Direct Observation of a New 2^+ State in ^{12}C through the $^{12}C + \gamma \rightarrow 3\alpha$ Reaction

William Zimmerman

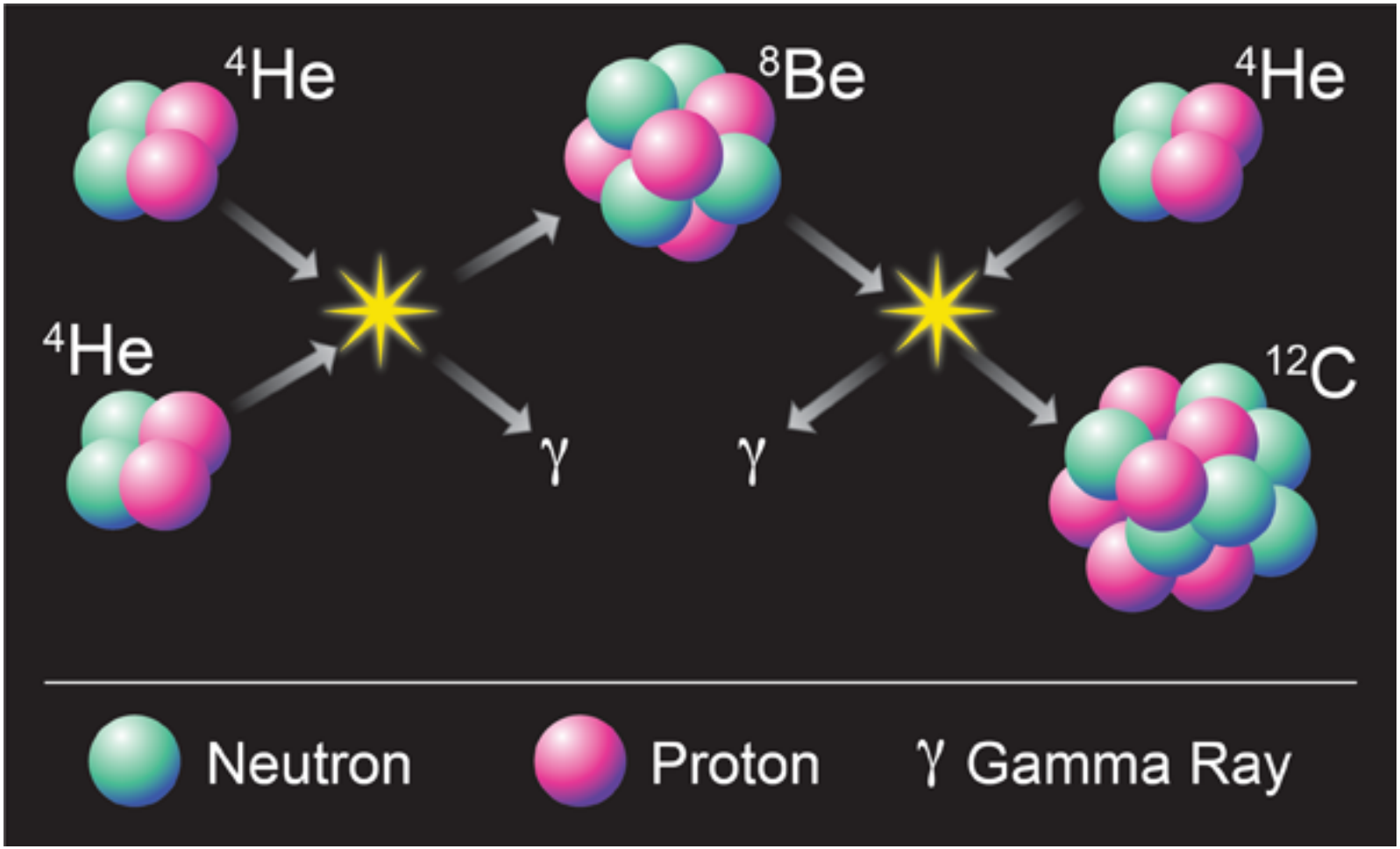
Triangle Universities Nuclear Laboratory

University of Connecticut

Chiral Dynamics 2012

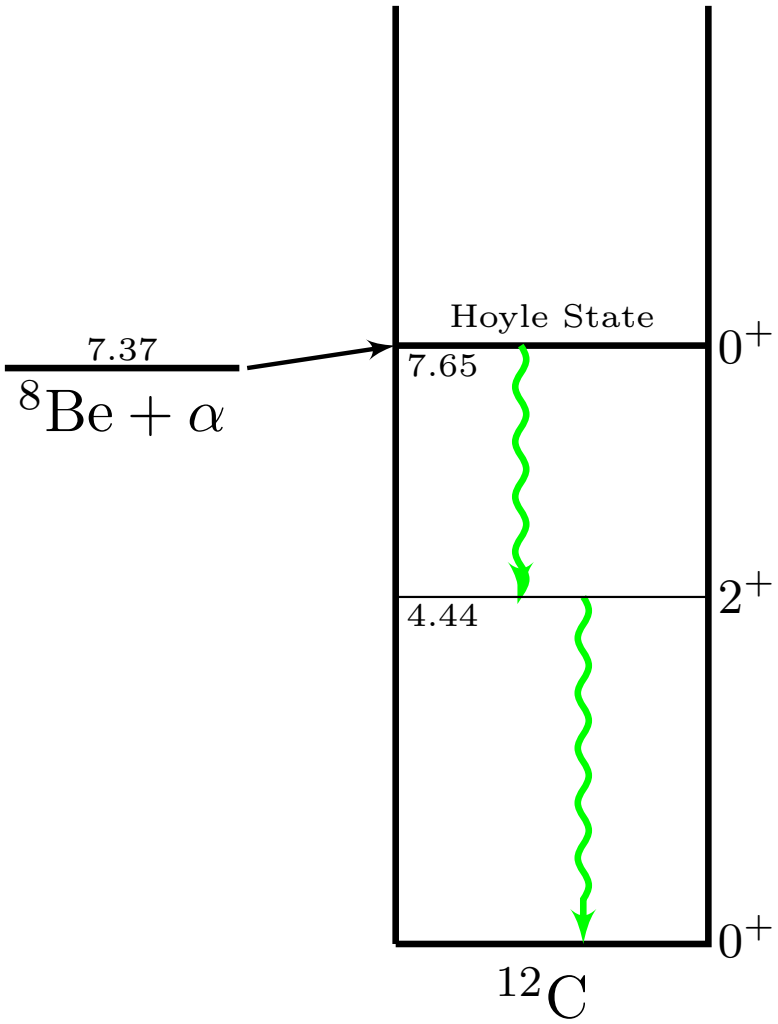
Astrophysics

Triple-α Process:

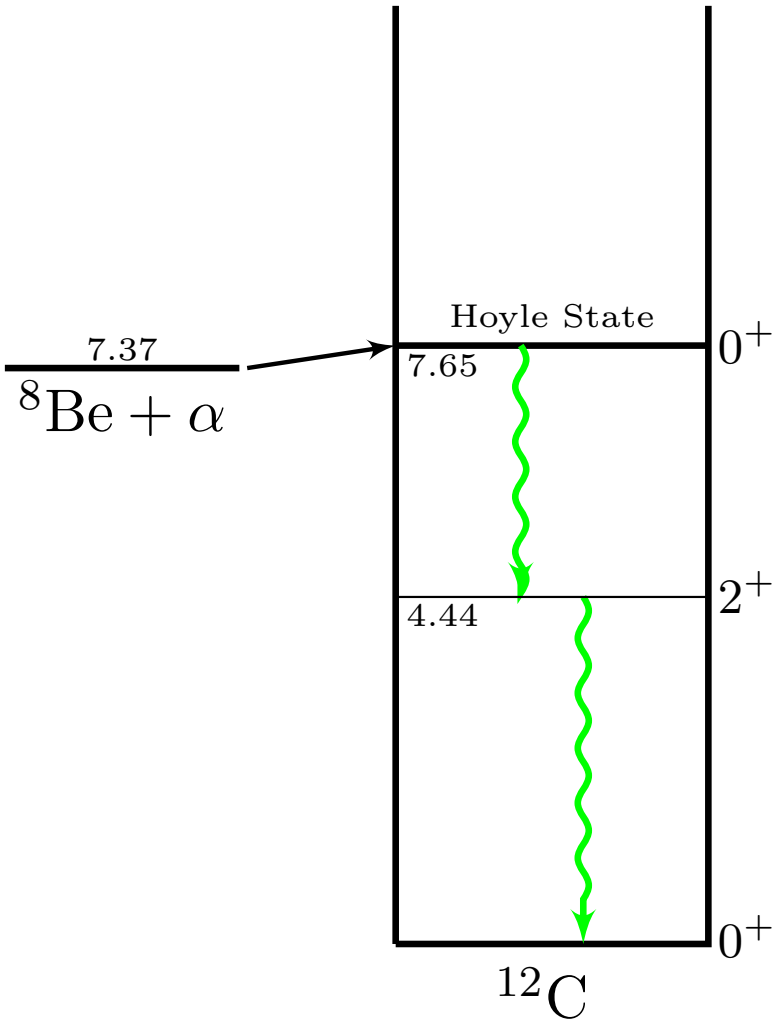


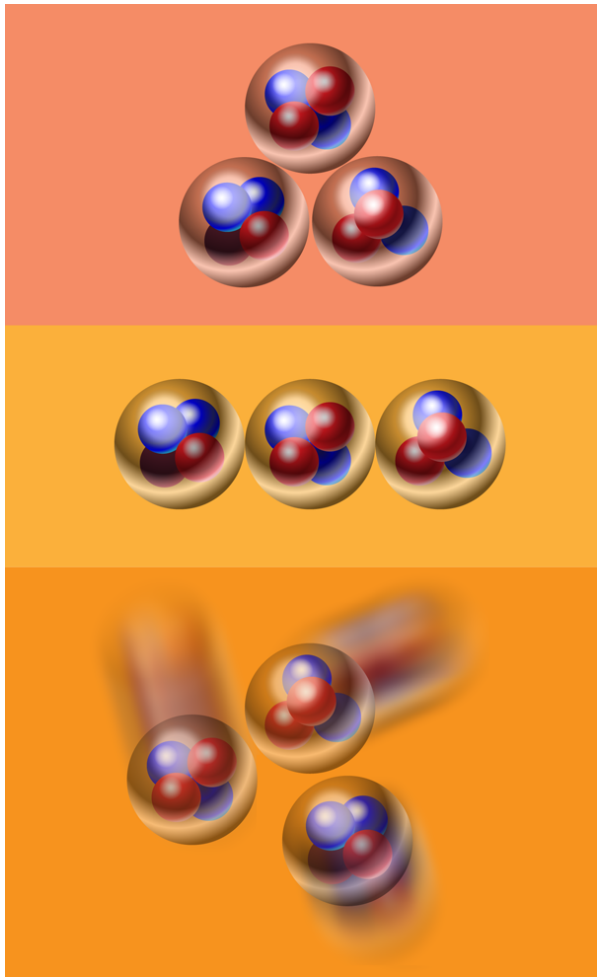
M. Hjorth-Jensen, Physics **4**, 38 (2011)

Hoyle State



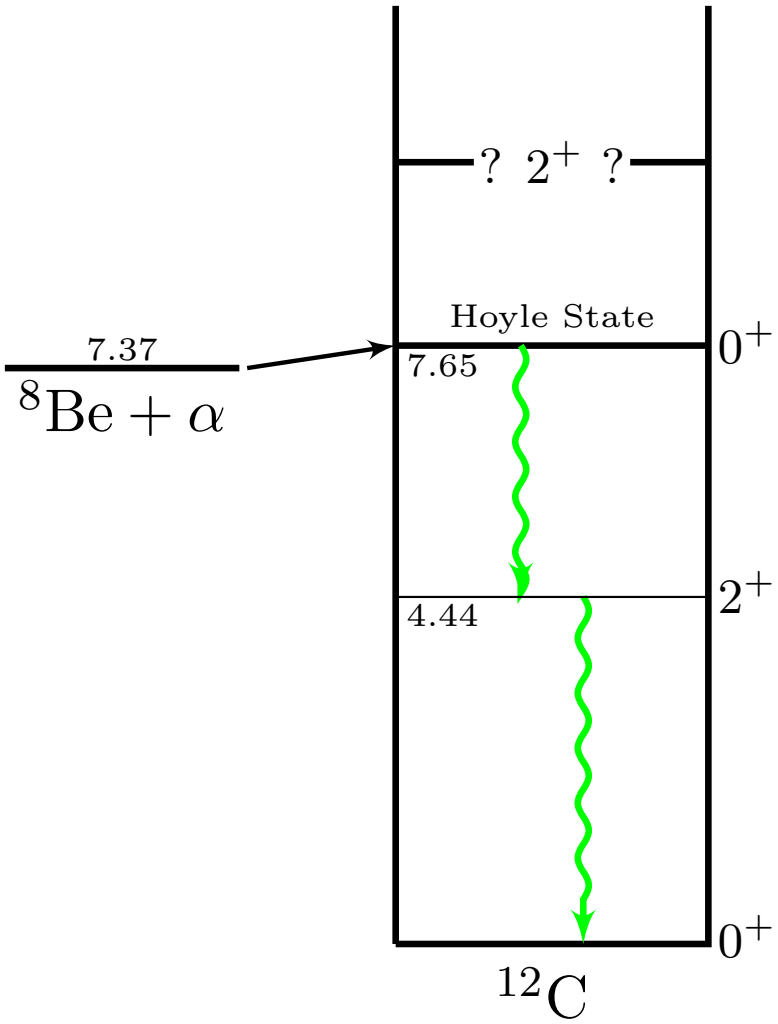
Hoyle State

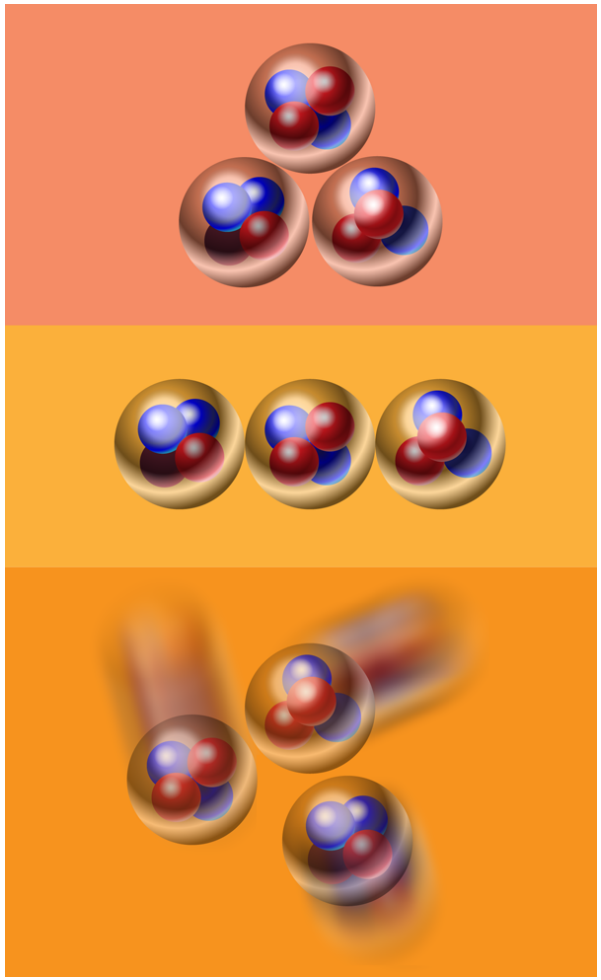




Fynbo & Freer, Physics **4**, 94 (2011)

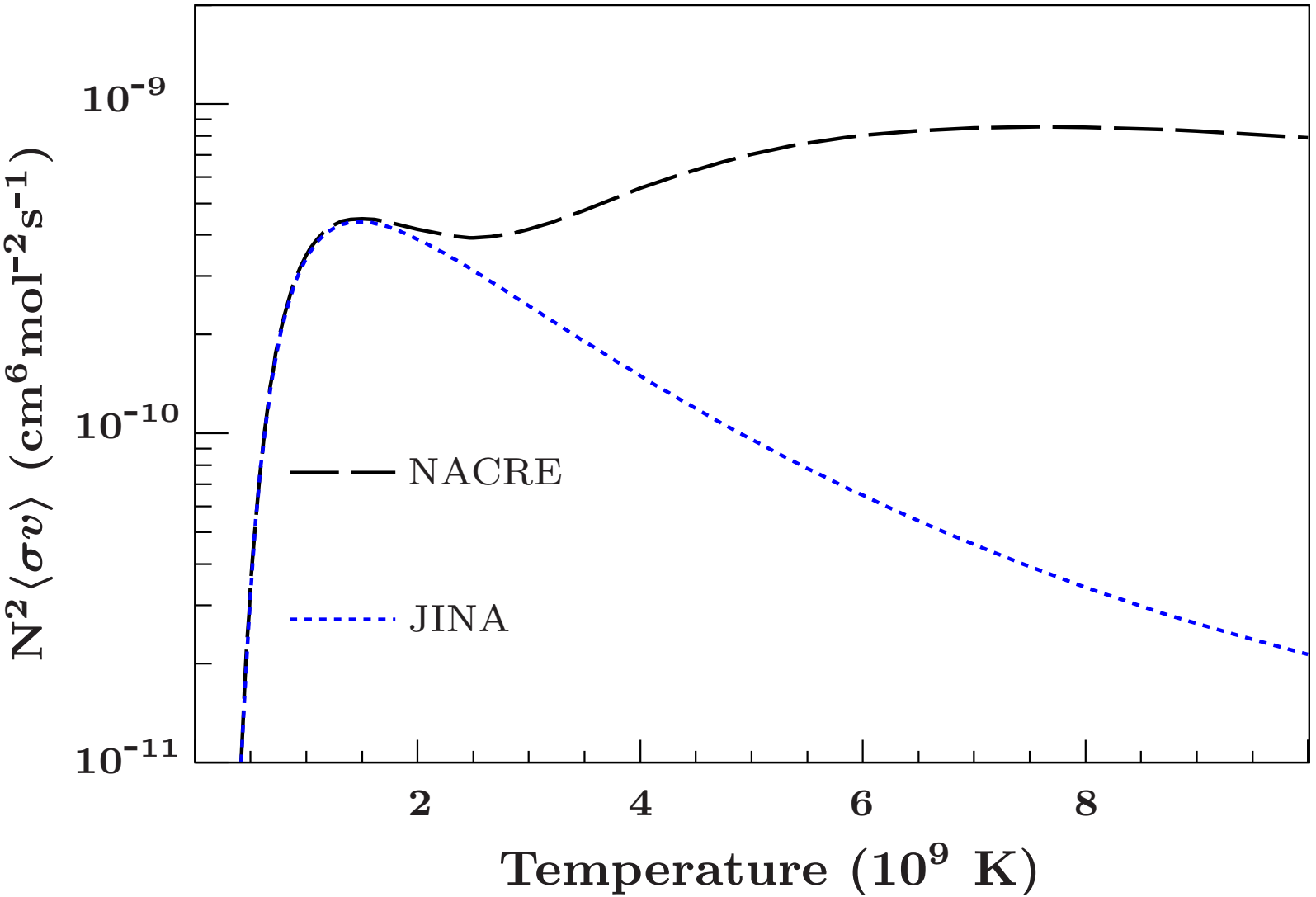
Hoyle State



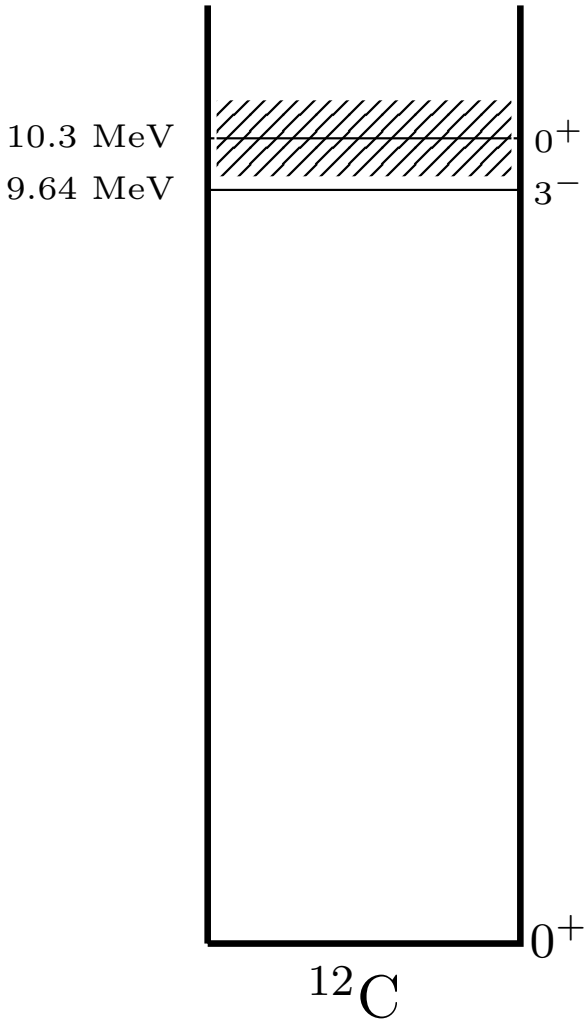


Fynbo & Freer, Physics **4**, 94 (2011)

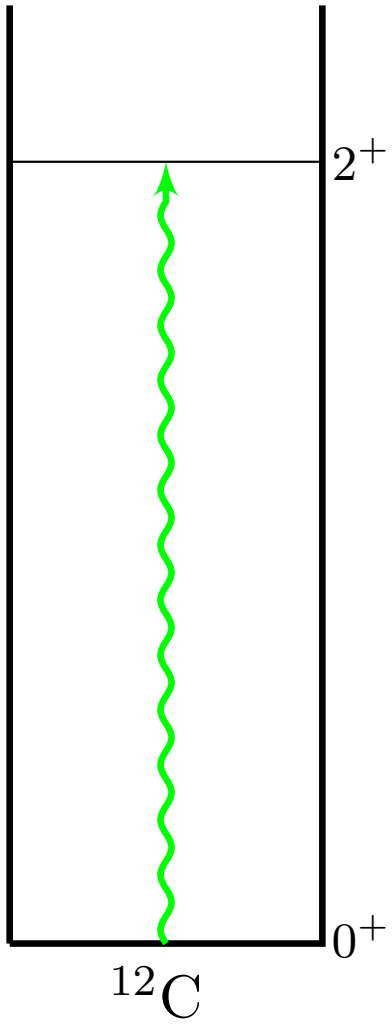
Triple-α Reaction Rates



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

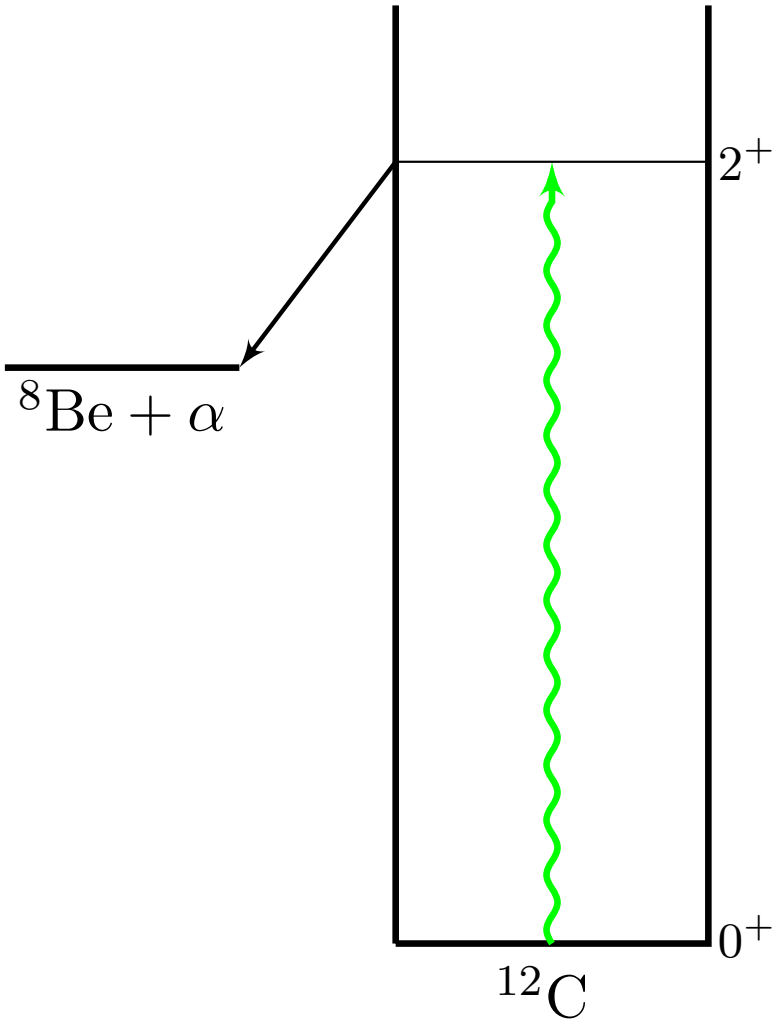


$^{12}C(\gamma,\alpha)^{8}Be$



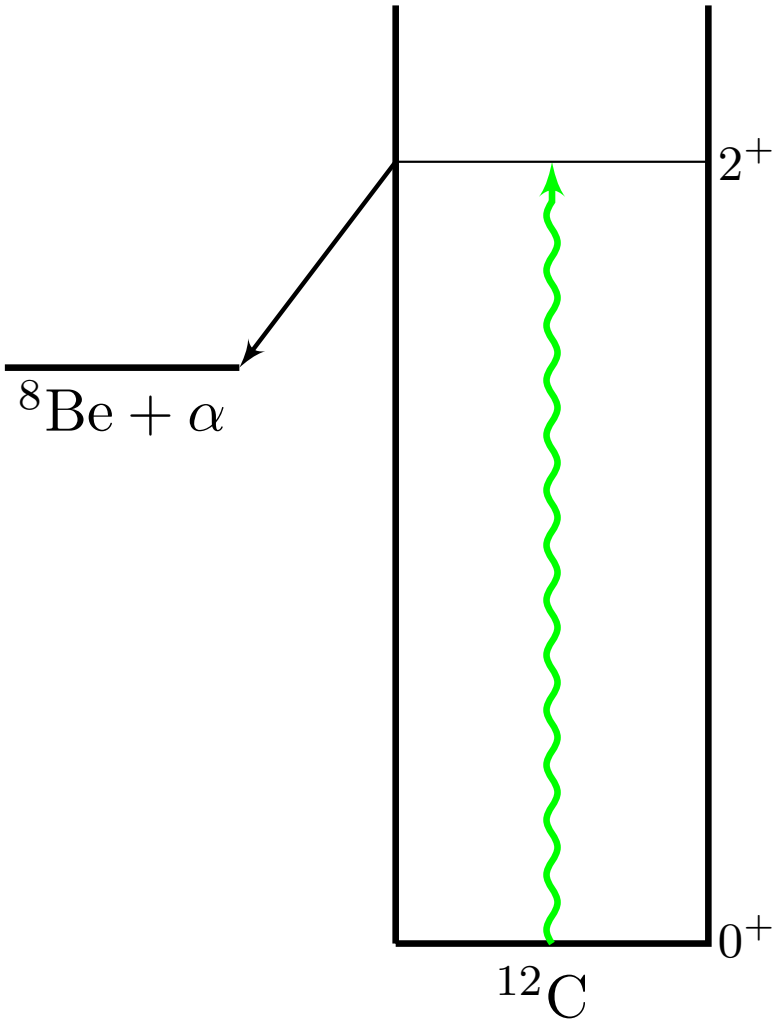
- γ-ray beam will not excite 0^+ state and will excite 3^- state with very small probability.

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



- γ-ray beam will not excite 0^+ state and will excite 3^- state with very small probability.
- Measuring α-particle angular distribution gives J^π of state.

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



- γ-ray beam will not excite 0^+ state and will excite 3^- state with very small probability.
- Measuring α-particle angular distribution gives J^π of state.
- Measuring cross section over several γ-ray beam energies gives Γ_α, Γ_γ, and E_{res}

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

Measuring $^{12}C(\gamma,\alpha)^{8}Be$ requires:

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

Measuring $^{12}C(\gamma,\alpha)^{8}Be$ requires:

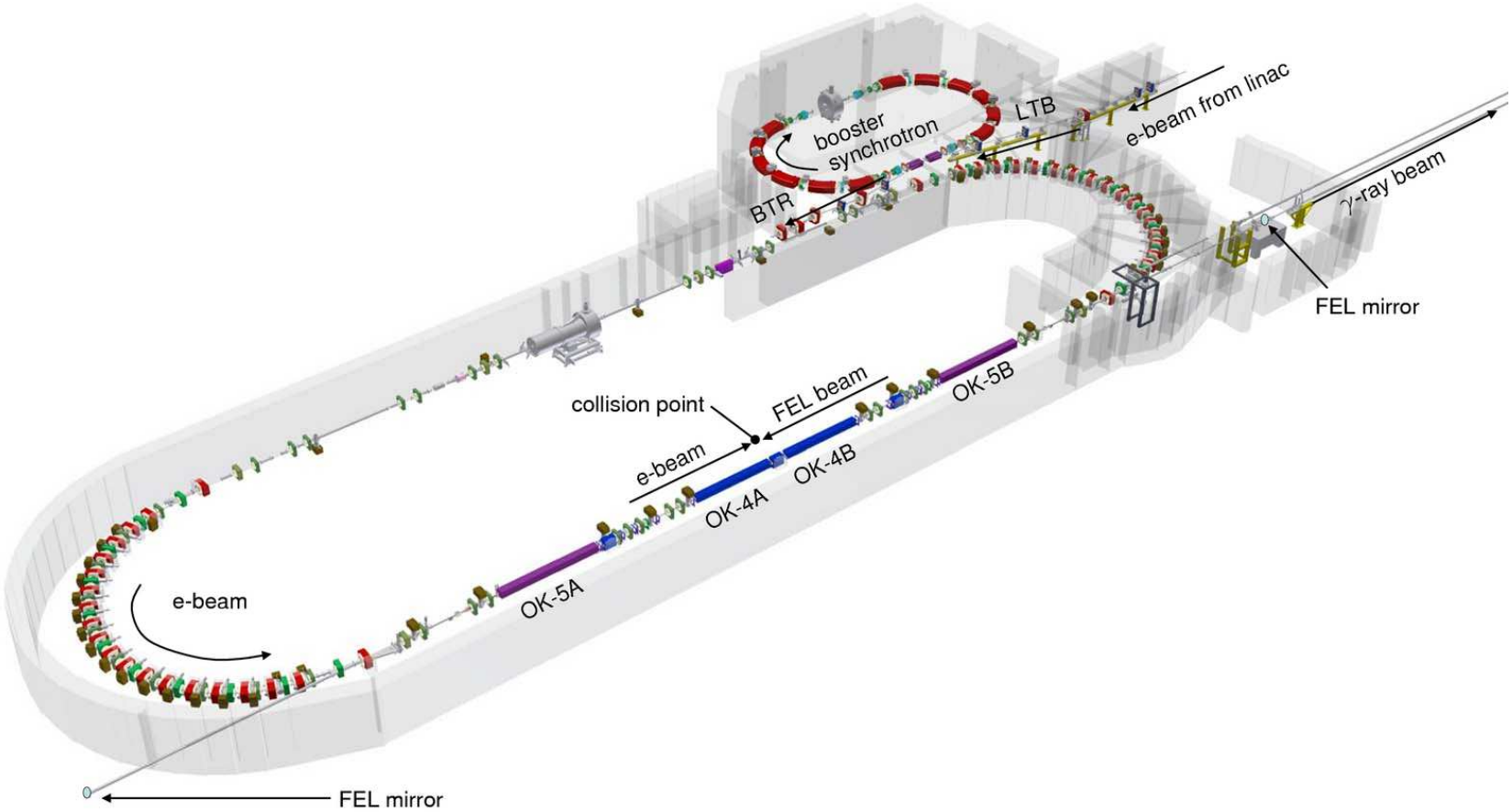
- Intense, monoenergetic γ-ray beam

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

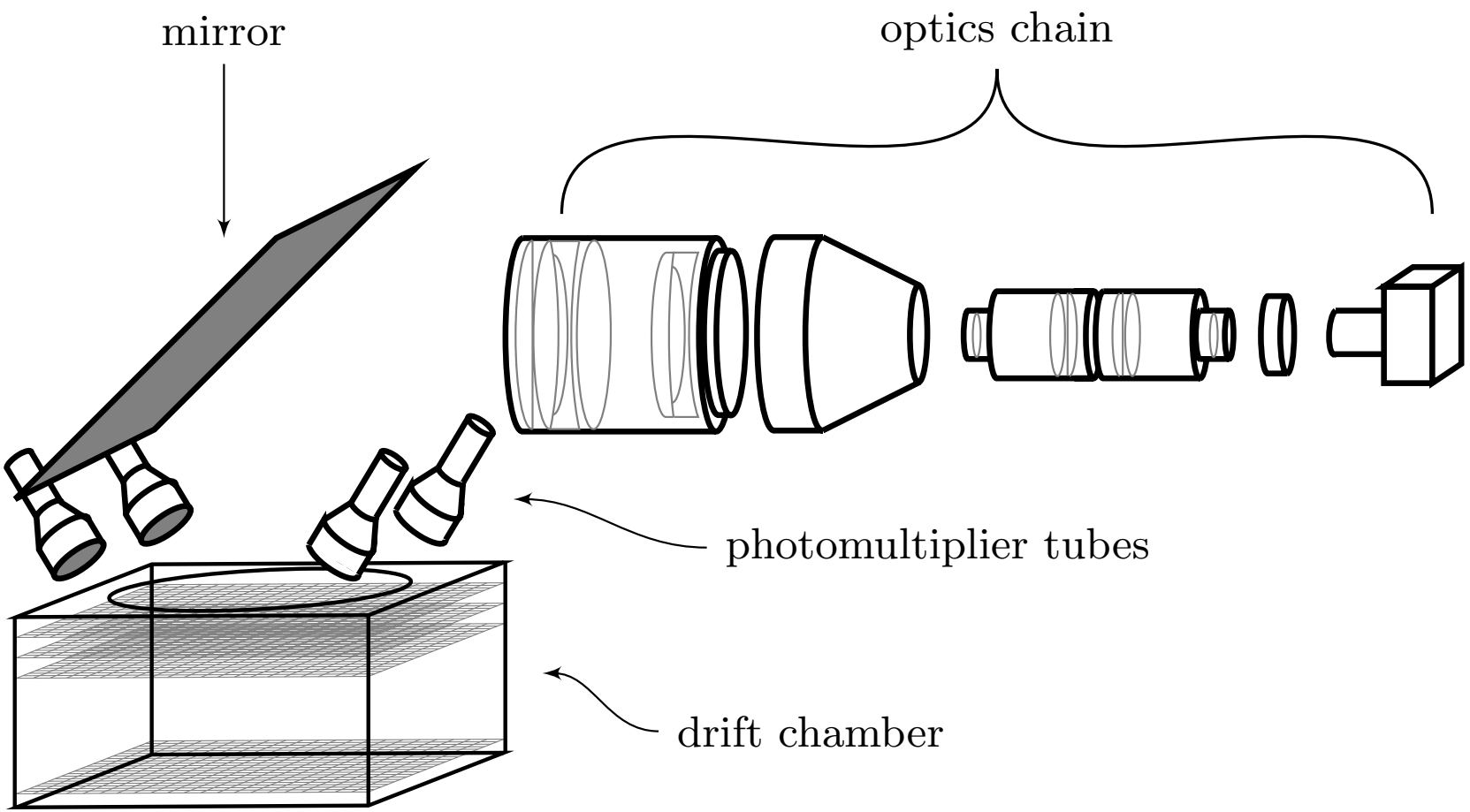
Measuring $^{12}C(\gamma,\alpha)^{8}Be$ requires:

- Intense, monoenergetic γ-ray beam
- Detector capable of measuring angular distributions of recoiling α-particles with little or no background

HIγS Facility

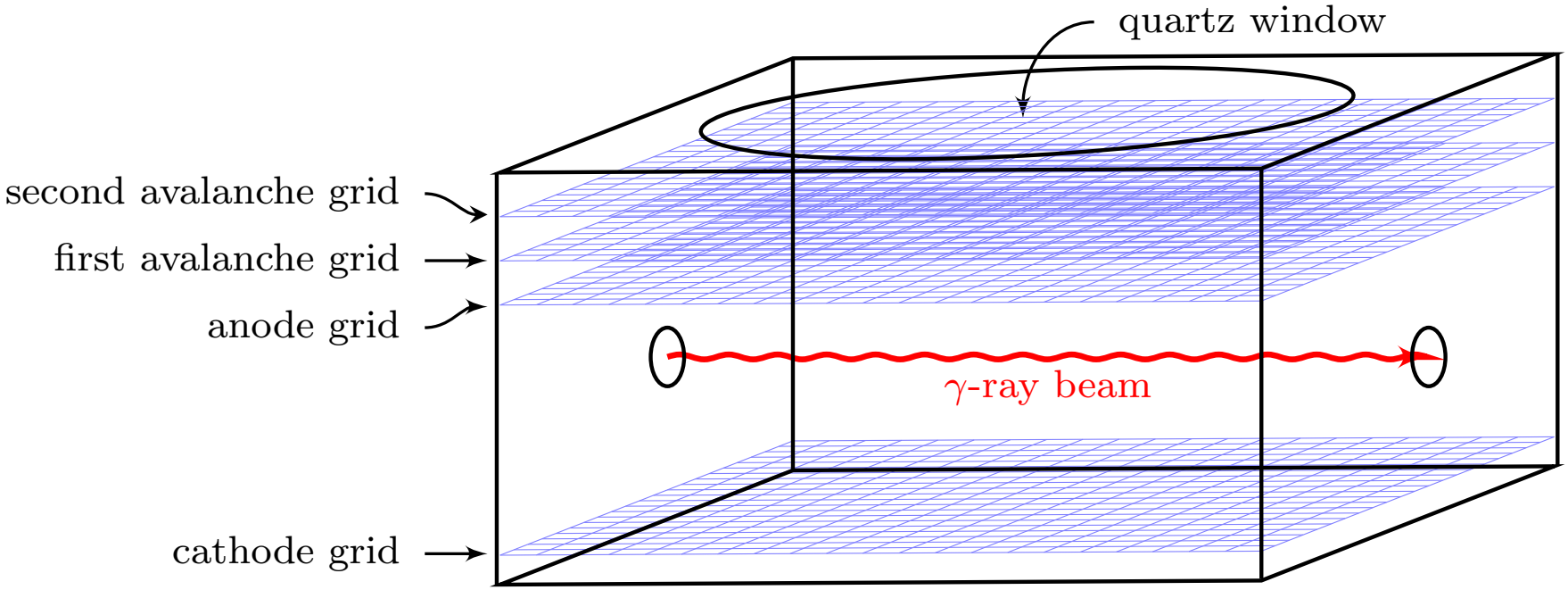


HIγS O-TPC



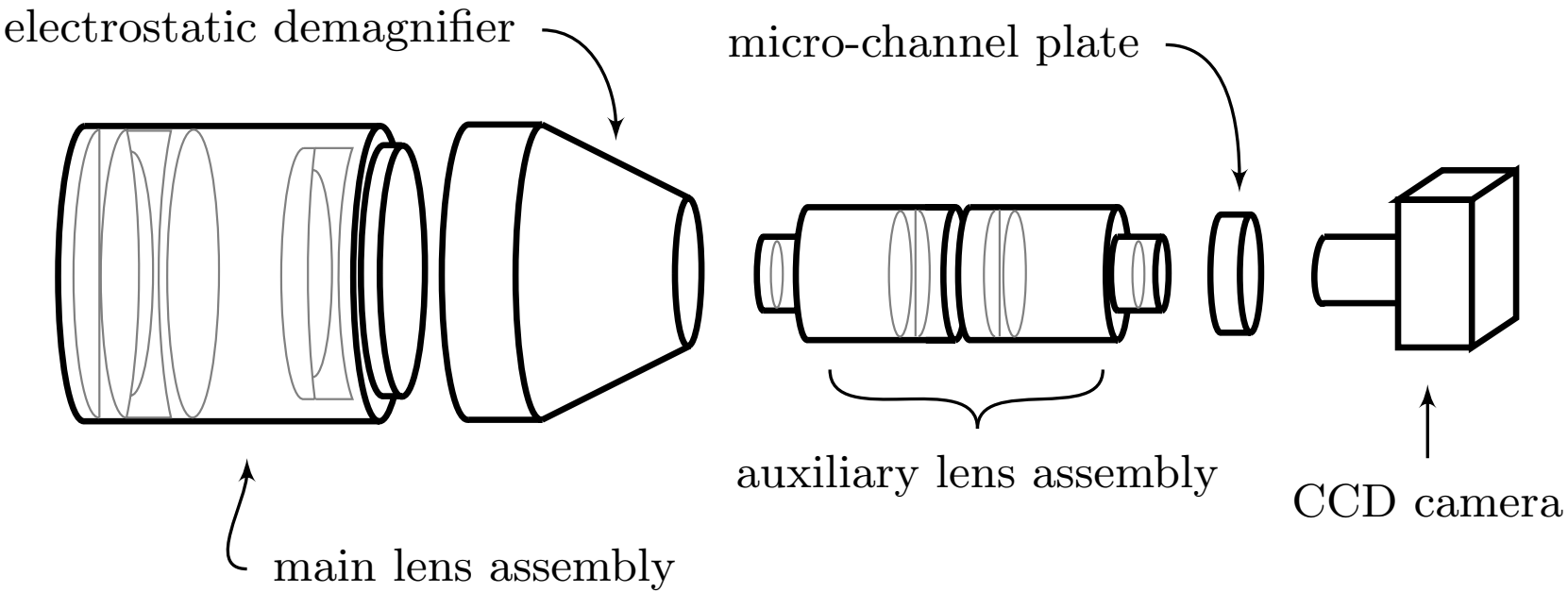
HIγS O-TPC

Drift Chamber

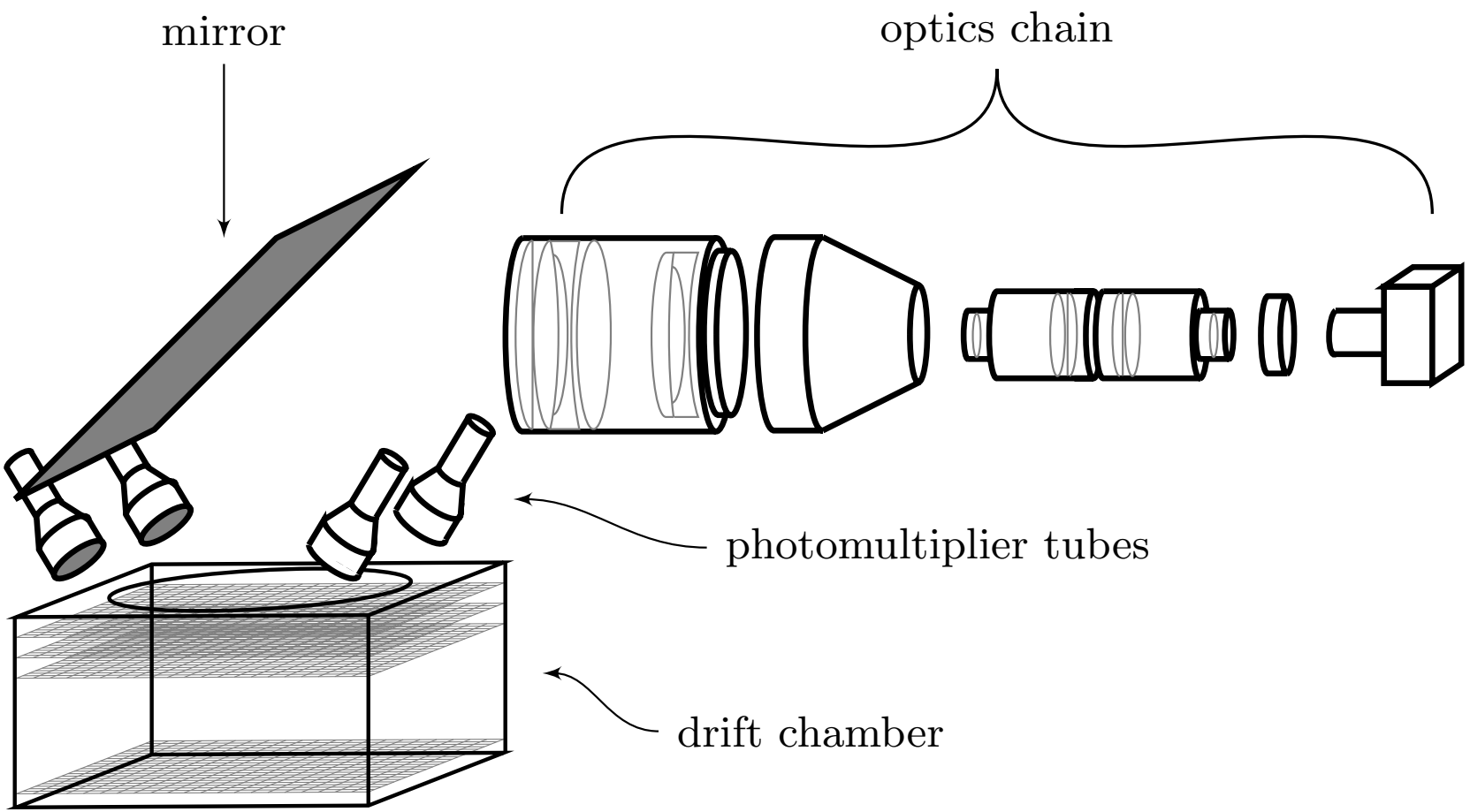


HIγS O-TPC

Optics Chain

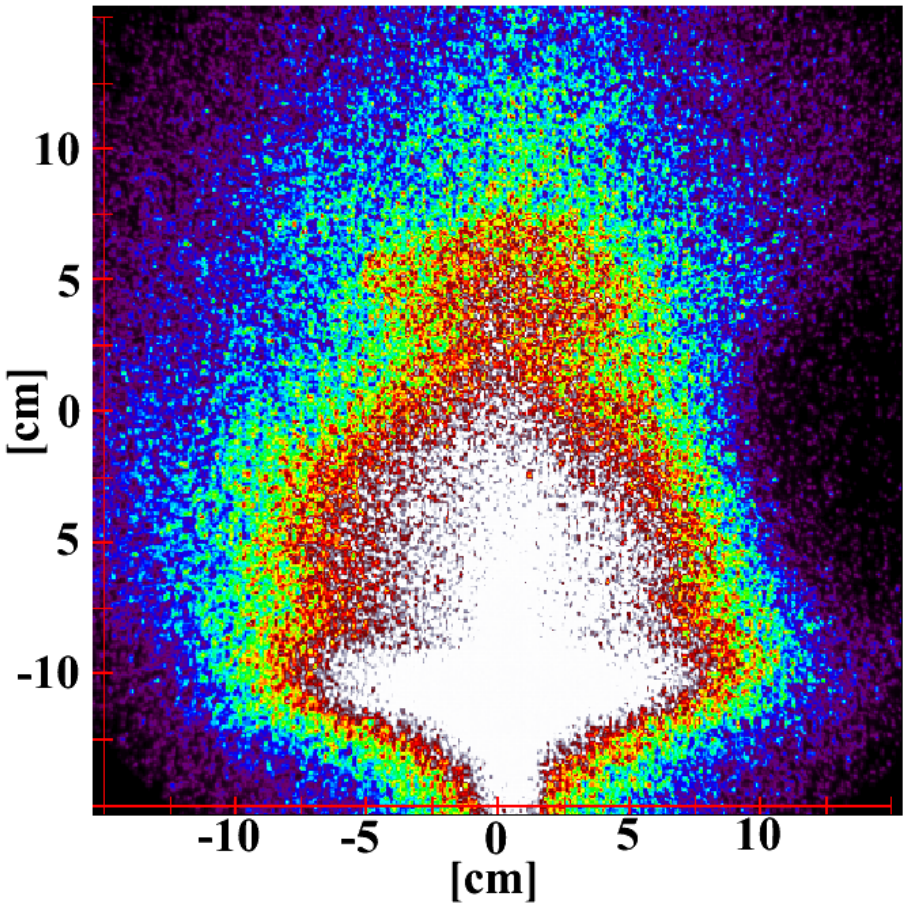


HIγS O-TPC

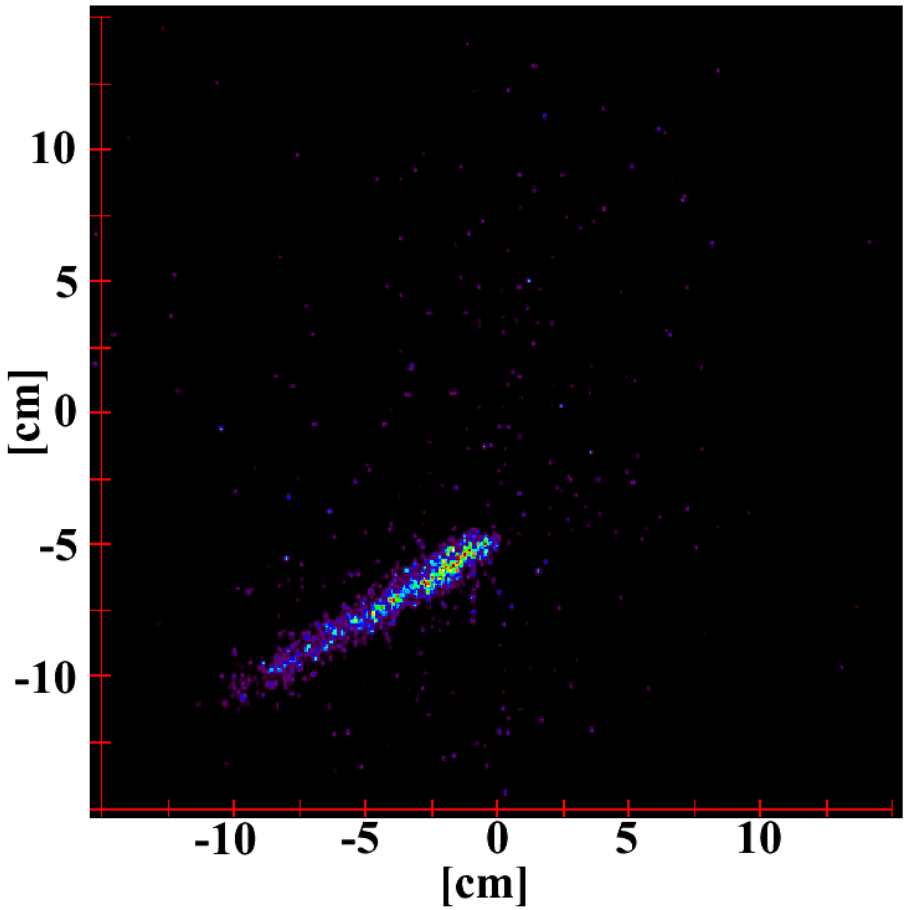


Background Rejection

Spark

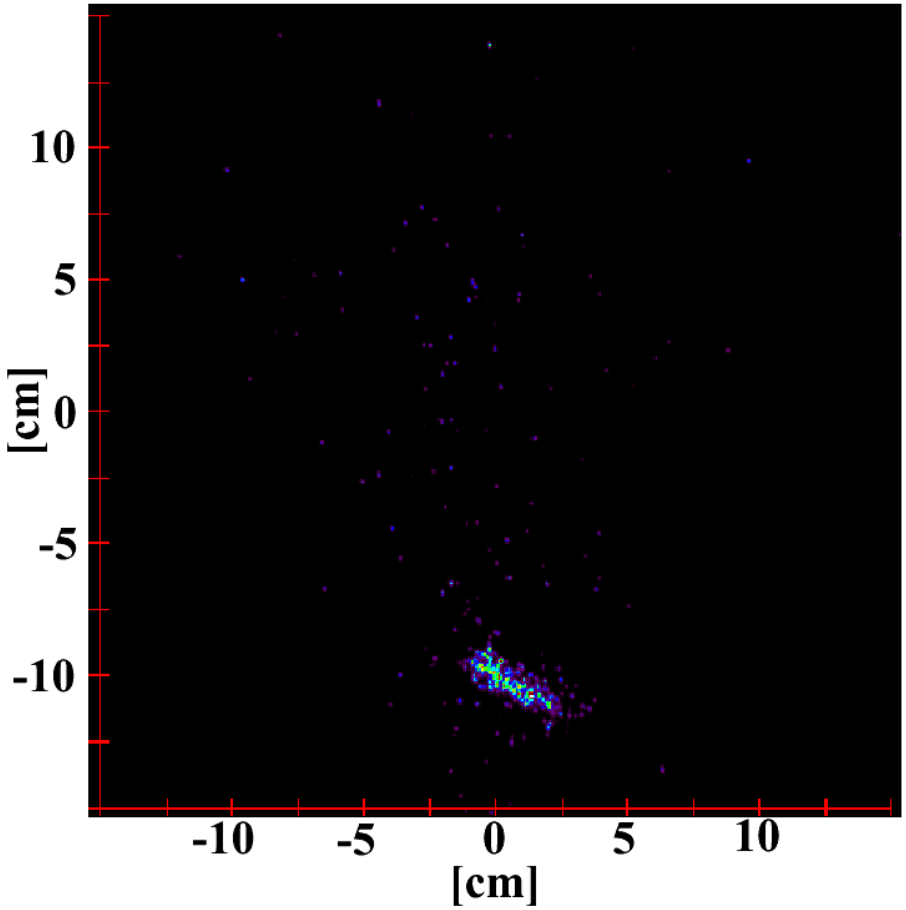


Cosmic

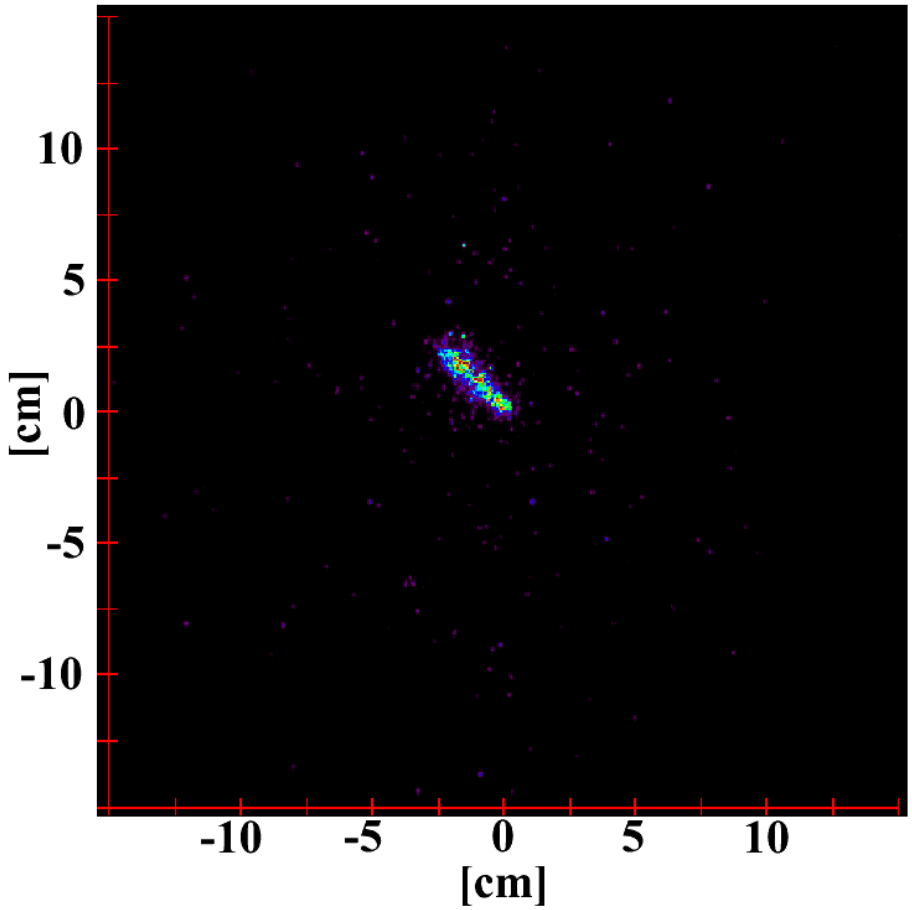


Event Identification

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

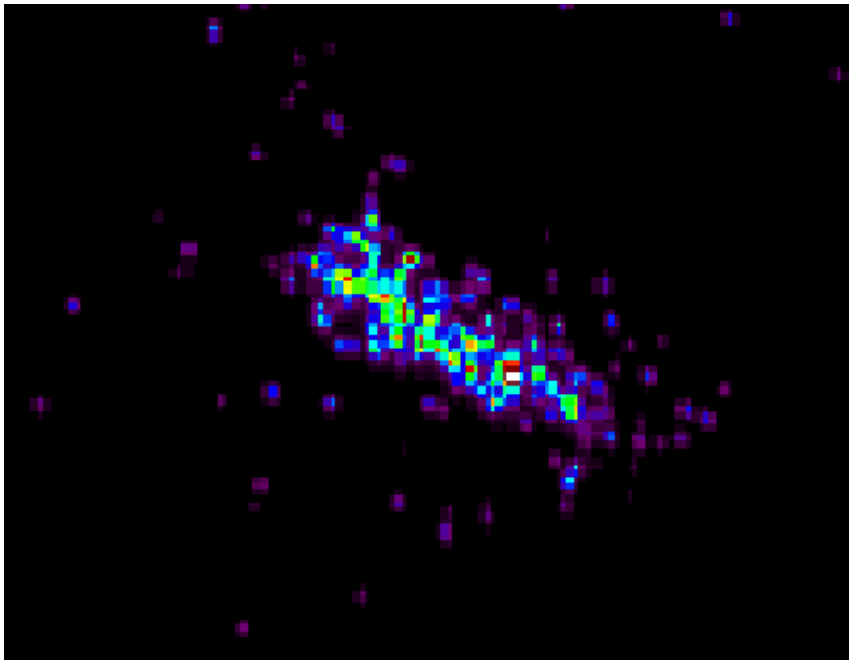


$^{16}O(\gamma,\alpha)^{12}C$

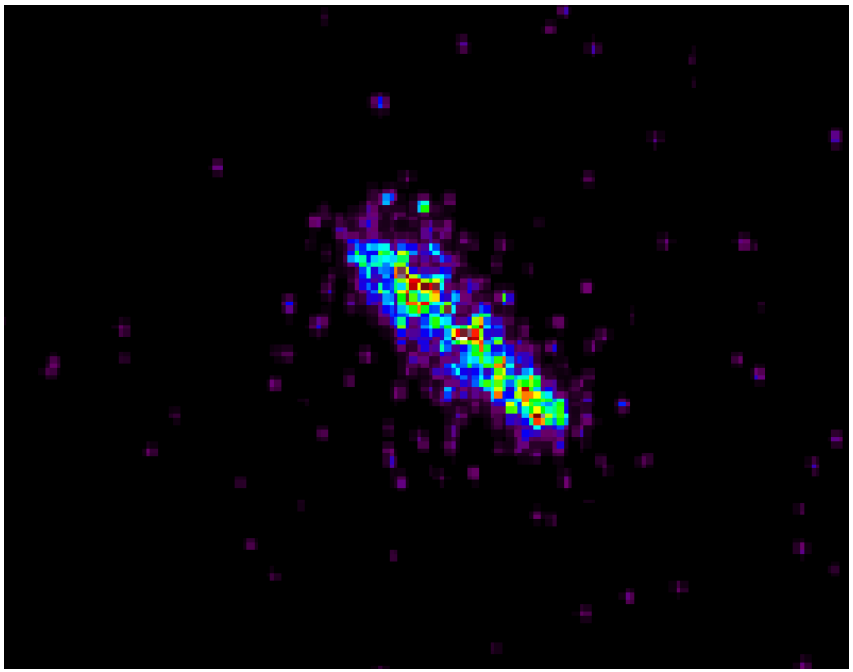


Event Identification

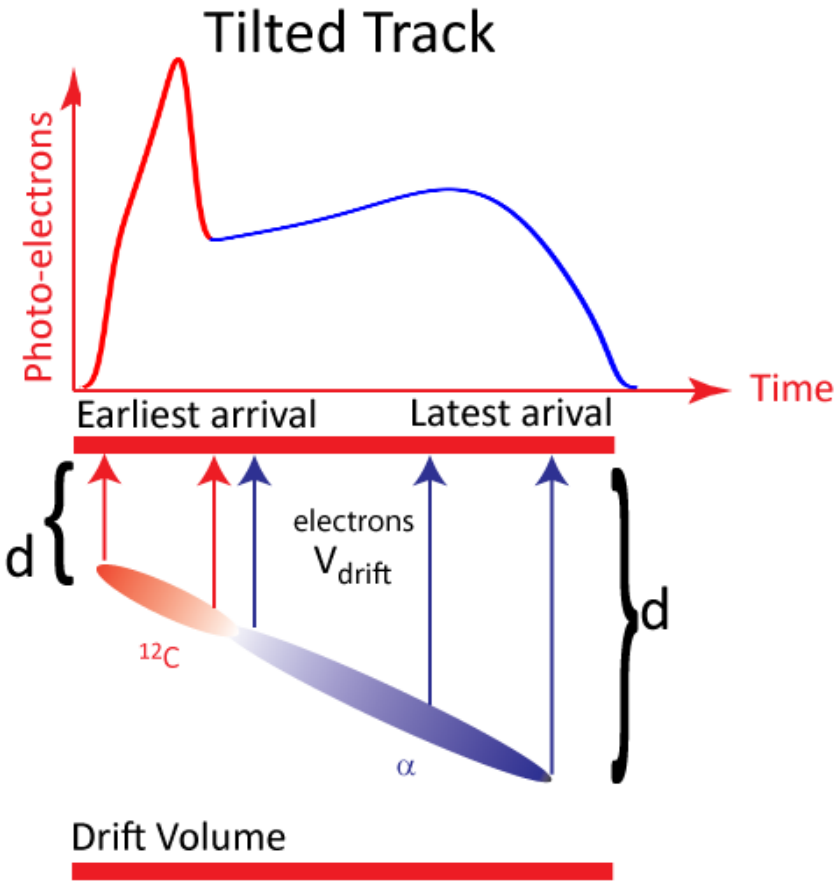
$^{12}C(\gamma,\alpha)^{8}Be$

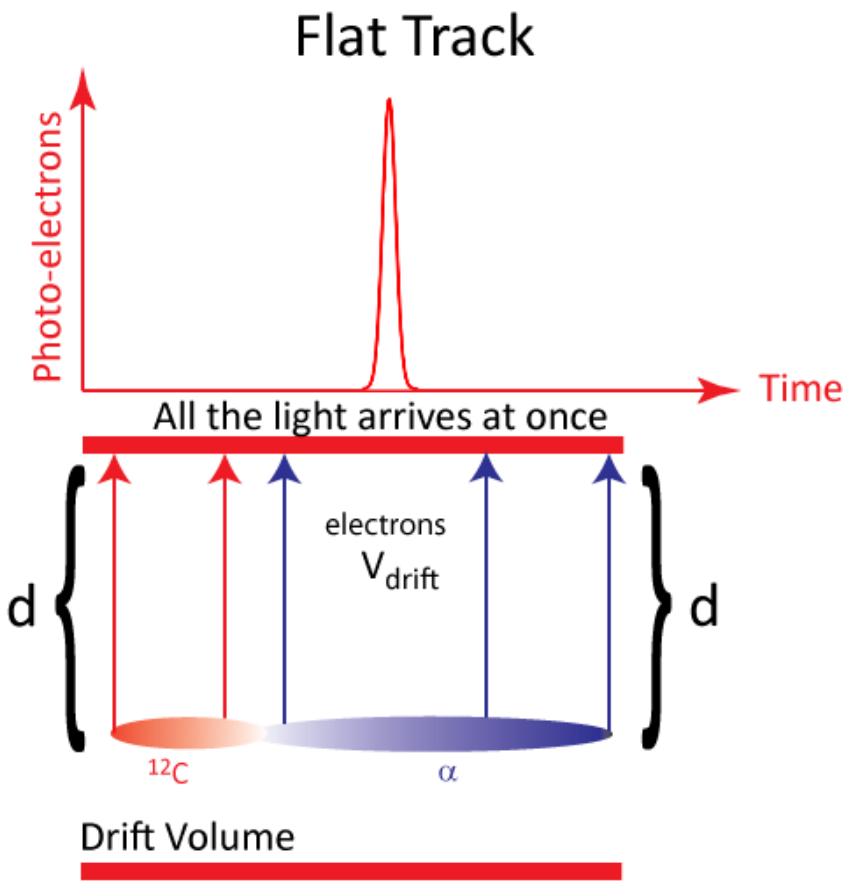


$^{16}O(\gamma,\alpha)^{12}C$



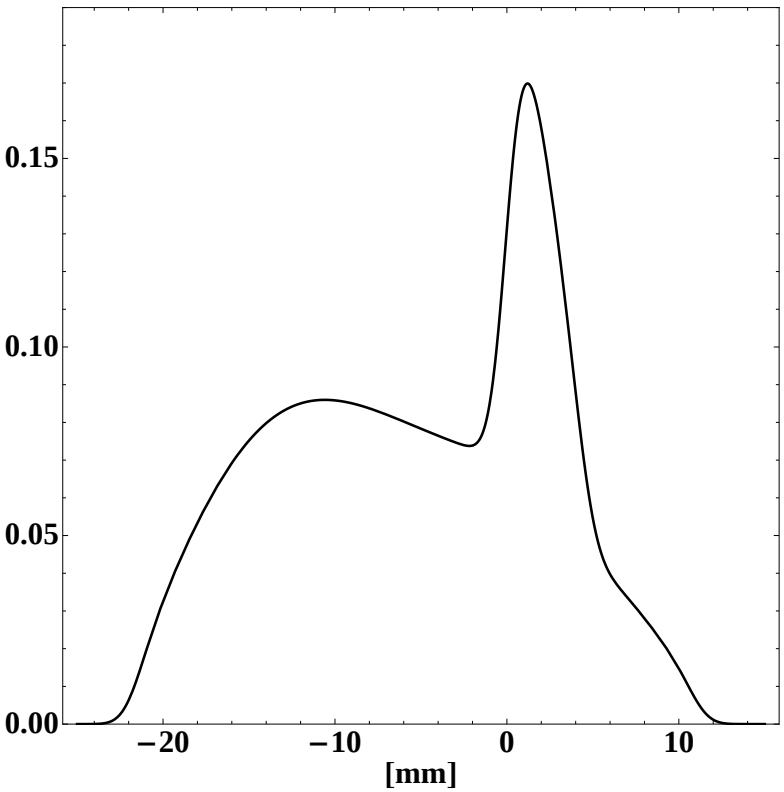
Time Projection



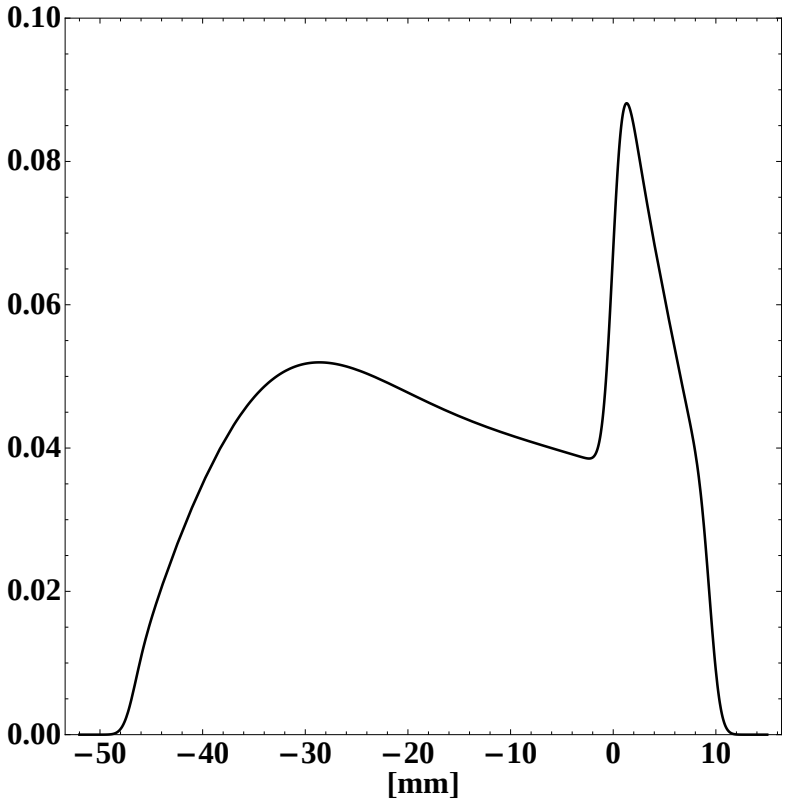


Time Projection

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

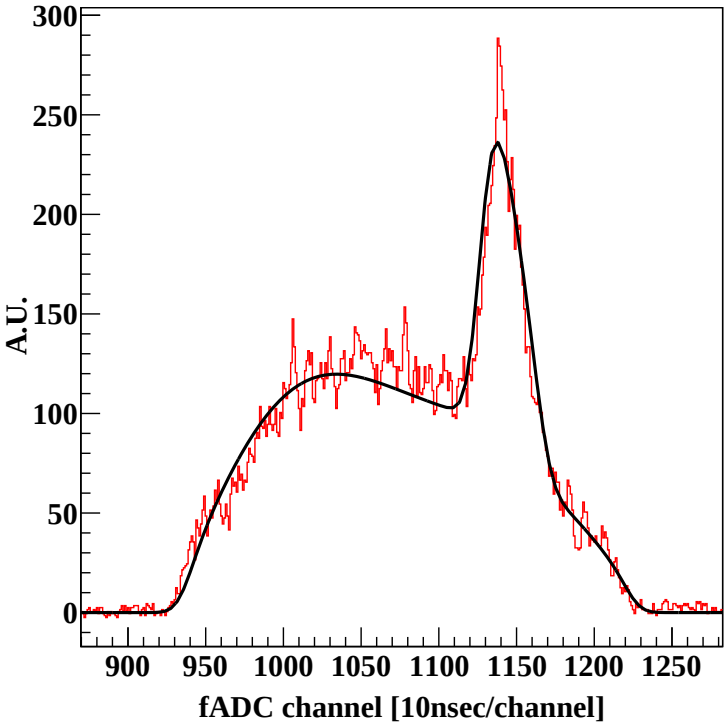


$^{16}O(\gamma,\alpha)^{12}C$

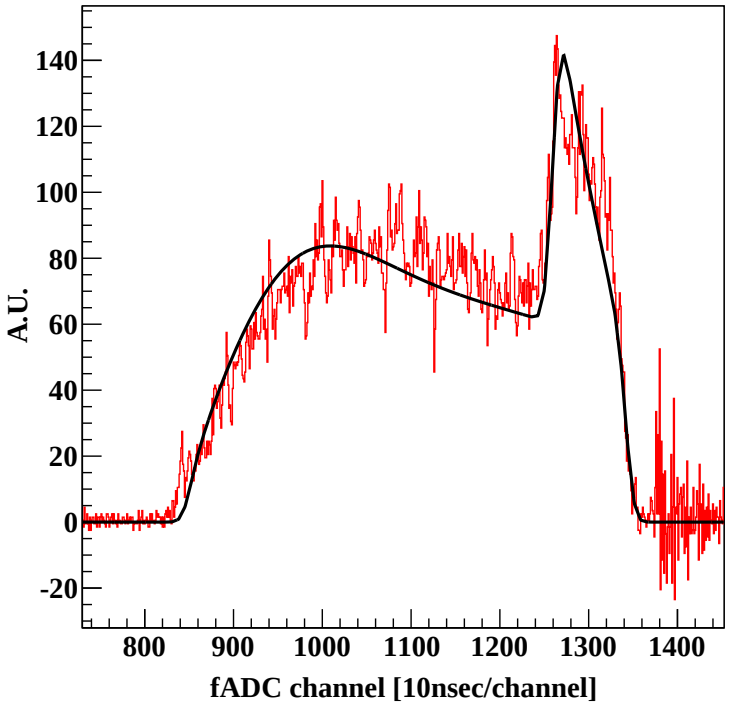


Time Projection

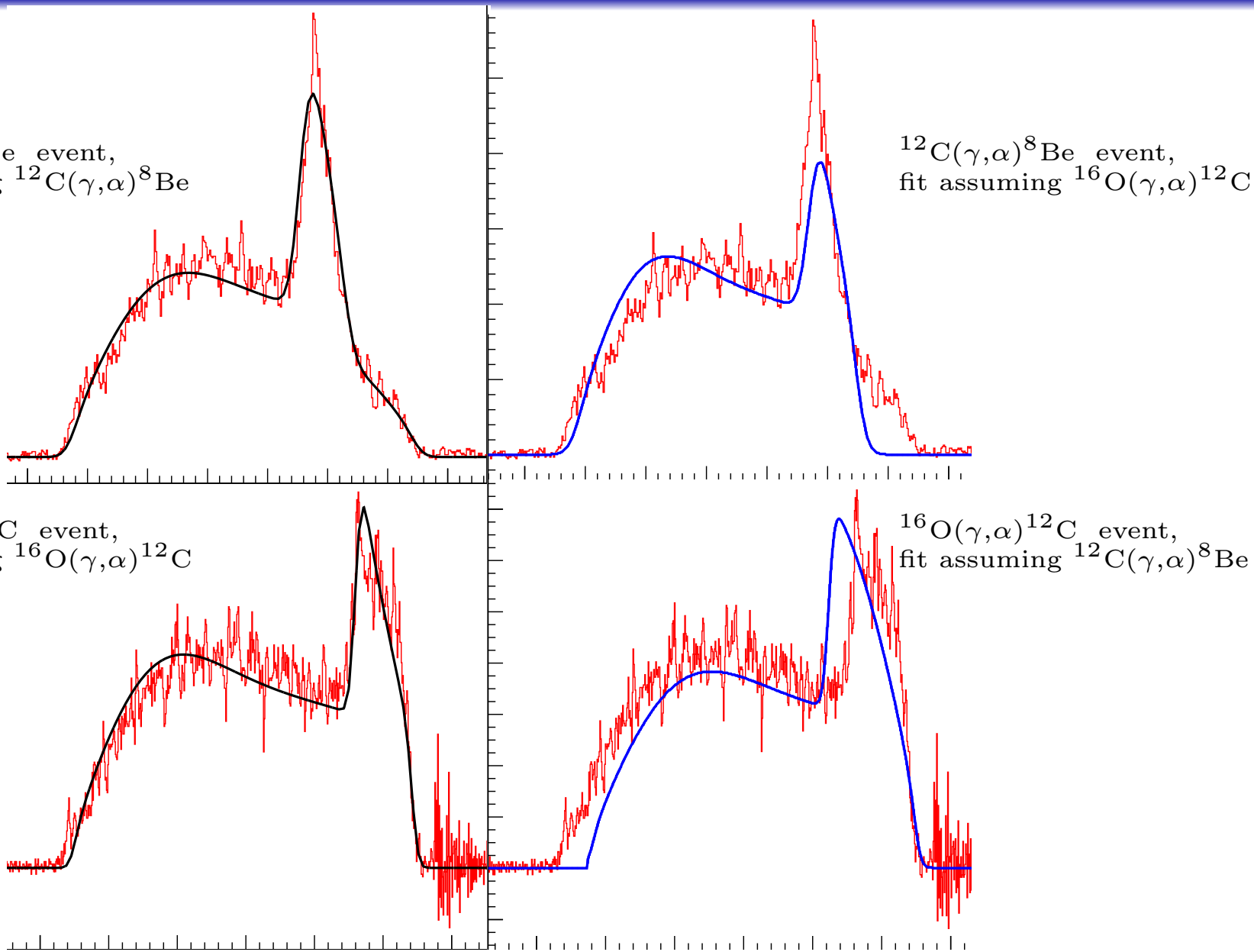
$^{12}C(\gamma,\alpha)^{8}Be$



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



Time Projection



Angular Distributions

- θ was calculated for each event from the track image and from the time projection.

Angular Distributions

- θ was calculated for each event from the track image and from the time projection.
- Angular distributions were fit in terms of $|E1|$, $|E2|$, ϕ_{12}:

$$W(\theta) = \frac{3}{2}\sin^2\theta \times \left(3|E1|^2 + 25|E2|^2\cos^2\theta + 10\sqrt{3}|E1||E2|\cos\phi_{12}\cos\theta\right)$$

Angular Distributions

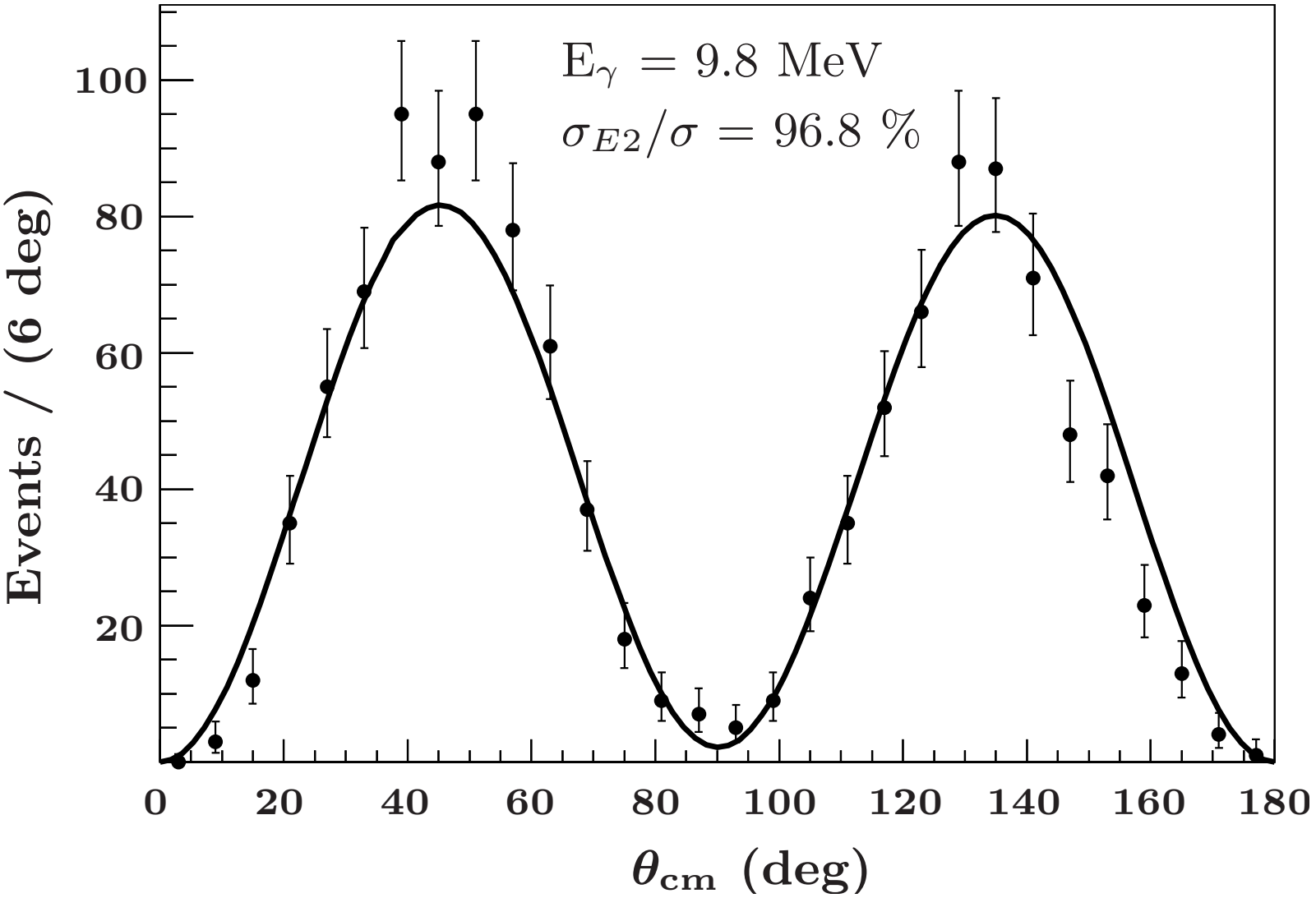
- θ was calculated for each event from the track image and from the time projection.
- Angular distributions were fit in terms of $|E1|$, $|E2|$, ϕ_{12}:

$$W(\theta) = \frac{3}{2}\sin^2\theta \times \left(3|E1|^2 + 25|E2|^2\cos^2\theta + 10\sqrt{3}|E1||E2|\cos\phi_{12}\cos\theta\right)$$

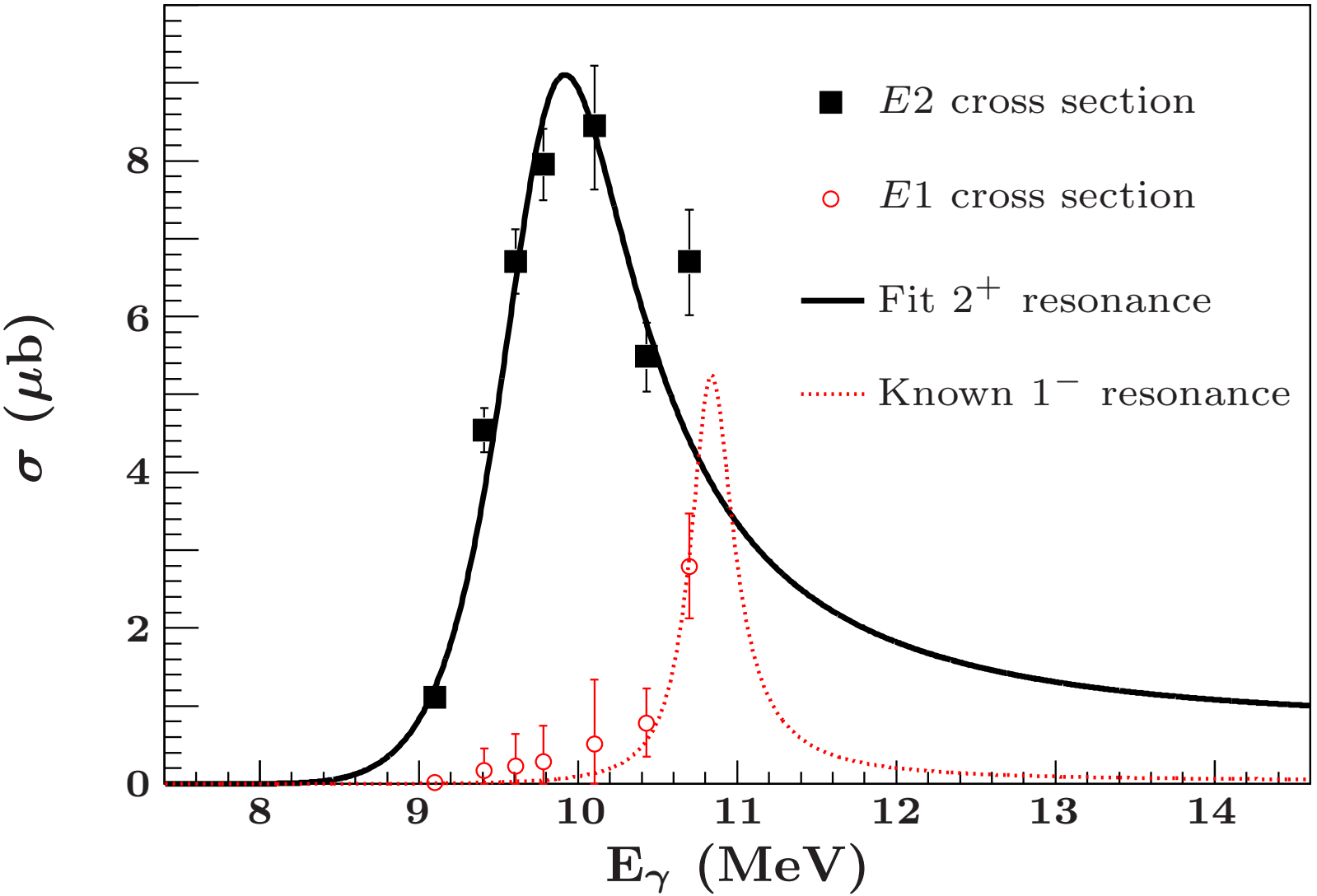
- Since angular information is available for each event, Unbinned Maximum Likelihood fits were used.

$$\mathcal{L}(|E1|, |E2|, \phi_{12}) = \prod_{i=1}^{n} W(\theta_i)$$

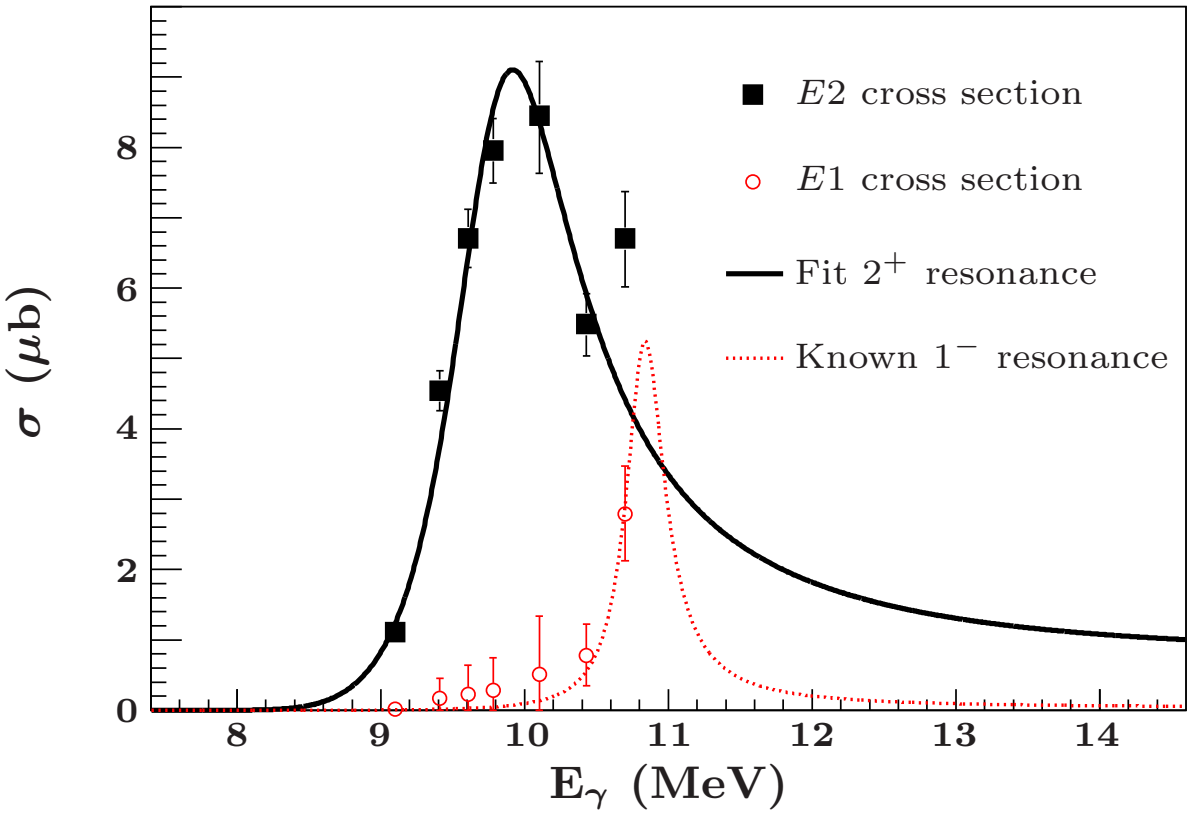
Angular Distributions



Cross Section



Cross Section



E_{res} (MeV)	Γ_α(res) (keV)	Γ_{γ_0}(res) (meV)	B($E2 : 2_2^+ \rightarrow 0_1^+$) ($e^2fm^4$)
10.03(11)	800(130)	60(10)	0.73(13)

Phase

$E1$-$E2$ phase difference:

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

Phase

$E1$-$E2$ phase difference:

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

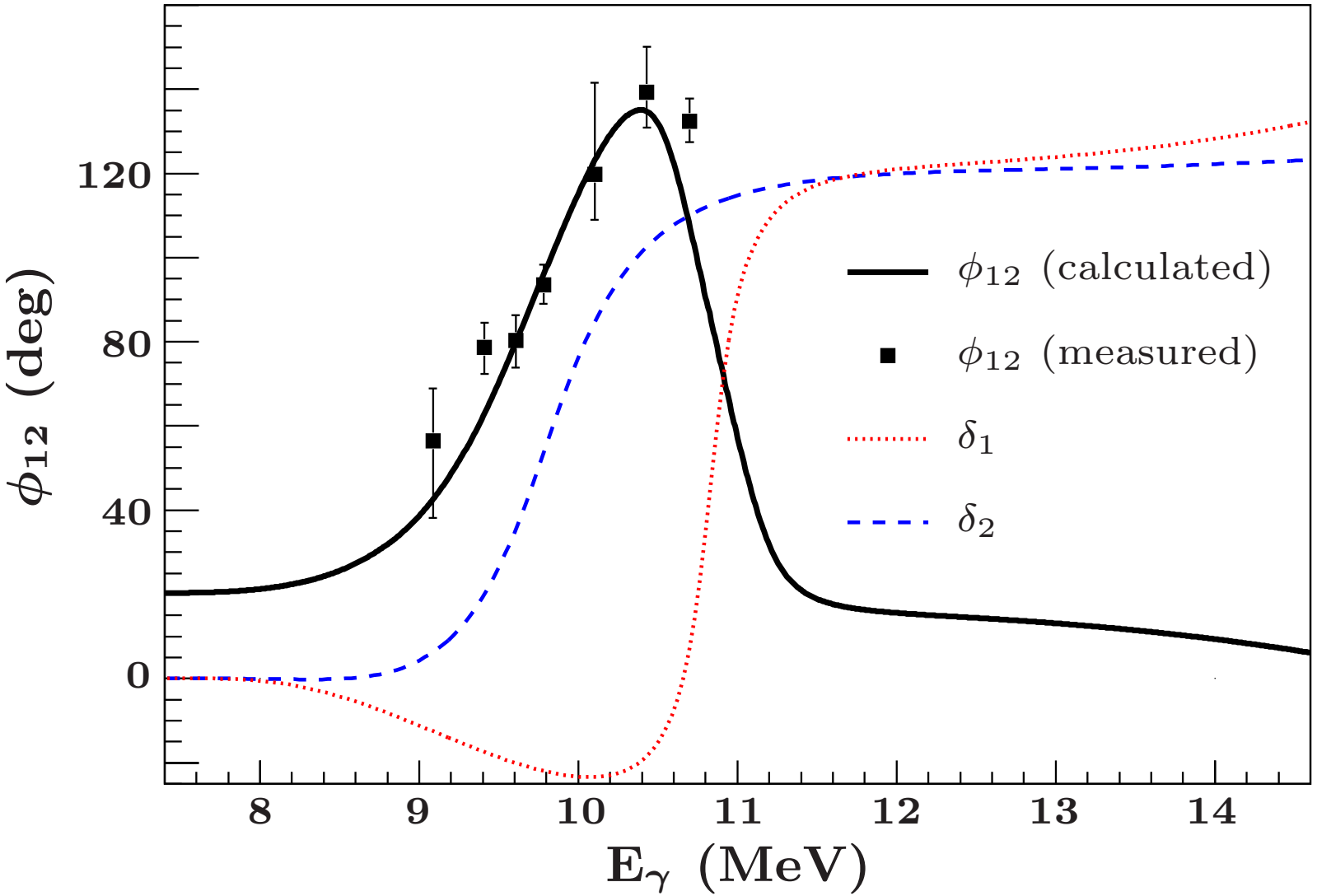
Nuclear phase shifts:

$$\delta_\ell = \arctan\left(\frac{\Gamma_\ell}{2\left(E_{r\ell} - \Delta_\ell - E_{cm}\right)}\right) - \phi_\ell$$

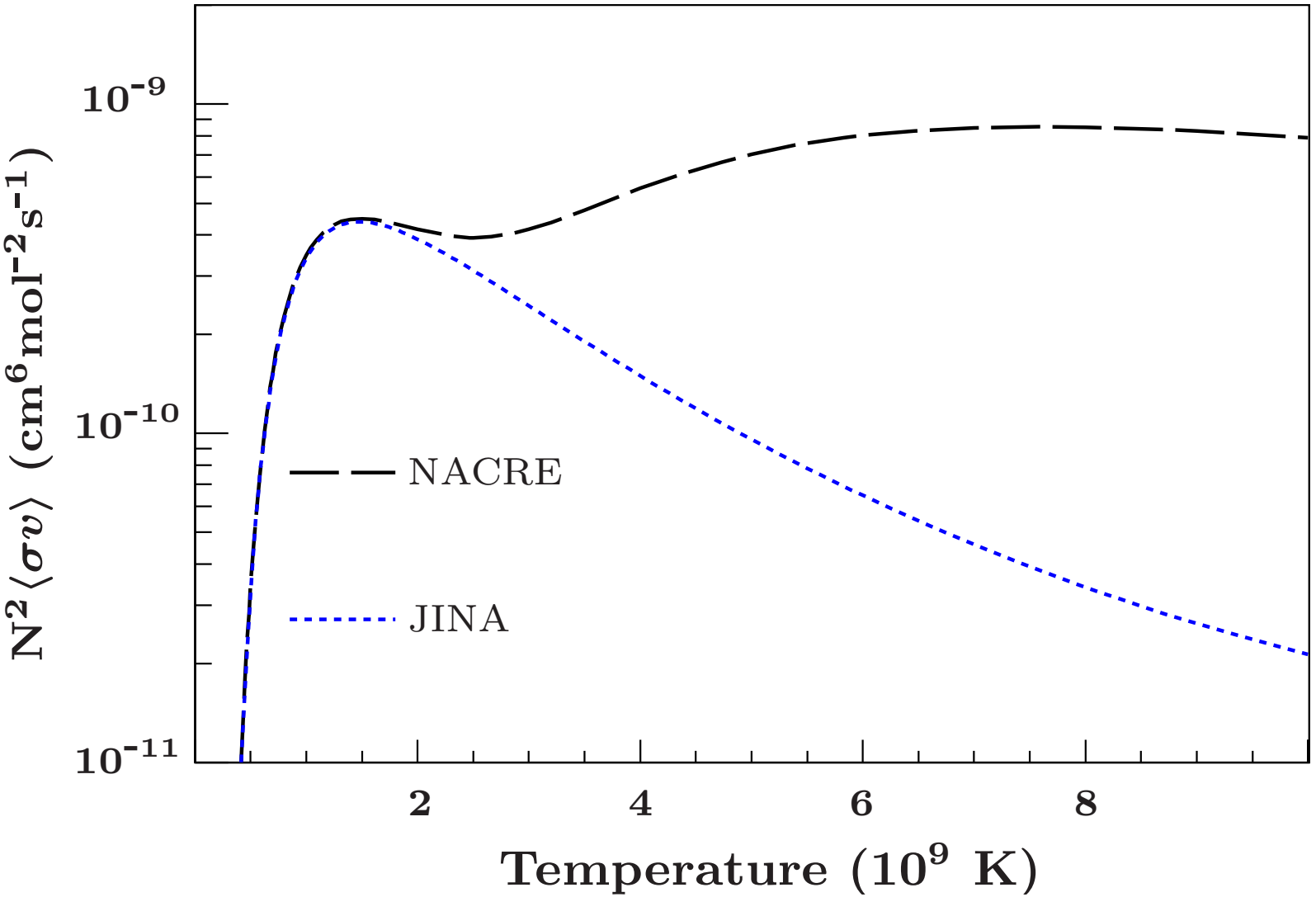
Hard sphere scattering phase shift:

$$\phi_\ell = \arctan\left[\frac{F_\ell}{G_\ell}\right]_{r=a}$$

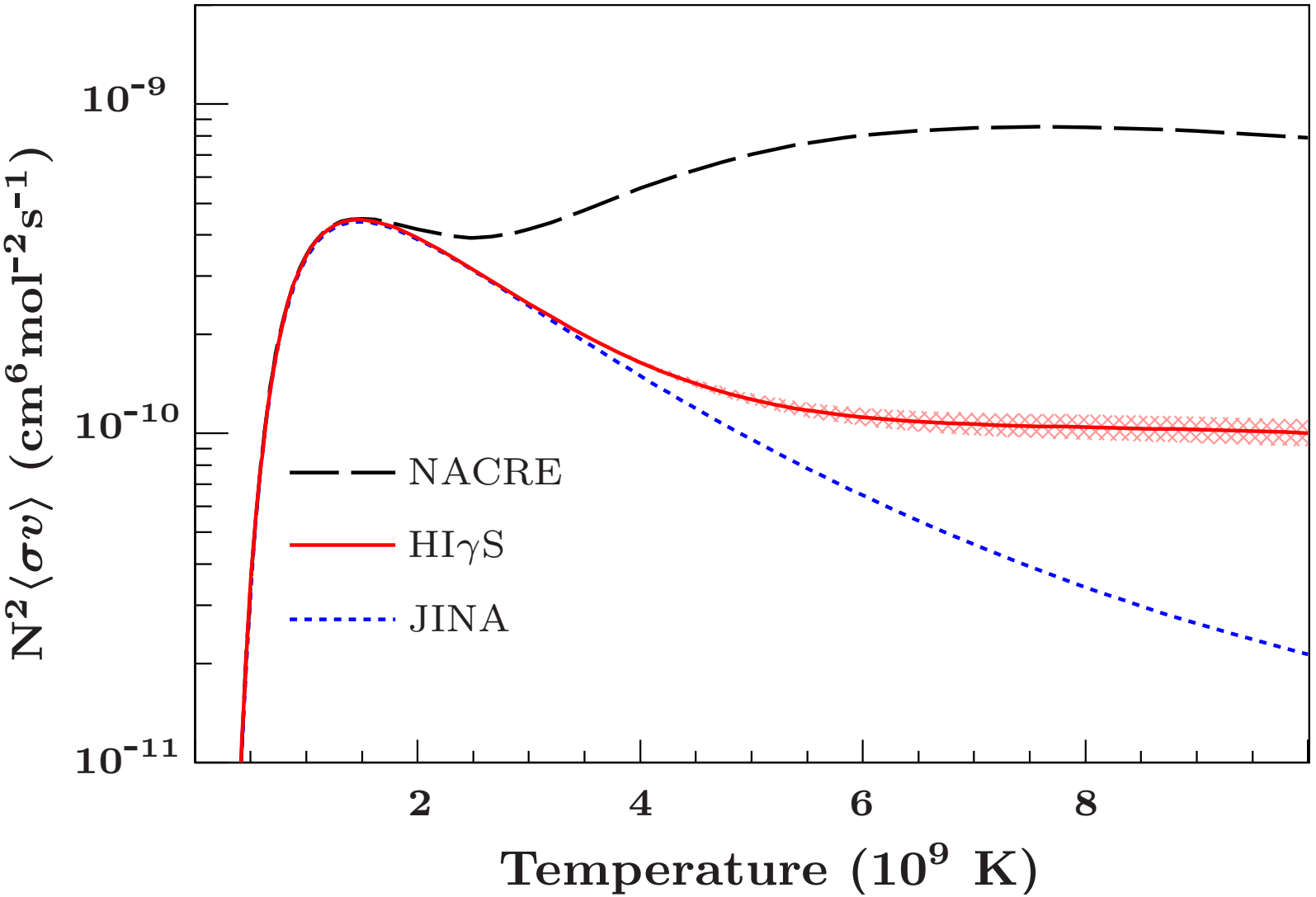
Phase


ϕ_{12} (deg)
120
80
40
0
8
9
10
11
12
13
14
E_γ (MeV)
ϕ_{12} (calculated)
ϕ_{12} (measured)
δ_1
δ_2

Triple-α Reaction Rates



Triple-α Reaction Rates



Summary

2_2^+			
E_{res} (MeV)	Γ_α(res) (keV)	Γ_{γ_0}(res) (meV)	B($E2 : 2_2^+ \rightarrow 0_1^+$) ($e^2fm^4$)
10.03(11)	800(130)	60(10)	0.73(13)

- 2_2^+ in ^{12}C has been directly observed through the $^{12}C + \gamma \rightarrow 3\alpha$ reaction.

Summary

2_2^+				
	E_{res} (MeV)	Γ_α(res) (keV)	Γ_{γ_0}(res) (meV)	B($E2 : 2_2^+ \rightarrow 0_1^+$) ($e^2fm^4$)
HIγS	10.03(11)	800(130)	60(10)	0.73(13)
EFT	9.65			2(1)

- 2_2^+ in ^{12}C has been directly observed through the $^{12}C + \gamma \rightarrow 3\alpha$ reaction.
- Recent *ab initio* EFT lattice calculations performed by Epelbaum, Krebs, Lähde, Lee, and Meißner predict the 2_2^+ 2 MeV above the Hoyle State.

Summary

2_2^+				
	E_{res} (MeV)	Γ_α(res) (keV)	Γ_{γ_0}(res) (meV)	B($E2 : 2_2^+ \rightarrow 0_1^+$) ($e^2fm^4$)
HIγS	10.03(11)	800(130)	60(10)	0.73(13)
EFT	9.65			2(1)

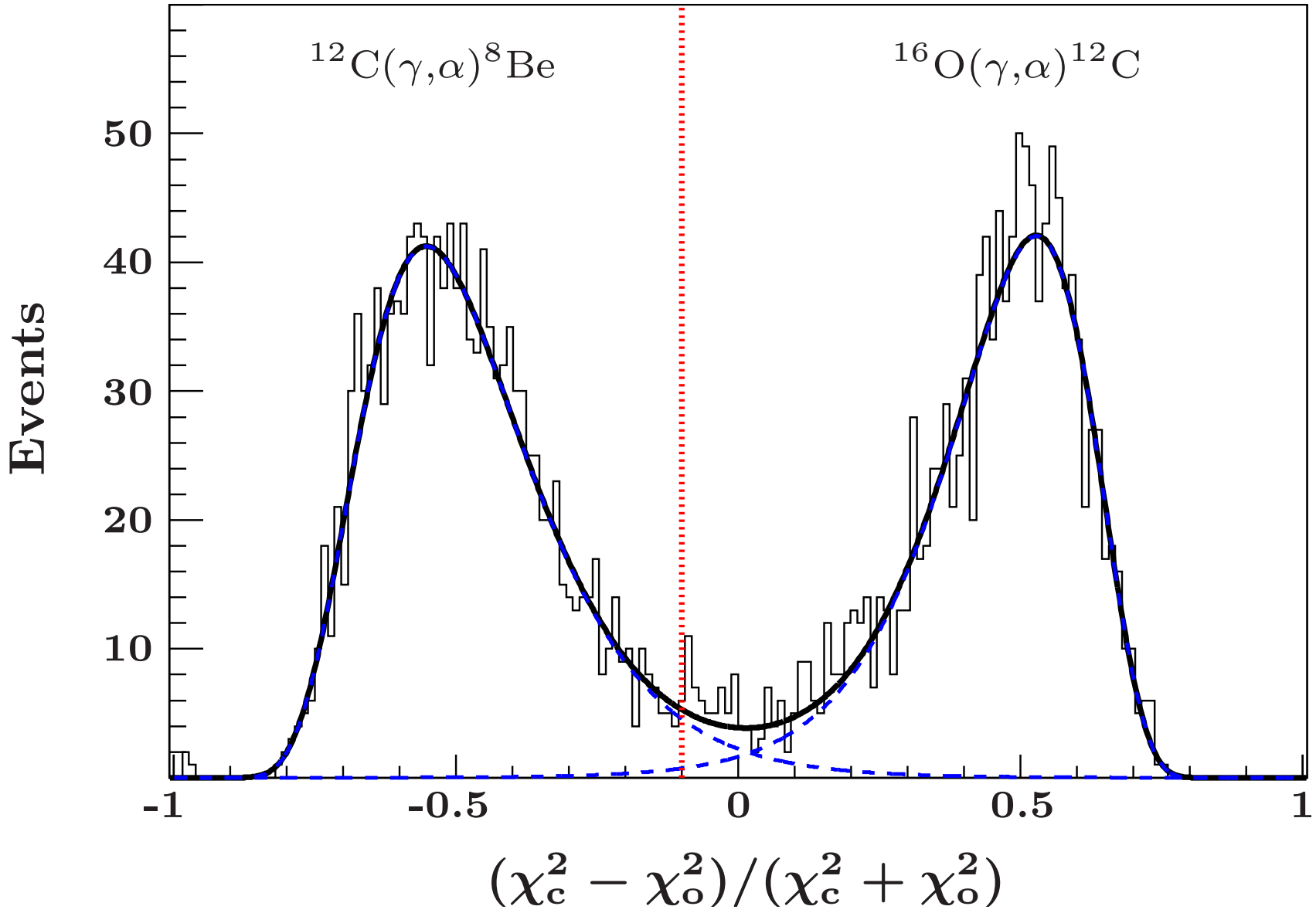
- 2_2^+ in ^{12}C has been directly observed through the $^{12}C + \gamma \rightarrow 3\alpha$ reaction.
- Recent *ab initio* EFT lattice calculations performed by Epelbaum, Krebs, Lähde, Lee, and Meißner predict the 2_2^+ 2 MeV above the Hoyle State.
- Revised triple-α reaction rates can affect nucleosynthesis of heavy elements during explosive astrophysics scenarios.

Acknowledgments

Mohammad Ahmed, Seth Henshaw, Jonathan Mueller,
Sean Stave, and Henry Weller
Triangle Universities Nuclear Laboratory

Moshe Gai
Laboratory for Nuclear Science at Avery Point

Event Identification



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