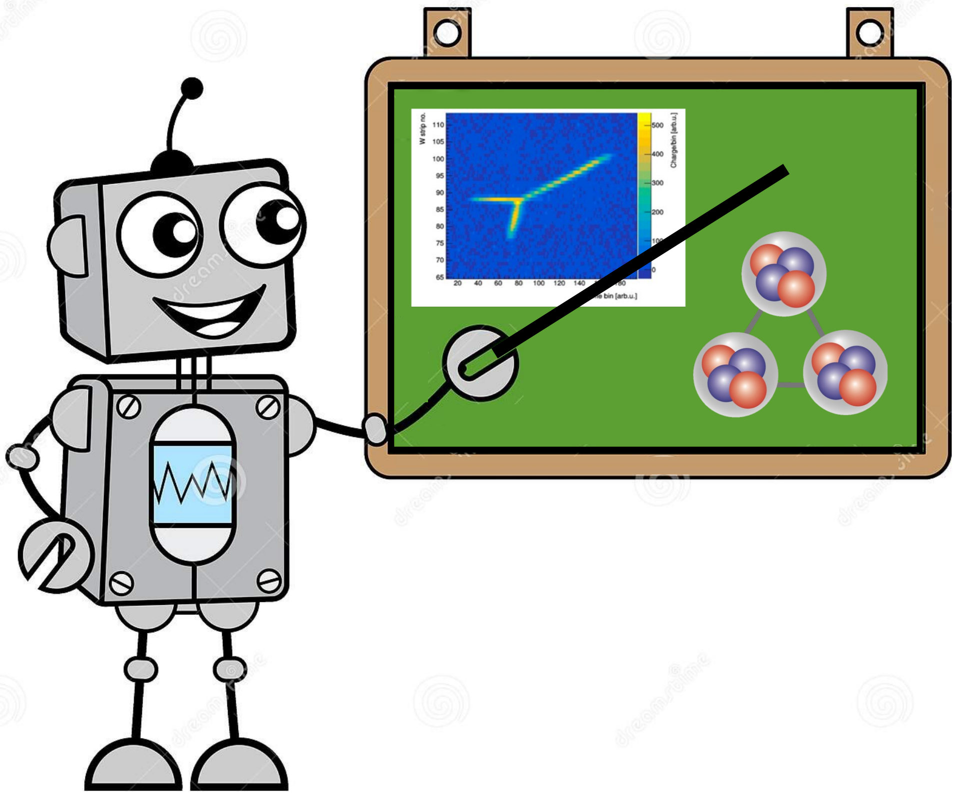
Investigating clustering in ^{12}C with gamma-beams and a TPC detector

Robin Smith, Kristian C. Z. Haverson



Sheffield Hallam University

UCONN
UNIVERSITY OF CONNECTICUT

WPCF 2023 – Catania – November 8th 2023

Collaborators

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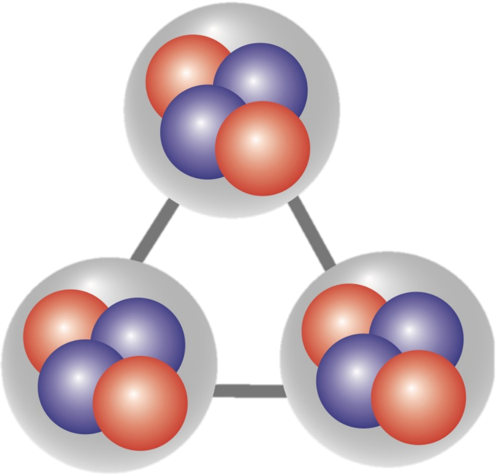
Overview

- Physics case – alpha clustering in ^{12}C
- Photo-excitation with gamma beams at HIgS
- Warsaw electronic TPC and experiment
- Data analysis challenges
- Event classification neural network
- Preliminary results



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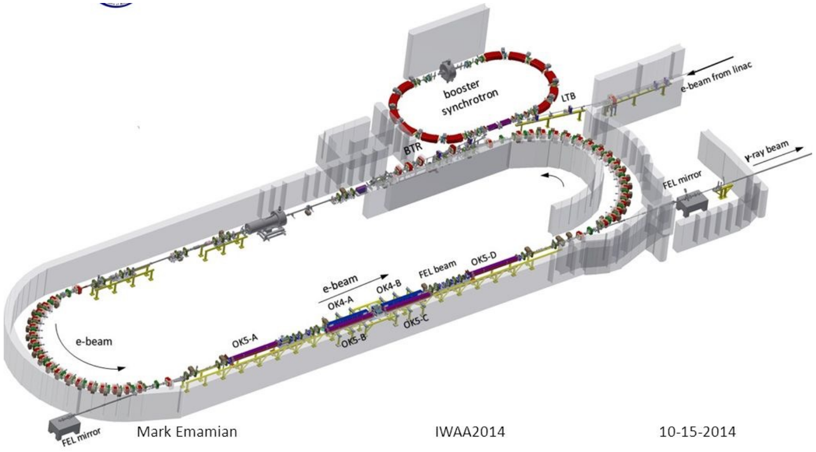

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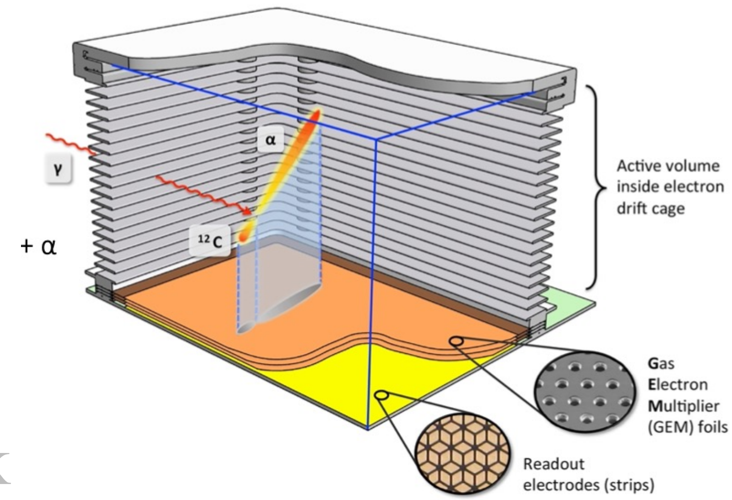

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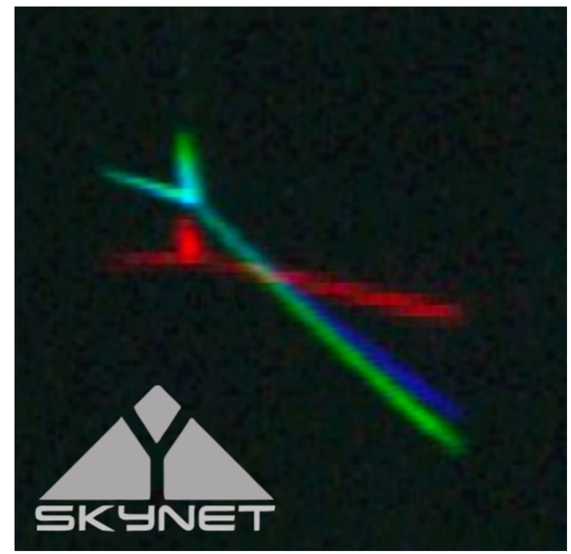

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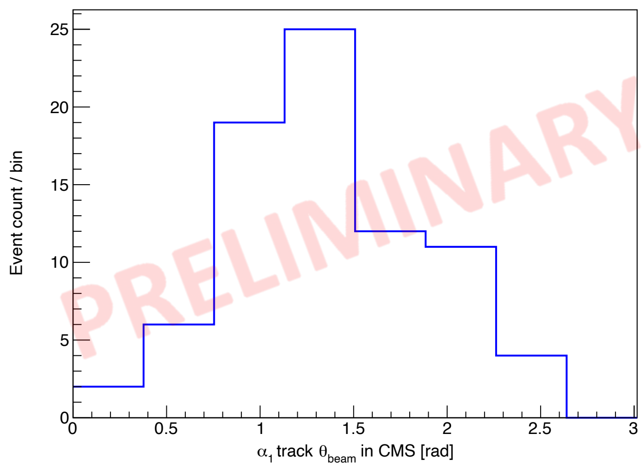
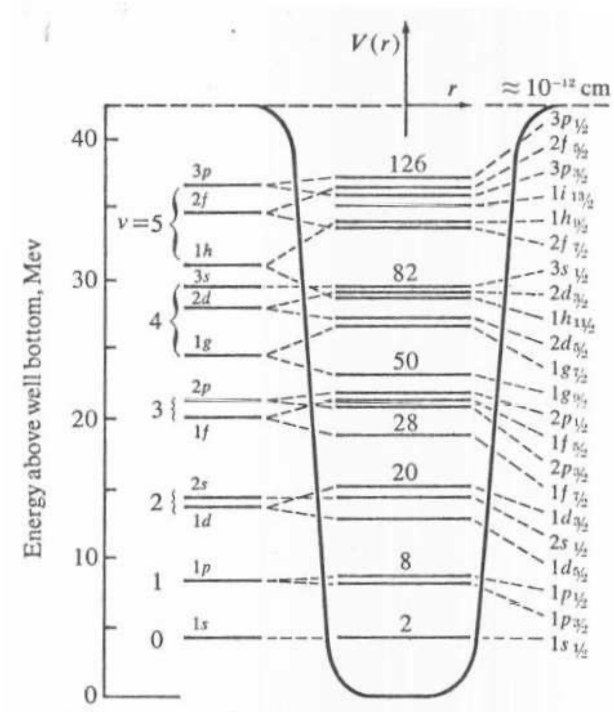


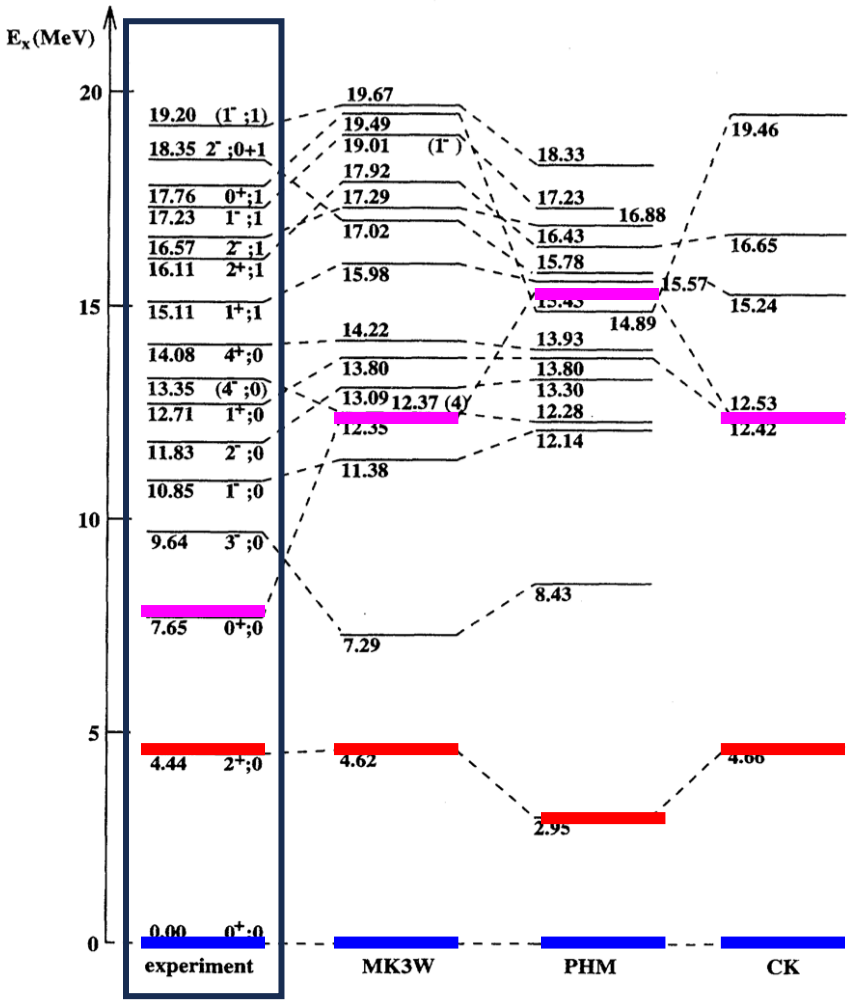
Nuclear physics – complexity to simplicity

- Atomic nuclei are a quantum many body problem
  - Ab initio calculations possible but intensive

- Develop simplified models to describe nuclear properties
  - Shell model
  - Very successful



^{12}C – Shell Model to alpha clustering

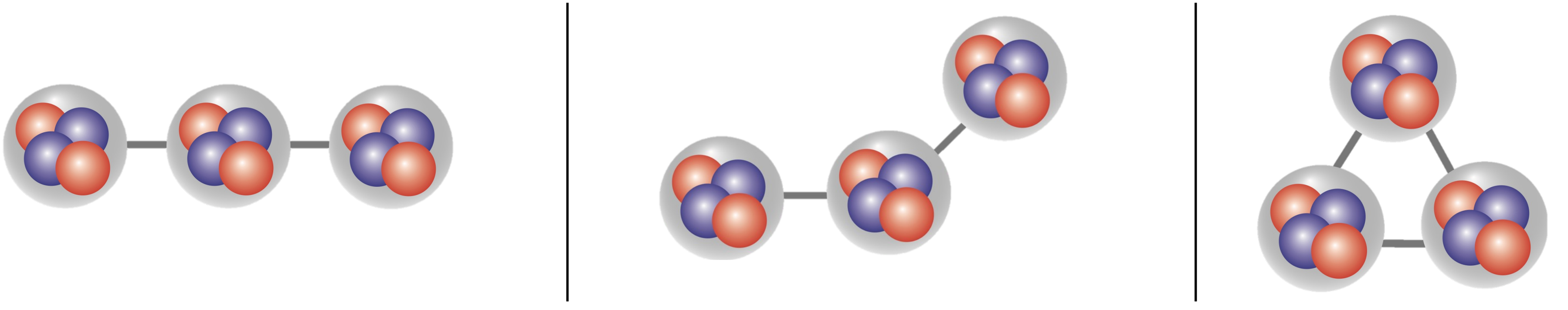


- **0$^+$ ground state** and **first excited 2$^+$ state** binding energies are well-reproduced
- **Hoyle state** systematically under-bound
- **Synthesised in nature – triple-α reaction**

S. Karataglidis, et al., Phys. Rev. C 52 (1995) 861.

F. Hoyle, Astrophys. J. Suppl. Ser. 1, 121 (1954).

Rotational Excitations: Nuclear Spinning Tops



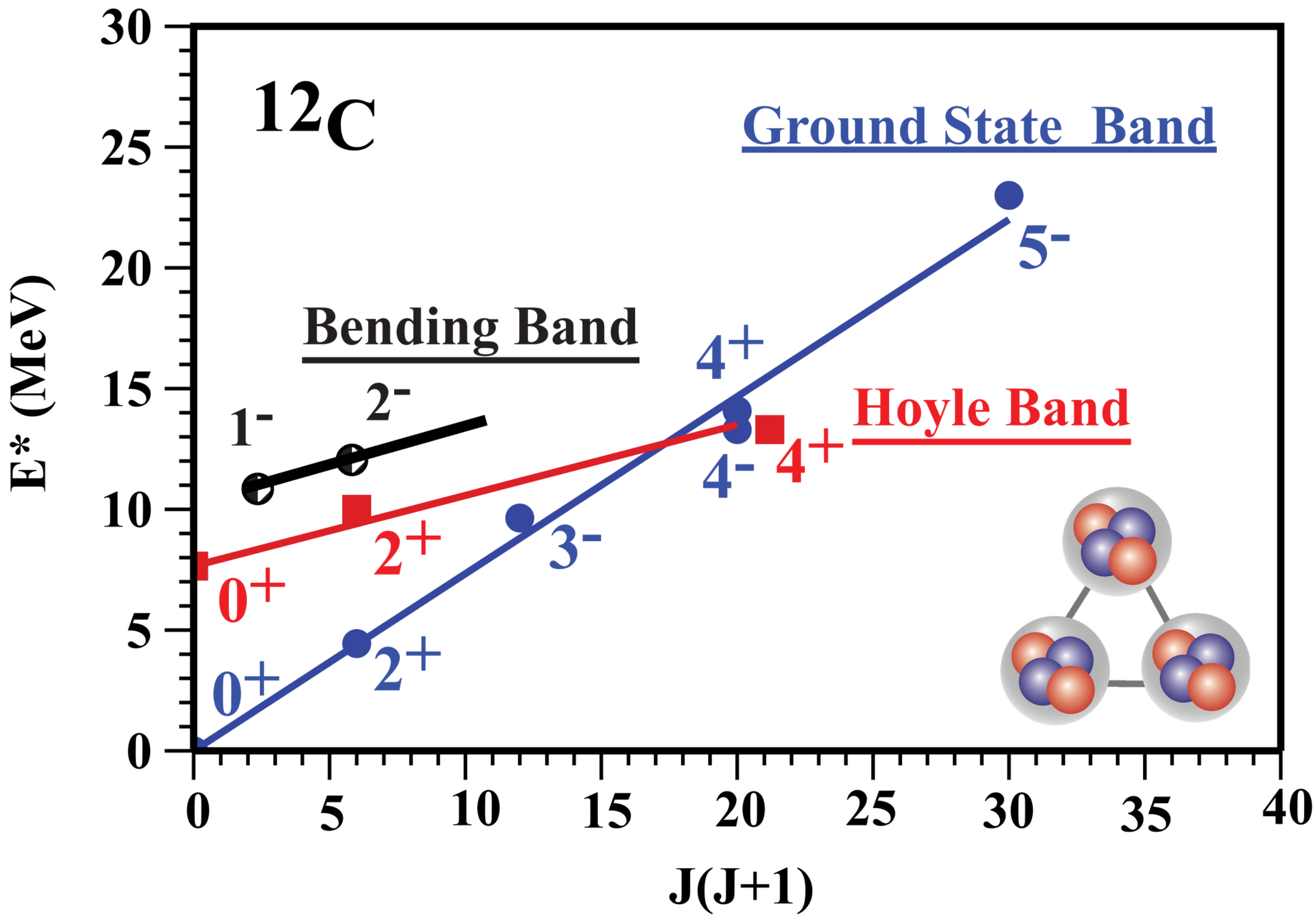
- Clustered nuclei can be excited by rotating the deformed system

- Deformed nuclei possess a moment of inertia, I

- $E_x = E_0 + \frac{\hbar^2}{2I} J(J+1)$

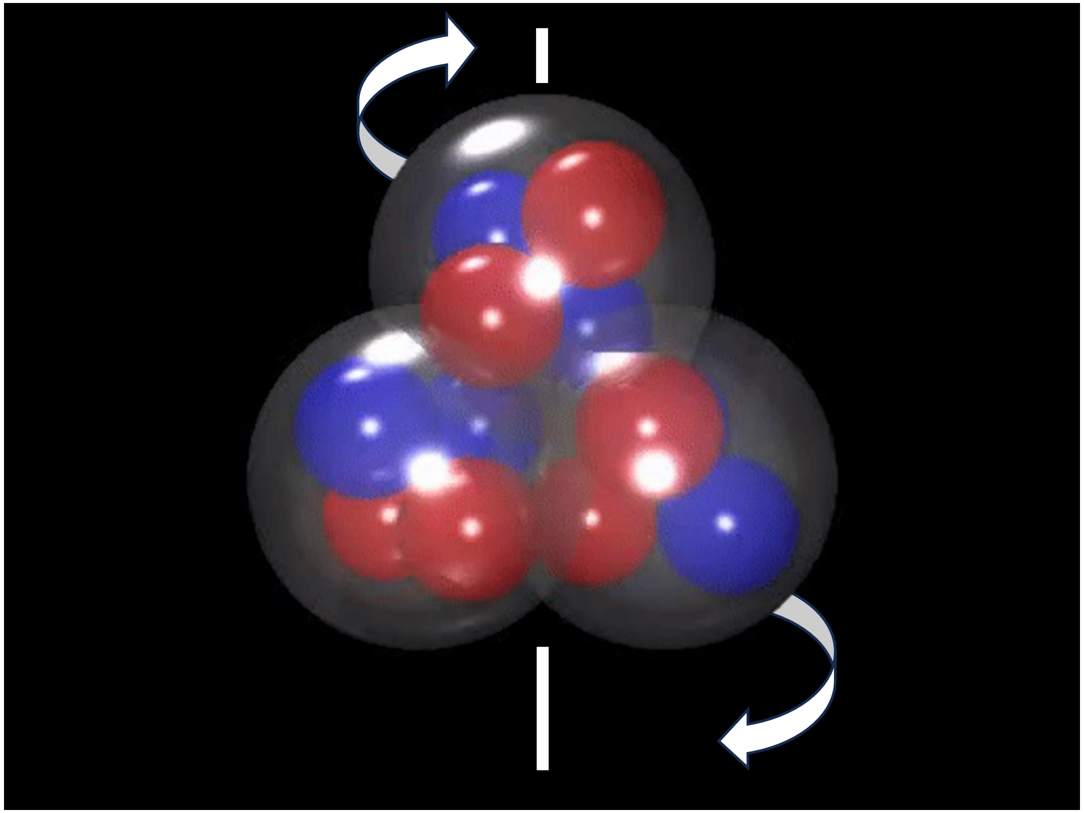
D. Jenkins, O. S. Kirsebom, Physics World, February 2013

Triangular D_{3h} Symmetry Algebraic Cluster Model



Bijker, R., & Iachello, F. (2002). *Annals of Physics*, *298*(2), 334-360.
D. J. Marin-Lambarri, et. al., Phys. Rev. Lett., 113, 012502 (2014).

Rotational Excitations



Generates states:

$0^+, 2^+, 4^+$

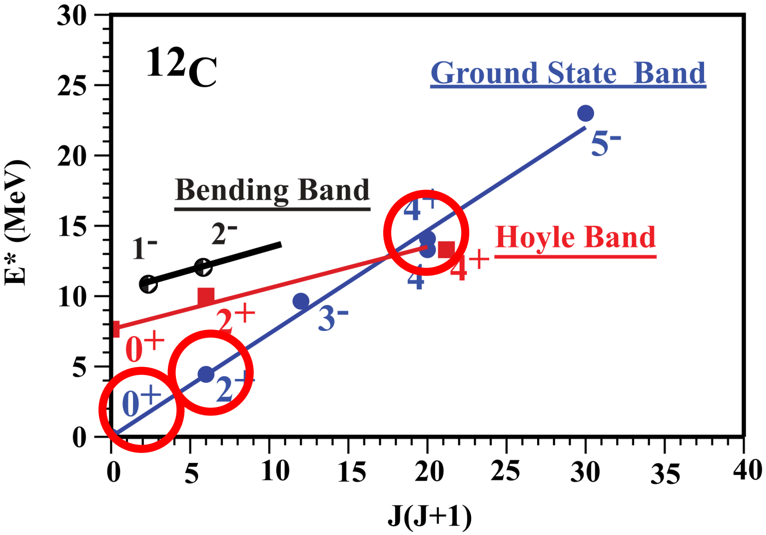
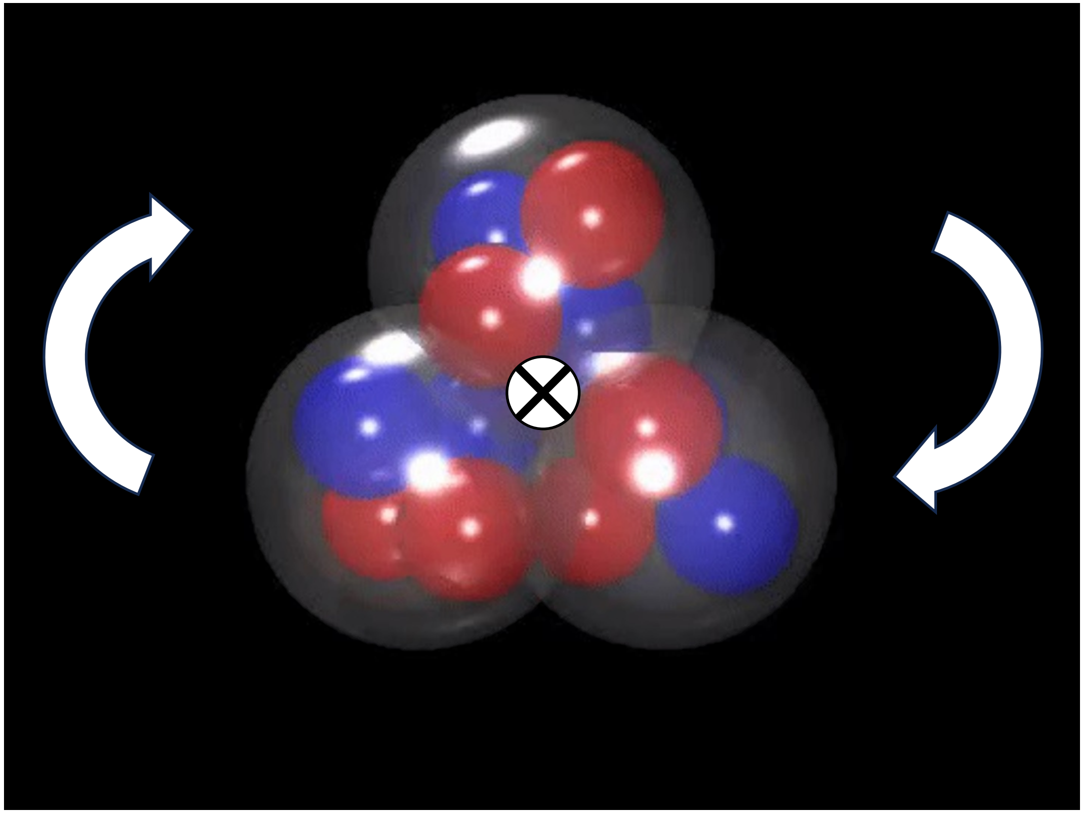


Image credit: M. Freer

Rotational Excitations



Generates state:

3⁻

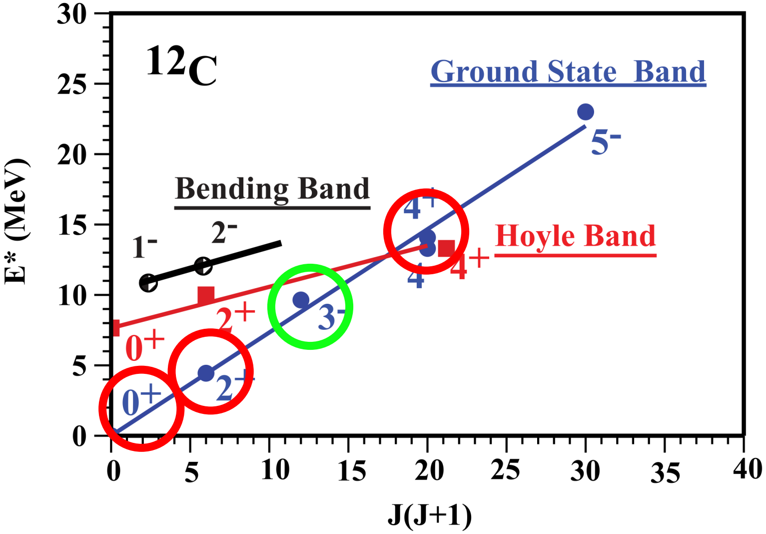


Image credit: M. Freer

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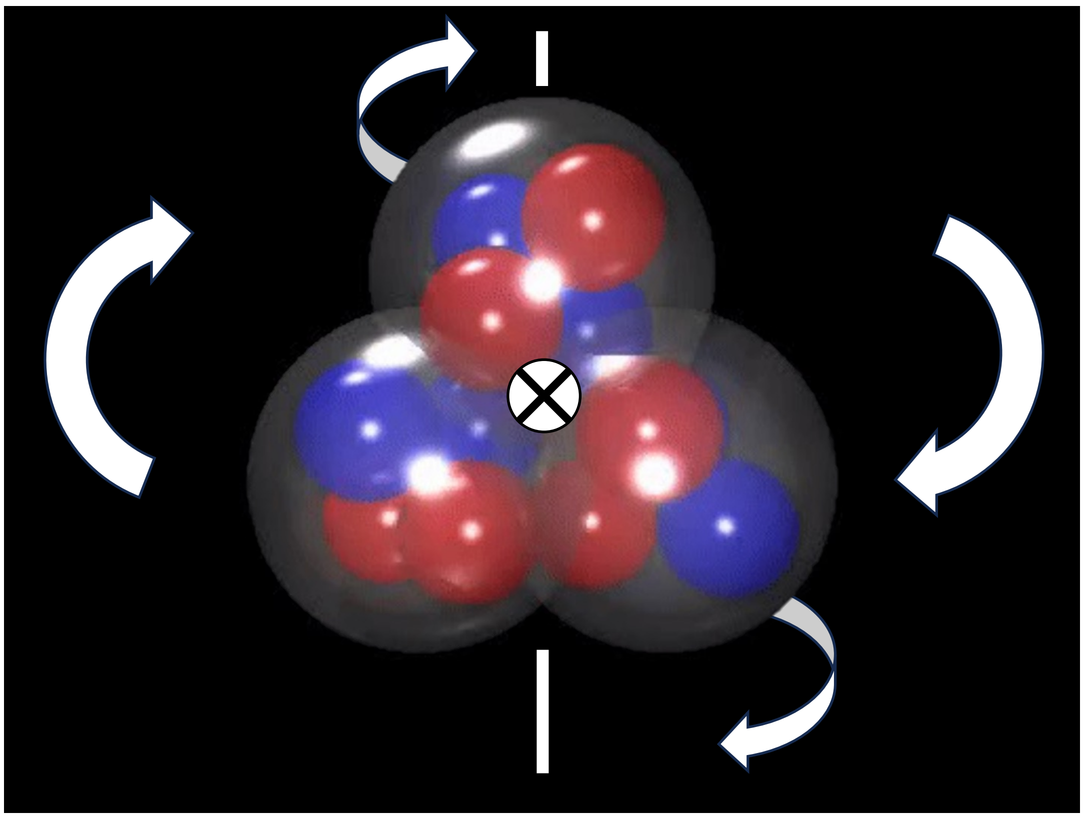
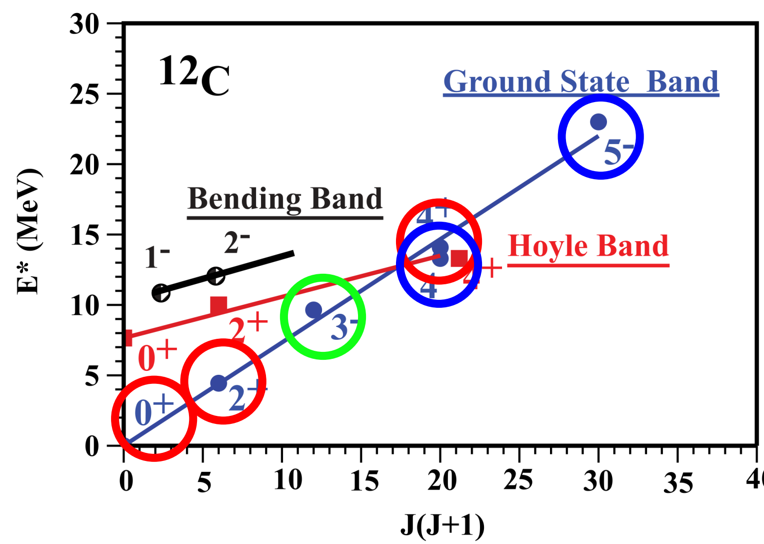


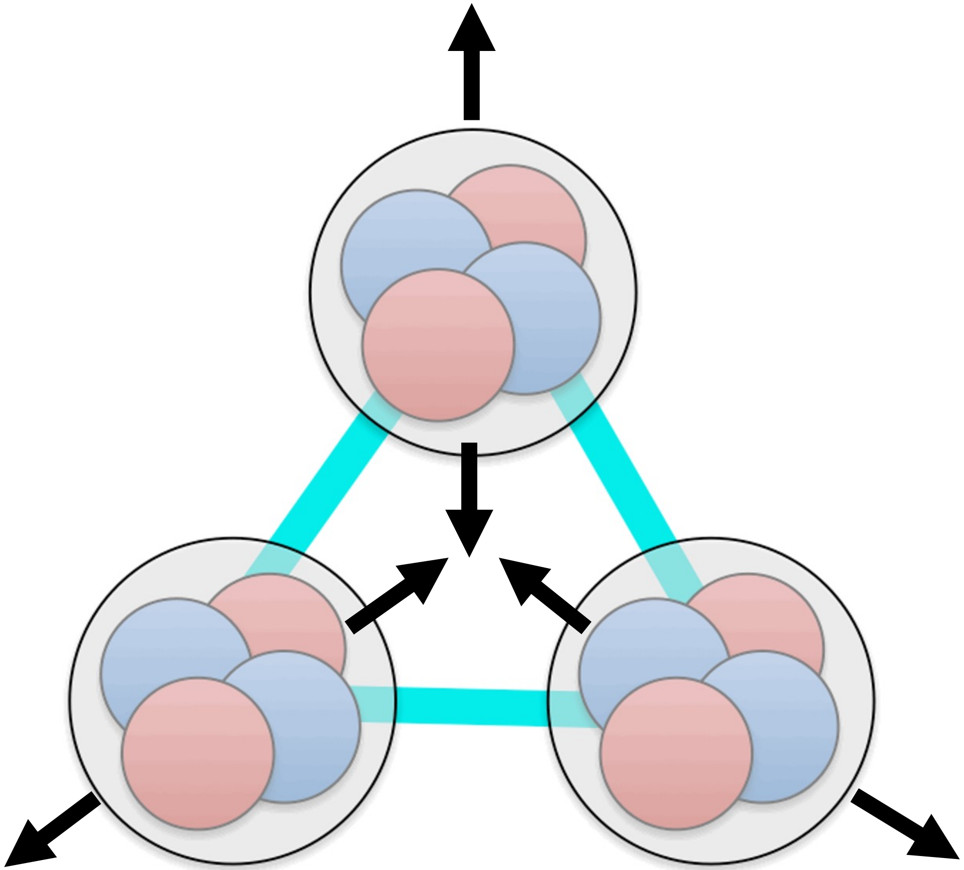
Generates state:

4^-, 5^-



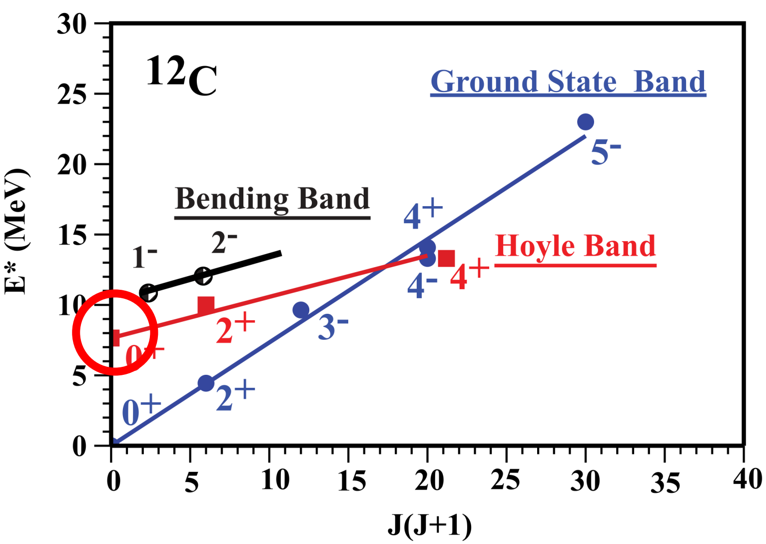
D. J. Marin-Lambarri, et. al., Phys. Rev. Lett., 113, 012502 (2014).

Hoyle State: Breathing Mode

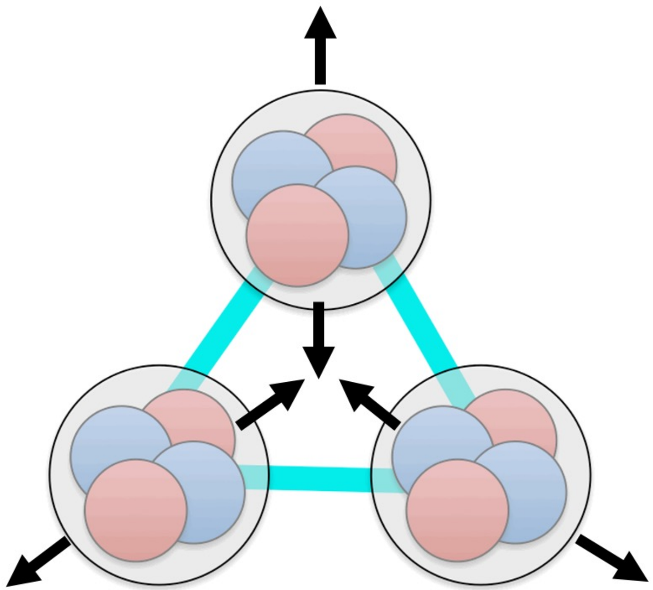


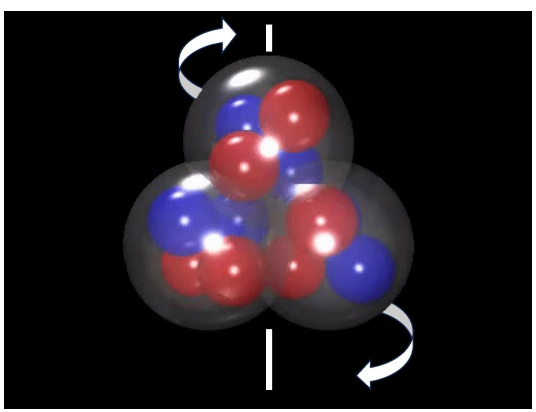
Generates states:

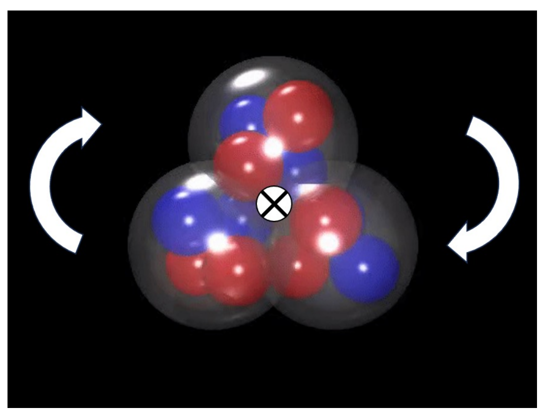
0⁺, 2⁺, 4⁺, 3⁻, 4⁻, 5⁻



Hoyle State: Rotational band

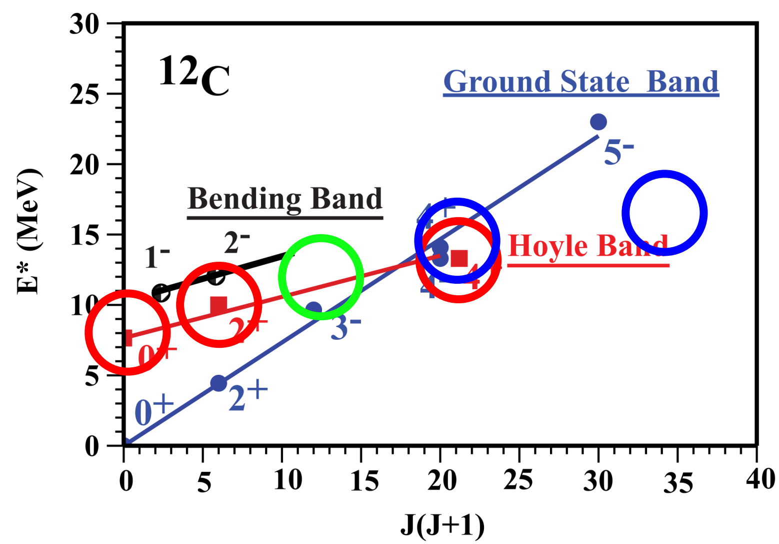




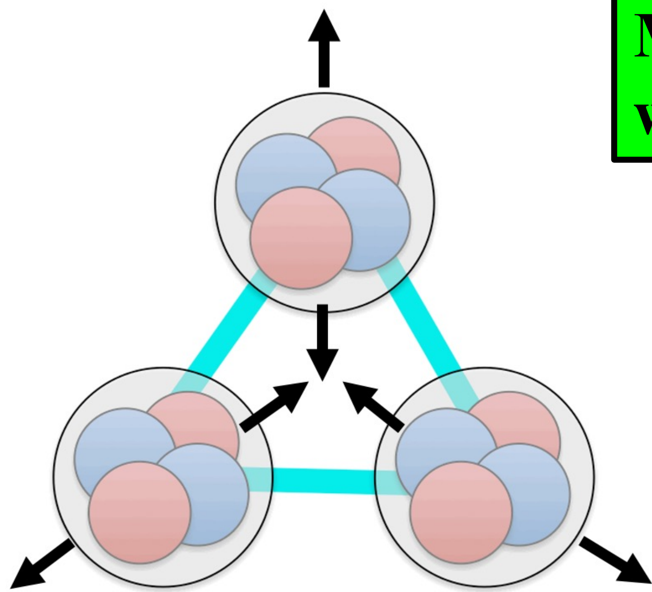


Generates states:

$0^+, 2^+, 4^+, 3^-, 4^-, 5^-$



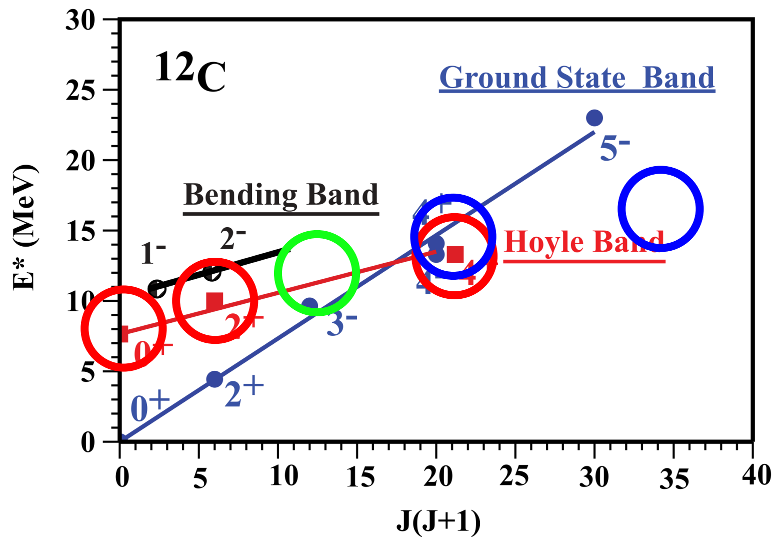
Hoyle State: Rotational band

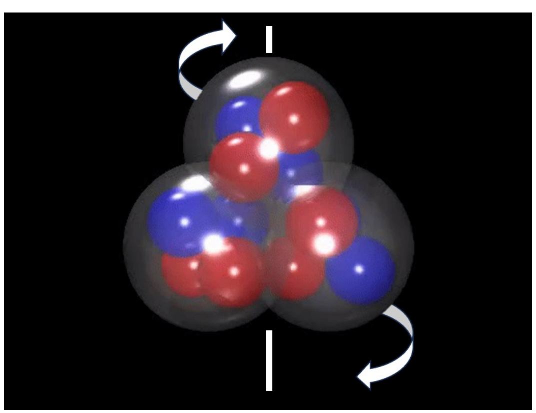


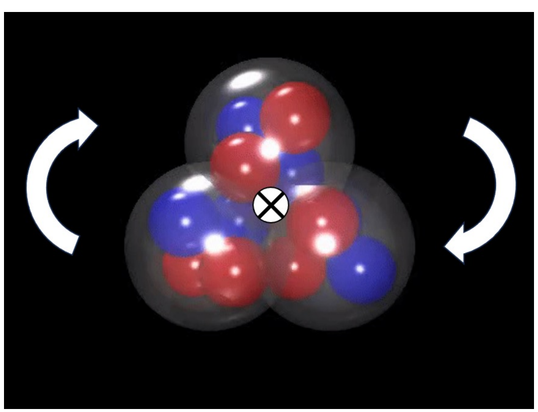
Measuring a 3^- state 11-14 MeV would support this model of ^{12}C

Generates states:

$0^+, 2^+, 4^+, 3^-, 4^-, 5^-$





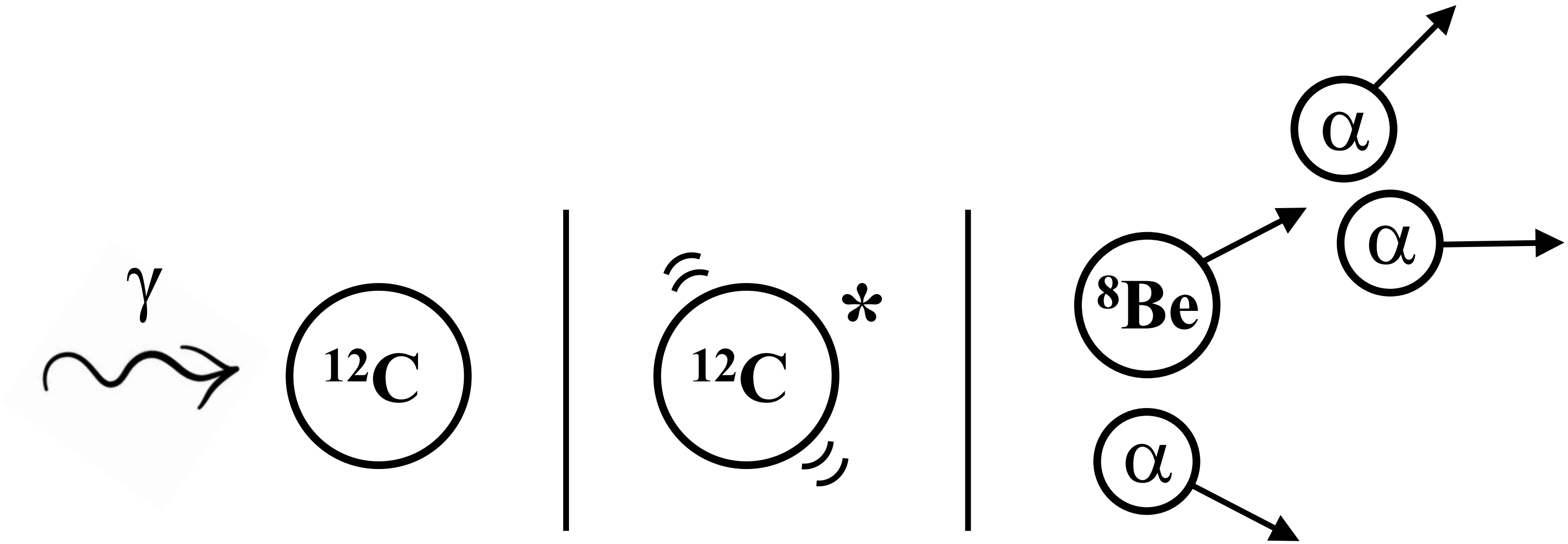


Experimental challenges

- States above 10 MeV often broad
- Very broad 0^+ state at 10 MeV (width 3 MeV) produces significant background in this region
- High density of states

Method – photo-dissociation reaction

- $^{12}C(\gamma,\alpha)^{8}Be$ $^{12}C(\gamma,\alpha_1)^{8}Be^{*}$



- Measuring kinematics of the final state particles elucidates angular momentum of the resonances

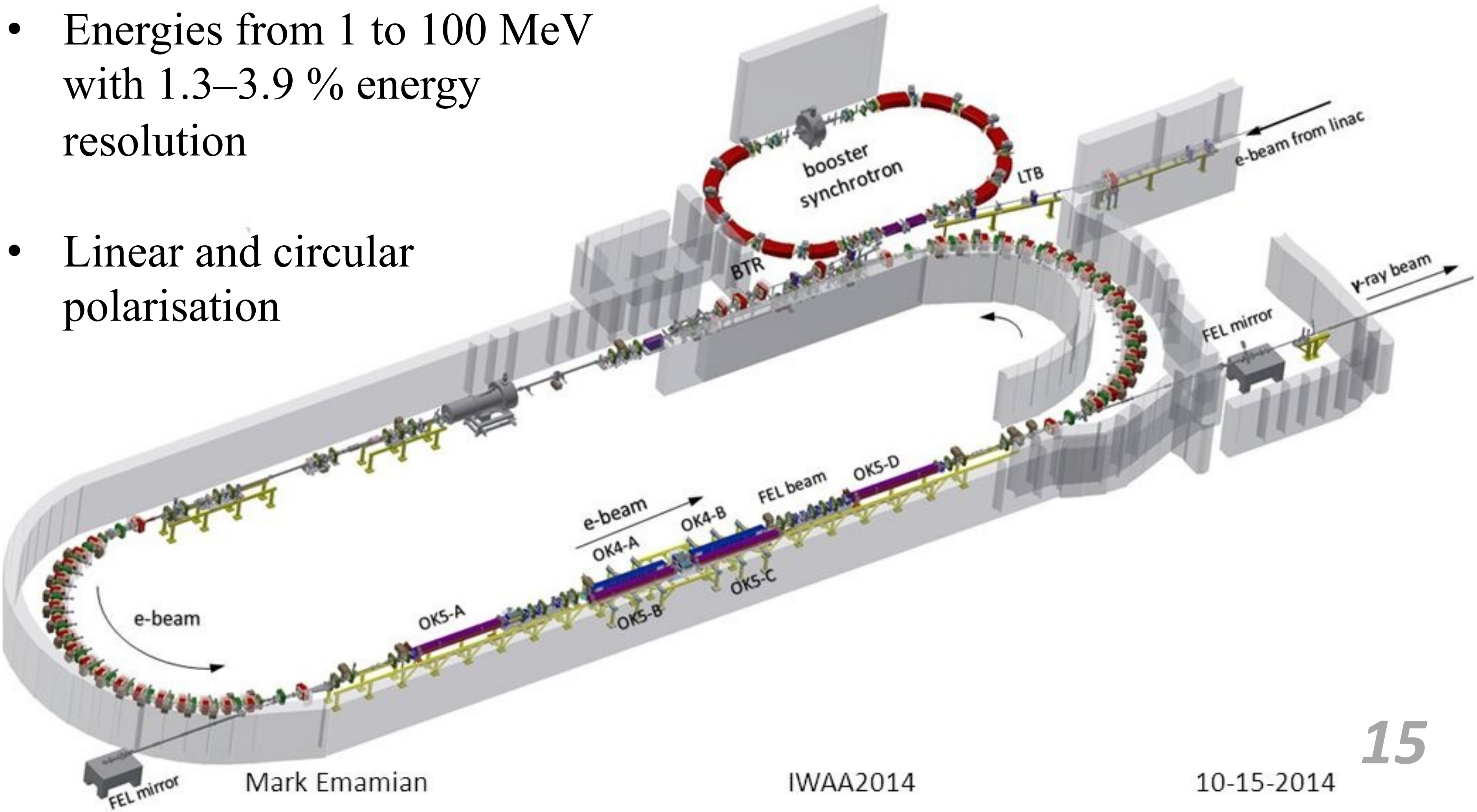
Zimmerman et al., Phys. Rev. Lett. 110, 152502 (2013)

Method – photo-dissociation reaction

- $^{12}C(\gamma,\alpha)^{8}Be$ $^{12}C(\gamma,\alpha_1)^{8}Be^{*}$
- Absorption of a photon cannot populate 0^{+} states
- Tagging decays through α + $^{8}Be_{gs}(0^{+})$ will restrict to natural parity states (1^{-}, 2^{+}, 3^{-})
- Angular distributions & partial wave decomposition E1, E2, E3 cross sections
- **Require high intensity gamma beam and high-resolution charged particle detector (TPC)**

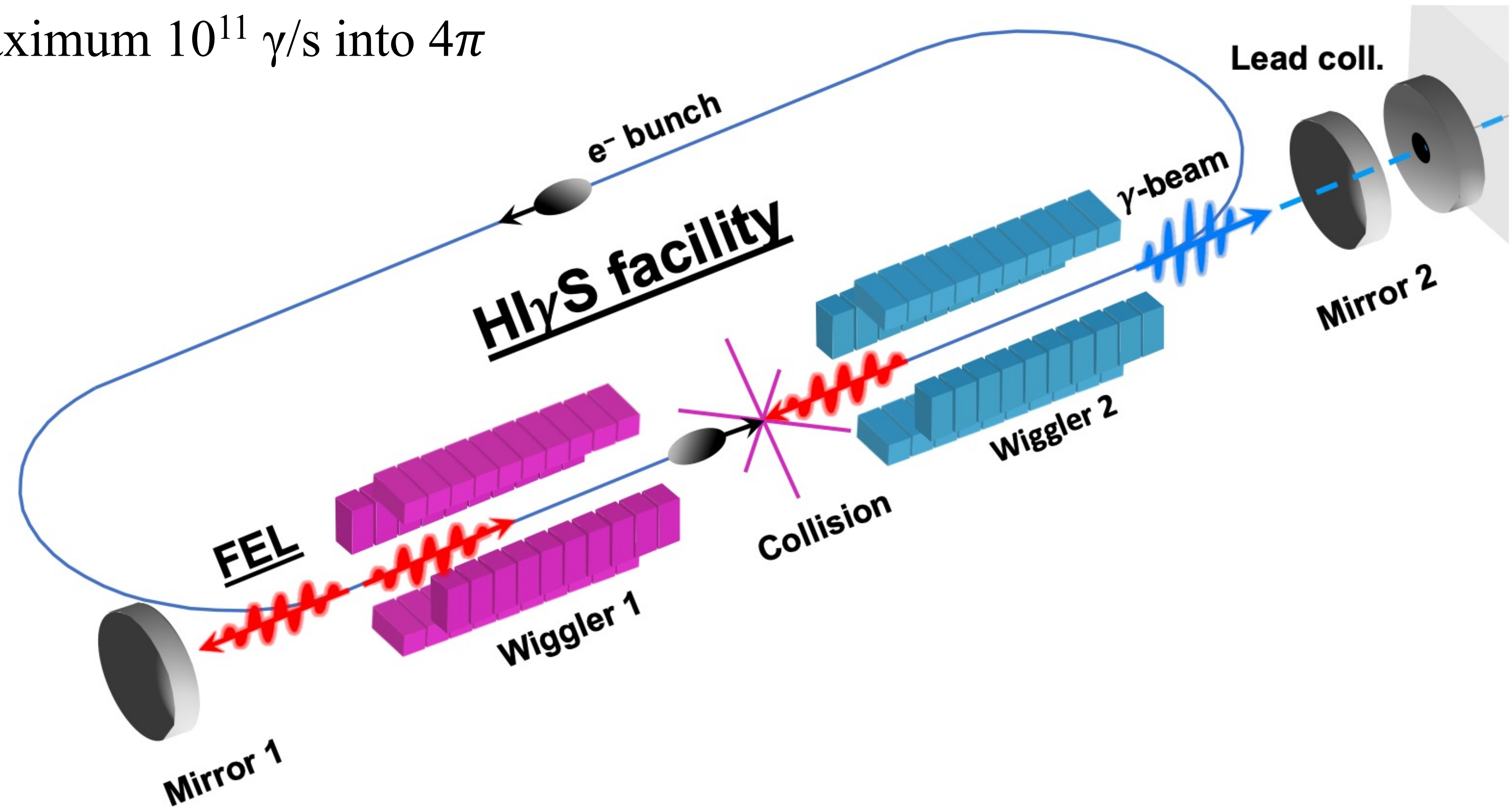
HIγS facility

- Quasi-monoenergetic γ-beams
- Energies from 1 to 100 MeV with 1.3–3.9 % energy resolution
- Linear and circular polarisation



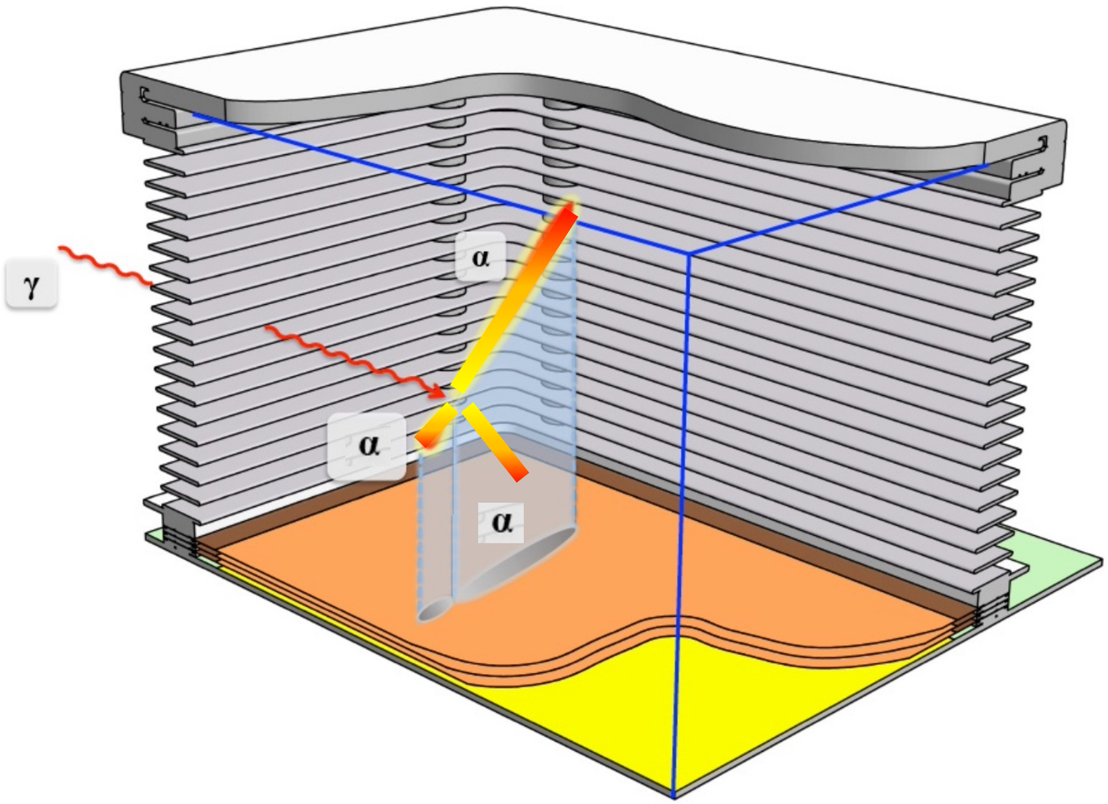
HIγS facility

- Free electron laser – λ = 190 -1064 nm
- Compton backscattering increases the γ energy
- Maximum 10^{11} γ/s into 4π



H.R. Weller et. al, Progress in Particle and Nuclear Physics **62** (2009)
A. Endo, Laser Pulses-Theory, Technology, and Applications. InTech, (2012)

Detector – Warsaw TPC



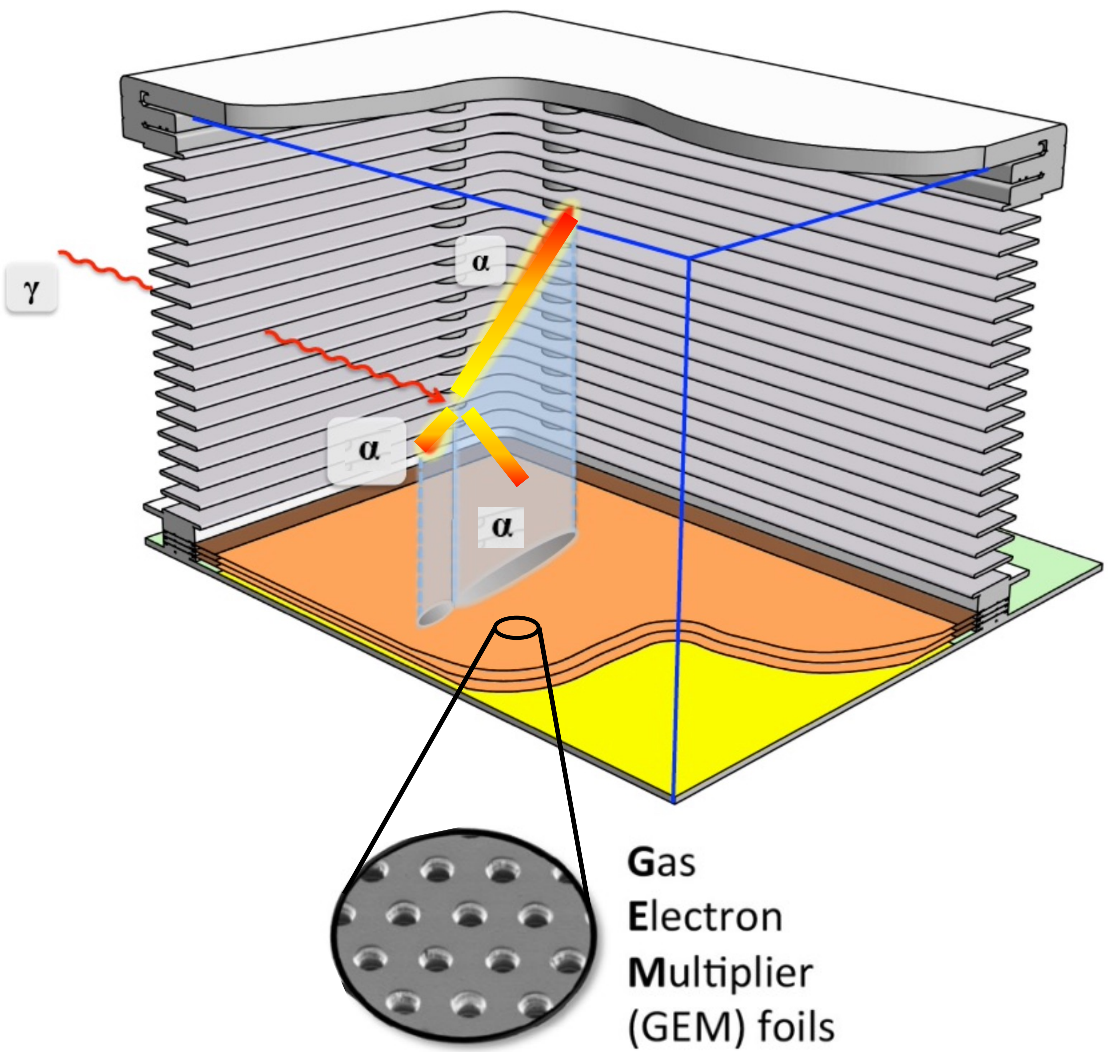
Active volume
33 x 20 cm^2 (readout) x 20 cm (drift)

Charge amplification
Gas Electron Multiplier (GEM) structures

Readout
Planar, 3-coordinate, redundant strip arrays, ~1000 channels
GET electronics
100 Hz triggering

Kuich, M., et al. "Active target TPC for study of photonuclear reactions at astrophysical energies." *arXiv preprint arXiv:2303.08048* (2023).
M. Ćwiok et al. Acta Phys.Pol. B, 49:509, 2018.
Gai, M., et al (2020). *Nuclear Instruments and Methods in Physics Research Section A*, *954*, 161779.

Detector – Warsaw TPC



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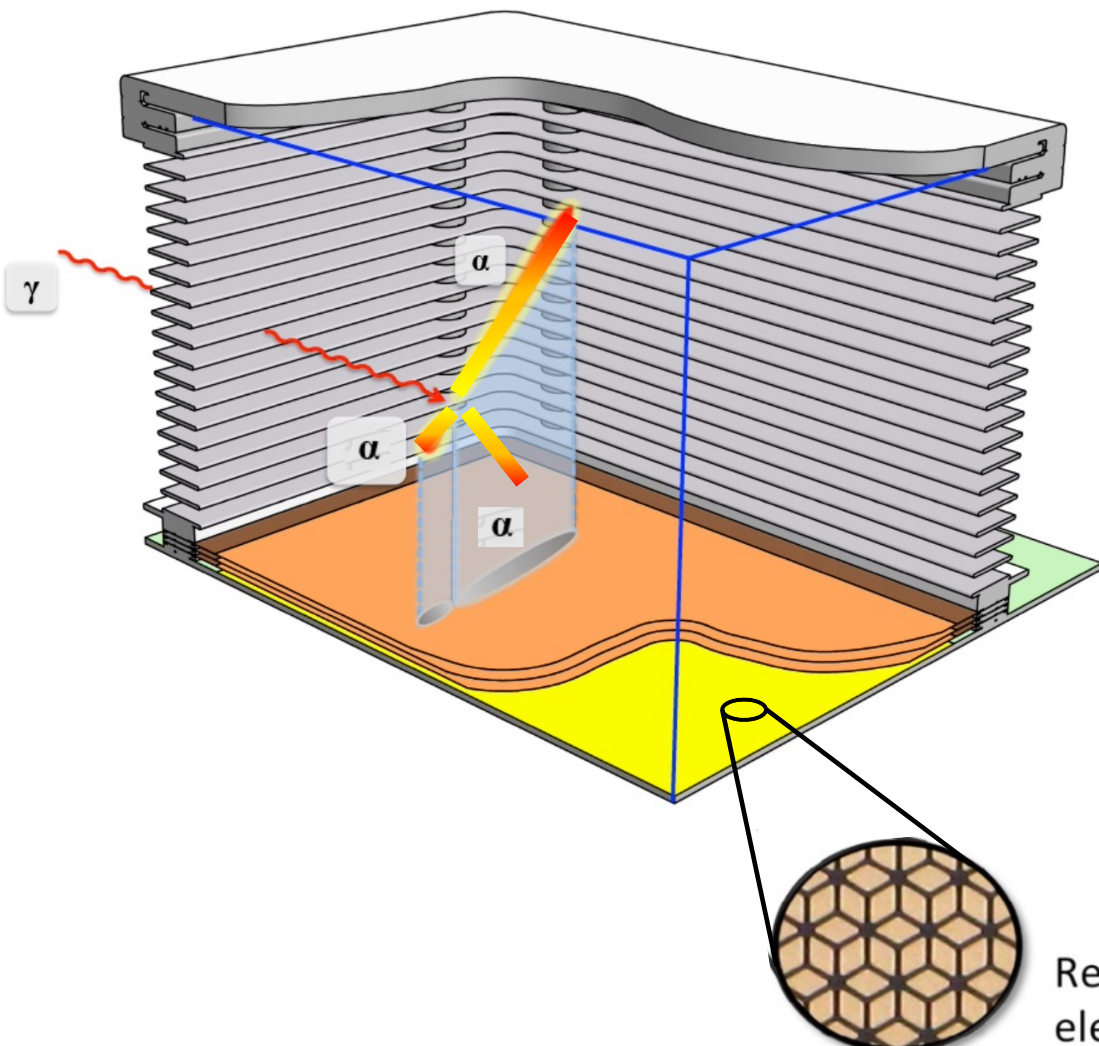

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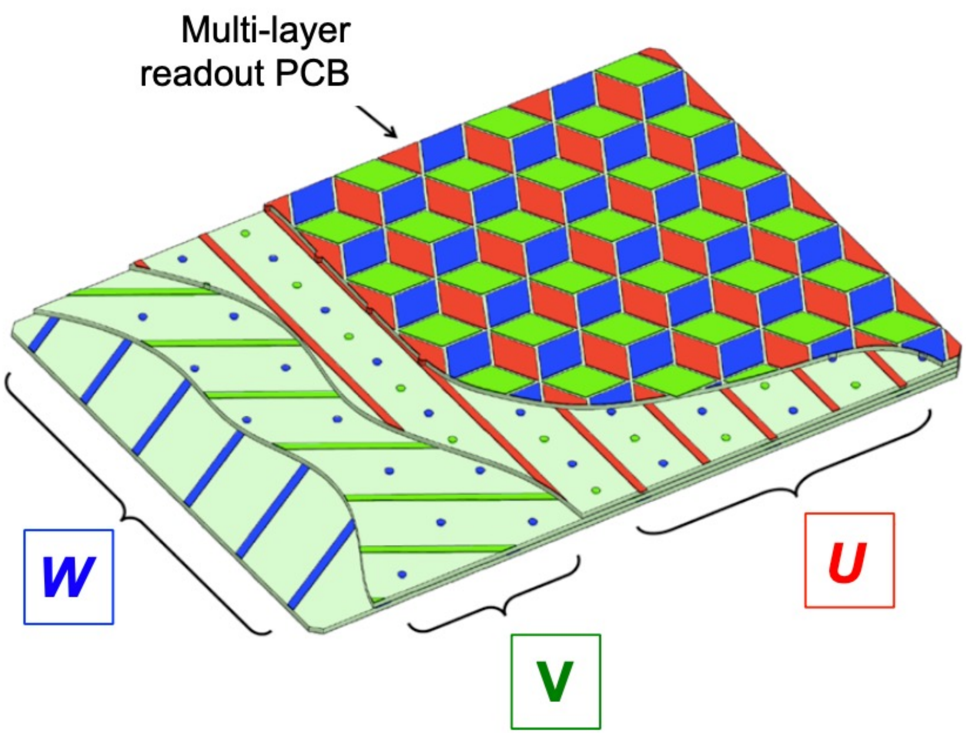

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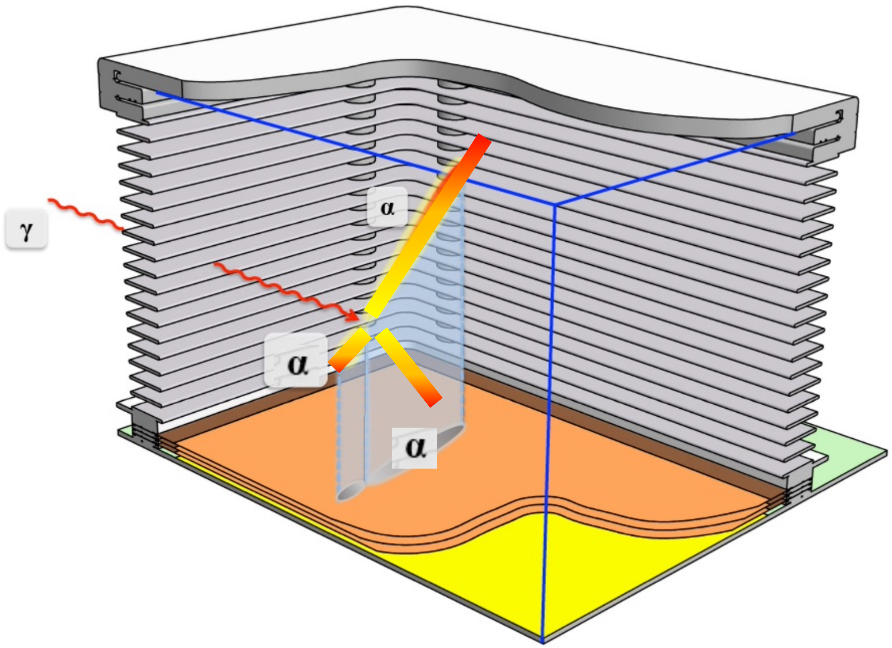
HIgS campaign – 2022



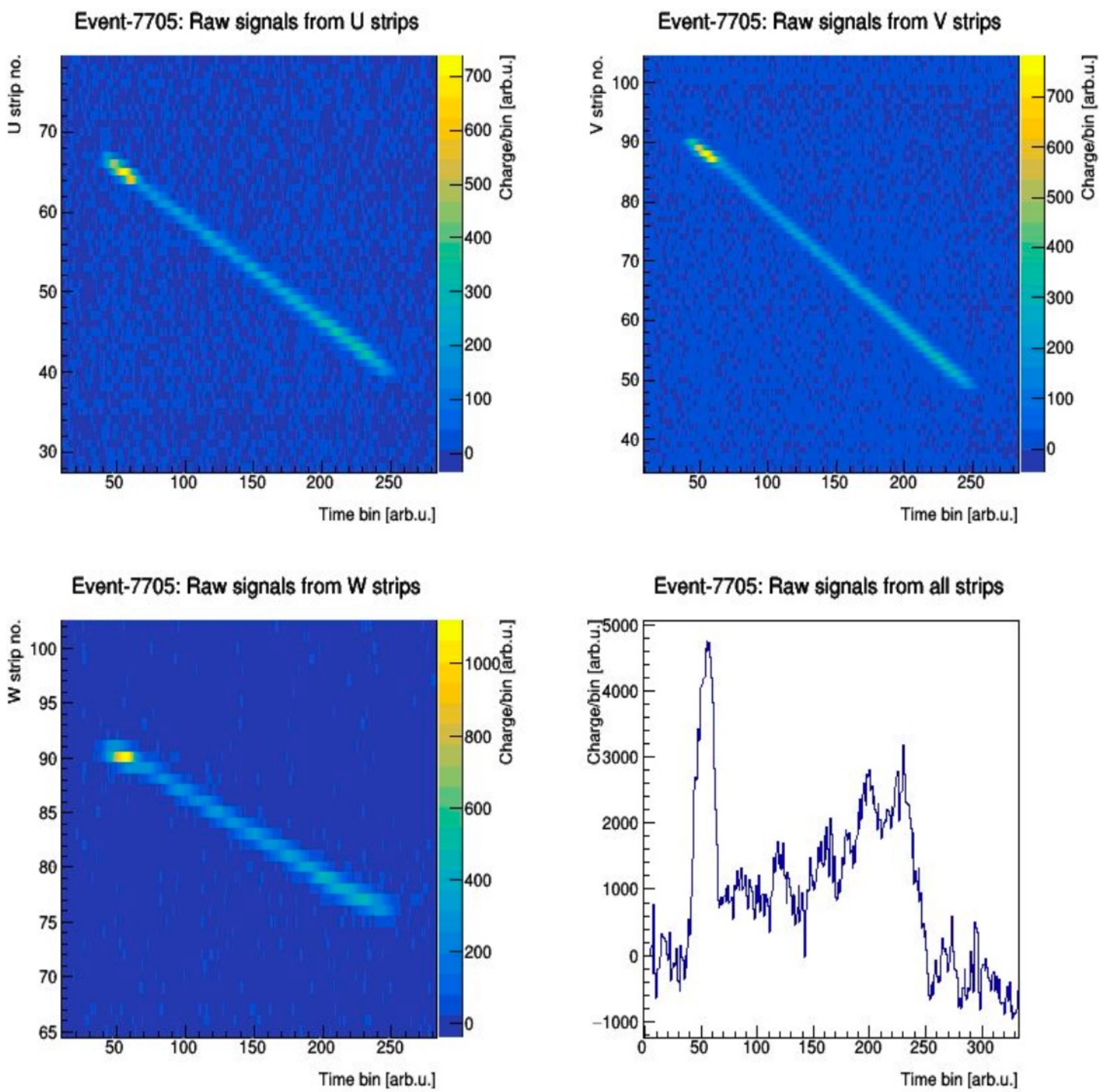
100–150 mbar pure CO_2 gas

γ-beams from between 8.6 and 13.9 MeV

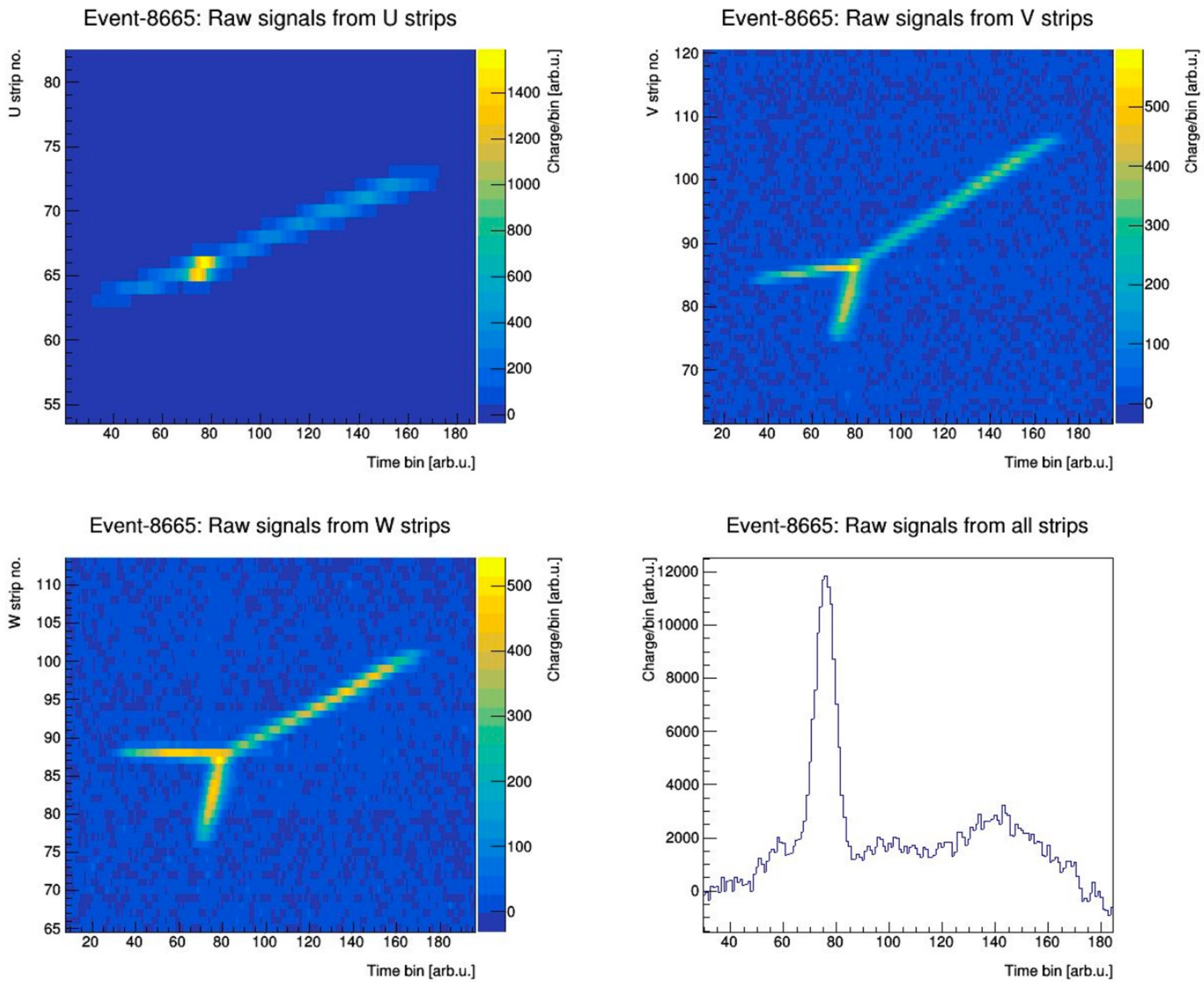
$\sim 4 \times 10^9$ γ/s and $\Delta E \sim 3\%$

Ćwiok, Mikołaj, et al. "Studies of photo-nuclear reactions at astrophysical energies with an active-target TPC." *European Physical Journal Web of Conferences*. Vol. 279. 2023.

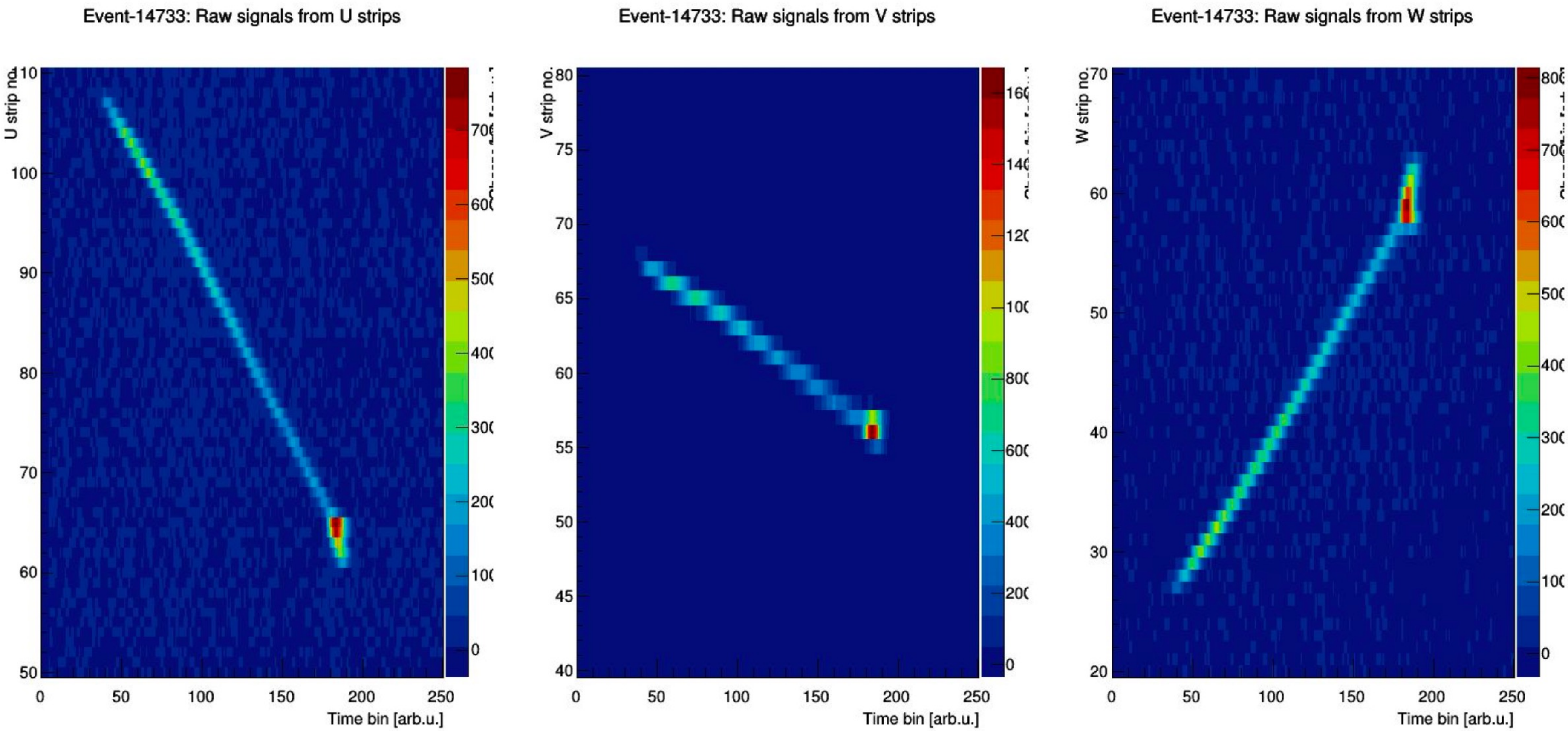
Example events – $^{16}O(\gamma,\alpha)^{12}C$



Example events – $^{12}C(\gamma,\alpha_1)$

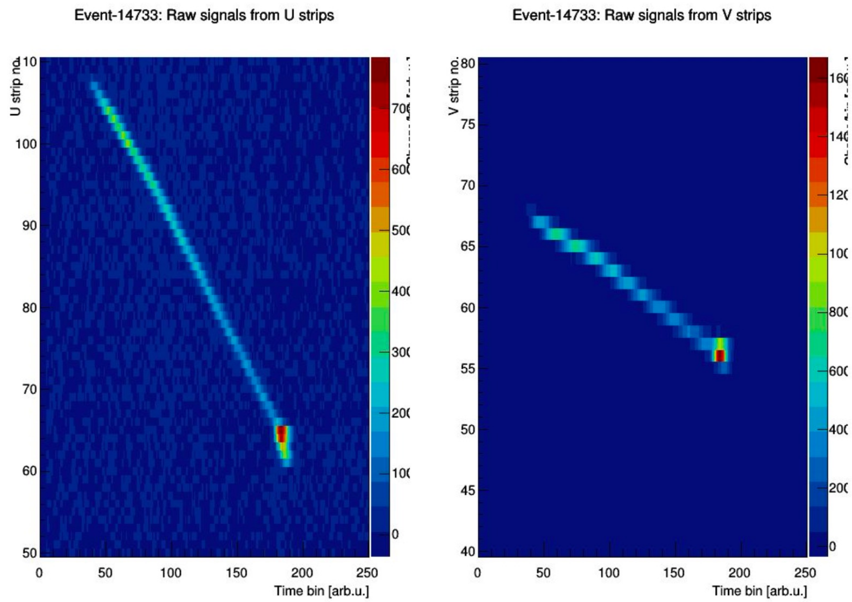


Example events – $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

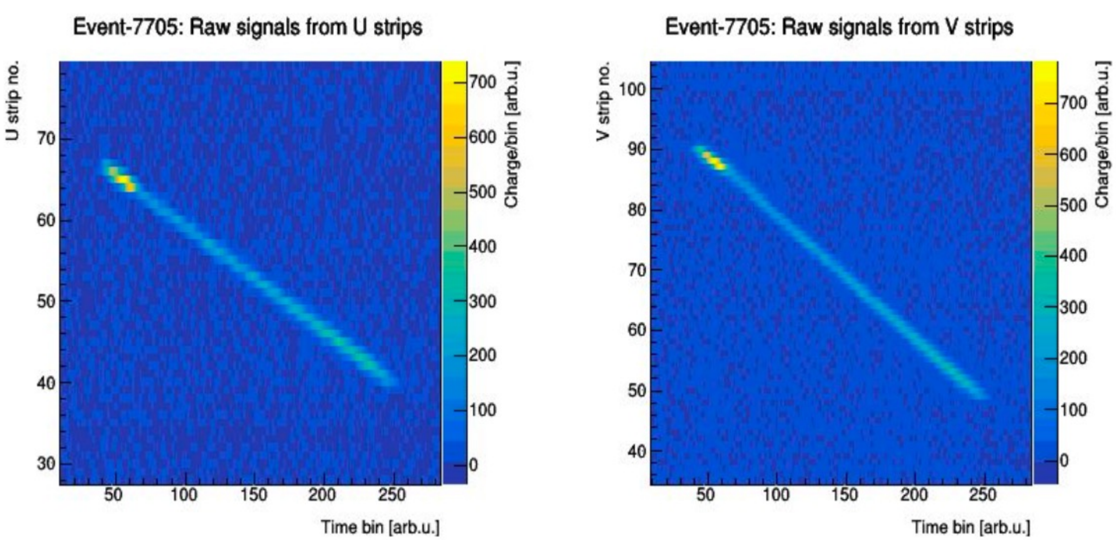


One long alpha track
^{8}Be decays to two short alpha tracks with small opening angle

Example events – comparison

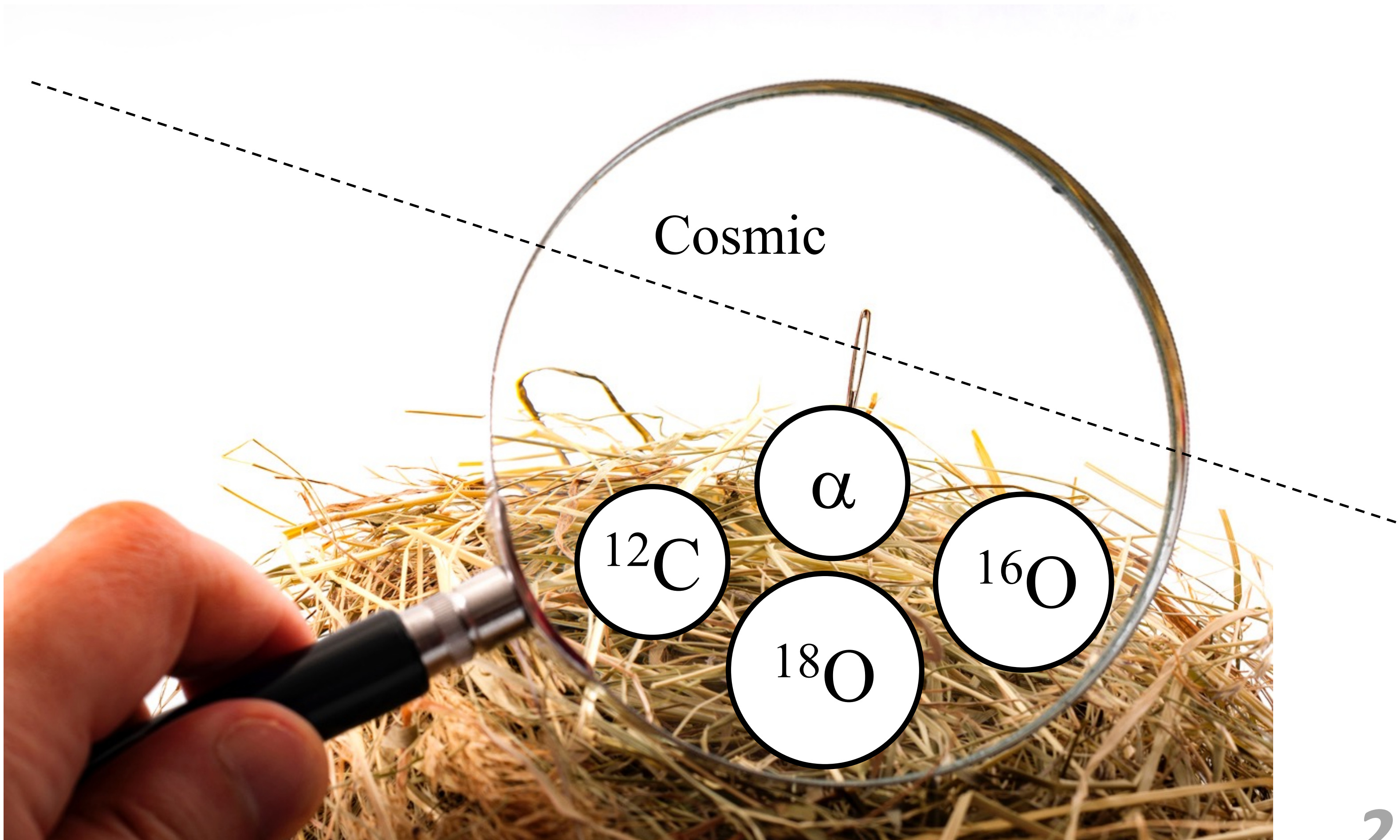


$^{12}C(\gamma,\alpha)^{8}Be_{gs}$



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

Analysis:
Finding a ^{12}C needle in a haystack



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Artificial Neural Network for event classification

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The New York Times

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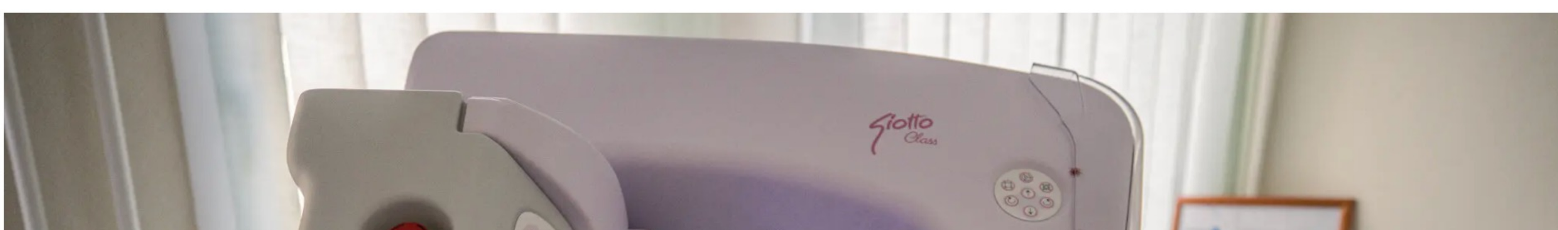

Artificial Neural Network for event classification

TIME

TECHNOLOGY

Google Builds a Brain that Can Search for Cat Videos

Finally, an artificial intelligence breakthrough worth caring about.

By Eliana Dockterman | June 27, 2012

Share Tweet Share Save Read Later

The Google X laboratory has invented some pretty cool stuff: refrigerators that can order groceries when your food runs low, elevators that can perhaps reach outer space, self-driving cars. So it's no surprise that their most recent design is the most advanced, highest functioning, most awesome invention ever… a computer that likes watching YouTube cats?

Timothy A. Clary / AFP / Getty Images

Okay, it's a bit more advanced than that. Several years ago, Google scientists began creating a neural network for machine learning. The technique Google X employed for this project is called the "deep

Artificial Neural Network for event classification

“If Artificial Neural Networks can recognise cats on YouTube videos they should be able to classify nuclear reactions in a TPC”

By Eliana Dockterman | June 27, 2012

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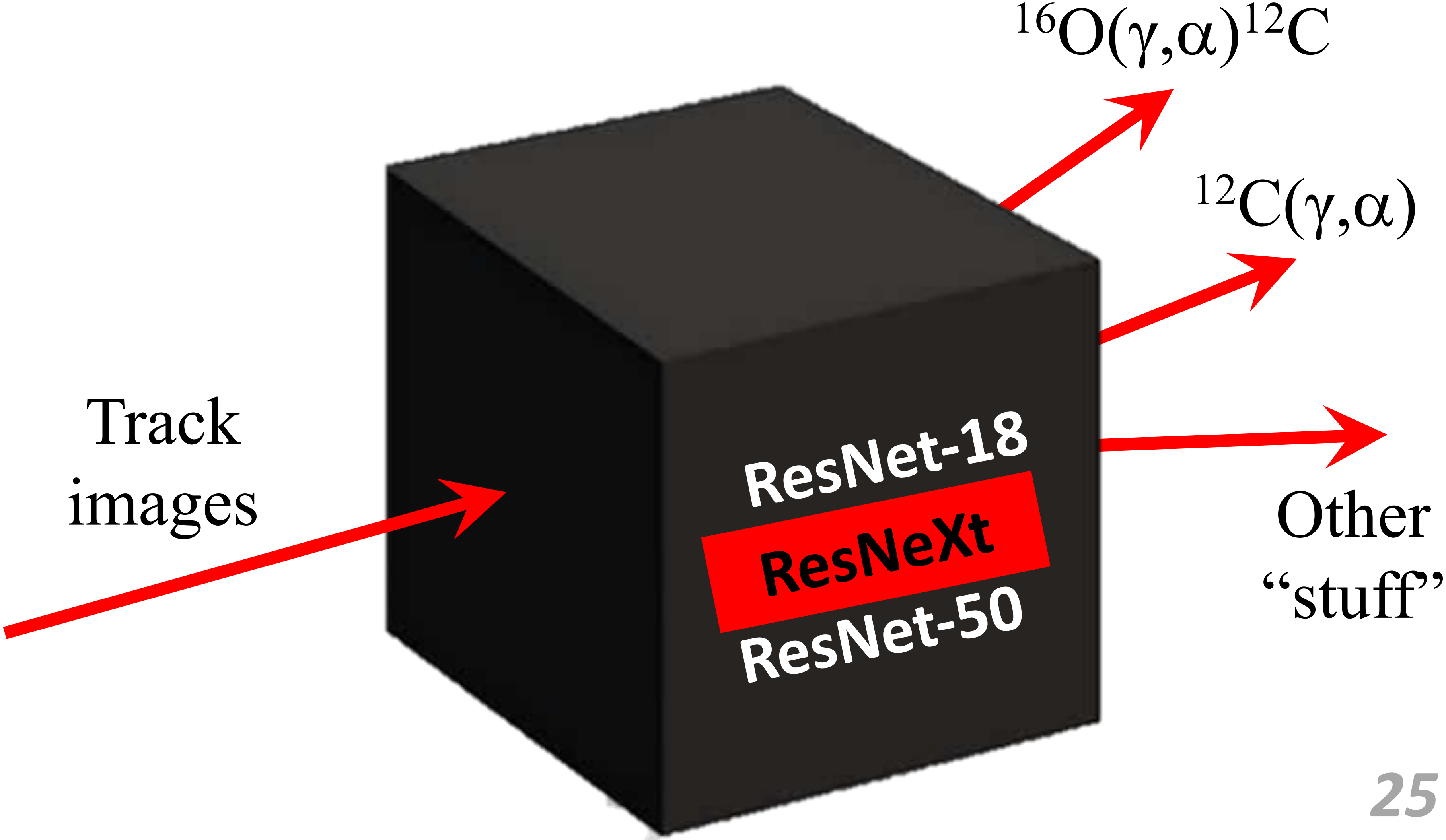
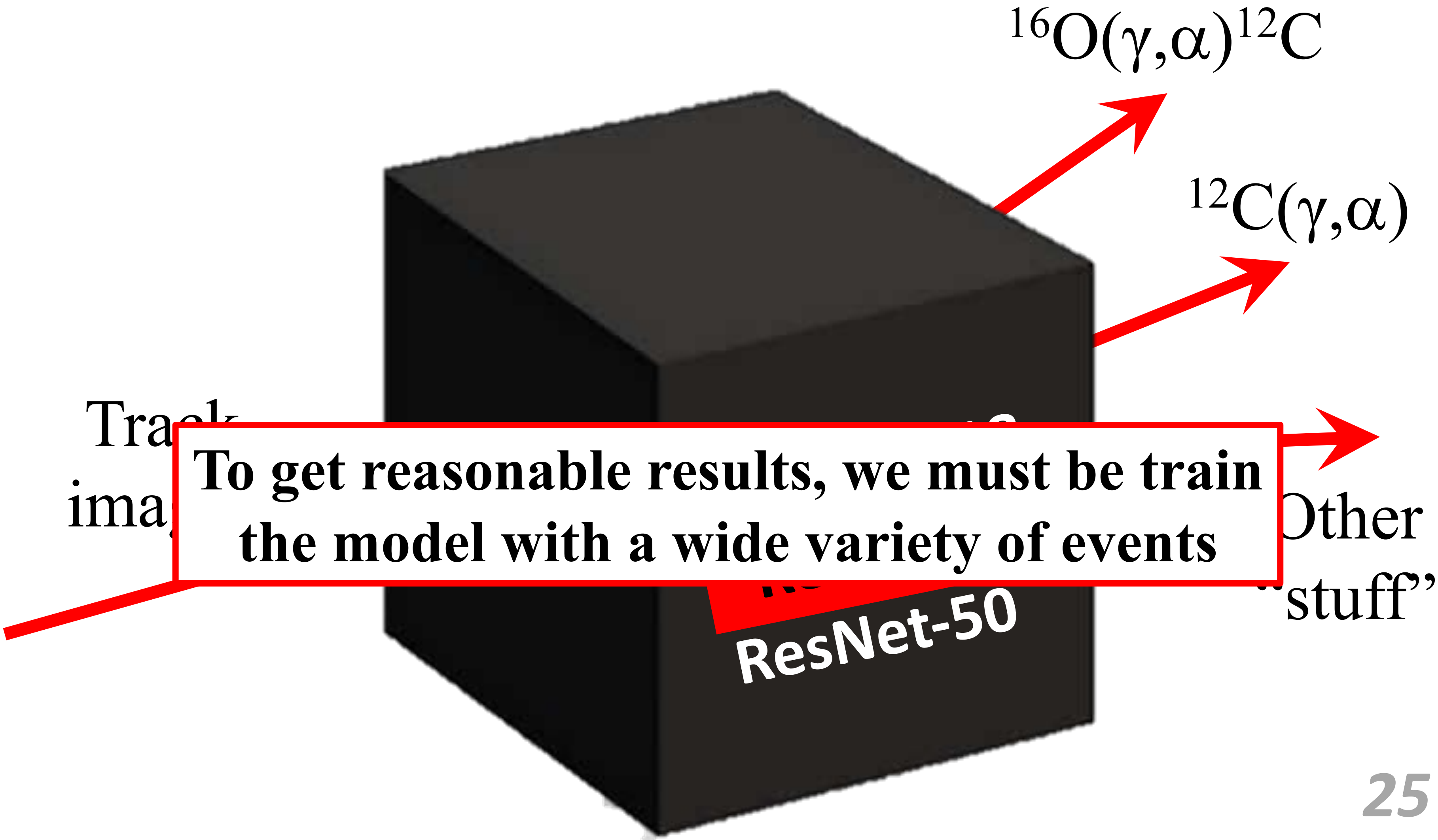
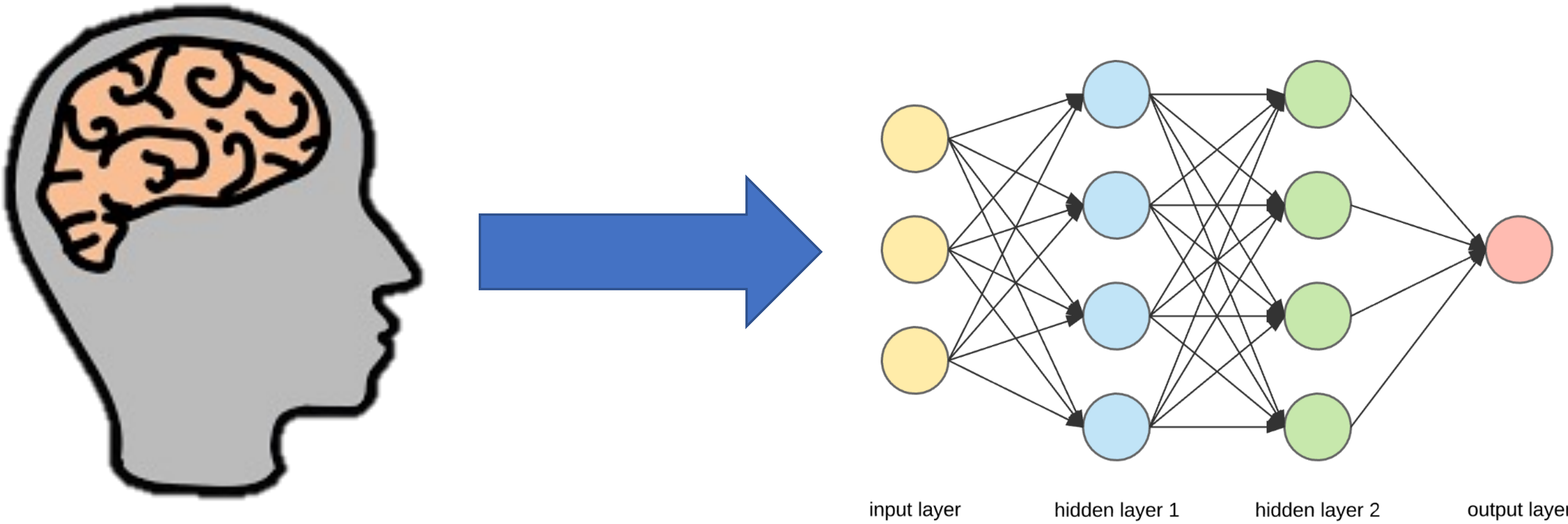
Artificial Neural Network for event classification



Artificial Neural Network for event classification



To get reasonable results, we must be train the model with a wide variety of events



1. Categorise a certain number of events by hand

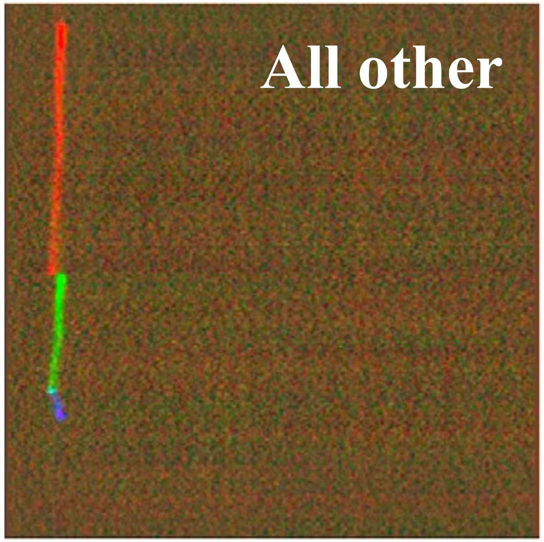
2. Use these to train the Artificial Neural Networks

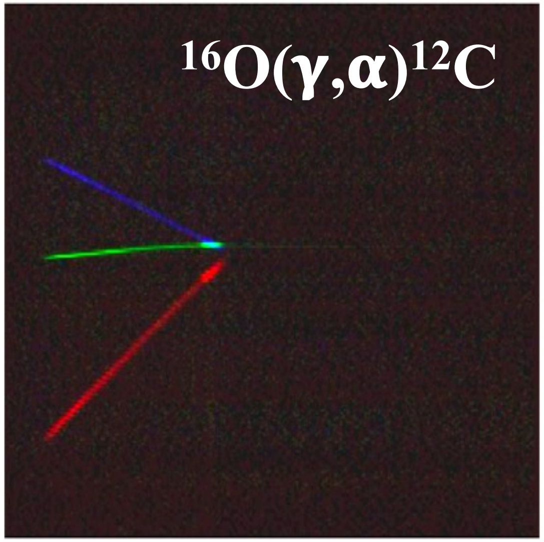
3. Categorise larger data set using the model

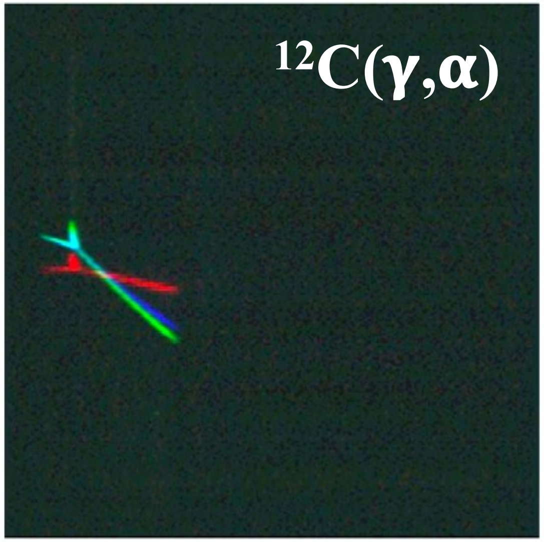
Pre-processing tracks

- The hand-categorised data were split into three categories:

- U,V,W projections combined to one image, with RGB channels

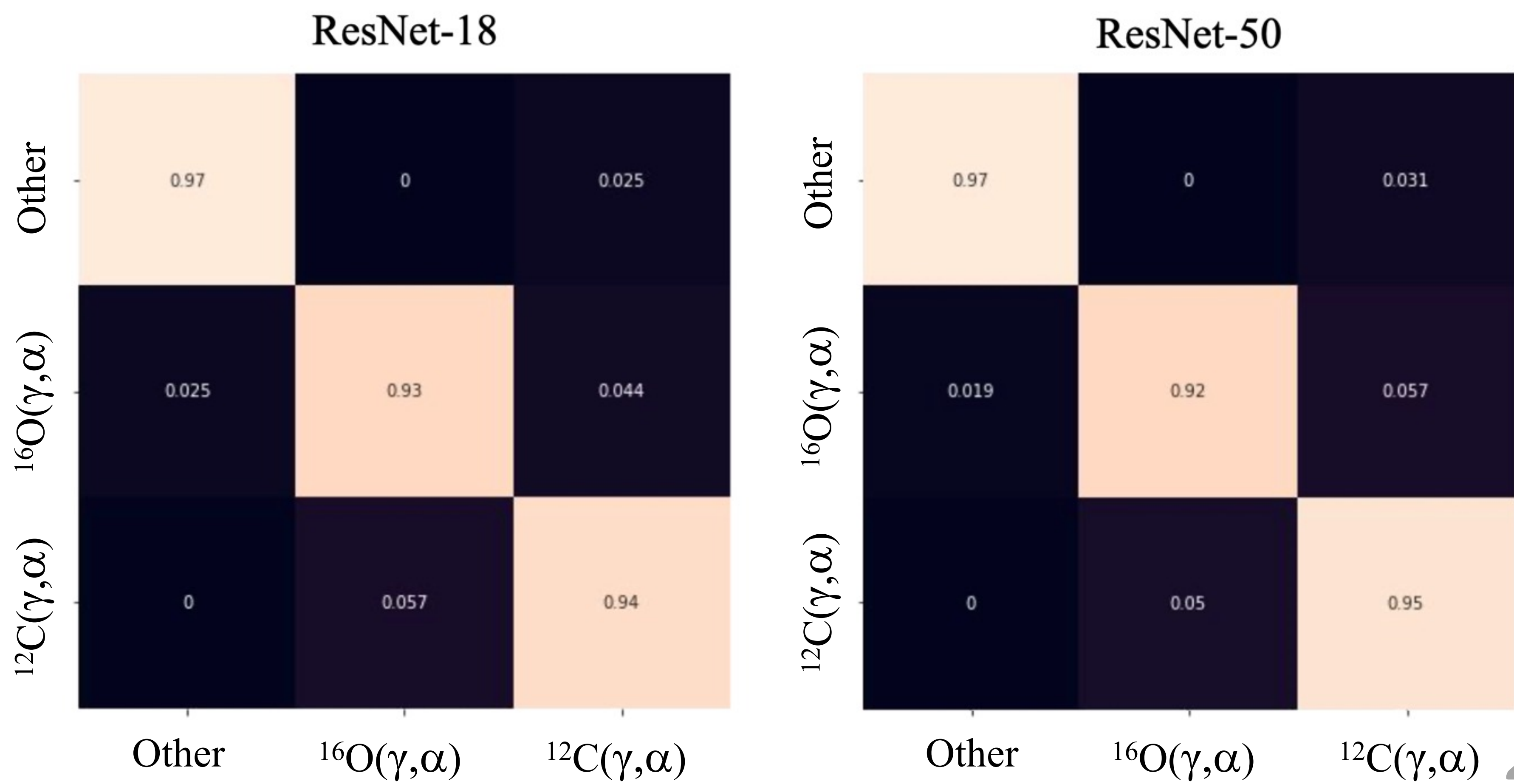






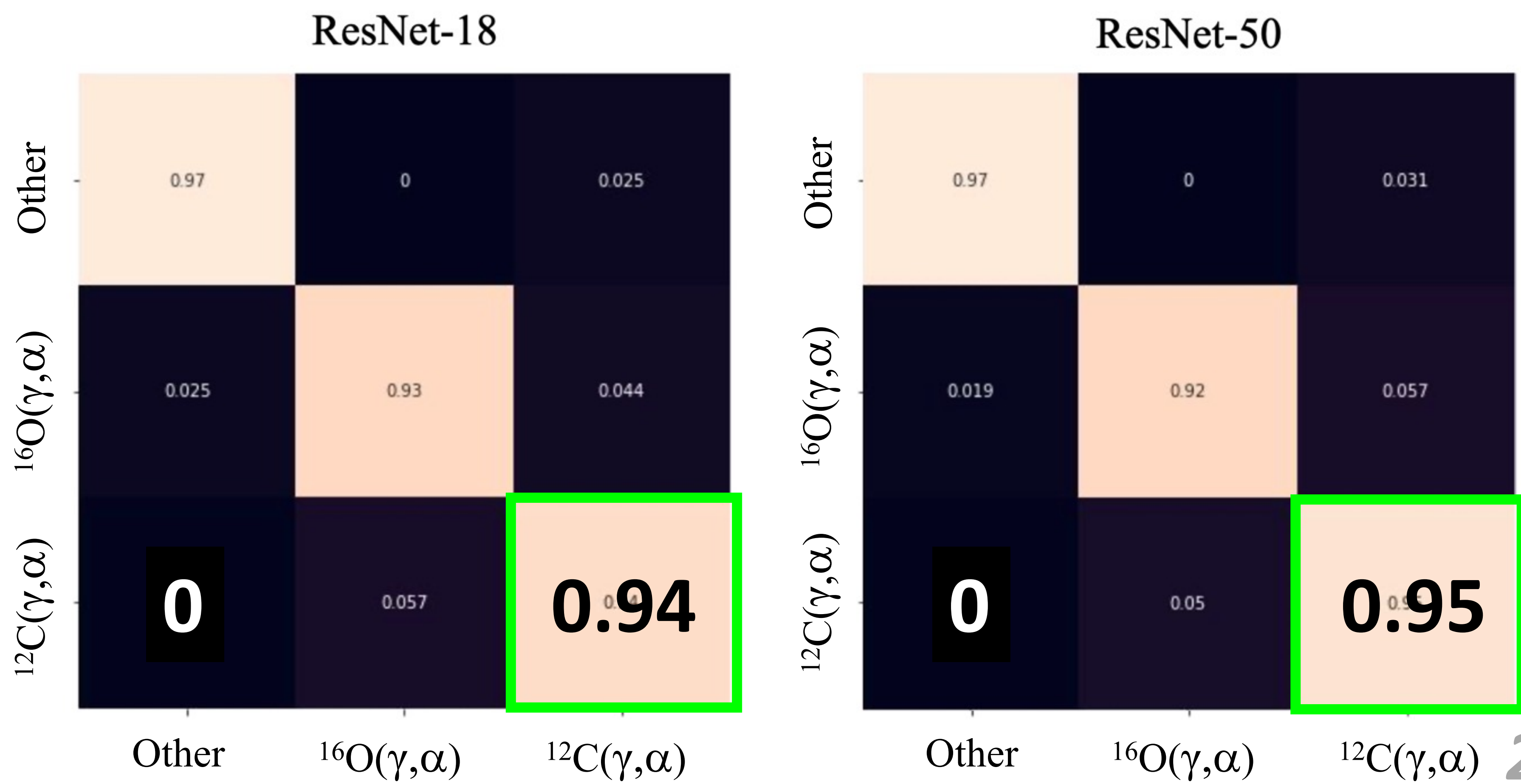
Performance

- Confusion matrices compare output of testing the network (x-axis) with known classification (y-axis)

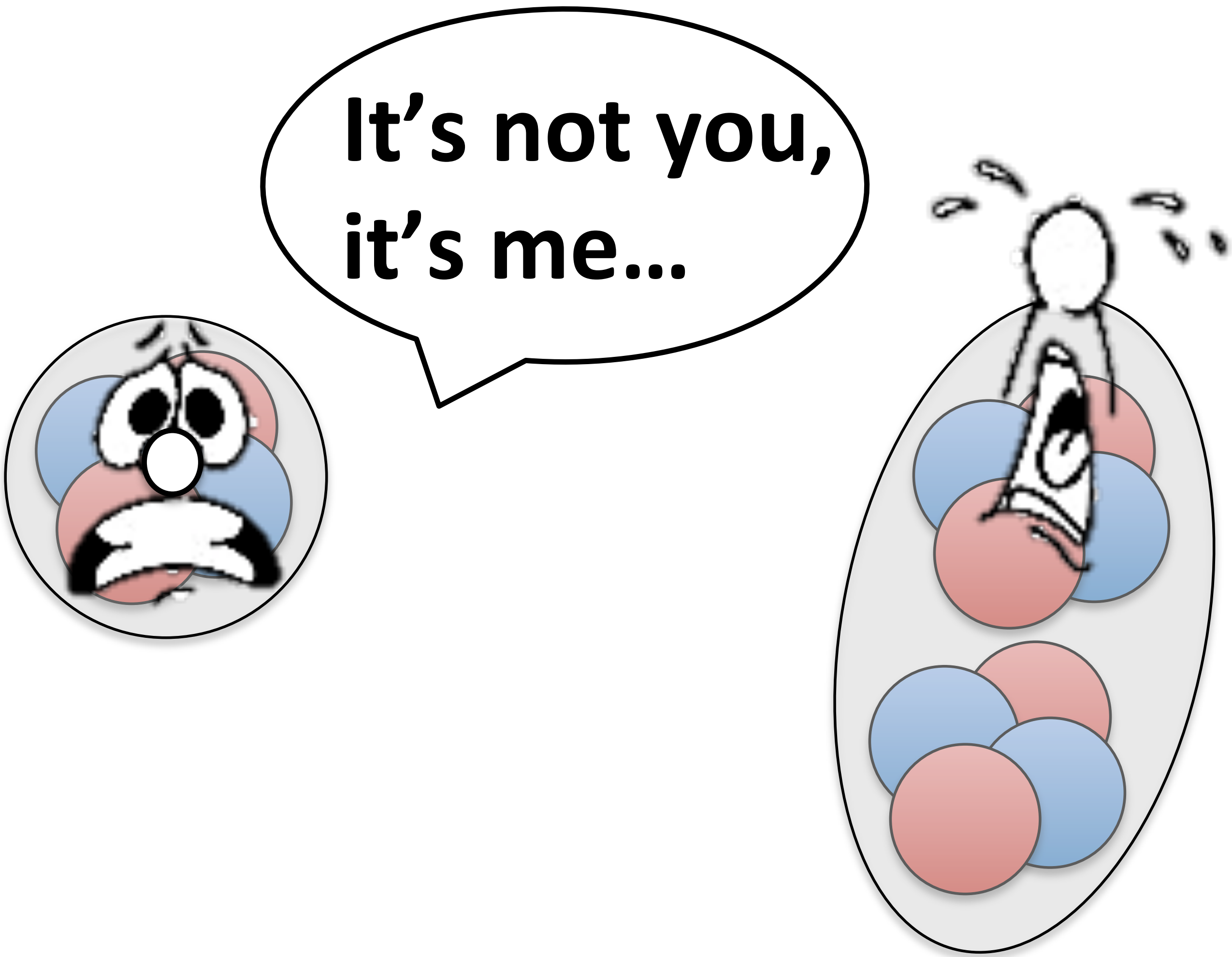


Performance

- 95% of the $^{12}C(\gamma,\alpha)$ were classified correctly
- Hand selection stage still required



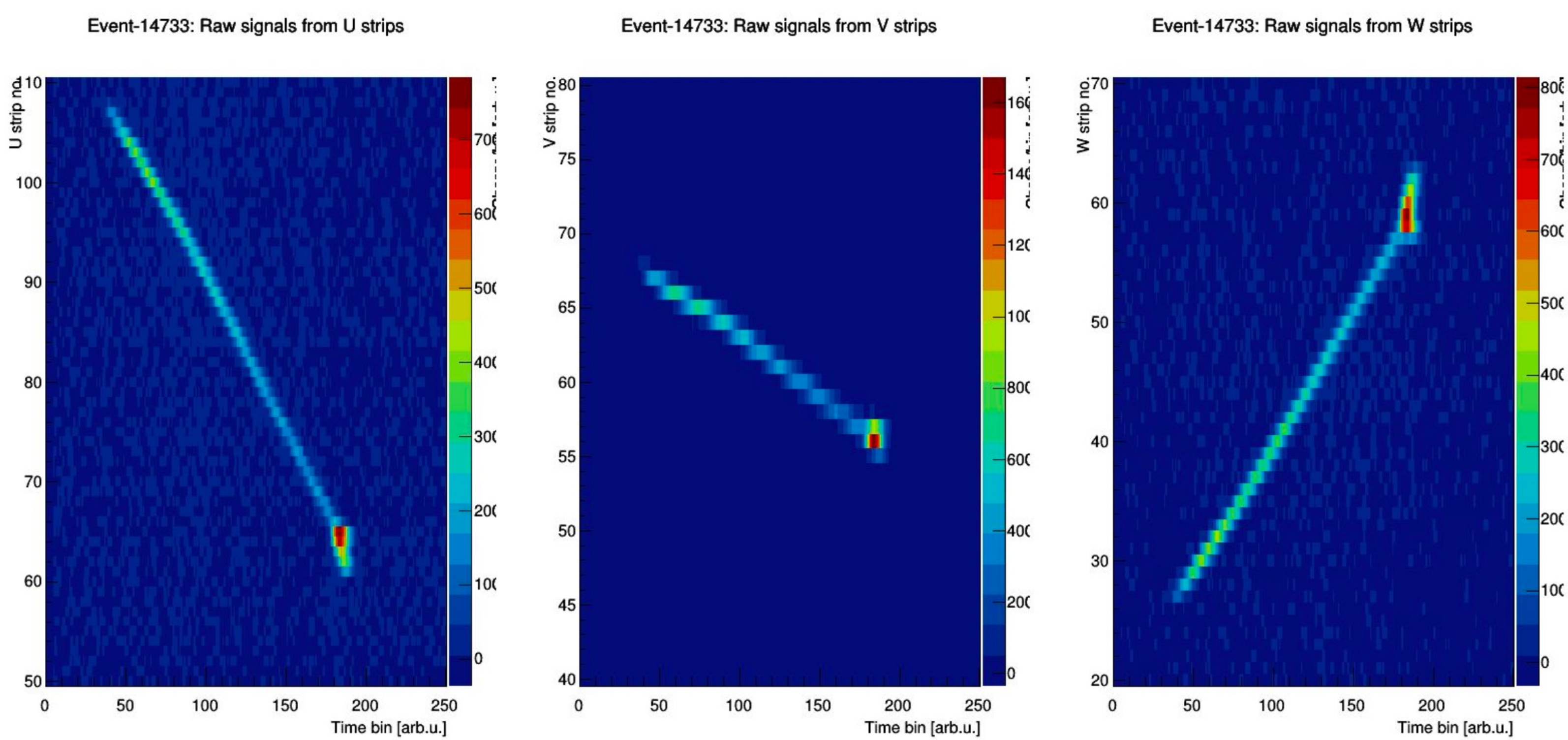
Preliminary results – breakup channels



Preliminary results – $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

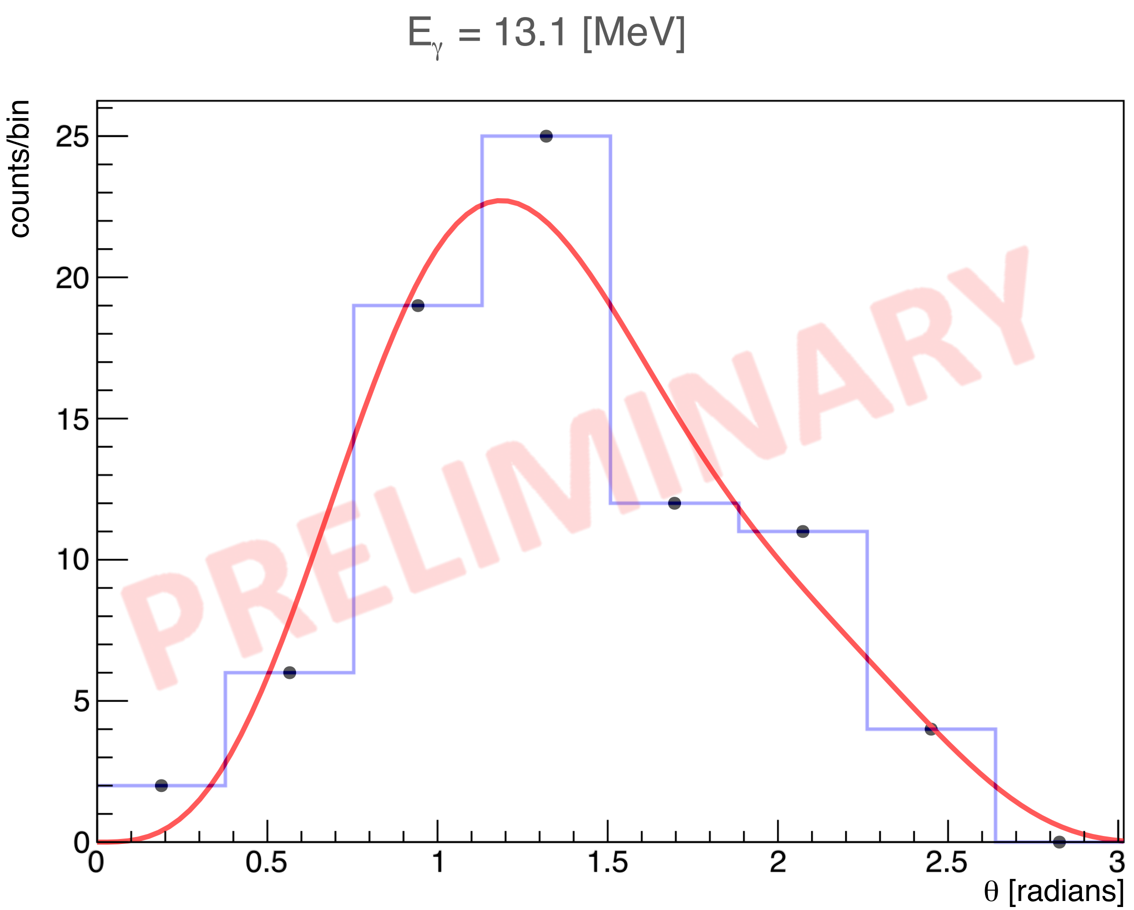
- Angular distribution of longest alpha track plotted

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



Preliminary results – $^{12}C(\gamma,\alpha)^{8}Be_{gs}$

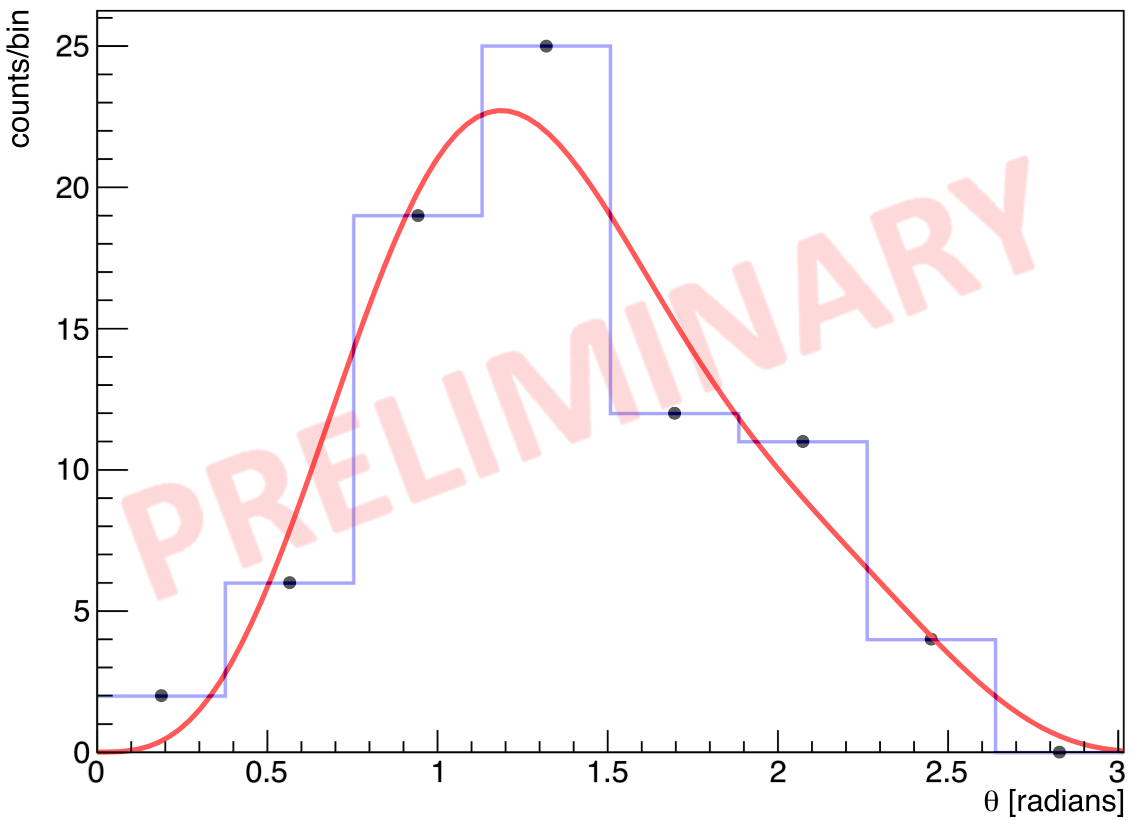
- Mainly 1^- with some 2^+ component



Preliminary results – $^{12}C(\gamma,\alpha)^8Be_{gs}$

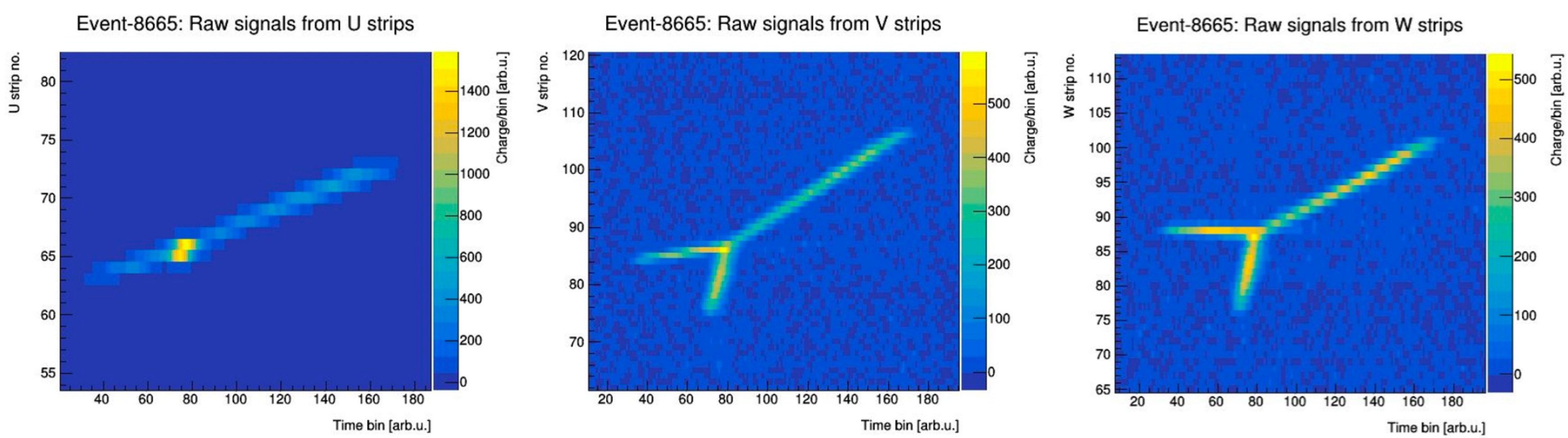
- With higher statistics, search for 3^-

$$W(\theta) = \frac{3}{2}\sin^2\theta\left(|E1|^2 + \frac{25}{4}|E2|^2\cos^2\theta + 3\sqrt{3}|E1||E2|\cos\phi_{12}\cos\theta + \frac{7}{2}\sqrt{6}(5\cos^2\theta - 1)|E1||E3|\cos\phi_{13}\right)$$

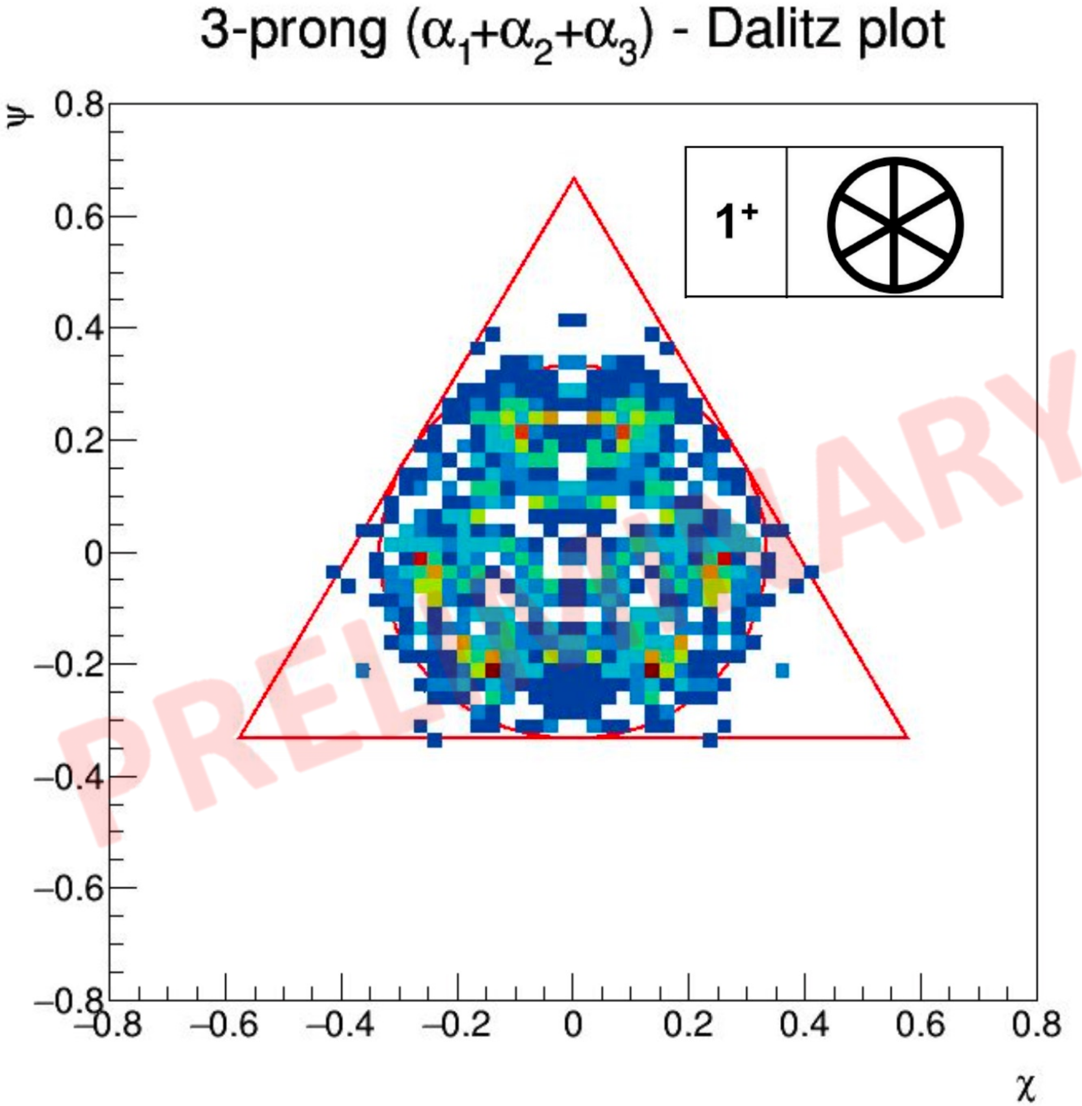


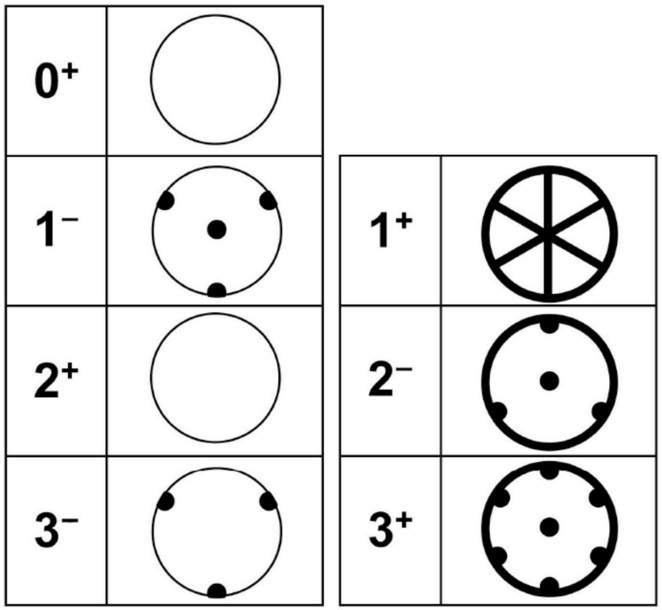
Preliminary results – $^{12}C(\gamma,\alpha_1)^8Be^*$

- Ambiguity over which alpha particle is emitted first
- Must analyse using Dalitz plots

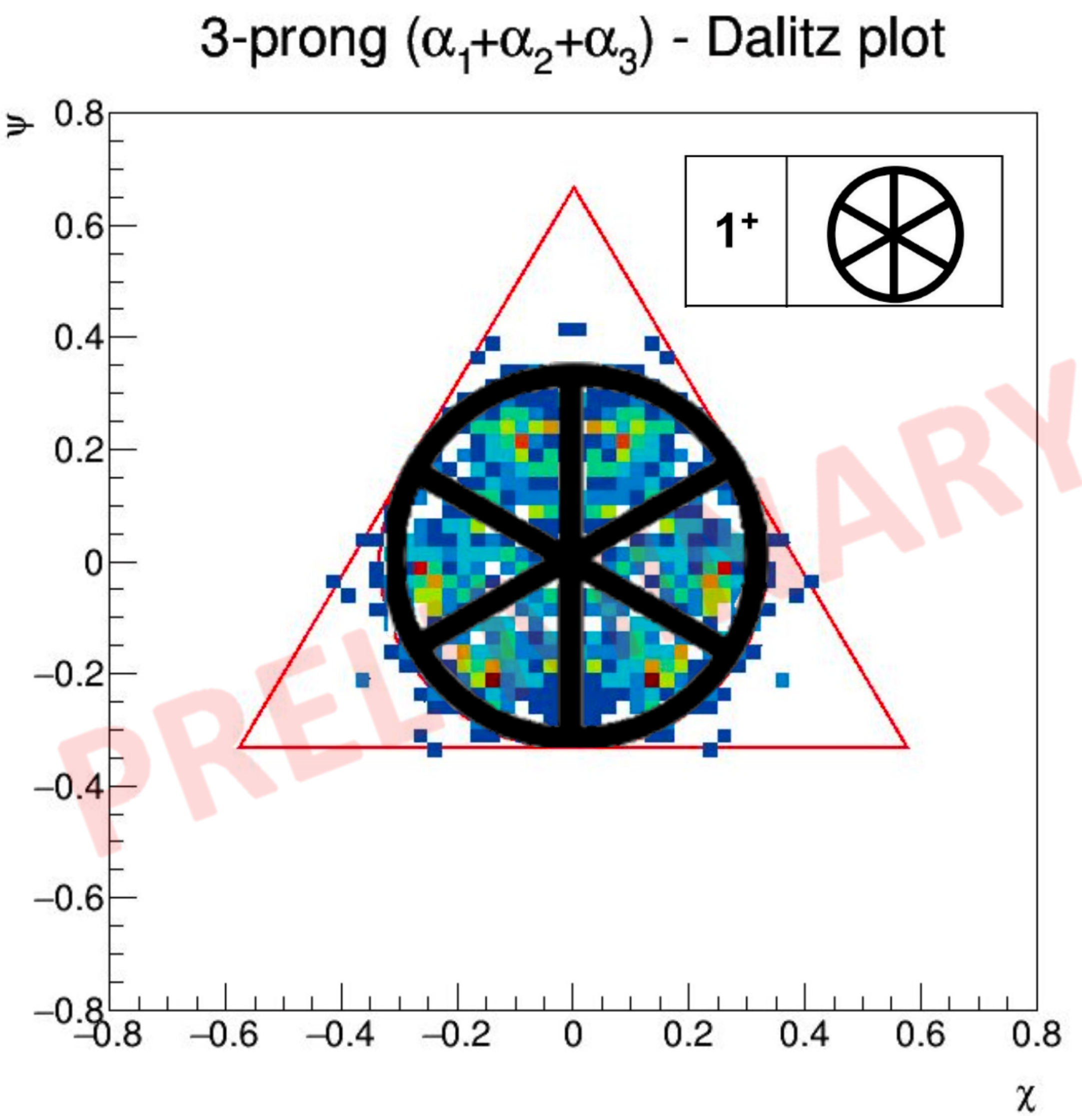


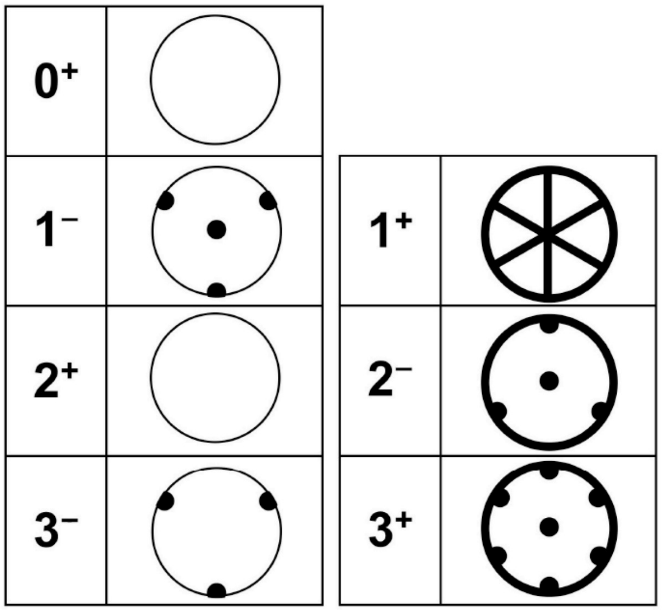
Preliminary results – $^{12}C(\gamma,\alpha_1)^8Be^*$





Preliminary results – $^{12}C(\gamma,\alpha_1)^8Be^*$





Summary

- Warsaw TPC used to study clustering in ^{12}C
- Gamma beams + TPC offer low backgrounds, high selectivity, 2º angular resolution
- ResNet-18 and -50 Neural Networks used for event classification
- Initial evidence of 1^+, 1^- and 2^+ strength at 13.1 MeV in ^{12}C
- With higher statistics, further work needed to include E3 to angular distributions

Collaborators

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