Investigating nuclear reactions at astrophysical energies with γ-ray beams and an active-target TPC

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Overview

- ✓ Physics goal
- ✓ How?
  - Direct capture versus photo-disintegration reactions
  - Monochromatic γ-ray beams @ELI-NP
  - An active-target Time Projection Chamber (ELITPC)
  - Status of the project: R&D and demonstrators
- ✓ Outlook

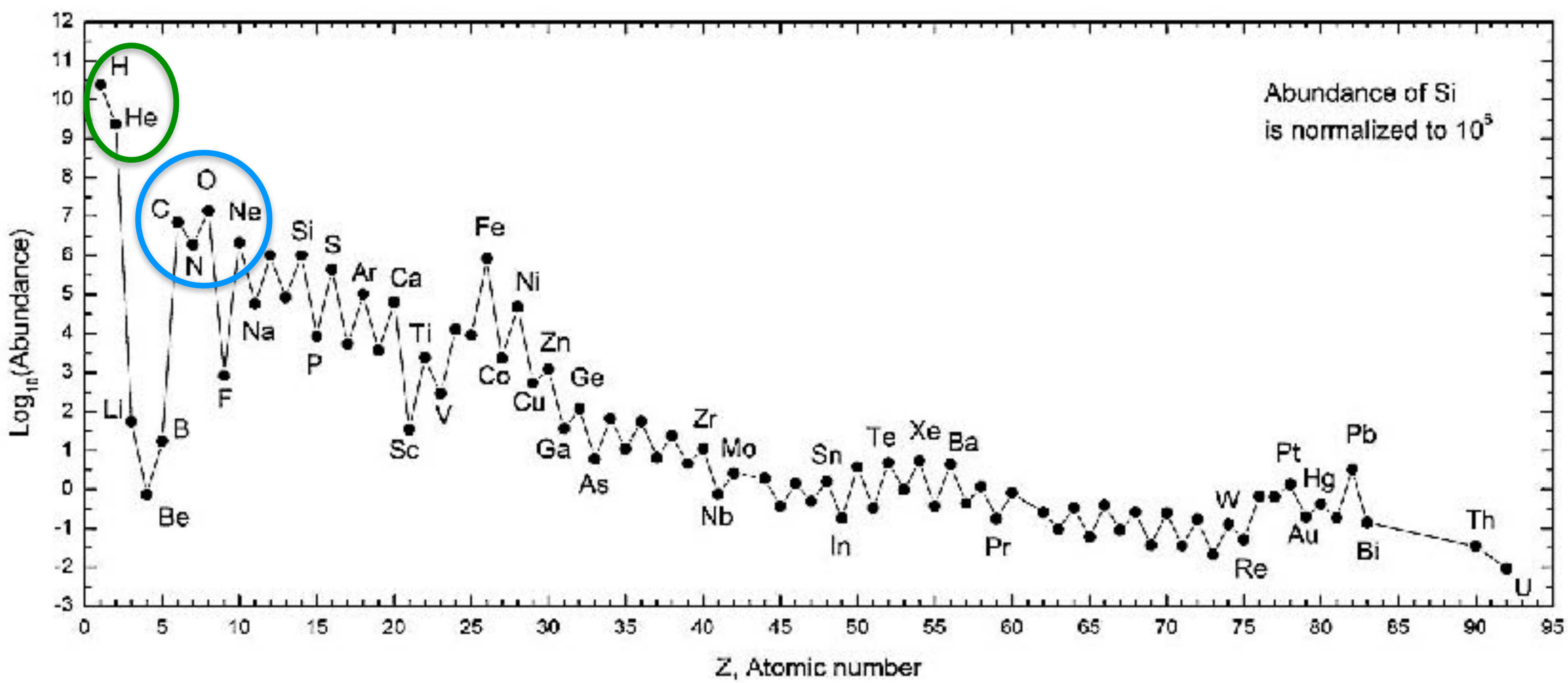
Physics motivations

✓ Abundance of the elements in the Universe

- in weight: **H - 74%**, **He - 24%**, **O - 0.85%**, **C - 0.39%**, …

✓ Abundance of elements in the human body:

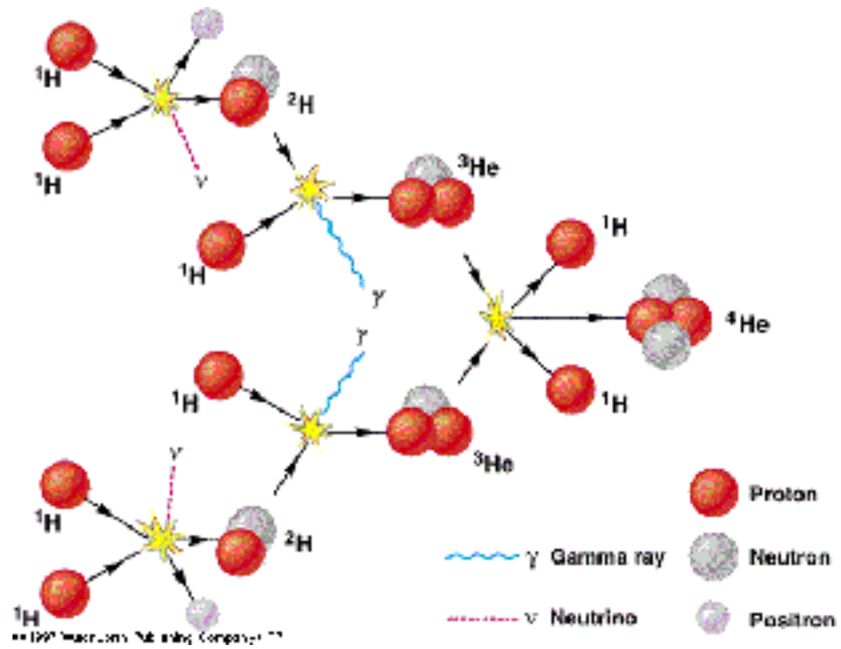
- in weight: **O - 65%**, **C - 18%**, H - 10%, N - 3%, other 4%

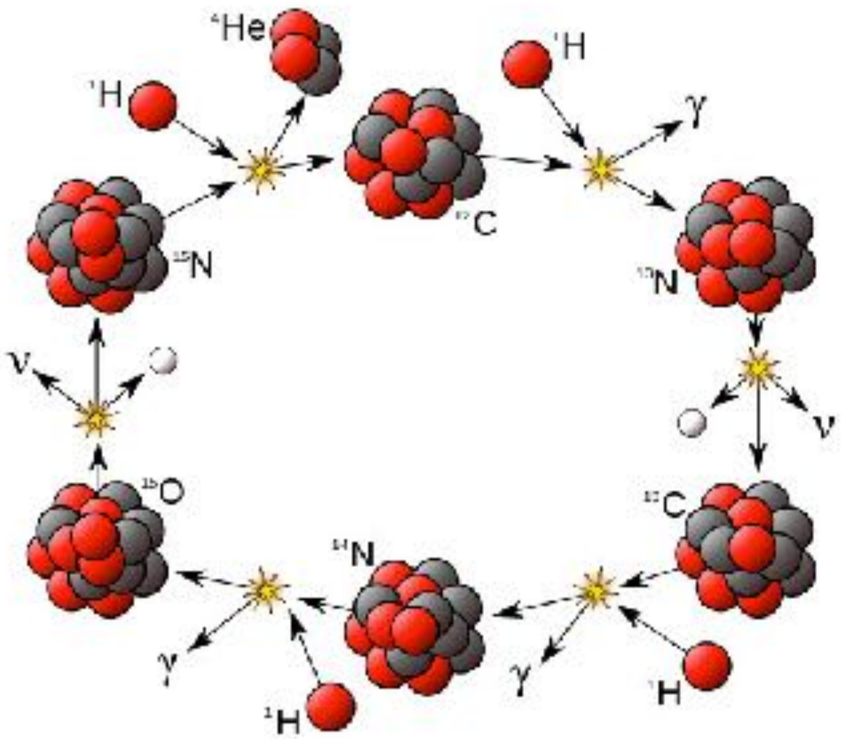


Physics motivations

Synthesis of He in *H-burning* reactions

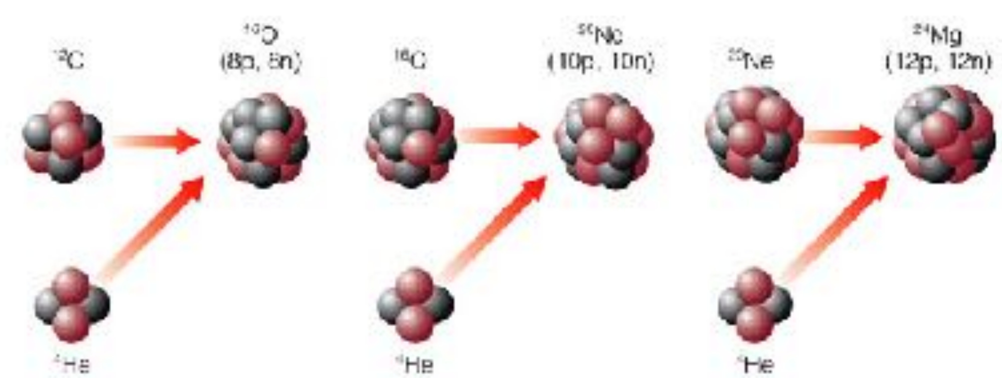
- **pp-chain**, **CNO cycle**, hot-CNO, NeNa cycle, MgAl cycle,…
- 4p —> $^{4}He + 2e^{+} + 2\nu$





Synthesis of C,O, Ne in He-burning

- 3α —> ^{12}C; $\mathbf{^{12}C(\alpha,\gamma)^{16}O}$, $^{16}O(\alpha,\gamma)^{20}Ne$, $^{20}Ne(\alpha,\gamma)^{24}Mg$

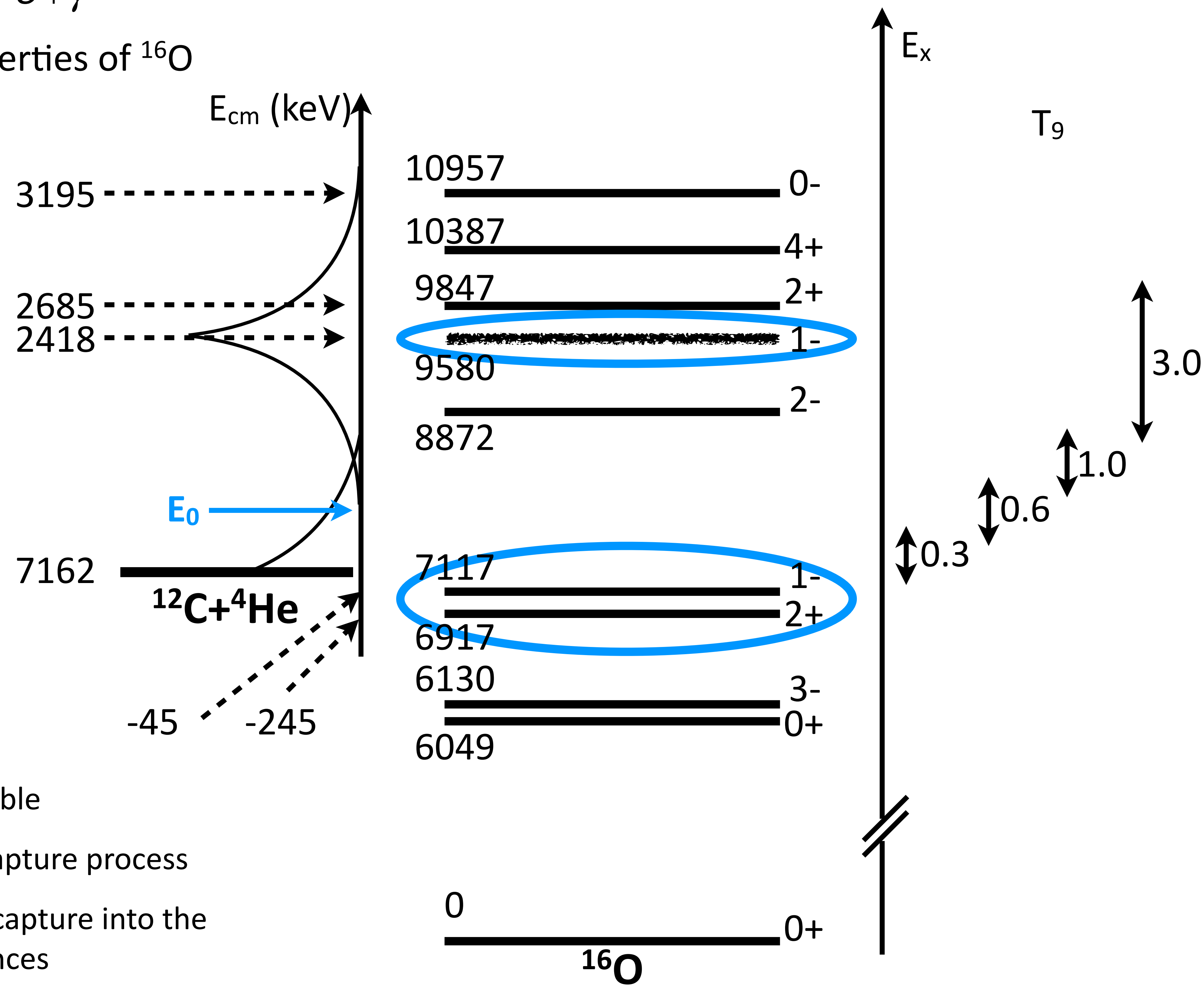


Cross-section measurement of (α,γ) and (p,γ) at astrophysical energies

Physics motivations: the flagship $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$

Survival of ^{12}C

- ✓ α-bruning in $^{12}C+\alpha \rightarrow {}^{16}O+\gamma$
- ✓ nuclear structure properties of ^{16}O



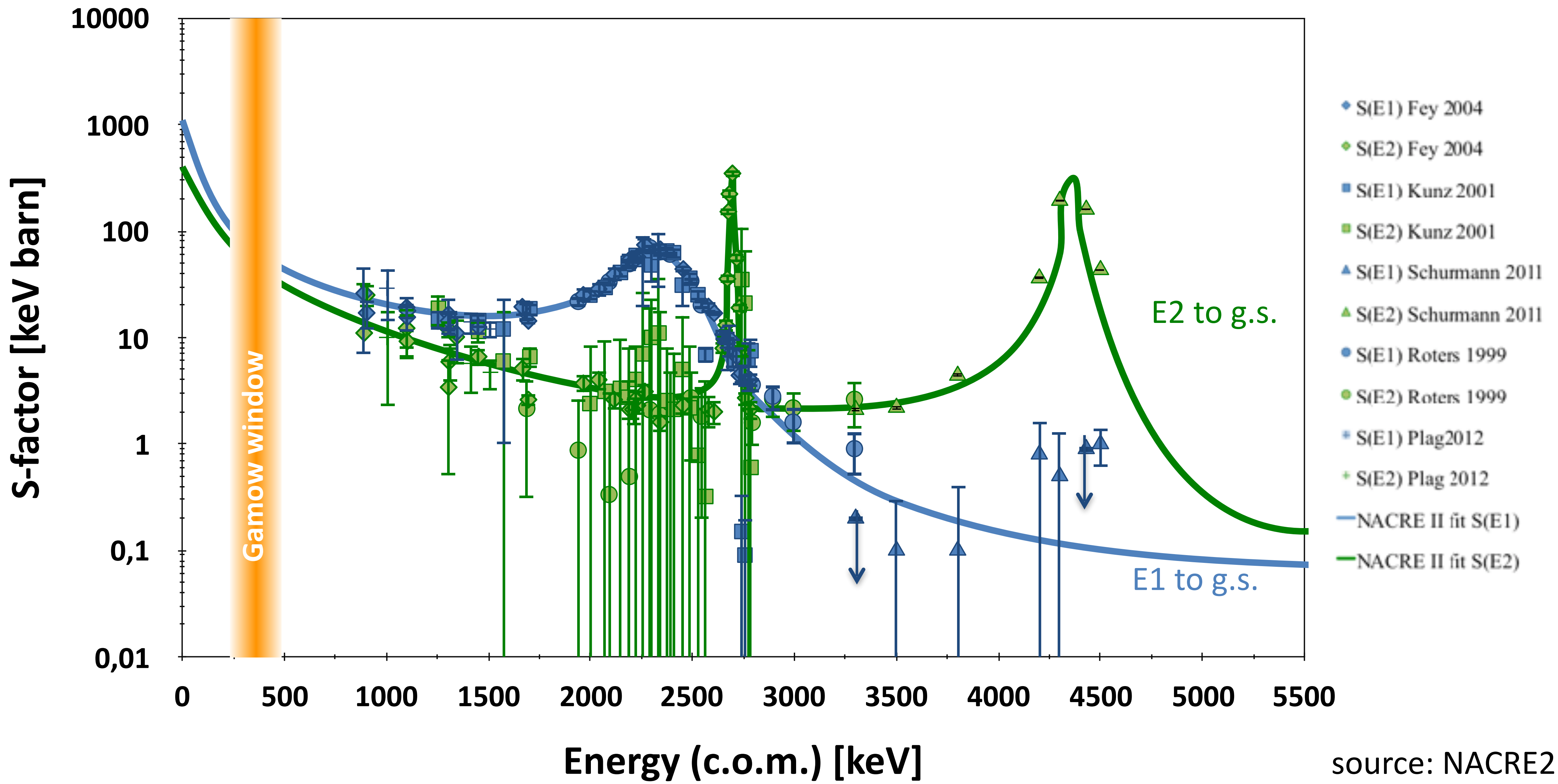
Two reaction mechanisms available

- non-resonant direct-capture process
- non-resonant type of capture into the tails of nearby resonances

The flagship $^{12}C+\alpha \rightarrow ^{16}O+\gamma$: status of the experimental knowledge

Extrapolated astrophysical S-factor for p-wave (E1) & d-wave (E2) $\alpha + ^{12}C$ capture
for the Gamow peak in red giants (300 MK):

40 – 80% uncertainty



source: NACRE2

Goal of the project

- ✓ Accurate measurements of (very small) cross sections of (α,γ) and (p,γ) nuclear reactions
- ✓ Particular effort is channeled towards the measurement of the $^{12}C(\alpha,\gamma)^{16}O$ reaction at low energies
- ✓ Estimated cross section for $^{12}C+\alpha$ at E_{cm}=1.0 MeV is ~50pbarn

Experimental challenges: how to improve the accuracy

✓ Strong and e.m. interactions invariant with respect to time reversal

✓ photo-disintegration vs capture reaction $B(b,\gamma)\mathrm{A} \rightleftharpoons \mathrm{A}(\gamma,b)B$

✓ principle of detailed balance in nuclear reactions:

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

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

$g_{b\gamma}$, $g_{\gamma b}$ = spin factors

Experimental challenges: how to improve the accuracy

✓ direct capture vs photo-disintegration reaction:

$$^{12}C + \alpha \rightarrow {}^{16}O + \gamma \qquad \Rightarrow \qquad \sigma = 47\ pb$$

at 1.0 MeV

$$^{16}O + \gamma \rightarrow {}^{12}C + \alpha \qquad \Rightarrow \qquad \sigma = 2\ nb$$

factor 50!!

⇒ measure the cross section for the α-capture reaction by means of the inverse photo-disintegration reaction

Experimental challenges: how to improve the accuracy

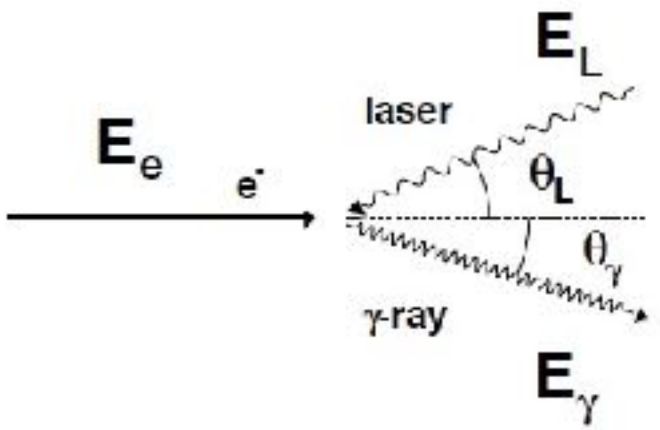
✓ Advantages of measuring the cross section for the p- and α-capture reactions by means of the inverse photo-disintegration reaction:

- 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 monochromatic and focussed γ-ray beams will be used!**

Monochromatic γ-ray beams @ELI-NP

✓ **Production of monochromatic γ-ray beams: Gamma Beam System (GBS)**
Compton Back Scattering of photons on ultra-relativistic electrons
(***the most efficient frequency amplifier***)



γ **beams**: **high-brilliance, good bandwidth & collimation**

intensity: 10^{13} γ/s [>10^4 γ/(s eV)]

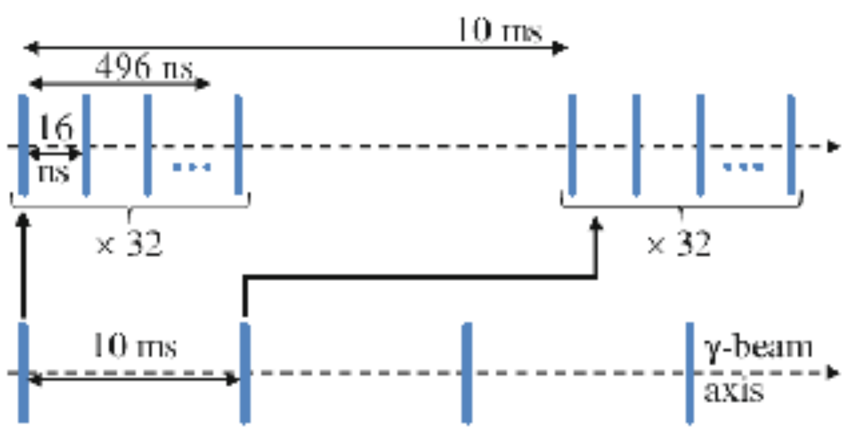
energy bandwidth: $\leqslant$0.5% !

energy range: 0.2 MeV < E_γ < 19.5 MeV

linear polarization: >95%

$$E_\gamma = 2\gamma_e^2 \cdot \frac{1+\cos\theta_L}{1+(\gamma_e\theta_\gamma)^2+\frac{4\gamma_e E_L}{mc^2}} \cdot E_L \approx 4\gamma_e^2 E_L$$

$\theta_L \ll 1$

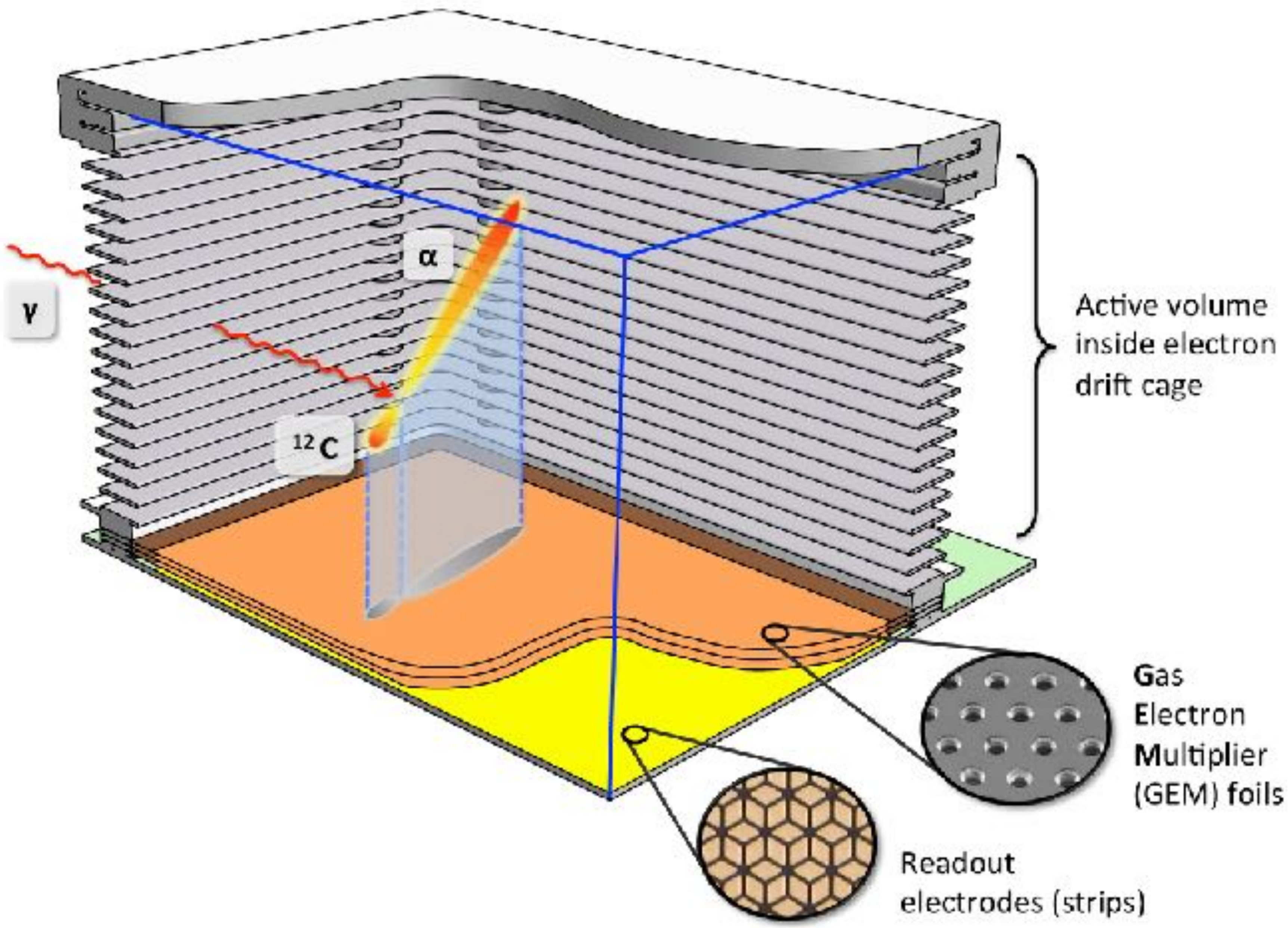


The ELITPC project

✓ An **active-target TPC** (ELITPC) to study reaction cross-sections of astrophysical interest where the reaction products are charged particles

—> full unambiguous reconstruction of multiple-particle events is possible

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



The ELITPC project: detector concept

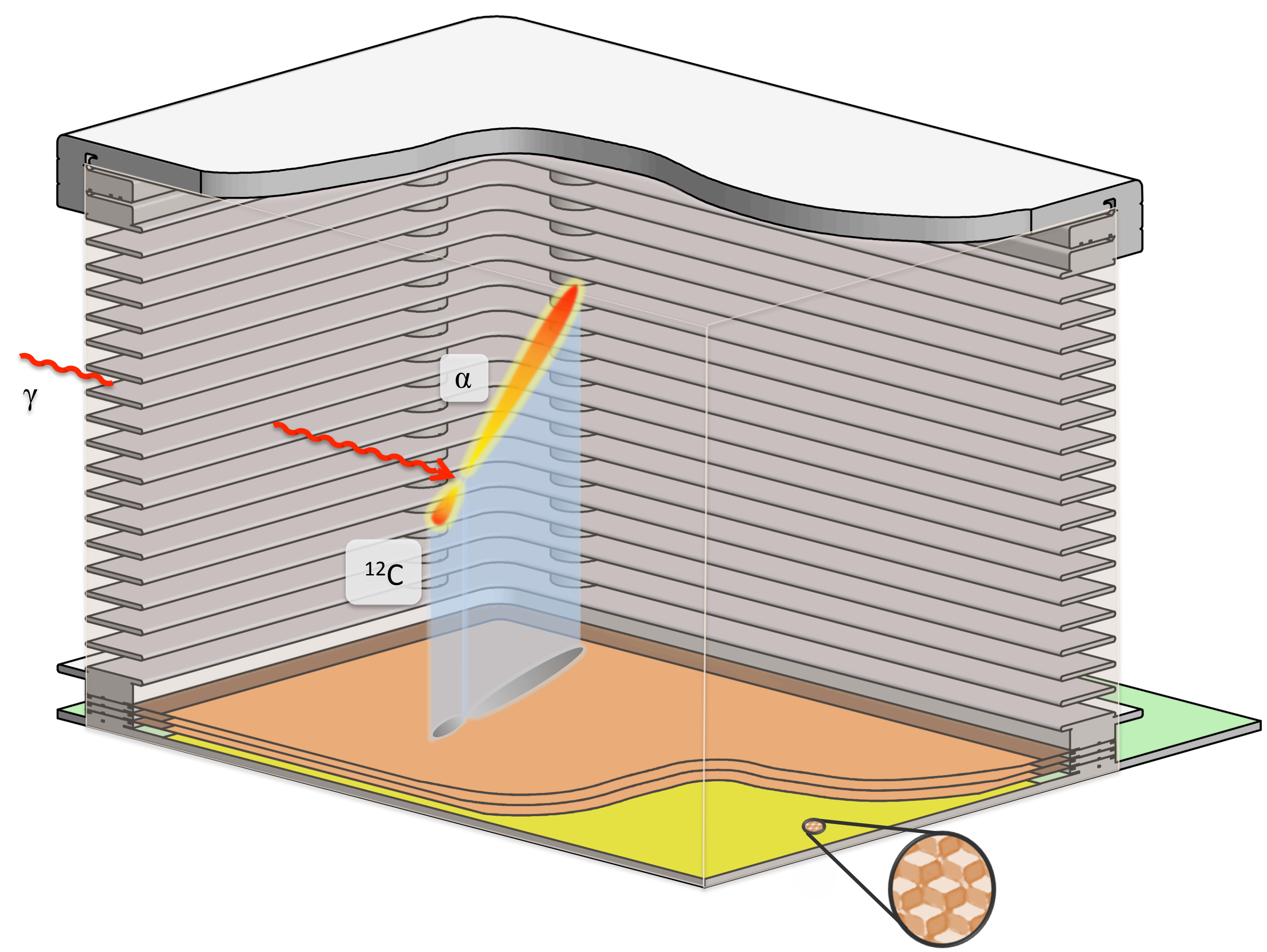
✓ **Active target**:

- active volume: 35 cm x 20 cm x 20 cm
- under-pressured (~100 mbar of CO_2): low-energy particles!
- gas-mixture and pressure tailored for the reaction of interest (containing $\mathbf{CO_2}$ for measuring oxygen photo-disintegration)

✓ **Charge-amplification**:

- 3 or 4 GEM structures

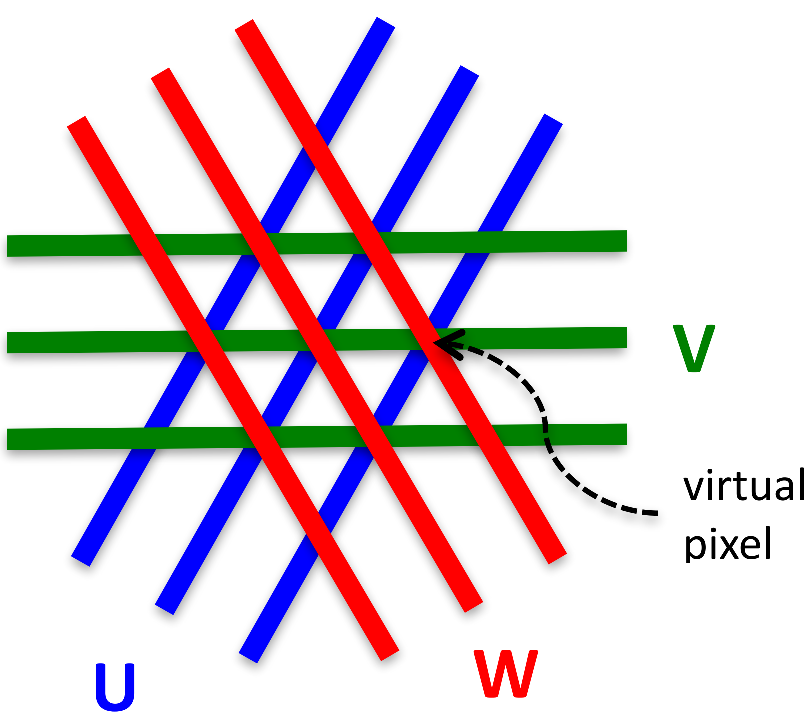
Example:
^{12}C+α

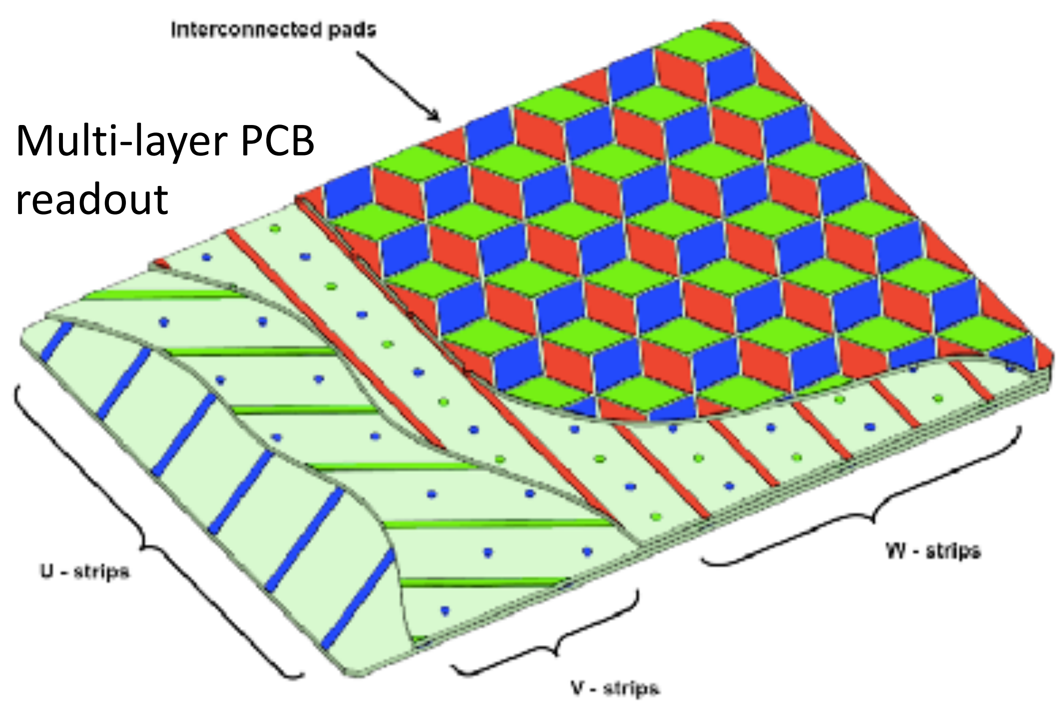


The ELITPC project: detector concept

✓ **Read-out**:

- 3-coordinate, planar, redundant electronic readout: 3 independent linear sets of strips (u-v-w): 1.5 mm pitch
- needs only ~1000 channels —> moderate cost of electronics
- u-v-w strip arrays for hit disambiguation in 2D —> virtual pixels
- z-coordinate from timing information
- aimed for relatively simple event topologies —> few tracks per event



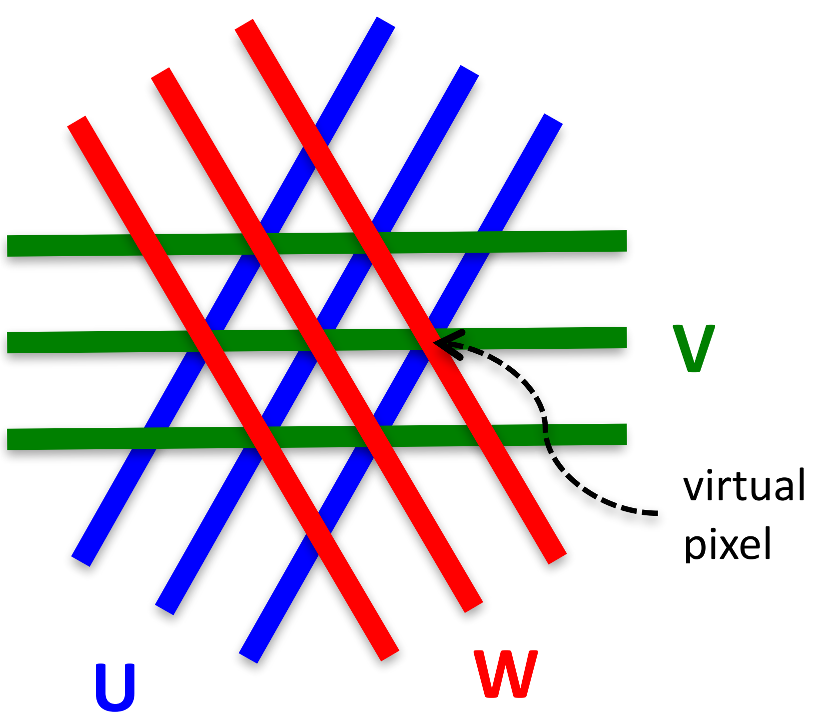


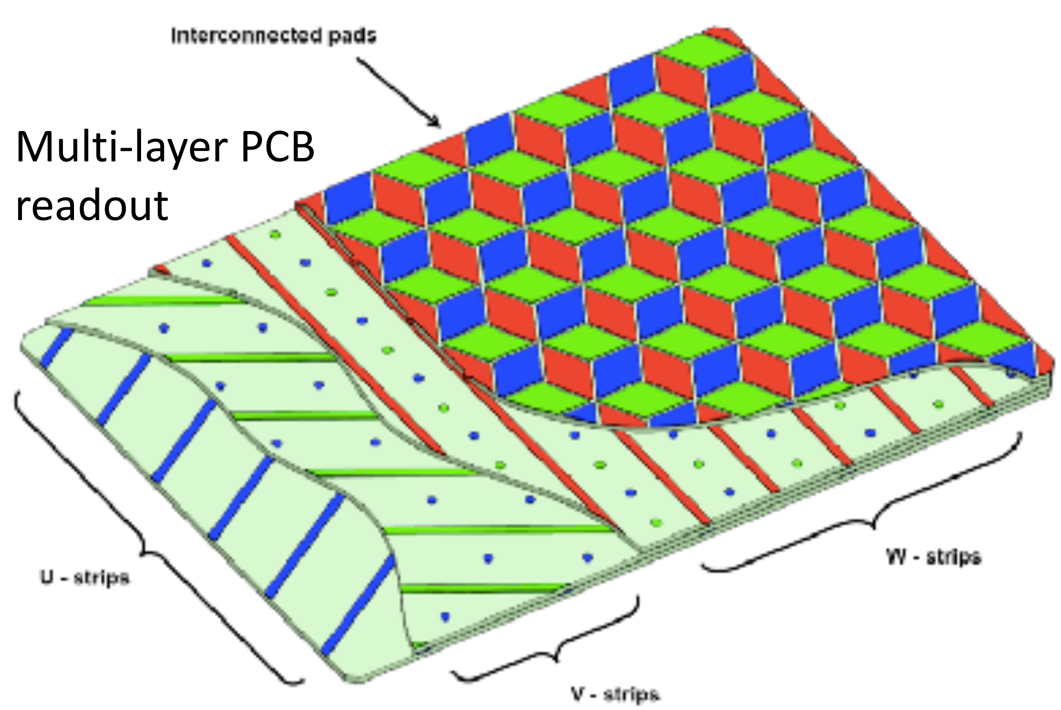
The ELITPC project: detector concept

✓ **Read-out**:

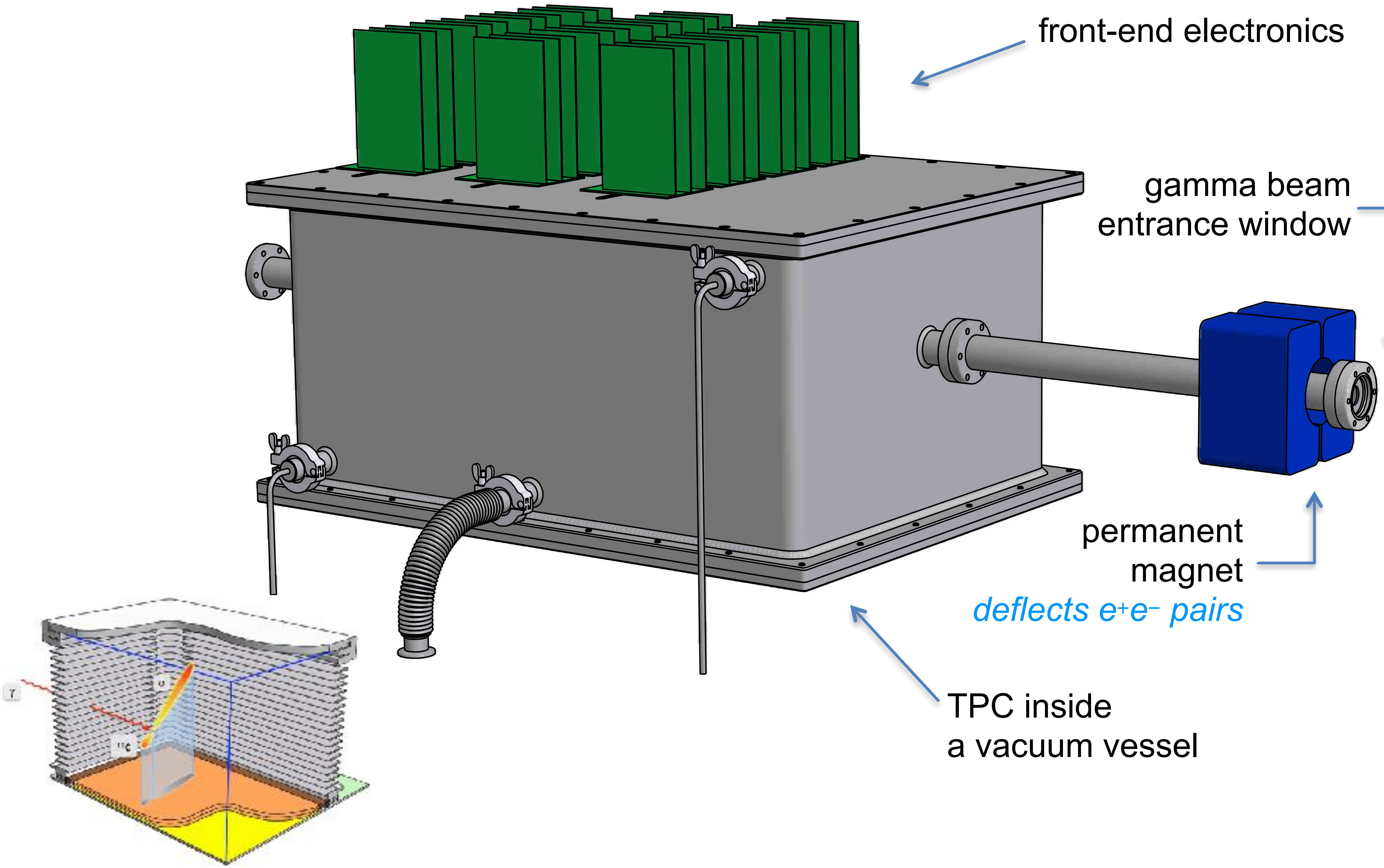
- General Electronics for TPCs (GET) for signal amplification & digitization:
  - flexible sampling frequency: 1-100 MHz
  - adjustable gain & filtering per channel

✓ **external trigger** from the time-structure of the γ beam (100 Hz)





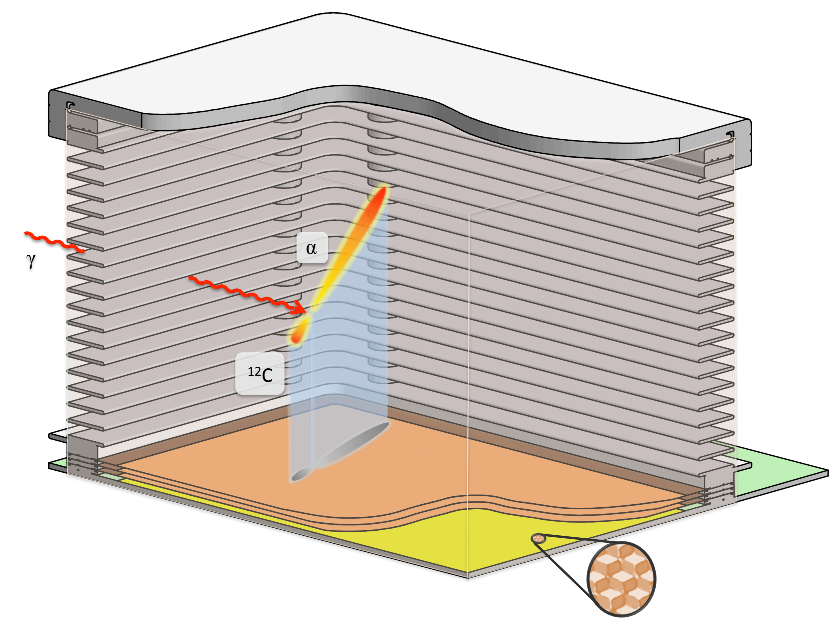
The ELITPC project: detector concept



The ELITPC project: expected yields for the flagship $^{16}O(\gamma,\alpha)^{12}C$

✓ 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%



✓ Target CO_2 @ 100 mbar

E_γ MeV	E_{cm} MeV	# events/week
8.26	1.1	~500
8.36	1.2	~900
8.46	1.3	~1900
8.56	1.4	~3000

beam intensity on target:
2.5×10^4 γ/s/eV, 0.5% bandwidth —> 10^9 γ/s
(D. Filipescu et al., Eur. Phys. J. A (2015) 51: 185)

Q=7.162 MeV for $^{12}C(\alpha,\gamma)^{16}O$

ELITPC: a versatile detector

- ✓ **Day1 experiments**: measure decay products of nuclear photo-dissociation reactions

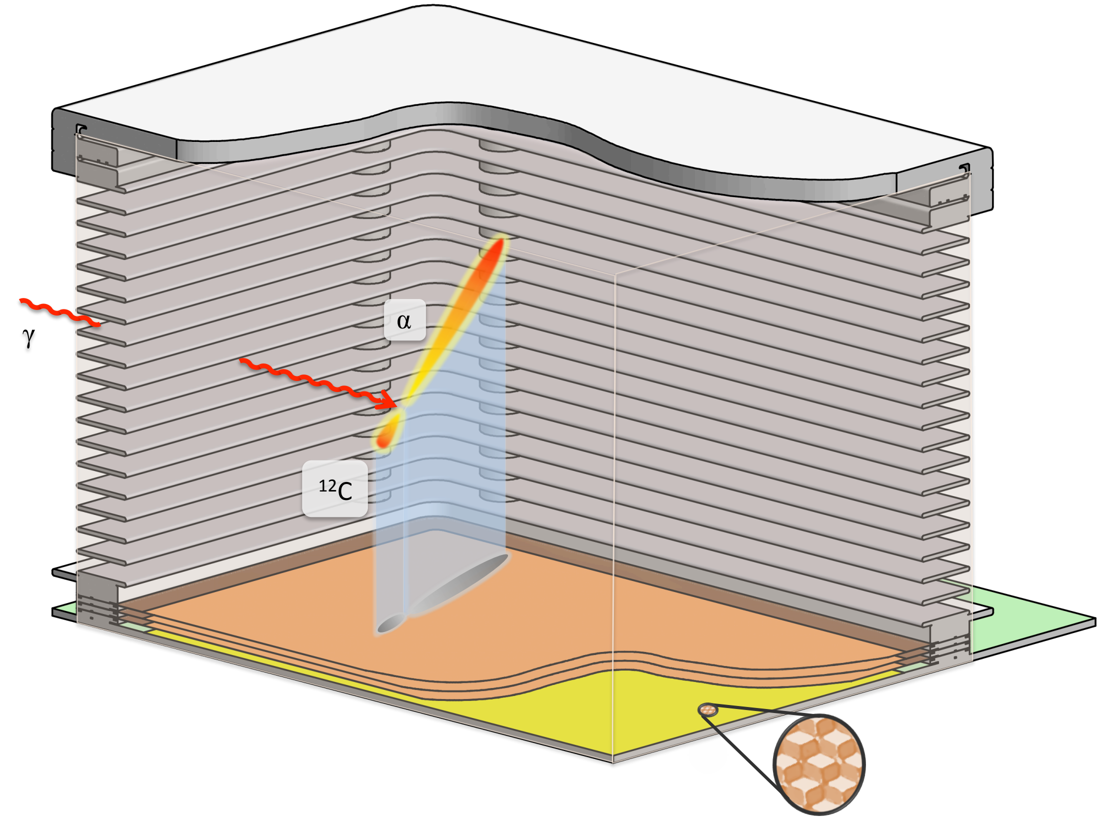
Reaction	Target	Astrophysical relevance
$^{16}O(\gamma,\alpha)^{12}C$	**CO_2**	**ratio C/O**
$^{21}Ne(\gamma,\alpha)^{17}O$	^{21}Ne	role of ^{16}O as neutron poison
$^{22}Ne(\gamma,\alpha)^{18}O$	^{22}Ne	ratio $^{16}O/^{18}O$, CNO-cycle synthesis of ^{22}Ne

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

The ELITPC project: background

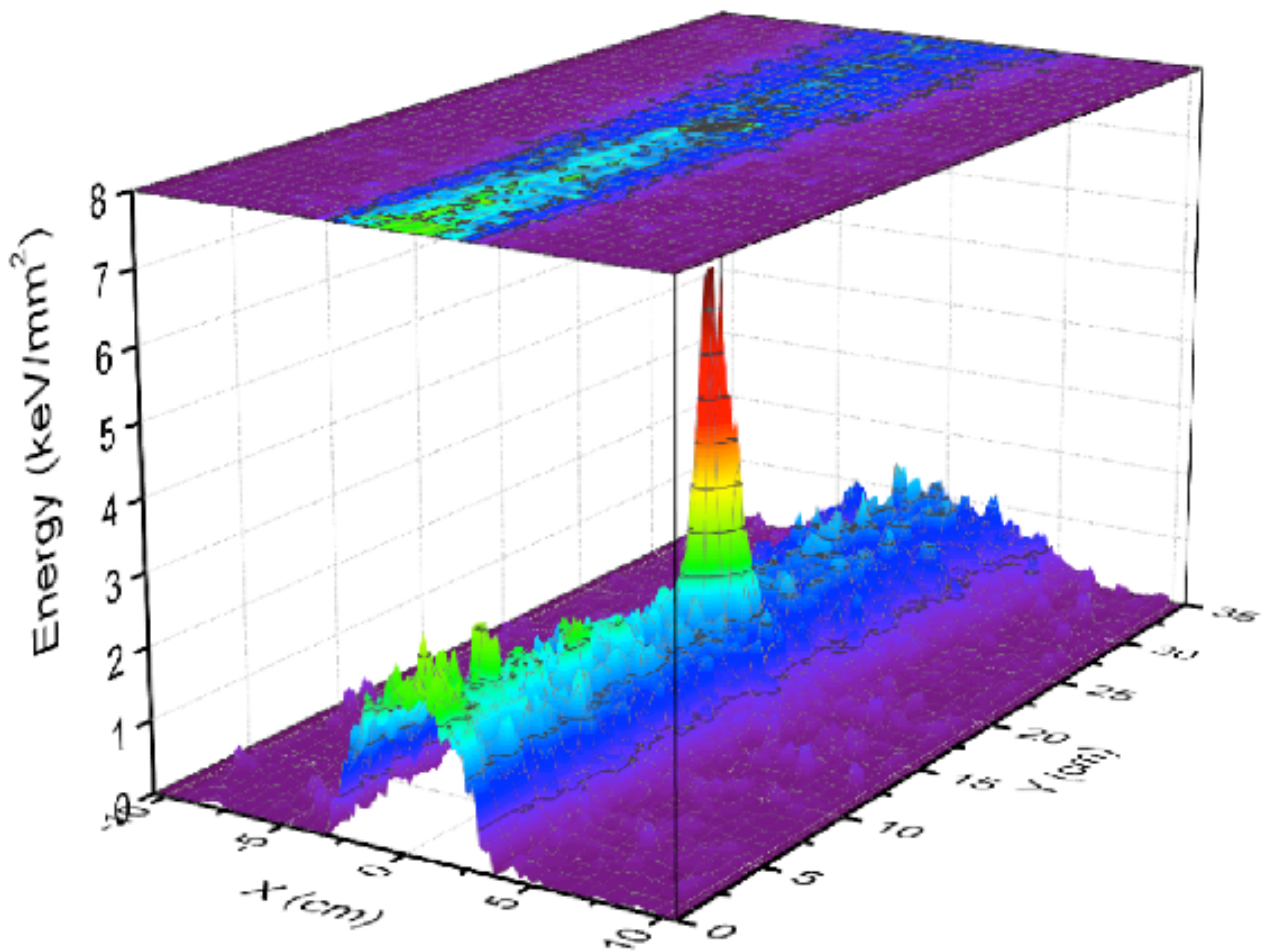
✓ Background:

- main sources of background:
  - Compton electrons
  - e^+e^- pairs in gaseous target & in thin mylar/kapton entrance window
  - at higher γ energies isotopic contaminants
- very small w.r.t. direct (α,γ) reaction experiments



The ELITPC project: background

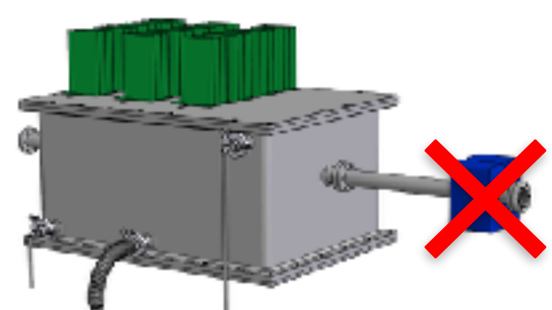
- ✓ Background: GEANT4 simulation of a single ELI-NP macro-pulse:
  - 10^7 γ-rays at 8 MeV
  - CO_2 @ 100 mbar
  - 0.5 MeV α-particle track added artificially to mimic ^{16}O photo-dissociation



Colour: integrated energy deposits on the 2D readout plane

The most unfavourable scenario is shown:

- entrance window very close to the active volume
- no permanent magnet after the entrance window

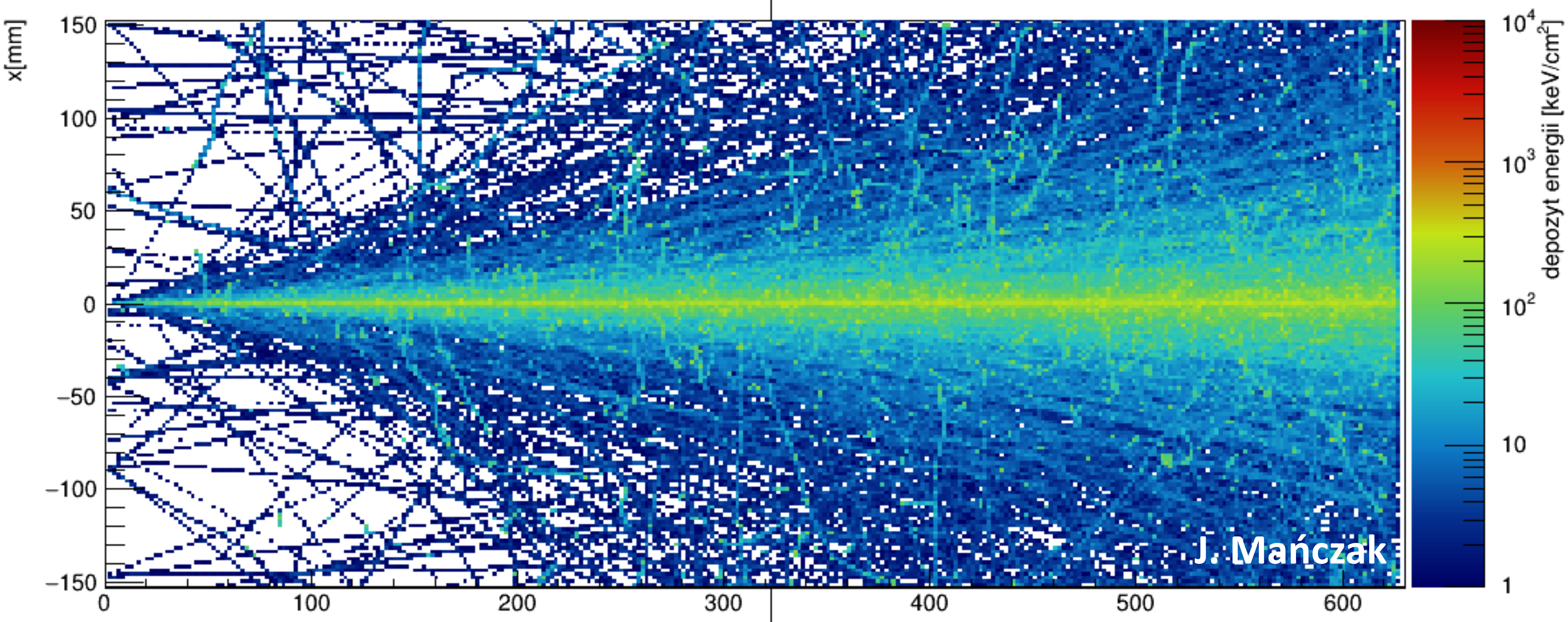


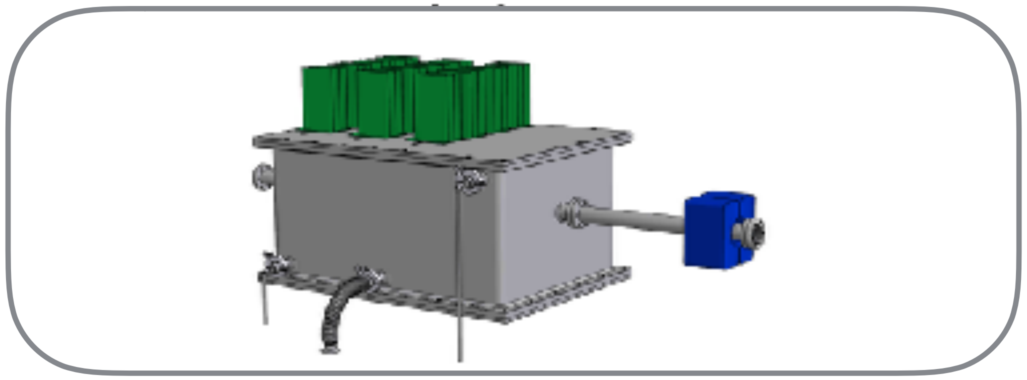
O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

The ELITPC project: background

✓ Background: GEANT4 simulation of a single ELI-NP macro-pulse:

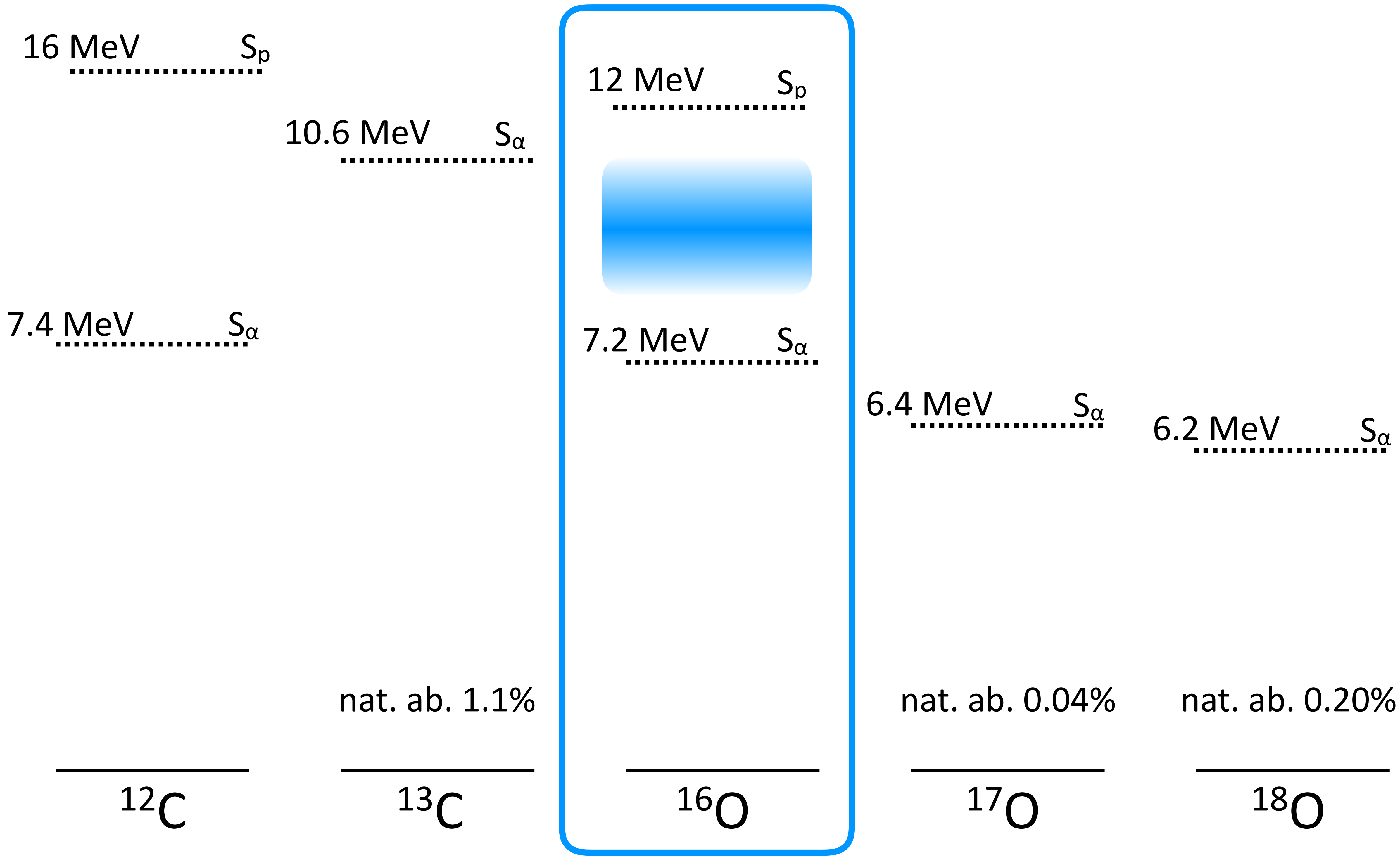
- 10^7 γ-rays at 10 MeV
- CO_2 @ 100 mbar





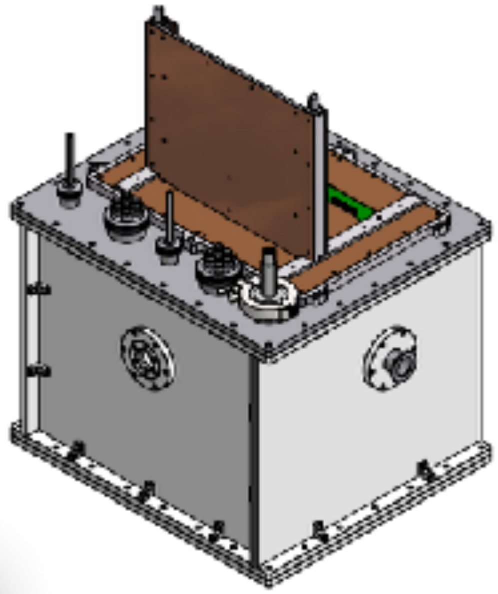
The ELITPC project: isotopic contaminants background for $^{16}O(\gamma,\alpha)^{12}C$

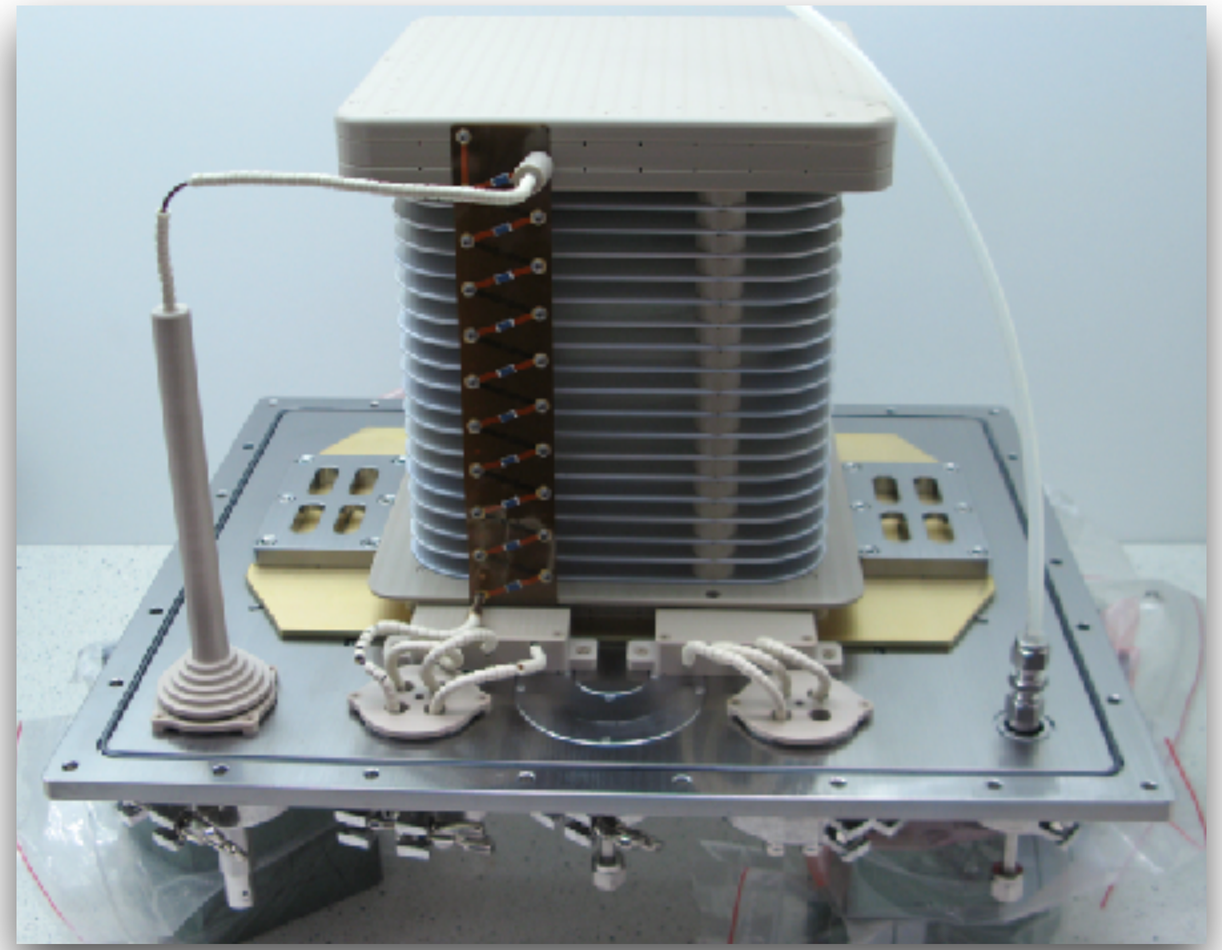
✓ Background: **isotopic contaminants** in the active gas

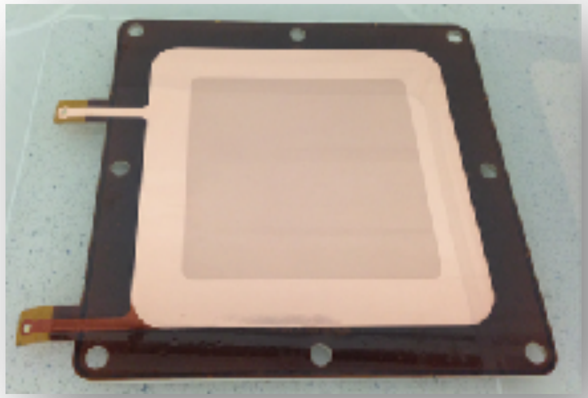


Demonstrator(s)

- ✓ Readout area: 10 × 10 cm^2, drift: 20 cm
- ✓ GET electronics: 256 channels
- ✓ Operating at atmospheric pressure

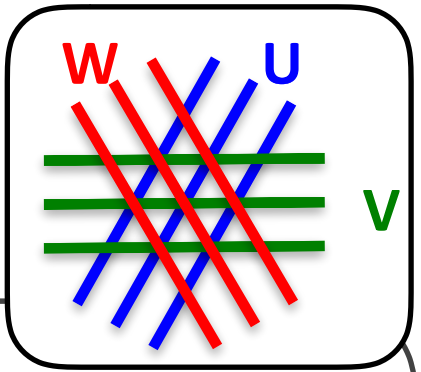






- ✓ Tested @ 9 MV Tandem (IFIN-HH, Romania) with 15 MeV α-particle beam (April 2016)
- ✓ Gas mixture: He+CO_2 (70:30) @1 atm

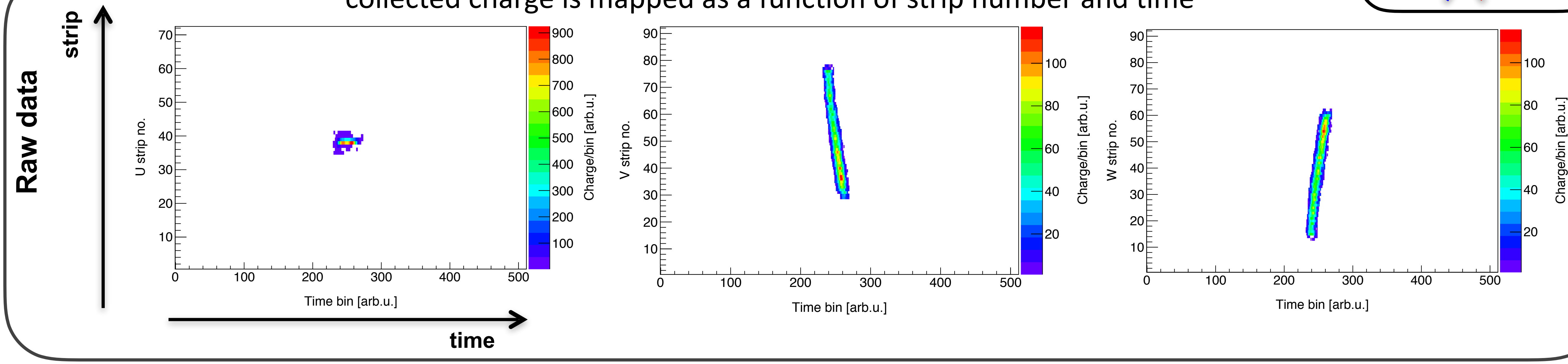
Demonstrator(s)

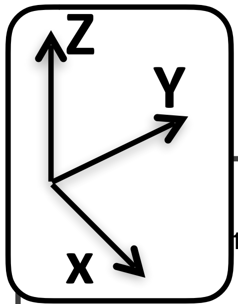


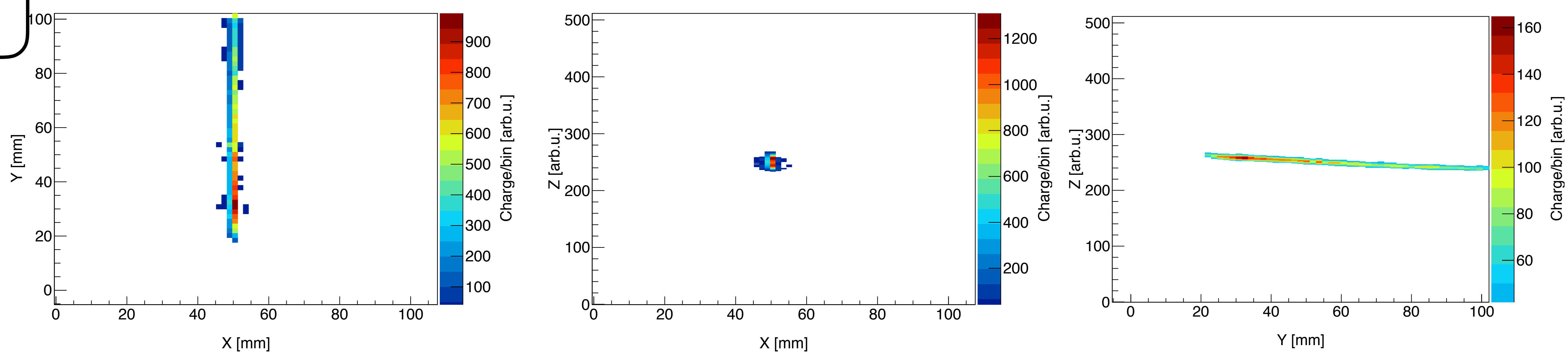
✓ **Example 1: Single tracks** from α-particle source:

- Gas mixture: He+CO_2 (90:10) **@1 atm**

collected charge is mapped as a function of strip number and time

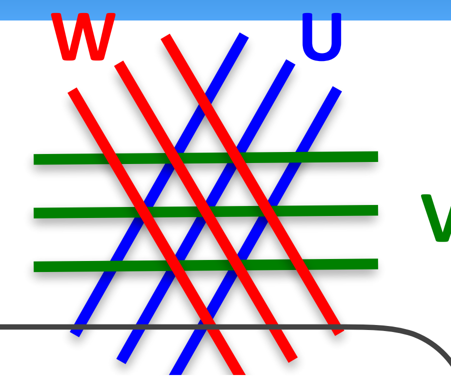


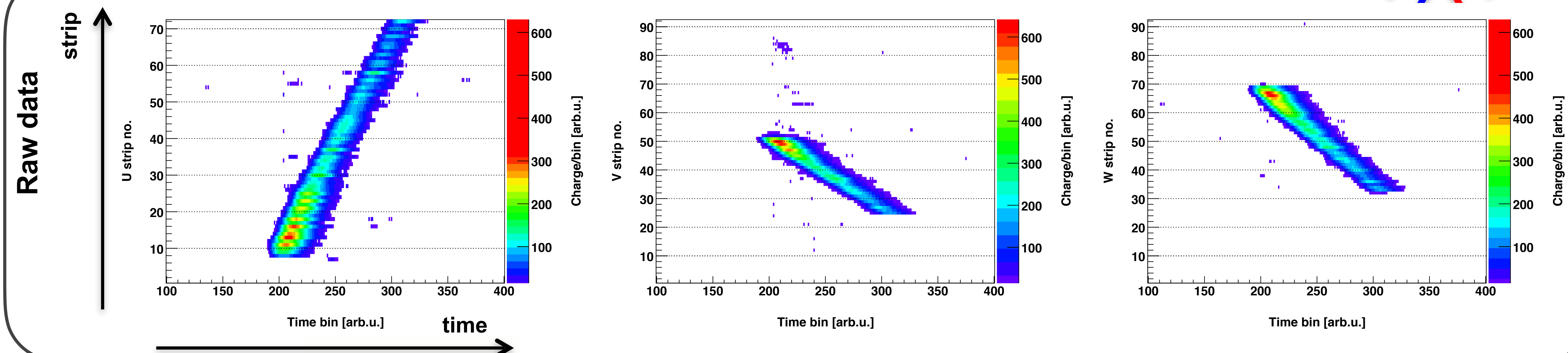




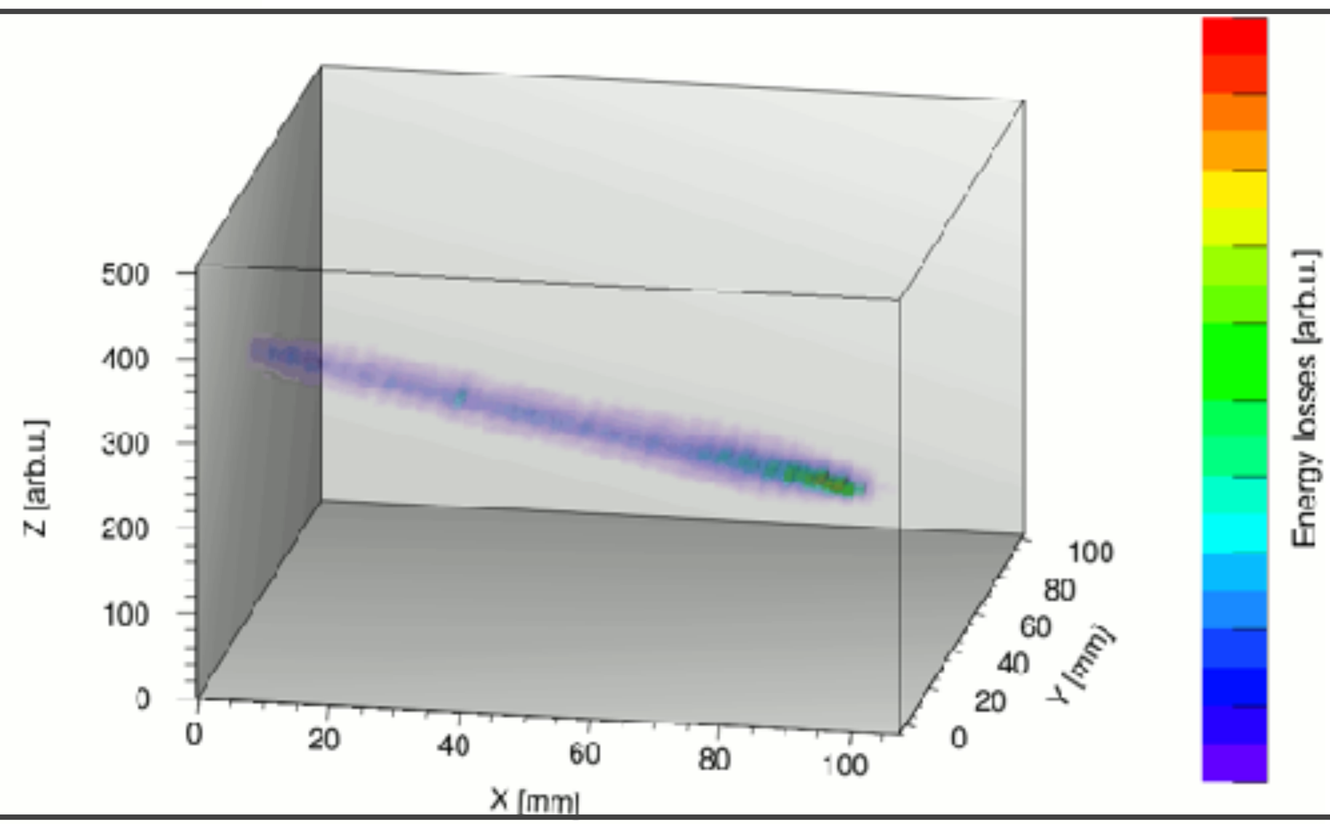
Demonstrator(s)

- ✓ **Example 2: Single tracks** from α-particle beam:
  - Gas mixture: He+CO_2 (70:30) **@1 atm**



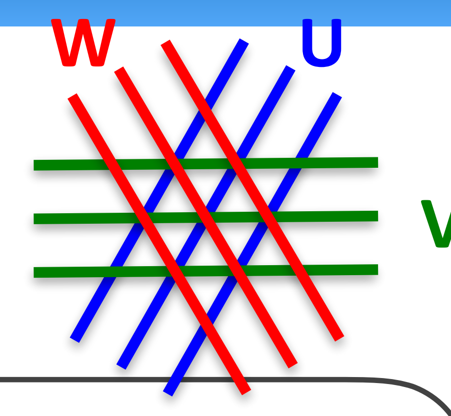


Reconstructed α-particle track in 3D

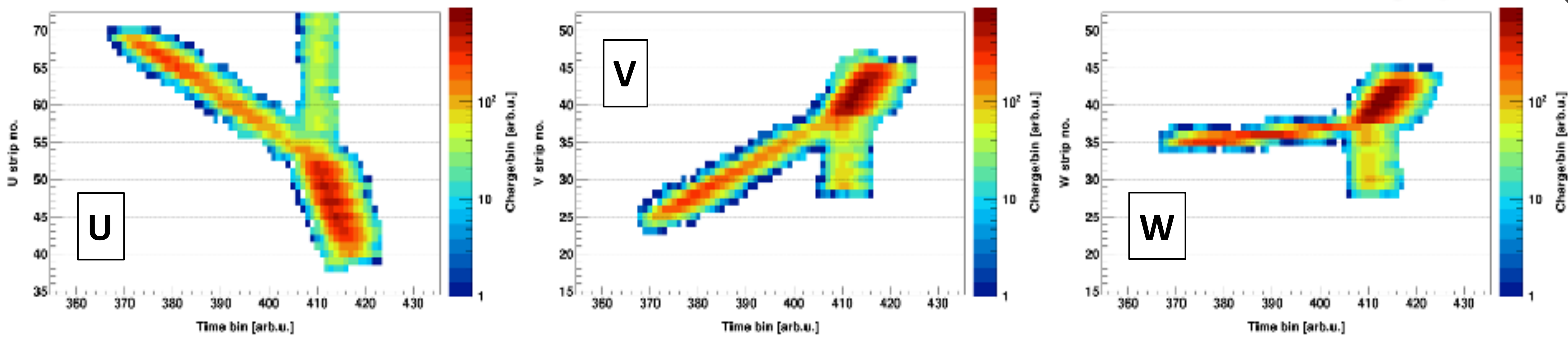


Demonstrator(s)

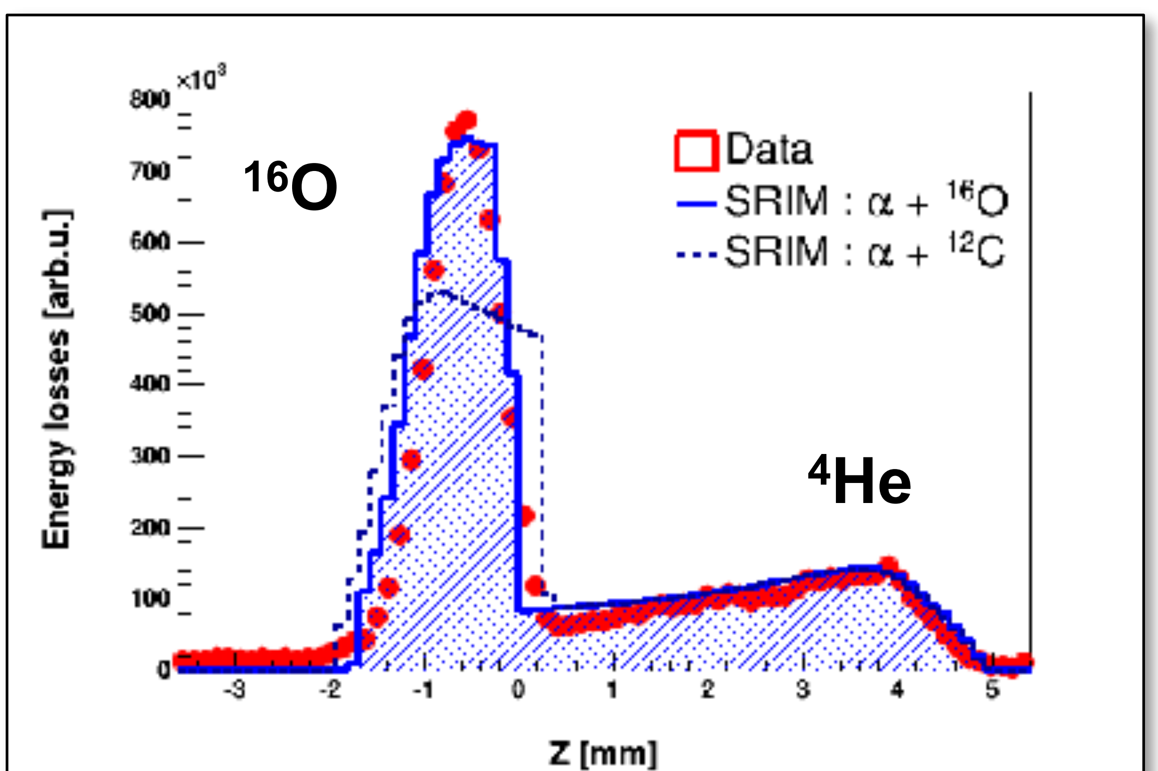
- ✓ **Example 3: events with 3 tracks —>** $^{4}He + ^{16}O$ **scattering**
  - Gas mixture: He+CO_2 (70:30) **@1 atm**

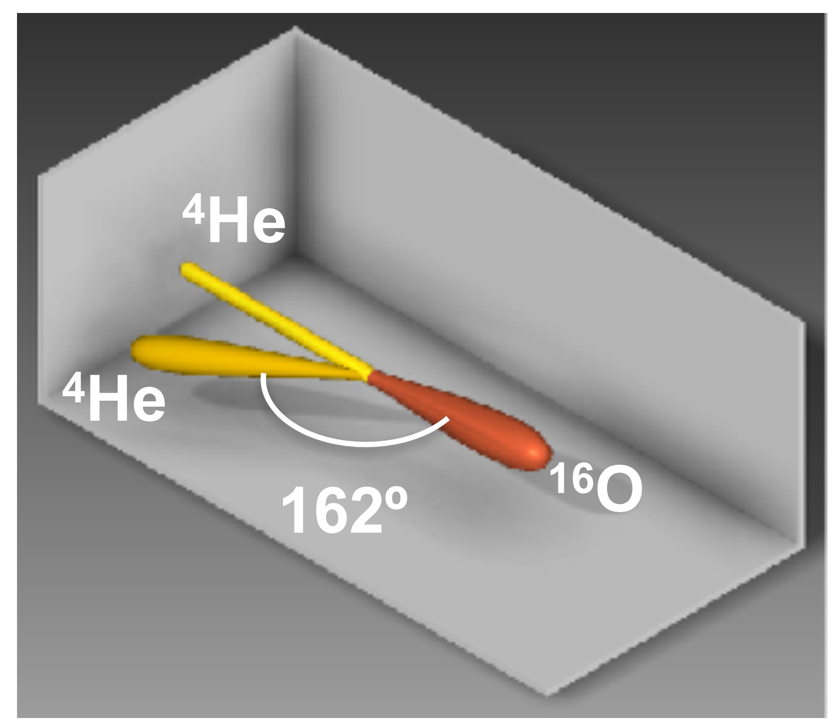


Raw data



Reconstruction





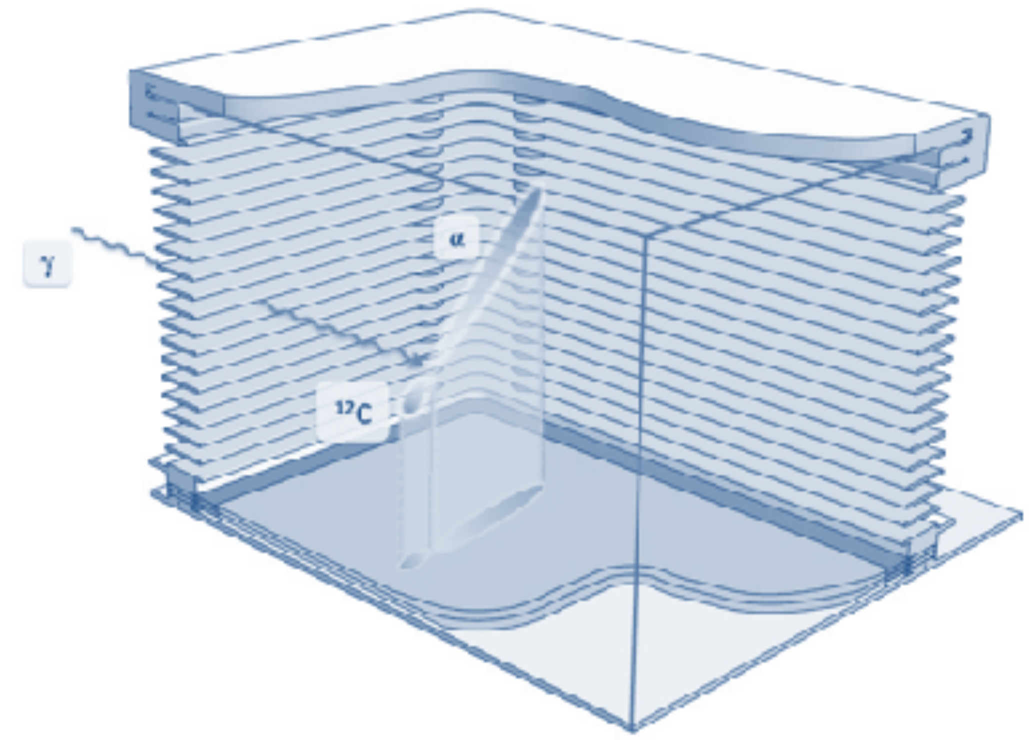
Summary

- ✓ $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ reaction cross section measurement is **flagship experiment** for the ELITPC collaboration at ELI-NP

- ✓ ELITPC detector among **DAY-1** experiments for ELI-NP

- ✓ 256 chn demonstrator detector is operational:
  - readout development
  - equipped GET electronics
  - reconstruction algorithms tests

- ✓ Other physics cases with ELITPC @ ELI-NP:
  - other astrophysical reactions (different gas targets)
  - nuclear structure physics (clustering phenomena)



Outlook

✓ R&D continues

- tests at lower-than-atmospheric pressure
- electronics developments
- simulations

✓ First commissioning experiments in 2018