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

A saga on the γ-decay branching ratio of the Hoyle state at the Oslo Cyclotron Laboratory

HELIUM25 - Dresden, Germany, 22.07.2025

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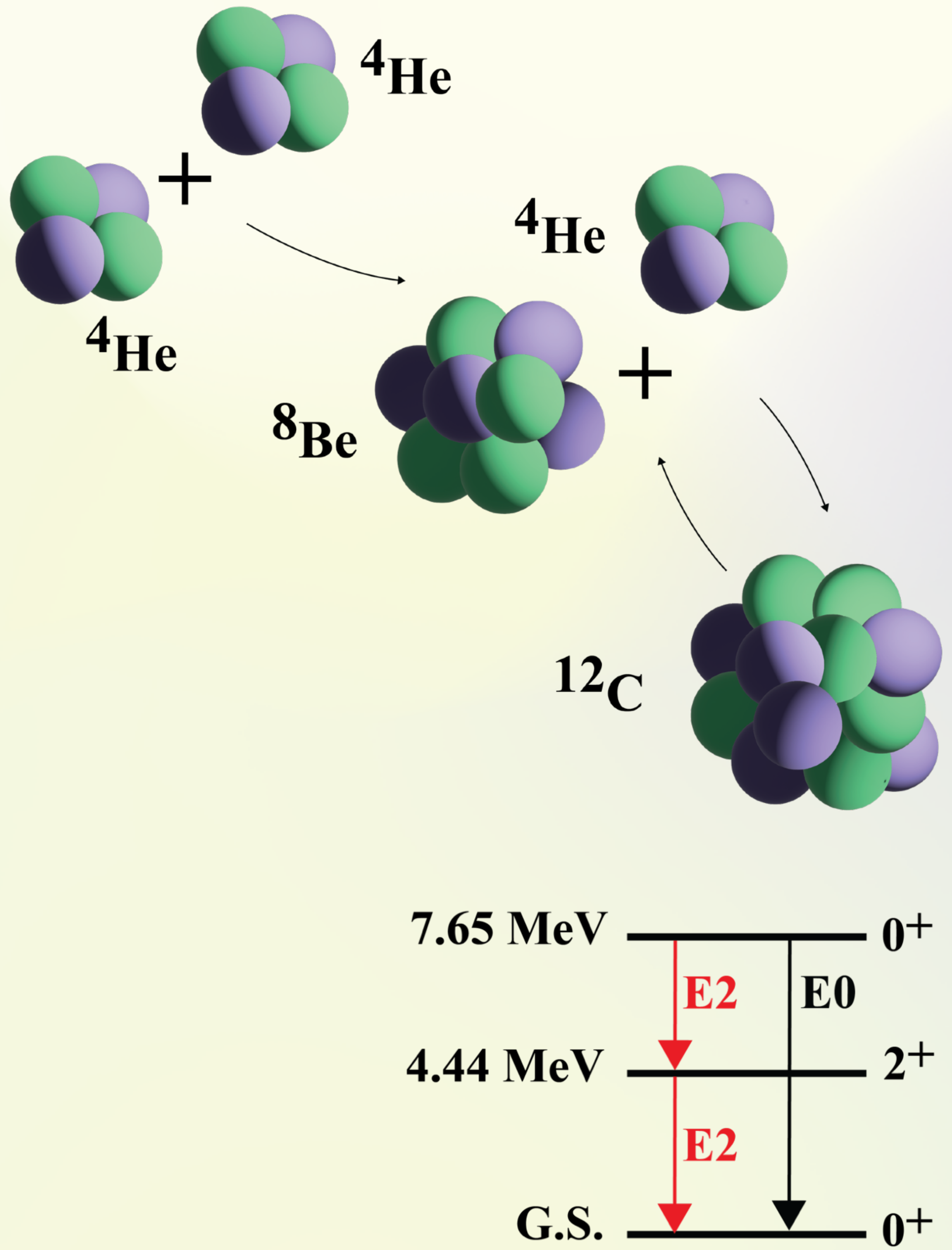
NUKLEÆRSENTERET

Triple alpha process

At medium stellar temperatures of T = 0.1-2.0 GK the dominant reaction mechanism of the triple-α process is two-step sequential fusion through the Hoyle state in ^{12}C (Freer *et al.* (2014) [1]).



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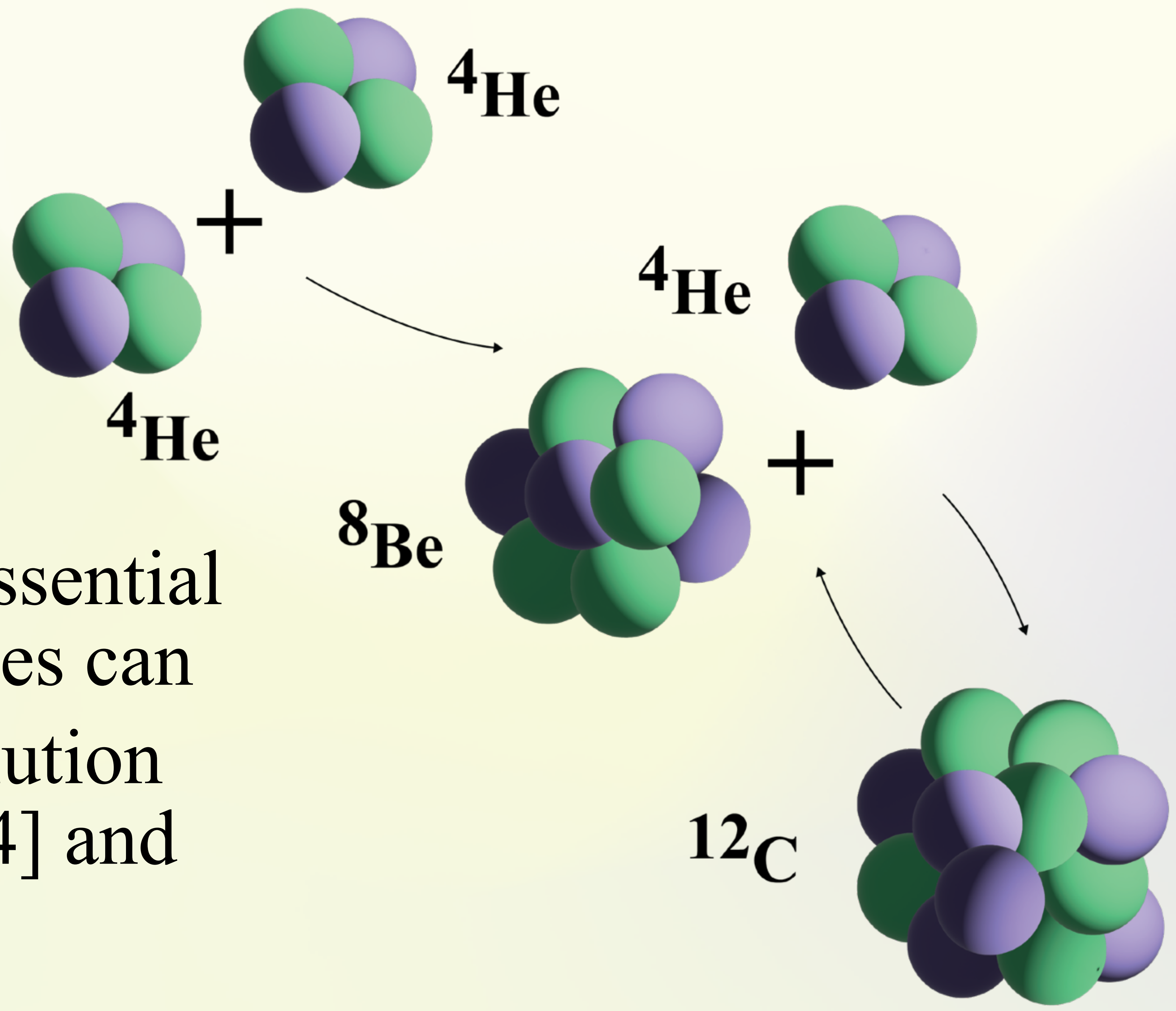
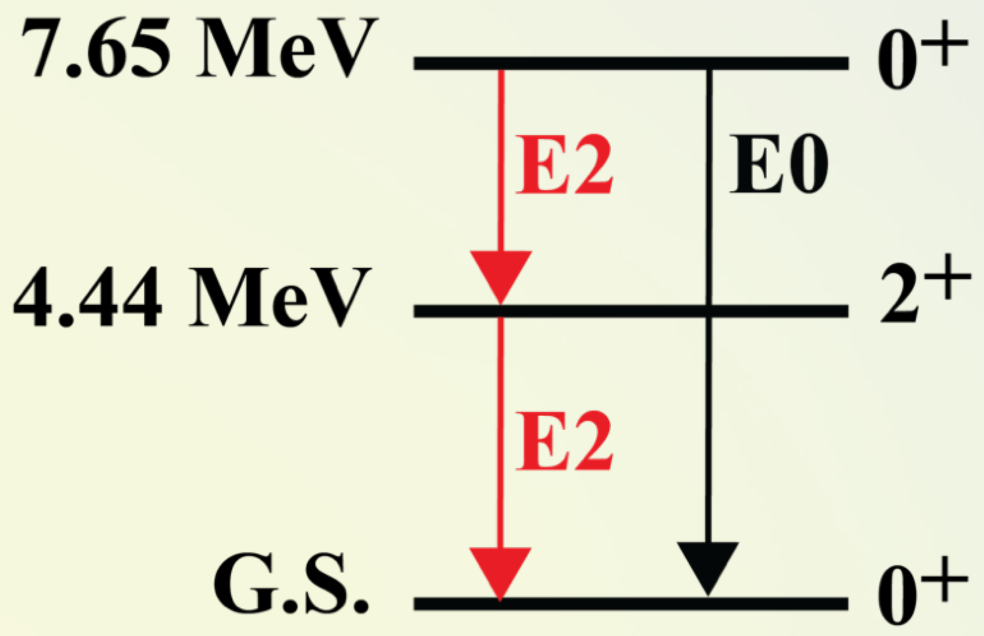
Accurate measurement of the Hoyle state's radiative width is essential for determining the triple-α process rate, as even minor changes can significantly influence elemental abundances and stellar evolution (Bear *et al.* (2017), Jin *et al.* (2020), Wanajo *et al.* (2011) [2-4] and full talk by Aldara Grichener).





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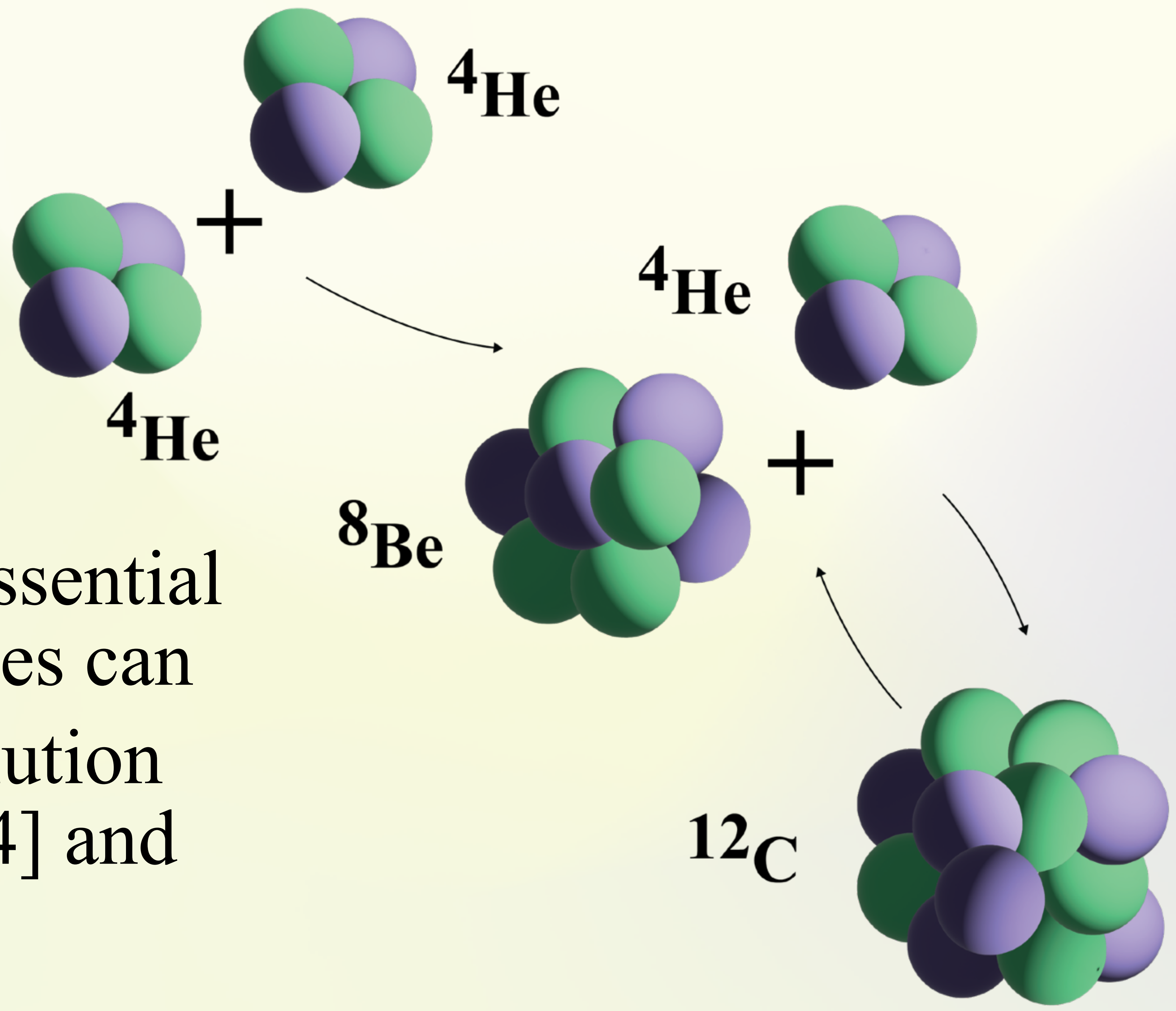
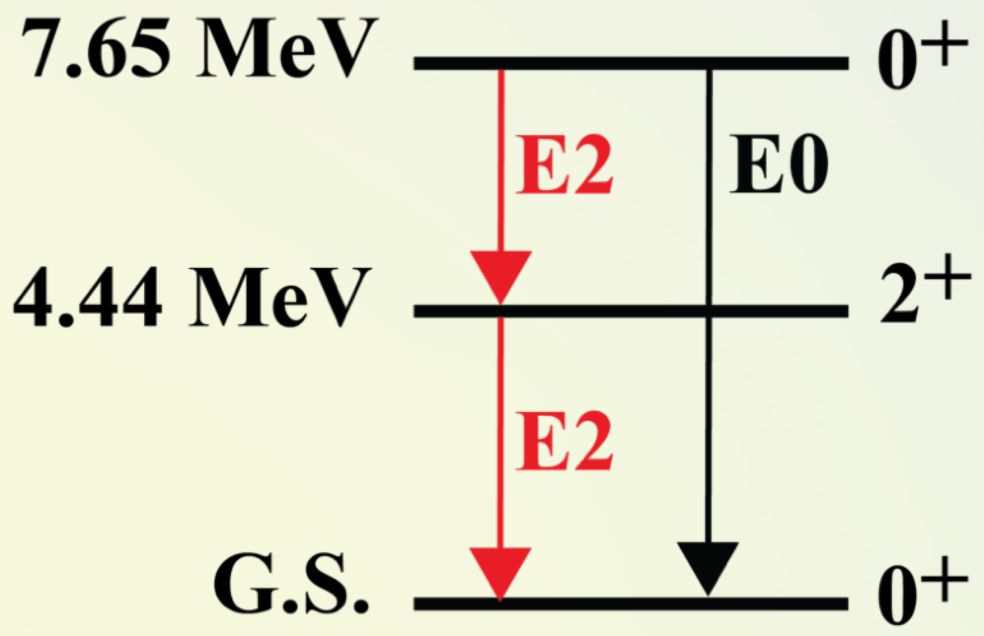


Accurate measurement of the Hoyle state's radiative width is essential for determining the triple-α process rate, as even minor changes can significantly influence elemental abundances and stellar evolution (Bear *et al.* (2017), Jin *et al.* (2020), Wanajo *et al.* (2011) [2-4] and full talk by Aldara Grichener).

The rate of the triple-α is crucial not only for the production of ^{12}C, it also influences the subsequent $^{12}C(\alpha,\gamma)^{16}O$ reaction rate (deBoer *et al.* (2017), deBoer *et al.* (2025) [5-6]). The balance of the C/O ratio, a key factor in stellar evolution (Woosley *et al.* (2021), Shen *et al.* (2023) [7-8] and full talk by Aldara Grichener) depends on the accuracy of the observables from these reactions.



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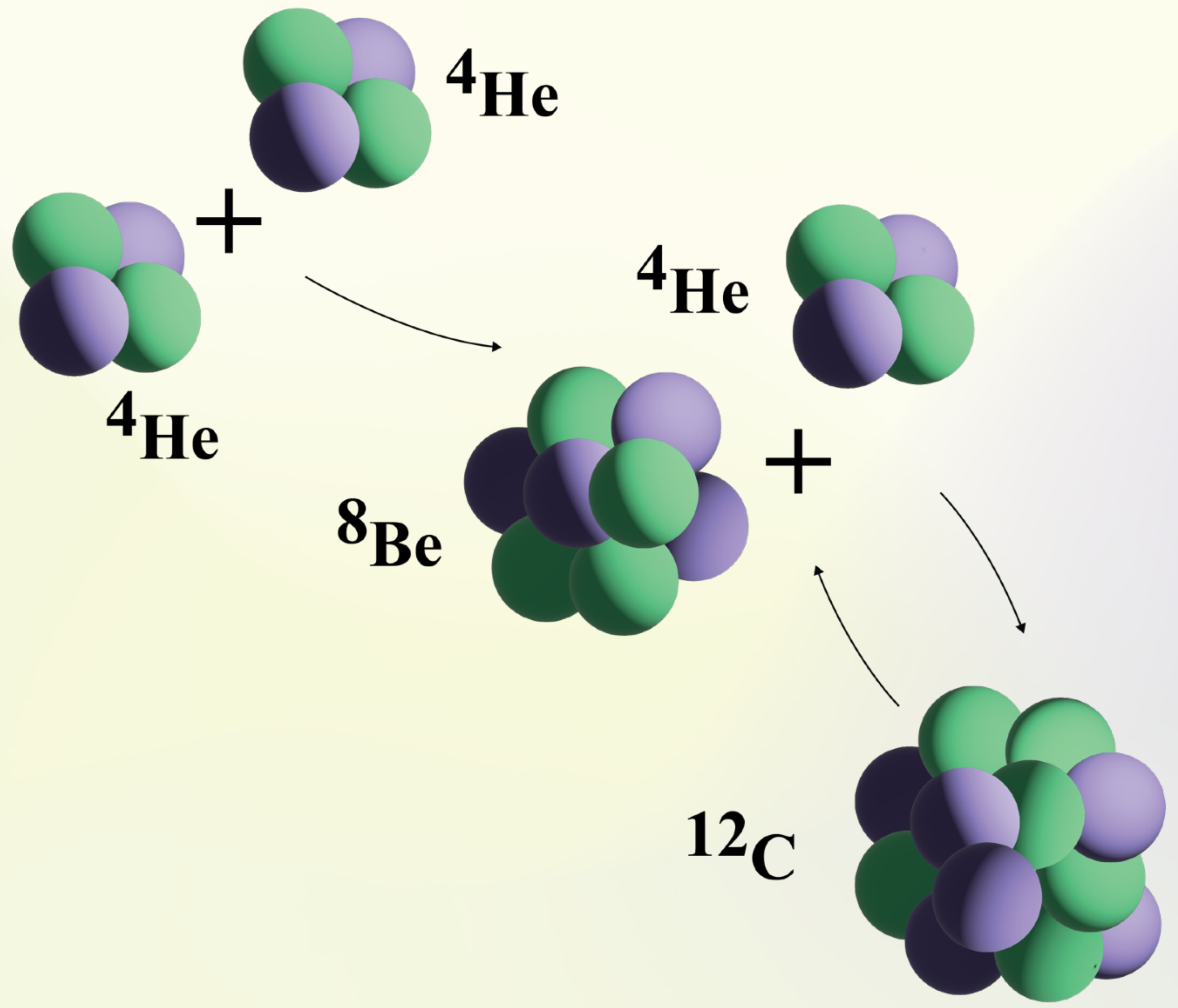
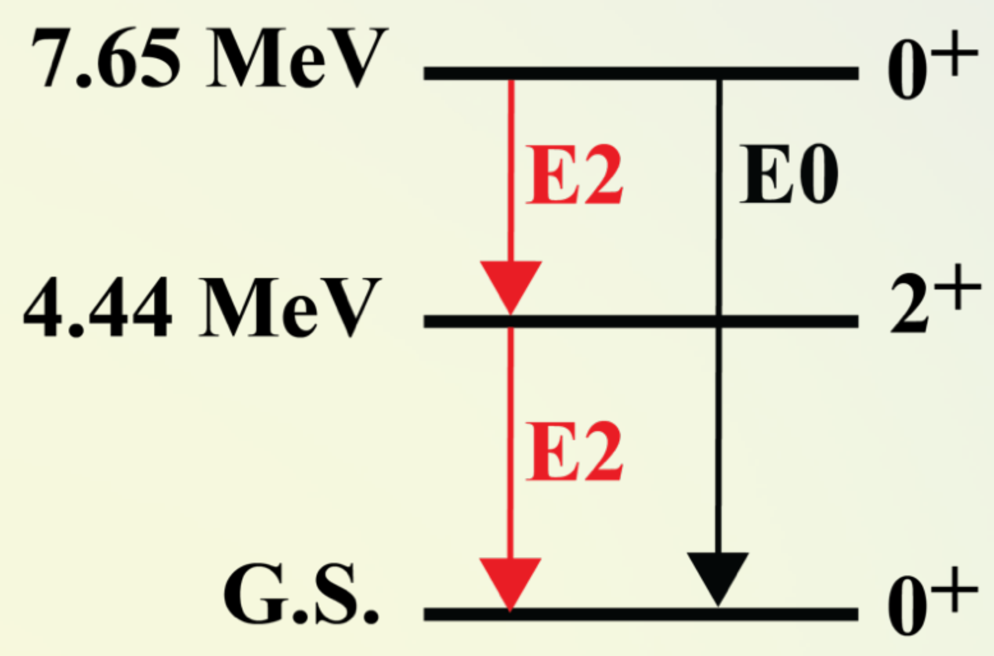
Triple alpha process

The radiative width of the Hoyle state **cannot** be measured **directly**, but it can be **deduced indirectly** with three independently measured quantities as

$$\Gamma_{7.65} = \Gamma_\alpha + \Gamma_{rad}$$

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





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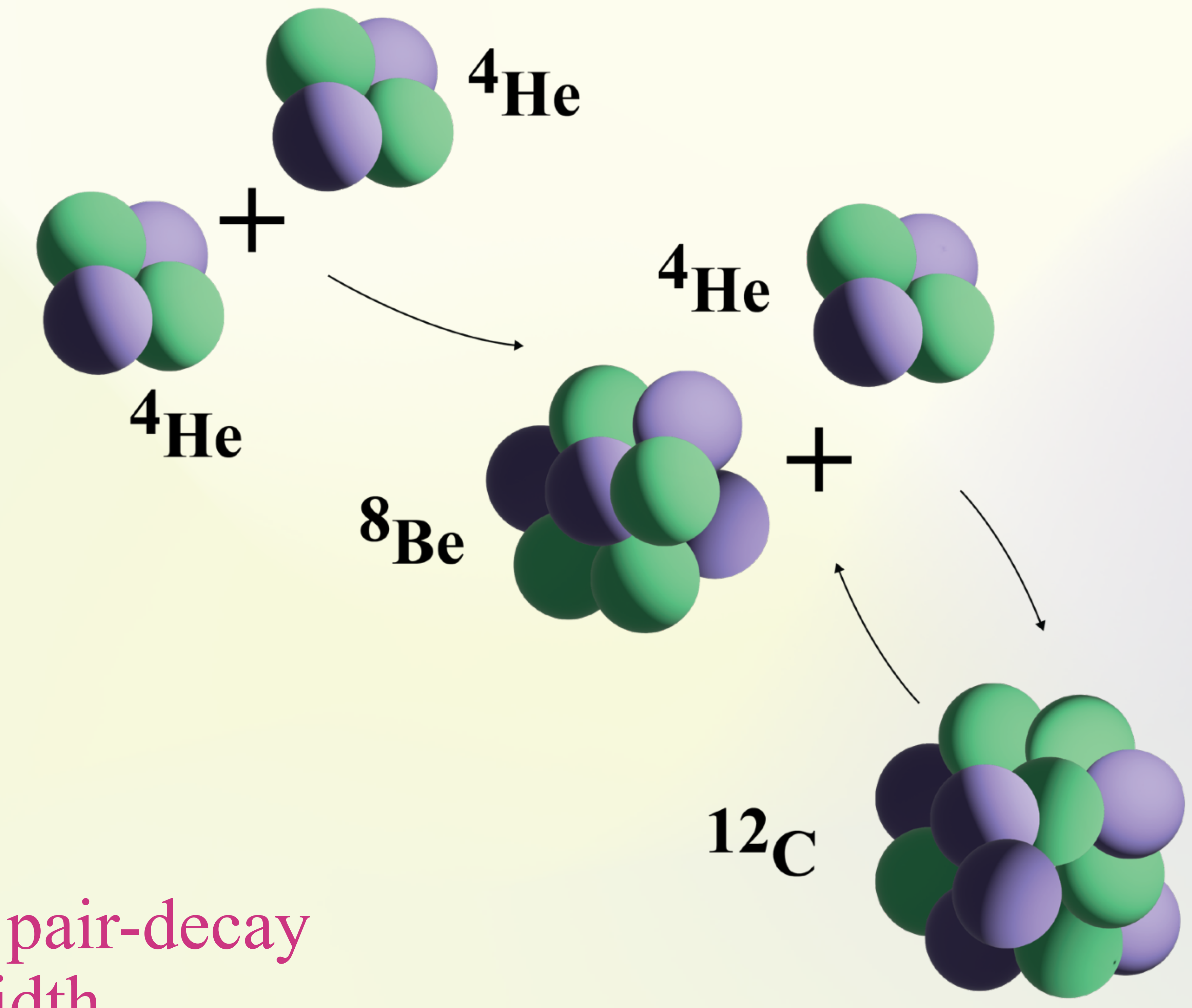
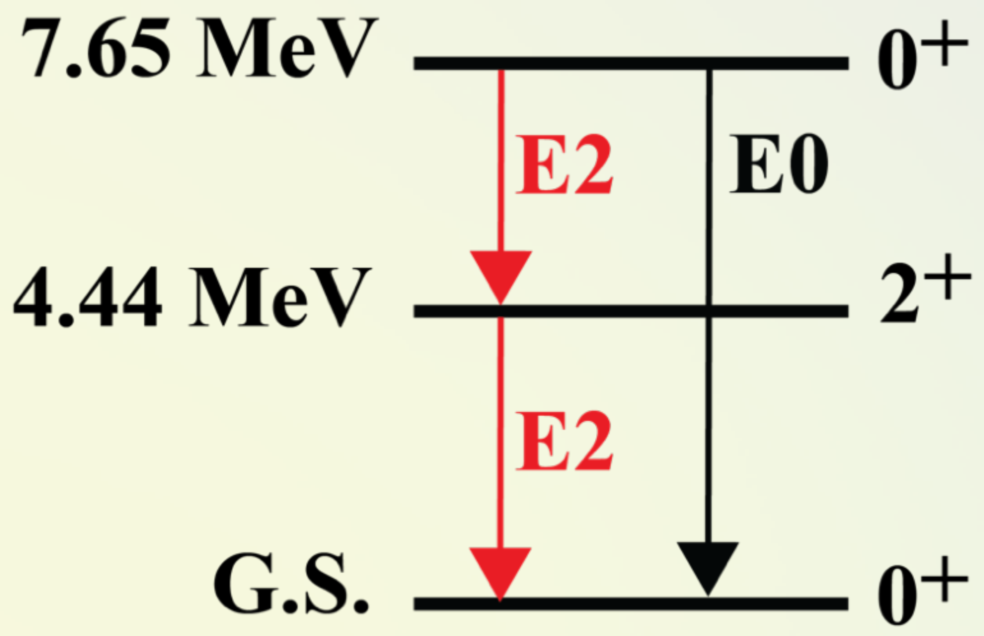
Radiative branching ratio

Pair-decay branching ratio

Absolute pair-decay width





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Triple alpha process

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

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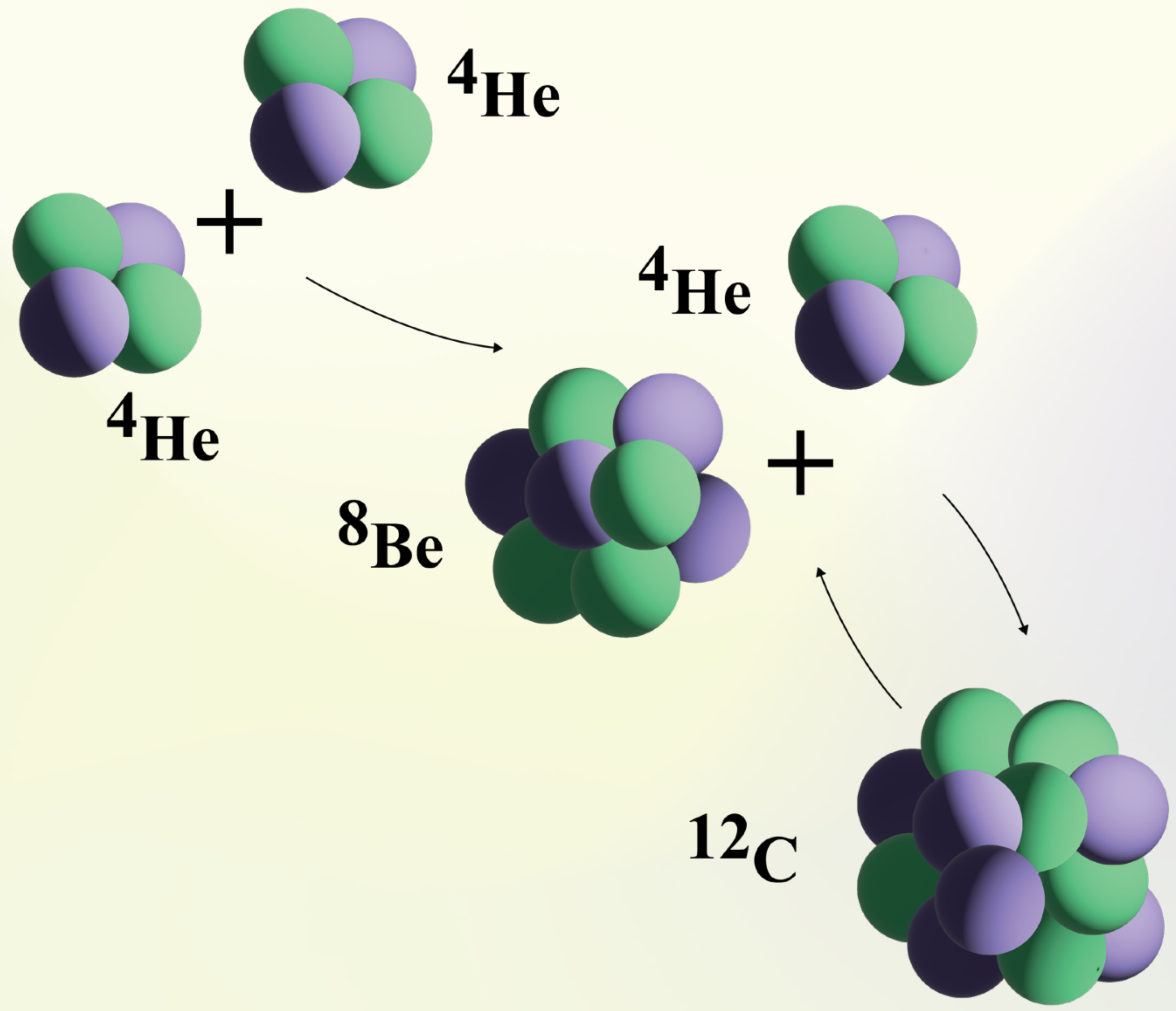

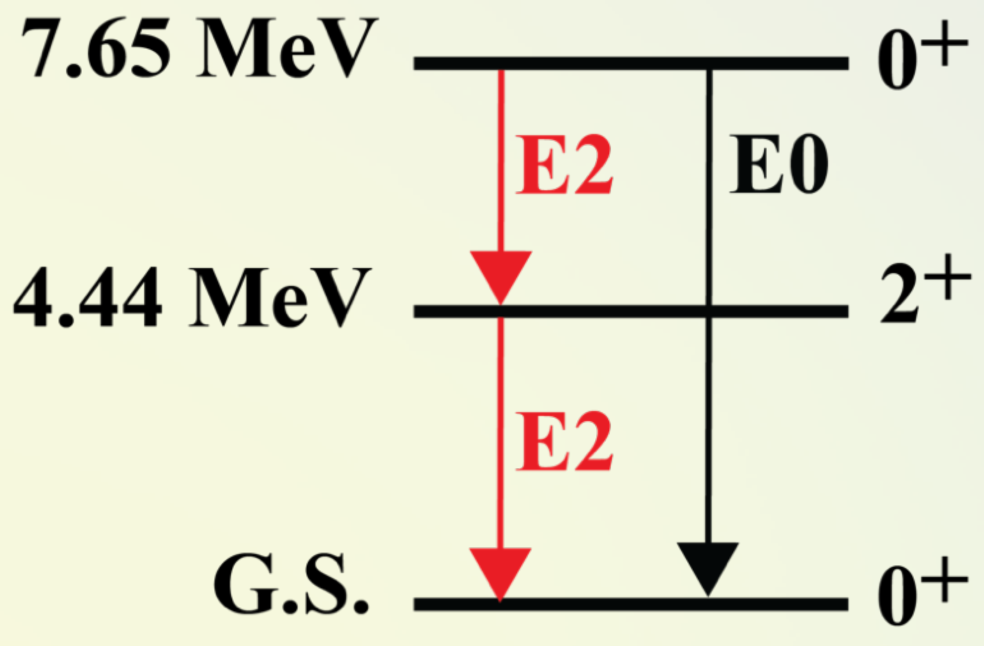

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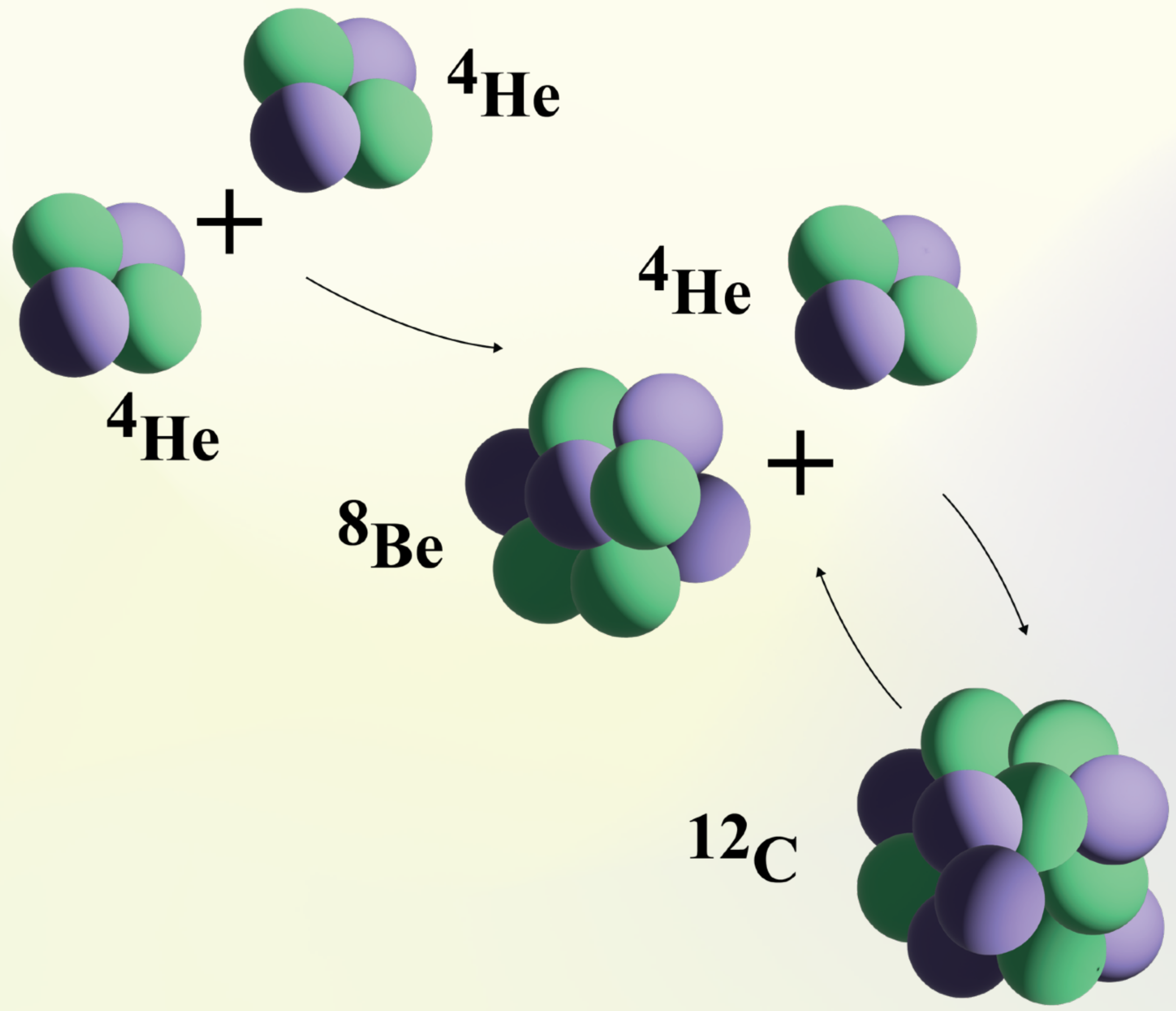
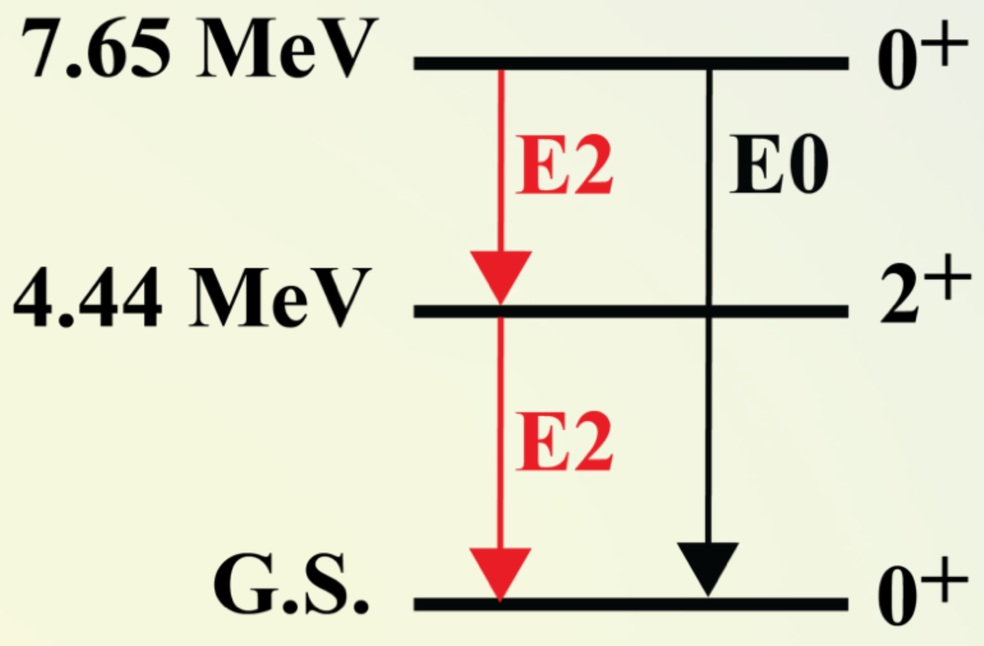
$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2}\left(1+\alpha_{\text{tot}}\right)+\Gamma_{\pi}^{E0}}{\Gamma}$$





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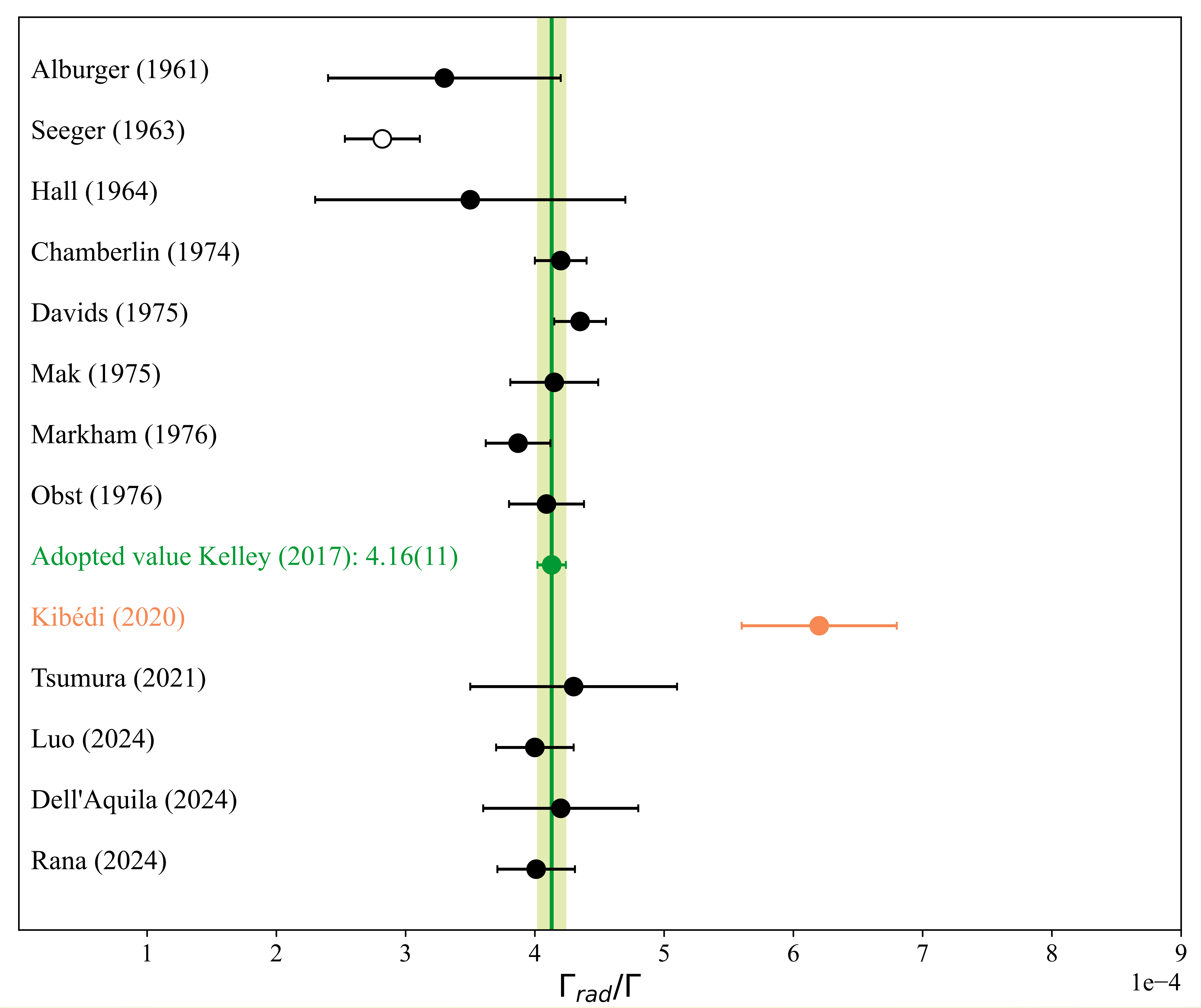
Previous measurements of the radiative branching ratio of the Hoyle state

Surviving recoil 12C

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

Combination of γ-decay and pair-decay branching ratio

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



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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

W. Paulsen,[1,2,*] K. C. W. Li,[1,2] S. Siem,[1,2] V. W. Ingeberg,[1,2] A. C. Larsen,[1,2] T. K. Eriksen,[1,2,3] 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. Valsdòttir[1,2]

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[2]*Norwegian Nuclear Research Centre, Oslo, Norway*

[3]*Department of Radiation Protection and Physics, Sector NUK Kjeller, Institute for Energy Technology, N-2007 Kjeller, Norway*

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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)].

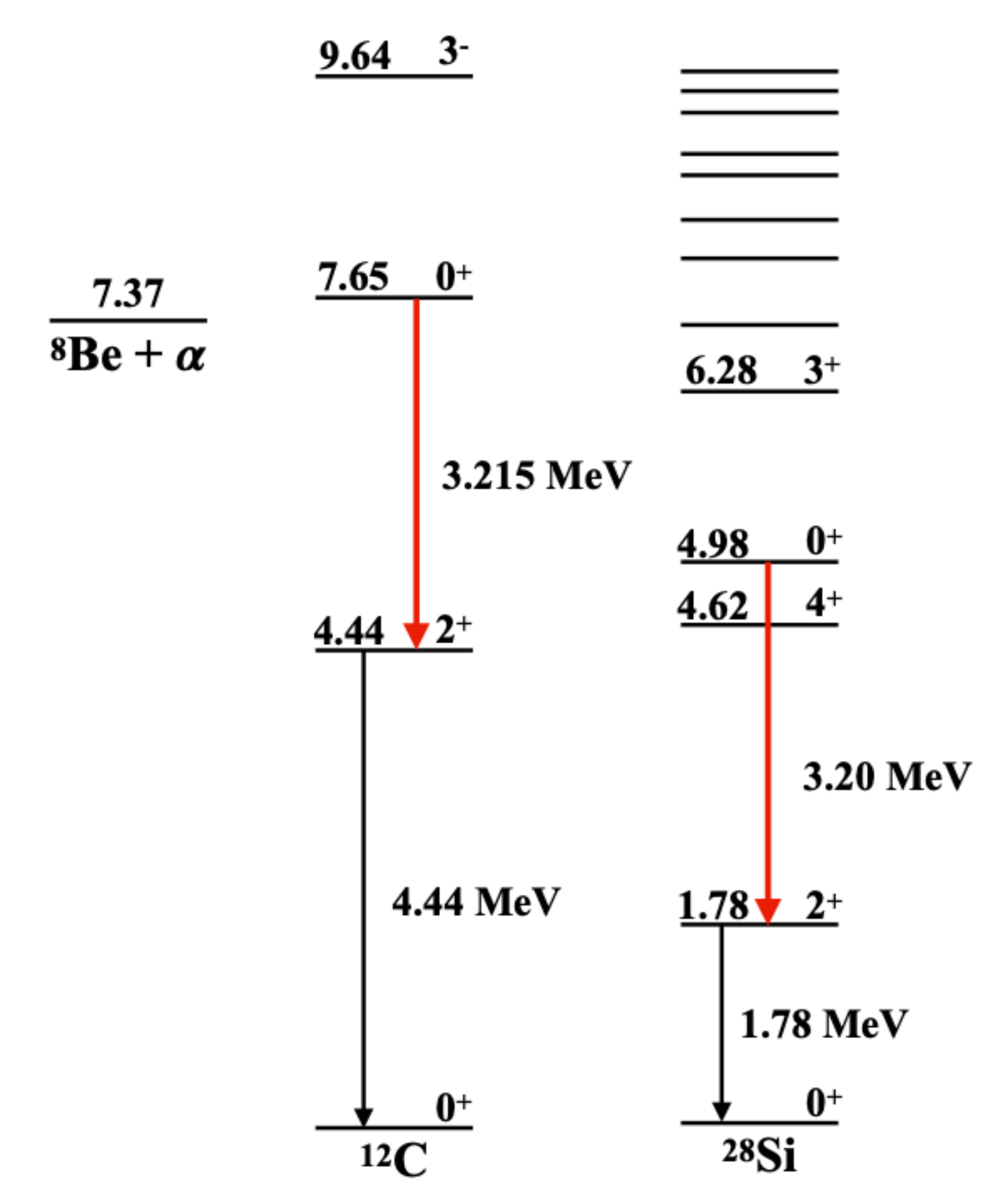
Method: For the primary experiment of this work the Hoyle state was populated by the $^{12}C(p, p')$ reaction at 10.8 MeV at the Oslo Cyclotron Laboratory. The γ-decay branching ratio was deduced through triple-coincidence events, each consisting of a proton-ejectile energy corresponding to population 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 $\Gamma_{\rm rad}/\Gamma = 4.1(4) \times 10^{-4}$. 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 $\Gamma_{\rm rad}/\Gamma = 4.6(6) \times 10^{-4}$.

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 $\Gamma_{\rm rad}/\Gamma = 4.16(11) \times 10^{-4}$. 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.

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

$$\frac{\text{Amount of particles populating the Hoyle state resulting in the desired gamma cascade } ^{12}\text{C}(p, p'\gamma_1\gamma_2)}{\text{Total amount of particles populating the Hoyle state } ^{12}\text{C}(p, p'\gamma_1\gamma_2 + p'3\alpha + \ldots)} \times \text{Correction factors} = \Gamma_\gamma/\Gamma$$



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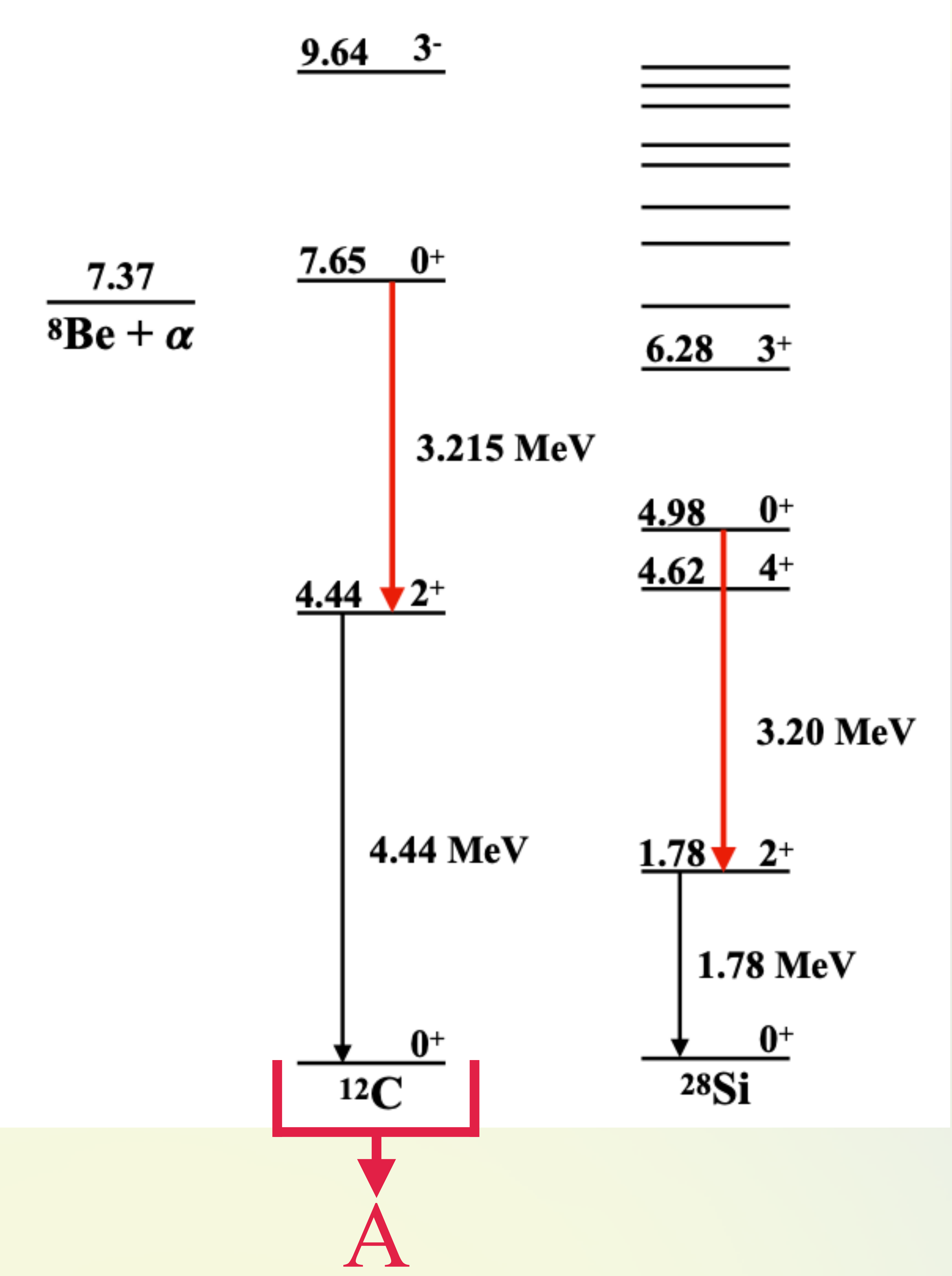
Same measurement: Two different analysis methods to obtain $\boldsymbol{\Gamma_\gamma/\Gamma}$

A

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



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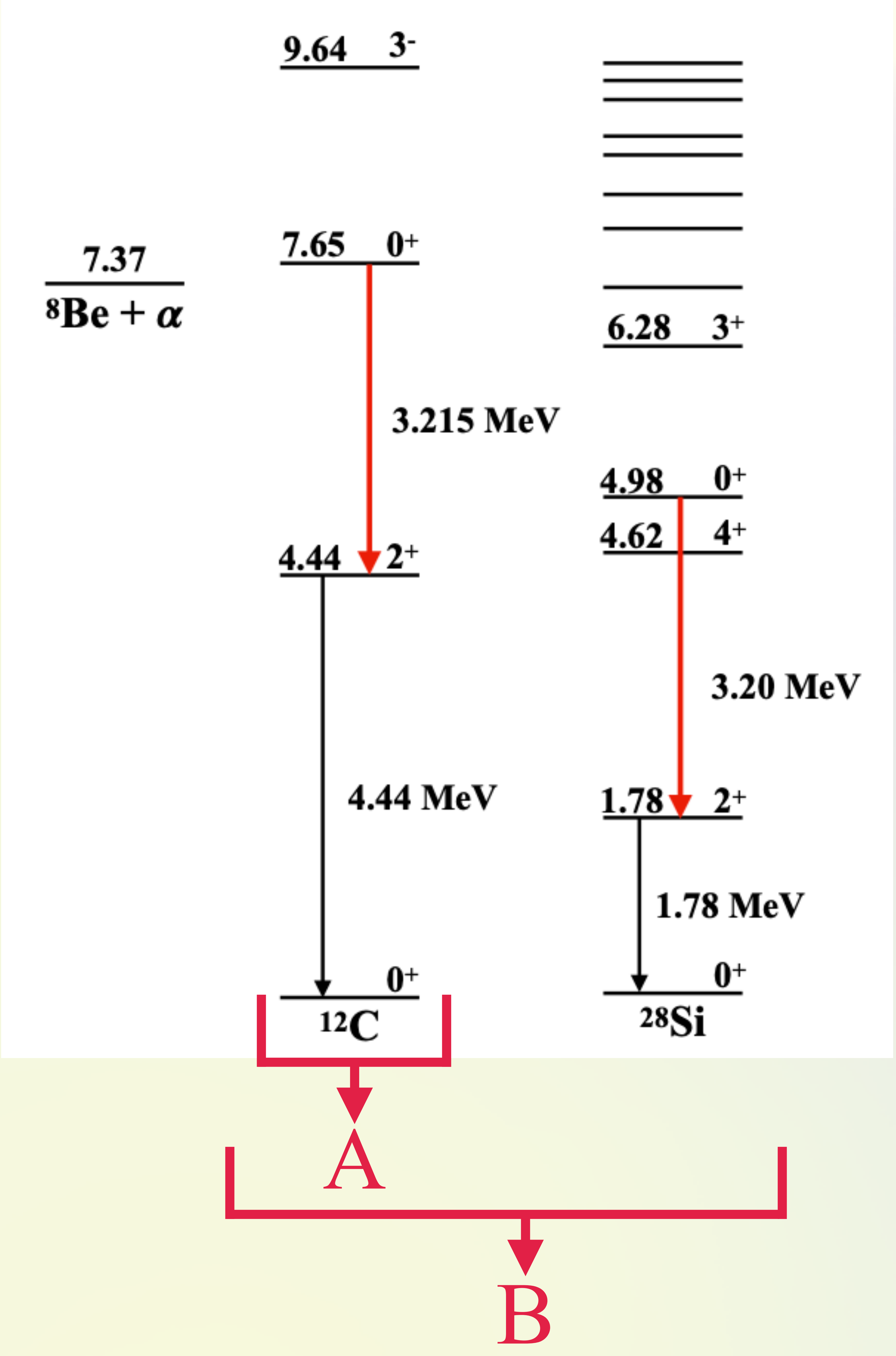
B
$$\frac{\Gamma_\gamma^{7.65}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{\text{inclusive}}^{4.98}}{N_{\text{inclusive}}^{7.65}} \times \frac{\epsilon_{1.78}}{\epsilon_{4.44}} \times \frac{\epsilon_{3.20}}{\epsilon_{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}} \times \frac{c_{\text{det}}^{4.98}}{c_{\text{det}}^{7.65}}$$



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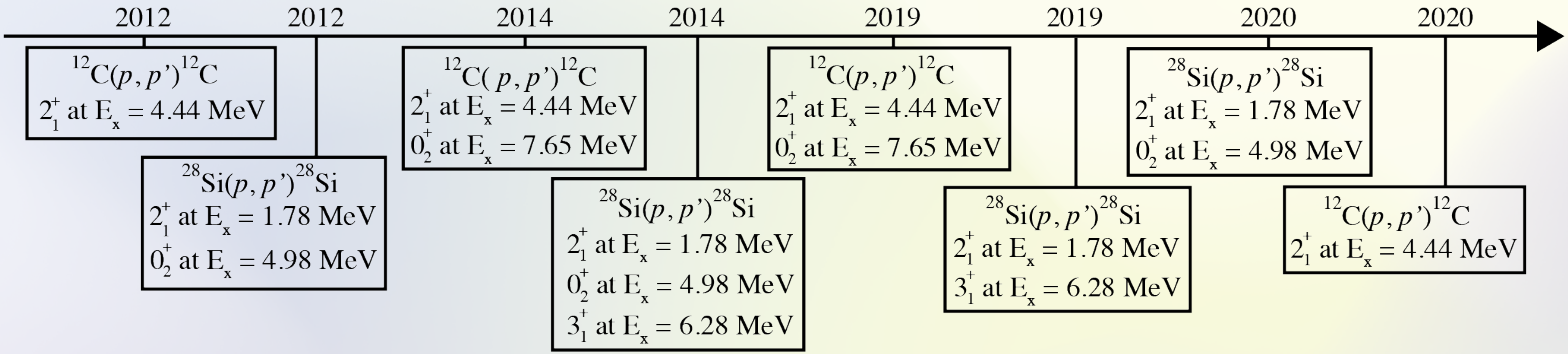
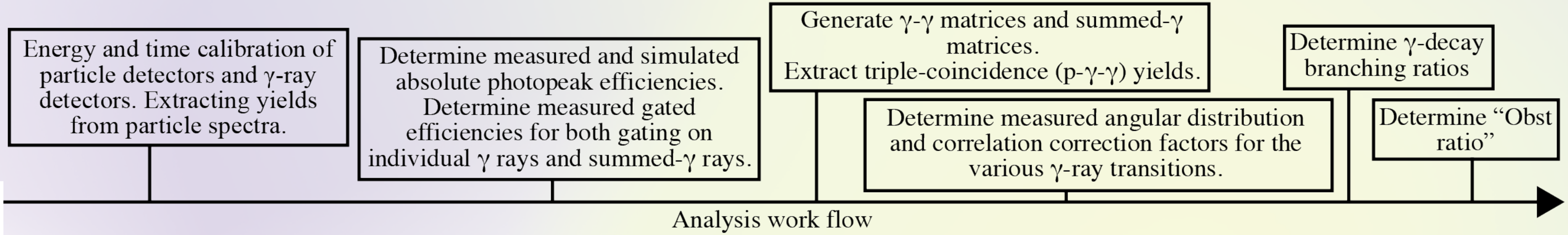
Measurements in this work and analysis pipeline





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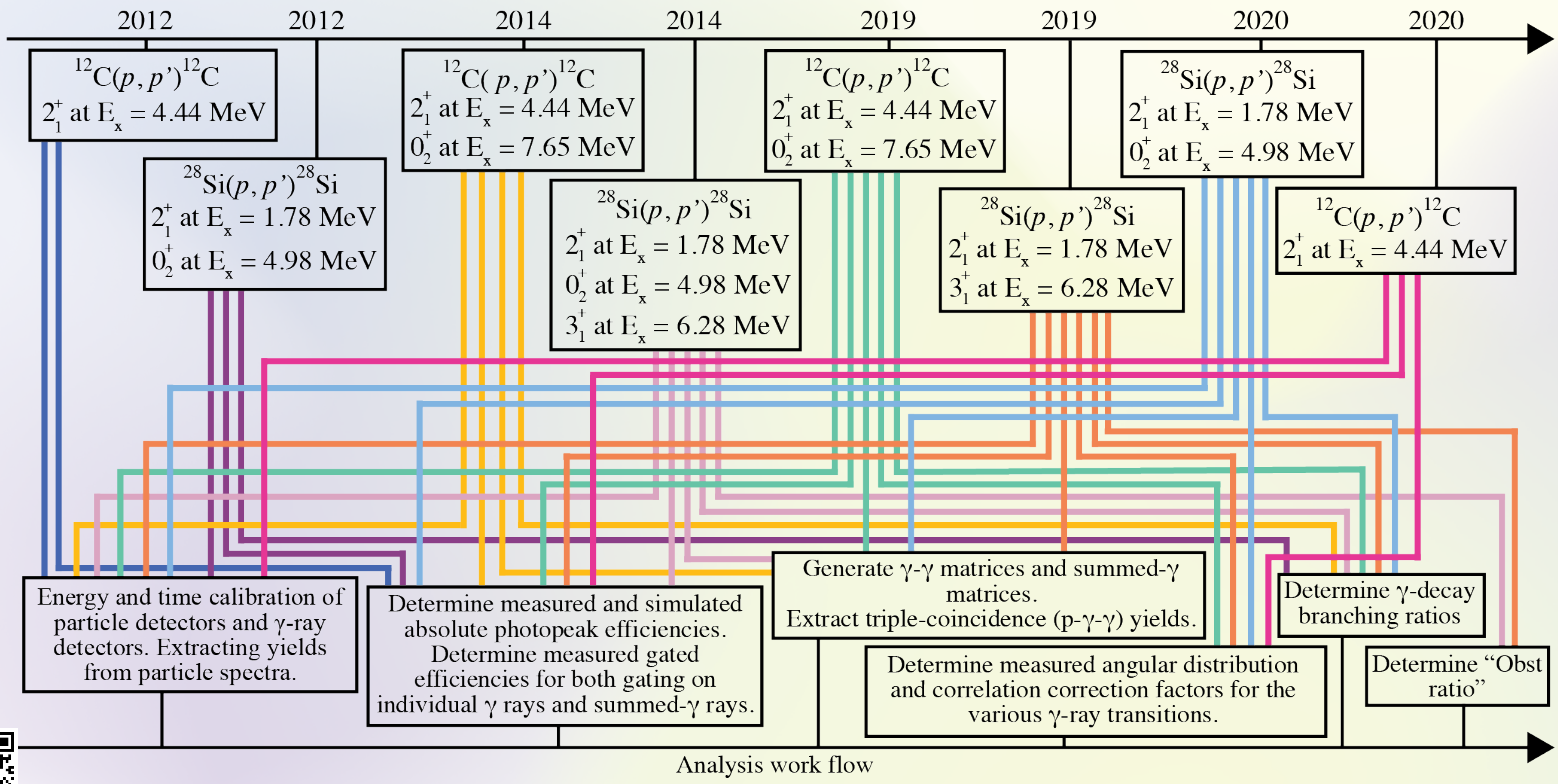

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Experimental equipment

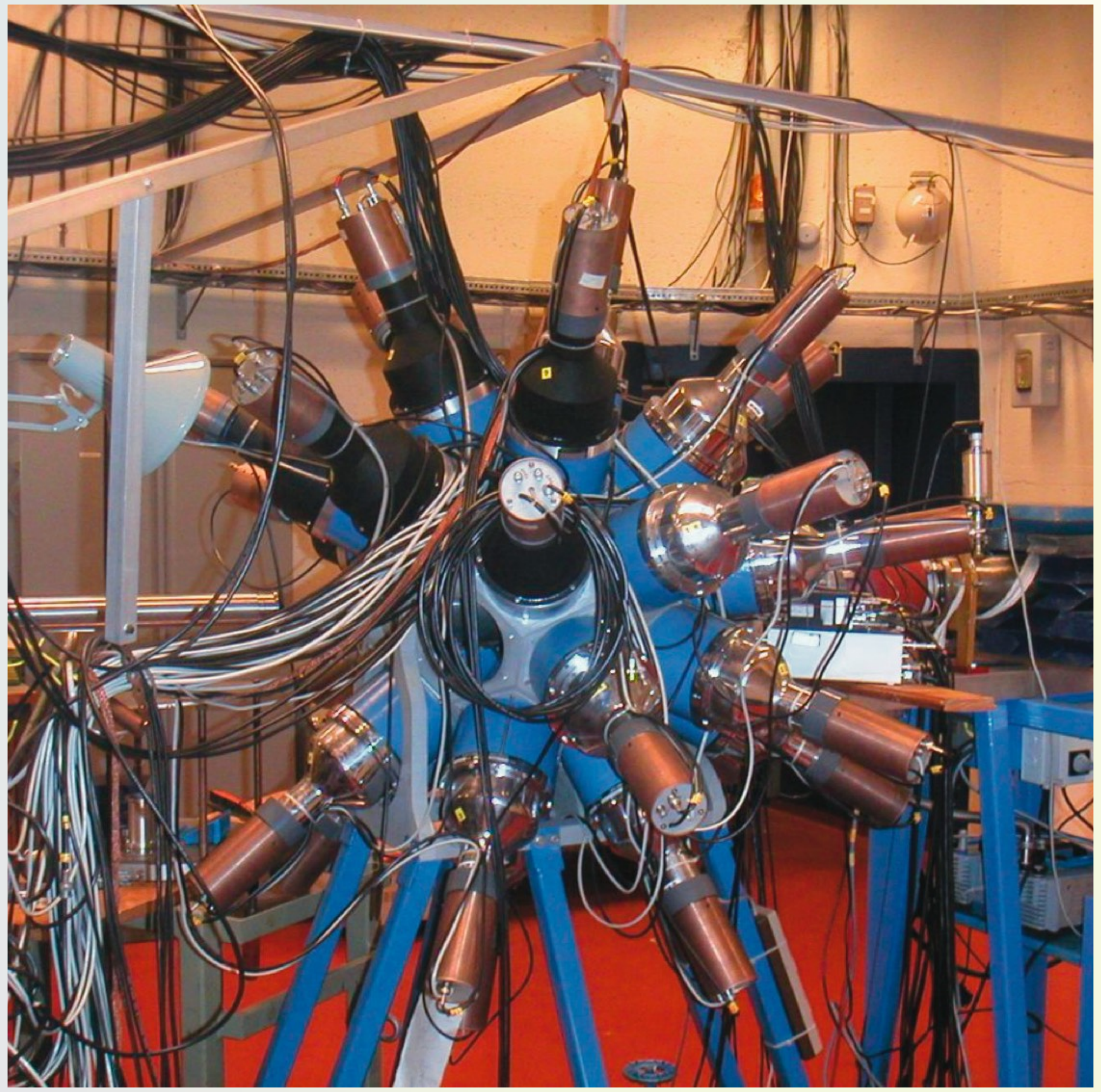
SiRi

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°-140°, 2° intervals
- Front position: theta = 40°-54°, 2° intervals
- dE-detectors 130 μm, E-detectors 1550 μm

CACTUS

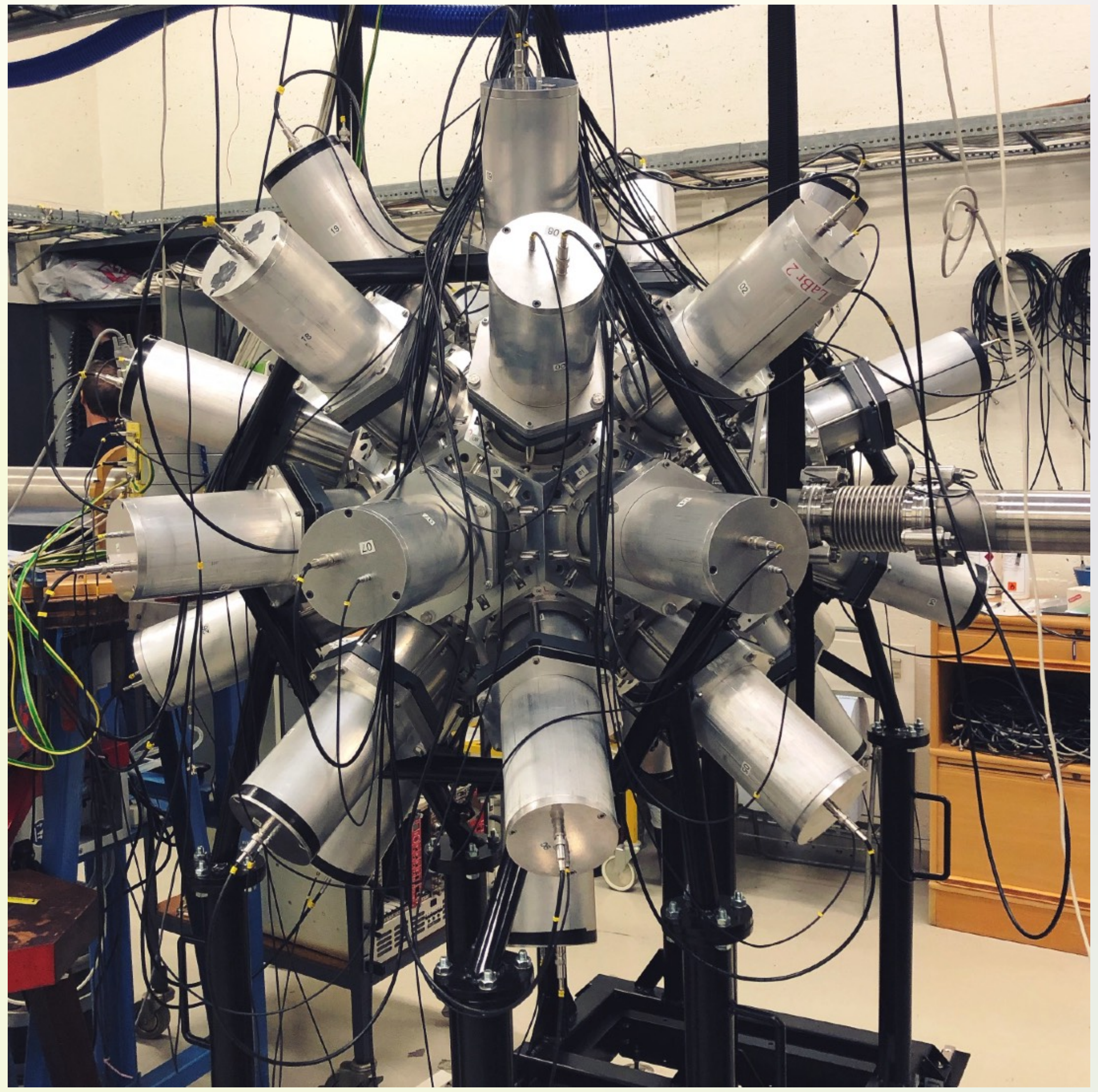
Guttormsen *et al.* (1990) [12]
DOI 10.1088/0031-8949/1990/T32/010



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

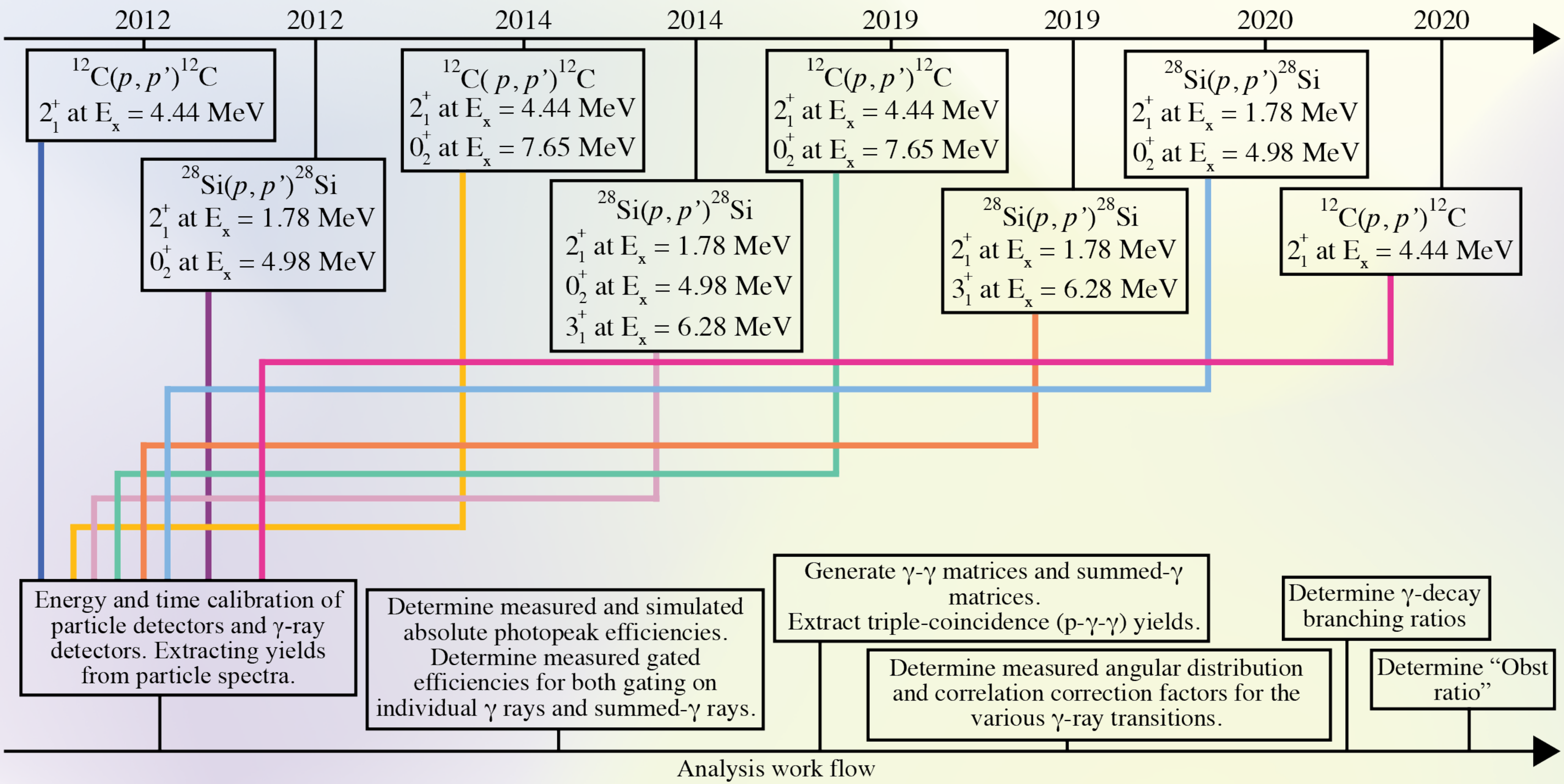
OSCAR

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



- 30 $LaBr_3$ detectors (3.5" x 8")
- No collimation
- Each detector subtending a solid angle of ~1.9% of 4π
- Total gamma-ray efficiency (1.3 MeV) ~ 56%
- Distance from target 16.3 cm

Measurements in this work and analysis pipeline



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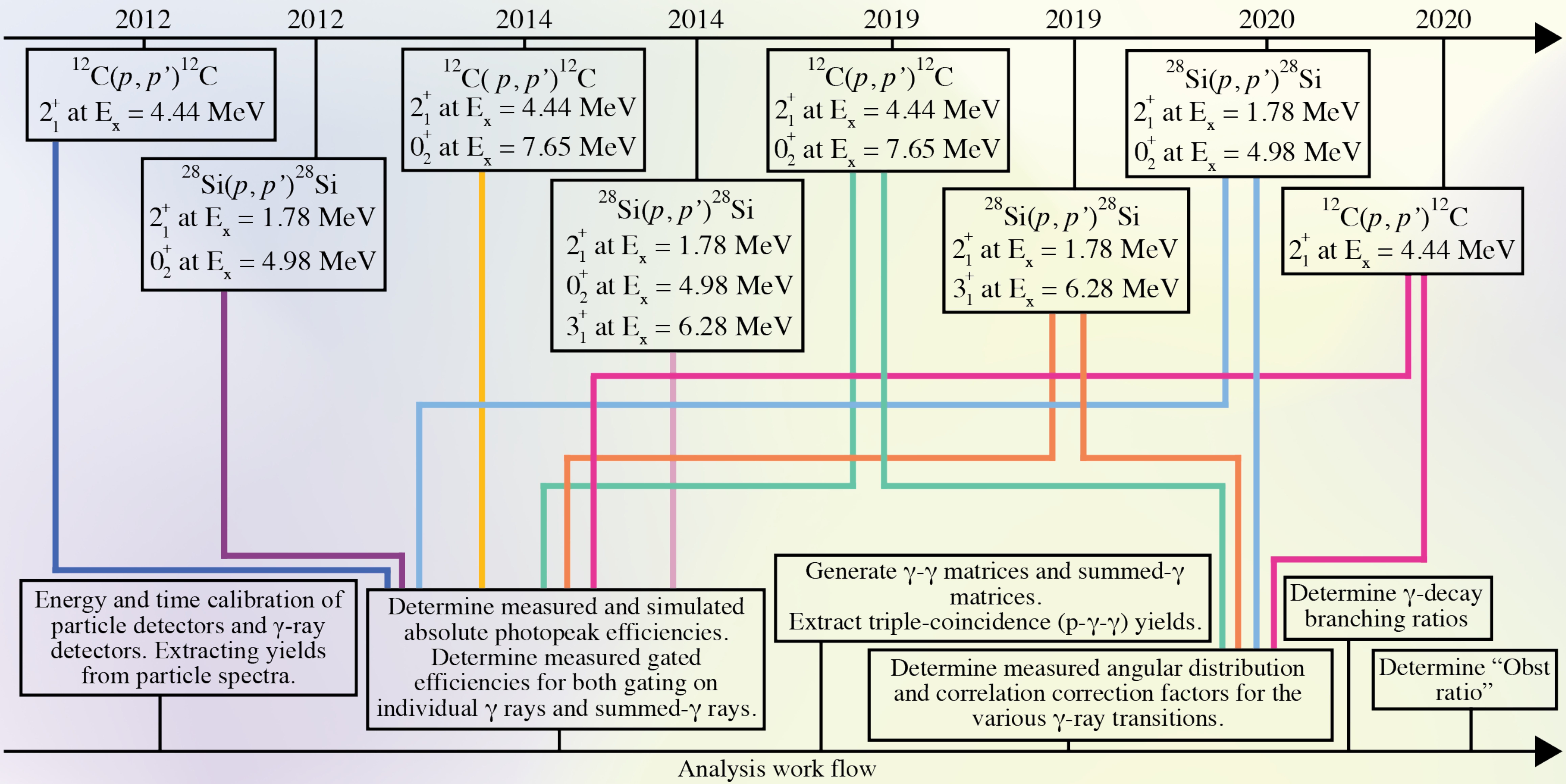

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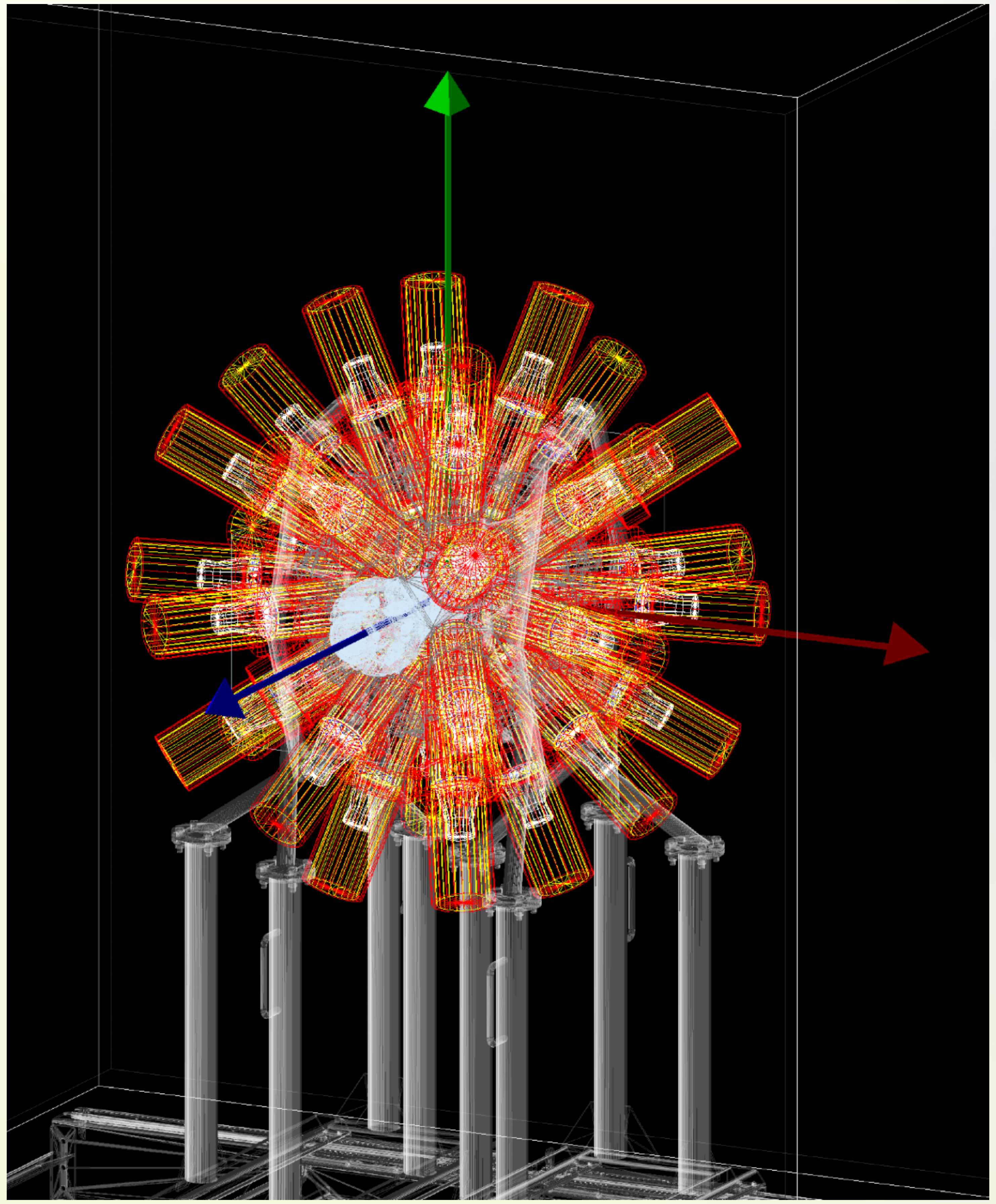
Efficiencies and angular correlation correction factors of OSCAR

- The efficiency and the angular correlation correction factors have been performed by K. C. W. Li using the OSCAR response function in GEANT4 created by Zeiser *et al.* (2021) [13].



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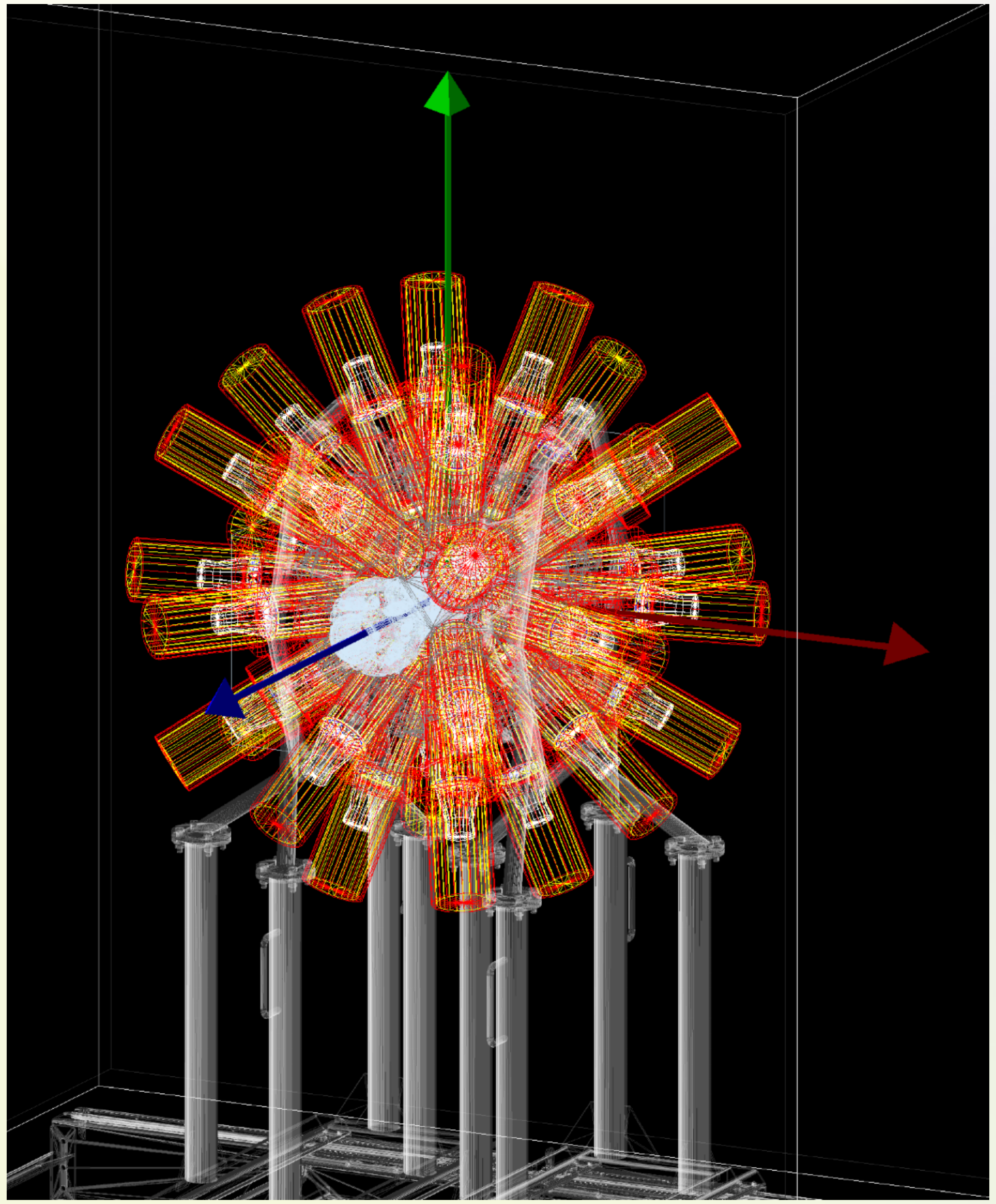

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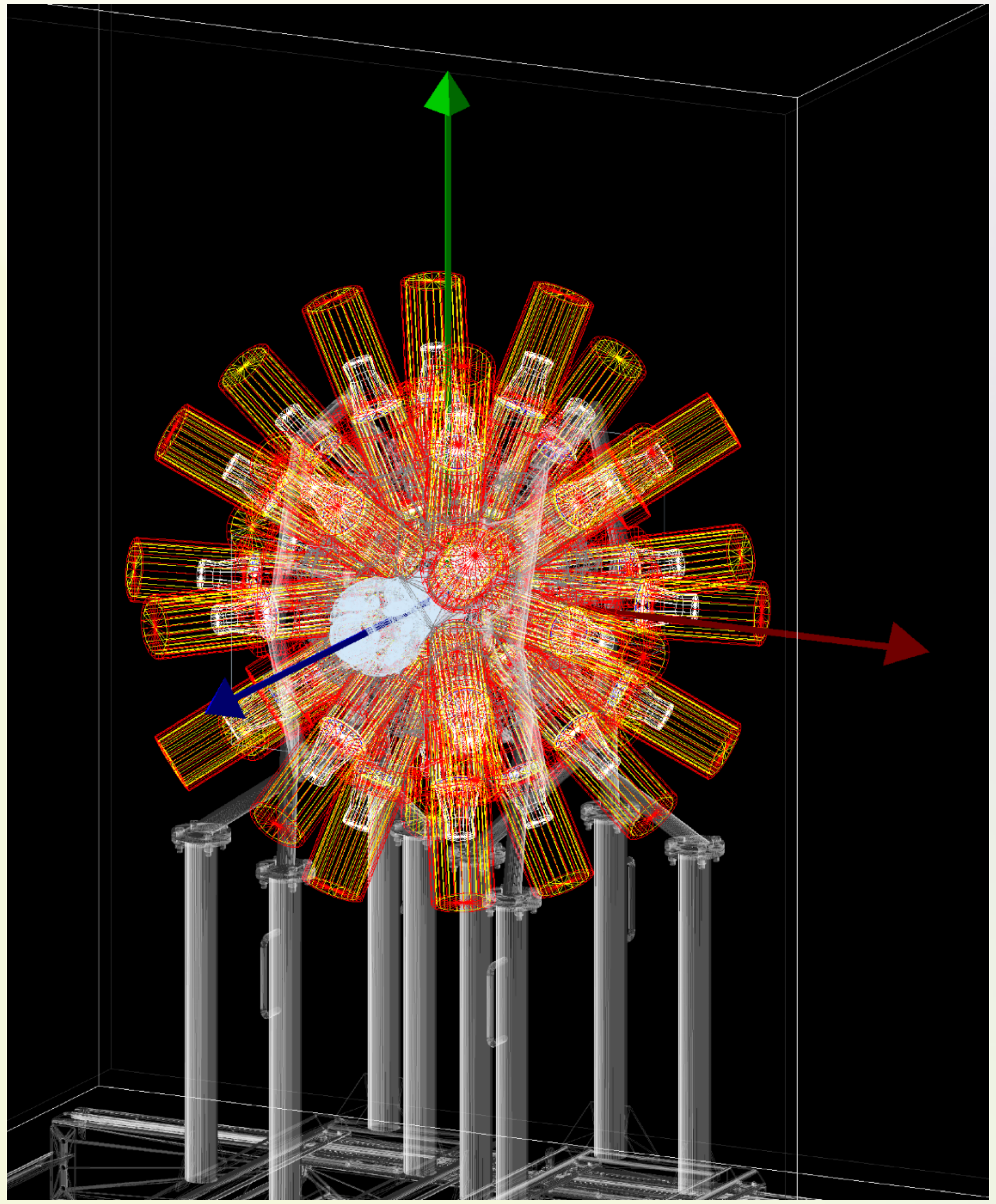
- Simulation accounts for ± 1 mm distance uncertainty for the OSCAR detectors, beam energy differences, corrections from measuring cascading gammas and finite-solid effects of the LaBr3-detectors of OSCAR.



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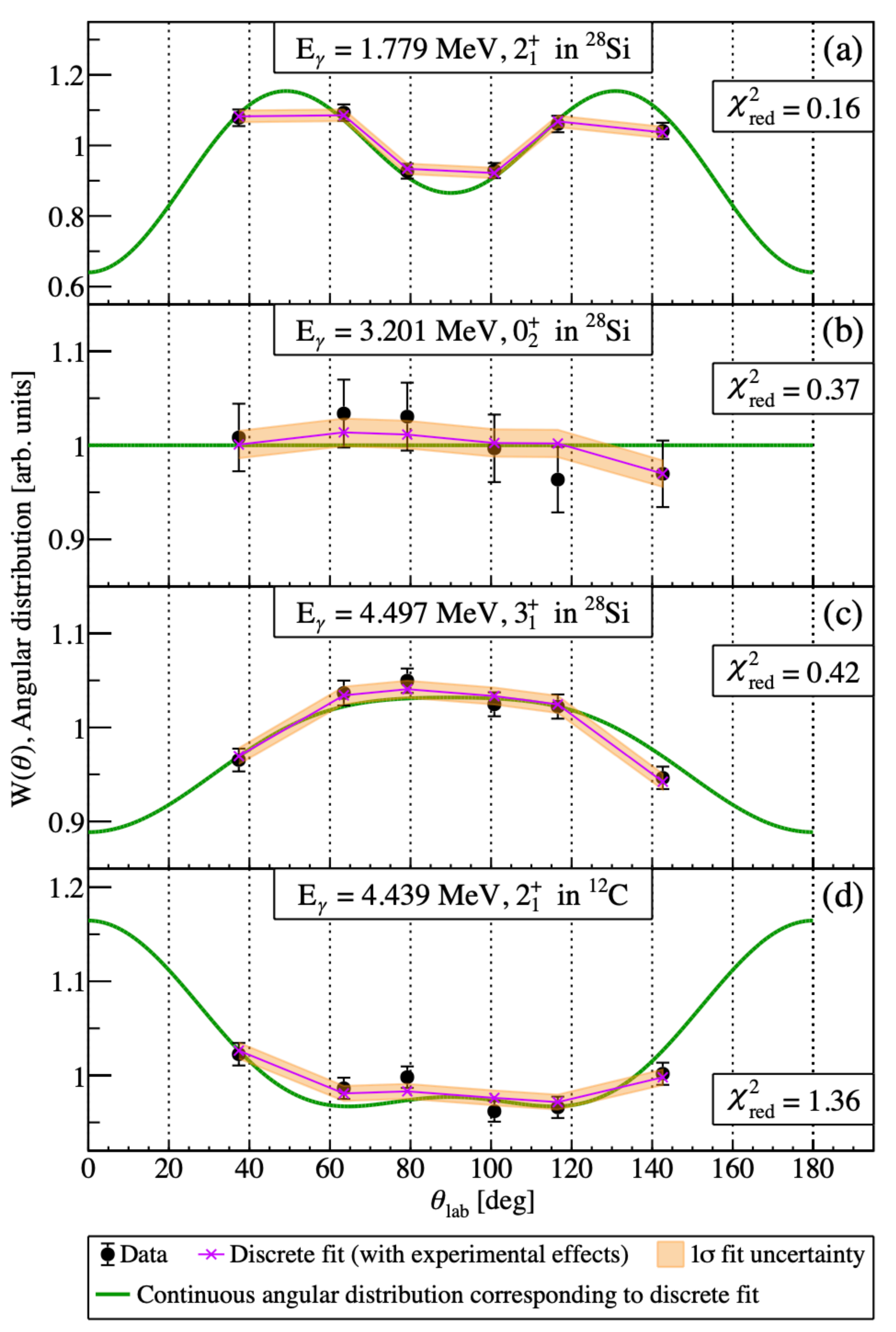
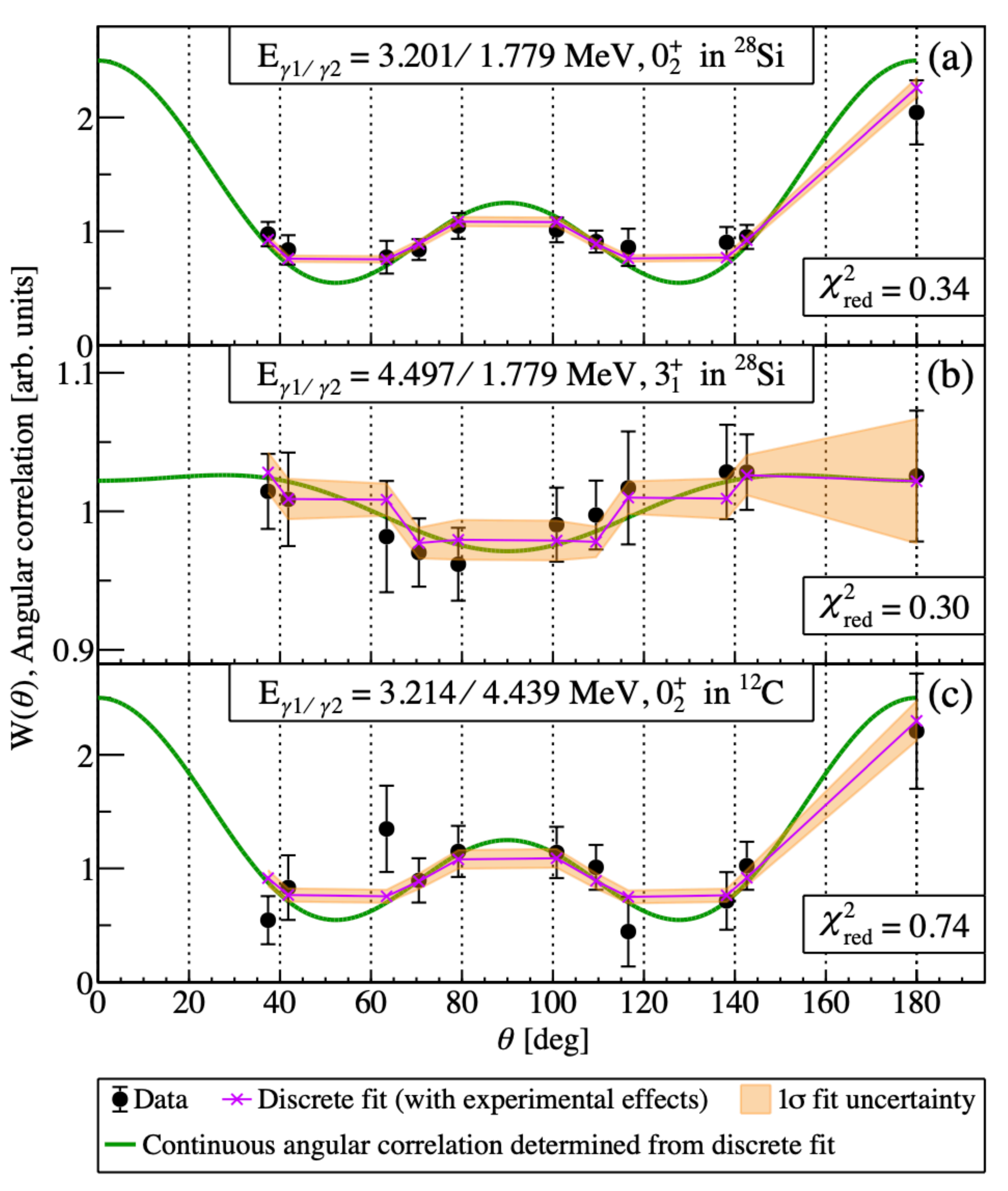


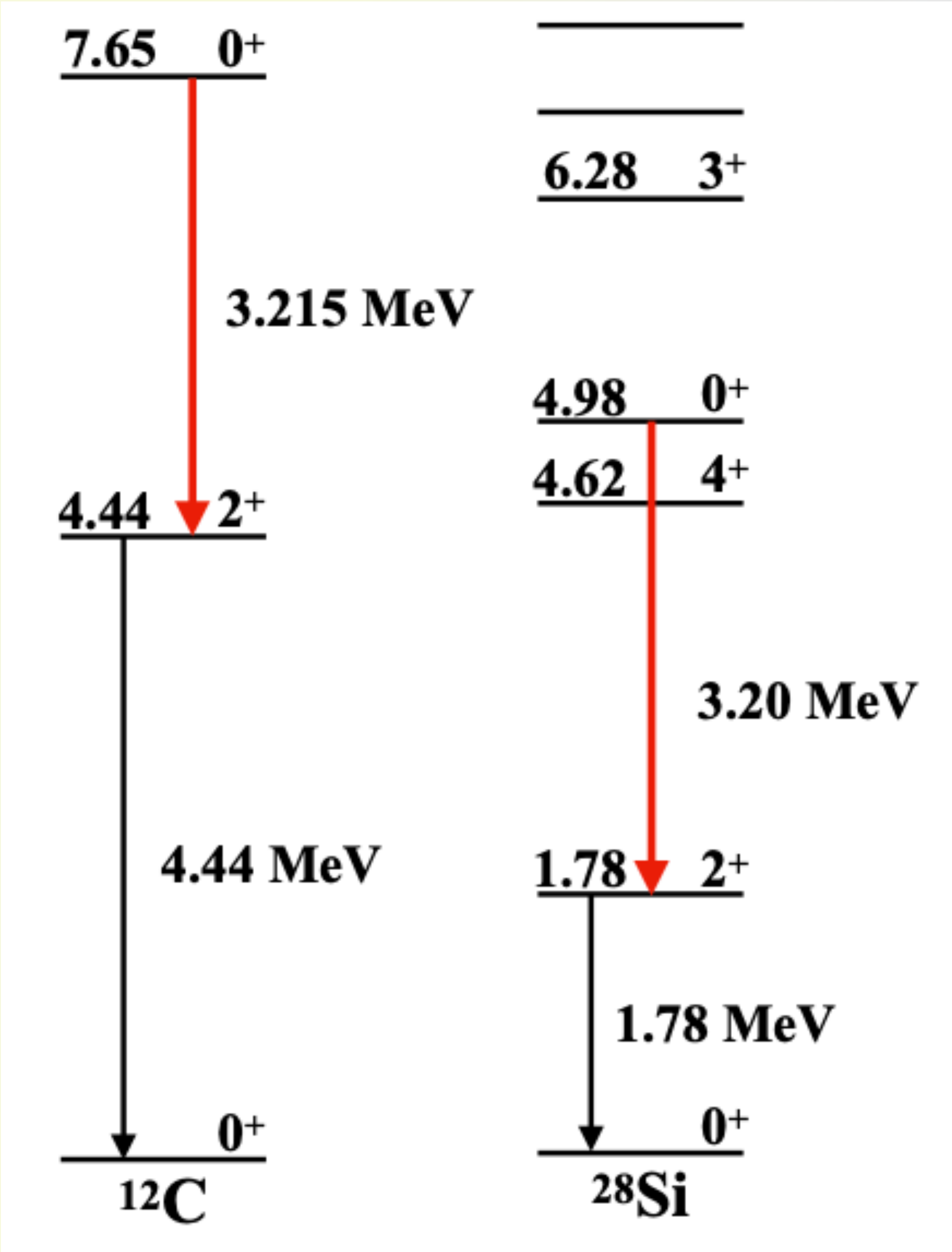


Efficiencies and angular correlation correction factors of CACTUS

- For the CACTUS array we do not have a full GEANT4 simulation available.
- For results of 2012 and 2014 measurements, no correction to the distance uncertainty for the detectors, beam energy differences, corrections from measuring cascading gammas and finite-solid effects of the NaI(Ti)-detectors of CACTUS.
- A 3% systematic uncertainty was added to all efficiencies to account for the missing corrections.
- Angular correlation correction factor W_{020} from Kibédi *et al*. (2020) was used for all measurements using CACTUS.

	^{12}C(p,p') / ^{28}Si(p,p') with $E_p = 16.0$ MeV performed in 2012	^{12}C(p,p') / ^{28}Si(p,p') with $E_p = 10.7$ MeV performed in 2014 [16]
$\epsilon_{1.78}$ (data, fitted)	0.0024(2)	0.0028(1)[a]
$\epsilon_{1.78}$ (data, gated)	0.0024(1)	0.0031(1)[a]
$\epsilon_{3.20}$ (data, fitted)	0.00168(8)	0.00169(6)
$\epsilon_{4.44}$ (data, fitted)	0.00136(4)	0.00143(4)
$\epsilon_{4.44}$ (data, gated)	0.00173(5)	0.00172(5)
$\epsilon_{4.49}$ (data, fitted)		0.00152(9)
$\epsilon_{1.78}\epsilon_{3.20}c_{\rm det}$ (data, gated)	0.0022(1)	0.0035(2)
$\epsilon_{1.78}\epsilon_{3.20}c_{\rm det}$ (generated, gated)	0.0023(1)	0.0032(2)
$\epsilon_{1.78}\epsilon_{4.49}c_{\rm det}$ (data, gated)		0.0030(2)
$\epsilon_{1.78}\epsilon_{4.49}c_{\rm det}$ (generated, gated)		0.0034(2)
$\epsilon_{3.20}\epsilon_{4.44}c_{\rm det}$ (generated, gated)		0.0025(2)

[a] These efficiency points were not used because of contamination from the 4_1^+ state at $E_x = 4.62$ MeV in ^{28}Si in the inclusive spectrum.



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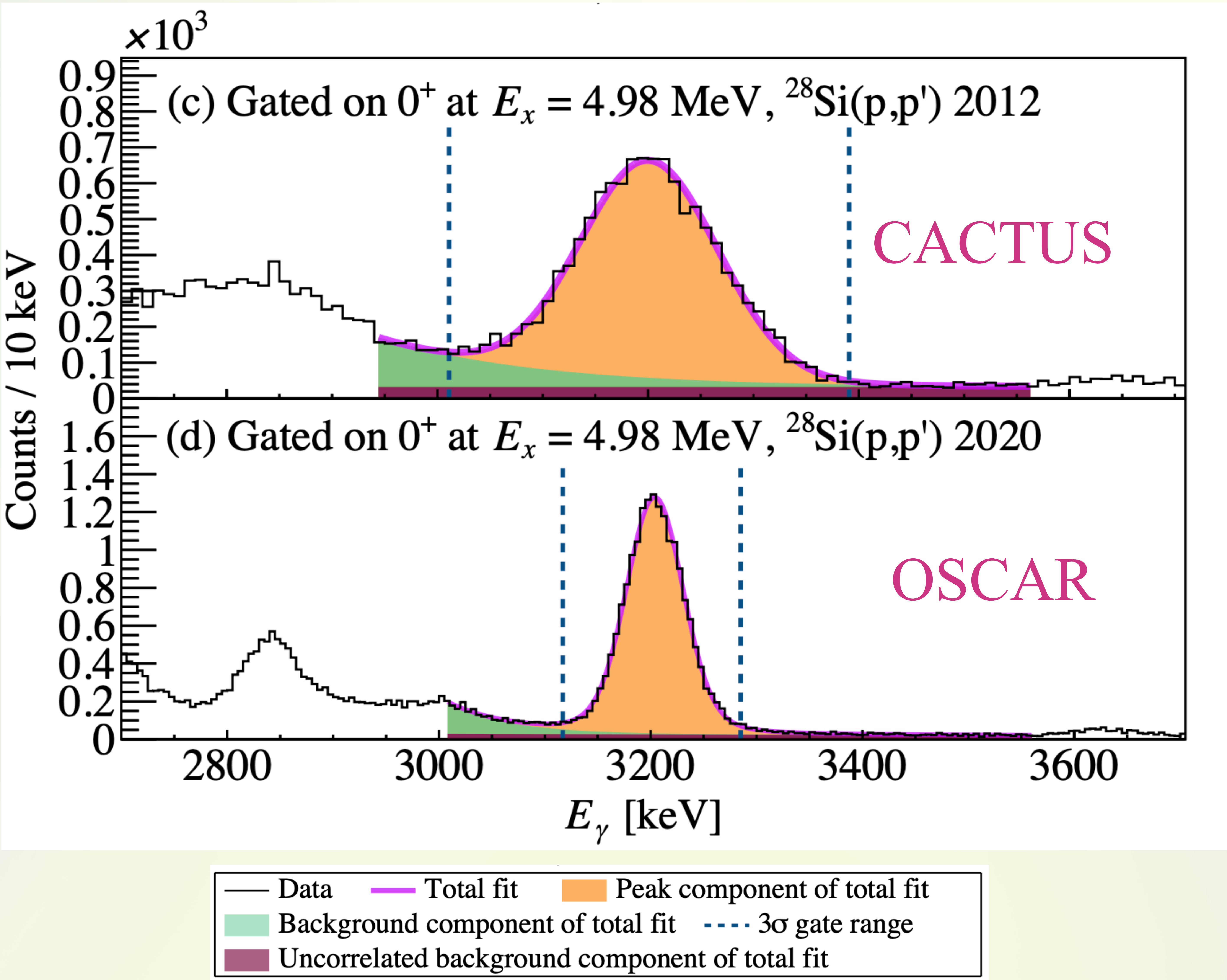
The effect of gating on a γ-ray on the definition of efficiency

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**.



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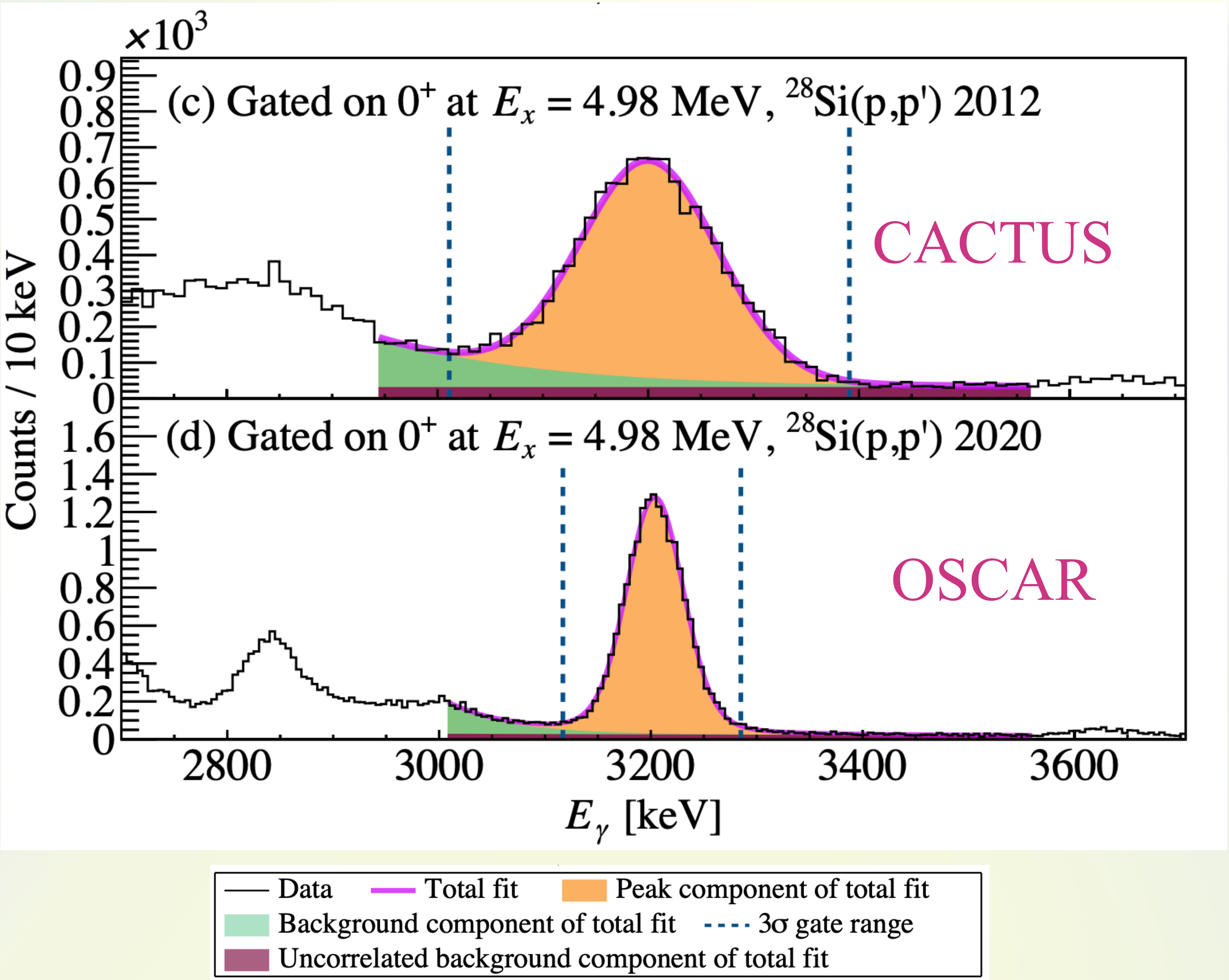

The effect of gating on a γ-ray on the definition of efficiency

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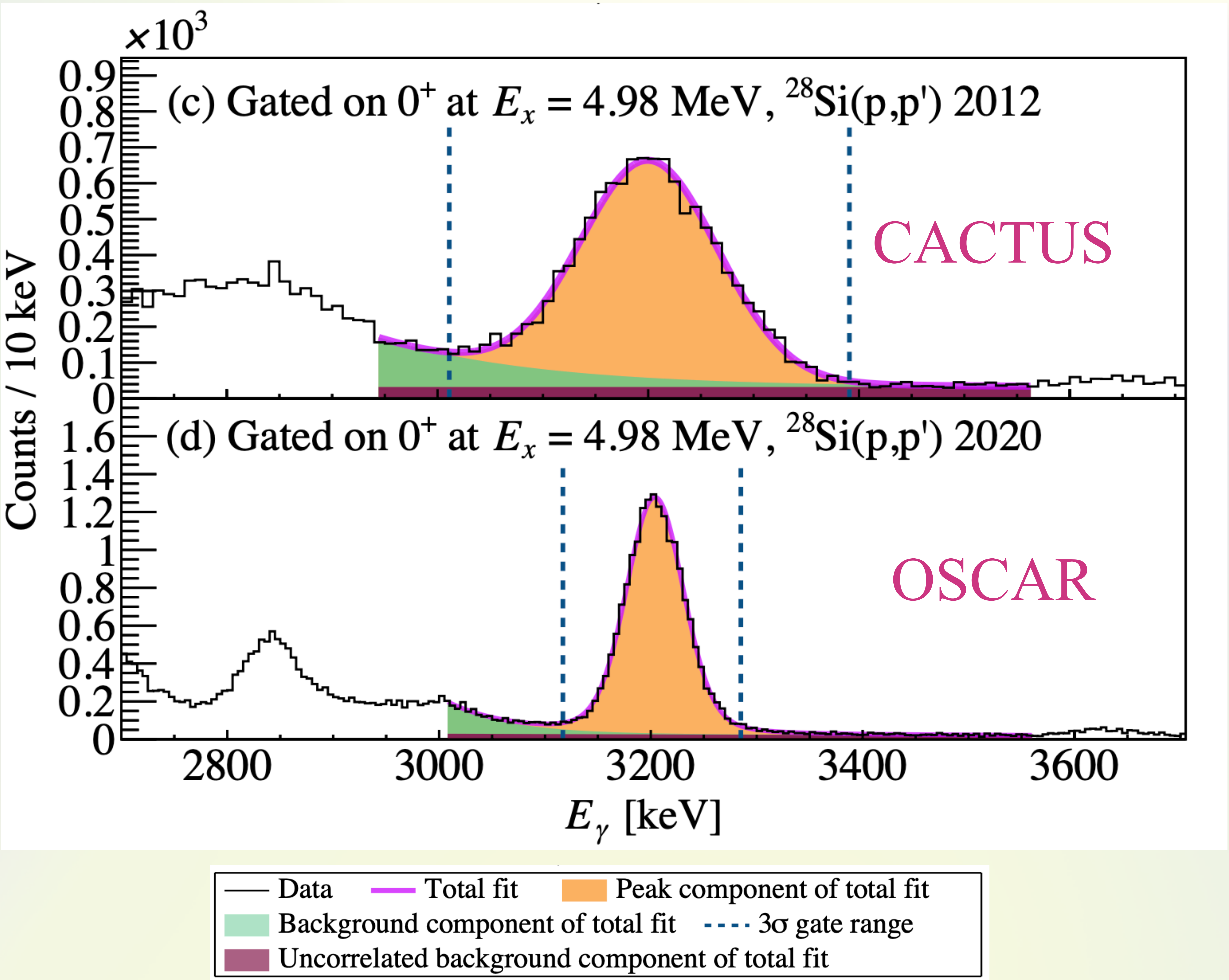
Depending on the **resolution** of the detectors, events within the gate might fall **outside** the **absolute photopeak**, but will still yield valid **triple coincidences**: These events **must** be accounted for.



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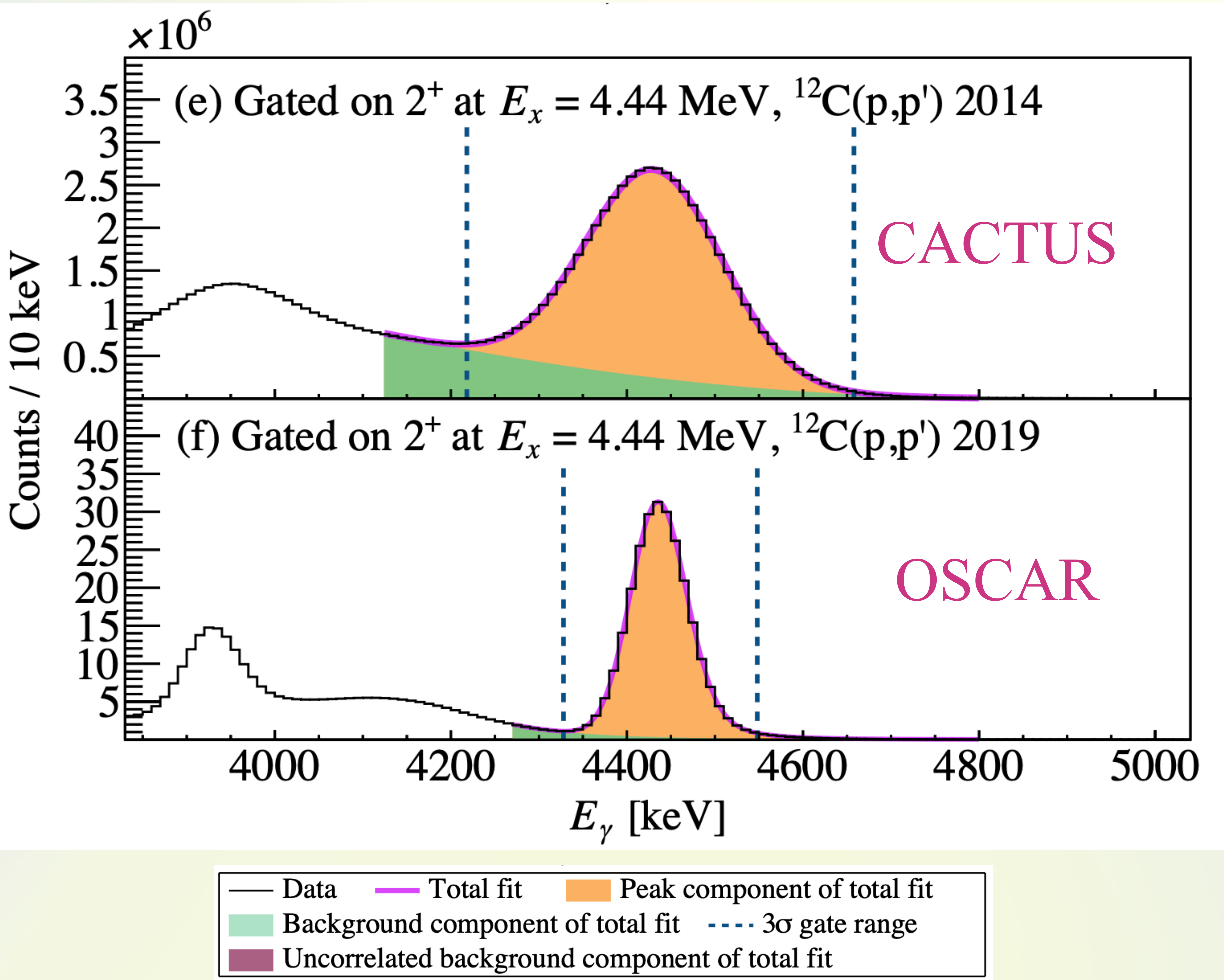

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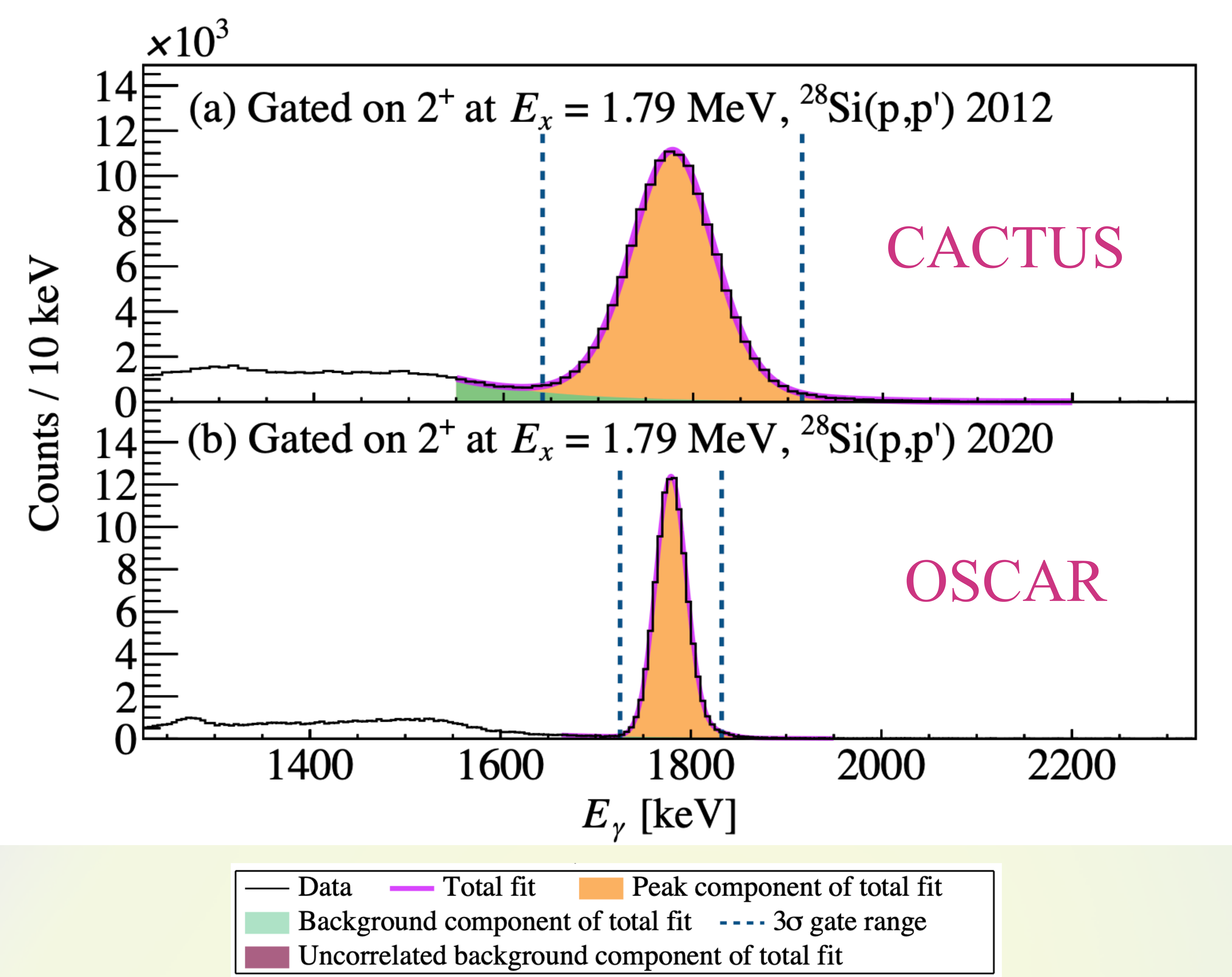
The effect of gating on a γ-ray on the definition of efficiency

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.

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



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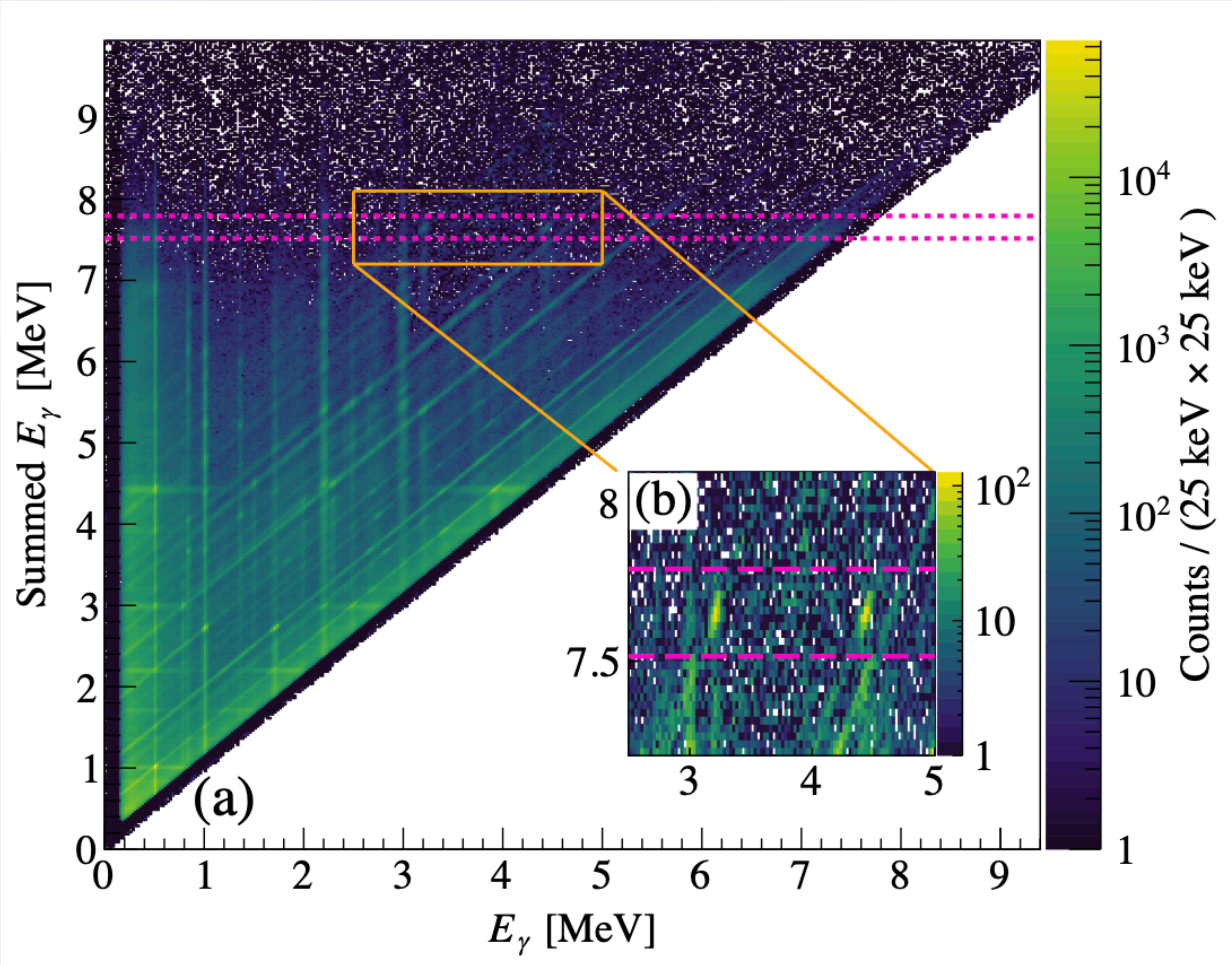
Efficiency for a sum of γ-rays and the effect on the peak shape

Summed-γ matrix for ^{12}C(p, p') 2019



- This is not the efficiency of a **single γ ray**, it is the efficiency of the **convolution of two γ rays** of different energies.

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

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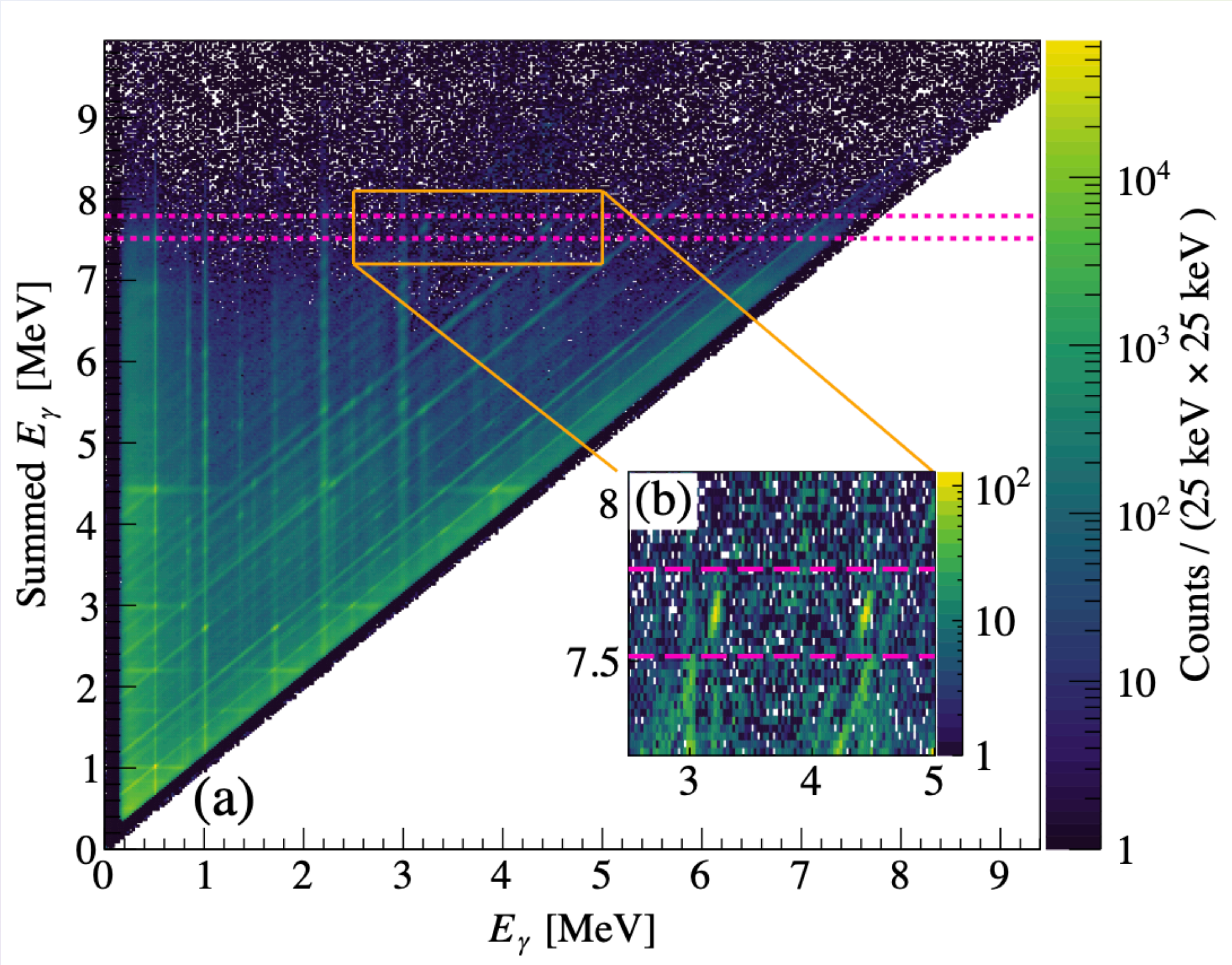

- This is not the efficiency of a **single γ ray**, it is the efficiency of the **convolution of two γ rays** of different energies.
- Not only do you need to have the response of this convolution of γ rays, you also need to extract the triple-coincidence yield from a **non-trivial peak shape**, originating from performing a gate on the sum.

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

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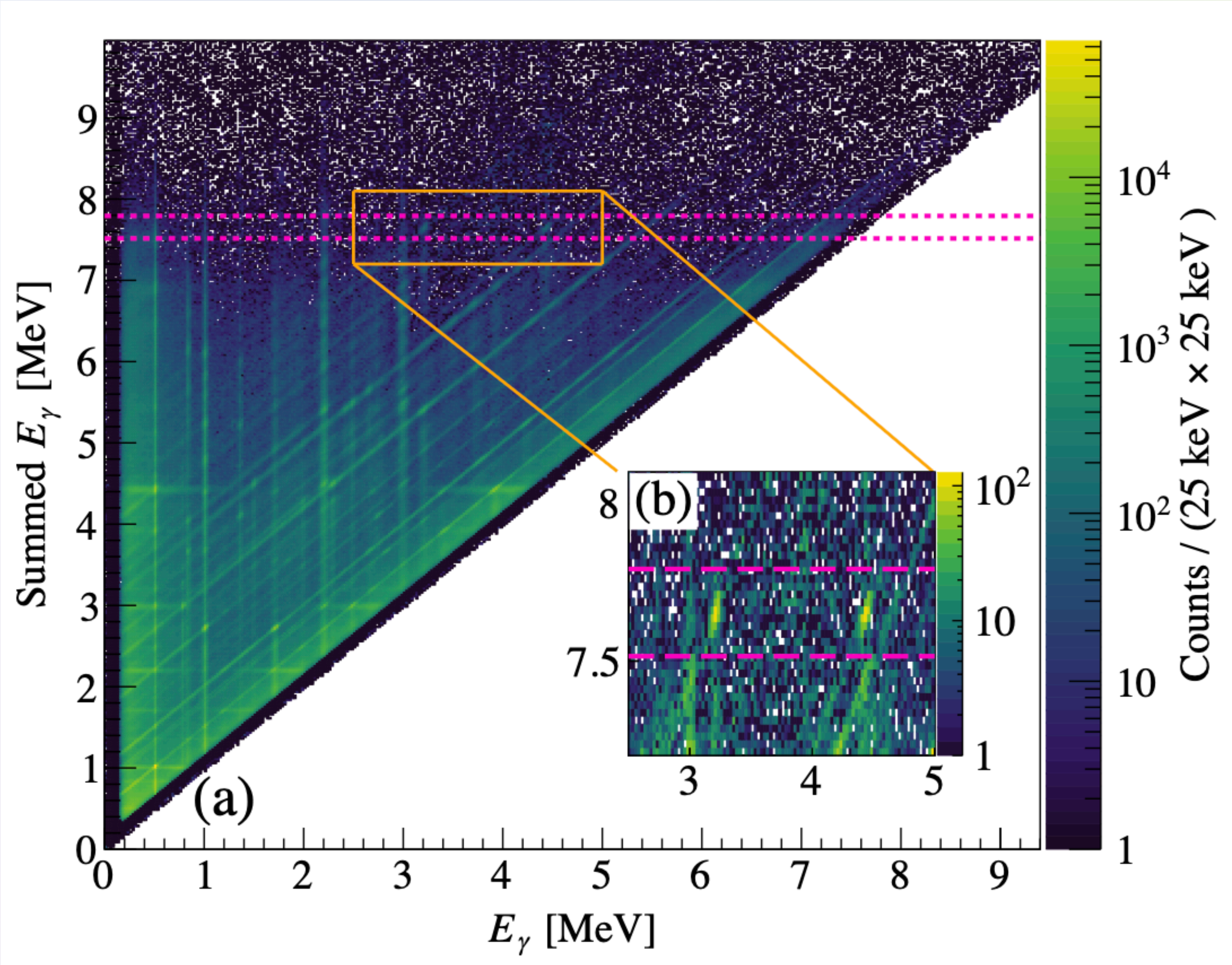

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- **How** do you get the experimental response when your cascade is very **weakly** populated?

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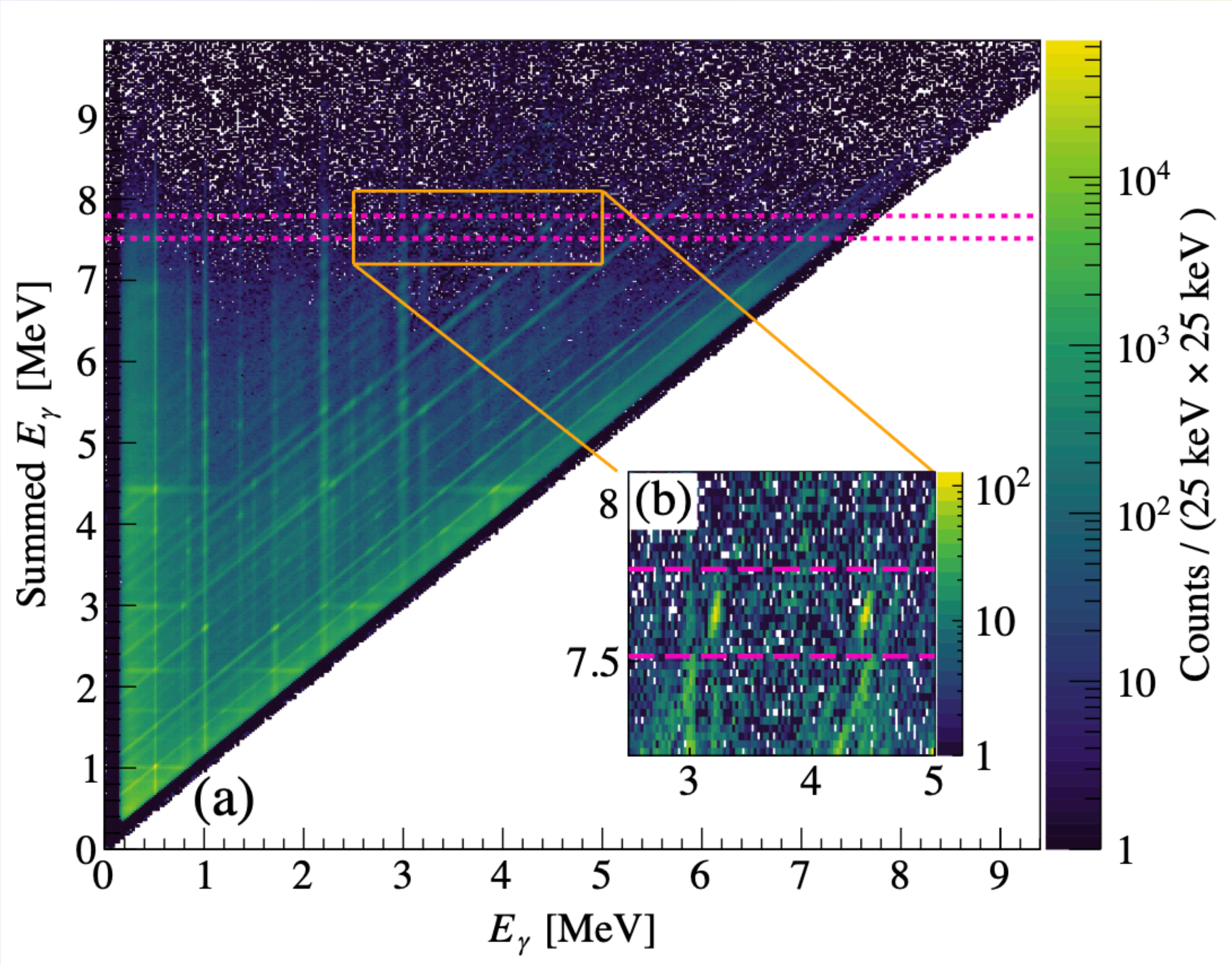

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  - **How** do you get the experimental response when your cascade is very **weakly** populated?
- We used the individual transitions as **probability distributions** and **generated/sampled** our convolved summed-γ efficiency

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

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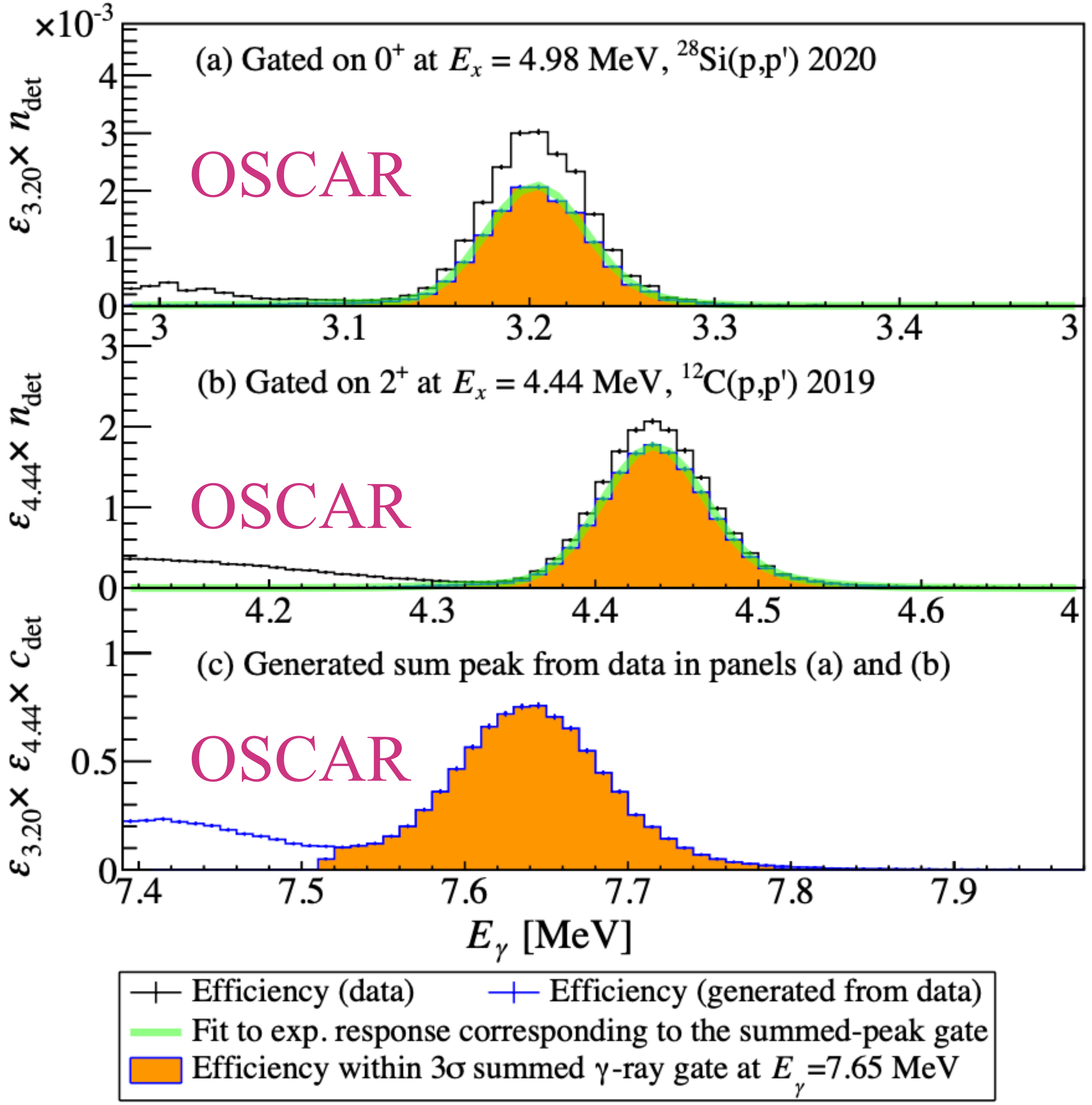
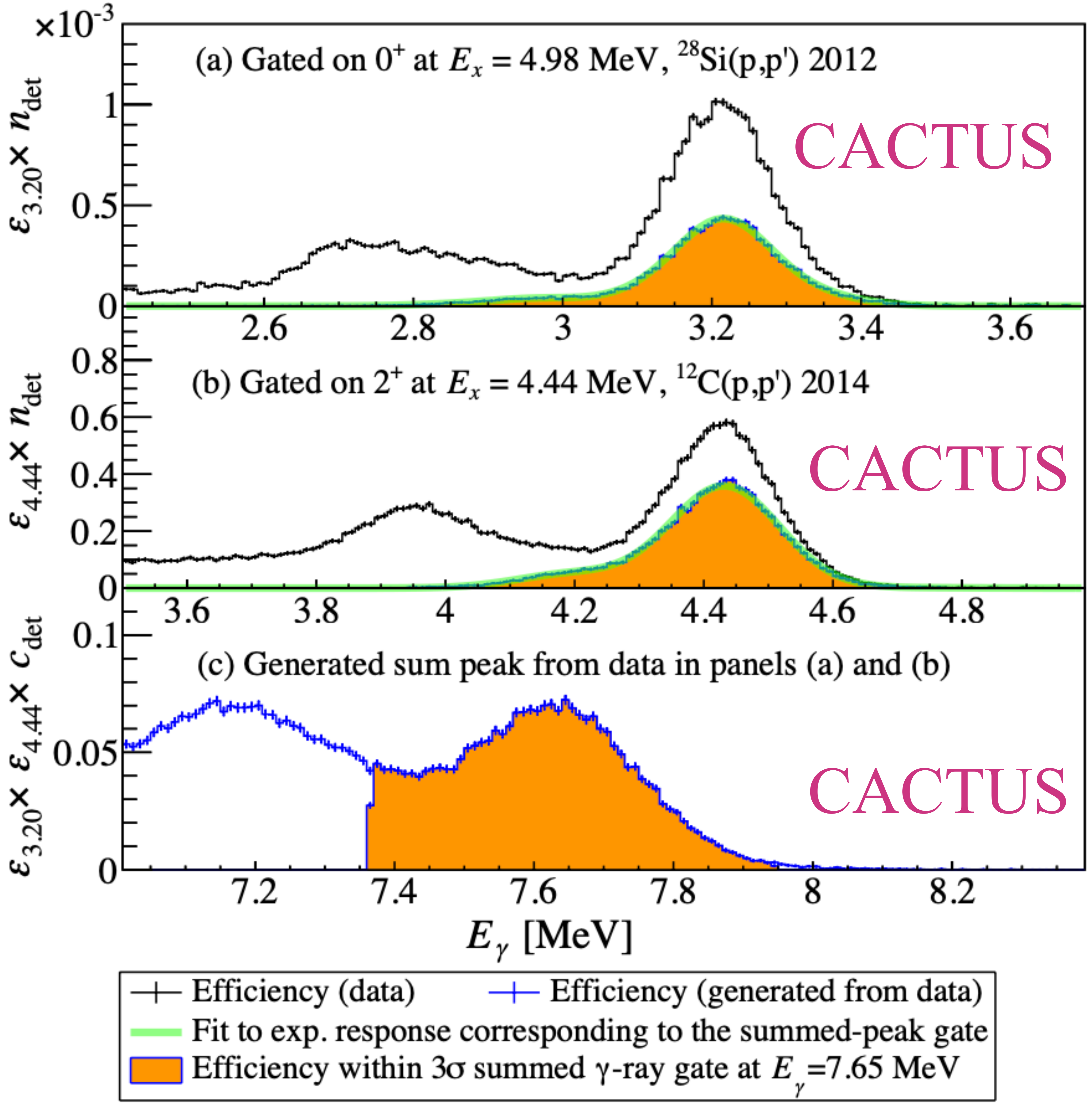
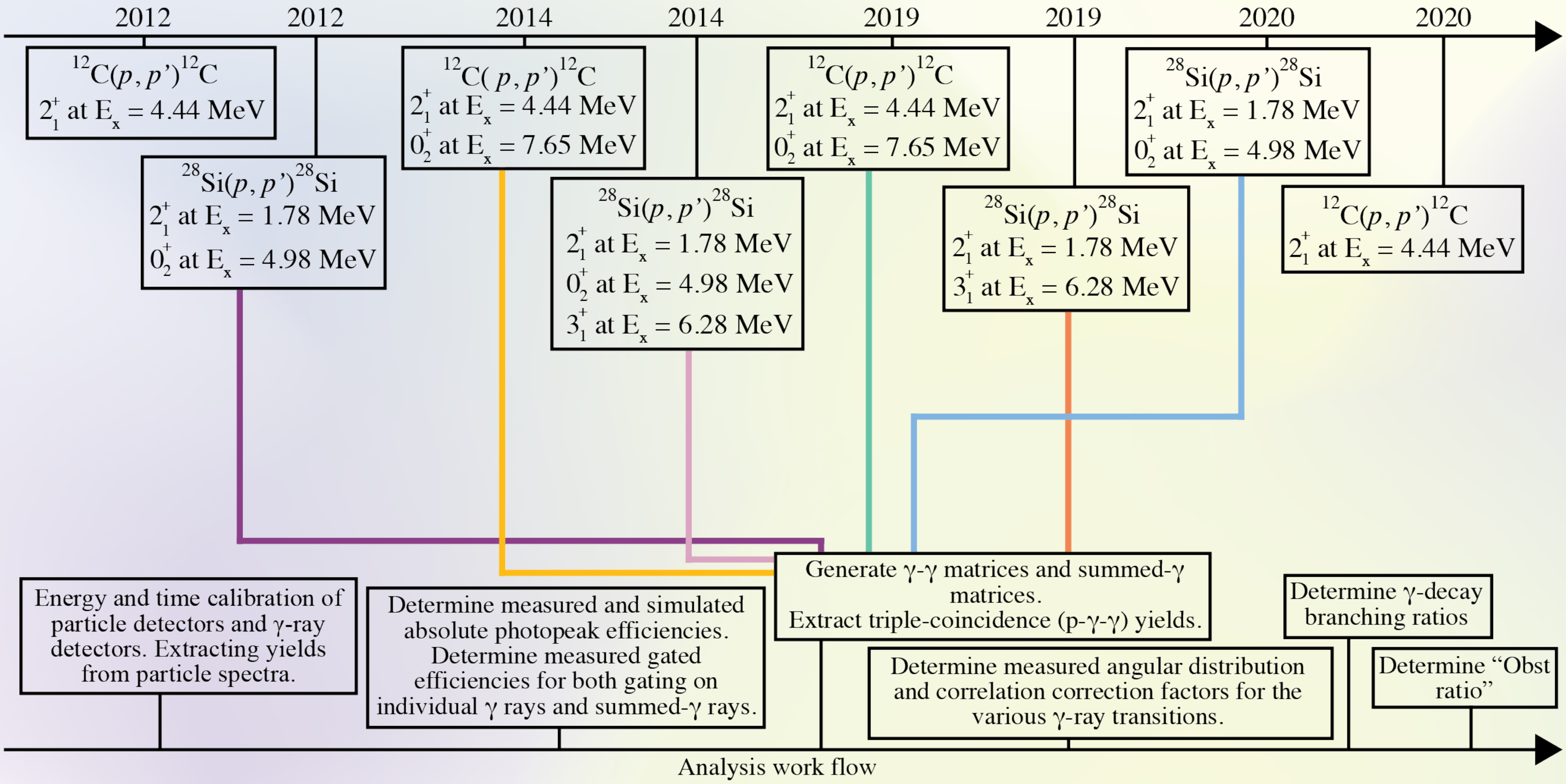




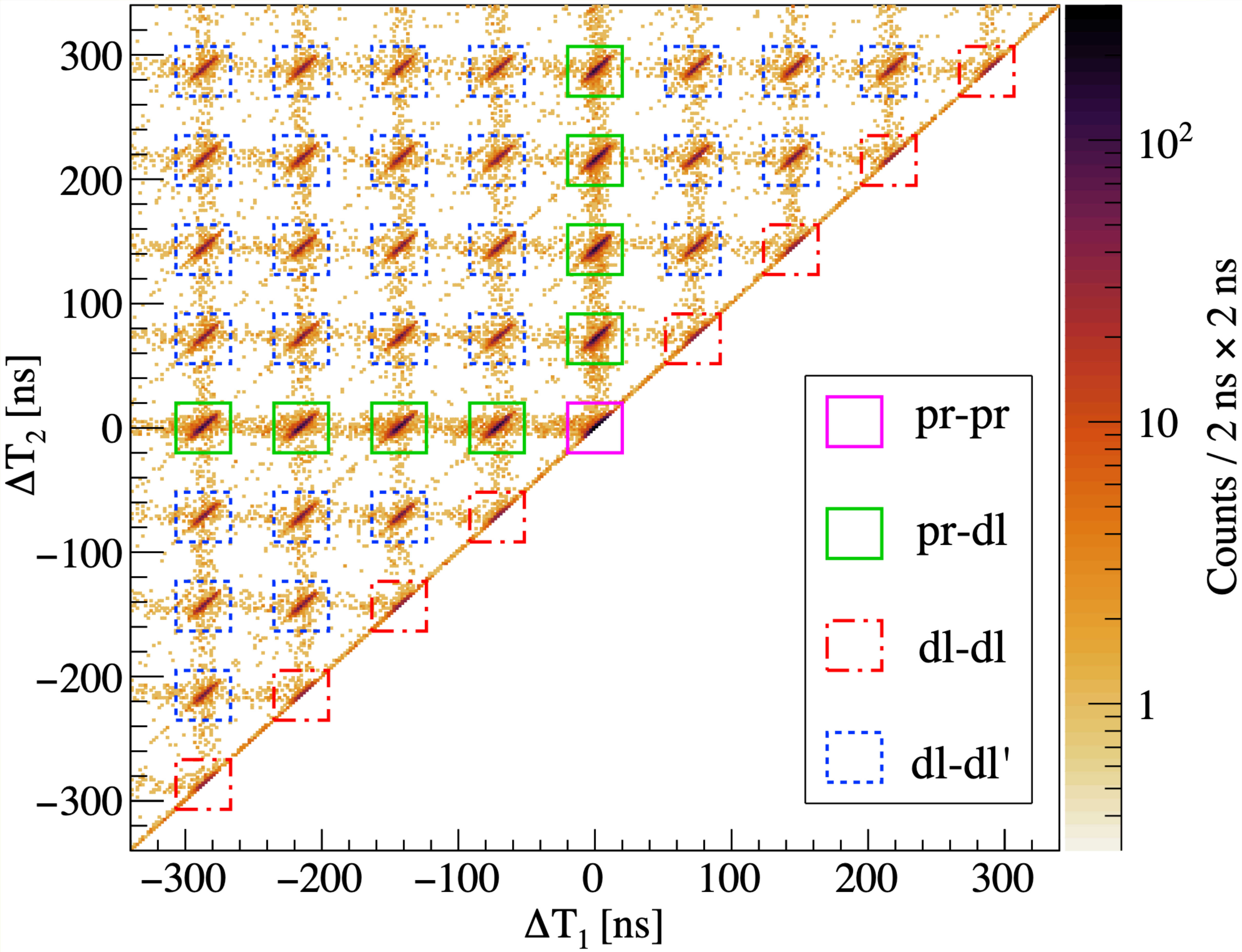
Measurements in this work and analysis pipeline



Time-correlated background subtraction

Different combinations of particles:

- Proton and both gammas are in coincidence with each other
- Proton and one gamma are in coincidence
- Both gammas are in coincidence with each other, but not with the proton
- Random background



Final yield of triple coincidences:

pr-pr − pr-dl − dl-dl + dl-dl'

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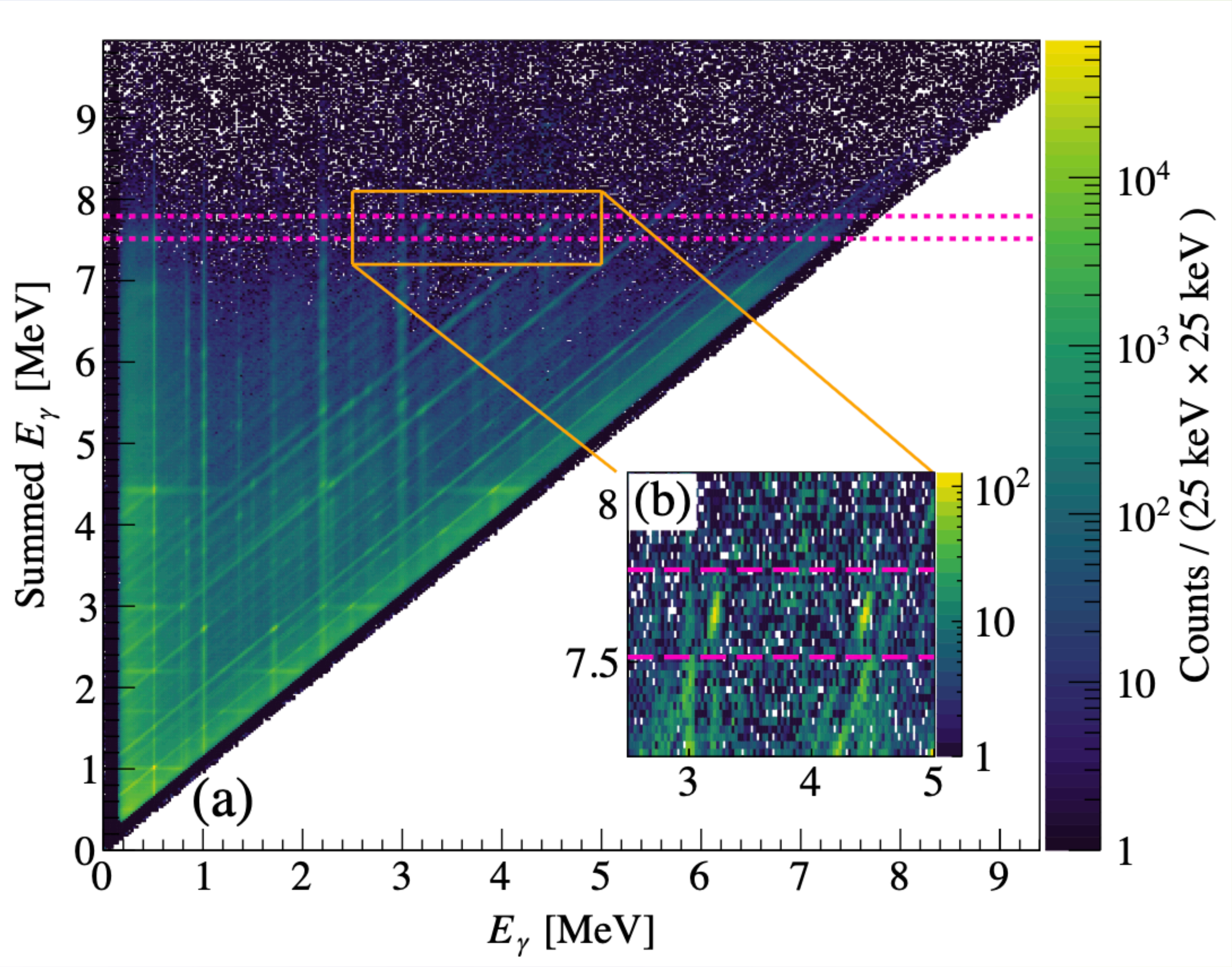
^{12}C(p,p') 2019: Extracting triple-coincidence yields

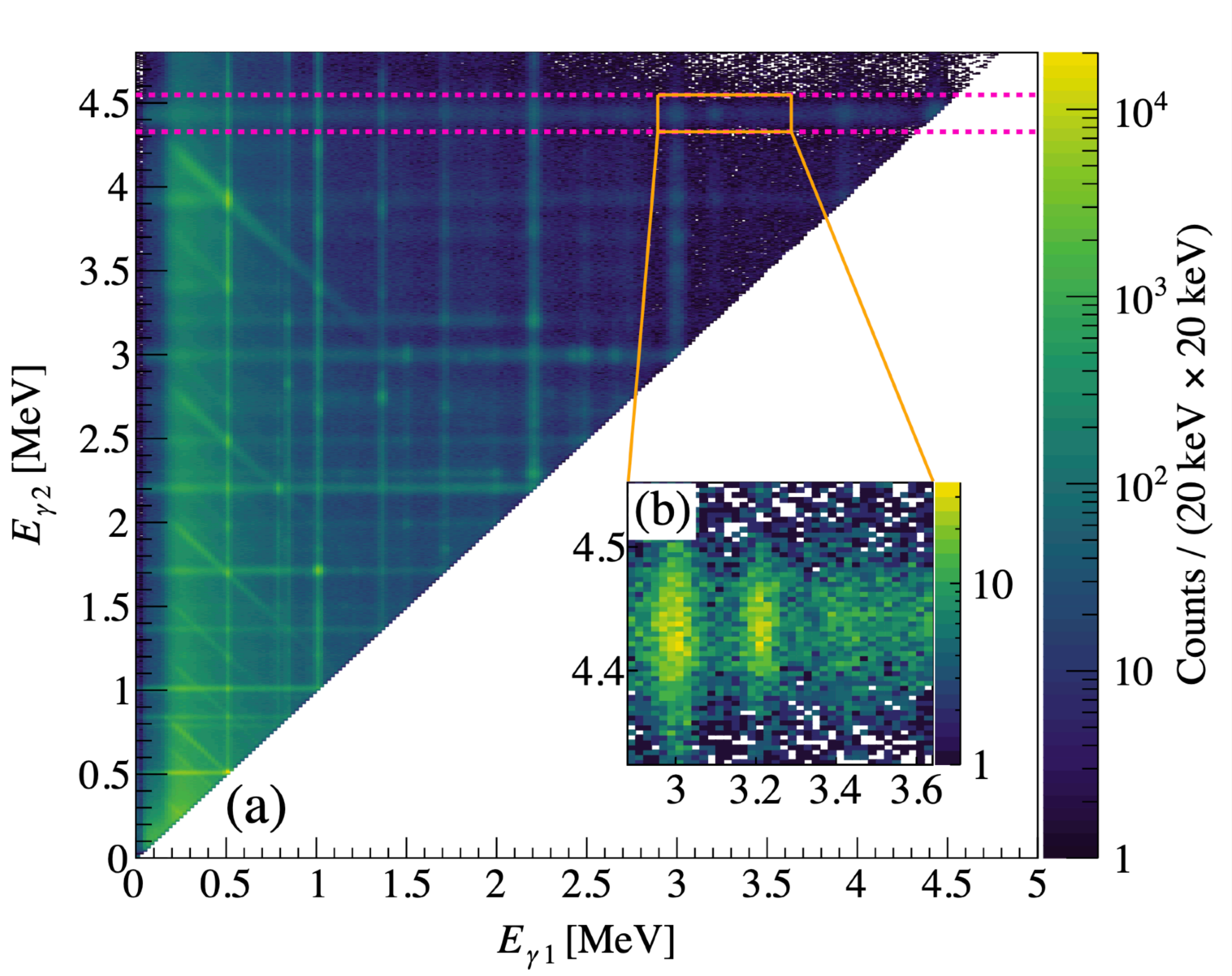
Summed E_γ

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



Gamma-gamma

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



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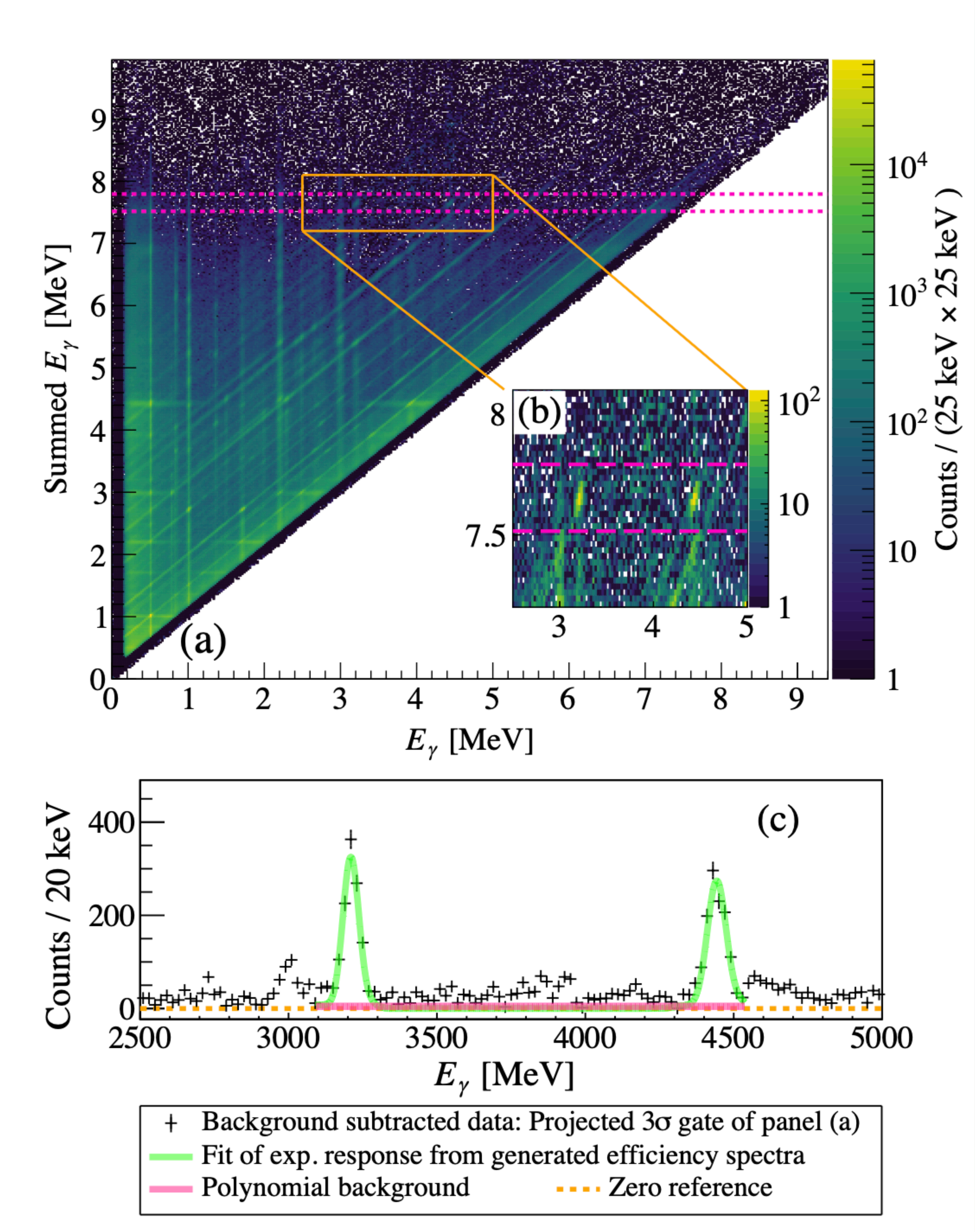

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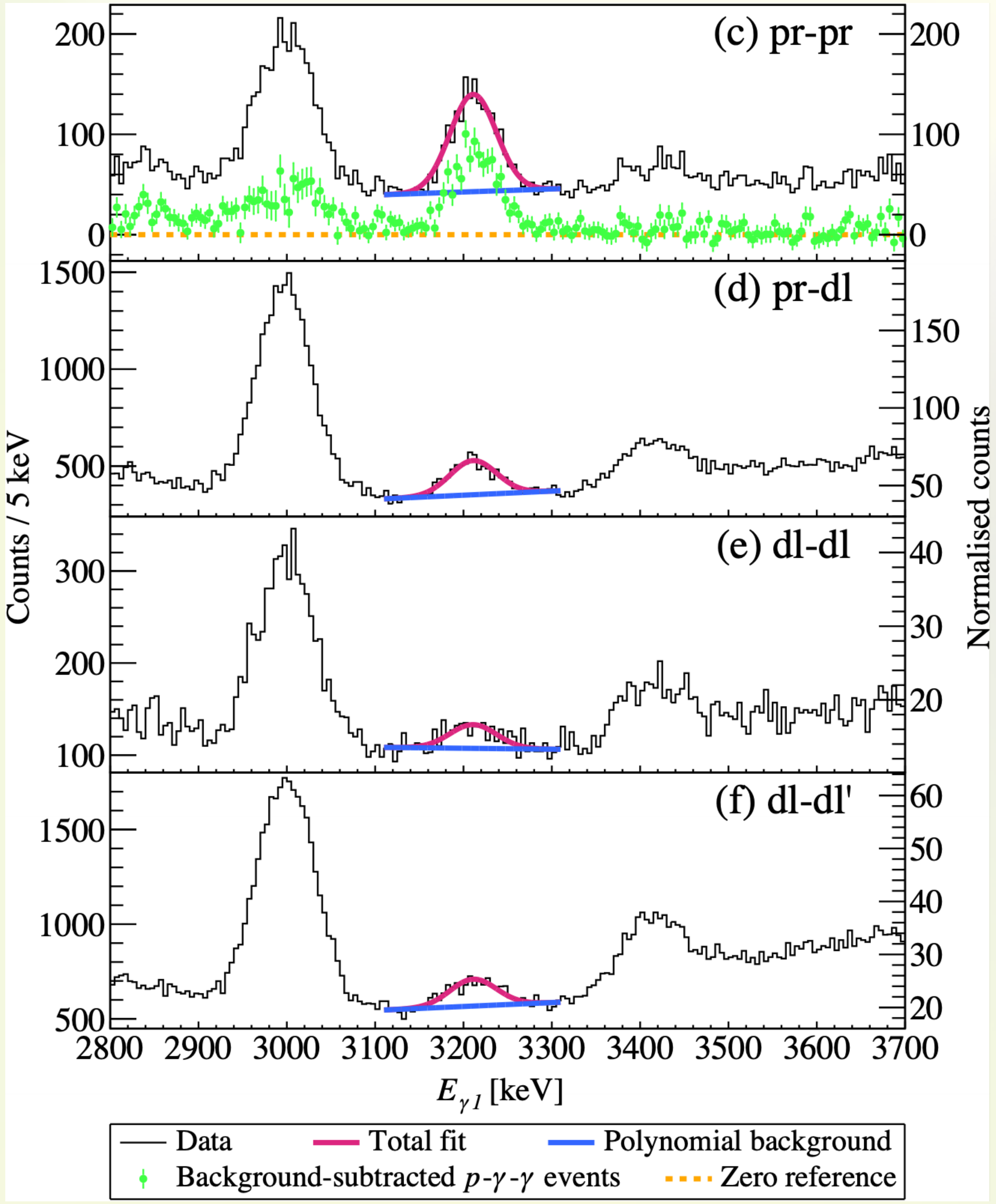

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^{12}C(p,p') **2014**: Extracting triple-coincidence yields

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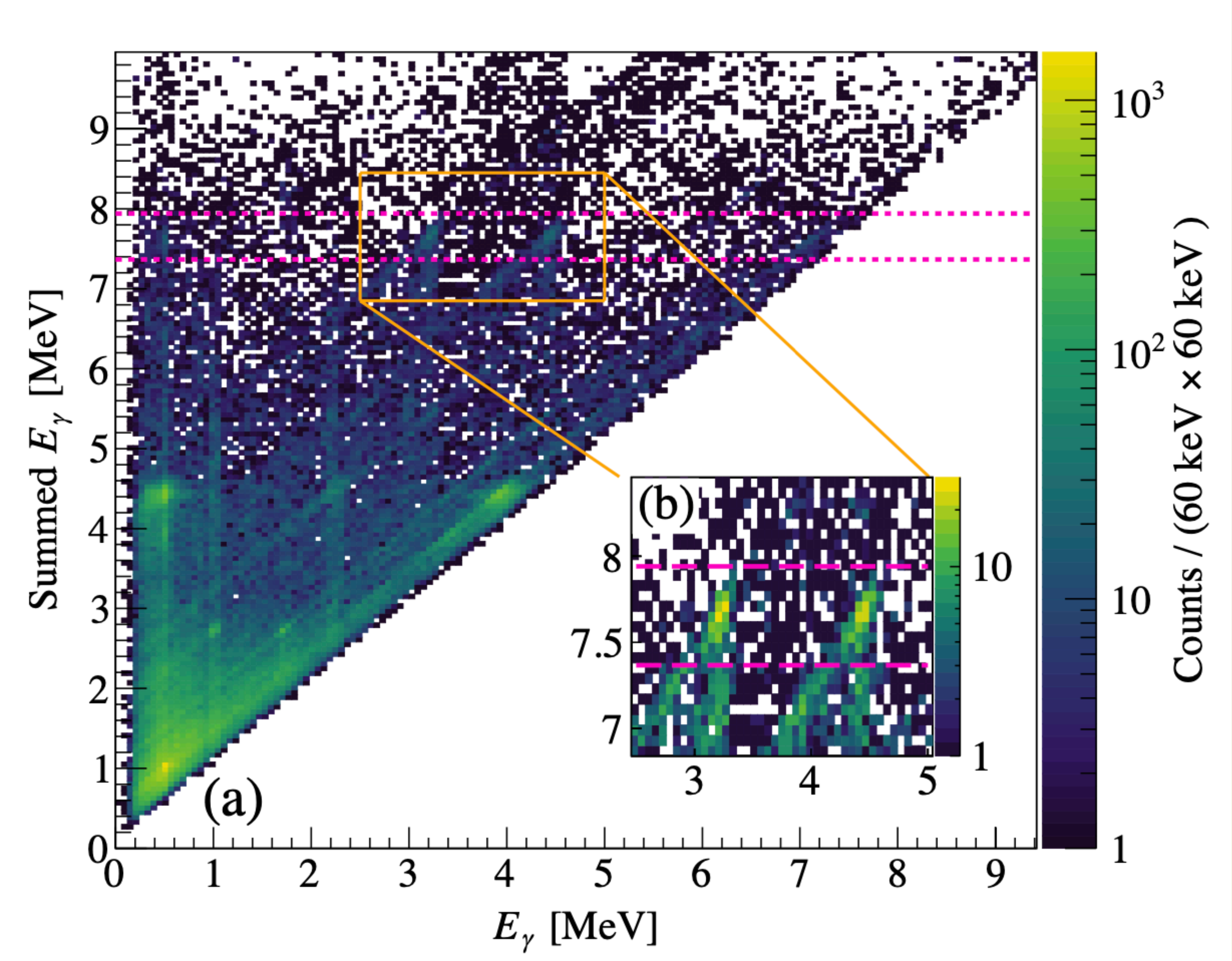

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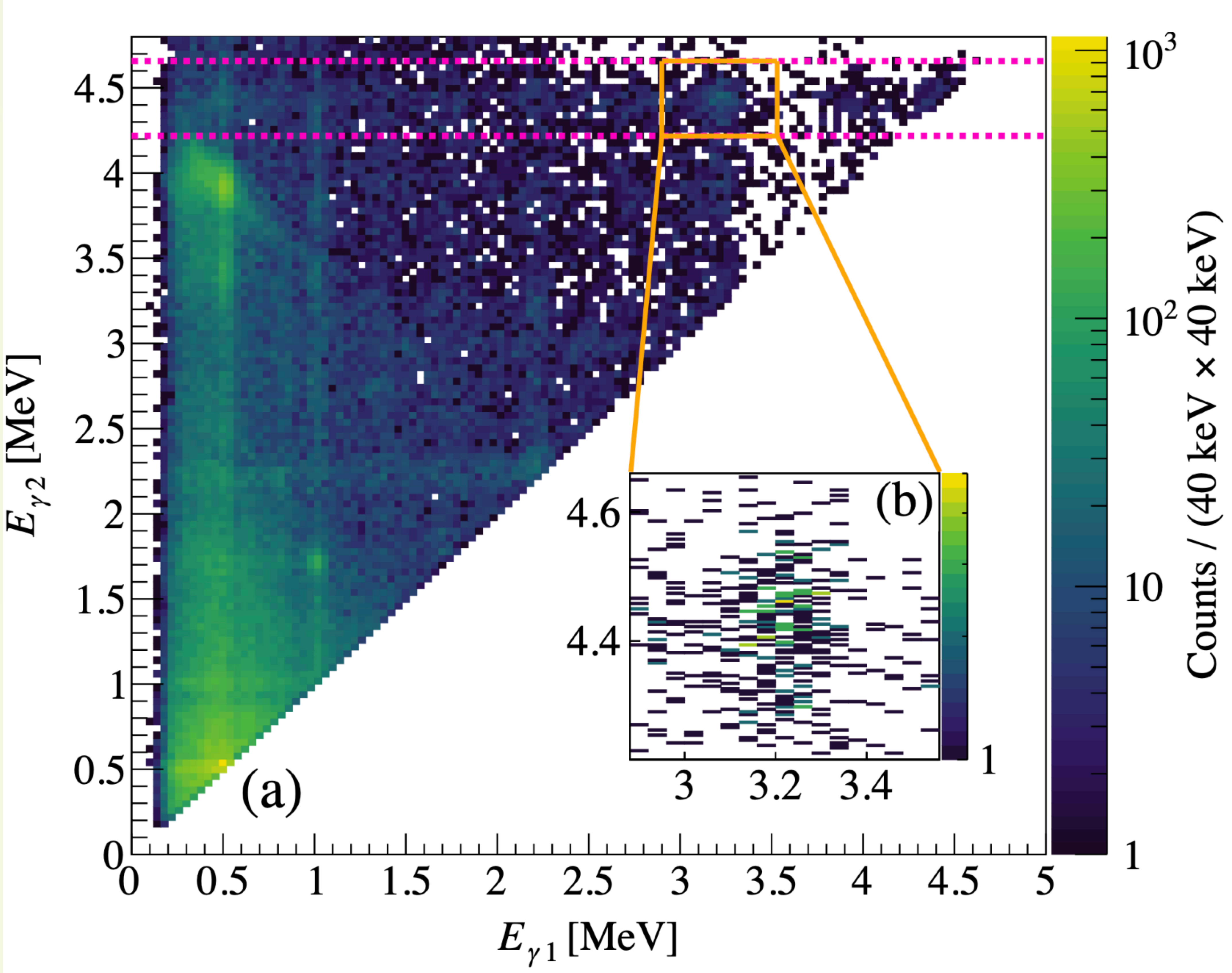

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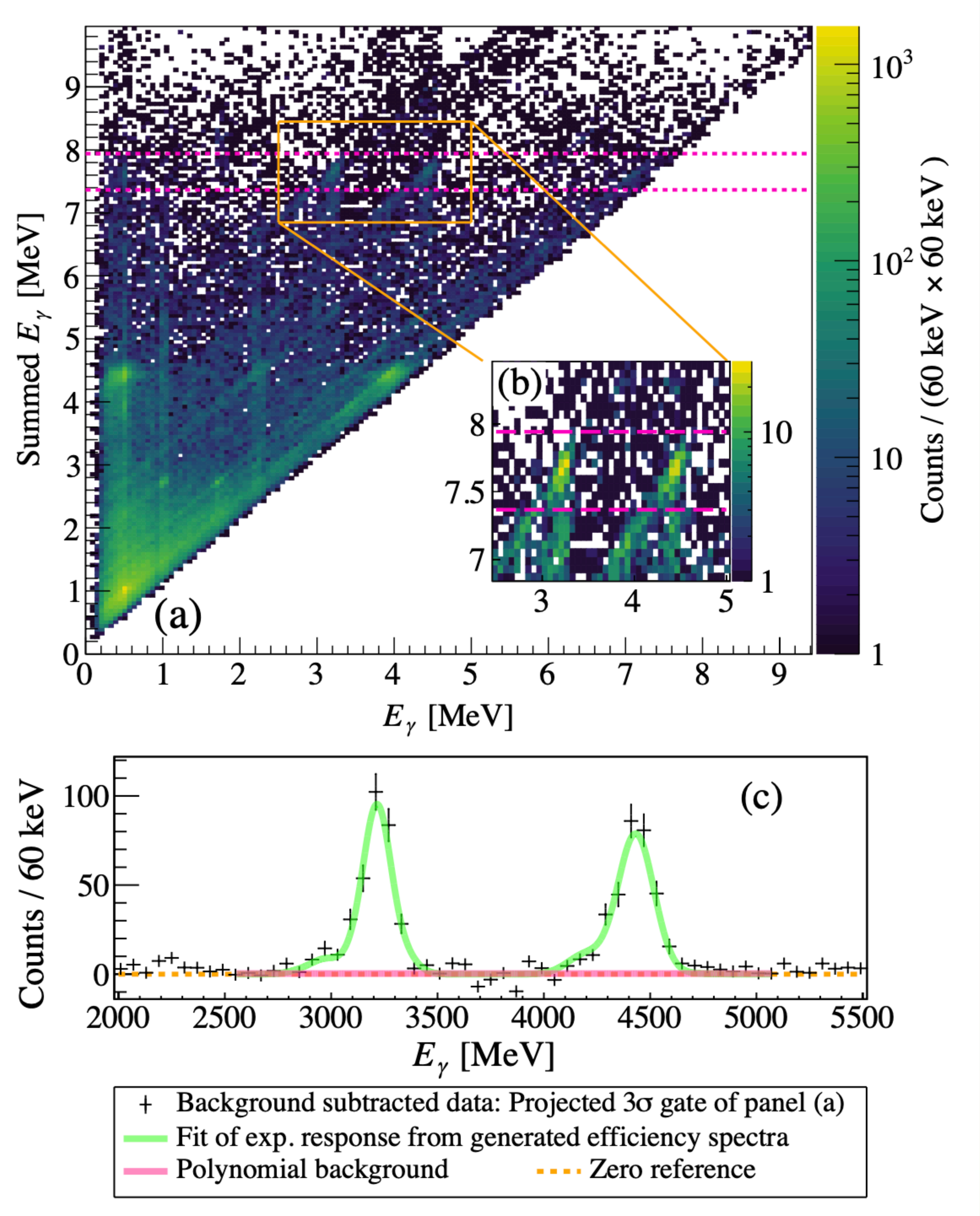
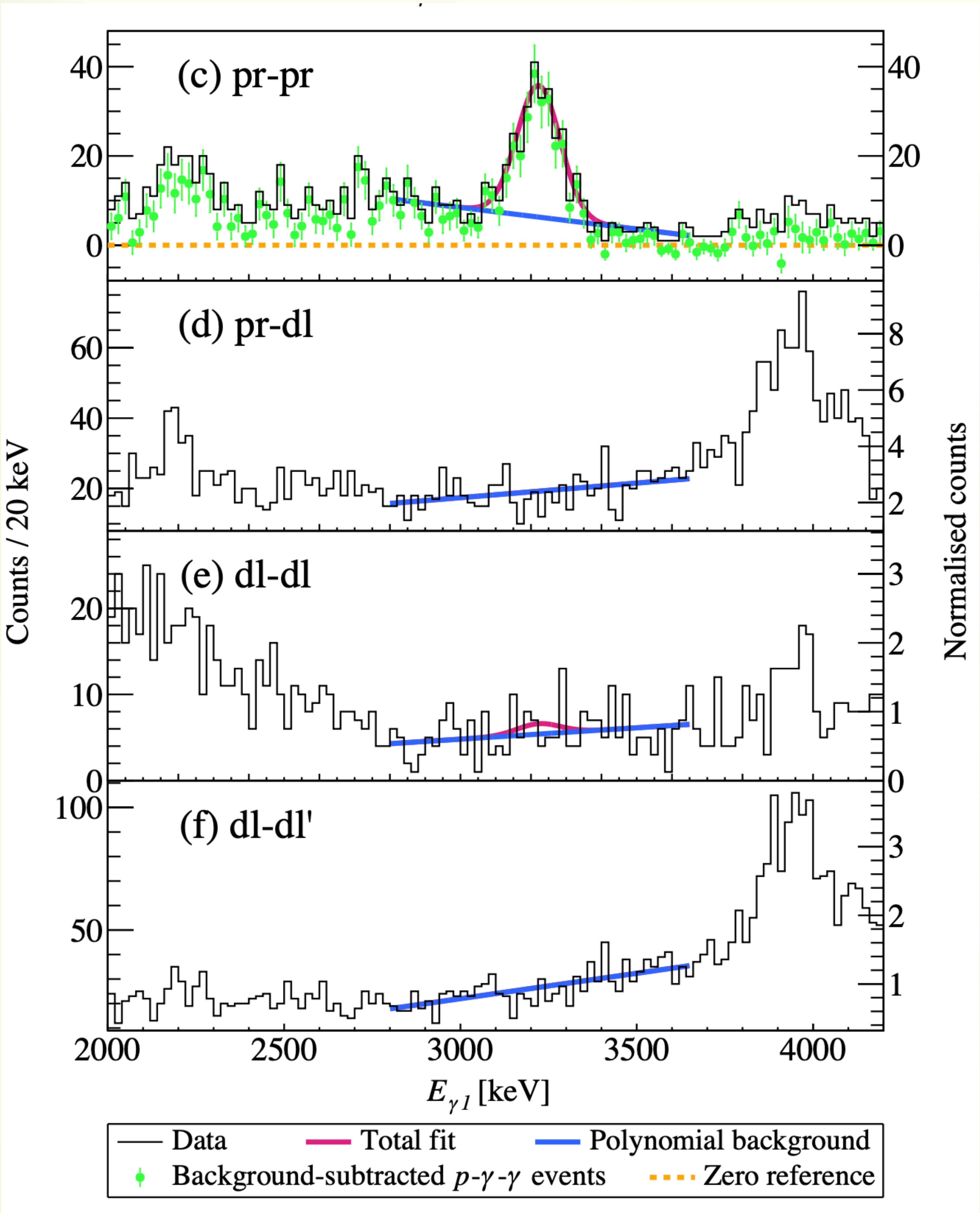
Summed E$_\gamma$



Gamma-gamma



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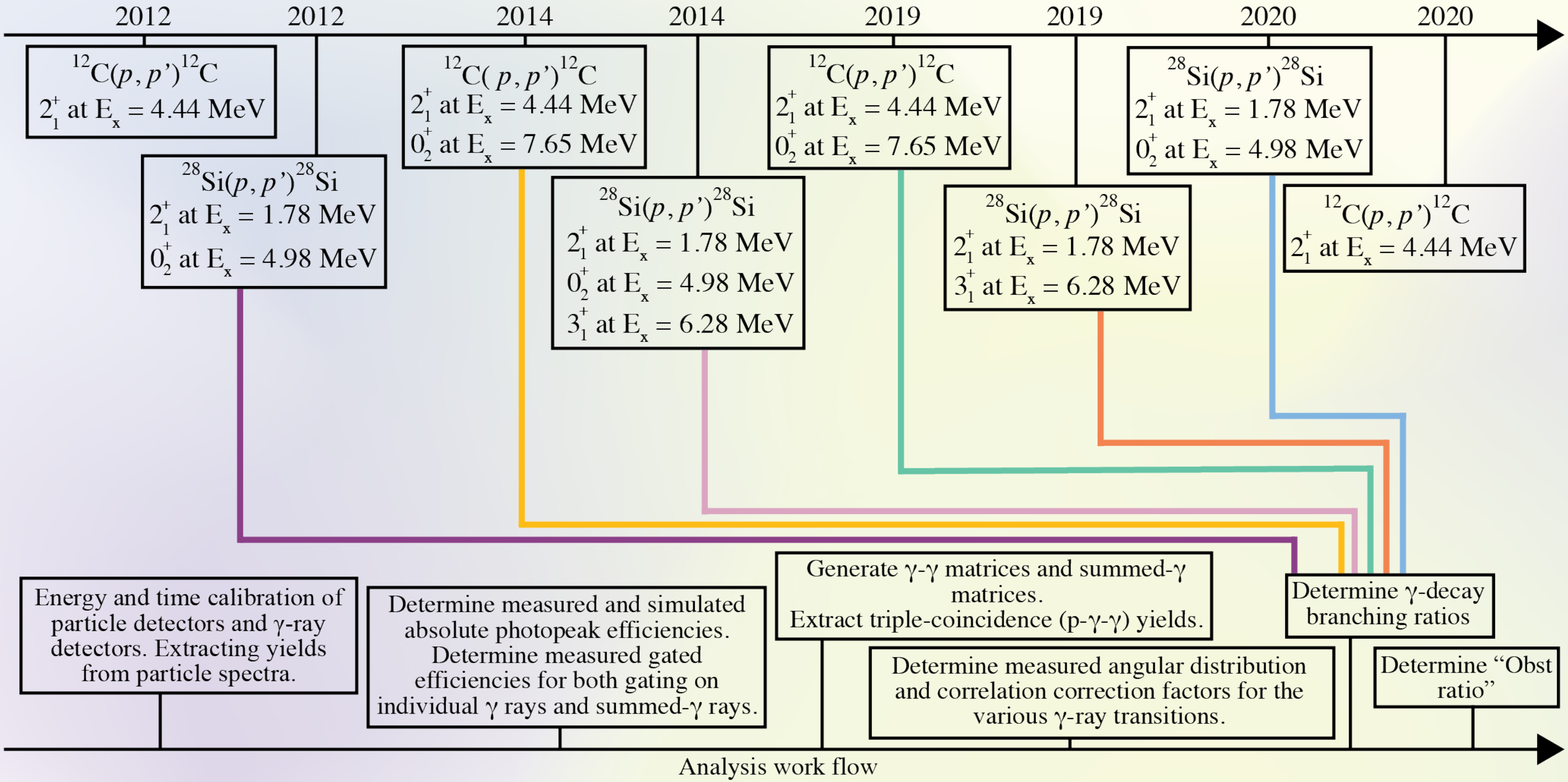


Results of this work

Original result as published

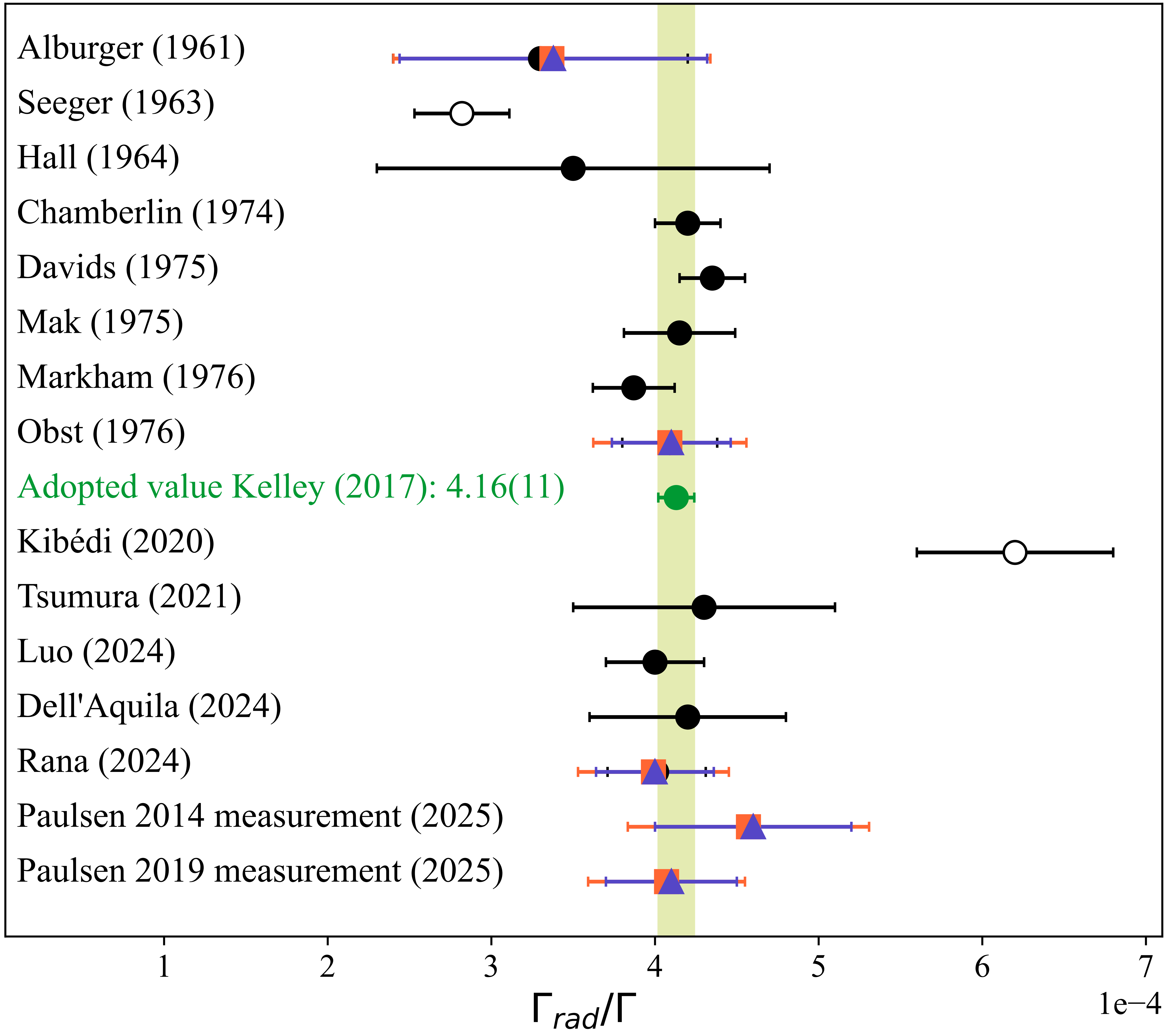
Published result is excluded

Indirect measurement utilizing **Γπ / Γ** from Kelley *et al.* (2017)

Indirect measurement utilizing **Γπ / Γ** from Eriksen *et al.* (2020)

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

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



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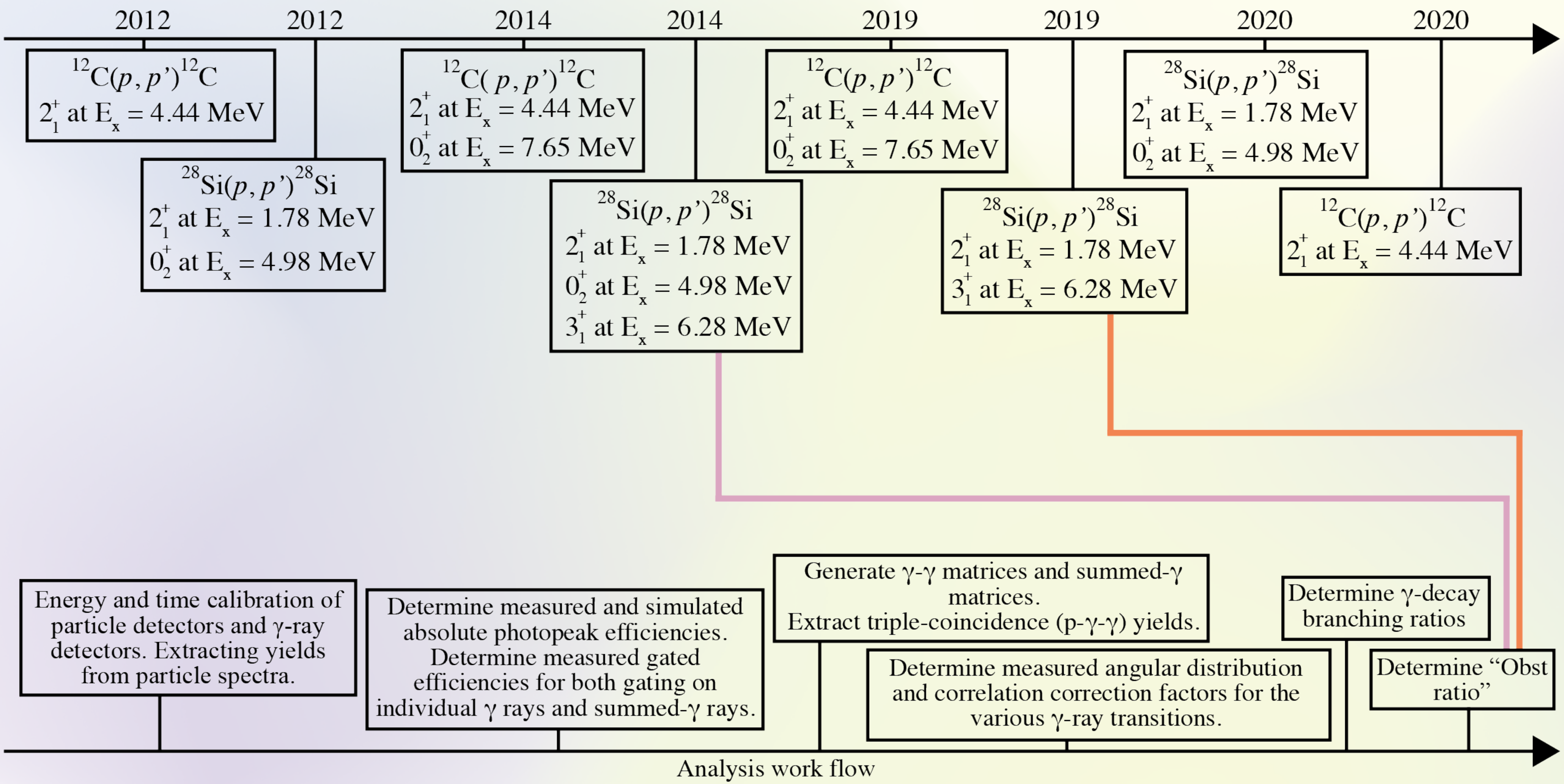

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Determine the "Obst" ratio

Obst *et al.* (1976) utilised a $3^+ \rightarrow 2^+ \rightarrow 0^+$ transition from the E_x = 6.28 MeV 3^+ state in ^{28}Si to normalise their final result. The final equation used to obtain the γ-decay branching ratio consisted of five ratios:

$$\frac{\Gamma_\gamma^{E2}}{\Gamma^{7.65}} = \underbrace{\frac{N_{020}^{7.65}}{N_{320}^{6.28}}}_{\text{A}} \times \underbrace{\frac{N_{320}^{6.28}}{N_{020}^{4.98}}}_{\text{B}} \times \underbrace{\frac{N_{\text{inclusive}}^{6.28}}{N_{\text{inclusive}}^{7.65}}}_{\text{C}} \times \underbrace{\frac{N_{\text{inclusive}}^{4.98}}{N_{\text{inclusive}}^{6.28}}}_{\text{D}} \times \underbrace{\frac{\epsilon_{1.78}}{\epsilon_{4.44}}}_{\text{E}}$$

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In Kibédi *et al.* (2020) the following statement was published regarding this equation in Obst *et al.* (1976): **"Despite some differences between their experiment and ours, various combinations of these ratios should agree within a few percent."**

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The largest difference occurred for the ratio B x D, dubbed the "Obst" ratio. By utilising the equations for the γ-decay branching ratios of the $E_x = 4.98$ MeV 0^+ and $E_x = 6.28$ MeV 3^+ states we can express the Obst ratio as

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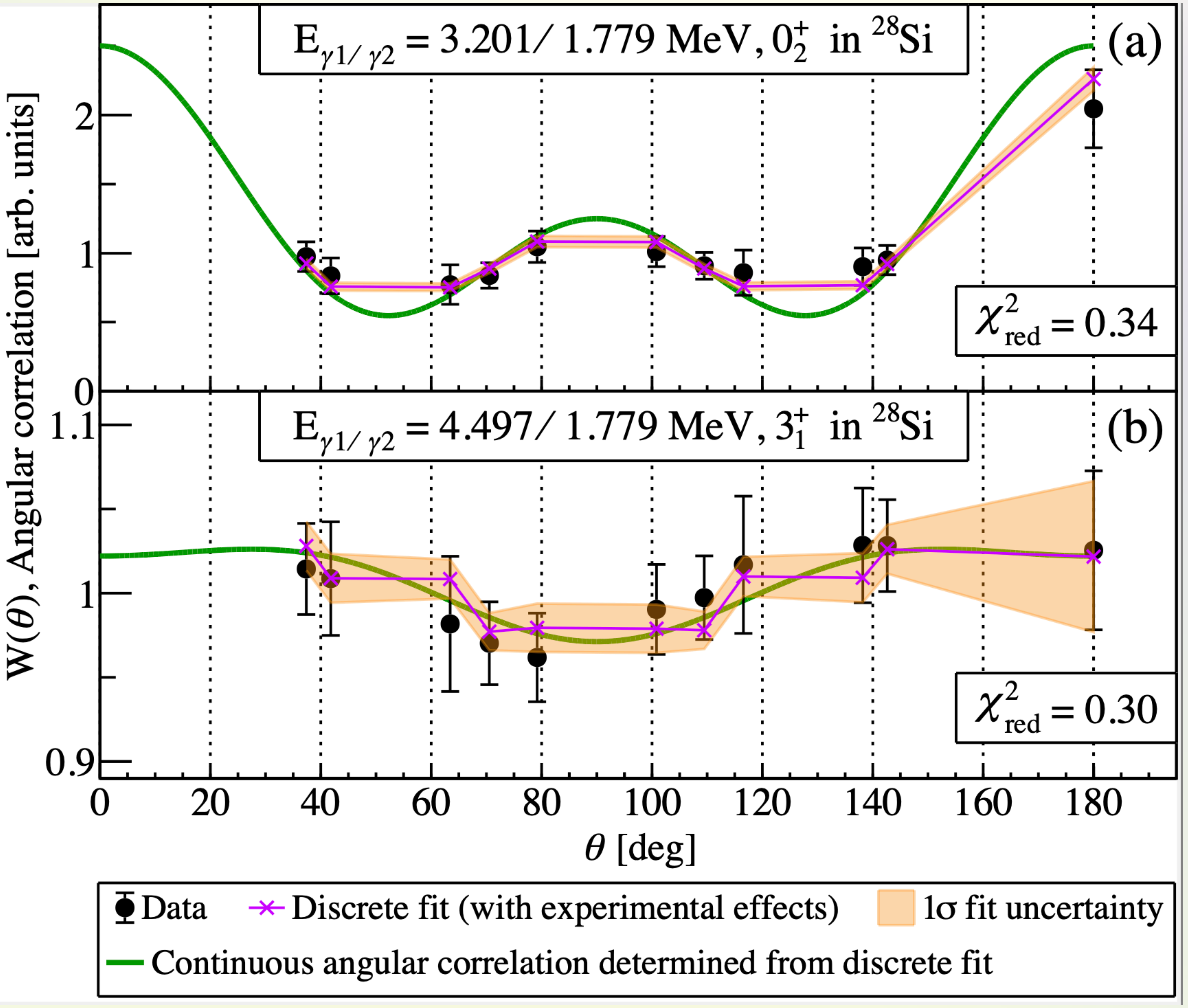
$$B \times D = \frac{\epsilon_{4.49}}{\epsilon_{3.20}} \times \frac{W_{320}^{6.28}}{W_{020}^{4.98}} \times \frac{\Gamma_\gamma^{E2}/\Gamma^{6.28}}{\Gamma_\gamma^{E2}/\Gamma^{4.98}}$$

Determine the "Obst" ratio

The Obst ratio is highly dependent on the efficiency and the angular correlation correction factors of the detector setup.

$$B \times D = \frac{\epsilon_{4.49}}{\epsilon_{3.20}} \times \frac{W^{6.28}_{320}}{W^{4.98}_{020}} \times \frac{\Gamma^{E2}_{\gamma}/\Gamma^{6.28}}{\Gamma^{E2}_{\gamma}/\Gamma^{4.98}}$$



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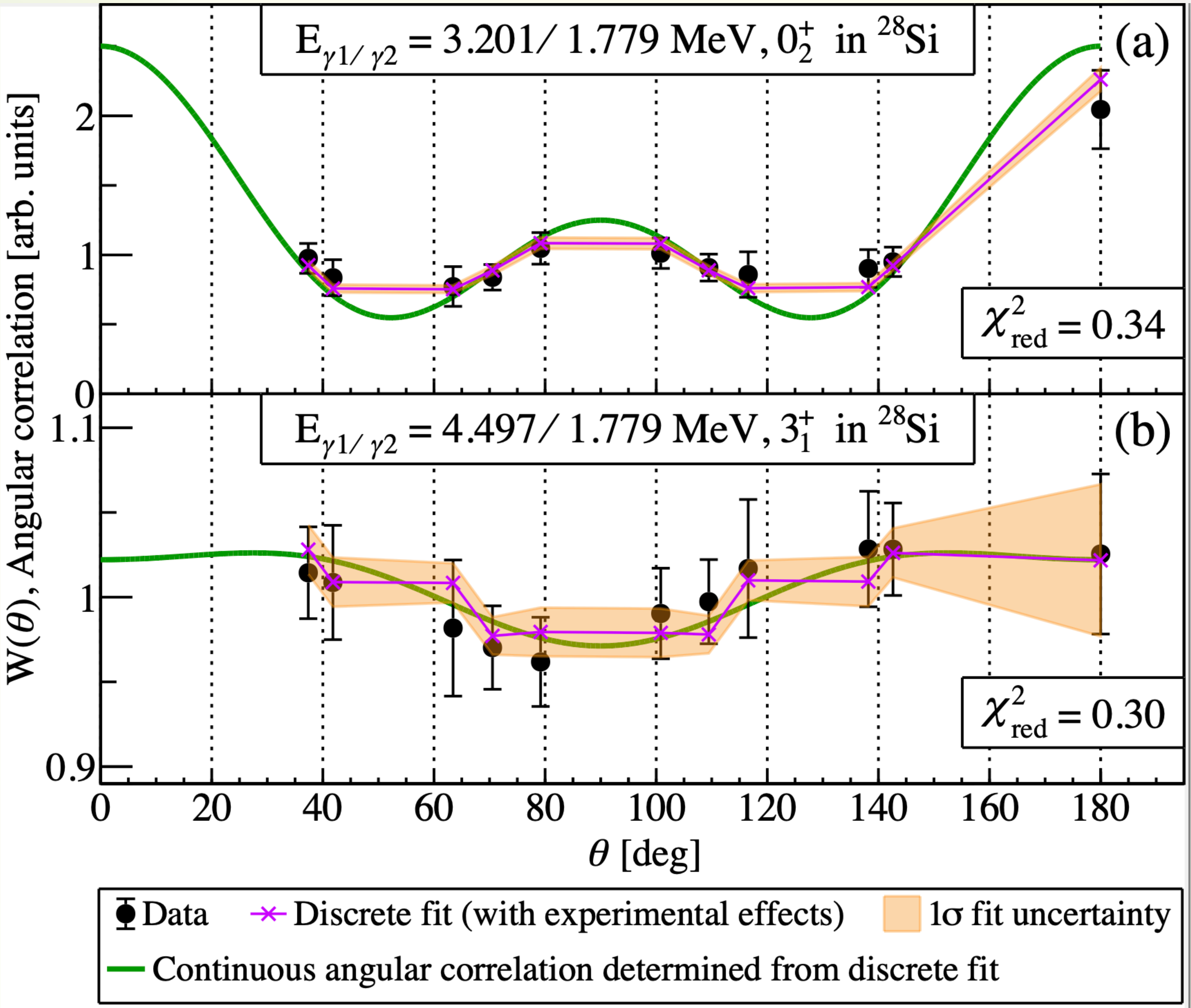
A GEANT4 simulation based on the description of the setup in Obst *et al.* (1976) [10] was performed. By comparing the angular correlation correction factors it is clear that

Simulation of Obst *et al.* (1976) [10] setup: $\frac{W^{6.28}_{320}}{W^{4.98}_{020}} = 0.787(2)$

Kibédi *et al.* (2020) [9]: $\frac{W^{6.28}_{320}}{W^{4.98}_{020}} = 1.057(2)$

Paulsen *et al.* (2025): $\frac{W^{6.28}_{320}}{W^{4.98}_{020}} = 1.047(1)$



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Determine the "Obst" ratio

From the resulting angular correlation correction factors and the simulated Obst *et al.* (1976) [10] setup it is clear that that the ratios A-E can vary by more than a few percent.

The simulated Obst ratio of this work is $\approx 3\sigma$ away from Obst *et al.* (1976) [10]. This level of agreement is reasonable given the approximate nature of the simulation, with the geometry based on figures and text in Obst *et al.* (1976) [10].

$$B \times D = \frac{\epsilon_{4.49}}{\epsilon_{3.20}} \times \frac{W_{320}^{6.28}}{W_{020}^{4.98}} \times \frac{\Gamma_\gamma^{E2}/\Gamma^{6.28}}{\Gamma_\gamma^{E2}/\Gamma^{4.98}}$$

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TABLE IX. Summarised results of the Obst ratio (see Sec. III C).

Reference	Obst ratio [Eq. (7)]
Obst *et al.* [19]	0.409(15)
Kibédi *et al.* [15]	0.80(4)
^{28}Si(p, p') data from 2014 (this work)	0.82(4)
^{28}Si(p, p') data from 2019 (this work)	0.70(2)
Simulation of Obst setup (this work)	0.52(3)

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Corrections to Kibédi *et al.* (2020)

- Throughout the reanalysis of the 2014 measurement, several necessary corrections to Kibédi *et al.* (2020) [9] were discovered.

A

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

B

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

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- **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.

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

B

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  - 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 $\mathbf{c_{det} = 325}$. The true number of detector combinations should be $\mathbf{c_{det} = 650}$.

A

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

B

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

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 $\mathbf{c_{det} = 325}$. The true number of detector combinations should be $\mathbf{c_{det} = 650}$.

- **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.

A

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

B

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

Has the collective efforts of the community reduced the uncertainty?

Converting from radiative branching ratio to radiative width

$$\frac{\Gamma_{\mathrm{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2}\left(1+\alpha_{\mathrm{tot}}\right)+\Gamma_{\pi}^{E0}}{\Gamma} \longrightarrow \Gamma_{\mathrm{rad}} = \left[\frac{\Gamma_{\mathrm{rad}}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}^{\mathrm{E0}}}\right] \times \left[\Gamma_{\pi}^{\mathrm{E0}}\right]$$

Radiative branching ratio

Radiative width

Direct measurement average of all measurements.

γ-decay branching ratio Kelley *et al.* (2017) [14]

Pair-decay branching ratio Kelley *et al.* (2017) [14]

$\mathbf{\Gamma}_{\mathrm{rad}} = 3.87(39)$ meV (10.1%)

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Has the collective efforts of the community reduced the uncertainty?

Converting from radiative branching ratio to radiative width

$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2}(1+\alpha_{\text{tot}}) + \Gamma_{\pi}^{E0}}{\Gamma} \longrightarrow \Gamma_{\text{rad}} = \left[\frac{\Gamma_{\text{rad}}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}^{\text{E0}}}\right] \times \left[\Gamma_{\pi}^{\text{E0}}\right]$$

Radiative branching ratio

Radiative width

Direct measurement average of all measurements.
γ-decay branching ratio Kelley *et al.* (2017) [14]
Pair-decay branching ratio Kelley *et al.* (2017) [14]

$\boldsymbol{\Gamma}_{\text{rad}} = 3.87(39)$ meV (10.1%)

Direct measurement average of all measurements.
γ-decay branching ratio average of all measurements.
Pair-decay branching ratio Kelley *et al.* (2017) [14]

Weighted average

$\boldsymbol{\Gamma}_{\text{rad}} = 3.80(14)$ meV (3.8%)

Non-weighted average

$\boldsymbol{\Gamma}_{\text{rad}} = 3.76(28)$ meV (7.4%)

Has the collective efforts of the community reduced the uncertainty?

Converting from radiative branching ratio to radiative width

$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{\Gamma_{\gamma}^{E2}(1+\alpha_{\text{tot}}) + \Gamma_{\pi}^{E0}}{\Gamma} \longrightarrow \Gamma_{\text{rad}} = \left[\frac{\Gamma_{\text{rad}}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}^{\text{E0}}}\right] \times \left[\Gamma_{\pi}^{\text{E0}}\right]$$

Radiative branching ratio — Radiative width

Direct measurement average of all measurements.
γ-decay branching ratio Kelley *et al.* (2017) [14]
Pair-decay branching ratio Kelley *et al.* (2017) [14]

$\mathbf{\Gamma}_{\text{rad}} = 3.87(39)$ meV (10.1%)

Direct measurement average of all measurements.
γ-decay branching ratio average of all measurements.
Pair-decay branching ratio Kelley *et al.* (2017) [14]

Weighted average: $\mathbf{\Gamma}_{\text{rad}} = 3.80(14)$ meV (3.8%)

Non-weighted average: $\mathbf{\Gamma}_{\text{rad}} = 3.76(28)$ meV (7.4%)

Direct measurement average of all measurements.
γ-decay branching ratio average of all measurements.
Pair-decay branching ratio Eriksen *et al.* (2020) [15]

Weighted average: $\mathbf{\Gamma}_{\text{rad}} = 3.357(99)$ meV (3.0%)

Non-weighted average: $\mathbf{\Gamma}_{\text{rad}} = 3.32(25)$ meV (7.4%)

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 $\Gamma_{rad}/\Gamma = 4.16(11) \times 10^{-4}$.
- An independent reanalysis of the measurement published by Kibédi *et al.* (2020) was performed.
  - Several necessary corrections to the results published by Kibédi *et al.* (2020) was found.
- A reanalysis of the data published by Kibédi *et al.* (2020) was performed.
  - The results agree well with the previously adopted value from Kelley *et al.* (2017) of $\Gamma_{rad}/\Gamma = 4.16(11) \times 10^{-4}$.
  - 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.

Thank you to all our collaborators

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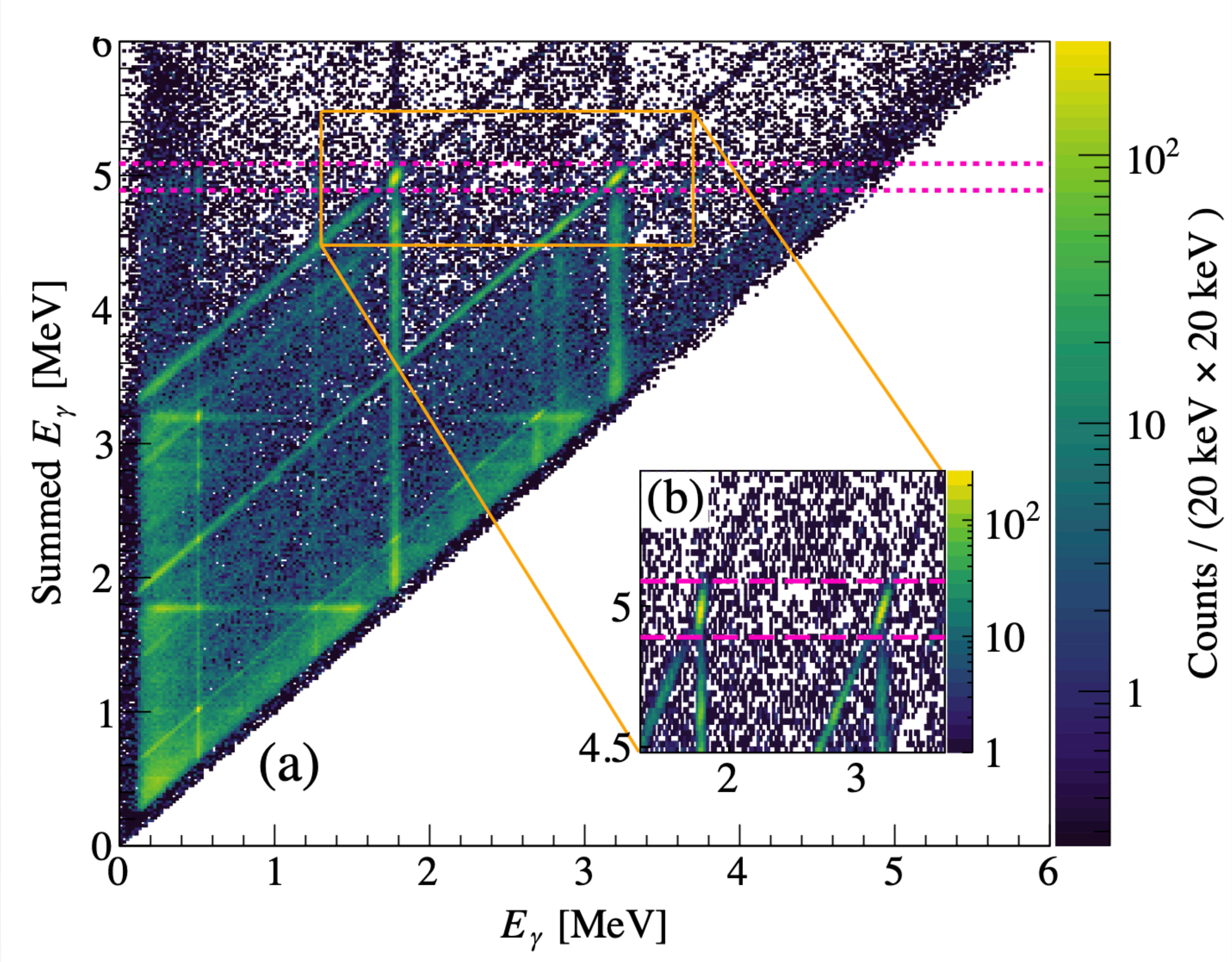
^{28}Si(p,p') 2020: Extracting triple-coincidence yields

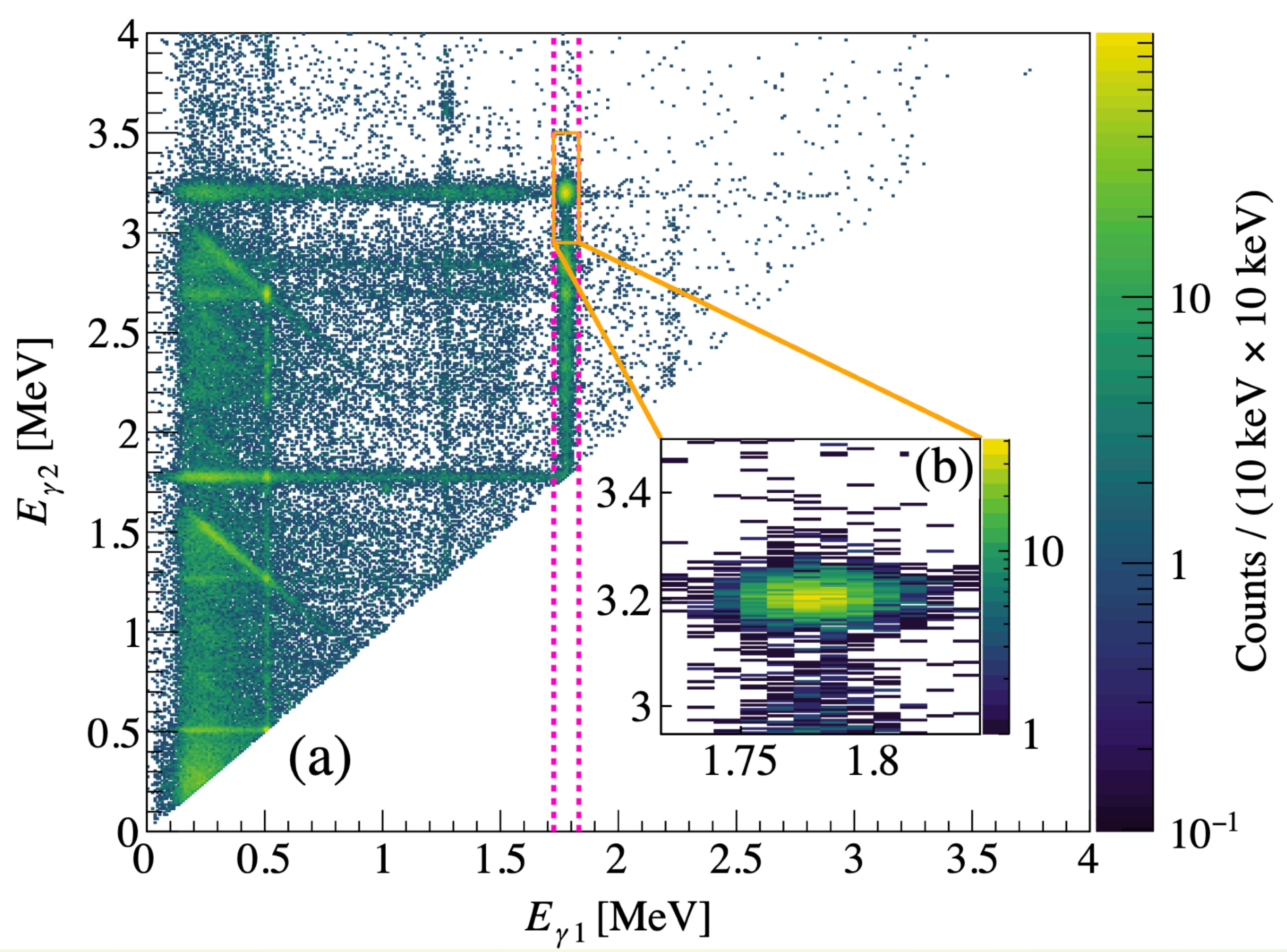
Summed E_γ

3σ gate around E_γ = 4.98 MeV and diagonal following the Compton scattered E_γ = 3.20 MeV γ ray from the E_x = 4.98 MeV 0_2^+ in ^{28}Si.



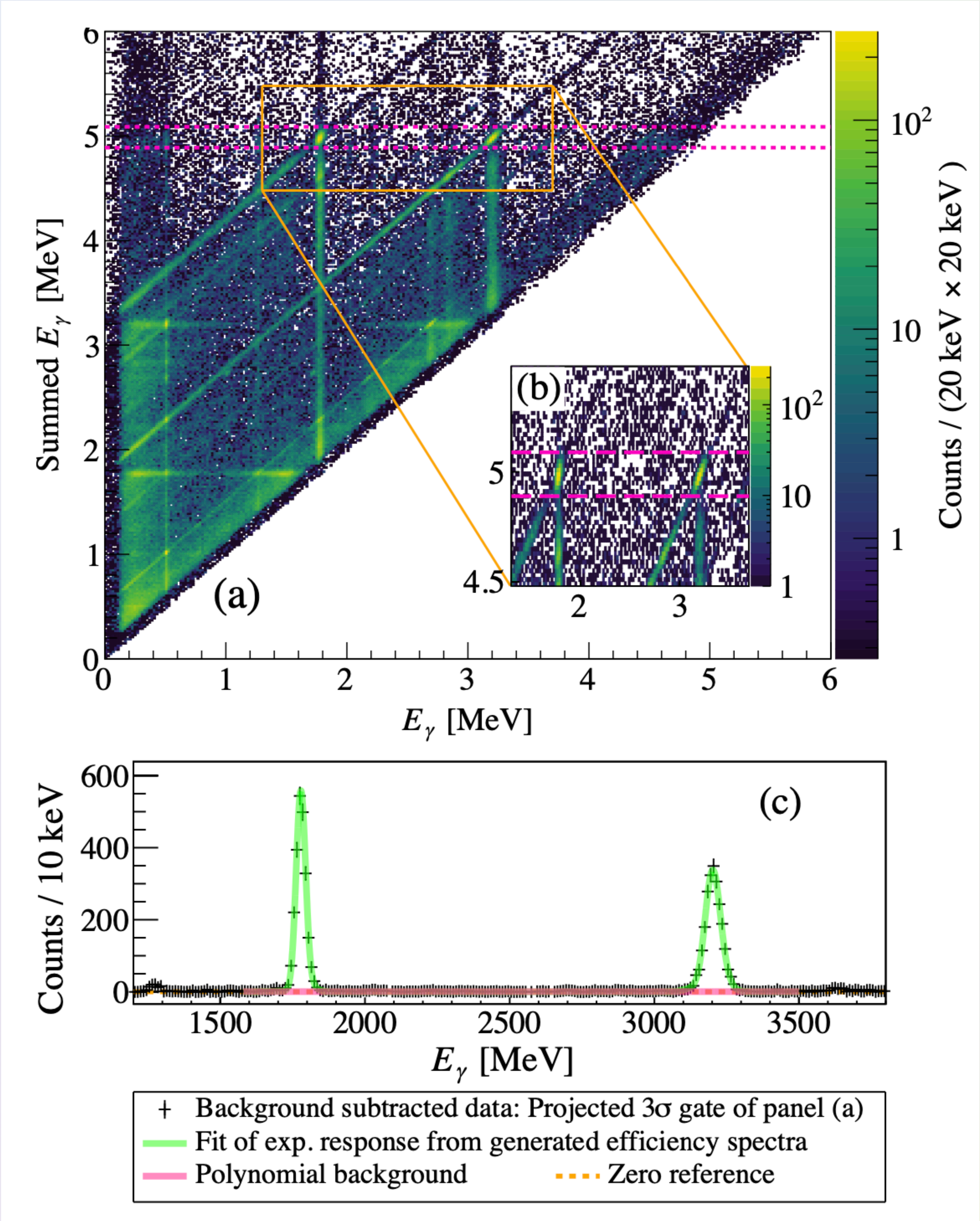
Gamma-gamma

3σ gate around E_γ = 1.79 MeV from the cascade from E_x = 4.98 MeV 0_2^+ in ^{28}Si.

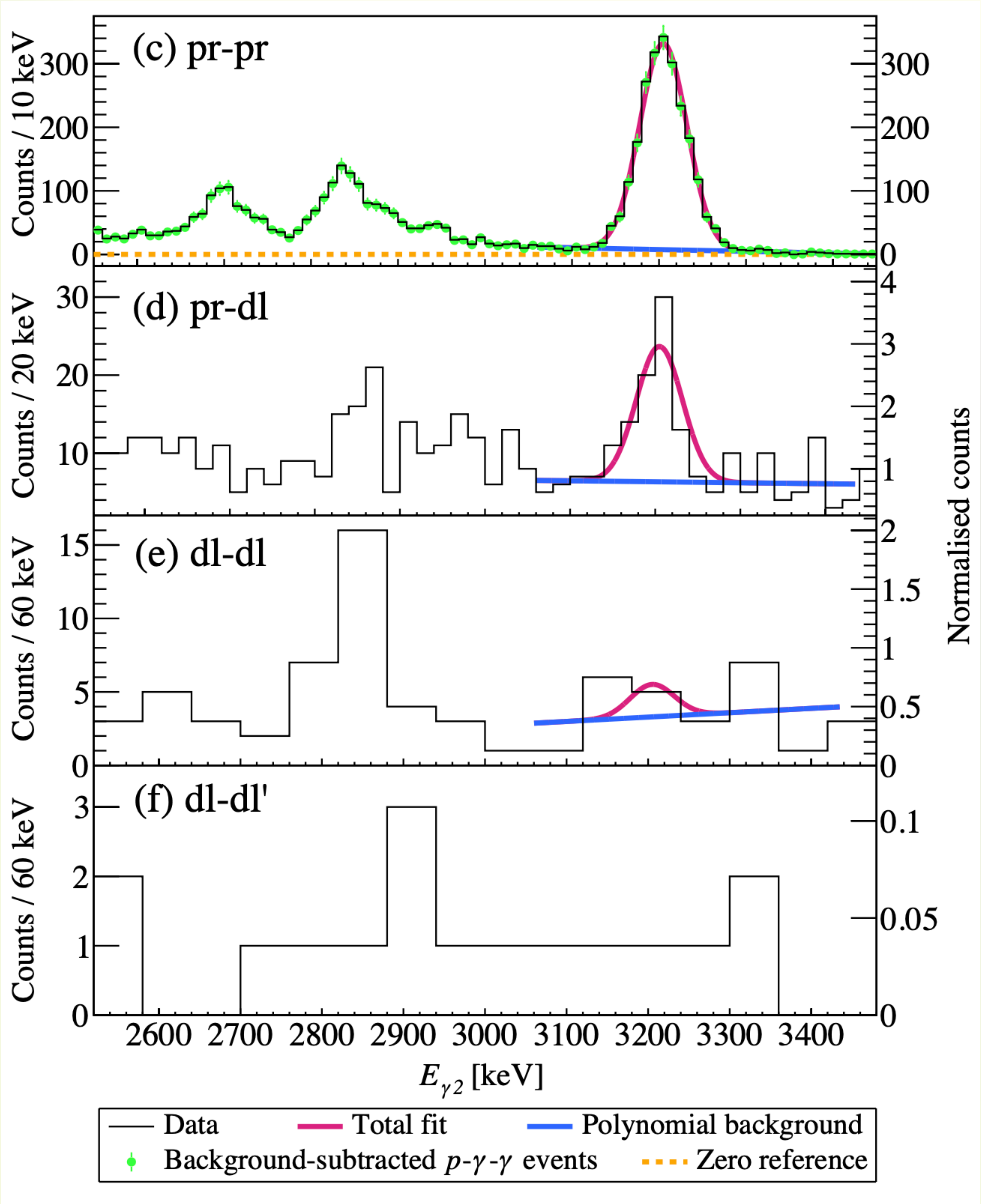


^{28}Si(p,p') **2020**: Extracting triple-coincidence yields

Summed E_γ



Gamma-gamma



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