# Indirect methods: a bridge between nuclei and stars

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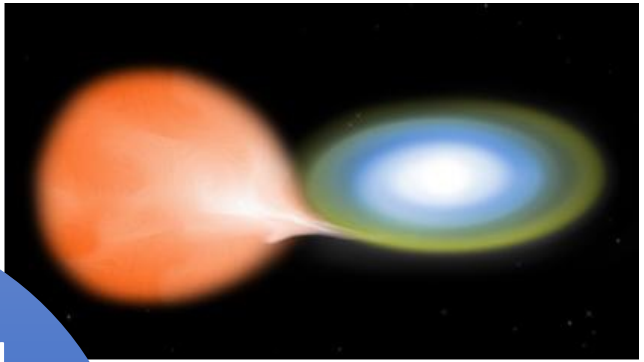
# Nuclear astrophysics: from the laboratory to the cosmos



The purpose of nuclear astrophysics is to provide reliable nuclear physics input for astrophysical models

Nuclear parameters (cross sections, …)

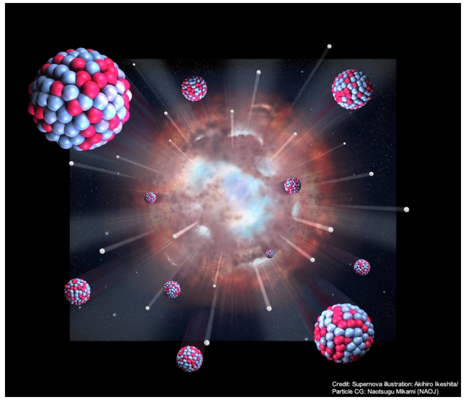
Astrophysical models: how a star works

Model input parameters: magnetic field, metallicity, …

Elemental yield → comparison with abundances observed in stars and meteorites to validate models

**PROBLEM: cross sections are needed at energy of 10-100 keV**

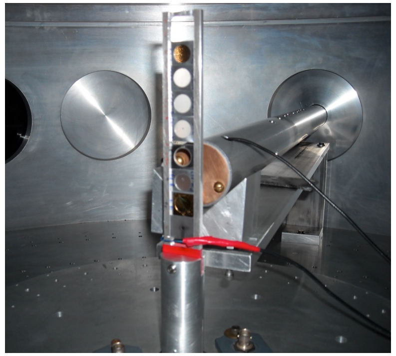
Change the model until observables are matched by predictions



Astrophysical models are very complex: assumptions on stellar structure and on stellar parameters (age, mass…) → need of multiple independent constrain

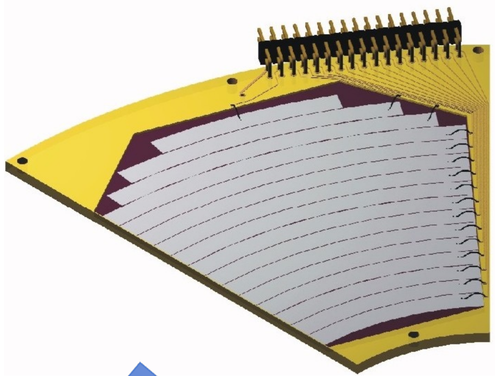
# The need of indirect methods: direct vs. indirect methods

How to measure the A+x→c+C reaction in a *direct* way?



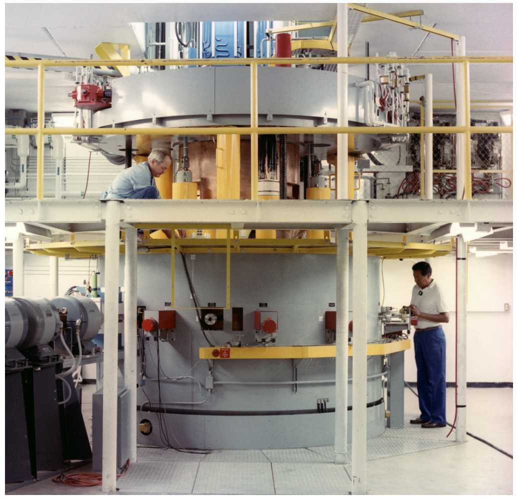
Target (A)

Detector →
kinematic observables
- Energy
- Emission angle
& Particle identification



Beam (x)

Reaction product (c)

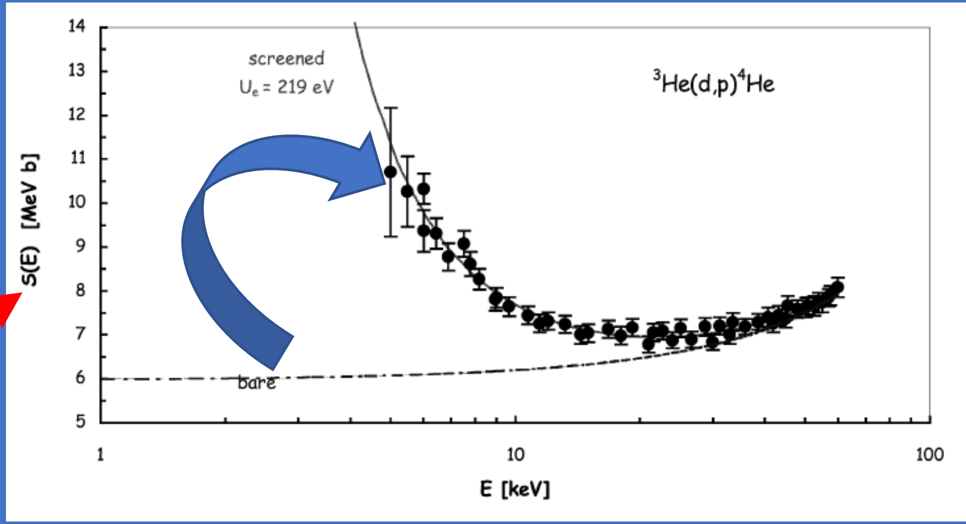


It looks *quite* simple!

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

**However**, several reasons make the low-energy region of astrophysical interest difficult to access

- Coulomb barrier suppression of the cross section
- Cosmic background and systematic errors due to, e.g., straggling in the target
- ***Electron screening hiding the nuclear cross section***



# The need of indirect methods: direct vs. indirect methods

Entrance channel:

***A+a***

**Several reaction mechanisms link the two channels**

Reaction products

***C+c+…***

**Nuclear reaction theory required**

→ cross checks of the methods needed

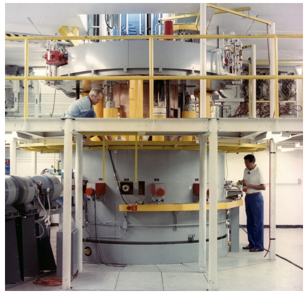
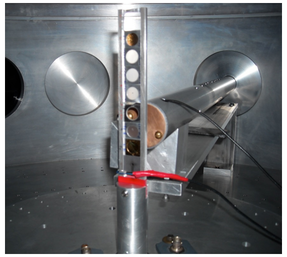
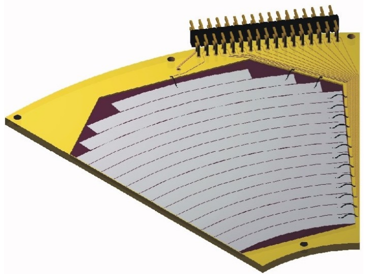
→ possible spurious contribution

→ additional systematic errors (is the result model independent?)

Advantages include no need of low energies → no straggling, no Coulomb suppression, no electron screening

**Possibility to access astrophysical energies with high accuracy**

To recall the previous sketch:

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R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

**Nuclear reaction theory**

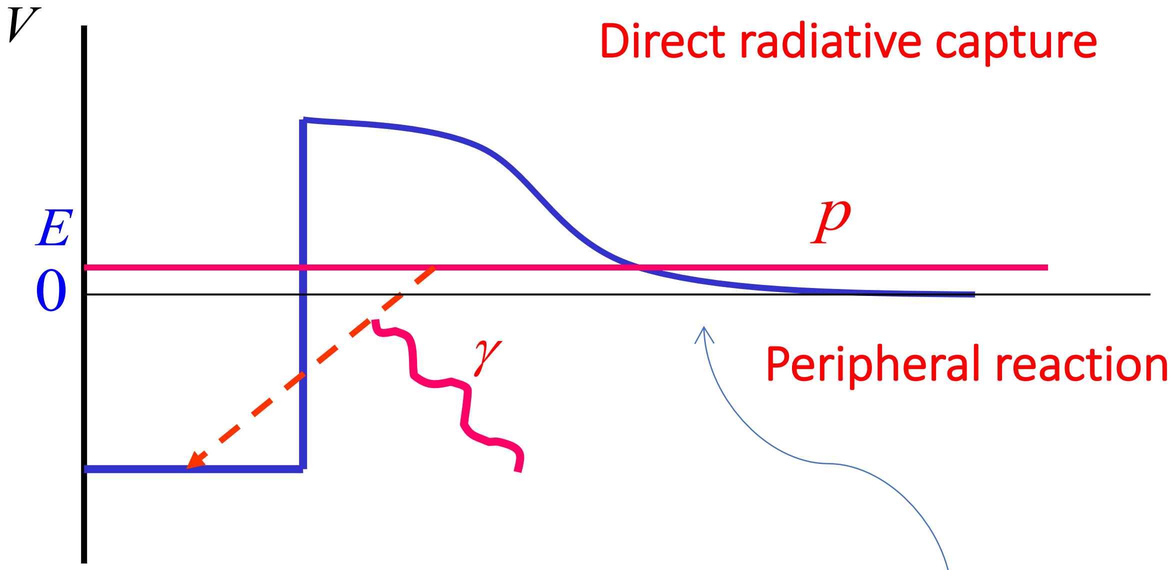
Indirect methods are especially useful in the case of reactions involving **radioactive nuclei**

- Higher cross sections
- Possibility to study reactions induced by neutrons on radioactive nuclei
- Reactions among unstable nuclei
- Easier experimental procedures

# About the ANC (Asymptotic Normalization Coefficient) method

Radiative *p* ($\alpha$) capture at stellar energies

- Classical **barrier penetration** problem




- **low energies $\Rightarrow$ capture at large radii**
- **very small cross sections**

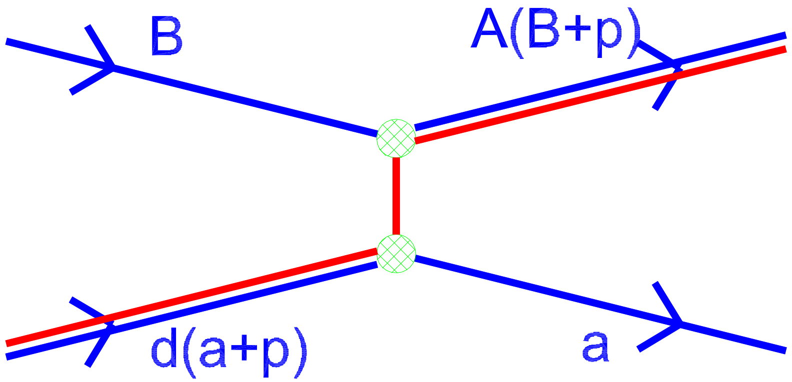
**The cross section is determined by ANCs**

$$\sigma \propto |M|^2 \qquad M = \left\langle I^A_{Bp}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

**Low B.E.:** $$I^A_{Bp}(r_{Bp}) \overset{r_B > R_N}{\approx} C^A_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

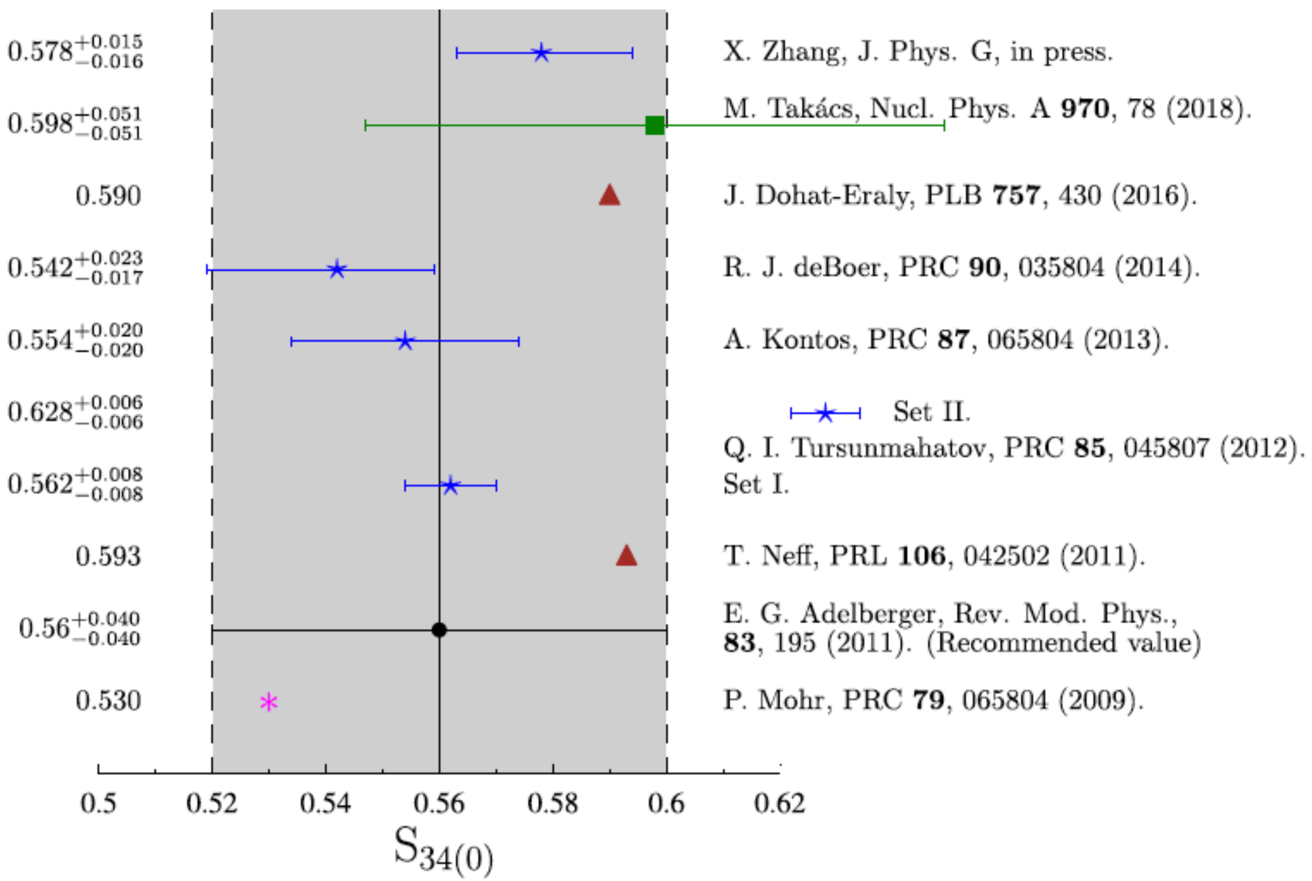
**Outside the nuclear radius**

**Find:** $$\sigma_{capture} \propto (C^A_{Bp})^2$$




**ANC $\Rightarrow$ amplitude for tail of overlap function → can be deduced from transfer reaction XS**

# The $^3He(\alpha,\gamma)^7Be$ and the $^6Li(p,\gamma)^7Be$ scientific cases




The zero-energy astrophysical factor of the **$^3He(\alpha,\gamma)^7Be$** shows a very large scatter. There is no general agreement between measurement (prompt vs activation) and calculations → NEED OF NEW INDEPENDENT DATA

The detection of the neutrinos coming directly from the core of the Sun became more and more precise after the construction of larger and more efficient neutrino detectors

Neutrinos are released in the β decay of the $^7Be$, $^8B$, $^{13}N$, $^{15}O$ isotopes produced in the p−p chain and in the CNO cycle.

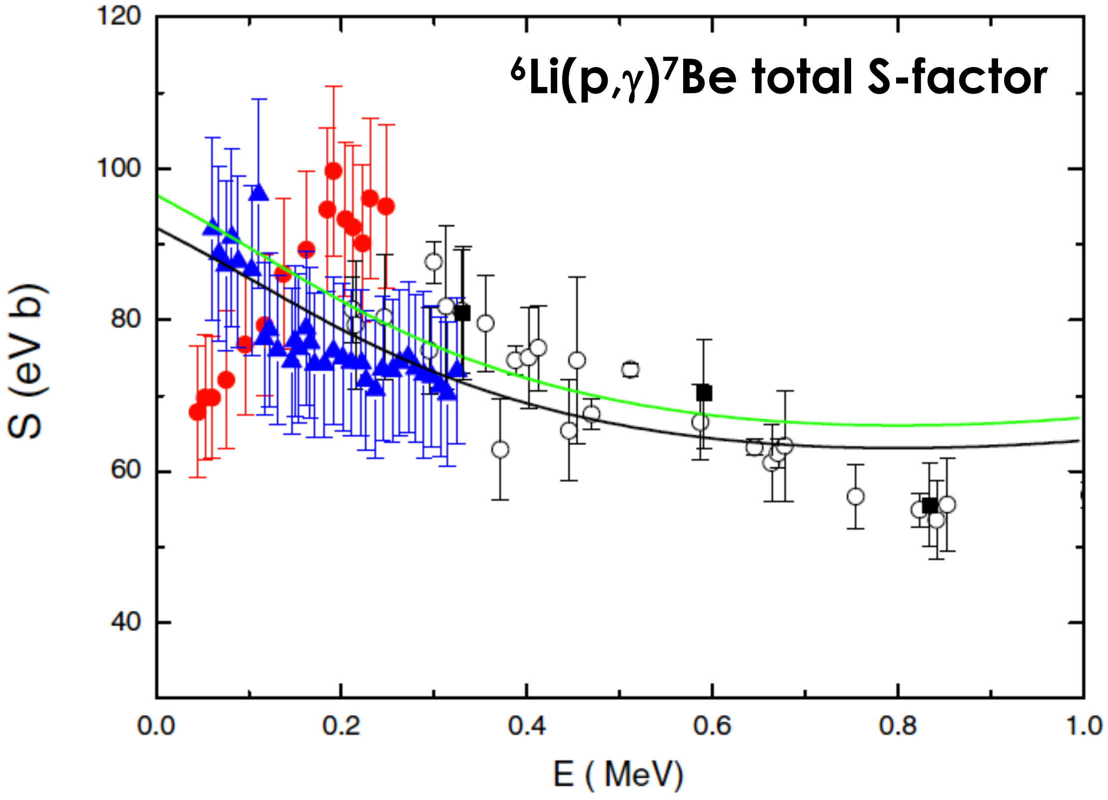
**The flux of the p−p neutrinos was measured with a precision of about 3.4% by the BOREXINO, SNO and Super-Kamiokande collaborations**

The precise neutrino flux measurements can constrain the Standard Solar Model (SSM)

**However, at present the uncertainties on cross sections are far too high, typically of the order of 5-8% contrary to the 3% precision required**

**The ANC approach has the opportunity**

# The $^3He(\alpha,\gamma)^7Be$ and the $^6Li(p,\gamma)^7Be$ scientific cases




**Blue solid triangles** → D. Piatti et al., Phys. Rev. C 102, 052802(R) (2020) (including systematic error)

**Red filled circles** → J. J.He et al., Phys. Lett. B 725, 287 (2013)

Direct measurements show a totally different low energy trend

Lithium is a key elements in astrophysics as big bang nucleosynthesis models coupled to chemical evolution models fail to find an agreement between predictions and observations.

$^7Li$ is the most abundant isotope, produced in the BBN and in stars

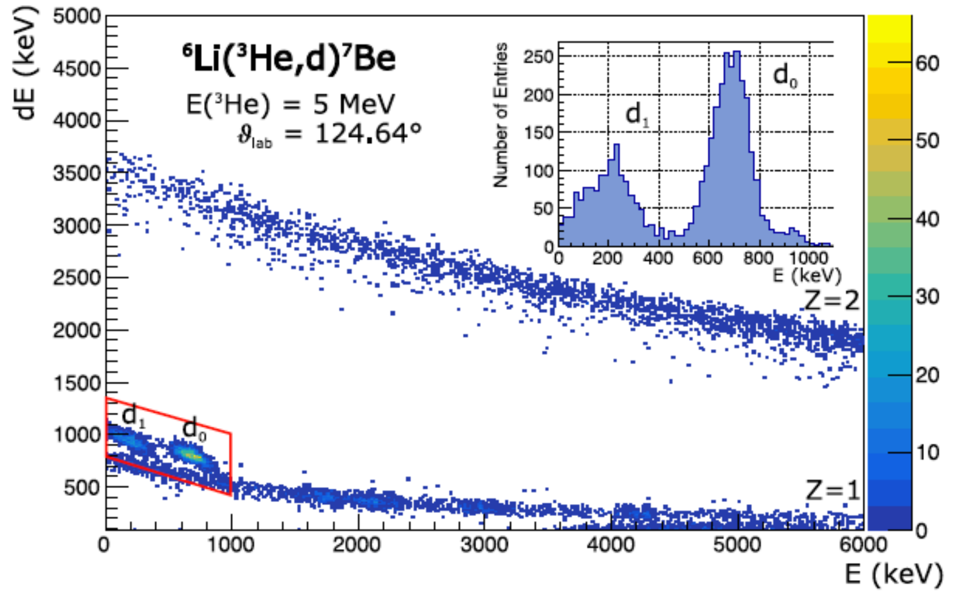
$^6Li$ is almost exclusively produced by cosmic rays and the possibility of a primordial $^6Li$ plateau, like the one for $^7Li$, is not presently confirmed

Since the production mechanism of $^6Li$ and $^7Li$ are completely different, the $^6Li/^7Li$ isotopic ratio can be used either to constrain the lithium production mechanisms and/or the galactic enrichment processes

**→ an accurate determination of the $^6Li(p,\gamma)$ $^7Be$ astrophysical S factor is needed.**

# Experimental spectra

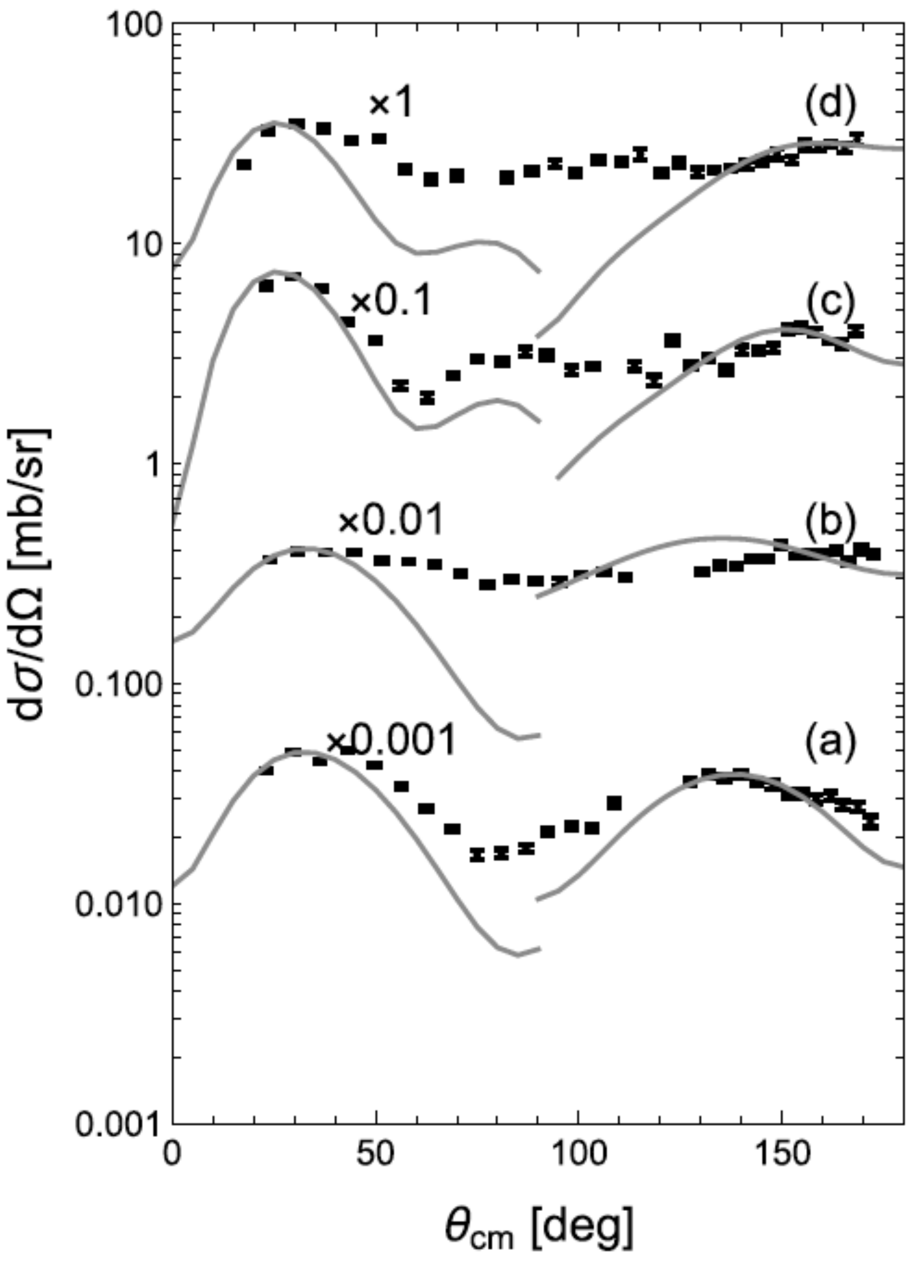
G.G. Kiss et al. Physics Letters B 807 (2020) 135606
G.G. Kiss et al. Physical Review C 104 (2021) 015807




DE−E spectrum measured with a silicon telescope

The peaks: $d_0$ and $d_1$

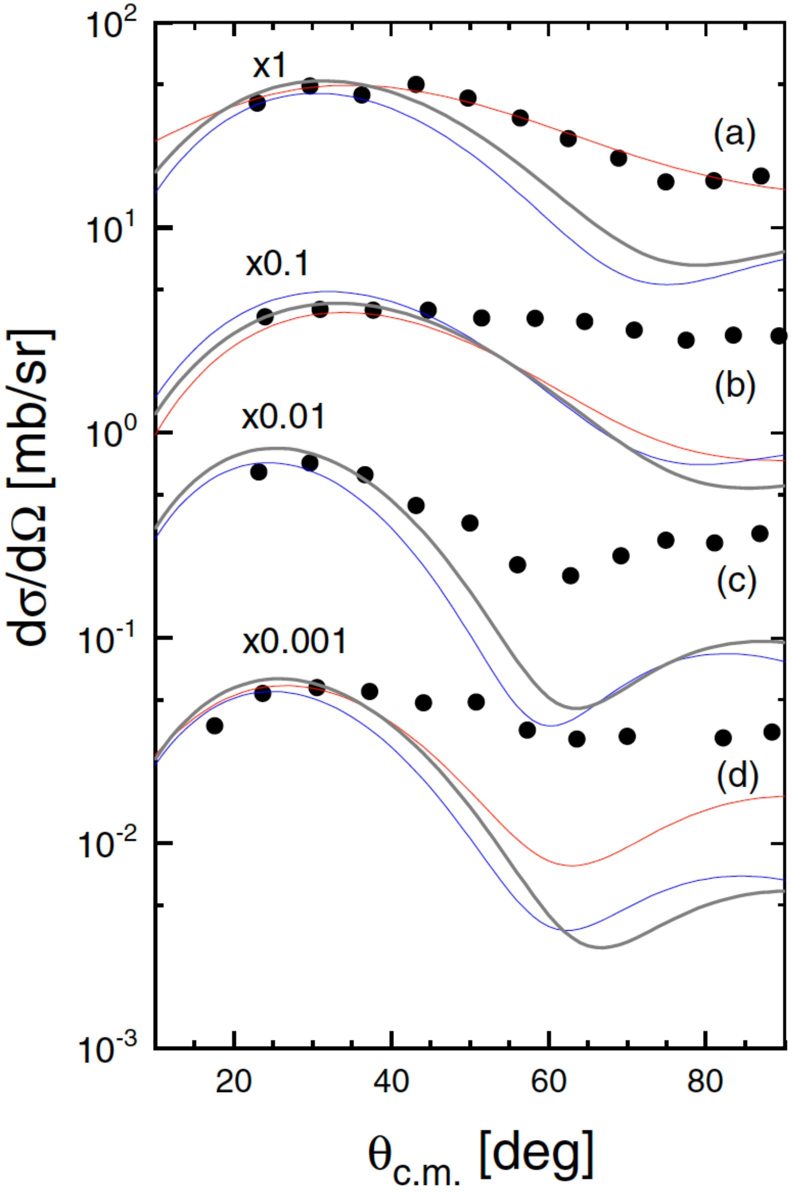
1. Very clean d ID
2. Observation of both $^7$Be gs and 1$^{st}$ excited state




Angular distributions of the $^6$Li($^3$He,d)$^7$Be reaction populating the ground ((a) and (c)) and first (0.429 MeV) excited ((b) and (d)) states of $^7$Be at the projectile $^3$He energies of 3 ((a) and (b)) and 5 ((c) and (d)) MeV.

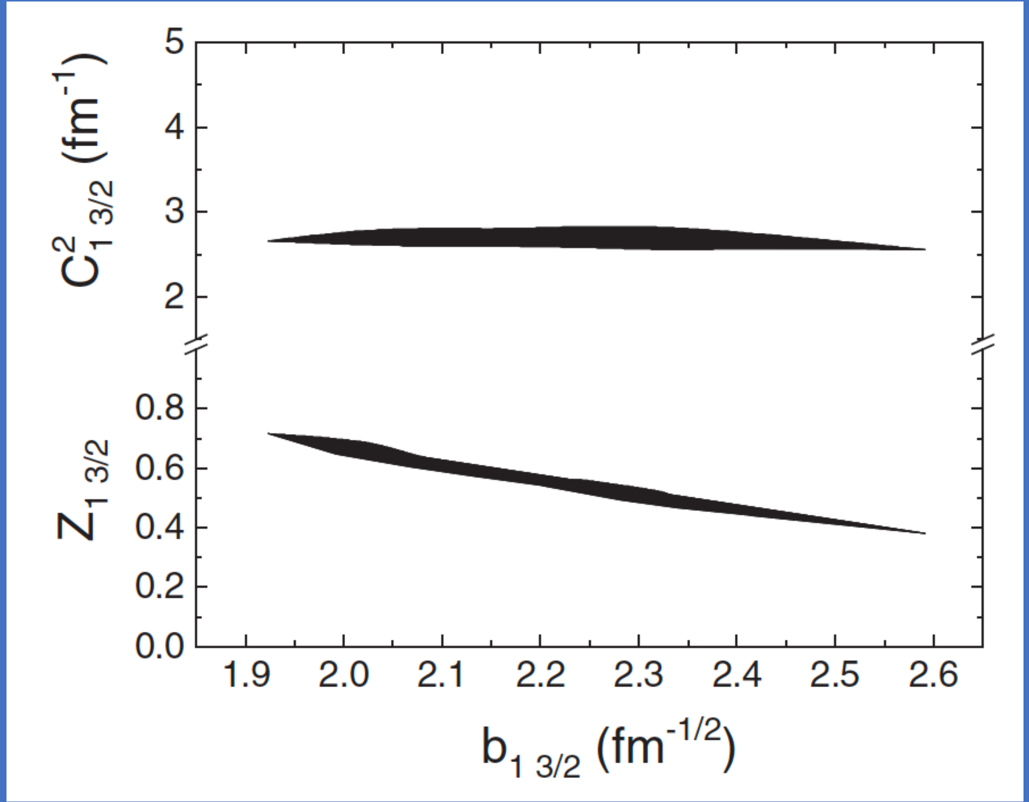
Gray lines are the calculated angular distributions, **for p−and α−transfer (forward and backward hemisphere, respectively) → possibility to deduce the ANC's for both channels** (no interference at the peaks)

# Test of the model dependence



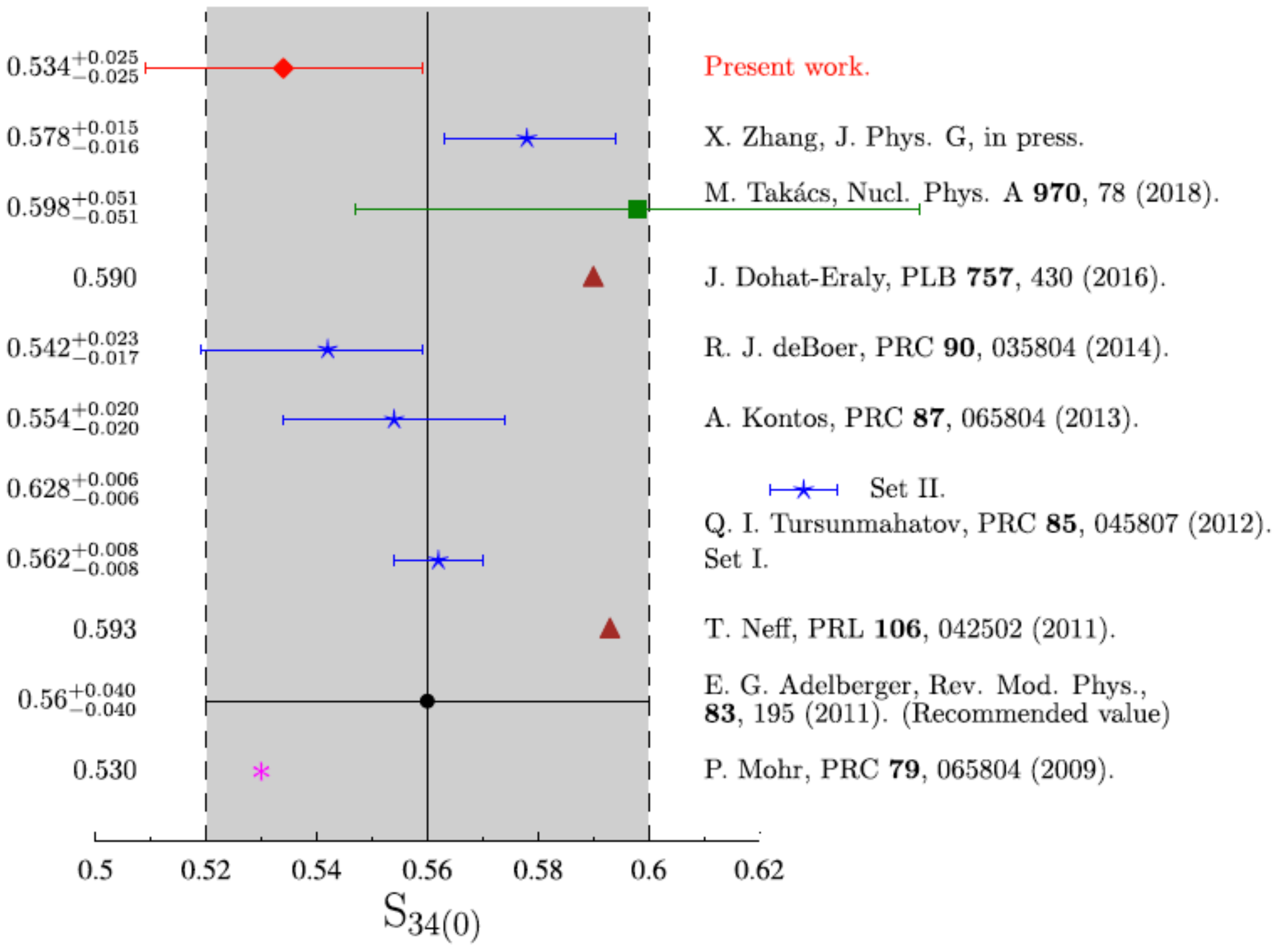

**Nuclear reaction theory in indirect approaches may introduce systematic errors**

The gray lines indicate the calculated angular distributions including coupled-channel effects for p transfer off 3He. The red and blue curves are the same calculations, but with other optical potentials




While the spectroscopic factor Z depends on the choice of the optical model potential parameters (lower band), the ANC $C^2$ is almost independent (upper band). The dependence is given by the width of the band

# The $^3He(\alpha,\gamma)^7Be$ $S_{34}(0)$ using ANC




- **Lower $S_{34}(0)$ values favored, with a total uncertainty equal to 4.7%.**
- **More than 50% of the error budget is due to the non-peripherality of the transfer process**

The post-form DWBA calculation contains:

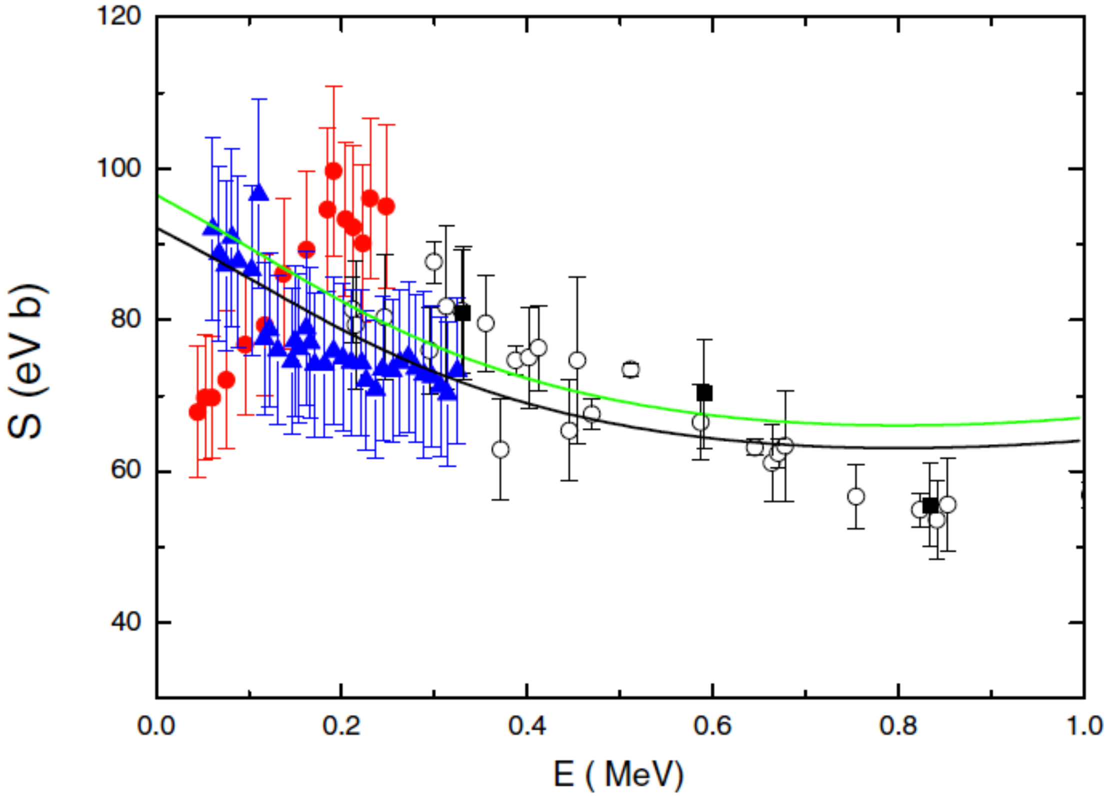
- ✓ s-wave ANC values for the d+p →$^3$He and the d+α→$^6$Li channels
- ✓ Test of the dependence on the choice of the optical potentials
- ✓ Test of the peripheral nature of the reaction
- ✓ channels coupling effects (CCE)

Further improvements to be implemented:

- ○ Test one-step process in modelling the transfer
- ○ Test the coupling between ground and excited states of $^6$Li and $^7$Be
- ○ Perform full coupled-channel analysis to derive the $^3$He+$^4$He and the *p*+$^6$Li ANCs

**$^3He(\alpha,\gamma)^7Be$**
**PLB 807 (2020) 135606**

# The $^6Li(p,\gamma)^7Be$ astrophysical factor




**Green line:** astrophysical S factor obtained by using the weighted average ANC values from the near-barrier proton transfer $^6Li(^3He,d)^7Be$ reaction at $E_{beam}$ = 3 and 5 MeV

**Black line:** astrophysical S factor obtained from the analysis of the $^6Li(p,\gamma)^7Be$ S-factor of Piatti et al. (2020)

**Our result strongly disfavors the resonant trend claimed by He et al. (2014)**

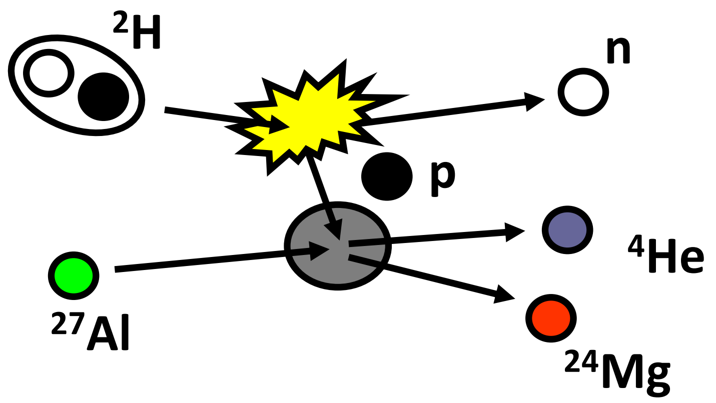
Two approaches:

1. the weighted means of the ANCs from the analysis of the $^6Li(^3He,d)$7Be transfer were used to calculate the total astrophysical S factor for the $^6Li(p,\gamma)^7Be$ reaction **using the modified two-body potential method [Igamov and R. Yarmukhamedov (2019)]**. In the calculation M1 and E2 are neglected as their contribution is lower than 1% at these energies

2. the ANCs for the $^6Li+p \rightarrow {}^7Be$(g.s.) and $^6Li+p \rightarrow$ 7Be(0.429 MeV) channels were derived from the experimental total astrophysical S factor and the branching ratios of Piatti et al. (2020) and then (**after checking the actual agreement**), we also calculated the astrophysical factor of the $^6Li(p,\gamma)$7Be reaction within the MTBPM

**$^6Li(p,\gamma)^7Be$**
**PRC 104 (2021) 015807**

# The Trojan Horse Method -THM (see, e.g., PRL 101, 152501 (2008))




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

Let's focus on resonance strengths

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

The strengths are calculated from resonance partial widths

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

In the THM approach we determine the strength in arb.units. Normalization to a known resonance is necessary

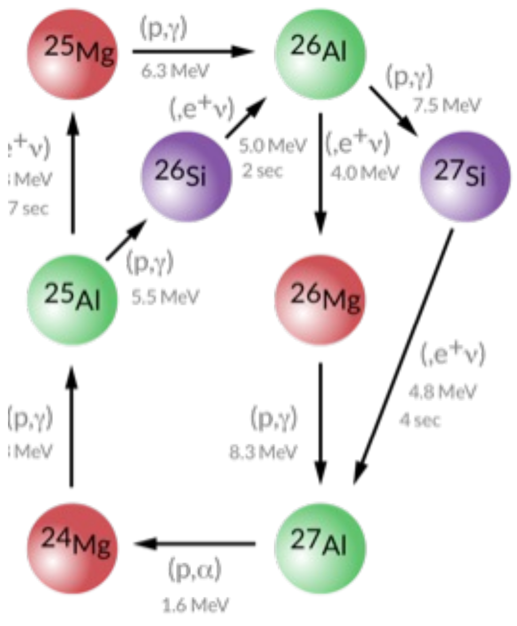
**What is its physical meaning?**
**Area of the Breit-Wigner describing the resonance**

**<u>Advantage:</u>**
**no need to know the resonance shape (moderate resolution necessary)**

# $^{27}$Al: an ingredient in multimessenger astronomy

**MgAl cycle in massive stars**

- It is ignited at temperatures > 0.03 GK and it is important to determine the abundances of medium mass nuclei

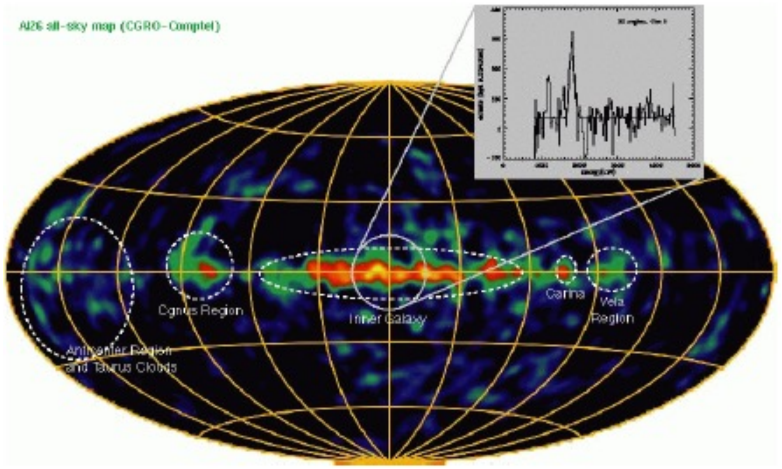



Mg-Al Cycles

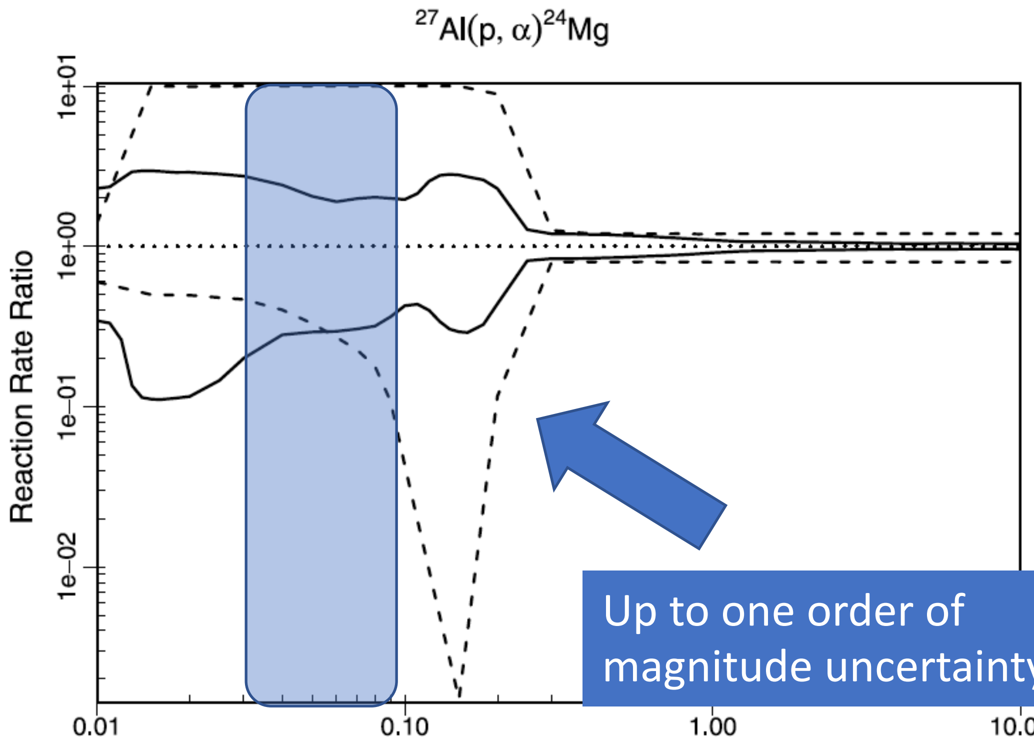
**$^{26}$Al/$^{27}$Al abundance ratio**

- $^{26}$Al abundance is used to estimate the number of Galactic neutron stars and, therefore, of neutron star mergers (sources of GW)

The $^{26}$Al/$^{27}$Al is generally estimated, so it is influenced by $^{27}$Al abundance predictions



# $^{27}Al(p,\alpha)^{24}Mg$ status of the art




Up to one order of magnitude uncertainty

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*************************************
Upper Limits of Resonances
Note: enter partial width upper limit
Note: ...PT <B> for g-rays [enter: "u
Ecm      DEcm     Jr     G1       DG1
  71.5   0.5      2      7.4e-14  0.0
  84.3   0.4      1      2.6e-12  0.0
 193.5   0.7      2      7.5e-4   0.0
 214.7   0.4      3      9.7e-5   3.9e-5
 282.1   0.4      4      6.4e-5   2.6e-5
 437.2   0.4      5      3.4e-5   0.0
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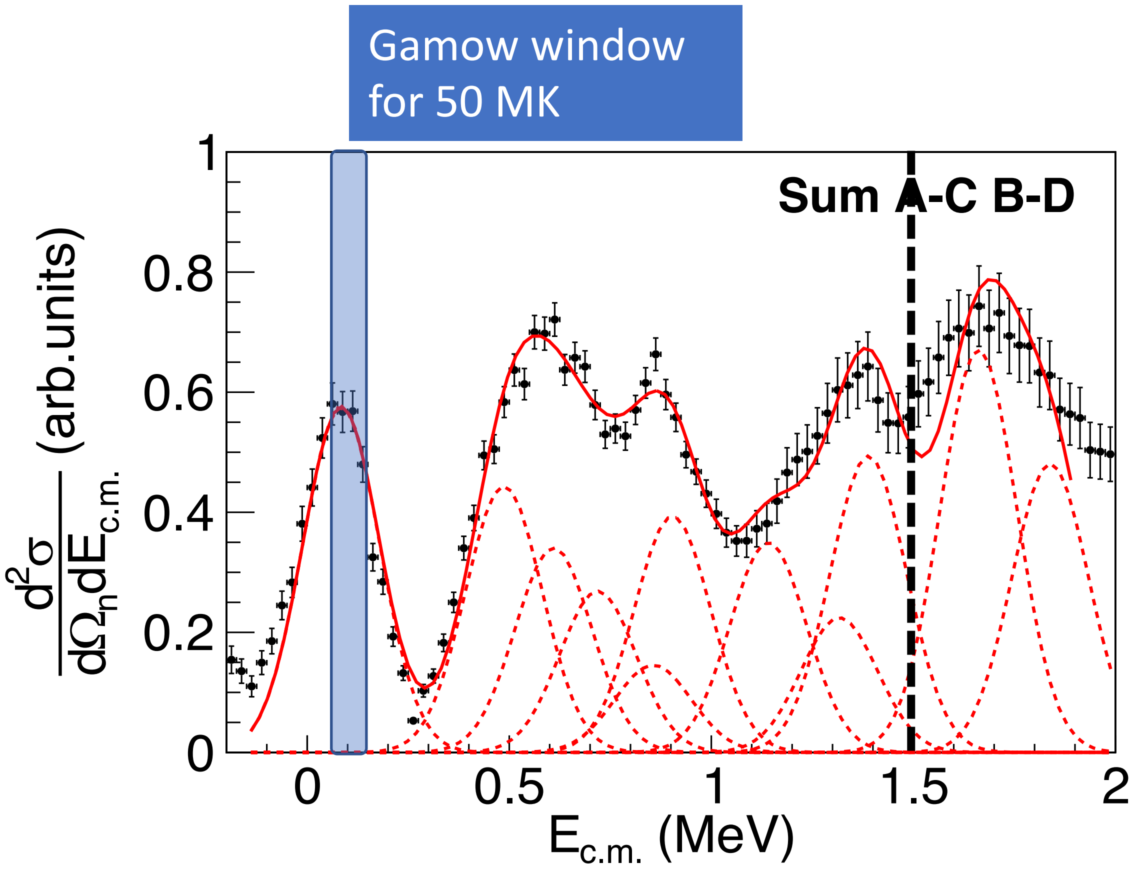
```

The most recent review [Iliadis et al. (2010)] shows that for most low-energy resonances only an upper limit is known

→ These resonances are the most influent for astrophysics

# Extraction of the resonance strengths

- Black dots: sum over the two spectra for A-C and B-D
- Following discussion in APJ 708 (2010) 796 the red line is a fit with a sum of Gaussian functions, with fixed energies and fixed widths (from MC). Heights are proportional to strengths
- The most intense resonances in STARLIB were all included in the fit down to about 200 keV




Tails of higher energy resonances affects the region above 1.5 MeV

# A bit of theory (from APJ 708 (2010) 796)

- 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 b fitted using the equation:

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

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

- $\boldsymbol{\Gamma}_{\mathrm{s.p.}}$ is calculated using the potential model

- $\boldsymbol{\sigma(\theta)}$ is calculated in PW using the same well & w.f.

$$\omega\gamma_i^{\mathrm{THM}} = \frac{\omega_i N_i}{\omega_{norm} N_{norm}} \frac{\dfrac{\Gamma^i_{p,\,\mathrm{s.p.}}}{\sigma^i_{(d,n)}(\theta_n^{c.m.})}}{\dfrac{\Gamma^{norm}_{p,\,\mathrm{s.p.}}}{\sigma^{norm}_{(d,n)}(\theta_n^{c.m.})}} \omega\gamma_i^{norm}$$

The double ratio ensures an extra small model dependence (6%)

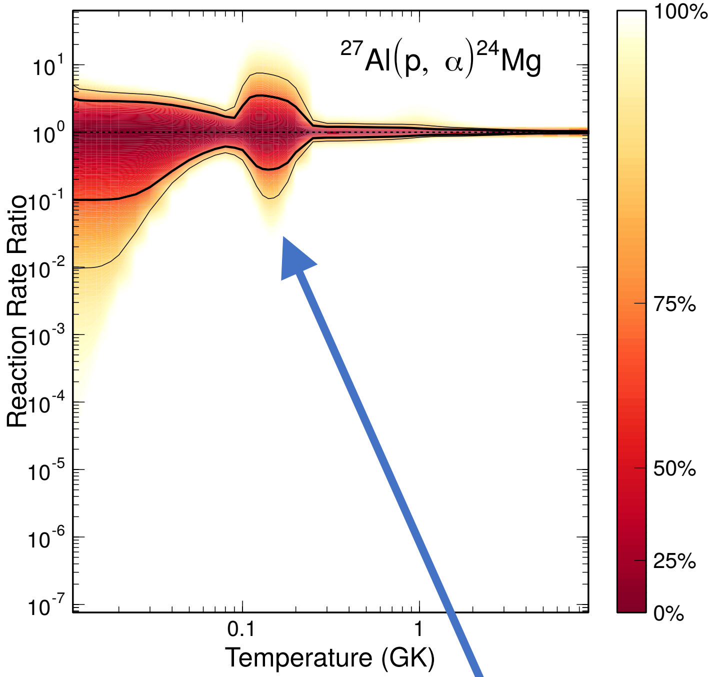
# Average values

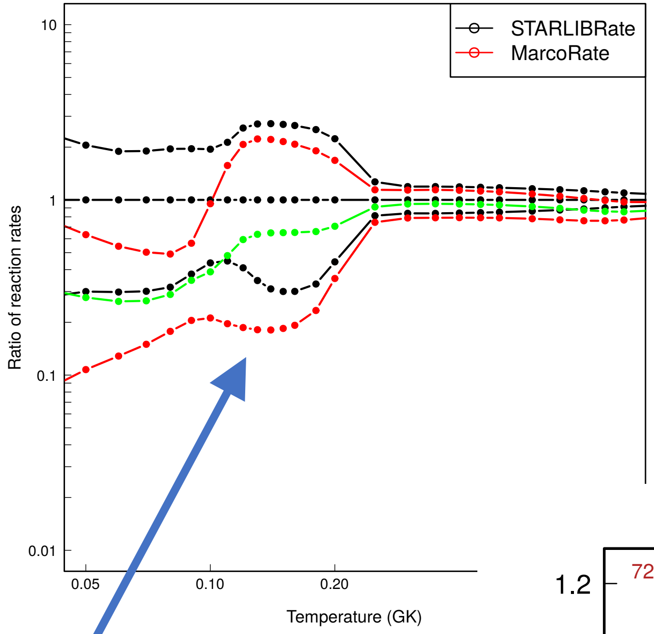
- We take the weighted average of the strengths obtained from the two normalizations procedure to reduce systematics errors

| Energy in cm (keV) [from STARLIB] | Jpi | Strength (eV) [from STARLIB] | error (eV) | Strength (eV) [from THM] | error (eV) |
|---|---|---|---|---|---|
| 71.5 | 2+ | 2.47E-14 | up lim | 8.23E-15 | up lim |
| 84.3 | 1- | 2.60E-13 | up lim | 1.67E-14 | 3.2E-15 |
| 193.5 | 2+ | 3.74E-07 | up lim | 2.50E-07 | up lim |
| 214.7 | 3- | 1.13E-07 | up lim | 4.36E-08 | up lim |
| 486.74 | 2+ | 0.11 | 0.05 | 0.107 | 0.021 |
| 609.49 | 3- | 0.275 | 0.069 | 0.245 | 0.054 |
| 705.08 | 1- | 0.52 | 0.13 | 0.261 | 0.065 |
| 855.85 | 3- | 0.83 | 0.21 | 0.61 | 0.35 |
| 903.54 | 3- | 4.3 | 0.4 | 4.20 | 0.38 |
| 1140.88 | 2+ | 79 | 27 | 73 | 14 |
| 1316.7 | 2+ | 137 | 47 | 124 | 28 |
| 1388.8 | 1- | 54 | 15 | 61 | 12 |

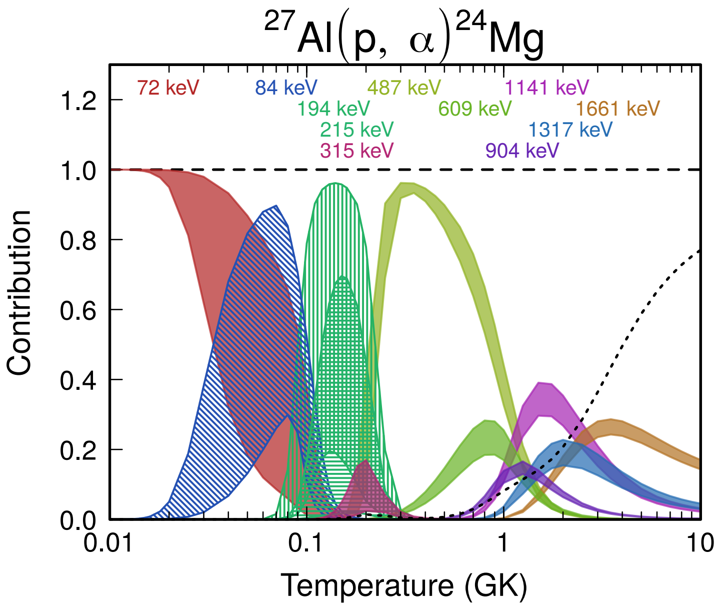
# The full calculation using STARLIB (by Philip Adsley)

- We run the full code (for STARLIB and STARLIB+THM replacing our results in the standard input)




The green line is the THM recommended rate




Is the upper limit for the resonance at about 200 keV overestimated?

# Thank you for your attention