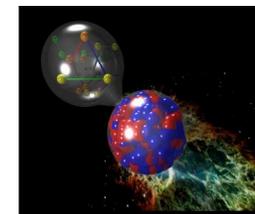




Physics results with the ultimate AGATA+MUGAST+VAMOS setup and ISOL beams at GANIL

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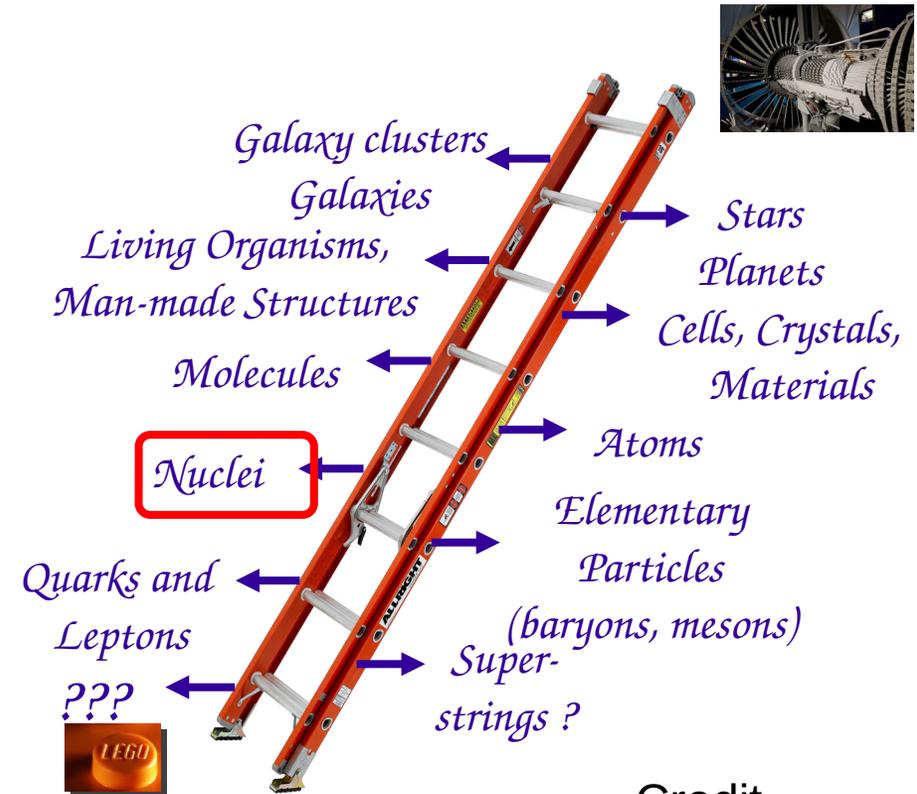
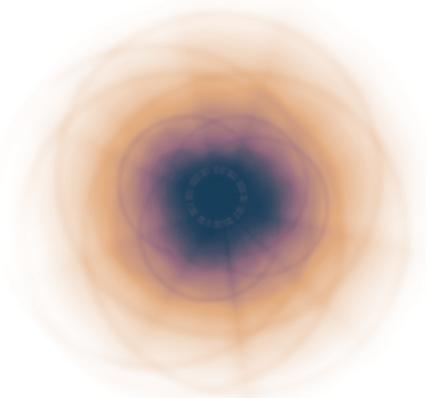
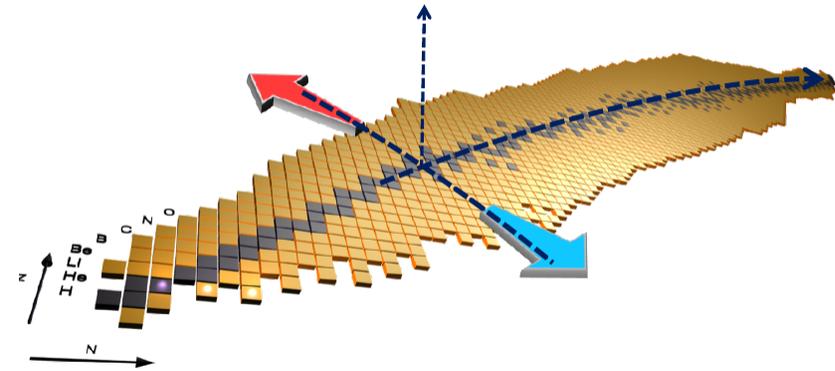


Outlook

- Intro
- Technological leap
- Science campaign: highlights
- Conclusion



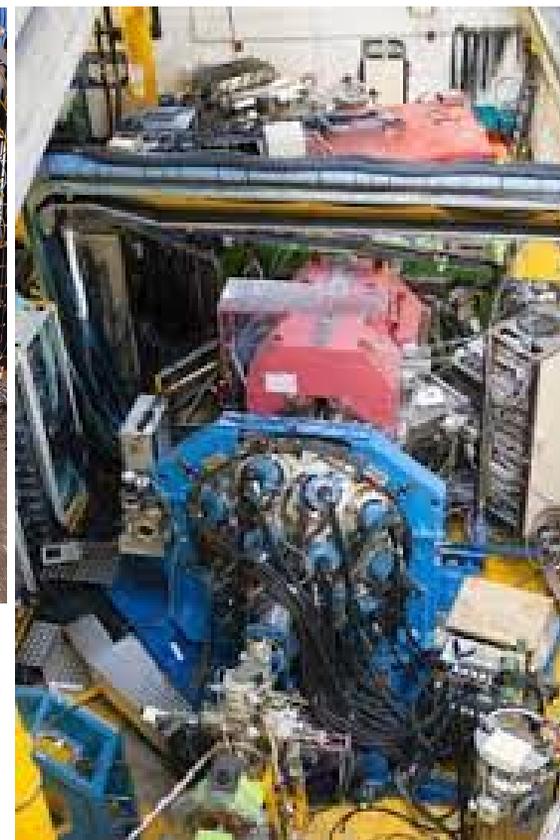
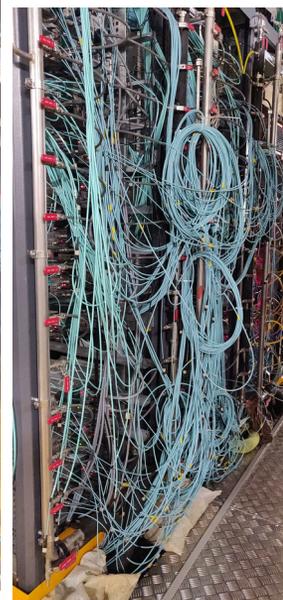
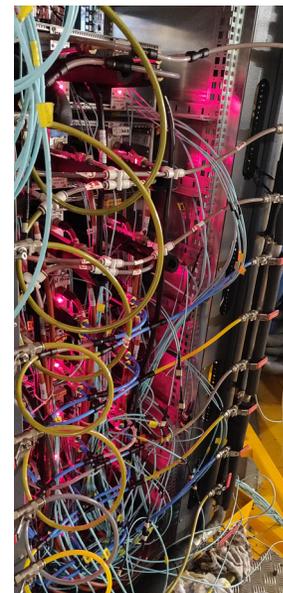
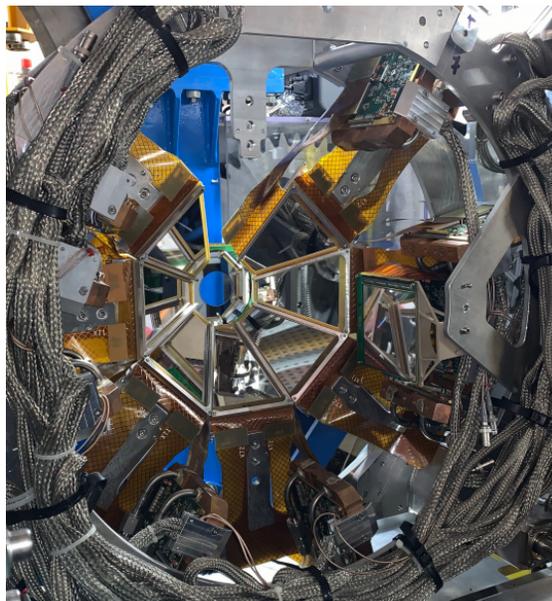
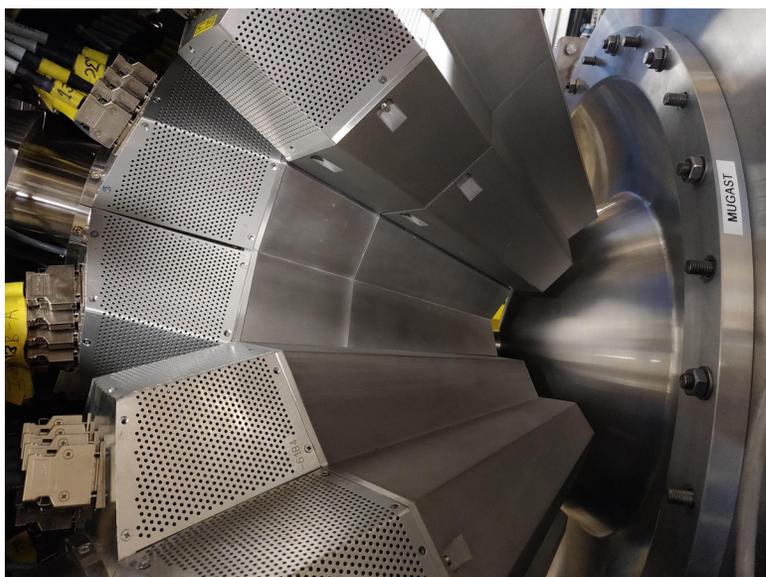
Why NS?



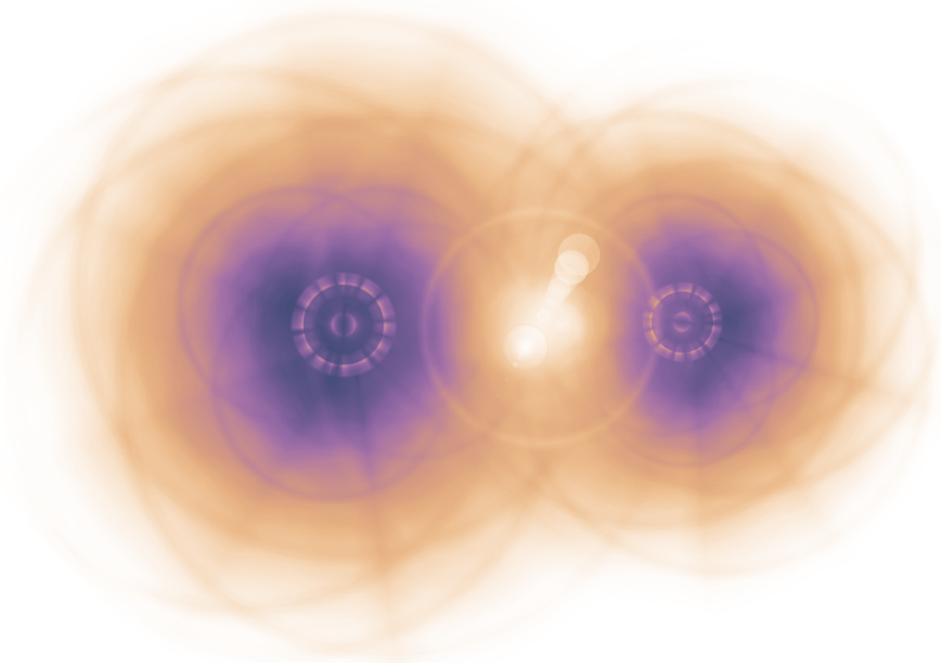
Credit
W.Nazarevicz

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

AGATA+MUGAST+VAMOS setup



Direct reactions [with ISOL RI beams]



Typically one/few nucleons exchange between the interacting nuclei

- Selectivity :

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

- Sensitivity:

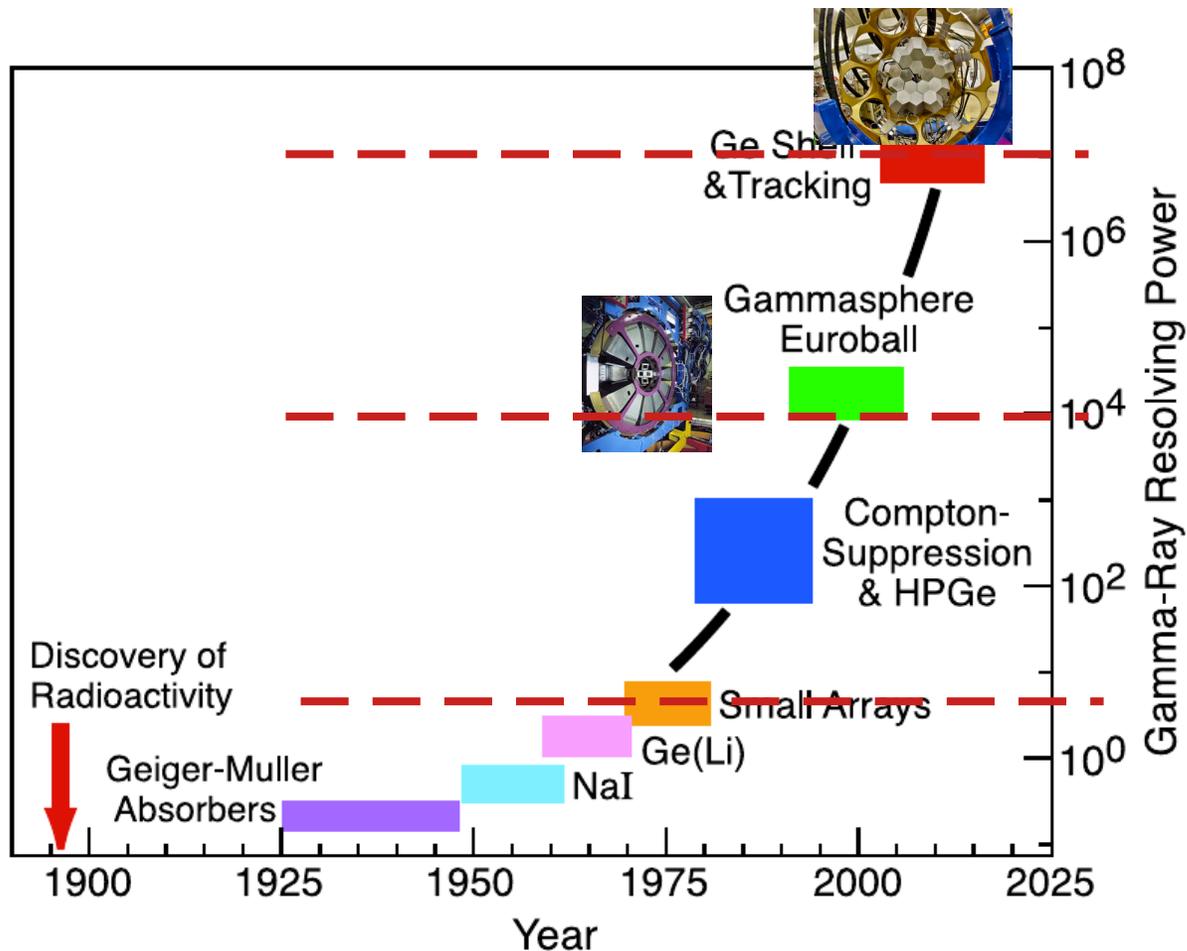
C.S. carries W.F. information

Specific state structure

Probe $\ll \Delta\Psi \gg$

adapted from A.Matta

Technological leap leading to γ -ray tracking

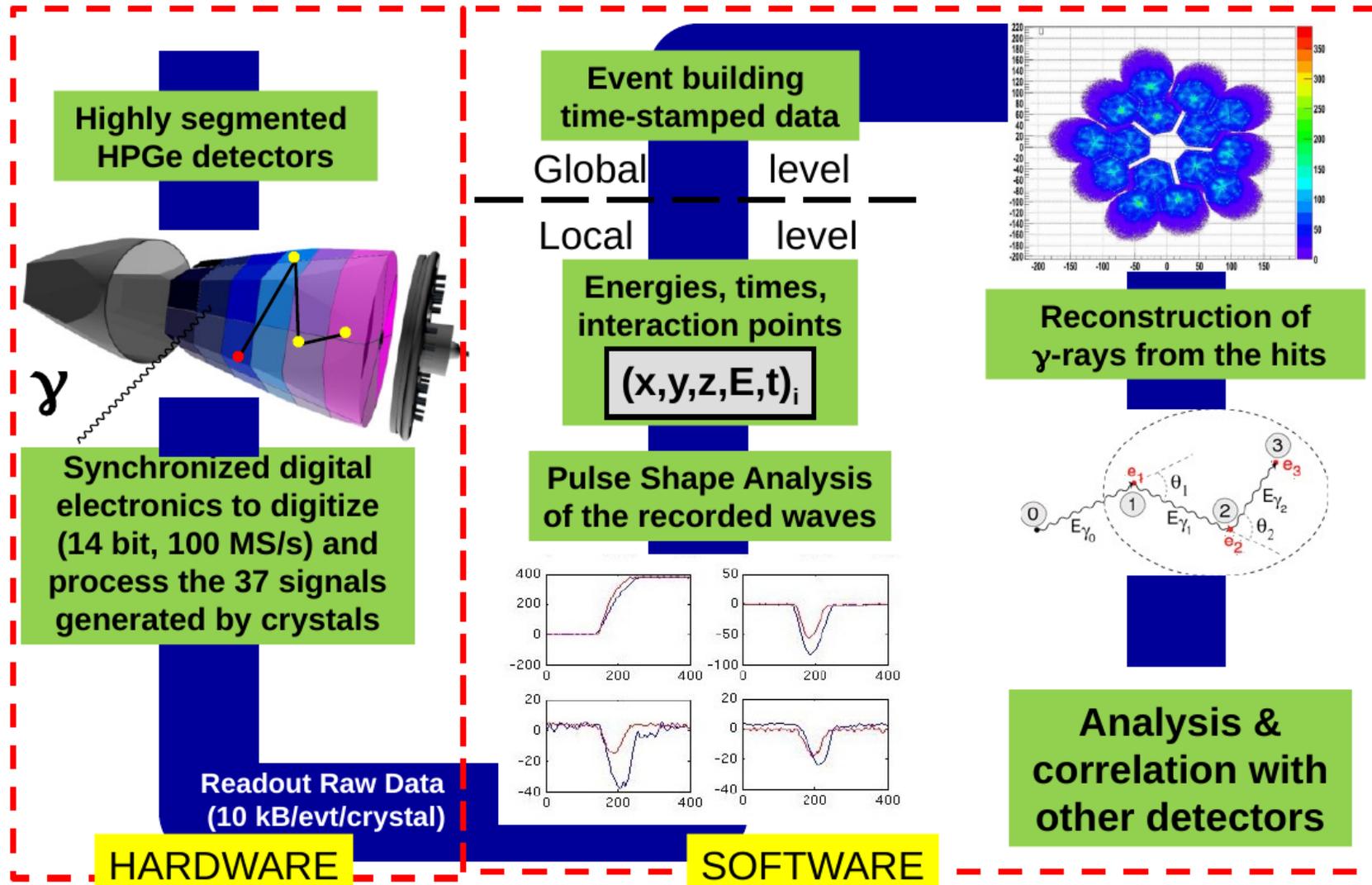


- Outstanding sensitivity for lifetime measurement ($\sim\Psi$)
- Reduced minimum detectable limit σ ($\sim E$)
- $E, \Psi \leftrightarrow \mathcal{H}$: Coherent description of nuclear many body complex system and nuclear matter

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

... but a price has to be paid ...

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

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

VAMOS

AGATA

MUGAST

AGATA

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

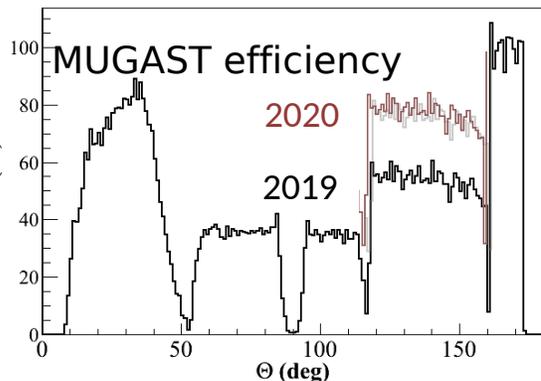
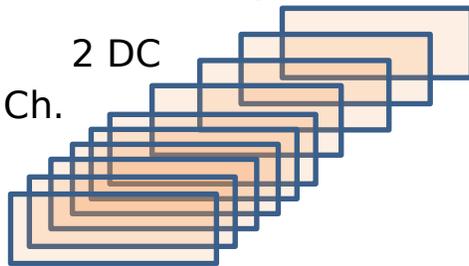
Spiral1 radioactive beams

BTD

2 PPAC

2 DC

6 Ion. Ch.



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



Science campaign and selected highlights

2019

UNBOUND STATES
Above barrier narrow resonances in ^{15}F

PhD : V. Alcindor

I. Stefan (IJC lab), F. de Oliveira (GANIL)

$^{14}\text{O}(p,p')$ with few 10^5 pps

★ NUCLEAR ASTROPHYSICS.
Determining the $\alpha+^{15}\text{O}$ radiative capture rate

PhD : J. Sanchez Rojo

C. Diget (York), N De Séréville (IJC lab)

$^{15}\text{O}(^7\text{Li},t\gamma)^{19}\text{Ne}$ with $4 \cdot 10^7$ 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

$^{46}\text{Ar}(^3\text{He},d\gamma)^{47}\text{K}$ with $4 \cdot 10^4$ 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)

$^{18}\text{O}(d,p\gamma)$ + DSAM

SHELL STRUCTURE
Proton-neutron interactions across the N = 28 shell closure via $^{47}\text{K}(d,p)^{48}\text{K}$

W. Catford (Surrey), A. Matta (LPC)

$^{47}\text{K}(d,p\gamma)^{48}\text{K}$ neutron transfer

First time:

- α -transfer (stripping) at Ganil
- Lifetime measurement of states populated by transfer
- $(^3\text{He},d)$ reaction

With radioactive ion beams

2021

SHELL STRUCTURE
Proton-neutron interactions across the N = 28 shell closure via $^{47}\text{K}(d,p)^{48}\text{K}$

W. Catford (Surrey), A. Matta (LPC)

$^{47}\text{K}(d,p\gamma)^{48}\text{K}$ neutron transfer

~~NUCLEAR ASTROPHYSICS
Neutron capture at the ^{85}Kr s-process branching~~

~~*F. Recchia (INFN), S. Palmerini*~~

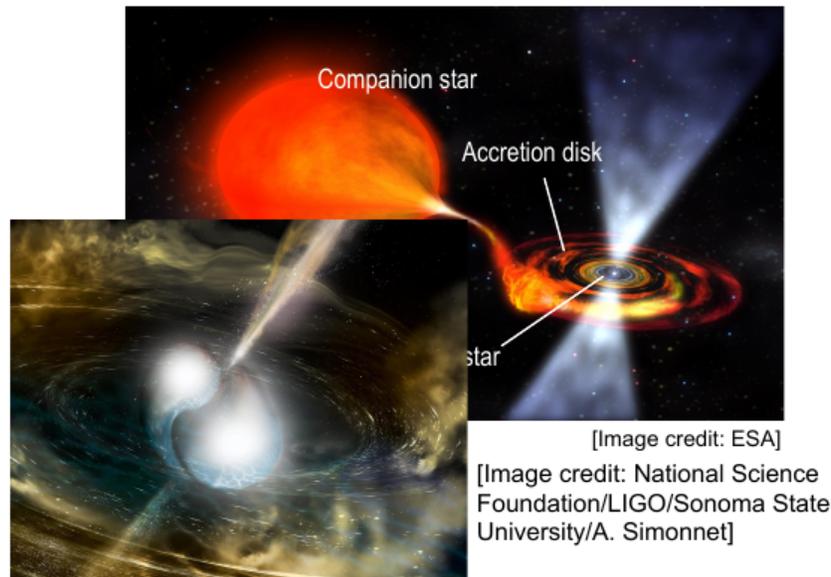
~~$^{85}\text{Kr}(d,p\gamma)^{86}\text{Kr}$ with 10^8 pps~~

~~Approved in 2019, backlog~~

MUGAST@LISE

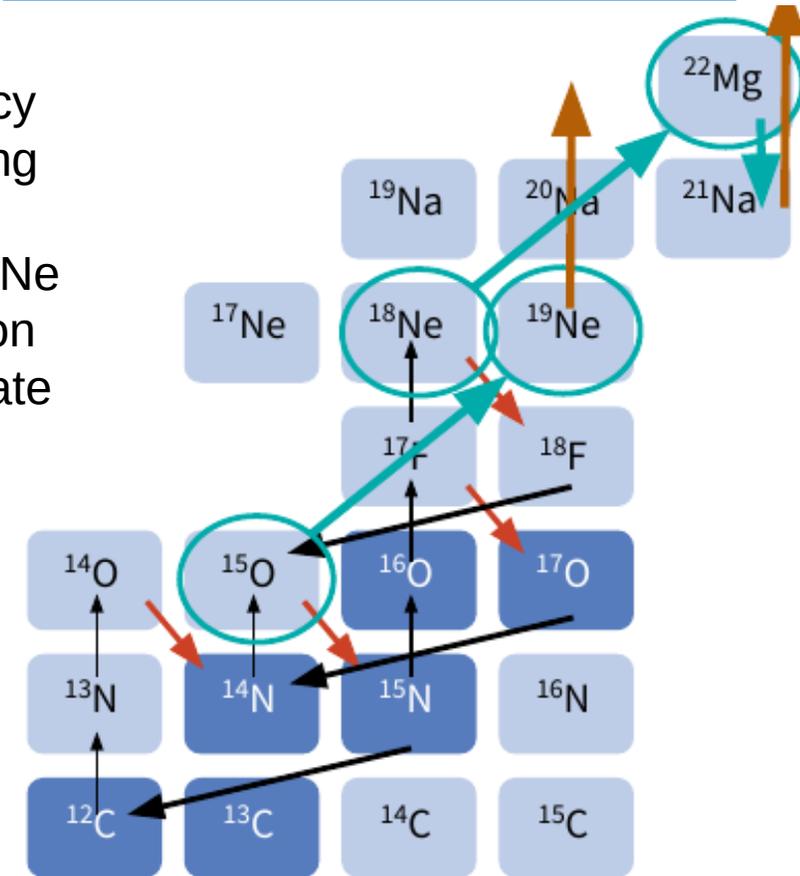
Accreting neutron stars & X-ray bursts

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

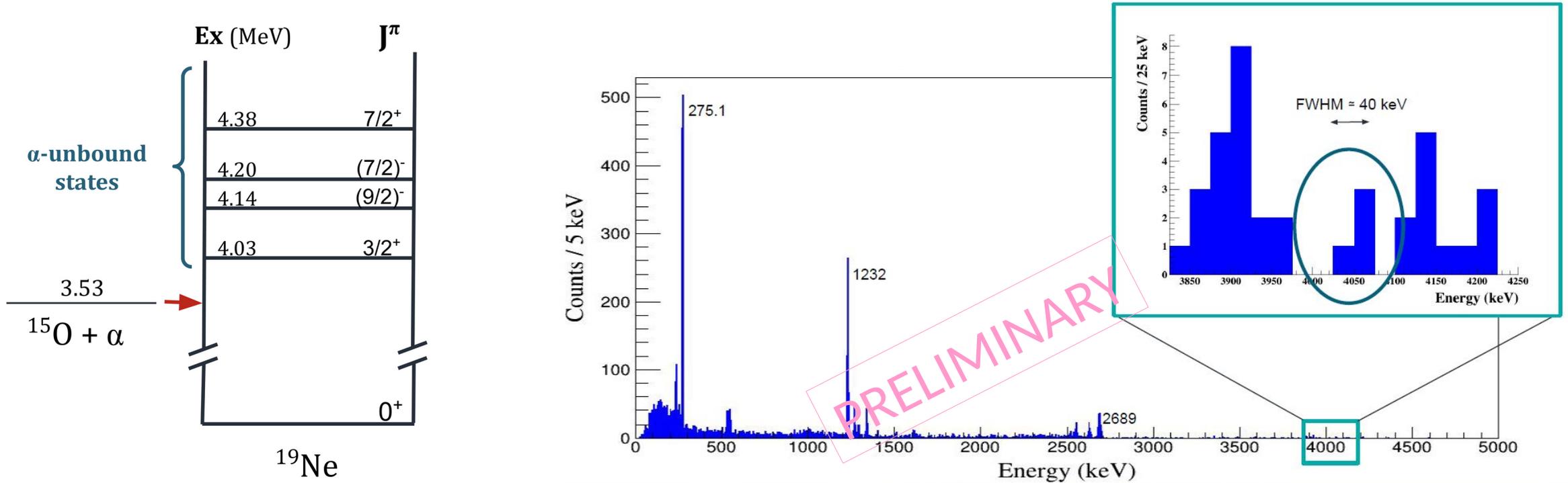


- NS accreting matter from companion; Accreted H is burned to He; ignition of Hot-CNO cycle
- Breakout from Neutron star Hot-CNO
- Break out point: $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

- 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



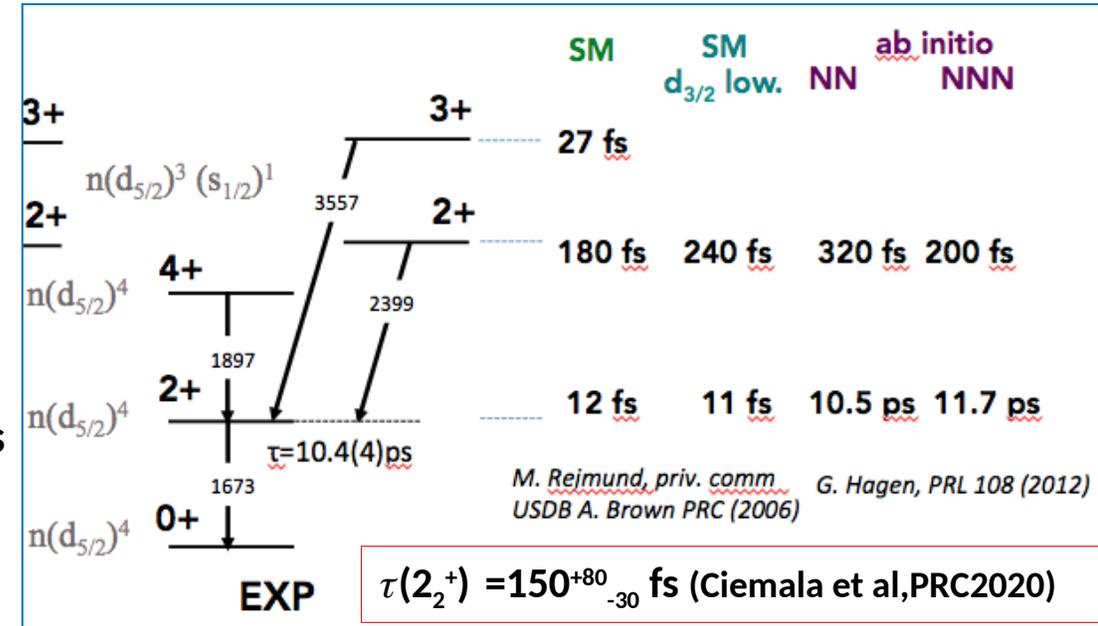
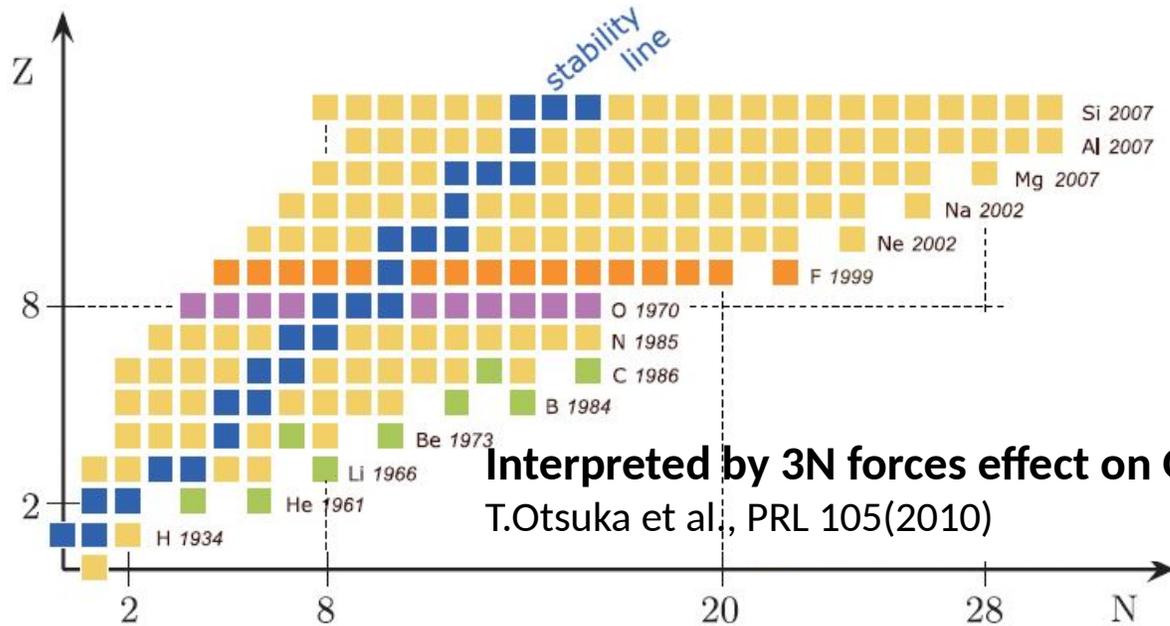
Pushing the limit of sensitivity



- $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne} \leftarrow ^{15}\text{O}(^7\text{Li}, t)^{19}\text{Ne}$
- Beam rate : $\sim 10^7$ pps and triple coincidence: $\gamma + t + ^{19}\text{Ne}$
- Minimum detection limit: **cross-section few $\mu\text{b}/\text{sr}$**
- New accurate results

From: J.Sanchez Rojo PhD thesis

The oxygen anomaly



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

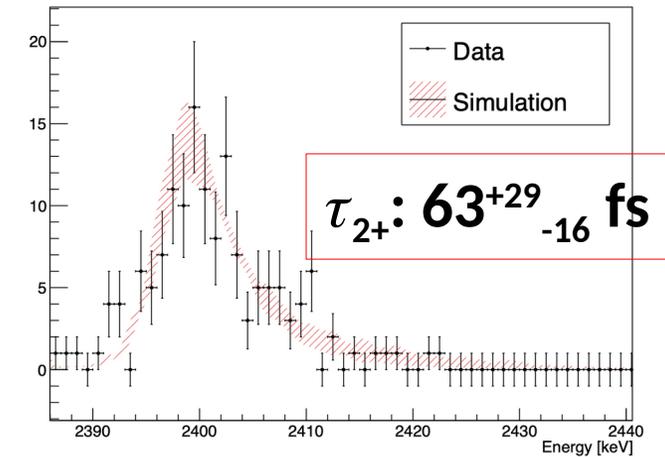
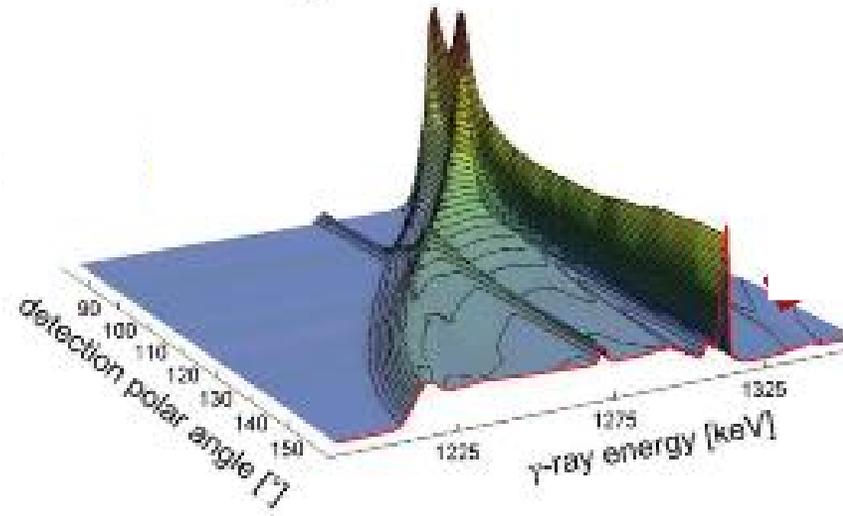
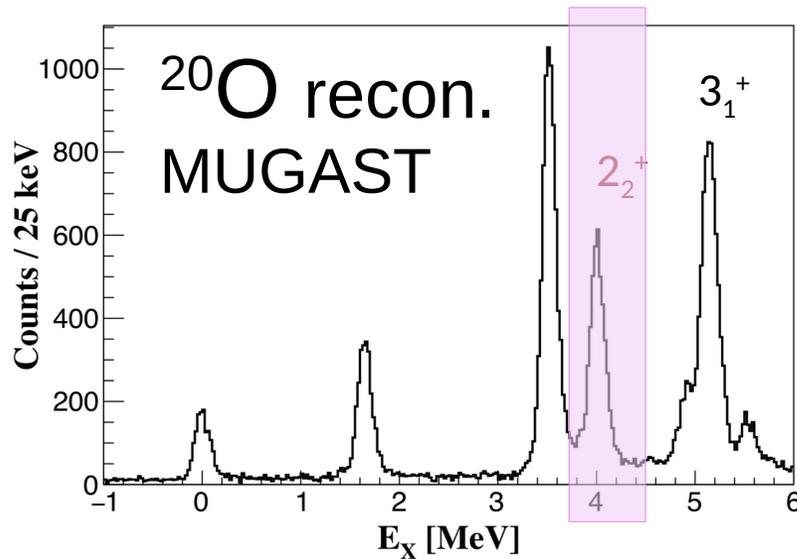
$^{19}\text{O}(d, p\gamma) + \text{DSAM}$

- ⇒ Constrain relative position of s_{1/2} and d_{3/2} 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



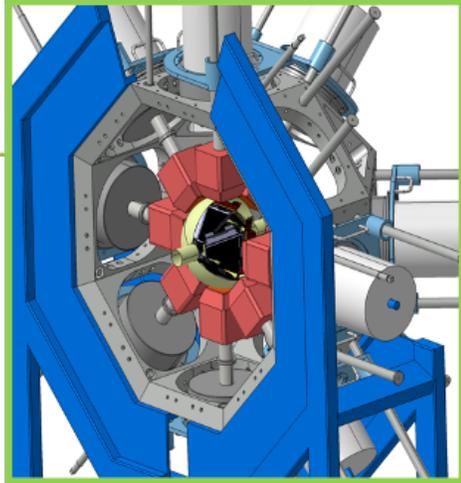
- Triple coincidences: reconstructed entry point (MUGAST) through transfer reaction to avoid top feeding + continuous-angle line shape (AGATA)+ channel selection (VAMOS)
- Lifetimes measured significantly shorter than predictions for the 2^+ , theoretical interpretation ongoing
- First lifetime measurement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

Conclusion and perspectives



MUGAST-
AGATA-VAMOS
@GANIL

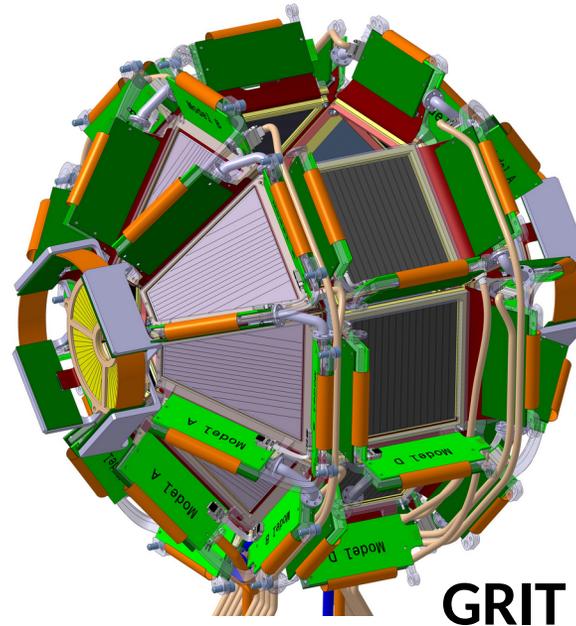
2021



MUGAST-
EXOGRAM-LISE
@GANIL

2023-2024

- Instrument of new generation enables large leap in detection sensitivity which translated in physics at the frontier
- Highlights from the AGATA+MUGAST+VAMOS campaign @GANIL
- Future campaigns are planned with upgraded setup for quality scientific results



GRIT



