Agenzia Spaziale Italiana

Istituto Nazionale di Astrofisica

Istituto Nazionale di Fisica Nucleare

Attività di studio per la comunità scientifica di astrofisica delle alte energie e fisica astroparticellare

Studi per future missioni scientifiche

(Accordo Attuativo ASI–INAF n.2017-14-H.0)

POX – PANGU Optimization and eXperimental verification

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on behalf of D.D'Urso (UniSS)

Outline

- The PANGU Concept
  - The Science Case
  - The Instrument
- The POX Project Structure
  - Objectives
  - Tasks and phases
  - Working Packages
  - Costs
  - Deliverables

The PANGU Concept

PANGU (PAir-productioN Gamma-ray Unit) is a sub-GeV γ–ray telescope with unprecedented angular resolution:

- energy range 10 MeV- 1 GeV
- point spread function (PSF) ≤1° @ 100 MeV
- novel concept for low weight mission (<100 Kg, but easily up-scalable)

Presented at the ESA-CAS Workshop for a joint scientific space mission on 2014 (arXiv:1407.0710 [astro-ph.IM])

The Science Case

- Source identification and multi-wavelength astronomy, e.g.
  - Millisecond Pulsars
  - γ-ray emission from solar flares
- Galactic and isotropic diffuse γ-ray emission
- Indirect DM search (low mass DM)
- Baryon asymmetry signature in diffused γ–ray background
- Origin and acceleration of high energy cosmic rays

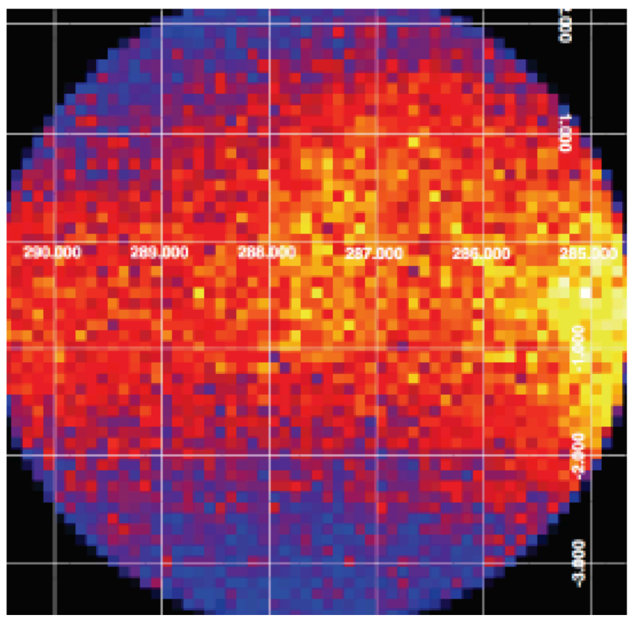
Source identification

Sub-GeV sky is dominated by diffuse –ray emission

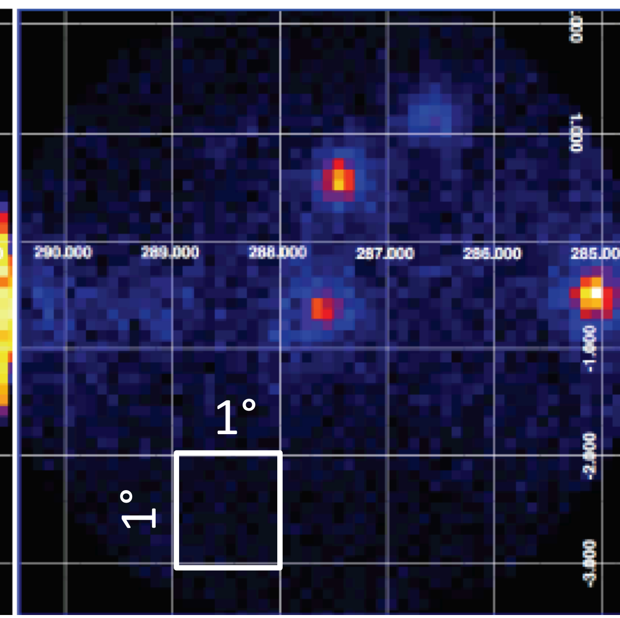
→ **good angular resolution to identify sources**

Eta Carinae (binary system) seen from Fermi with two different angular resolution (AR)

0.1-0.5 GeV



2-300 GeV



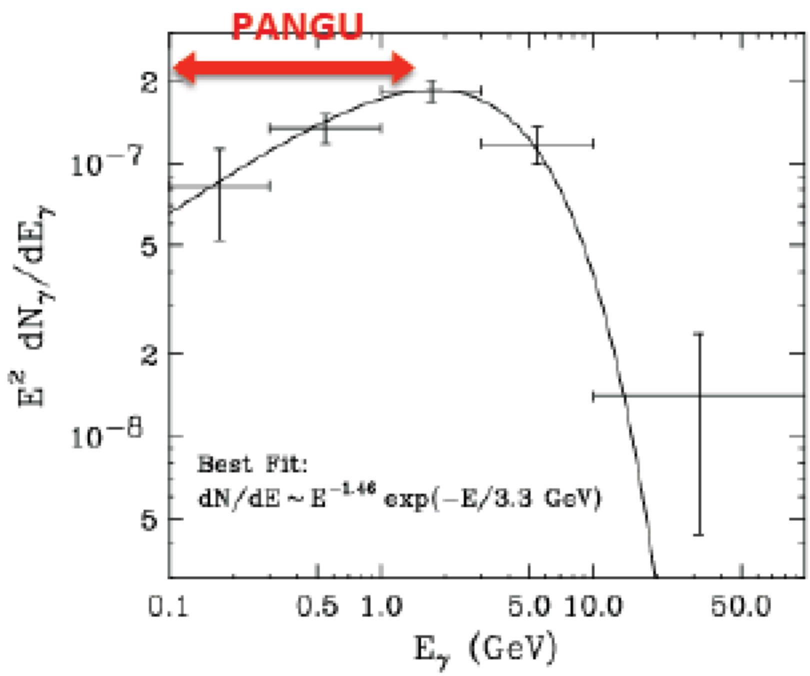
Goal: PANGU AR @0.1-0.5 GeV

Courtesy of X.Wu

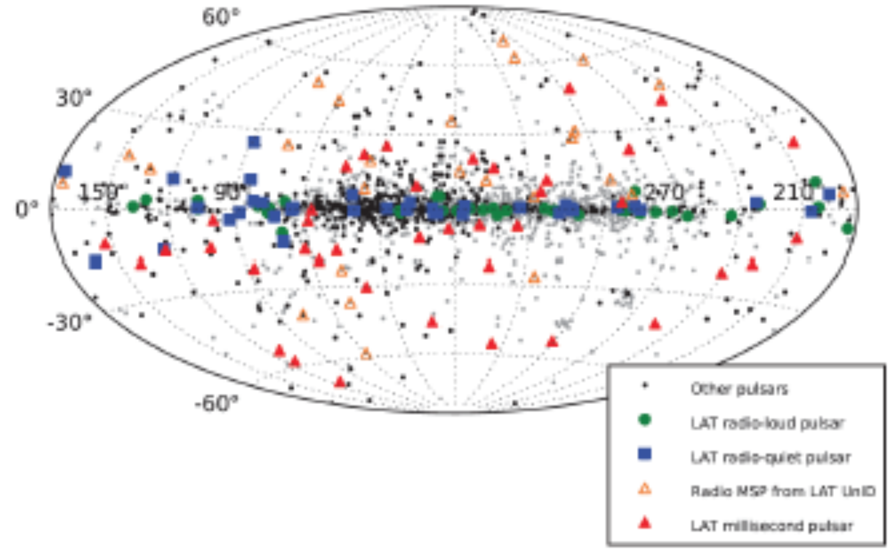
Millisecond Pulsars (MSP)

Millisecond pulsars emission peaked at ~GeV

better PSF → lower background



Example of MSP energy spectrum

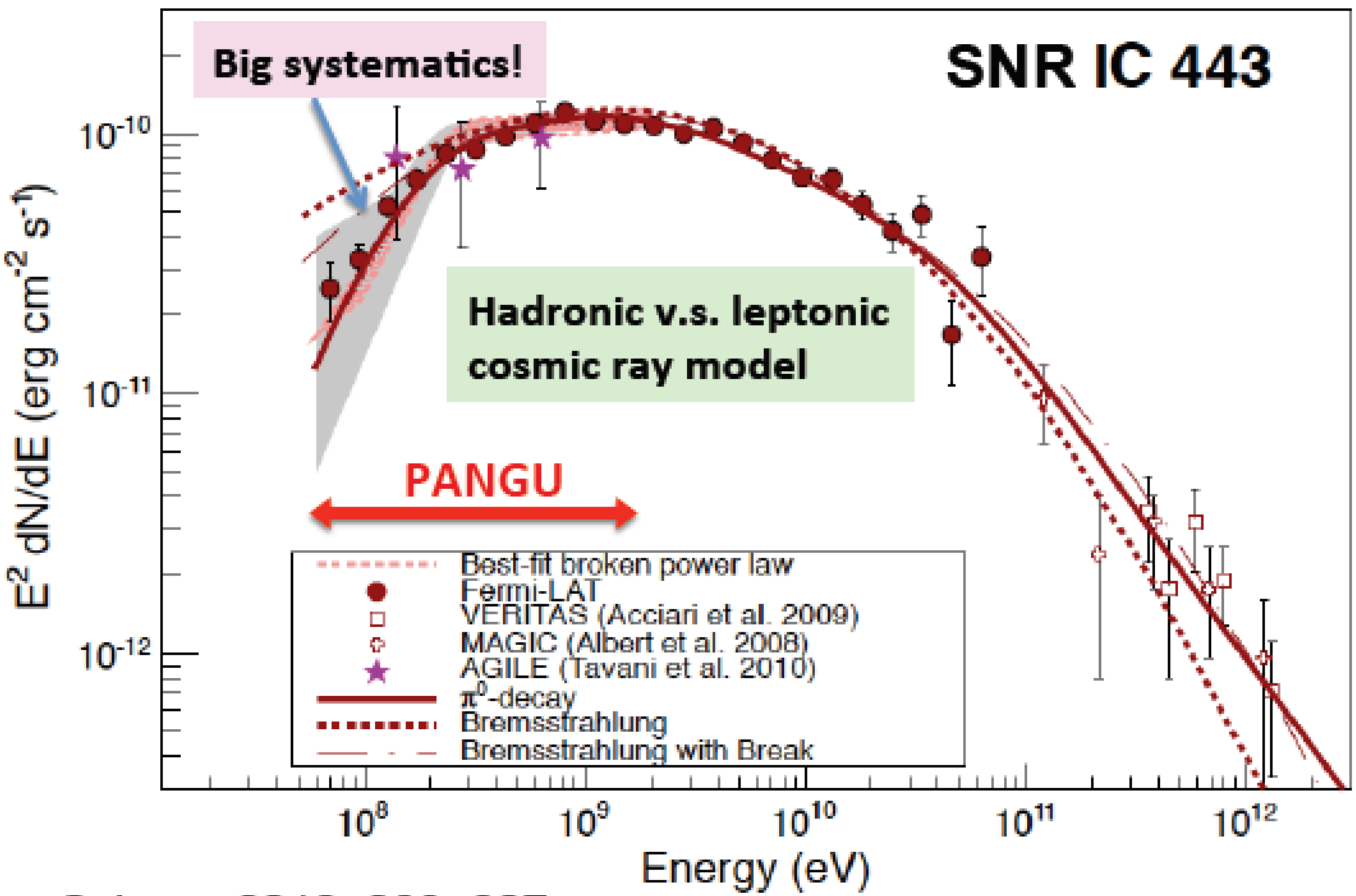


Fermi pulsar distribution affected by disk contamination **(small PSF required)**

γ-ray observations can help to disentangle the geometry of pulsar magnetospheres and emission regions

Courtesy of X.Wu

SNR and Particle Acceleration



Science 2013, 339, 807

PANGU will able to:

- distinguish between the two scenarios (hadronic vs leptonic)
- detect more SNR (thanks to a good resolution)

Courtesy of X.Wu

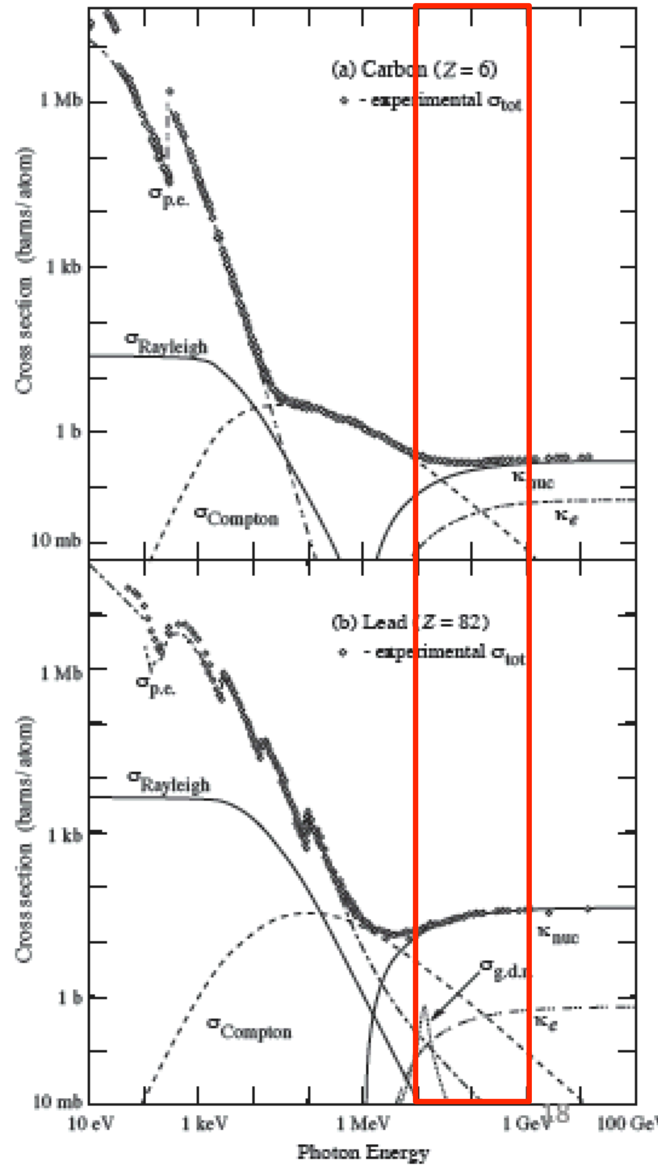
Detection principle

At ~100 MeV, pair production dominates

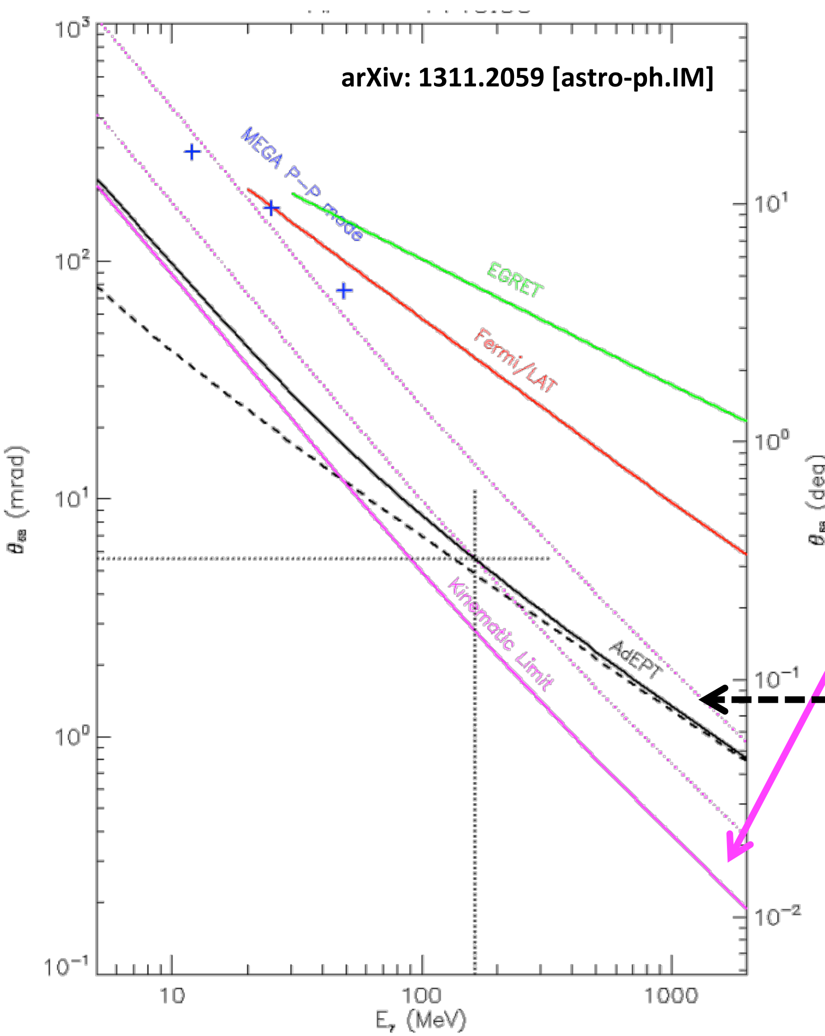
- small cross section → more material to increase acceptance
- material limiting factor of angular resolution, due to multiple scattering (MS) in the MeV energy range

The approach for PANGU is to:

- avoid the MS degradation with less material between consecutive measurements of the pair
- increase the cross section using many layers of converter



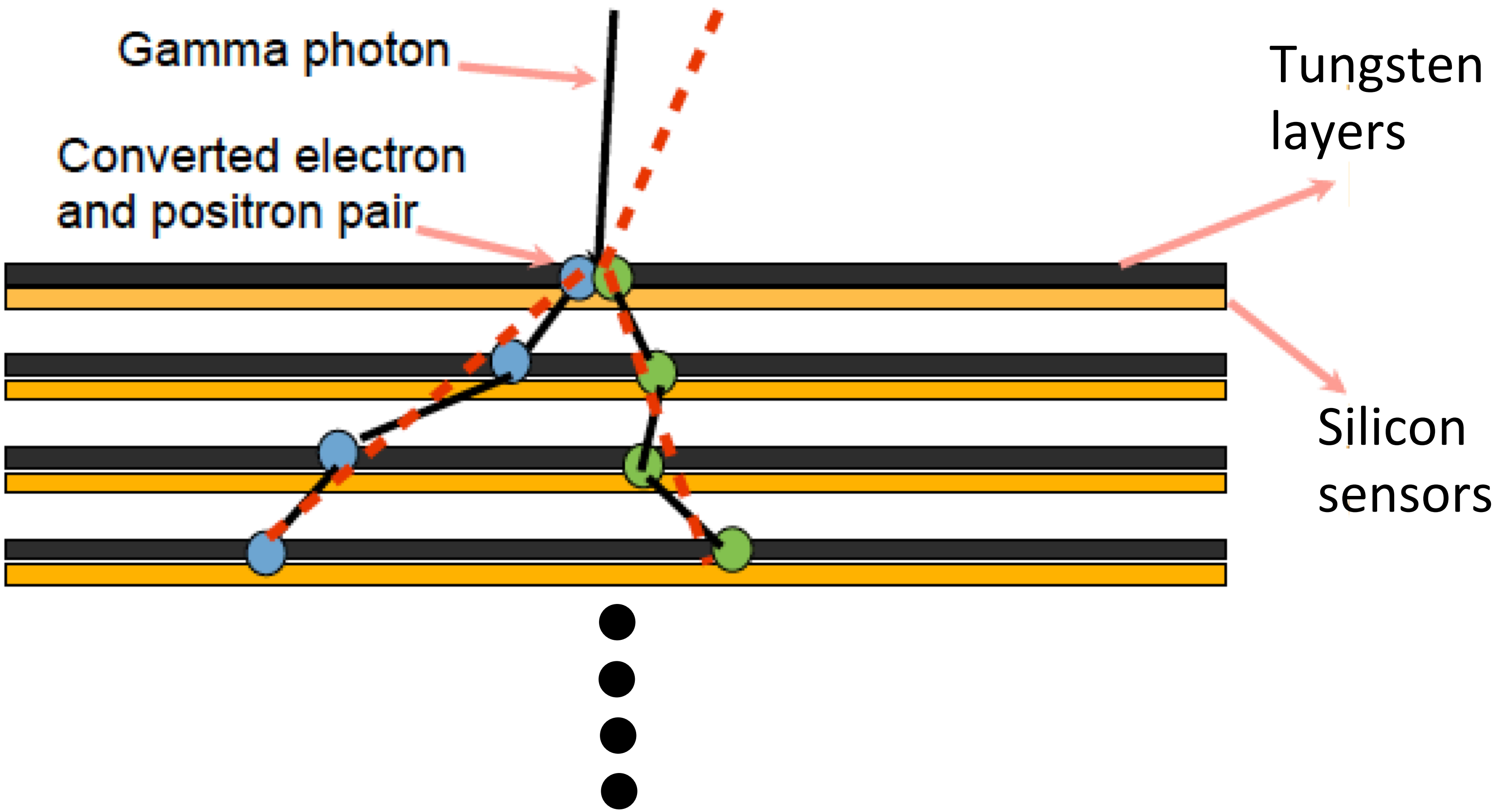
Pair-conversion telescope angular resolution



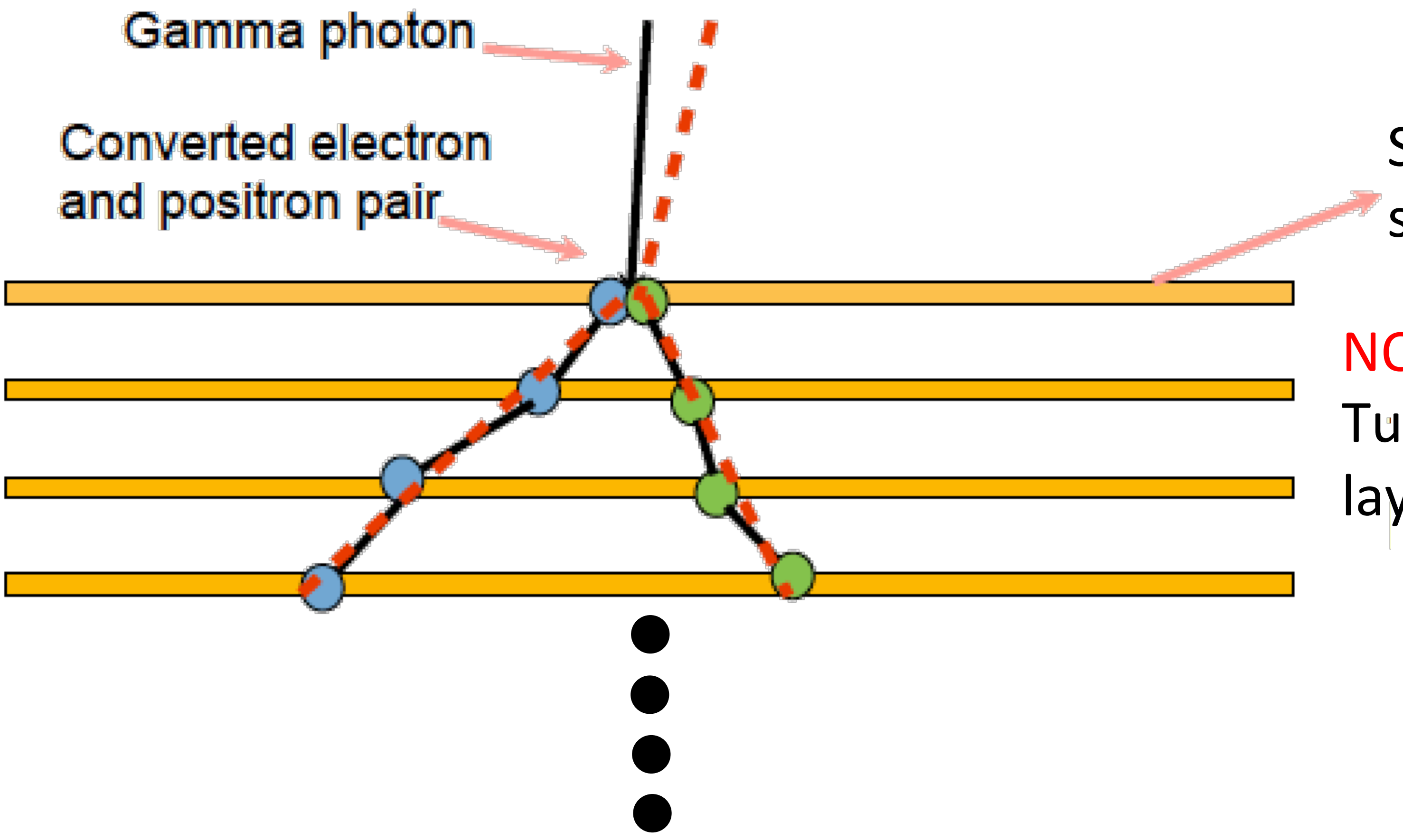
The angular resolution of a pair-conversion telescope:

- relies on the reconstruction of the photon incident angle by the <u>full</u> <u>kinematic</u> measurement of the electron-positron pair
  - → energy/rigidity measurement
  - → direction (i.e. tracking)
- is limited by the uncertainty on the nucleus (or electron) recoil energy (i.e. "kinematic limit")
- is limited by the Multiple Scattering changing the electron and positron direction
  - → the MS is dominating after few mX_0 (10 mX_0 for 900 MeV photons)
- decreases as the energy increases

Detection principle: Fermi-LAT



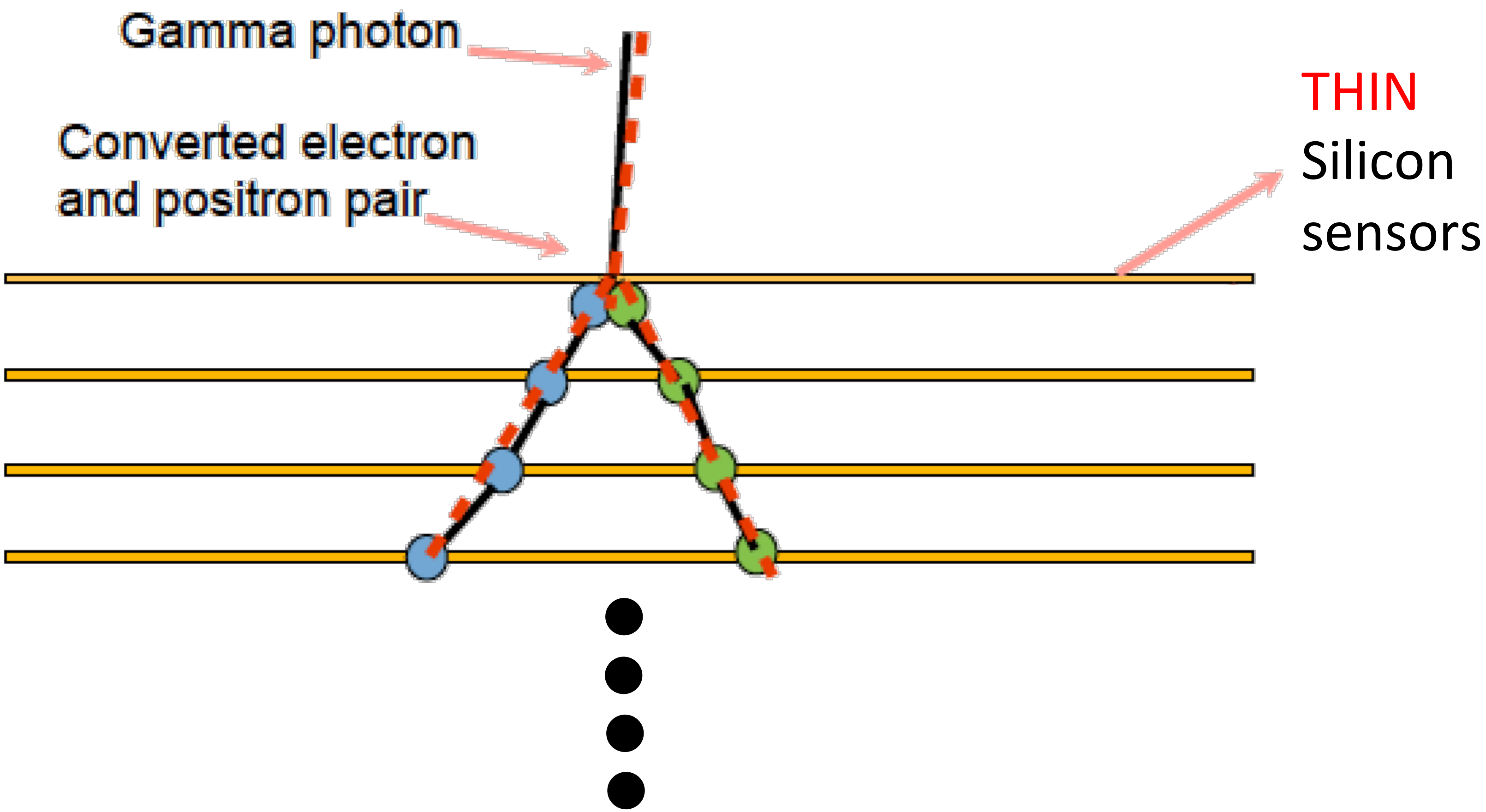
Detection principle



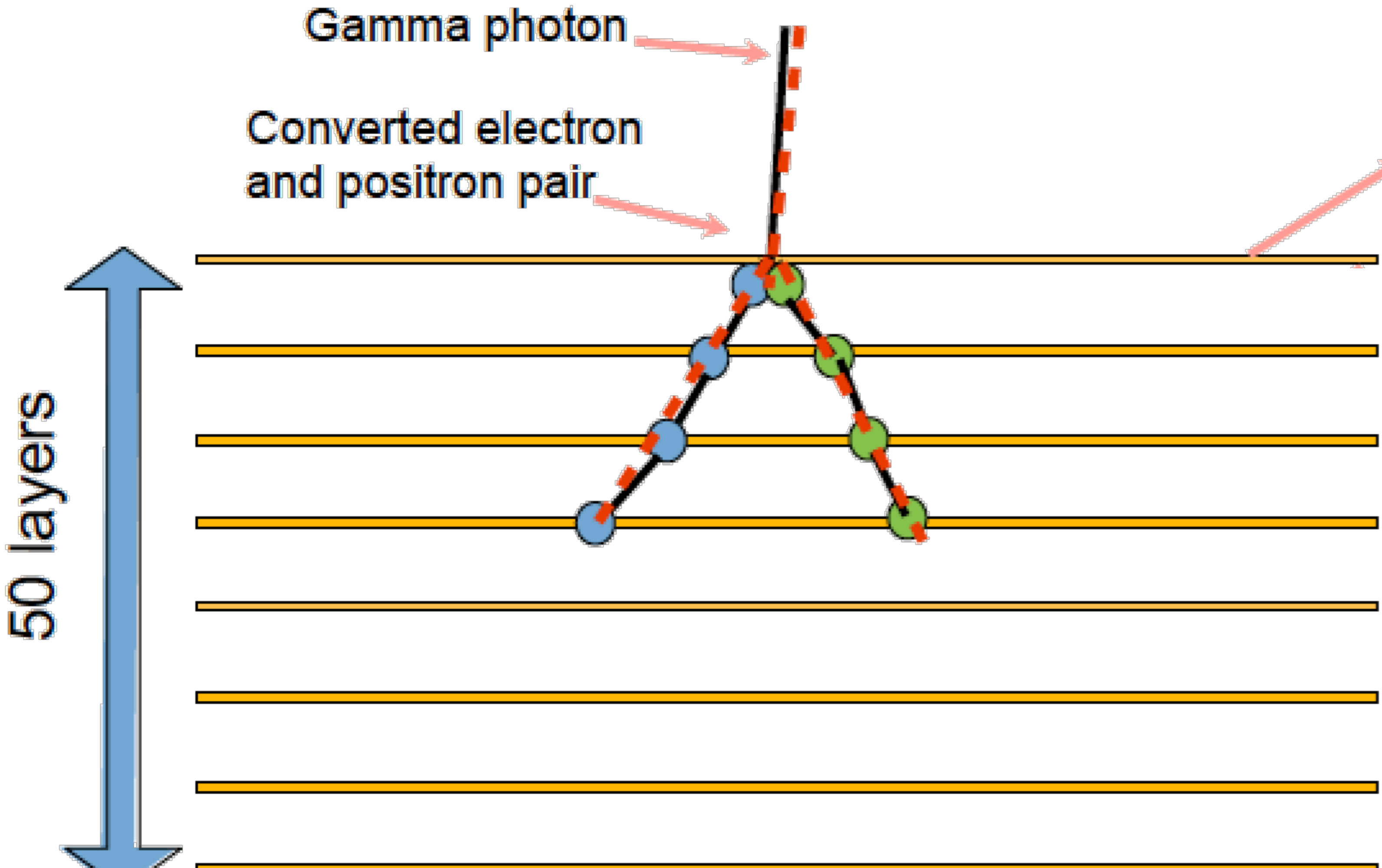
Silicon sensors

NO Tungsten layers!

Detection principle



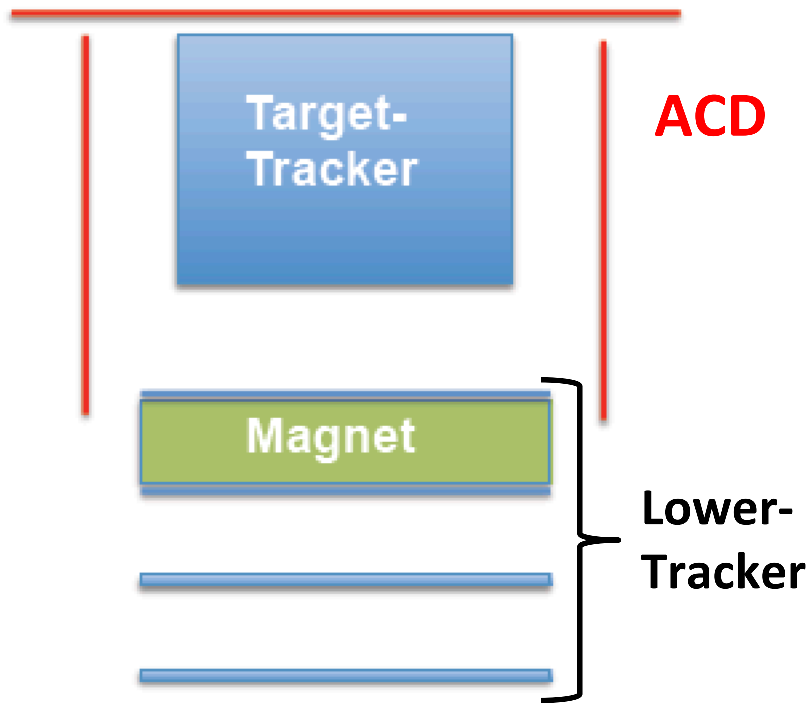
Detection principle: PANGU!



THIN Silicon sensors

PANGU Proposed Detector Layout

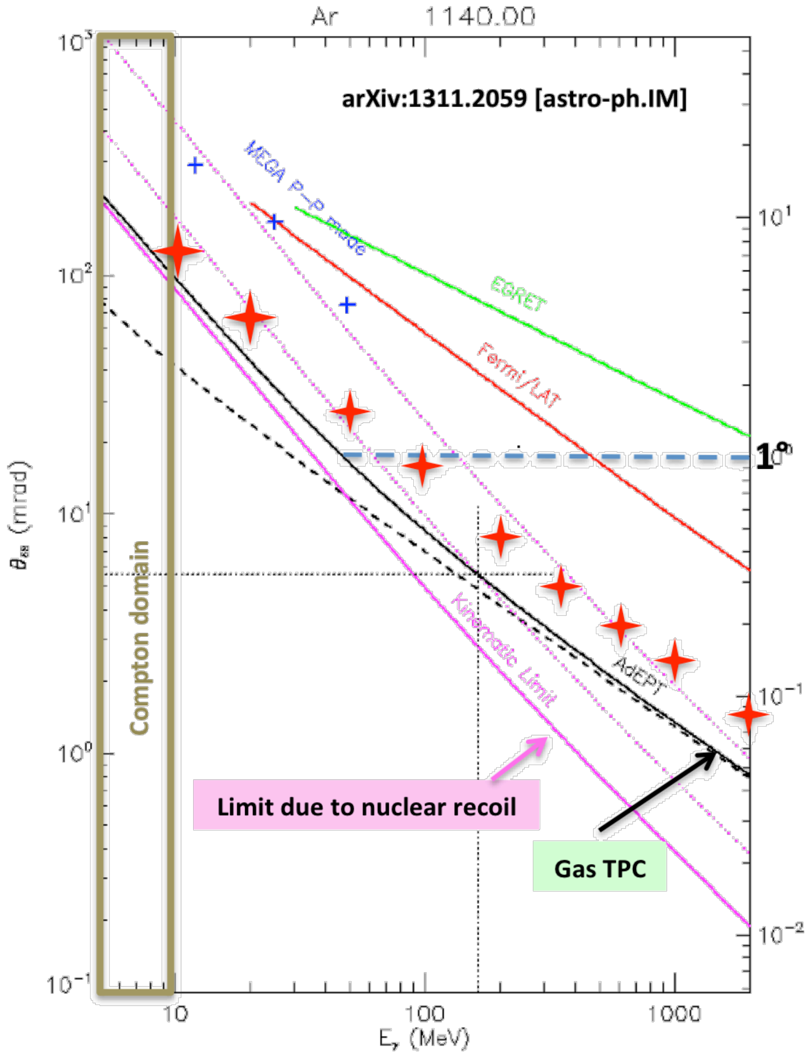
- ✓ Minimum passive material and active material thin to achieve an angular resolution <1°
- ✓ Many layers or large volume to increase effective area
- ✓ No calorimeter, to keep weight under 100 kg

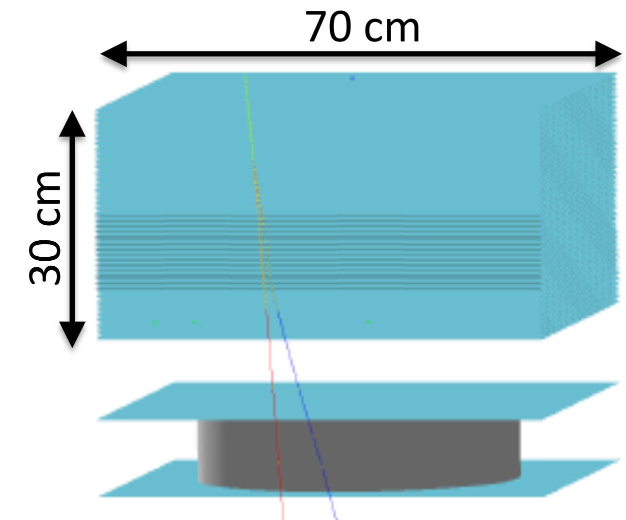


3 sub-system: target-tracker, magnet+lower tracker, Anti-Coincidence

- ❑ Target-tracker (TT): 50 Silicon layer, ~40x40x40 cm^3
- ❑ Magnet (M): r_2= 26 cm, r_1 = 25 cm, height 10 cm, B= 0.1 T
- ❑ Lower tracker (LT): 2 X-layers, 2 X-Y layers, ~10 cm inter-layer space
- ❑ Anti-Coincidence Detector (ACD) on 5 sides

PANGU telescope angular resolution



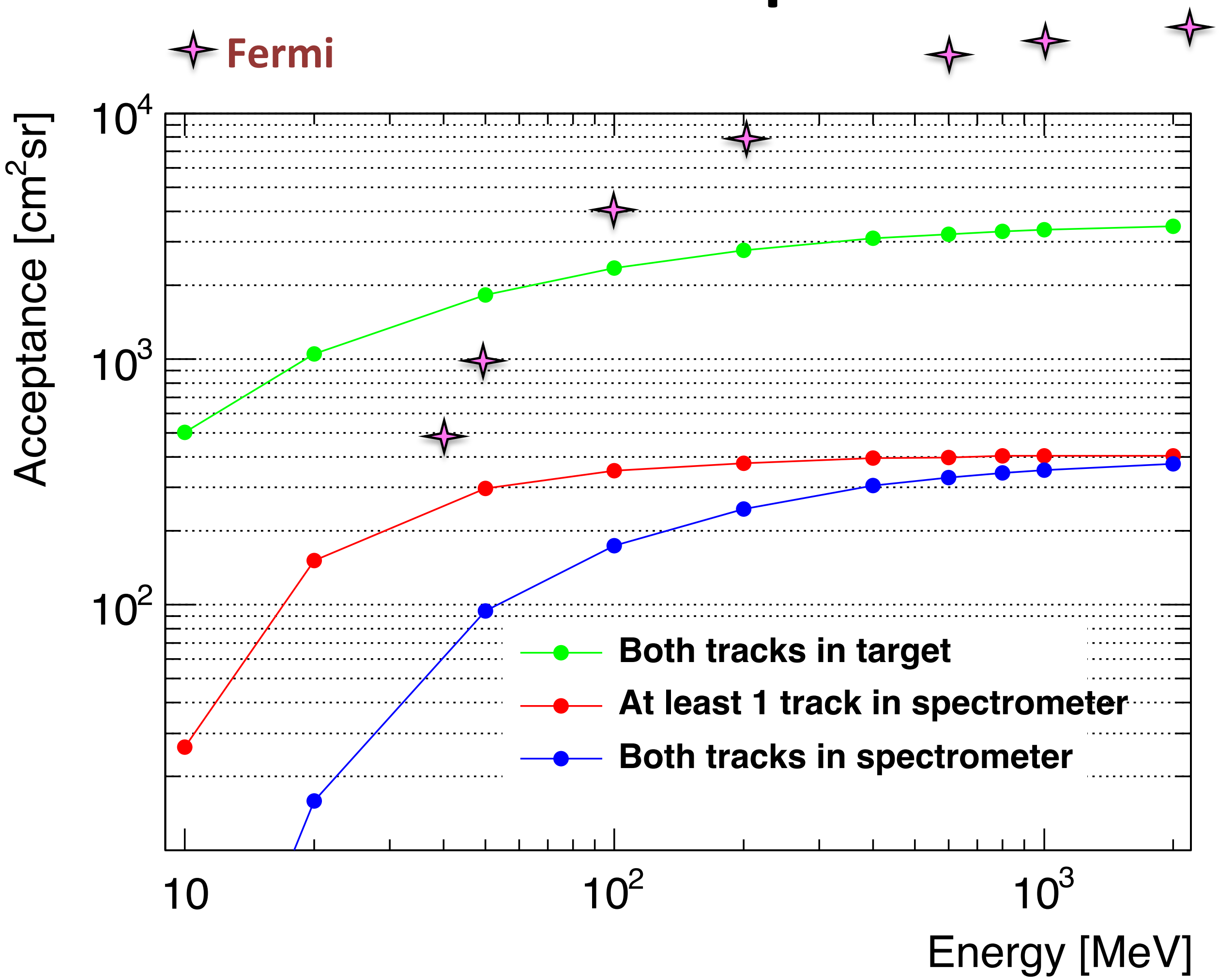


Geant4 “fast” Monte Carlo (MC) simulation:

- 150 µm Si detector;
- 242 µm pitch
  → 70 µm resolution simulated
  (very conservative:
  35 µm resolution @ 242 µm
  10 µm resolution @ 110 µm
  easily achievable)

→ results very preliminary and to be confirmed with a dedicated and reliable MC

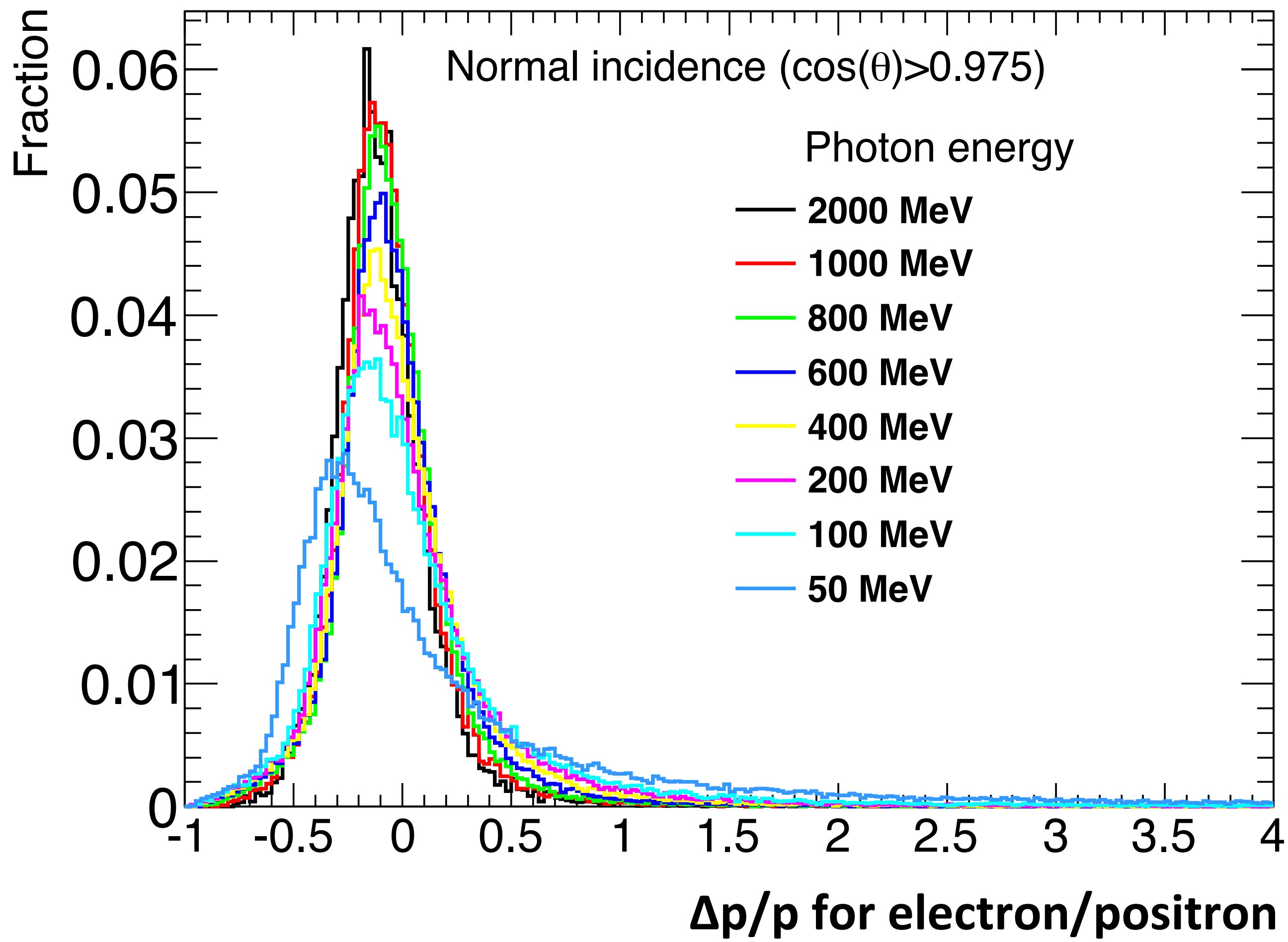
PANGU acceptance



Acceptance is small for a <100Kg mission,
but the design can be easily up-scaled for heavier payloads

Photon energy resolution

For normal incidence (cos(θ)>0.975), both tracks in the lower tracker



A 20-30% resolution in [0.1-1] GeV easily reachable

Pangu Optimization and eXperimental verification: Objectives

Design <u>optimization</u> of a PANGU-like detector

- detailed Monte Carlo (MC) detector simulation
  - ➢ minimize the PSF: trade off between high detection efficiency (thick tracker detector) and low multiple scattering effects (thin tracker detector)

Experimental verification of a PANGU-like demonstrator

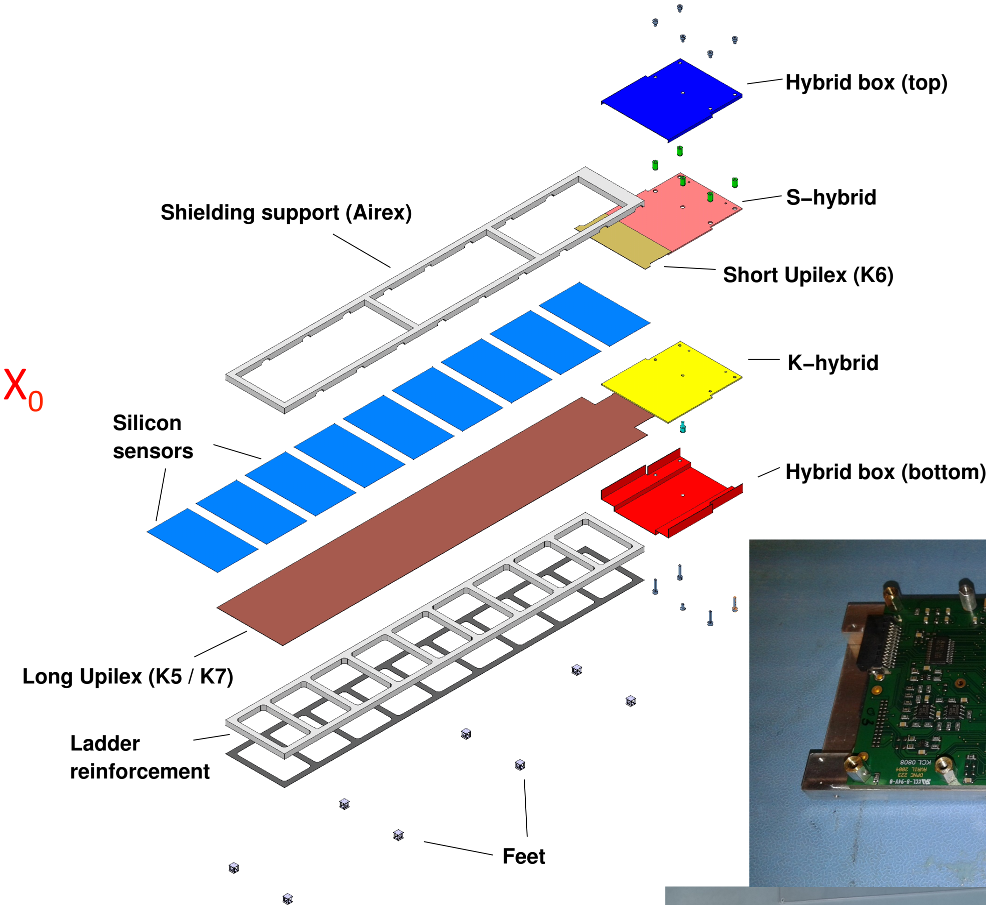
- beam test with tagged photons
  - ➢ validation of MC simulation with a demonstrator and a tagged photon beam
  - ➢ design and construction of new silicon tracking unit with optimal thickness
  - ➢ experimental measurement of the “final” figures of merit of the optimized demonstrator

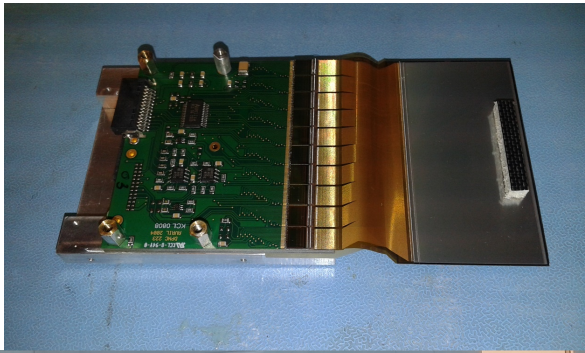
Available resources

- computing power to run the simulation code and for the data analysis (UniSS and INFN-UniPG);
- 7 AMS-02 spare silicon sensors;
- AMS-02 silicon detector spare Front-End hybrids;
- clean room with equipment for silicon sensors testing and assembly;
- cylindrical permanent magnet with uniform B-field (0.05T);
- 5(+3) researchers + 3 technicians

AMS-02 microstrip silicon sensors

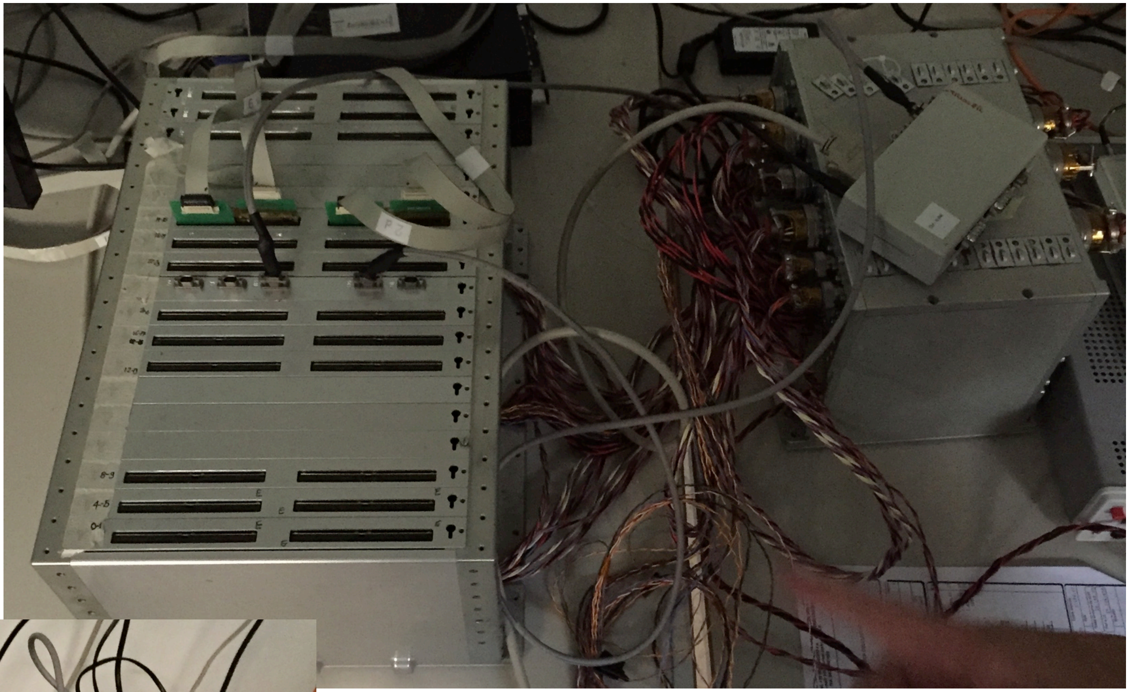
- 7(+2) AMS-02 spare microstrip silicon sensors
- resolution: 10μm/30μm
- size: 7x[4-48] cm^2
- thickness: 300μm → one sensor accounts for 0.3% X_0 (i.e. 3 mX_0 or 3mRL)





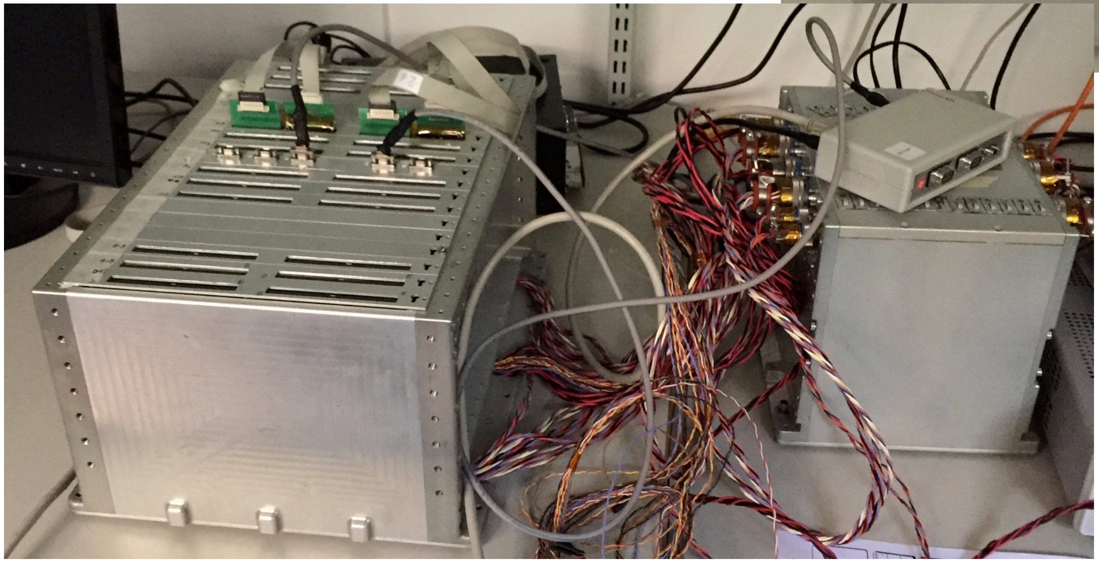
One of the “in kind” contribution given for the project is constituted by several spare part and modules built for the AMS-02 Silicon Tracker

AMS-02 DAQ



AMS "TCrate":

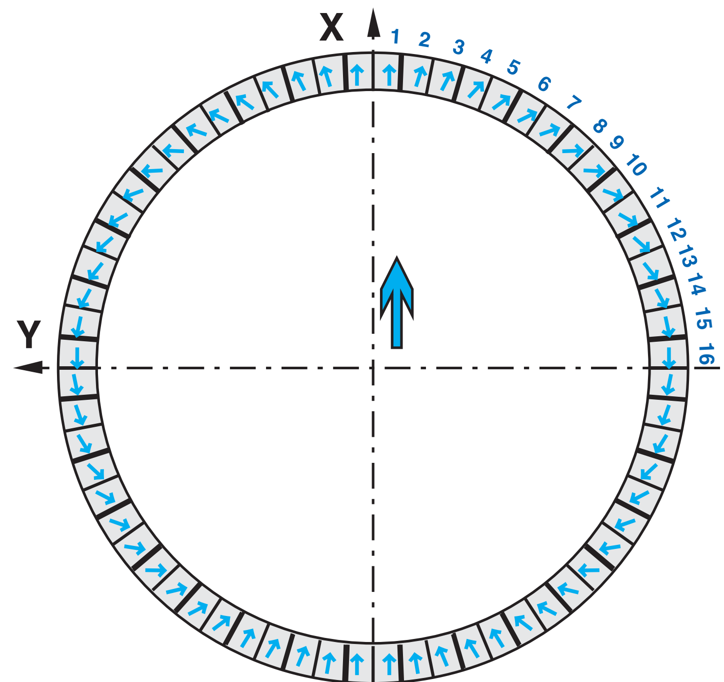
- up to 24 TDR's (i.e. silicon sensors)
- up to ~ 2 khz of rate
- busy management
- DAQ sw already implemented
- Analysis routines already implemented

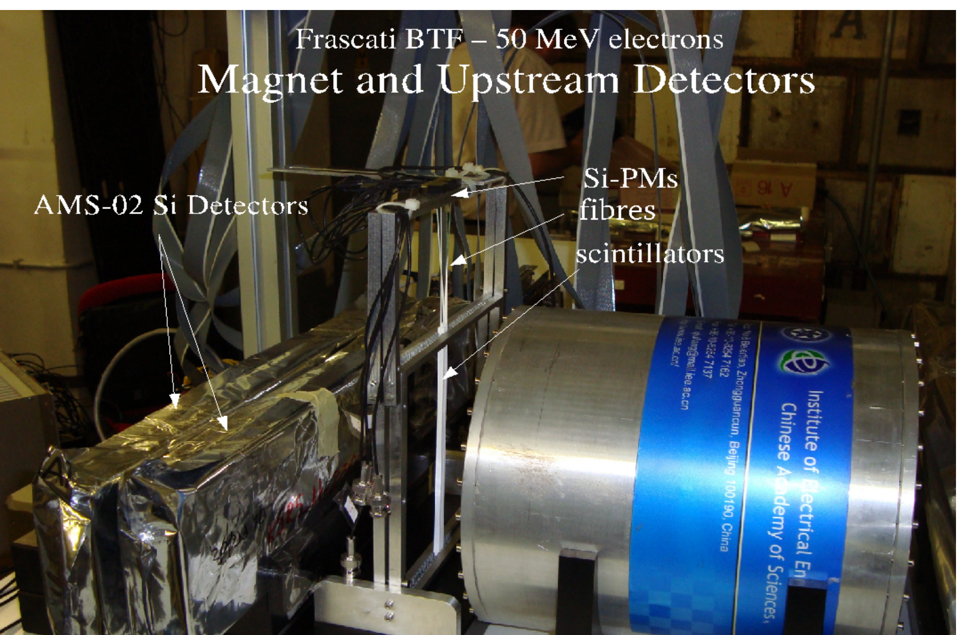


We have 2 complete setups: up to 48 silicon sensors

"AMS-like" small magnet

The PANGU spectrometer is based on a permanent magnet designed to provide a ~uniform field similar to the AMS02 magnet

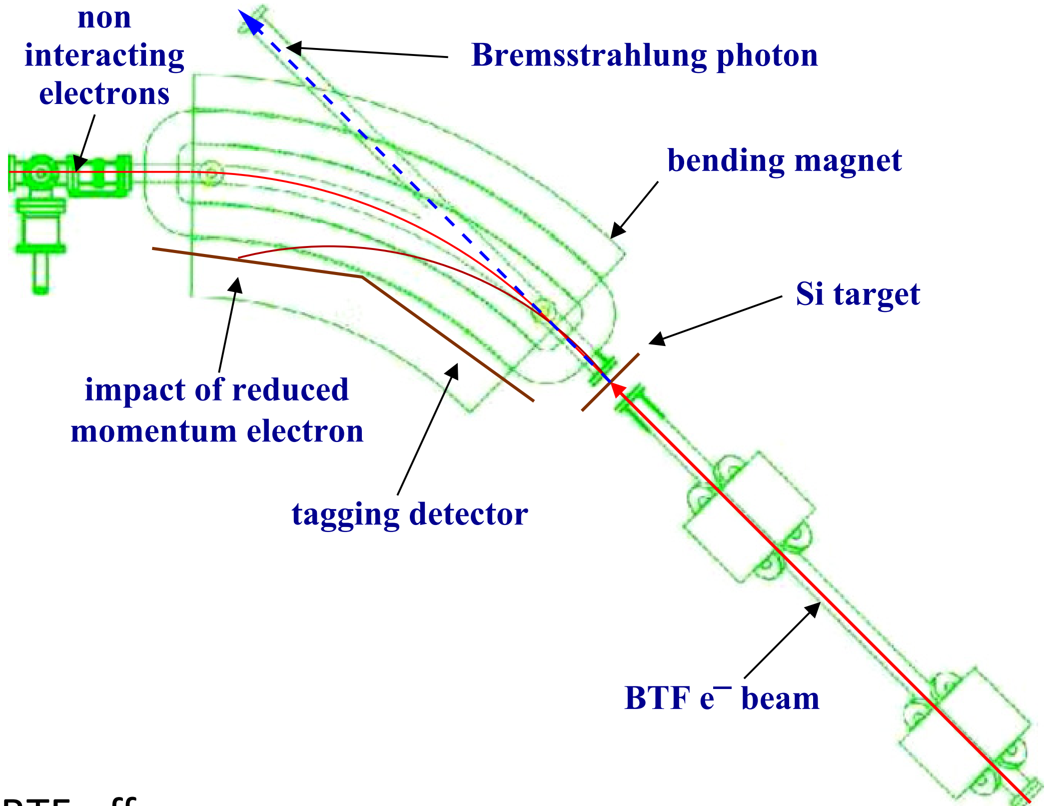




A small version of the AMS magnet was built and used in few BT's:

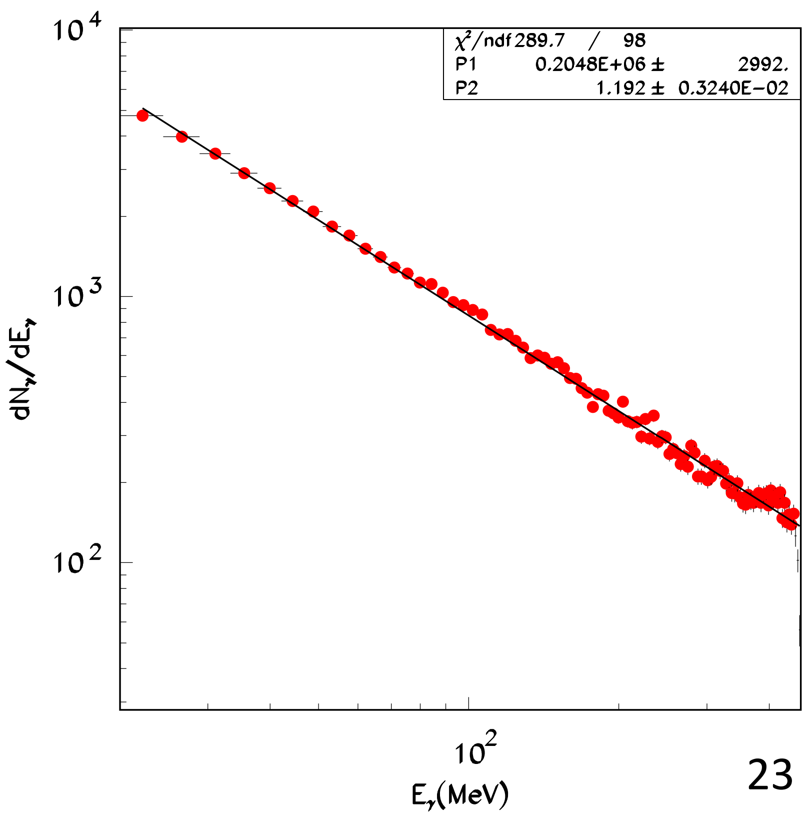
- 18 cm length
- 14 cm diameter
- 0.05 T (half of PANGU design)
- 5 Kg

Tagged photon beam @ BTF



Beam Test Facility @INFN-Frascati is the "natural" choice for the experimental verification of the merit figures of the demonstrator.

Has been used to validate, for example, AGILE



BTF offers:

- tagged photon beam;
- photons produced by brems in 30-750 MeV range;
- tunable photon multiplicity;
- partially polarized beam (still to be confirmed);

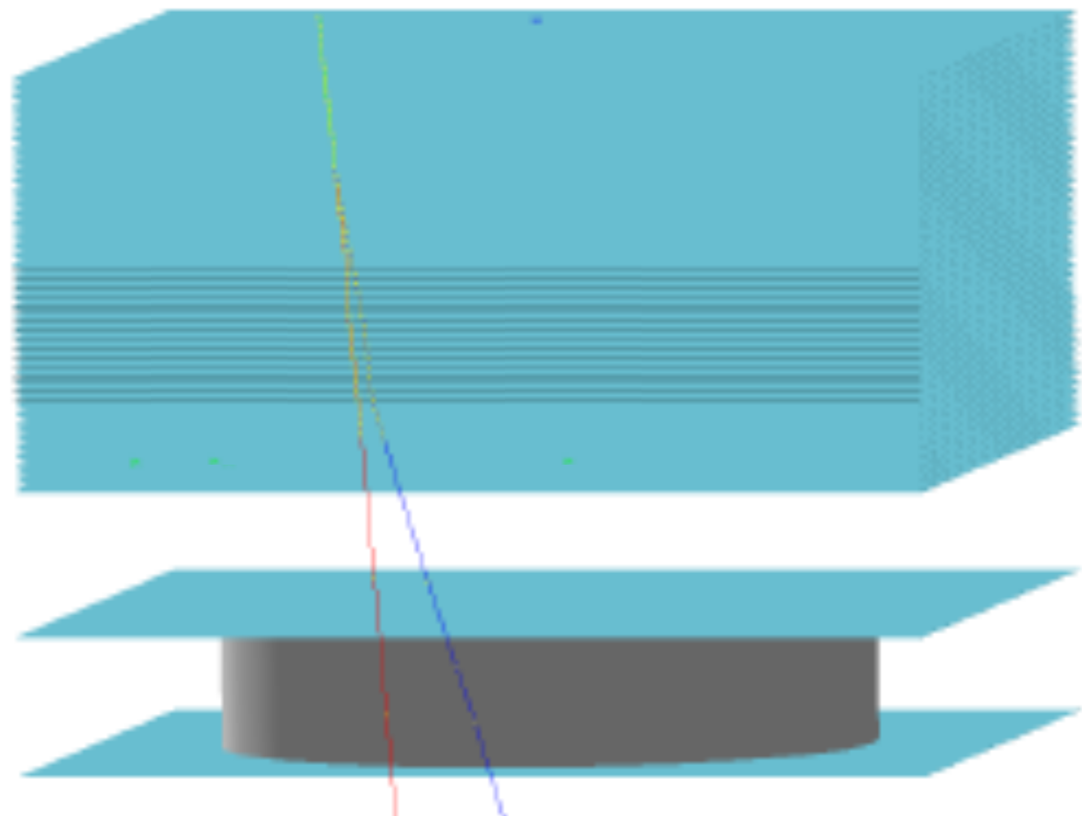
Project phases

MC development (phase 1)

A reliable custom *MC software* (based on *Geant4*) will be developed during the *phase 1* of the project.

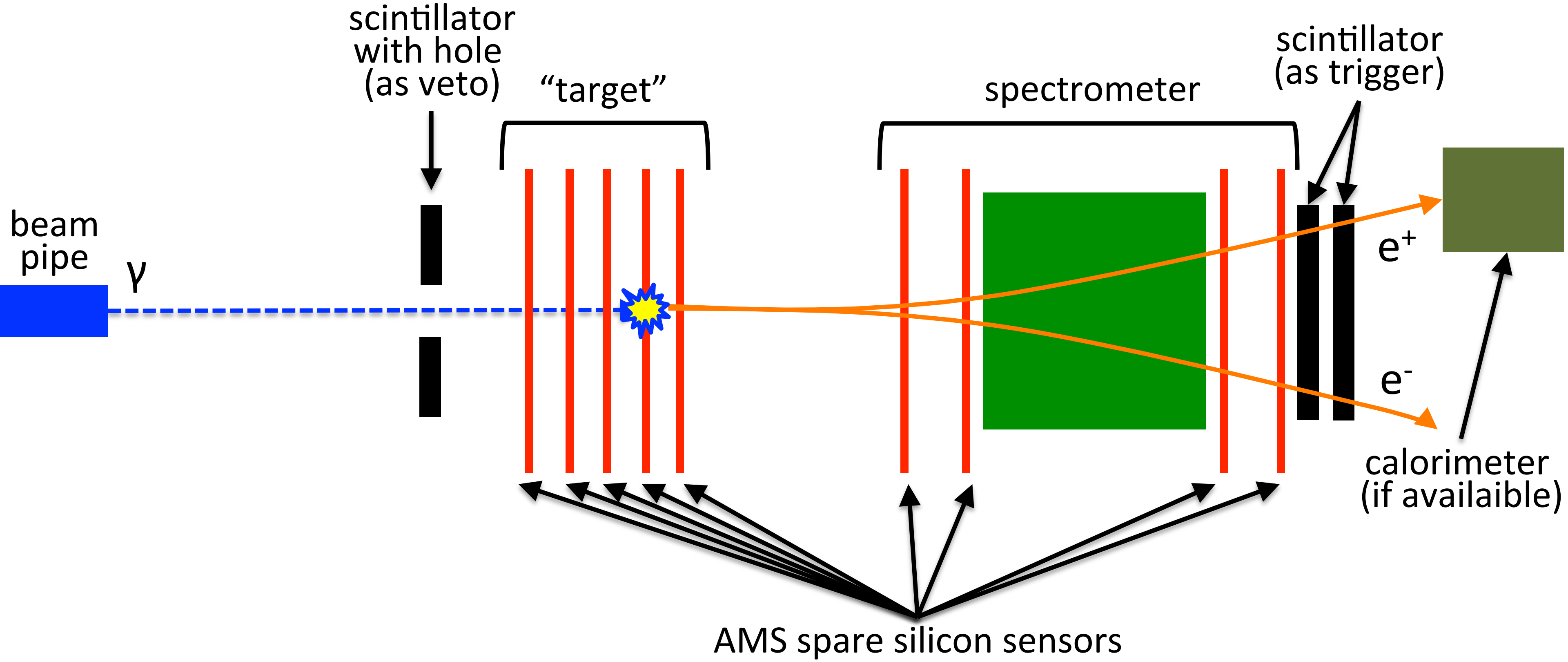
The *sw* will allow to:

- simulate the physical process
- predict the figures of merit of the detector
    - angular resolution
    - polarization measurement capability
    - energy resolution



→ this will allow to "plug" different detector geometries and, moreover, sensor thickness to improve the design

Beam Test (phase 2)



- last 4 silicon sensors are needed for the spectrometer
- pair-conversion can happen in any of the previous silicon sensors (3 guaranteed, 5 possible)
- the “true” incidence angle of the photon can be known with 1mrad accuracy if the beam pipe window is ~ cm, at 10m distance (if unknown divergence!)

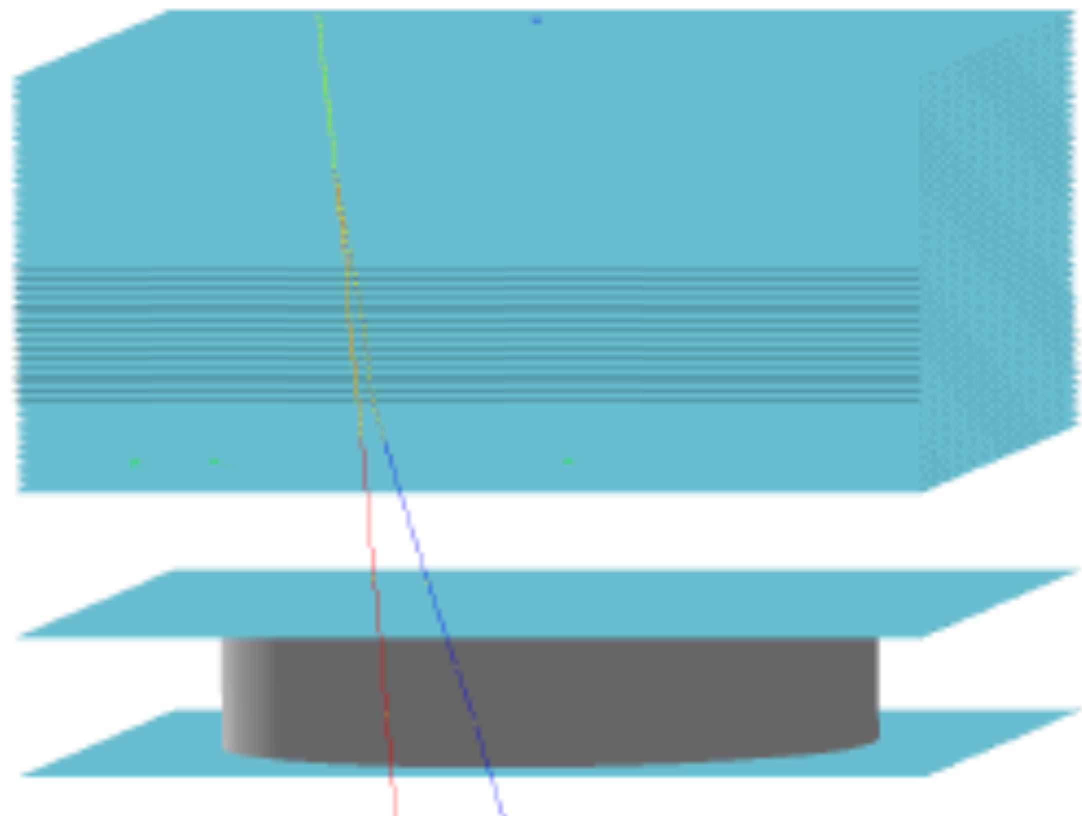
MC validation thickness optimization (phase 3)

After the analysis of the data collected at the Beam Test:

- the MC sw is validated;
- any discrepancy between real data and simulation are understood and tuned.

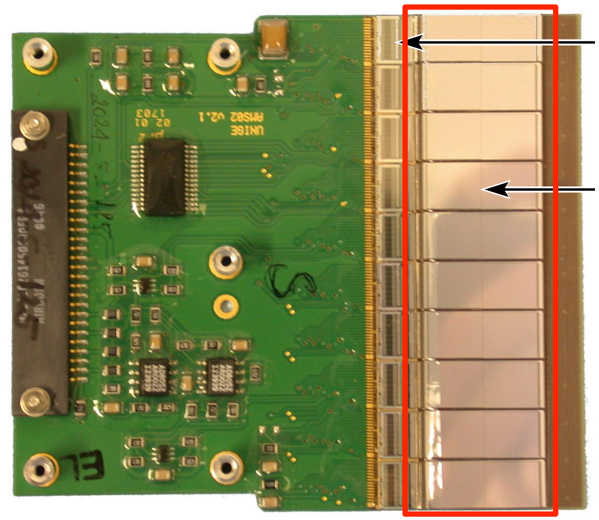
→ the MC sw is reliable;

→ we can "play" with the thickness of the sensors and the detector geometry to optimize the layout.



New silicon sensors to be built (phase 4)

- ??? µm
- 9.5*9.5 cm^2
- 640 (S), 640 (K) canali
- pitch 150 µm (S), 150 µm (K)
- resolution 15 µm (S), 20 µm (K)
- no multiplicity



Preamplifier-shaper ASICs, *VA*

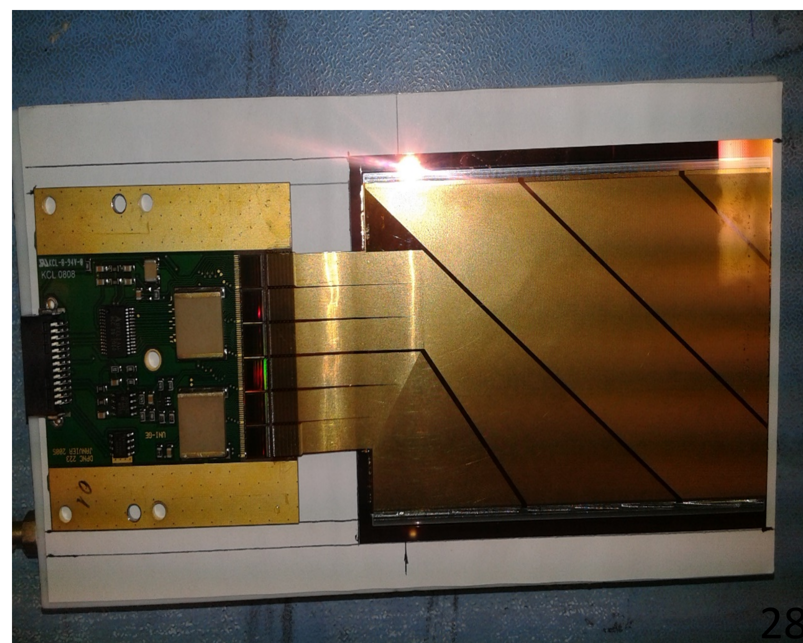
Each VA reads 64 micro-strips

Once the optimal "thickness" has been determined, we plan to build new microstrip silicon sensors:

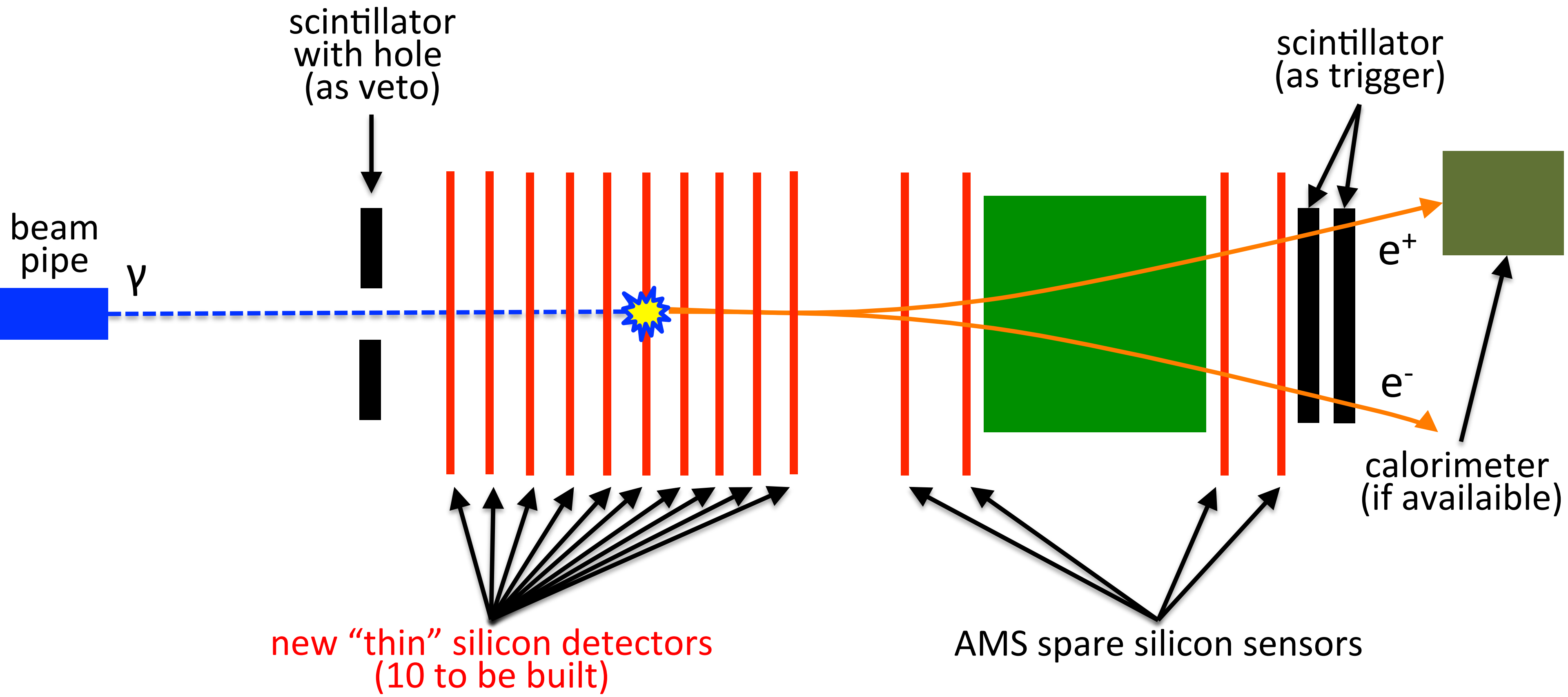
- the silicon batch production at the foundry has a fixed cost → 10 sensors is the minimum number
- 10 square sensors, with ~ 150 µm pitch, require 200 VA's

→ the important costs to be sustained for the project are:

- the batch production of the 10 silicon sensors (not function of their number)
- the 200 VA's to be bought



Beam Test (phase 5)



- last 4 silicon sensors are needed for the spectrometer
- pair-conversion can happen in any of the previous silicon sensors (10 new “thin”, to be built)
- the “true” incidence angle of the photon can be known with 1mrad accuracy if the beam pipe window is ~ cm, at 10m distance

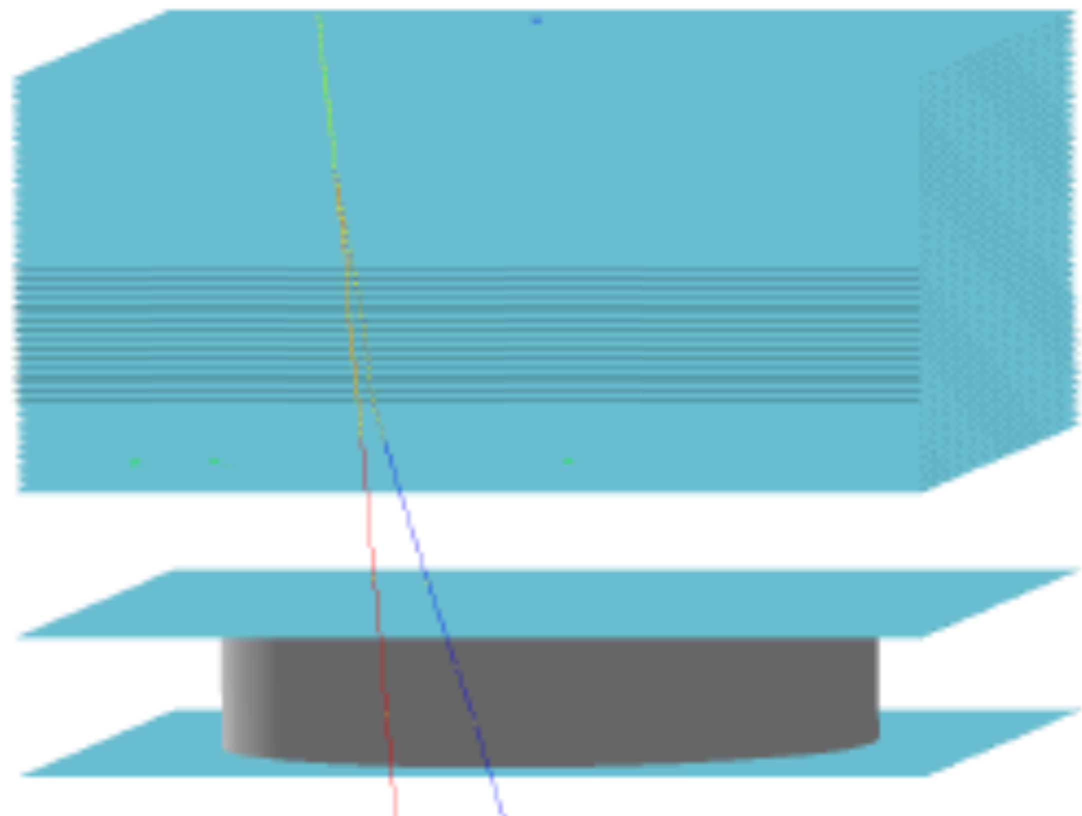
MC finalization and release (phase 6)

After the analysis of the data of the second Beam Test:

- the MC sw is completely validated;
- the PANGU measurement technique has been proven;

→ we can "release" the MC sw;

→ we can "play" with the detector geometry to "tailor" it to respond to particular call for missions;



Work Package Organization

WP1: Project Management – UniSS, UniPG-INFN

WP1.1 Organization of periodic Collaboration Meeting

WP1.2 Preparation of reports and documentation for report meeting to INAF/ASI

WP1.3 Monitoring of project status

WP1.4 Management of problems and opportunity

WP2: Detector Simulation and data analysis - UniSS, UniPG-INFN

WP2.1 Implementation of demonstrator

WP2.2 Characterization of detector unit

WP2.3 Validation of MC simulation with test beam data

Working Package Organization

WP3: Test beam activity – UniPG-INFN, UniSS

WP3.1 Assembly of detectors for the beam test

WP3.2 Equipment shipping

WP3.3 Beam test campaign management

WP4: Design and construction of a new prototype – UniPG-INFN, UniSS

WP4.1 Design of new detector unit

WP4.2 Construction of new detector unit

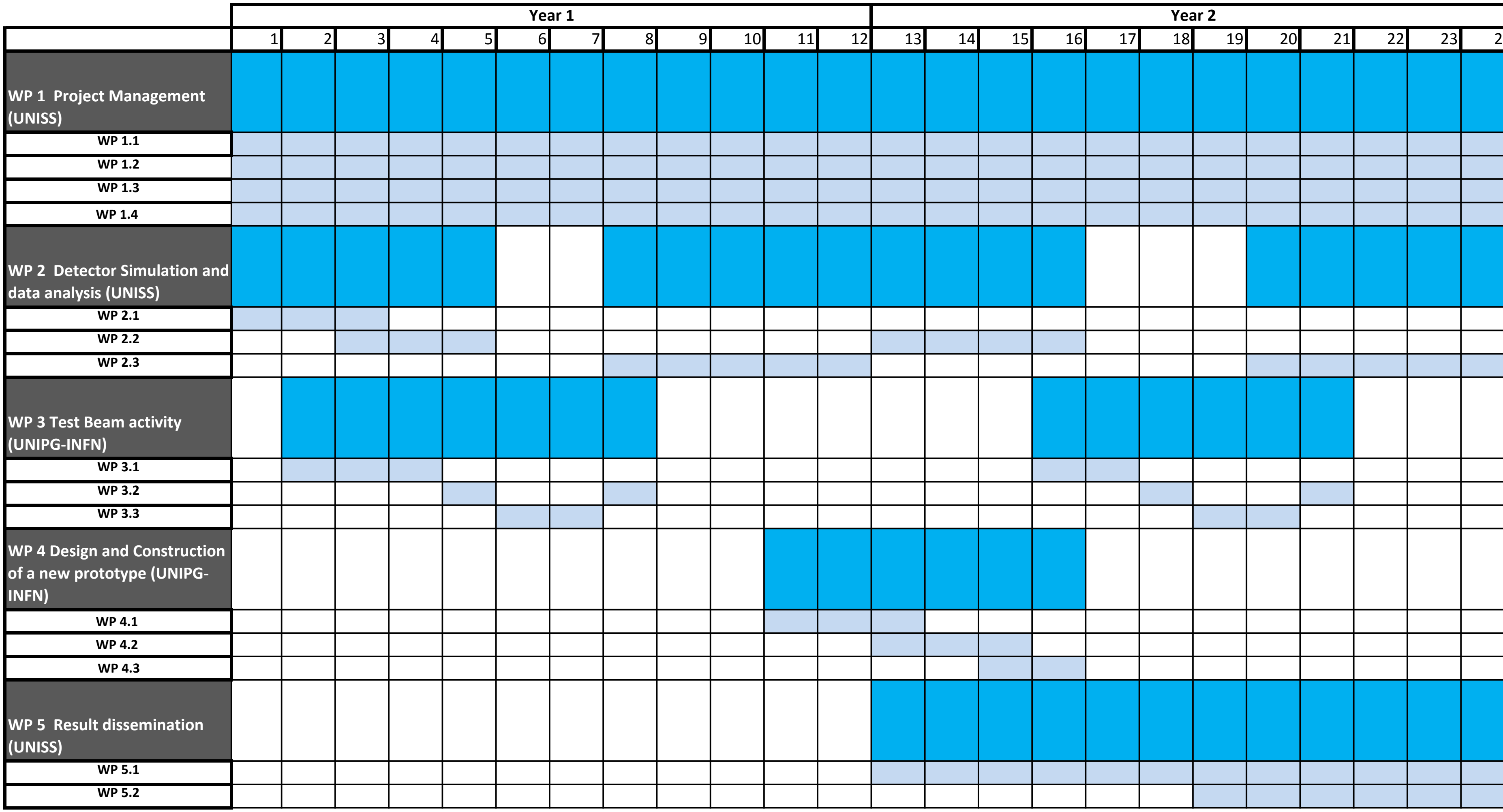
WP4.3 Test of new detector unit

WP5: Result dissemination – UniSS, UniPG-INFN

WP5.1 Publication on international scientific journals

WP5.2 Presentation of results and deliverables to International Conferences and Workshops

Project time evolution



Costs

❑ Personnel (1 fellowship + 1 post-graduated grant)	32k€
❑ 2 laptops + 2 workstations	7k€
❑ Microstrip Si sensor production (10 sensors)	50k€
❑ ASIC VA for front-end electronics (200 VA)	30k€
❑ Mechanics and consumable for test beam campaign	10k€
❑ Travels for test beam campaigns	20k€
❑ Travels for Collaboration/report meetings	4.8k€
❑ Conference participation	10k€
Total	163.8k€

Deliverables

- reliable MC tool to simulate the physical process and the detector layout;
- 10 complete sensor prototypes with optimal thickness;
- PANGU-like demonstrator and test “infrastructure” for the experimental verification (mechanical structures, front-end electronics, DAQ system, data handling and first data analysis)
- dissemination: publications on international referred journals and contribution at international conferences

Bibliography

PANGU:
https://arxiv.org/abs/1407.0710v2 arXiv:1407.0710v2 [astro-ph.IM]

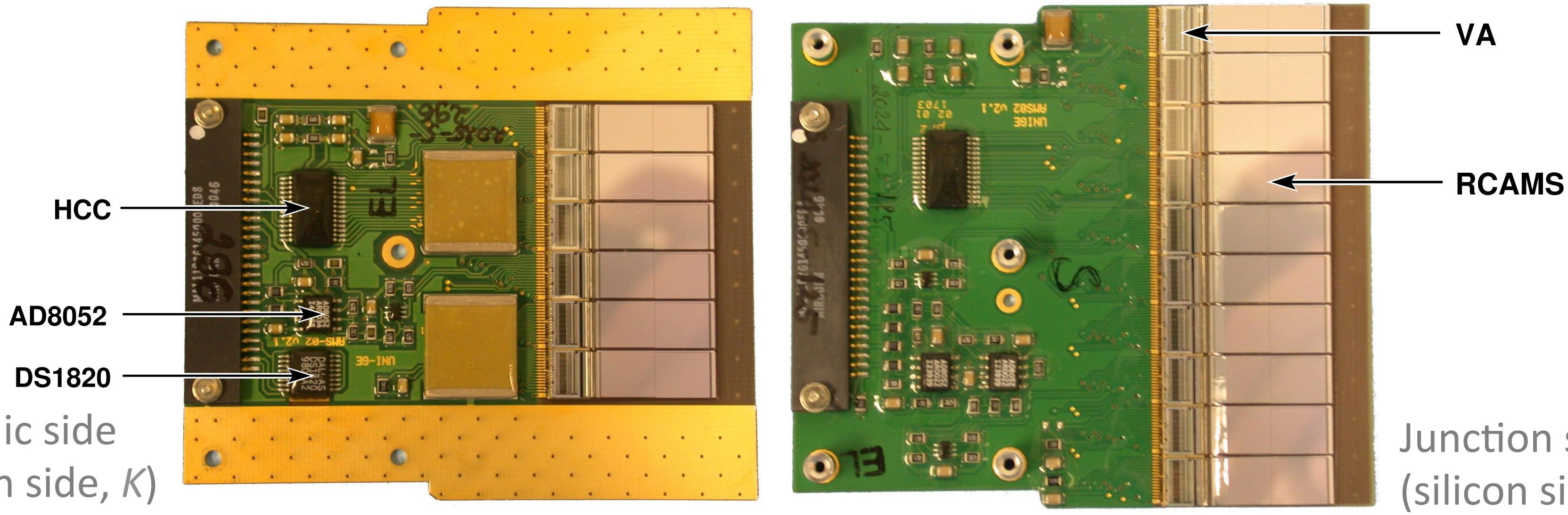
AdEPT:
https://arxiv.org/abs/1311.2059 arXiv:1311.2059 [astro-ph.IM]

Tagged photon beam at BTF / AGILE Beam Test:
https://arxiv.org/abs/1111.6147v2 arXiv:1111.6147v2 [physics.ins-det]

TPC in –ray astronomy:
https://arxiv.org/abs/1211.1534 arXiv:1211.1534v1 [astro-ph.IM]

Backup

AMS-02 Front End (“hybrids”)



Ohmic side
(kapton side, *K*)

Junction side
(silicon side, *S*)

We can “copy and paste” the AMS-02 Front End circuit:

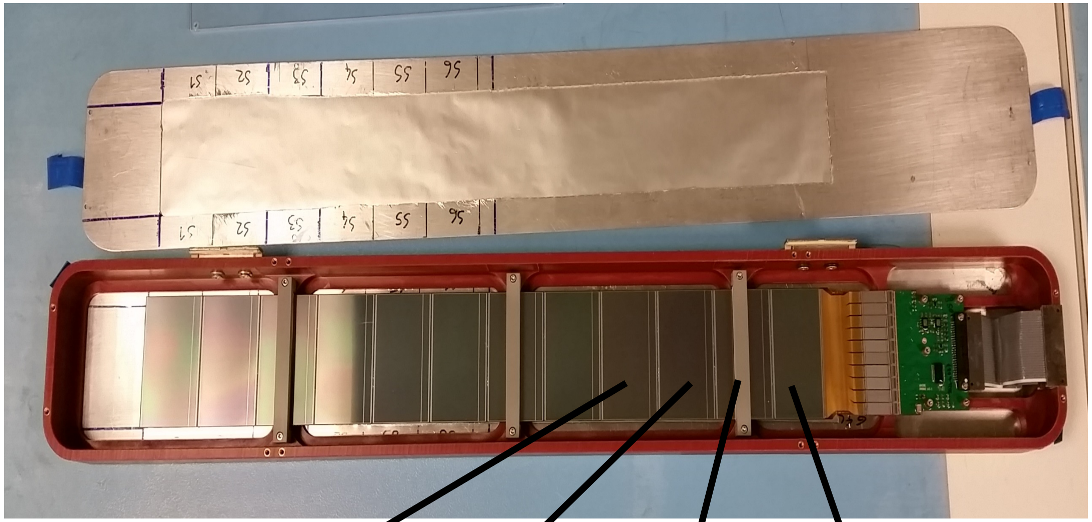
- preamplifier-shaper ASICs, *VA (this is the expensive part of the hybrid). Each VA reads 64 micro-strips*;
- VA digital control sequence circuit, *HCC;*
- doupling capacitor pad, *RCAMS* (can be easily removed is silicon already in DC);
- operational amplifier to send a differential signal to the ADC board (*TDR*), *AD8052*;
- ~~a temperature sensor, *DS1820*~~;
- two versions: ”grounded” for the junction side and “floating” the ohmic, biased, side. Up to 10 VA’s per side;

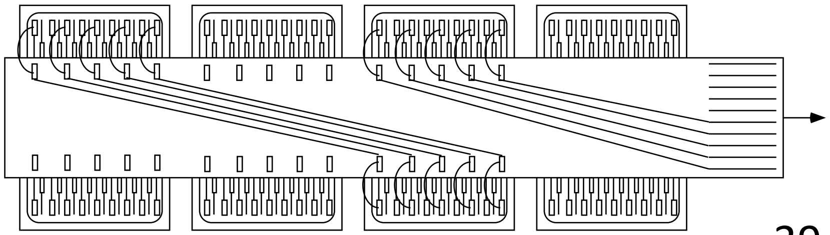
AMS-02 spare sensors

“AMS”:

- 300 μm
- 7*48 cm^2
- 640 (S), 384 (K) canali
- pitch 110 μm (S), 208 μm (K)
- resolution 10 μm (S), 30 μm (K)
- <u>multiplicity</u> on Kapton side

We have 2 sensors of this kind.





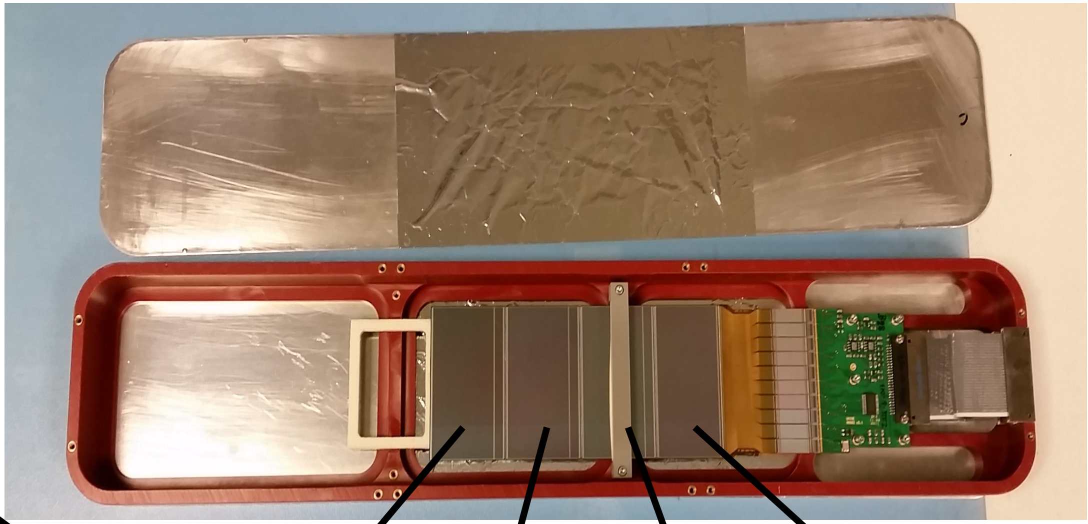
Being “long” (at least in one coordinate) they can cover a large angle even if positioned far, to increase the lever arm. To be used to the “external” telescope.

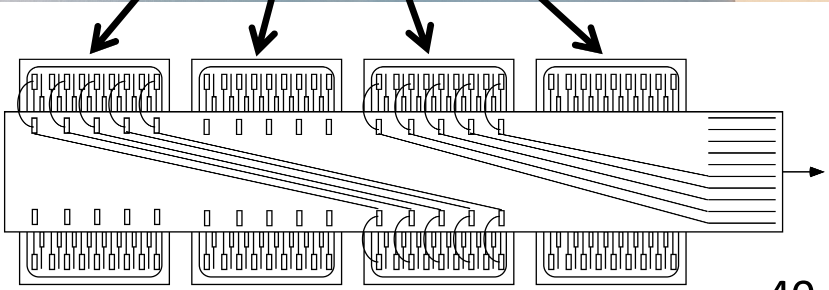
AMS-02 spare sensors

“AMS-short”:

- 300 μm
- 7*16 cm^2
- 640 (S), 384 (K) canali
- pitch 110 μm (S), 208 μm (K)
- resolution 10 μm (S), 30 μm (K)
- <u>multiplicity</u> on Kapton side

We have 3 sensors of this kind.





These sensors are smaller than the previous one, but still cover a large angle.
Can be used for the external telescope or under test in phase 1.

AMS-02 spare sensors

“AMS-mini”:

- 300 µm
- 7*4 cm^2
- 640 (S), 384 (K) canali
- pitch 110 µm (S), 104 µm (K)
- resolution 10 µm (S), 15 µm (K)
- no multiplicity

We have 2 sensors of this kind, but we have the material to build another 1 or 2

These sensors are small, so cannot be used far from the detector under test.
They are more accurate w.r.t. the previous one so can improve the overall telescope resolution.
They can be the detectors under test in phase 1.

Beam Test (phase 2)

- distance between two sensors of the "tracker-converter":

  $30\mu m/3cm = 1\mu m/1mm = 10^{-3} \rightarrow 1$ mrad

- spectrometer resolution with 1 GeV photons ($\rightarrow$ 500 MeV of $e^{+/-}$), 0.2m lever arm and 10cm distance between the two sensor of each pair, 0.05T magnetic field and 15µm spatial resolution:

  $\sigma_p/p = p(GeV)/(0.3\ B(T)\ L(m))\ 2\ \sigma_x/d =$

  $(5*10^2*10^{-3}$ GeV$) / (0.3*0.05T*0.2m) * (2*15*10^{-6}m / 10^{-1}m) =$

  $5*10^2*10^{-3}*3*10*10^{-6} / 3*10^{-1}*5*10^{-2}*2*10^{-1}*10^{-1} = 10^{-6} / 2*10^{-5} = ½*10^{-1} = =$ $0.5*10^{-1} = 5*10^{-2} = 5\% = \sigma_p/p$

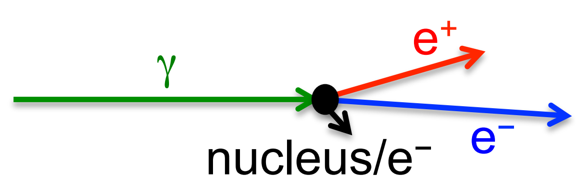
- 300m of air = $1X_0 \rightarrow$ 3m or air = $1\%X_0$ (i.e. ~ 3 silicon detectors 300µm thick), so 10 mRL that on the AdEPT is indicated as the limit to not to be dominated by MS.
  3m of air is > than the <u>total</u> experimental setup lenght (only the air between two consecutive measurements really matters)

Angular resolution

- **Angular resolution contributions**
  - **Nuclear recoil introduce ~0.3° on angular resolution @100 MeV**
  - **Reconstruction of the pair (energy measurement)**

    NIMA 701, 225-230

    - **Best if energy of both tracks can be measure**
    - **If not normally use the direction of the leading (longest and straightest) track**
      - **Extra error θ_{68} of ~0.65° @ 100 MeV**
  - **Track angular resolution**
    - **Multiple scattering: For θ_{MS} = 0.5° @70 MeV, total material between 2 measurements should be less than 0.33% X_0!**
      - **310µm Si, 1.3mm Fiber, 5.1cm Xe gas**
    - **Tracker nominal resolution: $\sqrt{2}\sigma_x/d$ = 1.35° for σ_x=100µm, d=6mm**
      - **Final resolution can approach 1.15×θ_{MS} when using many (~6) measurement points**

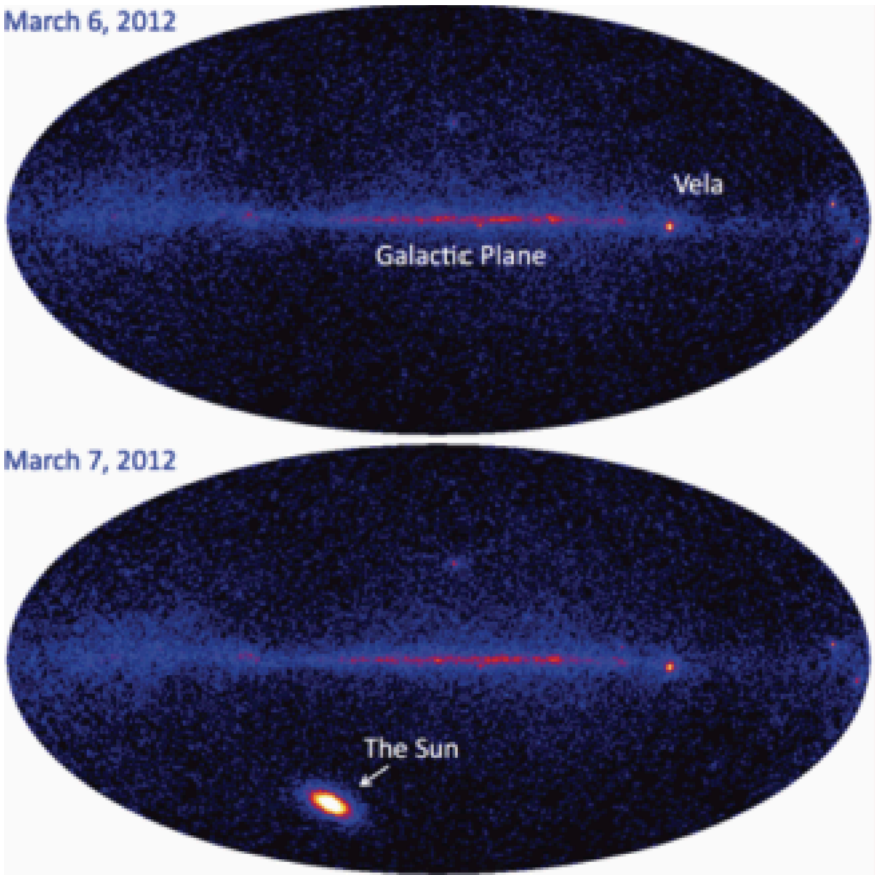


Polarization capability and MS effect

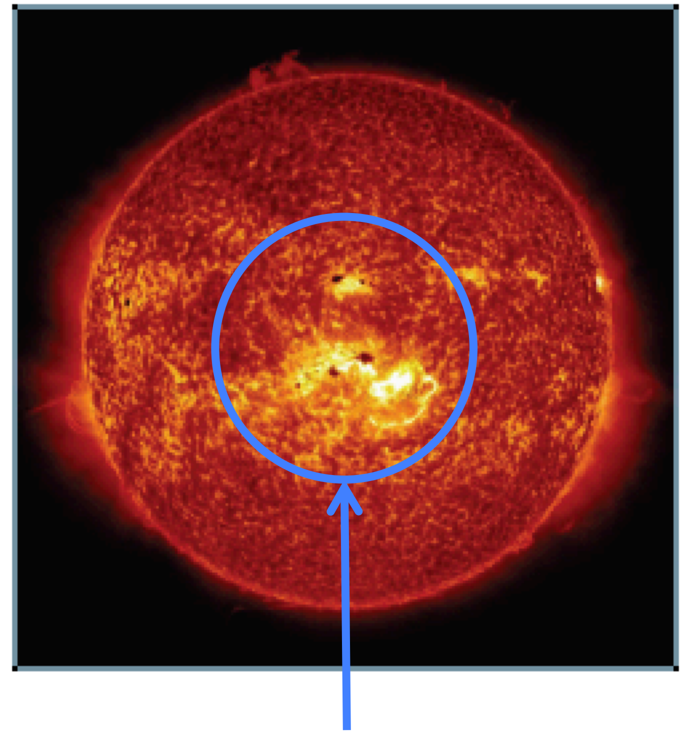
In low-Z material, $Z \lesssim 30$, gamma rays with energy below ~10 MeV, are more likely to interact via Compton scattering than pair production, however, the intrinsic modulation factor of polarized gamma rays interacting via pair production is higher above ~2 MeV, compared to Compton scattering and photo-electric absorption [26]. Thus, we are motivated to reduce the effective minimum energy of a pair telescope towards the threshold energy, to take advantage of the higher modulation factor. This requires that the direction of the electron and positron emanating from the pair vertex, which forms the basis of the gamma-ray direction and polarization determination, be measured in less than ~10 mRL of material after which their directions are dominated by multiple Coulomb scattering (MCS) [25].

γ-ray Emission from Solar Flares

LAT 1 day all sky data > 100 MeV



Bad PSF, Sun cannot be resolved
→ no information on acceleration site

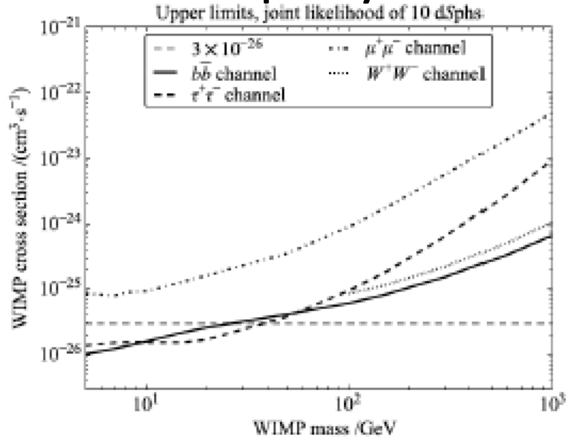


PANGU will resolve the flare in γ-ray

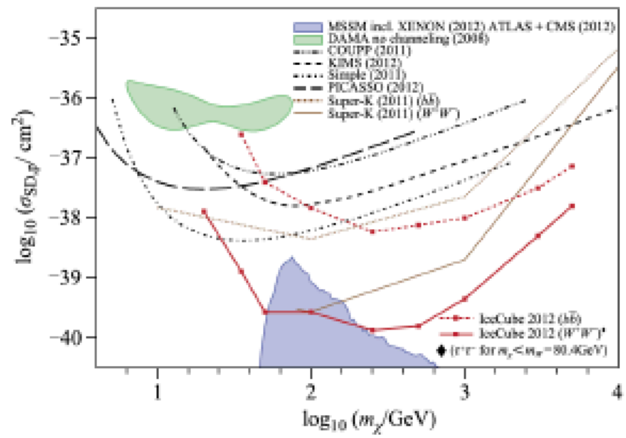
Low Mass Dark Matter Search

No missions are sensitive in the PANGU's energy range

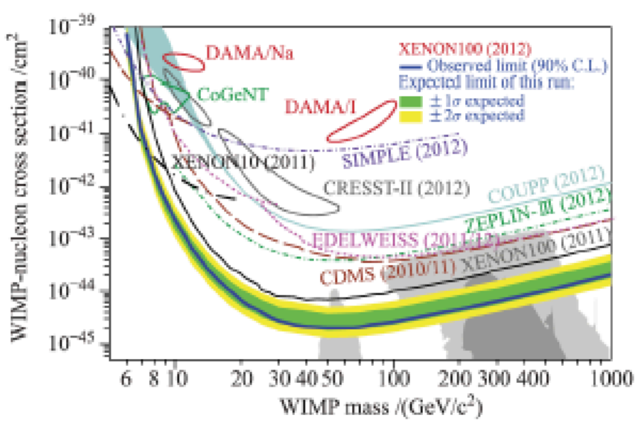
Fermi γ-ray search



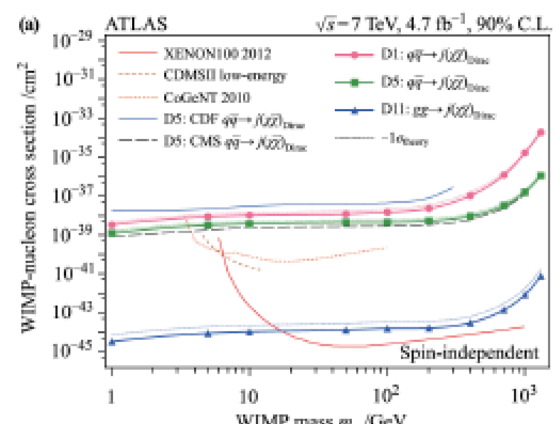
IceCube neutrino search



Direct detection search

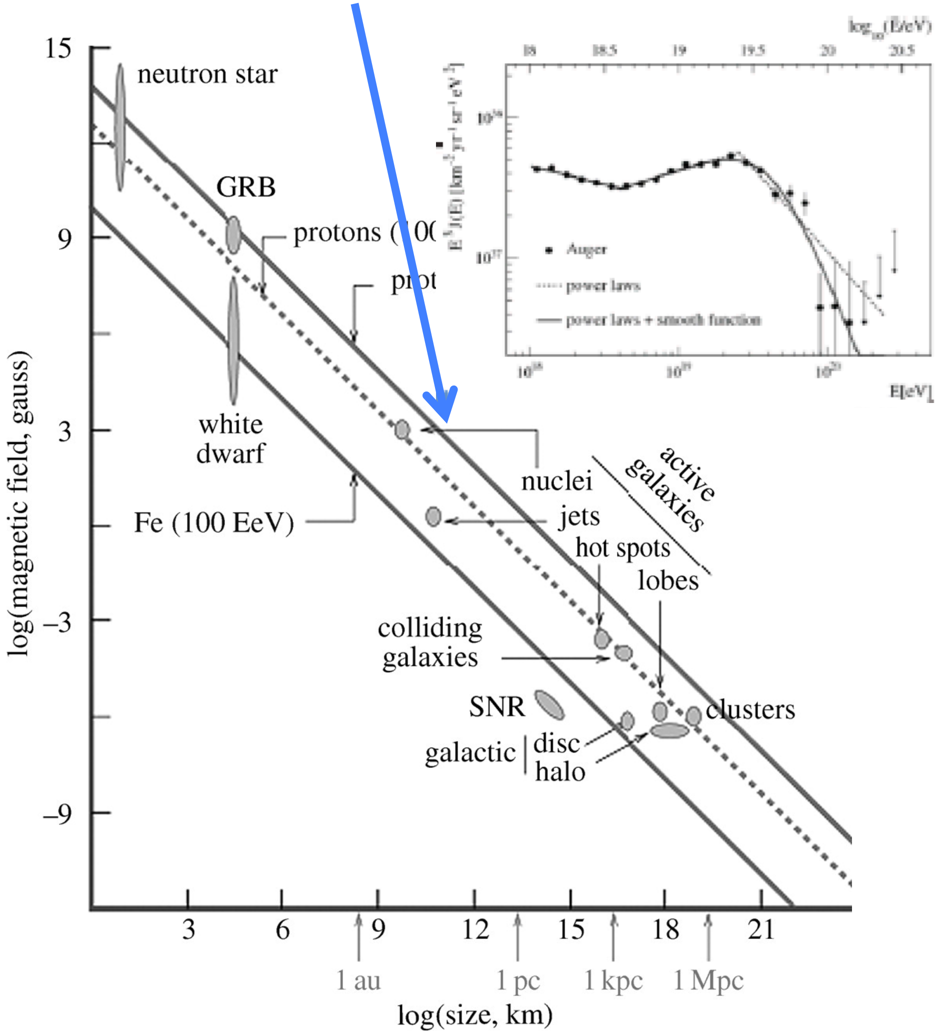


Collider DM search



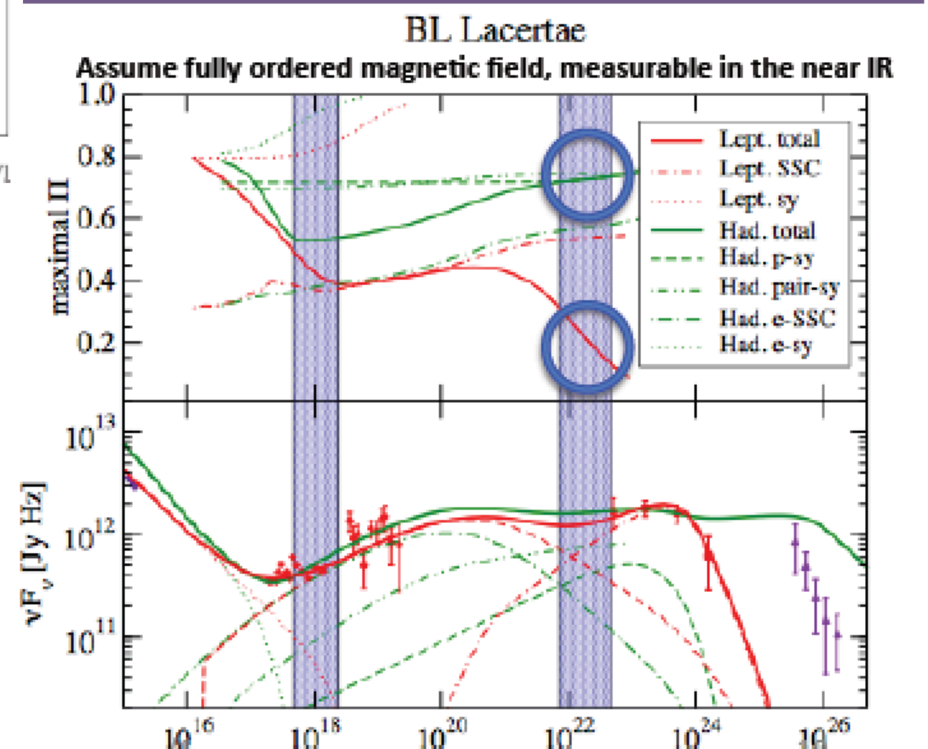
Blazars and UHECR Origin

Standard hypothesis: shocks in hadronic jets of Active Galactic Nuclei



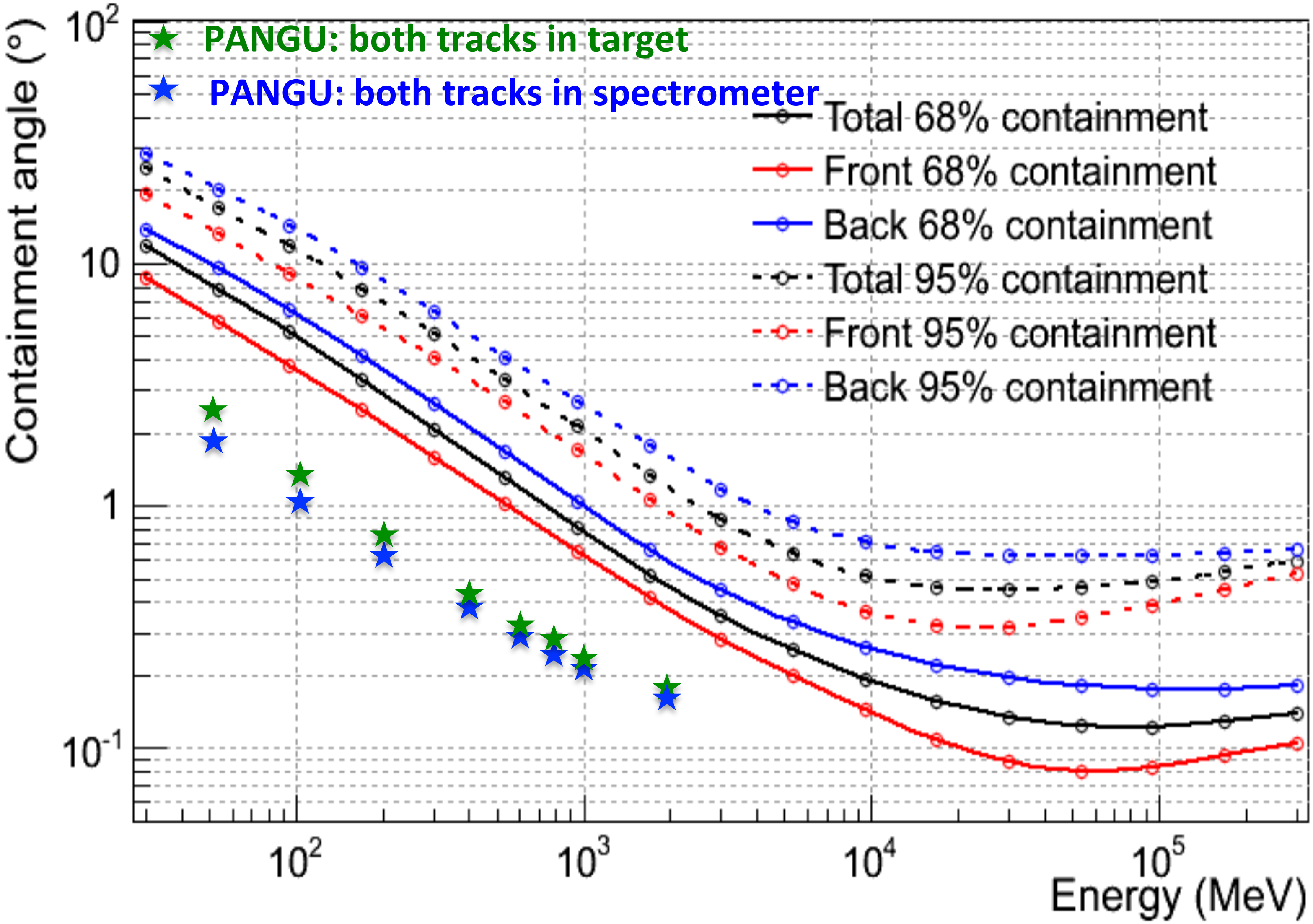
- **Jet spectra can be reproduced by leptonic or hadronic models**
  - **Only hadronic models predict neutrinos and high polarisation in sub GeV range.**

➡ PANGU observations of blazars flares

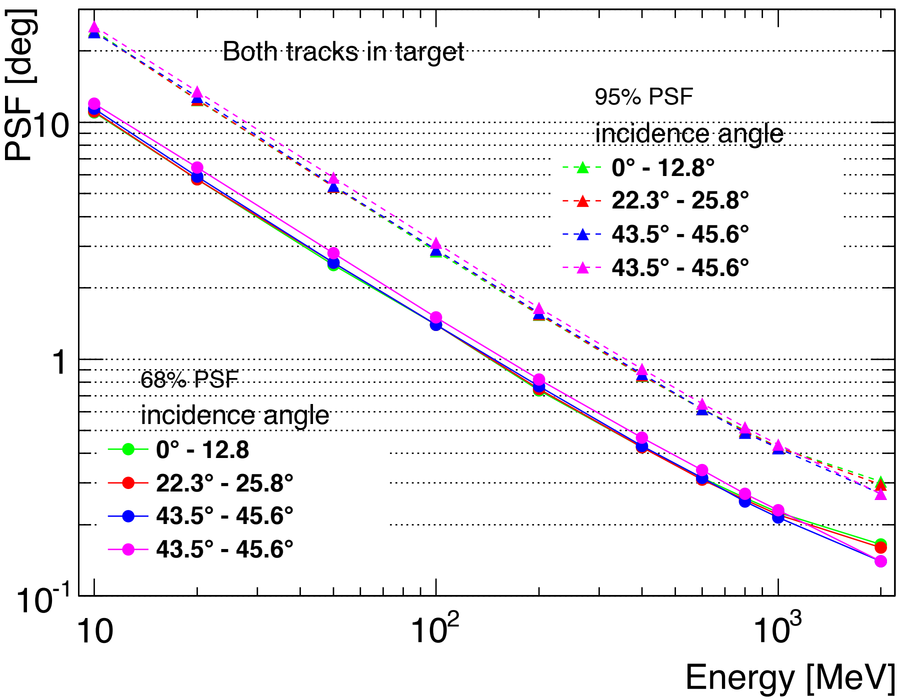


Zhang & Böttcher, 2013

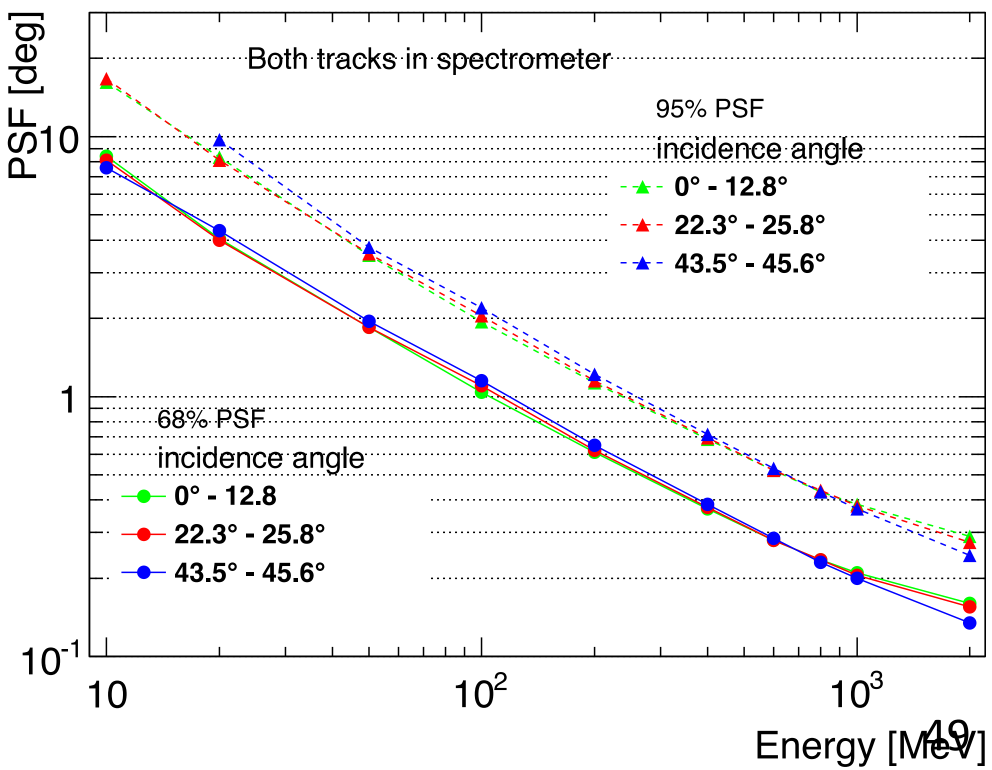
PSF


PANGU: both tracks in target
PANGU: both tracks in spectrometer
Total 68% containment
Front 68% containment
Back 68% containment
Total 95% containment
Front 95% containment
Back 95% containment
Containment angle (°)
Energy (MeV)
10^2
10
1
10^{-1}
10^2
10^3
10^4
10^5

PSF vs Angle



PSF [deg]
Both tracks in target
95% PSF
incidence angle
0° - 12.8°
22.3° - 25.8°
43.5° - 45.6°
43.5° - 45.6°
68% PSF
incidence angle
0° - 12.8
22.3° - 25.8°
43.5° - 45.6°
43.5° - 45.6°
Energy [MeV]



PSF [deg]
Both tracks in spectrometer
95% PSF
incidence angle
0° - 12.8°
22.3° - 25.8°
43.5° - 45.6°
68% PSF
incidence angle
0° - 12.8
22.3° - 25.8°
43.5° - 45.6°
Energy [MeV]

Polarization measurement

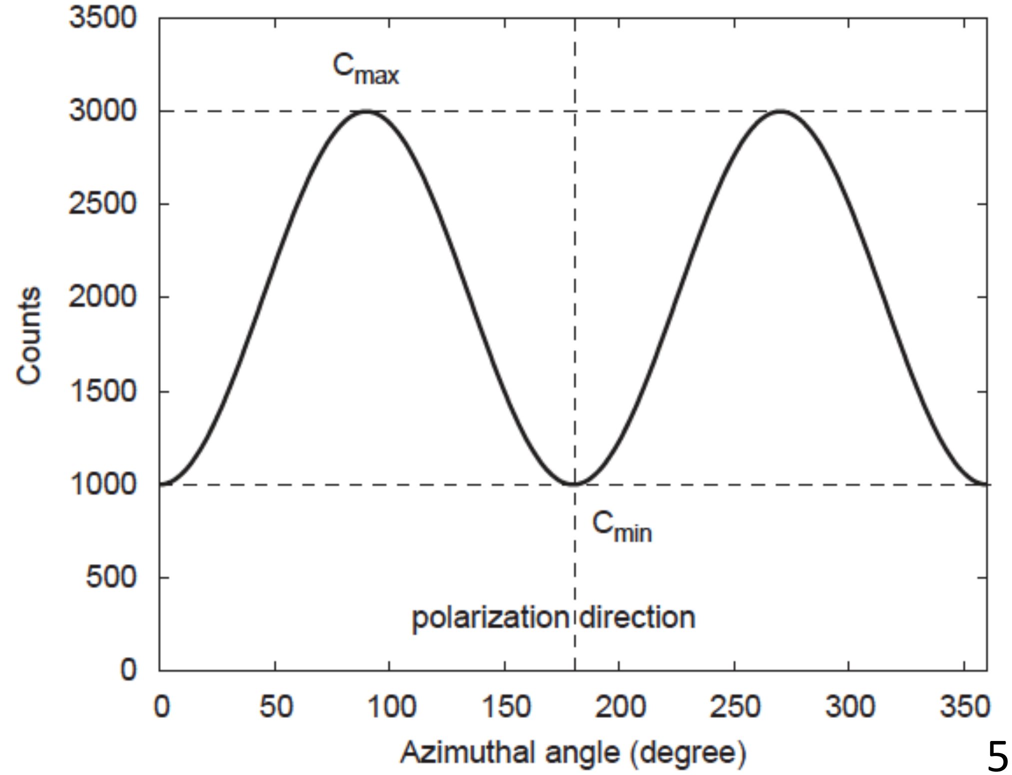
$$d\sigma/d\varphi = 2\pi\sigma_0\left(1 + P_\gamma \cdot A \cdot \cos(2\varphi - 2\varphi_{pol})\right)$$

Azimuthal angle distribution in the plane perpendicular to the γ direction

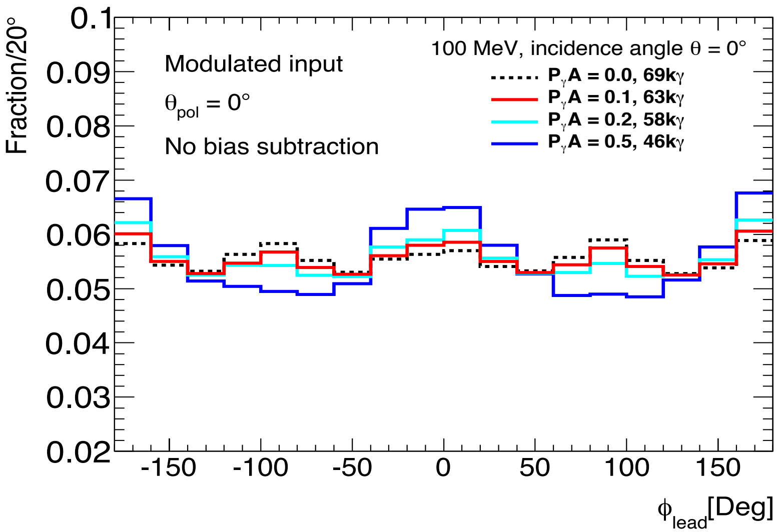
- **P_γ: degree of polarisation; ϕ_{pol}: polarisation direction**
- **A: Analyzing power, average ~0.2 for pair production (kinematic dependent)**

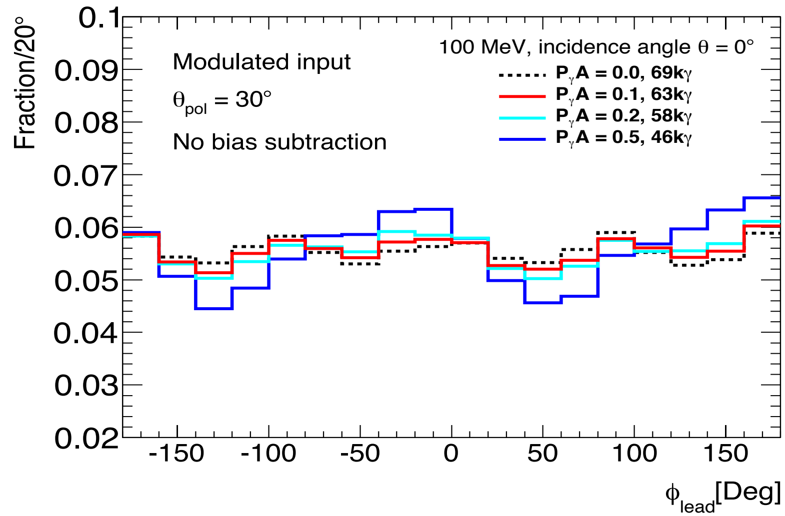
The key merit figures that allow the polarization measurements are:

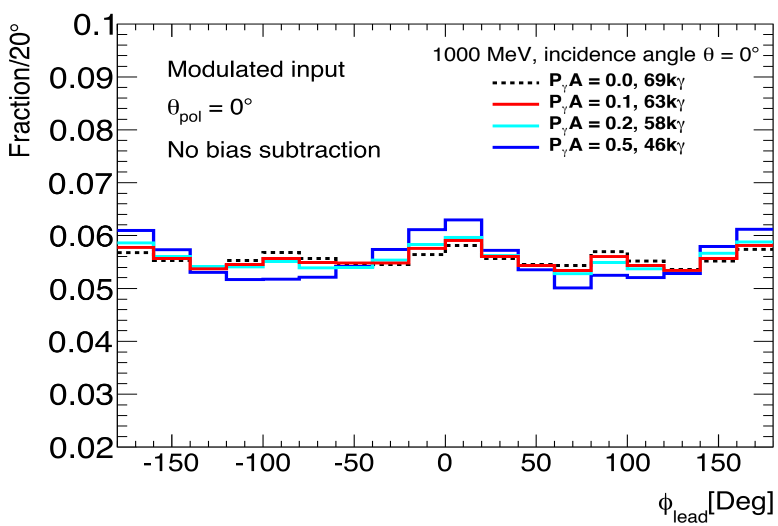
- the angular resolution
- the "uniformity" of the detector



Expected polarization capabilities



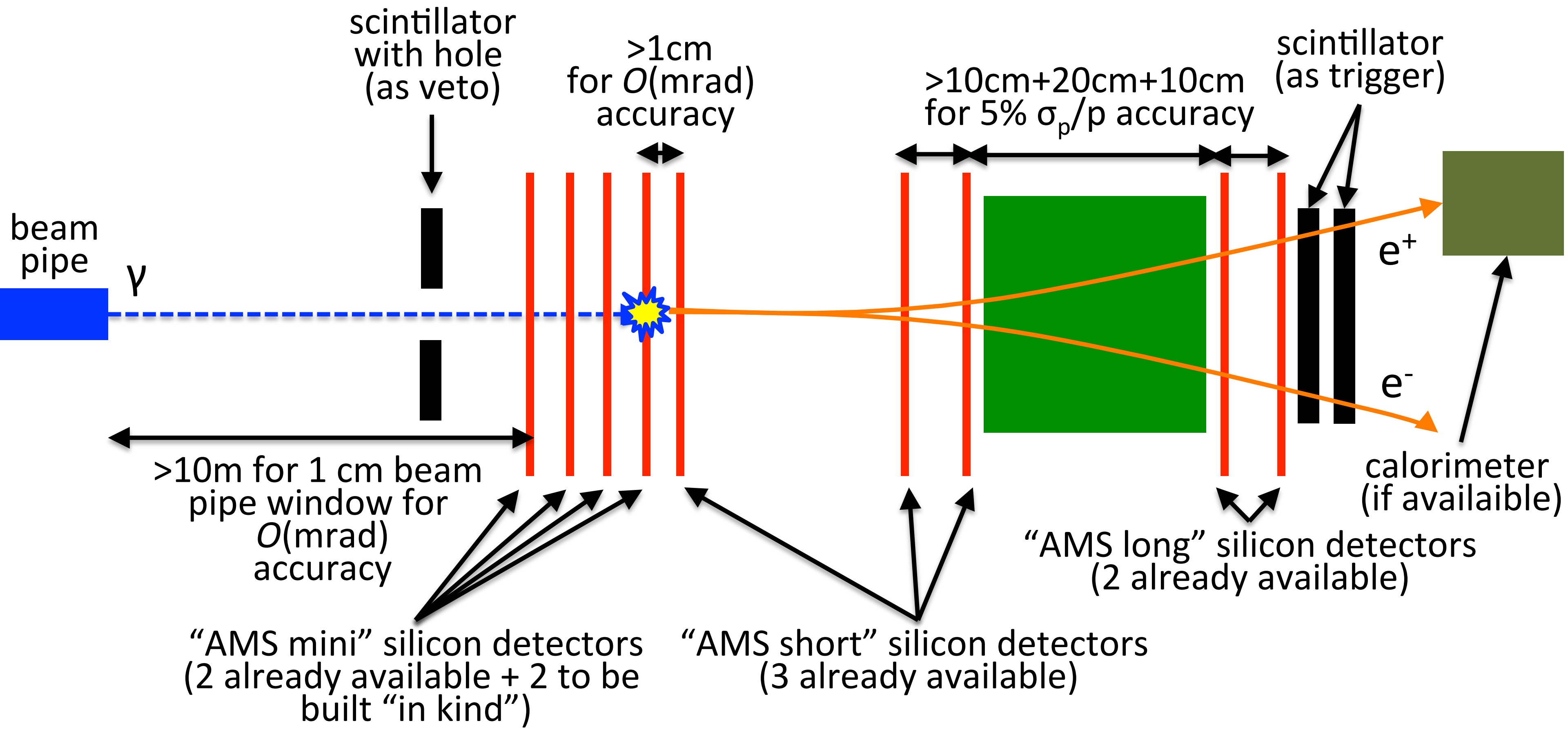




Also the response to a polarized “beam” has been simulated:

- **Possibility to detect polarisation**
- **Further studies needed**
  - **Need reliable simulation code for polarised pair production**

Beam Test (phase 2)



- last 4 silicon sensors are needed for the spectrometer
- pair-conversion can happen in any of the previous silicon sensors (3 guaranteed, 5 possible)
- the "true" incidence angle of the photon can be known with 1mrad accuracy if the beam pipe window is ~ cm, at 10m distance (if unknown divergence!)