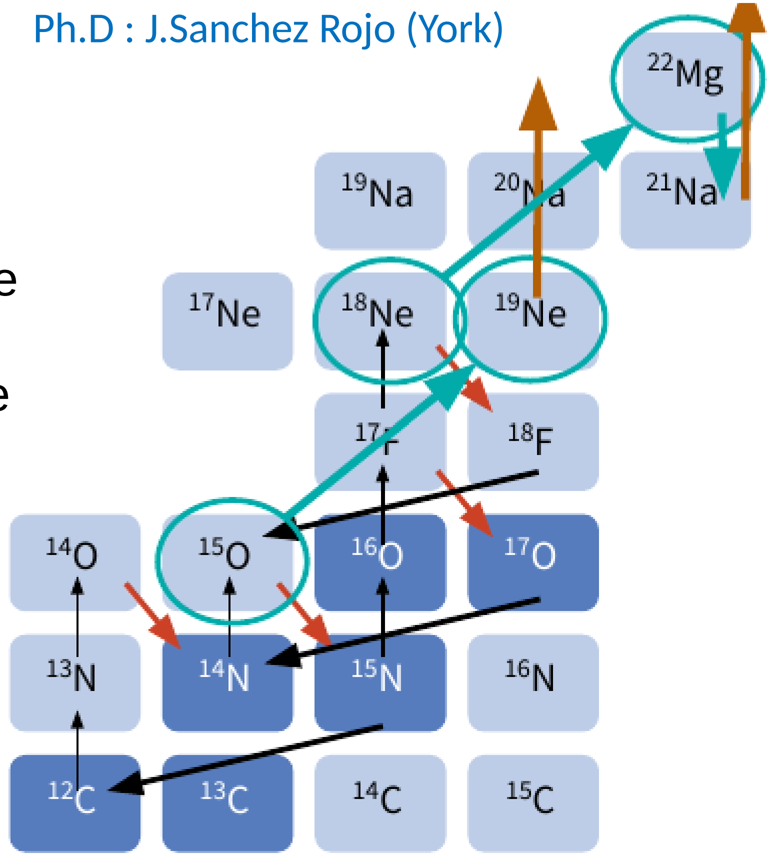
[Image credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet]

- NS accreting matter from companion; Accreted H is burned to He; ignition of Hot-CNO cycle
- Breakout from Neutron star Hot-CNO
- Break out point: $^{15}O(\alpha,\gamma)^{19}Ne$

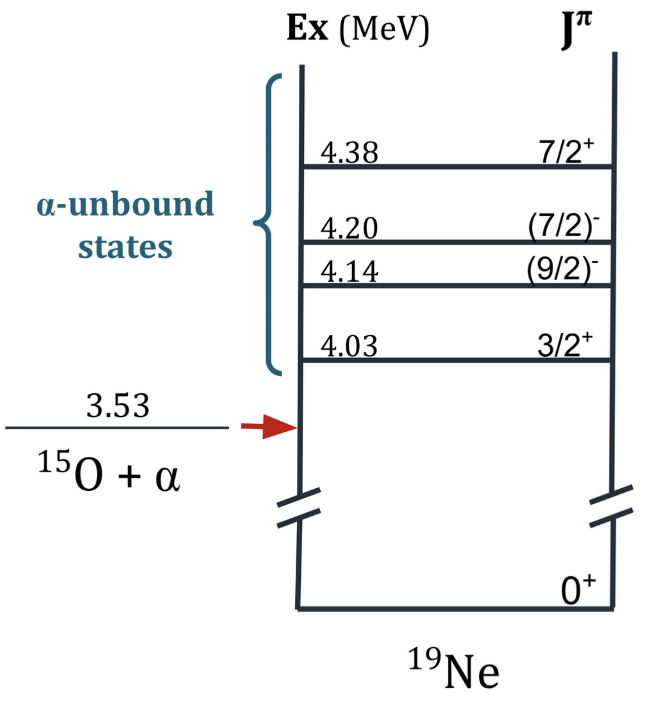
- Tension in former measurements, large uncertainty / inaccuracy
- Challenge of measuring the rate through the 4.033 MeV state in 19Ne
- sensitive determination of the alpha capture rate

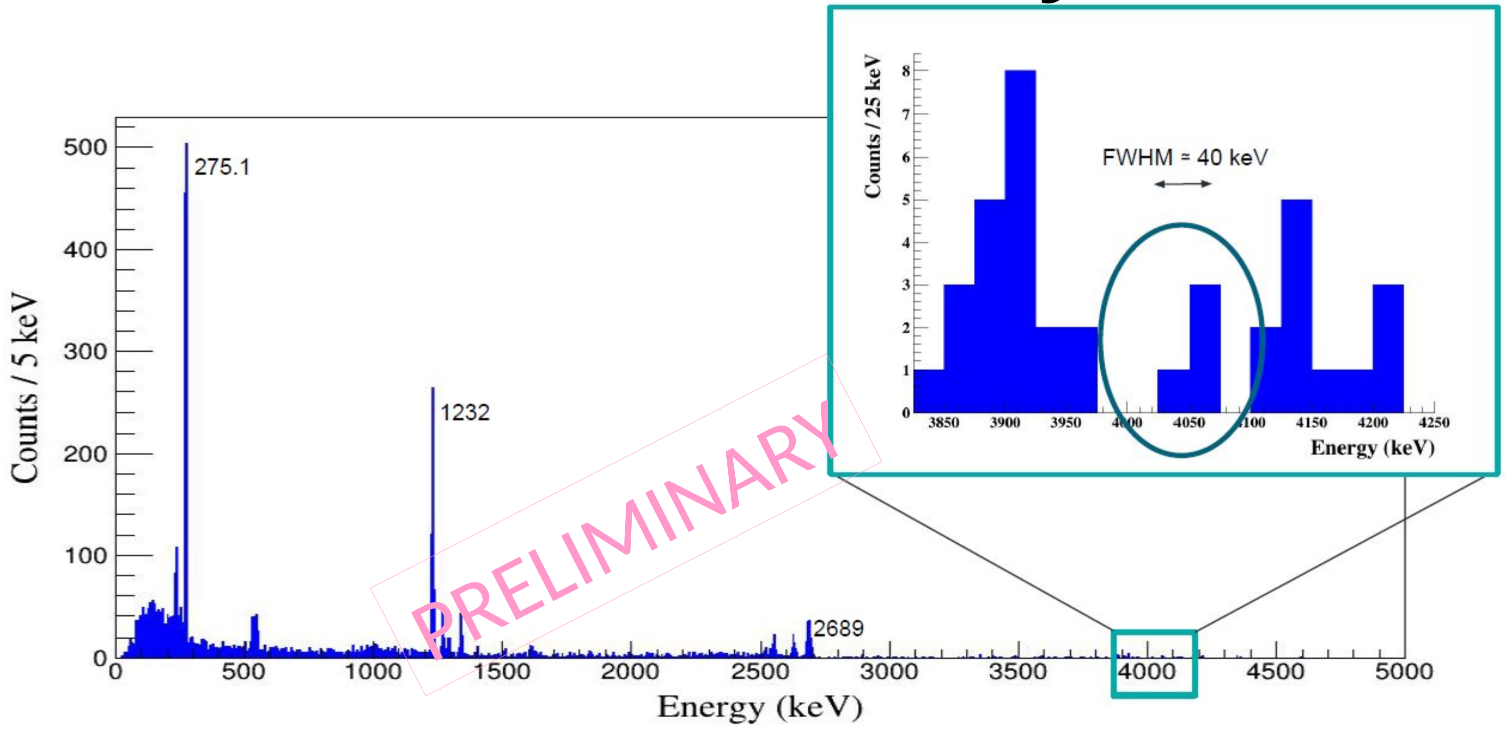
$\boxed{^{15}O(\alpha,\gamma)^{19}Ne \leftarrow {}^{15}O(^{7}Li,t)^{19}Ne}$

Spokespers: C.Diget(York), N.De Séréville(IJCLab)
Ph.D : J.Sanchez Rojo (York)



Pushing the limit of sensitivity





From: J.Sanchez Rojo PhD thesis

- $^{15}O(\alpha,\gamma)^{19}Ne \quad \leftarrow \quad ^{15}O(^{7}Li,t)^{19}Ne$
- Beam rate : ~10^7pps and **triple coincidence (exp no background!)**: γ+t+^{19}Ne
- First position of interaction an add back
- Minimum detection limit: **cross-section few μb/sr** → new and accurate results

PARTIAL WIDTH CALCULATION

- ★ Partial widths and spin-parities determine the reaction rates

$$\Gamma_\alpha = 2P_l(r_c, E_r)\frac{\hbar^2 r_c}{2\mu} C^2 S_\alpha |\phi(r_c)|^2$$

- ★ **New results** for the first 3 resonances

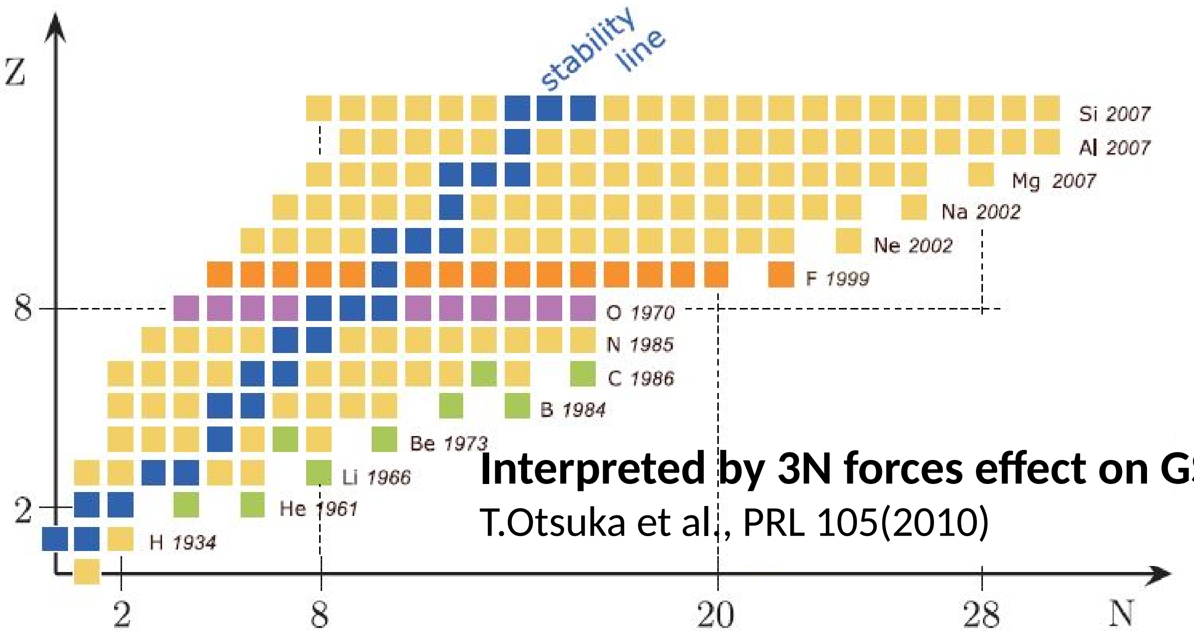
- ★ For the 4033 keV state (1σ C.L.):

$$\Gamma_\alpha = 3.0^{+4.0}_{-2.2}\ \mu\text{eV}$$

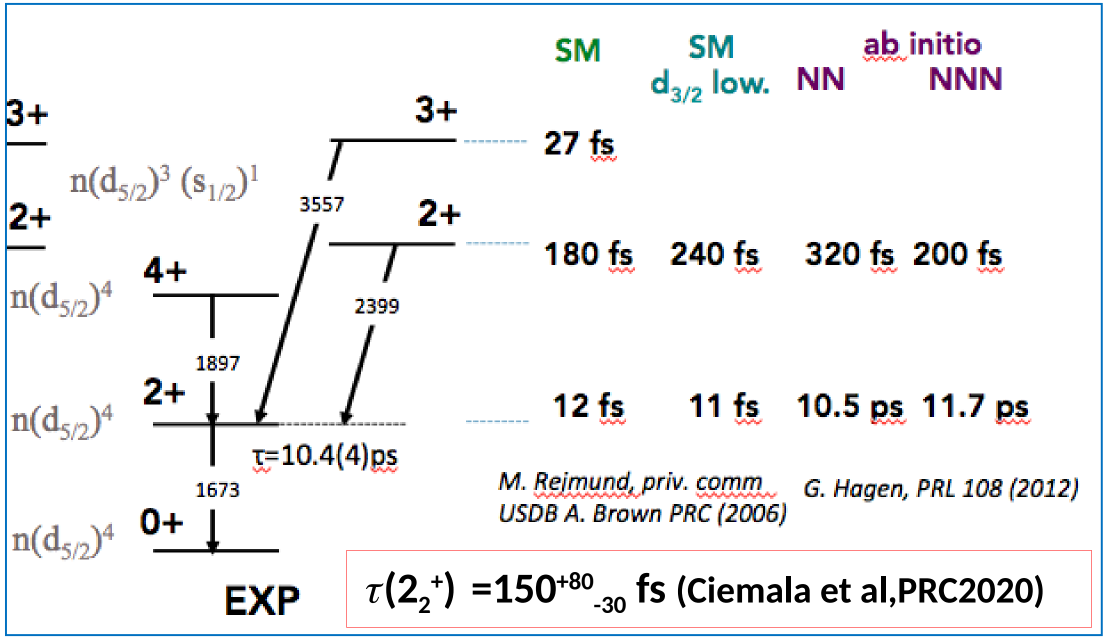
- ★ Reduced by a factor of 6, and below the previous lower (1σ) limit.

E_x (keV)	Γ_α (μeV) This work	[Tan09]	[FLS10]
4033	$3.0^{+4.0}_{-2.2}$	17 ± 13	24(18)
4140	0.28 ± 0.04	44 ± 20	
4197	3.0 ± 0.3	18 ± 9	
4379	128^{+123}_{-68}	160^{+110}_{-70}	150(6)
4600	$3.4^{+4.4}_{-2.2} \cdot 10^3$	$24^{+33}_{-10} \cdot 10^3$	$96(24) \cdot 10^3$

The oxygen anomaly



Interpreted by 3N forces effect on GS energies
T.Otsuka et al., PRL 105(2010)



$\tau(2_2^+)$ $=150^{+80}_{-30}$ **fs (Ciemala et al,PRC2020)**

Lifetime measurements of 2_2^+ and 3_1^+ in ^{20}O by nucleon transfer

^{19}O(d,pγ) + DSAM

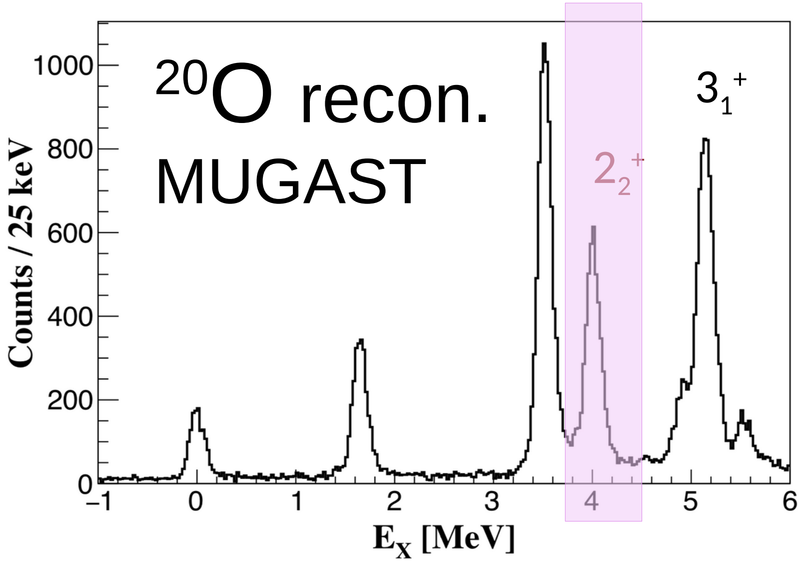
➟ Constrain relative position of s1/2 and d3/2 in n-rich oxygen

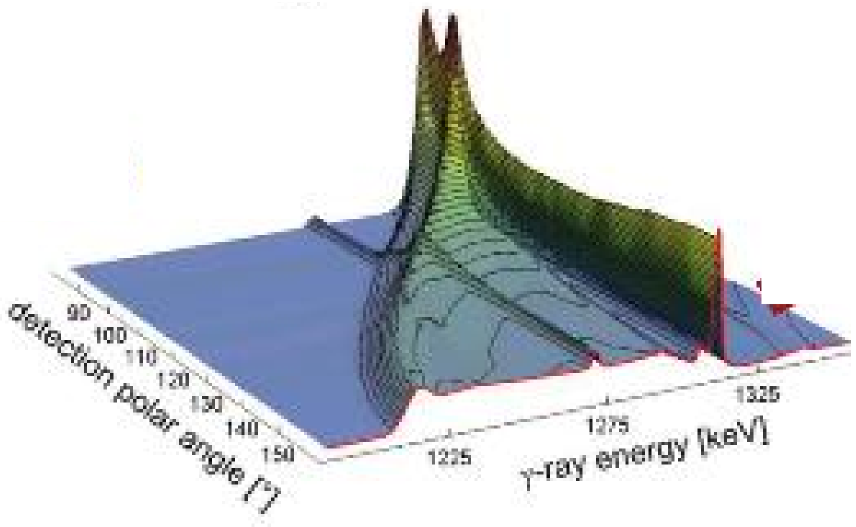
➟ Probe the 3-body interaction

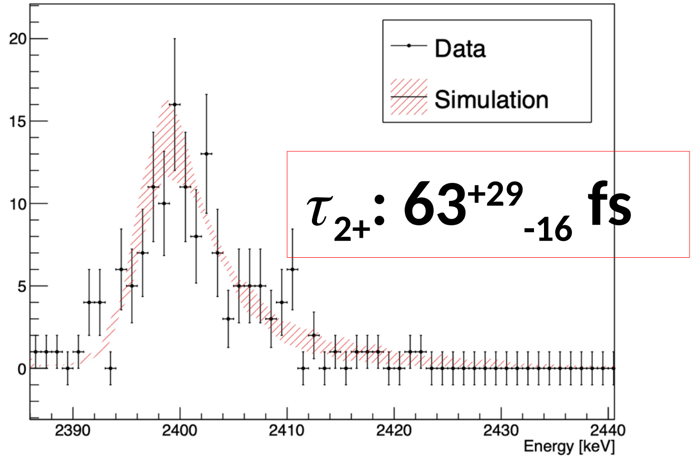
➟ Combination of DSAM + transfer to identify the entrance channel and control the feeding

E. Clément (GANIL), A. Goasduf (INFN)
Ph.D : I.Zanon (Ferrara U.)

Role of 3-body forces



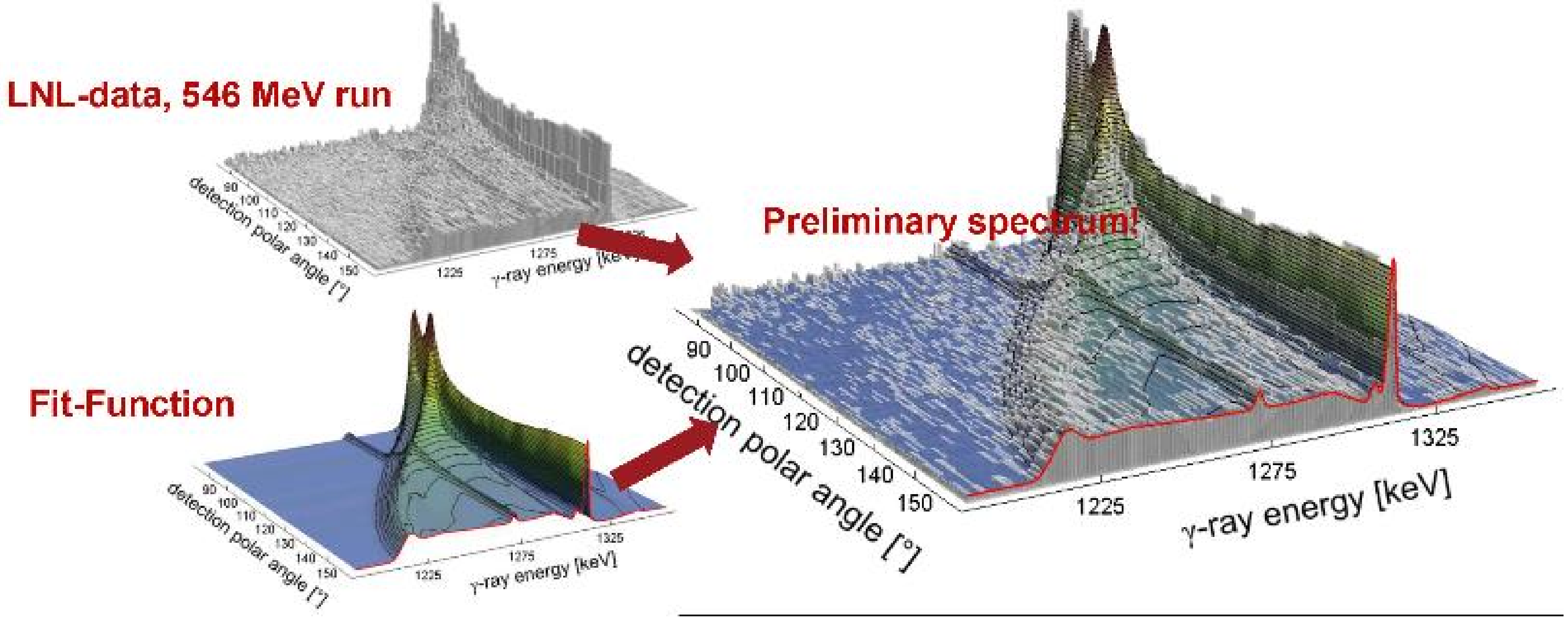




- **Triple coincidences**: reconstructed entry point (MUGAST) through transfer reaction to avoid top feeding + continuous-angle line shape (AGATA)+ channel selection (VAMOS)
- Lifetimes measured significanlty shorter (thanks to **continuous angle resolution**) than predictions for the 2^+, theoretical interpretation ongoing
- First lifetime measurement in the tens of femto-sec. scale (DSAM) using transfer reaction in inverse kinematics

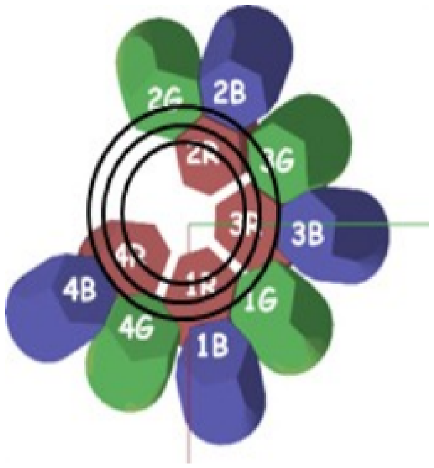
Angle → Doppler Effect → Lifetime

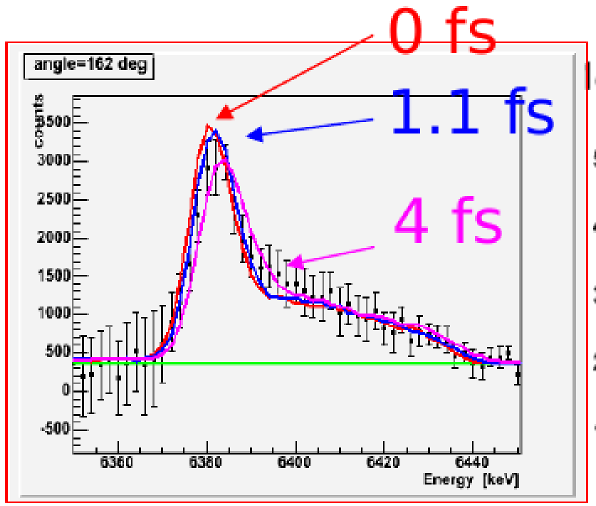
Continuous-angle DSAM represents an advancement of the “conventional” DSAM. It extends the γ-ray lineshapes analysis as a function of γ -ray energy to a lineshape analysis as a function of both γ-ray energy and polar angle of the γ-ray detection.

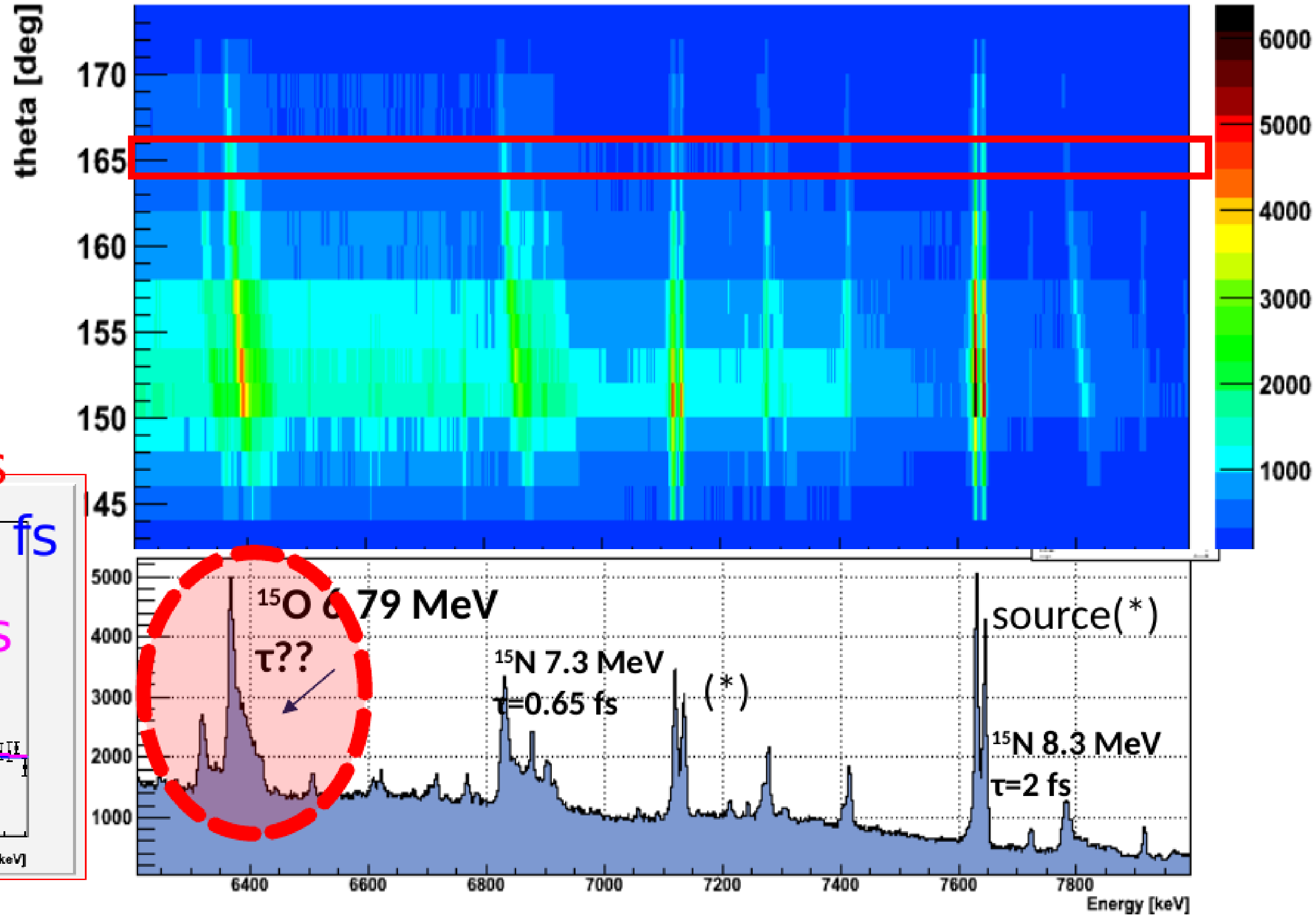


Ch. Stahl et al, CPC 214 (2017) 174

More convincing evidence for the lifetime sensitivity: sub fs !!







^{14}N(^{2}H,n)^{15}O reaction @ 32MeV (XTU LNL Tandem)

Direct lifetime measurement with 4 ATCs at backward angles (close to the beam-line)

Is there a problem with protons in N=28 ^{46}Ar ?

SHELL MODEL

Is there a problem with protons in N=28 nucleus ^{46}Ar ?

A.Gottardo INFN, M. Assié IJCLab)
D.M. (Univ of Padova)
Ph.D : D.Brugnara (Padova U.)

^{46}Ar(^{3}He,dγ)^{47}K proton transfer

GOAL:

Proton shell structure at N=28 :

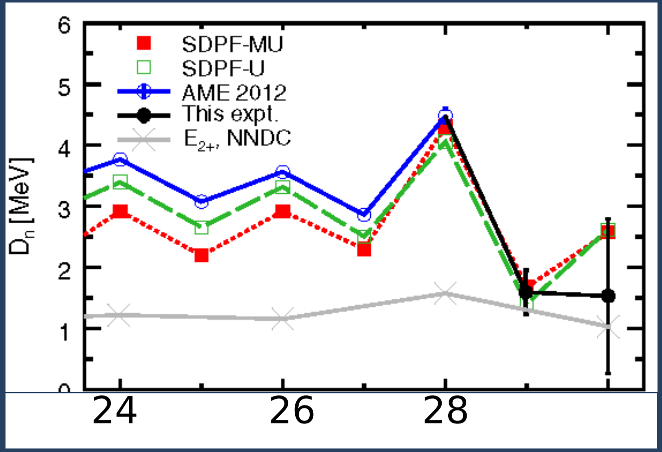
Measuring πs1/2 depletion in ^{46}Ar --> indication on possible change in the $\pi s_{1/2}$-$\pi d_{3/2}$

First experiment with ^{3}He cryogenic target !

- **Theory for neutrons WF :**
  - confirming N=28 shell closure in ^{46}Ar
  - SDPF interaction describes valence-core neutrons interaction very well

Large discrepancy with the measured B(E2) value at N=28: problem with the proton E2 contribution ?

Z. Meisel . PRL 114, (2015)



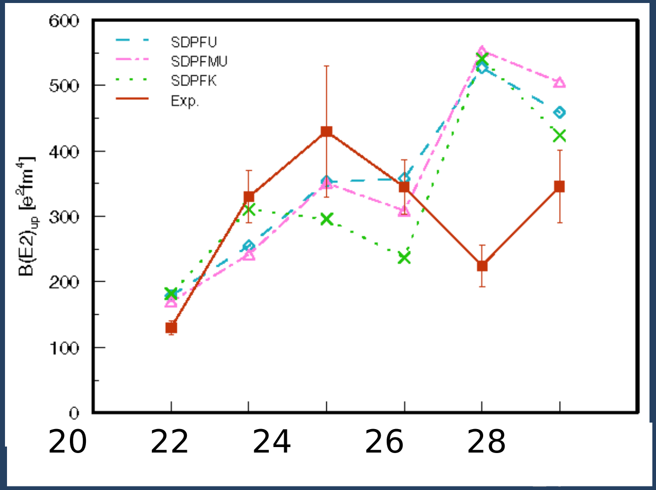
- **Proton shell structure at N=28 :**

inversion of $\pi s_{1/2}$ and $\pi d_{3/2}$

Measuring πs1/2 depletion in ^{46}Ar
--> indication on possible change in the π s1/2- π d3/2 positions

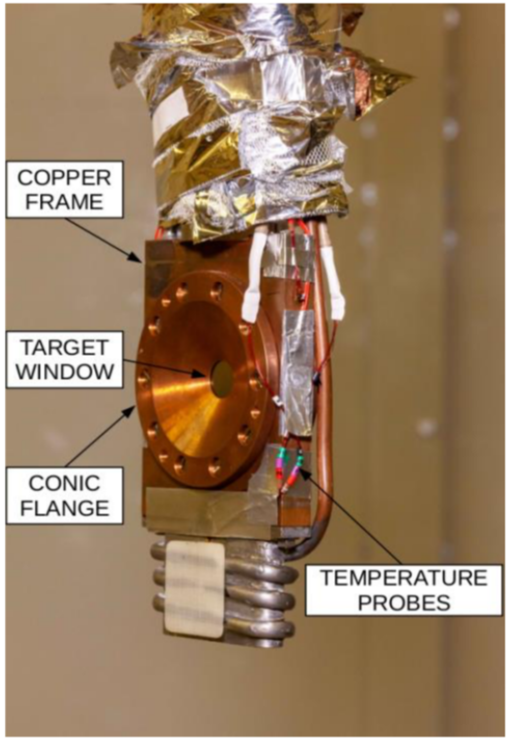
Central density depletion linked to spin-orbit splitting reduction

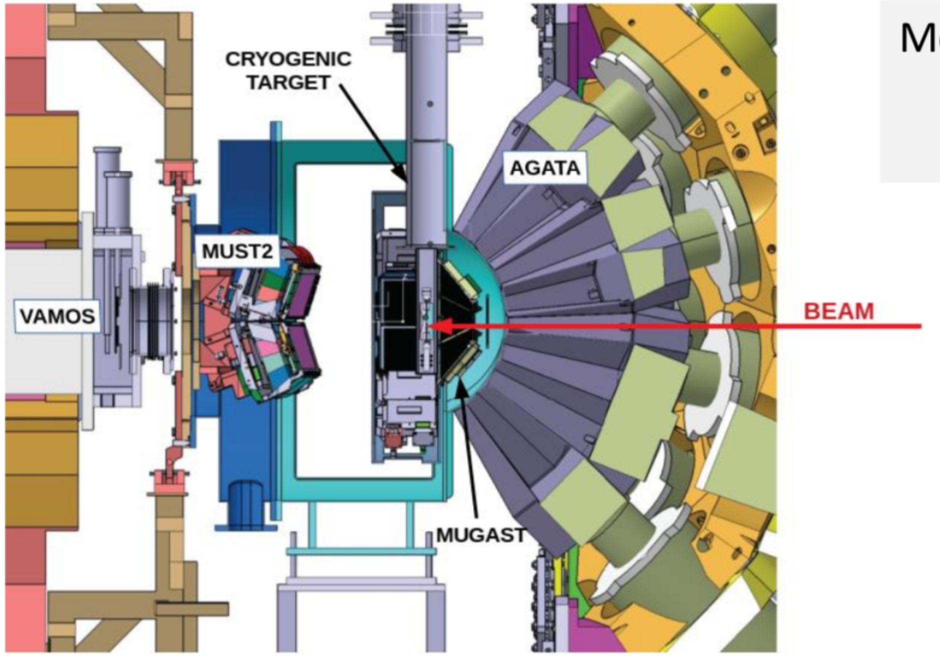
A. Gade et al., PRC 68, (2003)
S. Calinescu et al., PRC 93, (2016)



The HEcTOR cryogenic ^{3}He target

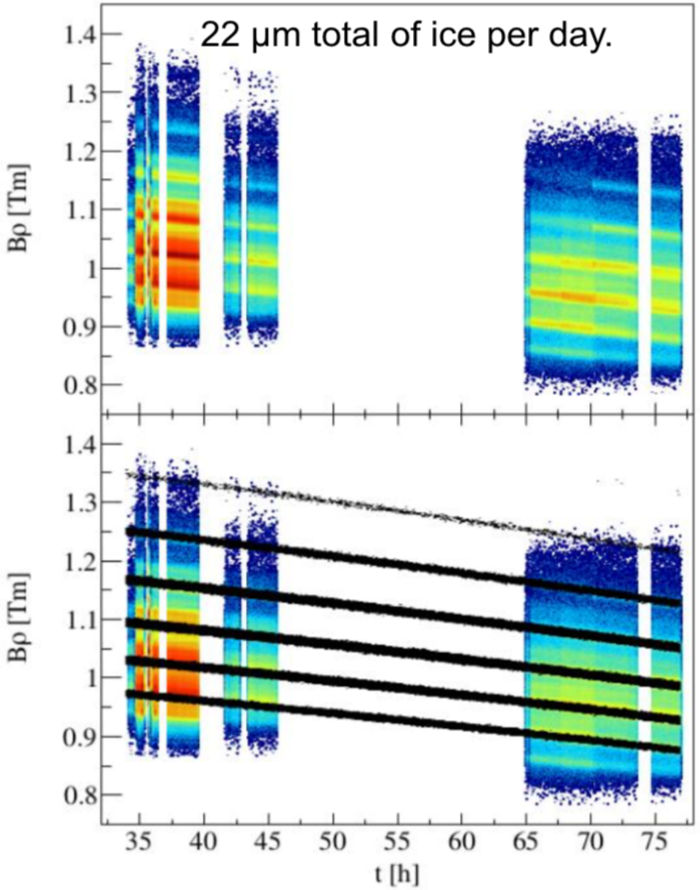
F. Galtarossa et al, NIMA (2021)



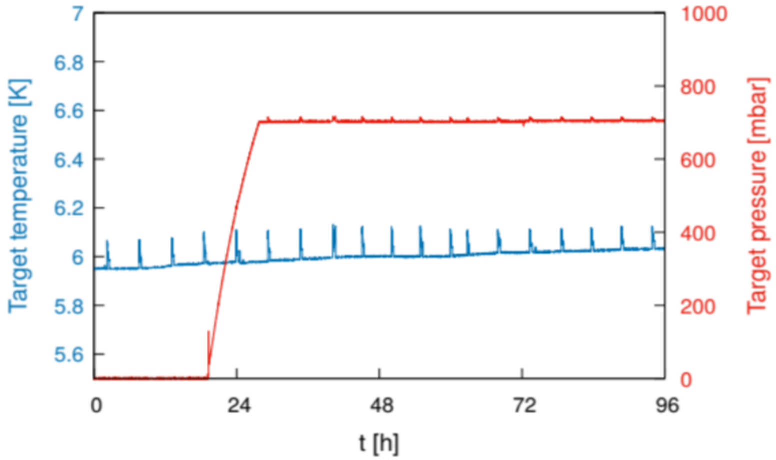


Monitoring of target with VAMOS :

- Target pressure & temperature stable
- Ice formation on the target with time

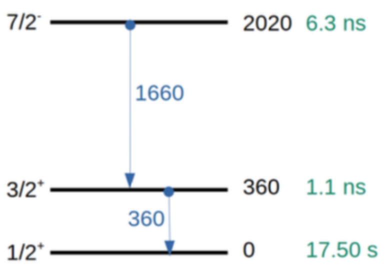


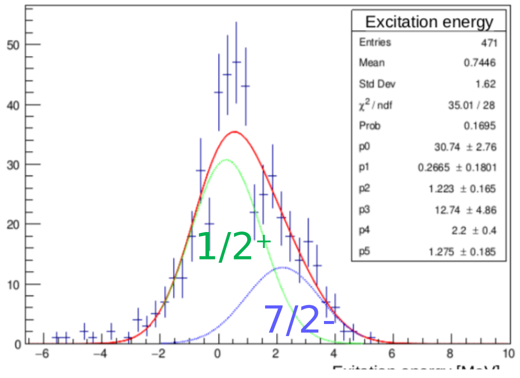
- Ø 16 mm
- Opening angle: 130 deg.
- Havar windows: 3.8um
- T ~ 6-7 K. / P up to 1 bar
- Equivalent thickness 2 mg/cm^2
- ^{3}He recycling
- LHe open circuit



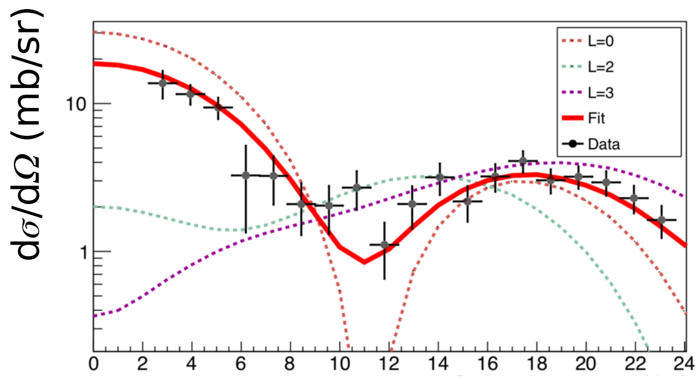
M. Pierens, V. Delpech,
F. Galet, H. Saugnac (IJCLab)
A. Giret & J. Goupil (GANIL)

Is there a problem with protons in N=28 ^{46}Ar ?

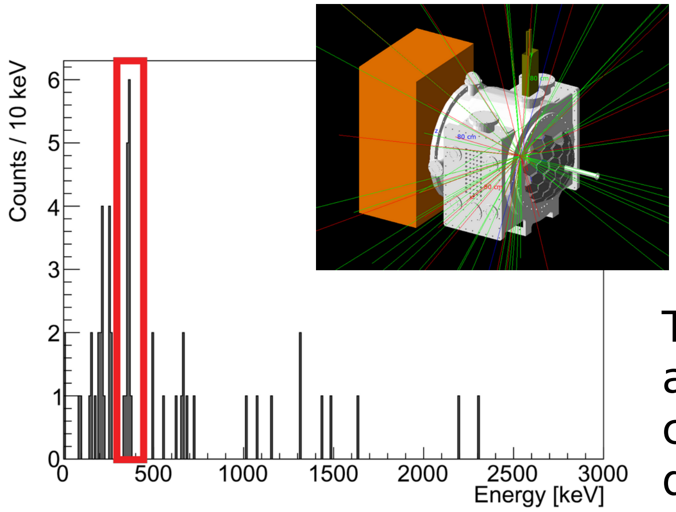




Excitation Energy (MeV)

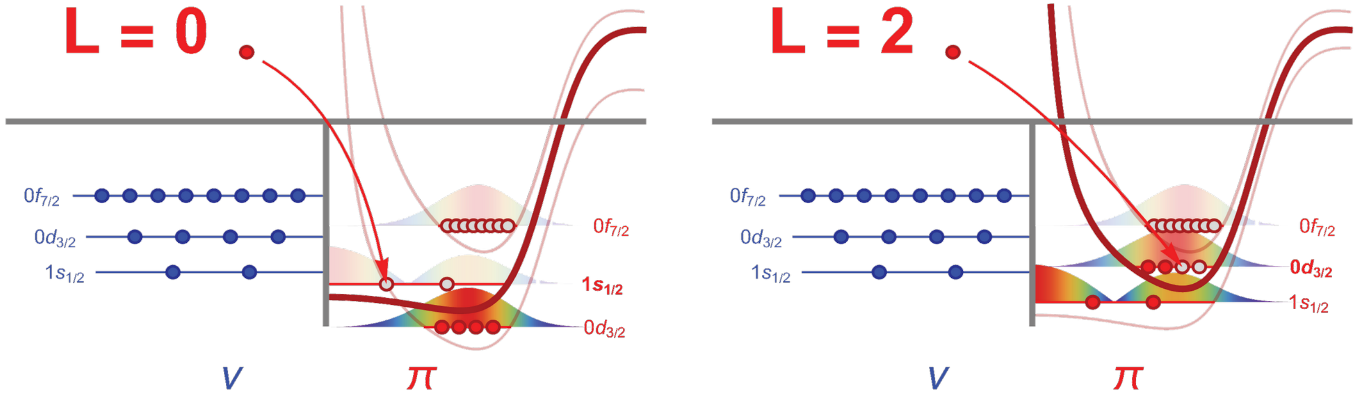


angle CM (deg)



^{47}K

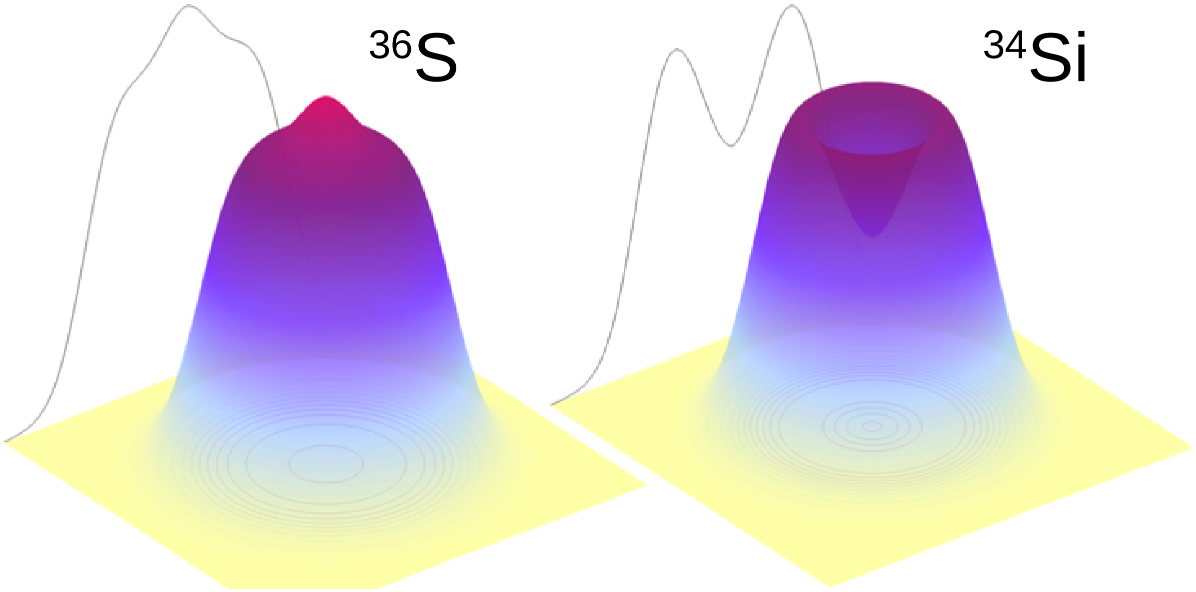
Triple coinc and simulation confirm the L=0 dominance



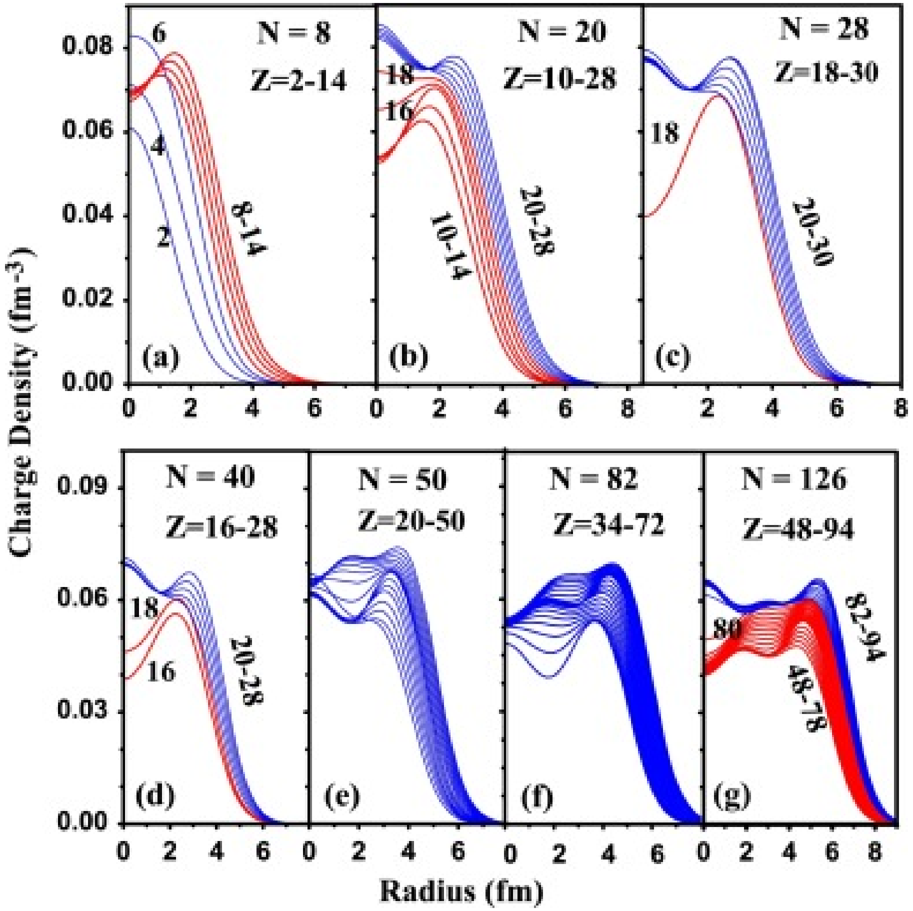
- L=2 transfer very much reduced !
- No direct gamma from 3/2$^+$ observed from AGATA+VAMOS
- Reduced transfer to 3/2$^+$
- High degree of occupancy of πd3/2 in ^{46}Ar inconsistent with SM calculations

Bubble inside

nature physics 13, pages 152 (2017)



The calculated proton density for silicon-34 (right) and, for comparison, sulfur-36 (left), as a function of the distance from the center of the nucleus. At its center, silicon-34 has about half the proton density of a comparable nucleus.



Relativistic mean field calculations

The Future


Eur. Phys. J. A (2020) 56:137
https://doi.org/10.1140/epja/s10050-020-00132-w
THE EUROPEAN PHYSICAL JOURNAL A

Review

Physics opportunities with the Advanced Gamma Tracking Array: AGATA

W. Korten[9,a], A. Atac[30,35], D. Beaumel[23], P. Bednarczyk[14], M. A. Bentley[34], G. Benzoni[21], A. Boston[17],

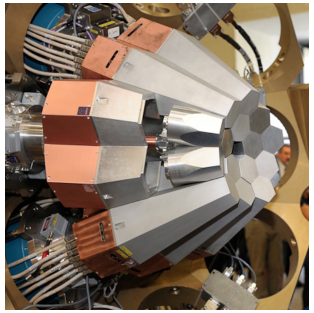
AGATA@LNL

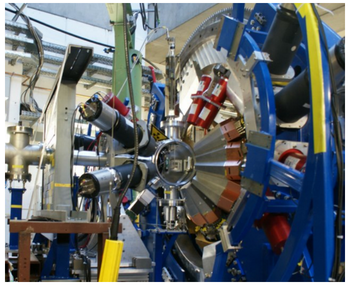
AGATA@LNL

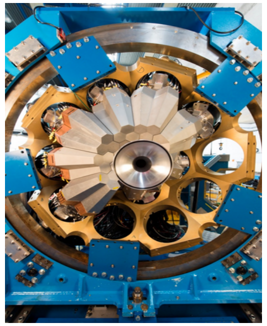
AGATA@GSI

AGATA@GANIL

- We close a circle after a ~10y journey of the array at the main European facilities
- This deserved a celebration..







F A I R

M. Zielinska physics coordinator

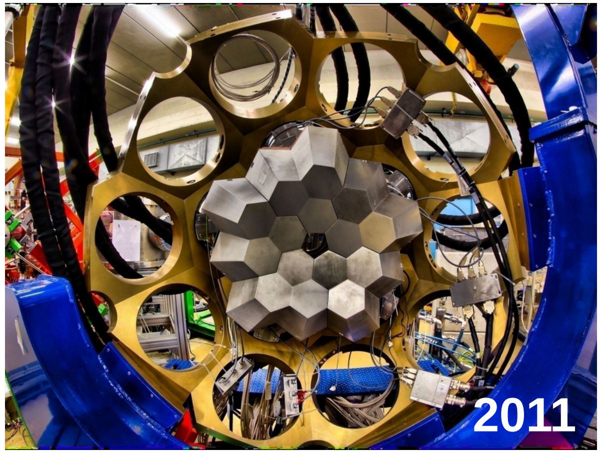
2009 → 2011 → 2014 → 2021

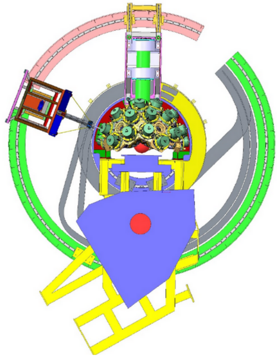
Phase 1

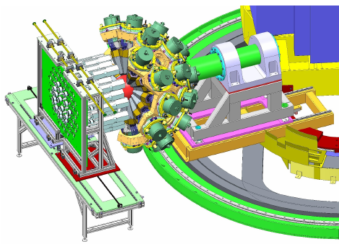
Phase 2


AGATA
10
+2
2022
CELEBRATION FOR THE 10(+2) YEARS
OF SCIENCE ACTIVITIES OF AGATA

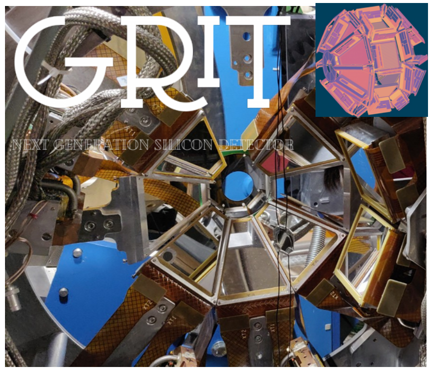
The parcel







- Proton drip line: around ^{100}Sn using
- **intense stable beams** and AGATA+NEDA+EUCLIDES
- Neutron drip line: around ^{132}Sn with
- **SPES** beam and AGATA+GRIT+PARIS



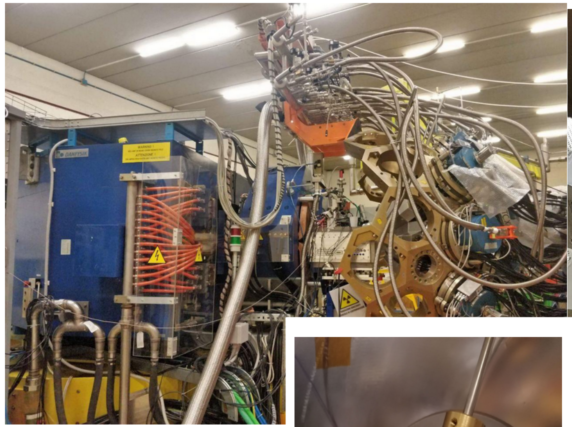
From ground breaking to first commissioning 1 (26/4-3/5, 2022)

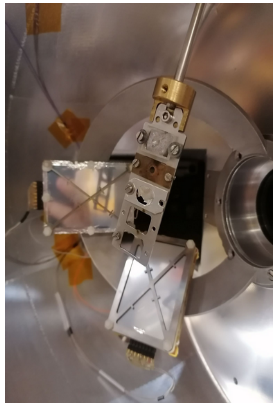
PRISMA setting
^{58}Ni @250MeV + ^{197}Au @ 0.2 mg/cm^2

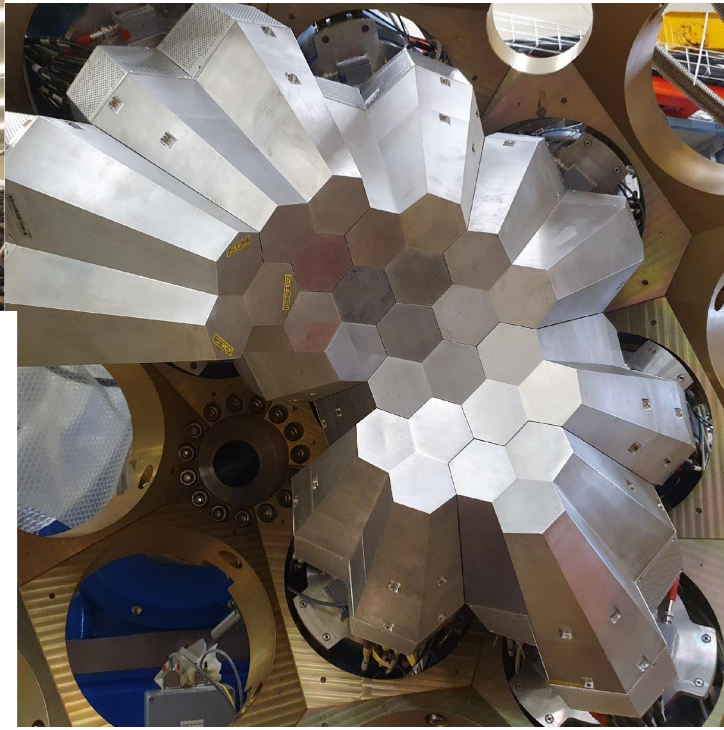
Multi-nucleon transfer
^{32}S @160MeV + ^{124}Sn @ 0.5 mg/cm^2
2.5 mg/cm^2

- Spokespersons: F. Crespi, F. Galtarossa, J. Pellumaj, M. Rocchini, M. Sedlak

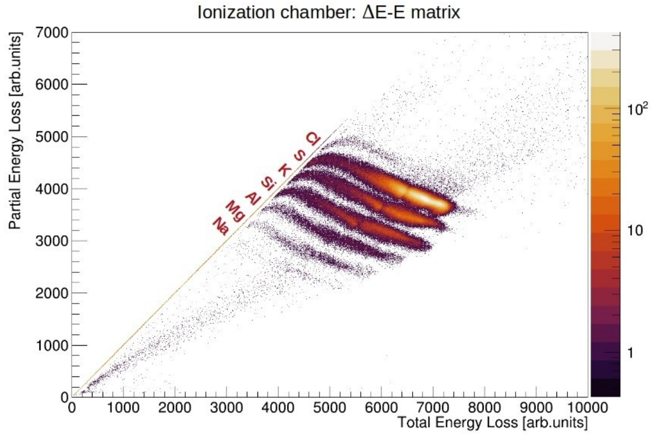
Ground breaking 10/3/2021

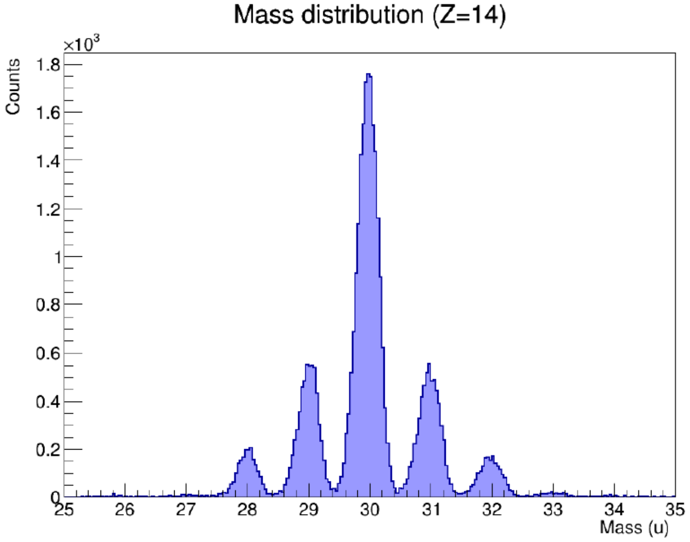


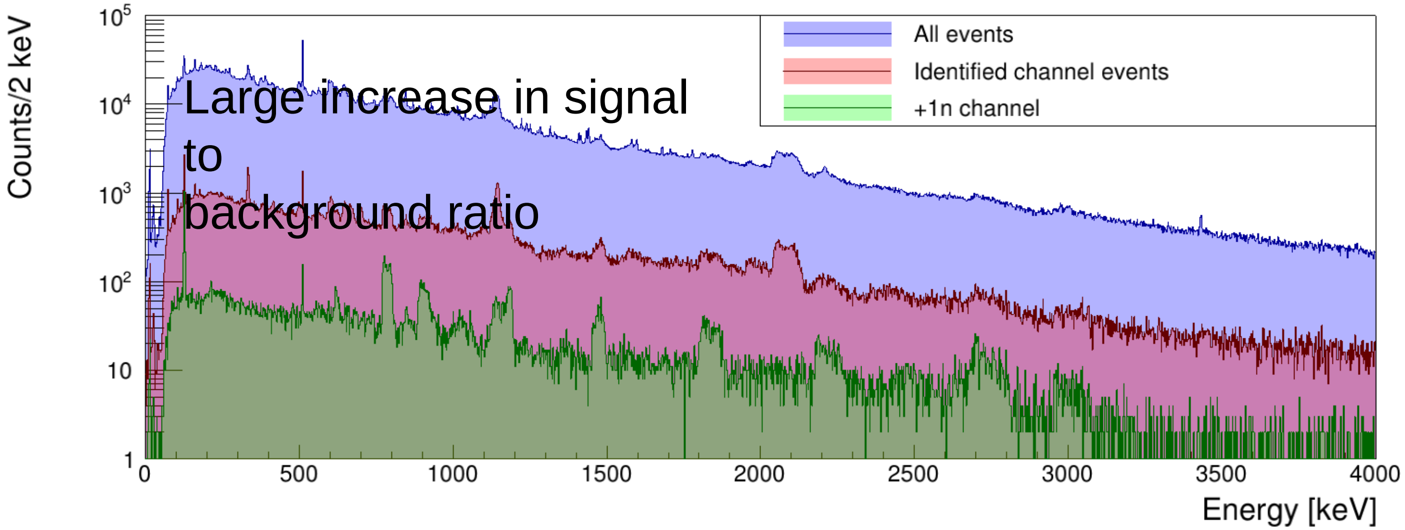


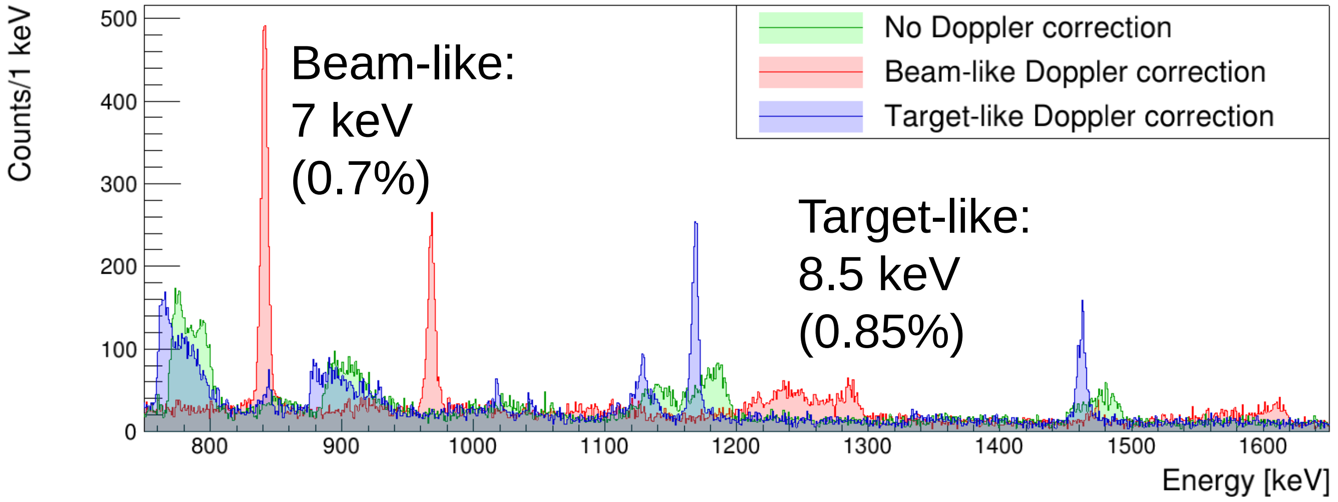


Commissioning: preliminary results





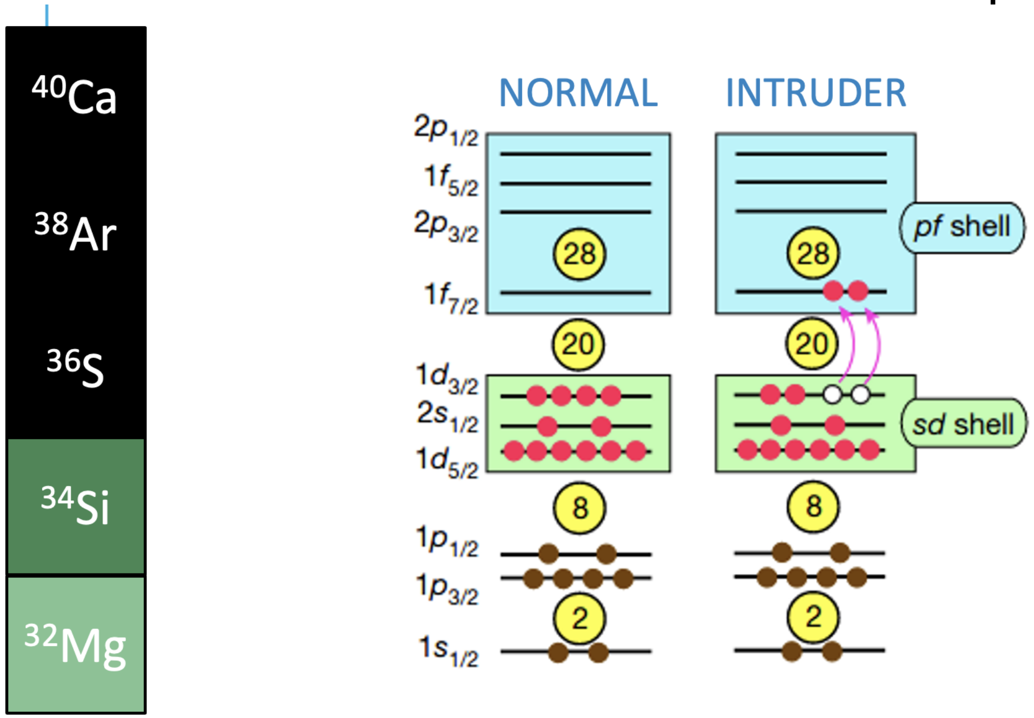




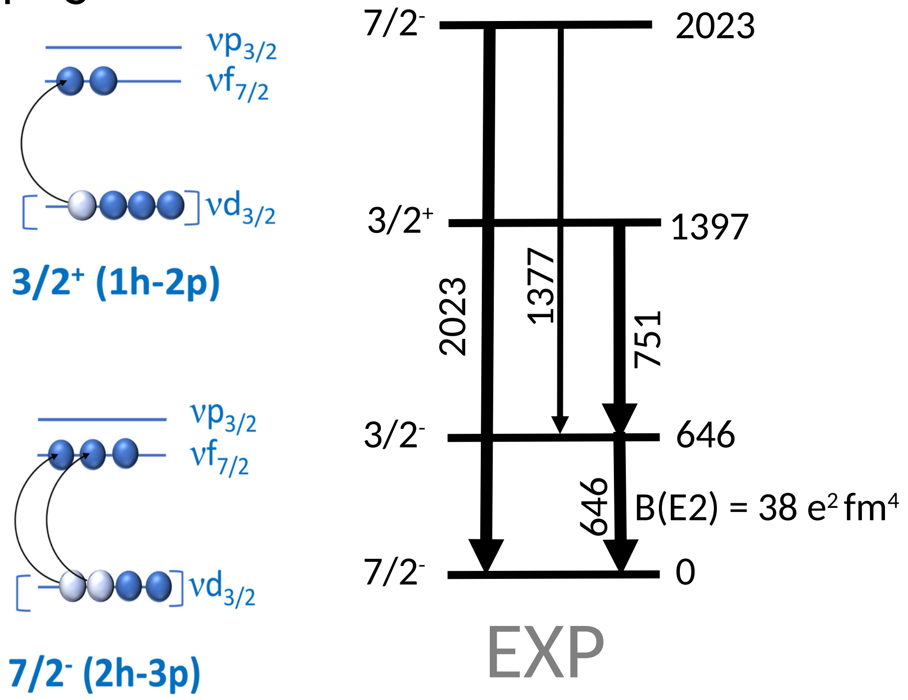
First experiment: intruder states in ^{37}S

- Spokepersons: F. Galtarossa and A. Gottardo/ PhD thesis L. Zago
- One n transfer reaction to spot the mixing between normal and intruder configuration
- Low-lying states can not be explained as single-particle fragment: *intruder* configuration from the N=20 core breaking?

Shell Model predictions for ^{37}S



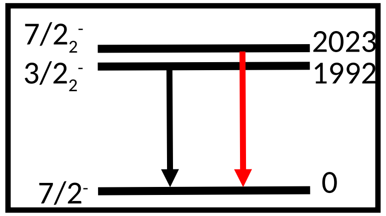
E. Caurier, F. Nowacki, and A. Poves, Phys. Rev. C **90** (2014) 014302

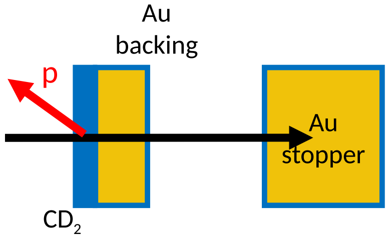


E. K. Warburton, Phys. Rev. C **35** (1987) 2278; Phys. Rev. C **37** (1988) 754

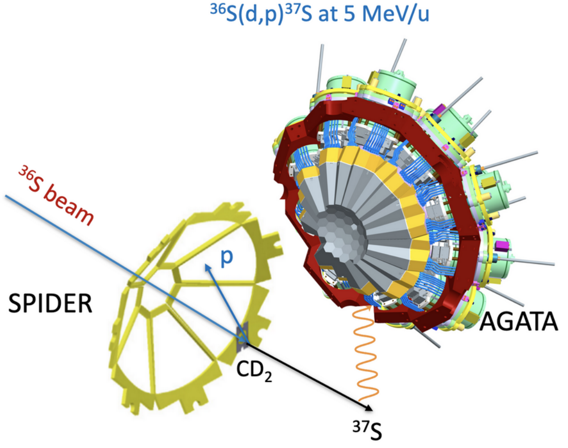
R. Chapman et al., Phys. Rev. C **93** (2016) 044318

Simulations for $^{36}S(d,p)^{37}S$ (N=21)

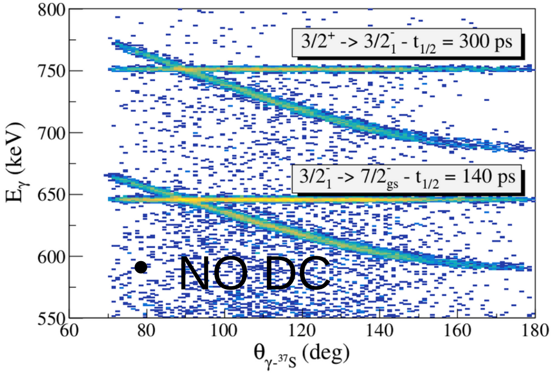




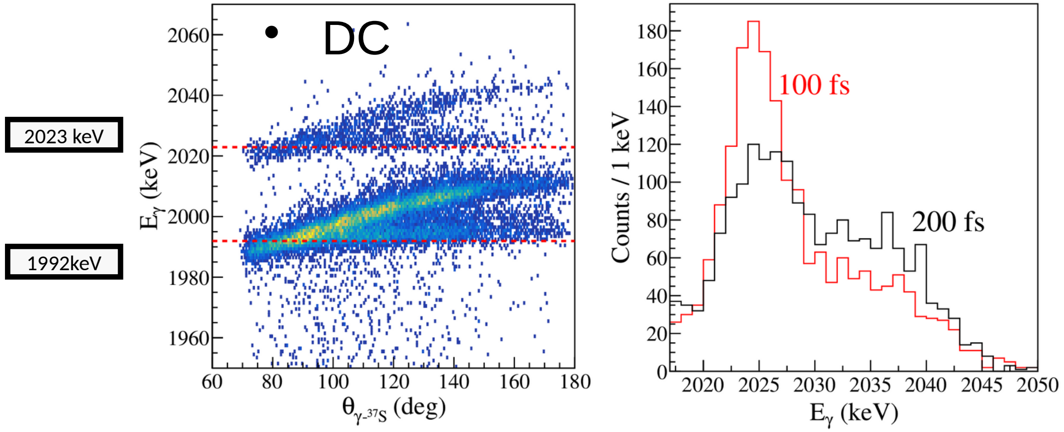
- The lifetime of the $3/2^+$ level is expected to be in the range **10-500 ps** -> PLUNGER;
- lifetime of the $7/2_2^-$ level is expected to be in the range **50-500 fs** -> DSAM
- ^{36}S beam provided by the TANDEM accelerator at **180 MeV** and **0.1 pnA** (~ 5×10^8 pps);
- CD_2 target of **0.5 mg/cm²** (~ 5×10^{19} atoms/cm² of ^2H);



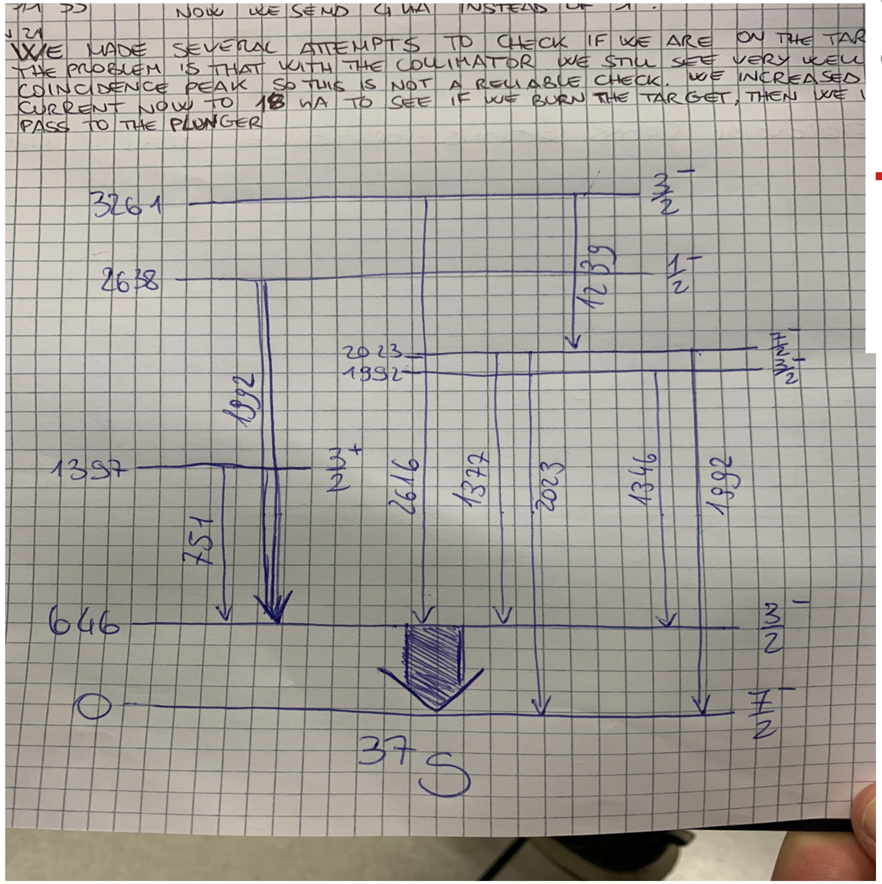
Plunger: $3/2^+$ -> $3/2^-$

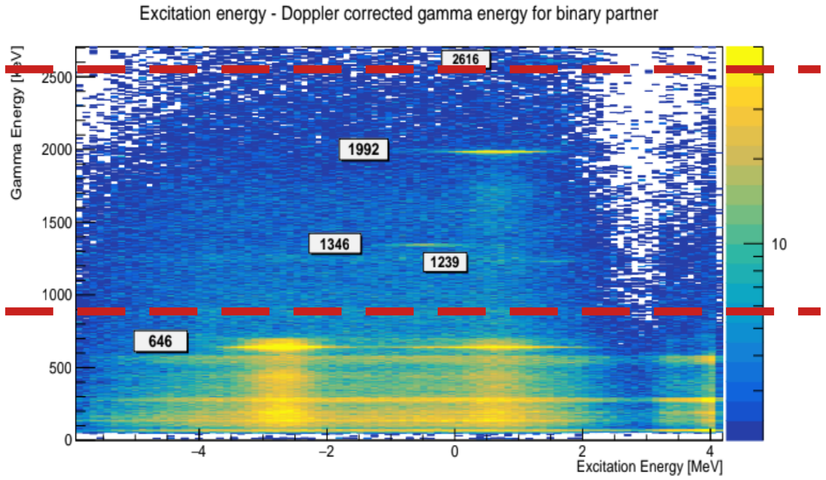


DSAM: $7/2_2^-$ -> $7/2_{gs}^-$

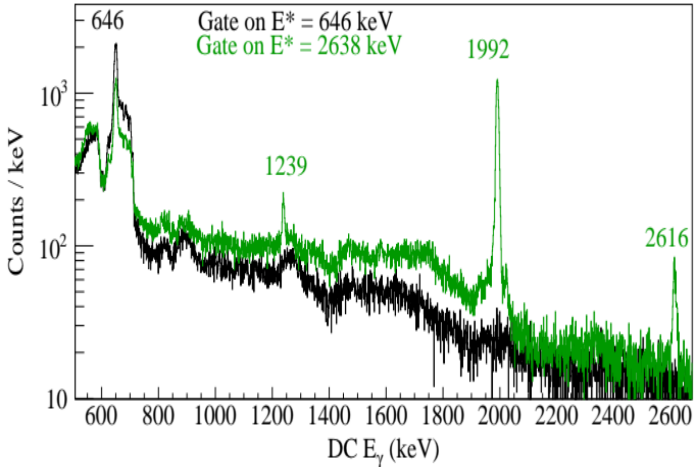


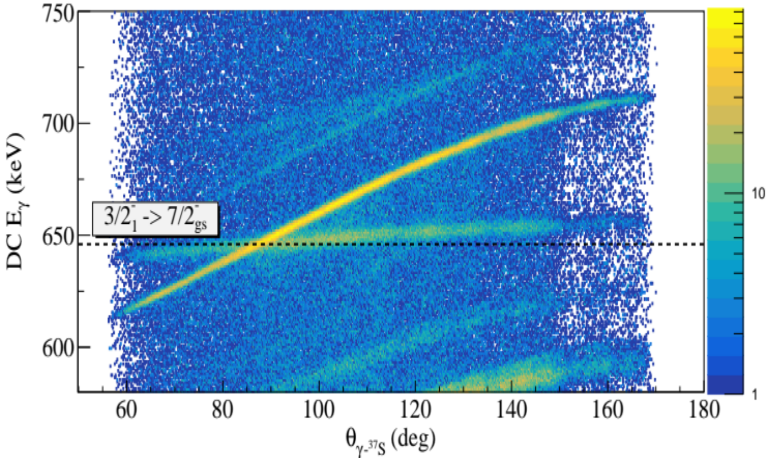
Freshly baked near line data





- Entry point constrained by the reconstructed E_{ex}: lines of interest visible
- Lifetime from literature confirmed ~650 keV line



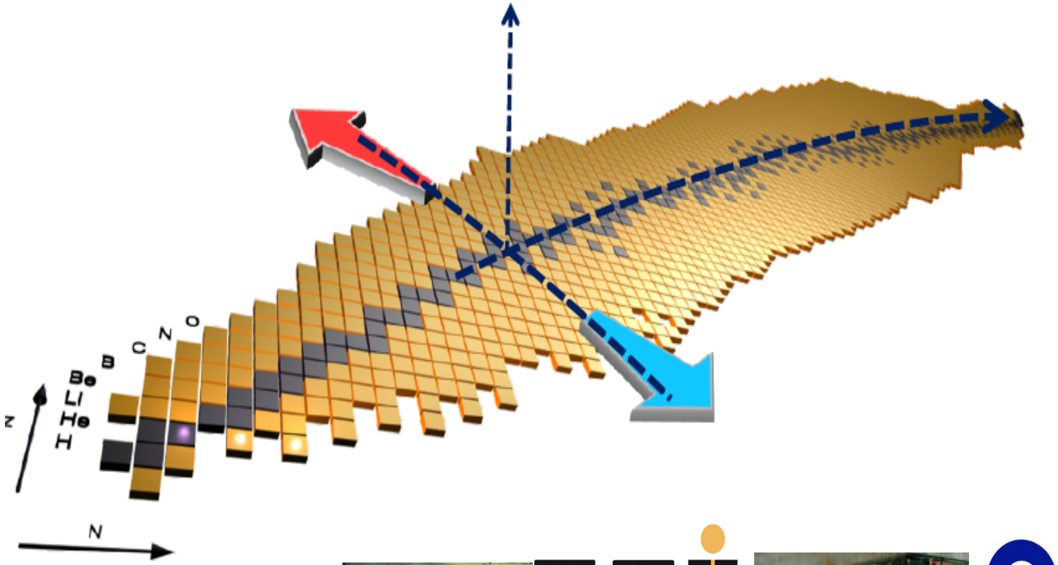


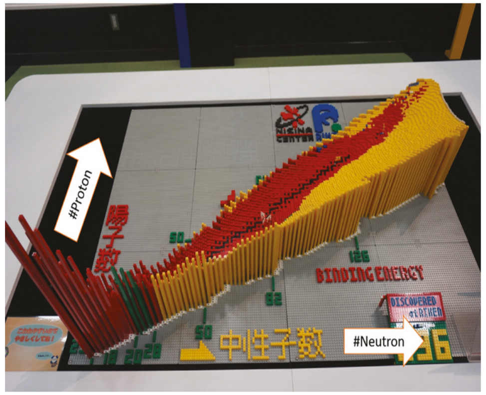
Conclusion and perspectives

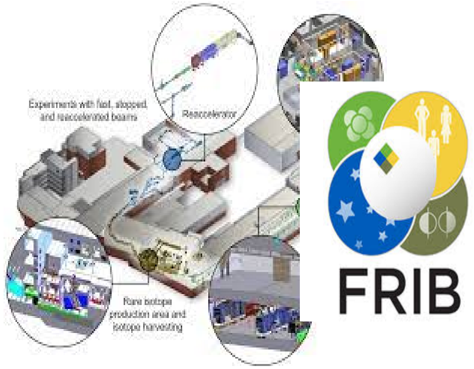
- Technological leap is in mutual dependence with scientific findings
- Success of the direct measurement campaign using AGATA MUGAST VAMOS @ GANIL strongly depended on the enhanced resolving power of the complete detection setup
- To push further the limit of discovery we need, next to complete major on-ongoing projects, to imagine new instruments

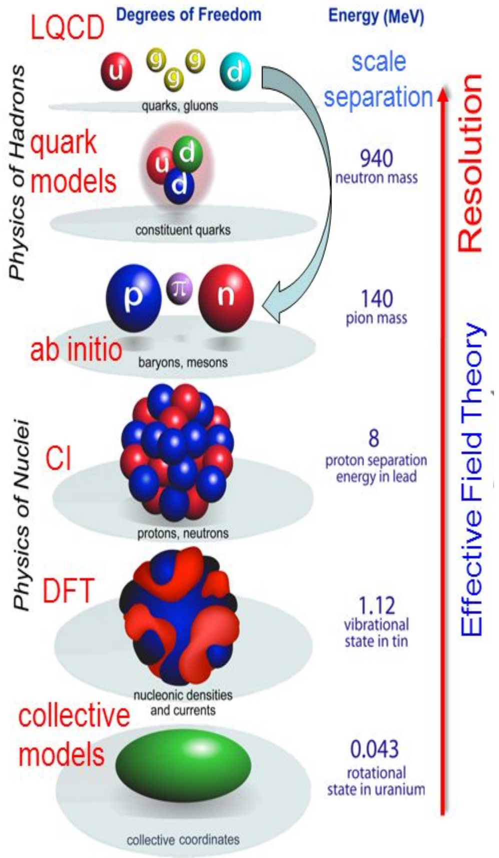
https://ecfa.web.cern.ch/ https://www.nupecc.org/ https://web.infn.it/nucphys-plan-italy/

Possibilities









Some possibilities

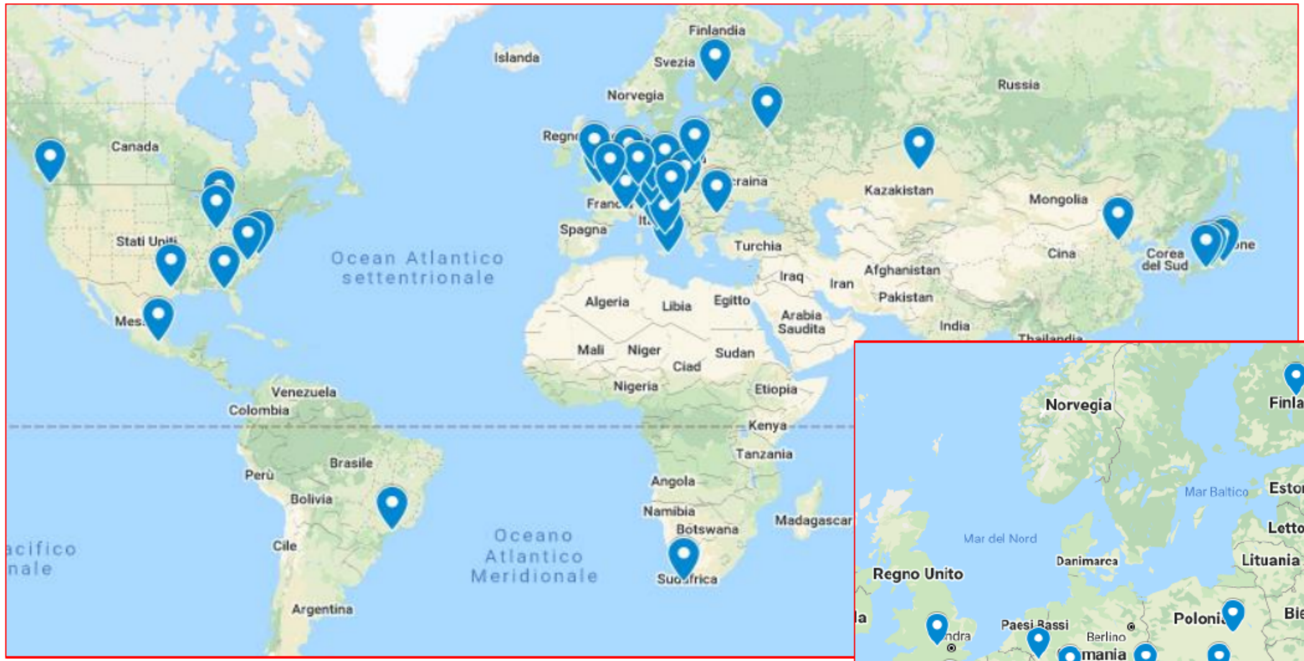
- Preparation, participation, data analysis of experimental runs

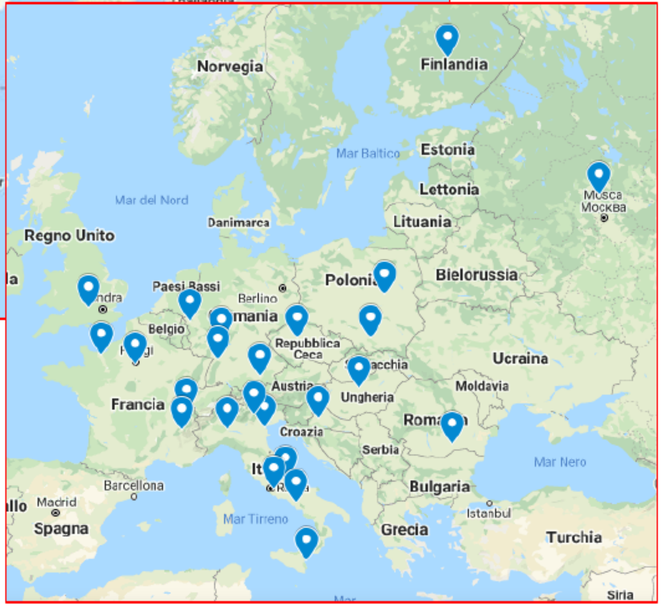
- Detector development and characterization

- Simulations

- Applications

Worldwide experiments





FRIB

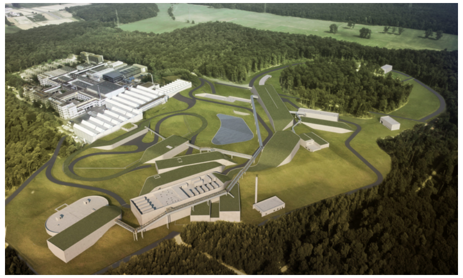
RIKEN

FAIR

ISOLDE

SPES exotic beams for science

Spiral2

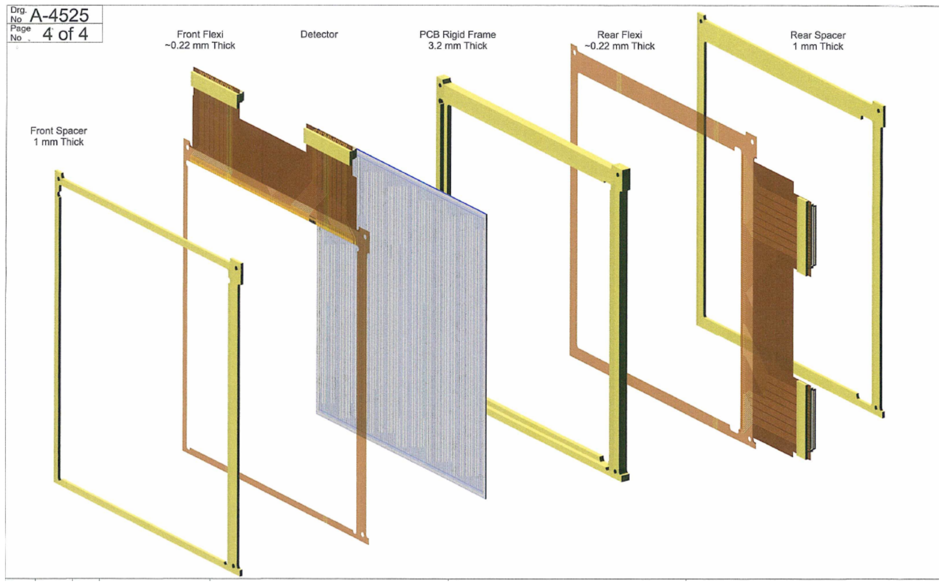


INFN Istituto Nazionale di Fisica Nucleare

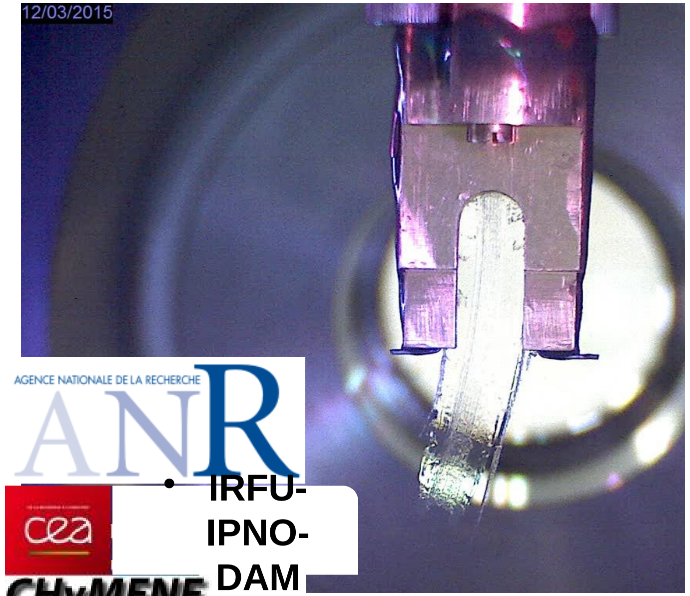
CERN

Detector development

- Montecarlo Simulation
- Detector test:Cutting-edge dets high segmentation, NTD (uniformity), 6” inches, Random cut (channeling)
- Exps @ ISOL facility in Italy and worldwide



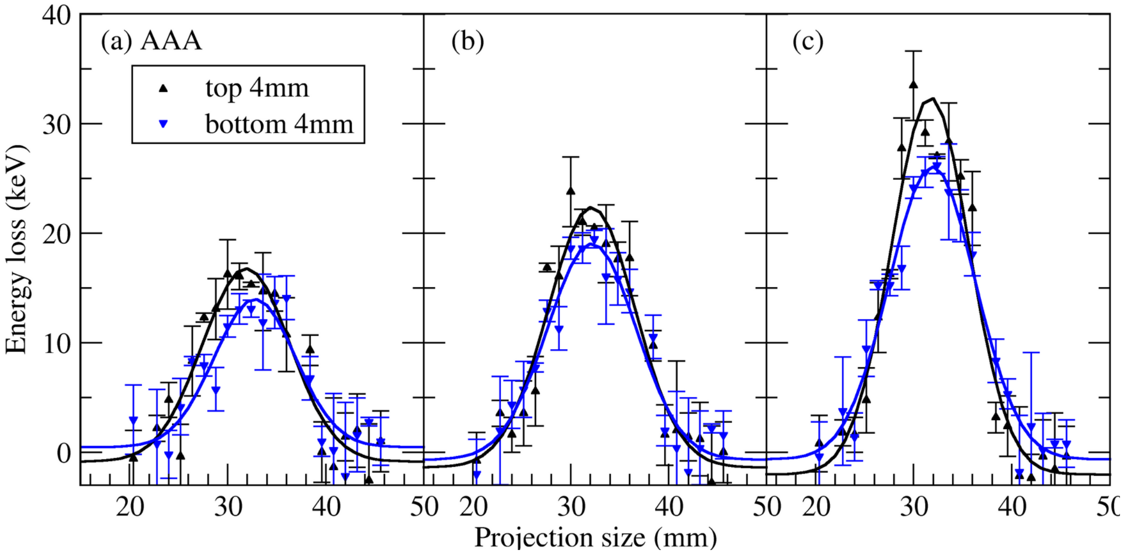
Target development



AGENCE NATIONALE DE LA RECHERCHE ANR

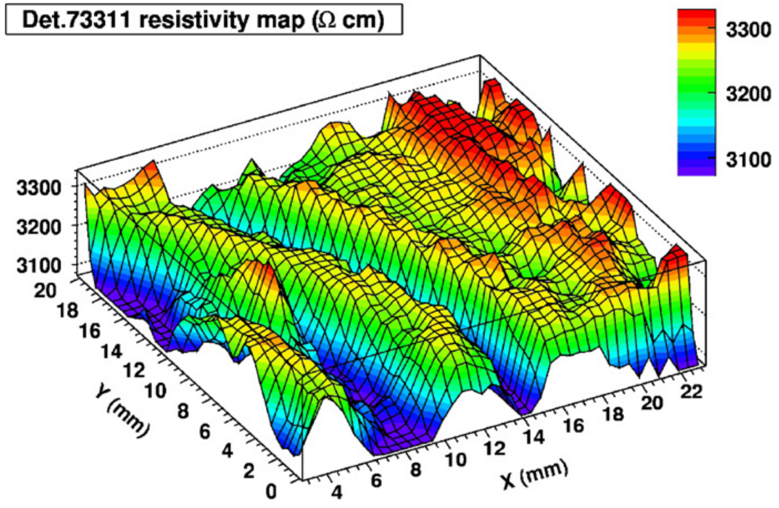
- IRFU-IPNO-DAM

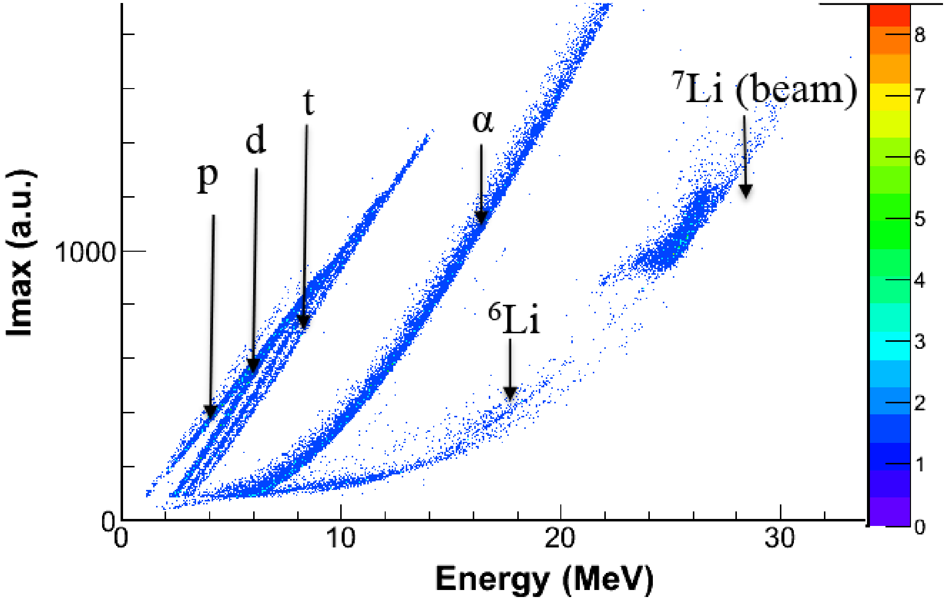
CHyMENE

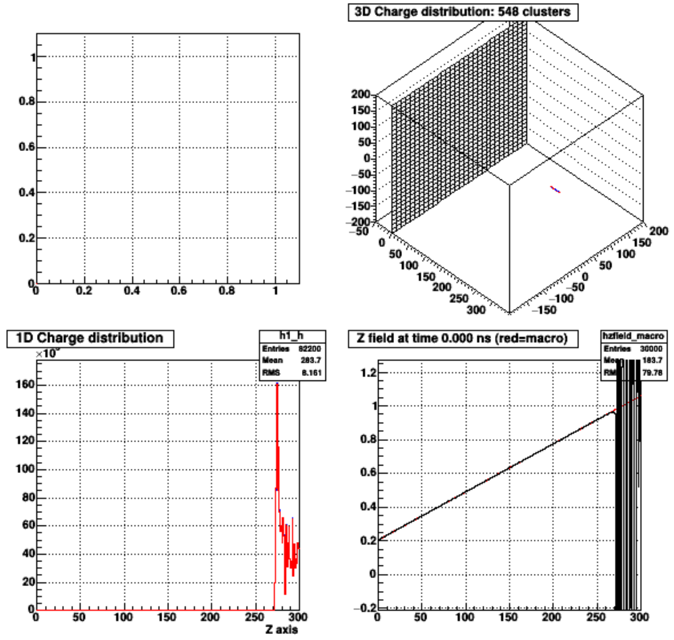


- Hydrogen (h,d) target in a solid phase near triple point (~17K)
- Thickness 50 – 200 µm
- Commissioning: temperature, density and profile

Detector development and characterization







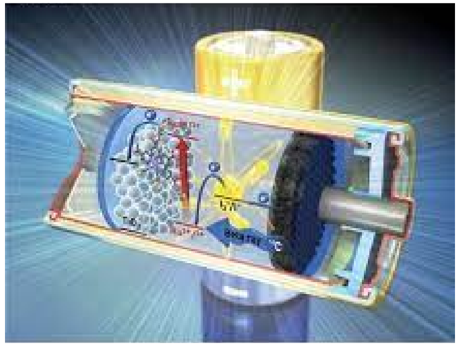
- Wire bonding (clean room)
- Non destructive Resistivity measurement: laser and alpha source

- Digital Pulse shape analysis:- numerical filters, NN (convolutional/ML perceptron)

- Signal simulation: drift/diffusion

Applications: beta batteries

Sviluppo batterie a bassa potenza e lunghissima durata per la medicina lo spazio e la sensoristica remota



Fisica di base

Applicazioni

Ambiente

INFN CSN3 :: MSc&BSC grants

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

daniele.mengoni@unipd.it

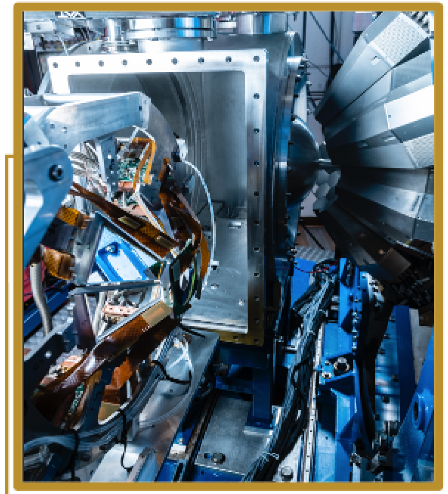
Further info on the group activity at the URLs:

[DFA fisica-e-astrofisica-nucleare] [Gr3 INFN Padova]

If you are interested, thesis, internship offer etc can be found here

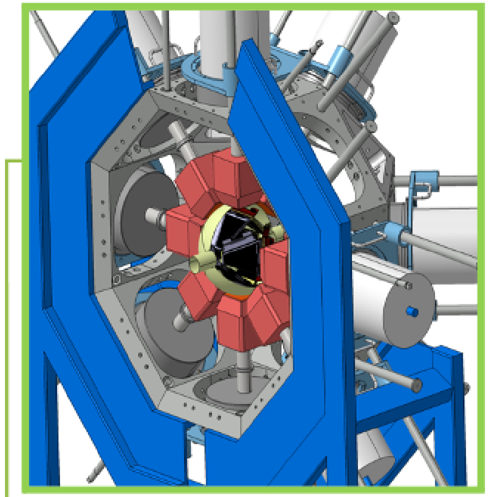

"That's all Folks!"

- MUGAST-AGATA@VAMOS : a technical & scientific success
- Valuable integration&operation exercise !
- Next step : MUGAST-EXOGAM@LISE



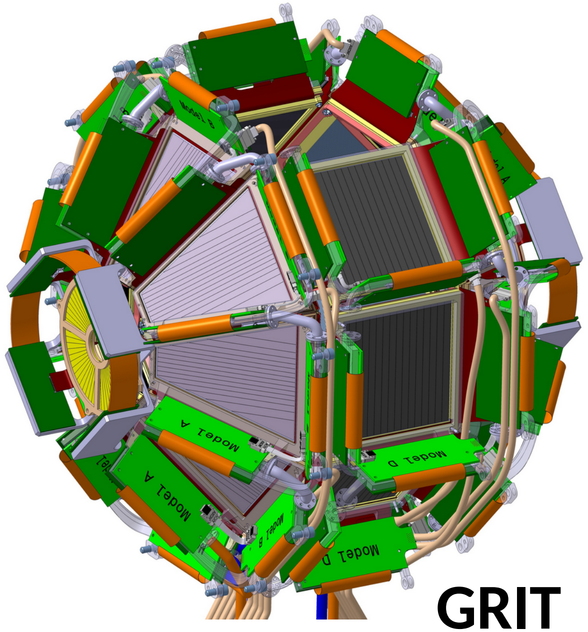
MUGAST-AGATA-VAMOS @GANIL

2021



MUGAST-EXOGAM-LISE @GANIL

2023-2024



GRIT

SPES

exotic beams for science