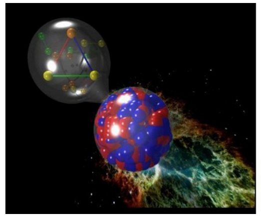
AFRICAN NUCLEAR PHYSICS CONFERENCE ANPC2023

NRF National Research Foundation
iThemba LABS Laboratory for Accelerator Based Sciences
ANPC African Nuclear Physics Conference

Physics results
with the ultimate AGATA-MUGAST-VAMOS setup and ISOL beams at GANIL

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

GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3
AGATA ADVANCED GAMMA TRACKING ARRAY
GRIT
SPES exotic beams for science



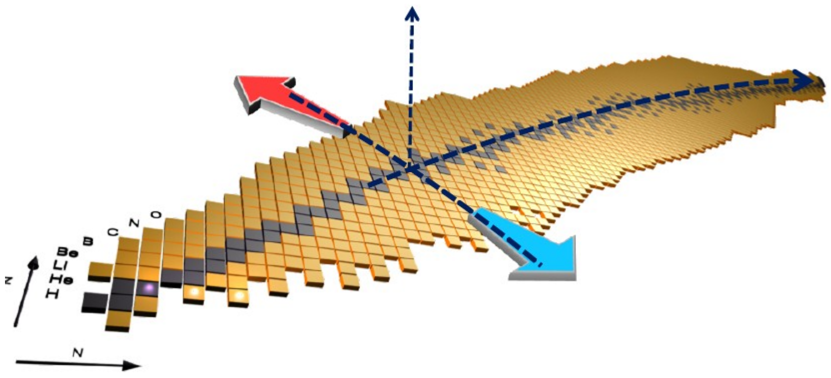
African Nuclear Physics Conference 2023
28 Nov - 03 Dec, 2023 – Kruger

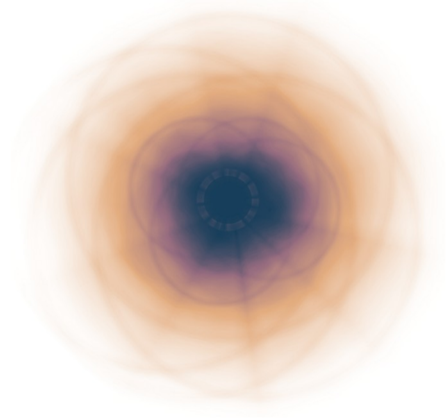
800 1222-2022 ANNI Università degli Studi di Padova
INFN Istituto Nazionale di Fisica Nucleare

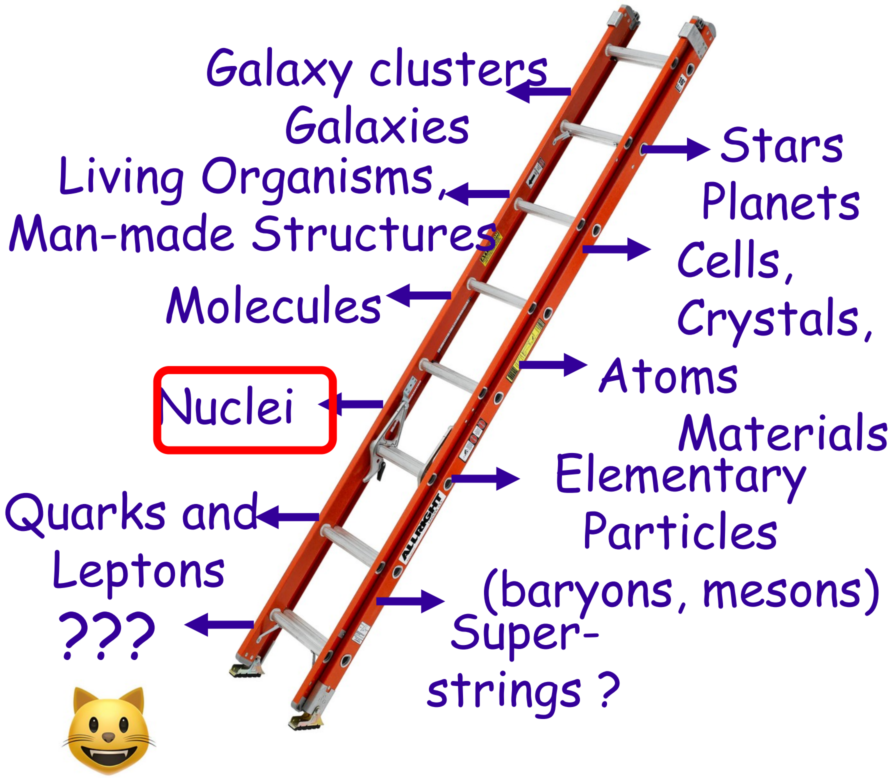
Outlook

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

Why NS?



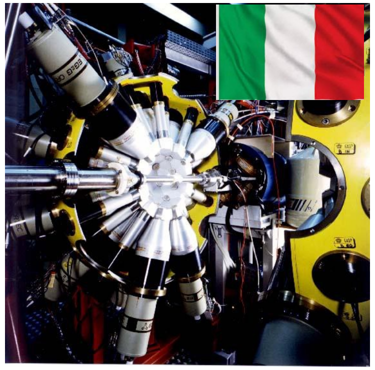




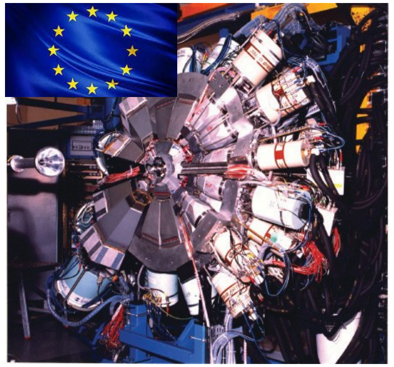
- Complex many-body quantal systems at mesoscopic scale
- Hamiltonian describes systems from few eV to GeV: 9 orders!!!
- Comprehensive theory starting from “first principles”

adapted from W.Nazarewicz

Nuclear Structure (t)rail

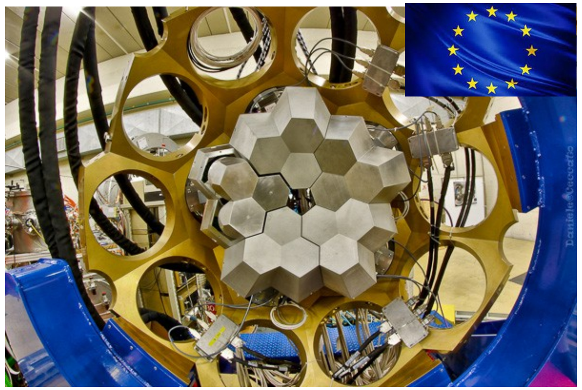


1990s



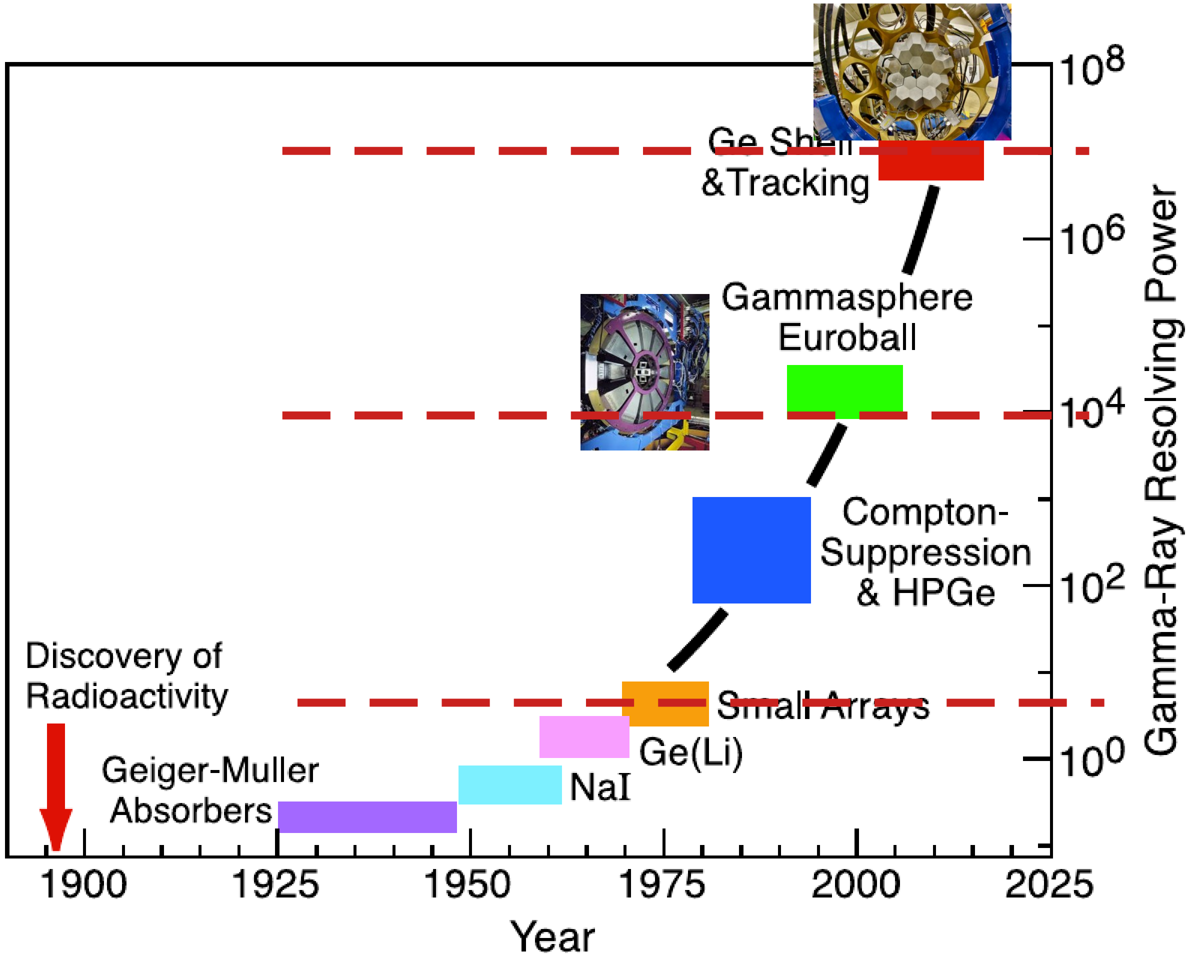
~2000

~2005



2010

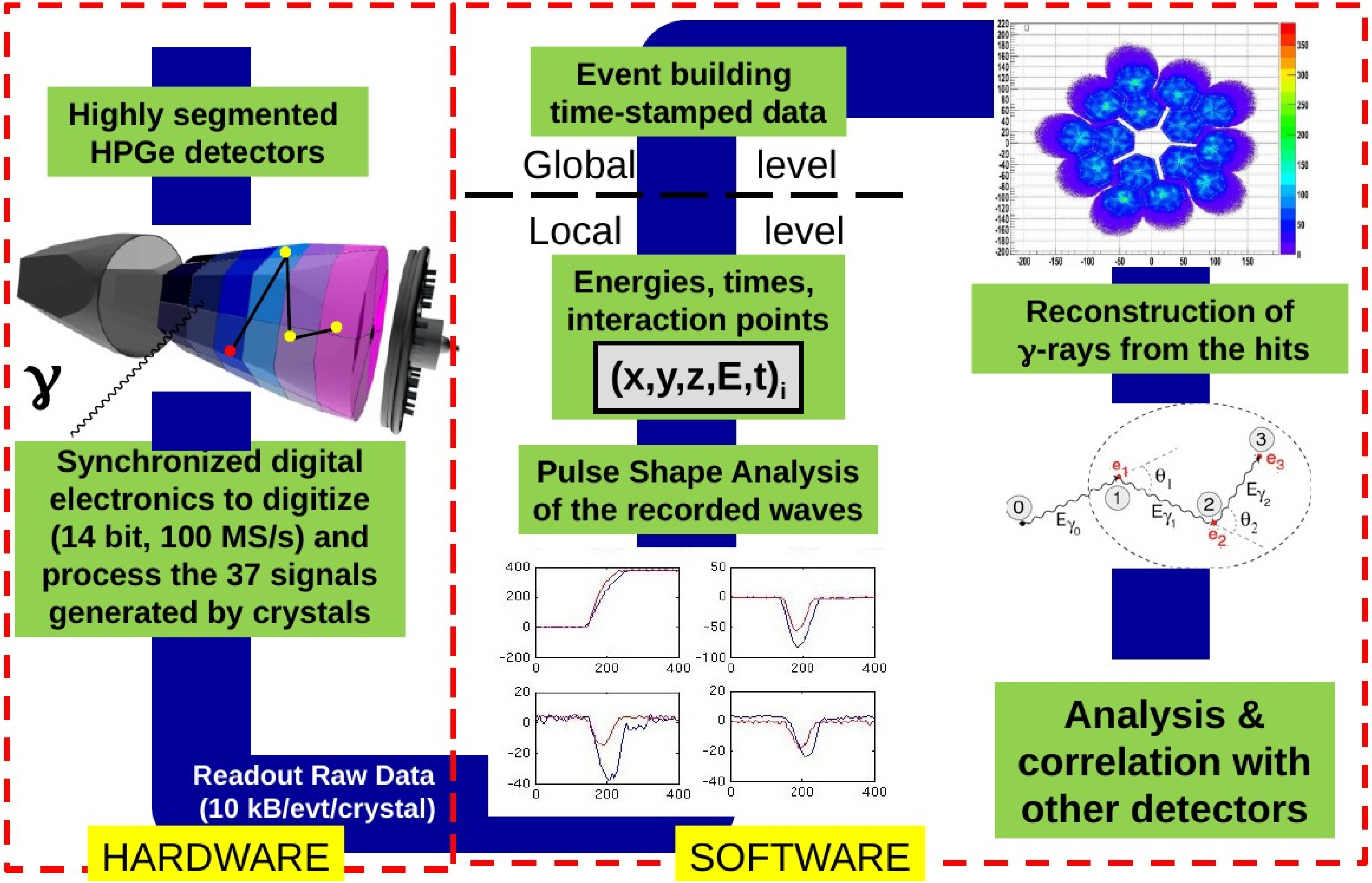
Technological leap leading to γ-ray tracking



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

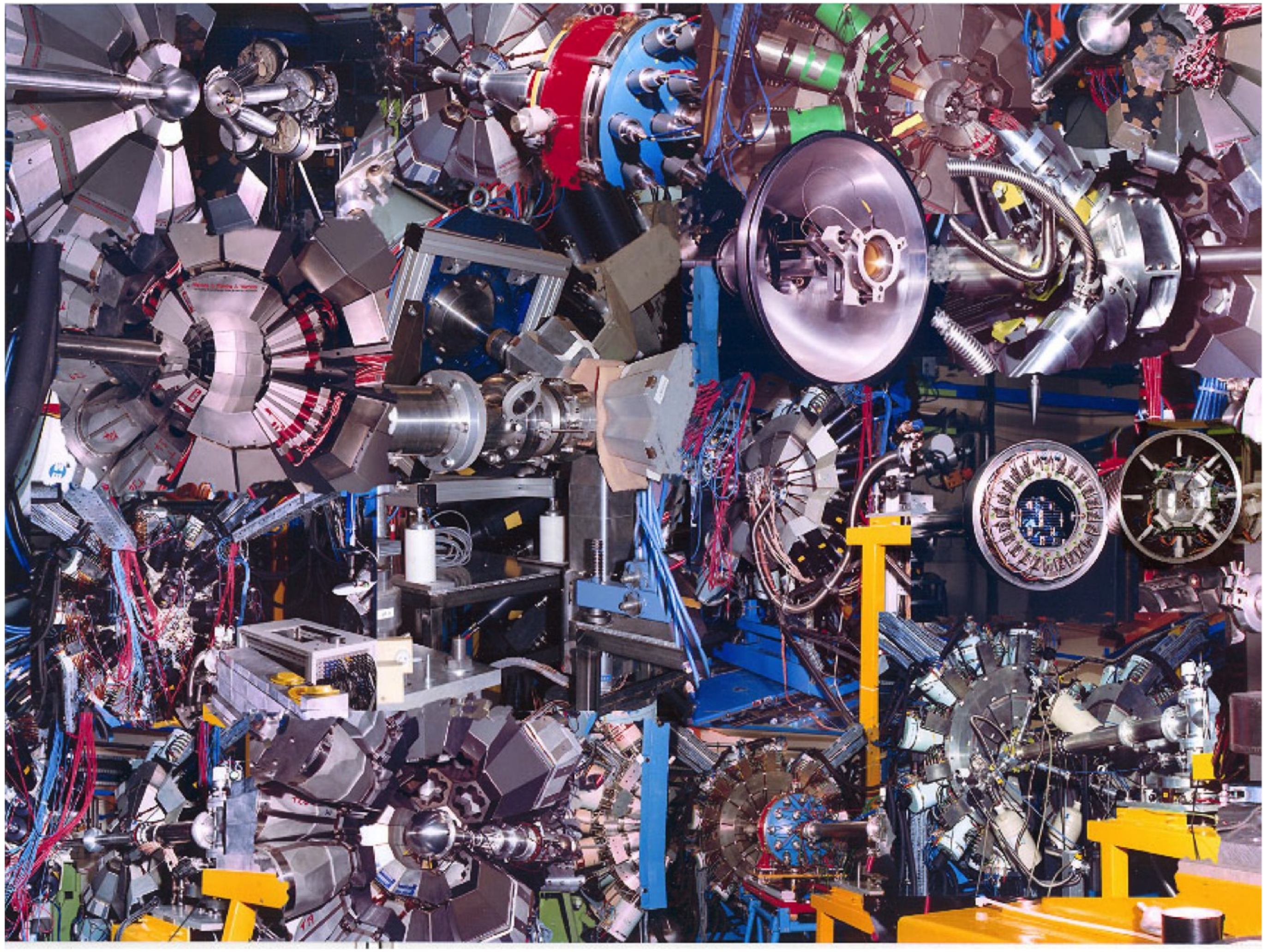
- Outstanding **sensitivity** for lifetime measurement (~Ψ)
- Reduced minimum detectable limit σ (~E)
- E, Ψ ←→ $\mathcal{H}$: Coherent description of nuclear many body complex system and nuclear matter
- … but a price has to be payed ...

price to pay: complexity and cost

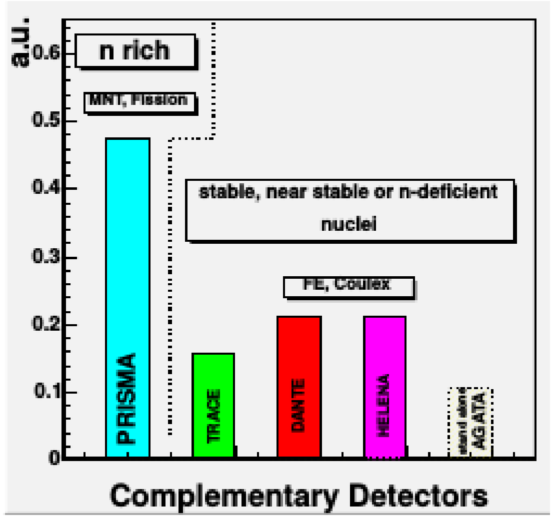


- **6660** high-resolution digital electronics channels
- High throughput DAQ / **computational** resources **load**
- Pulse Shape Analysis → position sensitive operation mode
- γ-ray tracking algorithms → maximum efficiency and P/T

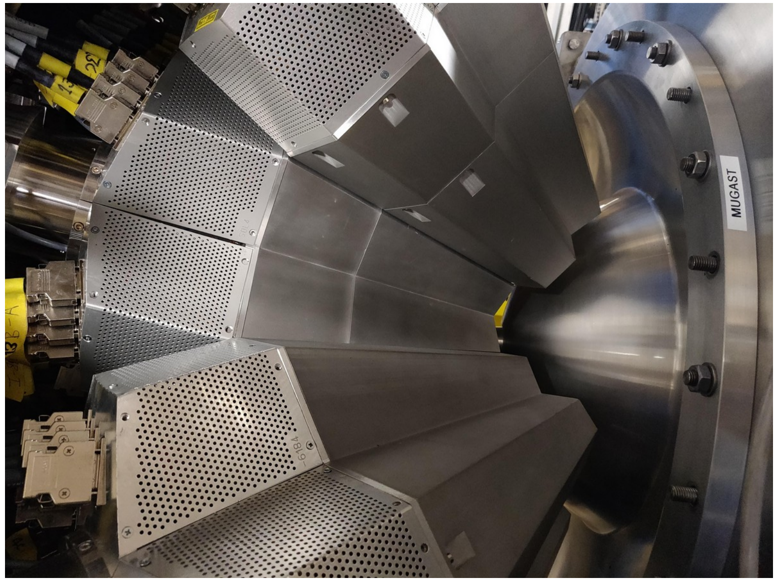
Complementarity is key: factorized the sensitivity

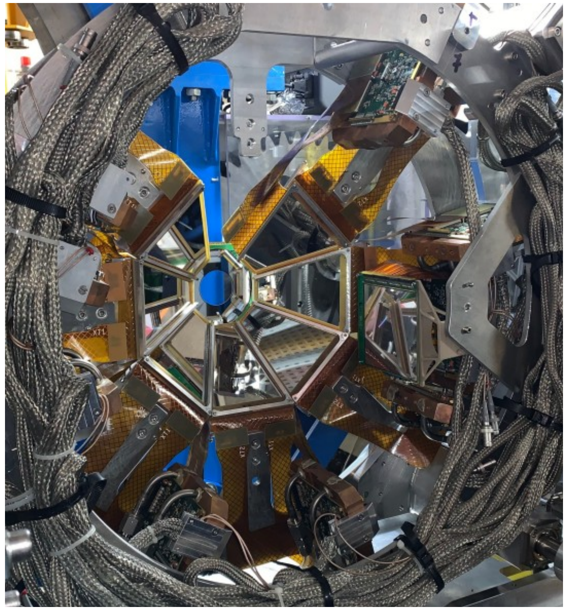
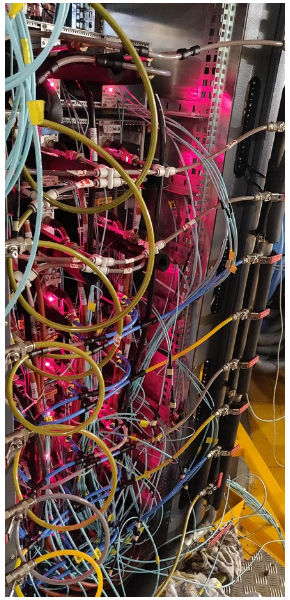
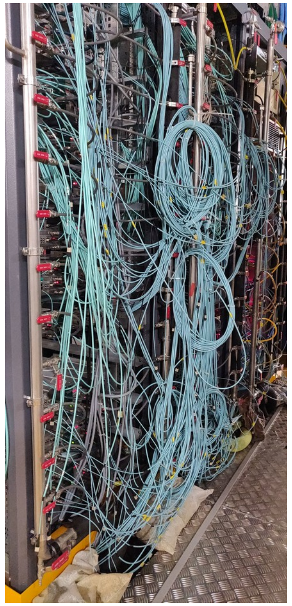
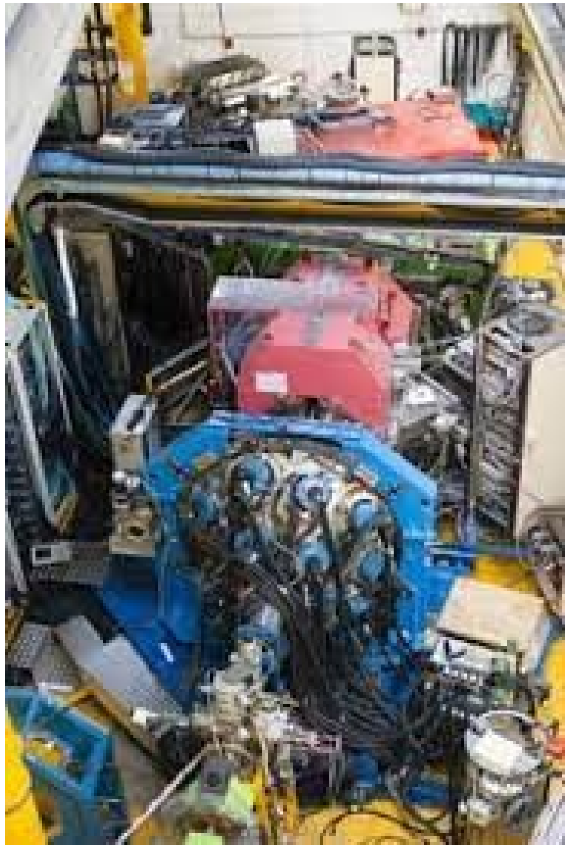


- In modern γ-ray spectroscopy, complementary instrumentation (magnetic spectrometers, particle and neutron array, high-efficiency scintillators, plunger etc etc) is key for challenging measurements at the limit of measurability



AGATA+MUGAST+VAMOS setup



GANIL spiral2
laboratoire commun CEA/DRF CNRS/IN2P3

DM et al. “Advances in nuclear structure via charged particle reaction with AGATA” EPJA 2023
M.Assié et al., “MUGAST-AGATA-VAMOS campaign: setup and performaces” NIMA 2021

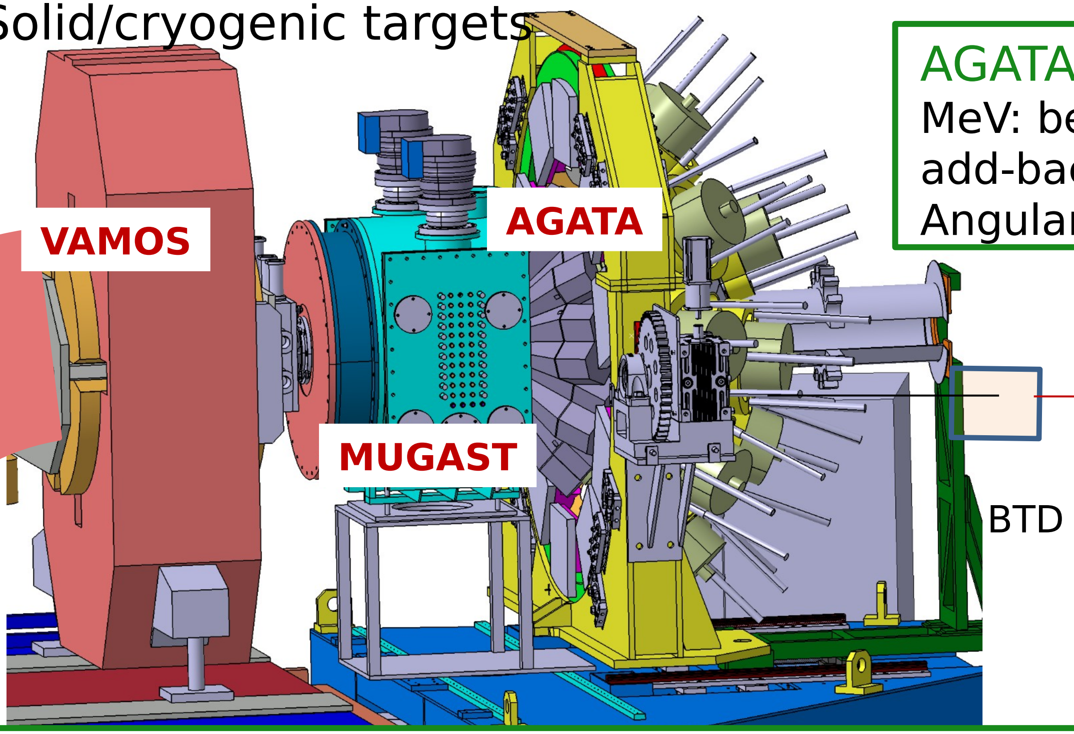
AGATA+MUGAST+VAMOS set-up @ GANIL with Spiral1 beams

Unmatched worldwide performances and versatility for direct reactions

VAMOS

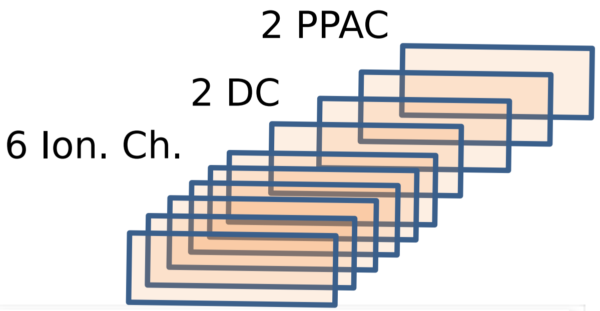
Acceptance of VAMOS : +/- 6 deg
VAMOS typical efficiency : ~80%
Numerical electronics NUMEXO2

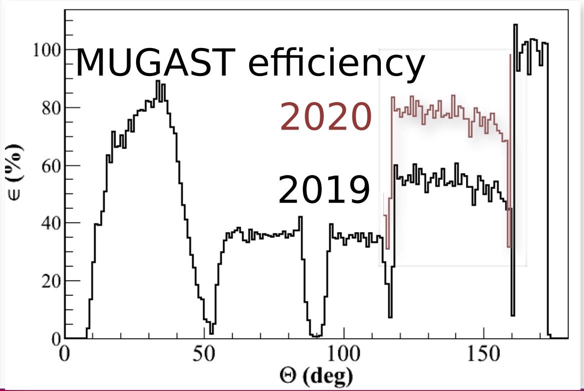
Solid/cryogenic targets



AGATA efficiency (18cm) at 1 MeV: before add-back 5.5%, after add-back : ~8%
Angular resolution **~1º**

Spiral1 radioactive beams





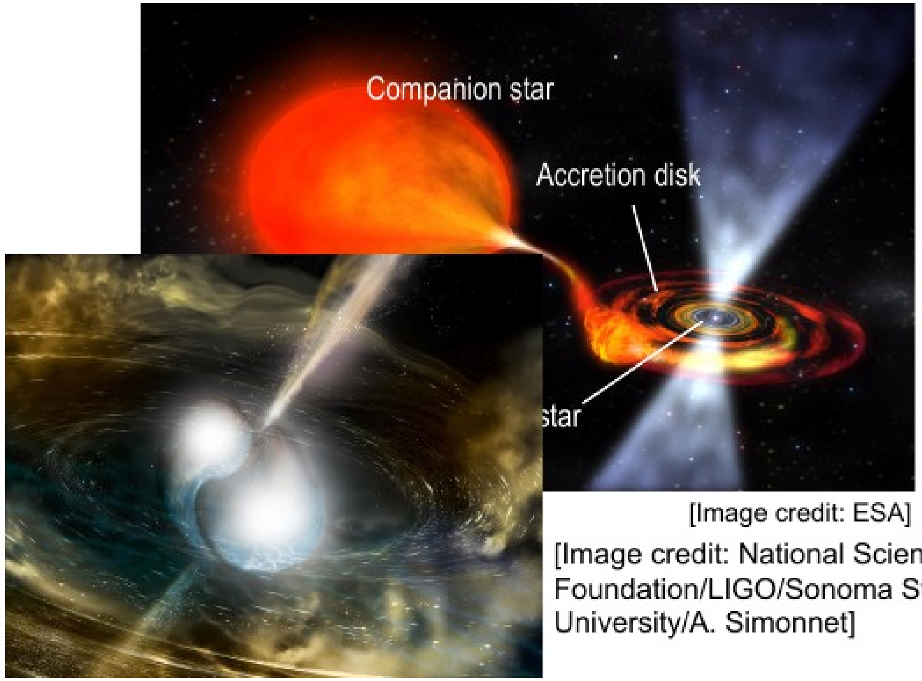
MUGAST

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

Accreting n stars and X ray bursts

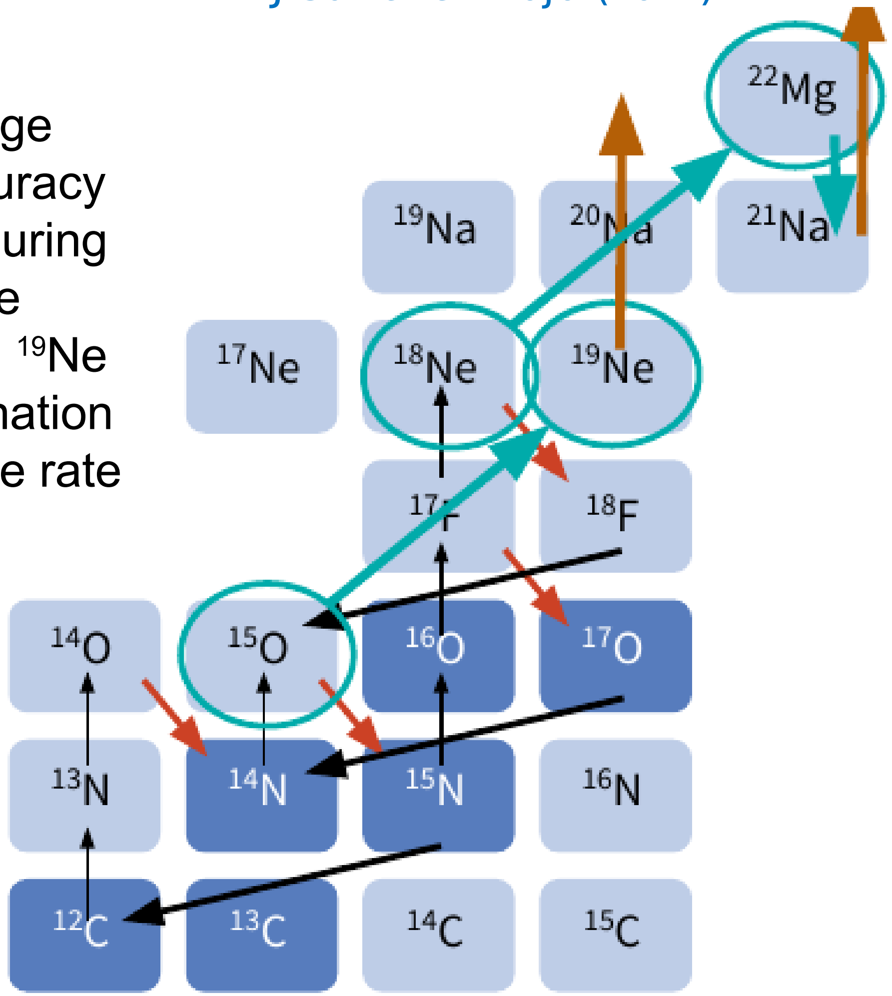
$^{15}O(\alpha,\gamma)^{19}Ne \leftarrow ^{15}O(^{7}Li,t)^{19}Ne$

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



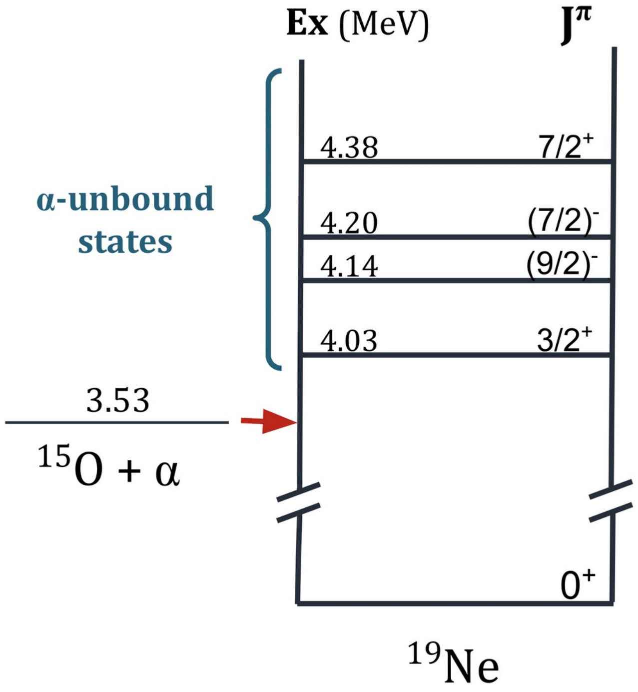
[Image credit: ESA]
[Image credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet]

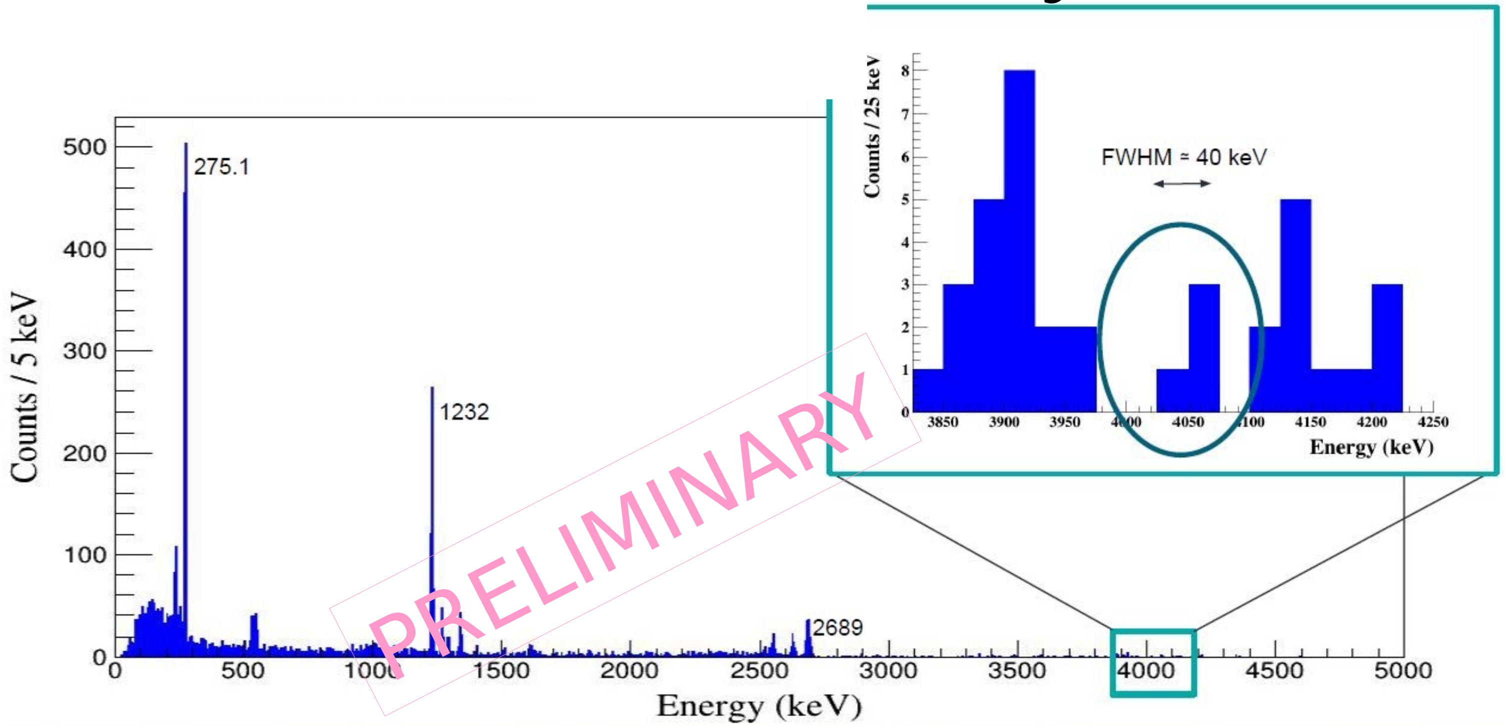
- Tension in former measurements, large uncertainty / inaccuracy
- Challenge of measuring the rate through the 4.033 MeV state in ^{19}Ne
- Sensitive determination of the alpha capture rate



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

Pushing the limit of sensitivity





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

From: J.Sanchez Rojo PhD thesis

- Beam rate : ~10^7pps and triple coincidence: γ+t+^{19}Ne
- Minimum detection limit: **cross-section few μb/sr**
- New accurate results

Partial width calculation

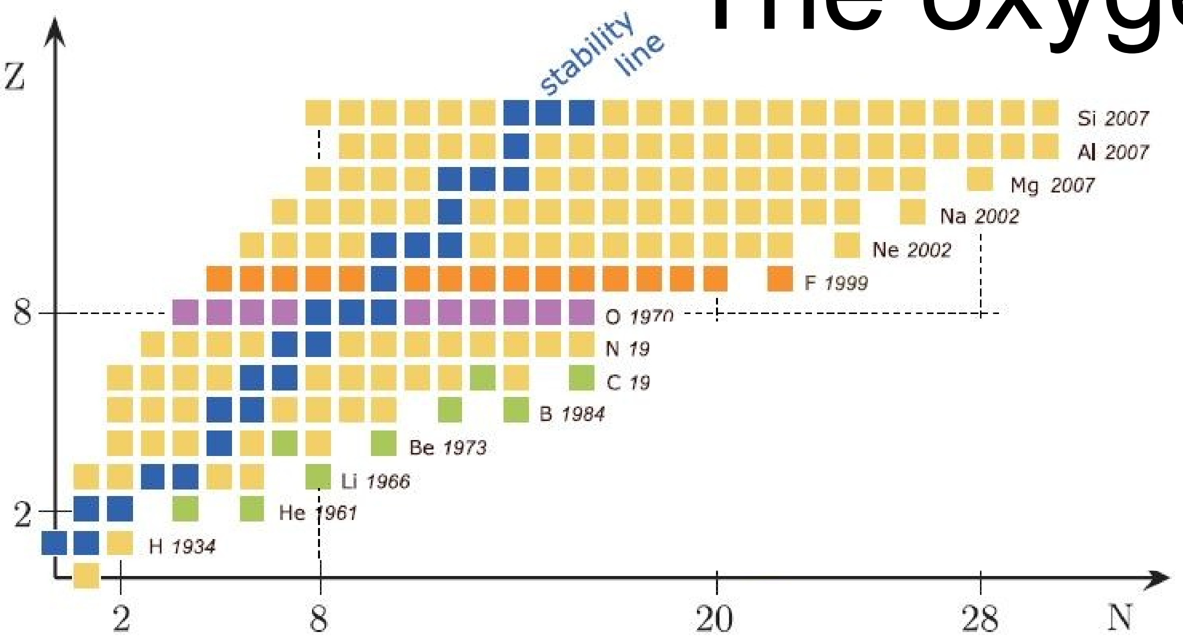
Calculation ongoing @BCN and draft in preparation

- Background estimate and subtraction: channel leak ^{20}Ne and compton(simulation)
- $C^2S\alpha$ calculation: bench mark over bound states of 19Ne: 1508 keV, double check with the SF of the mirror nucleus ^{19}F, assessed in literature
- Extrapolation to the unbound states (integral cross section low stat)
- New value for 4033 state, reduced of a factor of ~6

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

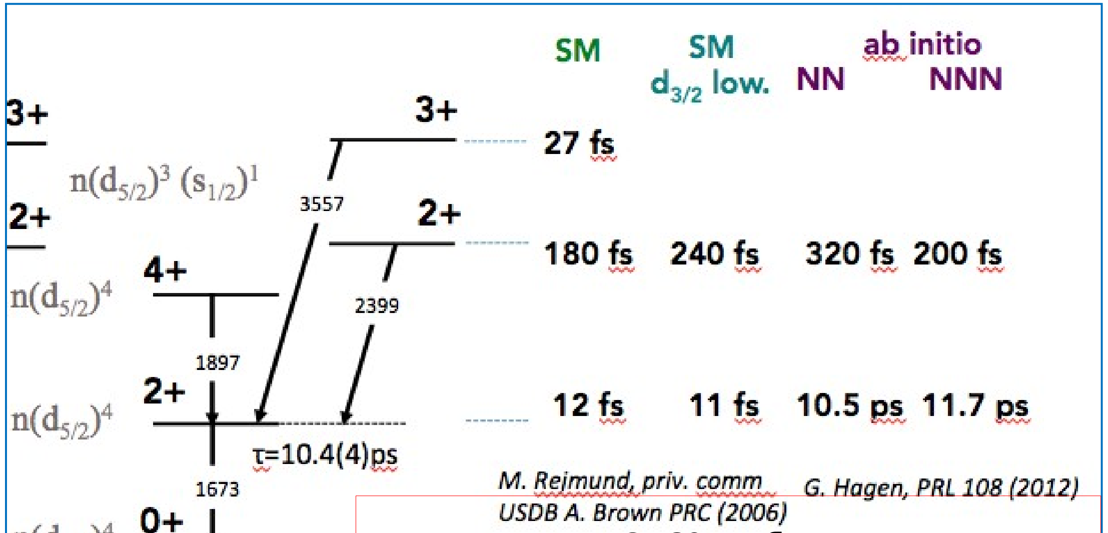
E_x (keV)	Γ_α (μeV) This work	[Tan09]	[FLS10]
4033	$3.0^{+4.0}_{-2.2}$	17 ± 13	24(18)
4140	0.28 ± 0.04	44 ± 20	
4197	3.0 ± 0.3	18 ± 9	
4379	128^{+123}_{-68}	160^{+110}_{-70}	150(6)
4600	$3.4^{+4.4}_{-2.2} \cdot 10^3$	$24^{+33}_{-10} \cdot 10^3$	$96(24)\cdot 10^3$

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

$^{19}O(d,p\gamma)$ + DSAM

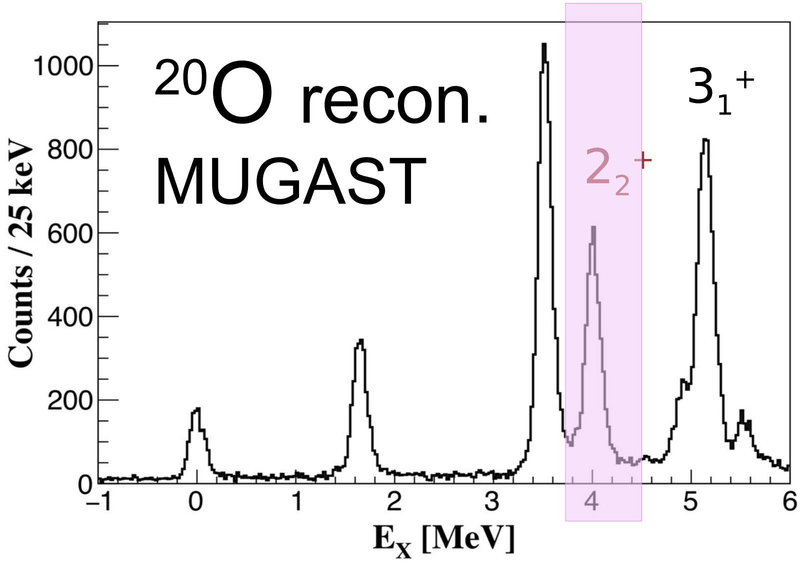
➟ Constrain relative position of $s_{1/2}$ and $d_{3/2}$ in n-rich oxygen

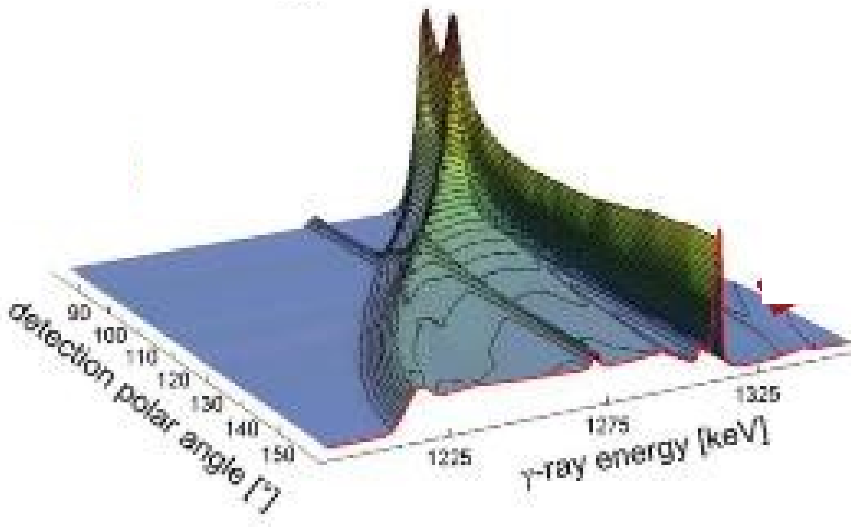
➟ Probe the 3-body interaction

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

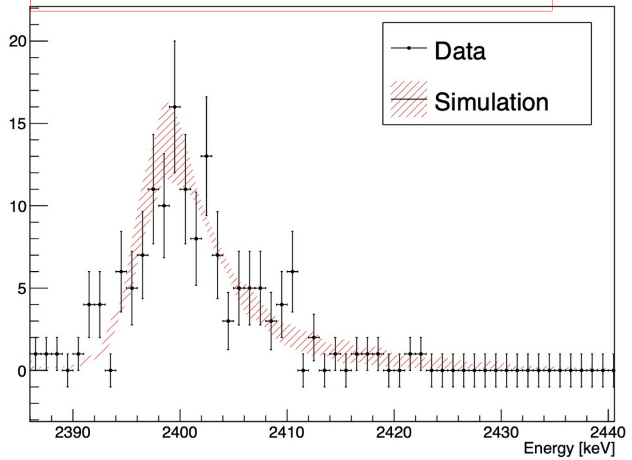
➟ Combination of DSAM + transfer to identify the entrance channel and control the feeding

Role of 3-body forces





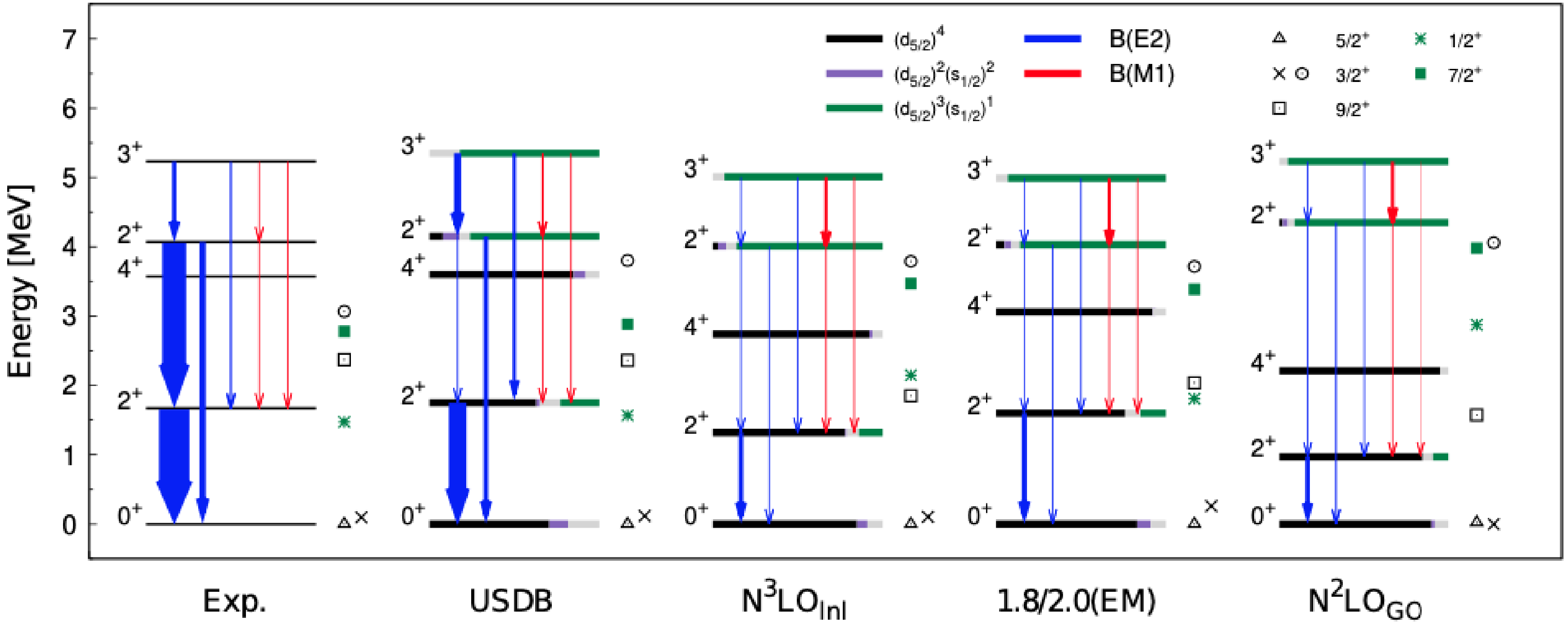
τ_{2+}: 63^{+29}_{-16} fs



- 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 than predictions for the 2^+
- First lifetime measurement in the tens of femto-sec. scale (DSAM) using transfer reaction in inverse kinematics

sub-fs lifetime measurable!!!

Theory



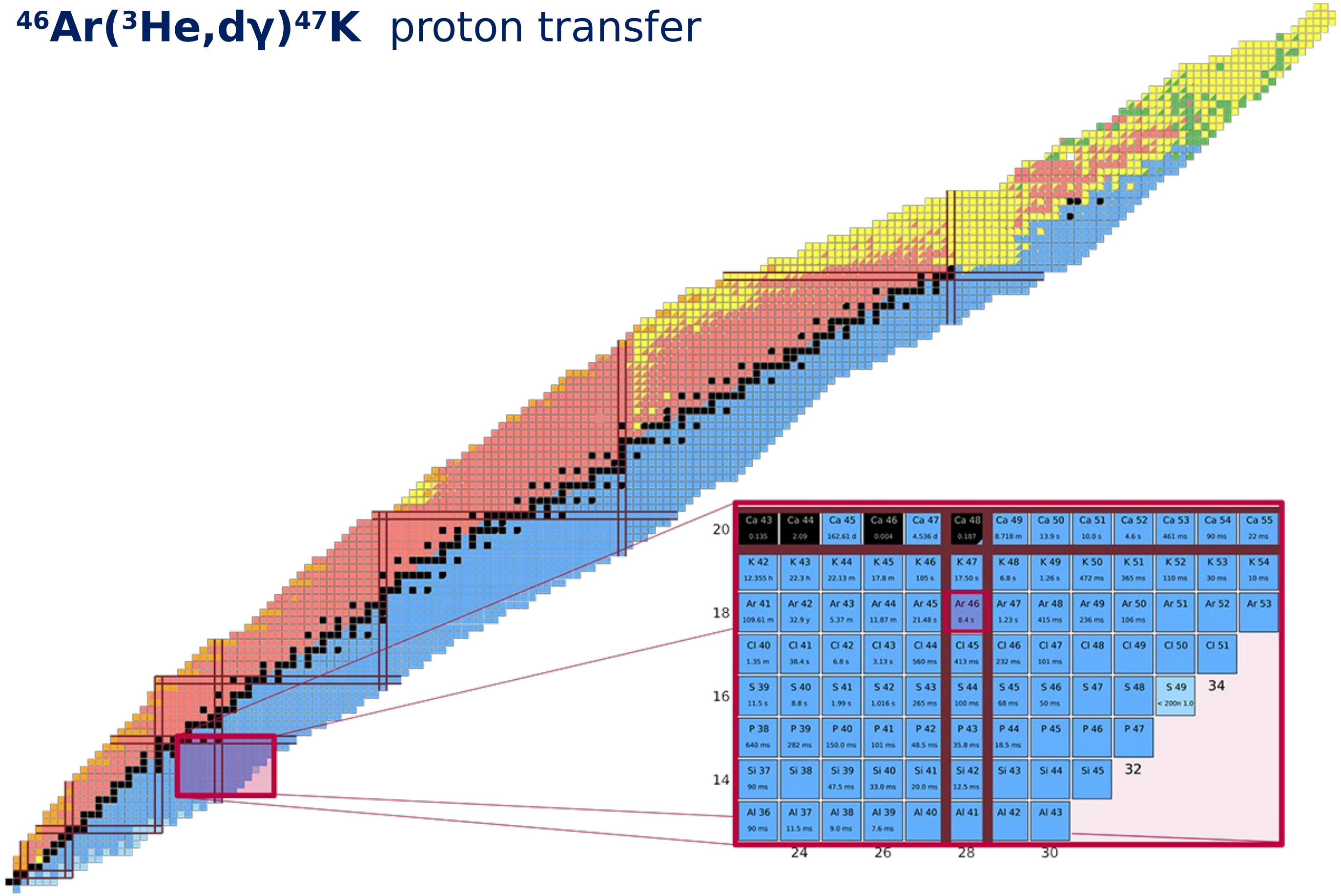
Comparison between experimental reduced transition probabilities and theoretical models: ab-initio VS-IMSRG and USDB

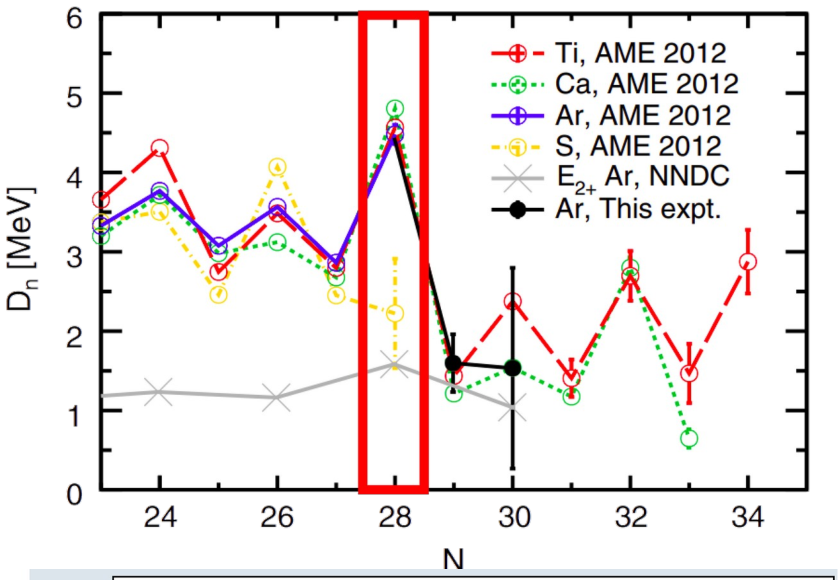
- Energies well described
- B(E2) overall underestimated of order of magnitude
- $B(E2;2^+_2 \rightarrow 2^+_1)$ heavily underestimated:limited space or mixing
- B(M1) also underestimated of factor 3

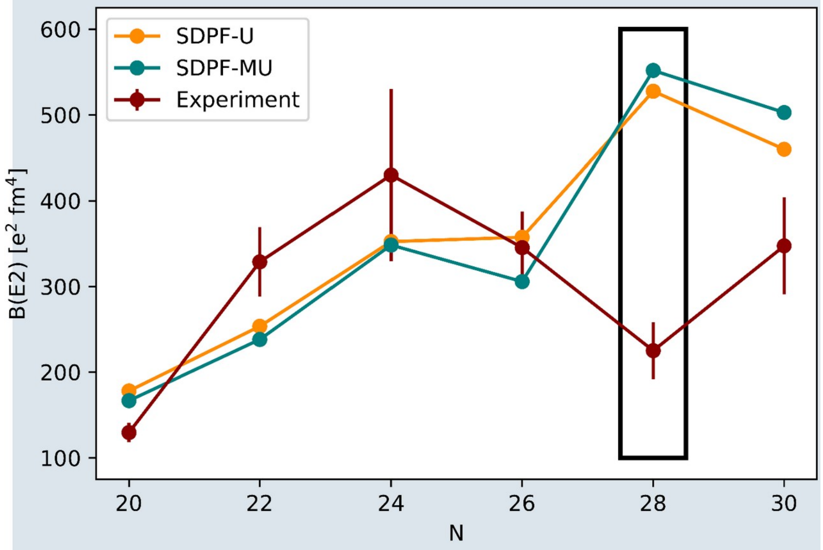
I.Zanon et al., PRL accepted Nov 21st

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

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

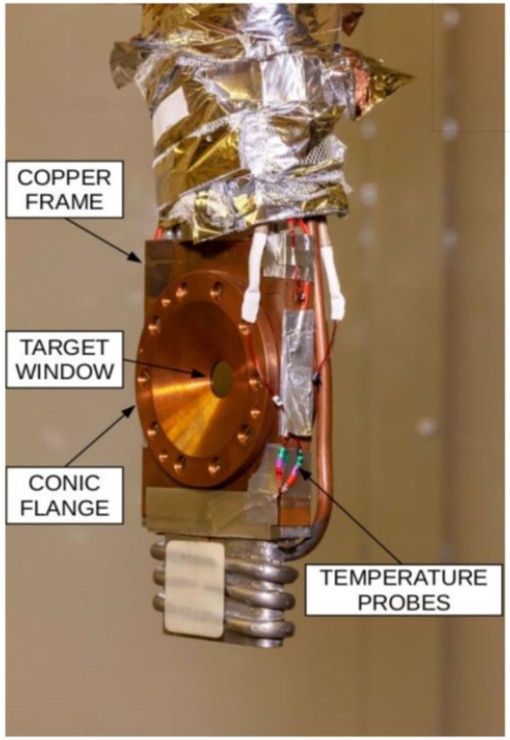


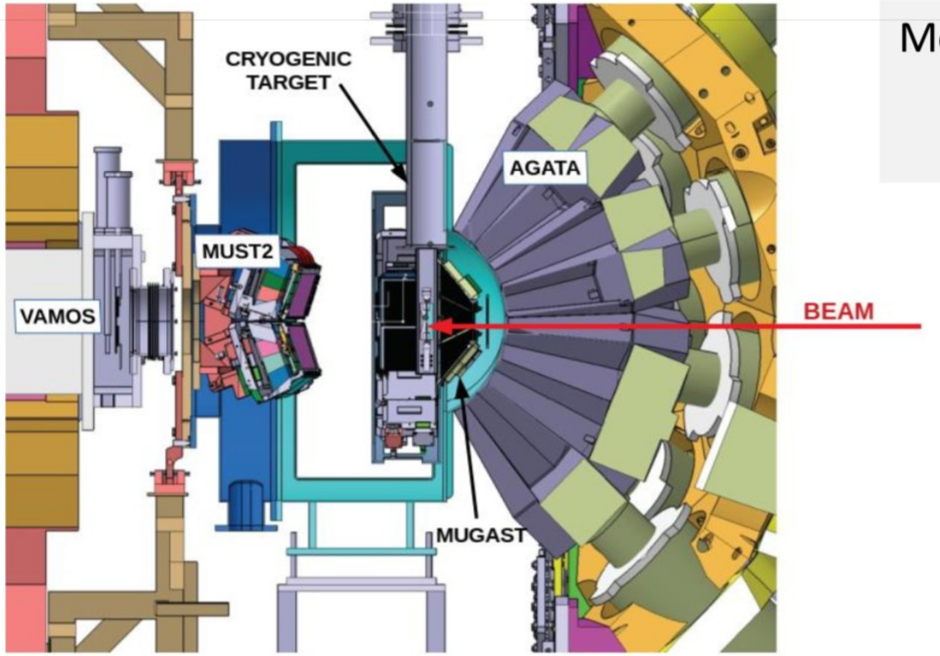




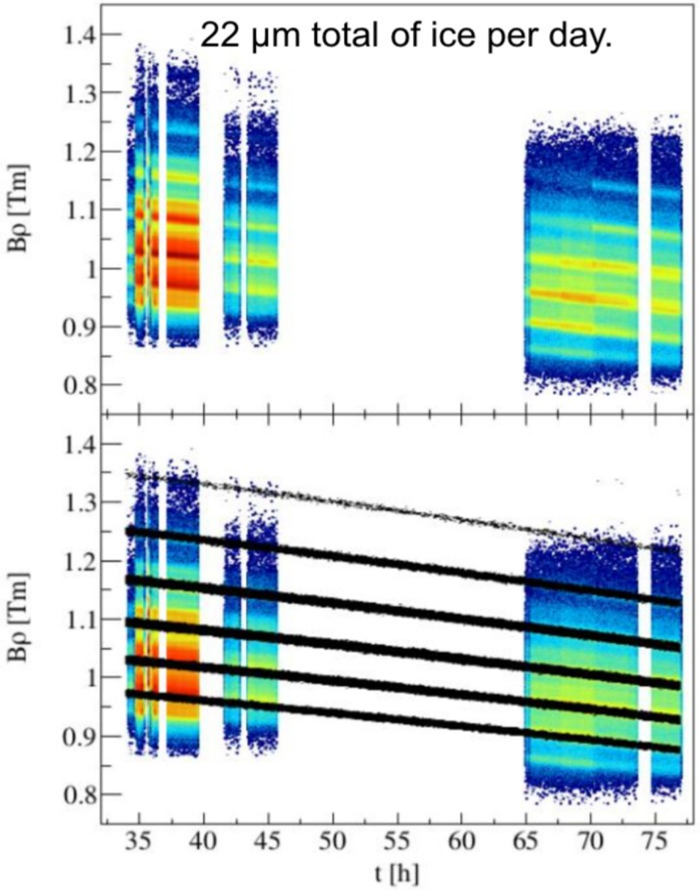
The HEcTOR cryogenic ^{3}He target

F. Galtarossa et al, NIMA (2021)

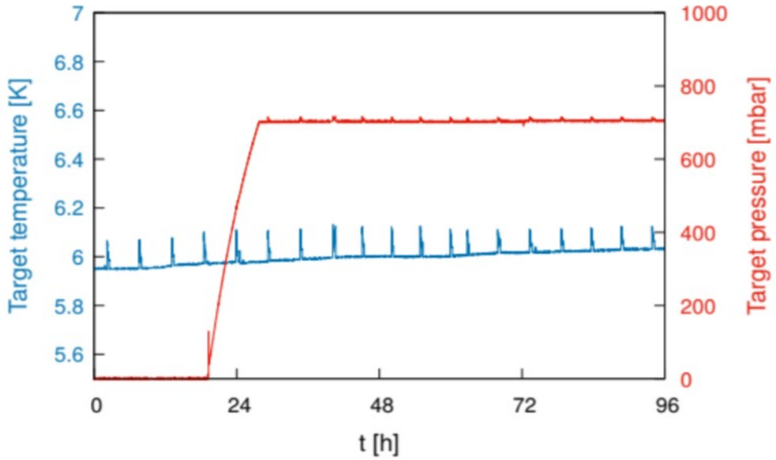




Monitoring of target with VAMOS :
- Target pressure & temperature stable
- Ice formation on the target with time

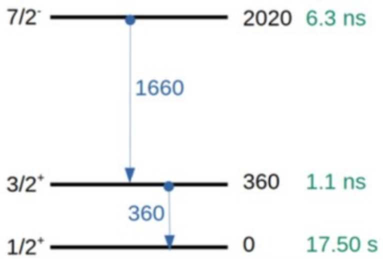


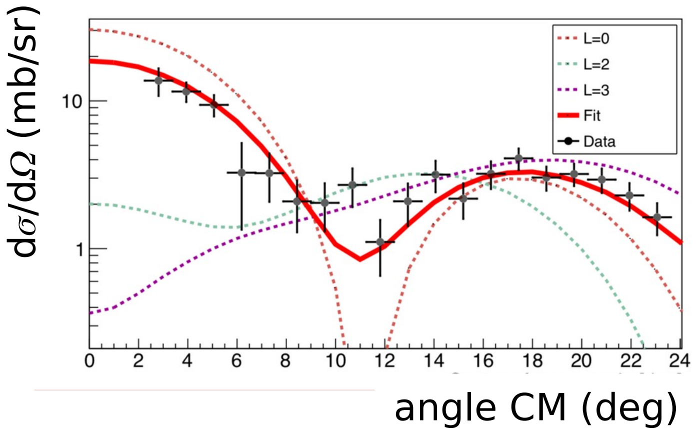
- Ø 16 mm
- Opening angle: 130 deg.
- Havar windows: 3.8um
- T ~ 6-7 K. / P up to 1 bar
- Equivalent thickness 2 mg/cm^2
- ^{3}He recycling
- LHe open circuit

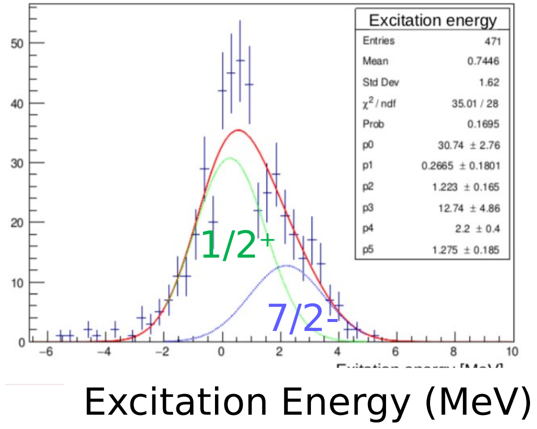


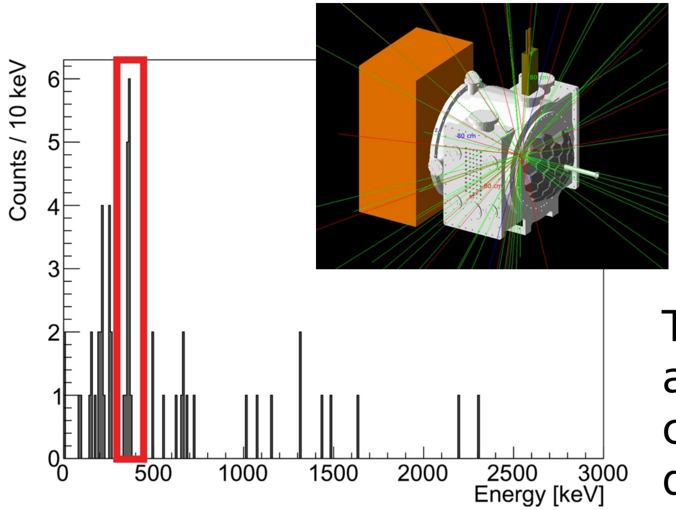
M. Pierens, V. Delpech,
F. Galet, H. Saugnac (IJCLab)
A. Giret & J. Goupil (GANIL)

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



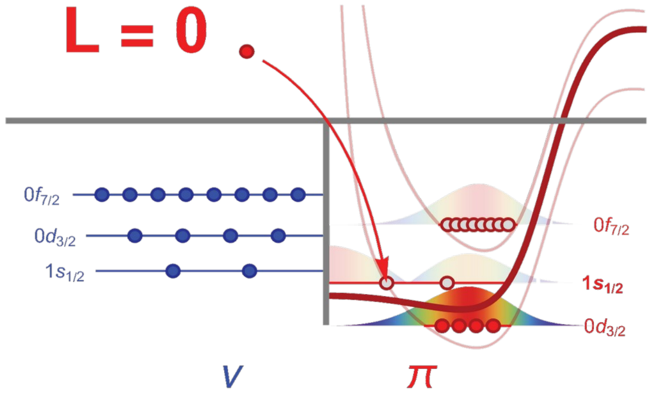


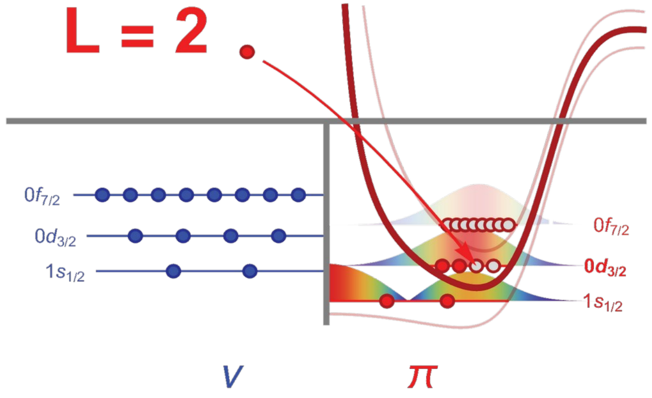




^{47}K

Triple coinc and simulation confirm the L=0 dominance

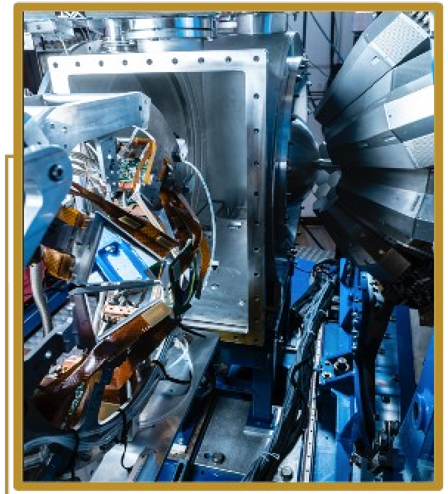


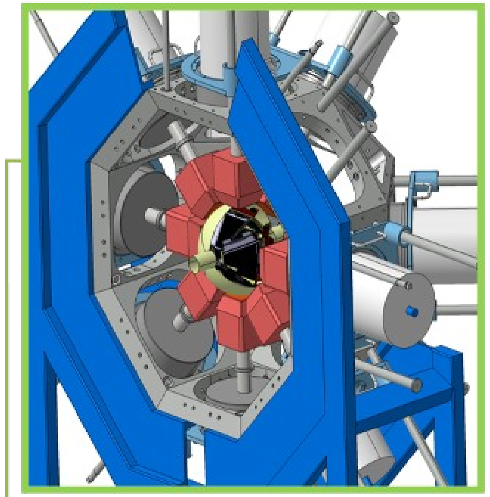


- L=2 transfer very much reduced !
- No direct gamma from 3/2$^+$ observed from AGATA+VAMOS
- Reduced transfer to 3/2$^+$
- High degree of occupancy of πd3/2 in ^{46}Ar inconsistent with SM calculations
- D.Brugnara et al., submitted

- Future opportunities @ GANIL and beyond

LISE Campaign @ GANIL





MUGAST-
AGATA-VAMOS
@GANIL

MUGAST-
EXOGAM-LISE
@GANIL

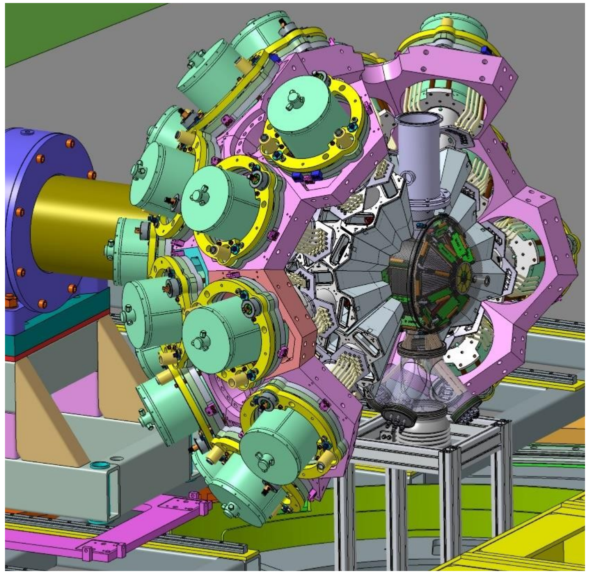
2021

2023-2024

2025

202x

SPES
exotic beams for science

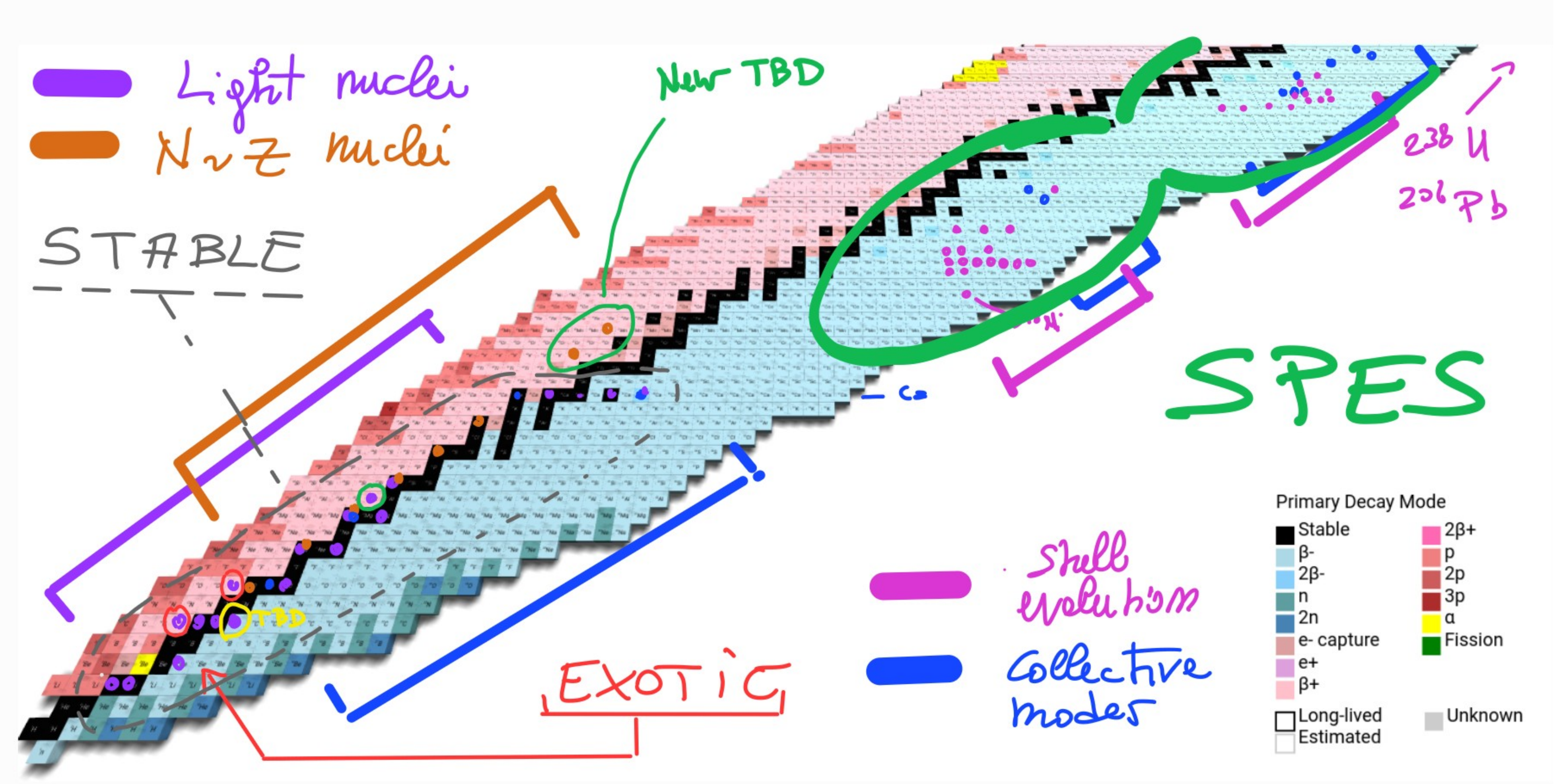


and SPES@LNL

Mid-term plan initiatives @ INFN national labs

https://web.infn.it/nucphys-plan-italy/

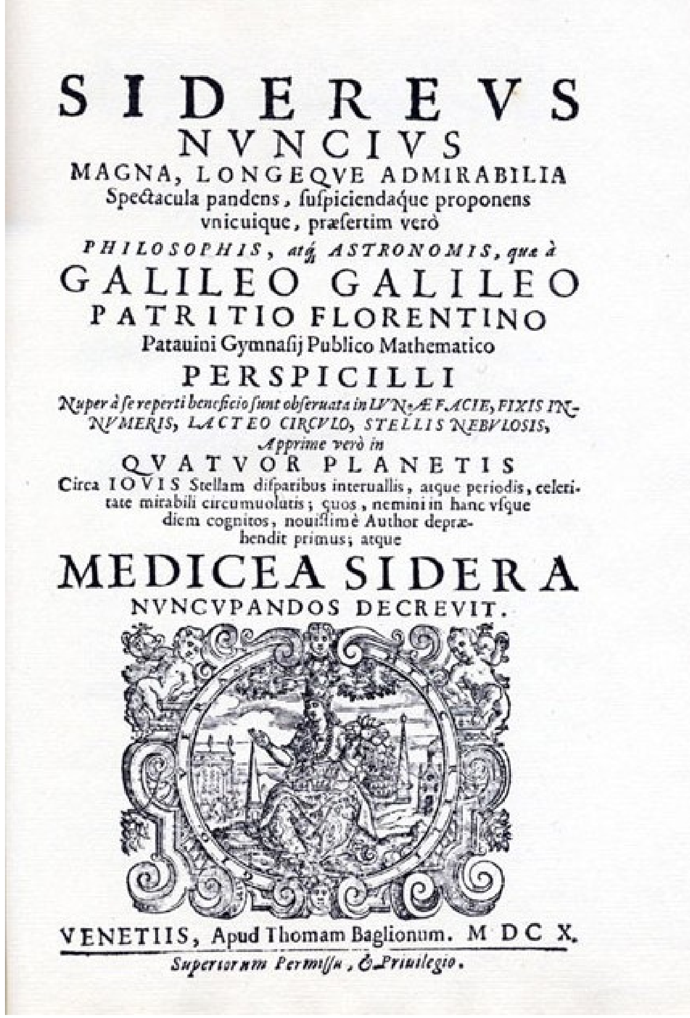
https://doi.org/10.1140/epjp/s13360-023-04249-x



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
- Awesome science campaign is ongoing at LISE-GANIL and next at SPES-LNL


"That's all Folks!"



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 INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author deprehendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

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

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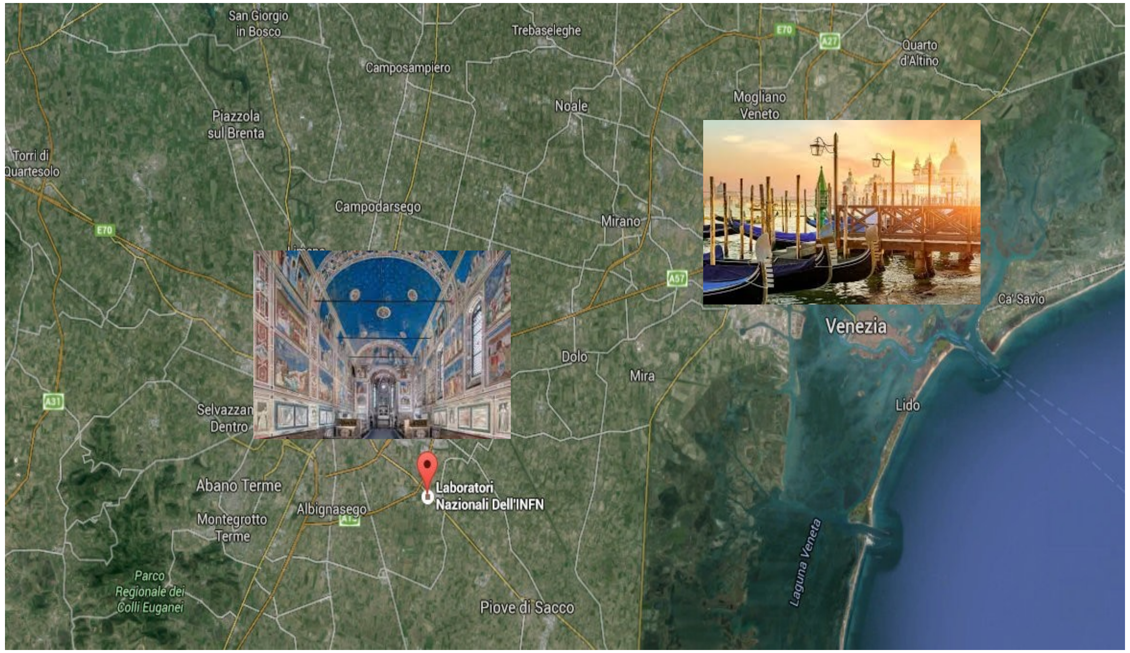
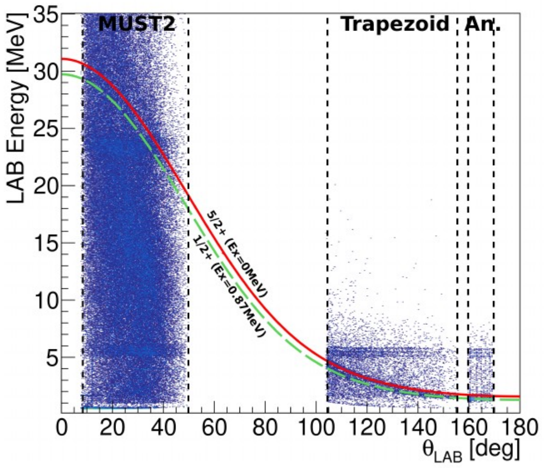
UNIVERSITÀ DEGLI STUDI DI PADOVA

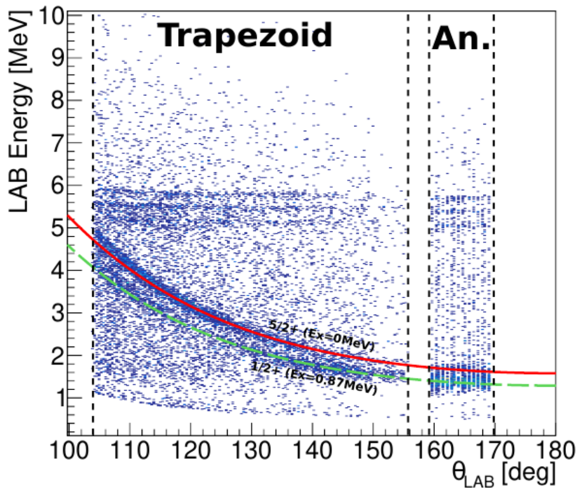

15 ottobre 2021
Laboratori Nazionali di Legnaro
LNL
60 anni
tra fisica nucleare e innovazione
INFN

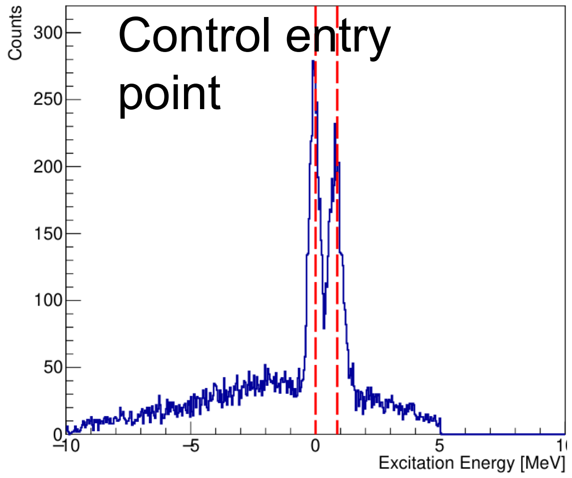

San Giorgio in Bosco
Trebaseleghe
Camposampiero
Quarto d'Altino
Noale
Mogliano Veneto
Piazzola sul Brenta
Torri di Quartesolo
Campodarsego
Mirano
Venezia
Ca' Savio
Dolo
Mira
Lido
Selvazzano Dentro
Abano Terme
Laboratori Nazionali Dell'INFN
Albignasego
Montegrotto Terme
Laguna Veneta
Parco Regionale dei Colli Euganei
Piove di Sacco

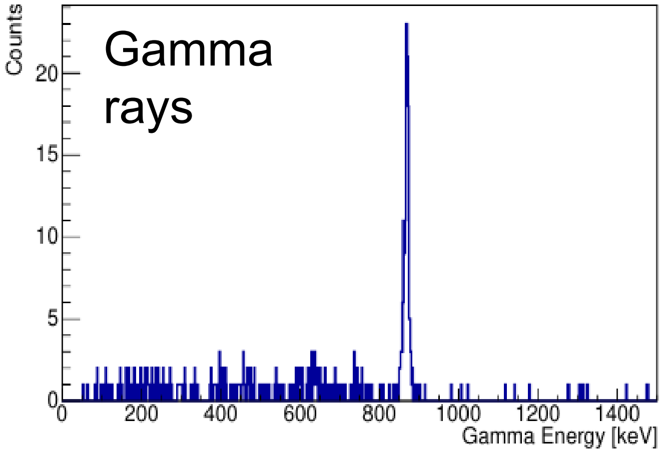
MUGAST ccommissioning: $^{16}O(d,p)$

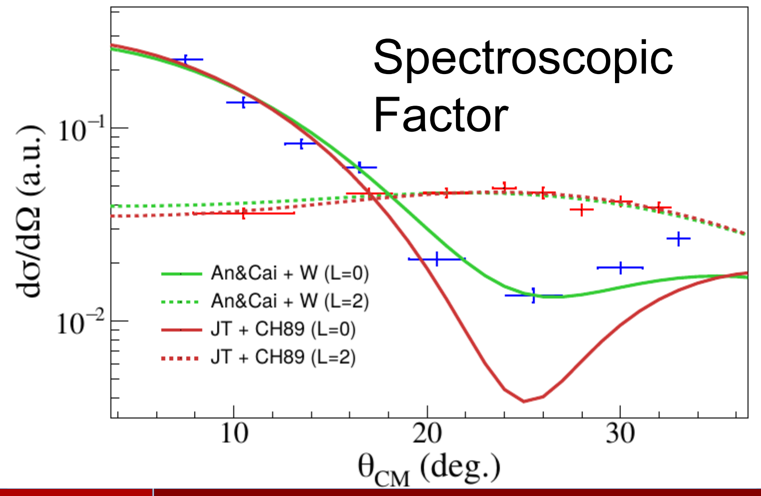
A.Raggio – Exp analysis
J.Casal – Theory





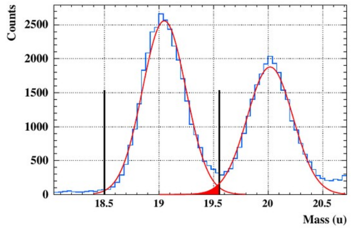


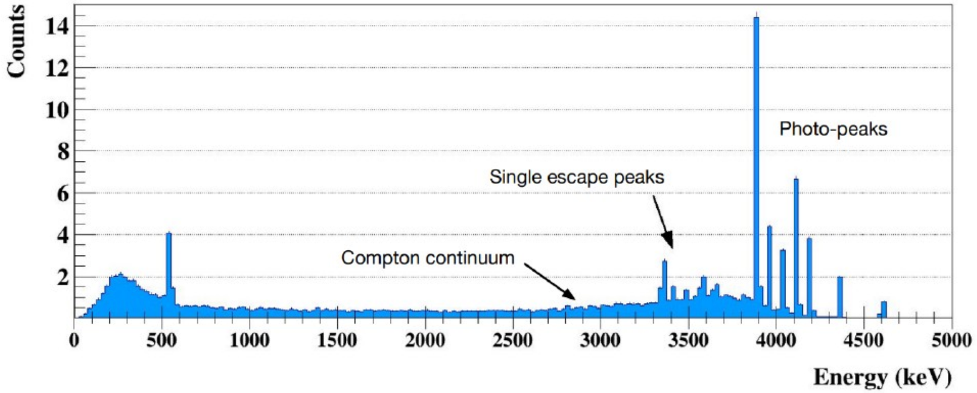


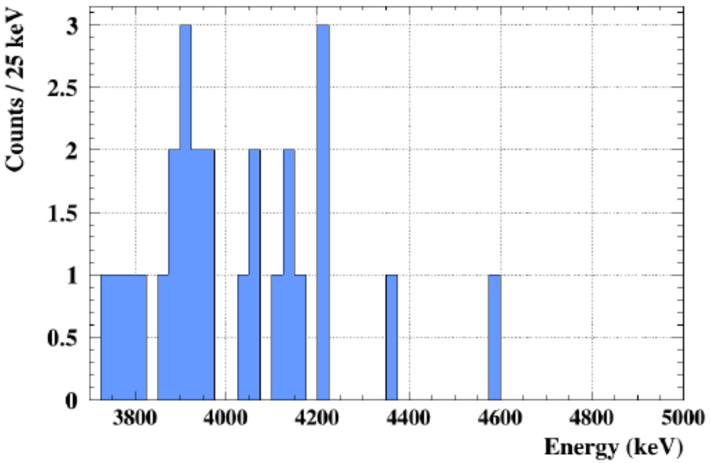


Background estimate

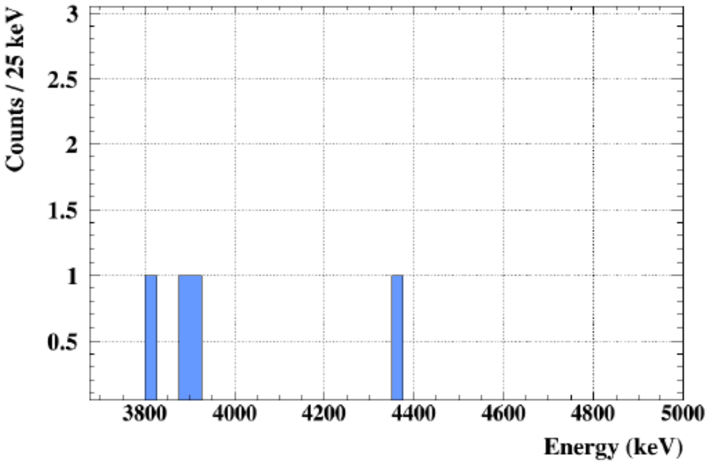
- Compton via simulation and peak normalization and gates at different exc energy: 0.67 count 4000 and 4075
- Leak from other channel ($^{20}Ne^{+9}$): 0.1 count between 4000 and 4075







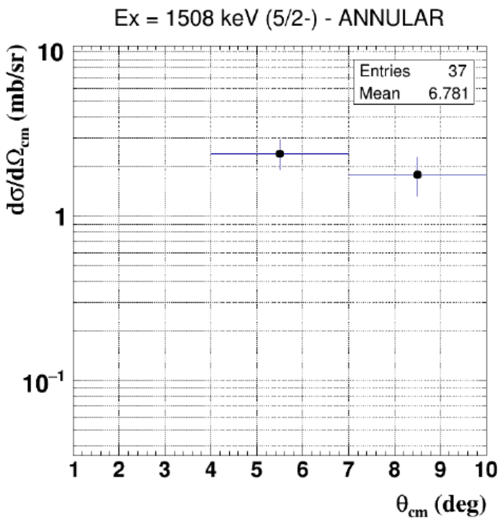
(a) E_x region: 3.0 - 5.2 MeV

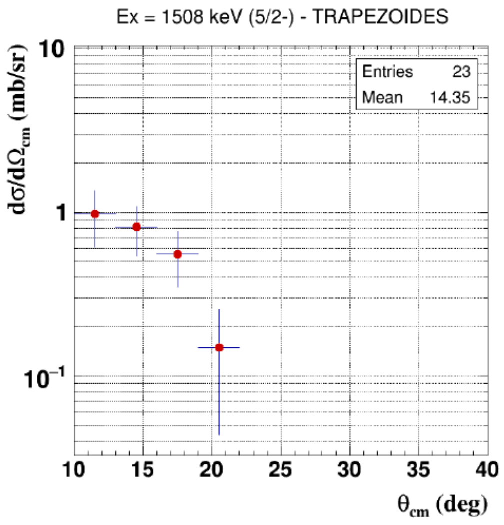


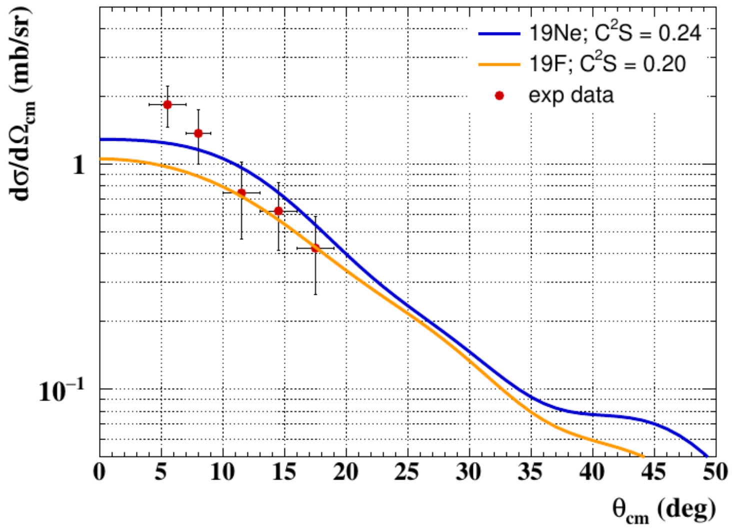
(b) E_x region: 5.2 - 7.4 MeV

C^2S_α

- Bench mark over bound states of 19Ne: 1508 keV
- Transferred quantum number form SM calculations
- Double check with the SF of the mirror nucleus 19F, assessed in literature
- Angular distribution fit 0.24+-10% or integral of the cross section 0.23+-10%
- Extrapolation to the unbound states (low stat) second method: $0.06^{+0.08}_{-0.04}$







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	
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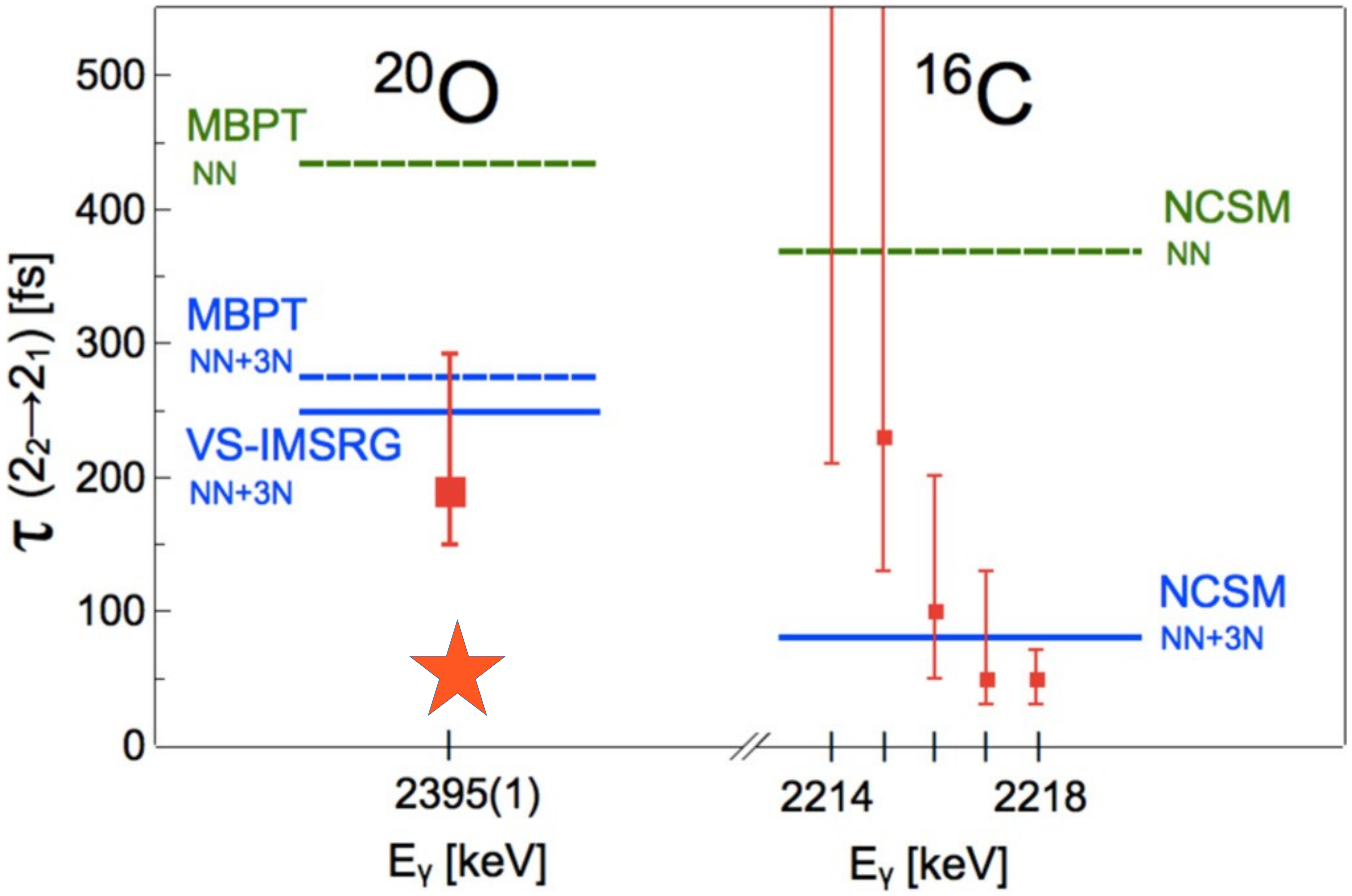
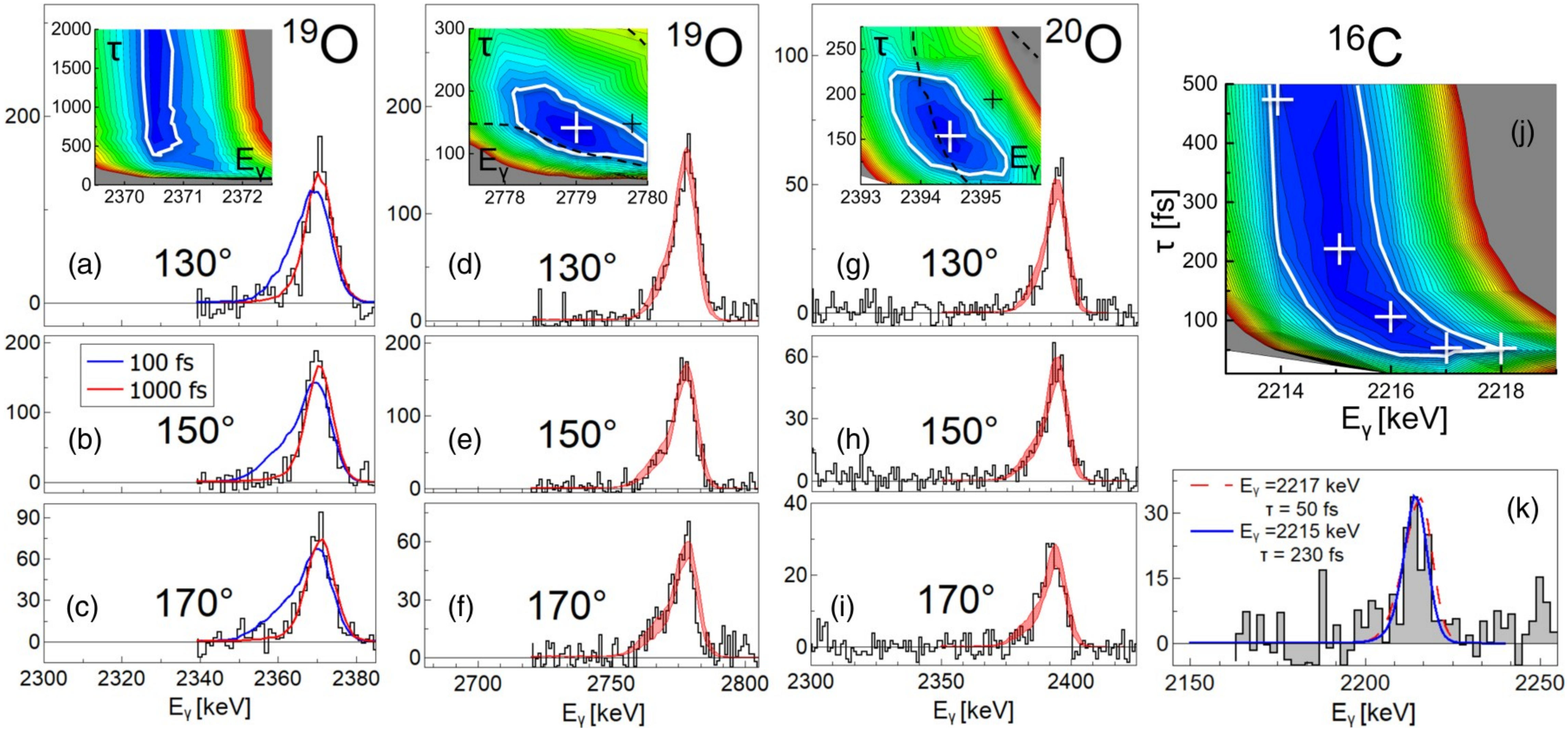
4379	128^{+123}_{-68}	160^{+110}_{-70}	150(6)
4600	$3.4^{+4.4}_{-2.2} \cdot 10^3$	$24^{+33}_{-10} \cdot 10^3$	$96(24)\cdot 10^3$



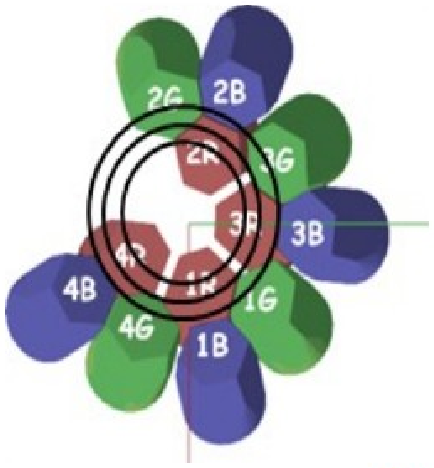
Ciemala_PhysRevC.101.02130
3

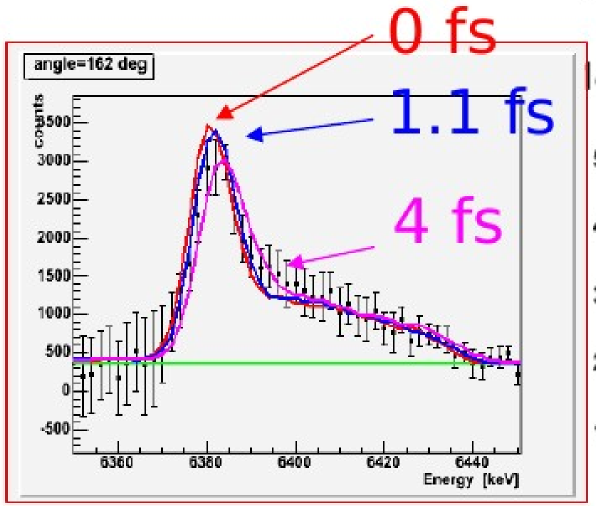
- In medium symilarity renormalization group
- No core shell model
- New calculation ongoing

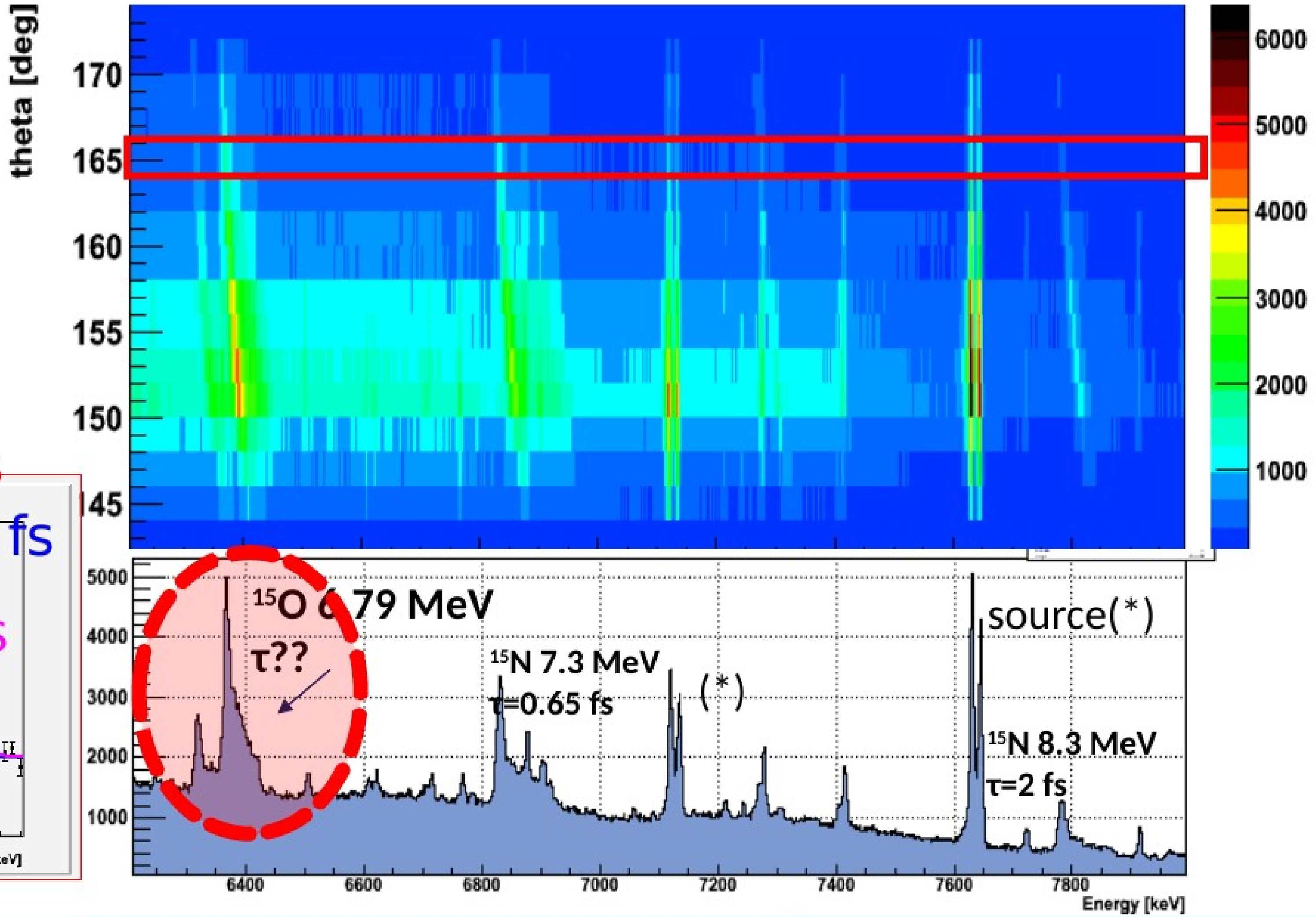


^{19}O
^{19}O
^{20}O
^{16}C
(a) 130°
(b) 150°
(c) 170°
(d) 130°
(e) 150°
(f) 170°
(g) 130°
(h) 150°
(i) 170°
(j)
(k)
100 fs
1000 fs
E_γ =2217 keV
τ = 50 fs
E_γ =2215 keV
τ = 230 fs
τ [fs]
E_γ [keV]

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:

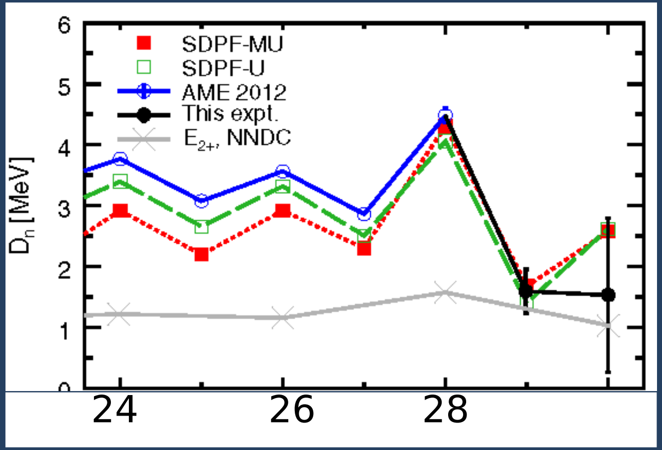
Proton shell structure at N=28 :

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)

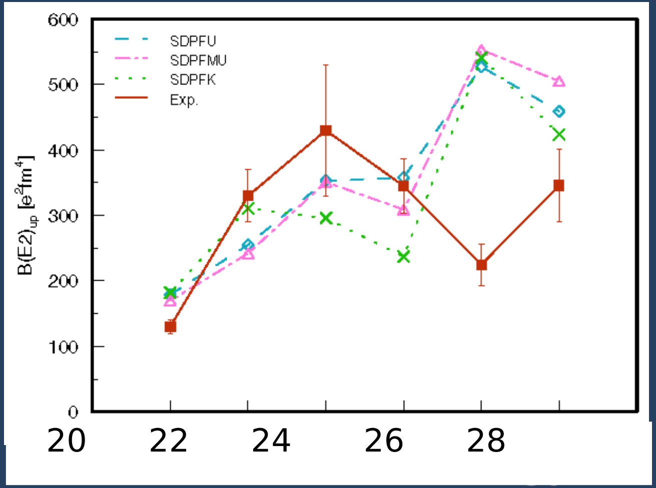
- **Proton shell structure at N=28 :**

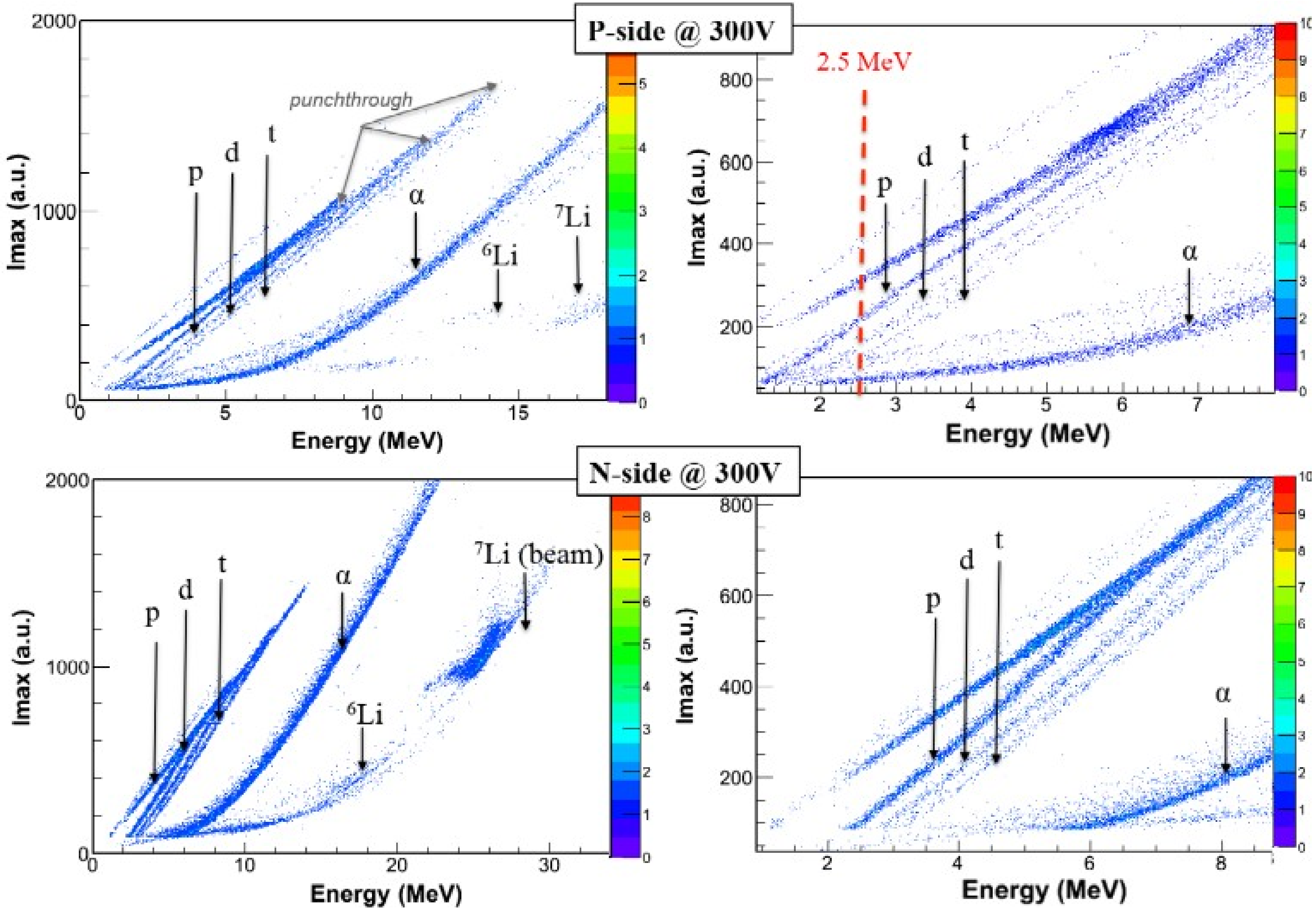
inversion of $\pi s_{1/2}$ and $\pi d_{3/2}$

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)



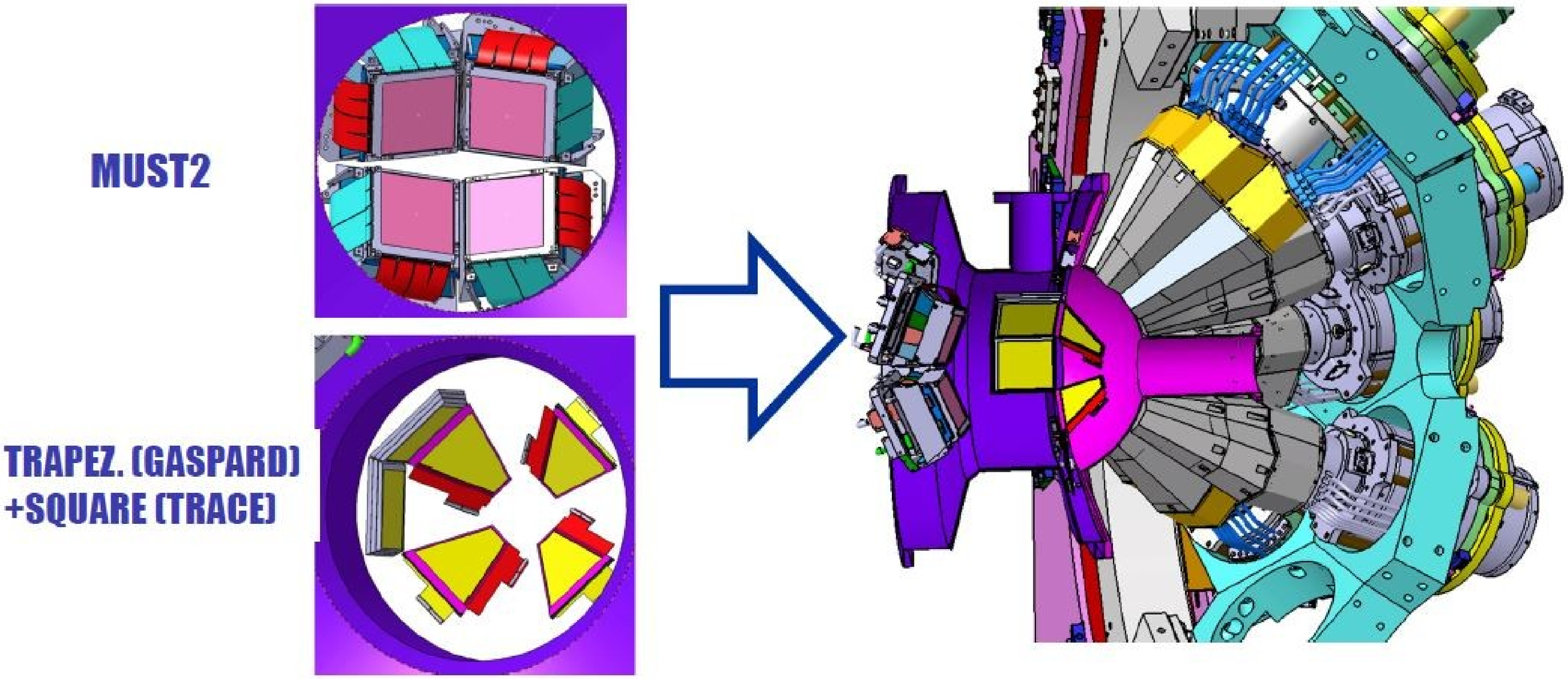


M. Assié et al., Eur. Phys. J A **51** (2015) 11

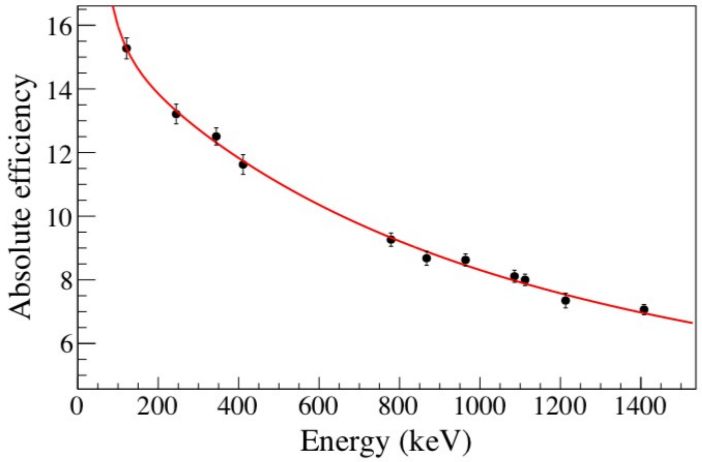
Once upon a time .... (2015)

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

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

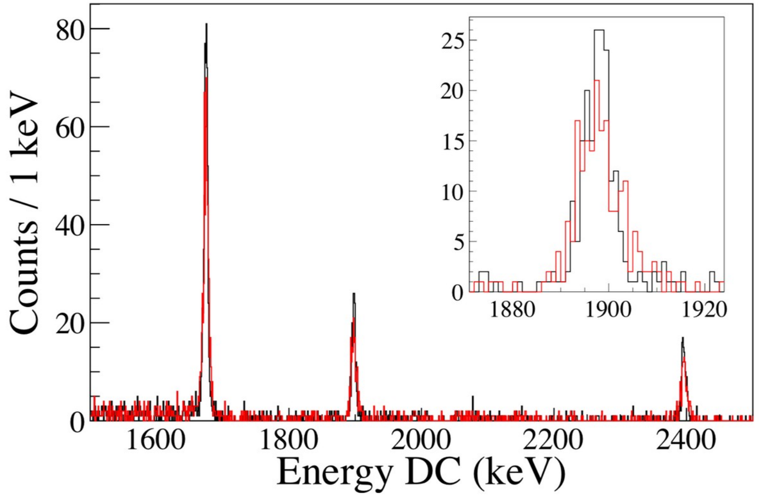


Performance set-up



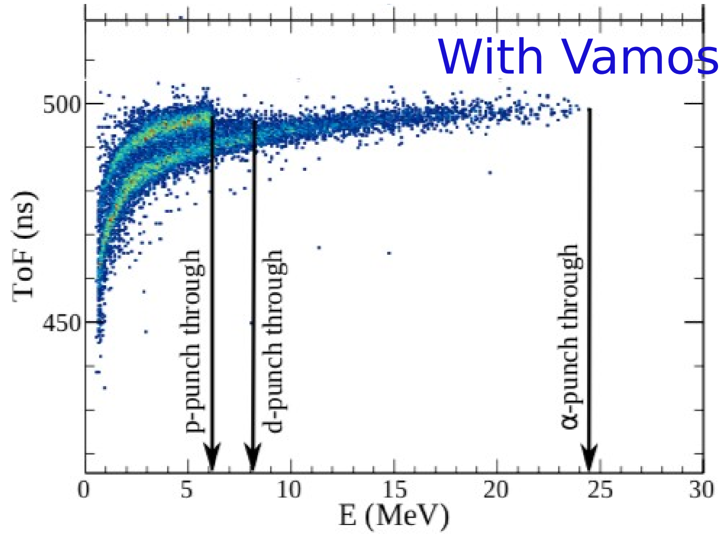
AGATA abs ε_{ph}

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



Doppler correction using:

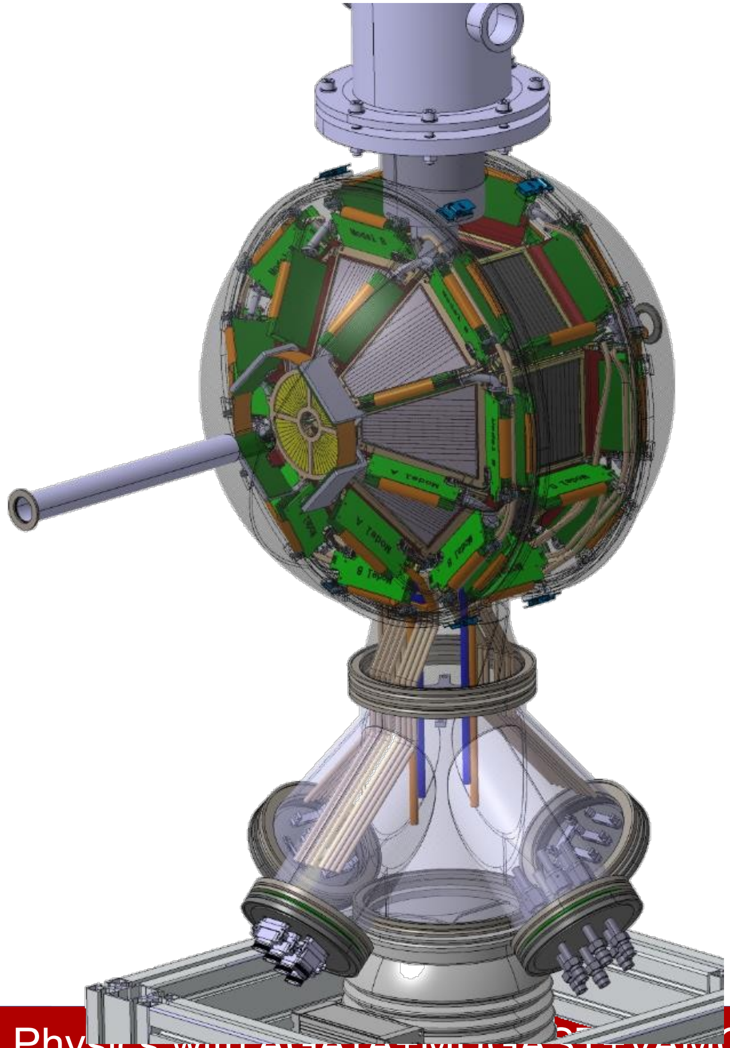
- β beam at mid-target(red, 10 keV FWHM)
- Using light particle info in MUGAST (black, 7 keV FWHM)



- Particle ID with MUGAST-VAMOS

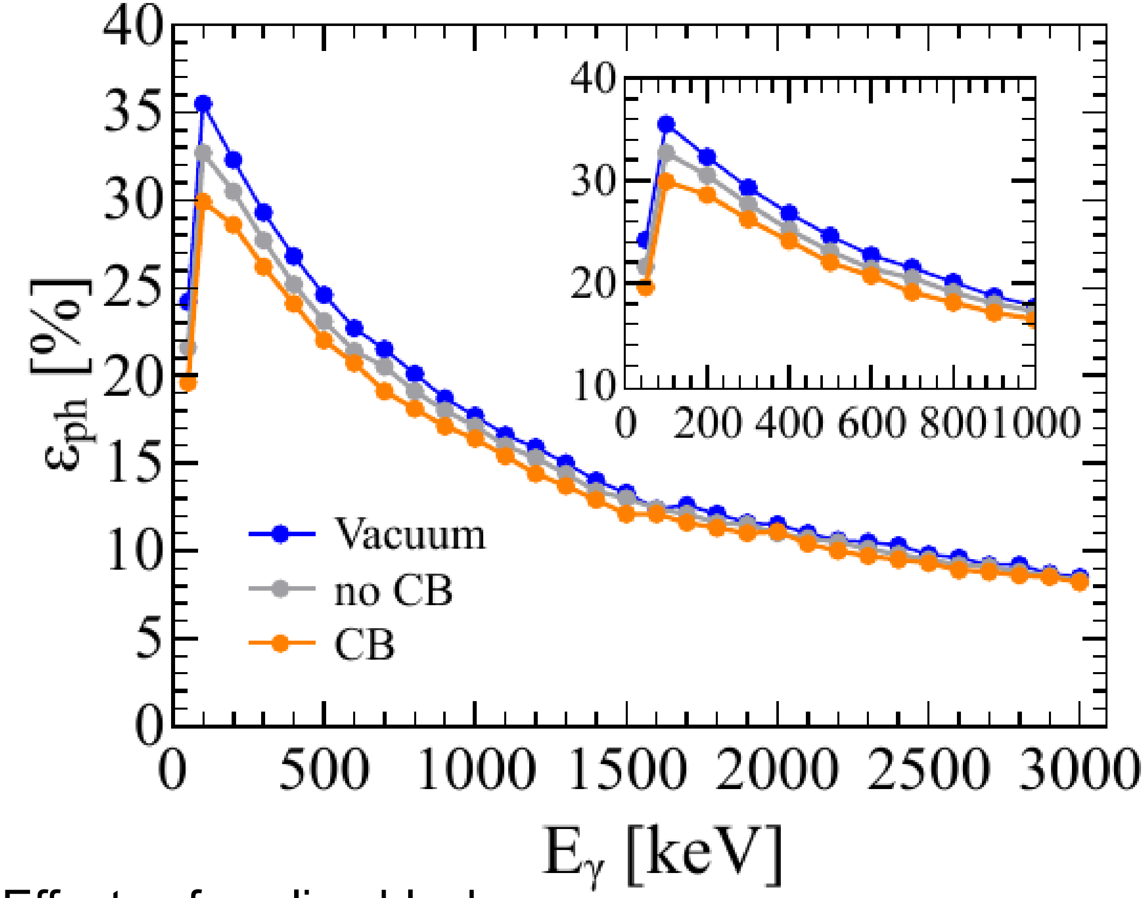
M. Assié et al, NIMA (2021)

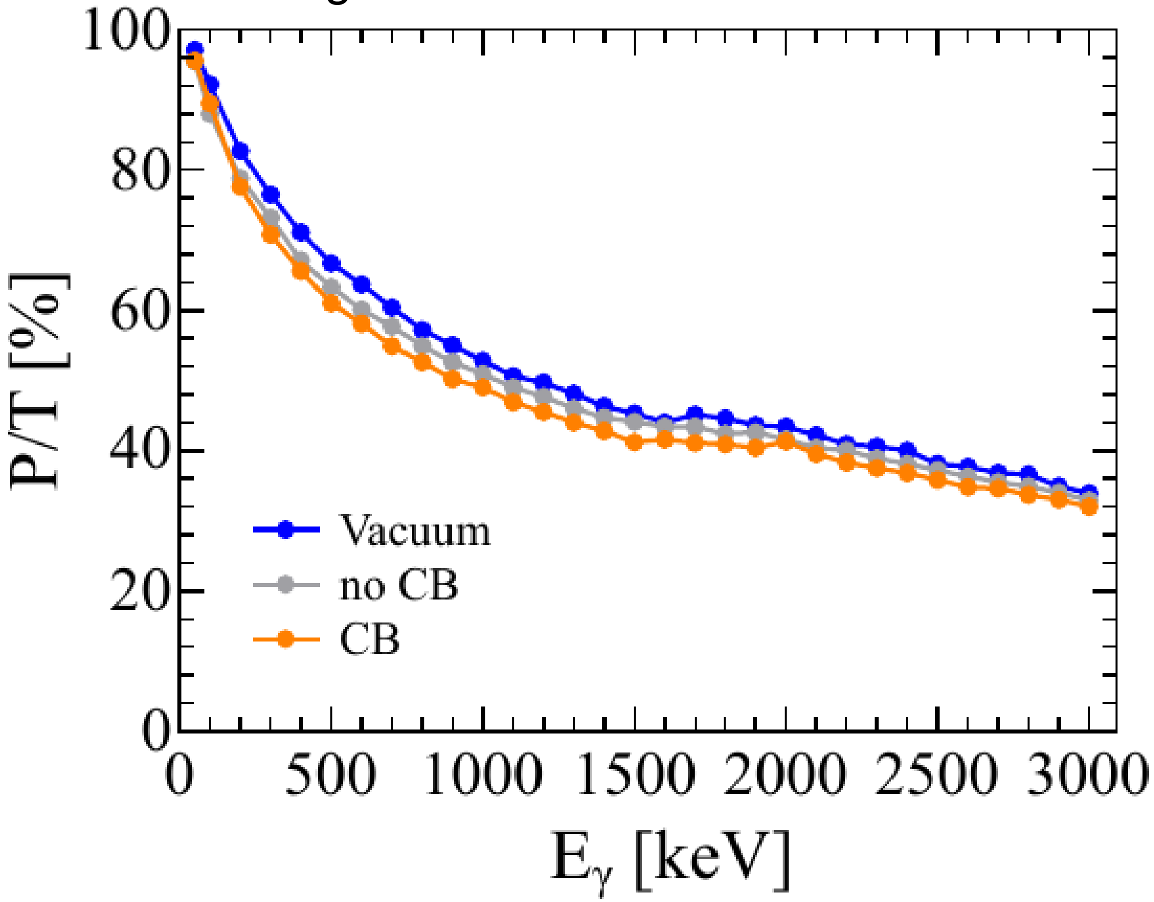
Option for the reaction chamber



Simulations: photopeak efficiency and P/T ratio

Credit for simulations Simone Bottoni & Eugenio Gamba

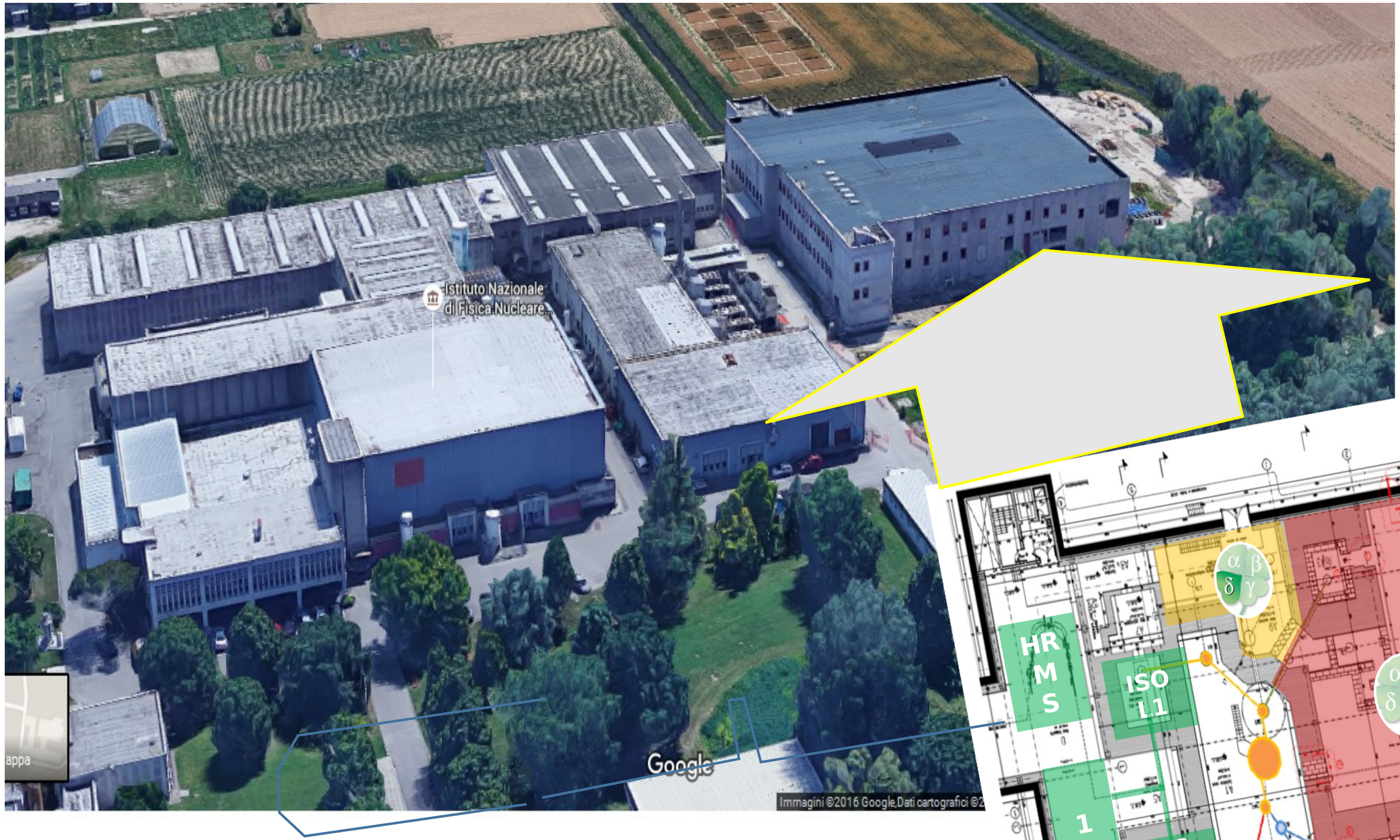


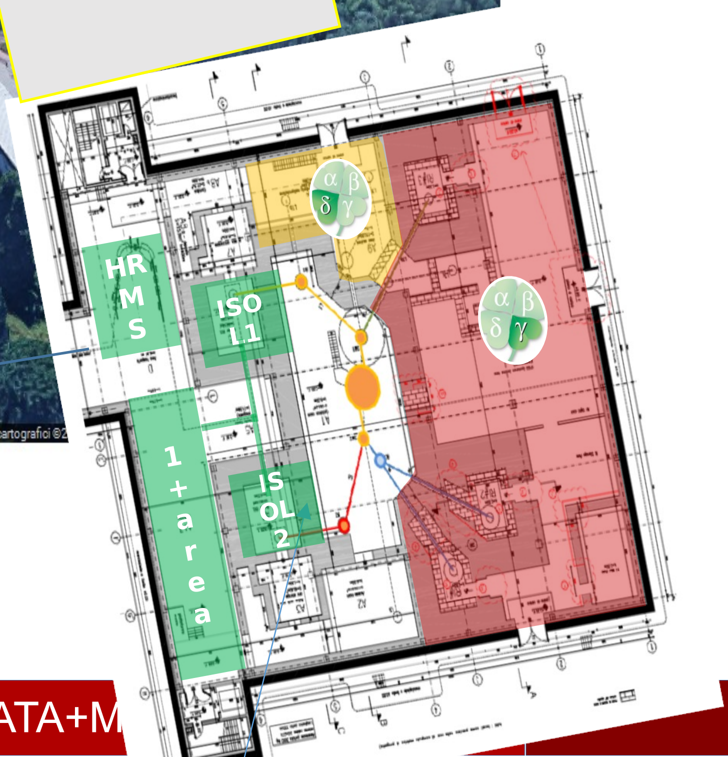


Effects of cooling blocks:

- Absorption at low energies
- Worsening of efficiency and P/T
- Acceptable? Other solutions? Aluminum?

SPES - Layout

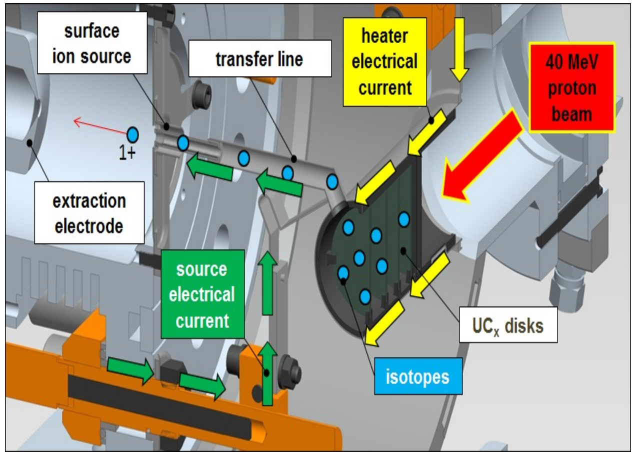




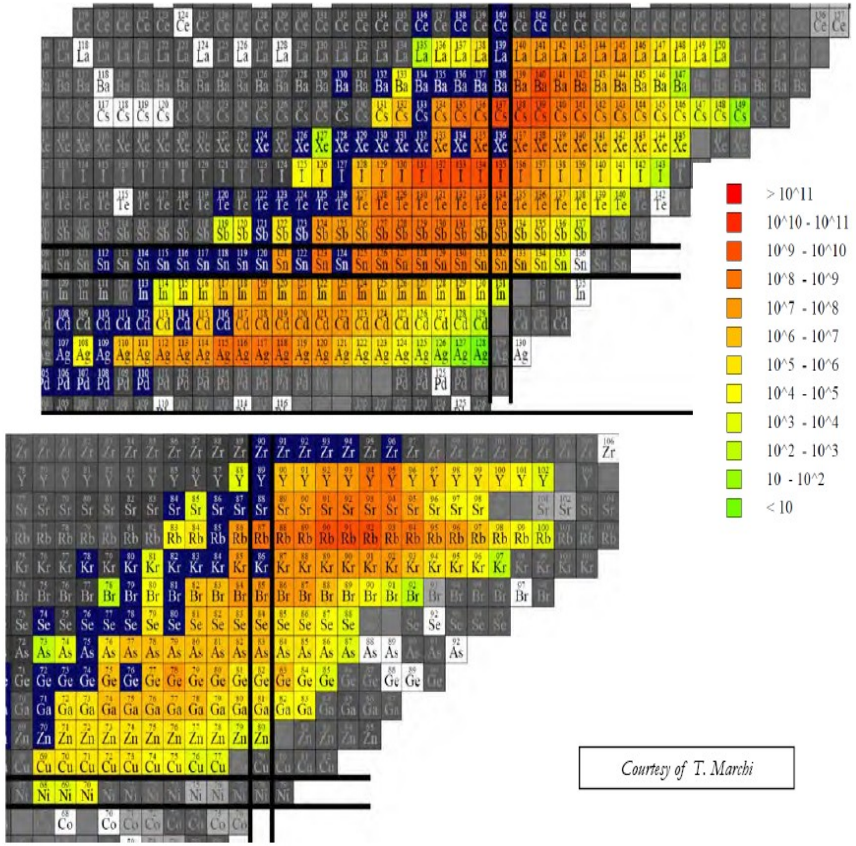
- 2^{nd} generation ISOL facility:pure and intense beam
- 10^{13} fissions/s

Yield

- UCx Target
- (... + not fissile also foreseen)

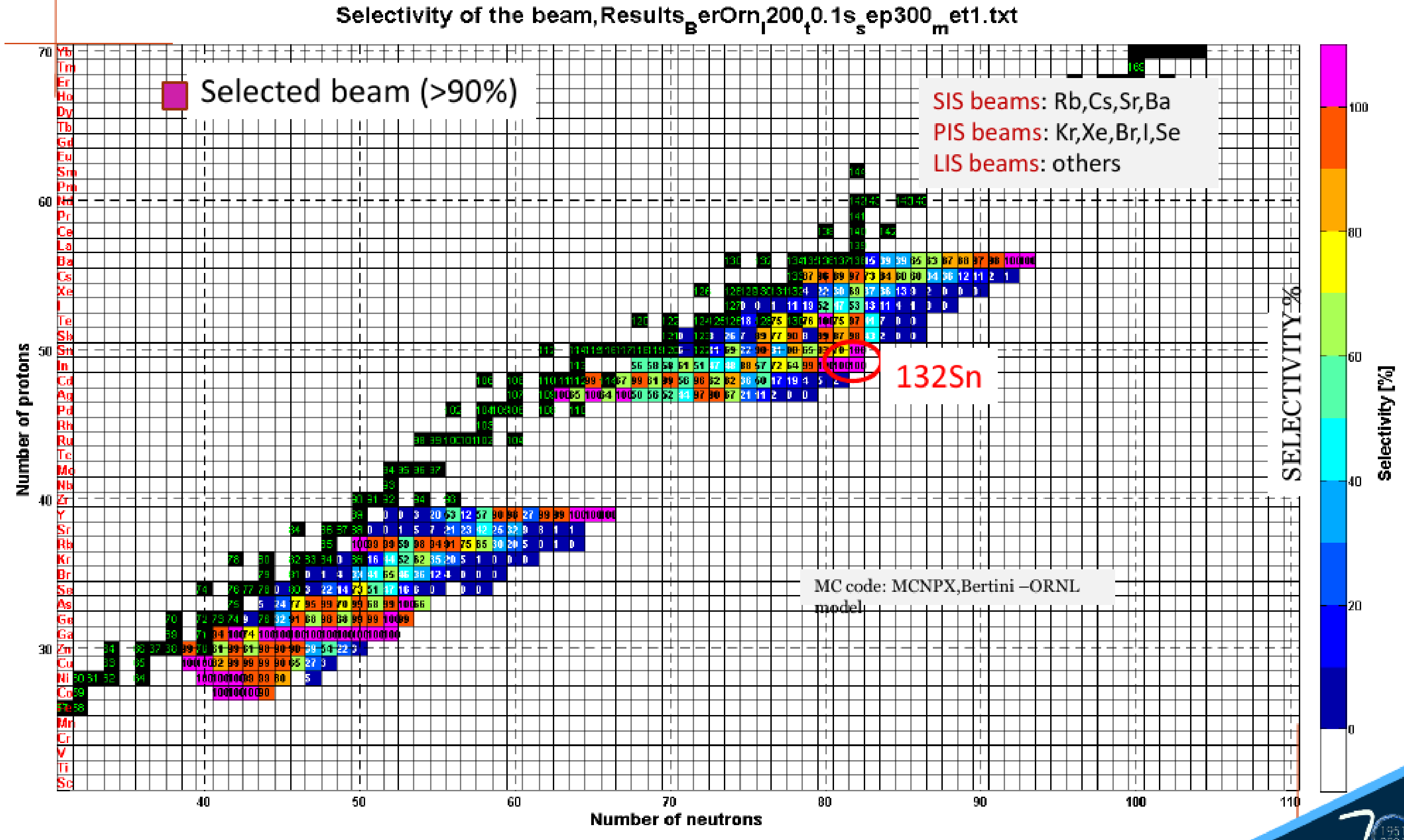


- Expected intensity for reaccelerated beams

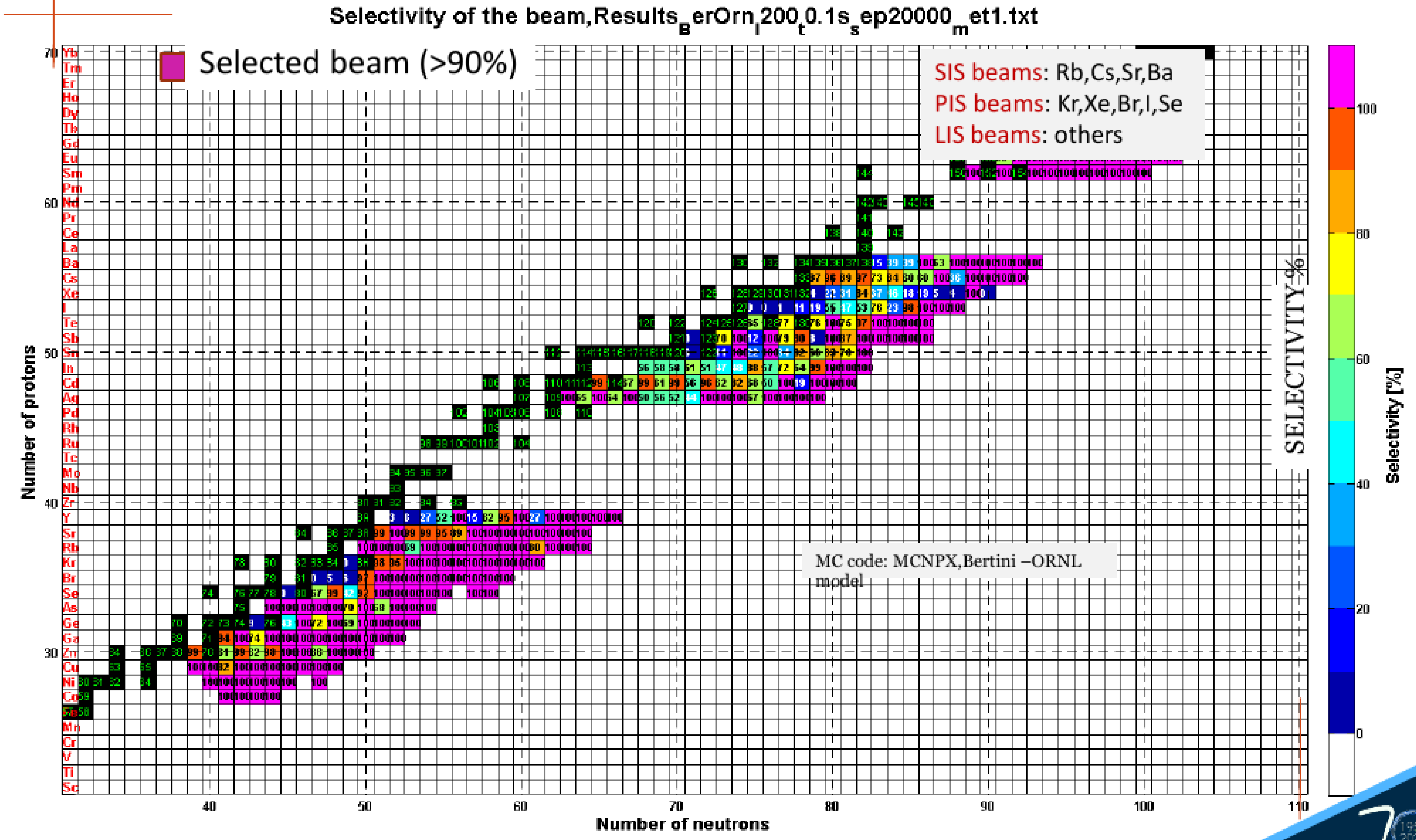


- **MCNPX Calculation**
- **BERTINI – ORNL** (FF cross- sections)
- **Release** & **ionization efficiency** in agreement and re-scaled on **HRIBF experimental values** and **currents** (**200μA/5μA**)

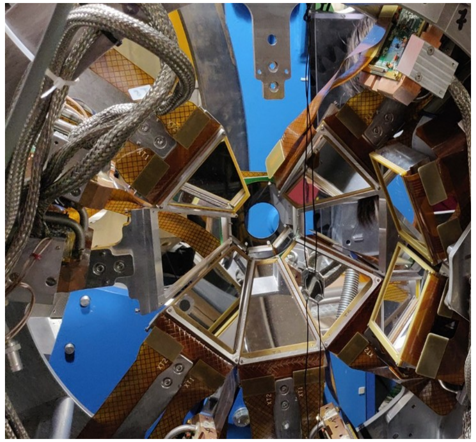
Beam selectivity with LRMS (ΔM/M=1/200)

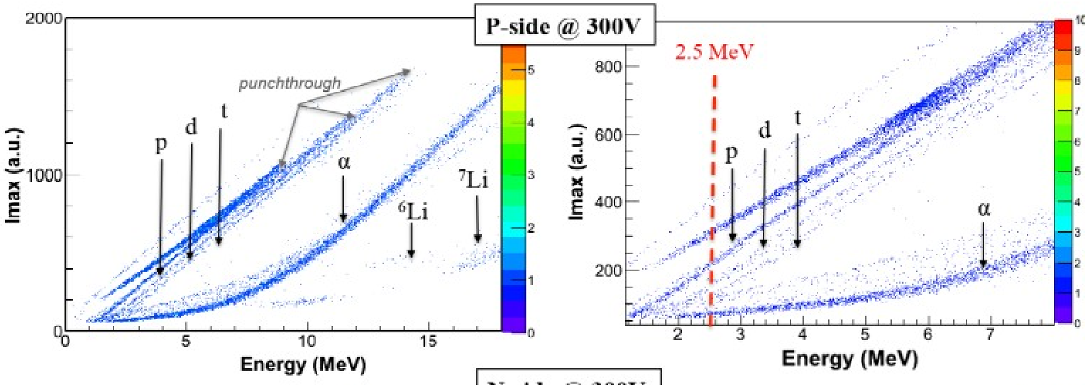


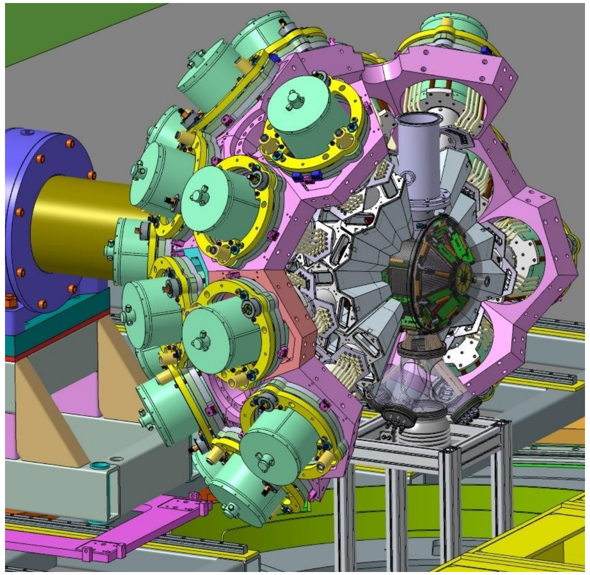
Beam selectivity with HRMS (ΔM/M=1/20000)



GRIT (France-Italy-Spain-UK)

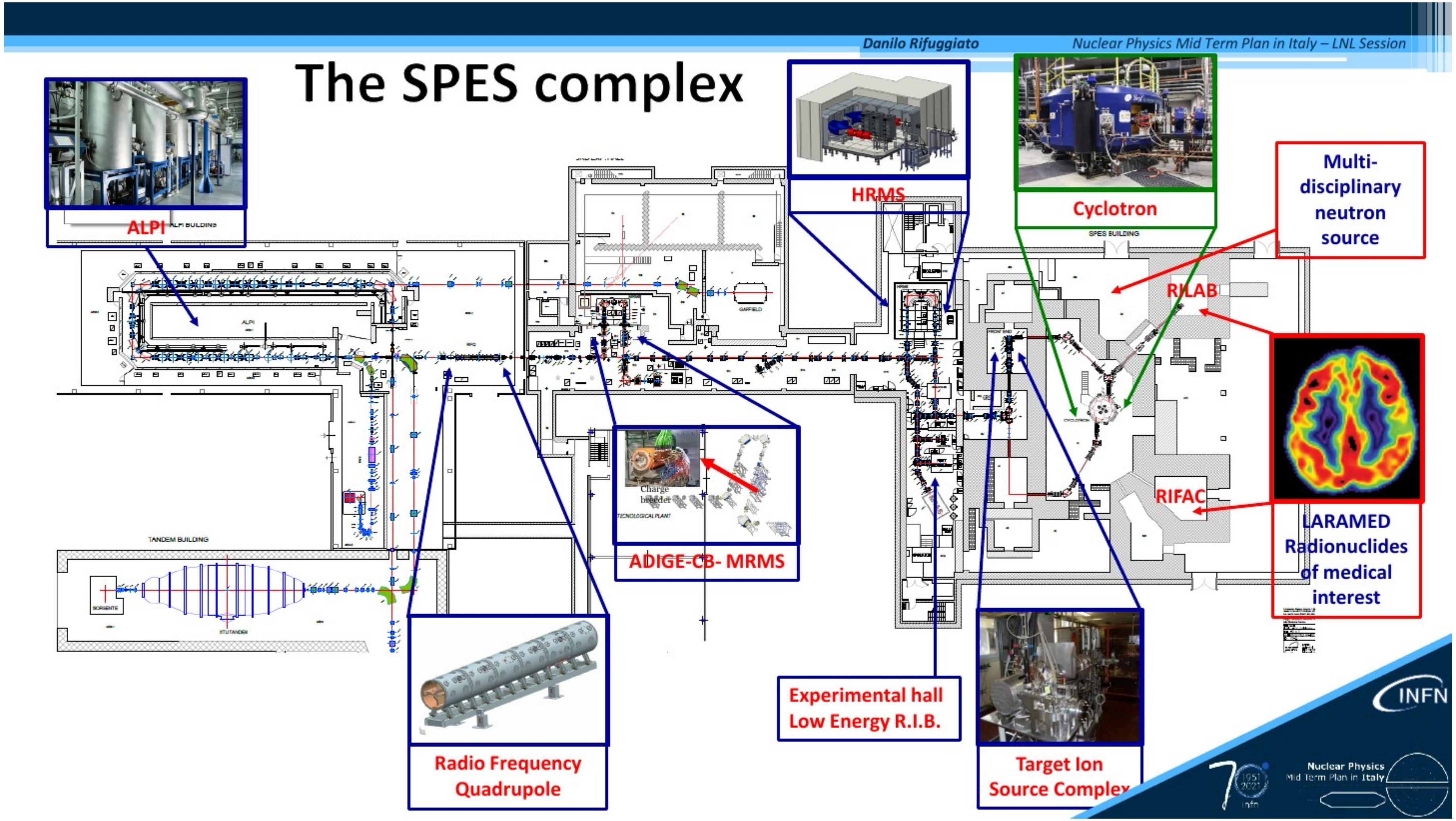




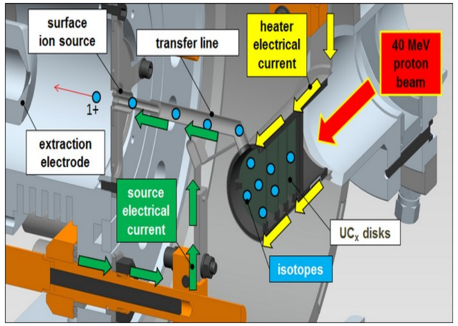


GRIT: **G**ranularity, **R**esolution, **I**ntegration, **T**ransparency,
+ modularity + embedded PSA + cryo target compatibility

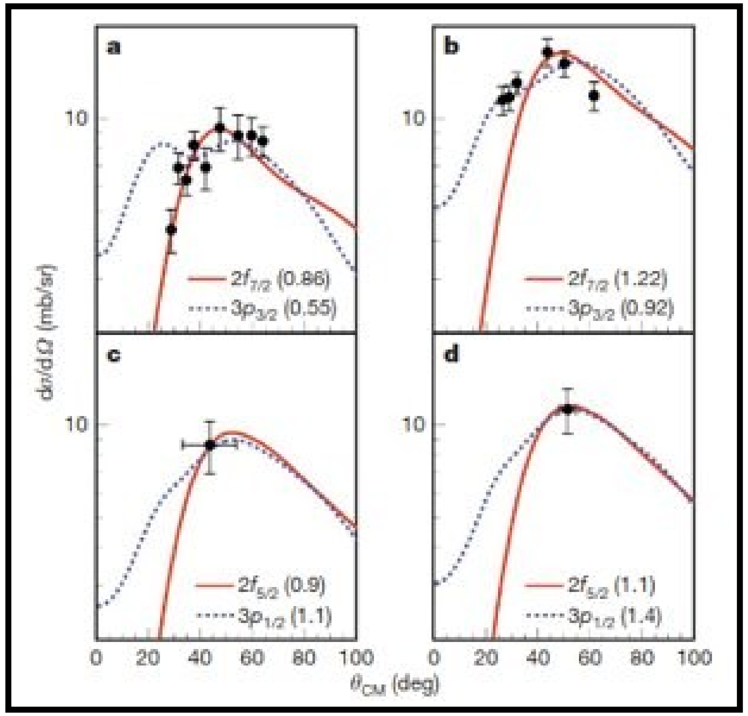
ISOL beam factory



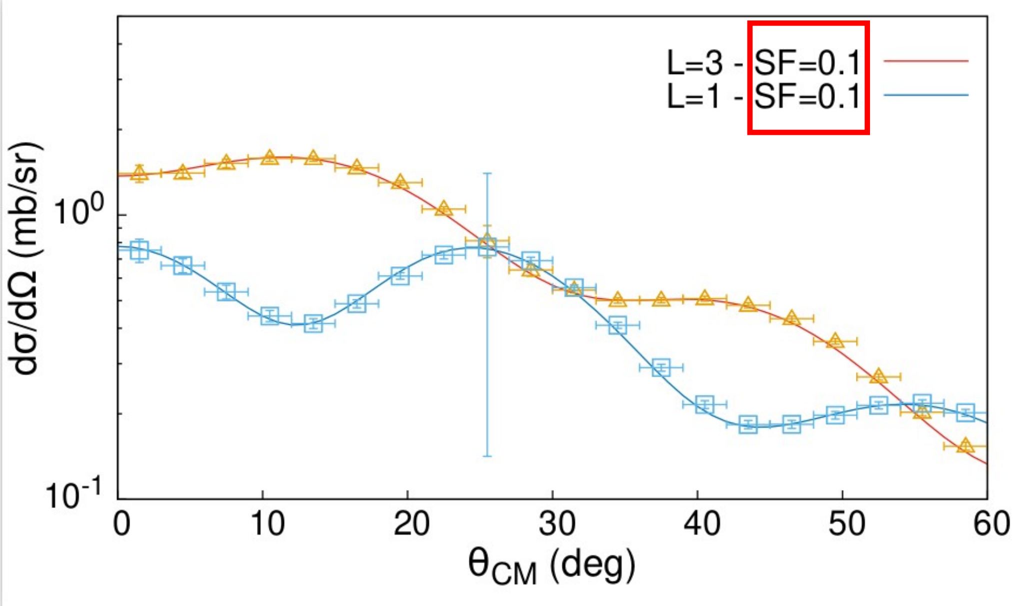
- UCx Target
- + not fissile also foreseen



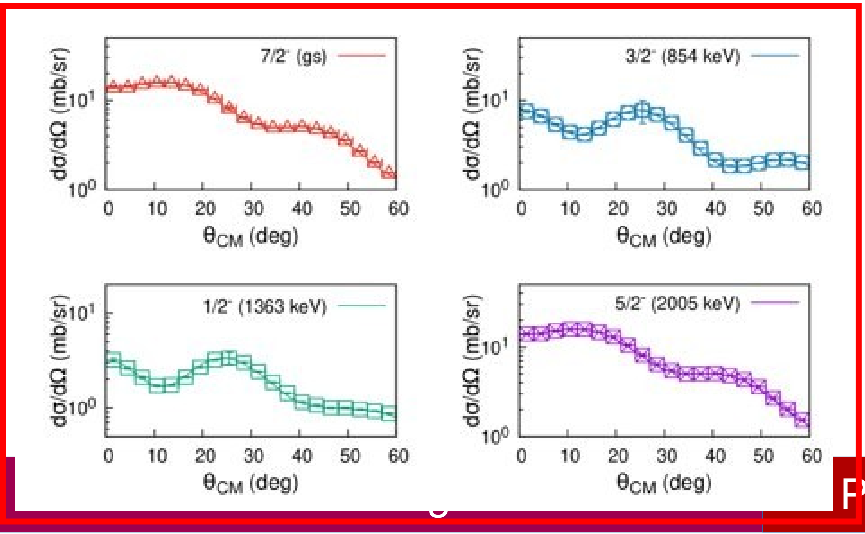
Simulations: the $^{132}Sn(d,p)^{133}Sn$ case



K. L. Jones et al., Nature 09048 (2010) 454



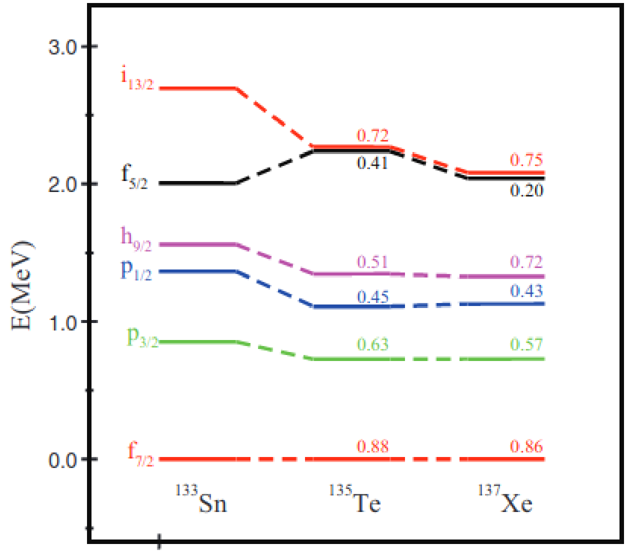
GRIT@SPES



The large beam intensity and cross sections allow to detect and characterize also small fragments of single-particle strength.

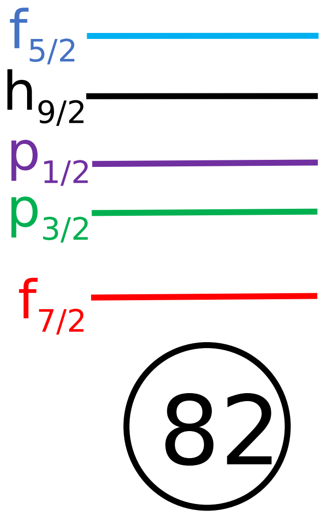
Possibility also to detect higher-ℓ states, like the $h_{9/2}$. Predicted cross section for the transfer to the $9/2^-$ state is of the order of few mb.

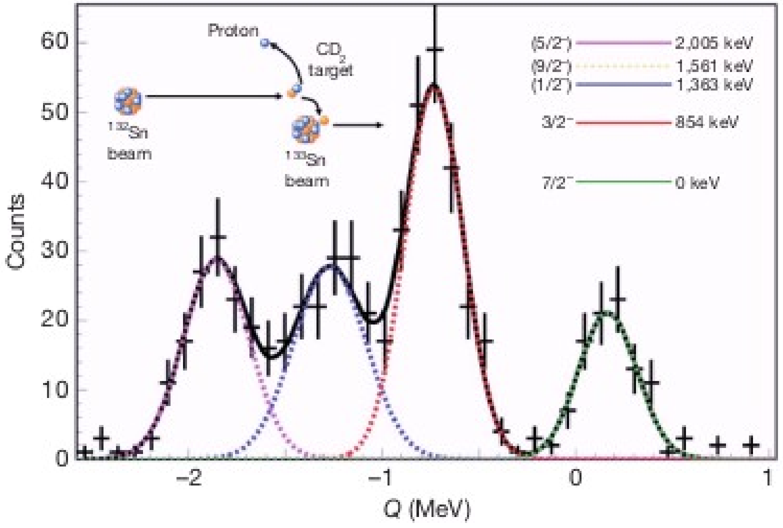
A physics case: shell evolution at N=82



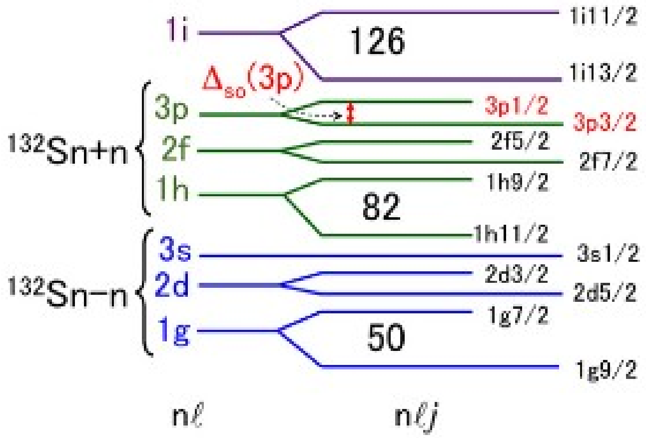
L. Coraggio et al., Phys. Rev. C **87** (2013) 034309

Shell evolution

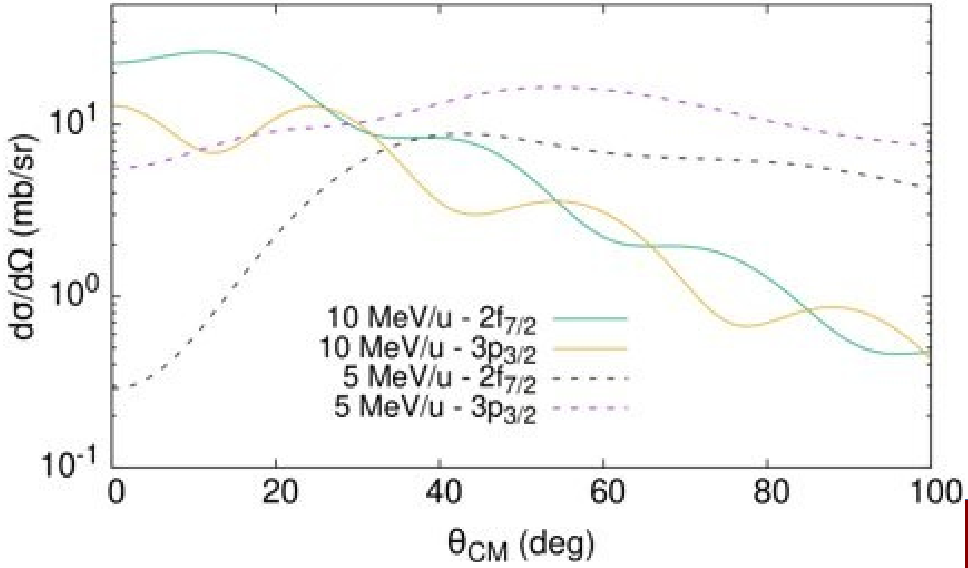




K. L. Jones et al., Nature 09048 (2010) 454

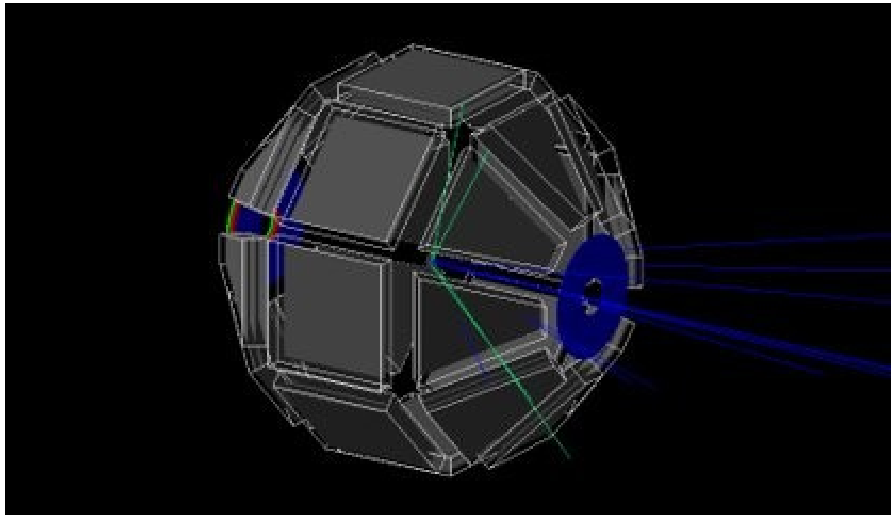


Spin-orbit splitting

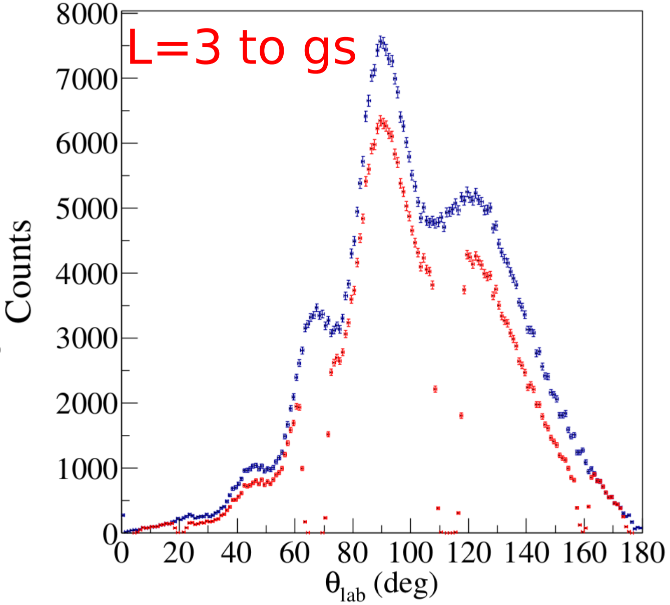


R. Orlandi et al., Phys. Lett. B **785** (2018) 615

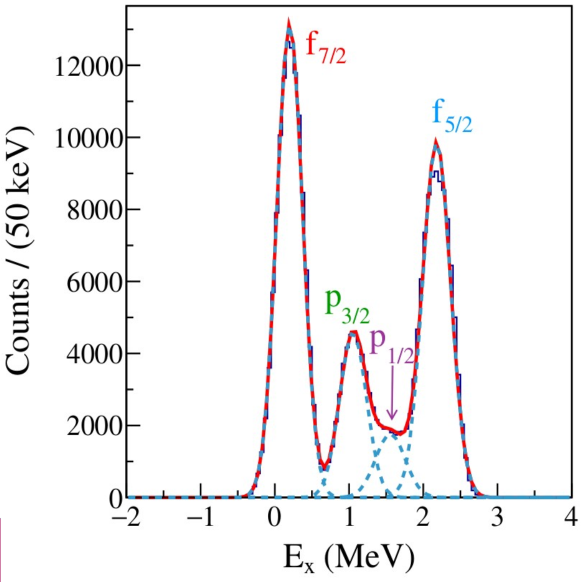
Simulations: the $^{132}Sn(d,p)^{133}Sn$ case



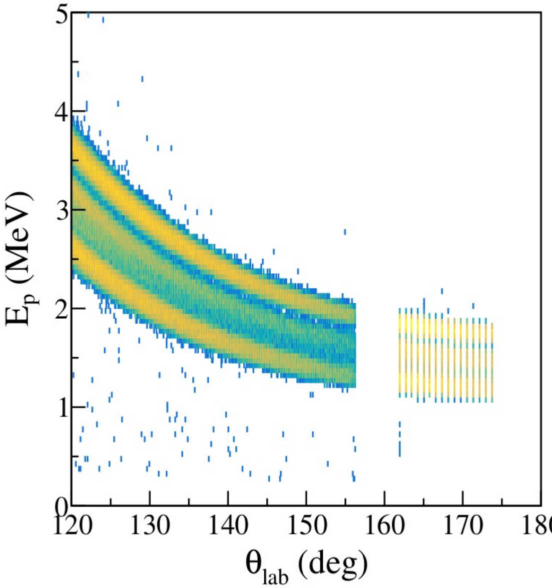
Simulations done with *nptool* (thanks to A. Matta for the detector file).
- Beam intensity: 10^6 pps;
- Target thickness: CD_2, 0.5 mg/cm^2;
- SF = 1 for all states

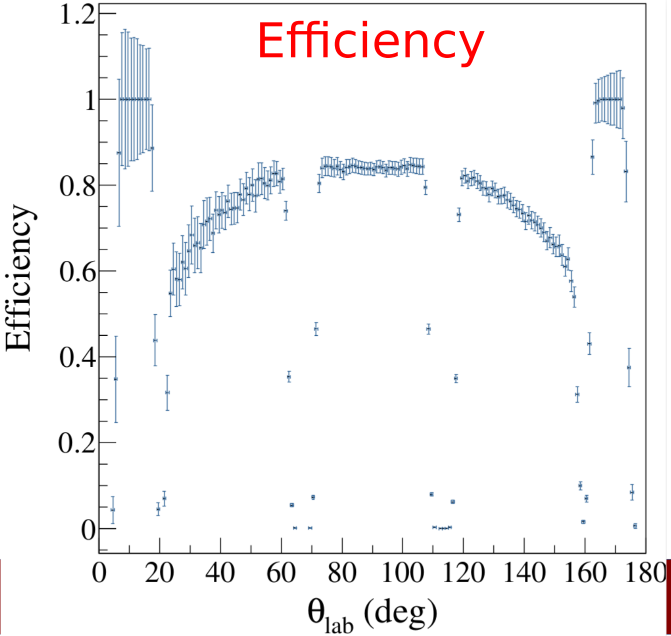


E* distribution



Kinematic lines





PARTIAL WIDTH CALCULATION

UNIVERSITY of York

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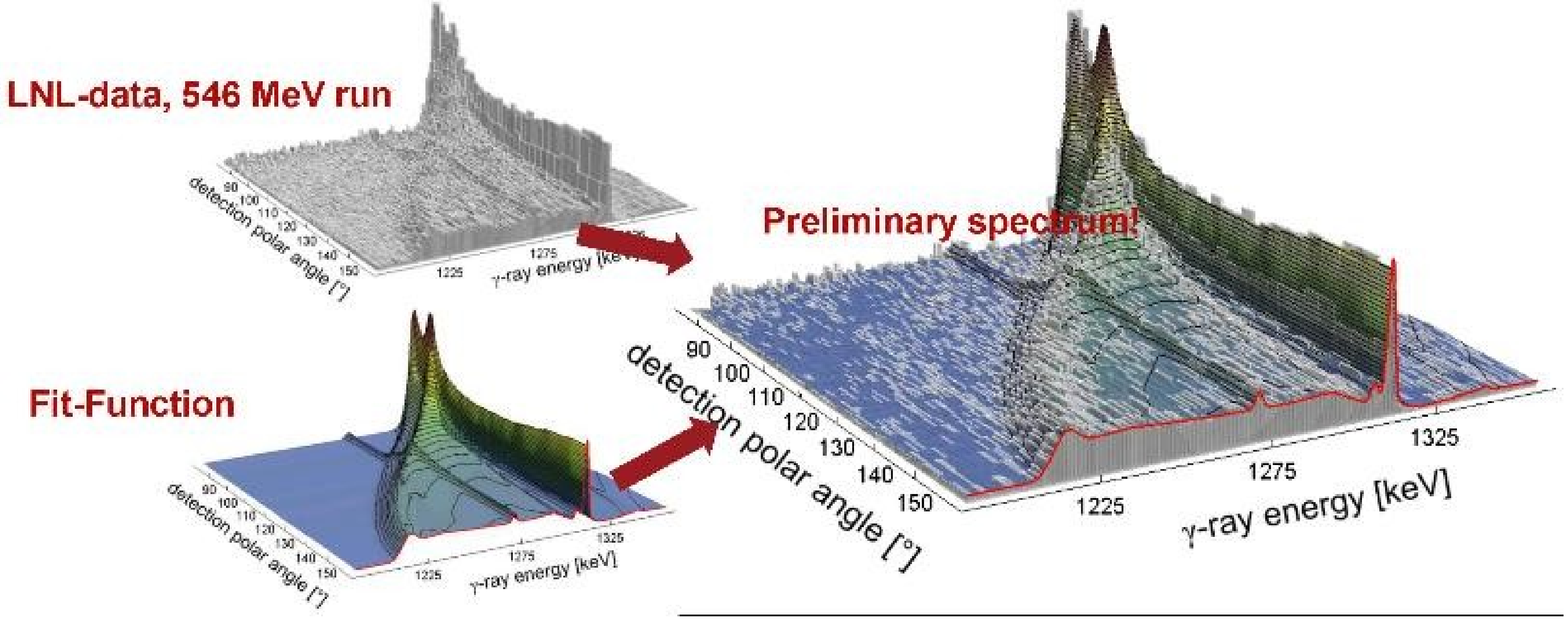
4600	$3.4^{+4.4}_{-2.2} \cdot 10^3$	$24^{+33}_{-10} \cdot 10^3$	$96(24)\cdot 10^3$

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

The Future

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

THE EUROPEAN PHYSICAL JOURNAL A

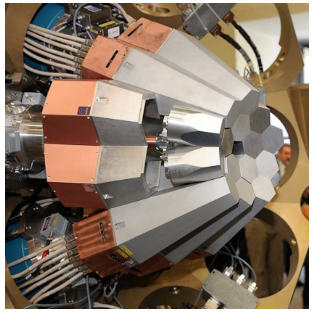
Review

Physics opportunities with the Advanced Gamma Tracking Array: AGATA

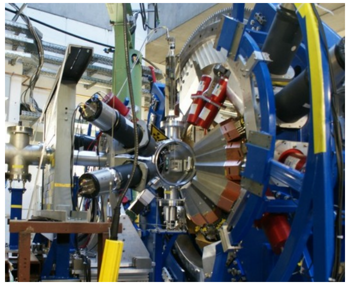
W. Korten[9,a], A. Atac[30,35], D. Beaumel[23], P. Bednarczyk[14], M. A. Bentley[34], G. Benzoni[21], A. Boston[17],

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

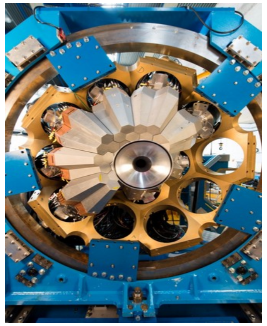
AGATA@LNL



AGATA@GSI



AGATA@GANIL



AGATA@LNL

M. Zielinska physics coordinator

2009 → 2011 → 2014 → 2021 → FAIR

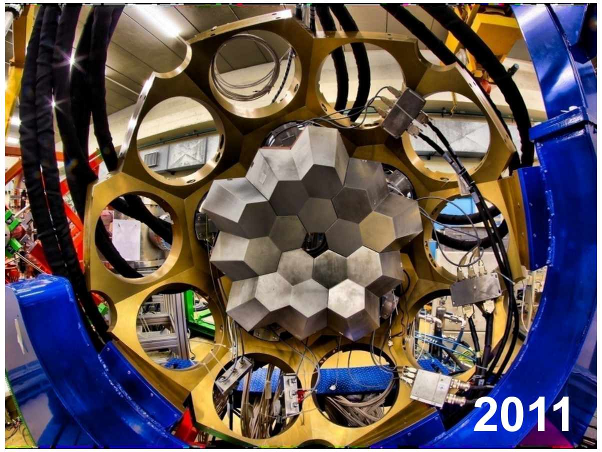
Phase 1

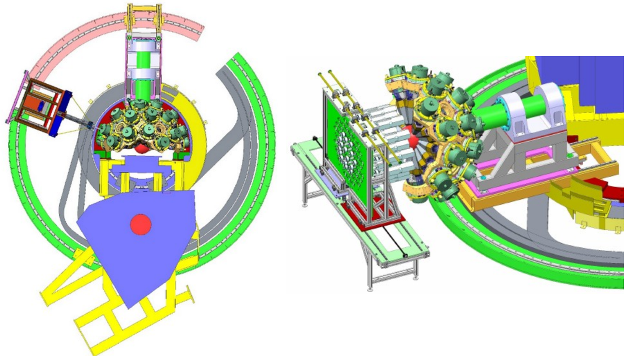
Phase 2


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

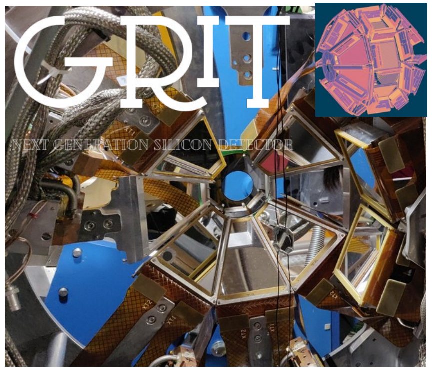
CSN3
Fisica
Nucleare

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