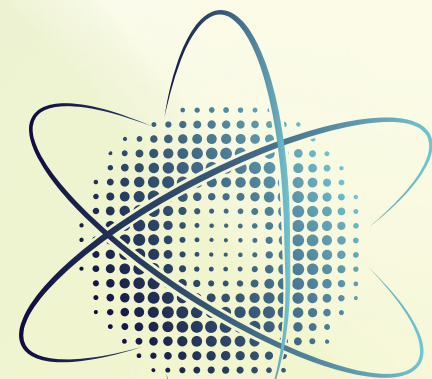




UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II



NUCLEAR RESEARCH CENTRE

**Resolving the Hoyle state measurement
performed at OCL and planned carbon-fusion
measurements in the AMiCARE project**

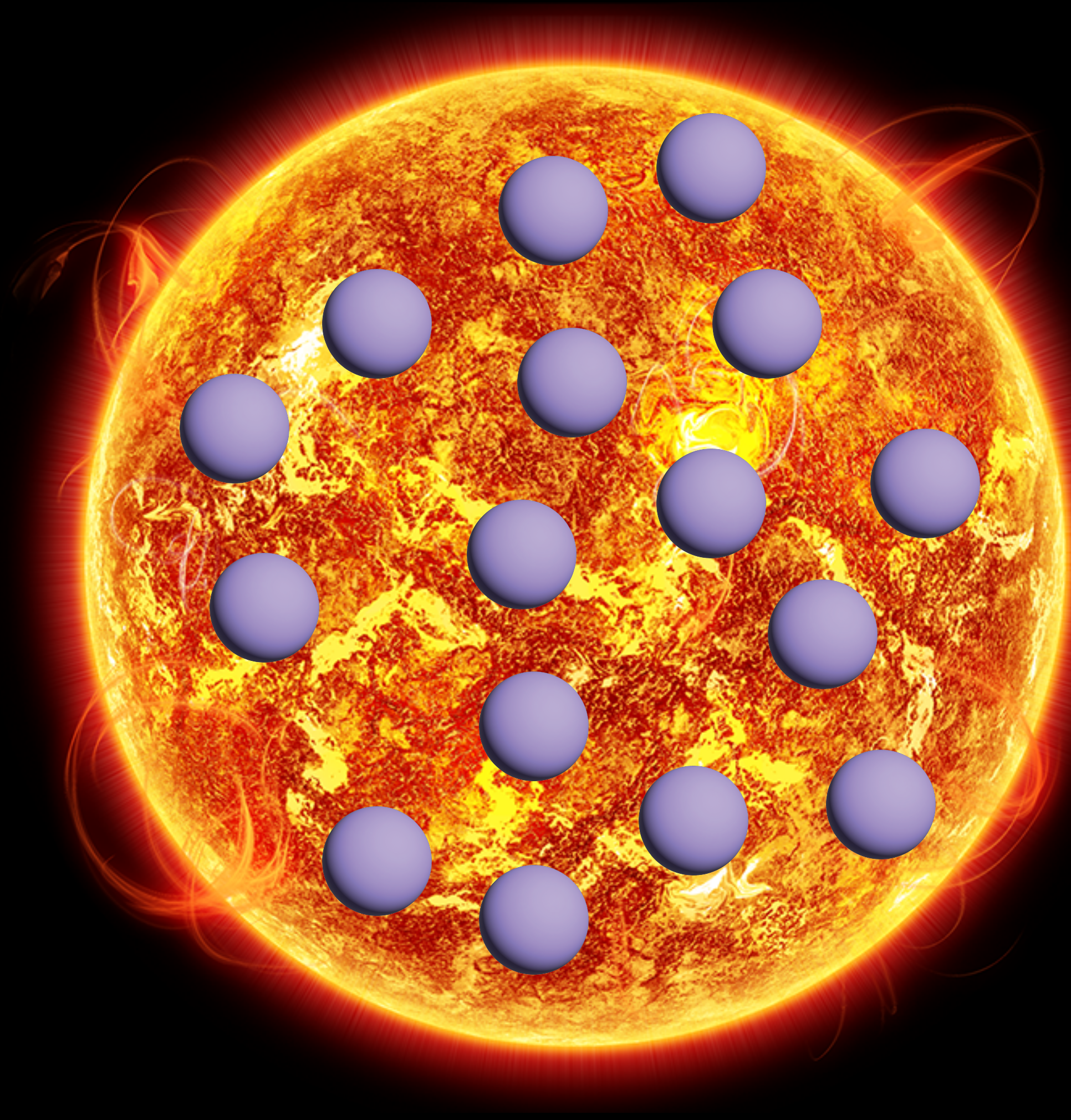
15th Nordic Meeting on Nuclear Physics

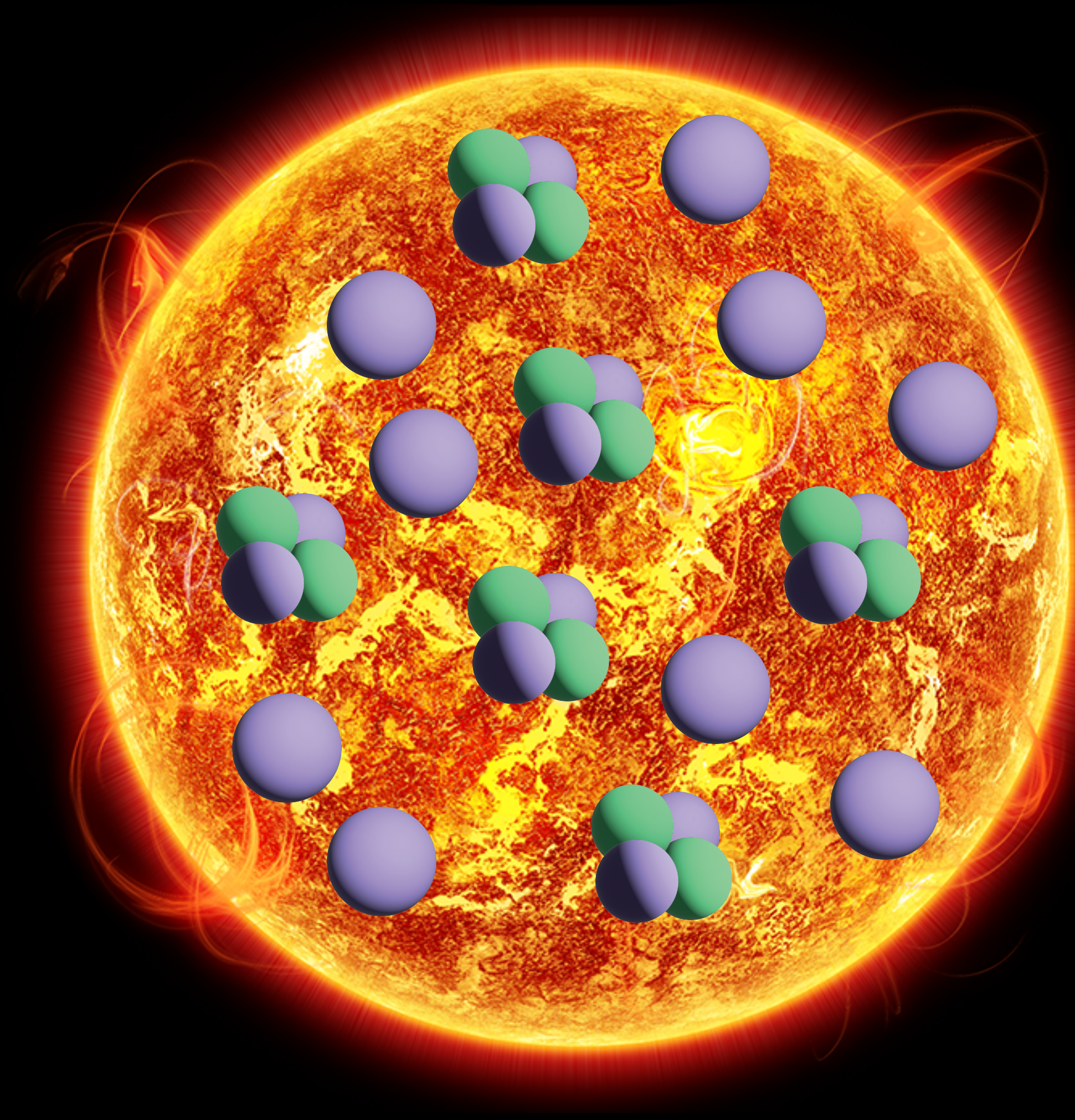
Wanja Paulsen

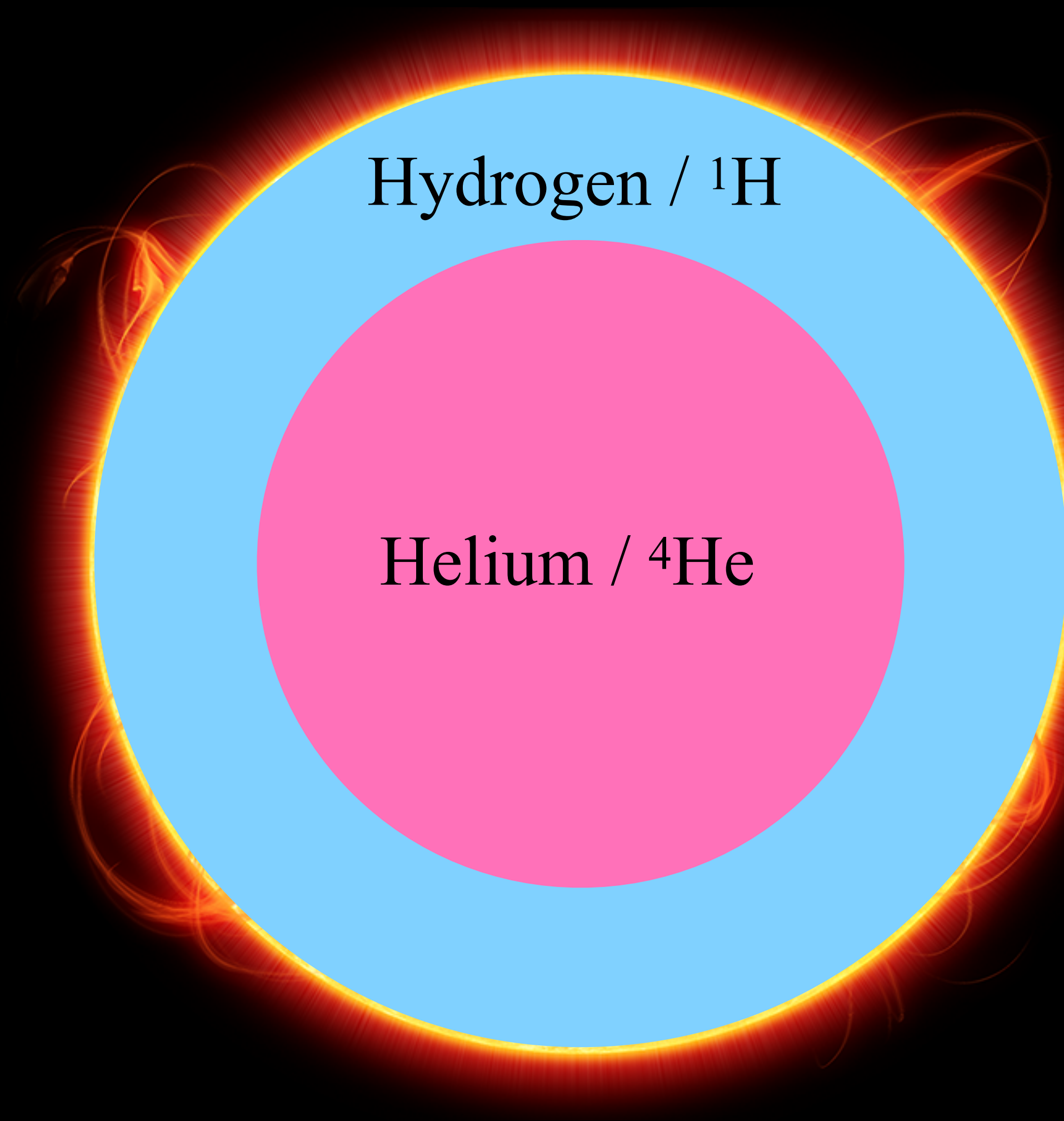
7th of May 2026



**The Research
Council of Norway**

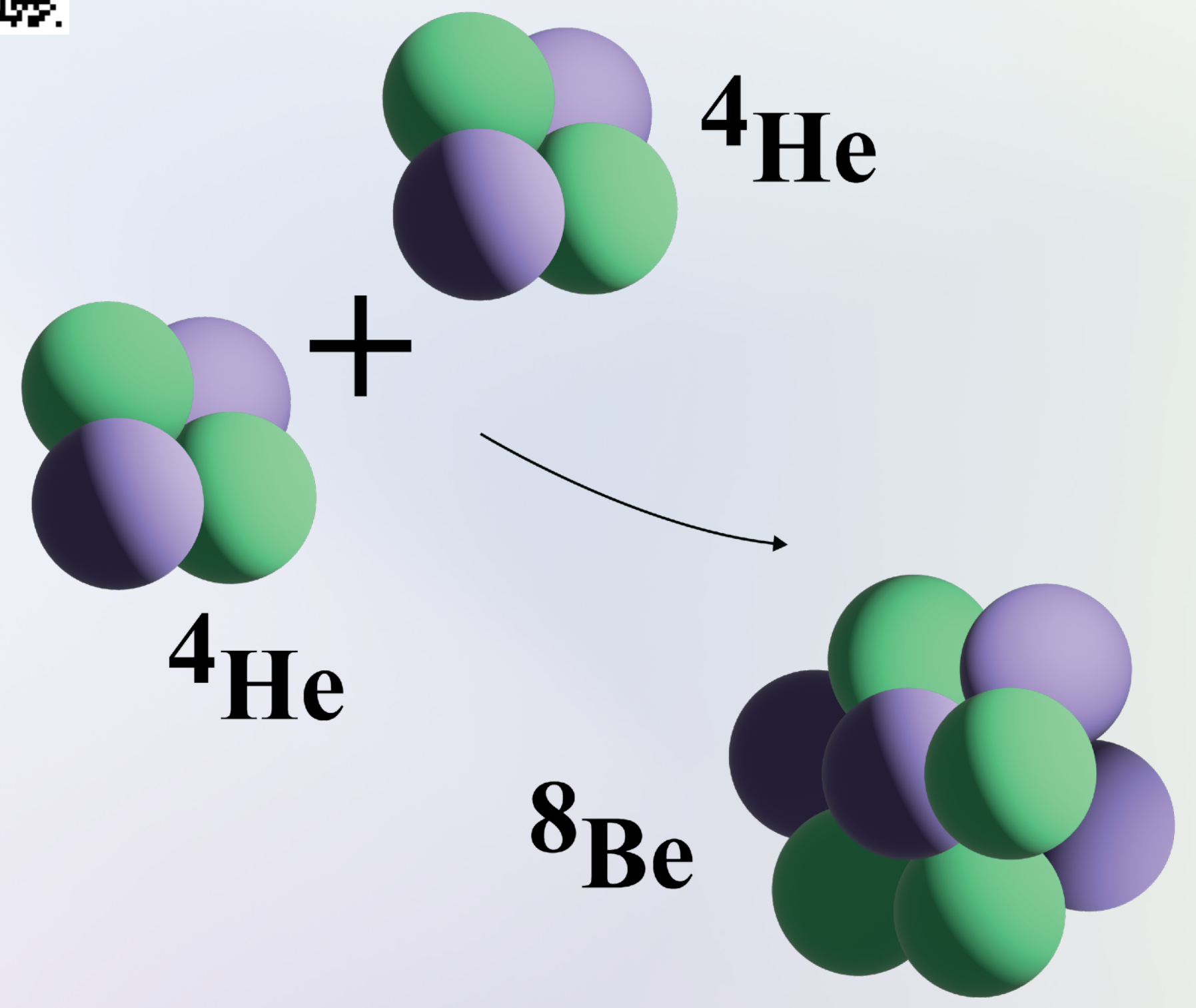




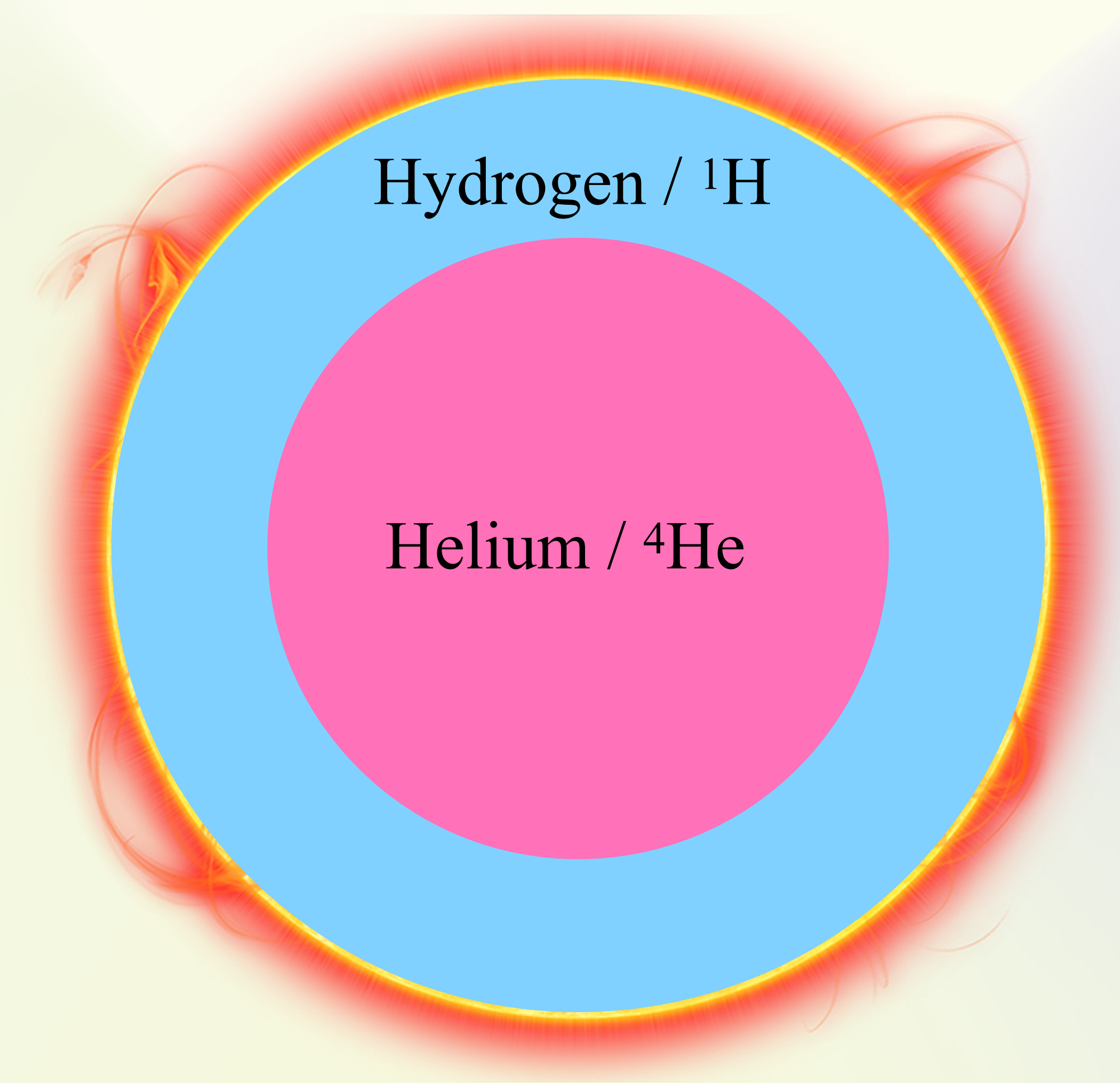


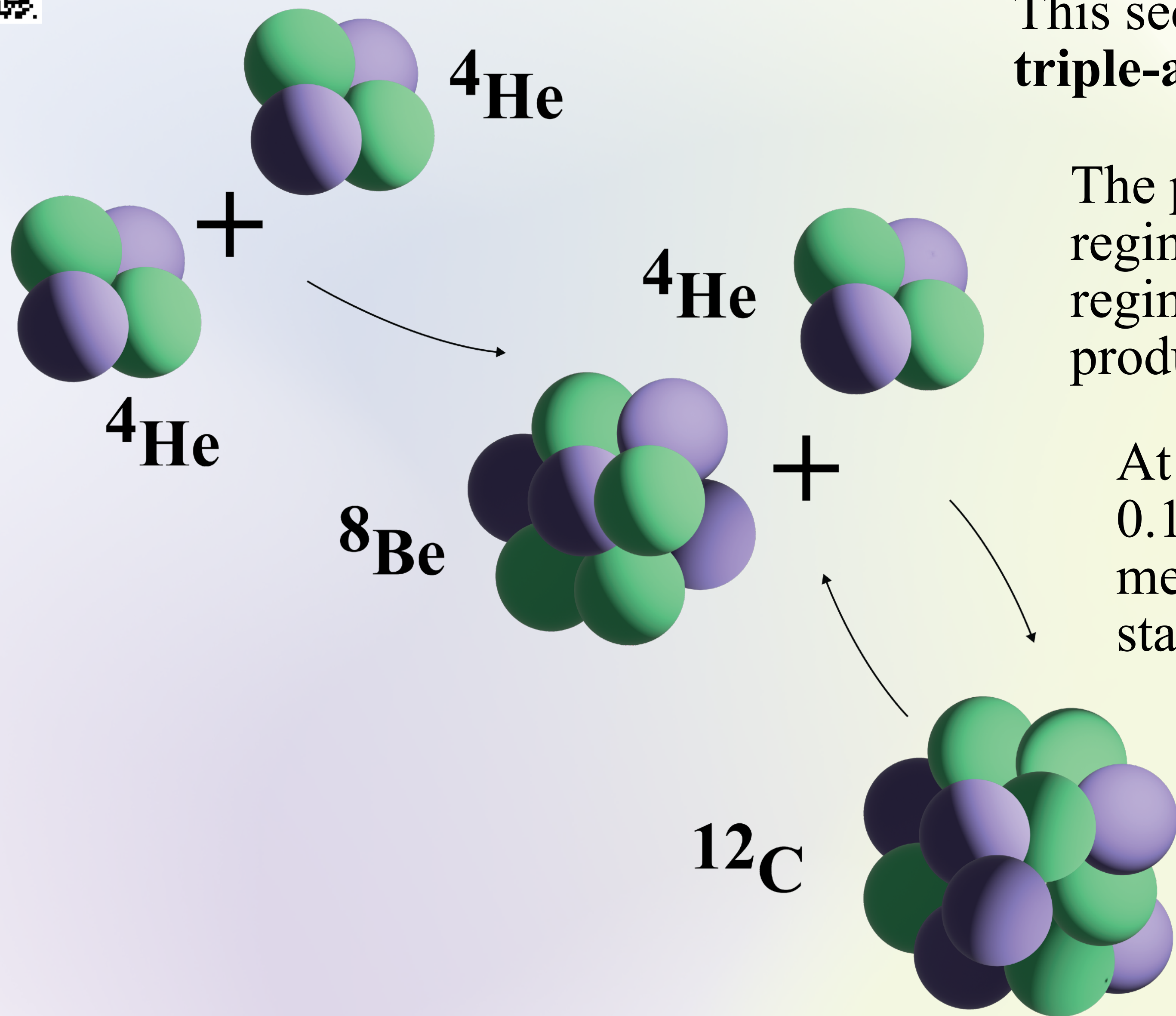
Hydrogen / ^1H

Helium / ^4He



Half-life of 8Be is $\tau \sim 10^{-17}\text{s}$





This sequential fusion process is called the **triple-alpha process**.

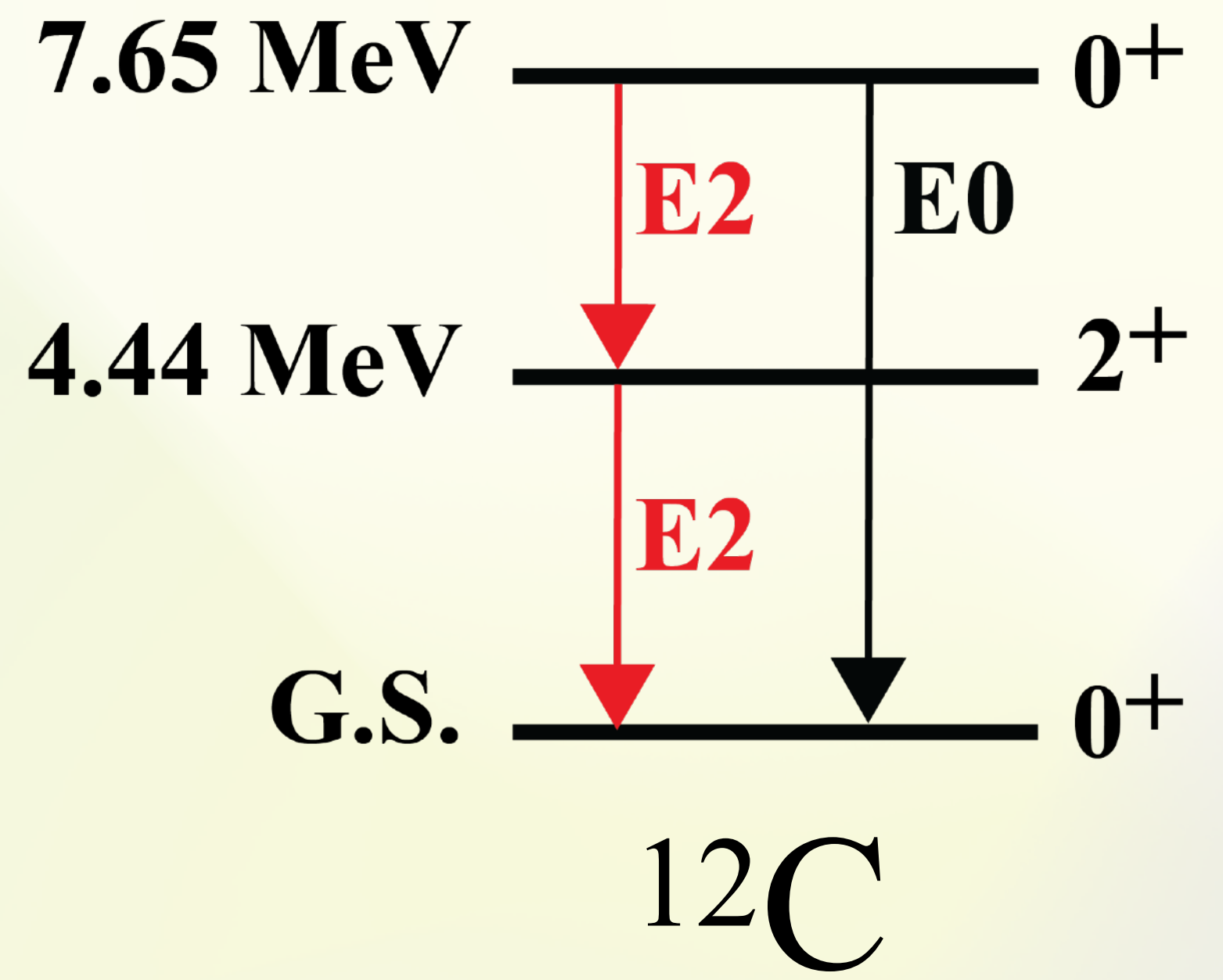
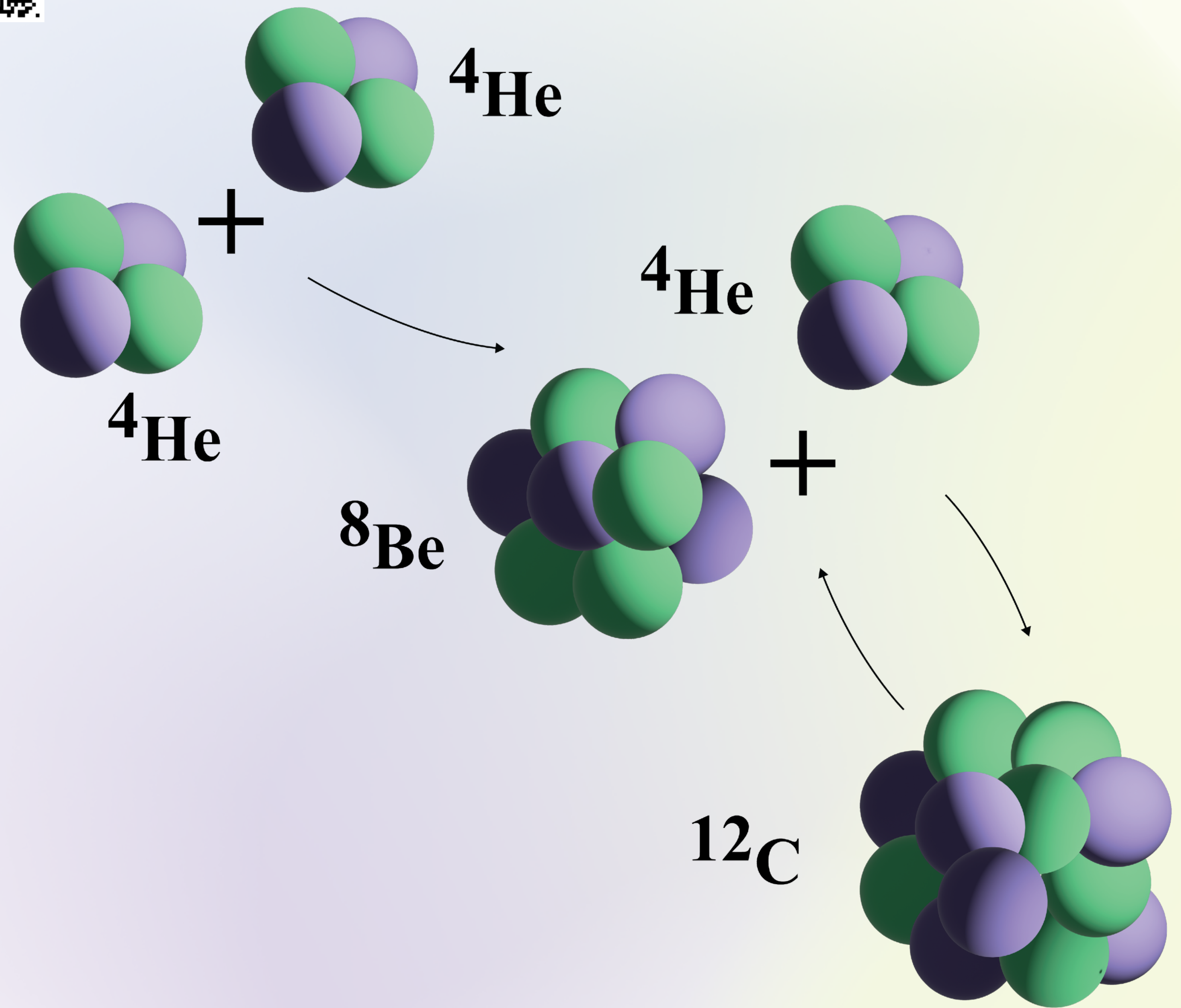
The process occurs in three temperature regimes, where the **medium** temperature regime contributes the most to the production of ${}^{12}\text{C}$.

At **medium stellar temperatures** between 0.1-2.0 GK, the **triple-alpha process** is mediated through the **resonant** excited state called the **Hoyle state**.

Sir Fred Hoyle (1915-2001)

Accurately predicted the existence of the Hoyle state and its properties in 1954.



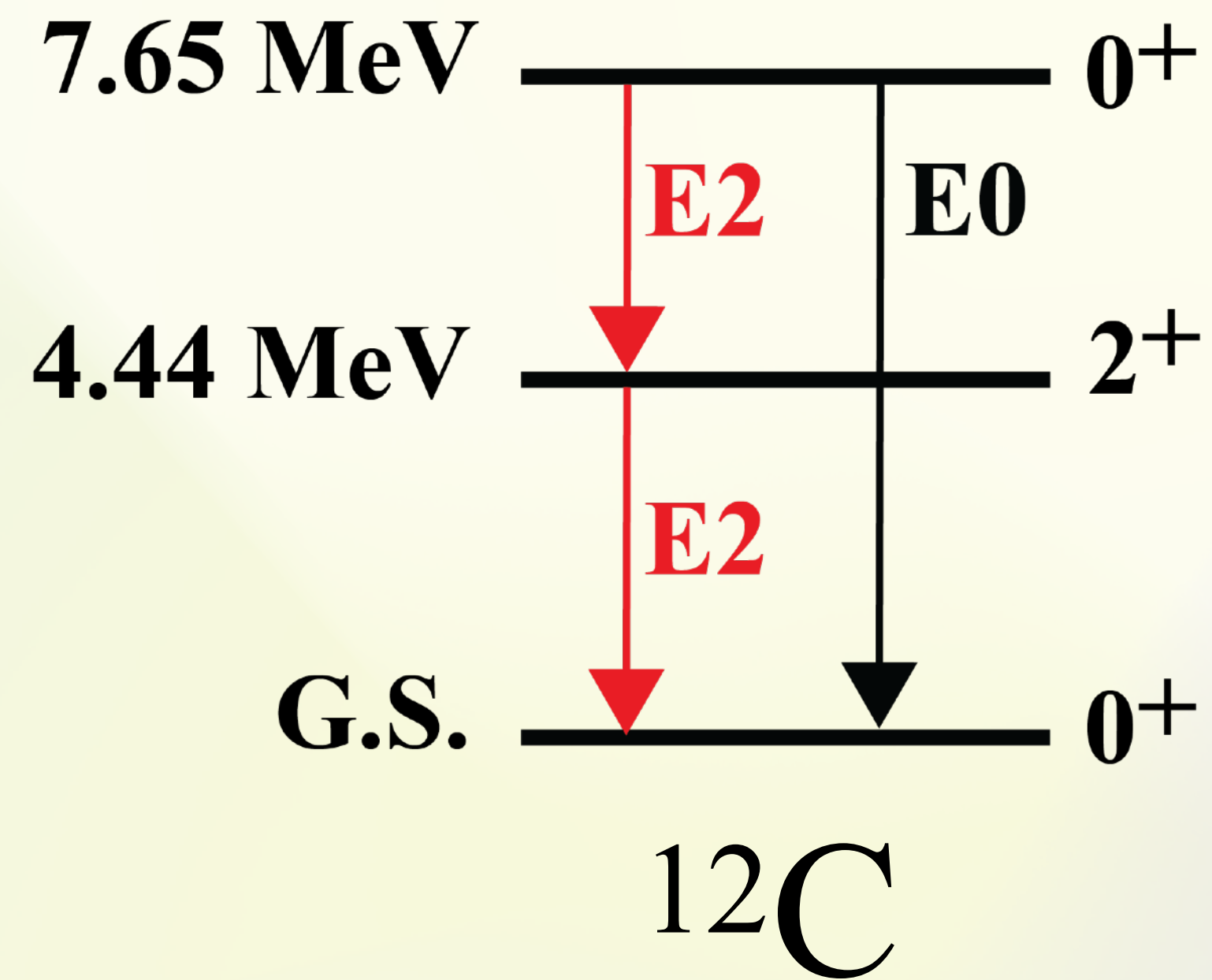
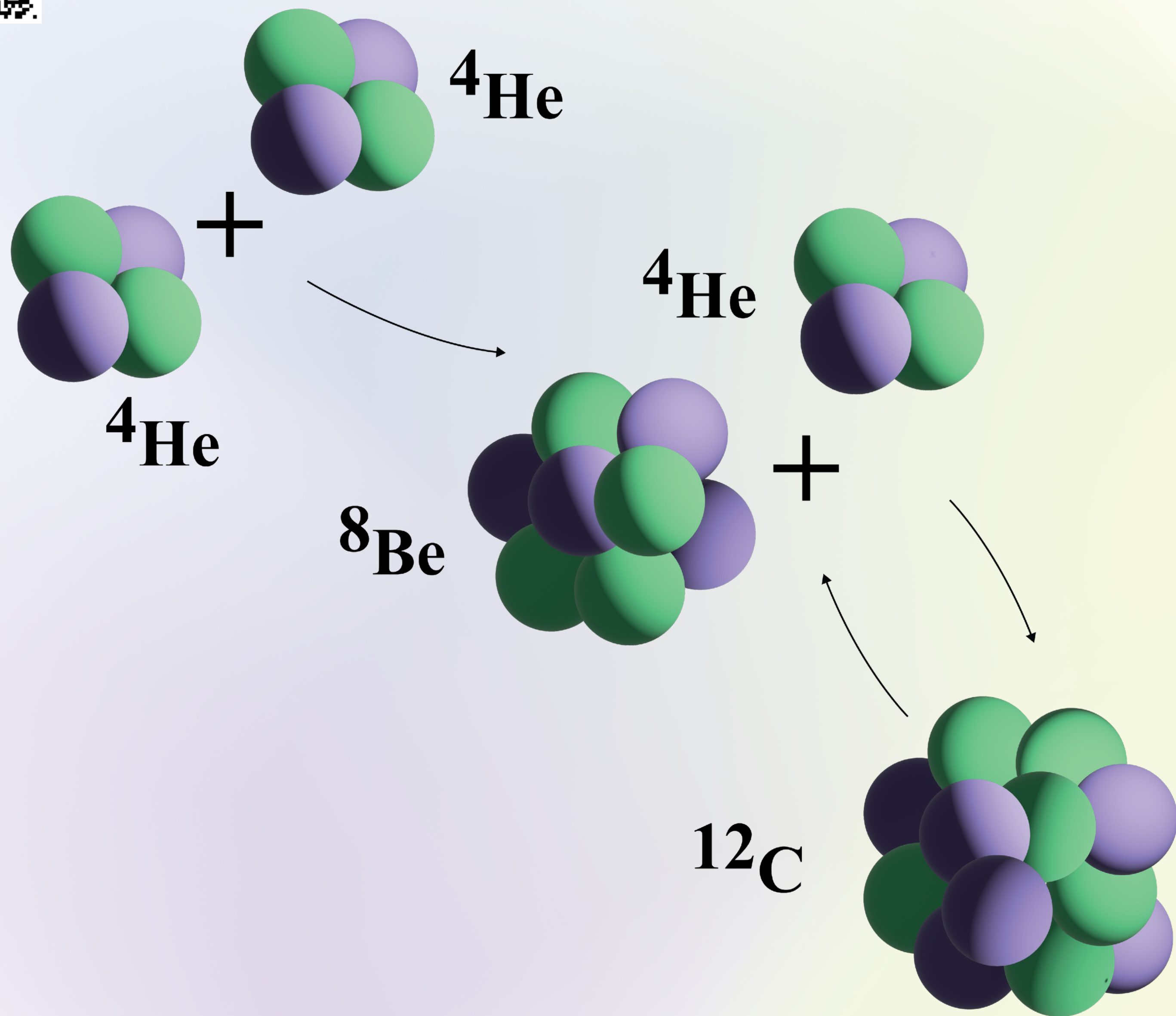


The width of the Hoyle state:

$$\Gamma = \Gamma_{\alpha} + \Gamma_{\text{rad}}$$

A dashed pink box encloses the Γ_{rad} term in the equation above. A dashed pink arrow points downwards from the box to the text below.

Describes the **probability** of **decaying** to stable ${}^{12}\text{C}$



The width of the Hoyle state:

$$\Gamma = \Gamma_{\alpha} + \Gamma_{\text{rad}}$$

Essential for calculating the reaction rate of the triple- α process



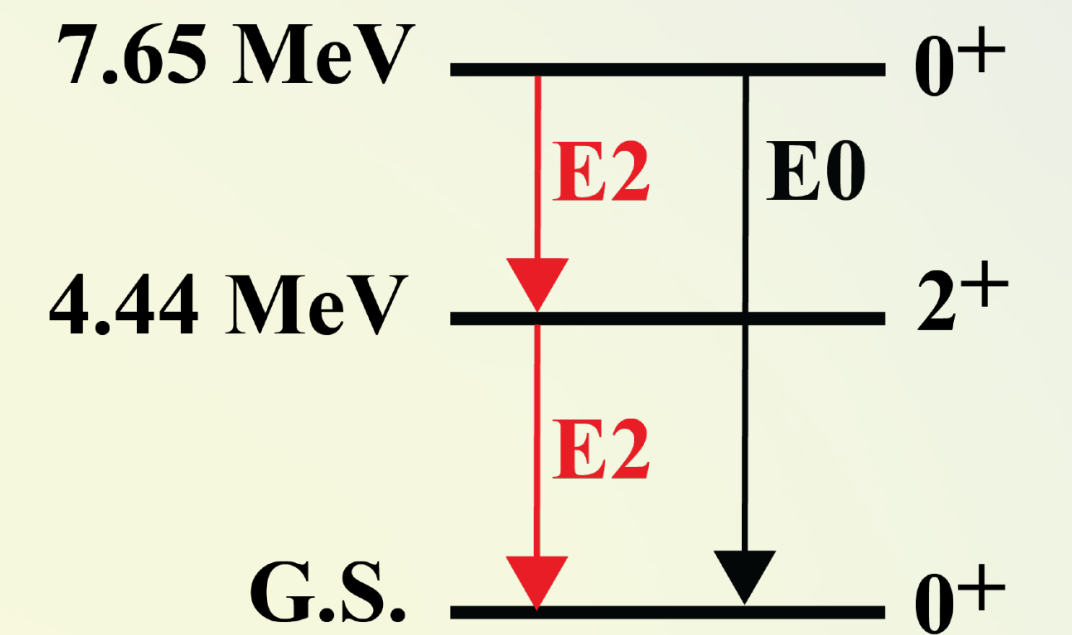
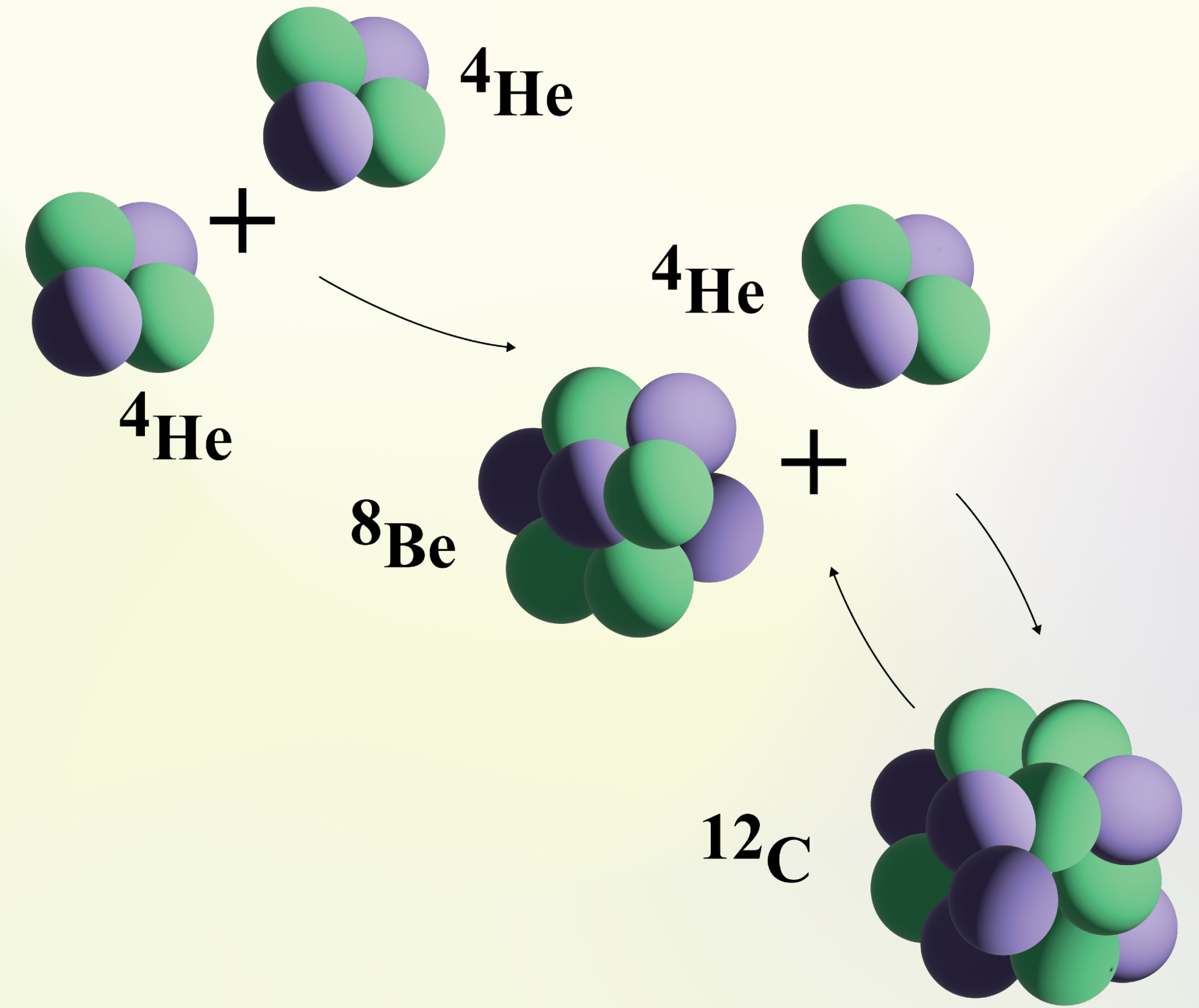
The radiative width of the Hoyle state is **difficult** to measure **directly**

$$\Gamma = \Gamma_{\alpha} + \Gamma_{\text{rad}}$$

~~$\alpha(^8\text{Be}, \gamma)^{12}\text{C}$ or $\alpha(^8\text{Be}, e^-e^+)^{12}\text{C}$~~

~~$^8\text{Be}(\alpha, \gamma)^{12}\text{C}$ or $^8\text{Be}(\alpha, e^-e^+)^{12}\text{C}$~~

~~$^{12}\text{C}(\gamma, \alpha)^8\text{Be}$, $^{12}\text{C}(\gamma, e^-e^+)^8\text{Be}$ or $^{12}\text{C}(\gamma, \gamma)^8\text{Be}$~~



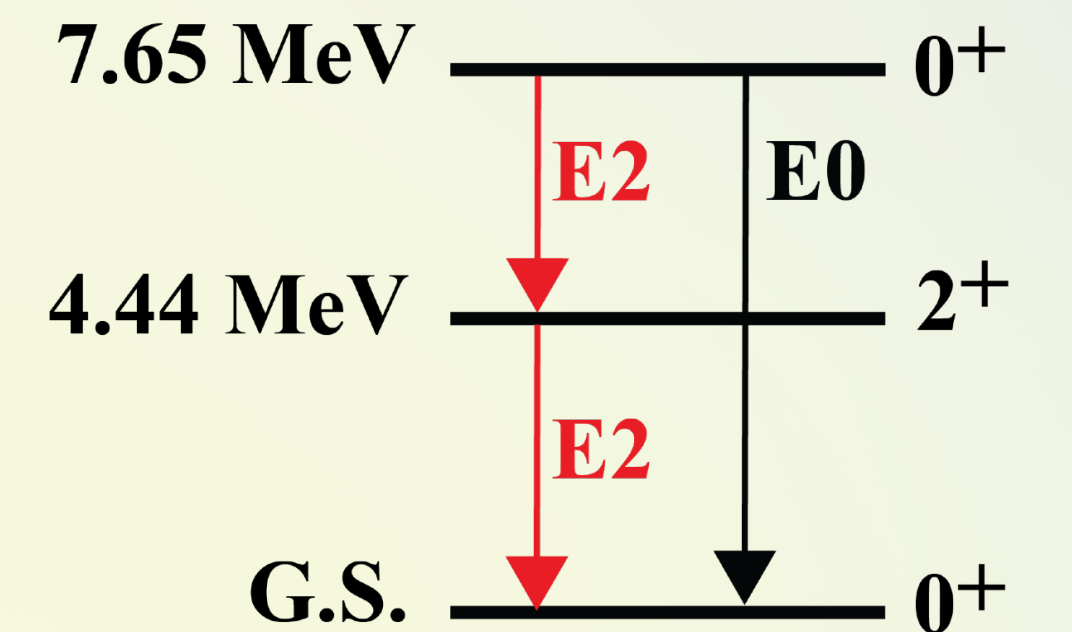
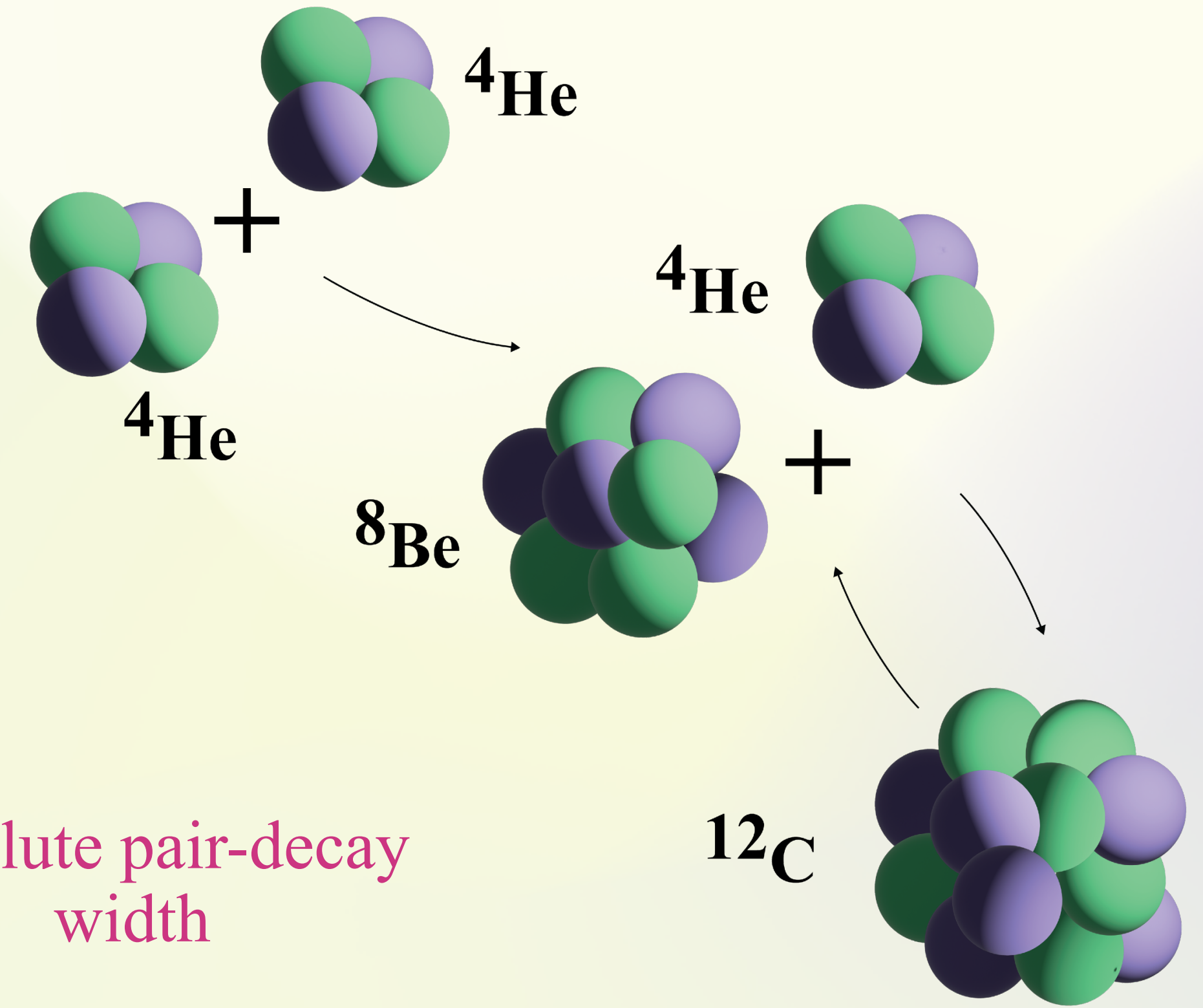


The radiative width of the Hoyle state is **experimentally inaccessible directly**, but it can be **deduced indirectly** with three independently measured quantities as

$$\Gamma = \Gamma_{\alpha} + \Gamma_{\text{rad}}$$

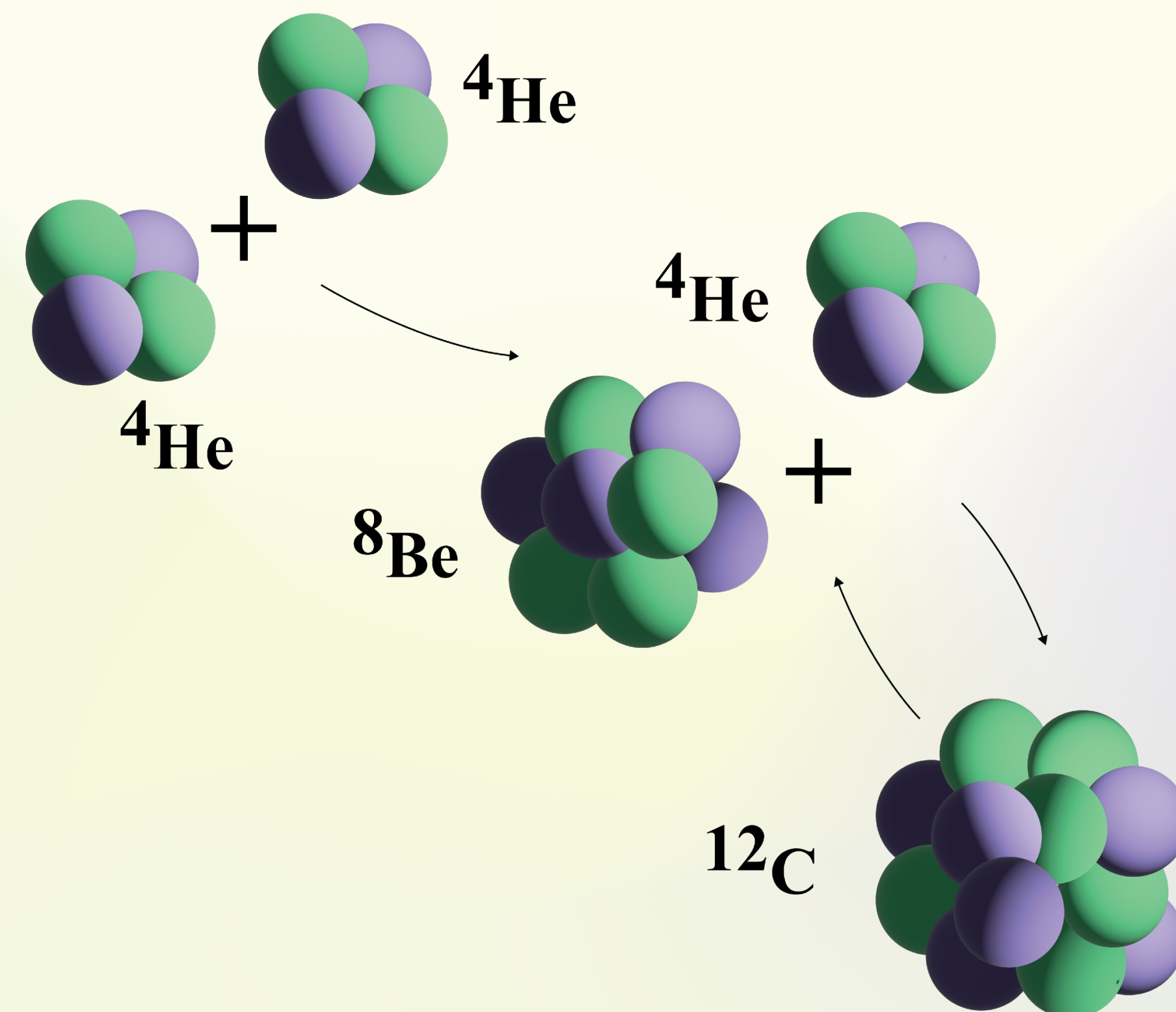
$$\Gamma_{\text{rad}} = \left[\frac{\Gamma_{\text{rad}}}{\Gamma} \right] \times \left[\frac{\Gamma}{\Gamma_{\pi}^{\text{E0}}} \right] \times \left[\Gamma_{\pi}^{\text{E0}} \right] \rightarrow \text{Absolute pair-decay width}$$

↓ Radiative branching ratio
↓ Pair-decay branching ratio



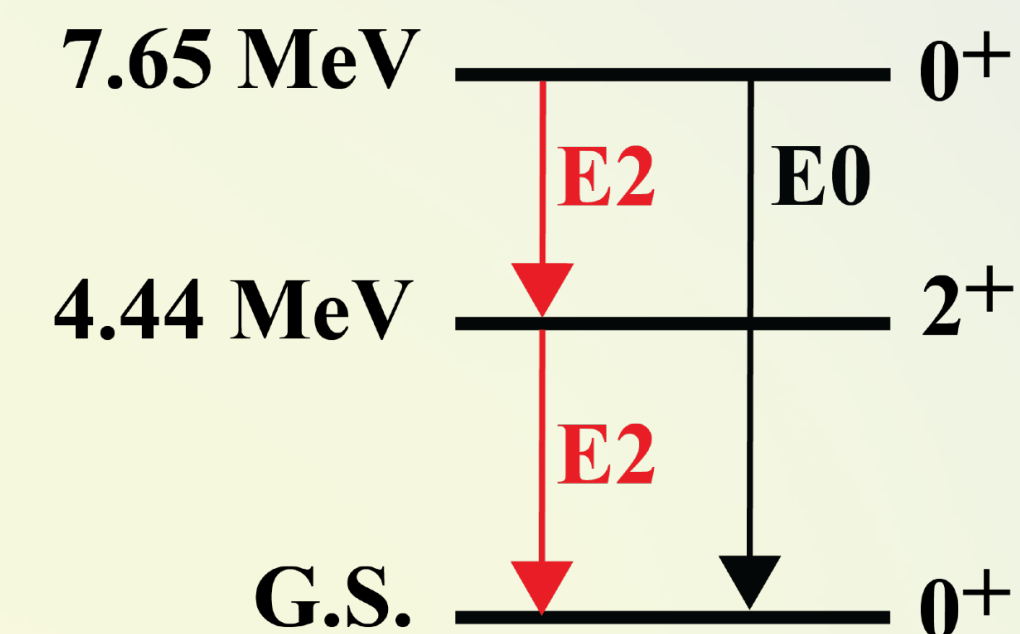


The radiative branching ratio can be measured **directly** by either measuring **surviving ^{12}C nuclei** in the reaction, or by measuring the **γ -decay** branching ratio and the **pair-decay** branching ratio



$$\Gamma_{\text{rad}} = \left[\frac{\Gamma_{\text{rad}}}{\Gamma} \right] \times \left[\frac{\Gamma}{\Gamma_{\pi}^{E0}} \right] \times [\Gamma_{\pi}^{E0}]$$

$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2} (1 + \alpha_{\text{tot}}) + \Gamma_{\pi}^{E0}}{\Gamma}$$



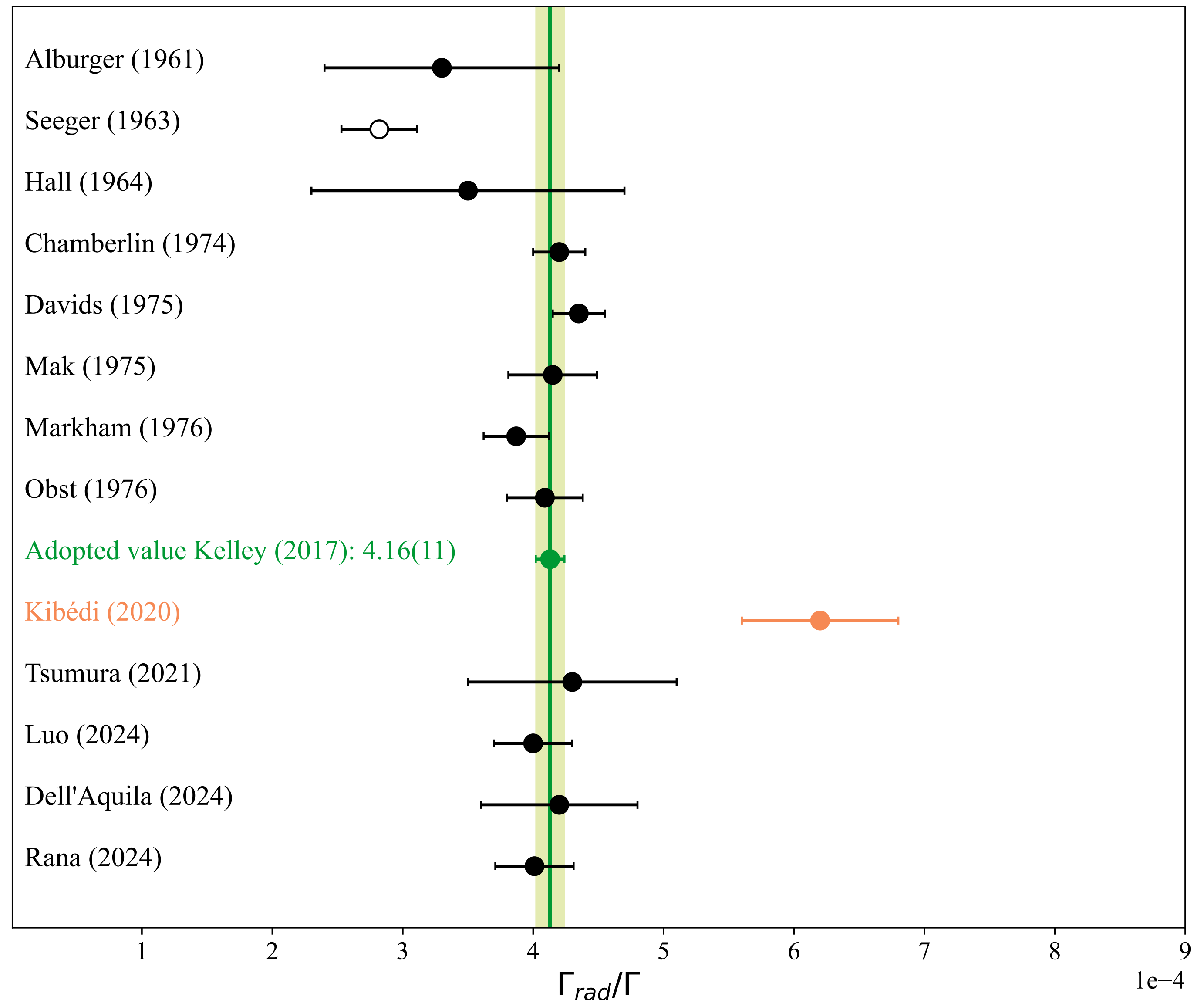
Previous measurements of the radiative branching ratio of the Hoyle state

Surviving recoil ^{12}C

Seeger (1963)	Markham (1976)
Hall (1964)	Tsukuba (2021)
Chamberlin (1974)	Luo (2024)
Dauids (1975)	Dell'Aquila (2024)
Mak (1975)	Rana (2024)

Combination of γ -decay and pair-decay branching ratio

Alburger (1961)
 Obst (1976) [9]
 Kibédi (2020) [10]
 Rana (2024)



The measurement by Kibédi *et al.*

- Performed at The Oslo Cyclotron Laboratory in 2014.
- Measured the γ -decay branching ratio of the Hoyle state.
- Initial results by B. Alshahrani agree with previous adopted value.
- Reanalysis resulted in this PRL in 2020.

PHYSICAL REVIEW LETTERS **125**, 182701 (2020)

Radiative Width of the Hoyle State from γ -Ray Spectroscopy

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F. Giacoppo^{3,‡}, A. I. Morales^{4,§}, E. Sahin³, G. M. Tveten³, F. L. Bello Garrote³, L. Crespo Campo³,
T. K. Eriksen³, M. Klintefjord³, S. Maharramova³, H.-T. Nyhus³, T. G. Tornyi^{3,5,||},
T. Renstrøm³ and W. Paulsen³


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 (Received 18 December 2019; revised 26 July 2020; accepted 22 September 2020; published 27 October 2020)

The cascading 3.21 and 4.44 MeV electric quadrupole transitions have been observed from the Hoyle state at 7.65 MeV excitation energy in ^{12}C , excited by the $^{12}\text{C}(p, p')$ reaction at 10.7 MeV proton energy. From the proton- γ - γ triple coincidence data, a value of $\Gamma_{\text{rad}}/\Gamma = 6.2(6) \times 10^{-4}$ was obtained for the radiative branching ratio. Using our results, together with Γ_{π}^{E0}/Γ from Eriksen *et al.* [*Phys. Rev. C* **102**, 024320 (2020)] and the currently adopted $\Gamma_{\pi}(E0)$ values, the radiative width of the Hoyle state is determined as $\Gamma_{\text{rad}} = 5.1(6) \times 10^{-3}$ eV. This value is about 34% higher than the currently adopted value and will impact models of stellar evolution and nucleosynthesis.

DOI: [10.1103/PhysRevLett.125.182701](https://doi.org/10.1103/PhysRevLett.125.182701)


















The purpose of this project



Purpose: The main purpose was to perform a new measurement of the γ -decay branching ratio of the Hoyle state to deduce the radiative branching ratio of the Hoyle state. An additional objective was to independently verify aspects of the aforementioned measurement conducted by Kibédi *et al.* [[Phys. Rev. Lett. 125, 182701 \(2020\)](#)].

PHYSICAL REVIEW C **112**, 015803 (2025)

Remeasuring the γ -decay branching ratio of the Hoyle state

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H. C. Berg ^{1,†} F. L. B. Garrote ¹ D. Gjestvang ^{1,2} A. Görgen ^{1,2} M. Markova ^{1,2} V. Modamio ^{1,2}
E. Sahin ^{1,2} G. M. Tveten ¹ and V. M. Valsdóttir ^{1,2}

¹Department of Physics, *University of Oslo*, N-0316 Oslo, Norway

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(Received 31 May 2024; revised 21 March 2025; accepted 13 May 2025; published 2 July 2025)

Background: The radiative branching ratio of the Hoyle state is crucial to estimate the triple- α reaction rate in stellar environments at medium temperatures of $T = 0.1$ to 2 GK. Knowledge of the γ -decay channel is critical as this is the dominant radiative decay channel for the Hoyle state. A recent study by Kibédi *et al.* [[Phys. Rev. Lett. 125, 182701 \(2020\)](#)] has challenged our understanding of this astrophysically significant branching ratio and its constraints.

Purpose: The main purpose was to perform a new measurement of the γ -decay branching ratio of the Hoyle state to deduce the radiative branching ratio of the Hoyle state. An additional objective was to independently verify aspects of the aforementioned measurement conducted by Kibédi *et al.* [[Phys. Rev. Lett. 125, 182701 \(2020\)](#)].

Method: For the primary experiment of this work the Hoyle state was populated by the $^{12}\text{C}(p, p')$ reaction at 10.8 MeV at the Oslo Cyclotron Laboratory. The γ -decay branching ratio was deduced through triple-coincidence events, each consisting of a proton-ejectile energy corresponding to population of the 0_2^+ Hoyle state, and the subsequent cascade of 3.21 and 4.44 MeV γ rays. To verify the analysis, a surrogate γ -ray cascade from the 0_2^+ state in ^{28}Si was also studied. Following the same methodology, an independent analysis of the 2014 data published by Kibédi *et al.* [[Phys. Rev. Lett. 125, 182701 \(2020\)](#)] was carried out.

Results: From the main experiment of this work, a γ -decay branching ratio of the Hoyle state was determined as $\Gamma_{\gamma}^{7.65}/\Gamma^{7.65} = 4.0(3) \times 10^{-4}$, yielding a radiative branching ratio of $\Gamma_{\text{rad}}/\Gamma = 4.1(4) \times 10^{-4}$. The independent reanalysis of the 2014 experiment published by Kibédi *et al.* [[Phys. Rev. Lett. 125, 182701 \(2020\)](#)] in this work yielded $\Gamma_{\gamma}^{7.65}/\Gamma^{7.65} = 4.5(6) \times 10^{-4}$, with a corresponding radiative branching ratio of $\Gamma_{\text{rad}}/\Gamma = 4.6(6) \times 10^{-4}$.

Conclusions: The radiative branching ratio of the Hoyle state reported in this work is in excellent agreement with several recent studies, as well as the previously adopted ENSDF average of $\Gamma_{\text{rad}}/\Gamma = 4.16(11) \times 10^{-4}$. In this work, several issues were found in the analysis of Kibédi *et al.* [[Phys. Rev. Lett. 125, 182701 \(2020\)](#)], with the corrected values no longer being discrepant with the ENSDF average.

Experimental equipment

SiRi

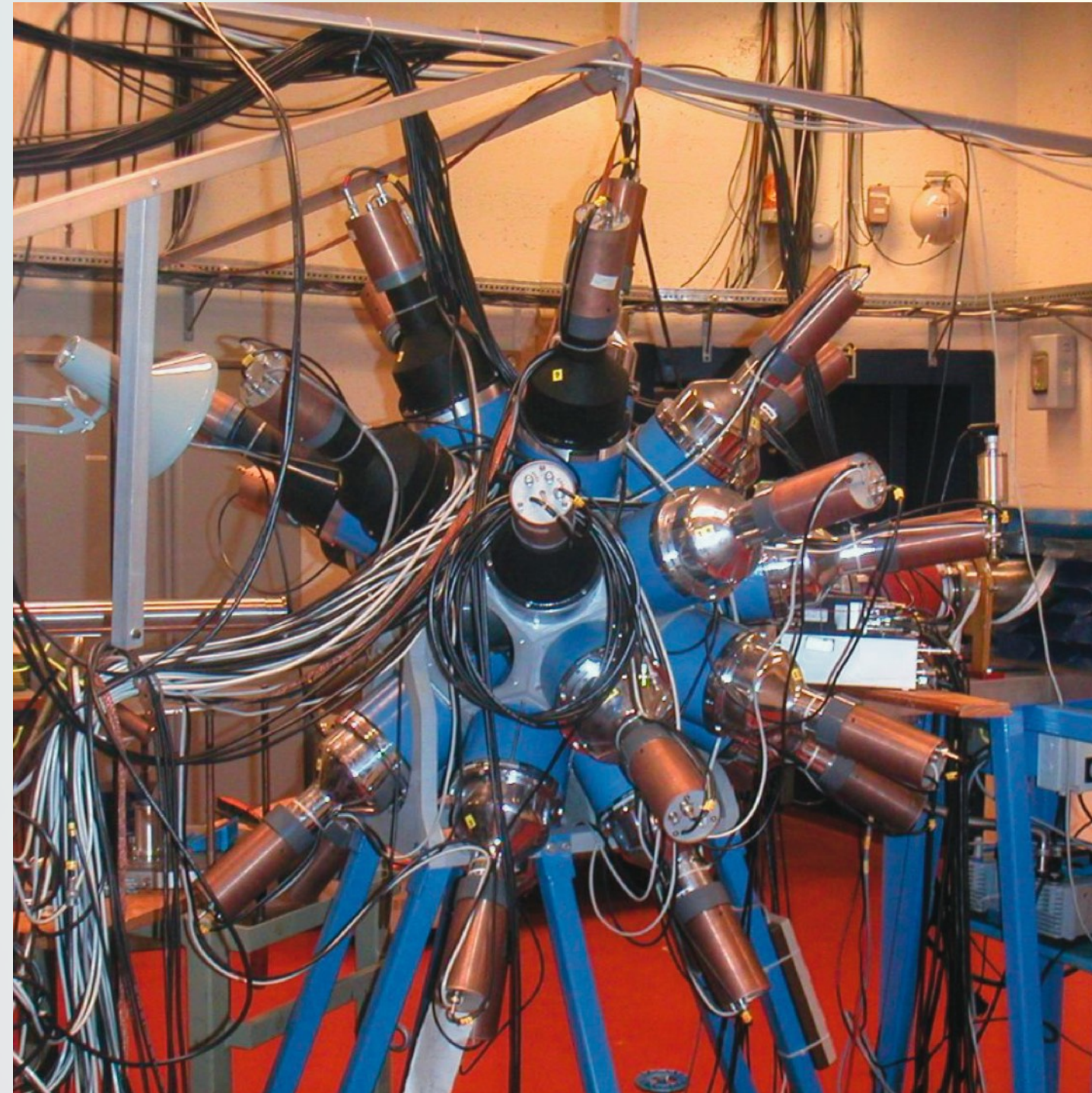
Guttormsen *et al.* (2011) [11]
<https://doi.org/10.1016/j.nima.2011.05.055>



- Silicon Ring (SiRi) particle telescope
- Eight trapezoidal dE-E detectors
- Backwards position: $\theta = 126^\circ\text{-}140^\circ$, 2° intervals
- Front position: $\theta = 40^\circ\text{-}54^\circ$, 2° intervals
- dE-detectors $130\ \mu\text{m}$, E-detectors $1550\ \mu\text{m}$

CACTUS

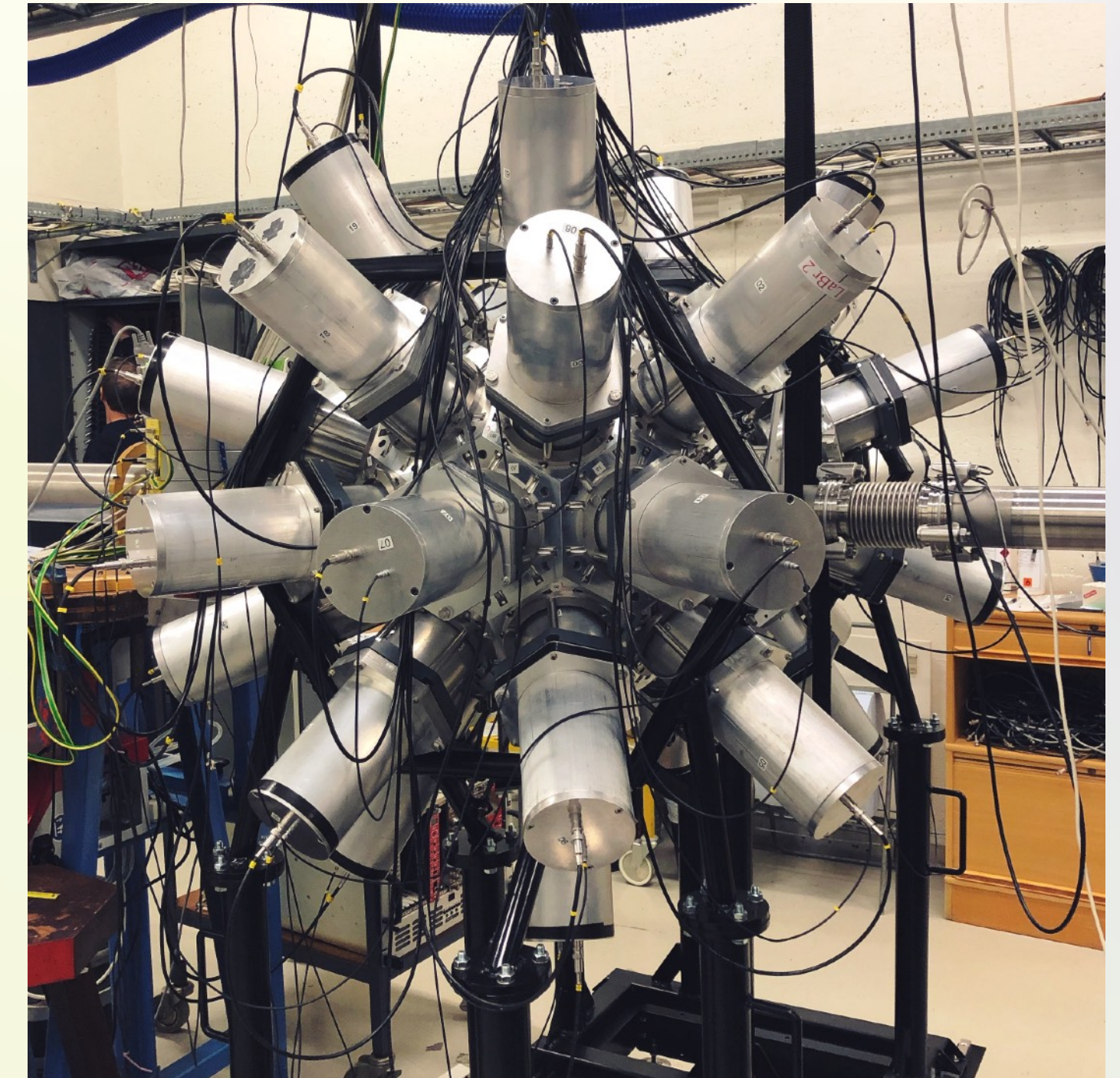
Guttormsen *et al.* (1990) [12]
DOI 10.1088/0031-8949/1990/T32/010



- 26 NaI detectors (5'' x 5'')
- Collimated with 10 cm of lead
- Each detector subtending a solid angle of $\sim 0.63\%$ of 4π
- Total gamma-ray efficiency (1.3 MeV) $\sim 14.1\%$
- Distance from target 22 cm

OSCAR

Zeiser *et al.* (2021) [13]
<https://doi.org/10.1016/j.nima.2020.164678>



- 30 LaBr₃ detectors (3.5'' x 8'')
- No collimation
- Each detector subtending a solid angle of $\sim 1.9\%$ of 4π
- Total gamma-ray efficiency (1.3 MeV) $\sim 56\%$
- Distance from target 16.3 cm

How can we measure the γ -decay branching ratio of the Hoyle state?

Amount of particles populating the Hoyle state resulting in the desired gamma cascade $^{12}\text{C}(p, p'\gamma_1\gamma_2)$

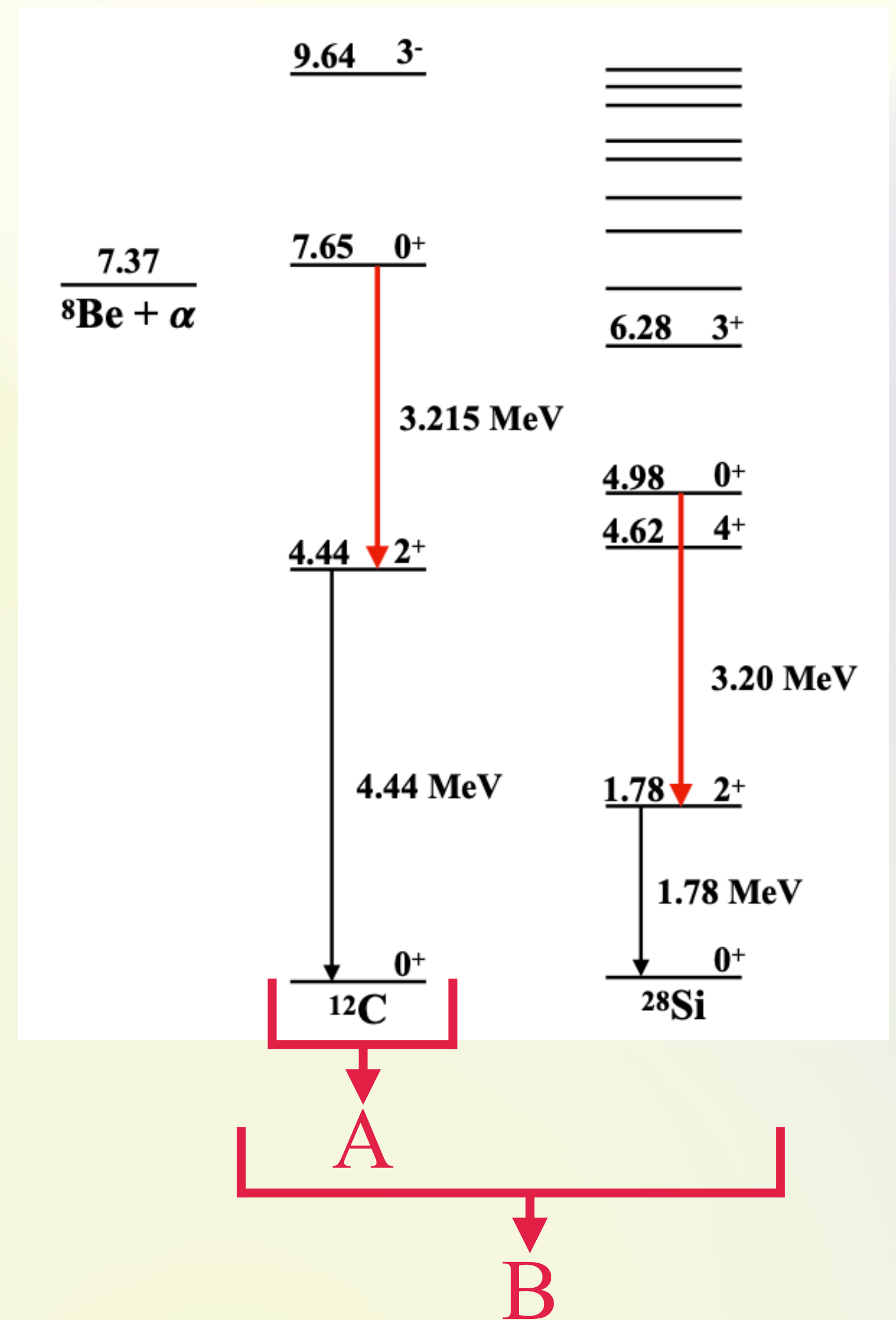
$$\times \text{Correction factors} = \Gamma_\gamma/\Gamma$$

Total amount of particles populating the Hoyle state $^{12}\text{C}(p, p'\gamma_1\gamma_2 + p'3\alpha + \dots)$

Same measurement: Two different equations to obtain Γ_γ/Γ

$$\mathbf{A} \quad \frac{\Gamma_\gamma^{E2}}{\Gamma^{7.65}} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

$$\mathbf{B} \quad \frac{\Gamma_\gamma^{7.65}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{\text{inclusive}}^{4.98}}{N_{\text{inclusive}}^{7.65}} \times \frac{\epsilon_{1.78}}{\epsilon_{4.44}} \times \frac{\epsilon_{3.20}}{\epsilon_{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}} \times \frac{c_{\text{det}}^{4.98}}{c_{\text{det}}^{7.65}}$$



How can we obtain the triple coincidences from the Hoyle state?

Amount of particles populating the Hoyle state resulting in the desired gamma cascade $^{12}\text{C}(p, p'\gamma_1\gamma_2)$

$$N_{020}^{7.65}$$

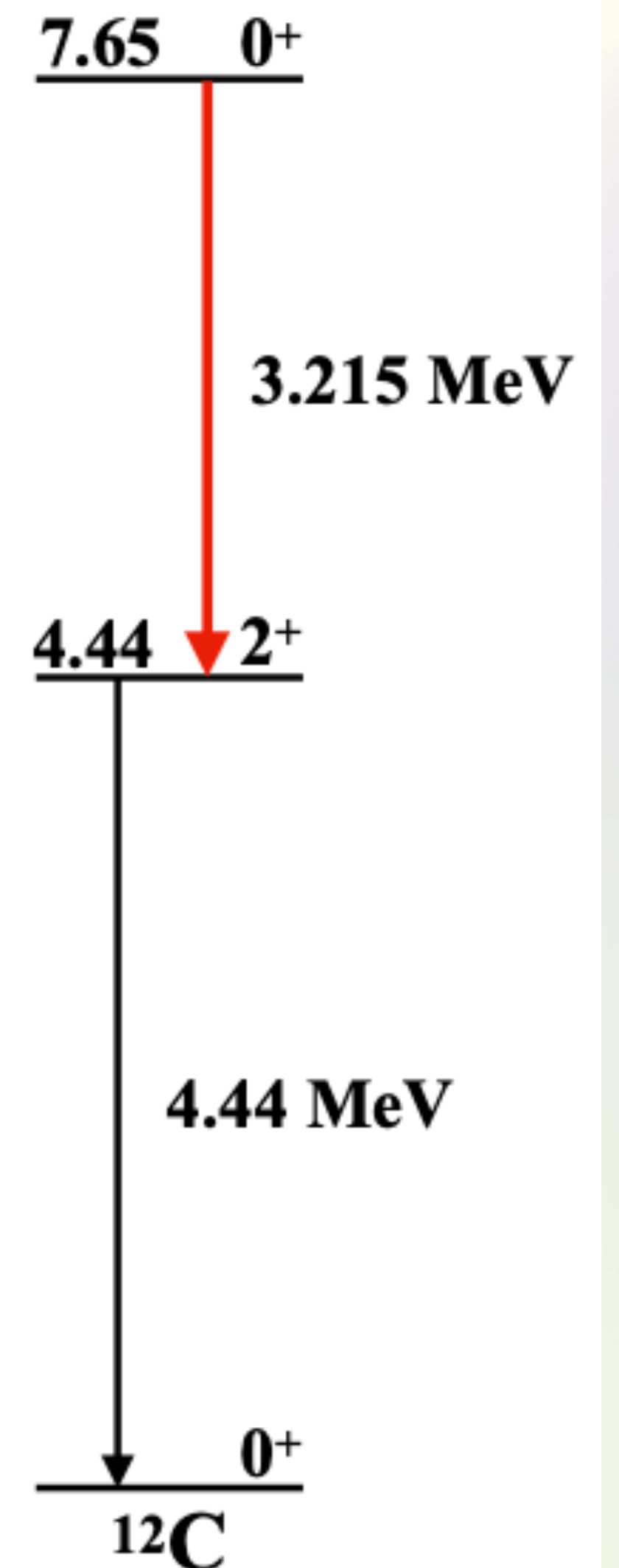
Correction factors depend on how triple coincidences are obtained

$$\frac{1}{\epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

Same measurement: Two different techniques to obtain triple coincidences

γ - γ method: Gate on proton and one γ ray and obtain the yield from the other.

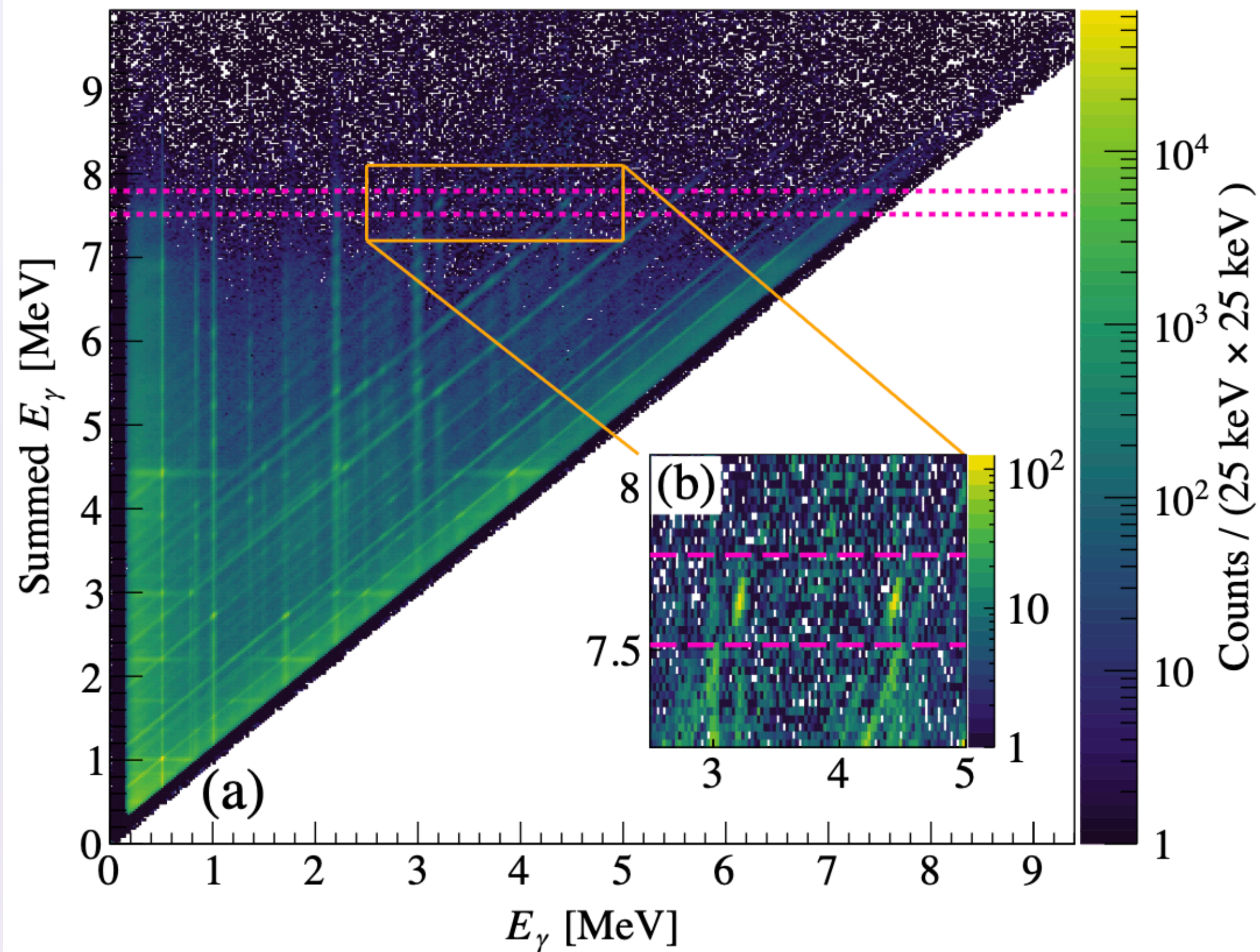
Summed- γ method: Gate on proton and both γ rays summed together.



$^{12}\text{C}(p,p')$ 2019: Extracting triple-coincidence yields

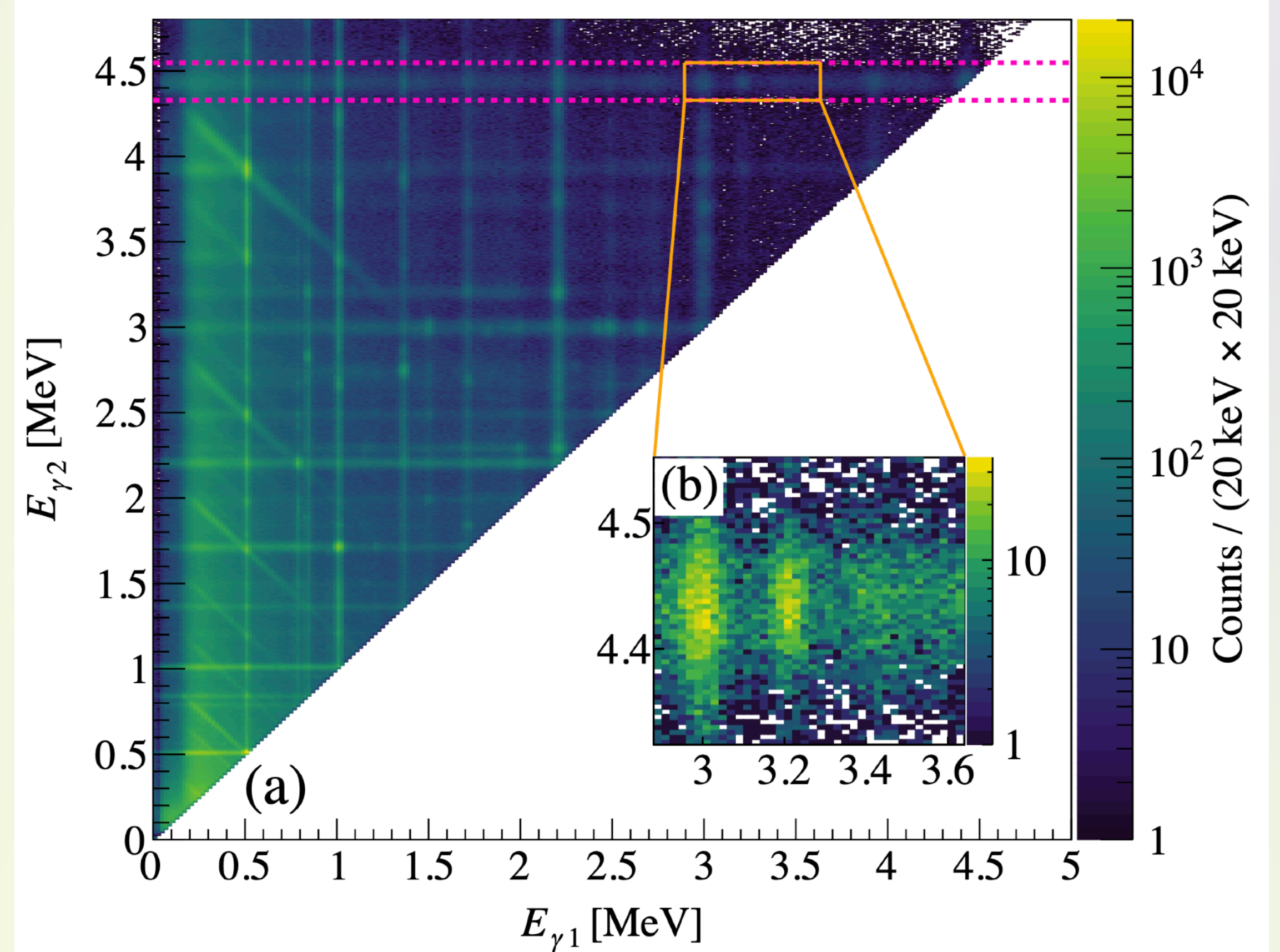
Summed- γ method

3σ gate around $E_\gamma = 7.65$ MeV and diagonal following the Compton scattered $E_\gamma = 4.44$ MeV γ ray from the $E_x = 4.44$ MeV 2_1^+ in ^{12}C .



γ - γ method

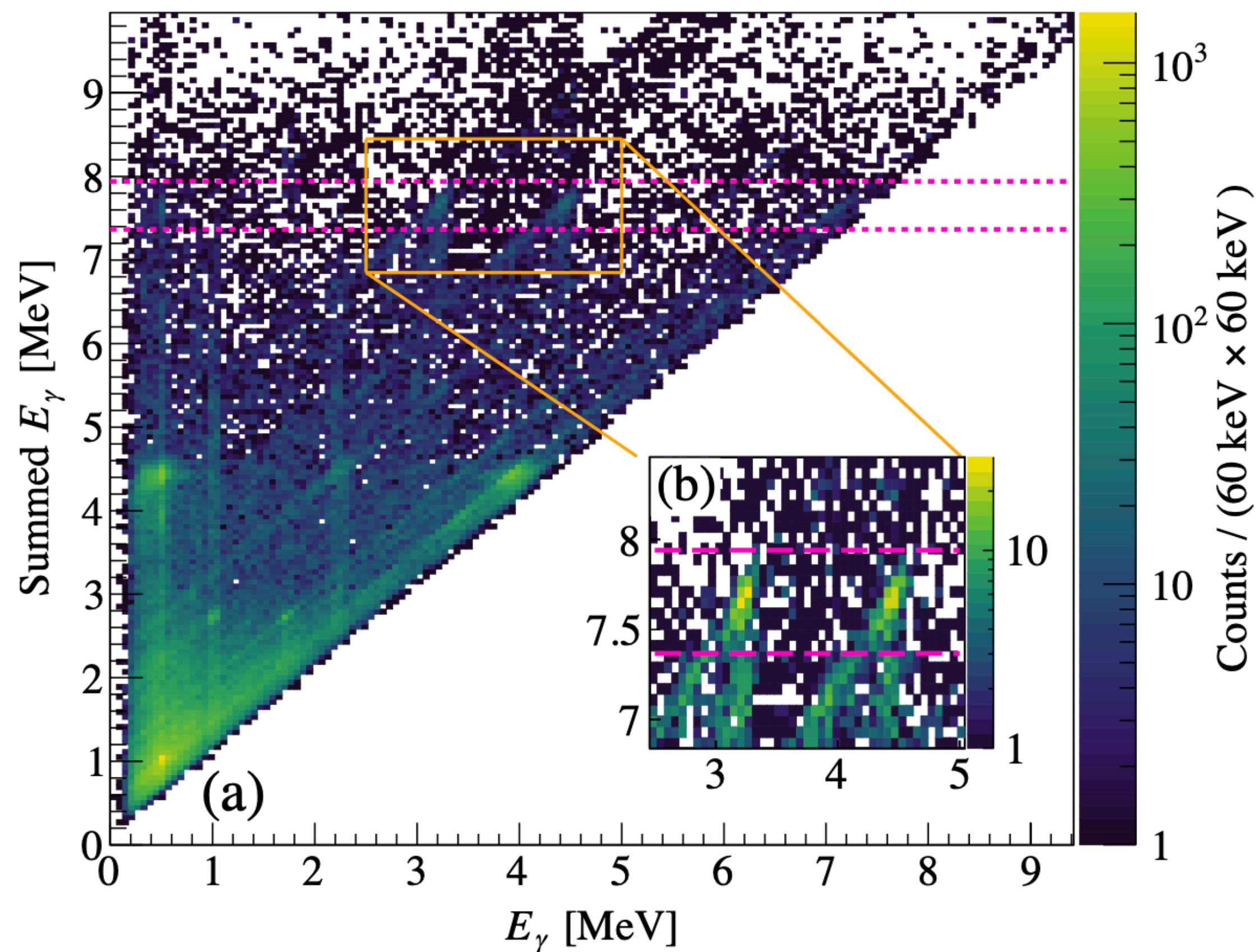
3σ gate around $E_\gamma = 4.44$ MeV from Hoyle state cascade of the $E_x = 7.65$ MeV 0_2^+ in ^{12}C .



$^{12}\text{C}(p,p')$ 2014: Extracting triple-coincidence yields

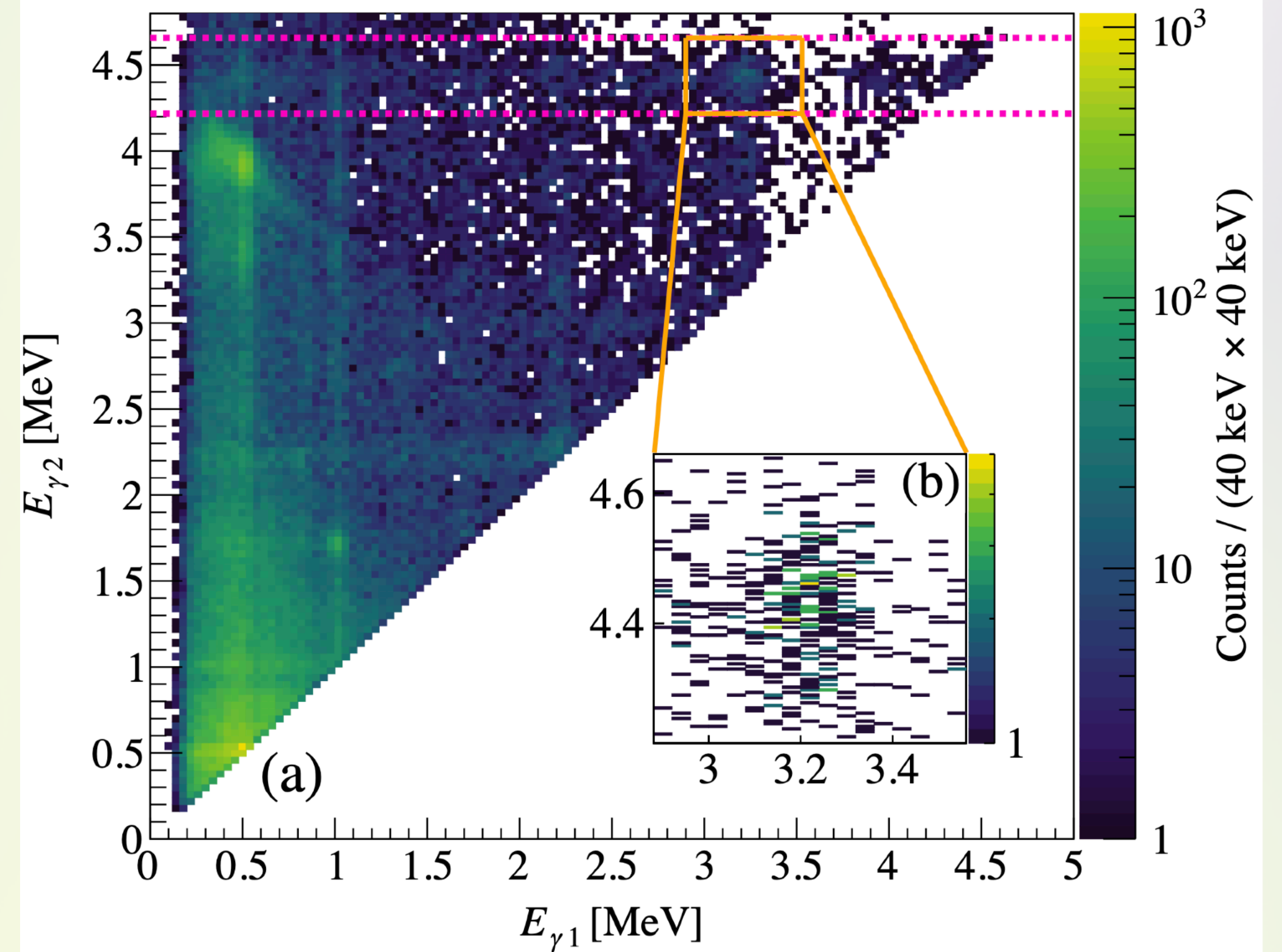
Summed- γ method

3σ gate around $E_\gamma = 7.65$ MeV and diagonal following the Compton scattered $E_\gamma = 4.44$ MeV γ ray from the $E_x = 4.44$ MeV 2_1^+ in ^{12}C .

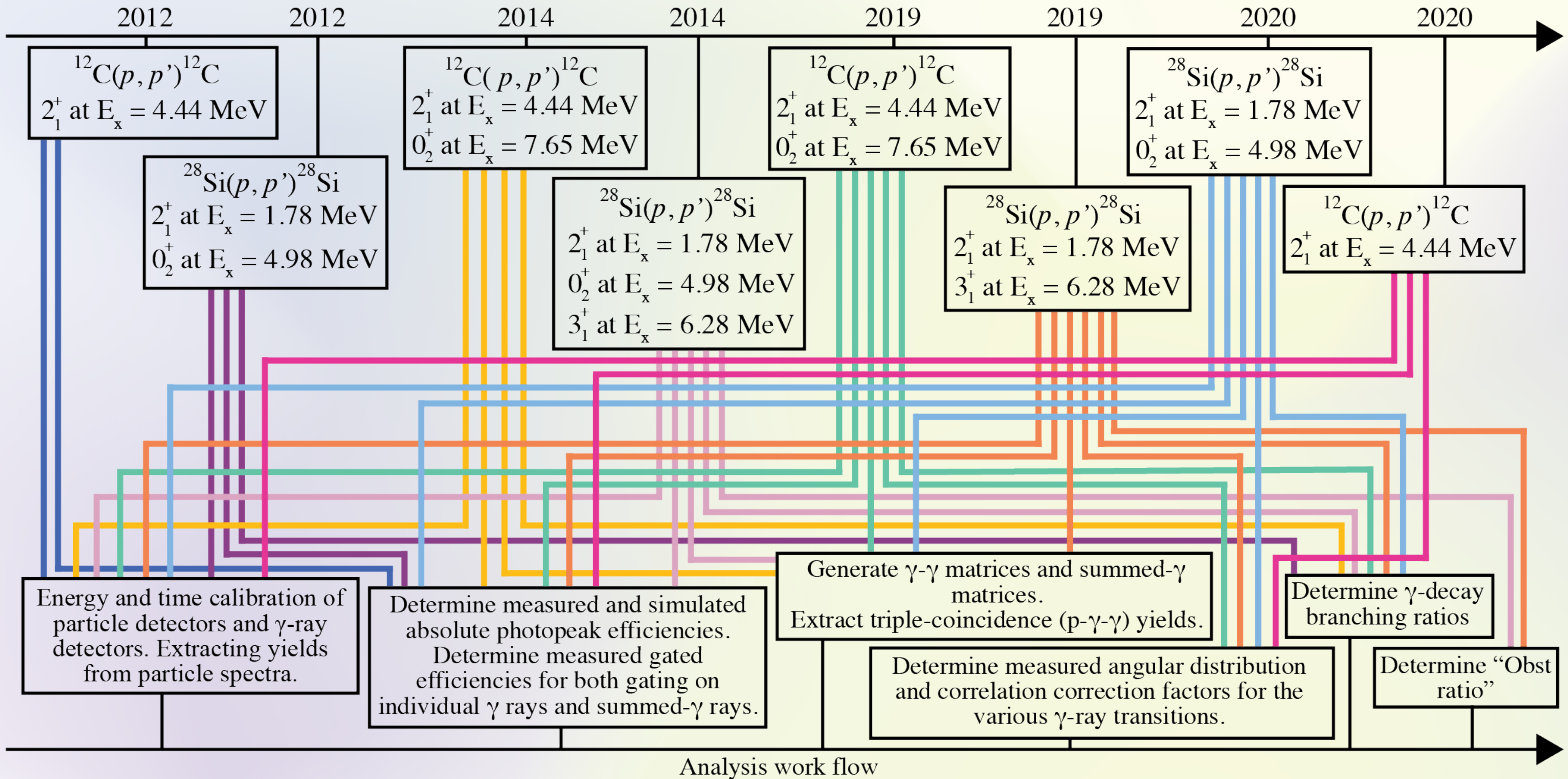


γ - γ method

3σ gate around $E_\gamma = 4.44$ MeV from Hoyle state cascade of the $E_x = 7.65$ MeV 0_2^+ in ^{12}C .



Measurements in this work and analysis pipeline

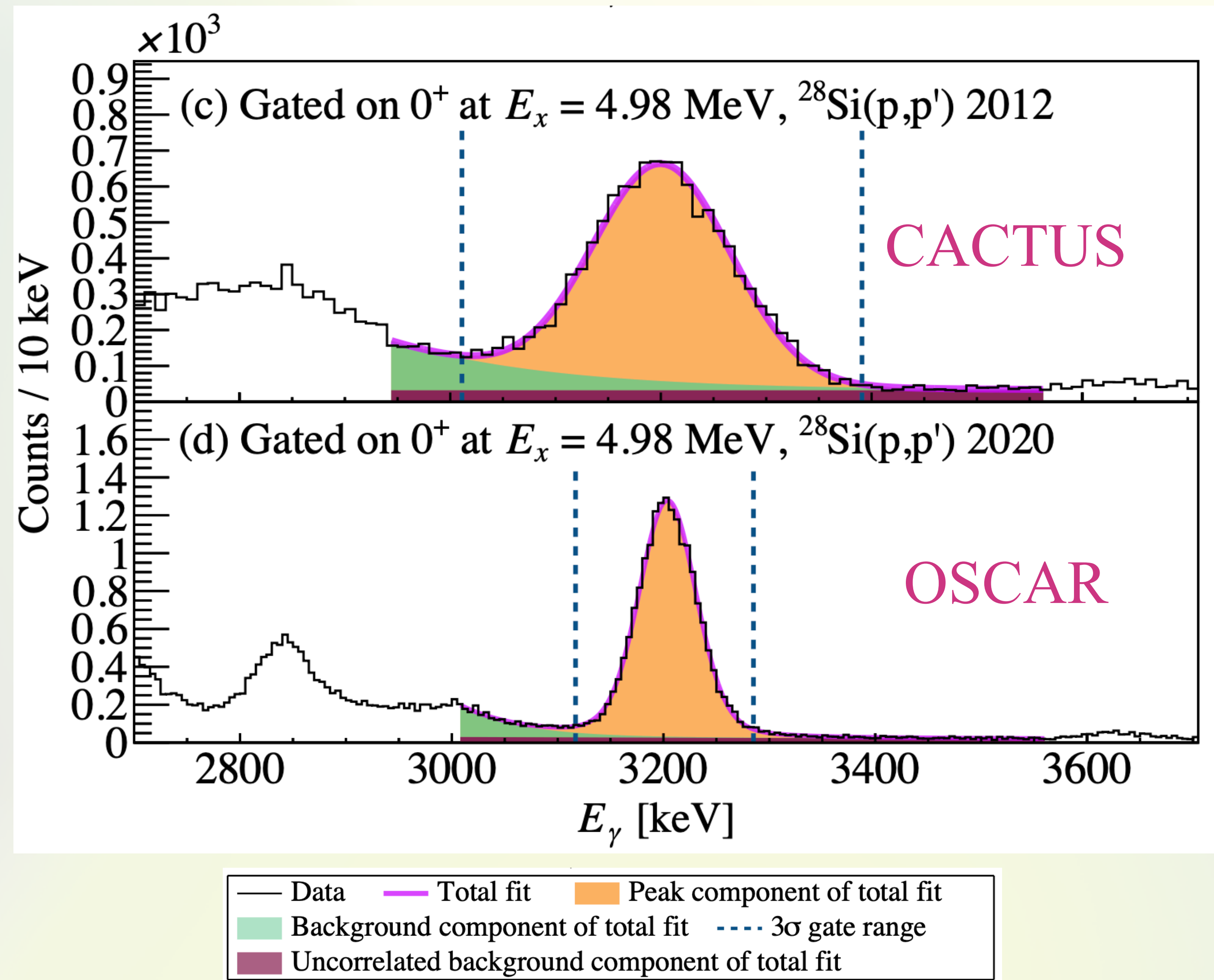


The effect of gating on a γ -ray on the definition of efficiency

When extracting the γ -decay branching ratio using **triple coincidences**, the γ ray being gated on **must** be defined as a **gated efficiency**, and not as **absolute photopeak efficiency**.

$$\frac{\Gamma_{\gamma}^{E2}}{\Gamma^{7.65}} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

Depending on the **resolution** of the detectors, events within the gate might fall **outside** the **absolute photopeak**, but will still yield valid **triple coincidences**: These events **must** be accounted for.

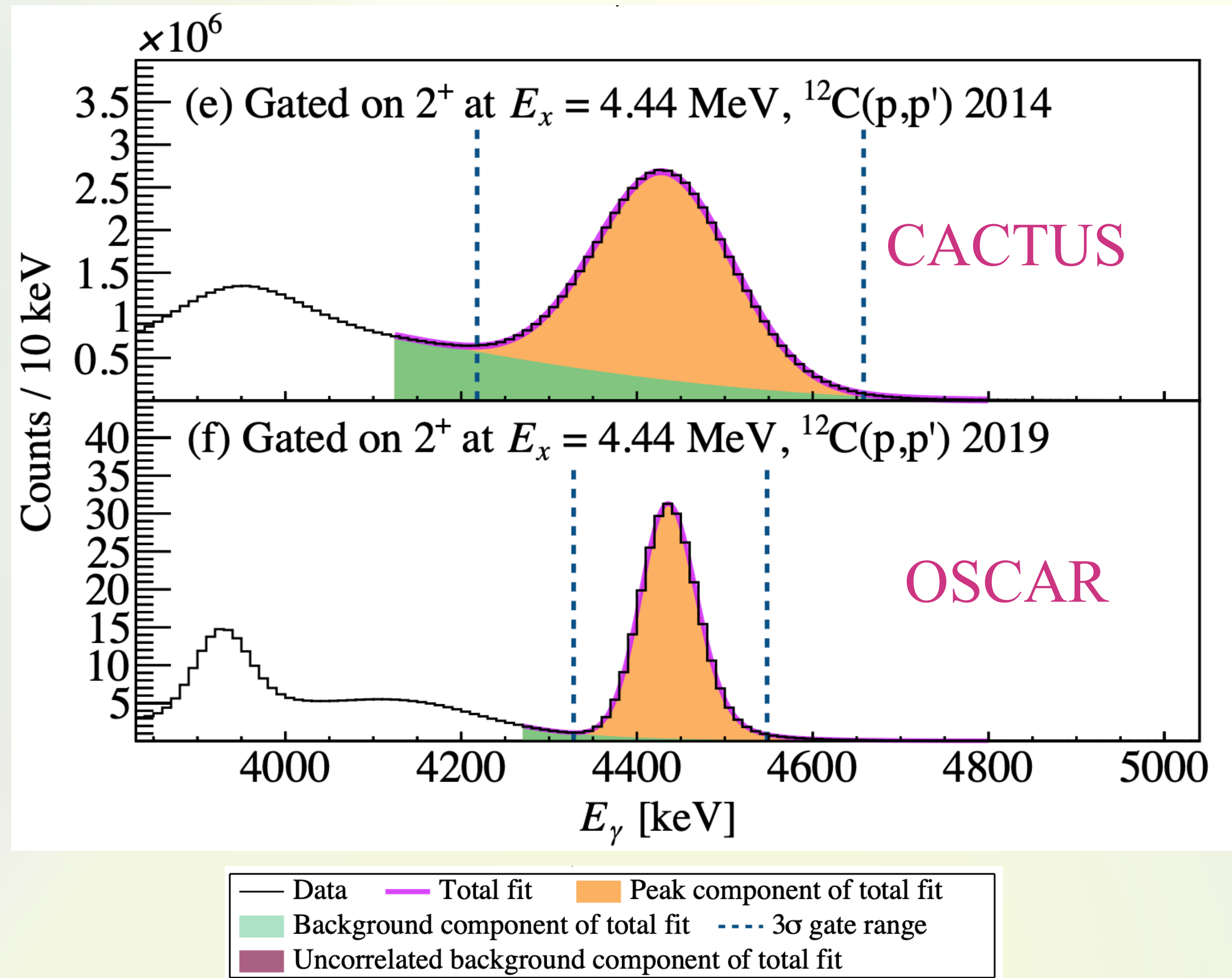


The effect of gating on a γ -ray on the definition of efficiency

When extracting the γ -decay branching ratio using **triple coincidences**, the γ ray being gated on **must** be defined as a **gated efficiency**, and not as **absolute photopeak efficiency**.

$$\frac{\Gamma_{\gamma}^{E2}}{\Gamma^{7.65}} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

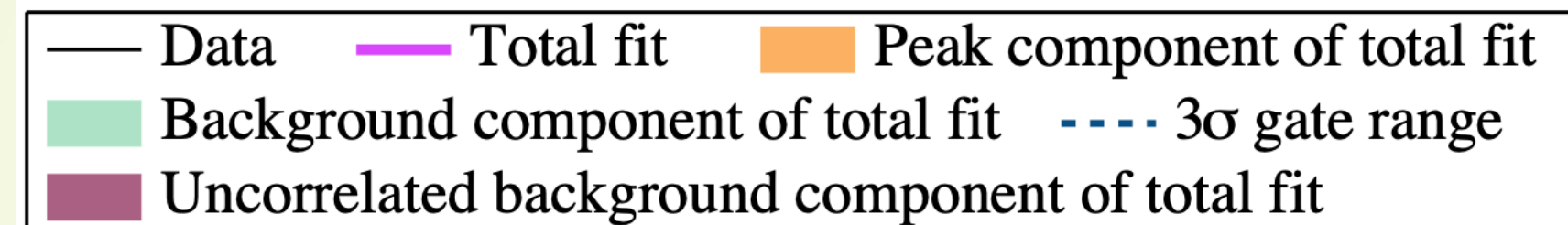
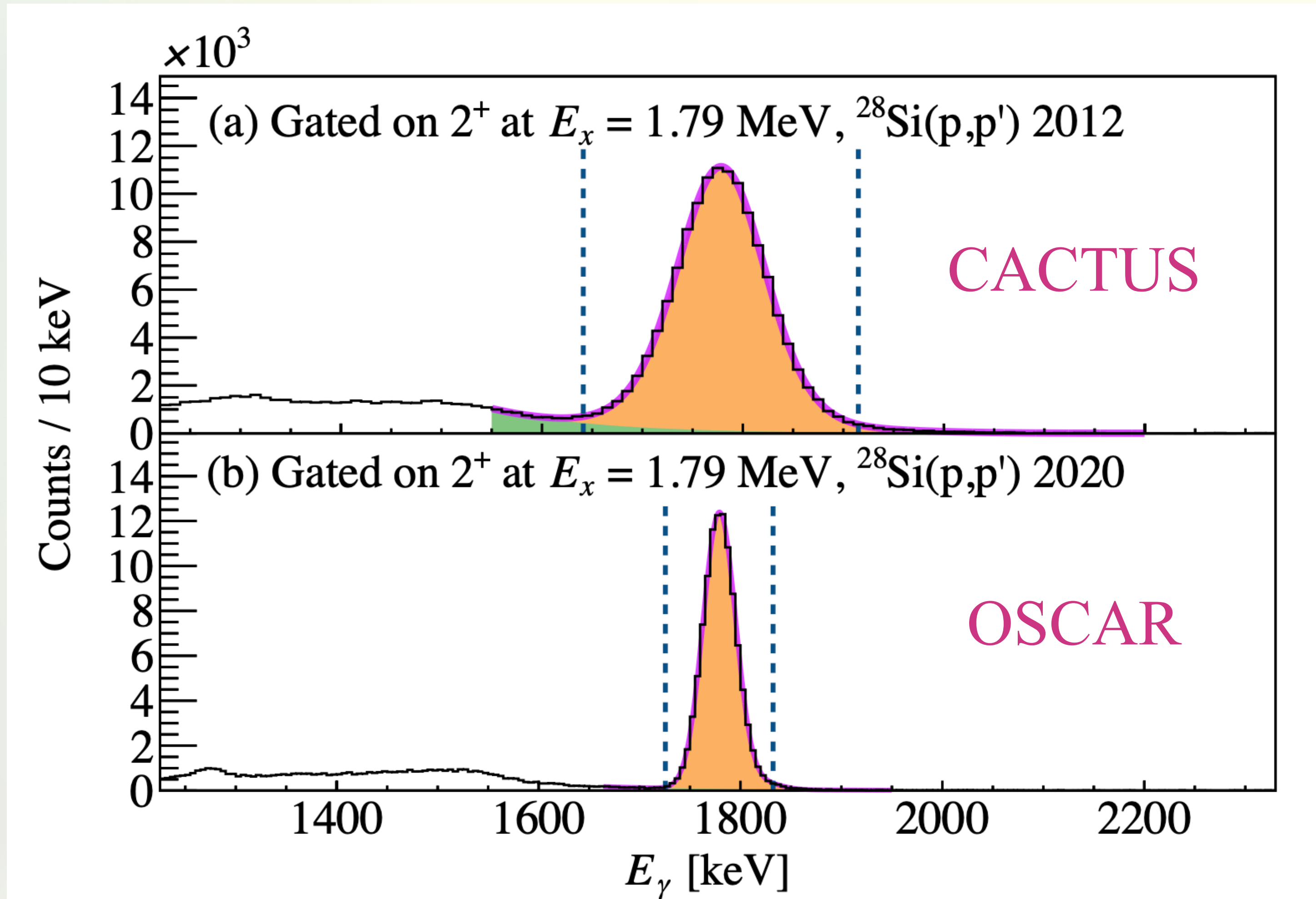
Depending on the **resolution** of the detectors, events within the gate might fall **outside** the **absolute photopeak**, but will still yield valid **triple coincidences**: These events **must** be accounted for.



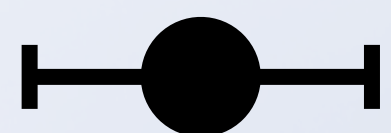
The effect of gating on a γ -ray on the definition of efficiency

Since this effect is **energy dependent**, validating with the $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in ^{28}Si will yield results consistent with **literature value** even **without** taking this effect into account.

$$\frac{\Gamma_{\gamma}^{E2}}{\Gamma^{4.98}} = \frac{N_{020}^{4.98}}{N_{\text{inclusive}}^{4.98} \times \epsilon_{1.78} \times \epsilon_{3.20} \times c_{\text{det}} \times W_{020}^{4.98}} = 1.0$$



Results of this work: Radiative branching ratio of the Hoyle state



Original result as published



Published result is excluded



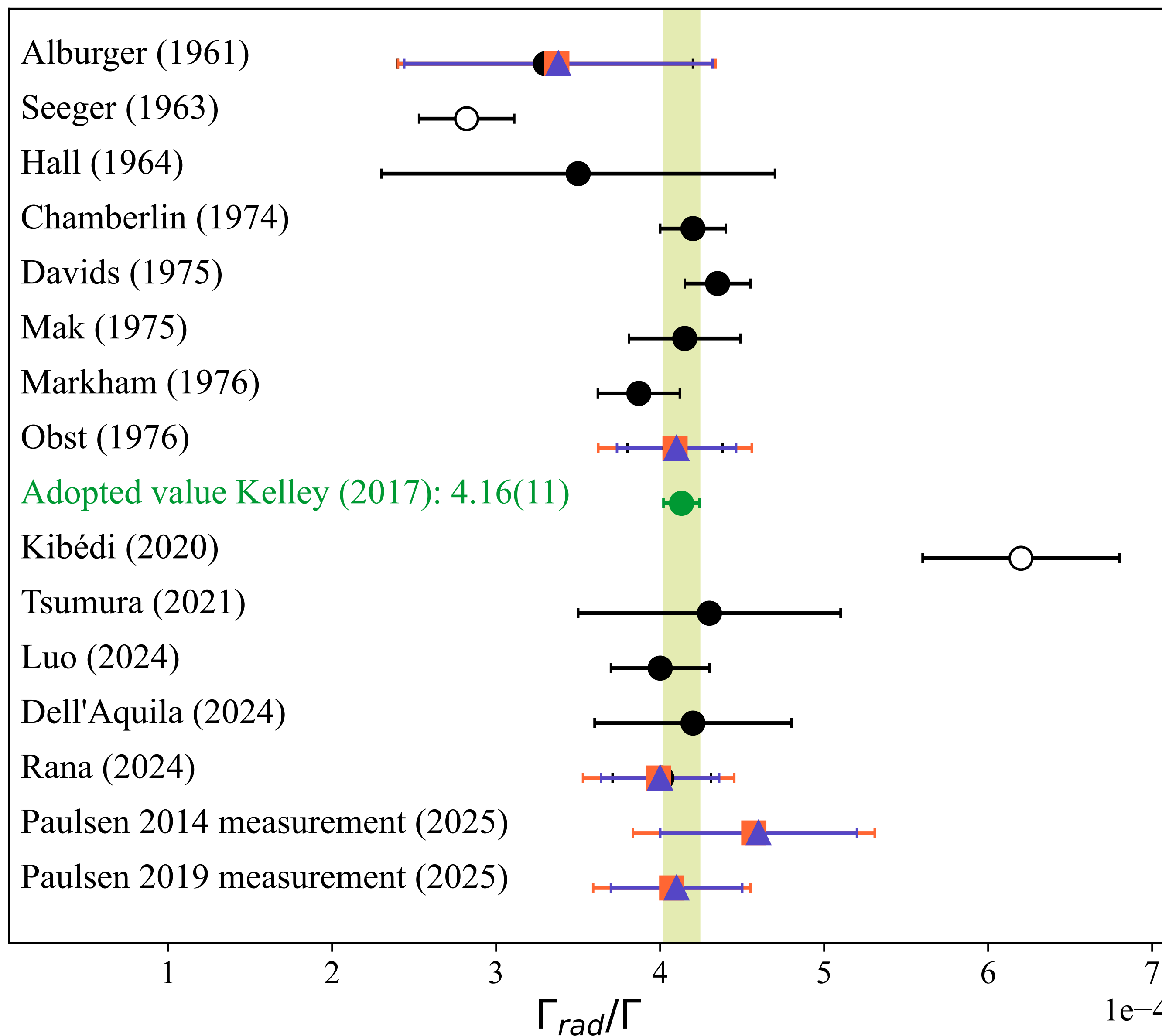
Indirect measurement utilizing Γ_{π} / Γ from Kelley *et al.* (2017)



Indirect measurement utilizing Γ_{π} / Γ from Eriksen *et al.* (2020)

(Adopted value uncertainty reduced from 9% to 5%)

$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2} (1 + \alpha_{\text{tot}}) + \Gamma_{\pi}^{E0}}{\Gamma}$$



Corrections to Kibédi *et al.* (2020)

- Throughout the reanalysis of the 2014 measurement, several necessary corrections to Kibédi *et al.* (2020) [9] were discovered.
- **The absolute photopeak efficiencies** presented in the Kibédi *et al.* (2020) [9] are not **absolute**, but **relative**.
 - Efficiencies in Kibédi *et al.* (2020) [9] are simulated using PENELOPE.
 - Approximately a factor $\sqrt{2}$ difference from the experimental efficiencies obtained in this work.
- **The detector combinations** used by Kibédi *et al.* (2020) [9] was $c_{\text{det}} = 325$. The true number of detector combinations should be $c_{\text{det}} = 650$.
- **The relative photopeak efficiencies** utilised in all results by Kibédi *et al.* (2020) [9] did **not** take the events in the **smooth Compton continuum** into account.

$$\mathbf{A} \quad \frac{\Gamma_{\gamma}^{E2}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{\text{inclusive}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times c_{\text{det}} \times W_{020}^{7.65}}$$

$$\mathbf{B} \quad \frac{\Gamma_{\gamma}^{7.65}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{\text{inclusive}}^{4.98}}{N_{\text{inclusive}}^{7.65}} \times \frac{\epsilon_{1.78}}{\epsilon_{4.44}} \times \frac{\epsilon_{3.20}}{\epsilon_{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}} \times \frac{c_{\text{det}}^{4.98}}{c_{\text{det}}^{7.65}}$$



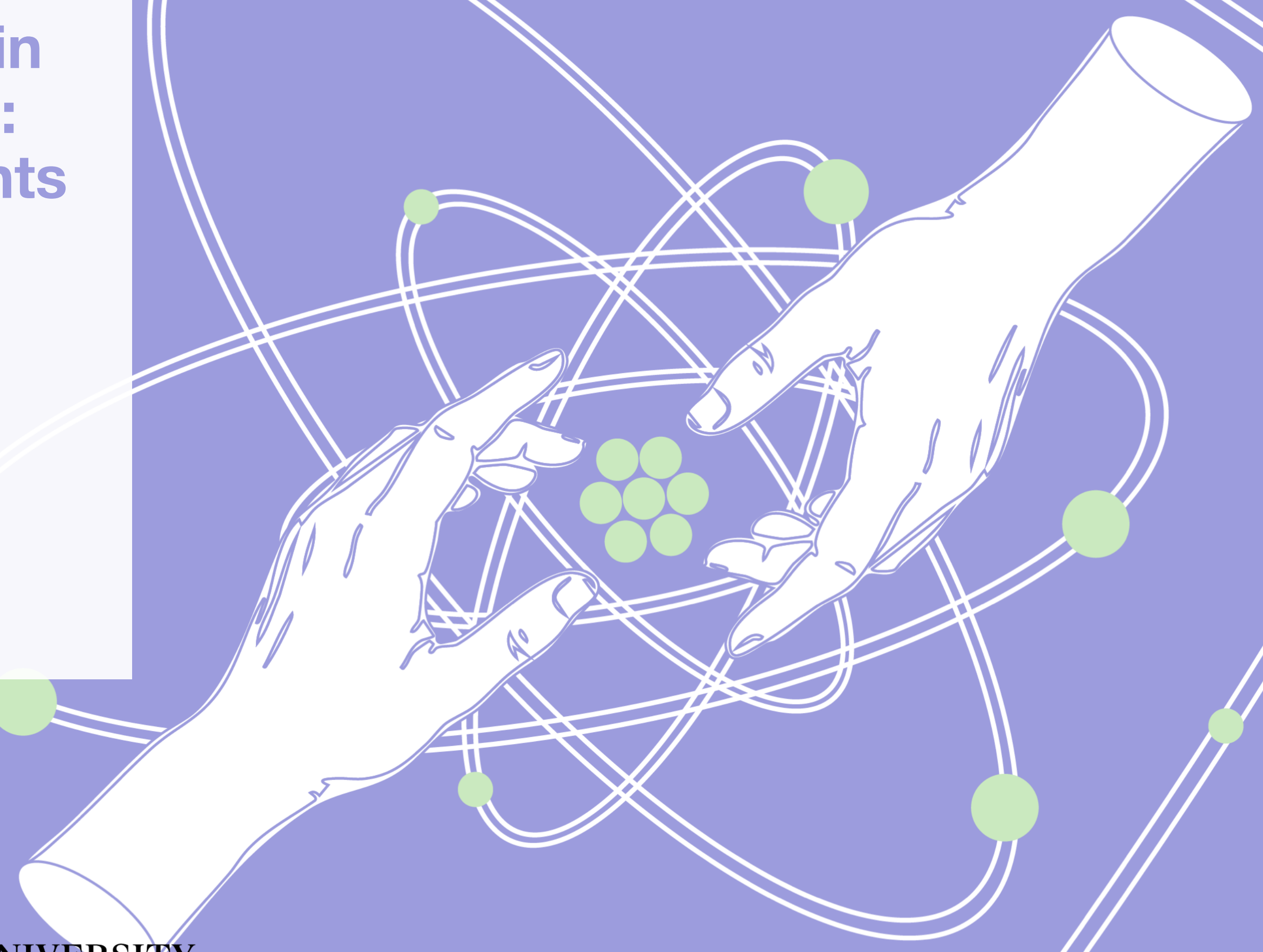
Summary

- A new measurement of the gamma-decay branching ratio of the Hoyle state in ^{12}C was performed at OCL.
 - The results agree well with the previously adopted value from Kelley *et al.* (2017) of $\Gamma_{rad}/\Gamma = 4.16(11) \times 10^{-4}$.
- A reanalysis of the data published by Kibédi *et al.* (2020) was performed.
 - Several necessary corrections to the results published by Kibédi *et al.* (2020) was found.
 - The source of the discrepancy in Kibédi *et al.* (2020) was discovered; the main contribution to the discrepancy originates in the efficiencies utilised.
- The scientific community has successfully reduced the uncertainty of the radiative width of the Hoyle state further.

Advanced Measurements in
Carbon-fusion REactions:
Cross-section Measurements
and Branching Ratios

AMiCARE

A FRIPRO international
mobility project



UNIVERSITY
OF OSLO

- Started 01.05.2026, ends: 30.04.2030.
- “The main objective of this call is **career development** and **independence** for a researcher at the **start** of their career. You get the opportunity to lead your own research project and spend 1-2 years at one or two foreign research organisations. “

The screenshot shows the website for the Research Council of Norway. The header includes the logo and name 'The Research Council of Norway', navigation links for 'Norsk', 'The Project Databank', and 'Log in', a search bar, and a 'Menu' button. The breadcrumb trail reads 'HOME | CALLS FOR PROPOSALS – APPLICATION RESULTS | RESEARCHER PROJECT WITH INTERNATIONAL MOBILITY (FRIPRO)'. Below this are buttons for 'APPLY NOW' and 'SEE RESULT'. The main title is 'Researcher Project with International Mobility (FRIPRO)'. Metadata includes 'PUBLISHED 17 JUN 2025 | LAST UPDATED 11 DEC 2025' and 'SHARE | DOWNLOAD' options. The content is organized into two columns. The left column lists: 'Financial scheme: Researcher Project', 'Application deadline: Open-ended', 'Relevant thematic areas for this call: [Ground-breaking research](#)', and 'Target groups: Research organisations'. The right column lists: 'Funding scale: NOK 4 700 000-7 400 000', 'Amount of funding presumed available for this call for proposals: NOK 40 000 000. The FRIPRO scheme's annual budget of up to NOK 1,3 billion is tentatively divided between our three open-ended calls for proposals: (Three-Year) Researcher Project with International Mobility (FRIPRO), Researcher Projects for Early Career Scientists (FRIPRO) and Researcher Projects for Experienced Scientists (FRIPRO).', 'Project duration: 36-48 months', and 'Contact: [Send us your question](#)'. At the bottom, there are buttons for 'Create application' and 'Download all files'.

The Research Council of Norway

Norsk The Project Databank Log in Search Menu

HOME | CALLS FOR PROPOSALS – APPLICATION RESULTS | RESEARCHER PROJECT WITH INTERNATIONAL MOBILITY (FRIPRO)

APPLY NOW SEE RESULT

Researcher Project with International Mobility (FRIPRO)

PUBLISHED 17 JUN 2025 | LAST UPDATED 11 DEC 2025 SHARE DOWNLOAD

Financial scheme: Researcher Project

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Contact: [Send us your question](#)

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**UNIVERSITY
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AMiCARE



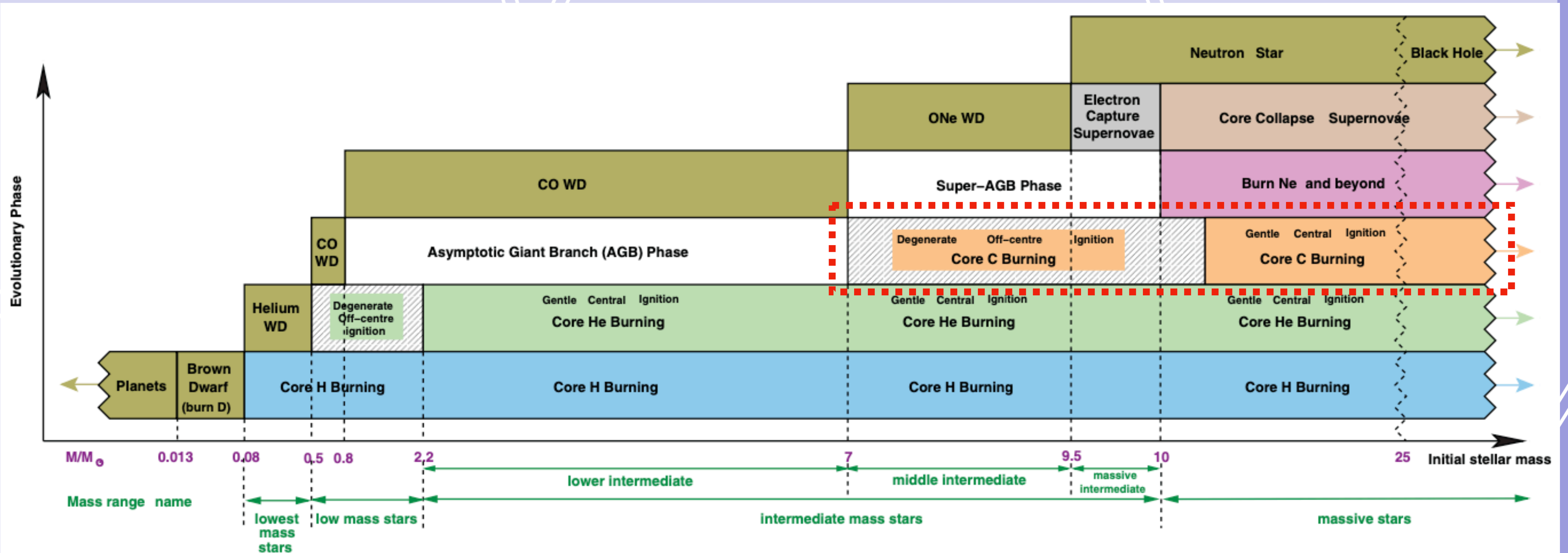
UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

- First two years at University of Naples Federico II in Italy, project collaborator is professor Gianluca Imbriani, part of the LUNA and ERNA collaborations.
- Will perform two carbon-fusion measurements at Centre for Isotopic Research on Cultural and Environmental Heritage (CIRCE) in Caserta, Italy.
- Last two years I will spend in Norway, performing experiments at the Oslo Cyclotron Laboratory, continue developing my research career and try to apply my experiences here.
- However, this grant is designed so I can change my plans as I go along.



AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$

The various phases of stellar fusion and the final outcomes

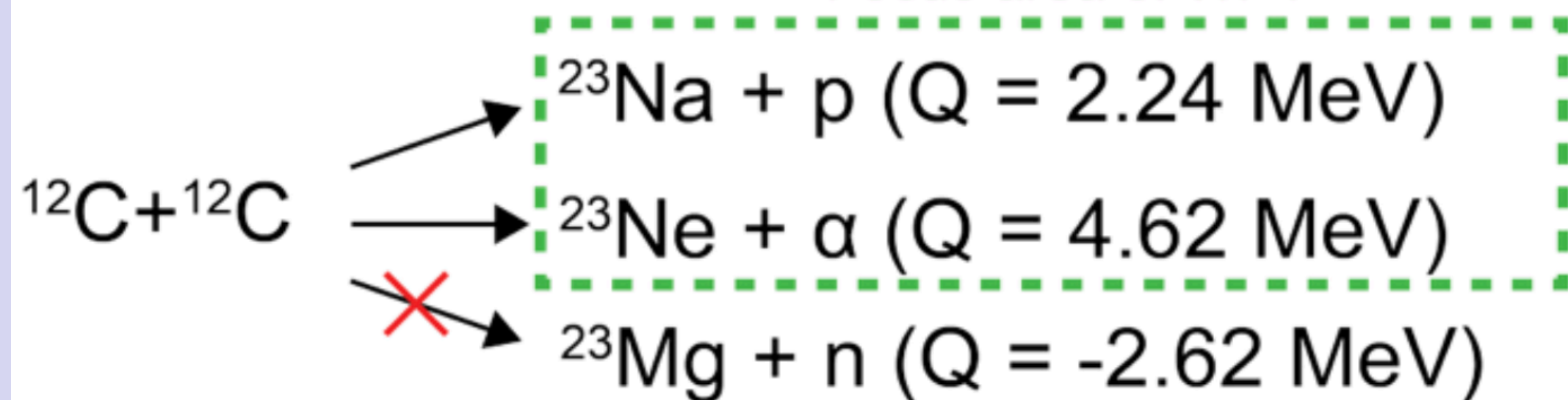


Karakas, A.I. and Lattanzio, J.C. (2014) 'The Dawes Review 2: Nucleosynthesis and Stellar Yields of Low- and Intermediate-Mass Single Stars', Publications of the Astronomical Society of Australia, 31, p. e030. doi:10.1017/pasa.2014.21.

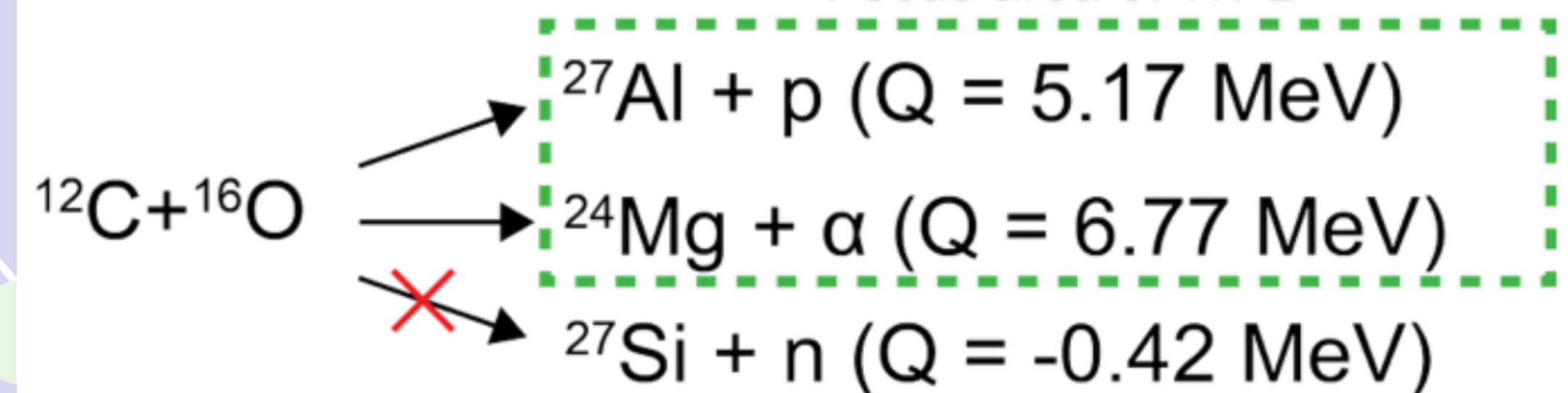
AMiCARE primary objective

- The $^{12}\text{C}+^{12}\text{C}$ and $^{12}\text{C}+^{16}\text{O}$ reactions are key areas for understanding evolution of massive stars and explosive scenarios such as type-Ia supernovae and superbursts in binary stars.
- The state-of-the-art measurements of these cross-sections have significant uncertainties and discrepancies.
- These cross-sections are important to obtain reaction rates used in large astrophysical stellar models.
- First part of AMiCARE: Cross-section measurements of $^{12}\text{C}+^{12}\text{C}$ and $^{12}\text{C}+^{16}\text{O}$ reactions.

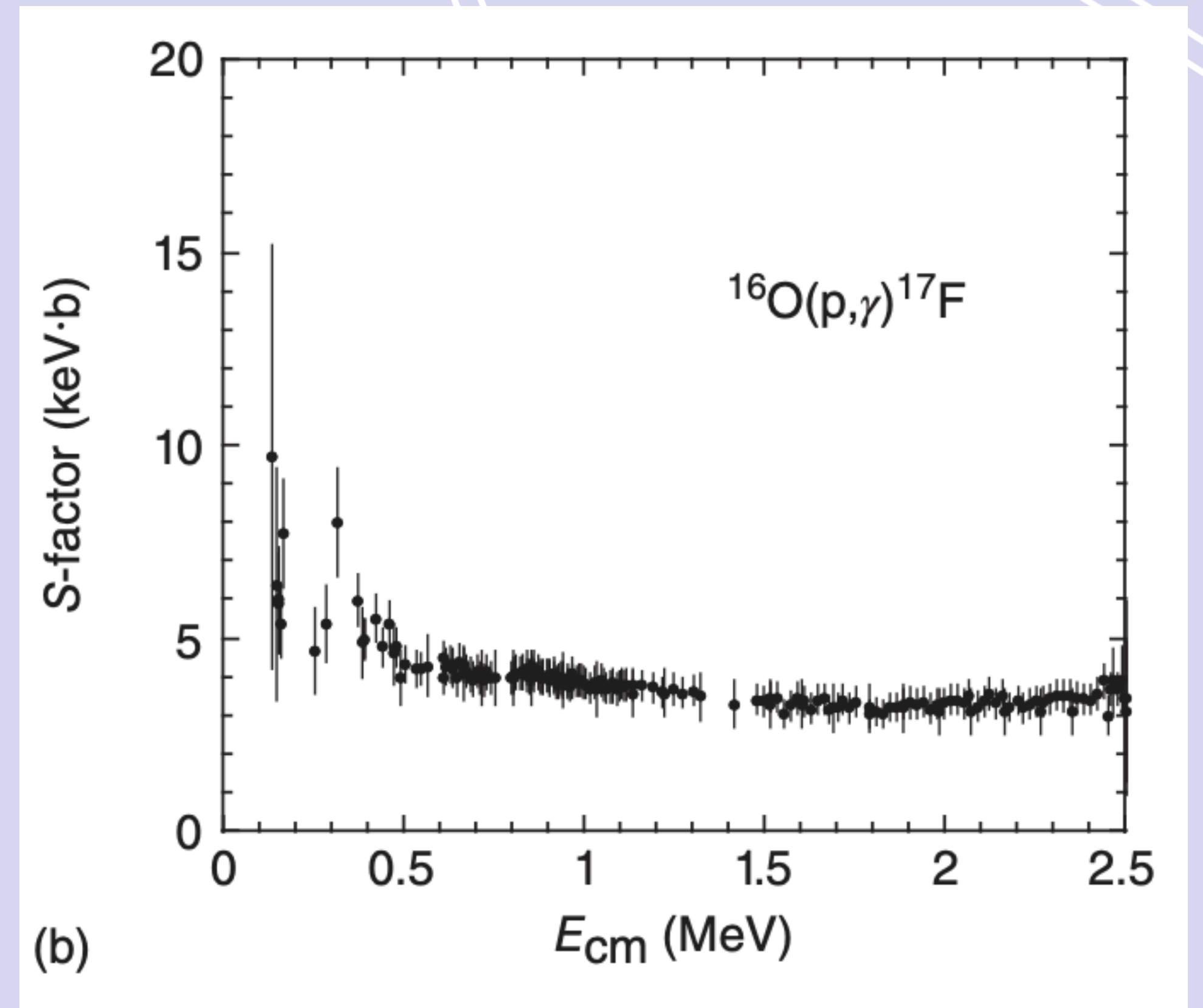
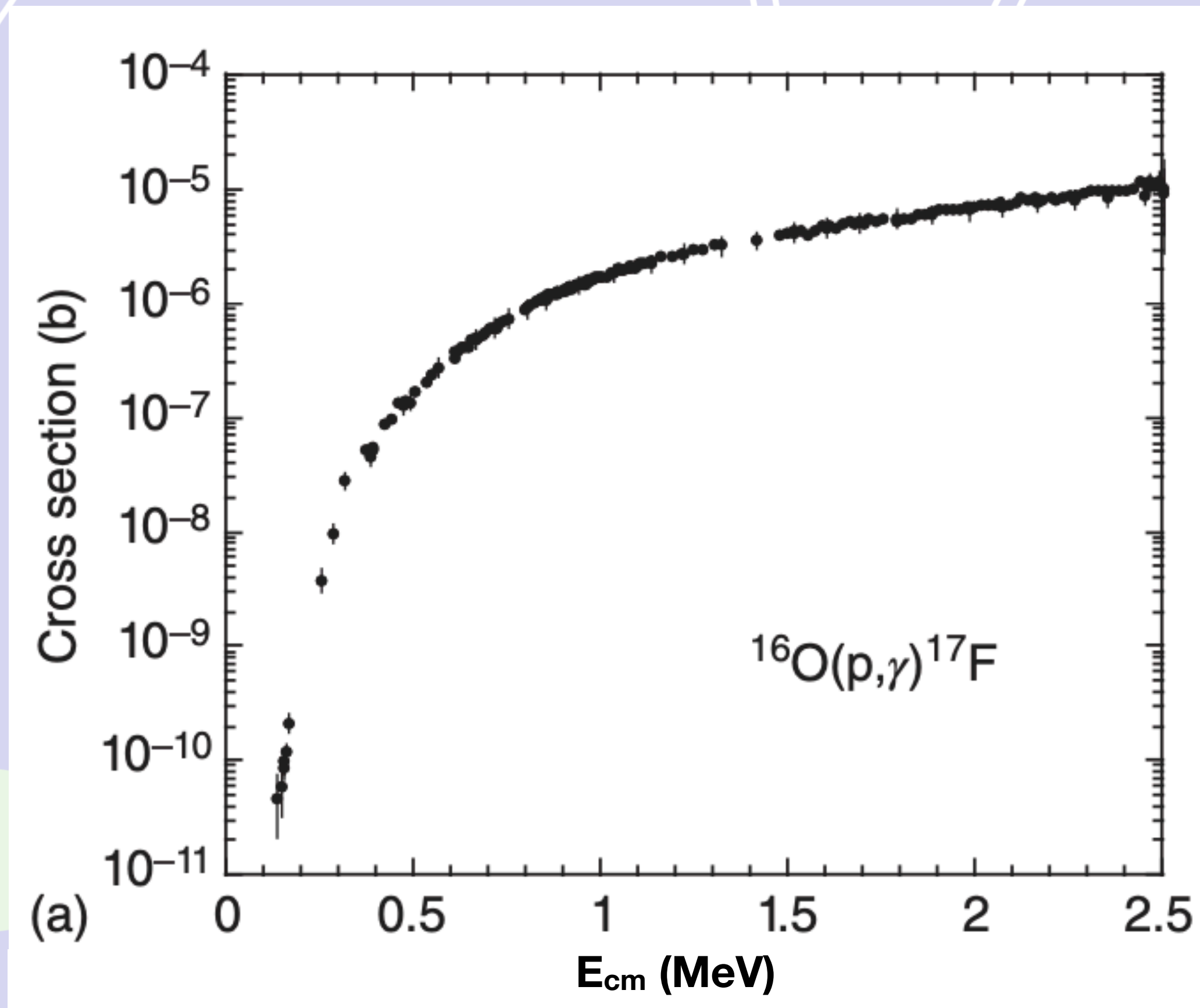
Focus area of WP1



Focus area of WP2



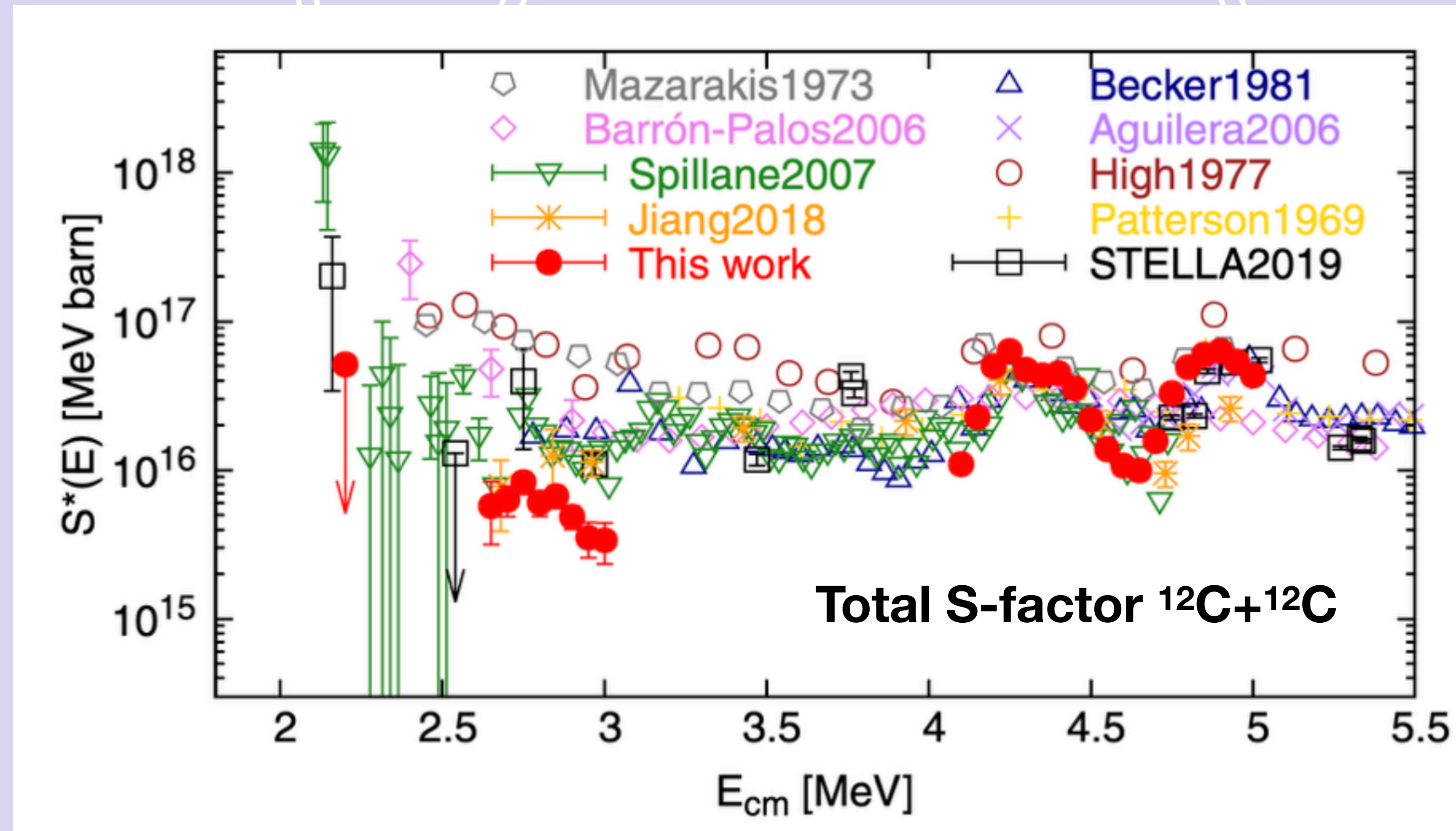
AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$



C. Iliadis, Nuclear physics of stars

The astrophysical S-factor: A way of rewriting nuclear reaction cross sections so that the strongly energy-dependent behaviour is factored out, leaving behind a much smoother function of energy.

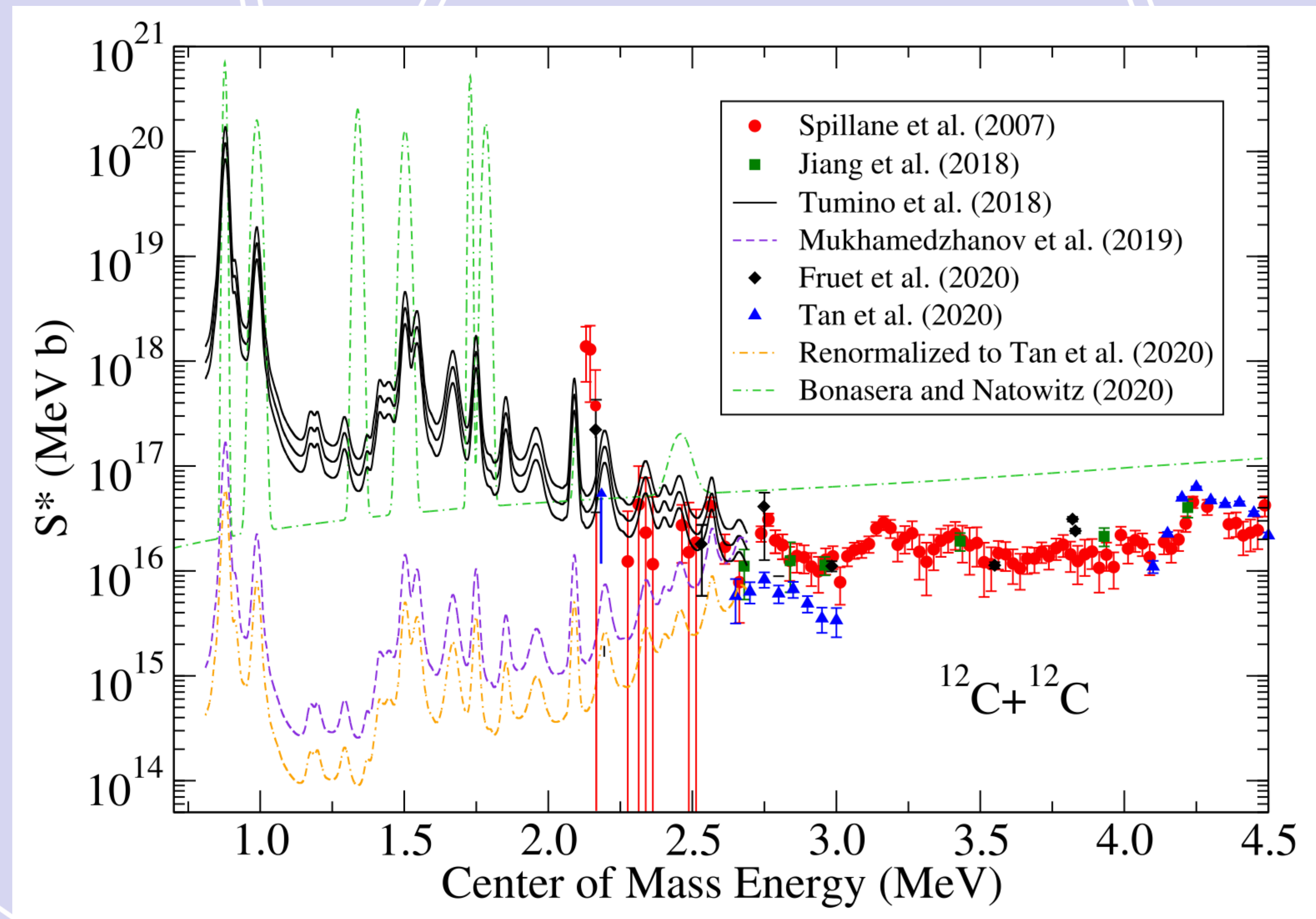
AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$



W. P. Tan *et al.*, Phys. Rev. Lett. 124, 192702 (2020)

The astrophysical S-factor: A way of rewriting nuclear reaction cross sections so that the strongly energy-dependent behaviour is factored out, leaving behind a much smoother function of energy.

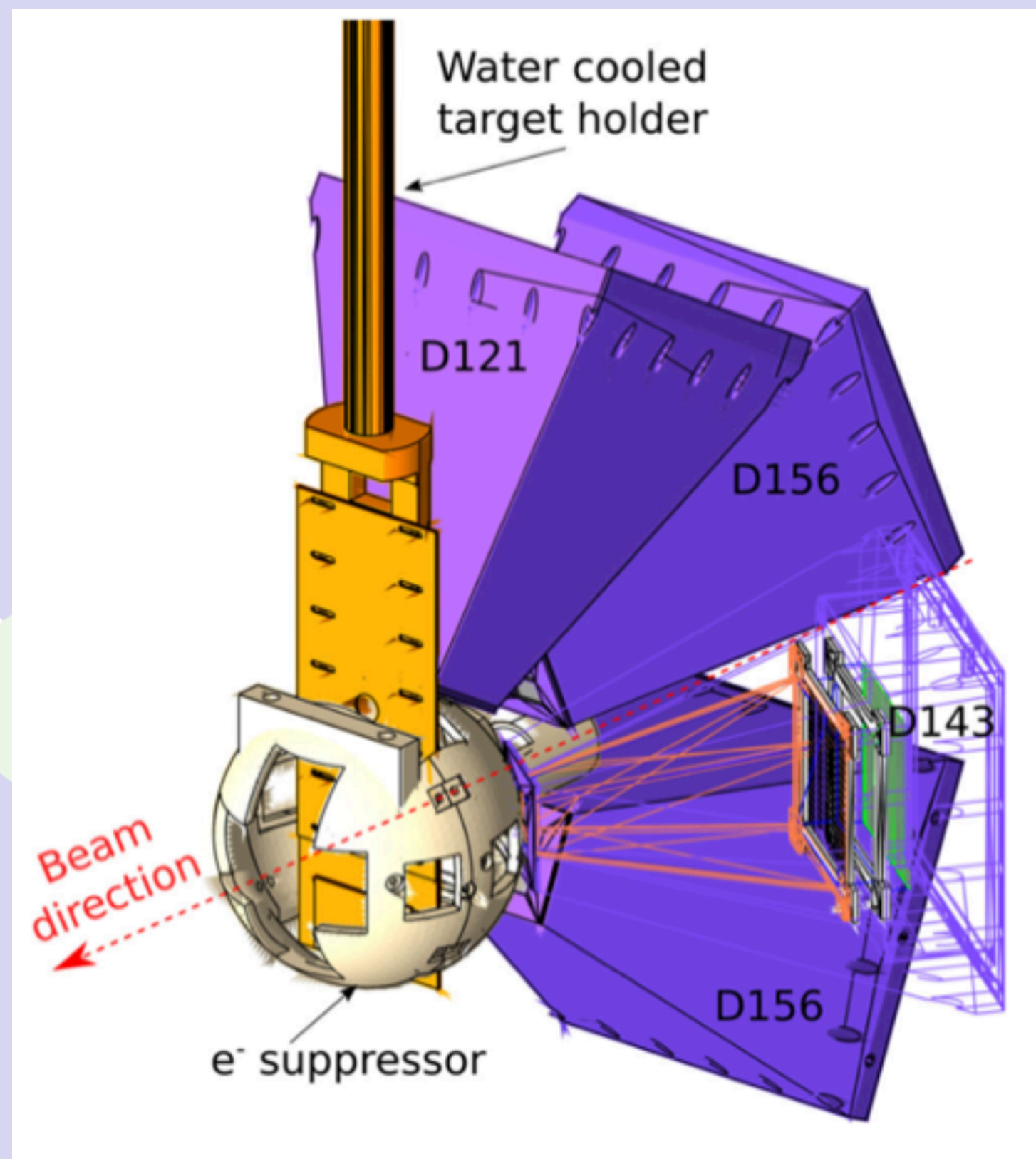
AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$



Aliotta, M. *et al.*, J. Phys. G: Nucl. Part. Phys. 49, 10501 (2022)

AMiCARE Work Package 1: CIRCE

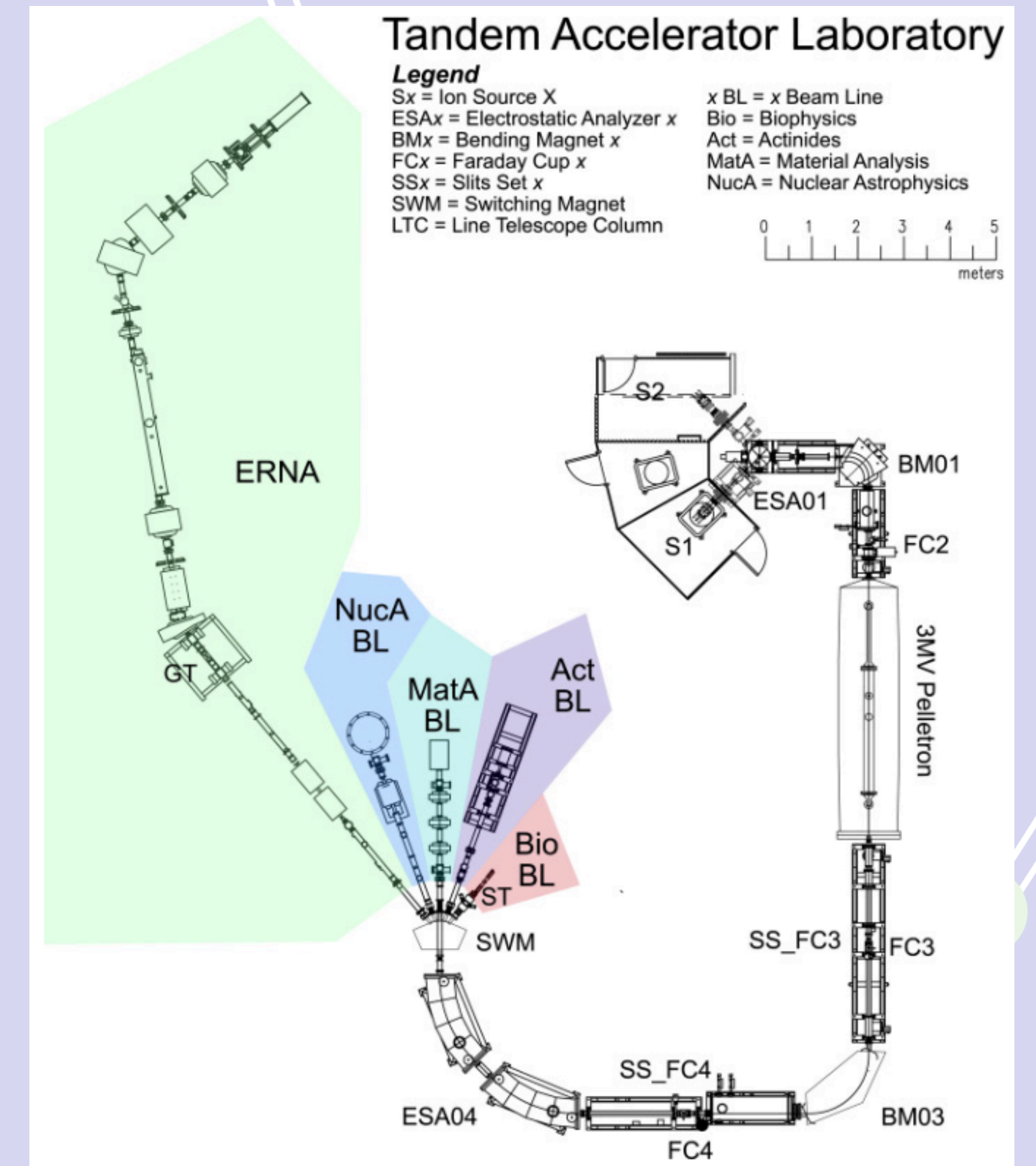
- WP1 and WP2 will be performed at Centre for Isotopic Research on Cultural and Environmental Heritage (CIRCE).



GASTLY (GAs-Silicon Two-Layer sYstem)

L. Morales-Gallegos *et al.*, Eur. Phys. J. A 60, 11 (2024)

Caserta, Italy

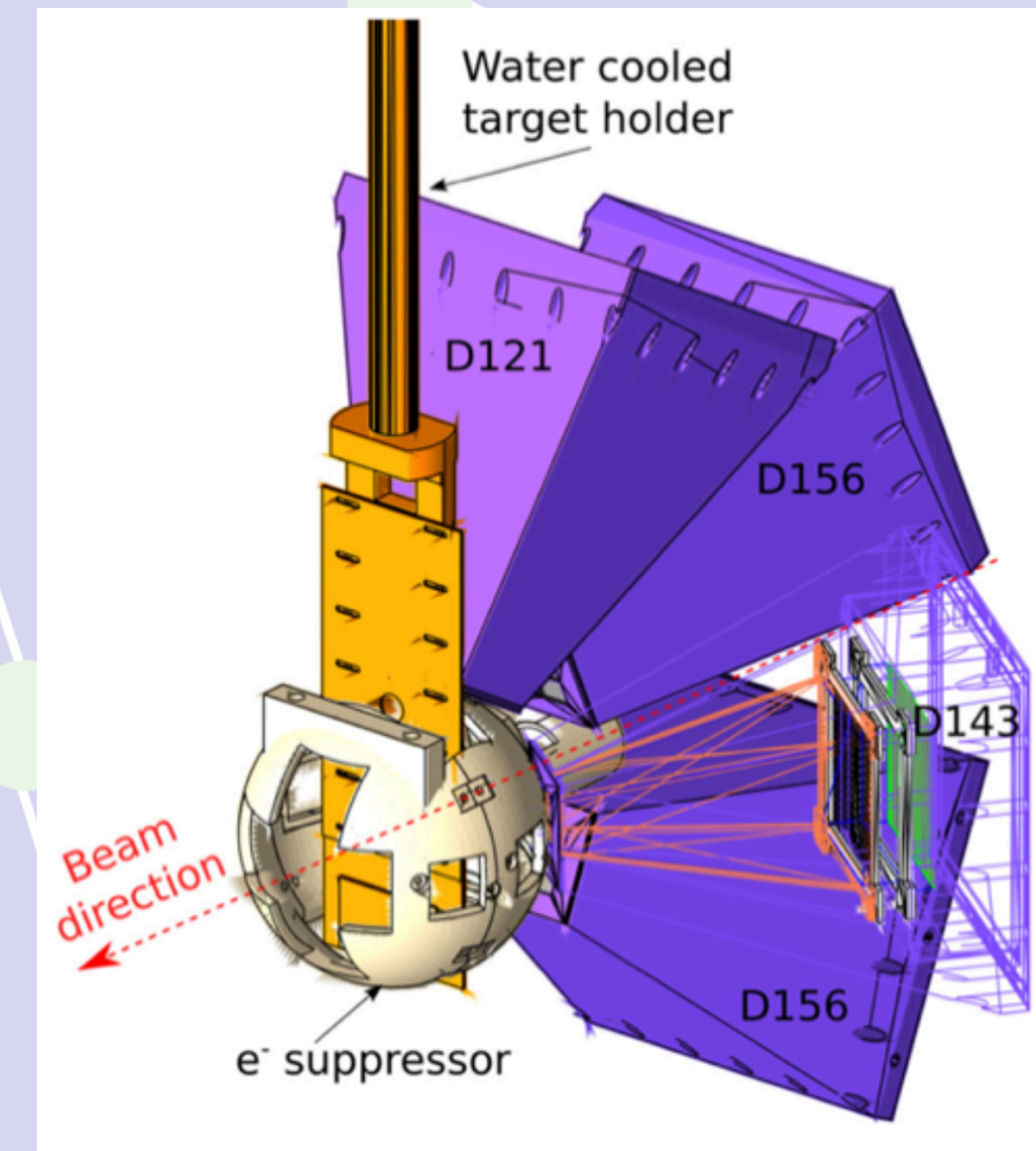


R. Buompane *et al.*, Nucl. Instrum.Methods Phys.Res. A, 1075, 170429 (2025).

AMiCARE Work Package 1: GASTLY

GASTLY (GAs-Silicon Two-Layer sYstem)

- Designed to meet the requirements of low-energy ion detection for nuclear astrophysics studies, namely large solid angle coverage, as well as high angular- and energy resolution [$\Delta E(\text{FWHM})/E$ of 2-3%].
- Eight $\Delta E/E$ modules, each comprising an ionisation chamber and a large area (and segmented area) silicon strip detector.



L. Morales-Gallegos *et al.*, Eur. Phys. J. A 60, 11 (2024)

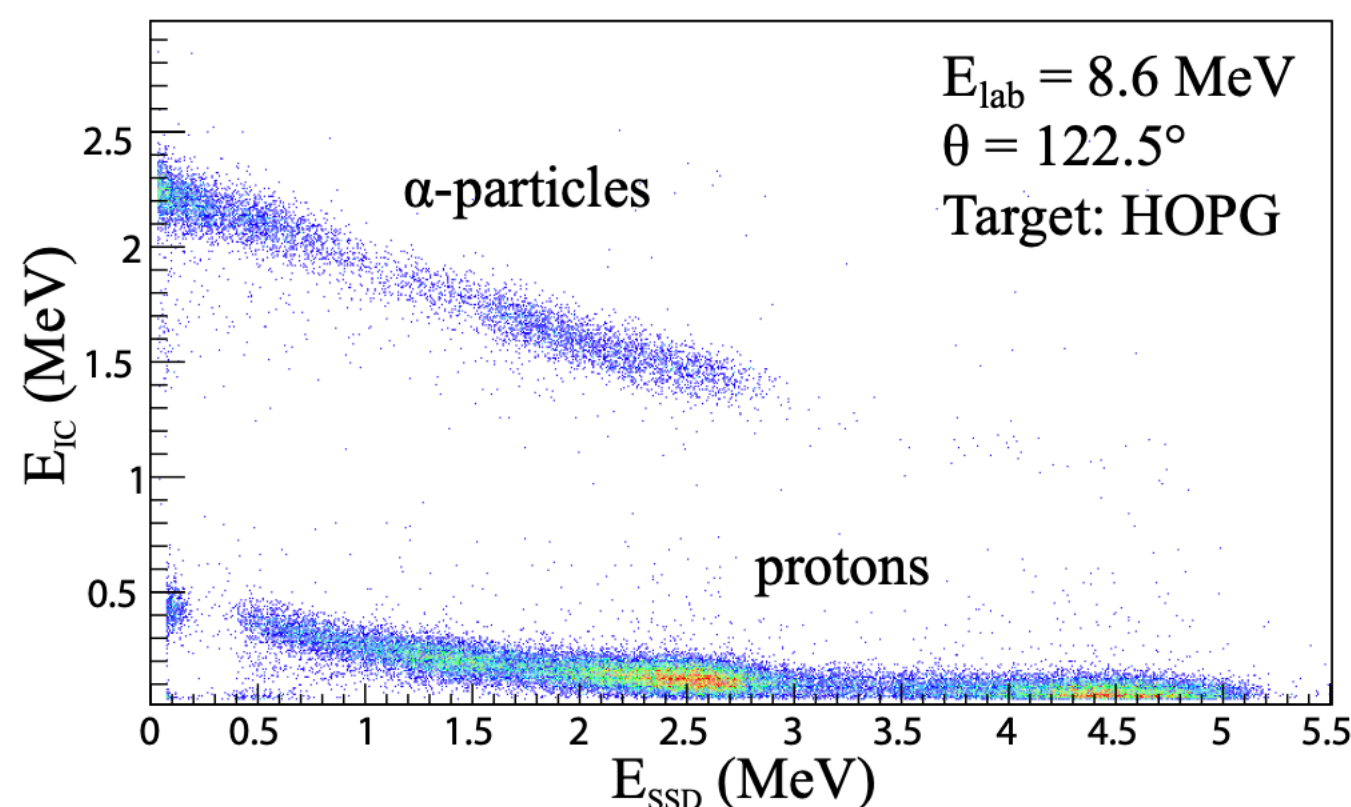


Fig. 9. E_{IC} vs. E_{SSD} matrix for the $^{12}\text{C} + ^{12}\text{C}$ fusion reaction. Distinct loci corresponding to protons and α -particles from the $^{12}\text{C}(^{12}\text{C}, p)^{23}\text{Na}$ and $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ reactions, respectively, can be clearly identified.

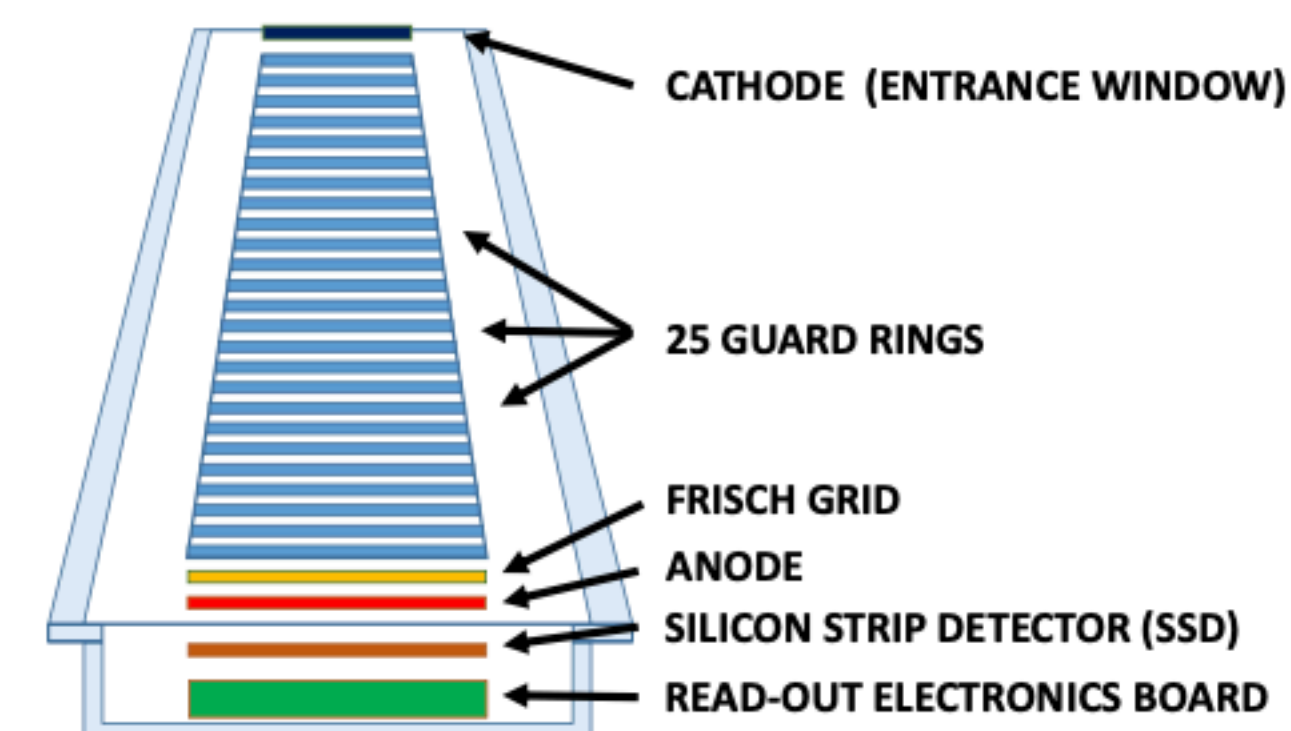
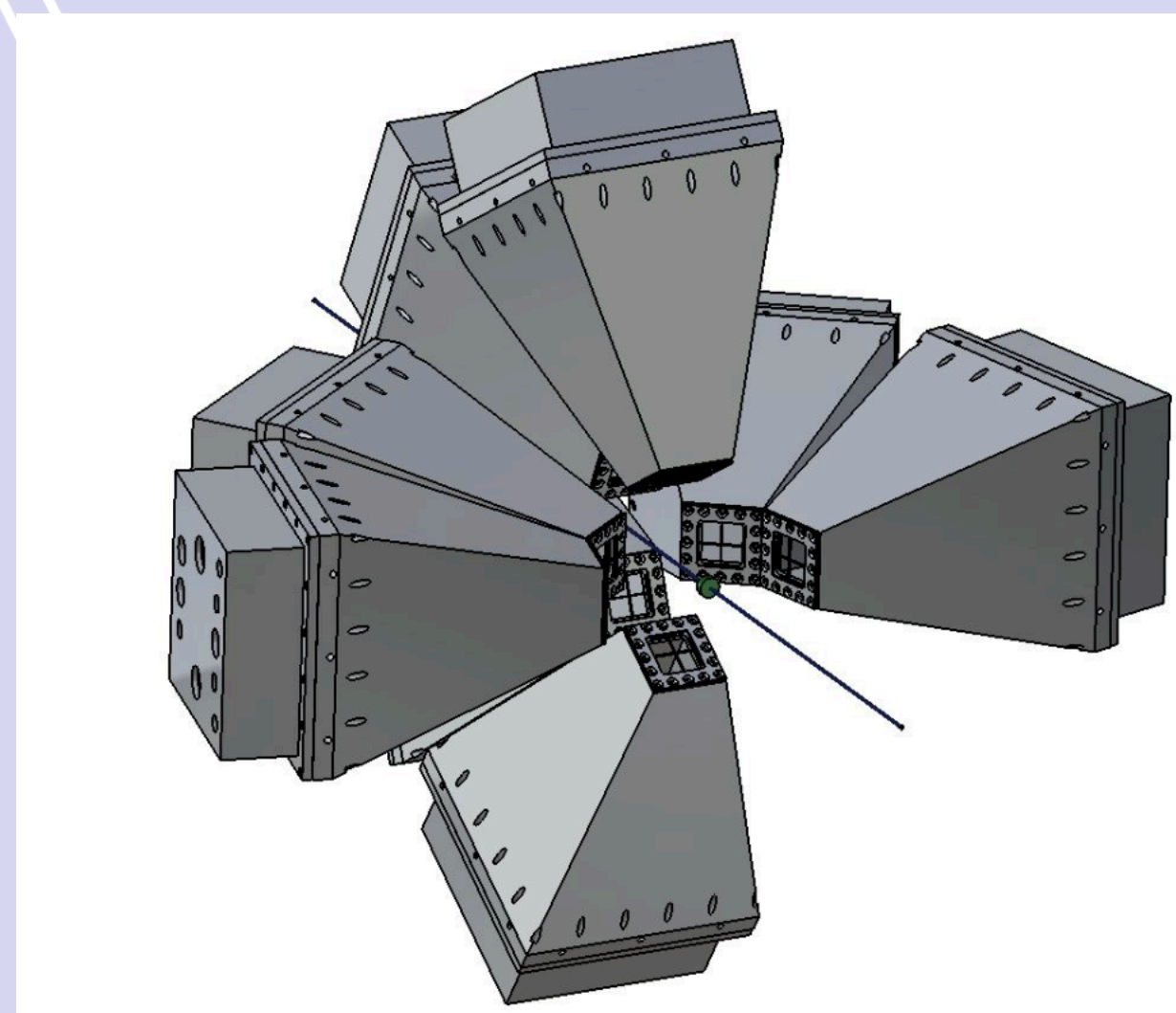
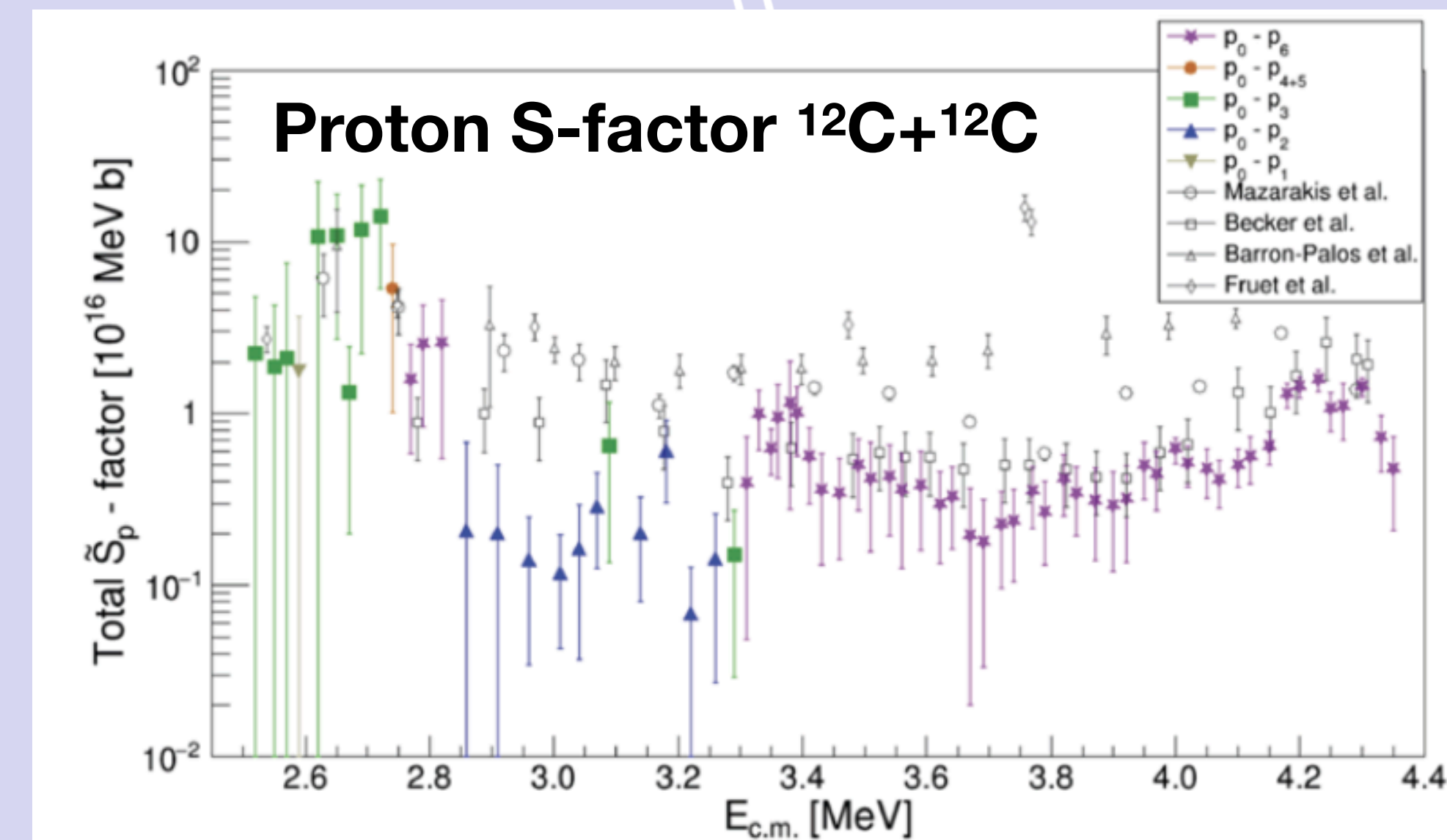
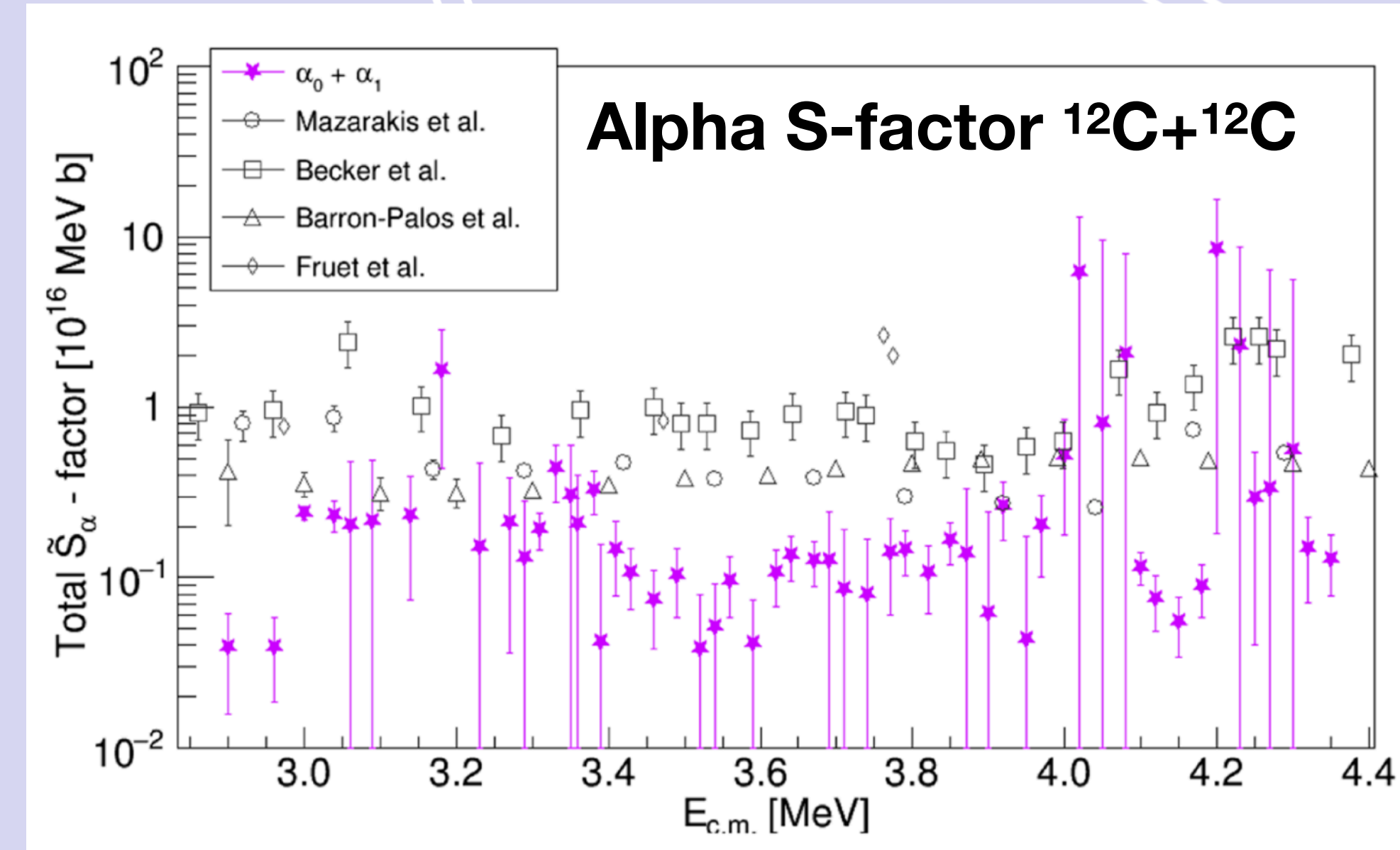
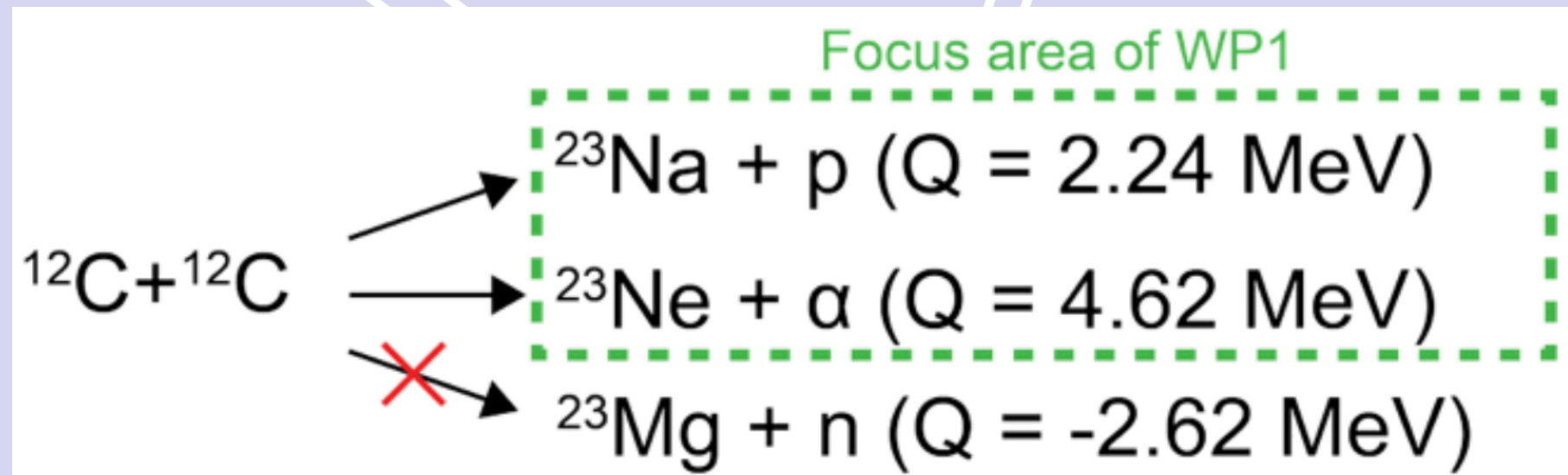


Fig. 2. Schematic cross-sectional view of a GASTLY module. Key components of the ionisation chamber are indicated. Both the ionisation chamber and the silicon strip detector are contained within an aluminium housing shaped as a truncated pyramidal structure with square section.

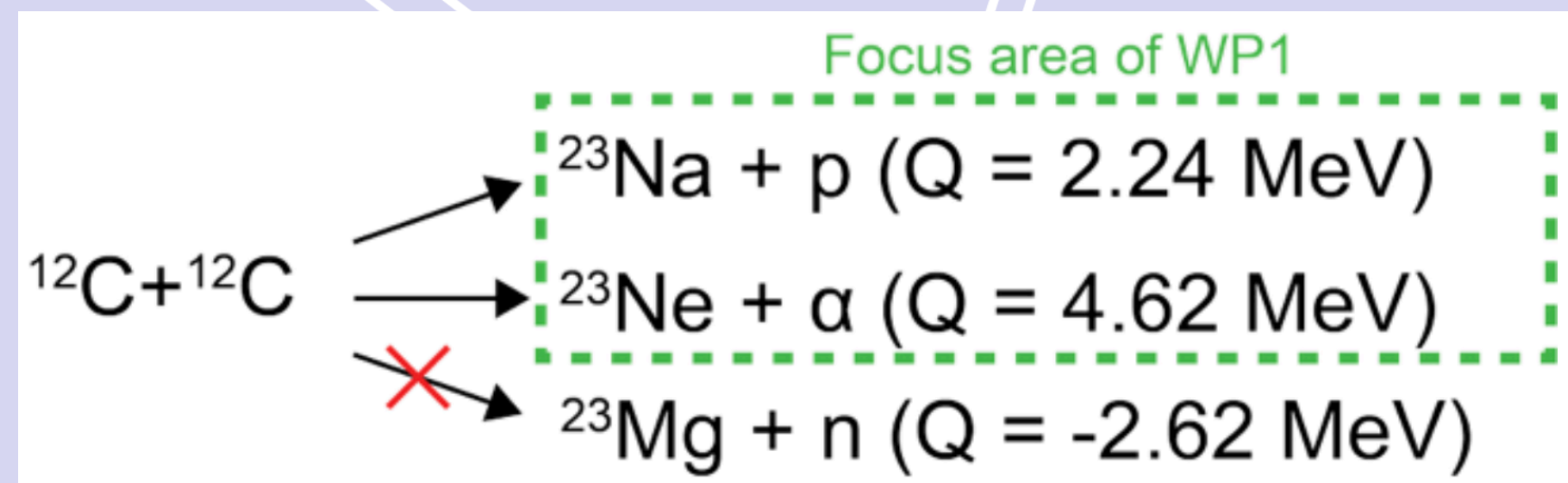
AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$

- Similar measurement by L. Morales-Gallegos in 2024.
- This new measurement will be similar but have several upgrades and lessons from the previous experiment.
- For example wider angular detection range for the detector array, as only four out of eight detectors were used.

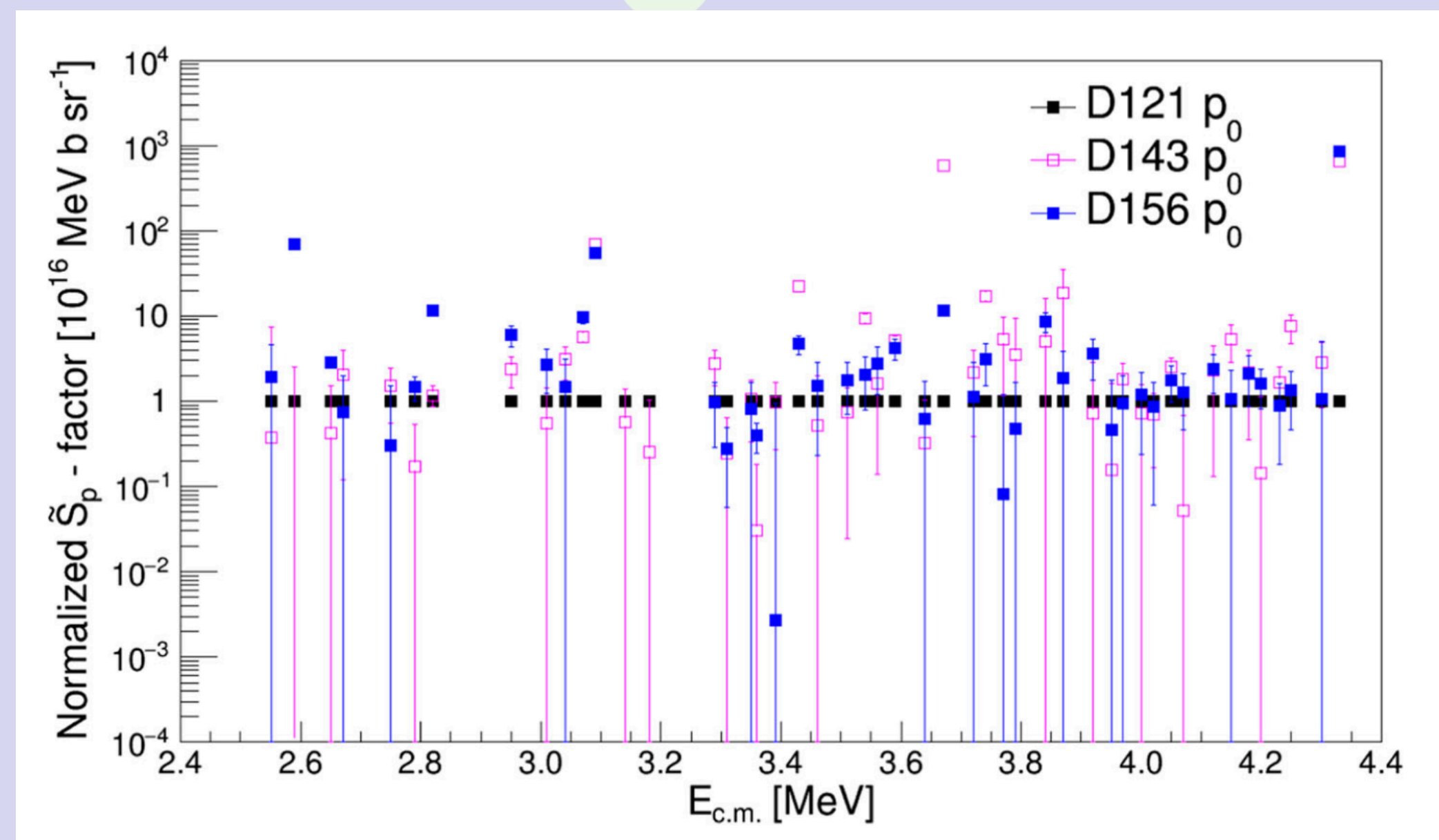


AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$

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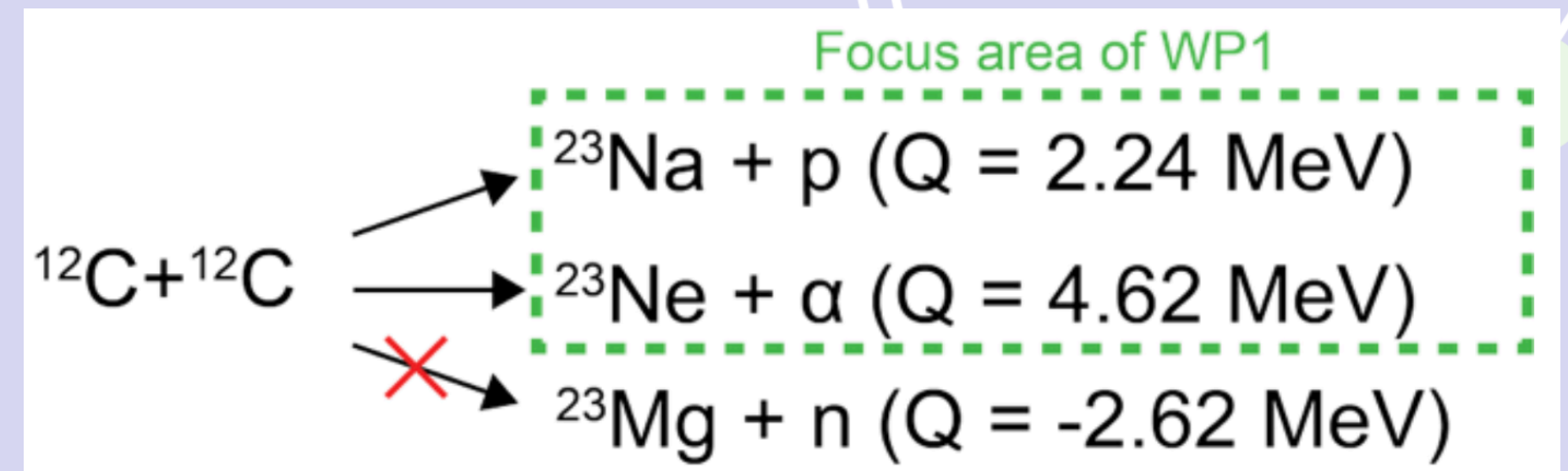
Partial differential S-factor for p_0 $^{12}\text{C}+^{12}\text{C}$



L. Morales-Gallegos *et al.*, Eur. Phys. J. A 60, 11 (2024)

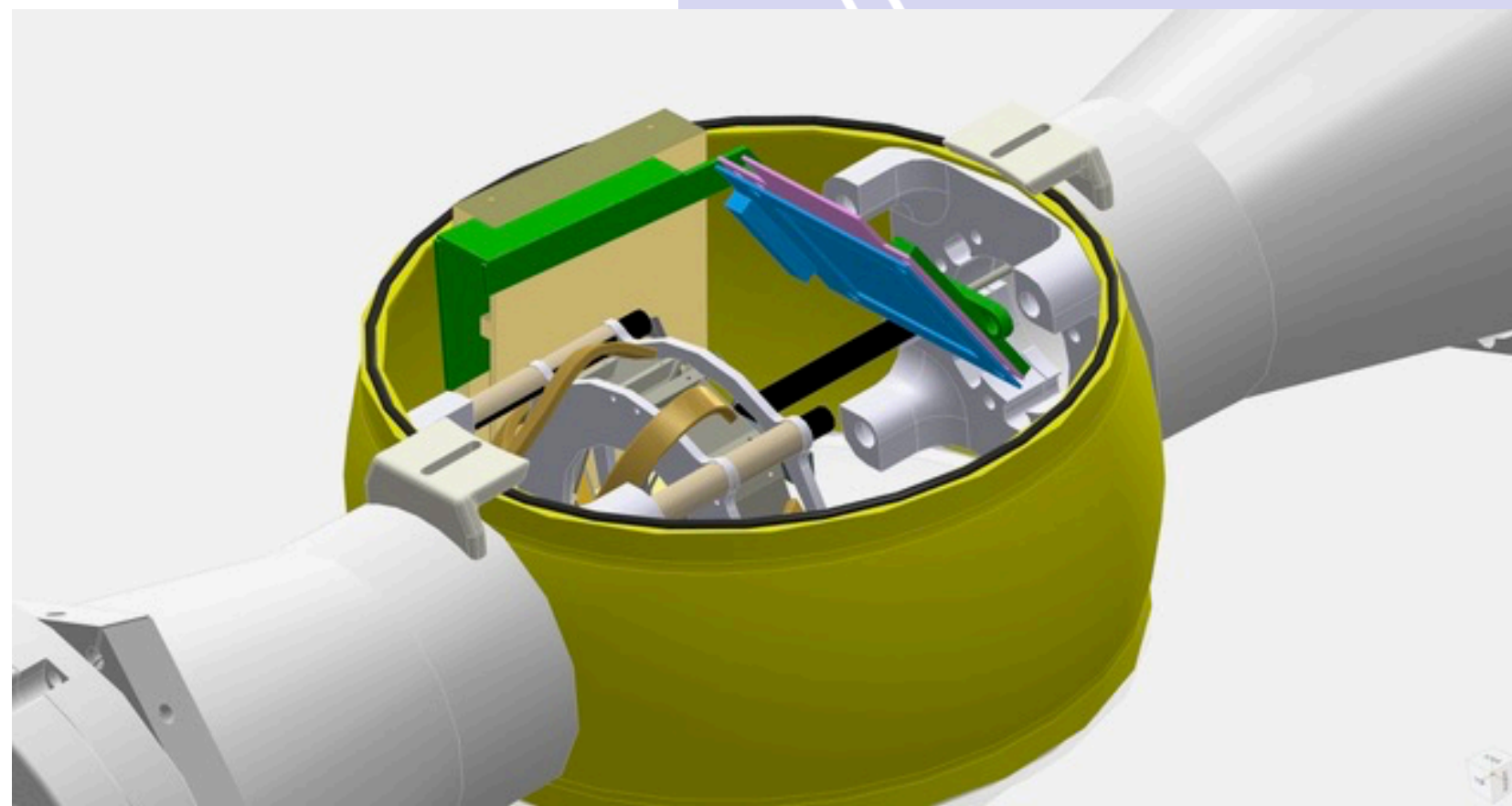
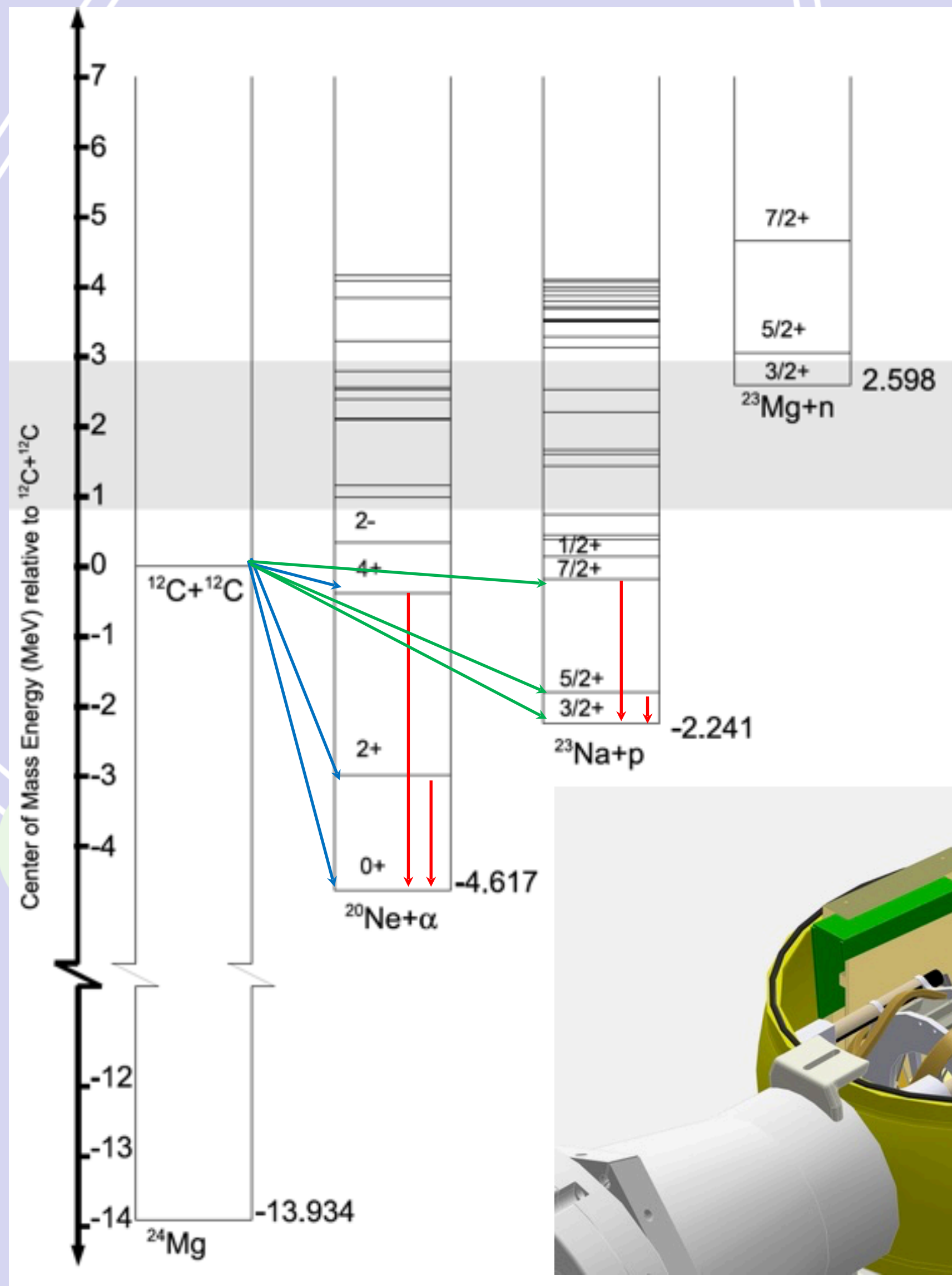
AMiCARE Work Package 1: $^{12}\text{C}+^{12}\text{C}$

- In the previous measurement only the α_0 and α_1 could be seen, therefore a total S-factor was not possible to obtain without normalising to previous data.
- In the new measurement:
 - Use all 8 GASTLY detectors, now with separate gas feeding.
 - Worked on improving leaks in the detectors.
 - GASTLY detectors will be used as ΔE -E detectors, previously only as single pad.
- Next in-beam tests with target: First half of July

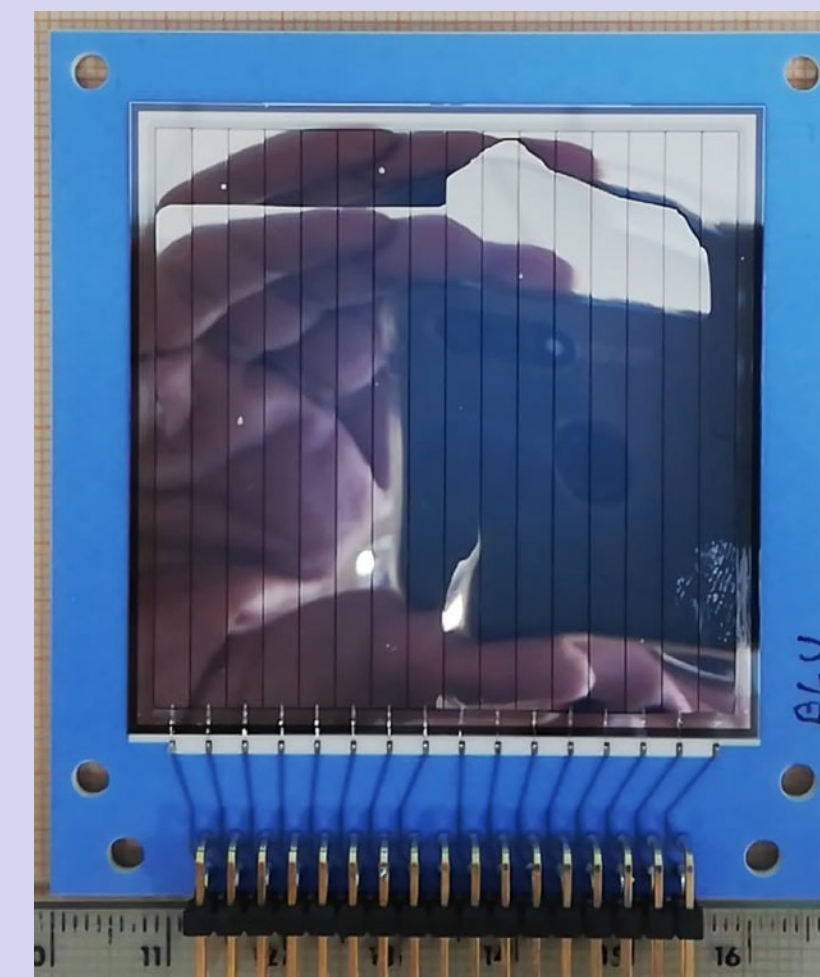


Next steps in Oslo-Napoli-Catania-iThemba collaboration

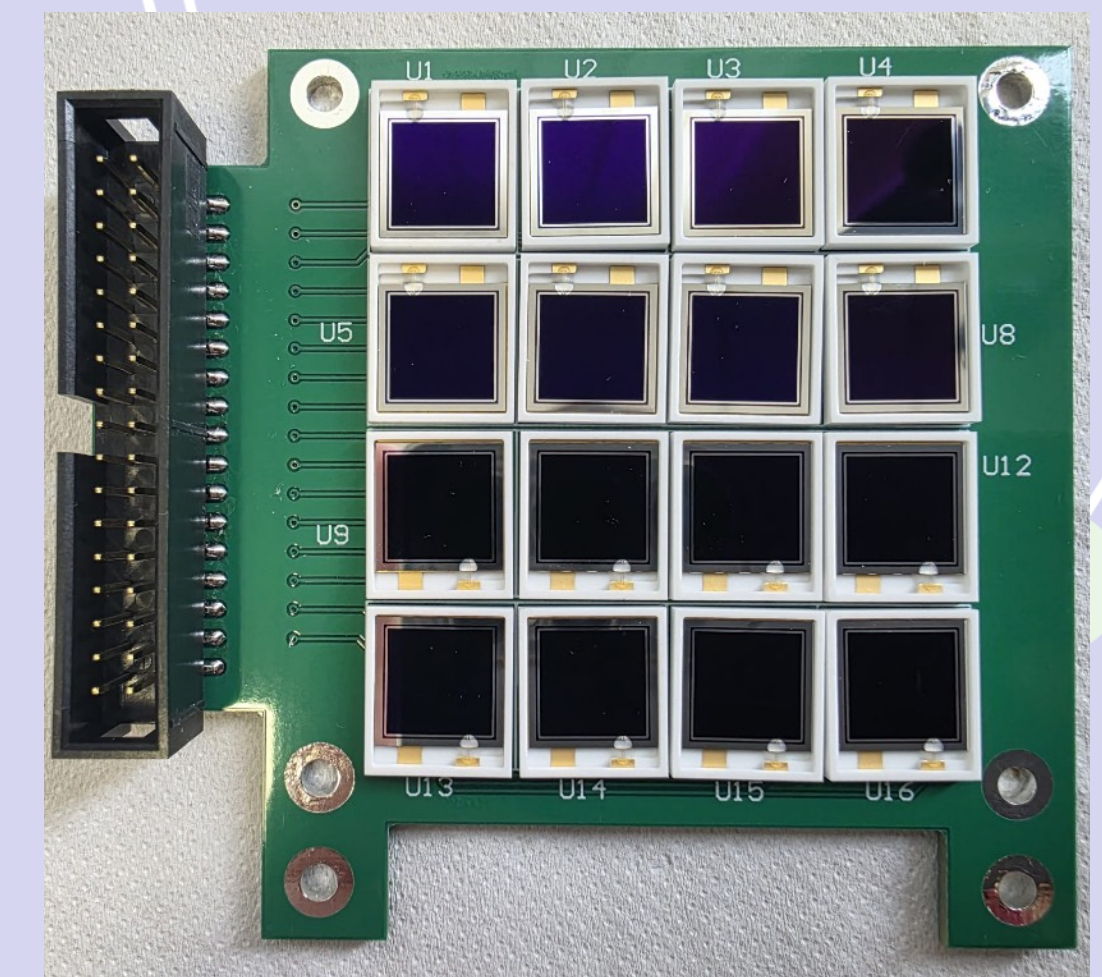
- Collaborative measurement of $^{24}\text{Mg}(\alpha, \alpha')$, $^{24}\text{Mg}(\alpha, \alpha')^{20}\text{Ne} + \alpha$ and $^{24}\text{Mg}(\alpha, \alpha')^{20}\text{Na} + p$ @ 30-32 MeV alphas, PhD project of Federica Ercolano.
- Next two weeks: Install ΔE -E OSCAR particle detector inside target chamber at OCL.
- Beam time starts 26.05.26, exciting!



OCL target chamber with OSCAR particle detector



Front OSCAR particle



Back OSCAR particle

Next steps in Oslo-Napoli-Catania-iThemba collaboration

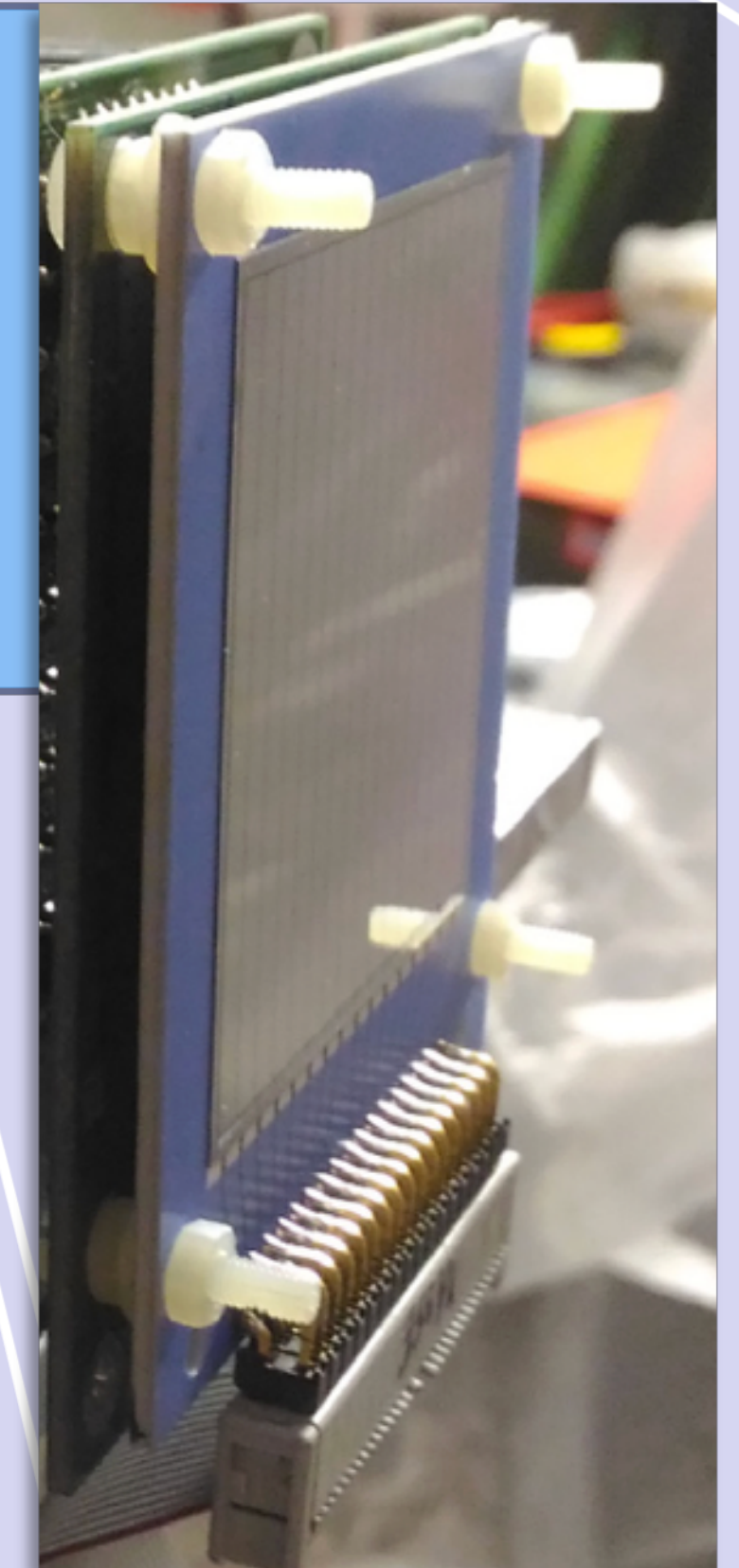


SiRi: modular array of 8 ΔE -E Si detectors; ΔE ($130 \mu m$) segmented into 8 annular strips.

M. Guttormsen et al. / Nuclear Instruments and Methods in Physics Research A 648 (2011).

OSCAR: ΔE -E telescope; first stage ($20 \mu m$) segmented into 16 Si strips, followed by 4x4 matrix of 16 Si pads.

D. Dell'Aquila et al. / Nuclear Inst. and Methods in Physics Research, A 877 (2018).



OSCAR: 30 $\text{LaBr}_3(\text{Ce})$ scintillating crystals.

F. Zeiser et al. / Nuclear Inst. and Methods in Physics Research, A 985 (2021).



Thank you to all collaborators



<https://doi.org/10.1103/2h2s-sbyx>

Supervisors during PhD

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J. C. Müller, P. A. Sobas, and J. C. Wikne at the Oslo Cyclotron Laboratory (OCL)

F. Zeiser P. Adsley

Research Council of Norway through its grant to the Norwegian Nuclear Research Centre (Project No. 341985, 245882 and 325714)

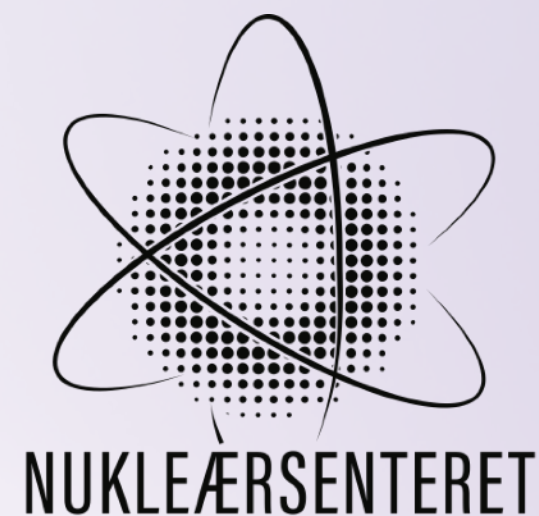
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AMiCARE FRIPRO project

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Oslo-Napoli-iThemba collaboration

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Aurora Tumino, Marco La Cognata, Riccardo Maria Gesuè, Jeppe Thingholm, Daniele Dell’Aquila,
Retief Neveling, Lindsay Donaldson, Pete Jones, Ivano Lombardo



References

1. Freer *et al.* (2014): M. Freer, H. O. U. Fynbo, The Hoyle state in ^{12}C , *Prog. Part. Nucl. Phys.* 78, 1 (2014).
2. Bear *et al.* (2017): M. Beard, S.M. Austin, R. Cyburt, *Phys. Rev. Lett.* 119 (2017) 112701.
3. Jin *et al.* (2020): Shilun Jin, Luke F. Roberts, Sam M. Austin, Hendrik Schatz, *Nature* 588 (2020) 57.
4. Wanajo *et al.* (2011): S. Wanajo, H. T. Janka, S. Kubono, *Astrophys. J.* 729 (2011) 46.
5. deBoer *et al.* (2025): R. J. de Boer, A. Best, C. R. Brune, A. Chieffi, C. Hebborn, G. Imbriani, W. P. Liu, Y. P. Shen, F. X. Timmes, M. Wiescher, The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction, in the laboratory and in the stars, *Eur. Phys. J. A* 61, 70 (2025).
6. deBoer *et al.* (2017): R.J. deBoer, J. Görres, M. Wiescher, R.E. Azuma, A. Best, C.R. Brune, C.E. Fields, S. Jones, M. Pignatari, D. Sayre, K. Smith, F.X. Timmes, E. Uberseder, The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction and its implications for stellar helium burning. *Rev. Mod. Phys.* 89(3), 035007 (2017).
7. Woosley *et al.* (2021): S.E. Woosley, A. Heger, *Astrophys. J. Lett.* 912 (2021) L31.
8. Shen *et al.* (2023): Y. Shen, B. Guo, R. J. deBoer, E. Li, Z. Li, Y. Li, X. Tang, D. Pang, S. Adhikari, C. Basu, J. Su, S. Yan, Q. Fan, J. Liu, C. Chen, Z. Han, X. Li, G. Lian, T. Ma, W. Nan, W. Nan, Y. Wang, S. Zeng, H. Zhang, and W. Liu, New Determination of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ Reaction Rate and Its Impact on the Black-hole Mass Gap, *Astrophys. J.* 945 (2023), 41.
9. Kibédi *et al.* (2020): T. Kibédi, B. Alshahrani, A. E. Stuchbery, A. C. Larsen, A. Görge, S. Siem, M. Guttormsen, F. Giacoppo, A. I. Morales, E. Sahin, G. M. Tveten, F. L. B. Garrote, L. C. Campo, T. K. Eriksen, M. Klintefjord, S. Maharramova, H.-T. Nyhus, T. G. Tornyi, T. Renstrøm, and W. Paulsen, Radiative width of the Hoyle state from γ -ray spectroscopy, *Phys. Rev. Lett.* 125, 182701 (2020).
10. Obst *et al.* (1975): A. W. Obst and W. J. Braithwaite, *Phys. Rev. C* 13, 2033 (1976).
11. M. Guttormsen *et al.* (2011), A. Bürger, T. Hansen, and N. Lietaer, The siri particle-telescope system, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 648, 168 (2011).
12. M. Guttormsen *et al.* (1990), A. Atac, G. Løvhøiden, S. Messelt, T. Ramsøy, J. Rekstad, T. F. Thorsteinsen, T. S. Tveten, and Z. Zelazny, Statistical gamma-decay at low angular momentum, *Physica Scripta* 1990, 54 (1990).
13. Zeiser *et al.* (2021): F. Zeiser, G. Tveten, F. Bello Garrote, M. Guttormsen, A. Larsen, V. Ingeberg, A. Görge, and S. Siem, The γ -ray energy response of the Oslo scintillator array OSCAR, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 985, 164678 (2021).
14. Kelley *et al.* (2017): J. Kelley, J. Purcell, and C. Sheu, Energy levels of light nuclei $A=12$, *Nucl. Phys. A* 968, 71 (2017).
15. Eriksen *et al.* (2020): T. K. Eriksen, T. Kibédi, M. W. Reed, A. E. Stuchbery, K. J. Cook, A. Akber, B. Alshahrani, A. A. Avaa, K. Banerjee, A. C. Berriman, L. T. Bezzina, L. Bignell, J. Buete, I. P. Carter, B. J. Coombes, J. T. H. Dowie, M. Dasgupta, L. J. Evitts, A. B. Garnsworthy, M. S. M. Gerathy, T. J. Gray, D. J. Hinde, T. H. Hoang, S. S. Hota, E. Ideguchi, P. Jones, G. J. Lane, B. P. McCormick, A. J. Mitchell, N. Palalani, T. Palazzo, M. Ripper, E. C. Simpson, J. Smallcombe, B. M. A. Swinton-Bland, T. Tanaka, T. G. Tornyi, and M. O. de Vries, Improved precision on the experimental E_0 decay branching ratio of the Hoyle state, *Phys. Rev. C* 102, 024320 (2020).