Study of astrophysically relevant photo-disintegration reactions

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Overview

- ✓ Physics case
- ✓ Where?
- ✓ How?
  - an active-target time-projection chamber: the e-TPC project
- ✓ Outlook

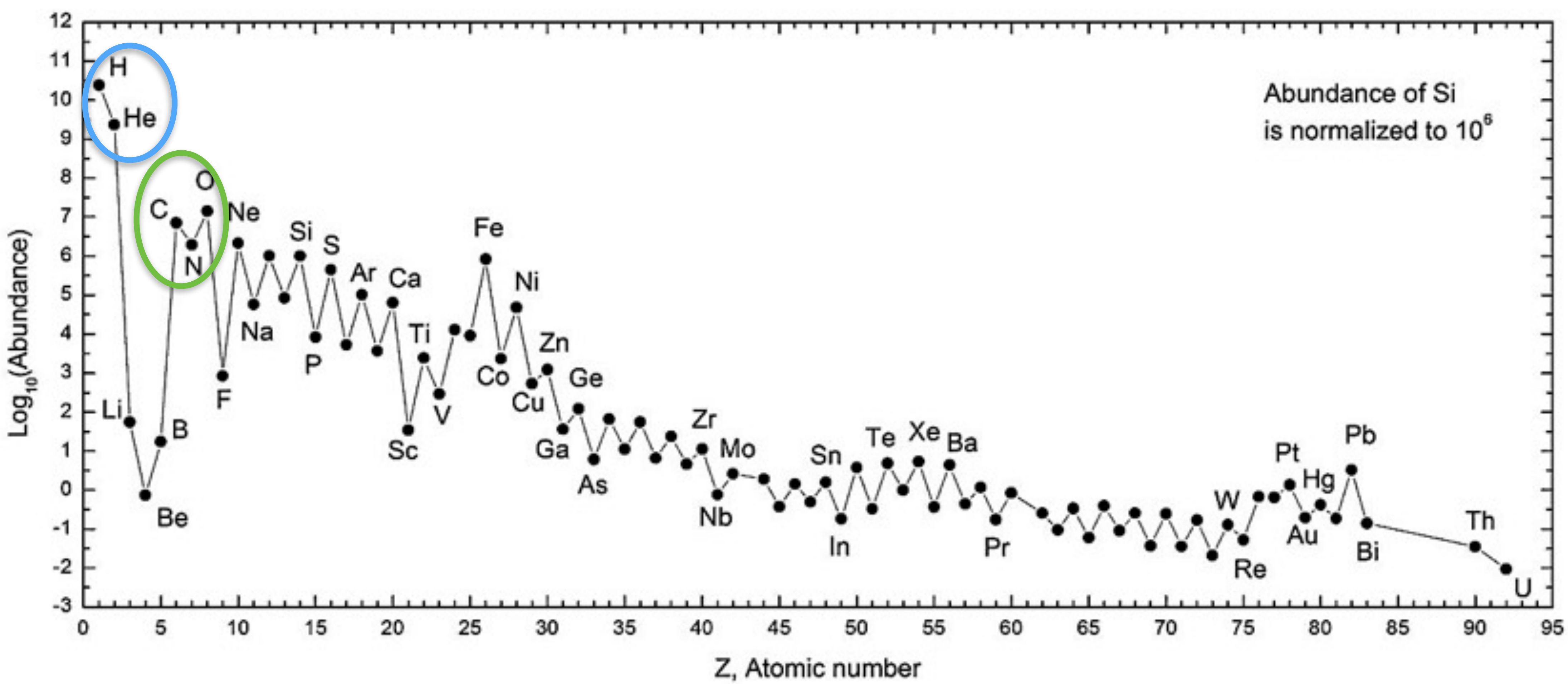
Physics motivations: nucleosynthesis

✓ 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: nucleosynthesis up to A=60

✓ **H-burning**:

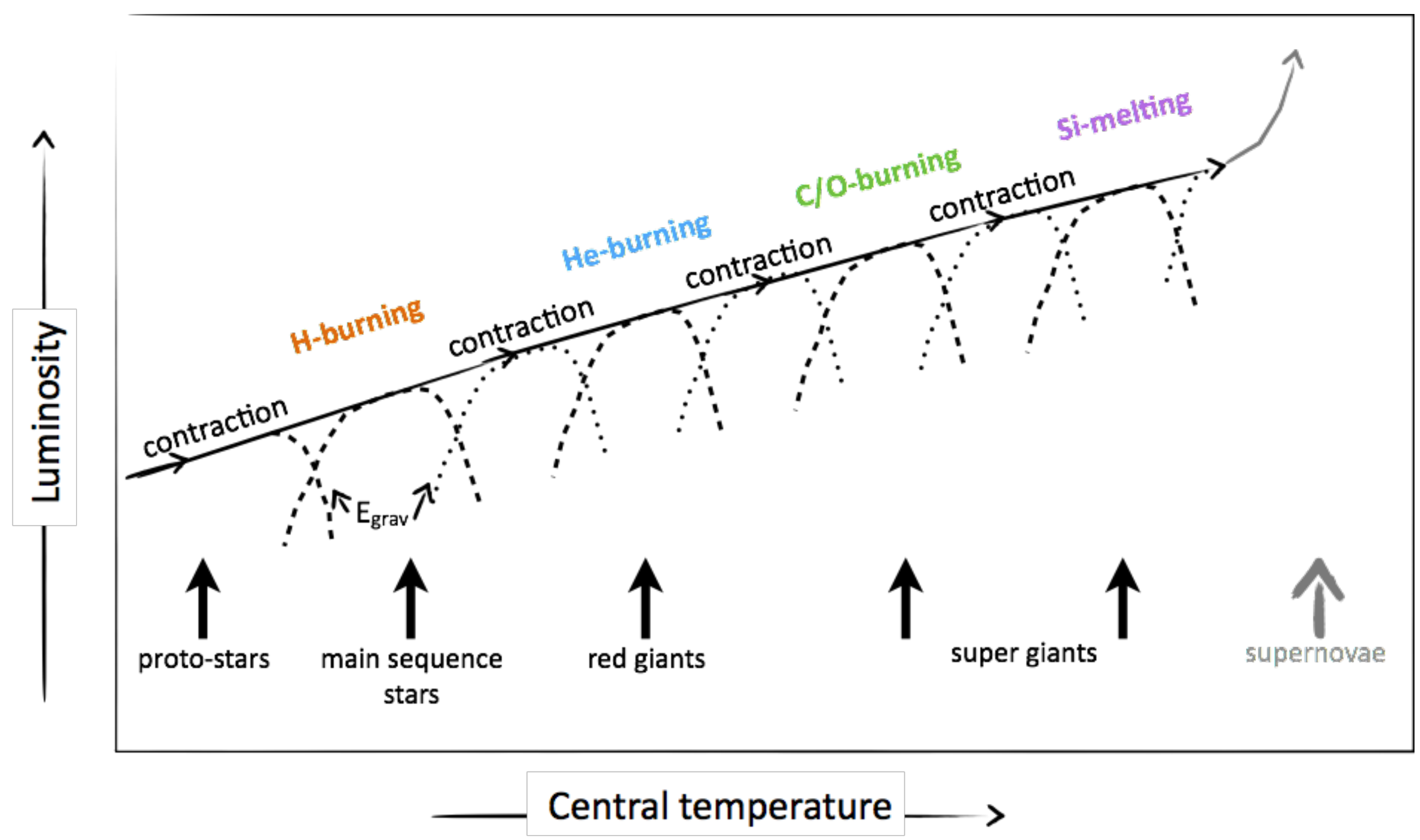
- $4p \longrightarrow {}^{4}He + 2e^{+} + 2\nu$ :: **pp-chain, CNO cycle**, hot-CNO, NeNa cycle, MgAl cycle,…
- synthesis of He

✓ **He burning**:

- **$3\alpha \longrightarrow {}^{12}C$; ${}^{12}C(\alpha,\gamma){}^{16}O$**, ${}^{16}O(\alpha,\gamma){}^{20}Ne$, ${}^{20}Ne(\alpha,\gamma){}^{24}Mg$
- synthesis of C, O, Ne

✓ **C/O, Ne, Si burning**:

- synthesis of elements with 16<A<60



Physics motivations: survival of ^{12}C

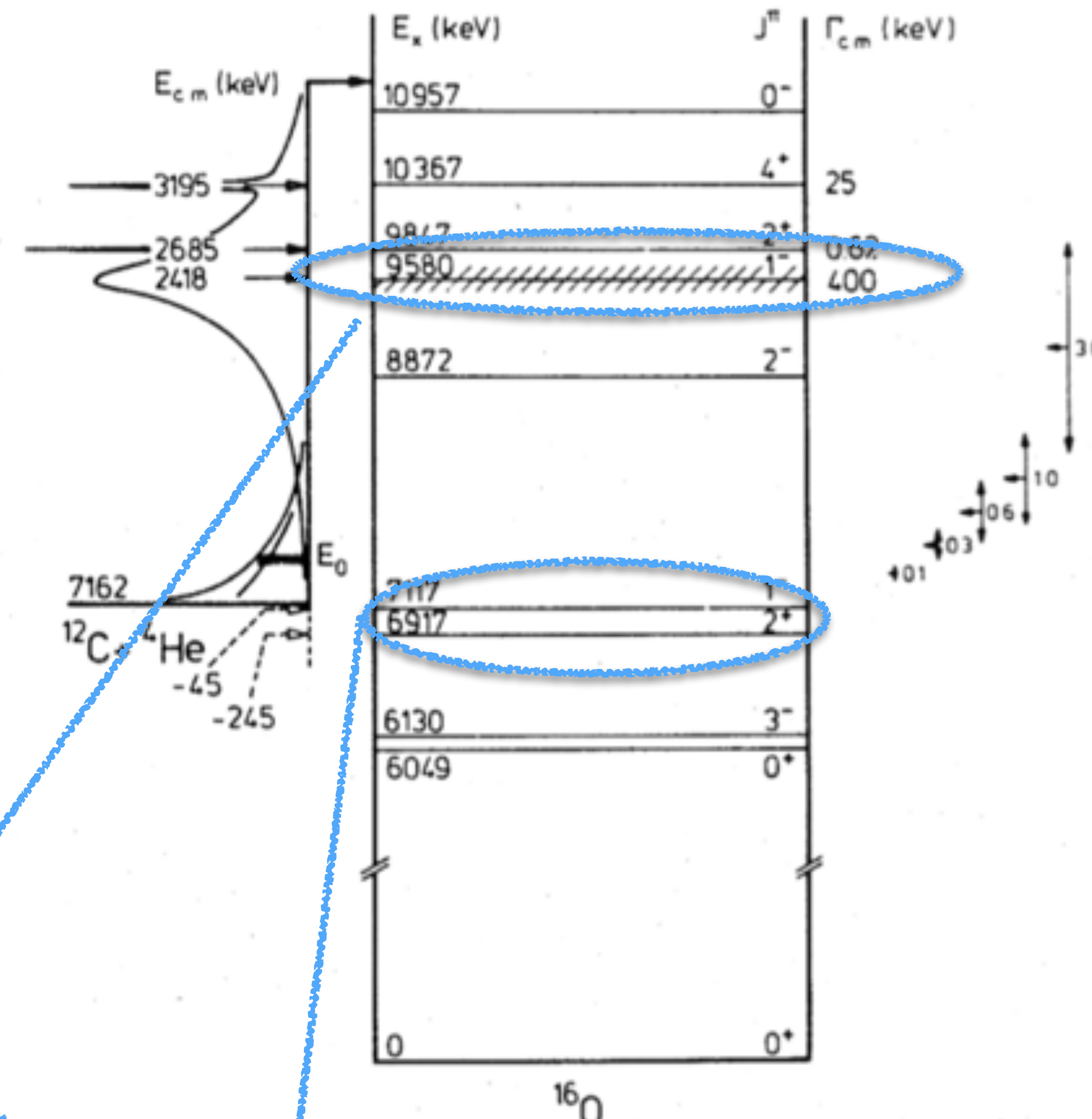
- ✓ Carbon is the 4th most abundant element in the universe, after H, He and O
- ✓ ^{12}C is created in the triple-α process or $3\alpha \rightarrow {}^{12}C$
- ✓ Carbon/Oxygen ratio = 0.6
- ✓ Assumption: nuclidic material is synthesised mostly during the major quiescent burning phase of stellar evolution
  - bulk of carbon abundance expected to be a direct product of the triple-α process
  - oxygen expected to be the ash of the subsequent $^{12}C(\alpha,\gamma)^{16}O$

-->> He-burning of ^{12}C must proceed at a **moderate rate** so that sufficient carbon remain after the He fuel is exhausted

Physics motivations: survival of ^{12}C

✓ Properties of the $^{12}C(\alpha,\gamma)^{16}O$ reaction:

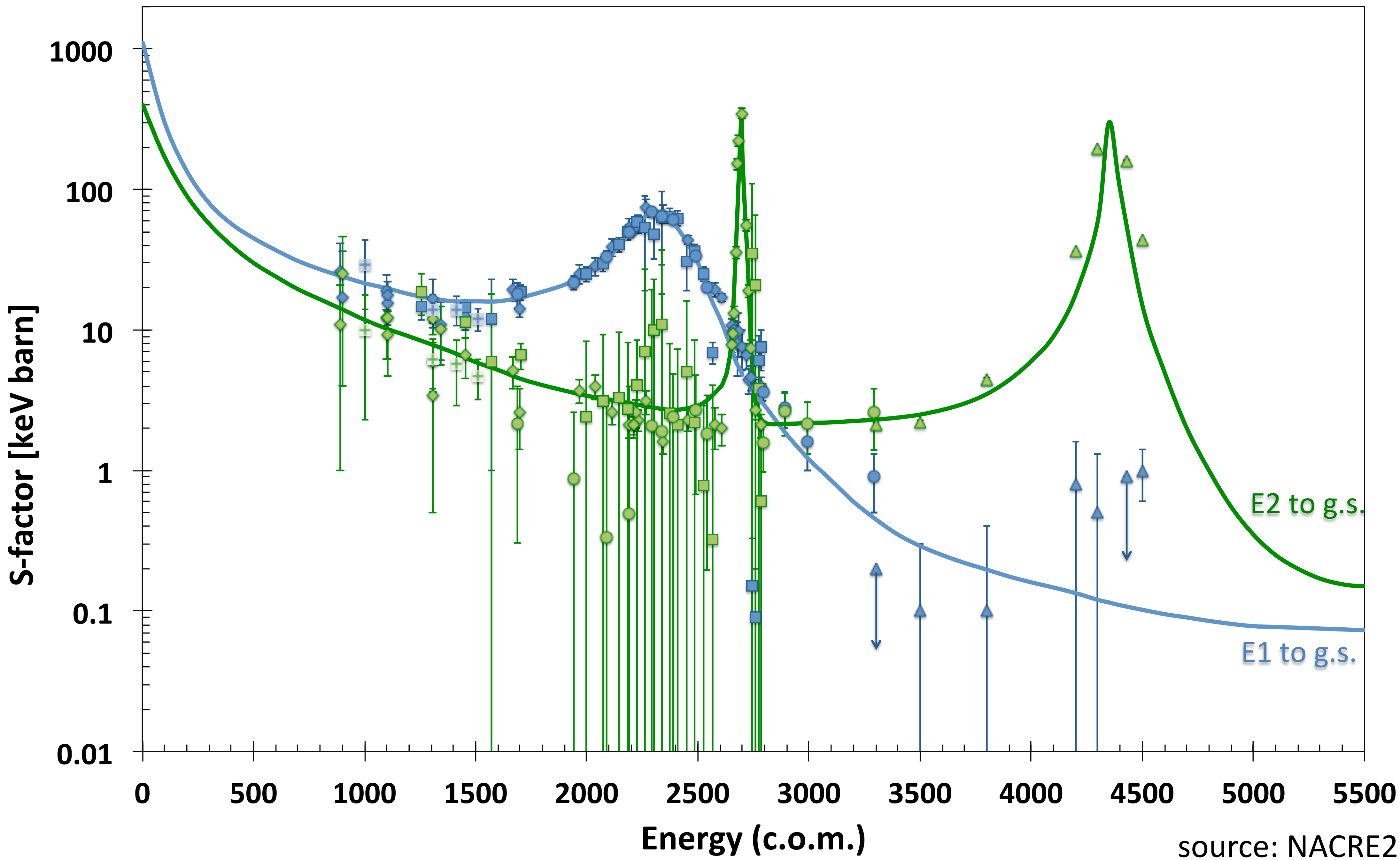
- if there were resonance near in the energy-range (Gamow peak) corresponding to He-burning temperatures ($T_6 \simeq 100$-200) then:
  - reaction would proceed at very high rate
  - carbon nuclei would be quickly destroyed
- Energy level scheme of ^{16}O shows no level available for such resonant behaviour up to $T_9=2$
- oxygen can only be produced in stars —>> another mechanism must enable the reaction to proceed at a rate consistent with the observed C/O ratio
- two mechanisms are available:
  - non-resonant direct-capture process
  - non-resonant type of capture into the tails of nearby resonances



sufficiently broad to influence the reaction-rate through its low-energy tail

by means of their high-energy tails they can enhance stellar burning

Status of the $^{12}C(\alpha,\gamma)^{16}O$ experimental knowledge



source: NACRE2

Physics motivations: He-burning and the reverse photo-disintegration reactions

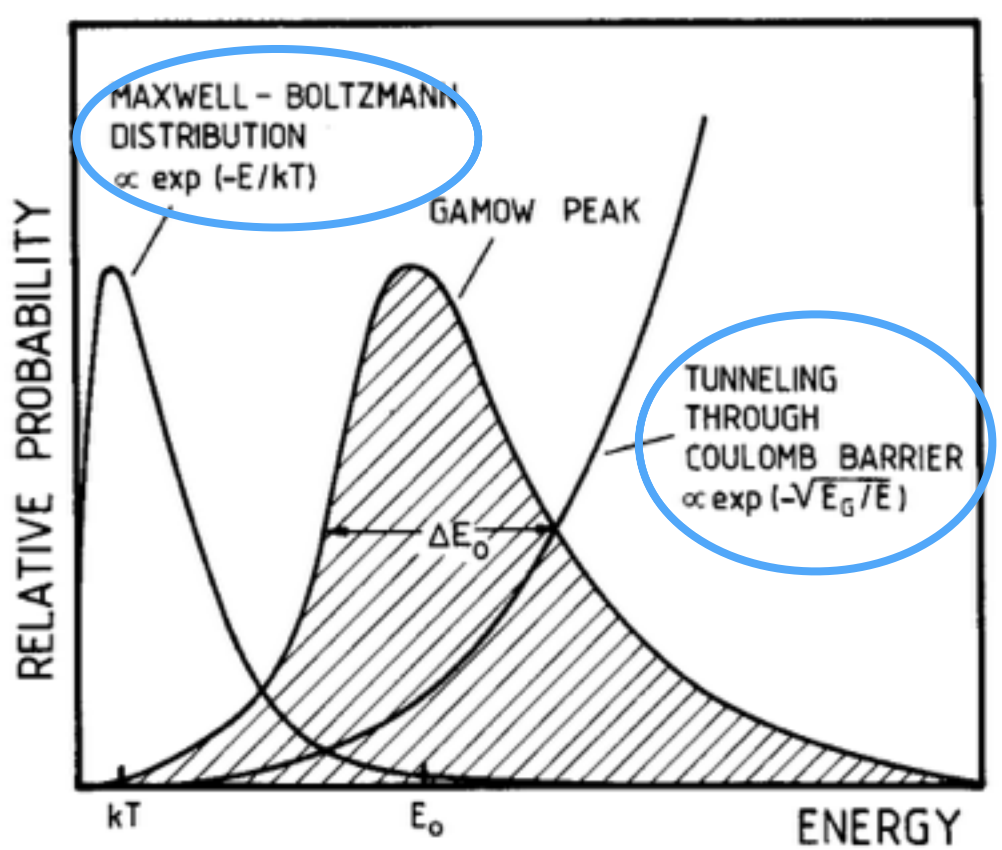
✓ The issue of the Coulomb barrier:

at typical He-burning temperatures of $T_6 \sim 300$, $KT \sim 200$ keV << E_{coul} (2 - 8MeV)

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-31.29 \cdot Z_1 \cdot Z_2 \cdot \sqrt{\frac{\mu}{E}} \right)$$

Astrophysical factor

Gamow factor



Nuclear reactions that generate energy and synthesise elements take place inside the stars in a relatively narrow energy window: the **Gamow peak**

Gamow Energy for He-burning reactions: few hundreds keV

Physics motivations: He-burning and the reverse photo-disintegration reactions

✓ Photodisintegration vs capture reaction: $B(b,\gamma)A \rightleftharpoons A(\gamma,b)B$

✓ Principle of detailed balance in nuclear reactions:

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

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

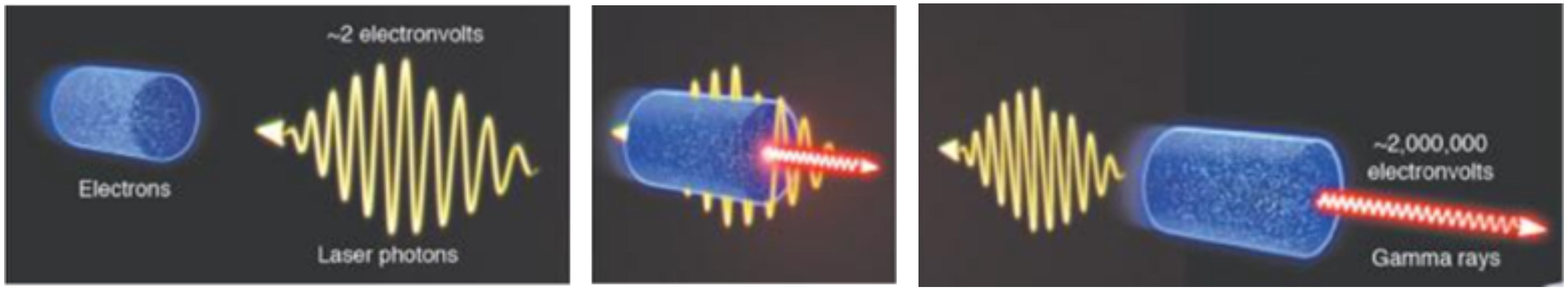
$g_{b\gamma}$, $g_{\gamma b}$ = spin factors

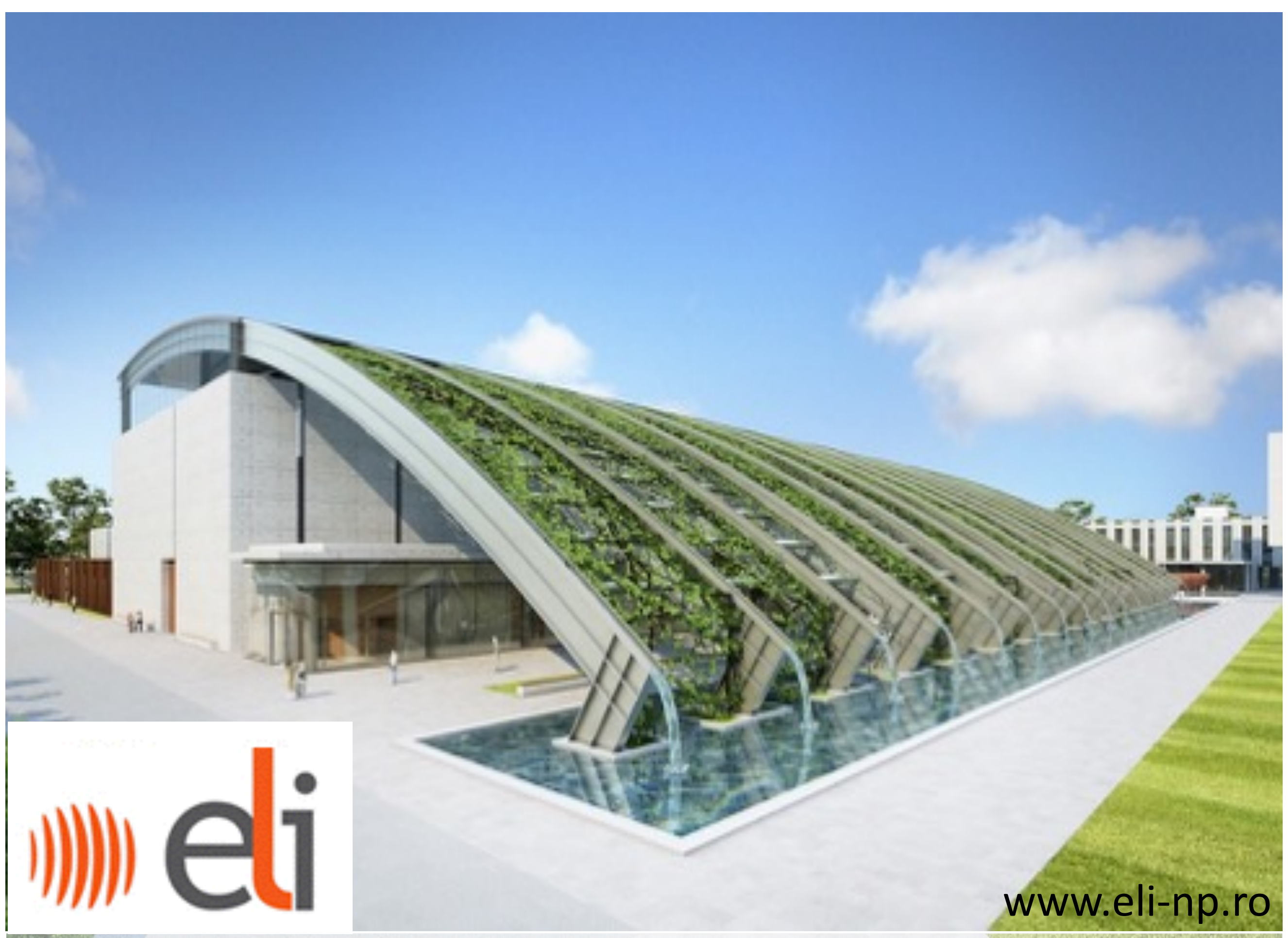
⇒ measure the cross section for the α-capture reaction by means of the inverse photo-disintegration reaction

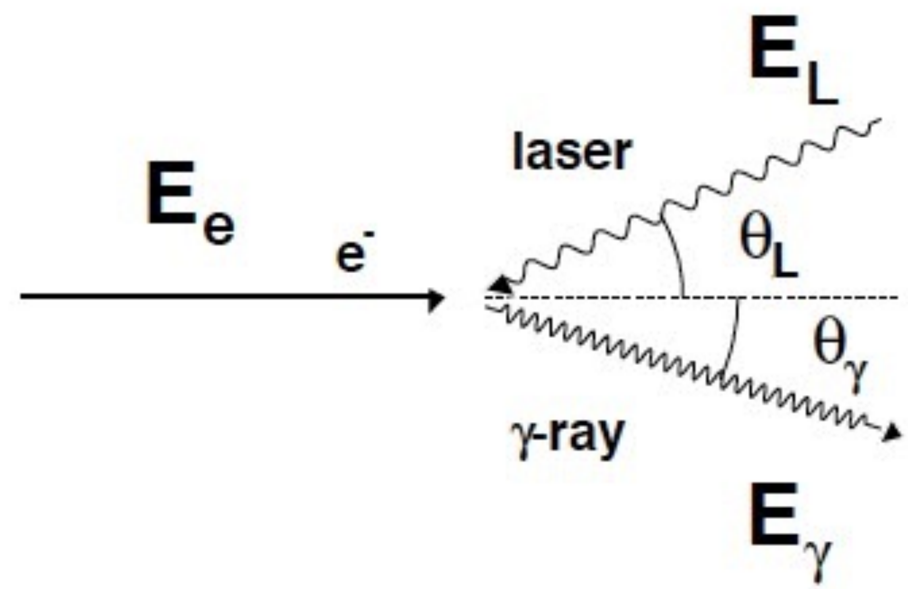
⇒ intense monochromatic γ-ray beams are needed

The ELI-NP facility

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







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

$\theta_L \ll 1$

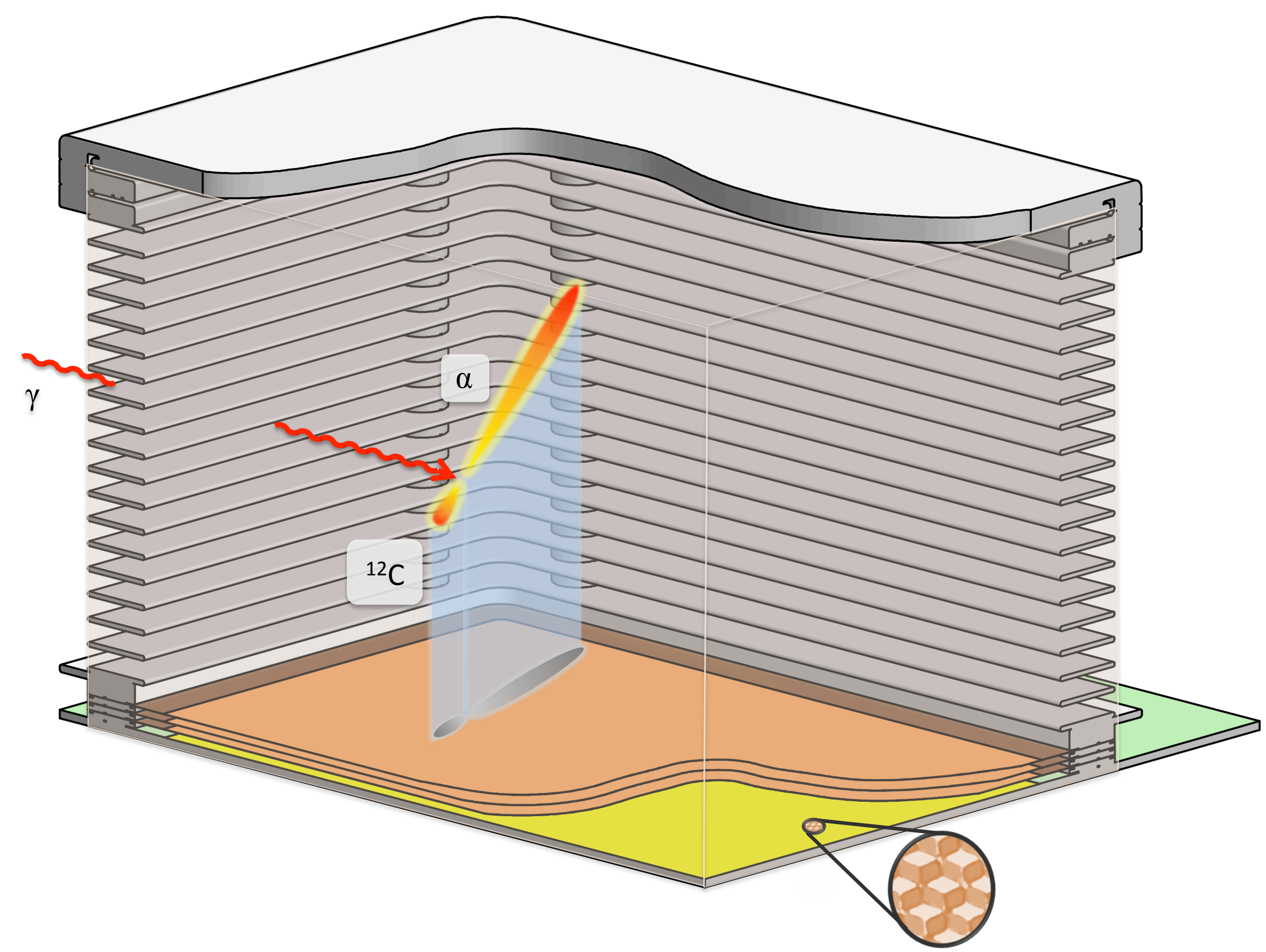
the e-TPC project

✓ An active-target TPC (e-TPC) to study reaction cross-sections of astrophysical interest where the reaction products are charged particles [developed in collaboration with ELI-NP]

✓ Electronic readout:

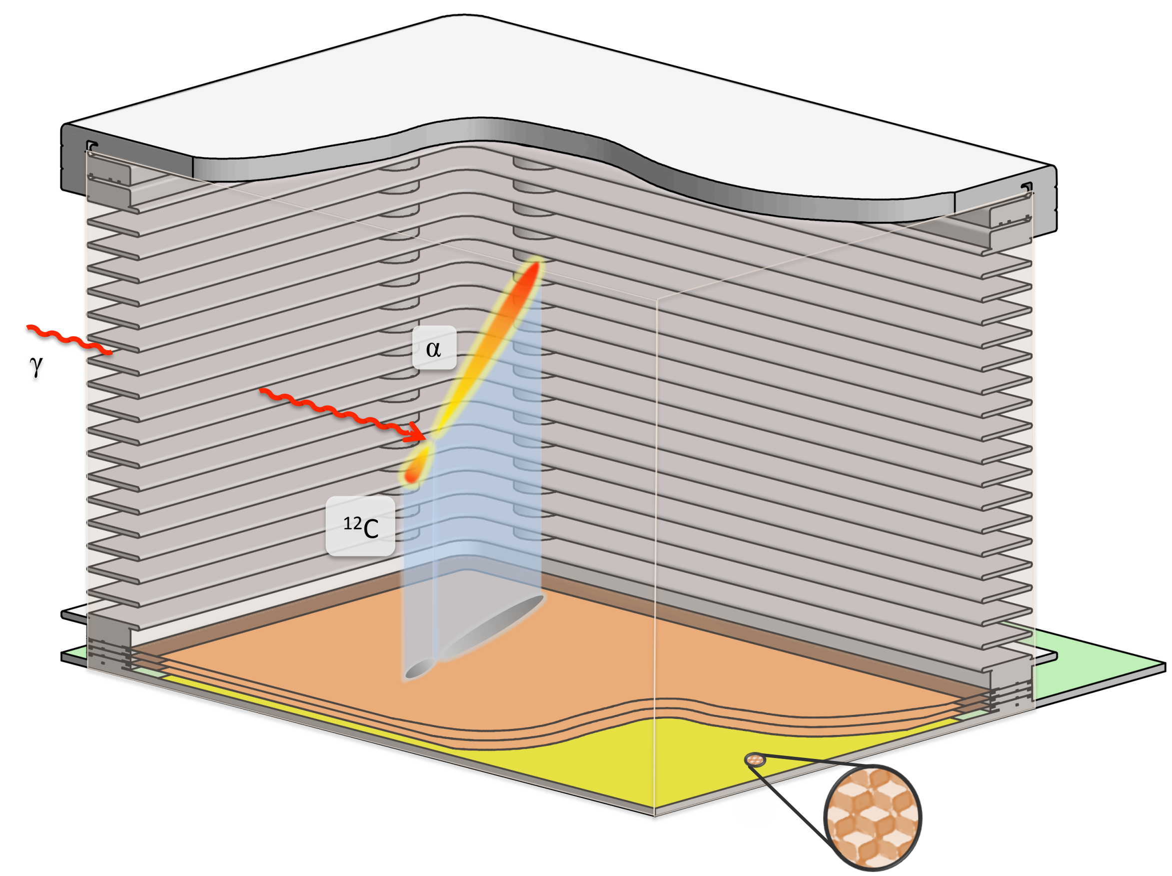
—> full unambiguous reconstruction of multiple-particle events is possible

—> more flexible than optical read-out: no need to have gases emitting photons in the visible (pure CO_2 can be used!!)

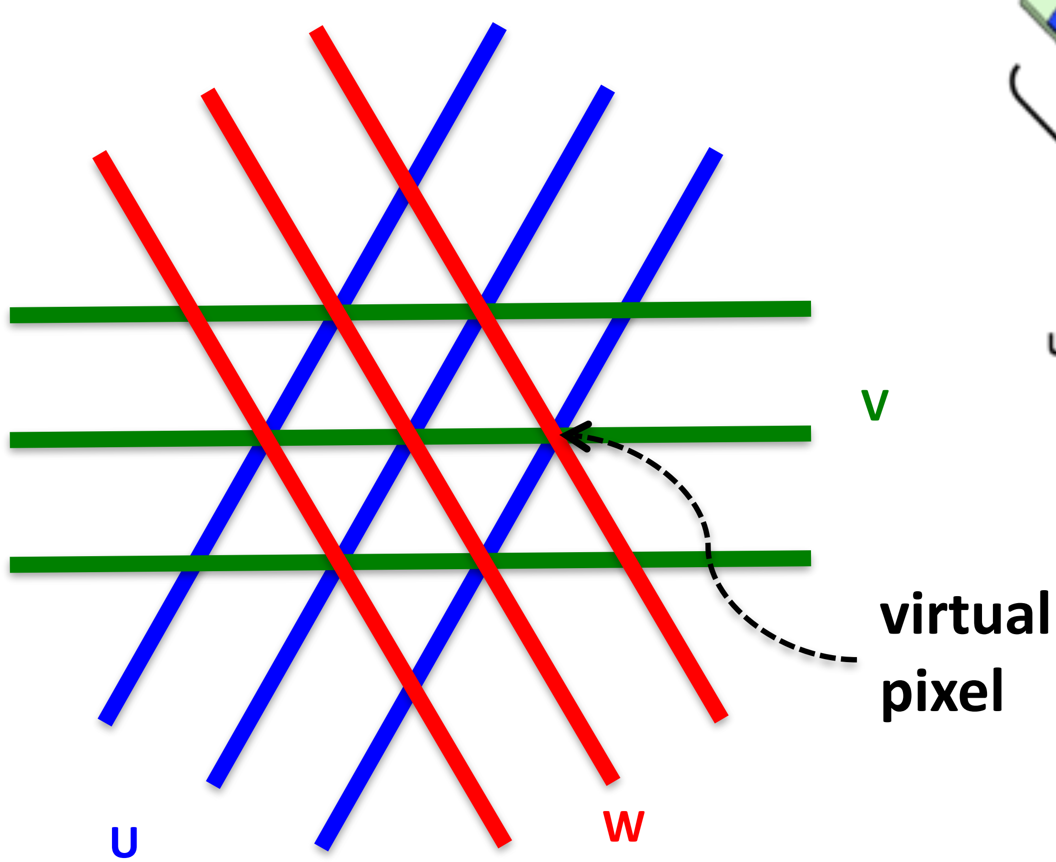


the e-TPC project

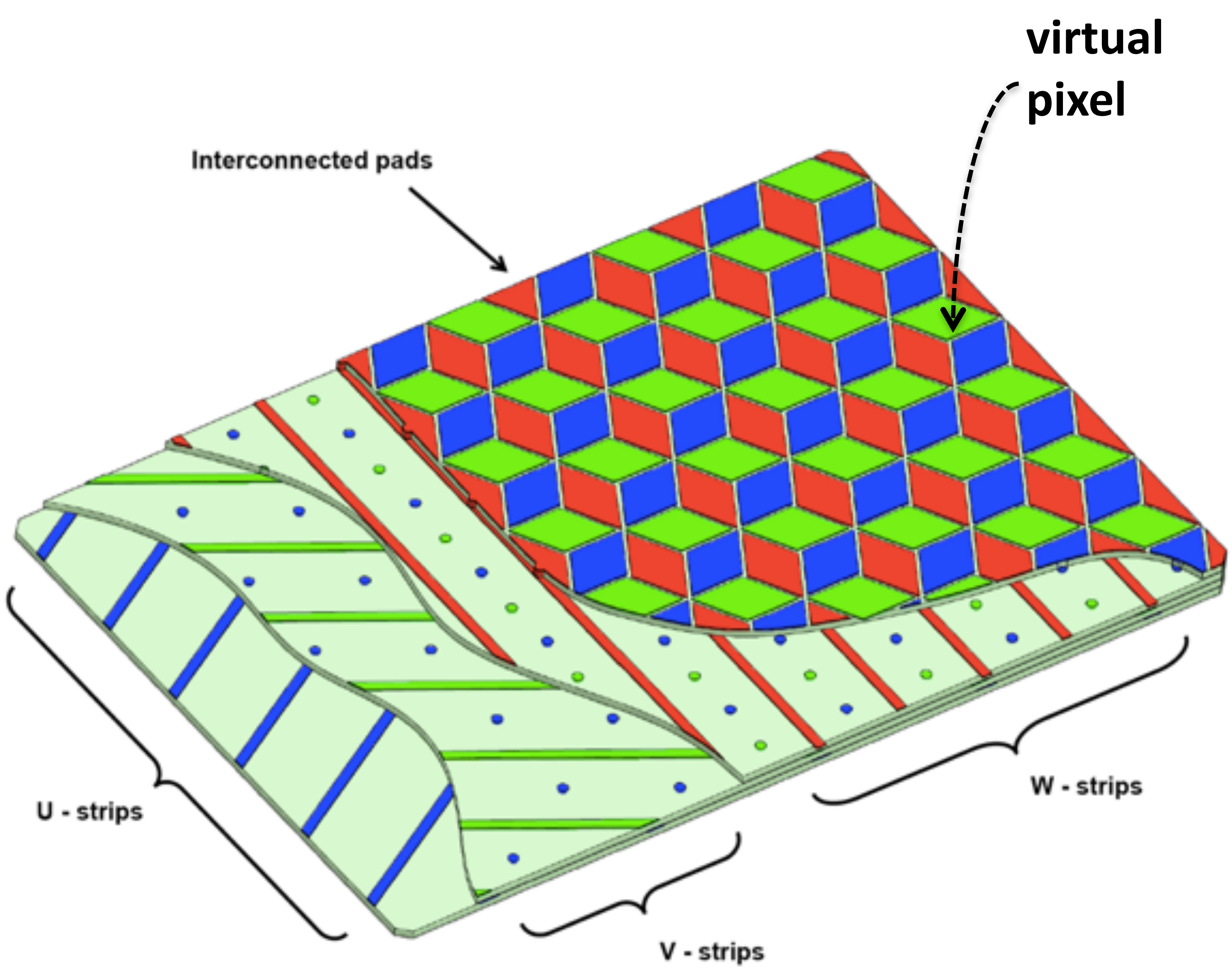
- ✓ **Active target**:
  - active volume: 35 cm x 20 cm x 20 cm
  - under-pressured (~100 mbar): low-energy particles!
  - gas-mixture tailored for the reaction of interest
- ✓ **Charge-amplification**:
  - 3 or 4 GEM structures
- ✓ **Electronic read-out**:
  - 3 independent linear sets of strips crossing at 60° (u-v-w)
  - fast multi-channel ADC (~1000 chn, 100 MS/s)
  - readout based on GET electronics
  - external trigger from the time-structure of the γ beam (100 Hz)



the e-TPC project: read-out electrode



multilayer printed circuit



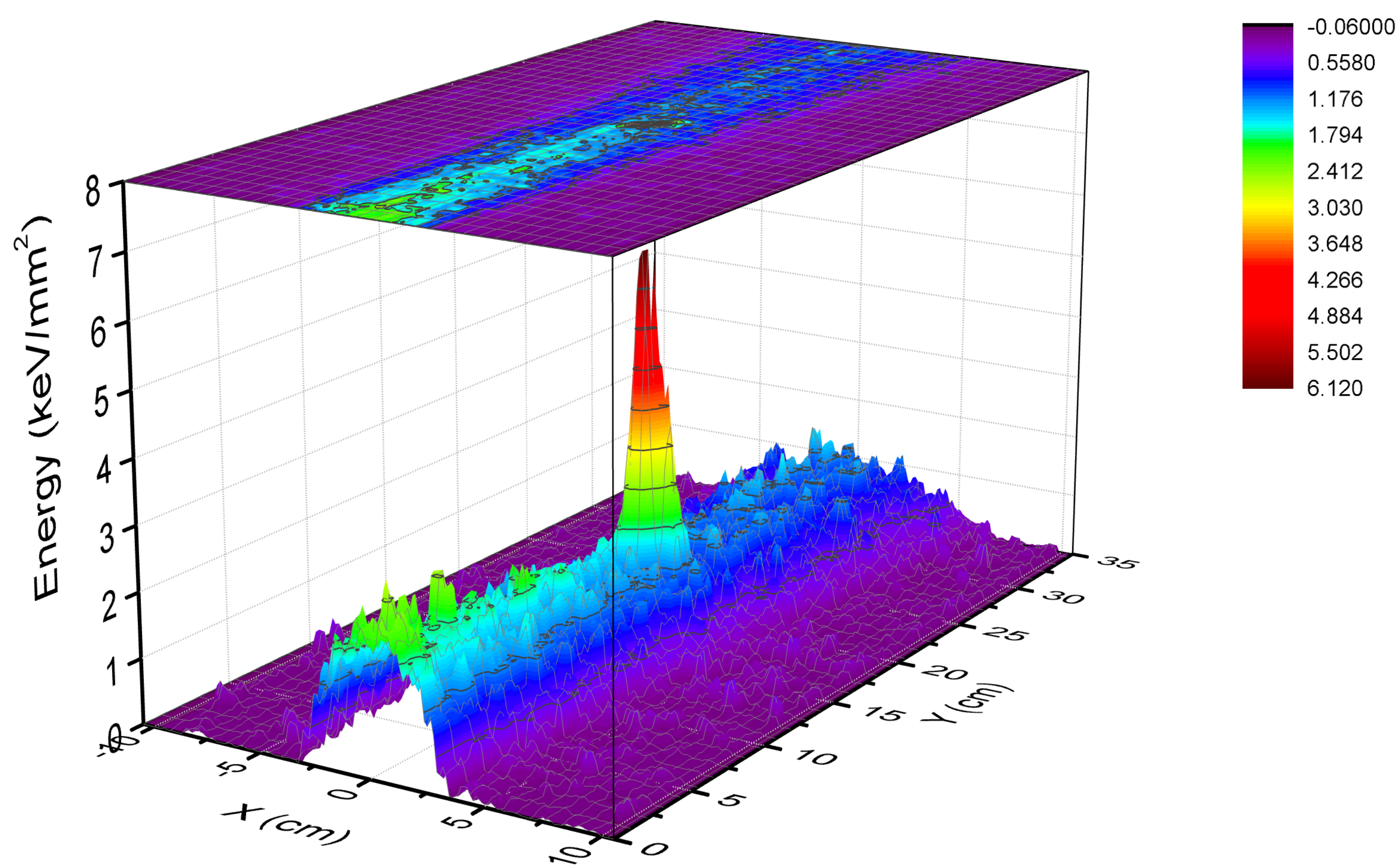
M. Ćwiok, Acta Phys. Pol. 47 (2016)
J. Bihałowicz *et al.*, Proc. of SPIE **9290** (2014) 92902C

the e-TPC project: Monte Carlo simulations

✓ GEANT4 simulation of the γ-beam induced background with superimposed 0.5 MeV α particle (parallel to the readout plane at an angle of 45° with respect to the beam direction)

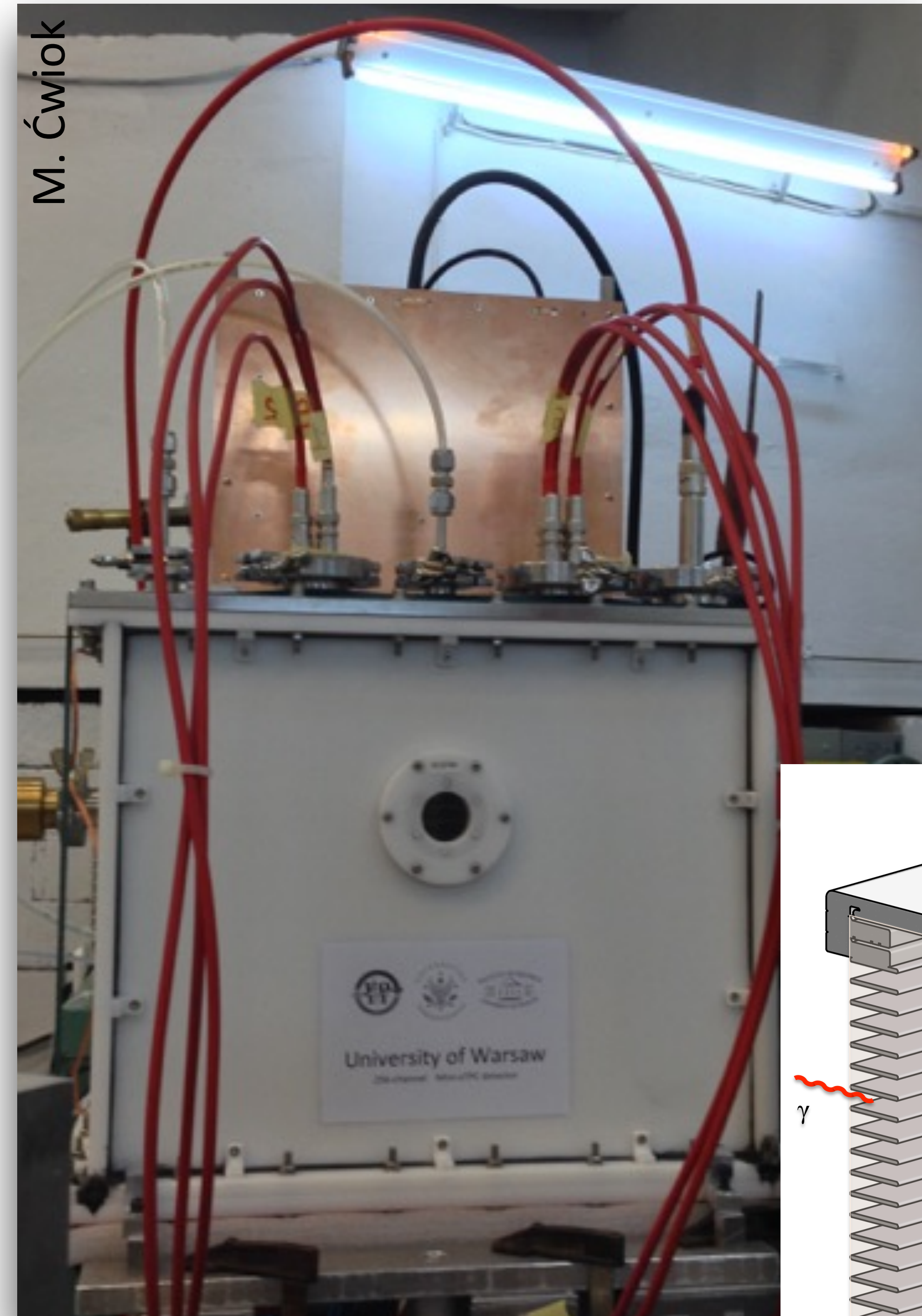
✓ Background: mainly electrons from γ conversion in the entrance window

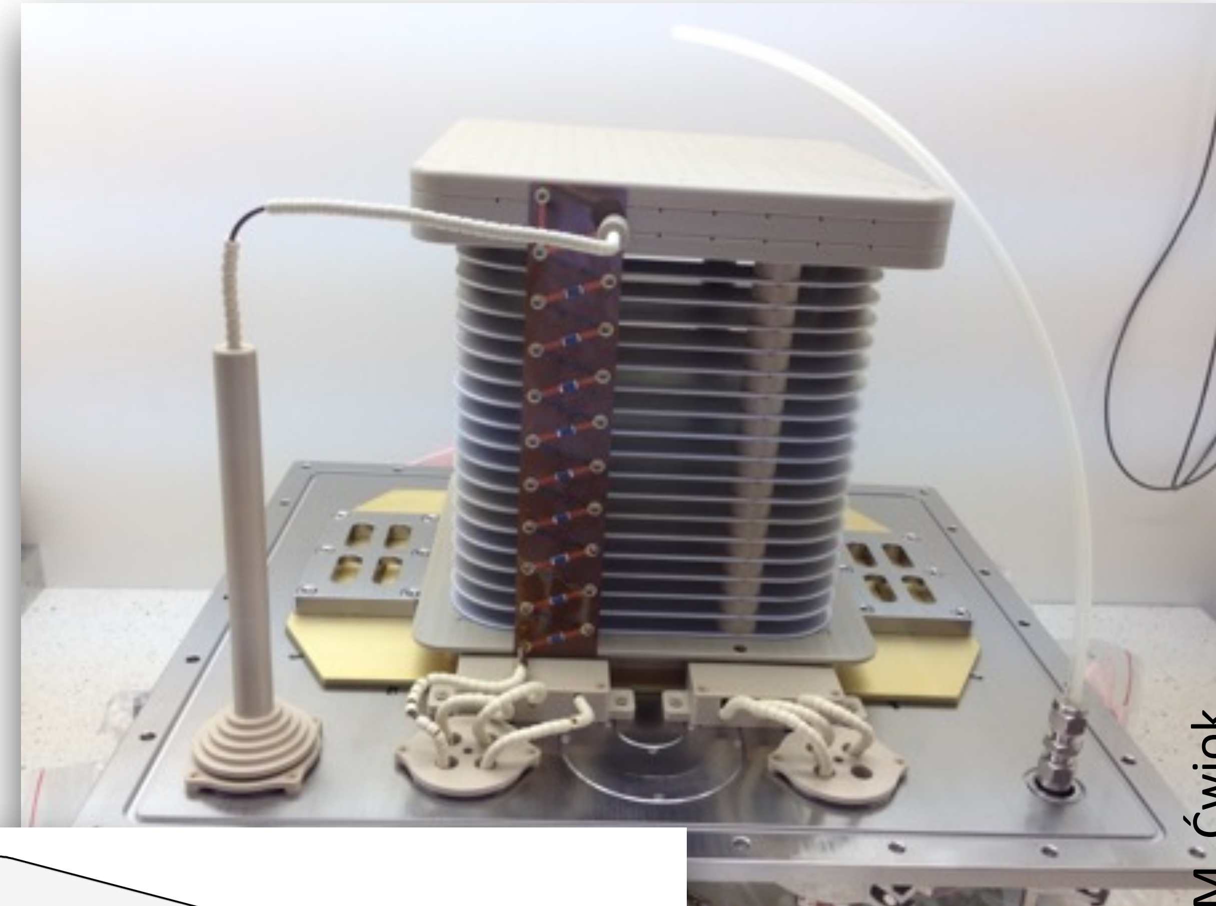
✓ Time window: single macro-bunch in the e-TPC detector (CO_2 gas @100 mbar)

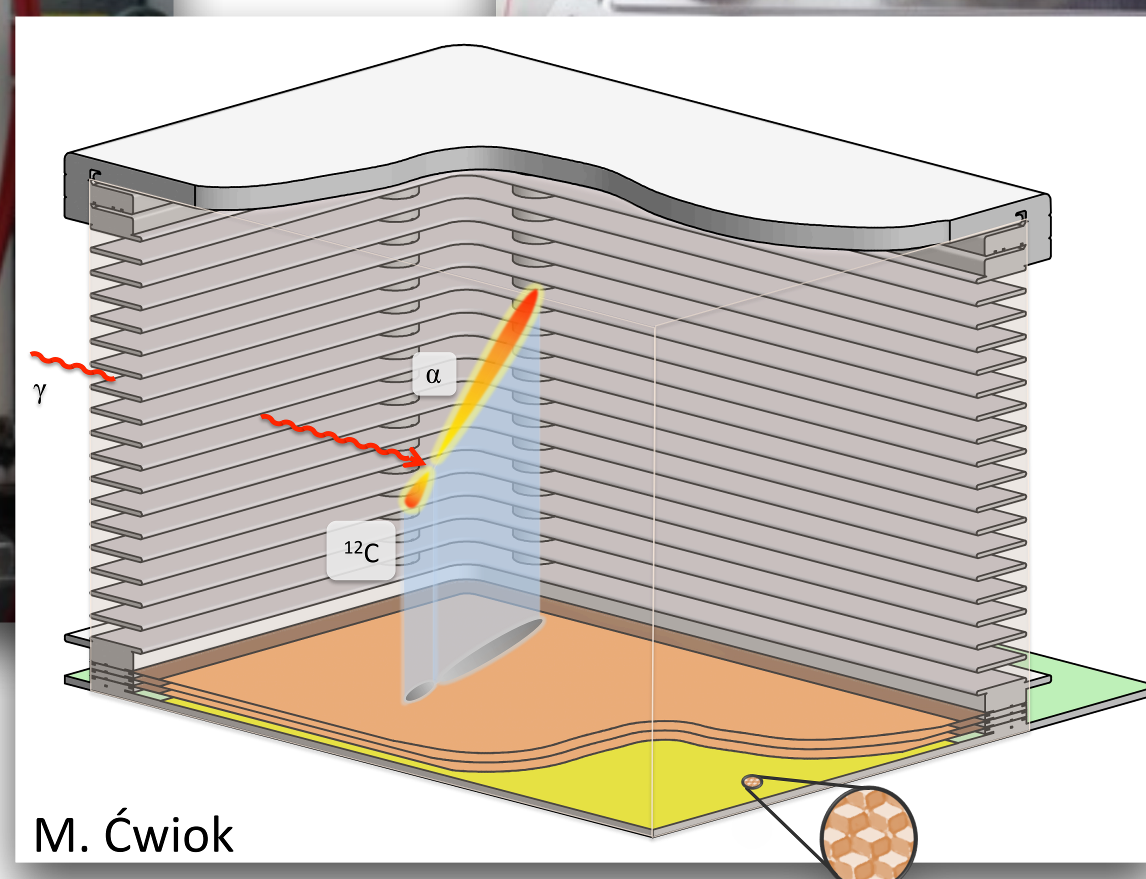


Charged Particle Detection at ELI–NP, Technical Design Report, RA4 – TDR 4, 2015

the e-TPC project: demonstrator detector

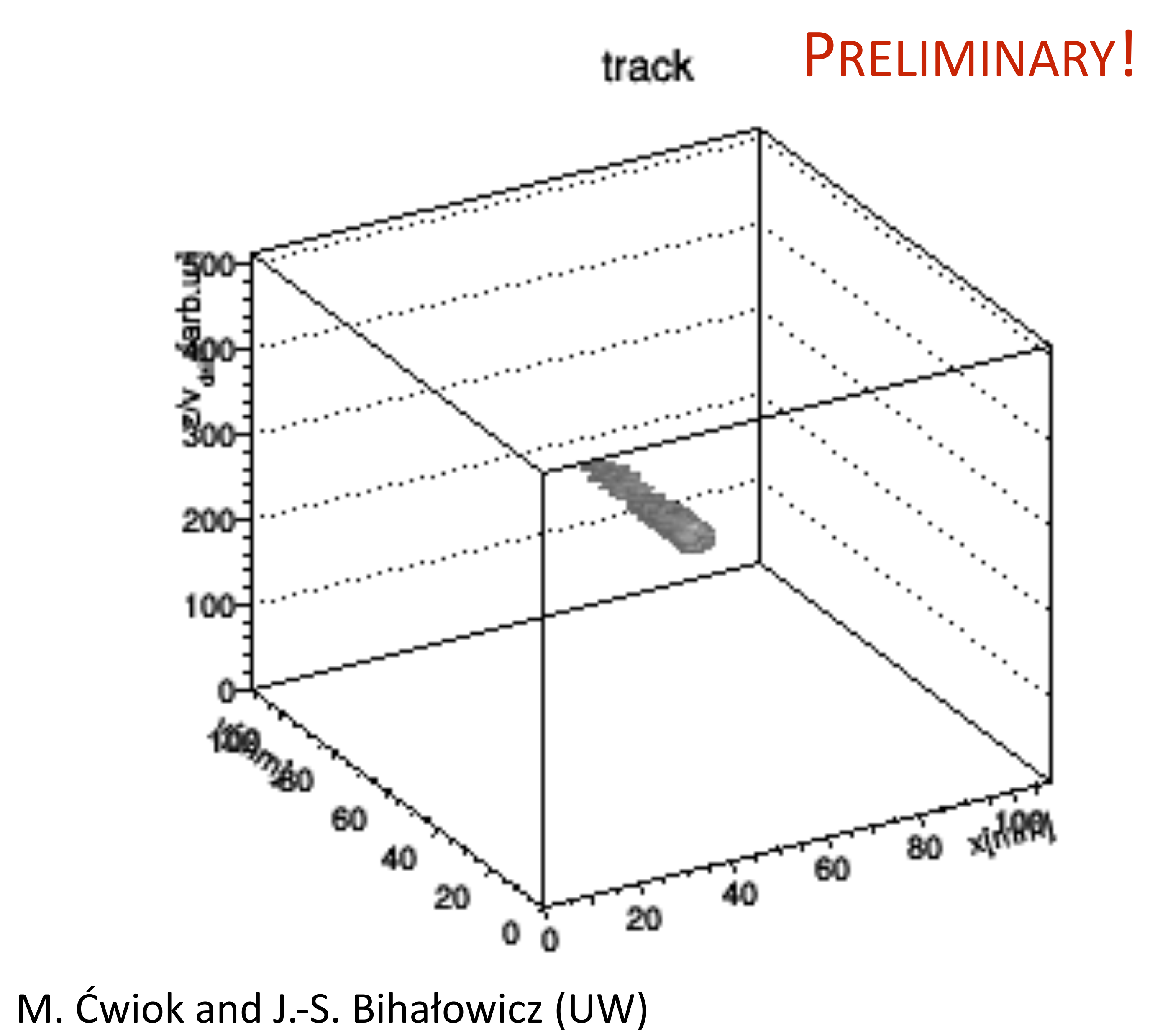






the e-TPC project: proof-of-principle studies

- ✓ **Demonstrator detector**:
  - tests with α source

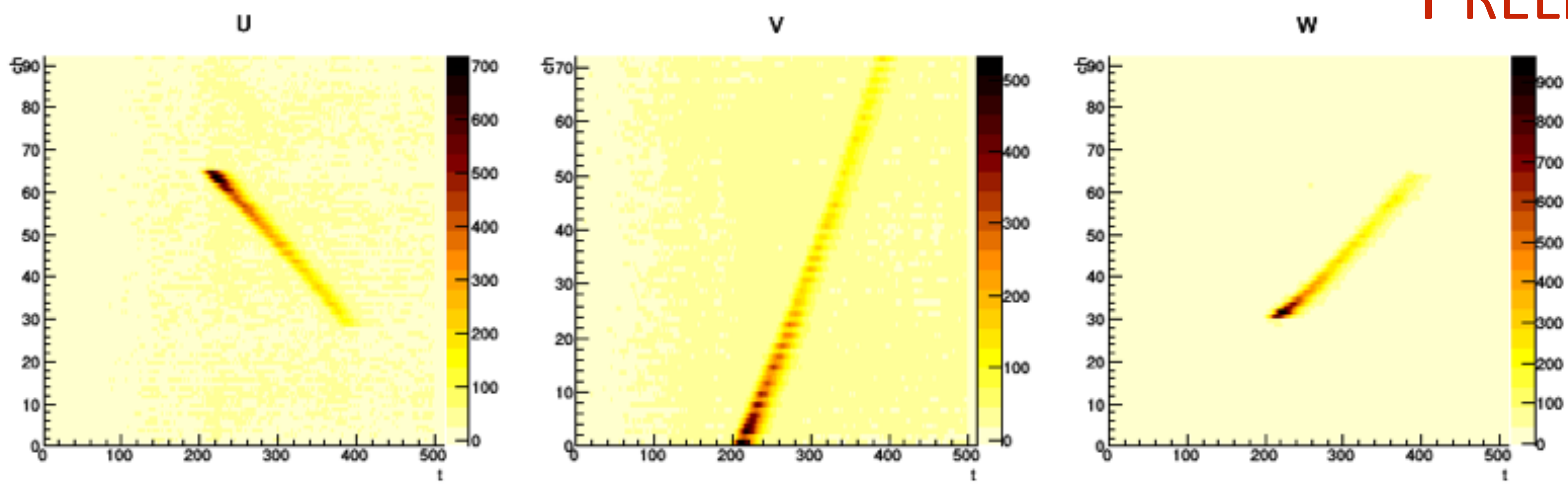


the e-TPC project: proof-of-principle studies

✓ **Demonstrator detector**:

– tests with particle beam (α): reconstruction

PRELIMINARY!



M. Ćwiok and J.-S. Bihałowicz (UW)

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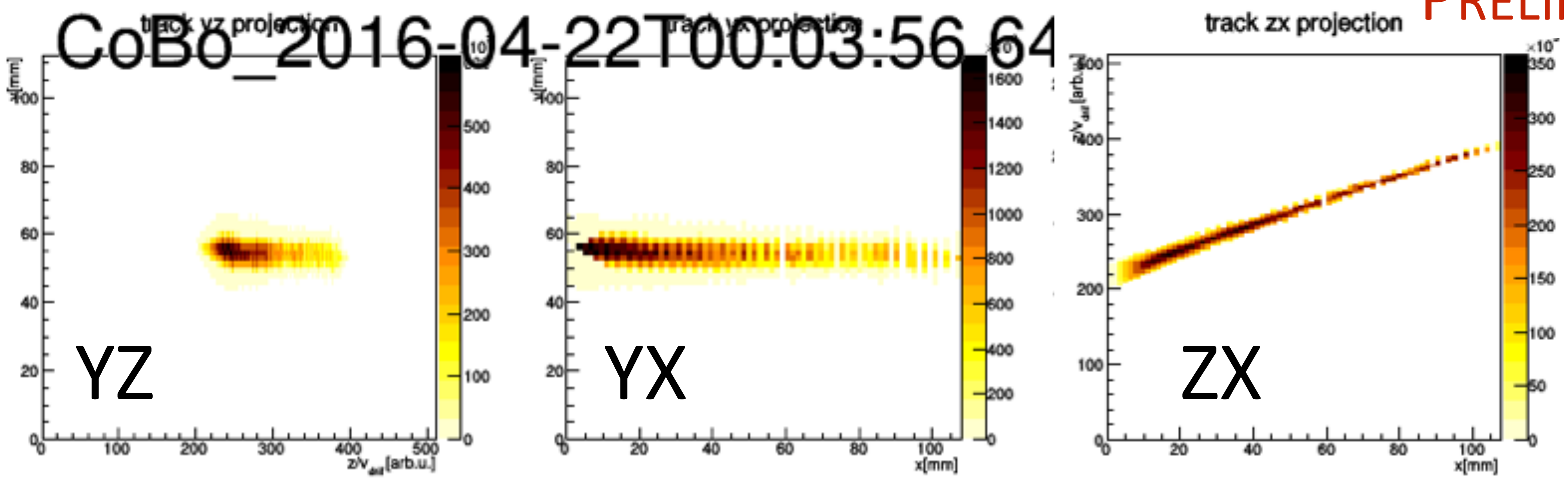

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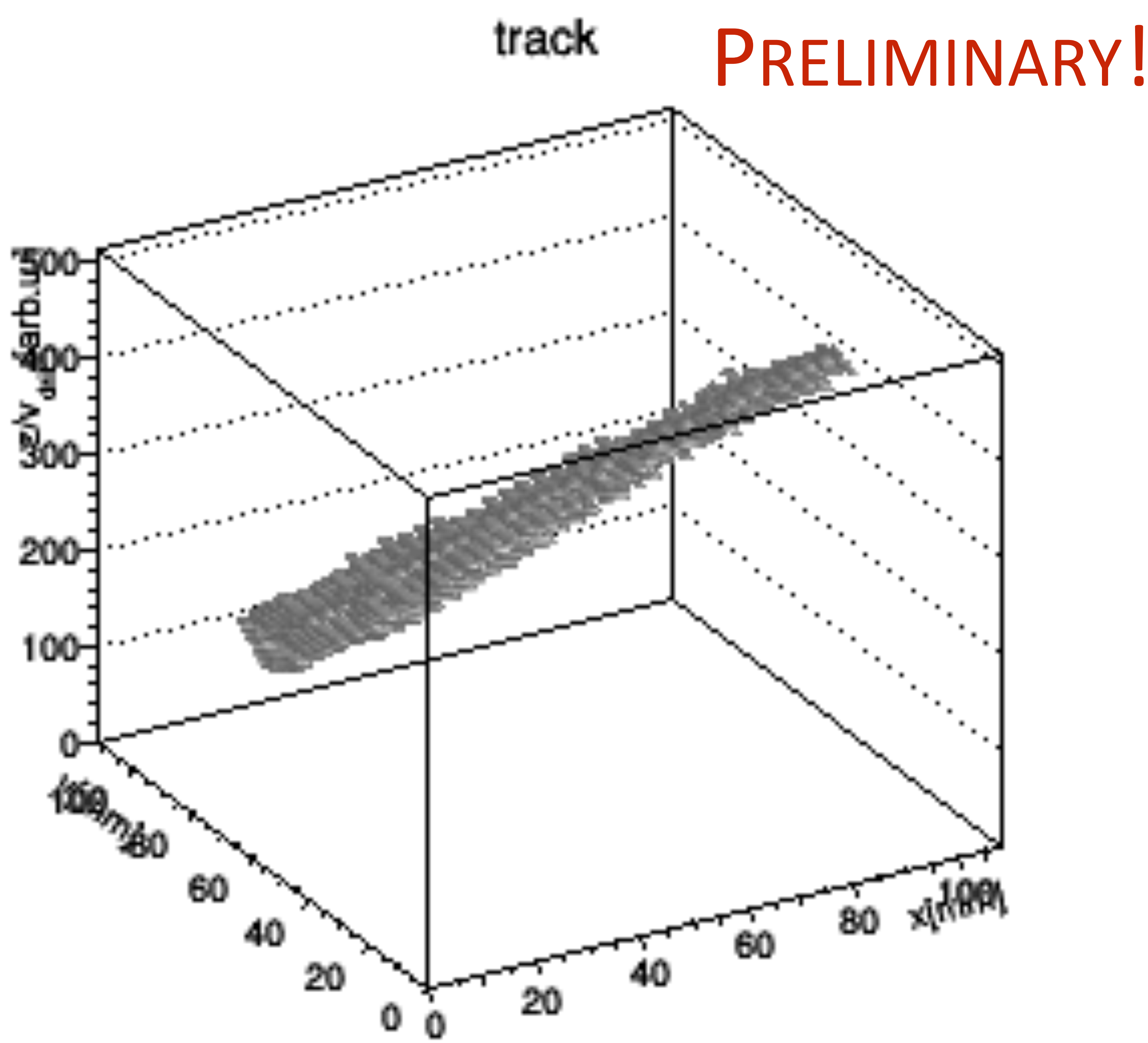

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the e-TPC project: outlook

- ✓ The intense and monochromatic γ-ray beams of the ELI-NP facility will enable the measurement of photo-disintegration cross-sections for nuclear reactions relevant for thermonuclear reaction-rates in stars

- ✓ An active-target TPC detector with electronic strip-readout is being developed to perform these studies

- ✓ R&D is in progress:

  - first tests with a demonstrator detectors showed that unambiguous reconstruction of tracks can be performed

  - Monte Carlo simulations are being performed to study the beam-induced background

- ✓ First tests with low-energy γ-beams at ELI can be performed at the end of 2017

- ✓ First experiments with high-energy γ-beams at ELI in 2018

the e-TPC project: collaboration with France

- ✓ Use / test of GET electronics @ UW since begin of 2015
- ✓ UW is joining GET developers community (CEA/IRFU, CENBG, GANIL, MSU, Padova):
  - natural continuation of GET R&D is GES (= General Electronics Systems), i.e. addressed not only for TPCs, but for more broader users community
  - engineering project is foreseen to last at least for next 2-3 years

the e-TPC project: UW & ELI-NP collaboration

M. Bieda, J.S. Bihałowicz, M. Ćwiok, W. Dominik, Z. Janas, J. Mańczak, T. Matulewicz, C. M., M. Pfützner, M. Zaremba (University of Warsaw)

O. Tesileanu, C. Balan, D. Balabanski, J. Kaur, G. Ciocan, D.G. Ghita, E. Udup (HH-IFIN/ELI-NP)