Nuclear Astrophysics With O-TPCs at the HIγS *

Moshe Gai, University of Connecticut

moshe.gai@uconn.edu http://Astro.uconn.edu

1. Oxygen Formation in Stellar Helium Burning/ the $^{12}C(\alpha,\gamma)$ Reaction
2. World Data
3. The HIγS Measurement with O-TPC
4. (Not covered) Data with Warsaw TPC @ HIγS, 2022

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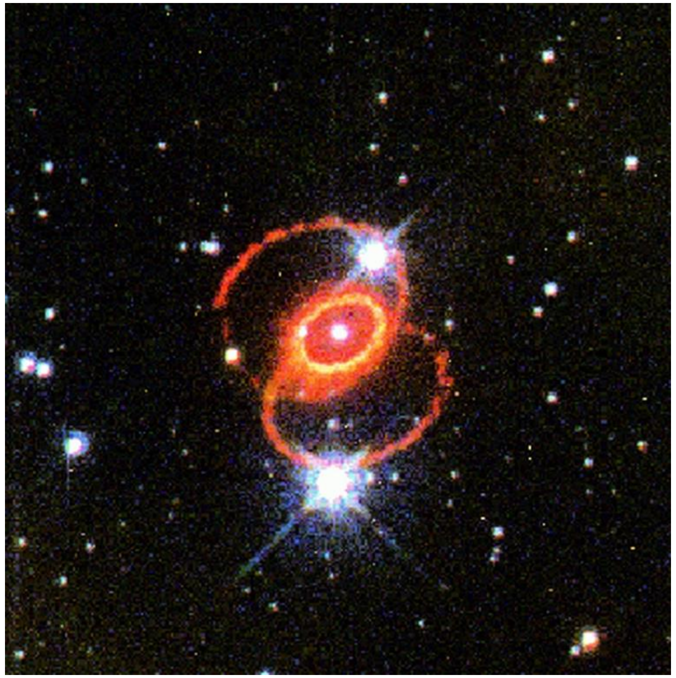
NN 2024, Whistler, BC, Canada, August 19, 2024

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



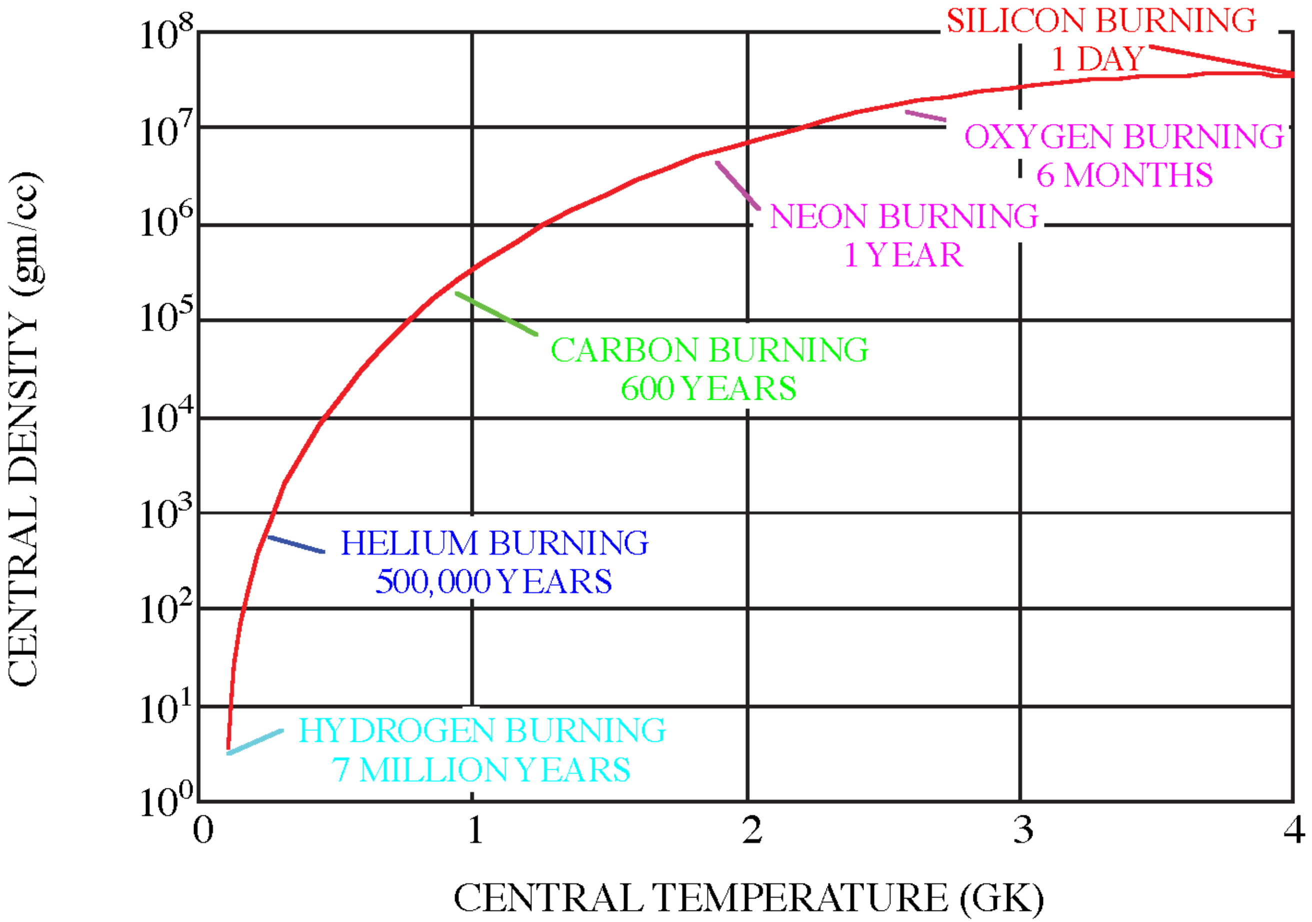
SN1987A: First MMA, Type II Supernova
Observed Neutrinos 4 HR Later Light Curve (EM)
Progenitor: Sanduleak −69 202 (Sk -69 202) Blue Supergiant ~17M$_\odot$
Is SN1987A: Black Hole or Neutron Star?
Determined by C/O, But = ???
Fusion Reaction: The $^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$ [$^{12}C(\alpha,\gamma)^{16}O$]

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

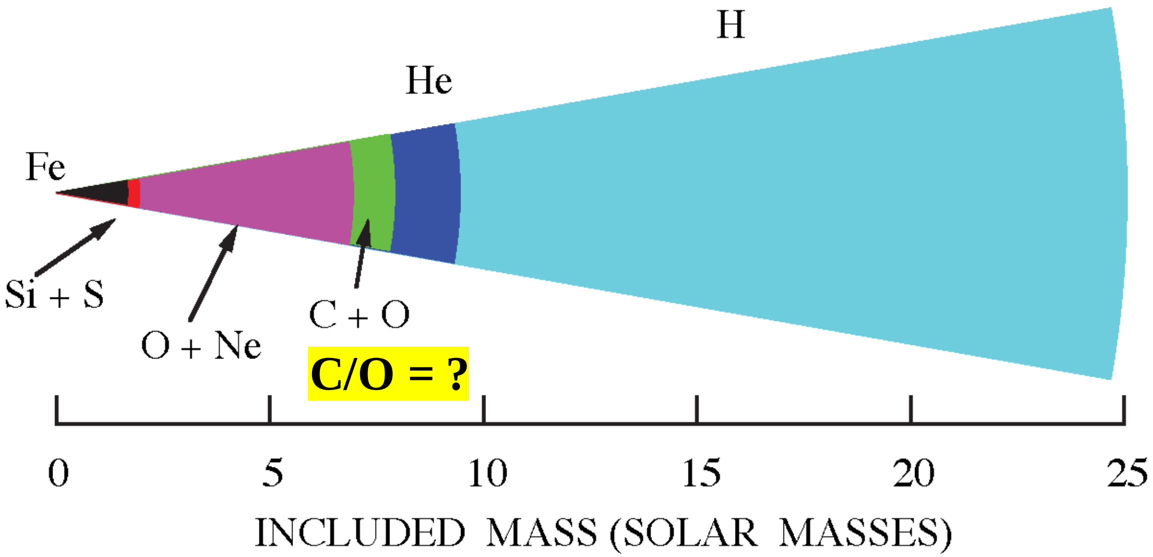
Helium Burning: $3\alpha \rightarrow ^{12}C$ (~11%) "Hoyle State"
$^{12}C(\alpha,\gamma)^{16}O$ @300 keV
C/O = ?

Two partial waves:
p-wave $S_{E1}(300)$
d-wave $S_{E2}(300)$ *E1-E2* Mixing Phase Angle (ϕ_{12})

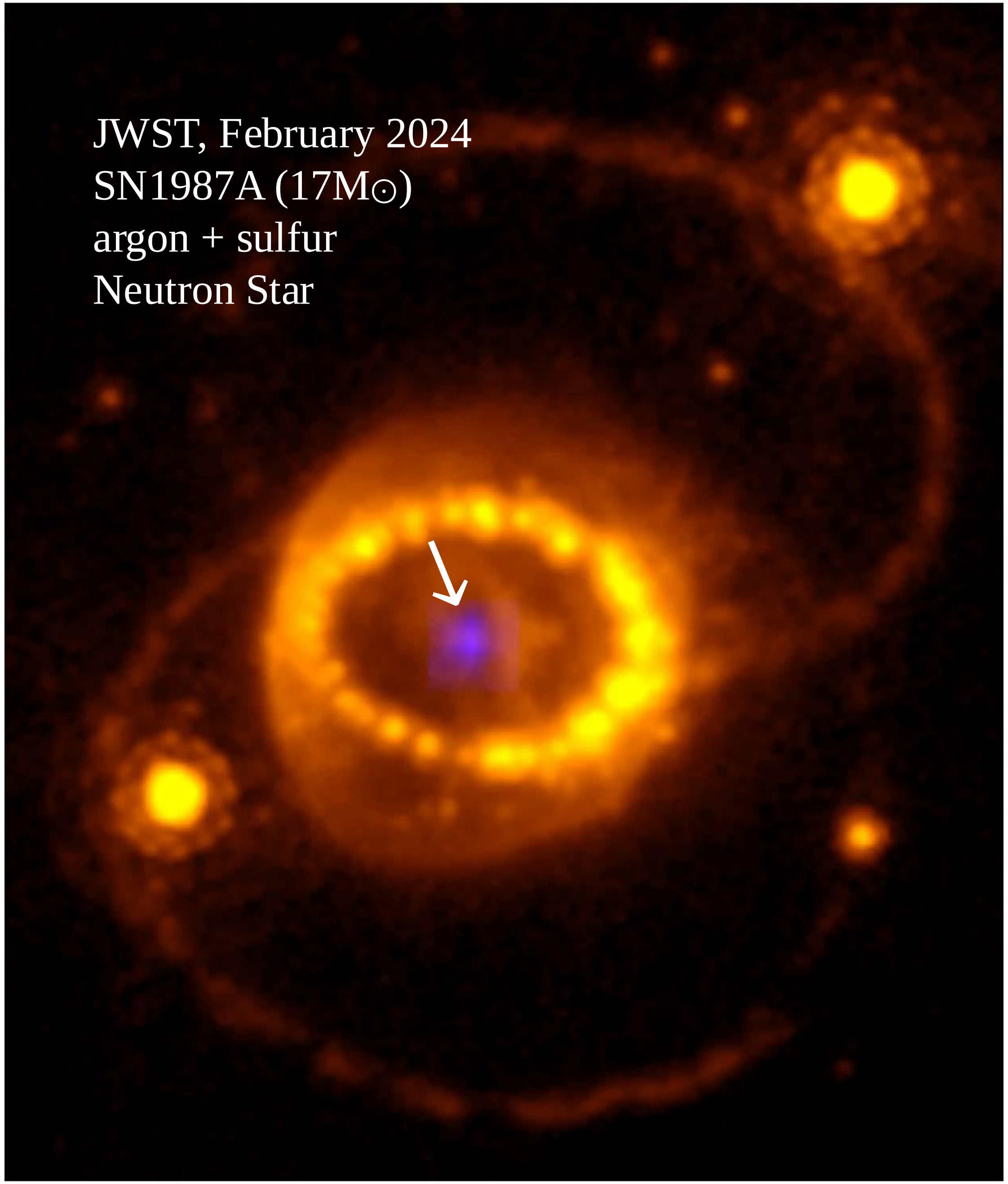
Type II (Core Collapse) Supernova



C/O > 1 Neutron Star
C/O < 1 Black Hole



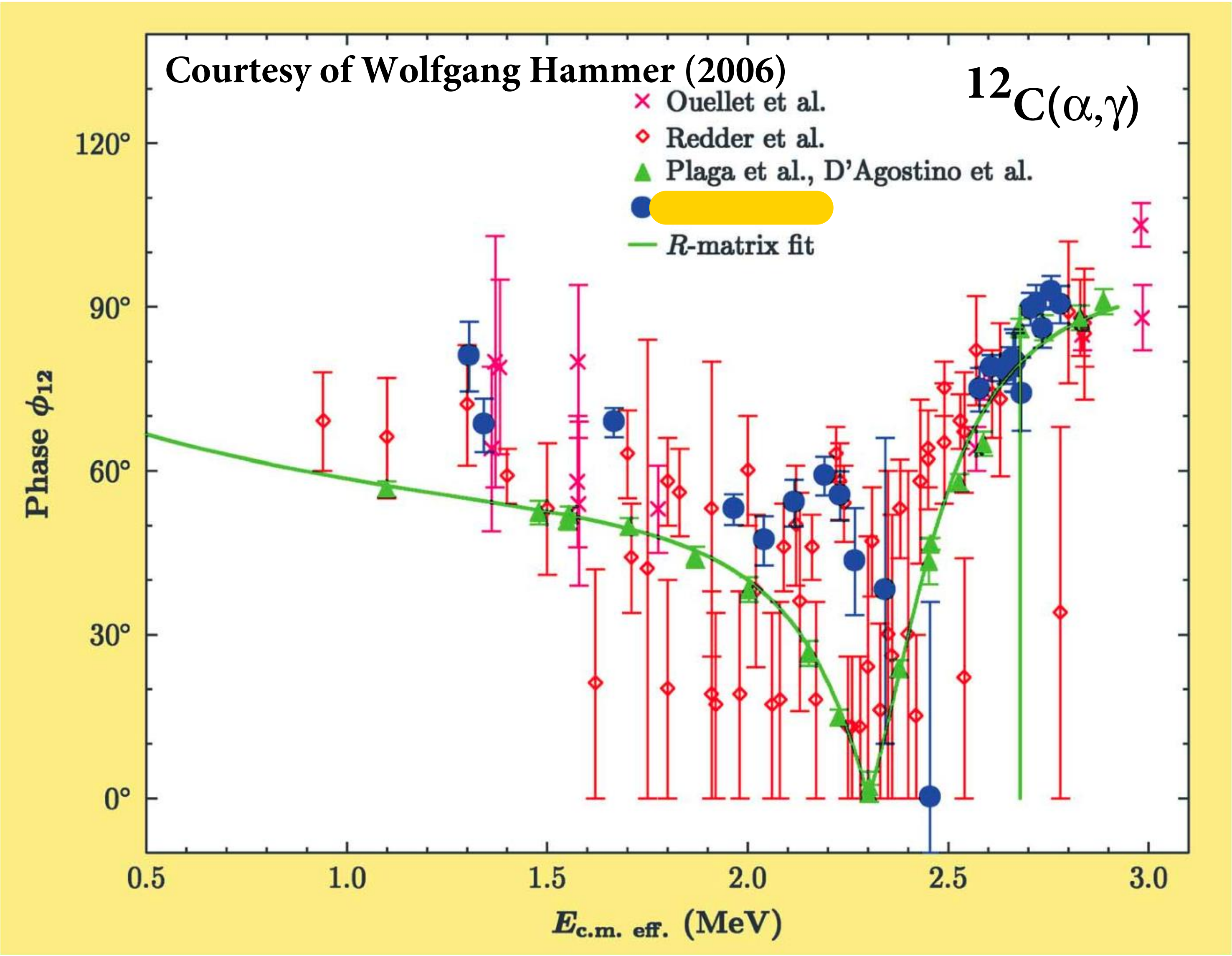
Bethe & Brown, Scientific American 1985
M. Gai, Nucl. Phys. A928, 313 (2014) (x10 Gai)



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 (ϕ_{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.*

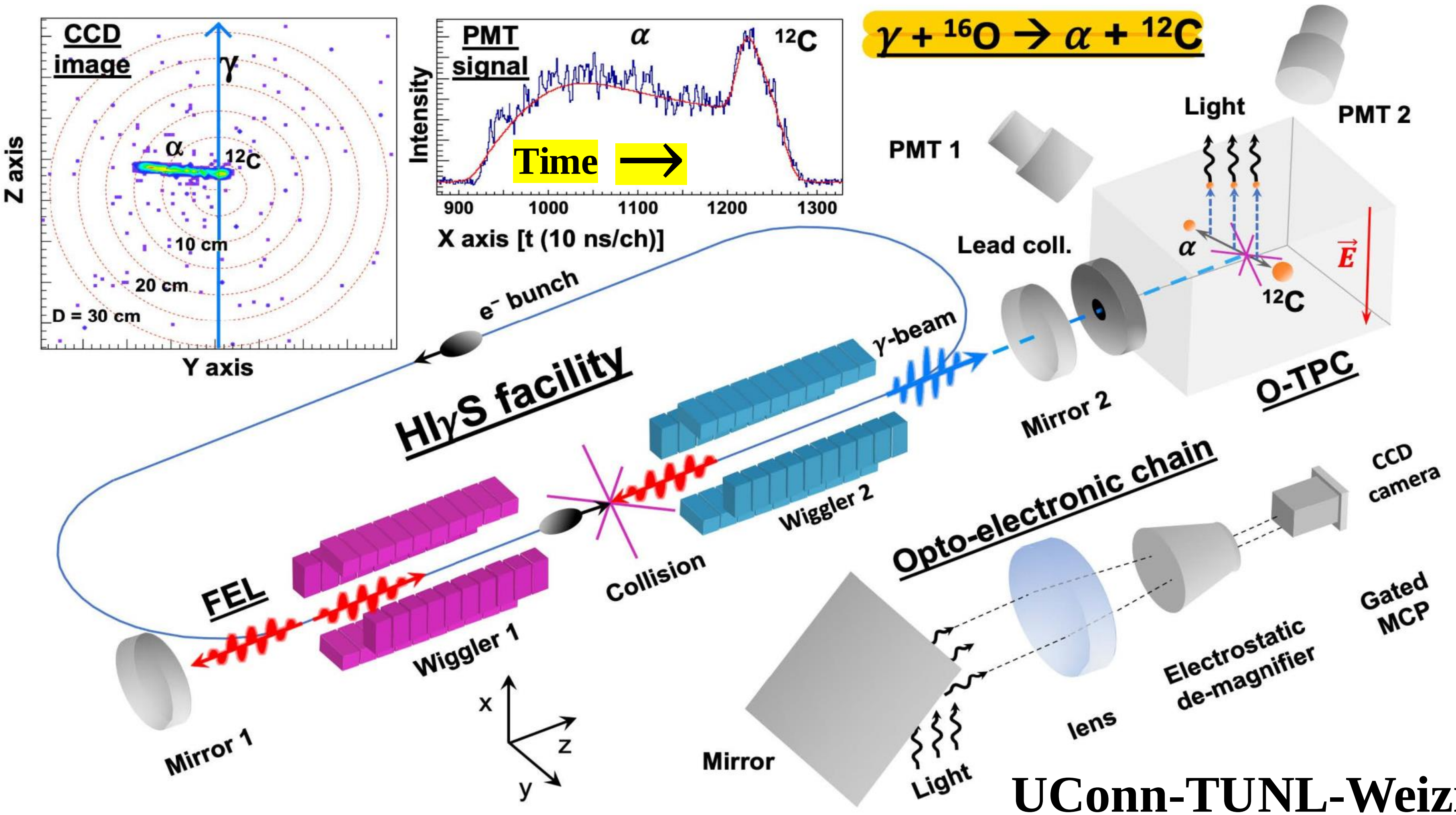
TABLE I. Final results of the present $^{12}C(\alpha, \gamma)^{16}O$ experiment for the $E1$ and $E2$ capture γ-ray cross sections and their relative phase ϕ_{12}. $E_{\alpha,\mathrm{lab}}$ is the uncorrected α-particle energy; $E_{\mathrm{c.m.\,eff.}}$ is the effective c.m. energy calculated as explained 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 $E_{\mathrm{c.m.\,eff.}}$ 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 ϕ_{12} was fixed according to Eq. (4.7) with the phases taken from elastic scattering [31,32]. The corresponding χ^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 χ^2 is the reduced value for six degrees of freedom (nine angles and three free parameters for the fit).

$E_{\alpha,\mathrm{lab}}$ (MeV)	$E_{\mathrm{c.m.\,eff.}}$ (MeV) (I)	(II)	2-parameter fit, phase fixed by Unitarity σ_{E1} (nb)	σ_{E2} (nb)	ϕ_{12} (deg)	χ^2	3-parameter fit, phase free σ_{E1} (nb)	σ_{E2} (nb)		ϕ_{12} (deg)	χ^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

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)

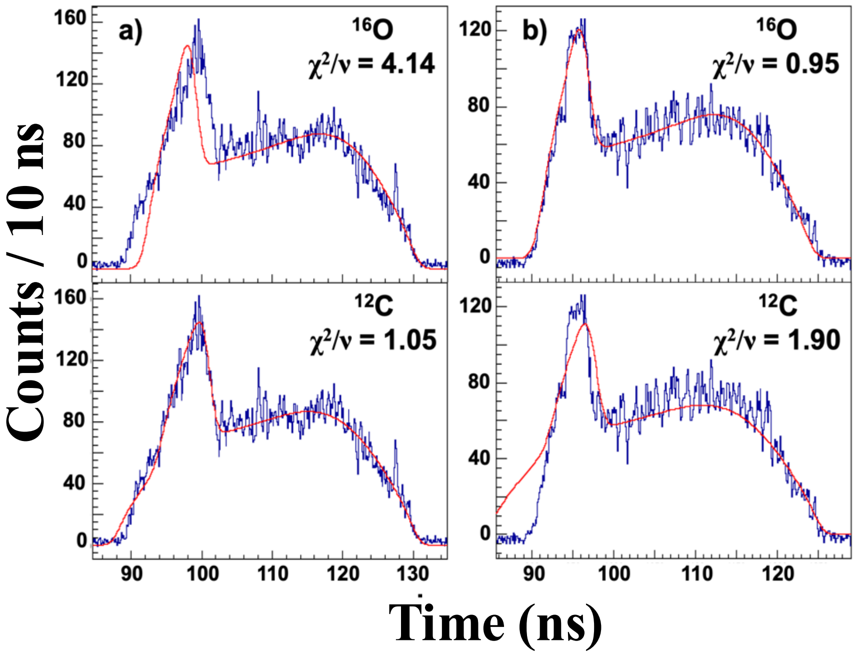
UConn-TUNL-Weizmann-PTB (2012)

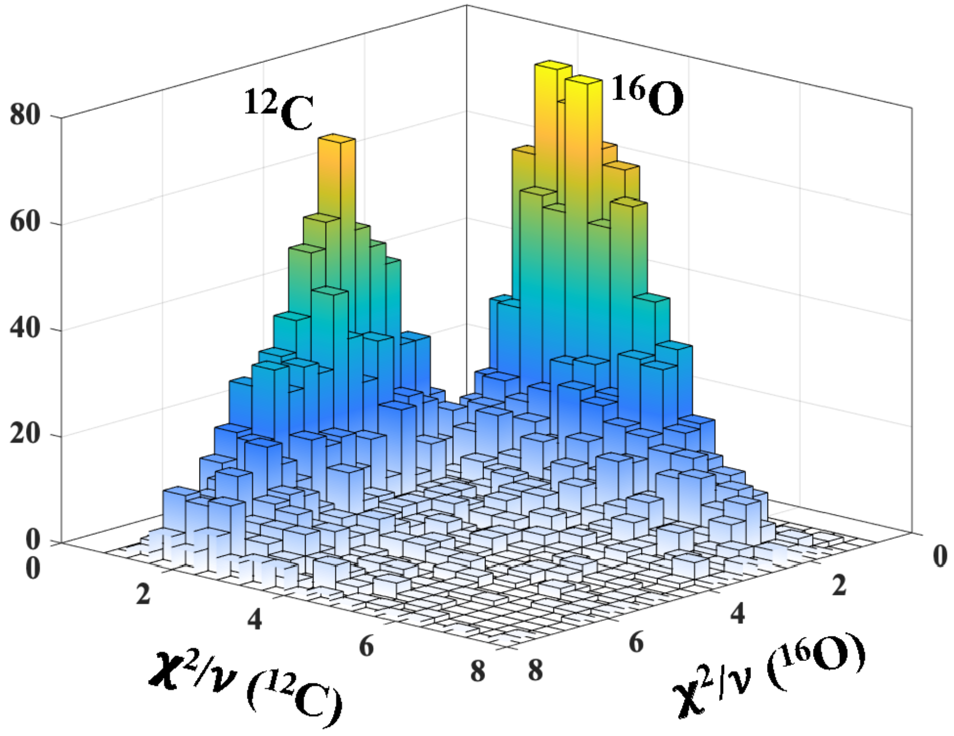
SHU-UConn-TUNL (2021)

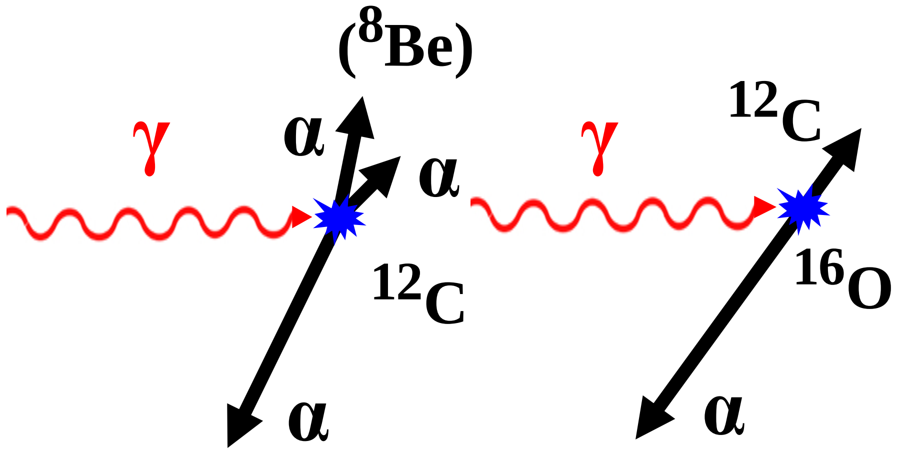
R. Smith, M. Gai, D.K. Schweitzer, S.R. Stern and M.W. Ahmed,
Nature Communications, 12, 5920 (2021).
https://www.nature.com/articles/s41467-021-26179-x

O-TPC at HIγS at TUNL/ Duke

Line Shape Analysis (CO_2 Gas)





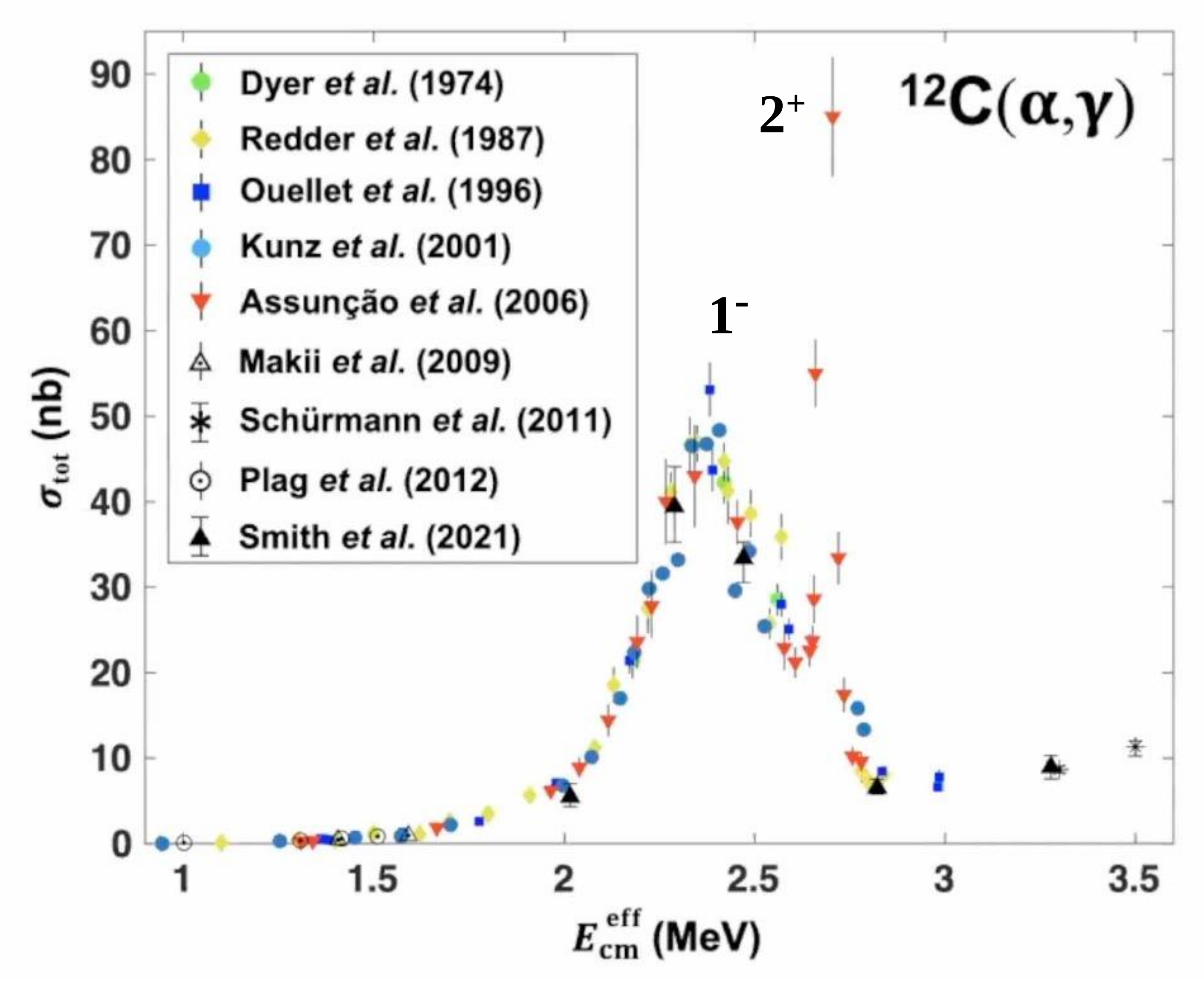


Machine Learning

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 (Stat ~2% Syst ~11%)

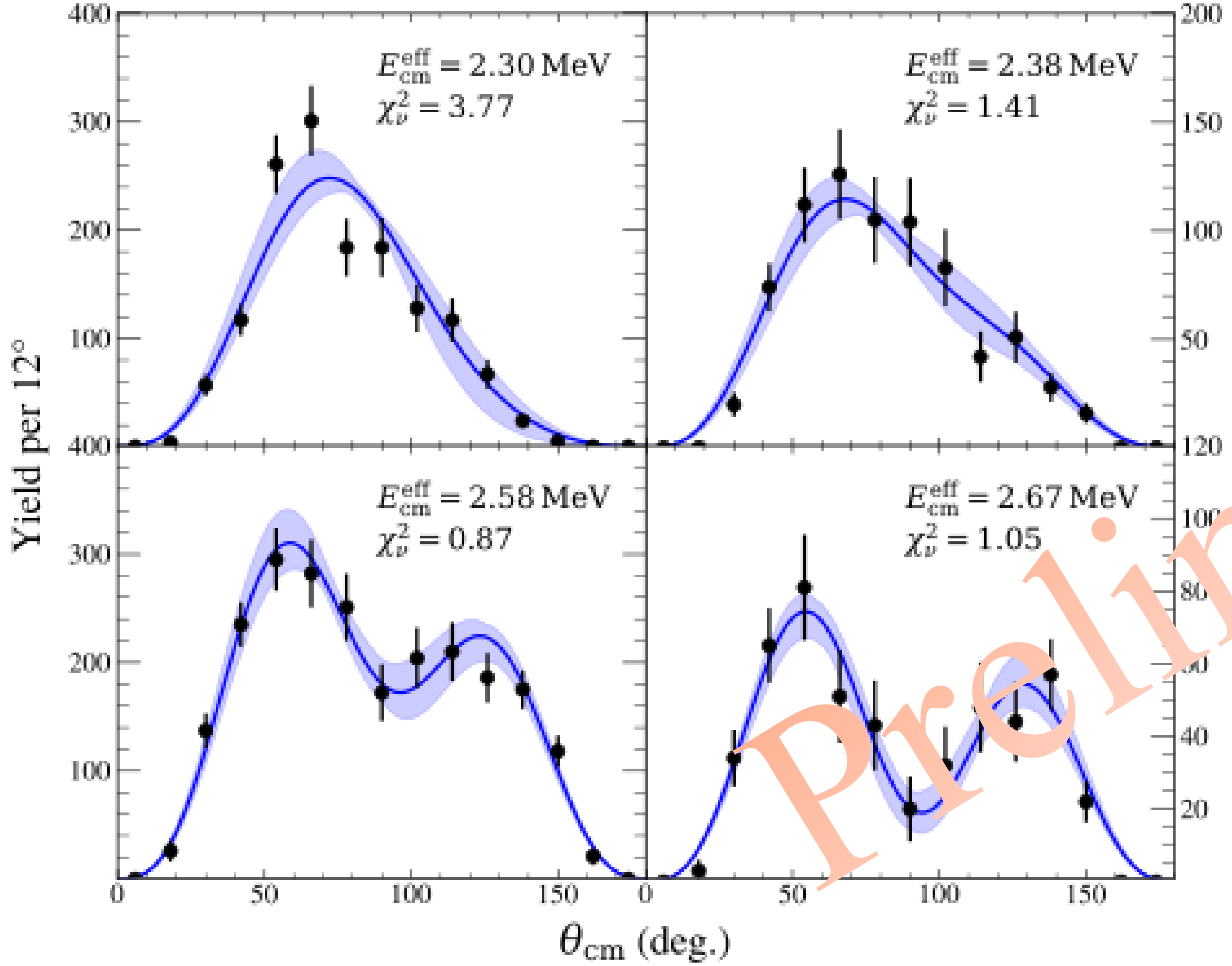


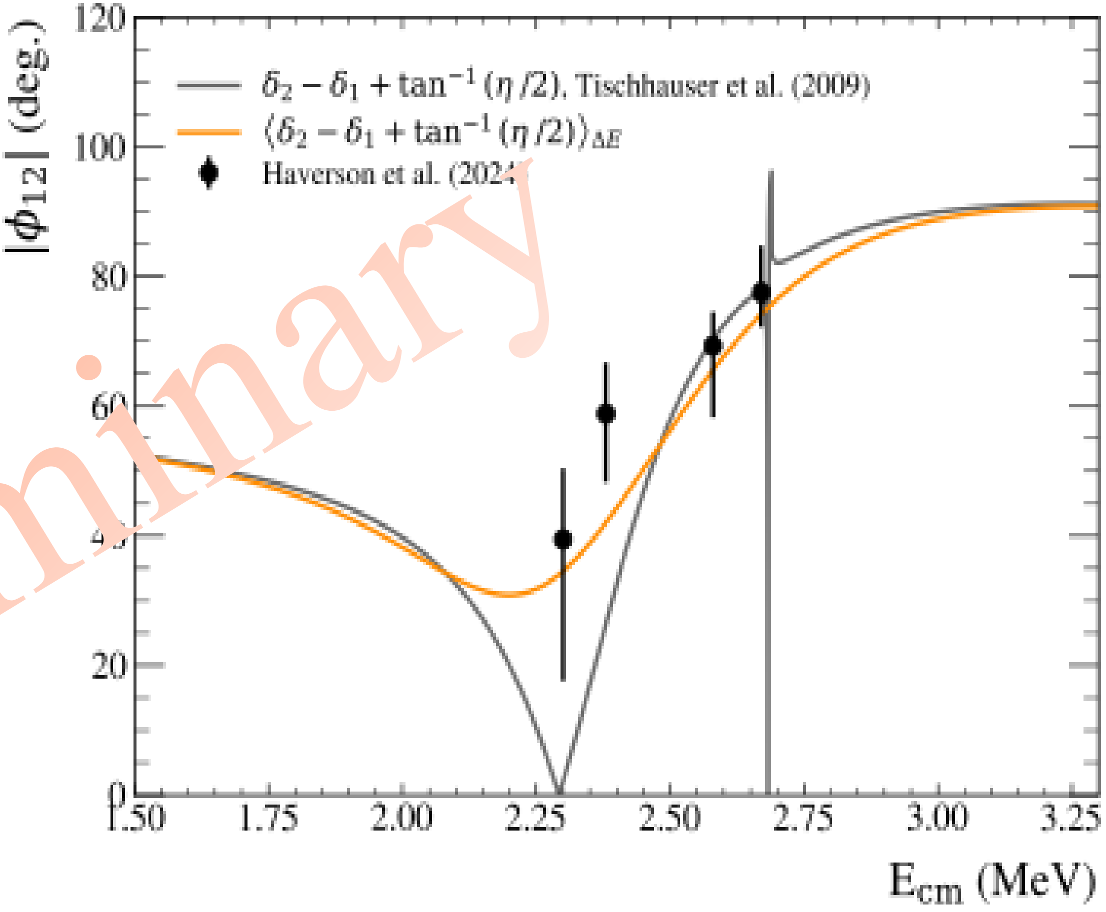
First measurement of the *E1-E2* mixing phase (ϕ_{12}) that agrees with Unitarity

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)





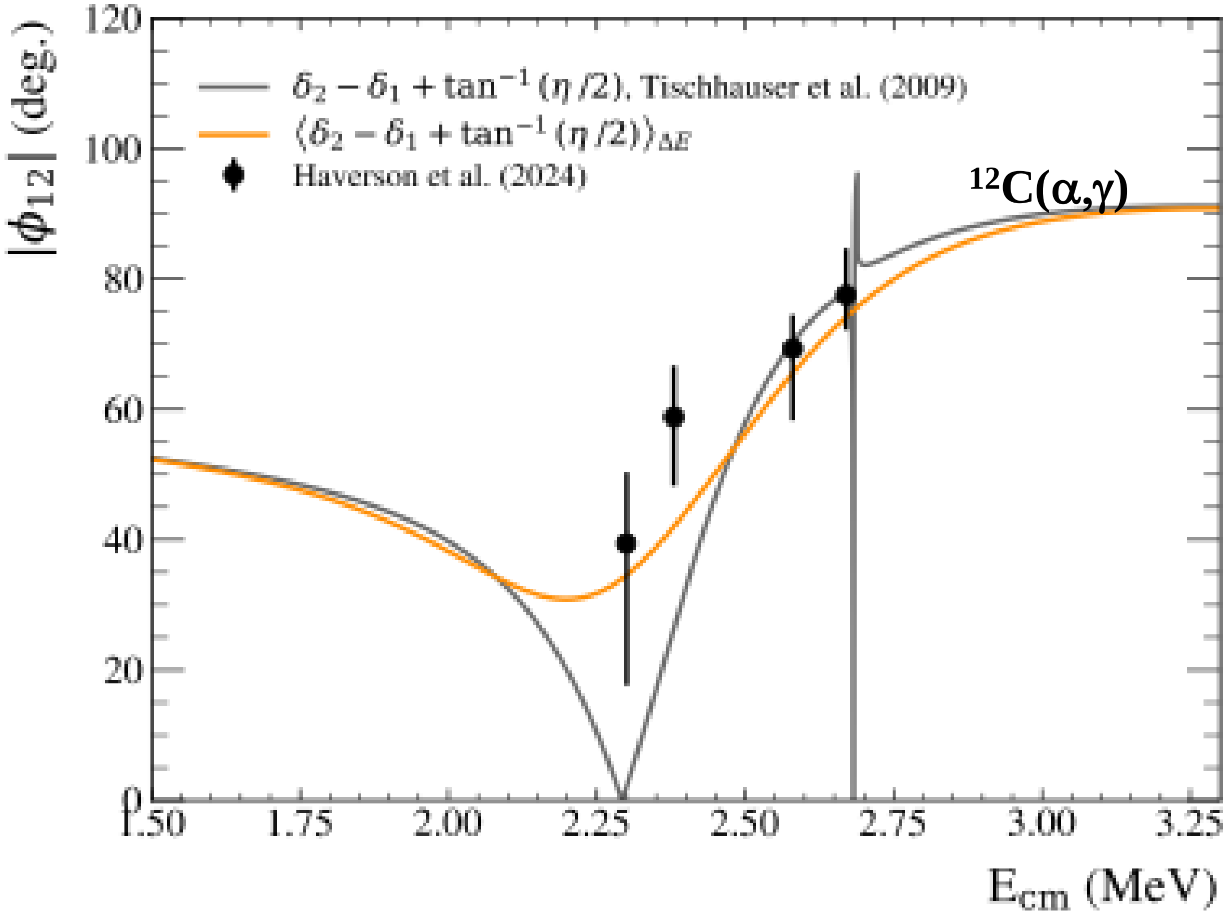
A new criteria for judging data:

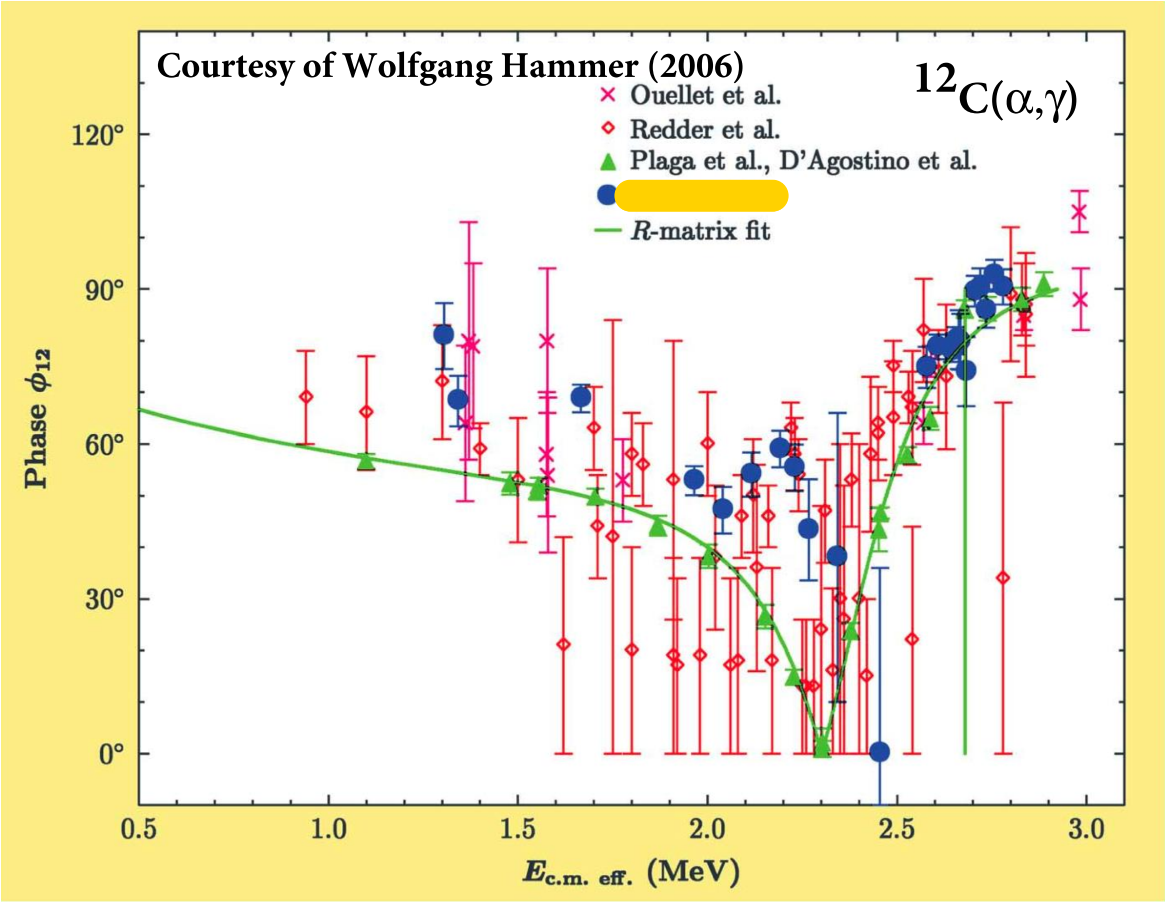
Do not use data that disagree with Quantum Mechanics

Desperately need New Data

O-TPC data

World data





The Warsaw Electronic Readout TPC at HIγS, 2022

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