# Understanding elemental anomalies in Globular Clusters:
# Experimental study of the $^{30}$Si(p,$\gamma$)$^{31}$P reaction

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Faïrouz Hammache

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**PARIS-SACLAY**

PhyNuBe
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**IJC**Lab
**Irène Joliot-Curie**
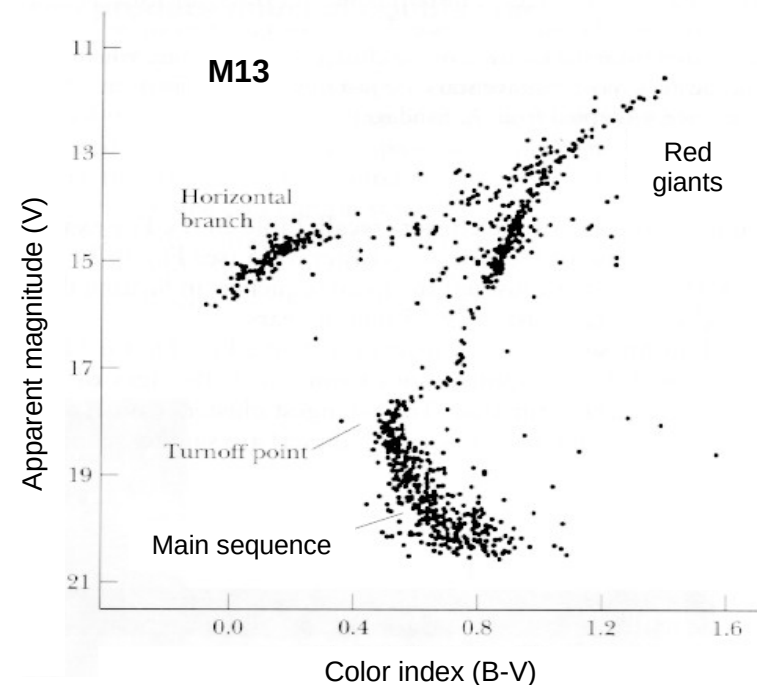**Laboratoire** de **Physique**
des 2 Infinis

# Globular Clusters

- Gravitationally bound systems of $10^5$ to $10^7$ stars, located in halo of spiral galaxies.

- Among the oldest structures in the Universe (age > 10 Gyr).



M13

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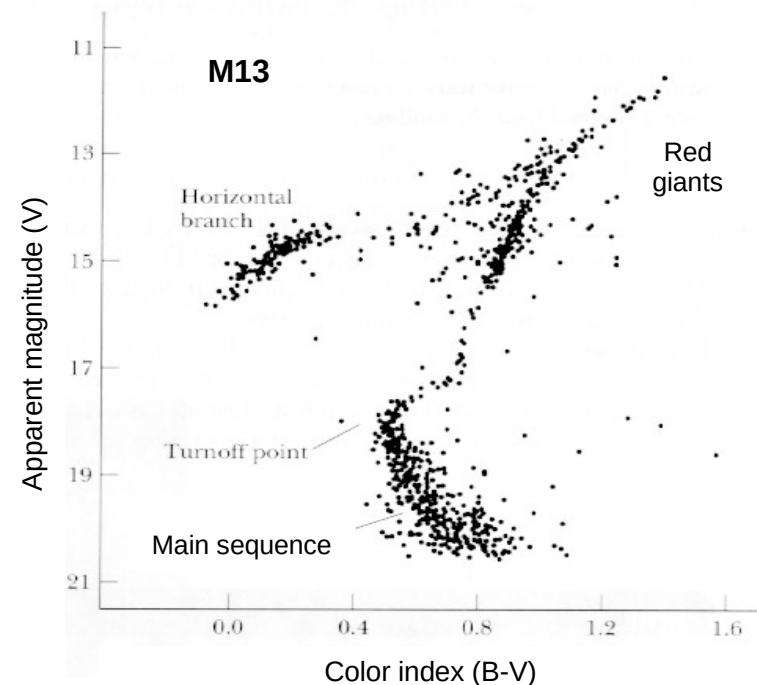  - Galactic physics (formation and early evolution of galaxies)

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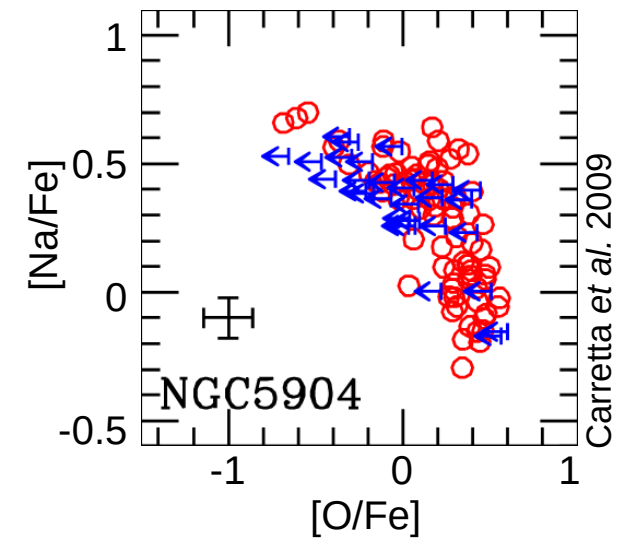
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M13



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Red giants

Horizontal branch

Turnoff point

Main sequence

Apparent magnitude (V)

Color index (B-V)

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- Paradigm: **Single stellar population**: same age and chemical composition.



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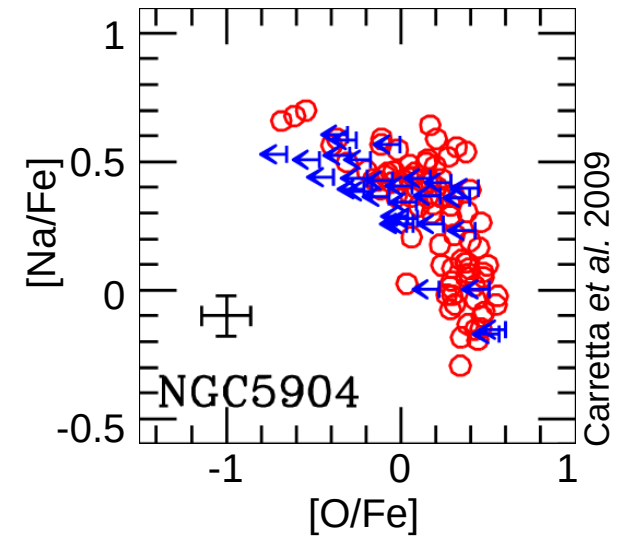Apparent magnitude (V)

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# Abundance anomalies in Globular Clusters

- Spectroscopic observations in Red Giant stars:
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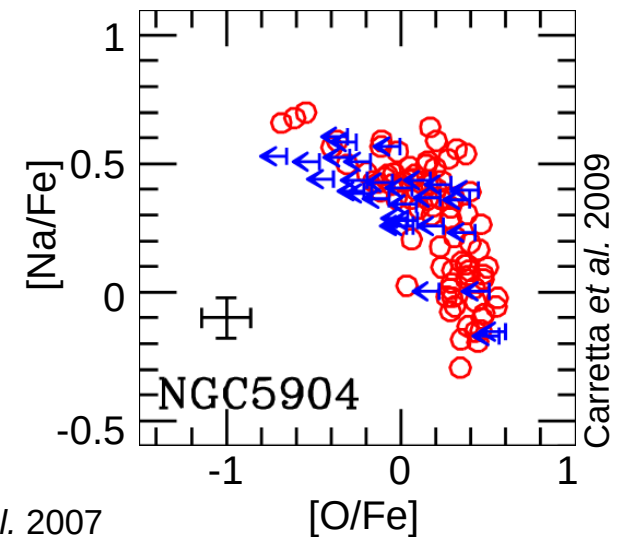
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*Carretta et al. 2009*

NGC5904

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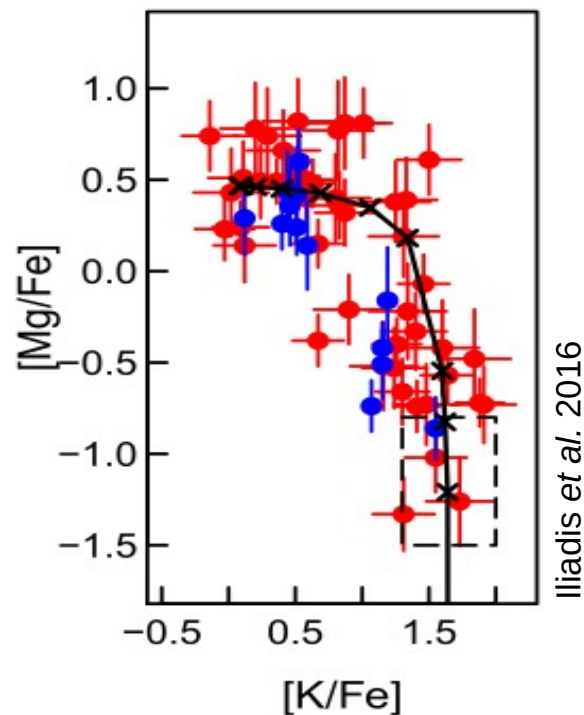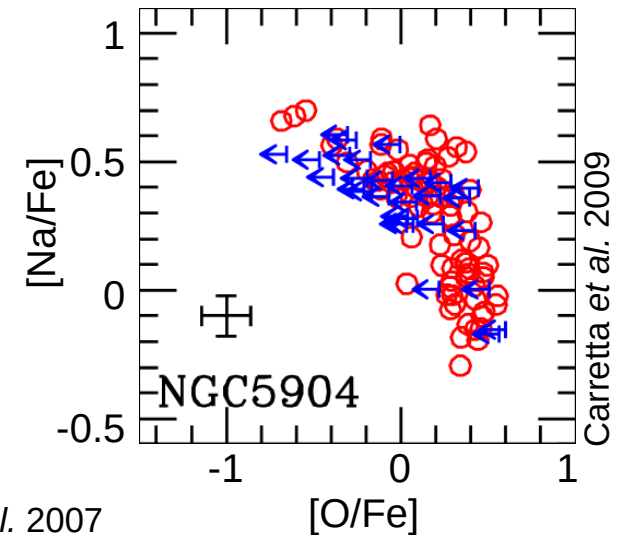    **Polluters must burn Hydrogen at T ~ 75 MK**  (Prantzos *et al.* 2007 & 2017)

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Axis labels: [Na/Fe], [O/Fe]

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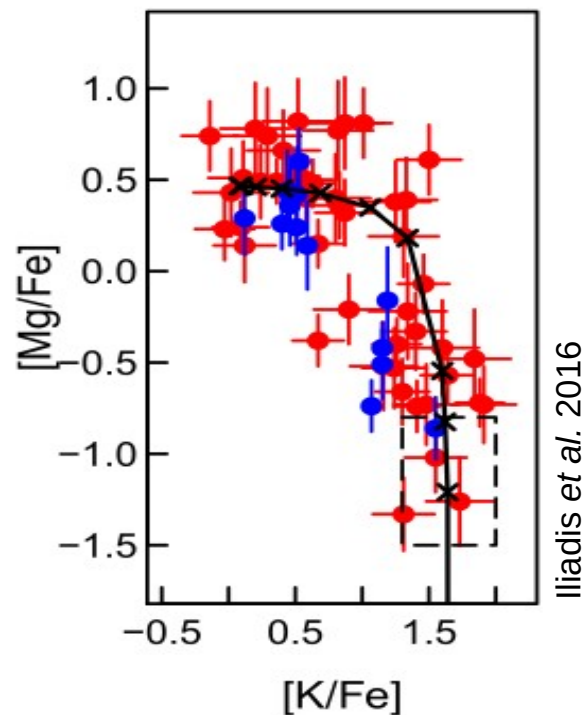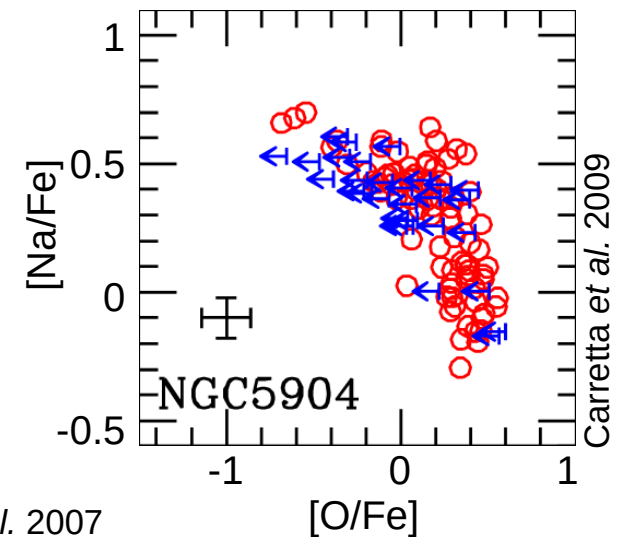


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NGC5904

**Extreme case of NGC2419**

- Observed **Mg-K** anticorrelation
- Requires much higher temperature in polluter site (between 100 MK and 200 MK) to overcome Coulomb barrier in proton capture reactions.



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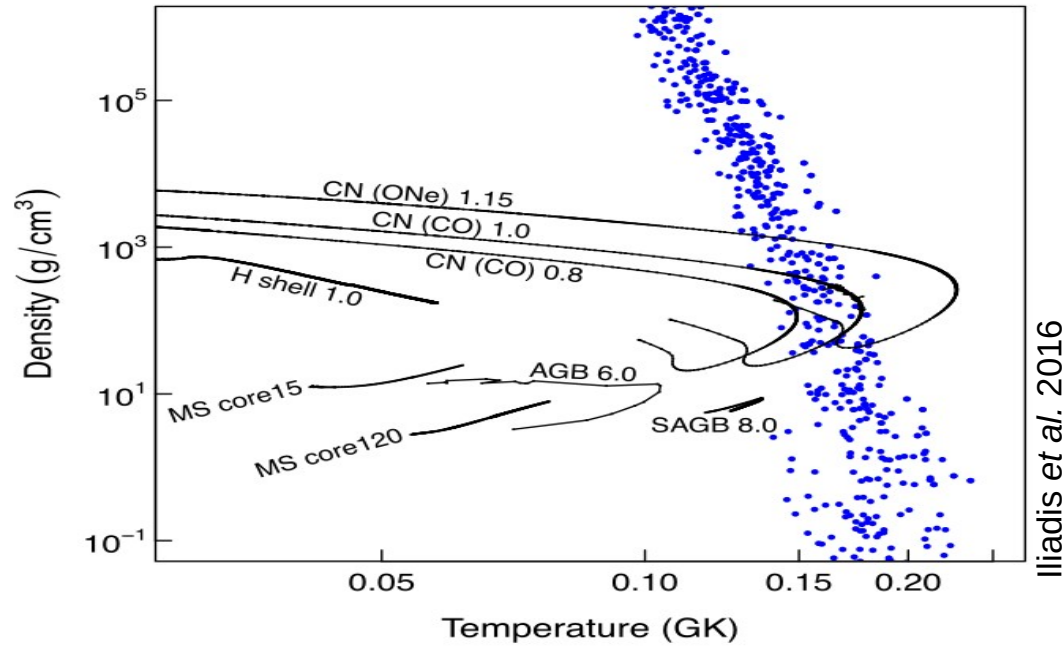  **Polluters must burn Hydrogen at T ~ 75 MK** (Prantzos *et al.* 2007 & 2017)



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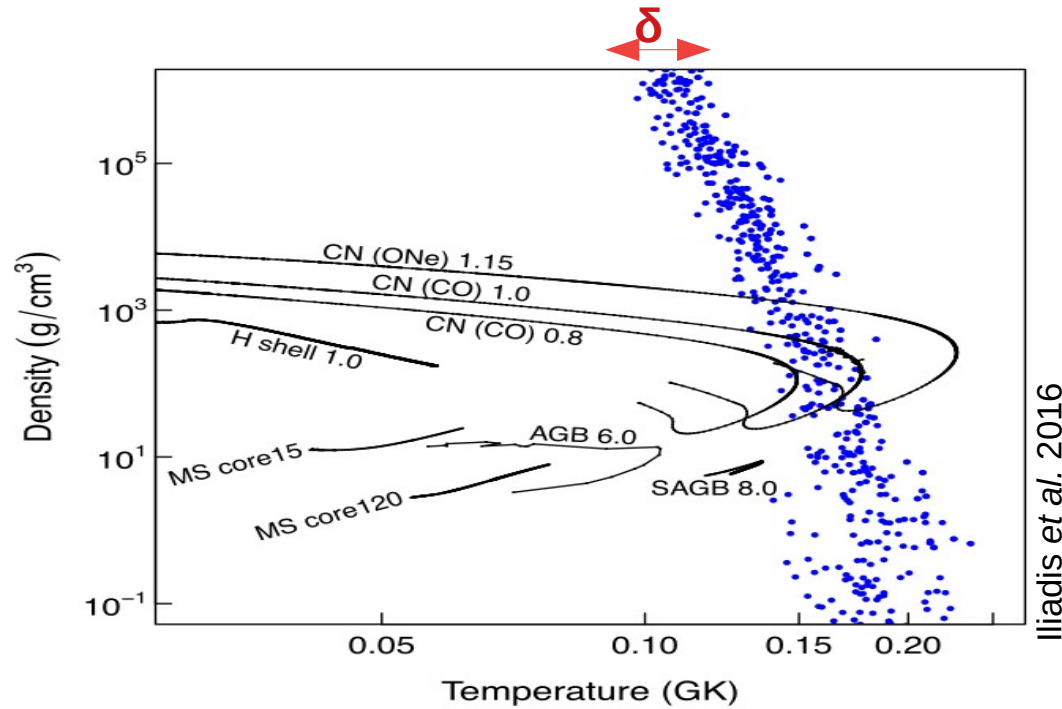


## What is the nature and type of polluter stars? (T,ρ)?

# NGC2419 Abundances



Iliadis *et al.* 2016

## Sensitivity Studies

- Simulate nucleosynthesis reaction network in **H-burning conditions** (with Monte Carlo calculation) for uniform T and ρ distributions, and varying reaction rates within uncertainties.
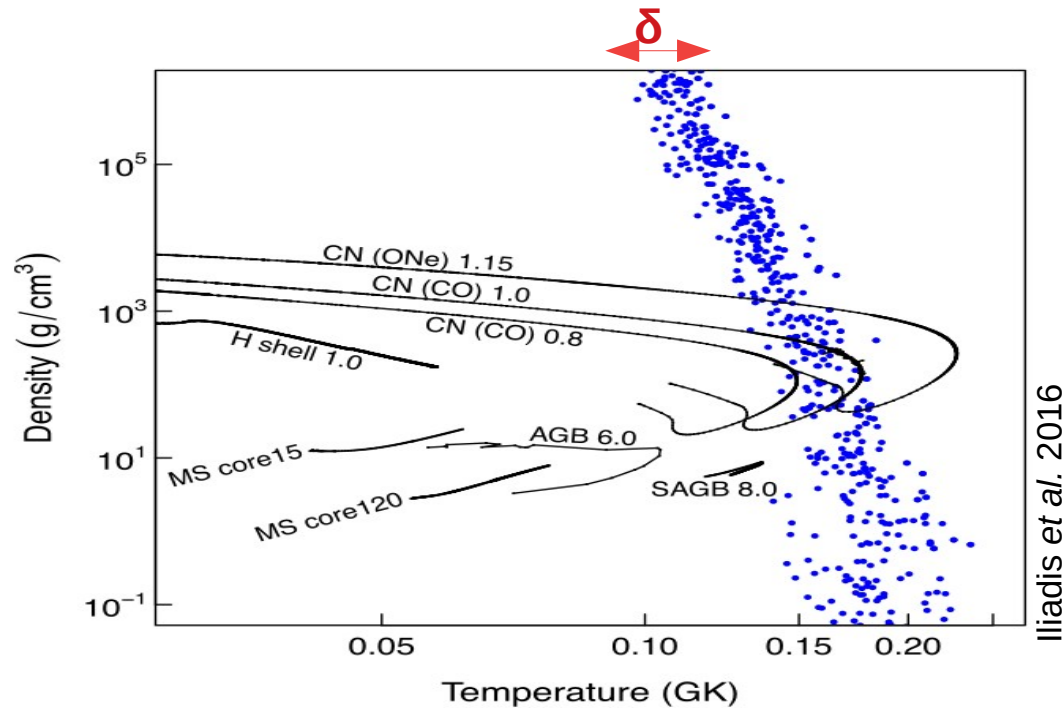
4

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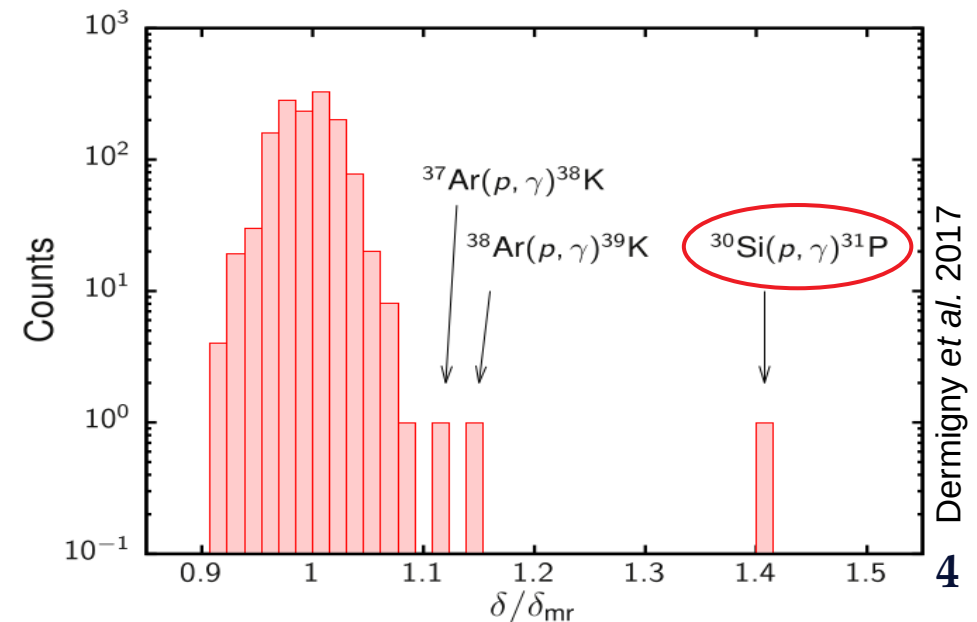- Uncertainty on reaction rates → T spread increased by 70%.
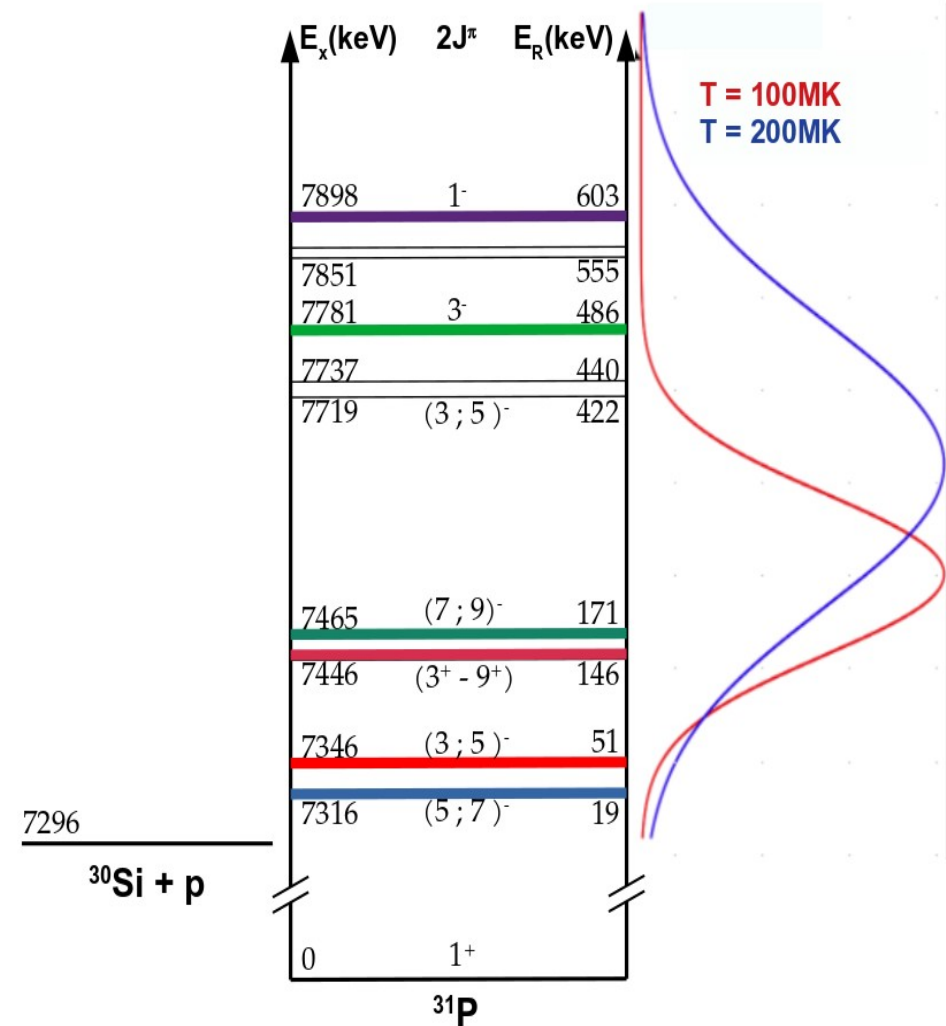
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## Key Reactions

- Individual variation of reaction rates within their uncertainties.

- Impact of a few $(p,\gamma)$ reactions.

- **$^{30}Si(p,\gamma)^{31}P$ reaction contributes the most to the spread of the $(T, \rho)$ locus for 100 MK < T < 200 MK**



$^{37}Ar(p,\gamma)^{38}K$

$^{38}Ar(p,\gamma)^{39}K$

$^{30}Si(p,\gamma)^{31}P$

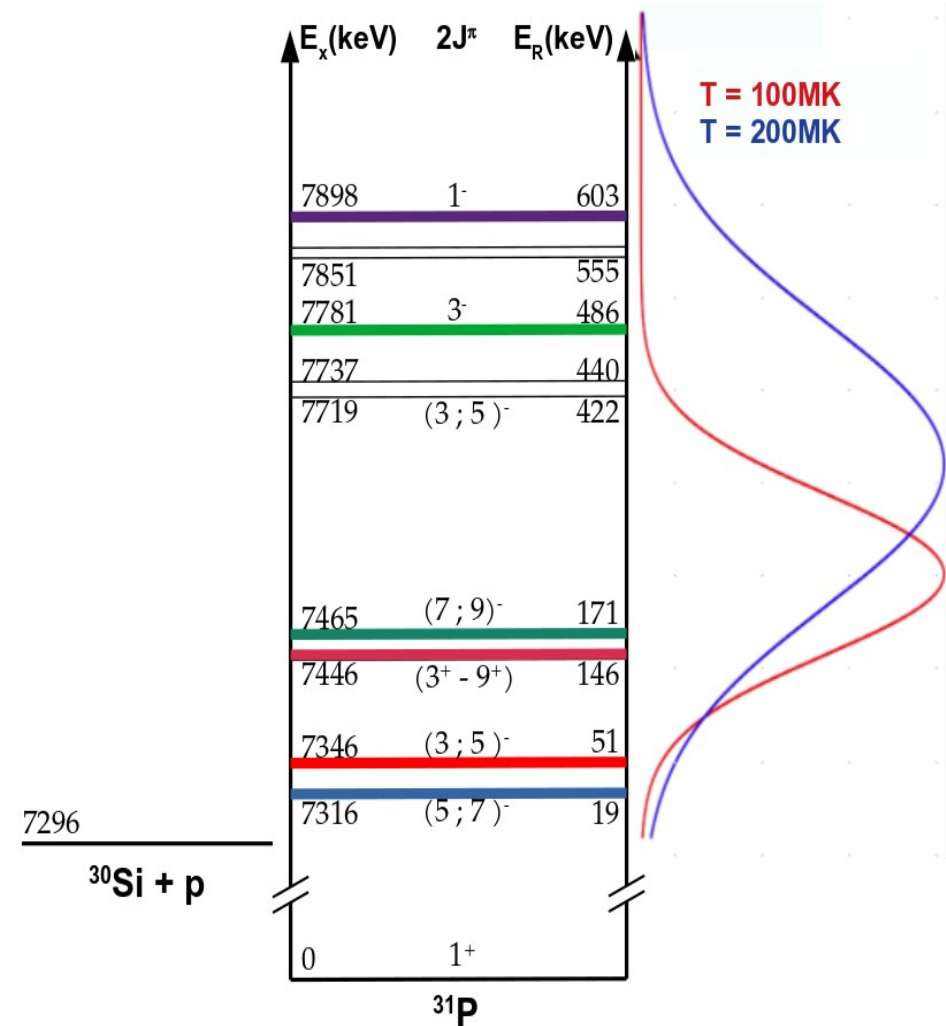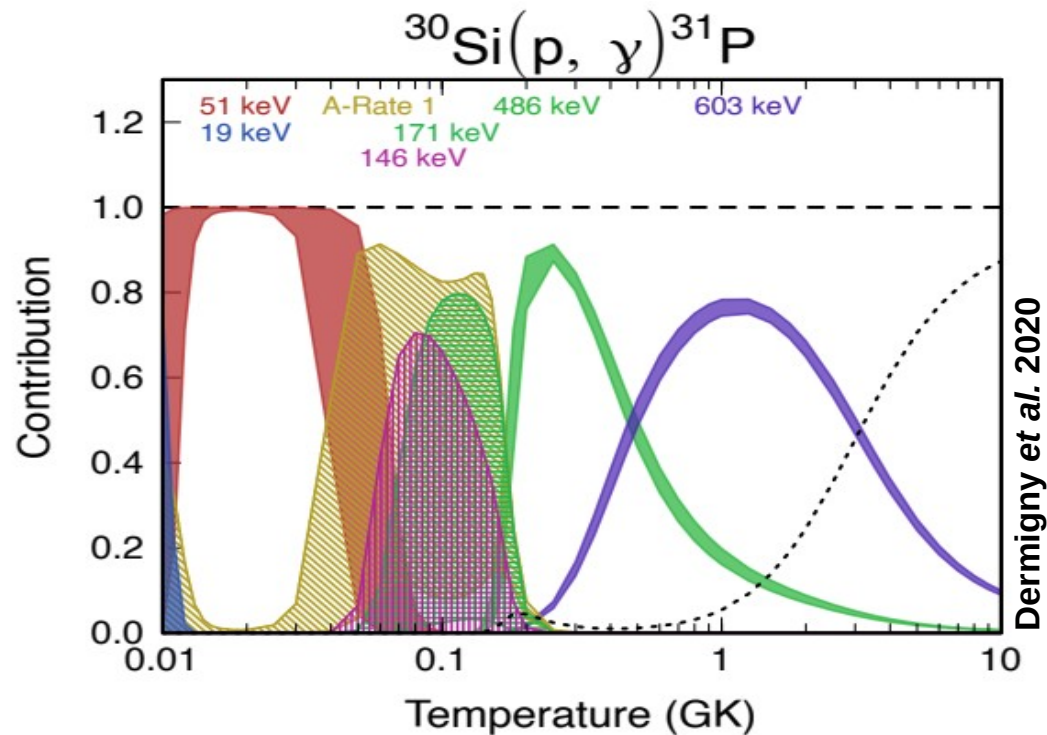Dermigny et al. 2017

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# State of the art for $^{30}Si(p,\gamma)^{31}P$ reaction

- Energies known with uncertainty better than 4 keV
- Spins and parities constrained but mostly unknown

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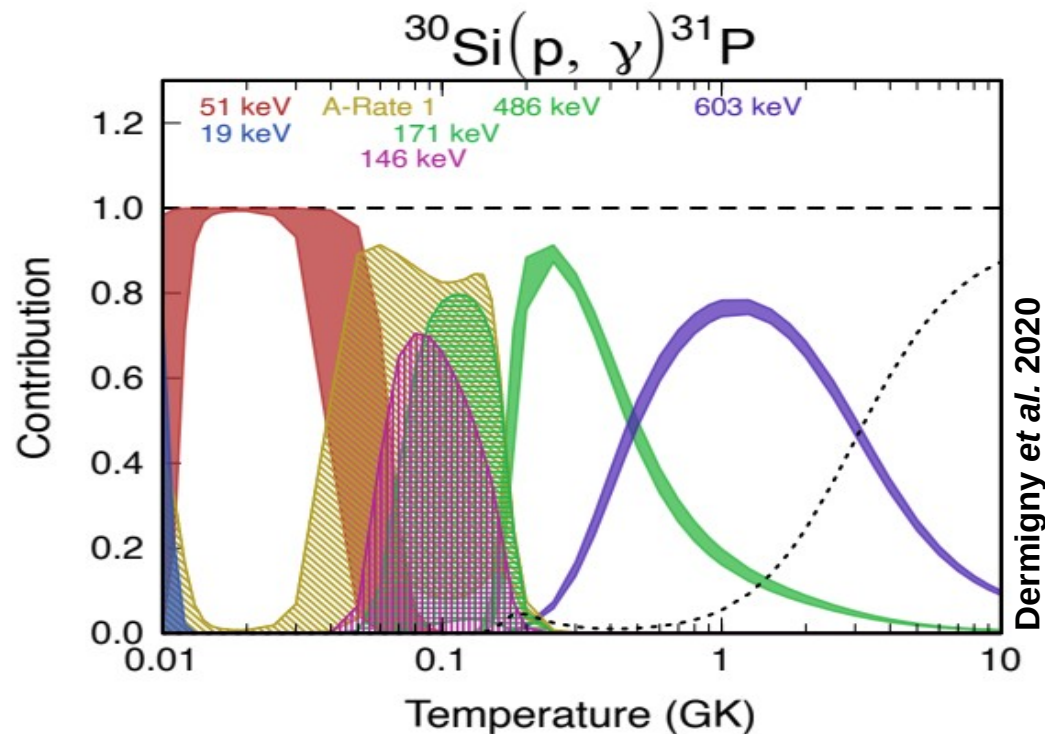


- $E_r$= 19 keV: C²S = 0.002 *(Vernotte et al. 1990)*
- $E_r$= 51 and 146 keV: Mean reduced widths, systematic study $\langle\theta^2\rangle = 0.0003$
- $E_r$= 171 keV: Upper limit C²S < 0.003
  *(Dermigny et al. 2020)*
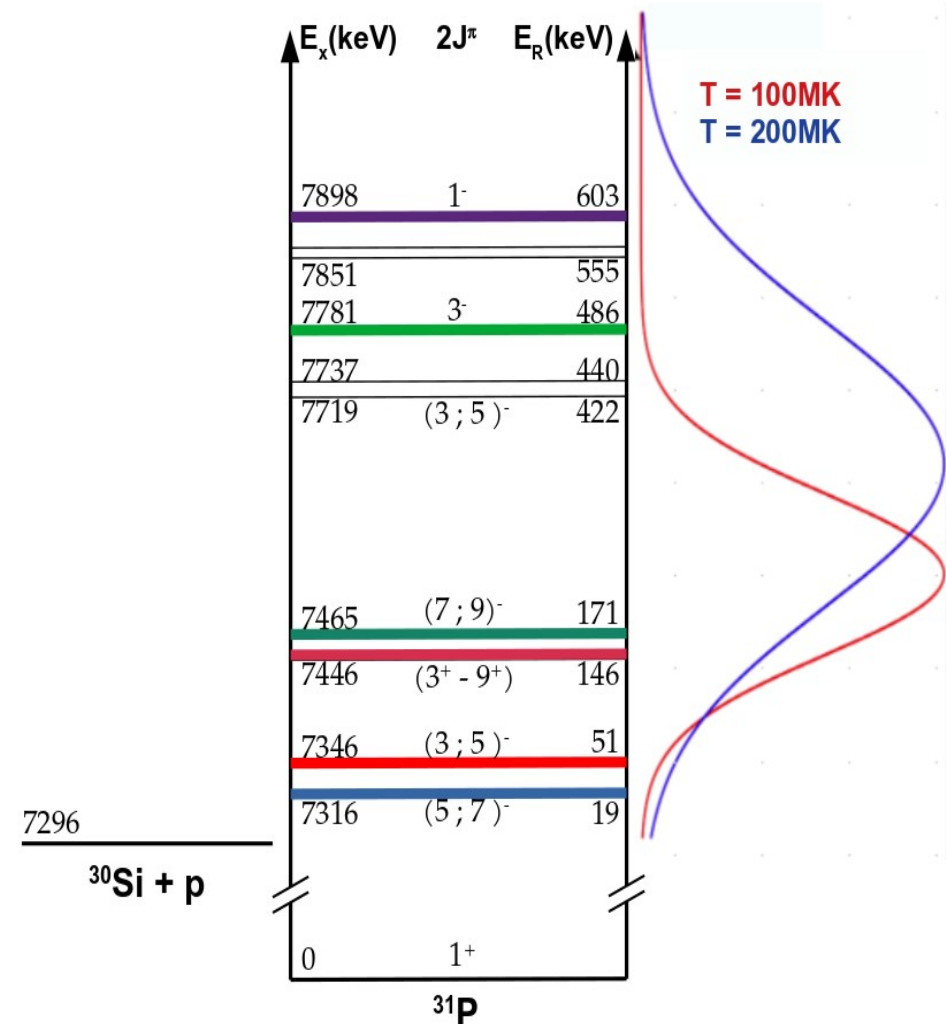
- $E_r$= 422, 486 keV sole direct measurements using γγ coincidences *(Dermigny et al. 2020)*
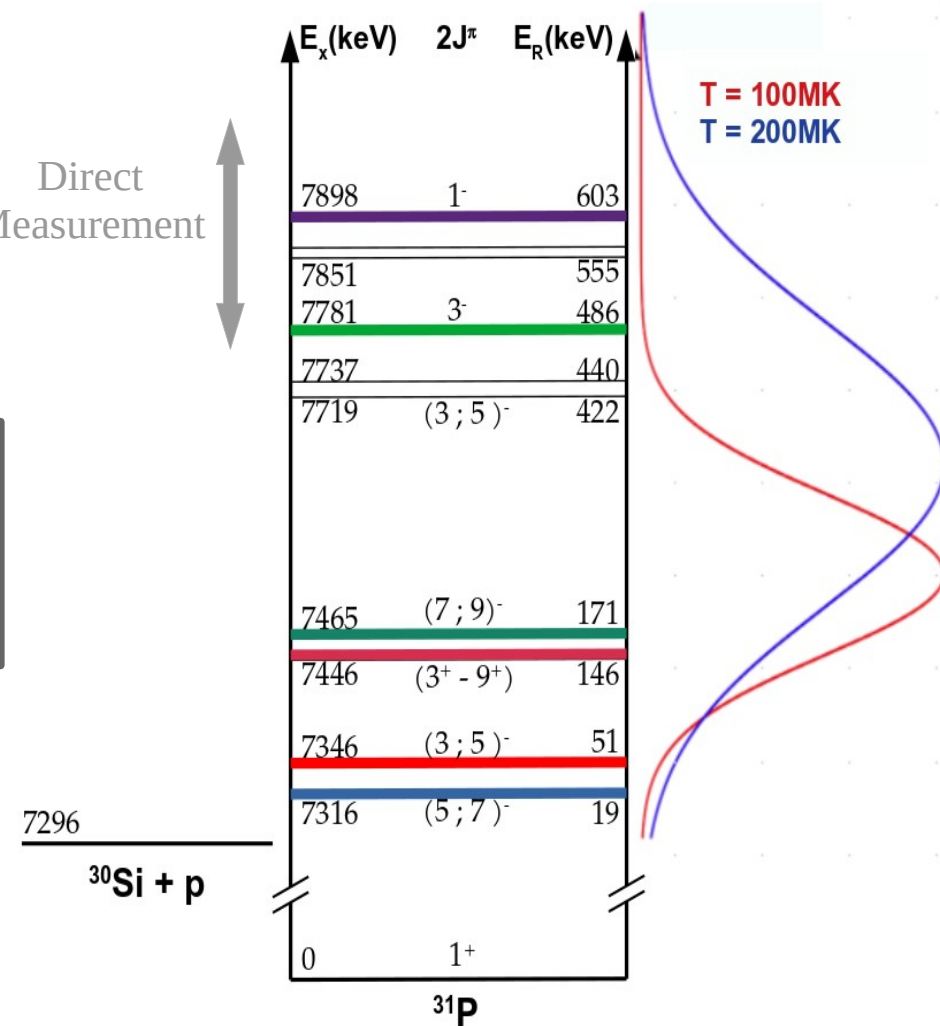- $E_r$= 603 keV: several direct measurements, reference resonance

# Experimental Strategy

Thermonuclear reaction rate for single and isolated narrow resonance :

$$\langle \sigma v \rangle \propto (\omega\gamma)e^{(-E_R/kT)}$$

**High energy**

- Direct measurement of resonance strength $\omega\gamma$ **@DRAGON** (Triumf)

- Independent strength determination of high energy resonances.

Direct
Measurement

| $E_x$(keV) | $2J^\pi$ | $E_R$(keV) |
|---|---|---|
| 7898 | 1⁻ | 603 |
| 7851 | | 555 |
| 7781 | 3⁻ | 486 |
| 7737 | | 440 |
| 7719 | $(3;5)^-$ | 422 |
| 7465 | $(7;9)^-$ | 171 |
| 7446 | $(3^+ - 9^+)$ | 146 |
| 7346 | $(3;5)^-$ | 51 |
| 7316 | $(5;7)^-$ | 19 |

7296

$^{30}$Si + p

0      1⁺

$^{31}$P

T = 100MK
T = 200MK

# Experimental Strategy

Thermonuclear reaction rate for single and isolated narrow resonance :

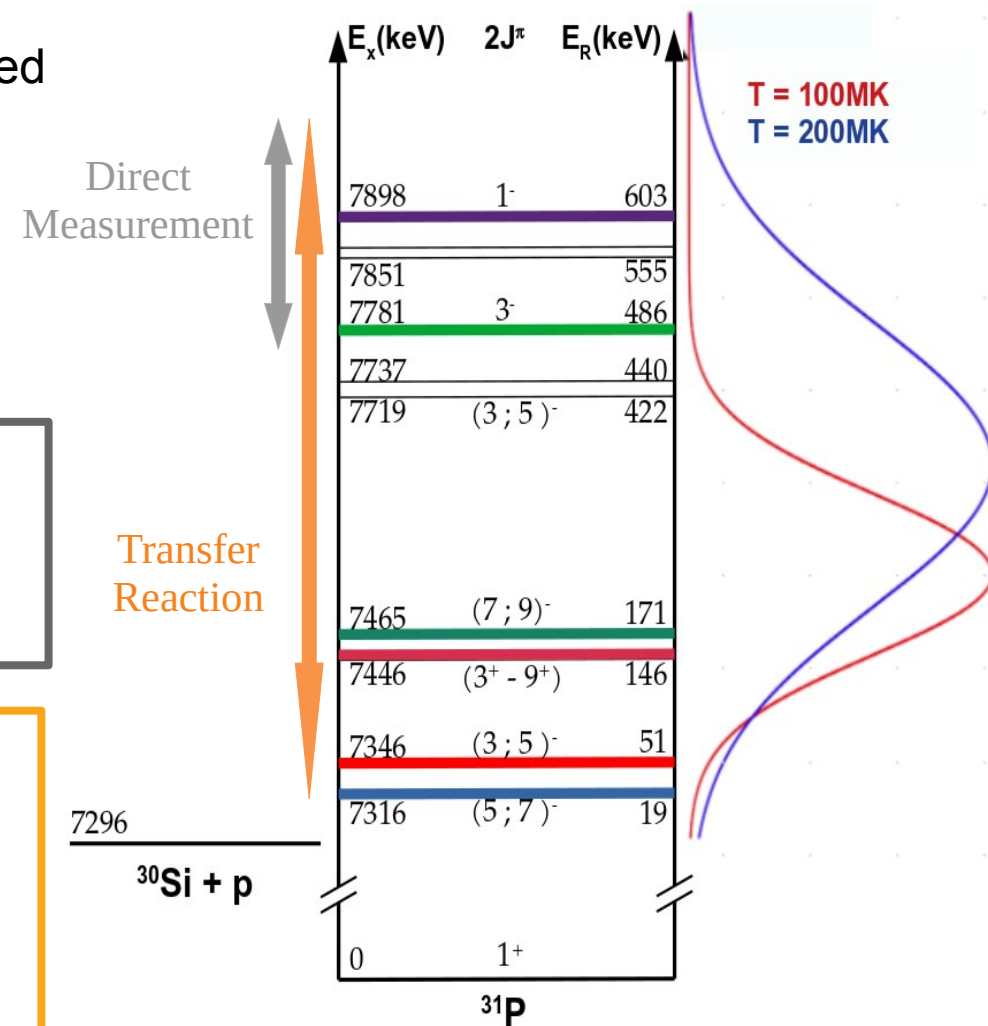$$\langle \sigma\nu \rangle \propto (\omega\gamma)e^{(-E_R/kT)}$$

$$\omega\gamma = \frac{2J_R + 1}{(2J_p + 1)(2J_{30Si} + 1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma}$$

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**Low energy**

$$\begin{cases} \Gamma = \Gamma_p + \Gamma_\gamma \\ \Gamma_p \ll \Gamma_\gamma \end{cases} \Longrightarrow \omega\gamma \simeq \omega\Gamma_p$$

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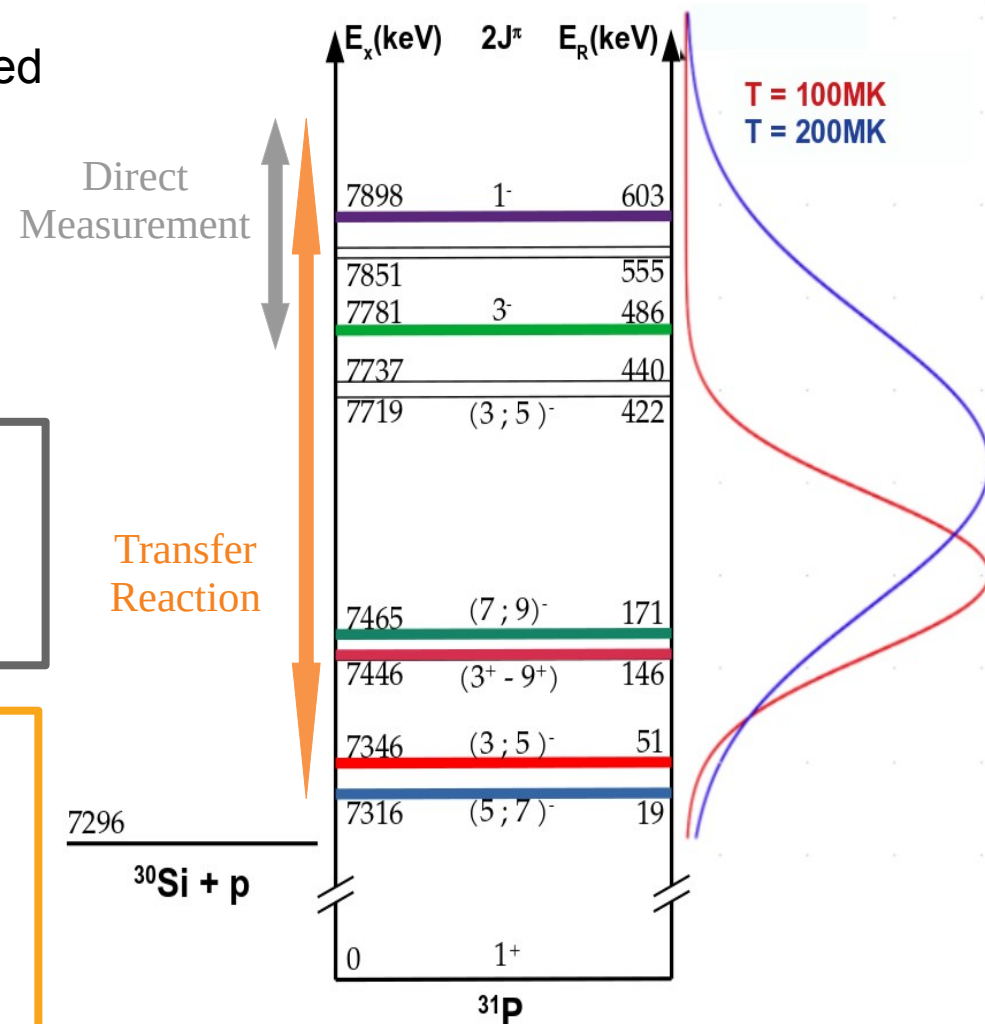
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**$^{30}$Si($^3$He,d)$^{31}$P transfer reaction**

- Experiment by Vernotte in 1990 at Orsay's SplitPole: low statistics, limited resolution and contaminations.

- → new measurements **@Q3D** (MLL) with improved energy resolution and sensitivity.



Direct Measurement

Transfer Reaction

| $E_x$(keV) | $2J^\pi$ | $E_R$(keV) |
|---|---|---|
| 7898 | $1^-$ | 603 |
| 7851 | | 555 |
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$^{30}$Si + p

| 0 | $1^+$ |

$^{31}$P

T = 100MK
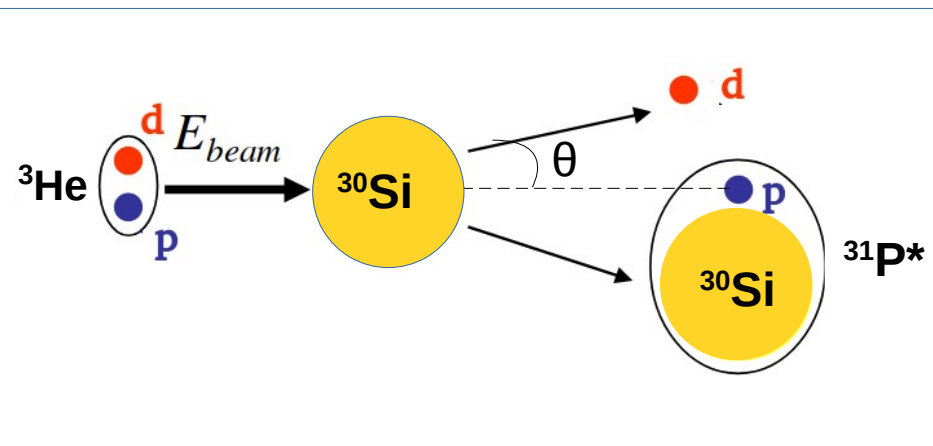T = 200MK

# Transfer Reaction
## $^{30}Si(^{3}He,d)^{31}P$

# One proton Transfer Reaction

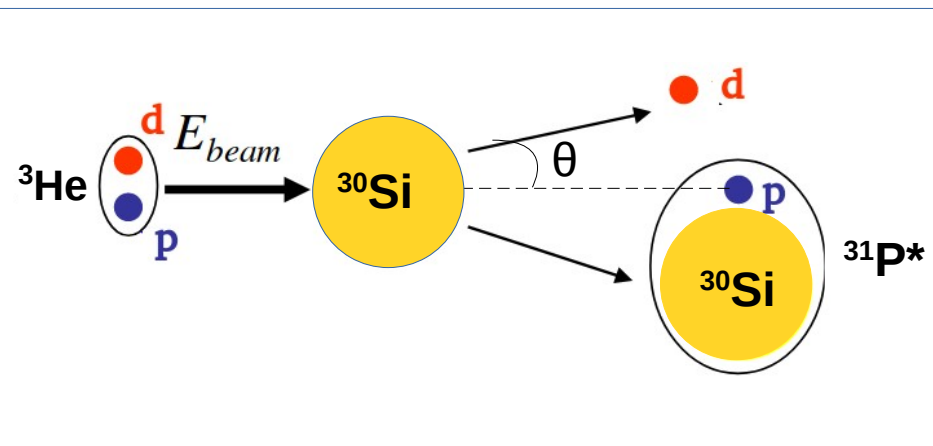$(p,\gamma)$ can be studied through one proton $(^3\text{He},d)$ transfer reaction

Experimental method



- Excitation energies
- Angular distribution

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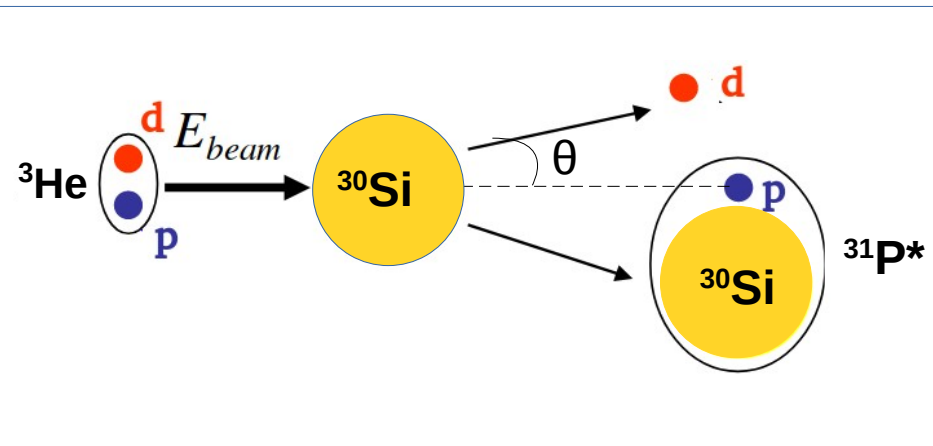- Angular distribution

### Theoretical model for direct transfer

**Distorted Wave Born Approximation:**

- Elastic scattering dominates entrance and exit channels (described by optical models)
- Transfer 1st order perturbation
- No configuration rearrangement

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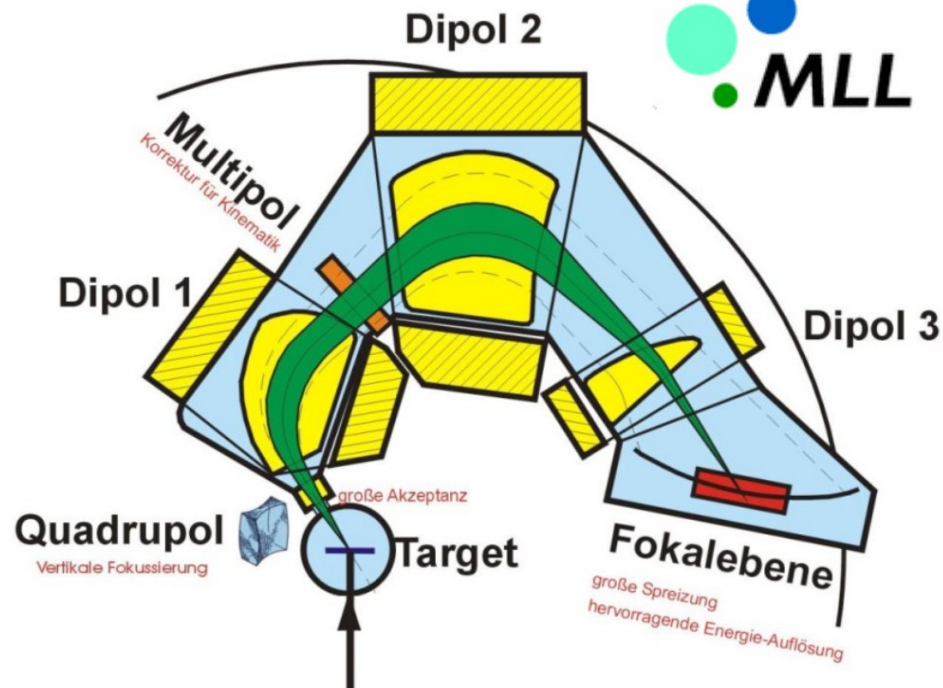- No configuration rearrangement

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- Angular distribution $\longrightarrow$

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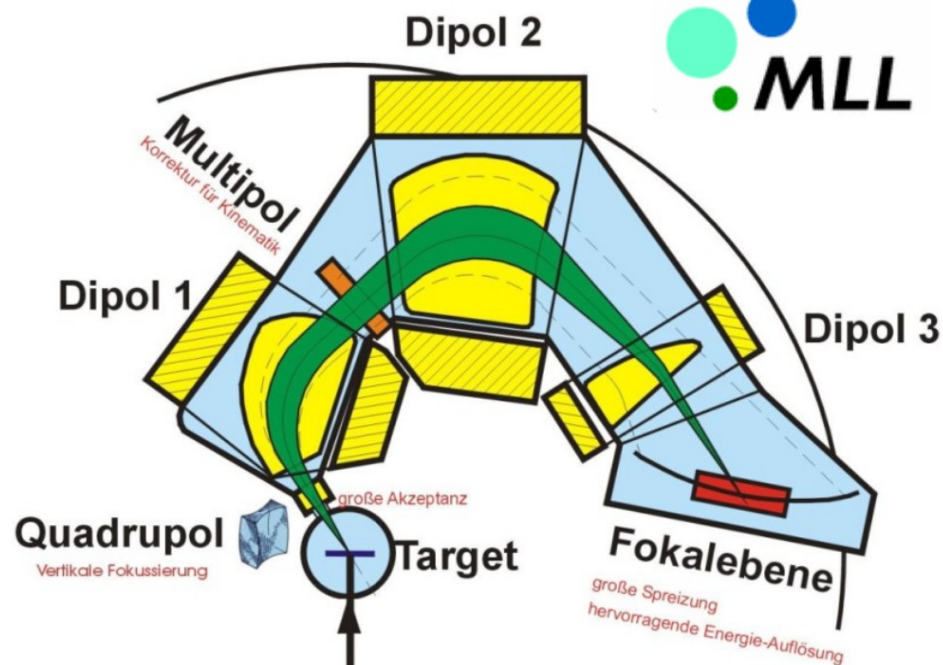
$$\Gamma_p = C^2 S \ \Gamma_p^{s.p}(E_r, \ell)$$

$\longrightarrow$ Shape of the distribution
$\rightarrow$ transferred angular orbital momentum $\ell$

# $^{30}$Si($^3$He,d)$^{31}$P reaction @Q3D



- ➢ Beam $^3$He :   E = 25 MeV
                    I = 200nAe

- ➢ Targets:  $^{30}$SiO$_2$ (40 µg/cm²) enriched at 95% on $^{nat}$C
              $^{nat}$SiO$_2$ (20 µg/cm²) on $^{nat}$C

- ➢ Solid Angle :   4 to 12 msr

- ➢ Energy resolution $\dfrac{\Delta E}{E} \sim 2.10^{-4}$
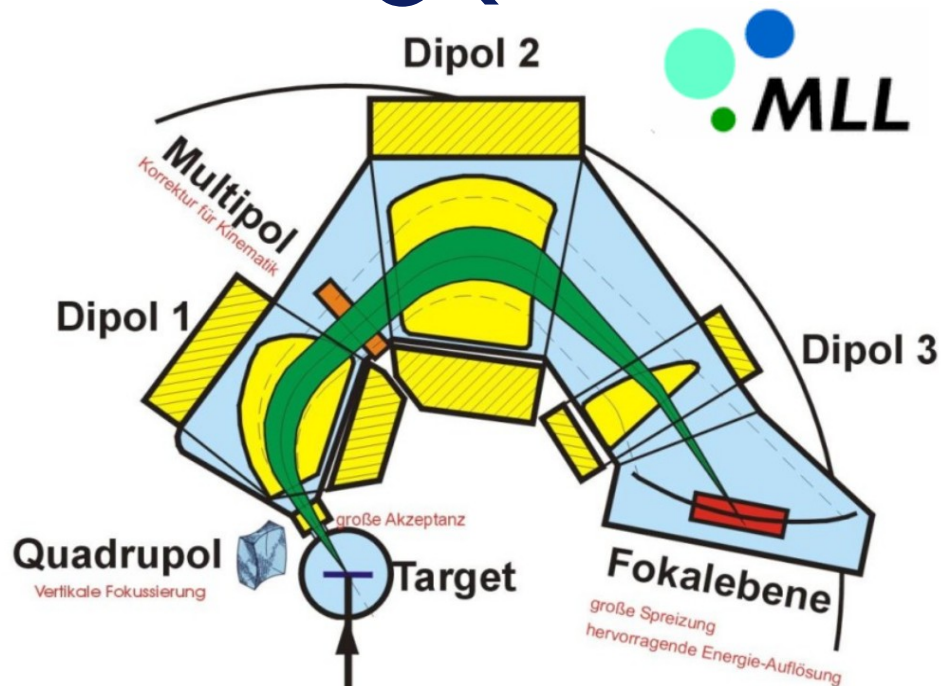
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**Focal plane detectors :**



- Single-wire proportional counters→ position on the focal plane and energy loss.
- Plastic scintillator → residual energy.
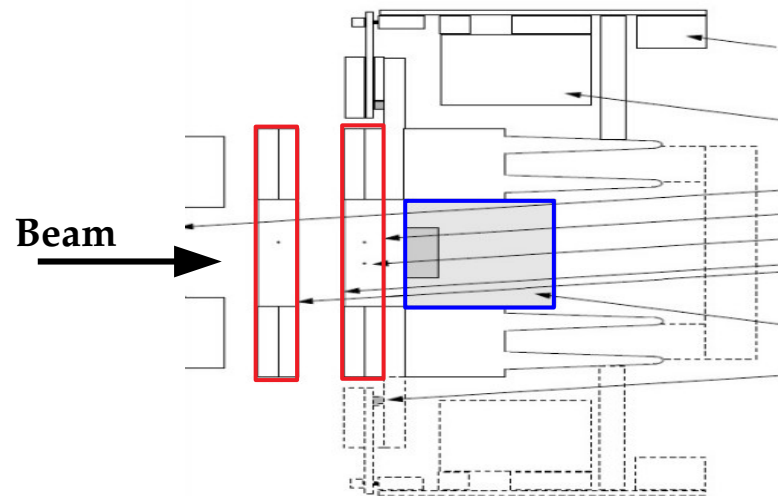
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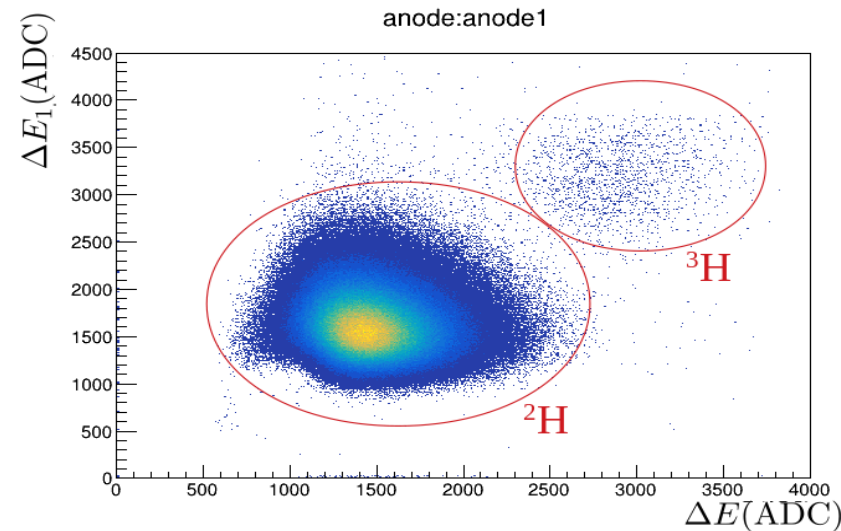
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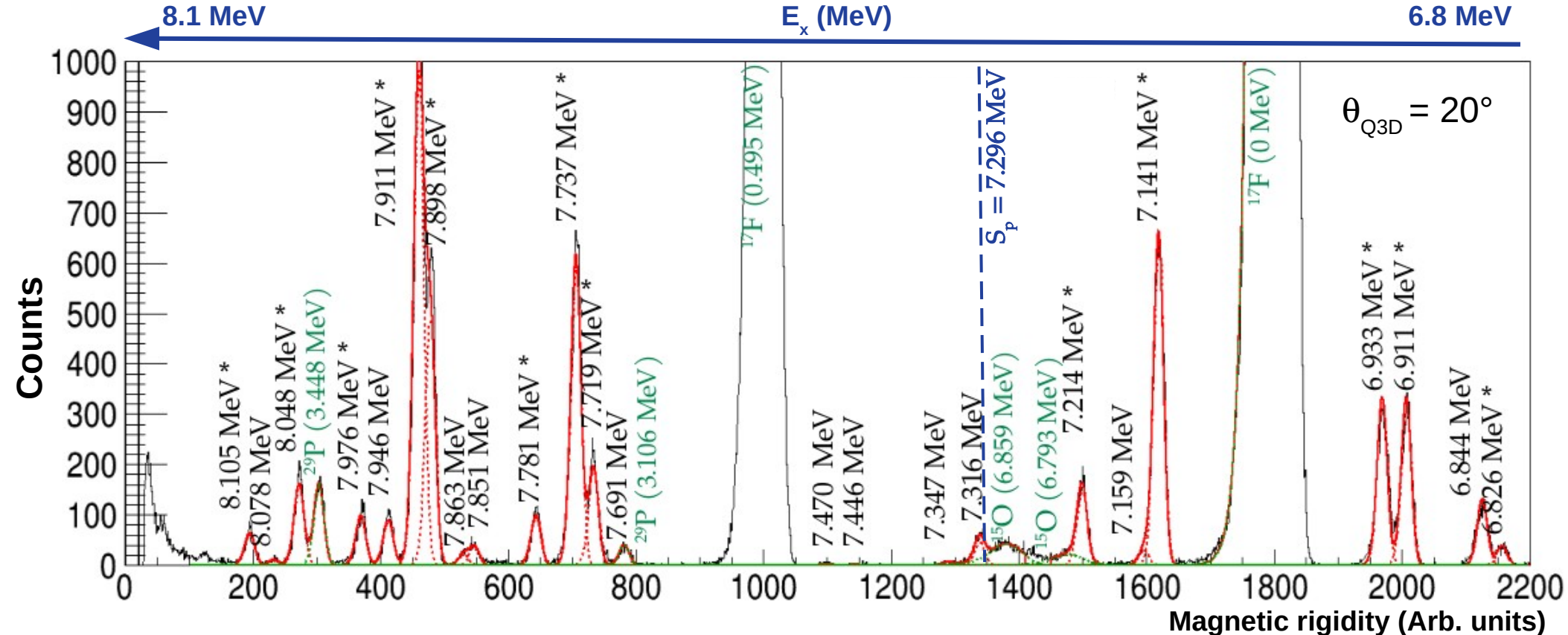
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# Magnetic rigidity spectrum



- Spectra for 7 lab angles : 6°, 10°, 12°, 16°, 20°, 23°, 32°

- Fit with multiple skewed gaussians with common width.

- Experimental resolution **FWHM ~ 7 keV**
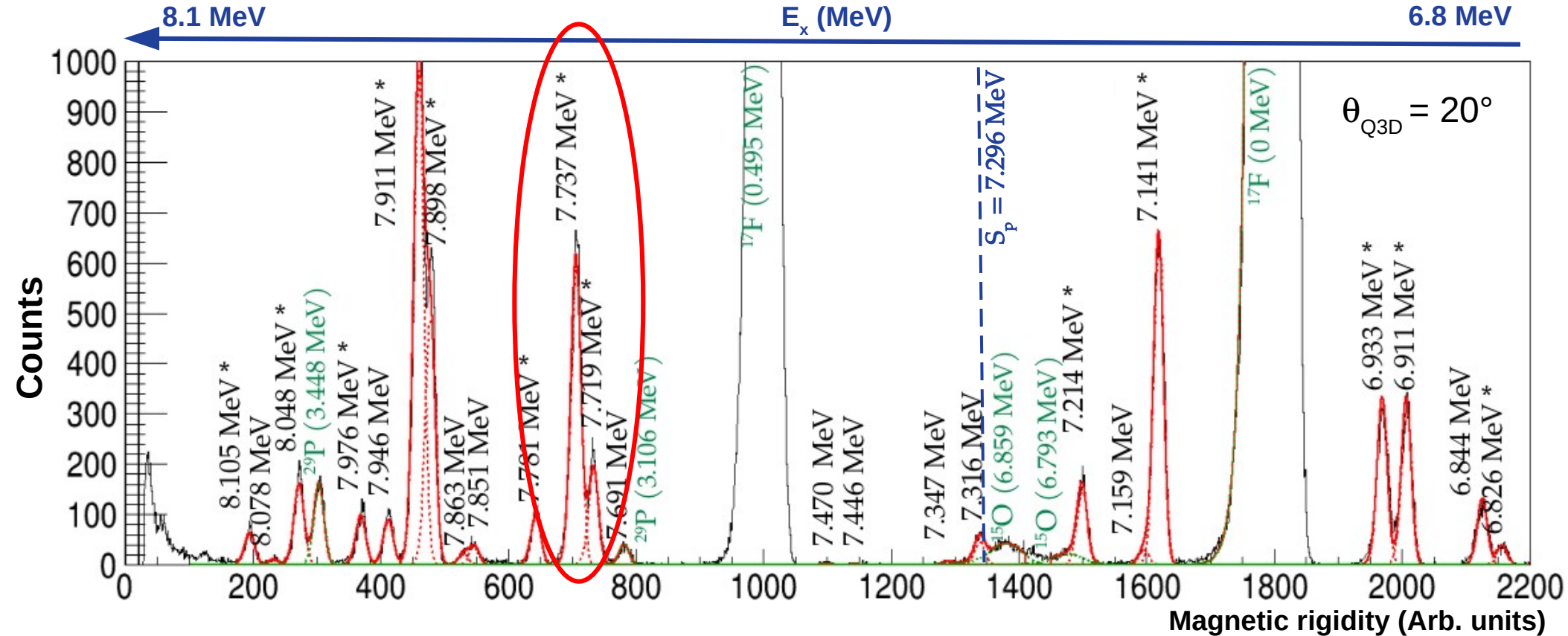  Vernotte (1990) ~25 keV

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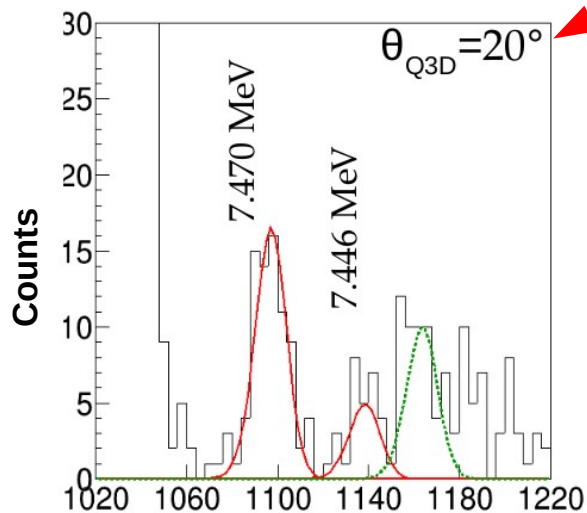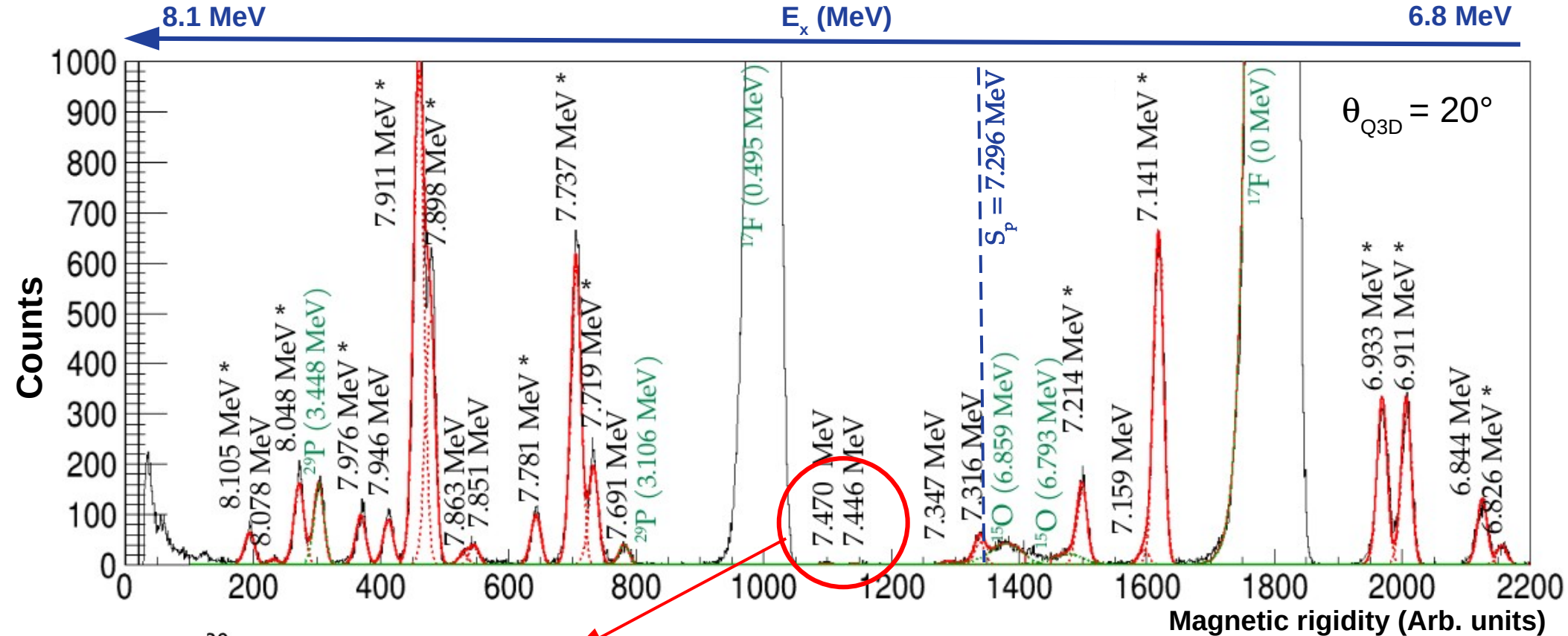- Experimental resolution **FWHM ~ 7 keV** Vernotte (1990) ~25 keV

- Doublet at $E_x$ = 7719 - 7737 keV separated.

# Magnetic rigidity spectrum



- Doublet at $E_x$ = 7719 - 7737 keV separated.

- Levels at $E_x$ = 7446 and 7470 keV observed for $\theta_{Q3D} \geq 20°$.

# Angular distributions

Differential cross section

$$\frac{d\sigma}{d\Omega}(\theta_{c.m})_{exp} = \frac{N_d(\theta_{c.m})}{N_{beam}N_{target}\Delta\Omega_{c.m}}$$

6844 keV
$\ell = 3 ; 5/2^-$
$C^2S = 0.0057$

7141 keV
$\ell = 0 ; 1/2^+$
$C^2S = 0.0496$

7446 keV
$\ell = 2 ; 3/2^+$
$C^2S = 0.0002$
$\ell = 3 ; 5/2^-$
$C^2S = 0.0001$

7470 keV
$\ell = 3 ; 5/2^-$
$C^2S = 0.0001$

7719 keV
$\ell = 3 ; 5/2^-$
$C^2S = 0.0074$

7898 keV
$\ell = 1 ; 1/2^-$
$C^2S = 0.0577$

$d\sigma/d\Omega$ (mb/sr)

$\theta_{c.m.}$

# Angular distributions



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**Finite-Range DWBA calculations**
→ performed with **FRESCO code.**

Optical potentials
$^{30}$Si + $^3$He: Vernotte et al (1982)
$^{31}$P  + d : Daehnick, (1980)

Binding Potentials
$^{30}$Si + p:  Wood-Saxon, volume + Spin-Orbit
<$^3$He|d+p> overlap: GFMC  Brida (2011)
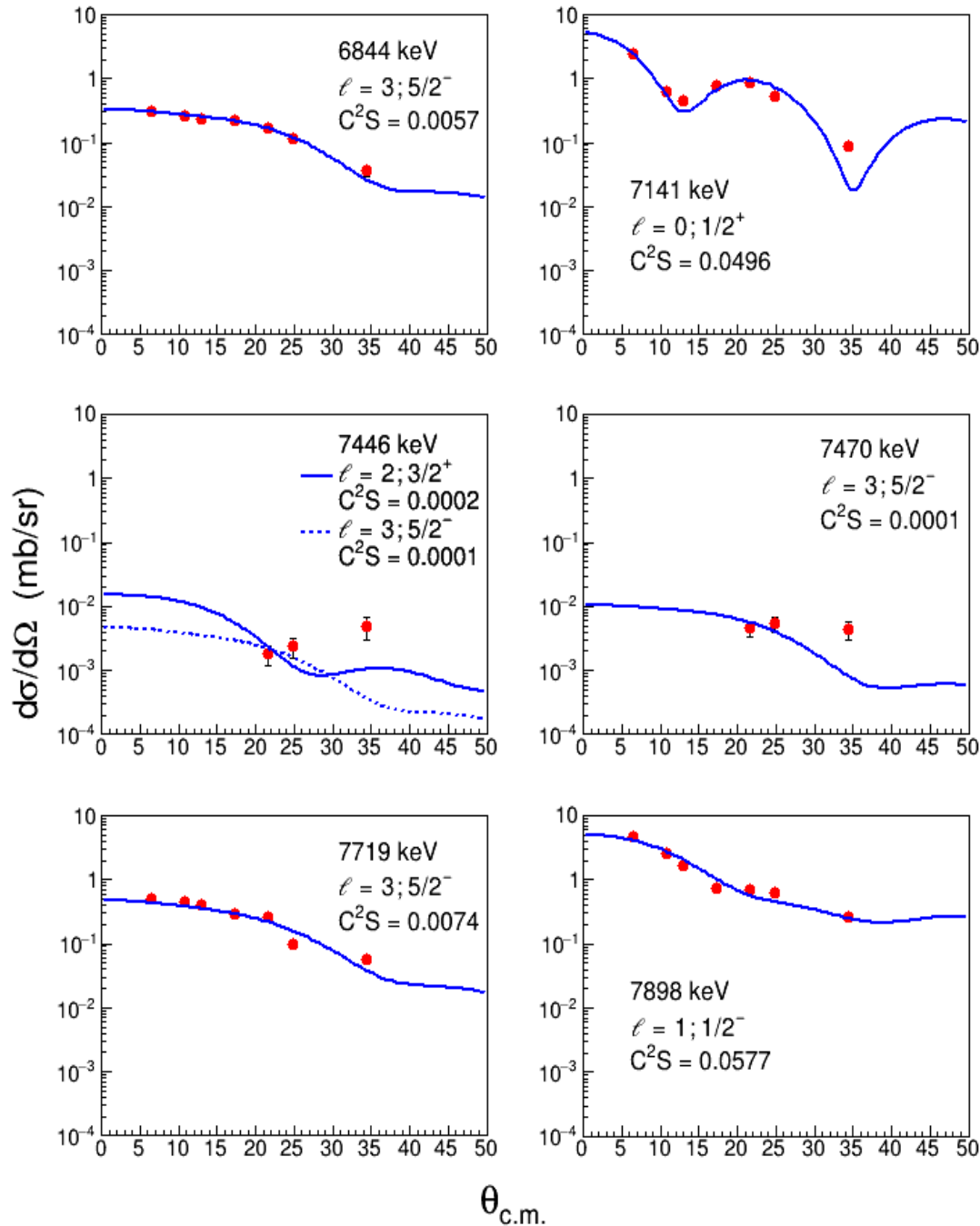
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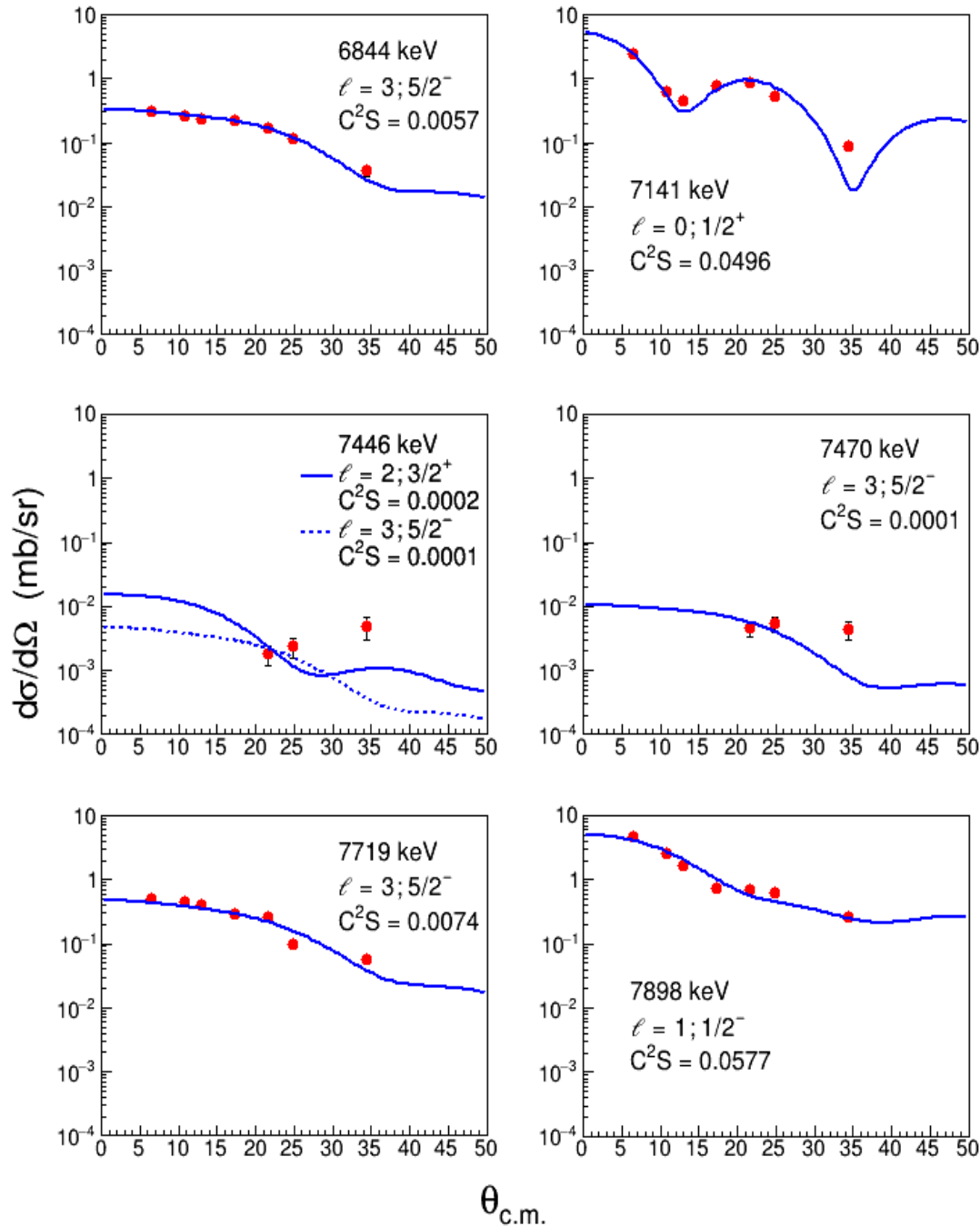$^{31}$P + d : Daehnick, (1980)

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$$\Gamma_p \propto C^2 S \mid R(r) \mid^2 \qquad r = 7fm$$

## Radial wave-function calculation
→ performed with **DWUCK4 code**

Vincent & Fortune (1970) procedure

- $\Gamma_p$ uncertainties ~ 30% (from optical pot.)

# Angular distributions



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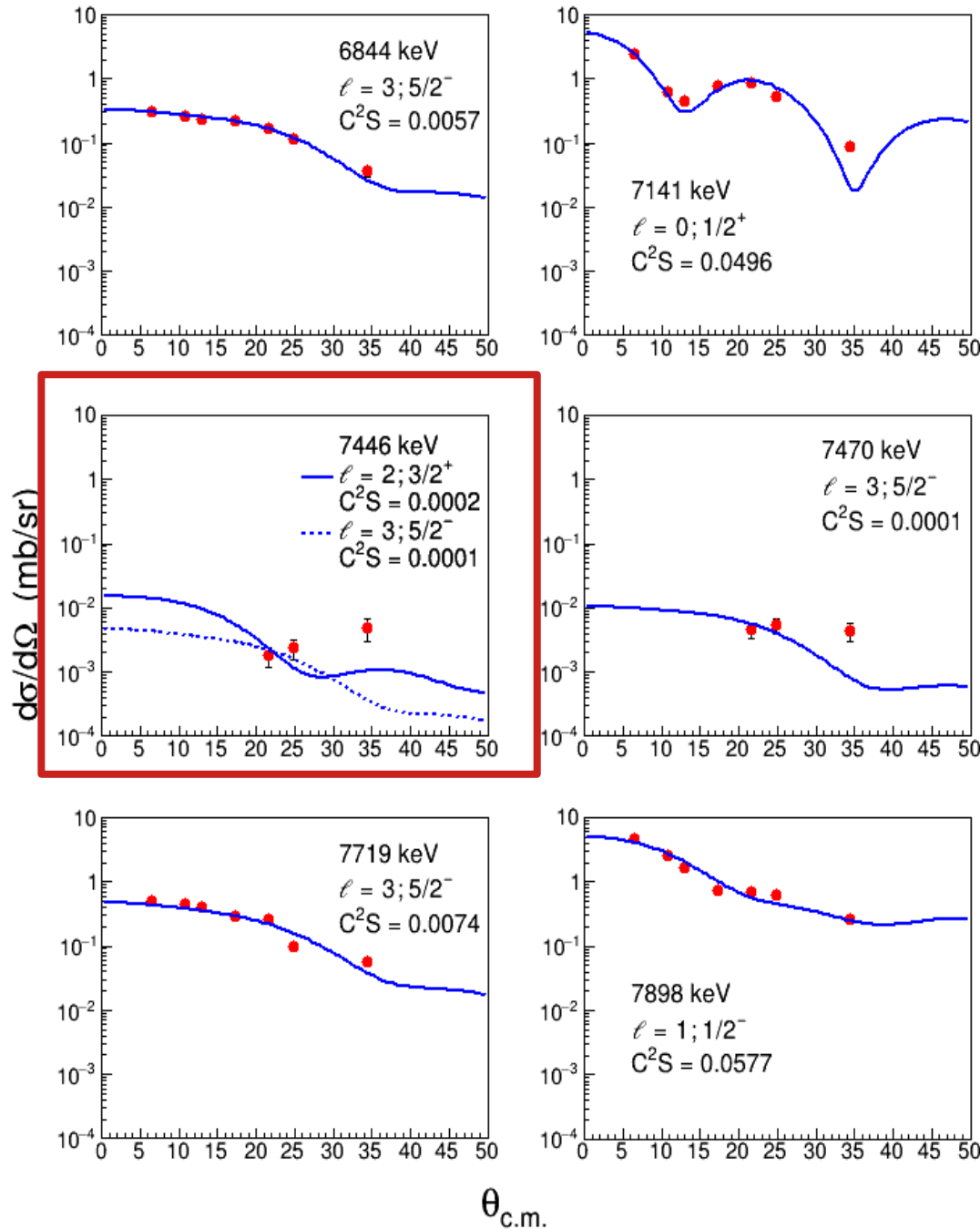$$\Gamma_p \propto C^2 S \mid R(r) \mid^2 \qquad r = 7fm$$

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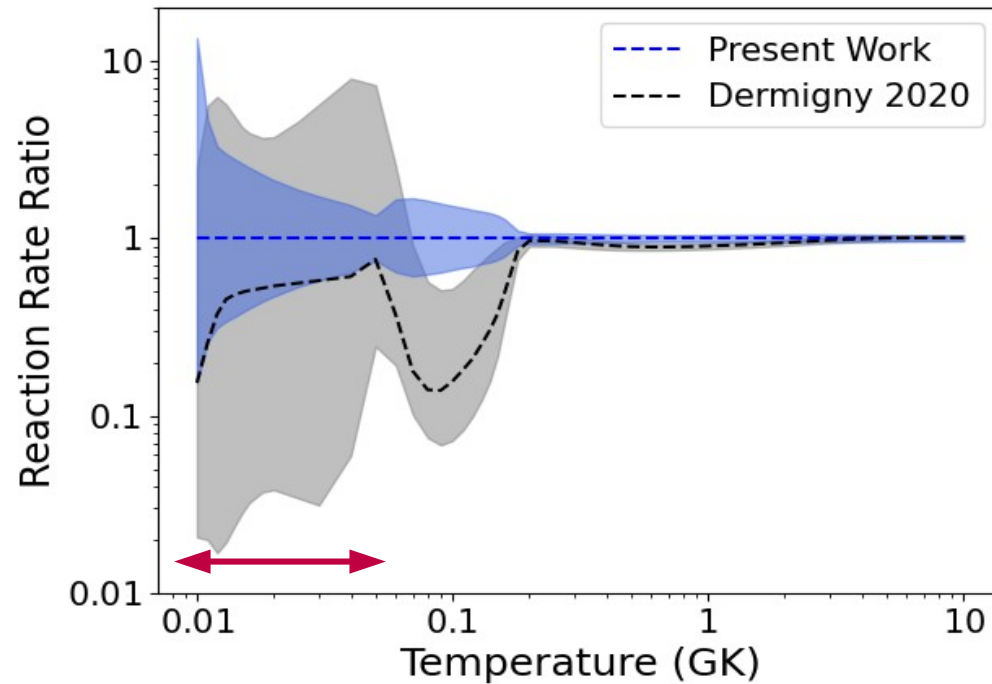
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# ³⁰Si(p,γ)³¹P Reaction Rate

- Monte Carlo calculations using **RatesMC.**

- 68% uncertainty bands (log-normal distribution)



- Determination of $C^2S$ for $E_r$ = 19 keV, $E_r$ = 51 keV and $E_r$ = 170 keV (previously upper limits)

# $^{30}Si(p,\gamma)^{31}P$ Reaction Rate



- Monte Carlo calculations using **RatesMC.**

- 68% uncertainty bands (log-normal distribution)

- Determination of C²S for $E_r$ = 19 keV, $E_r$ = 51 keV and $E_r$ = 170 keV (previously upper limits)

- Observation of the $E_r$ = 149 keV → **key resonance** in T = 100-200 MK
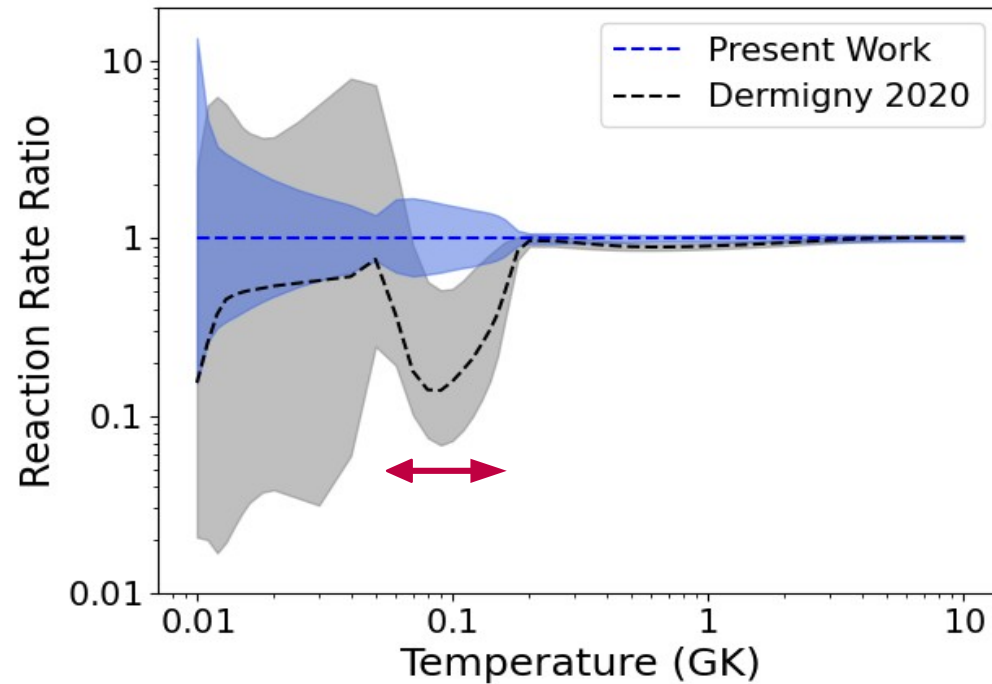
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  → **spin/parity have to be better constrained!**

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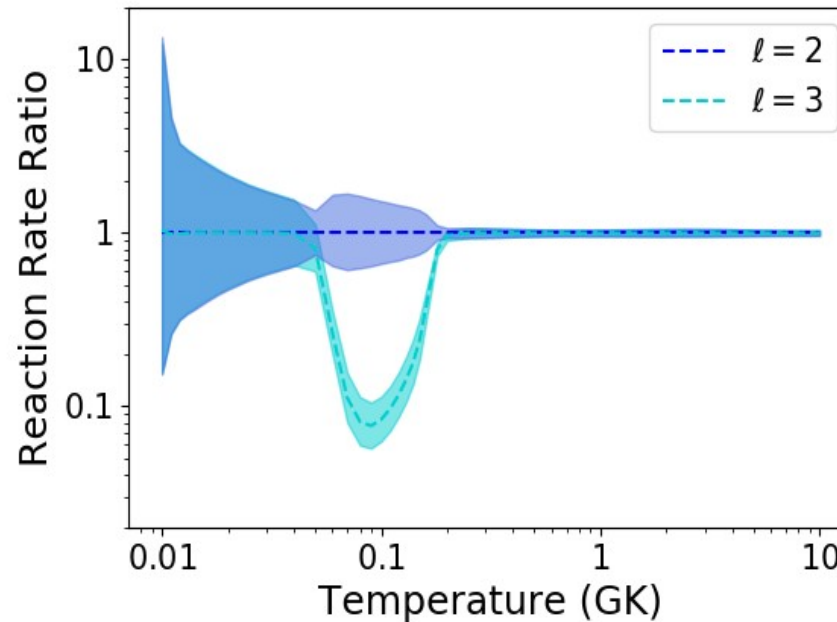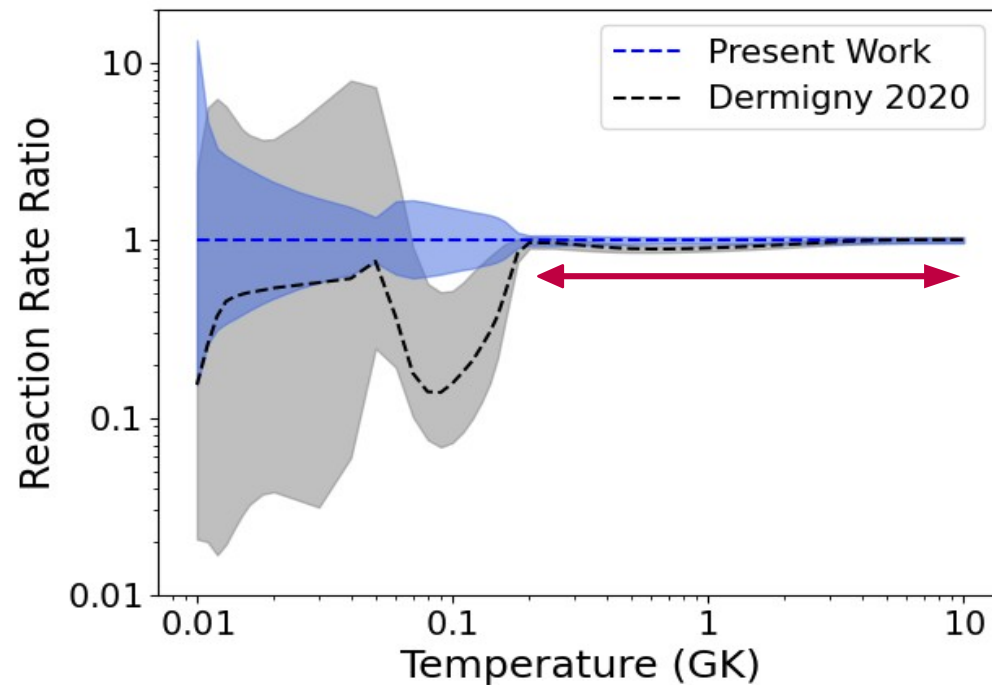


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- $E_r$ = 418 - 440 keV doublet resolved → $E_r$ = 418 keV has $\ell$=3, negligible contribution to the reaction rate, in agreement with direct measurements *(Dermigny et al. 2020)*

- $E_r$ = 486 keV: good agreement for strength values (within 30%) with direct measurements.

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Dermigny *et al.* 2020    **Before our experiment**

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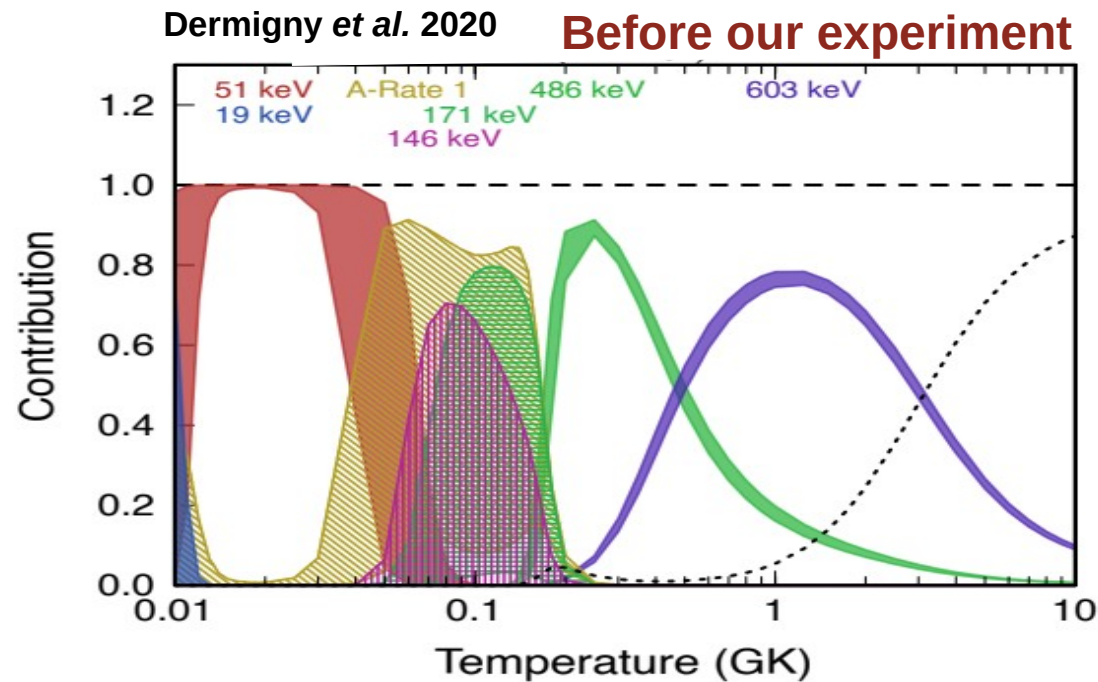  → **spin/parity have to be better constrained!**

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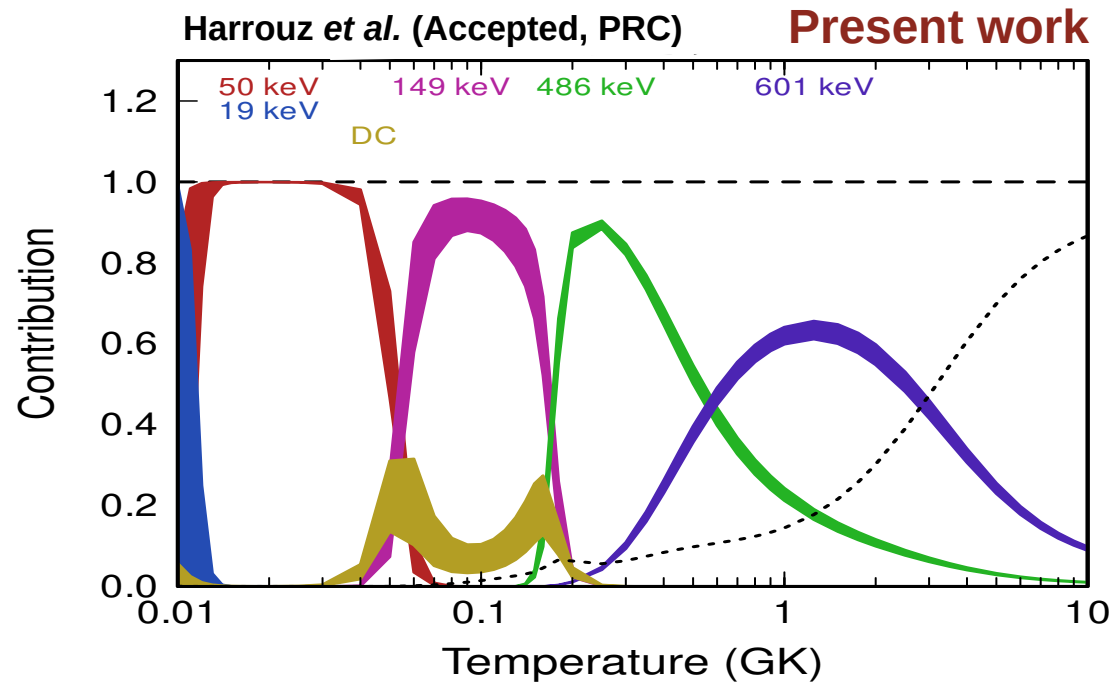
11

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# Direct Measurement
## $^{30}Si(p,\gamma)^{31}P$

# Direct strength measurement
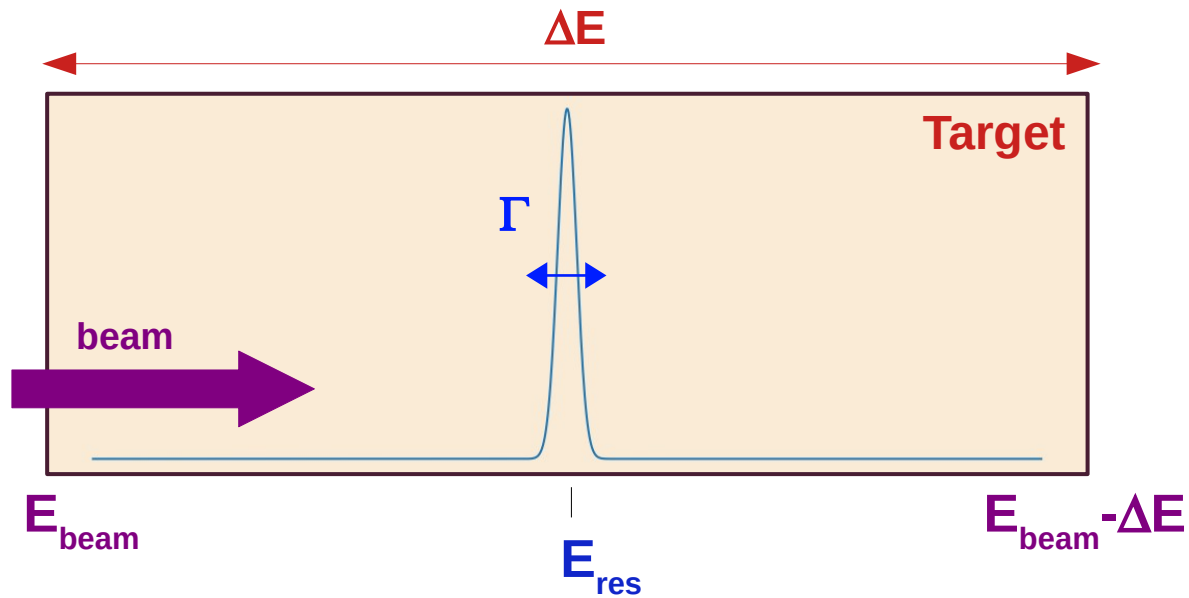


Yield : $Y = \dfrac{N_{\text{Reactions}}}{N_{\text{beam}}}$

# Direct strength measurement
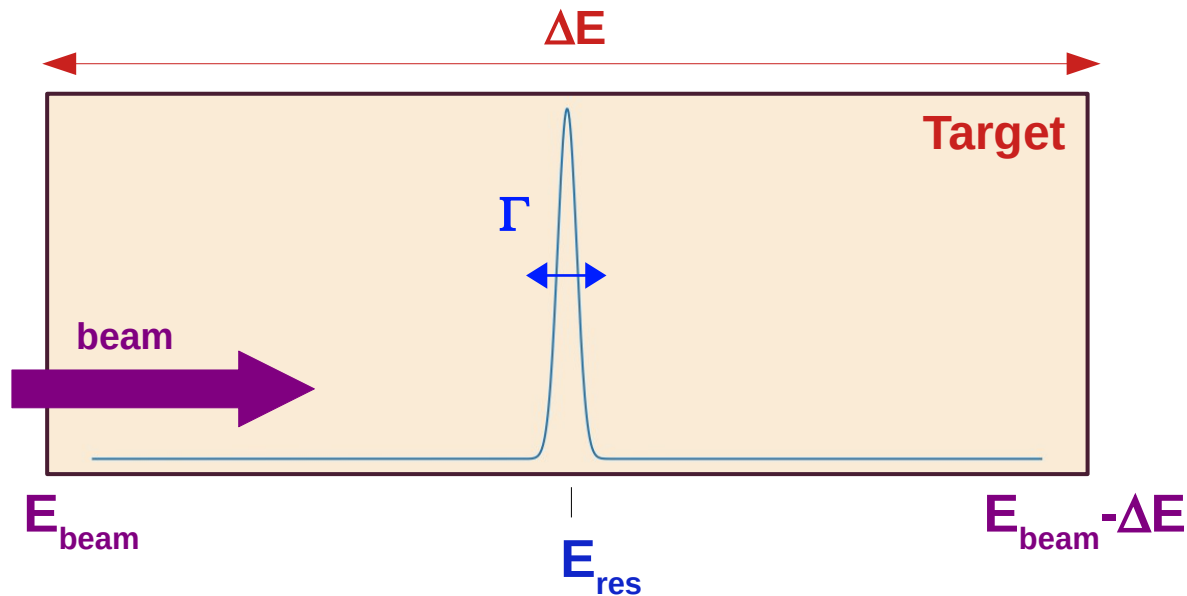


Yield : $\quad Y = \dfrac{N_{\text{Reactions}}}{N_{\text{beam}}}$

- If $\Gamma \ll \Delta E$ (thick target)

$$Y = \frac{\lambda_r^2}{2} \frac{m_b + m_t}{m_t} \frac{\omega\gamma}{\epsilon_r}$$

# Direct strength measurement

$\Delta E$

**Target**

$\Gamma$

**beam**

$E_{beam}$

$E_{res}$

$E_{beam}-\Delta E$
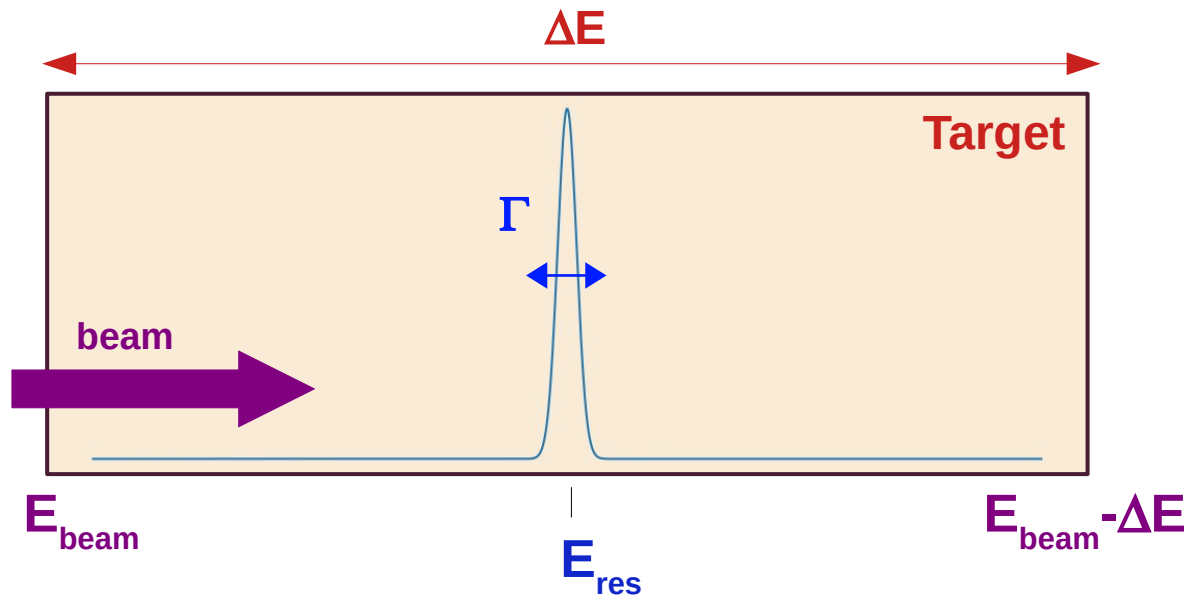
Yield : $\quad Y = \dfrac{N_{\text{Reactions}}}{N_{\text{beam}}}$

- If $\Gamma << \Delta E$ (thick target)

$$Y = \frac{\lambda_r^2}{2} \frac{m_b + m_t}{m_t} \frac{\omega\gamma}{\epsilon_r}$$

- Reaction in **inverse kinematics**
  $\rightarrow$ Detection of recoils
  in coincidence with $\gamma$-ray

$E_{beam}$

$\gamma$

$^{30}$Si

p

$^{31}$P

# DRAGON spectrometer
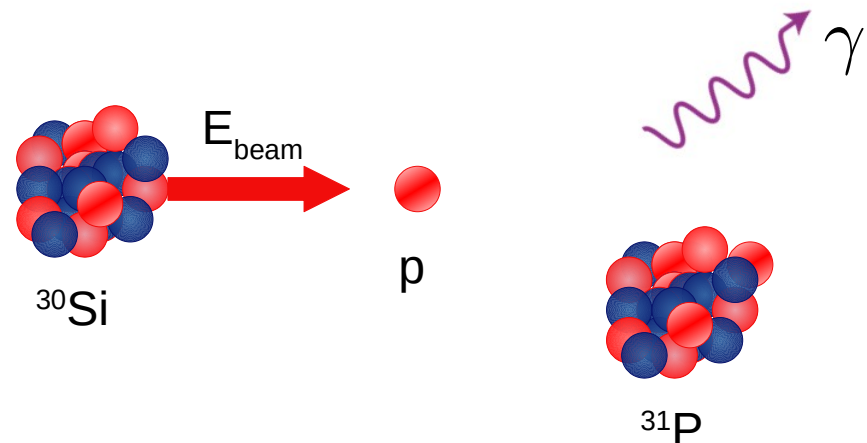
The **D**etector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear reactions.

Designed to measure the rates of nuclear reactions important in astrophysics (p,$\gamma$) and ($\alpha$,$\gamma$)

Beam suppression:
- Singles $10^8 - 10^{13}$
- Coincidences $10^{10} - 10^{16}$

Yield sensitivity down to **$10^{-15}$**



Gas Target  BCM  MD1
Beam
BGO Array  Q1 Q2
Focal Plane Q
Charge Slits
FCCH
S1
SX1
Q3
Q4
Q5  SX2
BCM
ED1
Focal Plane M
Mass Slits
FCM
S2
Q6
Q7  SX3
BCM
MD2
Q8
SX4  BCM
S3
Focal Plane F
Final Slits
FCF  Q10 Q9  S4
BCM
End Detector  ED2
1m

**DRAGON**
Q    = quadrupole
MD   = magnetic dipole
ED   = electric dipole
SX   = sextupole
FC   = Faraday cup
BCM  = beam monitor
S    = horizontal & vertical steerer

# DRAGON spectrometer

## DRAGON Head

Windowless Gas target

**P= 4 – 6.5 Torr**
Target density:
**3 – 5 10$^{18}$ cm$^{-2}$**

Elastic monitor detectors

**ε ~ 40-60%**

**σ ~ 7%(FMHW) @6.13MEV**



Ion Beam — Ion Beam and Recoils

Gas Cell

Lead Shielding — BGO Scintillator

Photomultiplier Tube

Gas Target Box

Ion beam and Recoils

Aluminum Collimators

5 cm



Beam — Gas Target — BCM — MD1

BGO Array  Q1 Q2

Focal Plane Q
Charge Slits
FCCH

S1
SX1
Q3
Q4
Q5
SX2
BCM

ED1
Focal Plane M
Mass Slits
FCM

S2
Q6
Q7
SX3
BCM

MD2

Q8
SX4
BCM
S3

Focal Plane F
Final Slits
FCF
Q10 Q9 S4
BCM
End Detector
ED2

1m

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# DRAGON spectrometer

## DRAGON Tail



beam

End detection equipped with:

- **MCPs**

- **Ionisation chamber**

- **DSSSD**
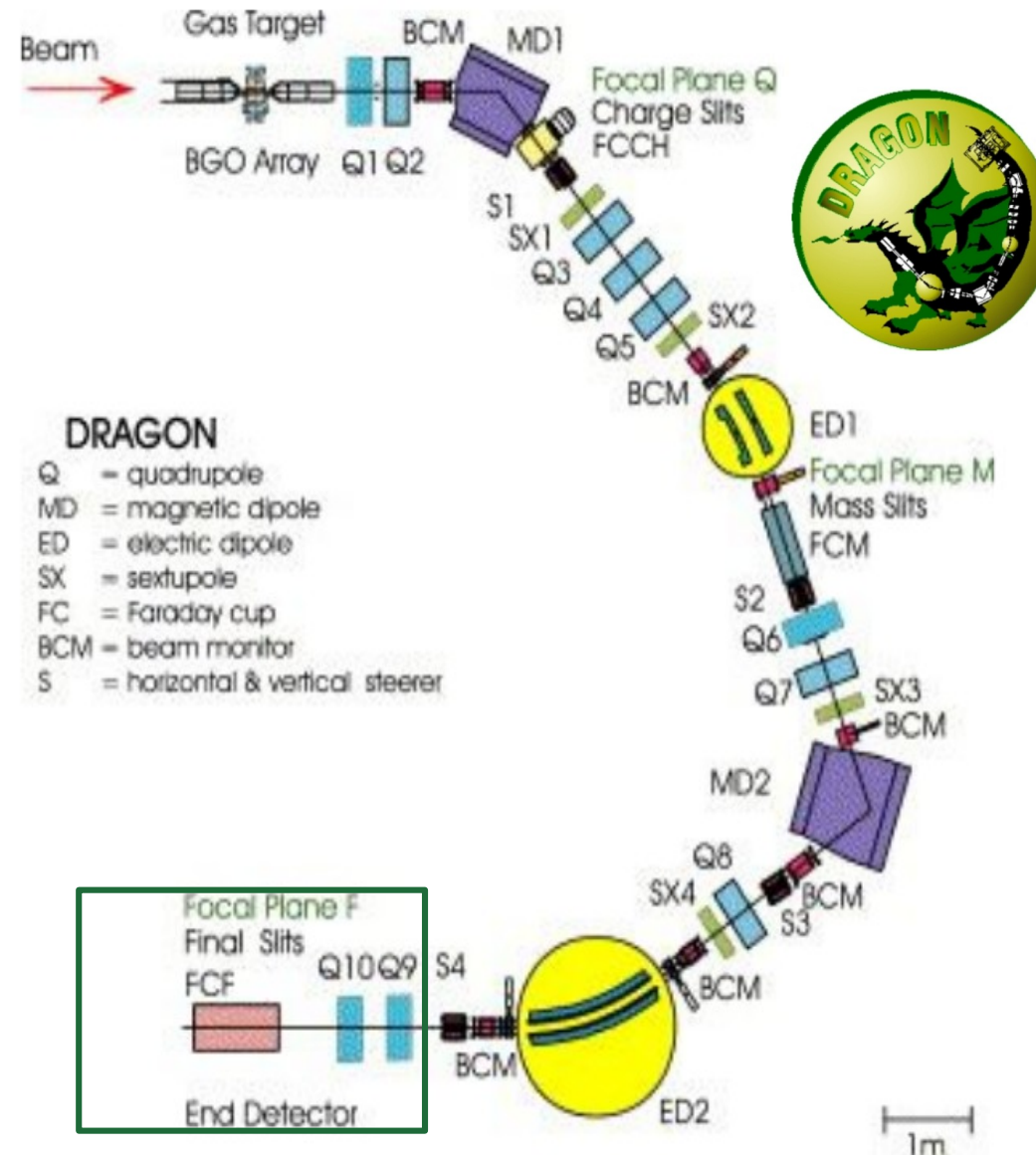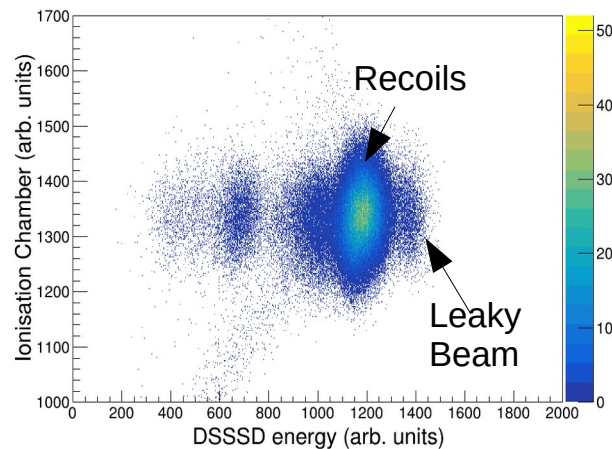
# Ongoing Analysis
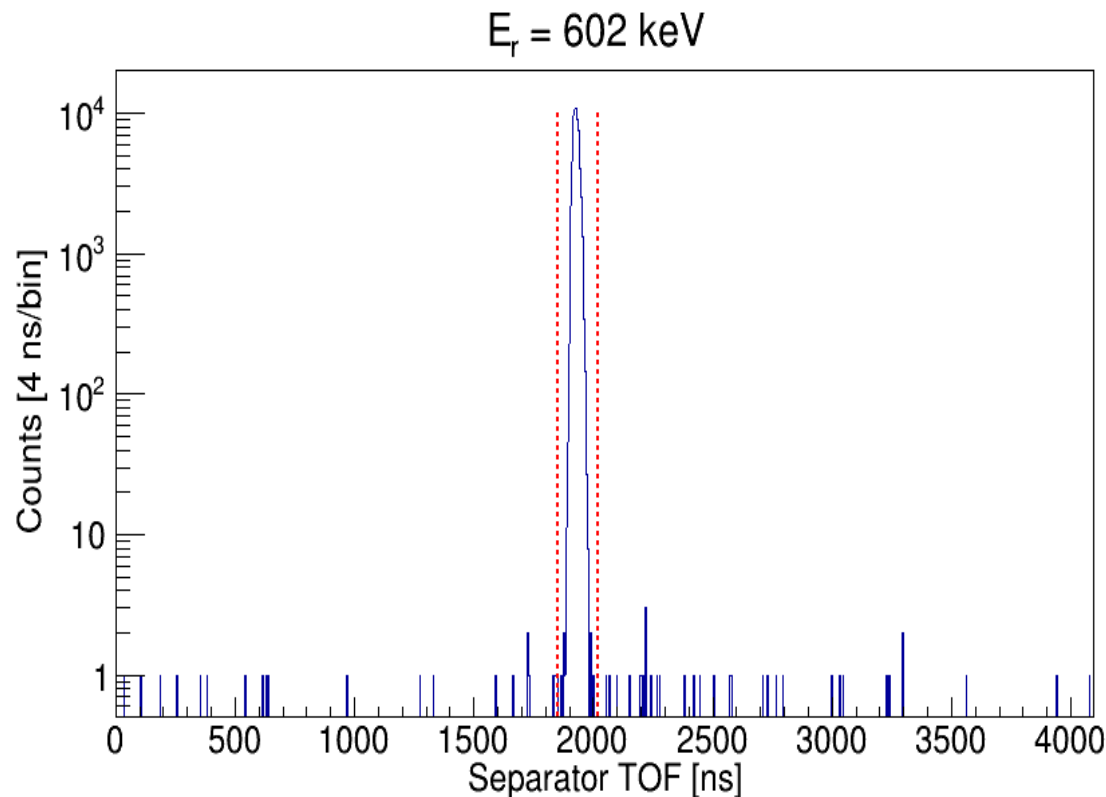
Measured resonances: $E_r$ = **485, 555, 602**, 752, 911 and 950 keV



$$Y = \frac{N_R^{det}}{N_b \varepsilon_{DRA}}$$

$$\varepsilon_{DRA}^{coinc} = f_q\, \tau_{MCP}\, \varepsilon_{MCP}\, \varepsilon_{DSSSD}\, \varepsilon_\gamma\, \lambda_{coinc}$$

$f_q$ : Recoil charge state fraction

$\tau$ : Transmission efficiency

$\varepsilon$ : Detection efficiency

$\lambda$ : DAQ live time fraction

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Measured resonances: $E_r$ = **485, 555, 602**, 752, 911 and 950 keV



$E_r$ = 602 keV

$$Y = \frac{N_R^{det}}{N_b \varepsilon_{DRA}}$$

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$f_q$ : Recoil charge state fraction

$\tau$ : Transmission efficiency

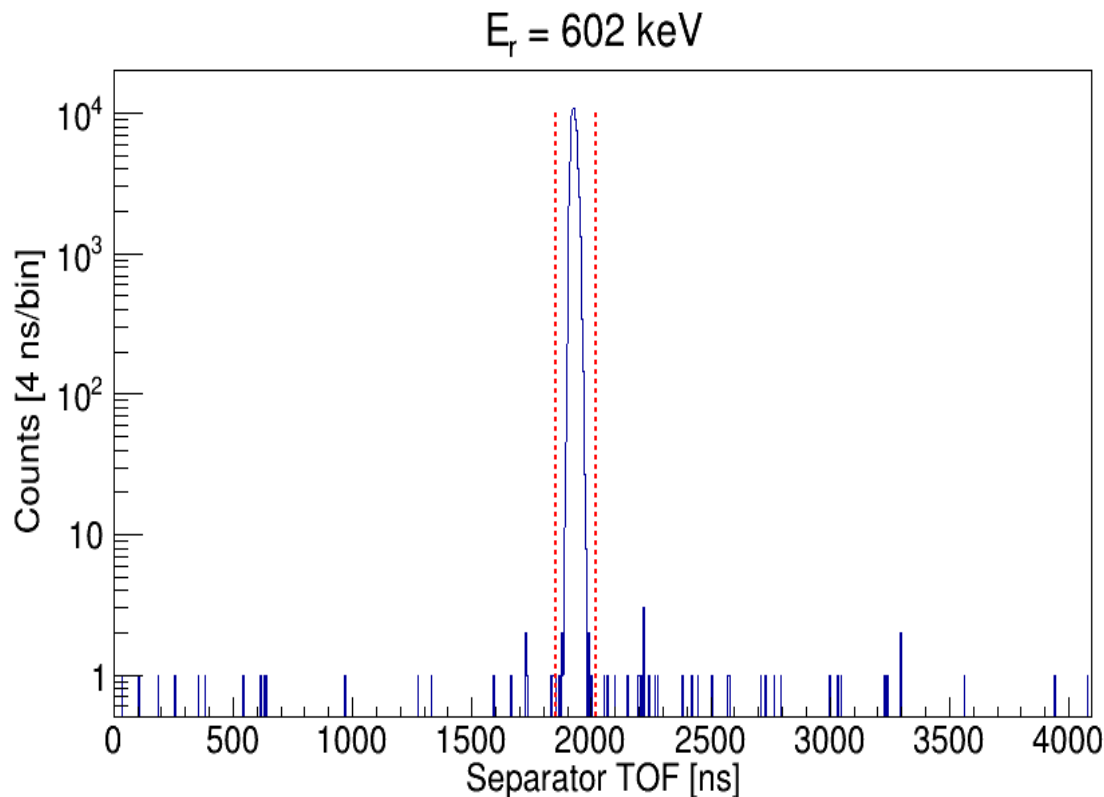$\varepsilon$ : Detection efficiency

$\lambda$ : DAQ live time fraction

$$\varepsilon_{DRA}^{coinc} = 0.37\; 0.88\; 0.90\; 0.93\; 0.6\; 0.72$$

$$\omega\gamma_{(\mathrm{preliminary})} \approx 2\ eV$$

$$\omega\gamma_{(\mathrm{literature})} = 1.95 \pm 0.10\ eV$$

# Conclusion

- Extraction of spectroscopic information for the $^{31}$P nucleus between $E_x$ = 6800 – 8100 keV from the $^{30}$Si($^3$He,d)$^{31}$P reaction.

- Calculation of strengths for resonances up to $E_r$ = 600 keV.

- Improved determination of the $^{30}$Si(p,$\gamma$)$^{31}$P reaction rate.



Harrouz *et al.* (Accepted, PRC)

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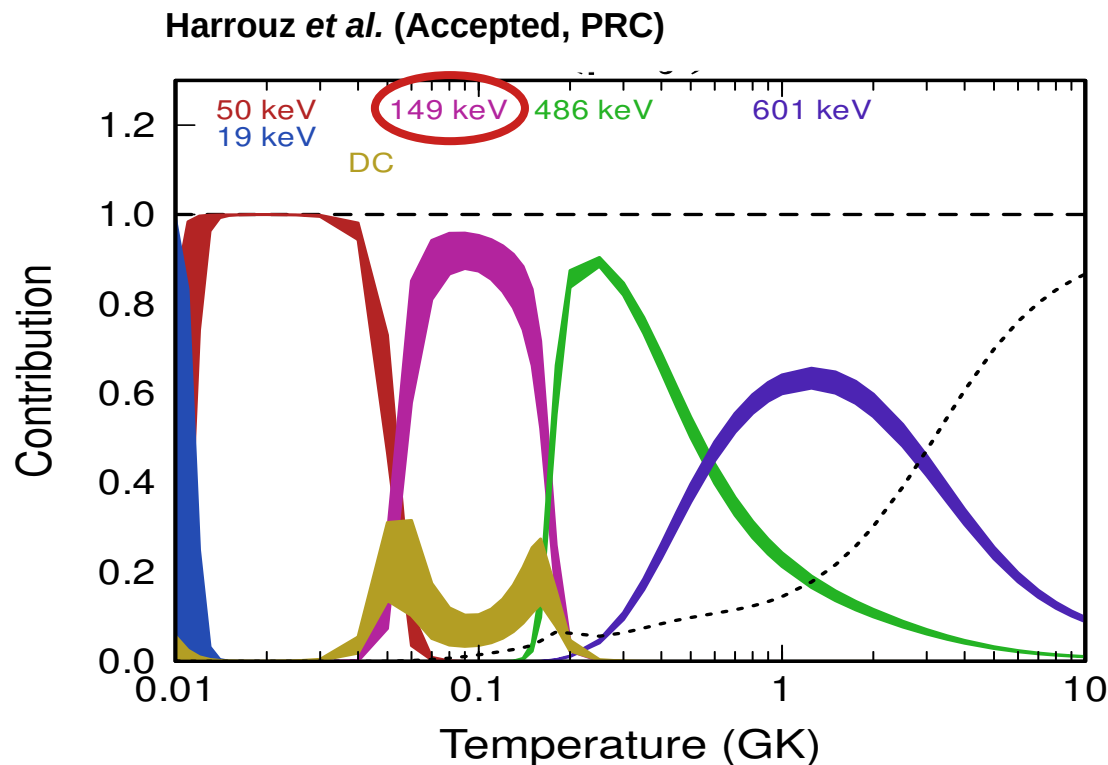


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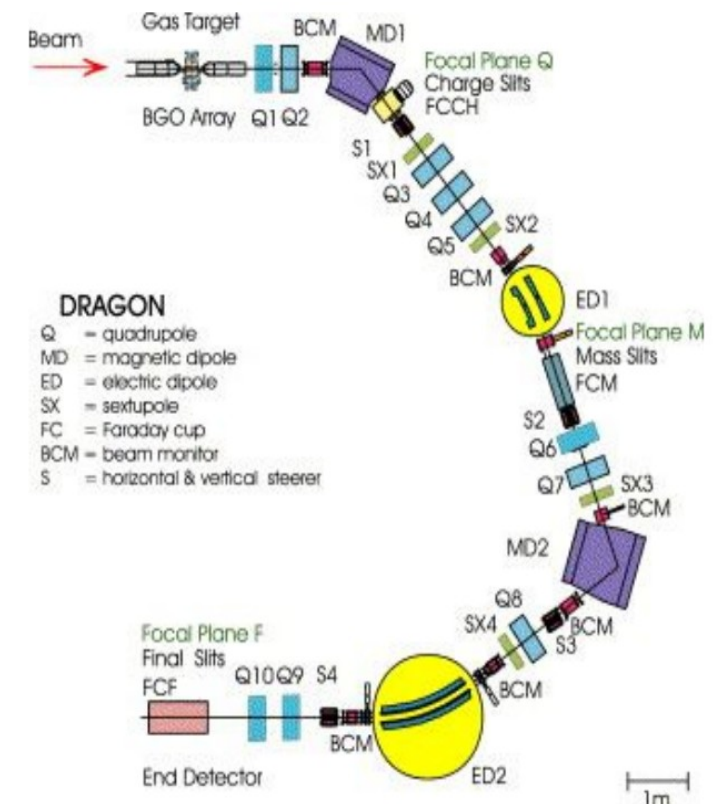FC = Faraday cup
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# Perspectives

- Complete the analysis of the $^{30}$Si(p,$\gamma$)$^{31}$P reaction rate with the Recoil spectrometer **DRAGON**

- Investigate the impact of the new measurements on the temperature locus for constraining "the polluter" candidates in **Globular Clusters.**

NGC 2419

M13

## Collaborators :

### Q3D

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Beyhan Bastin (*GANIL*)           Sara Palmerini (*LNS*)

Thomas Fastermann (*TUM*)     Gianluca Pizzone (*LNS*)

Faïrouz Hammache (*IJCLab*)    Stefano Romano (*LNS*)

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Keerthi Jayamanna (*TRIUMF*)  Sriteja Upadhyayula (*TRIUMF*)

Spencer Kiy (*TRIUMF*)           Matthew Williams (*TRIUMF*)

Alison Laird (*York*)

# Thank you for your attention

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M13
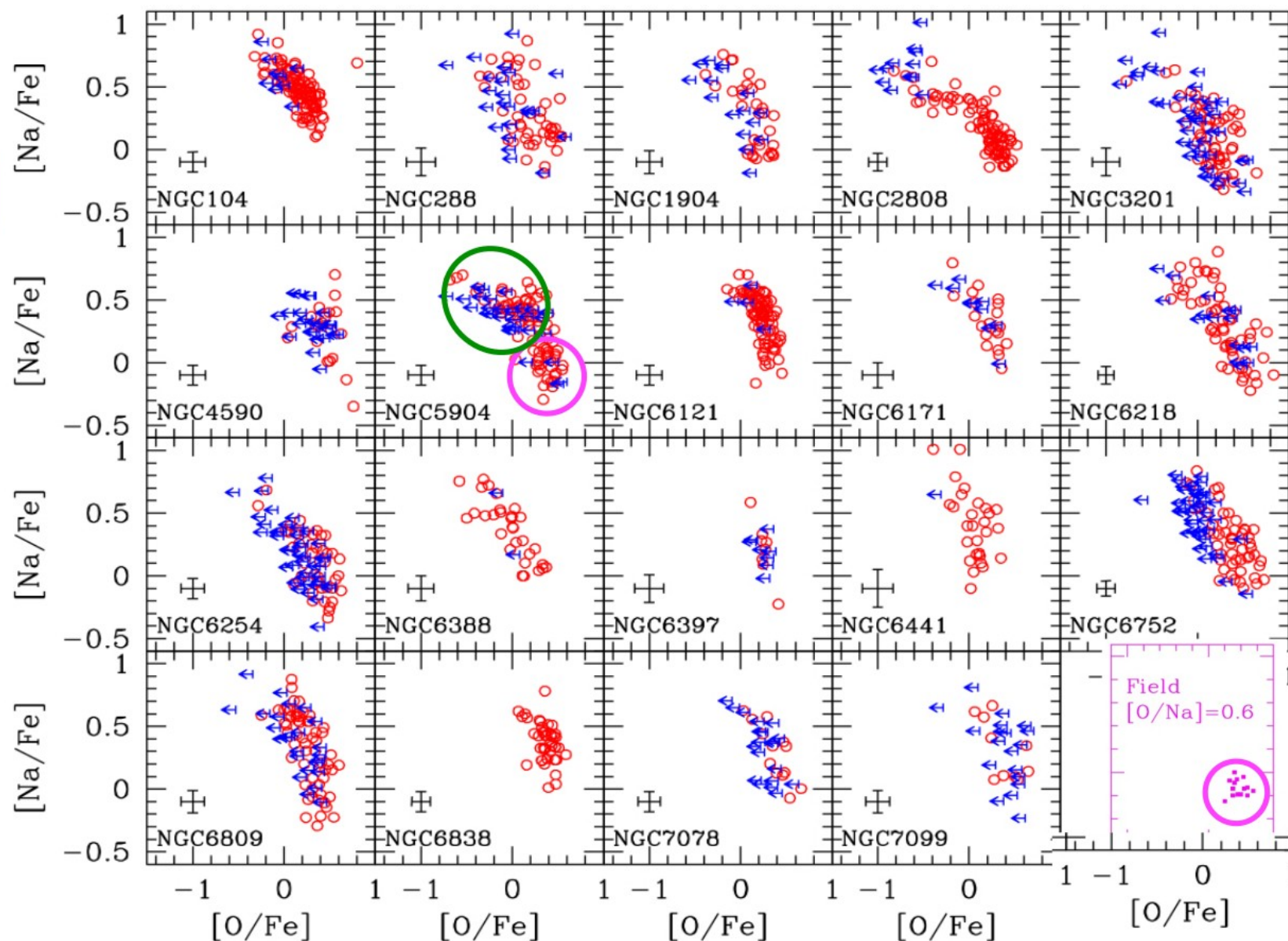
# Backup

# GC anomalies

1st population

~ 30 ± 7 %

2d population

~ 70 ± 7 %



*Carretta et al. 2007, adapted by Charbonnelle 2016*

# Spectra



Focal-Plane Position (arb. units)
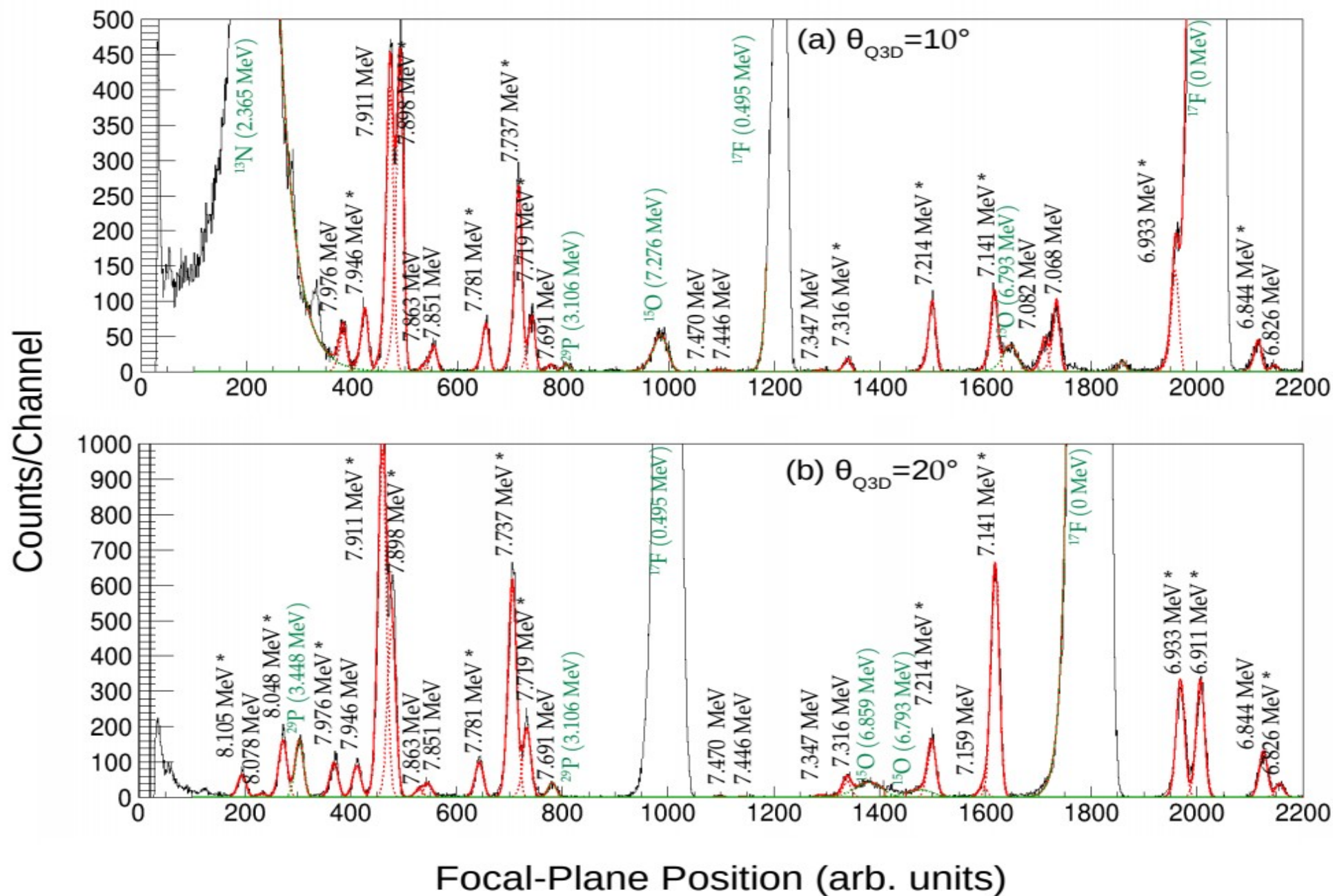
# Spectroscopic factor
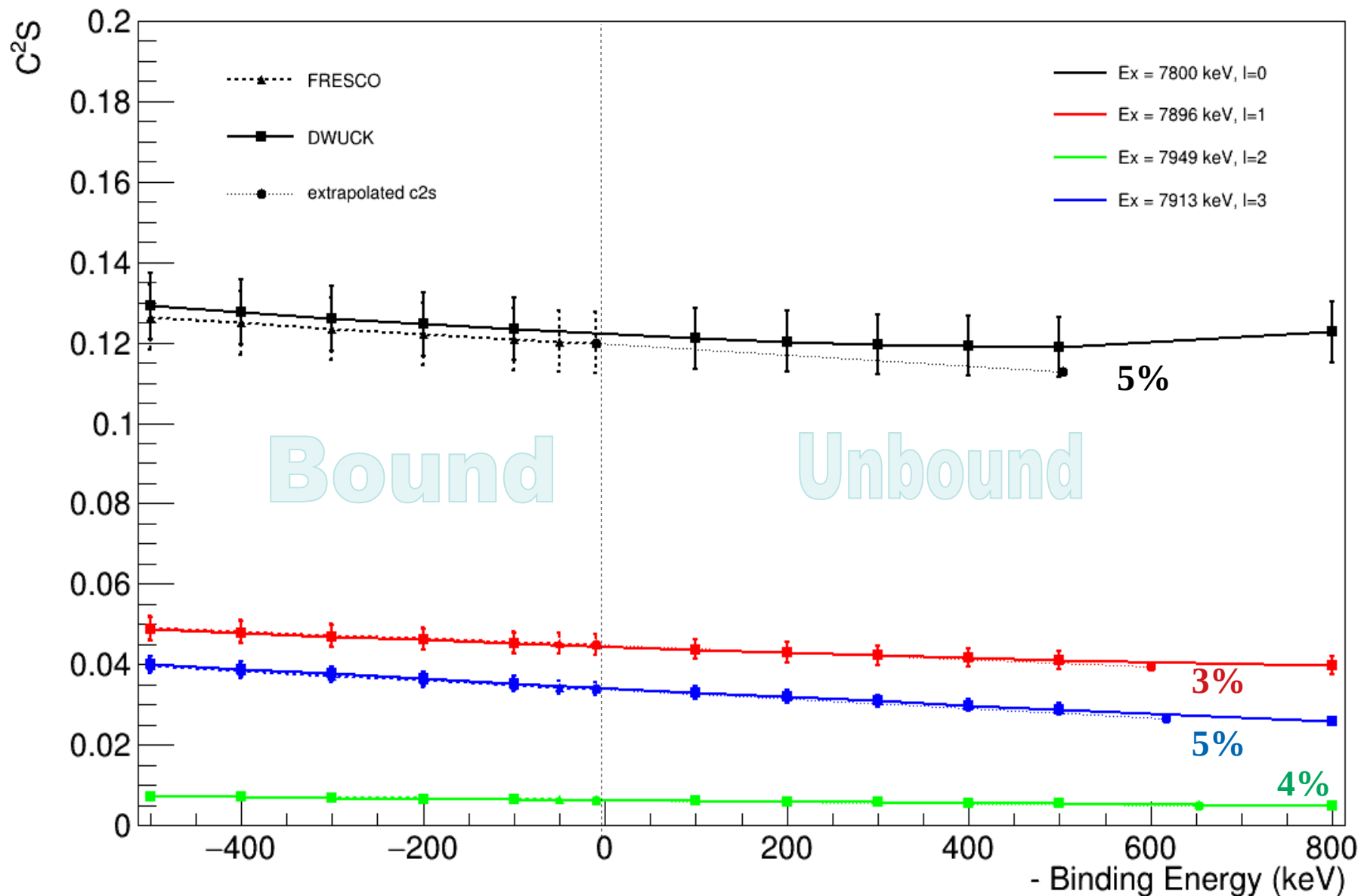
# Reduced Partial Width s.p (DWUCK4)

# Reduced width

$$\Gamma_p = \theta_p^2 \Gamma_{Wigner}$$

In Dermigny 2020 :
$$\langle \theta^2 \rangle = 0.0003$$



Pogrebnyak et al 2013



Longland et al 2010

$$f(\theta^2) = \frac{c}{\sqrt{\theta^2}} e^{-\theta^2/(2\langle\theta^2\rangle)}$$

# Partial widths uncertainties

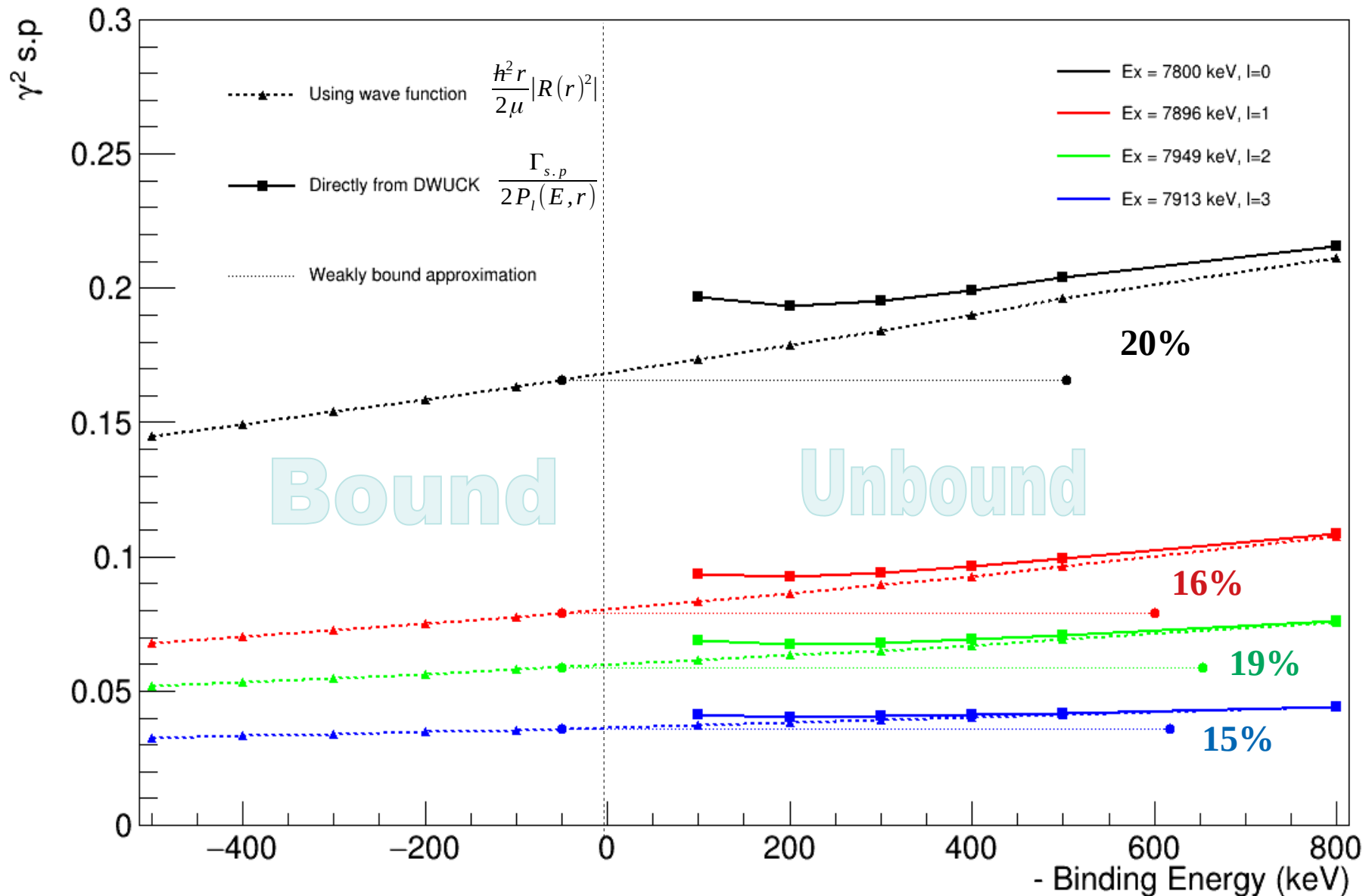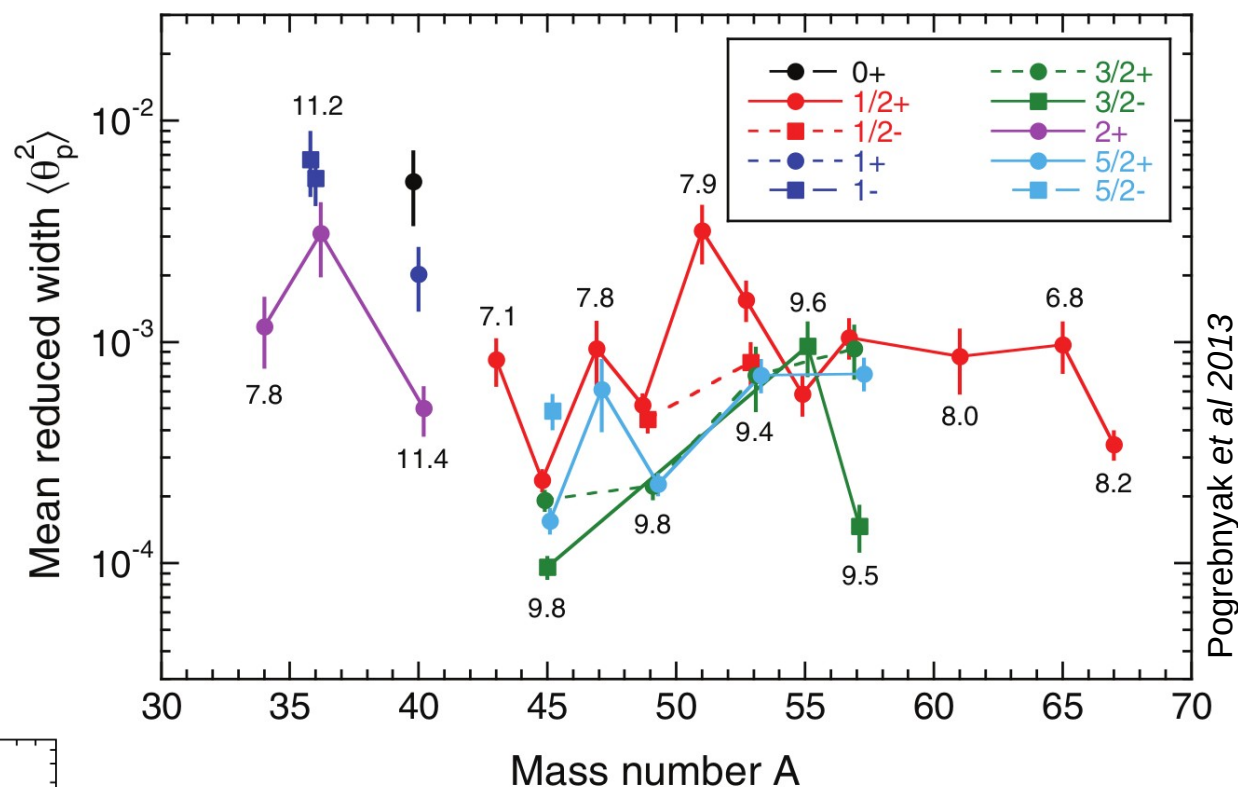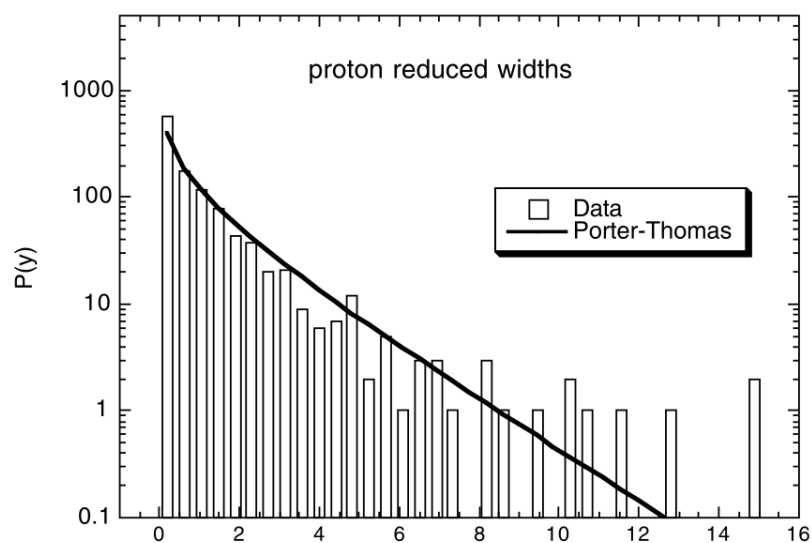- Uncertainties comes from optical potentials for entrance/exit channels and geometry of binding potential. → 20 – 30% (Keeley *et al*. 2013)

- Use same wave function coming from DWBA analysis.

$$\Gamma_a = C^2 S_a \Gamma_a^{s.p.} = C^2 S_a \times \frac{\hbar^2 s}{\mu} |\mathcal{R}(s)|^2 P_l(E_r, s)$$

- Comparison of partial widths: transfer vs. direct:

Direct: (p,p) & (p,γ) reactions

Transfer: (3He,d) reaction

**Agreement within a factor 2**



Levels in $^{25}$Al, $^{27}$Al and $^{31}$P

(a)  $C^2S$

$\Gamma_{direct} / \Gamma_{transfert}$
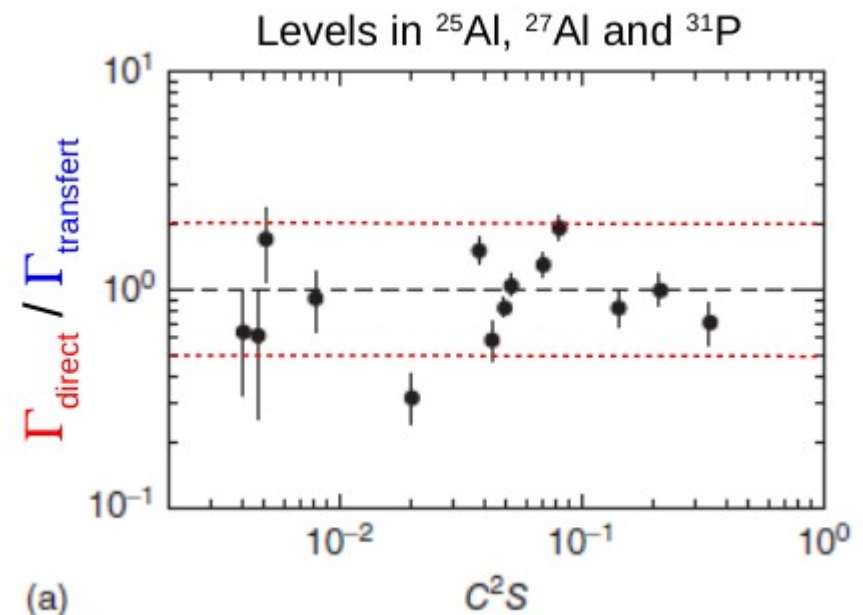
Iliadis, Nuclear Physics of Stars (2015)

| | | | | | ωγ (eV) | | | | | ωγ (eV) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7719.5 | 8 | 423.0 | 8 | 3 | 0.044 | $2.48 \times 10^{-5}$ | $7.42 \times 10^{-5}$ | $(3/2, 5/2)^-$ | | $(1.14 \pm 0.25) \times 10^{-4}$ | [11] |
| 7737.3 | 7 | 440.8 | 7 | 3 | 0.114 | $9.79 \times 10^{-5}$ | $3.92 \times 10^{-4}$ | $(5/2, 7/2)^-$ | 3 | $\approx 3.72 \times 10^{-4}$ | [35] |
| 7781.1 | 8 | 484.6 | 8 | 1 | 0.015 | 0.061 | 0.123 | $3/2^-$ | | $0.188 \pm 0.014$ | [11] |

TABLE III. Properties of resonances above the $^{30}$Si$+p$ threshold from the present work and comparison with the literature.

| $E_x$ (keV) | $E_r^{c.m.}$ (keV) | Present work | | | | Literature | | | |
| | | $\ell$ | $(2J+1)C^2S$ | $\Gamma_p$ (eV) | $\omega\gamma$ (eV)[a] | $J^\pi$ | $\ell$ | $\omega\gamma$ (eV) | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 7313.7 *16* | 18.6 *16* | | | $1.45\times10^{-35}$ [b] | $1.45\times10^{-35}$ | $(1/2, 3/2)^+$ | 0, 2 | $\leq6.50\times10^{-37}$ | [35] |
| 7316.2 *9* | 19.6 *9* | 3 | 0.0075 | $2.94\times10^{-39}$ | $1.18\times10^{-38}$ | $(5/2, 7/2)^-$ | 3 | $\approx8.60\times10^{-40}$ | [35] |
| 7347.0 *12* | 50.5 *12* | 1 | 0.0007 | $5.20\times10^{-21}$ | $1.04\times10^{-20}$ | $(3/2, 5/2)^-$ | 1, 3 | $\leq5.04\times10^{-17}$ | [35] |
| 7356 *16* | 59.4 *16* | | | | | | | | |
| 7442.3 *3* | 145.8 *3* | | | $4.33\times10^{-17}$ [b] | $2.60\times10^{-16}$ | $11/2^+$ | 6 | $\leq1.24\times10^{-15}$ | [35] |
| 7445.7 *27* [c] | 149.2 *29* | 2 | 0.0007 | $1.16\times10^{-11}$ | $2.33\times10^{-11}$ | $(3/2^+, 5/2, 7/2, 9/2^+)$ | 2, 3, 4 | $\leq7.60\times10^{-8}$ | [35] |
| 7470.5 *23* | 174.0 *23* | 3 | 0.001 | $1.59\times10^{-12}$ | $6.38\times10^{-12}$ | $(7/2, 9/2)^-$ | 3, 5 | $\leq1.27\times10^{-10}$ | [35] |
| 7572 | 275.5 | | | | | | | | |
| 7691.1 *10* | 394.6 *10* | 3 | 0.006 | $1.47\times10^{-6}$ | $4.40\times10^{-6}$ | | | | [35] |
| 7719.5 *8* | 423.0 *8* | 3 | 0.044 | $2.48\times10^{-5}$ | $7.42\times10^{-5}$ | $(3/2,5/2)^-$ | | $(1.14\pm0.25)\times10^{-4}$ | [11] |
| 7737.3 *7* | 440.8 *7* | 3 | 0.114 | $9.79\times10^{-5}$ | $3.92\times10^{-4}$ | $(5/2, 7/2)^-$ | 3 | $\approx3.72\times10^{-4}$ | [35] |
| 7781.1 *8* | 484.6 *8* | 1 | 0.015 | 0.061 | 0.123 | $3/2^-$ | | $0.188\pm0.014$ | [11] |
| 7825 *9* | 528.5 *9* | | | | | | | | |
| 7851.4 *8* | 554.9 *8* | 1 | 0.009 | 0.244 | $0.181^{\text{d}}$ | | | | |
| 7863.4 *14* | 566.9 *16* | 3 | 0.004 | $5.55\times10^{-5}$ | $1.67\times10^{-4}$ | | | | |
| 7897.8 *7* | 601.3 *7* | 1 | 0.115 | 6.49 | | $1/2^-$ | | $1.95\pm0.10$ | [42] |

[a] Assuming $\Gamma_p \ll \Gamma_\gamma$, so that $\omega\gamma = 0.5(2J+1)\Gamma_p$.
[b] A dimensionless reduced width $\langle\theta_p^2\rangle = 0.0045$ is assumed.
[c] 7441.4 keV in literature
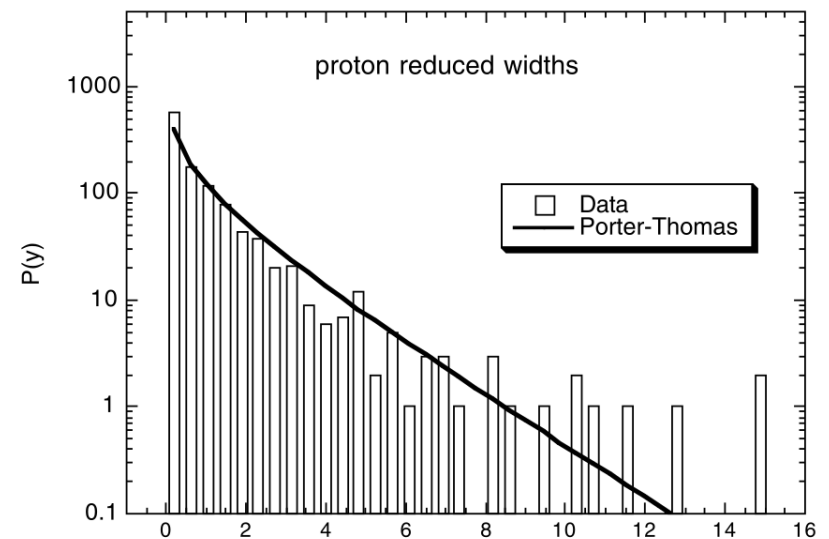[d] The complete resonance strength formula has been used (see text).

# 149 keV resonance
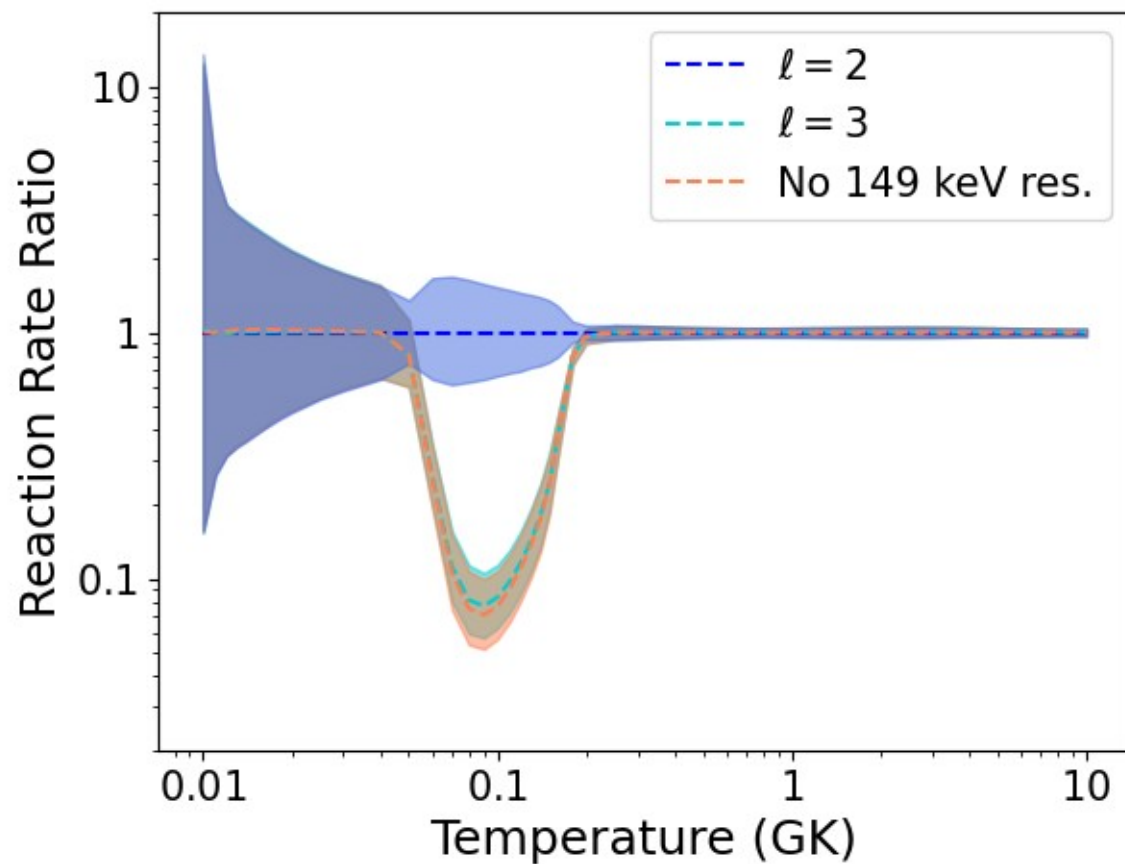
# RatesMC

Thermonuclear reaction rate for single and isolated narrow resonance :

$$\langle \sigma v \rangle \propto (\omega\gamma) e^{(-E_R/kT)}$$

$$\omega\gamma = \frac{2J_R + 1}{(2J_p + 1)(2J_{^{30}Si} + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$

- Resonance energies $\rightarrow$ Normal distribution

- Resonance strengths
  or Partial widths $\rightarrow$ Log-Normal distribution

- Not observed level: upper limits on widths
  $\rightarrow$ Porter Thomas distribution

$$\Gamma_{sp} = 2P_\ell \gamma_{sp}^2, \quad \gamma_{sp}^2 = \frac{\hbar^2}{2\mu} \mid R(r) \mid^2$$

$\dfrac{\gamma_{sp}^{2 \; fresco}}{\gamma_{sp}^2}$

~ 7 fm

FRESCO/Whittaker

FRESCO/DWUCK

r (fm)