Indirect measurement of the $^{19}F(p,\alpha\gamma)^{16}O$ and $^{19}F(p,\gamma)^{20}Ne$ reactions and direct observation of the 11 keV resonance

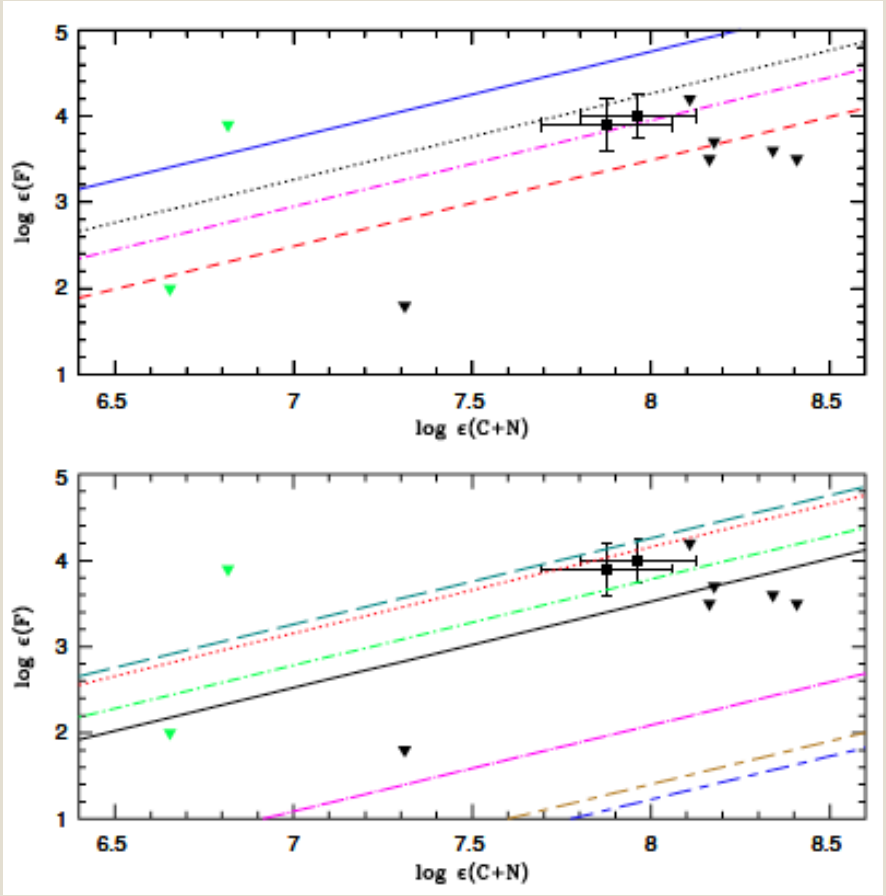
Marco La Cognata

Outline

- The physical problem
- The method
- The experiment
- Some details on the data analysis
- ^{20}Ne spectroscopy
- The astrophysical factors
- The reaction rates
- Some very preliminary astrophysical consequences

The astrophysical context

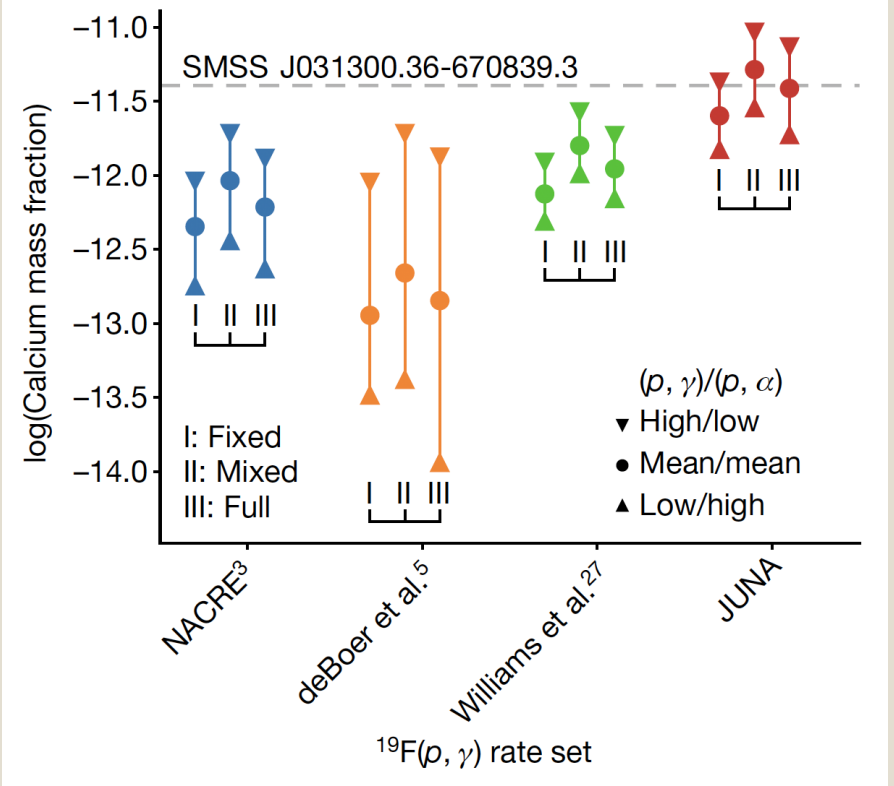
- s-nuclei are produced and brought to the surface thanks to mixing phenomena, together with fluorine that is produced in the same region from the same n-source.
- ^{19}F is a key isotope as it can be used to probe AGB star mixing phenomena and nucleosynthesis. But its production is still uncertain!
- Mostly, unphysical AGB models produce fluorine abundances compatible with observations



Lucatello, S., et al. 2011, ApJ, 729, 40

And recently

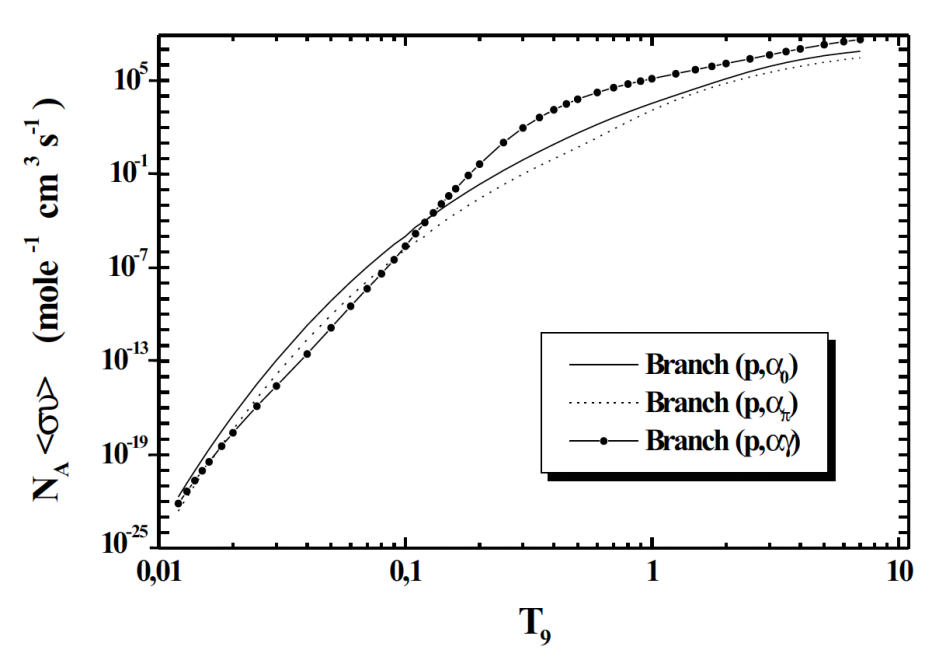
- The most metal-poor stars observed in the Milky Way's halo today display the diluted nucleosynthetic signatures resulting from pop III stars that preceded them
- Observers discovered one of the oldest known stars in the Universe, SMSS0313-6708, and suggested that a CNO breakout during hydrogen burning is the source of calcium production, reporting [Ca/H] = –7.2



Liyong Zhang et al., 656 | Nature | Vol 610 | 27 October 2022

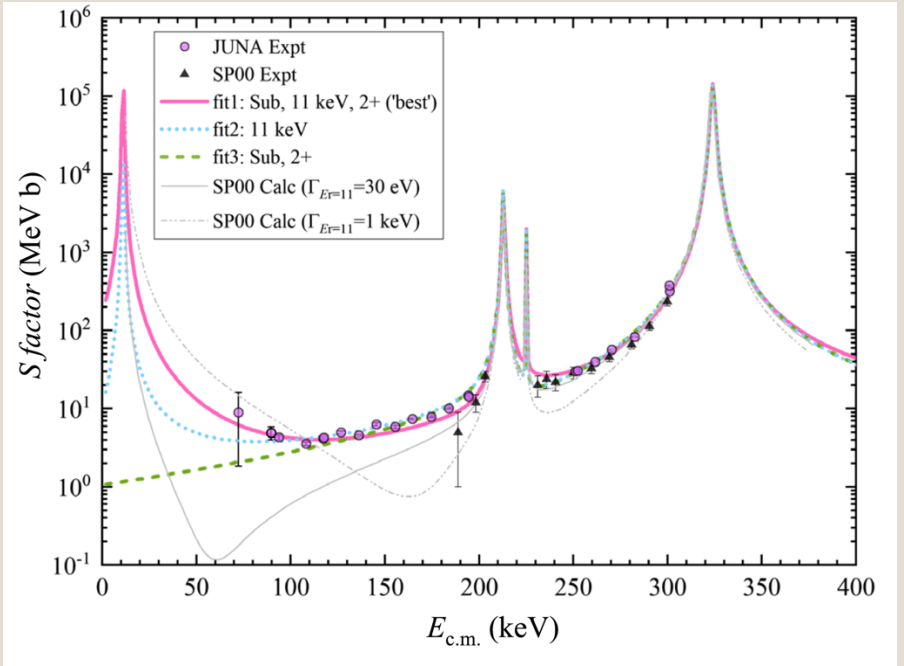
The turning point

- From the dominance of the α_0 channel



K. Spyrou et al., Eur. Phys. J. A 7, 79-85 (2000)

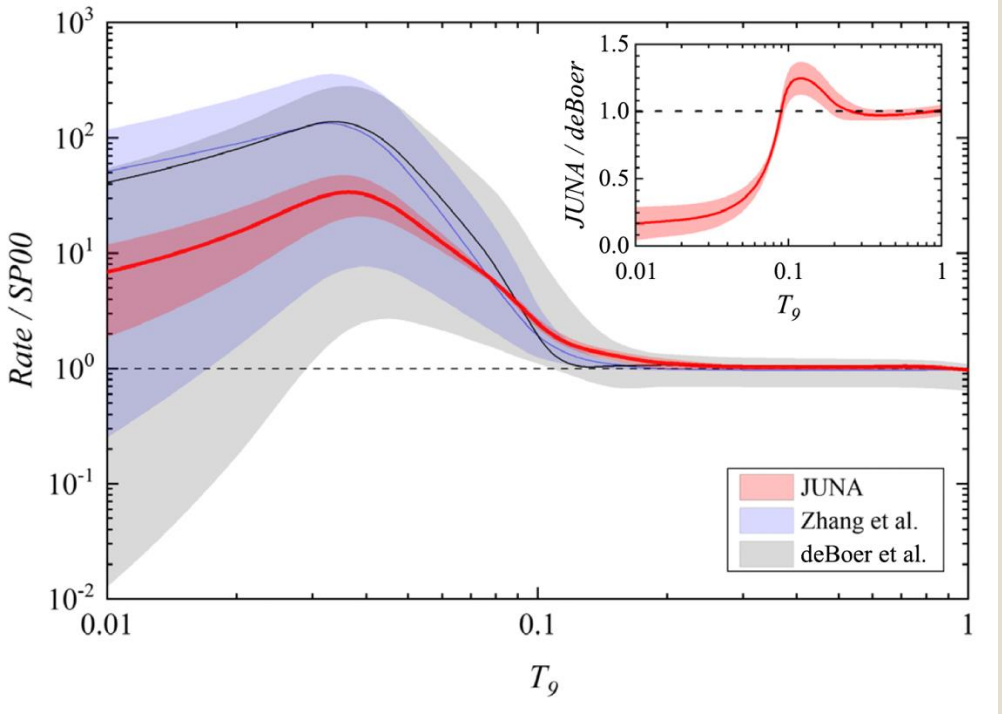
- To the appearance of the 11 keV peak



L. Y. Zhang et al., PHYSICAL REVIEW LETTERS 127, 152702 (2021)

Why?

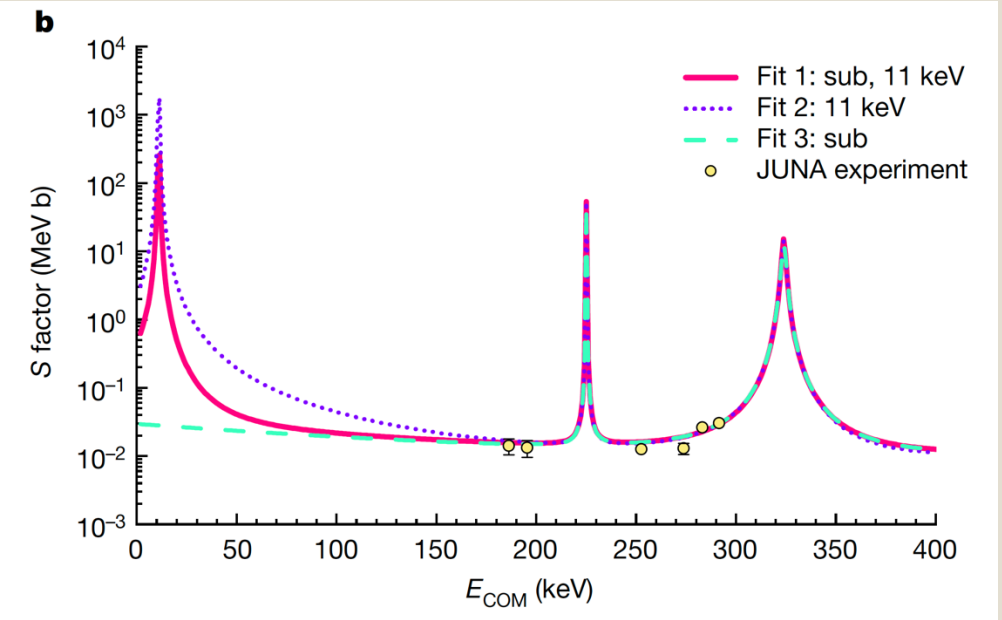
- The JUNA collaboration corroborates the occurrence of a resonance at 11 keV based on their R-matrix analysis
- This resonance determines a huge increase in the rate of the (p,$\alpha\gamma$) channel, even higher than a factor of 10 with respect to Spyrou et al. work at some temperatures.
- The resonance is so large that the effect extends up to 0.1 GK, with potential impact on several astrophysical scenarios



L. Y. Zhang et al., PHYSICAL REVIEW LETTERS 127, 152702 (2021)

The radiative capture channel

- This result has impacted also the investigation of the gamma-emission channel
- The ratio of the new rate to the NACRE one is as large as 200 at 0.01 GK, and the contribution of the 11 keV resonance is probably relevant event at 0.1 GK
- The new rate would justify the observations of Ca in old stars through the breakout from the CNOF cycles.



Liyong Zhang et al., 656 | Nature | Vol 610 | 27 October 2022

However

- Even if the JUNA collaboration could reach record low energies by measuring deep underground, the lowest energy points were measured at 70 keV for the (p,$\alpha\gamma$) channel and 185 keV for the (p,γ) channel.

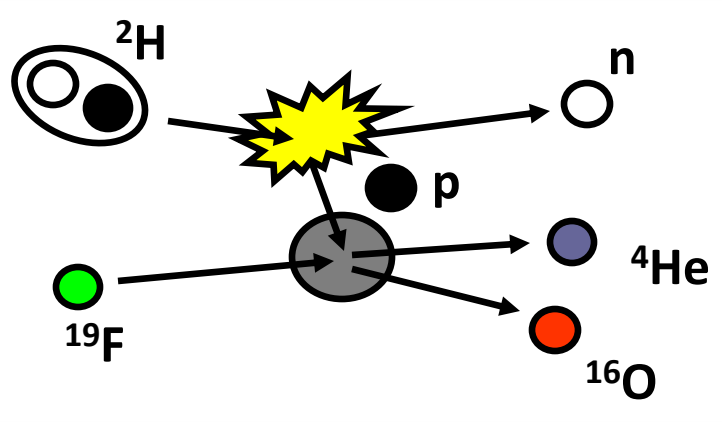
- 70 keV Gamow energy corresponds to 50 MK and 185 keV to 220 MK, above the typical temperatures for fluorine burning in AGB stars (<40 MK), and also for hot CNO breakout in early stars (~100 MK).

- Extrapolation was carried out using R-matrix analysis, including a -448 keV subthreshold resonance. The existence of the 11 keV state and of the latter, their spin-parities and strengths of such states, would be crucial to verify the conclusions based on extrapolations

So let's THM

When narrow resonances dominate the S-factor the reaction rate can be calculated by means of the resonance strengths and resonance energies only. Both can be deduced from the THM cross section.

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}\mathrm{Al}})} \frac{\Gamma_p^i \Gamma_\alpha^i}{\Gamma_{\mathrm{tot}}}$$



When you have a resonant reactions, the THM cross section can be written as the product of a proton transfer term (upper pole) and compound nucleus decay term (lower pole). In PW, the upper pole is proportional to the p-n momentum distribution

$$\frac{d^2\sigma}{dE_{Cc}\, d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\, |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

La Cognata M., et al, APJ 708 (2010) 796

So let's THM

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}\mathrm{Al}})} \frac{\Gamma_p^i \Gamma_\alpha^i}{\Gamma_{\mathrm{tot}}}$$

What is its physical meaning of the resonance strength?

Area of the Breit-Wigner describing the resonance

- For narrow resonances:

$$\delta(x - E_{R_i}) = \lim_{\Gamma_i \to 0} \frac{1}{2\pi} \frac{\Gamma_i}{(x - E_{R_i})^2 + \left(\frac{\Gamma_i}{2}\right)^2}$$

- The THM cross section can be fitted using the equation:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E_{c.m.}\,\mathrm{d}\Omega_n} = \sum_{i=1}^{n} N_i \times \exp\left[-\frac{1}{2}\left(\frac{E_{c.m.} - E_{R_i}}{\sigma}\right)^2\right]$$

$$\omega\gamma_i^{\mathrm{THM}} \approx \omega_i N_i \frac{\Gamma_{p,\,\mathrm{s.p.}}^i}{\sigma_{(d,n)}(\theta_n^{c.m.})}$$

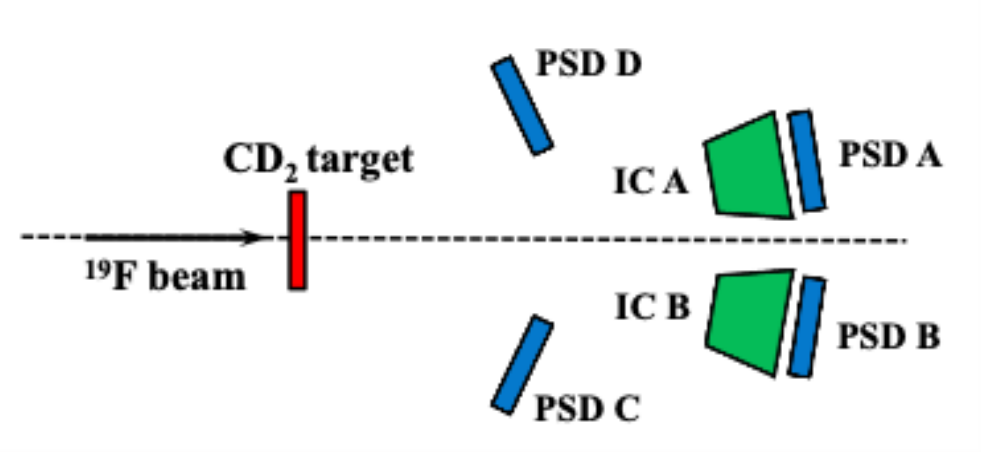
- $\boldsymbol{\Gamma}_{\mathrm{s.p.}}$ is calculated using the potential model
- $\boldsymbol{\sigma(\theta)}$ is calculated in PW using the same well & w.f.

$$\omega\gamma_i^{\mathrm{THM}} = \frac{\omega_i N_i}{\omega_{norm} N_{norm}} \frac{\frac{\Gamma_{p,\,\mathrm{s.p.}}^i}{\sigma_{(d,n)}^i(\theta_n^{c.m.})}}{\frac{\Gamma_{p,\,\mathrm{s.p.}}^{norm}}{\sigma_{(d,n)}^{norm}(\theta_n^{c.m.})}} \omega\gamma_i^{norm}$$

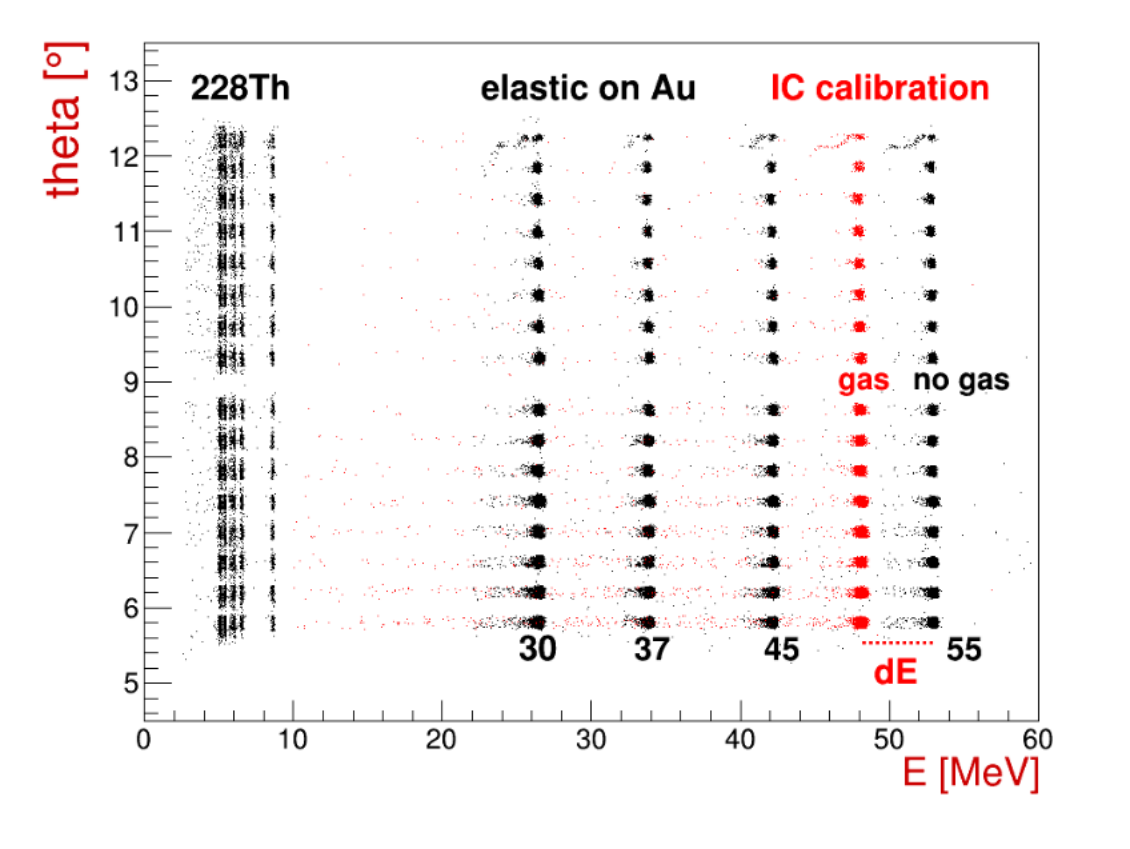
The double ratio ensures an extra small model dependence (~10%)

The experiment

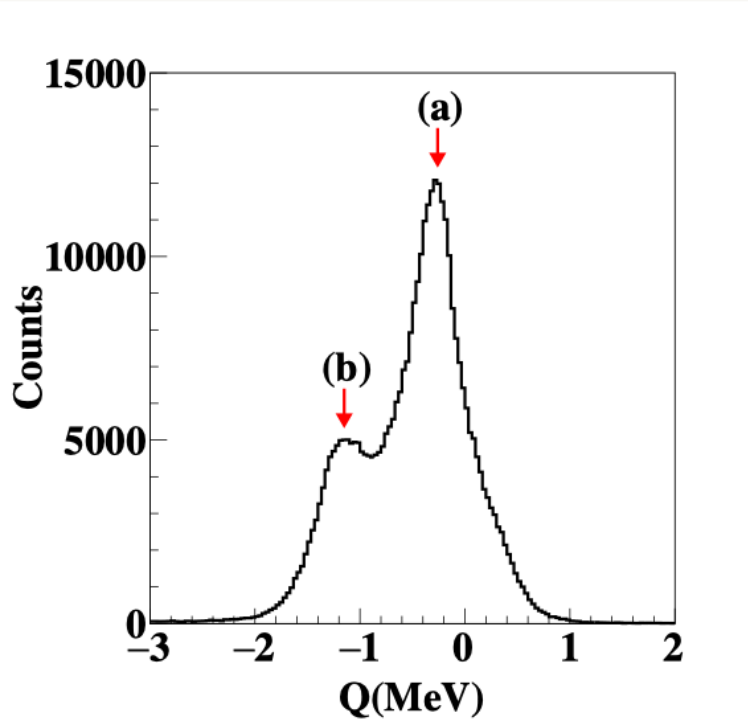
- We run at LNS Tandem using a 55 MeV ^{19}F beam and CD_2 target



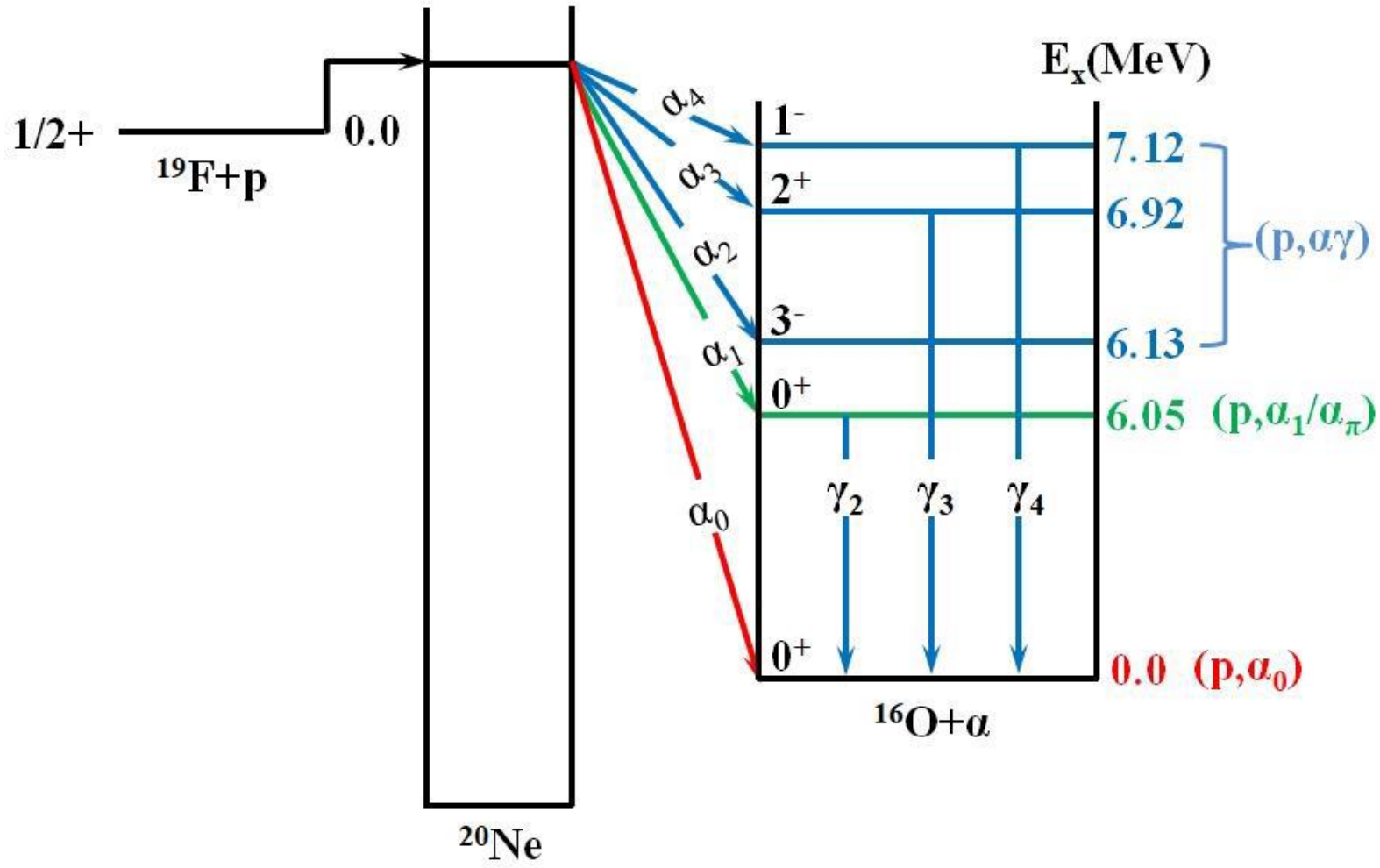
- Calibrations



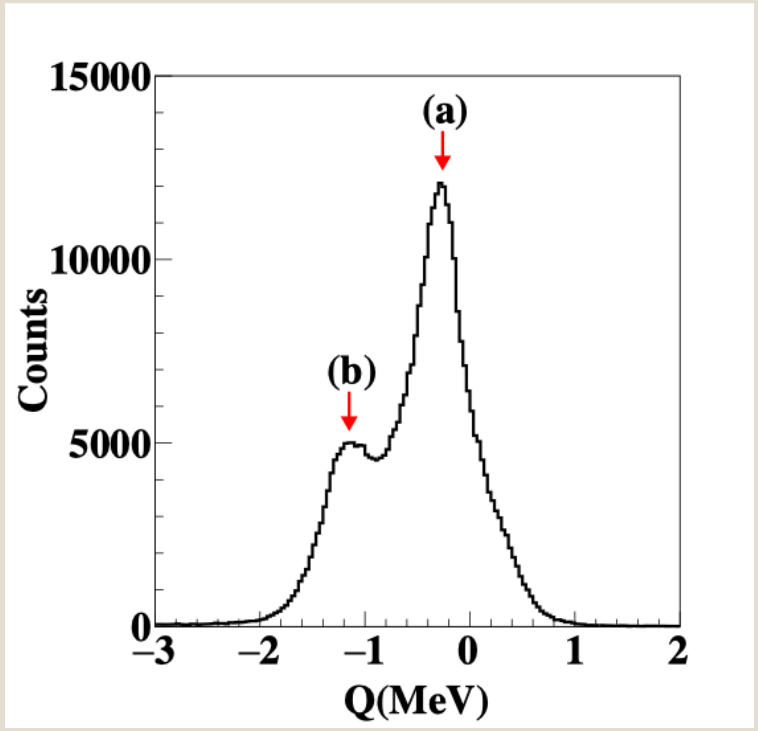
Channel selection



Coincidence + Z=8 selection

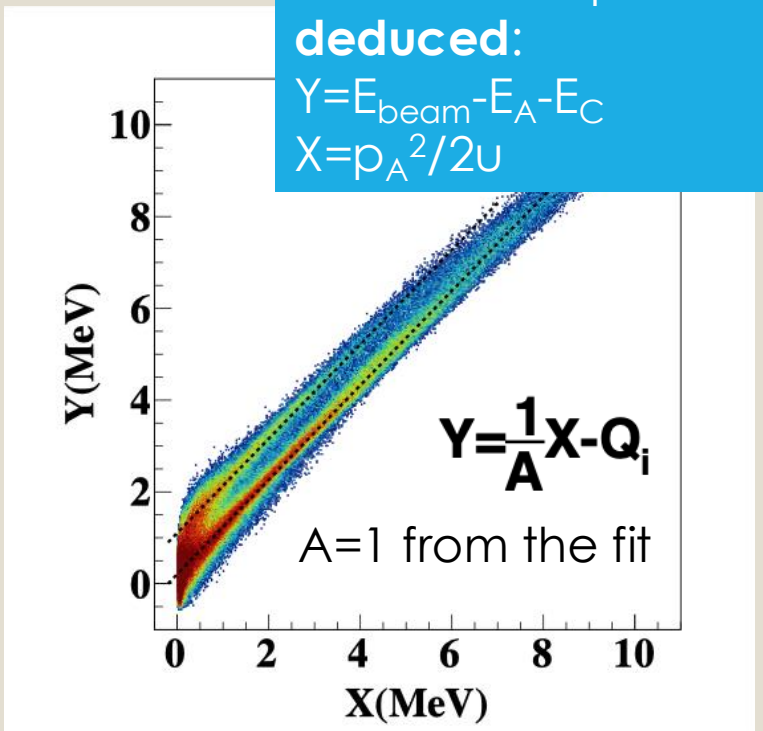


Channel selection

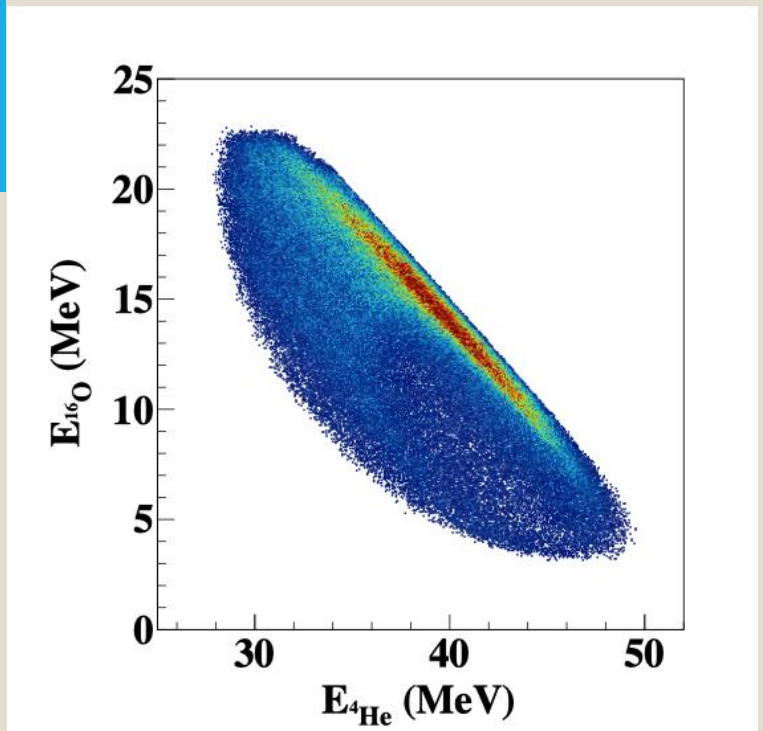


Coincidence + Z=8 selection

The mass of the undetected particle is **deduced**:
$Y=E_{beam}-E_A-E_C$
$X=p_A^2/2u$

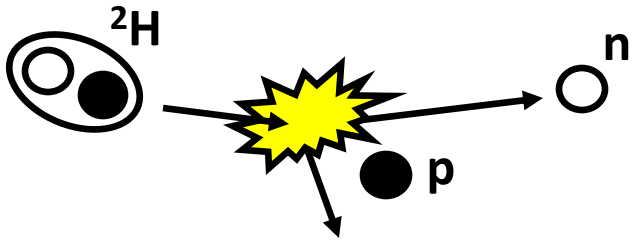


Badalà et al., La Rivista del Nuovo Cimento 45, 189-277 (2022)



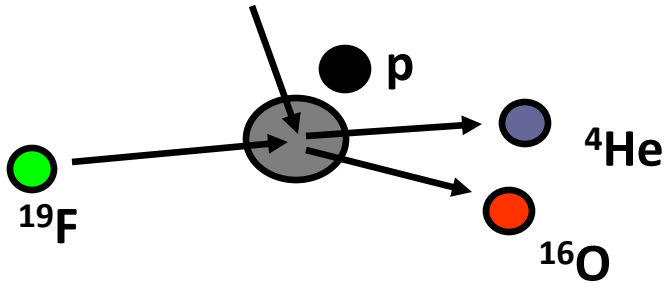
Kinematic locus for $\alpha_1+\alpha_2$ channel

Selection of QF

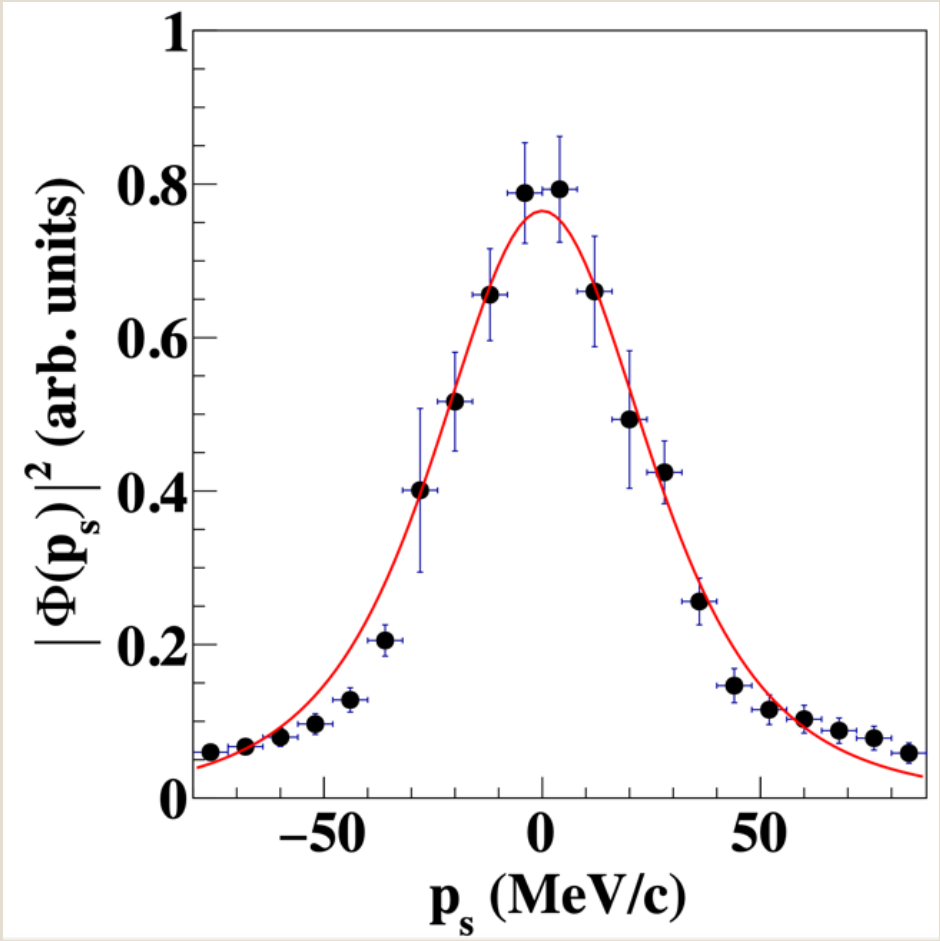


Quasi-free (QF) break

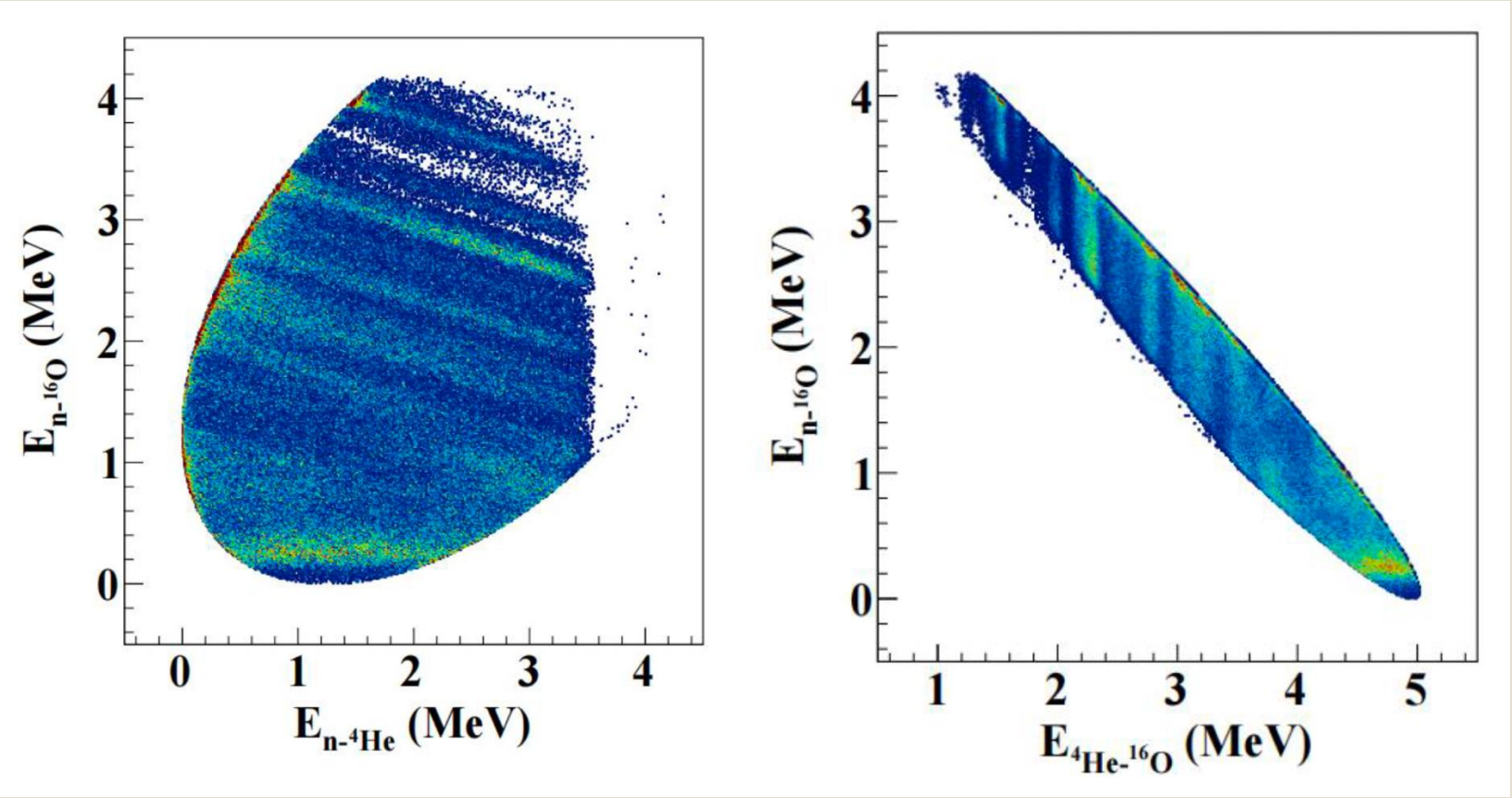
→ Used to induce the reaction of astrophysical interest



- If the process is direct, the experimental n-momentum distribution is **the same as inside deuteron**
- If the n-p relative distance is larger than the nuclear interaction radius (so if p-n relative momenta are small), **p and n and independent (QF)** particles and n acts as spectator to $^{19}F(p,\alpha)^{16}O$

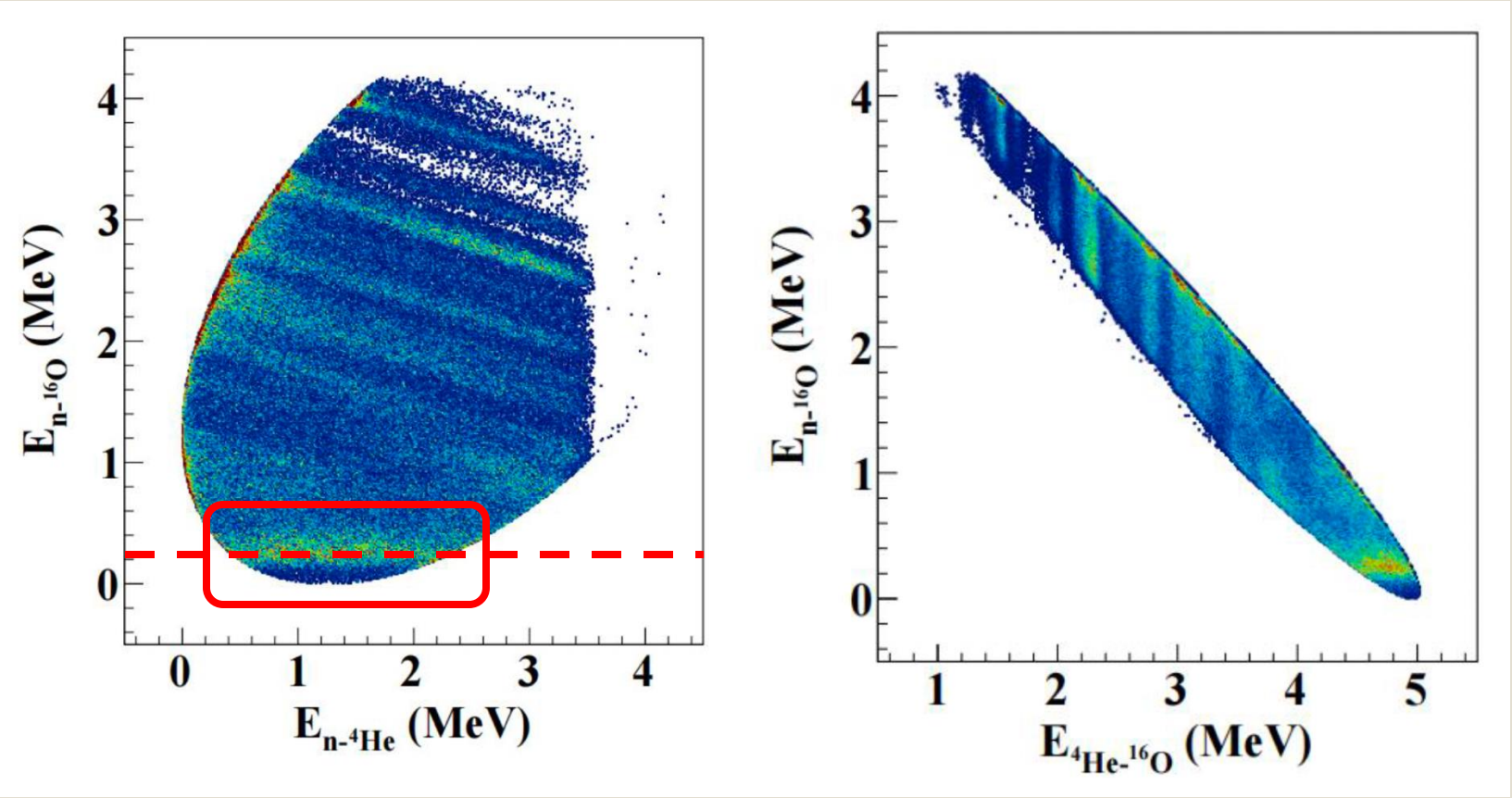


Other reaction mechanisms?



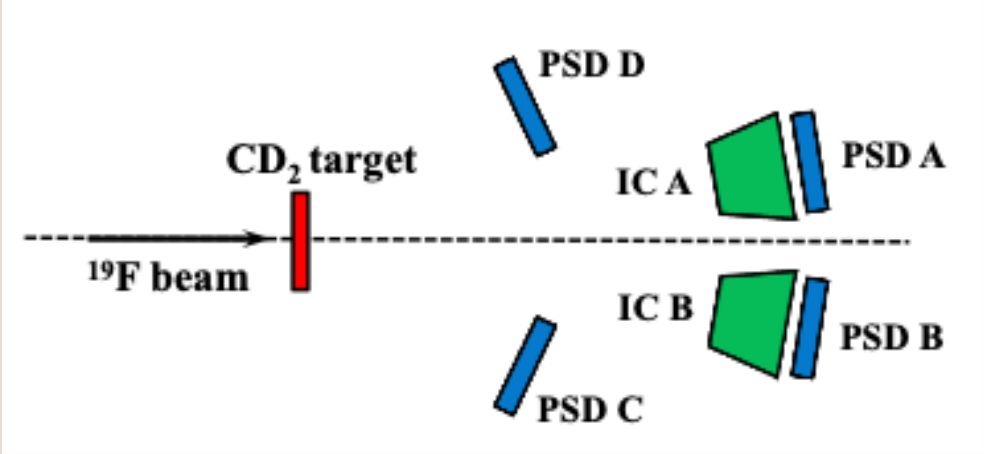
- Population of states in ^{17}O or ^{5}He (produced in sequential decay processes) would lead to the appearance of loci in the relative-energy plots
- The 2D spectra show the presence of **resonances in ^{17}O but they lie outside** the phase-space region of interest for the $^{19}F(p,\alpha)^{16}O$ reaction

Other reaction mechanisms?

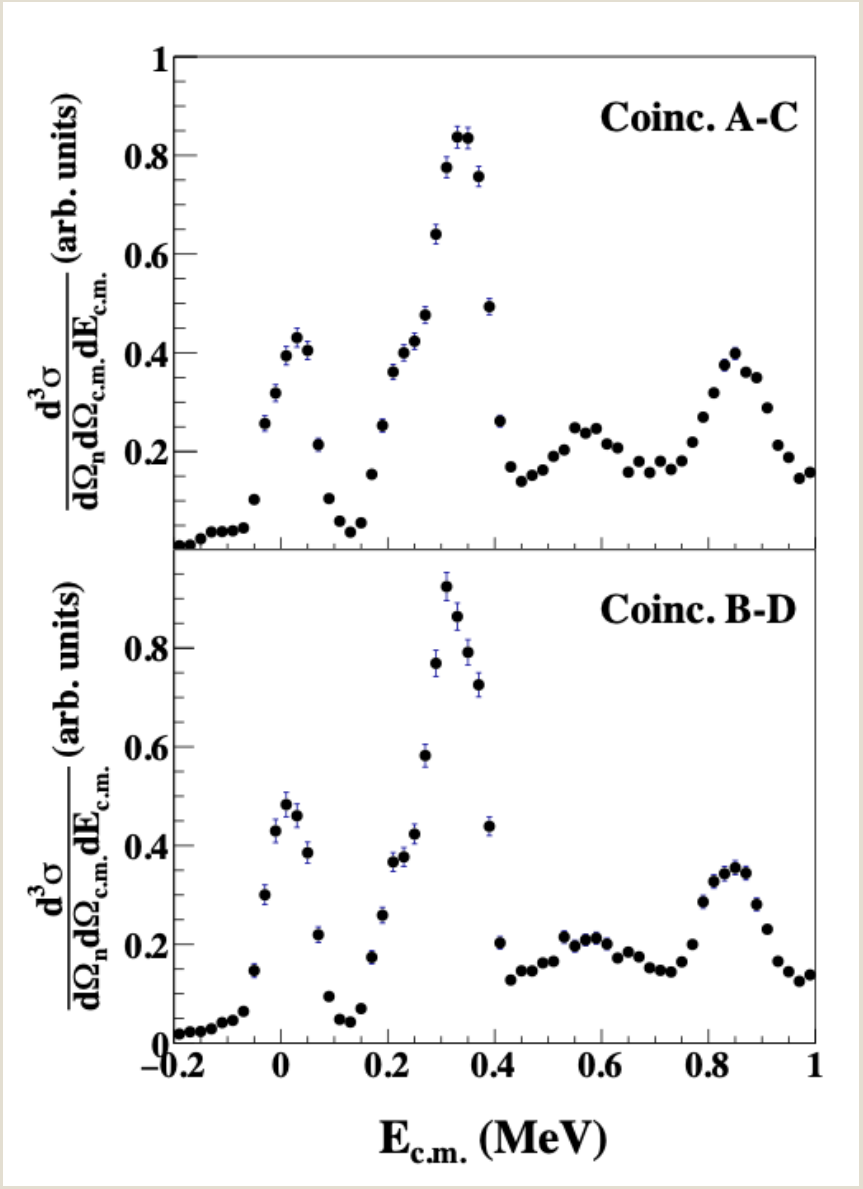


- Population of states in ^{17}O or ^{5}He (produced in sequential decay processes) would lead to the appearance of loci in the relative-energy plots
- The 2D spectra show the presence of **resonances in ^{17}O but they lie outside** the phase-space region of interest for the $^{19}F(p,\alpha)^{16}O$ reaction

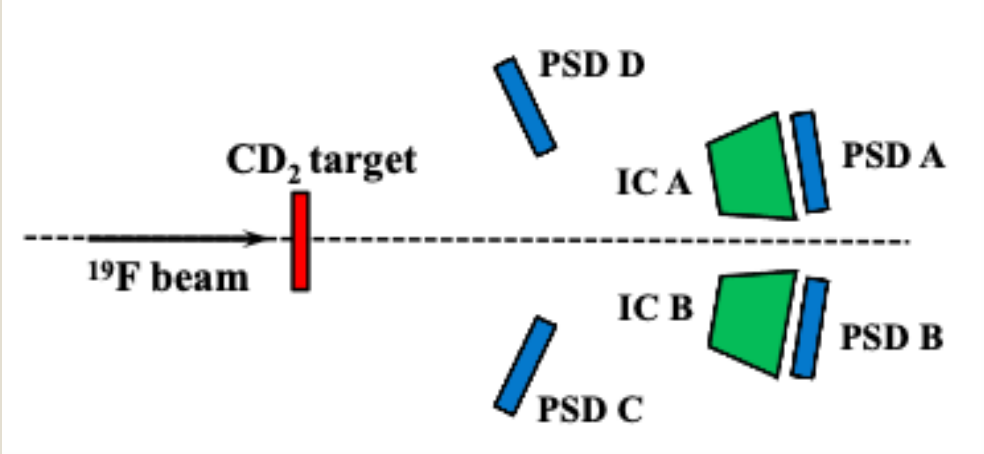
QF yield: consistency test



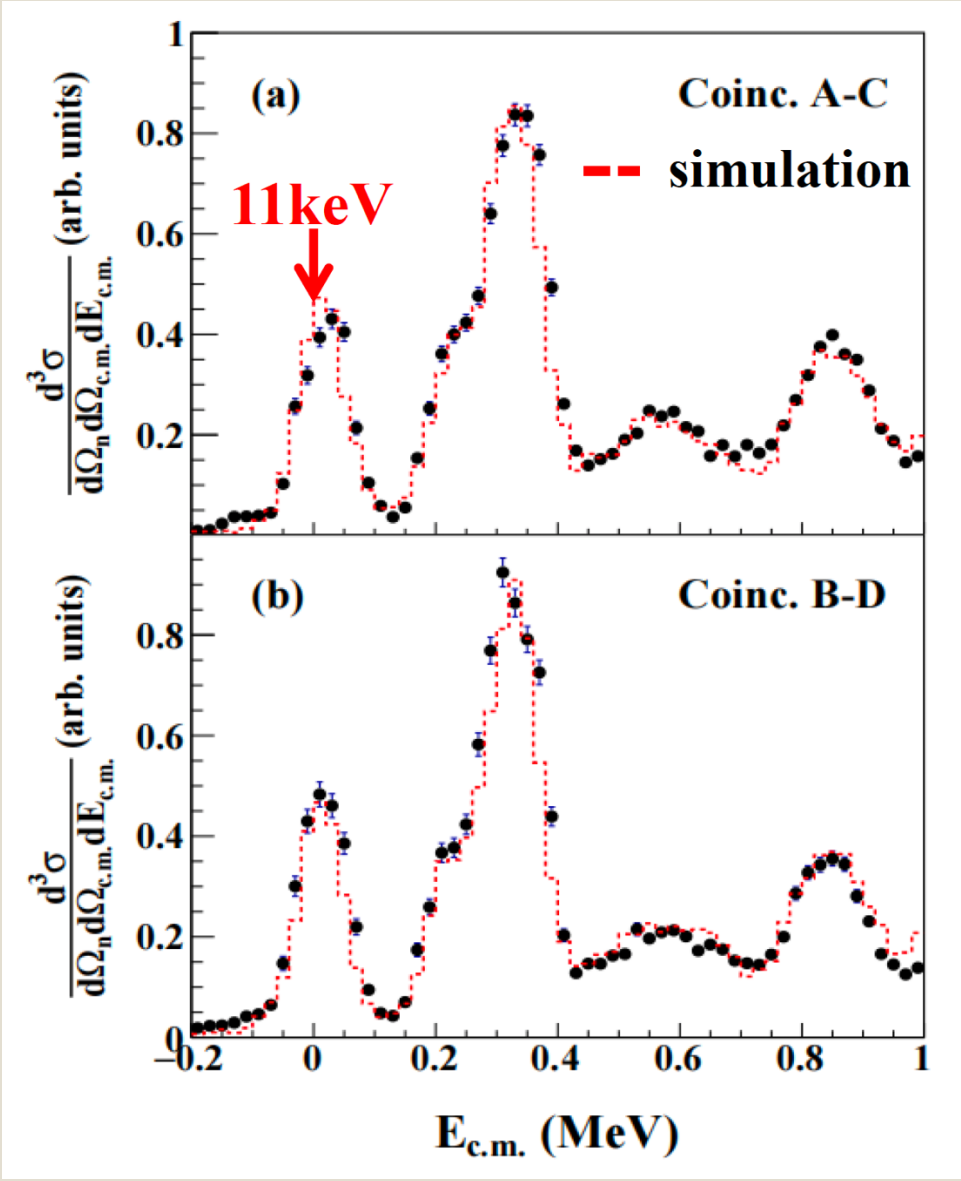
- A-C and B-D detector couples are symmetric with respect to the beam axis, so we expect equal spectra (apart from experimental effects such as energy resolution)
- The experimental spectra look very similar, and they perfectly agree with a MC simulation including all experimental effect (beam and detector resolutions, emittance and so on).



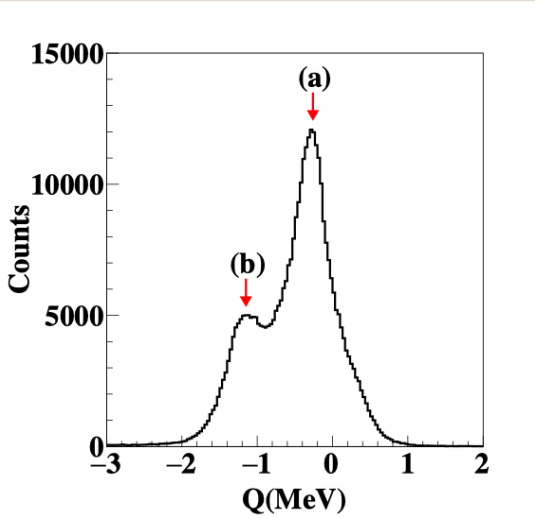
QF yield: consistency test



- A-C and B-D detector couples are symmetric with respect to the beam axis, so we expect equal spectra (apart from experimental effects such as energy resolution)
- **The experimental spectra look very similar, and they perfectly agree with a MC simulation** including all experimental effect (beam and detector resolutions, emittance and so on).



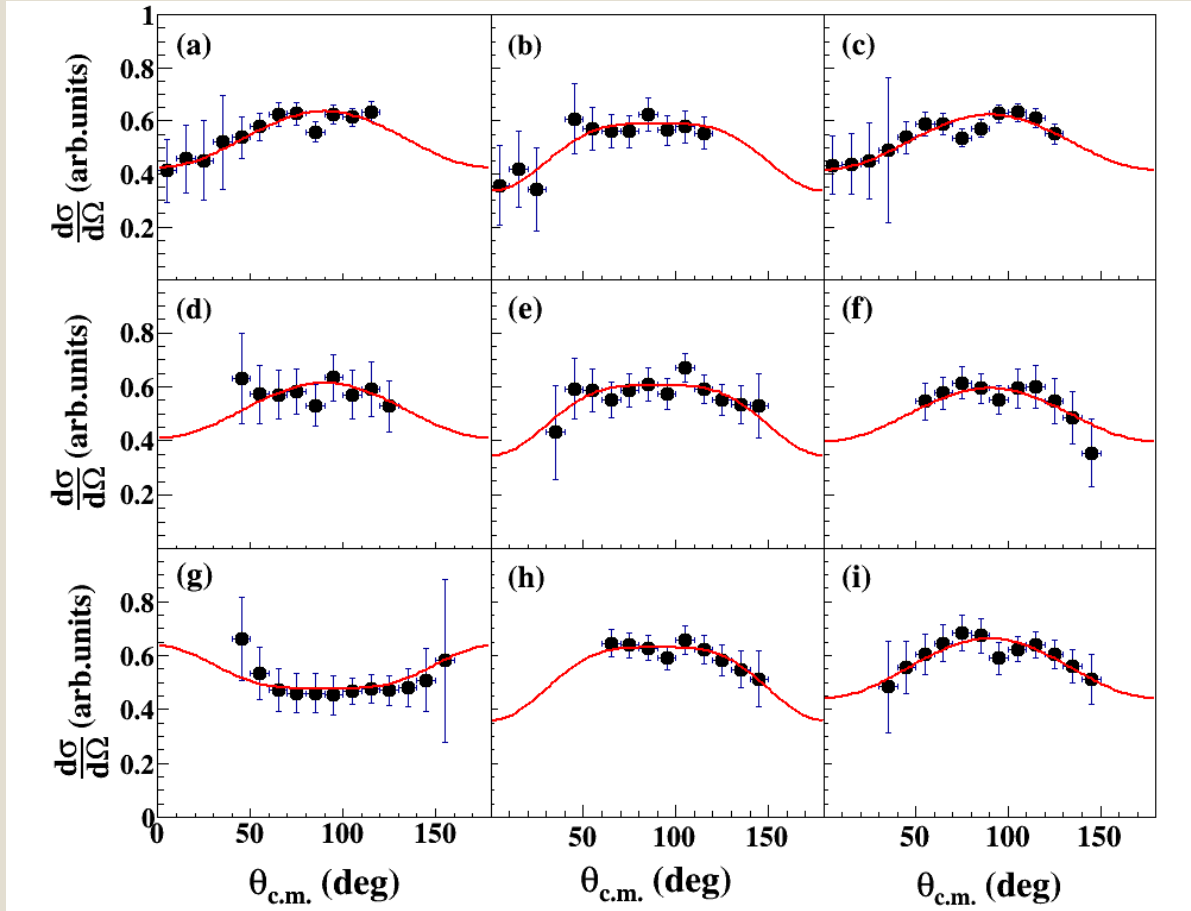
Angular distributions



The $\alpha_1+\alpha_2$ channels are not separated

→ ^{16}O spin-parities for 1st and 2nd excited states are 0+ and 3-

→ Angular distributions are significantly different, and the contributions can be disentangled

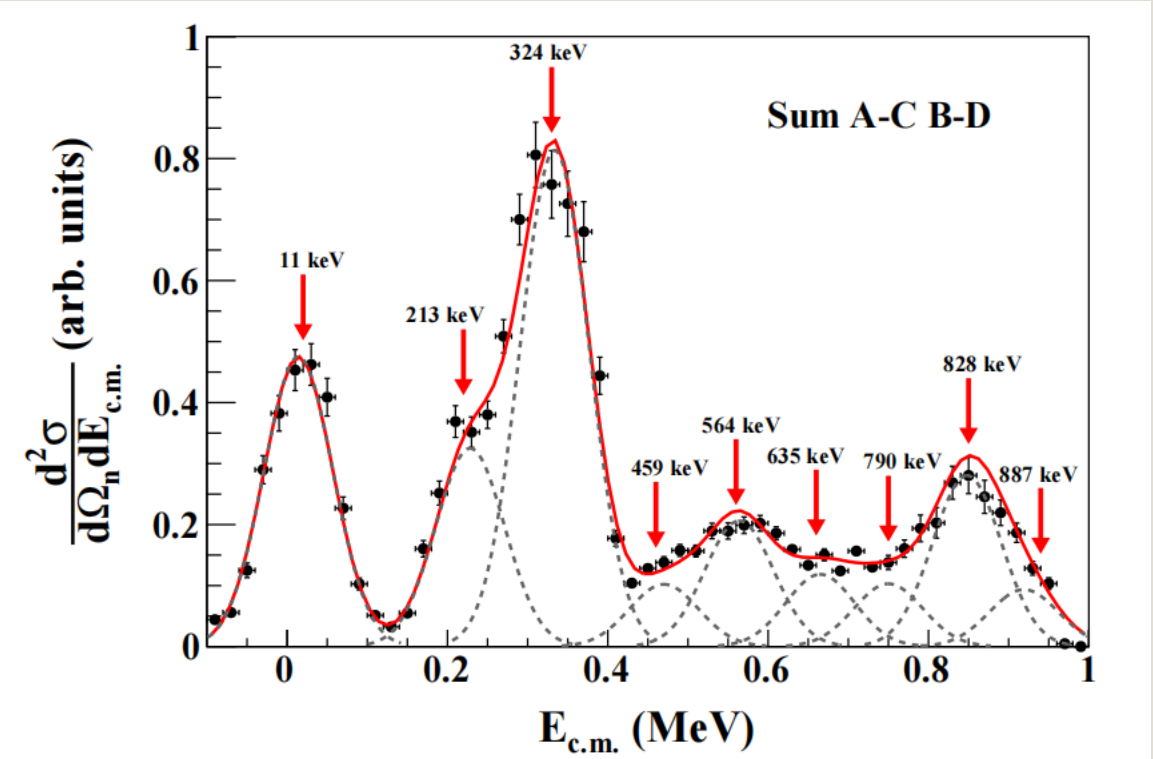


α_1 channel is negligible in the energy range

(**a**) -0.01 - 0.06 MeV, (**b**) 0.18 - 0.22MeV, (**c**) 0.3 - 0.34 MeV, (**d**) 0.45 - 0.47 MeV, (**e**) 0.55 - 0.57 MeV, (**f**) 0.625-0.645 MeV, (**g**) 0.77 - 0.79 MeV, (**h**) 0.82 - 0.84 MeV, (**i**) 0.88 - 0.90 MeV.

The red lines are the theoretical angular distributions from Blatt & Biedenharn, Reviews of Modern Physics 24 (1952) 258

From the THM cross section…



A-C and B-D detector couples are consistent, so data are summed up to improve precision

$$\omega\gamma_i^{\mathrm{THM}} \approx \omega_i N_i \frac{\Gamma^i_{p,\,\mathrm{s.p.}}}{\sigma_{(d,n)}(\theta_n^{c.m.})}$$

$$\frac{d^2\sigma}{dE_{c.m.}\,d\Omega_n} = \sum_{i=1}^{n} N_i \times \exp\left[-\frac{1}{2}\left(\frac{E_{c.m.} - E_{R_i}}{\sigma}\right)^2\right]$$

From the fitting of the THM cross section we deduce the resonance strengths in arbitrary units (only fitting parameters: strengths)

Normalization to the most prominent peaks at 324 keV and 828 keV (each has a strength known with 4% accuracy)

Normalization error is about 3%
Model dependence at most 13%

Theory in (e.g.) La Cognata M., et al, APJ 708 (2010) 796

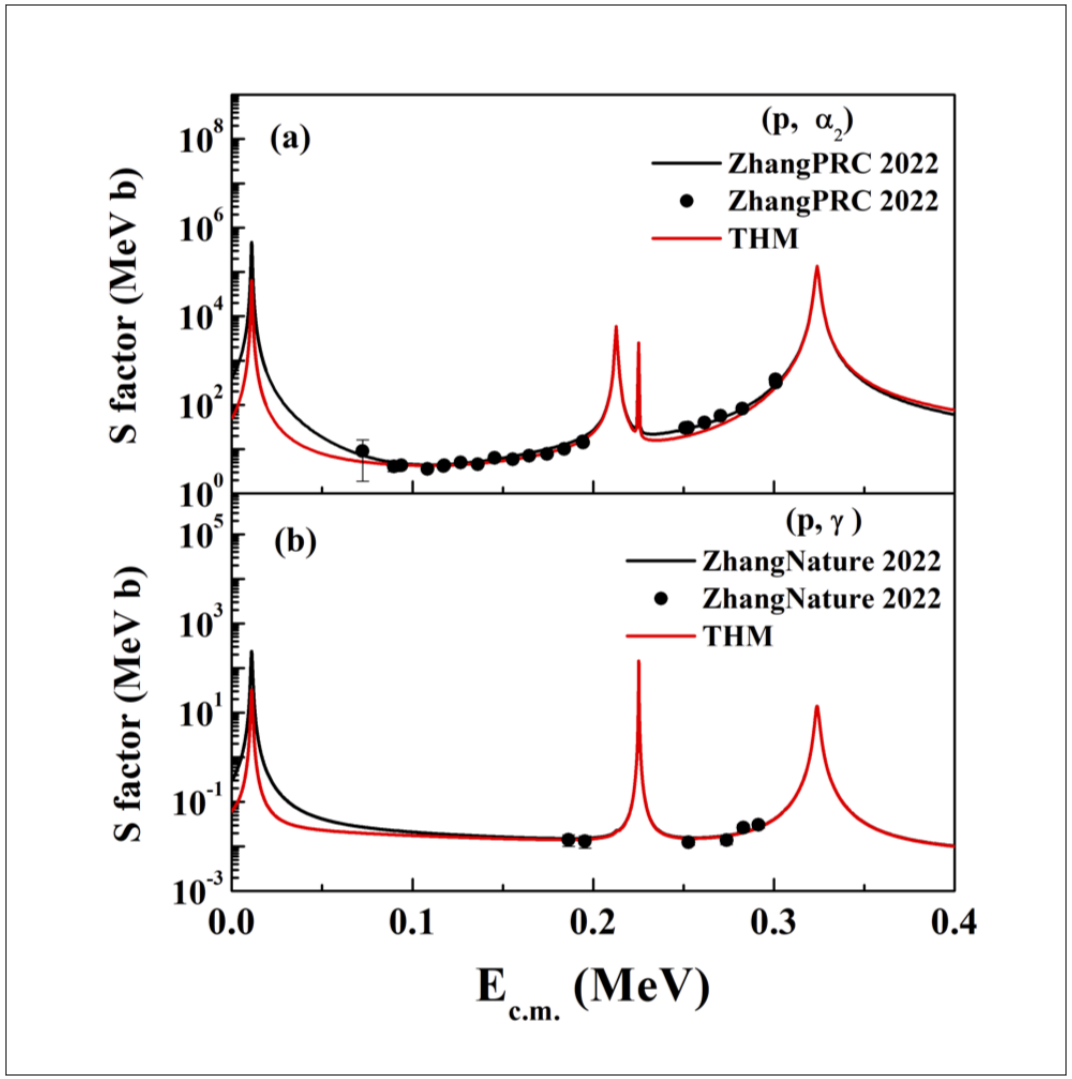
…to the resonance strengths

- **The main result of our work is the first time observation of the 11 keV resonance**
- we confirm the 1^+ spin parity attribution based on our experimental angular distributions analysis
- Our measured strength is 5.8 times smaller than the extrapolated values
- The analysis was extended to all resonances below 1 MeV to conduct a validity test of our method → the perfect agreement (with a maximum deviation of 1.8σ) indicates a lack of systematic errors within uncertainties
- We do not observe the 225 keV resonance due to energy resolution effects

	E_i^R (keV)	J^π	$\omega\gamma$ (eV) [a]	$\delta\omega\gamma$ (eV) [a]	$\omega\gamma$ (eV) [b]	$\delta\omega\gamma$ (eV) [b]
(1)	11	1^+	7.5×10^{-29}	3×10^{-29}	1.3×10^{-29}	1.6×10^{-30}
(2)	212.71	2^-	2.2×10^{-2}	4×10^{-3}	2.3×10^{-2}	2.7×10^{-3}
(3)	323.31	1^+	23.1	0.9	24.5	1.8
(4)	459.53	1^+	9.5	0.7	11.4	1.3
(5)	564.42	2^-	50	6	43.7	4.1
(6)	635.31	1^+	88	10	103.4	11.4
(7)	790.53	2^+ [c]	27	6	23.7	2.7
(8)	828.17	2^-	785	32	664.2	59.0
(9)	887.14	1^+	452	31	567.1	63.2

[a] Strengths as reported in NACRE.
[b] Present-work strengths.
[c] Our analysis suggests this state is 2^+.

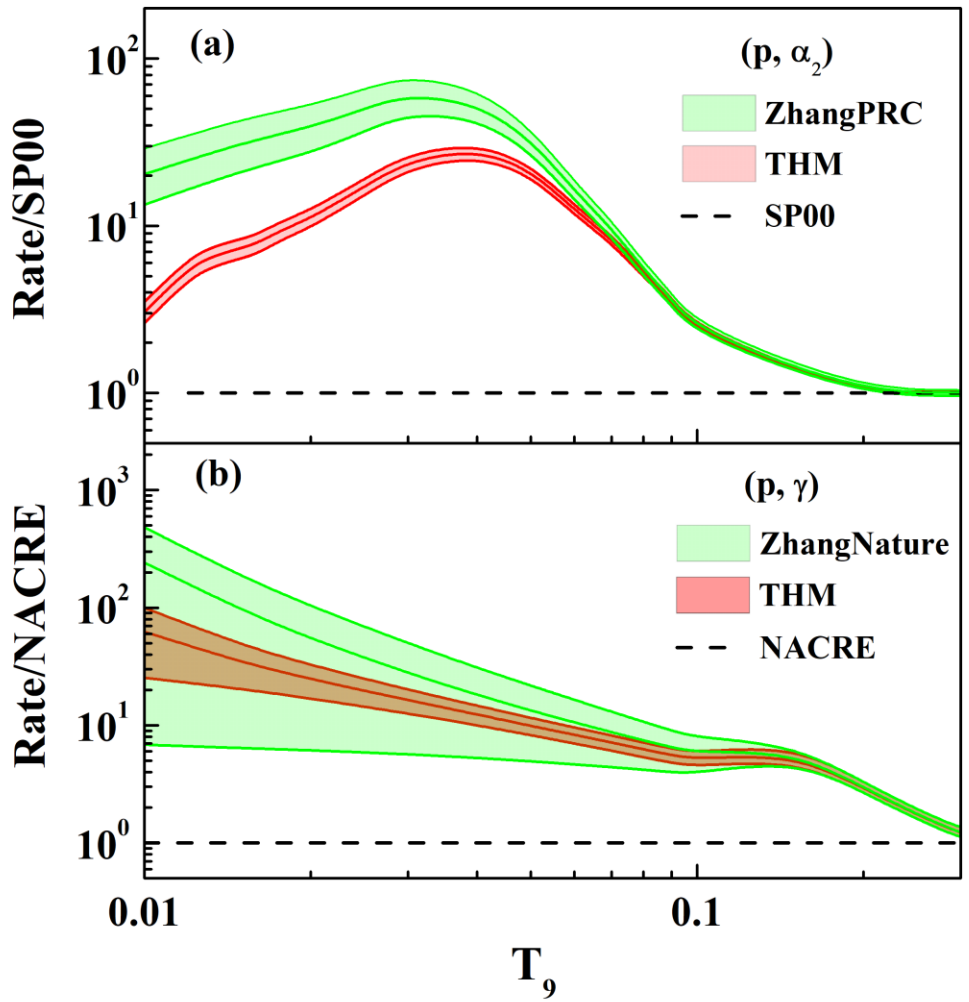
List of the measured strengths and comparison with the literature. Progressive number, resonance energies, NACRE strengths and their errors, and present work's strengths and their uncertainties, respectively.



The THM S-factors

- To evaluate the compatibility of the present $^{19}F(p,\alpha\gamma)^{16}O$ and $^{19}F(p,\gamma)^{20}Ne$ S-factors with Zhang et 2022 results, we have used the THM strength of the 11 keV resonance, alongside the strengths available in the literature for the other resonances, to calculate the astrophysical factor S(E) in the R-matrix framework using AZURE2
- The corresponding astrophysical factors are in good agreement with available experimental data where available, denoting a poor constraint set by direct experimental data taken at energies far from the region of interest

Calculation of the reaction rate



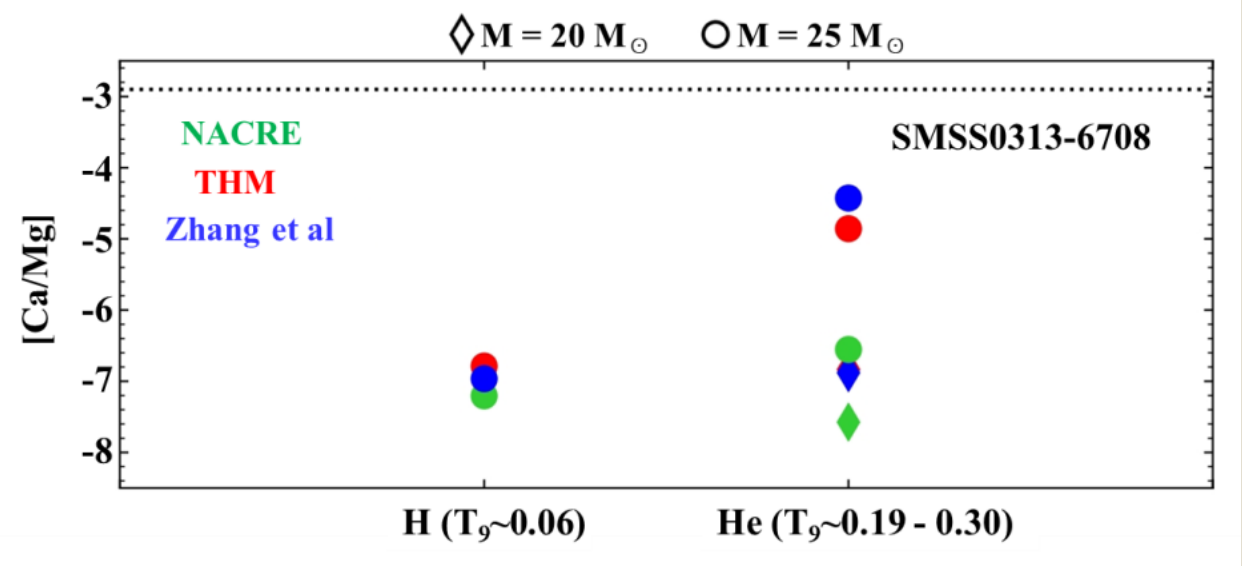
The reaction rate was calculated from the S-factor.

$$N_A < \sigma v >= N_A \sqrt{\frac{8}{\pi \mu}} \frac{1}{kT^{3/2}} \int_0^\infty S(E) \exp[-\frac{E}{kT} - 2\pi\eta] dE$$

- **(p,αγ) channel:** the THM rate is lower than Zhang+ PRC (2022) below ~10^8 K due to the reduced strength of 11keV resonance. At AGB CBP temperatures (~10^7 K) the reduction is a factor of ~7
- **(p,γ) channel:** uncertainties are greatly reduced thanks to our measurement. Also in this case a significant reduction is found, 25% at 5x10^7 K
- **(p,γ)/(p,α):** this ratio is the most important one to set the breakout rate from the CNO cycle. At ~10^8 K this ratio is 4.6-6.4 to be compared with a factor of 5.4-7.4 in Zhang+ Nature (2022), taking NACRE as reference

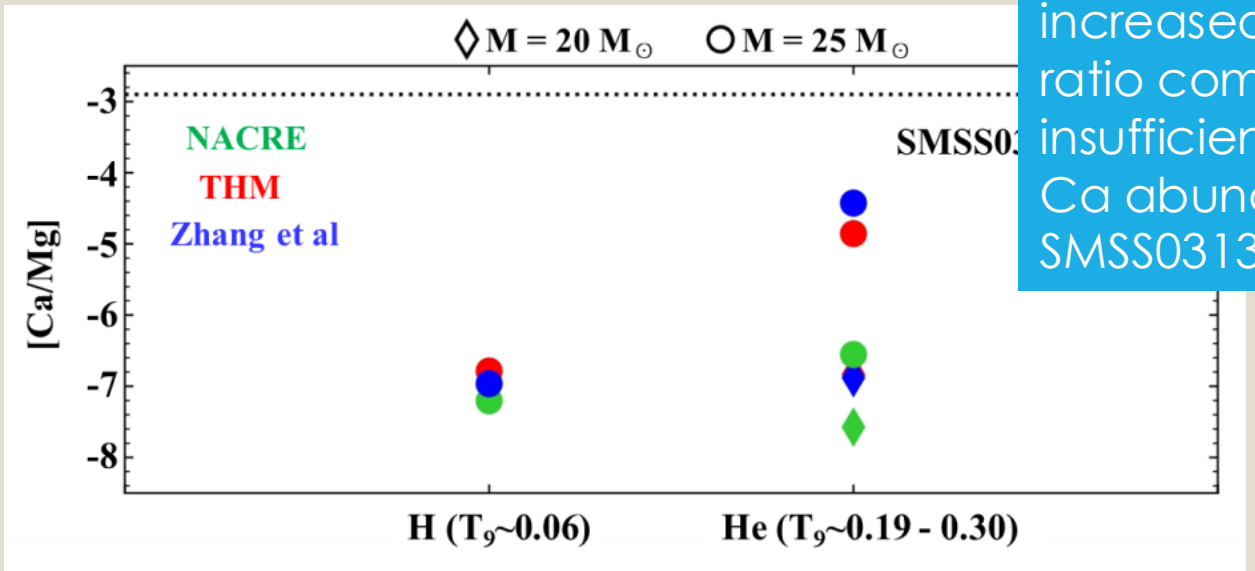
[some] Astrophysical consequences

- Our measurement will impact several astrophysical scenarios. Of course, fluorine production in AGB stars, where CBP and stellar rotation (for instance) influence fluorine production
- **Here we focus on the breakout from the CNO cycle in pop.3 stars.** The $^{19}F(p,\gamma)^{20}Ne$ reaction may lead to a leakage of material towards the NeNa mass region, facilitating calcium production and potentially accounting for the observed Ca abundances in the most metal-poor stars known, such as SMSS0313-6708



[some] Astrophysical consequences

- Our measurement will impact several astrophysical scenarios. Of course, fluorine production in AGB stars, where CBP and stellar rotation (for instance) influence fluorine production
- **Here we focus on the breakout from the CNO cycle in pop.3 stars.** The $^{19}F(p,\gamma)^{20}Ne$ reaction may lead to a leakage of material towards the NeNa mass region, facilitating calcium production and potentially accounting for the observed Ca abundances in the most metal-poor stars known, such as SMSS0313-6708



Our findings indicate that the increased $^{19}F(p,\gamma)^{20}Ne/^{19}F(p,\alpha)^{16}O$ ratio compared to NACRE is insufficient to explain the observed Ca abundance in stars like SMSS0313-6708

Conclusions

- The THM allowed us to reach zero energy in the $^{19}F(p,\alpha\gamma)^{16}O$ and $^{19}F(p,\gamma)^{20}Ne$ S-factors, making it possible to measure the strong 11 keV resonance just hypothesized in previous works
- Results indicate a much lower strength than predicted in recent works, about a factor of 7, though still in agreement with directly measured data at higher energies
- This impacts the reaction rates and their ratios, which are closer to the NACRE one reducing the leakage of material towards the NeNa mass region
- Significant astrophysical consequences are expected, stay tuned

Acknowledgements

X.D. Su,[1,2,3] M. La Cognata,[4,*] N. Vukman,[5,6,7] G. G. Rapisarda,[4,8] M. Mazzocco,[2,3,†] A. A. Oliva,[4] L. Roberti,[4,9,10,11] G.L. Zhang,[1,‡] B. Becherini,[5,12] S. Cherubini,[4,8] M. Costa,[4] A. Di Pietro,[4] P. Figuera,[4] G. L. Guardo,[4] M. Gulino,[4,13] S. Hayakawa,[4,14] I. Indelicato,[4,8] M. La Commara,[15,16] L. Lamia,[4,8,17] D. Lattuada,[4,13] S. Palmerini,[5,12,9] R. G. Pizzone,[4,8] S. M. R. Puglia,[4,8] S. Romano,[4,8,17] M. L. Sergi,[4,8] R. Spartà,[4,13] C. Spitaleri,[4,8] D. Torresi,[4] O. Trippella,[5,12] and A. Tumino[4,13]

[1] *School of Physics, Beihang University, Beijing, 100191, China*
[2] *Dipartimento di Fisica e Astronomia, Università di Padova, Padova, 35131, Italy*
[3] *Sezione di Padova, Istituto Nazionale di Fisica Nucleare, Padova, 35131, Italy*
[4] *Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, Catania, 95123, Italy*
[5] *Sezione di Perugia, Istituto Nazionale di Fisica Nucleare, Perugia, 06123, Italy*
[6] *Ruder Boskovic Institute, Zagreb, 10001, Croatia*
[7] *Faculty of Science, University of Split, Split, 21000, Croatia*
[8] *Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Catania, 95123, Italy*
[9] *Osservatorio Astronomico di Roma, Istituto Nazionale di Astrofisica, Monte Porzio Catone 20(RM), 00078, Italy*
[10] *Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Konkoly Budapest, H-1121, Hungary*
[11] *CSFK HUN-REN, MTA Centre of Excellence, Konkoly Budapest, H-1121, Hungary*
[12] *Department of Physics and Geology, University of Perugia, Perugia, 06123, Italy*
[13] *Dipartimento di Ingegneria e Architettura, Kore University, Enna, 94100, Italy*
[14] *Center for Nuclear Studies, The University of Tokyo, Wako-shi (Saitama), 351-0198, Japan*
[15] *Sezione di Napoli, Istituto Nazionale di Fisica Nucleare, Napoli, 80126, Italy*
[16] *Dipartimento di Farmacia, Università di Napoli "Federico II", Napoli, 80131, Italy*
[17] *Centro Siciliano di Fisica Nucleare e Struttura della Materia, Catania, 95123, Italy*

ML was supported in part by the European Union (ChETEC-INFRA, project no. 101008324)