Liquid Argon Gamma-ray Observatory
LArGO
A new concept of gamma-ray telescope

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for

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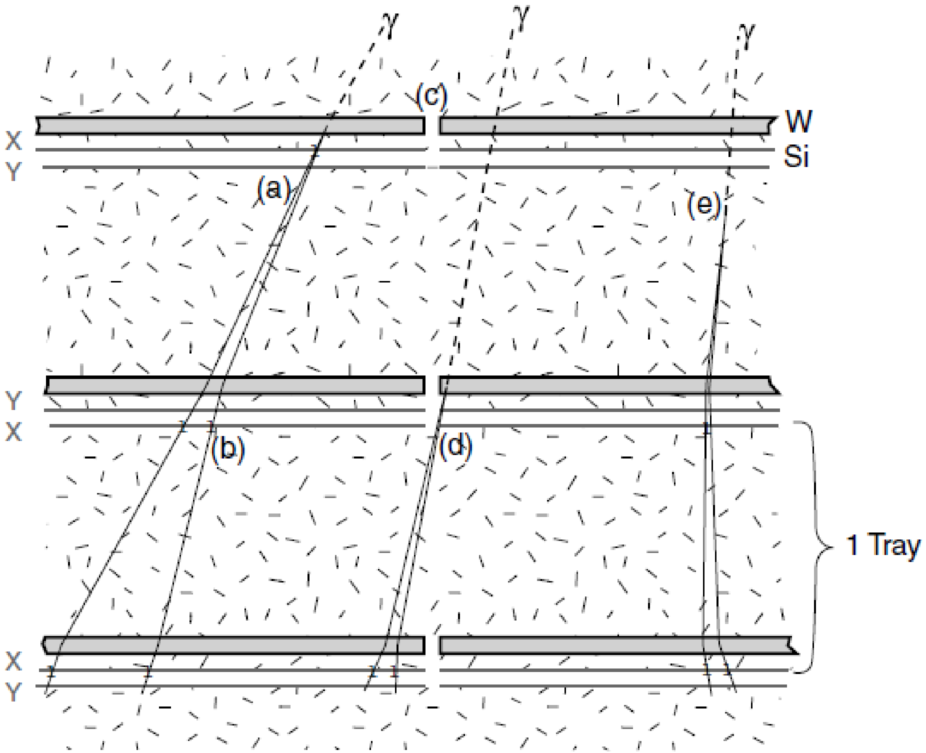
Main goals

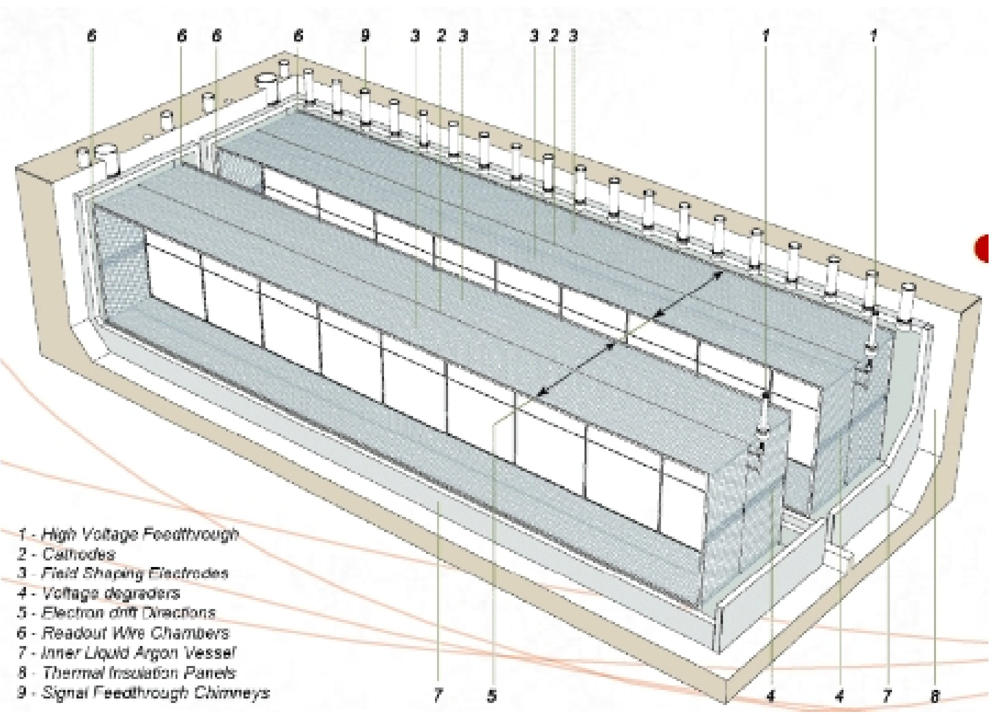
- A new gamma-ray satellite has to be better than Fermi-LAT
  - Not an easy task, because the LAT is very good!
  - A ground-braking new technique is necessary
- LArGO focus mainly on the improvement of the angular resolution
  - Gamma-ray polarization
  - Better sky mapping
- Maintaining the conversion efficiency, and wide field of view as in the LAT
  - Better sensitivity
- LArGO can efficiently work as Compton telescope
  - Thus covering a very broad energy range ~100 KeV – 100 GeV

Tracker–converter and Neutrino detectors

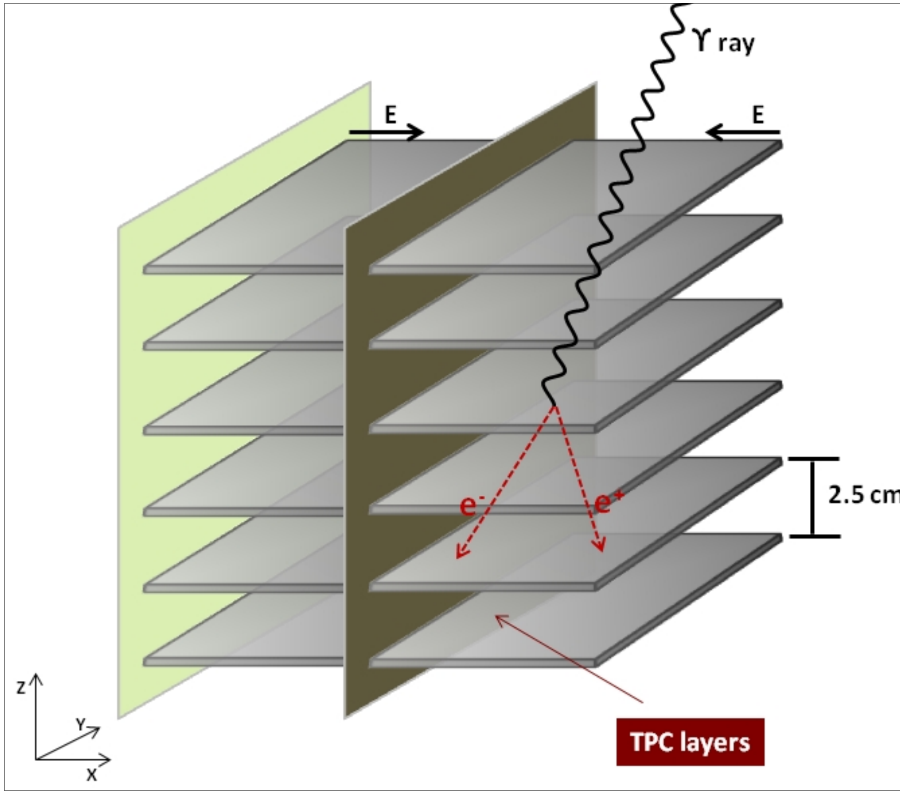
- **The tracker-converter has the double goal to convert the incident photon, and to track the pair produced**
  - **For the first aim is necessary large converting material (high Z) to maximize the effective area.**
  - **For a good tracking the high Z material should be minimized to reduce the multiple scattering.**

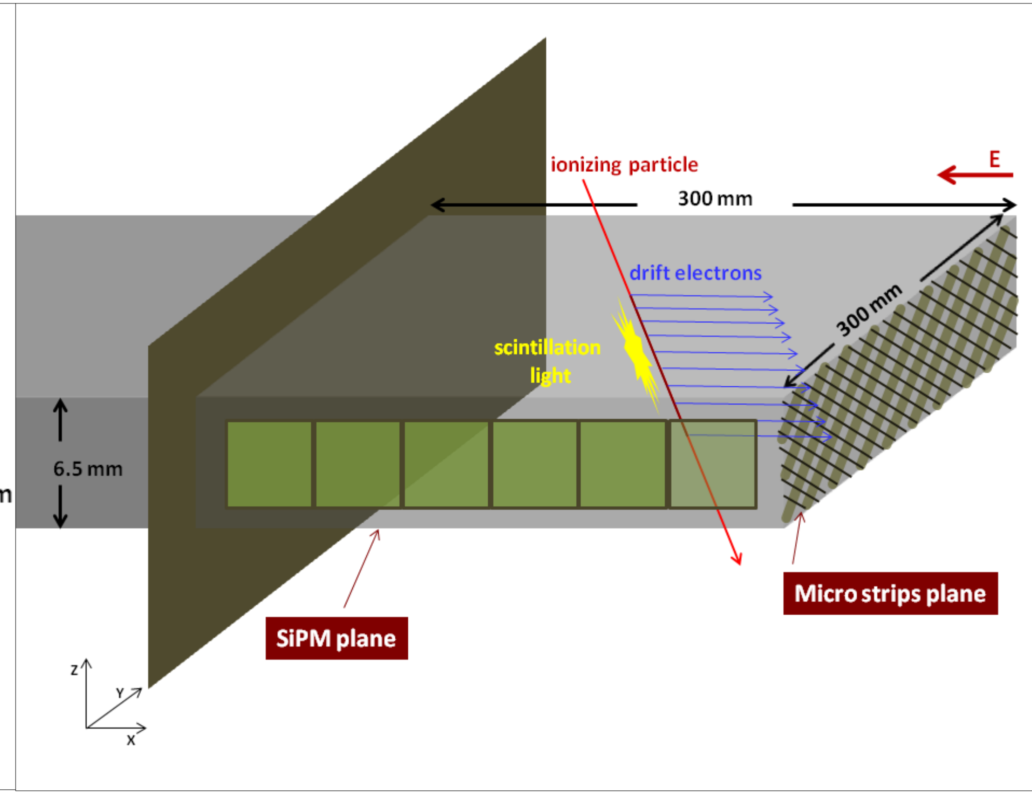


- **Neutrino detectors with the goal to observe the vertex of the neutrino interaction need a very massive target, and a good tracking resolution**
  - **The solution adopted by ICARUS is a liquid Argon TPC where the massive material is also active for the tracking. A full active detectors without dead zones.**



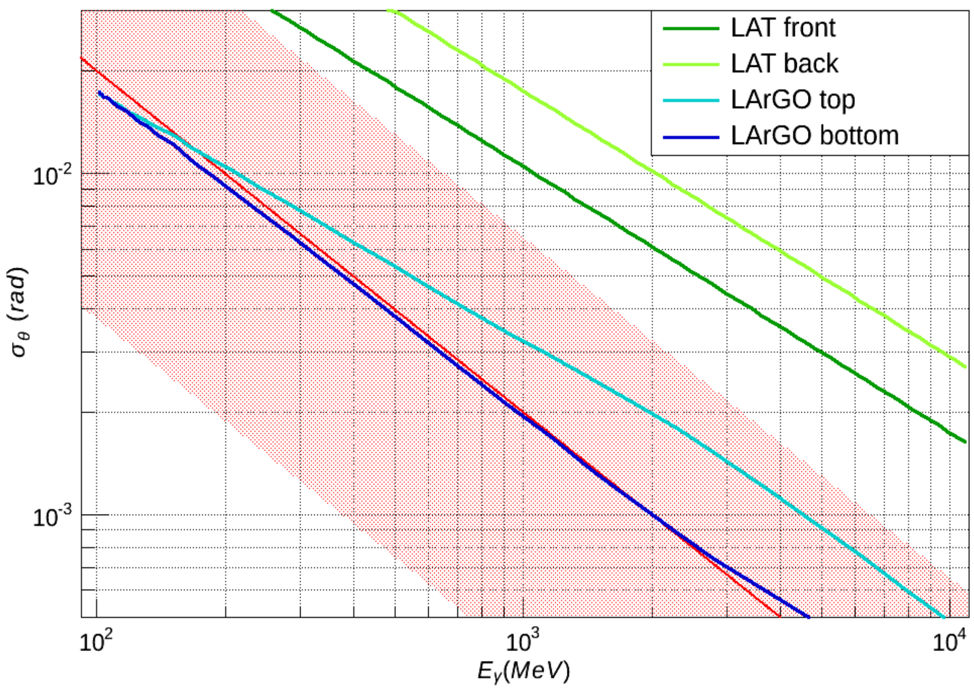
LArGO

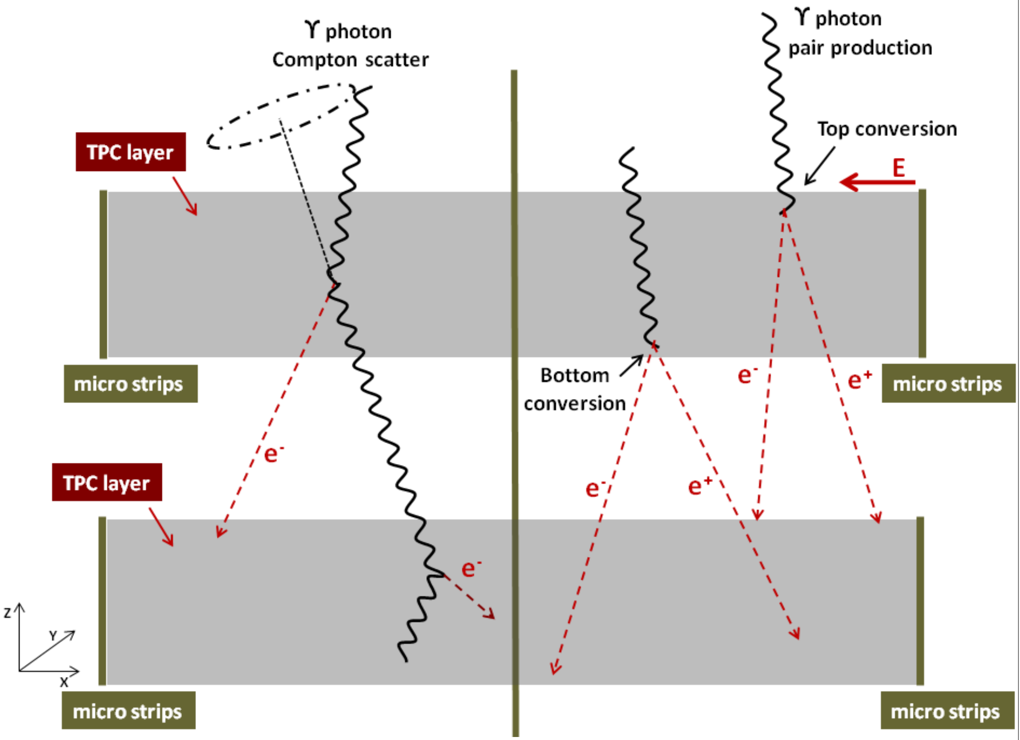




- **LArGO design elements**
  - a stack of 32 very thin (6.5 mm) LAr-TPCs (TPC-layers),
  - Inter-layer distance 2.5 cm
    - the e^+e^- tracks by 1 GeV photon converted in a TPC-layer are separated at the underlying layer by twice the TPC pitch.
  - 1 X_0 diluted in 1 m
  - Pitch of the drift charge readout plane p = 100 µm
  - Spatial resolution 25 µm
    - Current LAr-TPC have pitch and spatial resolution of ~1 mm,
  - LAr close to triple point (84 K, 70 kPa)
    - X_0 = 20 cm. Minimum multiple scattering

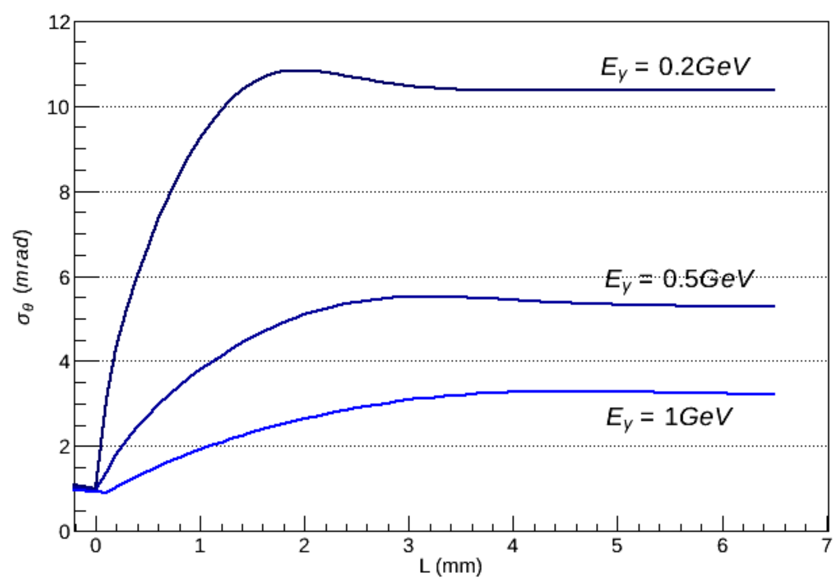
Performance in pair production regime



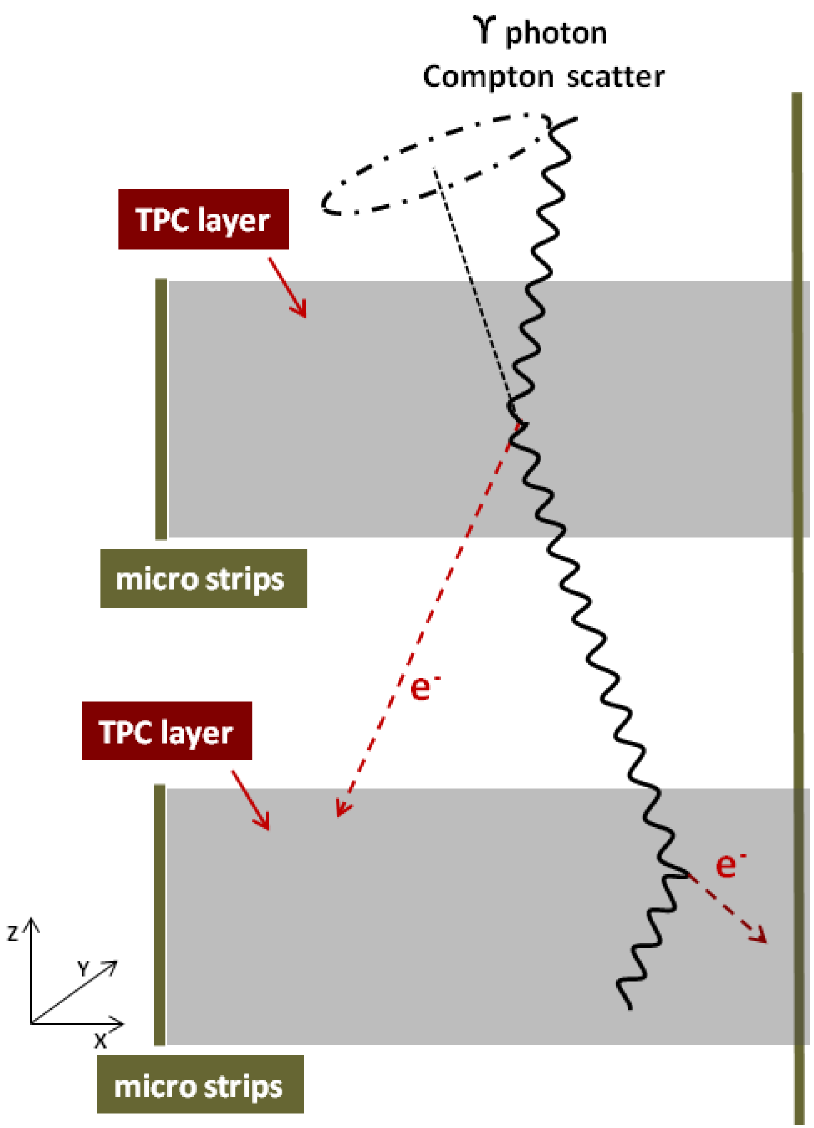


Top left: angular resolution of LArGO versus the energy of incident photons converting in the top of a TPC-layer (LArGO top), or at 1 mm from its bottom (LArGO bottom). The red line is the average aperture angle of the converted pair, while the shadowed red area shows its 95% probability distribution.

Right. Profile of the angular resolution versus the depth of the conversion point in a TPC-layer for photons with energy 200 MeV, 500 MeV, and 1 GeV. L = 0 mm is the deepest point of a TPC-layer.



Compton with LArGO



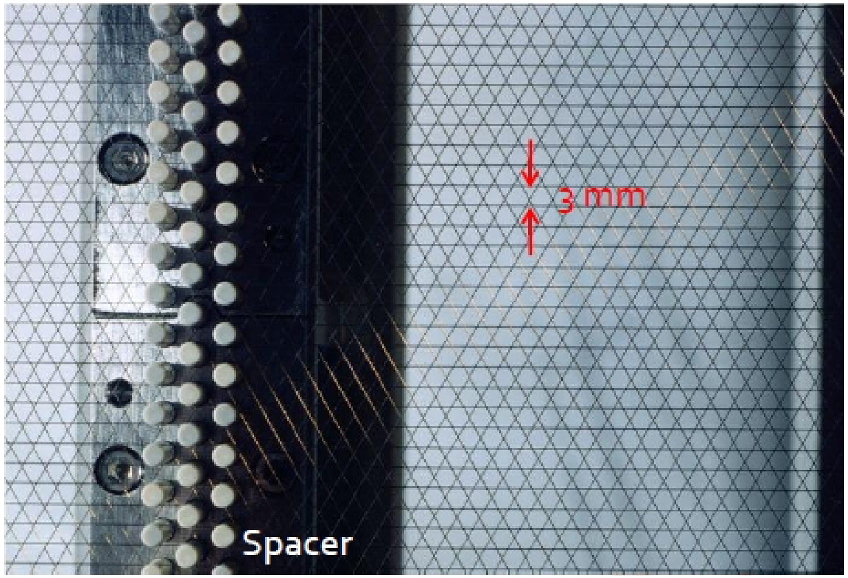
- Two consecutive Compton interactions in LArGO will happen in different TPC-layers
  - attenuation length of 1 MeV photons in LAr at ~70kPa is 180 mm
  - minimum distance d=2.5 cm, spatial resolution σ=0.025 mm -> $\delta\theta_r$ negligible
  - the angular resolution of LArGO in Compton regime is dominated by its energy resolution
- Energy resolution < 3%
  - strong anti-correlation between ionization and scintillation signals

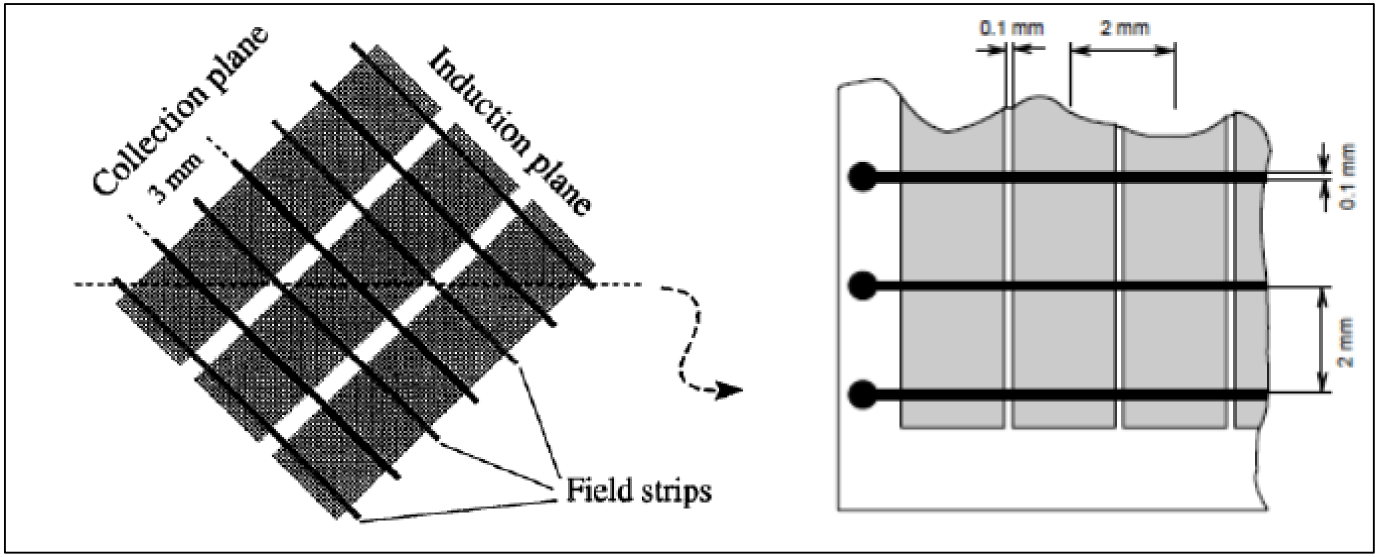
    Crawford, et al., 1987, NIMP A, 256

    Aprile, et al., 2007, PhysRev B, 76
  - high photon detection efficiency of SiPMs
- Angular resolution of ~1° @ 1.8 MeV.
- Polarization above ~2 MeV
  - LArGO is able to track the scattered electron of the first Compton interaction
  - stopping power of the electrons in LAr at ~70 kPa is approximately 1.4 MeV/cm.

Readout plane: wires vs printed circuits

- ICARUS uses 3 planes of wires (3 mm pitch) to record the drifting electrons
  - This is a good technique to cover the very large areas of the ICARUS TPC
- A valid alternative are multi-layer printed strips
  - This technique was developed in the ICARUS R&D (P. Cennini, et al., 1994, NIMP A, 346), and for the COIMBRA PET (Solovov, V. et al., 2002, NIMP A, 477)

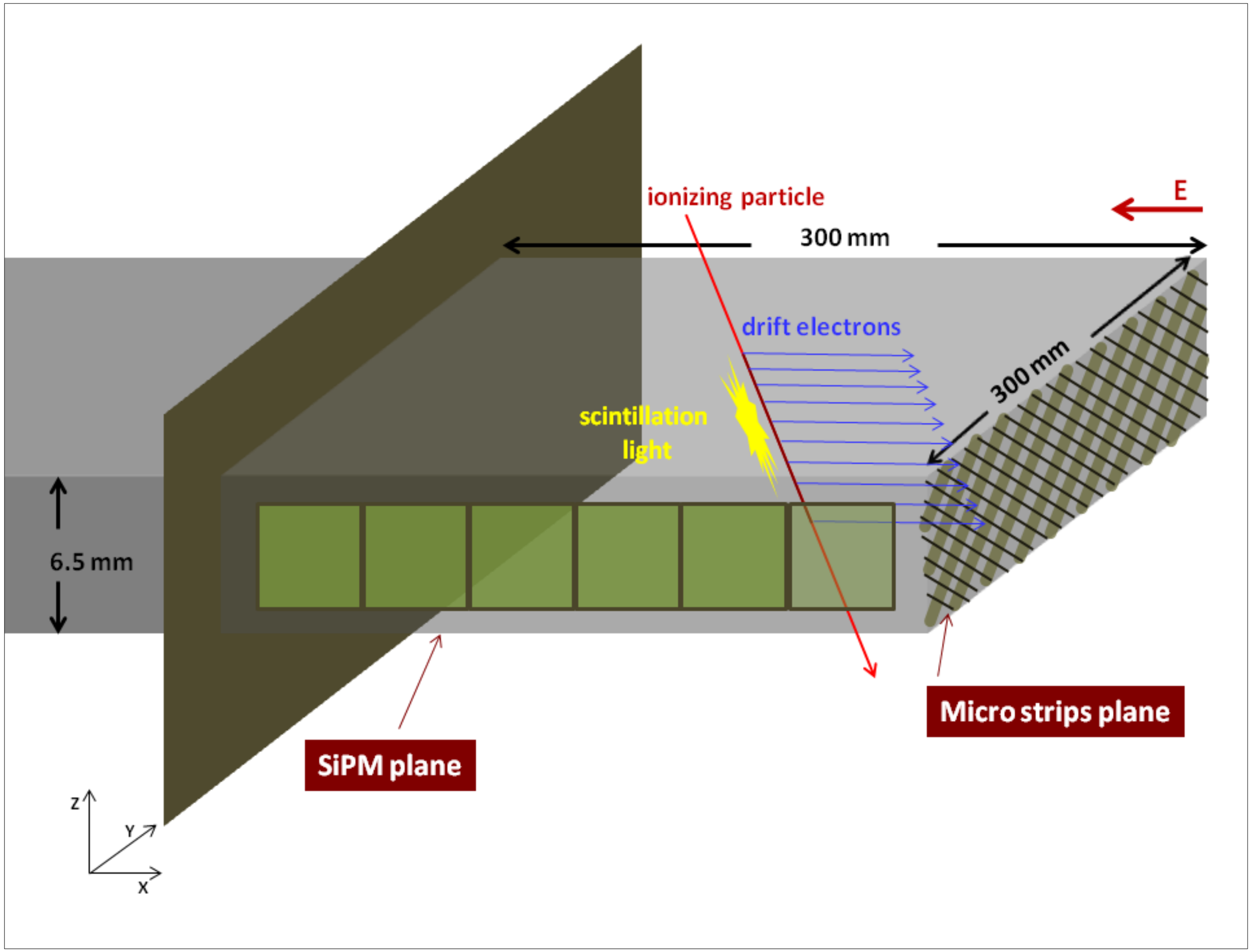




Muli-layer printed strips are very suitable

- for covering small surfaces (like for a TPC-layer of LArGO),
- and to realize strips with very small pitch (~100 μm)

Multi-layer printed strips applied to LArGO



- The strips are placed at 45° respect the Z-axis of a TPC-layer
  - The resolution of on-axis tracks is optimized
  - The length of the strips is as short as ~ 1 cm
  - This configuration is very useful especially for the signal to noise ratio, and the power consumption

Signal to Noise

- **Signal/Noise**
  - A MIP in LAr produce ~5000 e^-/mm. There is no charge amplification in LAr
  - The main source of noise is from the readout electronics.
  - ICARUS has ENC ~ 1000 e- per wire (3 mm pitch). S/N~15.

- **The ENC is proportional to the total capacitance of the detector**
  - The inter-strip capacitance (C_{is}) dominates when the pitch is very small

$$C_{is} = l\left(a + b\frac{w+c}{p}\right) \propto \frac{l}{p}$$

    - *l, w* are the length and the width of the strip, respectively
    - *a,b,c* are constants depending by the substrate material

  - In ICARUS *l/p* ~500
  - In LArGO, *l/p* ~100, thanks to the 45° strip configuration
  - The ENC is reduced by a factor 5 just for the strip configuration in LArGO, and their shortness

How to reduce the electronic noise

- **Low-noise electronics developed for new neutrino and dark matter experiments have reached very low ENC values**

Readout electronics for the MicroBooNE LAr TPC, with CMOS front end at 89K

$\mathrm{ENC} < 600\ e^{-}$

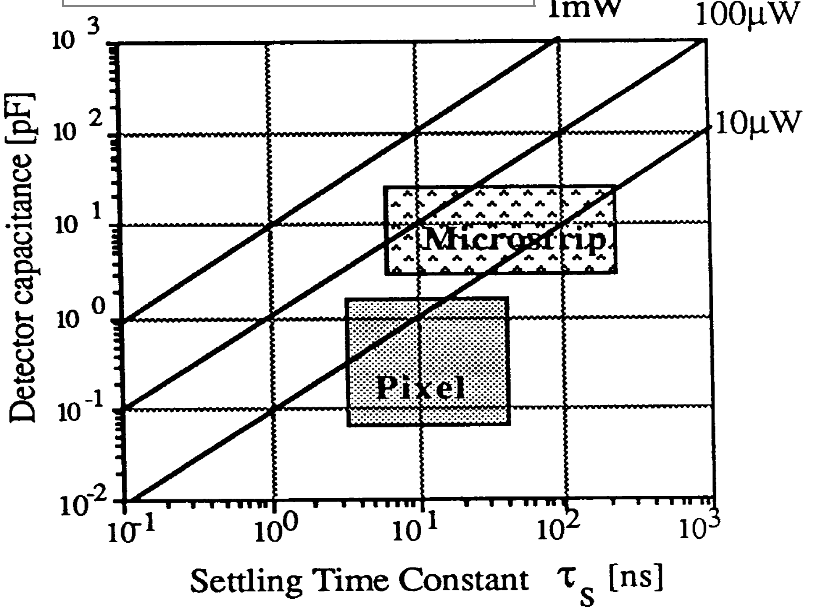
H. Chen,[1] K. Chen, G. De Geronimo, F. Lanni, D. Lissauer, D. Makowiecki, V. Radeka, S. Rescia, C. Thorn and B. Yu

- **Other considerations**
  - The electronic of ICARUS is not cold.
  - It is outside the Dewar. There are very long cables (few meters long) to connect the readout planes with the electronic (50pF/m)
  - The total capacitance per wire in ICARUS is ~300 – 400 pF
  - The inter-strip capacitance estimated for LArGO with the formula in the previous slide using the constant for a silicon substrate give $C_{is} < 2$ pF

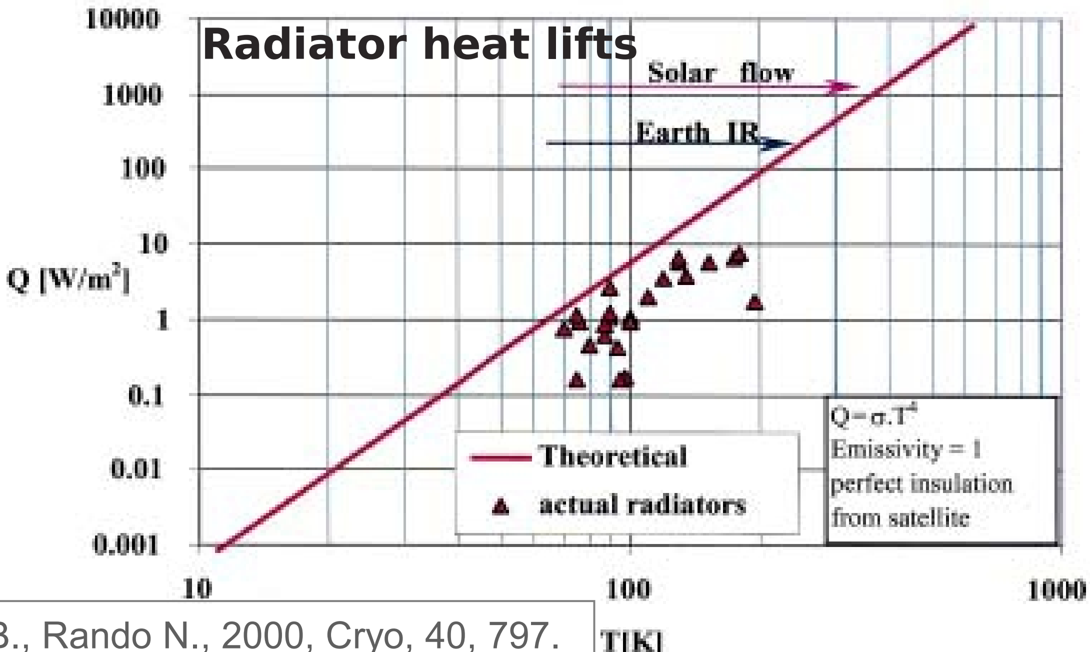
Power consumption and cryogenic

- Number of channels in LArGO is of the same order of magnitude than the LAT-tracker
  - Power consumption of the LAT ~160 W
- The power consumption is proportional to the detector capacitance
  - Hence to the length of the strips
  - Stript length ratio LAT/LArGO ~ 40
  - Same ratio for the power consumption
  - Power consumption of LArGO O(10 W)

Pierre Jaron, CERN EF.

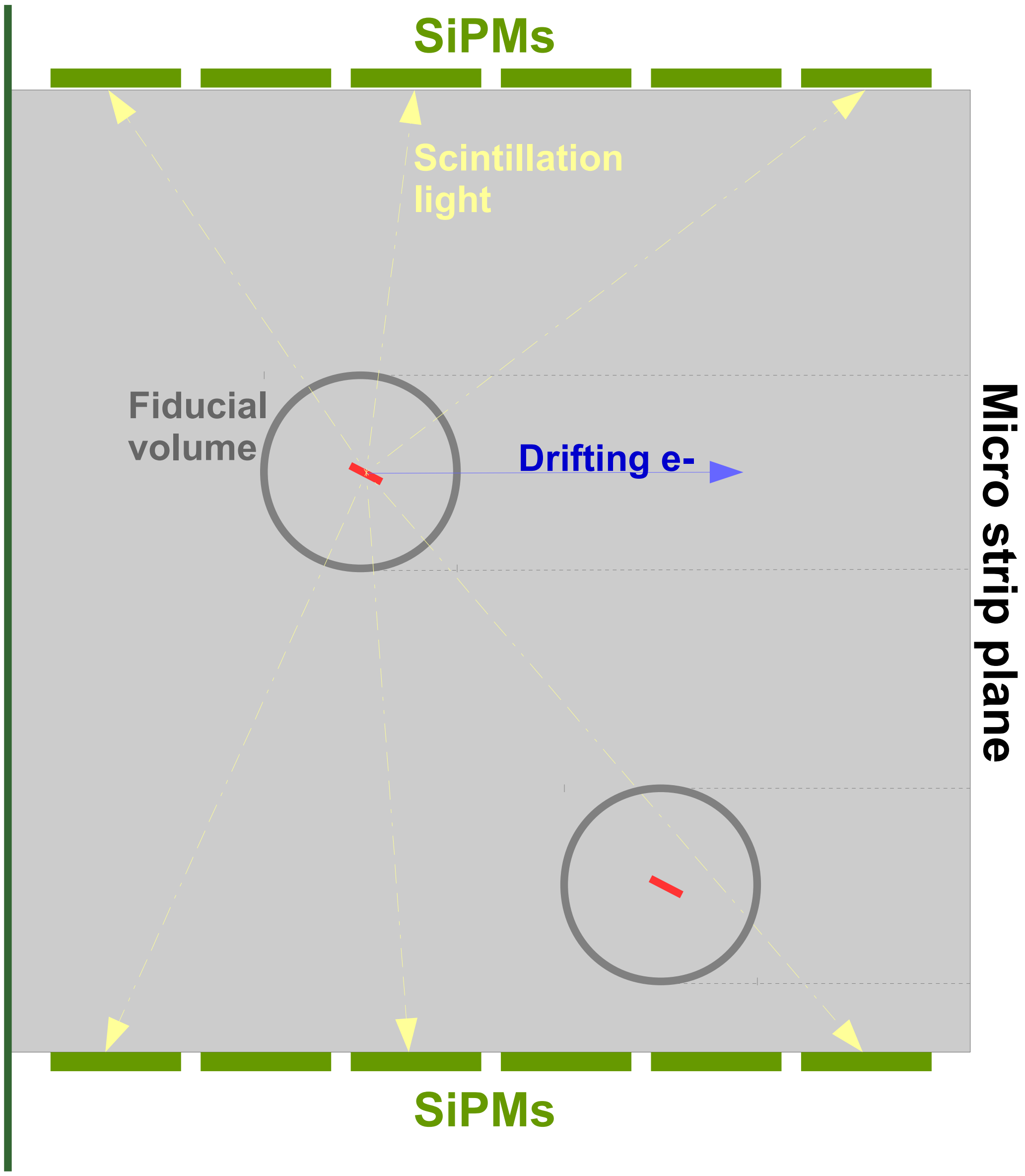


- The cryogenic temperature of ~84 K required by the liquid argon in LArGO can be reached even by passive radiators
  - At 80 K the radiators can dissipate ~ 1W/m²



Collaudin B., Rando N., 2000, Cryo, 40, 797.

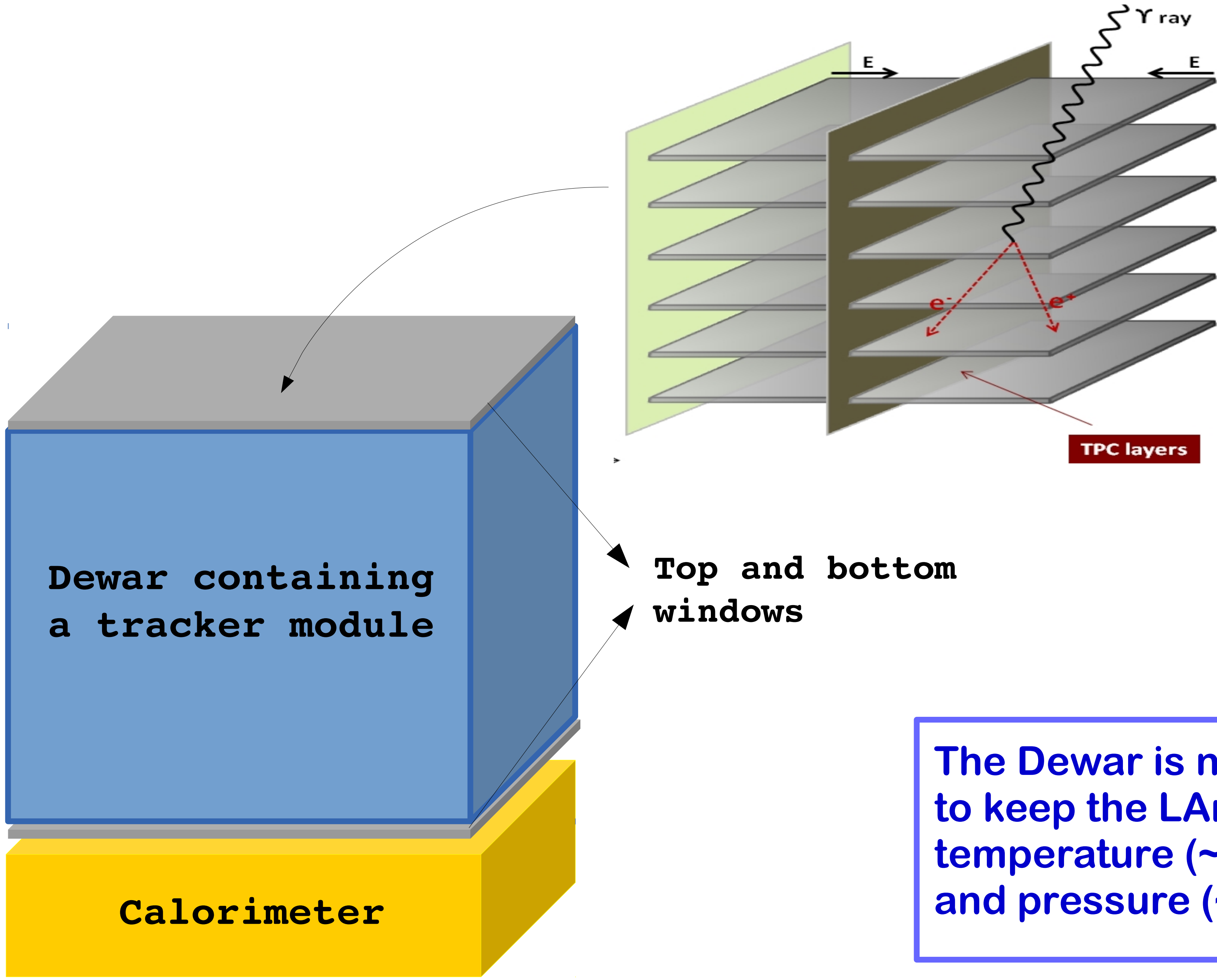
Scintillation light and SiPM



- Primary task of SiPM is to trigger and define the time stamp of an event
- A fiducial volume of the track can be evaluated from the asymmetry of the scintillation light collected by SiPMs
  - Helpful for the reconstruction
  - Helpful to discriminate a second event arrived during the e- drift time of the previous one
    - Expected ~0.4 particles/300μs in 50x50 cm^2 TPC-layer

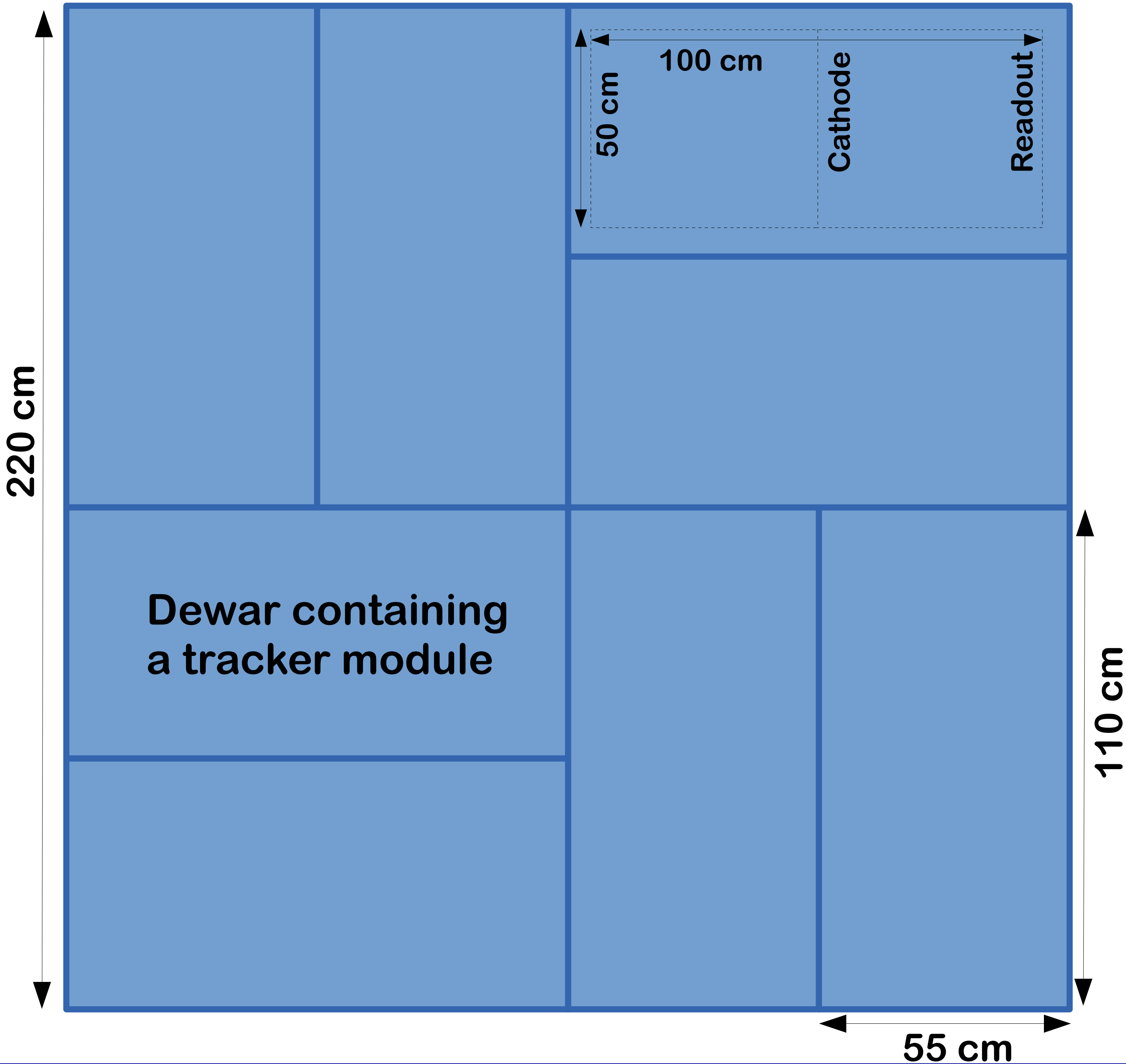
Scintillator	Liquid Argon
Photon Yield [ph/MeV]	4.0×10^4
Fast Decay Time [ns]	6
Slow Decay Time [ns]	1200-1500

Single module



The Dewar is needed to keep the LAr temperature (~84 K) and pressure (~70 kPa)

Satellite design hypothesis



- Height tracker modules with a total geometrical area of 4 m^2
- FoV of each module 45° x 30°
- Full FoV >60° x 60°
- The 8 modules are covered by an Anti Coincidence Detector

Summary

- The challenge of LArGO is to adapt the LAr-TPC technology to the needs of γ-ray astrophysics
  - The performance of a γ-ray telescope is summarized by 3 parameters:
    - Angular resolution, Effective Area (Aeff), Field of view (FoV)

- Main features of LArGO
  - Unprecedent angular resolution without reducing Aeff and FoV
    - LArGO has at 100 MeV approximately the same angular resolution that currently Fermi-LAT has at 1 GeV
  - Working in both Compton and pair conversion regimes
  - Wide energy range ~100 keV – 100 GeV if coupled with a calorimeter 10 X_0 deep
  - Polarization measurement in both Compton and pair conversion regime
    - Polarization energy range ~ 2 MeV – 1 GeV

- LArGO is very promising for a future multipurpose γ-ray telescope

Backup slides

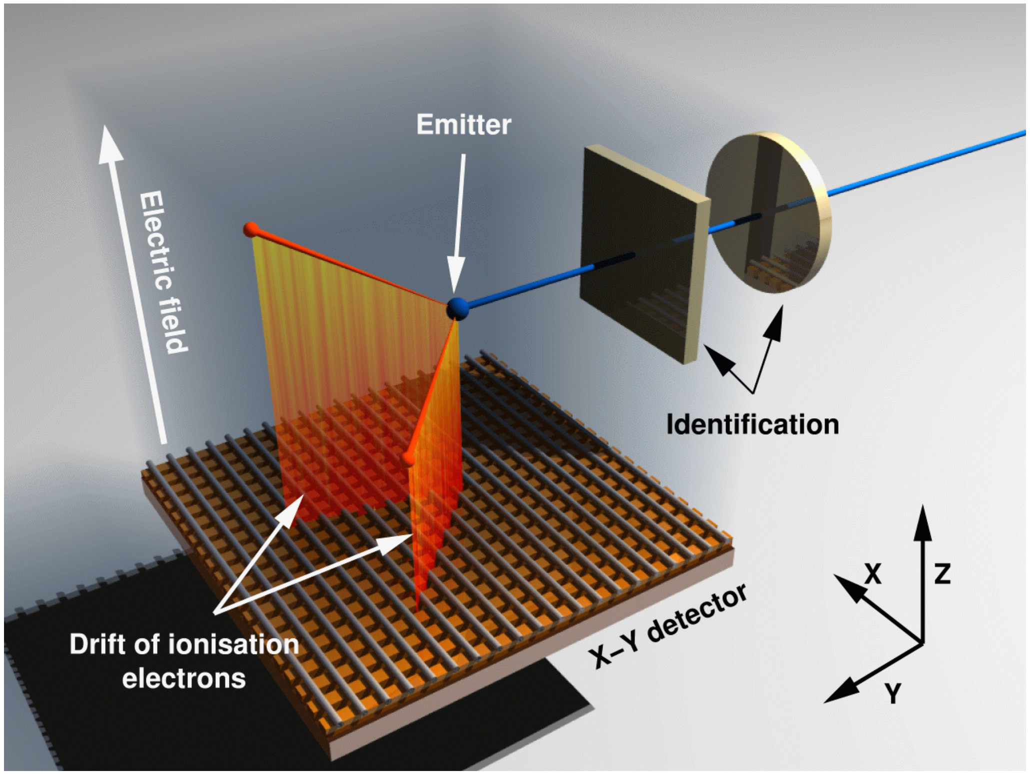
Orbits and Rockets

Orbits

Equatorial LEO	Langrangian point L2	ISS
• Low CR bkg • High down link rate	• Good for Cryogenic • No Earth albedo/occultation	• Possible human operations after the launch

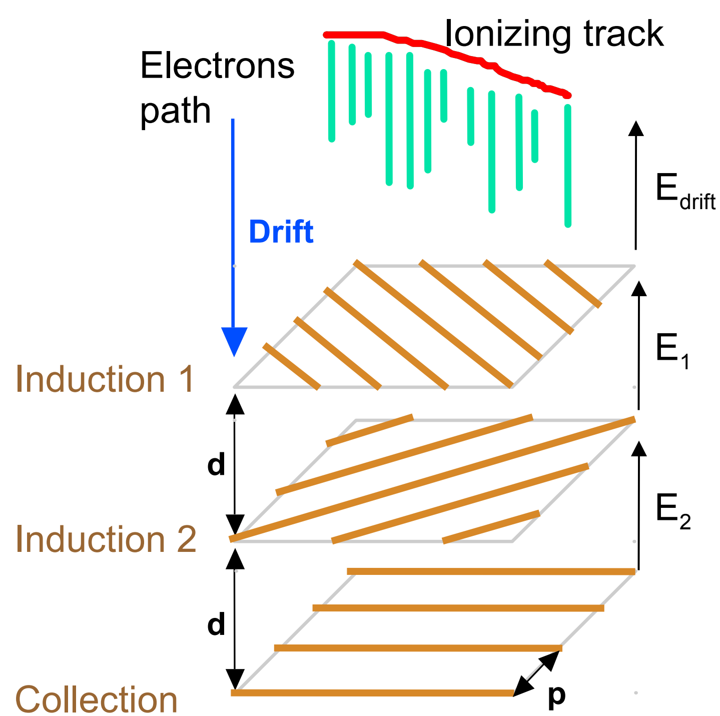
Rockets	Diameter (m)	Payloads Weight (t)	Launch Site	Cost
Soyuz-2 (EU-Russia)	3.7	7.8 (LEO) 4.5 (GTO)	Plestsk Kourou (French Guiana)	50M EU?
Arianne 5 (EU)	5.4	16-21 (LEO) 7-10 (GTO)	Kourou (French Guiana)	120M EU
Vega (EU)	3.0	1.5 – 2.0	Kourou (French Guiana)	~30M EU
Delta II (US)	2.44	2.7- 6.1 (LEO) 0.9 - 2.17 (GTO) 1 (open orbit)	Cape Canaveral	36,7M USD (1987)
Delta IV (US)	5.0	8.6 – 25.8 (LEO) 3.9 – 10.9 (GTO)	Cape Canaveral/ Vanderberg	
ATLAS V (US)	3.81	9.8 – 18.8 (LEO) 4.7 – 8.9 (GTO)	Cape Canaveral/ Vanderberg	
Falcon 9	3.7	10.4 – 26.3 (LEO) 4.5 – 15.0 (GTO)	Cape Canaveral/ Kwajalein	

LAr TPC working principle and status of the art

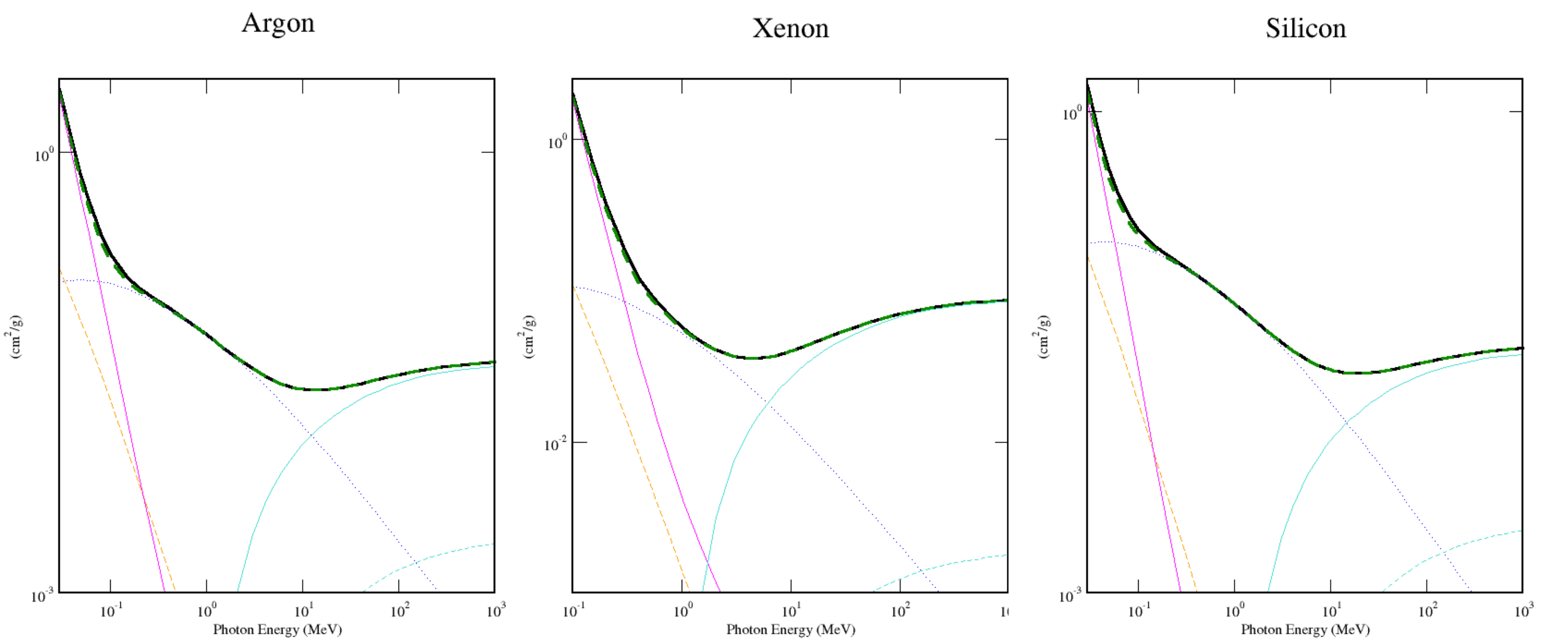


- Status of the art: 3ton prototype
  - 2 grid of wires with a pitch of 2 mm
  - Spatial resolution in the drift direction 0.2 mm
  - Spatial resolution in the readout plane ~0.6 mm

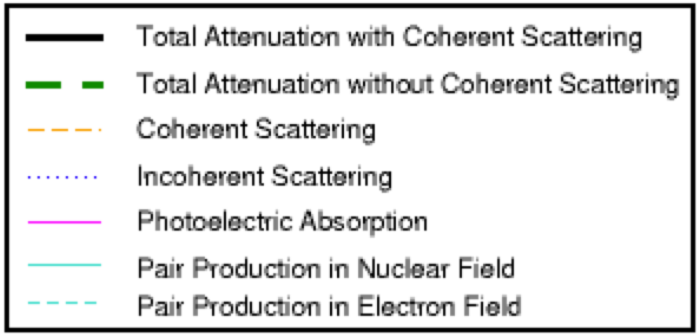
- Status of the art: ICARUS
  - 3 grid of wires with a pitch of 3mm
  - Spatial resolution in the drift direction 0.7 mm
  - Spatial resolution in the readout plane ~1mm
  - E_{drift} = 500 V/cm
  - Electron drift velocity ~ 1.5 mm/μs



Liquid Argon characteristic features



	LAr	LXe	Si
Cross Section (cm^2/g @ 1 MeV)	**5.7×10^{-2}**	**5.2×10^{-2}**	**6.3×10^{-2}**
Density (g/cm^3)	**1.39**	**3.06**	**2.33**
Attenuation length (cm @ 1MeV)	**12.6**	**6.3**	**6.8**
Radiation length	**14.3**	**2.77**	**9.3**



γ-ray polarization

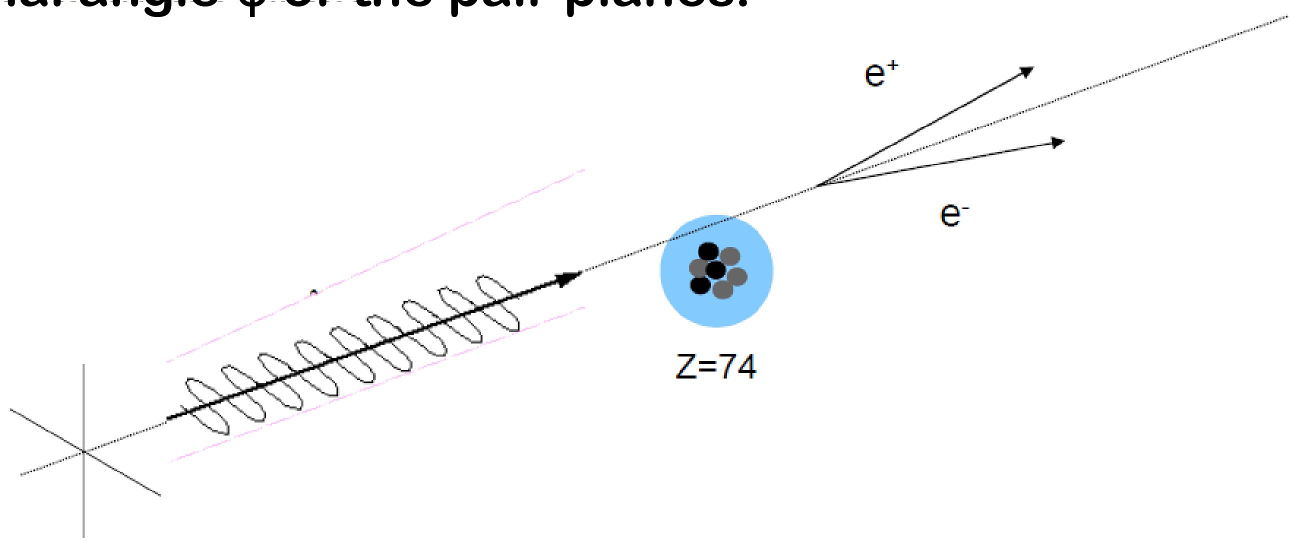
- **Pairs are produced preferentially in the plane identified by the linear polarization of the incident photons and its direction**
  - **In case of small nuclear recoil (γ, e^+, e^- coplanar) the photon conversion cross section is:**

$$\sigma_\gamma(\varphi) = \frac{\sigma_0}{2\pi}\left[1 + P\lambda\cos^2(\varphi)\right]$$

Maximon L. C., Olsen H., 1962, Phys. Rev. 126, 310

  - **φ is the angle between the e+e- plane and the photon's electric field vector**

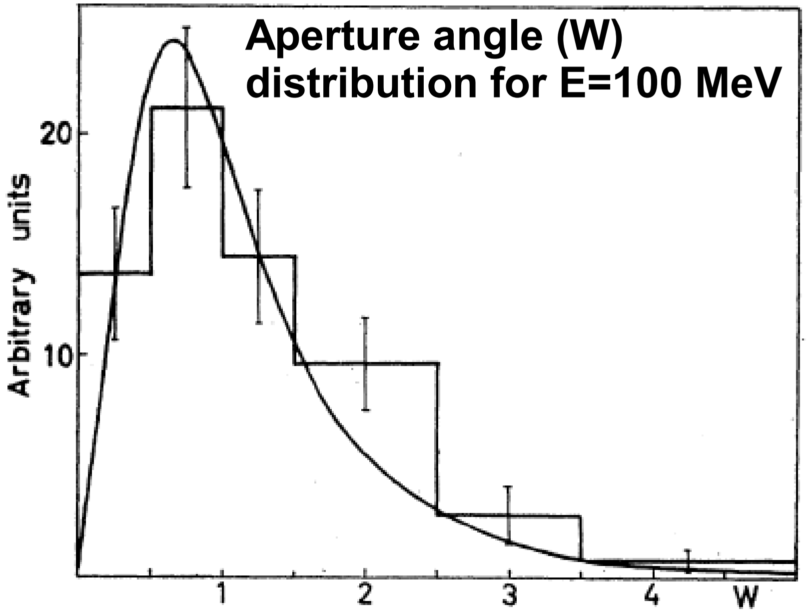
- **The gamma-ray polarization can be detected looking for the modulation of the azimuthal angle φ of the pair planes.**



Ingredients for the design of LArGO

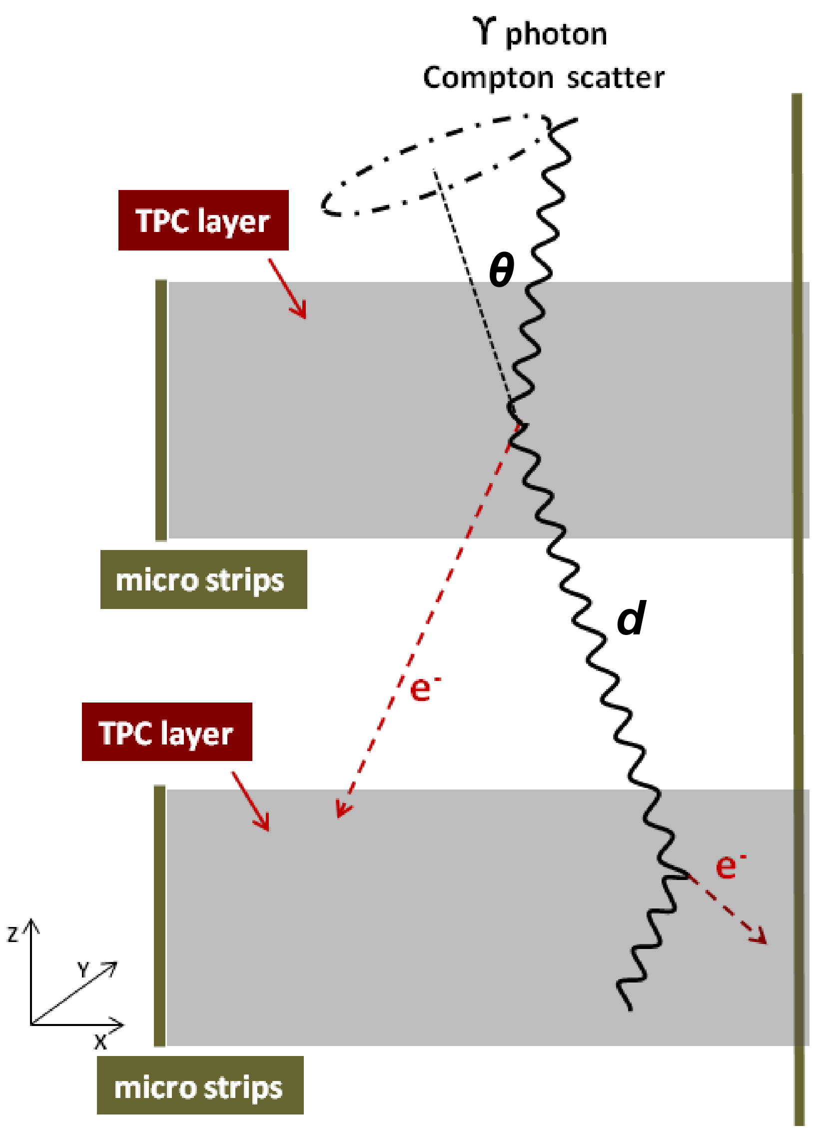
- **The purpose is to project a tracker for γ-ray telescope which has better performance than Fermi-LAT, and which can work as γ-ray polarimeter at least until photon energies of 1 GeV.**
  - Tracker depth ≥ $1X_0$
  - Tracker full height ~1m
- **γ-ray polarizzation**
  - In order for the polarization to be detected, the plane of the converted pair needs to be identified.
  - The tracker has to discriminate the two tracks with an angular resolution lower than their aperture angle

$$\sigma_\theta \leqslant \frac{4\,m_e}{E_\gamma}\ , \qquad for\ \ E_\gamma \leqslant 1\,GeV$$



Compton regime

- **When a photon undergoes one or more Compton scatters within the detector, and then is photoelectrically absorbed, its direction can be reconstructed from the kinematics of the scatterings.**



The angular resolution is $\delta\theta=\sqrt{\delta\theta_E^2+\delta\theta_r^2}$

$\delta\theta_E \propto \Delta E/E$ **uncertainty due to energy measurement**

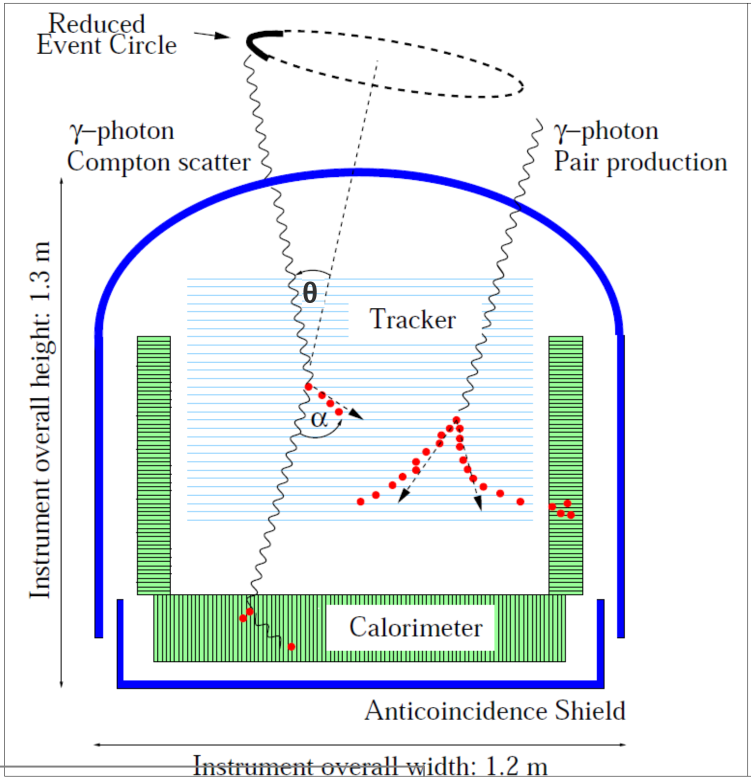
$\delta\theta_r \propto \sigma/d$ **due to the error on the position of the scattering points**

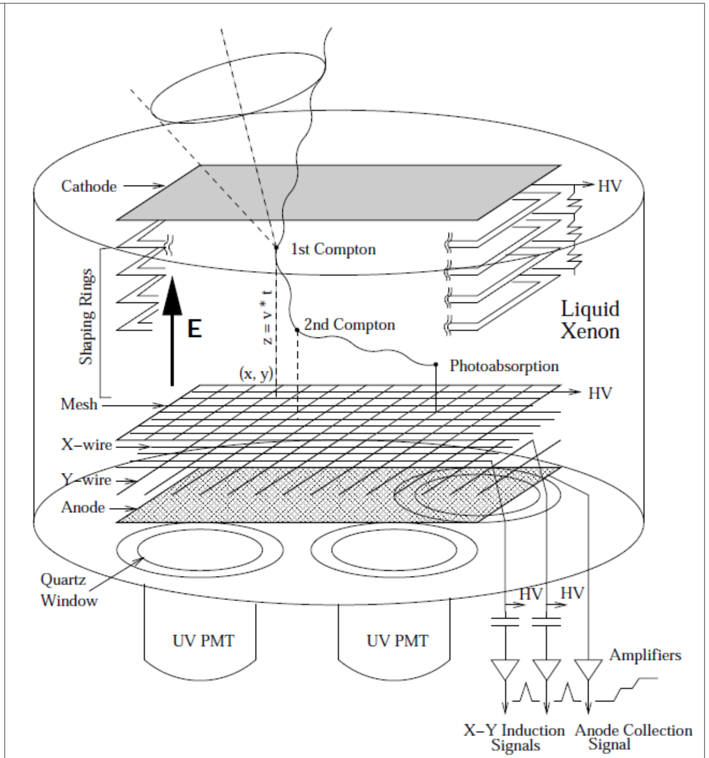
- **Tracking the recoil electron of the first Compton interaction**
  - **Solve the ambiguity in the sky direction of single photon**
  - **the circle of possible positions on the sky is reduced to a small arc proportional to the angular resolution (σ_a) of the electron track.**
  - **the background of gamma-rays from diffuse emission or close sources is reduced, and the sensitivity is improved by a factor** $\sqrt{\sigma_a/2\pi}$
- **The measurement of the recoil electron allows the detection of the gamma-ray polarization**

$$\frac{d\sigma_{Cs}}{d\Omega}=\frac{1}{2}\left(r_e\frac{E}{E_0}\right)^2\left[\frac{E}{E_0}+\frac{E_0}{E}-2\sin^2\theta\cos^2\varphi\right]$$

Compton prototypes

- **MEGA**
  - 32 double sided Si-strip detectors (not interleaved by tungsten foils) surrounded by a pixelated CsI calorimeter
  - energy range is 0.4 – 50 MeV
  - angular resolution of 2°, energy resolution of 8% @ 2 MeV
- **LXeGRIT**
  - liquid Xenon TPC
  - energy range is 0.3 - 10 MeV
  - angular resolution of 3°, energy resolution of 8.8% @ 1 MeV





Bloser P., et al., 2003, NIMPA, 512, 220

E. Aprile 1998, NIMP A, 412, 425

Diffusion

- The electrons drifting toward the anode are affected by diffusion

Transverse diffusion S_t

$$S_t = \sqrt{2DL_d / v_d}$$

- D~4 cm^2/s: diffusion coefficient
- V_d = 1.5 mm/μs

– For a drift length of 50 cm S_t~0.5 mm

– S_t is small compared with the thickness of a TPC-layer (6.5 mm), but larger than the pitch.

Space resolution in the drift direction

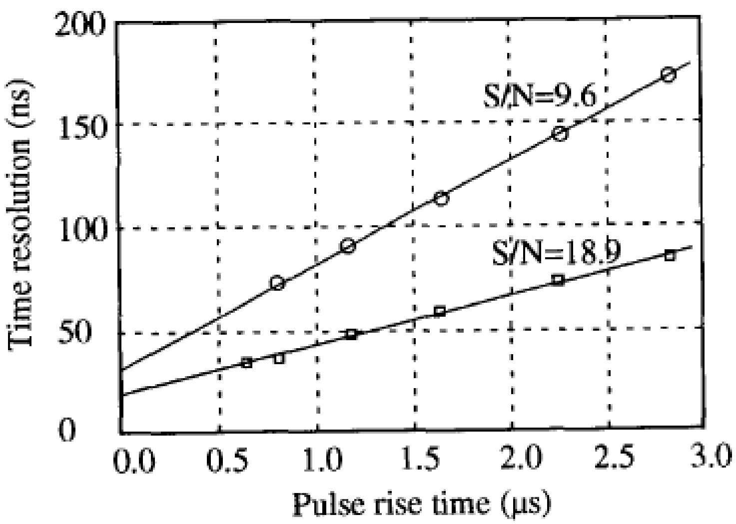


Fig. 11. Resolution on the time measurement as measured for test pulses of different rise times and of different amplitudes (different signal to noise ratios).

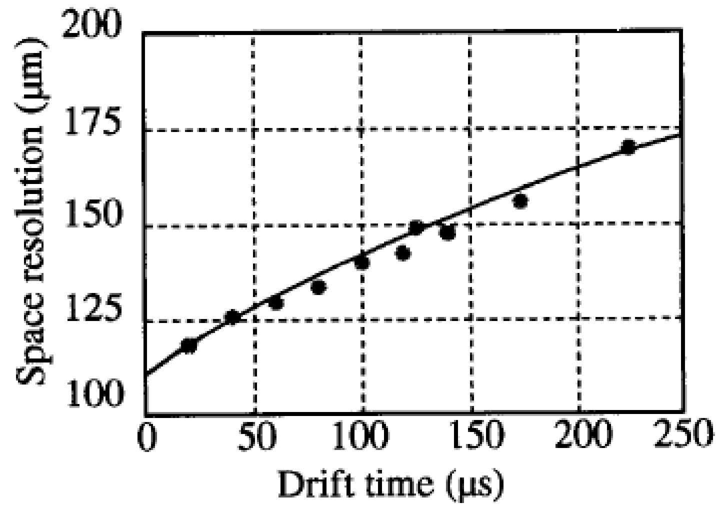


Fig. 20. Resolution in the drift time (350 V/cm). Curve is from described in

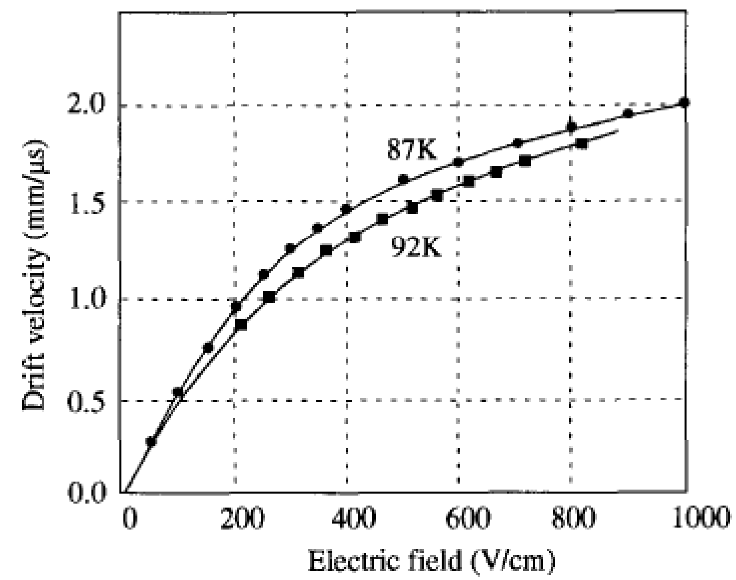
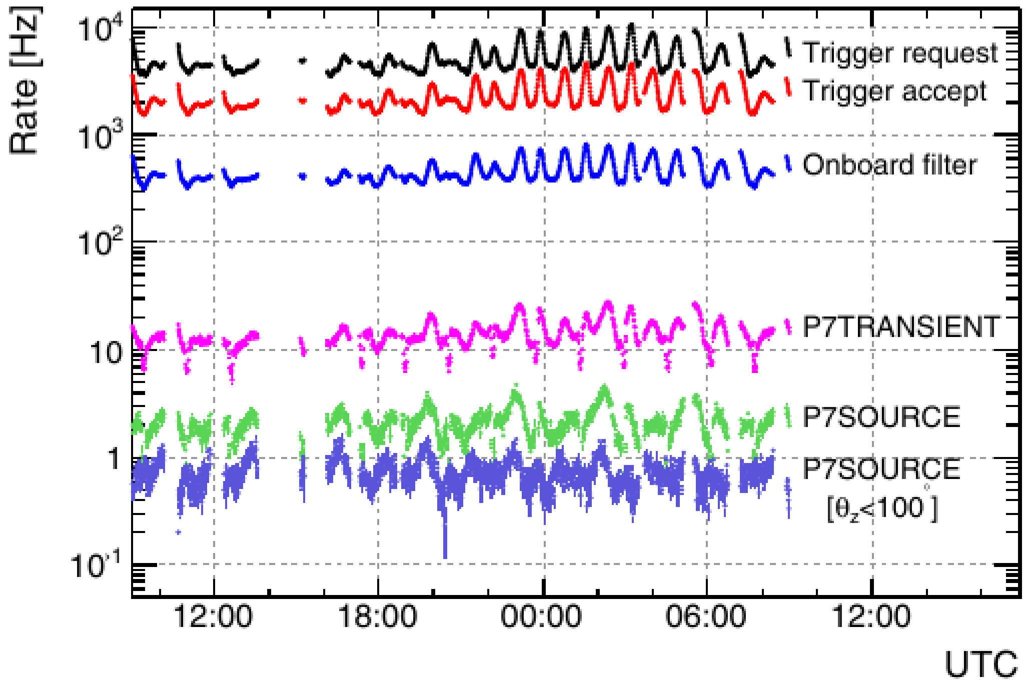
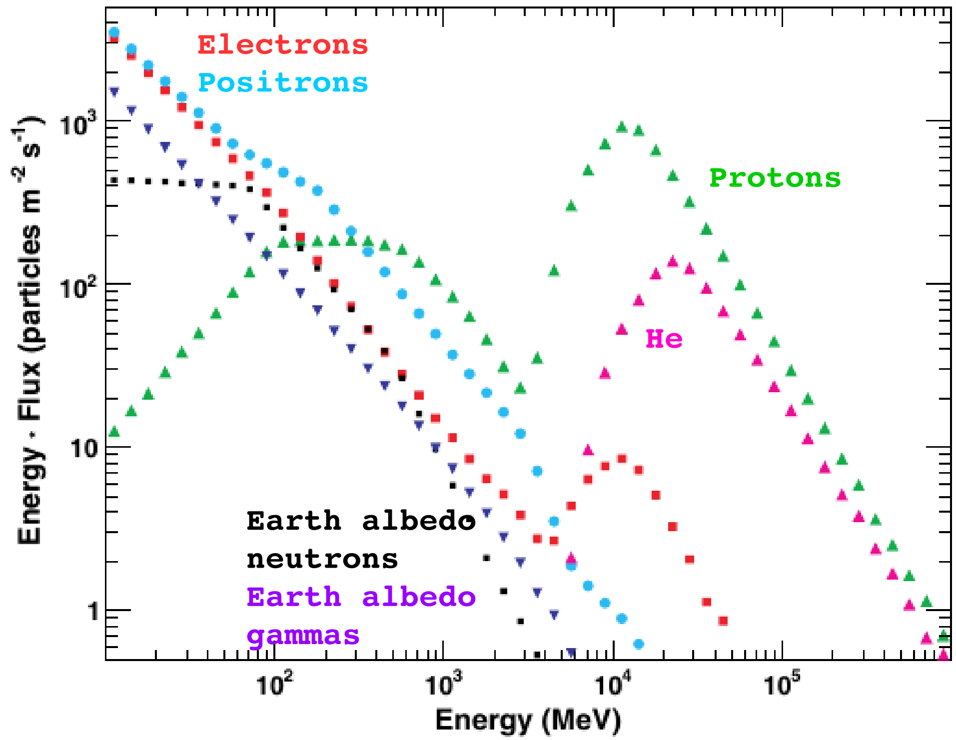


Fig. 13. Free electrons drift velocity in liquid argon as a function of the electric field. Circles at 87 K, squares at 92 K. Curves are to guide the eye

Cennini, P. et al., 1994, NIMP A, 345.

Particle rate





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