Nuclear Astrophysics:
a textbook case study

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Outline

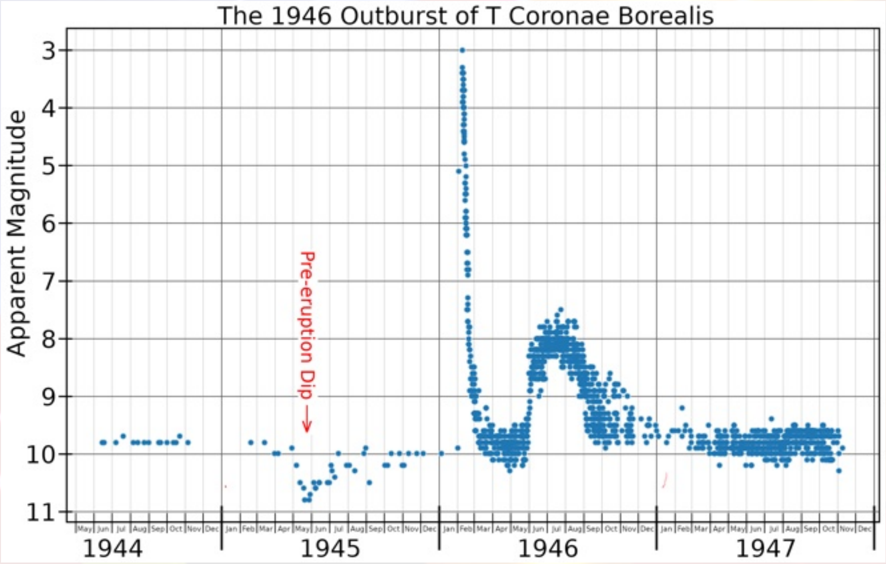
The $^{18}F(p,\alpha)^{15}O$ reaction is the most studied in nuclear astrophysics, with more than 50 studies published over the last two decades.

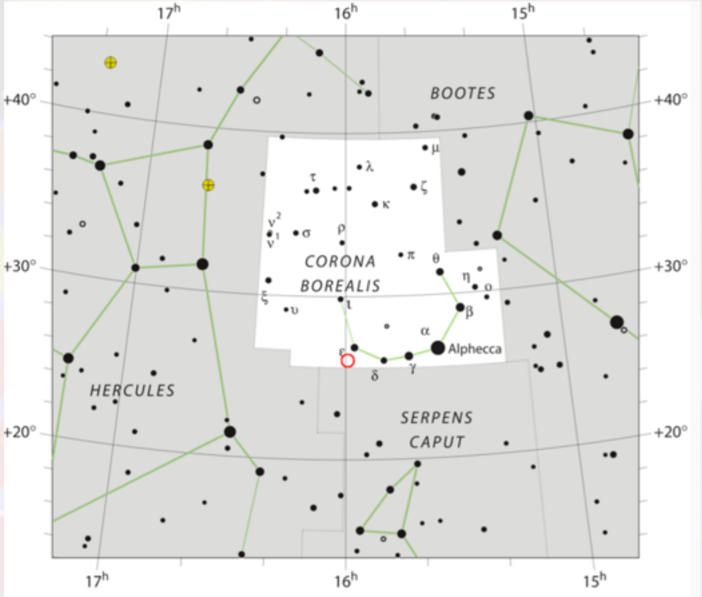
- Astrophysical motivation
- Reaction-rate measurement
- Direct cross-section measurement
- Indirect measurements
- Conclusion

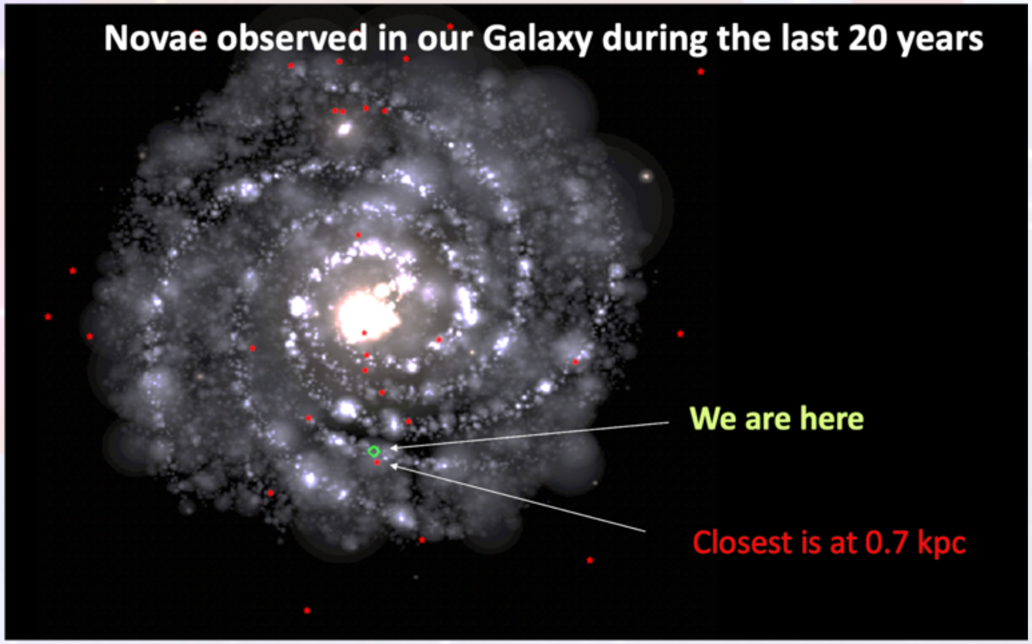
Astrophysical motivation

A new star is born

It's really topical: T CrB

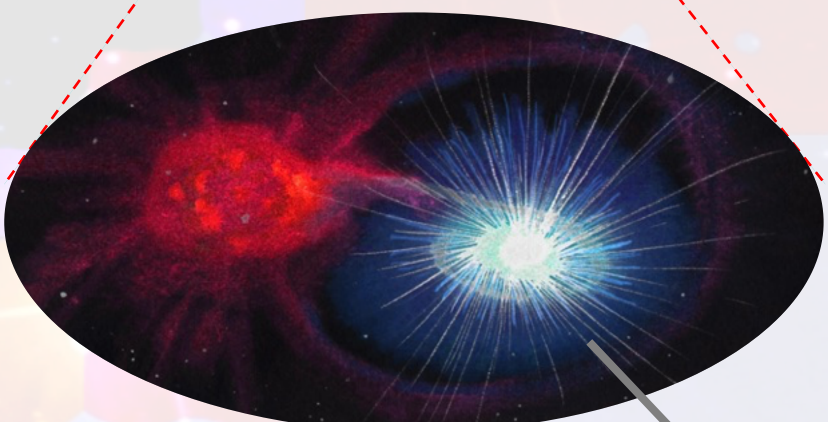






~2 600 ly

What is a nova?



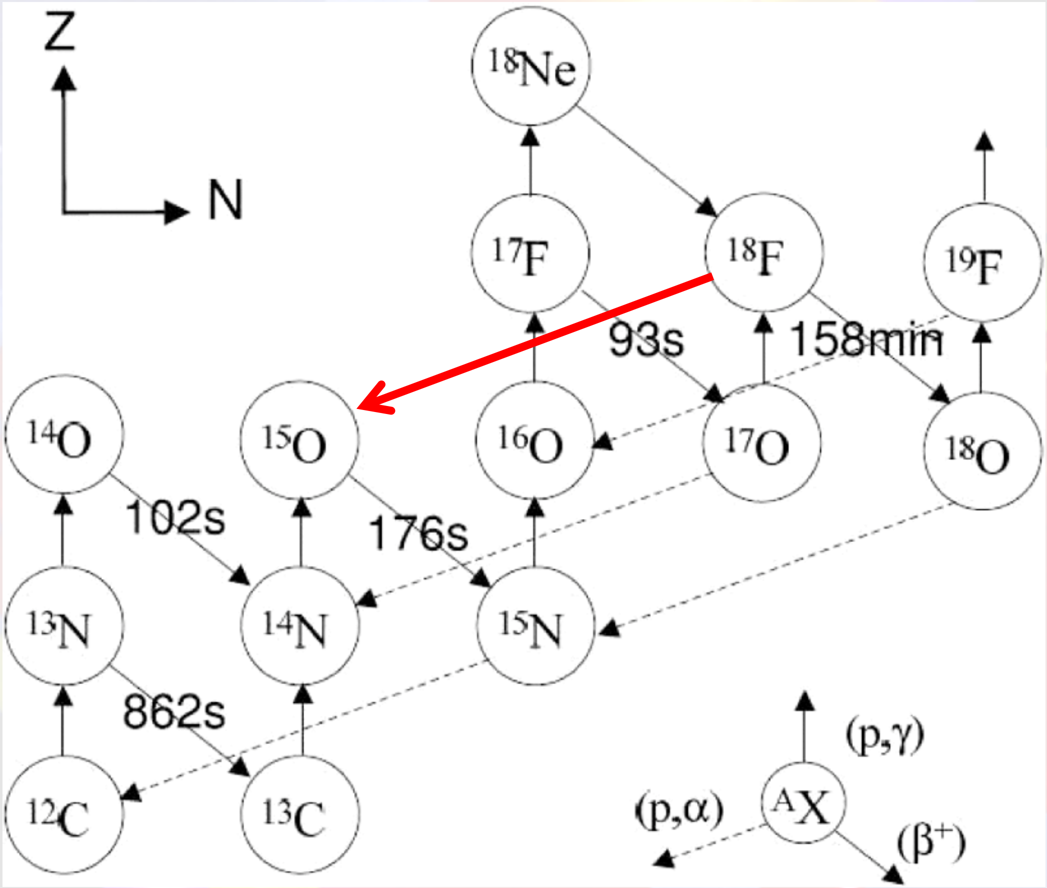
Nova outburst
T ~ 200 MK

White dwarf star

Nova Persei 1901 remnant

10^{-3} – 10^{-7} $M_\odot$ ejected

A network of reactions



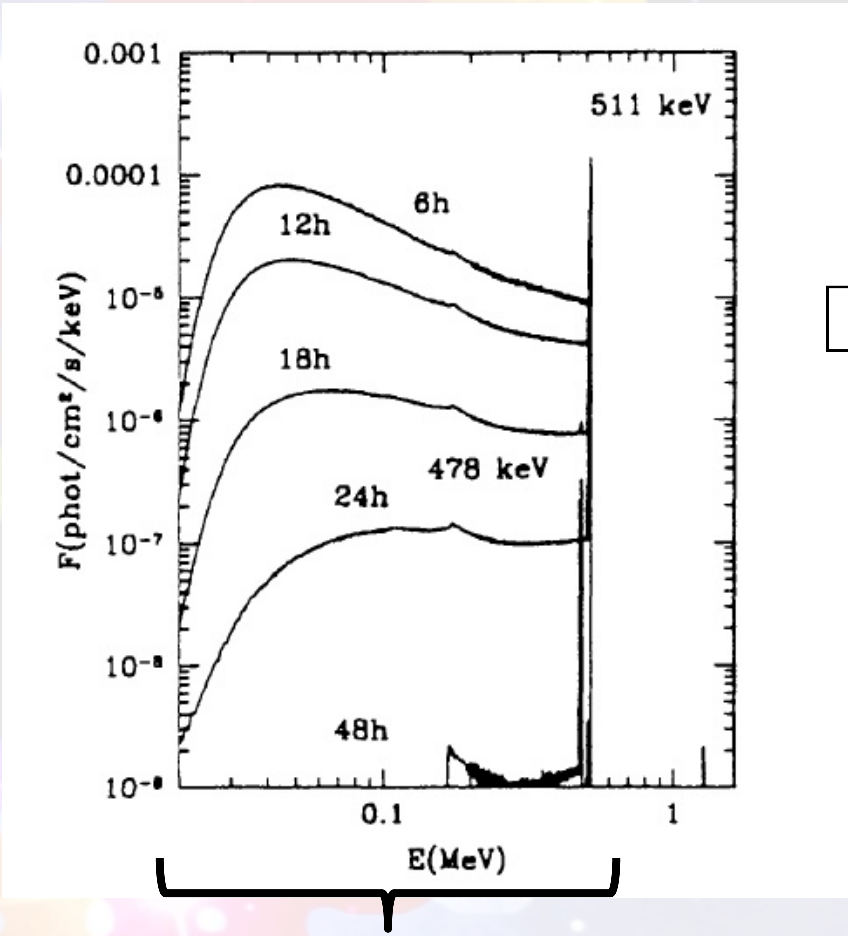
- Radioactive nuclei are produced
- ^{18}F is one of the best candidates for direct observation
- From the elemental abundance (Fluorine) to the isotopic abundance (^{18}F)

^{18}F$(p,\alpha)^{15}$O has the greatest impact on the ^{18}F yields in novae

Astrophysical motivation

Predicted γ-flux

M. Hernanz, J. Jose, A. Coc, J. Gomez-Gomar, and J. Isern, Astrophys. J. 526, L97 (1999).
A. Coc, M. Hernanz, J. Jose, and J.-P. Thibaud, Astron. Astrophys. 357, 561 (2000).



Mostly from the ^{18}F β decay

Will be observe by COSI space telescope?

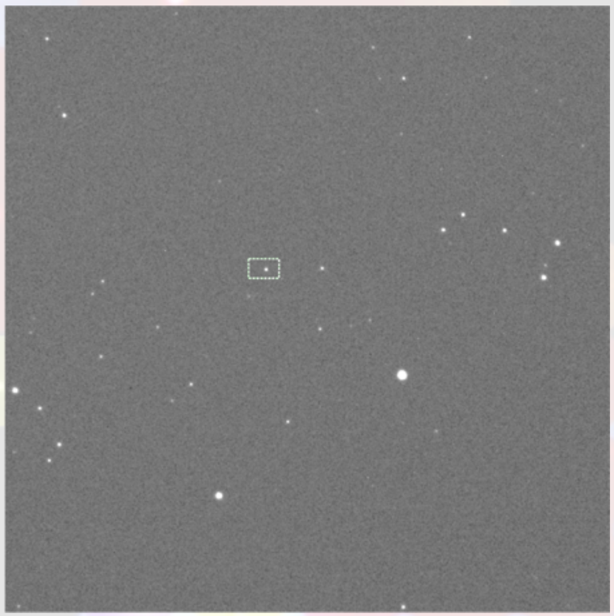
Goal

To predict the ^{18}F production to within a factor of 2

Need the **$^{18}F(p,\alpha)^{15}O$** rate uncertainties < 30%

Astronomers

YZ Reticuli
Nova Reticuli 2020



Discovered on July 15

Mag = 3.7

Distance = 2.53 kpc (8 000 light-years)

eROSITA

Fireball observed
July 7, 16h47, 2020

13h

21h

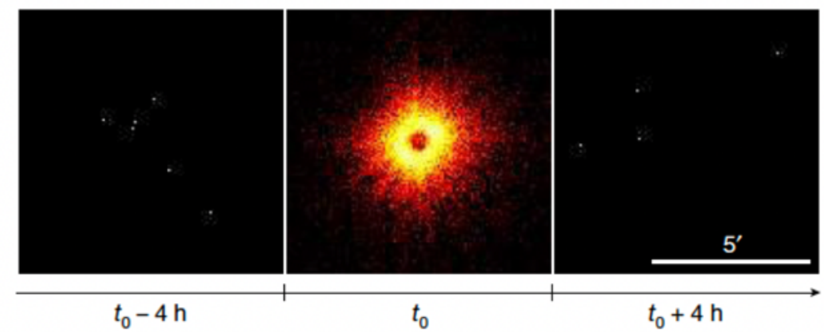


Fig. 1 | Sky images of all seven eROSITA cameras combined (0.2–0.6 keV). On t_0 = 2020 July 7, 16 h 47 min 20.64 s TT, during the second all-sky survey, eROSITA detected a bright, new, soft X-ray flash that was severely affected by pile-up. No source can be seen in the scans 4 h before and after the event.

Nature, May 2022

No X-ray source
4h before and after the event

Duration of the event < 8 h

Direct measurement of the reaction rate

Direct measurement of the reaction rate

d(d,n)^{3}He

D. Lattuada et al, Phys. Rev. C 93 (2016) 045808

https://texaspetawatt.ph.utexas.edu/overview.php

Texas Petawatt Laser (TPW)

$$^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$$

$$\int \sigma(E)\phi(v)v\,dv \approx 1\ \mathrm{cm^3 mol^{-1} s^{-1}}$$

at T=250 MK

e.g.

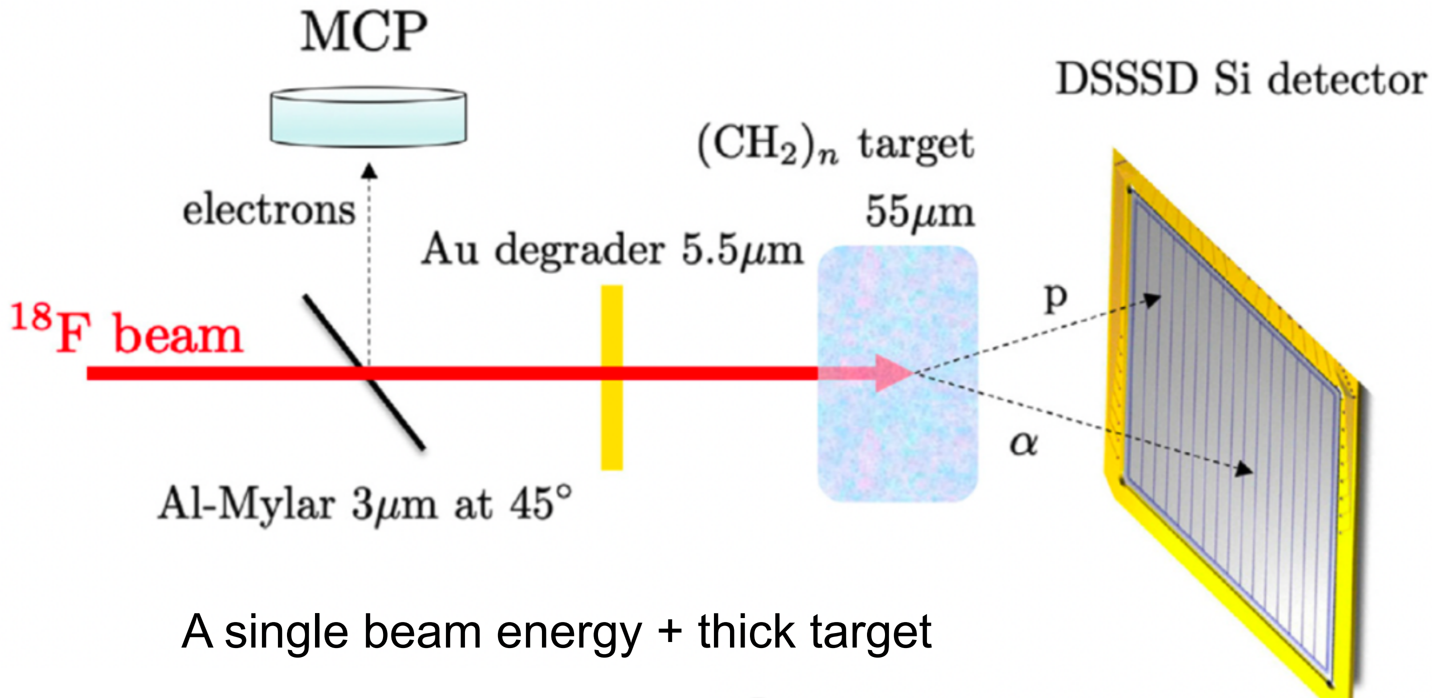
1 mm^3 of hydrogen, 1 g cm^{-3}, mixed with 10^9 atoms of ^{18}F

At 250 MK for 1 ns (the plasma disassembly time)

Only 1 atom of ^{15}O would be produced

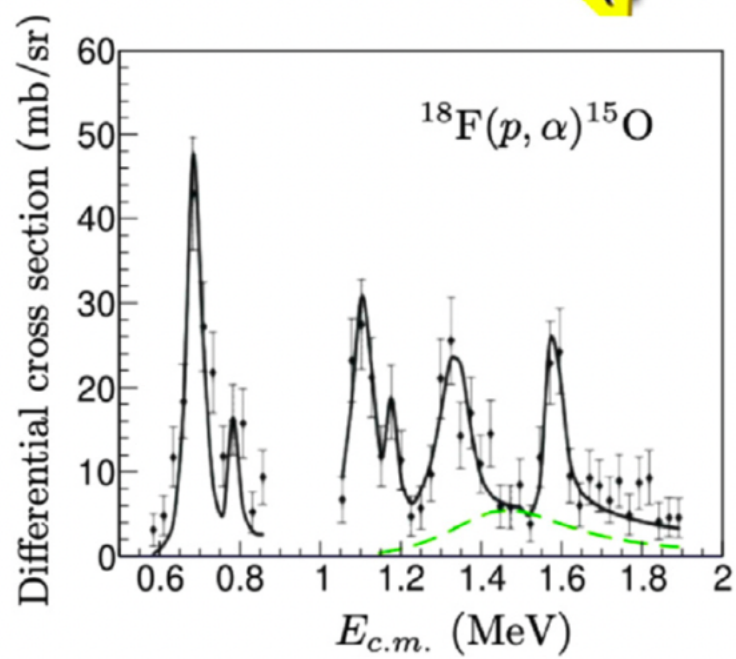
Not possible for the moment

Direct measurement of $\sigma(E)$



A single beam energy + thick target

$$^{18}F(p,\alpha)^{15}O$$



Direct measurements of σ(E)

$$^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$$

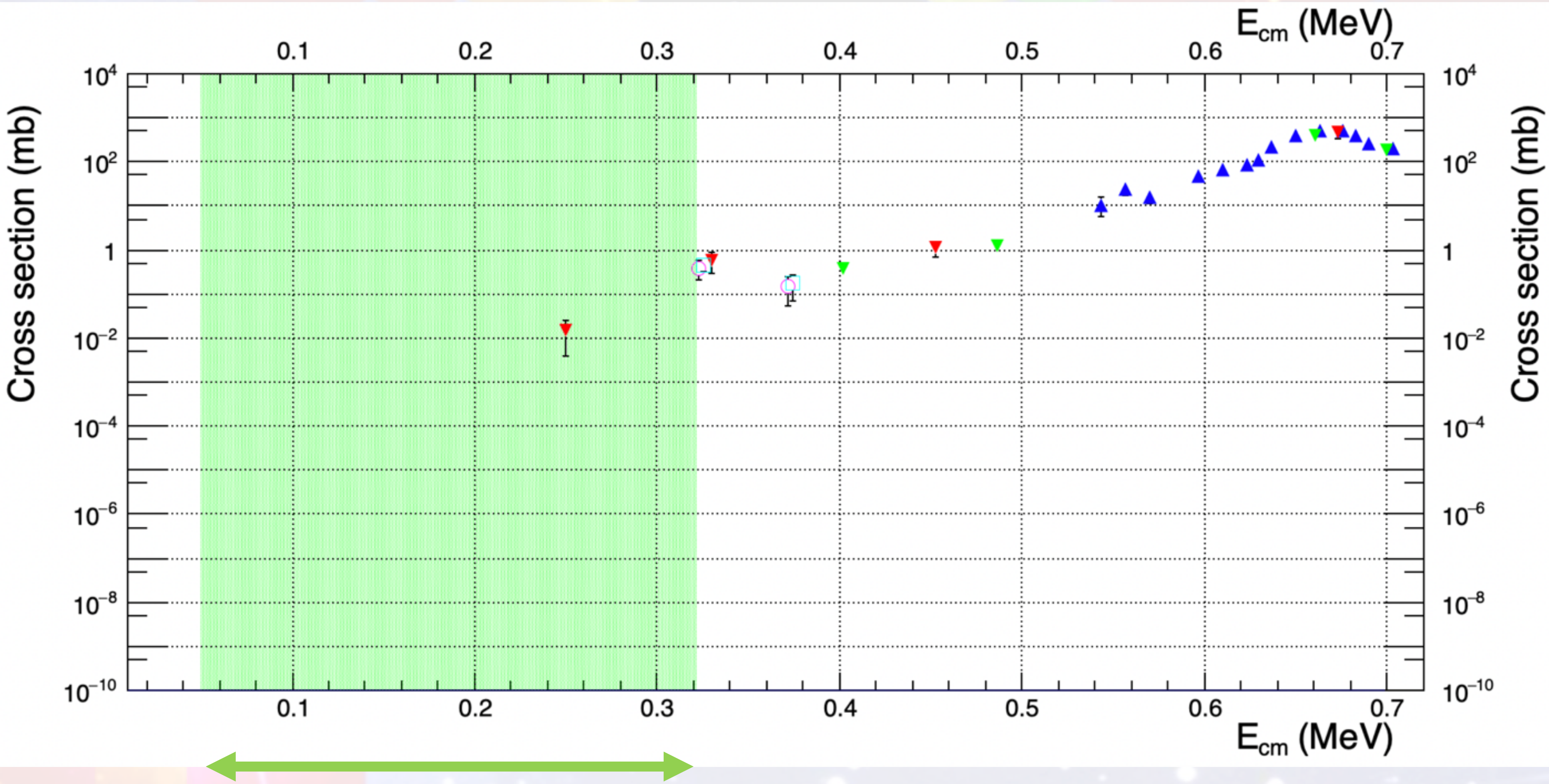
10 different experiments performed in 5 different laboratories

Table 1
List of all direct measurements of the ^{18}F(p, α)^{15}O reaction.

Laboratory	^{18}F beam Intensity (pps)	Purity %
LLN	10^6	100
ANL	5×10^5	0.4
HRIBF	2×10^5	20
TRIUMF	5×10^6	60–95
GANIL	2×10^4	97

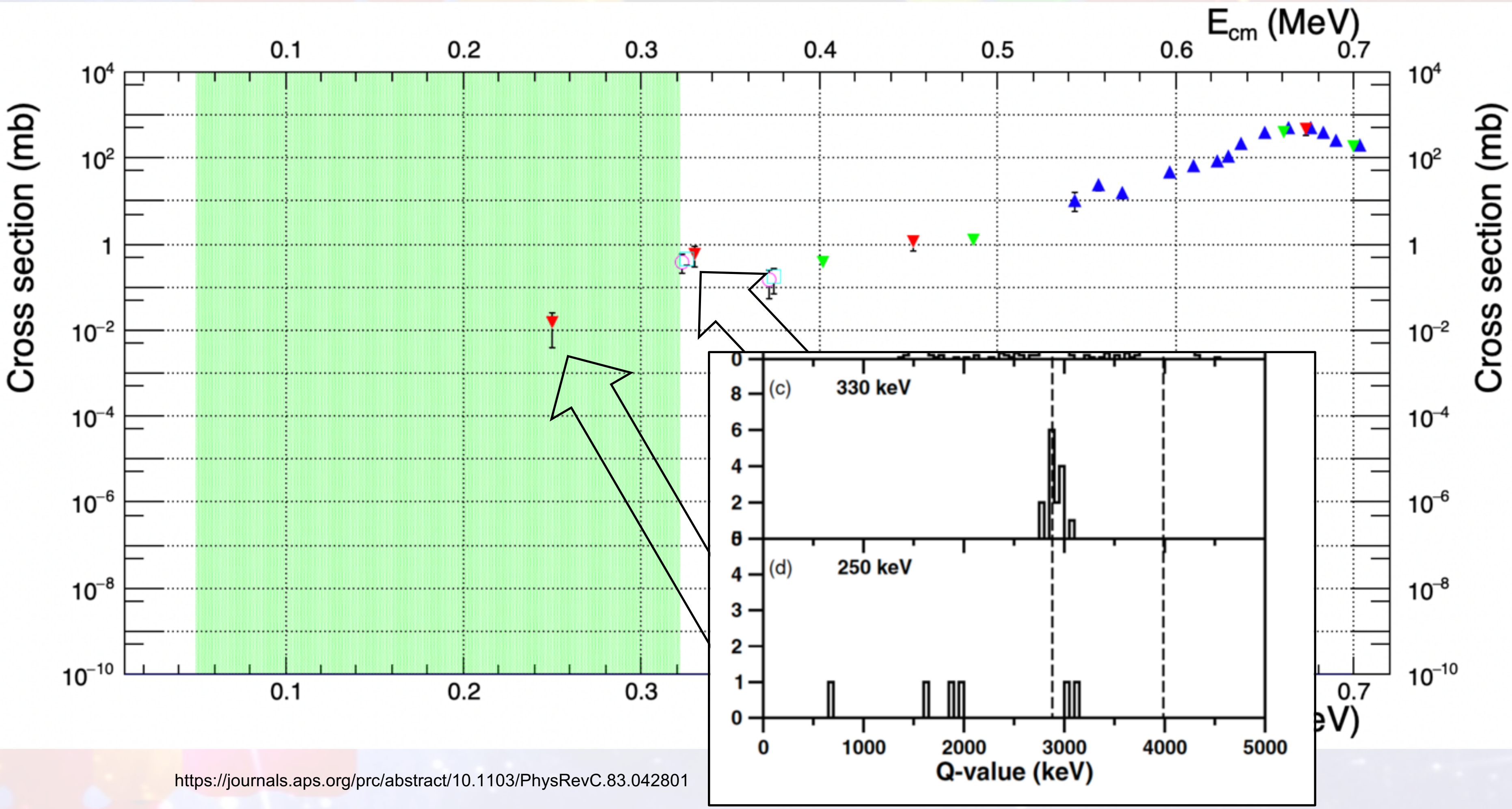
Progress in Particle and Nuclear Physics 142 (2025) 104154

Direct measurements $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$



The green area corresponds to the Gamow window of novae explosions

Direct measurements $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$

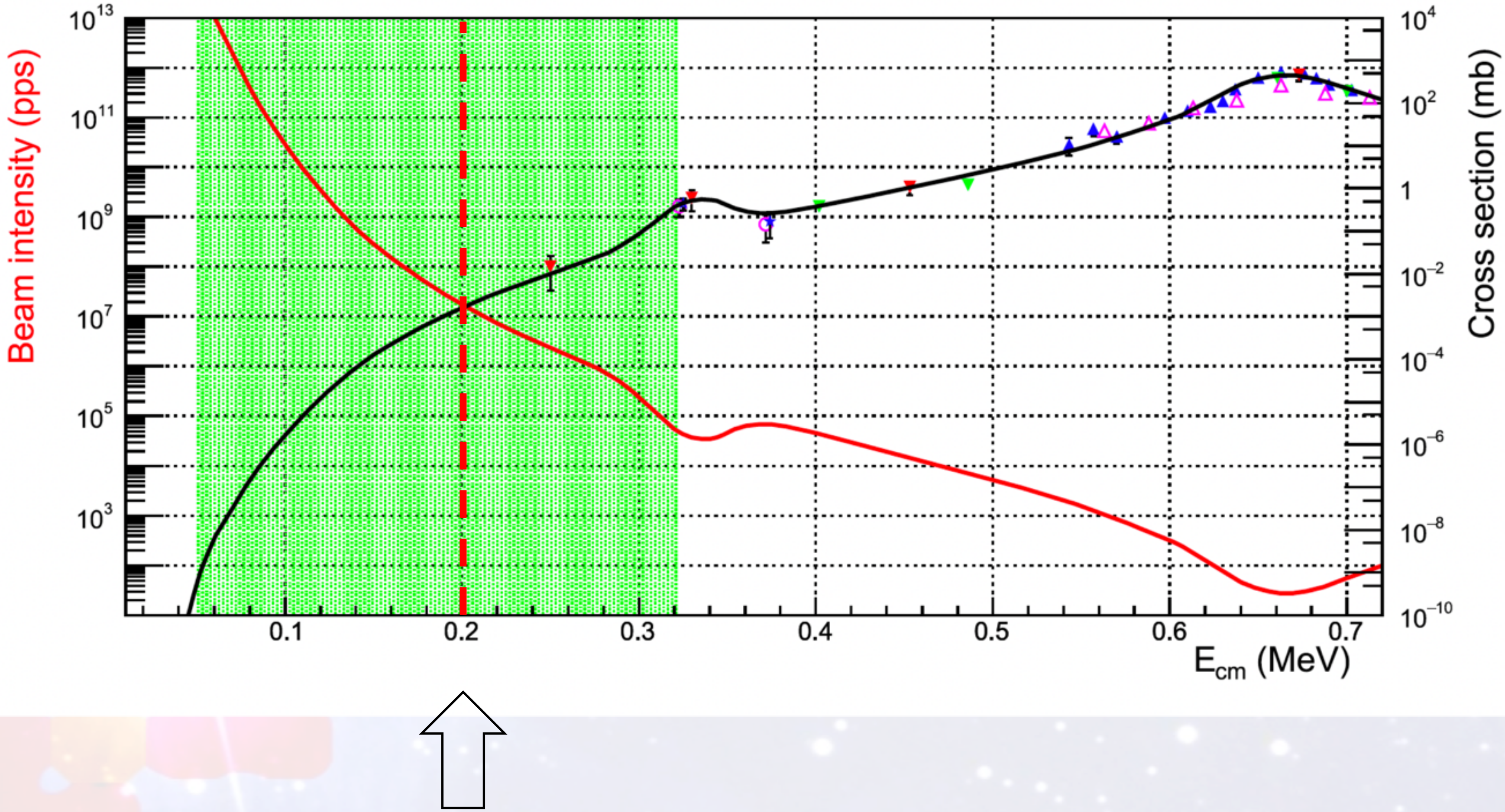


https://journals.aps.org/prc/abstract/10.1103/PhysRevC.83.042801

Beer et al.
PRC 2011 TRIUMF

Lowest measured energy

Direct measurements $^{18}F(p,\alpha)^{15}O$



Need 10^7 pps to measure 1 reaction / week

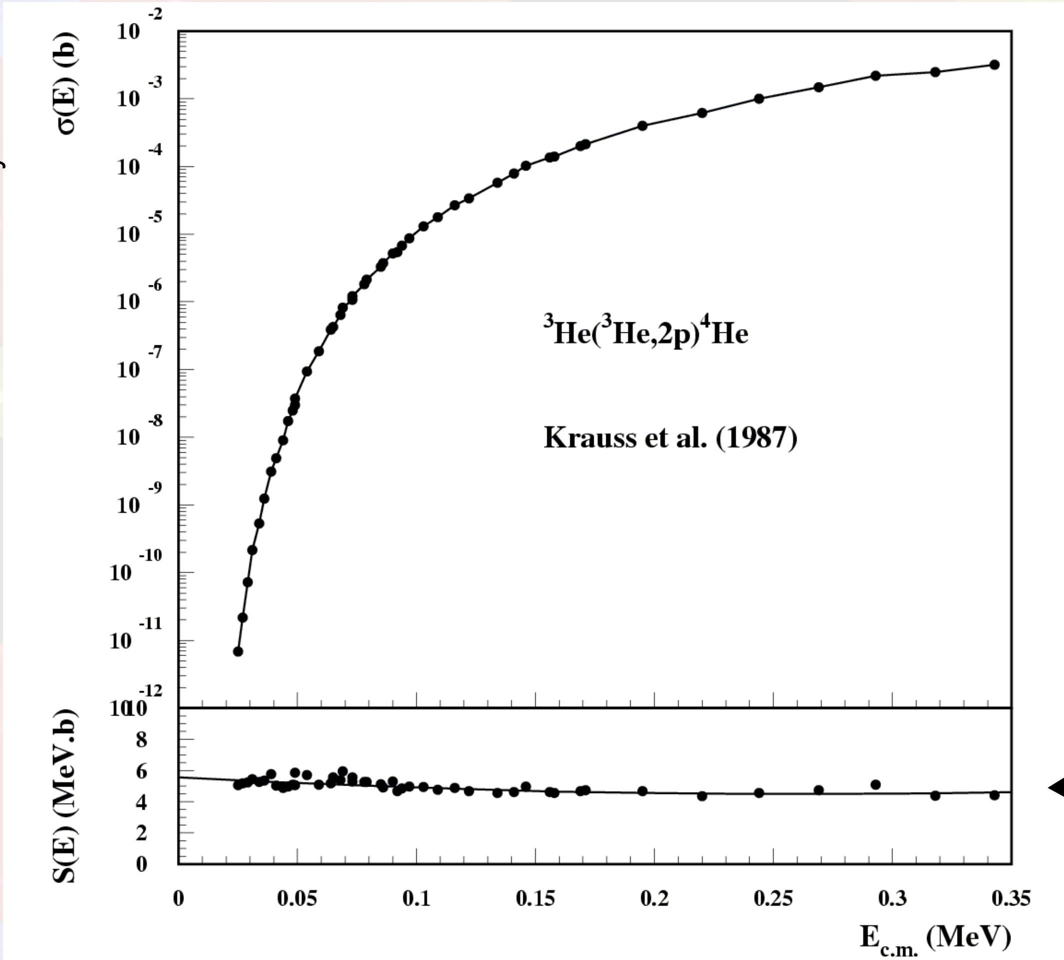
Theory

The Astrophysical S-Factor

$$\sigma(E) \equiv \frac{S(E)}{E} \exp(-2\pi\eta)$$

Tunnel Effect

Cauldrons in the Cosmos C. Rolfs & W. Rodney

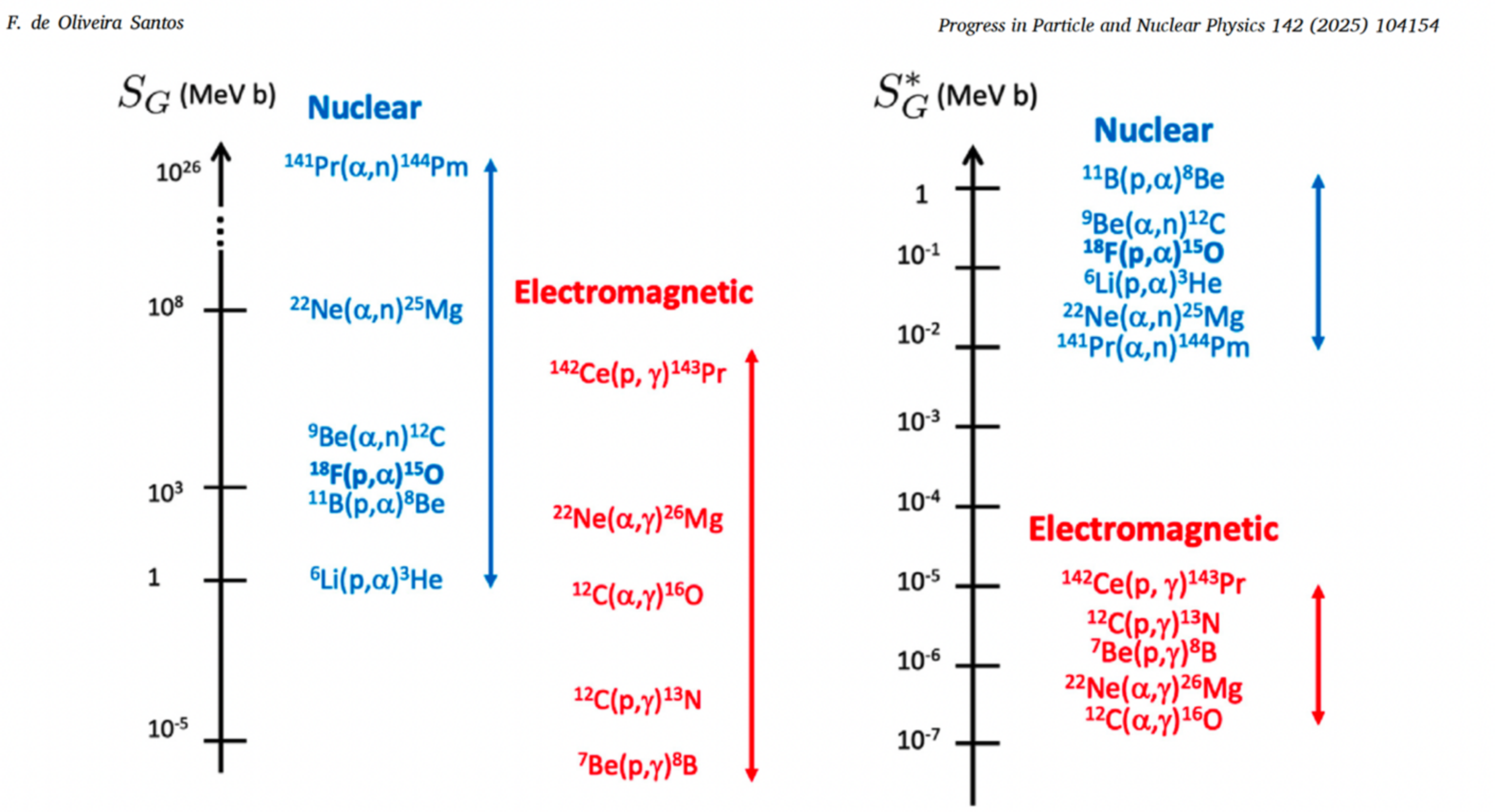


Astrophysical S-Factor

S(E) ~ constant

$$S(E) \sim \left| \langle f | H_{nuclear} | i \rangle \right|^2$$

The Astrophysical S-Factor

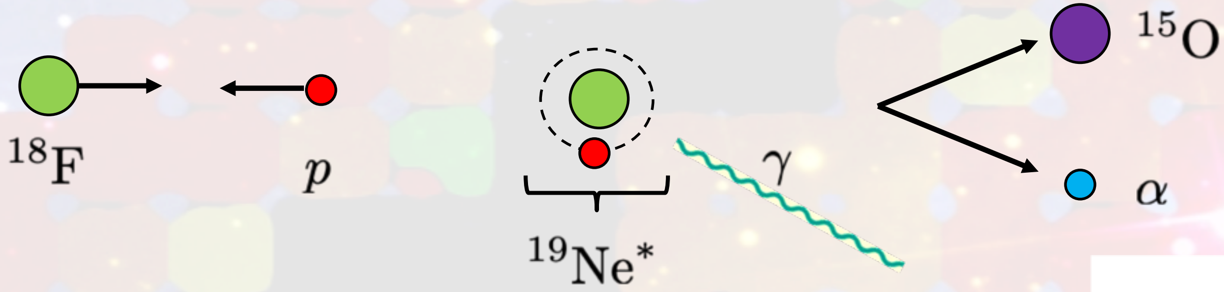


Better, but still a factor of 100

Nuclear reactions mechanisms

$$^{18}F(p,\alpha)^{15}O$$

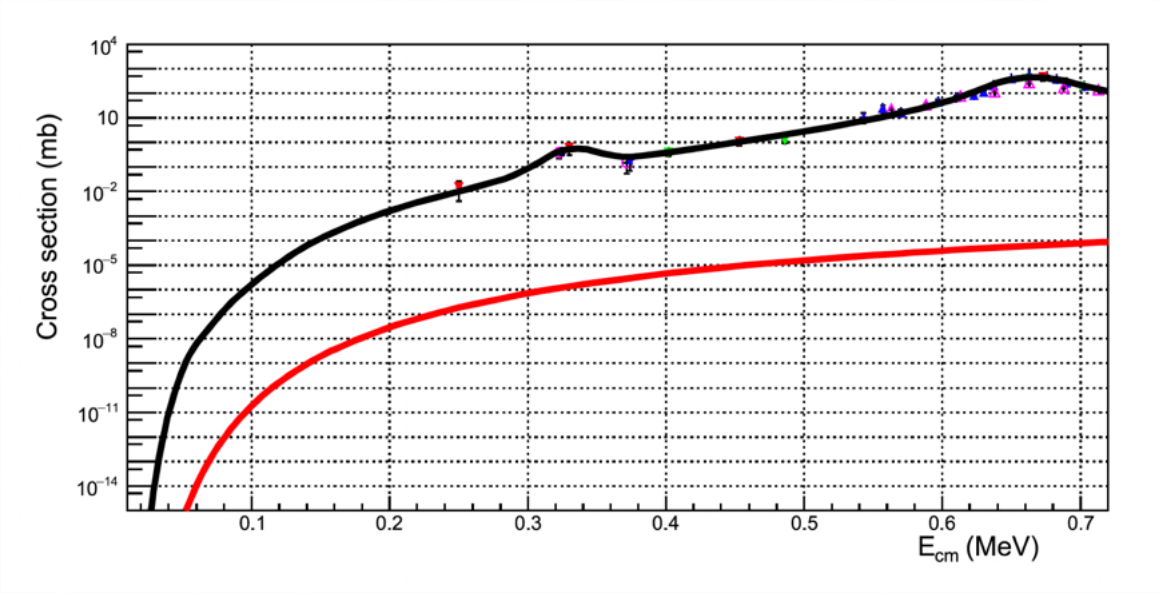
Direct radiative capture reaction



(RADCAP code)

$$^{18}F(p,\gamma)^{19}Ne^*(\alpha)^{15}O$$

$$\sigma(E) \propto |< \psi_{B^*+\gamma} \mid M_\lambda \mid \psi_{A+x} >|^2$$



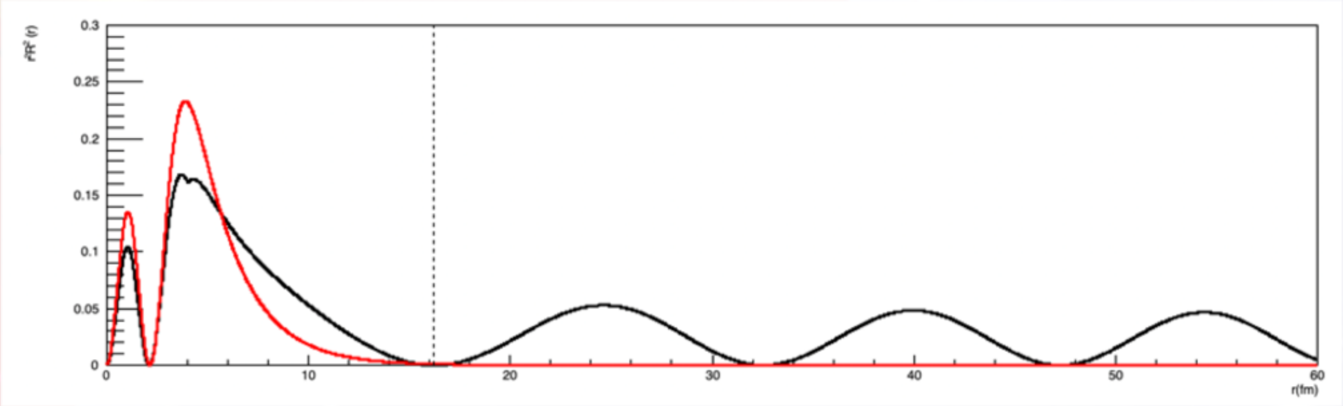
Negligible

Nuclear models for the resonances

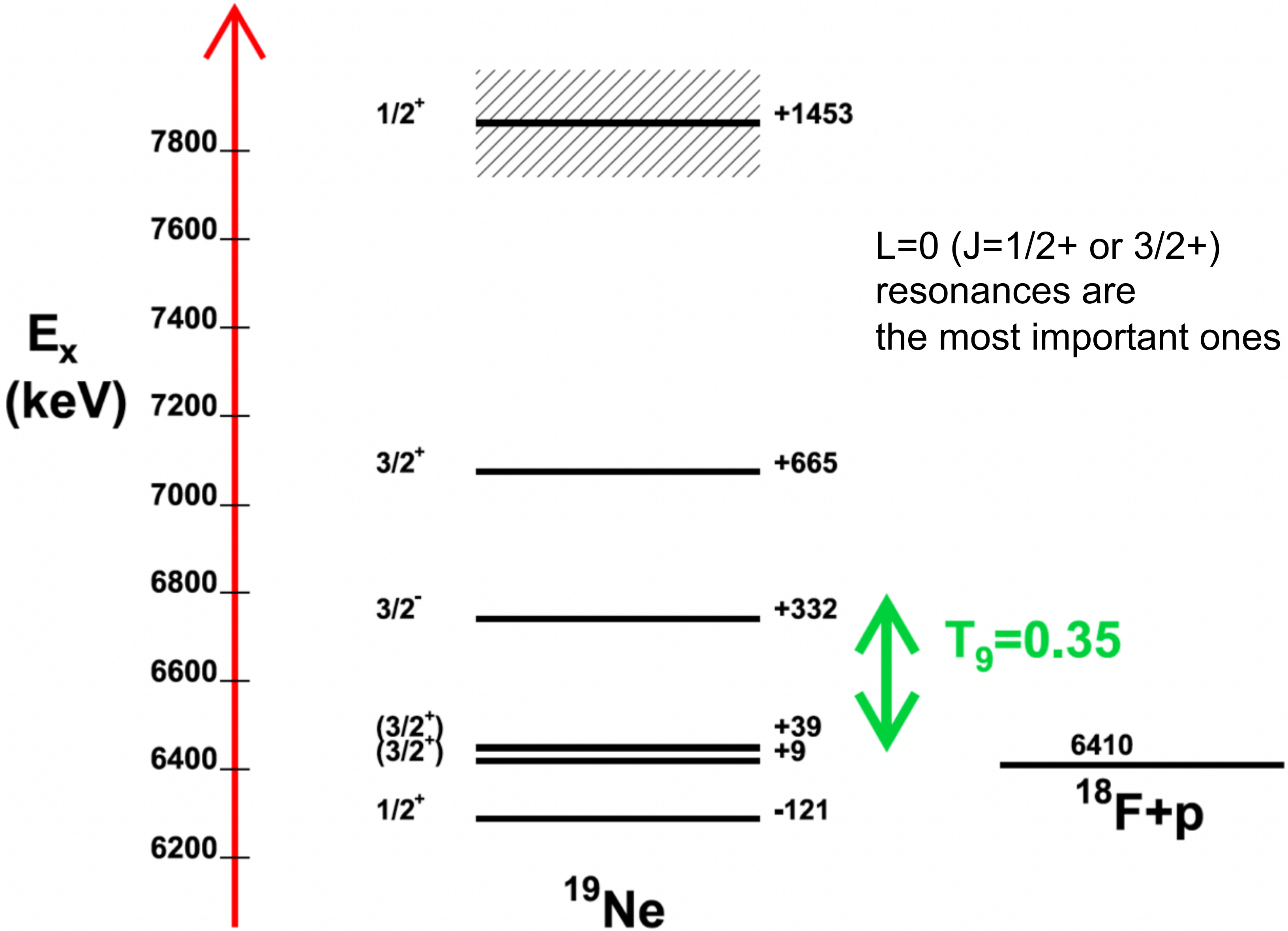
- The Breit-Wigner formula

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J_{^{19}\mathrm{Ne}^*}+1}{(2J_p+1)(2J_{^{18}\mathrm{F}}+1)} \frac{\Gamma_p \Gamma_\alpha}{(E-E_r)^2+(\Gamma/2)^2}$$

- R-Matrix formalism (multichannel R-matrix code AZURE2)

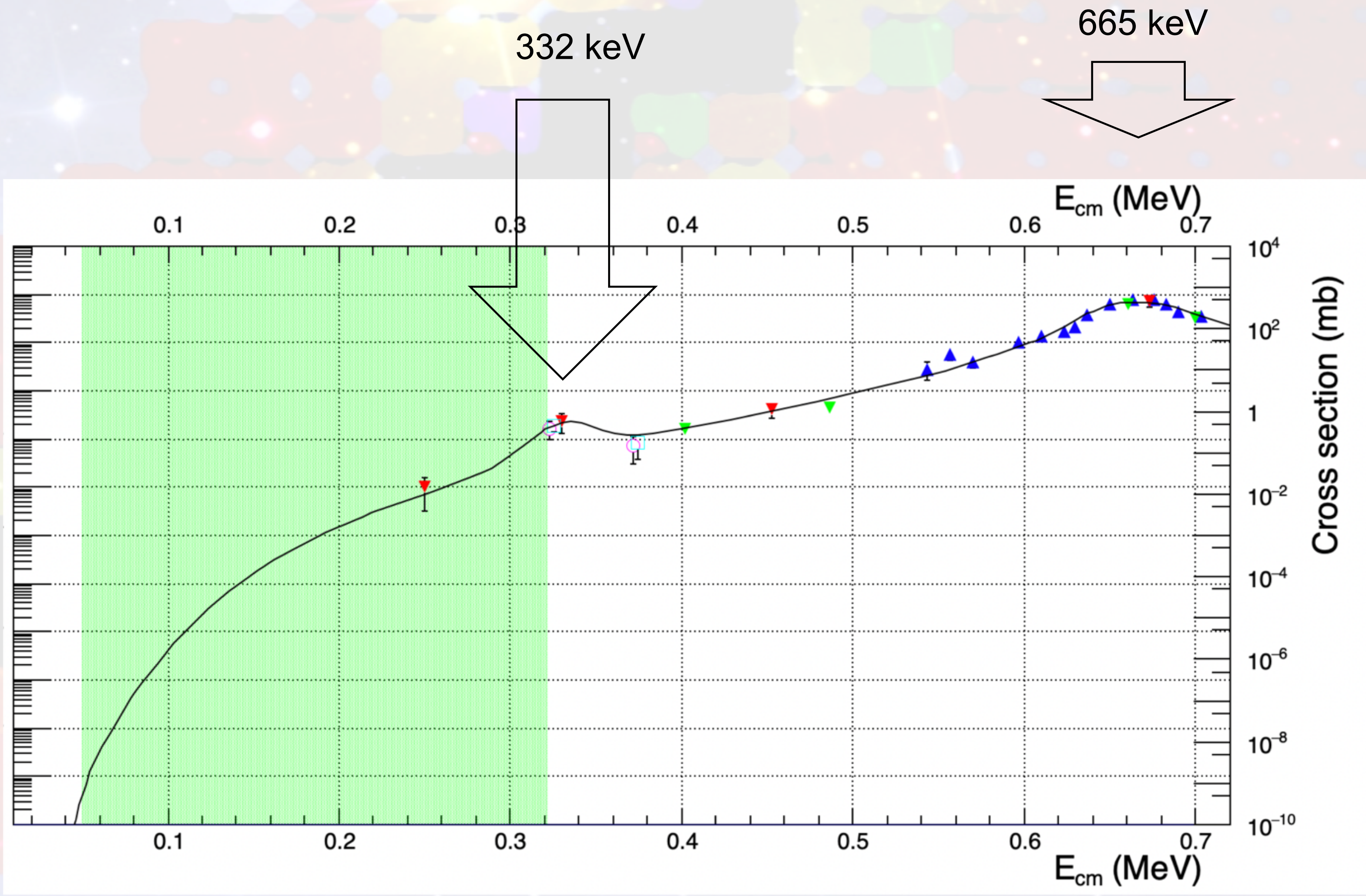


Needed Parameters: $\Gamma_p, \Gamma_\alpha, E_r, J^\pi, (+++)$



L=0 (J=1/2+ or 3/2+) resonances are the most important ones

Two resonances in the compound nucleus

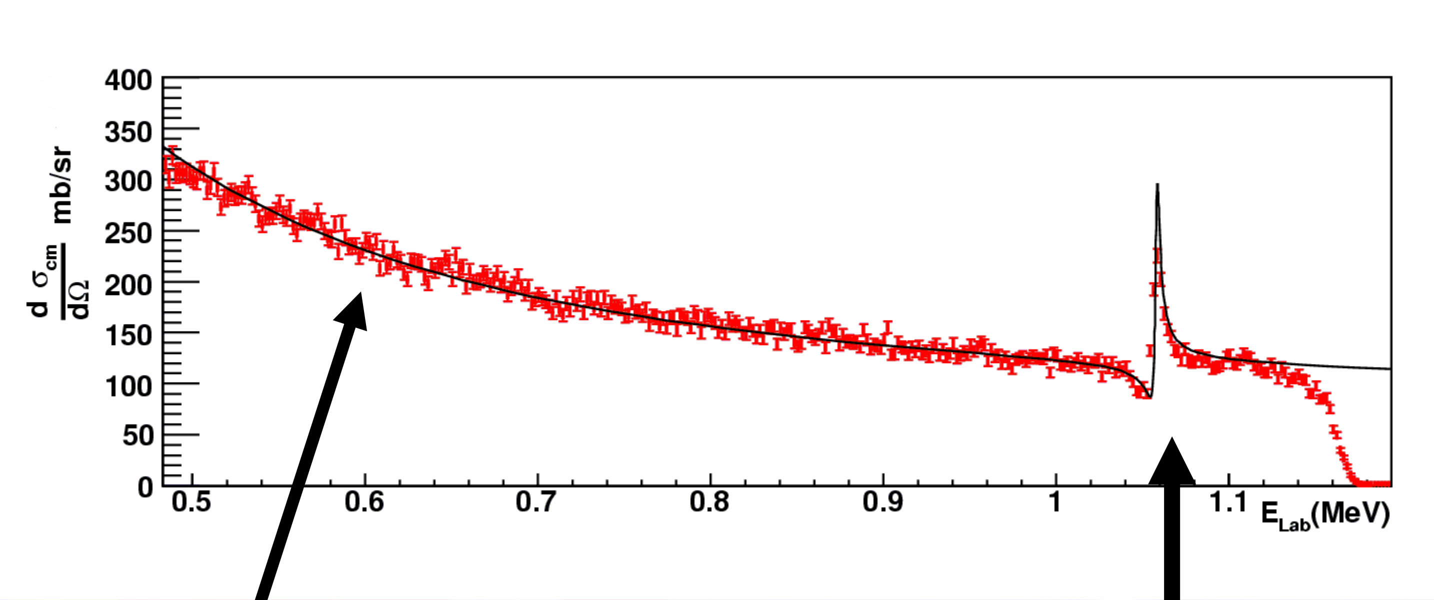


Indirect methods

Resonant Elastic Scattering

Resonant Elastic Scattering

$^{14}N\,(p,p)^{14}N$



(thesis of Iulian Stefan GANIL 2007)

Rutherford scattering

Resonant Elastic Scattering

$$\frac{d\sigma}{d\Omega}_{\text{Rutherford}} = \left[\frac{z_1 z_2 e^2}{4\ E \sin^2\left(\frac{\theta}{2}\right)}\right]^2$$

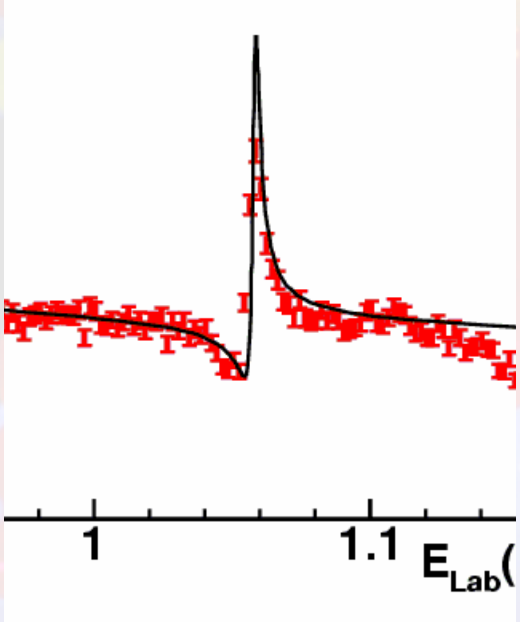
Spin

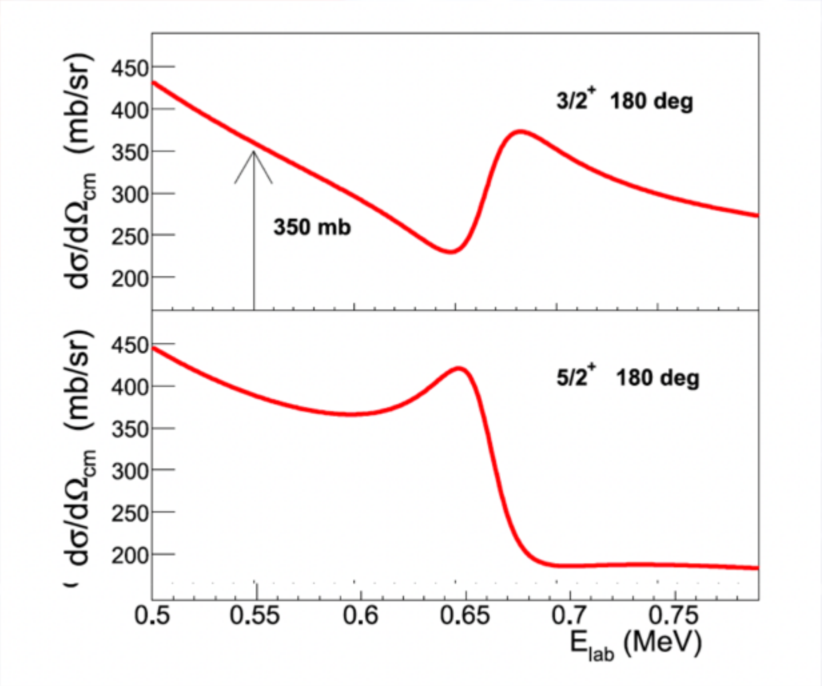
$$\sigma(E) = \frac{\pi}{k^2} \left| 2\sin(ka)e^{ika} - \frac{\Gamma}{(E_\lambda - E) - i\frac{\Gamma}{2}} \right|^2$$

Other terms (Rutherford, hard sphere…)

Breit-Wigner

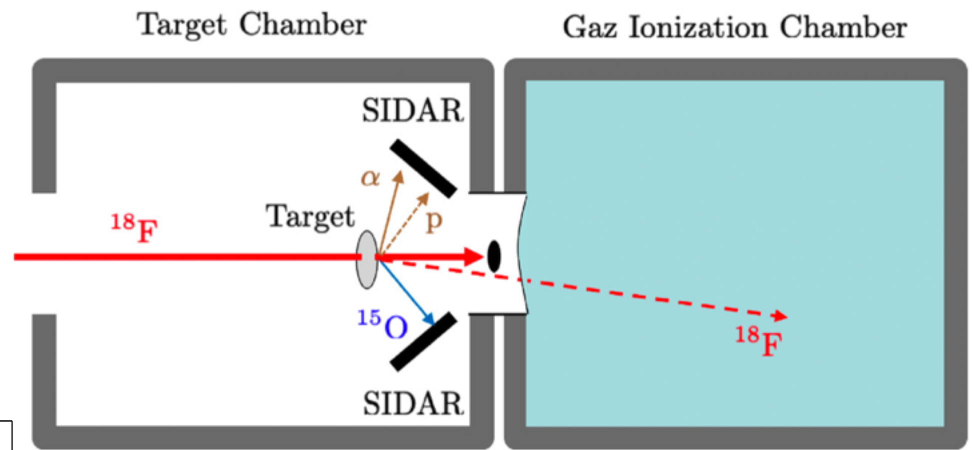
Interference effect



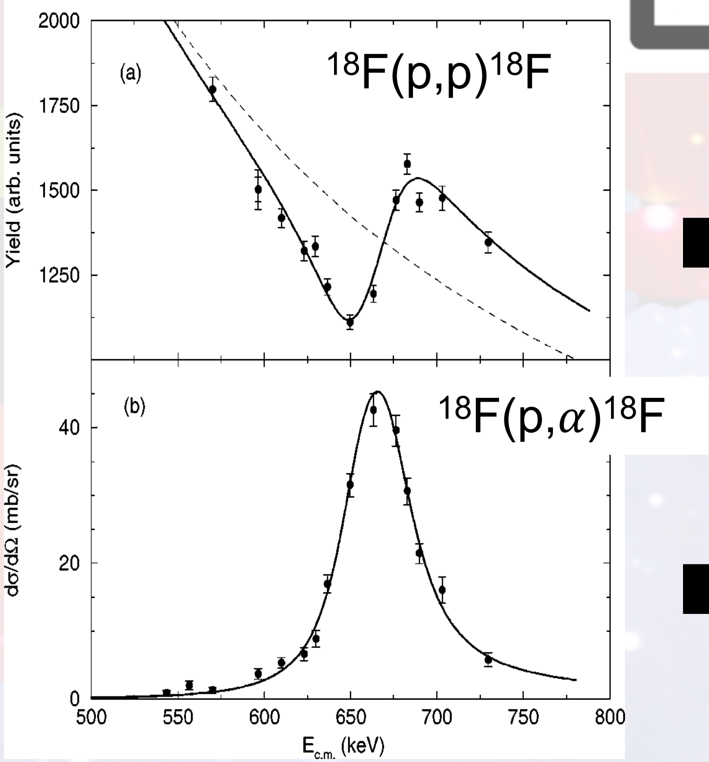


Direct measurements of σ(E)

Bardayan et al, Holifield Radioactive Ion Beam Facility



Several beam energies + thin target



E_x = 7076 ± 2 keV (665 keV)

ℓ = 0 1/2+ or 3/2+

Γ= 39.0 ± 1.6 keV

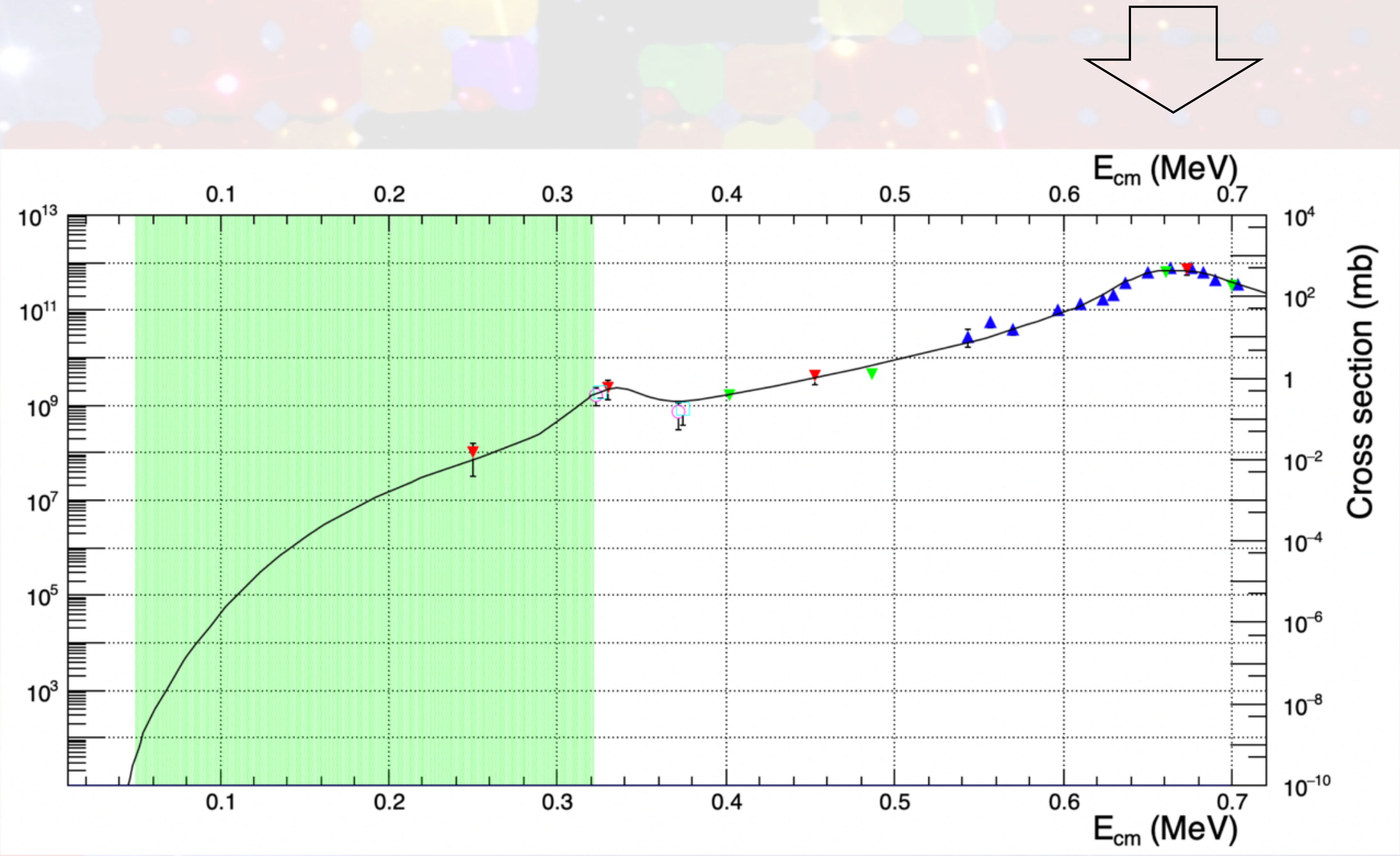
Γ_p/Γ= 0.39 ± 0.02

$$J^\pi = \frac{3}{2}^+$$

Analysis of the two spectra through the R-Matrix formalism

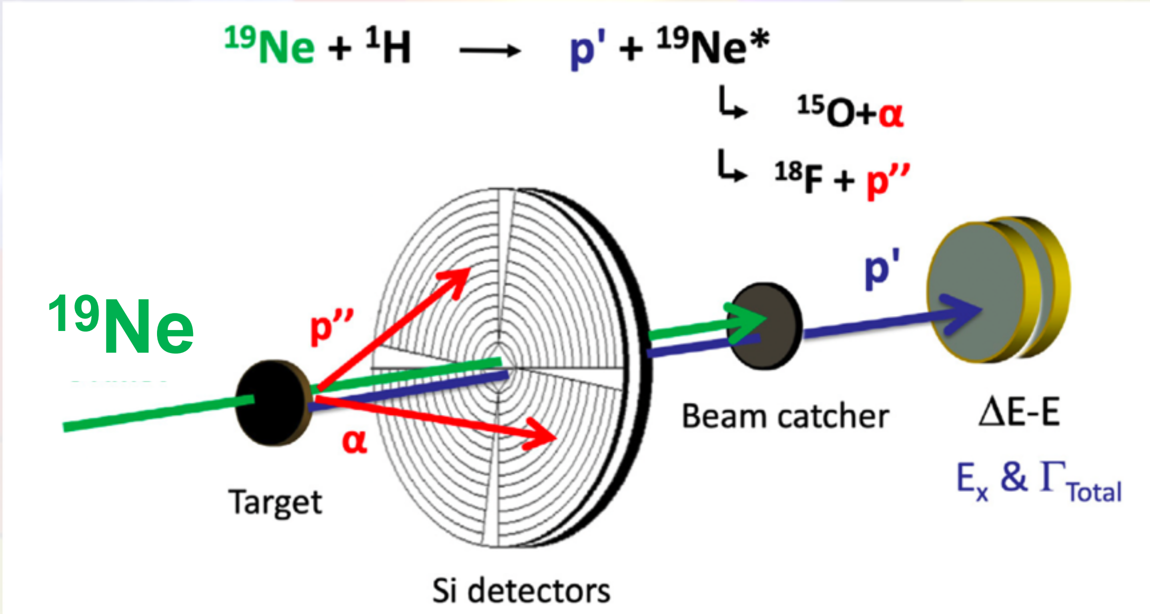
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.63.065802
Bardayan et al, Phys. Rev C, V63, 065802 (2001)

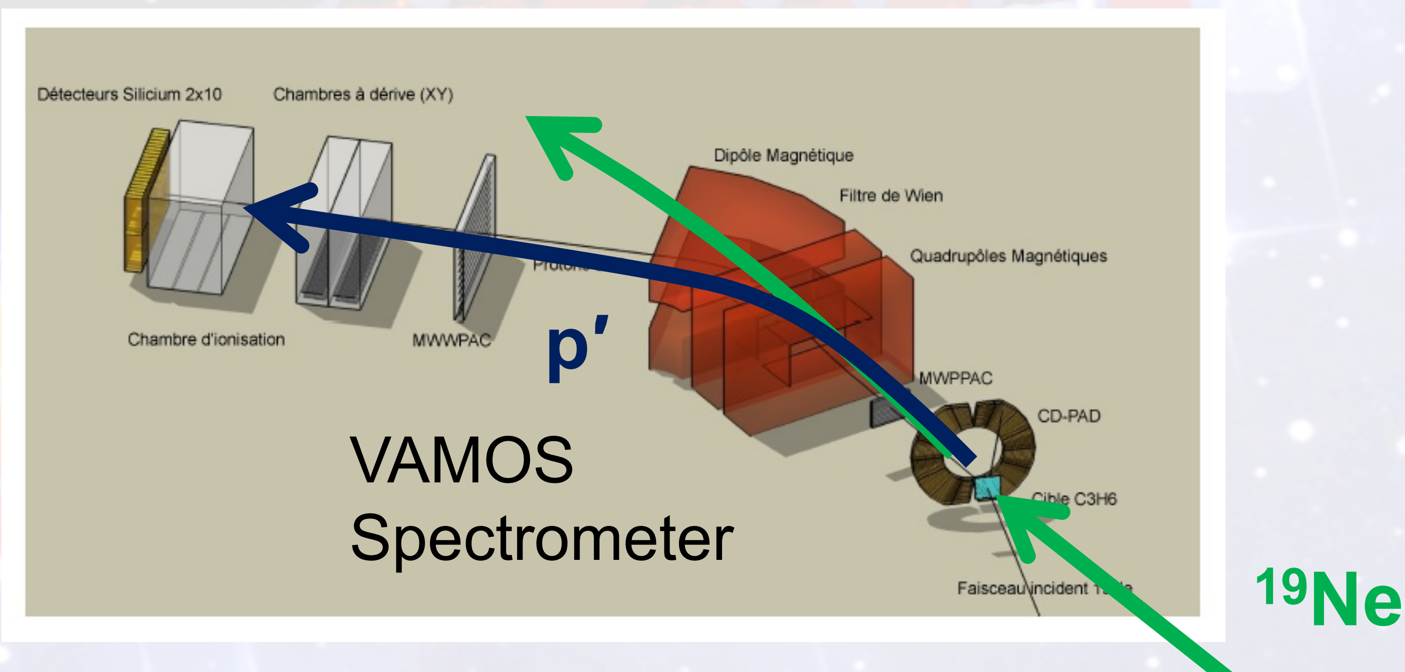
This 665 keV peak is the 3/2+ resonance



Inelastic scattering

Experimental setup

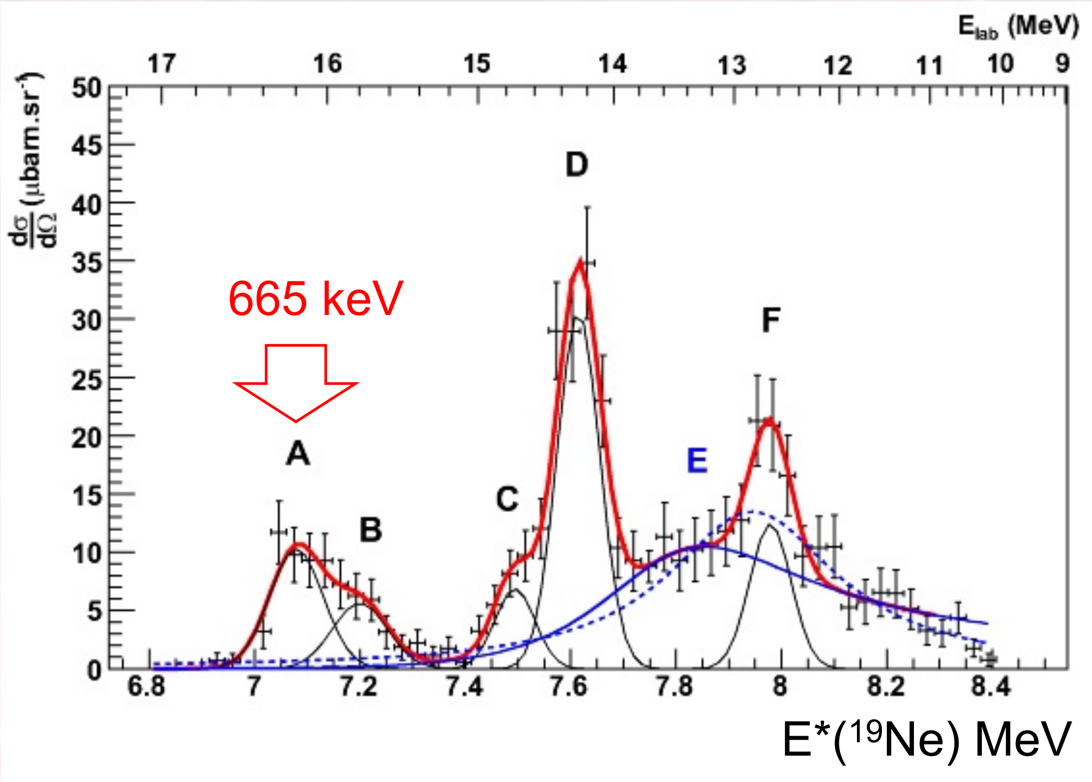




Excitation energy and total width

Missing mass technique

$^{19}Ne(p,p')^{19}Ne^*$

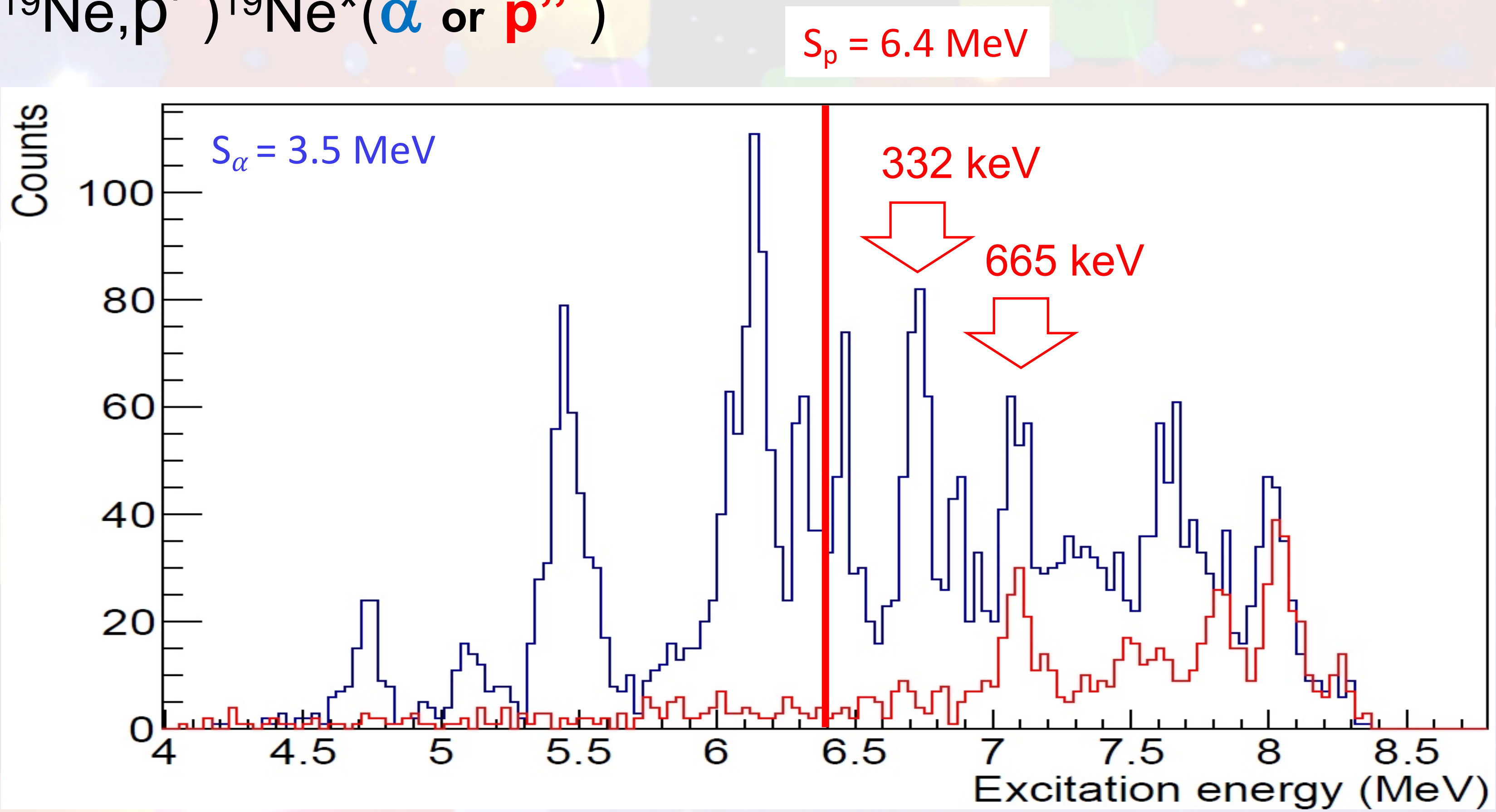


Excitation Energy
Total width (if broad enough)

J.C. Dalouzy et al, Physical Review Letters 102, 162503 (2009)

Branching ratios and partial widths

H(^{19}Ne,p′)^{19}Ne*(α or p”)



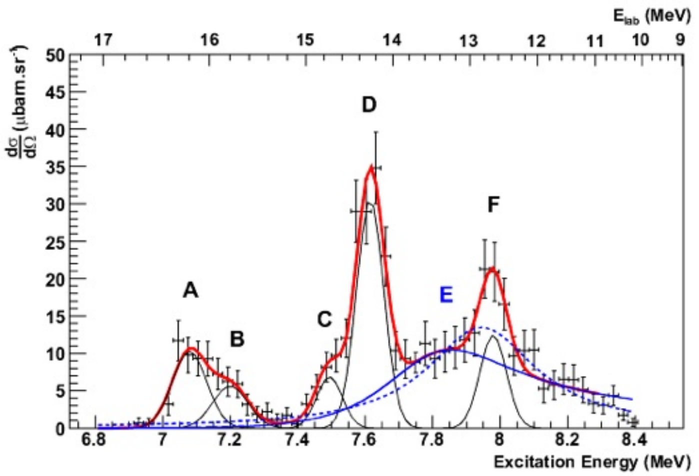
Thesis of F. Boulay (Caen –Normandy)

⇨ Branching ratios $$\mathrm{BR}_p = \frac{N_p}{N_p + N_\alpha}$$

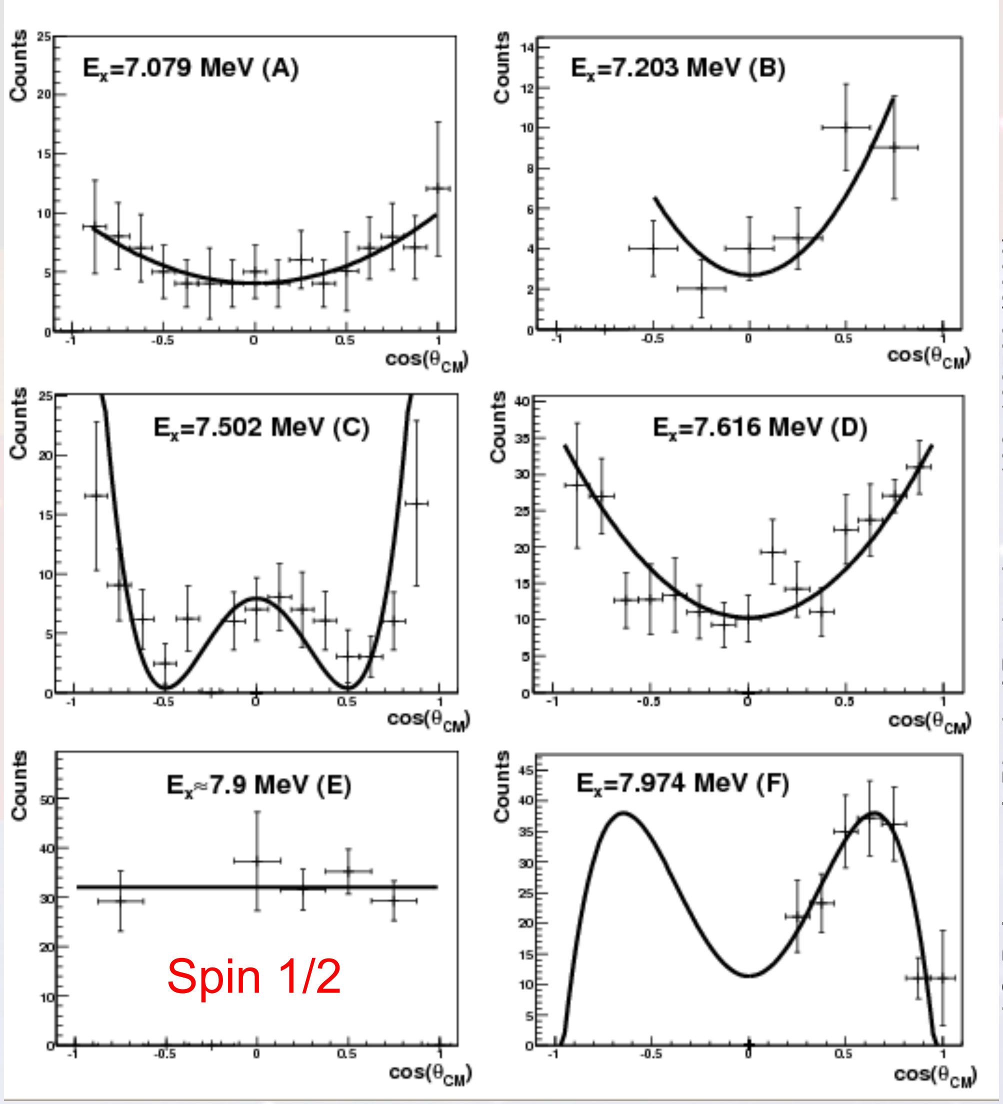
Partial widths $$\Gamma_p = \mathrm{BR}_p \times \Gamma_{tot}$$

Spin

$H(^{19}Ne,p')^{19}Ne^{*}(p'')^{18}F$



p'-p'' angular correlation



Particle-particle angular distribution is a function of J^{π}

Model-independent J^{π} determination

$$\left(\frac{d\sigma}{d\Omega}\right)_{\frac{5}{2}} = N(a_0 + a_1 cos^2(\theta_{CM}) + a_2 cos^4(\theta_{CM}))$$

J.C. Dalouzy et al, Physical Review Letters 102, 162503 (2009)

Transfer reactions

Definition / Theory

One or several nucleons are transferred from one nucleus to another one

ex: $^{18}F(d,n)^{19}Ne^*$ $^{20}Ne(p,d)^{19}Ne^*$ $^{19}F(p,n)^{19}Ne^*$

Theoretical Models: DWBA, CC, CCBA, CDCC, CRS, ADWA, PWAI, THM, ANC…

$^{18}F(d,n)^{19}Ne^*$

$$\left(\frac{d\sigma}{d\Omega}\right)^{DWBA}_{^{18}F(d,n)^{19}Ne^*} = \frac{\mu\mu^*}{4\pi^2\hbar^4}\,\frac{k_n}{k_d}\,\left|T^{DWBA}_{^{18}F(d,n)^{19}Ne^*}\right|^2$$

Direct transfer

$$T^{DWBA}_{^{18}F(d,n)^{19}Ne^*} = \int \chi_2^{(-)}\,\Psi_n^*\,\Psi^*_{^{19}Ne^*}\,V_2\,\Psi_d\Psi_{^{18}F}\,\chi_1^{(+)}\,d^3w_1 d^3w_2$$

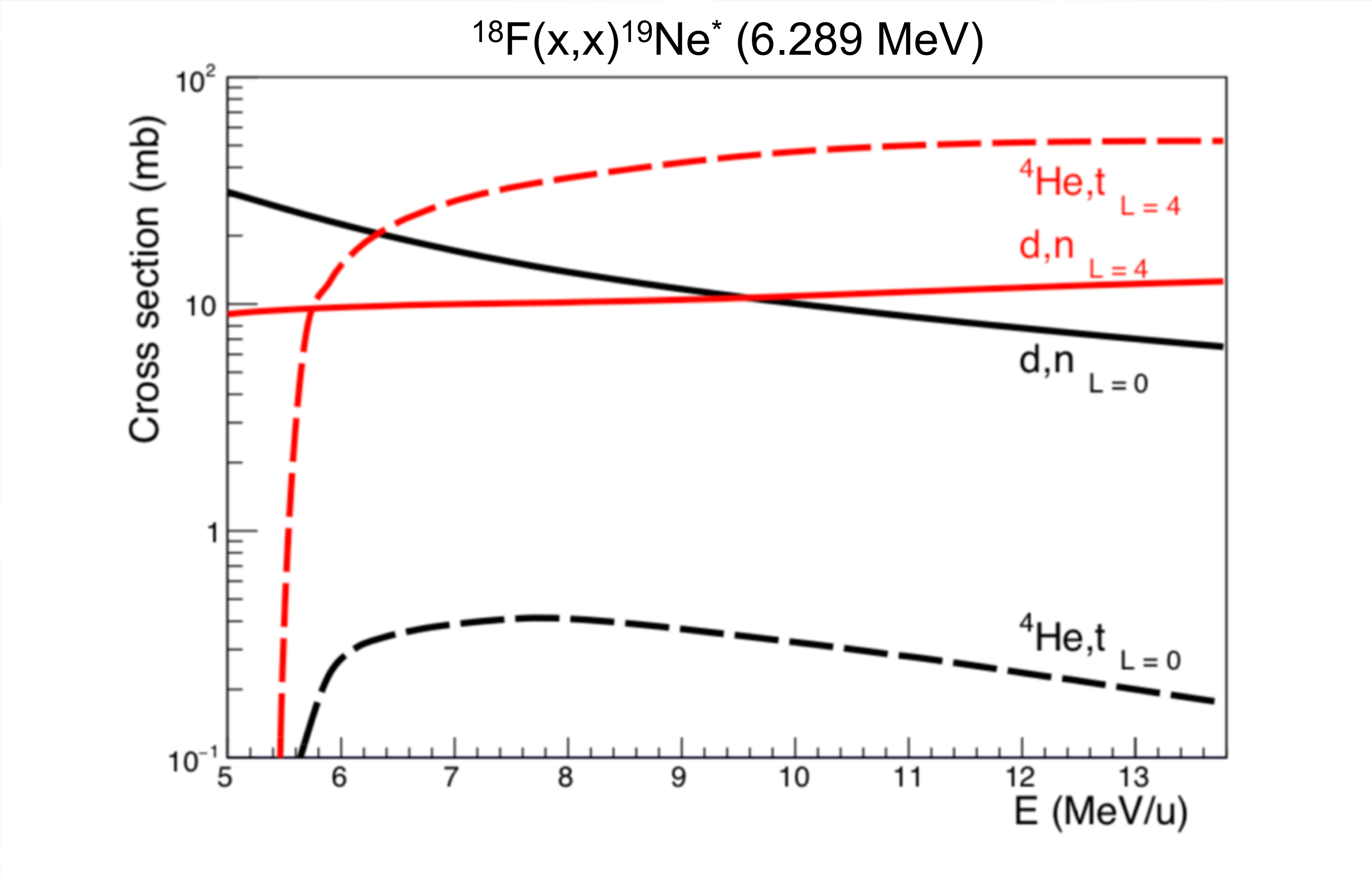
^{19}Ne+n

^{18}F+d

Nuclear potential

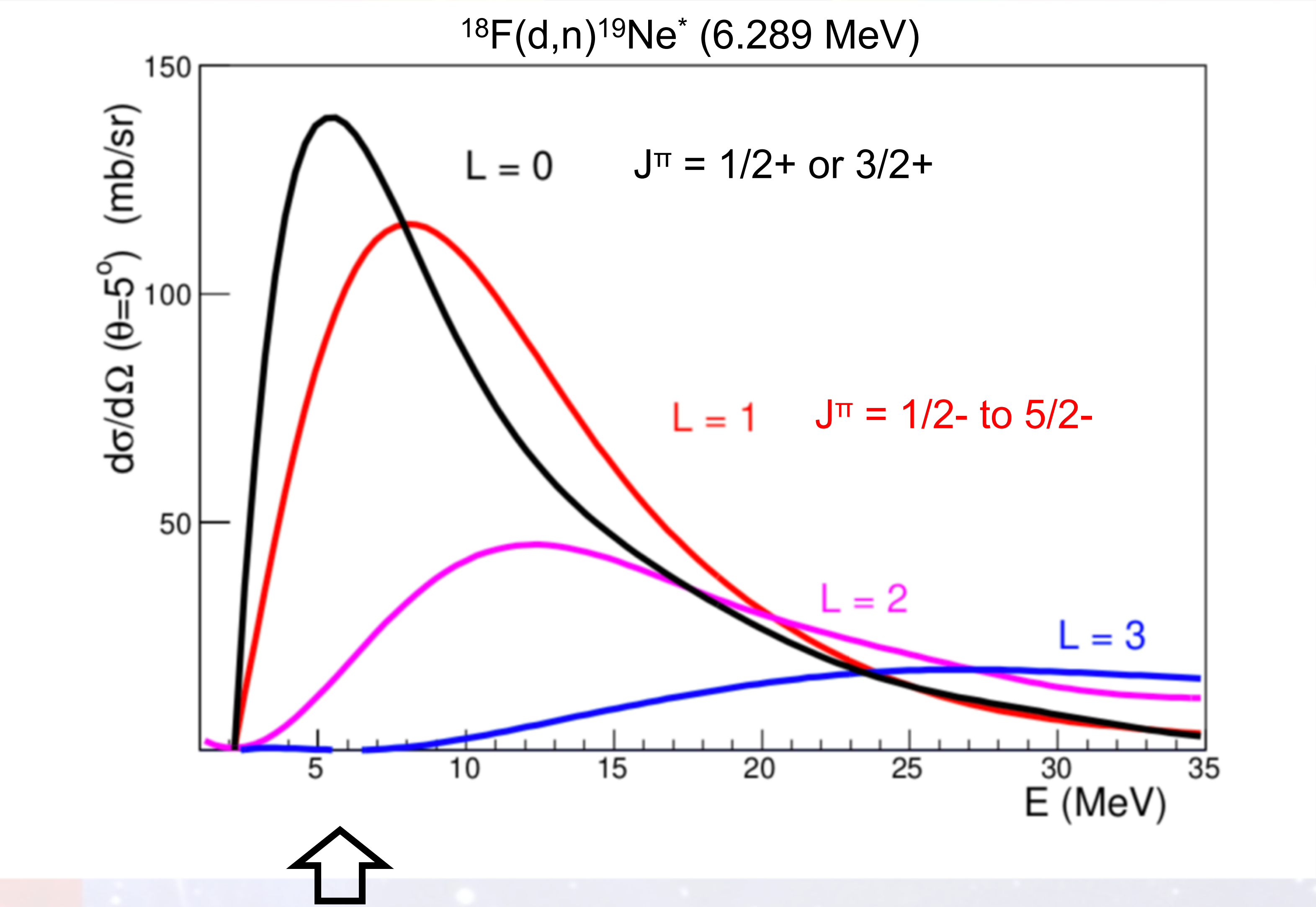
Codes: DWUCK, PTOLEMY, FRESCO…

Which reaction?



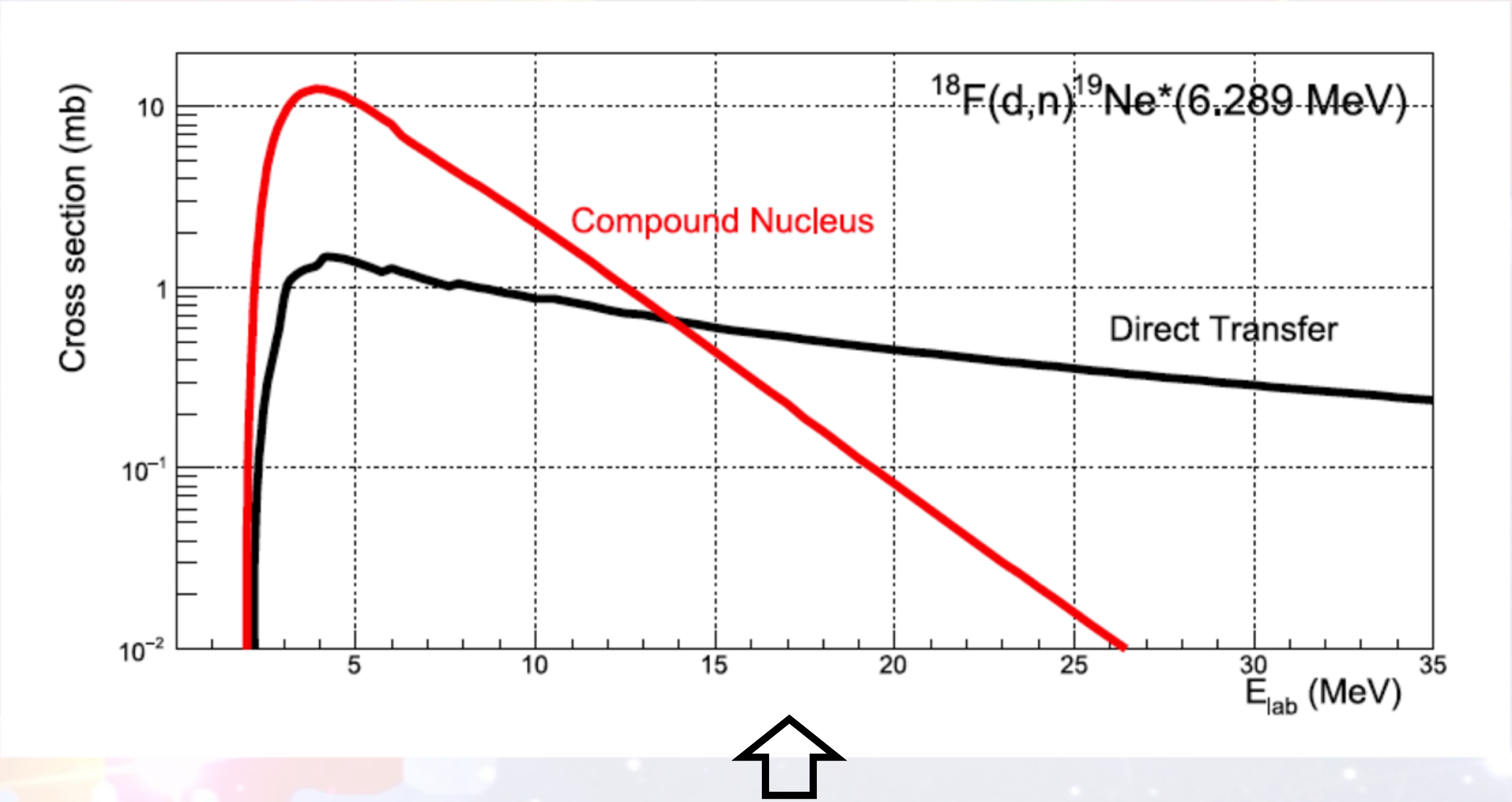
(d , n) reaction (Q = –1 MeV/u)
(^{4}He, t) reaction (Q = –4.9 MeV/u)

Which beam energy?



L=0, low energy is better

Which beam energy?



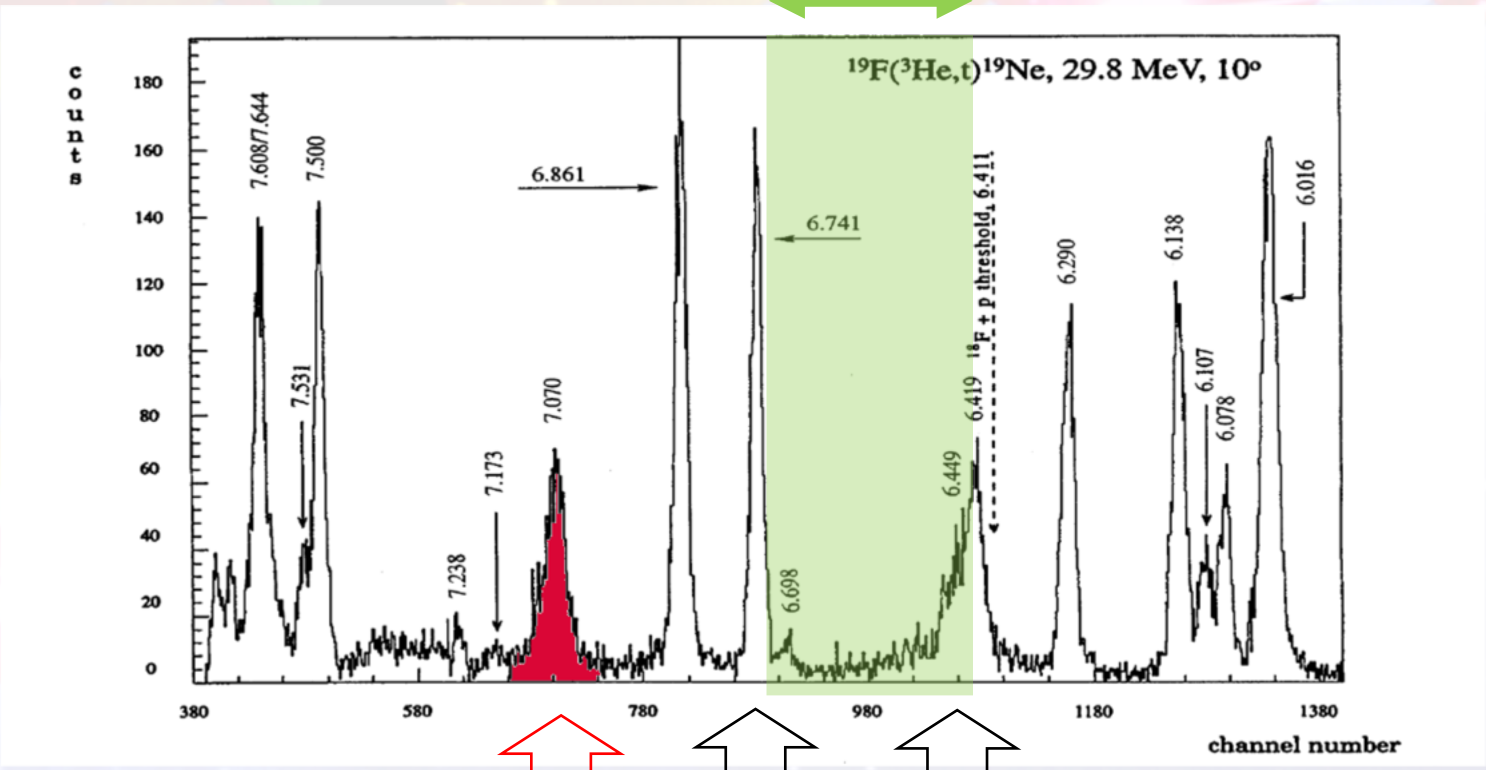
L=0, the lower the better BUT polluted by compound nucleus formation (not direct transfer mechanism)
Better at ~17 MeV

Excitation energy

Two body kinematics $^{18}F(^{3}He,t)^{19}Ne^{*}$ ⟹ E_x

(Missing mass technique)

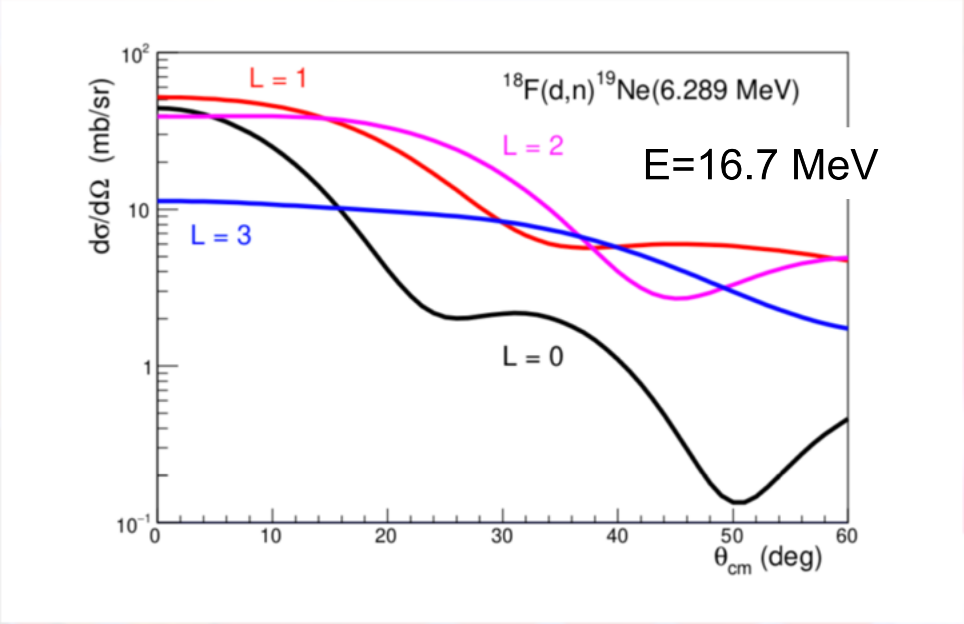
Gamow peak



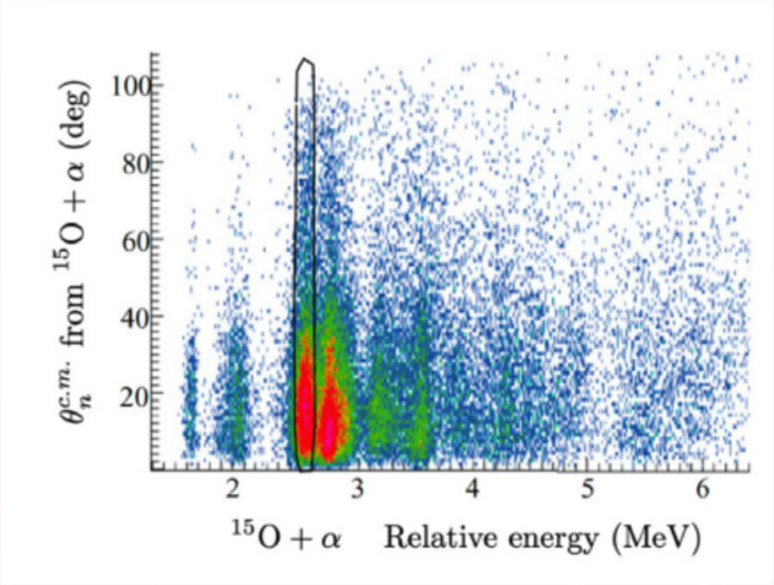
From Utku et al. PRC 1998

665 keV 330 keV New resonances here

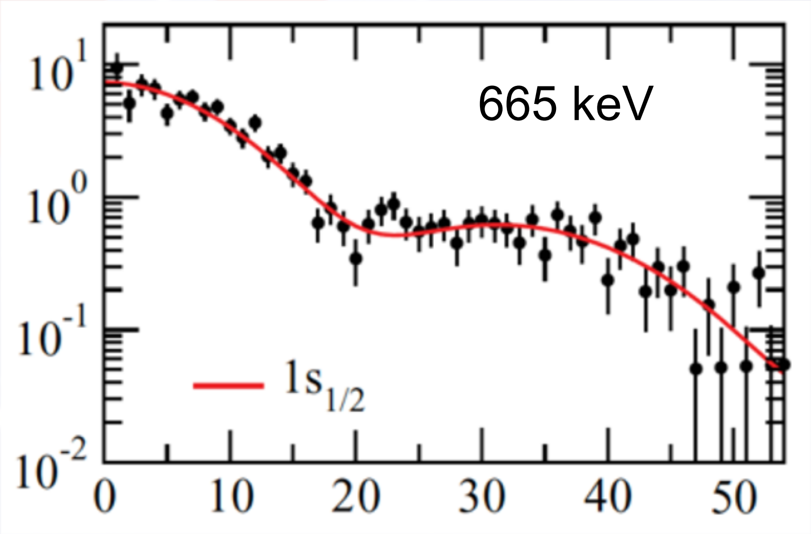
Spin assignment



A.S. Adekola et al, Phys. Rev. C 83



$^{18}F(d,n)^{19}Ne^{*}$



J=3/2+ confirmed

Partial Widths

To measure the proton width, a proton transfer has to be measured

$^{18}F(d,n)^{19}Ne^*$

$$C^2S = \frac{\frac{d\sigma}{d\Omega}^{exp}}{\frac{d\sigma}{d\Omega}^{theo}}$$

Present work				
ℓ	$(2J+1)S_p$			E_x (keV)[a]
	$2s_{1/2}$	$1p_{1/2}$	$1d_{5/2}$	
2			0.47(3)	5092(6)
0,2	0.02(4)		0.03(7)	5351(10)
2			0.38(2)	5463(20)
2			2.36(3)	6092(8)
0,2	0.92(3)		0.52(3)	6288(7)
1		0.50(2)		6419(6)
1		0.56(2)		6741(6)
0	1.46(5)			7076(16)

Adekola et al PRC 84, 054611 (2011)

665 keV

$$\Gamma_{exp} = C^2S \;\; \Gamma_{sp}$$

$$\Gamma(E) \propto C^2S \times a^2 R^2(a)$$

$$\frac{d\sigma}{d\Omega}_{\text{transfer}} \propto C^2S \times r_t^2 R^2(r_t)$$

E_x (keV)	J^π	Present work	Ref. [13]
6419	$3/2^-$	$1.27(4) \times 10^{-38}$	$2.2(4) \times 10^{-37}$[a]
	$1/2^-$	$2.54(4) \times 10^{-38}$	–
6449	$3/2^+$	$\leqslant 2.35(4) \times 10^{-15}$	$4.0(4.0) \times 10^{-15}$
6741	$3/2^-$	$7.3(6) \times 10^{-3}$	$2.22(68) \times 10^{-3}$
7076	$3/2^+$	13.5(7)	15.2(1.0)

[a]This value is from previous works that assumed $J^\pi = 3/2^+$.

$\Gamma_p \sim 10^{-38}$ keV !!
not accessible otherwise

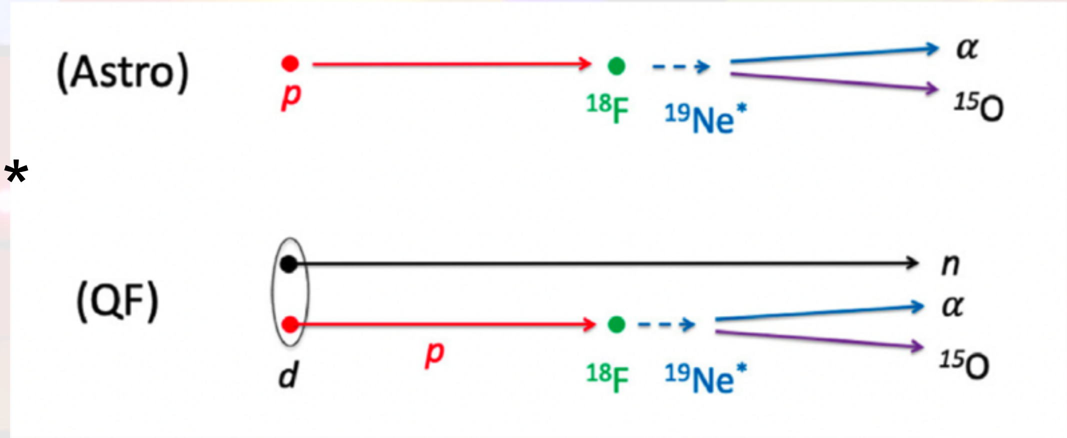
Very good agreement with measured value

Trojan Horse

Trojan Horse Method

$^{18}F(d,n)^{19}Ne^*$

Quasi free reaction

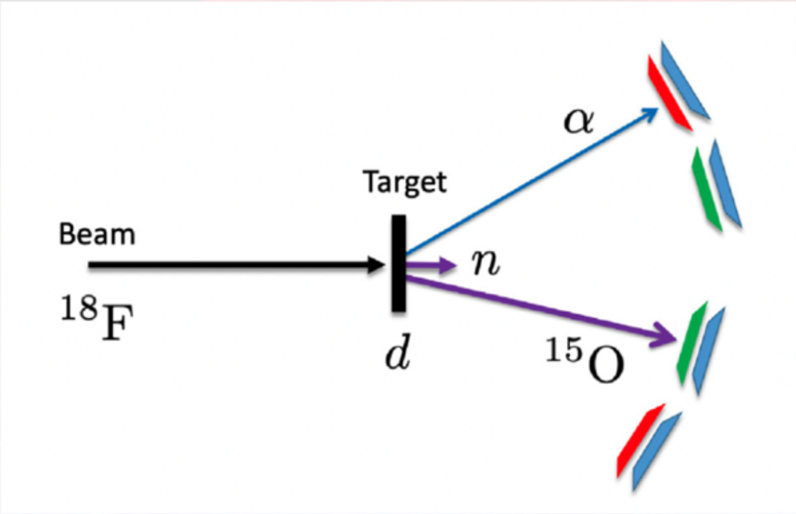


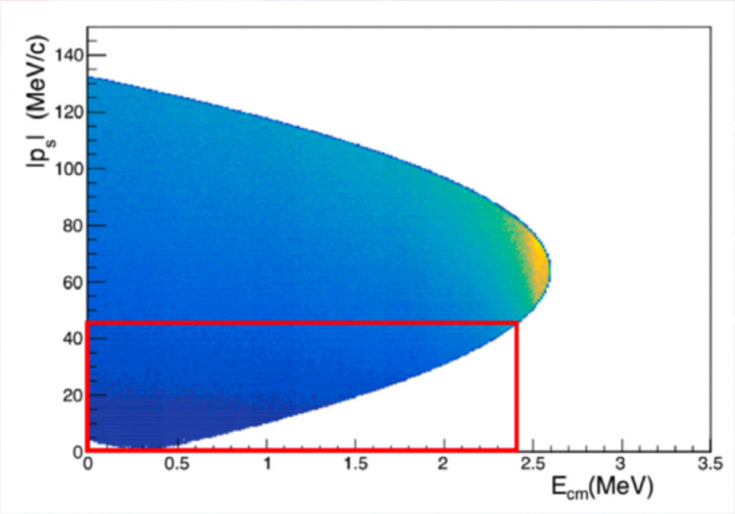
n is spectator

$$\left(\frac{d^3\sigma}{dE_{^{15}O\alpha}\,d\Omega_\alpha\,d\Omega_{^{15}O}}\right)^{c.m.}_{^{18}F(d,\alpha\ n)^{15}O} = K|\Phi(\mathbf{p}_{pn})|^2\left(\frac{d\sigma}{d\Omega}\right)^{\text{c.m. HOES}}_{^{18}F(p,\alpha)^{15}O}$$

Experimental

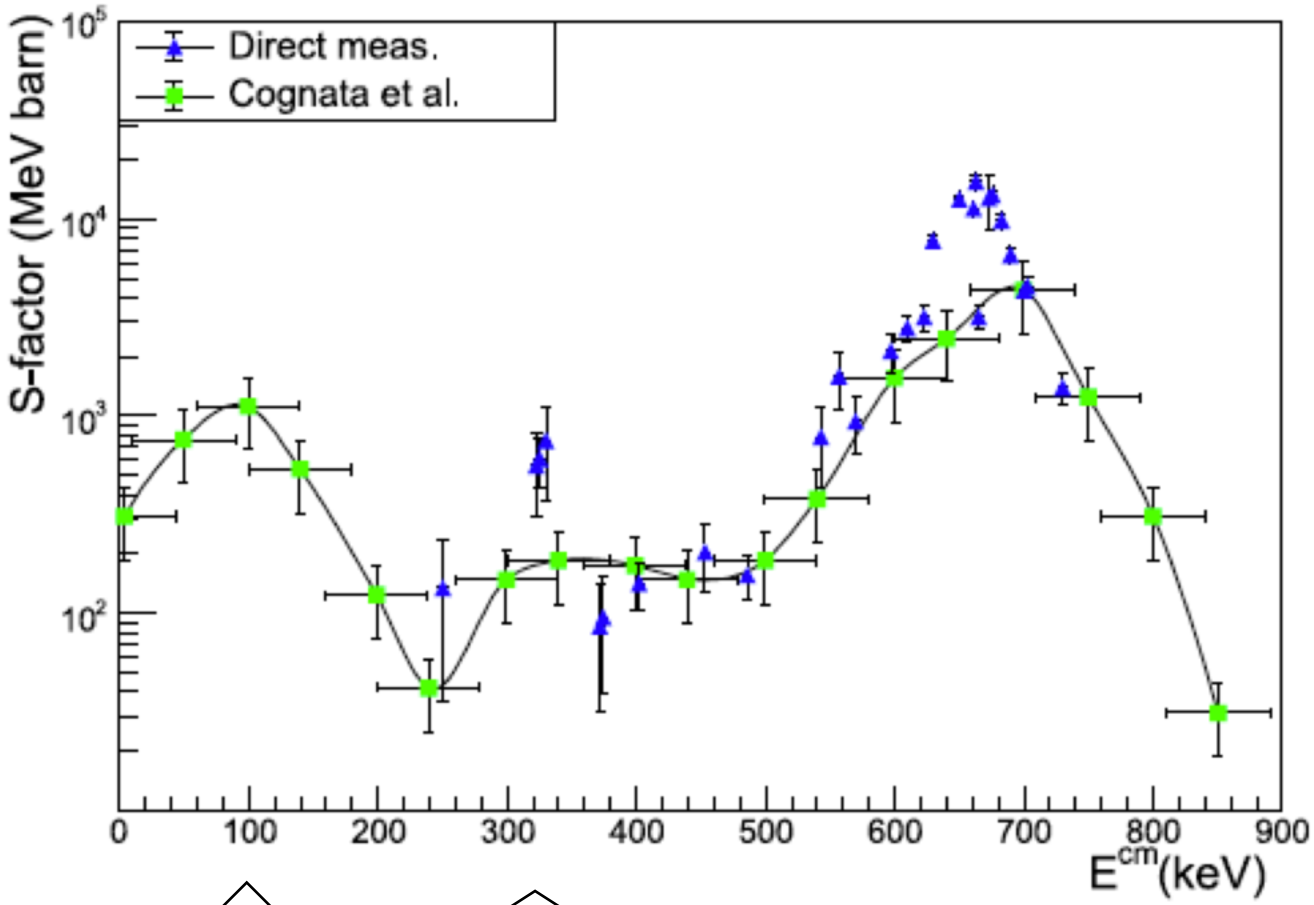
Half Off-Energy-Shell





Trojan Horse Method

La Cognata et al Astrophys. J. 846 (1) (2017) 65
Cherubini et al PRC 92, 015805 (2015)



330 keV

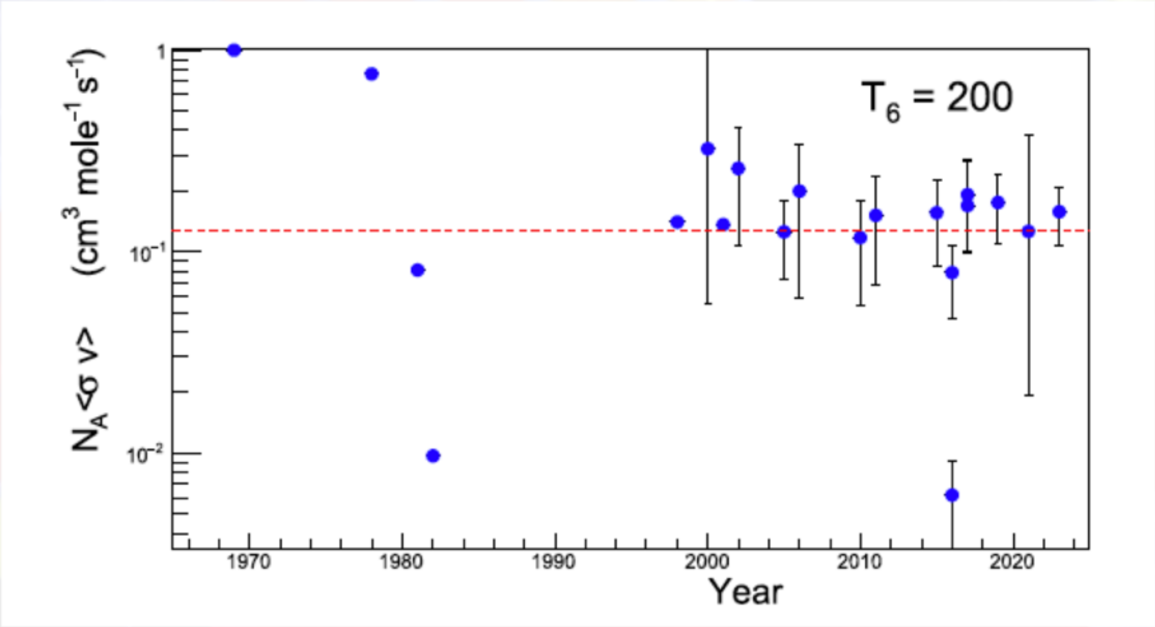
665 keV

Low energy resonance(s) confirmed

Conclusion

Conclusion

Reaction rate at 200 MK

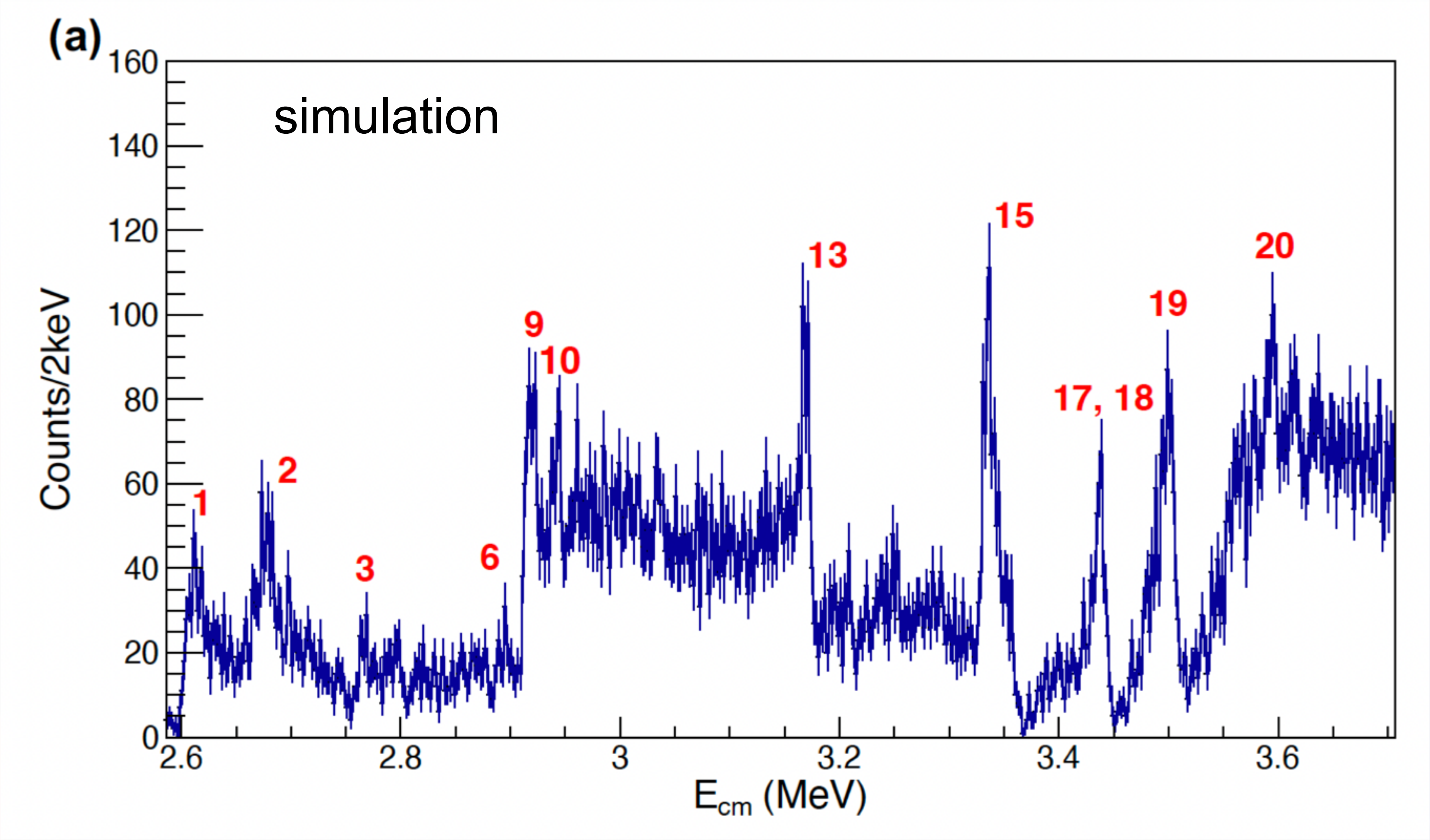


Factor ~3 uncertainty

Mainly due to unknown 3/2+ states at low energy

This reaction illustrates the current challenges of nuclear astrophysics, linked in particular to the new radioactive beams recently produced in various facilities around the world.

Next experiment: $^{15}O(^4He,^4He)^{15}O$



Resolution ~ 5 keV

Thank you

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