Developing system arrays for new experimental approach in nuclear astrophysics

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on behalf of the AsFiN group

THE 12TH EUROPEAN SUMMER SCHOOL ON EXPERIMENTAL NUCLEAR ASTROPHYSICS

Aci Trezza, 16-22 June 2024

INFN
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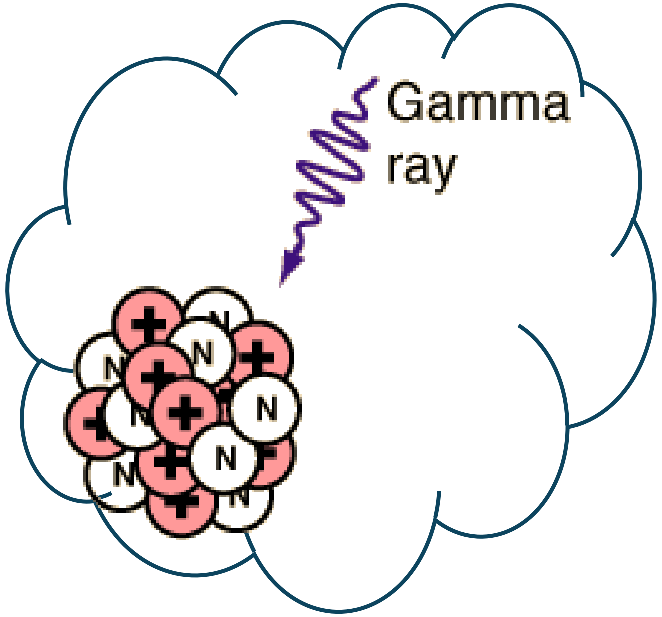
Photodissociation processes in astrophysics

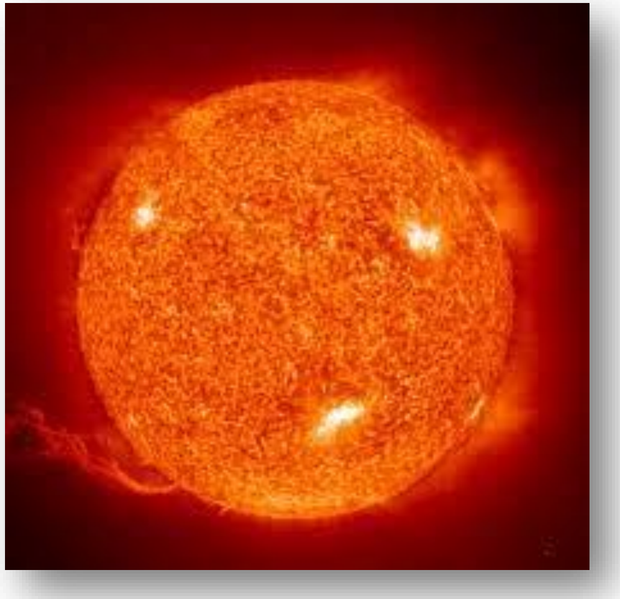
In evolved stars, high photon densities are present, making it possible to dissociate stable seed nuclei the photon energies being as large as many MeV.

For the first time high intensity ($3 \cdot 10^8$ γ/s) high resolution ($<10^{-3}$) will be available, making it possible to measure photodissociation reactions of astrophysics importance (HIGS, NEW SUBARU, ELI-NP??)

- **Big Bang Nucleosinthesys and Li-problem**
  $^{7}Li(\gamma,t)^{4}He$
- **Si-burning in stars and presupernova phase**
  $^{24}Mg(\gamma,\alpha)^{20}Ne$
  $^{28}Si(\gamma,p)^{27}Al$
- **p-process (production of proton rich nuclei)**
  $^{96}Ru(\gamma,\alpha)^{92}Mo$
  $^{74}Se(\gamma,p)^{73}As$



Astrophysical scenarios



Typical temperatures of plasmas experiencing nuclear burning range from 10^7 K for hydrostatic hydrogen burning to 10^{10} K or more in explosive events, such as supernovae or neutron star mergers.

Photodisintegration reactions only significantly contribute when the plasma temperature is sufficiently high to have an appreciable number of photons (given by a Planck radiation distribution) at energies exceeding the energy required to separate neutrons, protons, and/or α particles from a nucleus.

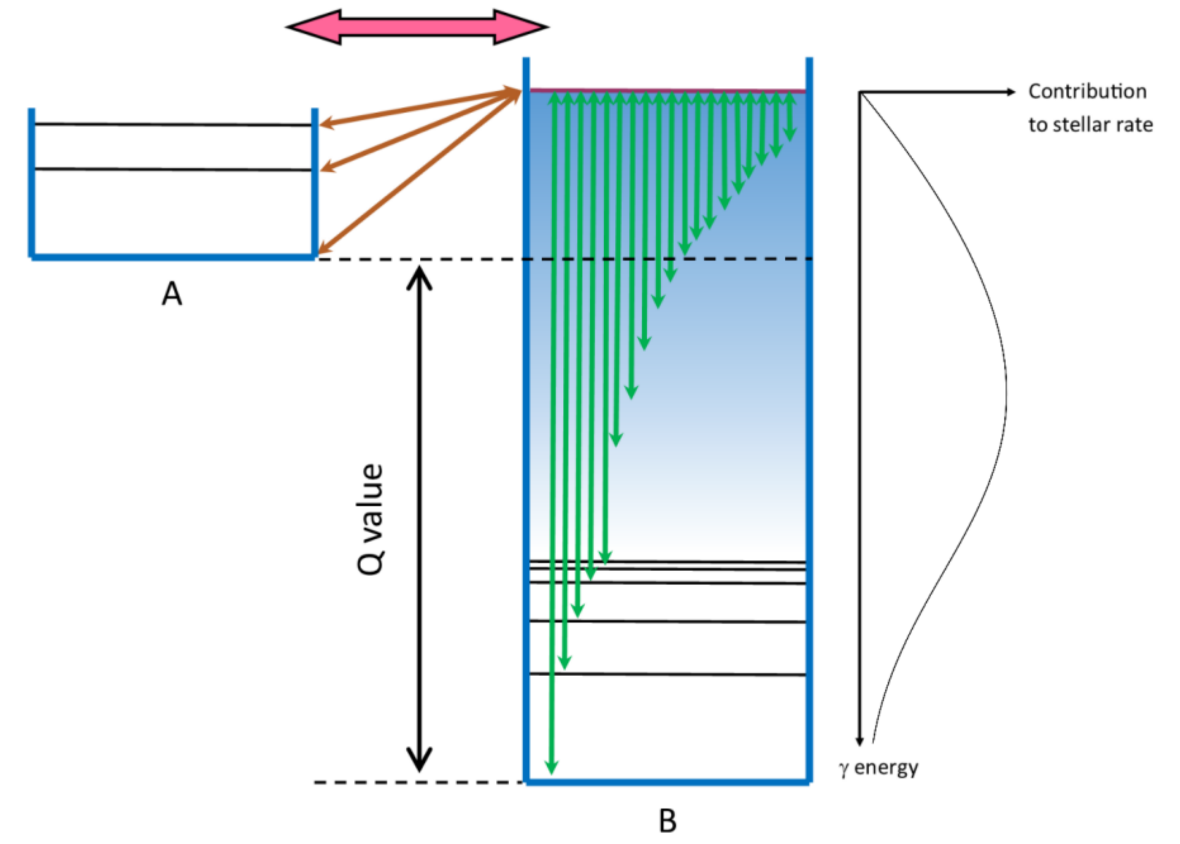
Forward and reverse reactions are always competing in a stellar plasma and thus photodisintegrations have to be at the same level or faster than capture reactions in order to affect nucleosynthesis. Since the number of captures per second and volume (the capture rate) not only scales with temperature but also with plasma density, the threshold temperature at which photodisintegrations cannot be neglected is higher for denser plasmas. On the other hand, photons require less energy when the particle separation energies are small.

Astrophysical scenarios

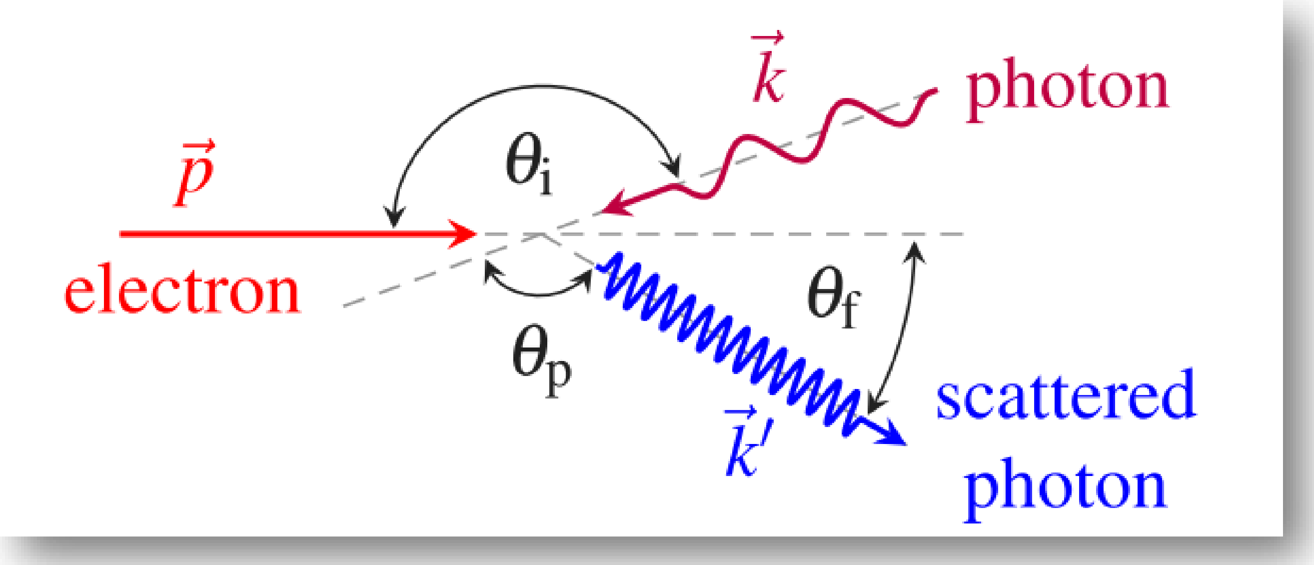
This means that the Q-value sets the temperature at which the reverse reaction becomes fast enough to compete with the forward reaction and affect the amount of a given nuclide in the stellar plasma. The Q-value of a capture reaction is just the separation energy of the projectile in the final nucleus.

Due to the above relations, photodisintegrations are found to be important in roughly three contexts:

1. (Almost) complete photodisintegration at the onset of a hydrostatic burning phase;
2. Partial photodisintegration in explosive burning;
3. Reaction equilibria between captures and photodisintegrations in explosive burning when both types of rates are fast and affecting nuclear abundances at a timescale much shorter than the process duration.



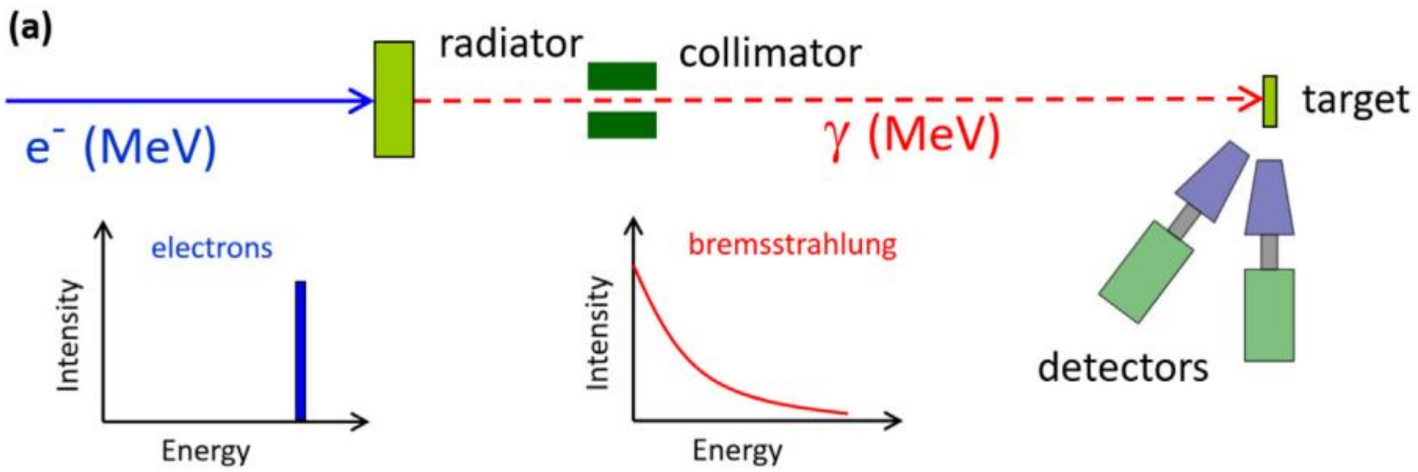
Laser Compton Backscattering



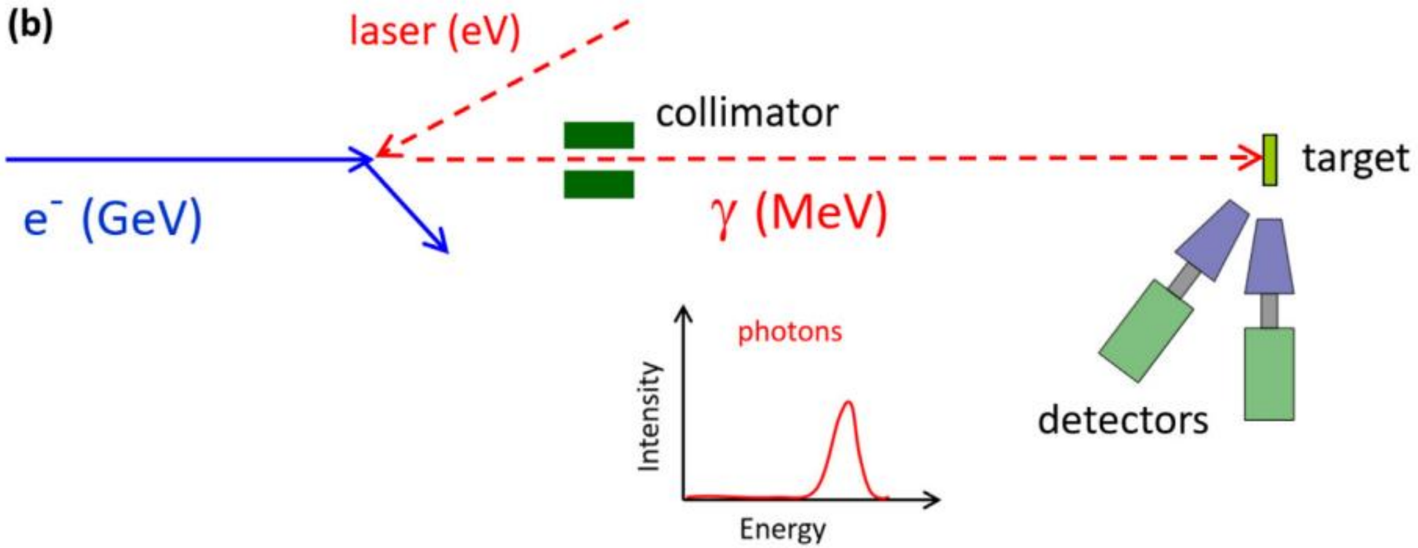
$$E_\gamma = \frac{(1+\beta)E_L}{(1-\beta\cos\theta_f)+(1+\cos\theta_f)E_L/E_e}$$

Laser photons are boosted into the MeV regime, which is the interesting range for nuclear physics experiments, when scattered off ultrarelativistic electrons with energies of several hundreds of MeV. By a proper collimation system, the scattered photons at very backward angles can be selected resulting in an almost monoenergetic photon beam, that can be tuned by varying the electron or laser photon energy.

Compton Backscattering vs Bremsstrahlung

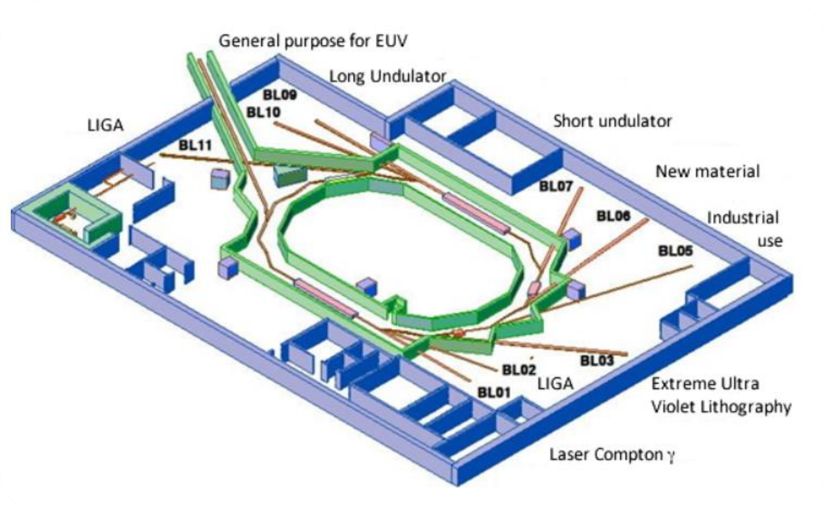


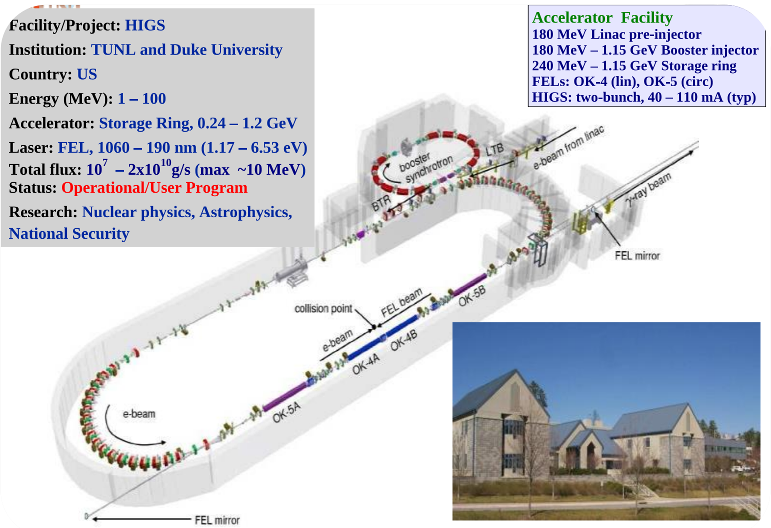
- Continuos spectra of γ energies
- Need a tag system



- (Almost) mono-energetic γ beams
- Need a laser-electron interaction system

New facilities for gamma beams




Facility/Project: HIGS
Institution: TUNL and Duke University
Country: US
Energy (MeV): 1 – 100
Accelerator: Storage Ring, 0.24 – 1.2 GeV
Laser: FEL, 1060 – 190 nm (1.17 – 6.53 eV)
Total flux: 10^7 – $2\text{x}10^{10}$g/s (max ~10 MeV)
Status: Operational/User Program
Research: Nuclear physics, Astrophysics, National Security

Accelerator Facility
180 MeV Linac pre-injector
180 MeV – 1.15 GeV Booster injector
240 MeV – 1.15 GeV Storage ring
FELs: OK-4 (lin), OK-5 (circ)
HIGS: two-bunch, 40 – 110 mA (typ)

Location	Durham USA	Okazaki Japan	Shanghai China	Xi'an China	Magurele Romania
E_e (MeV)	240–1200	750	3500	120–360	234–742
λ_L (nm)	190–1060	1940/10600	10640	800	515/1030
$\langle I \rangle$ (mA)	10–120	300	100–300	N/A	non-disclosed
E_γ (MeV)	1–100	1–5.4	0.4–20	0.1–3	1–19.5
$\Delta E_\gamma / E_\gamma$ (FWHM)	0.8%–10%	2.9% ($\phi = 2$ mm)	<5% ($\phi = 2$ mm)	1.2%–10%	<0.5%
f_{rep} (MHz)	5.58	90	347	pulsed, 10 Hz	71.4
Polarization	lin, circ	lin, circ	lin, circ	lin, circ	lin
$N_{\gamma,total}$ (γ/s)	10^6-$3 \cdot 10^{10}$	10^7	10^6 - 10^8	10^8 - 10^9	10^{11}
$N_{\gamma,on-target}$ (γ/s)	10^3 - $3 \cdot 10^9$	$4 \cdot 10^5$	10^5 - 10^7	10^6 - 10^8	$\sim 10^8$

Nuclear AstroPhysics experiments with γ beams

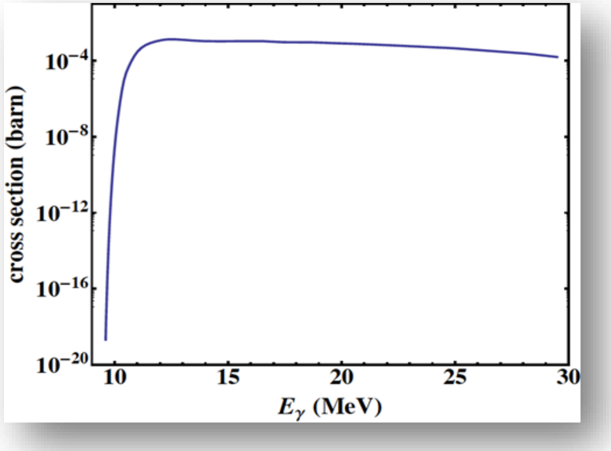
Features of NA Experiment:

→ Gamma energies around 10 MeV are typically necessary

→ Particles are emitted with energies ranging from hundreds keV up to few MeV

→ Typical cross section should be very low

→ ~$3 \cdot 10^4$ events per day expected at 11 MeV



A SSD array is very flexible as it can be used to measure photodissociation on many nuclei, including noble gases (using a gas cell) and long lived unstable nuclei (such as ^{7}Be, ^{14}C or ^{26}Al)

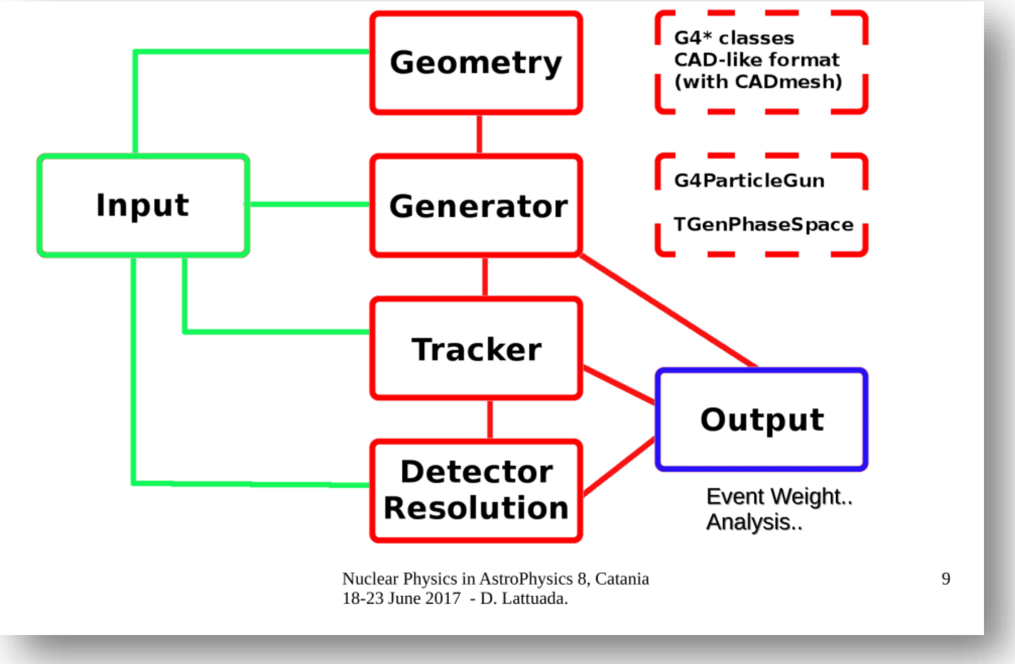
Requirements:

- Large area coverage
- Two or three particles at most are emitted per reaction event
- Low detection threshold
- No PSD or DE techniques are viable for particle ID
- High energy and angular resolution for kinematical particle ID

MC simulation: the GROOT code

- ✓ Estimate the gamma-induced e.m. background
- ✓ Estimate the full background of photonuclear reactions and the detector’s resolution effect
- ✓ Optimization of the detector geometry
- ✓ Estimate the event rate (provided that we have reliable cross-section calculations) or calculate the minimum cross-section we can measure because of the background

Based on GEANT4 tracking + ROOT event generator engine



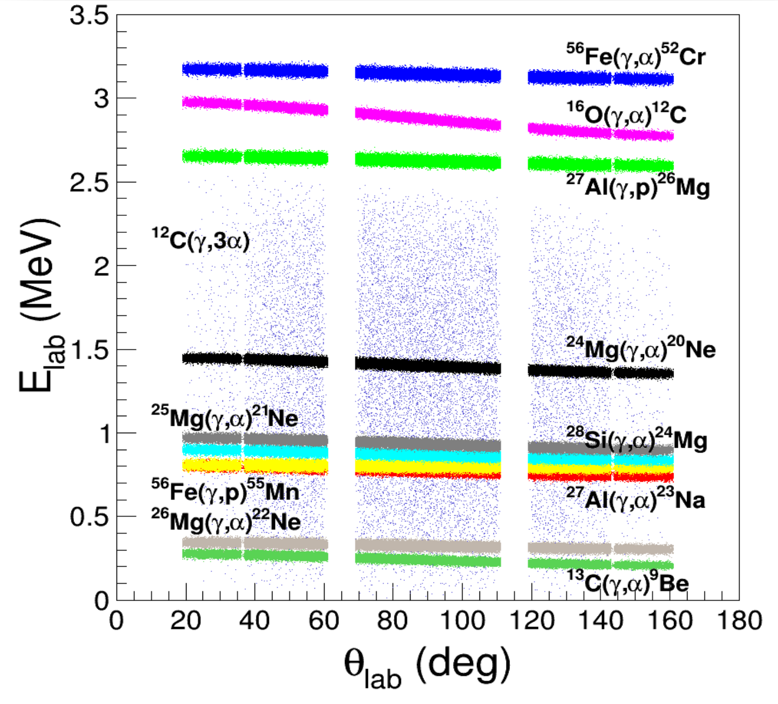
Nuclear Physics in AstroPhysics 8, Catania
18-23 June 2017 - D. Lattuada.

9

D. Lattuada et al. EPJ Web of Conf. 165, 01034 (2017)

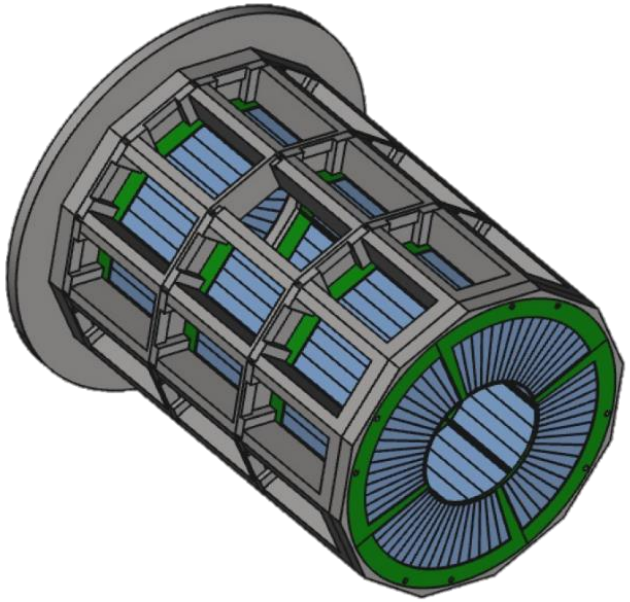
Particle Identification with compact arrays

- **A compact device such as a silicon strip detector array would make it impossible to use ToF for particle ID;**
- **Owing to the low particle energies the standard ΔE-E approach is not applicable;**
- **Pulse shape discrimination has presently proven very hard at such low energies.**



Solution: kinematical identification thanks to the great angular and energy resolution of the SSD array as well as high gamma beam quality

Extreme Light Infrastructure Silicon Strip Array



Characteristics:

- Wide angular range coverage
- Low energy threshold
- Compactness
- Angular resolution better than 0.5 cm
- Energy resolution better than 1%
- Kinematical identification of outgoing particle

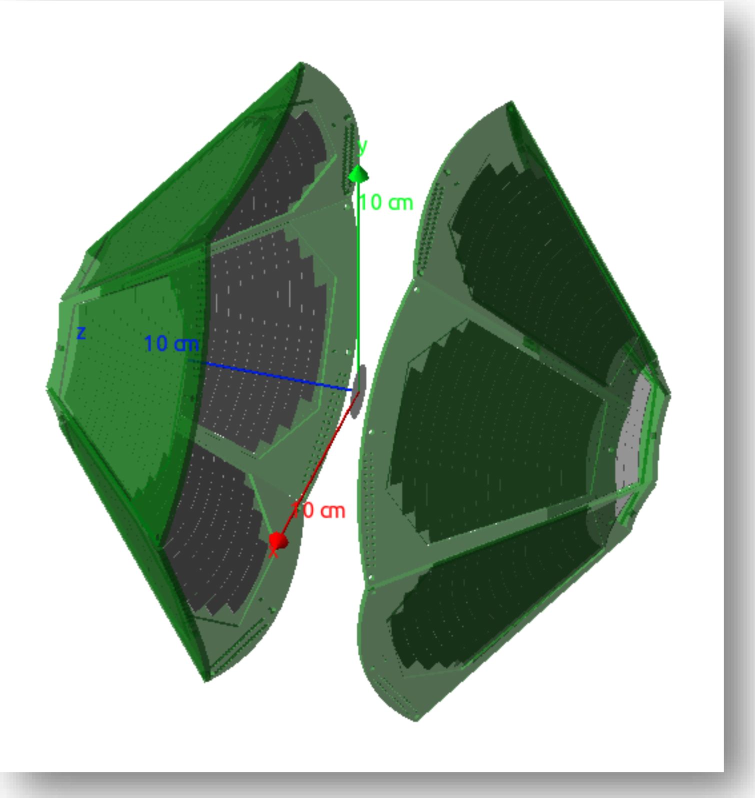
Barrel configuration:

- ✓ 3 rings of 12 position sensitive X3 silicon-strip detectors by Micron
- ✓ 2 end cap detectors made up of 4 QQQ3 DSSSD by Micron
- ✓ >550 channels readout with GET electronics/standard electronics

Perfectly suited for nuclear astrophysical studies!!

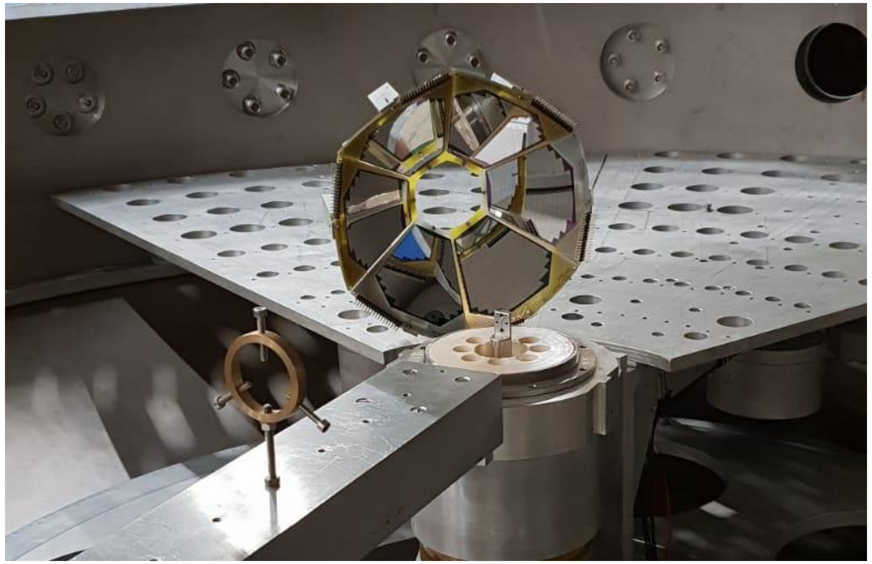
G. L. Guardo et al. EPJ Web of Conf. 165, 01026 (2017)

Large High-resolution Array of Silicon for Astrophysics



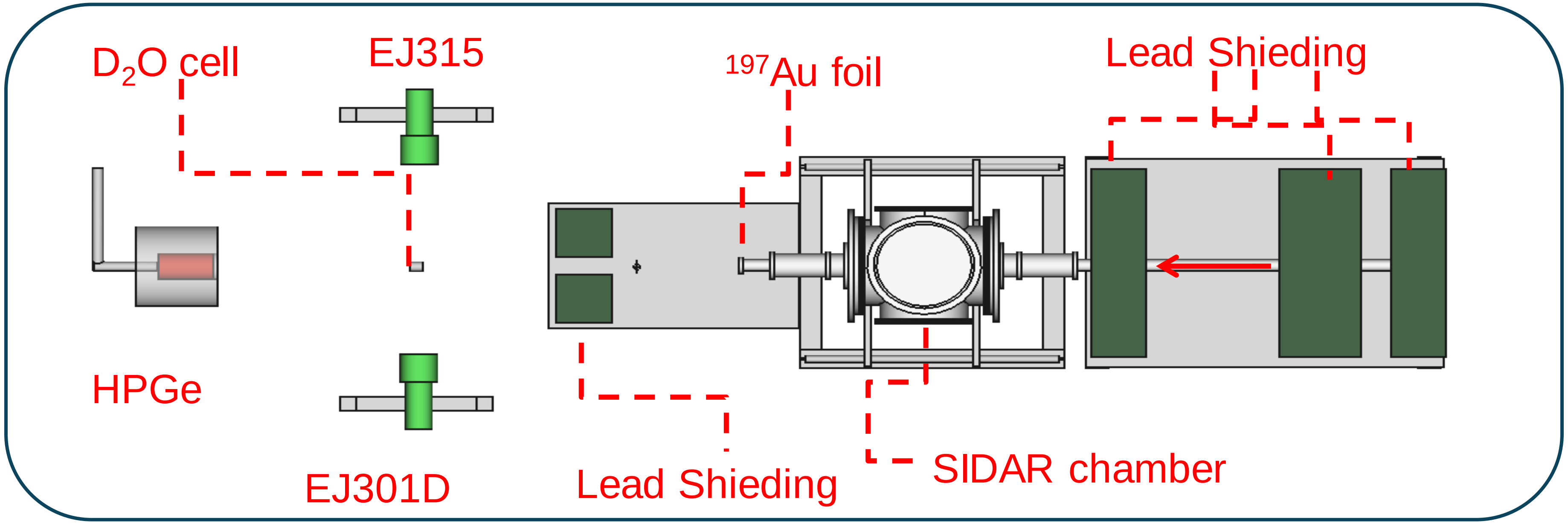
Characteristics:

- Wide angular range coverage
- Low energy threshold
- Compactness
- High energy resolution
- Angular resolution allows for PID



The ^{7}Li(γ,t)^{4}He reaction

Experimental setup



- E_γ = 4.4 – 10 MeV provided by HIGS facility
- 1.2 cm collimator defines beam spot
- LiF target on mylar(180 μg/cm^2)
- SIDAR array from ORNL(lamp-shade)
- 12 YY1 detectors (200 ch)
- two lamp-shades of YY1: 300, 500, 1000 μm
- Standard electronic read-out (mesytec preamp + amp + caen adc)

See Talk I. Kuncser

p-process experimental campaing @HIGS

BBN reactions

- ^{7}Li(g,t)^{4}He – estensione a basse energie
- energy range 3.5-6 MeV
- P-20-19: C. Matei (ELI-NP)
- 70 ore di fascio APPROVATE

cluster dipole resonance in ^{9}Be

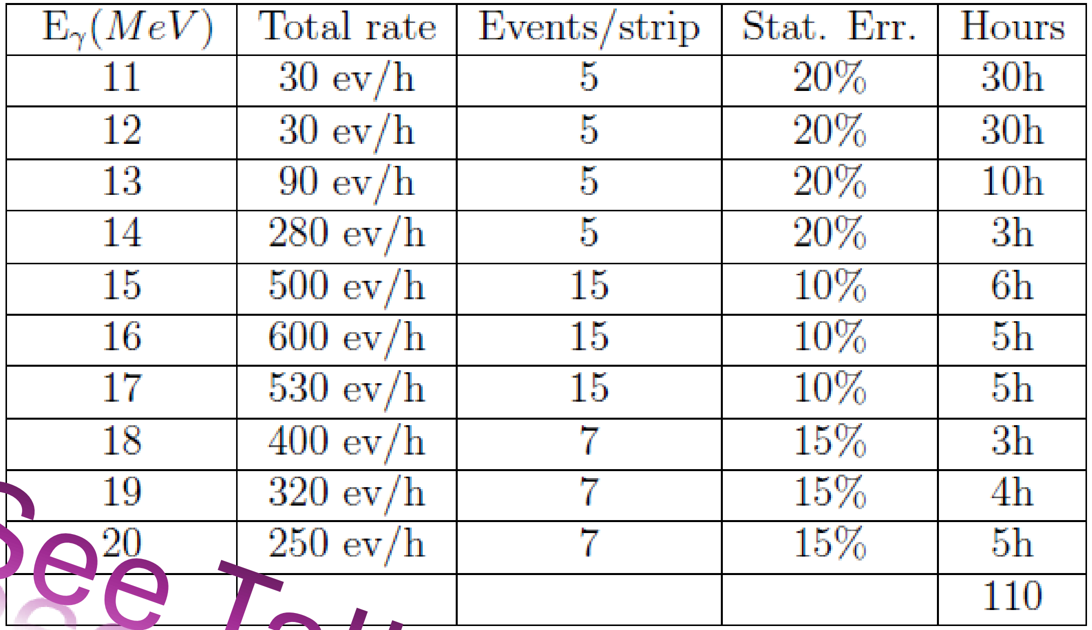
- probing the collective cluster-dipole resonance
- 40% uncertainty in the cross section between 8 and 16 MeV
- P-21-19: R Smith (SHU)
- 45 ore di fascio APPROVATE

p-process reactions

- ^{112}Sn and ^{102}Pd – test case
- energy range 11-20 MeV
- P-17-19: D Lattuada & G.L. Guardo (INFN)
- P-15-19: K.A. Chipps (ORNL)
- 110+90 ore di fascio APPROVATE

p-process experimental campaing @HIGS

The ^{112}Sn(γ,x) measurement

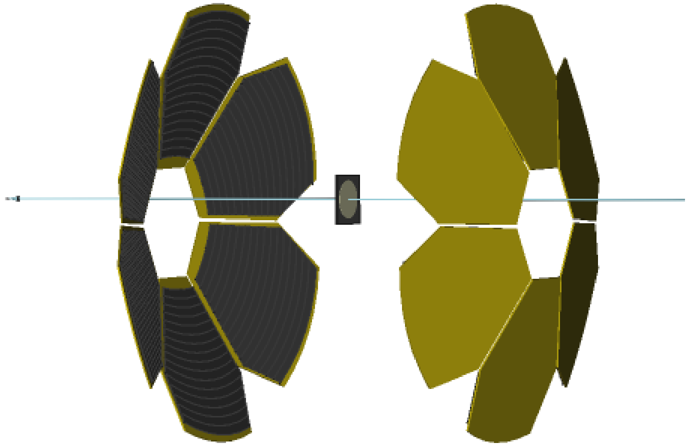


$E_\gamma(MeV)$	Total rate	Events/strip	Stat. Err.	Hours
11	30 ev/h	5	20%	30h
12	30 ev/h	5	20%	30h
13	90 ev/h	5	20%	10h
14	280 ev/h	5	20%	3h
15	500 ev/h	15	10%	6h
16	600 ev/h	15	10%	5h
17	530 ev/h	15	10%	5h
18	400 ev/h	7	15%	3h
19	320 ev/h	7	15%	4h
20	250 ev/h	7	15%	5h
				110

Table 1: Run plan.

See Talk G. Restifo

- Two measured channels: ^{112}Sn(γ,α)^{108}Cd e ^{112}Sn(γ,p)^{111}In
- 11-20MeV γ-beam
- Self-supported ^{128}Sn target 750ug/cm^2 or 1,5mg/cm^2
- Intensity $5\cdot10^7$ and $5\cdot10^8$ γ/s
- Beam spot 12.5 mm



New proposal @HIGS

The ^{24}Mg(γ,α) measurement

In Si-burning, preceding the core-collapse supernova stage, fusion reactions such as ^{28}Si+^{28}Si or ^{28}Si+^{32}S are too unlikely to occur owing to the Coulomb barrier.

Instead, nucleosynthesis takes place through photodisintegration of less bound nuclei and radiative captures of the dissociated light particles (protons, neutrons, and α-particles) to gradually create heavier and more tightly bound nuclei.

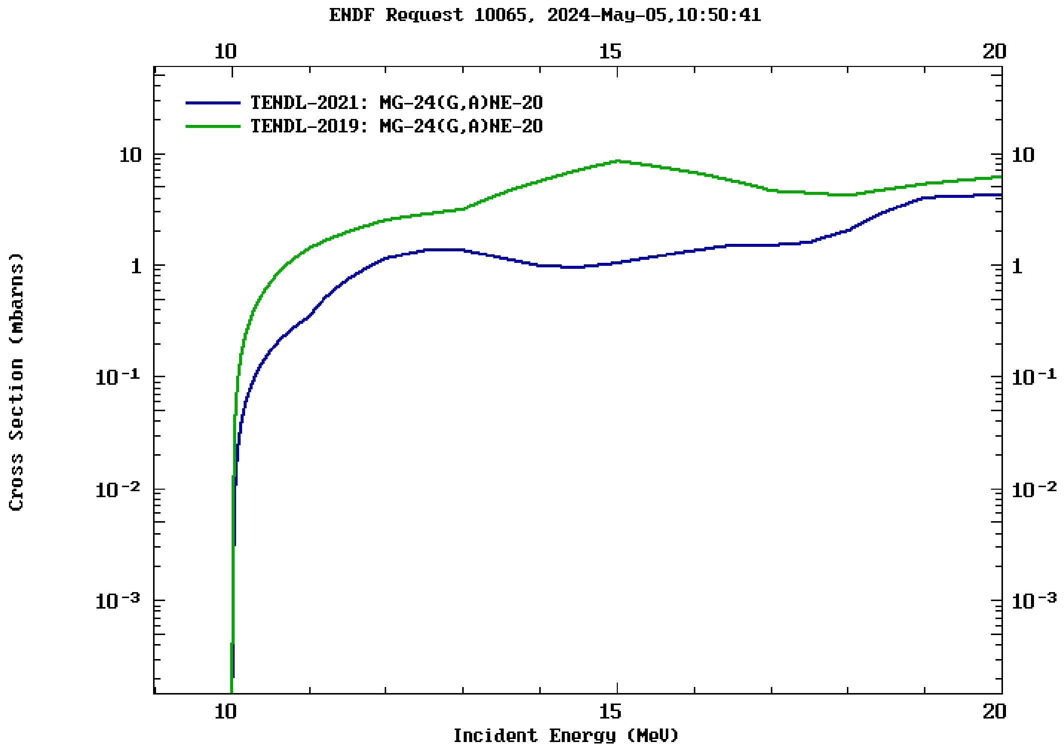
New proposal @HIGS

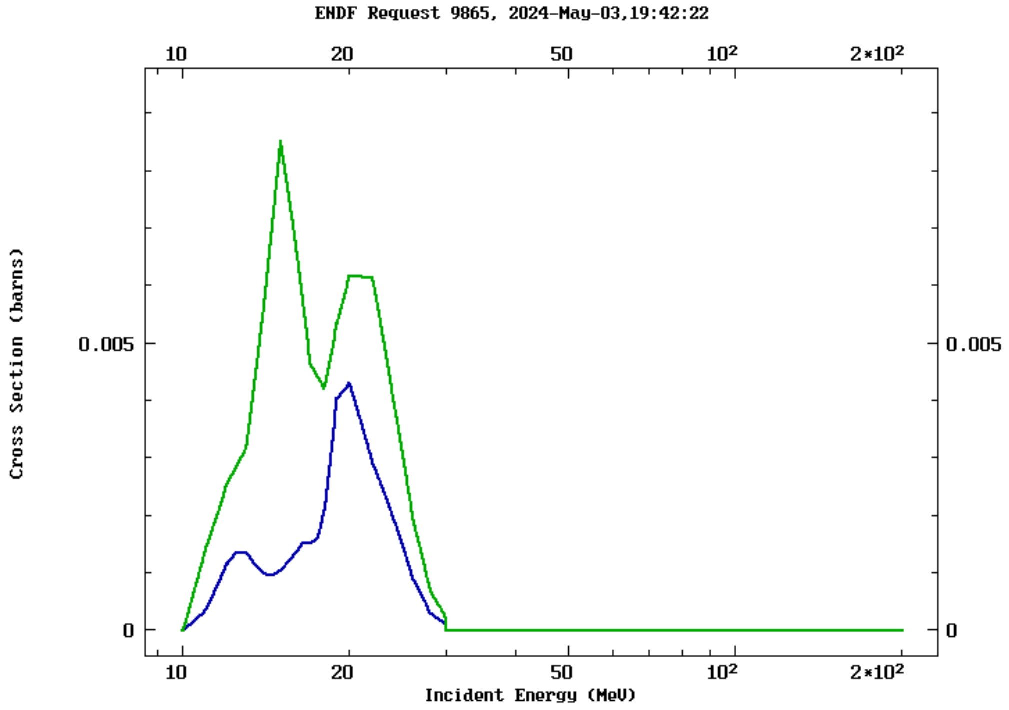
The ^{24}Mg(γ,α) measurement

The nucleosynthesis is governed by the slowest reaction in the network:

^{24}Mg(γ,α)^{20}Ne

Its cross section is calculated from the inverse reaction and is affected by a factor of 2 uncertainty.





New proposal @HIGS

The ^{24}Mg(γ,α) measurement

T e nucleosynthesi rn owest
reactic
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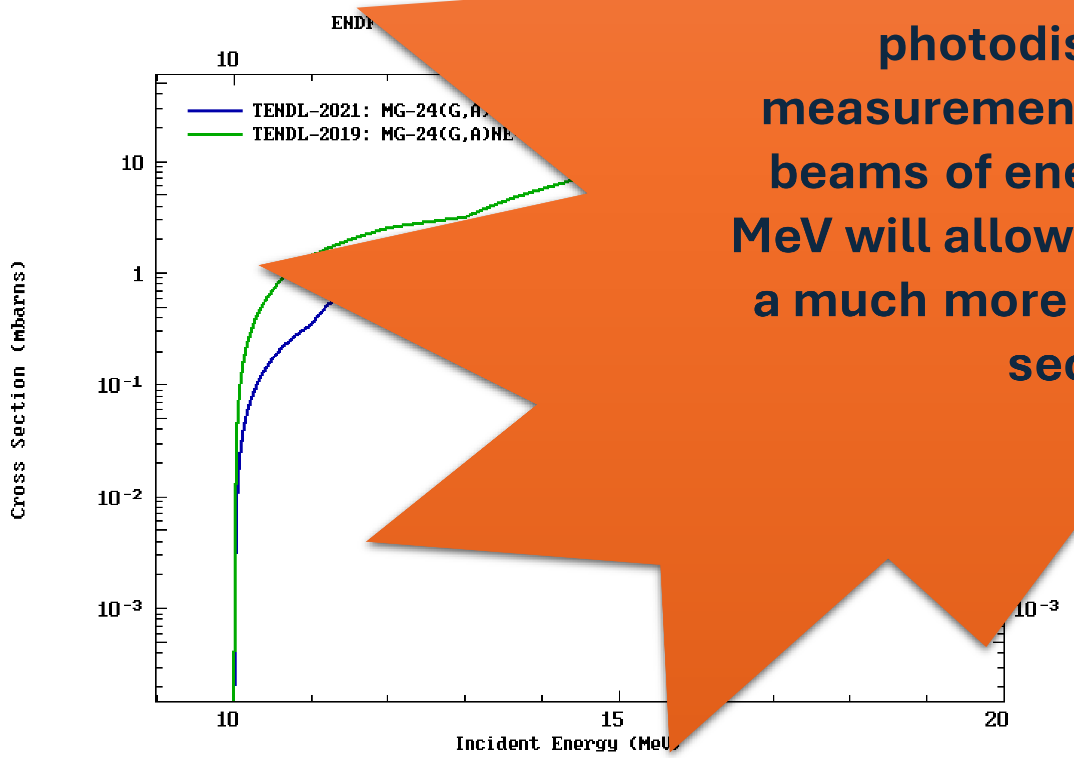
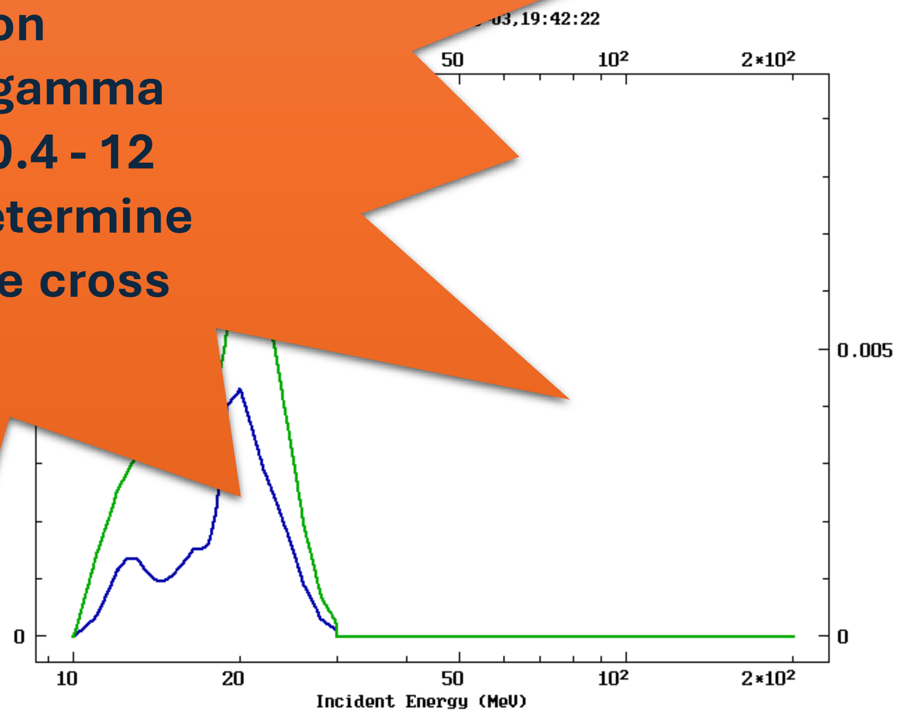
Its cross section is calculated tainty.

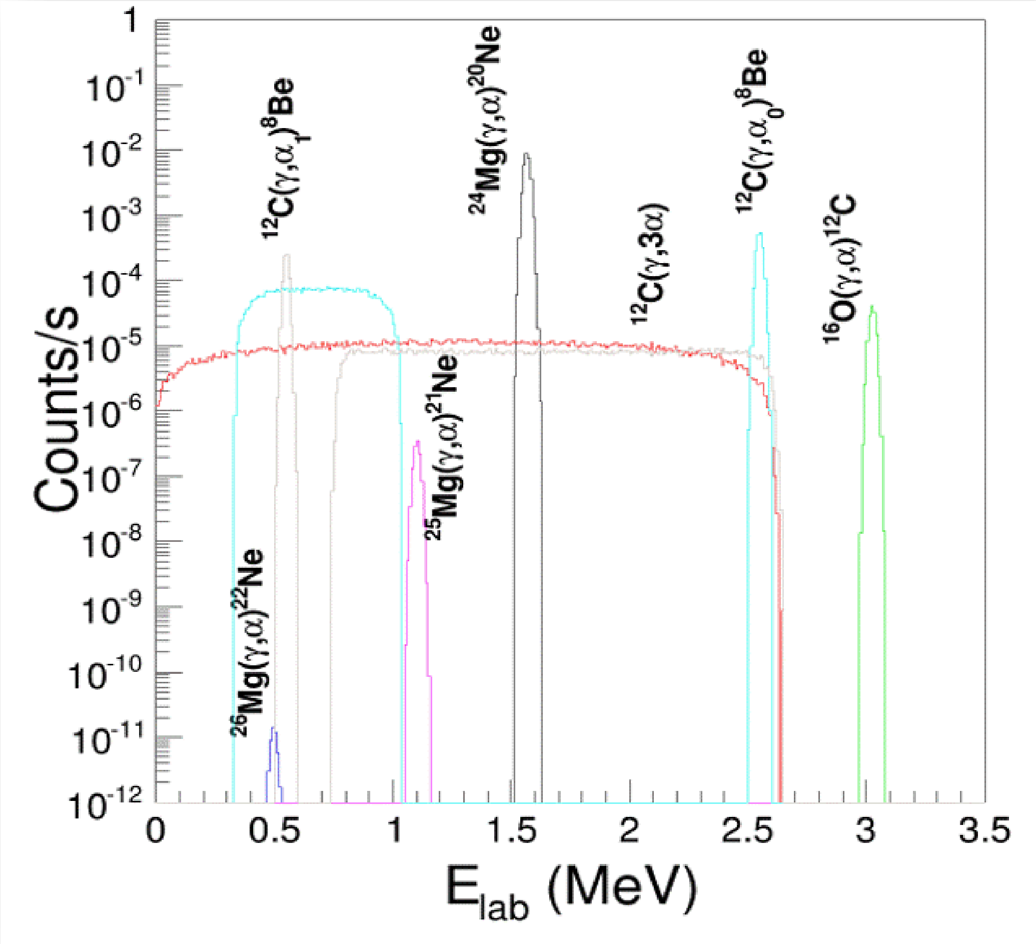
A direct ^{24}Mg photodissociation measurement using gamma beams of energies 10.4 - 12 MeV will allow us to determine a much more accurate cross section





New proposal @HIGS

The ^{24}Mg(γ,α) measurement

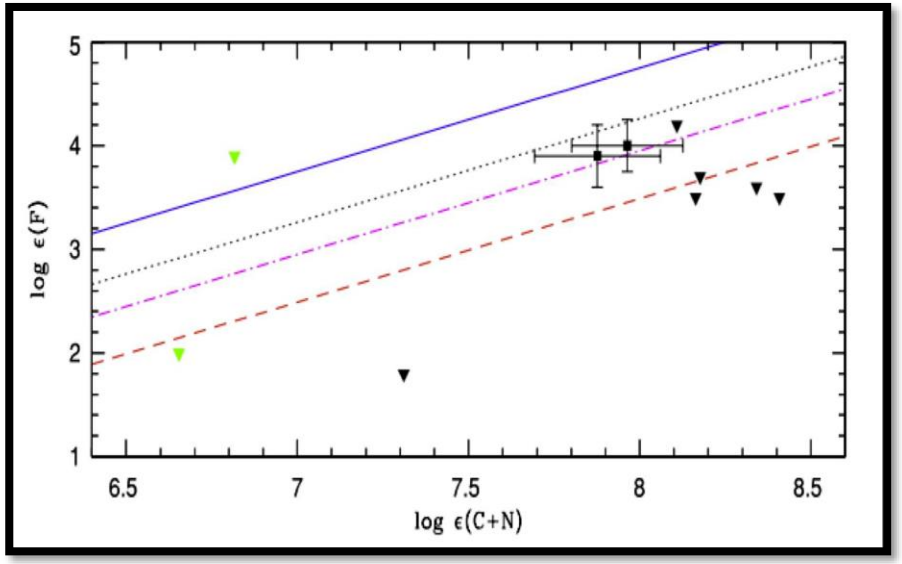


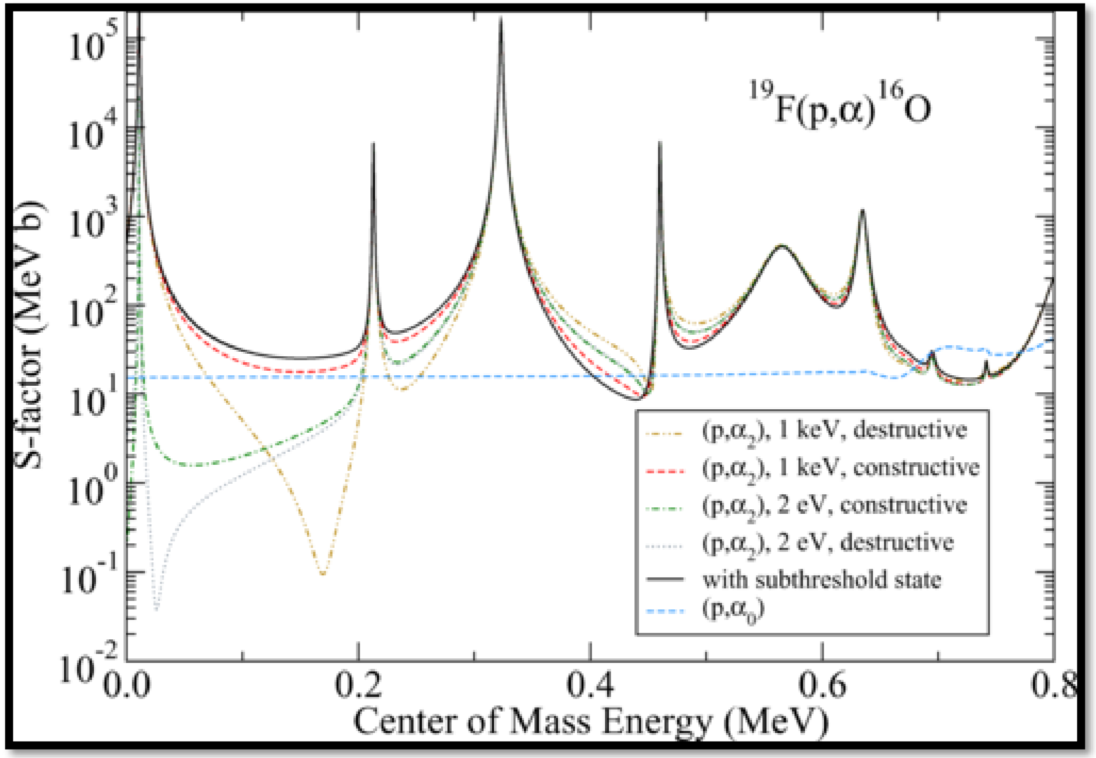
Eγ (MeV)	Total rate	Event/strip	Stat.Err.	Hours
10	15 ev/h	0.5	30%	72
10.5	100 ev/h	3	15%	12
11	100 ev/h	3	15%	12
11.5	100 ev/h	3	15%	12
12	100 ev/h	3	15%	12
12.5	100 ev/h	3	15%	12
13	100 ev/h	3	15%	12

ELISSA & LHASA for direct measurements

The ^{19}F(p,α) reaction

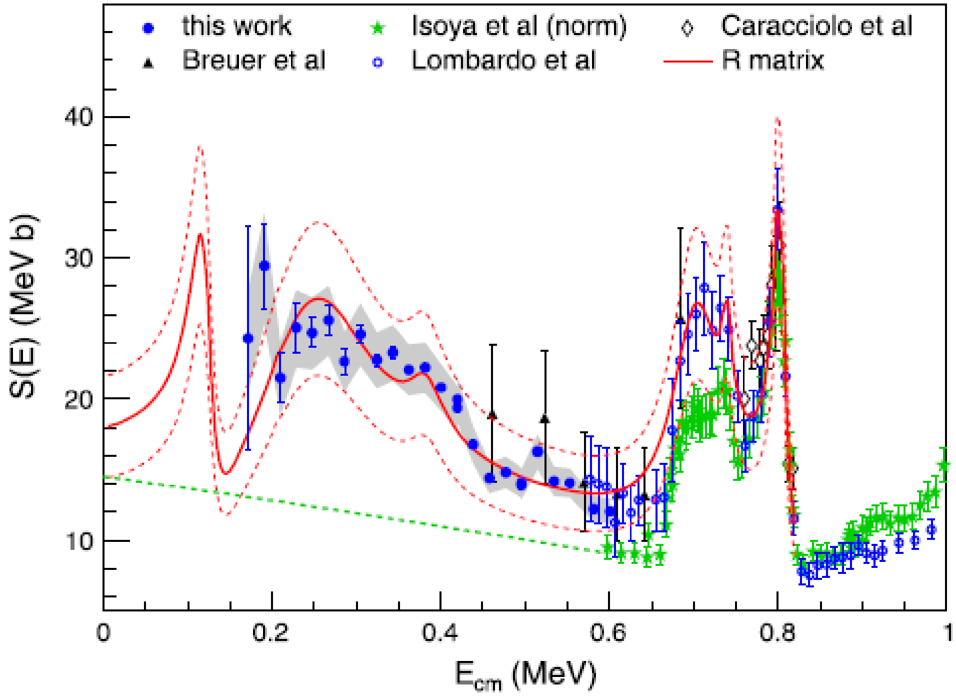
^{19}F is a key isotope in astrophysics as it can be used to probe AGB star mixing phenomena and nucleosynthesis but also it plays a crucial role in Ca formation in Population III stars.
<u>Nevertheless its production is still uncertain!!</u>





ELISSA & LHASA for direct measurements

The $^{19}F(p,\alpha)$ reaction



ELISSA & LHASA for direct measurements

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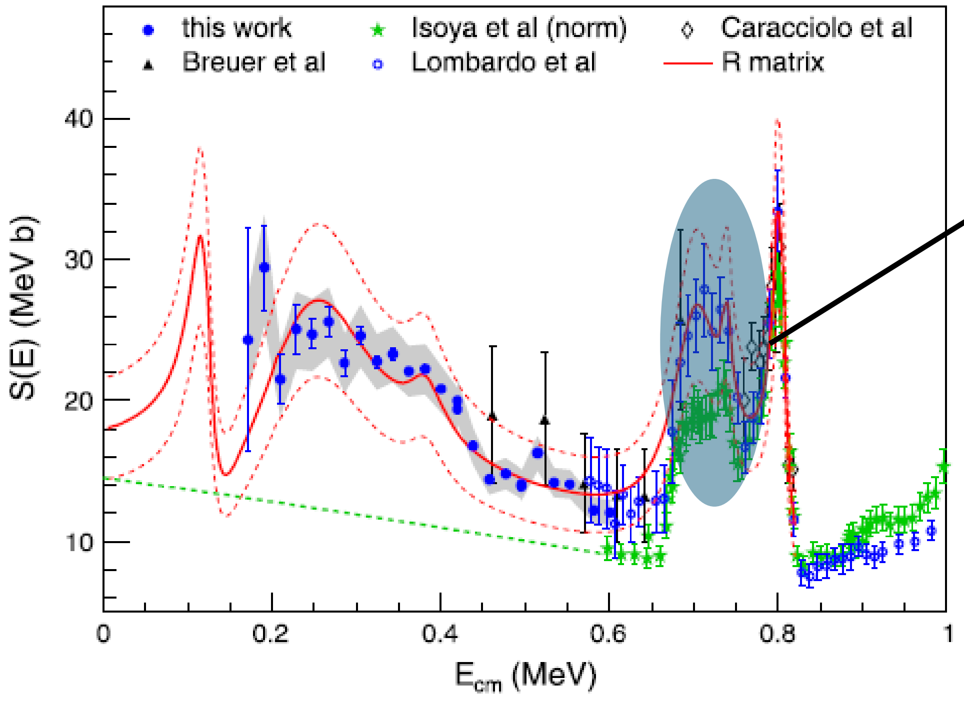
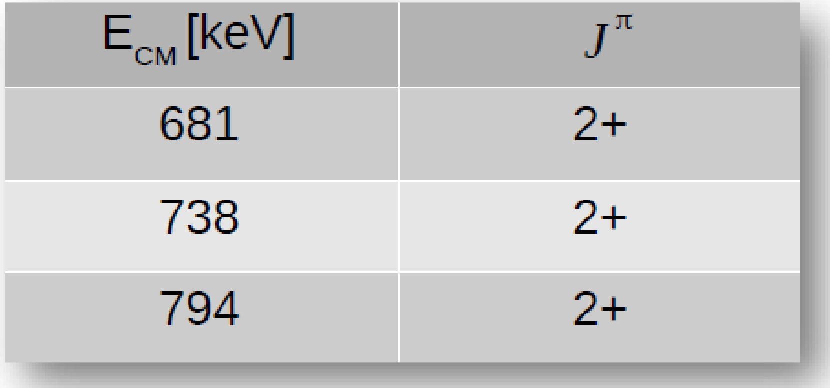


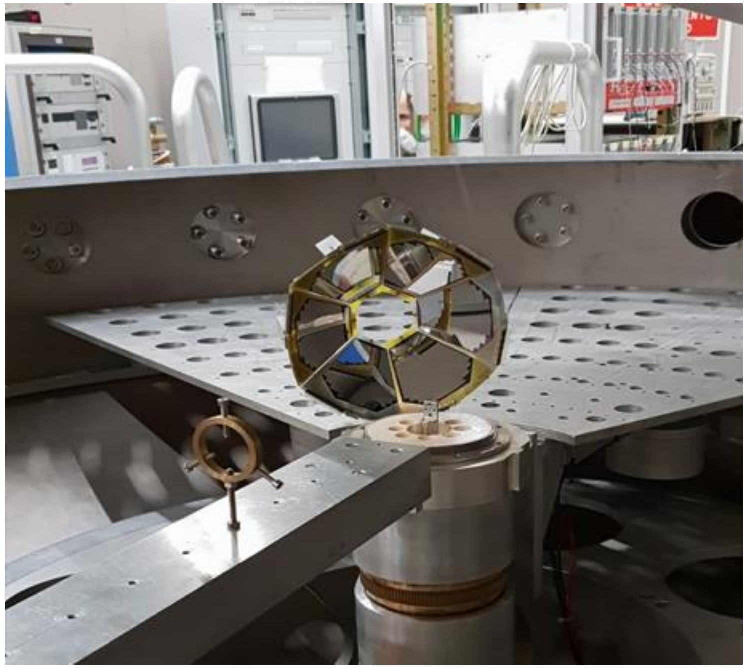
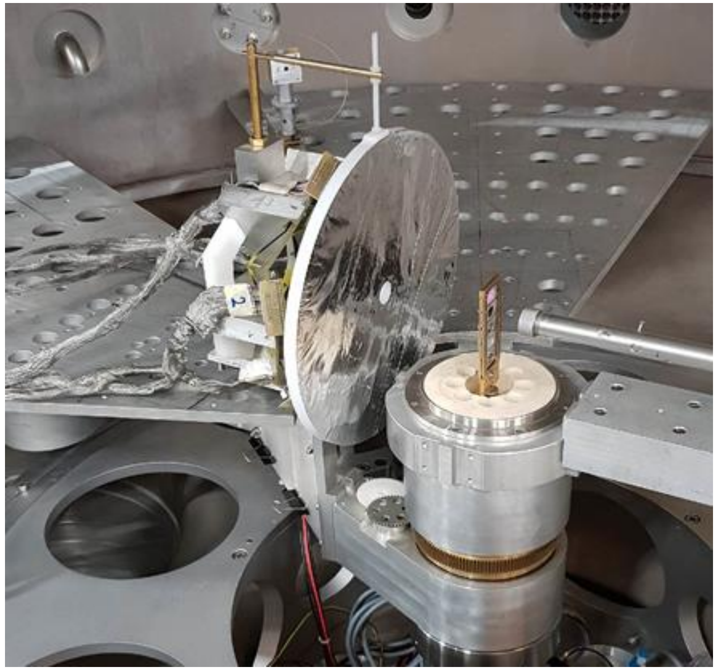
Discrepancies in the normalization region for the THM data



E_{CM} [keV]	J^{π}
681	2+
738	2+
794	2+

ELISSA & LHASA for direct measurements

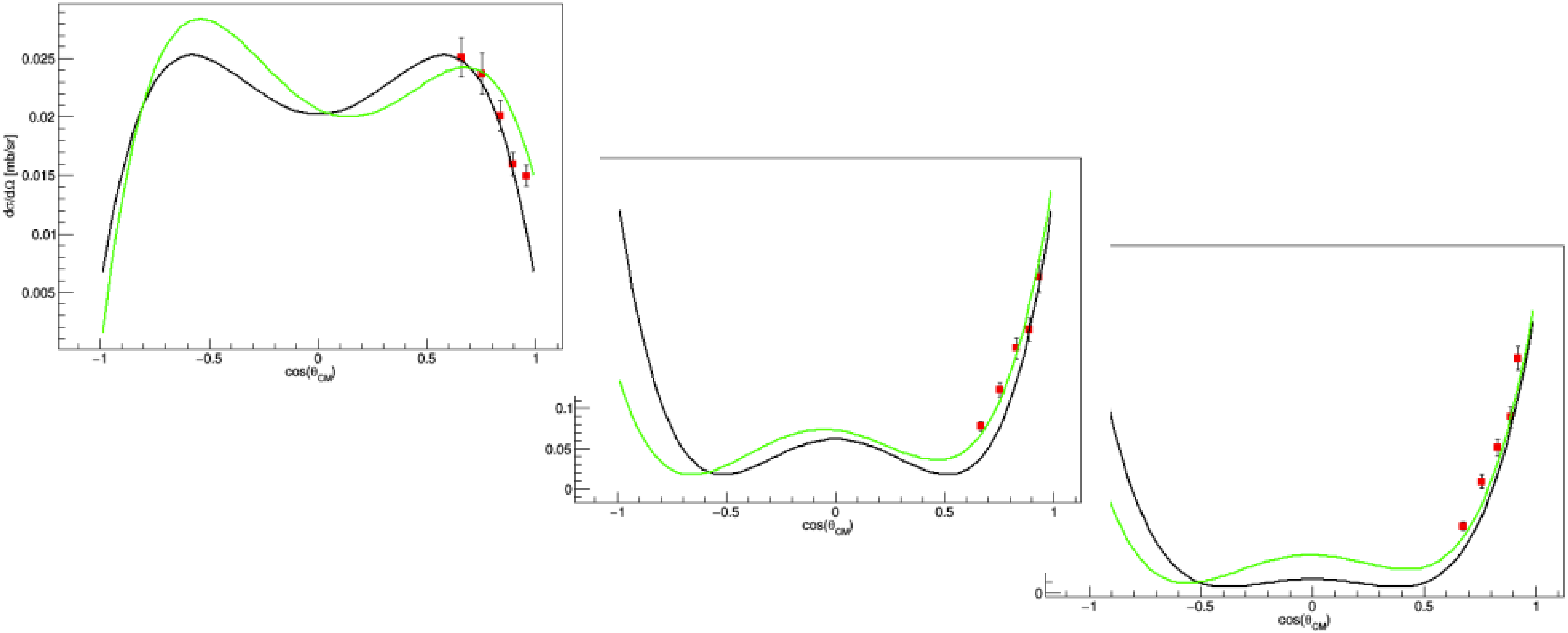
The ^{19}F(p,α) reaction

- The measurement was performed at **LNS**
- ^{19}F beam with the energy range from 9 to 18.5 MeV
- CH_2 of about 100 μg/cm^2 was placed at 90° with respect to the beam direction
- The experimental setup consisted of 6 YY1 detectors

ELISSA & LHASA for direct measurements

The ^{19}F(p,α) reaction



ELISSA & LHASA for direct measurements

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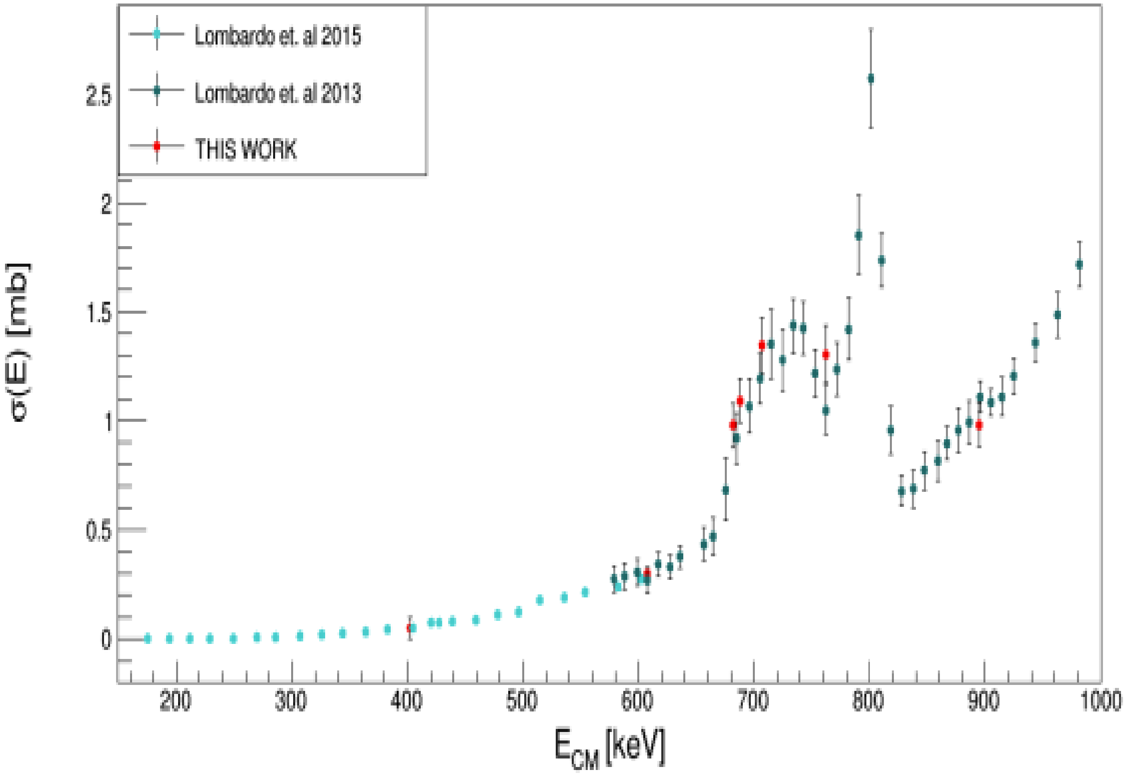
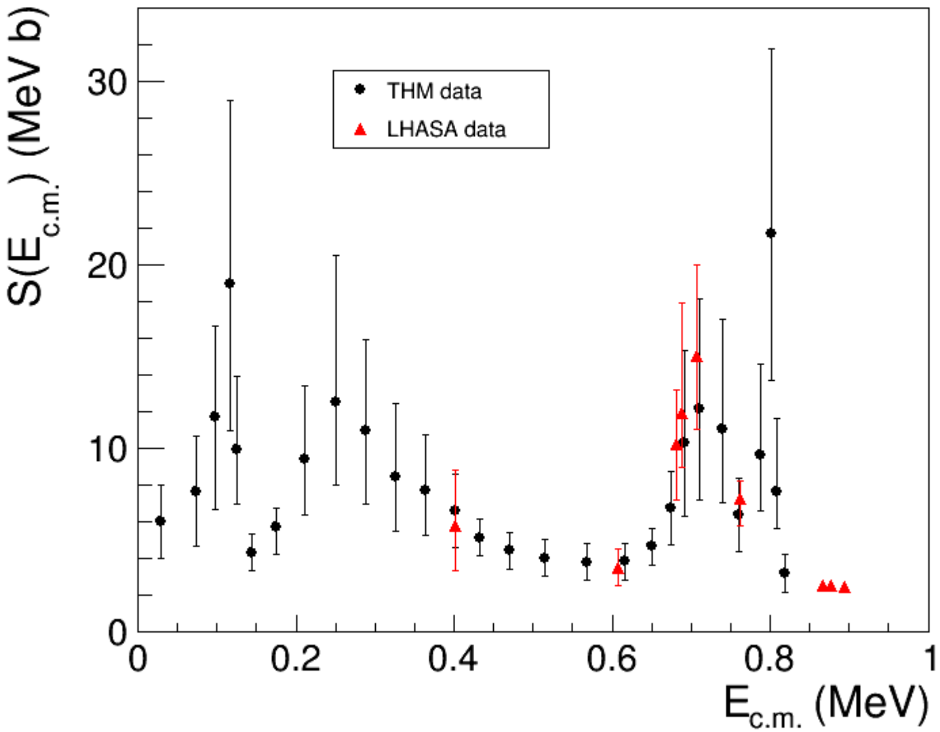
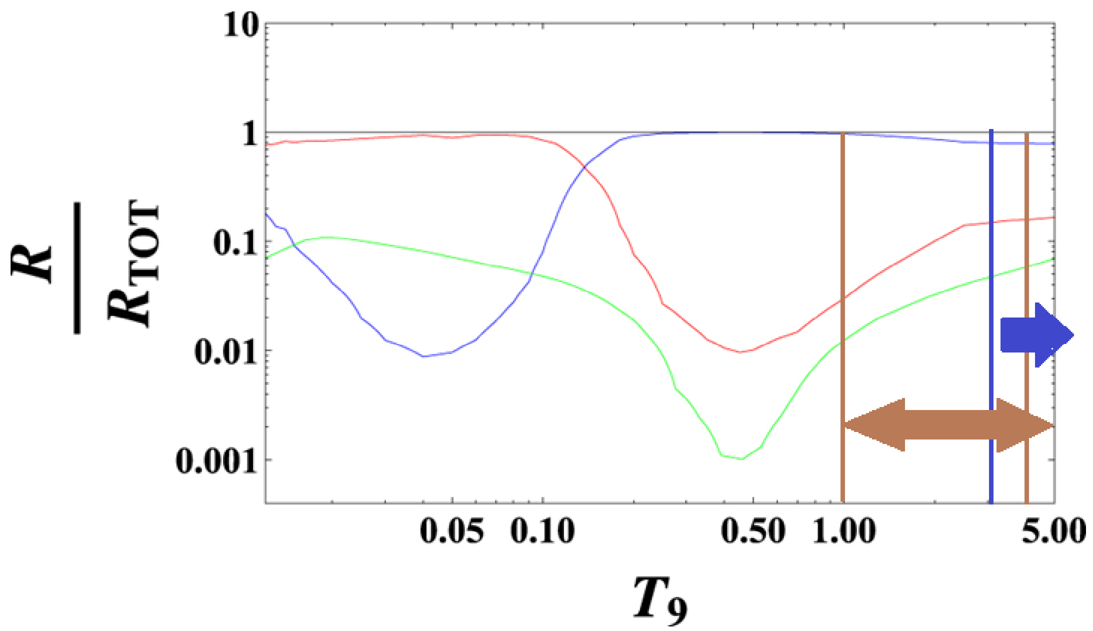


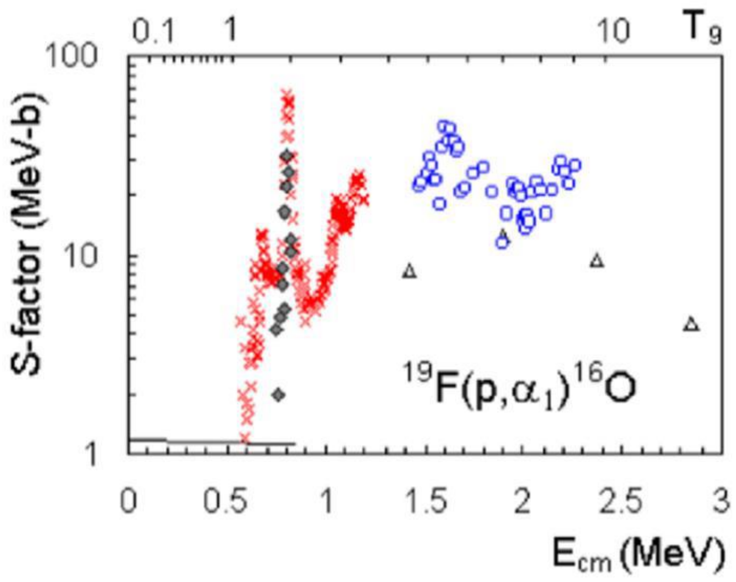


ELISSA & LHASA for direct measurements

The ^{19}F(p,α) reaction

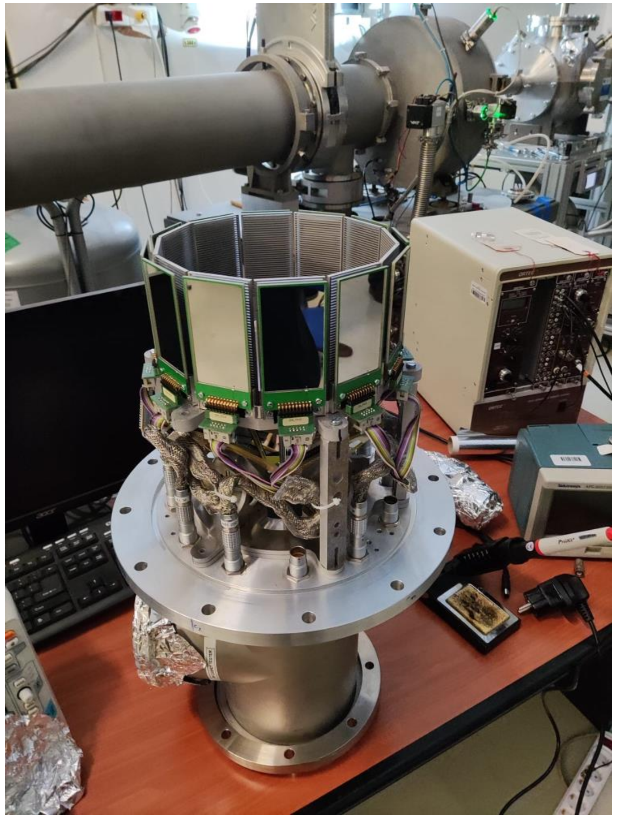
At very low temperatures, the (p,a_0) channel (red line) dominates the total rate. The (p,α_γ) channel (blue line) became dominant at least above T9≈0.2, while the (p,α_π) channel (green line) gives a maximum contribution of 20%. BUT

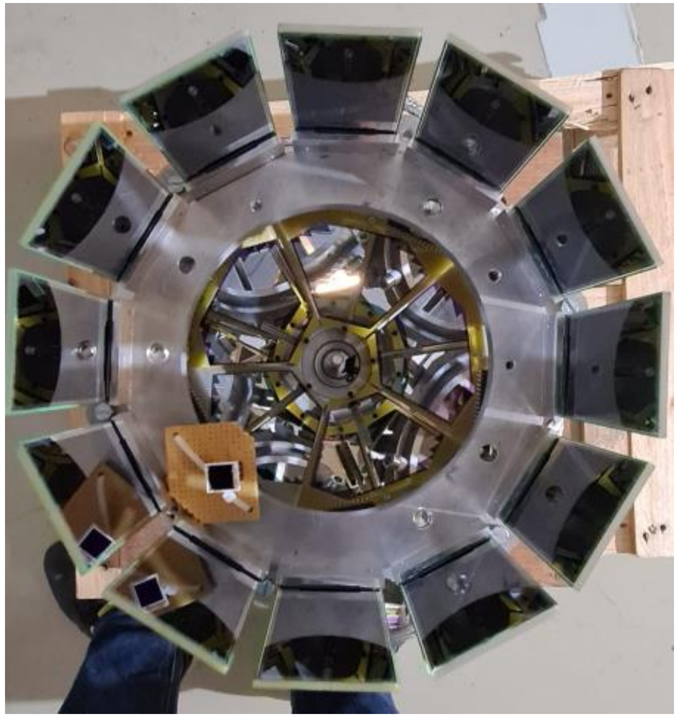


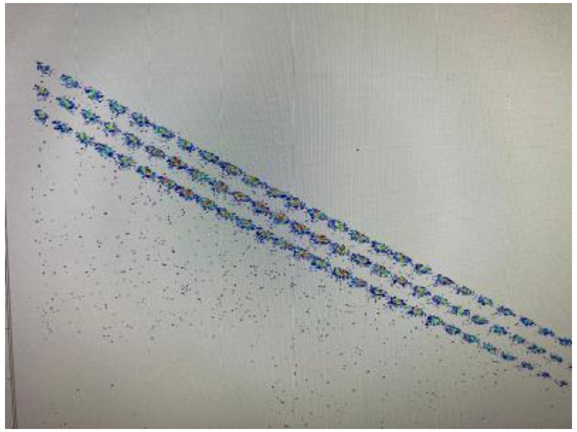


ELISSA & LHASA for direct measurements

The ^{19}F(p,α) reaction



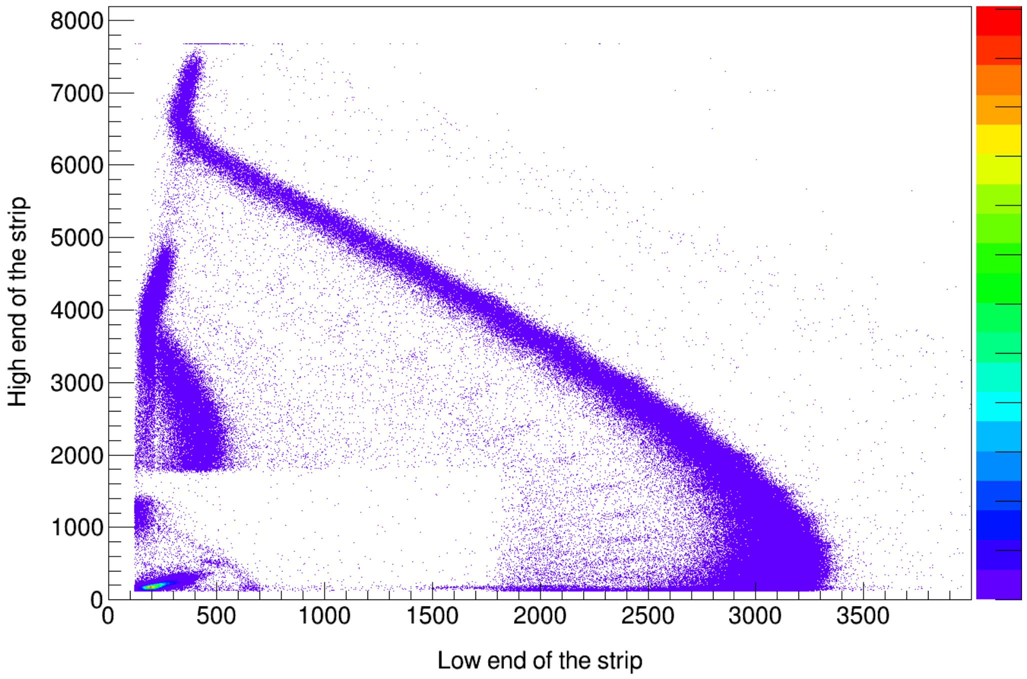


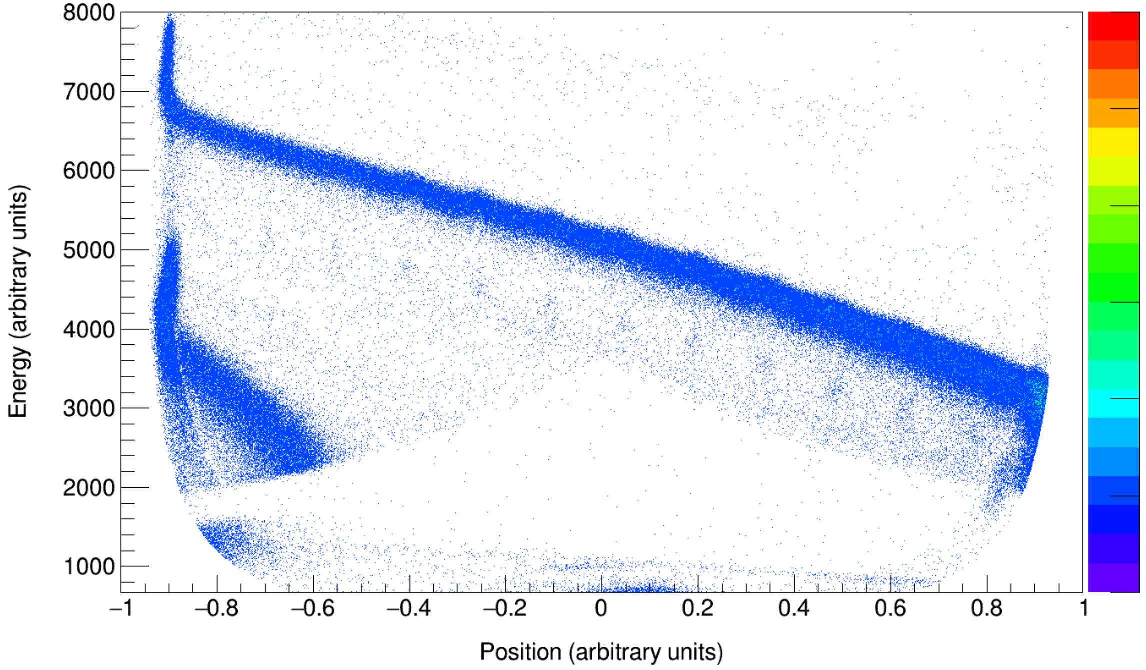


ELISSA & LHASA for direct measurements

The ^{19}F(p,α) reaction

Beam energy: 19F at 12 MeV;
Beam intensity: 4.2 nA;
Target: CH2 100 ug/cm2;
One hour and 50 minutes run.





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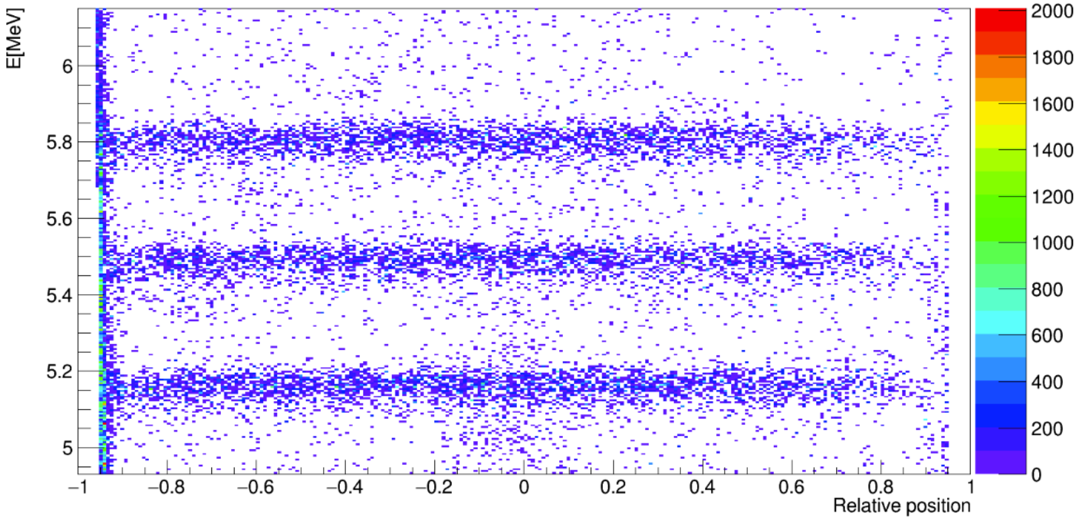

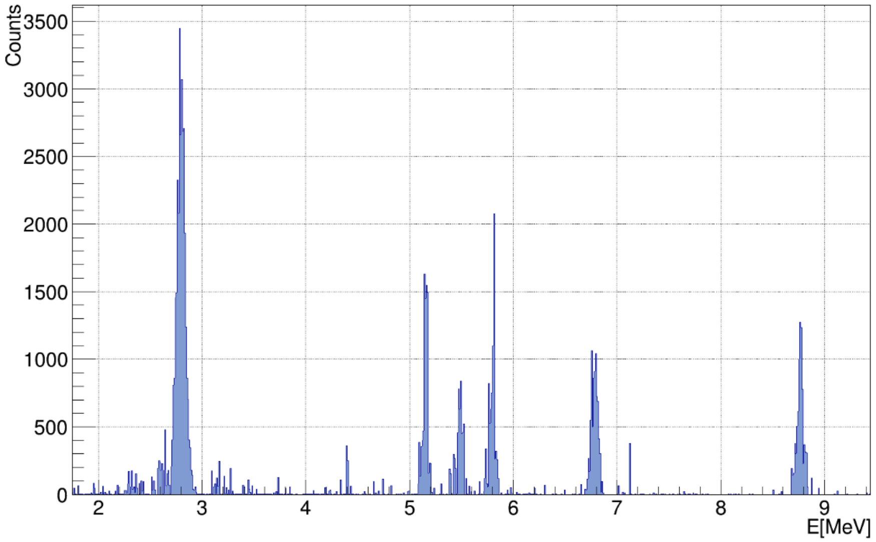

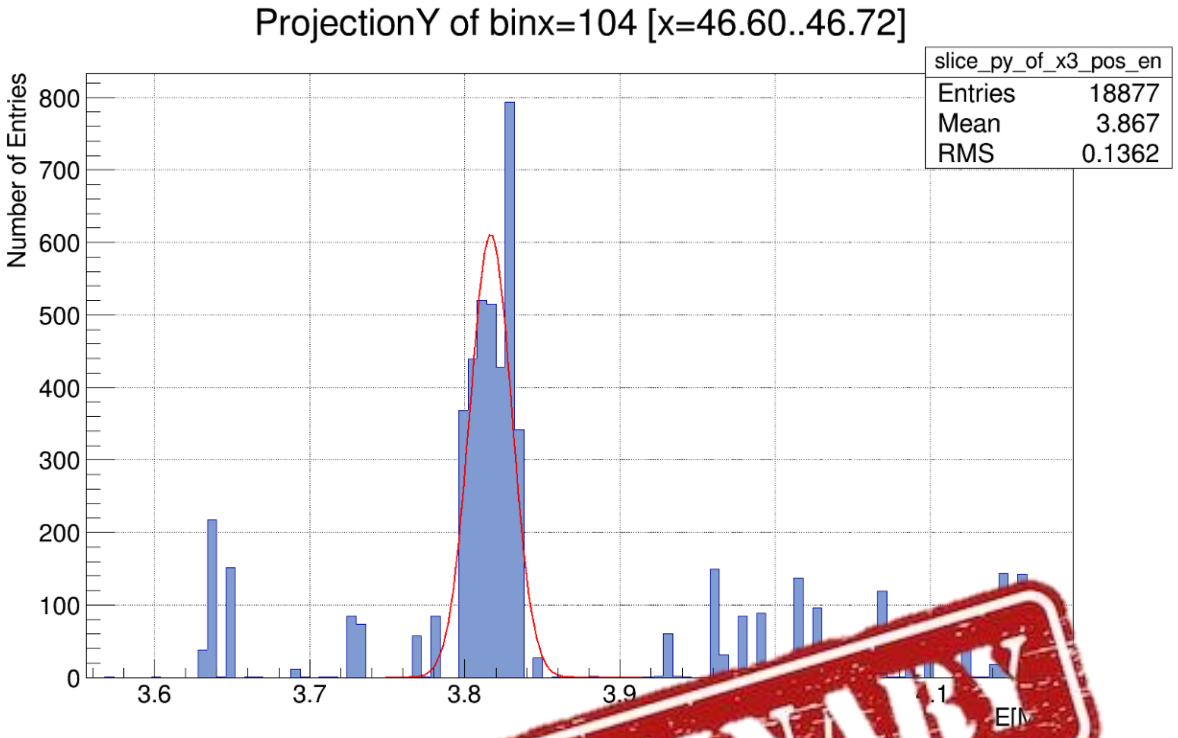

PRELIMINARY

Conclusions

- **The advent of high-intensity & high resolution gamma-ray beam facilities is a great opportunity for nuclear physics and astrophysics, as a number of reaction of primary astrophysical importance can be measured for the first time**

- **To catch these new experimental opportunities, the Asfin group is developing new arrays with peculiar characteristics: high-resolution, low-threshould, high-efficiency, compactness…**

- **Preliminary results on methods and arrays make us confident for the new perspectives and open the way for new experimental campaigns**

- **WAITING FOR ELI-NP!!!!!!**

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Thank you for your attention