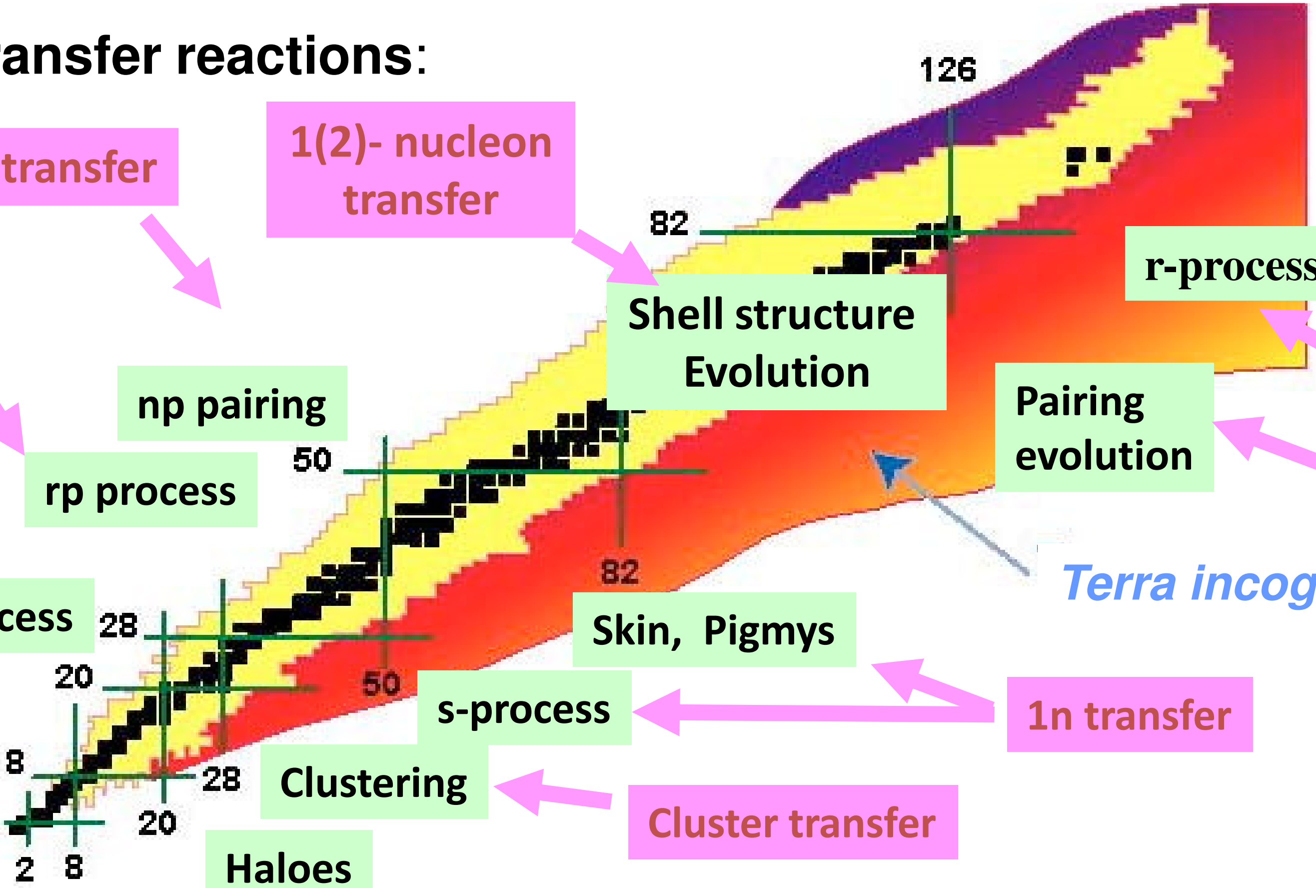
The GRIT project for reaction studies

D.Beaumel, IPN Orsay
For the GRIT collaboration

Direct reactions

A great tool to investigate Exotic Nuclei and Astrophysical processes

Case of **transfer reactions**:



d transfer

1(2)- nucleon transfer

p transfer

Shell structure Evolution

r-process

1n transfer

np pairing

rp process

Pairing evolution

2n transfer

Terra incognita

αp process

Skin, Pigmys

s-process

1n transfer

Hot CNO

Clustering

Cluster transfer

Haloes

Good energy regime : 5 ~ 50 MeV/u → **Core program for ISOL facilities**

GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

SPES exotic beams for science

ISOLDE

Direct reactions

A great tool to investigate Exotic Nuclei and Astrophysical processes

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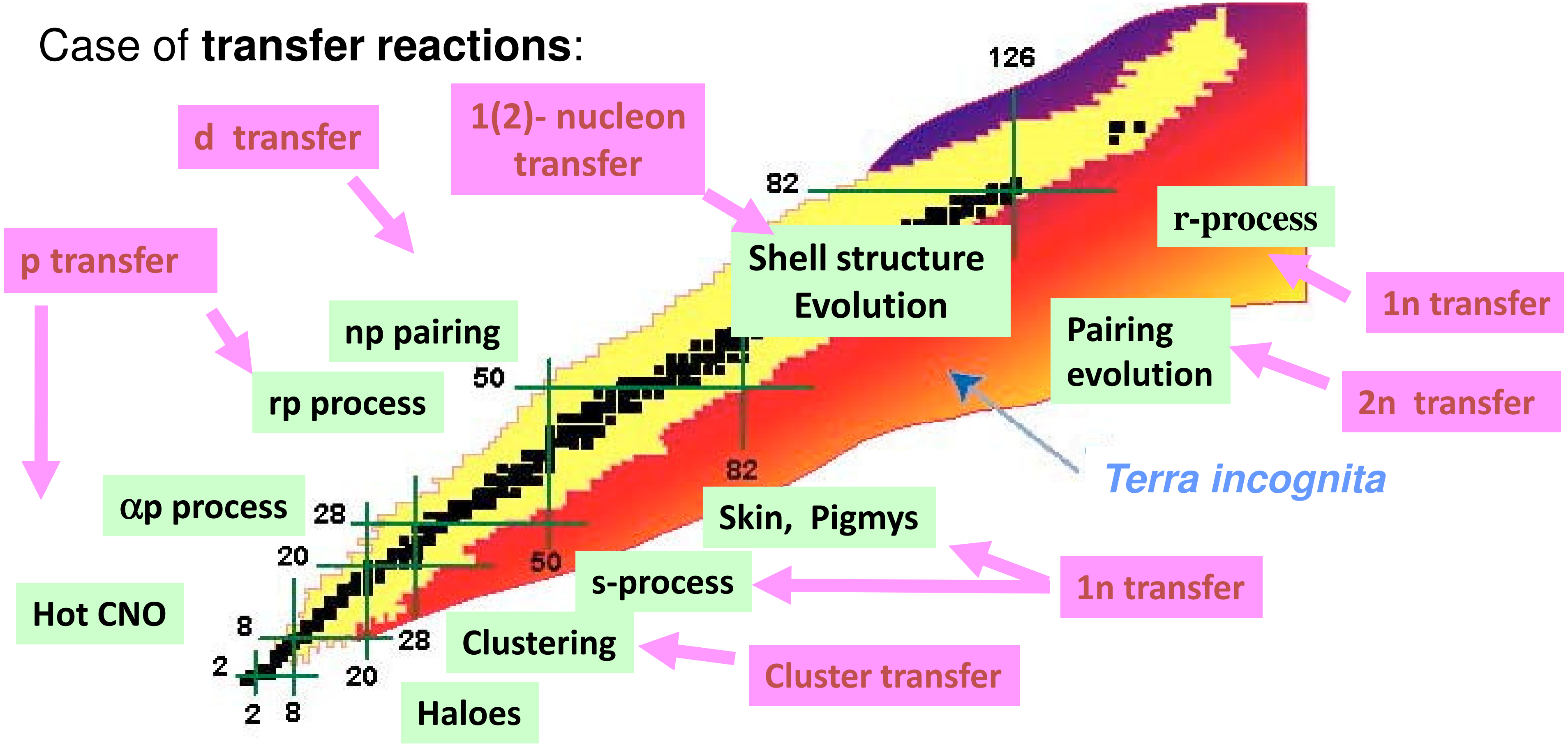

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Cluster transfer

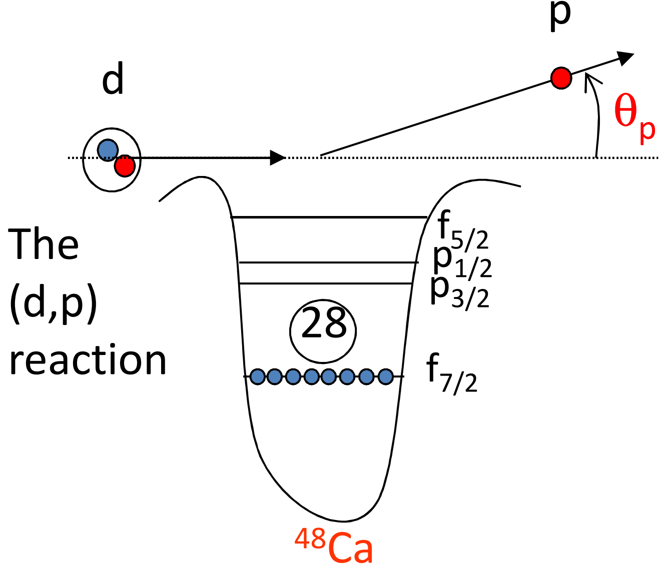
Haloes

Good energy regime : 5 ~ 50 MeV/u ➡ **Core program for ISOL facilities**

Methodology : **Radioactive Ion Beam** ➡ **Light target (H,He…)**
Detect the recoil particle with high accuracy

Transfer reactions as a tool

- ✓ **Selective spectroscopy**
- ✓ **Quantitative information on wave functions**

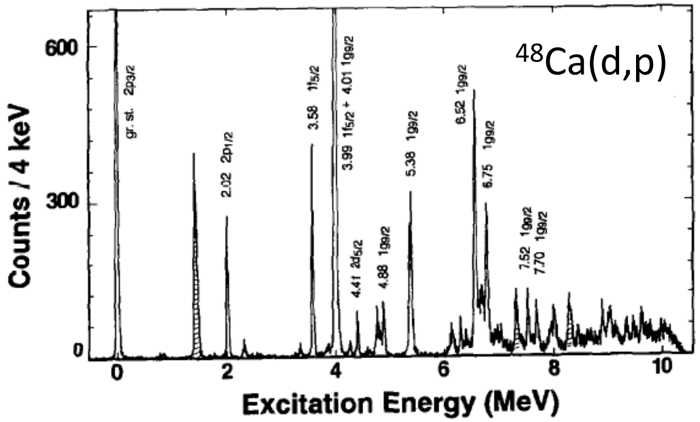


The (d,p) reaction

1-nucleon transfer
Single particle properties
Orbital energies, occupancies
1-nucleon overlaps (A+1|A)
Information on *individual* configurations

2-nucleon transfer
Test 2 nucleon overlaps (A+2|A)
Probe coherence effects of several config.

Cluster Transfer
Clustering features
Quartetting



Y.Uozumi et al., Nucl. Phys. A 576 (1994)

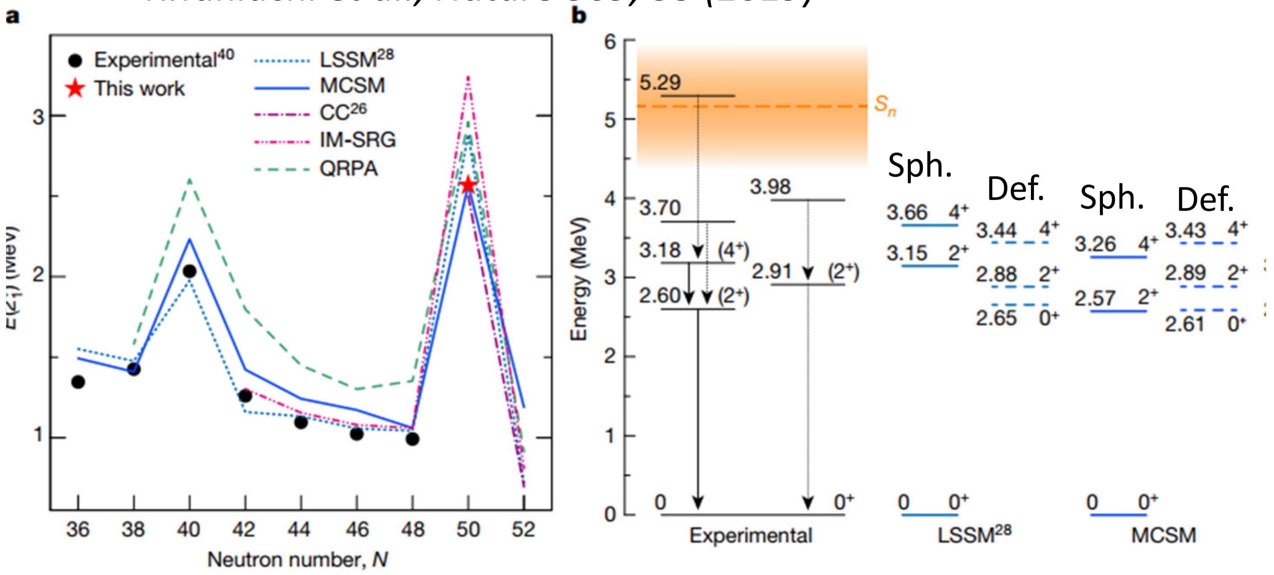
Indirect methods for astrophysics e.g (n,g) ↔ (d,p)
Millibarns of cross-sections for transfer !
Use of Radioactive Ion beams in inverse kinematics

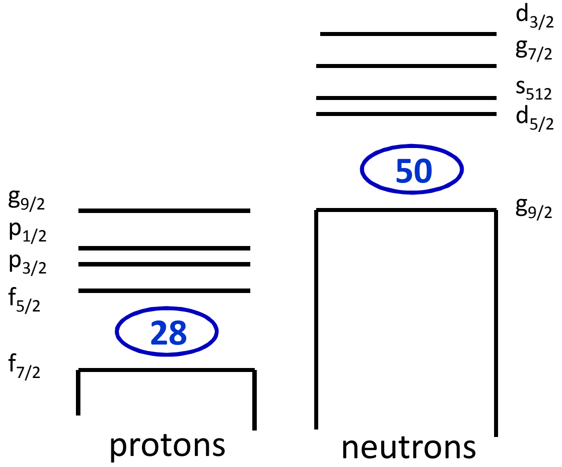
STUDIES WITH RADIOACTIVE NUCLEAR BEAMS

Understanding the N=50 shell closure

✓ **Recent RIKEN results on low-lying properties of ^{78}Ni**

R.Taniuchi et al., Nature 569, 53 (2019)





✓ **Recent identification of shape coexistence just below N=50**

β-decay of N=48 ^{80}Ge *A. Gottardo et al., PRL 116, 182501 (2016)*

Laser spectroscopy of N=49 ^{79}Cu *X. F. Yang et al., PRL 116, 219901 (2016)*

- ➢ **What is the underlying shell structure and evolution mechanisms ?**
- ➢ **Role of the intruder configurations ?**

  (Multiparticle-multihole excitations above the N=50 and Z=28 gaps)

Crucial for a global description of this region of the nuclear chart
And for reliable predictions for astrophysical processes (r-process)

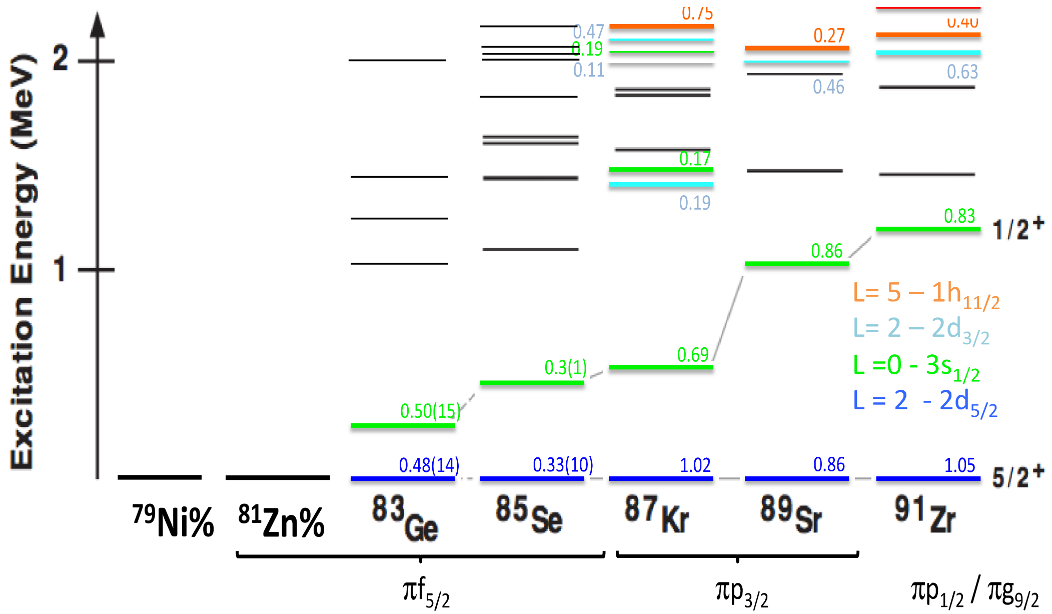
Understanding the N=50 shell closure - II

1. Characterize directly the energy evolution of valence orbitals

First indications from ^{82}Ge(d,p) @ Oak ridge
J.S.Thomas et al., PRC71(2005)

Origin of the drift of 1/2+ state ?

- ✓ Tensor part of nn interaction as for N=20 ?
  not for 1/2$^+$ states
- ✓ Central part ?
- ✓ pseudo-spin symmetry ?
- ✓ ….



Method

- ➢ ^{82}Ge, ^{80}Zn(d,p)(d,t) reactions
  → locate the 2d$_{5/2}$, 2s$_{1/2}$, 2d$_{3/2}$, 1g$_{7/2}$
  with GRIT- AGATA at SPES facility

2. Investigate Intruder configurations

Methods

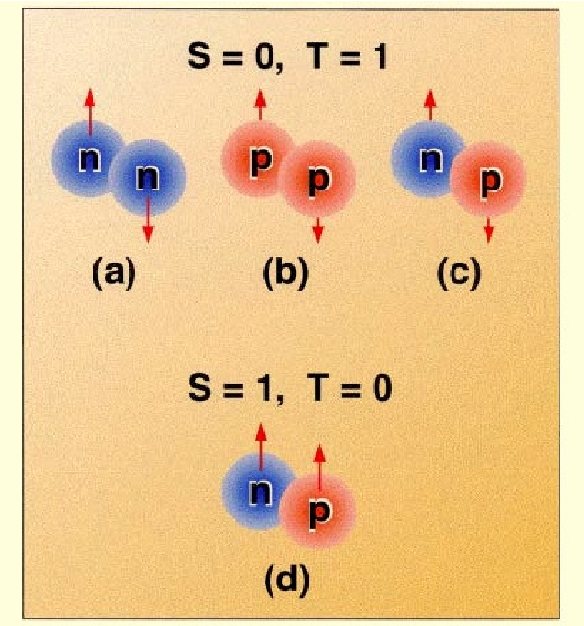
- ➢ Investigate 2 neutron transfer (t,p) reaction on N=49 (neutron hole) isotones
  → Selective population of 2p-1h intruder states $(\nu(g_{9/2})^{-1}(sd)^{+2}$ configurations)
  → Study (t,p) on ^{87}Kr, ^{87}Se, ^{83}Ge, ^{81}Zn with GRIT-AGATA at SPES
- ➢ (d,p) reaction on long-lived intruder 1/2+ states in e.g. ^{81}Ge and ^{79}Zn
  Beams produced by selective laser ionization (Zn)

Evidencing neutron-proton pairing by np pair transfer

Nuclei : a unique system where superconductivity can develop over two fluids (neutron and proton)

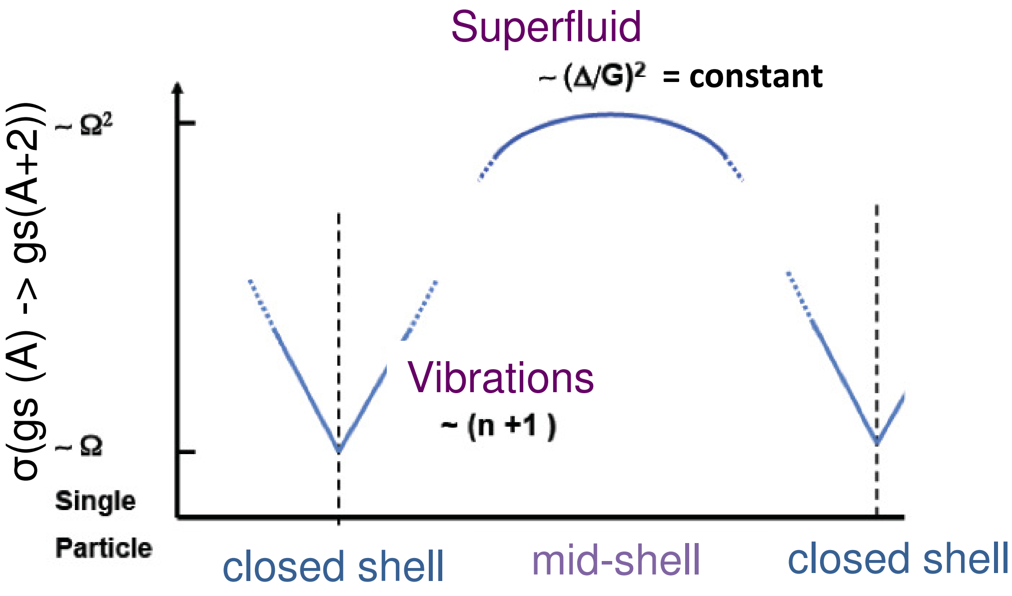
4 types of Cooper pairs

- T=1 nn, pp, np
  - np should be similar to nn and pp
- T=0 np pairs → new phase of nuclear matter
  - ***no clear evidence***



nn pairing by 2n transfer -> dynamical aspects

Collective states in the part.-part. channel



adapted from Frauendorf & Macchiavelli Prog. in Part. and Nucl. Phys. 78 (2014) 24

For np pairing study → N=Z nuclei to maximize overlap of n and p WF

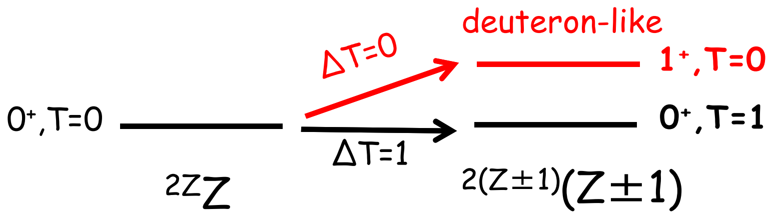
Pattern confirmed in 2n transfer results from (p,t) and (t,p) studies

Broglia, Hansen, Riedel, Adv. Nucl. Phys. 6, 287 (1973)

Evidencing neutron-proton pairing by np pair transfer II

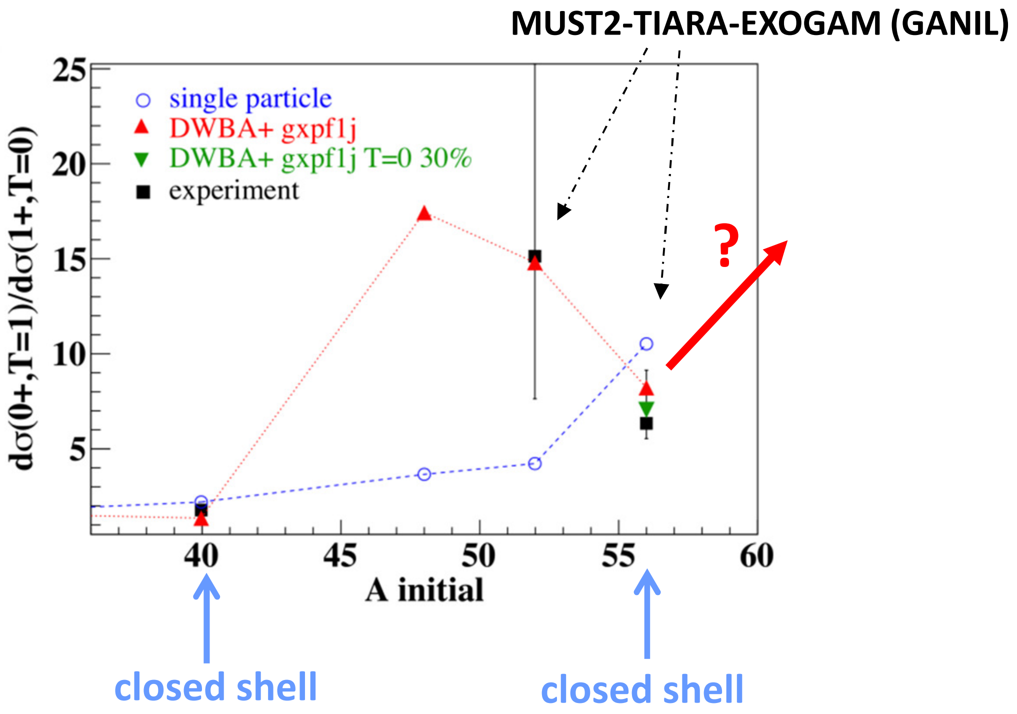
Deuteron transfer reaction on N=Z nuclei
The "smoking gun" for probing T=0 pairing ?

σ (0^+)/σ (1^+) gives the relative strength of T=0/T=1 pairing


deuteron-like
ΔT=0
1^+,T=0
0^+,T=0
0^+,T=1
ΔT=1
^{2Z}Z
$^{2(Z\pm1)}(Z\pm1)$

Complementary reactions :
(p, ^{3}He), (^{3}He,p) ΔT=0,1
(d,α), (α ,d) ΔT=0
(α, ^{6}Li), (^{6}Li,α) ΔT=0

Study with GRIT- AGATA
^{60}Zn and ^{64}Ge beams
SPIRAL1 / GANIL
Isolde


MUST2-TIARA-EXOGAM (GANIL)

closed shell
closed shell

Explaining the origin of heavy elements (A > 56)

Vast majority of A>56 nuclei are created through neutron capture (n,γ)

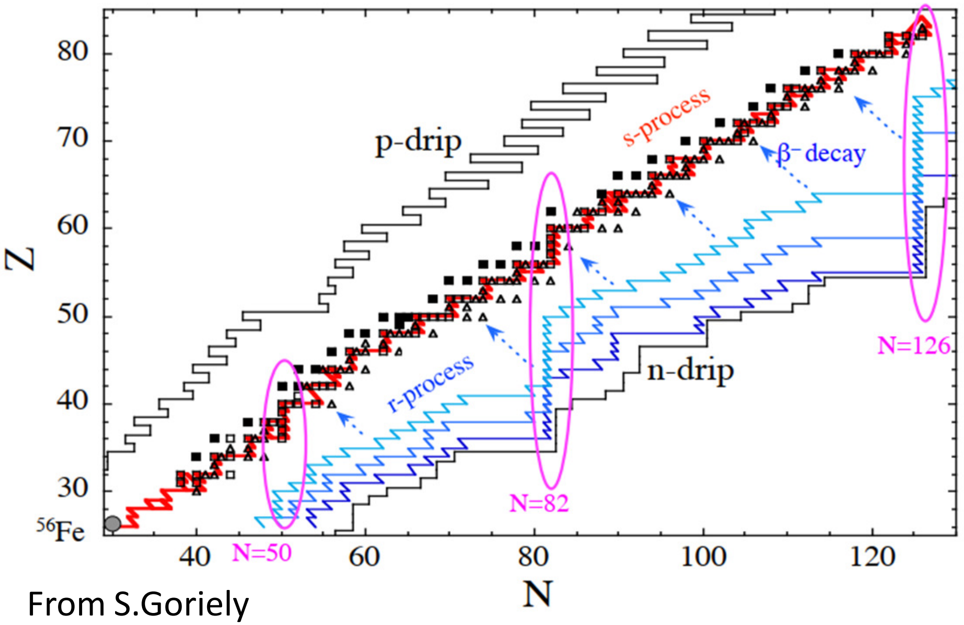
Slow neutron-capture process: $\tau_\beta \ll \tau_n$

N_n ~10^7-10^{11} cm^{-3} T~1-3.10^8K duration ~ 10-10^4 yr

Rapid neutron-capture process: $\tau_\beta \gg \tau_n$

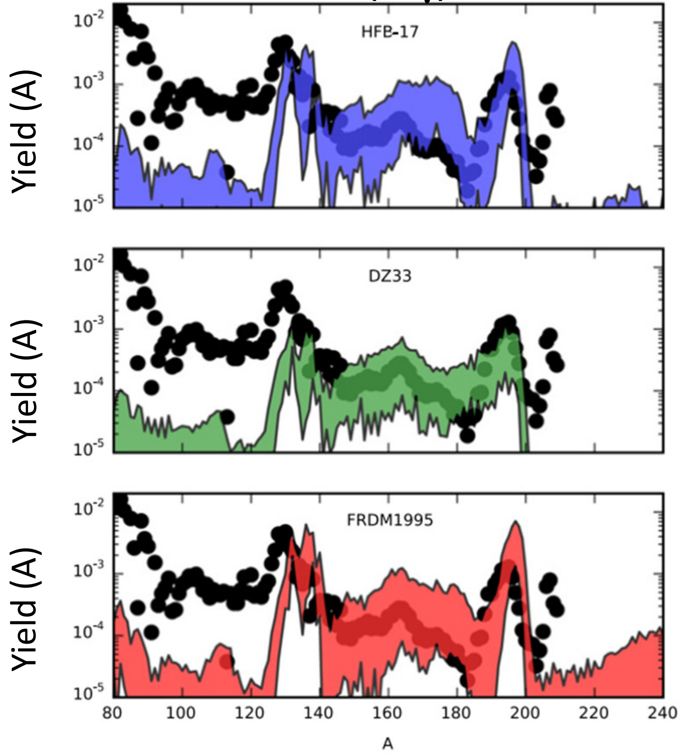
$N_n \gg 10^{20}$cm^{-3} T~10^9K duration ~ 1s

Artist view of kilonova as observed from neutron- star mergers on May 17, 2017



From S.Goriely

Effect of σ(n,γ) variance



M.R. Mumpower et al., PPNC 86, 86 (2016)

<u>Nuclear Physics aspects:</u>

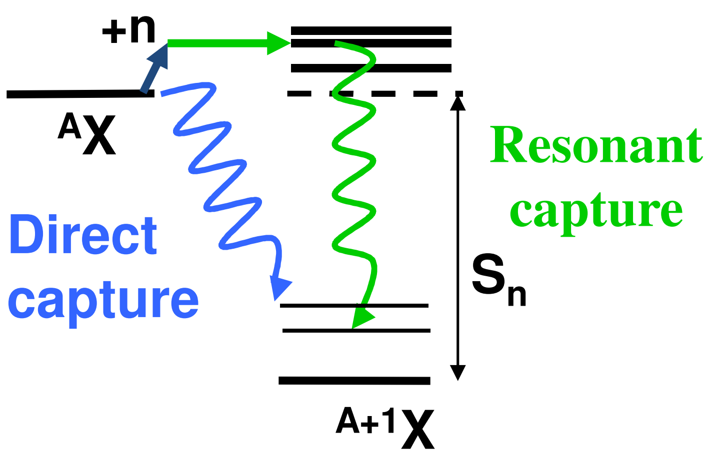
Masses, β-decay half-lives, **capture cross-sections (n,γ)**

Photo-disintegration rates, fission rates. ν-N rates

Indirect determination of $\sigma(n,\gamma)$ from $(d,p\gamma)$

2 cases

- Low Level Density (n-rich nuclei)
  Capture to **individual states/resonances**
  $(d,p\gamma)$ → relevant properties (E, L, SF, Γ)



- High Level Density (near or at stability)
  - Calculated compound nucleus probab.

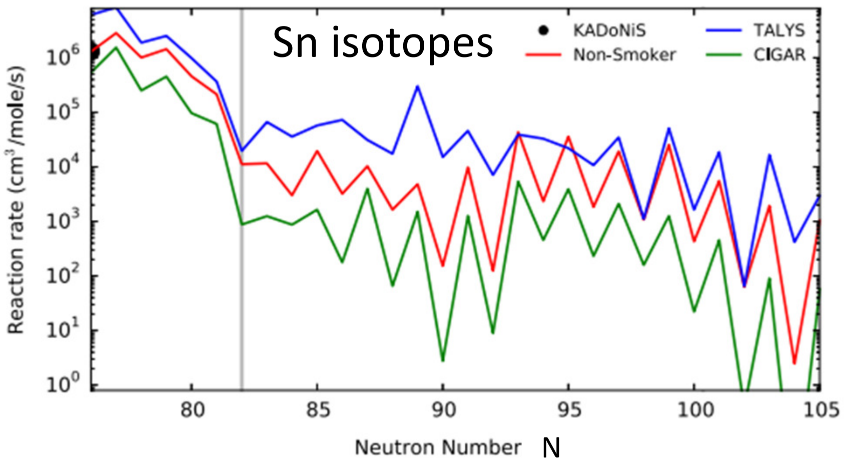
  $(d,p\gamma)$ → Branching ratios

  A.Ratkiewicz et al., PRL 122, 052502 (2019)
  “Surrogate method”

Early application by the collaboration

Determination of ^{46}Ar$(n,\gamma)^{47}$Ar using ^{46}Ar$(d,p)^{47}$Ar reaction studied with the MUST array at GANIL
L.Gaudefroy et al., EPJA 27, 309 (2006)

Presently, all (n,γ) rates for r-process come from Hauser-Feshback calculations

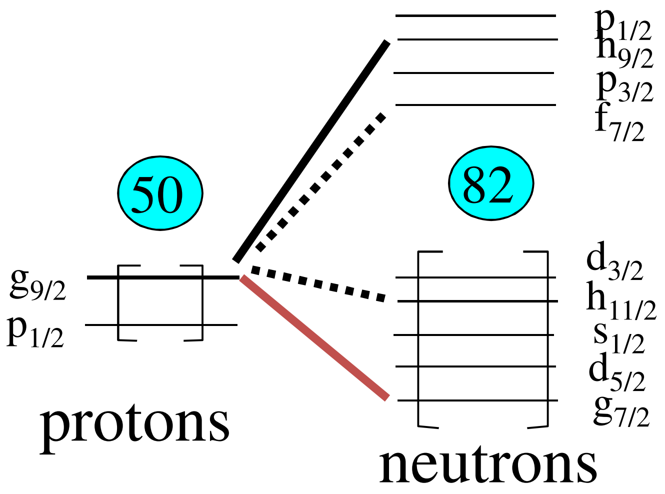


M.R. Mumpower et al., PNPP 86, 86 (2016)

Strong model dependence
(fact ~1000) far from stability

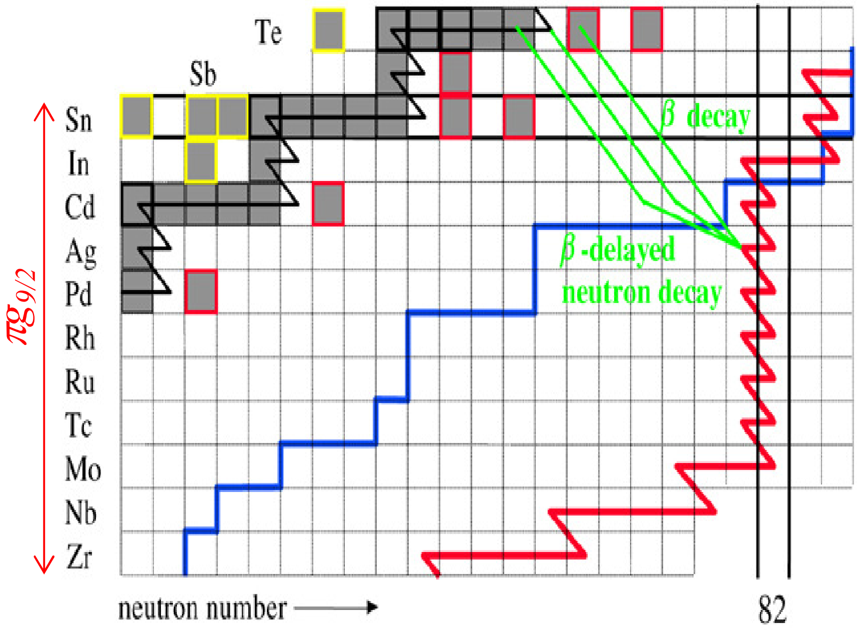
r-process and shell structure in the N~82 region

From ^{122}Zr to ^{132}Sn → fill up the proton g9/2 shell



Importance of neutron $p_{1/2}$ and $p_{1/2}$ for capture !

r-process “bumps” on the N=82 shell closure



1. How to predict their evolution south of ^{132}Sn ?
   - **Study the (d,pg) reaction on ^{132}Sn and ^{130}Cd**
   - Extract the neutron-proton monopole matrix elements + occupancies
   - Predict evolution of single-part. energies down to ^{122}Zr

2. For >^{132}Sn a gap may appear at N=90 due to nn interaction

   From ^{132}Sn to ^{140}Sn : fill up the neutron $2f_{7/2}$ shell

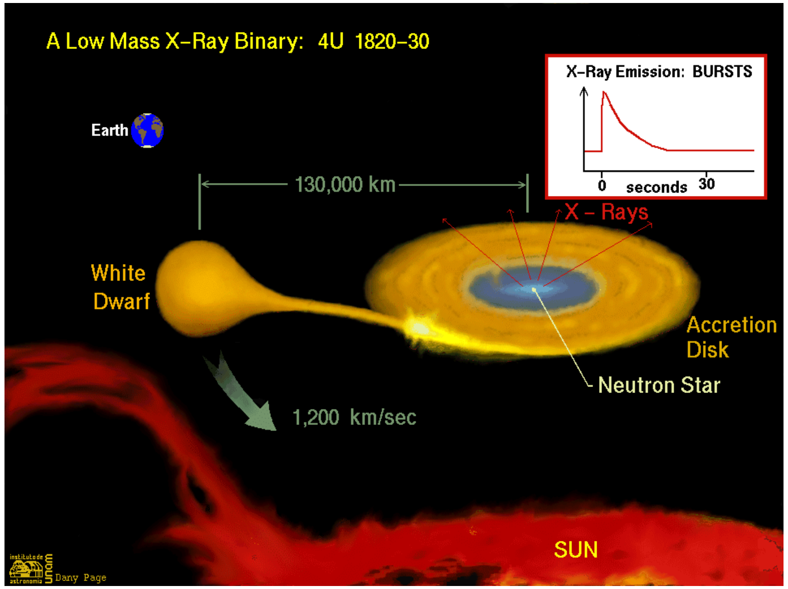
   similar monopole M.E. and possibly 3-body forces are at play as in the case of N=28

   → **Study ^{134}Sn(d,p)** to deduce gap evolution (and p orbits s.p.e.)

GRIT-AGATA experiments at SPES

Type I X-ray bursts

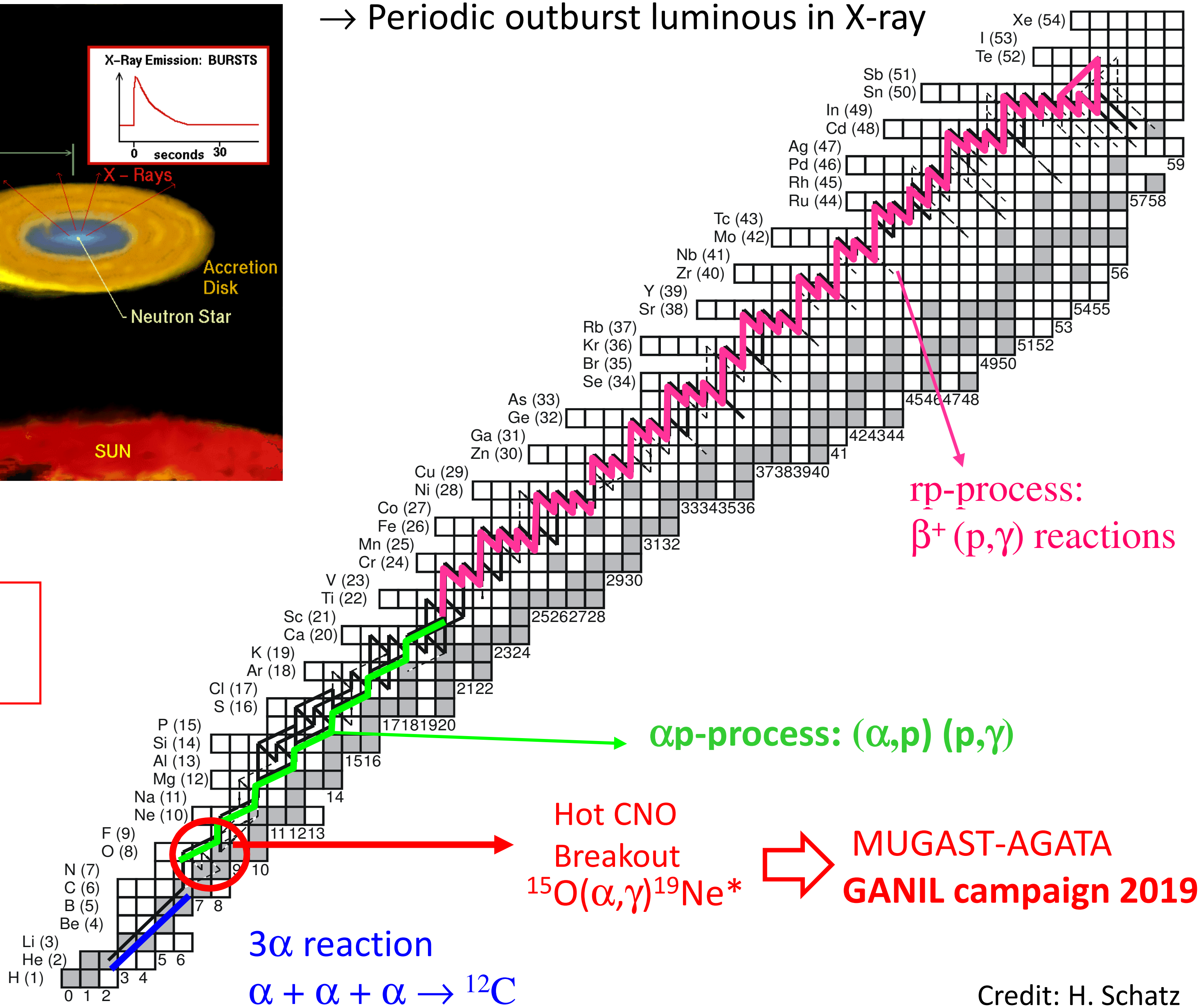
Accretion from companion star



→ Periodic outburst luminous in X-ray

T ~ 10^9 K

ρ ~ 10^6 g cm^{-3}



rp-process:
β+ (p,γ) reactions

αp-process: (α,p) (p,γ)

Hot CNO
Breakout
$^{15}O(\alpha,\gamma)^{19}Ne^*$

⇨

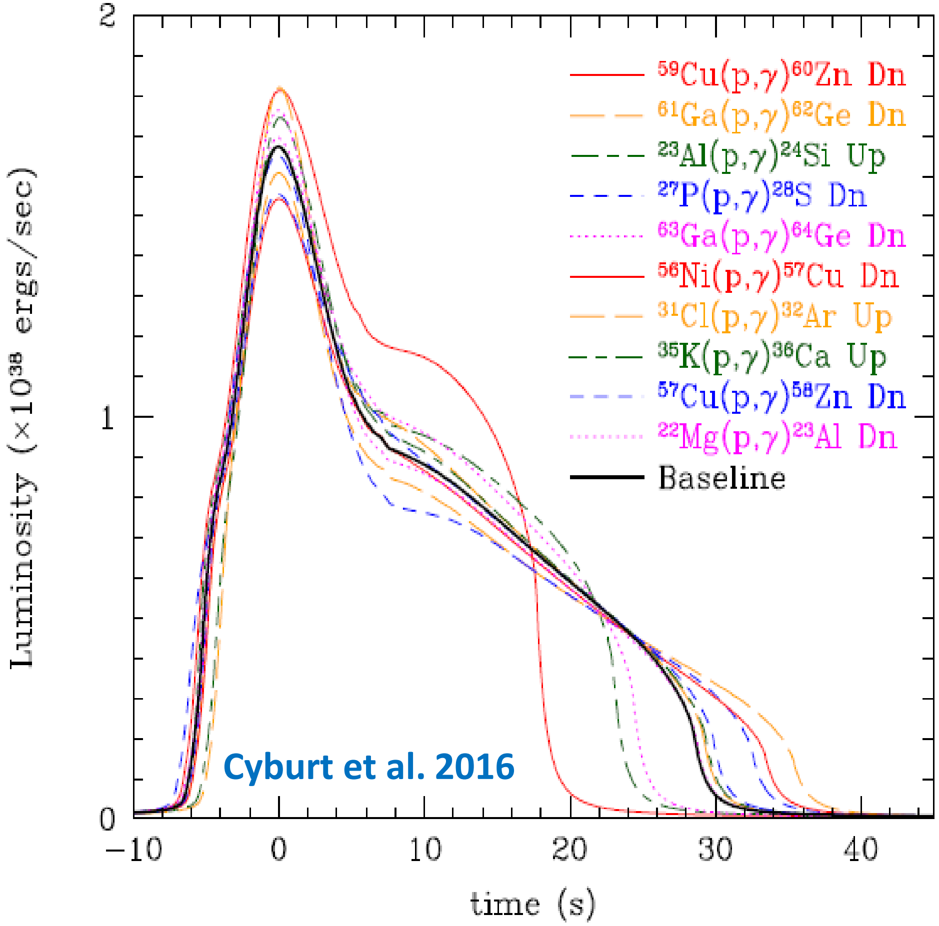
MUGAST-AGATA
GANIL campaign 2019

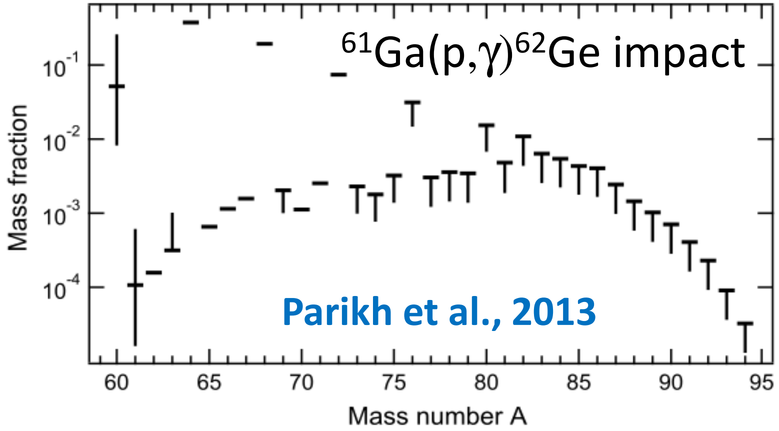
3α reaction
α + α + α → ^{12}C

Credit: H. Schatz

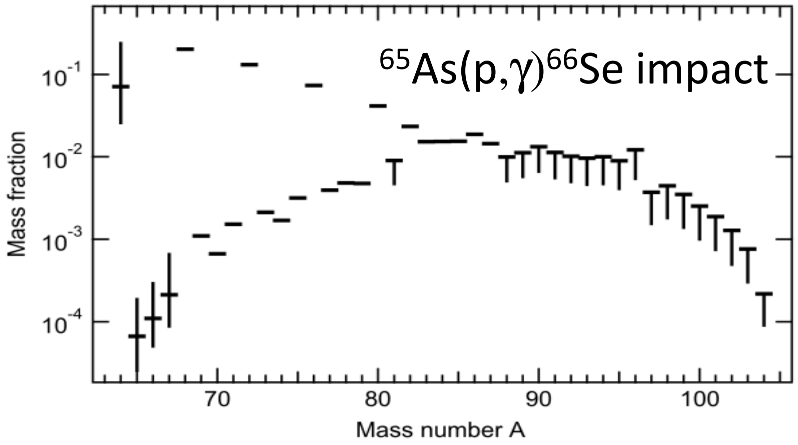
(p,γ) key reactions

- The **(p,γ)** reactions play an important role in **luminosity profile** & **XRB abundance**
  Isotopic yields are mostly those at waiting points
- **(p,γ) cross-section can be deduced from proton transfer (^{3}He,d)**


Cyburt et al. 2016


^{61}Ga(p,γ)^{62}Ge impact

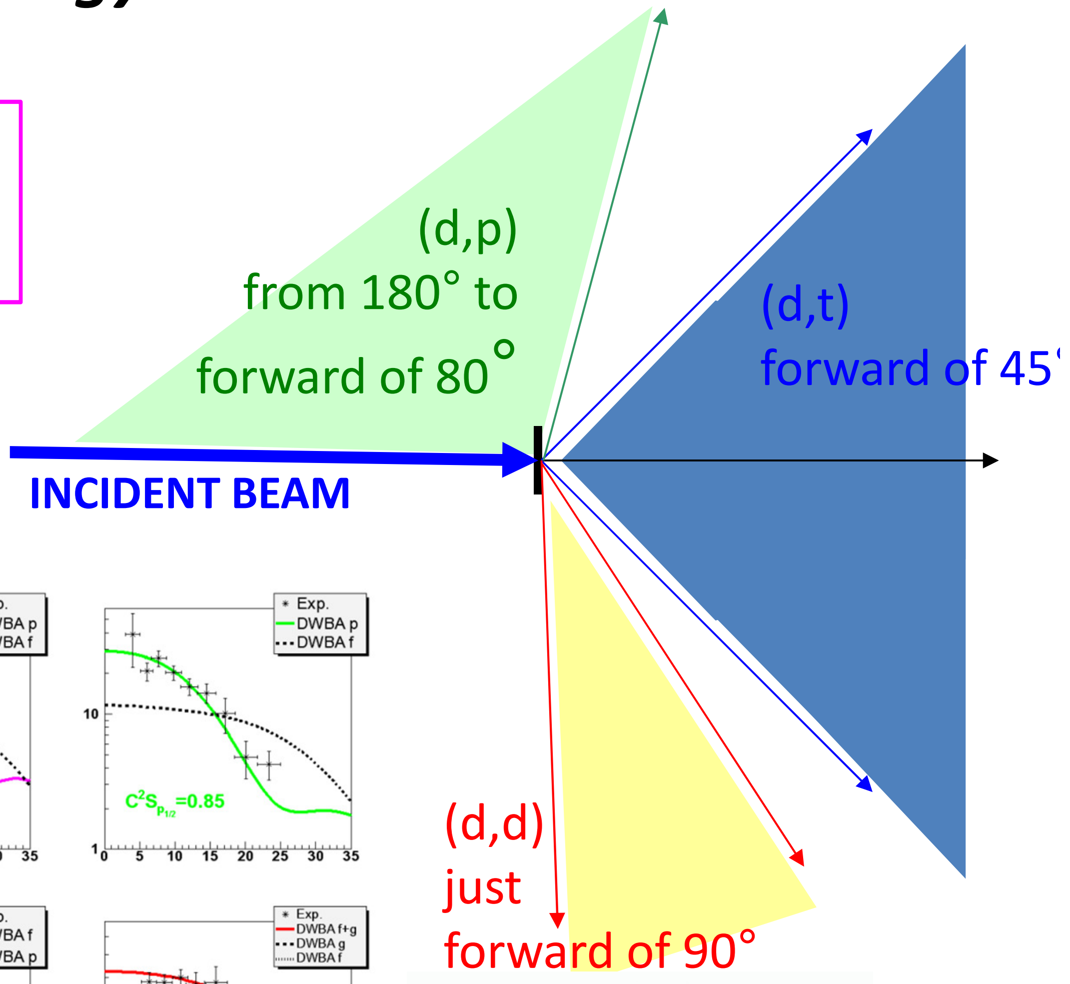
Parikh et al., 2013


^{65}As(p,γ)^{66}Se impact

At **GANIL** using SPIRAL or LISE beams:
Study ^{56}Ni(^{3}He,d), ^{65}As(^{3}He,d), ^{60}Zn(^{3}He,d)
or alternatively the (d,p) reaction in the mirror nuclei

(Initial) methodology with exotic beams

Detect the light recoiling particle E_L , Θ_L
- **Excitation energies**
- **Differential cross-sections**



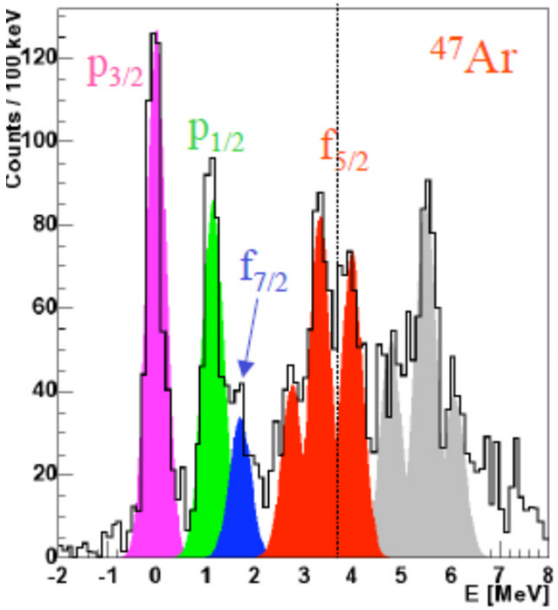
(d,p)
from 180° to
forward of 80°

(d,t)
forward of 45°

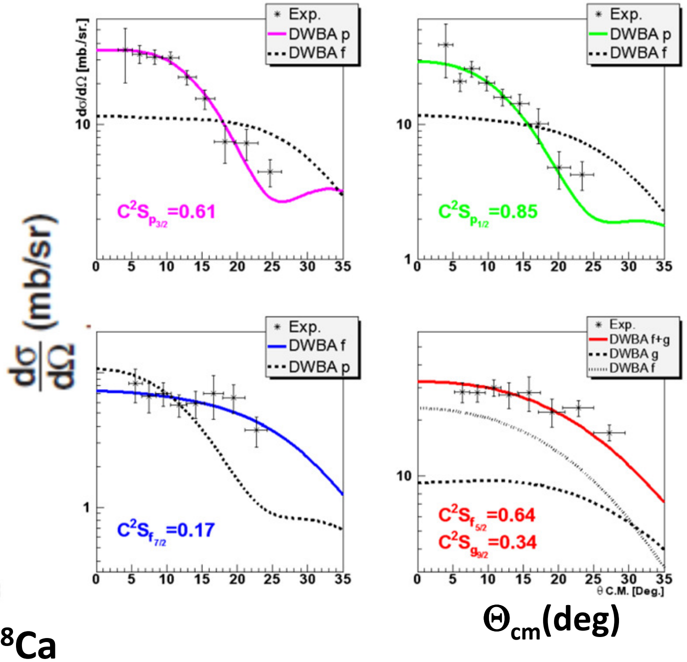
INCIDENT BEAM

(d,d)
just
forward of 90°

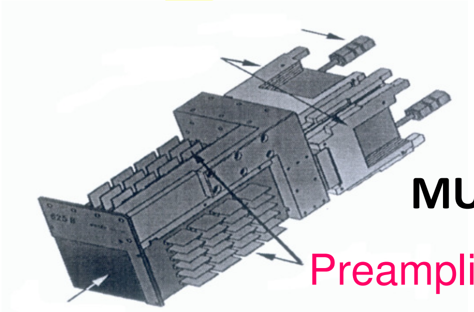
Ex: ^{46}Ar(d,p) @ GANIL/SPEG
using the **MUST** array



Reduction of N=28 gap w/r ^{48}Ca
L.Gaudefroy, et al., PRL (2006)



Few 100's keV resolution although very thin target



MUST

Preamplifiers

Detectors

Y.Blumenfeld et al.. NIM A421 (1999)

Constraints due to kinematics

Need

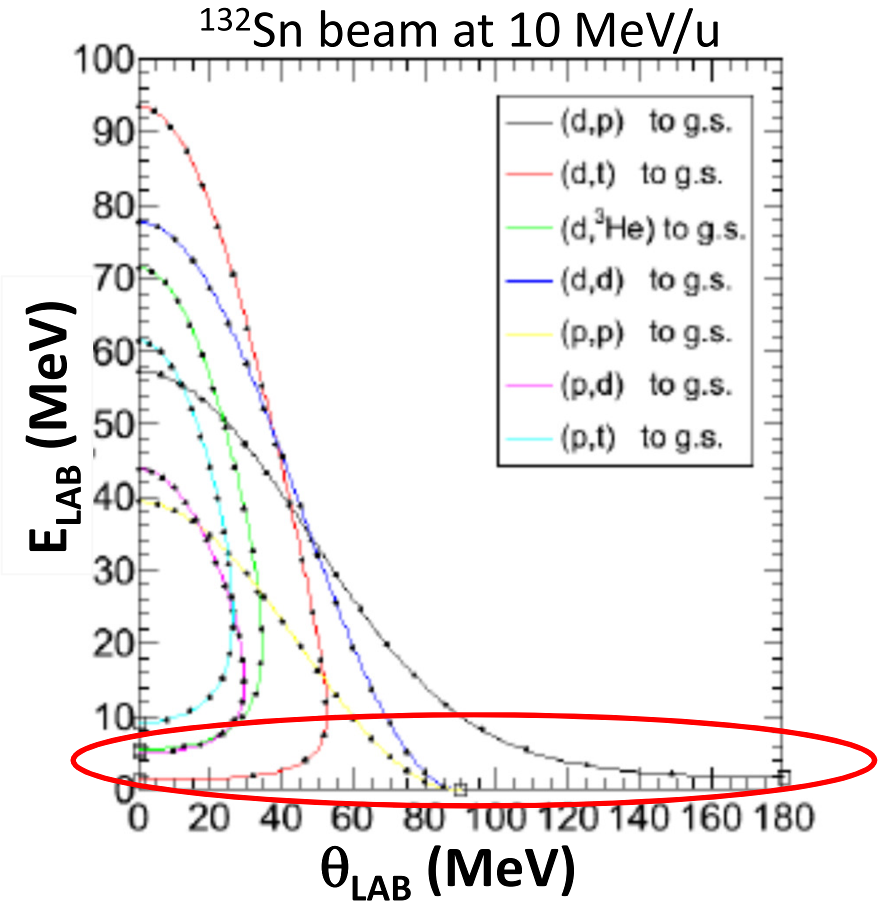
- ➢ **Large angular acceptance**
- ➢ **Large dynamic range**
- ➢ **Low threshold**
- ➢ **Thin target**

Kinematics weakly dependent
On mass (and on E) of the beam

➡ **General purpose system**

Limitations

- ➢ **Target thickness**
- ➢ **Kinematical compression**
  (d,p) with 1mg/cm2 CD2
  ΔEp ~100 keV $\Rightarrow$ ΔEx ~ 400 keV



NB: Need also

- ➢ **Good PID for the recoil and the beam-like residue**

➡ **Development of new systems / combinations**

Silicon arrays developments

Light beams

Fission fragments

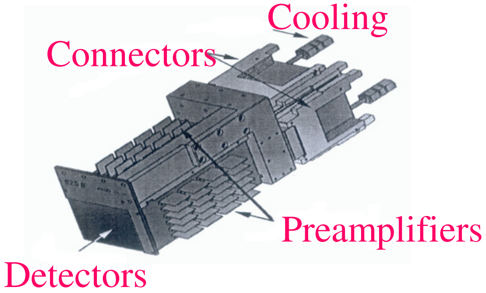
1997

2007

2019/23

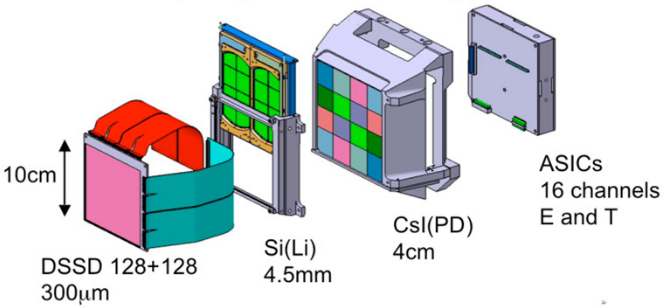
MUST

<u>Coll.</u>: IPN,CEA-Saclay, DAM



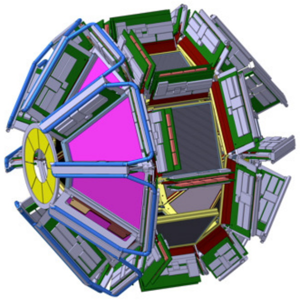
MUST2

<u>Coll.</u>: IPN,CEA-Saclay, GANIL



MUGAST/GRIT

Coll.: IPN, LPC, INFN, BARC,
Surrey,GANIL,
Valencia,Santiago,Huelva



Particle spectroscopy

E_x resolution: ~500 keV

Particle-γ Spectroscopy

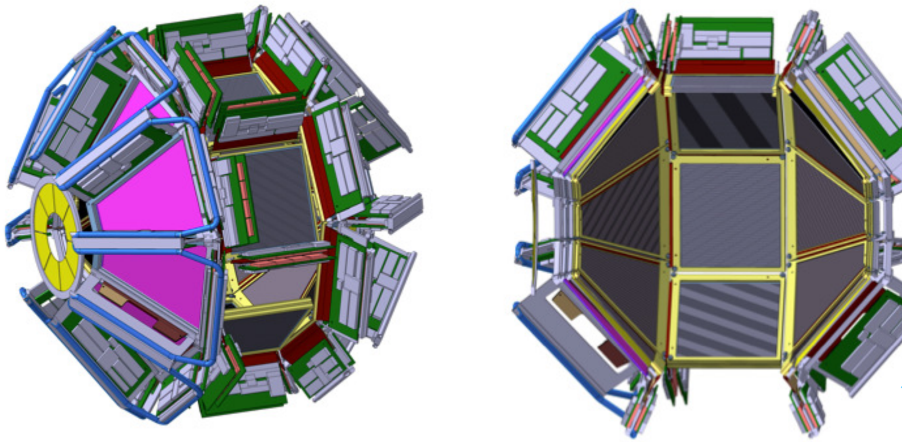
E_x resol.: ~5keV (AGATA)

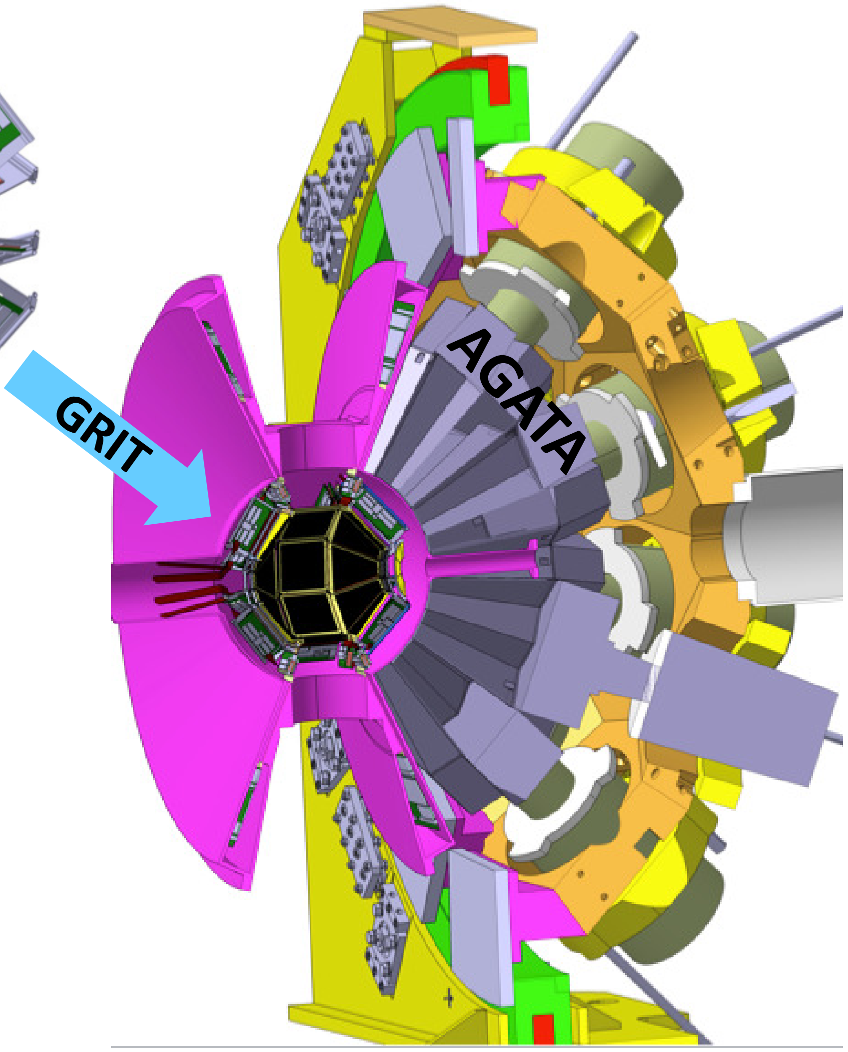
The GRIT project

(Granularity, Resolution, identification, Transparency)

(GASPARD-TRACE collaboration)

4π Si array fully integrable in AGATA & PARIS





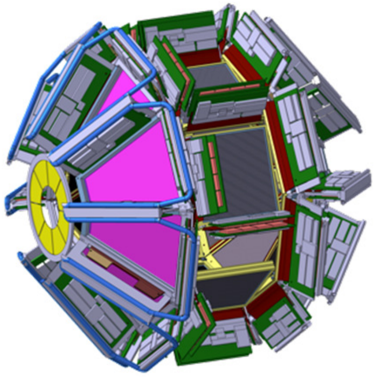
- High efficiency for particles
- High granularity (strip pitch < 1 mm)
- Large dynamical range

Layers of Silicon

- 500 um DSSD pitch < 1mm
- 1.5 mm DSSD pitch ~5mm

- Special targets (Cooled ^{3,4}He cell, pure H, tritium)
- PID using Pulse Shape Analysis techniques
- New Integrated electronics

The GRIT/MUGAST collaboration



Management Board:

M. Assié (IPNO), **D. Beaumel** (IPNO, spokesperson)
D. Mengoni (INFN Padova), **A. Pullia** (INFN Milano)

Steering committee :

R. Bougault (LPC Caen), Y. Blumenfeld (IPN Orsay), S. Leoni (INFN-Milano), G. De Angelis (LNL, Italy) , A. Gadea (Valencia, Spain), W. Catford (U. of Surrey, UK), A. Shrivastava (BARC Mumbai, India), G. De France (GANIL) = chair

Collaboration:

France:	**In2p3 (IPNO, LPC), GANIL, CEA Saclay (CHyMENE)**
India:	**BARC Mumbai**
Italy:	**INFN/U. Padova, INFN Legnaro, INFN/U. Milano, INFN/U.Firenze**
Spain:	**Univ. of Valencia, Univ. of Santiago,** Univ. of Huelva
UK:	**Univ. of Surrey,** STFC Daresbury

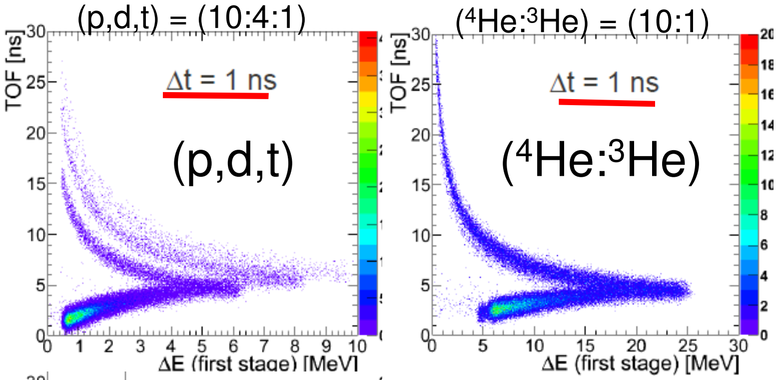
MoU in progress

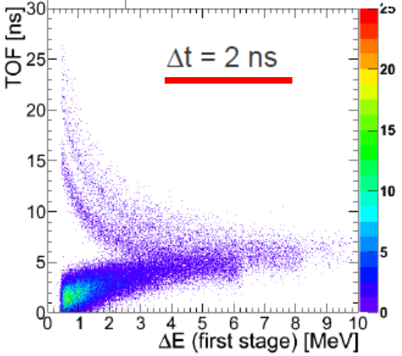
R&D on Pulse Shape Discrimination

Motivation: improve (TOF-based) PID of low-E charged particles

Simulations (N.De Séréville)

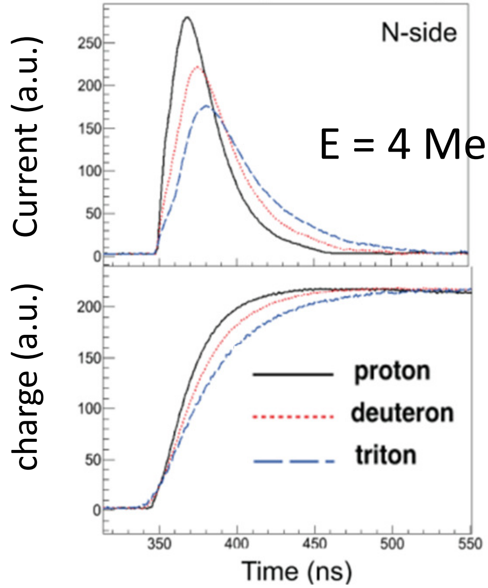
Z = 1 **Z = 2**





No separation
for
t/^{3}He, ^{6}He/^{6}Li

PULSE SHAPE DISCRIMINATION
Based on signal sampling



- More compact device (crucial!)
- Digital electronics

Initial R&D program by GASPARD / HYDE / TRACE collaboration

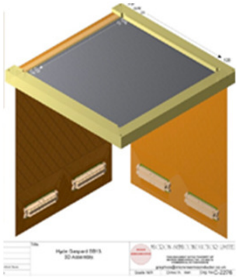
GRIT

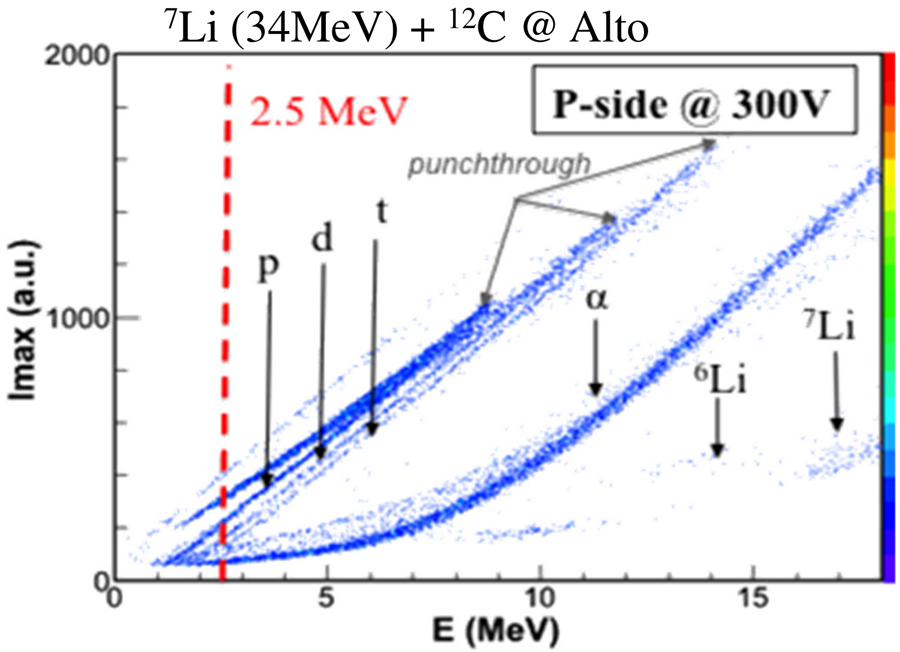
Granularity, Resolution, Identification, Transparency

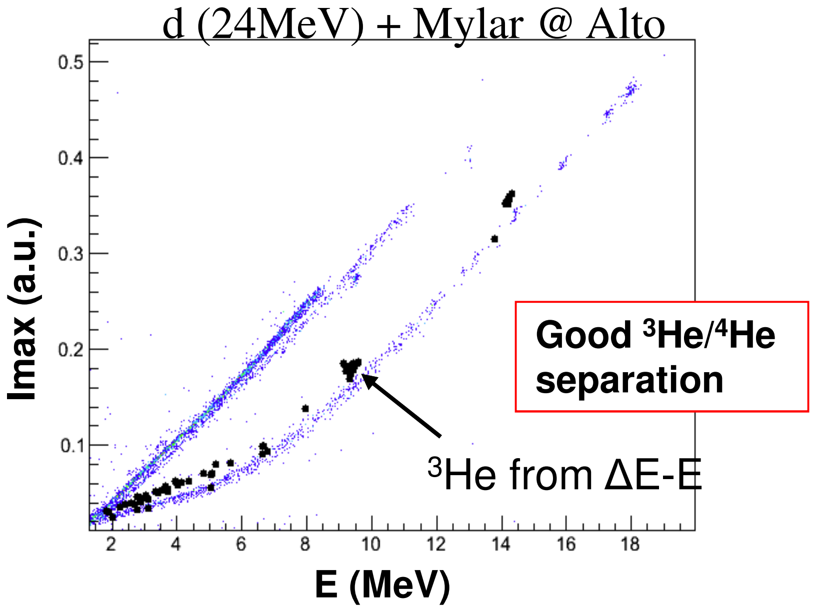
J. Duenas et al, NIMA 2012
J. Duenas et al, NIMA 2013
B. Genolini et al, NIMA 2013
J. Duenas et al, NIMA 2014
D. Mengoni et al, NIMA 2014
M. Assié et al, EPJA 2015
M. Assié et al, NIMA 2018

R&D on Pulse Shape Discrimination

Initial detector:
- 500 um nTD DSSD
- 128X+128Y, 8° cut
- Pitch<500um
- Special packaging




^{7}Li (34MeV) + ^{12}C @ Alto

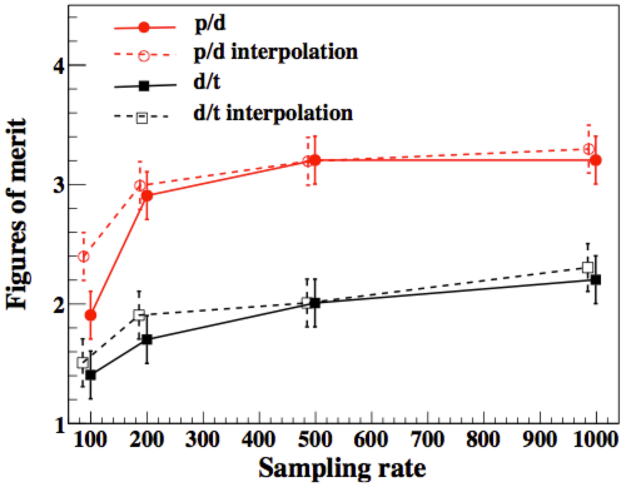

d (24MeV) + Mylar @ Alto

Good ^{3}He/^{4}He separation

^{3}He from ΔE-E

New data under analysis
- ➢ Test of PSD with trapezoid
- ➢ Effect of radiation damage

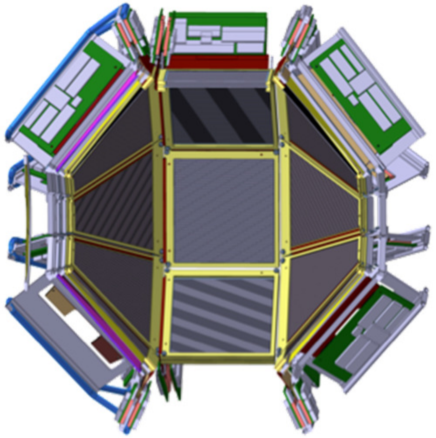
Crucial to set electronics specs. (e.g. sampling rate,…)



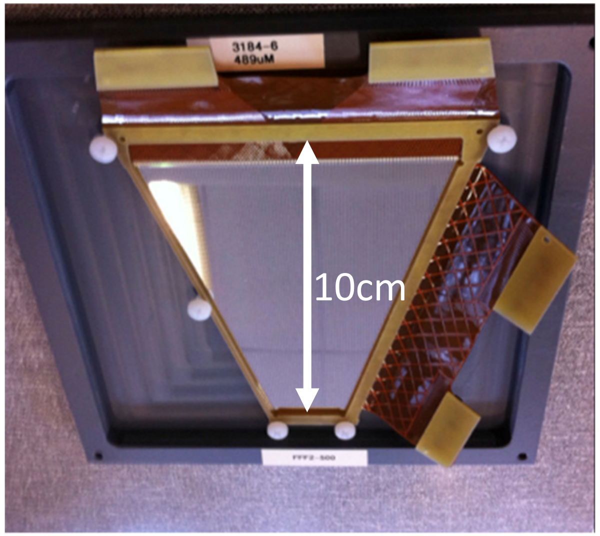
Detectors for GRIT

Detectors for the first layer

- Trapezoid and squared geometries
- 6'' wafers, 128 X + 128 Y
- Special packaging: very thin frame
- Kapton readout, ~90° w/r surface
- NTD, random cut, reverse mount
- Thin and thick



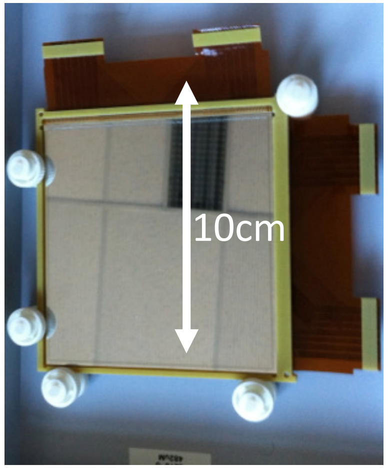
Trapezoidal DSSD



Commissioned:

- ✓ 2 prototypes 500um IPNO
- ✓ 4 pre-series (Surrey U., IPNO, Santiago) (MICRON SC Ltd., UK)

Squared DSSD



Commissioned :

- ✓ 2 prototypes 500um INFN (MICRON SC Ltd, UK)

Under development

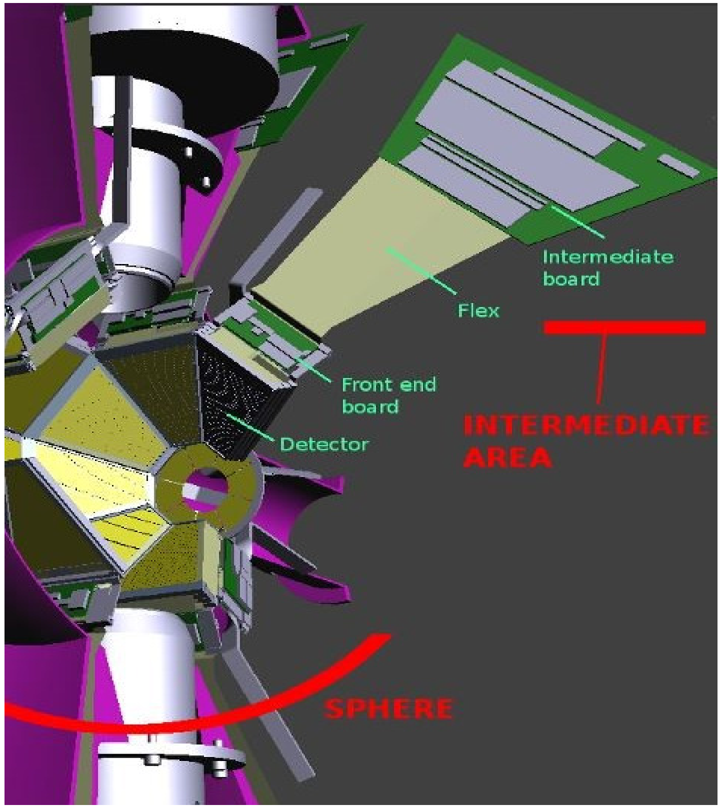
- ✓ 2 proto 500 um BARC Mumbai (Semiconductor Lab , Chandigarh, India)

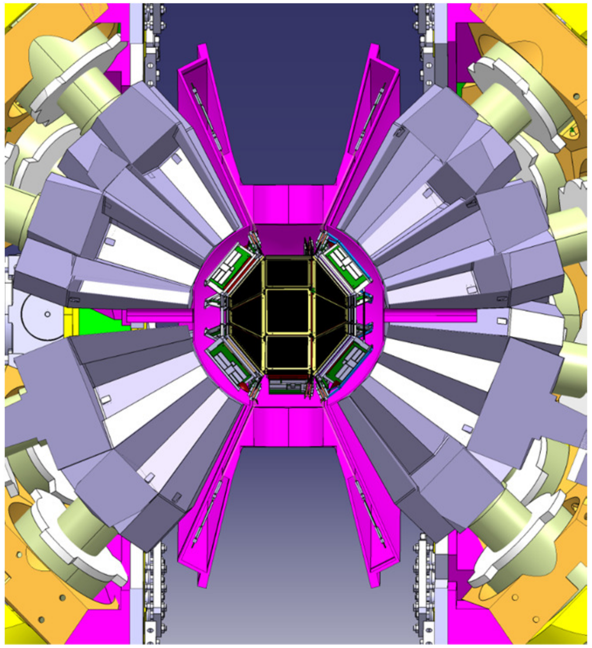
Detectors for the second layer to be developed

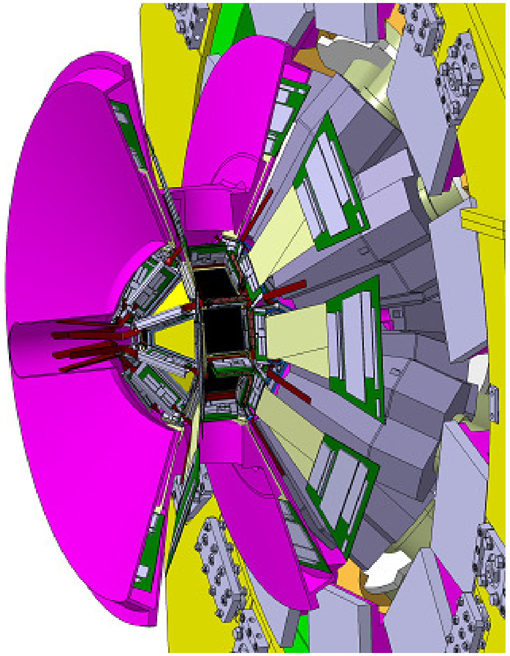
GRIT Mechanical design

Constraints

- AGATA inner radius = 23cm
- Transparency to gamma-rays
- Special targets integration (CHyMENE, Orsay He)
- 7000 electronics channels
  FEE under vacuum -> few KW
  Connectics and feedthroughs
- …



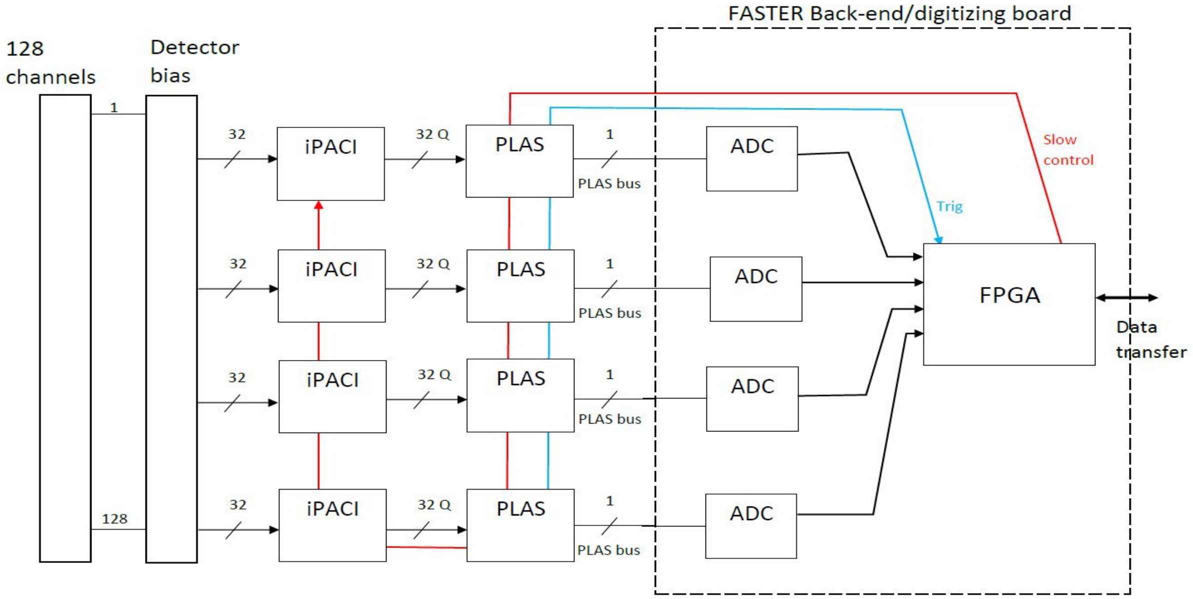




- ➢ Preliminary detailed design was achieved
- ➢ Final version to be completed (IPN Orsay)
  (see workplan)

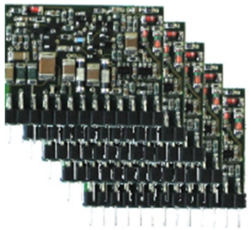
Electronics of GRIT

GLOBAL SCHEME

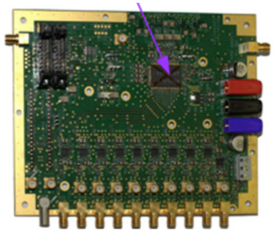


BUILDING BLOCKS

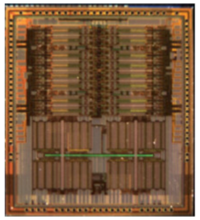
- **ASIC version of the PACI preamp. (IPNO)**
  + TOT preamp ASIC for 2nd layer (Milano)
  Version 3 to be submitted



iPACI



- **PLAS Analog memory circuit**
  R.Aliaga et al., NIM A800(2015)
  Fast sampling analog memory (200Mhz)
  Version 1 available
  LPC Caen now in charge for next versions
  Change of technology requited
  Need contract engineer (CDD)



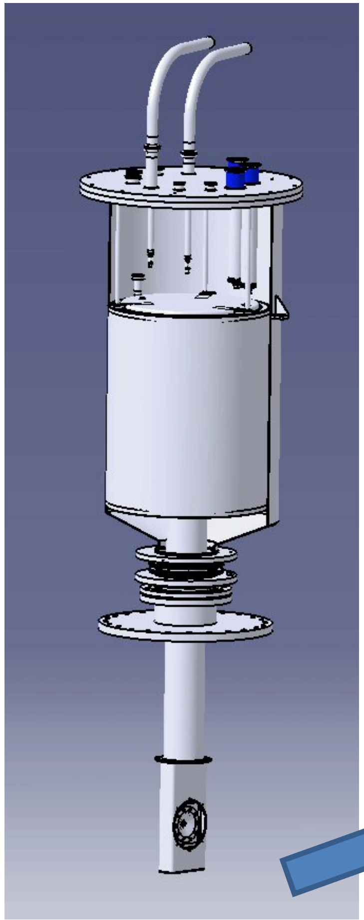
- **FASTER backend**

Special targets for GRIT

The Orsay Helium target

Cooled gas cell at T~ 5K

^{4}He and ^{3}He versions



Reactions with ^{3,4}He probe

- **(^{3}He,d) *proton* shell evolution**
- **(^{3}He,p) for np pairing**
- **(^{4}He,^{3}He) for neutron shells selective for high-L orbitals Complementary to (d,p)**

….

Ø 16 mm,
2-3mm-thick cell
Havar windows 3.8μm
T = 5K , P = 1 bar

Status:

- ^{3}He version has been developed
- Currently used in MUGAST-AGATA campaign at GANIL

The CHyMENE system

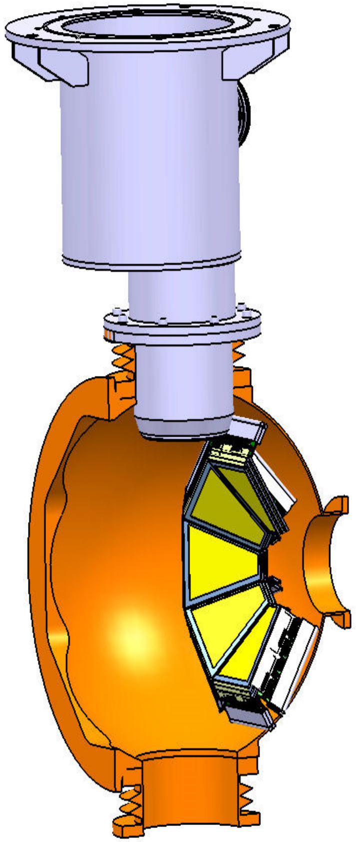
Continuous extrusion of ^{1}H or ^{2}H through an extruder nozzle

Collaboration: CEA/IRFU Saclay
(*project coordinator: A. Gillibert)*
CEA/DAM Bruyères, IPN Orsay
Funded by the French agency ANR

Suppresion of ^{12}C-induced background
(in CH2 and CD2 targets)

Status:

- Tested under beam at ALTO in May 2019 20 and 100 μm ^{1}H
- ^{2}H version to be developed

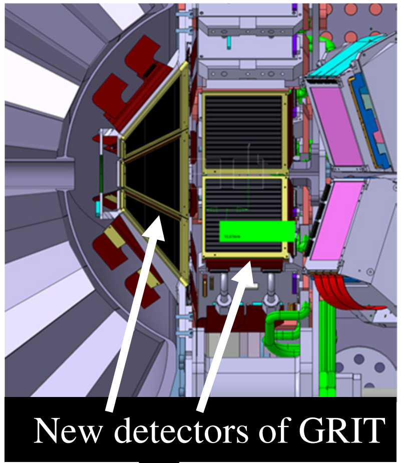


MUGAST: an intermediate step towards GRIT

[MUst2 – GASpard – Trace]

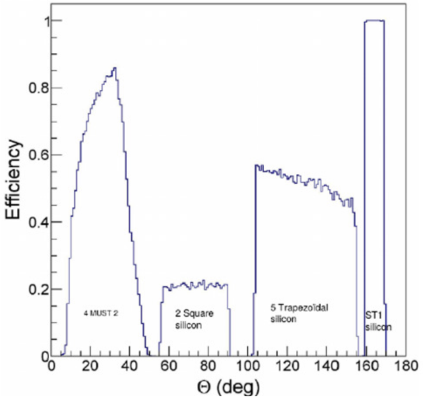
MUGAST: **-** *New detectors of GRIT + MUST2 electronics + few telescopes*
- *Coupled with AGATA @ VAMOS*

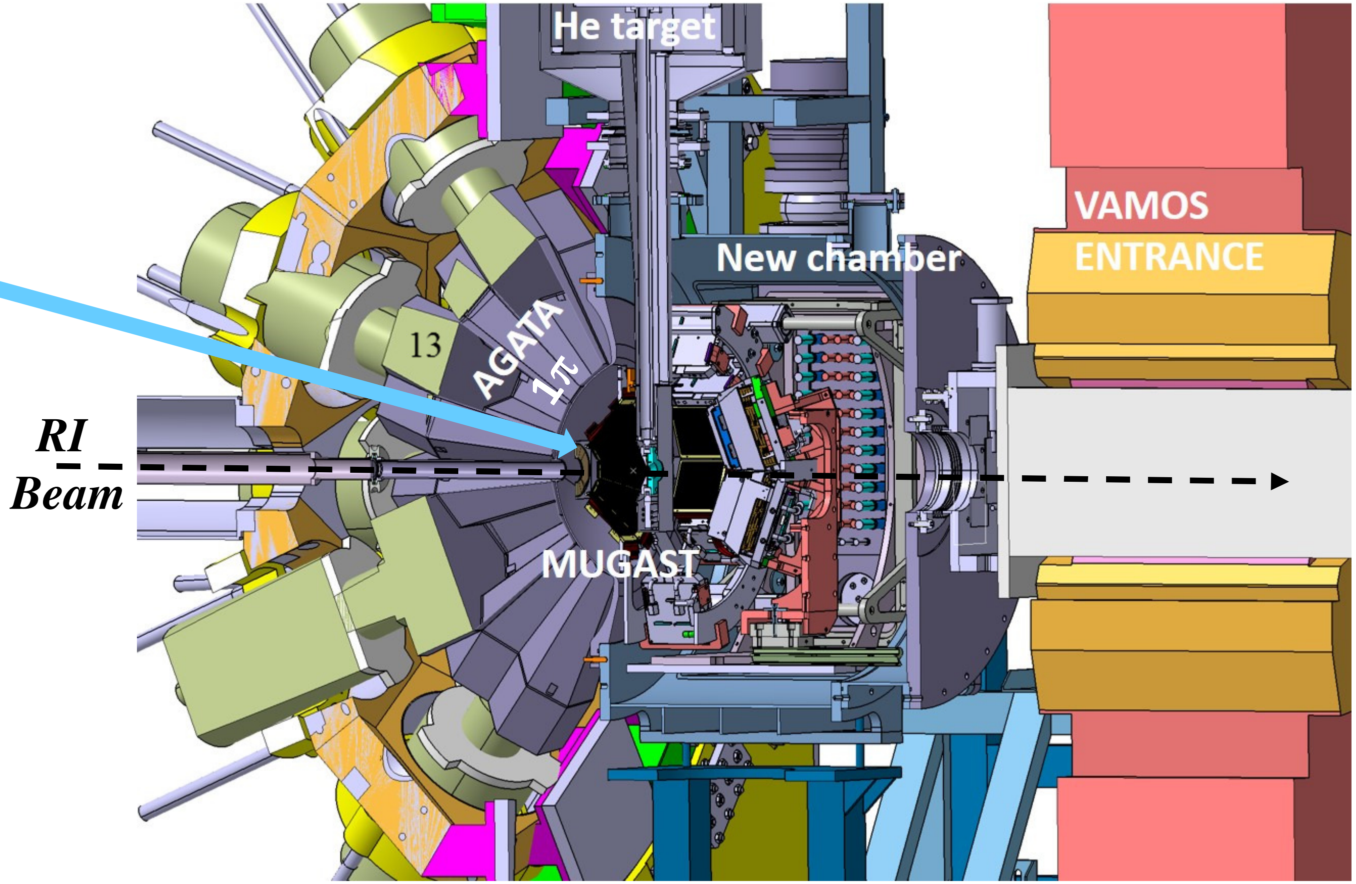
⇒ ***First High resolution Direct Reactions studies at Ganil (new SPIRAL1 beams)***



~ 3000 channels

MUGAST configuration:
- 5 trapezoids backward
- 2 Squared around 90deg.
- 4 MUST2 telescopes forward





Efficiency for 1π AGATA : ~10% at 1 MeV

Funding: In2p3,P2iO,INFN,GANIL
Surrey, Santiago

First Campaign in 2019

Coordinator: M. Assié, IPNO

Present: MUGAST@GANIL/VAMOS

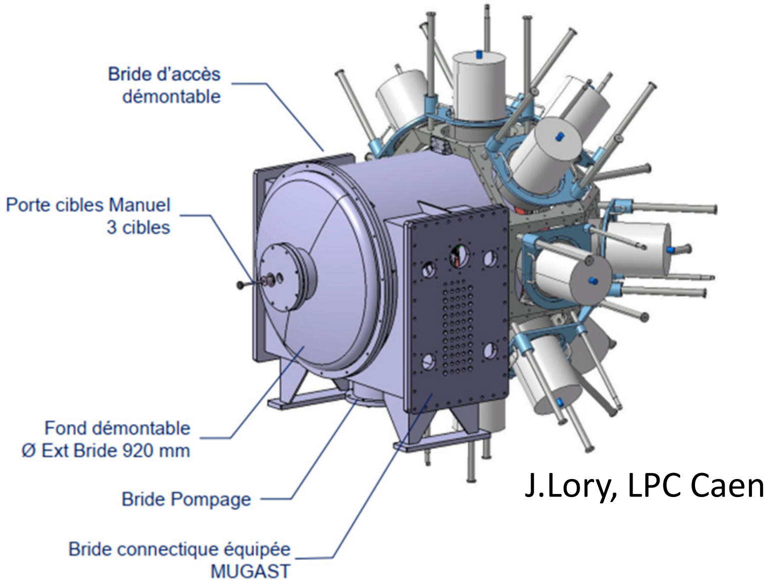
First step towards
GRIT

- ➢ **Positive scientific evaluations**
  - ✓ GANIL PAC
  - ✓ GANIL Scientific committee
  - ✓ IPNO Scientific committee
- ➢ **Selected for AGATA campaigns at GANIL in 2019 and 2020**

Next Step: MUGAST@GANIL/LISE

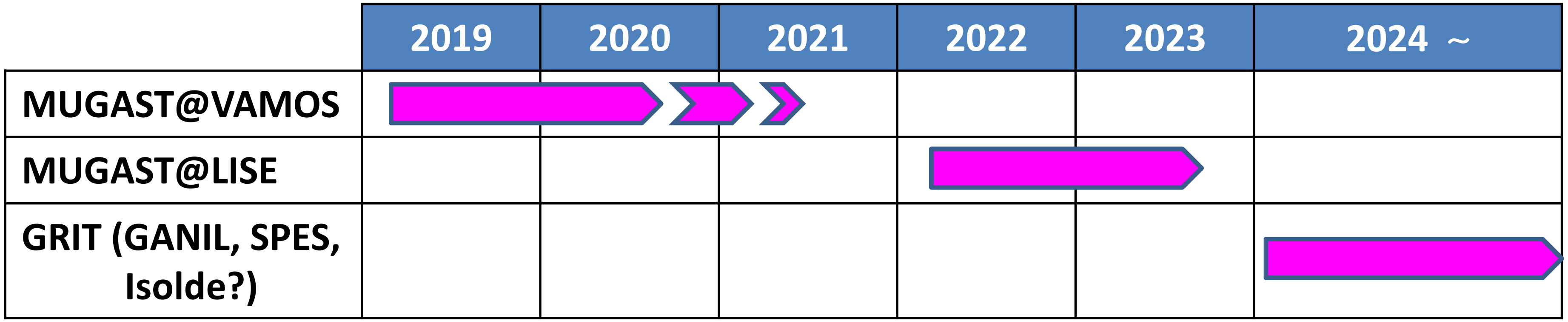
A new compact, 2-layer Si configuration
12 EXOGAM modules at 15cm from target

- ➢ **Detectors for 2nd layer (1.5mm)**
  Status: to be ordered in 2019-20
- ➢ **New chamber /connectics**
  Status: Designed / to be designed



J.Lory, LPC Caen

Global strategy



	2019	2020	2021	2022	2023	2024 ~
MUGAST@VAMOS	▶	▶	▶			
MUGAST@LISE				▶	▶	
GRIT (GANIL, SPES, Isolde?)						▶

Gantt chart for GRIT development and construction

Major developments

- Si detectors

  In close collaboration with MSL (UK), and Mumbai (SLC Chandigharg, India)
- Electronics

  Main developments by In2p3 IT's (iPACi, PLAS, boards,connectics) and use of FASTER backend (LPCC)
- Mechanics

  Challenging design (Detectors, targets and FEE integration, cooling, connectics),
  to be performed at IPN Orsay

Capital cost and manpower for GRIT

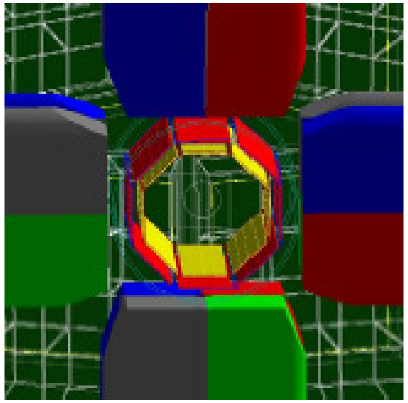
	2019	2020	2021	2022	2023	2024	2025	Total (k€)
Detectors								
Thin DSSD proto (500um, SCL)	76							**76**
Thick Si protos (1.5mm, MSL)	80							**80**
Serie DSSD (1st layer, MSL+SCL)		63	36	45		18		**162**
Serie DSSD (2nd layer, MSL)		60	50			40	**90**	**240**
Annular detectors						30		**30**
Electronics								
ASICs, boards, modules, power supply, connectics	20	40	82	90	90			**322**
Mechanics								
MUGAST@LISE chamber			30					**30**
GRIT final reaction chamber				40	40			**80**
IN2P3	**10**	**37**	**60**	**65**	**65**	**30**	**31**	**298**
Normandy Region	**40**	**40**	**40**					**120**
GANIL (*)								
INFN	**50**	**59**	**62**	**65**	**65**	**58**	**59**	**418**
BARC	**76**		**36**	**36**				**148**
Univ. of Surrey		**18**						**18**
Univ. of Santiago de Comp^{lla}		**9**		**9**				**18**
TOTAL (k€)	**176**	**163**	**198**	**175**	**130**	**88**	**90**	**1020**

	2019	2020	2021	2022	2023	2024	2025
In2p3							
Eng./tech.	3.7	3.1	5.1	5.1	3.3	0.5	0.5
Physicists	6.4	6.4	6.	5.	5.	5.	5.
GANIL							
Eng./tech.	2.4	2.4	2.3	0.8	0.8	0.8	0.8
Physicists	1.	1.	1.	1.	1.	1.	1.
INFN							
Eng./tech	1.	1.	1.	1.	1.	0.	0.
Physicists	5.9	4.2	4.0	4.	4.	5.	5.
BARC							
Eng./tech.	1.	1.	1.	1.	1.	0.	0.
Physicists	2.	2.5	2.5	2.	2.	2.	2.

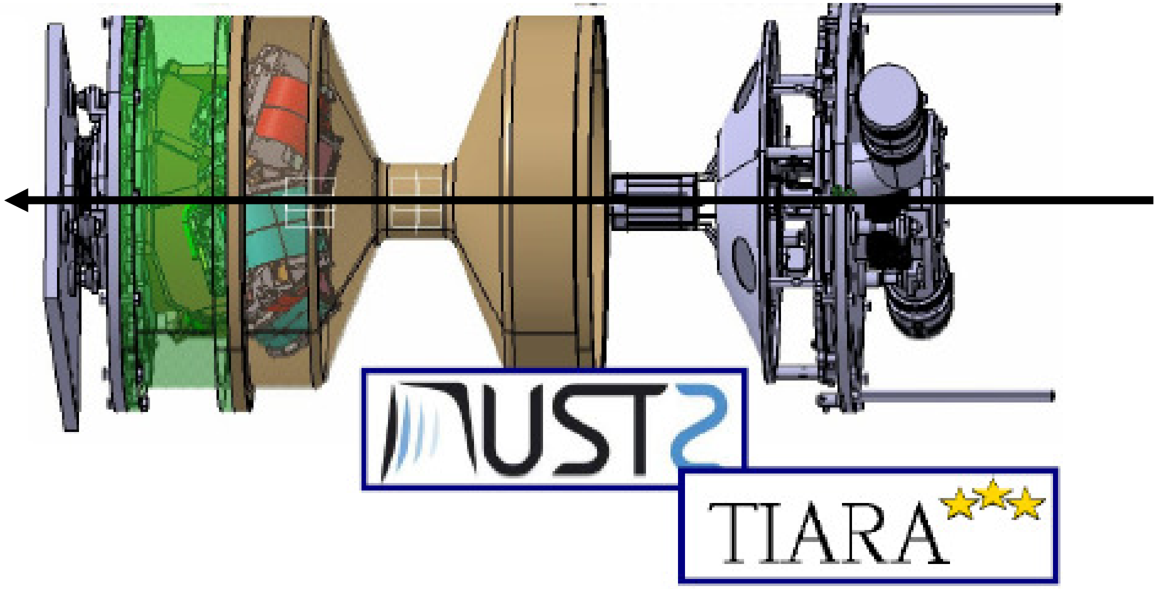
Backup slides

Si-based systems currently operating for particle-γcoincidence measurements

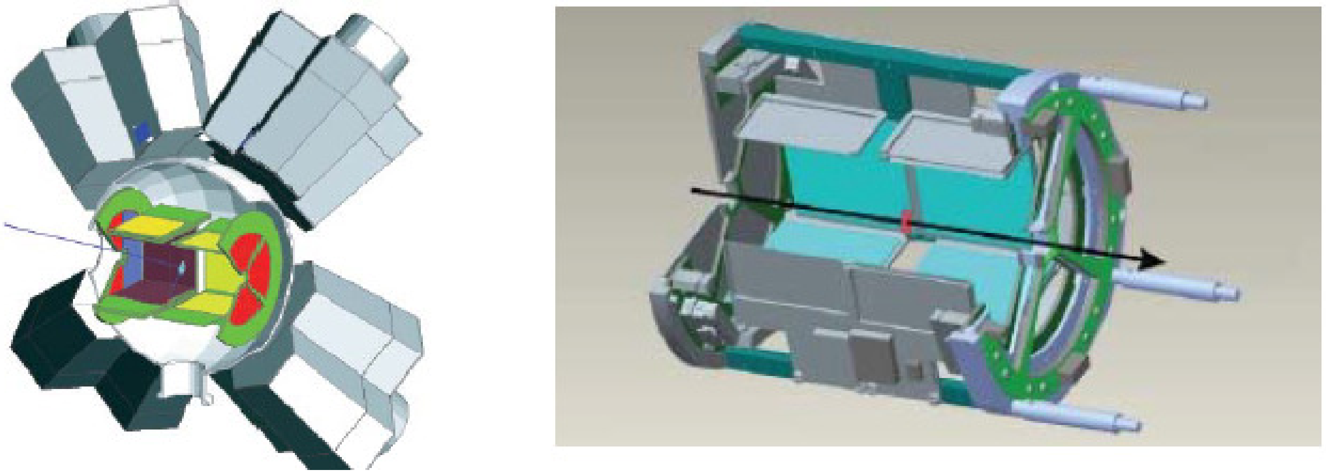
γ-rays ⇒ E_x



4 EXOGAM

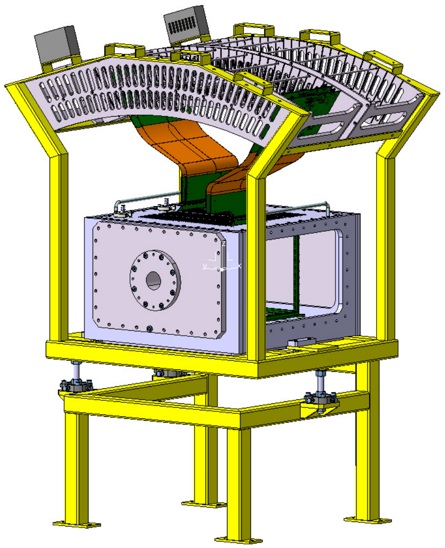


T-REX + MINIBALL



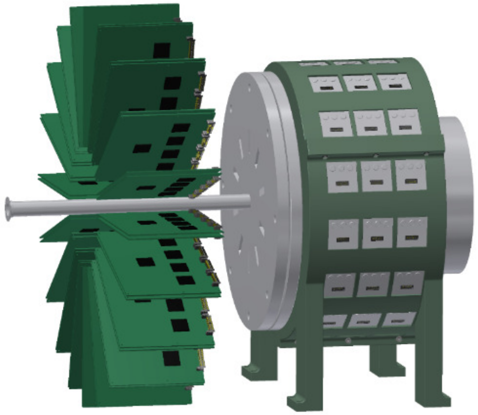
New Instruments for Direct Reactions studies in Europe

actar TPC

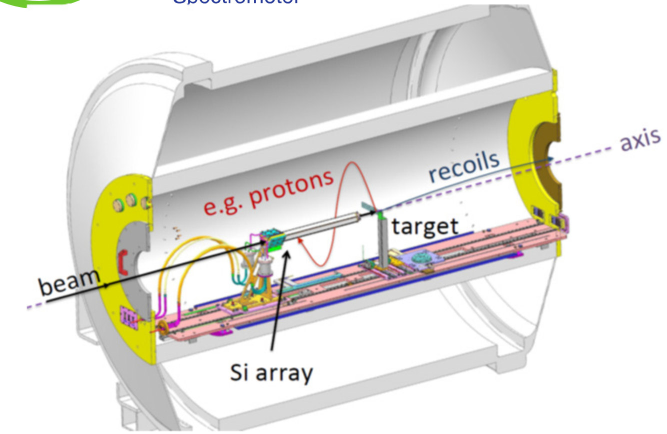


SpecMAT

Spectroscopy in a Magnetic Active Target



ISOLDE Solenoidal Spectrometer



GRIT Si array