# In Memoriam, a Colleague and Beloved Friend

## Sydney Benjamin Galès

**November 1, 1943 – November 29, 2024**

**Corrine and Sydney Galès, Jaffa, Tel Aviv, April 27, 2019**

# Nuclear Astrophysics With TPCs and Gamma-Beams *

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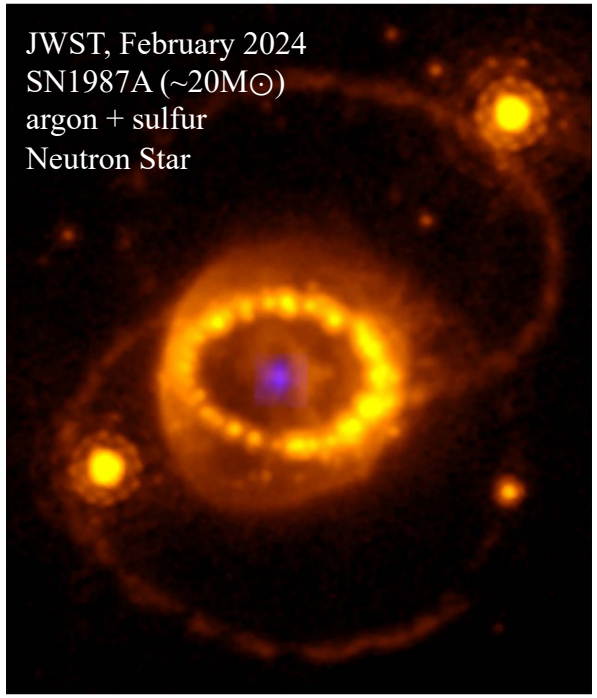
1. Oxygen Formation in Stellar Helium Burning/ the $^{12}C(\alpha,\gamma)$ Reaction
2. Status of World Best Data (Stuttgart's Heroic Effort)
3. UConn Measurement, Optical Readout TPC (O-TPC @ HIγS)
4. Present/ Future: The Warsaw electronic readout (eTPC @ HIγS)

* Supported in part by the USDOE grant No. DE-FG02-94ER40870.

VII Workshop…, Bormio, February 2-9, 2025

# Nuclear Astrophysics in the Era of Windows on the Universe
# Multi-Messenger Astrophsyics (WoU-MMA)




**SN1987A:** First MMA, Type II Supernova
Observed Neutrinos & 4 HR Later Light Curve (EM)/ MMA object
Progenitor: Sanduleak −69 202 (Sk -69 202) Blue Supergiant ~20M⊙
SN1987A (JWST 2024): Neutron Star, Not Black Hole
**Type II SN:** Neutron Star or Black Hole, Determined by C/O

**Helium Burning:** $3\alpha \rightarrow {}^{12}C$ (~11%) "Hoyle State"
$^{12}C(\alpha,\gamma)^{16}O$ @300 keV ???
$^{12}C(\alpha,\gamma) \rightarrow$ C/O = ?

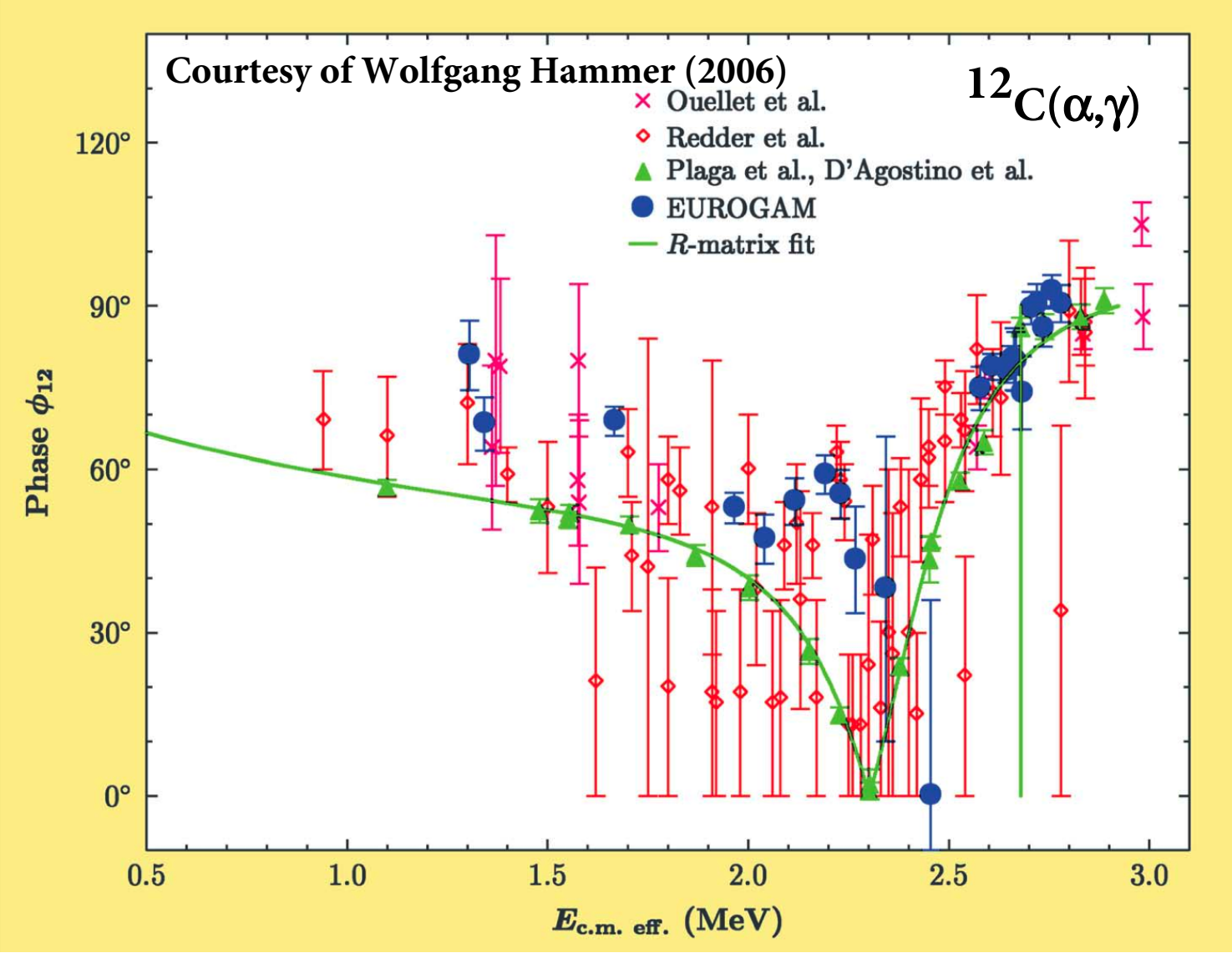
**Two partial waves:**
p-wave $S_{E1}(300)$
d-wave $S_{E2}(300)$

***E1-E2* Mixing Phase Angle ($\phi_{12}$)**


**W.A. Fowler: Rev. Mod. Phys. 56, 149 (1984)**
"The $^{12}C(\alpha,\gamma)$ reaction is of paramount importance"

$$\varphi_{12} = \delta_2 - \delta_1 + \arctan(\eta/2)$$

**F.C. Barker and T. Kajino, Aust. J. Phys. 44, 369 (1991), R-Matrix Theory.**




## E1-E2 Mixing Phase Angle ($\phi_{12}$)

M. Gai, Phys. Rev. C 88, 062801(R) (2013).

C. R. Brune, Phys. Rev. C 64, 055803 (2001).

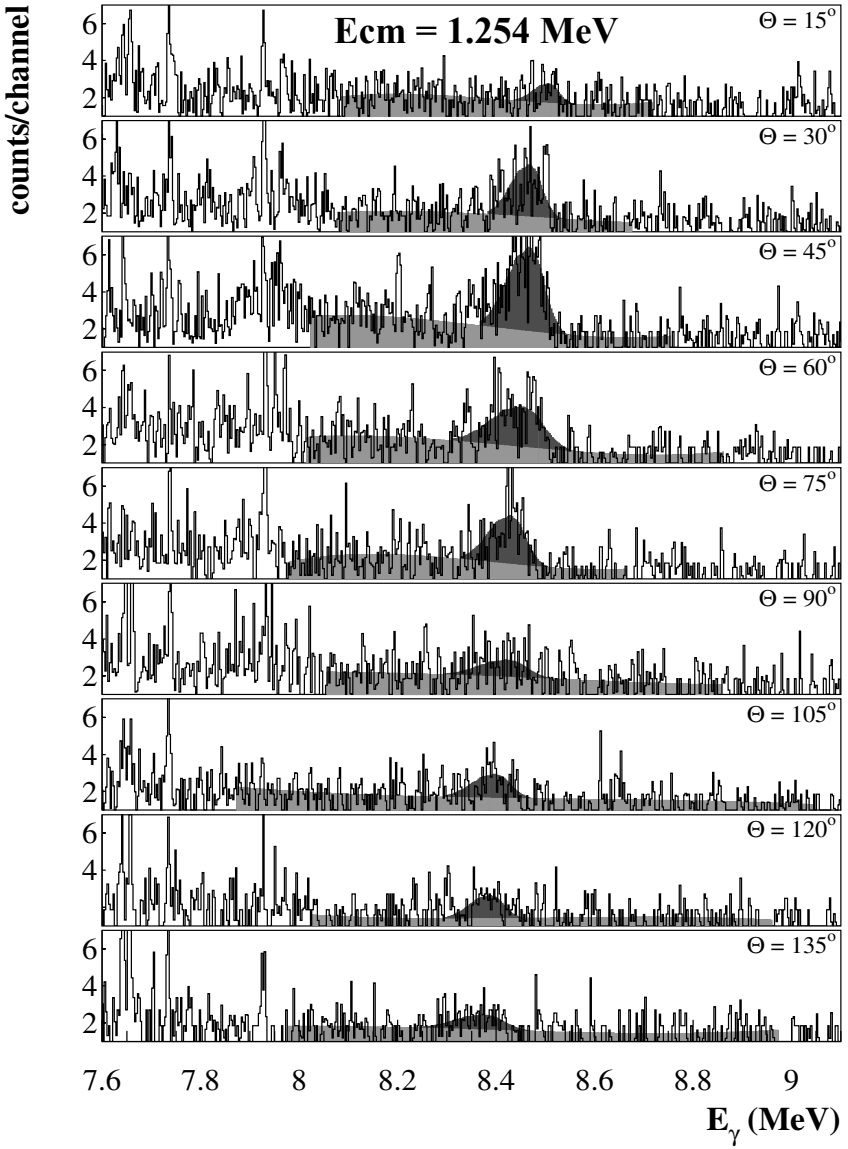
L.D. Knutson, Phys. Rev. C 59, 2152 (1999).

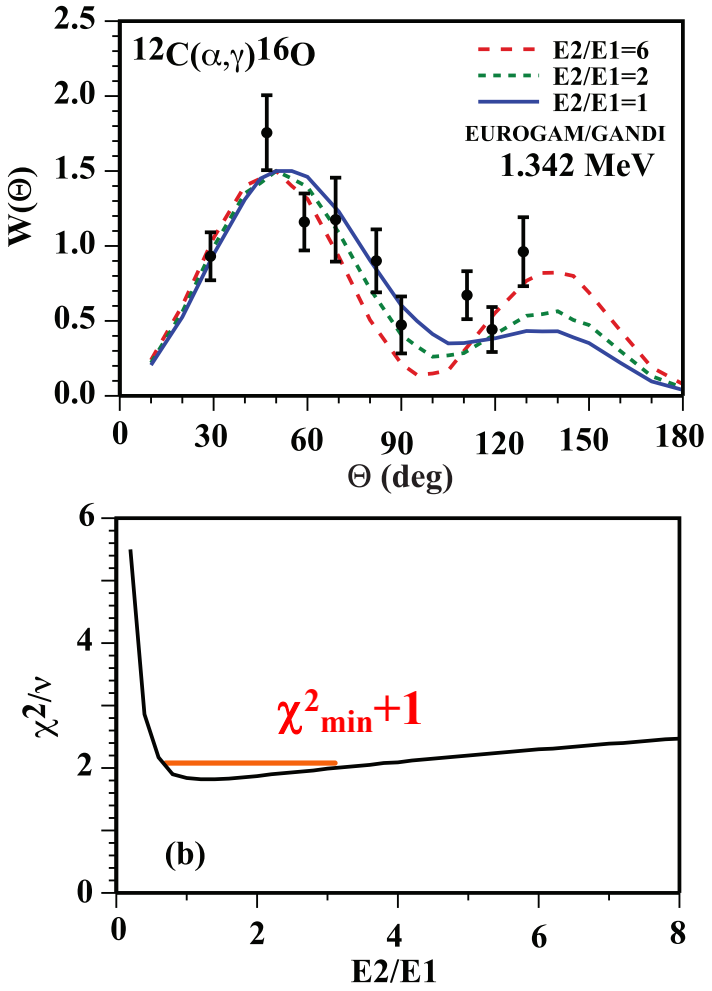
K.M. Watson, Phys. Rev. 95, 228 (1954).

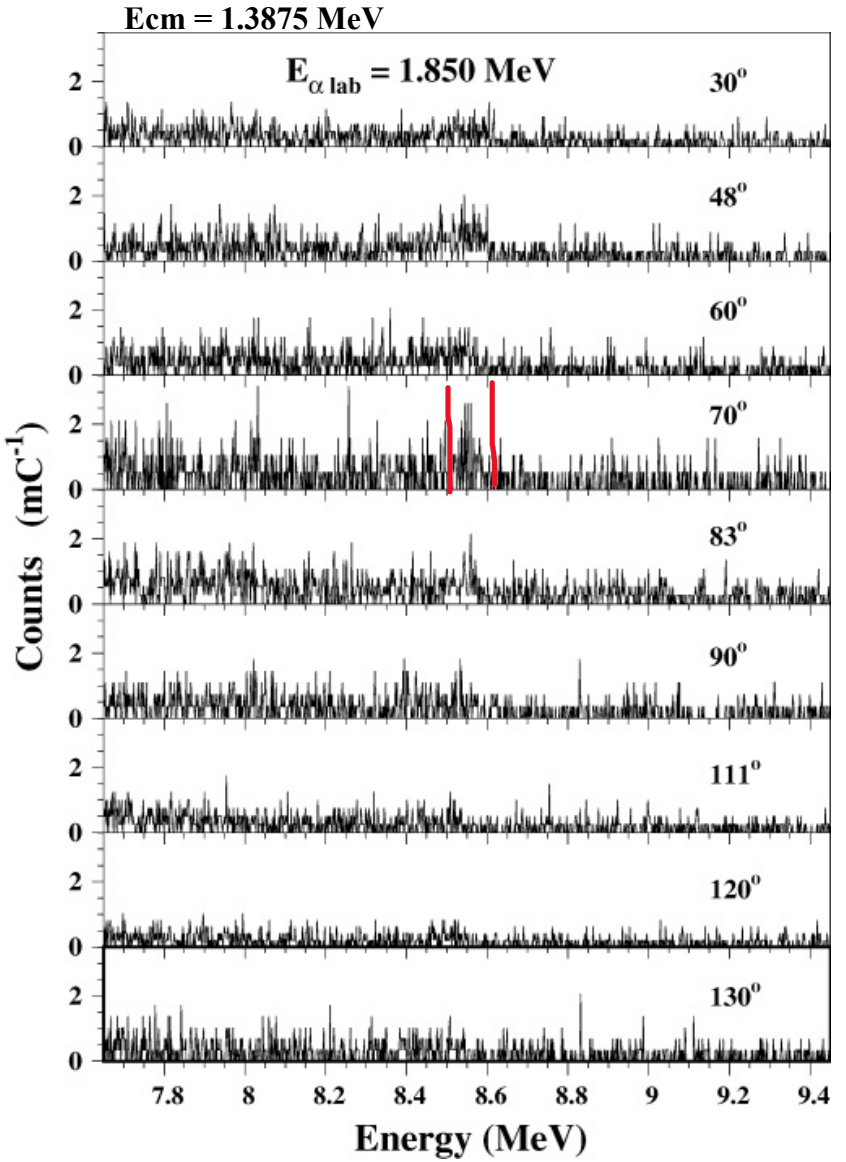
**Required by Unitarity**

# The (heroic) Stuttgart Effort: 1) 450 μA 2) 700 HRs 3) Four x 100% HPGe 4) EUROGAM 5) 0.01% $^{13}$C [x100 Reduced $^{13}$C(α,n)]

**R. Kunz *et al*., PRL, 86, 3244 (2002)** **M. Gai, PRC, 88, 062801(R) (2013)** **M. Assuncao *et al*.. PRC 73, 055801 (2006)**



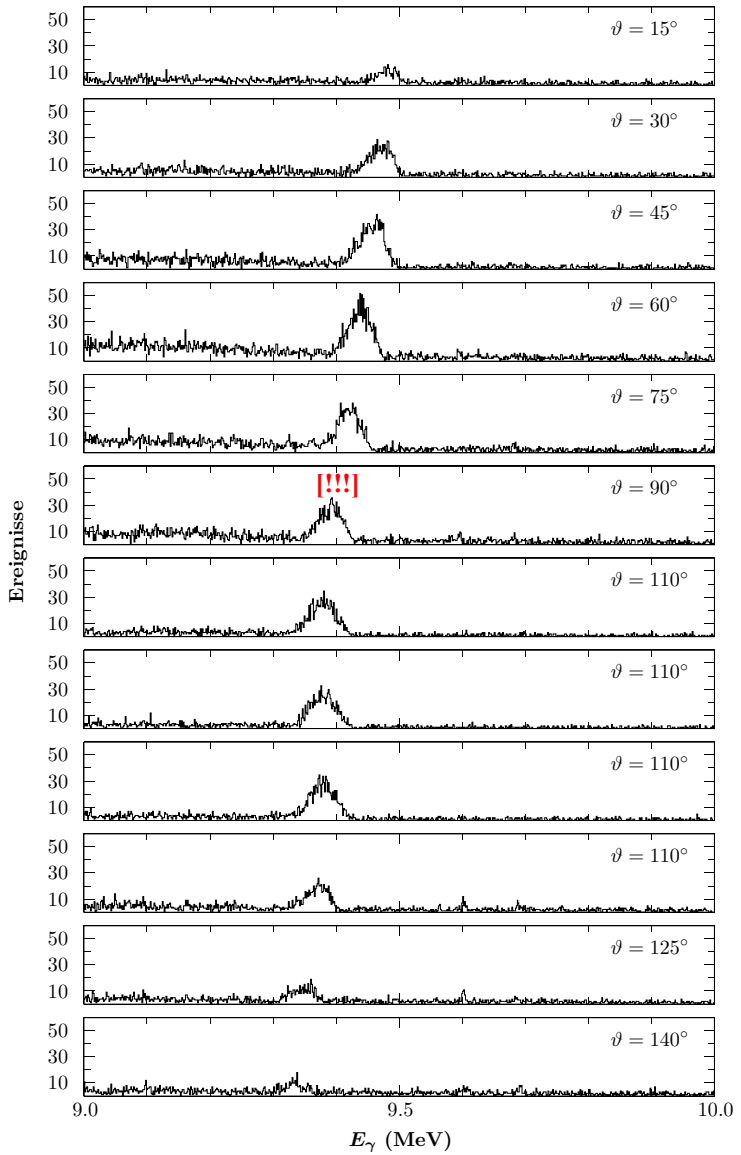



**Abbildung C.35:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\mathrm{c.m.}} = 2.209\,\mathrm{MeV}$. $E_L$=2.945 MeV



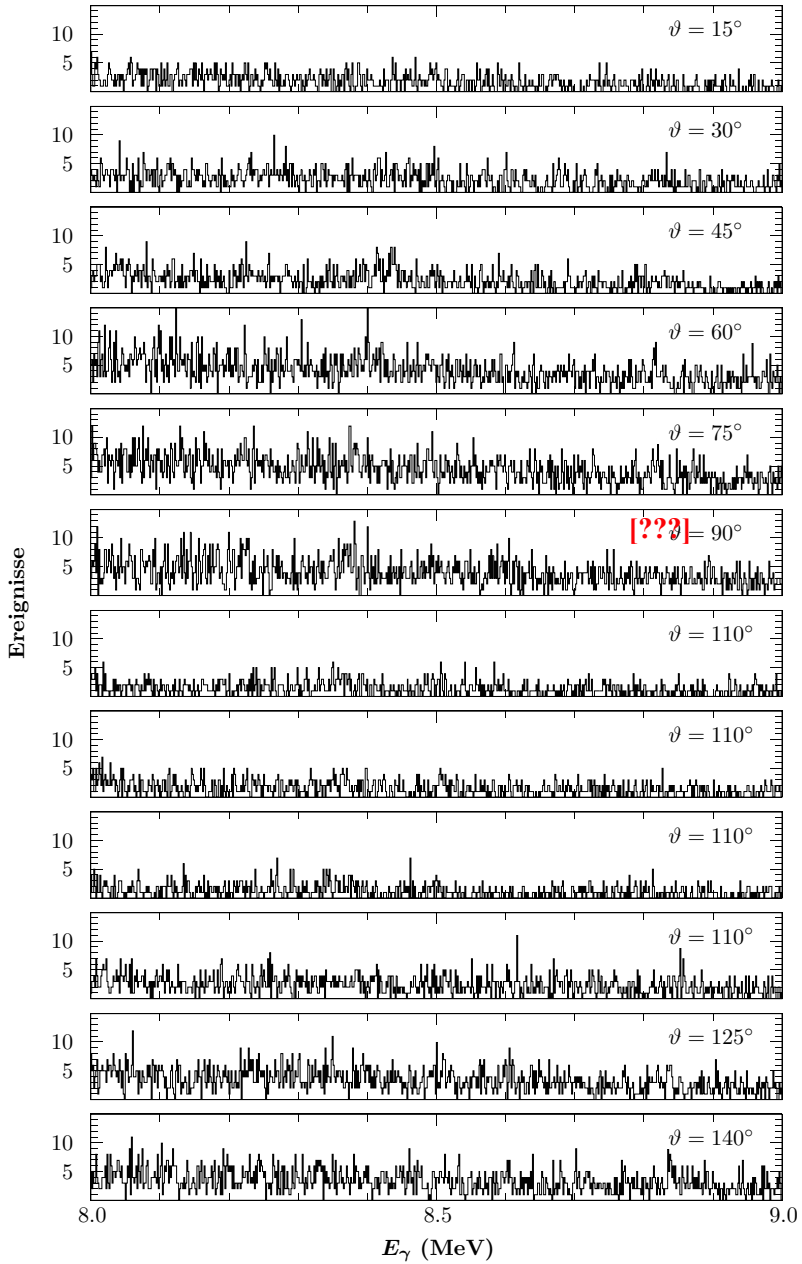



**Abbildung C.34:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.696\,\mathrm{MeV}$. $E_L$=2.261 MeV



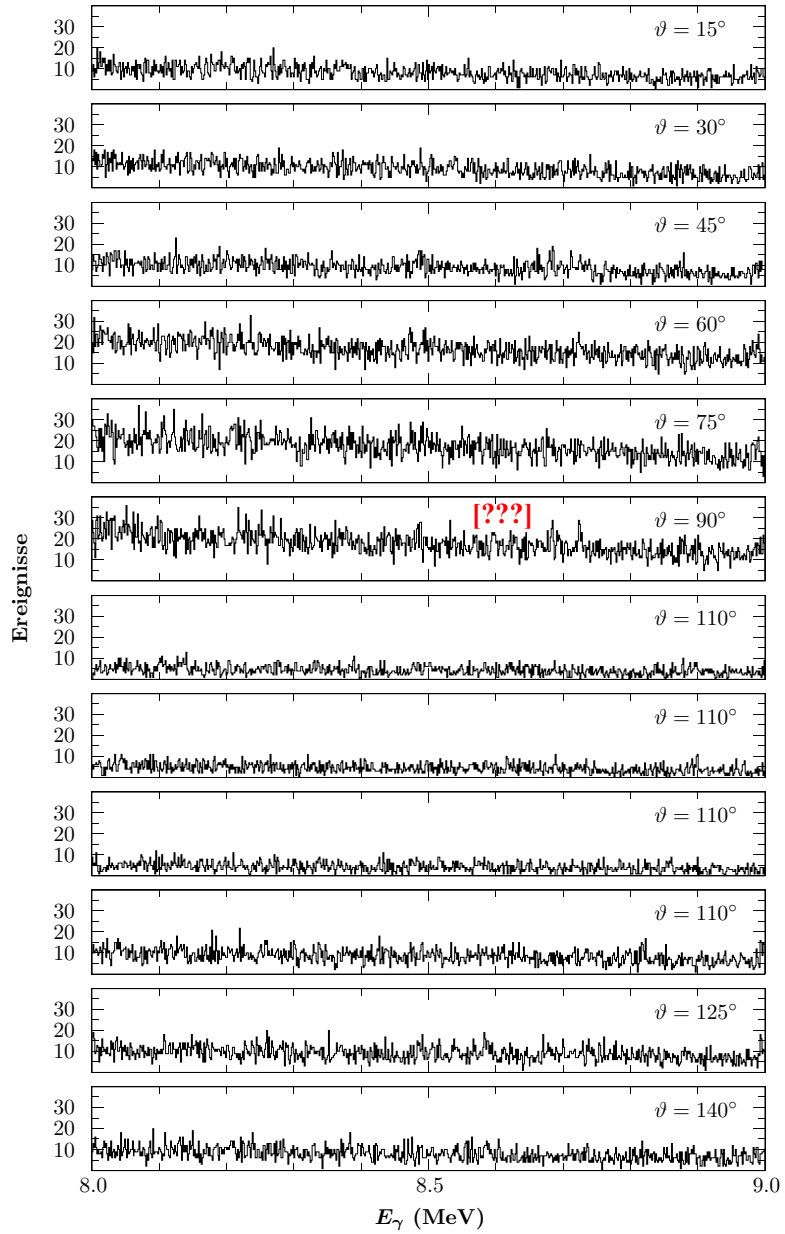



**Abbildung C.33:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\mathrm{c.m.}} = 1.452\,\mathrm{MeV}$. $E_L$=1.936 MeV

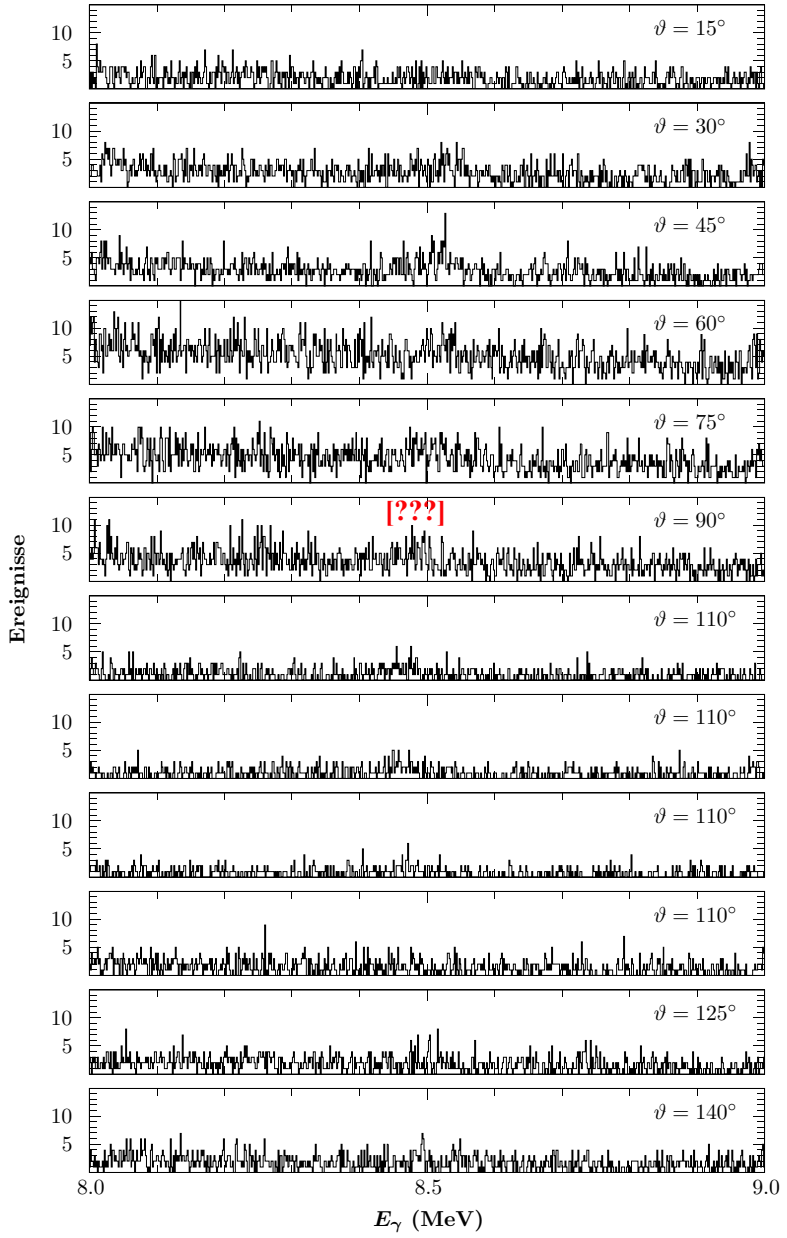



**Abbildung C.32:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\text{c.m.}} = 1.308\,\text{MeV}$. **$E_L$=1.744 MeV**



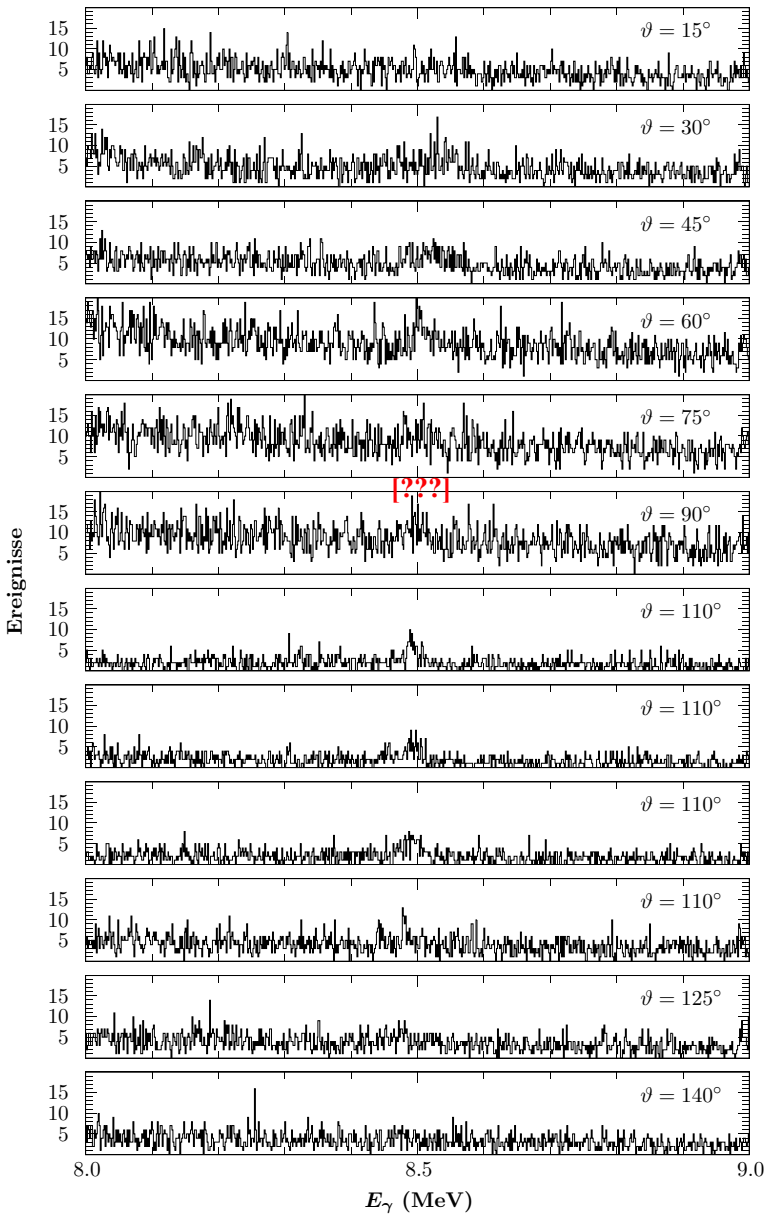



**Abbildung C.31:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\text{c.m.}} = 1.305\,\text{MeV}$. **$E_L$=1.740 MeV**



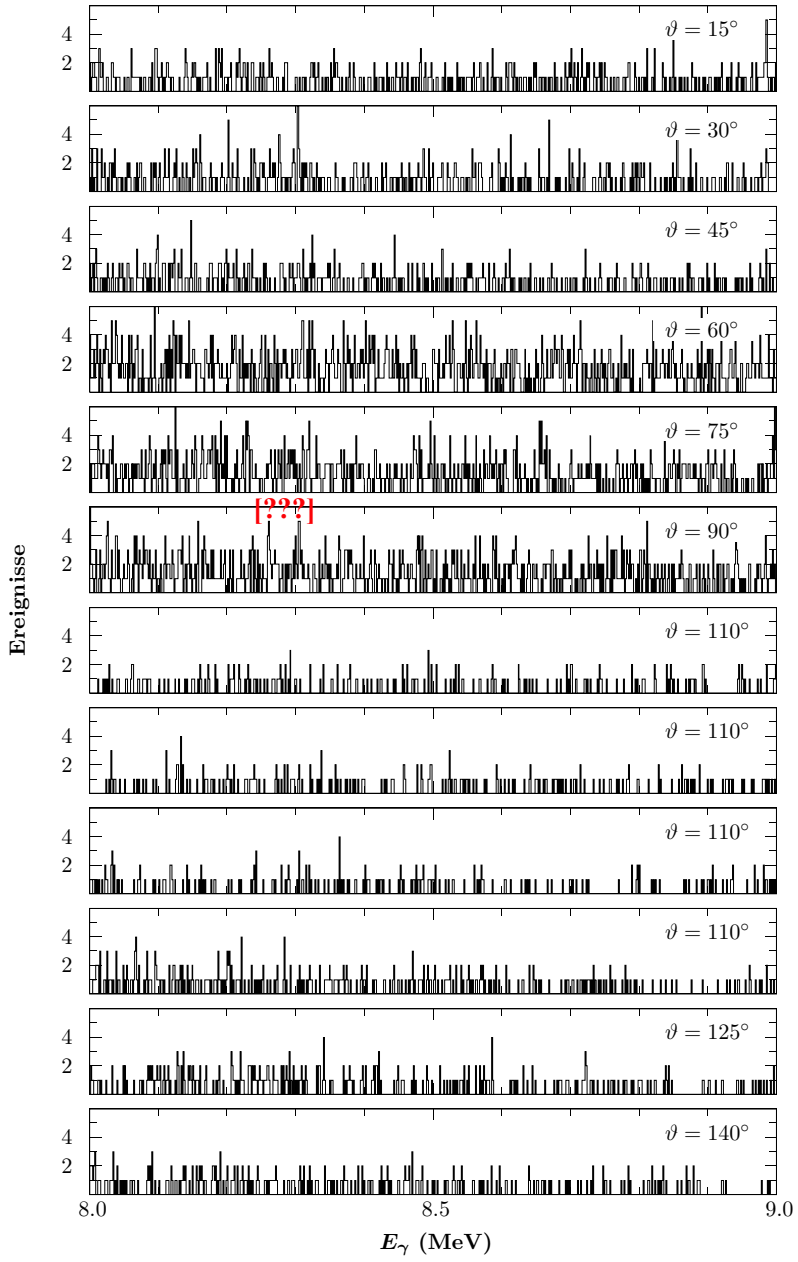



**Abbildung C.30:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\text{c.m.}} = 1.103\,\text{MeV}$. **$E_L$=1.470 MeV**

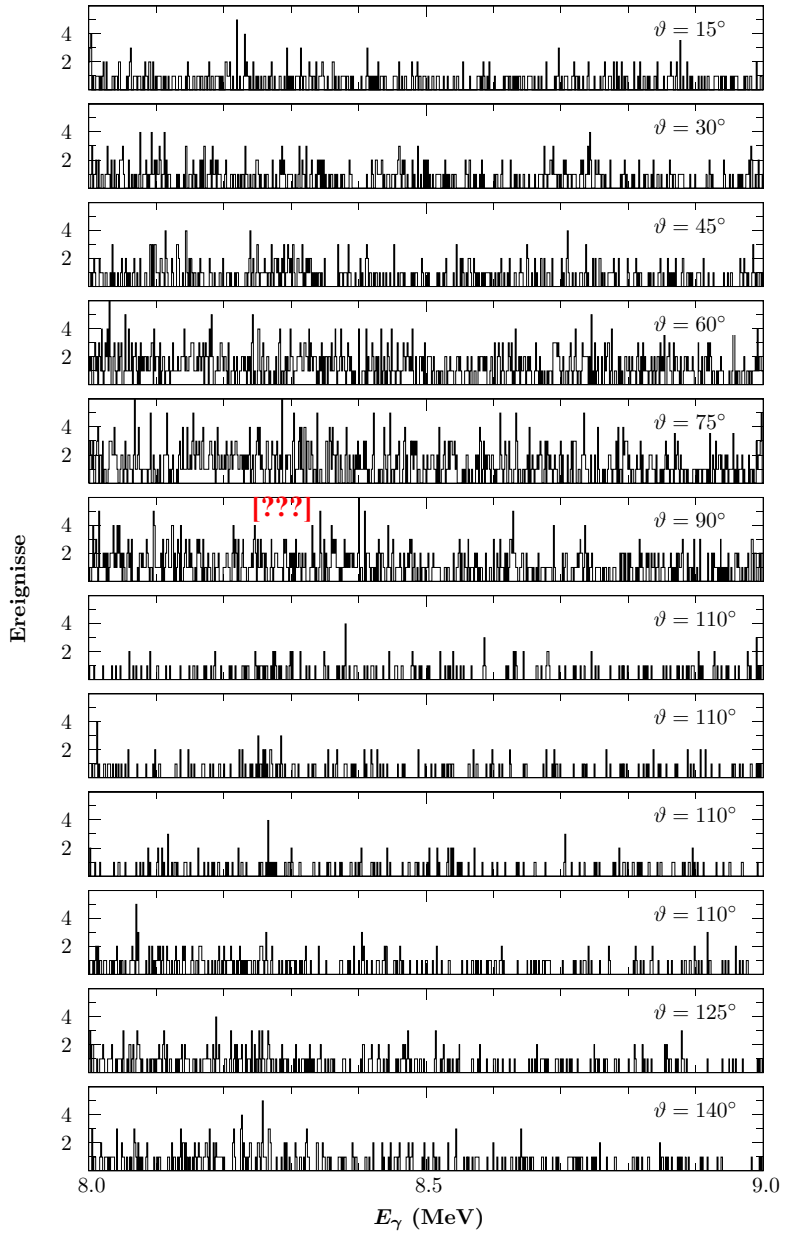



**Abbildung C.29:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\text{c.m.}} = 1.102\,\text{MeV}$. $E_L$=1.469 MeV



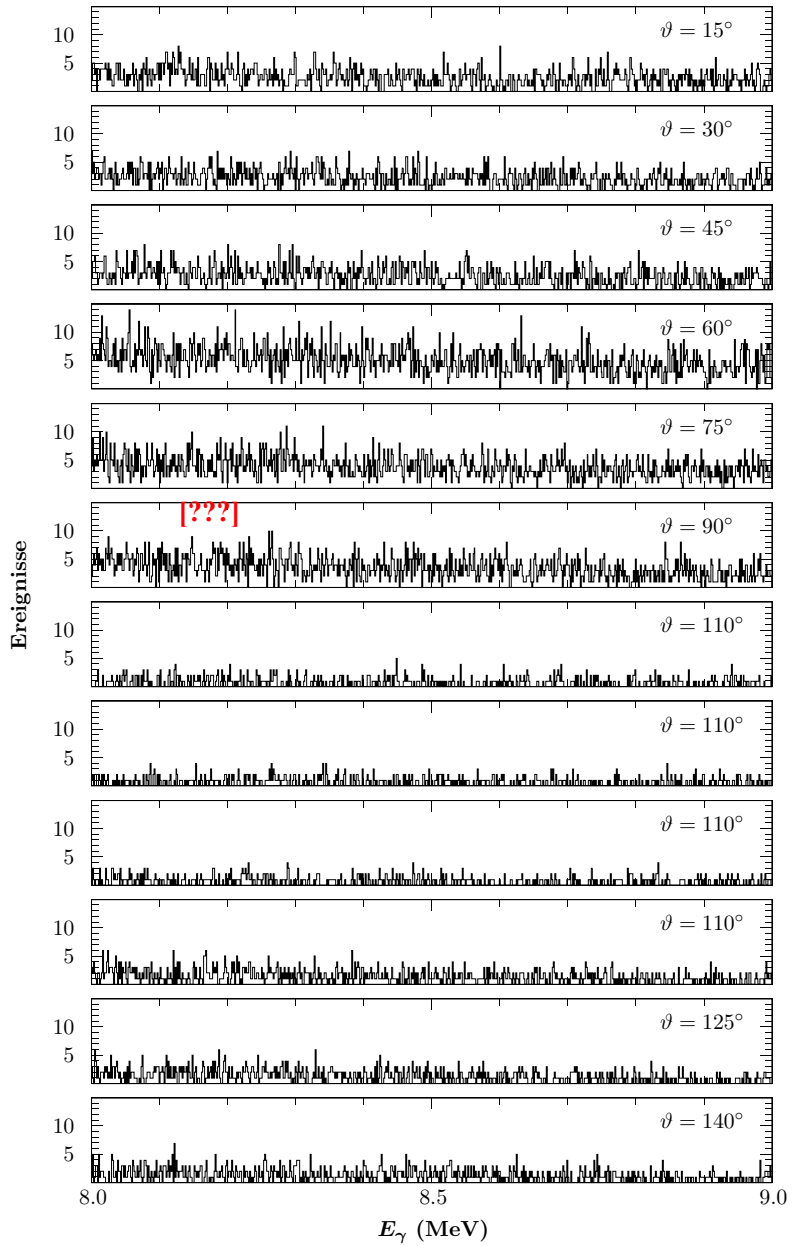



**Abbildung C.28:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\text{c.m.}} = 1.099\,\text{MeV}$. $E_L$=1.465 MeV



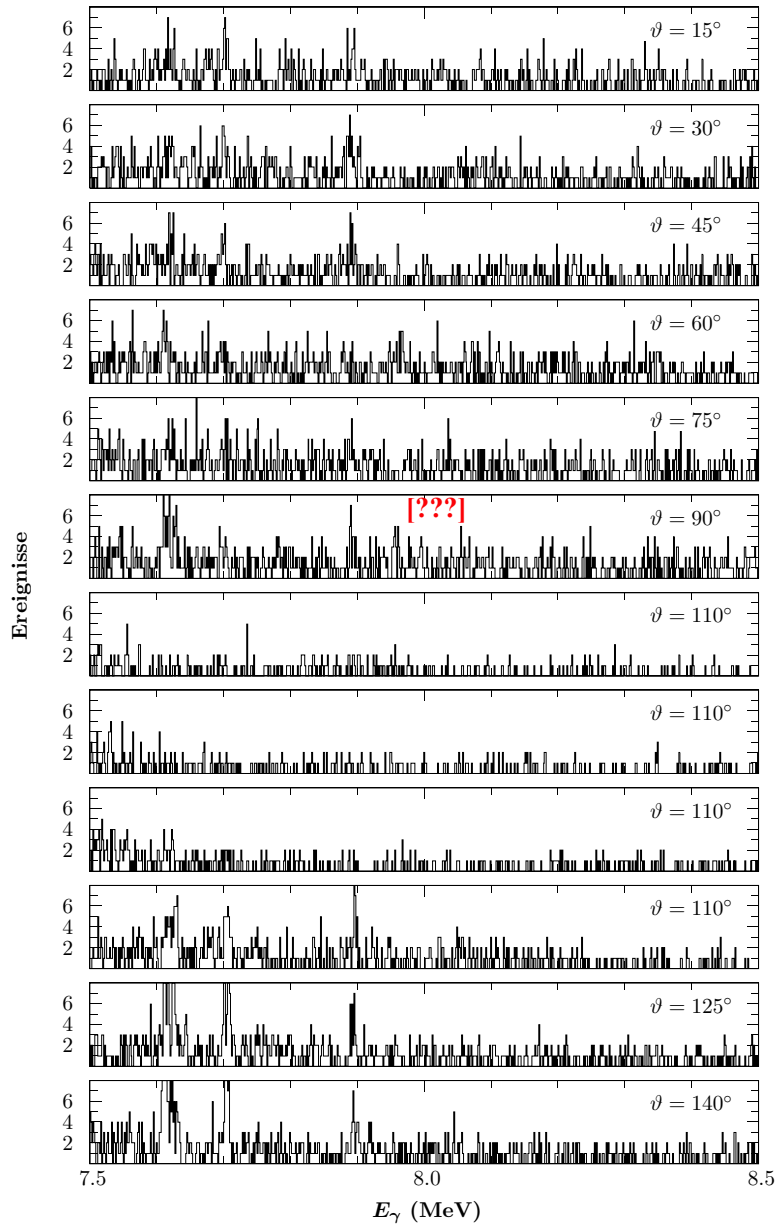
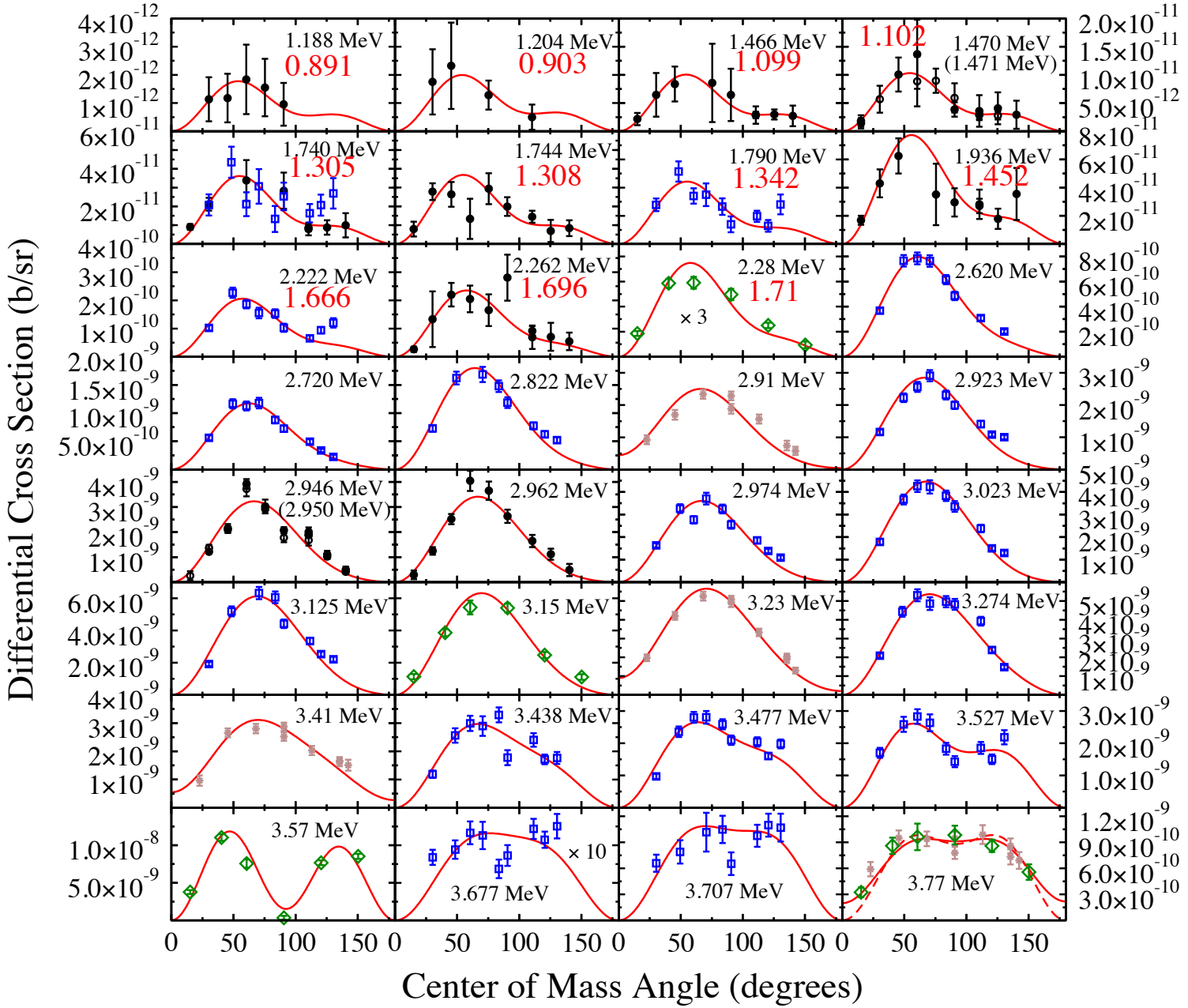



**Abbildung C.27:** Im Rahmen des Drehtisch-Experiments gemessene $\gamma$-Roh-Spektren bei $E_{\text{c.m.}} = 0.903\,\text{MeV}$. $E_L$=1.204 MeV

**Richard deBoer et al., RMP 89, 03500742 (2017)**




**deBoer *et al.* rely on the ANC**
**The S-factor is derived from**
**Alpha-transfer, e.g. ($^7$Li,t)**
**Not from capture gamma-ray**
**Indirect Method ala 1980's**

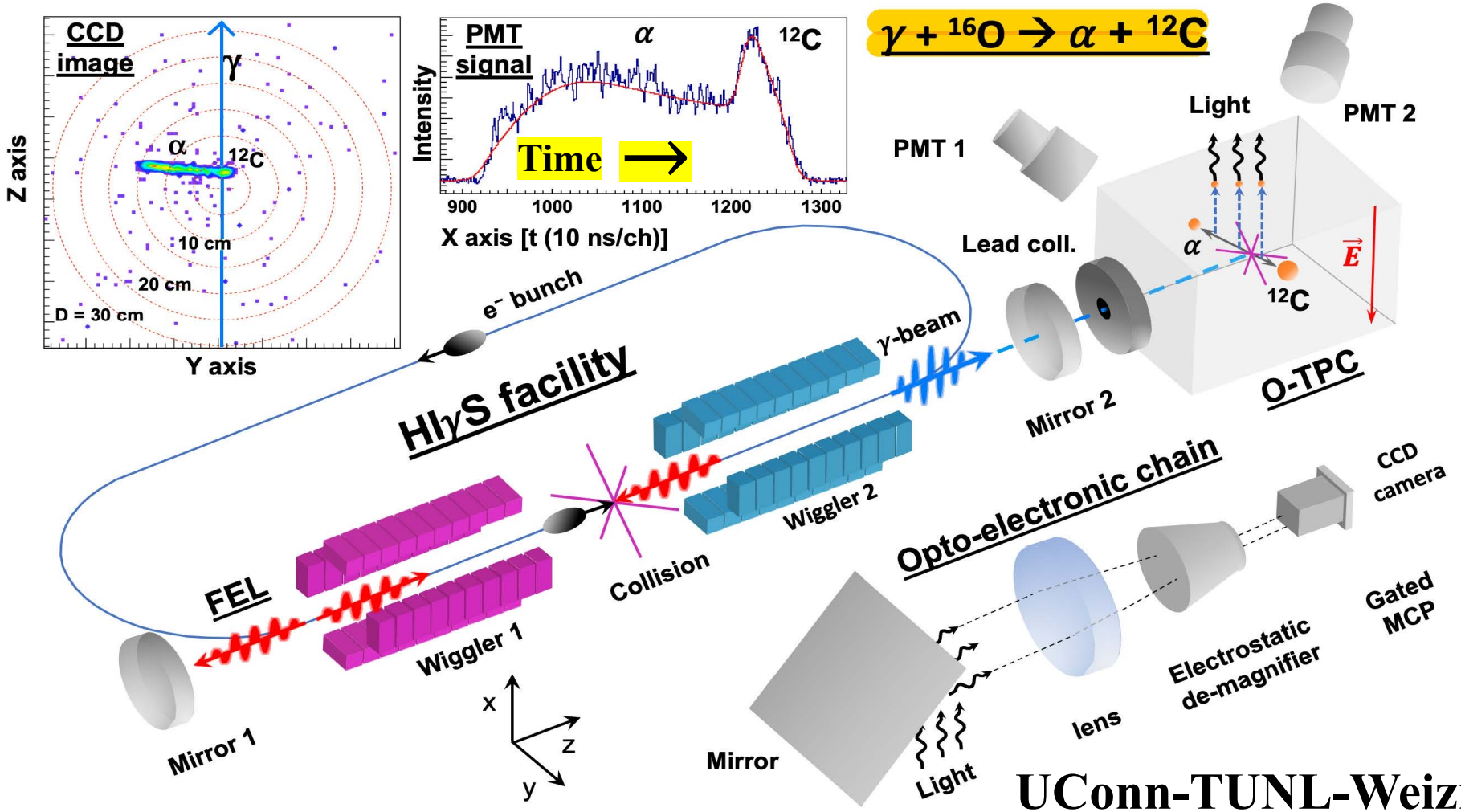
**51 years after Dyer & Barnes**
**We still do not have the needed**
**Capture Gamma-Ray Data**

**This is the status of our field**
**(NOT a personal criticism)**

**Detailed Balance:** $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ (in Stars)

$^{16}O + \gamma \rightarrow {}^{12}C + \alpha$ (at HIγS)

(O-TPC: $CO_2$)




Active Target TPC

M. Gai *et al*,

JINST 5, 12004 (2010)

UConn-TUNL-Weizmann-PTB (2012)

SHU-UConn-TUNL (2021)

R. Smith, M. Gai, D.K. Schweitzer, S.R. Stern and M.W. Ahmed,

Nature Communications, 12, 5920 (2021).

https://www.nature.com/articles/s41467-021-26179-x

# Detailed Balance:

## (Inverse, Time Reversed Reaction)

$$\sigma[^{12}C(\alpha,\gamma)^{16}O] = \frac{2\,k_\gamma{}^2}{k_\alpha{}^2}\,\sigma[^{16}O(\gamma,\alpha)^{12}C]\ *$$

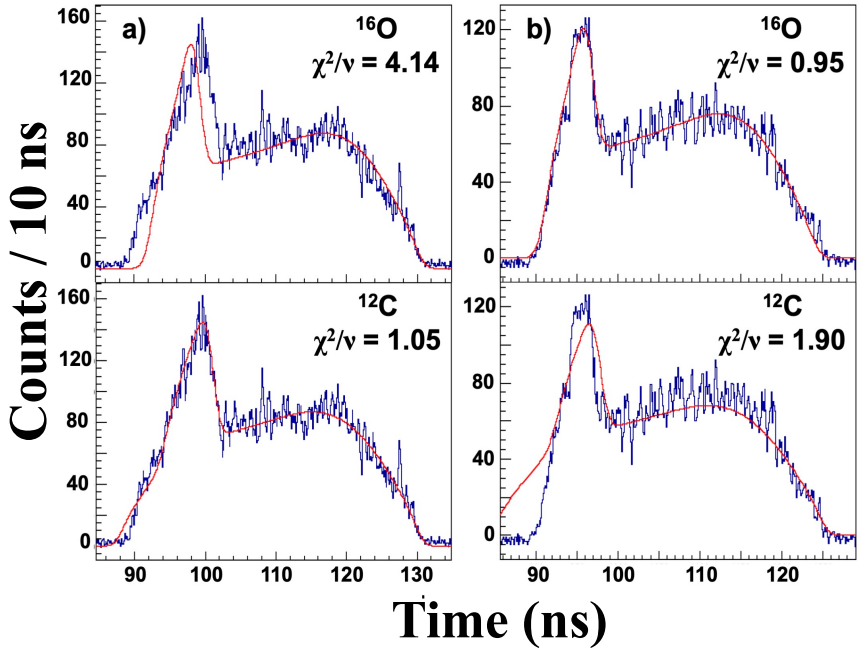
$$\sigma[^{16}O(\gamma,\alpha)^{12}C] \approx \sim 50 \text{ x } \sigma[^{12}C(\alpha,\gamma)^{16}O]$$

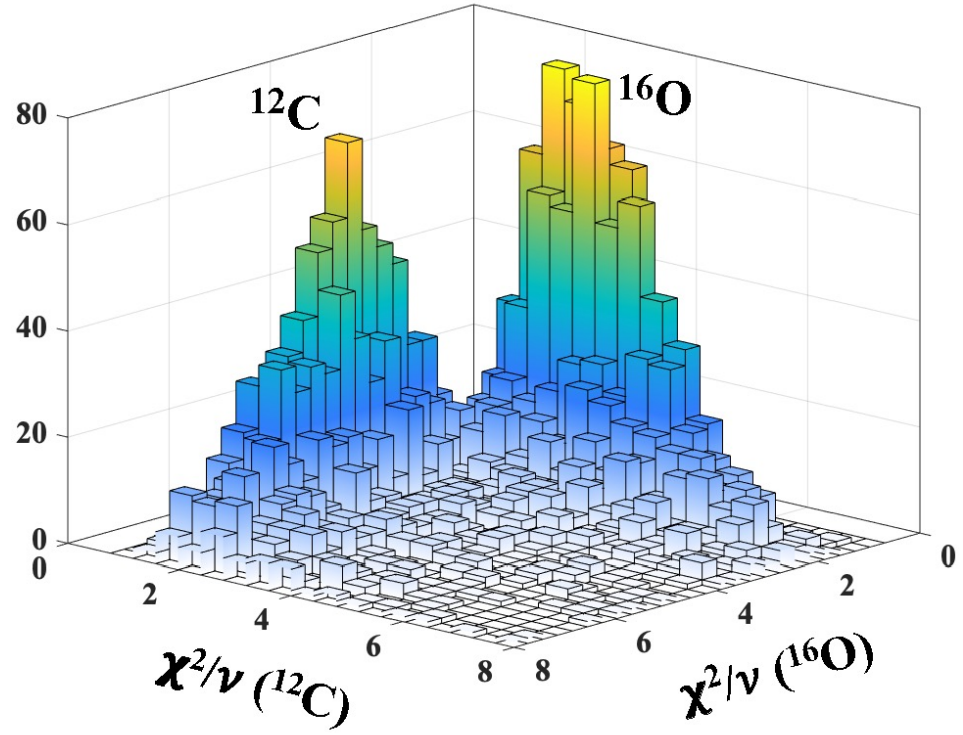
* For Real Photons 2S+1 = 2 (not 3)

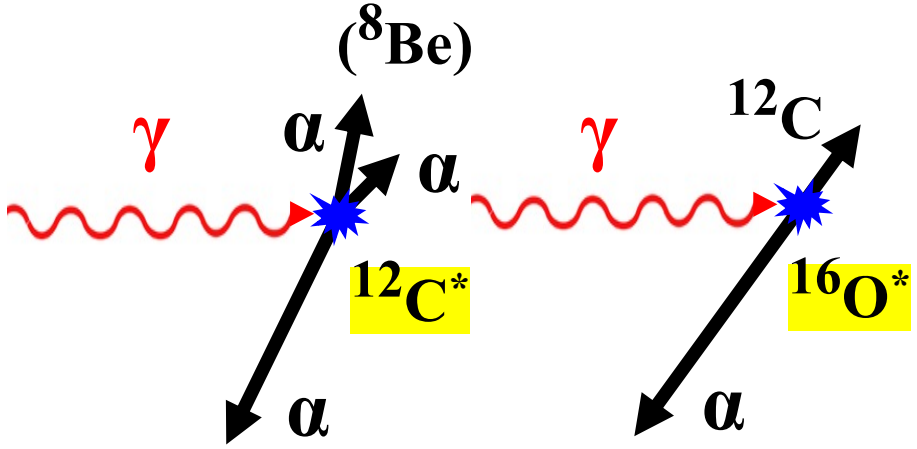
**Not a "Surrogate Reaction"**

**Not an Indirect Measurement**

# Line Shape Analysis ($CO_2$ Gas)

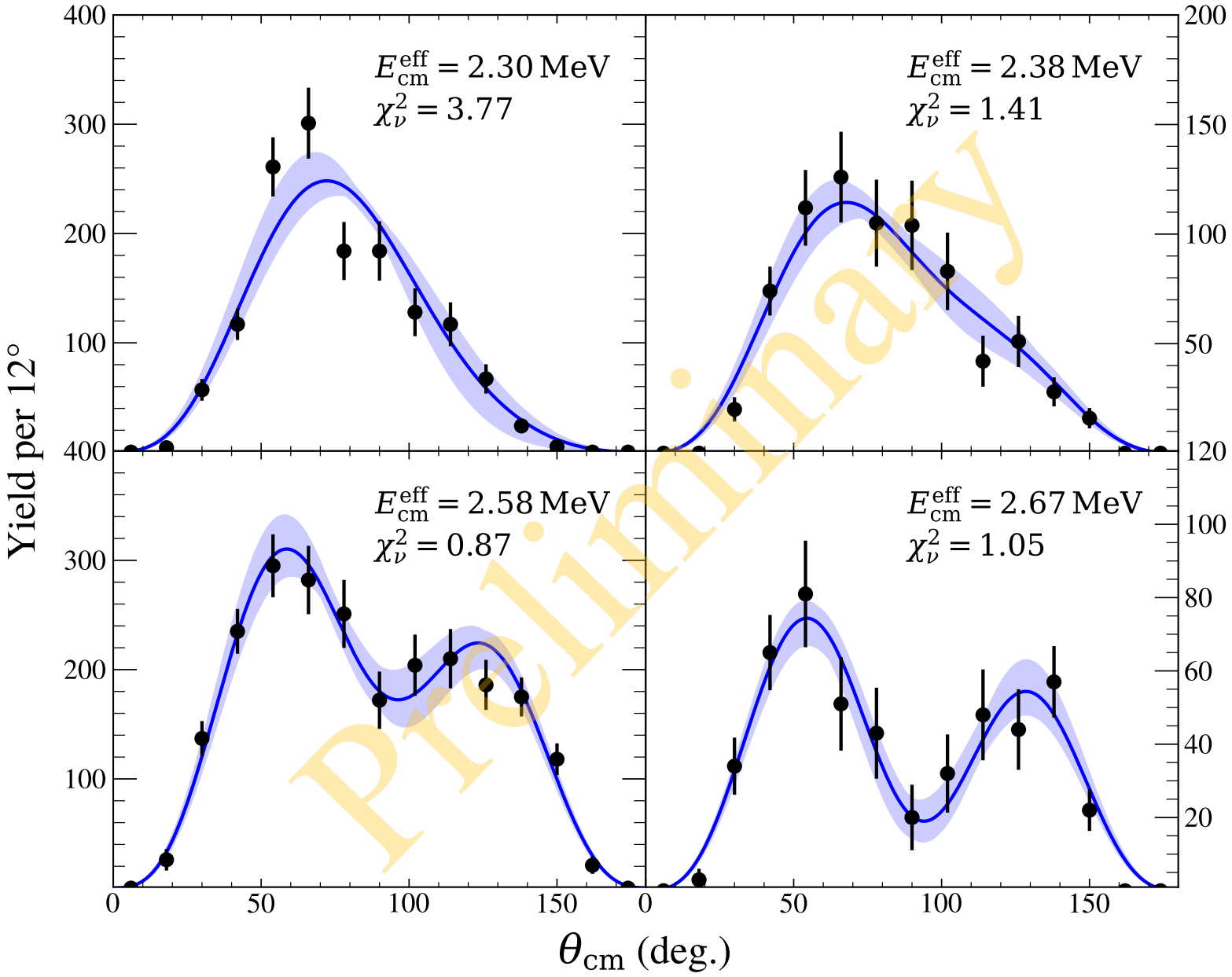



**Machine Learning**

**$Q(^{16}O^*) - Q(^{12}C^*) = 112$ keV**

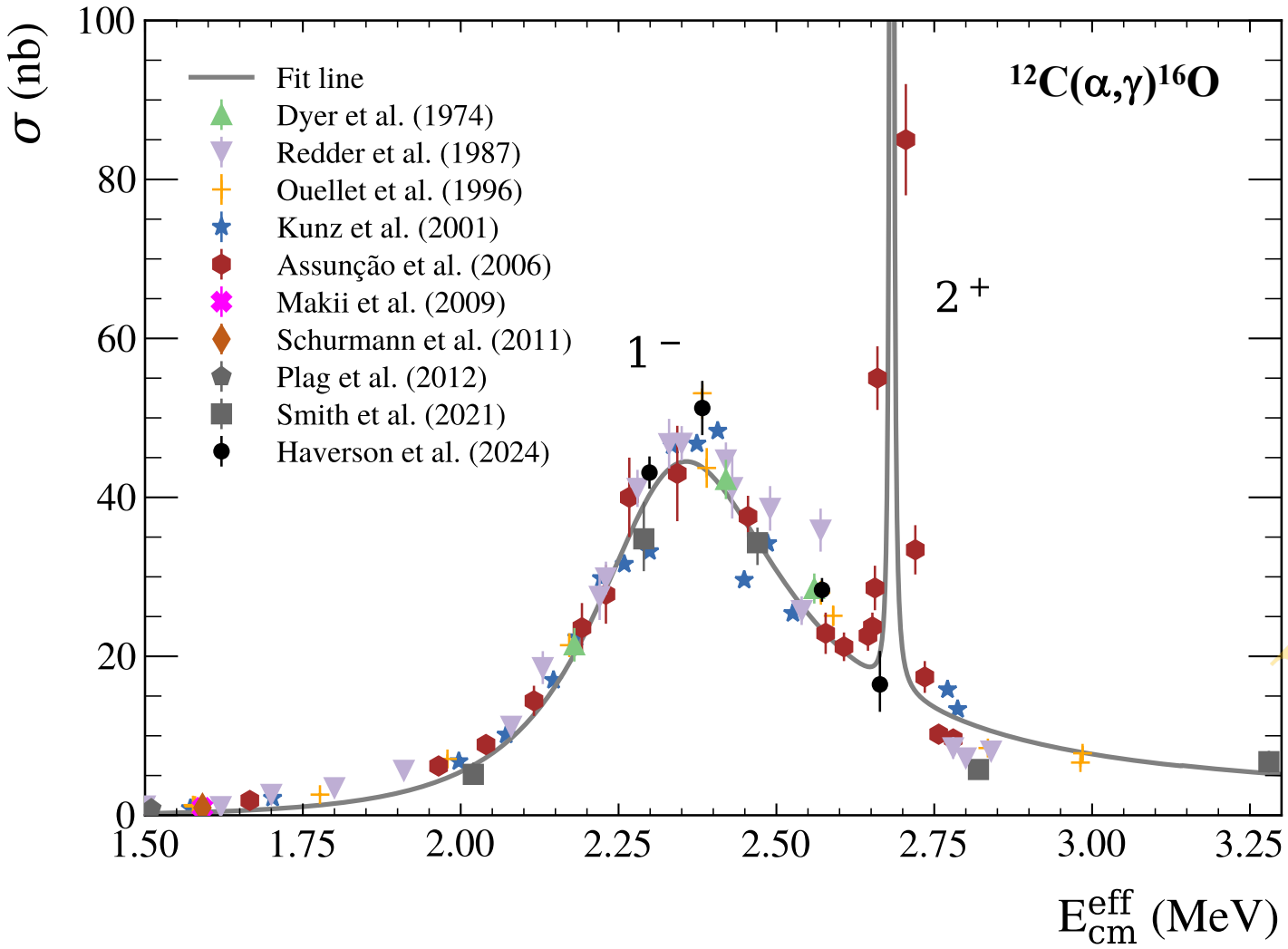


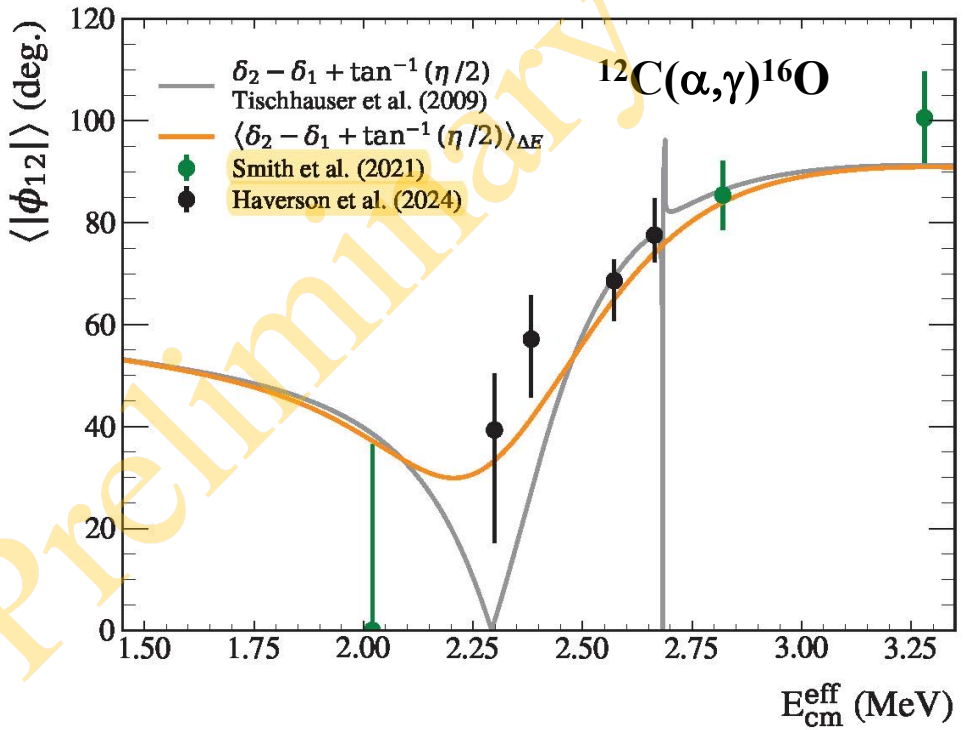

# $^{16}O(\gamma,\alpha)^{12}C$

**O-TPC Data $N_2O$ gas**
**Angular distributions**
**measured at 17 angles**

**Kristian C.Z. Haverson**
**@ SHU, UConn-SHU (2024)**

# O-TPC (Nature + $N_2O$) Data Benchmarked against World Data
# First Agreement of data on $\phi_{12}$ with Quantum Mechanics



## UConn O-TPC @ HIγS (2012)

## Warsaw eTPC @ HIγS (2022)

**Looking forward to ELI-NP, Bucharest/ M. Gai Fulbright US Scholar, 2025**

# Sneak peek, 2022 Measurement with the Warsaw eTPC:

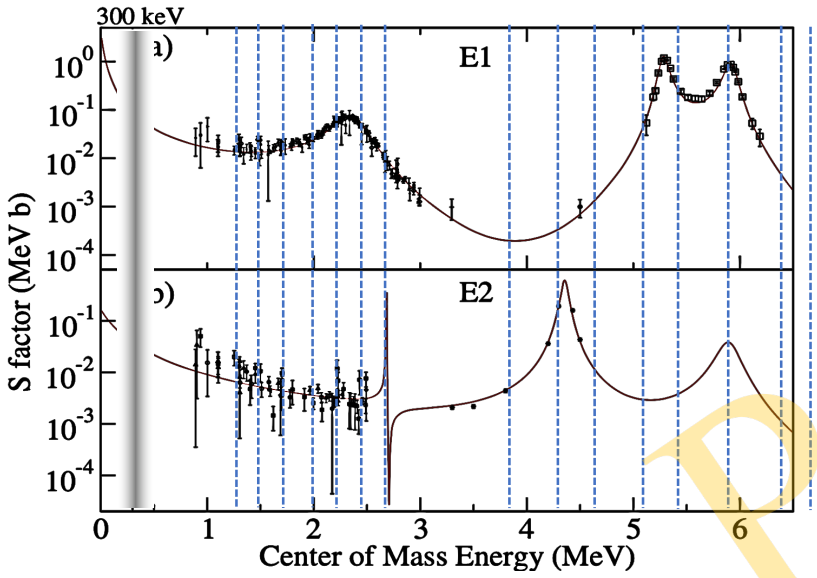
## Mateusz Fila, Ph.D. Thesis, Warsaw 2023

https://repozytorium.uw.edu.pl/bitstreams/5049fd46-45eb-4b32-9edb-fa121cba7812/download

## Complete Angular Distributions, 20 Angular Bins down to ~1.3 MeV

**We measured at the shown 15 Energies**

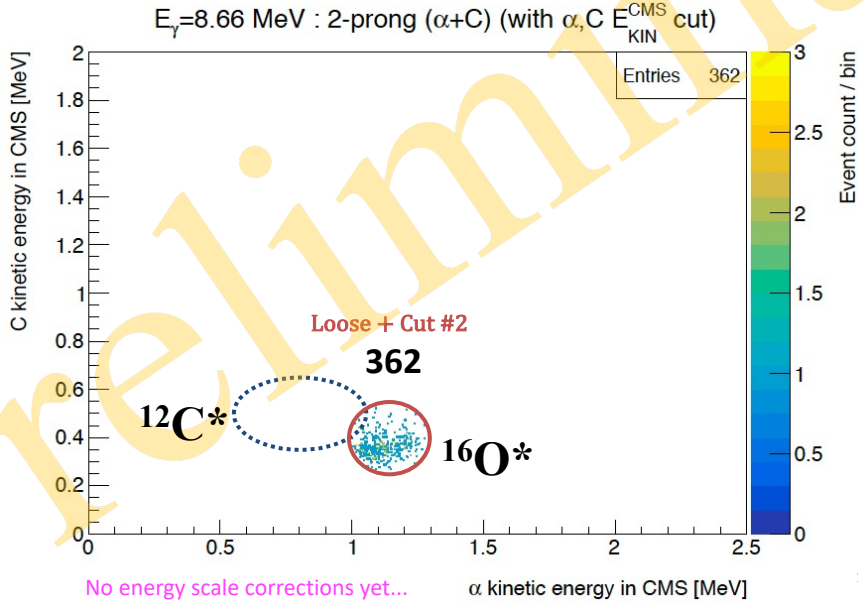
**(Curve E1&E2 from deBoer *et al.*)**

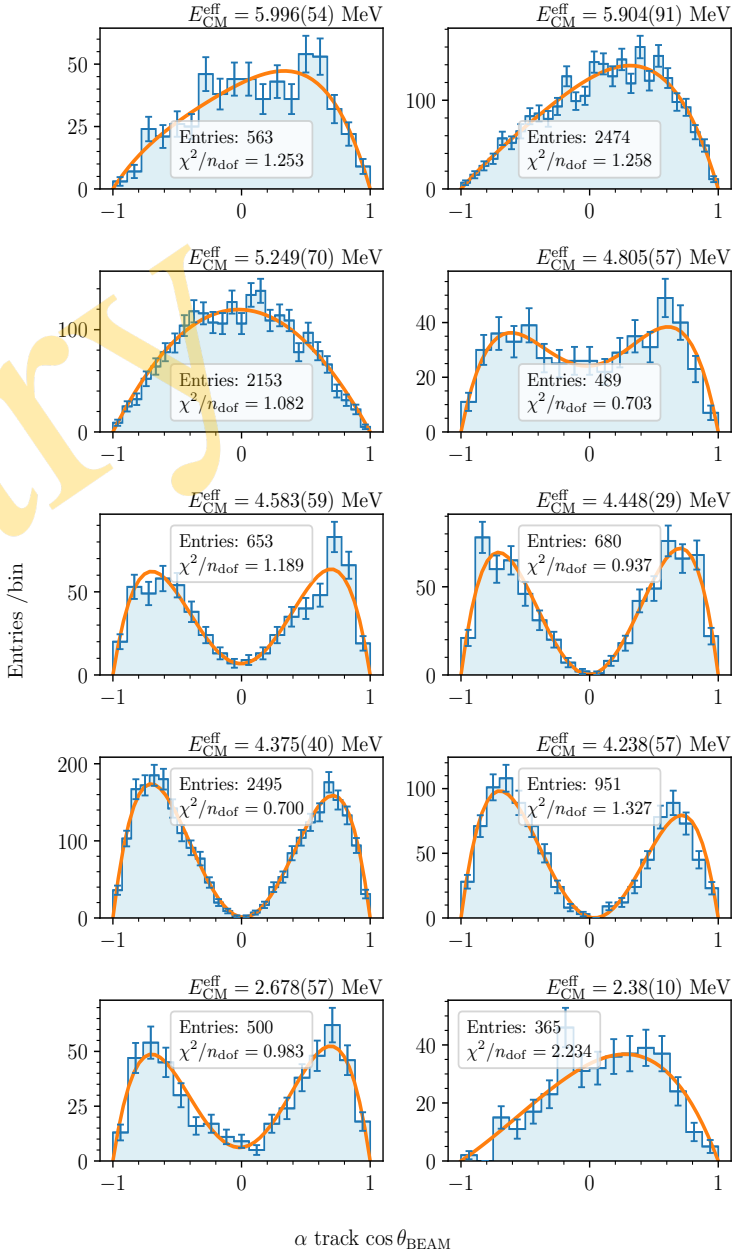



**Exploratory Measurement:**

**Mikołaj Ćwiok, Eγ = 8.66 MeV**

**Ecm = 1.5 MeV**




## Conclusions

**TPC data of unprecedented quality:**

1. **Low background, if any**
2. **Measurement in one detector (response, simple Monte Carlo)**
3. **Complete angular distribution (0° – 180°)**
   **(Measured at 17-20 bin-angles)**
4. **First Physics Result, First Agreement with Unitarity**
5. **New Criteria for Judging Data (Agreement with QM)**
6. **Further data measured at HIγS, Warsaw TPC, 2022**

**(Please do not publish or analyze data that disagree with QM)**