Nuclear Astrophysics

(program at the University of Warsaw)

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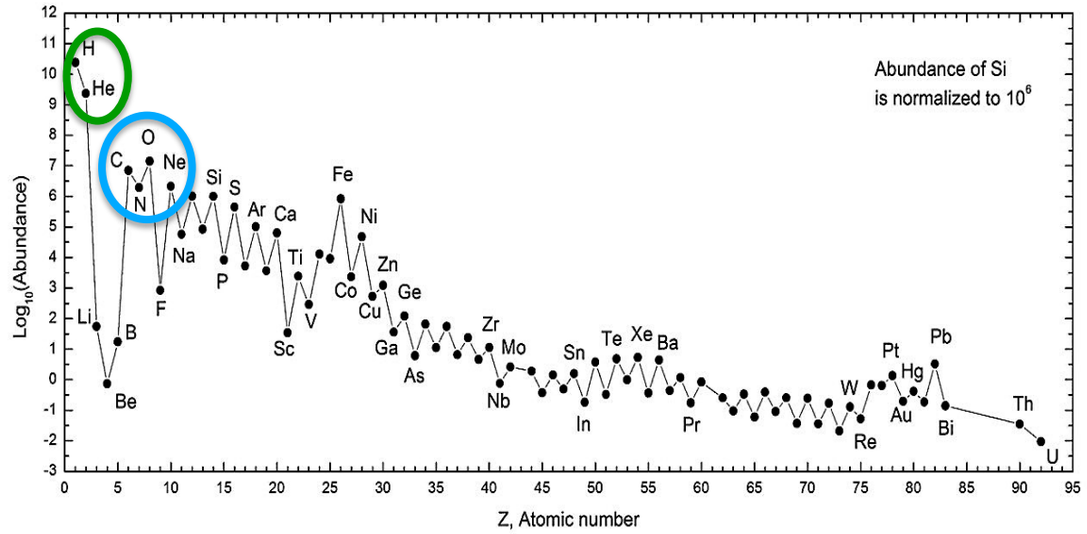
Physics motivations

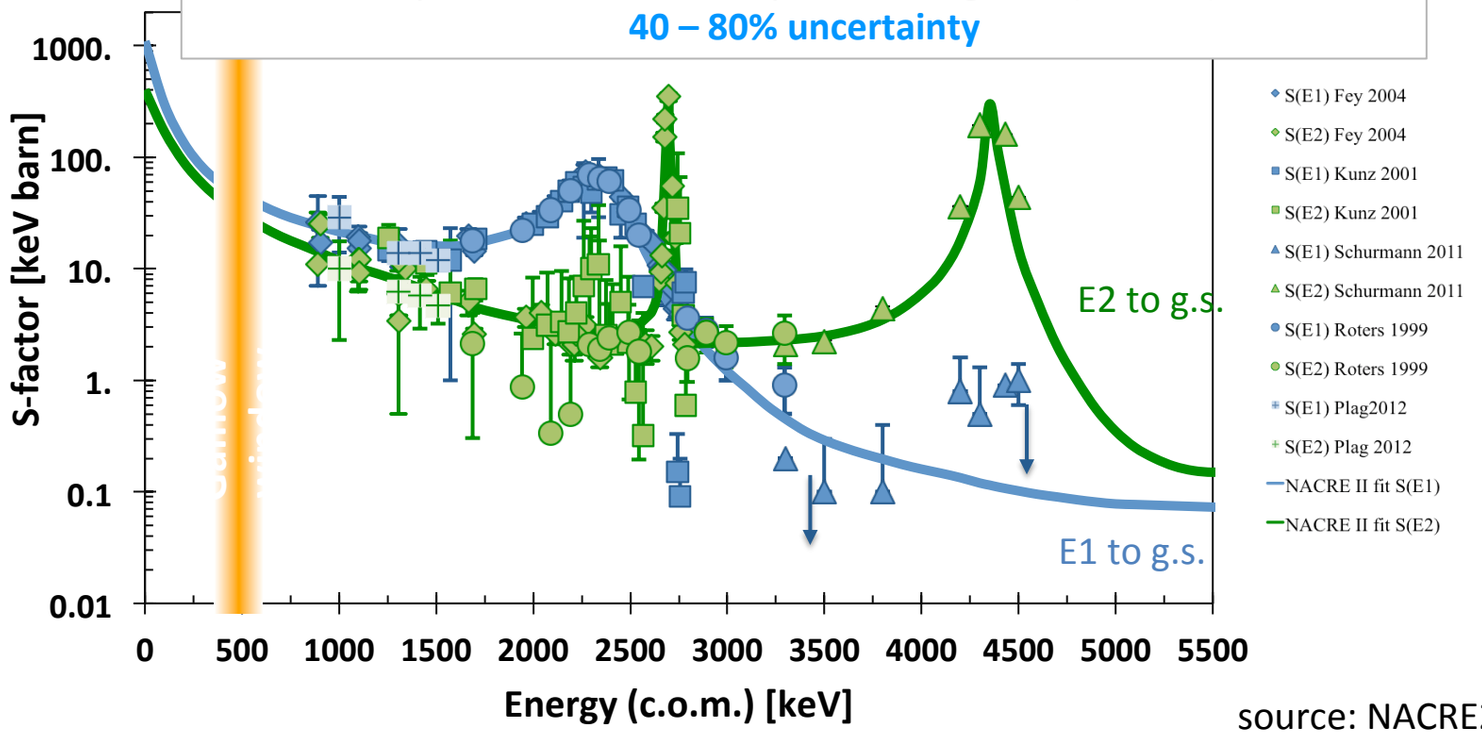
- ✓ Synthesis of **He** in ***H-burning*** reactions
  - **pp-chain**, **CNO cycle**, hot-CNO, NeNa cycle, MgAl cycle,…
  - 4p —> $^{4}He + 2e^{+} + 2\nu$



- ✓ Synthesis of C,O, Ne in He-burning
  - 3α —> ^{12}C; **$^{12}C(\alpha,\gamma)^{16}O$**, $^{16}O(\alpha,\gamma)^{20}Ne$, $^{20}Ne(\alpha,\gamma)^{24}Mg$

- ✓ Reaction rates for (p,γ) reactions on medium mass nuclei:
  - β-delayed charged particle spectroscopy

Extrapolated astrophysical S-factor for p-wave (E1) & d-wave (E2) α + ^{12}C capture for the Gamow peak in red giants (300 MK):
40 – 80% uncertainty



source: NACRE2

Science goals

- ✓ Accurate measurements of (very small) cross sections of (α,γ) and (p,γ) nuclear reactions by means of the inverse photo-disintegration (γ, α) and (γ, p) reactions:
  - advantages of such approach:
    - inherently low background measurements
    - different systematic uncertainty w.r.t. charged-particle induced reactions at low energies
      - ✦ target and its deterioration
      - ✦ (effective) beam energy definition
      - ✦ etc.
  - intense and monochromatic γ-beams at ELI-NP

- ✓ Particular effort is channeled towards the measurement of the $^{16}O(\gamma,\alpha)^{12}C$ reaction at low energies
  - estimated cross-section for $^{12}C+\alpha$ at E_{cm}=1.0 MeV is ~50pbarn, for $^{16}O(\gamma,\alpha)^{12}C$ is ~2nbarn

- ✓ Complementary studies:
  - measurement of resonance width for astrophysically-relevant levels by means of β-delayed charged-particle emission studies
    - e.g. $^{29}P(p,\gamma)^{30}Si$: proton width of the relevant states above $^{29}P+p$ threshold can be studied by β2p decay of ^{31}Ar

Methodology of choice

Low-pressure Active-Target TPC

for

determining reaction cross-sections of astrophysical interest

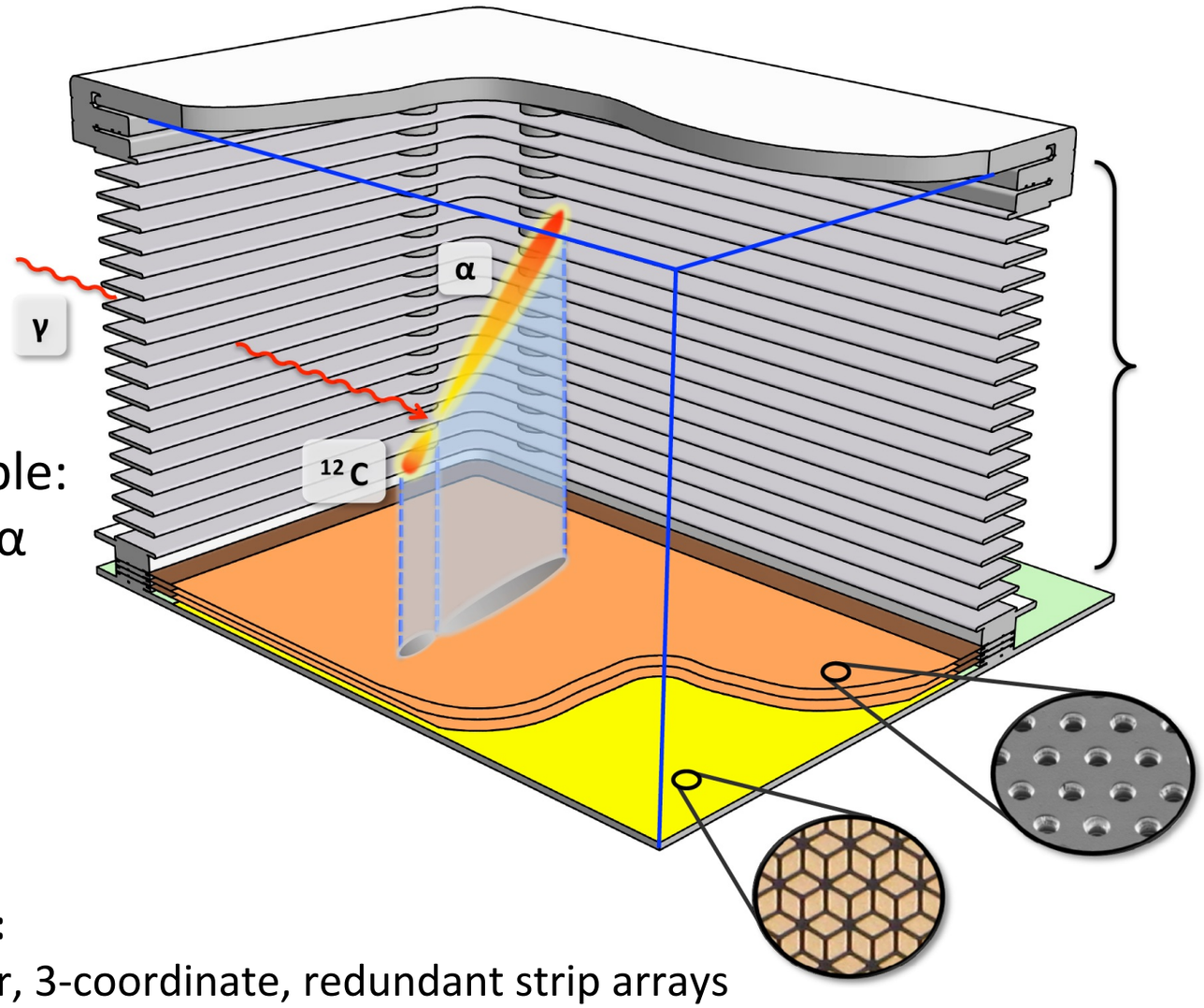
where the **reaction products are charged particles**

Low-pressure Active-Target TPC – ELITPC

ELITPC

✓ Allows for full, unambiguous reconstruction of multiple-particle events (reaction products)

Example:
$^{12}C+\alpha$



Active volume:
- 33 cm x 20 cm x 20 cm
- under-pressured (100-200 mbar):
  low-energy particles!
- gas-mixture and pressure tailored for the reaction of interest, e.g. **CO_2** for measuring oxygen photo-disintegration)

Charge amplification:
Gas Electron Multiplier (GEM) structures

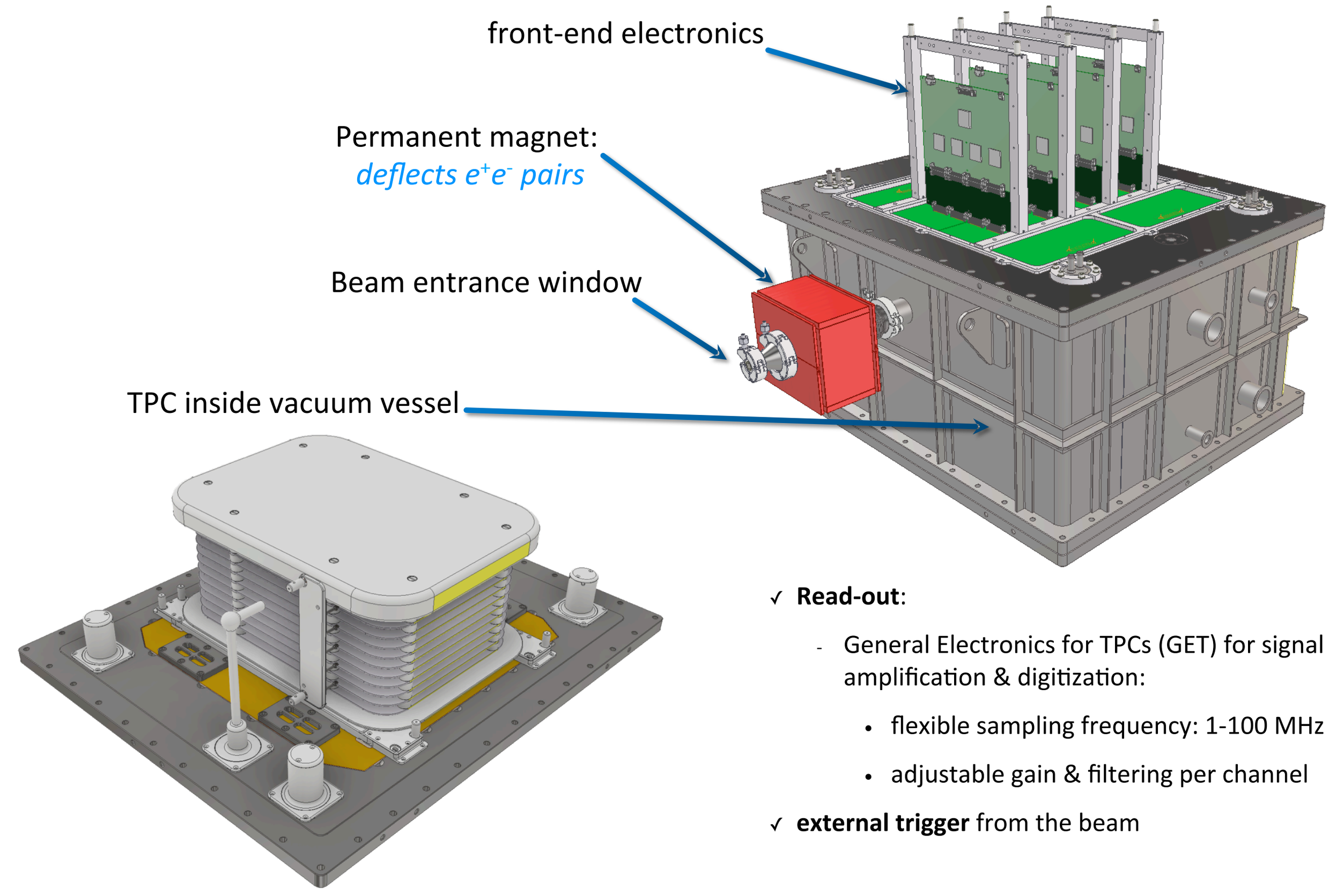
Readout:
- Planar, 3-coordinate, redundant strip arrays
- about 1000 channels
- GET electronics for signal amplification & digitization
- external trigger (100 Hz)

Relatively-simple event topologies (few tracks per event)

M. Ćwiok et al., Acta Phys. Pol. **B 49** (2018) 509; Ćwiok, Acta Phys. Pol. **B 47** (2016) 707
O.Tesileanu et al., Rom. Rep. in Phys. 68, Supp (2016) S699

Low-pressure Active-Target TPC – ELITPC

ELITPC



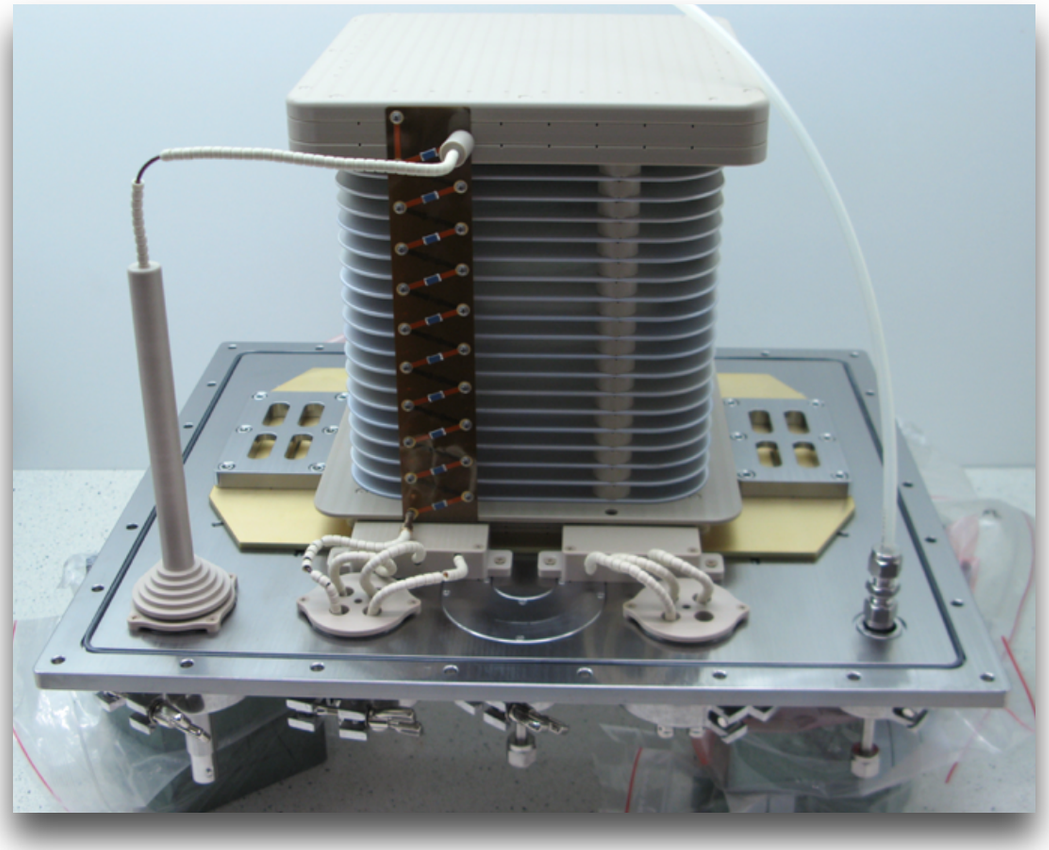
- ✓ **Read-out**:
  - General Electronics for TPCs (GET) for signal amplification & digitization:
    - flexible sampling frequency: 1-100 MHz
    - adjustable gain & filtering per channel
- ✓ **external trigger** from the beam

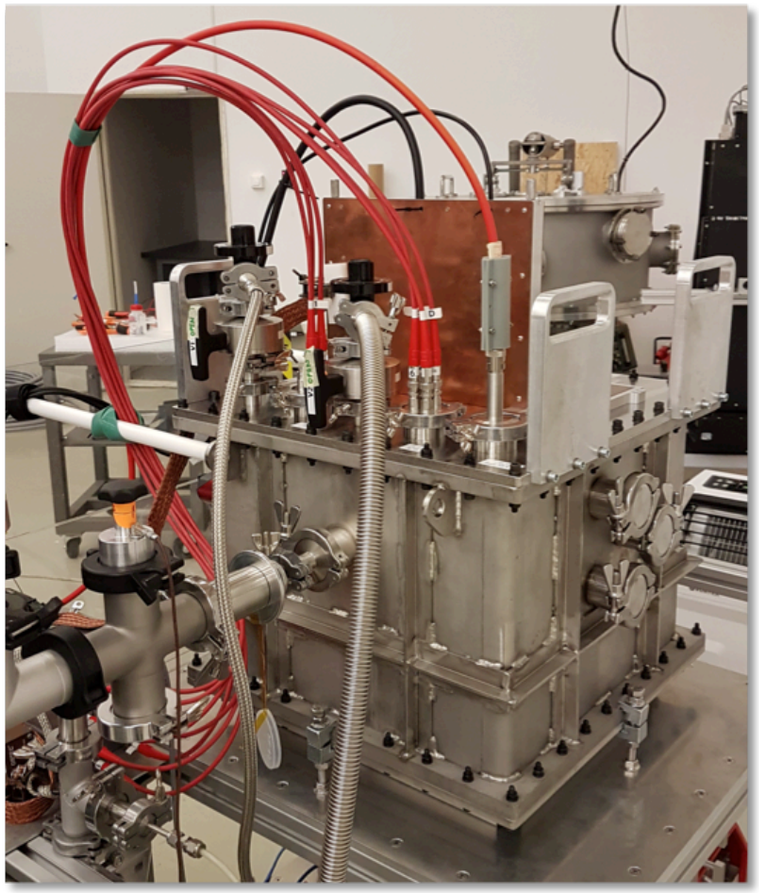
Low-pressure Active-Target TPC – ELITPC demonstrator detector

ELITPC

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

- ✓ Tested @ 3 MV and @ 9 MV Tandem (IFIN-HH, Romania)





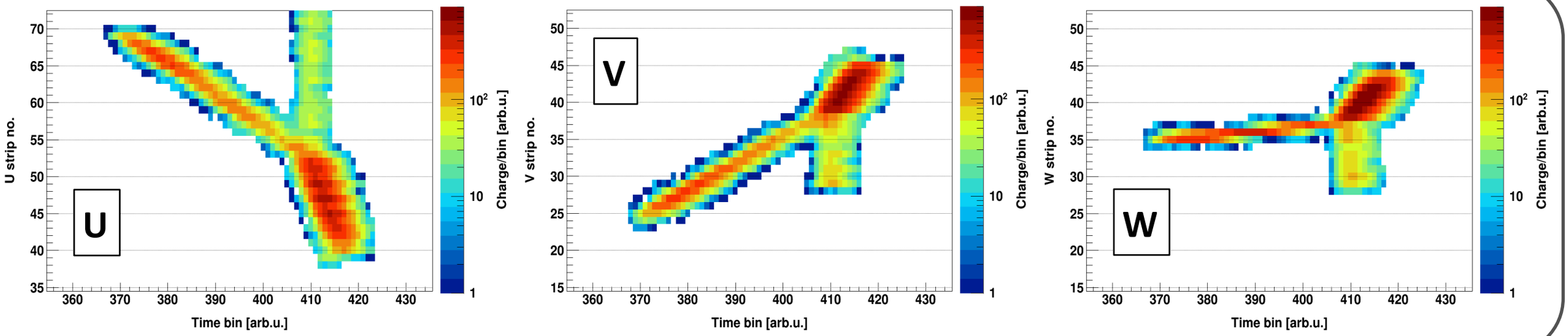
Low-pressure Active-Target TPC – ELITPC demonstrator detector

ELITPC

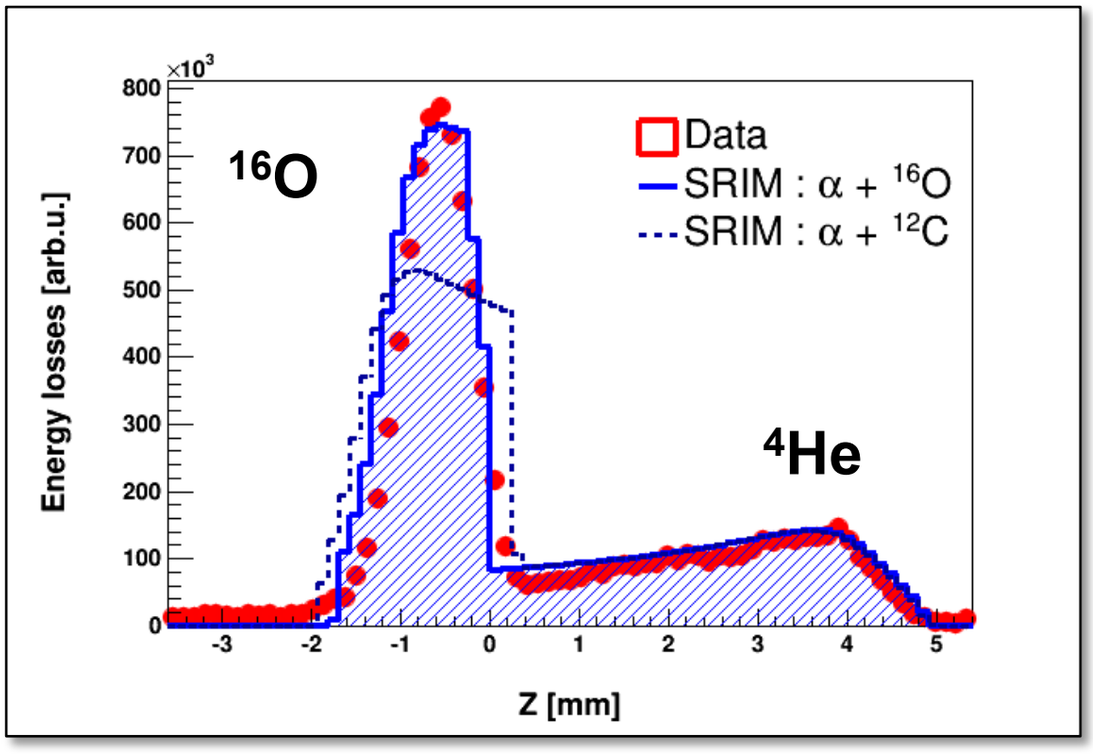
- ✓ Gas mixture: He+CO_2 (70:30) @1 atm

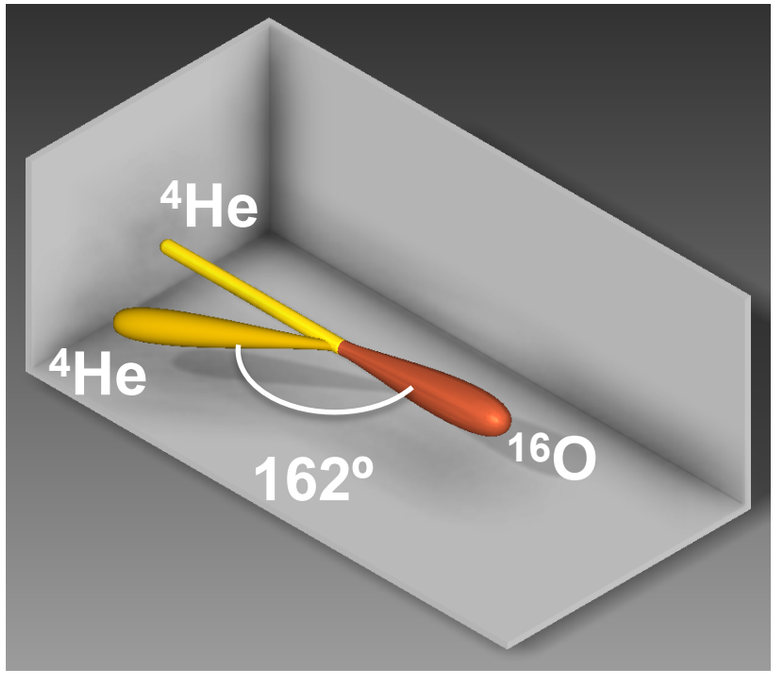
^{4}He + ^{16}O scattering

Raw data



Reconstruction



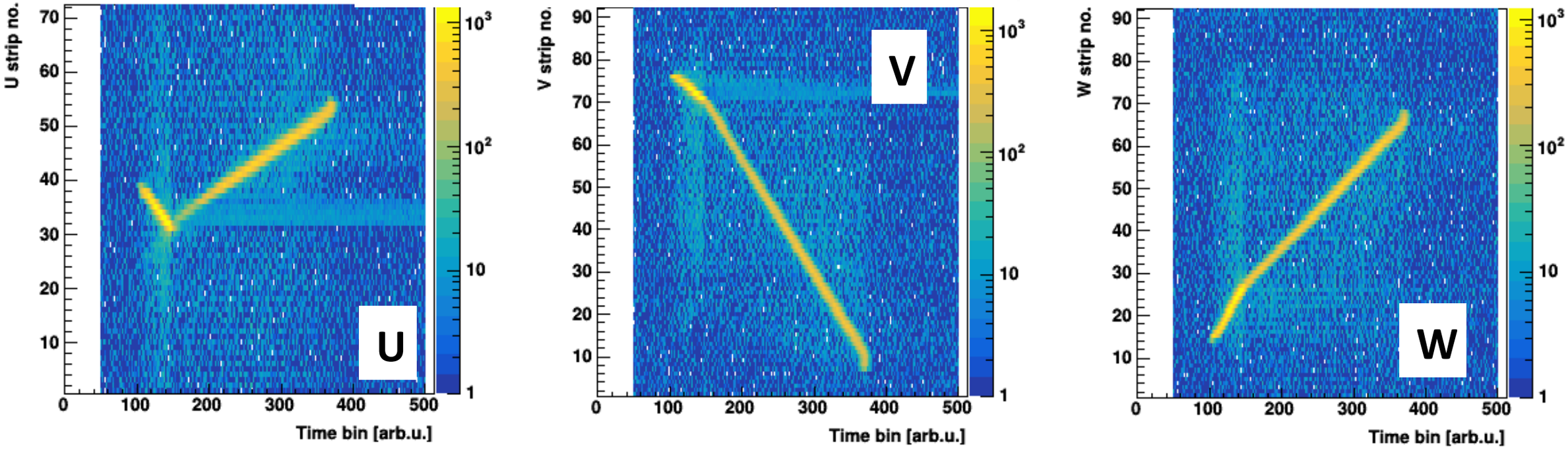


Low-pressure Active-Target TPC – ELITPC demonstrator detector

ELITPC

- ✓ 100 mbar CO_2, neutrons produced by 6.5 MeV α-particle beam on Be target
- ✓ Neutrons reacting with nuclei of CO_2 gas molecules
- ✓ Example:

Raw signals from U, V, W strips



Low-pressure Active-Target TPC – ELITPC demonstrator detector

ELITPC

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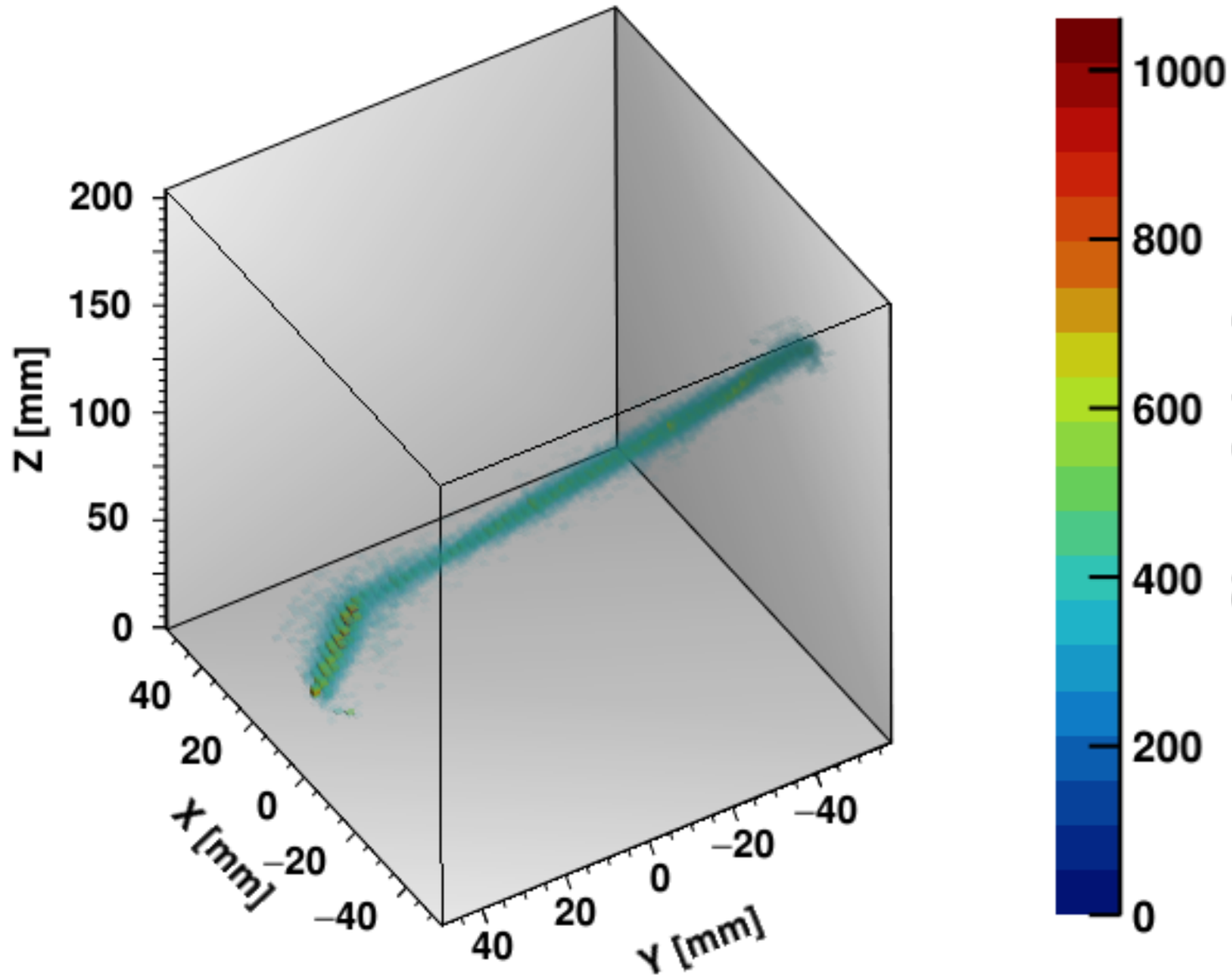
- ✓ Example:

after dE/dx reconstruction in 3D



Low-pressure Active-Target TPC – ELITPC a versatile detector

✓ **Day1 experiments**:

- measure decay products of nuclear photo-dissociation reactions

Reaction	Target	Astrophysical relevance
$^{16}O(\gamma,\alpha)^{12}C$	**CO_2**	**ratio C/O**
$^{21}Ne(\gamma,\alpha)^{17}O$	^{21}Ne	role of ^{16}O as neutron poison
$^{22}Ne(\gamma,\alpha)^{18}O$	^{22}Ne	ratio $^{16}O/^{18}O$, CNO-cycle synthesis of ^{22}Ne

- Flagship experiment @ ELI-NP: time-reverse reaction $^{16}O(\gamma,\alpha)^{12}C$
  - measure energy & angular distributions of charged particles
  - obtain accurate values of E2/E1 components
  - reduce uncertainty from 40-80% to 10%

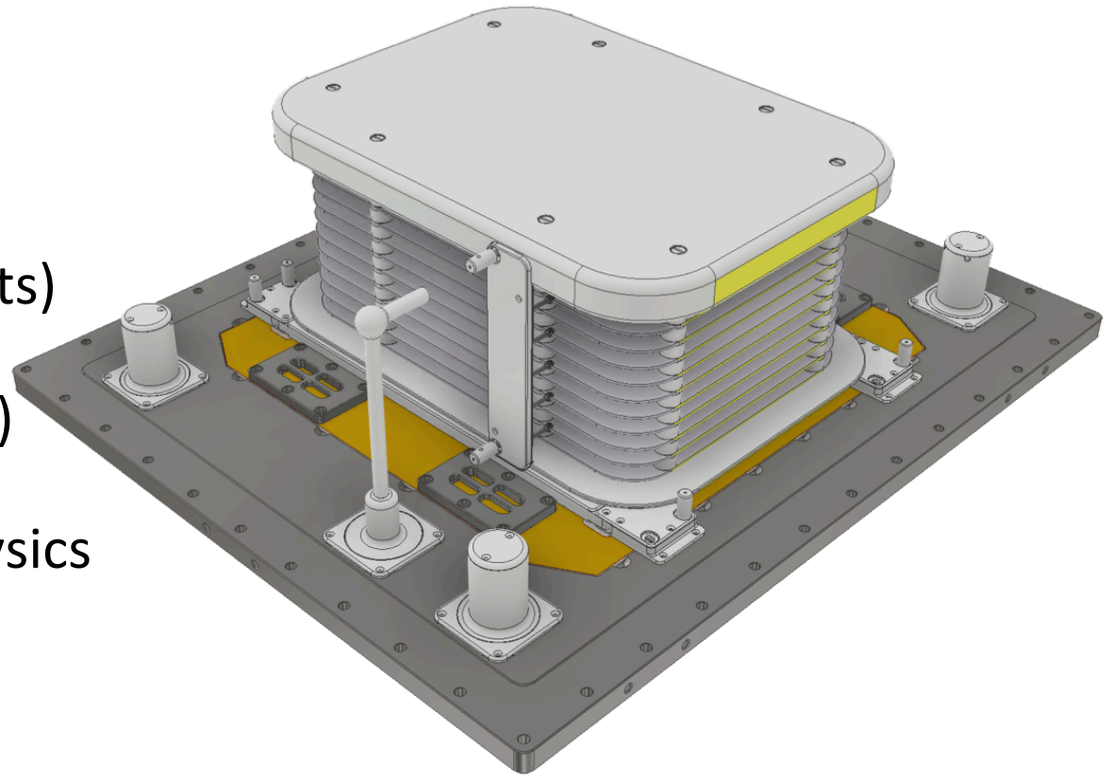
- the structure of ^{30}S above the proton threshold and the proton and γ branching for these levels

Reaction	Production method	Astrophysical relevance
$^{29}P(p, \gamma)^{30}S$	$\beta 2p(^{31}Ar)$	Uncertainties on its reaction rate influence the abundances of $^{29,30}Si$ produced in O novae

Summary

- ✓ **$^{16}O(\gamma,\alpha)^{12}C$ reaction** cross section measurement is **flagship experiment** for the ELITPC collaboration at ELI-NP
- ✓ ELITPC detector among **DAY-1** experiments for ELI-NP
- ✓ Demonstrator detector used online for proof-of-principle studies and R&D
- ✓ Design of the ELITPC system is completed in Warsaw and we are ready to produce the prototype in 2019

- ✓ Other physics cases with ELITPC :
  - other astrophysical reactions (different gas targets)
  - nuclear structure physics (clustering phenomena)
  - β-delayed charged-particle emission for astrophysics



ELITPC collaboration*

M. Ćwiok, J.S. Bihałowicz, H. Czyrkowski, R. Dąbrowski, W. Dominik, A. Fijałkowska, Z. Janas, Ł. Janiak, K. Kierzkowski, A. Korgul, M. Kuich, T. Matulewicz, C. Mazzocchi, W. Okliński, M. Pfützner, M. Zaremba *(University of Warsaw)*

D. Balabanski, D.G. Ghita, L. Guardo, D. Lattuada, C. Matei *(IFIN-HH/ELI-NP, Romania)*

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