This research was supported by TRIUMF and the Natural Sciences and Engineering Research Council of Canada

Exclusive Indirect Measurement at the ISAC-II Facility of the $^{22}Ne(\alpha,\gamma)^{26}Mg$ Reaction for *s*-process Nucleosynthesis

Thomas Chillery

Nuclear Physics in Astrophysics XII – Cluj-Napoca, Romania

07/09/2026

Astrophysical Motivation: *s*-process

- ½ of elements heavier than Fe produced in slow neutron-capture (*s*-) process
- **Massive Stars**
  - Convective He core and C shell burning, 0.25 – 1 GK
  - Weak *s*-process component
- Asymptotic Giant Branch **(AGB) stars** ($M/M_\odot$ = 1.5 – 3)
  - He-rich inter-shell region
  - Main and strong *s*-process components
- Dominant neutron sources: **^{22}Ne(α,n)^{25}Mg** and ^{13}C(α,n)^{16}O

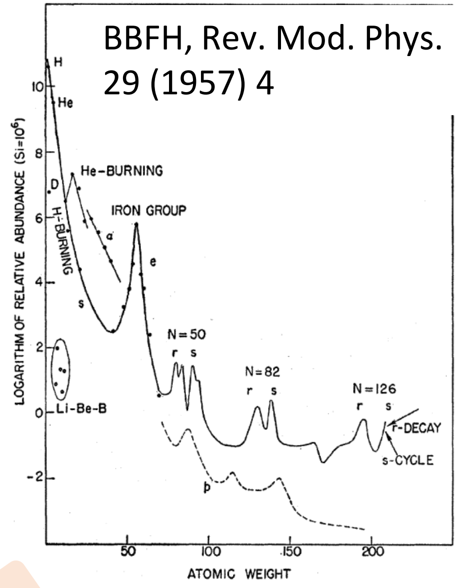
BUT:

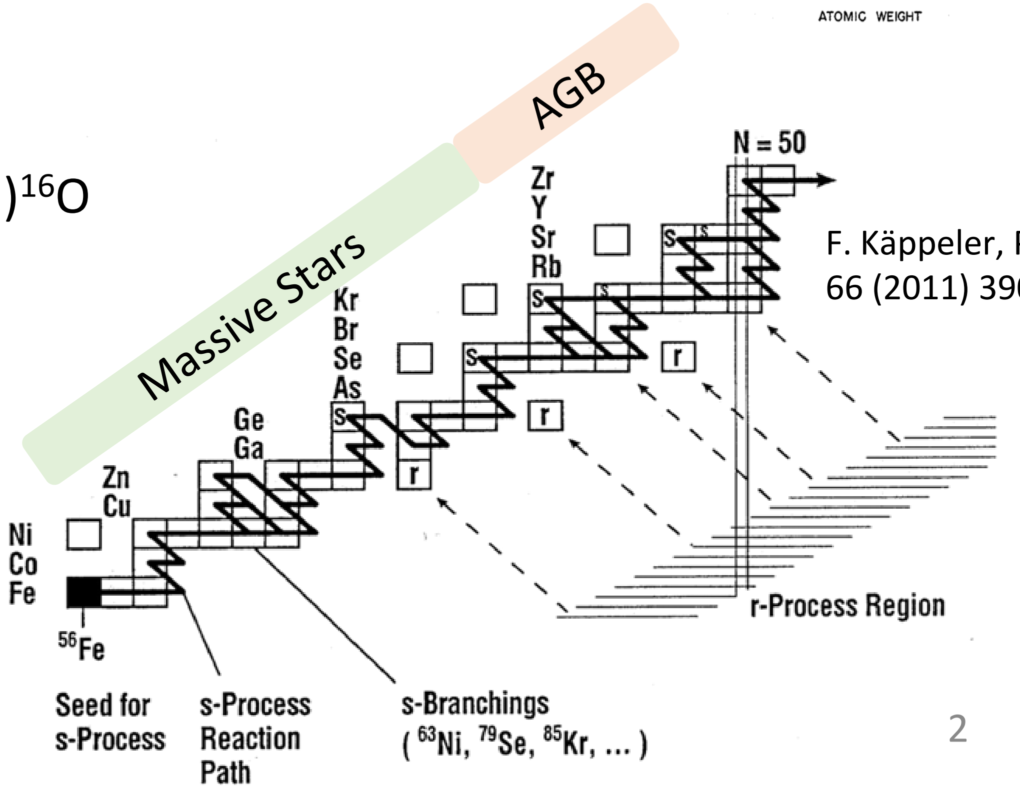
^{22}Ne(**α,n**)^{25}Mg ⇋ ^{22}Ne(**α,γ**)^{26}Mg

AND:

Large uncertainties in these stellar rates; 0.2 – 0.3 GK

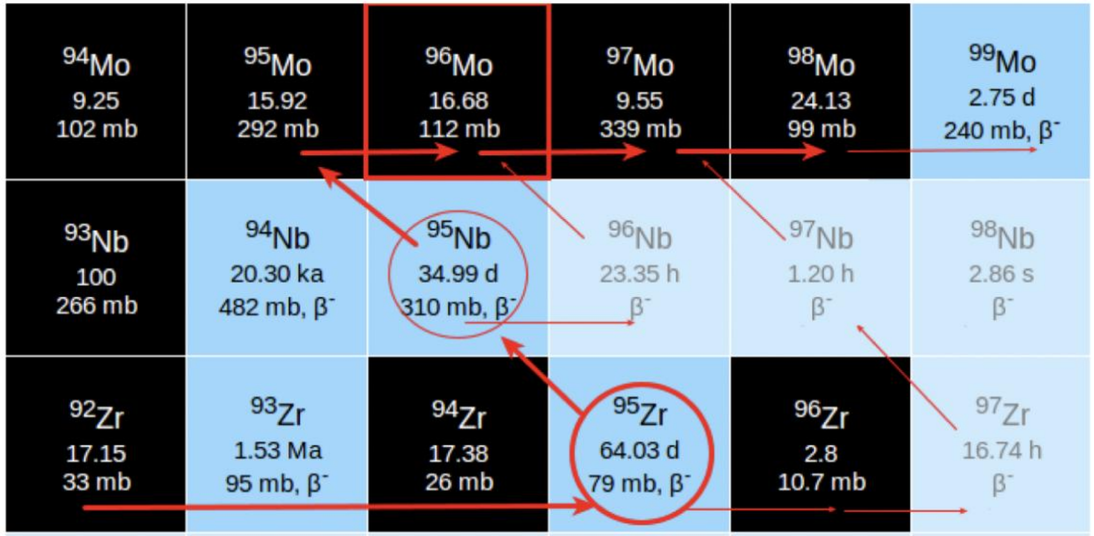
BBFH, Rev. Mod. Phys. 29 (1957) 4



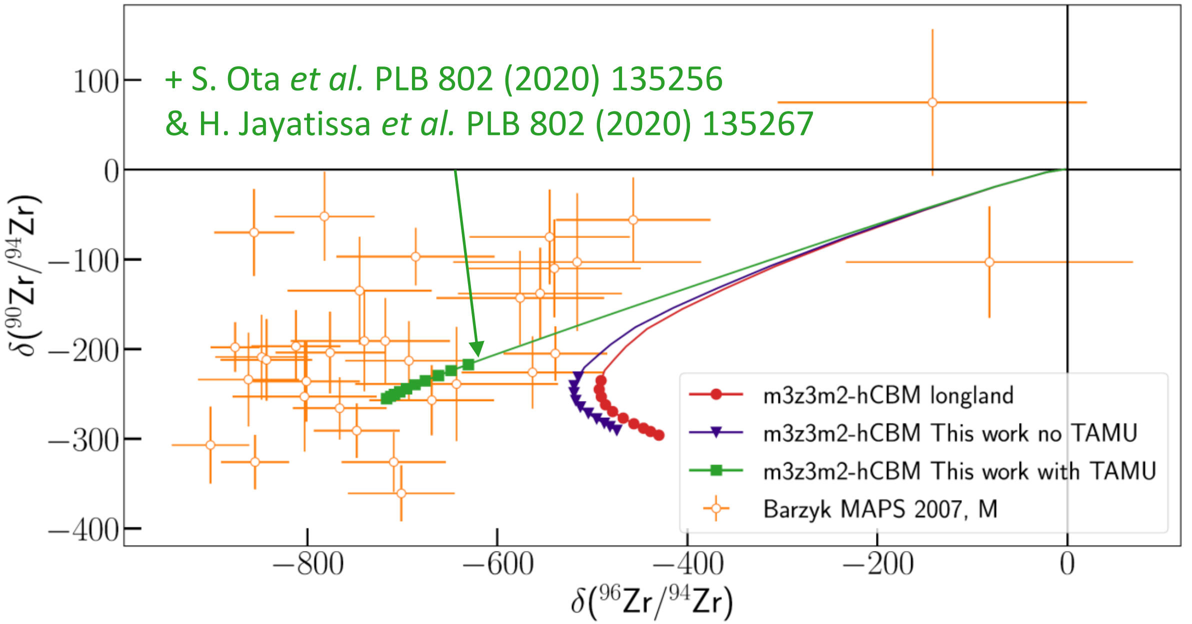


F. Käppeler, PPNP 66 (2011) 390-399

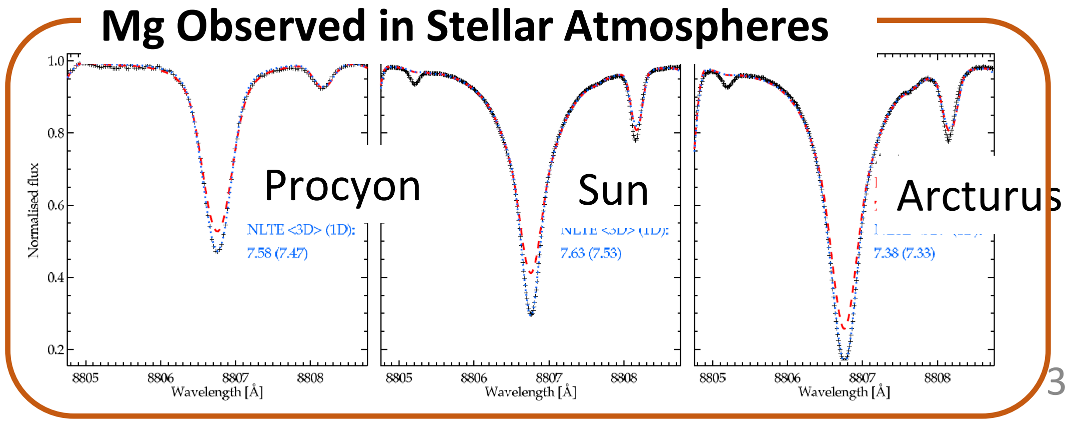
$^{22}Ne(\alpha,[n,\gamma])^{25,26}Mg$



P. Adsley *et al.* PRC 103 (2021) 015805



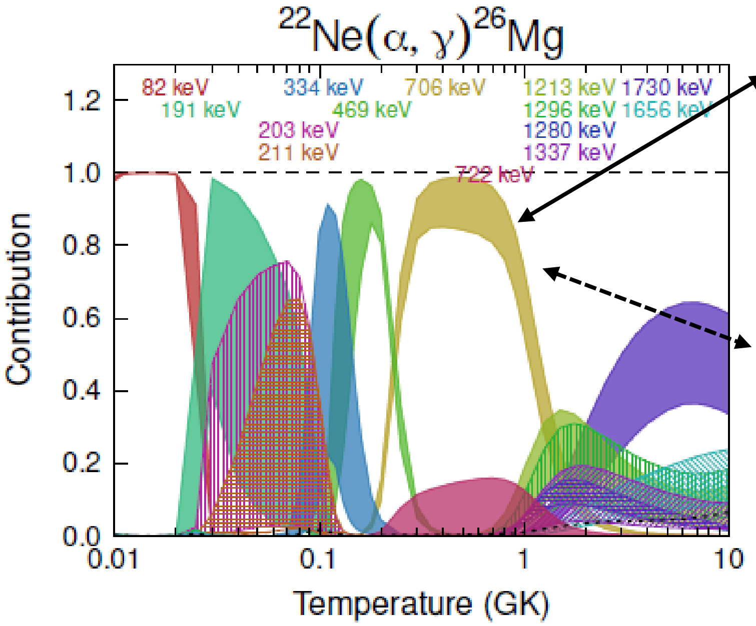
Y. Osorio *et al.* A&A 579 (2015) A53



- (α,n) channel -> late-stages of main *s*-process (AGB)
- Resonance info -> branching point population
- Mg observations in stellar atmospheres -> (α,n) vs (α,γ)
- Both channels important

State-of-art: Direct Measurements
Ex = 11.316 MeV, E_{cm} ~ 706 keV

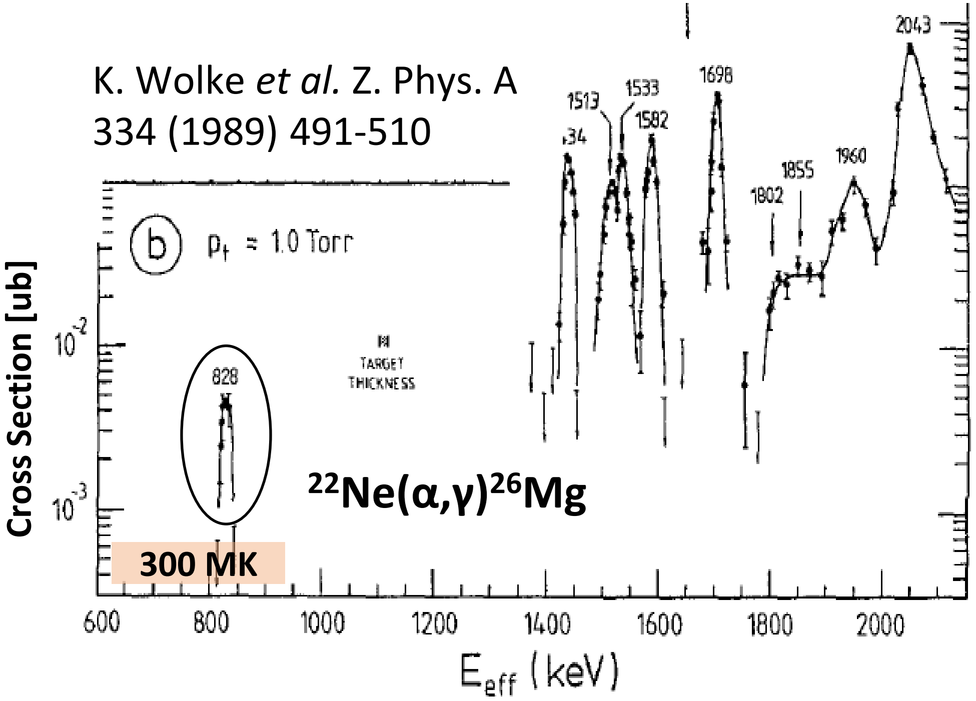
Courtesy: A. Best
Generated from P. Adsley *et al.* PRC 103 (2021) 015805

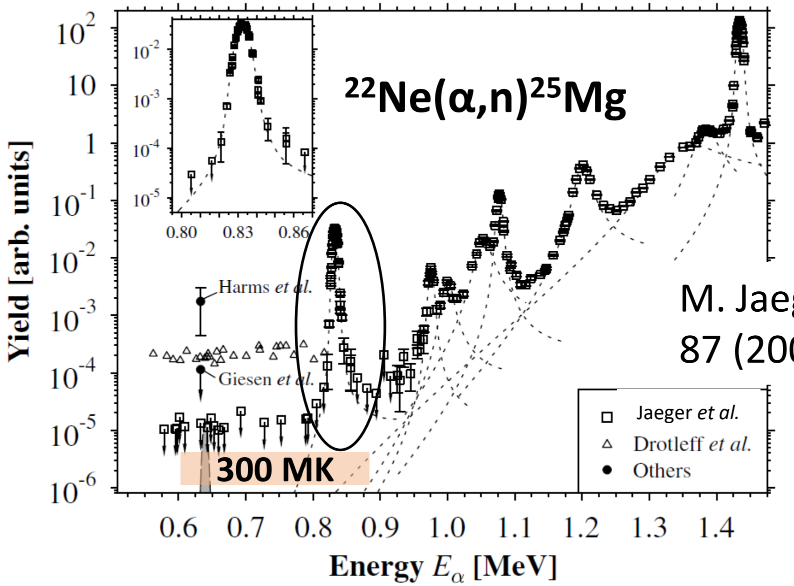


^{22}Ne(α,γ)^{26}Mg	ωγ (α,γ) [μeV]
Wolke 1989	36 (4)
Jaeger 2001	33 (4)
Hunt 2019	46 (12)
Shahina 2022	35 (4)

^{22}Ne(α,n)^{25}Mg	ωγ (α,n_0) [μeV]
Drotleff 1991	81 (30)
Harms 1991	83 (24)
Giesen 1993	234 (77)
Jaeger 2001	118 (11)
Shahina 2024	100 (22)
Indirect: Ota 2021	42 (11)

K. Wolke *et al.* Z. Phys. A 334 (1989) 491-510



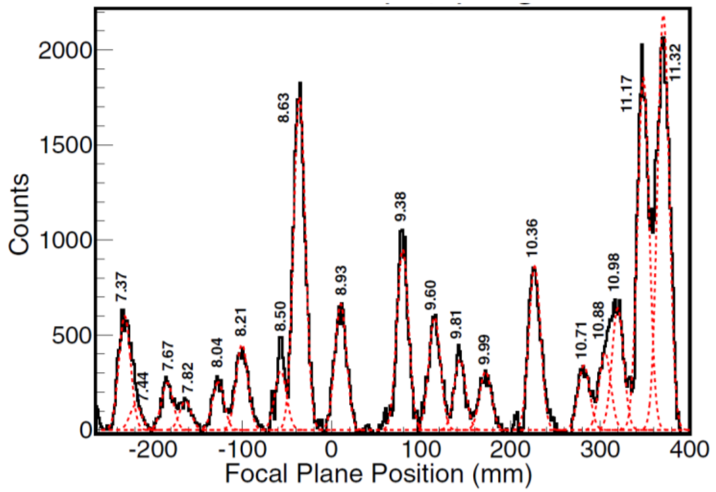


M. Jaeger *et al.* PRL 87 (2001) 202501

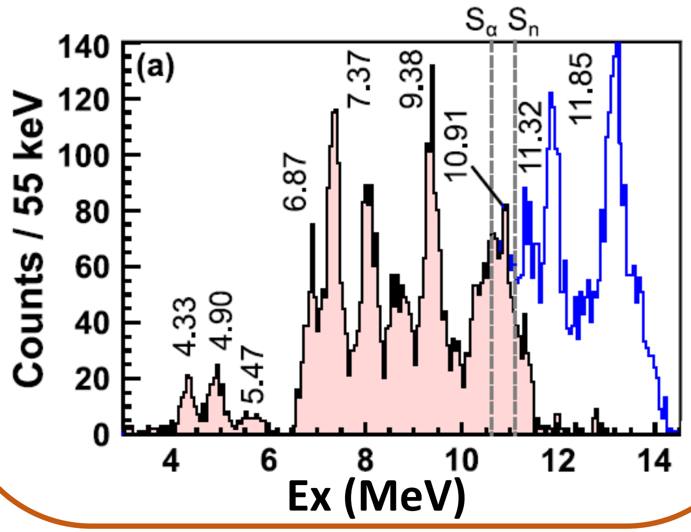
State-of-art: Indirect Measurements

$^{22}Ne(^{6}Li,d)^{26}Mg$

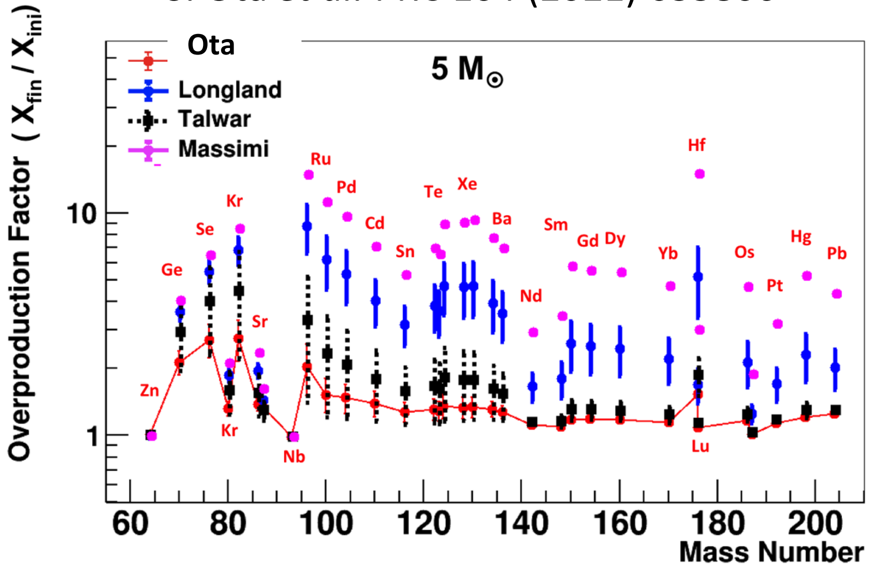
R. Talwar *et al.* PRC 93 (2016) 055803

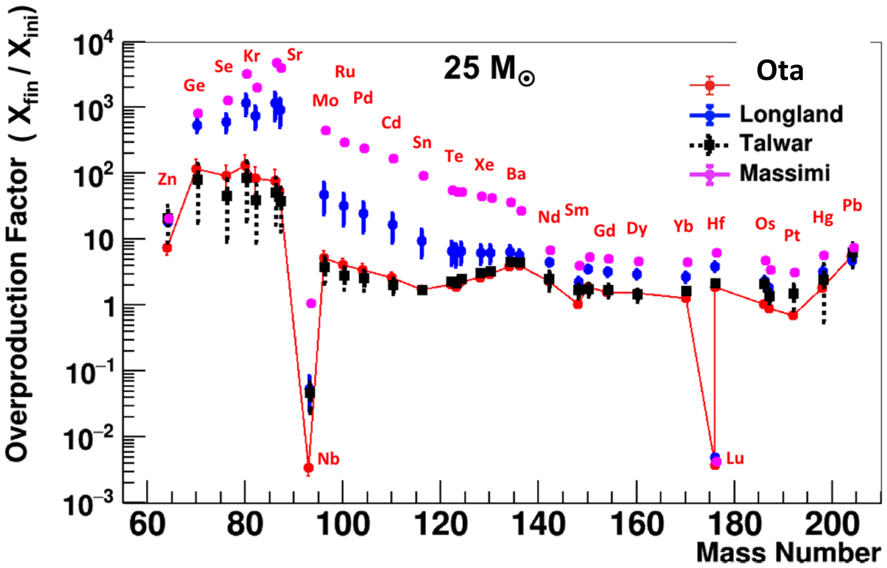


S. Ota *et al.* PLB 802 (2020) 135256



S. Ota *et al.* PRC 104 (2021) 055806





Several indirect studies

Alpha widths uncertain

-> Huge uncertainties on modelled abundances

$^{26}Mg + \gamma$

$^{25}Mg + n$

See summaries:

A. Best *et al.* EPJ A (2025) 61:99

M. Wiescher *et al.* EPJ A (2023) 59:11

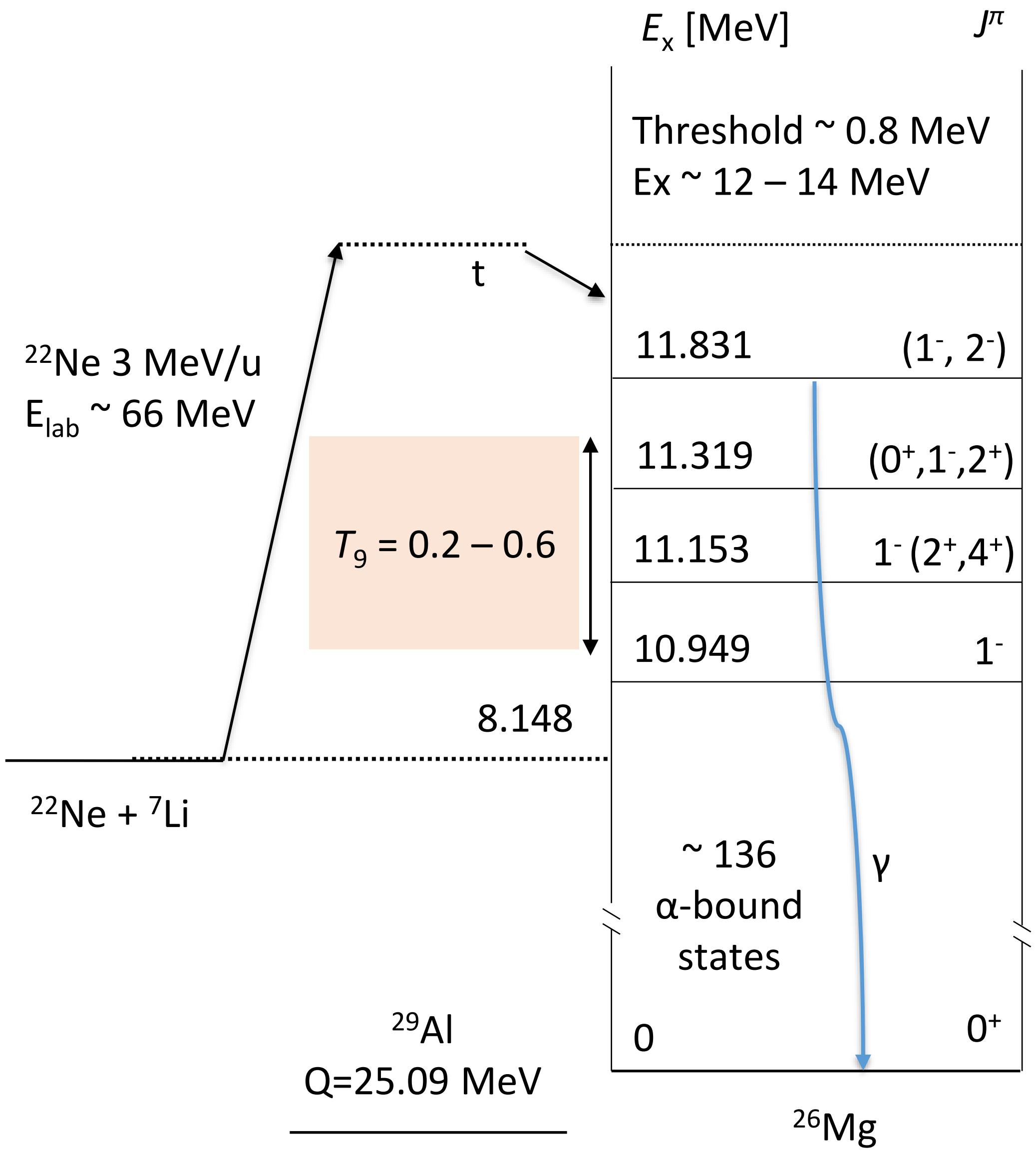
P. Adsley *et al.* PRC 103 (2021) 015805

Our TRIUMF “S2223” Experiment Goals

Study the ^{26}Mg compound using (^{7}Li,t) alpha-transfer:

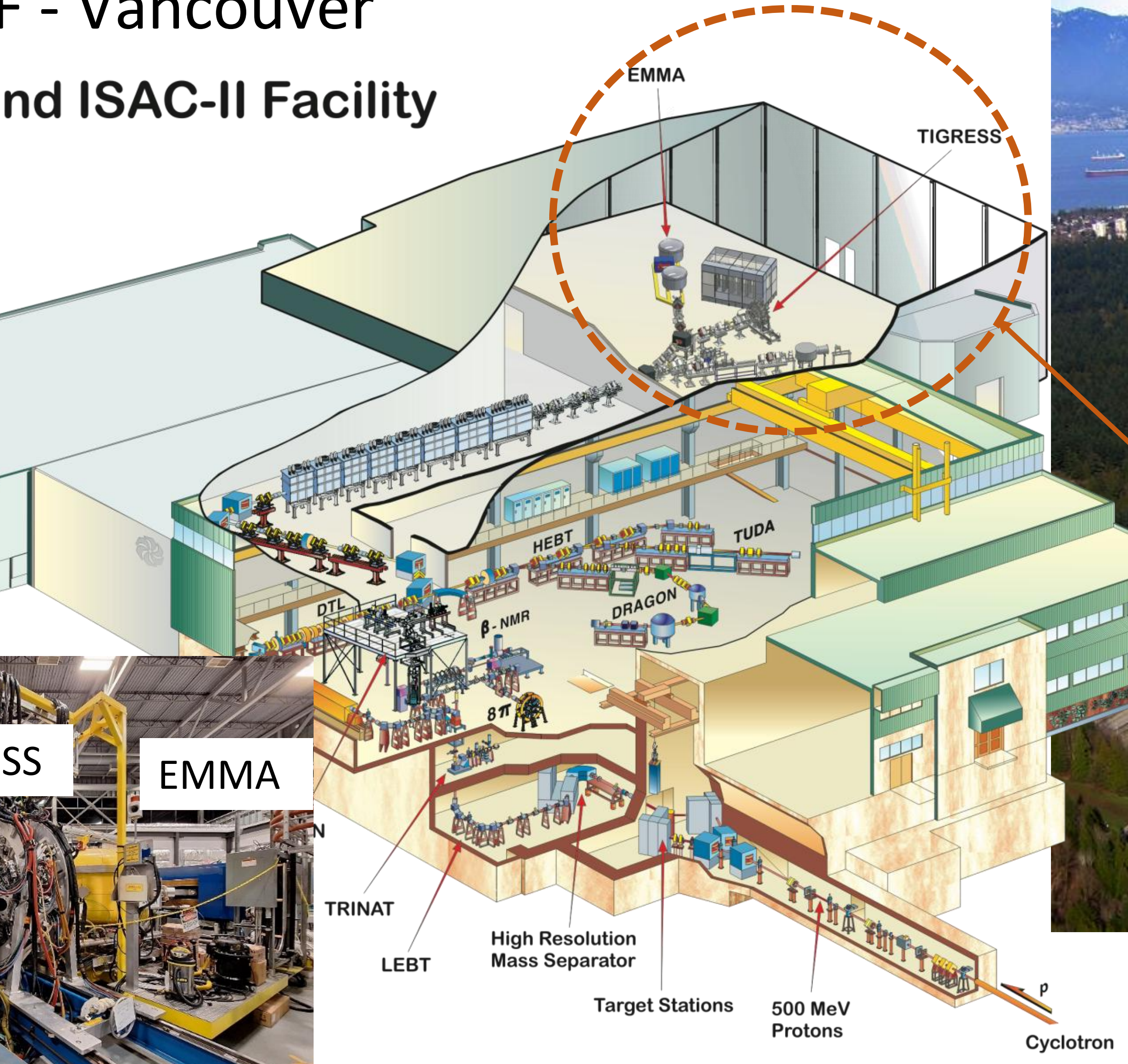
1. Determine **differential cross-sections**
2. Extract alpha-particle **partial widths**
3. Calculate ^{22}Ne(α,γ)^{26}Mg and ^{22}Ne(α,n)^{25}Mg **reaction rates**

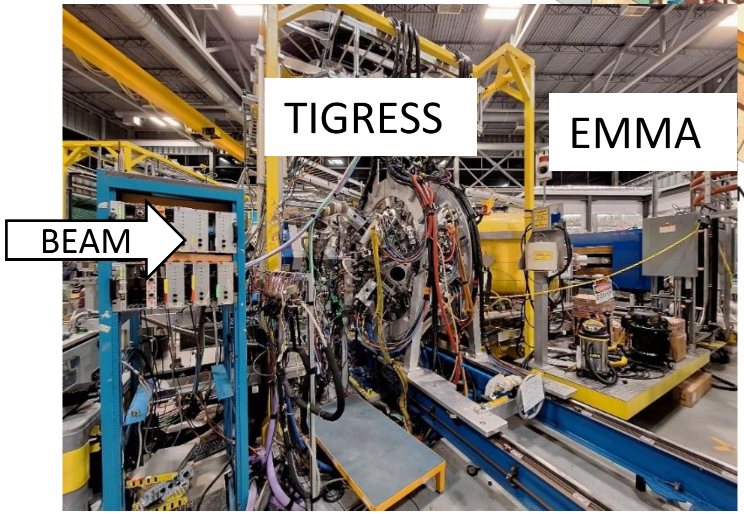
Model impact on *s*-process isotopic abundances



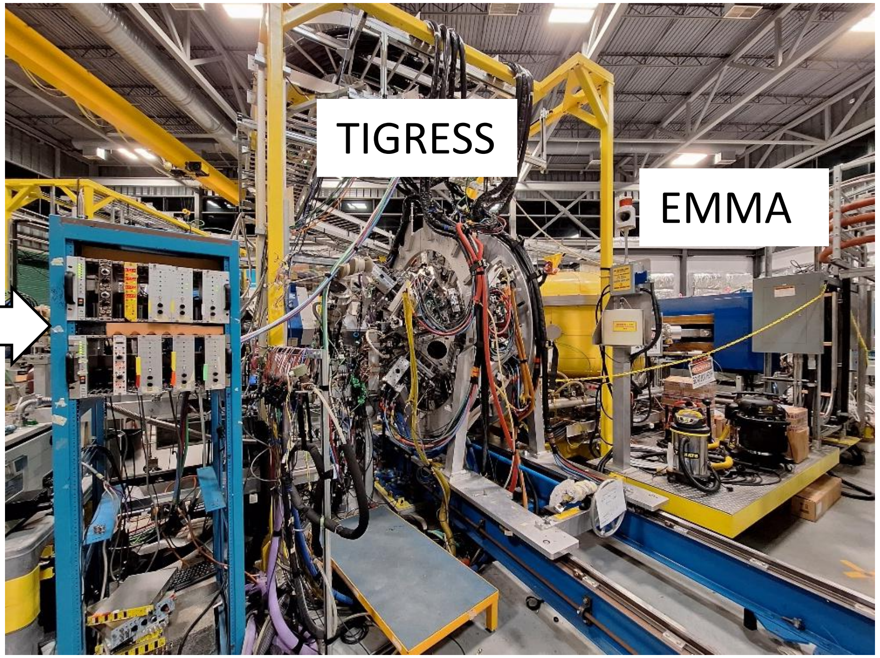
TRIUMF - Vancouver

ISAC-I and ISAC-II Facility



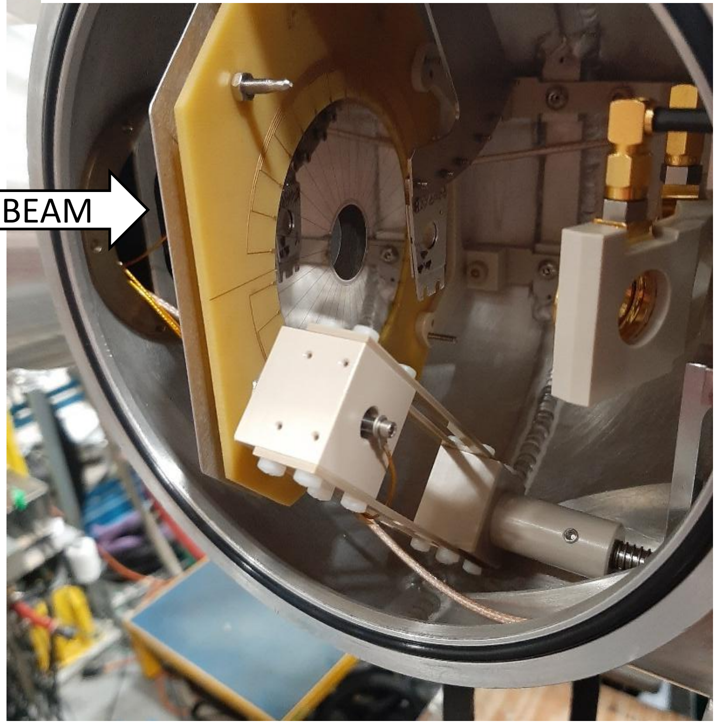


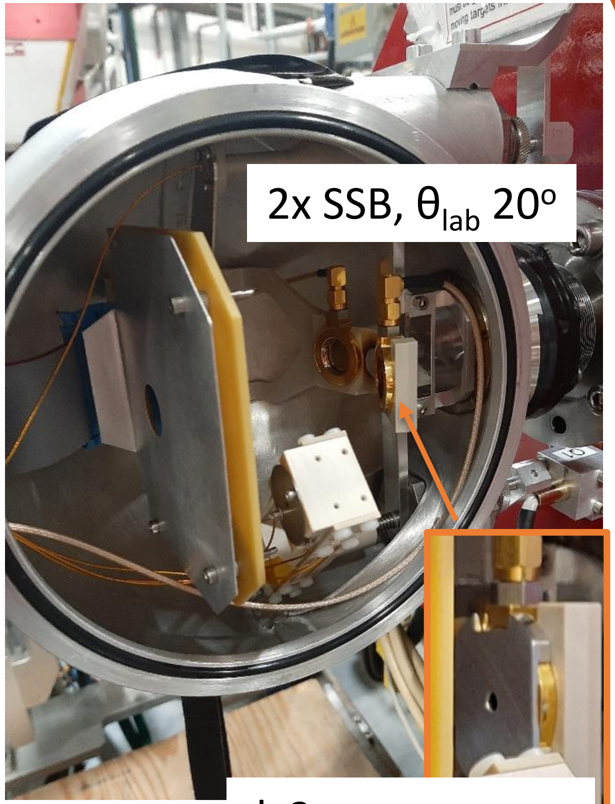
S2223 Experimental Setup



Reaction Chamber

Micron **S3 DSSD** 308μm thick
θ_{lab} ~ 130º – 160º



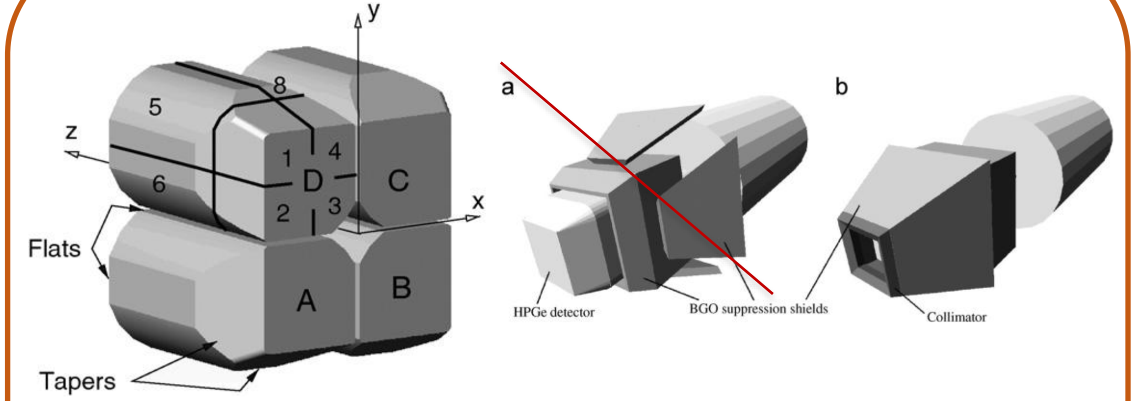


2x SSB, θ_{lab} 20º

ϕ 3mm aperture

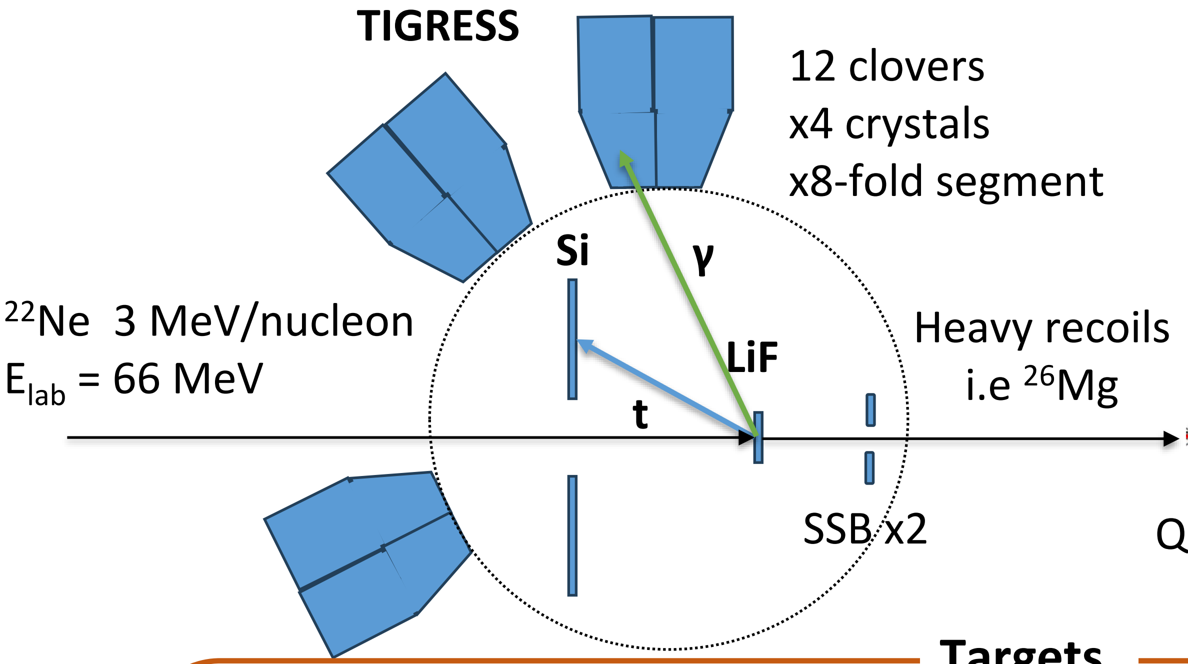
* S3 thick enough to stop < 9.5 MeV tritons
0.74μm Si Dead Layer

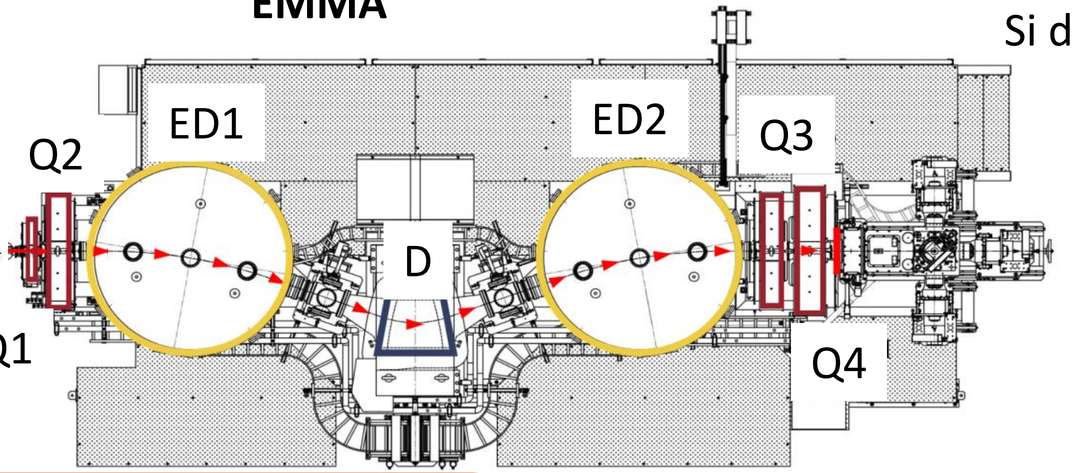
TIGRESS HPGe + BGO Suppressor



S2223 used b) Optimised peak-to-total
For 1 MeV γ-ray: 9.4% absolute, 61% peak-to-total

S2223 Experimental Setup - Sketch

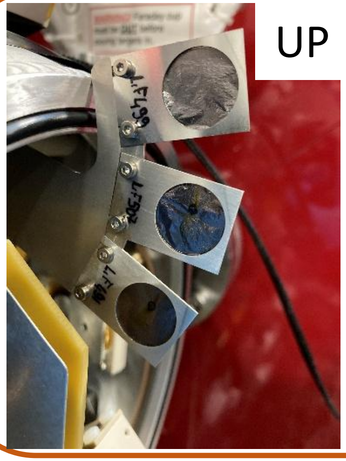




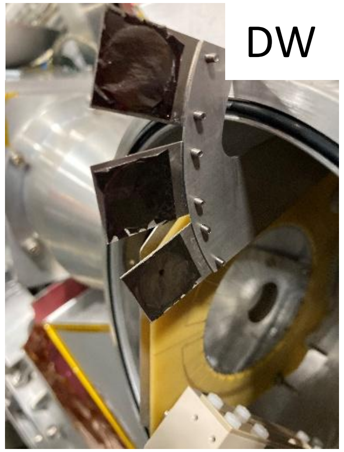
B. Davids *et al.* NIM A 930 (2019) 191

Targets

UP



DW

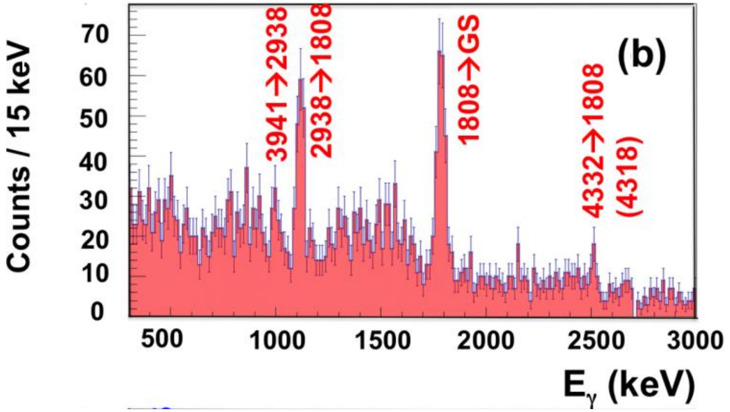


LiF Thickness		^{nat}C Backing Thickness [μg/cm^2]
[μg/cm^2]	[μm]	
507	1.92	44
491	1.86	45

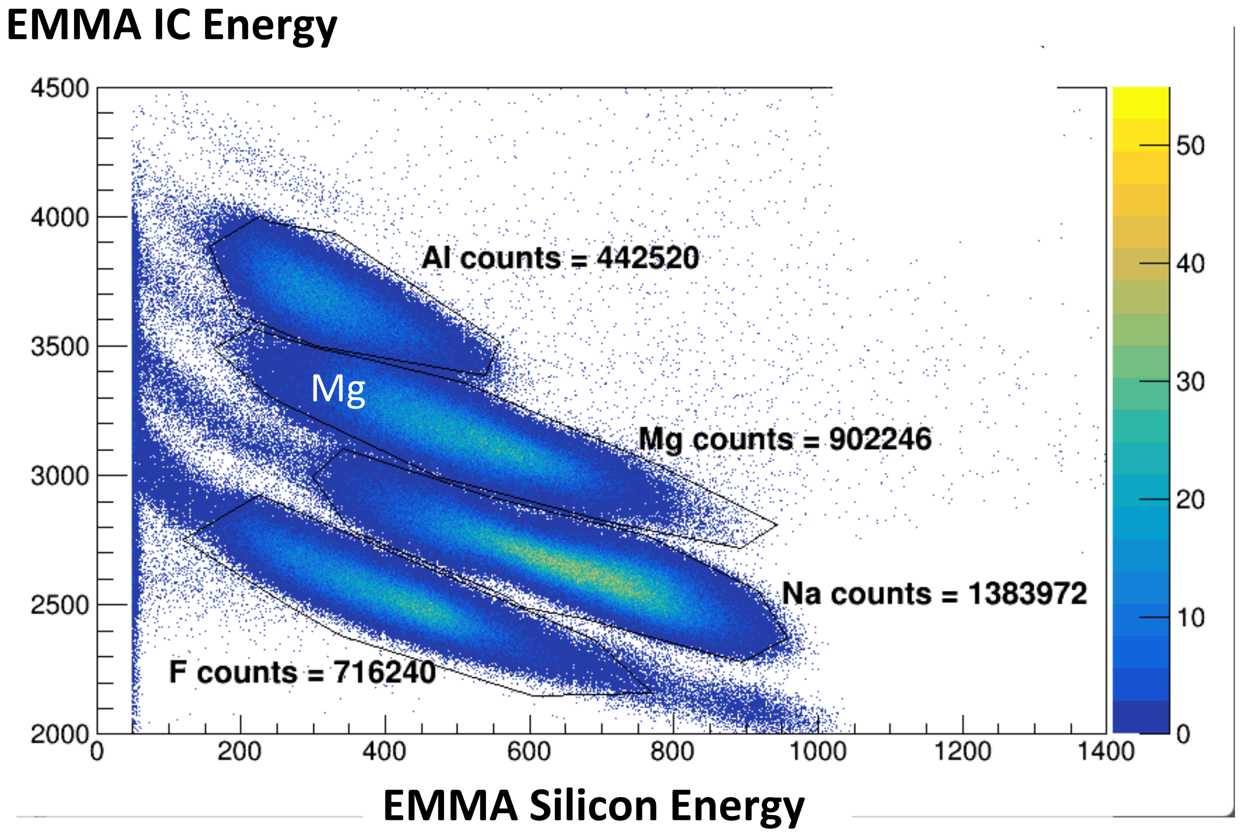
Provided by INFN-LNS

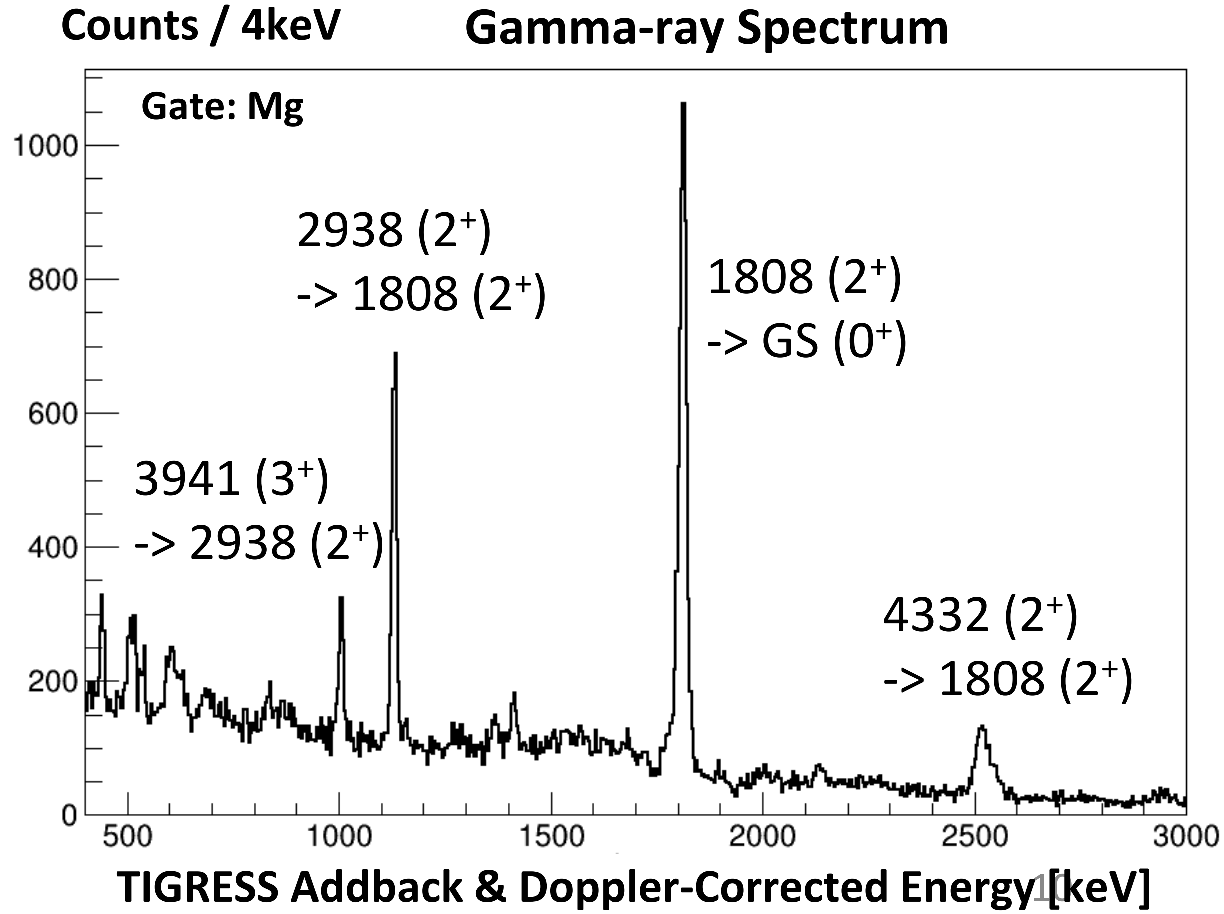
Data Analysis
Heavy Recoil ID

S. Ota *et al.* PRC 104 (2021) 055806 Fig 8b



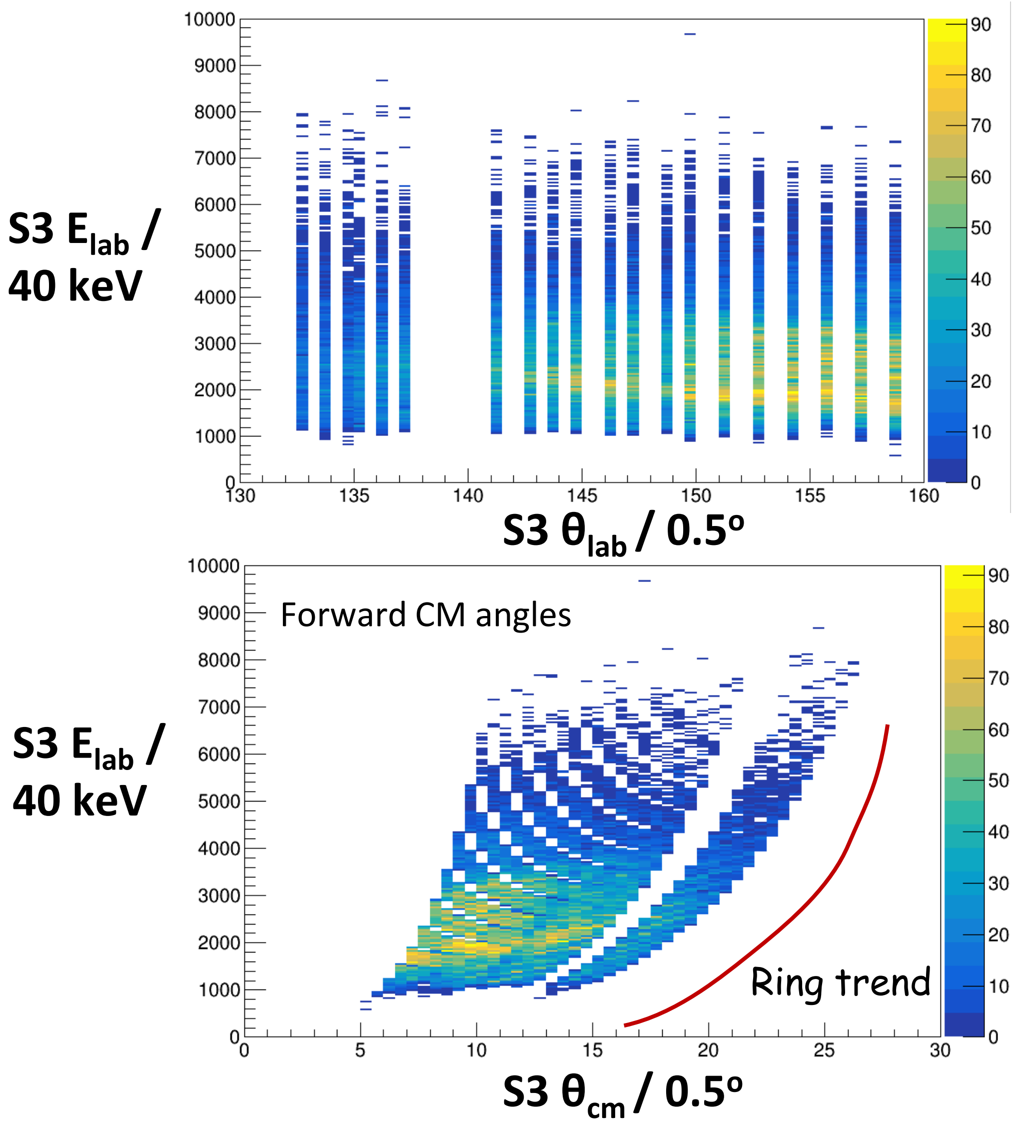
^{26}Mg Particle Identification



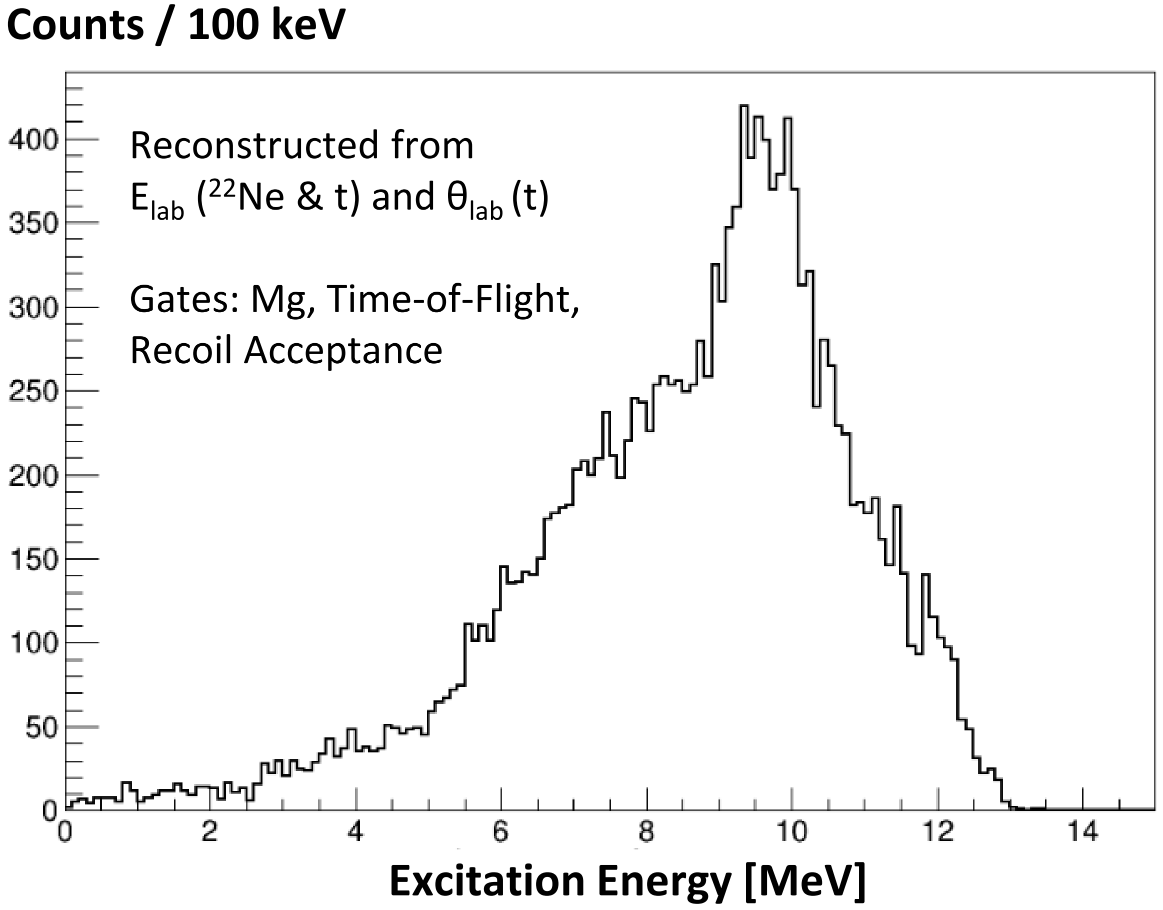


Data Analysis
^{26}Mg Excitation Energy Reconstruction

* Beam energy corrected for ½ LiF Thickness
* Triton energy corrected for S3 DL and ½ LiF Thickness



S3 E & θ_{lab}
-> Mg Exc E

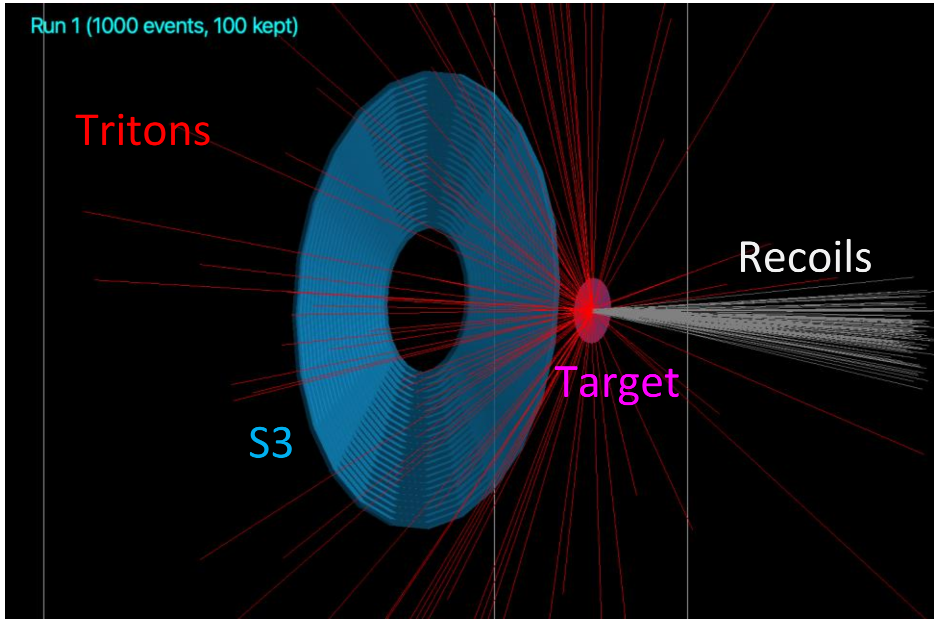


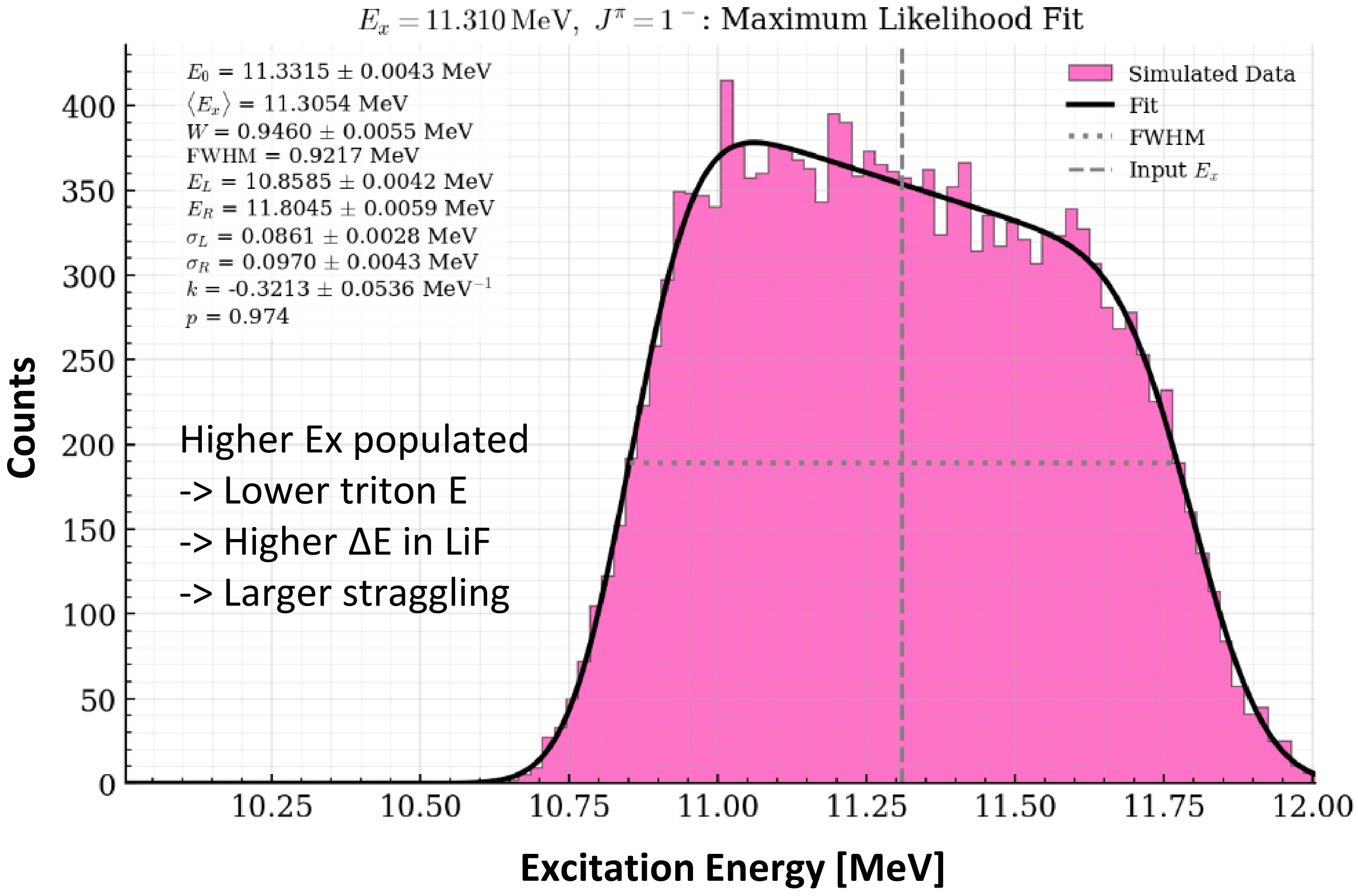
Courtesy: Mike Qiu, Simon Fraser University

Simulation: Target Thickness Effect

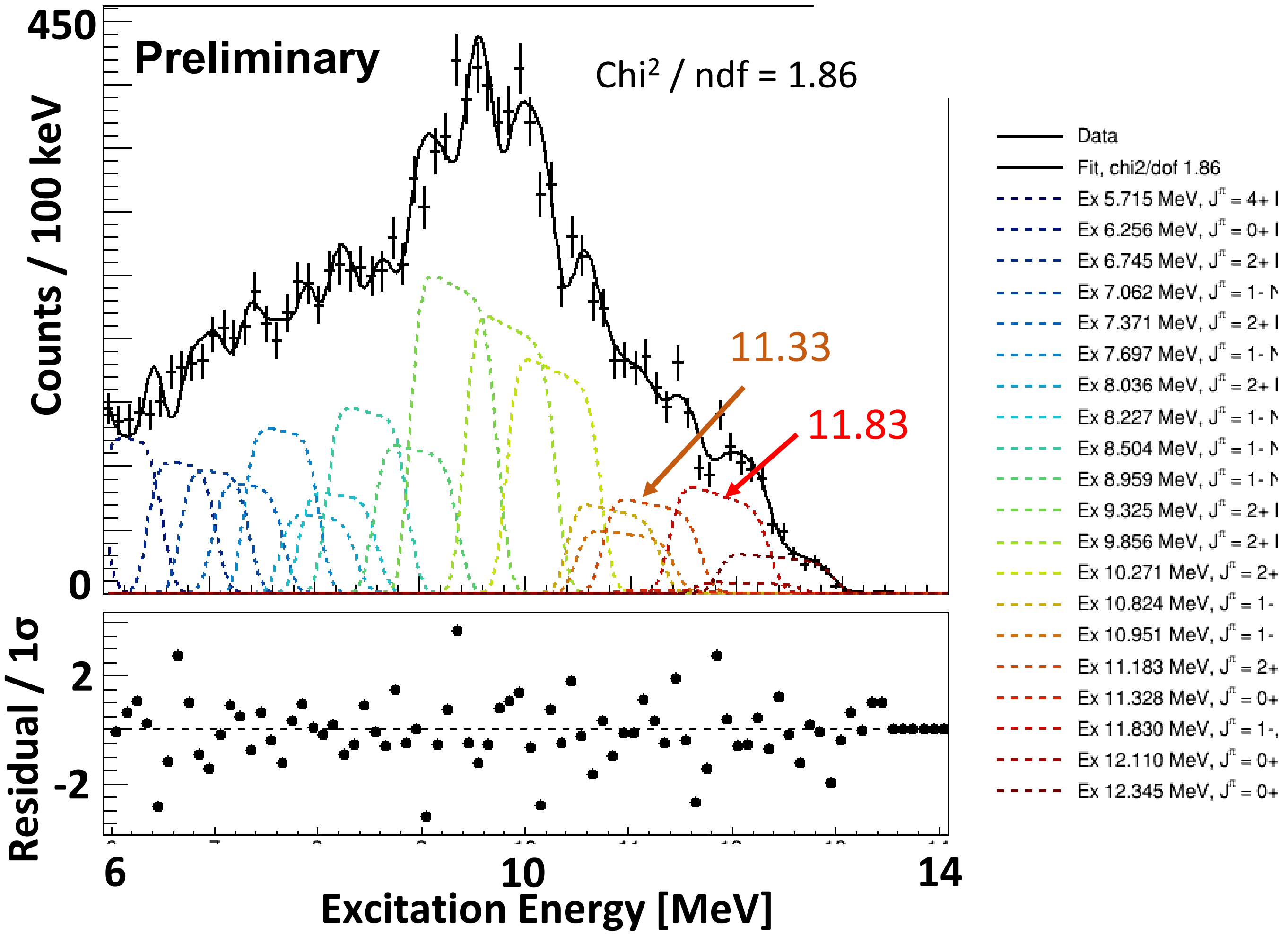
Geant4 MC

1. Simulate tritons emitted from select states throughout target
2. "Detect" energy & angle in S3 silicon
3. Reconstruct Ex -> "target-smearing" effect

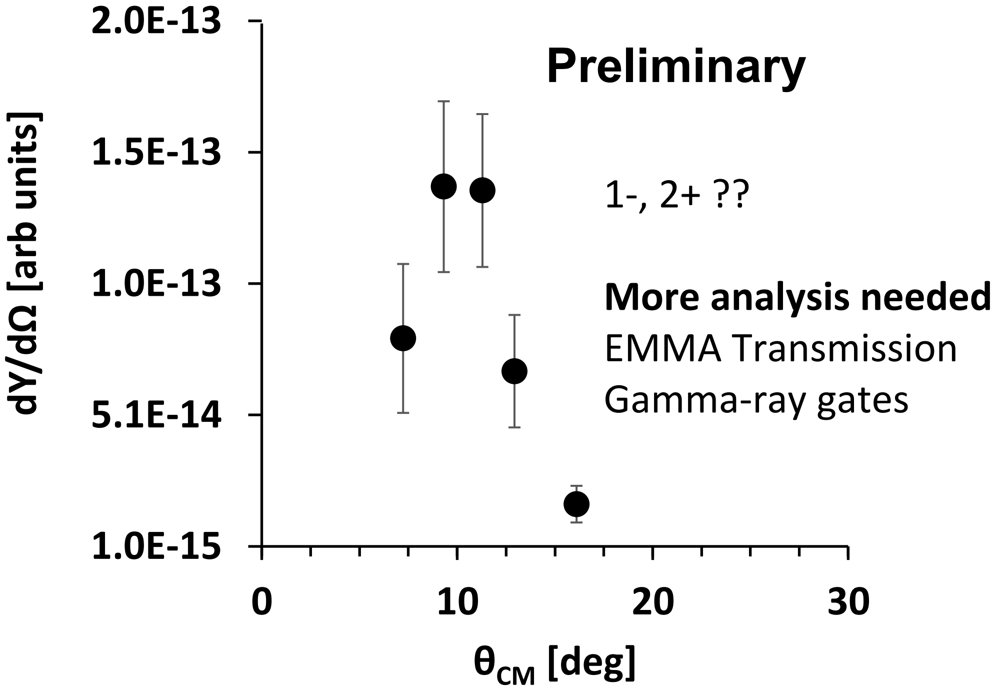


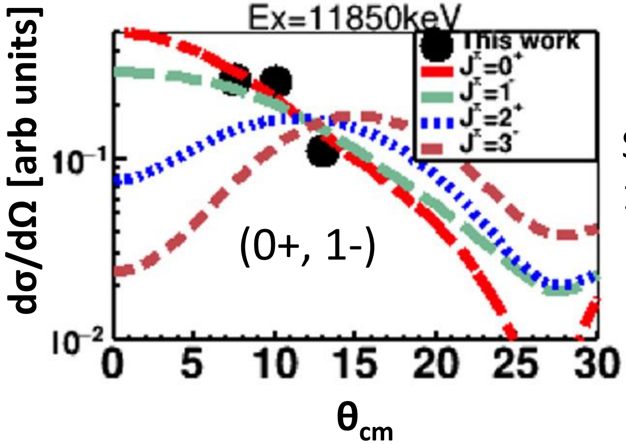


Data Analysis
Preliminary Ex Fits & Yields



Ex = 11.83 MeV





S. Ota *et al.* PRC 104 (2021) 055806

Conclusions & Future Work

- ✓ ^{22}Ne beam successfully bombarded LiF targets at ISAC-II
- ✓ ^{26}Mg states occupied via (^{7}Li,t) α-transfer
- ✓ Silicon detector response simulated
- ✓ Triple-coincidence gates applied between EMMA – S3 – TIGRESS
- ❑ State fits and cross sections in progress
  - Informed by simulation and EMMA transmission
- ❑ Final goal to extract α-width -> Astro-impact

Special thanks to Collaborators:

A. Best, D. Rapagnani, D. Mercogliano | University of Naples / INFN-Naples

P. Adsley, R. Amberger | Texas A&M University

A. M. Laird, C. Aa. Diget, G. Carter-Richardson | University of York

M. Qiu, B. Davids, G. Hackman | Simon Fraser University and TRIUMF

C. Angus, A.A. Avaa, S. Chakraborty, S. Dubé, J.R. Murias, M. MacRitchie, L. Mantle, S. Murillo-Morales, J. Williams, D. Yates, Y. Zhu | TRIUMF

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and Horizon 2020 No 101008324 (ChETEC-INFRA)

Low-Energy Underground Measurement of $^{22}Ne(\alpha,n)^{26}Mg$

David Rapagnani (Thomas Chillery)

Nuclear Physics in Astrophysics XII – Cluj-Napoca, Romania

07/09/2026

The SHADES Project

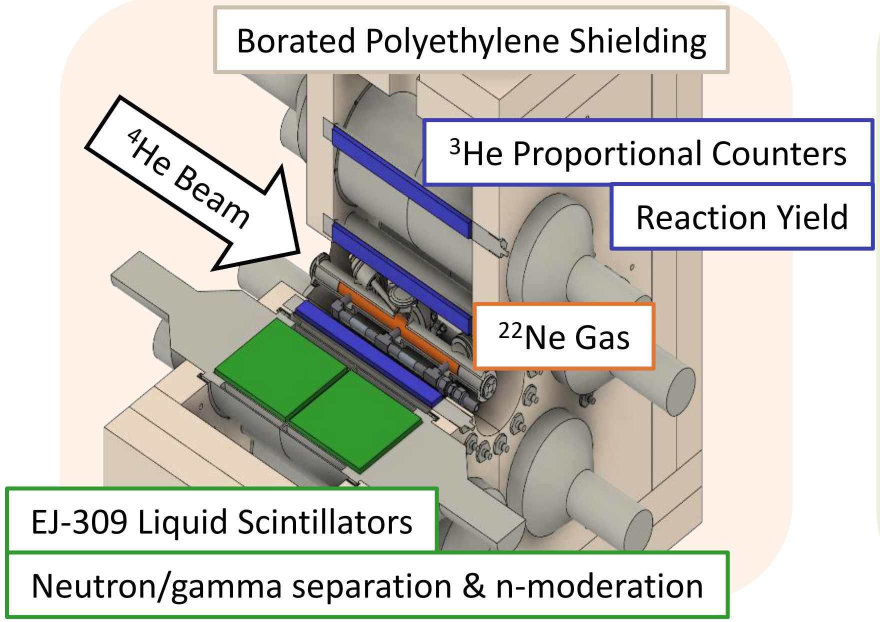
Scintillator-^{3}**He** **A**rray for **D**eep-underground **E**xperiments on the ***S***-process

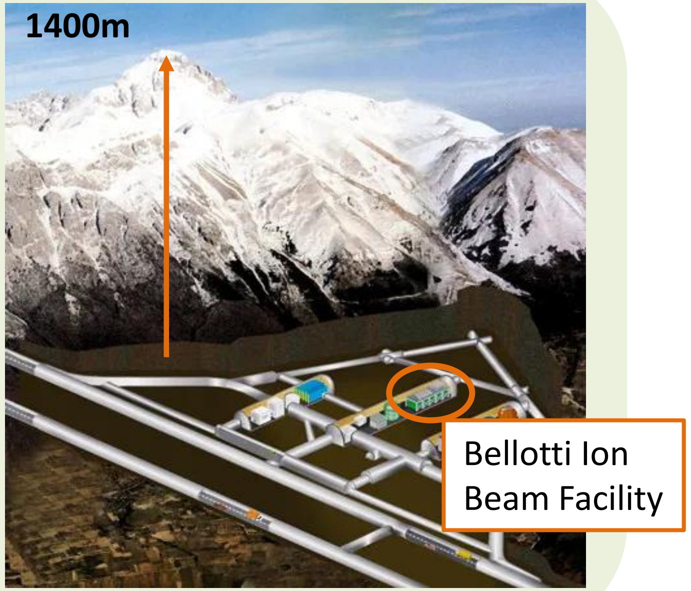
- Low natural background
- BPE shielding
- n-detector array
- Enriched ^{22}Ne gas

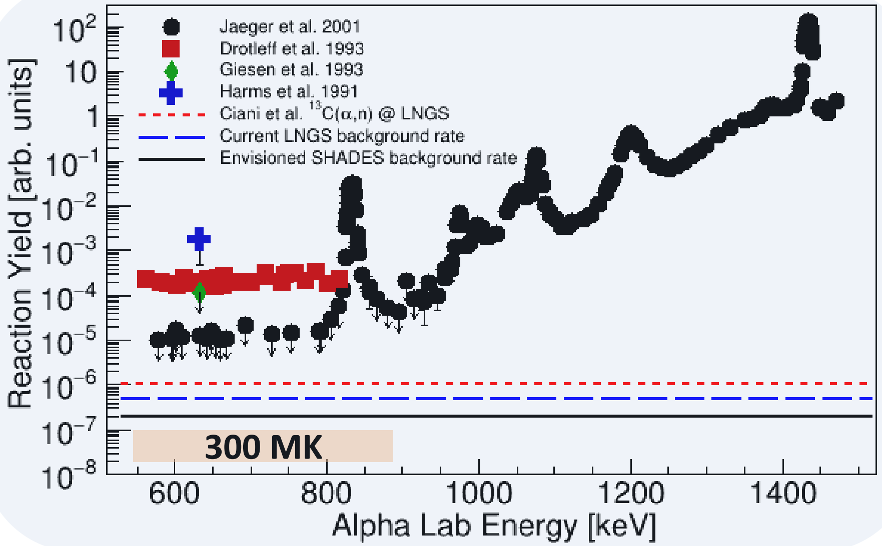
- Goals:

(E_{thresh} = 561 keV)

1. Measure ^{22}Ne(α,n)^{25}Mg across $\boldsymbol{E_\alpha}$ **= 600 – 886 keV** (E_{cm} = 507 – 750 keV)
2. Remeasure $\boldsymbol{E_\alpha}$ **= 832 keV** resonance, search for $\boldsymbol{E_\alpha}$ **= 635 keV** resonance

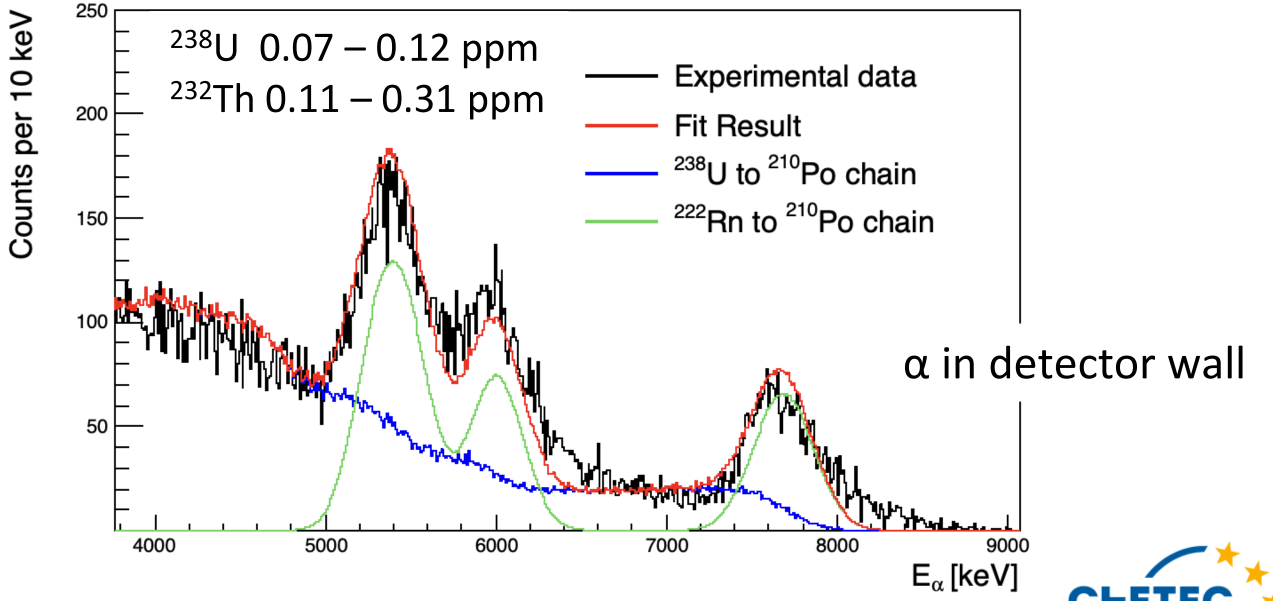


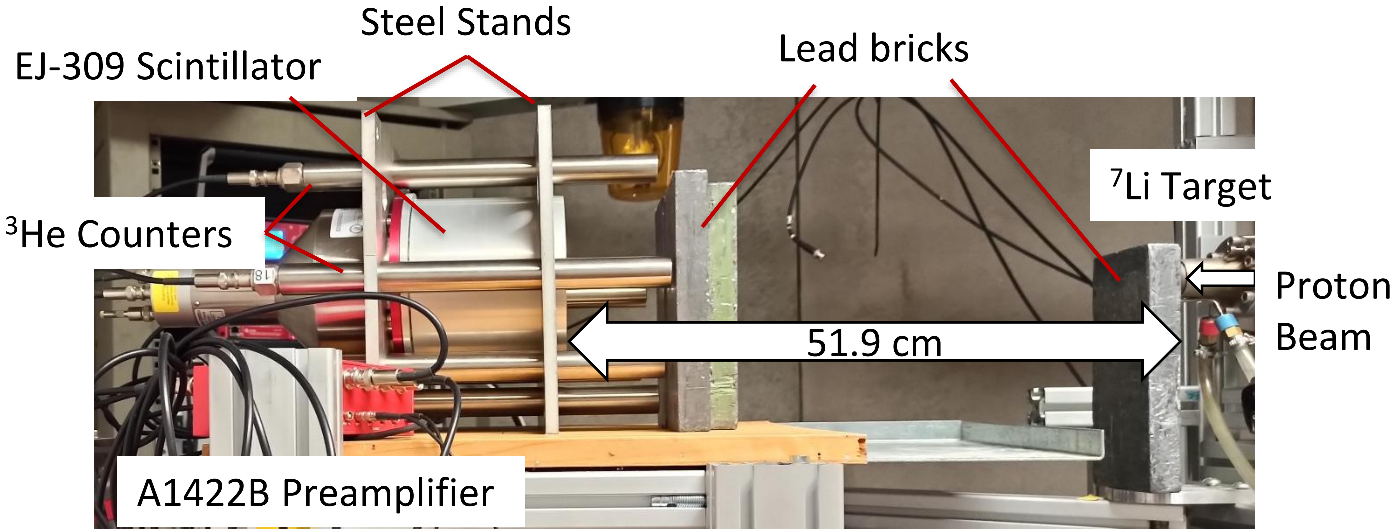


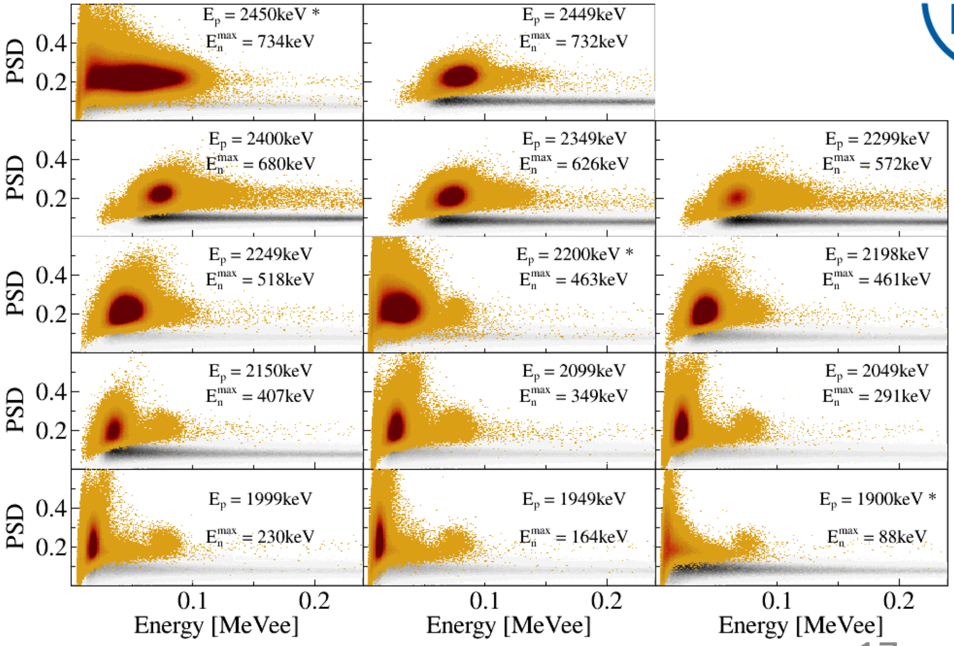


Preparation

- 1st target setup and characterization @ CIRCE (Italy)
- Scintillator intrinsic background
  Paper: C. Ananna *et al.* NIM A 1060 (2024) 169036
- Detector Characterisation at FRANZ (Germany)
  Paper: T. Chillery *et al.* JPG 52 (2025) 075202







Efficiency Measurements at Debrecen – April 2025

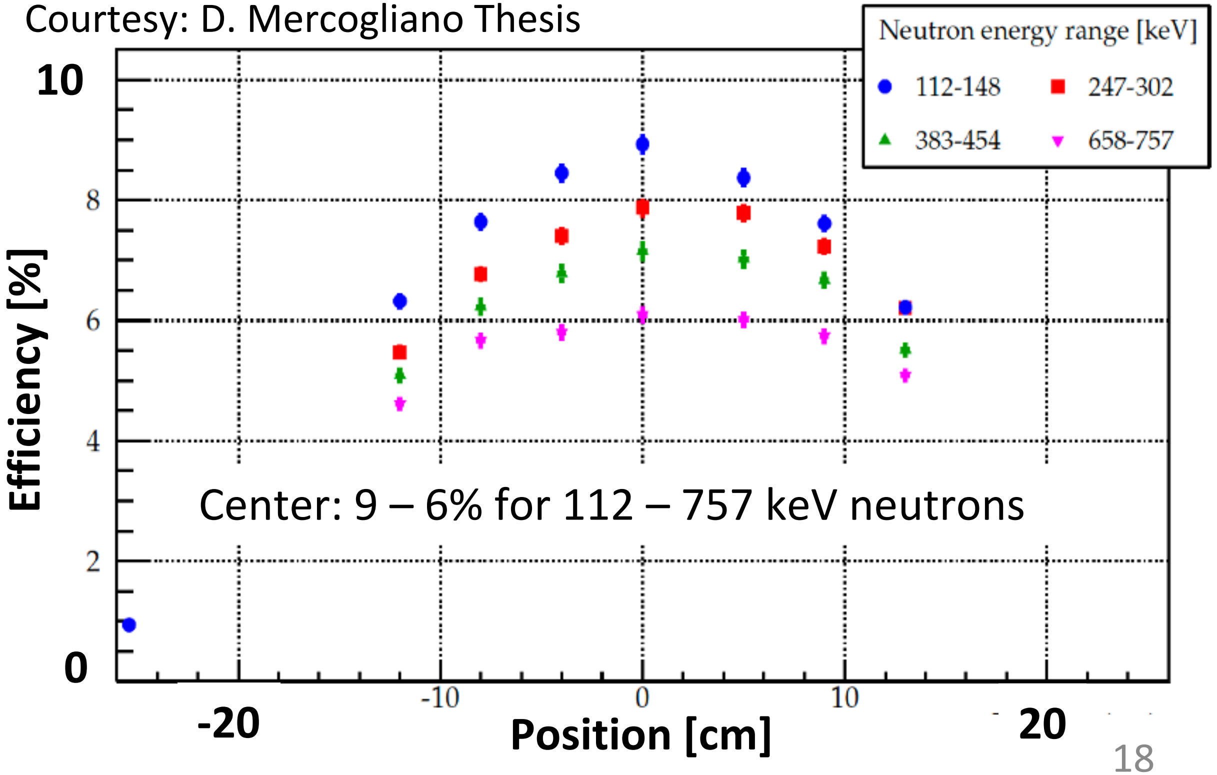
- Van de Graaf Laboratory of Institute for Nuclear Research ATOMKI
- Using the well-known ^{51}**V(p,n)**^{51}**Cr** reaction, Q = -1534.92 (24) keV

$$\eta(E,x) = \frac{N_n}{N_R}$$

$N_n \longrightarrow$ Irradiation measurement

$N_R \longrightarrow$ Activation measurement

Courtesy: D. Mercogliano Thesis

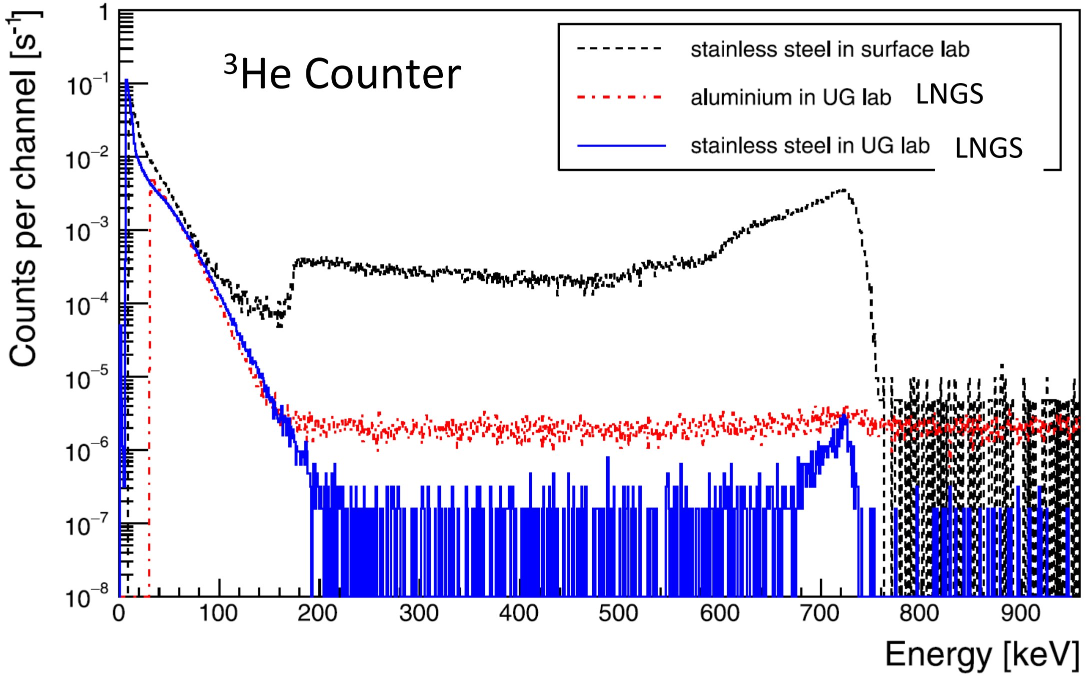


Going Deep Underground: INFN-IBF (LNGS)

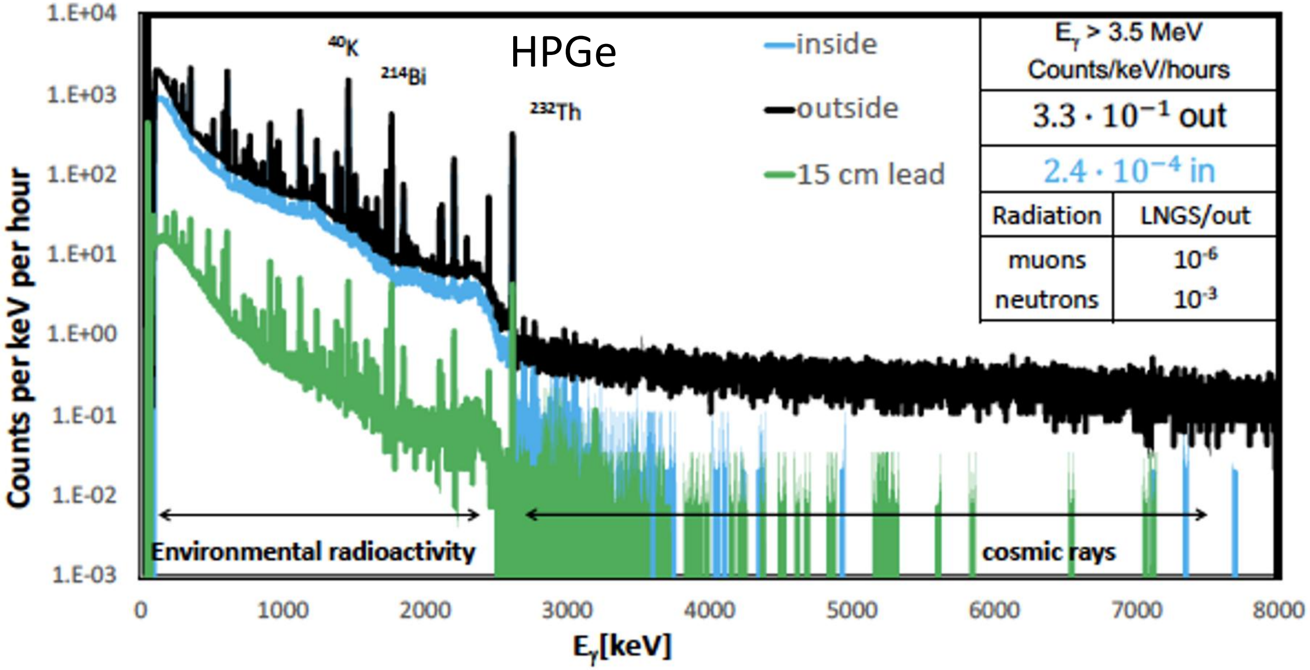
See talks by R. Depalo on Tuesday and F. Ferraro on Friday!

- Atmospheric neutrons reduced by rock layer -> X 1000
- 18 ^{3}He counters: 1 neutron / hour
- Add passive shielding and pulse-shape discrimination (PSD)

- Eγ > 3 MeV: Cosmic muons absorbed by rock -> X 1000
- Eγ < 3 MeV: Further reduce by lead, copper, radon box



L. Csedreki *et al.* NIMA 994 (2021) 165081

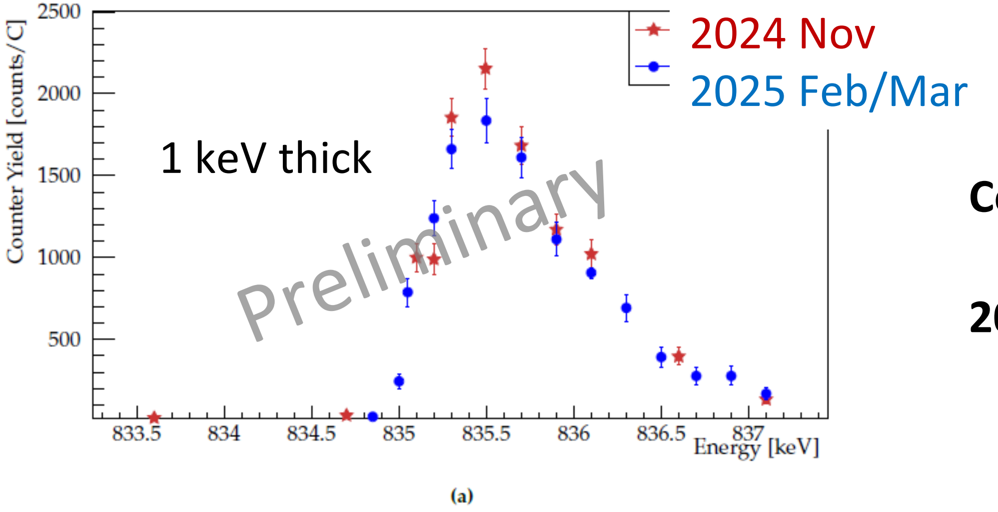


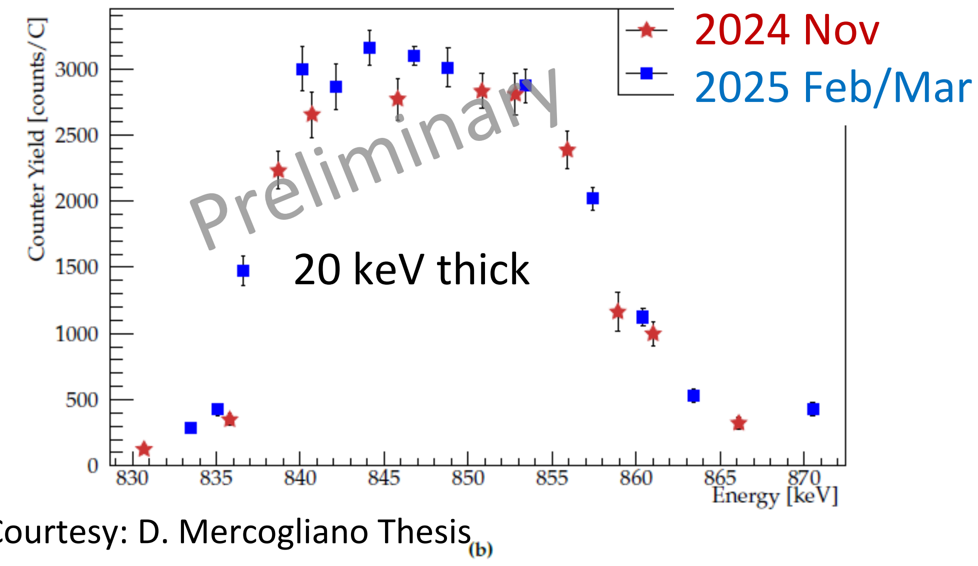
E_γ > 3.5 MeV Counts/keV/hours	
$3.3 \cdot 10^{-1}$ out	
$2.4 \cdot 10^{-4}$ in	
Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

A. Boeltzig *et al.* JPG 45 (2018) 023503

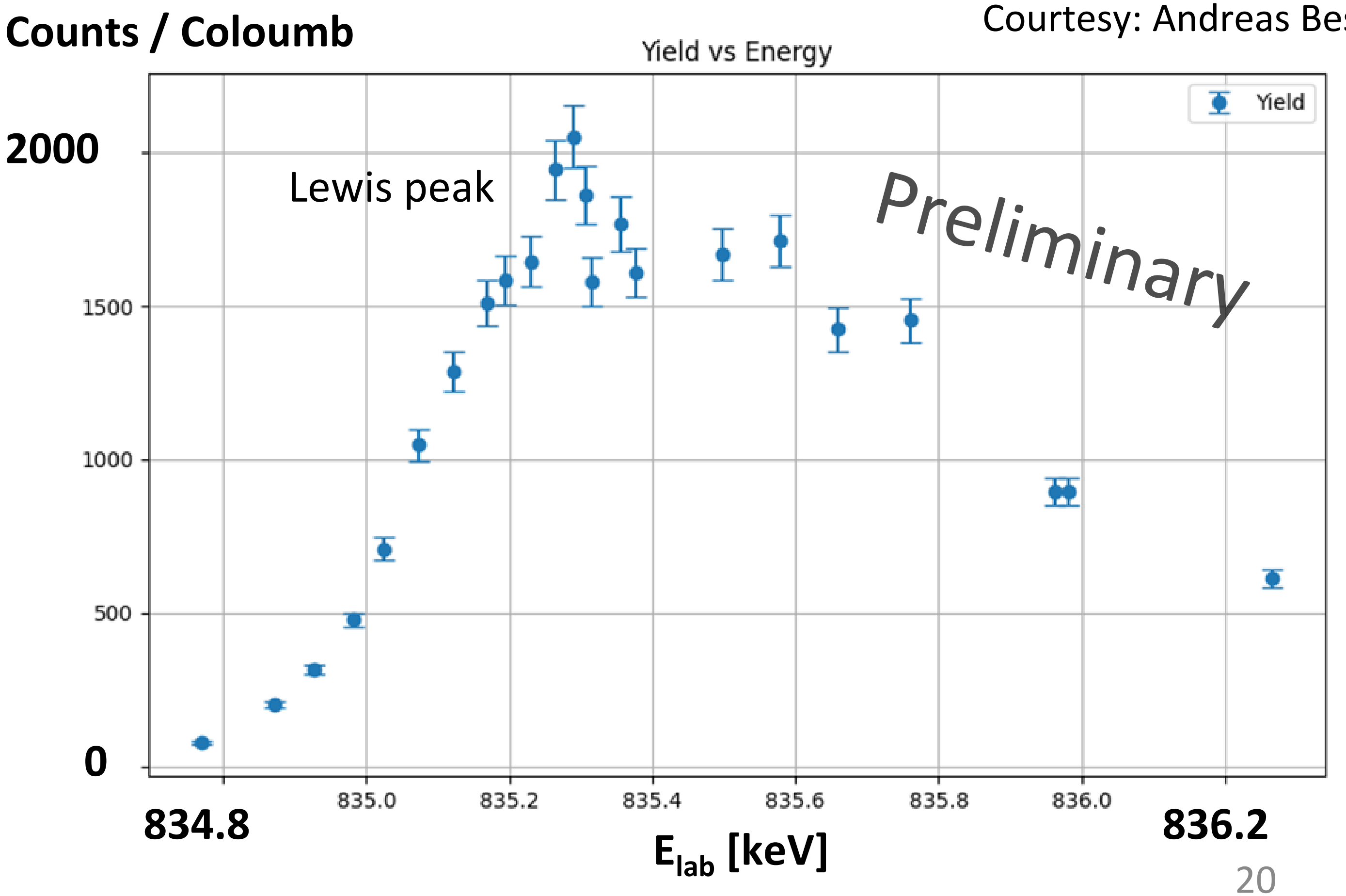
SHADES Measurements @ LNGS

- 835 keV resonance measured
- Target scans: 0.5 – 35 keV
- Analysis ongoing -> **strength** and **width** extraction



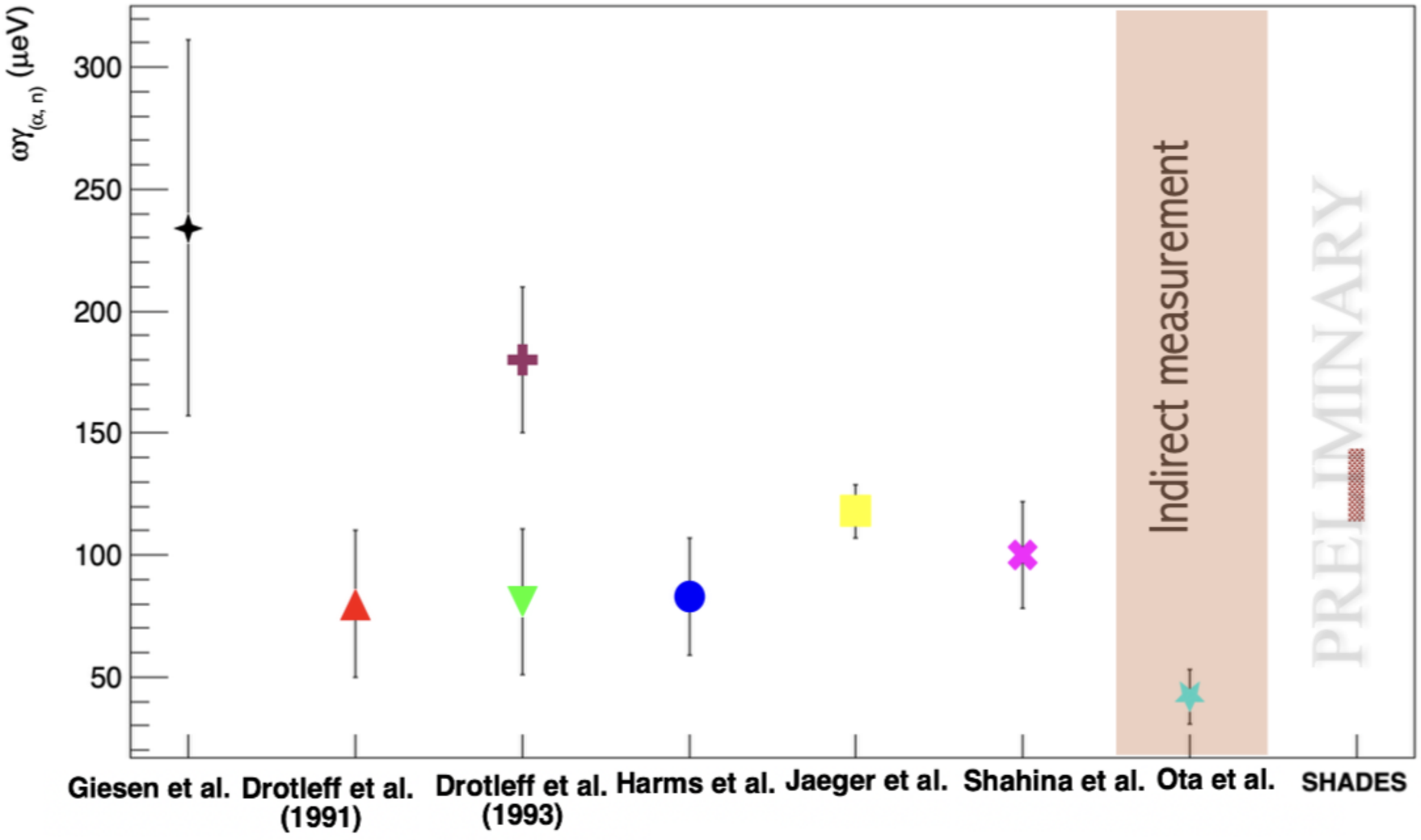


Courtesy: D. Mercogliano Thesis



Courtesy: Andreas Best

The 835keV strength



- **Close** to literature average
- **Improved Ex and Γ** in progress
- **Low energy** (< 700 keV) runs under analysis

Summary

- ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg progressively studied, need more direct data
- Pushing directly into Gamow energy range: **SHADES** @ LNGS
- First ^{22}Ne(α,n)^{25}Mg low-energy resonance search in **20 years**
- Expecting improved results of the **835 keV** resonance, low energy in progress
- Bringing together all the experiments should give a big step towards understanding these reactions in the *s*-process

Friendly competition:
CASPAR & JUNA

Special thanks to the LUNA Collaboration!

F. Ferraro, *R. Gesuè, M. Junker, D. Basak, G. Saturno | Laboratori Nazionali del Gran Sasso, INFN, Italy/*GSSI, Italy

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M. Lugaro | Konkoly Observatory, Hungarian Academy of Sciences, Hungary

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M. Campostrini, V. Rigato | INFN Laboratori Nazionali di Legnaro, Italy

R. Depalo, G. Gosta, A. Guglielmetti | Università degli Studi di Milano and INFN, Italy

A. Best, D. Dell'Aquila, A. Di Leva, G. Imbriani, D. Mercogliano*, S.Montella, D. Rapagnani | Università degli Studi di Napoli "Federico II" and INFN, Italy

R. Biasissi, C. Broggini, A. Caciolli, R. Menegazzo, D. Piatti, J. Skowronski, S. Turkat | Università degli Studi di Padova and INFN, Italy

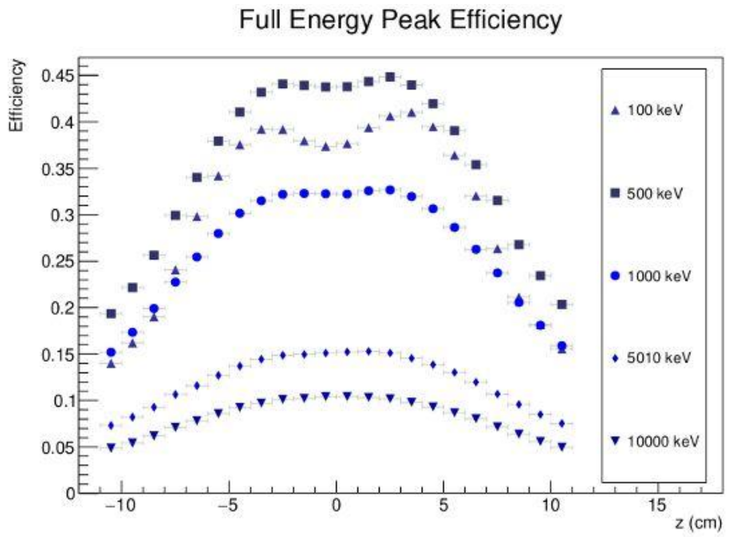
A. Formicola, C. Gustavino, M. Vagnoni | INFN Roma, Italy

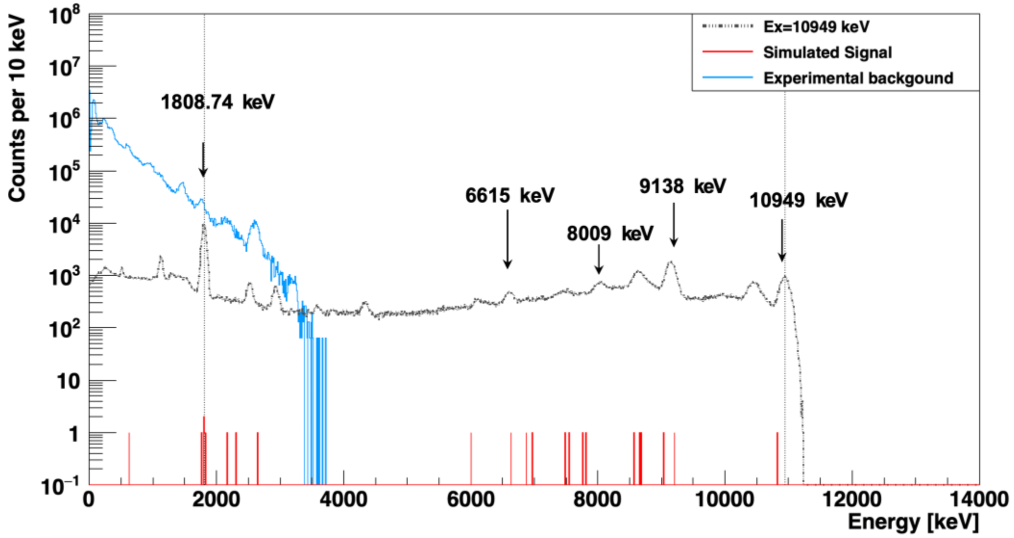
O. Straniero, U. Battino | Osservatorio Astronomico di Collurania, and INFN LNGS, Italy

F. Cavanna, P. Colombetti, G. Gervino, R. Sariyal | Università di Torino and INFN, Italy

Extra Slides

Future: EASγ Experiment, $^{22}Ne(\alpha,\gamma)^{26}Mg$ @ INFN-IBF (LNGS)





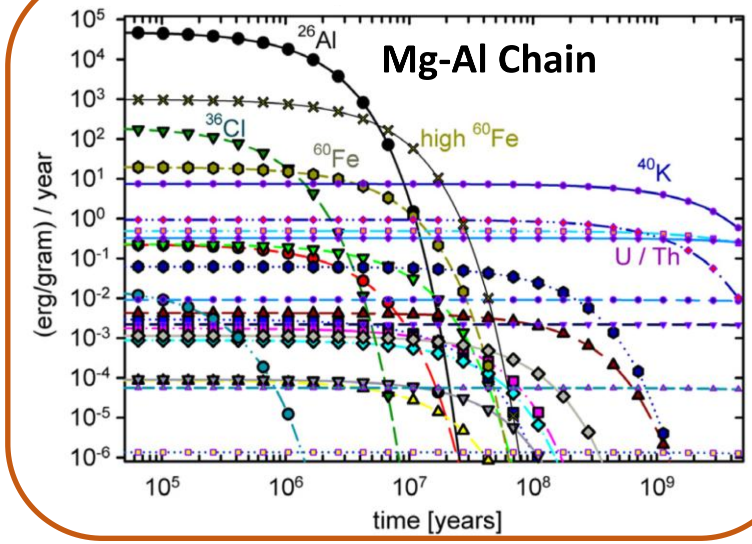
- Goal: cross section of $^{22}Ne(\alpha,\gamma)$ channel in Gamow region
- Use SHADES gas target, DAQ, etc…
- NaI Detector Array
- Characterised last February in CIRCE (Italy)
- First beam 7 weeks ago, more to come…

Background: Formation of Solar System and Mg Observations

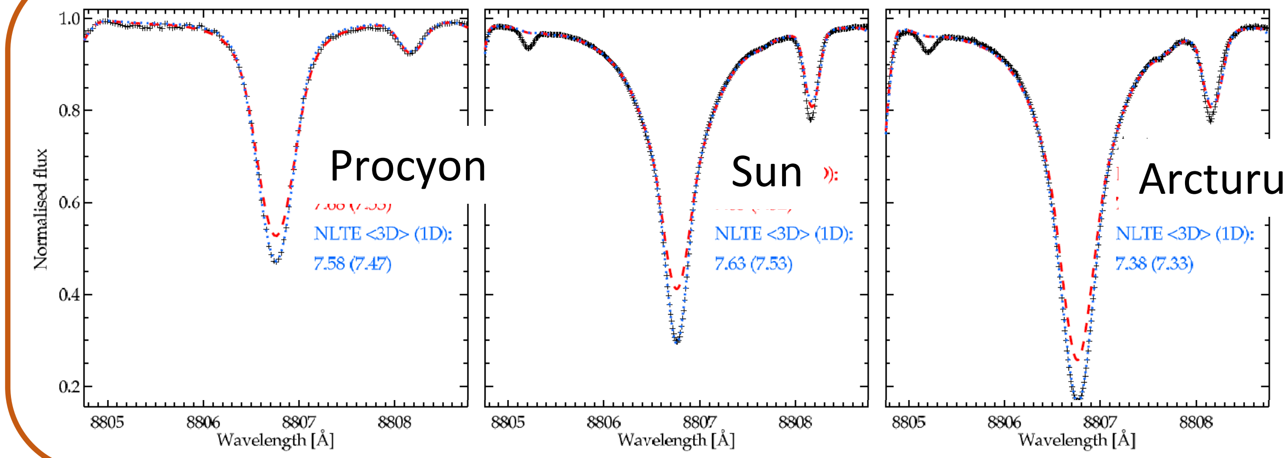
M. Lugaro, U. Ott, Á. Kereszturi, PPNP 102 (2018) 1 - 47

Y. Osorio *et al.* A&A 579 (2015) A53

Solar System Heat Sources



Mg Observed in Stellar Atmospheres



nature communications **(2026) 17:2902**

Article

https://doi.org/10.1038/s41467-026-69610-x

A Stellar magnesium to silicon ratio in the atmosphere of an exoplanet

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Check for updates

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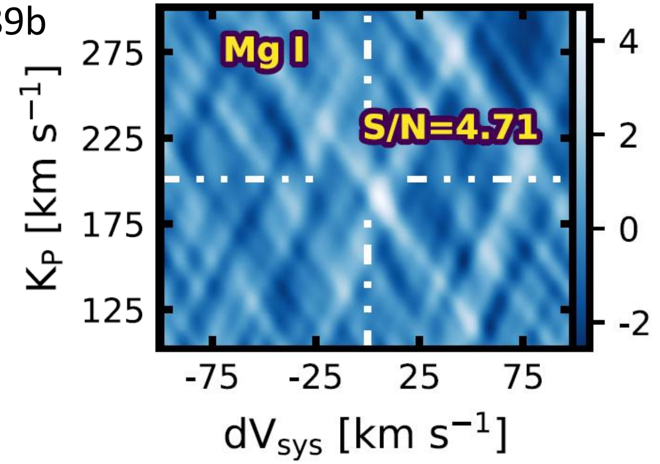
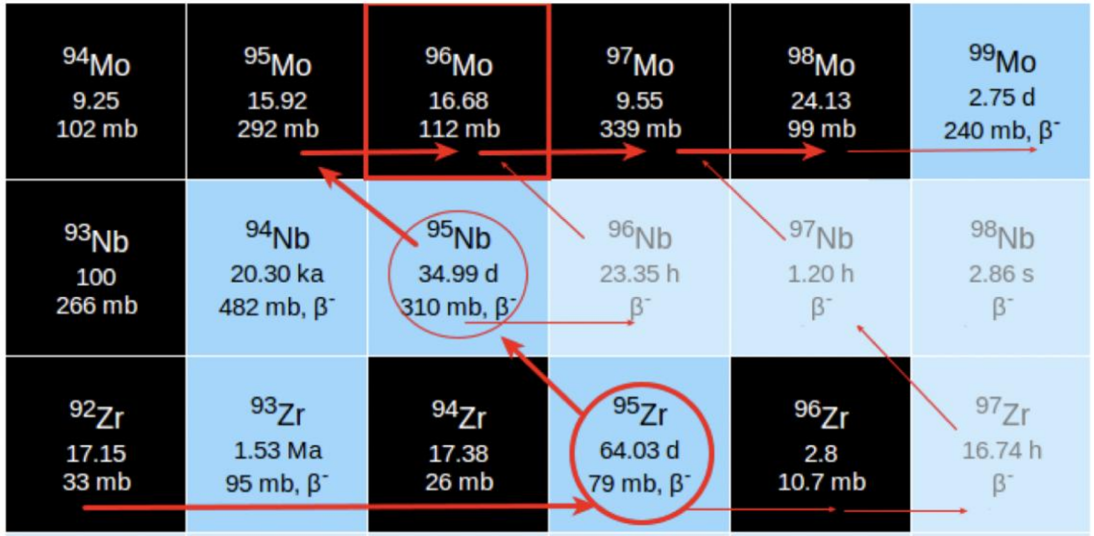
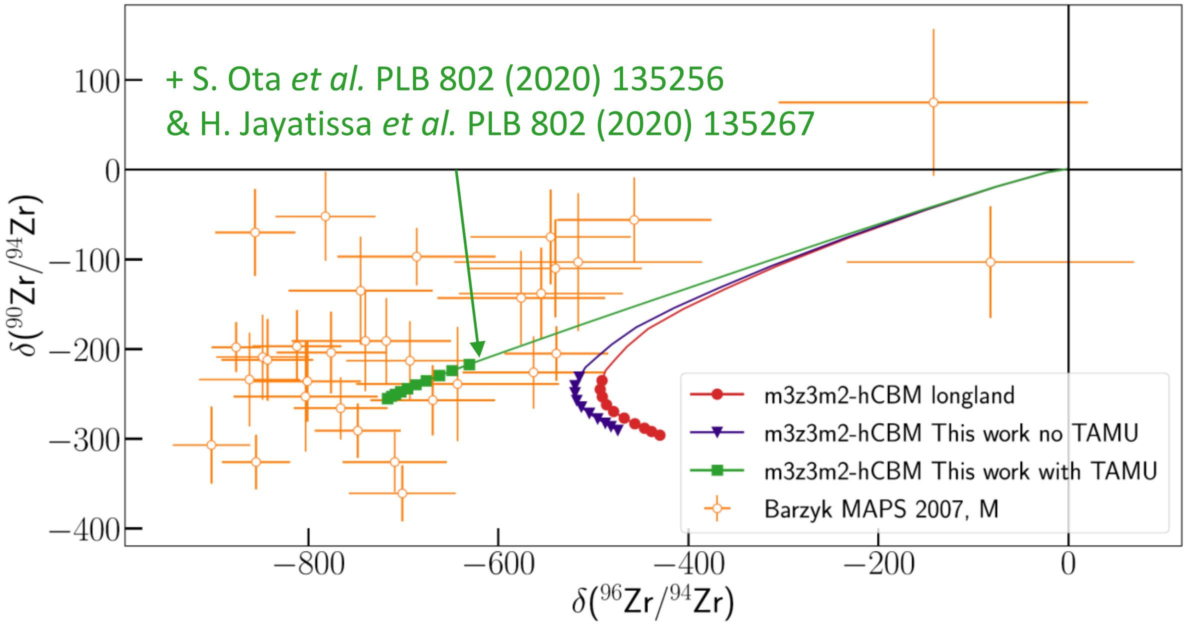
WASP-189b



$^{22}Ne(\alpha,[n,\gamma])^{25,26}Mg$

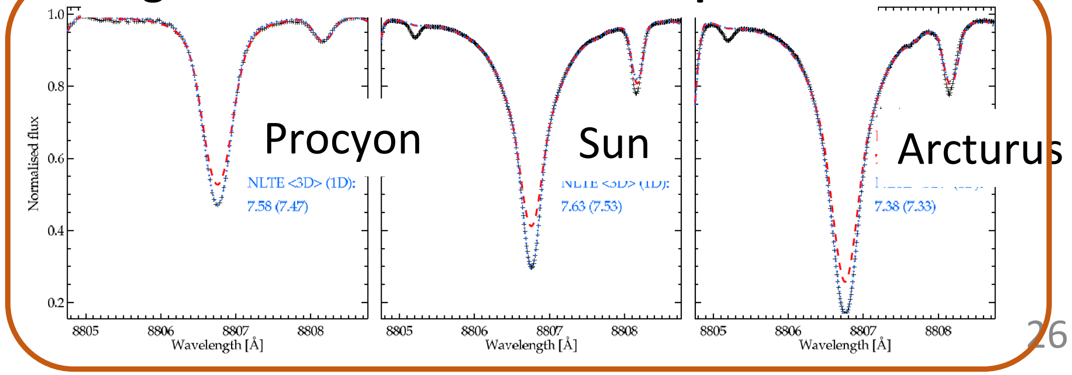


P. Adsley *et al.* PRC 103 (2021) 015805



Y. Osorio *et al.* A&A 579 (2015) A53

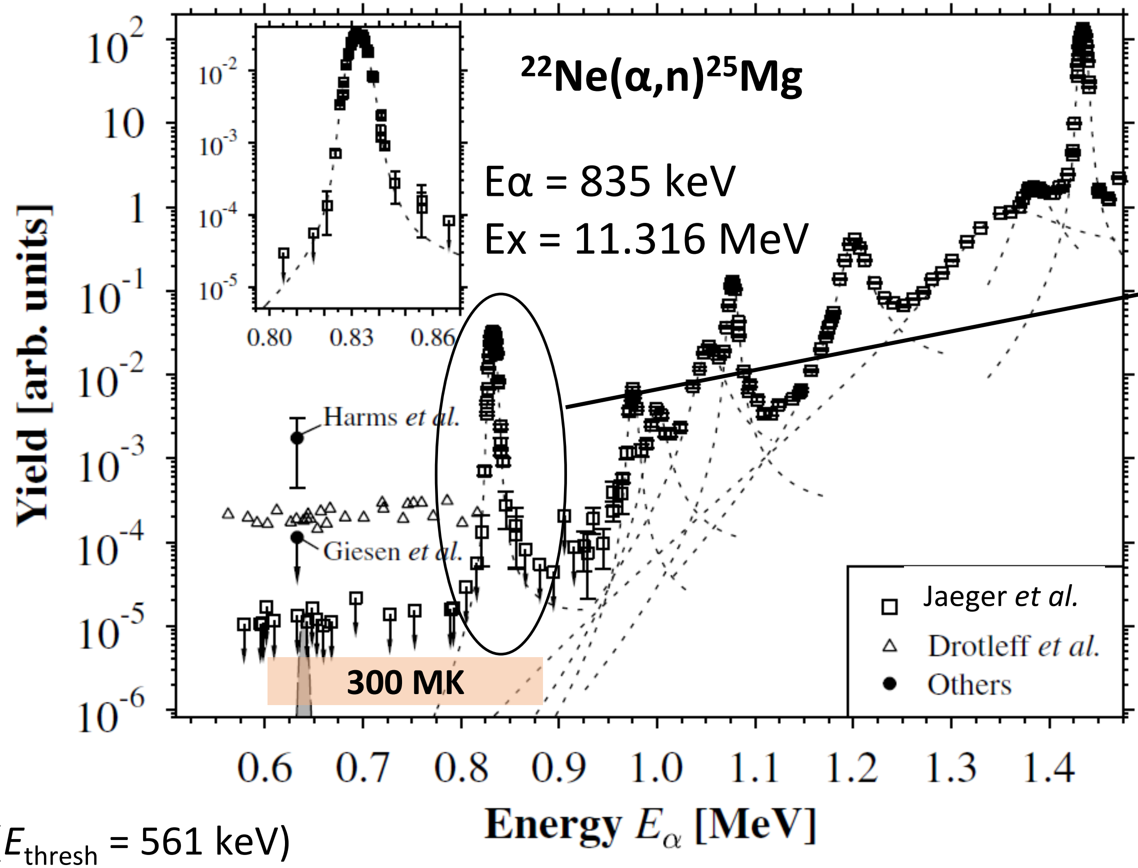
Mg Observed in Stellar Atmospheres



- (α,n) channel -> late-stages of main *s*-process (AGB)
- Resonance info -> branching point population
- Mg observations in stellar atmospheres -> (α,n) vs (α,γ)
- Both channels important

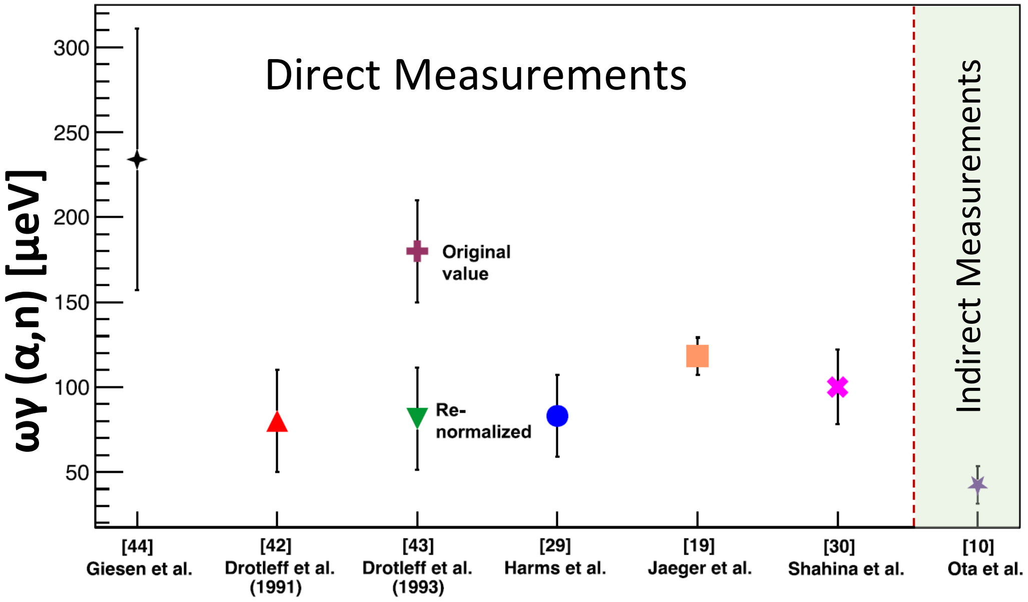
State-of-art: Resonances above n-threshold

M. Jaeger *et al.* PRL 87 (2001) 202501



(E_{thresh} = 561 keV)

A. Best *et al.* EPJA 61 (2025) 61-99



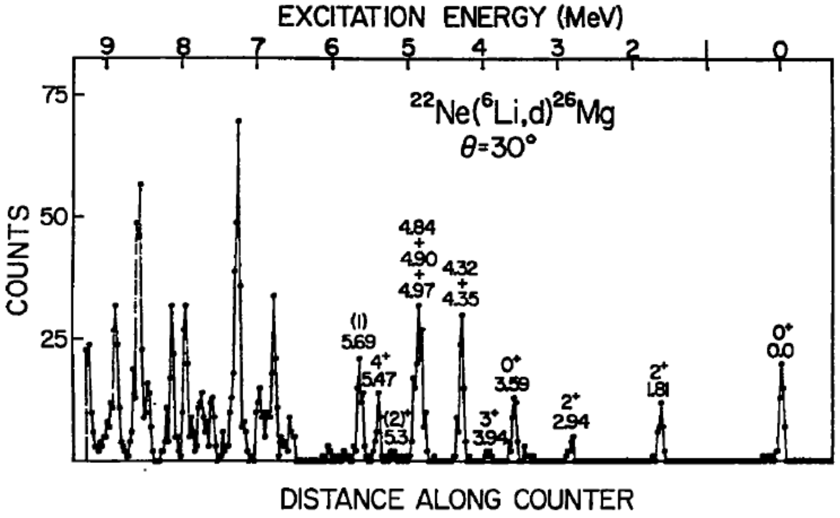
Lower-energy resonances, lack information

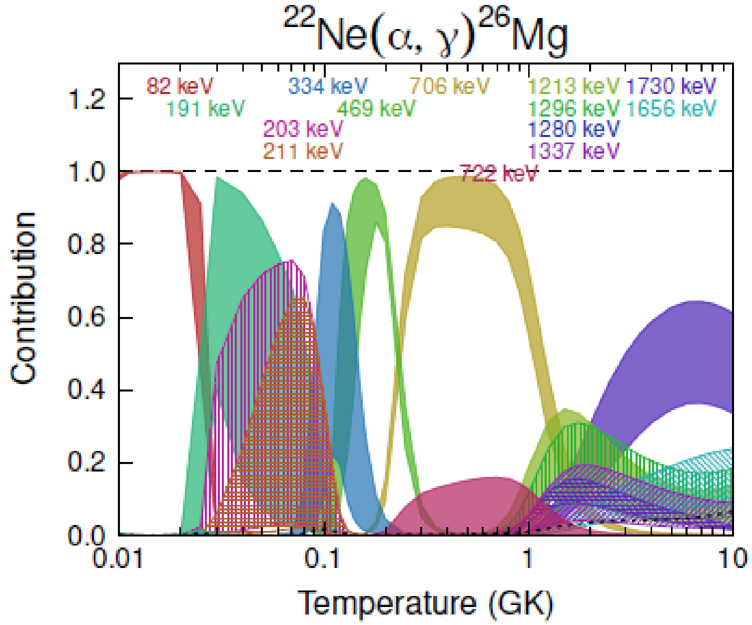
Ex [MeV]	Eα [keV]	Jπ	Γ_n [keV]
11.328	843 ?	?	0.171
11.280	786	3-	1.810
11.274	779	2+	0.410
11.169	**656**	**3-**	**1.940**
11.163	649	2+	5.310
11.112	589	2+	2.095

C. Massimi *et al.* PLB 768 (2017) 1-6

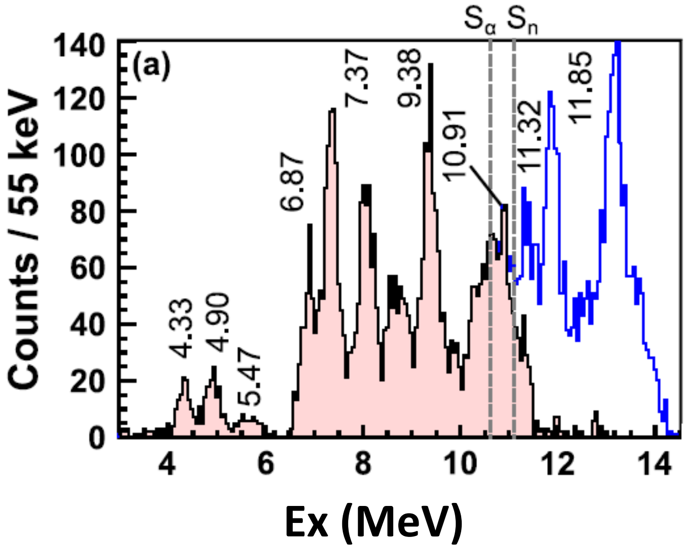
State-of-art
Indirect Measurements

N. Anantaraman *et al.*
Nucl. Phys. A (1977)
$^{22}Ne(^{6}Li,d)^{26}Mg$

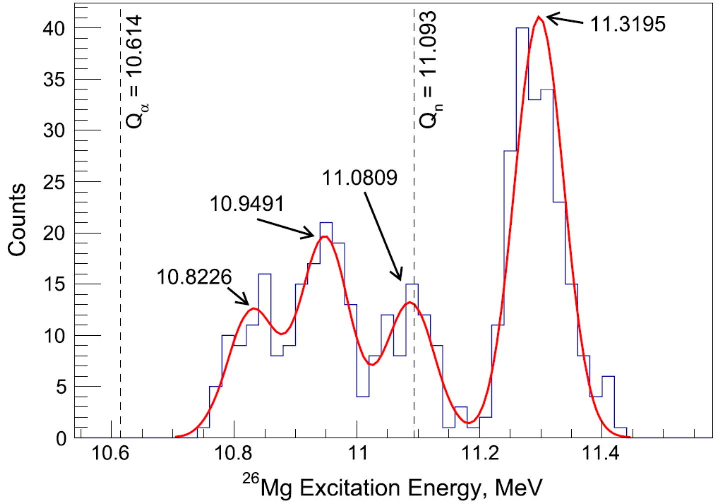




S. Ota *et al.* PLB (2020)
$^{22}Ne(^{6}Li,d)^{26}Mg$



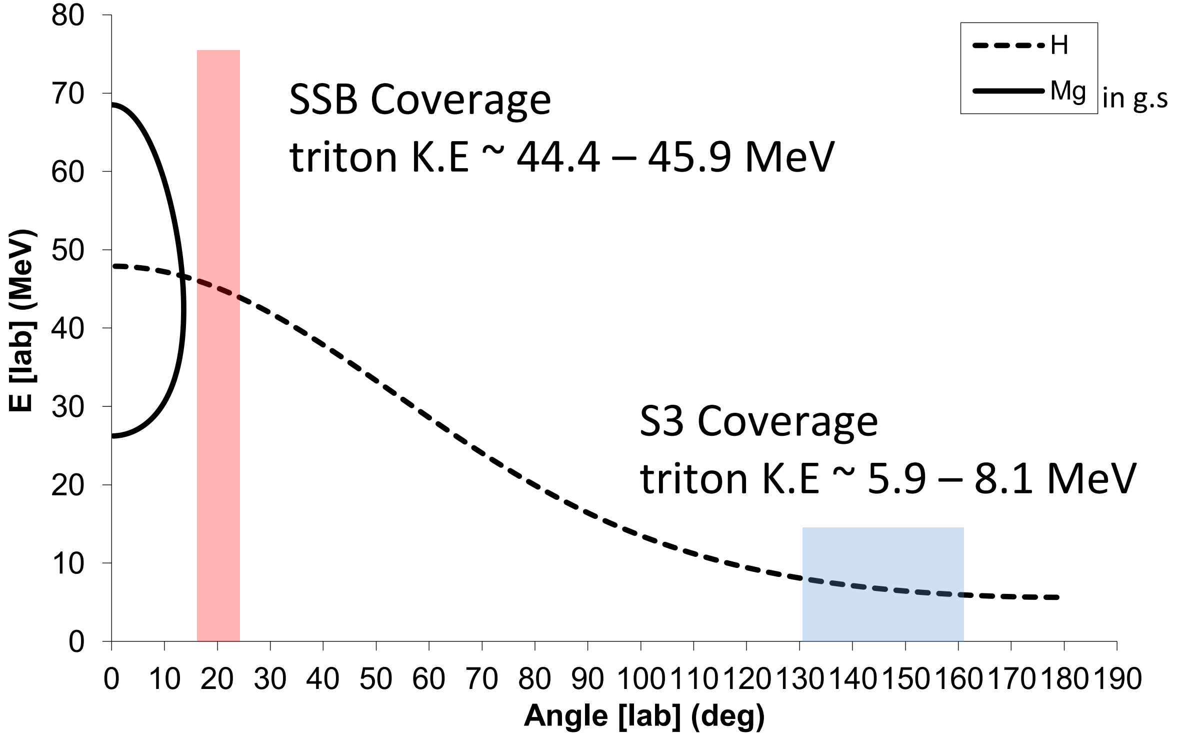
H. Jayatissa *et al.* PLB (2020)



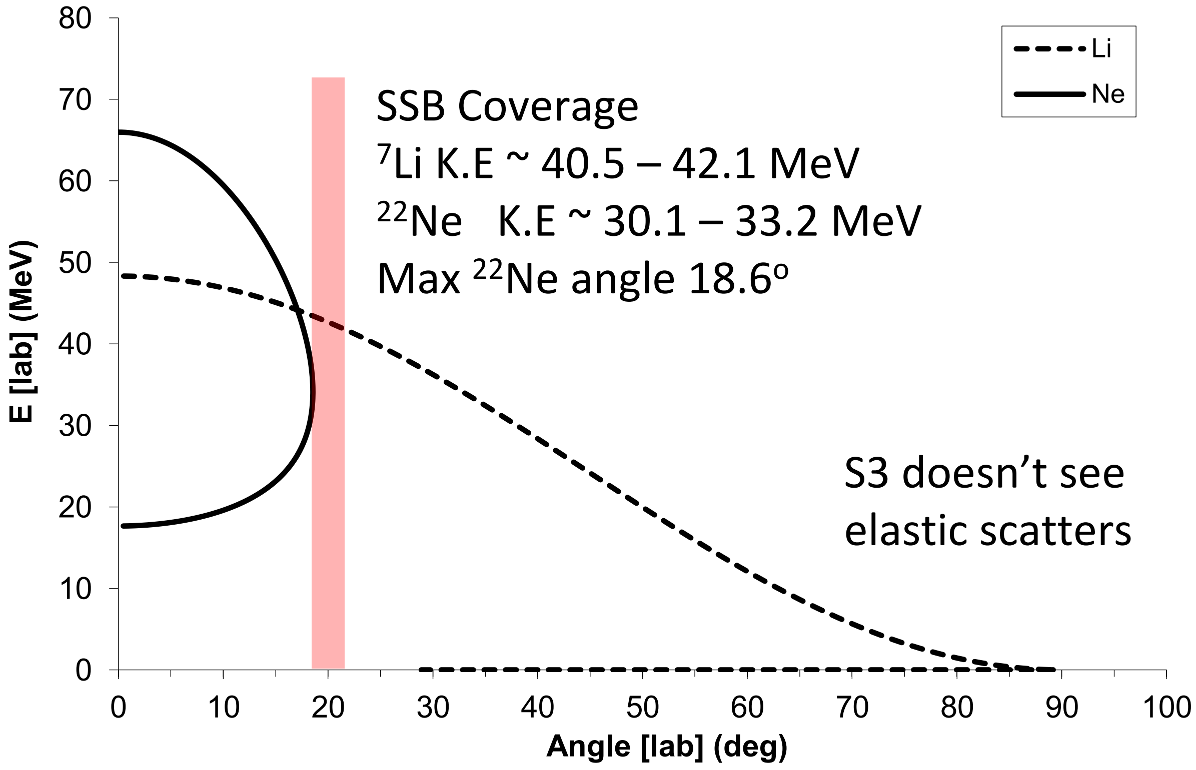
Kinematic Curves

^{22}Ne beam E_{lab} = 3 MeV/u

Transfer reaction 22Ne(7Li,t)26Mg

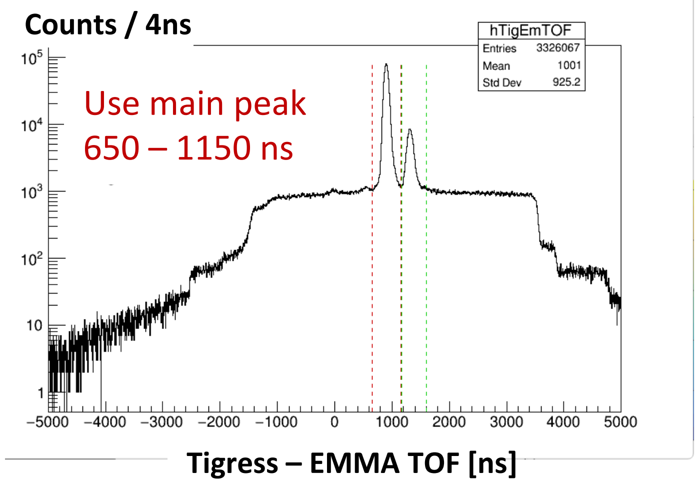


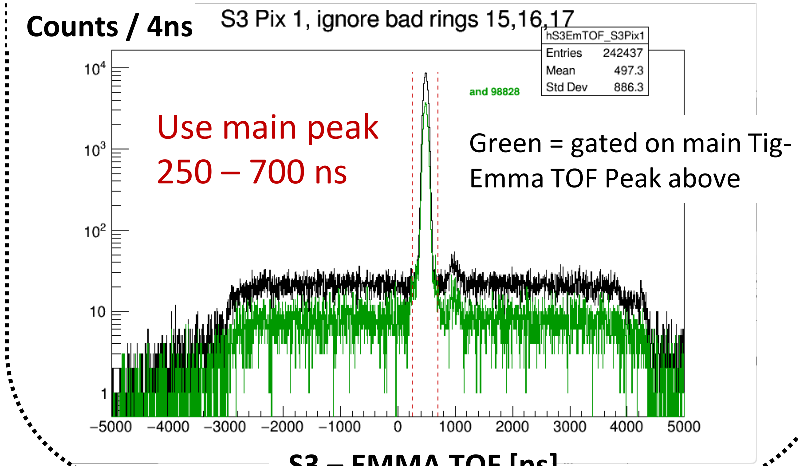
Elastic scattering 22Ne(7Li,7Li)22Ne



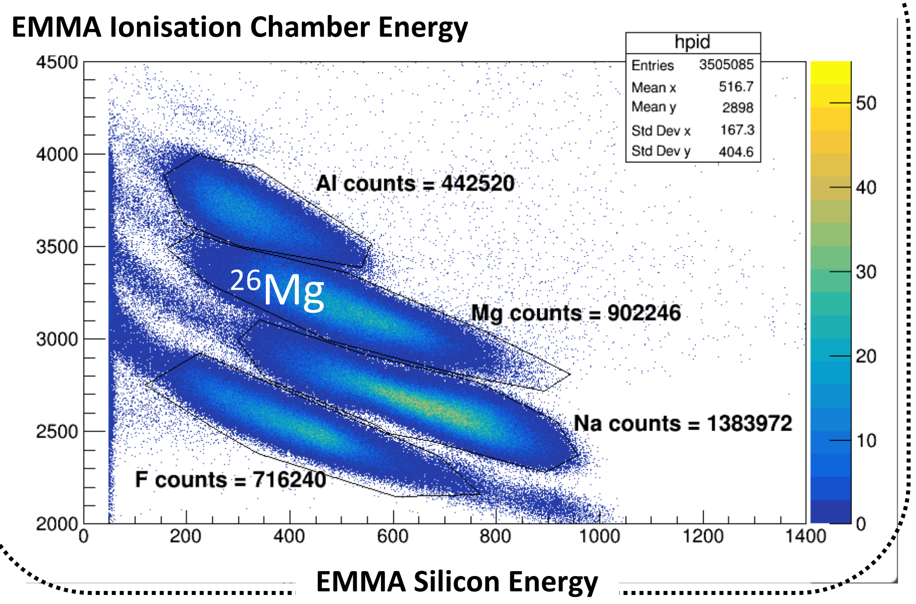
Gates: Cleaning the Data

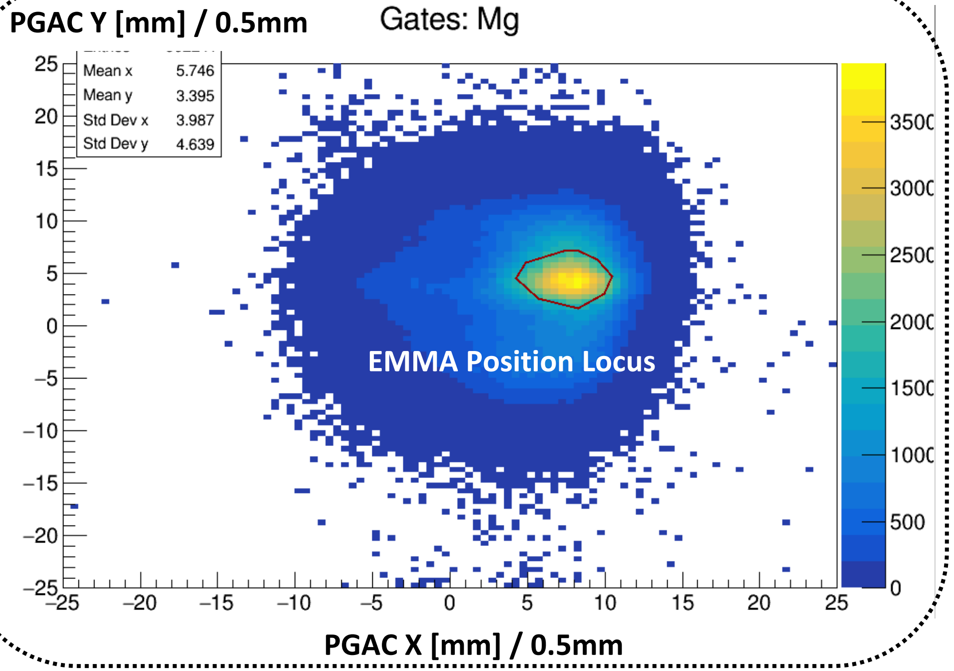
Time-of-Flight Cuts – remove random noise





EMMA ^{26}Mg Particle Identification





* Beam energy corrected for ½ LiF Thickness
* Triton energy corrected for S3 DL and ½ LiF Thickness

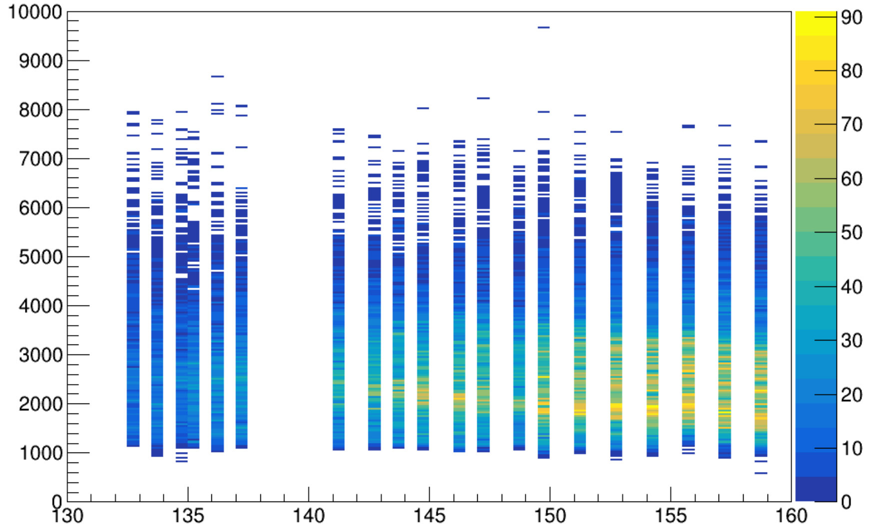
Ex Energy Calculation

a(A,b)B

$$E_x(\theta, T_b) = \Big\{m_A^2 + m_a^2 + m_b^2 + 2m_A m_a + 2m_a T_A - 2(m_b + T_b)(m_A + T_A + m_a) + 2\cos\theta\sqrt{T_A^2 + 2m_A T_A}\sqrt{T_b^2 + 2m_b T_b}\Big\}^{1/2} - m_B$$

Require:
- Masses, m
- Beam energy, T_A
- Triton energy, T_b
- Triton angle, θ

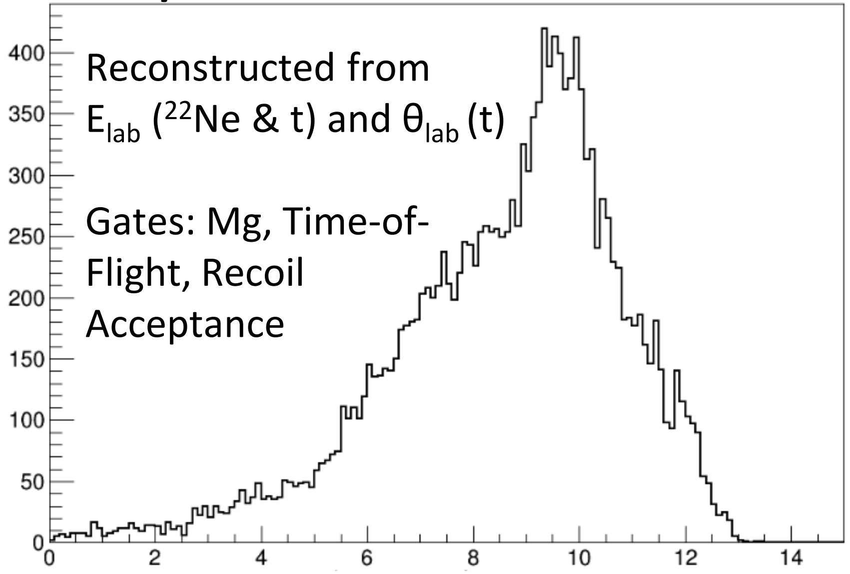
S3 E_{lab} / 40 keV



S3 θ_{lab} / 0.5°

S3 E & θ_{lab}
-> Mg Exc E

Counts / 100 keV



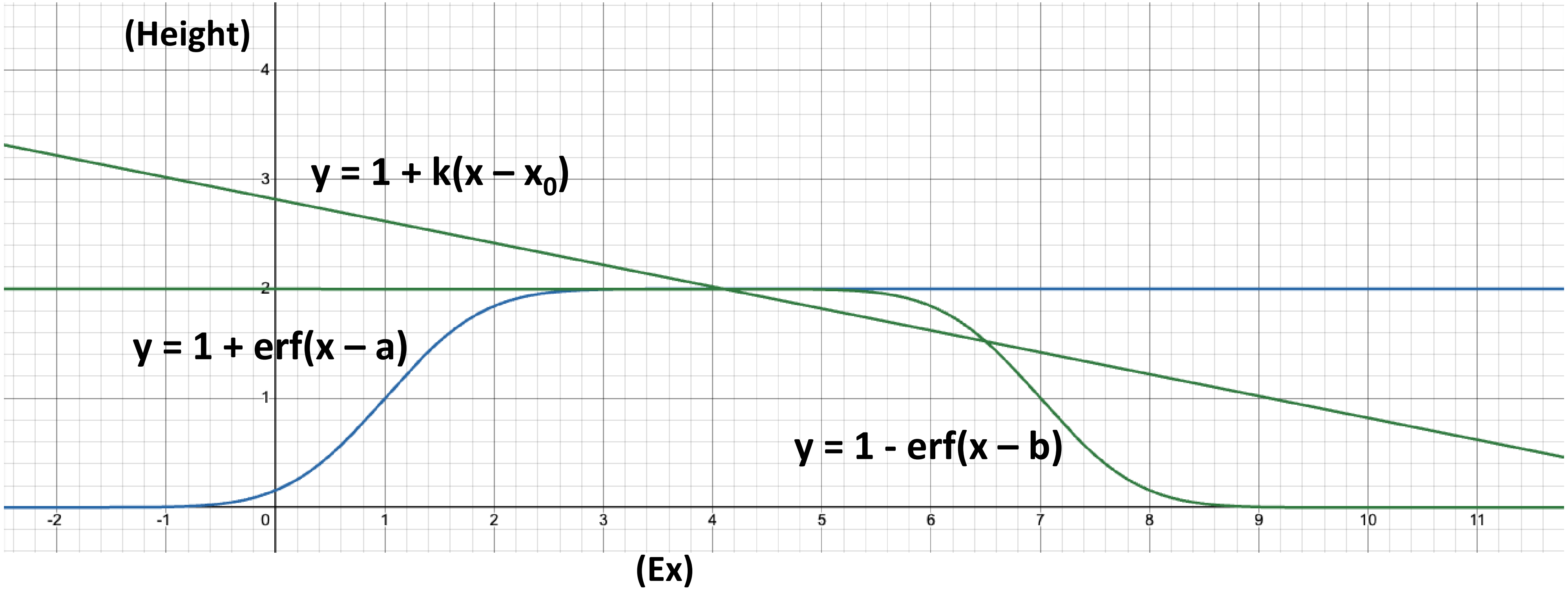
Excitation Energy [MeV]

Courtesy: Mike Qiu

Ex Model Fit Formula

dE/dx Slope | Low energy edge | High energy edge

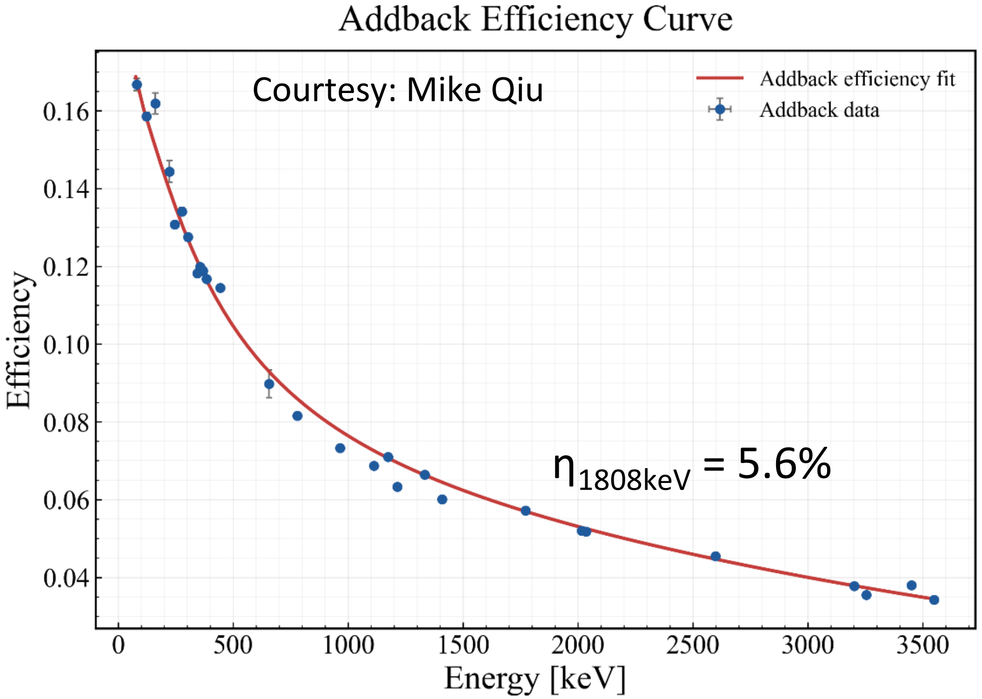
$$f(x) = \frac{1}{4}[1 + k(x - x_0)]\left[1 + erf(\frac{x-a}{\sqrt{2}\sigma_L})\right]\left[1 - erf(\frac{x-b}{\sqrt{2}\sigma_R})\right]$$

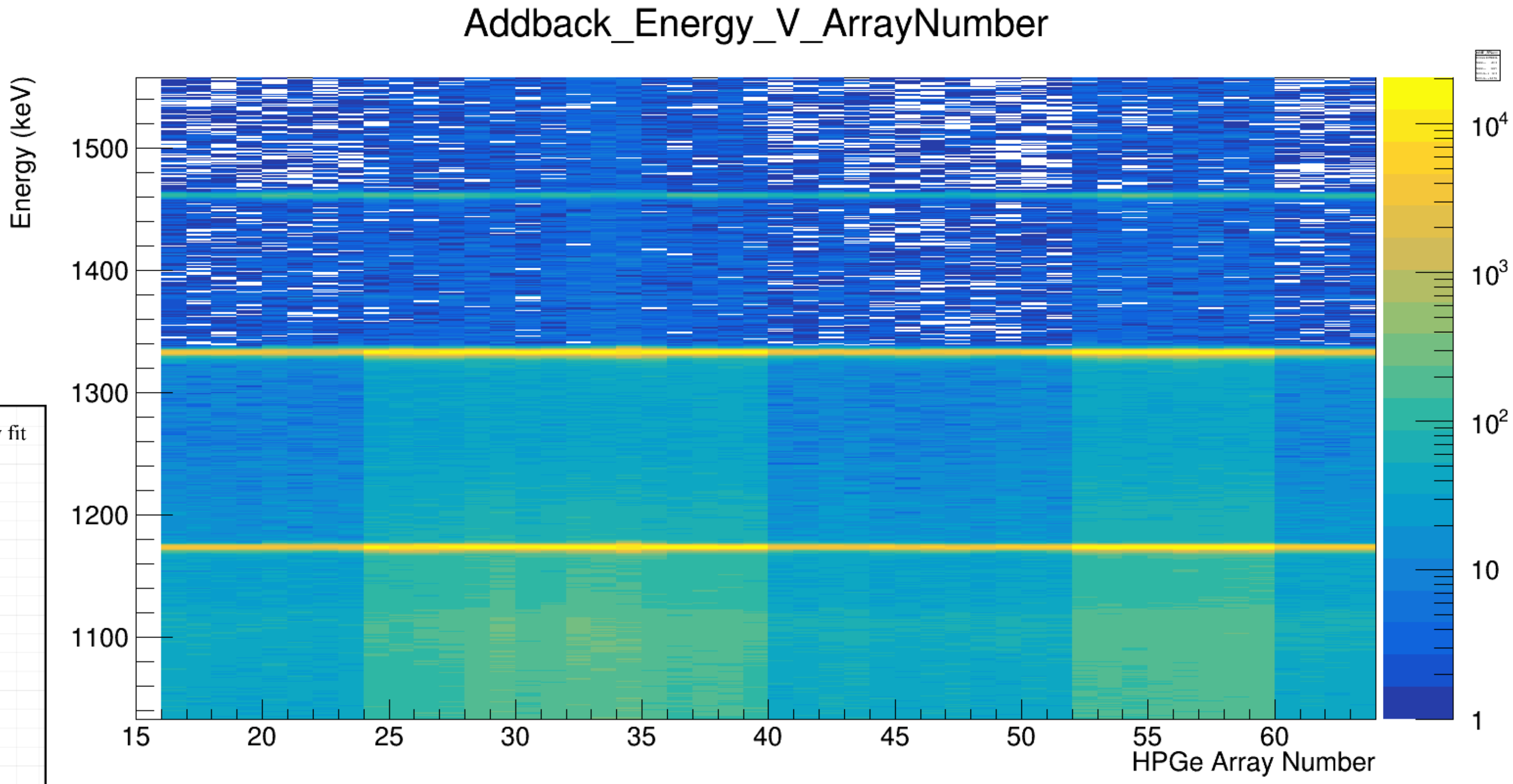


TIGRESS Energy Calibration & Addback Efficiency

TIGRESS Calibrated using

- ^{152}Eu 39.4 kBq on 1 May 2016
- ^{56}Co No certified activity – rel eff
- ^{60}Co 37 kBq on 15 May 2020
- ^{133}Ba 38.79 kBq on 1 June 2007



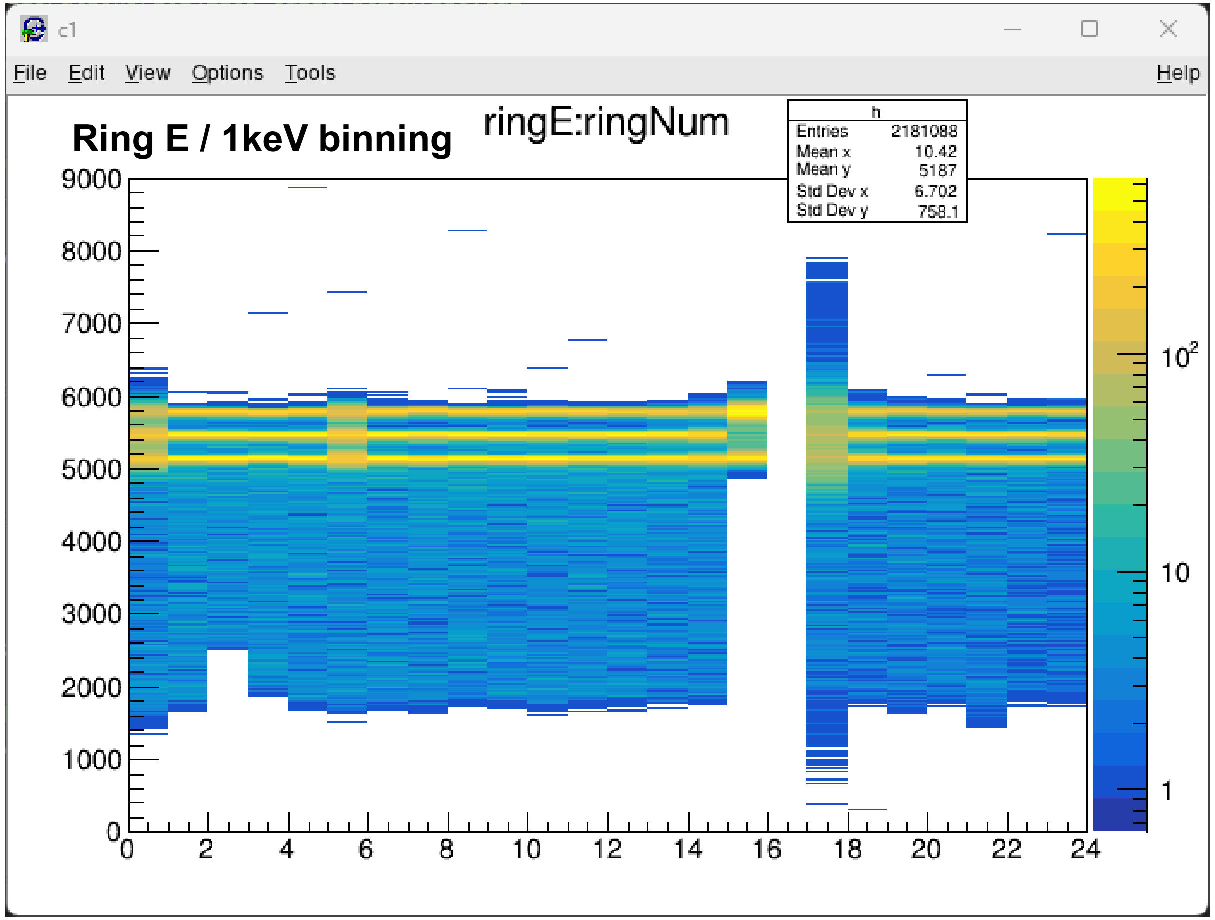


^{60}Co calibrated spectra
1332 keV, average resolution = 2.77 keV, std dev 0.26 keV, max 3.99 keV

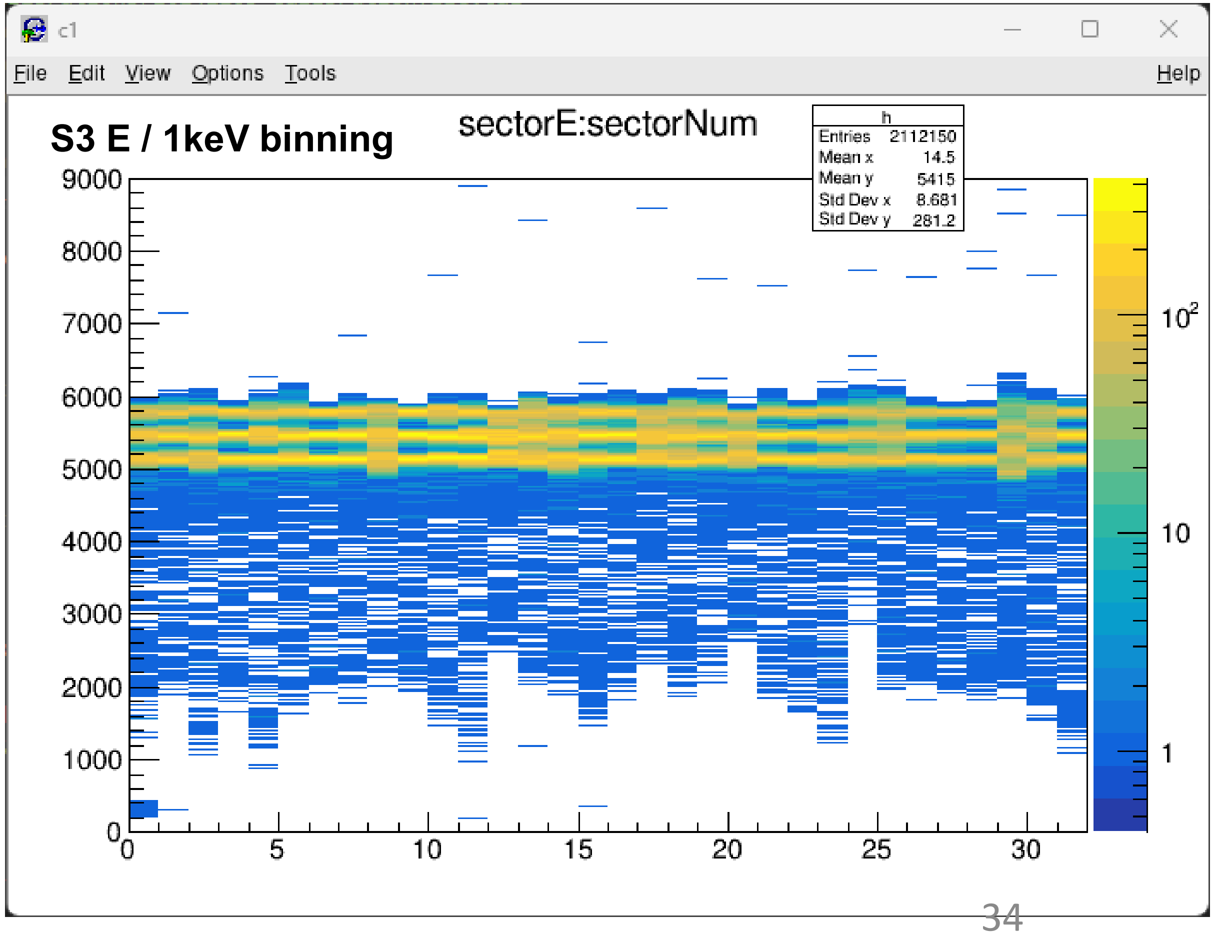
Source	Alpha Energy [keV]	Intensity [%]
^{239}Pu	5105.5 [8]	11.94 [7]
	5144.3 [8]	17.11 [14]
	5156.59 [14]	70.77 [14]
^{241}Am	5388	1.660 [20]
	5442.80 [13]	13.1 [3]
	5485.56 [12]	84.8 [5]
	5544.5 [16]	0.37 [3]
^{244}Cm	5762.64 [3]	23.10 [10]
	5804.77 [5]	76.90 [10]

S3 + SSB Energy Calibration

S3 rings + sectors and SSBs calibrated using triple alpha source



S3 ring number



S3 sector number

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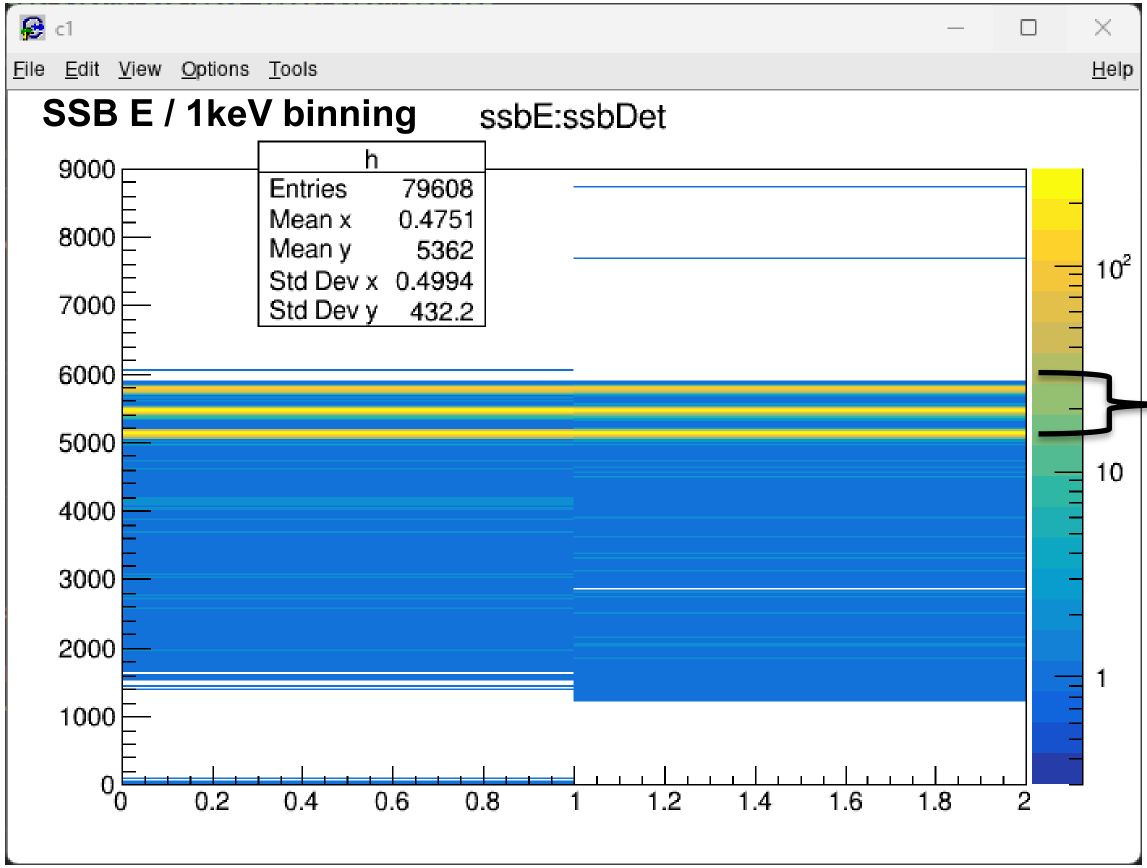

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