Development of Instruments for MeV Gamma Rays

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“Multimessenger Astrophysics”

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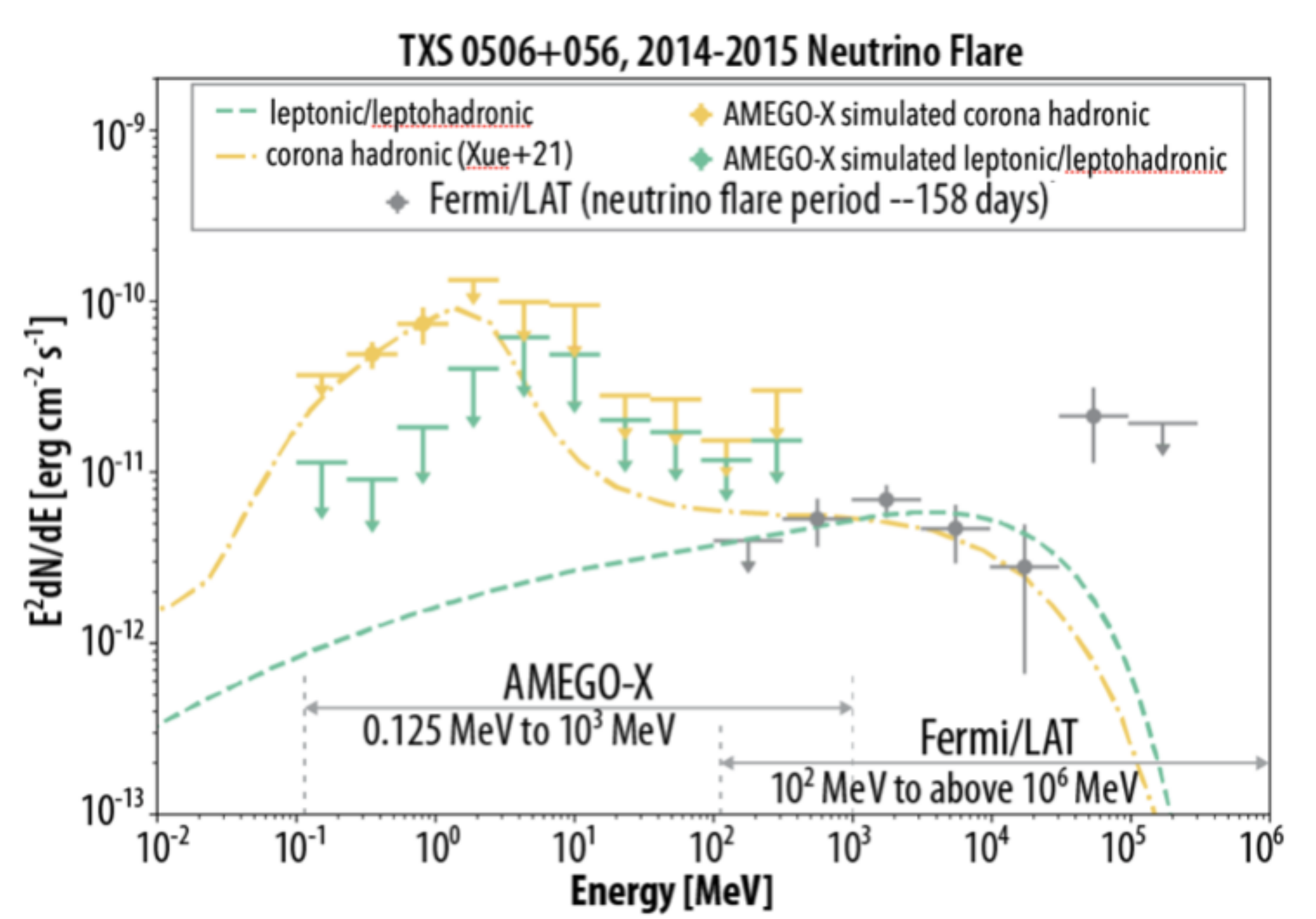
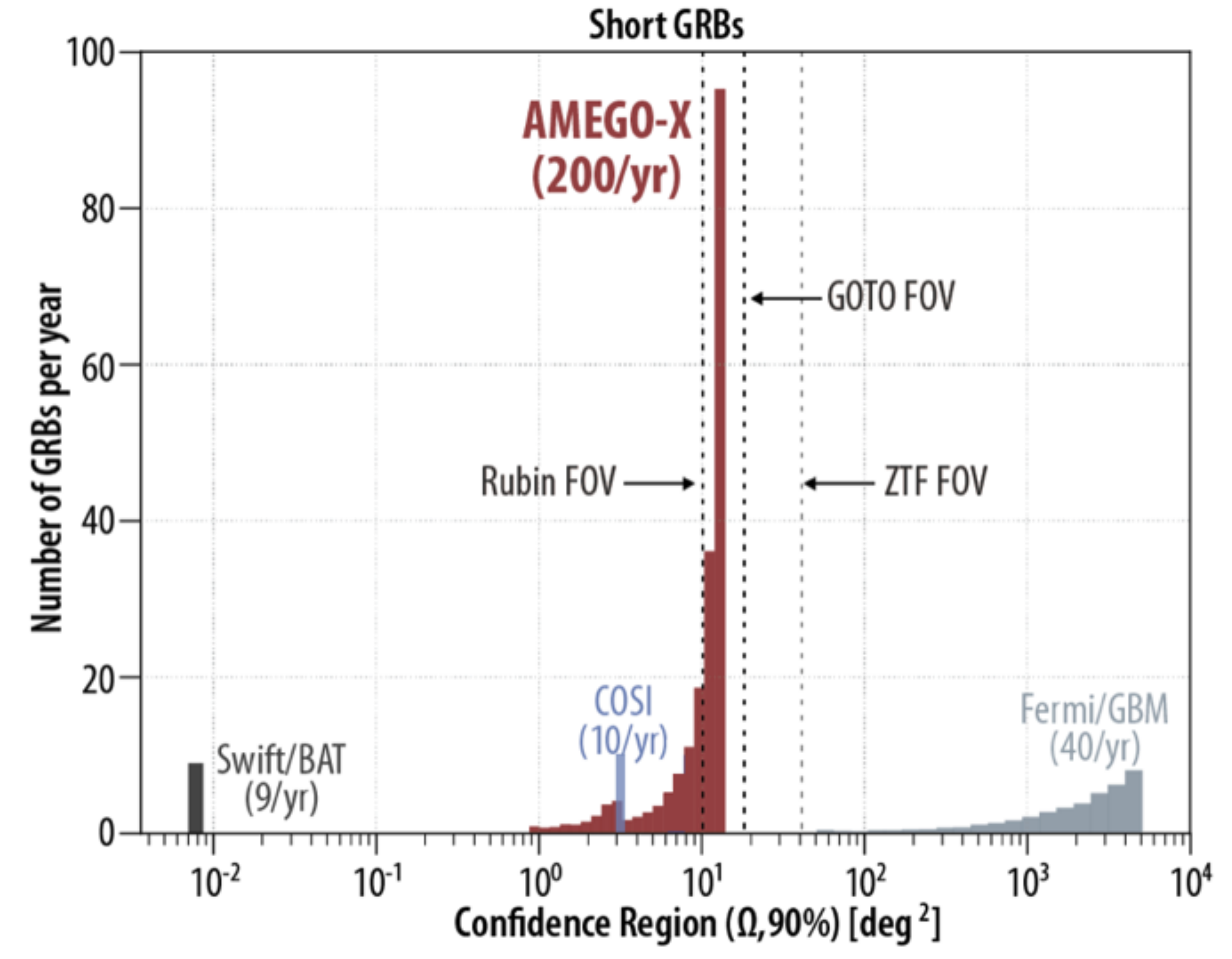
MeV Gamma rays for Multi-Messenger Astrophysics

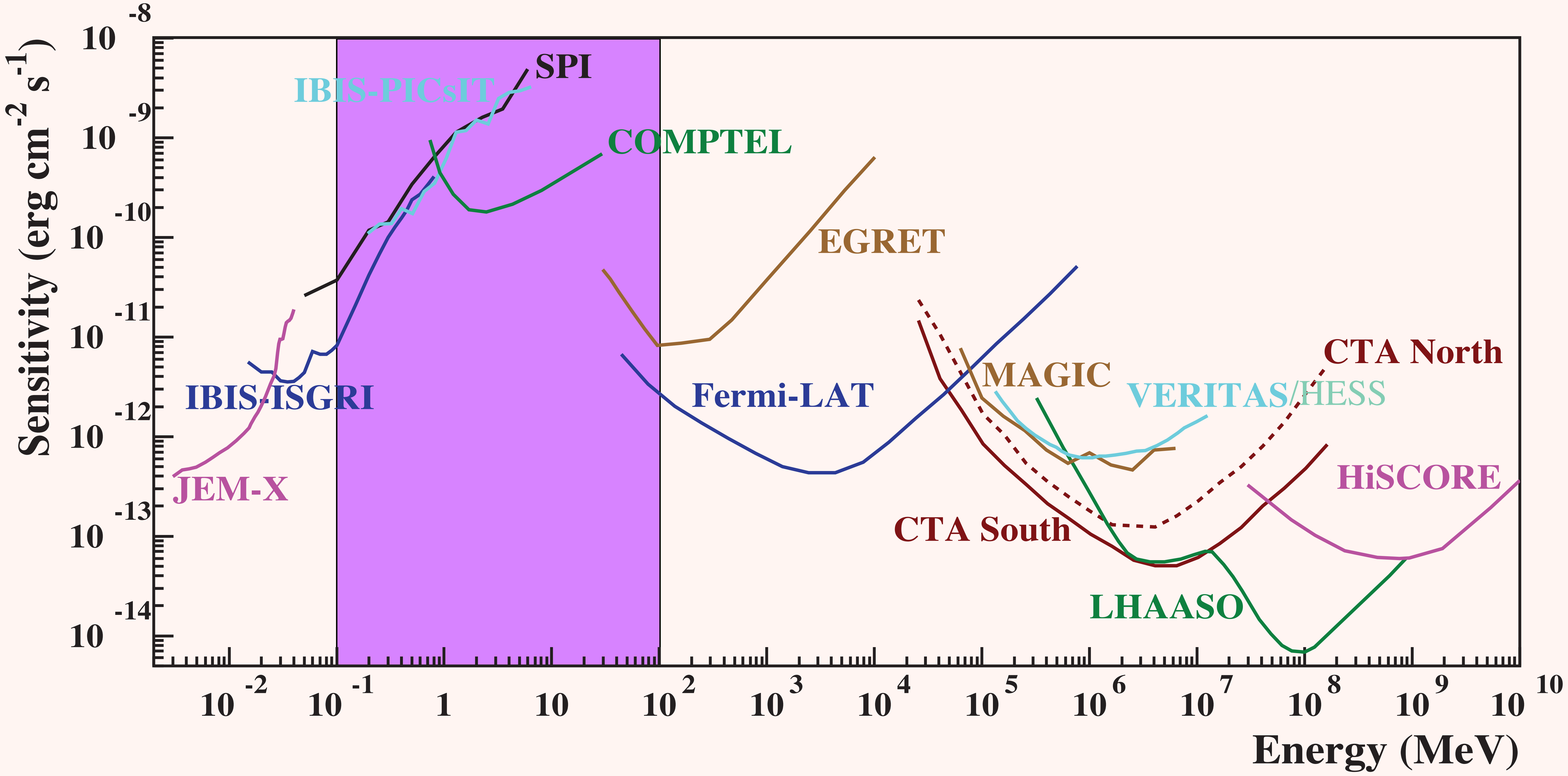
- ❖ **MeV gamma rays play a key role in multi-messenger astrophysics**
  - ✤ **Measurement of gamma-ray spectra in neutrino sources**
    - **Studies of cosmic-ray acceleration and emissions of neutrino and gamma rays**
    - **Resolve gamma-ray attenuation at Seyfert galaxies, NGC 1068 and NGC 4151**
  - ✤ **Localizations and spectral measurements of gamma-ray bursts associated with neutron star mergers detected by gravitational wave instruments**
    - **Localization capability much better than Fermi-GBM is highly desired**
    - **Wide-band spectral measurements and high polarization sensitivity**





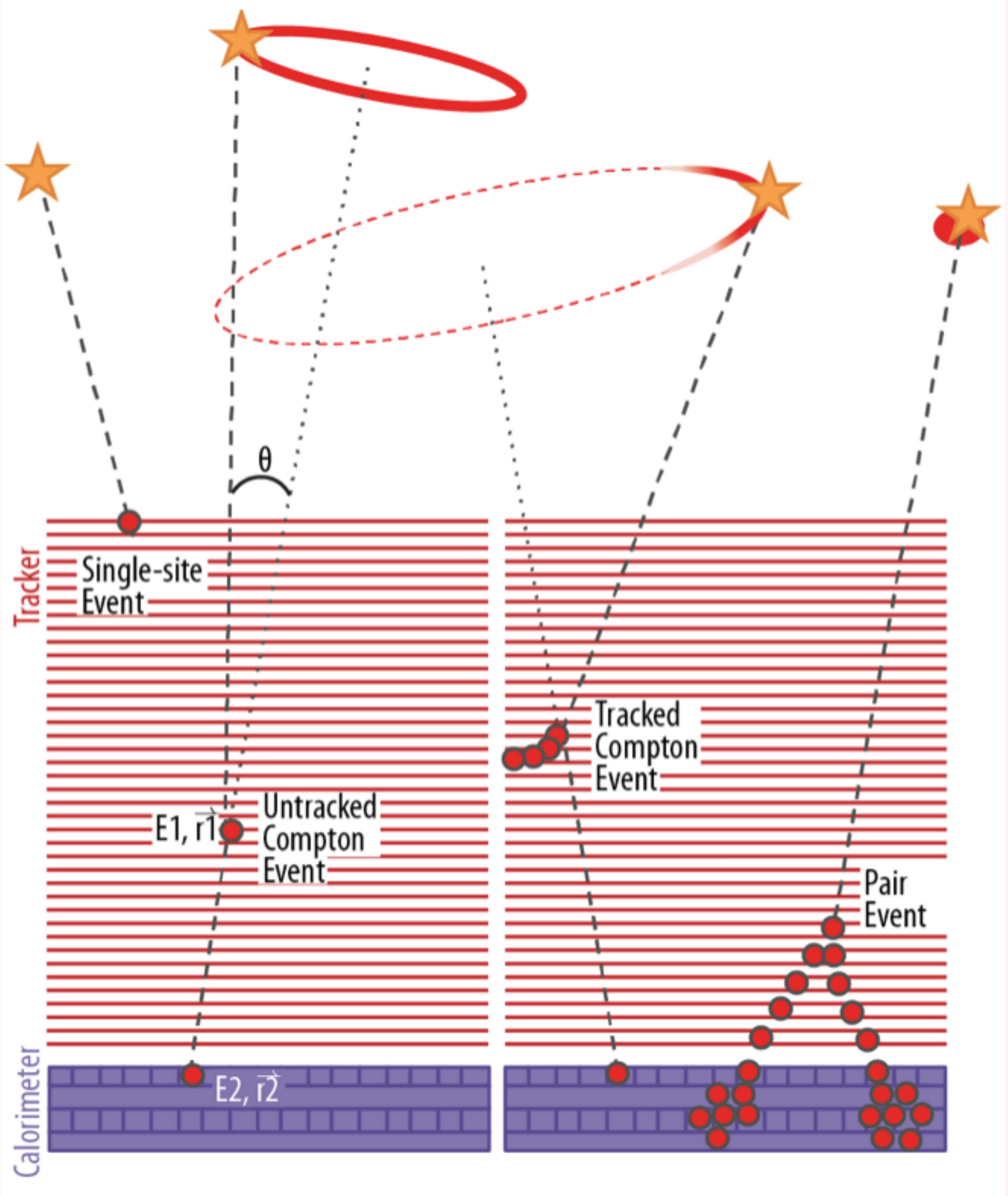
MeV Gap of Gamma-ray Sensitivities

- We have large sensitivity gap between 0.1 MeV and 100 MeV
  - > 10 MeV: **Pair conversion** is a dominant process
    - Angular resolution **limited by Coulomb scattering** in conversion material
  - < 10 MeV: **Compton scattering** is a dominant process
    - **Incident direction is not well constrained**
    - Backgrounds are hard to reject (activation of detector materials)



ONE SOLUTION: AMEGO

- ❖ **General approach to improve the situation from Fermi**
  - ✤ **Remove tungsten converter to improve angular resolution**
  - ✤ **Focus on 1 MeV – 1 GeV energy region**
- ❖ **Employ 2-dimensional silicon sensor to minimize the detector thickness and obtain 2D position**
  - ✤ **Tracking of recoil electrons due to Compton scattering to constrain incident gamma-ray direction**
- ❖ **All-sky Medium Energy Gamma-ray Observatory (AMEGO)**
  - ✤ **Consists of 2×2 towers**
    - **Geometrical area: ~5,800 cm² (1/4 × Fermi)**
  - ✤ **40–60 layers of Si tracker**
    - **0.5 mm thick, 0.5 mm pixel sensor: AstroPix**
    - **Total X_0: 20–30% (Fermi; 78%)**
  - ✤ **6 layers of CsI(Tl) crystal bars**
    - **9 cm thick, 4.8 X_0**
    - **SiPM readout for better energy resolution at low energies**



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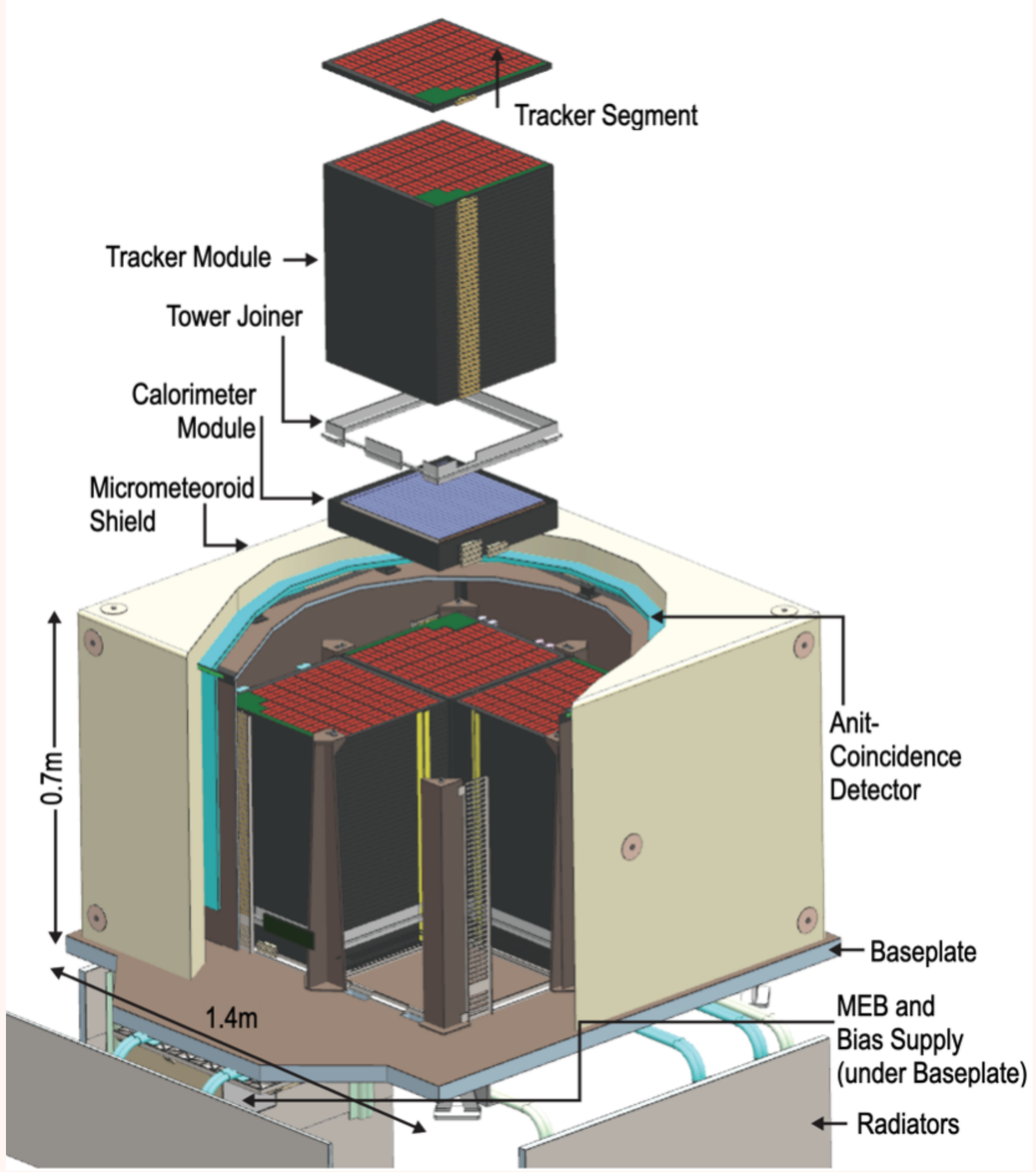

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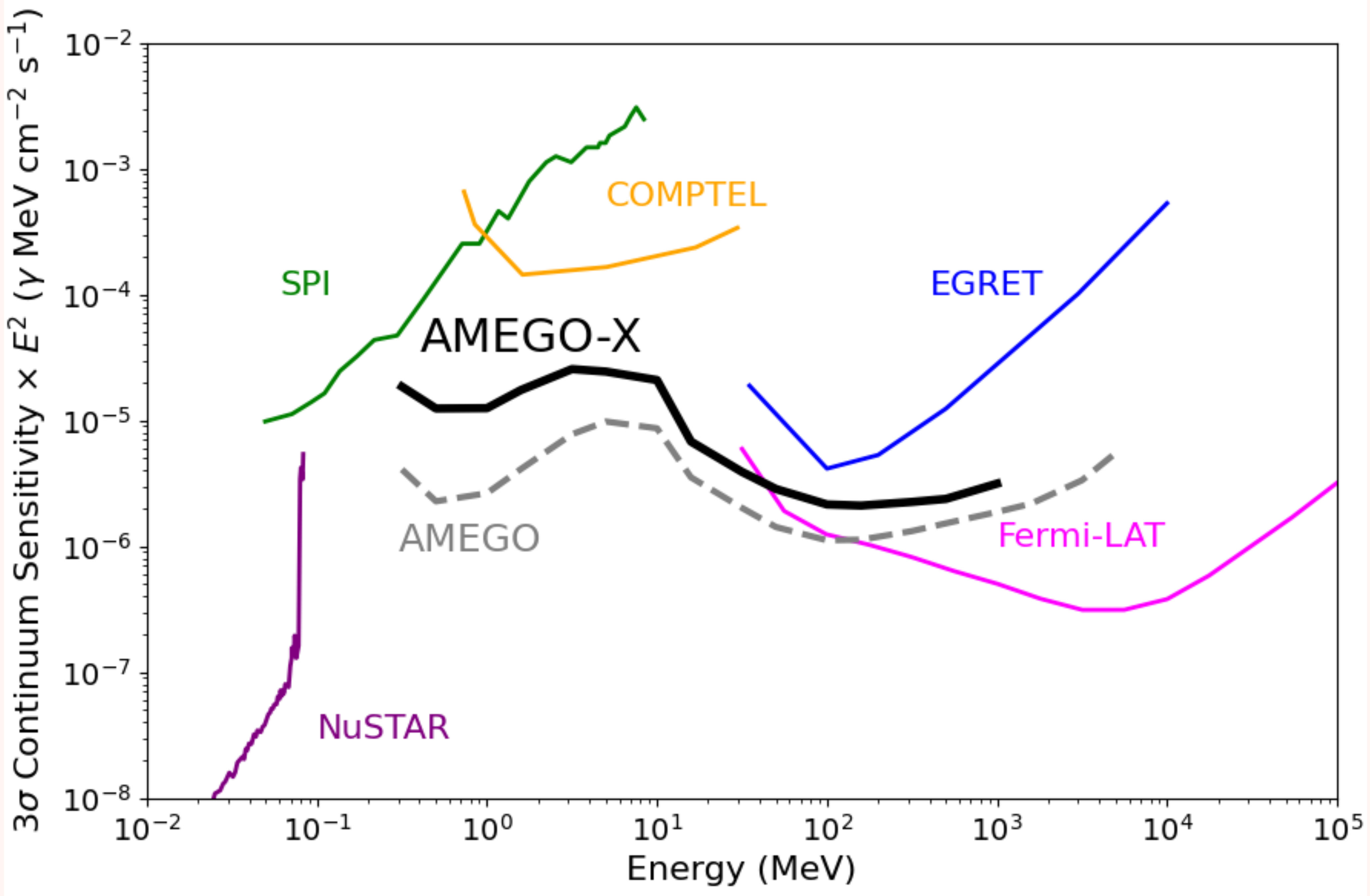
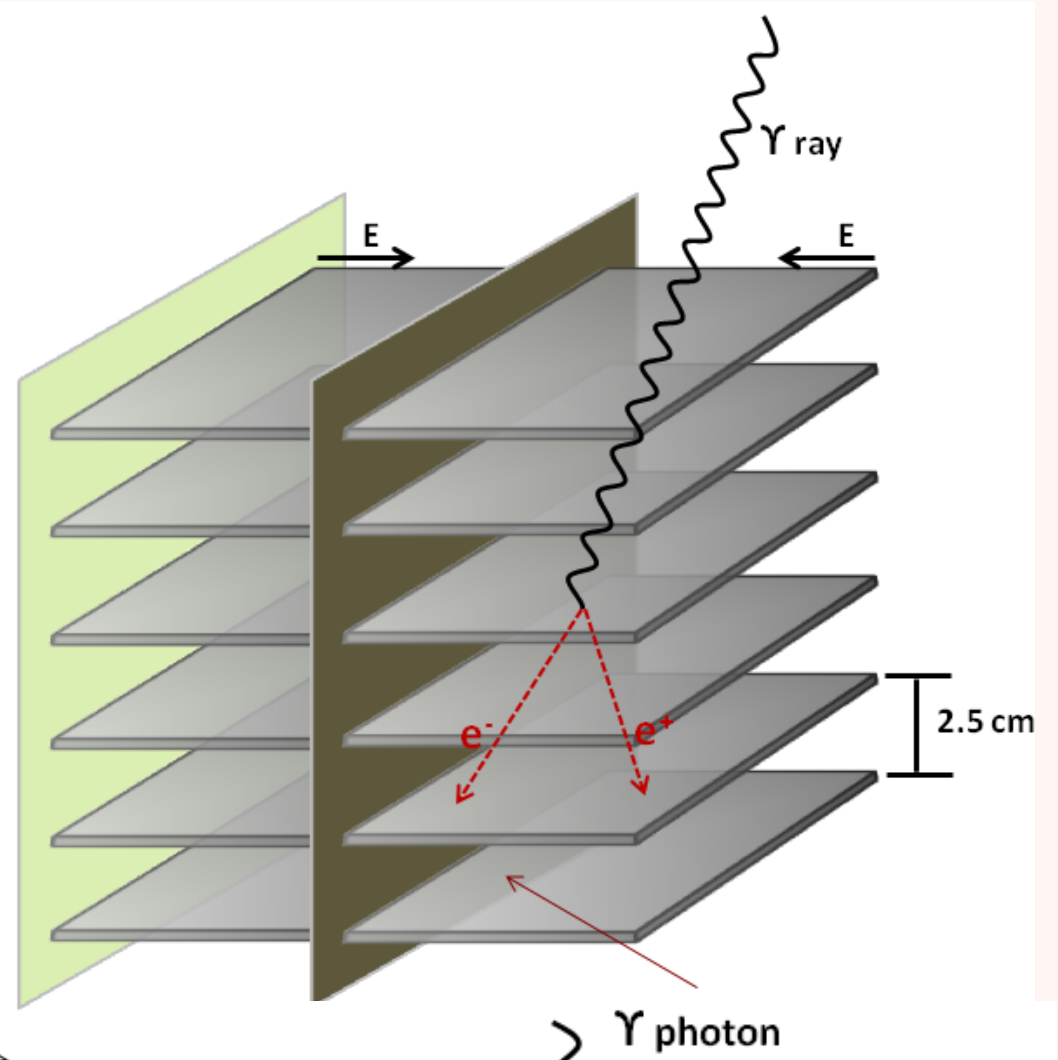


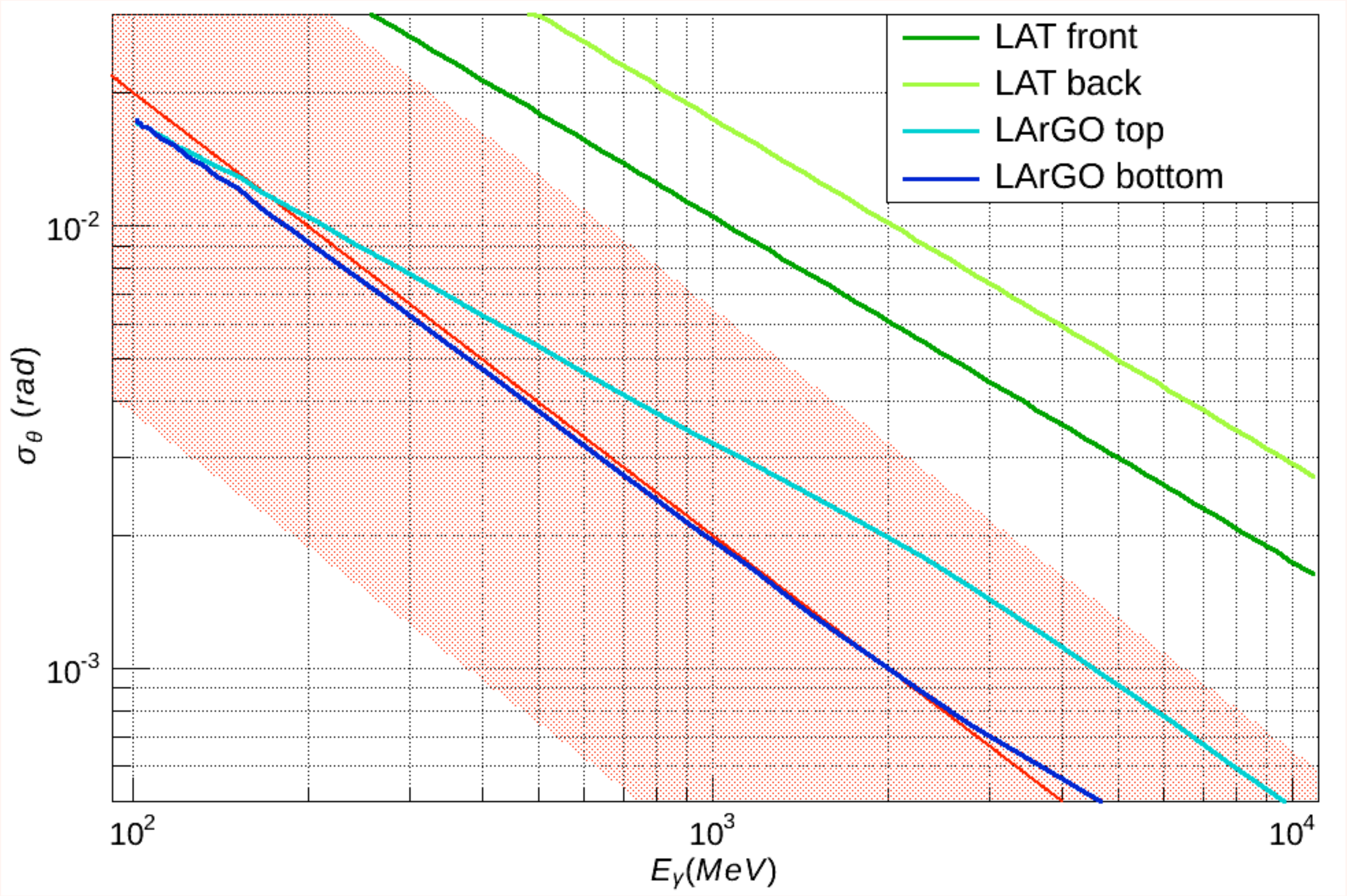
Alternative Sensor for AstroPix

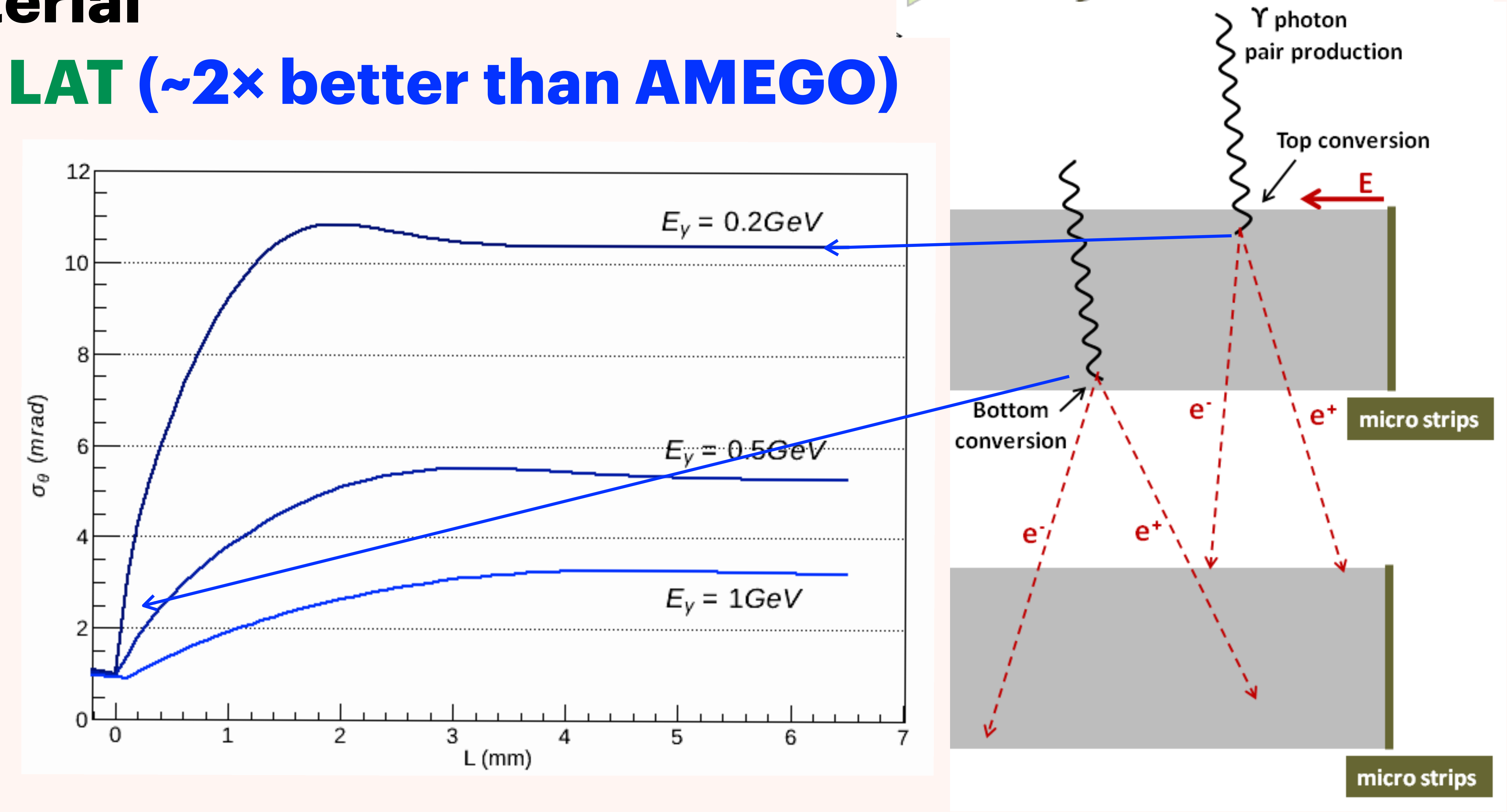
- **Low Gain Avalanche Diode (LGAD)**
  - LGADs were originally developed to realize superb time resolution (~30 ps) of charged particle detectors for LHC experiments
    - Distinguish initial interaction points among 100 of p-p collisions
    - The multiplication gain of LGADs are typically set to 5–10
  - Double-sided Strip LGAD sensor holds promise as a technology for MeV gamma-ray instruments
    - Comparable or better energy resolution than CMOS pixel sensor
      - Better detection efficiency for lower-energy gamma rays
    - Lower power consumption than CMOS pixel sensor: $2N$ vs N^2
    - Enhanced time resolution could be a powerful tool to
      - discern the sequence of multiple Compton scatterings
      - discriminate neutron scattering by pulse shape
        - major backgrounds for Compton camera
    - Extensive development is required to realize Double-sided Strip LGAD sensor

Future Tracker Alternative

- **Liquid-Argon (LAr) Time-Propagation Chamber (TPC)**
  - **Fully active tracking detector (and converter)**
    - **32 × LAr-TPCs: 3.2% X_0 (6.5 mm) per layer**
      - **X_0 = 20.4 cm (×2 Si) @ 83.8 K, 68.9 kPa**
      - **~100% X_0 diluted in 1 m (>5 × AMEGO-X)**
  - **Conversions close to the bottom of the TPC layer gives better angular resolution due to less material**
  - **~5× better angular resolution than Fermi LAT (~2× better than AMEGO)**

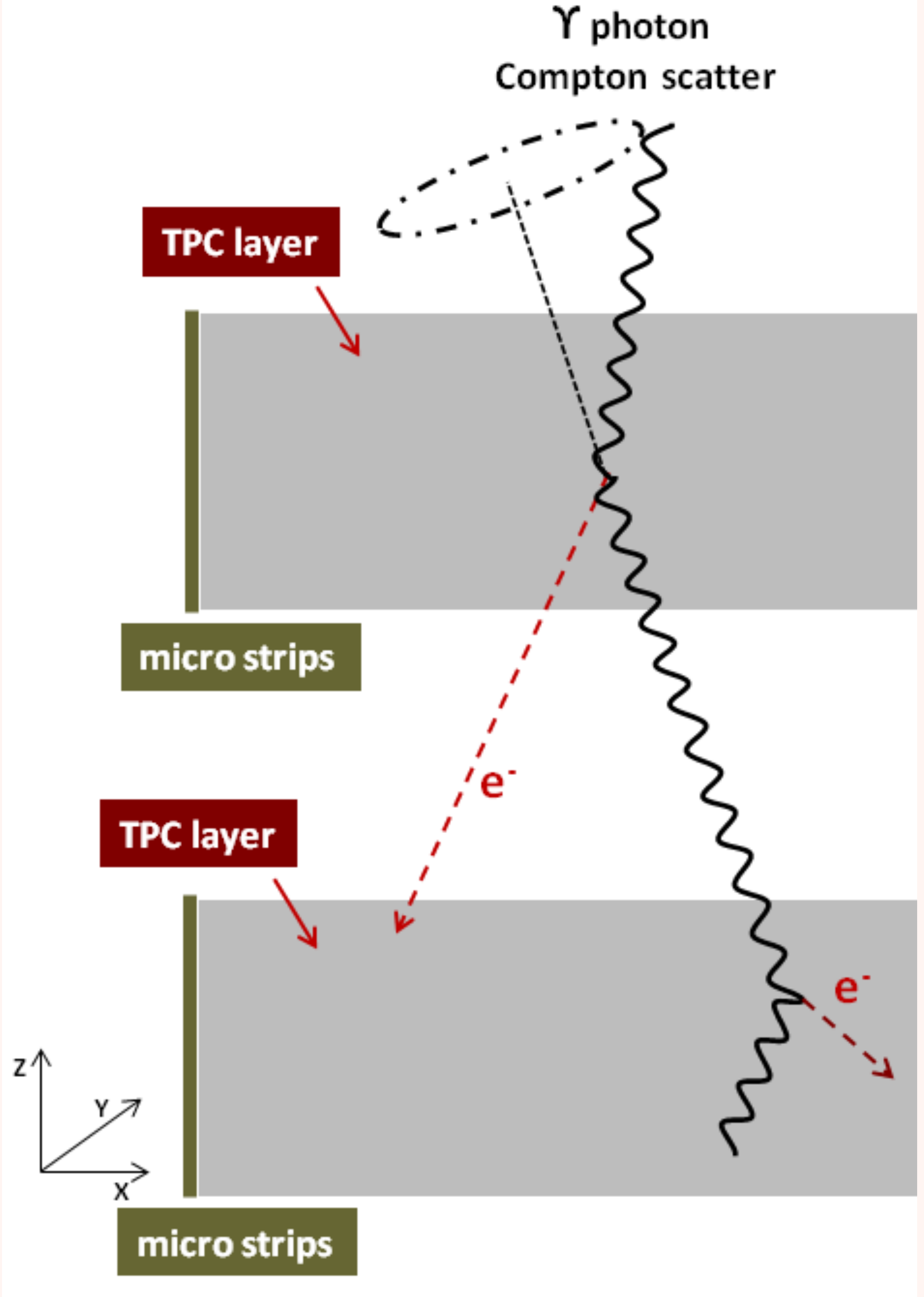






Compton Telescope Performance of LAr TPC

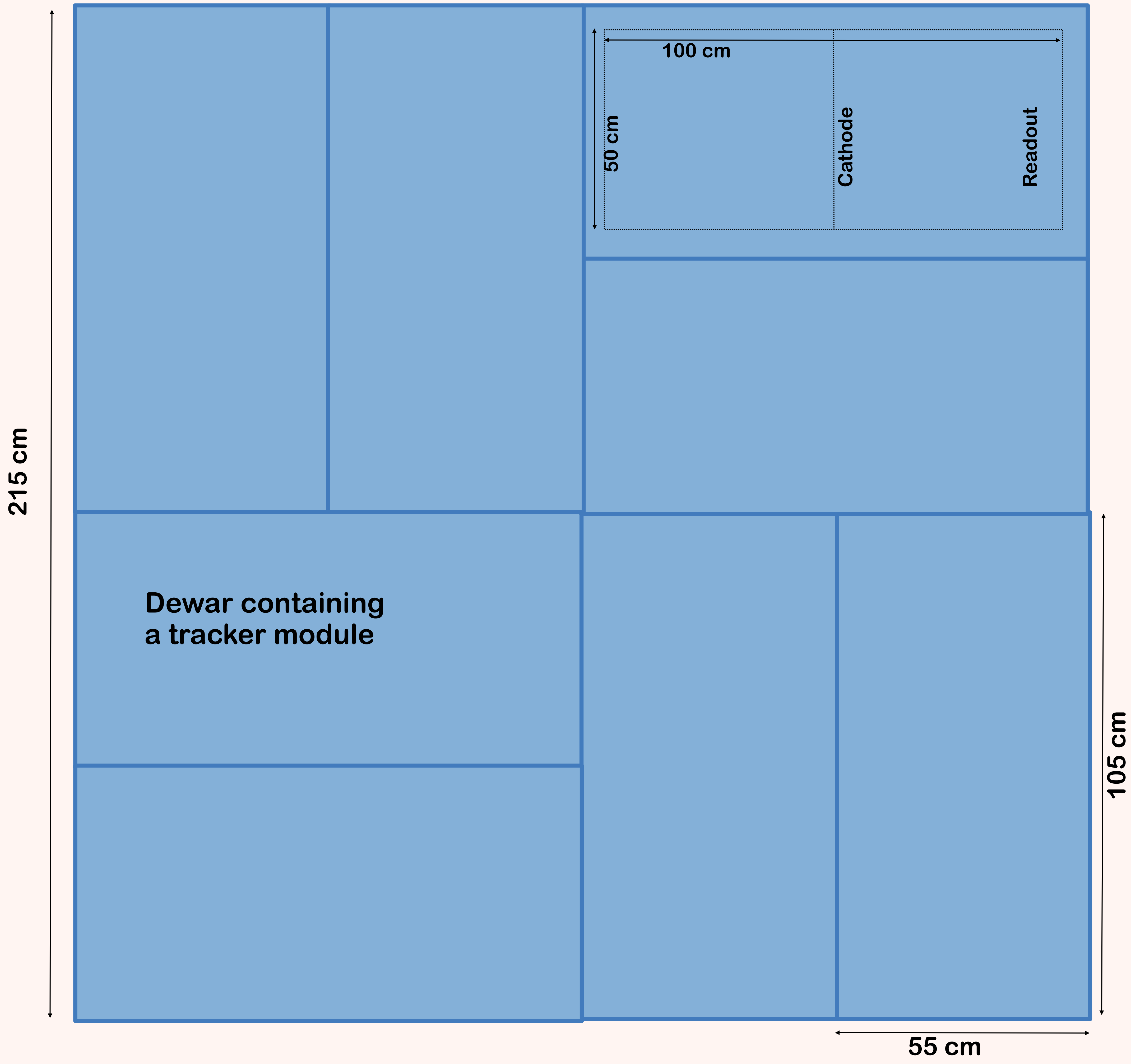
- LAr-TPC also functions as scatterer of Compton telescope
  - Full tracking (3D measurements) of recoil electrons
    - 500 keV electrons can provide ~20 space (3D) points in LAr
      - Only 2–3 space points in Si sensors
      - ~3× finer segmentation in z direction
    - ~2× longer radiation length for LAr than Si
    - Stopping power of the electrons in LAr @~70 kPa is ~1.4 MeV/cm
- Compton telescope performance
  - Attenuation length: 12 cm for 1 MeV
  - Energy resolution ≈ 3% FWHM @ 1MeV (AMEGO: 5%)
    - Strong anti-correlation between ionization and scintillation signals
    - High photon detection efficiency of SiPMs
  - Angular resolution ≈ 1° FWHM @ 1.8 MeV (AMEGO: 4° at 1 MeV)
  - Attenuation length ≈ 18 cm @ 1 MeV (Total thickness of LAr ≈ 21 cm)



Instrument Design of LArGO

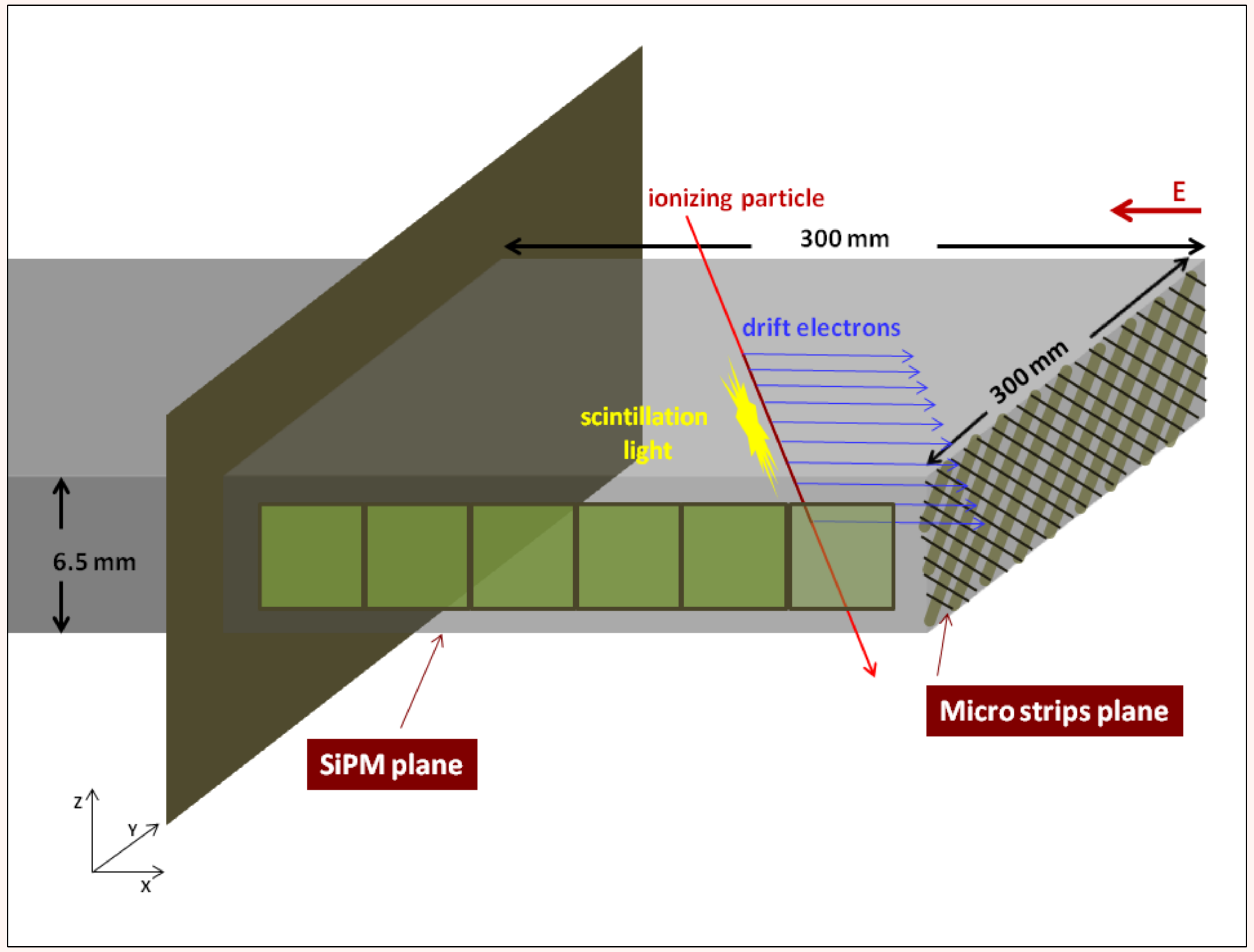
❖ **Conceptual design specifications of LAr Gamma-ray Observatory (LArGO)**

- **Geometrical area: 4 m^2 (7 × AMEGO-X)**
  - **8 modules × (100 cm × 50 cm)**
- **Active depth: 100% X_0 (5 × AMEGO-X)**
- **Weight: ~6 ton**
- **Full FoV > 60° × 60°**
- **> ×5 effective area of Fermi LAT**



ADVANTAGES AND CHALLENGES FOR LARGO

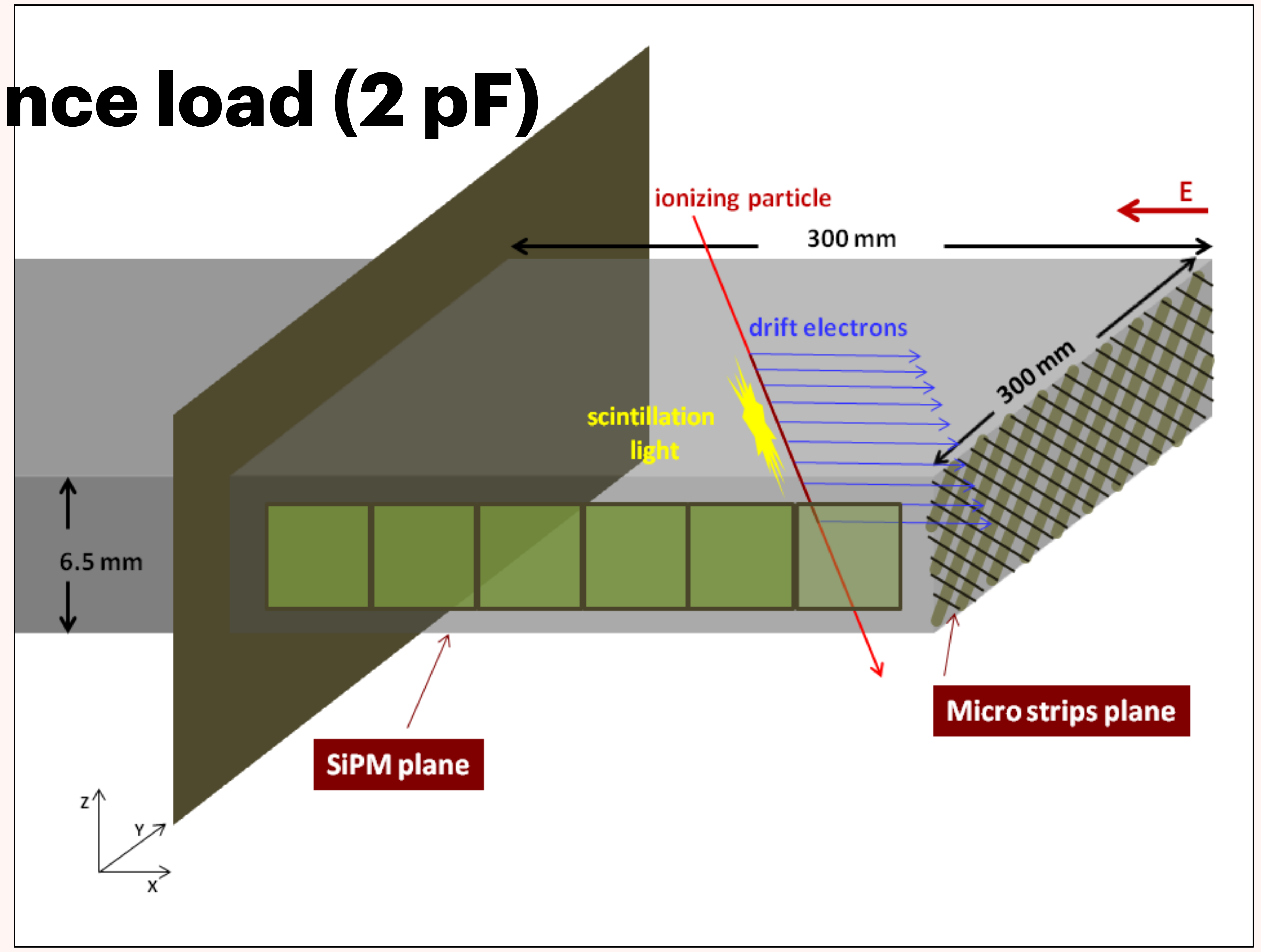
- ❖ **Fully active tracking of electrons (and positions) produced by gamma rays**
  - ✤ **Better tracking capabilities than Si detectors with less channels for larger volume and less cost**
  - ✤ **Better background rejection capability**
  - ✤ **Two-dimensional processing of ionization signal with ~150 μm pitch is required**
    - **AstroPix-like ASIC with 150 μm pixel size can be adequate solution**
      - ◉ **low power, low noise and good time resolution**
      - ◉ **Normal CMOS process: non fully-depleted device**



- ❖ **Scintillation light provide excellent time resolution**
  - ✤ **Determine the sequence of multiple Compton scatterings**
  - ✤ **Discriminate neutron scattering: major backgrounds for Compton scattering**
  - ✤ **Discriminate tracks back scattered from calorimeter: major background for Fermi**
  - ✤ **Detection of VUV scintillation photons (λ≈128 nm) by SiPMs with a time resolution < 200–300 ps (cΔt < 10 cm) is required**

Processing Ionization Signal from LAr TPC

- **Ionization signal**
  - **~32,500 e–h pairs/layer (5,000 e–h pairs/mm @ ~70 kPa)**
  - **110–180 μm drift distance resolution with 40–80 ns time resolution @350 V/cm**
- **Multi-layer printed cross strips**
  - **This technique was developed in the ICARUS R&D (NIM A, 346, 1994), and for the COIMBRA PET (NIM A, 477)**
  - **45° with respect to z axis**
  - **Length of the longest strip is ~ 1cm to minimize capacitance load (2 pF)**
  - **100 μm pitch is possible**
- **CMOS pixel readout (AstroPix)**
  - **125–500 μm pixel pitch**
  - **Low power**
  - **Low noise**



AstriPix for LArGO

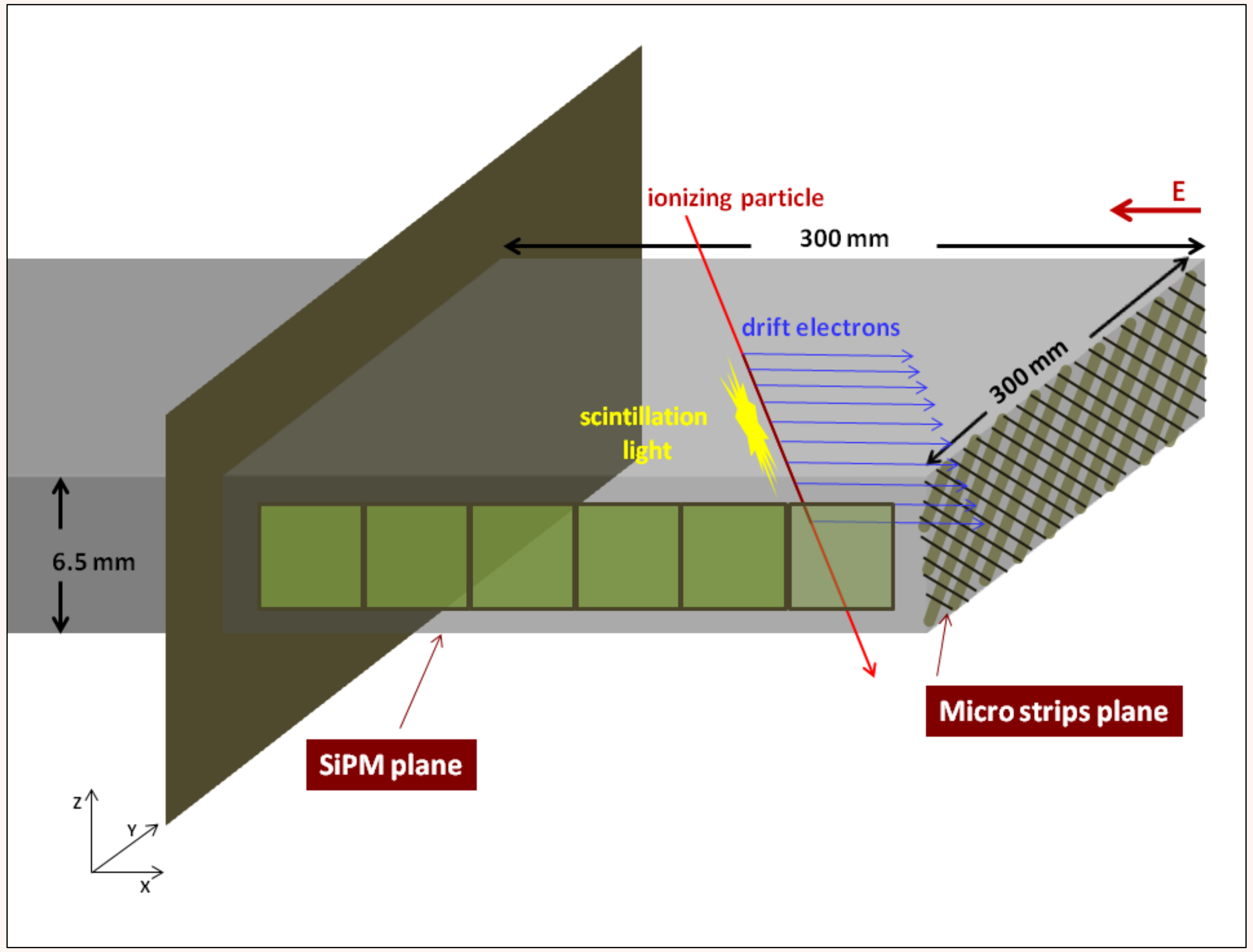
❖ **Comparison of AstroPix specifications between LArGO and AMEGO**

	LArGO	AMEGO
Pixel size	100–150 μm	500 μm
Power	5–10 mW/cm^2 (Total power: 100–200 W)	2.5 mW/cm^2 (Total power: 900 W)
Noise	3% FWHM @ 1 MeV	5% FWHM @ 1 MeV
Dynamic range	300 keV	700 keV
Time resolution	< 30 ns	3 ns
Depeletion depth	not required	500 μm

Time Resolution of Scintillation Photons

- ❖ **LAr is a very good scintillator**
  - ✤ **Bright:** light yield ≈ 51,000 photons/MeV (1.2 × NaI)
  - ✤ **Fast:** decay time ≈ 4.3 ns
  - ✤ **VUV:** λ ≈ 128 ns
- ❖ **Intrinsic time resolution of SiPM is better than 100 ps**
- ❖ **64-ch ASIC with 30 ps time resolution available**

- ❖ **Need to demonstrate time resolution < 300 ps after correcting photon transmission delay**



Summary

- **LAr TPC is a promising technology to observe MeV gamma rays**
  - **Can leapfrog AMEGO-X by more than an order of magnitude in sensitivities**
    - **More active volume than silicon with better tracking capabilities (more space points and better resolution) and less power**
    - **Better background rejection capabilities**
    - **Better reconstruction capability of Compton sequences**

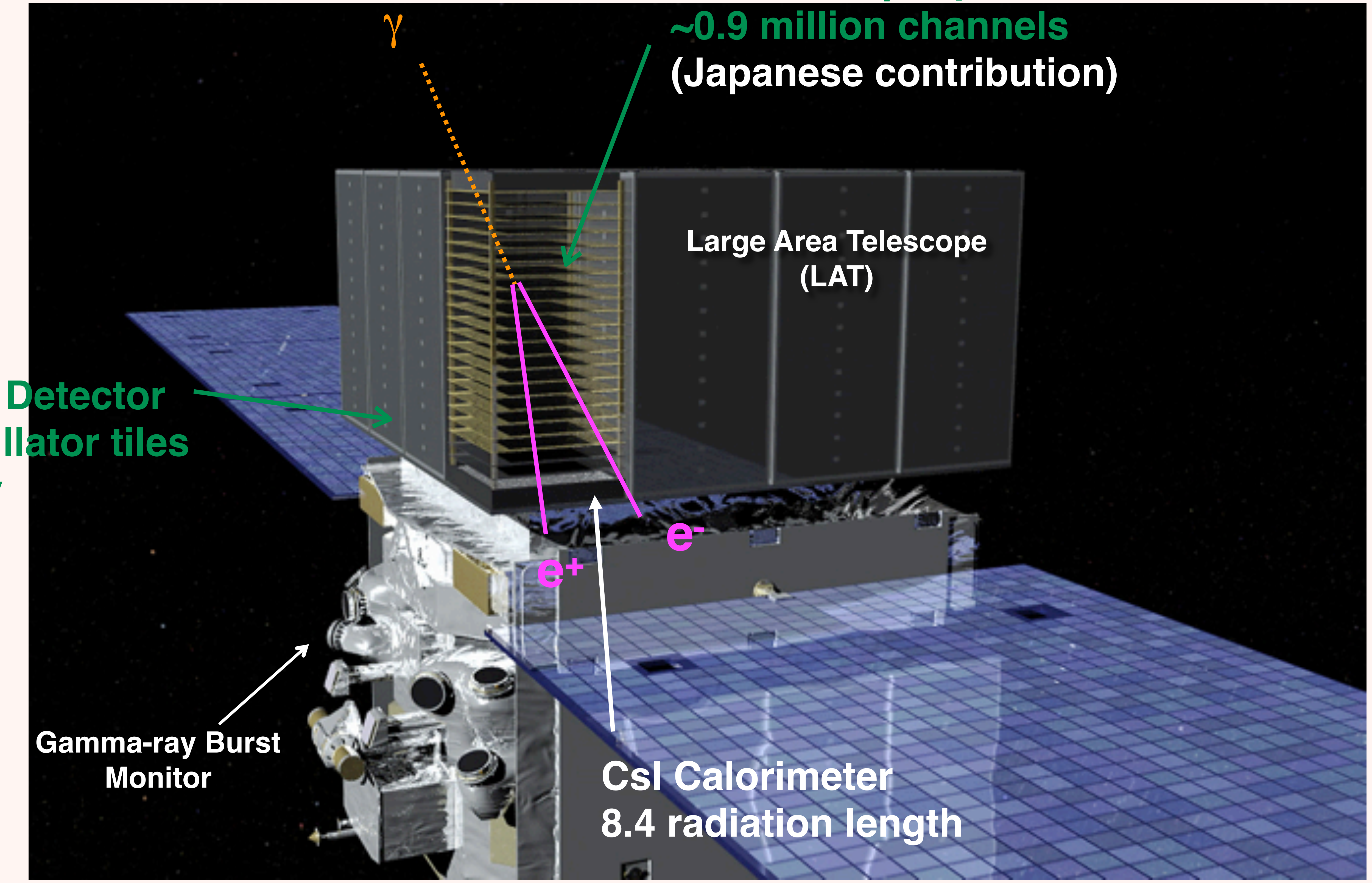
- **Need to demonstrate (to take full advantage of LAr TPC)**
  - **Three-dimensional tracking of ionization signal with ~150 μm precision**
  - **Time resolution < 300 ps after correcting photon transmission delay**

Supplemental Slides

Fermi LAT (Large Area Telescope)

- Pair-conversion telescope
  - Good background rejection due to "clear" gamma-ray signature
- Tracker (TKR): pair conversion, tracking
  - Angular resolution is dominated by scattering below ~GeV
- Calorimeter: energy measurement
  - 8.4 radiation length
  - Use shower development to compensate for the leakage
- Anti-coincidence detector:
  - Efficiency > 99.97%

Energy band: 20 MeV to >300 GeV
Effective area: > 8000 cm^2 (~6×EGRET)
Field of view: > 2.4 sr (~5×EGRET)
Angular resolution: 0.04 – 10°
Energy resolution: 5 – 10%



IMPROVEMENTS FROM FERMI LAT

- ❖ Trade off between pair-conversion efficiency (more material) vs. angular resolution (less material)
  - ✤ Tungsten converter + Si tracking in Fermi LAT
    - Angular resolution is constrained by thickness of Tungsten converter (not active)
      - ◉ 3% X_0 × 12 layers + 18% X_0 × 3 layers ≈ 76% X_0
- General approach to improve the situation
  - Focus on 1 MeV – 1 GeV energy region
  - Remove tungsten converter to improve angular resolution
    - Effective area may be reduced
  - Employ 2-dimensional silicon detector to minimize the detector thickness and obtain 2D position
    - Tracking of recoil electrons due to Compton scattering to constrain incident gamma-ray direction
    - 0.5% X_0 × 40–60 layers ≈ 20–30% X_0 (e-ASTROGAM, AMEGO, AMEGO-X)