# Badanie reakcji jądrowych o znaczeniu astrofizycznym z wiązką fotonów gamma

(Nuclear reactions of astrophysical interest with gamma-ray beams)

UW
Dwa stulecia
Dobry początek

Uniwersytet Warszawski


**Mikołaj Ćwiok**
Uniwersytet Warszawski


*Eksperyment **ELITPC**: UW, ELI-NP / IFIN-HH, Univ. of Connecticut*

Uniwersytecki Ośrodek Transferu Technologii

**ELI - Extreme Light Infrastructure Seminar**
Relativistic Optics and Nuclear Photonics

Wydział Fizyki, Uniwersytet Warszawski – 7 listopada 2016

# Nuclear reactions of astrophysical interest with gamma-ray beams

(Badanie reakcji jądrowych o znaczeniu astrofizycznym z wiązką fotonów gamma)

UW Two centuries Good beginning


**Mikołaj Ćwiok**

University of Warsaw

*for the **ELITPC** Collaboration:*

*UW, ELI-NP / IFIN-HH, Univ. of Connecticut*

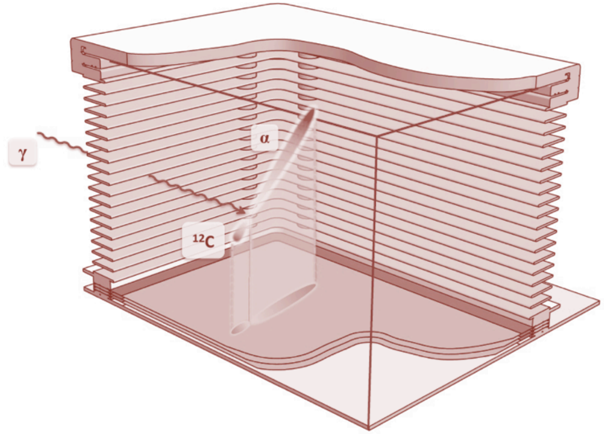

**ELI - Extreme Light Infrastructure Seminar**

Relativistic Optics and Nuclear Photonics

Faculty of Physics, University of Warsaw – November 7$^{th}$, 2016

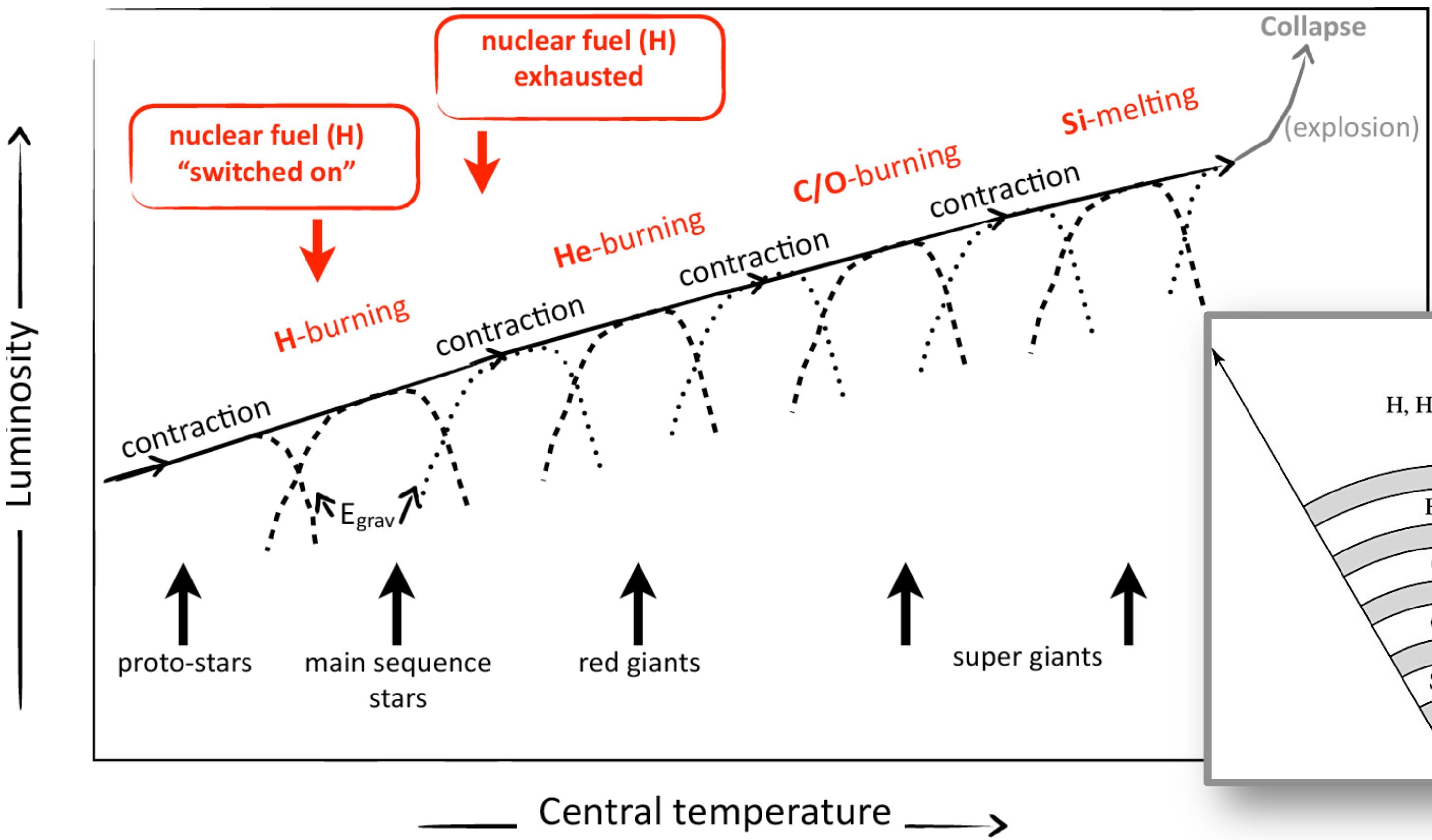
# Outline

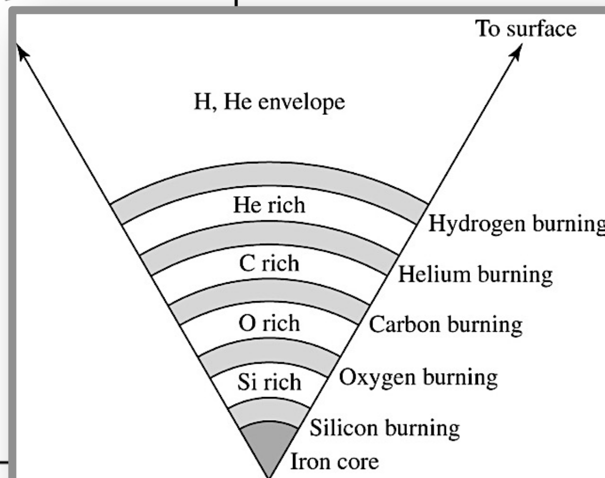
1. Physics motivation
2. Concept of ELITPC (ELI-NP Time Projection Chamber)
3. Status of R&D
4. Summary & outlooks



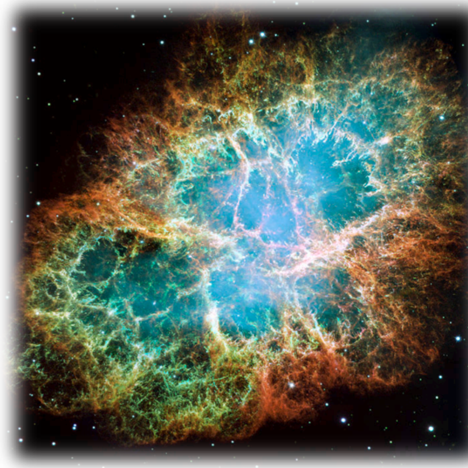
# Stellar Nucleosynthesis

- **H** - burning: **p-p** & **CNO** cycles, Hot-CNO, Ne-Na, Mg-Al → synthesis of **He**
- **He** - burning: $3\alpha \rightarrow {}^{12}C$, ${}^{12}C(\alpha, \gamma){}^{16}O$, ... → synthesis of: **C, O, Ne**
- Subsequent burning of: **C, O, Ne, Si** → synthesis of elements with **16 ≤ A ≤ 60**
- ***s*, *r*, *p*** - processes → synthesis of elements with **A ≥ 60**



# Carbon / Oxygen Ratio



*Crab Nebula - HST/NASA*

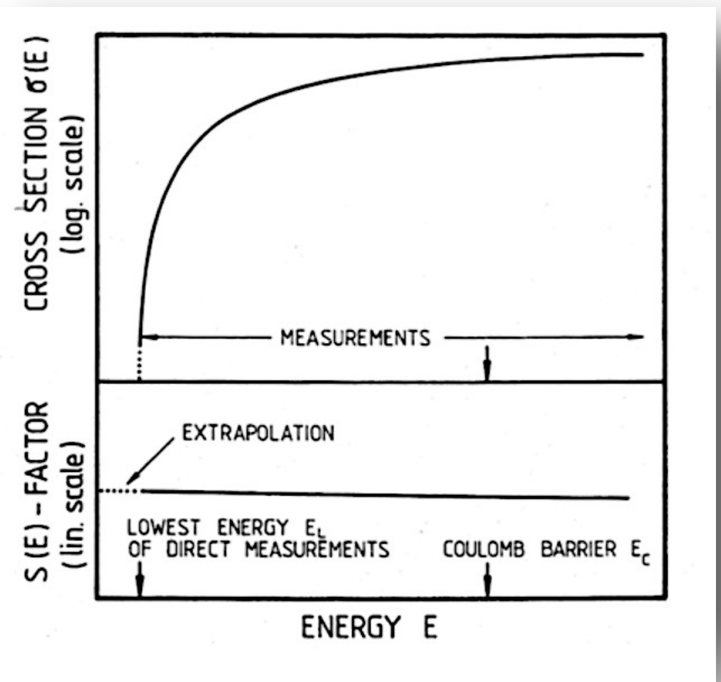
- 4 most abundant elements: *H, He,* **O, C**
- Observed **C/O ratio = 0.6**
- Reactions that regulate **C/O ratio** in the universe:
  - Bulk of $^{12}$**C** abundance: 3$\alpha$-process
  - $^{16}$**O** is the "ash" of subsequent $\alpha$-capture reaction: **$^{12}C(\alpha, \gamma)^{16}O$**
- Significance of C/O ratio:
  - **Stars with M > 8 M$_\odot$ :** modelling of **C/O** ratio during the final phase of He-burning in **red giants** remains **unsolved for 30 years**
  - **Stars with M ~ 1.4 M$_\odot$ :** explode as ***Ia*-type supernovae**

    thanks to these **"standard candles"** accelerated expansion of the Universe and existence of the dark energy have been discovered

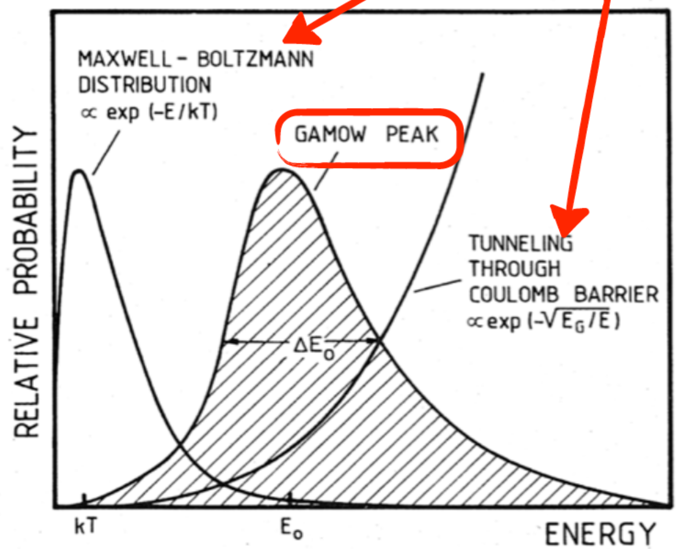
    precise modelling of of **C/O** ratio is needed to describe **production of $^{56}$Ni**, which in turn modifies **light-curves** of these important "standard candles"

# Stellar Nucleosynthesis

- **Problem of Coulomb barrier in direct α-capture (α,γ) measurements:**
  - in the interesting energy regime the cross sections are very small
  - exp. data need to be extrapolated to the Gamow peak
  - significant exp. background




$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{K_B T}\right)^{3/2} \int_0^\infty S(E) \exp\left(-\frac{E}{K_B T} - \sqrt{\frac{E_G}{E}}\right) dE$$

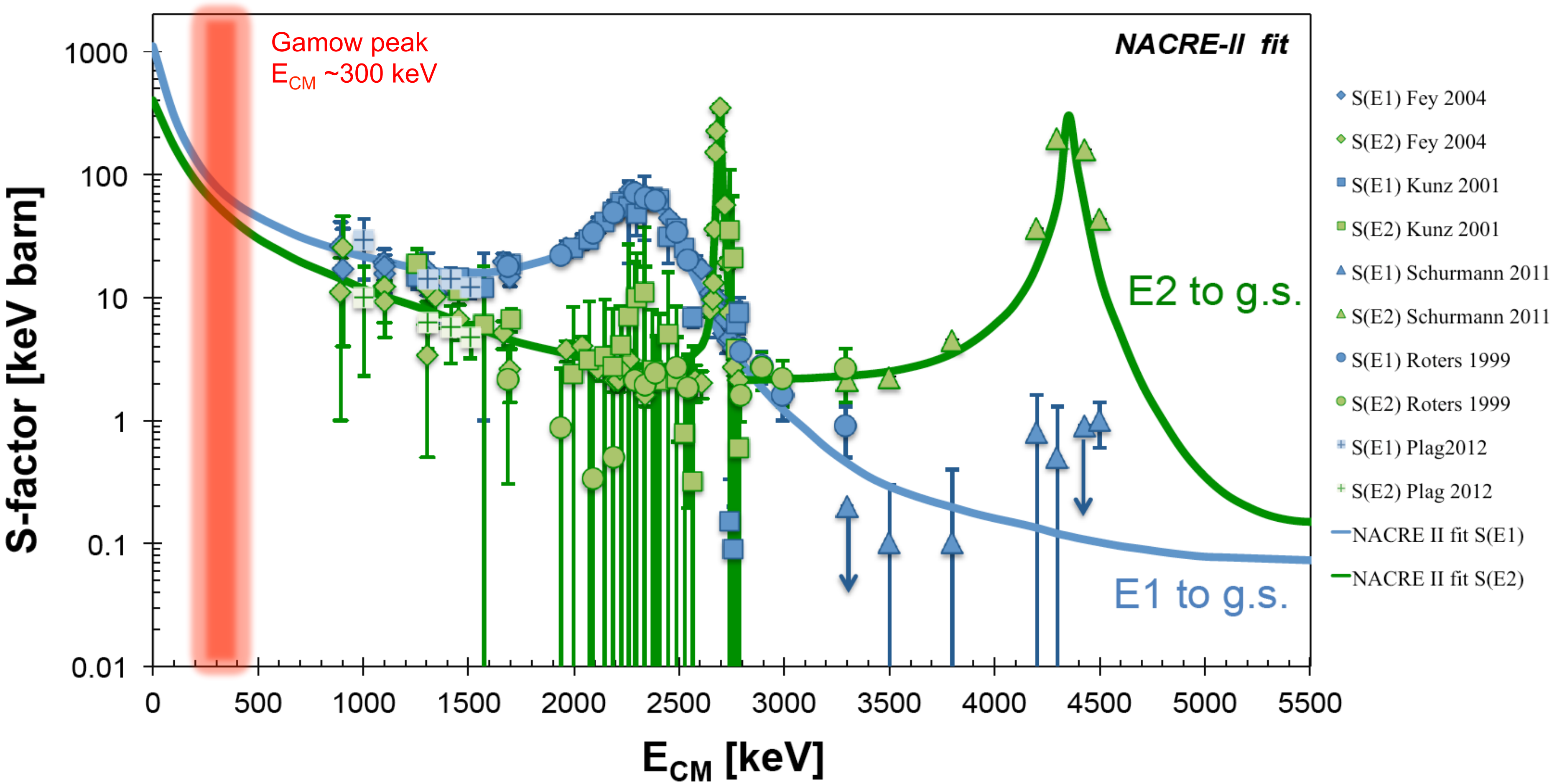



**Gamow energy**

$$E_G = 2\mu \frac{\pi^2 e^4}{\hbar^2} (Z_1 Z_2)^2 \, MeV$$

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

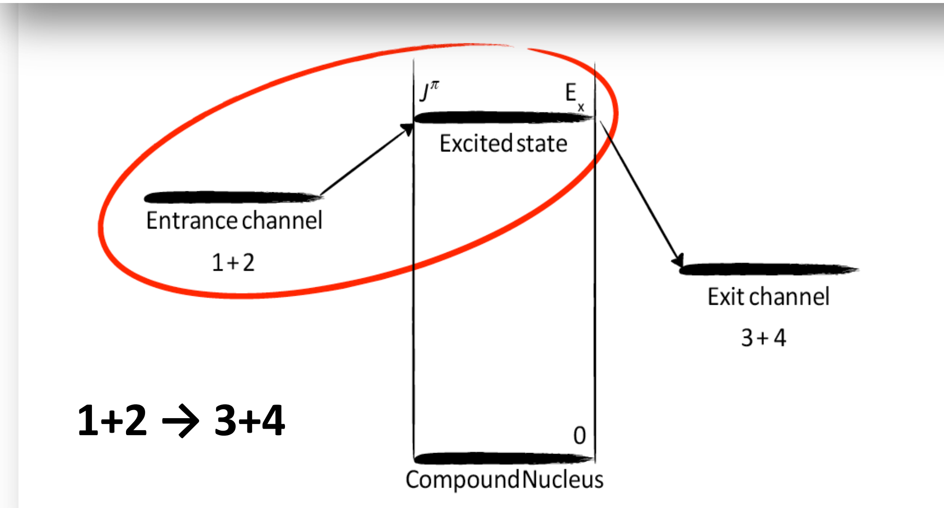
- Extrapolated p-wave (E1) & d-wave (E2) astrophysical **S-factors** to the Gamow peak in red giants: **40 – 80% uncertainty**



# How to improve accuracy?

- Measure **time-reverse** *(photo-dissociation)* reaction → $^{16}$**O** **(**$\gamma,\alpha$**)** $^{12}$**C:**
  - strong and e-m interactions invariant w.r.t. time reversal
  - cross sections from detailed balance principle
  - LOW experimental background

$$\frac{\sigma_{12}}{\sigma_{34}} = \frac{m_3 m_4}{m_1 m_2}\frac{E_{34}}{E_{12}} \times \frac{(2J_3+1)(2J_4+1)}{(2J_1+1)(2J_2+1)} \times \frac{(1+\delta_{12})}{(1+\delta_{34})}$$



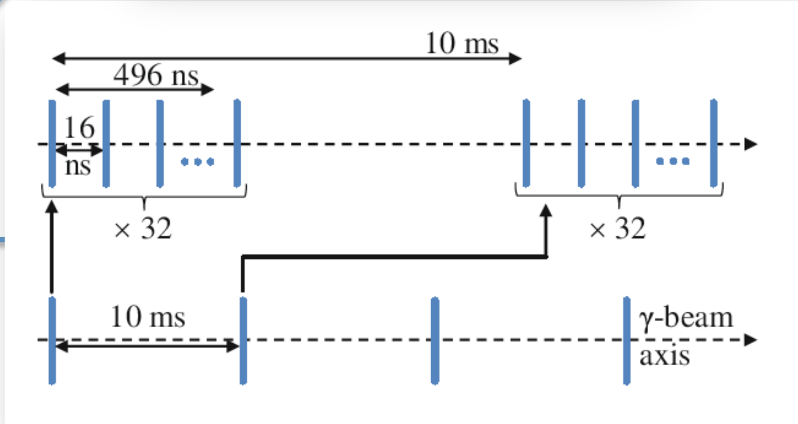

**REQUIREMENTS:**

- **Intense, monochromatic** $\gamma$-ray beams
- **Detection of low-energy charged products** of photo-dissociation reaction

# Gamma-ray beam @ ELI-NP facility

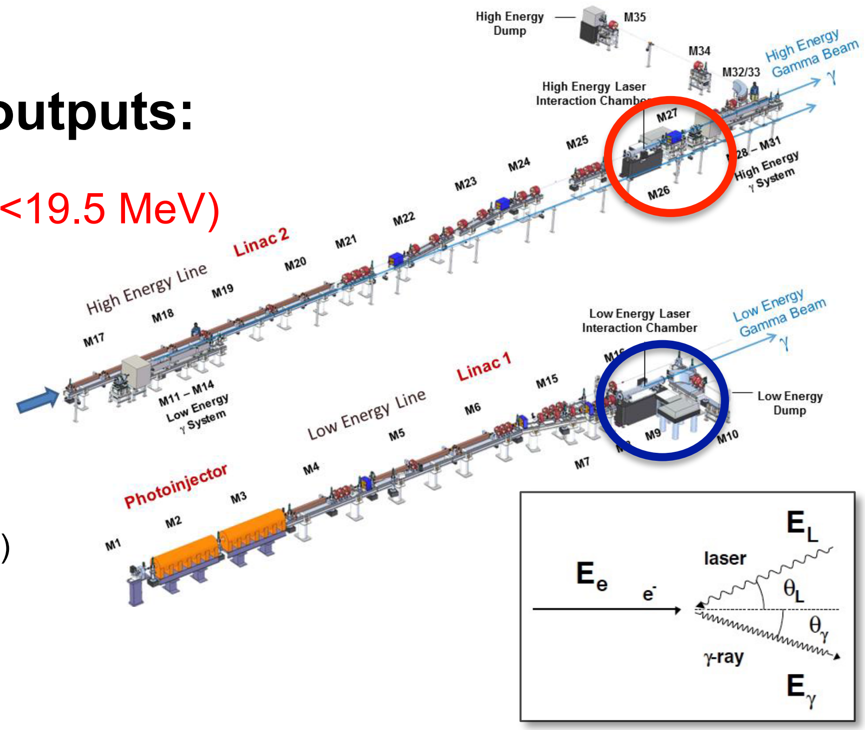
- **Compton Back Scattering**
- High-brilliance,
  good bandwidth & collimation

| | |
|---|---|
| Energy range | **0.2 – 19.5 MeV** |
| BW (rms) | **< 0.5 %** |
| Spectral density | **> 0.5 $10^4$ γ/s/eV** |
| Peak brilliance | **$10^{20}$ – $10^{30}$ γ/(s mm² mrad² 0.1%BW)** |
| Angular divergence (rms) | **25 – 200 μrad** |
| Photons within FWHM BW | **< 2.6 $10^5$ γ/pulse** |
| Macro-pulse rate | **100 Hz** |
| Linear polarization | **> 95%** |


D.Filipescu et al., Eur. Phys. J. A 51 (2015) 185

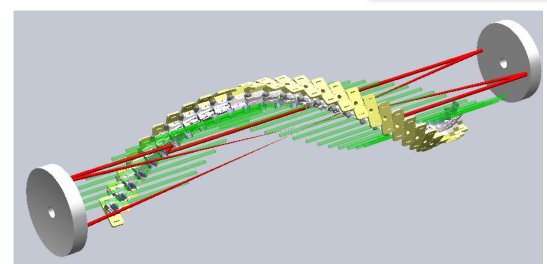
# Gamma-ray beam @ ELI-NP facility




- **Gamma Beam System (GBS) has 2 outputs:**
  - low energy ($E_\gamma$<3 MeV) & high energy ($E_\gamma$<19.5 MeV)
- **GBS components:**

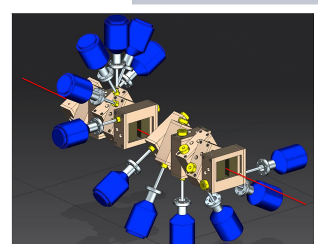
### 1. Electron LINAC:
- tunable energy: $E_e$ = 80 – 720 MeV
- laser photo-injector (32 pulses, 100 Hz rate)
- two stages (Linac1, Linac2)
- total length: 90 m

### 2. Laser system:



- green light ($E_L$=2.4 eV, λ=515 nm, 500 mJ / 3.5 ps)
- fixed electron-photon crossing angle ($\theta_\gamma$=7.5°)
- multi-pass laser beam recirculation

### 3. Collimation & diagnostics systems



O. Adriani et al., arXiv:1407.3669 [physics.acc-ph], July 2014

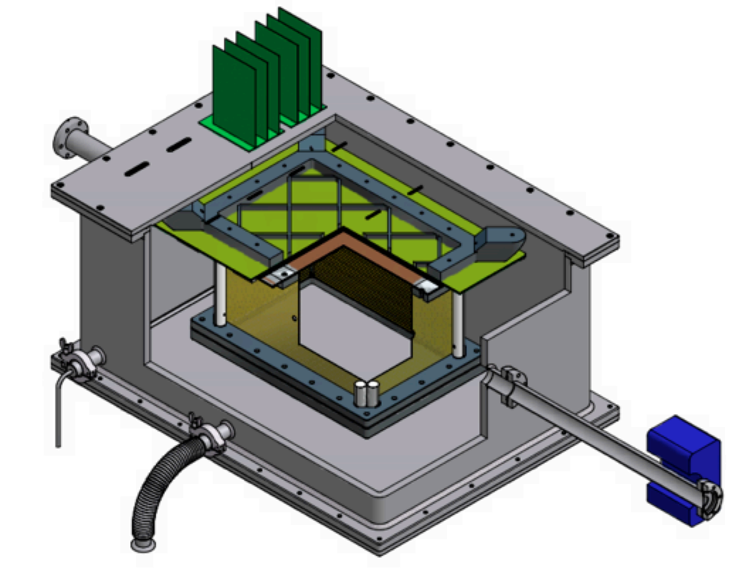
# DAY-1 γ-ray beam experiments @ ELI-NP for charged particles detection

## ELITPC

**active gaseous target**

low-pressure Time Projection Chamber

*U. of Warsaw, ELI-NP/IFIN-HH, U. of Connecticut*

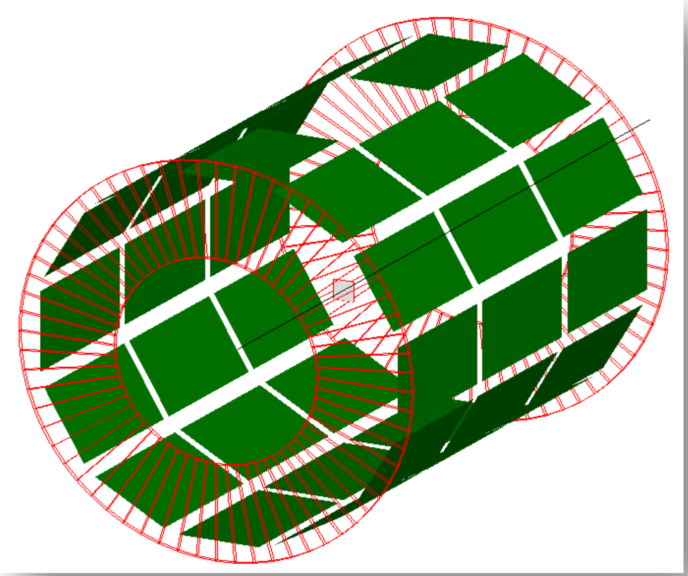


## ELISSA

**solid, removable target**

Silicon Strip Detector array in vacuum

*INFN-Catania, ELI-NP/IFIN-HH*



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

# DAY-1 $\gamma$-ray beam experiments @ ELI-NP for charged particles detection

## Nuclear Astrophysics studies:

- use detailed balance principle for time-reverse reactions
- measure decay products of nuclear photo-dissociation reactions

| Time-reverse reaction | Detector type | Target | Astrophysical relevance |
|---|---|---|---|
| **$^{16}O(\gamma,\alpha)^{12}C$** | TPC | **$CO_2$** | **ratio C/O** |
| $^{19}F(\gamma,p)^{18}O$ | TPC | $CF_4$ | ratio $^{16}O/^{18}O$, CNO-cycle |
| $^{21}Ne(\gamma,\alpha)^{17}O$ | TPC | $^{21}Ne$ | role of $^{16}O$ as neutron poison |
| $^{22}Ne(\gamma,\alpha)^{18}O$ | TPC | $^{22}Ne$ | ratio $^{16}O/^{18}O$, CNO-cycle<br>synthesis of $^{22}Ne$ (source of *n* in *s*-processes) |
| $^{24}Mg(\gamma,\alpha)^{20}Ne$ | SSD | $^{24}Mg$ | Si-burning |
| $^{96}Ru(\gamma,\alpha)^{92}Mo$ | SSD | $^{96}Ru$ | synthesis of elements with A>73 in *p*-processes |

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

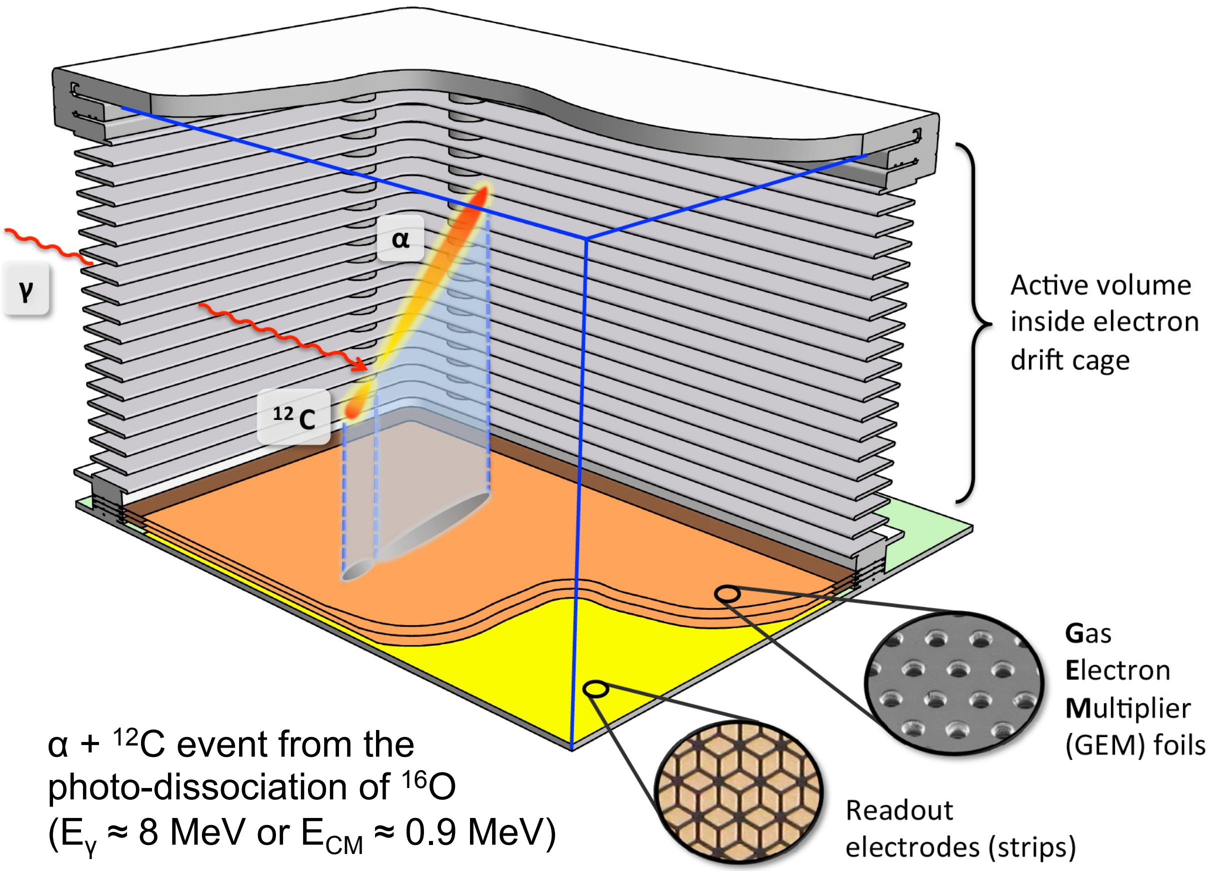
# ELITPC detector concept (1)

**Active volume:**

- **35 x 20** cm$^2$ (readout) **x 20** cm (drift)
- gas pressure **~100 mbar** to increase track lengths

**Charge amplification**:

- 3 **GEM** foils (or Thick-GEMs)




α + $^{12}$C event from the photo-dissociation of $^{16}$O ($E_\gamma \approx 8$ MeV or $E_{CM} \approx 0.9$ MeV)

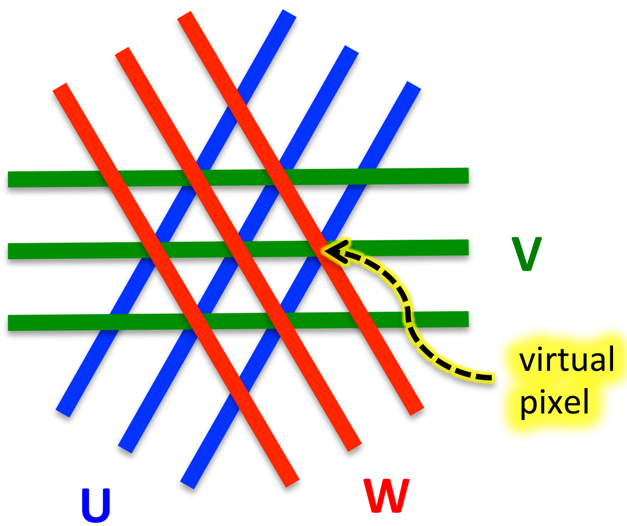
**Readout:**

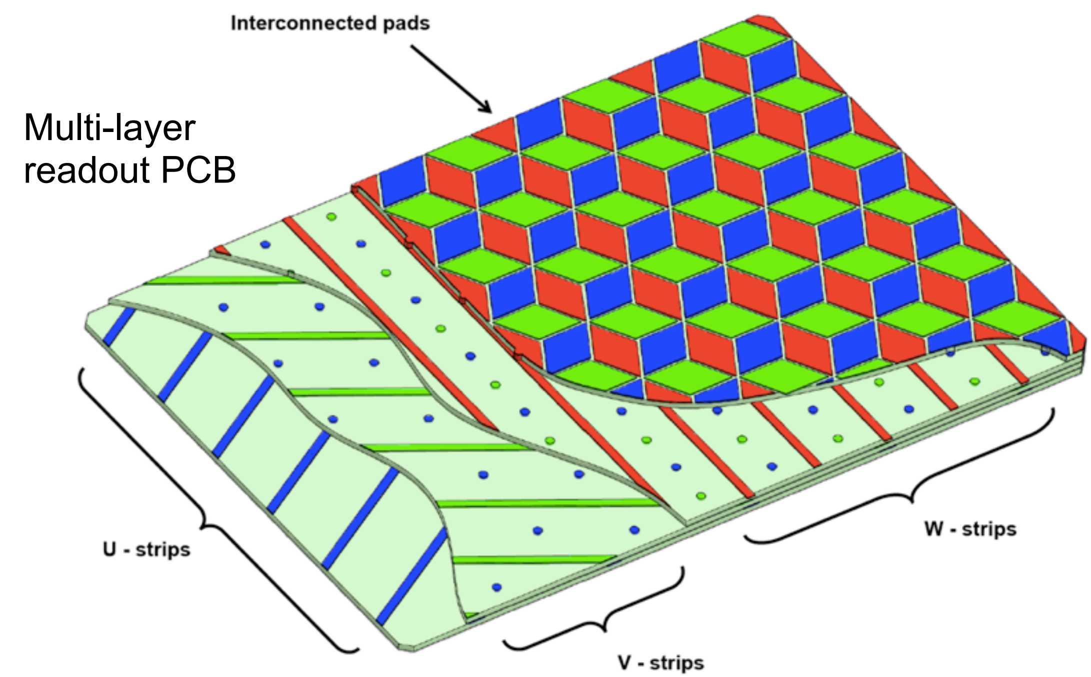
- **3-coordinate, planar, redundant** strips (***u-v-w***)
- **1.5 mm** strip pitch
- about **1000 channels**
- **GET** electronics for signal amplification & digitization
- external trigger (100 Hz)

# ELITPC detector concept (2)

**3-coordinate, planar, redundant electronic readout:**

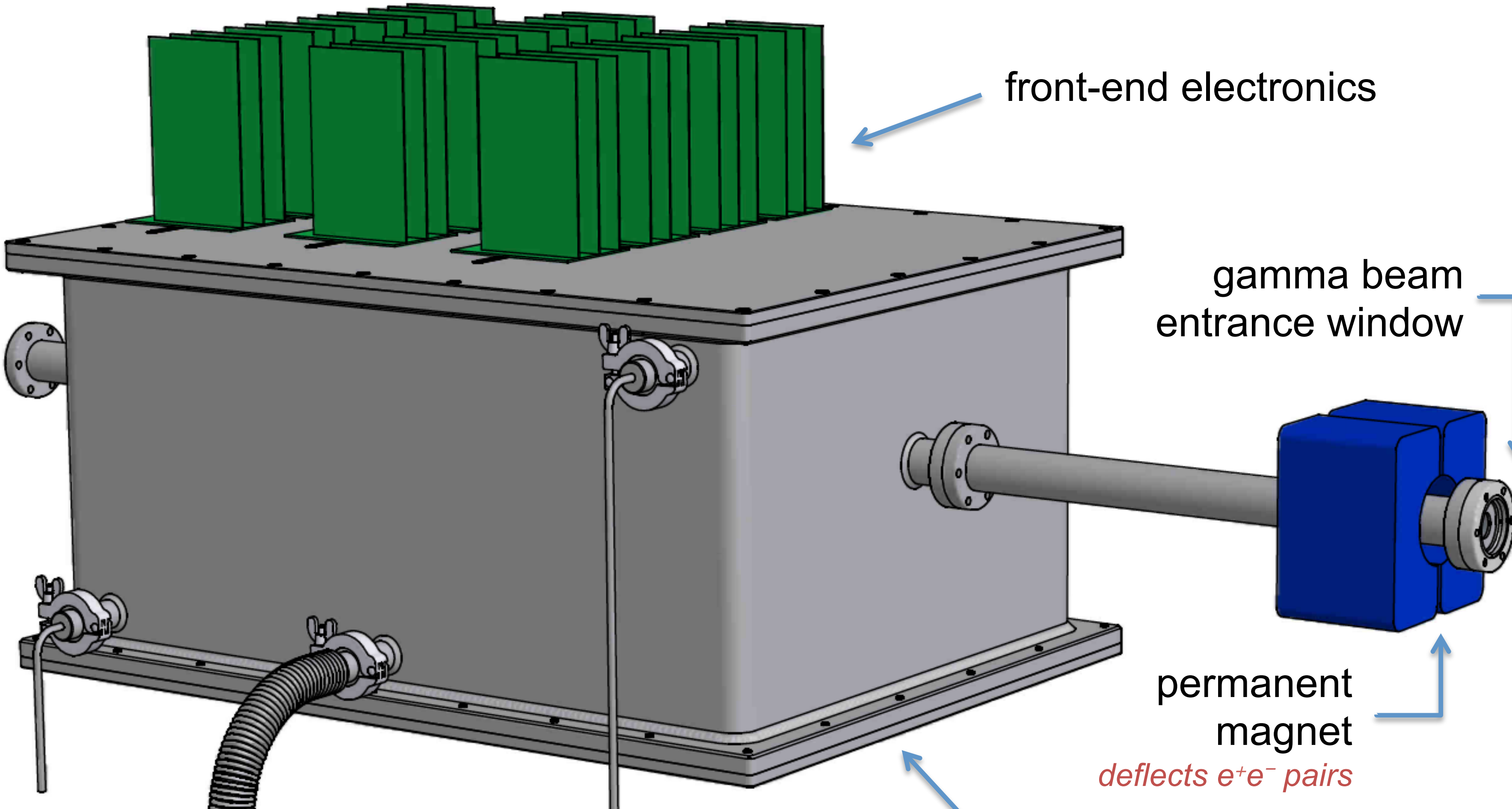
- ***u-v-w*** strip arrays for hit disambiguation in 2D → virtual pixels
- ***z***-coordinate from timing information
- aimed for relatively simple event topologies → few tracks per event
- need only ***O*(10³)** channels → moderate cost of electronics




S. Bachmann et al., NIMA 478 (2002) 104
V. Ableev et al., NIMA 535 (2004) 294
M. Ćwiok, Acta Phys. Pol. B 47 (2016) 707
J. Bihałowicz et al., Proc. of SPIE 9290 (2014) 92902C

# ELITPC detector concept (3)



front-end electronics

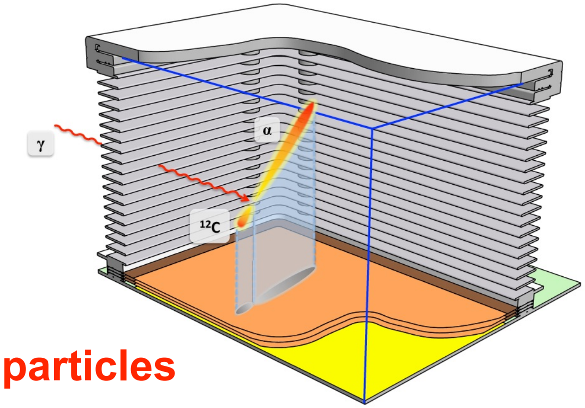
gamma beam
entrance window

permanent
magnet
*deflects $e^+e^-$ pairs*

TPC inside
a vacuum vessel

| | |
|---|---|
| Location: | E8 experimental vault |
| Beam footprint: | $\phi < 2$ mm |

# ELITPC – event yields




**Time-reverse reaction → $^{16}O(\gamma,\alpha)^{12}C$:**

- **Method:**
  - **measure energy & angular distributions of charged particles**
  - **obtain accurate values of E2 / E1 components**

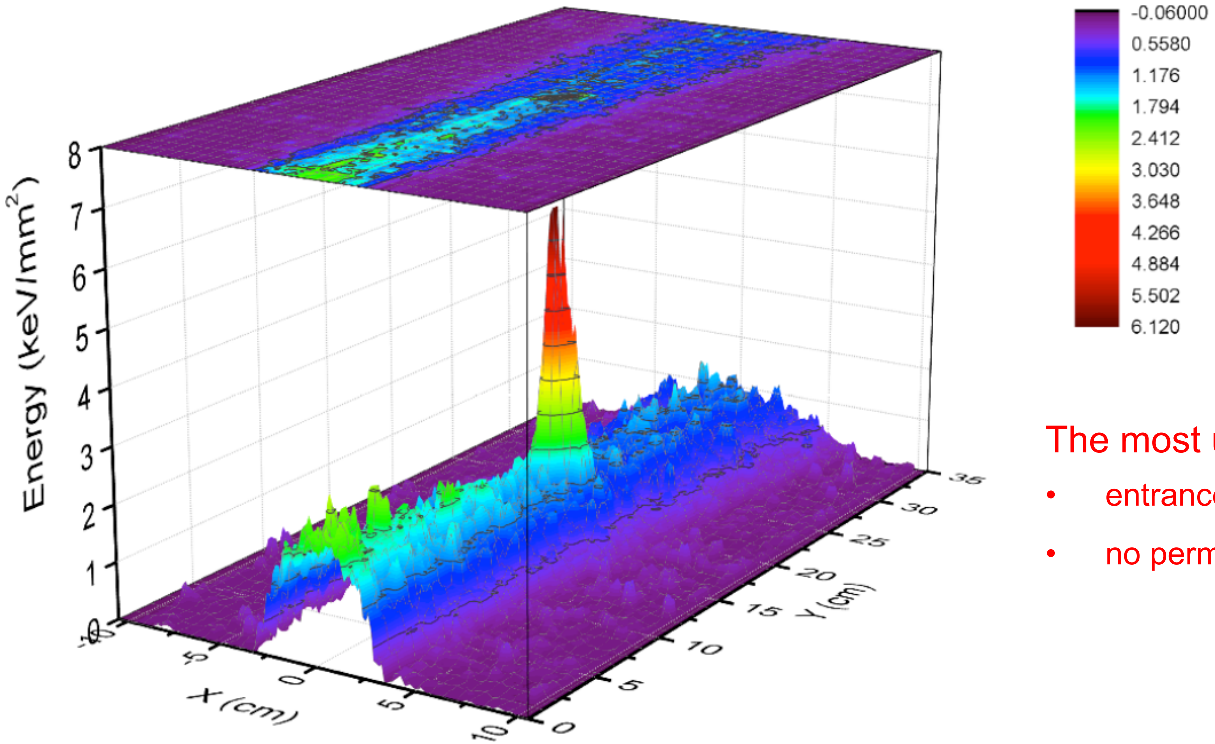
- **Efficiency** (example for $CO_2$ @ 100 mbar):
  - beam energy: $E_\gamma$=8.26 MeV → **$E_{CM}$=1.1 MeV** [Q=7.162 MeV for $^{12}$**C(α,γ)**$^{16}$**O**]
  - beam intensity on target: 2.5 × $10^4$ γ/s/eV, 0.5% bandwidth → **$10^9$ γ/s**
  - 1500 events to measure angular distributions → **21 days of beam time**

- **Background:**
  - main sources of background: Compton electrons & $e^+e^-$ pairs in gaseous target and in a thin mylar/kapton entrance window
  - very small w.r.t. direct (α,γ) reaction experiments

# ELITPC – background

**GEANT4 simulation of a single ELI-NP macro-pulse:**

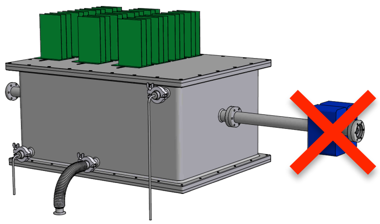
- $10^7$ γ-rays at 8 MeV
- $CO_2$ @ 100 mbar
- 0.5 MeV α-particle track added artificially to mimic $^{16}O$ photo-dissociation




Colors correspond to integrated energy deposits on the 2D readout plane

The most unfavourable scenario is shown:

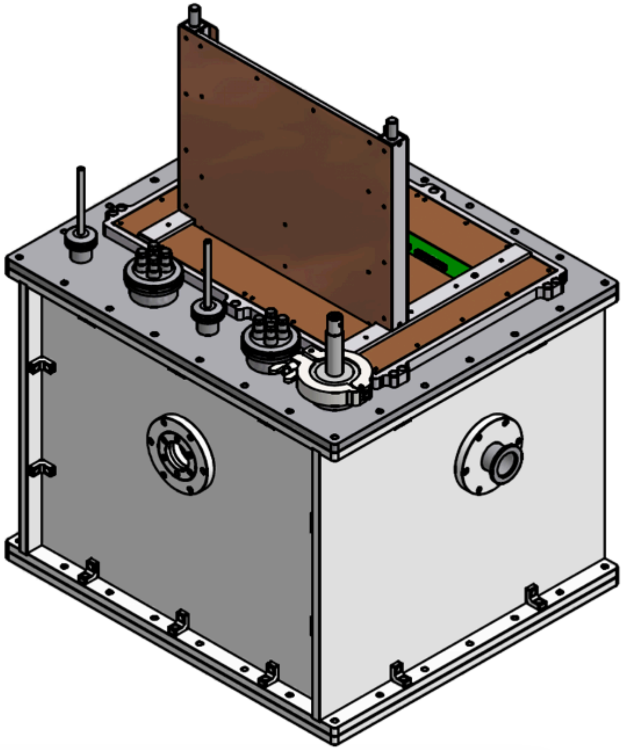
- entrance window very close to the active volume
- no permanent magnet after the entrance window

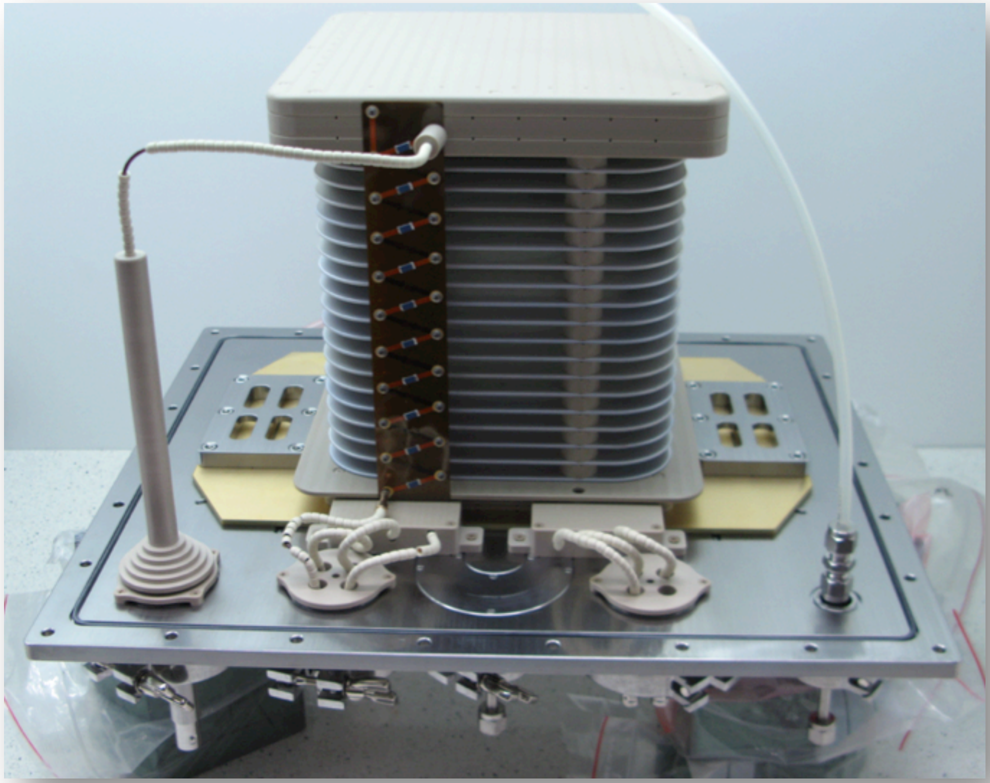


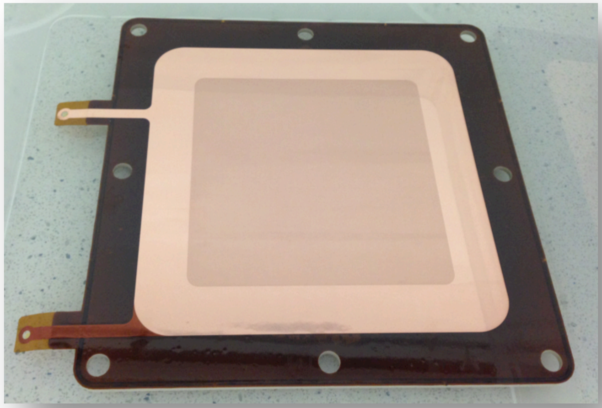
O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

# Demonstrator detector (1)

- Readout area: **10 × 10 cm²**, drift: **20 cm**
- GET electronics: **256 channels**
- Operating at atmospheric pressure

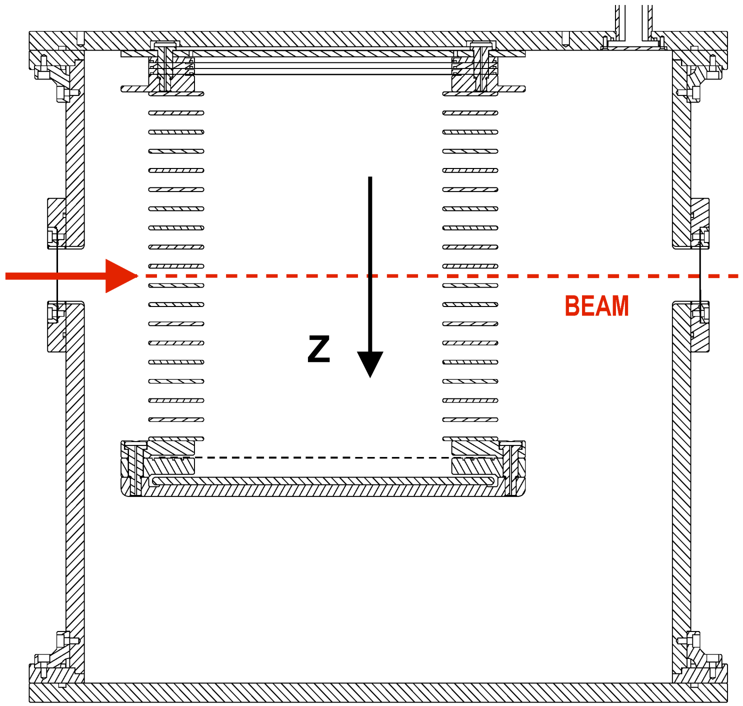




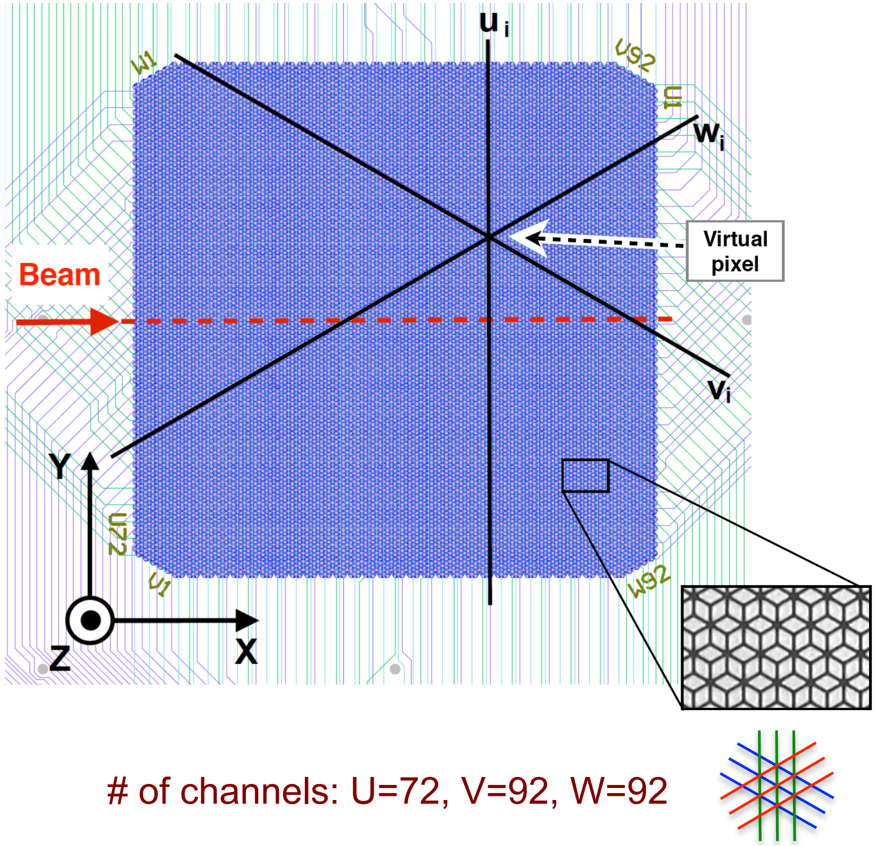


# Demonstrator detector (2)

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




SIDE view - XZ plane along beam axis

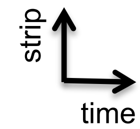


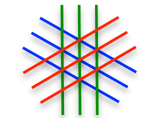

# of channels: U=72, V=92, W=92

TOP view – XY readout plane

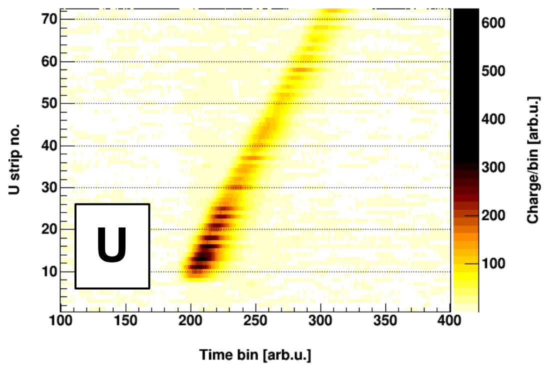
# Demonstrator detector (3)

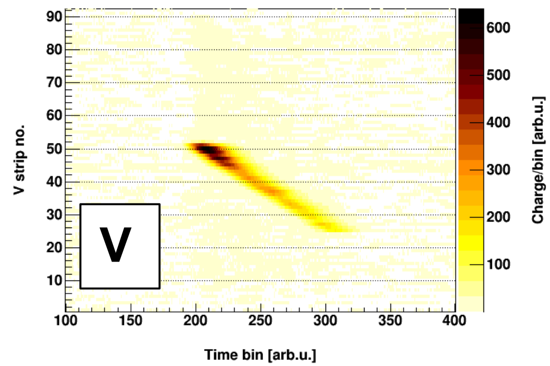
- **Single tracks** from α-particle beam:
  - Gas mixture: He+$CO_2$ (70:30) **@1 atm**

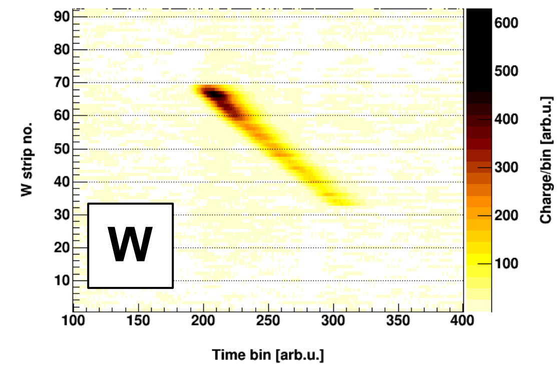


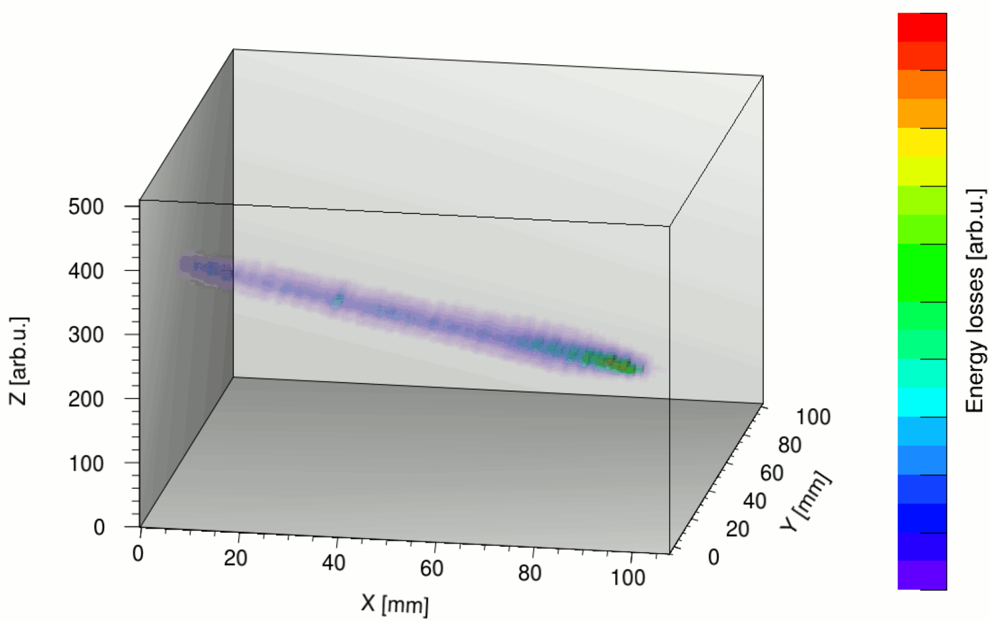
Raw data



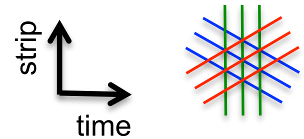




Reconstructed α-particle track in 3D

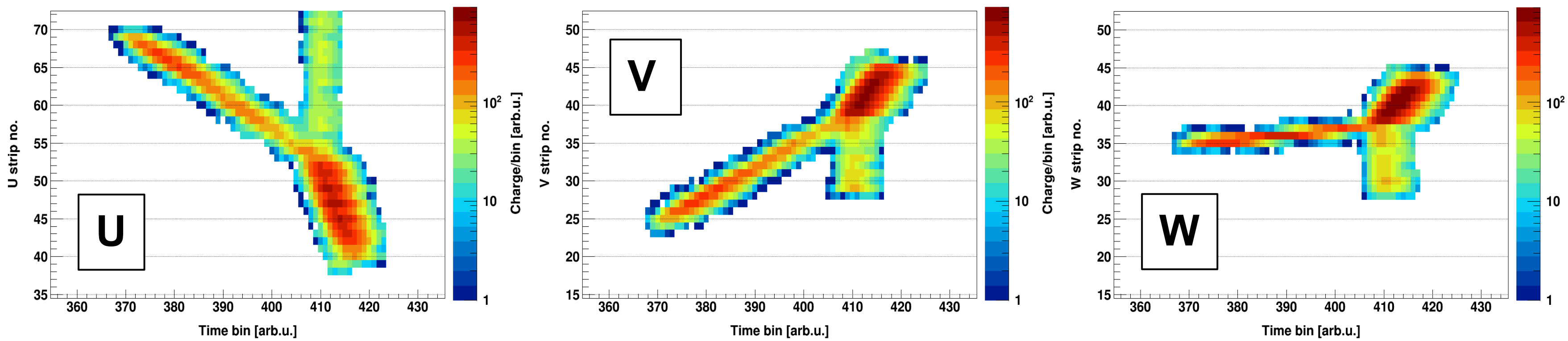


# Demonstrator detector (4)

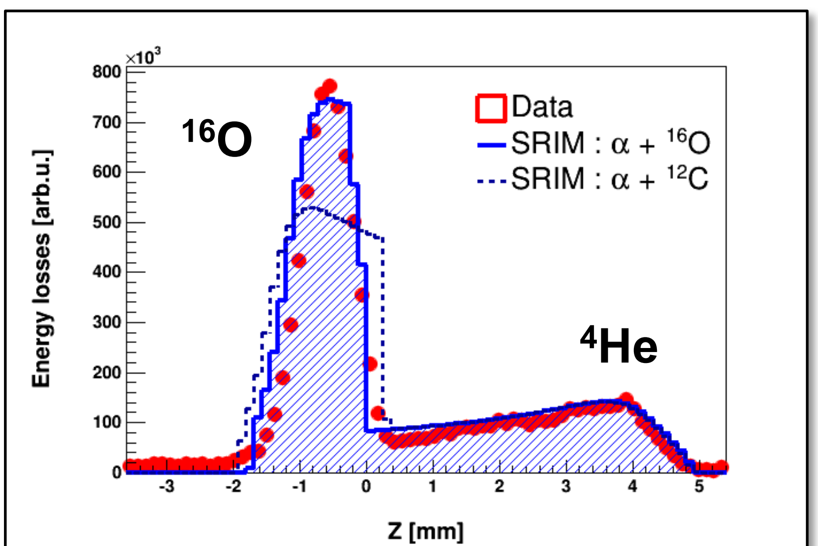
- **Events with 3 tracks:** $^{4}$He + $^{16}$O scattering:
  - Gas mixture: He+$CO_2$ (70:30) **@1 atm**

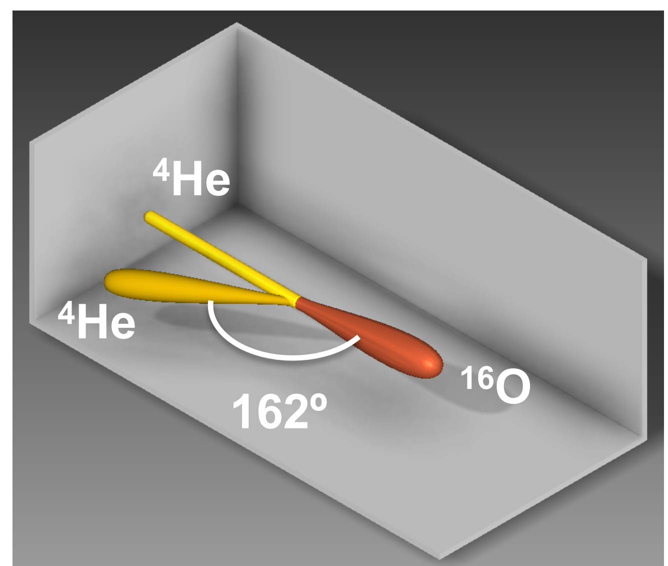



Raw data



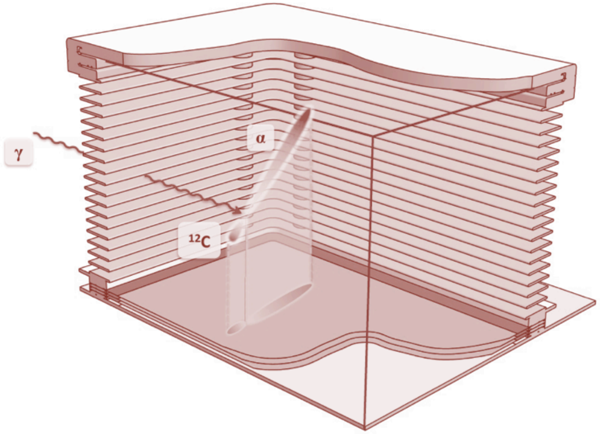

Reconstruction



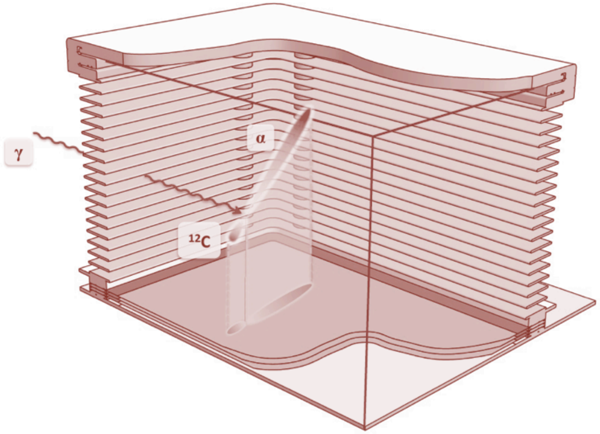
# Summary

- **ELITPC detector approved as one of DAY-1 experiments for ELI-NP.**
- **256-ch demonstrator detector is operational:**
  - first beam tests (with charged particles) done in 2015 and 2016
  - proof-of-principle of the readout method
- **Oct 2016 – UW and ELI-NP signed a 2-year R&D contract for designing full-scale, low-pressure ELITPC detector:**
  - in time for beam commissioning at end of 2018
- **Other physics cases with ELITPC @ ELI-NP:**
  - other astrophysical reactions (different gas targets)
  - nuclear structure physics (clustering phenomena)
  - nano-dosimetry & radiation damage to DNA



# Some R&D outlooks

- **Compare 50-µm GEMs vs 125-µm Thick-GEMs at low pressures:**
  - selected He + $CO_2$ gas mixtures
  - pressure range: 100-500 mbar
- **Test demonstrator detector at low pressures:**
  - influence of diffusion, attachment & gas purity on charge collection efficiency
  - correcting for electronics effects → signal de-convolution, inter-channel calibration
  - different 3D reconstruction methods → clustering, Hough transform, SRIM simulations
- **Adapt GET electronics for specific ELITPC needs:**
  - develop standalone Zynq FPGA readout board optimized for O(1000) channels
  - collaboration with: CEA-IRFU, CENBG, GANIL, MSU/NSCL
- **Realistic GEANT4 background simulations:**
  - optimization of readout structure & number of channels
  - better S/N ratio



# ELITPC Collaboration (Oct 2016)

**Univ. of Warsaw, Poland**

M. Bieda, J.S. Bihałowicz, M. Ćwiok, W. Dominik, Z. Janas, Ł. Janiak, J. Mańczak, T. Matulewicz, C. Mazzocchi, M. Pfützner, P. Podlaski, S. Sharma, M. Zaremba

**IFIN-HH / ELI-NP, Romania**

D. Balabanski, C. Balan, A. Bey, D.G. Ghita, O. Tesileanu

**Univ. of Connecticut, USA**

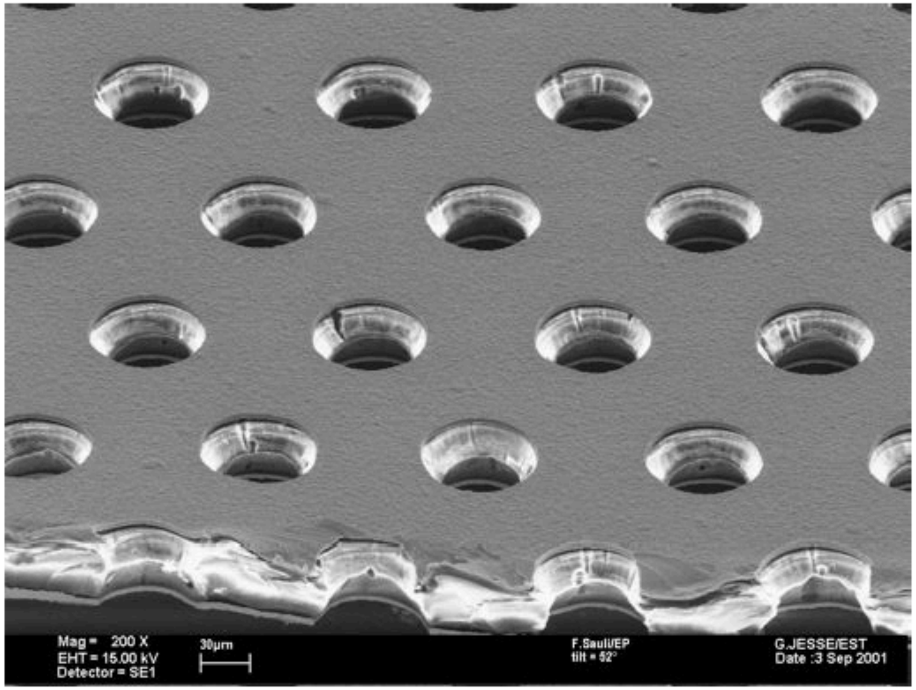
M. Gai, D.P. Kandellen

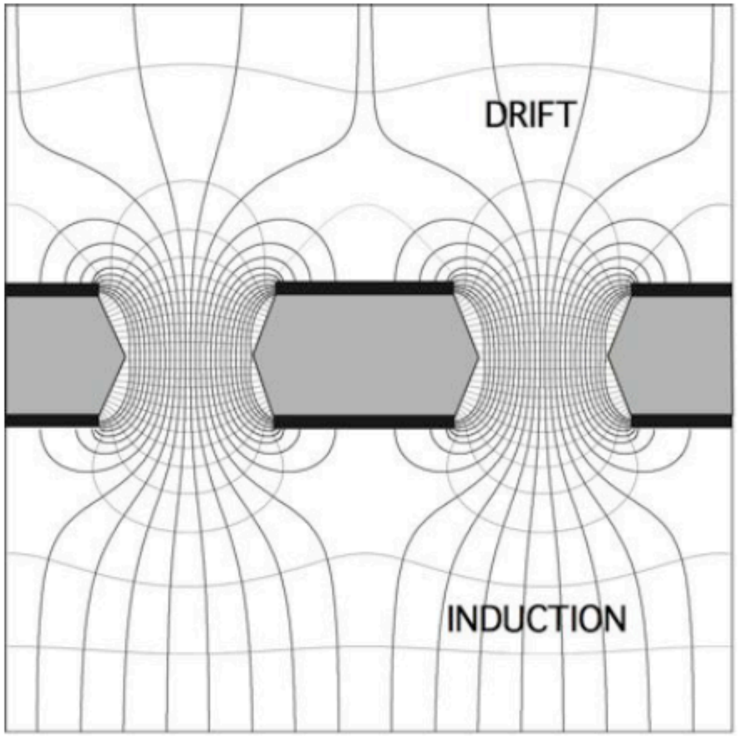
# BACKUP SLIDES

# Gas Electron Multiplier (GEM)

- **GEM charge amplification structures:**
  - developed at CERN in late 1990's
  - thickness: Kapton – **50 μm**, copper – 5 μm
  - electric fields **~40 kV/cm**, electron charge gain factors **~10$^3$**
  - several GEM foils can be stacked together

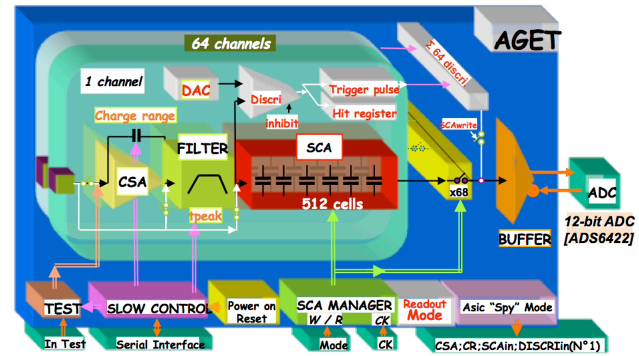
F. Sauli, NIM A386 (1997) 531



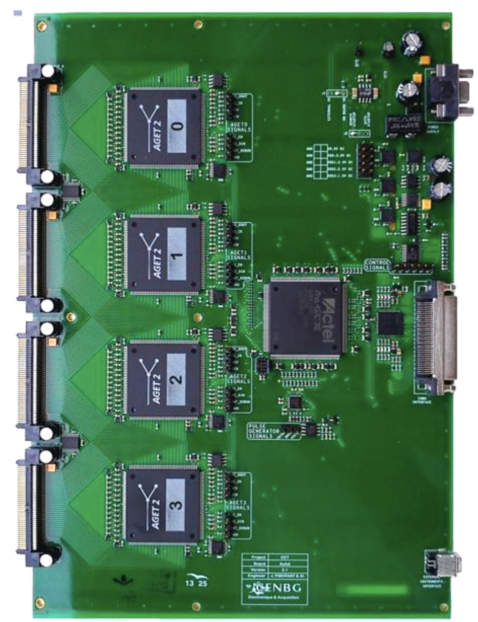



# Generic Electronics for TPCs

- **Developed by: CEA/IRFU, CENBG, GANIL, MSU/NSCL**
  - in use over **20 labs** worldwide
- **64-ch ASIC chip (*AGET* = *ASIC for GET*):**
  - flexible sampling frequency: **1-100 MHz**
  - **512 time-cells** per channel, analog SCA memory
  - adjustable gain & filtering per channel



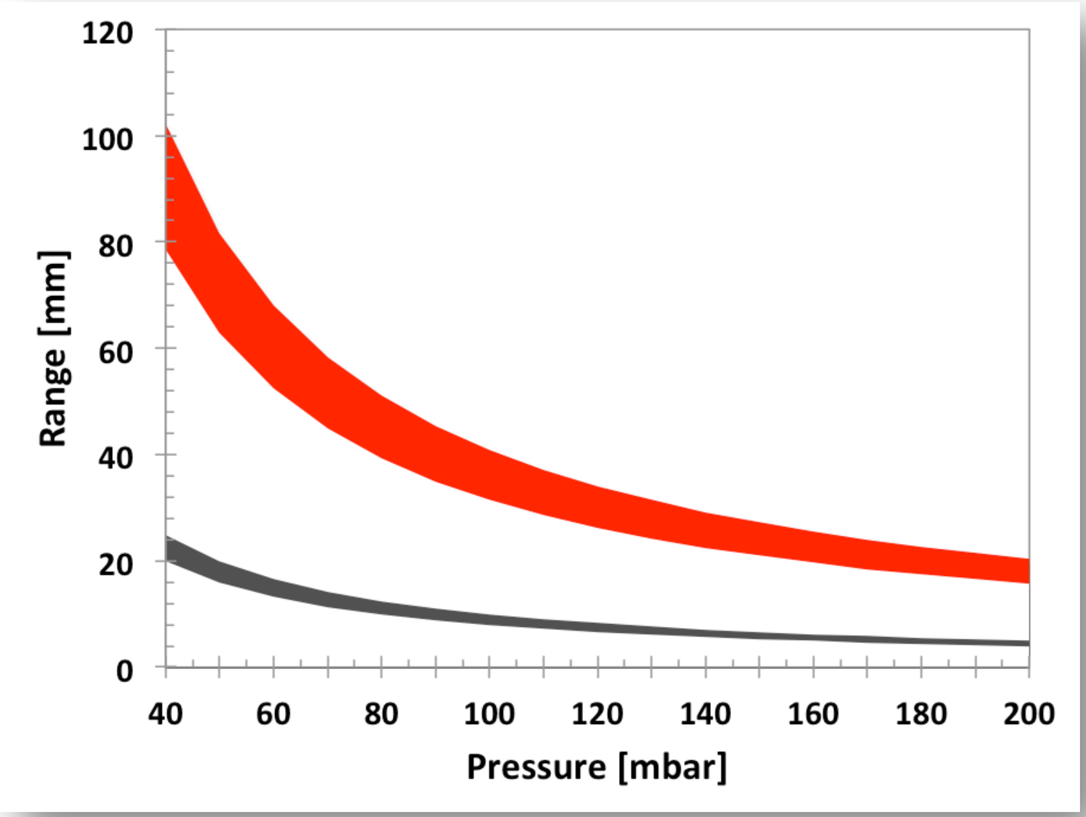

- **1024-ch front-end board (*AsAd* = *ASIC & ADC*):**
  - hosts 4 AGET chips
  - **12-bit ADC**, one channel per AGET chip
- **Data concentration, timing & trigger boards:**
  - big systems: **uTCA** crate, **CoBo** boards, **MuTant** boards (up to 32,000 channels)
  - small systems: standalone FPGA board (up to 256 channels)



E. Pollacco et al., Physics Procedia 37 (2012) 1799

# ELITPC – track lengths

- **Studies of $^{12}C(\alpha,\gamma)^{16}O$:**
  - SRIM-simulated ranges of charged particles as a function of $CO_2$ pressure




**Red band (α particles)**

**Grey band ($^{12}C$ ions)**

Bands correspond to:

- Eγ range: 8.26 - 8.67 MeV
- 90° emission angles w.r.t. γ-beam axis

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

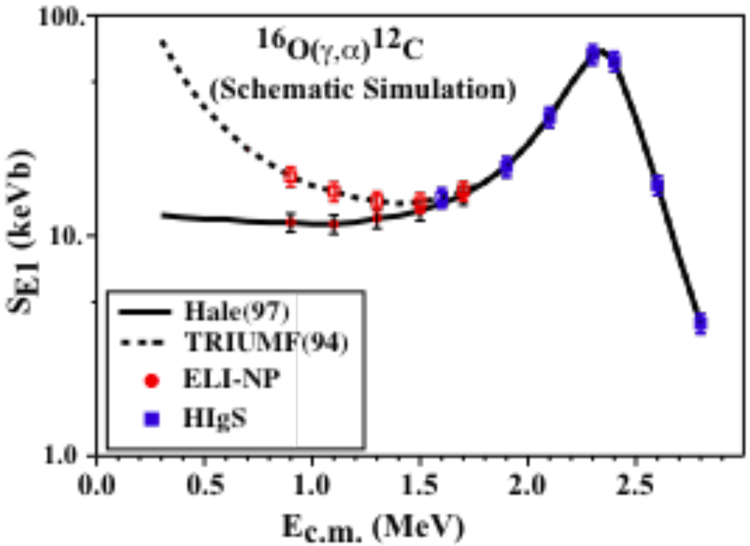
# Motivation for ELITPC @ ELI-NP

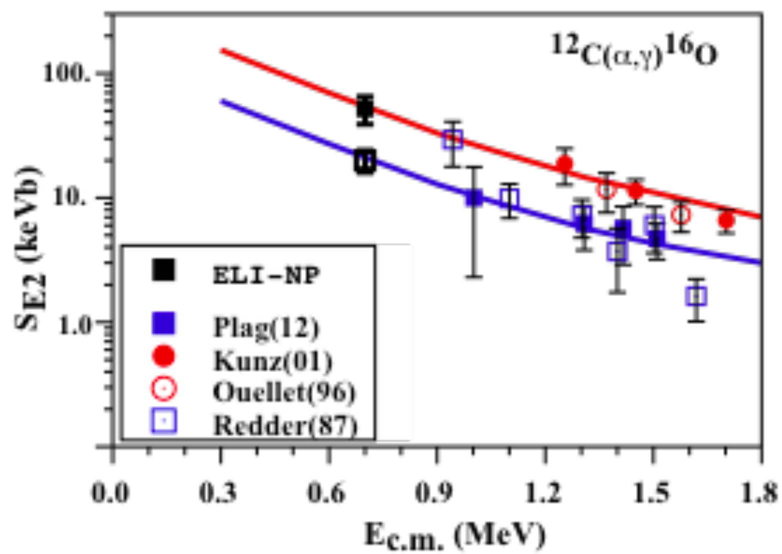
## Studies of $^{12}C(\alpha,\gamma)^{16}O$:

– **Present experimental data start from $E_{CM}$ ~ 1 MeV**

– **Goal:** measure astrophysical *S*-factor near the Gamow peak in red giants

- $E_{CM}$ ~ $\mathbf{E_G}$ **= 300 keV**
- $\boldsymbol{S_{E1}}$**(300)** and $\boldsymbol{S_{E2}}$**(300)** corresponding to ***p*** and ***d***-waves
- reduce uncertainty on *S*-factor from 40-80% to **10%**




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

# Abundance of chemical elements

- **Universe** (by mass): **H – 74%**, **He – 24%**, **O – 0.85%, C – 0.39%** + others (<1%)
- **Human body** (by mass): **O – 65%, C – 18%**, H – 10%, N – 3% + others (4%)