Nuclear reactions at astrophysical energies with γ-ray beams: a novel experimental approach

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COMEX5, Kraków, September 17th, 2015

Overview

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

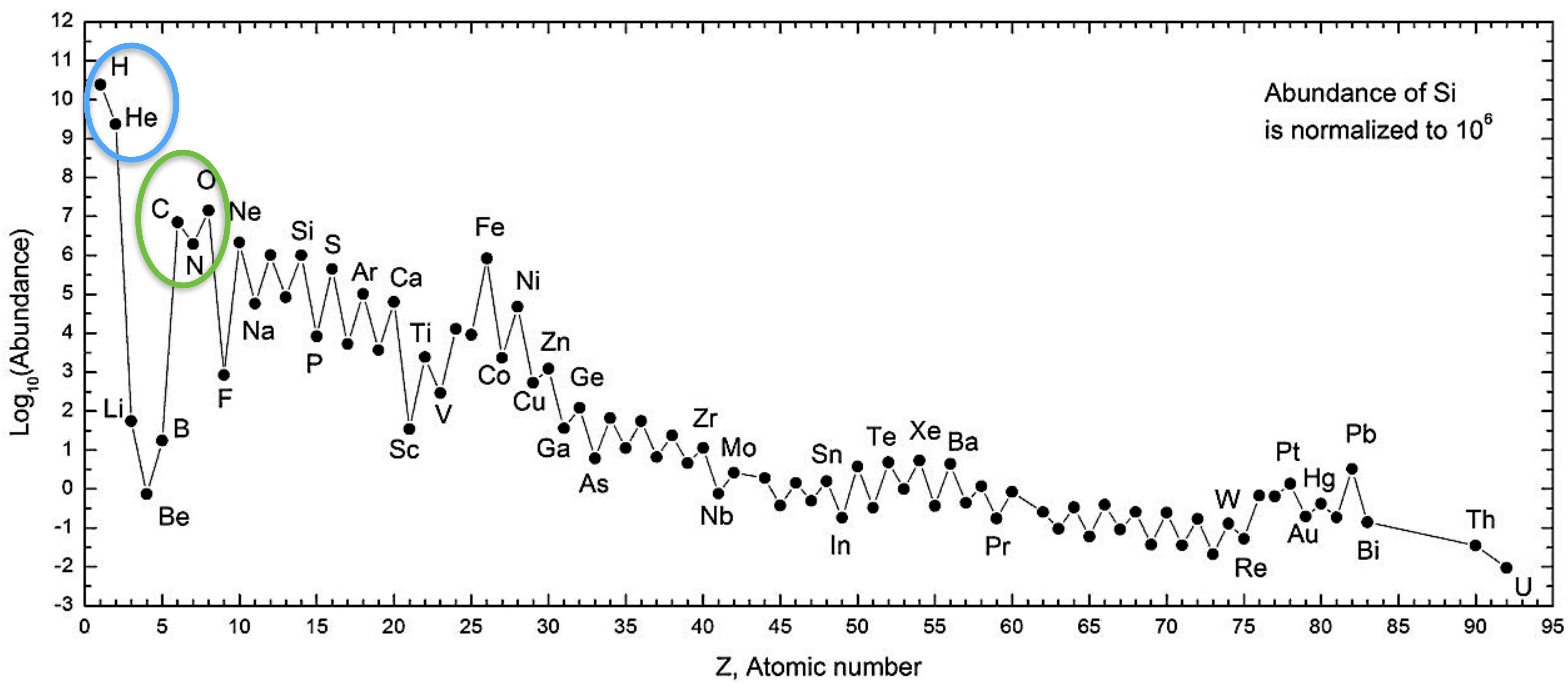
Physics motivations: nucleosynthesis

✓ Abundance of the elements in the Universe

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

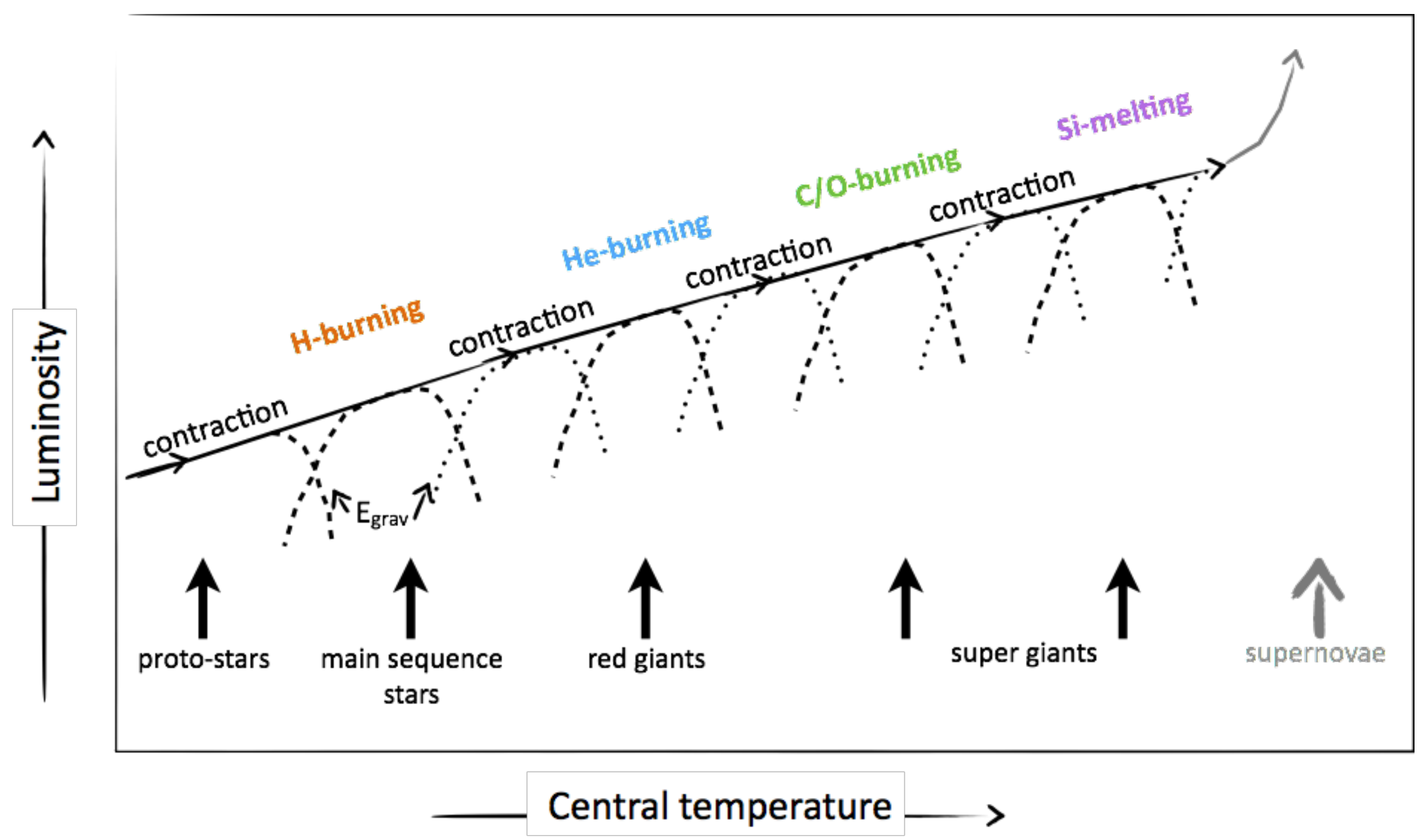
✓ Abundance of elements in the human body:

- 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

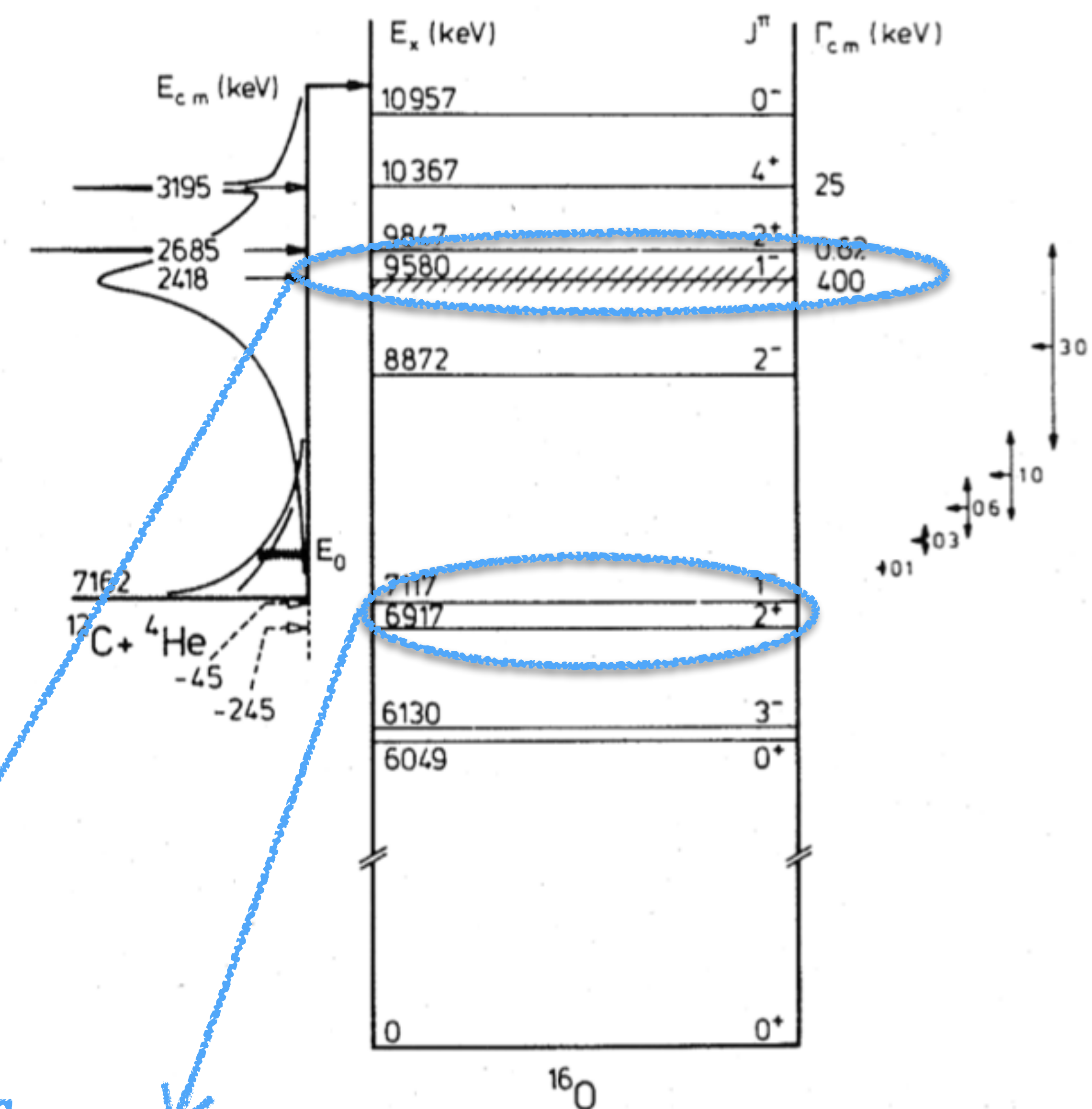
- ✓ Carbon is the 4^{th} most abundant element in the universe, after H, He and O
- ✓ ^{12}C is created in the triple-α process or $3\alpha \rightarrow {}^{12}C$
- ✓ Carbon/Oxygen ratio = 0.6
- ✓ Assumption: nuclidic material is synthesised mostly during the major quiescent burning phase of stellar evolution
  - 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

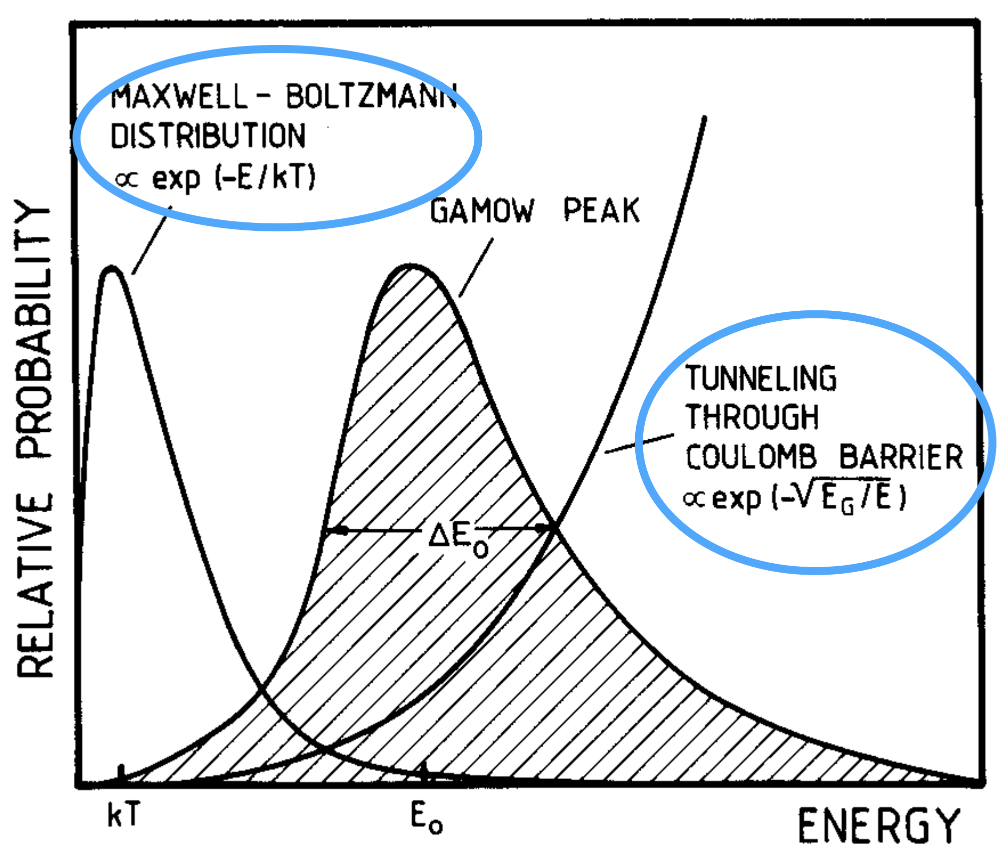
Physics motivations: He-burning and the reverse photo-disintegration reactions

✓ 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: $B(b,\gamma)\mathrm{A} \rightleftharpoons \mathrm{A}(\gamma,b)B$

- ✓ Principle of detailed balance in nuclear reactions:

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

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

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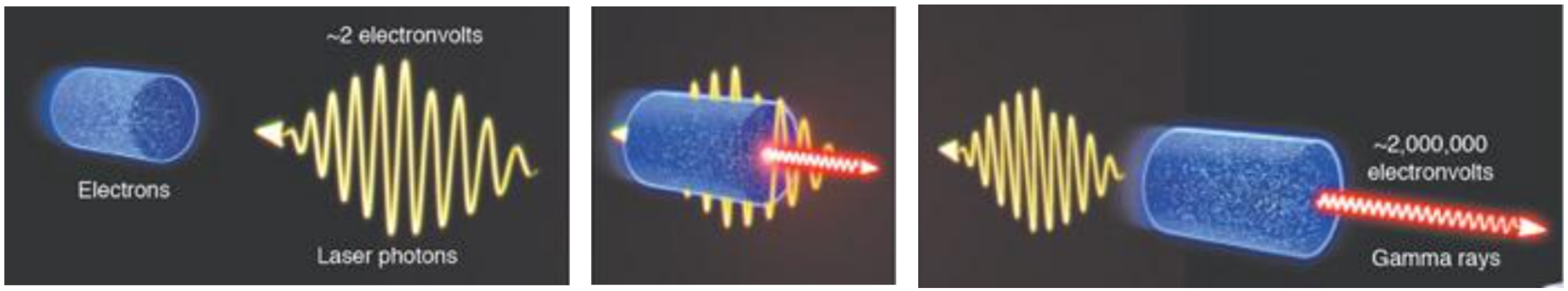
⇒ measure the cross section for the α-capture reaction by means of the inverse photo-disintegration reaction

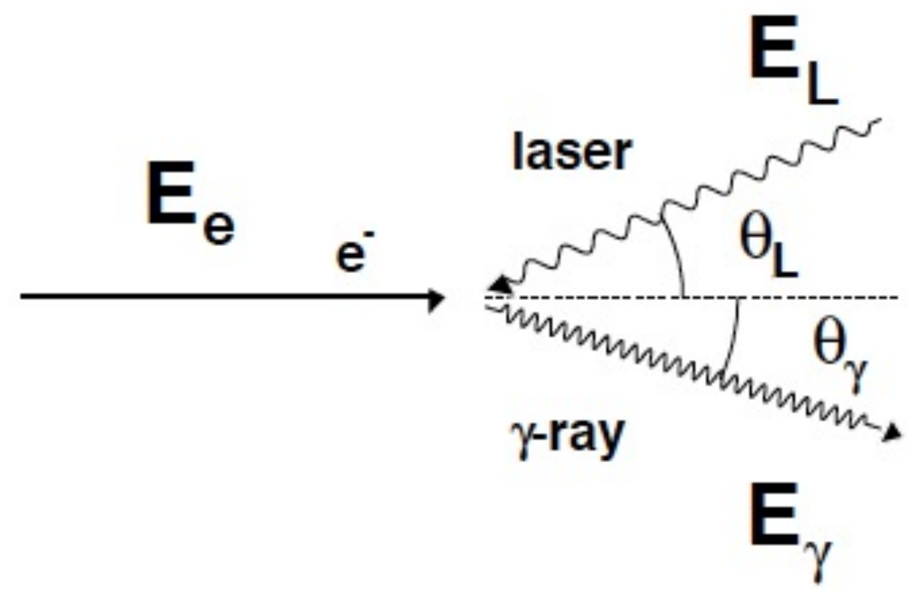
⇒ intense monochromatic γ-ray beams are needed

The ELI-NP facility

See Talk by Calin Ur, Friday 18th

- ✓ 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*)





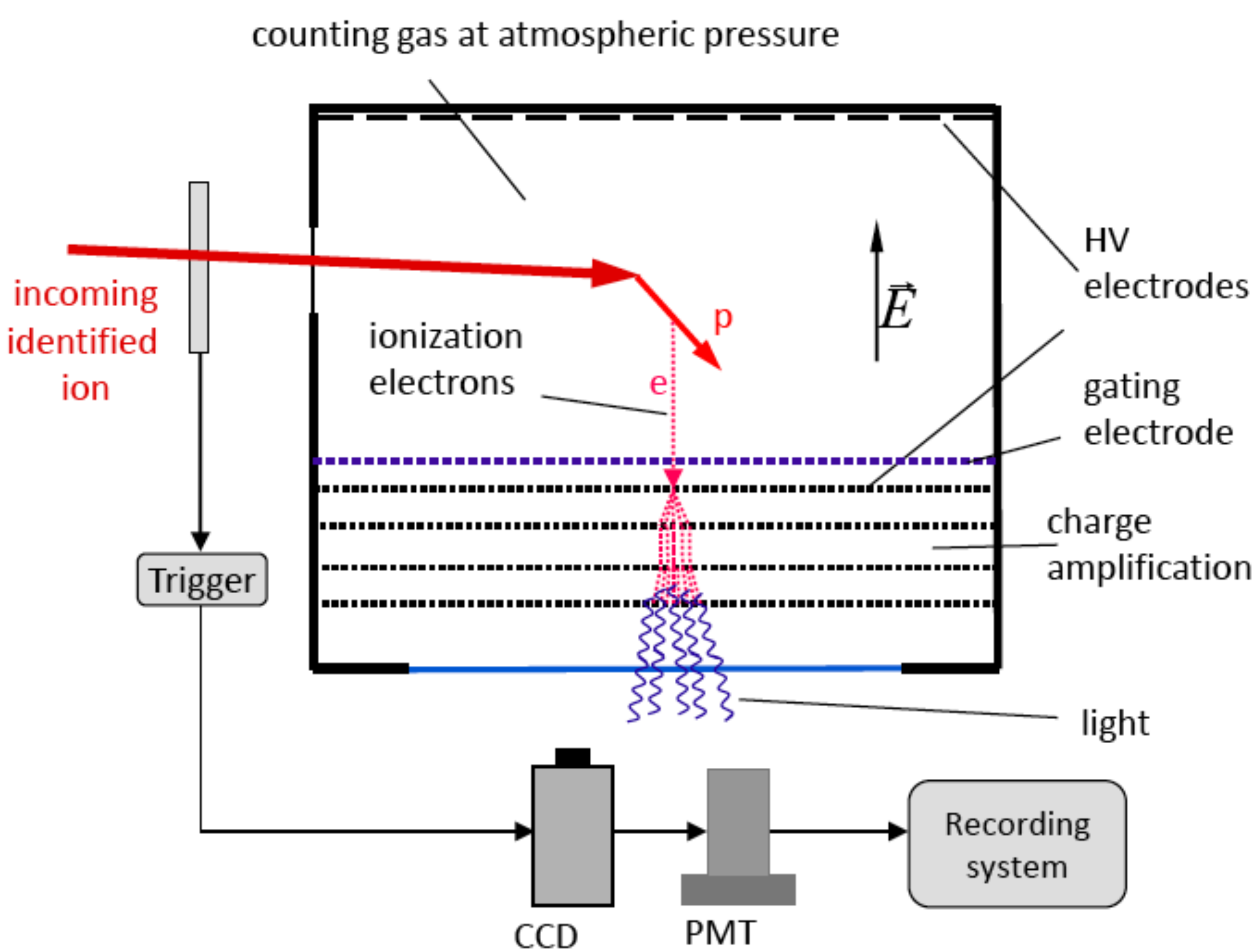
$$E_\gamma = 2\gamma_e^2 \cdot \frac{1+\cos\theta_L}{1+\left(\gamma_e\theta_\gamma\right)^2+\frac{4\gamma_e E_L}{mc^2}} \cdot E_L \approx 4\gamma_e^2 E_L$$

$\theta_L \ll 1$

the inspiration

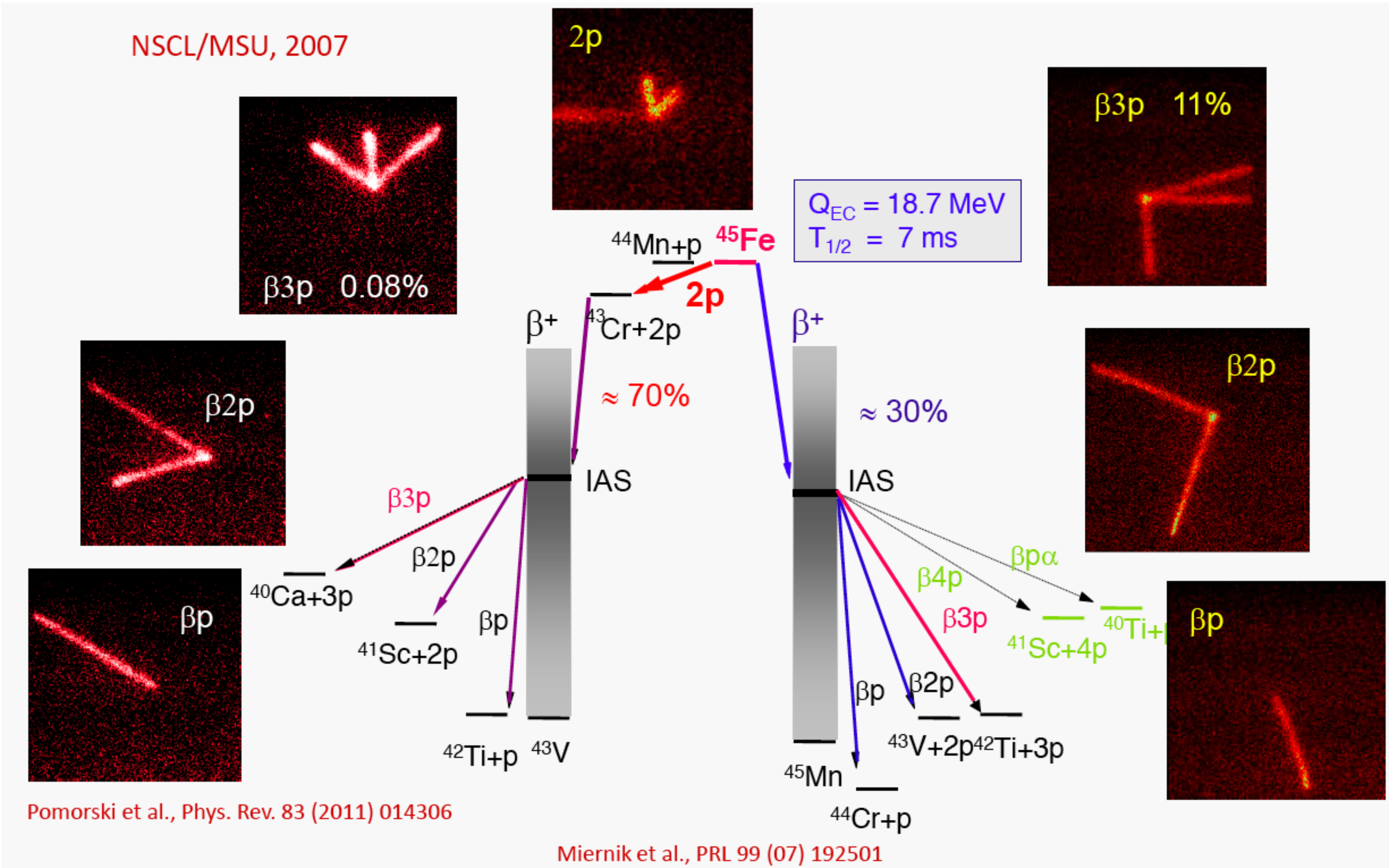
✓ OTPCs with GEMs (FUW): Optical-readout TPC with active areas of 20 x 20 and 35 x 20 cm^2

- developed for studying 2-proton radioactivity of exotic nuclei
- employed at NSCL, GSI, ISOLDE, Dubna



the inspiration

- ✓ OTPCs with GEMs (FUW): decays of ^{45}Fe and ^{43}Cr (NSCL/MSU, 2007)



the e-TPC project

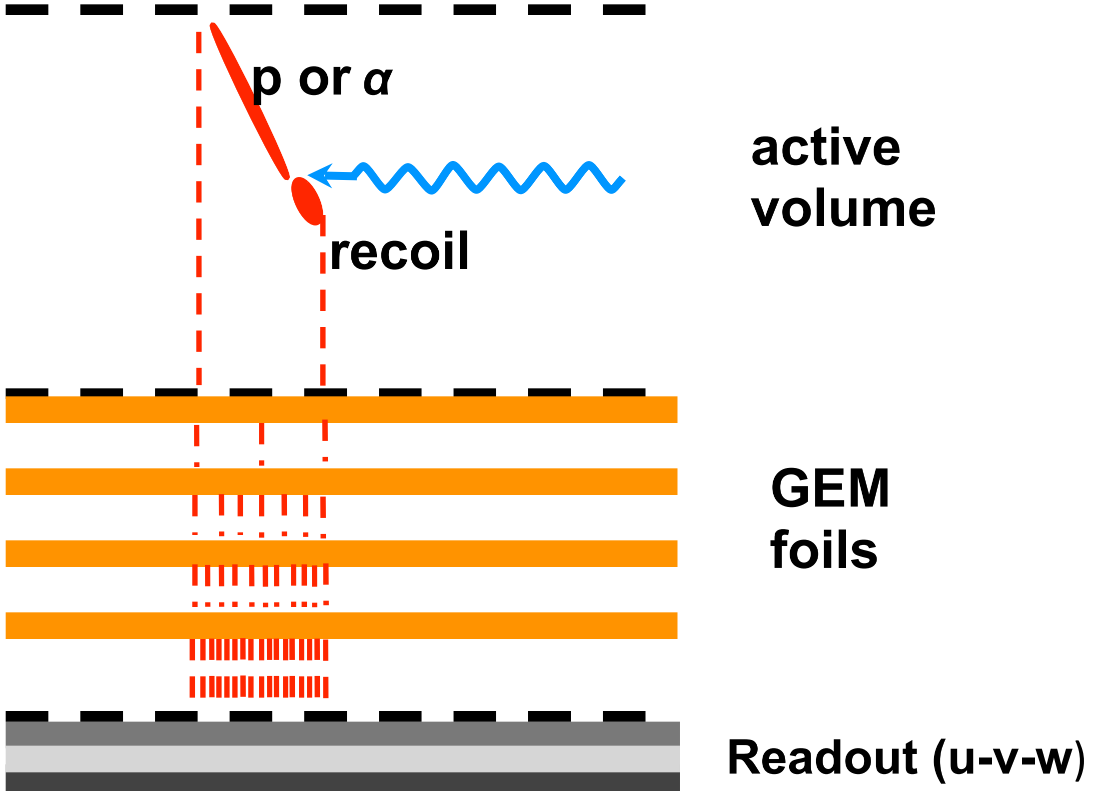
✓ **Next generation**:

- an active-target TPC (e-TPC) to study reaction cross-sections of astrophysical interest where the reaction products are charged particles

- electronic readout:

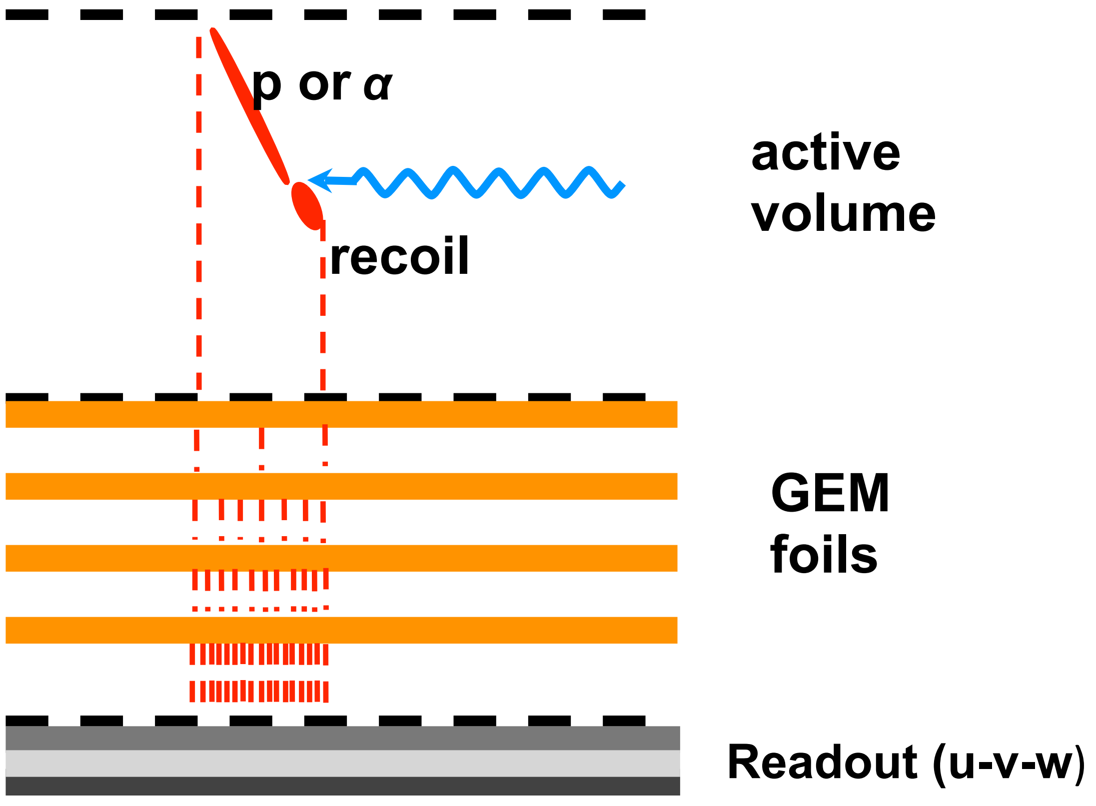
  —> full unambiguous reconstruction of multiple-particle events is possible

  —> more gas mixtures can be uses:
  no need to have gases emitting photons in the visible (pure CO_2 can be used!!)

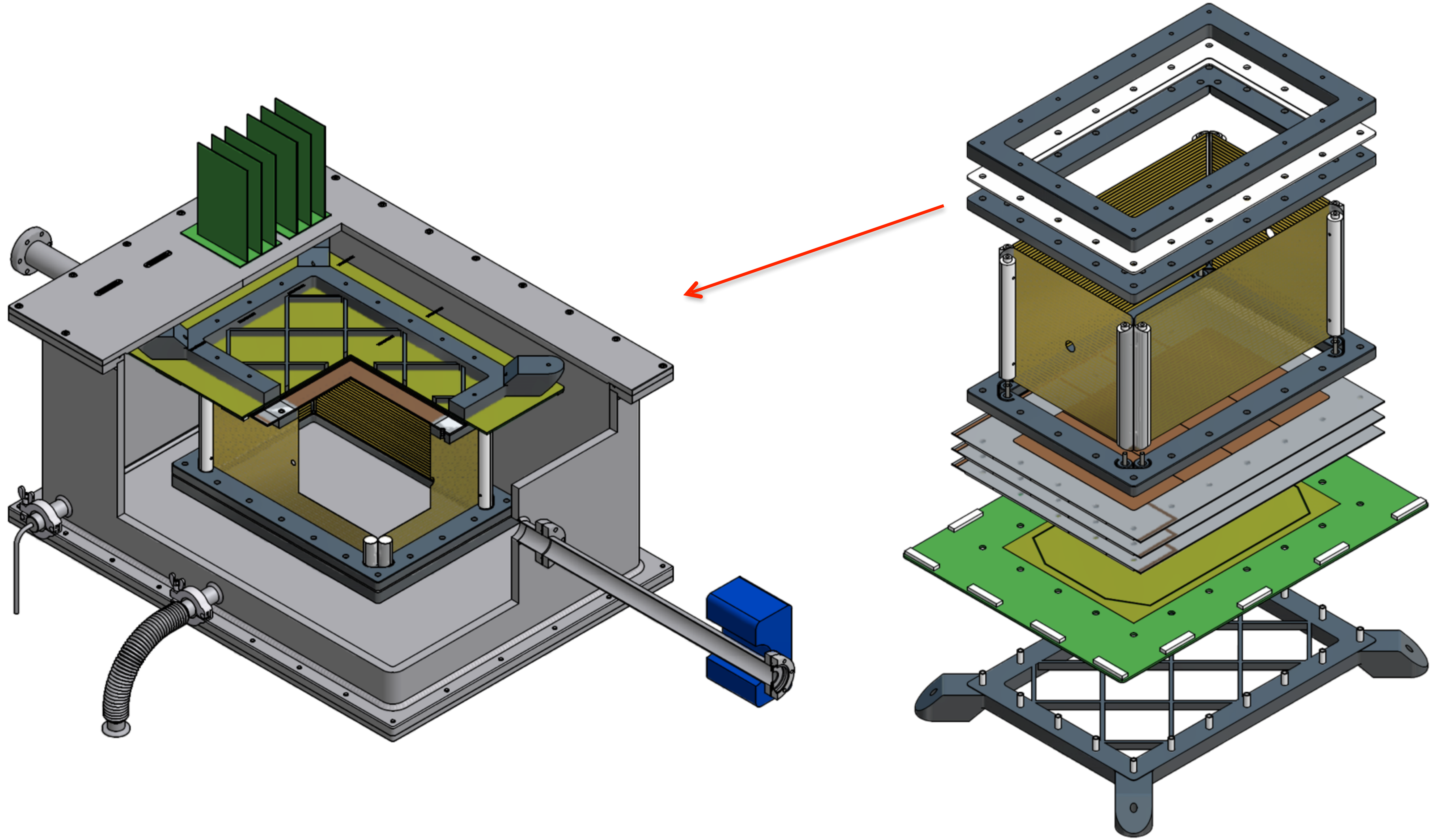


the e-TPC project

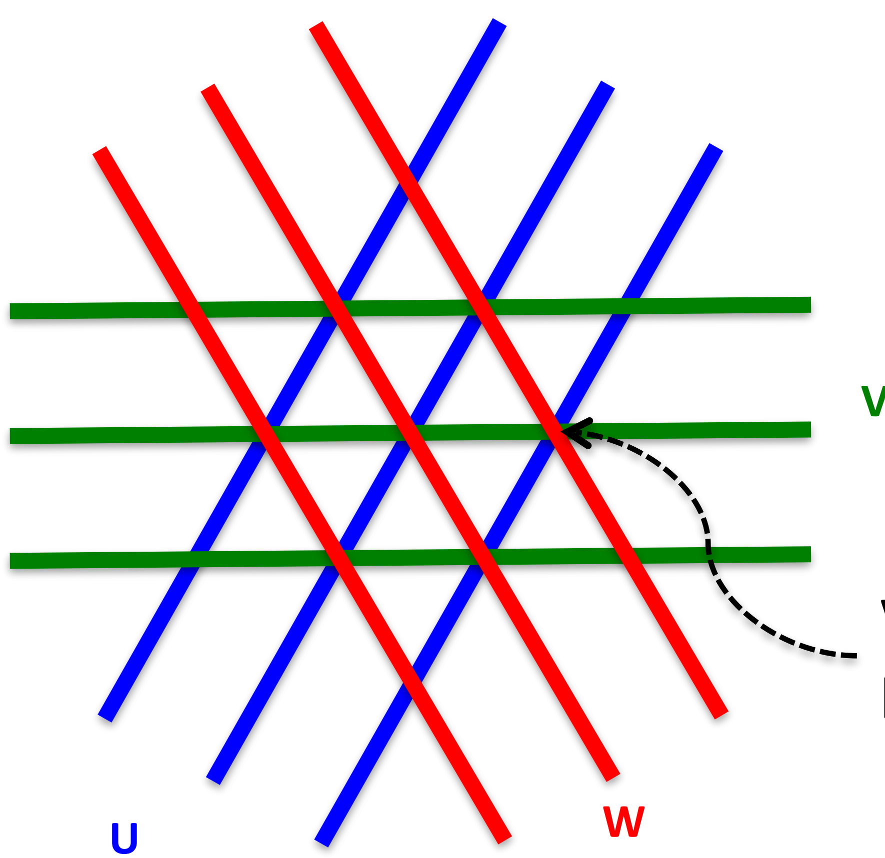
- ✓ **Active target**:
  - active volume: 35 cm x 20 cm x 20 cm
  - under-pressured (~100 mbar): low-energy particles!
  - gas-mixture tailored for the reaction of interest
- ✓ **Charge-amplification**:
  - 3 or 4 GEM structures
- ✓ **Electronic read-out**:
  - 3 independent linear sets of strips crossing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



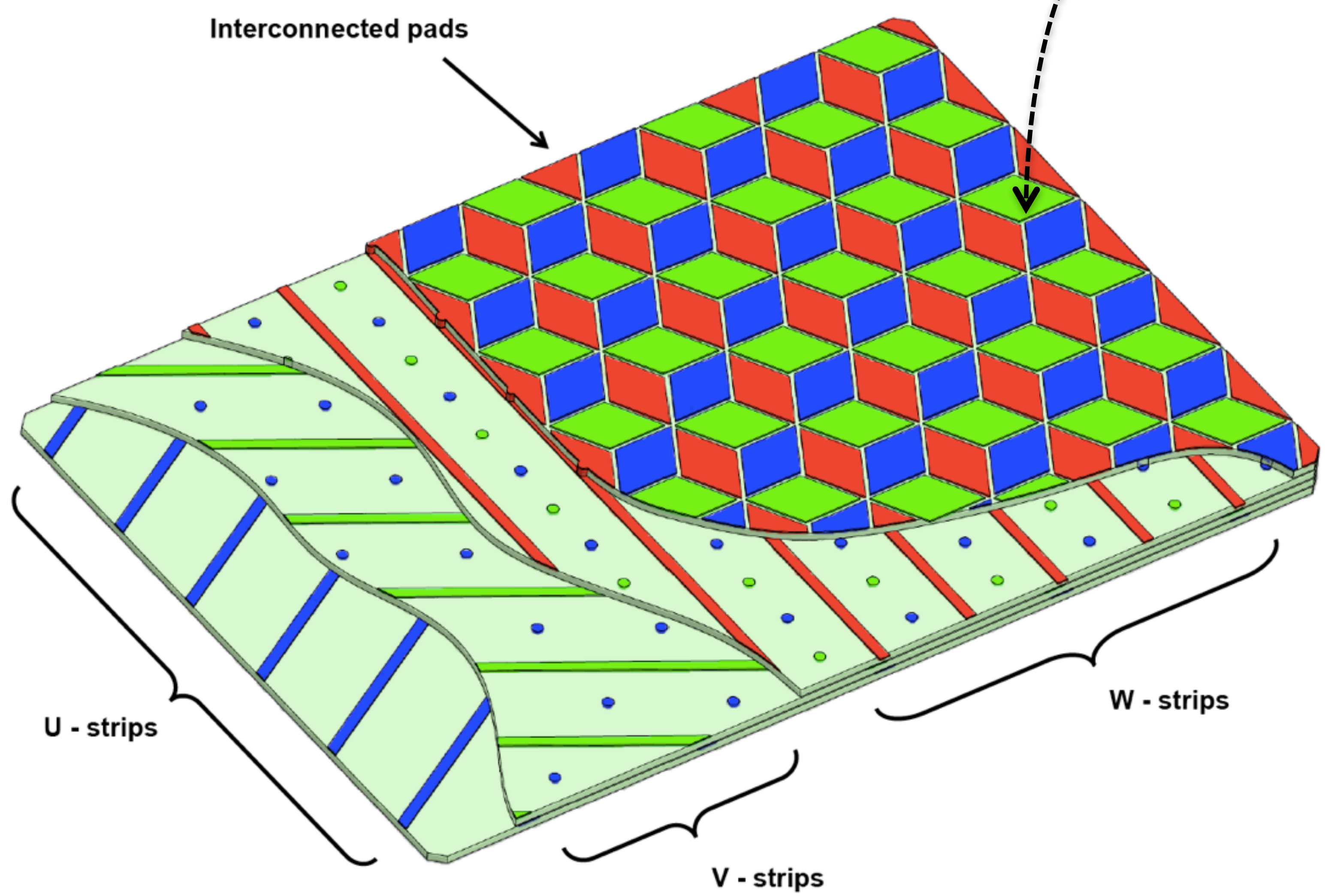
the e-TPC project: cross-section



the e-TPC project: read-out electrode

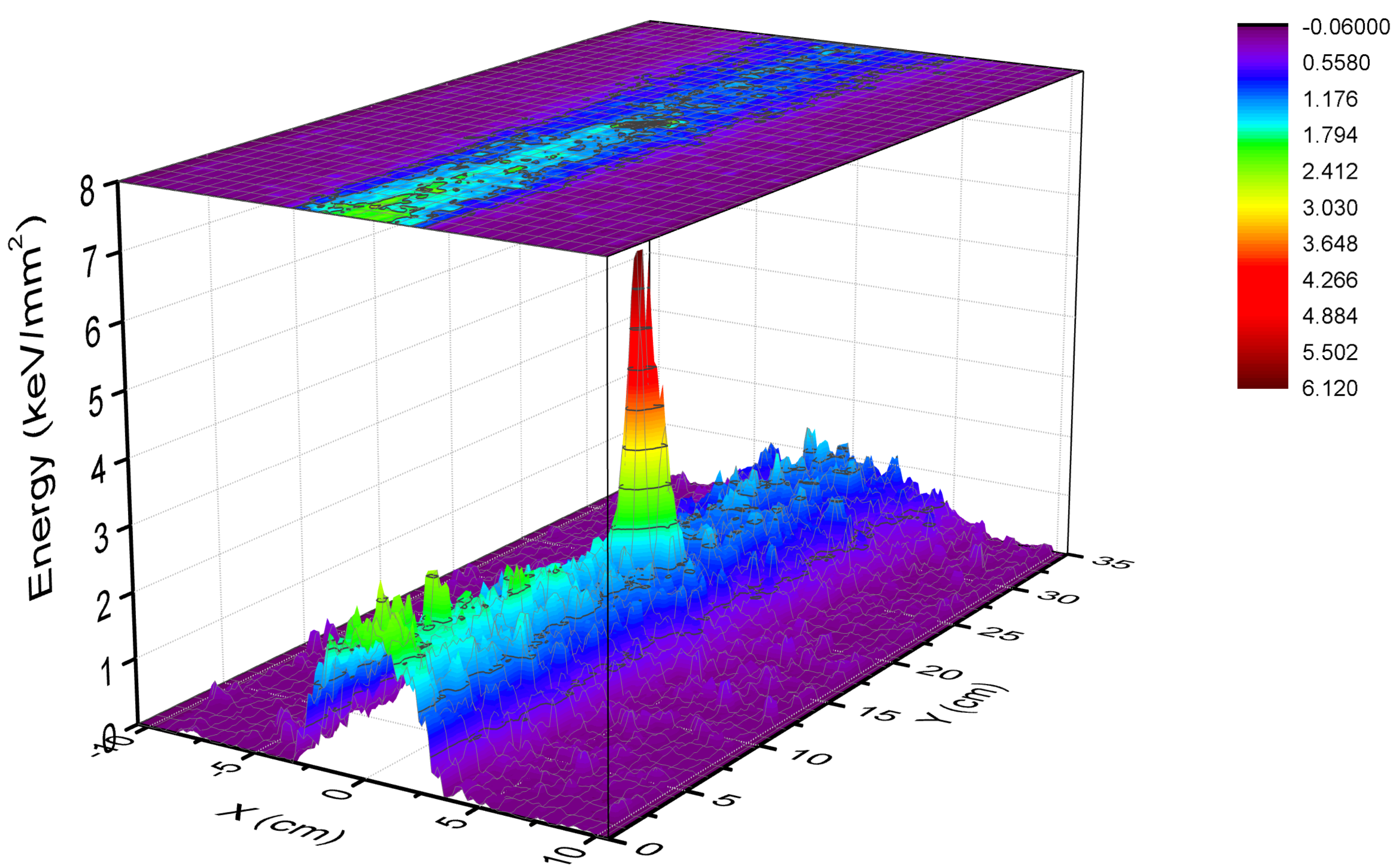


multilayer printed circuit



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)

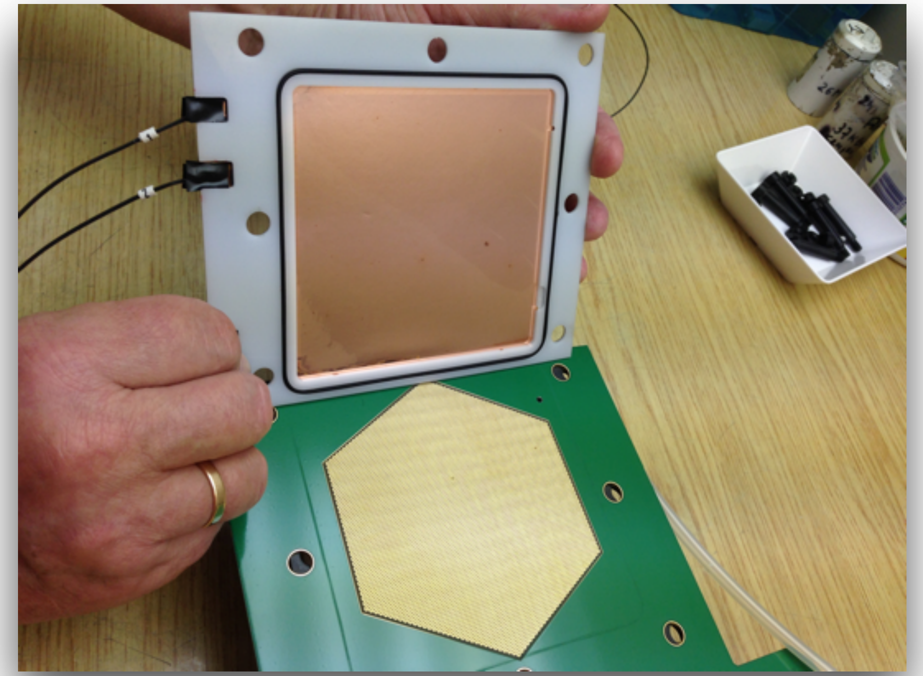


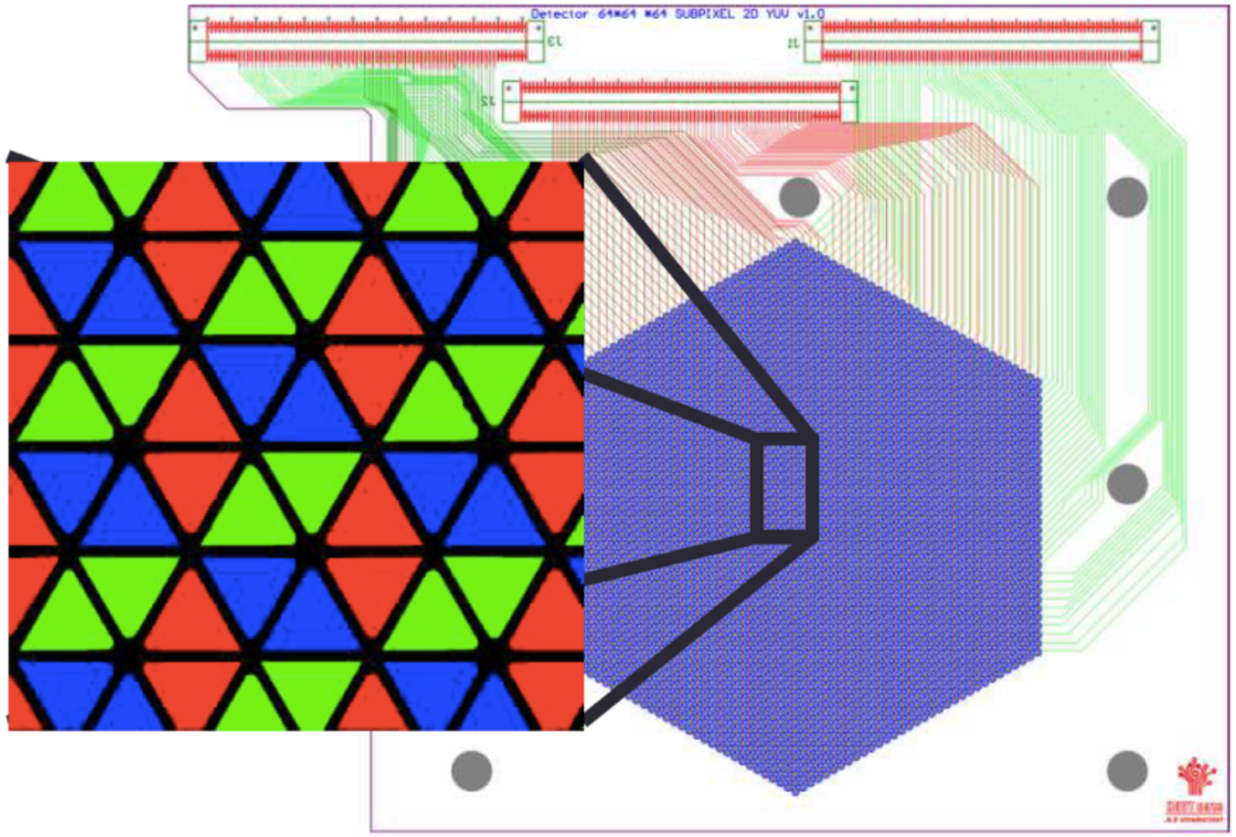
Charged Particle Detection at ELI–NP, Technical Design Report, RA4 – TDR 4, 2015

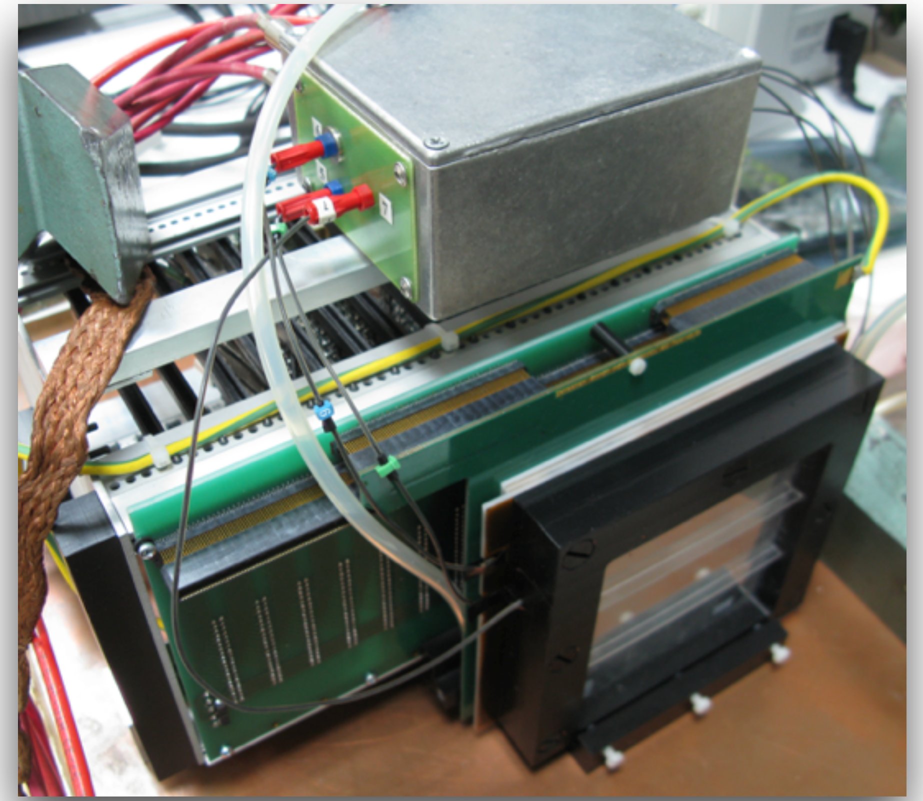
the e-TPC project: proof-of-principle studies

✓ **Demonstrator detector**:

- active volume: 10 cm x 10 cm x 3 cm
- u-v-w strip read-out: 192 channels (3x64)
- 3 GEM foils
- gas: 70% Ar + 30% CO_2 @ 1 atm



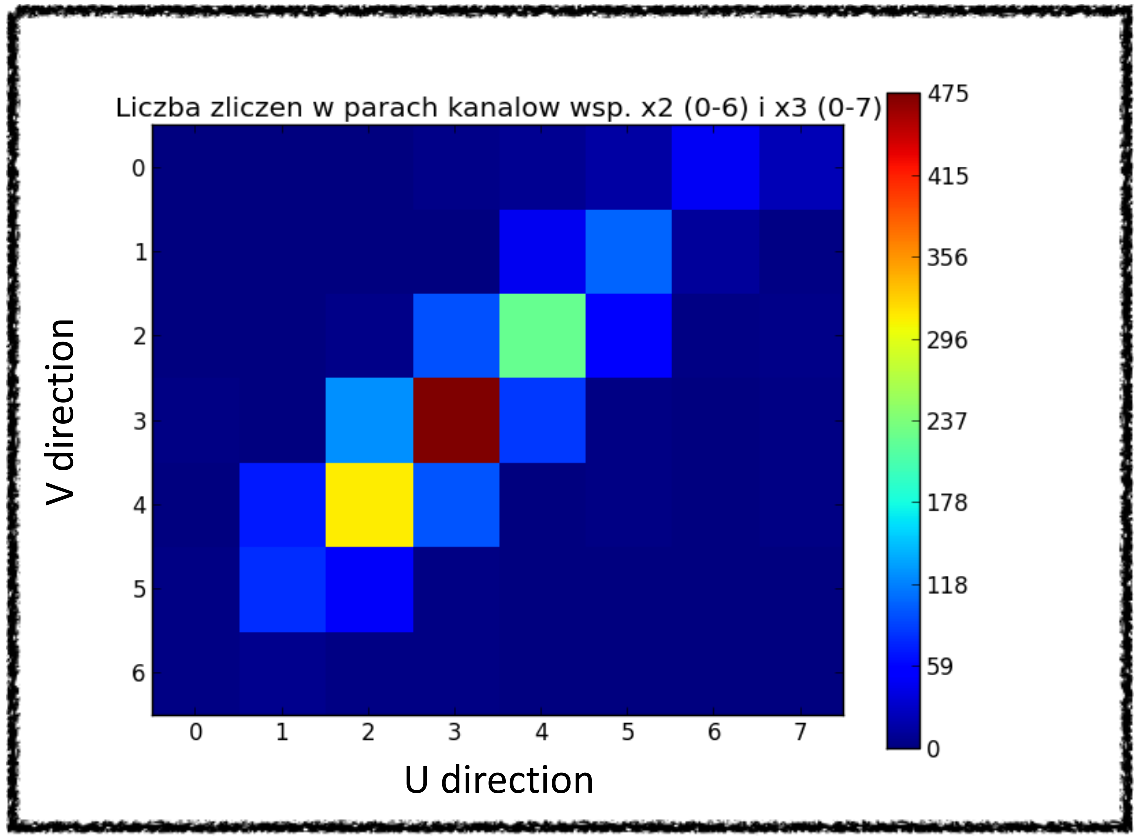


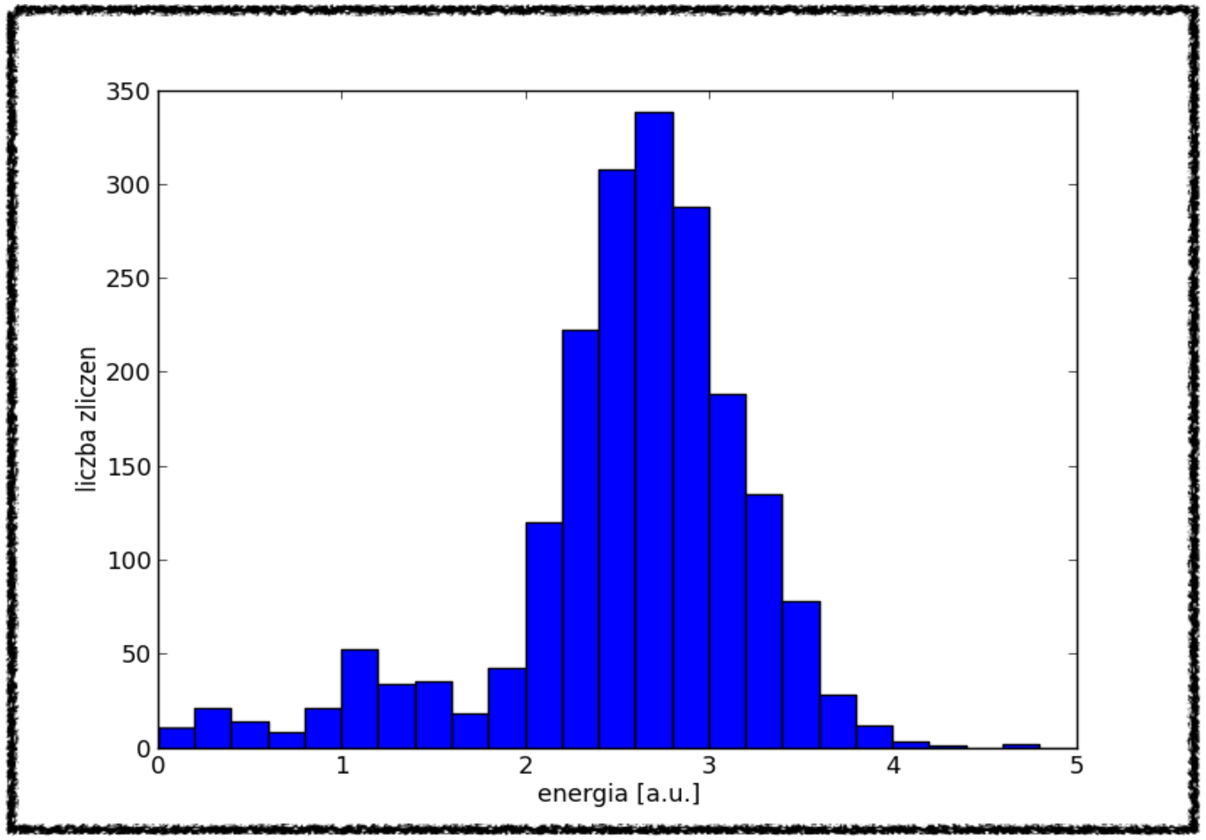


the e-TPC project: proof-of-principle studies

✓ **Demonstrator detector**:

- tested first with 2-GEM configuration
- 16 read-out channels (oscilloscopes), point-like ^{55}Fe X-ray source





Aleksandra Lis (Univ. of Warsaw, 2013)

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

✓ **Demonstrator detector**:

- detection of α-particle tracks (5.5 MeV from ^{222}Rn decay)

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

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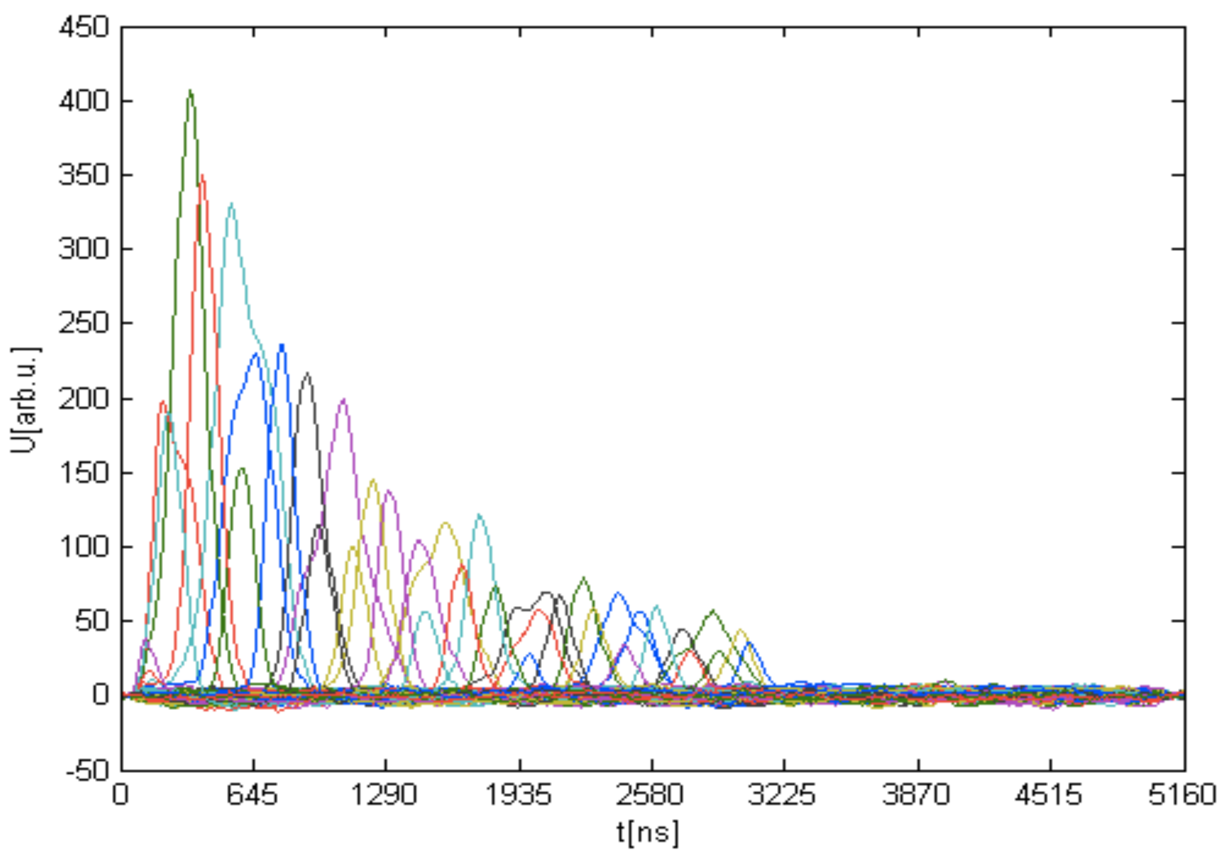
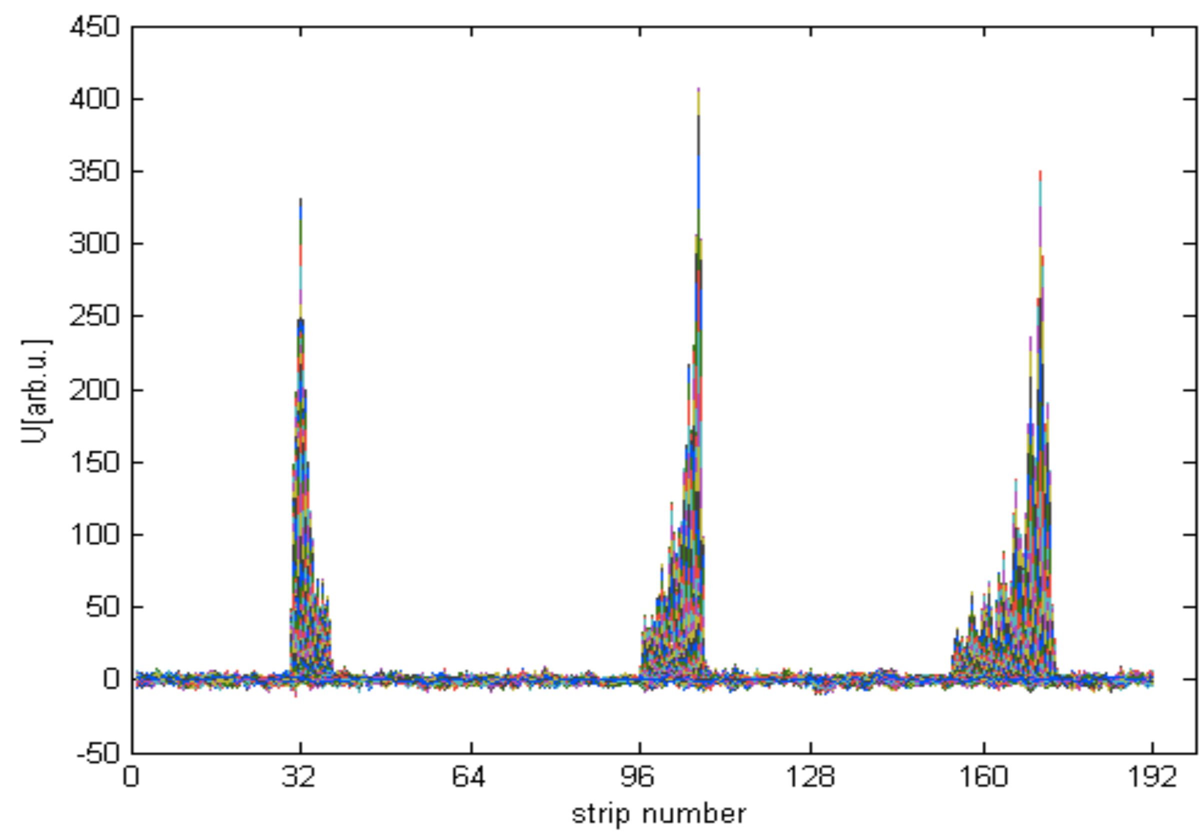
- detection of α-particle tracks (5.5 MeV from ^{222}Rn decay)
- **step 1: raw data**

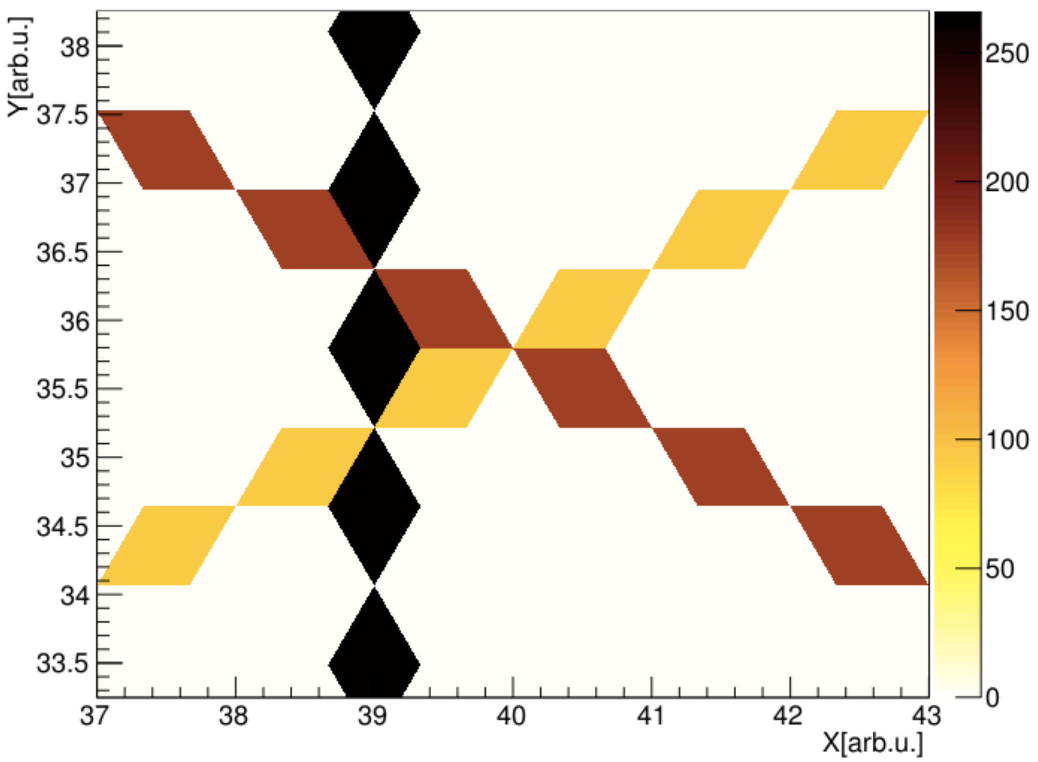


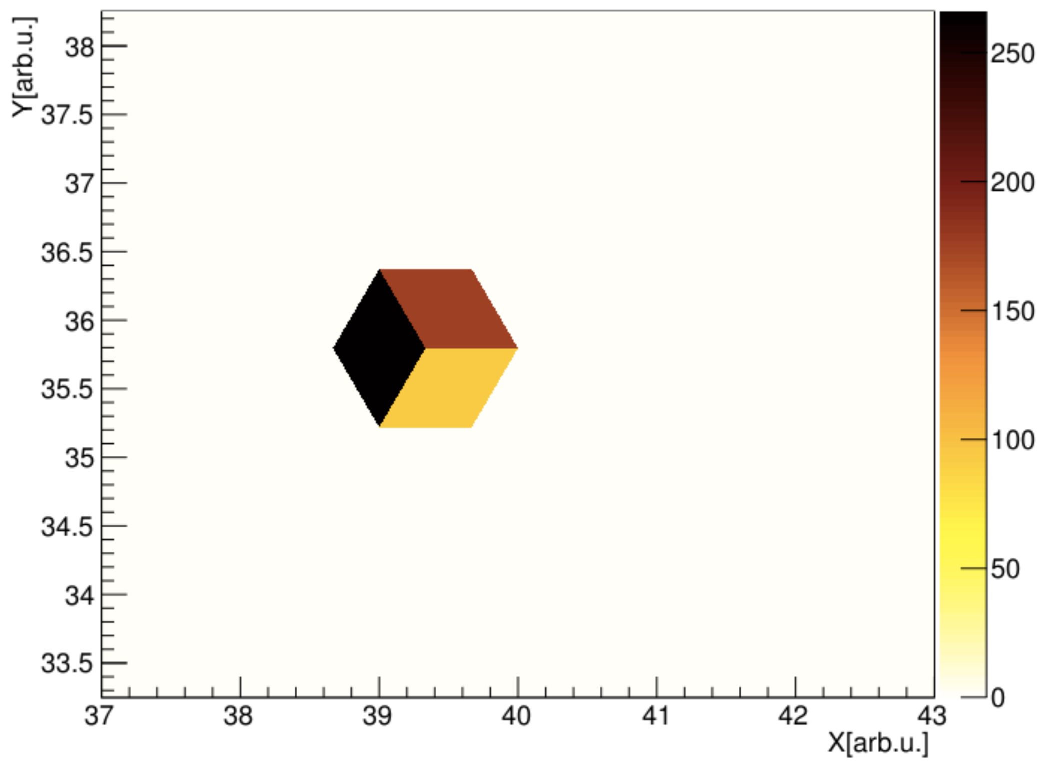


Jan S. Bihałowicz, Bsc Thesis (UW, 2014)

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

- ✓ **Demonstrator detector**:
  - detection of α-particle tracks (5.5 MeV from ^{222}Rn decay)
  - **step 2: clusterization**





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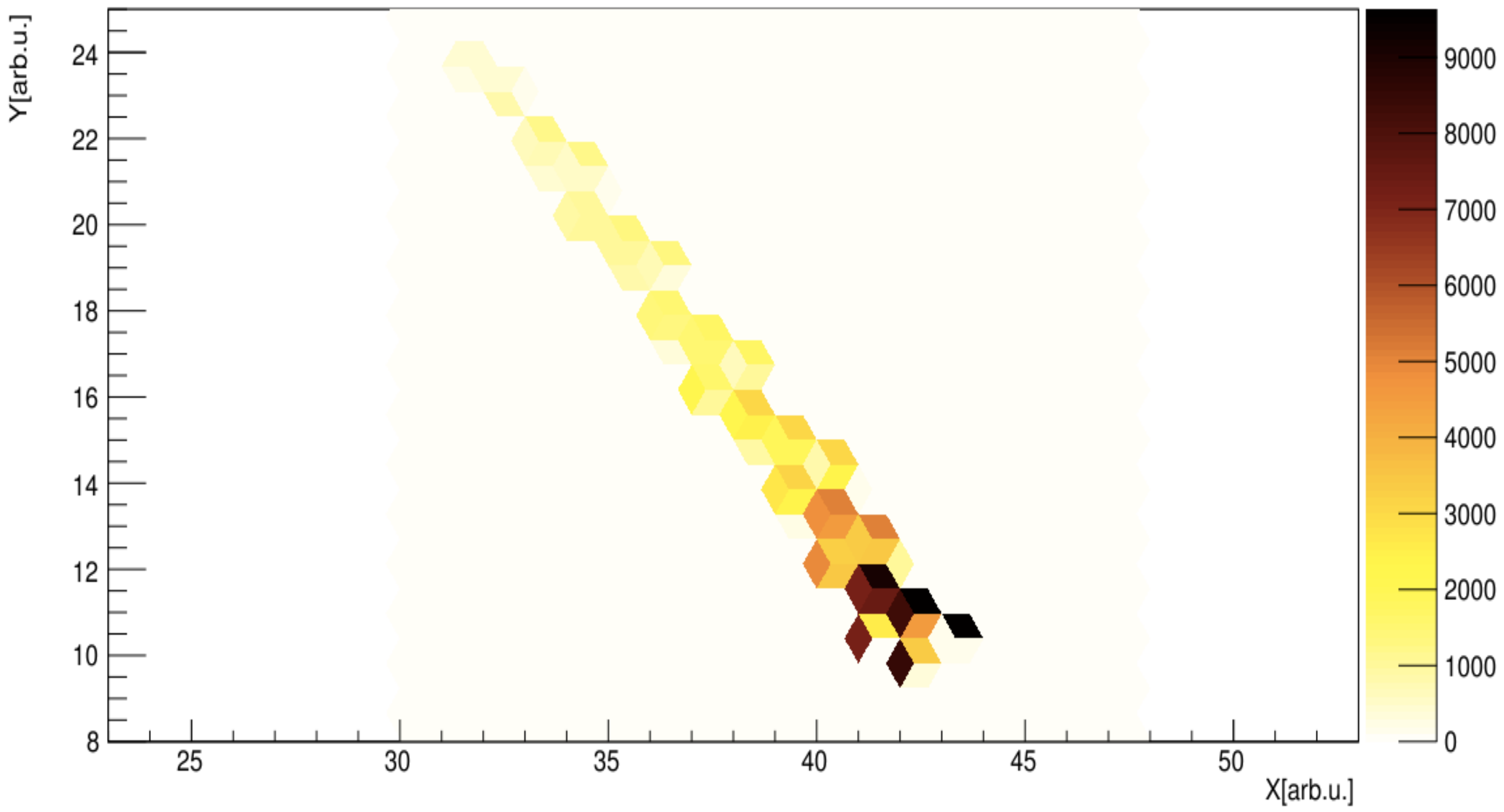
the e-TPC project: proof-of-principle studies

✓ **Demonstrator detector**:

- detection of α-particle tracks (5.5 MeV from ^{222}Rn decay)
- **step 3: reconstruction in 2D…**



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

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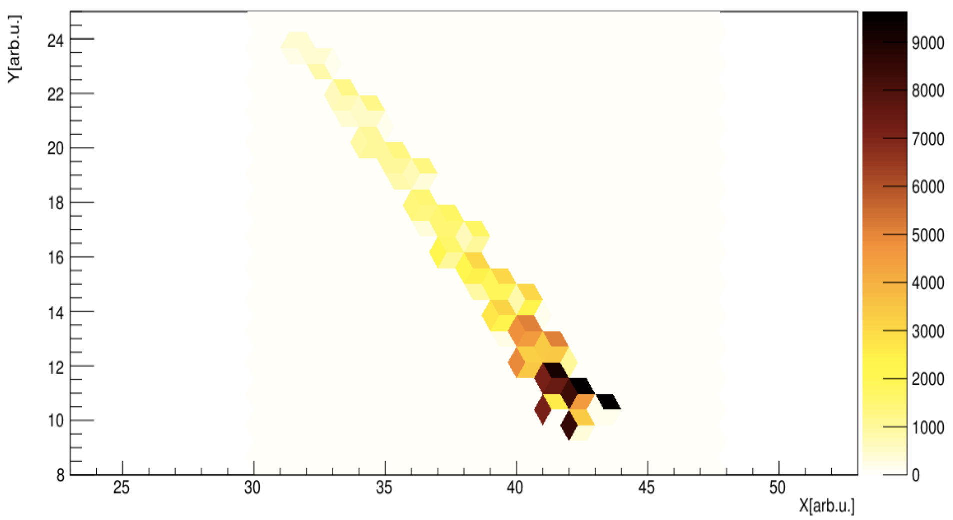
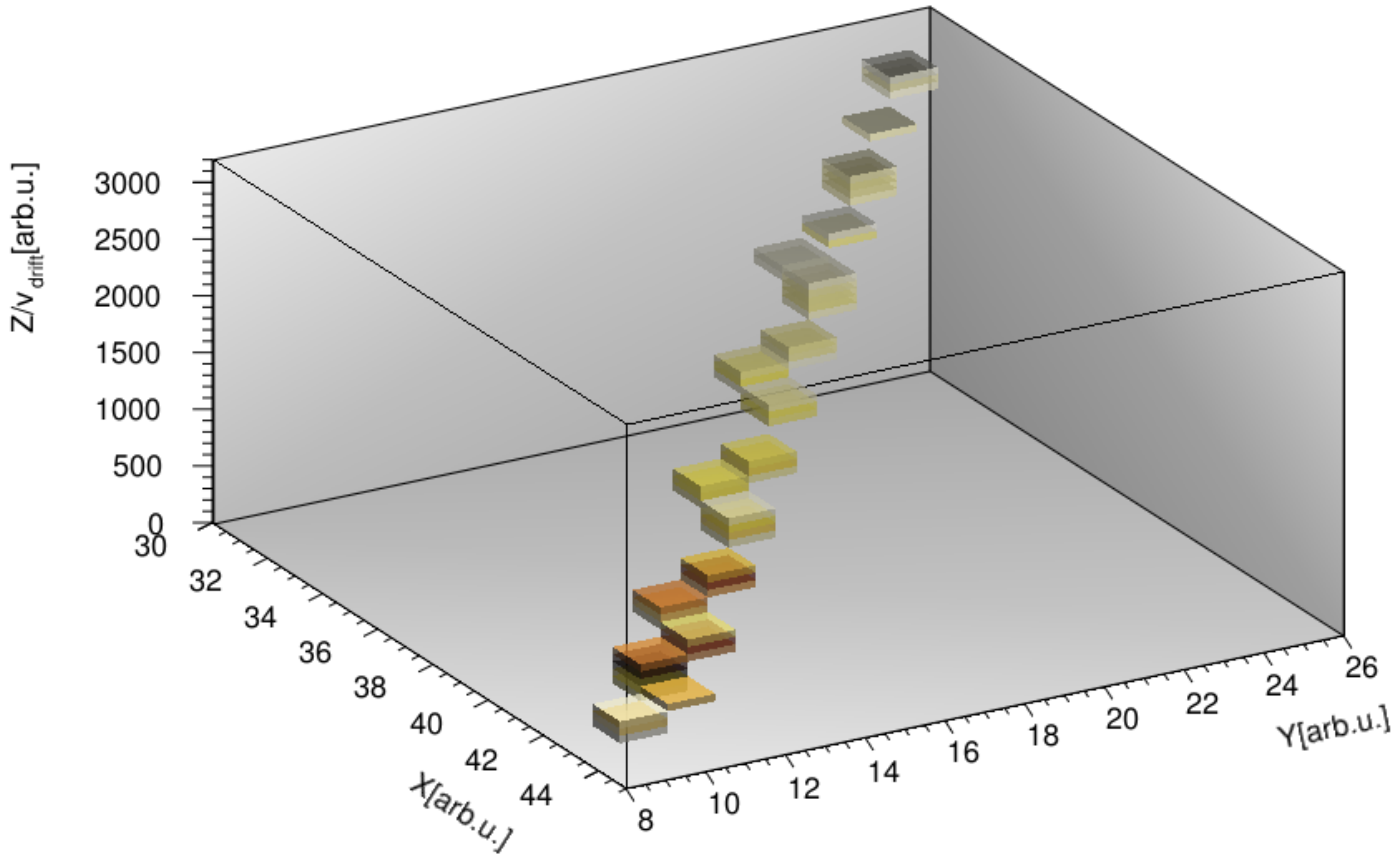
- **step 3: …and in 3D…**





Jan S. Bihałowicz, Bsc Thesis (UW, 2014)

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 at the University of Warsaw (in collaboration with ELI-NP and University of Connecticut) to perform these studies

- ✓ R&D is in progress:

  - first tests with a model 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 collaboration

FUW

J.S. Bihałowicz, M. Ćwiok, W. Dominik, Z. Janas, T. Matulewicz, C. M., K. Mikszuta, M. Pfützner

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Ovidiu Tesileanu

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M. Gai