# Nuclear Astrophysics With TPCs in Gamma-Beams

## I. Measurements of the $^{12}C(\alpha,\gamma)$ Reaction With O-TPC at the HIγS *

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1. Oxygen Formation in Stellar Helium Burning/ the $^{12}C(\alpha,\gamma)$ Reaction
2. World Data
3. The HIγS Measurement with O-TPC

II. Data with Warsaw TPC @ HIγS, 2022 Next Talk, Mikolaj Cwiok

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ISNS 2024, Sofia, Bulgaria, September 12, 2024

**Fulbright US Scholar Award**

**Happy Birthday**

**To my Host Prof. Dimiter Balabanski**

**(and Thank You)**

**December 9, 2024 – May 8, 2025**

**ELI-NP**

**Shinning Light**

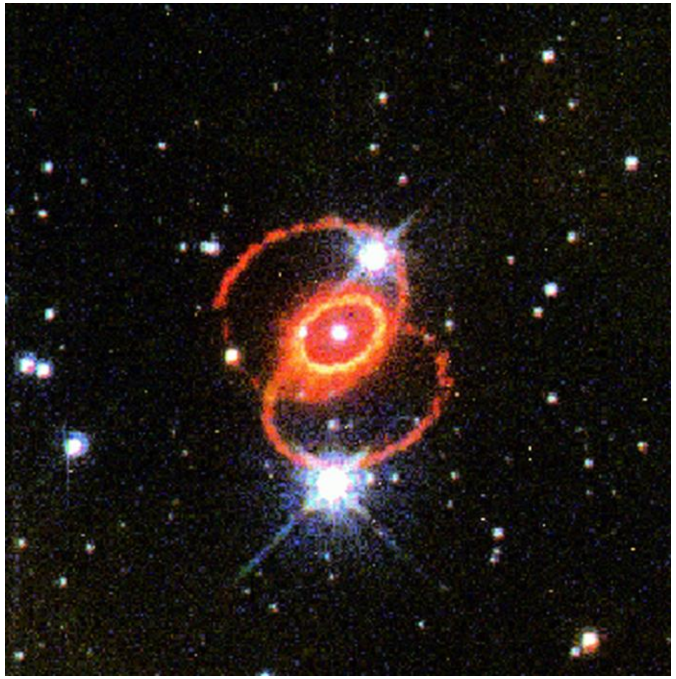
**On**

**Nuclear Astrophysics**

**And thank you Prof. Georgi Georgiev for saving my bank account**

# 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)
Progenitor: Sanduleak −69 202 (Sk -69 202) Blue Supergiant ~17M$_\odot$
Is SN1987A: Black Hole or Neutron Star?
Determined by C/O, But = ???
Fusion Reaction: The $^{12}C+^{4}He \rightarrow ^{16}O+\gamma$ [$^{12}C(\alpha,\gamma)^{16}O$]



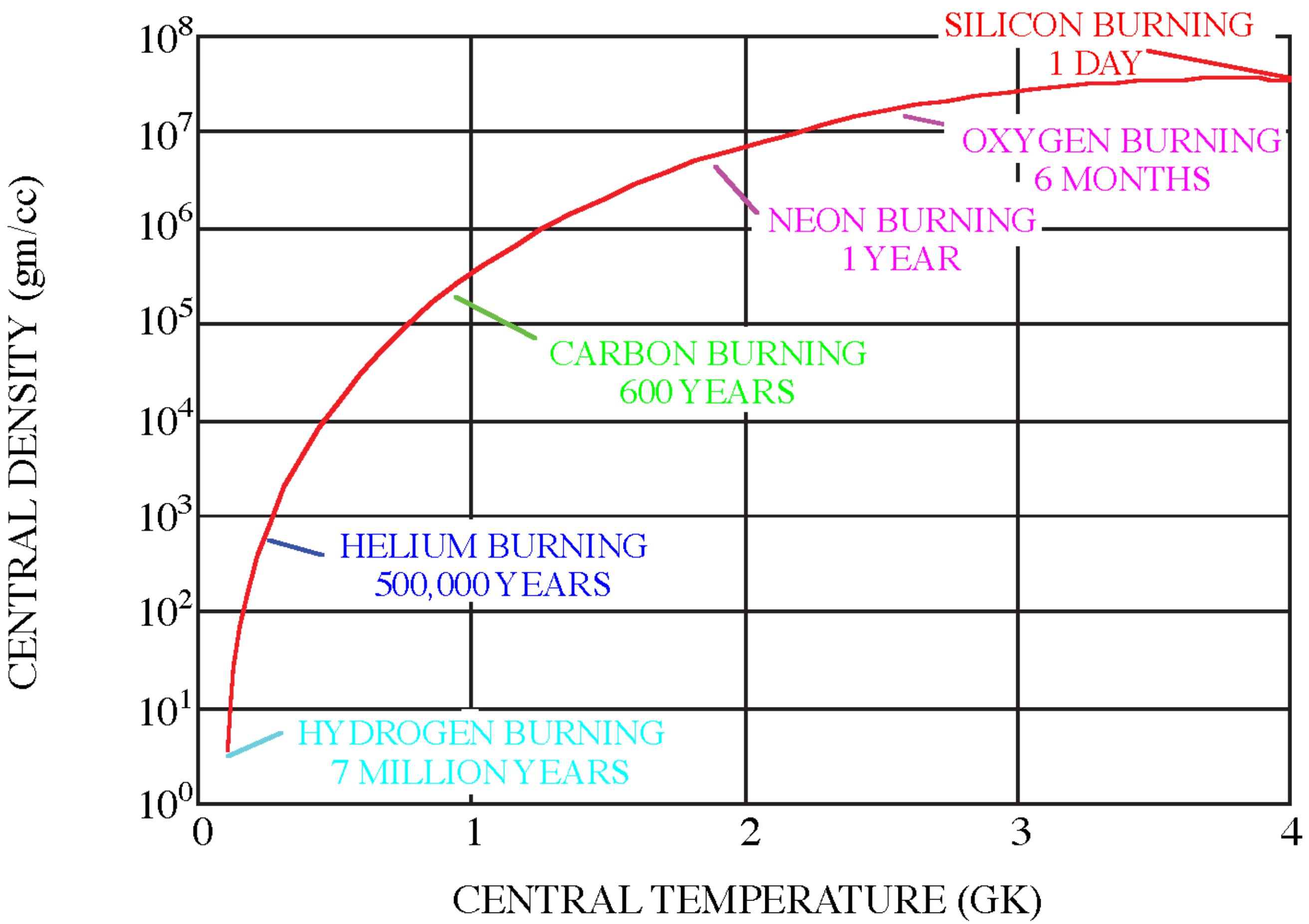
W.A. Fowler: Rev. Mod. Phys. 56, 149 (1984)
"The $^{12}C(\alpha,\gamma)$ reaction is of paramount importance"

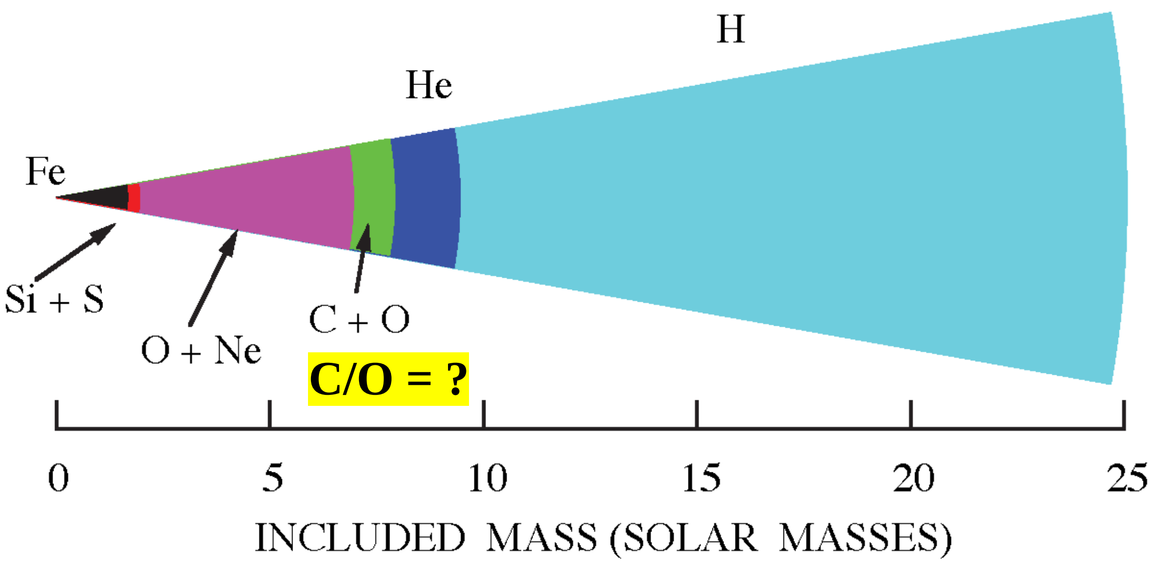
**Helium Burning:** $3\alpha \rightarrow ^{12}C$ (~11%) "Hoyle State"
$^{12}C(\alpha,\gamma)^{16}O$ @300 keV
C/O = ?


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

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

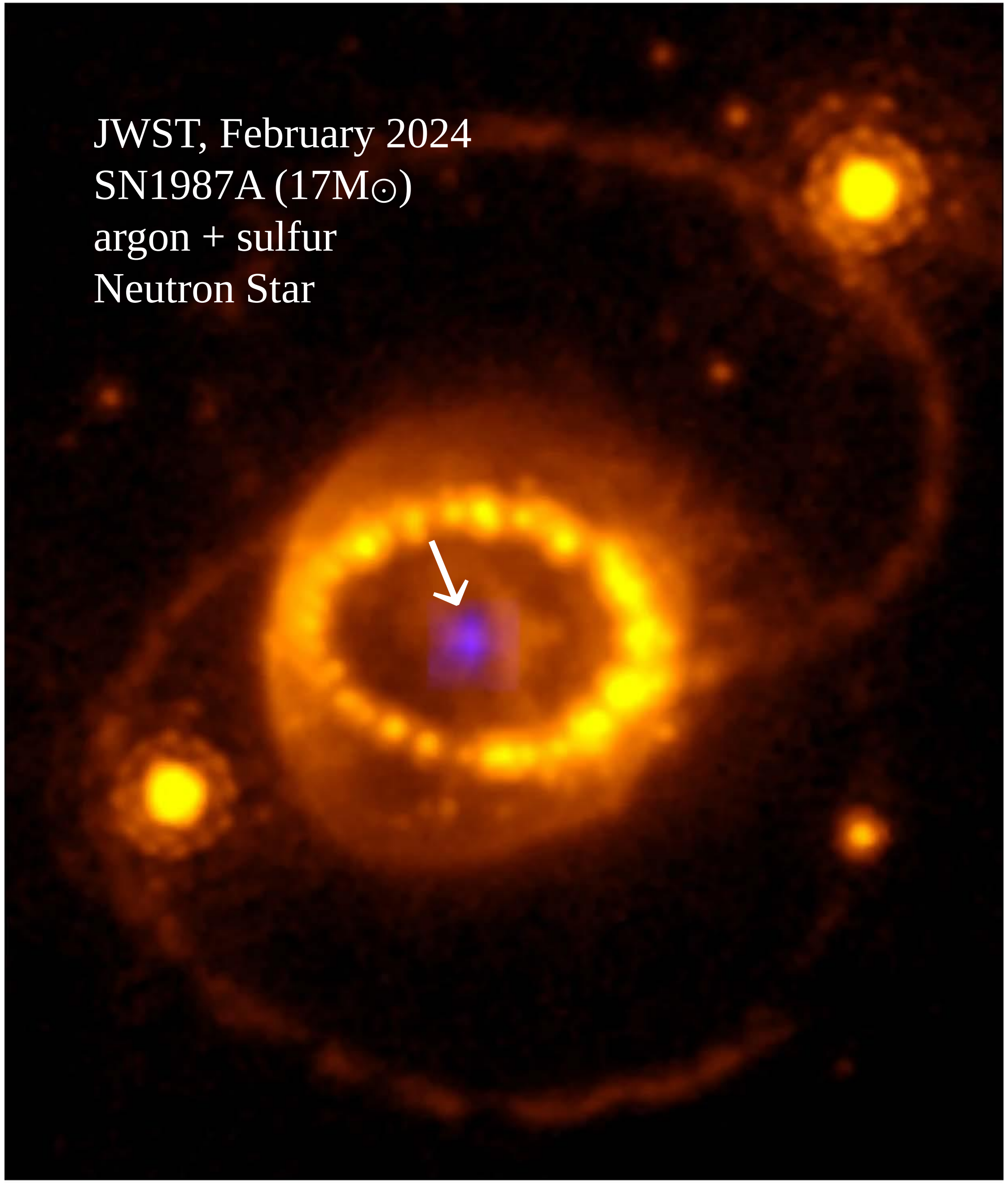
# Type II (Core Collapse) Supernova




**Bethe & Brown, Scientific American 1985**

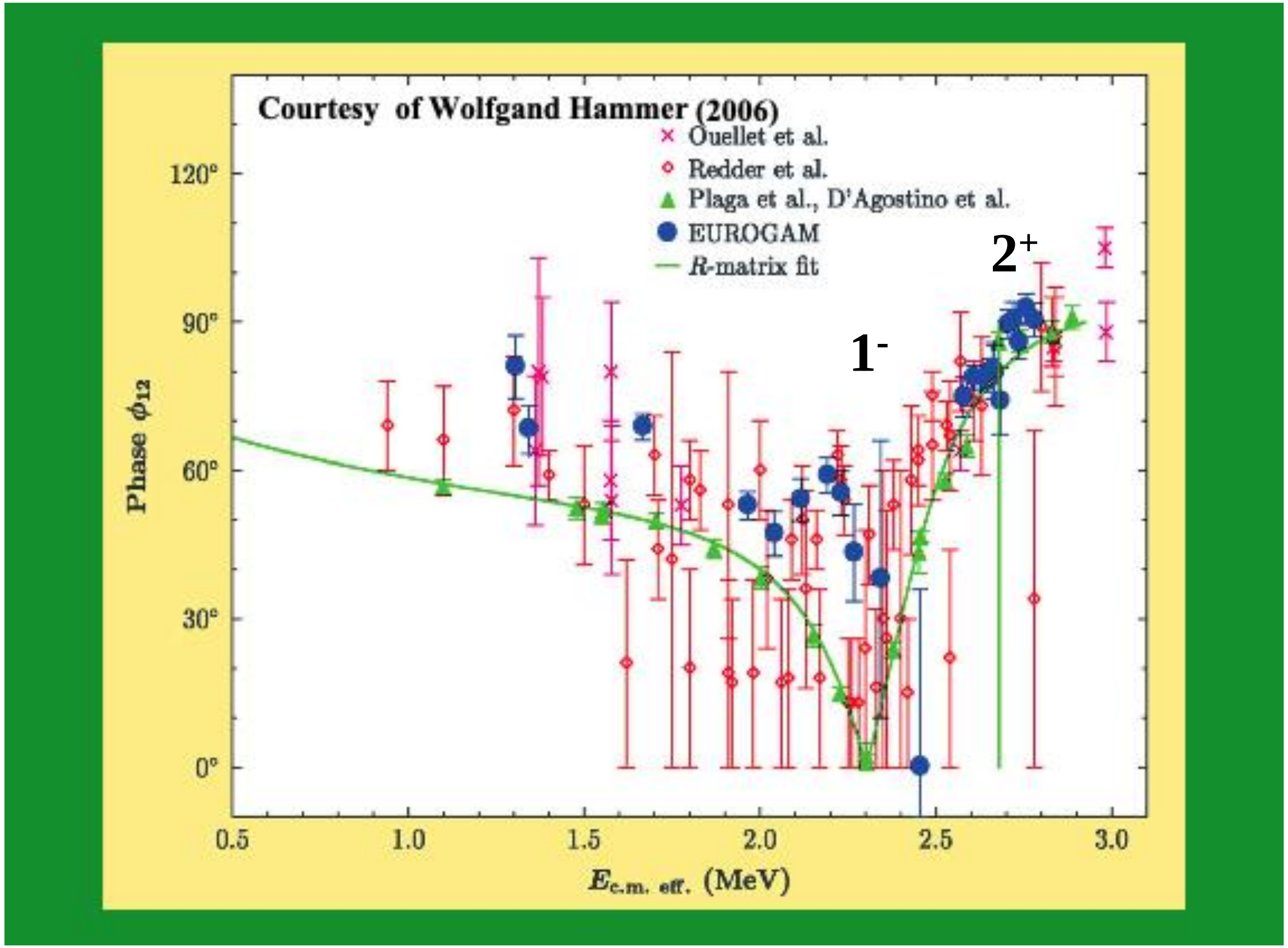
**M. Gai, Nucl. Phys. A928, 313 (2014) (x10 Gai)**




**Stellar upper bound on the rate of Oxygen Formation**
**The $^{12}C(\alpha,\gamma)$ reaction**

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

**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**

**EUROGAM**

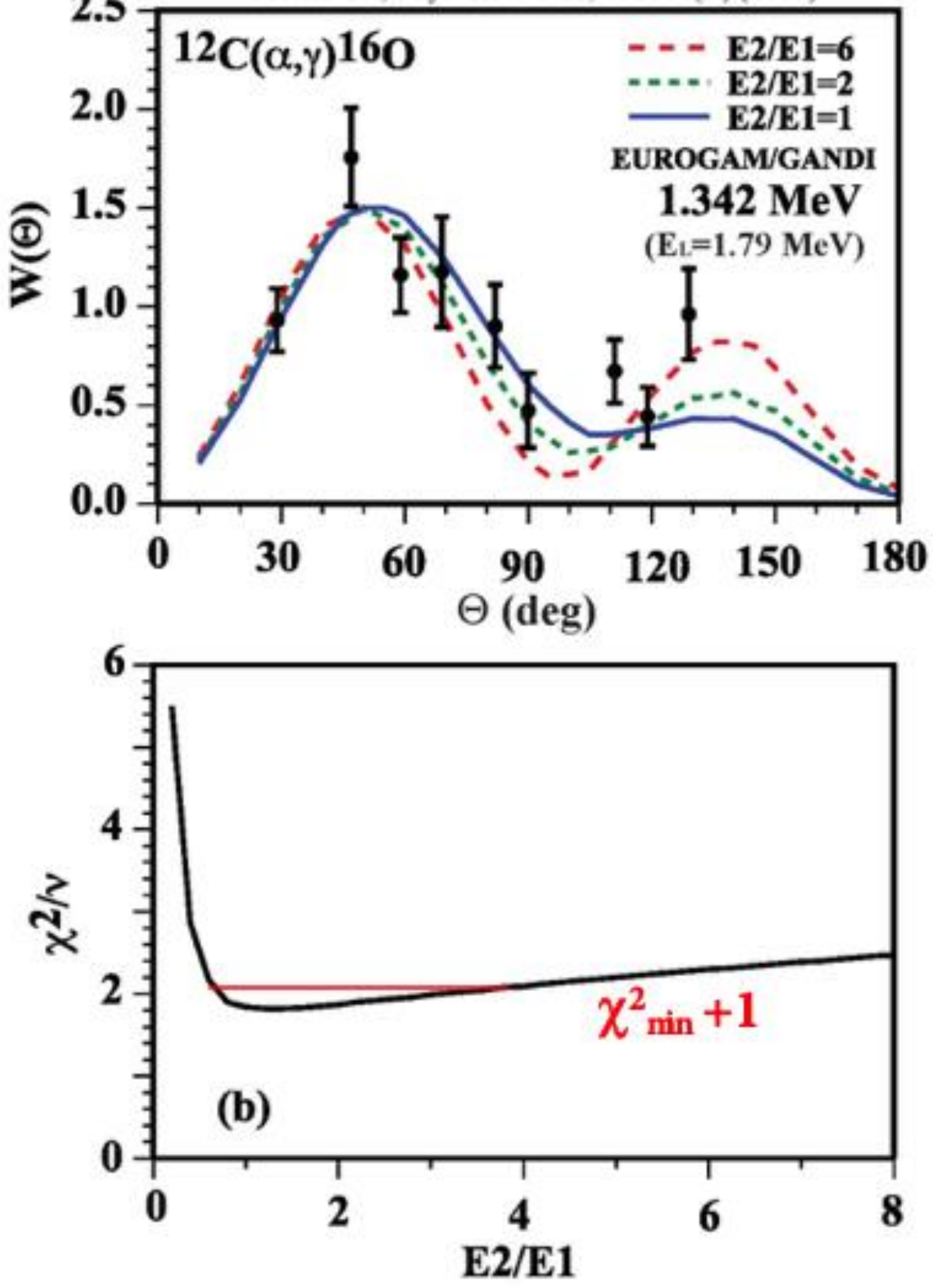
Assuncao *et al.*



TABLE I. Final results of the present $^{12}C(\alpha, \gamma)^{16}O$ experiment for the $E1$ and $E2$ capture $\gamma$-ray cross sections and their relative phase $\phi_{12}$. $E_{\alpha,\text{lab}}$ is the uncorrected $\alpha$-particle energy; $E_{\text{c.m. eff.}}$ is the effective c.m. energy calculated as explained in the text for the two considered cases: (I) using constant $S$ factors for $E1$ and $E2$ contributions to calculate the tabulated value and constant cross sections to calculate a limiting value contribution to the uncertainty; (II) a limiting value of $E_{\text{c.m. eff.}}$ calculated using a pure Breit-Wigner $E2$ resonance for the $E2$ contribution and a constant $S$ factor for the $E1$. For the two-parameter fit, the phase $\phi_{12}$ was fixed according to Eq. (4.7) with the phases taken from elastic scattering [31,32]. The corresponding $\chi^2$ values are reduced values for seven degrees of freedom (nine angles and two free parameters for the fit). For the three-parameter fit, the phase was determined according to Eq. (4.1) solely from the data of this experiment. The $\chi^2$ is the reduced value for six degrees of freedom (nine angles and three free parameters for the fit).

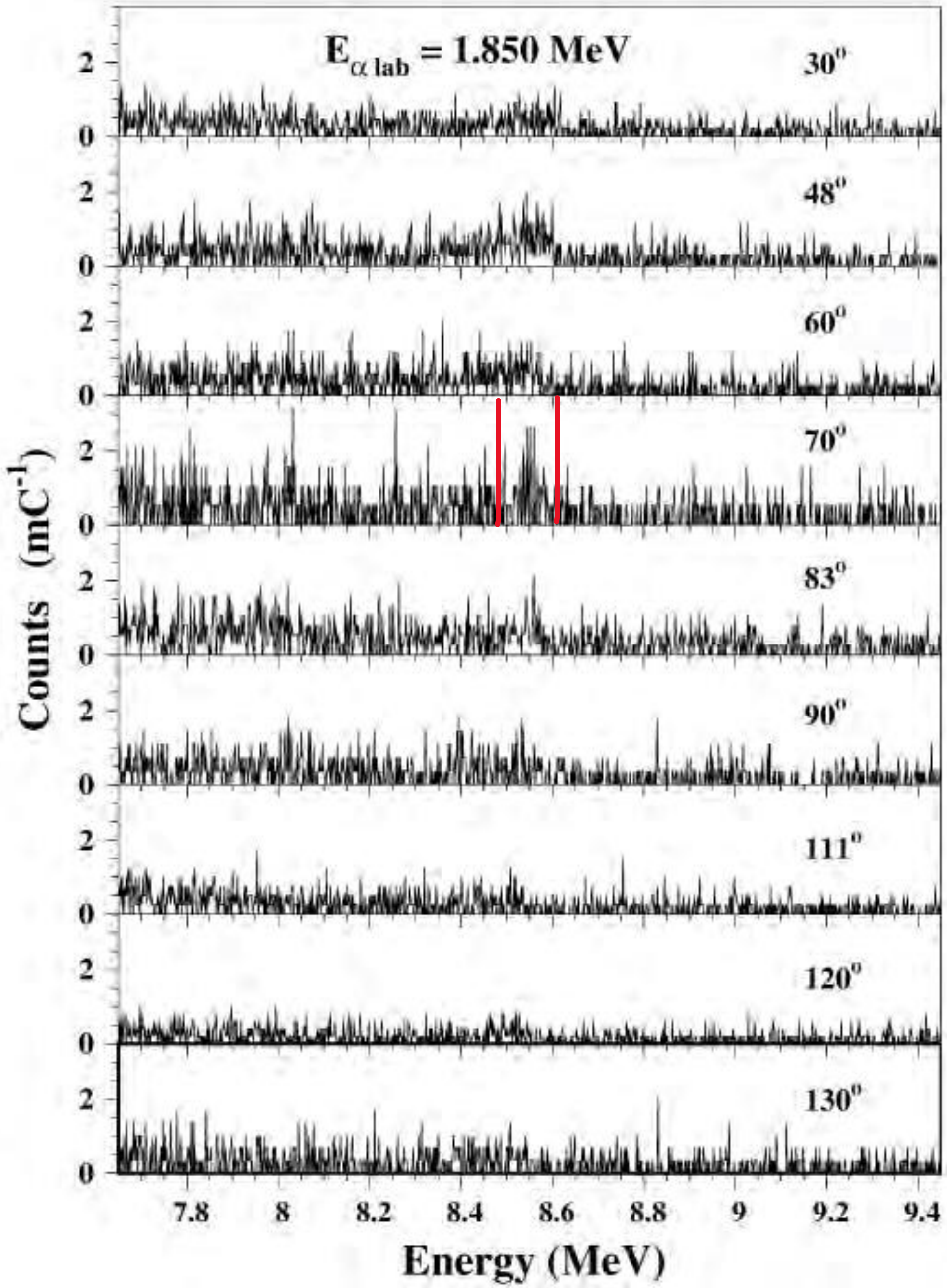
| $E_{\alpha,\text{lab}}$ (MeV) | $E_{\text{c.m. eff.}}$ (MeV) (I) | (II) | 2-parameter fit, phase fixed **by Unitarity** $\sigma_{E1}$ (nb) | $\sigma_{E2}$ (nb) | $\phi_{12}$ (deg) | $\chi^2$ | 3-parameter fit, phase free $\sigma_{E1}$ (nb) | $\sigma_{E2}$ (nb) | | $\phi_{12}$ (deg) | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.850 (2) | 1.310(40) | E1/E2 = 4.9 | 0.19(5) | 0.039(34) | 54.4(20) | 2.4 | 0.12(4) | 0.14(4) | = 0.9 | 81(6) | 1.1 |
| 1.900 (2) | 1.340(40) | 1.1 | 0.16(6) | 0.15(6) | 54.0(20) | 2.0 | 0.16(4) | 0.17(4) | 0.9 | 68(5) | 1.3 |
| 2.300 (2) | 1.666(14) | 3.9 | 1.39(22) | 0.36(9) | 49.9(20) | 6.4 | 1.13(19) | 0.73(14) | 1.5 | 69(3) | 3.2 |
| 2.700 (2) | 1.965(9) | 6.6 | 5.4(8) | 0.80(14) | 40.4(20) | 2.8 | 5.0(7) | 1.24(24) | 4.0 | 53(3) | 1.5 |
| 2.800 (2) | 2.040(8) | 7.2 | 7.8(11) | 1.09(21) | 35.9(20) | 1.4 | 7.3(11) | 1.6(4) | 4.6 | 47(5) | 1.1 |
| 2.900 (2) | 2.116(7) | 14.9 | 13.4(19) | 0.90(18) | 29.9(20) | 2.3 | 12.3(18) | 2.1(5) | 5.9 | 54(4) | 1.3 |
| 3.000 (2) | 2.192(7) | | 22.7(33) | 0.90(17) | 20.5(20) | 3.1 | 20.5(30) | 3.1(8) | | 59(4) | 1.4 |

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




M. ASSUNCAO et al. PHYSICAL REVIEW C **73**, 055801 (2006)

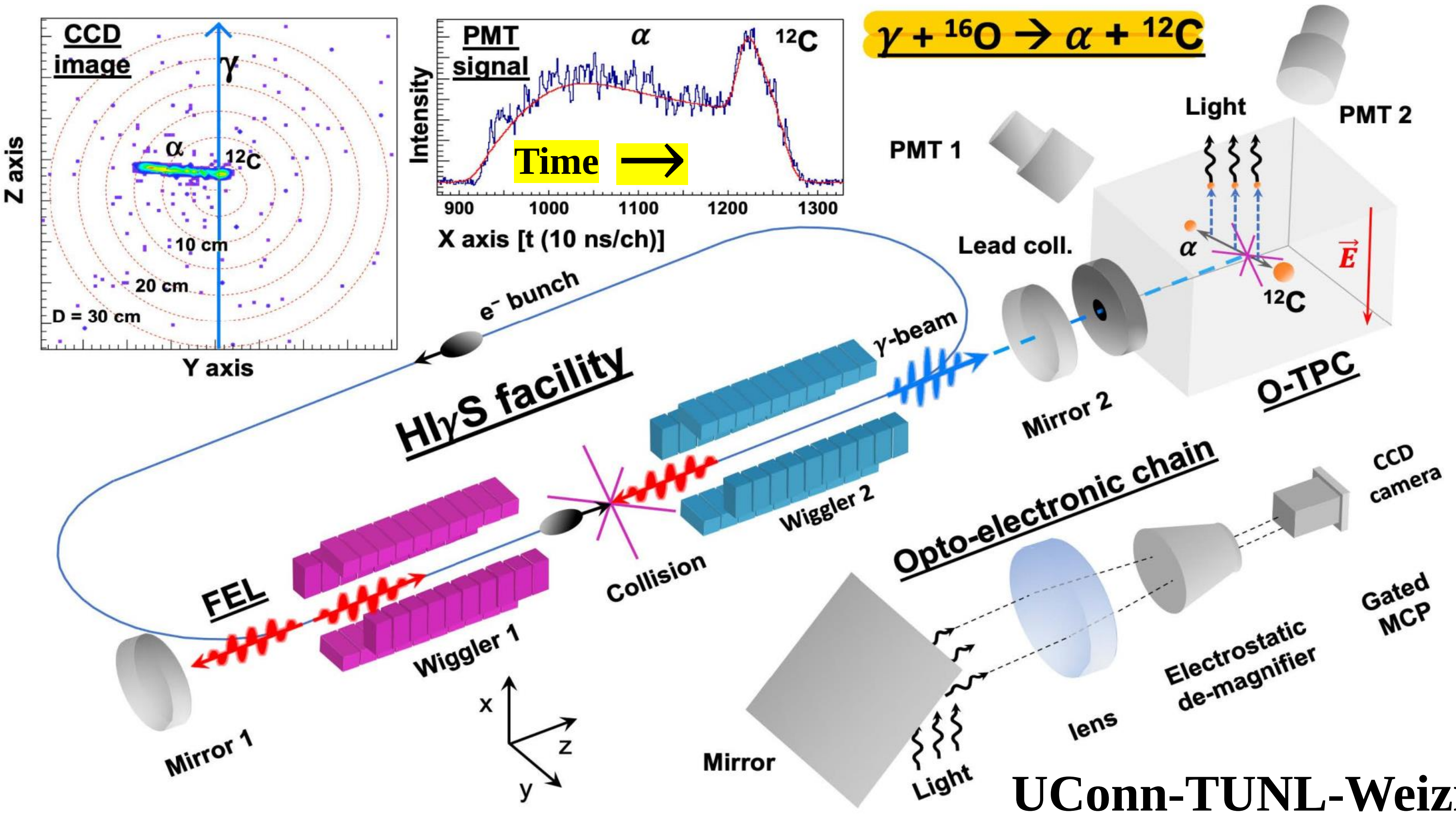
**Ecm = 1.39 MeV**



**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**
**(AT-TPC)**

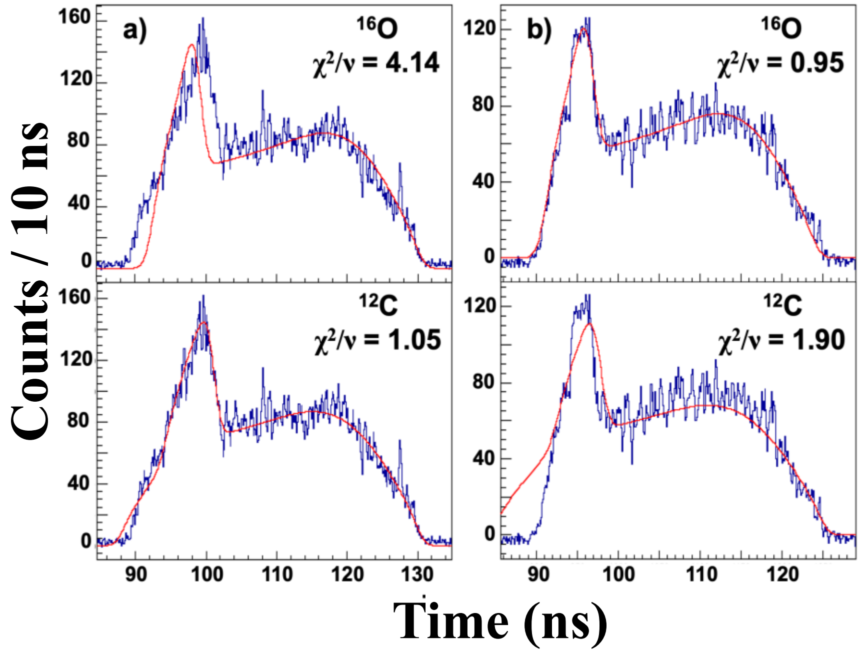
**UConn-TUNL-Weizmann-PTB (2012)**

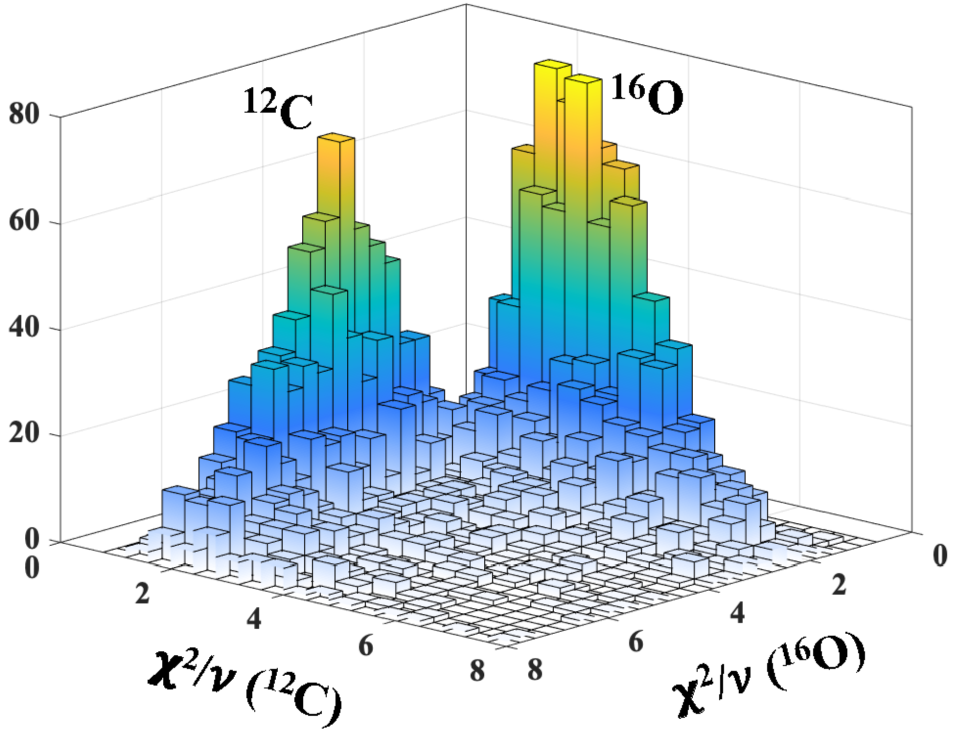
**SHU-UConn-TUNL (2021)**

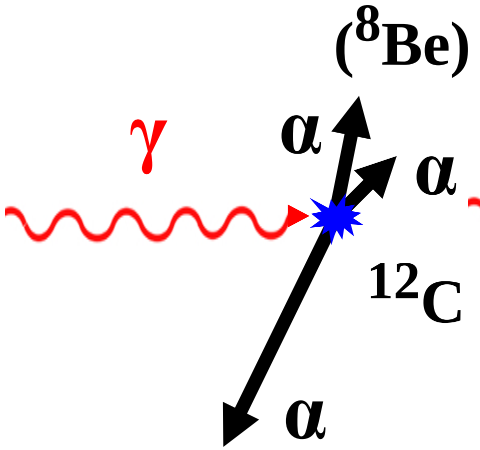
**R. Smith, M. Gai, D.K. Schweitzer, S.R. Stern and M.W. Ahmed,**
**Nature Communications, 12, 5920 (2021).**
**https://www.nature.com/articles/s41467-021-26179-x**

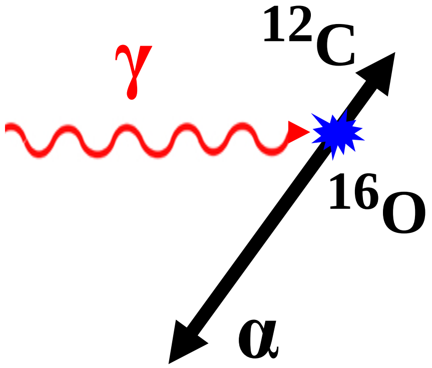
# O-TPC at HIγS at TUNL/ Duke

# Line Shape Analysis ($CO_2$ Gas)



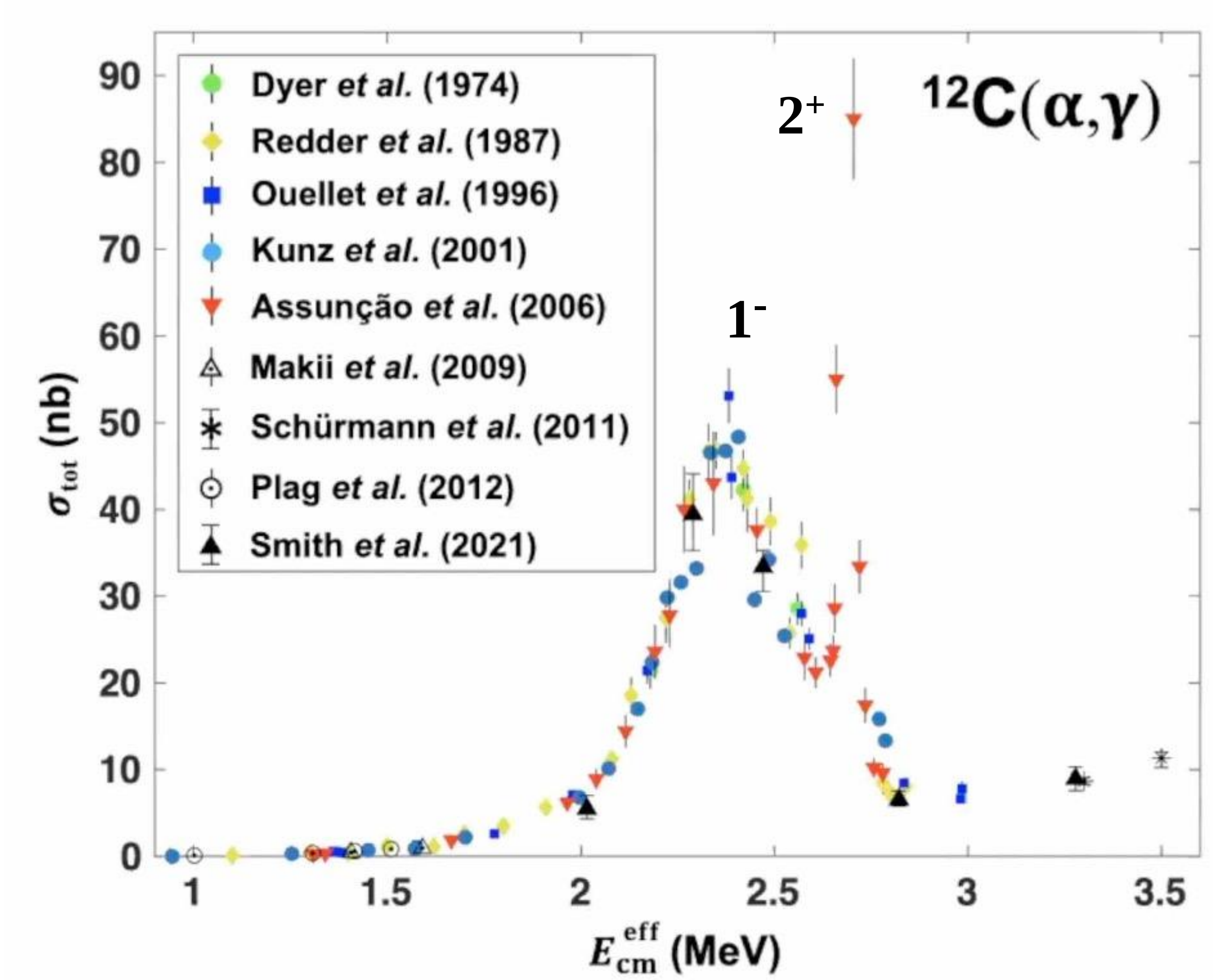




**Machine Learning**

R. Smith, M. Gai, D.K. Schweitzer, S.R. Stern and M.W. Ahmed, Nature Communications, 12, 5920 (2021).

# Total cross section

(Measure Beam Intensity @ HIγS (Relative ~2% Absolute ~11%)

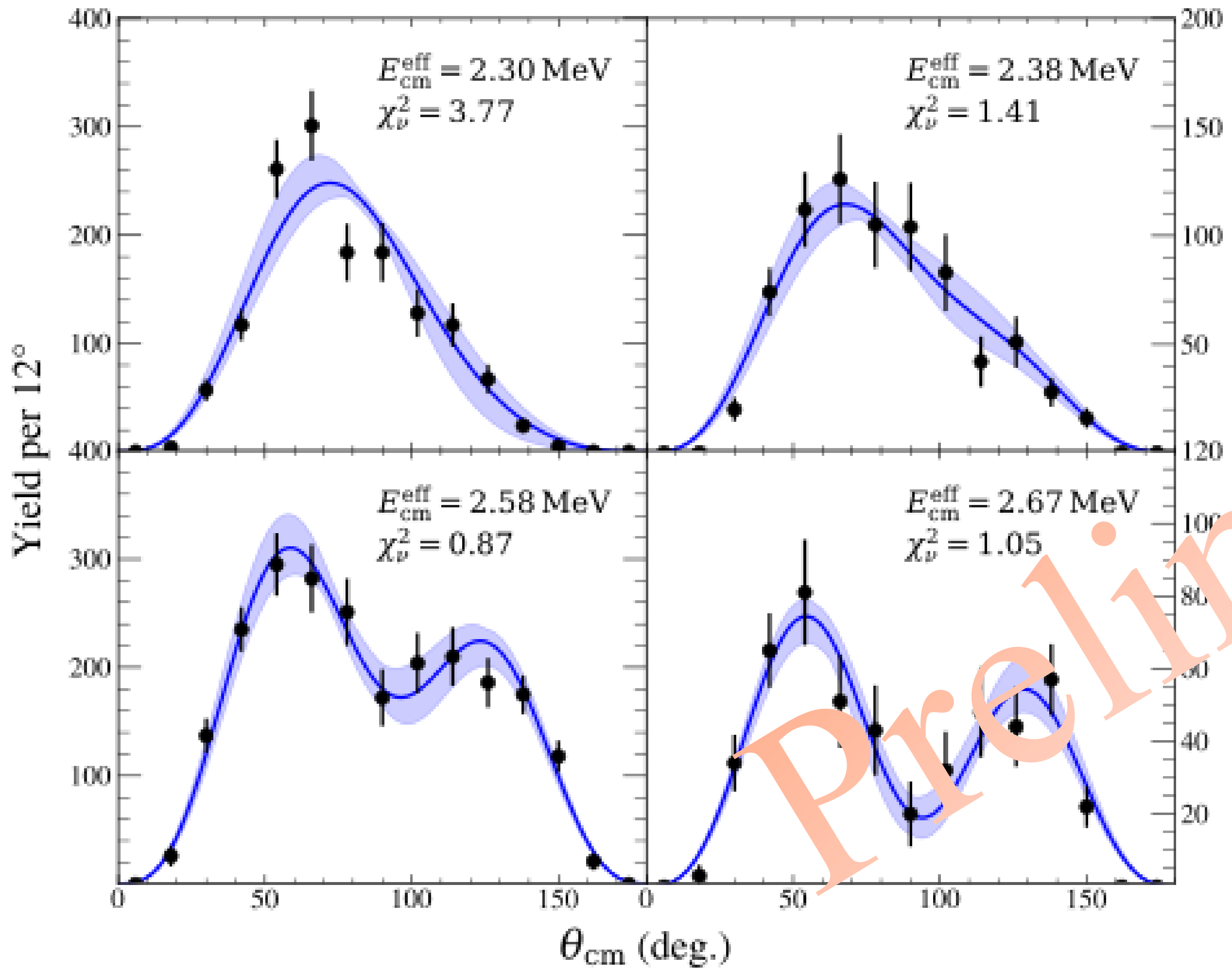


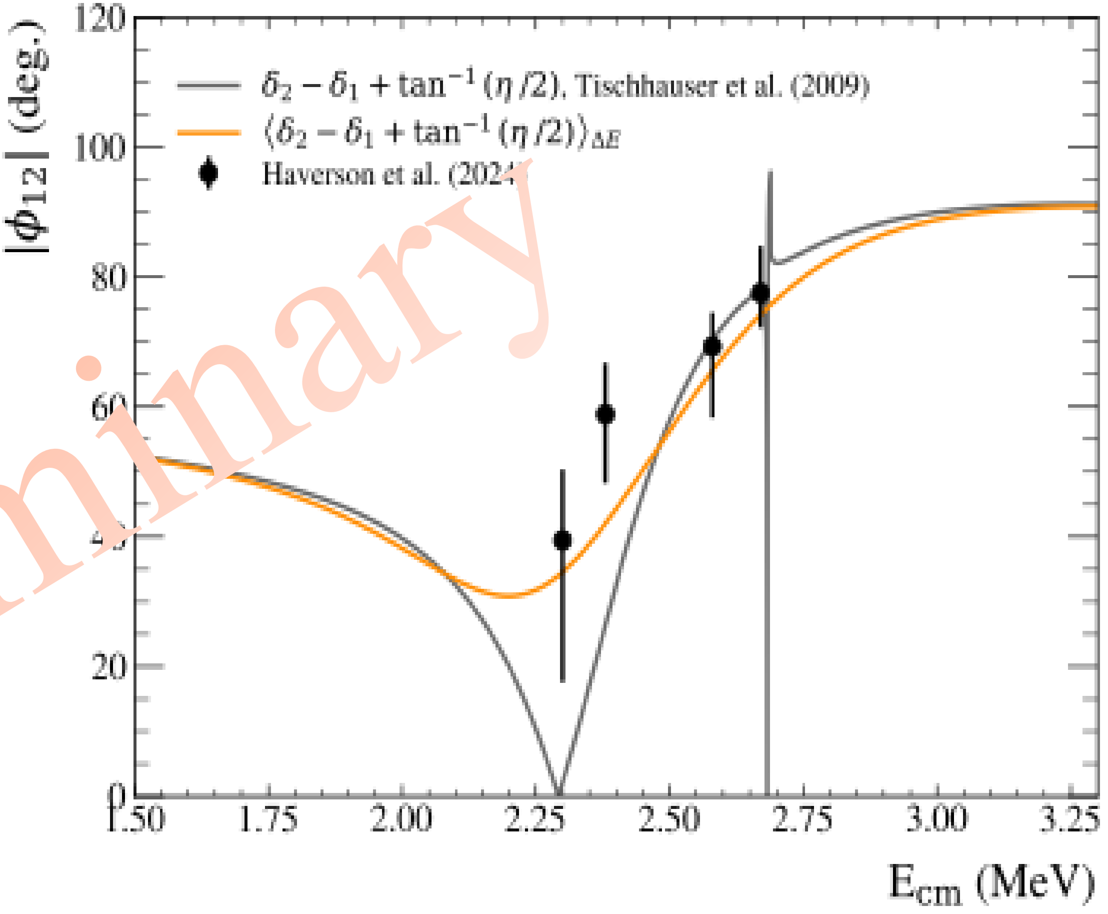
# First measurement of the *E1-E2* mixing phase ($\phi_{12}$) that agrees with Unitarity

**O-TPC data measured with $N_2O$ gas, UConn-TUNL (2012)**

**Analyses by <u>Kristian C.Z. Haverson</u> @ SHU, UConn-SHU (2024)**

**(Complete angular distributions measured at 17 angles)**



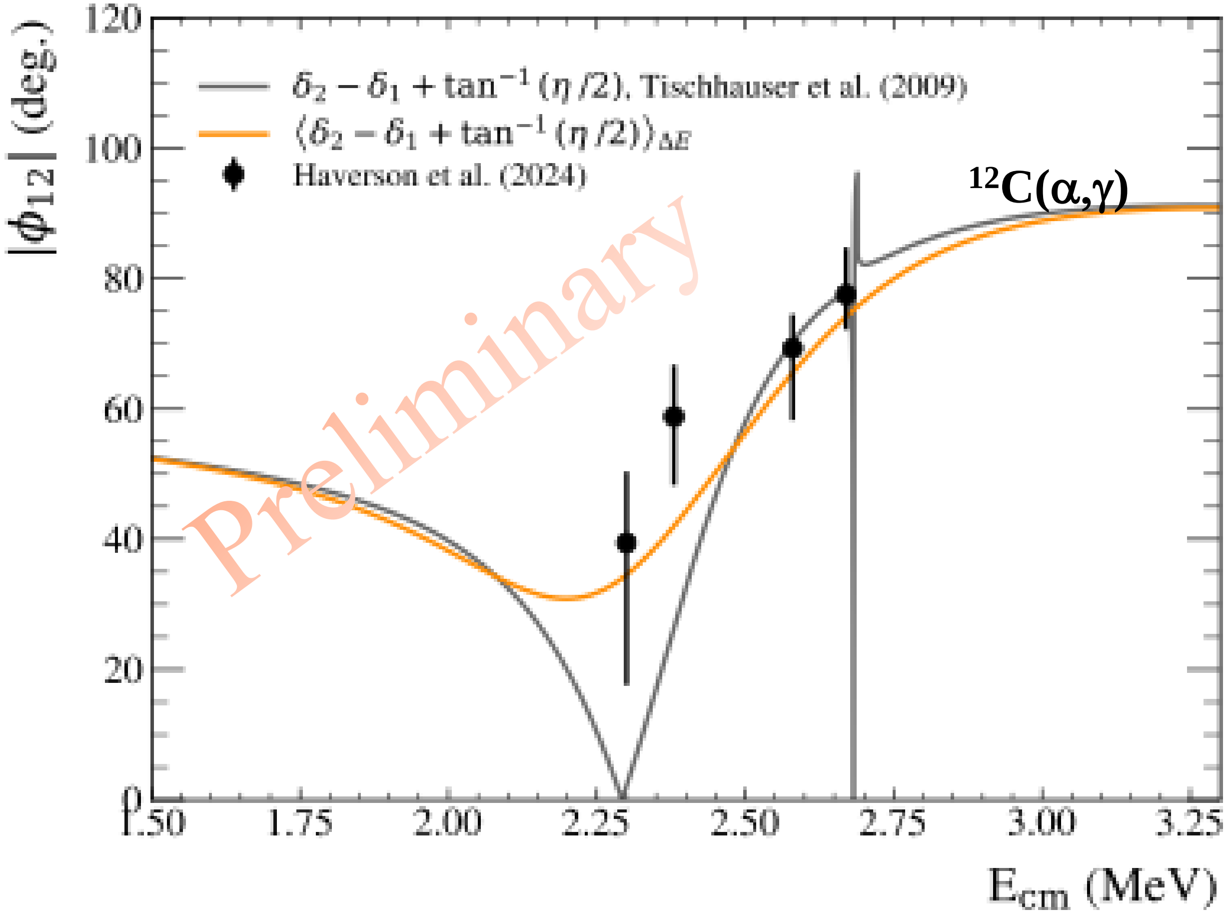
# A new criteria for judging data:

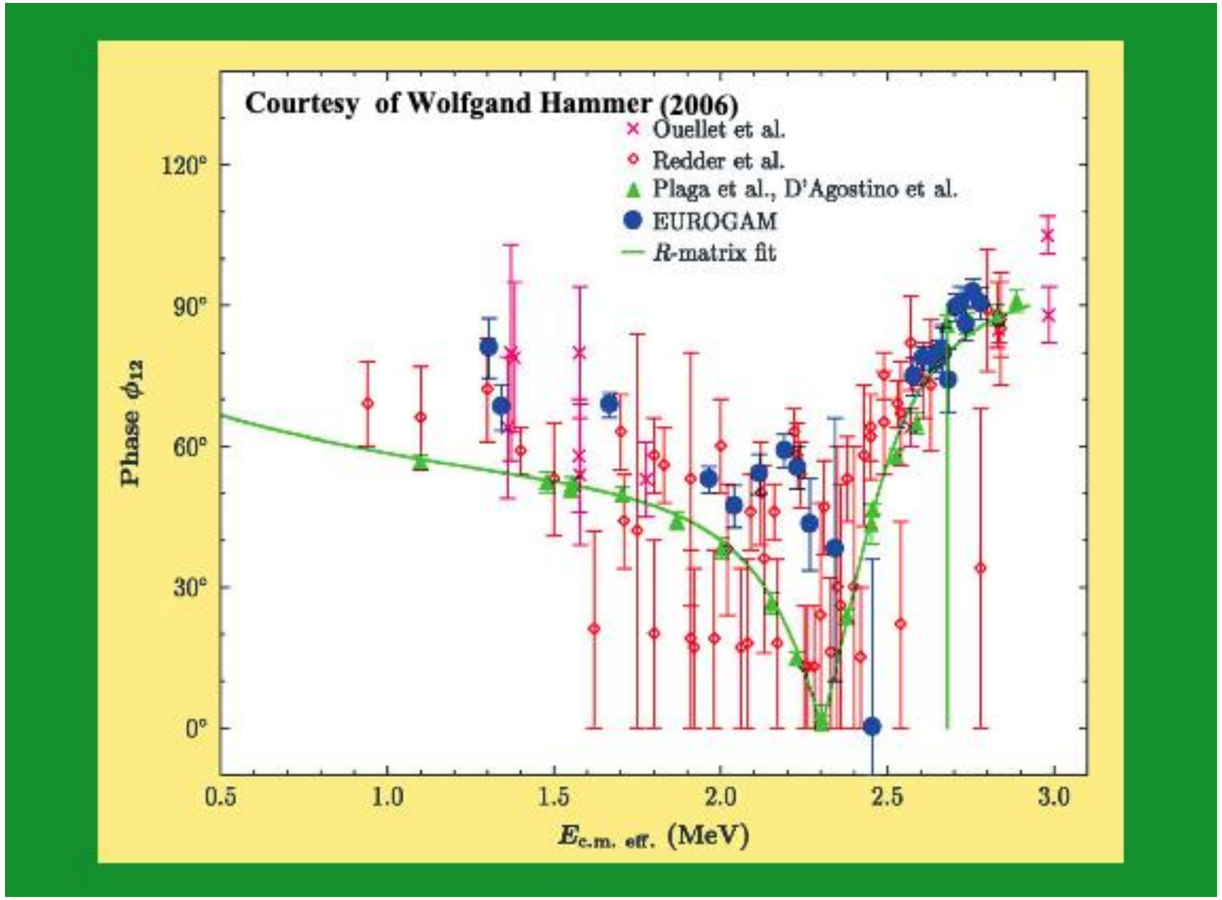
## Why use data that disagree with Quantum Mechanics

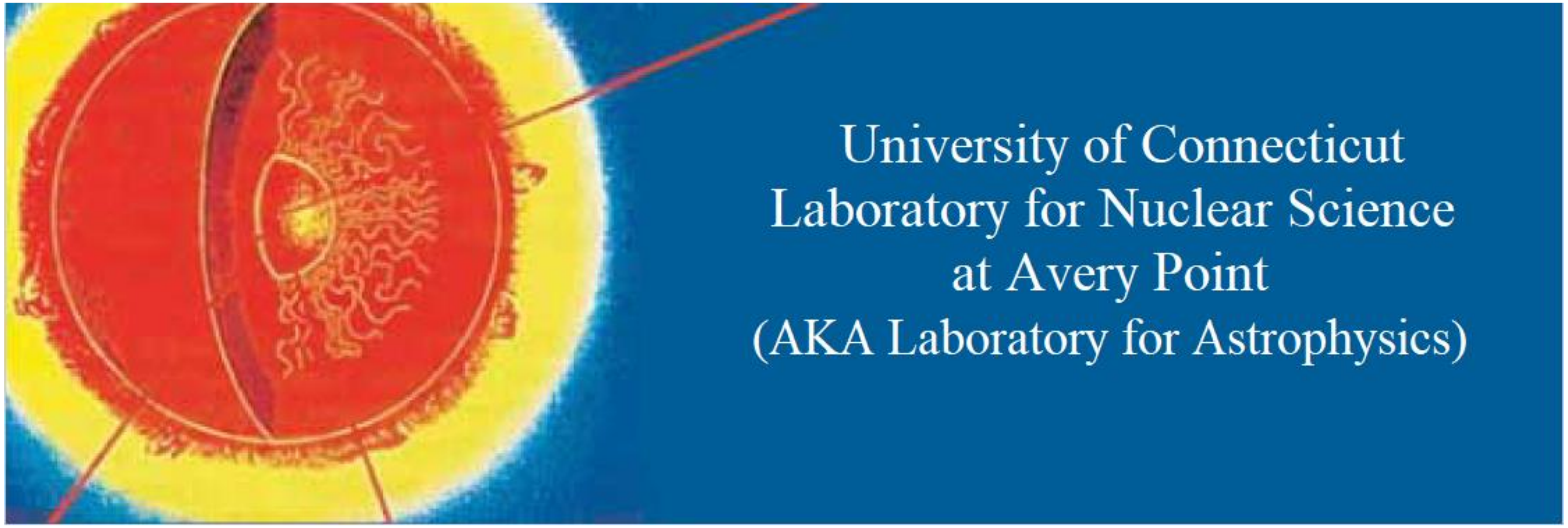
## Desperately need New Data

**O-TPC data**

**World data**






## Conclusions

**TPC data of unprecedented quality:**

1. Low background, if any
2. Measurement in one detector
3. Complete angular distribution measured in detail
   (angular distributions measured at 15-25 bin-angles)

1. First Physics Result, Agreement with Unitarity
2. New Criteria for Judging Data (Agreement with QM)
3. Further data measured at HIγS, Warsaw TPC, 2022