Fiber based tracking systems for space applications

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Outline

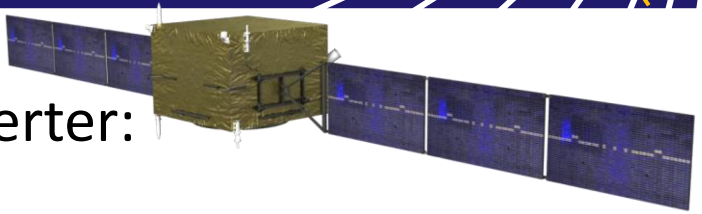
- Present experiments using trackers
- Next generation gamma-ray experiments
- Gamma-ray detection in the Compton regime
- NUSES mission
  - Detector mechanics & DAQ
  - Simulation studies
  - BeamTest @ PS (CERN)
- APT (The Advanced Particle-astrophysics Telescope)
  - SiPM readout and DAQ
  - Simulation studies
  - Prototype Lab tests

Present experiments with trackers

Fermi-LAT tracker/converter:

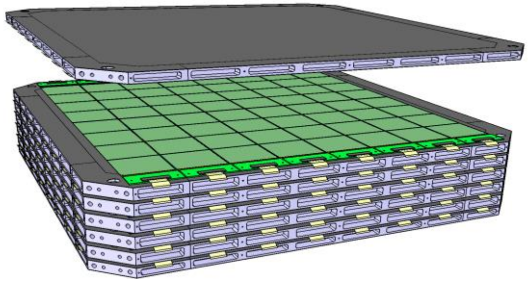
- nearly 74 m^2 of single-sided silicon strip detectors
- 4x4 towers
  - 37.3 cm wide and 66 cm tall
- 19 trays
  - 16 trays with tungsten
    - 12 top thin W (2.7% X0)
    - 4 bottom thick W (18% X0)
- 36 layers (18 X-Y measurement) with 4x4 wafers 8.95 cm wide and 400 μm thick

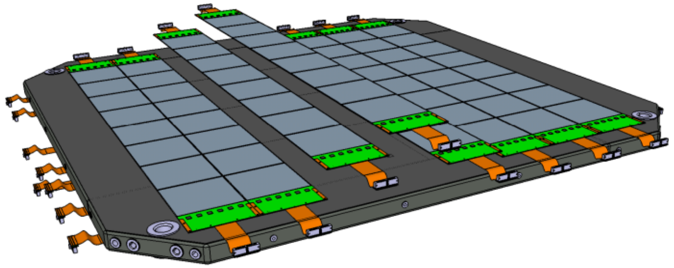
- Similar design in AGILE satellite

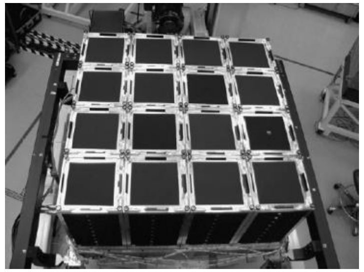


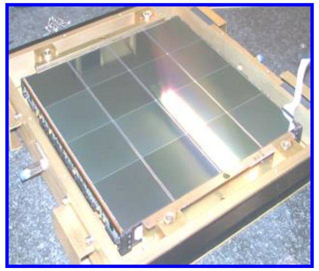
DAMPE tracker/converter:

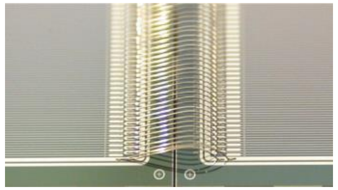
- 7 trays
  - 3 tungsten layer 1 mm each thick
- 12 SSSD layers (6 X-Y)
- 768 SSDs 9.5 cm wide and 320µm thick
- Nearly 7 m^2 of SSSDs
- Strip pitch of 121µm and read-out pitch of 242µm







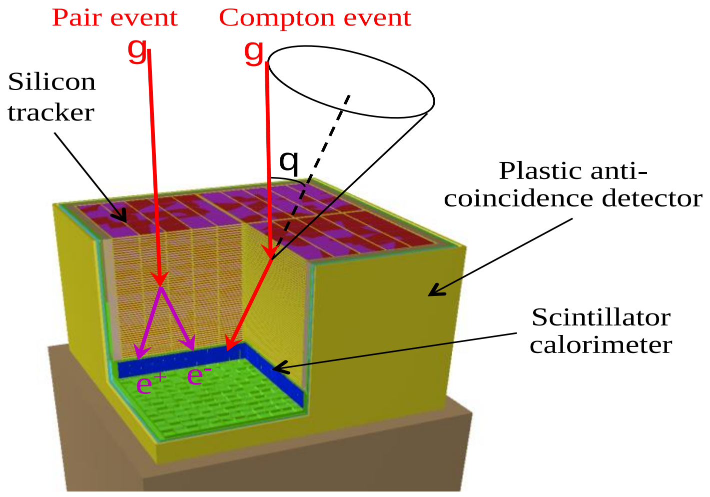


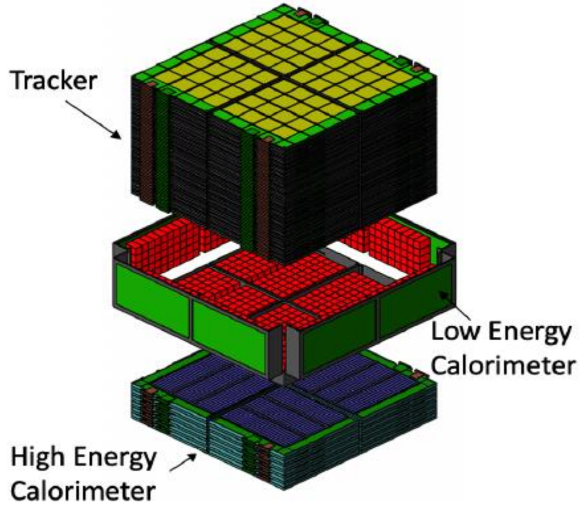


Next generation experiments

- MeV-GeV satellites
- **ASTROGAM**:
  - nearly 56 m^2 of double-sided Si strip detectors (DSSDs)
  - 4 towers, 56 layers of 5×5 DSSDs
    - 5600 DSSDs
  - Each DSSD has a total area of 9.5×9.5 cm^2, a thickness of 500 μm and pitch of 240 μm (384 strips per side)
  - Strips of the DSSDs are wire-bonded to form 5×5 2-D ladders
- **AMEGO**
  - 4 towers, 60 layers of 4×4 DSSDs
    - 4800 DSSDs
  - DSSD 9.5 cm wide, 500 μm thick and pitch of 500 μm (190 strips per side)
  - Strips of the DSSDs are wire-bonded to form 4×4 2-D ladders
- **AMEGO-X**
  - Silicon pixel detector

See talk by
A. Pastore



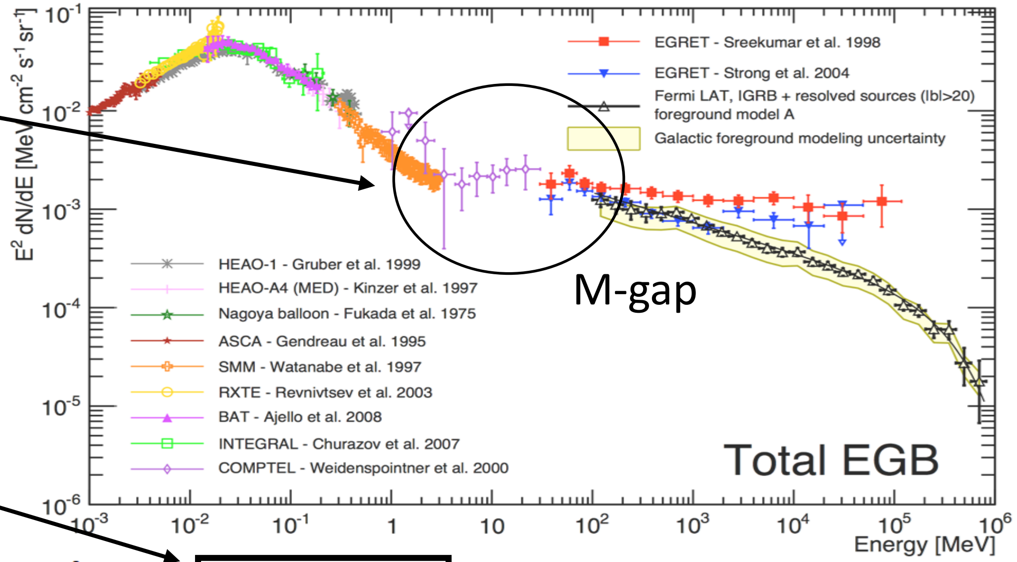


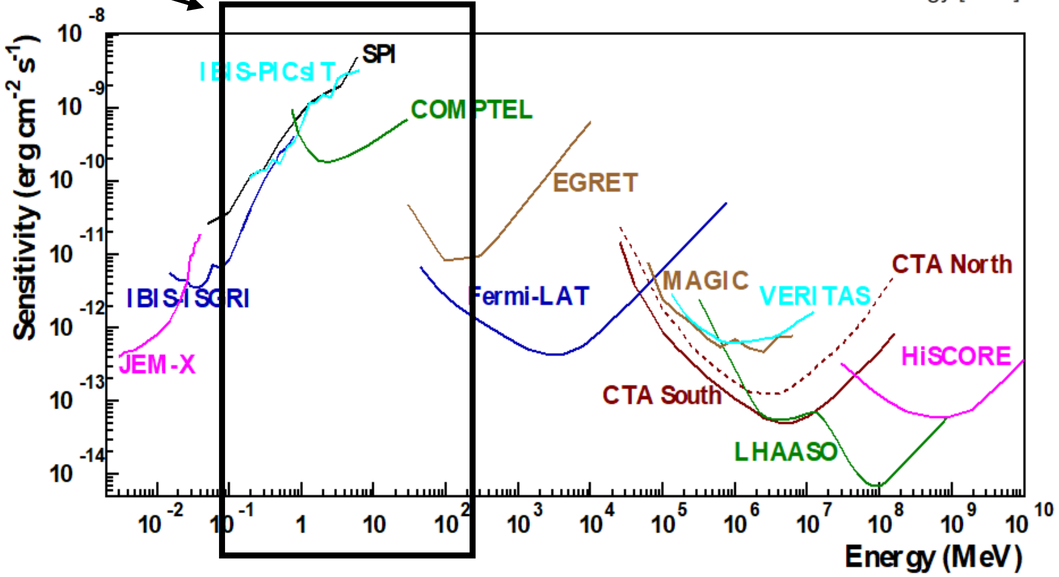
- **APT** - The Advanced Particle-astrophysics Telescope
  - Hodoscopic active tracker-converter based on thin crystal scintillator CsI(Na) read-out by external wavelength shifting (WLS) optical fibers and single SiPM readout
  - ADAPT - The Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (2025)

- **NUSES** – Pathfinder for new technologies
  - Compact tracker/converter based on scintillating fibers with SiPM array readout

New generation satellite experiments to explore gamma-ray MeV-GeV domain

- Poorly covered region of the electromagnetic spectrum ("M"-gap)
  - Only a few tens of steady sources detected so far between 0.2 and 30 MeV
  - Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)
- New generation of MeV-GeV gamma-ray telescopes
  - Should operate in both Compton and pair conversion regimes
- Need for a sensitive, wide-field gamma-ray space observatory operating at the same time as facilities like SKA and CTA, as well as GW and neutrino detectors, to get a coherent picture of the transient sky and the sources of gravitational waves and high-energy neutrinos



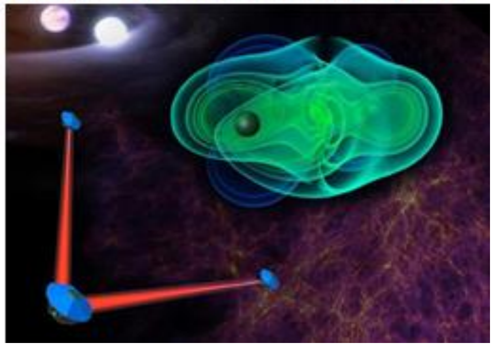


MeV-GeV gamma-ray telescope core science motivation

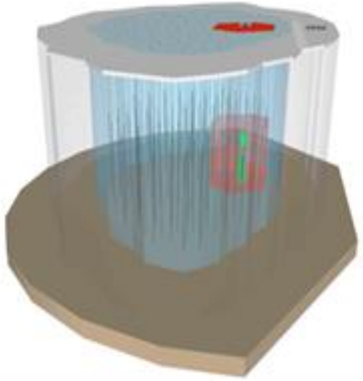
- Processes at the heart of the extreme Universe (AGNs, GRBs, microquasars): prospects for the Astronomy of the 2030s
  - Multi-wavelength, multi-messenger coverage of the sky (with Ligo/Virgo, CTA, SKA, eLISA, ...), with special focus on transient phenomena

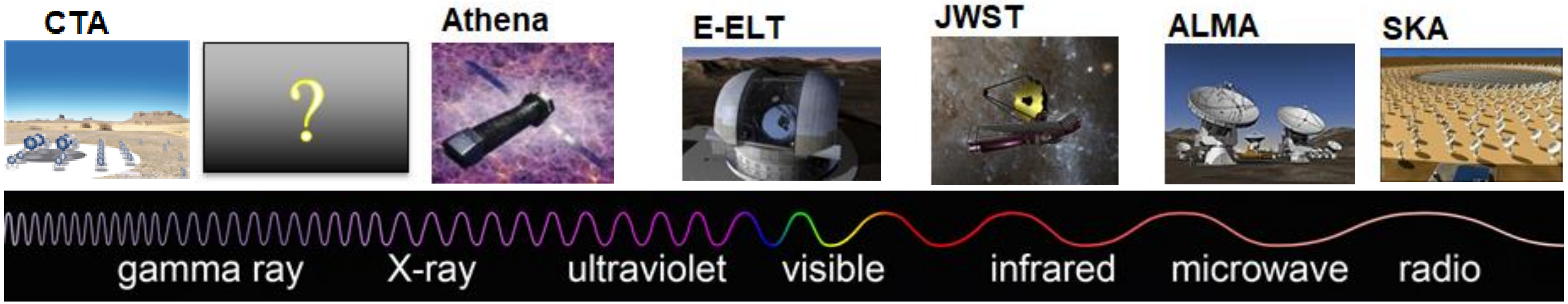
- The origin of high-energy particles and impact on galaxy evolution, from cosmic rays to antimatter
- Nucleosynthesis and the chemical enrichment of our Galaxy

eLISA – Gravitational waves

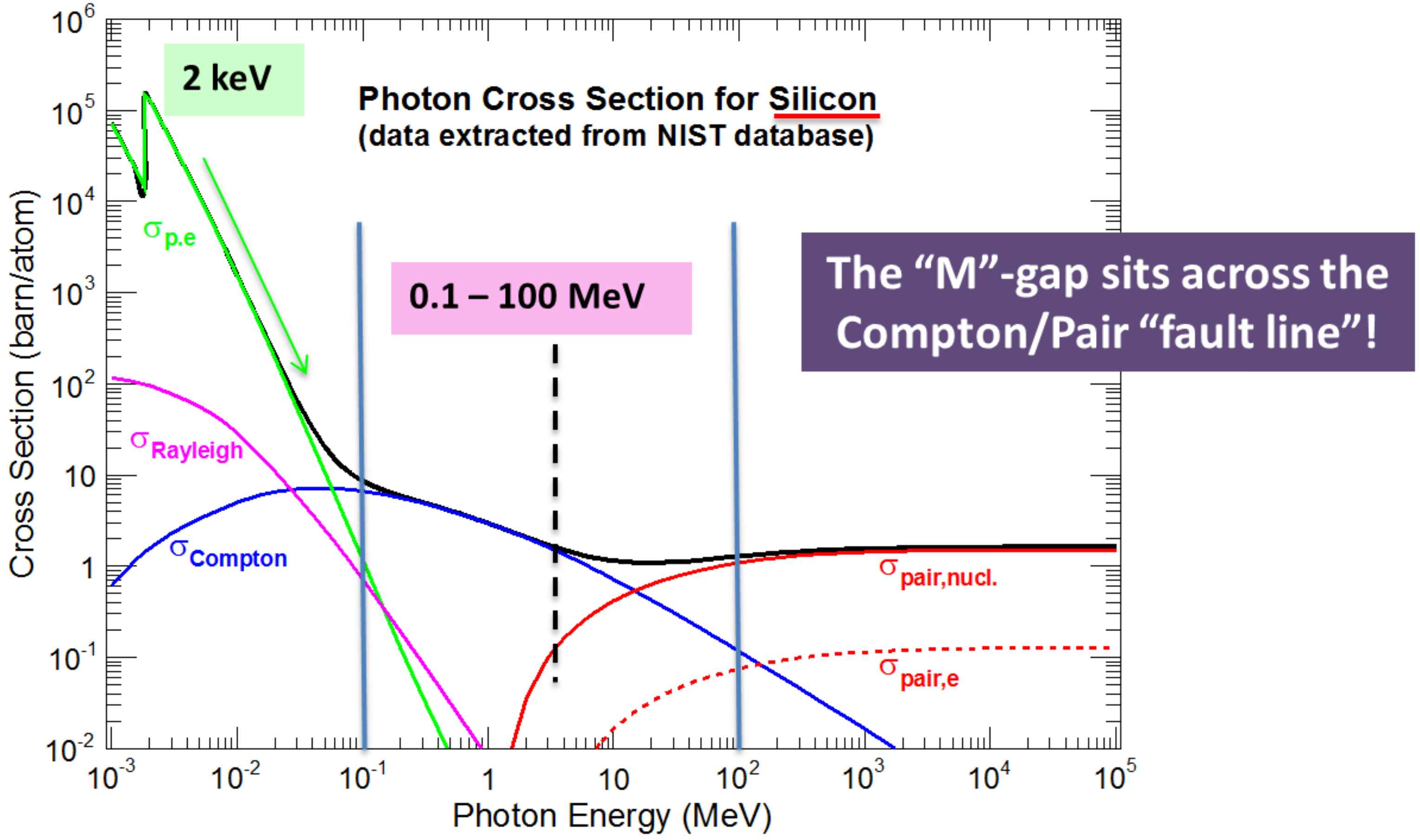


Km3Net/IceCube-Gen2 - ν





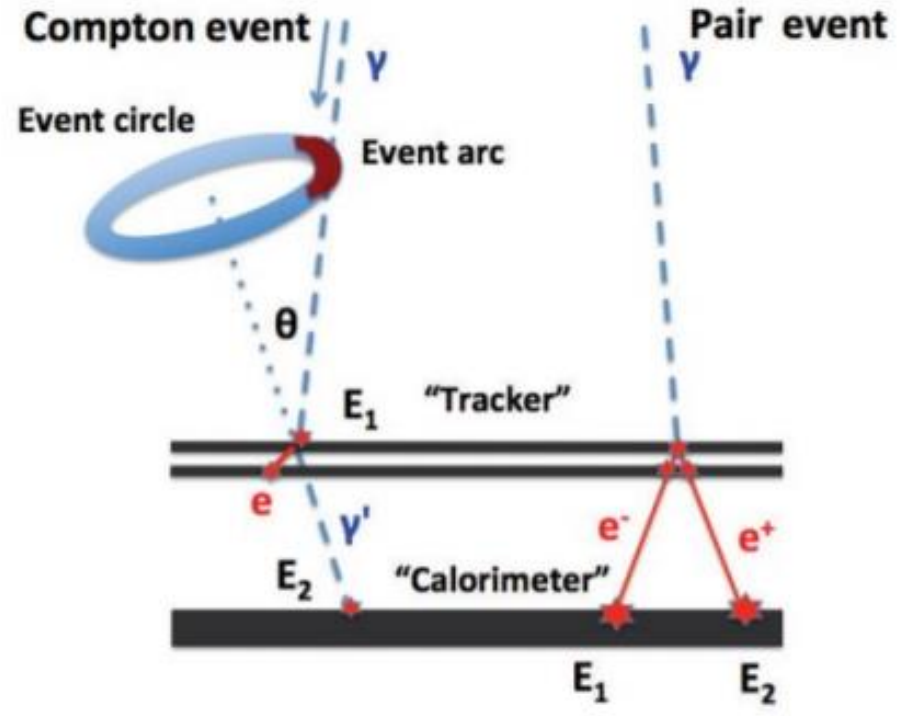
Gamma ray detection with Compton conversion



- Photon detection: need both Compton scattering and Pair production
  - Compton: 0.1 – 10 MeV
  - Pair : >10 MeV (in silicon)

Compton vs Pair Telescope

- Compton regime
  - Require excellent 3D-point resolution and energy resolution
  - Event reconstruction with 2 points and 2 energy measurements!
- Pair regime
  - Tracking resolution is most important
  - Dominated by Multiple Scattering effect in the “M”-gap region
  - Main concern is detector layer thickness
- Challenging to be truly optimal in both regimes across the gap with one detector



$$\cos\theta = 1 - \frac{m_e}{E_\gamma} + \frac{m_e}{E_\gamma - E_e} = 1 - \frac{m_e}{E_1 + E_2} + \frac{m_e}{E_2}$$

$$\sigma_\theta = \frac{13.6}{\beta p} z \sqrt{\frac{x}{x_0}} \left[1 + 0.038 \ln\left(\frac{x}{x_0}\right)\right]$$ p in MeV

Scintillating Fiber Tracker

- Plastic scintillating fibers (SciFi) in tracking detectors have been used for more than 30 years
  - Standard PMTs
  - Also proposed for gamma-ray space telescopes, e.g. FiberGLAST
- Thanks to the recent developments on SiPMs, trackers based on long SciFi now represent a valuable alternative option to silicon detectors
  - No strip-to-strip wire bonding
  - Spatial resolution < 100 µm
  - Time resolution ≈ 100 ps
  - Tested up to 6×10^{11} n_{eq}/cm^2 total neutron fluence
  - Non-planar geometries can also be easily implemented
- HERD design includes a fiber tracker (FIT) based on the LHCb one
- Scintillation tracker for space application prototype studies at INFN Bari
  - Scintillator materials and simulation,
  - Detector mechanics,
  - SiPM-fiber coupling,
  - DAQ electronics

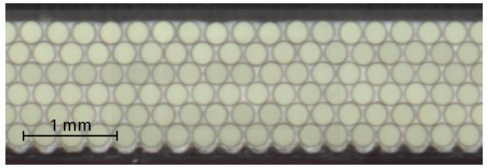
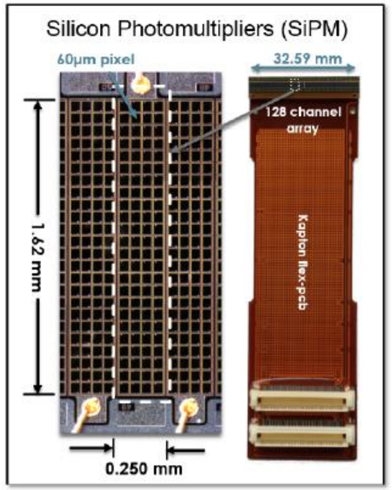
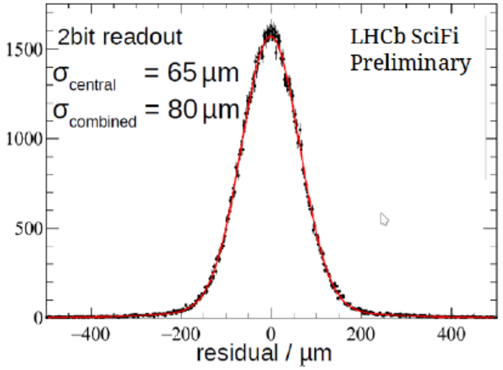


Figure 5: Cross-section of a scintillating fibre mat.





NUSES mission

- A pathfinder satellite for new technologies
  - Development of new observational techniques, sensors (e.g. SiPM) and related electronics/DAQ for space mission
  - New solutions for the satellite platform
- Experiments and scientific goals
  - Terzina
    - UHE CR
    - Astrophysical neutrinos
    - Space-based atmospheric Cherenkov light detection
  - Zirè
    - Low energy (<250 MeV) CR, electrons, protons
    - Sub GeV gamma ray domain for transients (GRB, GW follow up, SN emission lines) and steady sourses
- Scientific collaboration among GSSI, INFN, TAS-I and many other universities

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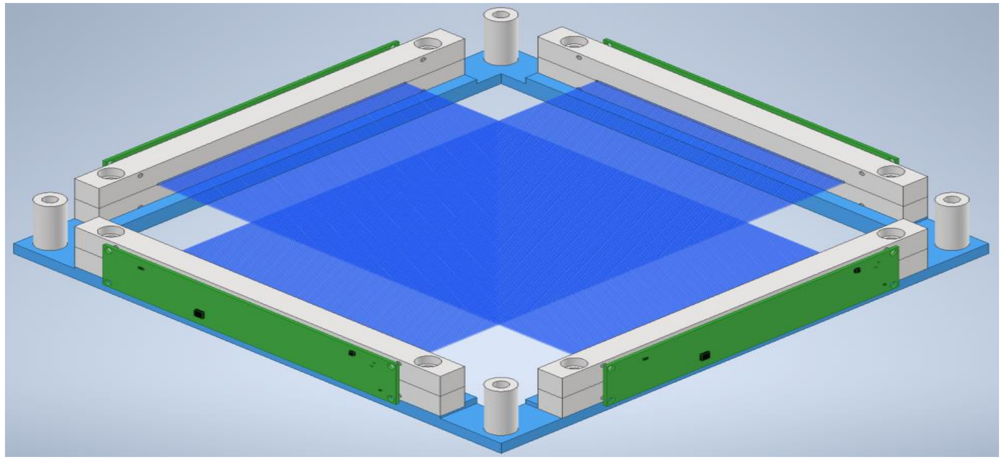
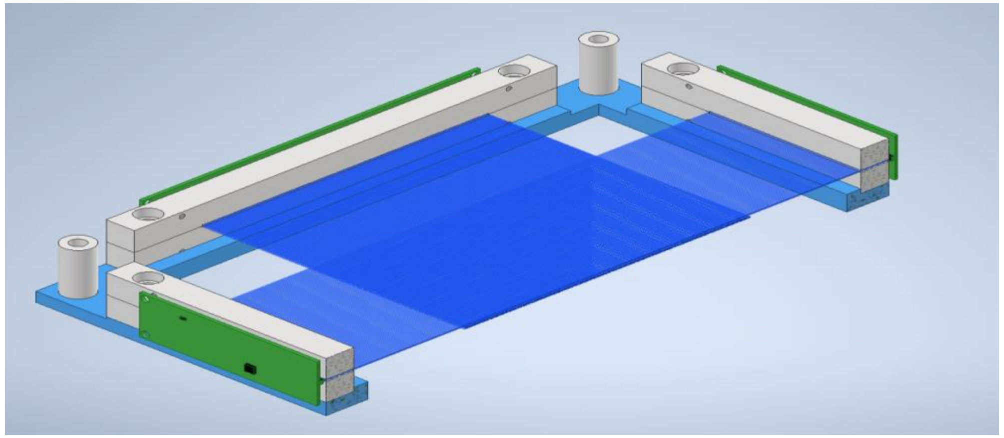
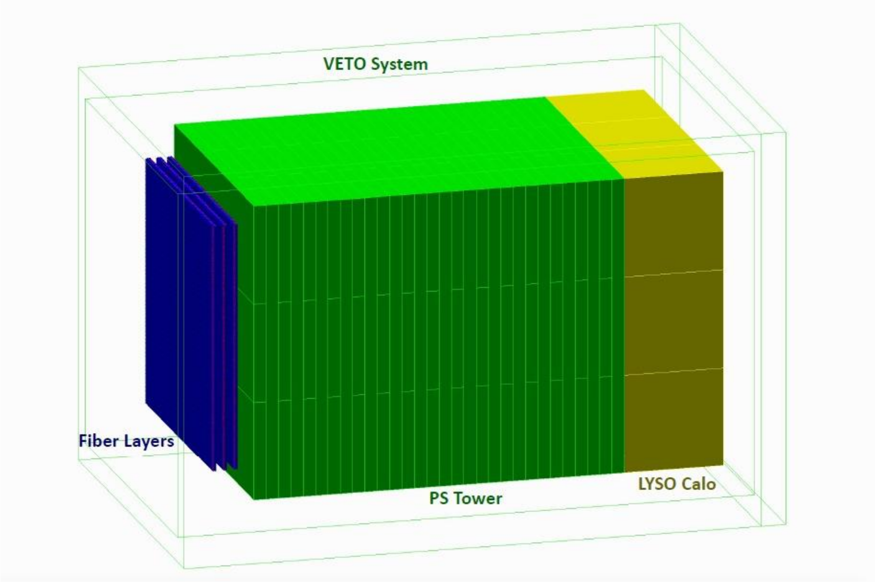
NUSES-Zirè concept module

The Zirè experiment will have a fiber tracker with SiPM readout.

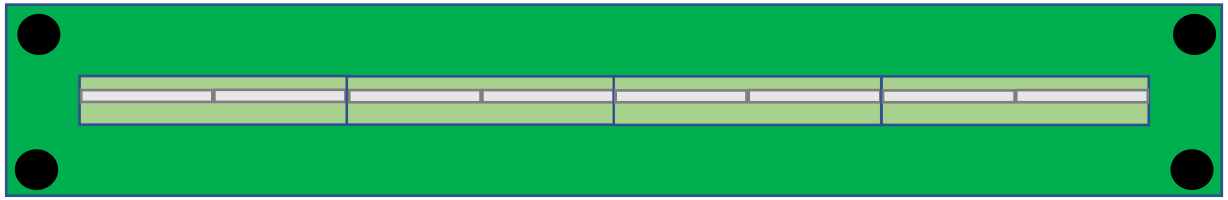


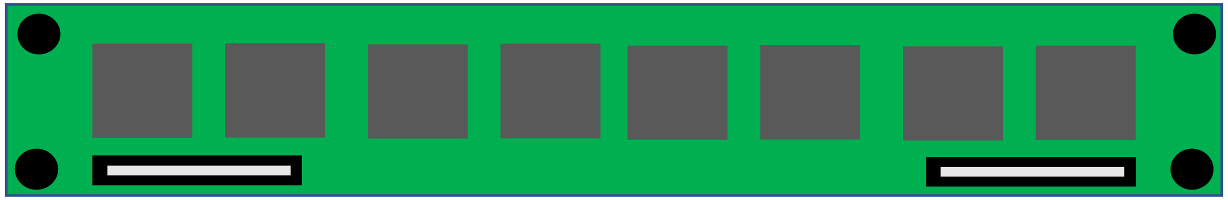


Credits to R. Triggiani and M. Mongelli INFN-Bari



Fiber / SiPM (array) side

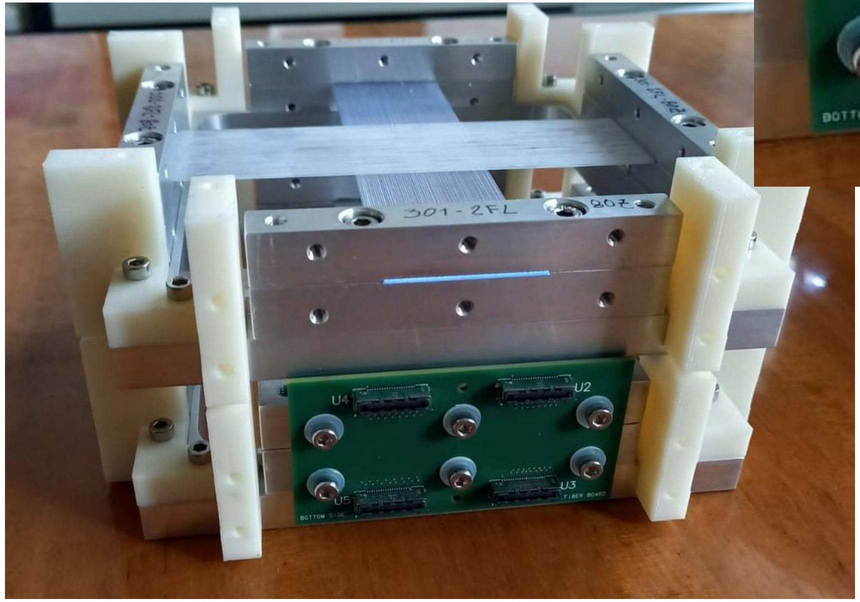




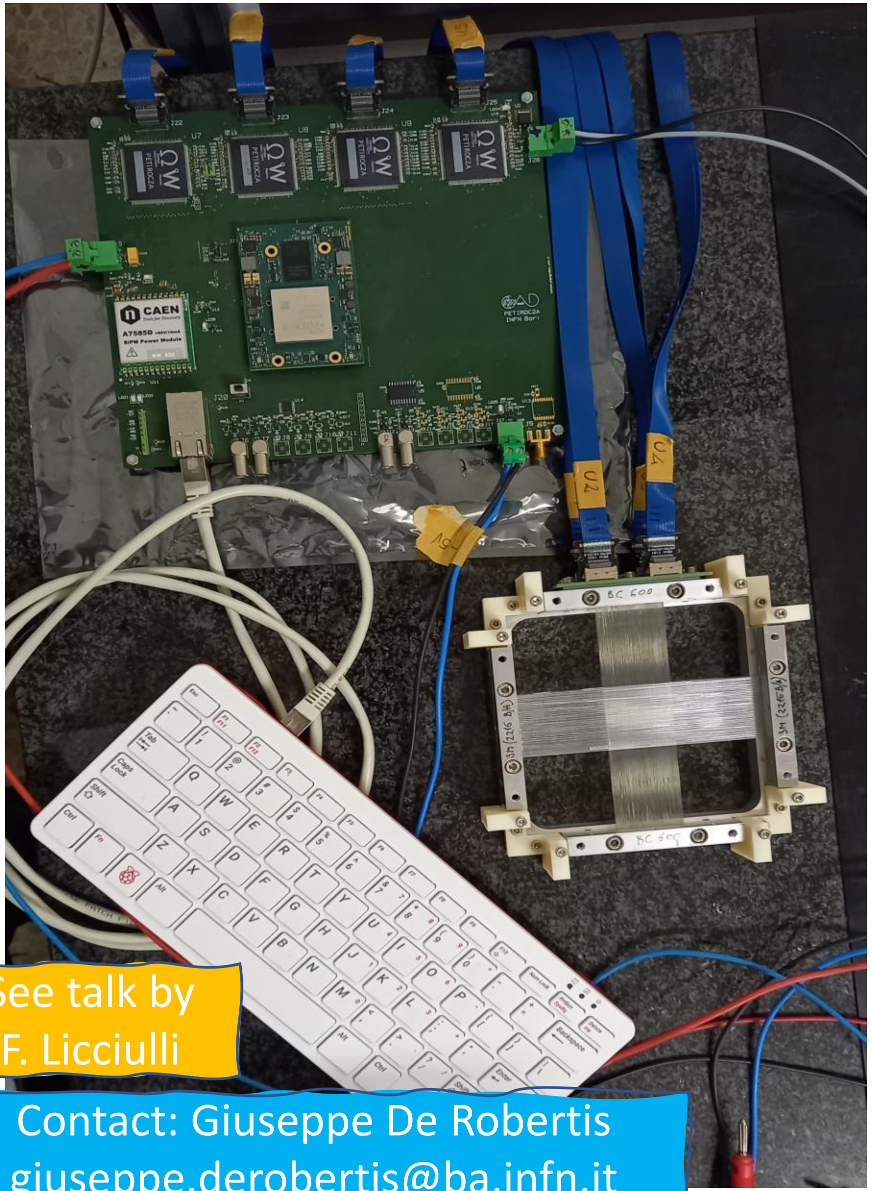
Front End ASIC side

INFN Bari prototype R&D

- X-Y module with 500 μm diameter fiber
  - Two staggered layers in each view
- SiPM: Hamamatsu 128-channel 250 μm strip pitch
  - The odd channels (top pads) and the even ones (bottom pads) are connected to two different FE ASICs



- Read-out board by INFN Bari
  - 4 Petiroc 2A ASICs
  - CAEN A7585D SiPM voltage module
  - Kintex-7 FPGA module
- DAQ based on the Raspberry Pi4



See talk by F. Licciulli

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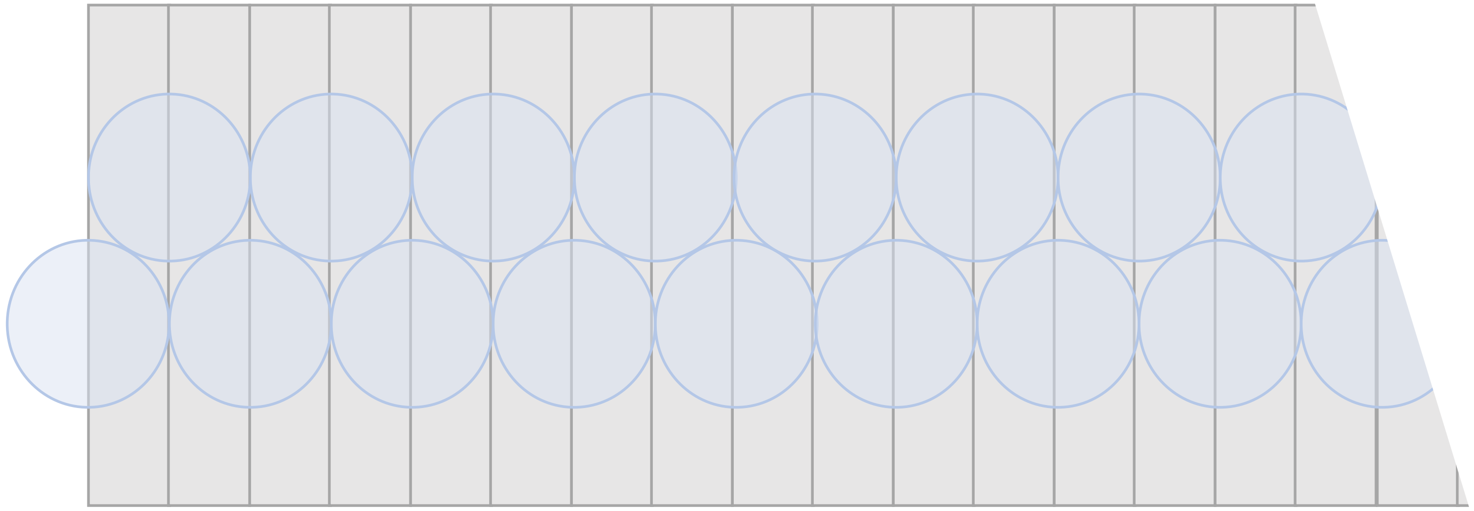
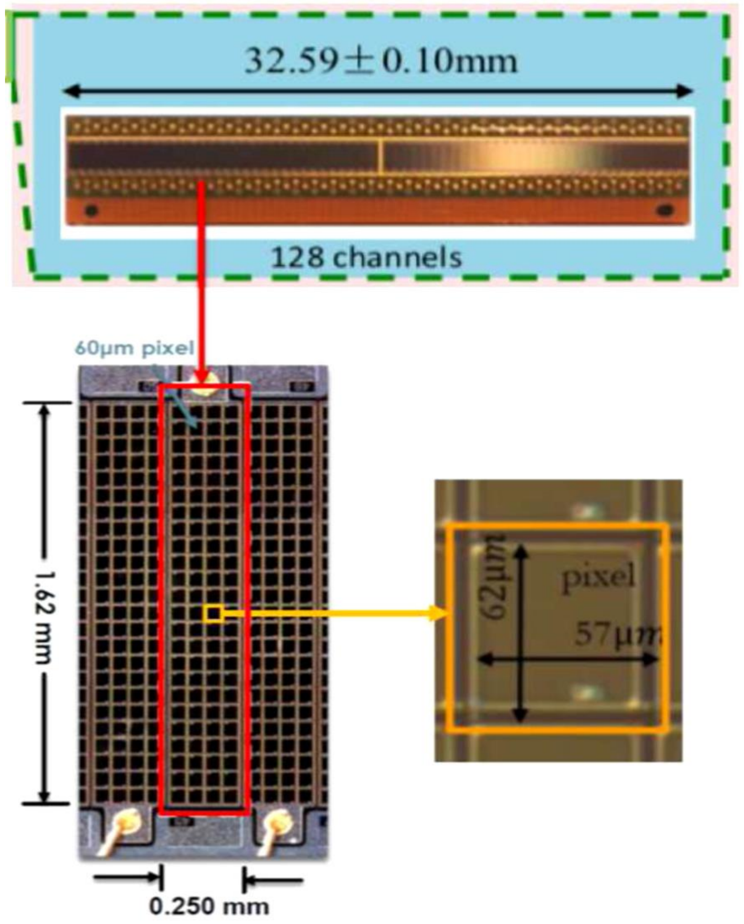
INFN Bari prototype R&D

500 μm diameter fibers, 128 ch SiPM array 250 μm strip pitch



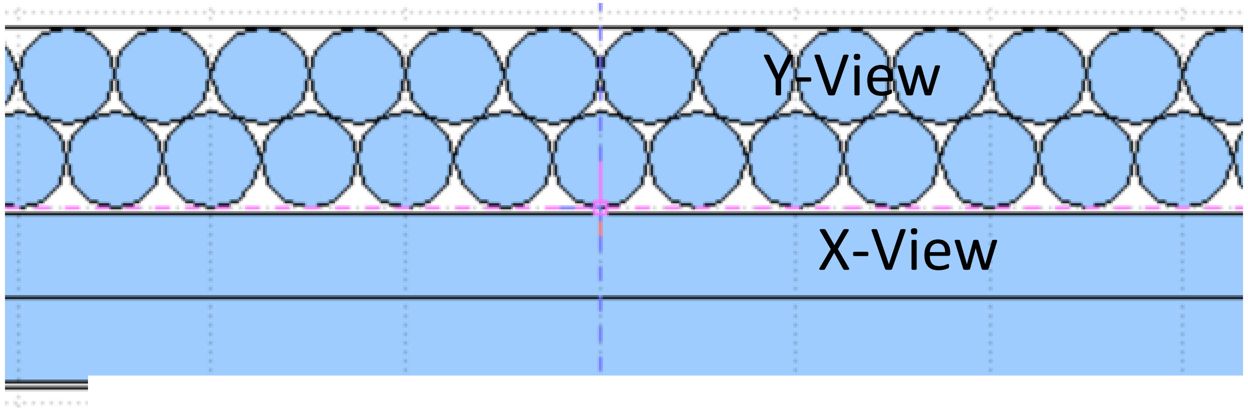


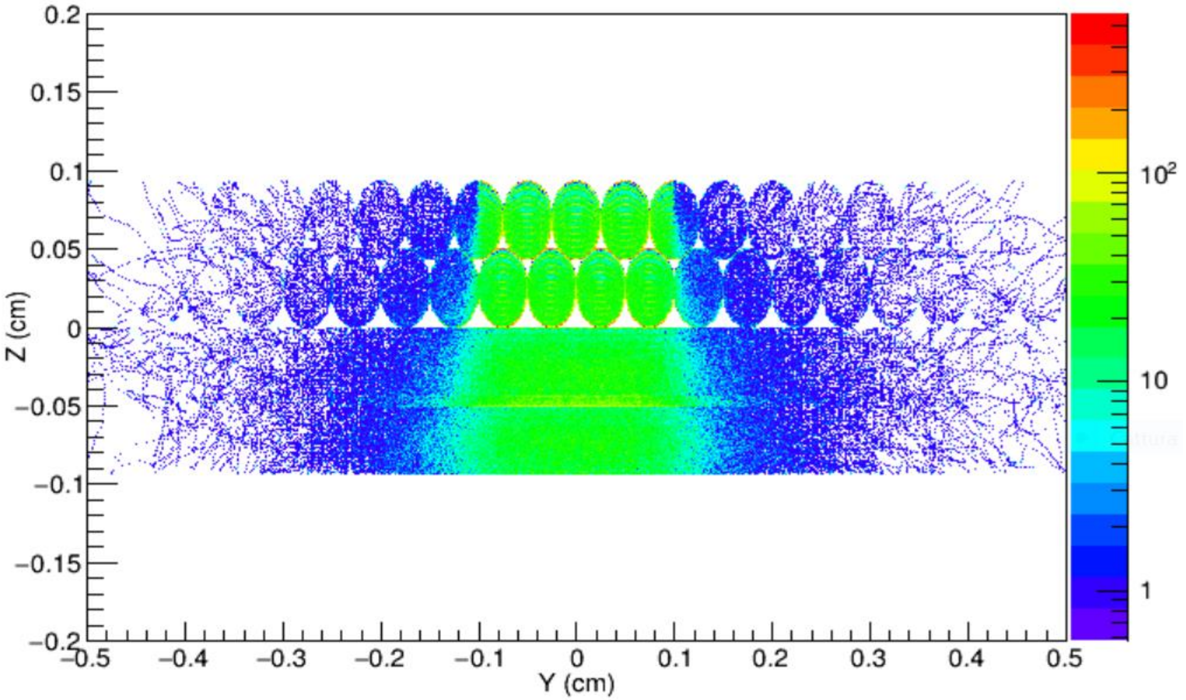
- Two staggered layers
  - Fibers/layer = 64(+1)/SiPM
  - Fibers/view = 130/SiPM

- Hamamatsu SiPM from LHCb fiber tracker
- HERD SiPM array by Hamamatsu
- R&D INFN-FBK of similar SiPM array
  - Rad hard, high fill factor, low cross talk

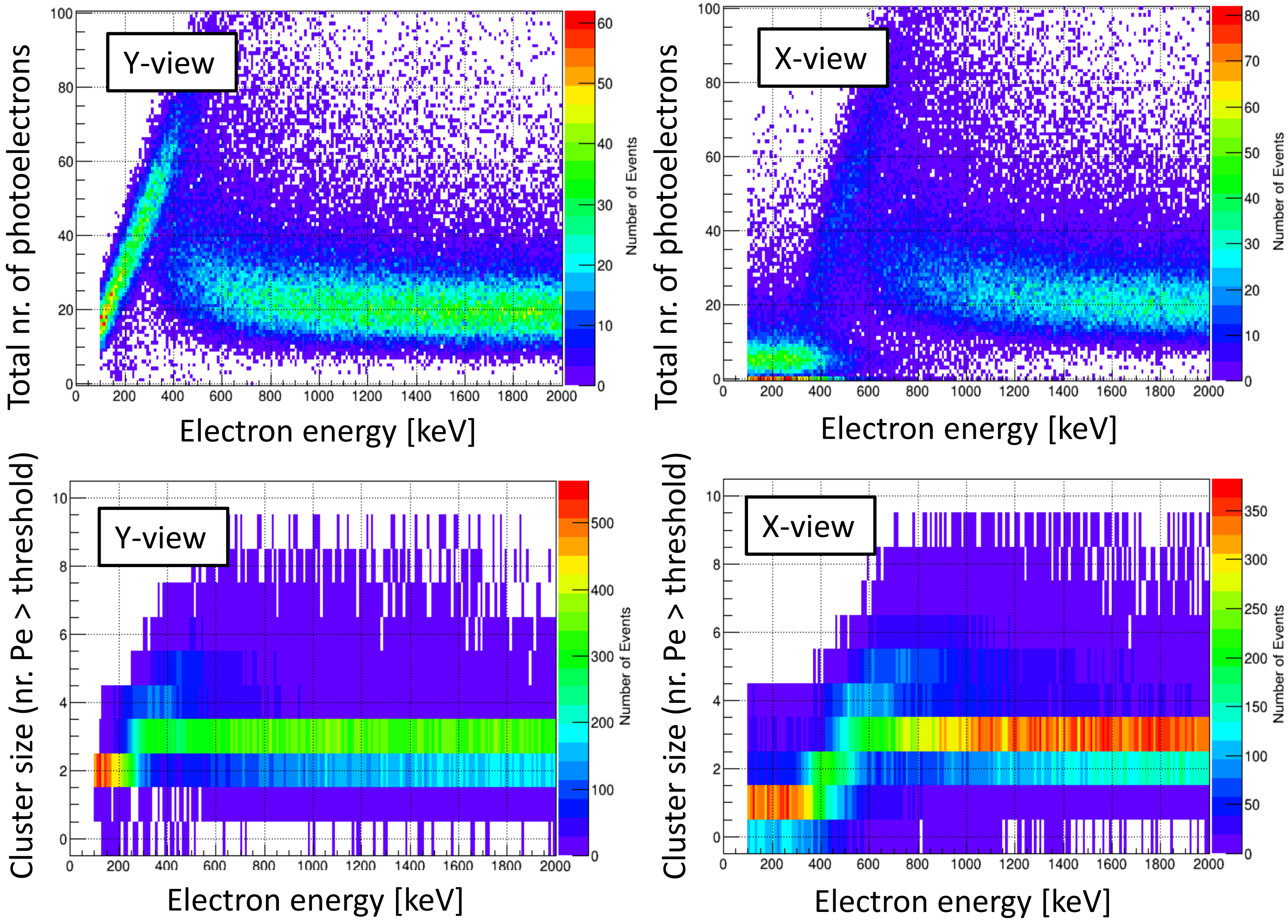
Expected performance: FLUKA simulation (1)

- X-Y module:
  - Two staggered layers/view
  - 500 μm diameter fiber
- Fiber Yield: 8 ph/keV
- Fiber Trapping Efficiency = 5.4%
- SiPM PDE = 0.4
- SiPM strip threshold = 3 pe
- On-axis electrons 100 keV – 2 MeV

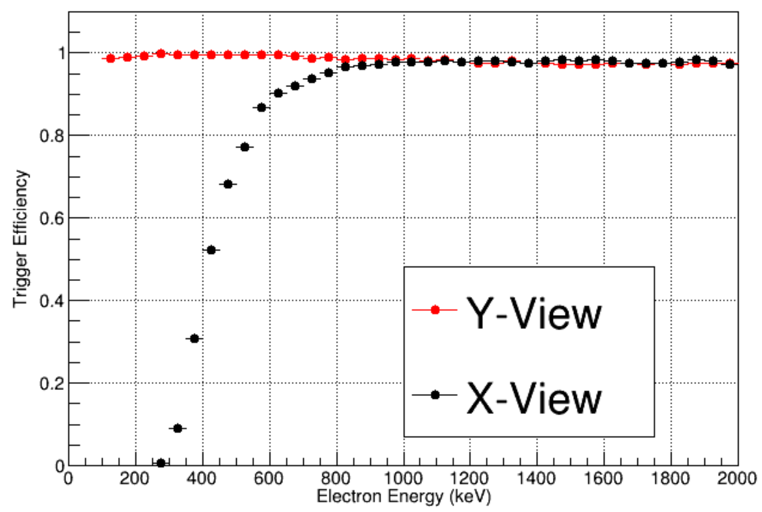




Expected performance: FLUKA simulation (2)



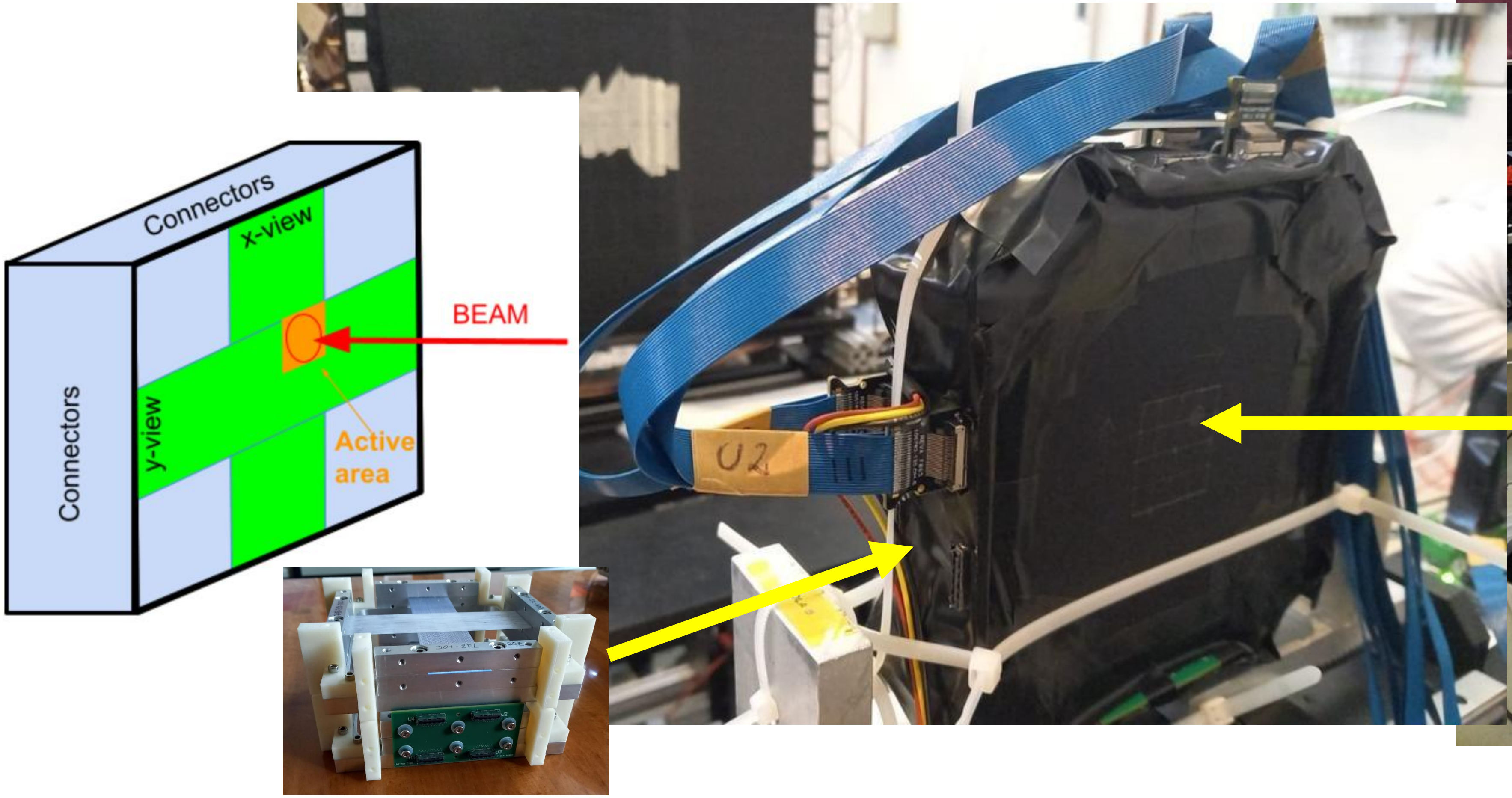
Trigger efficiency

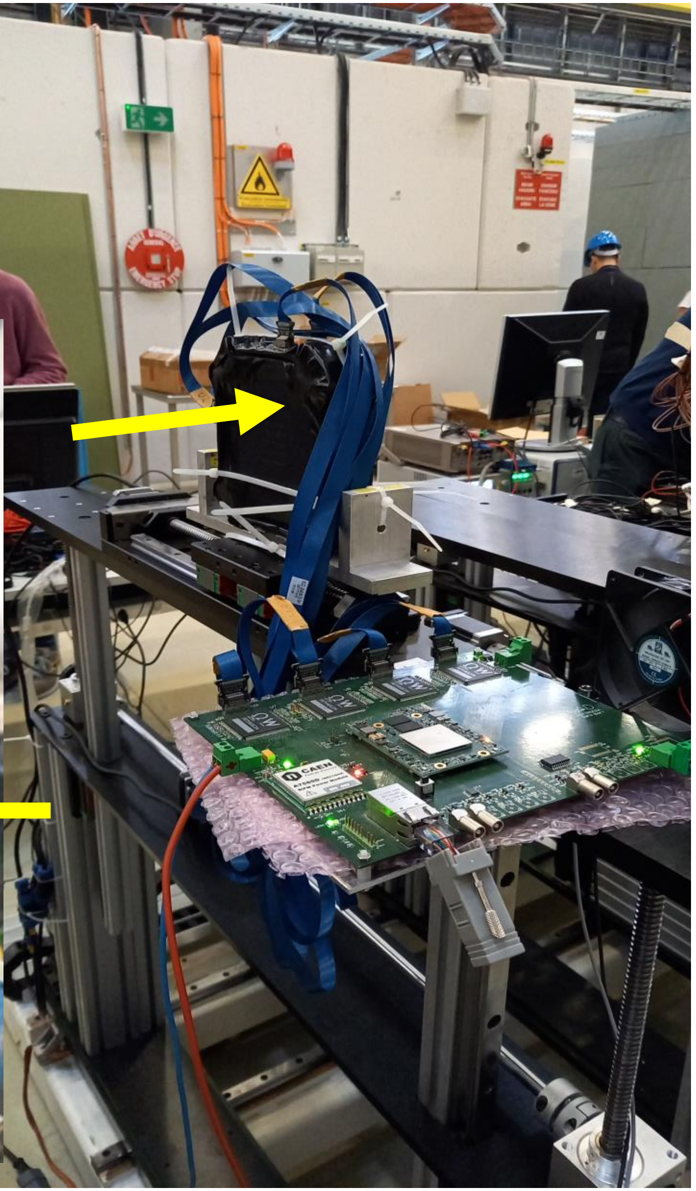


Threshold @ 3pe

CERN T9-PS beam test 2021 (BT21)

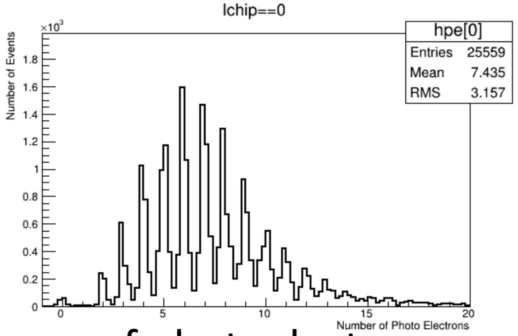
- Two Petiroc 2A ASICs for each view
  - About 1.6 cm x 1.6 cm active fibers





Preliminary BT21 results

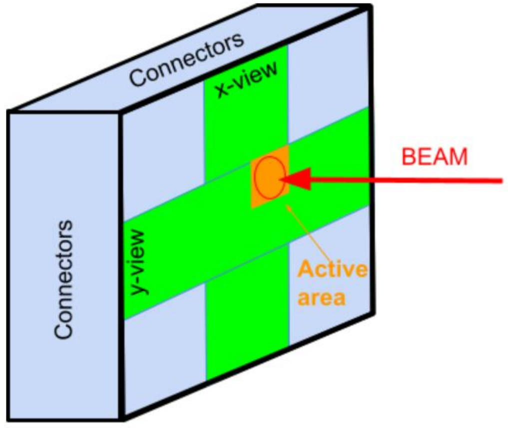
OV = 4.5Volt



nr. of photoelectrons

Y-view

X-view

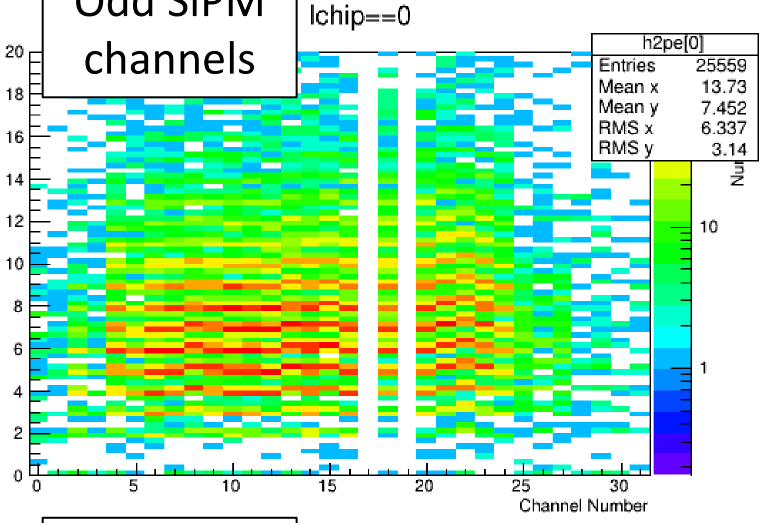


External Trigger:

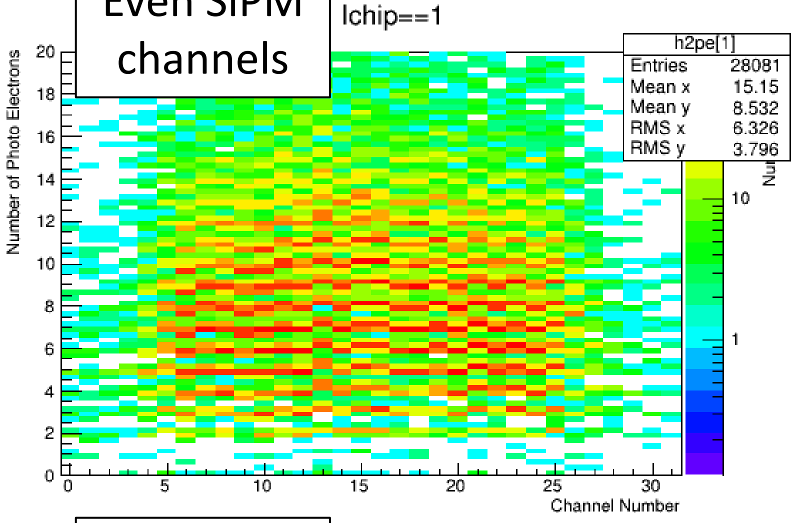
1 cm x 1 cm beam spot

nr. of photoelectrons

Odd SiPM channels

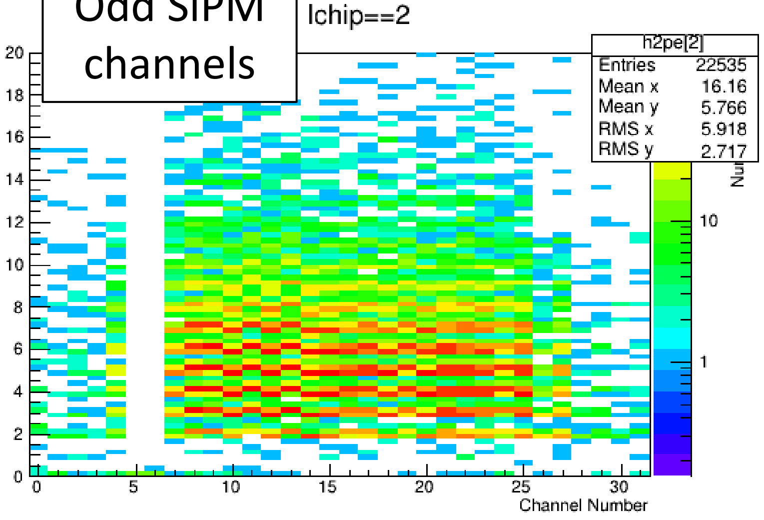


Even SiPM channels

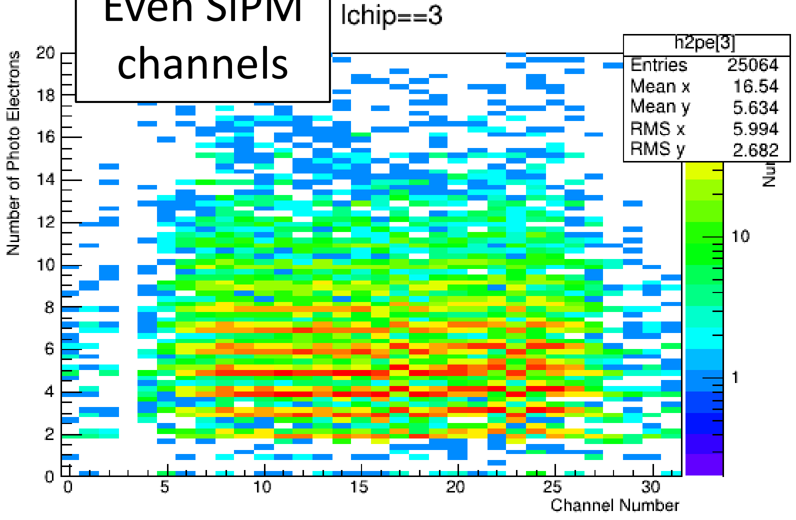


nr. of photoelectrons

Odd SiPM channels



Even SiPM channels

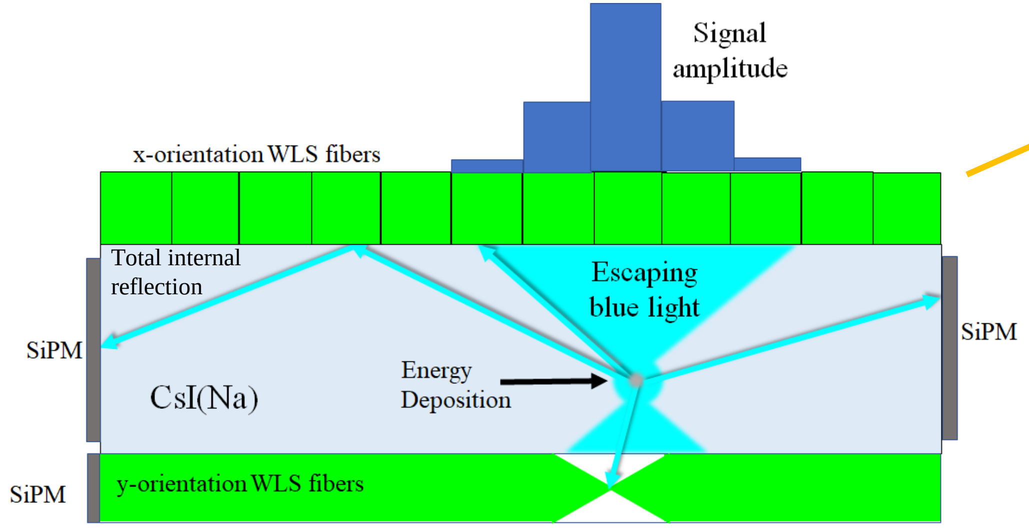


The Advanced Particle-astrophysics Telescope (APT)

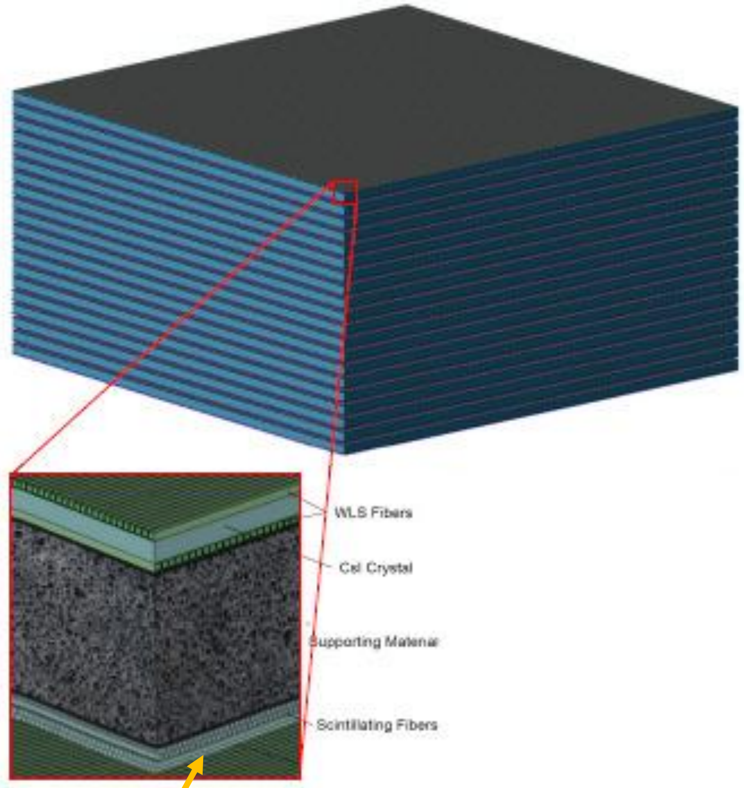
- Active tracker-converter based on thin crystal scintillator CsI(Na) read-out by external wavelength shifting (WLS) optical fibers
- Light scintillating optical fiber tracker
- Adding foam radiators, the CsI detectors could detect the transition radiation X-rays from very-high-energy light cosmic rays

➢ Tracker layer

➢ Imaging Compton Converter (ICC)



ICC layer: 5 mm thick tile coupled to a top and a bottom planes of 2 mm side square wavelength shifting (WLS) fibers

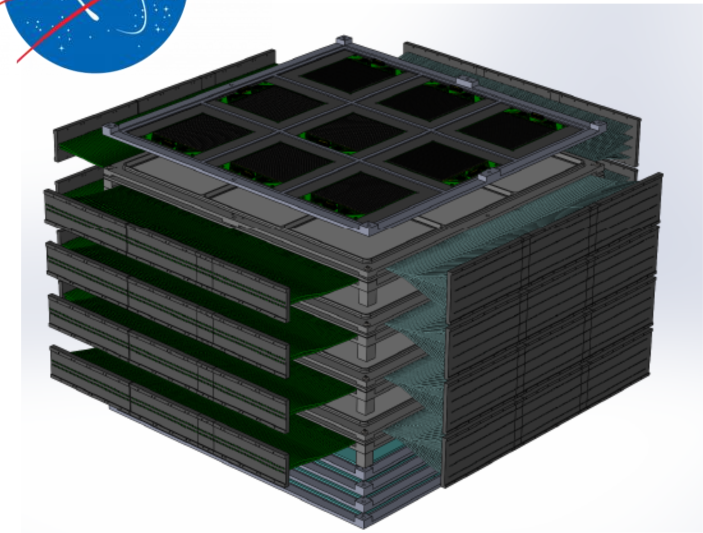


Alnussirat, S. et al., 2021. The Advanced Particle-astrophysics Telescope: Simulation of the Instrument Performance for Gamma-Ray Detection

Tracker layer: 2 crossed planes of 2 close-packed, staggered layers of cylindrical scintillating fibers of 1.5 mm diameter

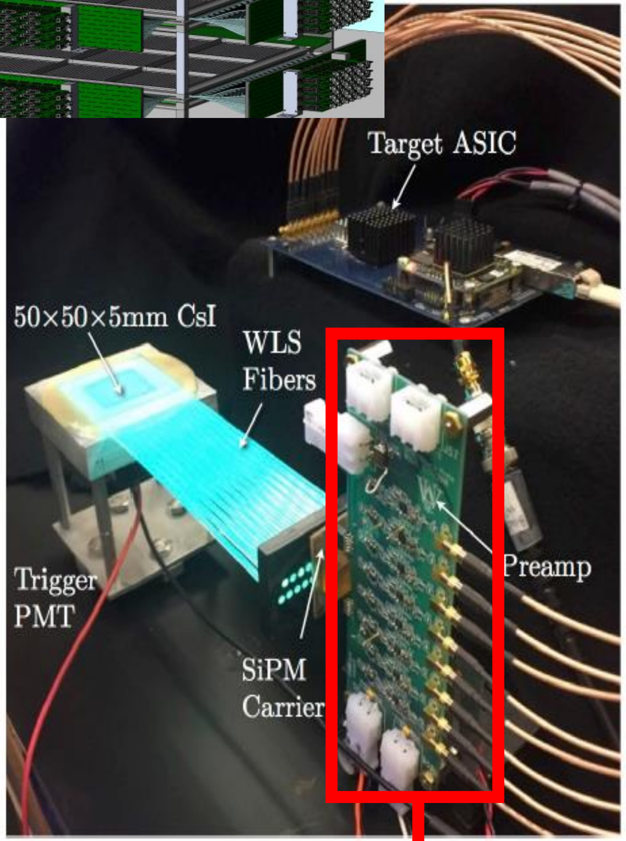
ADAPT program (Nov 2021 – Nov 2025) NASA grant

The Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT)

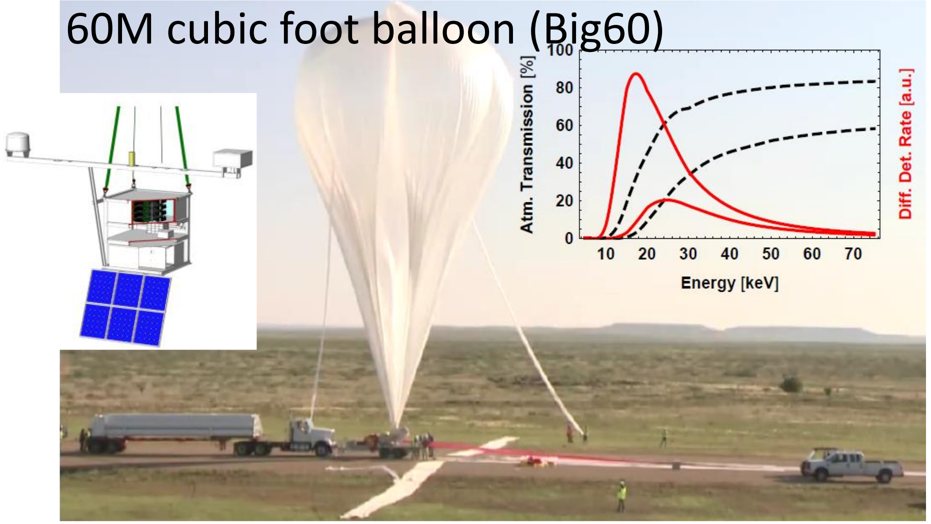


- INFN Contributions would include SMART ASICs for 2x2mm^2 SiPMs on Hodoscope 1.5 mm fibers comprising the scintillating fiber tracker
- Additional INFN Contributions would also be FBK SiPMs
- Approach advances TRL of SMART ASICs, SiPMs and Scintillating Fiber trackers for future space experiment

See talk by F. Licciulli

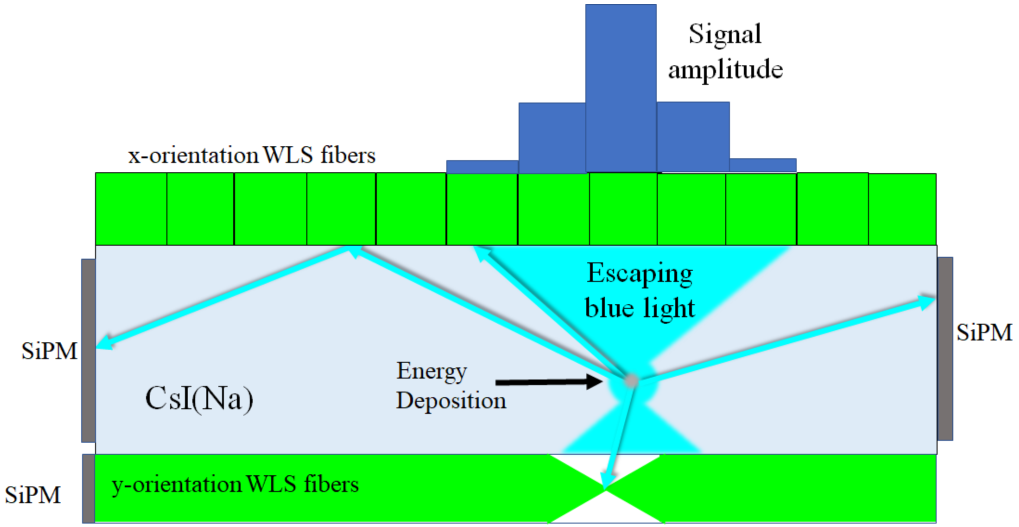


SMART ASIC



- Readout electronics will be based on ALPHA ASICs ('revised' TARGET)
  - Lower sampling rate
  - Low power consumption
- SMART could be employed as preamplification stage to replace the discrete preamp boards used in the prototype
- Need to match the APT requirements:
  - Smaller SiPMs (2x2mm^2)
  - Smaller bandwidth
  - Lower power consumption

Simulations with Geant4



- Ideal SiPMs collect all photons reaching the right/left sides of the crystal
- Front/back sides: perfect absorbers
- Top/bottom sides: WLS fibers
- All fibers are equipped with ideal SiPMs at both ends, which collect all the light reaching the fiber ends
- Photons reaching the interfaces between different media are propagated following Snell's law

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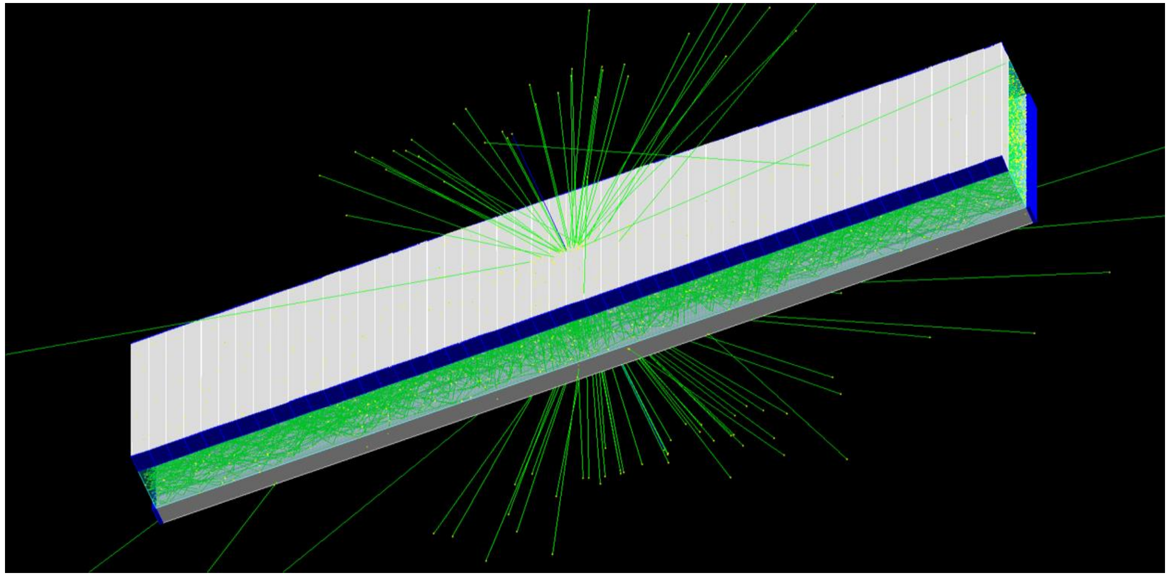
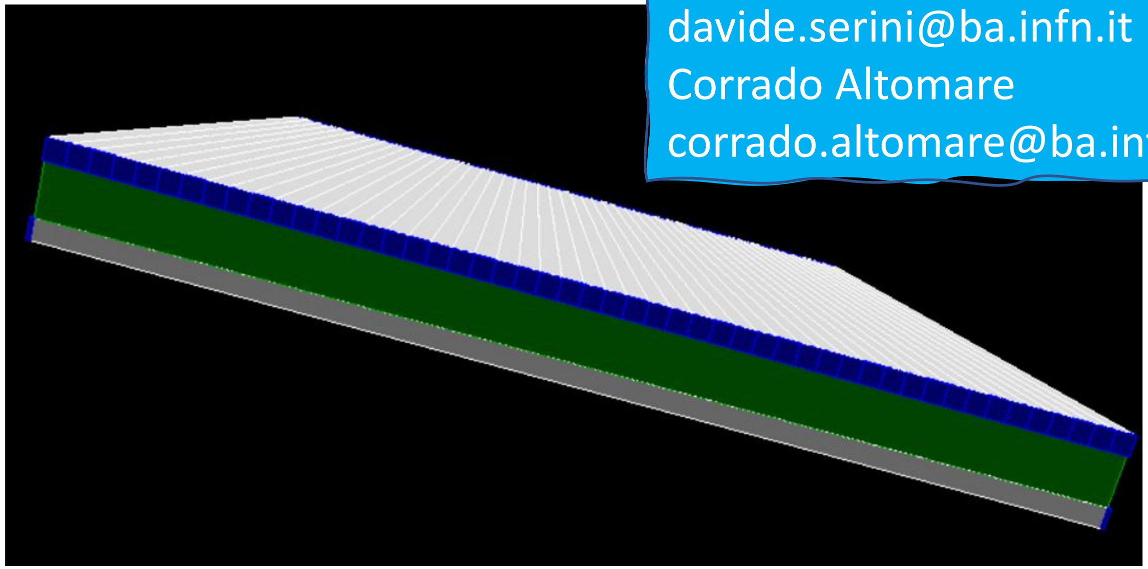




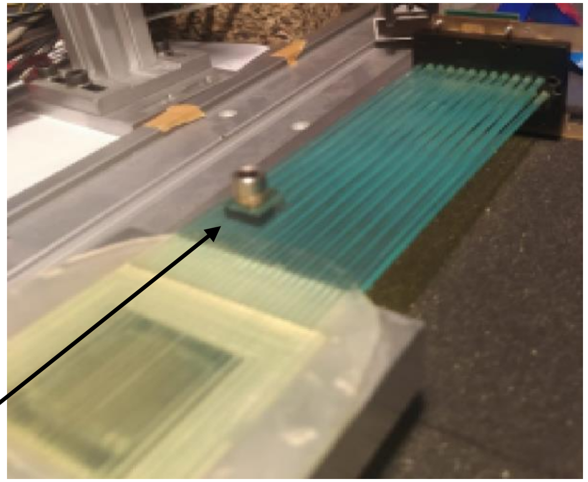
The LYSO scintillator

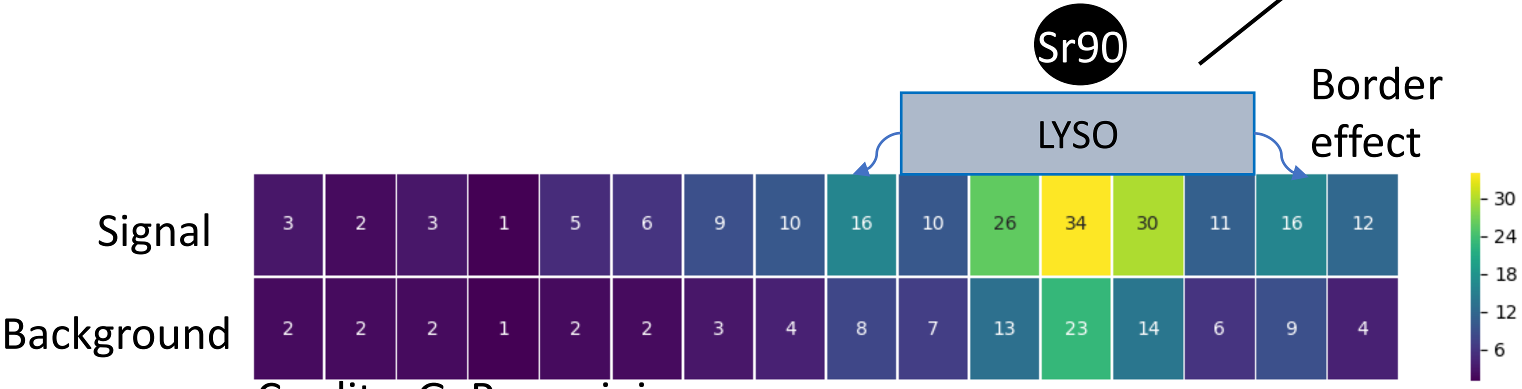
Cerium doped Lutetium

- High density
- Fast, single exponential decay time
- Non-hygroscopic
- Three to four times the light emission of BGO
- LYSO has intrinsic activity

Prototype setup

- 5-mm thick LYSO crystal with a square cross section of 1 x 1cm^2 on the plane of WLS fibers covering 5 fibers
- Sr-90 source on top of the LYSO crystal
- The electron must pass through the scintillator before reaching the fibers





Credits: G. Panzarini

Position reconstruction
Only three fibers show a signal above background

- ➢ compatible with aperture cone in 5 mm thick LYSO (taking into account that coupling with fibers is not optimal)

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Summary

- Further prototype developments and upgrades
- Future beam tests
- Ongoing simulation research activities

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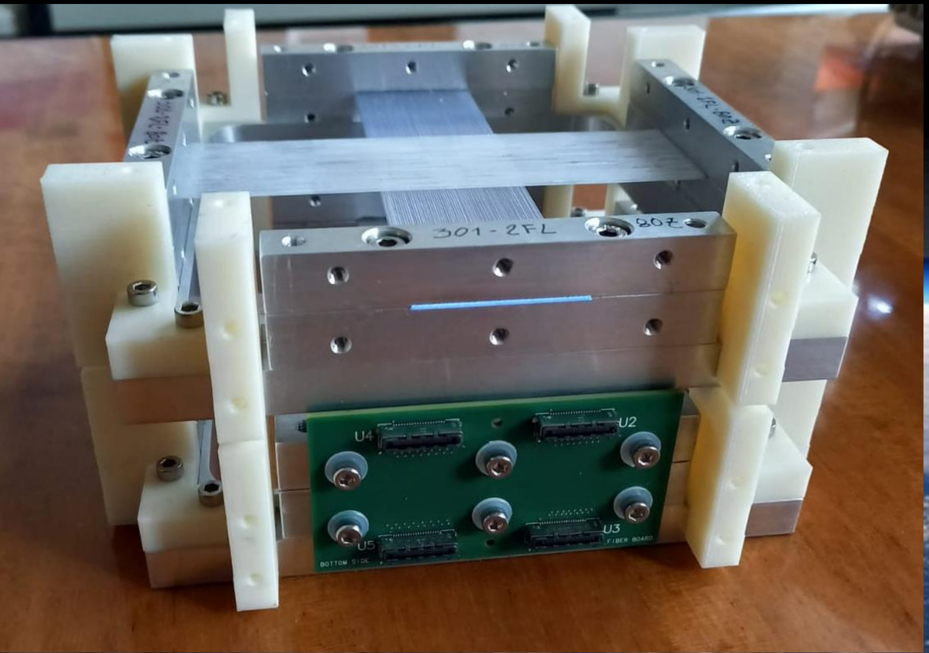
Scintillation fiber based tracking systems for space applications



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