The EXOTIC project at INFN-LNL

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Outline

- EXOTIC facility
- Experimental program
- Experimental set-up
- Some selected recent experiments at EXOTIC
- Conclusions and perspectives

The EXOTIC project @ LNL

A facility to produce in-flight low-energy light radioactive ion beams (RIBs) through two-body inverse kinematics reactions induced by high intensity heavy-ion beams from the XTU Tandem accelerator impinging on light gas targets (p, d, ^{3}He, ^{4}He)

- **Commissioning** of the EXOTIC facility in 2004

V.Z. Maidikov et al., Nucl. Phys. A 746 (2004) 389c, D. Pierroutsakou et al., EPJ SP 150 (2007) 47, F.. Farinon et al., NIM B 266 (2008) 4097, M. Mazzocco et al., NIM B 266 (2008) 4665

- First **"beam for experiment"** (^{17}F) in 2006

D. Pierroutsakou et al., EPJ SP150 (2007) 47, C. Signorini et al., EPJA44 (2010) 63

- A **substantial upgrade process** was subsequently held in 2012

M. Mazzocco et al., NIM B 317, 223 (2013)

The EXOTIC project @ LNL

1 – 1st slit system

2 – production gas target

3 – 1st quadrupole triplet

4 – 2nd slit system

5 – 30° analysing magnet

6 – 3rd slit system

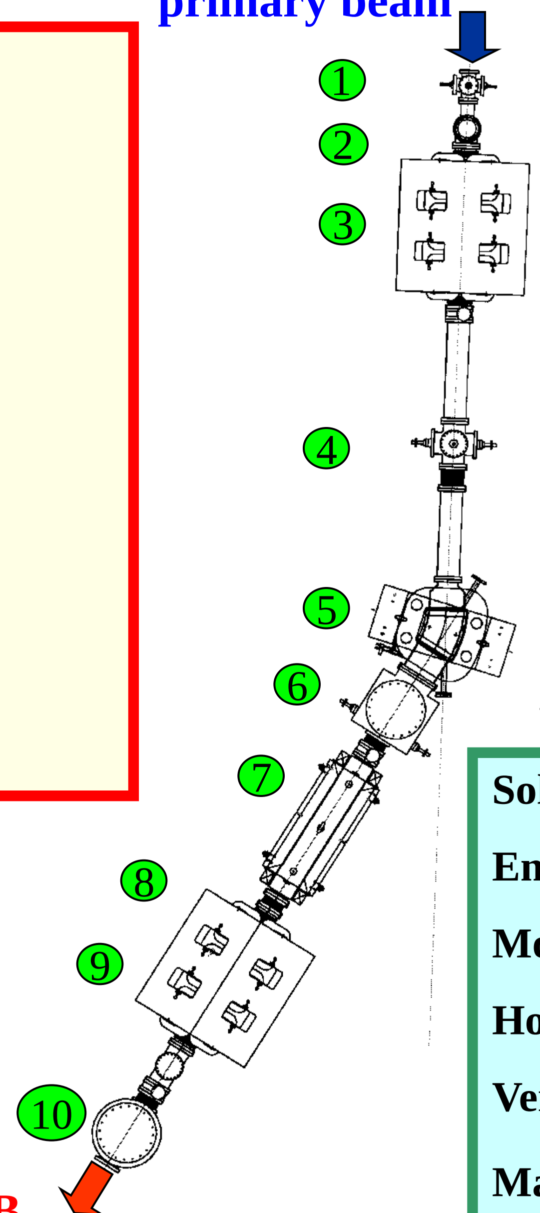
7 – Wien filter

8 – 2nd quadrupole triplet

9 - 4th slit system

10 – scattering chamber

primary beam

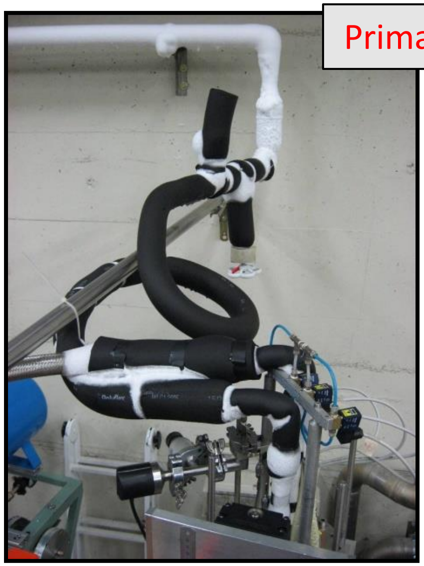


1 m

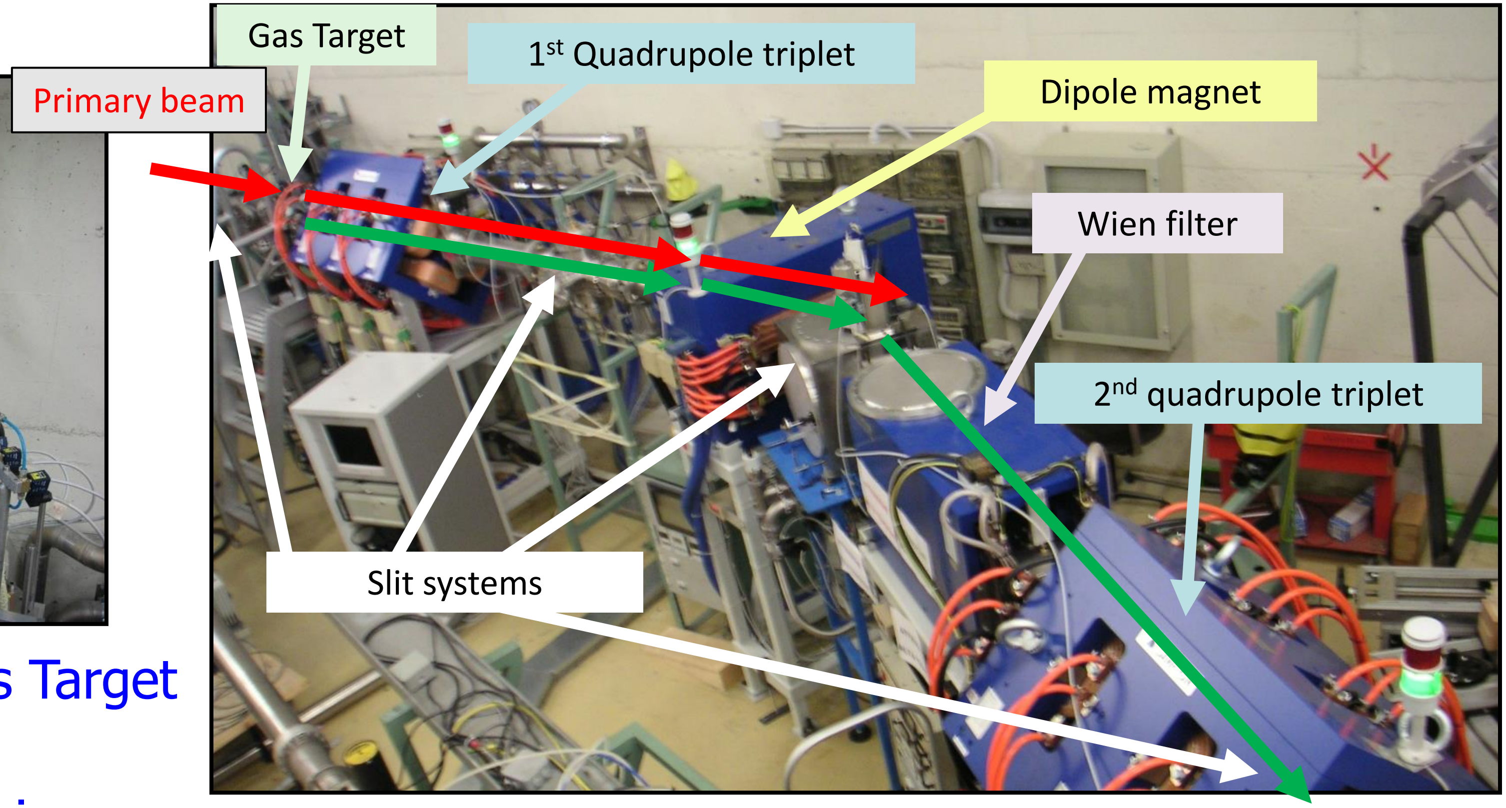
Cryogenic production gas target: 5-cm long double-walled cylindric cell
Entrance (exit) windows: 14 (16) mm
2 havar: 2.2 μm
Pressure: up to 1.2 bar.

Solide angle Δω	~ 10 msr
Energy acceptance ΔE/E	±10%
Momentum acceptance Δp/p	± 5%
Horizontal acceptance Δθ	± 50 mrad
Vertical acceptance Δϕ	± 65 mrad
Magnetic rigidity Bρ	0.98 Tm

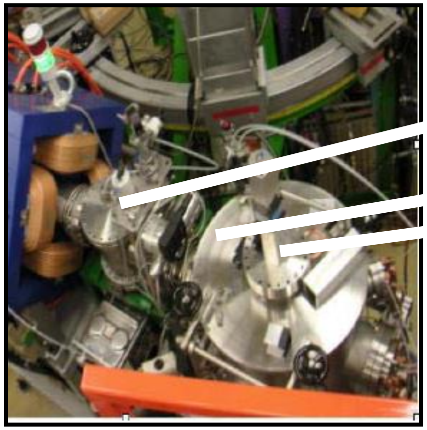
The EXOTIC project @ LNL

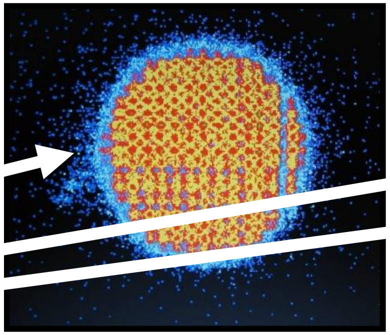


Cryogenic Gas Target

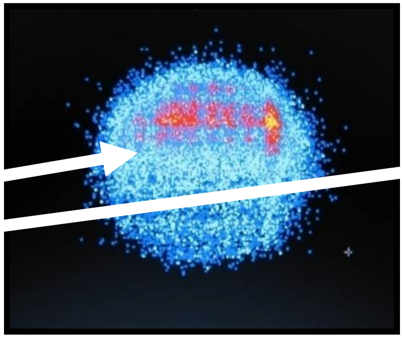


Beam-Tracking

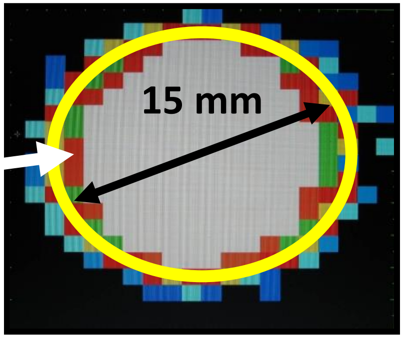




PPAC A
909 mm

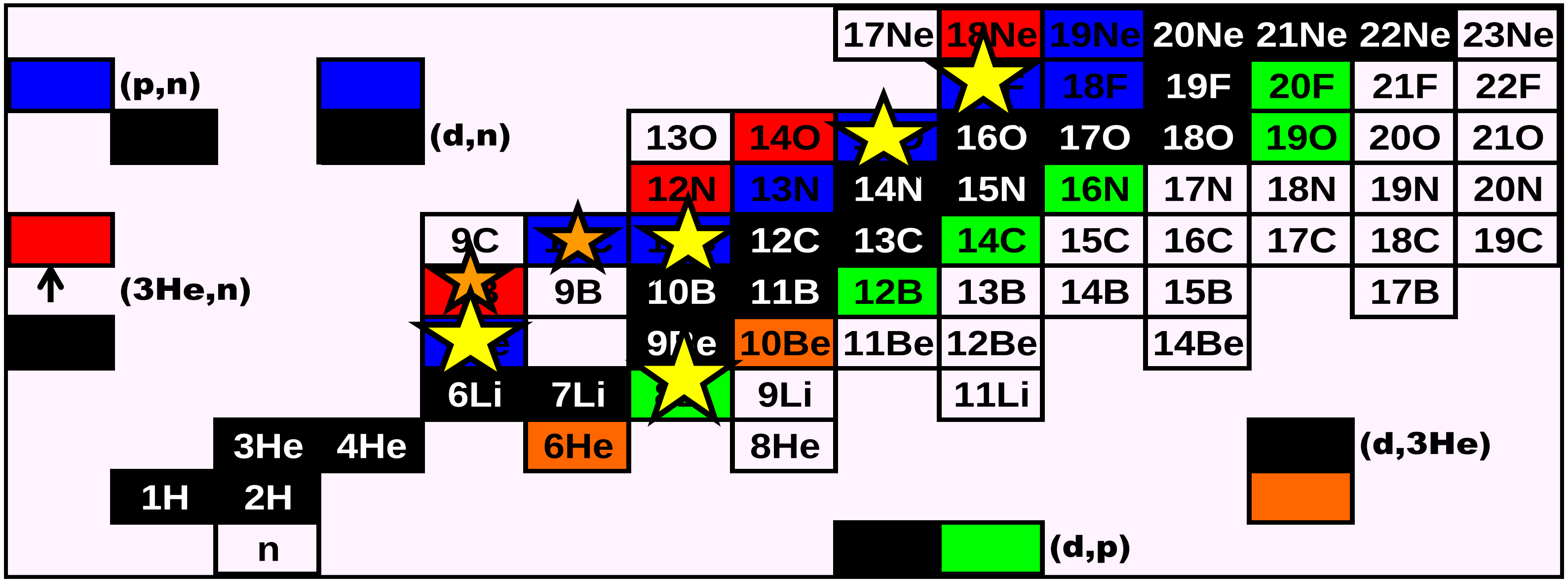


PPACB
365 mm



Reconstruction on the target

Light RIBs @ EXOTIC



^{17}F (Sp=600 keV)	***p(^{17}O,^{17}F)n***	Q=–3.54 MeV	E=3–5 MeV/u	P:93-96%	I:10^5 pps
^{8}B (S_p=137.5 keV)	***^{3}He(^{6}Li,^{8}B)n***	Q=–1.97 MeV	E=3–5 MeV/u	P:30-43%	I:10^3 pps
^{7}Be (S_α=1.586 MeV)	***p(^{7}Li,^{7}Be)n***	Q=–1.64 MeV	E=2.5–6 MeV/u	P:99%	I:10^6 pps
^{15}O (S_p=7.297 MeV)	**p(^{15}N,^{15}O)n**	Q=–3.54 MeV	E=1.3 MeV/u	P:98%	I:4*10^4 pps
^{8}Li (S_n=2.033 MeV)	**d(^{7}Li,^{8}Li)p**	Q=–0.19 MeV	E=2–2.5 MeV/u	P:99 %	I:10^5 pps
^{10}C (S_p=4.007 MeV)	**p(^{10}B,^{10}C)n**	Q=–4.43 MeV	E=4 MeV/u	P:99 %	I:5*10^3 pps
^{11}C (S_p=8.689 MeV)	**p(^{11}B,^{11}C)n**	Q=–2.76 MeV	E=4 MeV/u	P:99 %	I:2*10^5 pps

Experimental program @ EXOTIC

- Study of reaction dynamics with light RIBs
- Study of α clustering phenomena in light exotic nuclei
- Direct and indirect measurements of astrophysical interest
- The use of the facility EXOTIC as a separator for Heavy-Ion Fusion Evaporation Residues from stable beams for measurements at sub-barrier energies is under investigation: recent tests performed with encouraging results

From 2006 14 experiments have been performed in the framework of international collaborations.

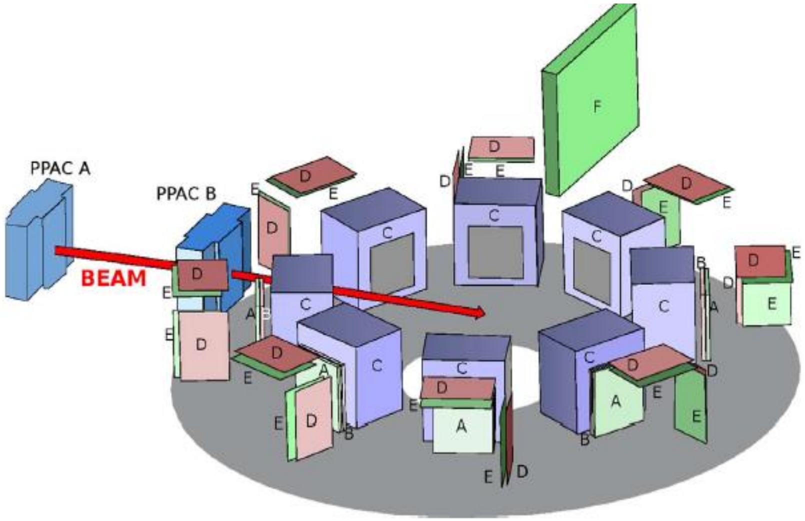
Experimental requirements for the detection system

- Z- and A-identification of the reaction fragments;
- Large solid angle coverage to compensate the low intensity of the RIB;
- Good angular resolution (1° FWHM);
- Δt = 1-1.5 ns (FWHM);
- ΔE < 250-400 keV (FWHM overall energy resolution) for discriminating the elastic from the inelastic scattering of the projectile from the target (^{58}Ni, ^{208}Pb) in direct kinematics for the most demanding cases (^{11}Be, ^{17}F);
- event-by-event beam tracking system to compensate the poor emittance of the in-flight produced RIB with a fast signal for handling counting rates up to 10^6 Hz and for ToF measurements;
- flexibility in order to be suitable for different experimental needs.

The experimental set-up of the EXOTIC facility

Experimental set-up entirely developed by our collaboration

- 2 **position-sensitive Parallel Plate Avalanche Counters** (PPACs) for beam tracking and ToF measurements
- **EXPADES:** a high-granularity, compact, flexible, portable charged-particle detection array



8 EXPADES Telescopes

ΔE1 – IC

ΔE2 (40/60 μm) + E_{res} (300 μm) - DSSSDs

DSSSDs: 64 x 64 mm^2 active area
32 x 32 strips (2 mm pitch size - 40 μm interstrip separation)
2mm x 2mm pixel
$\Delta\theta$=1° at d=10.5 cm

→

Z and A identification through ΔE-E TOF information
Good energy, time and angular resolution
High granularity
Distance from target varies from 10.5 to 22.5 cm
Coverage: 22% of 4π sr at 10.5 cm

D. Pierroutsakou et al, NIM A 834 (2016) 46

The experimental set-up of the EXOTIC facility

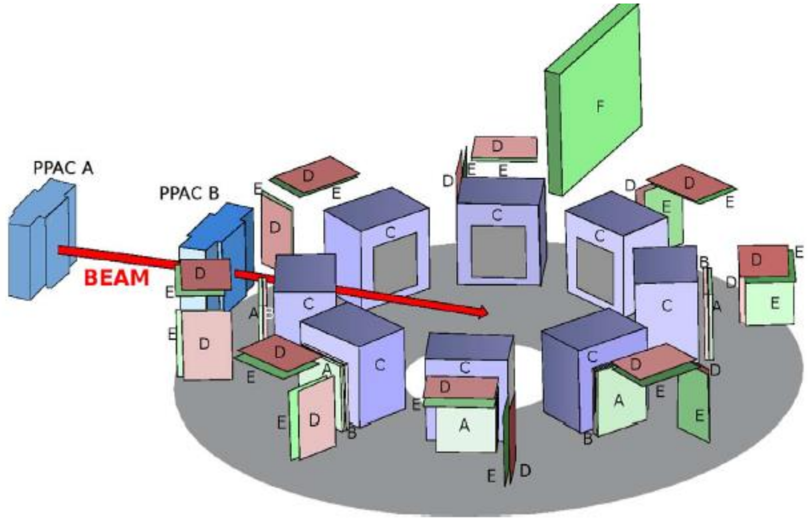
Experimental set-up and electronics
entirely developed by our collaboration

Compact low-noise electronics with large dynamic range and good energy and timing characteristics for the 40/60 μm DSSSD ΔE stage.

ASIC-based electronics for the 300 μm DSSSD E_{res}

Electronic boards placed in the proximity of the array in vacuum:

- to have a compact set-up (detectors + electronics);
- to minimize the internal and external connections and
- to overcome the environmental noise at the EXOTIC beamline.



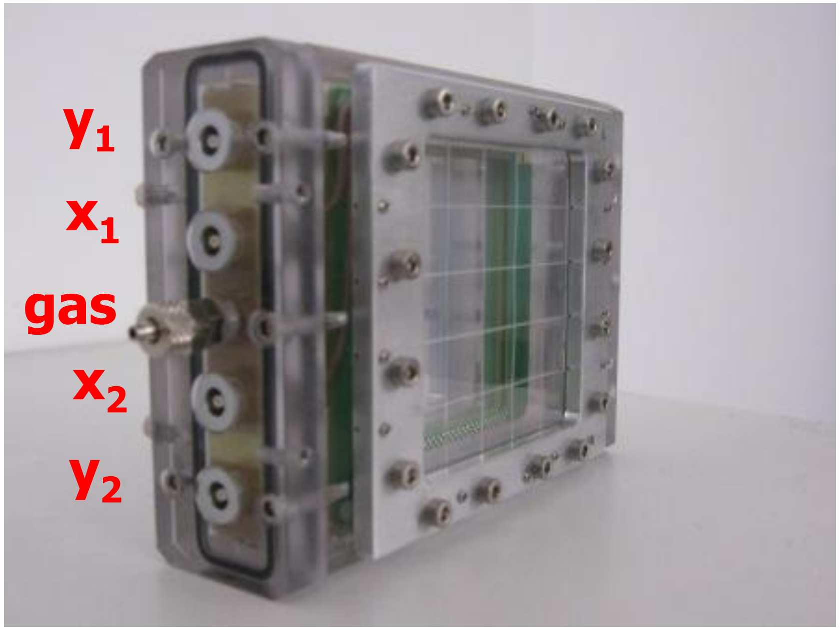
D. Pierroutsakou et al, NIM A 834 (2016) 46

Two newly designed front-end electronic modules: a **sampling ADC** and a **Trigger Supervisor Board (TSB)**

Sampling ADC: A single-slot standard VME card devoted to sample, analyze and digitize the multiplexed analogue signals coming out from the electronic front end of the set-up. The module has 8 differential input channels and is based on a 50 MHz 12-bit ADC integrated circuit

TSB: The TSB is a general purpose VME-standard card accepting up to 64 differential TTL input channels for the proposed trigger signals coming from the different detectors and handles the trigger logic of the whole set up

RIB tracking detectors @ EXOTIC: PPACs

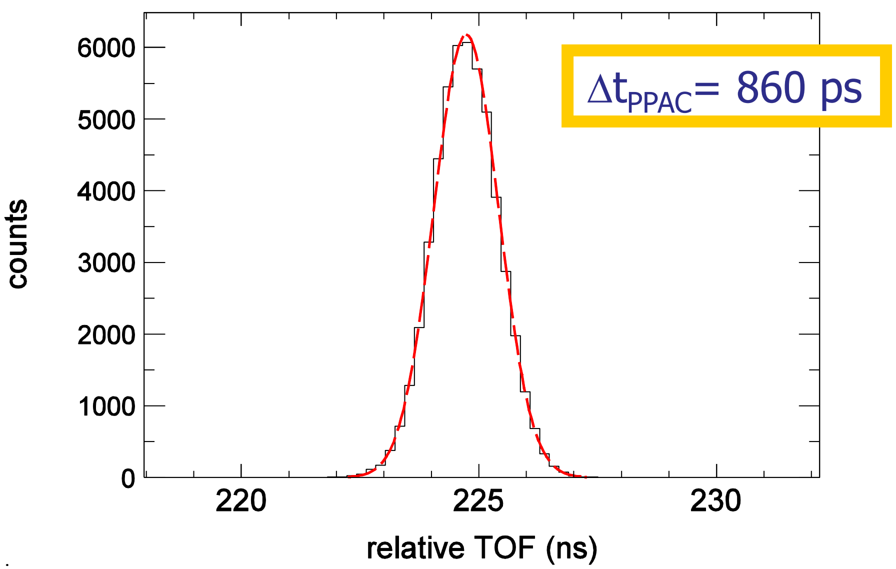


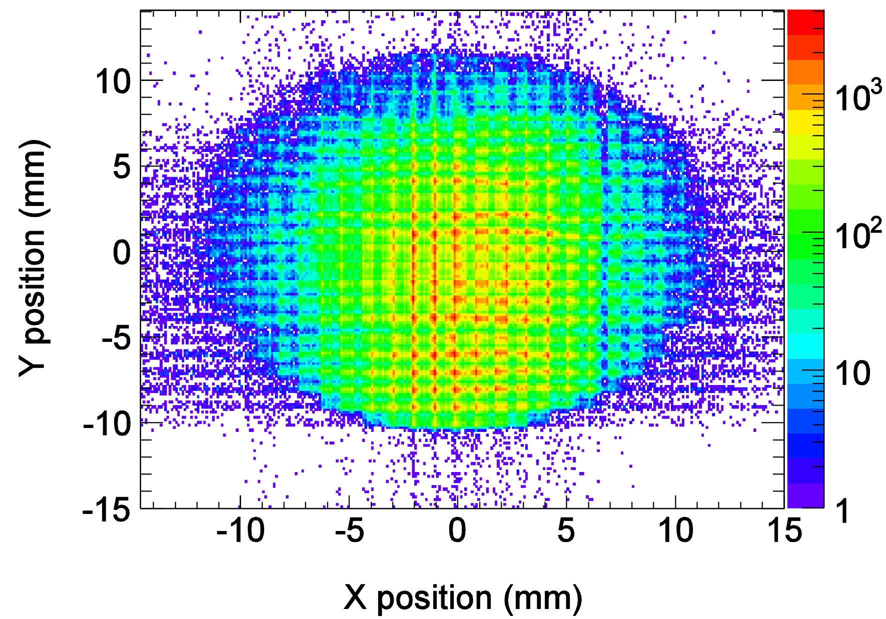
Sustains **counting rates up to 10^6 Hz**

High tracking efficiency
98% for a ^{15}O RIB (2 x 10^4 pps)
94% for a ^8B RIB (10^3 pps)

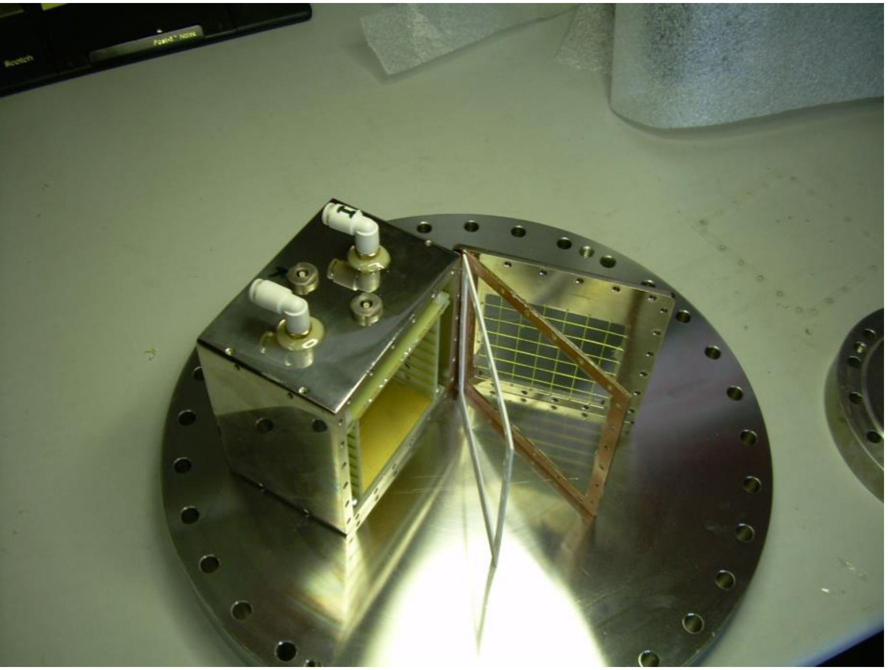
with 1 mm position resolution -> **2.3 mm resolution** (FWHM) of the position hit on the reaction target.

E_{lab}=31 MeV ^{15}O RIB profile on PPAC B
(1 mm position resolution)





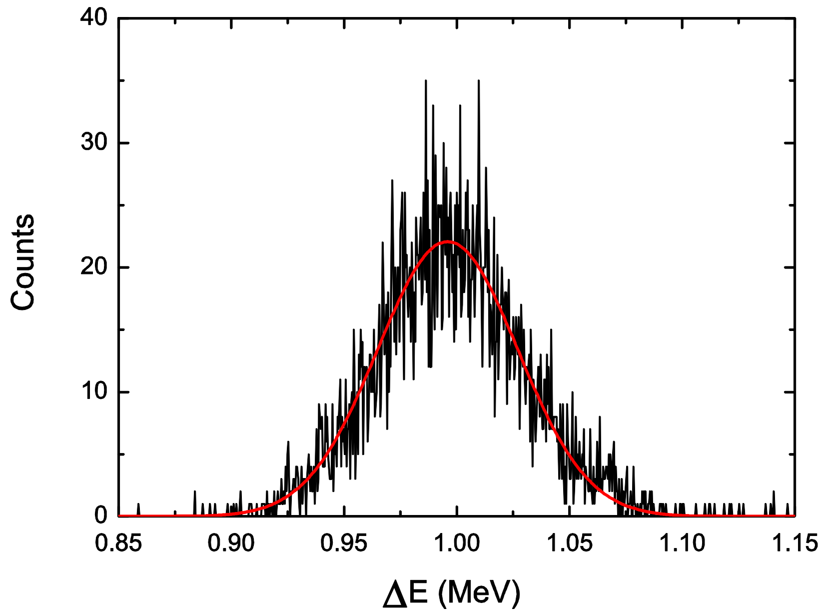
EXPADES ΔE stage transverse field IC



Easy handling, thickness uniformity, possibility to tune the effective thickness, large detection surface, no radiation damage problems, low thresholds

Entrance and exit windows: 1.5 μm-thick mylar
External dimensions: 10 cm x 10cm x 6.8 cm

Frish grid
Gas: CF_4 at 50-100 mbar

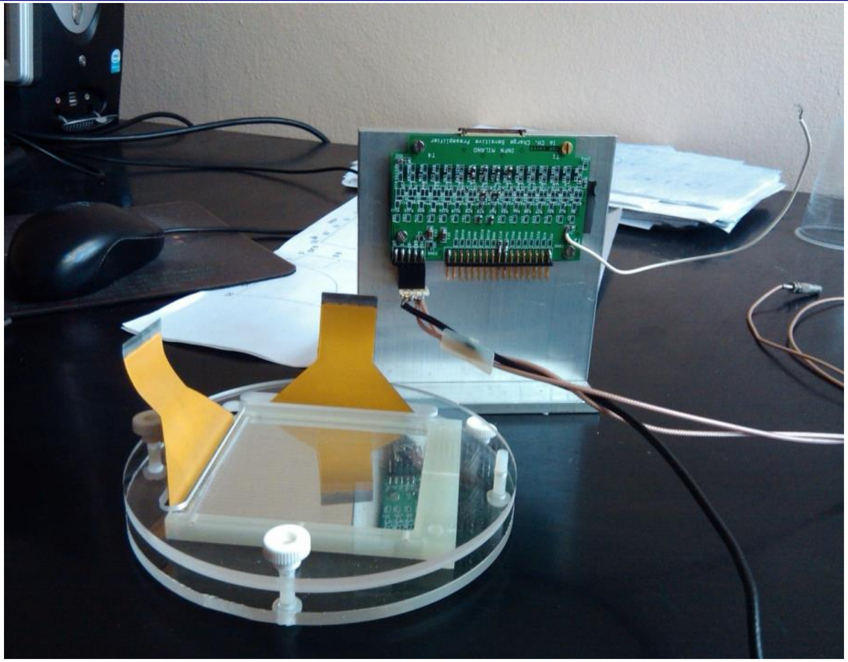


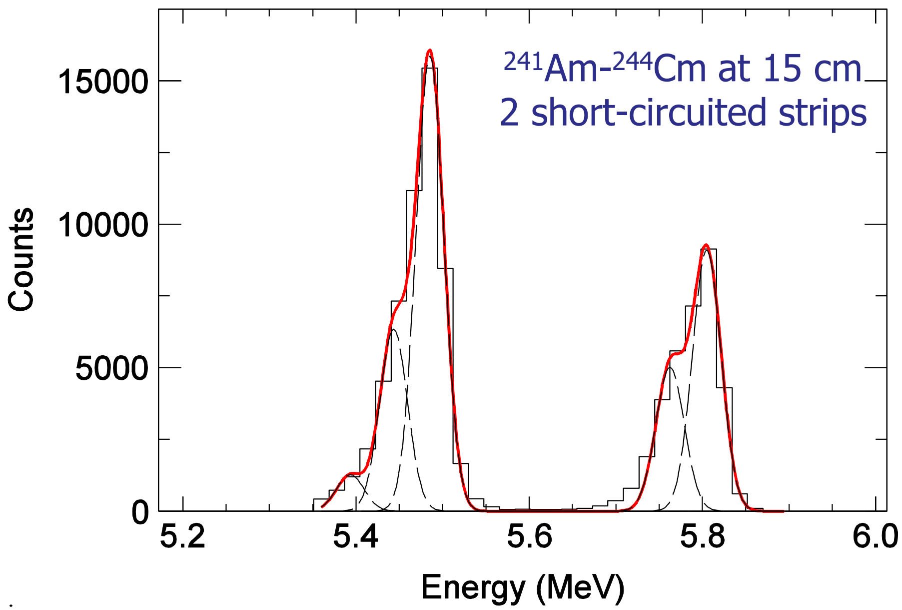
Offline tests: readout traditional electronics

^{241}Am α source at 22 cm illuminated through a Ø=0.3 cm hole
P=61.5 mbar CF_4

FWHM 73 keV for ΔE=1 MeV
7.3% (6.5% intrinsic)

ΔE stage: DSSD 40/60 μm





Readout: home made highly integrated low-noise electronics

16 channel low-noise **pre–amplifier** boards

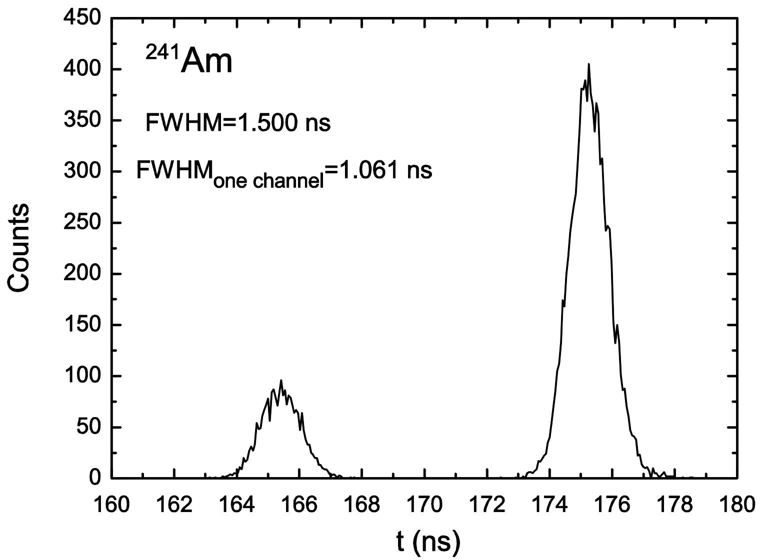
16 channel **MEGAMP**: (SA+CFD+TAC) modules that allow a sequentially read out of both energy and timing information by means of a fast multiplexer circuit

C. Boiano et al, 2012 IEEE NSS 2012

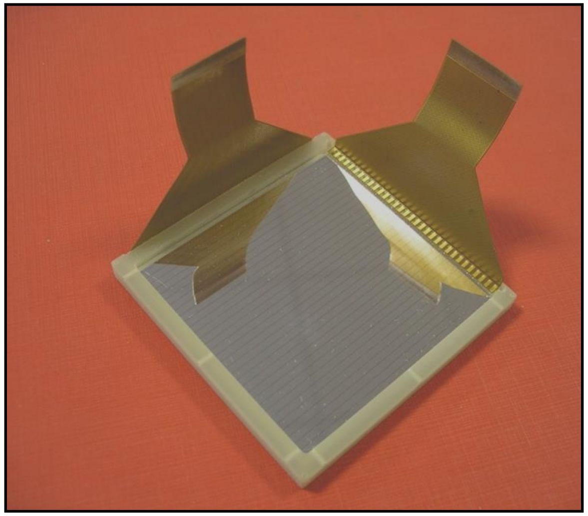
FWHM ΔE=38 (34 intrinsic) keV for E=5.6805 MeV

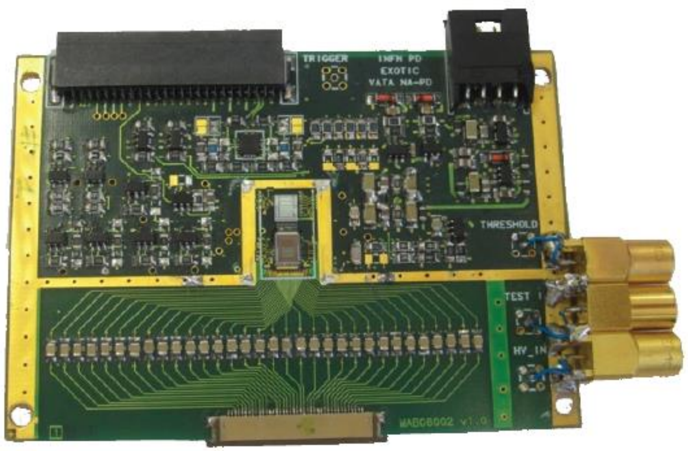
ΔE/E= 0.65%

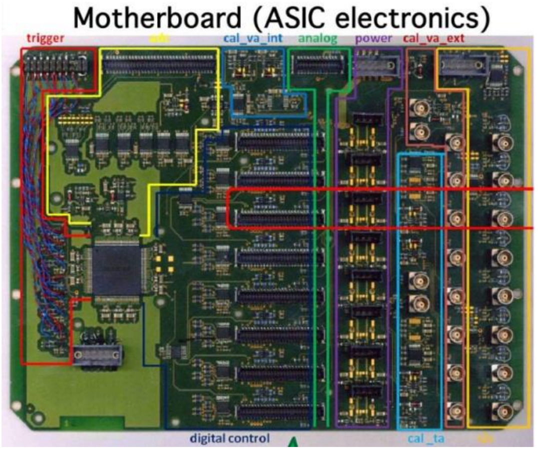
FWHM Δt (FWHM): 1 ns (71 ps from the CFD module)
For the overall chain DSSSD+electronics



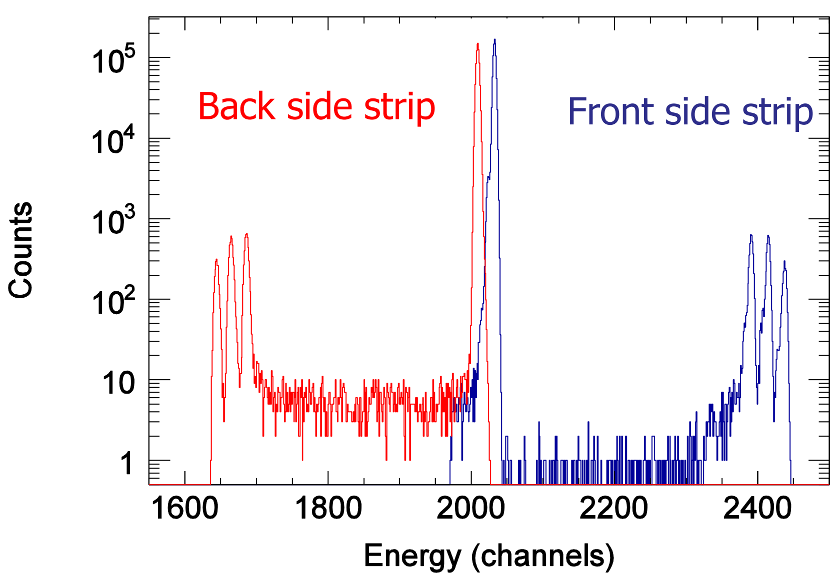
EXPADES E_{res} stage 300 μm DSSSD

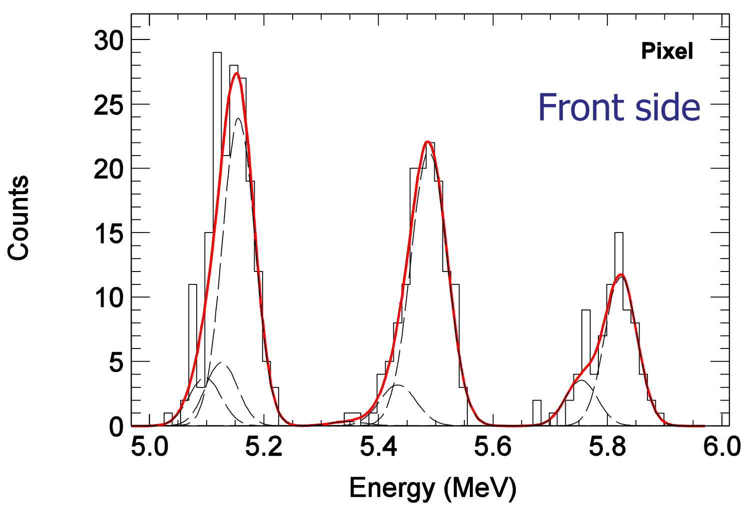






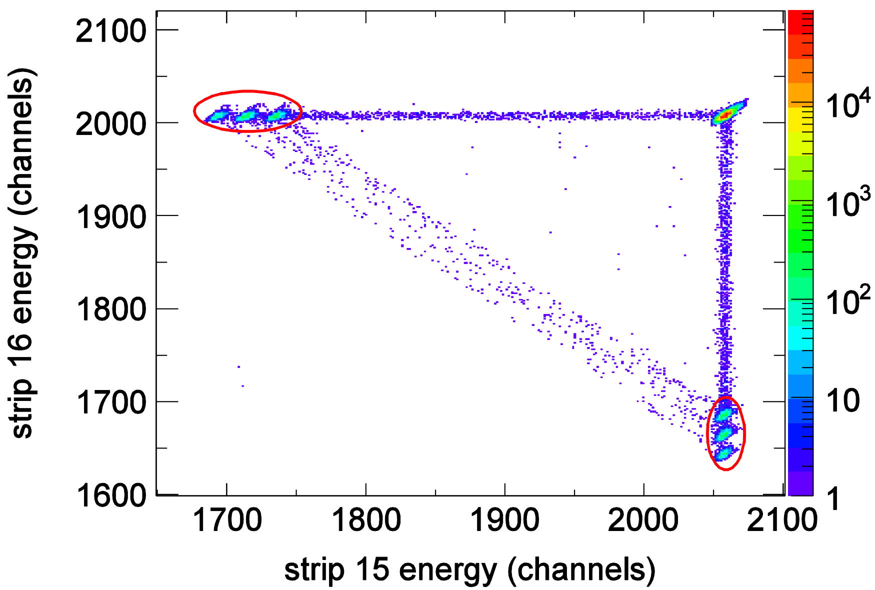
Innovative readout electronics by means of an 32-channel ASIC chip manufactured by IDEAS-GM (Norway) dedicated to the treatment of the linear and the logical part of the electronic signals coming from the detector strips.

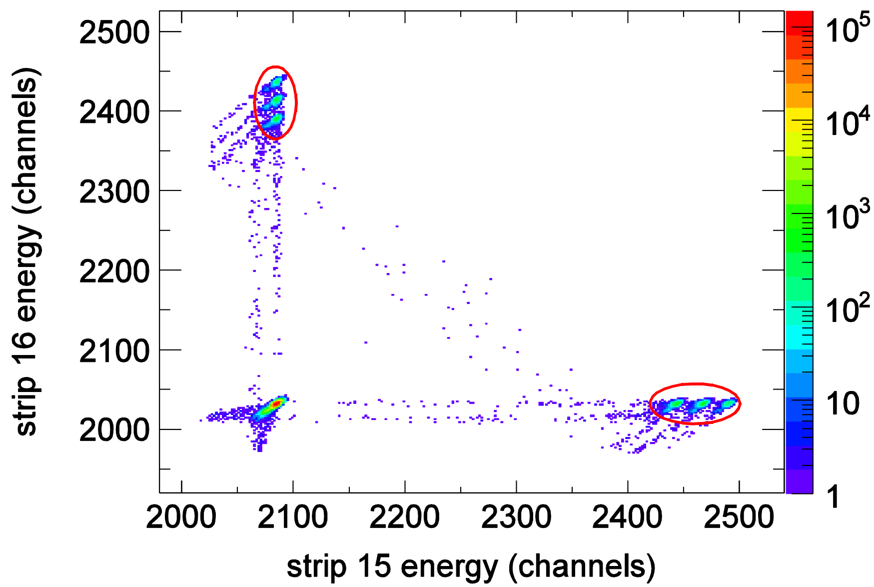




EXPADES E_{res} stage 300 μm DSSSD: interstrip events

^{239}Pu - ^{241}Am - ^{244}Cm





``full energy events": particles entering the detector through the central region of a strip and producing in this strip a full energy signal and no signal in the adjacent one

interstrip events: particles entering the detector through the region of separation between two adjacent strips. The behaviour of front and back interstrip events is in agreement with that observed in previous works [D. Torresi et al., Nucl. Instr. and Meth. A 713 (2013) 11]

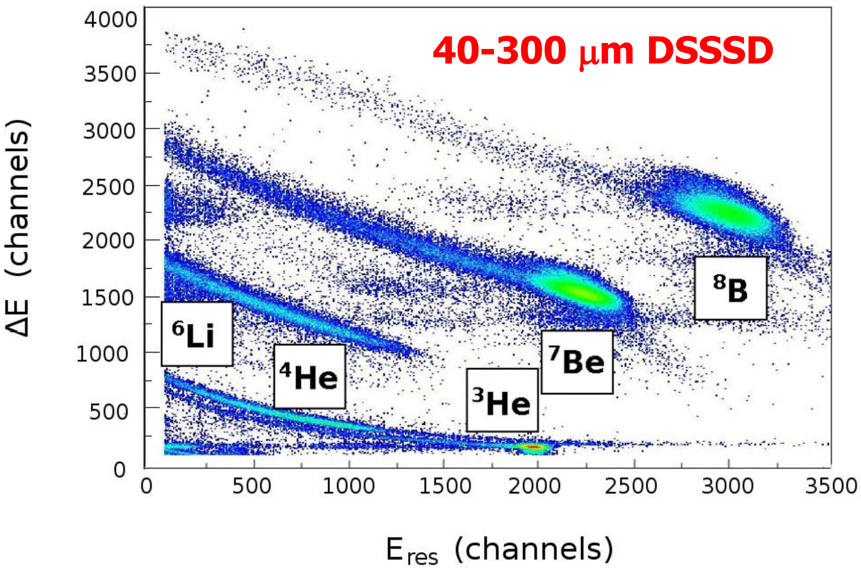
For the **back side**, just charge sharing is observed, i.e. the full energy of the event can be recovered summing the signal of the two adjacent strips.

For the **front side** this operation is not possible due to the generated opposite polarity signals.

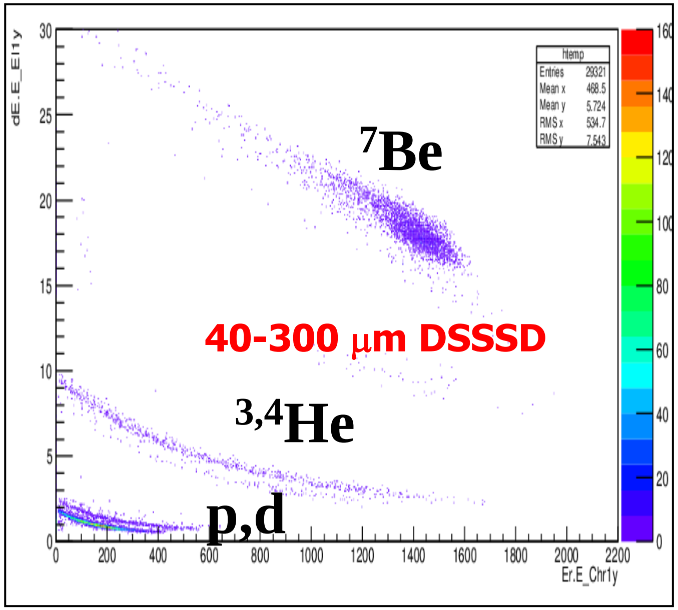
In the data analysis, the imposed condition requires that the full energy of the event be equal for the front and the back sides.

EXPADES: particle identification

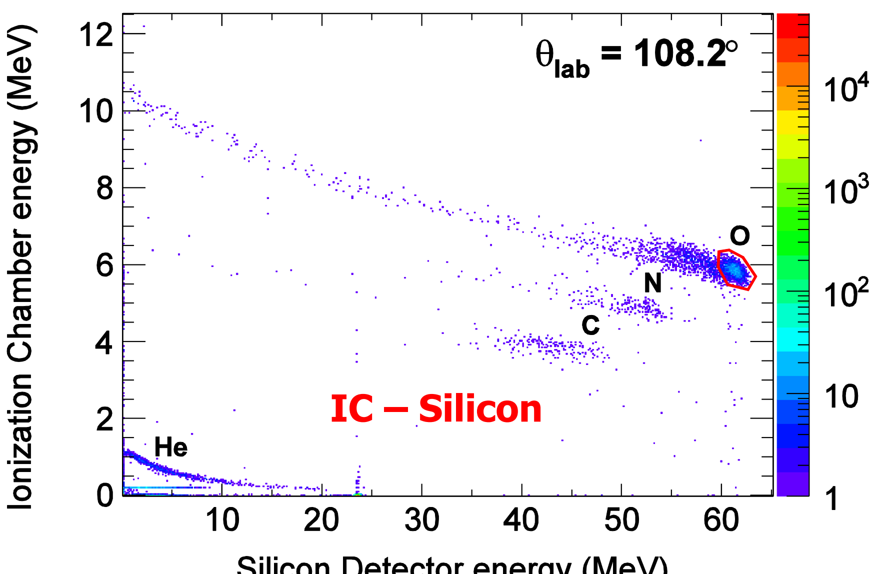
$^{8}B + ^{208}Pb$ at CRIB (RIKEN, Japan)



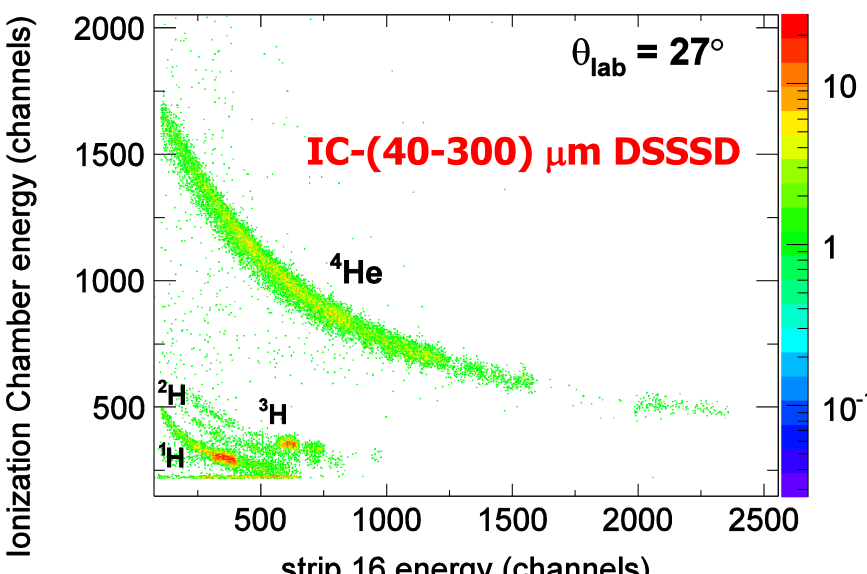
$^{7}Be + ^{208}Pb$ at EXOTIC



$^{17}O + ^{208}Pb$ at LNL

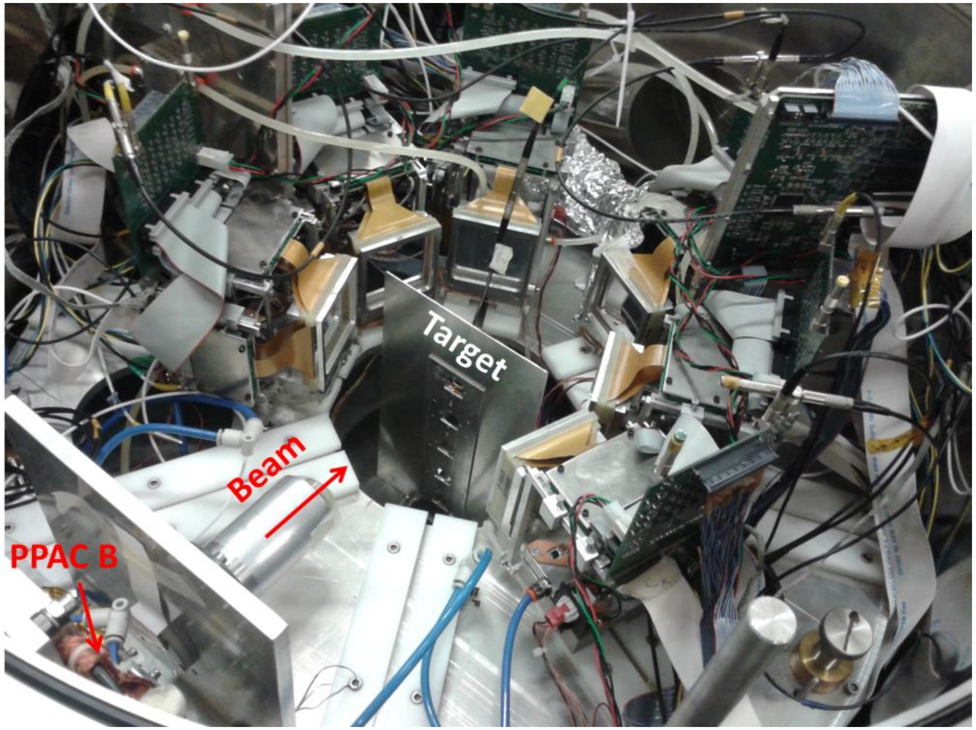


$^{7}Li + ^{12}C$ at EXOTIC

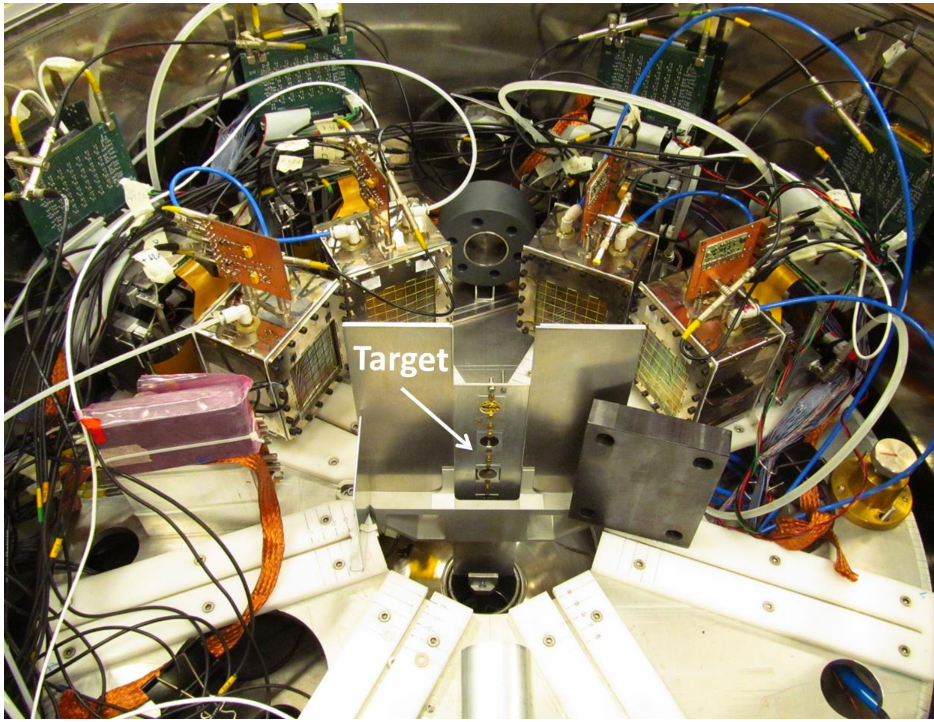


EXPADES configurations

6 two-stage DSSSD telescopes



4 three-stage IC-DSSSD telescopes



EXPADES was installed at the focal plane of the EXOTIC facility in June 2013 and has been used in various configurations for experimentation.

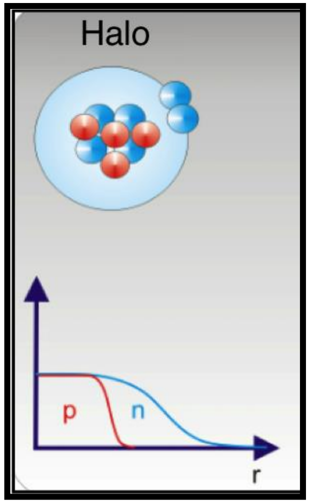
Upgrade : 1.5 μm-thick DSSSD for the detection of more energetic particles in addition or in alternative to the 300 μm-thick E_{res} DSSSDs.

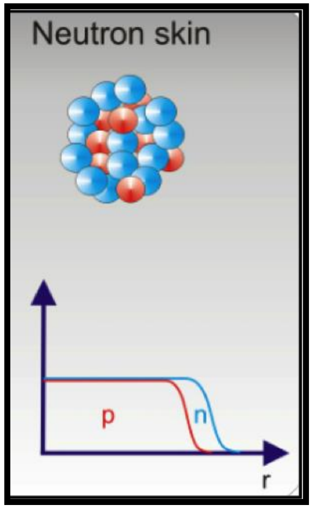
EXPERIMENTS @ EXOTIC (1)

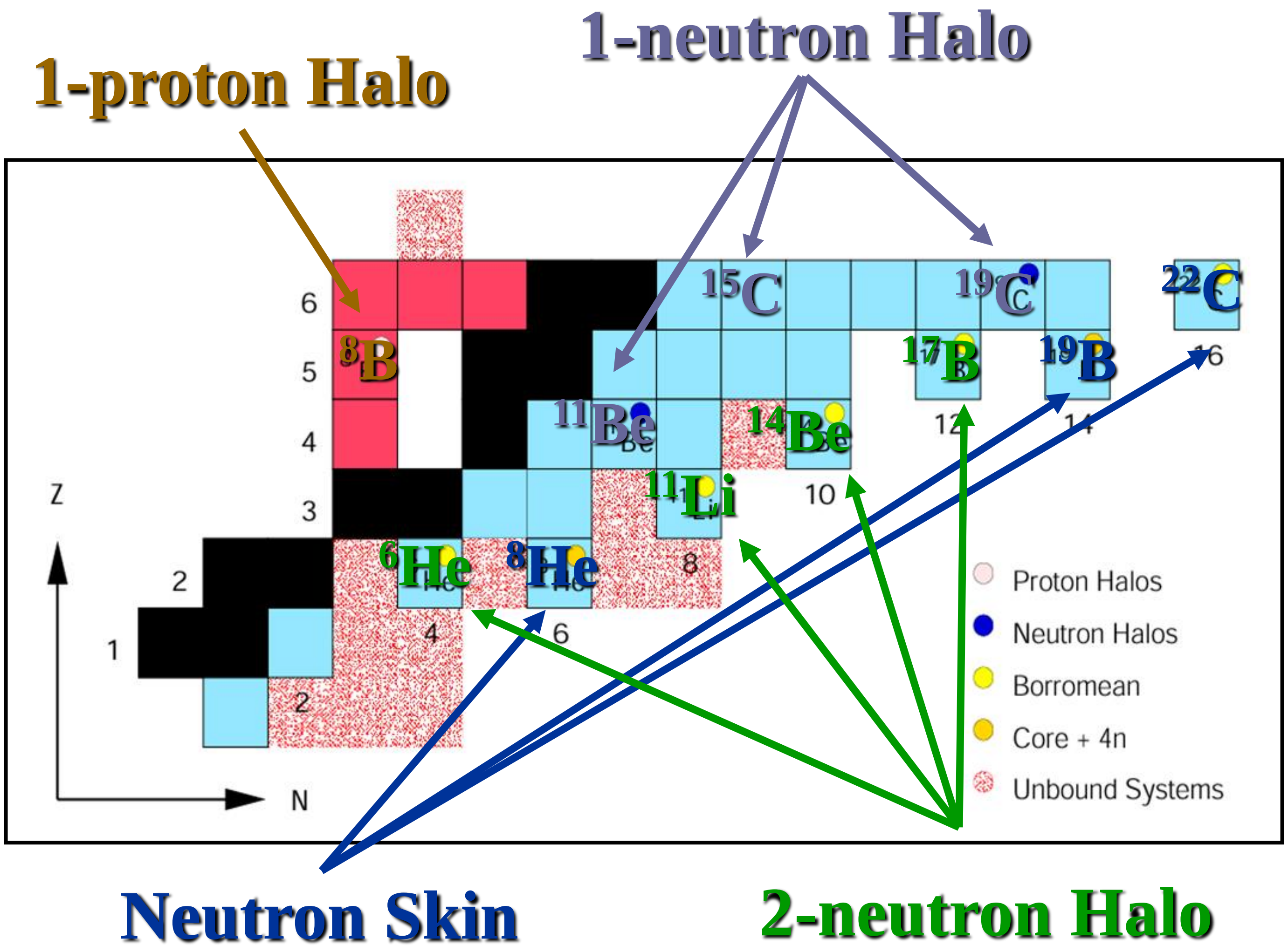
Light Exotic nuclei: reaction dynamics at near and sub-barrier energies

Light Exotic nuclei

The light portion of the nuclide chart is full of **weakly-bound nuclei** with **unusual** matter distributions (**halo** and **neutron skin** nuclei).



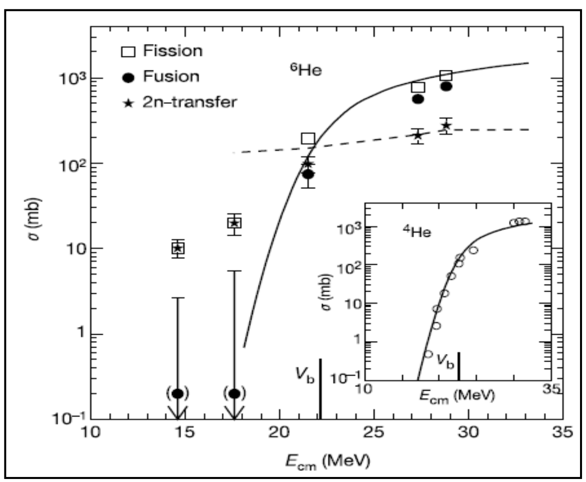




Reaction dynamics at near and sub-barrier energies: Overview of recent results

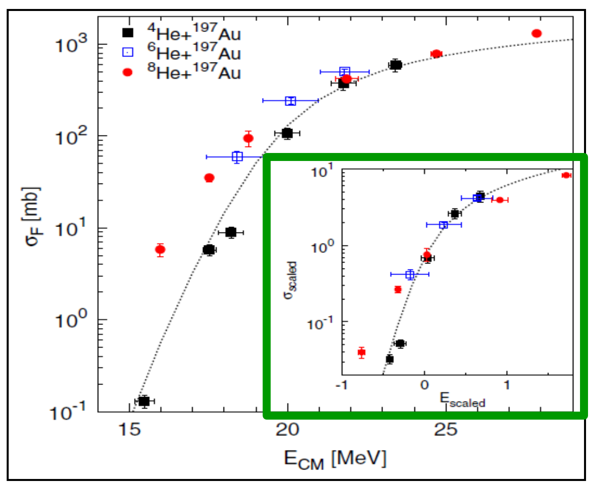
Due to the **peculiar features** of the light exotic nuclei, **new phenomena** are expected to appear in their reaction dynamics with target nuclei at Coulomb barrier energies with respect to those met with well bound encounters:

- **Large reaction cross section** with target nuclei at sub-barrier energies mostly due to **direct processes** (n-transfer for ^{6,8}He, breakup for ^{11}Li and ^{8}B)
- **Strong Coupling Effects** (^{11}Li and ^{11}Be)**:** elastic scattering angular distribution differs from the expected classical Fresnel scattering pattern or deviates from the Rutherford one below the barrier
- **Very moderate sub-barrier fusion enhancement.**



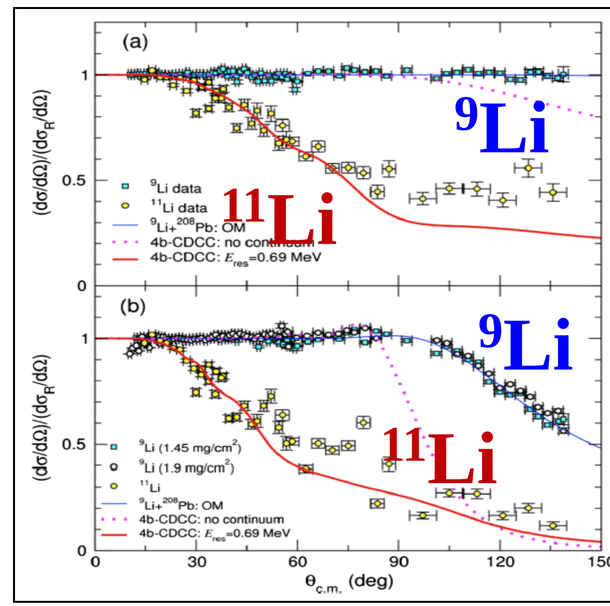
^{6}He + ^{238}U

R. Raabe et al., Nature 431 (2004) 823



^{8}He + ^{197}Au

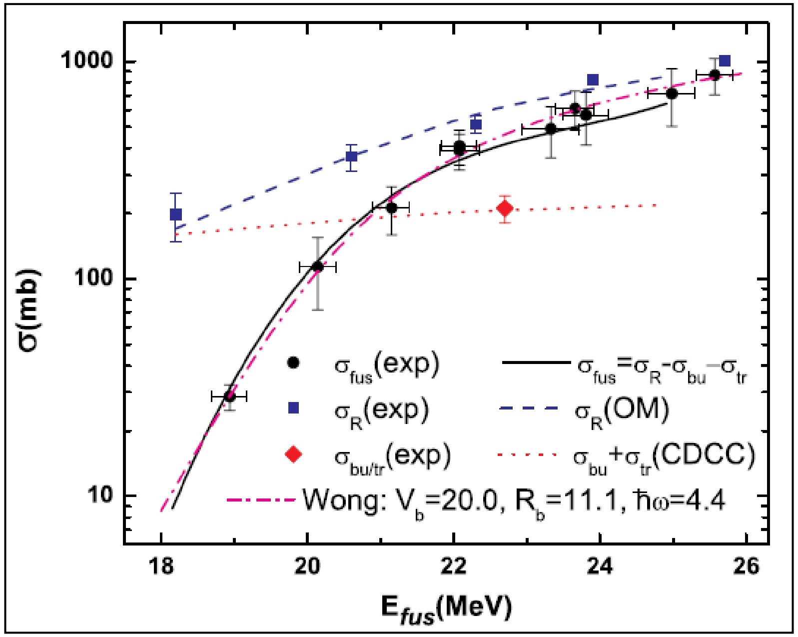
A. Lemasson et al., Phys. Rev. Lett. 103 (2009) 232701



^{11}Li + ^{208}Pb

M. Cubero et al., Phys. Rev. Lett. 109 (2012) 262701

Reaction dynamics at near and sub-barrier energies: Overview of recent results

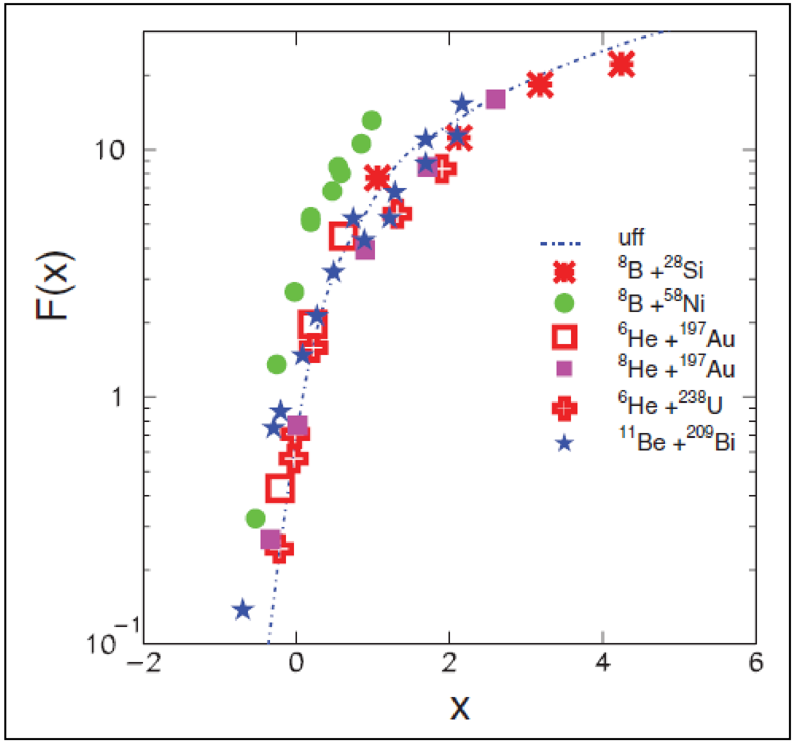


$^{8}B+^{58}Ni$ (Notre Dame, USA): Fusion **enhancement** above and below the Coulomb barrier.

E.F. Aguilera et al., PRL 107 (2011) 092701

Fusion estimated from **proton evaporation** at backward angles.

J. Rangel et al., Eur. Phys. J. A 49 (2013) 57



$^{8}B+^{28}Si$ (EXOTIC, Italy) Fusion measured with the active target technique: **agreement with systematics (UFF)**.

A. Pakou et al., Phys. Rev. C 87 (2013) 014619

^{7}Be (S_{α} = 1.586 MeV, $T_{1/2}$ = 53.22 d g.s. $J^{p}=3/2^{-}$)

Nucleus	Breakup Threshold (MeV)
^{7}Be	1.6
^{6}Li	1.48
^{7}Li	2.45

^{7}Be is the mirror weakly bound radioactive nucleus of **^{7}Li** with a well-pronounced **^{3}He+^{4}He** cluster structure.

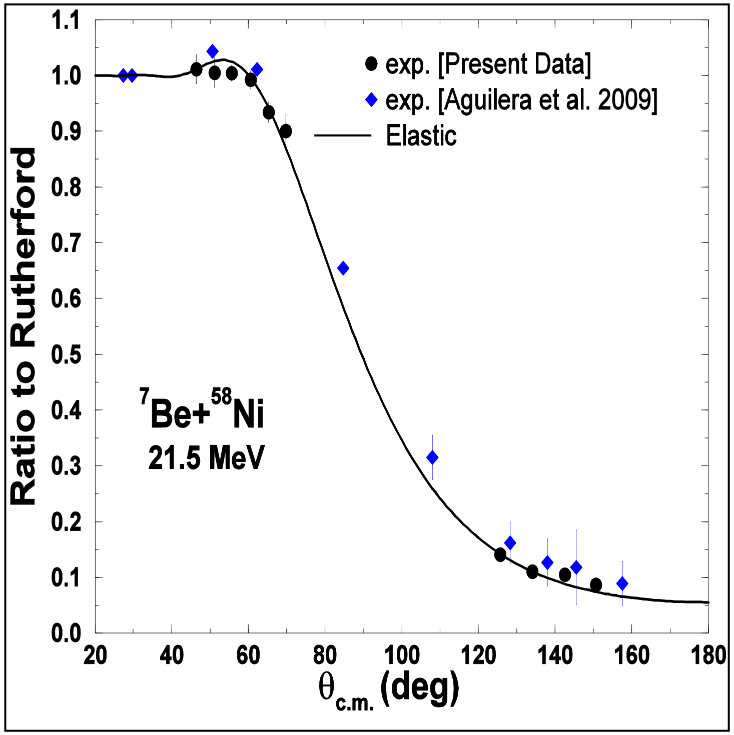
^{7}Be breakup threshold in **^{3}He+^{4}He** is similar to that of the weakly bound **^{6}Li.**

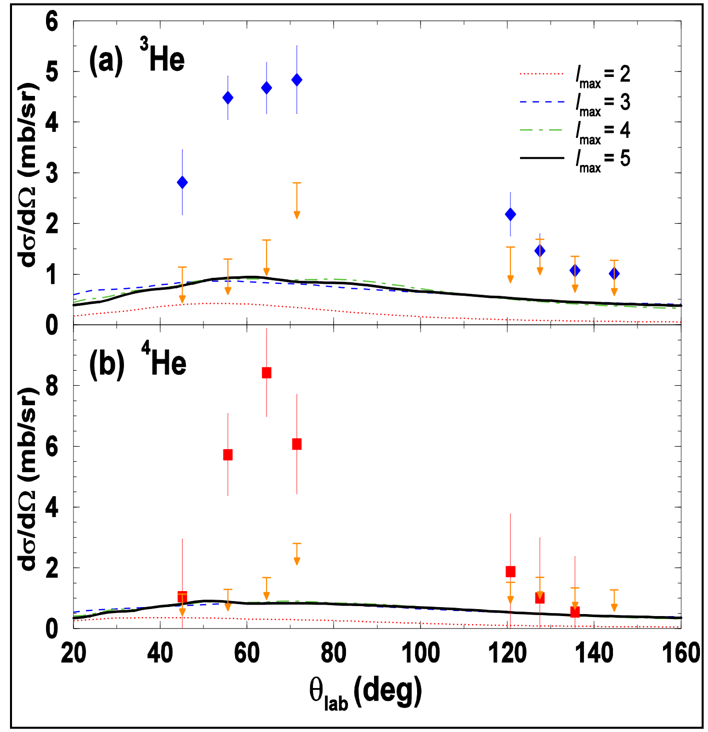
Interesting to study:

- **Elastic scattering** of ^{7}Be: does it behave like the **^{7}Li** or **^{6}Li** one?
- **Reaction mechanisms: ideal case** (among all light ions) where the **interplay** between **different reaction mechanisms** at Coulomb barrier energies can be easily addressed quite in detail.

From ^{7}Be+ ^{58}Ni .....to ^{7}Be + ^{208}Pb @ EXOTIC

DINEX array for charged particles





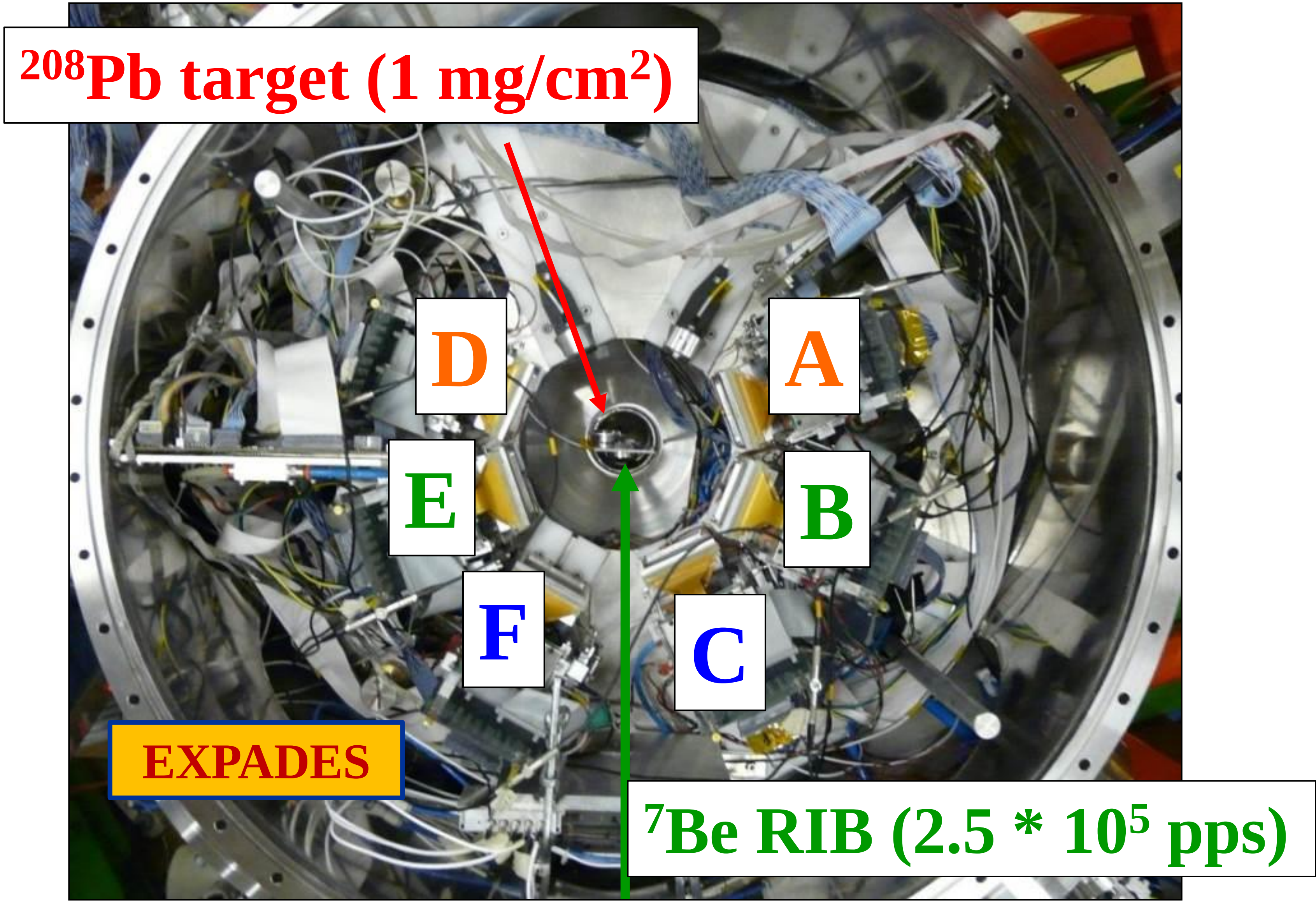
Elastic Scattering: agreement with an **earlier measurement** by E.F. Aguilera and collaborators [Phys. Rev. C. 79, 021601(R) (2009)].

Direct Processes: larger production of ^{4}He than ^{3}He. **No coincidences detected** [M. Mazzocco et al., Phys. Rev. C. 92, 024615 (2015)].

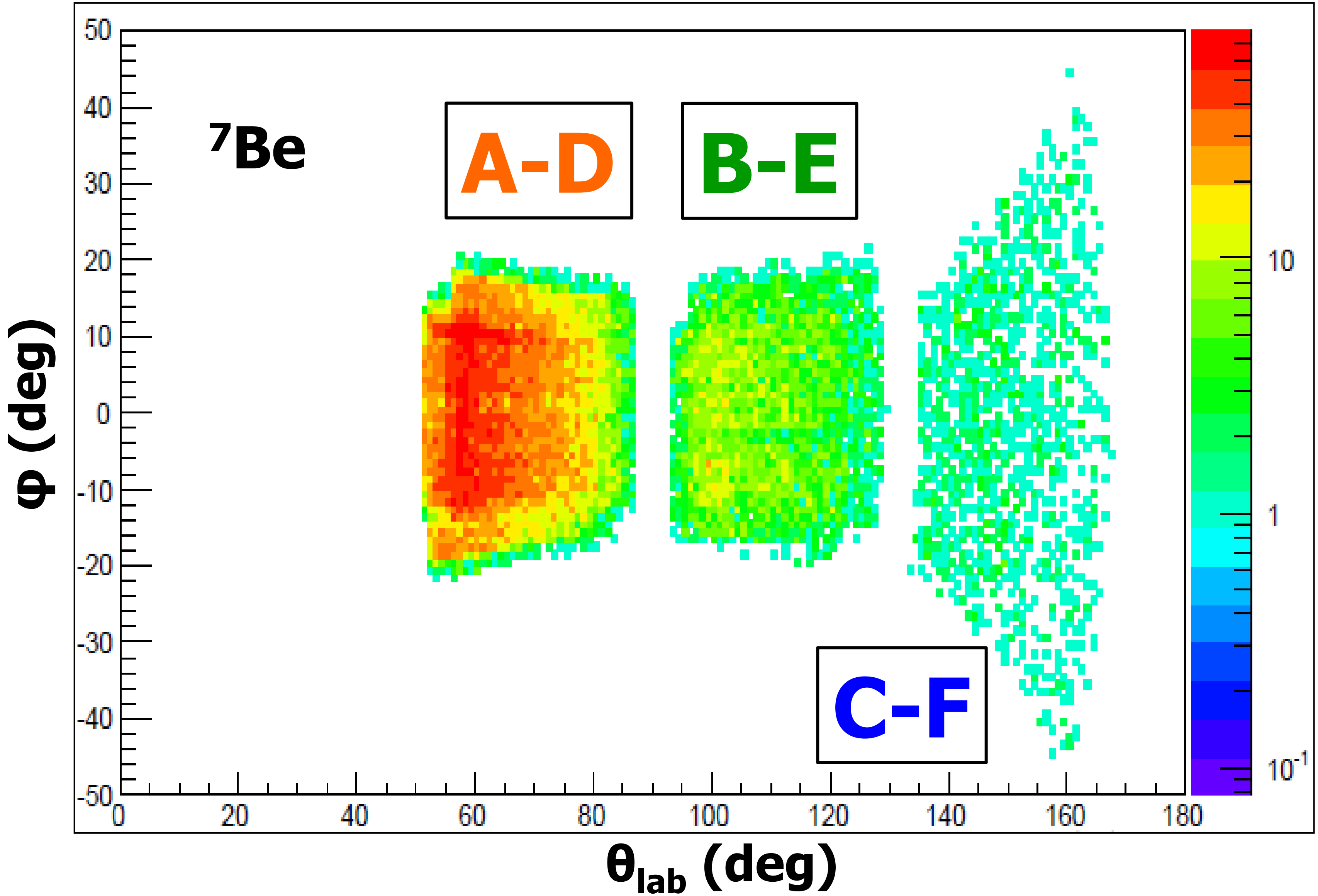
^{7}Be + ^{208}Pb **Never Measured Before!** **Goal**: to Detect Coincidences

$^{7}Be + ^{208}Pb$ @ EXOTIC

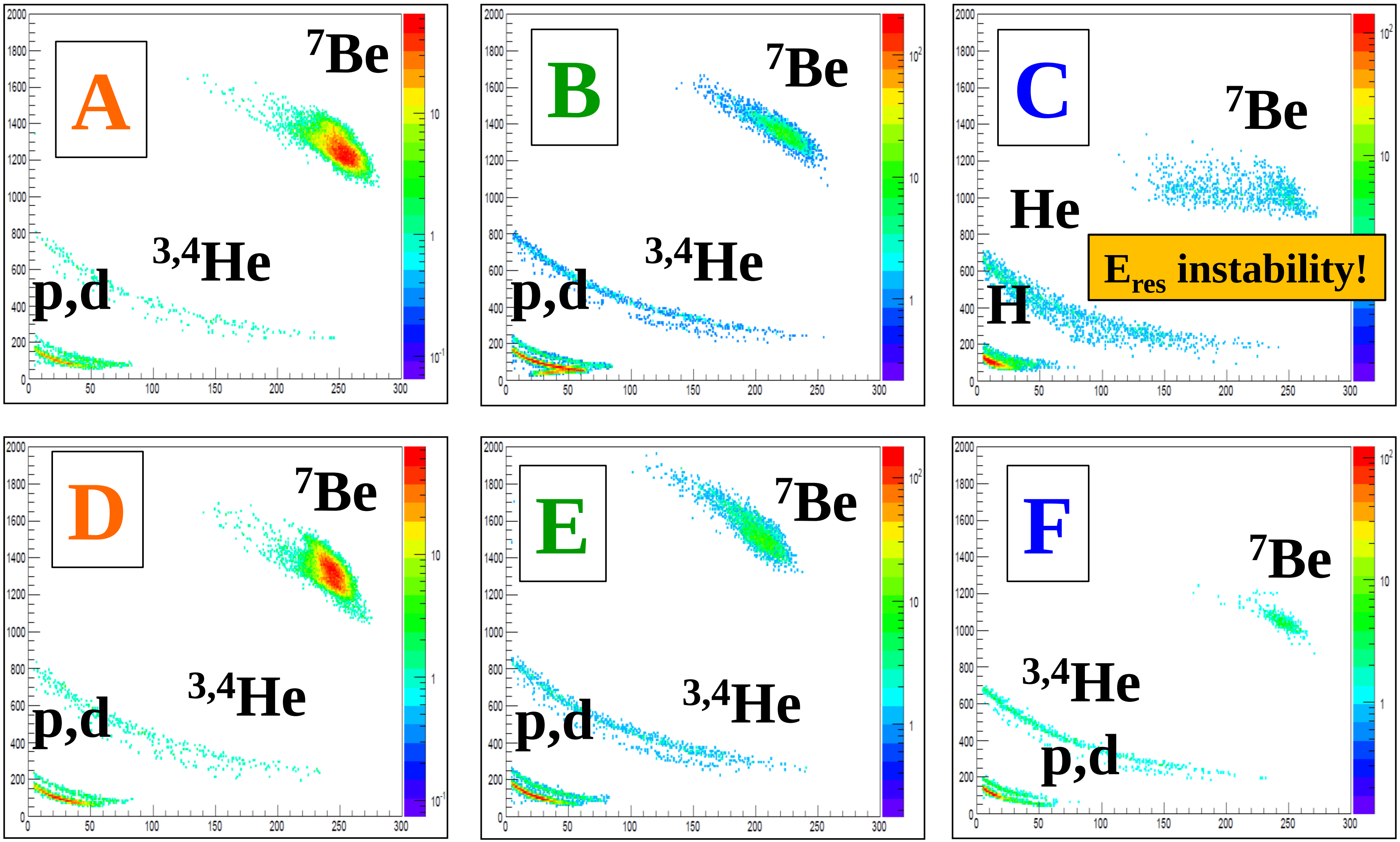
Spokespersons: M. La Commara, L. Stroe, M. Mazzocco



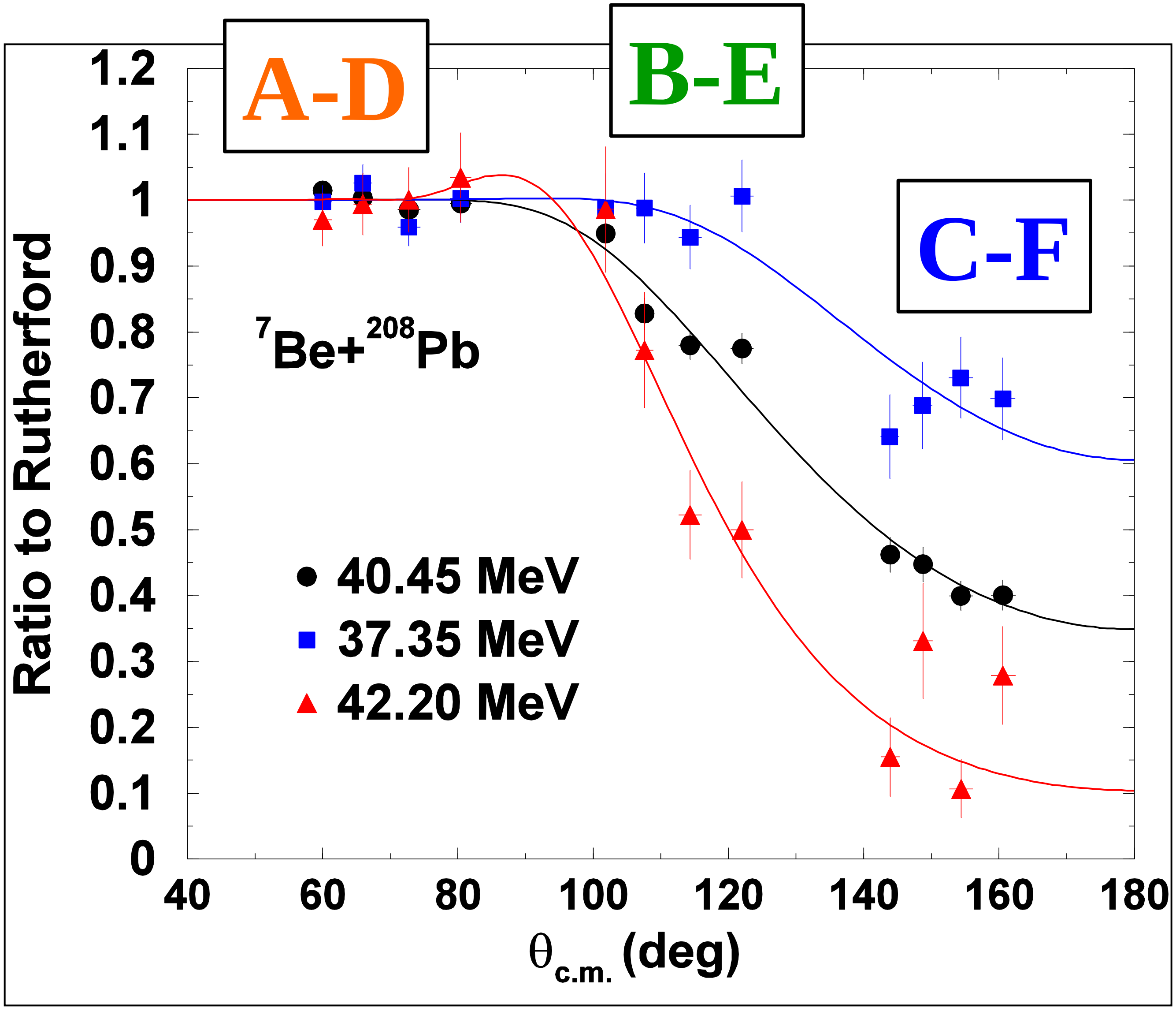
Solid Angle Coverage (Scattering)



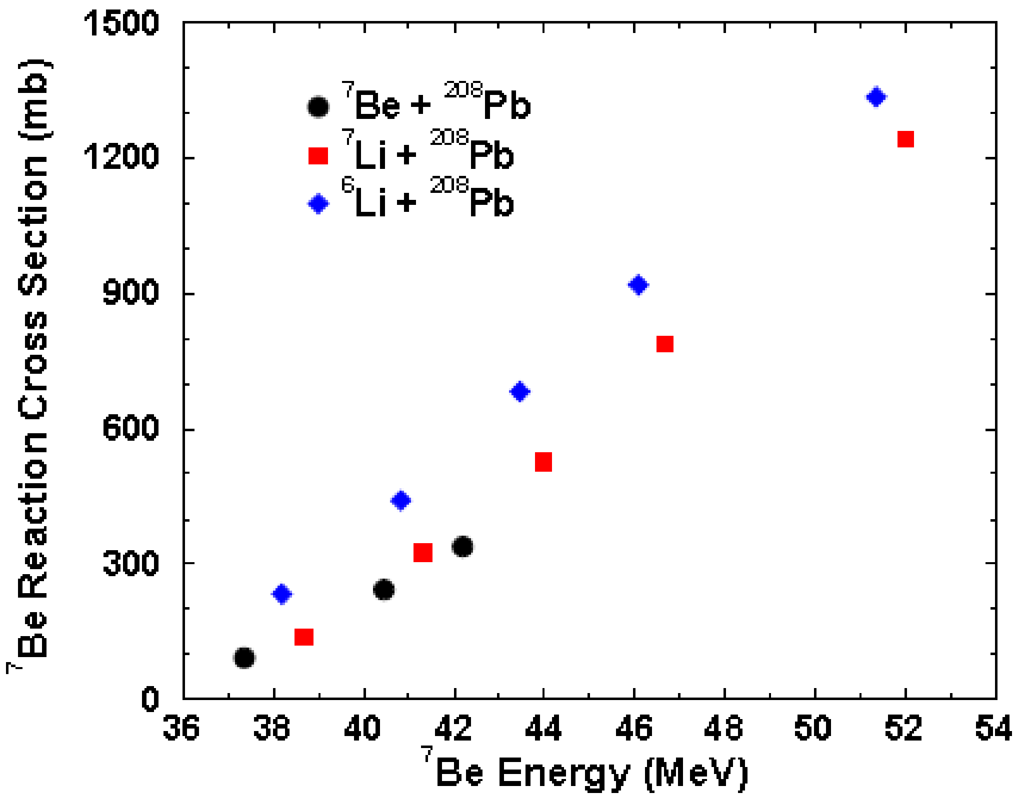
ΔE-E_{res} Plots



(Quasi-) Elastic Scattering

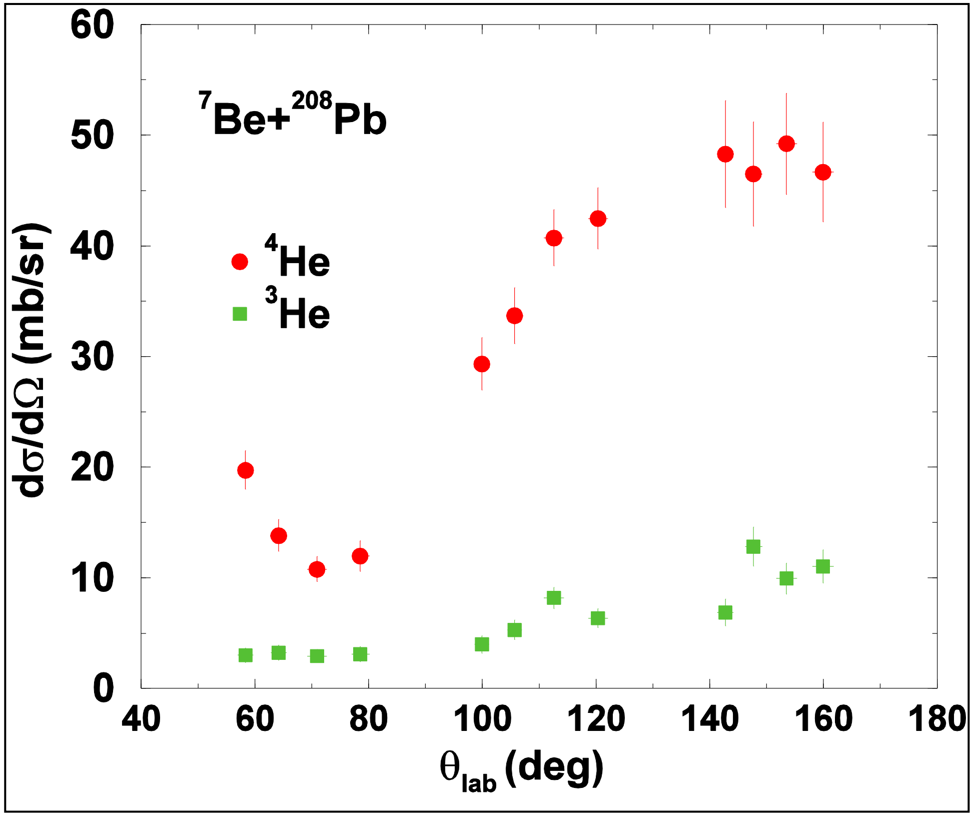


Total Reaction Cross Section



A preliminary **optical model best-fit analysis** of the quasi-elastic scattering angular distributions suggests for **^{7}Be (S_α = 1.586 MeV)** a **behaviour** more similar to **^{7}Li (S_α = 2.468 MeV)** than to **^{6}Li (S_α = 1.475 MeV)**.

^{3,4}He Production

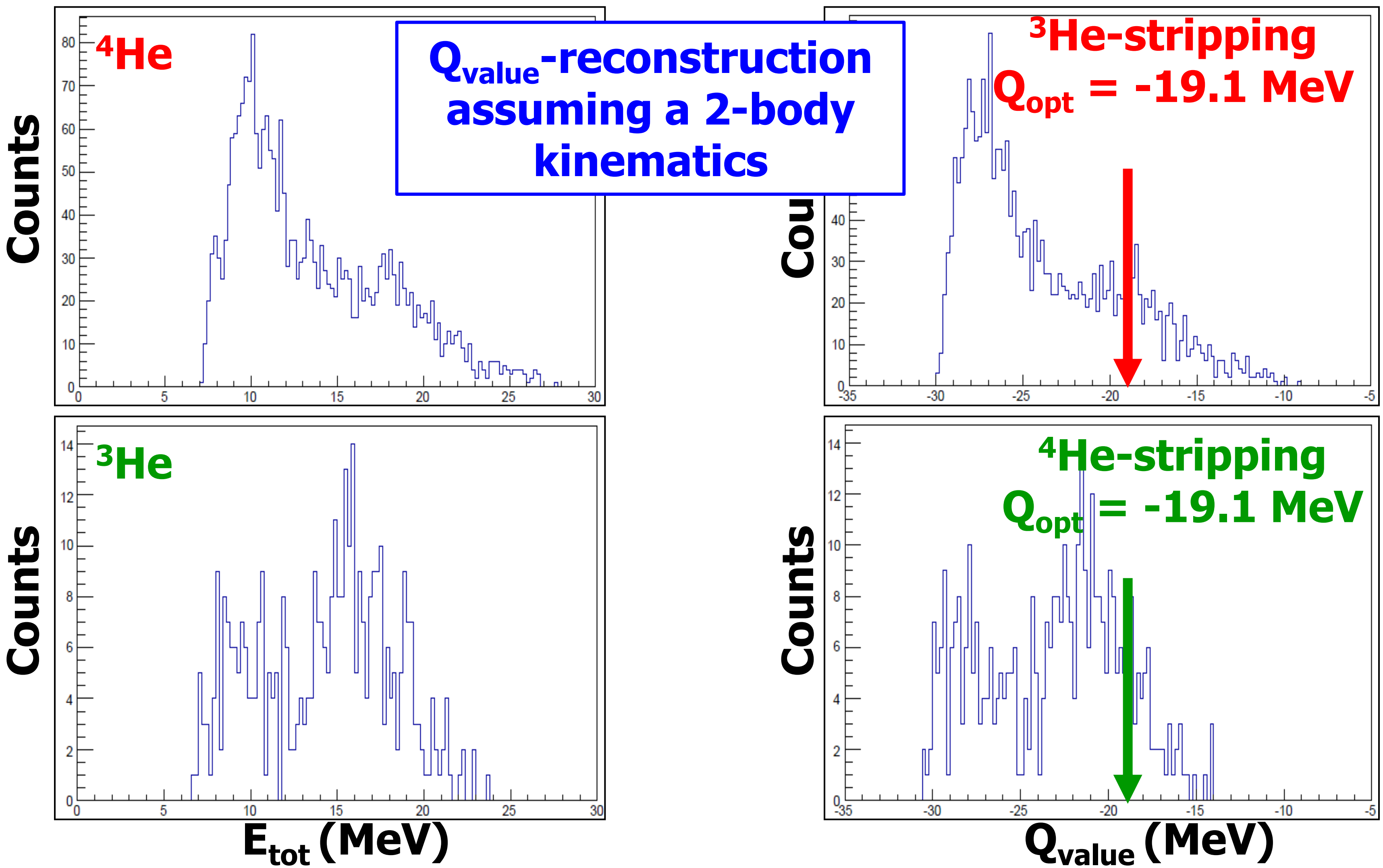


^{3}He and **^{4}He** have significantly different yields, thus the **breakup** process **does not dominate the reaction dynamics**.

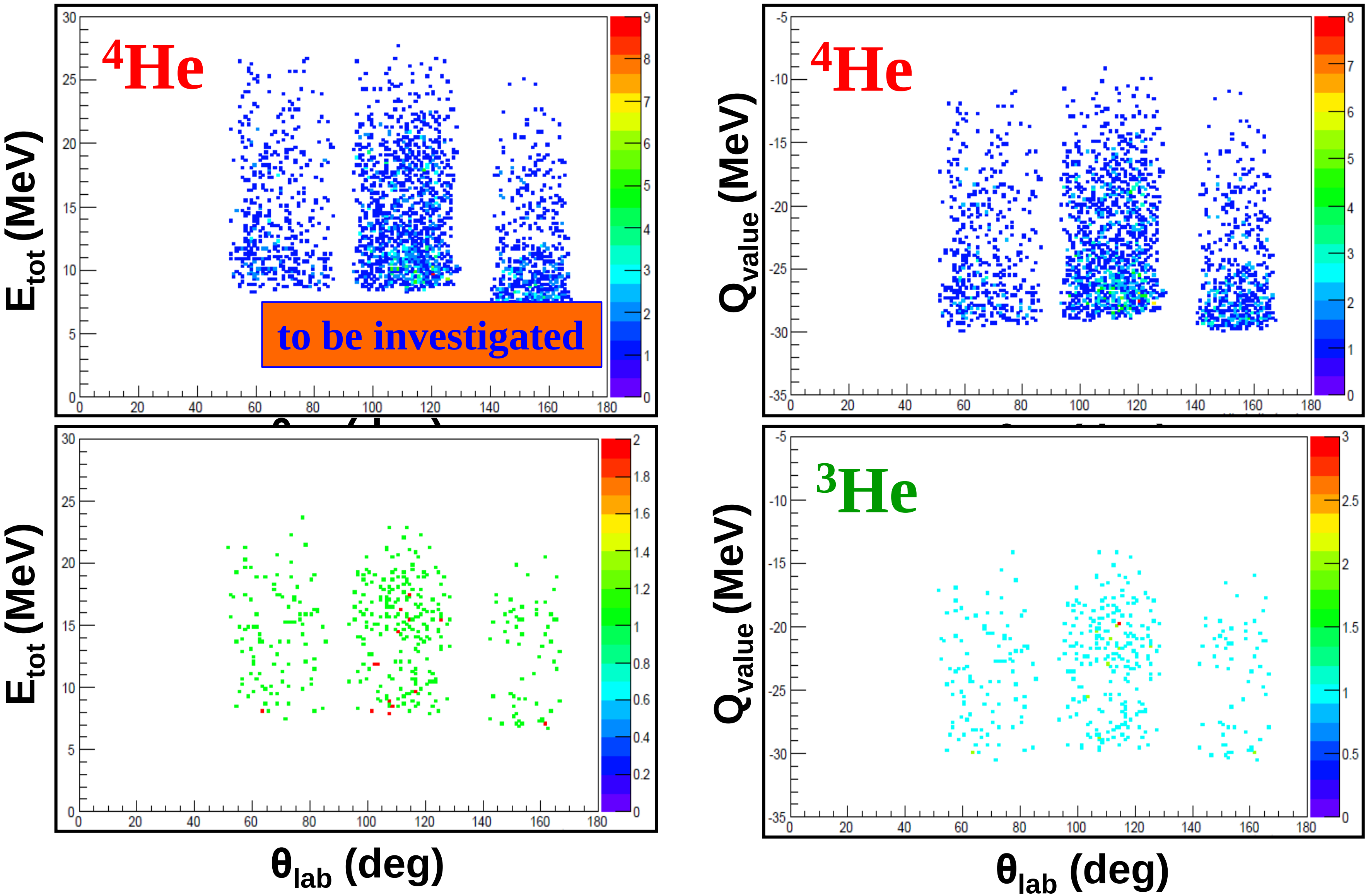
The **^{4}He** production yield is much larger than the **^{3}He** production yield, **qualitatively confirming** our previous result for the system **^{7}Be + ^{58}Ni** [Phys. Rev. C 92, 024615 (2015)]

What is the Origin of $^{3,4}He$?

^{3}He (97.5%) and ^{4}He (99.5%) mostly come as **single events**.



E/Q_{value} *vs.* θ_{lab} 2D-correlation



What About Coincidences?

We detected a few !!!

(19) - ^{3}He + ^{4}He: Exclusive Breakup
(S_{α} = 1.586 MeV)

(19)- ^{4}He + ^{4}He (^{8}Be): n-pickup
$^{7}Be + ^{208}Pb \rightarrow ^{8}Be + ^{207}Pb$ (Q_{gg} = 11.53 MeV)

(13) - ^{4}He + ^{2}H: p-stripping
$^{7}Be + ^{208}Pb \rightarrow ^{6}Li + ^{209}Bi$ (Q_{gg} = -1.81 MeV)

(17) - ^{4}He + p: d-stripping (?)
$^{7}Be + ^{208}Pb \rightarrow ^{5}Li\ (^{4}He+p) + ^{210}Bi$ (Q_{gg} = -2.87 MeV)
Or n-stripping ?
$^{7}Be + ^{208}Pb \rightarrow ^{6}Be\ (^{4}He+2p) + ^{209}Pb$ (Q_{gg}=-6.74 MeV)

A **detailed kinematical analysis** is needed to investigate the possible origin of the **detected coincidences**

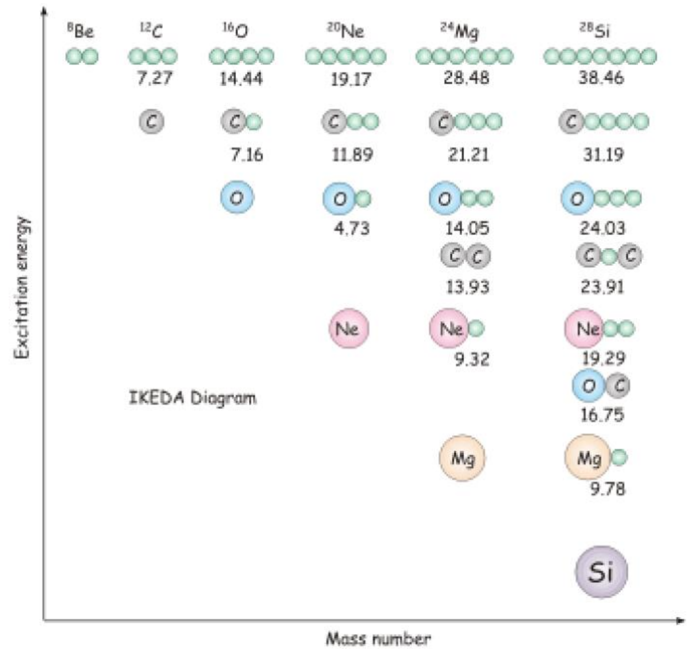
The data analysis is going on….

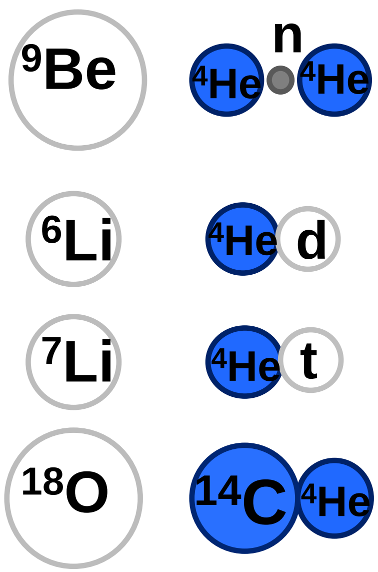
EXPERIMENTS @ EXOTIC (2)

Search for exotic nuclear clustering

Clustering in nuclei

α clustering manifests itself in α-conjugate nuclei through the existence of twin quasi-rotational bands of states of alternating parities and large α-particle width.





Also non α-conjugate nuclei manifest cluster configurations like ^{6}Li and ^{7}Li or ^{9}Be

Exotic Clustering in nuclei

How the clustering evolves going out of the stability valley?

It is expected that light exotic nuclei may show cluster configurations where at least one of the clusters is unbound or weakly bound, thus not satisfying the strong internal correlation requirement of classical clusters. This is the **exotic clustering regime**, that was claimed to become more and more favoured for nuclei approaching the drip-lines.

Search for ^{15}O-α configurations associated to ^{19}Ne excited states @ EXOTIC

Spokespersons: D. Torresi, C. Wheldon

The experimental technique called Thick Target Inverse Kinematics method (TTIK) was employed to study the elastic scattering of the system ^{15}O+^{4}He, never measured before.

✓ Measurements of the elastic scattering excitation function

✓ R-matrix analysis for the extraction of

- Energy and width of the resonances
- Reduced α-width

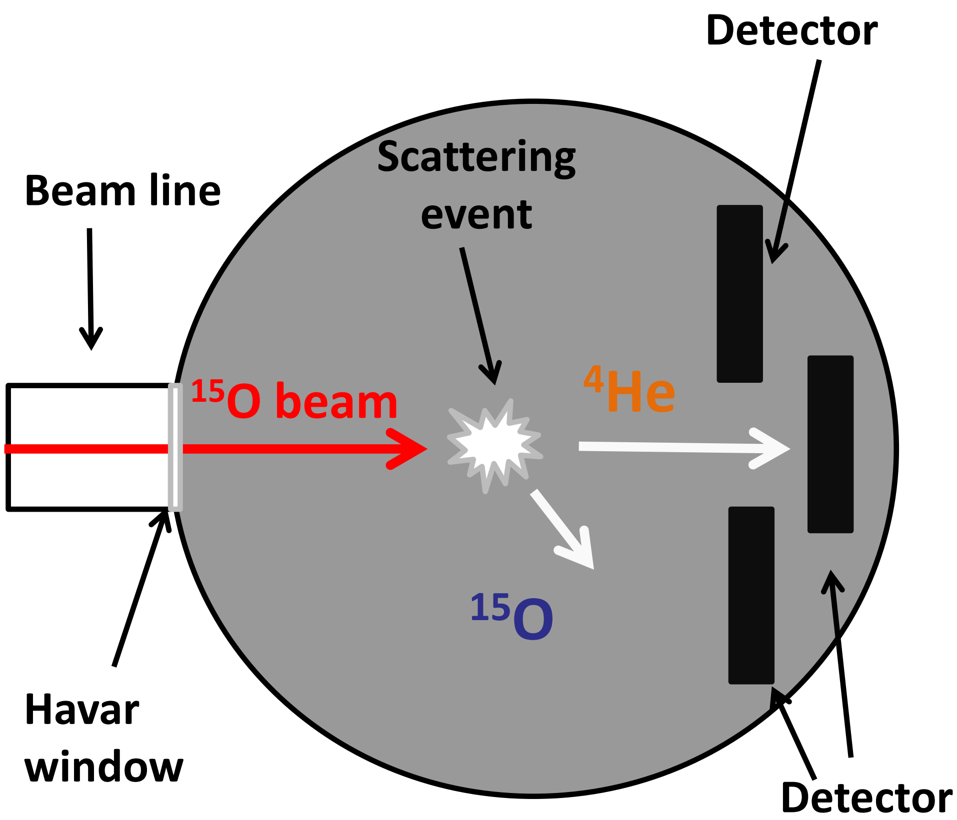
Why ^{19}Ne?

1. A number of Ne isotopes manifest evidences of clustering phenomena. This makes the ^{19}Ne a good candidate to manifest cluster structures.
2. The structure of low-lying levels in ^{19}Ne near the ^{15}O+^{4}He and p threshold in ^{19}Ne are important: their study can improve our knowledge on the ^{15}O(α,γ) ^{19}Ne and ^{8}F(p,α)^{15}O reaction rate of astrophysical interest.

The Thick Target Inverse Kinematics (TTIK) Method

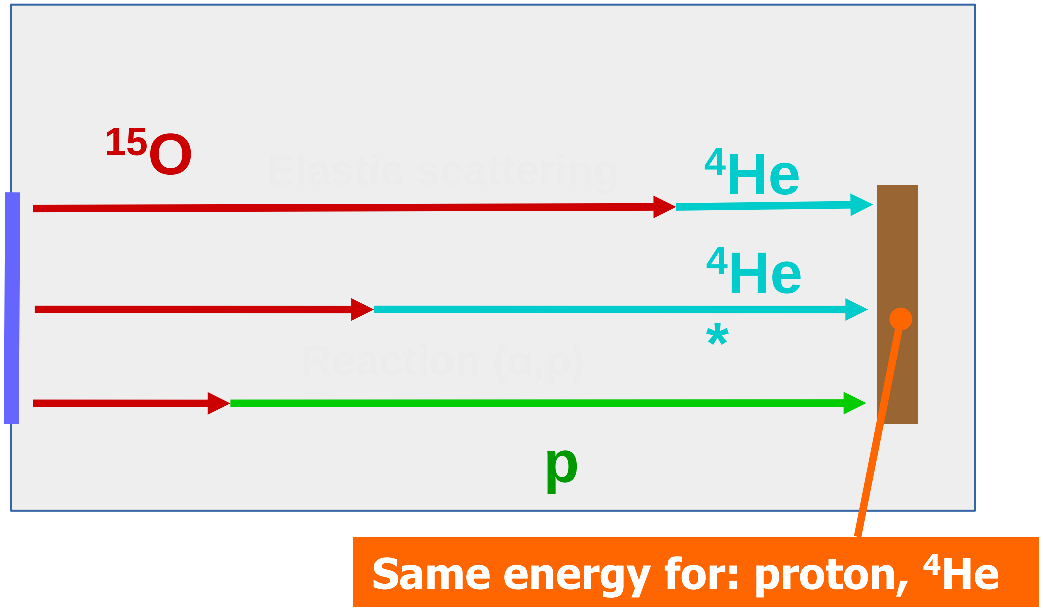
K. P. Artemov et al., Sov. J. Nucl. Phys. 52, 408(1990)
G. Rogachev PhD thesis

Measurements of elastic scattering excitation function in a wide range of energies using a single beam energy. Suitable for low intensity beams.



- ✓ The chamber is filled with gas at such a pressure to stop the beam
- ✓ The beam slows down into the gas
- ✓ Elastic scattering occurs at different positions in the chamber
- ✓ Detectors placed at 0° and around detect the recoiling α particles
- ✓ Energy and position where the reaction occurs can be reconstructed from the energy and position of the detected α particle
- ✓ stopping power of the beam and α particle should be known

The Thick Target Inverse Kinematics (TTIK) Method: ToF



Different processes can
- **Occur at different position of the chamber**
- **Produce particles with the same energy on the detector**

But the time of flight will be different

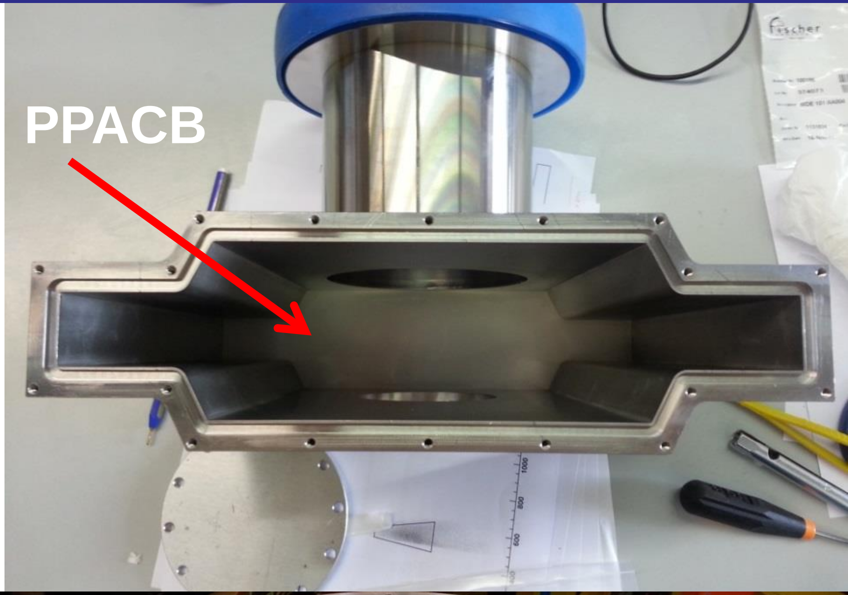
ToF:
Start: entering of the particle in the chamber
Stop: recoil of the reaction impinges on the detector

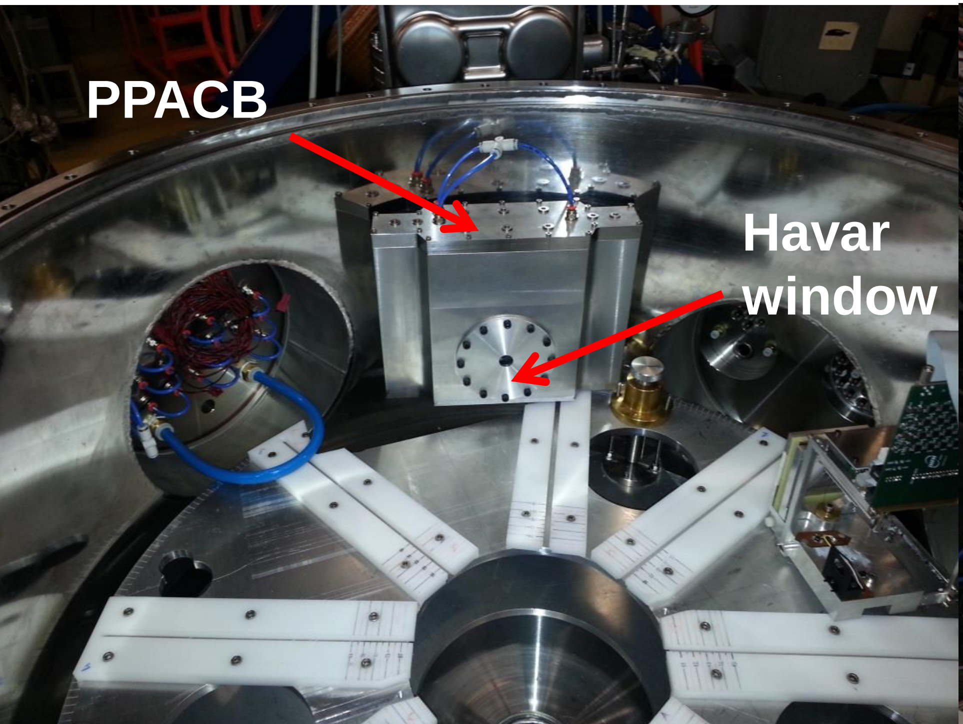
ToF measurements allow to distinguish not only different particles but also different processes!

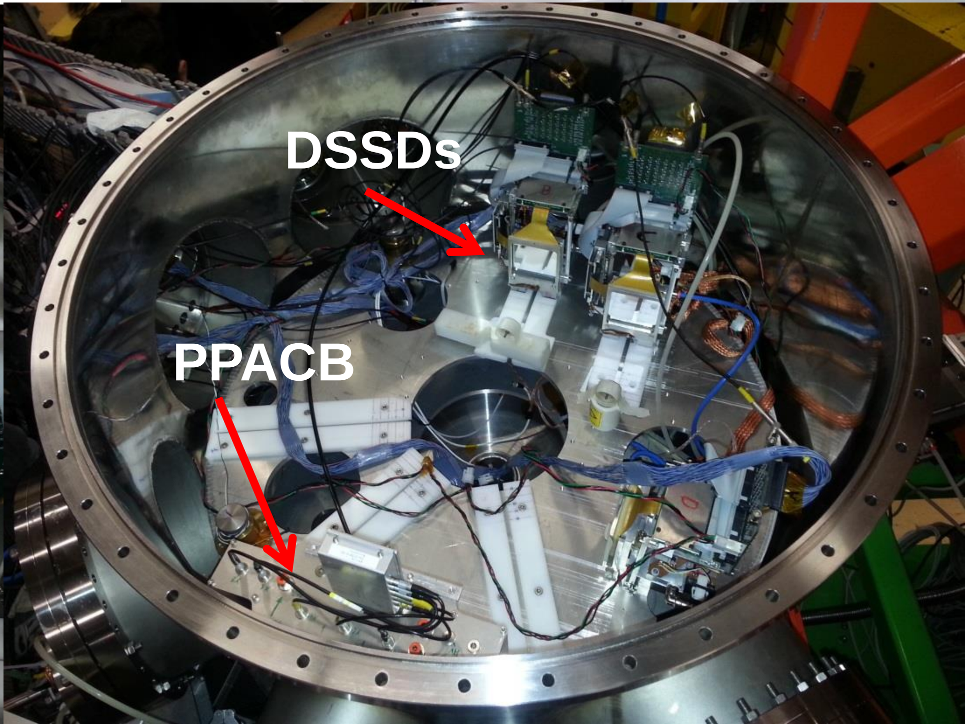
EXOTIC upgrade for experiments with reaction gas targets

Modifications of the EXOTIC beam line were performed in early 2015, to allow the realization of experiments by employing **RIBs** impinging on reaction **gas targets (thick targets)**.

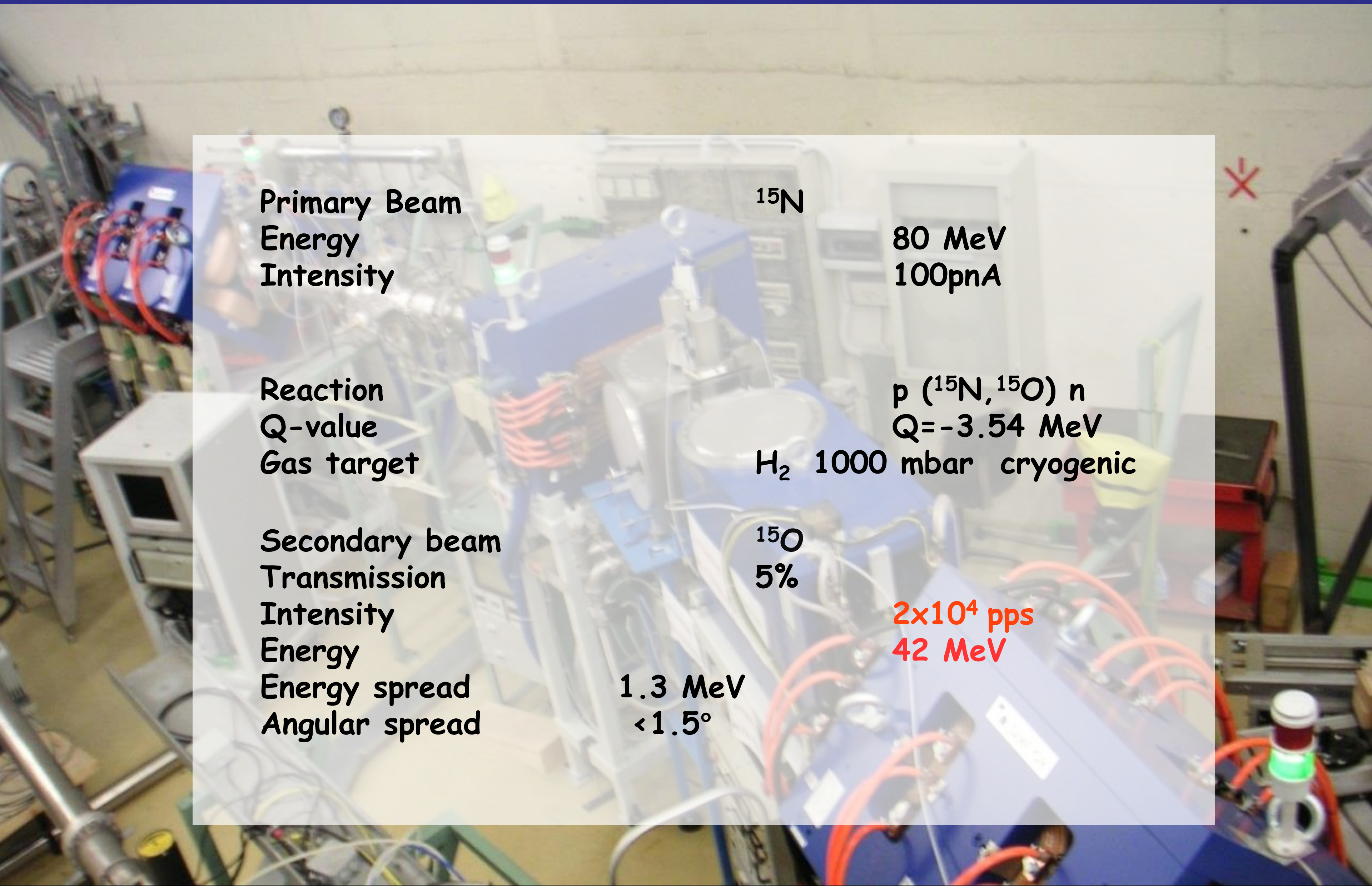
A new small chamber was built hosting the PPACB that separates, through a havar window, the scattering chamber (filled with ^4He gas) from the beam line (at high vacuum).





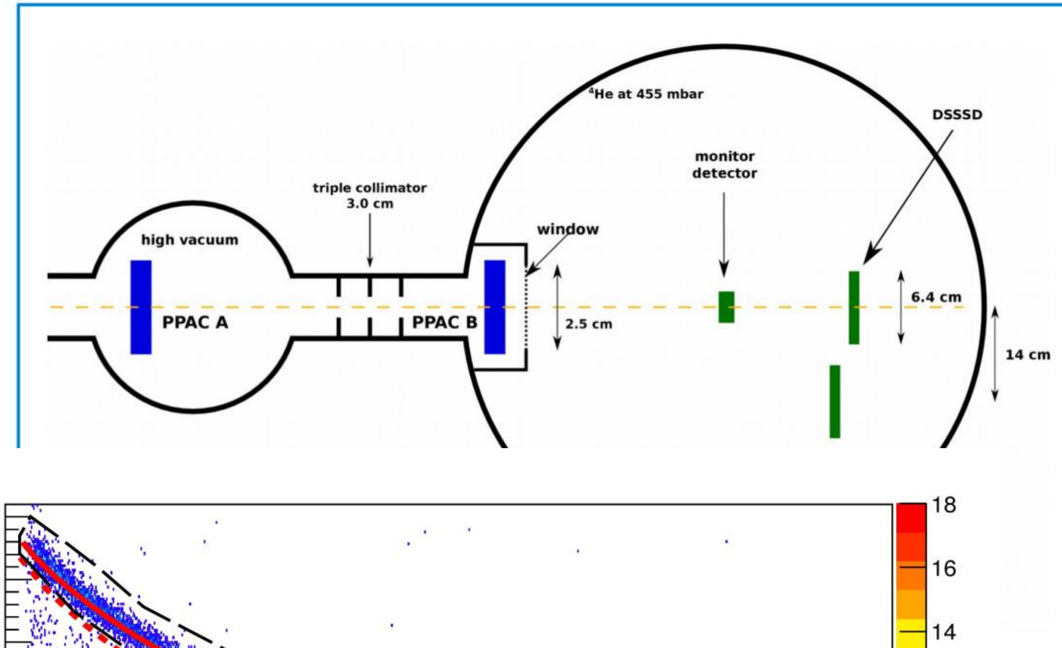


The ^{15}O Beam @ EXOTIC

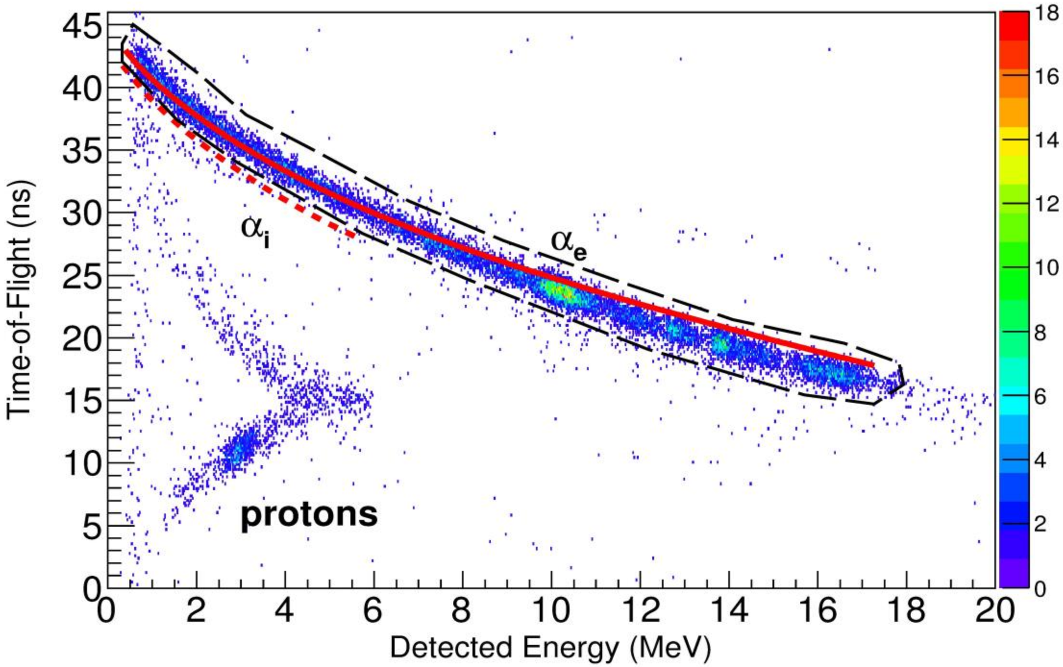


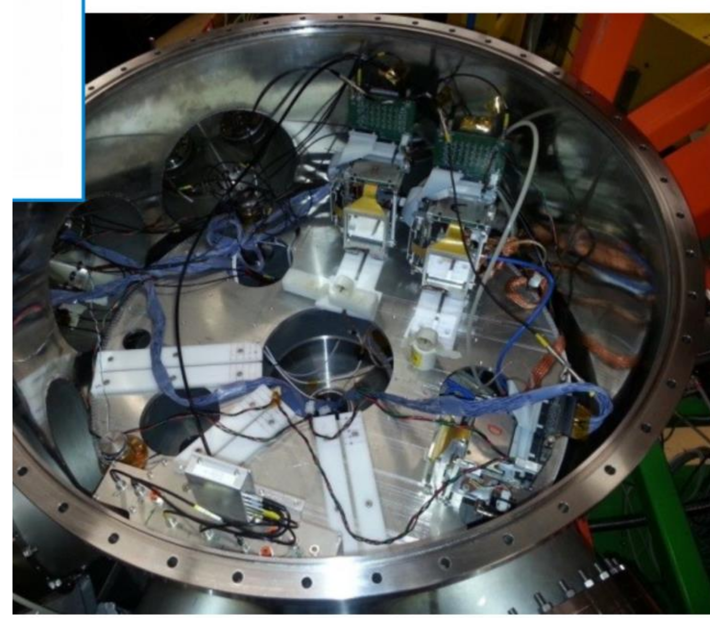
Primary Beam	^{15}N
Energy	80 MeV
Intensity	100pnA
Reaction	p (^{15}N,^{15}O) n
Q-value	Q=-3.54 MeV
Gas target	H_2 1000 mbar cryogenic
Secondary beam	^{15}O
Transmission	5%
Intensity	2×10^4 pps
Energy	42 MeV
Energy spread	1.3 MeV
Angular spread	$<1.5°$

The Experimental set-up



- **Two PPACs**: ToF, beam counting and diagnostic purposes.
- **Two DSSSDs:** recoiling detection.
- **Temperature** and **pressure** of the gas continuously monitored.



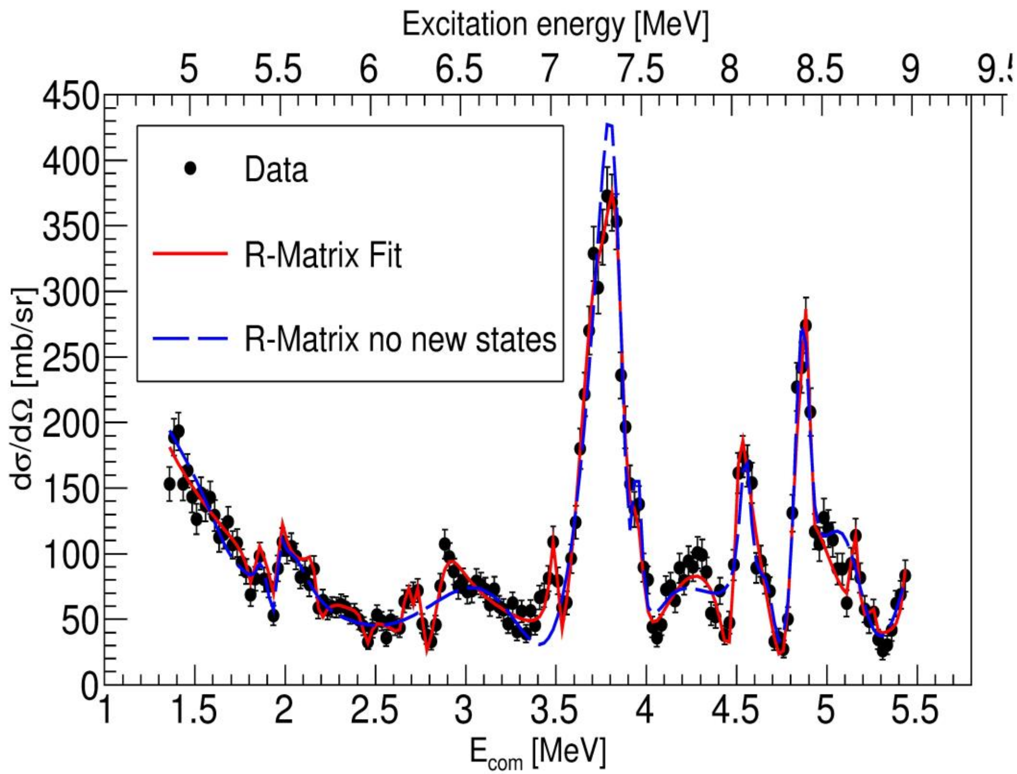


$^{15}O + ^{4}He$ Elastic Scattering Excitation Function

The R-matrix fit was performed with **AZURE2**

- Data at 180° in COM frame.
- R_0 = 1.4 fm.
- Convolution with 50 keV for experimental resolution (FWHM).
- χ^2/d.o.f. = 1.2.

E_a= 3.58 MeV
E_p= 6.41 MeV



Significant new results using *R*-Matrix formalism for resonant reactions.
– spins and parities of the states have been established
– large number of partial decay widths
- Clustering below the proton threshold suspected from previous studies confirmed by the present one

D. Torresi, XL Symposium on Nuclear Physics – January 4-7 , 2017 Cocoyoc Mexico

EXPERIMENTS @ EXOTIC (3)

Experiments with RIBs of astrophysical interest

^{7}Be(n,α)^{4}He @ EXOTIC

Spokespersons: L. Lamia, M. Mazzocco

Study of the **^{7}Be(n,α)^{4}He (Q_{value} =18.99 MeV)** reaction by applying the Trojan Horse Method (THM) that allows us to span the energy region of interest for Bing Bang Nucleosynthesis E_{cm}= 0-1.5 MeV, at which the reaction rate is still assumed with an order of magnitude of uncertainty.

Large discrepancy (about a factor 3) between predicted and observed primordial ^{7}Li abundance, essentially determined by the production and destruction of ^{7}Be nucleus.

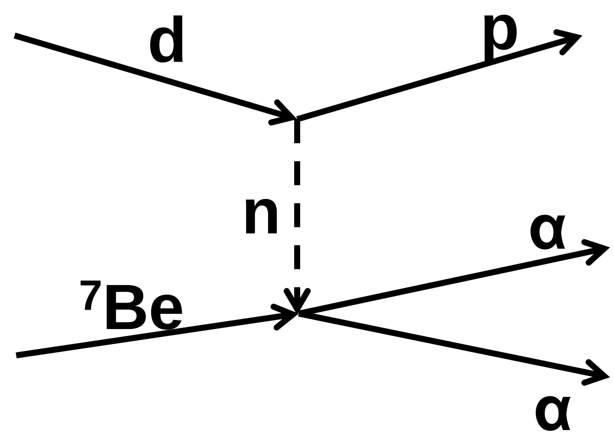
^{7}Li with E_{lab}(^{7}Li)= 34 MeV and I= 150-200 pnA
^{7}Be RIB with E_{lab}(^{7}Be)= 22 MeV with I=2*10^{5} pps
0.2 mg/cm^{2}-thick CD2 target

A **ΔE=300 keV** resolution is enough as no resonance structure is expected in the considered energy range

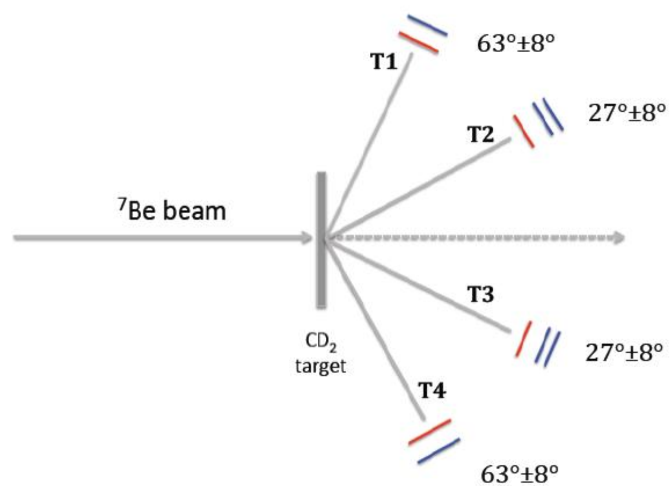
Expected statistical error around **14%** for a 150 keV bin in the center-of-mass n+^{7}Be

The data analysis is going on …

^{7}Be+d → α +α + p



EXPADES: IC- 300 μm DSSD

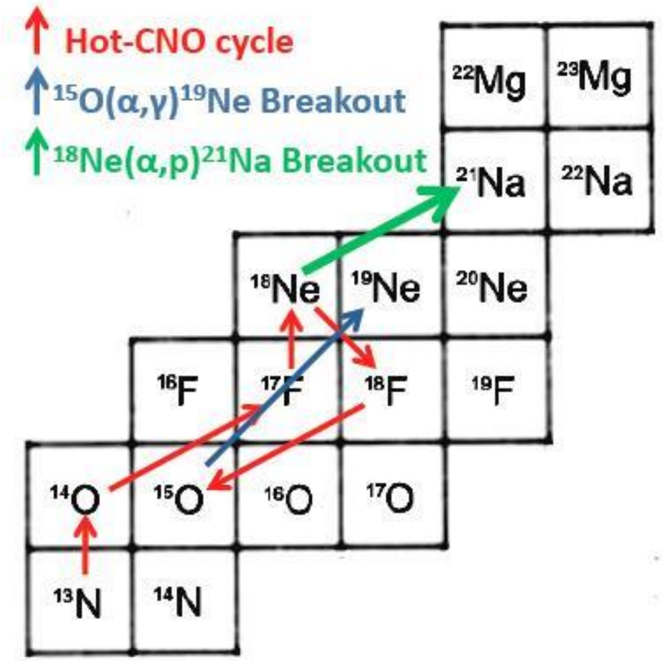


Future experiments @ EXOTIC
$^{18}Ne(\alpha, p)^{21}Na$

(Astro)physical motivation

In ambients like novae and x-ray bursts the hydrogen explosive combustion occurs through a series of reactions called **hot cycle CNO (HCNO)**
-> with a net result of a large energy production.

At T~0.75 GK a rupture of this cycle could occur, depending on the **β+** decay of **$^{18}Ne(T_{1/2}$=1.67 s)** and the capture reaction rate **$^{18}Ne(\alpha,p)^{21}Na$.** The formed ^{21}Na in this reaction constitutes the initial seed of the **rp process,** which forms elements with maximum mass around A=100.



Energies of astrophysical interest:
E_{cm} =500 keV - 2 MeV in c.m.
(E_{cm}= 1 MeV -> E_{Lab}=5.5 MeV)

$^{18}Ne(\alpha, p)^{21}Na$

- LLN:

*** Direct reaction measurement**

* 1.7 - 3 MeV c.m. (a measurement from 2 to 3 MeV and another from 1.7 to 2.9 MeV)

* I(^{18}Ne) ~10^5 pps in ~30 hours.

- ANL:

***Time inverse reaction cross section measurements**

$^{21}Na(p,\alpha)^{18}Ne$

* Energies up to 2.5 MeV c.m. (scaled for the direct reaction)

* Upper limits from 1.5 to 2 MeV in the c.m.

There is a factor of ~50 with the direct measurements at E_{cm}= 2.5 MeV!!!

-ISAC-II TRIUMF:

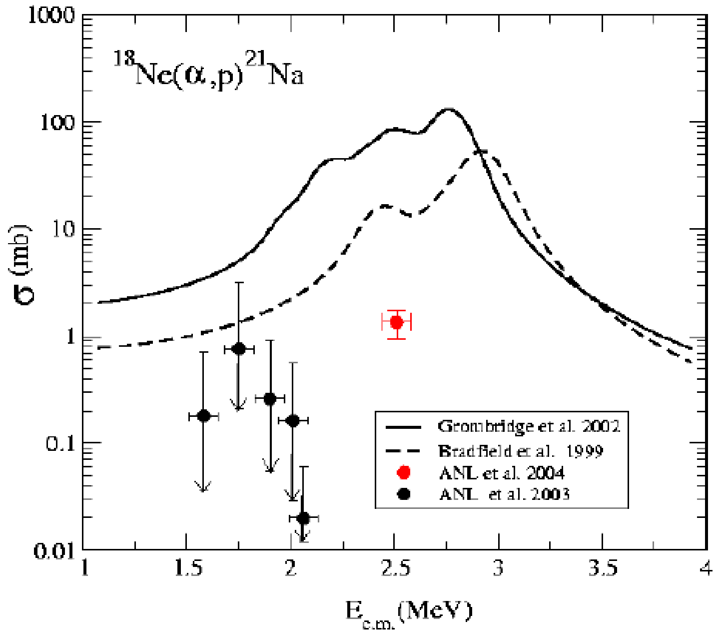
Data of a very recent measurement performed for 1.19< E_{cm} <2.57 MeV are different at E_{cm}= 2.5 MeV by a factor 25 with the LLN direct data and are a factor 2 lower with respect to Hauser-Feshbach calculations in the whole energy range

Accurate study of the direct reaction is highly desirable down to 700 keV

^{18}Ne (1.7 s) production via the reaction ^{3}He (^{16}O, **^{18}Ne**) n at E(^{16}O) = 40 MeV (50-100 pnA) and P=1000 mbar

I(^{18}Ne)=6 *10^4 pps - 3*10^5pps @ EXOTIC

Experimental set up: (40+300) μm DSSD



Solid line :
LLN from 1.7 to 2.9 MeV

Dashed line :
LLN from 2 to 3 MeV

$^{30}P(p, \gamma)^{21}Na$ at EXOTIC

(Astro)physical motivation

- This reaction influences the production of elements between Si and Ca in the explosion of O-Ne novae
- The isotopic ratio $^{30}Si/^{28}Si$ depends on this reaction (destroys the ^{30}P before decaying to a ^{30}Si)
-Anomalously high isotopic ratios $^{30}Si/^{28}Si$ measured in pre-solar grains of possible O-Ne novae origin

Existing measurements:

-Yale -> somes resonances were measured through the indirect measurement
-($^{31}P(^{3}He, t)^{31}S$) but the derived cross section has a large uncertainty

-There is also a large uncertainty in the calculation of the reaction rate

$\Rightarrow$**direct measurements with a RIB are necessary**

$^{27}Al\,(^{4}He, n)^{30}P$ or $^{29}Si\,(d, n)^{30}P$ at 50 pnA of primary beam I(^{30}P) ~10^{4}-10^{5} pps @ EXOTIC
Experimental set up: IC+DSSD 300 μm + γ scintillators

EXOTIC facility: velocity filter

Spokepersons: G. Montagnoli, A.M. Stefanini, M. Mazzocco

We performed a test of the facility EXOTIC used as a **beam separator** for detecting **Fusion Evaporation Residues** by studying the $^{32}S+^{48}Ca,^{64}Ni$ reactions.

The fusion excitation function of $^{32}S+^{48}Ca,^{64}Ni$ has been recently studied at LNL (by the PRISMA-FIDES collaboration) in a wide energy range, from above the Coulomb barrier down to cross sections in the sub-barrier region with the PISOLO set up.

Re-measuring this fusion excitation function with EXOTIC at selected energies can provide a useful comparison of the performance of the two set-ups (PISOLO and EXOTIC) to determine whether the larger acceptance of EXOTIC allows us to measure cross sections at the level of a few tens of nanobarn.

PISOLO *vs* EXOTIC

Param. \ Set-up	Pisolo	Exotic
Geometrical solid angle	0.04 msr	10msr
Rejection Factor	10^7-10^8	10^9
Total detection efficiency	~0.5%	~5-10%

EXOTIC facility: velocity filter

Higher Rejection factor at 0°

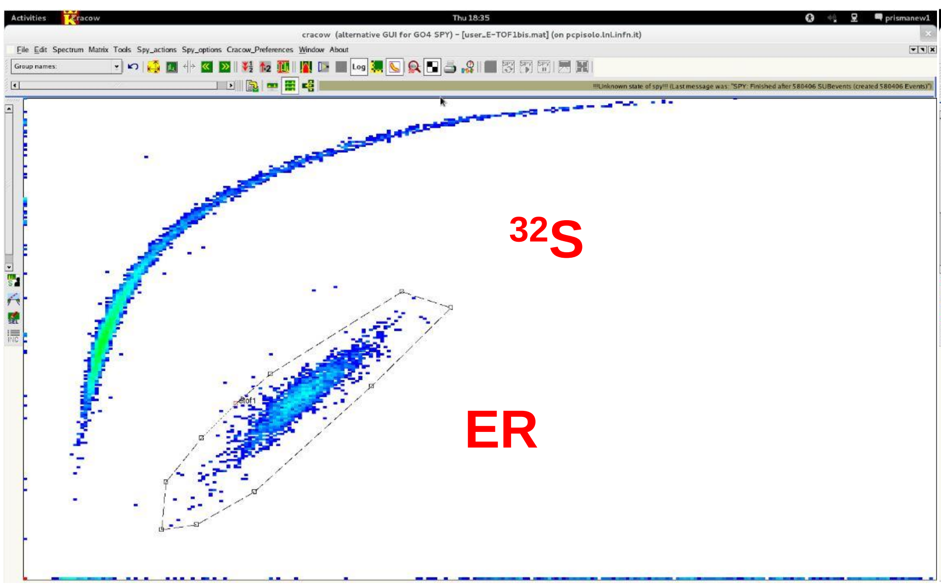
The **ER detection rate** was found to be 3 times larger and this can be improved in the next future by using a lower voltage Wien filter and a larger solid angle detector

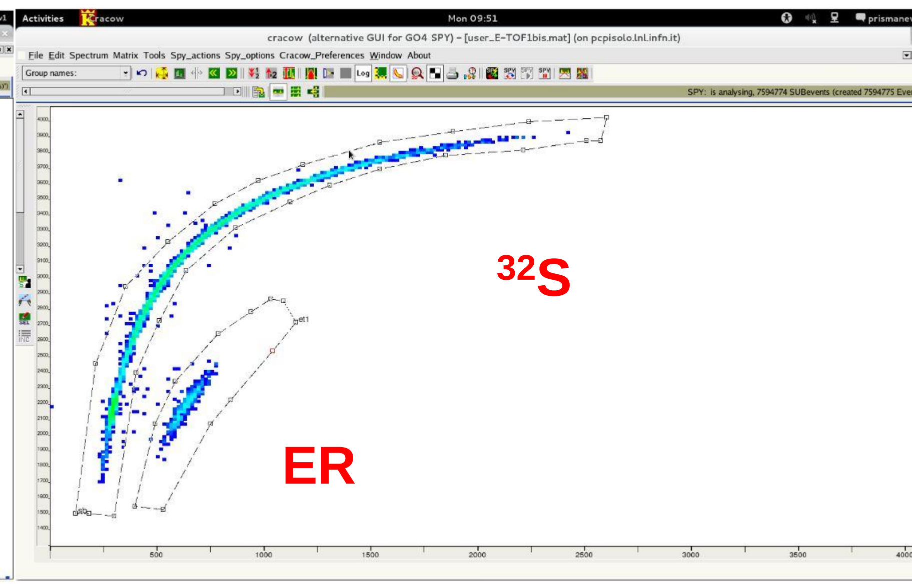
Possible use of the EXOTIC facility with the SPES RIBs for sub-barrier fusion measurements

$^{32}S + {}^{48}Ca$ @ E_{lab}= 84 MeV
344 mb

$^{32}S + {}^{64}Ni$ @ E_{lab}= 84 MeV
3.2 mb

TOF





E **E**

EXOTIC: conclusions and perspectives

EXOTIC is a facility for the in-flight production of low-energy light RIBs, fully operational at INFN-LNL. The **experimental set-up** installed at EXOTIC consists of: two PPACs for the RIB tracking and for ToF measurements and the compact, high-granularity, flexible, portable charged-particle detection array EXPADES.

Stimulating nuclear physics and nuclear astrophysics measurements can be performed employing the produced RIBs, in the framework of international collaborations.

Possibility to use the facility as a velocity filter to perform **fusion-evaporation** experiments at **sub-barrier energies** with **stable** beams and also with the **RIBs** of the next generation ISOL-type facility **SPES**, that is being constructed at INFN-LNL.

EXOTIC Collaboration

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C. Parascandolo, D. Pierroutsakou, C. Signorini, F. Soramel, E. Strano

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Thank you for your attention !