The GRIT project for reaction studies

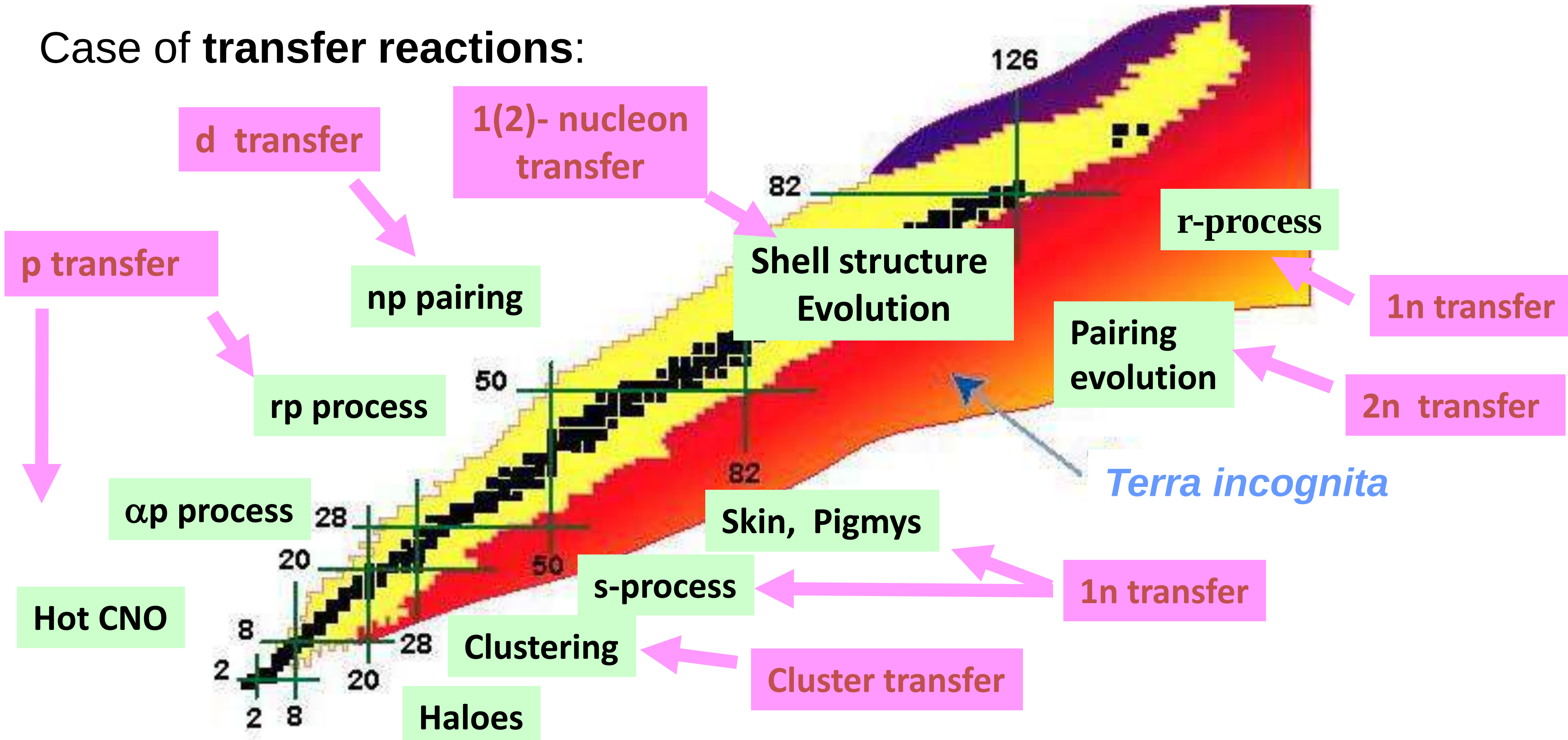
D.Beaumel, IPN Orsay
For the GRIT collaboration

Conseil scientifique de l'in2p3, 26-27 juin 2019

Direct reactions

A great tool to investigate Exotic Nuclei and Astrophysical processes

Case of **transfer reactions**:



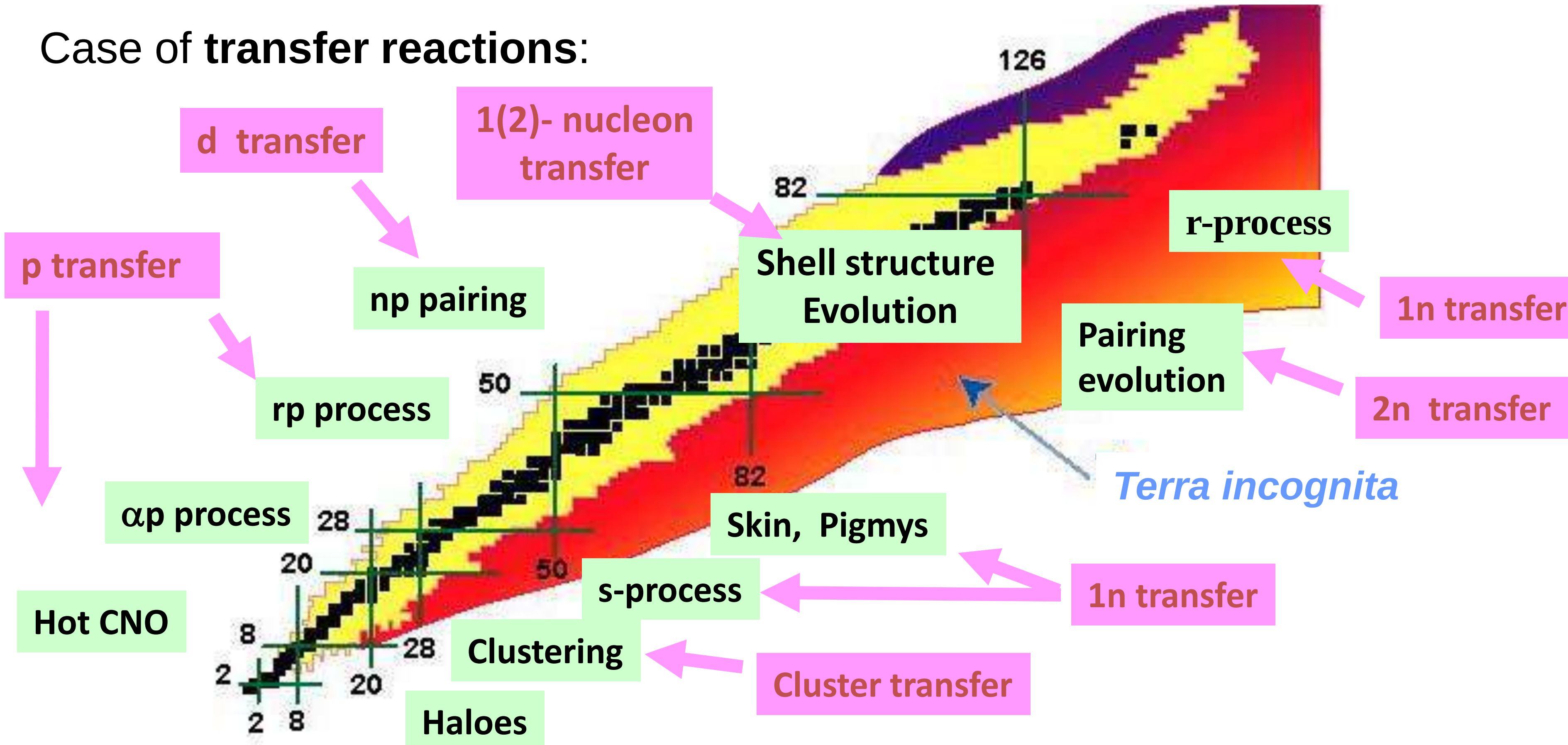
Good energy regime : 5 ~ 50 MeV/u → **Core program for ISOL facilities and slowed-down beams**

Low Energy Branch

Direct reactions

A great tool to investigate Exotic Nuclei and Astrophysical processes

Case of **transfer reactions**:

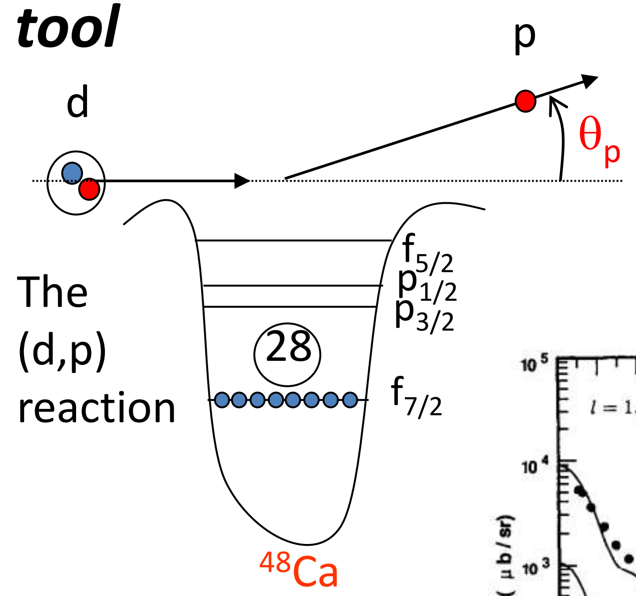


Good energy regime : 5 ~ 50 MeV/u ➡ **Core program for ISOL facilities**

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

Transfer reactions as a tool

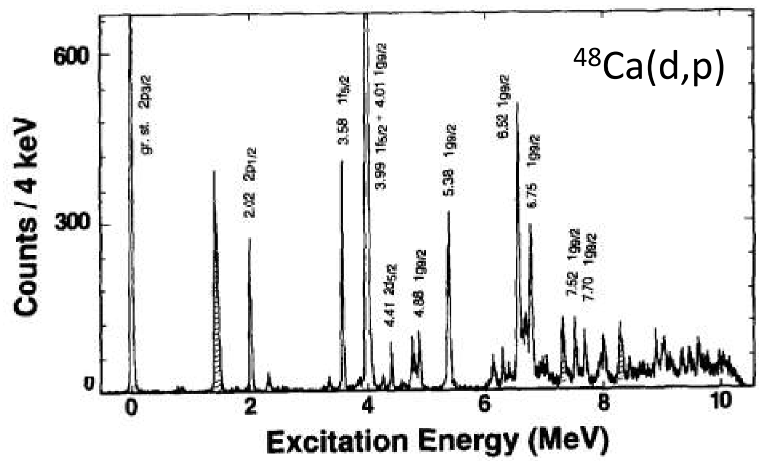
- ✓ **Selective spectroscopy**
- ✓ **Quantitative information on wave functions**

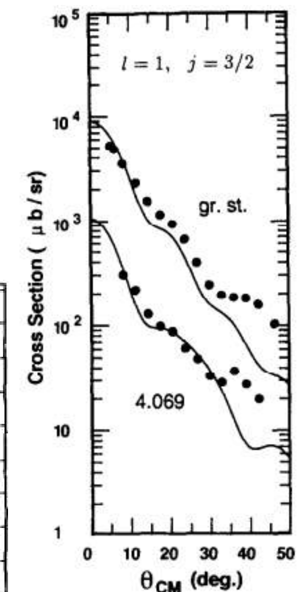


1-nucleon transfer
Single particle properties
Orbital energies, occupancies
1-nucleon overlaps (A+1|A)
Information on *individual* configurations

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)

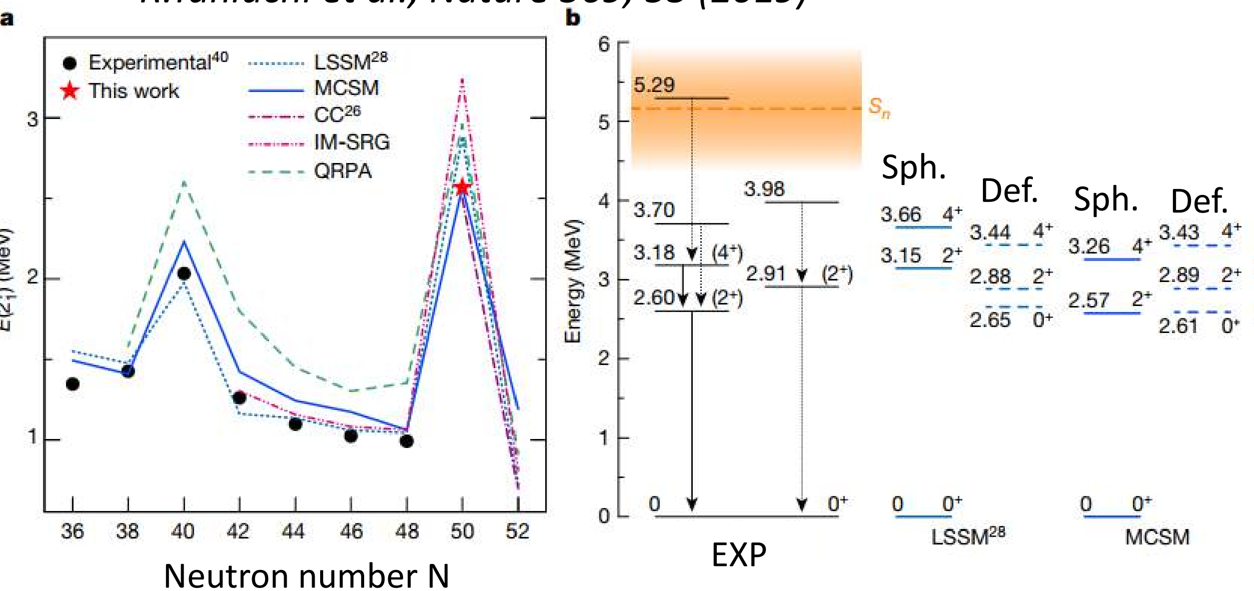
Indirect methods for astrophysics e.g **(n,γ) ↔ (d,p)** and **(p,γ) ↔ (^{3}He,d)**
Millibarns of cross-sections for transfer !
Use of Radioactive Ion beams in inverse kinematics

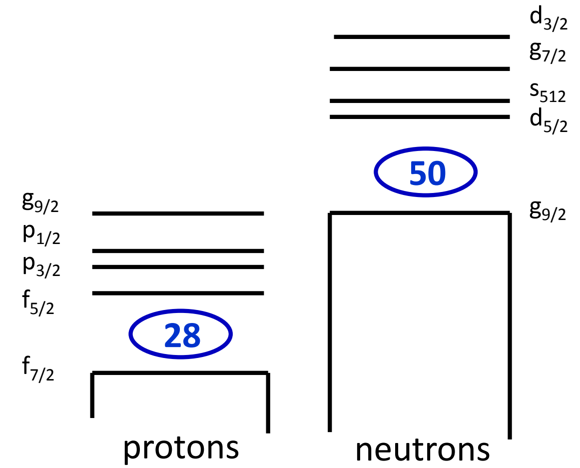
STUDIES WITH RADIOACTIVE NUCLEAR BEAMS

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)

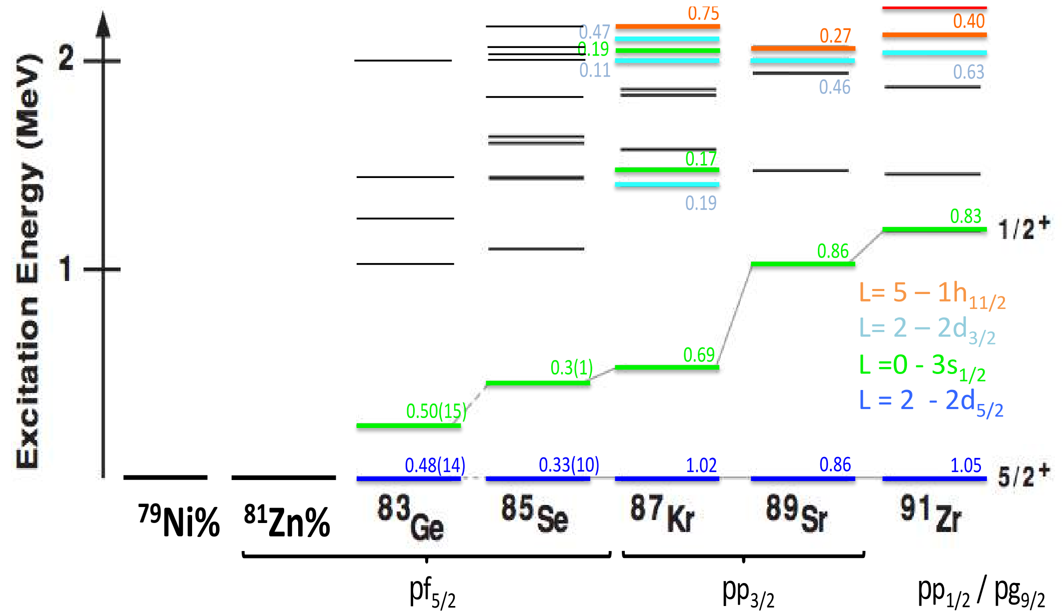
Understanding the N=50 shell closure - II

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)

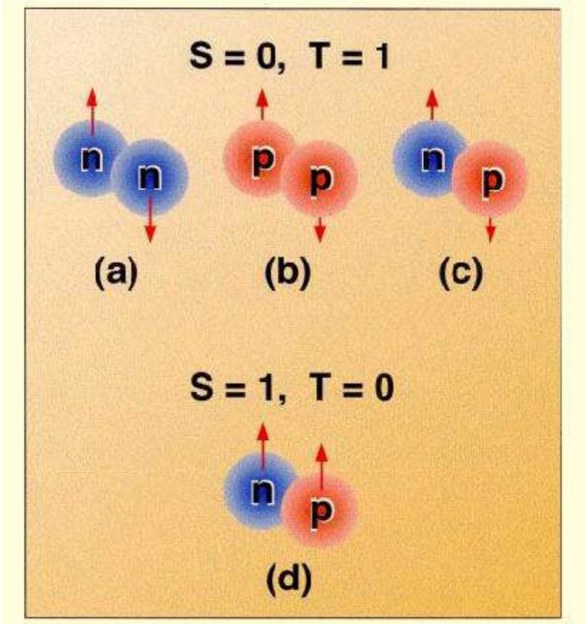
4 types of Cooper pairs

T=1 nn, pp, np

np should be similar to nn and pp

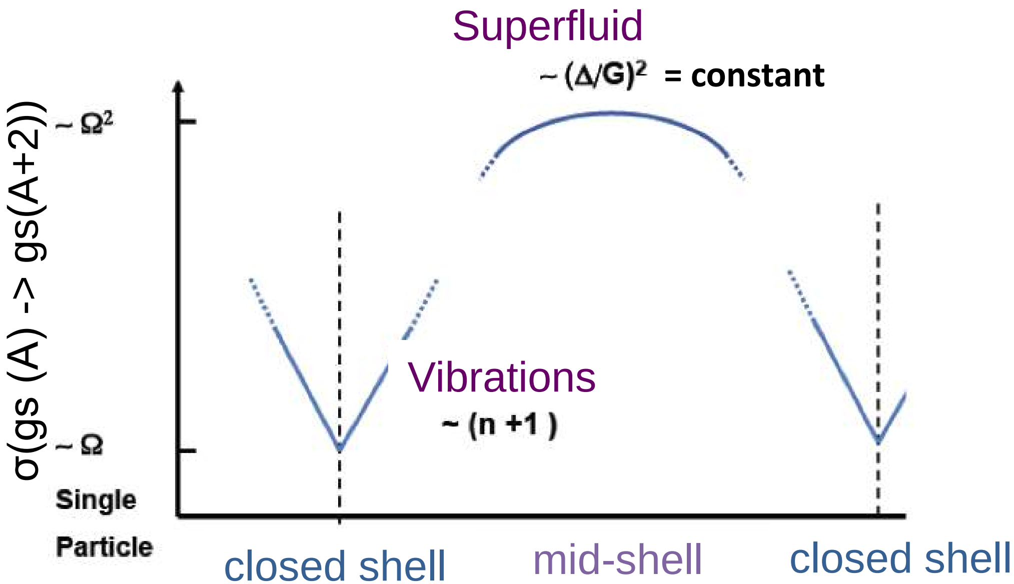
T=0 np pairs → new phase of nuclear matter

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

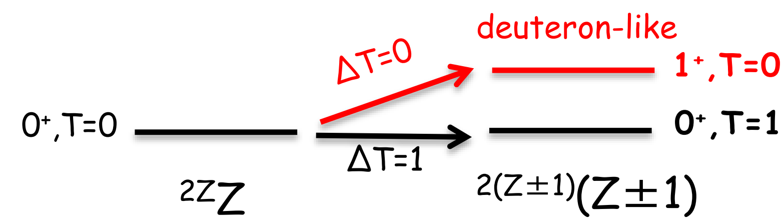
Pattern confirmed in 2n transfer results from (p,t) and (t,p) studies

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

Evidencing neutron-proton pairing by np pair transfer II

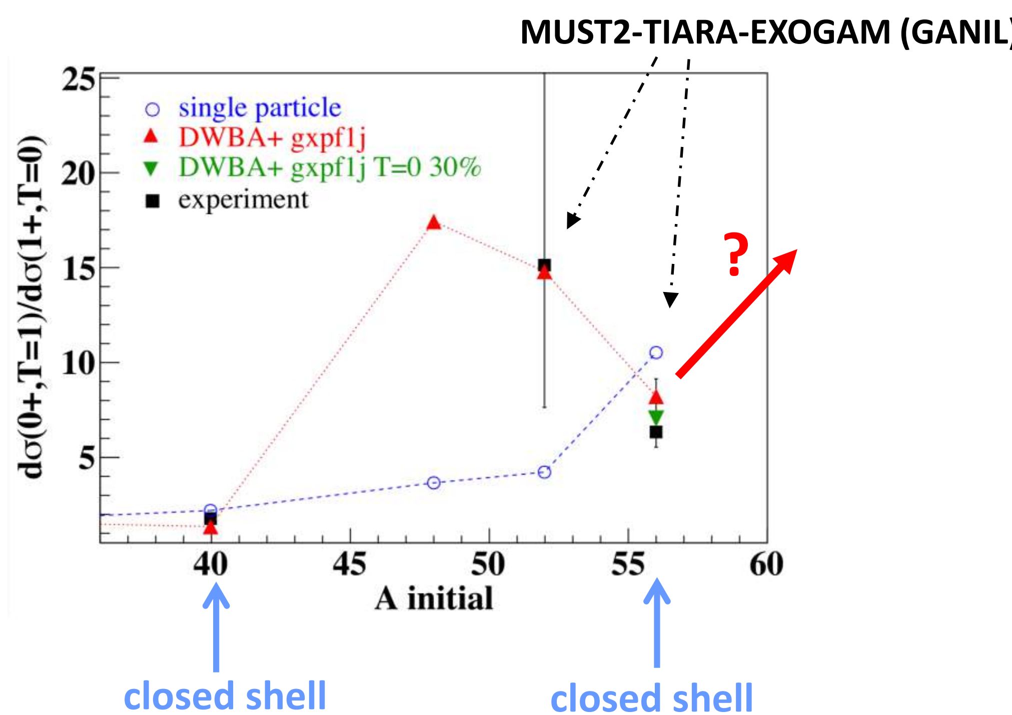
Deuteron transfer reaction on N=Z nuclei
The "smoking gun" for probing T=0 pairing ?

$\sigma\ (0^+)/\sigma\ (1^+)$ gives the relative strength of T=0/T=1 pairing



Complementary reactions :
(p, ^3He), (^3He,p) $\Delta T=0,1$
(d,α), (α ,d) $\Delta T=0$
(α, ^6Li), (^6Li,α) $\Delta T=0$

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



Explaining the origin of heavy elements (A > 56)

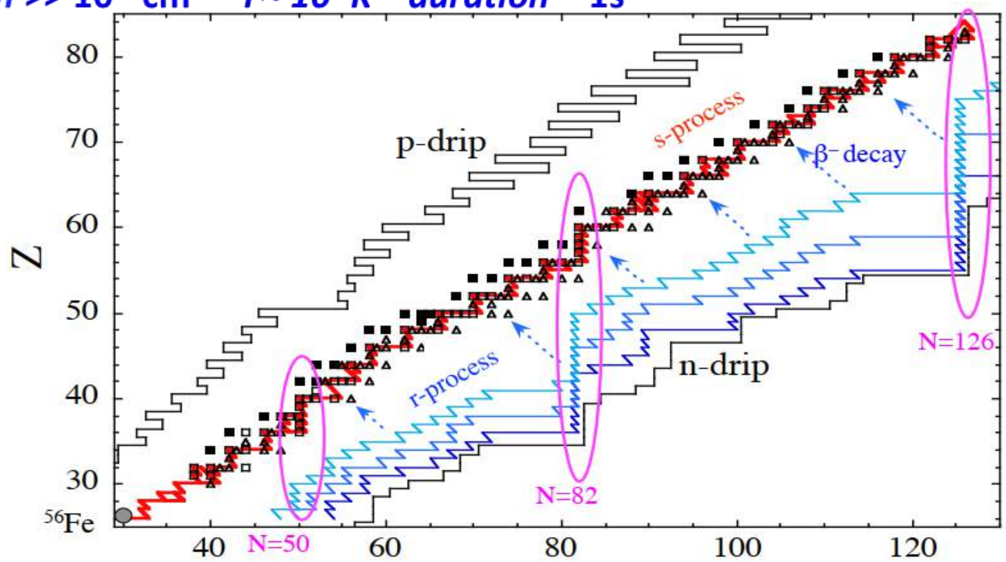
Vast majority of A>56 nuclei are created through neutron capture (n,γ)

Slow neutron-capture process: τ_β << τ_n

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

Rapid neutron-capture process: τ_β >> τ_n

***Nn* >> 10^{20}cm^{-3} *T ~ 10^9 K* *duration* ~ 1s**

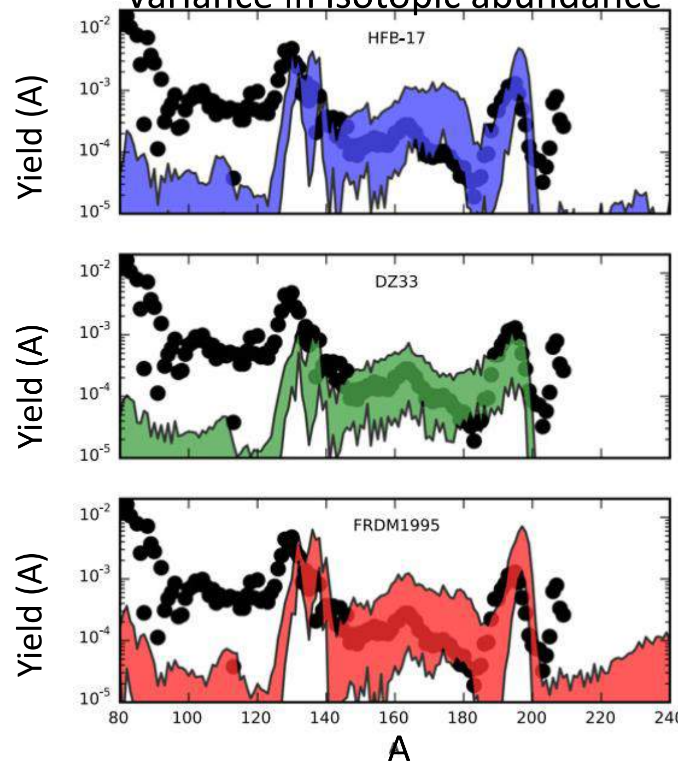


From S.Goriely

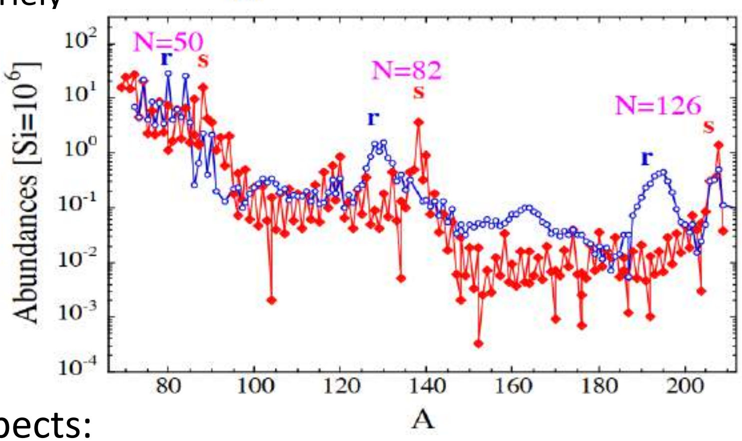
Artist view of kilonova as observed from neutron- star mergers on May 17, 2017

Effect of σ(n,γ) variation

Variance in isotopic abundance



Signature of Nuclear Physics properties



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

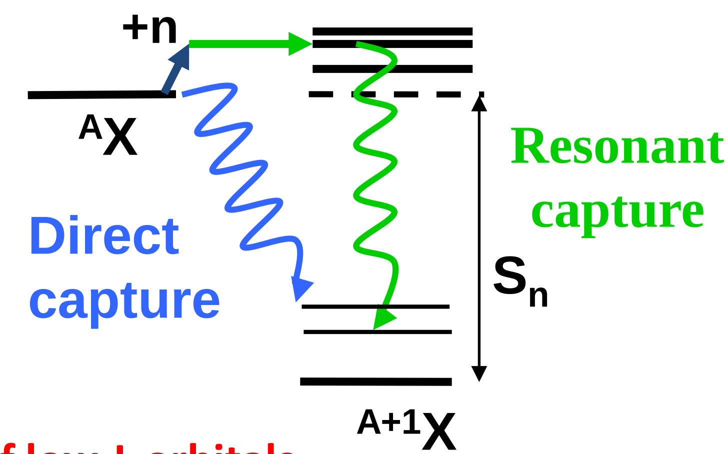
Nuclear Physics aspects:

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

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)

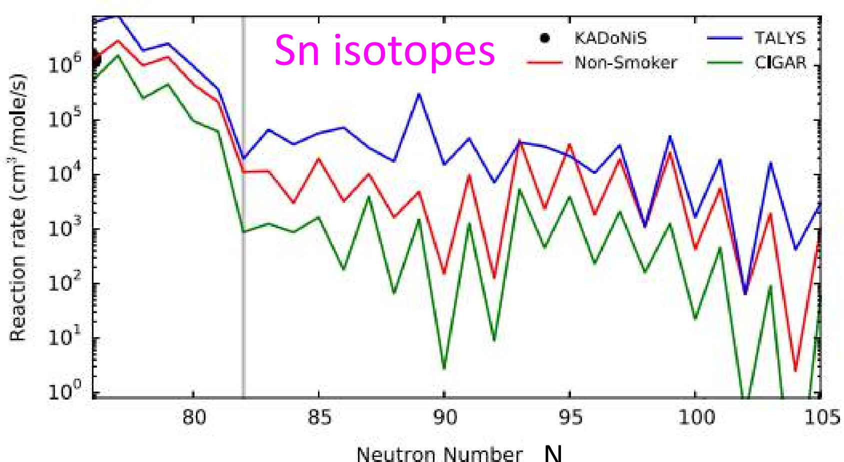


- High Level Density (near or at stability)
  - Calculated compound nucleus probab.
  $(d,p\gamma)$ → Branching ratios
  A.Ratkiewicz et al., PRL 122, 052502 (2019)
  "Surrogate method"

Importance of low-L orbitals

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

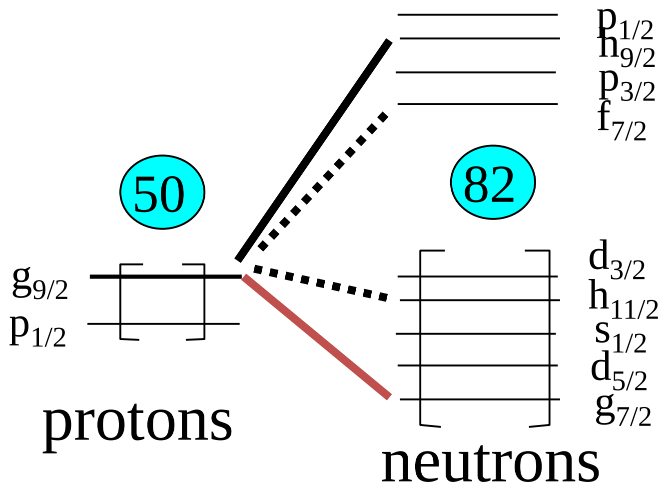


M.R. Mumpower et al., PNPP 86, 86 (2016)

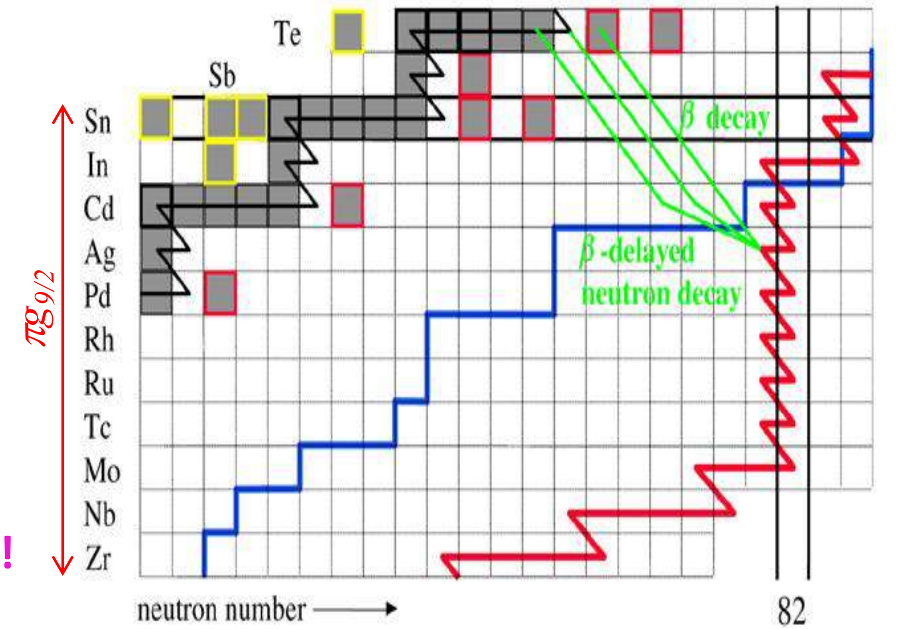
Strong model dependence (fact ~1000) far from stability

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

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



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



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

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

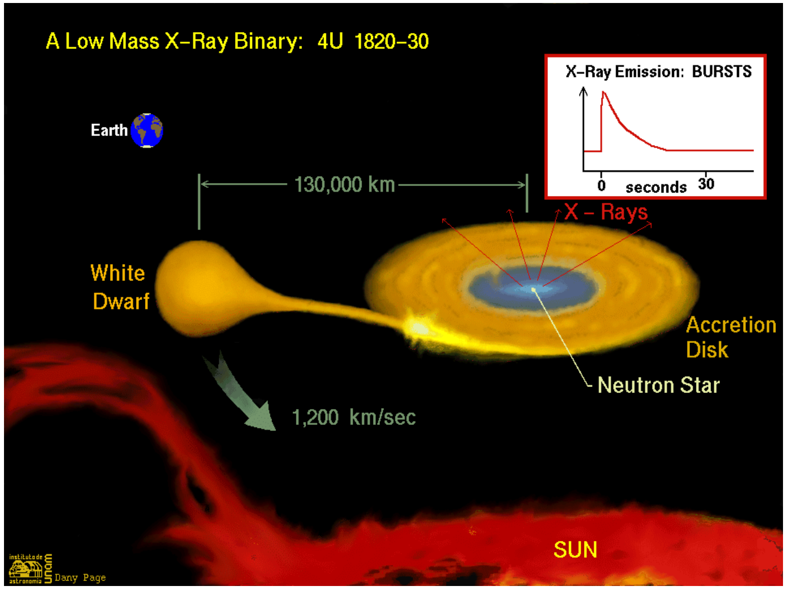
   similar monopole M.E. and possibly 3-body forces are at play as in the case of N=28

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

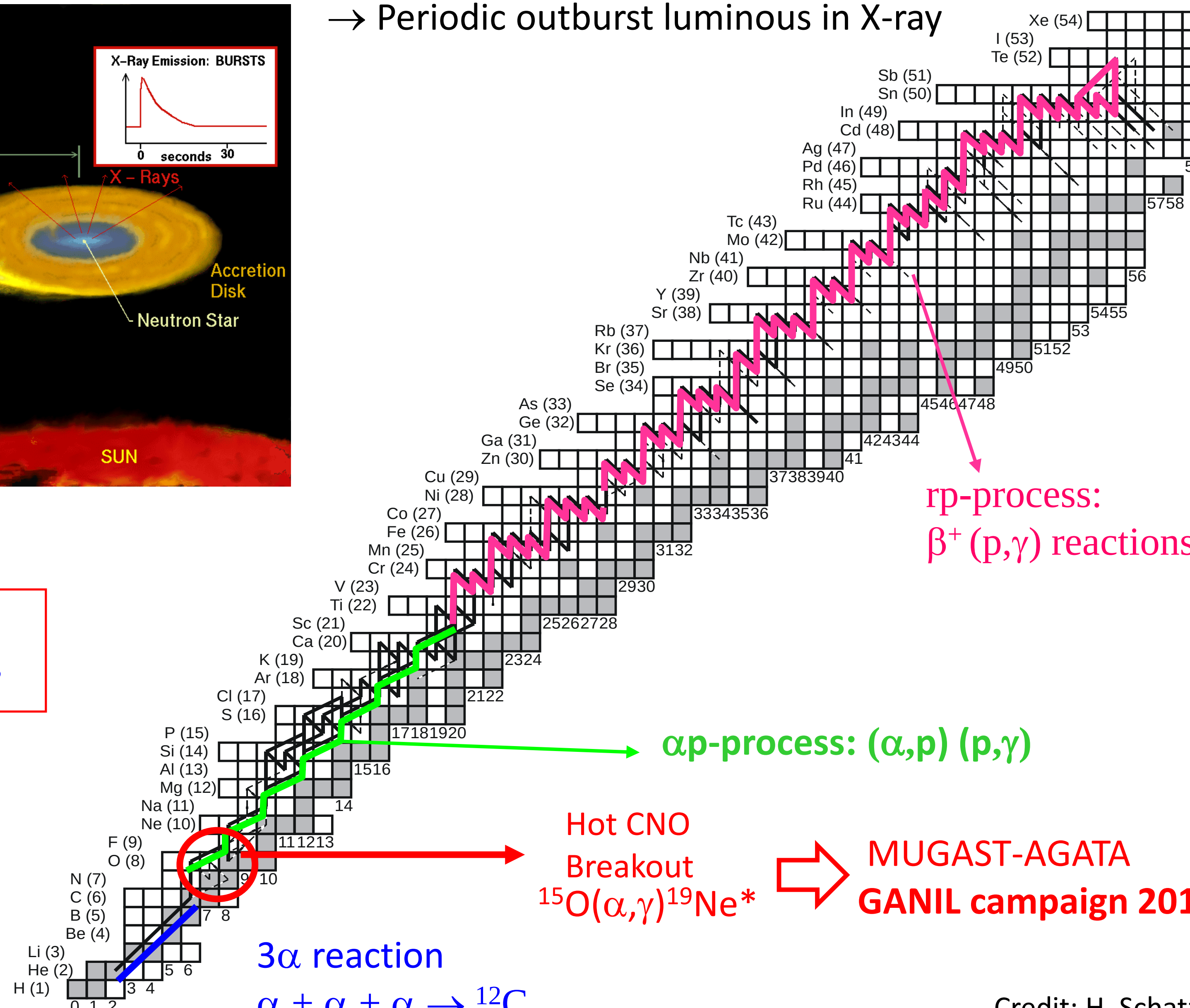
GRIT-AGATA experiments at SPES

Type I X-ray bursts

Accretion from companion star



→ Periodic outburst luminous in X-ray



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

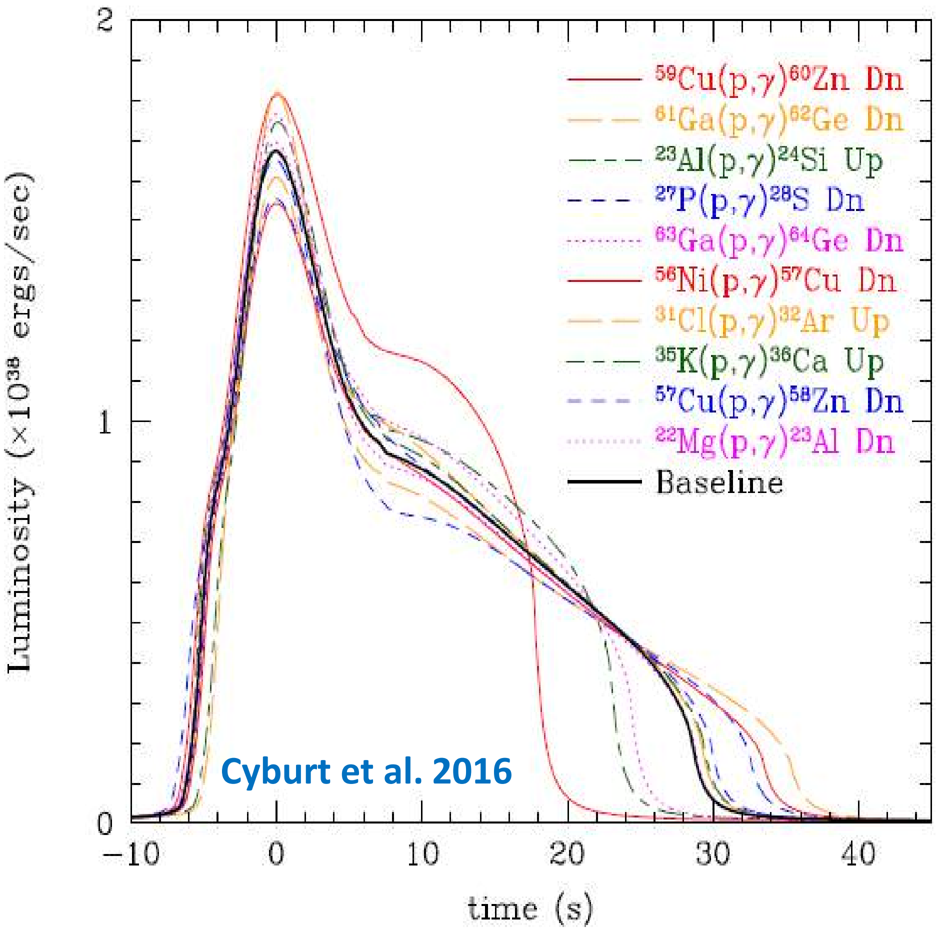
3α reaction
$\alpha + \alpha + \alpha \rightarrow {}^{12}C$

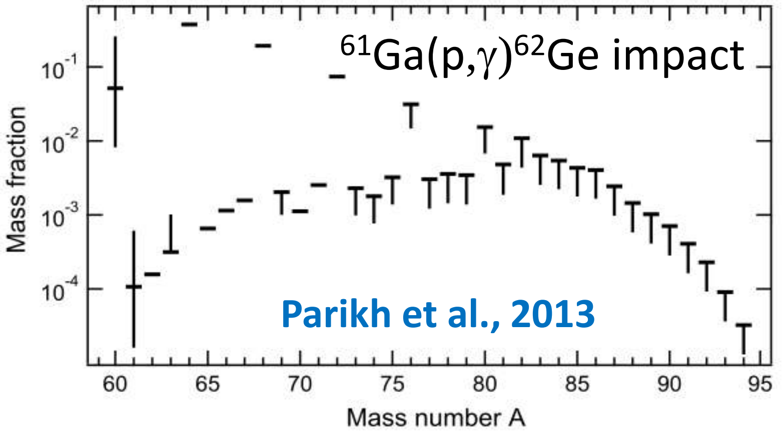
T ~ 10^9 K
ρ ~ 10^6 g cm^{-3}

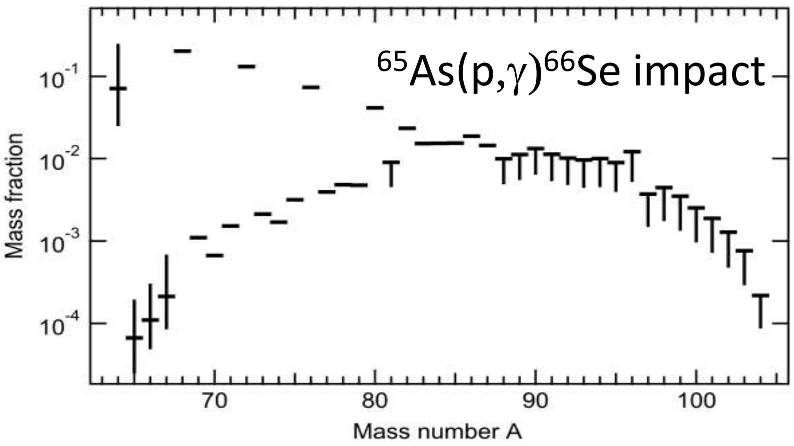
Credit: H. Schatz

(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)**



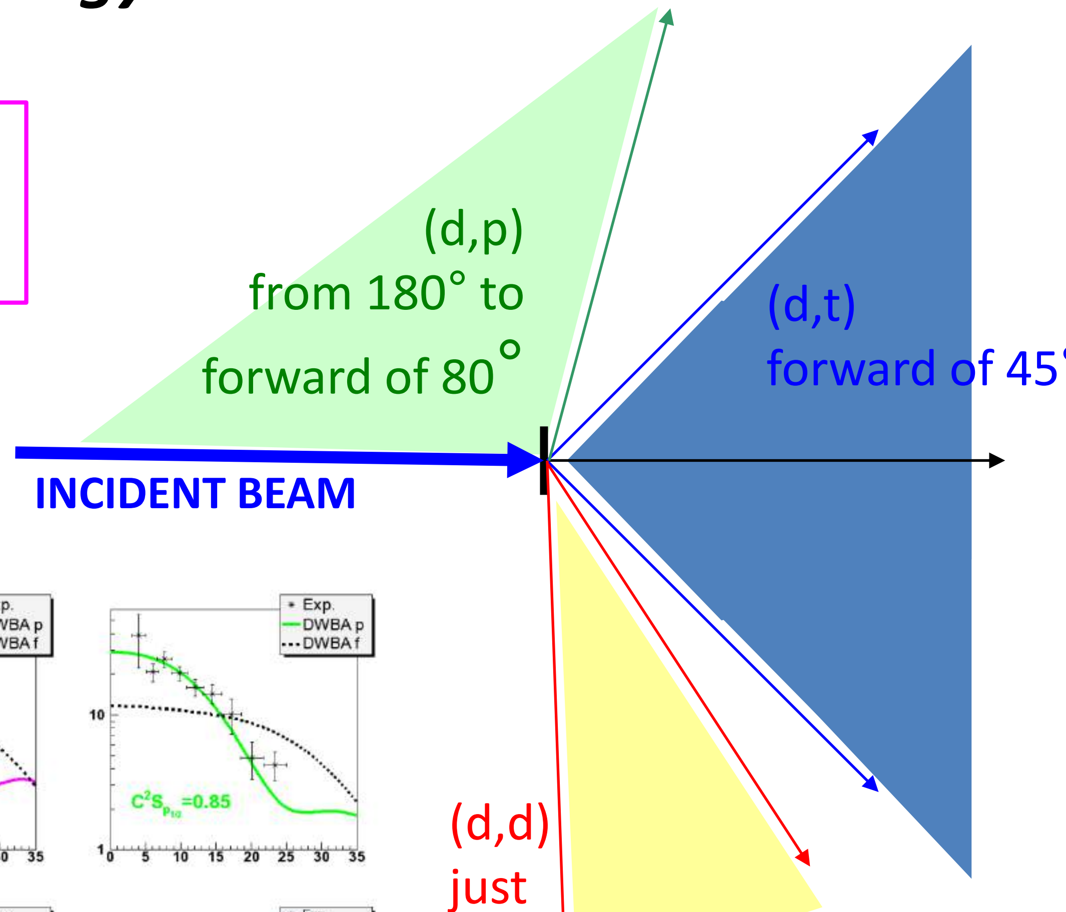




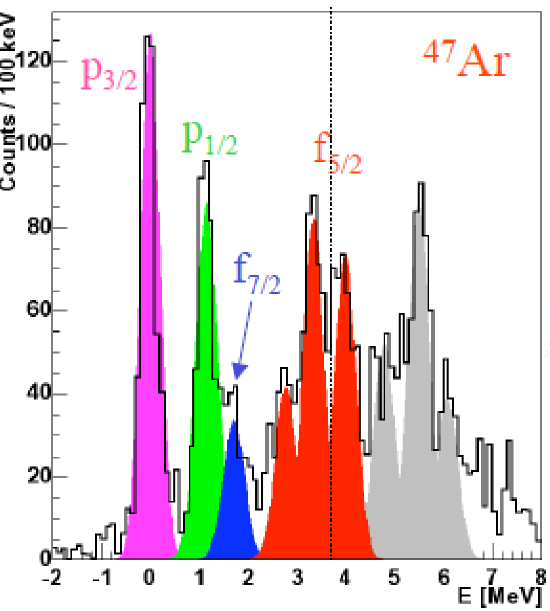
At **GANIL** using SPIRAL or LISE beams:
Study ^{56}Ni(^{3}He,d), ^{65}As(^{3}He,d), ^{60}Zn(^{3}He,d)
or alternatively the (d,p) reaction on the mirror nuclei

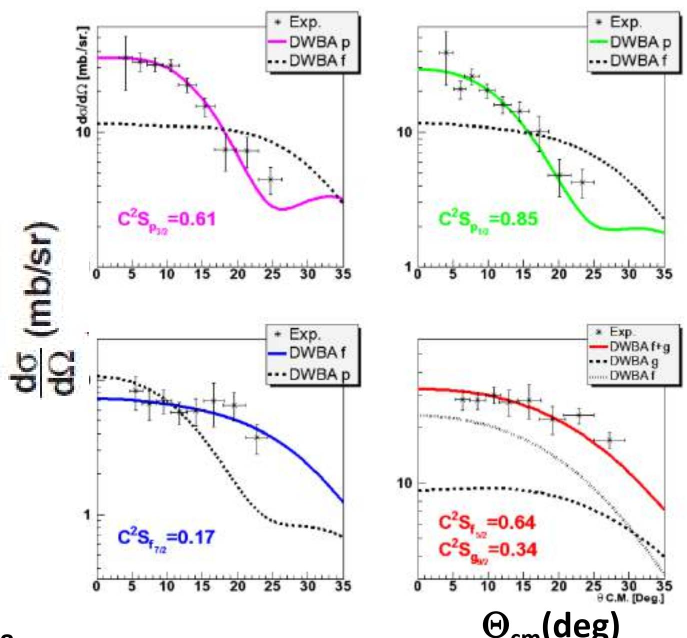
(Initial) methodology with exotic beams

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

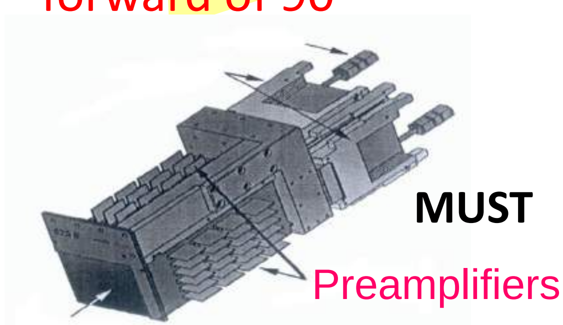


Ex: ^{46}Ar(d,p) @ GANIL/SPEG
using the **MUST** array





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



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

Few 100's keV resolution although very thin target

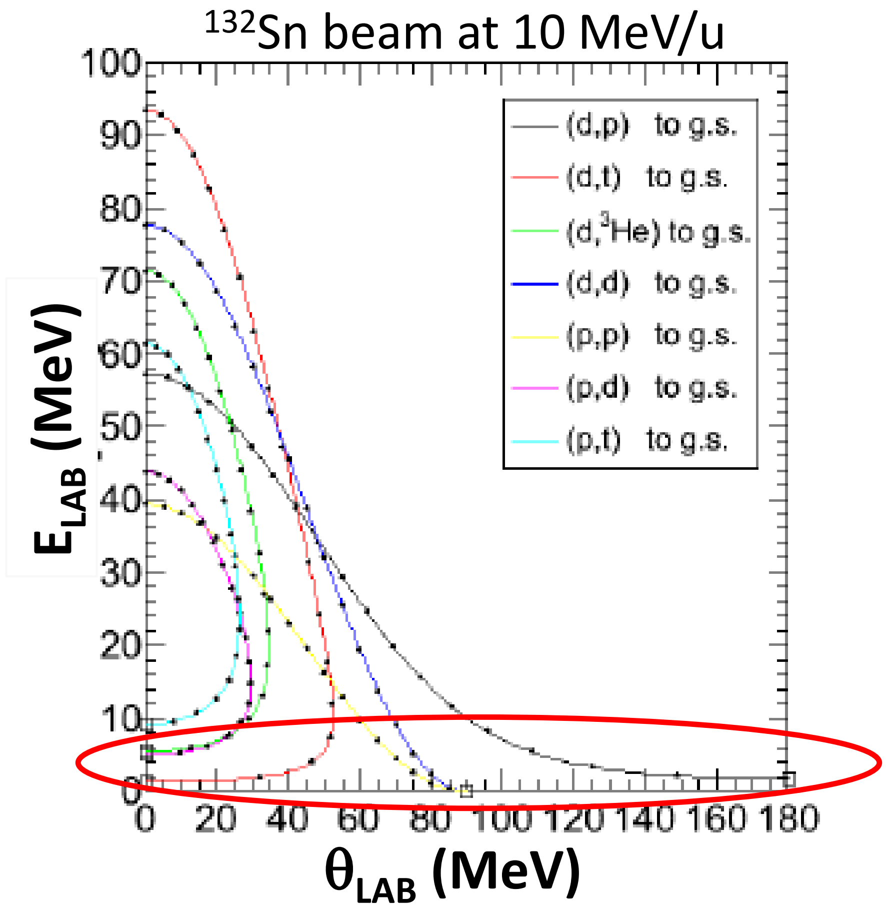
Constraints due to kinematics

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



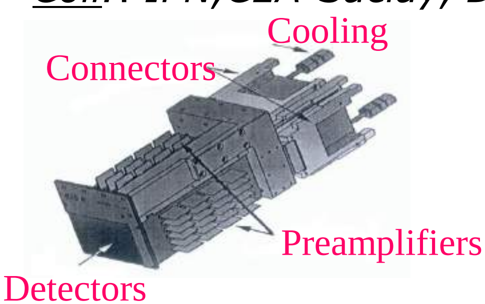
Silicon arrays developments

Light beams **Fission fragments**

1997 2007 2019/23

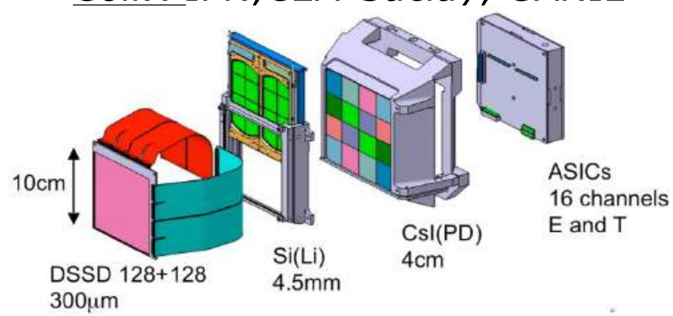
MUST

Coll.: *IPN,CEA-Saclay, DAM*



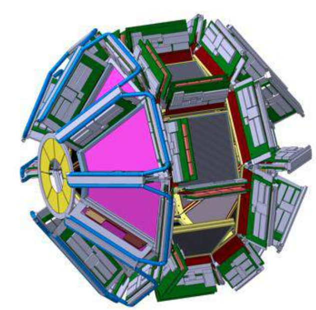
MUST2

Coll.: *IPN,CEA-Saclay, GANIL*



MUGAST/GRIT

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



Particle spectroscopy → **Particle-γ Spectroscopy**

E_x resolution: ~500 keV

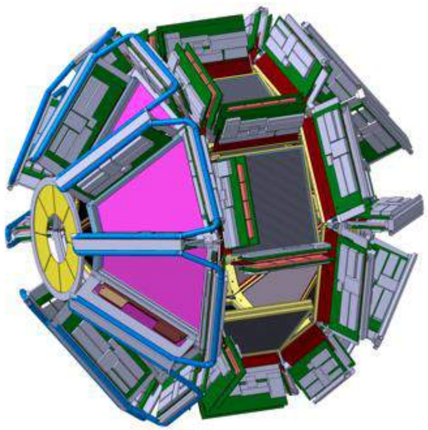
E_x resol.: ~5keV (AGATA)

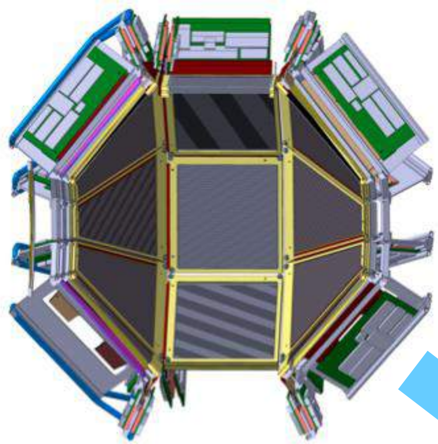
The GRIT project

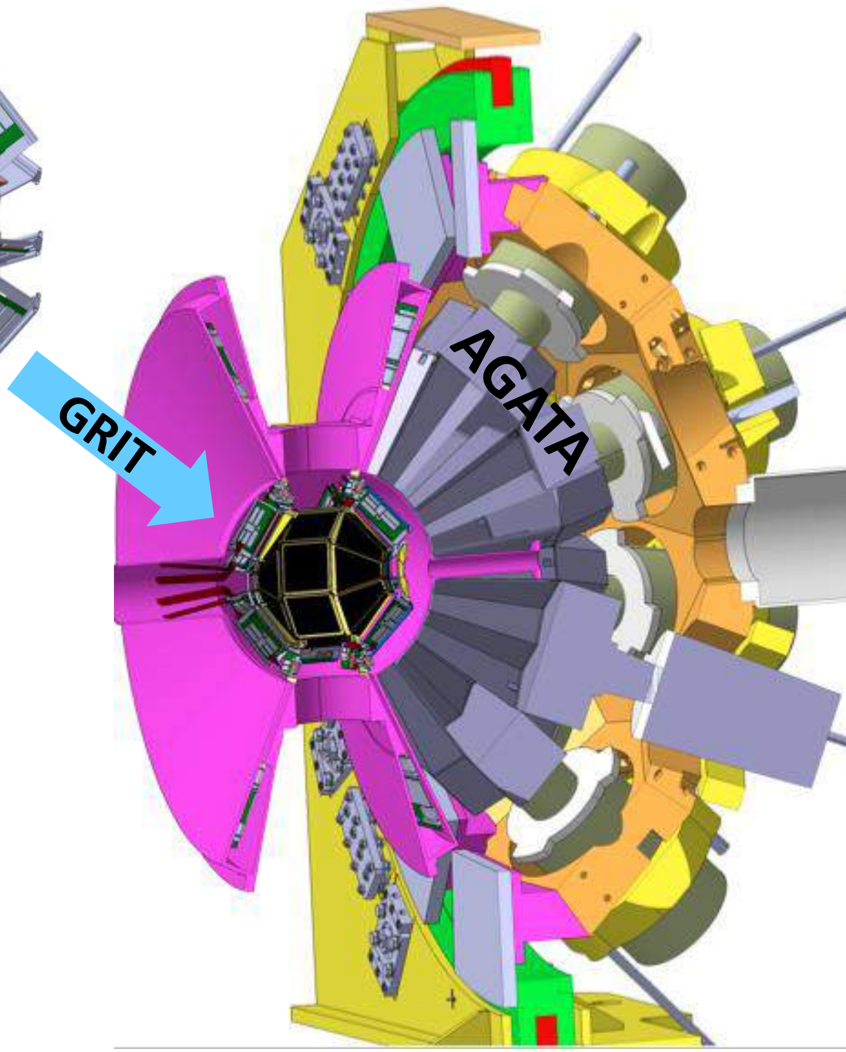
(Granularity, Resolution, identification, Transparency)

(GASPARD-TRACE collaboration)

4π Si array fully integrable in AGATA & PARIS







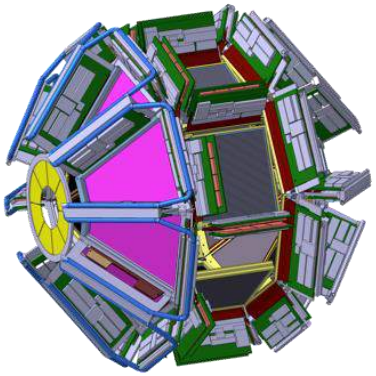
- High efficiency for particles
- High granularity (strip pitch < 1 mm)
- Large dynamical range

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

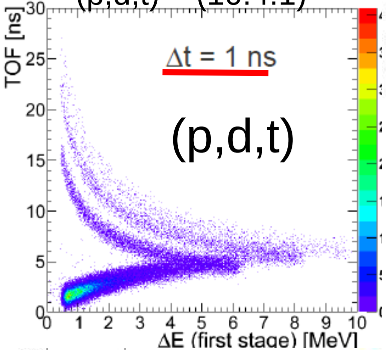
R&D on Pulse Shape Discrimination

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

Simulations (N.De Séréville)

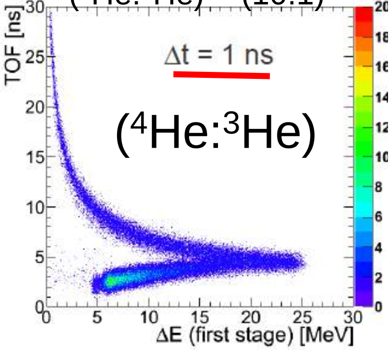
Z = 1

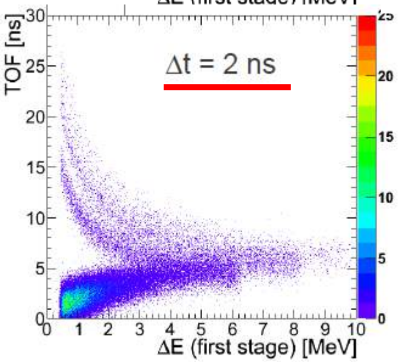
(p,d,t) = (10:4:1)



Z = 2

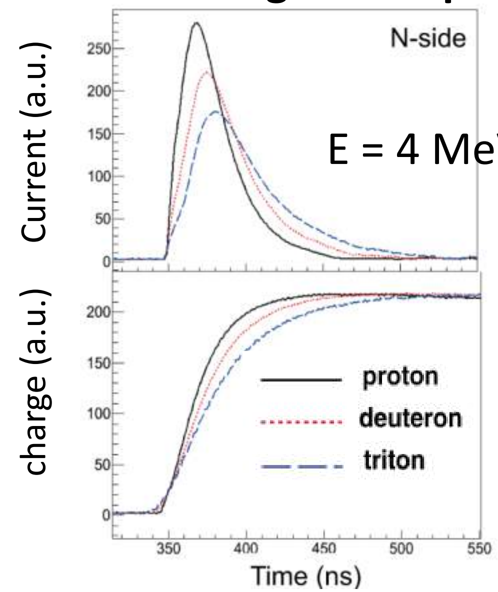
(^{4}He:^{3}He) = (10:1)





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

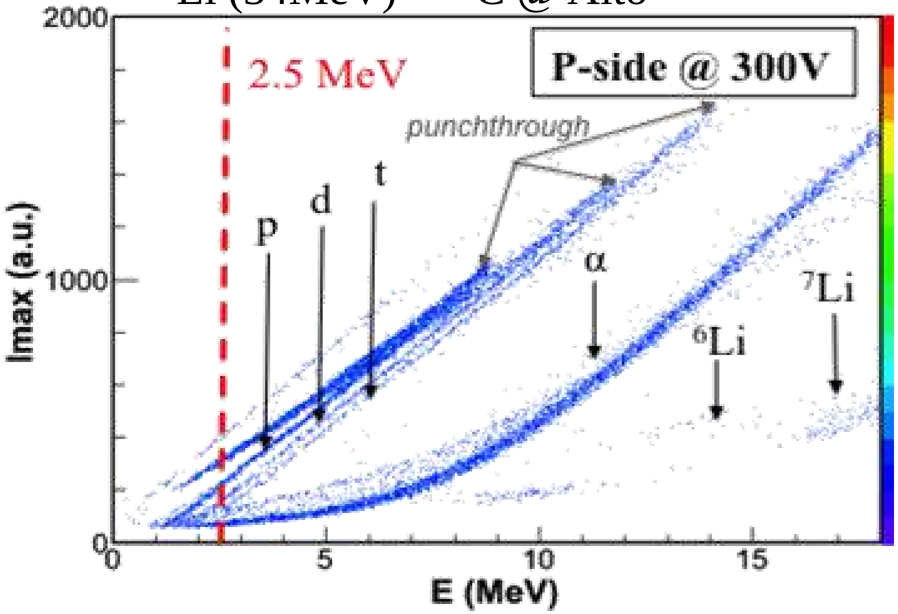
J. Duenas et al, NIMA 2012
J. Duenas et al, NIMA 2013
B. Genolini et al, NIMA 2013
J. Duenas et al, NIMA 2014
D. Mengoni et al, NIMA 2014
M. Assié et al, EPJA 2015
M. Assié et al, NIMA 2018

R&D on Pulse Shape Discrimination

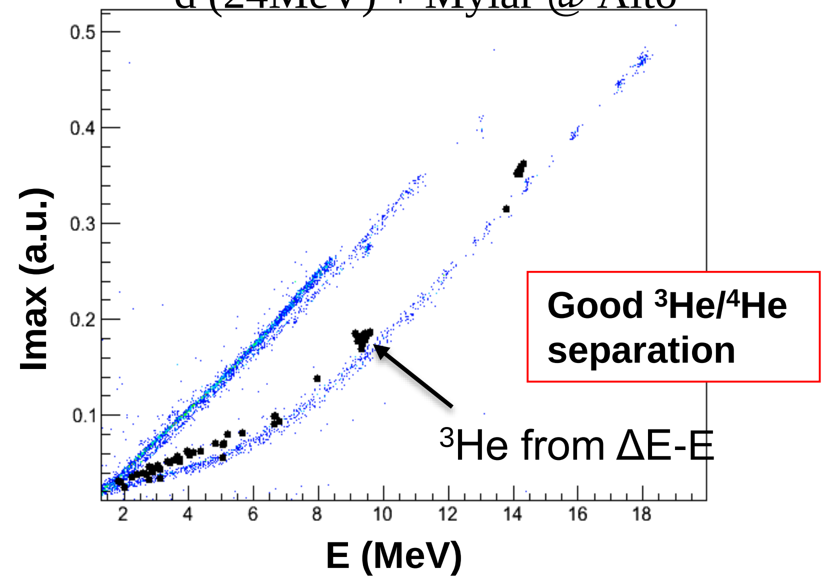
Initial detector:

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

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

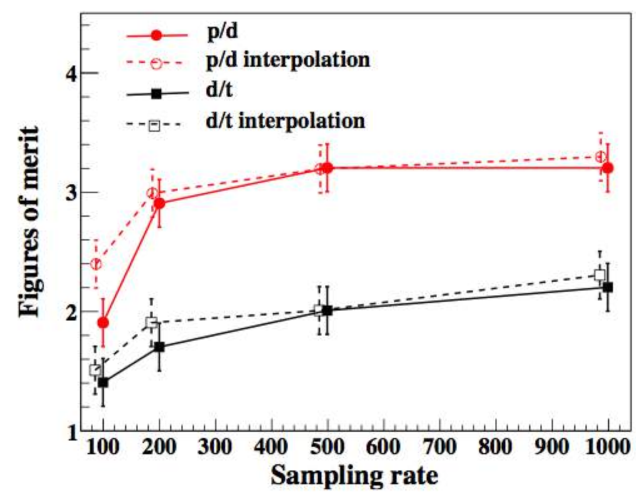


d (24MeV) + Mylar @ Alto



New data under analysis

- Test of PSD with trapezoid
- Effect of radiation damage

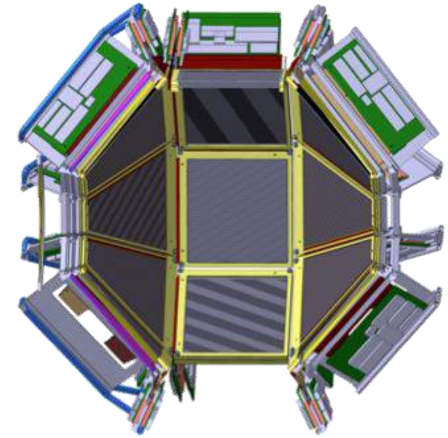


Crucial to set electronics specs. (e.g. sampling rate,…)

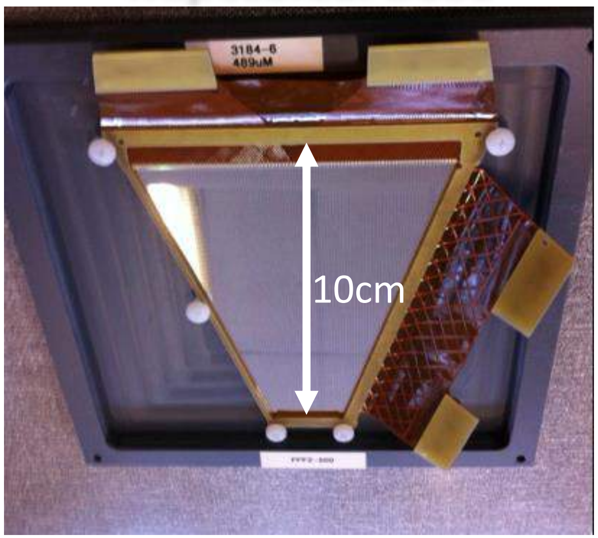
Detectors for GRIT

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



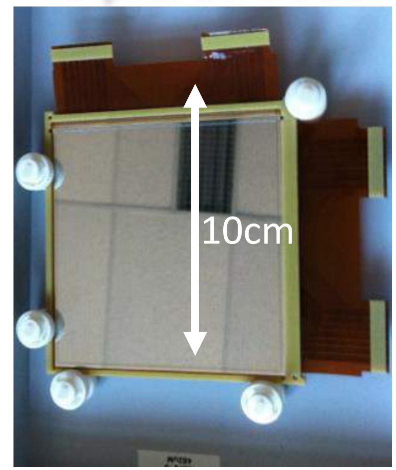
Trapezoidal DSSD



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

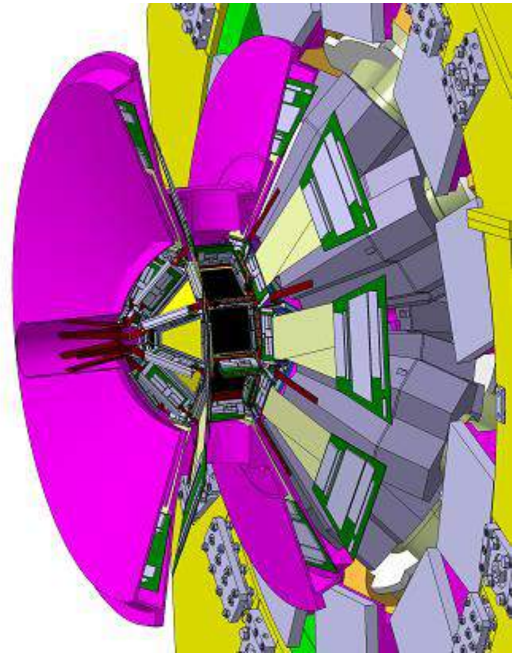
- ✓ 2 proto 500 um BARC Mumbai (Semiconductor Lab , Chandigarh, India)

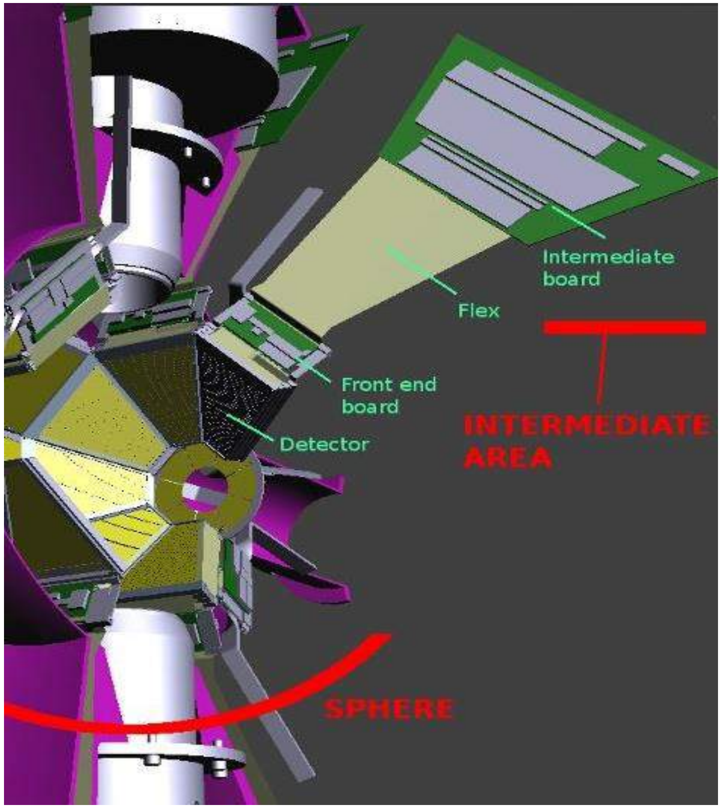
Detectors for the second layer to be developed

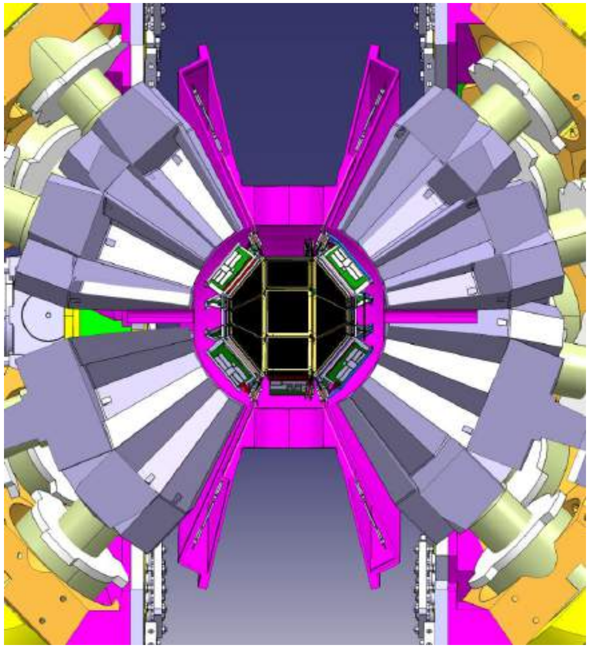
GRIT Mechanical design

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
- …



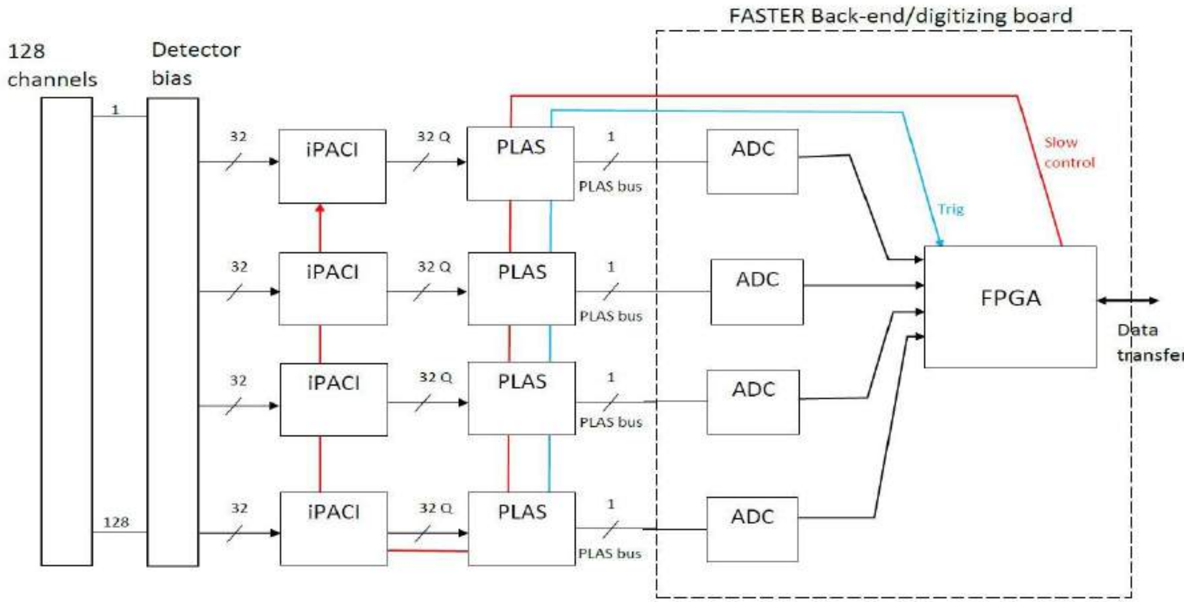




- ➢ **Preliminary detailed design was achieved**
- ➢ **Final version to be completed (IPN Orsay) (see workplan)**

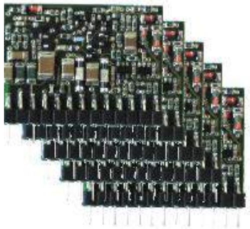
Electronics of GRIT

GLOBAL SCHEME



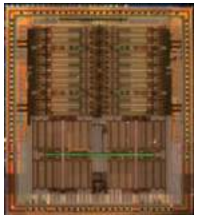
BUILDING BLOCKS

- **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 required
  Need contract engineer (CDD)

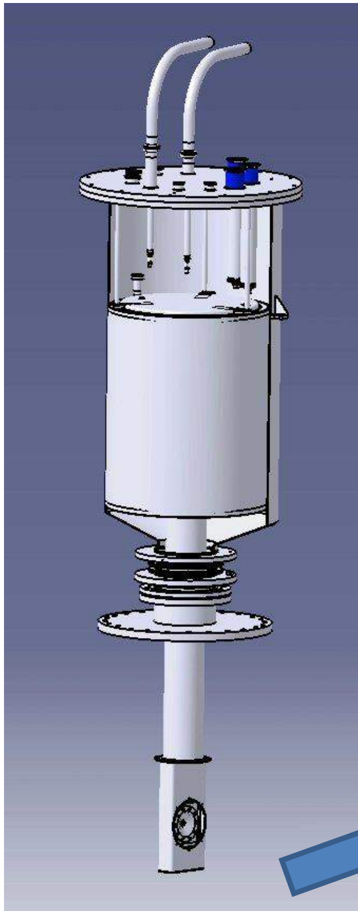


- **FASTER backend**

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)**

....

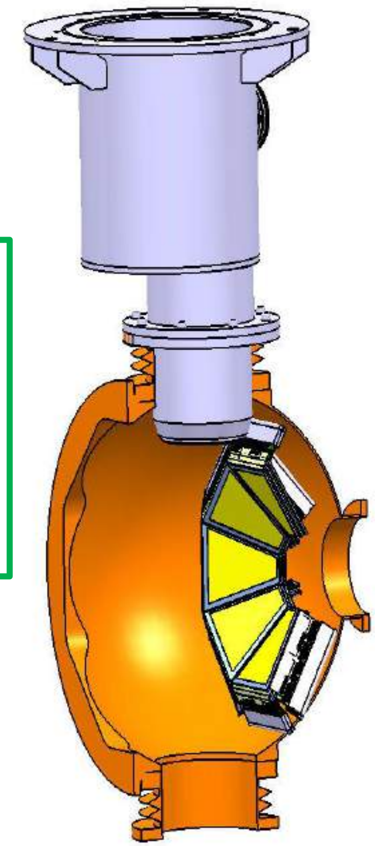
Ø 16 mm,
2-3mm-thick cell
Havar windows 3.8μm
T = 5K , P = 1 bar

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



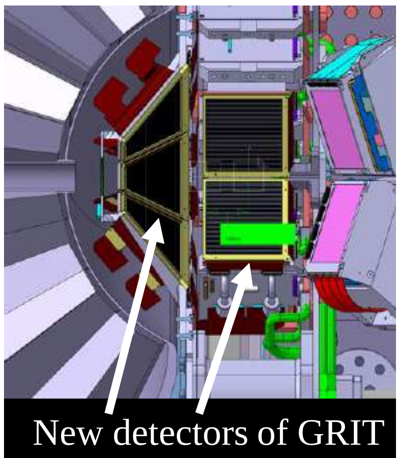
MUGAST: an intermediate step towards GRIT

[MUst2 – GASpard – Trace]

MUGAST: - *New detectors of GRIT + MUST2 electronics + few telescopes*

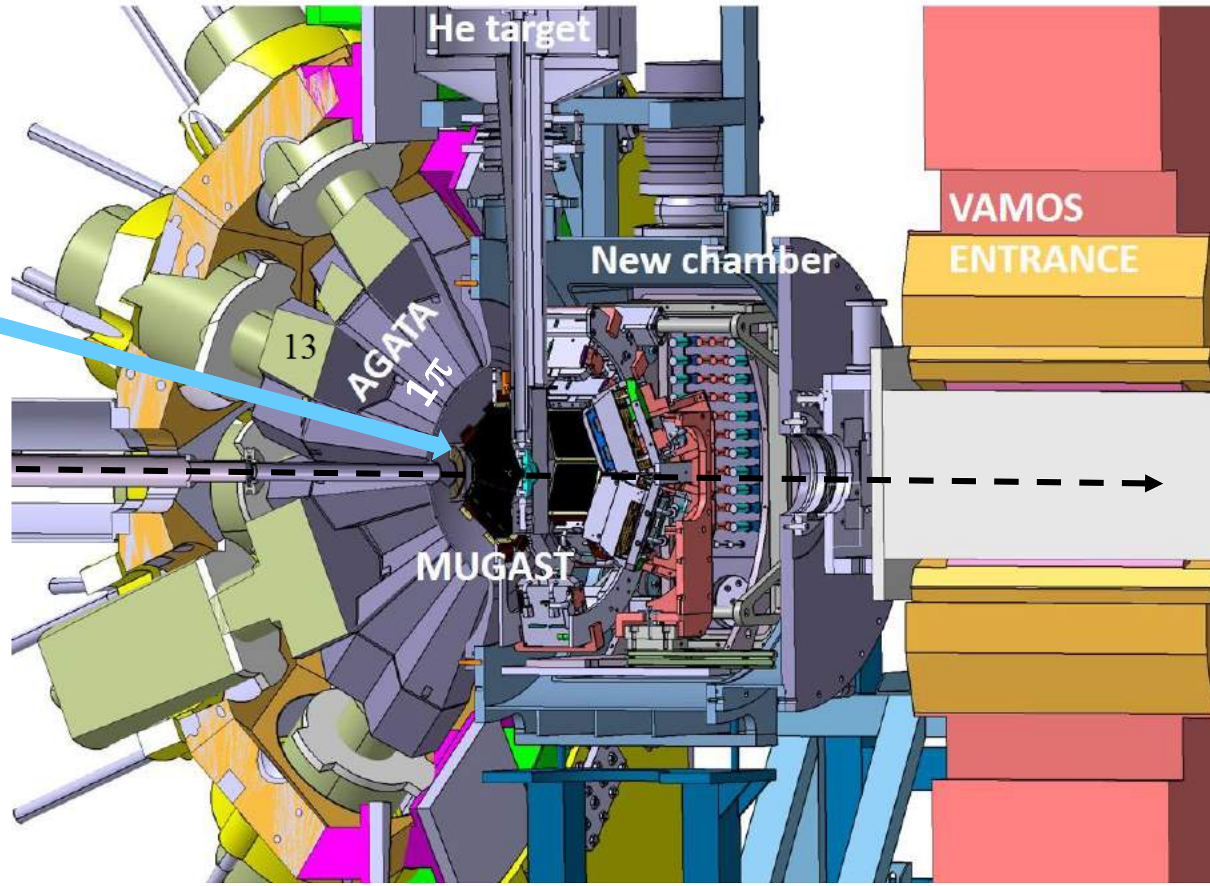
- *Coupled with AGATA @ VAMOS*

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



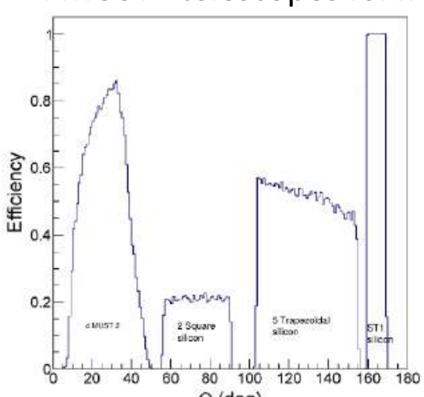
~ 3000 channels

RI Beam



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

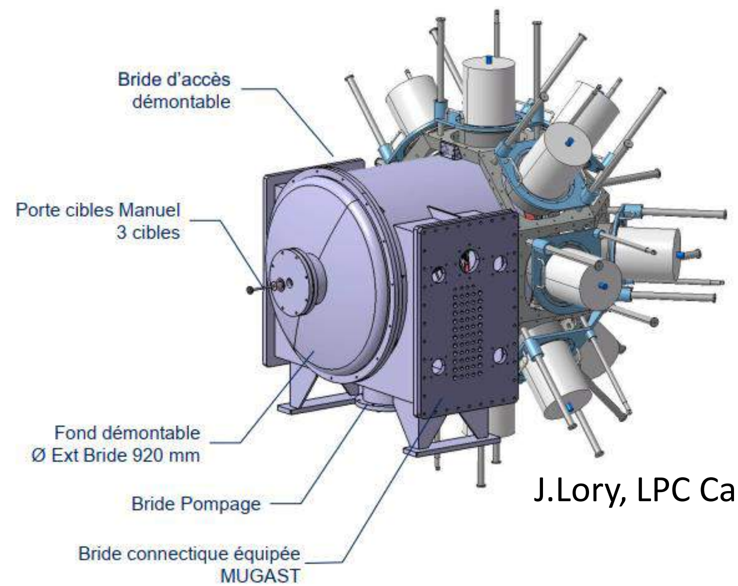
First step towards
GRIT

- **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.	4.	3.5	5.1	4.6	3.8	0.4	0.4
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.

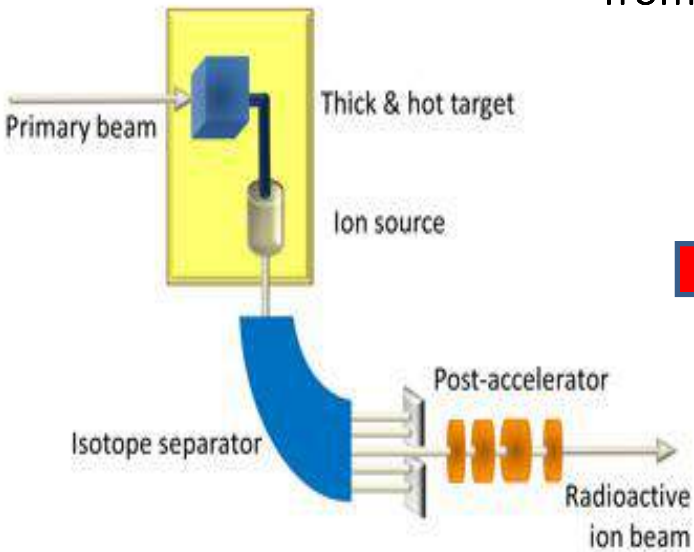
Backup slides

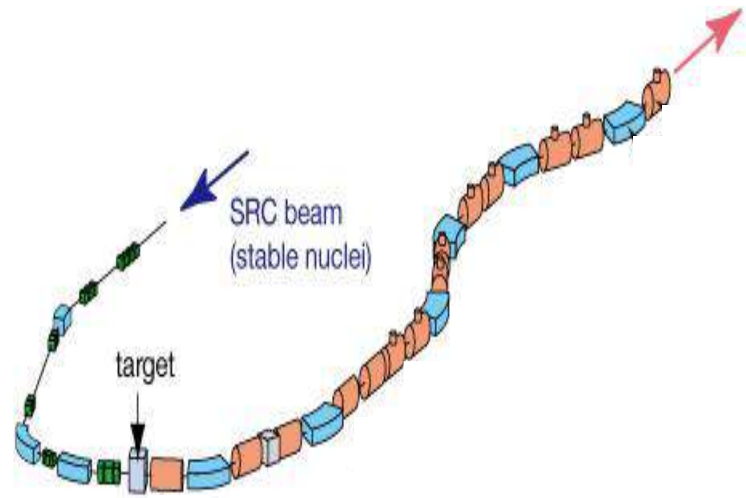
Physics opportunities with slowed-down beams

ISOL method
"1 sec extraction"

Shorter half-life far
from stability

In-flight method
"100ns production-detection"





Independence from
chemical properties

Purpose to slow-down in-flight beams : implement reactions/techniques of the low energy regime

Key issue : Characteristics of the SD beams

Direct reaction studies at using SD beams

- **Take advantage of chemical independence and fast production process of in-flight beams**
- **Reactions at intermediate energies (10~50 MeV/u)**

A broad physics program of direct reaction studies can be envisioned

Stripping reactions

- Nucleon, pair or cluster **addition modes**
  - ✓ unique selectivity
  - ✓ no high-energy equivalent (as e.g. quasifree scattering ↔ pickup reaction)

- **(d,p) well established tool for neutron shell structure**
  Experimentally tractable in inverse kinematics with RIB
  - ✓ Recoil protons in the backward hemisphere
  - ✓ Accurate detection of residue not mandatory

SIMULATIONS

Using the NPTool package for simulations of Direct reactions

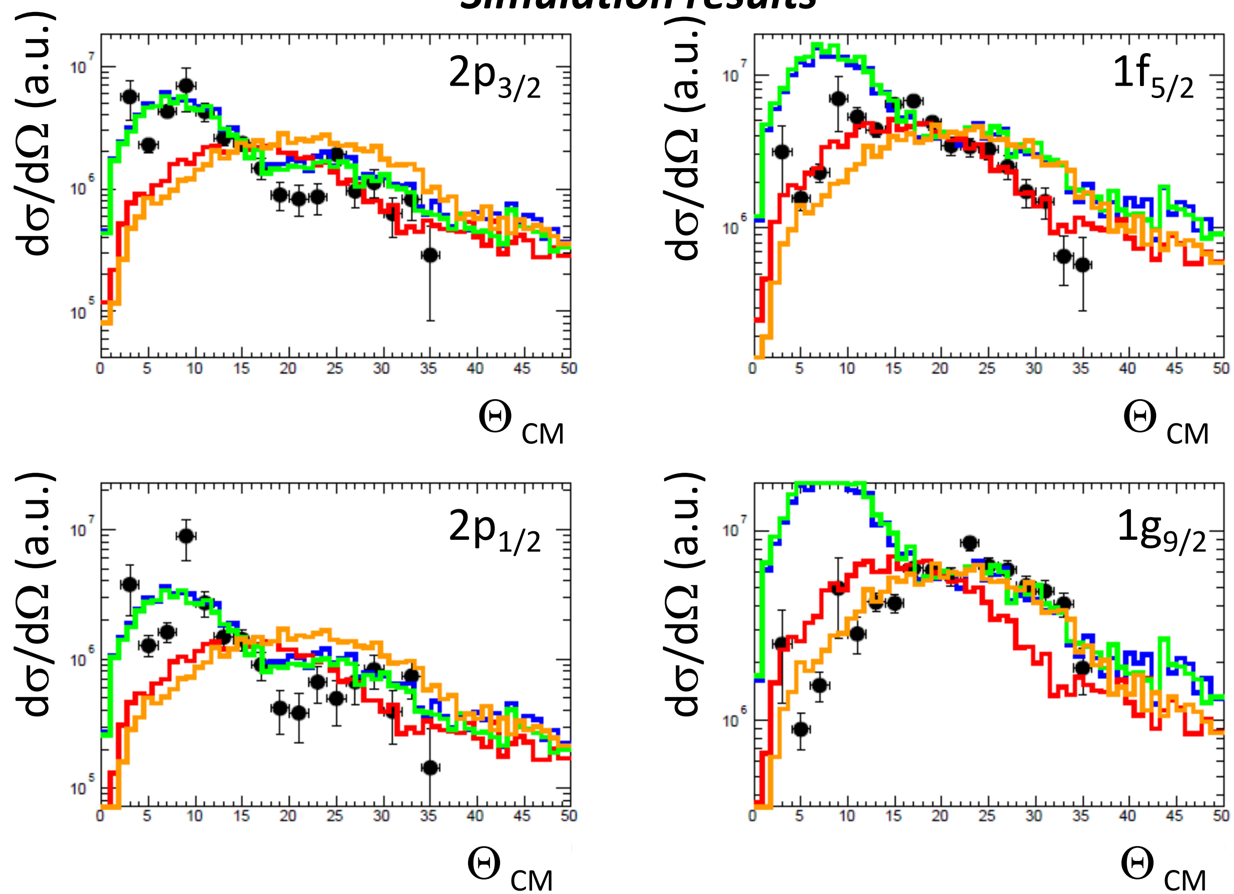
- Event generator: 2Body kinematics and DWBA cross-sections
- Realistic detector configuration
- Detector's resolutions
- Target effects

New event generator :
Includes

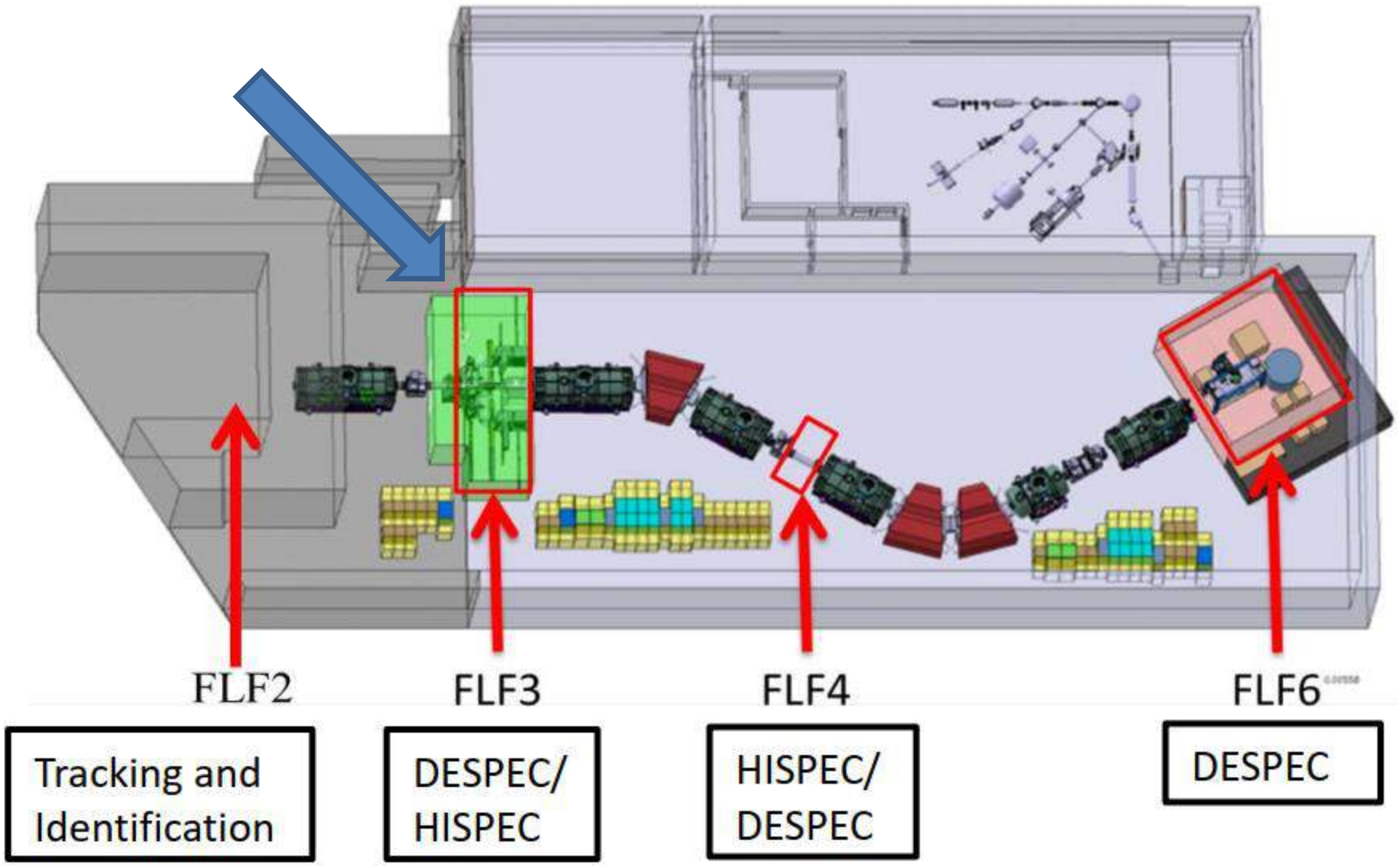
- ❑ beam energy distribution
- ❑ ADWA for each energy

Application:
^{54}Ti(d,p) at RIKEN
Population of p,f,and g orbits

Simulation results



Low Energy Branch of the super-FRS



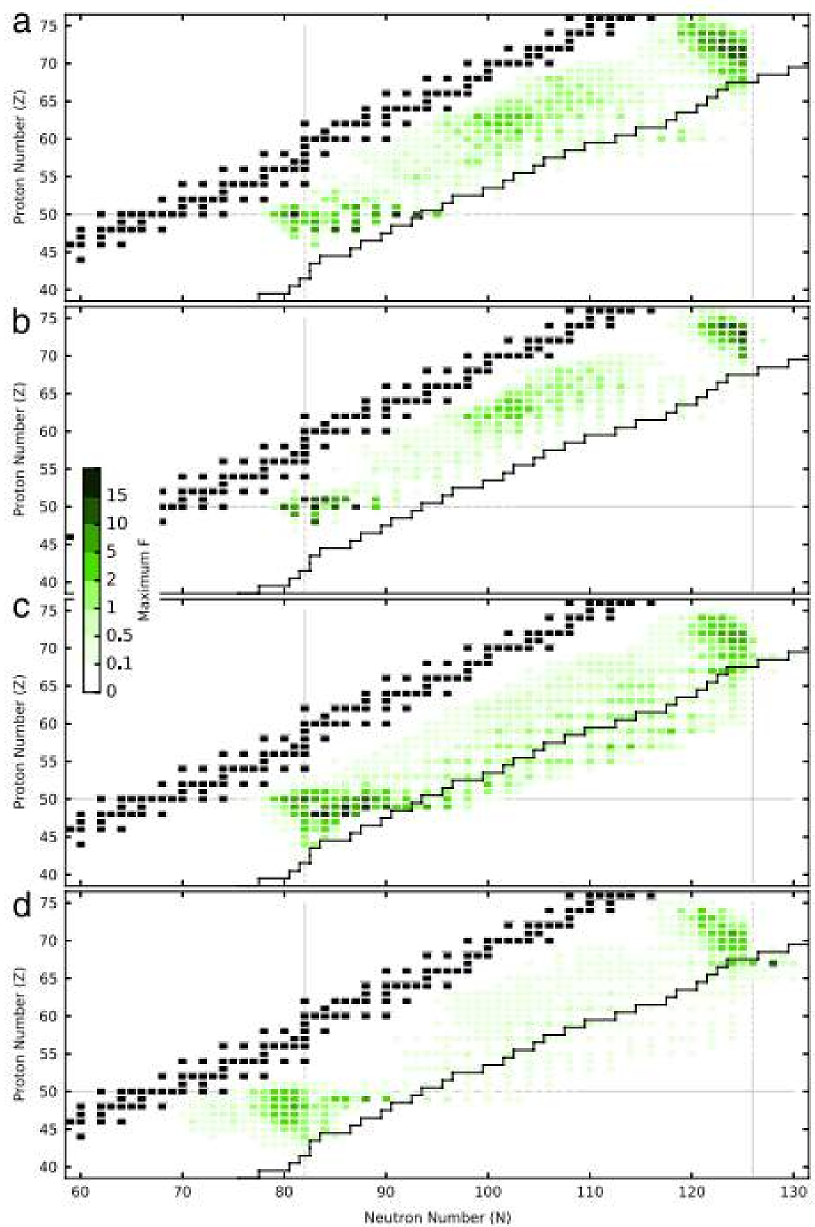
Important neutron capture rates in 4 astroph. environments

Low entropy
Hot wind

High entropy
Hot wind

Cold wind

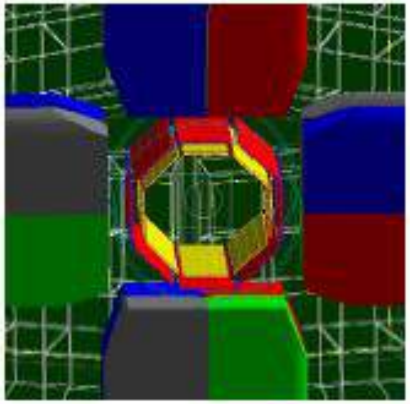
Neutron-star
merger



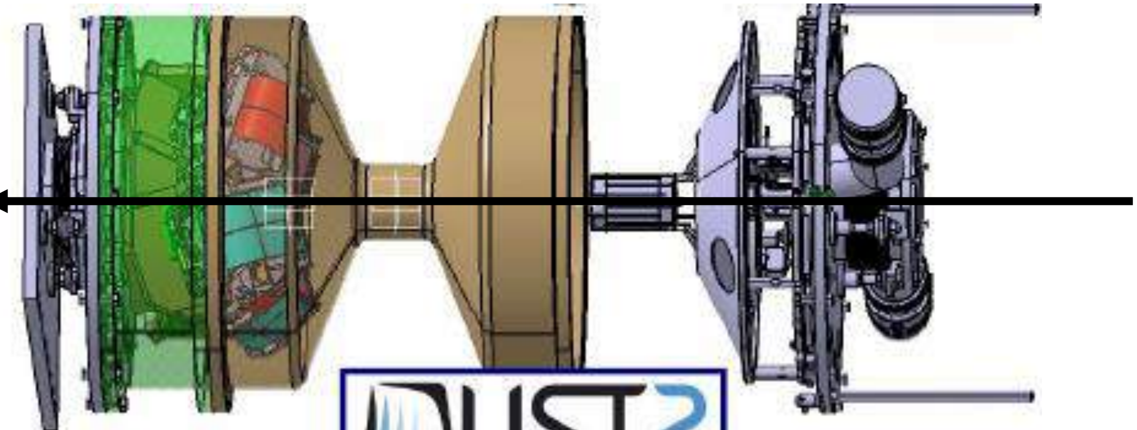
M.R. Mumpower et al., PPNC 86, 86 (2016)

Si-based systems currently operating for particle-γ coincidence measurements

γ-rays $\Rightarrow E_x$



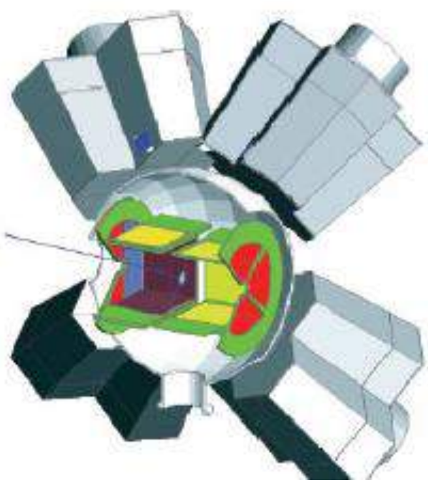
4 EXOGAM

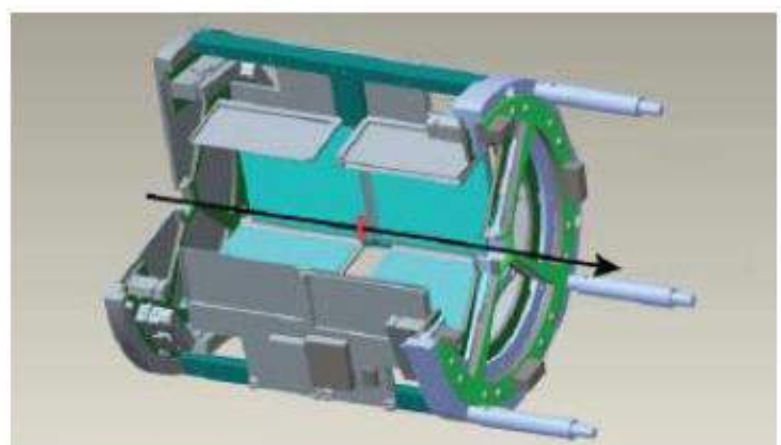


MUST2

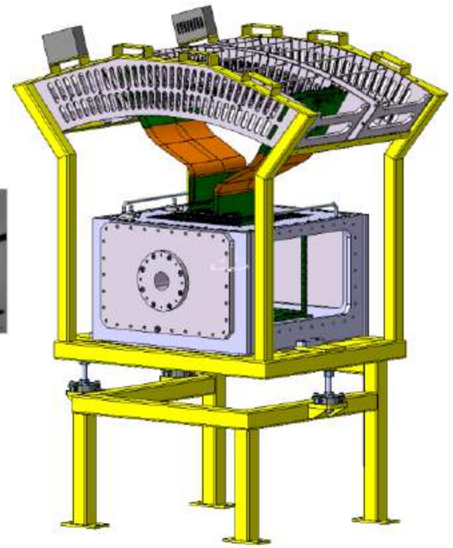
TIARA

T-REX + MINIBALL

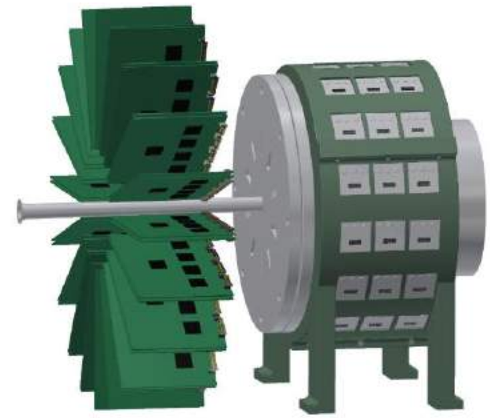




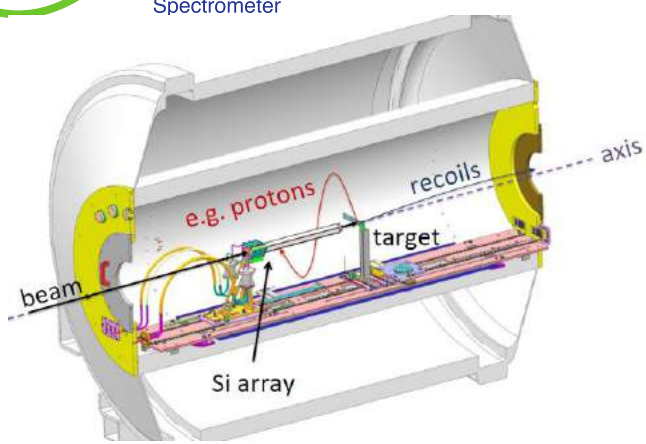
New Instruments for Direct Reactions studies in Europe



SpecMAT
Spectroscopy in a Magnetic Active Target



ISOLDE Solenoidal Spectrometer



GRIT Si array