Advancements in Gamma-ray Spectroscopy: Expanding Sensitivity and Experimental Capabilities

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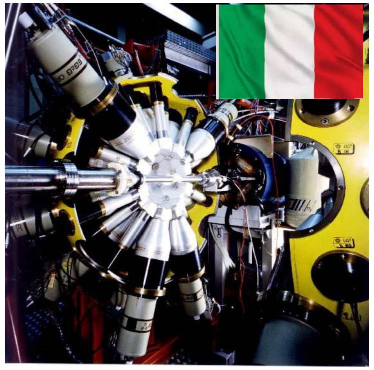
European Conference on Nuclear Physics
21- 26 Sept, 2025 – Caen, France

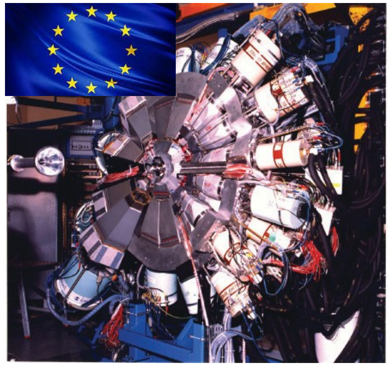
Outlook

- Introduction
- Technological leap
- Science cases (selec)
- Conclusions

Nuclear Structure (t)rail

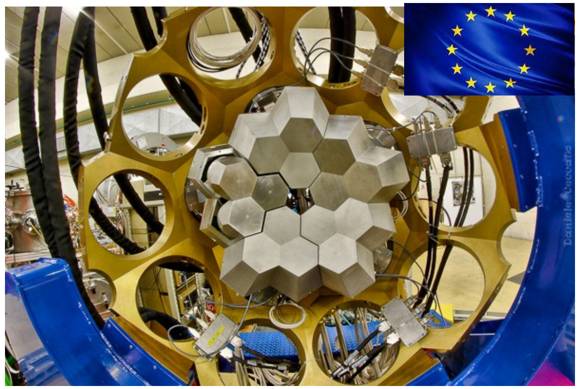


1990s



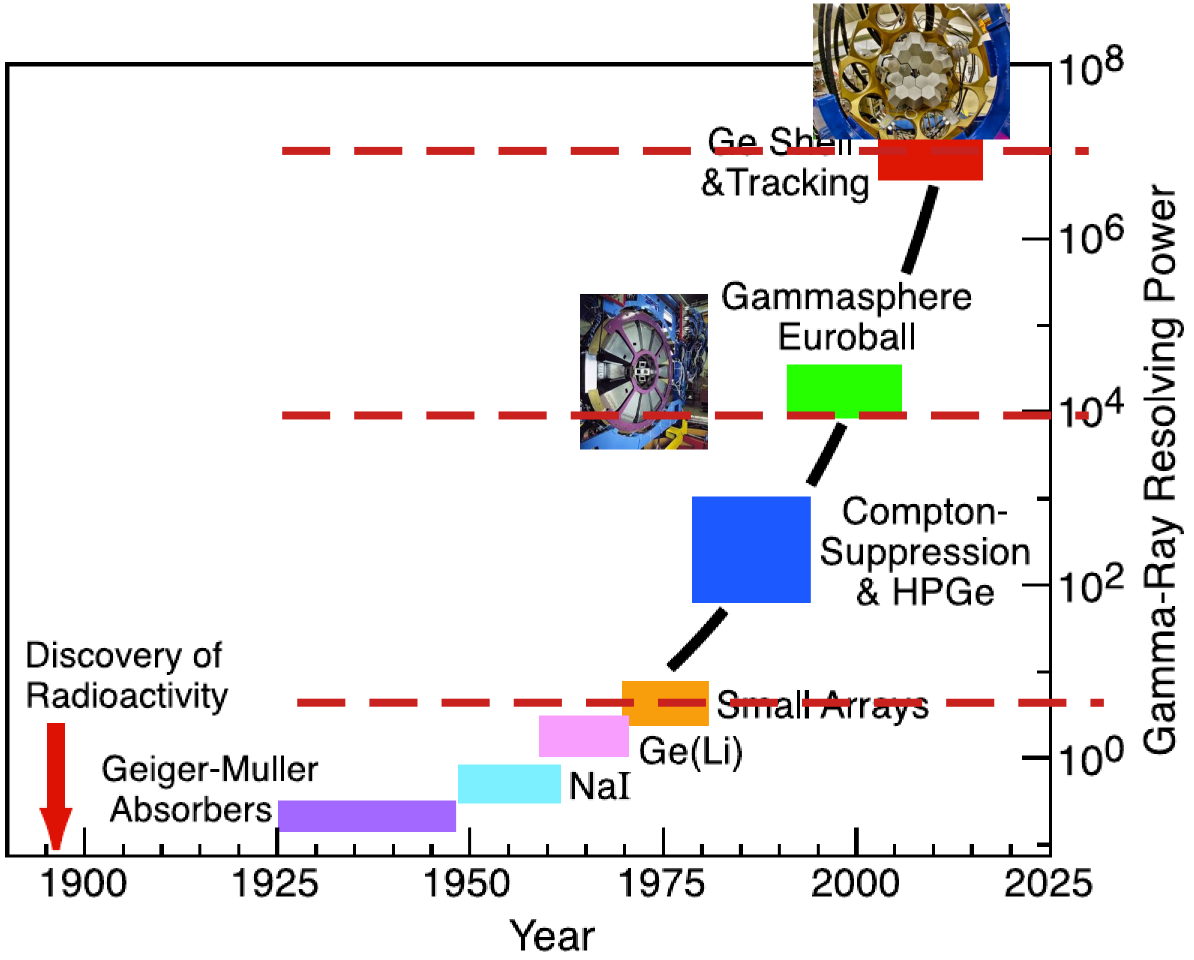
~2000

~2005



2010

Technological leap leading to γ-ray tracking

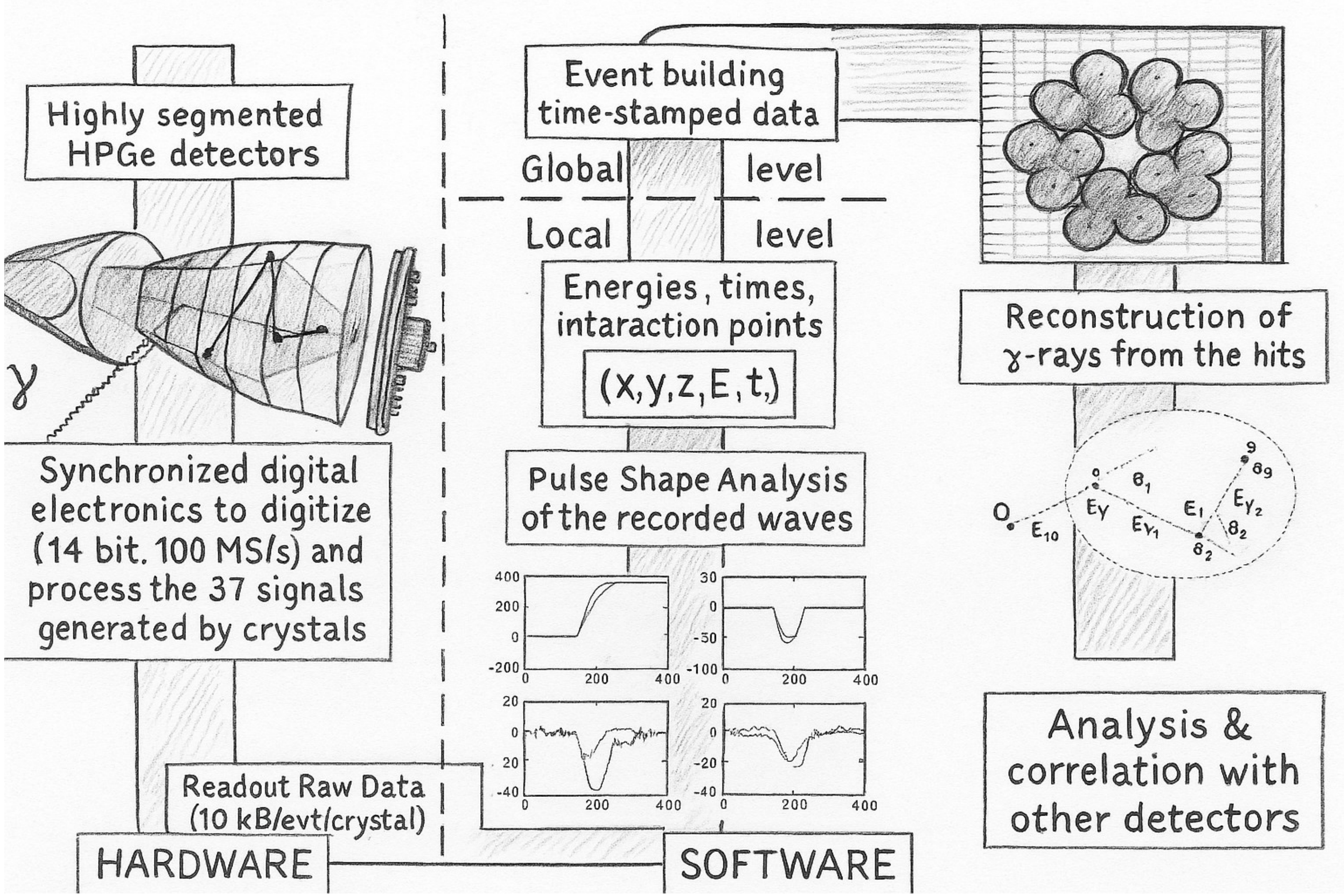


- Outstanding **sensitivity** for lifetime measurement (~Ψ)
- Reduced minimum detectable limit σ (~E)
- E, Ψ ←→ $\mathcal{H}$: Coherent description of nuclear many body complex system and nuclear matter
- … but at a price

ΔE_γ ⇔ $\sim\sigma_\theta$ (relatively fast moving ions)

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
- Lots of other stuff we are still learning ..



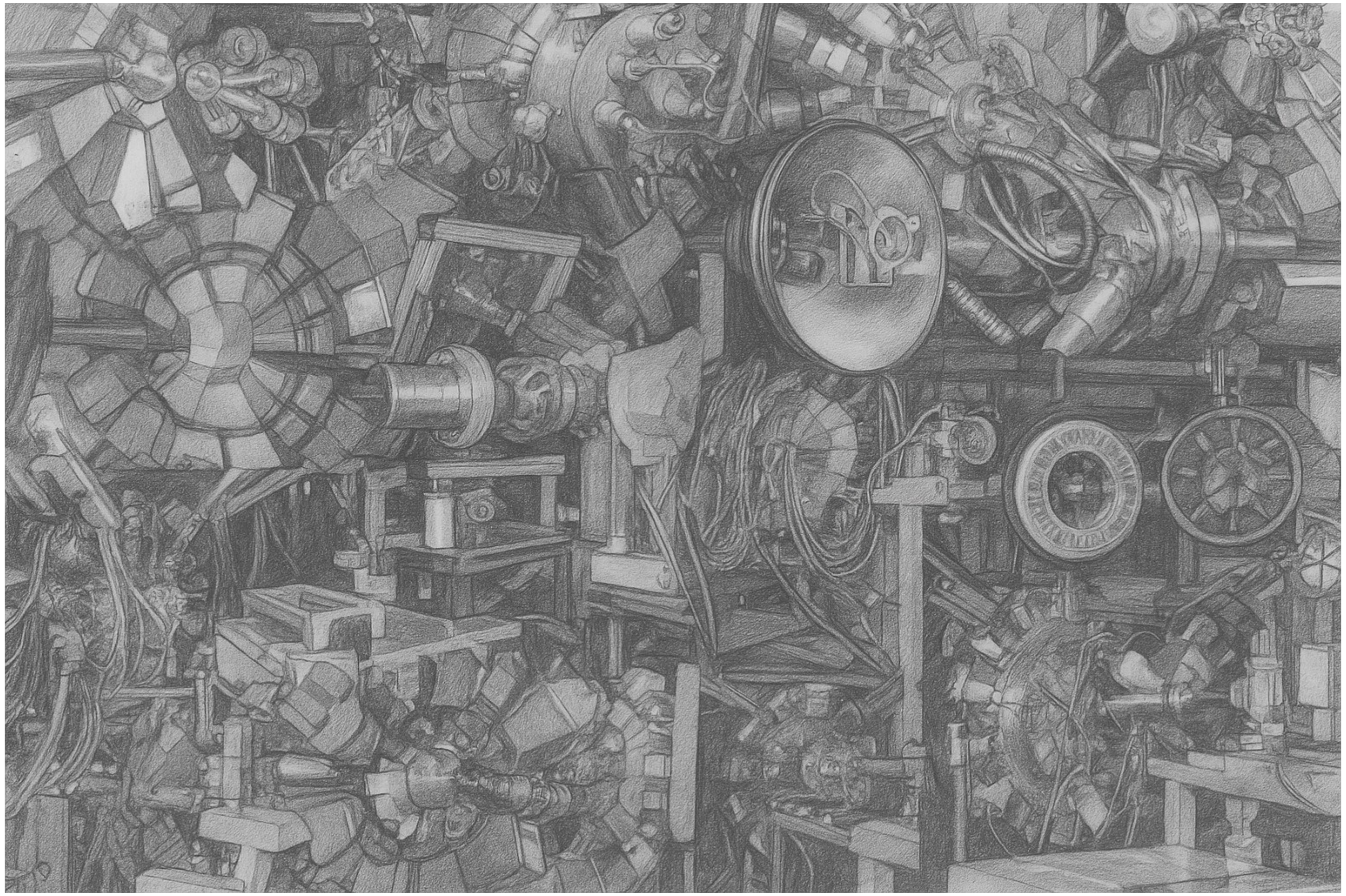
Higher sensitivity in:

L.Corradi, Thursday NS13

- Cross section: ~40 nb
- **Lifetime** 
- ….
- Polarization: factor 10 gain
- Angular distribution

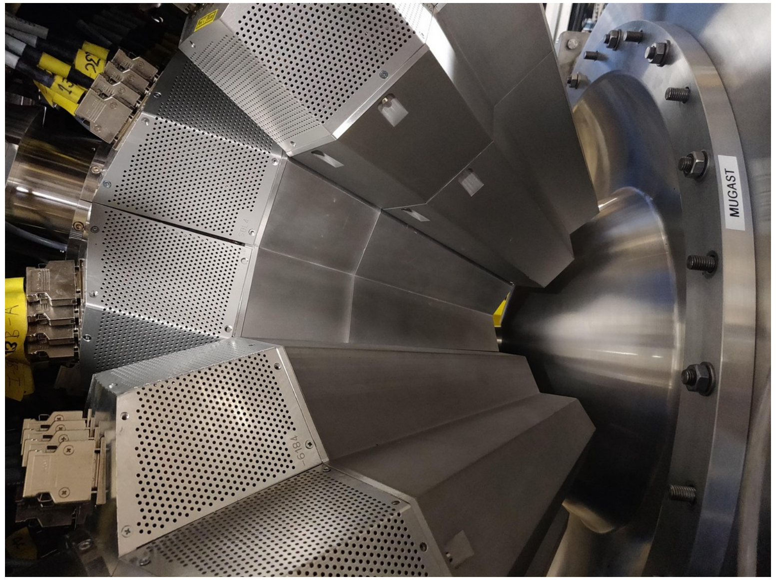
Complementarity is key: factorized the sensitivity

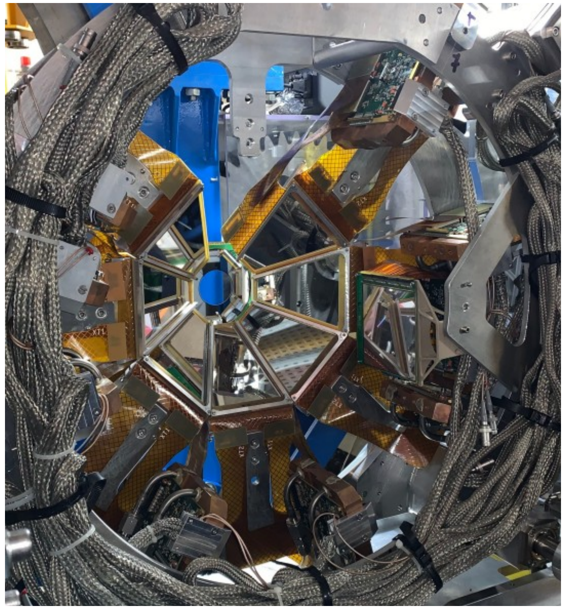
Credit D.Curien, adapted

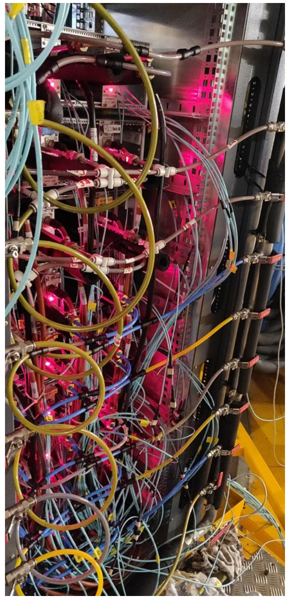


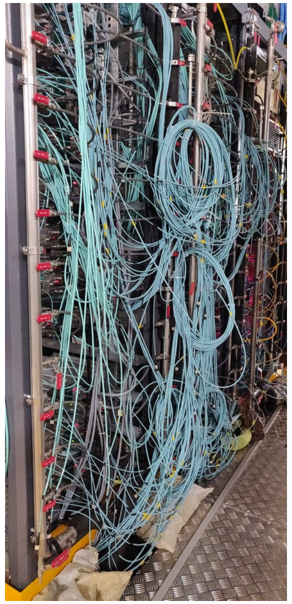
- In modern γ-ray spectroscopy, complementary instrumentation (magnetic spectrometers, particle and neutron array, high-efficiency scintillators, plunger etc etc) is key for challenging measurements at the limit of measurability

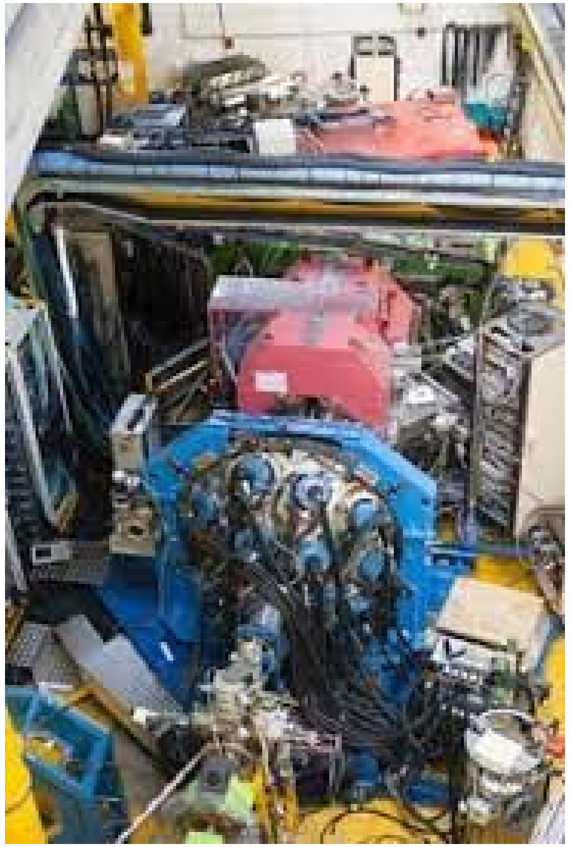
AGATA+MUGAST+VAMOS setup









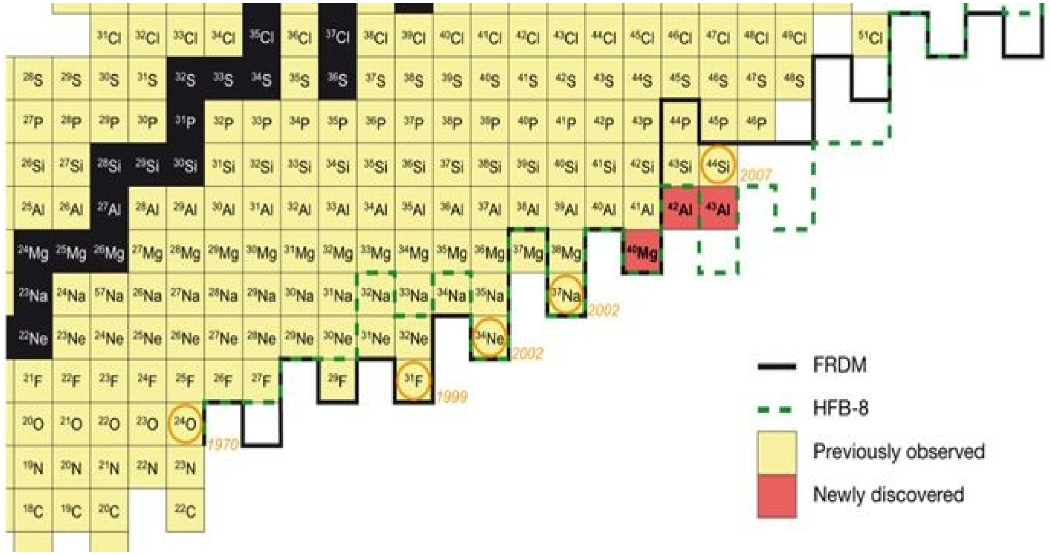


- 1st AGATA campaign with ISOL beam
- Setup guarantees the angular resolution of AGATA ~1 deg

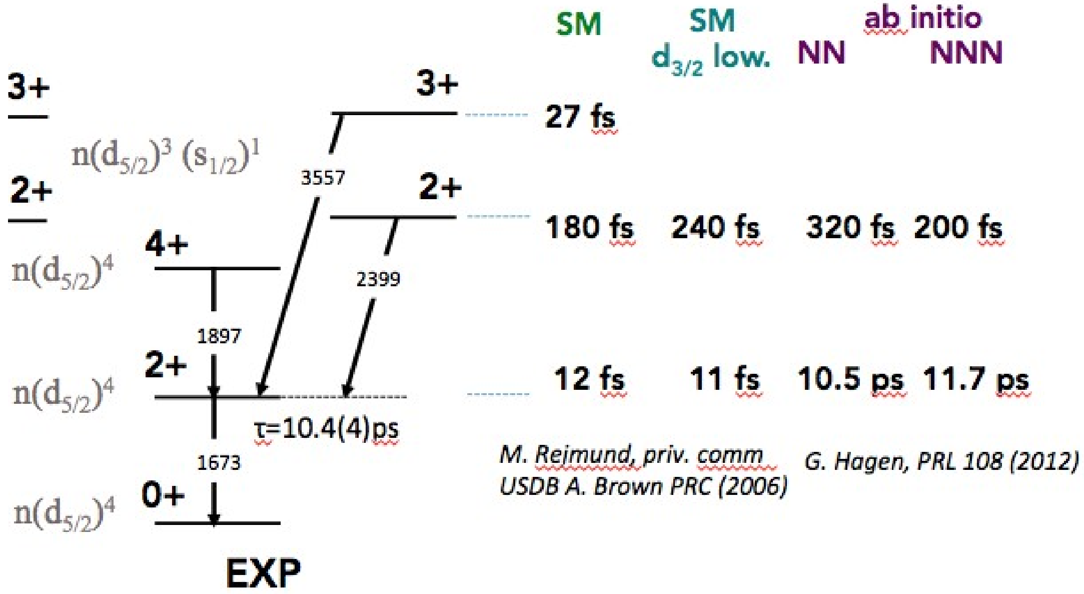
M.Assié et al., “MUGAST-AGATA-VAMOS campaign: setup and performaces” NIMA 2021
DM et al. “Advances in nuclear structure via charged particle reaction with AGATA” EPJA 2023

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

n-drip line: the oxygen anomaly



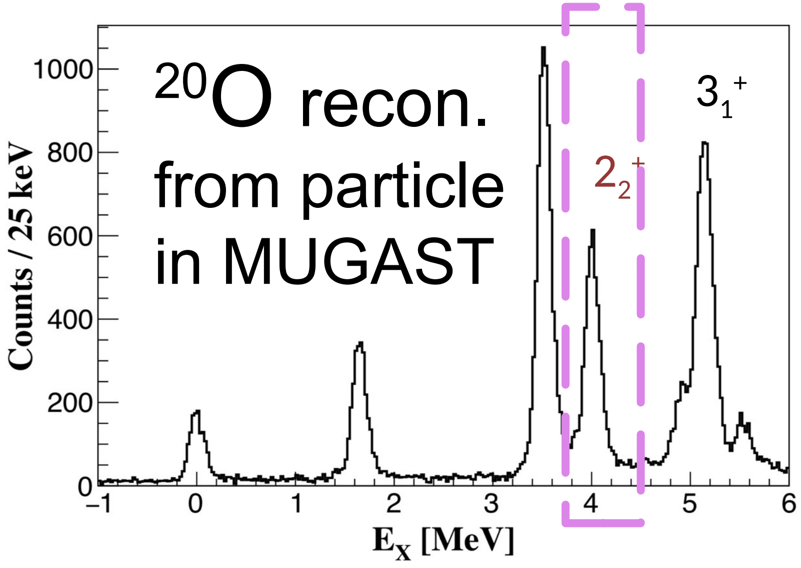
Interpreted by 3N forces effect on GS energies in ^{24}O
T.Otsuka et al., PRL 105(2010)

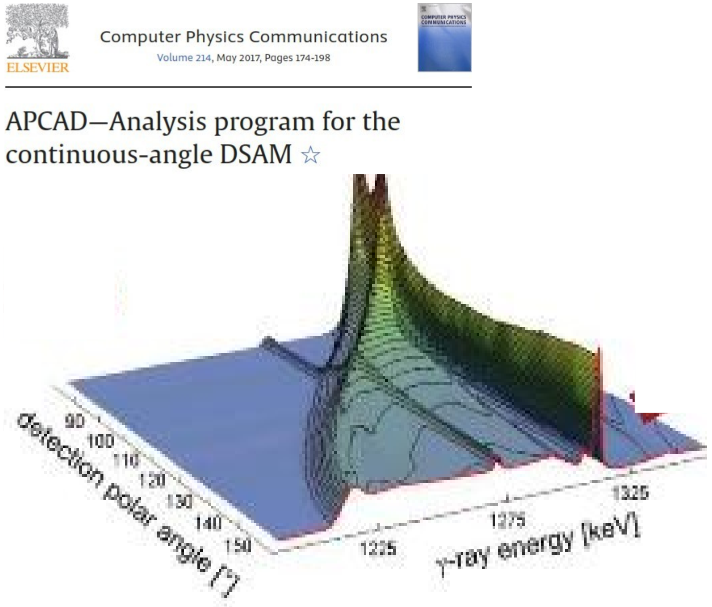


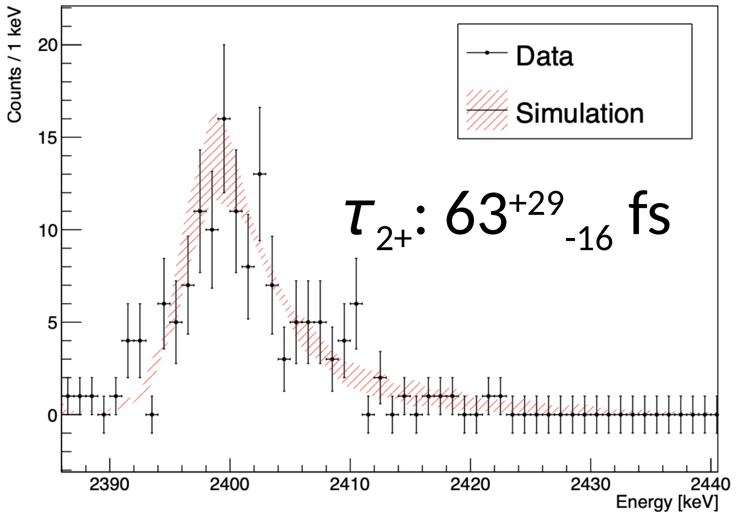
- neutron-rich nuclei, the neutron drip line evolves regularly from light to medium-mass: yet 24O is the last boungd system
- Microscopically 3N repulsion: constrain relative decomposition of $s_{1/2}$ and $d_{3/2}$ in n-rich oxygen
- Lifetime measurements of 2_2^+ and 3_1^+ in ^{20}O by direct transfer: ^{19}O(d,pγ) + DSAM
- Probe the 3-body interaction: 2_2^+, 3^+ sensitive to NNN
- Pioneering measurement: $\tau(2_2^+)$ =150^{+80}_{-30} fs (M.Ciemala et al, PRC2020 (R))

$^{19}O(d,p\gamma)^{20}O$

Role of 3-body forces in Oxygen isotopes

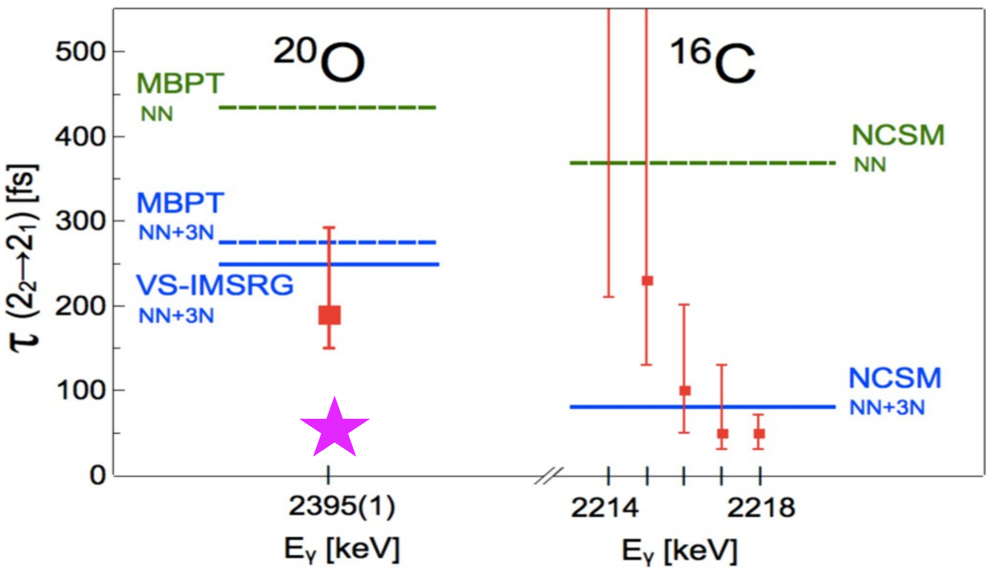


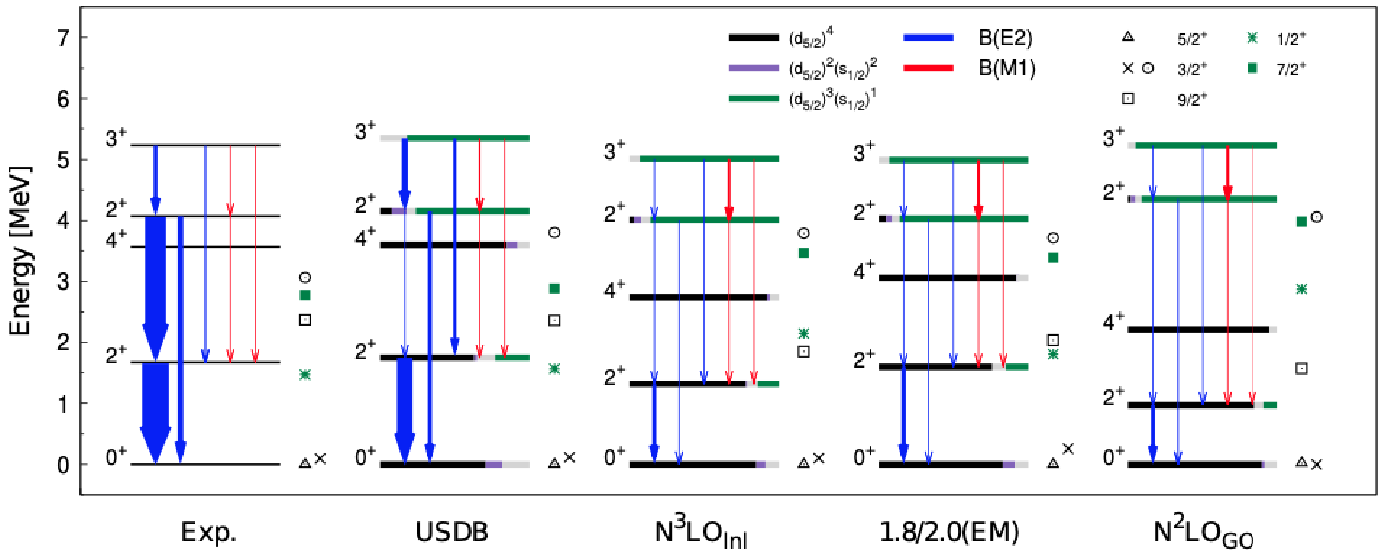




- Clean (d,p) binary reaction to constrain the excitation energy of the heavy partner
- Triple coincidences: reconstructed entry point (MUGAST) through transfer reaction to avoid top feeding + continuous-angle line shape (AGATA)+ channel selection (VAMOS)
- Lifetimes measured significanlty shorter than theoretical predictions for the 2^+
- First lifetime measurement in the tens of femto-sec. scale (DSAM) using transfer reaction in inverse kinematics

Increase in sensitivity and physics results

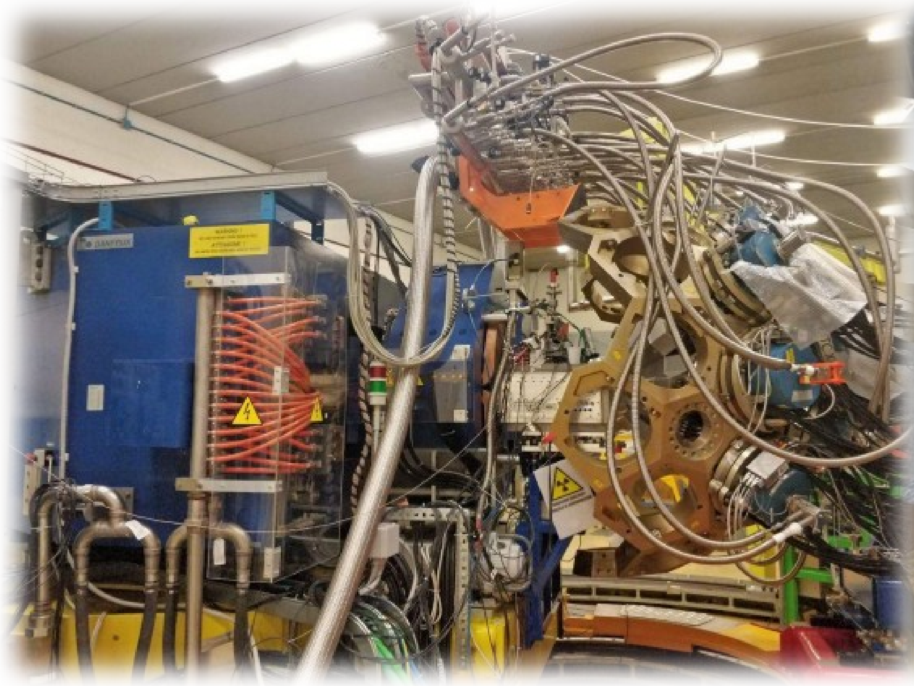


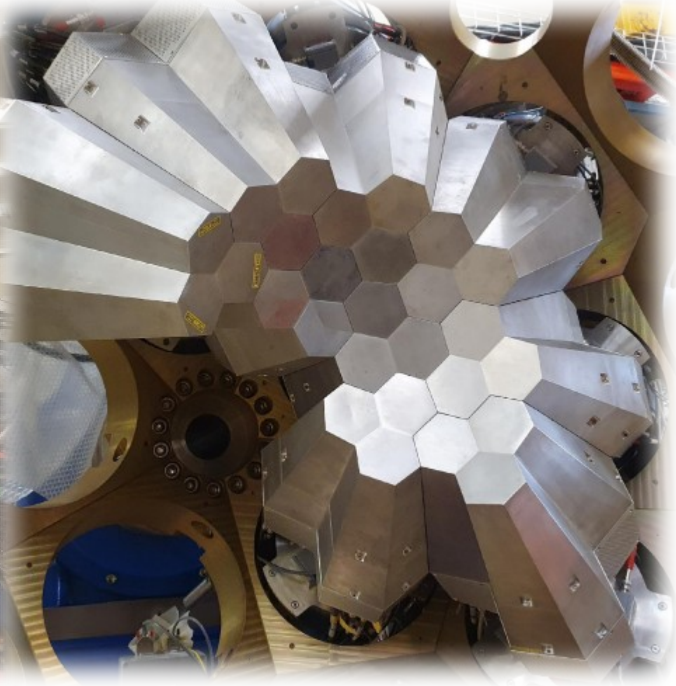


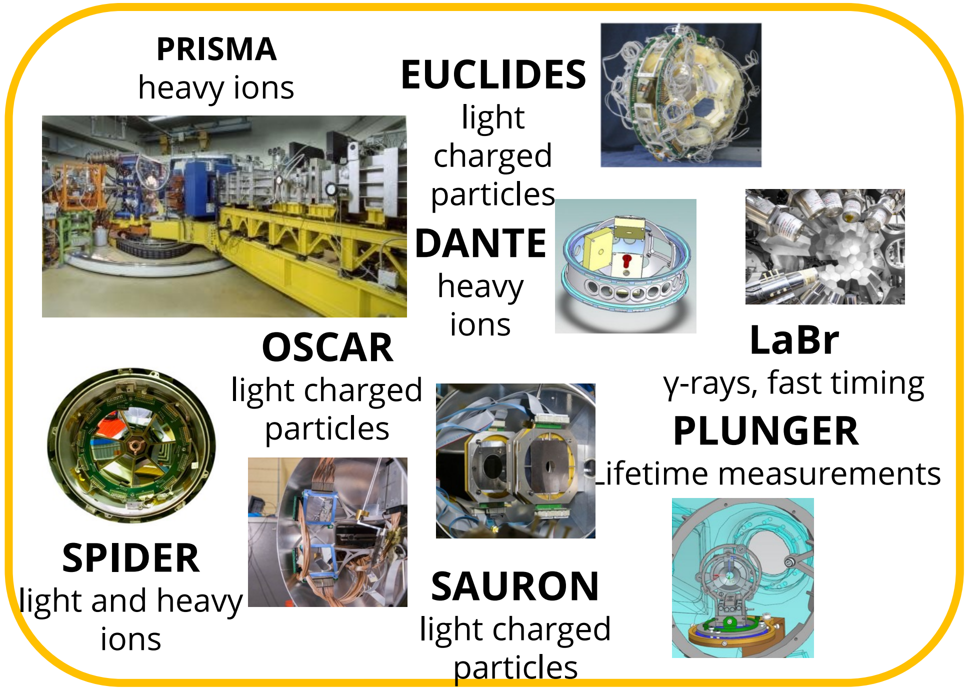
- Shorter lifetime for the 2^+_2 confirms the role of the 3-body contribution
- Energies well described
- $2^+_2 \rightarrow 2^+_1$: B(E2) overall underestimated of order of magnitude, better for the B(M1)
- Relative good agreement on the occupancy for all state between the USDB and the *ab-initio*

I.Zanon et al., Phys. Rev. Lett. 131 (2023) 262501
M. Ciemala_PhysRevC.101 (2020) 021303 (R)

AGATA @ LNL, 2021 onward







- Configuration facing the optical center of the PRISMA magnetic spectrometer
- Integrated with various auxiliary detectors

F.Galtarossa, Monday NS5

J.J.Valiente Dobón, R.Mengazzo, A.Goasduff et al.,NIMA 1049 (2023) 168040

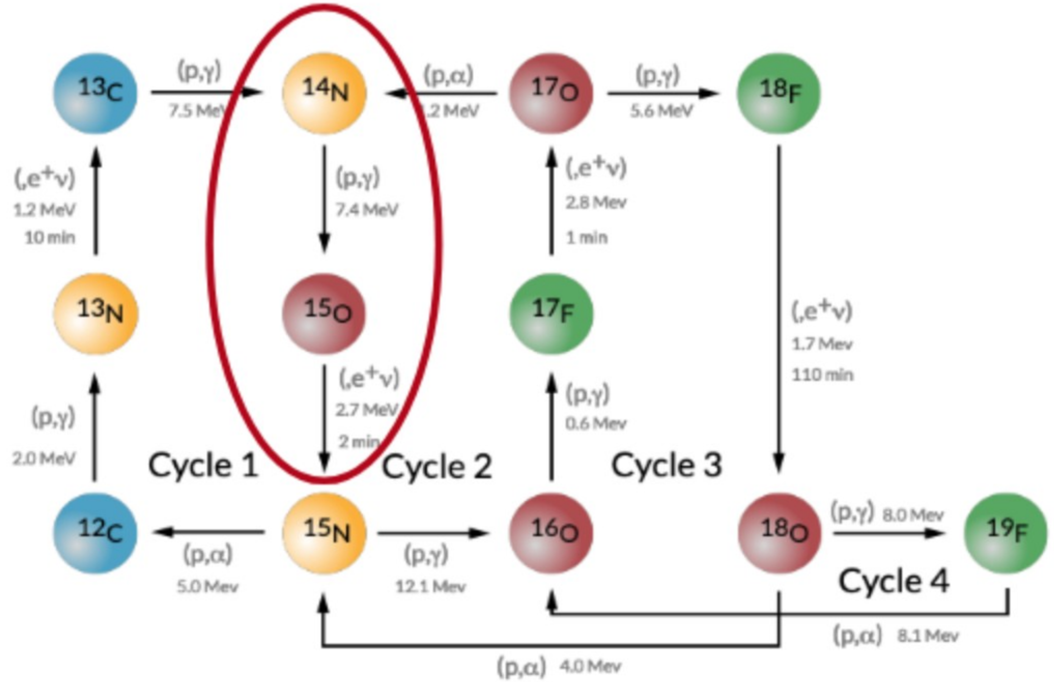
Elia Pilotto PhD , Jakub Skowronski PDRA, Univ Padova and INFN

M.L.Aliotta
A.Caciolli
G. Imbriani

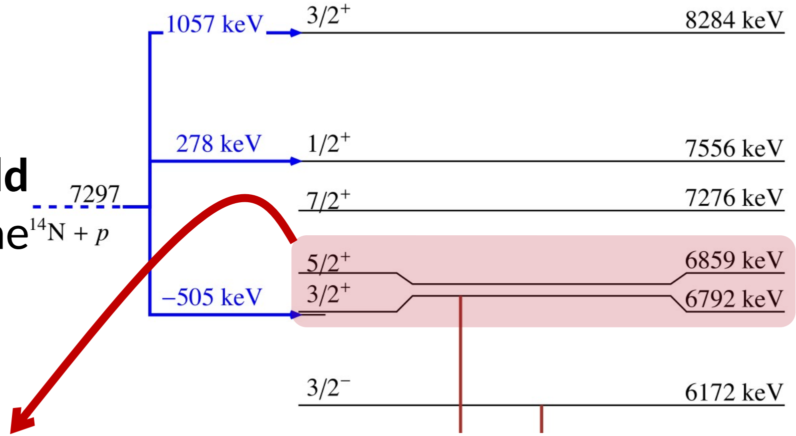
$^{14}N(p,\gamma)^{15}O$ Reaction

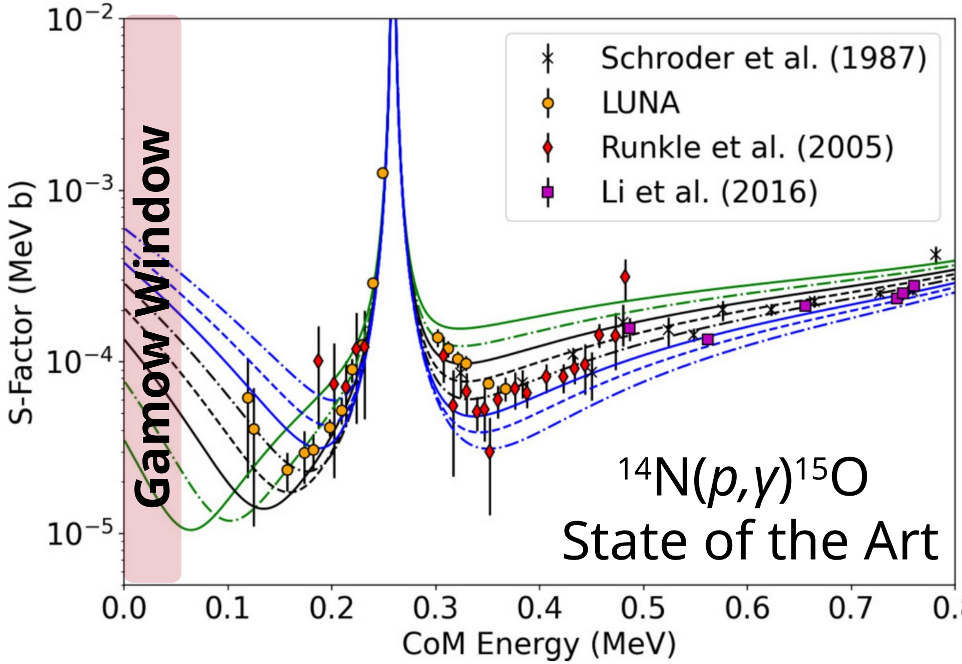
CNO Cycle

$^{14}N(p,\gamma)^{15}O$ is the **slowest reaction** in the cycle: evolution of massive stars, metallicity, ..



6.79 MeV sub-threshold resonance dominates the cross section: $\Gamma \rightarrow \tau$





Existing measurements in literature

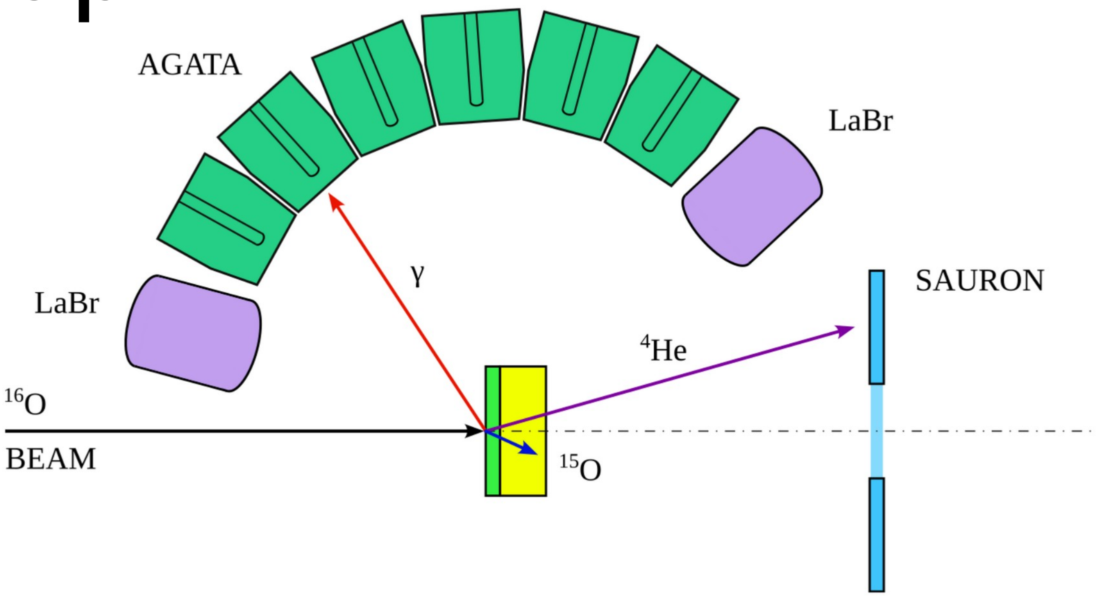
Year	Facility	τ (fs)	Author and Reference
2001	TUNL	$1.60^{+0.75}_{-0.72}$	Bertone *et al.* [30]
2004	RIKEN	$> 0.42^{\dagger}$	Yamada *et al.* [31]
2008	Ruhr-Universität Bochum	< 0.77	Schürmann *et al.* [32]
2012	INFN - LNL	< 1.0	Michelagnoli [33]
2014	TRIUMF	< 1.8	Galinski *et al.* [34]
2021	University of Notre Dame	0.6 ± 0.4	Frentz *et al.* [16]

- Moslty DSAM (1 Rel. Coulex), few HPGe (one displaced at different angle) or NAI(Tl)
- Direct measurements (p+N) might suffer by the not so well controlled implantation on N on a backing (Ta.)
- Indirect measurements needed to control the 3He profile
- Already performed with **AGATA demonstrator**: problem due to the ^{14}**N(*d*,*n*)**^{15}**O** reaction channel (in inverse kinematics) which did not allow a precise **kinematic reconstruction:** insufficient sensitivity

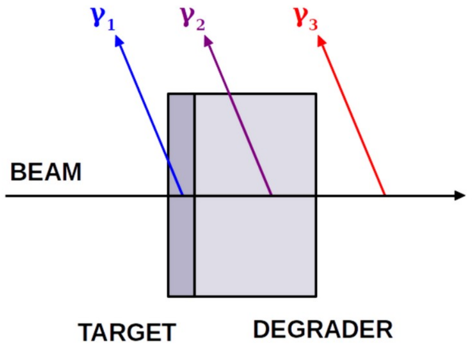
Our setup

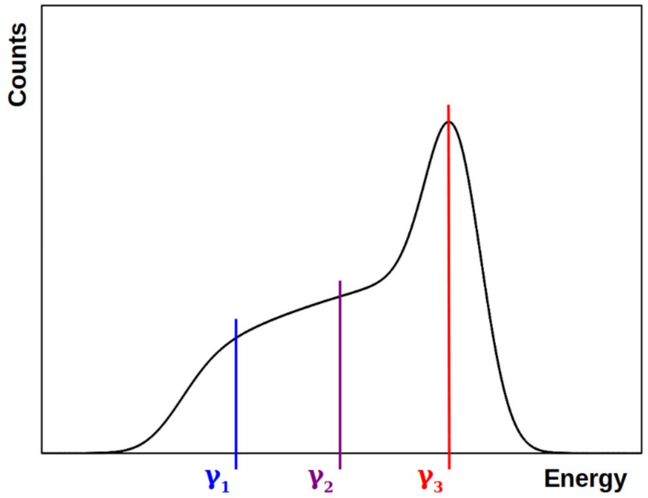
$^{16}O(^3He,^4He)^{15}O$ @ 50 MeV

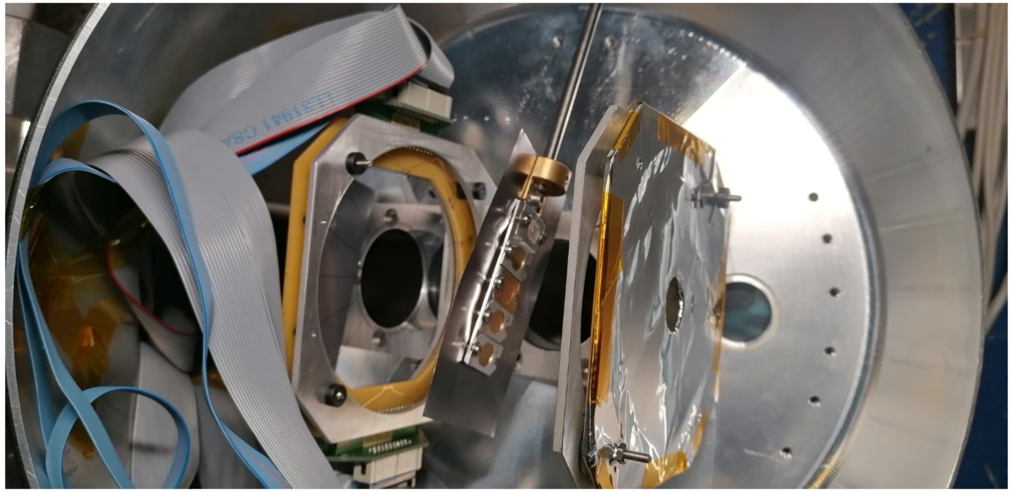
- ^{16}O beam impinged on two types of **^3He targets**
- ^4He recoils detected with the **SAURON** (DSSD) array
- AGATA at **40 – 160 deg** for the γ-rays
- **AmBe** source with **Fe** for constant energy calibration



Doppler Shift Attenuation Method



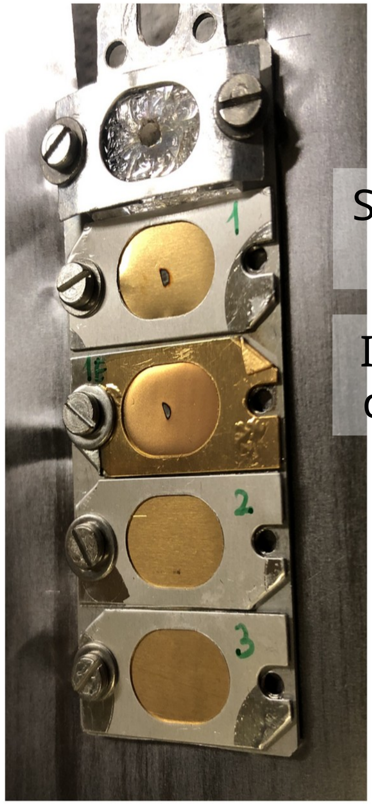




^{3}He Targets

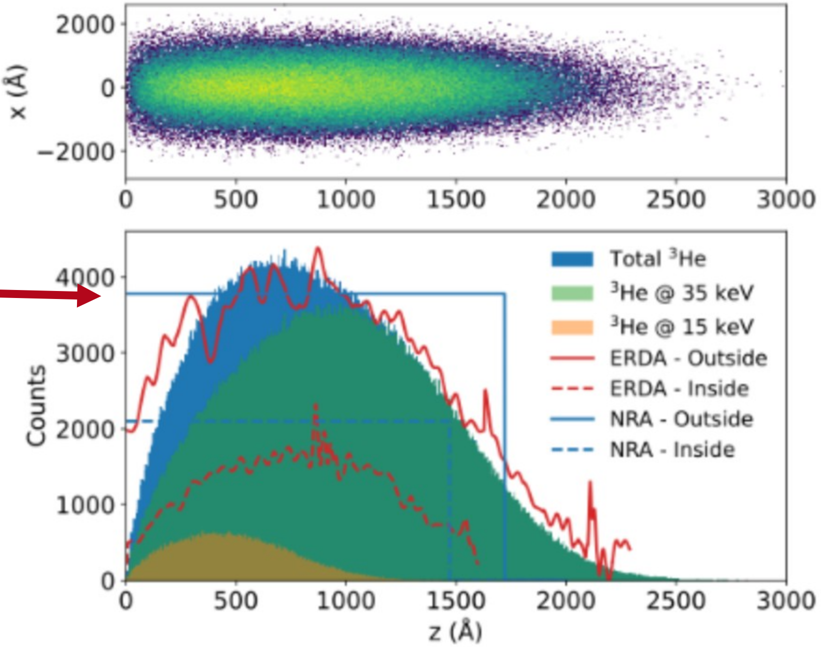
Two different types of **^{3}He targets** in **Au** backing were used:

- Sputtered ones produced at CNA (Seville) ~ **2.2 × 10^{18} at/cm^2**
- Implanted ones produced at HZDR (Dresden) ~ 4.7 × 10^{17} at/cm^2



Sputtered (CNA)

Implante
d (HZDR)



Eur. Phys. J. A (2025) 61:117
https://doi.org/10.1140/epja/s10050-025-01590-w
THE EUROPEAN PHYSICAL JOURNAL A
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Regular Article - Experimental Physics

Comparing ^{3}He content in magnetron sputtered and implanted targets for nuclear studies

E. Pilotto[1,2], F. J. Ferrer[3,4], S. Akhmadaliev[5], A. Fernández[6], A. Gadea[7], J. Gómez Camacho[3,4], D. Hufschmidt[6], M. C. Jiménez de Haro[6], E. Masha[5], F. Munnik[5], M. Osswald[8], D. Piatti[1,2], J. Skowronski[1,2,a], S. Turkat[1,2], J. J. Valiente-Dobón[7,9]

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[9] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

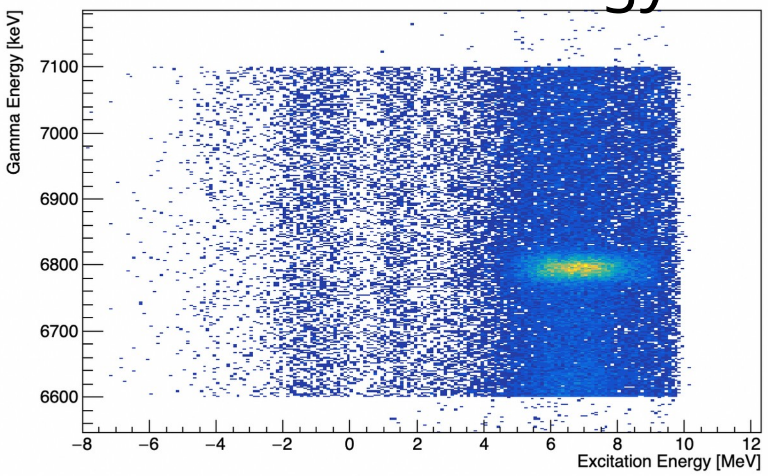
[Pilotto et al. (2025) Eur. Phys. J. A 61:117]

Table 1 ^{3}He areal density calculated by NRA and ERDA

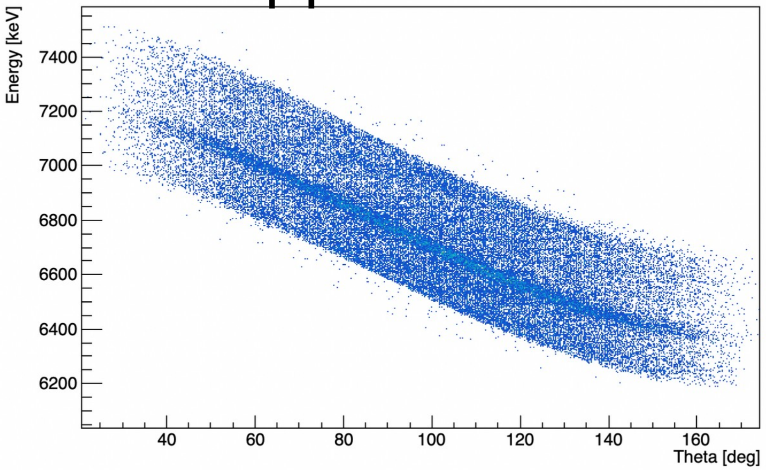
Target	^{3}He areal density NRA [10^{15} at/cm^2]	^{3}He areal density ERDA [10^{15} at/cm^2]
HZDR-2 (Fresh)	478 ± 35	
HZDR-1 - Outside	470 ± 34	445 ±45
HZDR-1 - Inside	224 ± 17	143 ±14
ICMS-2 (Fresh)	2221 ± 153	
ICMS-1 - Outside	2206 ± 152	
ICMS-1 - Inside	1732 ± 120	

6792 keV state observables

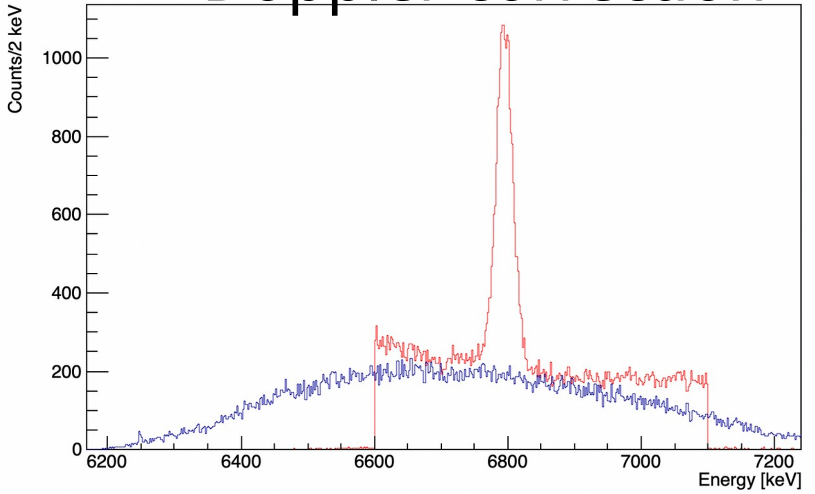
Excitation energy



Doppler shift



Doppler correction



- Meticulous data presorting is a prerequisite to tackle fs lifetime
- Neutron correction, time oscillation, calibration of the detectors and optimization of the positions.
- Evidence of the 6792-keV transition to the gs both in the excitation energy and gamma-ray spectrum. Other known states equally well populated (later used for calibration)
- How to extract a possibly sub-fs lifetime?

Emission *vs* Reaction velocity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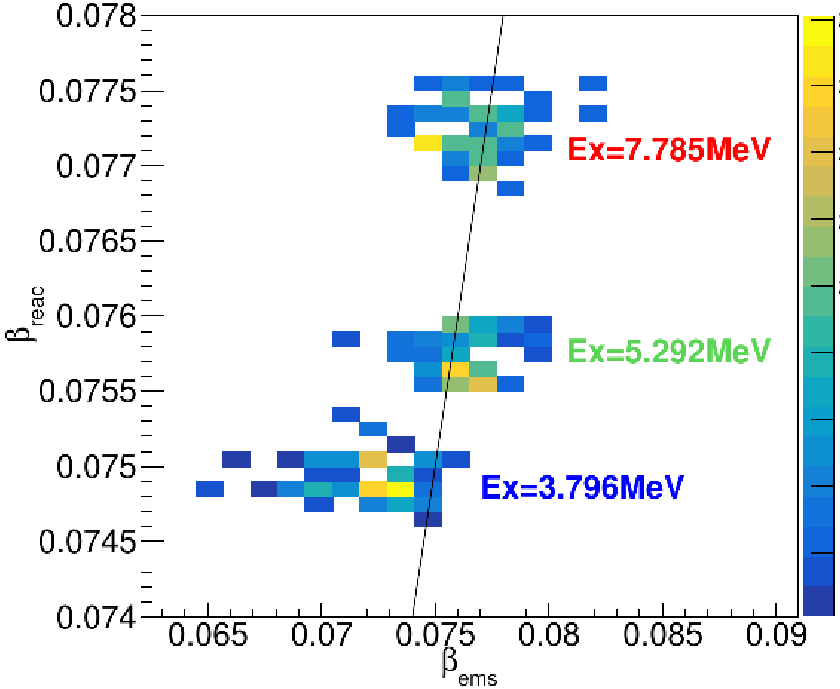
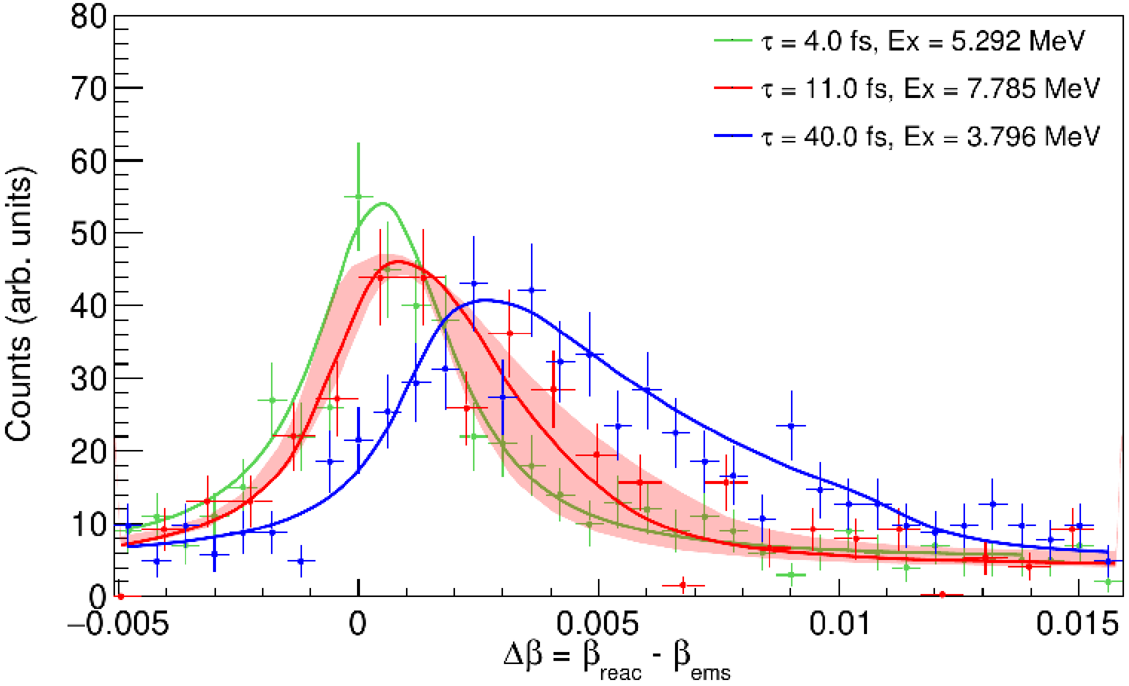
Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes

Chloé Fougères, François de Oliveira Santos, Jorc

C.Fougeres
Friday 12^{40}

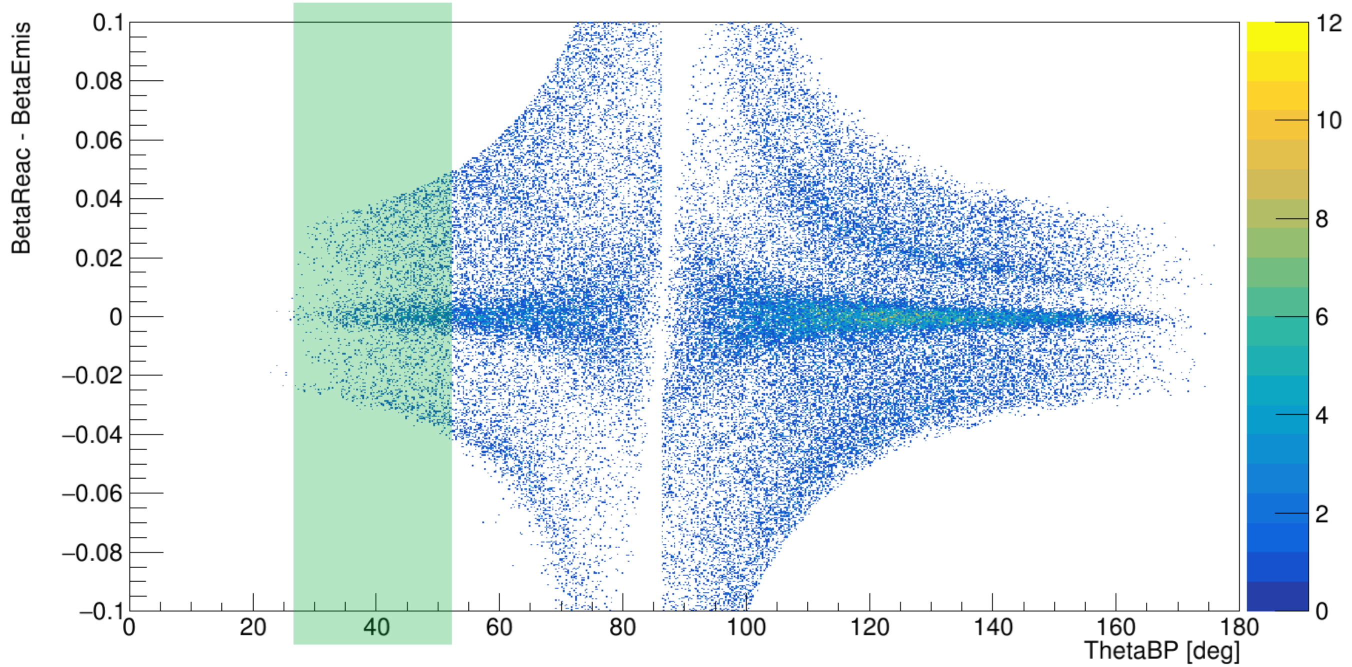


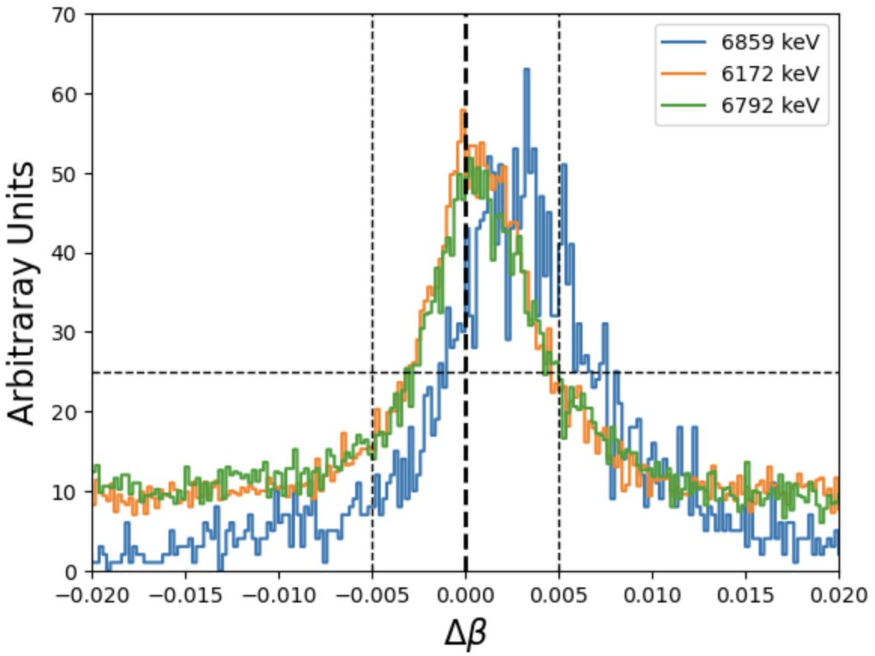


- Classical novae - important ^{26}Al, ^{22}Na sources, but ^{22}Na undetected
- ^{22}Na(p,γ)^{23}Mg reaction rate highly uncertain
- Dominated by ^{23}Mg 7785 keV resonance state lifetime
- Proposed method: Particle-particle correlations + velocity-difference profiles
- Measure **femtosecond ^{23}Mg lifetimes**, constrain ^{22}Na novae yields

τ= 10.2(26) fs
allow to set detectable limit for new space mission

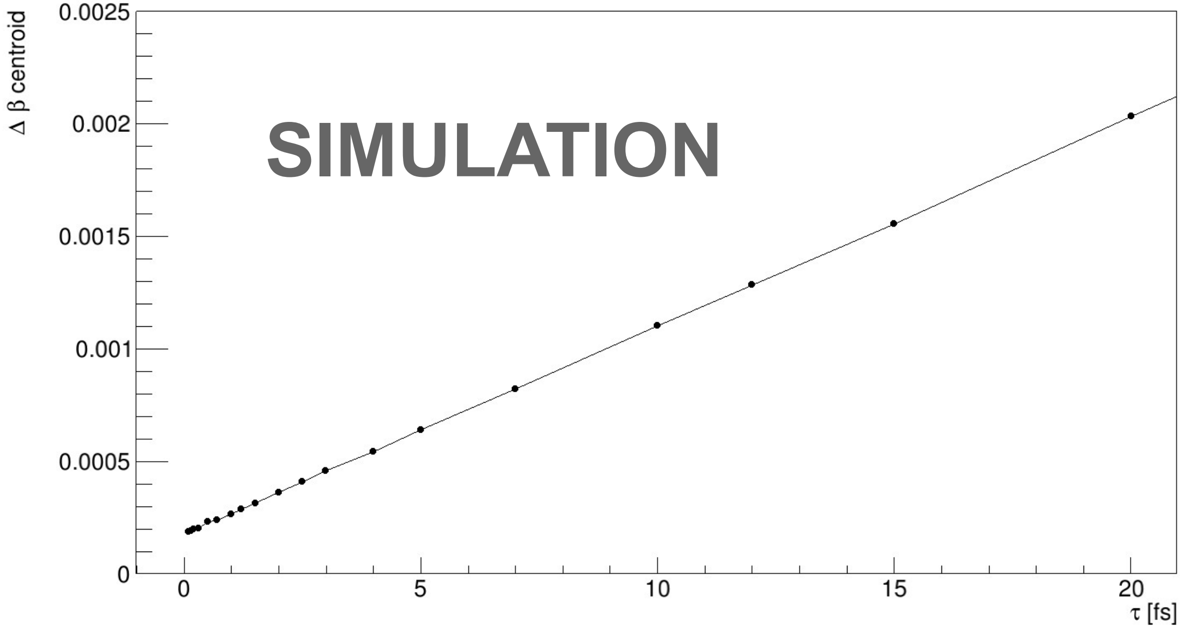
DSAM analysis

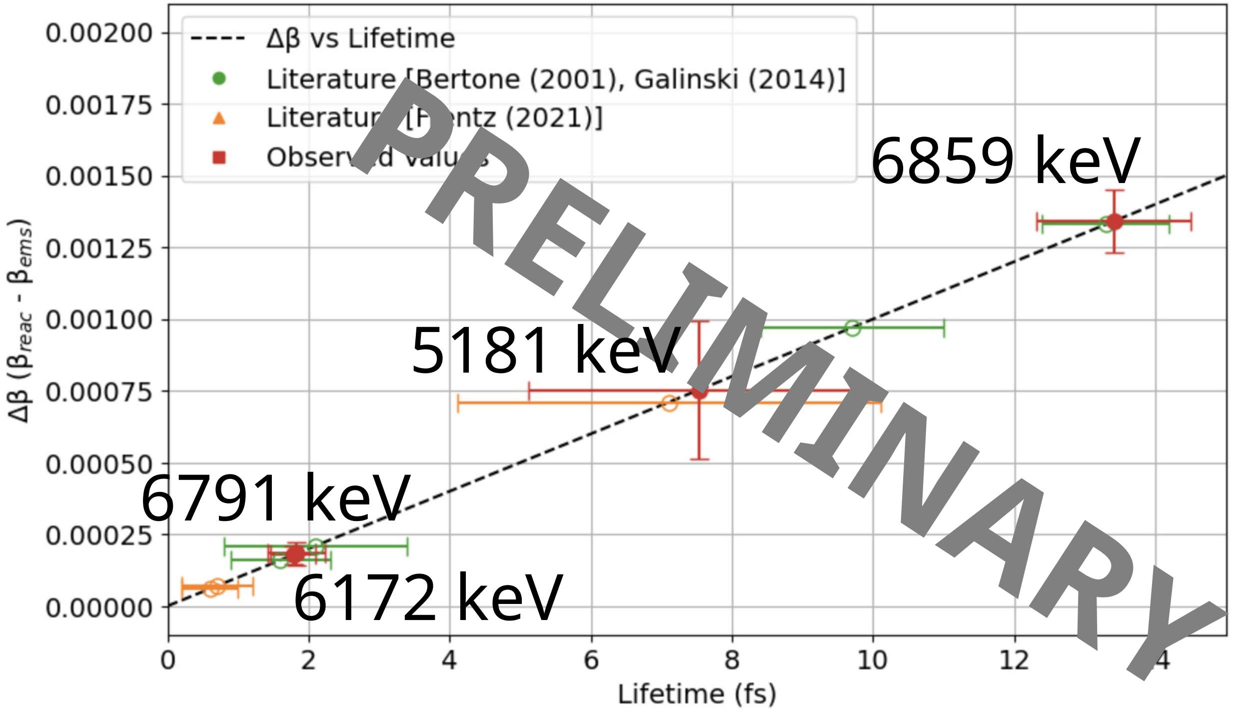




- **β_{reac}** at reaction time using **DSSD reconstruction**
- **β_{emiss}** emission obtained from the centroid energy in **AGATA**
- **Δβ** of the two **centroids allows to extract τ:** the larger the displacement the longer the lifetime. However, what's the necessary level of precision and accuracy ?

Lifetime: ~fs measurement **NEW** attempt

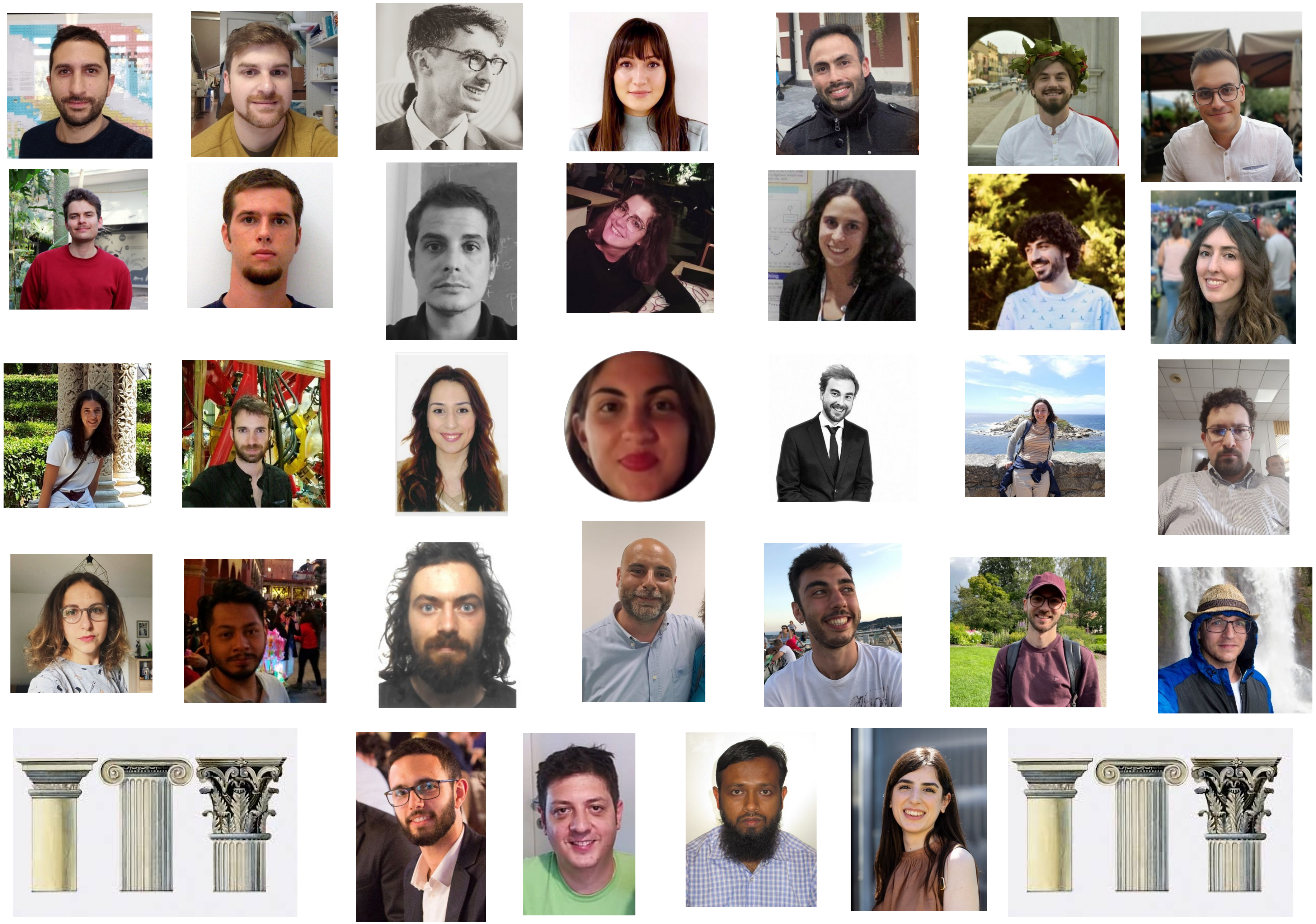




- $^{16}O(^{3}He,^{4}He)^{15}O$ new reaction chosen to control the exit channel
- Δβ method between reaction and emission velocity. Calibration with known state lifetime used to calibrate the simulations.
- Preliminary results are promising and close to Bertone and Galinski, far from Frentz
- **=> High sensitive method!**

Conclusion and perspectives

- Technological leap is in mutual dependence with scientific findings
- Increase in sensitivity, e.g. ~fs lifetime and ~nb cross section and more, is key to continue exploring nuclear physics and astrophysics



“Local” AGATA team

moslty MSc, PhD, Post doc

more than 10 nationalities

merci