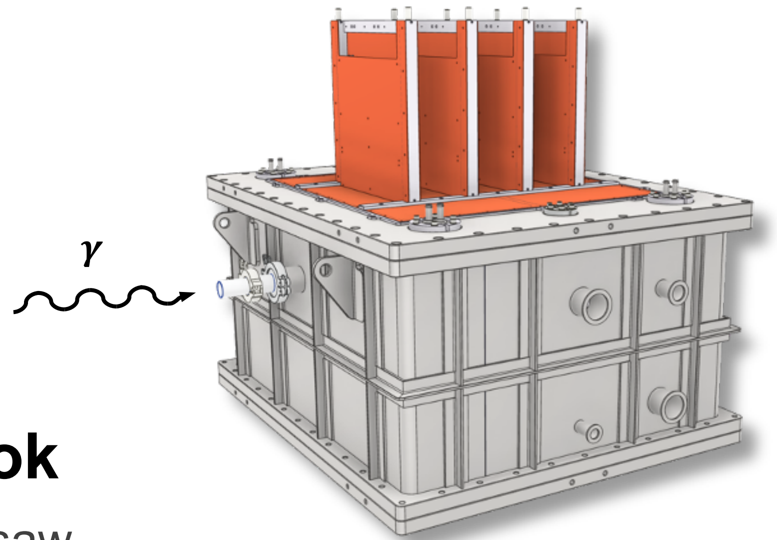
Warsaw active-target Time Projection Chamber for studying astrophysical reactions with gamma and neutron beams



Mikołaj Ćwiok

University of Warsaw

Faculty of Physics

Division of Particles and Fundamental Interactions

4th African Nuclear Physics Conference (ANPC 2025)

iThemba LABS, Cape Town, South Africa – 24-28 November, 2025

Nuclear Astrophysics with monochromatic γ-ray beams

Experimental approach for (α,γ) and (*p*,γ)

direct capture *photo-disintegration*

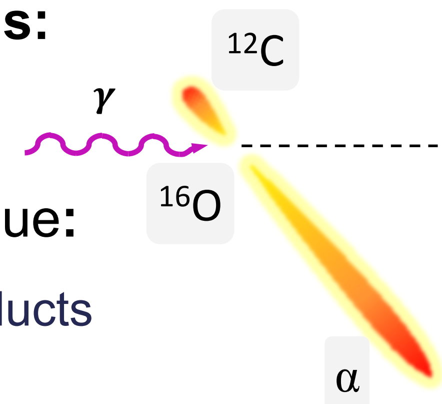
$$\mathbf{B}\,(\boldsymbol{b},\boldsymbol{\gamma})\,\mathbf{A} \;\leftrightharpoons\; \mathbf{A}\,(\boldsymbol{\gamma},\boldsymbol{b})\,\mathbf{B}$$

- Measure **photo-disintegration** instead of direct capture process:
  - detailed balance principle for time-reverse reactions
  - different systematics and experimental challenges
  - **^{16}O(γ,α)^{12}C reaction**: gain of factor 40 in cross section at E_{CM}~1 MeV

$$\sigma_{b\gamma} = \sigma_{\gamma b}\cdot\frac{g_{\gamma b}}{g_{b\gamma}}\cdot\frac{p_{\gamma b}^2}{p_{b\gamma}^2} =$$

$$= \sigma_{\gamma b}\cdot\frac{2J_{CN}+1}{(2J_b+1)(2J_B+1)}\cdot\frac{E_\gamma^2}{E_{CM}}\cdot\frac{1}{\mu_{bB}c^2}$$

- Use quasi-monochromatic **intense gamma-ray beams:**
  - facilities such as: HIγS (USA), ELI-NP (Romania)
- Use **active-target Time Projection Chamber** technique:
  - measure kinematics of low-energy charged particle products
  - obtain accurate values of E1 / E2 components



TPC R&D timeline @ UW

Warsaw TPC

Since 2004 – building & operating **TPCs with optical-readout** (OTPC)
for studying: *2p radioactivity, β-delayed emissions* & *rare decays* with radioactive ion beams.

Since 2013 – developing GEM-based **active-target TPCs with UVW strip readout**
for studying *Nuclear Astrophysics reactions* with neutral beams (γ-rays, neutrons):

- detector R&D partners: **ELI-NP / IFIN-HH** (Romania), **U. of Connecticut** (USA), **Sheffield Hallam U.** (UK)
- DAQ R&D partner: General Electronics for TPCs (CEA/Saclay, CENBG/Bordeaux, GANIL/Caen, MSU/FRIB)
- 2015-2018 : low-pressure prototype **mini-TPC** with **256** readout channels
- 2019-2020 : low-pressure full scale **Warsaw TPC** with **1024** readout channels

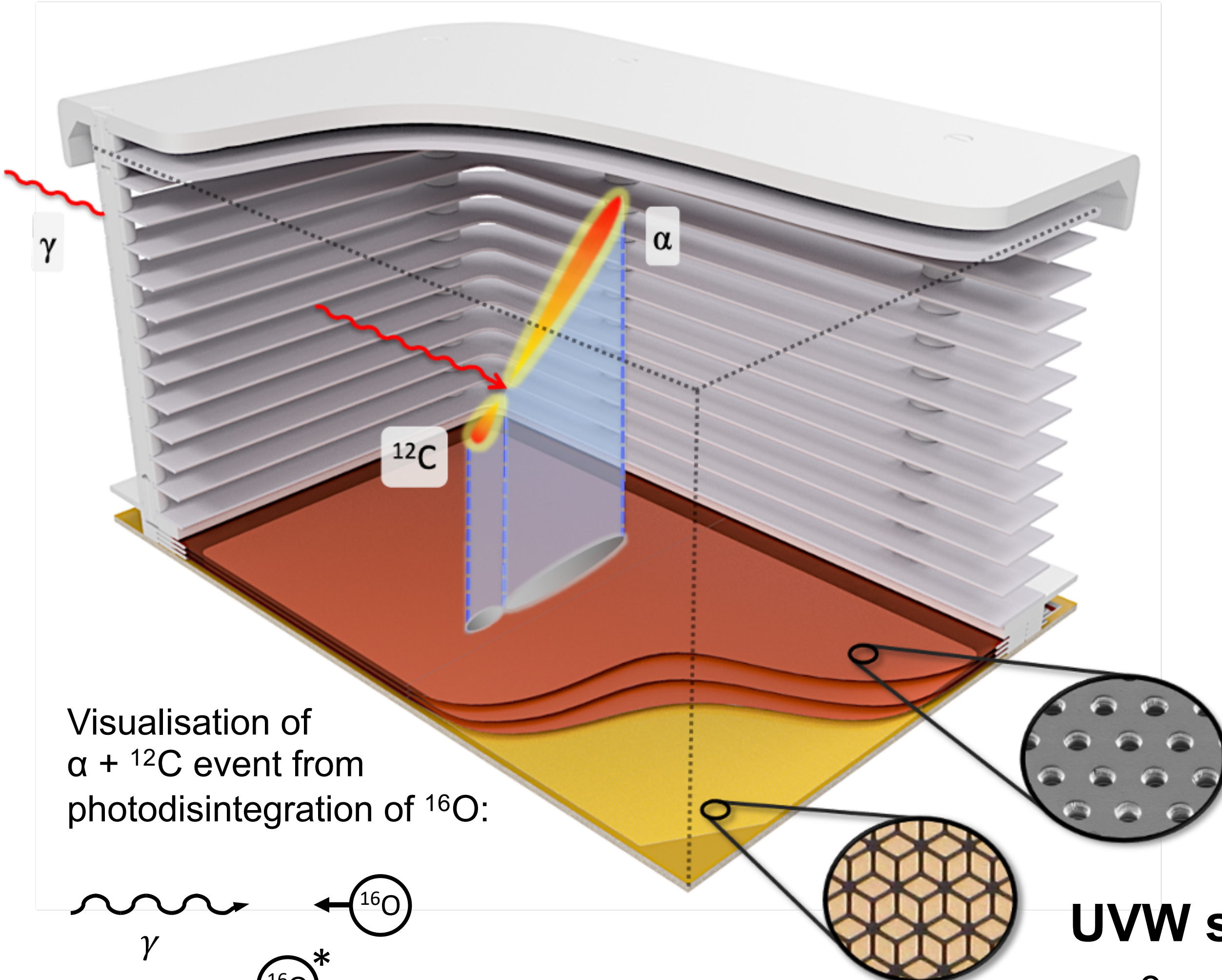
2021-2022 – first experiments with Warsaw TPC:

- 2021 : Institute for Nuclear Physics, Polish Academy of Science (IFJ-PAN), Cracow, Poland:
  - ✓ experiment with 13 MeV gamma source : $^{16}O(\gamma,\alpha)^{12}C$
  - ✓ experiment with 14.1 MeV neutron source : $^{12}C(n,n')^{12}C^{(\text{Hoyle state})}$
- 2022 : High Intensity Gamma-Ray Source (HIgS) / TUNL, Duke U., Durham, NC, USA:
  - ✓ experiment with 8.5 - 13.9 MeV gamma-ray beams : $^{16}O(\gamma,\alpha)^{12}C$ and $^{12}C(\gamma,3\alpha)$

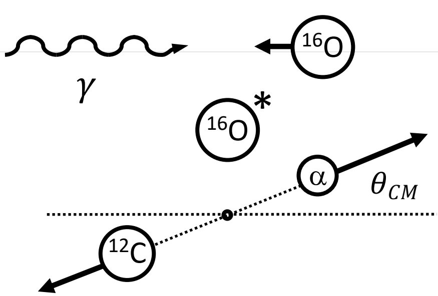
Since 2023 – developing multi-purpose TPC with added ion gating capability
that can work with both: neutral beams (active-target) & radioactive ion beams.

Active-target TPC for γ-rays beam

Warsaw TPC



Visualisation of
α + ^{12}C event from
photodisintegration of ^{16}O:



Active volume

- readout: **330 x 200 mm^2**
- drift length: **196 mm**
- gas: CO_2 @ 80 - 250 mbar

Charge amplification

- Micro-Pattern Gas Detector
- 3 layers of 50-μm thick **Gas Electron Multiplier** foils (GEM)
  F.Sauli, NIMA 386, 531 (1997)

UVW strip readout

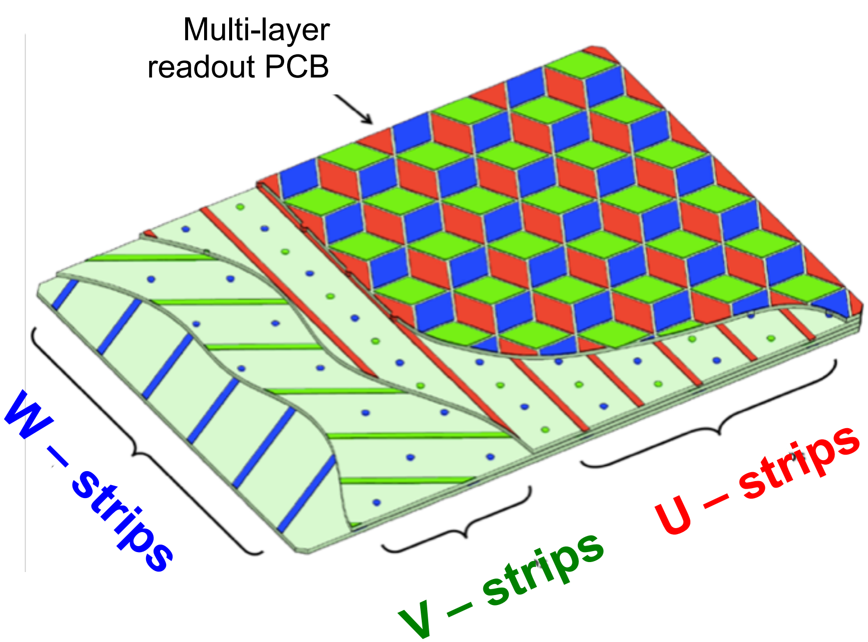
- 3-coordinate planar redundant strips
- about **1000 channels**
- GET front-end electronics

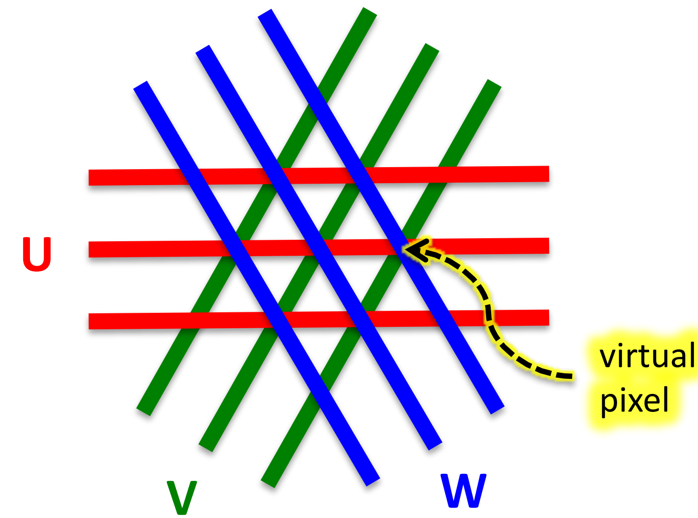
UVW readout strips

Warsaw TPC

3 grids of strips – crossed at 60° :

- diamond-shaped pads, interconnected to form strips, *Via-in-Pad* technology
- 3-coordinate, planar, redundant strip readout, 1.5 mm strip pitch
- {***UVW*** strip information on ***XY*** plane} + {***Z*** coordinate from drift time} → virtual 3D pixels
- suitable for simple event topologies → few tracks per event
- cost-effective solution → only ***O*(10^3)** channels needed to cover 30 × 20 cm^2 area

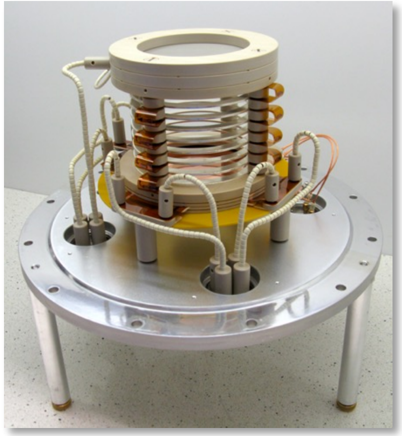




[1] S. Bachmann et al., NIM A **478**, 104 (2002)
[2] V. Ableev et al., NIM A **535**, 294 (2004)
[3] J. Bihałowicz et al., Proc. of SPIE **9290**, 92902C (2014)
[4] M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

Low-pressure GEM-based TPCs @ UW

Warsaw TPC



2-channel model detector

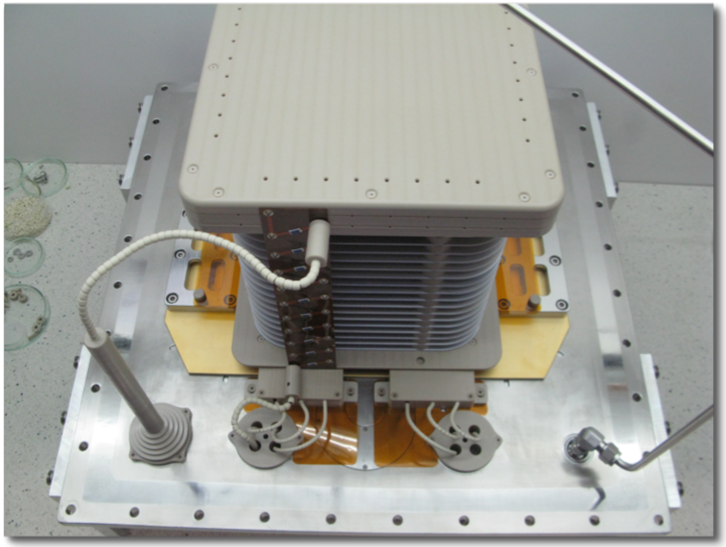
ϕ 5 cm (active area) × 10 cm (drift)

1024-channel Warsaw TPC

33 × 20 cm^2 (active area) × 19.6 cm (drift)

256-channel mini-TPC

10 × 10 cm^2 (active area) × 20 cm (drift)



Warsaw TPC – detector structure

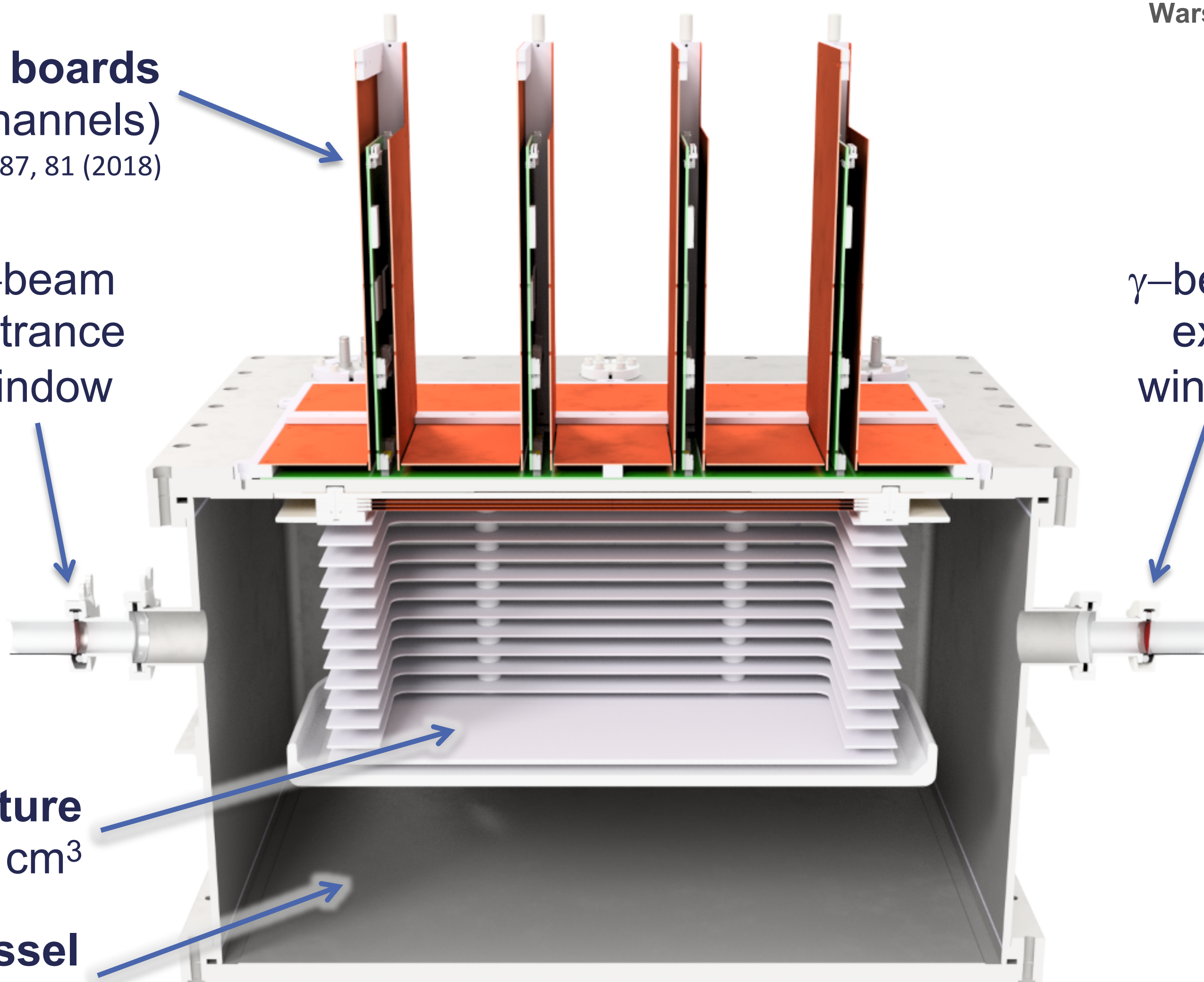
Warsaw TPC

4 × **AsAd FE boards**
(1024 channels)
E. Pollacco et al., NIMA 887, 81 (2018)

γ–beam entrance window

γ–beam exit window

γ – beam



Internal TPC structure
$33 \times 20 \times 19.6\ \mathrm{cm}^3$

Low-pressure vessel
$170\ \mathrm{dm}^3$

Warsaw TPC half-section view

Warsaw TPC – data acquisition

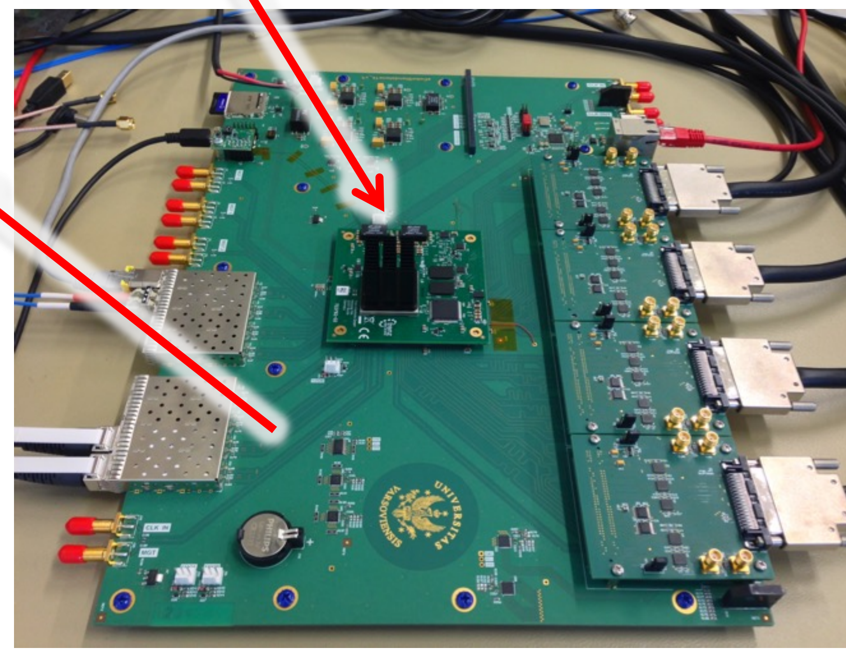
Warsaw TPC

- Custom UW-designed FPGA data concentrator module (z-CoBo):
  - **reads 4 GET AsAd boards (1024 channels)**
  - employs Xilinx Zynq-7000 SoC (Trenz TE-0782) with custom UW firmware
  - data output: up to 8 SFP+ ports (10 Gbit/s)
  - internal or external triggering
  - 2U 19”-rack form-factor

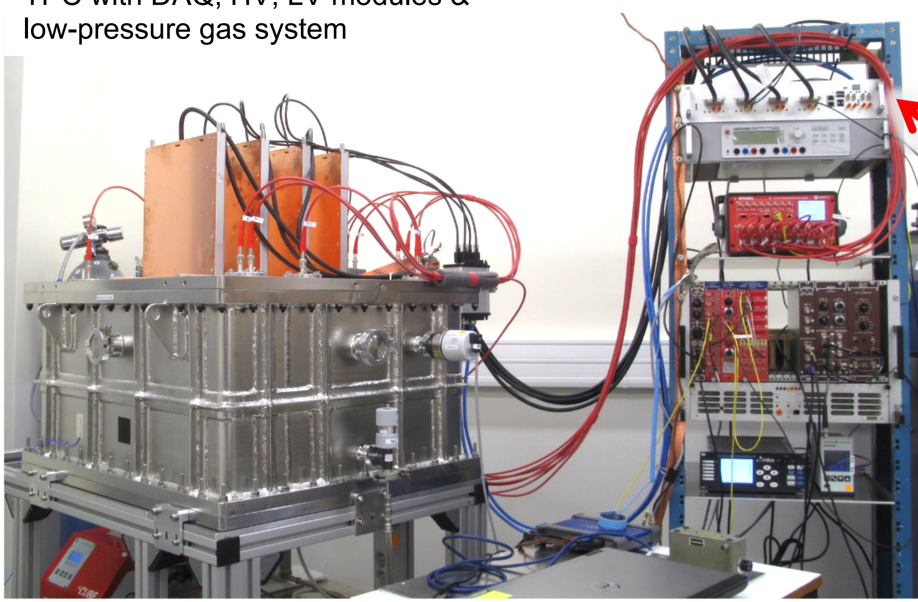
Commercial ZYNQ-7000 mezzanine

M. Zaremba
K. Kierzkowski
W. Okliński

Custom DAQ main board



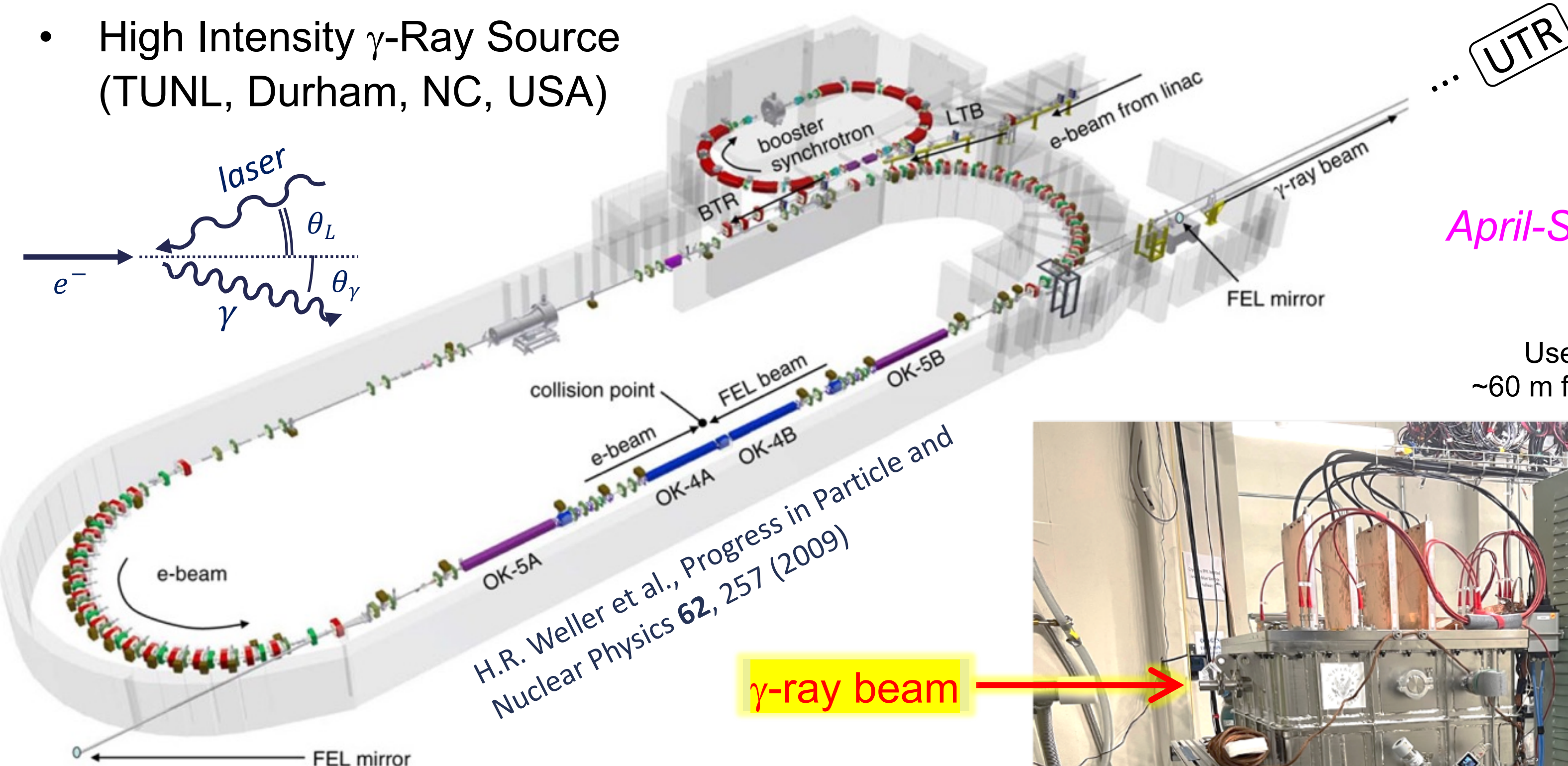
TPC with DAQ, HV, LV modules & low-pressure gas system



^{16}O photodisintegration experiment @ HIγS

Warsaw TPC

- High Intensity γ-Ray Source (TUNL, Durham, NC, USA)



April-September 2022

Warsaw TPC in the User Target Room (UTR) ~60 m from the collision point

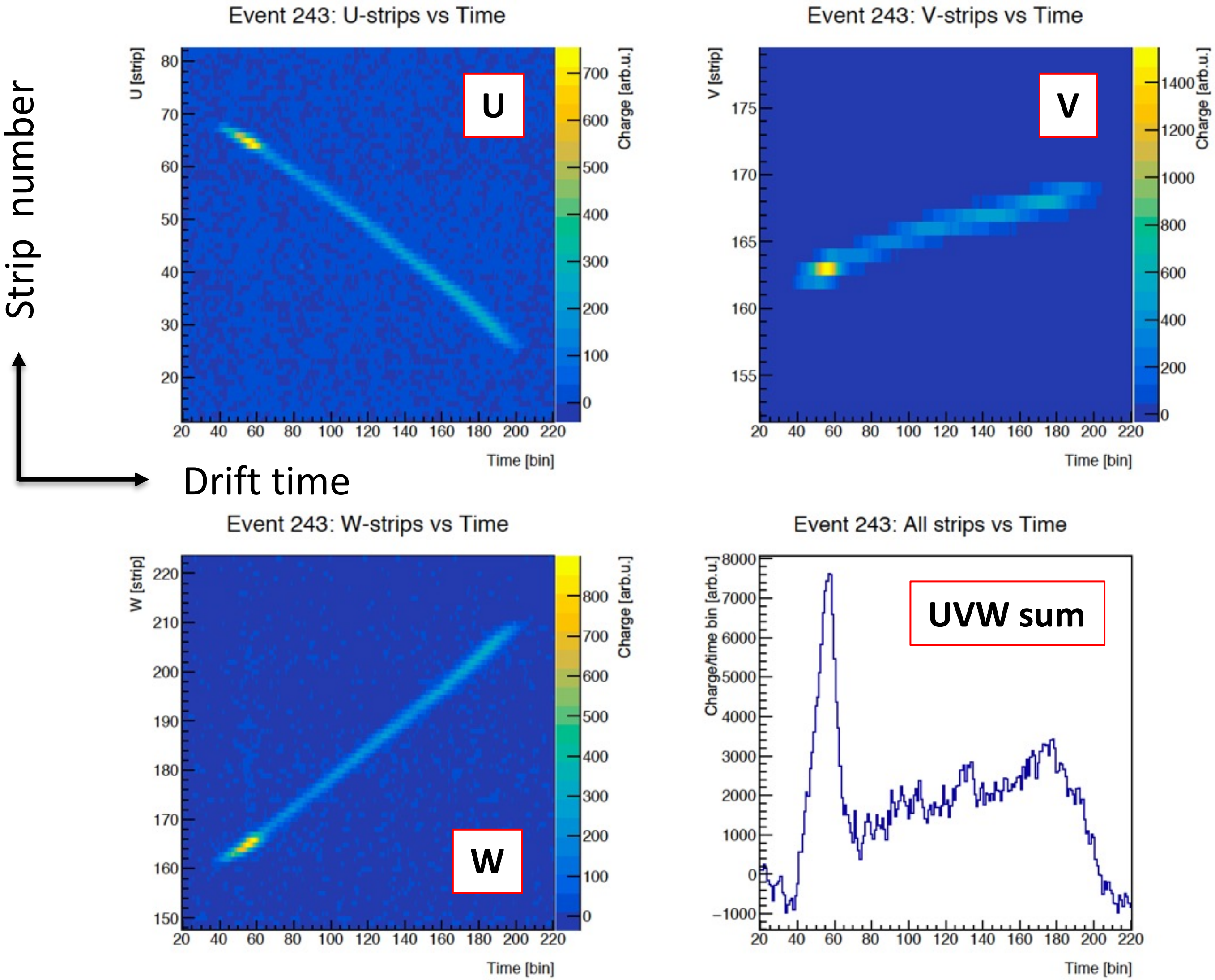
γ-ray beam

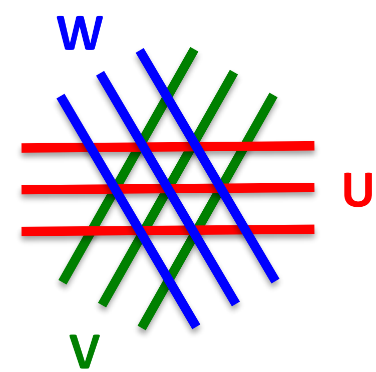
- Warsaw TPC operated with pure CO_2 @ 130 / 190 / 250 mbar
- Reactions studied: **^{16}O(γ,α)^{12}C**, **^{12}C(γ,3α)**
- Nominal E_γ : **8.5 – 13.9** MeV

HIγS ’2022 : example raw data

Warsaw TPC

2-particle topology: $^{16}O(\gamma,\alpha)$ candidate event





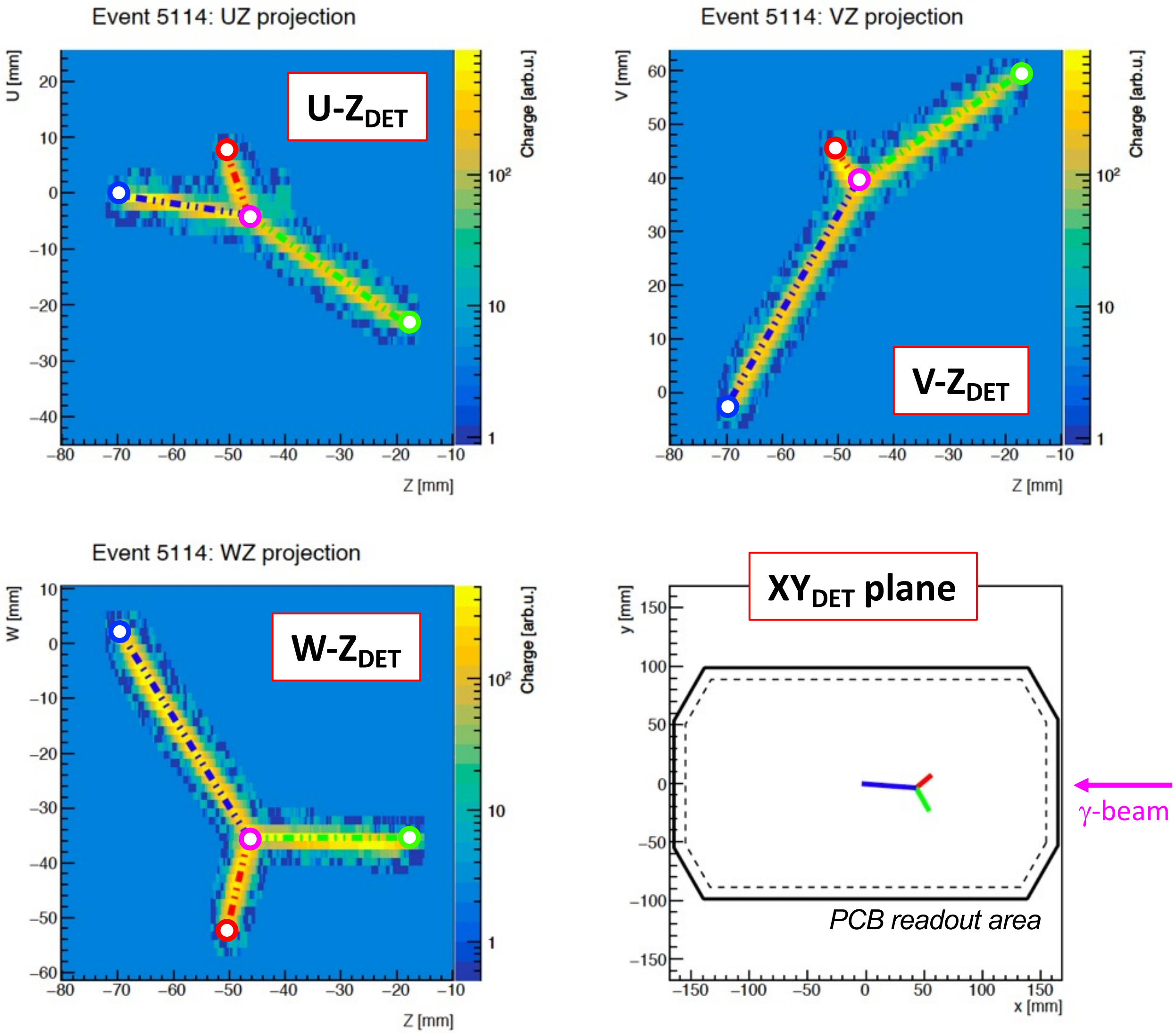
E_γ=13.9 MeV

- Zoomed region of interest
- Pressure: 250 mbar
- Sampling: 12.5 MHz

HIγS ’2022 : manual track finding

Warsaw TPC

3-particle topology: reconstructed α tracks in 3D



E_γ=13.9 MeV

- Pressure: 250 mbar
- Sampling: 12.5 MHz

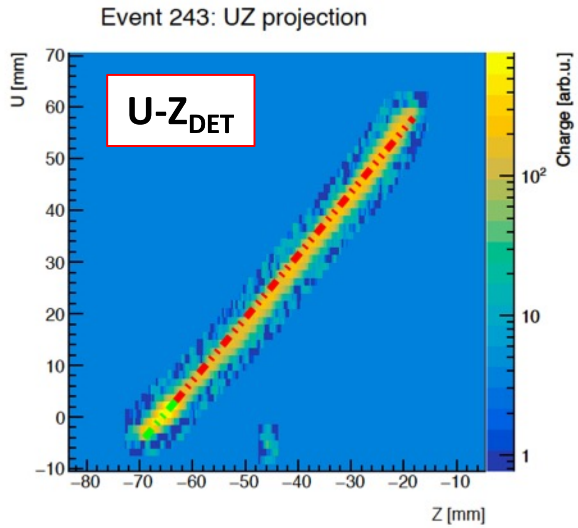
- **Manual procedure** for 1/2/3-particle topology *(current default)*
- Vertex & track ends selected by expert

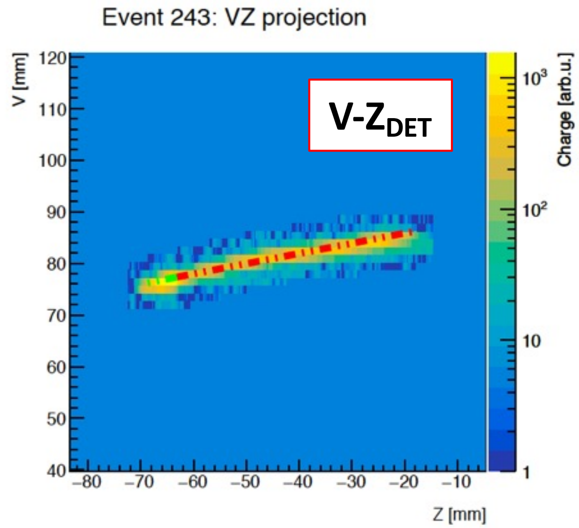
A. Kalinowski

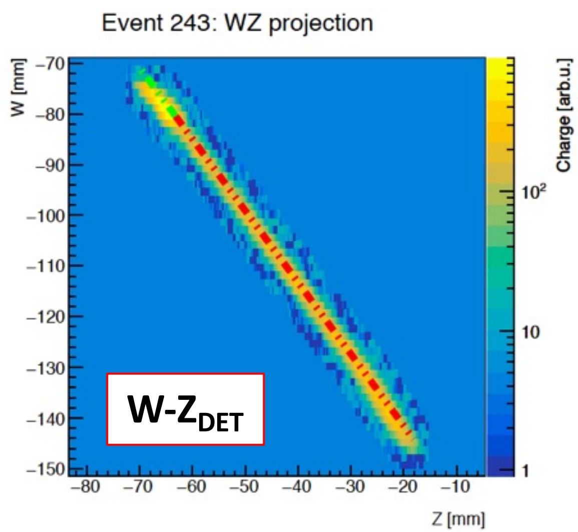
HIγS ’2022 : automatic track finding

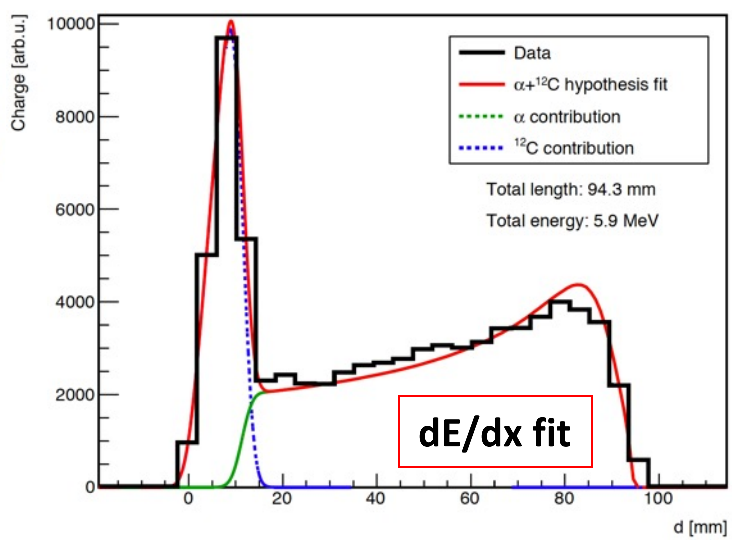
Warsaw TPC

2-particle topology: reconstructed α + carbon track in 3D









E_γ=13.9 MeV

- Pressure: 250 mbar
- Sampling: 12.5 MHz

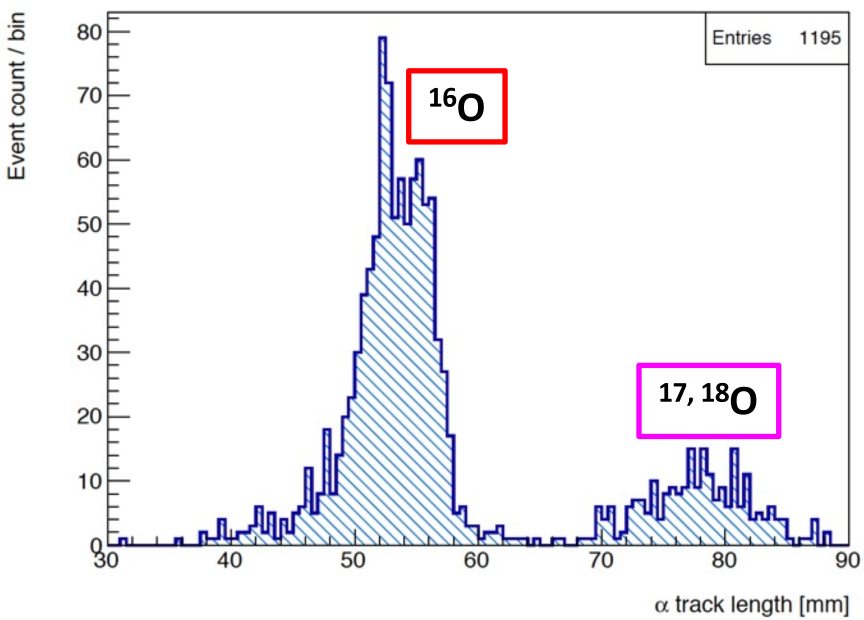
- **Automatic track finding** for 2-particle events *(work in progress)*
- Clustered data fitted to dE/dx templates (SRIM + diffusion)

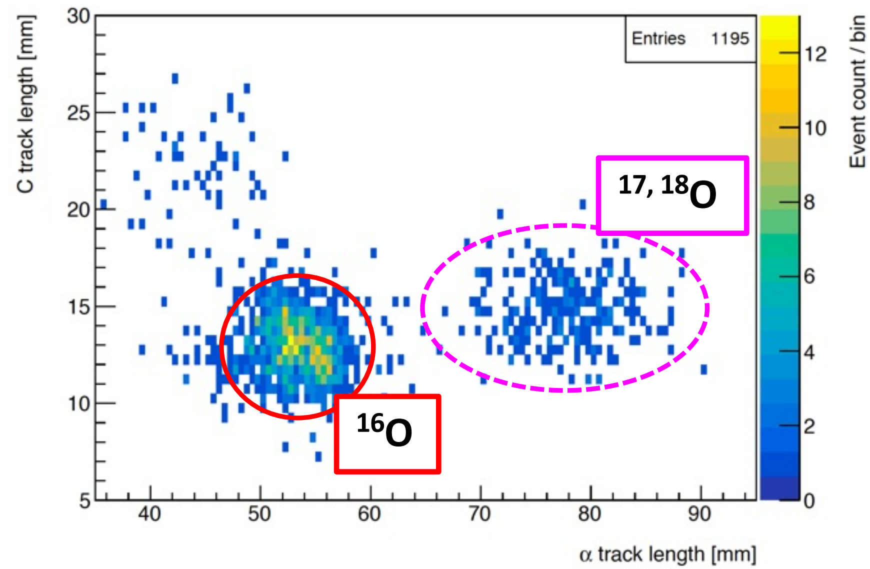
A. Kalinowski

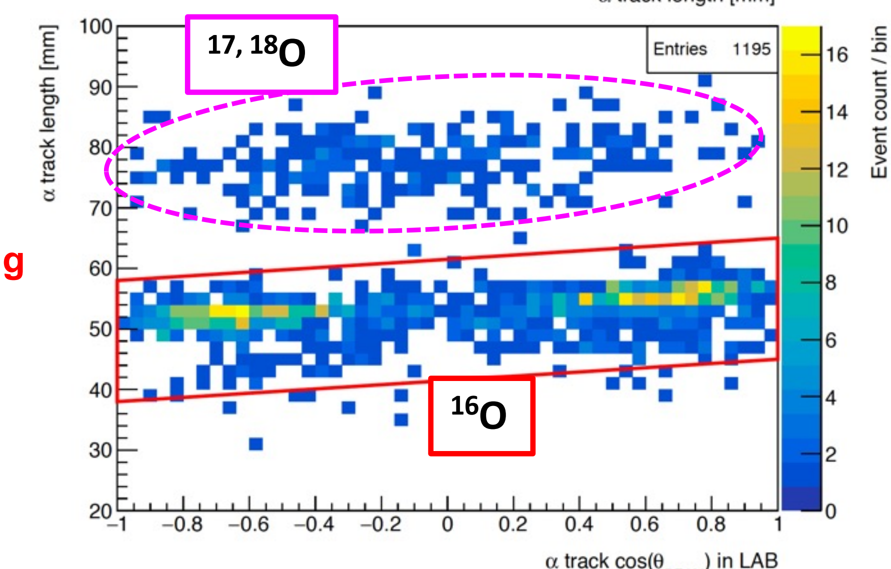
HIγS '2022 : reaction identification

Warsaw TPC

Separation of ^{16}O photo-disintegrations based on track length:







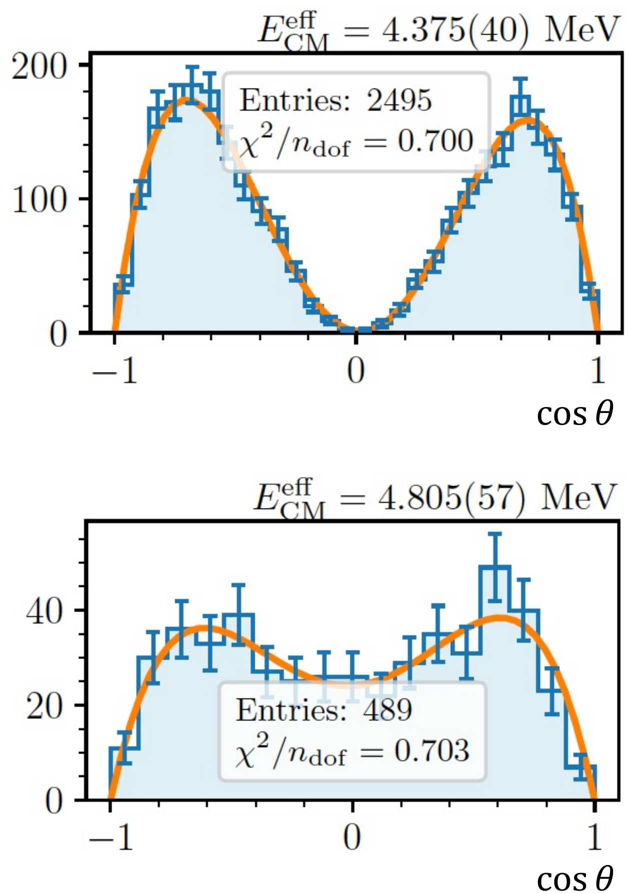
E_γ=9.85 MeV

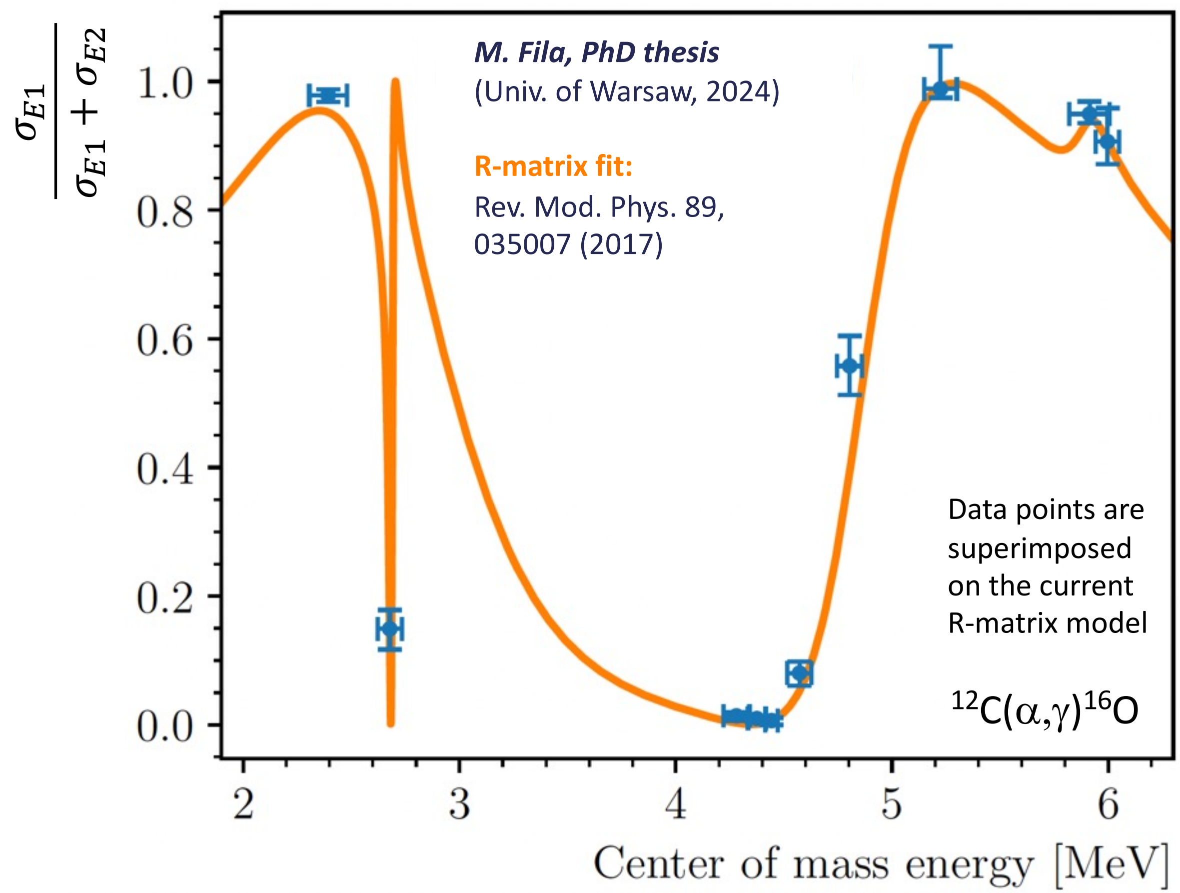
- **Manual track finding**
- 2-particle events
- Pressure: 130 mbar
- Sampling: 25 MHz

$^{16}O(\gamma,\alpha)^{12}C$: E1 / E2 multipolarity

Warsaw TPC

- **Distributions of polar angle θ_{CM} of α-particles:**
  - **manual track finding**, $^{16}O(\gamma,\alpha)^{12}C$ candidate events
  - evolution of E1 / E2 ratio & E1-E2 mixing angle extracted for several E_{CM} bins

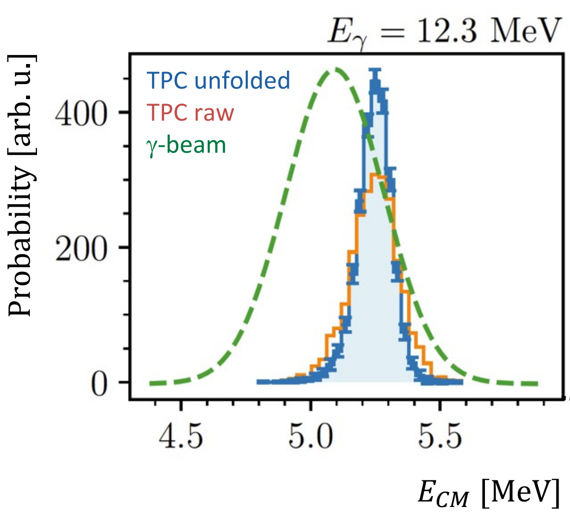


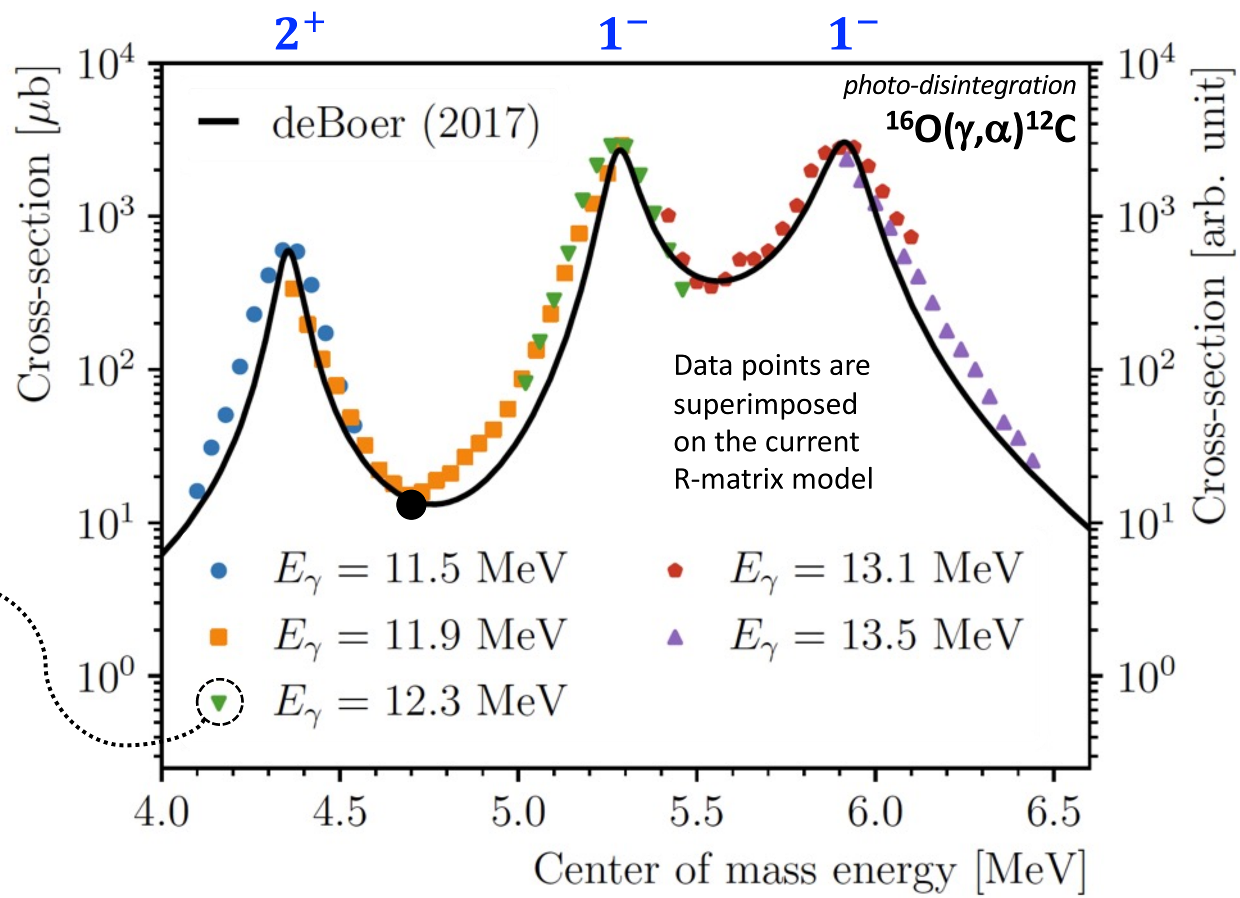


$^{16}O(\gamma,\alpha)^{12}C$: relative E1+E2 x-sec

Warsaw TPC

- **Unfolded TPC spectra divided by γ-beam spectra:**
  - **manual track finding,** $^{16}O(\gamma,\alpha)^{12}C$ candidate events, σ_E ~ 45 keV for 2 MeV α-particles
  - combined 5 beam energy runs using overlapping E_{CM} energy bins
  - resulting stitched curve normalized to R-matrix model at a single point (●)
  - information about absolute γ-beam intensity not used





M. Fila, PhD thesis
(U. of Warsaw, 2024)

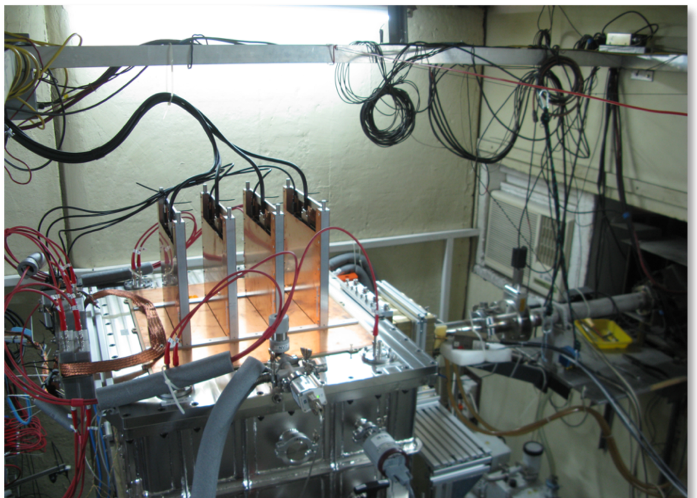
R-matrix fit for E1+E2:
Rev. Mod. Phys. 89, 035007 (2017)

Neutron source experiment @ IFJ (Poland)

Warsaw TPC

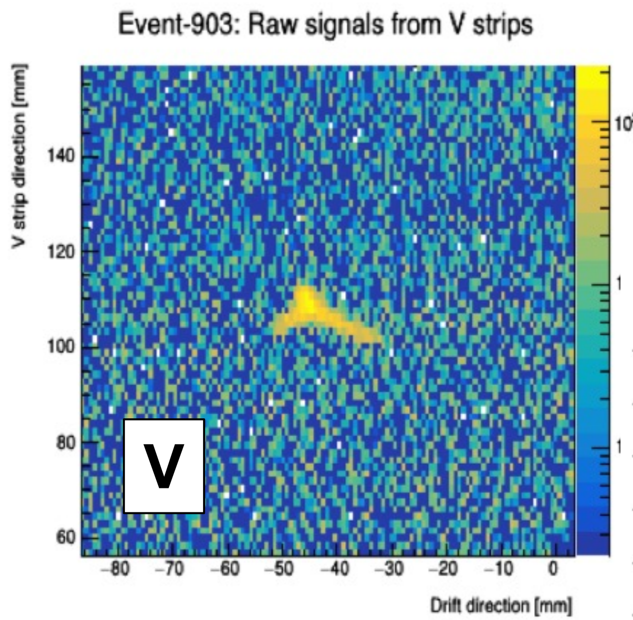
- Institute for Nuclear Physics, Polish Academy of Science, Cracow, Poland (IFJ)
- IGN-14 pulsed neutron generator: 14.1 MeV neutrons from T(d, n)α

Warsaw TPC at IGN-14
~20 cm from neutron source



July-September 2021

Example of candidate event for $^{12}C(n,n')^{12}C^{(\text{Hoyle state})}$:

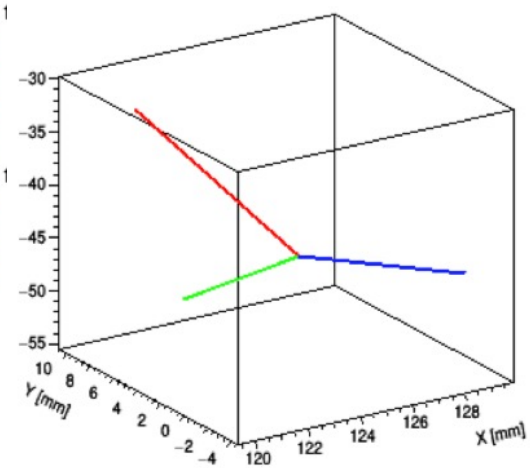


$E_{\alpha 1}$ = 145 keV

$E_{\alpha 2}$ = 108 keV

$E_{\alpha 3}$ = 60 keV

$E_x(^{12}C)$ =7.60 MeV



M. Kuich et al., Acta Phys. Pol. B Proc. Suppl. **16**, 4-A17 (2023)

- Warsaw TPC operated with pure CO_2 @ 80 mbar
- Reactions observed:

$^{12}C(n, n')^{12}C$

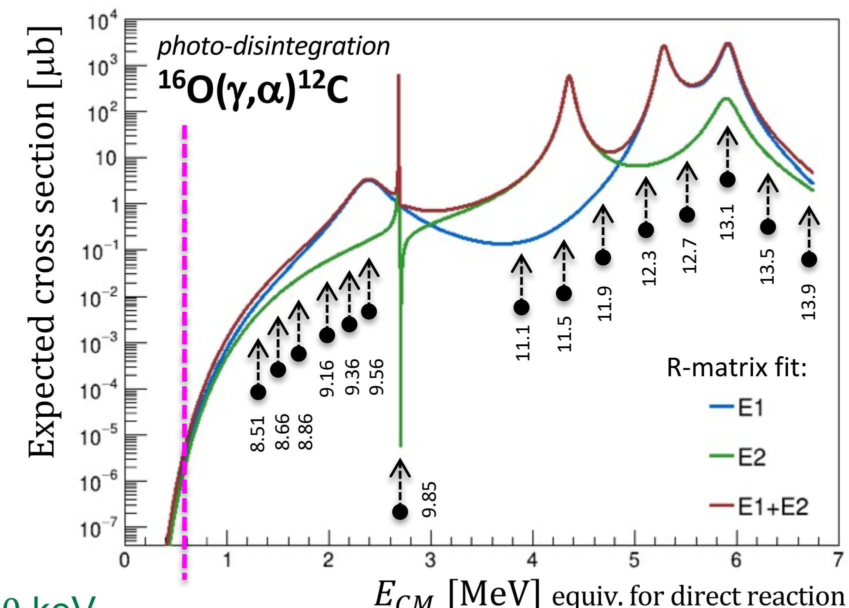
$^{12}C(n, \alpha)^9Be$

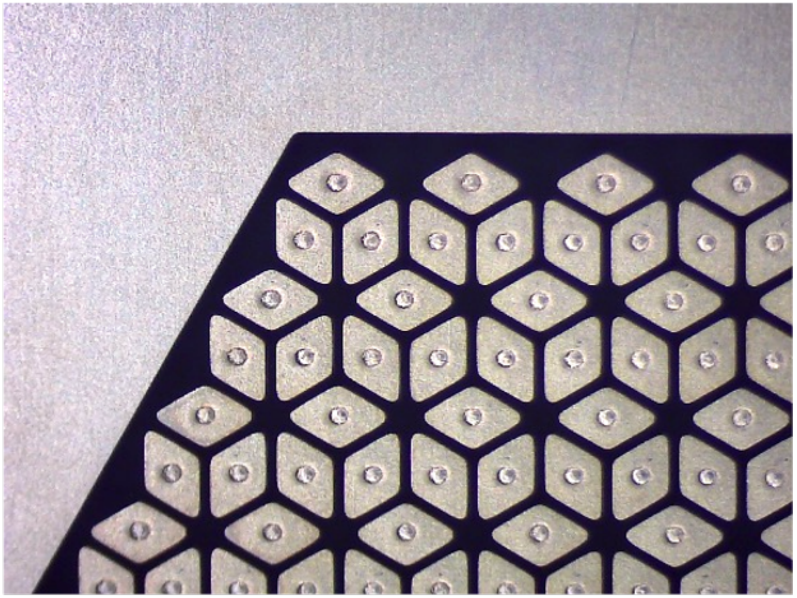
Summary & Outlook

Warsaw TPC

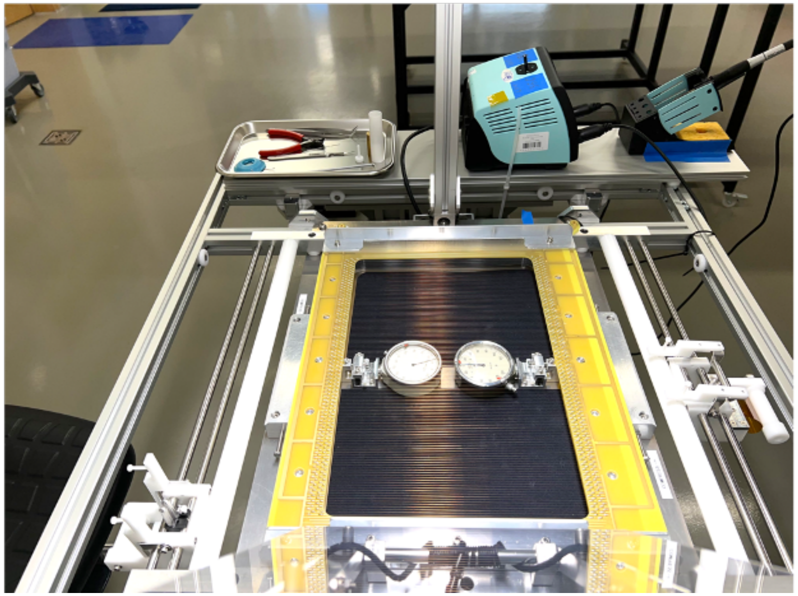
- ✓ Active-target TPCs commissioned with successful experiments using γ-ray beams & neutron sources
  - 1 PhD thesis defended (UW, 2024), 3 more PhDs under way (UConn, SHU)
- ✓ Working on improved automated track finding algorithms
  - both, classic & Machine Learning approaches
- ✓ Building new multi-purpose TPC (active-target / radioactive ion beam)

- Future plans:
  - **Summer 2026** : next experiment approved by the HIγS PAC
    - $E_{CM}\sim$1 MeV region of $^{16}O(\gamma,\alpha)$ reaction
    - increased beam intensity
  - Looking forward for even more intense γ-ray source in the ELI-NP facility (Bucharest-Magurele, Romania)
    - move closer to the Gamow region at $E_{CM}\sim 300$ keV





Thank you for your attention !!!



Collaboration

Warsaw TPC

Experimental team – HIγS '2022:

M. Ćwiok, W. Dominik, A. Fijałkowska, M. Fila, Z. Janas, A. Kalinowski, K. Kierzkowski, M. Kuich, C. Mazzocchi, W. Okliński, P. Podlaski, M. Zaremba, R. Dąbrowski, H. Czyrkowski

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M. Gai, S. Stern, D. Schweitzer

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D.L. Balabanski, C. Matei, A. Rotaru

IFIN-HH / ELI-NP, Bucharest-Magurele, Romania

K. Haverson, R. Smith

Sheffield Hallam University, UK

R. Allen, M.R. Griffiths, S. Pirrie, P. Santa Rita Alcibia

University of Birmingham, School of Physics and Astronomy, UK

Acknowledgements:

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Special thanks to teams from Duke University and University of North Carolina at Chapel Hill.

List of publications

Warsaw TPC

[1] K.C.Z. Haverson et al., Il Nuovo Cimento **48 C**, 17 (2025)

[2] M. Ćwiok et al., EPJ Web Conf. **290**, 01004 (2023)

[3] M. Ćwiok et al., EPJ Web Conf. **279**, 04002 (2023)

[4] C. R. Brune, C. Matei , S.D. Pain and R. Smith, Eur. Phys. J. A **59**, 165 (2023)

[5] M. Kuich et al., Acta Phys. Pol. B Proc. Suppl. **16**, 4-A17 (2023)

[6] M. Gai et al., NIM A **954**, 161779 (2020)

[7] M. Ćwiok et al., Acta Phys. Pol. B **49**, 509 (2018)

[8] M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

[9] O. Tesileanu et al., Romanian Rep. in Phys. **68** Supplement, S699 (2016)

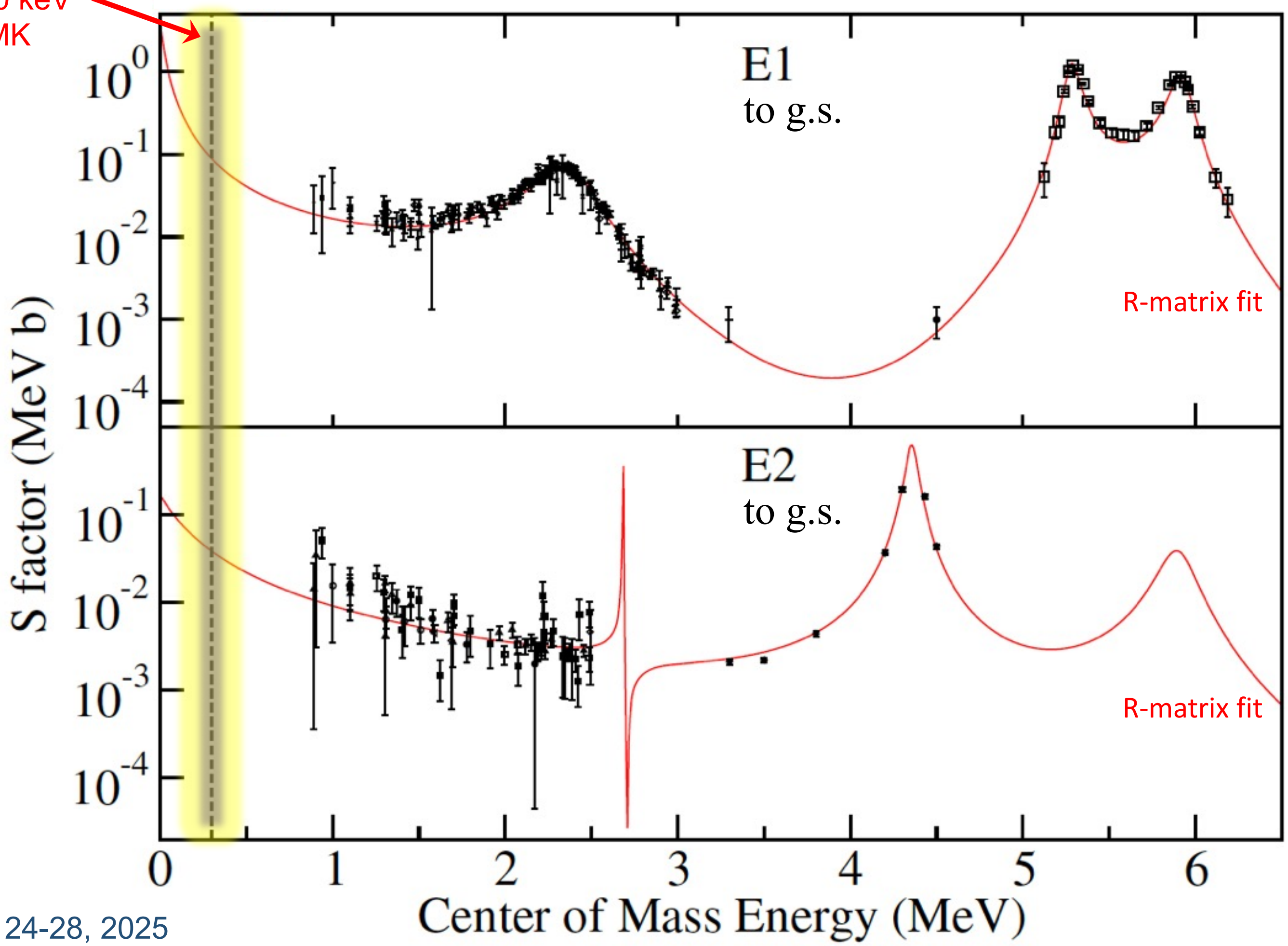
BACKUP slides

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

Extrapolated p-wave (E1) & d-wave (E2) **astrophysical S-factors** to the Gamow peak in red giant stars: **40 – 80% uncertainty**

Gamow peak
E_{CM} ~ 300 keV
T ~ 300 MK

R.J. de Boer et al., Rev. Mod. Phys. **89**, 035007 (2017)



Brochard (1973)	E1
Dyer, Barnes (1974)	E1
Redder (1987)	E1, E2
Kremer (1988)	E1
Ouellet (1996)	E1, E2
Roters (1999)	E1, E2
Gialanella (2001)	E1
Kunz (2001)	E1, E2
Fey.(2004)	E1, E2
Assunção (2006)	E1, E2
Makii (2009)	E1, E2
Schürmann (2011)	E1, E2
Plag (2012)	E1, E2

^{16}O photodisintegration experiment @ HIγS

(April-September, 2022)

Warsaw TPC

- **Delivered γ-ray beams:**
  - 275 hours / 15 energy points
  - beam collimator: ⌀10.5 mm
  - **E_γ nominal : 8.51 – 13.9 MeV**
    $\Leftrightarrow E_{CM}$: 1.35 – 6.7 MeV of ^{12}C(α,γ)^{16}O
  - E_γ fwhm : 350 keV @ 8.51 MeV
  - **I_γ on target : (1.5 – 5) x 10^8 γ/s**
- **Beam monitoring:**
  - E_γ spectra : from HPGe detector
  - relative $I_\gamma(\mathrm{t})$: from scintillators
  - absolute $\int I_\gamma(t)dt$: from activation of Au foils from (γ,n)
- **Active-target TPC working points:**
  - **pure CO_2 gas** @ 130 / 190 / 250 mbar
  - gas density, electron drift velocity, electronics sampling rate optimized for charged particle ranges in detector's active volume

BEAM

⇒ can study **^{16}O(γ,α)^{12}C** and **^{12}C(γ,3α)**

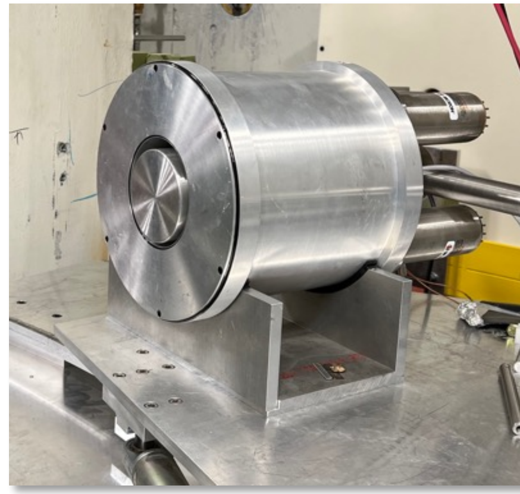
HIγS ’2022 : beam monitoring / alignment

Warsaw TPC

Collimator
ϕ =10.5 mm
(upstream)

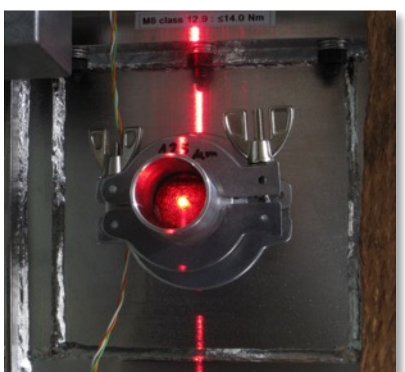
Scintillators
(upstream)

HPGe
(downstream)

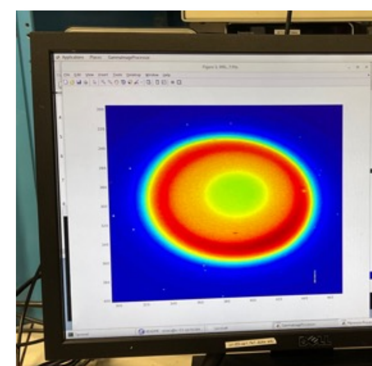


Au foil activation
(downstream)

Alignment – laser



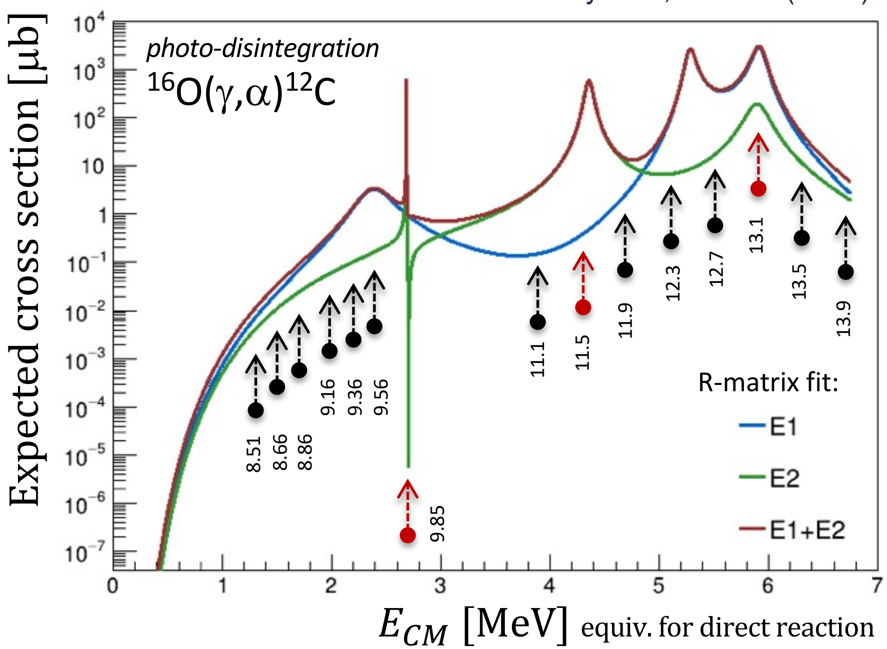
Alignment – BGO CCD gamma camera & lead plugs:

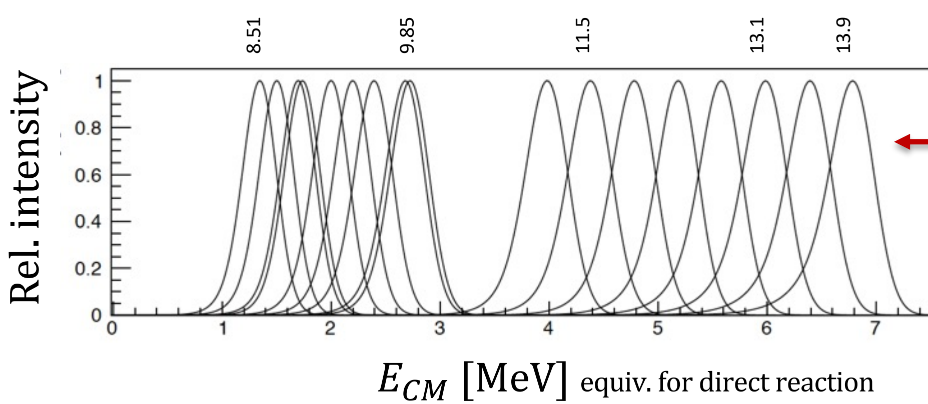


HIγS '2022 : energy scans

Warsaw TPC

R-matrix fit from: Rev. Mod. Phys. 89, 035007 (2017)





Overview of experimental conditions:

- scanned 15 nominal energy points split into two data-taking periods
- 3 resonant energies used for *in situ* tuning of α-track energy scale
- several TPC working points:
  - 3 gas target densities
  - 2 front-end electronics sampling rates
  - 7 electron drift velocities

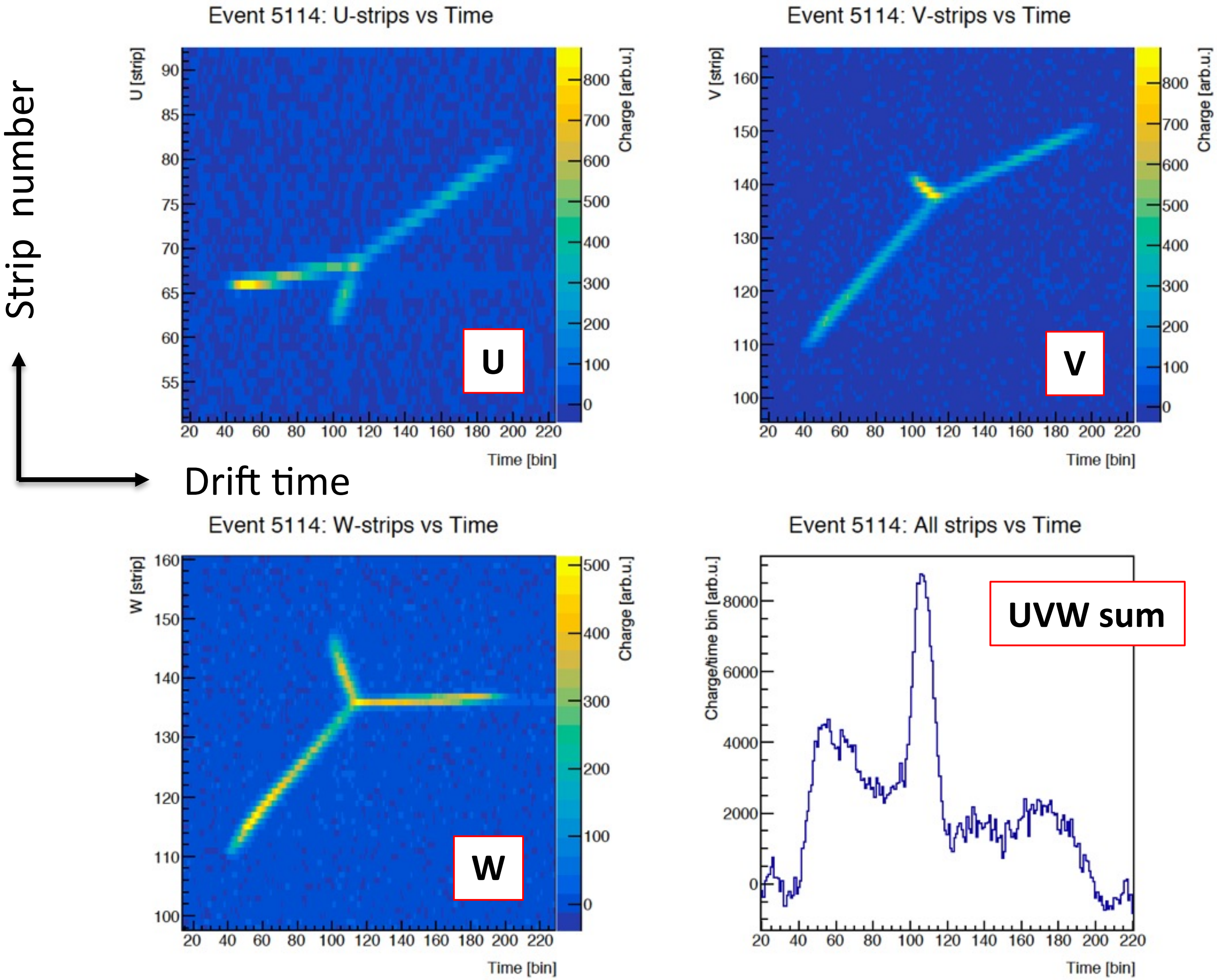
typical shapes of γ-beam spectra on target (TPC volume) for all studied nominal energy points

(courtesy of prof. Y. Wu, HIGS/TUNL)

HIγS ’2022 : example raw data

Warsaw TPC

3-particle topology: $^{12}C(\gamma,3\alpha)$ candidate event



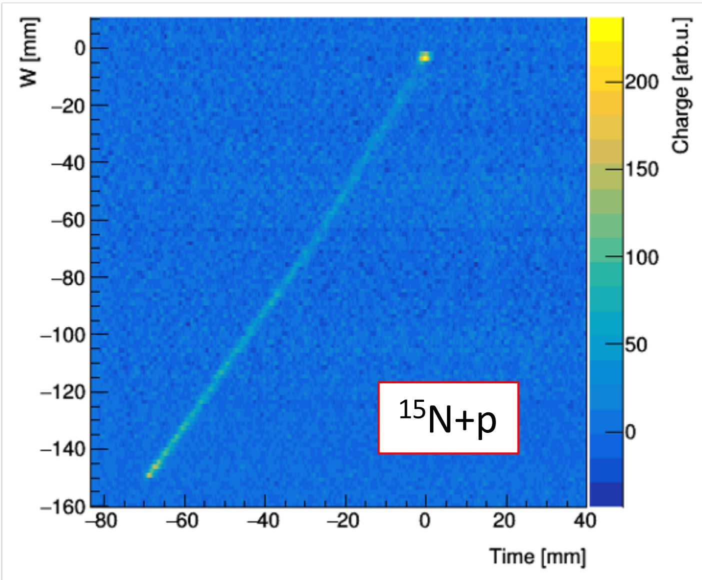
E_γ=13.9 MeV

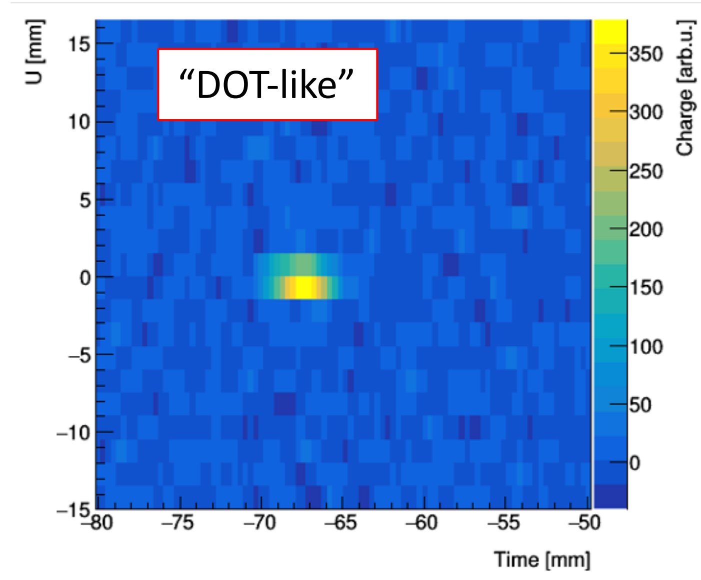
- Zoomed region of interest
- Pressure: 250 mbar
- Sampling: 12.5 MHz

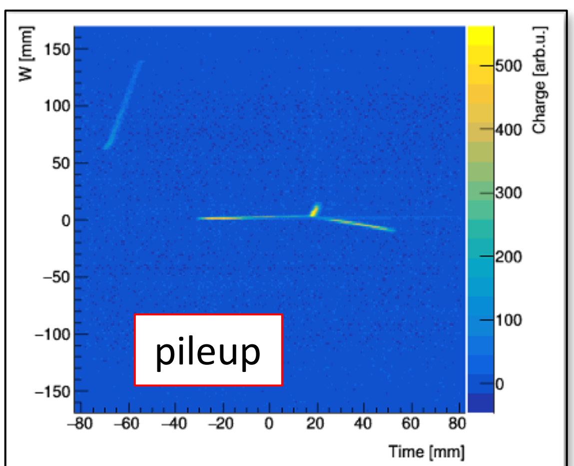
HIγS ’2022 : background

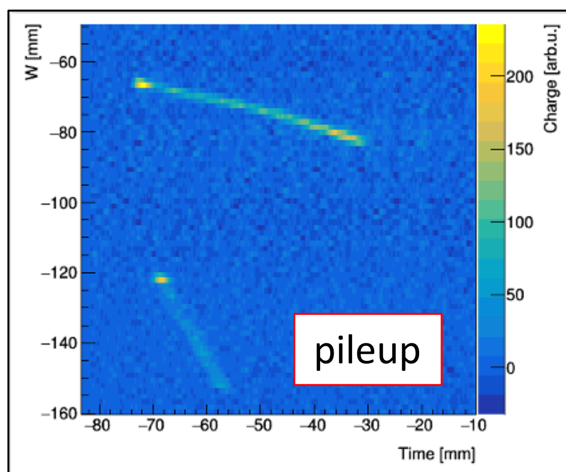
Warsaw TPC

Examples of background & more complex events:









E_γ=13.9 MeV

- Only 1 out of 3 projections is shown for simplicity
- Pressure: 250 mbar
- Sampling: 12.5 MHz

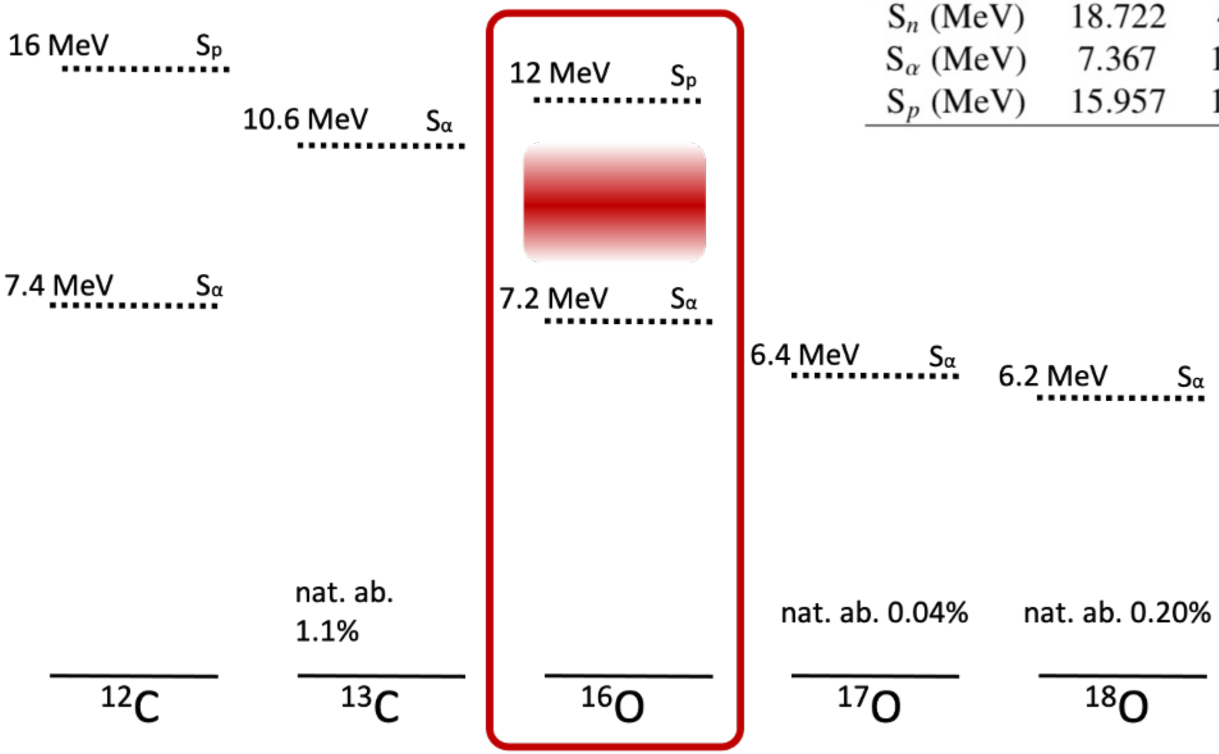
HIγS '2022 : reaction identification

Warsaw TPC

Possible **reaction channels** with gaseous **CO_2 target:**

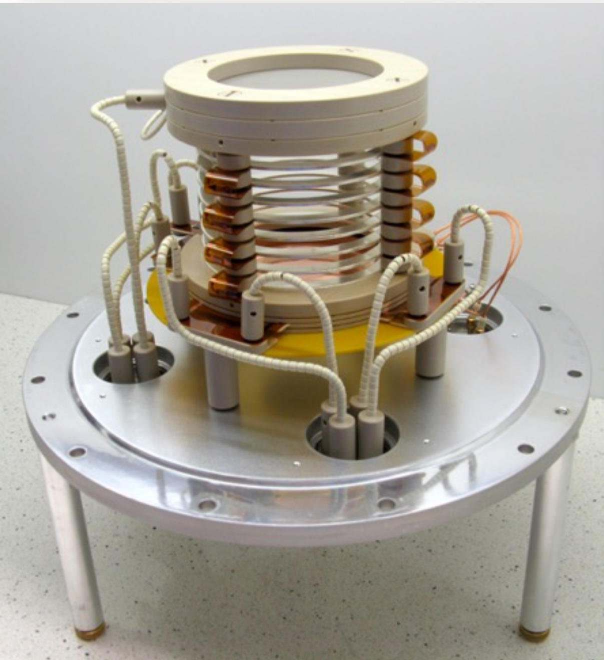
Separation energies for neutrons, protons and alpha particles in ^{12,13}C and ^{16,17,18}O isotopes

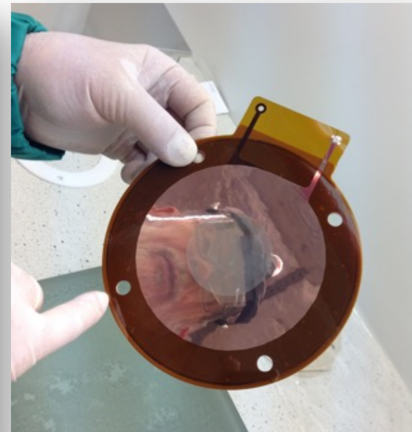
	^{12}C	^{13}C	^{16}O	^{17}O	^{18}O
S_n (MeV)	18.722	4.946	15.664	4.144	8.044
S_α (MeV)	7.367	10.648	7.162	6.359	6.227
S_p (MeV)	15.957	17.533	12.128	13.780	15.942

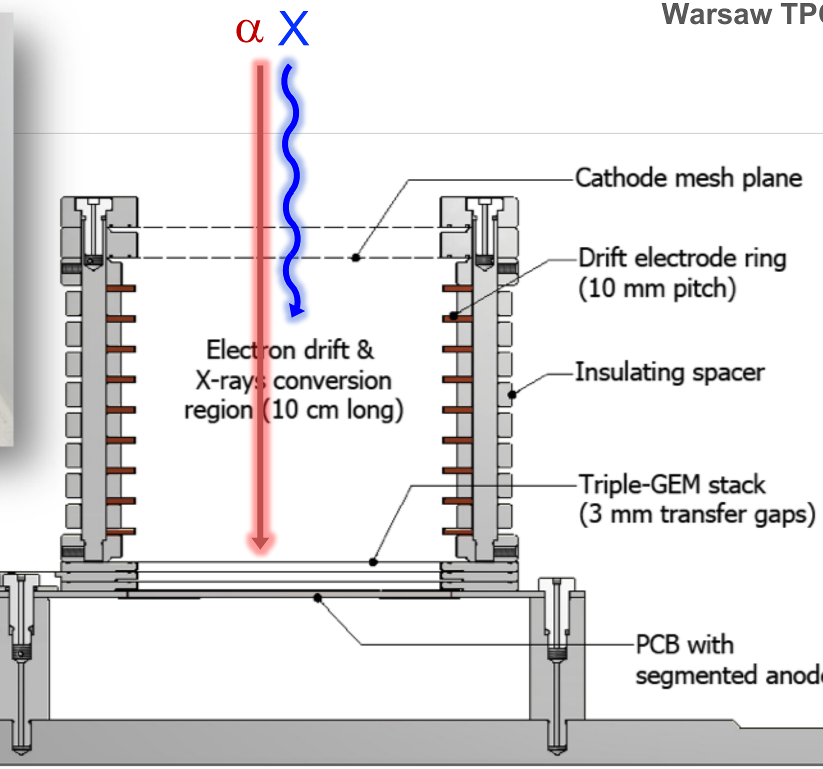


Test bench for GEM studies

Warsaw TPC







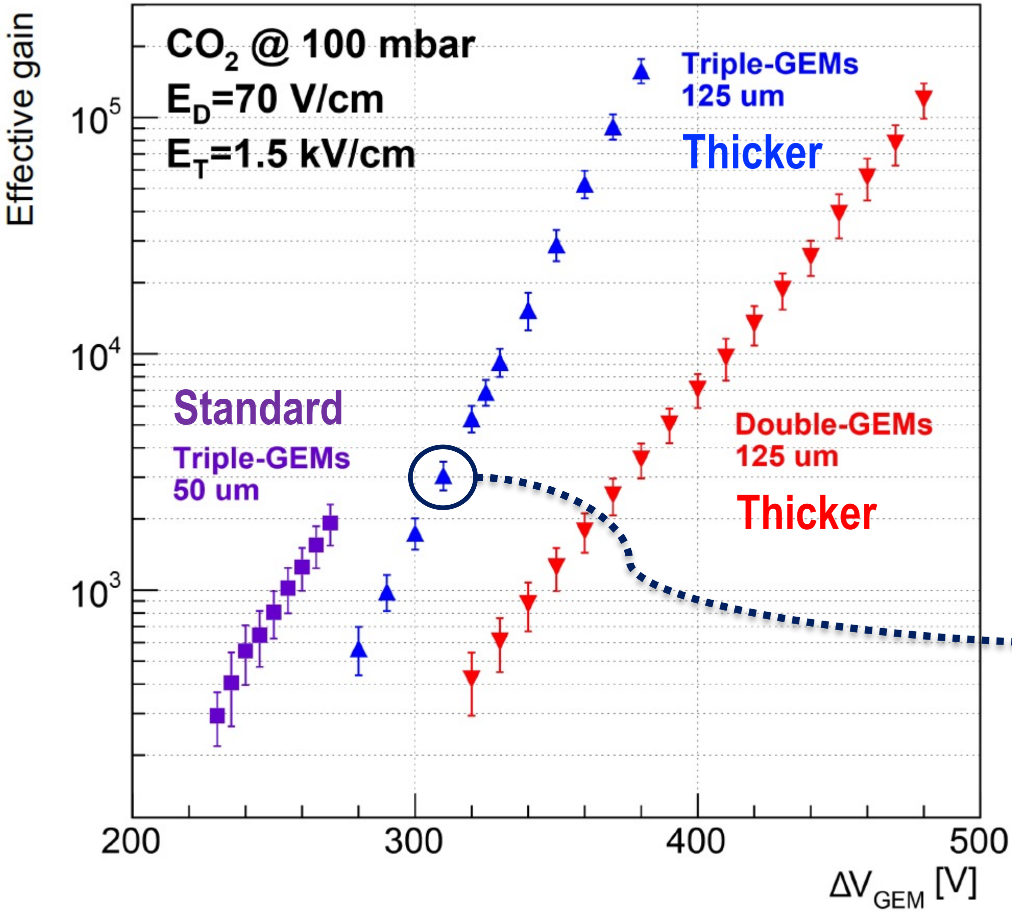
M. Ćwiok et al., Acta Phys. Pol. B **49**, 509 (2018)

- Low-pressure test bench:
  - model detector: 14 dm^3 vessel, 3 or 2 GEM foils, ϕ5 cm {active area} × 10 cm {drift}
  - GEM foil thickness: **50 µm** (standard) or **125 µm** (custom designed **thicker-GEM**)
  - soft X-rays (~5 keV) ⇒ **gas gain**, energy resolution
  - alpha-particle source (~5.5 MeV) ⇒ **electron drift velocity**, diffusion

Gas gain studies

Warsaw TPC

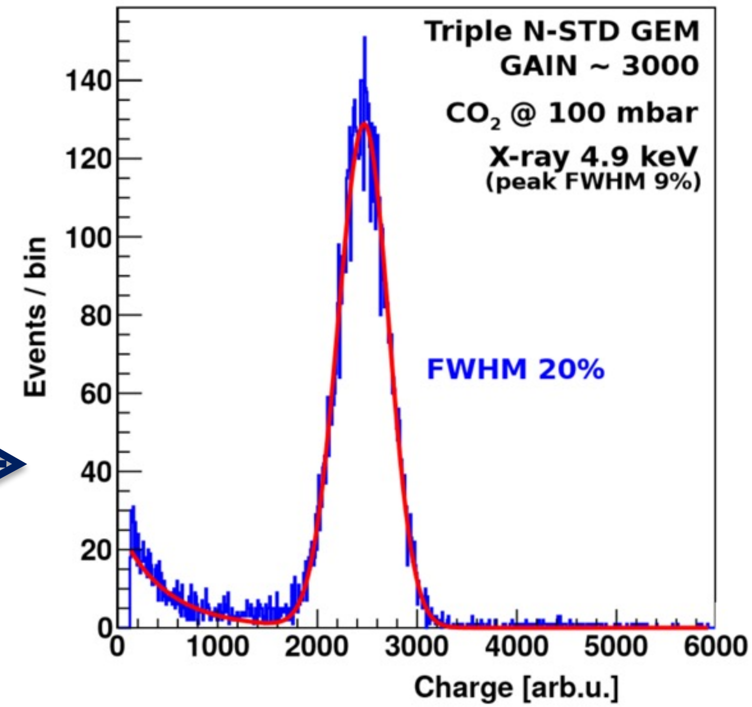
M. Kuich



Pure CO_2 at 100 mbar

M. Kuich

Pulse-height spectrum



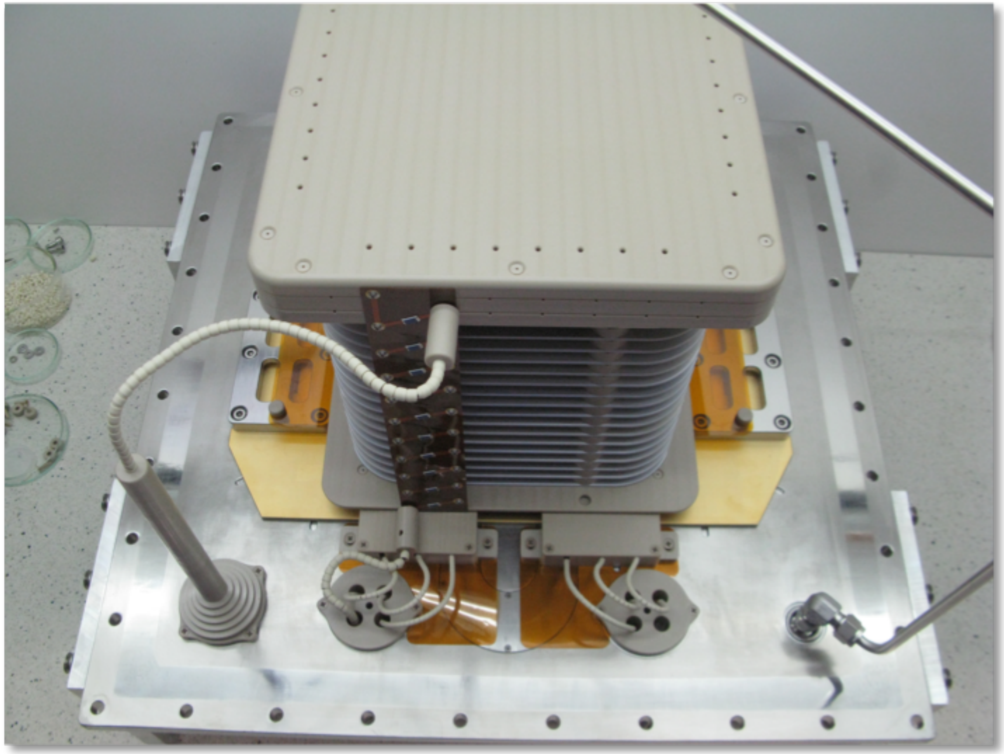
- **Thicker (125-μm)** triple-GEM & thicker double-GEM stacks offer **higher effective gains** than standard (50-μm) triple-GEMs in low-pressure applications

Mini-TPC demonstrator

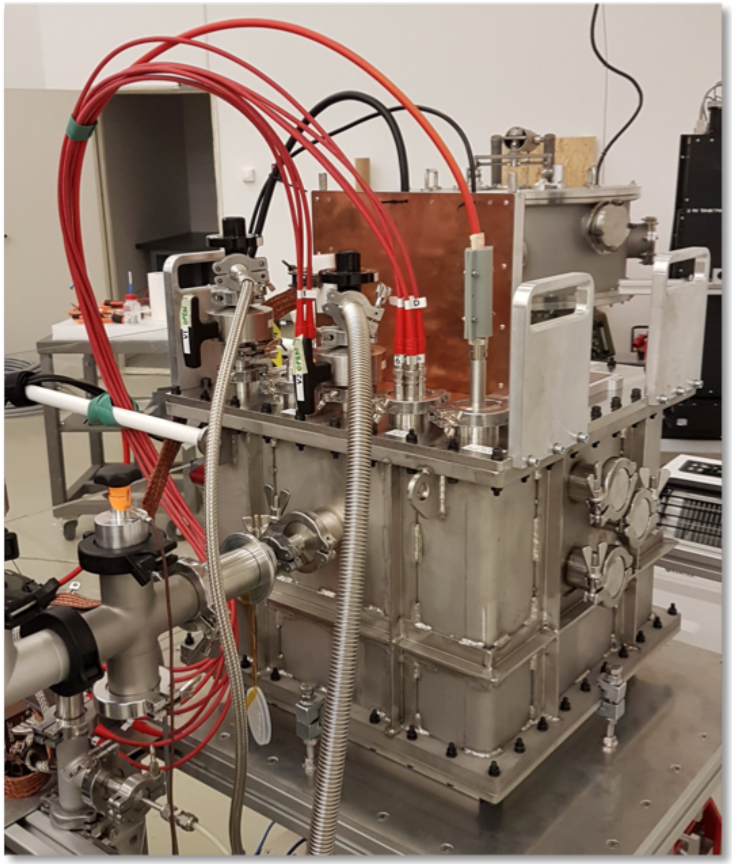
Warsaw TPC

- Readout area: **10 × 10 cm²**, drift length: **20 cm**
- Vacuum vessel (53 dm^3), low-pressure gas system
- GET electronics: **256 channels** (z-CoBo)

Assembled internal TPC structure



Vacuum vessel with 1 AsAd board



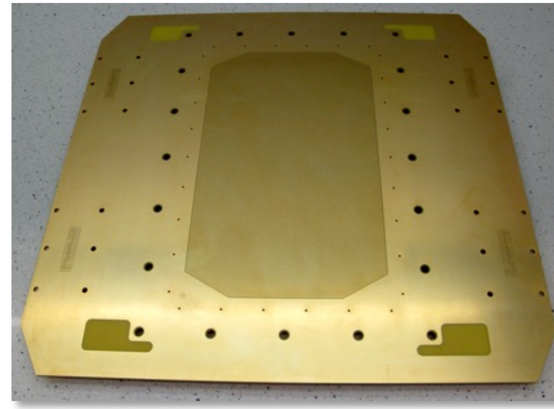
M. Ćwiok, Acta Phys. Pol. B **47**, 707 (2016)

Full scale detector - assembly

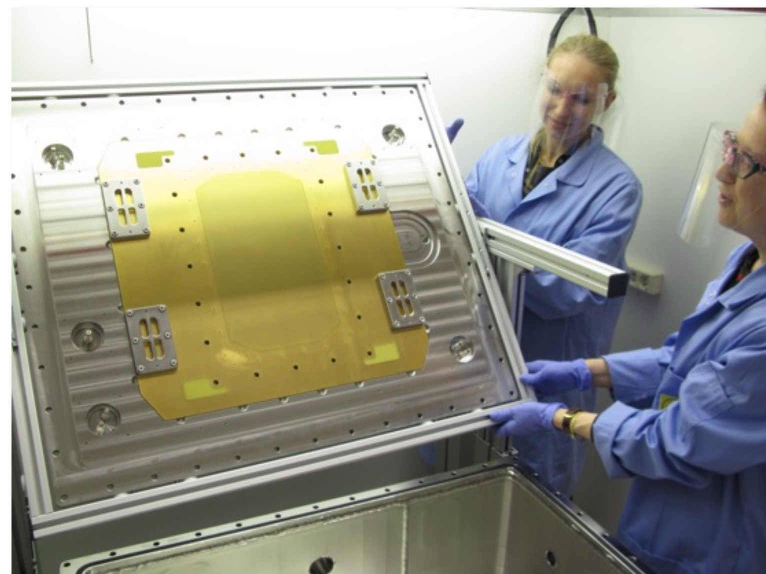
Warsaw TPC

- Warsaw TPC detector is operational since March 2020

Fully assembled TPC structure with
33 × 20 × 19.6 cm^3 fiducial volume



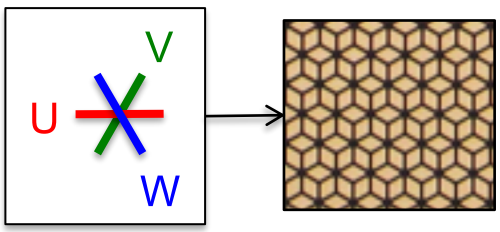
Integration tests of UVW readout PCB



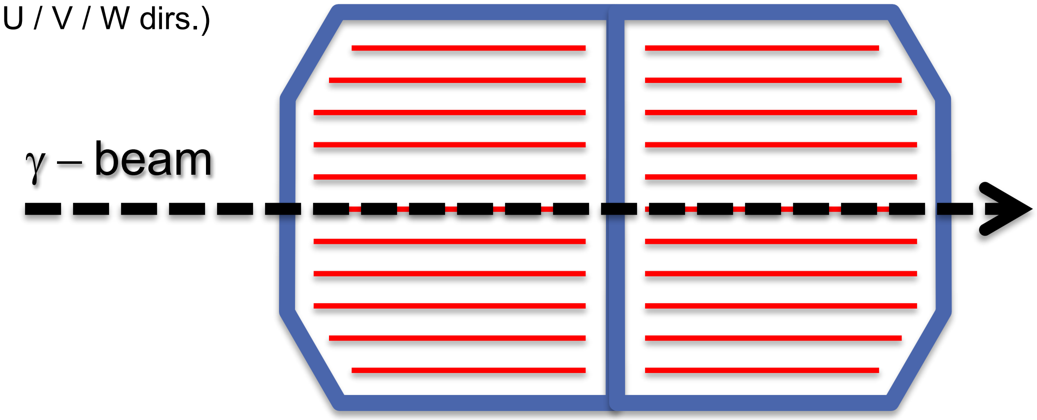
1K-channel UVW readout PCB

Warsaw TPC

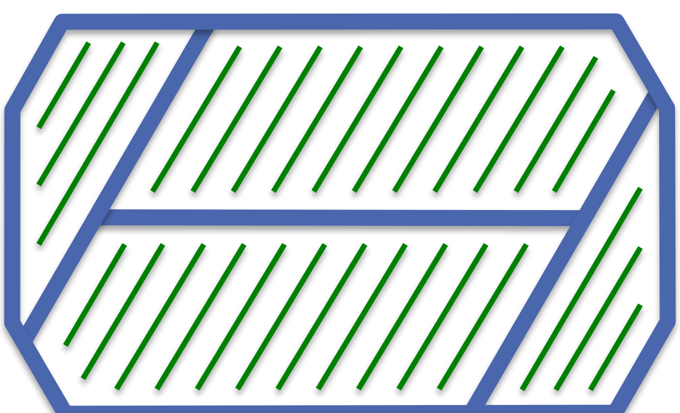
- **1018 strips** in total
- 1.5 mm strip pitch (in each of U / V / W dirs.)



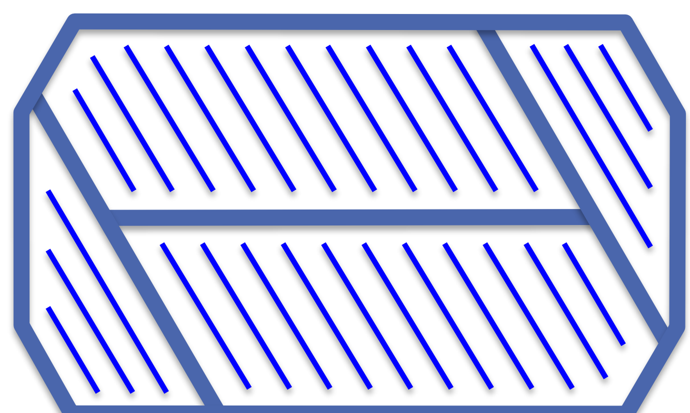
264 U-strips (2 sections)



376 V-strips (4 sections)



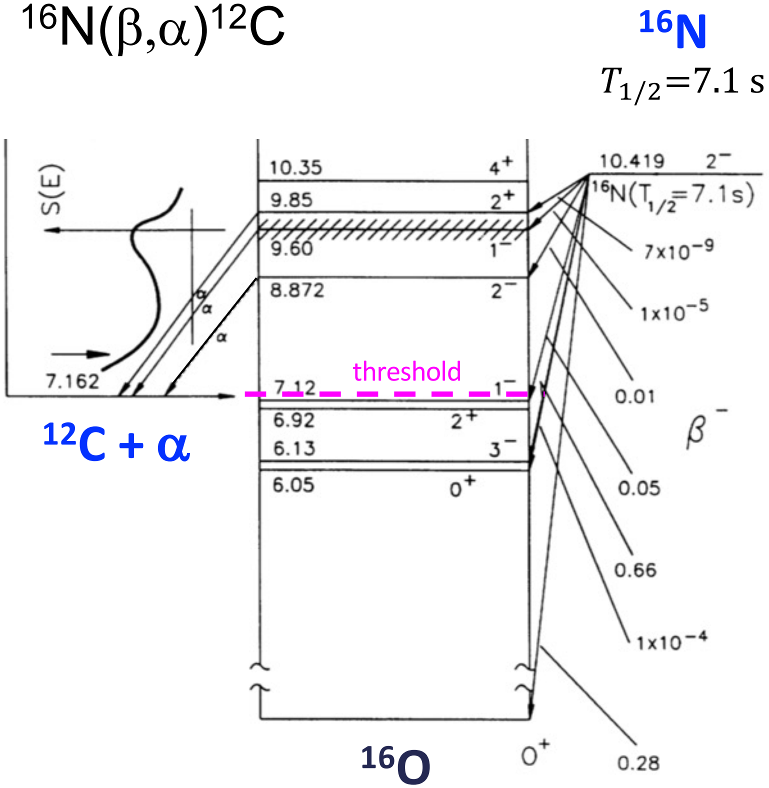
378 W-strips (4 sections)



Nuclear Astrophysics with RI beams

- ^{12}**C(α,γ)**^{16}**O** reaction can probed via **β-delayed α decay of** ^{16}**N**

$^{16}N(\beta,\alpha)^{12}C$



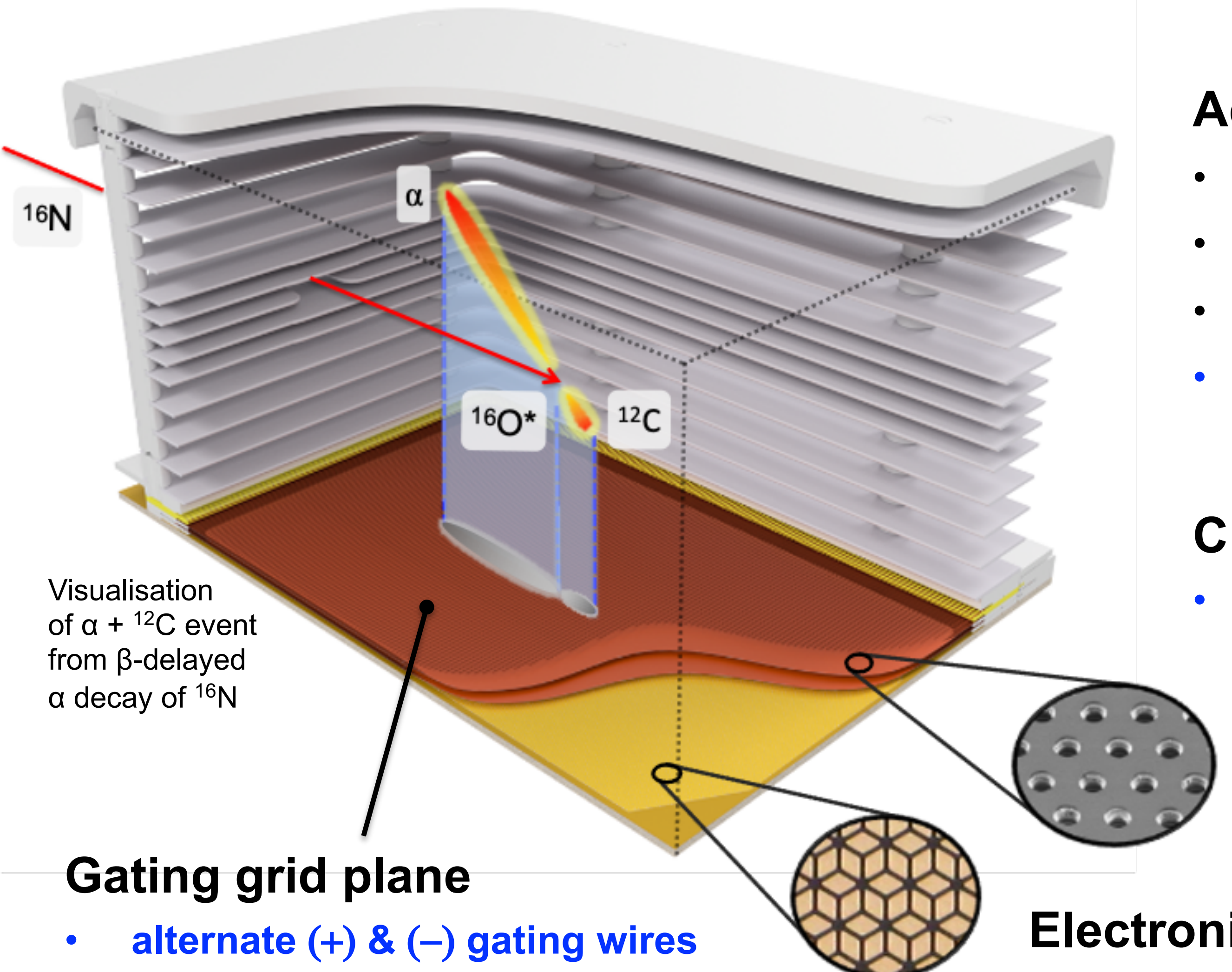
R. Azuma et al., Phys. Rev. C **50**, 1194 (1994)

Experimental approach:

- Use TPC as a stopping cell:
  - operate below electron detection threshold
  - reconstruct kinematics of α-particles from ^{12}C + α events
  - β-delayed α spectra constrain E1 component at low E_{CM} region
- Use pulsed **radioactive ion beam**:
  - stop & accumulate some ^{16}N ions in the gas before switching TPC from "blocked" to "active" mode

Progress in TPC development

Warsaw TPC



Visualisation of α + ^{12}C event from β-delayed α decay of ^{16}N

Active volume

- readout: **330 x 200 mm^2**
- drift length: **200 mm**
- low-pressure gas: TBD
- **larger central opening for incoming RI beam**

Charge amplification

- **2 layers** of **125-μm thick GEM** foils

Gating grid plane

- **alternate (+) & (–) gating wires placed before amplification region**
- fast HV pulser

Electronic readout

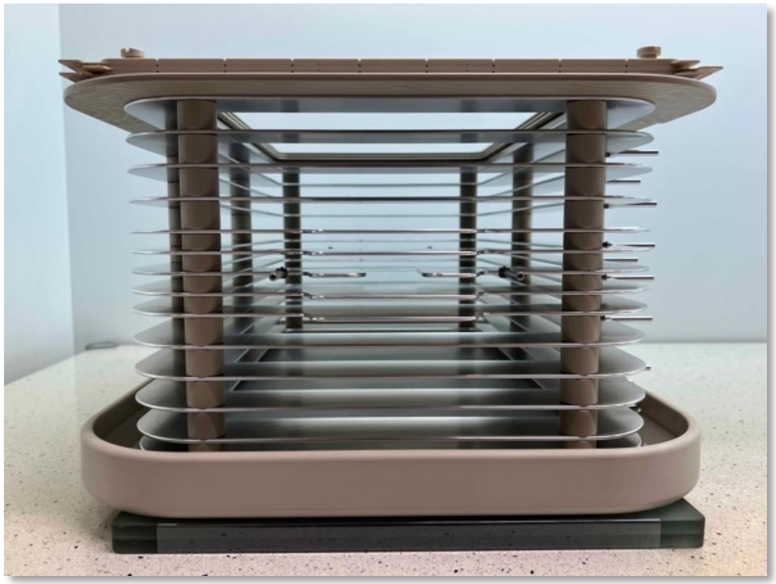
- same UVW segmentation
- same GET front-end electronics

Progress in TPC development

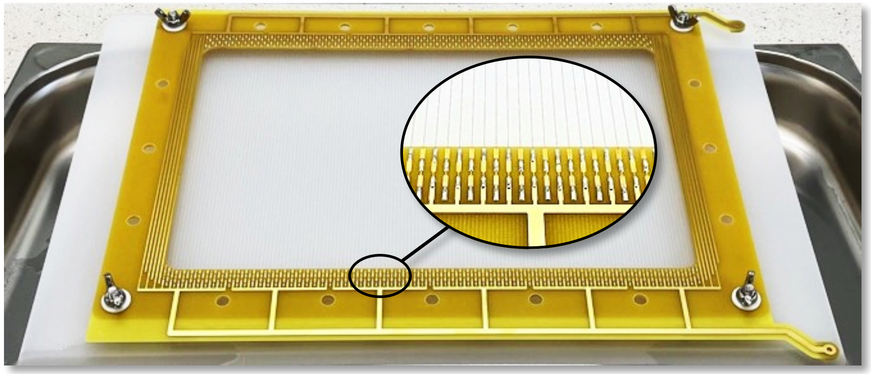
Warsaw TPC

- Details of new TPC with thicker-GEMs (125 um) and gating grid

TPC drift cage dry assembly test



Vacuum vessel (250 dm^3) with removable endcaps & side walls



Gating grid frame with 50 μm wires, 2.5 mm wire pitch