PANGU 盘古

A High Resolution Gamma-Ray Space Telescope

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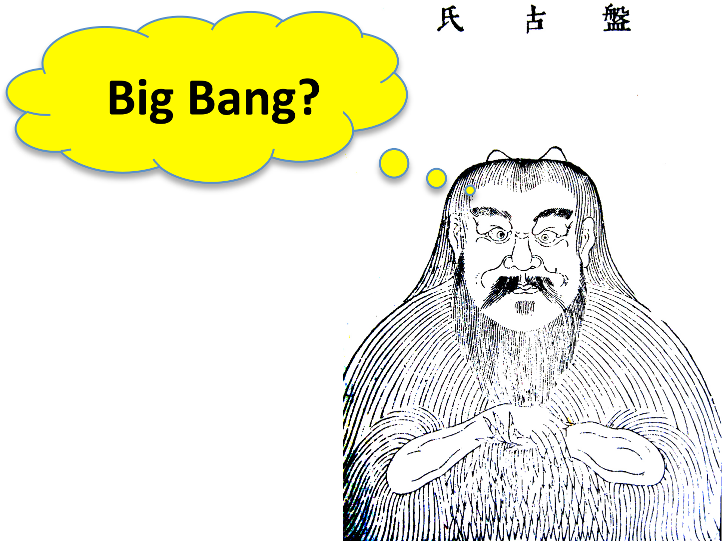
25-26 February 2014, Chengdu

Outline

- Overview
- Scientific objectives
- Suggested Payload
- Mission Concept
- Potential Collaboration projects
- Conclusions



PANGU
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Overview

- **PANGU (PAir-productioN Gamma-ray Unit)**
  - **An unprecedented high resolution ($\lesssim$ 1°) γ-ray space telescope dedicated to the sub-GeV (~100 MeV to ~1 GeV) region**

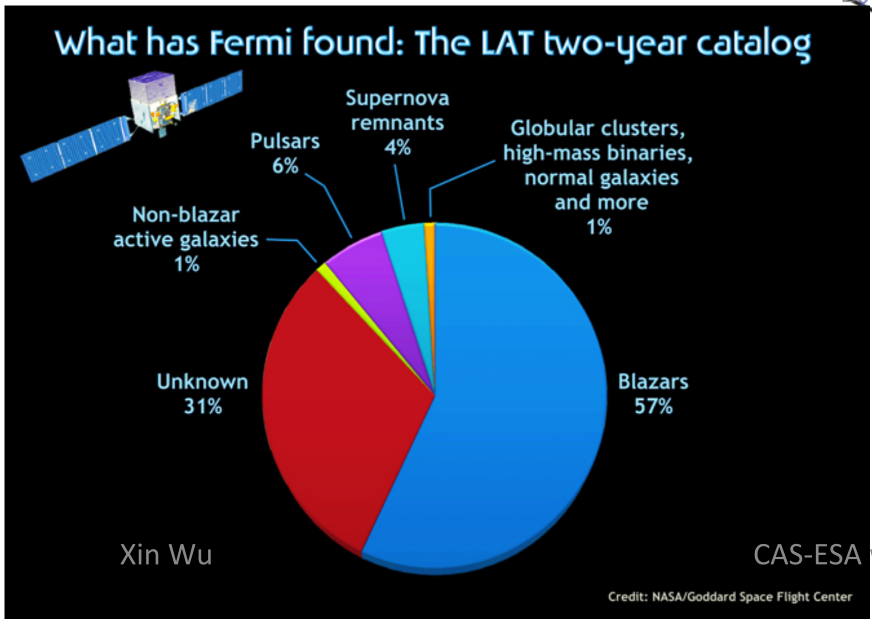
An unique instrument to open up a frequency window that has never been explored with great precision

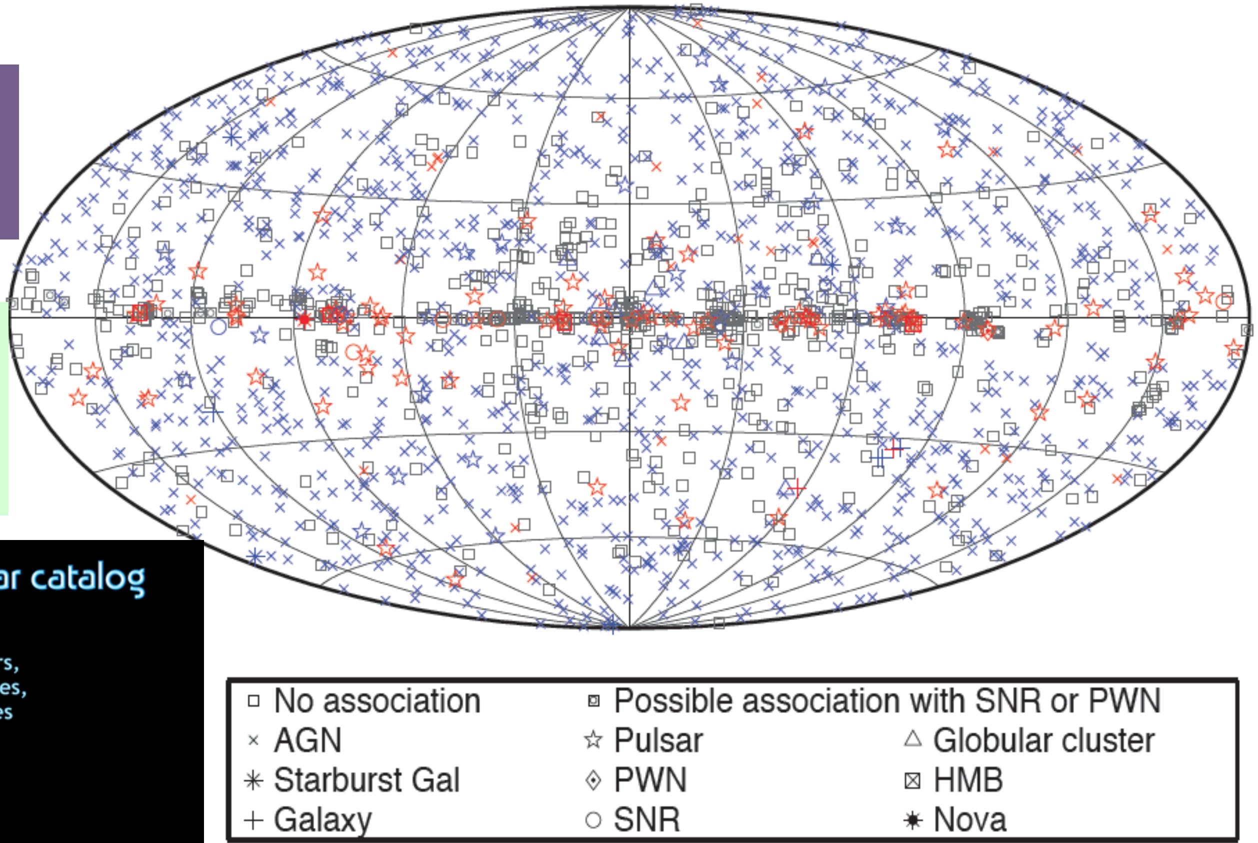
- **A wide range of topics of Galactic and extragalactic astronomy and fundamental physics can be attacked**
  - **Extreme physics of extended/compact objects (extensive targets)**
  - **Galactic and extragalactic cosmic rays (origin, acceleration mechanism)**
  - **Search for Dark Matter (unique capability)**
  - **Detect and determine the high-energy behavior of gamma-ray transients.**
  - **Fundamental Physics, e.g. Baryon asymmetry in early universe**
  - **Solar and terrestrial high energy phenomena**
- **Innovative instrument concept**
  - **Thin target material (scintillating fiber) with magnetic spectrometer**

PANGU: All-sky explorer for the 100 MeV - GeV Universe

Many sources, big discovery space

~1/3 are "unassociated" sources with unknown nature!





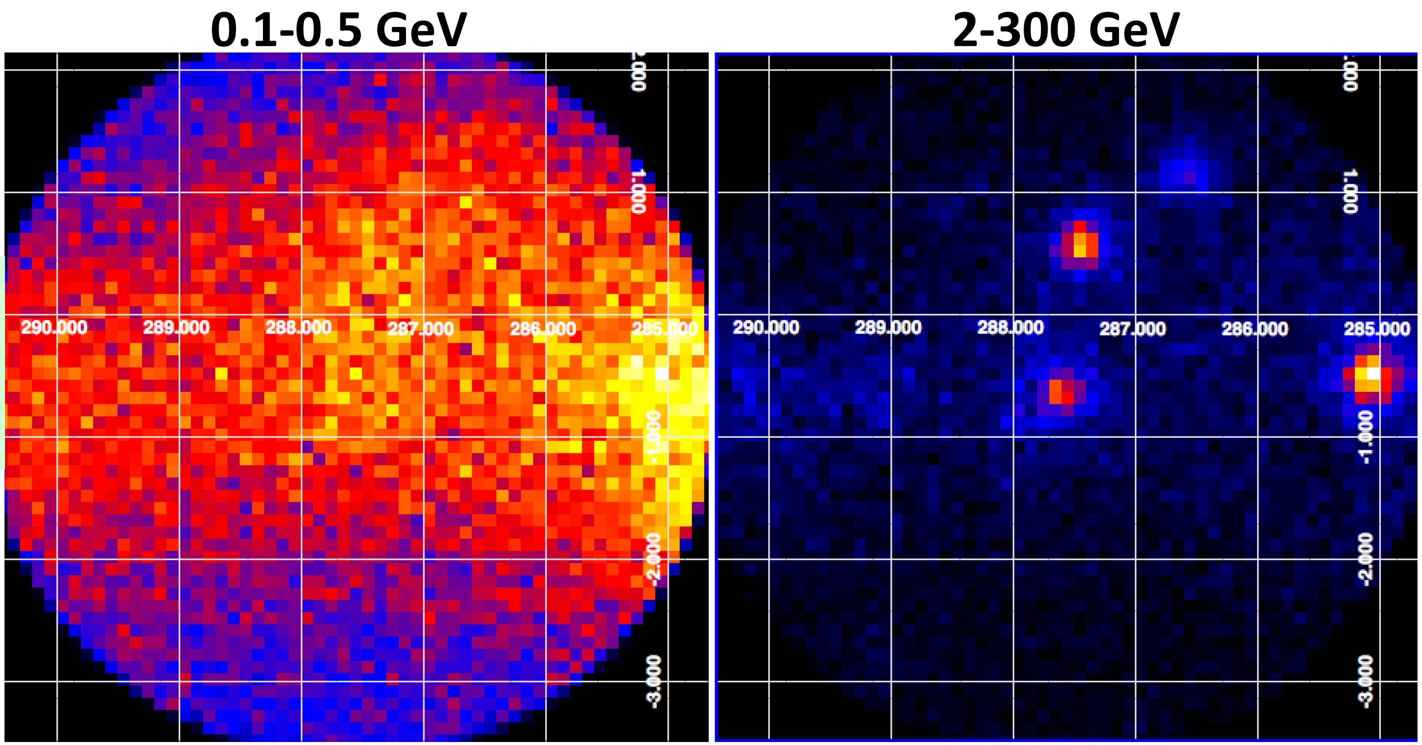
The Second Fermi LAT Catalog

Nolan et al. (2012), ApJ, 199, 31

What a better angular resolution brings you?

- **Sub-GeV sky is dominated by diffuse γ-ray emission (>80%)**
  - **Need good angular resolution to identify sources**

Image of Eta Carinae from Fermi with 2 different resolutions



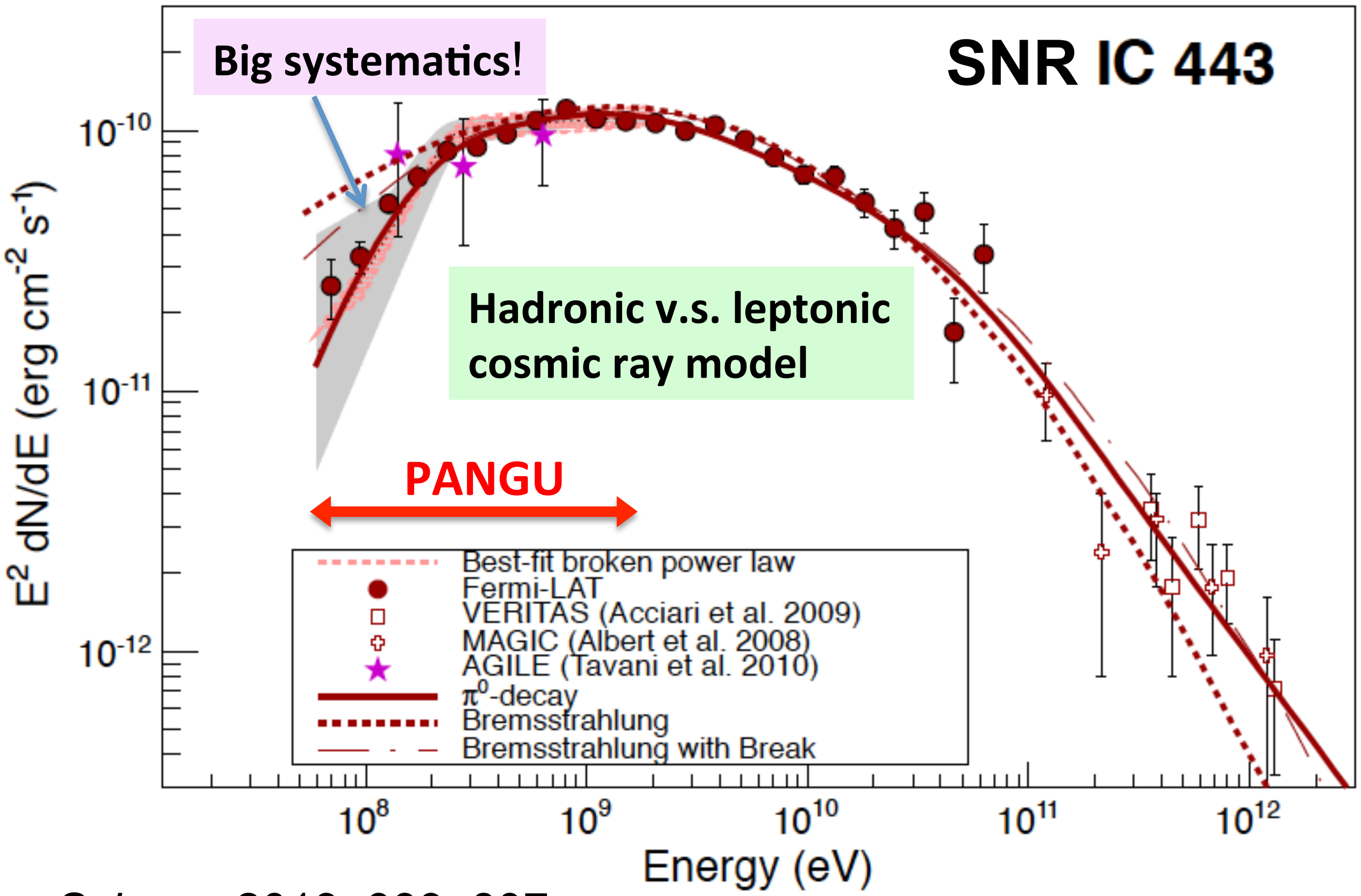
Goal: PANGU 0.1-0.5 GeV

Scientific Objectives: Highlights

- **Origin and acceleration of high energy cosmic rays**
  - **Low energy spectrum of supernova remnants (SNR), OB associations (super bubbles) and galaxy clusters**
  - **Gamma-ray burst (GRB)**
  - **Fermi bubble**
  - **Polarization**
- **Low mass Dark Matter search**
- **Gamma-ray emission from the inner galaxy**
- **Pulsation search in millisecond pulsar**
- **Baryon asymmetry signature in diffused γ-ray background**
- **Gamma-ray emission from solar flares**

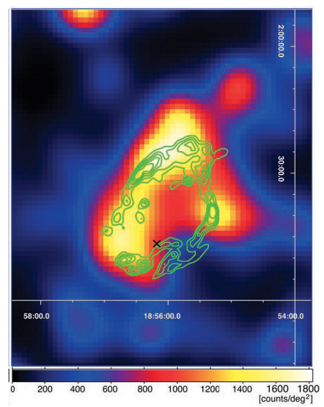
Supernovae Remnants and Particle Acceleration

Science's Top 10 Breakthroughs of 2013!



Science 2013, 339, 807

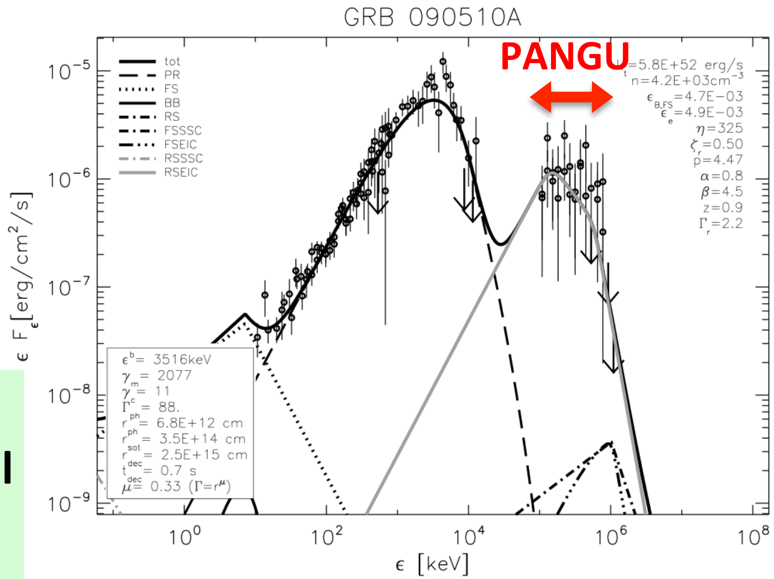
- **PANGU will distinguish two scenarios without ambiguity**
- **PANGU will detect more supernova remnants with at least x5 better resolution!**

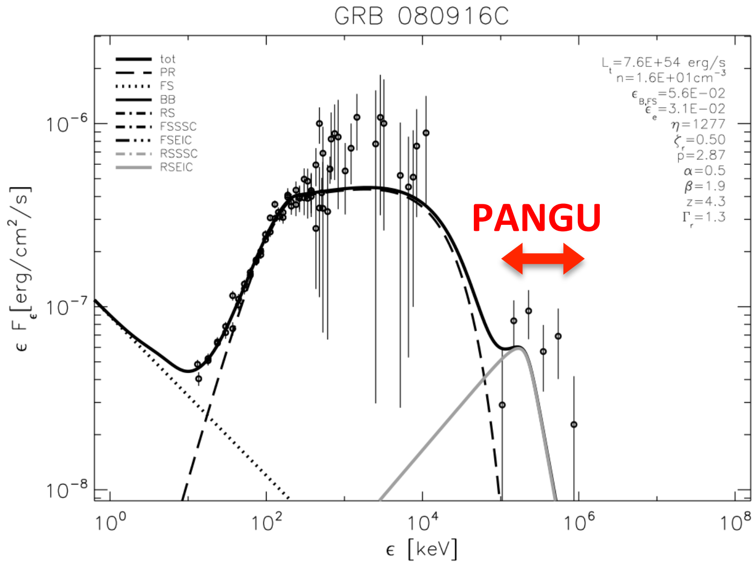


W44 Fermi

Finding Gamma-Ray Burst (GRB)

GRB maxima at 100 keV and 100 MeV

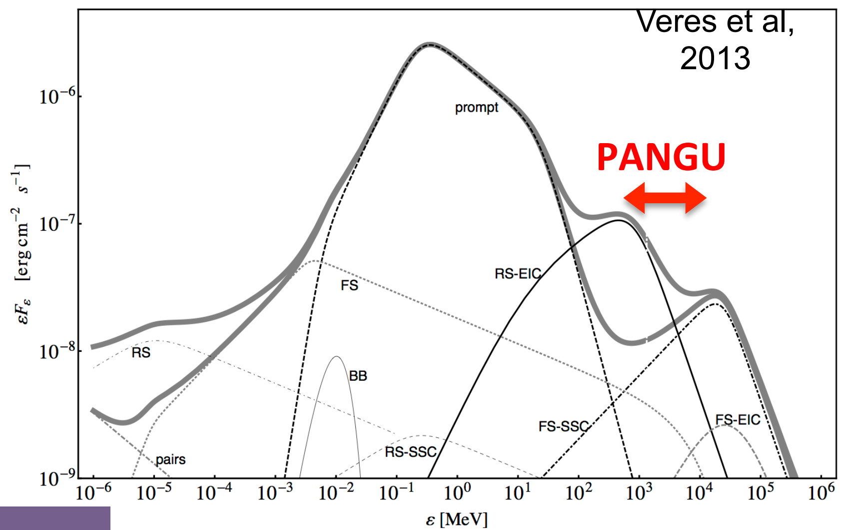




Remember: PANGU is a full sky Monitor!

- **Sub-GeV sky prompt emission**
  - **Peak at 100 keV**
- **Reverse and forward shocks**
  - **Delayed pair dominated flash of GeV-TeV (EIC). Only few detected**
  - **Delayed Interaction of blast wave with the progenitor wind. ➡shock distance, Γ and wind density**

(Pohl & Eichler, 2011)

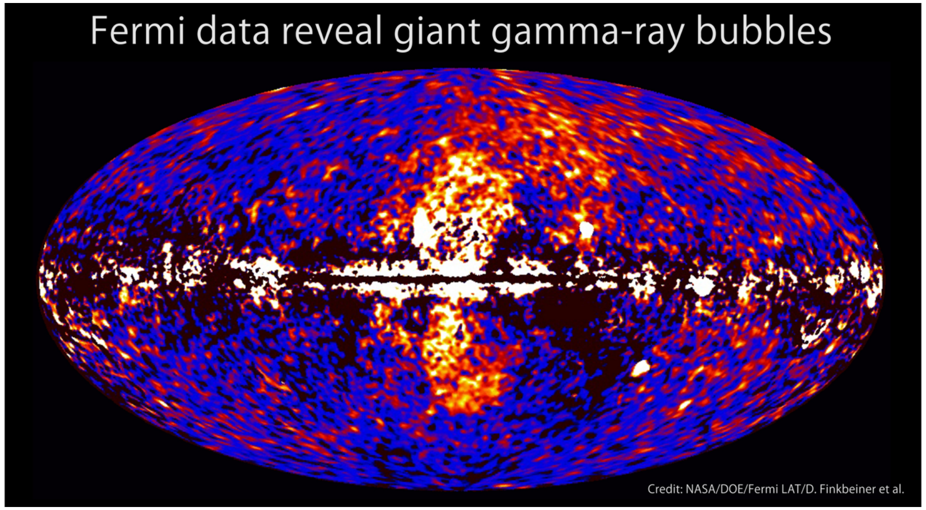


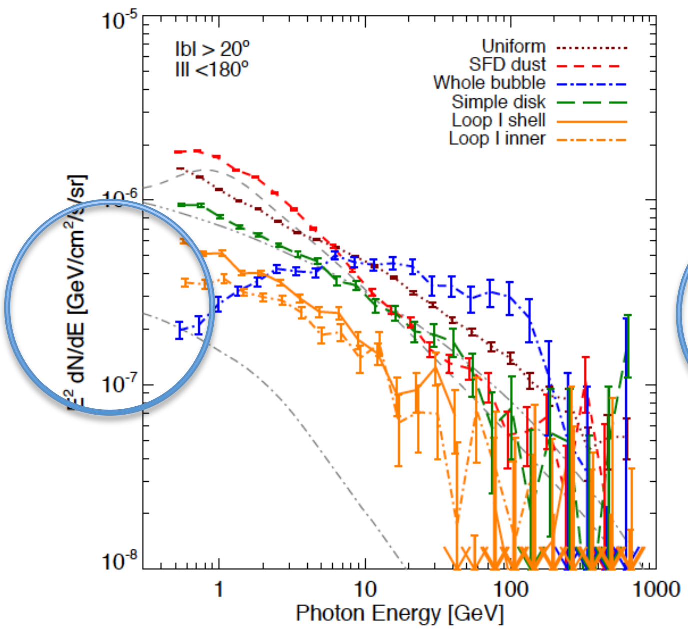
Are GRB energetic enough to account for UHECR ?

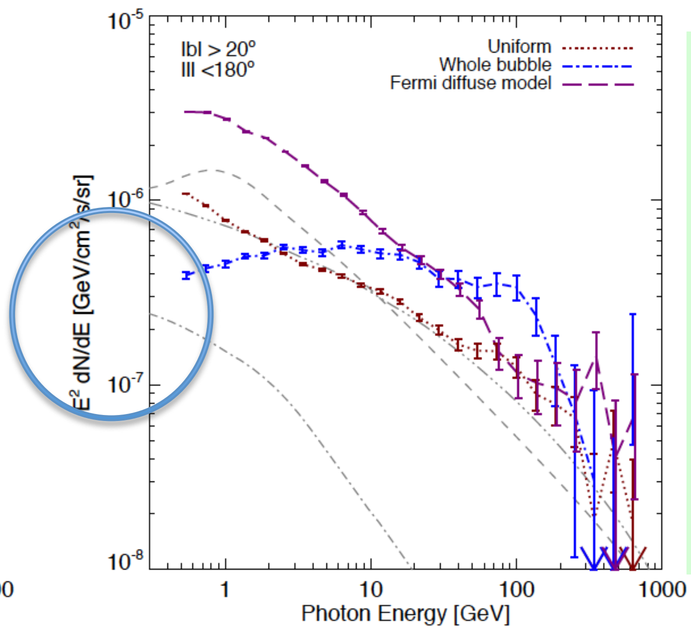
Fermi Bubbles --- Hadronic v.s. Leptonic

2014 Rossi Prize!

- **Gigantic pair of bubbles in gamma-ray**
  - **Unexpected discovery, measurement at < GeV is systematics dominated**
  - **100 MeV to GeV range is crucial to distinguish leptonic origin of the gamma rays from hadronic origin**





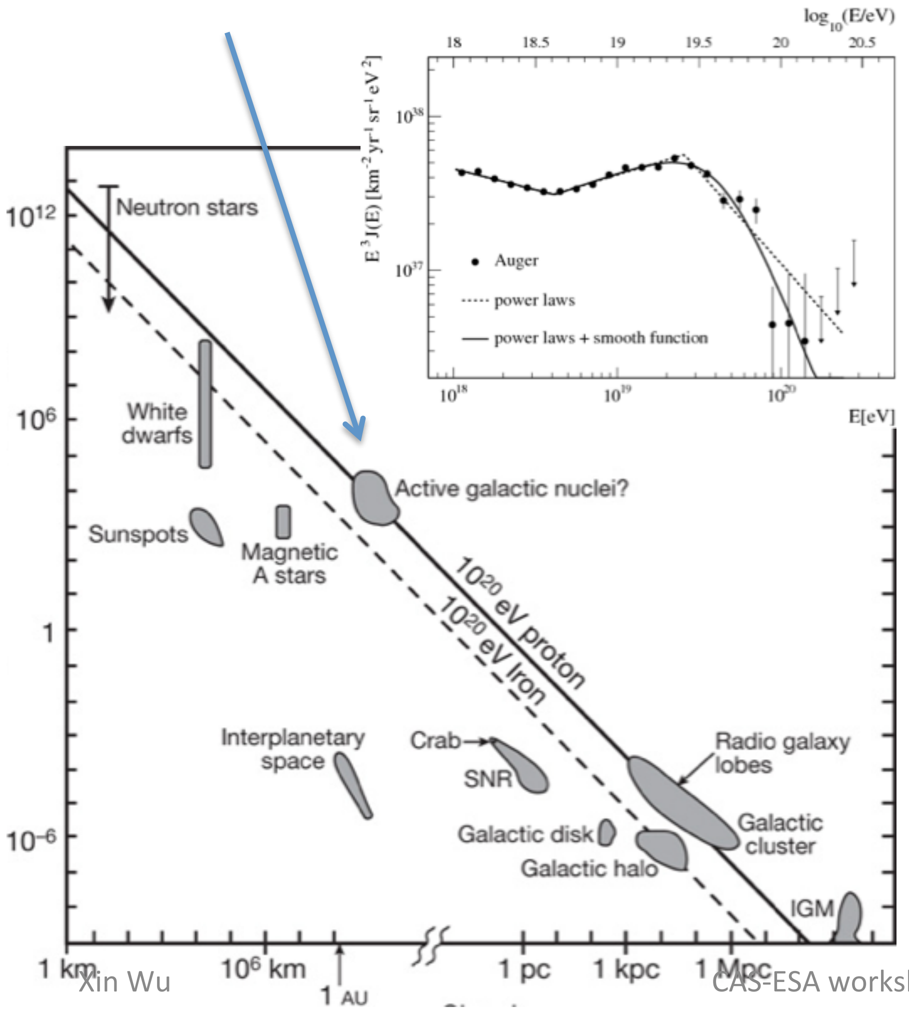


Measurement of < GeV cutoff is the key to infer the cosmic ray electron/proton spectrum at low energy

Origin of cosmic ray Cutoff within the Fermi bubbles is unclear.

Blazars and Origin of the UHECRs

Standard hypothesis: shocks in hadronic jets of Active Galactic Nuclei

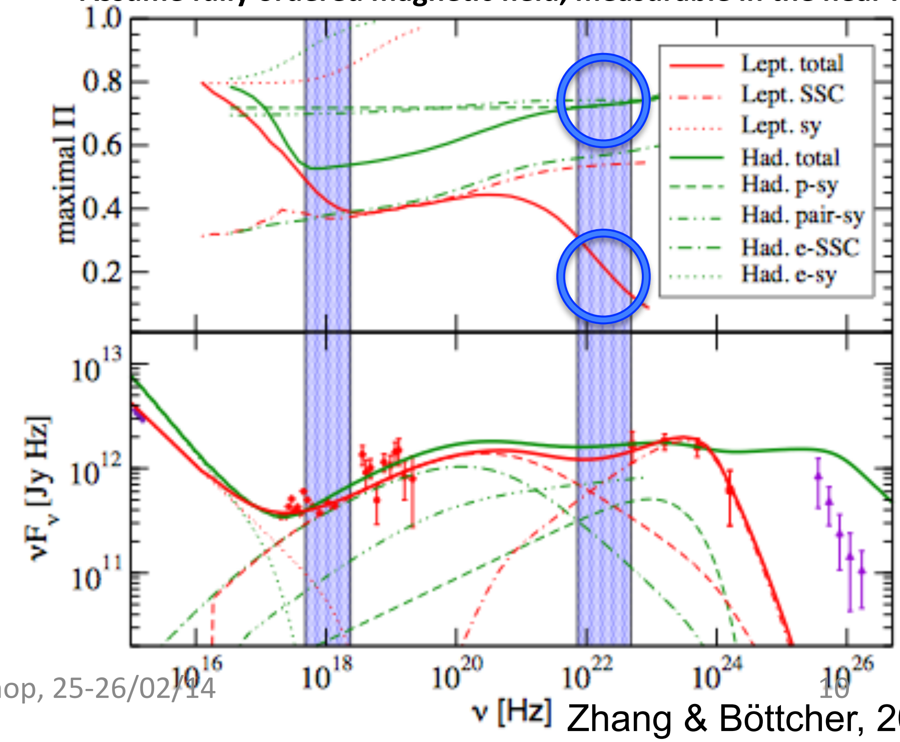


- **Jet spectra can be reproduced by leptonic or hadronic models**
  - **Only hadronic models predict neutrinos and high polarisation in sub GeV range.**

➡ PANGU observations of blazars flares

BL Lacertae

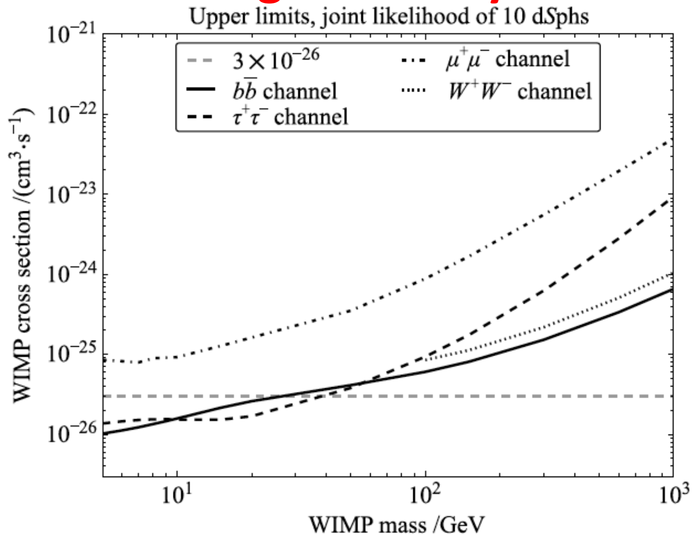
Assume fully ordered magnetic field, measurable in the near IR



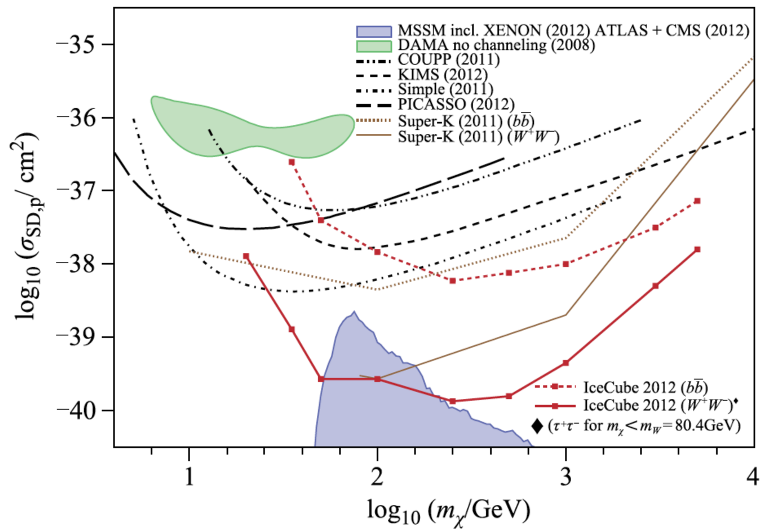
Zhang & Böttcher, 2013

Unique Role in Low Mass Dark Matter Search

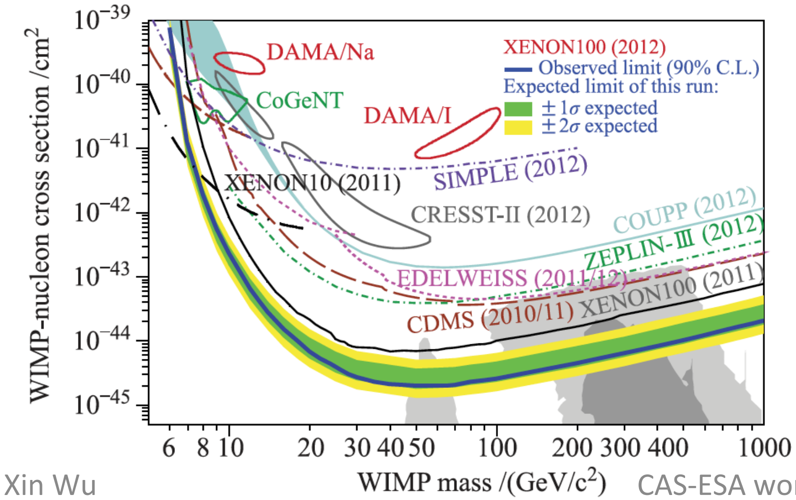
Fermi gamma-ray search



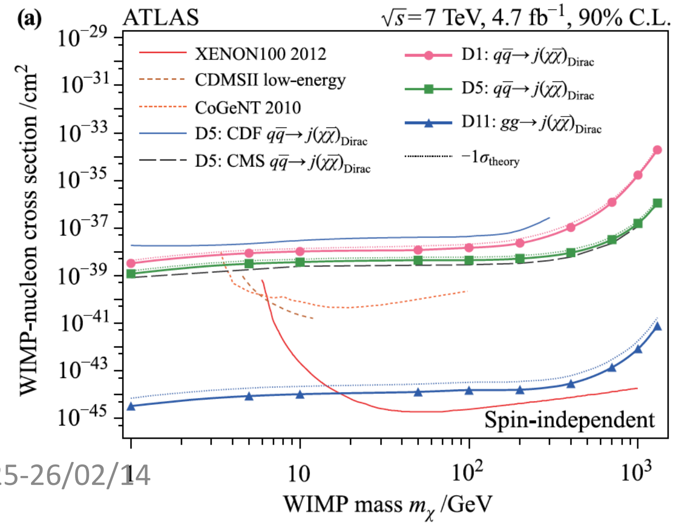
IceCube neutrino search



Underground direct detector search



Collider search for dark matter



Unique Role in Low Mass Dark Matter Search

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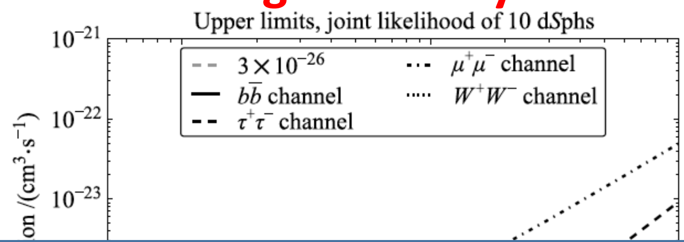
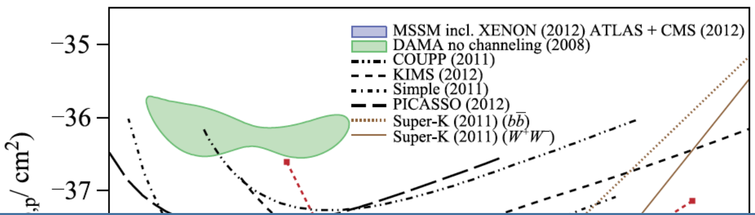
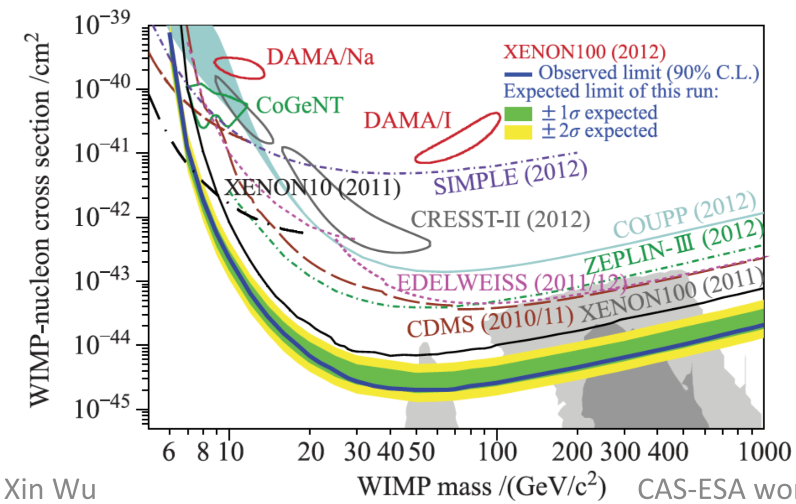
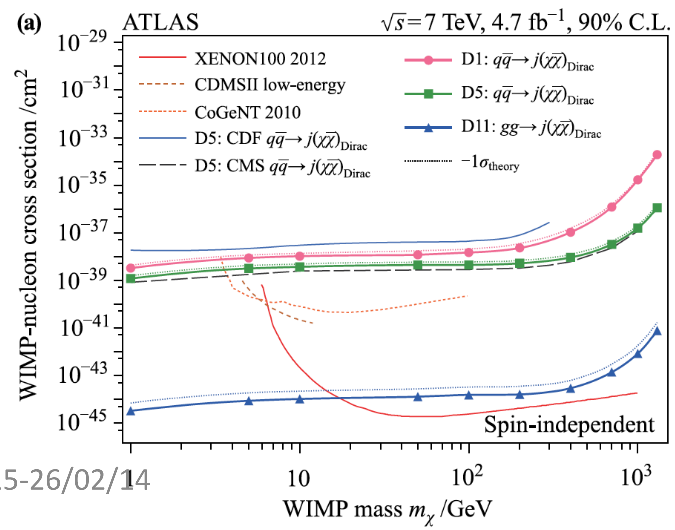


IceCube neutrino search

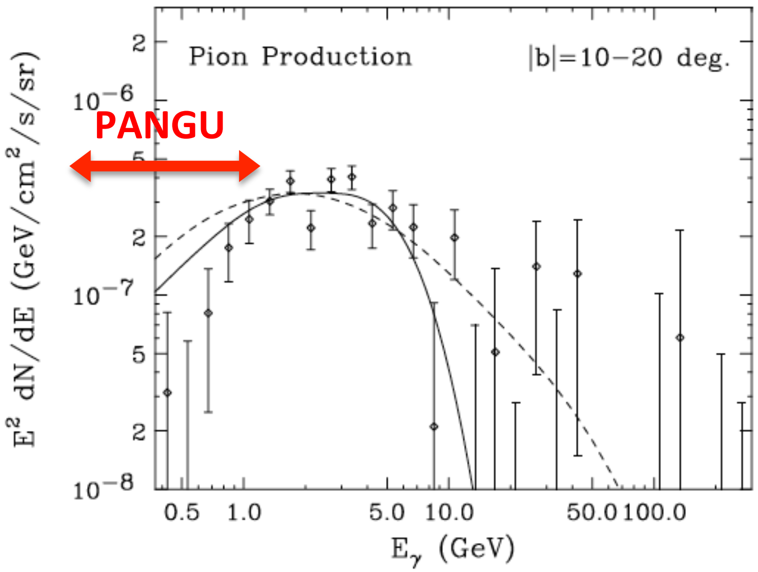


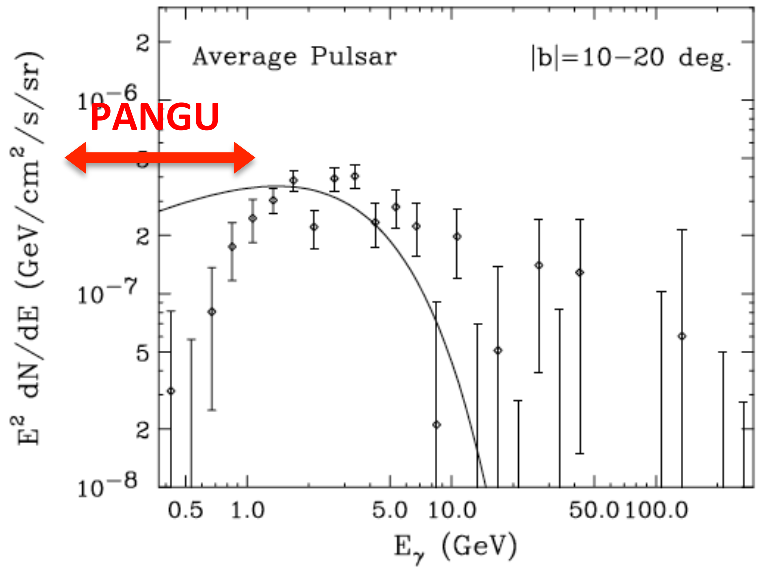
No missions are sensitive to PANGU's energy range --- unique in dark matter search, chance for discovery





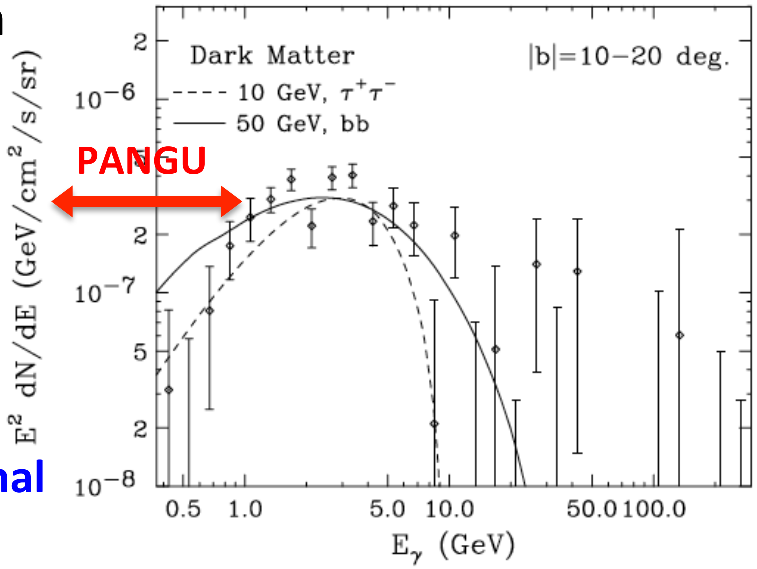
Mysterious Gamma-ray Emission from Inner Galaxy





Excess of γ-ray emission from the inner Galaxy, spectrum consistent with three mechanisms

- **Unknown CR protons**
- **A new type of pulsar population**
- **Dark matter annihilation signal**



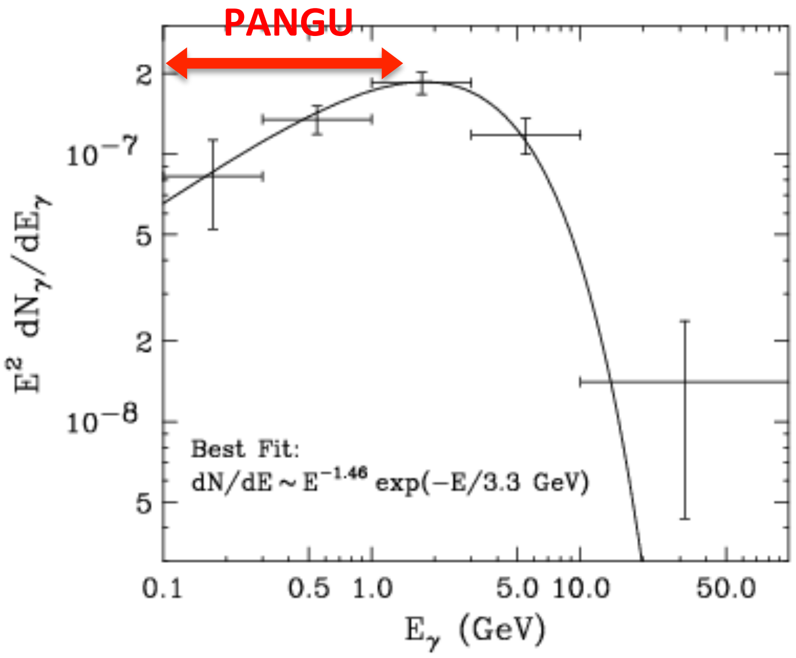
> GeV spectrum same for all three models

< GeV spectrum is key to distinguish models!

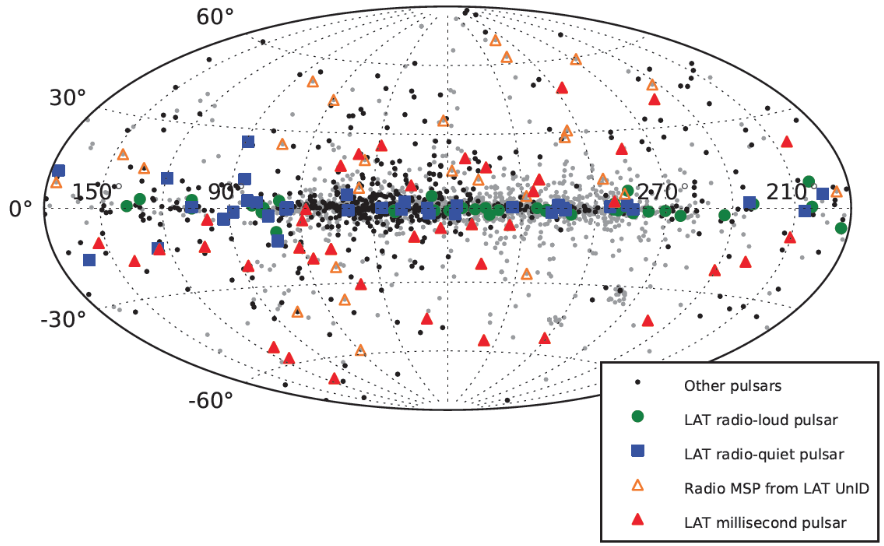
Pulsars: Ideal Targets for PANGU

Millisecond pulsars (MSP) peaked at ~GeV ➠ Unique for PANGU!

~5 better PSF ➠ ~30 lower background to search pulsations



Example of MSP energy spectrum



Fermi γ-ray pulsar distribution: contamination from disk is important (small PSF required!)

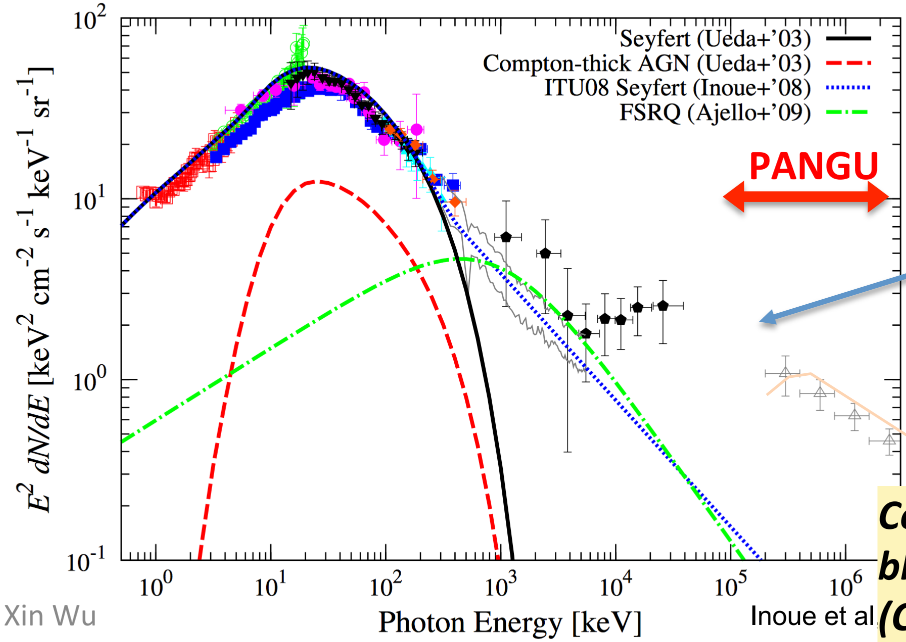
Gamma-ray observations can help to disentangle the geometry of pulsar magnetospheres and emission regions

Baryon Asymmetry

- **Baryon asymmetry in the early universe predict redshifted baryon (i.e. pion) annihilation signal**
  - **The observed 1-100 MeV cosmic γ-ray background has large uncertainty. Its anisotropy is unknown.**

➡ PANGU will measure the anisotropy of the CGB and give limit on the existence of anti-matter in the Universe on scales of 0.1 Gpc

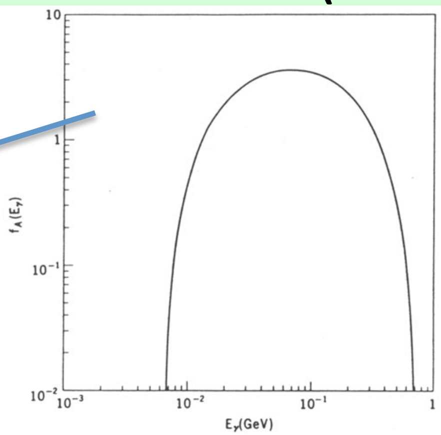
Cosmic gamma-ray diffuse background



Inoue et al

redshifted ?

Gamma-ray spectrum from proton-antiproton annihilation (rest frame)

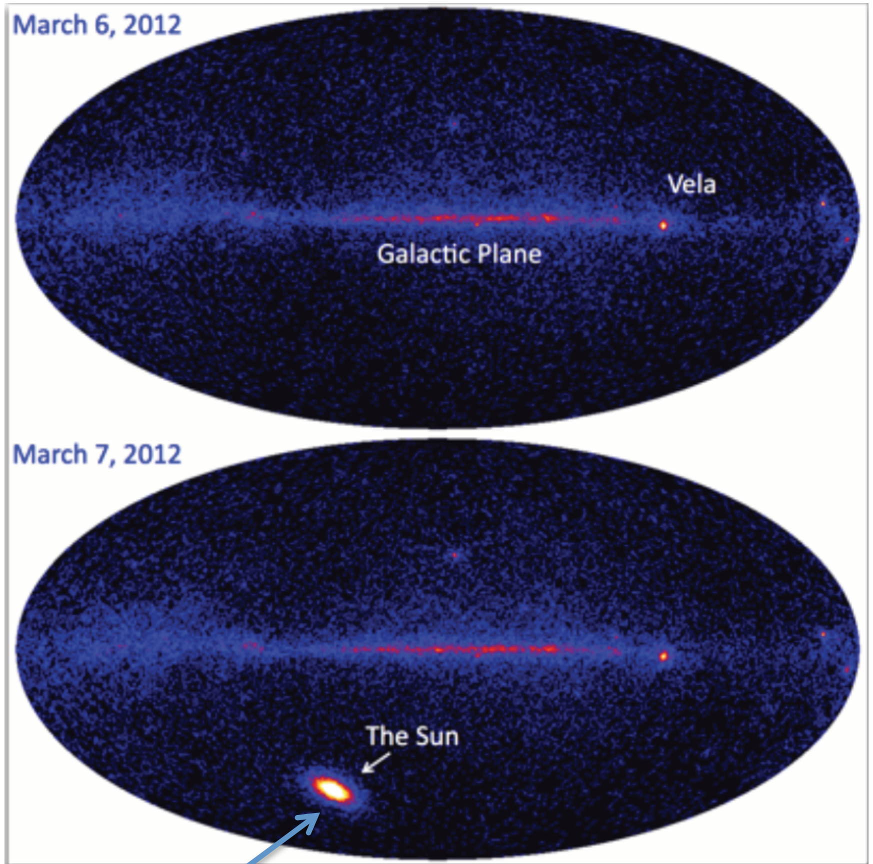


Stecker, 1971

Contribution from blazars and galaxies (Cavadini et al 2011)

Gamma-ray Emission from Solar Flares

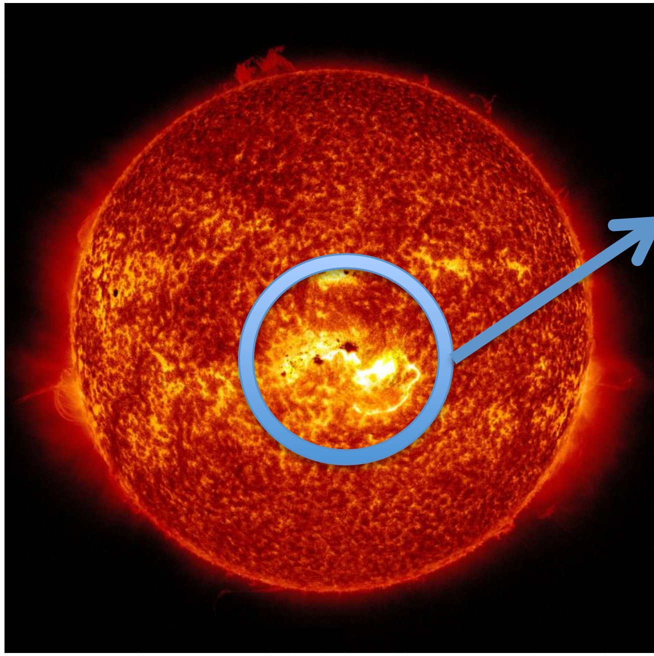
LAT 1 day all sky data >100 MeV



Bad PSF, cannot resolve the Sun ➡ no information on particle acceleration cite

Bright solar flares have been detected by Fermi

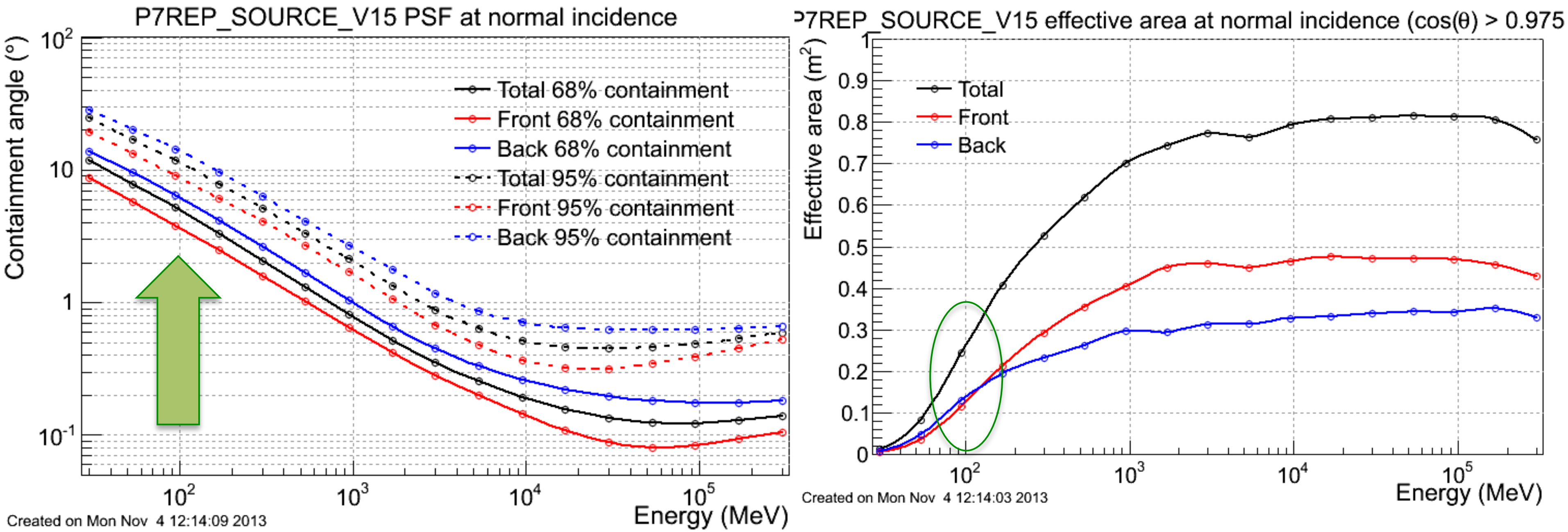
- 1000 time the flux of the steady Sun
- 100 times the flux of Vela
- 50 times the Crab flare
- High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours
- Softening of the spectrum with time



PANGU can resolve the flare in γ-ray!

Sub-GeV Gamma Ray Detection

- **The science case for high resolution (≲ 1°) gamma-ray space telescope around 100 MeV is very compelling**
  - **But it has yet to be realized, best instrument up to now is Fermi**

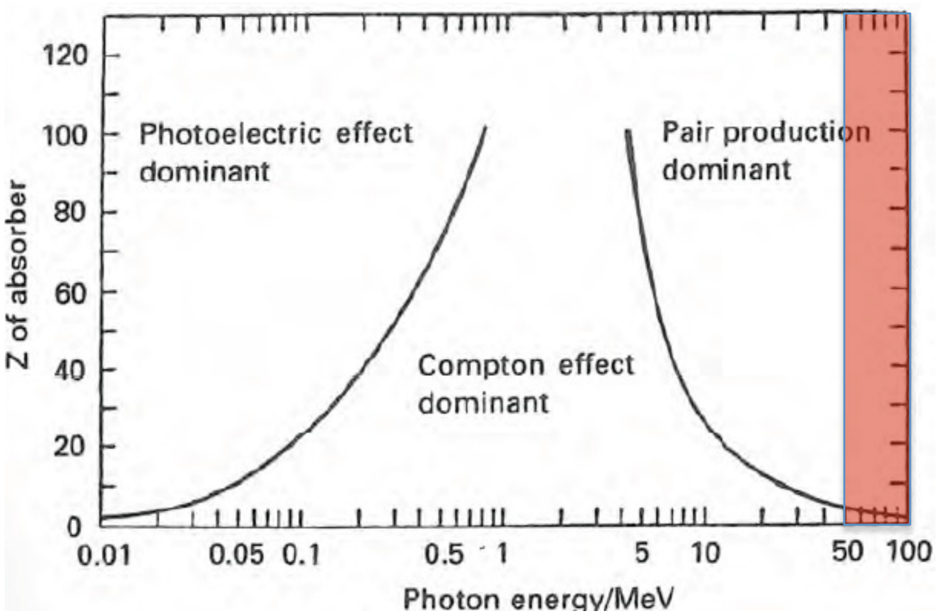


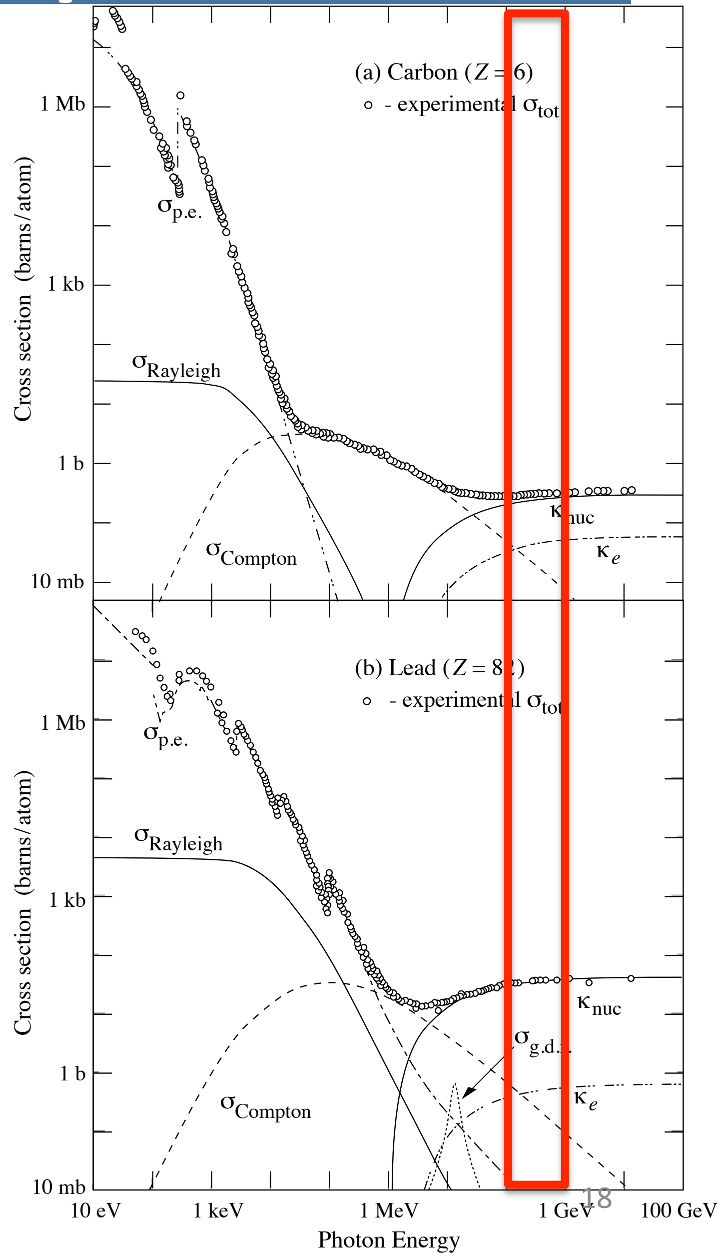
PSF ~4-6° @100 MeV

Why so hard?

Detection Principle

- At ~100 MeV, pair production dominates
  - Very small cross section ⟹ need more material for good acceptance
  - Material is the limiting factor of angular resolution because of important multiple scattering at ~MeV

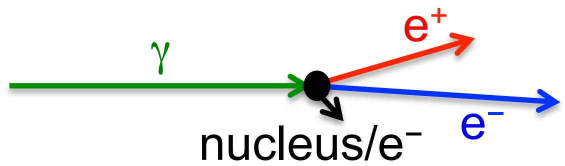




Angular resolution at 100 MeV

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

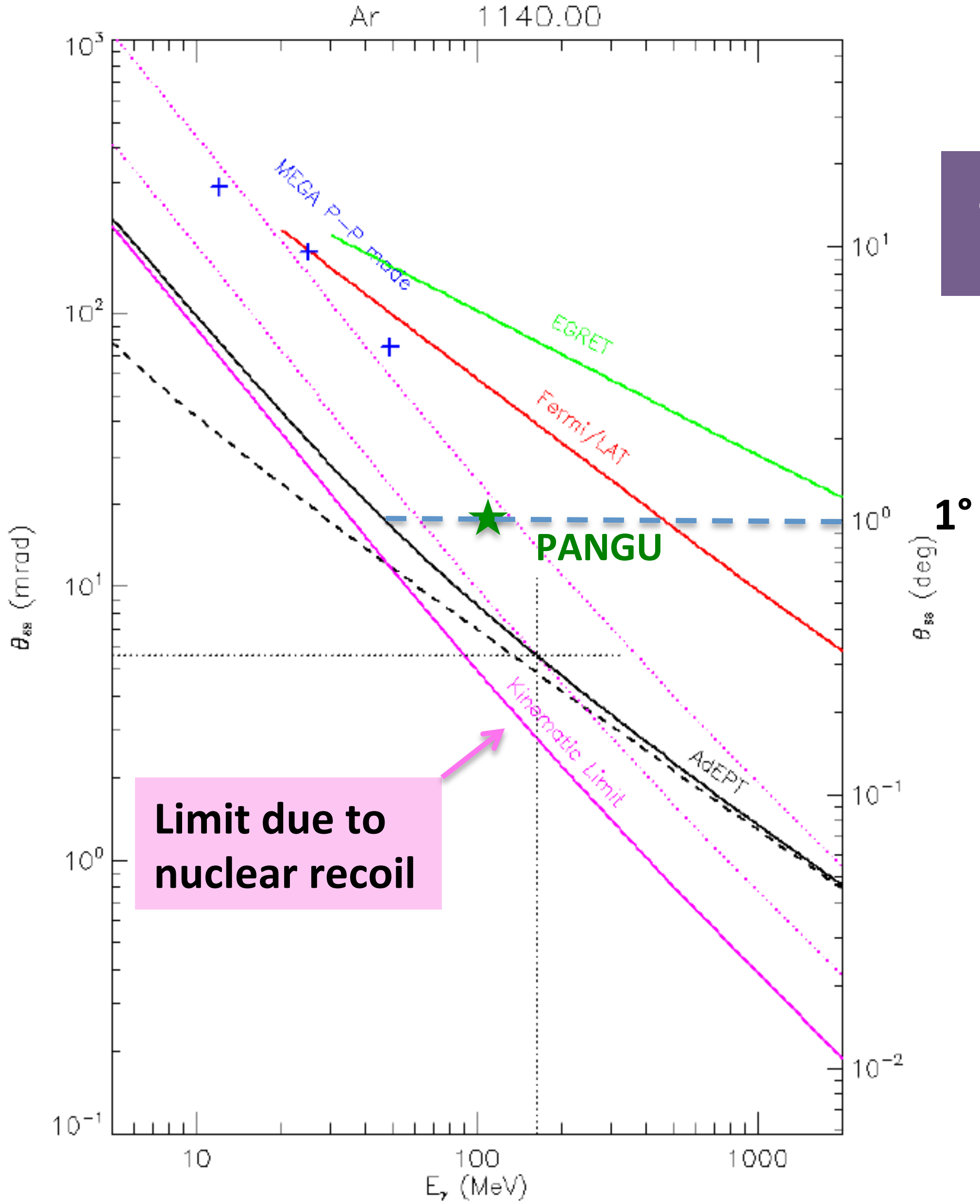
    NIMA 701, 225-230
    - Best if energy of both tracks can be measure
    - If not normally use the direction of the leading (longest and straightest) track
      - Extra error θ_{68} of ~0.65° @ 100 MeV
  - Track angular resolution
    - Multiple scattering: For θ_{MS} = 0.5° @70 MeV, total material 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



Possible Detector Concepts

- To achieve $\lesssim 1°$ angular resolution passive material should be minimized and active detector should be thin or low density
  - To increase effective area (mass!) needs many layers or large volume
- Concepts for high resolution gamma pair telescope studied before
  - Low density gas TPC: HARPO, AdEPT (5-200 MeV), …
    - Potentially very good resolution
    - Need large pressure vessels (AdEPT: $6 \times 1 m^3$ vessels for 20 kg gas)
  - All silicon : MEGA/GRIPS, TIGRE, CAPSiTT …
    - Optimized for both Compton and pair detection (0.1 – 100 MeV)
    - MEGA/GRM: Double-sided SSD, distance 5 mm, 500 µm thick
    - CAPSiTT: Double-sided SSD, distance 1 cm, 2 mm thick
    - TIGRE: Double-sided SSD, distance 1.52 cm, 300 µm thick
  - Scintillating fiber: this proposal: a new all-fiber concept
    - Previous concepts with converter: SIFTER, FiberGLAST

Angular resolution of pair telescopes

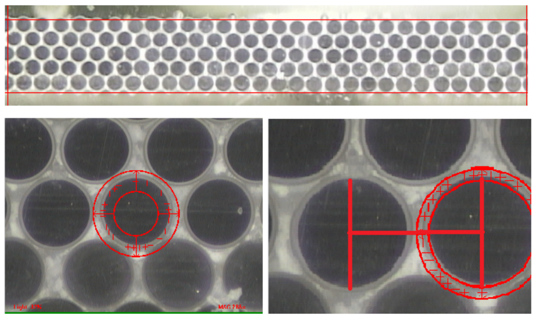


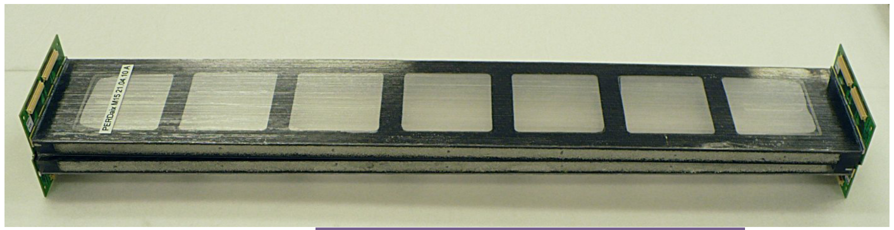
arXiv:1311.2059 [astro-ph.IM]

Our Proposal

- All-fiber (or all silicon) tracker, both mature technologies
  - Challenges are mainly engineering: optimal use of the limited weight and power budgets
- Silicon has been successfully used in similar space missions
  - Fermi, AGILE, Pamela, AMS-02, …
- Fiber is cheaper, less fragile, less dead material, flexible geometry, but the technology of multichannel scintillating photon detector (SiPM), as well as readout electronics, is newer
  - Rapid development lately because of application in high energy physics, eg. LHCb, Mu3e, …
    - Also in space: balloon prototype Perdaix of PEBS
  - Position resolution ~70 μm can be achieved

NIMA 628(2011)403



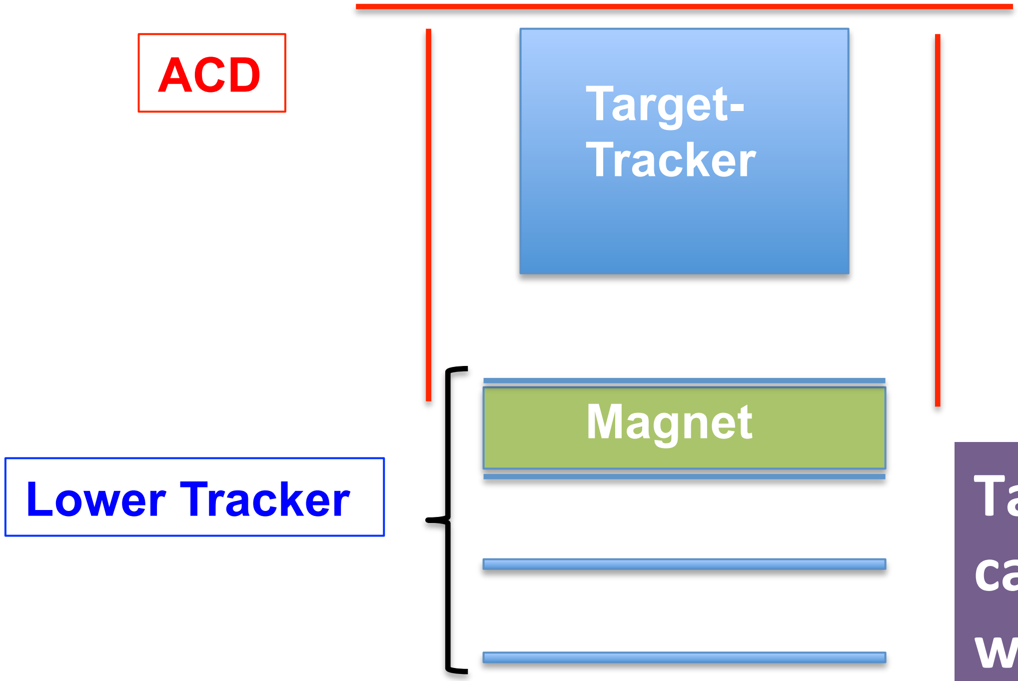


Perdaix module

How about the energy measurement?

- Standard way is to use a calorimeter under the tracker
  - Eg. AGILE mini-calorimeter, CsI, 1.5X_0, 37x37x3 cm^3, ~20 kg (30 kg total)
    - But energy resolution ~70% at 100 MeV because of leakage
- Use multiple scattering: average deflection angle $\propto 1/p$
  - Need very good position resolution
  - Only usable below ~100 MeV
- Magnetic spectrometer with permanent magnet
  - Tracker-target inside magnet
    - Allows early separation of 2 tracks
    - Need small σ_x or strong field since distance between layers is small
    - Size of the magnet is coupled to the size of the target
  - Magnet below the tracker-target (preferred configuration)
    - Magnet can be smaller and more independently optimized
    - Only measures momentum, no early separation of 2 tracks

Sketch of a Possible PANGU Layout



Target and magnet sizes can be easily scaled to fit with resource constraints!

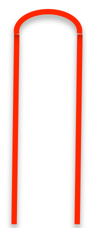
- **3 sub-systems: target-tracker, magnet + lower tracker, Anticoincidence**
  - **Target-tracker : ~ 40 x 40 x 40 cm^3**
  - **Magnet: r_2 = 26 cm, r_1 = 25 cm, height 10 cm, field in +y direction**
  - **Lower tracker: one X-layer above, one X-layer, and two X-Y layers below, ~10 cm between layers**
  - **Anticoincidence detector (ACD) on 5 sides**

The Target-Tracker

- Possible layout
  - x-y double layers with 6mm inter-distance, 50 double layers
  - Requirement: each layer measure x and y to ~70 µm, total material every 6mm is ~0.3% X_0
- Tracking layer with ~0.3% X_0 total
  - 2 layers SciFi of 0.65 mm each (Polystyrene equivalent), ⇒ each layer formed by a stack of 3 layers of ø=250 µm fibers
    - If silicon: 1 double-sided SSD of 300 µm or 2 single sided SSD of 150 µm each
- Total weigh of fiber alone ~10kg (polystyrene density ~0.9 g/cm^3)
  - Fiber layers need to be supported by very light weigh structure!
    - A double layer of fiber is very light, only ~200 g
- Support structure, electronics, ACD and possible shielding needs to fit into the remaining 20 kg

Power Consumption

- **Total number of readout channels of 50 double-layers in the target + 6 layers in the lower tracker, with 250 µm readout pitch, is ~170k channels (1600 per single layer)**
  - **Fibers can be can be readout by SiPM of 250 µm pitch**
  - **Readout ASIC needs to be developed. First interaction with some companies indicates it is possible to achieve ~0.2mW/channel, similar to the current performance ASICs of Si strip detectors**
    - **Total ASIC power ~35 W**
  - **With some weight and complexity penalty, it could be possible to use one fiber to 2 measurement locations some distance apart**
    - **Ambiguity is negligible because of the low occupancy**
    - **Power consumption of the ASICs reduced by x2**



- **Other readout ides like ICCD (rate and weight limitation?)**

PANGU Magnetic Spectrometer

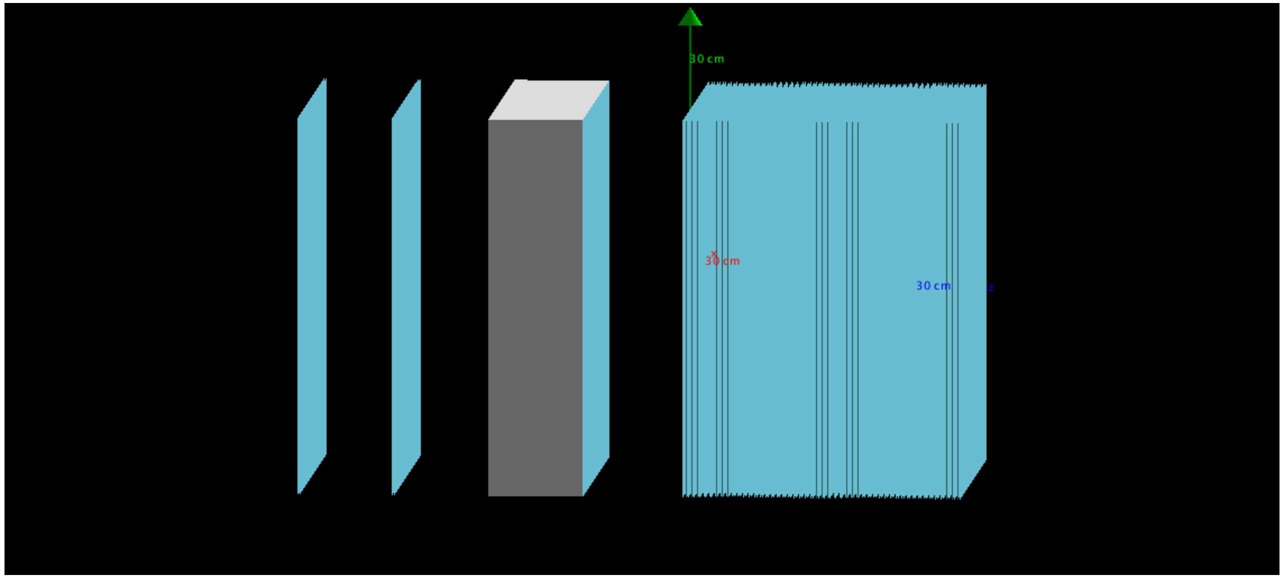
- **Momentum measurement through bending angle**
  - **$\theta = 0.3\ LB/p$ [mm T MeV^{-1}] = 3/p radian (p in MeV)**
    - **3 mrad (0.17°) for 1 GeV, 30 mrad (1.7°) for 100 MeV**
  - **$\Delta p/p = p/(0.3\ LB)\ \Delta\theta = (p/3)\ \Delta\theta$ (p in MeV)**
    - **$\Delta\theta$ dominated by tracking resolution (σ_x/d) at high energy, and by multiple scattering at low energy**
    - **$\Delta p/p$ ~30%-50% reachable with B=0.1 T, L = 10 cm, σ_x=70 µm, d = 10 cm for p = 100 -1000 MeV**
- **How to produce a magnetic field?**

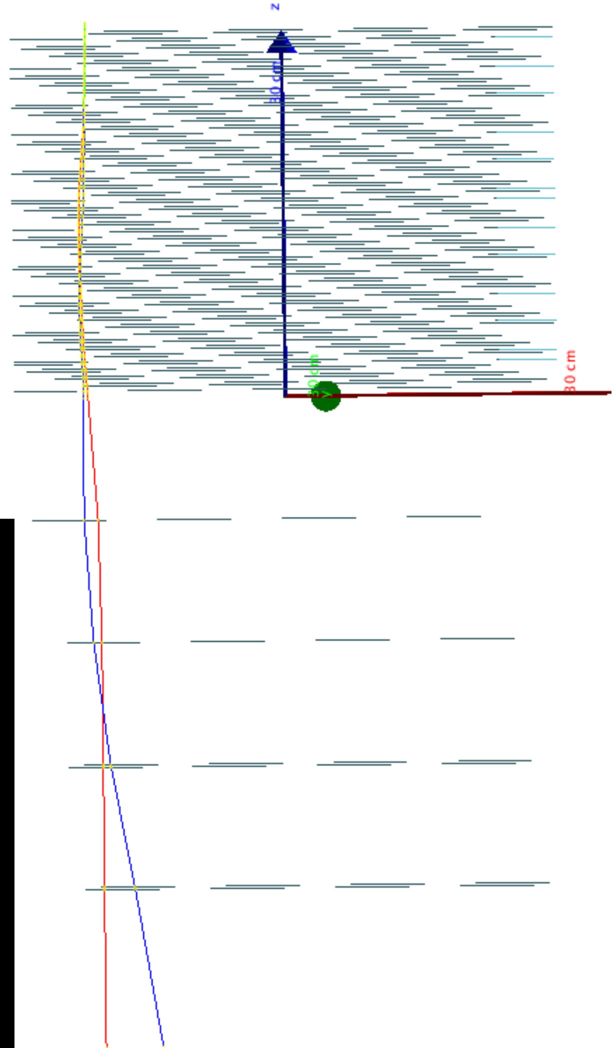
Permanent Magnet

- **Halbach array with NdFeB magnet**
  - **$B = B_0 V_f \ln(r_2/r_1)$**
    - **B_0 is the remnant field, assume 1.5 T (strongest available today)**
    - **V_f is the the filling factor, assume 0.9**
    - **r_1 is the inner radius, assume 25 cm**
  - **For B = 0.1 T, $r_2 = r_1 \exp(0.1/(1.5*0.9)) = 26.9$ cm**
  - **Magnet volume = 10 x $(26.9^2-25^2)\,\pi$ =3098 cm^3**
  - **Density of magnet = 7.5 g/cm^3 $\Longrightarrow$ weight of magnet = 23.2 x 0.9 = 21 kg**
  - **It is possible to allocate about half of the weight budget (~30 kg) for a magnet with a field ~0.1 T**

Performance Estimation

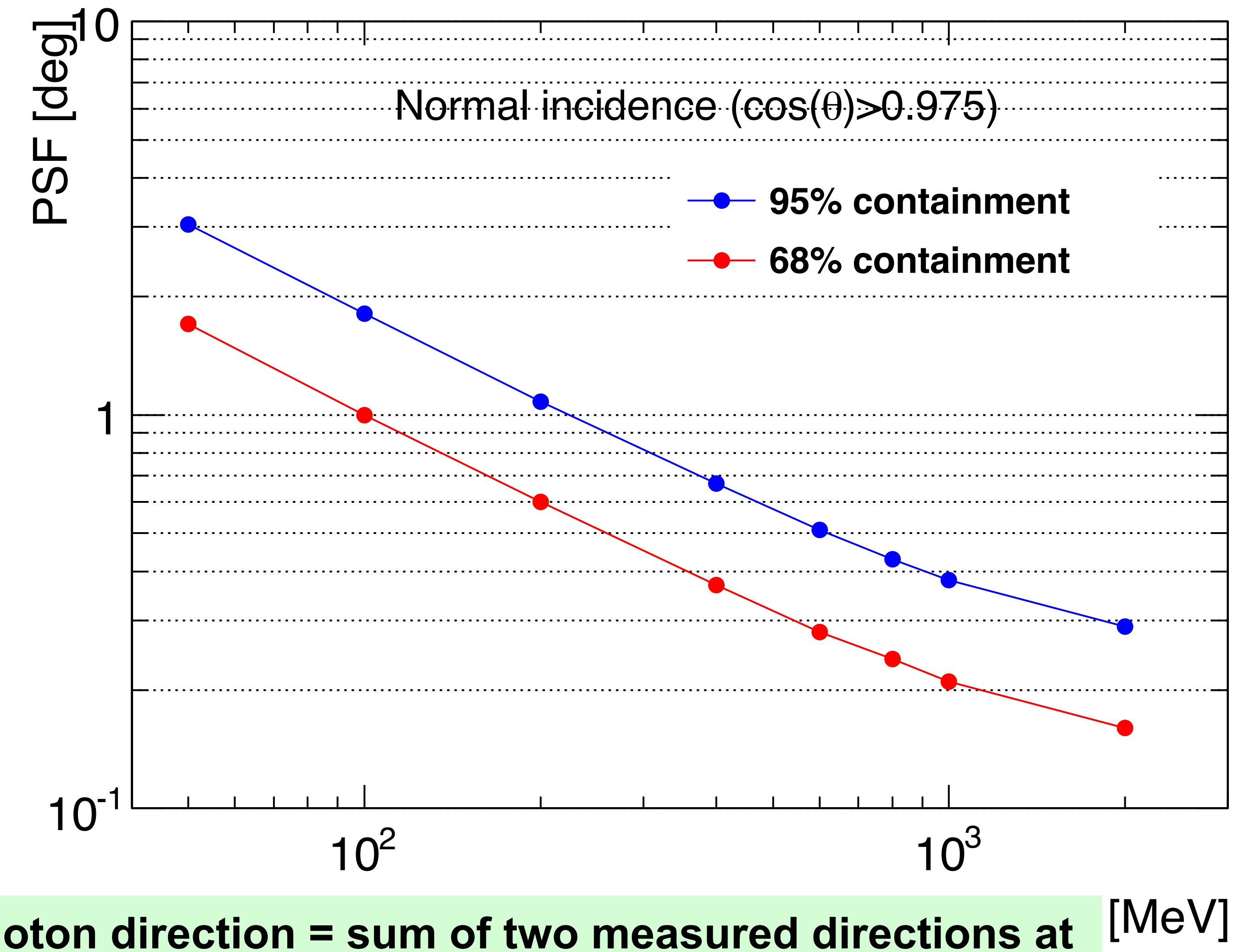
- **Geant4 simulation to asses the performance**
  - **For practical reasons uses 150 µm single sided silicon detector, 242 µm pitch, digital readout $\Longrightarrow$ 70 µm position resolution**
- **Results are very preliminary**





Point Spread Function

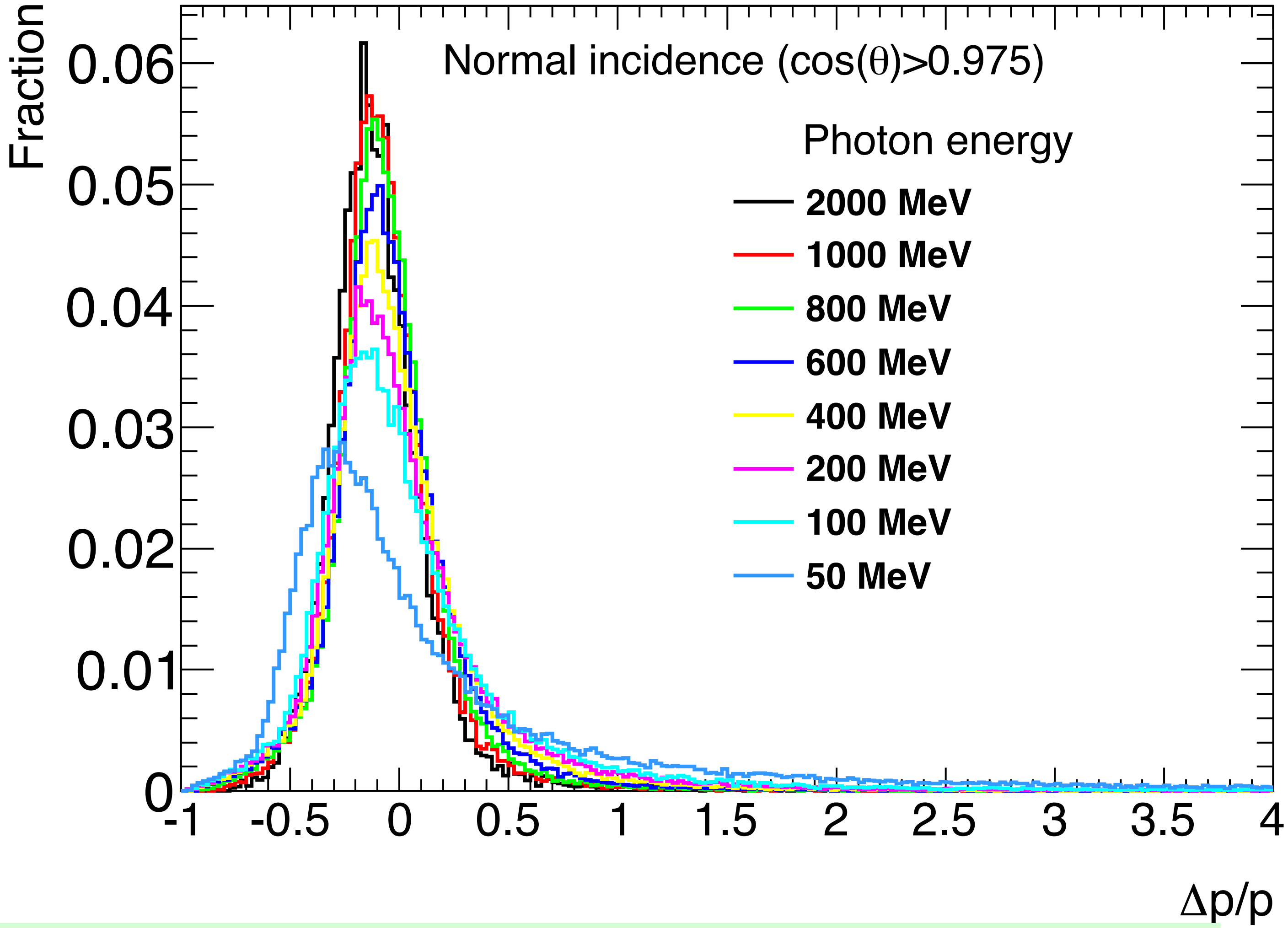
- For normal incidence (cos(θ)>0.975), both tracks in the lower tracker



Measured photon direction = sum of two measured directions at the first measurement point weighted by measured momenta

Photon Energy Measurement

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

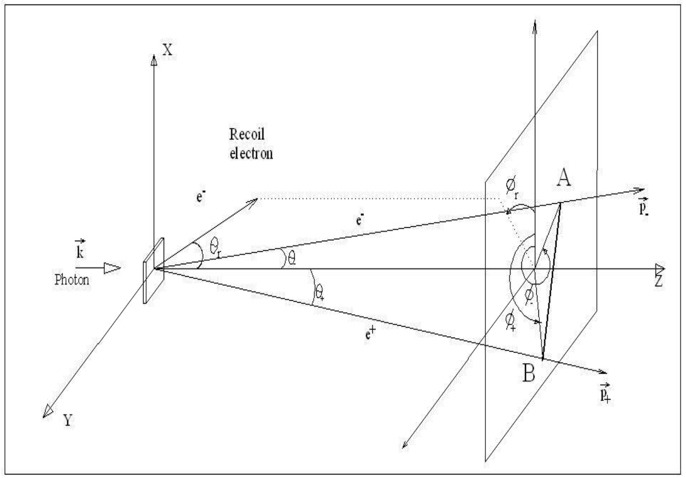


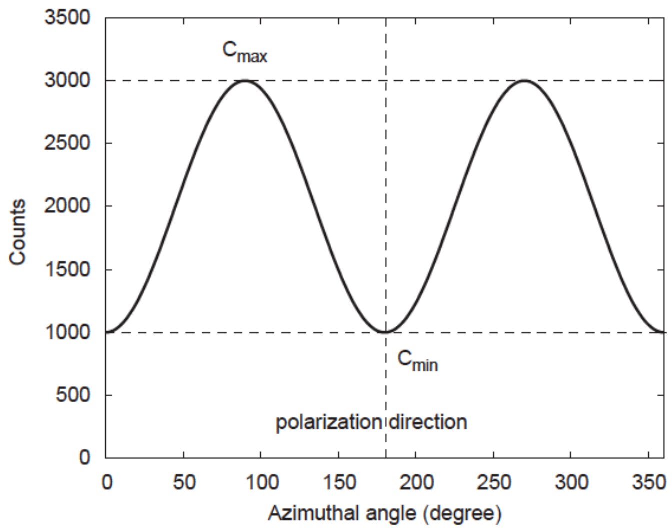
Raw width ~20-30% for 100MeV – 1GeV, bias should be corrected

Polarisation 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)**

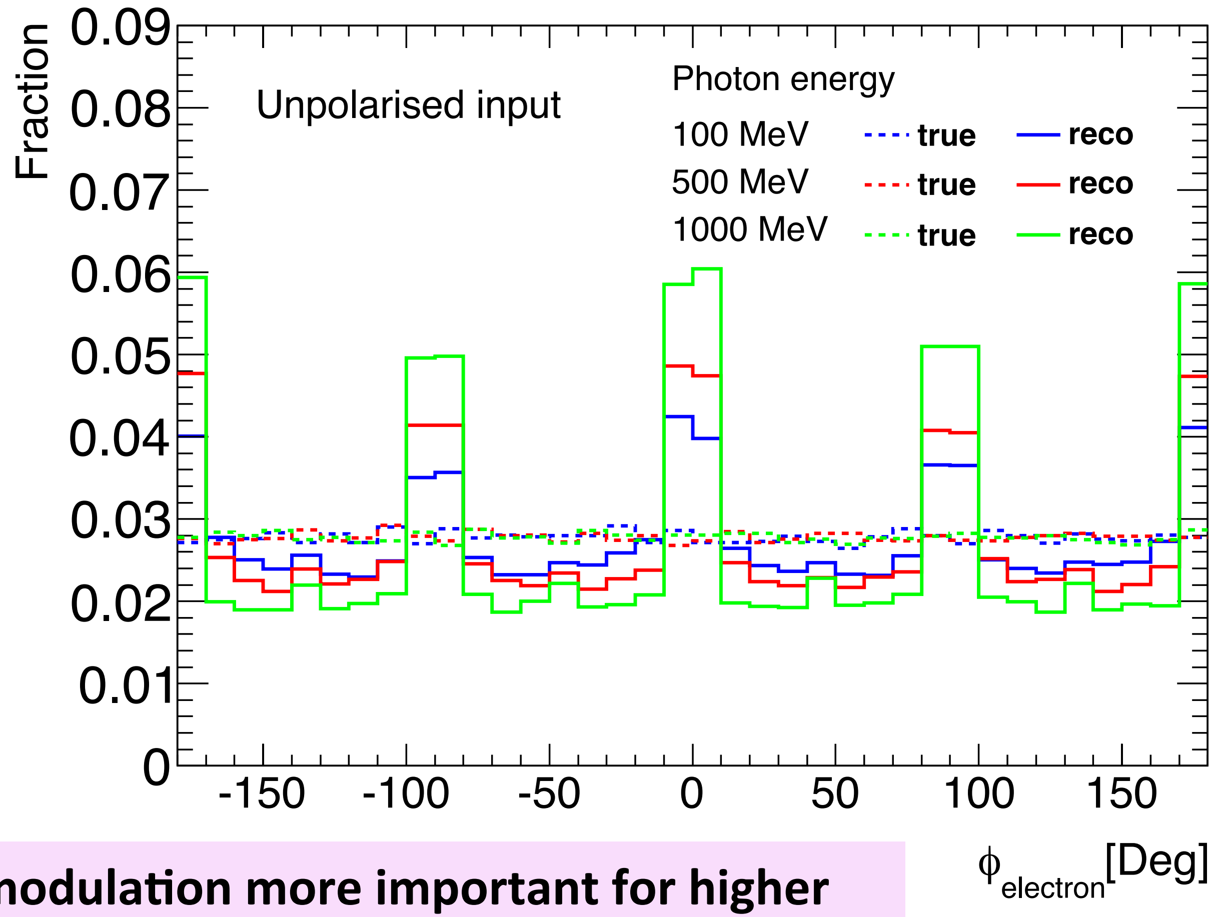




- **Key to the measurement**
  - **Azimuthal angular resolution: opening angle and momentum**
  - **Anisotropy of the detector!**

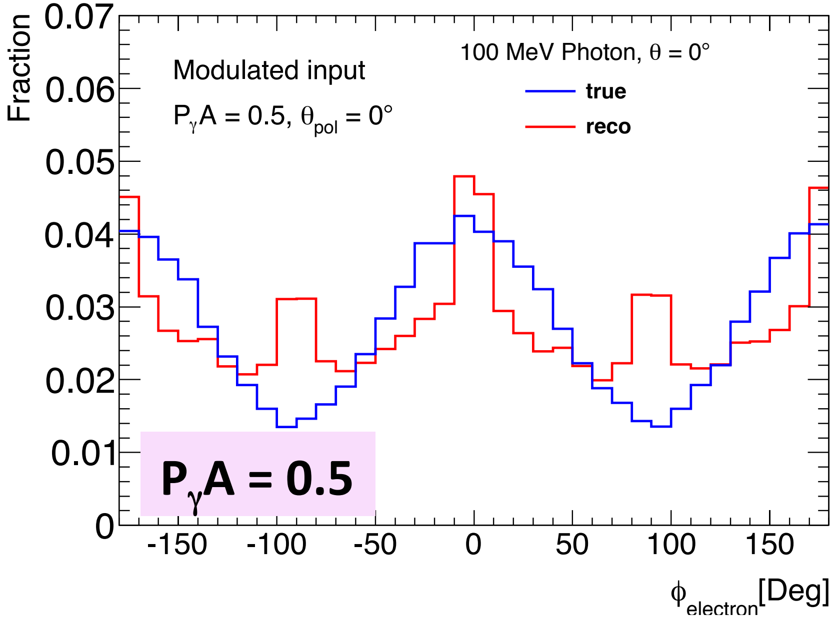
Detector Anisotropy (Modulation)

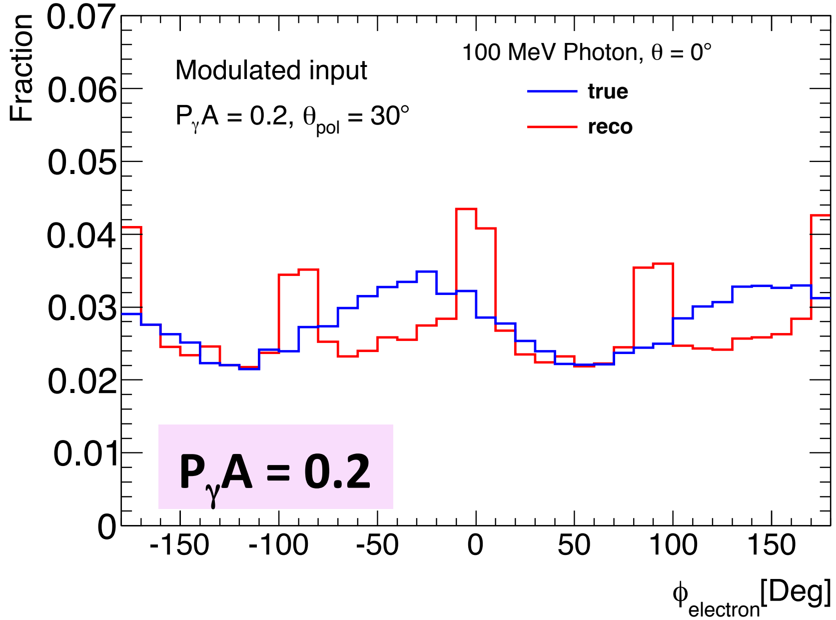
- **Detector modulation because of bad ϕ resolution when particle goes in parallel to the strip direction**

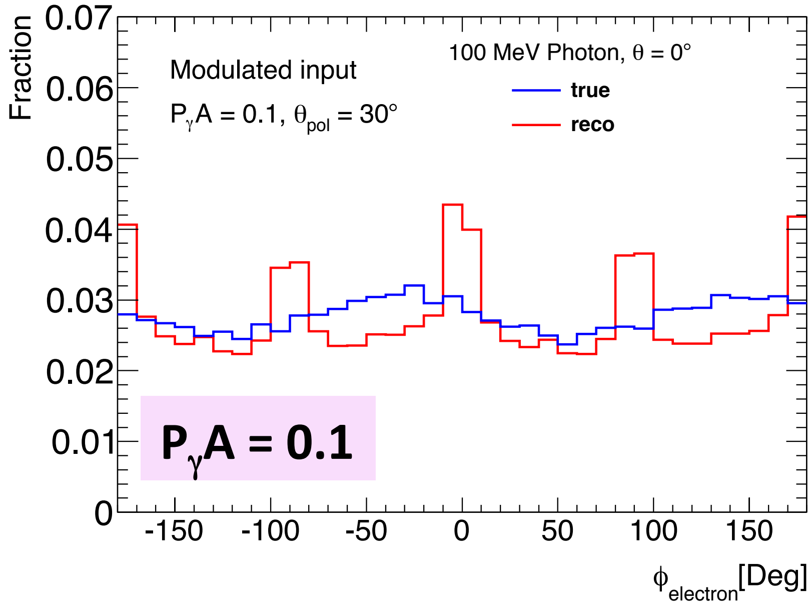


Detector modulation more important for higher energy because of smaller opening angle

Polarisation Detection Capability







Input ϕ distribution modulated with fixed $P_g A$

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

Mission Concept

- **Low earth orbit**
- **All-sky survey and pointed observations**
  - **With possibility to rotate the payload to study systematic effect of polarisation measurement**
- **Minimum lifetime three years**
- **Science data open to the world community**

Potential Collaboration Projects

- Many interesting and challenging topics for collaboration
  - Conceptual Design: Payload performance and optimization
  - Permanent magnet: light weight, uniformity
  - SciFi tracking layer: automatic winding process, placement precision, gluing process, light weight support, …
  - Target-tracker: integration of layers on precise light weigh frame
  - Photon detector
    - SiPM: high efficiency, low dark current, high density
    - Other photon detection scheme?
  - FE ASIC: low power
  - Trigger, Readout and DAQ: low power consumption, low dead time, robust trigger algorithm, flexibility for different observation mode
  - ACD: low weight, coverage, segmentation
  - On-ground data processing, science preparation: Science data center

Conclusions

- PANGU is an *unique opportunity* for high energy astrophysics. It will resolve and monitoring the sub-GeV sky with unprecedented spatial resolution, separating diffuse gamma-ray emission from point sources
  - PANGU science is not "incremental science", it will lead to fundamental discoveries and understanding.
- PANGU is synergic with Gamma-400, DAMPE, HERD, CTA and other ground-based and space detectors (e.g., radio, optical, X-ray, TeV, gravitational wave experiments)
- Payload concept is innovative but the technology is ready
  - The qualification of scintillating fiber tracker for space application would be a major technological advance

Thank You!

Welcome to join!