Precision measurement of the $^{12}C(\alpha,\gamma)$ reaction with gamma-beam and an O-TPC

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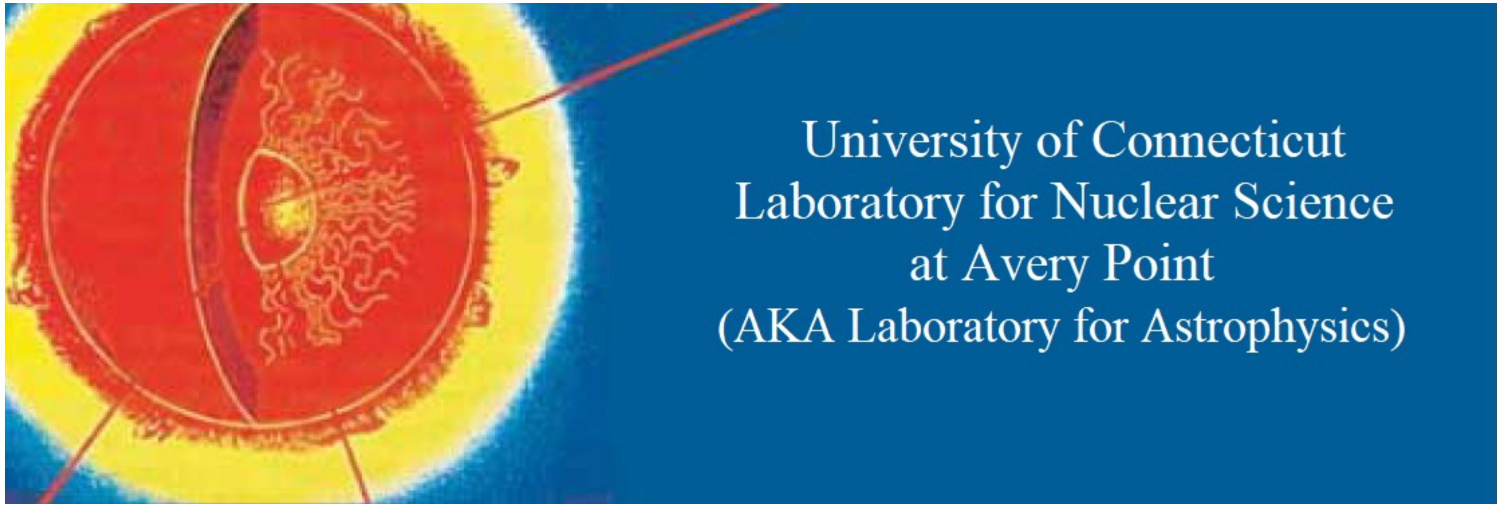


1. **The Science**
2. **The Problem [$^{12}C(\alpha,\gamma)$ Reaction]**
3. **Gamma-Beams: HIγS (and ELI-NP)**
4. **The O-TPC Detector**
5. **The Precision Measurement (Robin Smith)**

ECT*, KRINA virtual workshop, June 22-23, 2021, Online

W.A. Fowler; Rev. Mod. Phys. 56, 149 (1984)

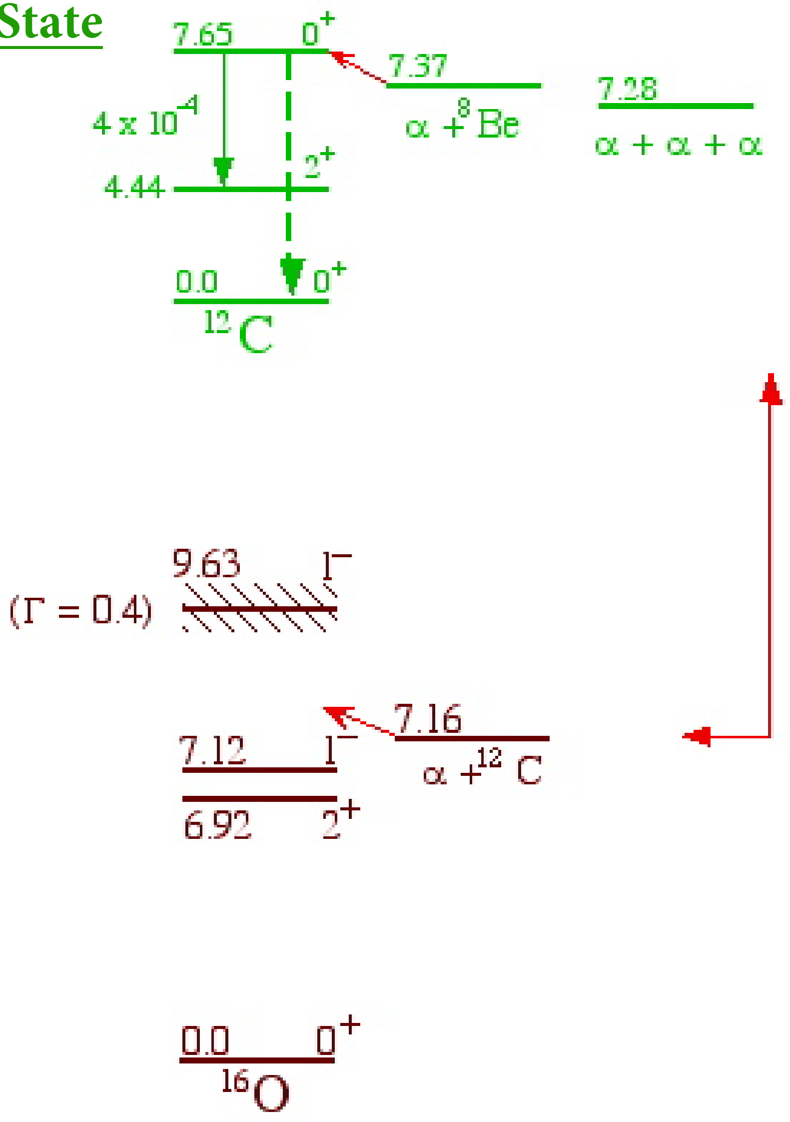
$^{12}C(\alpha,\gamma)^{16}O$: "of Paramount Importance"

C/O = ???

HELIUM BURNING IN (MASSIVE) STARS

I. $3\alpha \longrightarrow {}^{12}C + \gamma$

Hoyle State



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

II. $\alpha + {}^{12}C \longrightarrow {}^{16}O + \gamma$

1. Energy
2. $^{12}C/^{16}O$
3. Heavier Elements

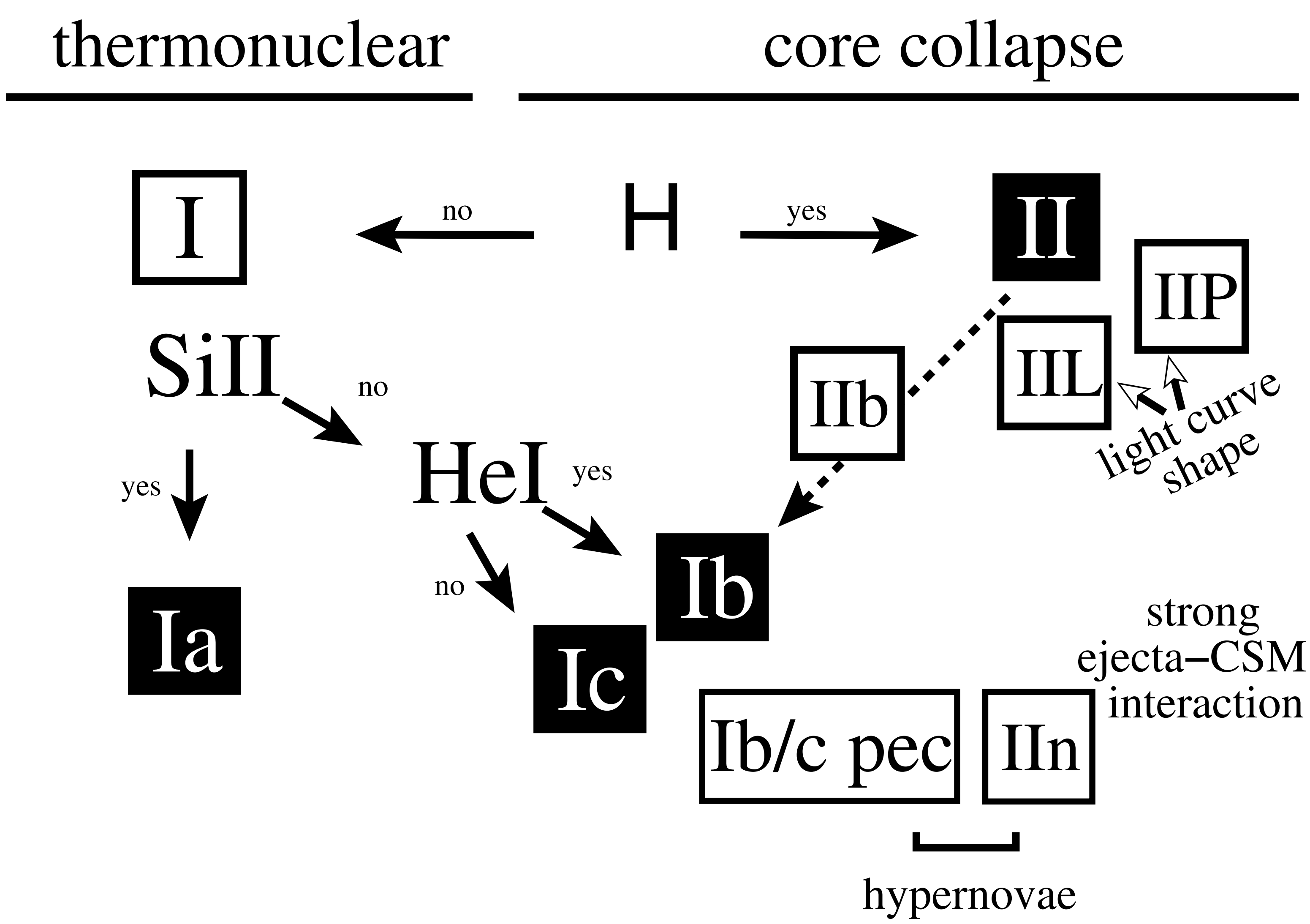
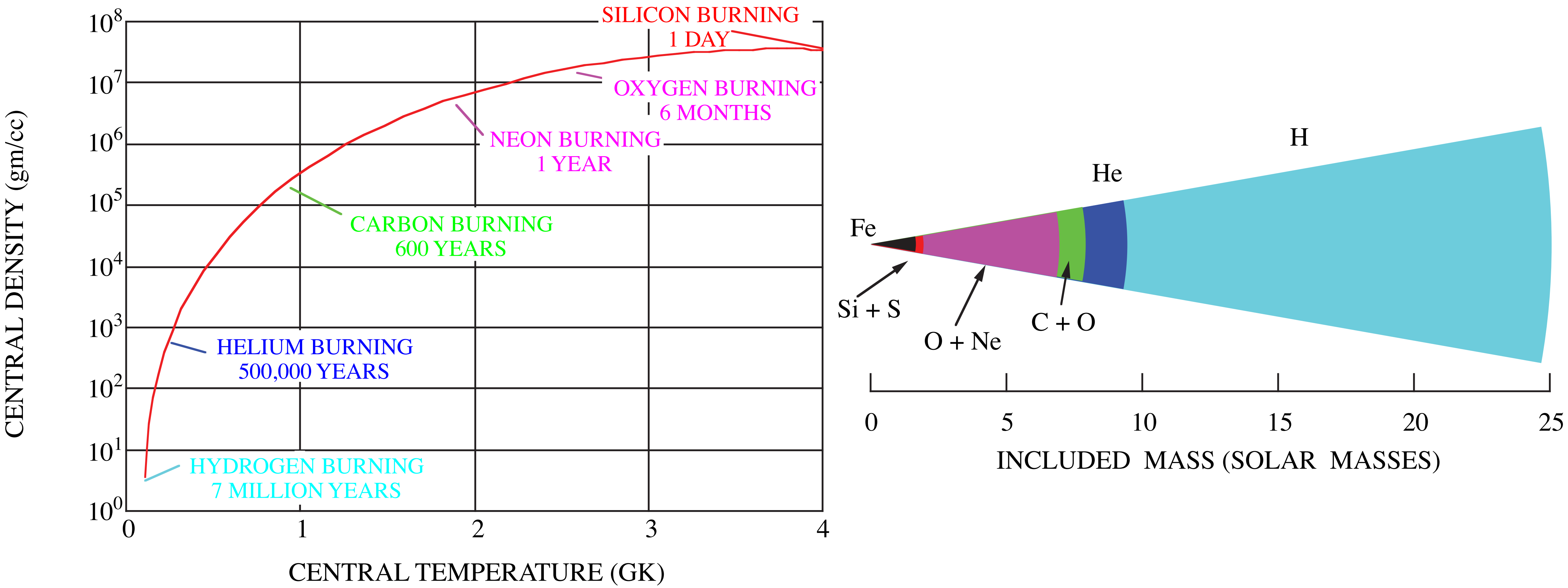
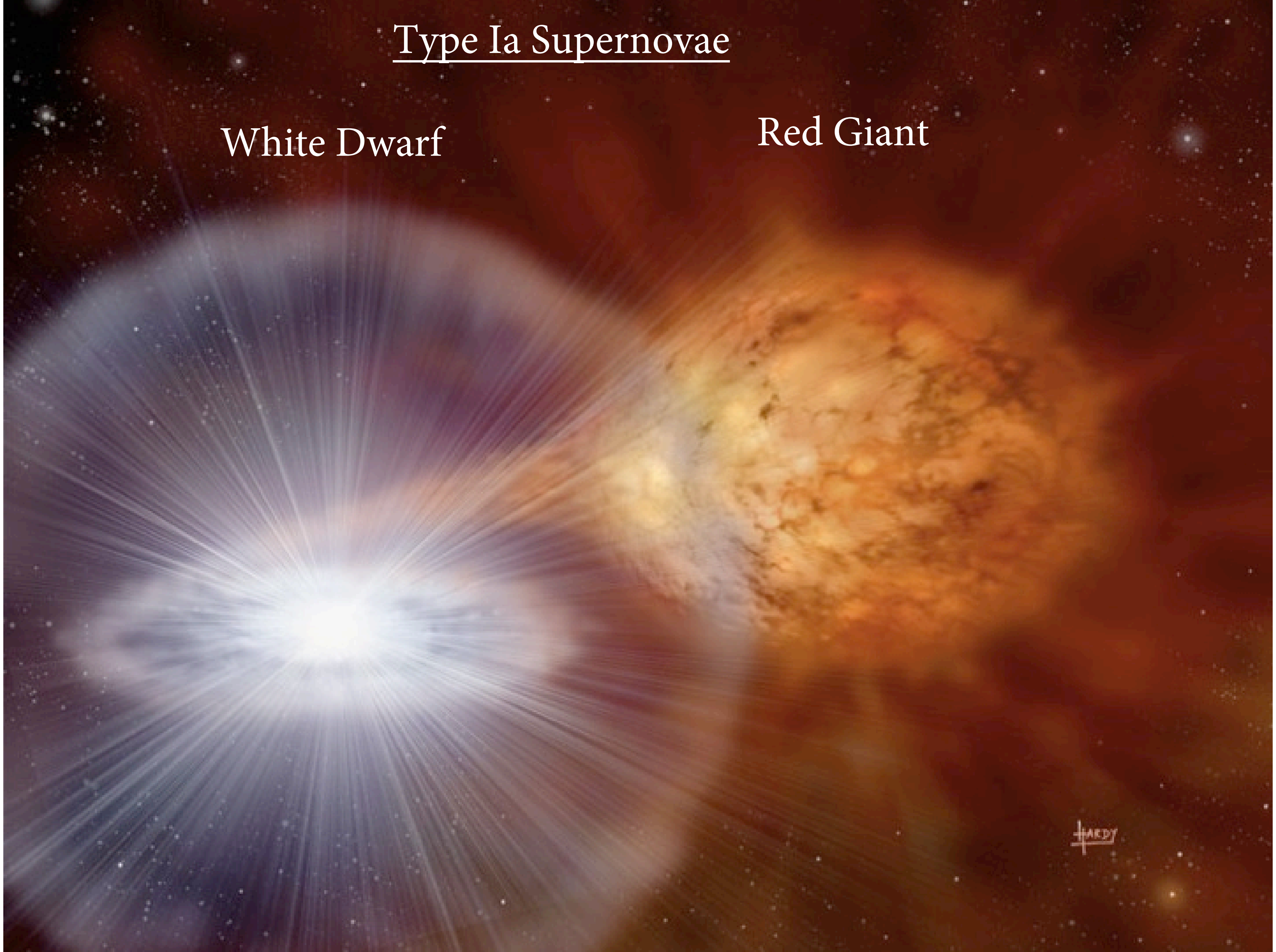


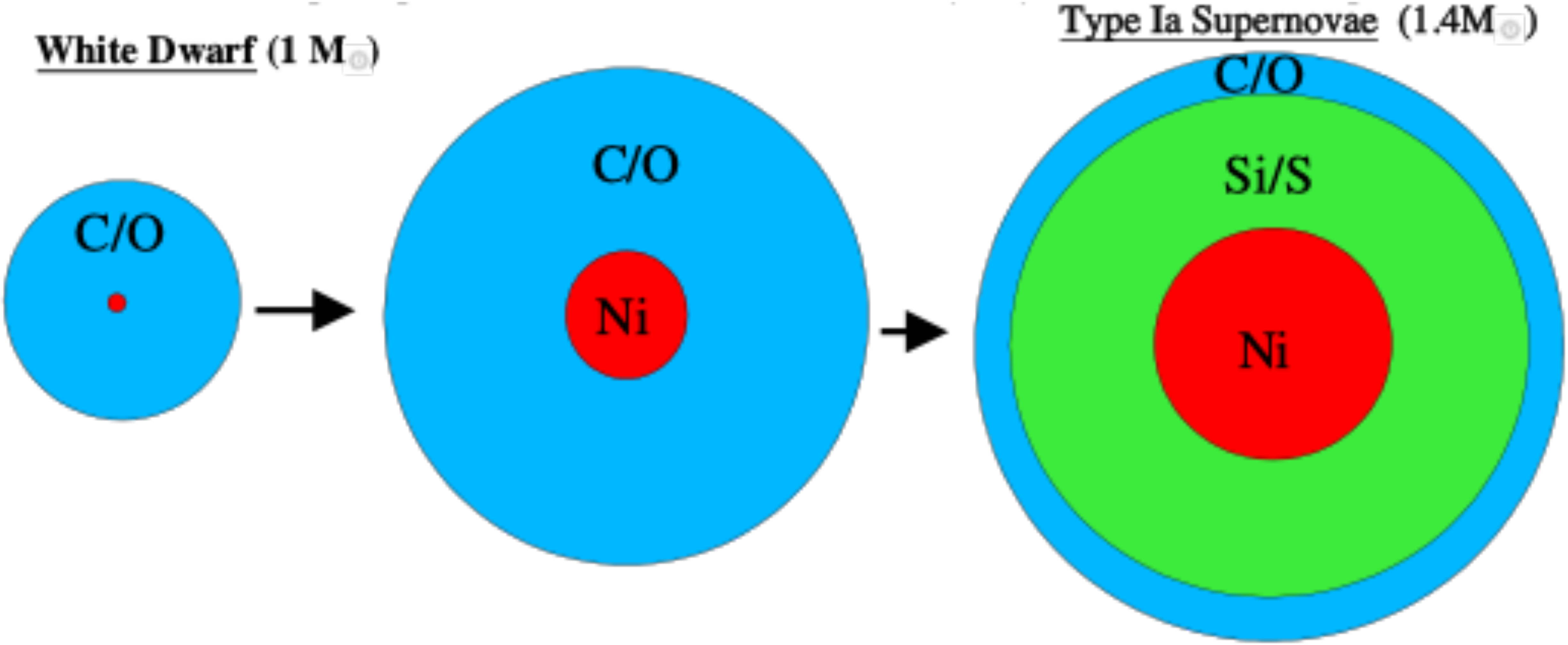
Fig. 1. The current classification scheme of supernovae. Type Ia SNe are associated with the thermonuclear explosion of accreting white dwarfs. Other SN types are associated with the core collapse of massive stars. Some type Ib/c and IIn SNe with explosion energies $E > 10^{52}$ erg are often called hypernovae.



Bethe & Brown, Scientific American 1985 (x10 Gai)

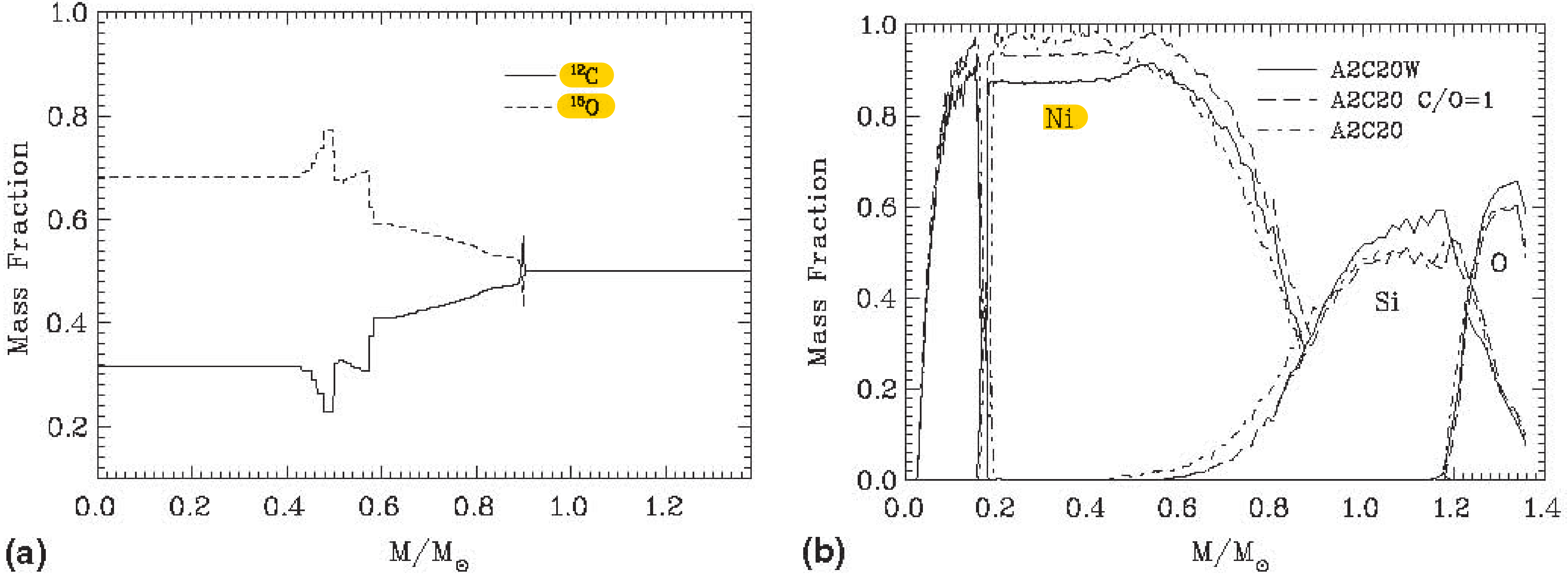
Type Ia Supernovae




White Dwarf (1 $M_\odot$)
C/O
C/O
Ni
Type Ia Supernovae (1.4$M_\odot$)
C/O
Si/S
Ni

The physics of type Ia supernovae

F.-K. Thielemann *et al.*; New Astronomy Reviews 48(2004)605



Helium Burning:

$3\alpha \rightarrow {}^{12}C$ Known

$\alpha + {}^{12}C \rightarrow {}^{16}O$???

C/O = ?

${}^{12}C(\alpha,\gamma){}^{16}O$ (E_{cm} = 300 keV)

$$\sigma(\alpha,\gamma) = S/E \times e^{-2\pi\eta}$$

$$(\eta = e^2 Z_1 Z_2 / \hbar \upsilon = Z_1 Z_2 \alpha / \beta)$$

Astrophysical Cross Section Factor (P and D waves)

$S_{E1}(300)$

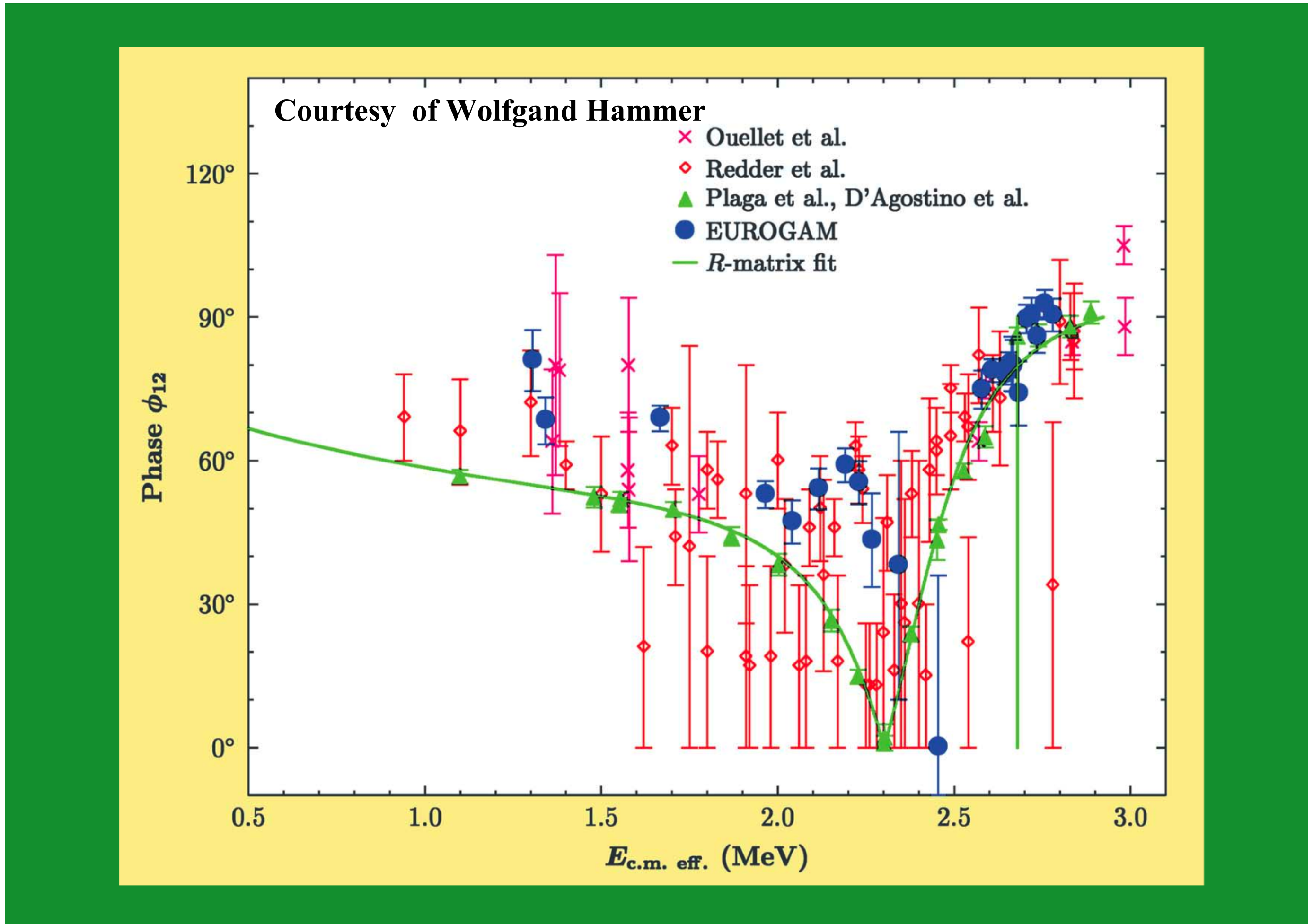
$S_{E2}(300)$

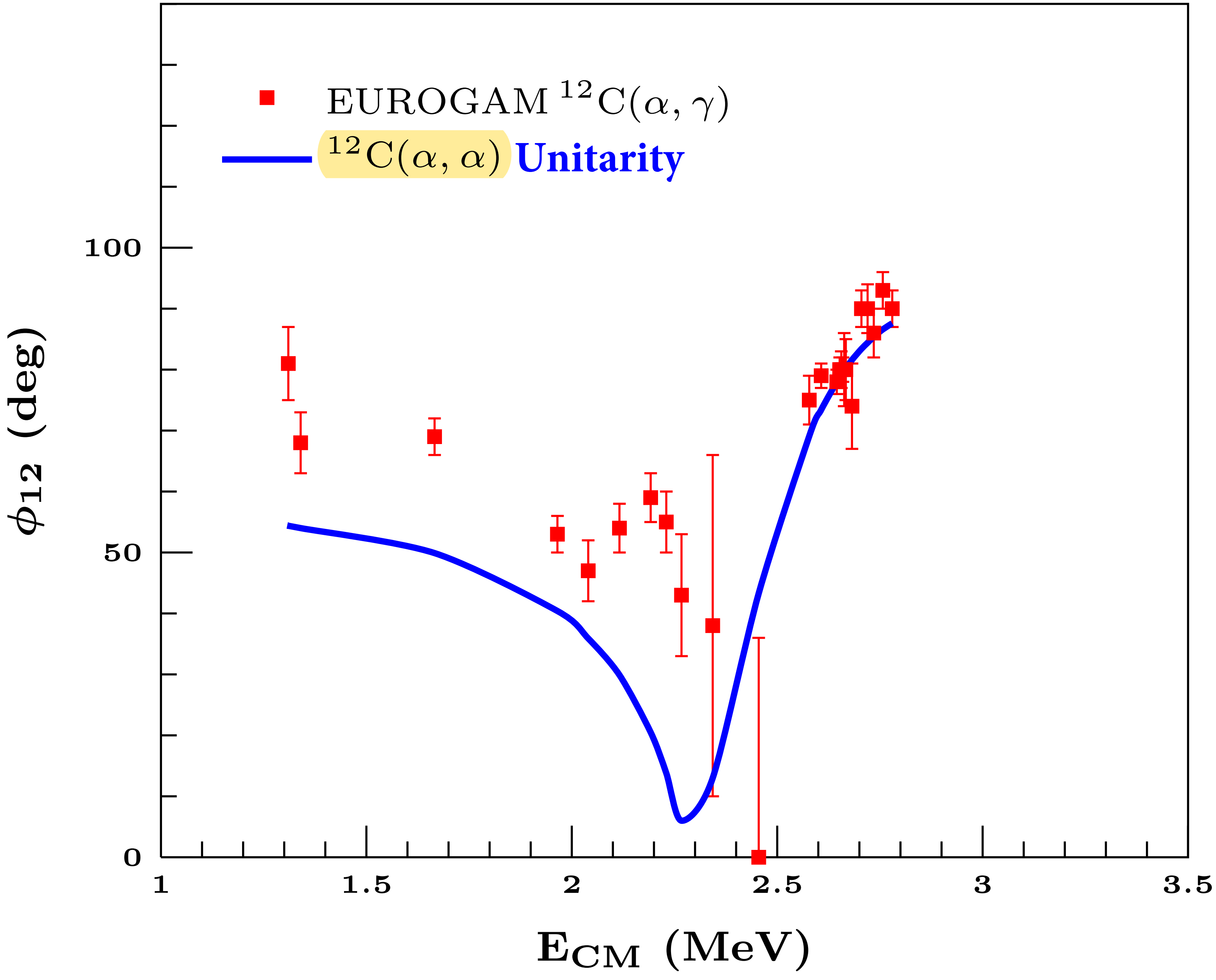
±15%

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

(Unitarity!)

K. M. Watson; Phys. Rev. 95(1954)228
L. D. Knutson; Phys. Rev. C 59(1999)2152
C. R. Brune; Phys. Rev. C 64(2001)055803
M. Gai; Phys. Rev. C 88(2013)062801(R)

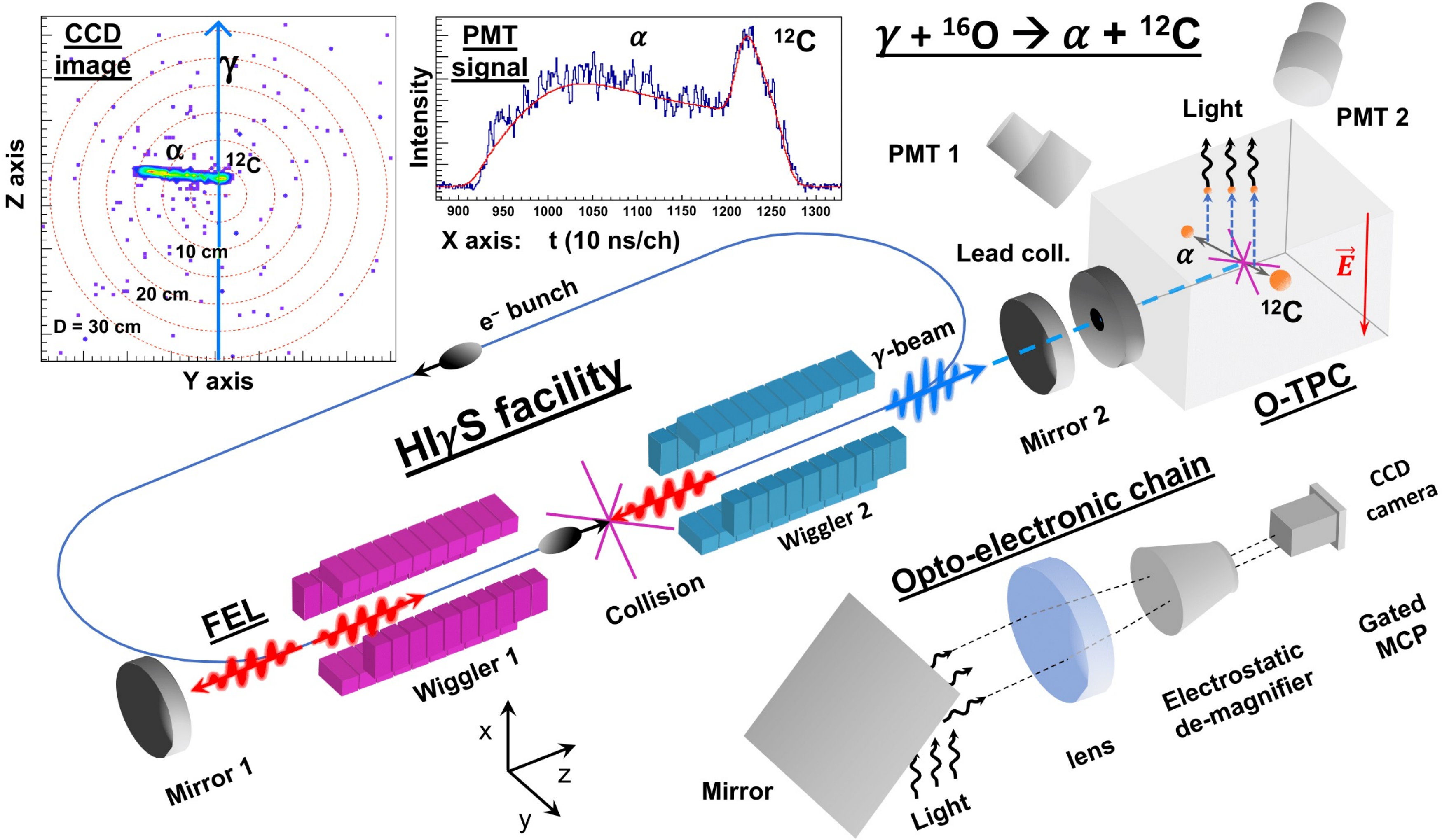




EUROGAM $^{12}C(\alpha,\gamma)$
$^{12}C(\alpha,\alpha)$ Unitarity
ϕ_{12} (deg)
100
50
0
1
1.5
2
2.5
3
3.5
E_{CM} (MeV)

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}. $E_{\alpha,\text{lab}}$ is the uncorrected α-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 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).

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



- **Beam parameters:**
  - Intensity: ~10^8 γ / sec (resolution of ~3%)
  - Nominal energies: 9.08, 9.38, 9.58, 9.78, 10.1, 10.4 MeV

R. Smith, M. Gai, S.R. Stern, D.K. Schweitzer, M.W. Ahmed, 2021.
Nature Preprint DOI: 10.21203/RS.3.RS-291379/V1

Progress in Particle and Nuclear Physics 114 (2020) 103790

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Review

Low energy nuclear physics with active targets and time projection chambers

D. Bazin [a,b,*], T. Ahn [c], Y. Ayyad [a], S. Beceiro-Novo [b], A.O. Macchiavelli [d], W. Mittig [a,b], J.S. Randhawa [a]

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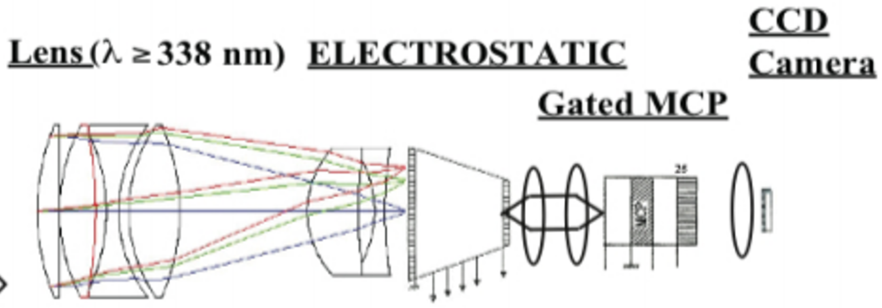
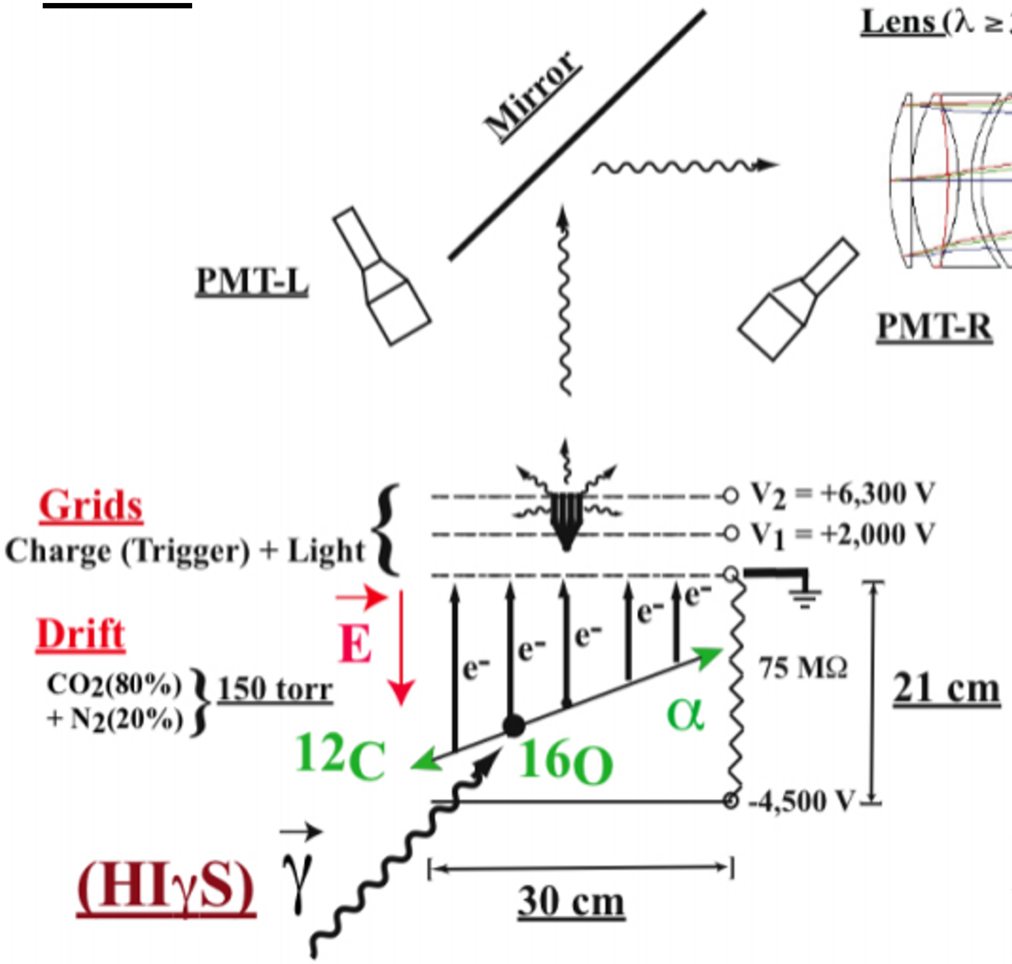
[d] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States

Opto-Electronic Chain

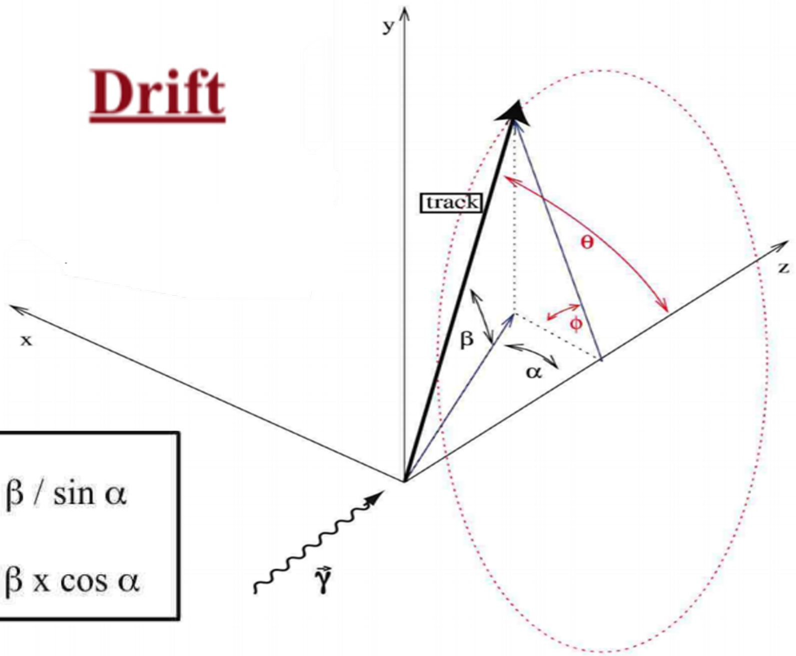


O-TPC



Multiplication

Drift



$\tan\phi = \tan\beta / \sin\alpha$

$\cos\theta = \cos\beta \times \cos\alpha$

M. Gai *et al.*, JINST 5, 12004 (2010)

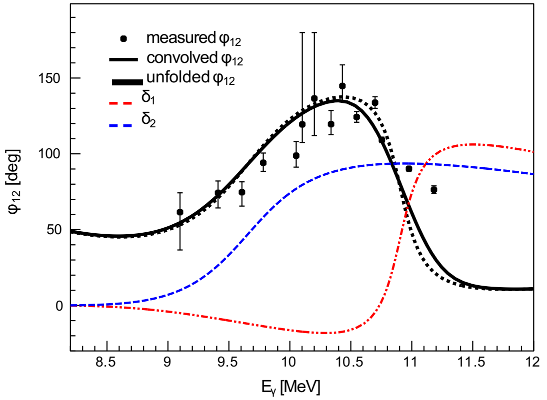
O-TPC: UConn-TUNL-Weizmann-PTB-ULB

O-TPC at HIγS at TUNL/ Duke

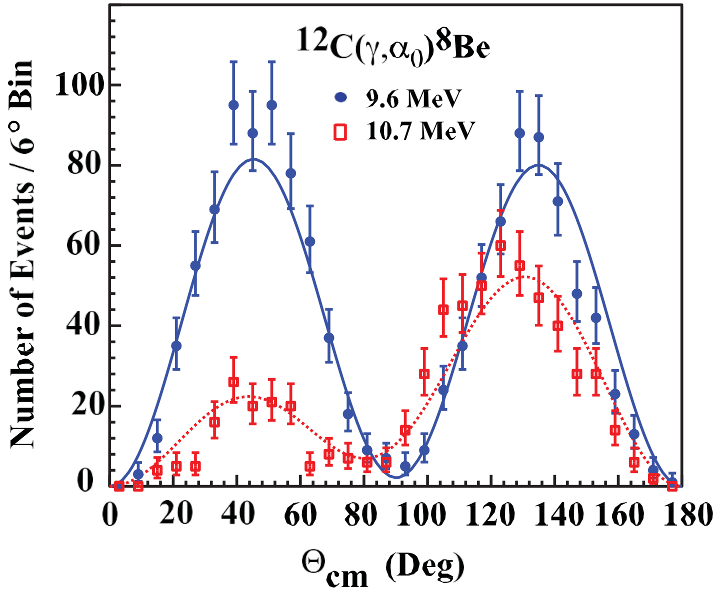
W.R. Zimmerman *et al.*; Phys. Rev. Lett. 110(2013)152502

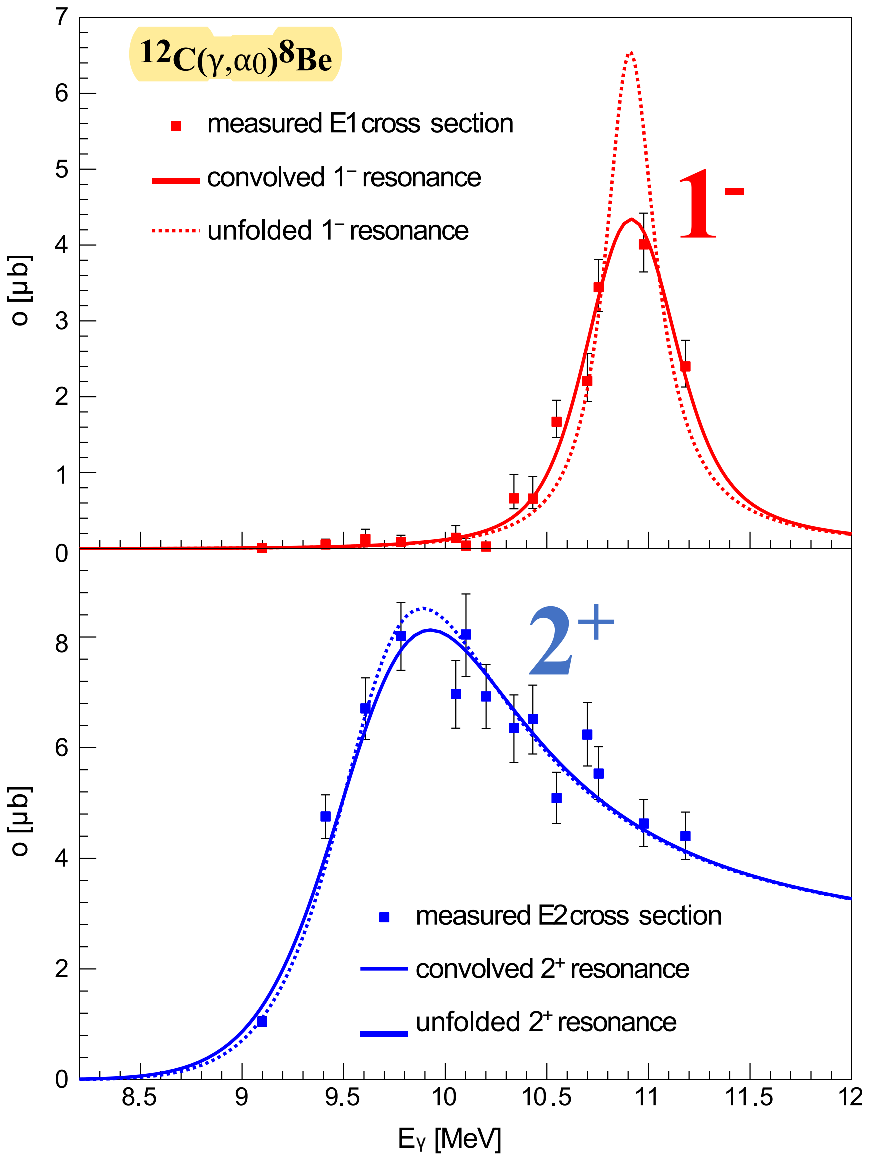
UConn-HIγS O-TPC

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

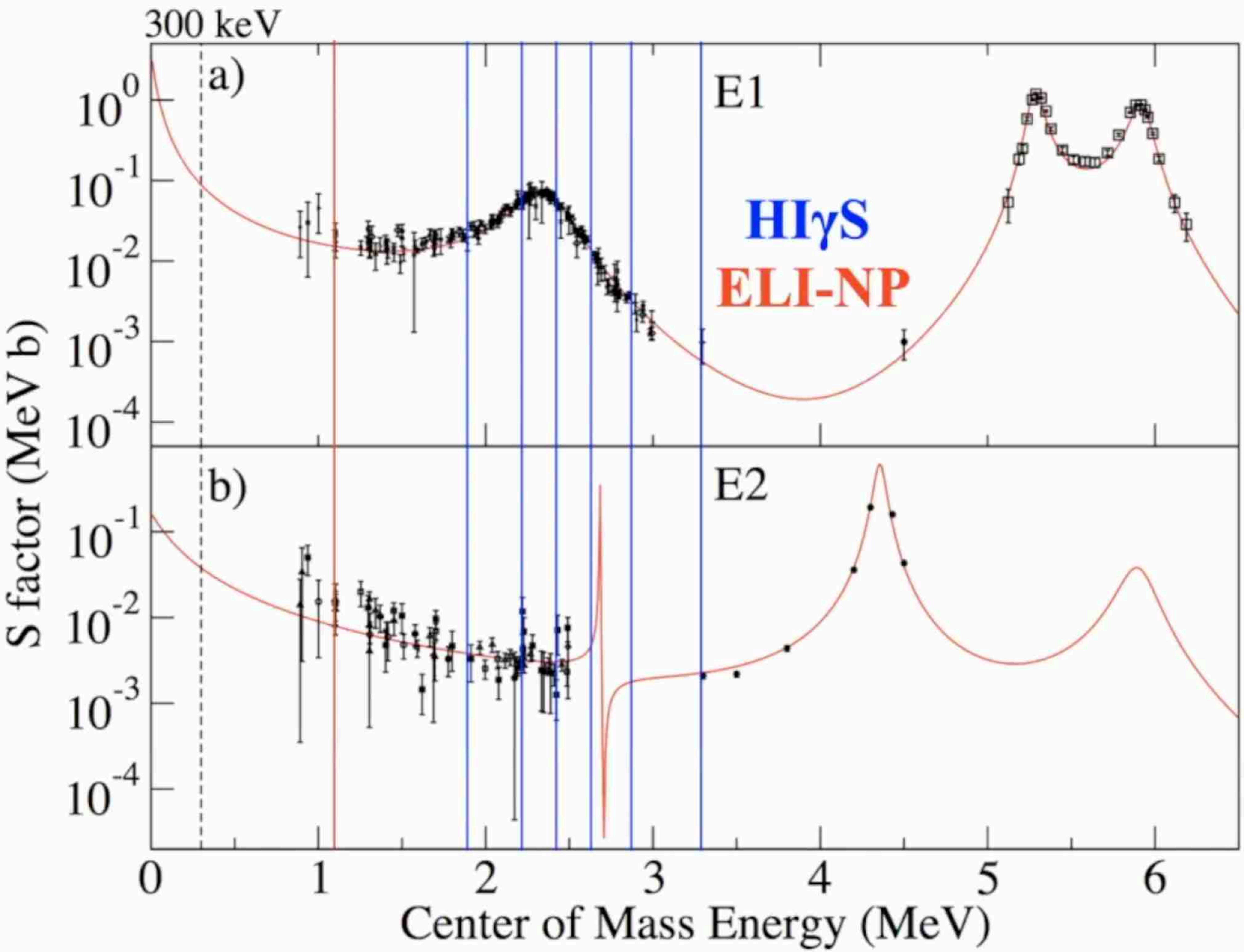


	9.6 MeV	10.7 MeV
E2/(E1+E2)	= 0.97 ± 0.02	0.71 ± 0.05
φ_{12}	= 80 ± 6°	132 ± 5°

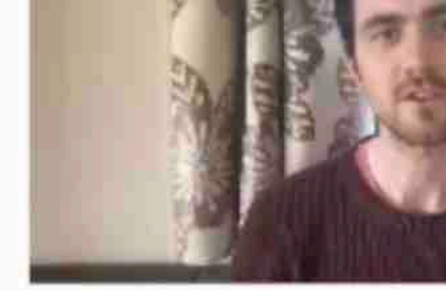




The HIγS campaign

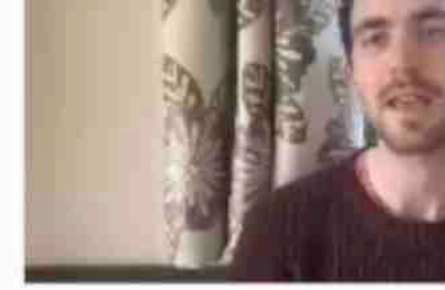


- "Proof-of-principle" for our new technique
- Re-measure the total cross section in a region where it is well understood
- Resolve long-standing disagreement with unitarity



R. J. deBoer et. al, The $^{12}C(\alpha,\gamma)^{16}O$ reaction and its implications for stellar helium burning,

Primary analysis

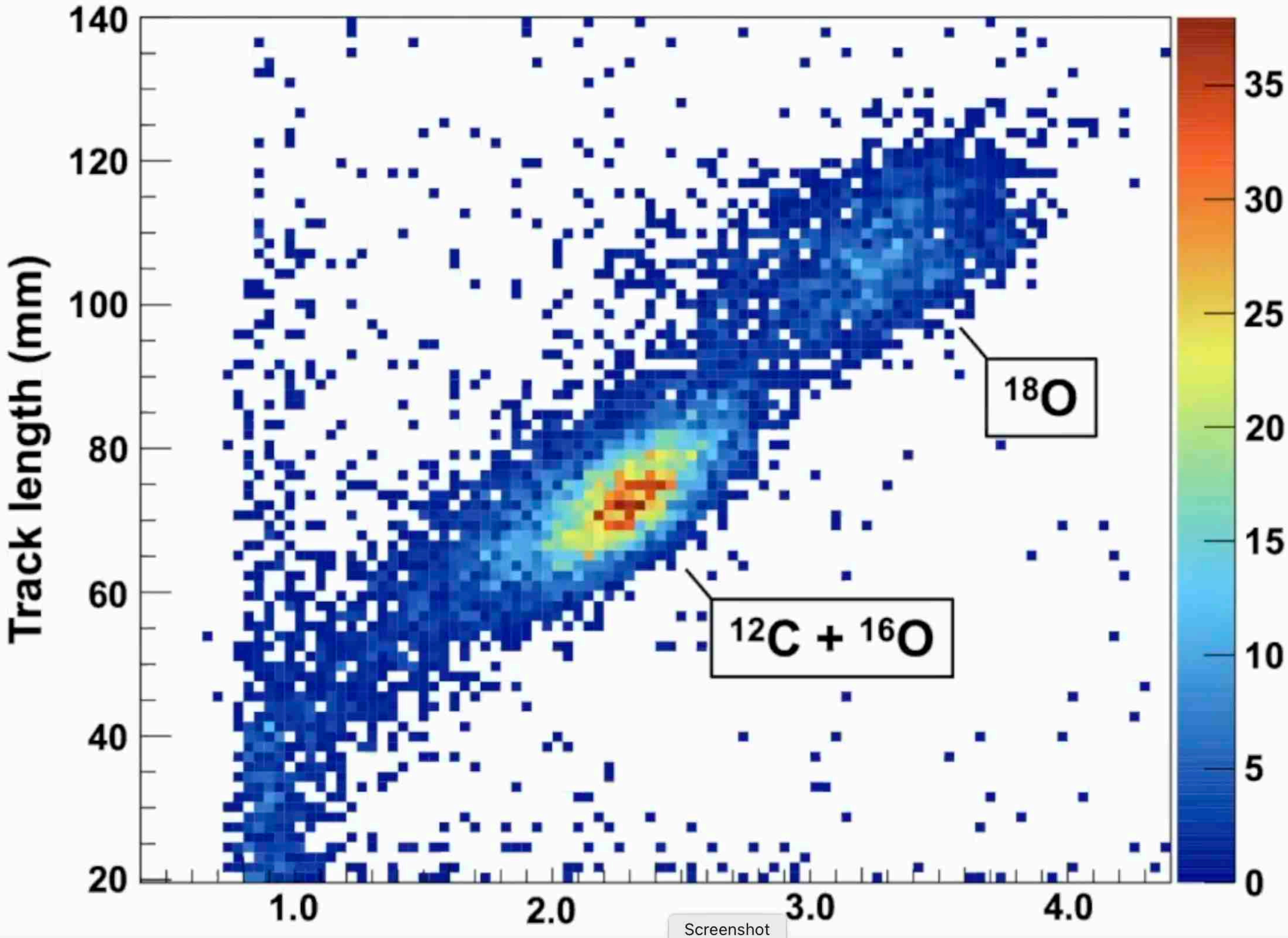


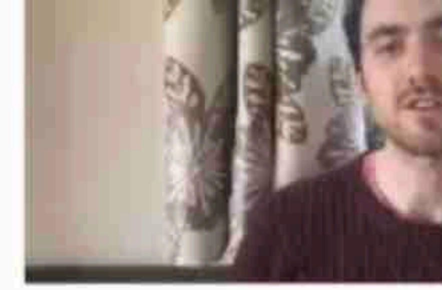
- <u>6 classes of events</u>
  - **"Good" $^{16}O(\gamma,\alpha)^{12}C$**
  - $^{12}C(\gamma,3\alpha)$ events
  - ~~$^{18}O(\gamma,\alpha)^{14}C$~~
  - ~~$^{14}N(\gamma,p)^{13}C$~~
  - ~~Cosmic rays~~
  - ~~Sparks~~

- <u>Number of tools at our disposal</u>
  - Track length, energy deposited, track clustering, proximity to the beam

Screenshot

Grid (energy) signal and track len

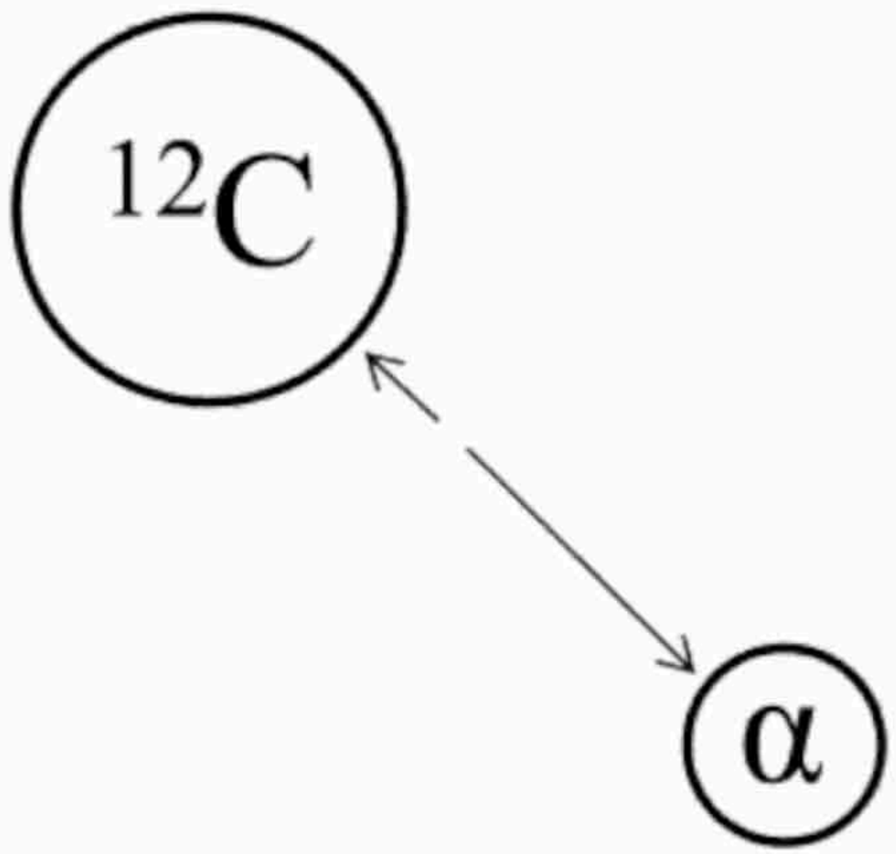




Identifying $^{16}O(\gamma,\alpha)^{12}C$

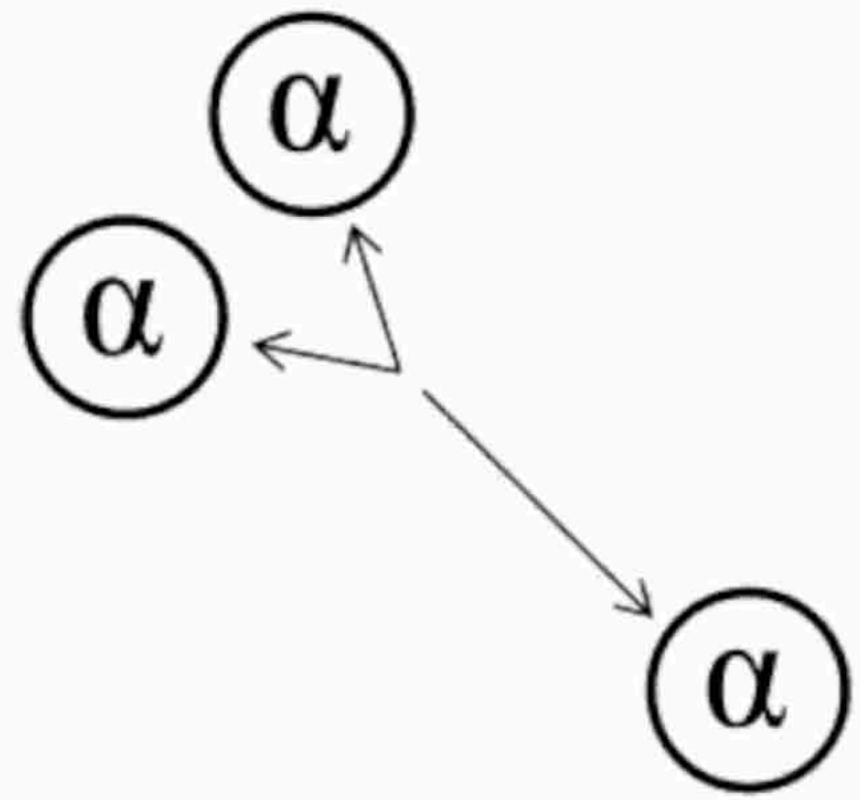
- CO_2 gas target – open reaction channels

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



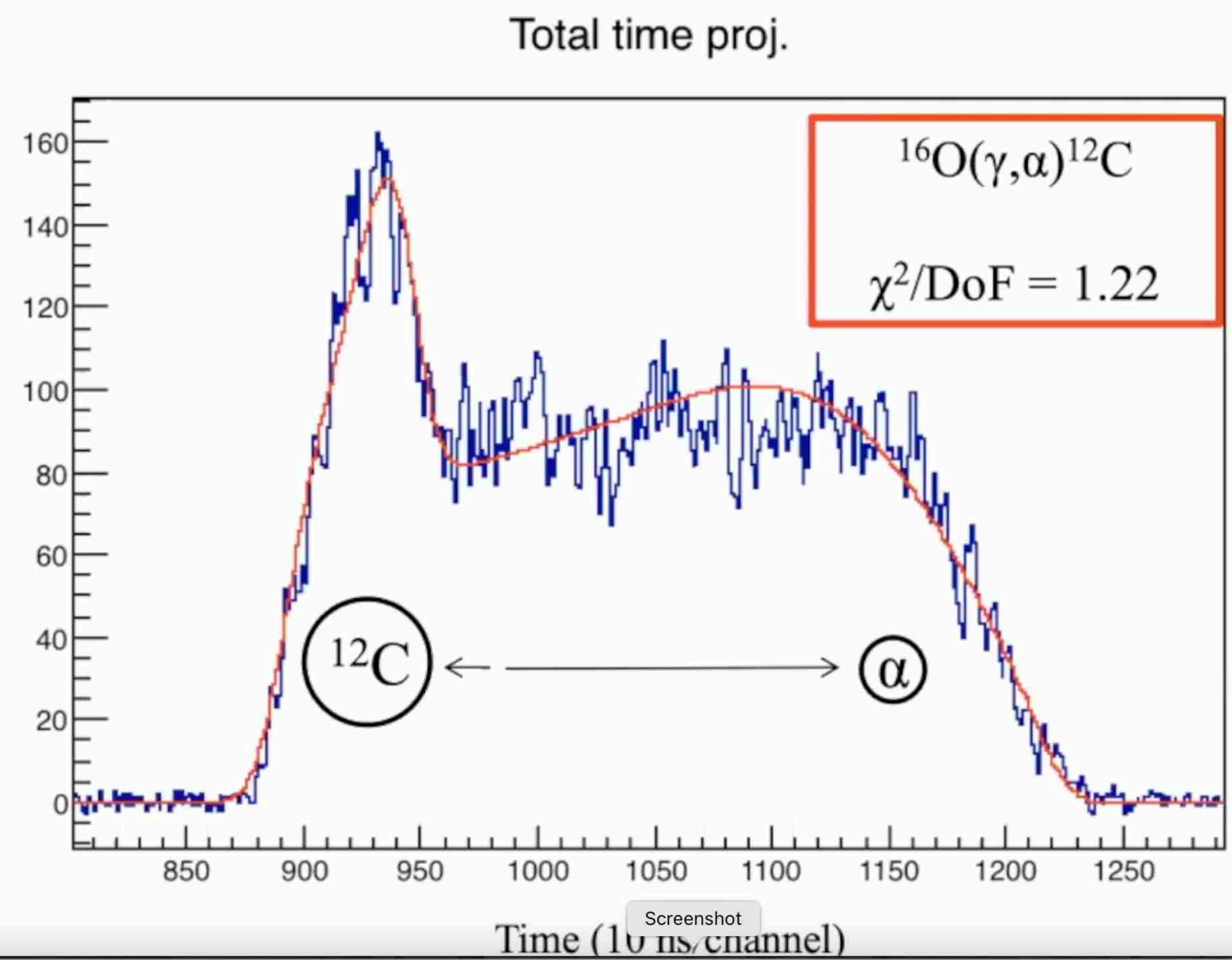
E = 2.42 MeV

$^{12}C(\gamma,\alpha_0)^{8}Be$

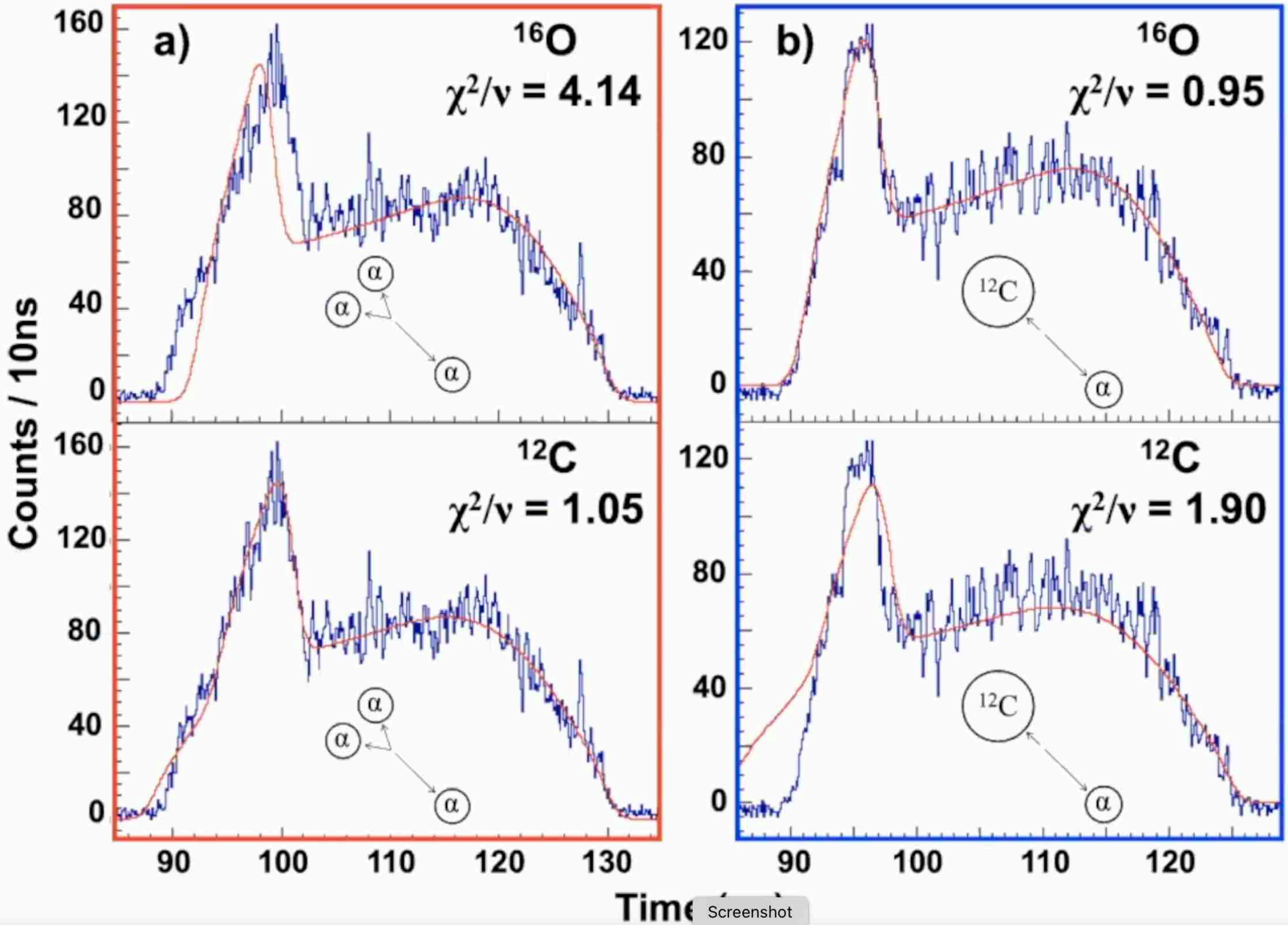


E = 2.30 MeV

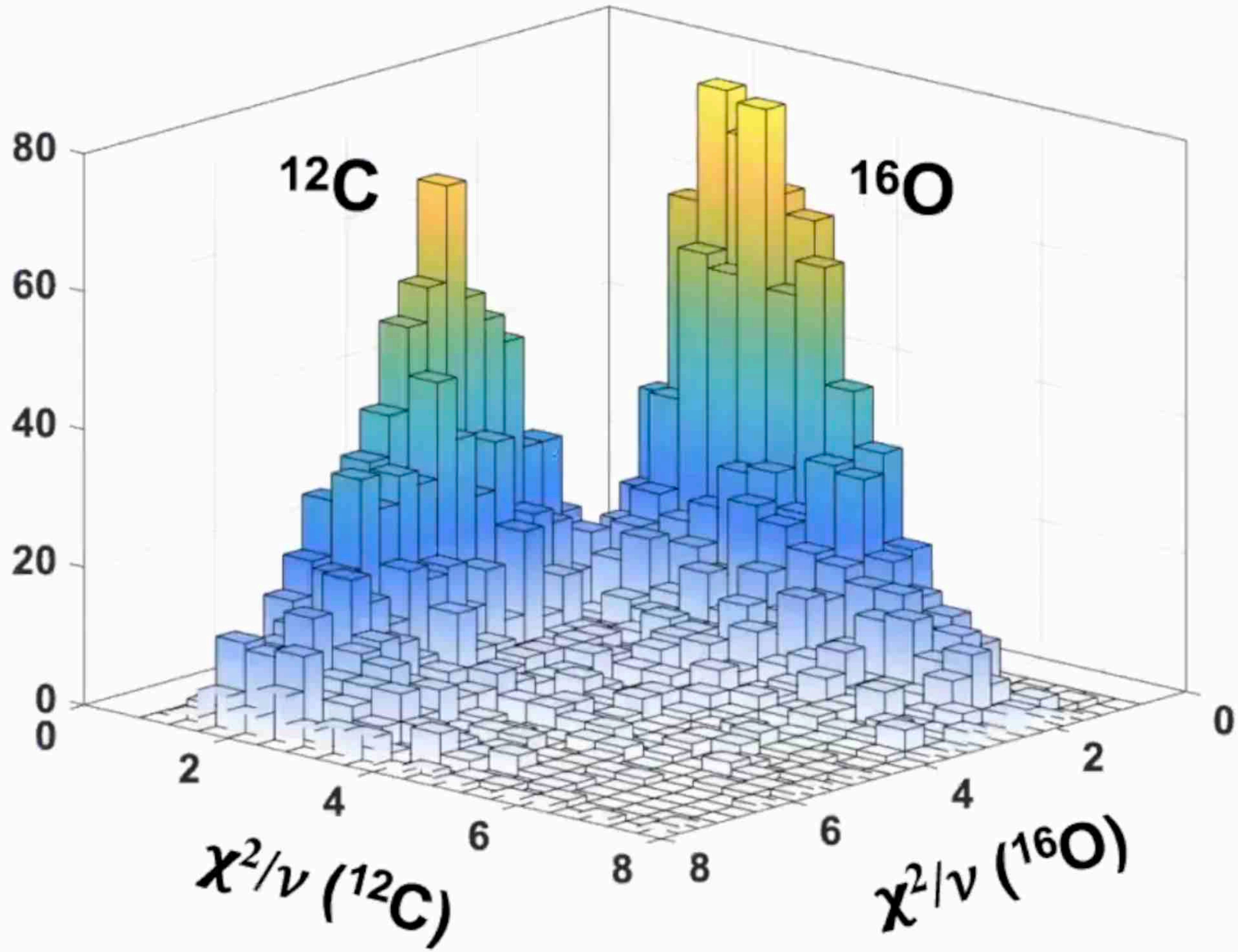
Lineshape analysis
Time projection

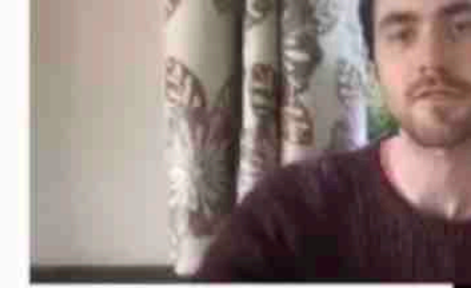


Lineshape analysis comparison



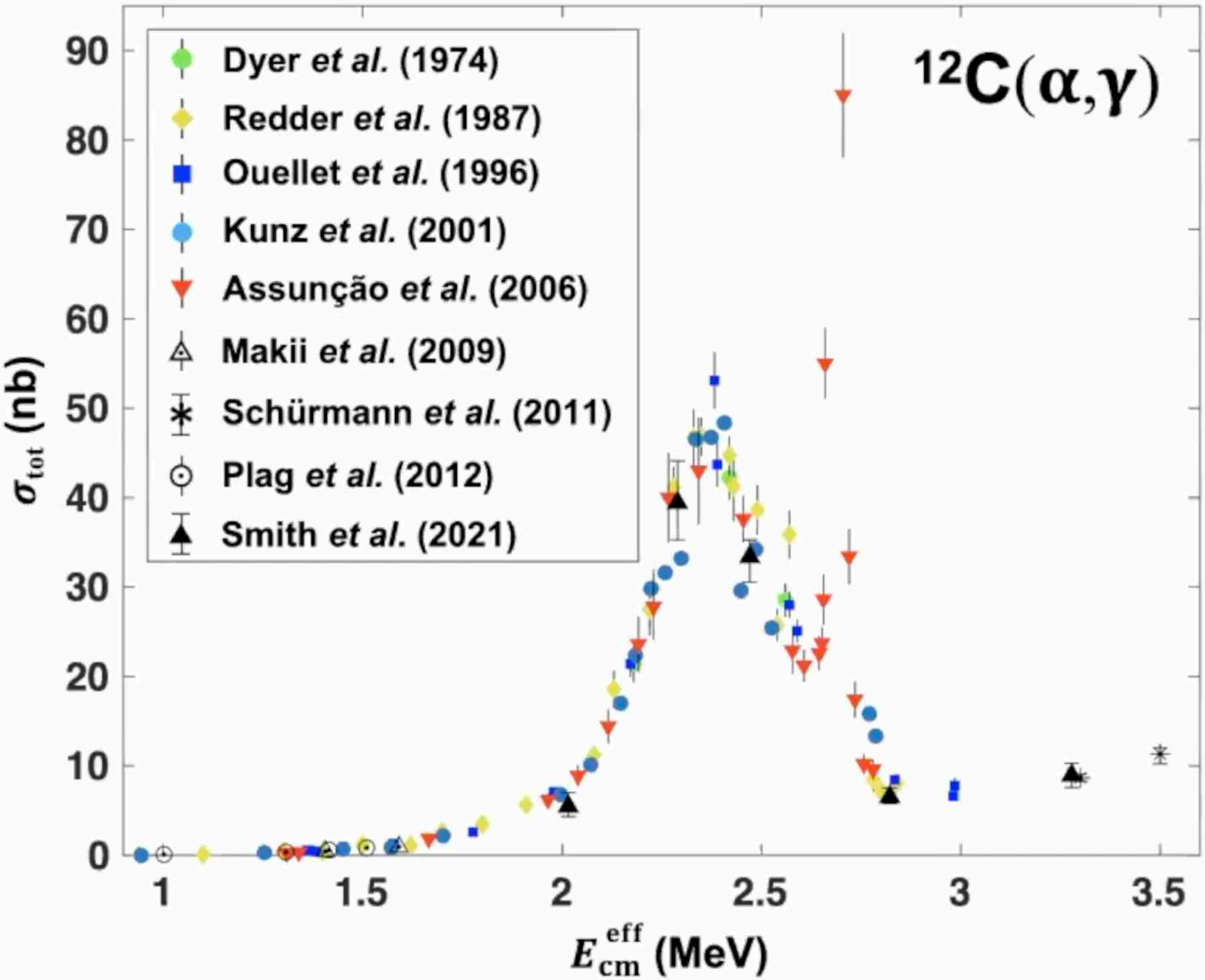
The χ^2 separation





R. Smith, M. Gai, S. R. Stern, D. K Schweitzer, M. A[illegible]ed, Submitted 2021.

Total cross section



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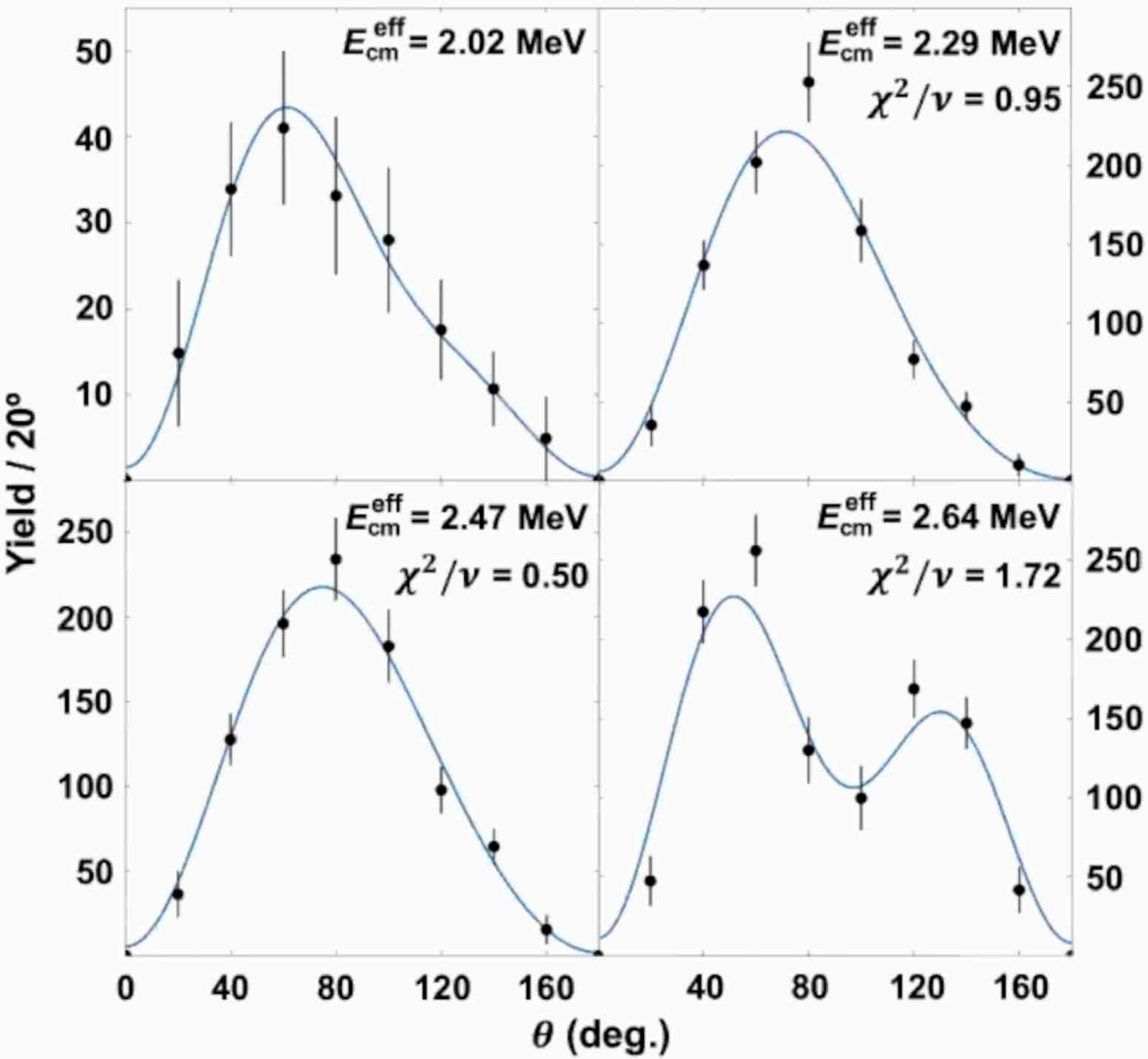
Angular distributions



- Unprecedented angular resolution of ~2°
- Fit the data with the partial wave decomposition:

$$W(\theta) = (3|A_{E1}|^2 + 5|A_{E2}|^2)P_0(\cos\theta) + \left({}^{25}/_{7}|A_{E2}|^2 - 3|A_{E1}|^2\right)P_2(\cos\theta) - {}^{60}/_{7}|A_{E2}|^2 P_4(\cos\theta) + 6\sqrt{3}|A_{E1}||A_{E2}|\cos\phi_{12}\,[P_1(\cos\theta) - P_3(\cos\theta)]$$

- Fit the binned data using a χ^2 minimisation
- Low-statistics data – unbinned maximum log likelihood fit

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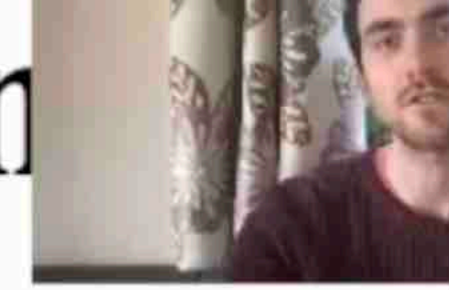
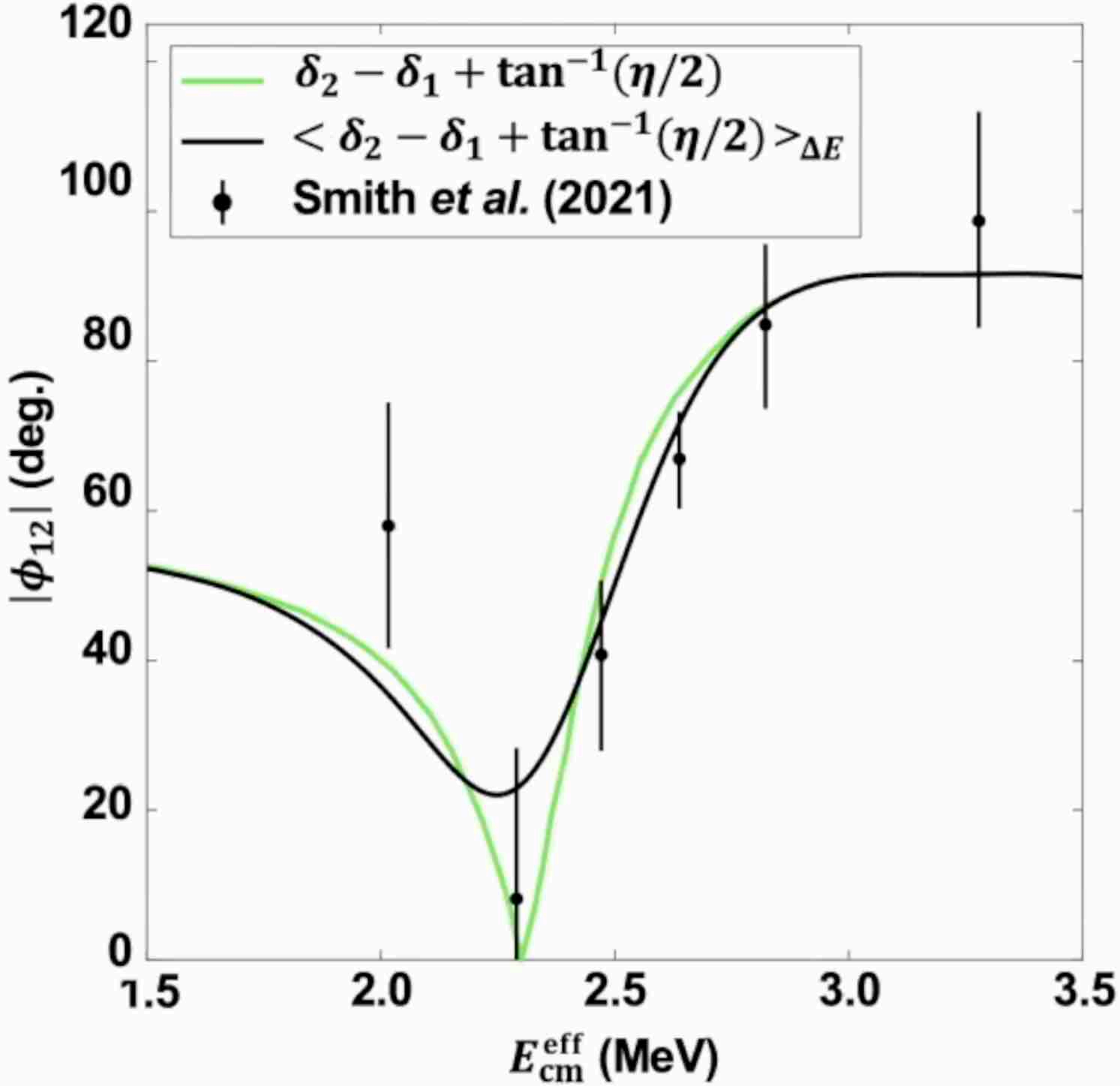
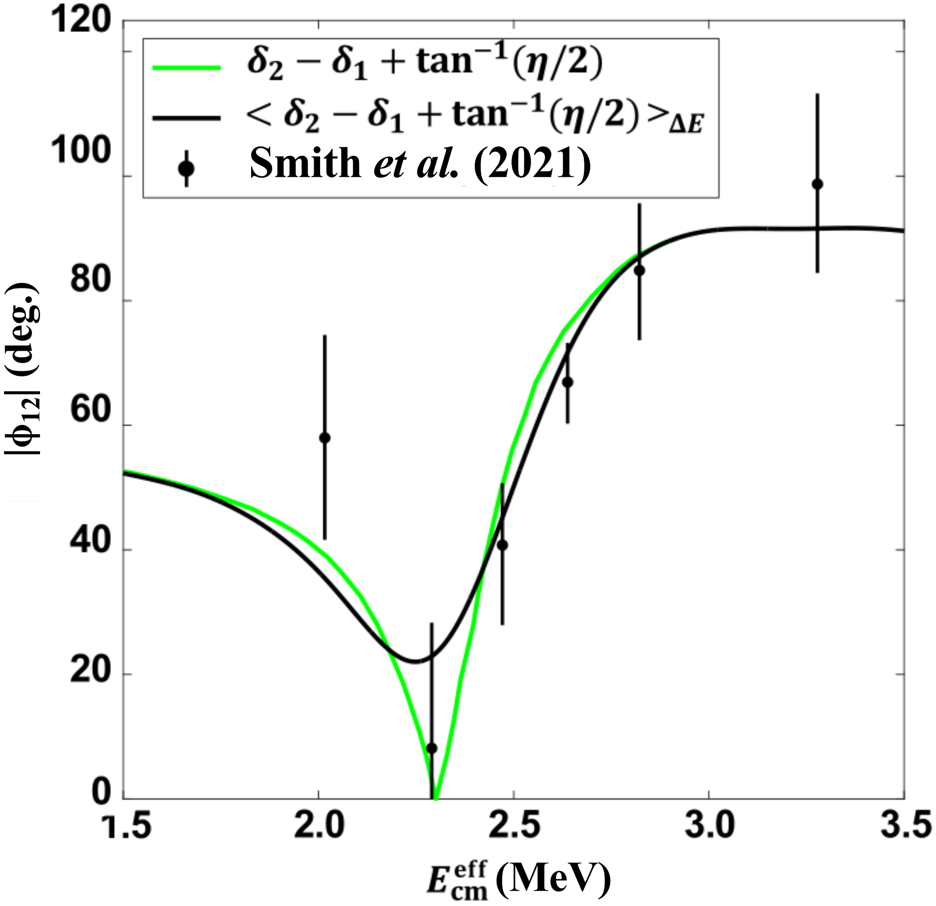
Extracted E1/E2 mixing phase an

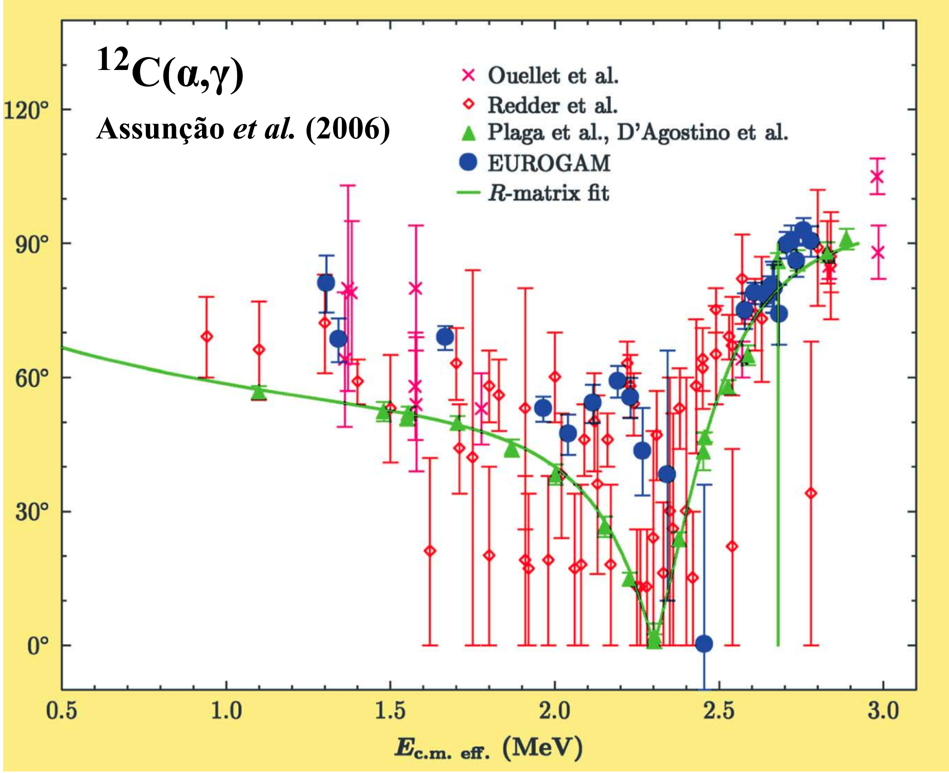




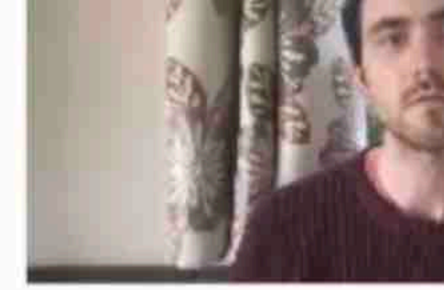
R. Smith, M. Gai, S. R. Stern, D. K Schweitzer, M. Ahmed, Submitted 2021.

E1-E2 mixing phase (ϕ_{12})





Measurement conclusions



- The $^{12}C(\alpha, \gamma)$ cross section was measured at effective centre-of-mass energies 2.02, 2.29, 2.47, 2.64, 2.82 and 3.28 MeV

- Detailed angular distributions with ~2° resolution were measured inside the TPC detector

- Fits to the angular distribution agree with the fundamental prediction of unitarity across this energy region