PANGU

盤古

A High Resolution Gamma-Ray Space Telescope

Meng Su

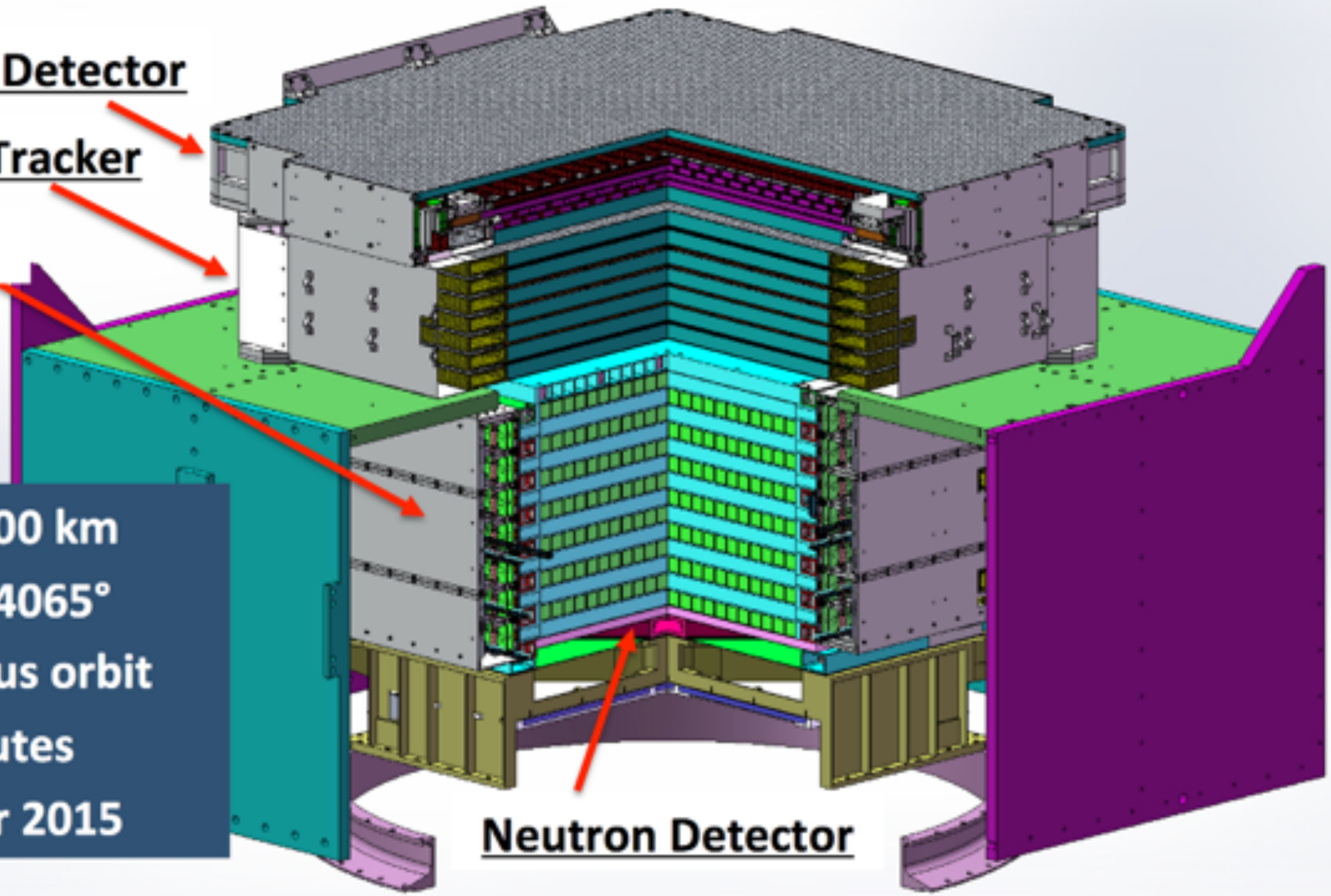
On behalf of the PANGU collaboration

Pappalardo/Einstein fellow
MIT

GammaSIG Meeting at the 225th AAS meeting, Seattle

January 4th, 2015

The DAMPE Detector

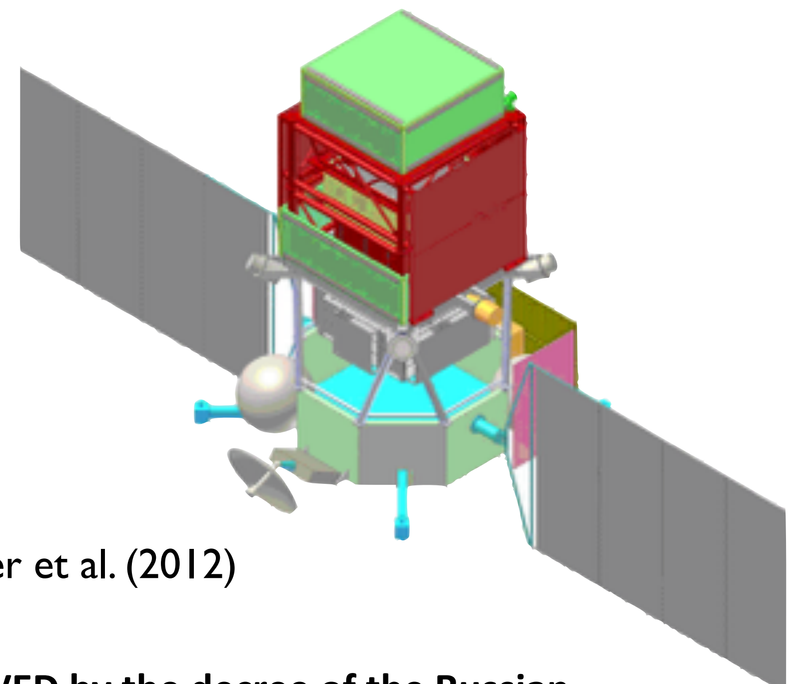


- Altitude: LEO 500 km
- Inclination: 87.4065°
- Sun-synchronous orbit
- Period: 95 minutes
- Launch October 2015

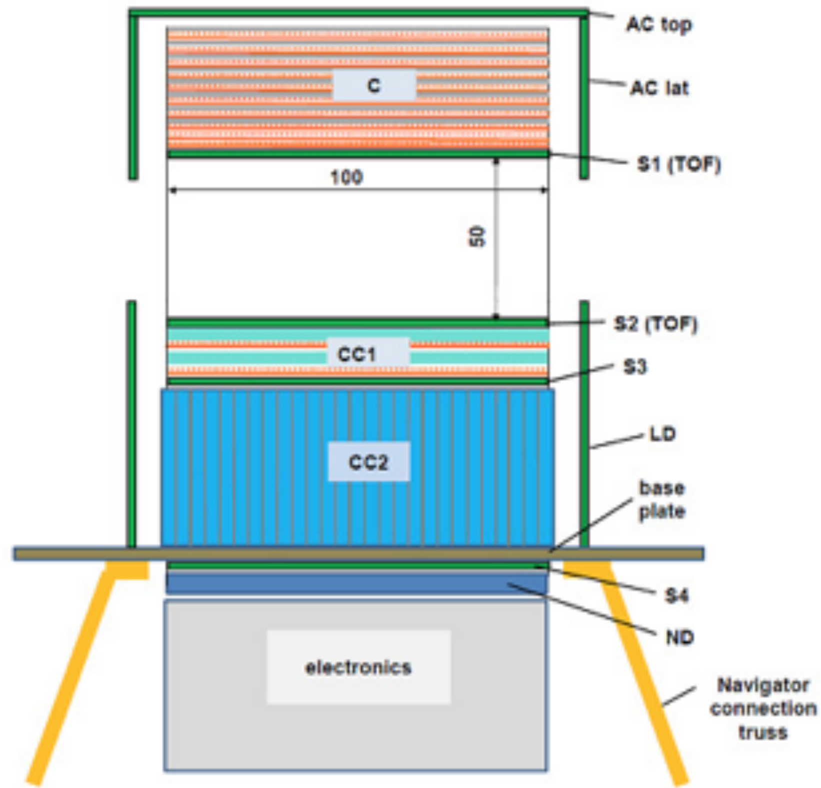
W converter + thick calorimeter (total 32 X_0) + precise tracking + charge measurement ➡ high energy γ-ray, electron and CR telescope

Gamma-400

(launch ~2020)



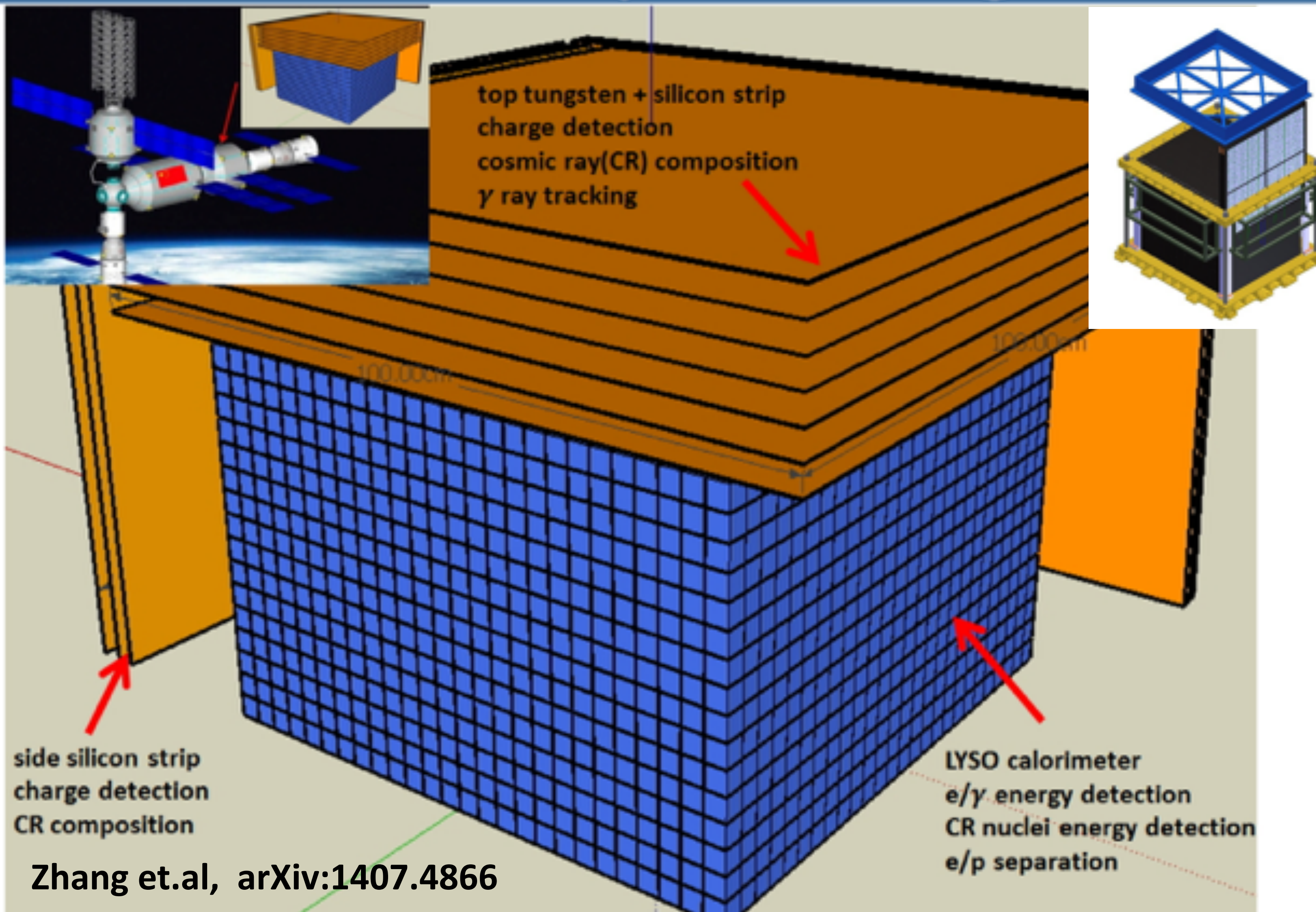
Galper et al. (2012)



APPROVED by the decree of the Russian Government of December 28, 2012 No. 2594-R

“Russian Cosmic Activity in 2013–2020”

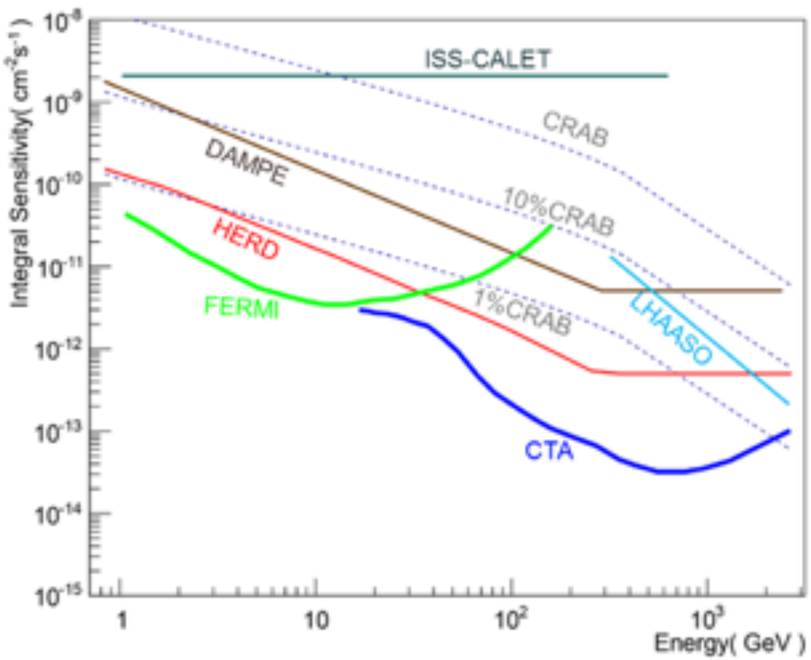
HERD Conceptual Design

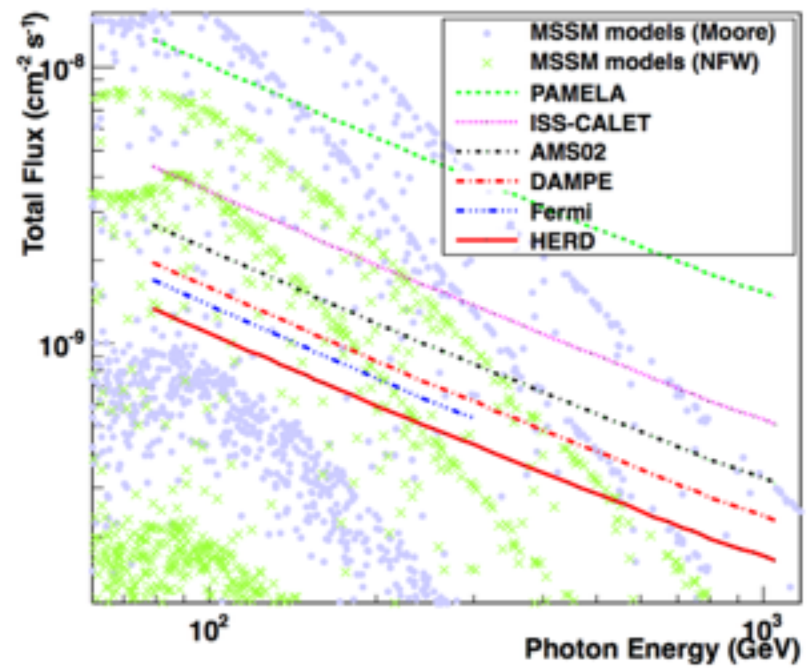


Zhang et.al, arXiv:1407.4866

Silicon-Tungsten Tracker + LYSO Calorimeter

Expected gamma-ray sky sensitivity of HERD





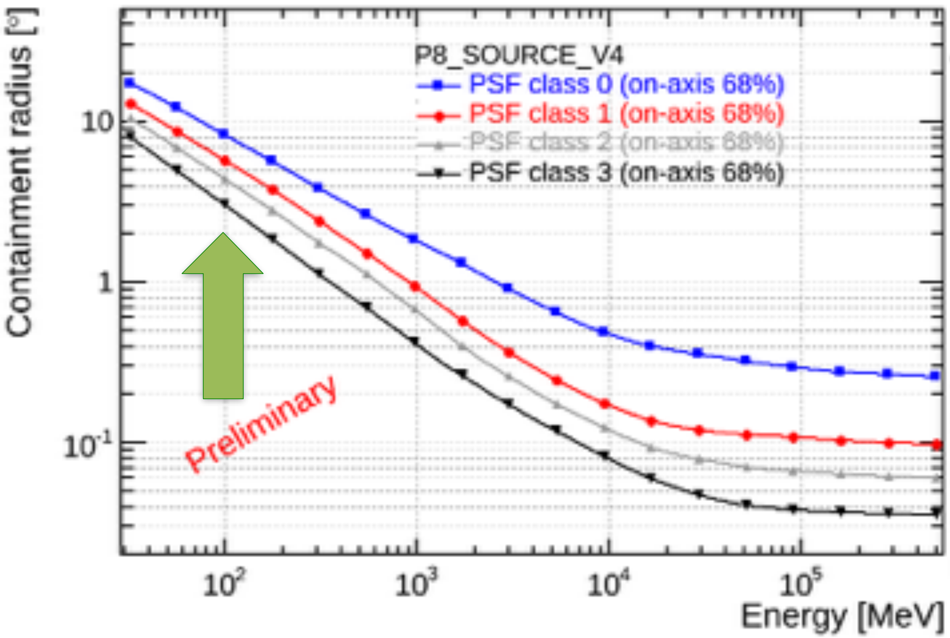
HERD 5σ continuum sensitivity for one year observation in comparison with all other missions with gamma-ray observation capability

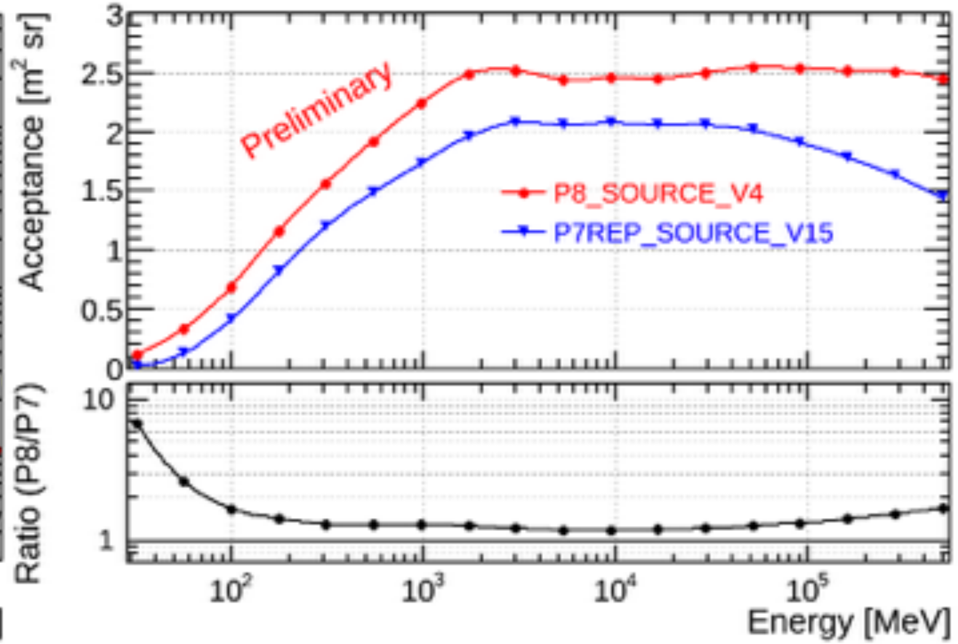
HERD one-year 5σ line sensitivity in comparison with predictions of different dark matter models

Sub-GeV detection is NOT improved

- **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 3°-8° @100 MeV after latest software (Pass 8) improvement

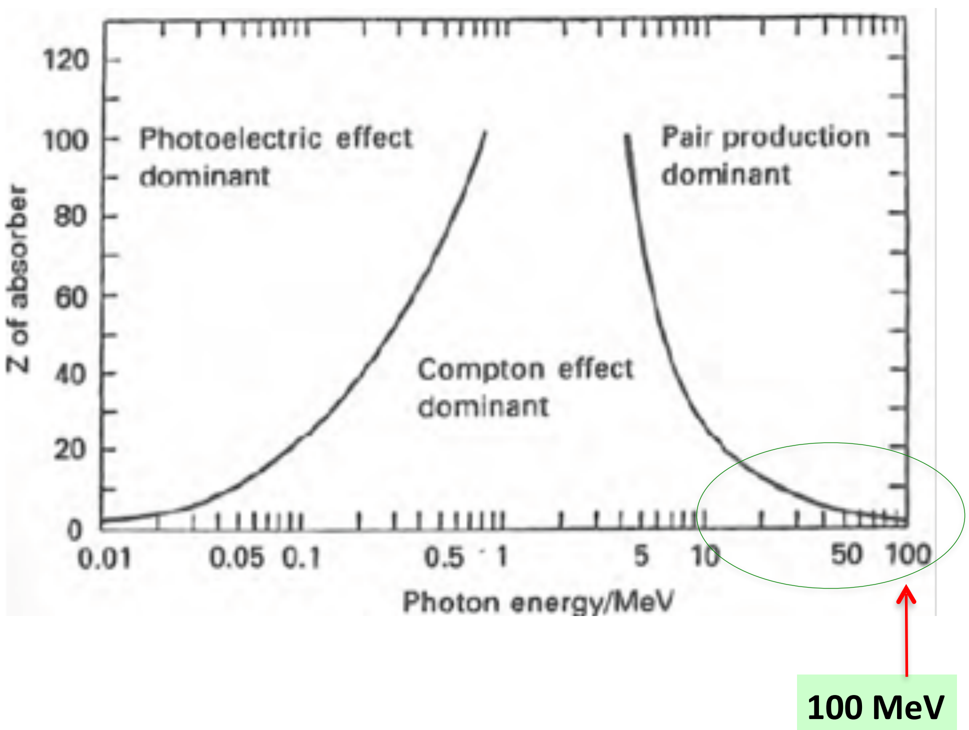


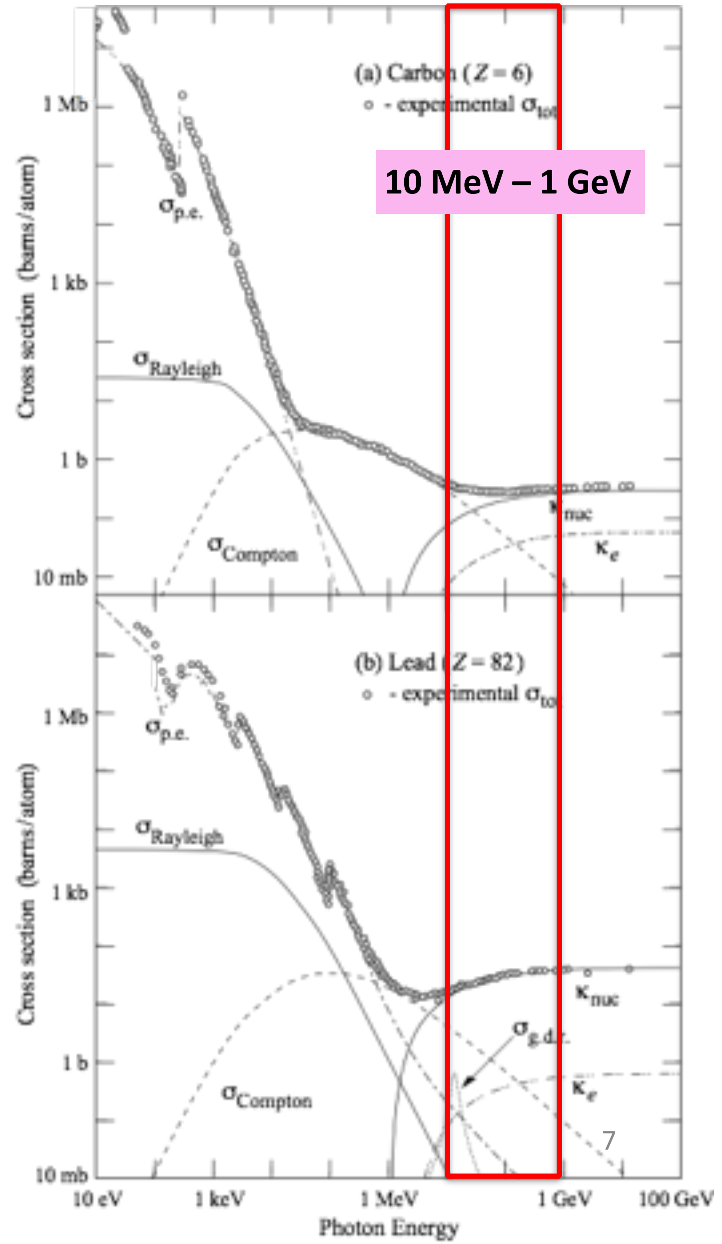


No planned missions to improve ~<GeV observations

Gamma-ray 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





PANGU
盤古

盤古氏

The first living being and the creator of the Universe from chaos in Chinese mythology.

Formless chaos

coalesced ↓

Cosmic egg

balanced ↓

Yin and Yang

woke up ↓

Pangu





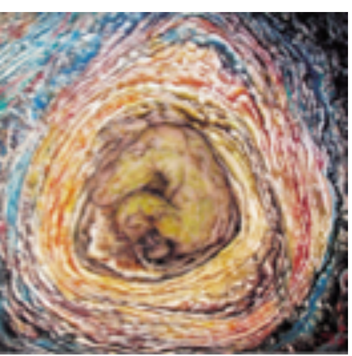


What does PANGU mean to me?

PAir productioN Gamma-ray Unit

PANoramic Gamma-ray Unit

Polarized ANd Gamma-ray Universe



Wu et. al, arXiv:1407.0710

Overview

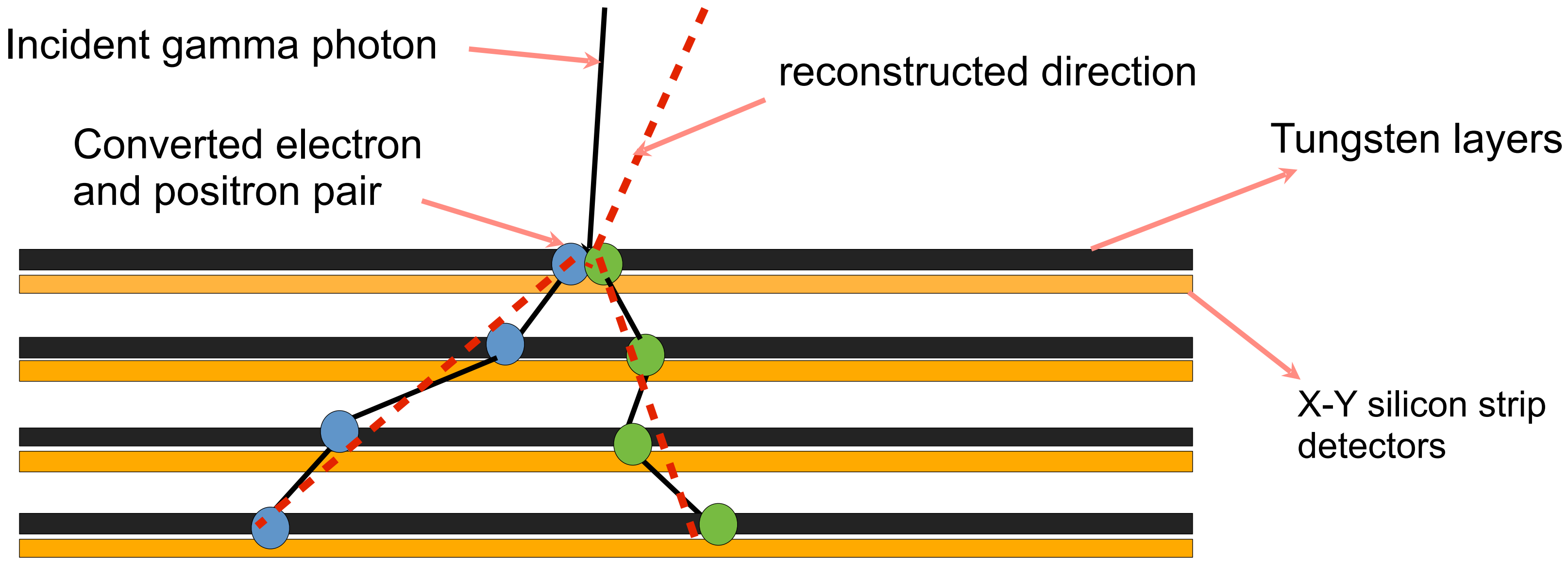
PANGU: PAir-productioN Gamma-ray Unit

- **Sub-GeV γ-ray telescope with unprecedented angular resolution**
  - Energy range of 10 MeV – 1 GeV with $\lesssim 1^\circ$ point spread function at 100 MeV
  - With polarization measurement capability
- **Innovative payload concept for a small mission**
  - Thin target material (SciFi or Si) with magnetic spectrometer
- **Wide range of topics of galactic and extragalactic astronomy and fundamental physics**
  - Complementary to the world-wide drive for a next generation Compton telescope (0.1-100 MeV)

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

Detection principle:

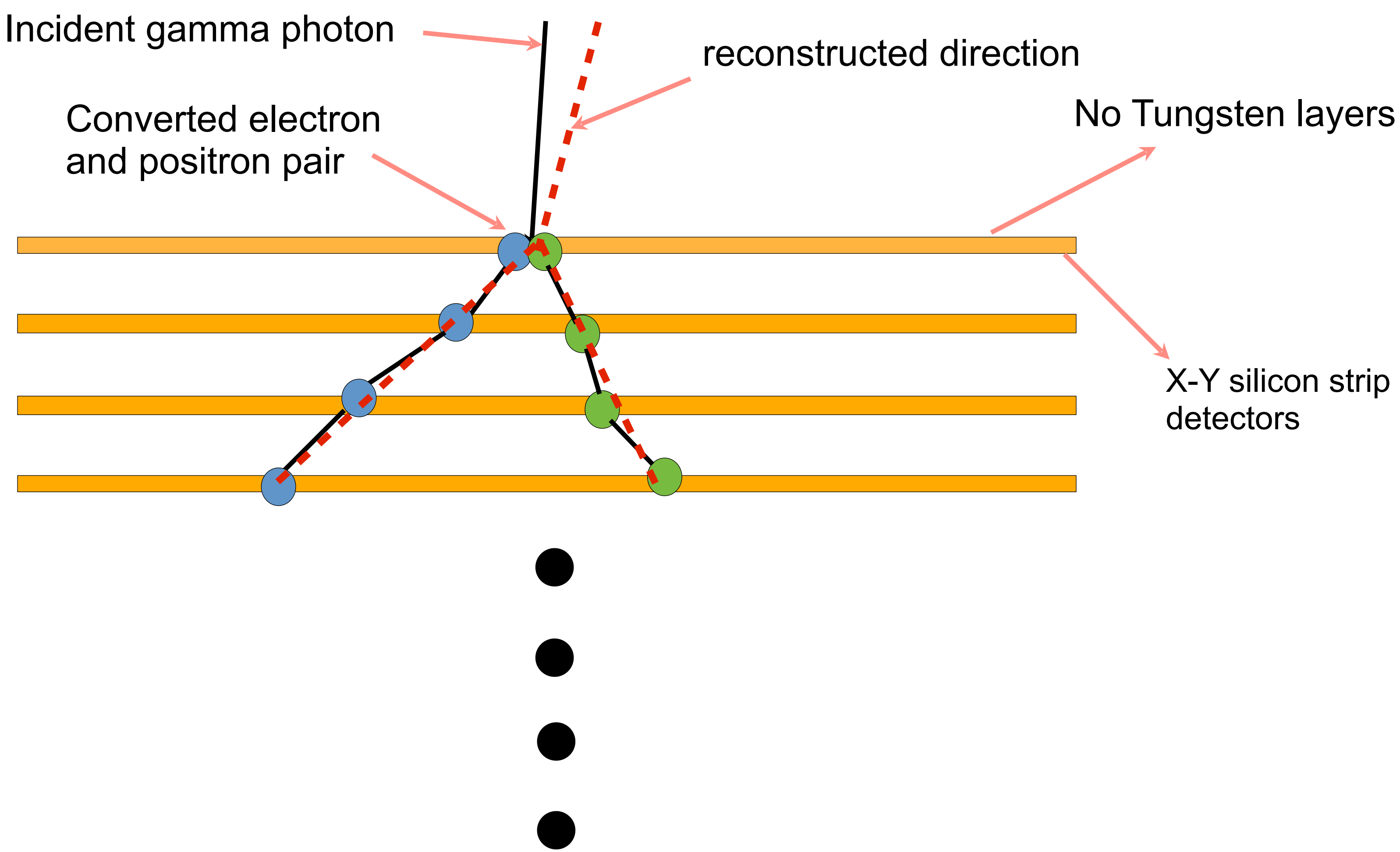
How Fermi-LAT detects gamma-ray photons



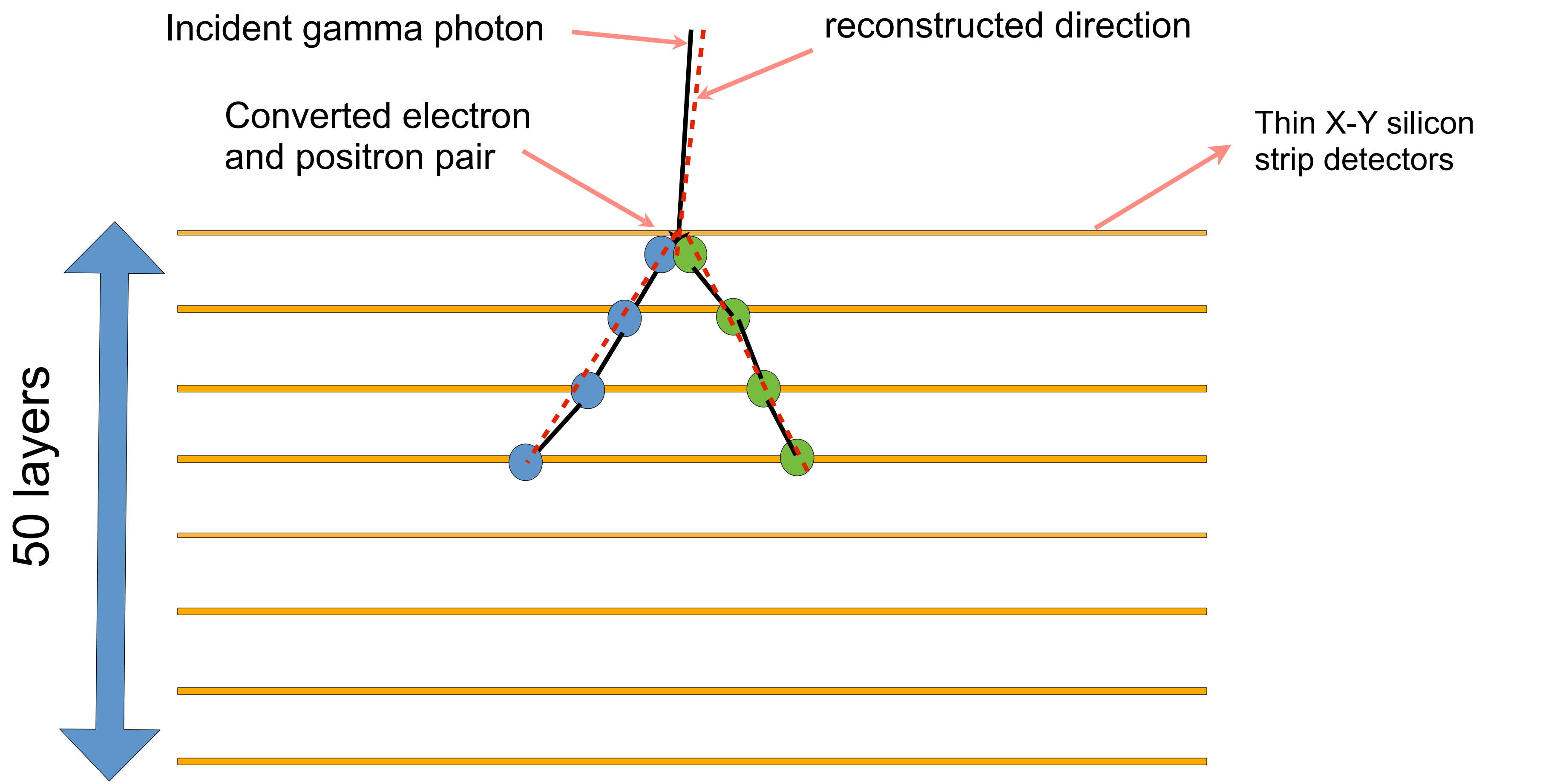
Converted electron/positron pair carries information about the direction, energy and polarization of the gamma-ray photon

Detection principle:

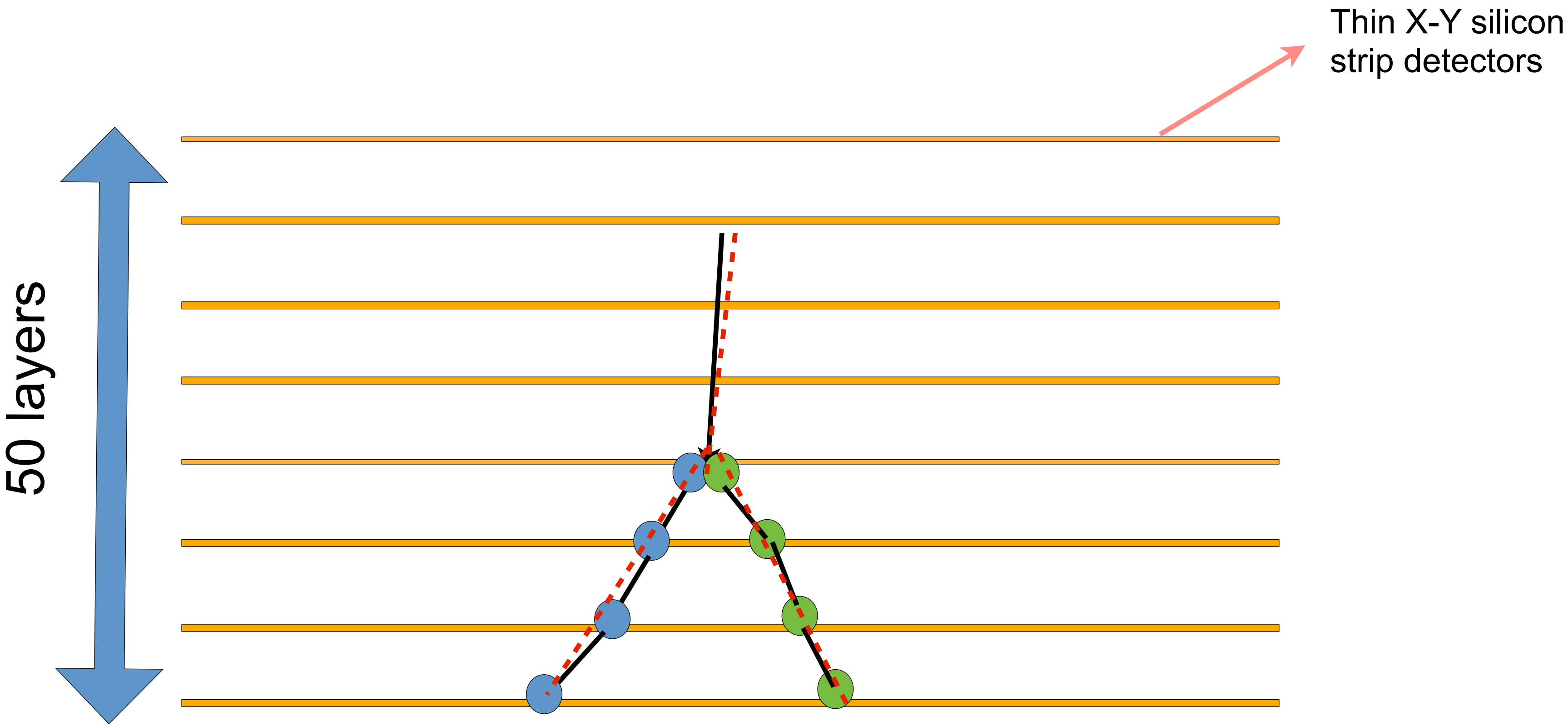
How PANGU detects gamma-ray photons



Detection principle:
How PANGU detects gamma-ray photons



Detection principle:
How PANGU detects gamma-ray photons



Response to the ESA-CAS small mission call for proposal

EUROPEAN SPACE AGENCY | ABOUT SCIENCE & TECHNOLOGY | FOR PUBLIC | FOR EDUCATORS

cosmic vision

esa

ESA | SCIENCE & TECHNOLOGY | COSMIC VISION

Missions
- Show All Missions

Cosmic Vision 2015-2025
- Cosmic Vision
- Candidate Missions
- M-class Timeline
- L-class Timeline

The four themes
- Planets and Life
- The Solar System
- Fundamental Laws
- The Universe

PLANNING FOR A JOINT SCIENTIFIC SPACE MISSION AN INITIATIVE OF THE EUROPEAN SPACE AGENCY AND THE CHINESE ACADEMY OF SCIENCES

FIRST ANNOUNCEMENT

1st Workshop
Planning for a joint scientific space mission
Chinese Academy of Sciences (CAS) - European Space Agency (ESA)
Chengdu (China)
25-26 February 2014

http://sci.esa.int/esa-cas-workshop
http://jm.nssc.ac.cn

Search here

4-Apr-2014 13:52 UT

Shortcut URL
http://sci.esa.int/jump.cfm?oid=53072

Related Articles
- First Announcement
- Boundary conditions for the candidate missions
- Practical information
- Programme
- List of posters

The PANGU Collaboration

- A growing international collaboration from China, Europe and US
  - 64 members from 21 Chinese institutes
  - 20 members from 11 European institutes (Switzerland, Italy, Germany, France, Netherlands)
  - 4 members from 4 US institutes

Strong interest and broad support from the Chinese and European astrophysics communities

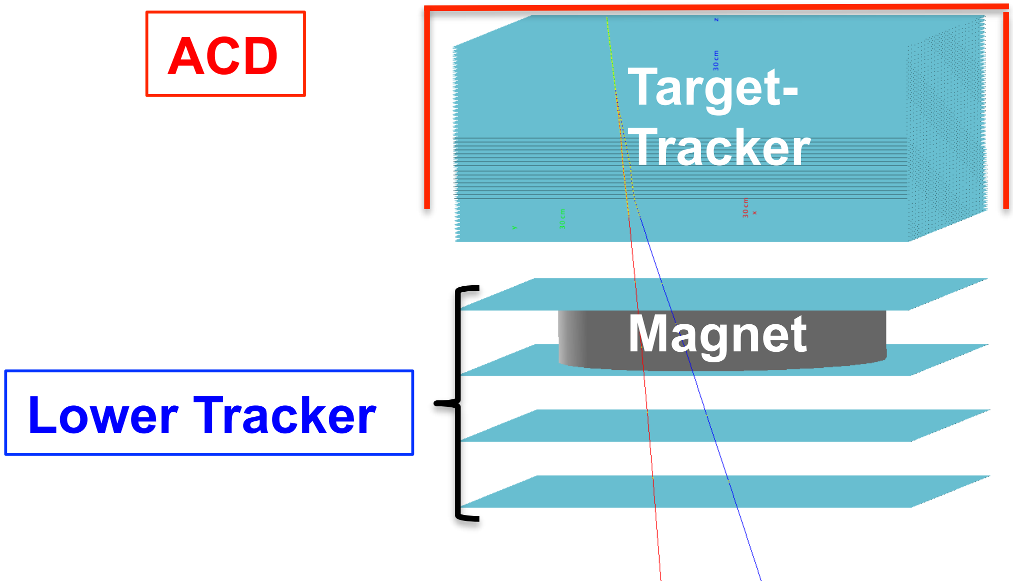
Conference presentations of PANGU: strong interest from community

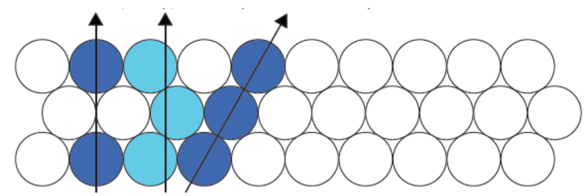
- **10th INTEGRAL Workshop**
- **SPIE Astronomical Telescopes + Instrumentation 2014**
- **International Conference on Particle Physics and Cosmology (COSMO-14)**
- **Debates on the Nature of Dark Matter (Sackler meeting 2014)**
- **High Energy Astrophysics Division 2014 Meeting**
- **Identification of Dark Matter and TeV Particle and Astrophysics**
- **Cosmic Frontier 2014 (Beijing)**
- **Zeldovich-100 International Conference**
- **224th American Astronomy Society Meeting**
- **APS Physics April Meeting 2014**
- **2014 IEEE Nuclear Science Symposium (November)**

Possible Detector Concepts

- **To achieve ≲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: 6×1m^3 vessels for 20 kg gas)**
  - **All-silicon, many optimized as Compton telescope (with calorimeter):**
    - **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**
    - **Gamma-Light: single-sided, distance 1 cm, 400 µm thick**
  - **Scintillating fiber**
    - **Previous concepts with converter: *SIFTER, FiberGLAST***
  - **PANGU: a new all-fiber or all-Si tracker light weight concept**

Sketch of a Possible PANGU Layout





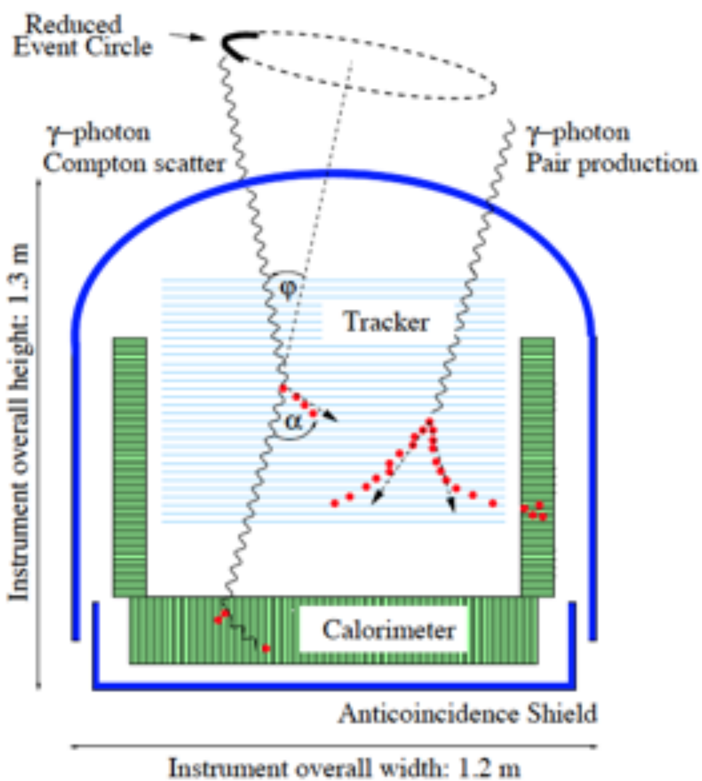
Target and magnet sizes can be easily scaled to fit with resource constraints!

- **3 sub-systems: target-tracker, magnet + lower tracker, Anticoincidence**
  - **Target-tracker : ~ 70 x 70 x 30 cm^3**
  - **Magnet: B=0.1 T, h = 10 cm, field in +y direction**
    - **Halbach array with 1.5 T NdFeB magnet, r_2 (r_1) = 27 (25) cm, 21 kg**
  - **Lower tracker: one X-layer above, one X-layer, and two X-Y layers below, ~10 cm between**
  - **Anticoincidence detector (ACD) on 5 sides**

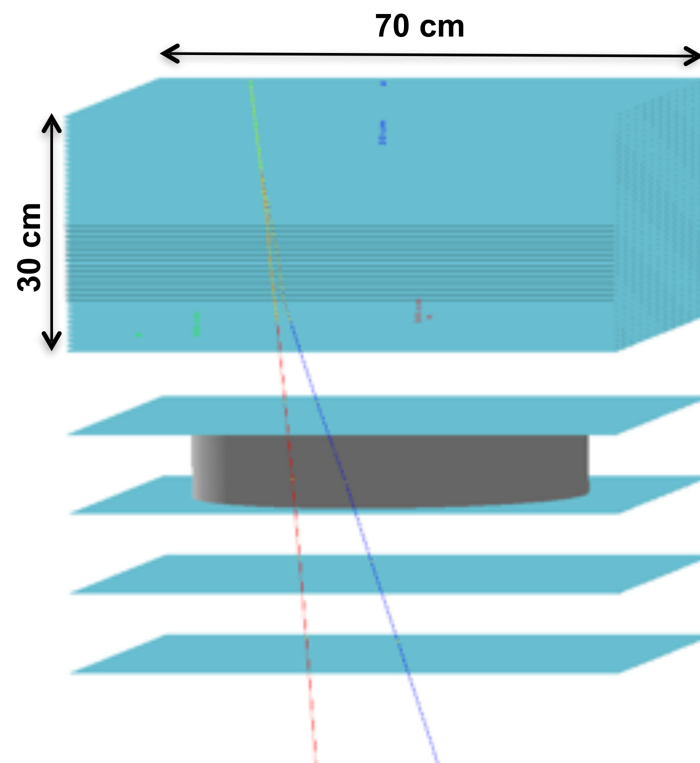
Compton vs Pair Telescope

- **Below 10 MeV, Compton scattering dominates**
  - **Detection rely on multiple Compton scattering -> need calorimeter**

MEGA ~650 kg



PANGU <100 kg



- **PANGU: dedicated pair telescope with thin tracking layers and no converter**
  - **Push the "thinness" to the limit for best PSF!**
    - **Silicon SSD of 150µm, or ribbon of 3-4 layers of ϕ=250µm fiber**

The Target-Tracker

- Possible layout
  - x-y double layers with 6mm inter-distance, 50 double layers
- Tracking layer with ~0.3% X_0 total (requirement)
  - Silicon: 2 single sided SSD of 150 µm each
  - SciFi: 2 layers of ~0.65 mm each (Polystyrene equivalent), each layer formed by a stack of 3 layers of ø=250 µm fibers, readout by SiPM
- Total tracker active material
  - Silicon: ~17kg (silicon density ~2.33 g/cm^3)
  - Fiber: ~25kg (polystyrene density ~0.9 g/cm^3)
- Both need support substrate
  - Probably more for Si: biasing, bonding, more fragile
- Baseline: ~50kg for fiber/silicon, support structure, FE electronics
  - Plus: 30 kg for magnet, 20 kg for the rest (ACD, DAQ, …)

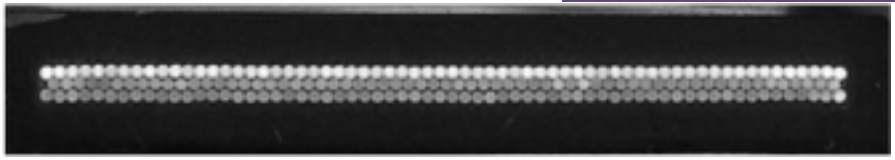
    $\Longrightarrow$ total weight ~100 kg
- Can be re-optimized to 60kg with reduced acceptance if limit is strict!

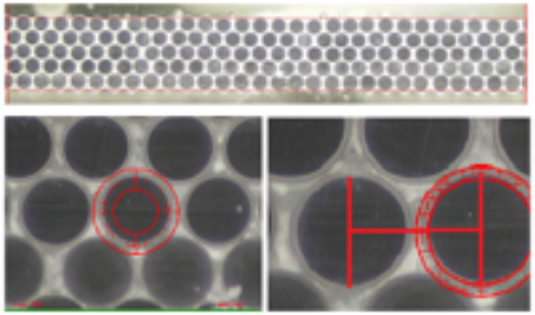
PANGU-Si vs PANGU-Fi

- Silicon and fibers trackers are both viable technologies
  - Challenges are mainly engineering: optimal use of the limited weight (ultra-light module) and power budgets (low power ASICs)
- Silicon has been successfully used in similar space missions
  - Fermi, AGILE, Pamela, AMS-02, …

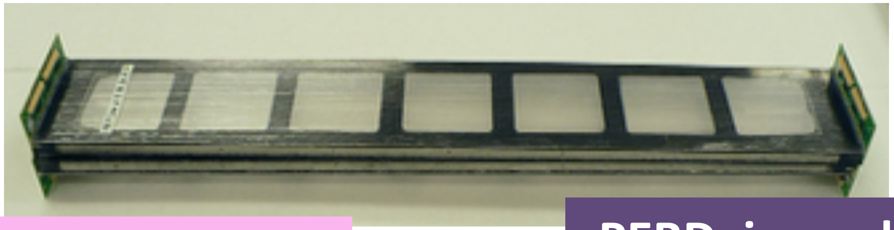
- Fiber is cheaper, less fragile, more flexible geometry, but the technologies of scintillating photon detector (SiPM) and readout ASICs are newer
  - Recent developments in high energy physics, eg. LHCb, Mu3e, …
    - Also in space: balloon prototype PERDaix of PEBS
  - Position resolution ~70 μm can be achieved

Mu3e module





NIMA 628(2011)403



PERDaix module

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 ~300k channels
  - Si strip detector pitch ~250µm, fibers can be readout by SiPM of 250 µm pitch
- Current Si readout ASIC consumes ~0.2mW/channel
  - Push for ~0.1mW/channel with some R&D
  - Similar for readout ASIC for SiPM
    - Total ASIC power ~30-60 W
- Total power consumption of payload 60-90 W
  - Including CPU for online selection

Satellite Platform and Mission Concept

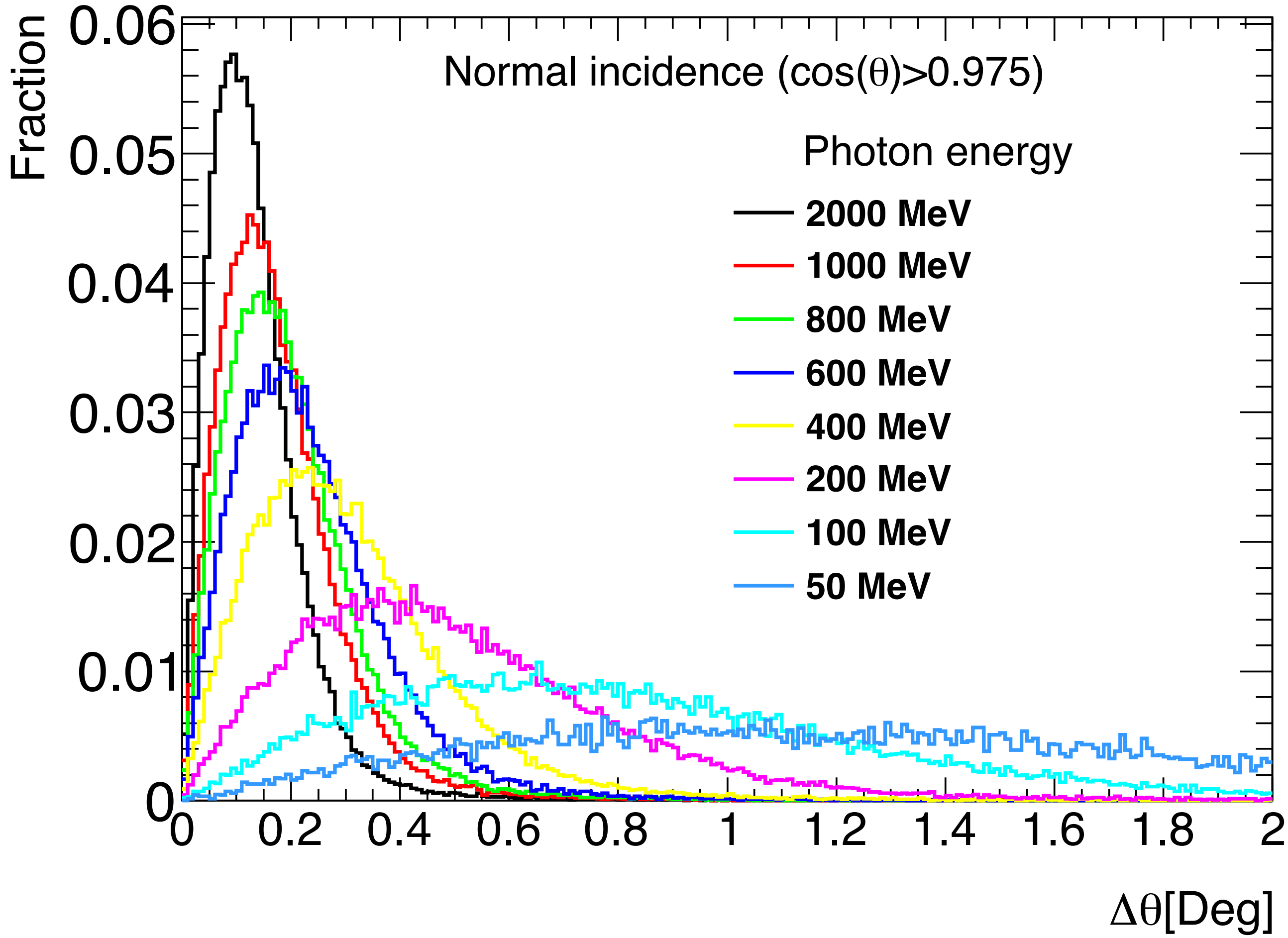
- Satellite platform
  - Temperature stability
    - Low temperature preferred for magnet and SiPM
  - Magnetic shielding
    - For satellite navigation system, not for payload
  - Pointing stability and precision
    - ~0.1° is sufficient
- Mission concept
  - Low earth orbit
  - All-sky survey and pointed observations
    - With possibility to rotate the payload to study systematic effect of polarisation measurement
    - GRB fast alert downlink
  - Minimum lifetime three years
  - Science data open to the world community

Potential Collaboration Projects

- Many interesting and challenging topics for collaboration
  - Science study: Science potential of a high resolution detector
  - 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, timing
  - 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

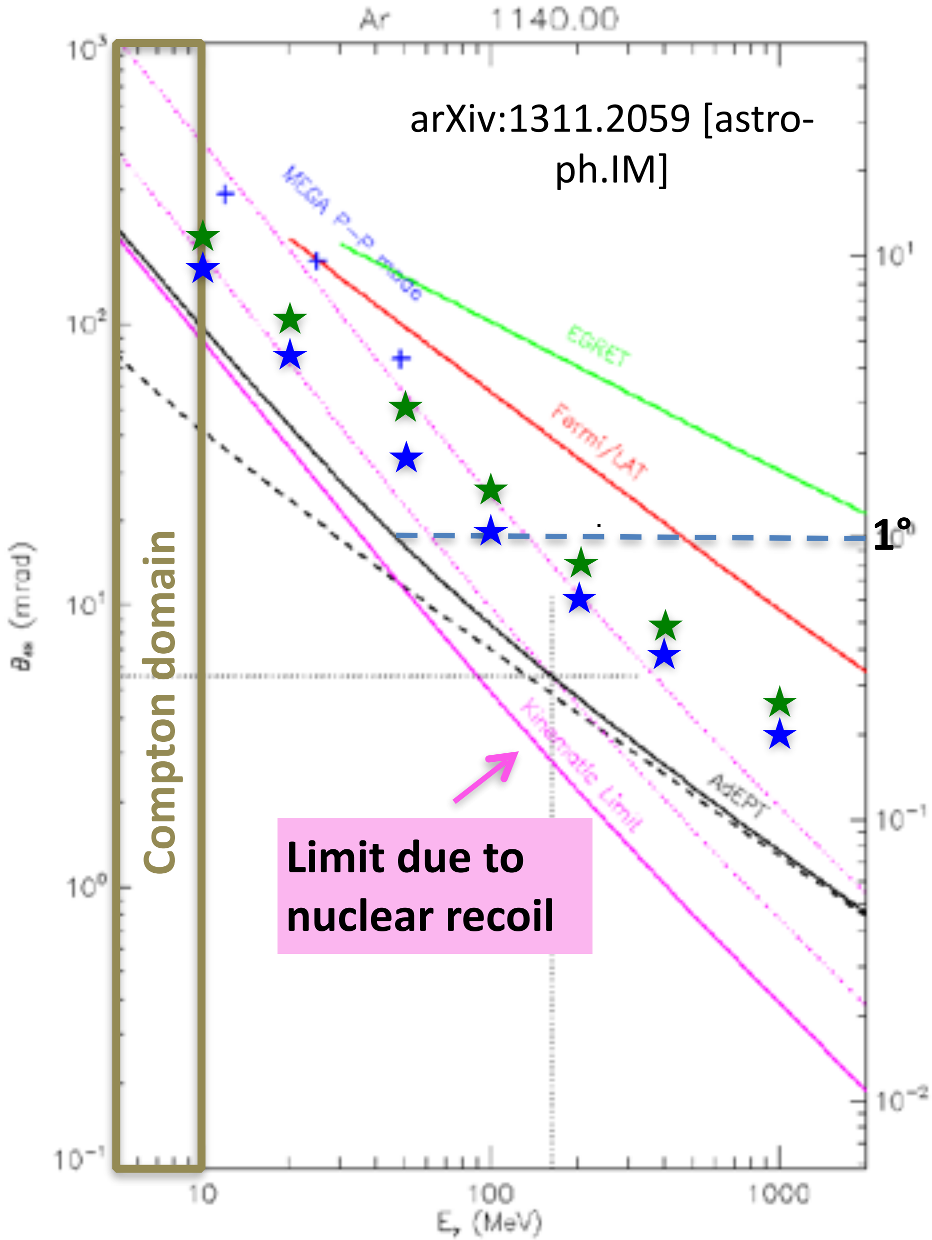
Photon Angle Measurement

- **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

Angular resolution of pair telescopes



★ PANGU: both tracks in target

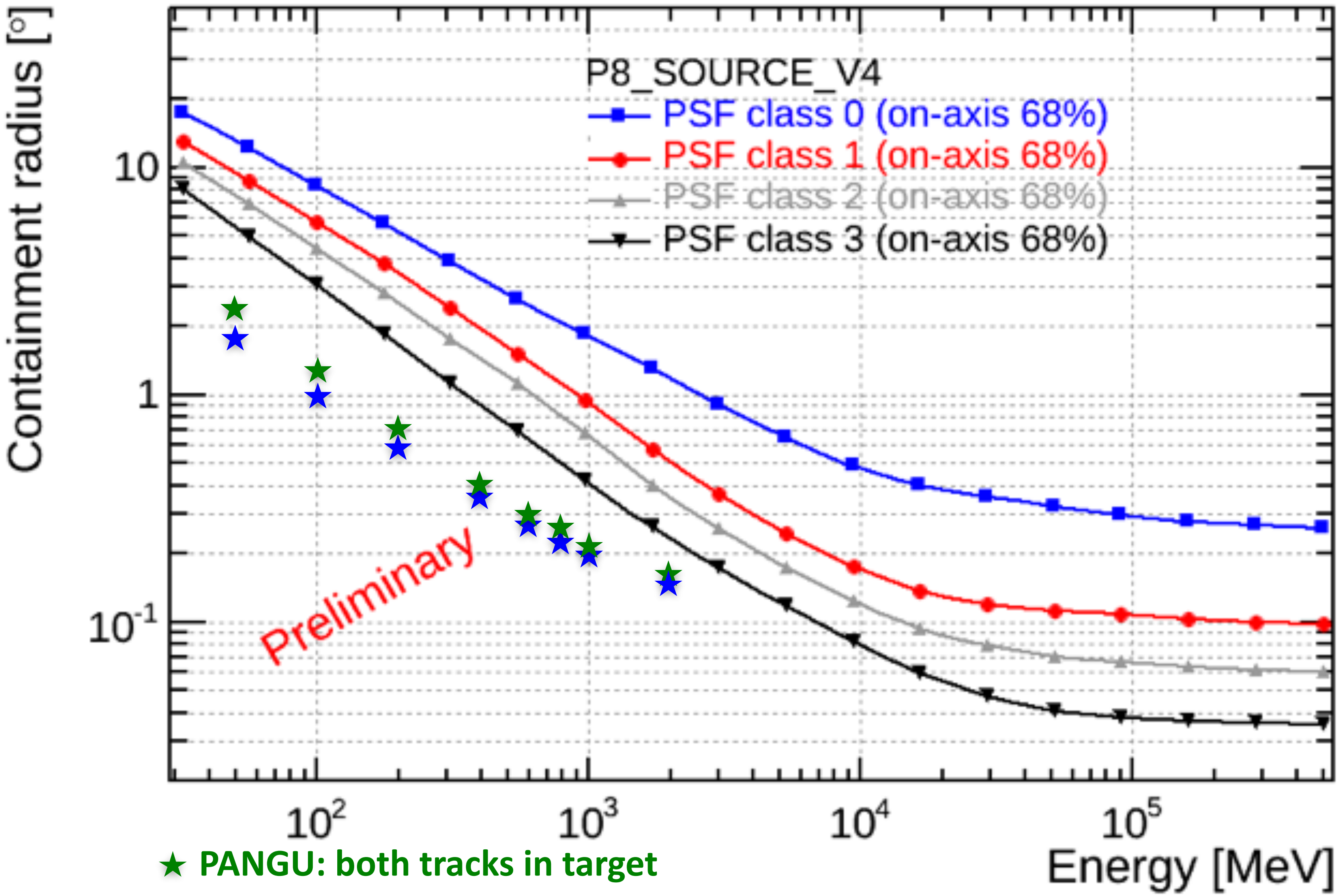
★ PANGU: both tracks in spectrometer

- Geant4 simulation with 150 μm thick single-sided Si detector, 242 μm pitch
  - ⟹ position resolution ~70 μm
- Results are preliminary

Very limited energy measurement if no tracks in spectrometer

- indication of energy with opening angle and dE/dx in tracker

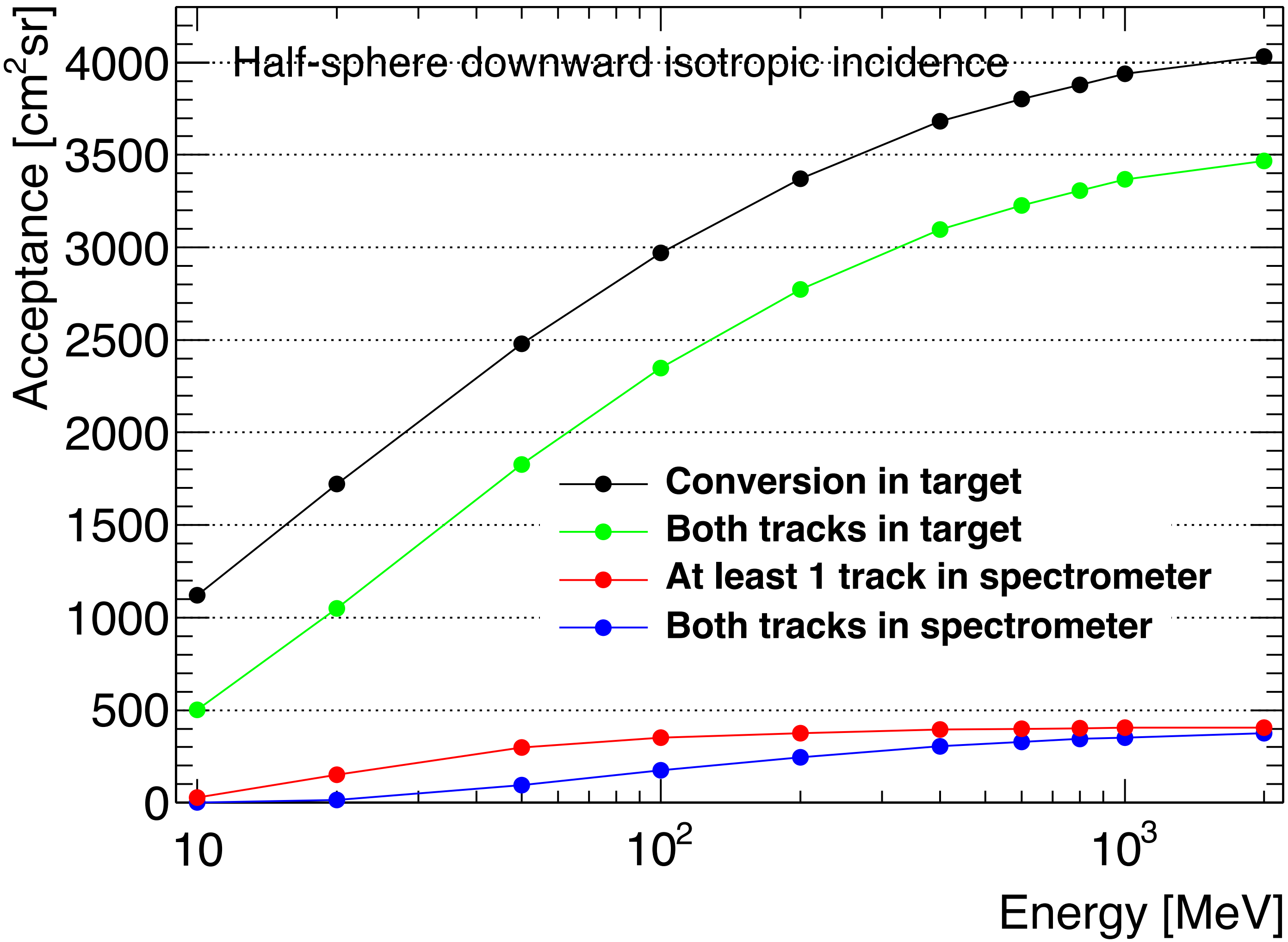
PSF Comparison with Fermi Pass 8



★ PANGU: both tracks in target

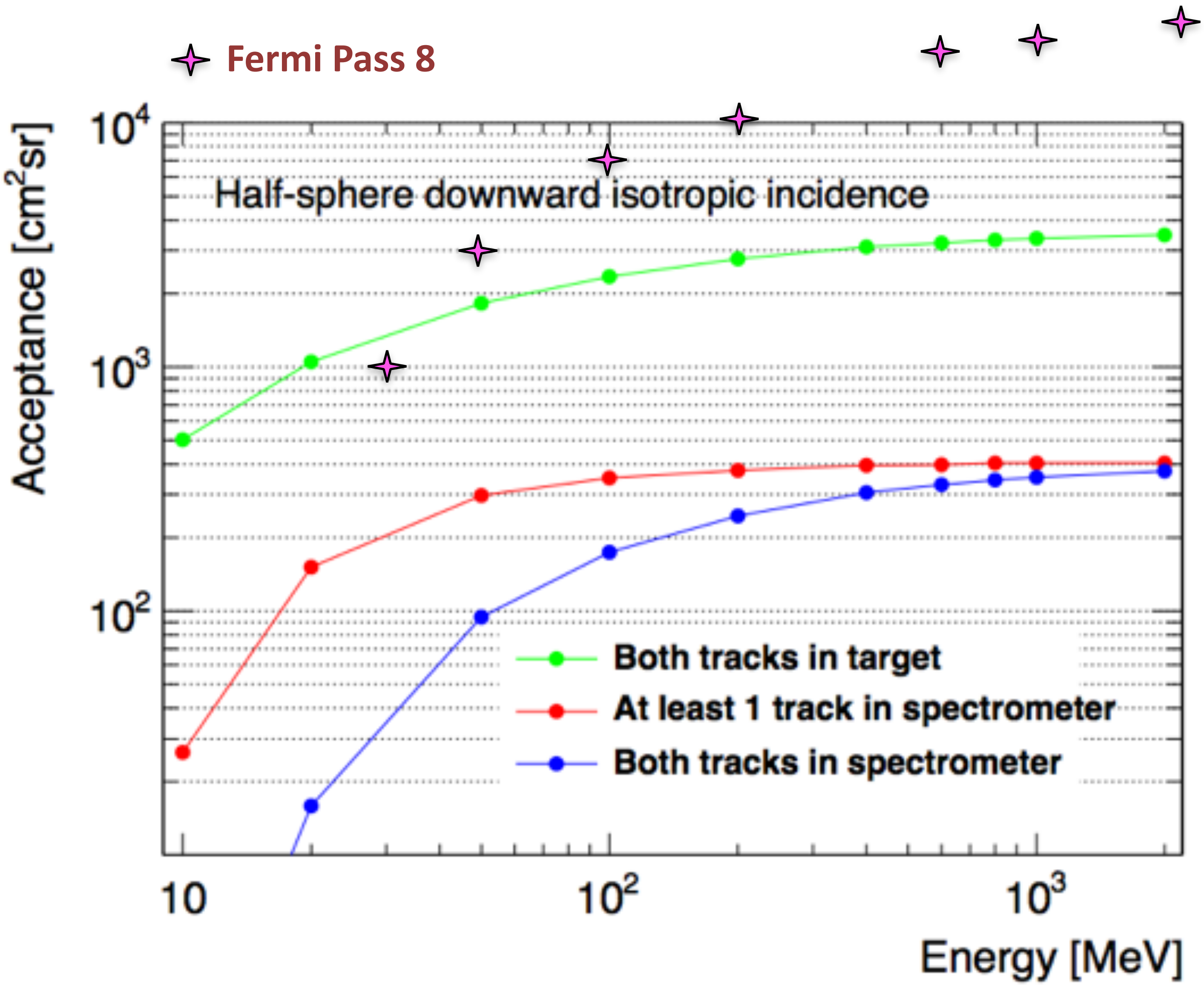
★ PANGU: both tracks in spectrometer

Acceptance

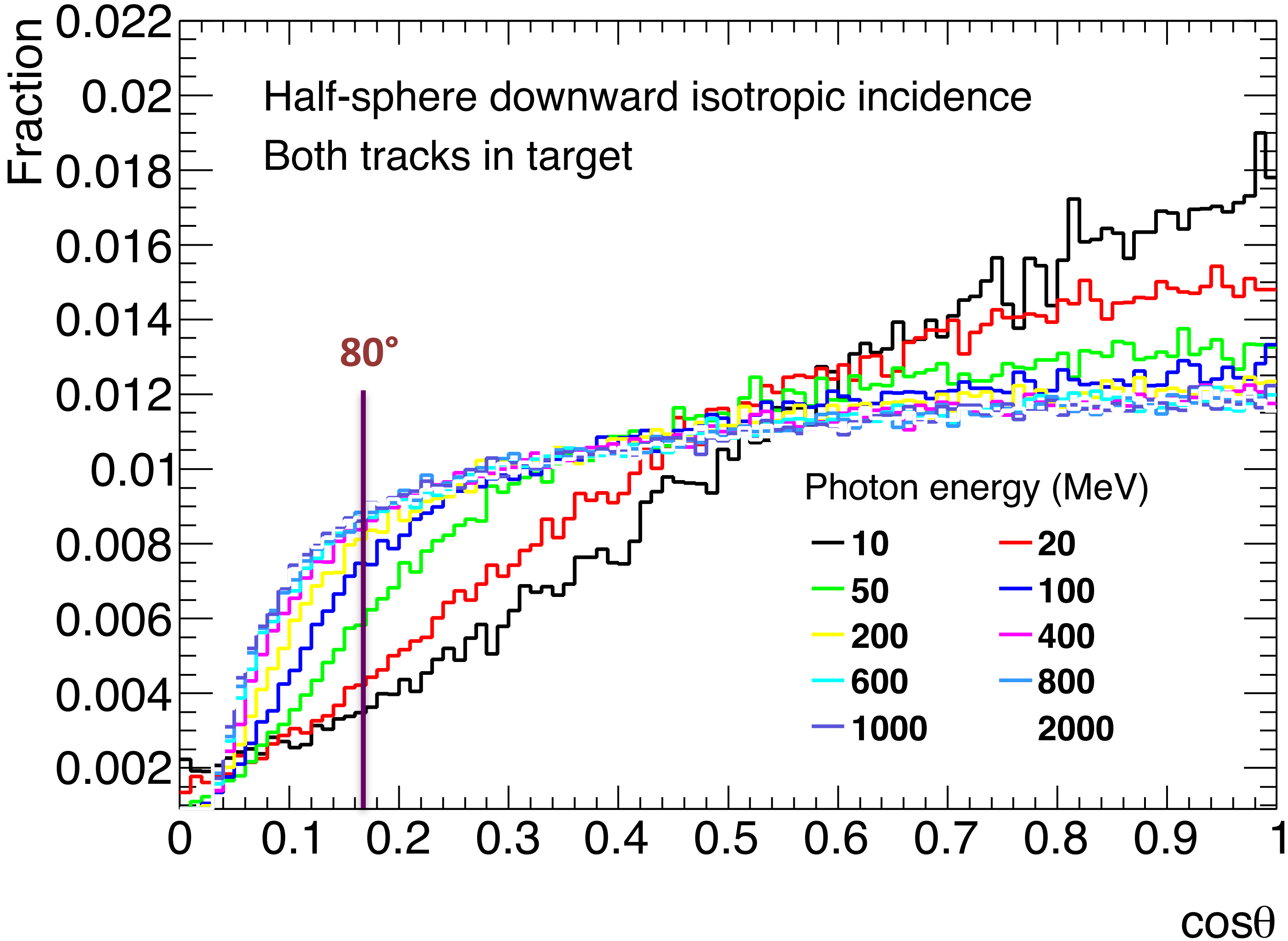


Half-sphere downward isotropic incidence
Acceptance [cm^{2}sr]
4000
3500
3000
2500
2000
1500
1000
500
0
10
10^2
10^3
Energy [MeV]
Conversion in target
Both tracks in target
At least 1 track in spectrometer
Both tracks in spectrometer

Acceptance Compared to Fermi Pass 8



Angular Relative Acceptance

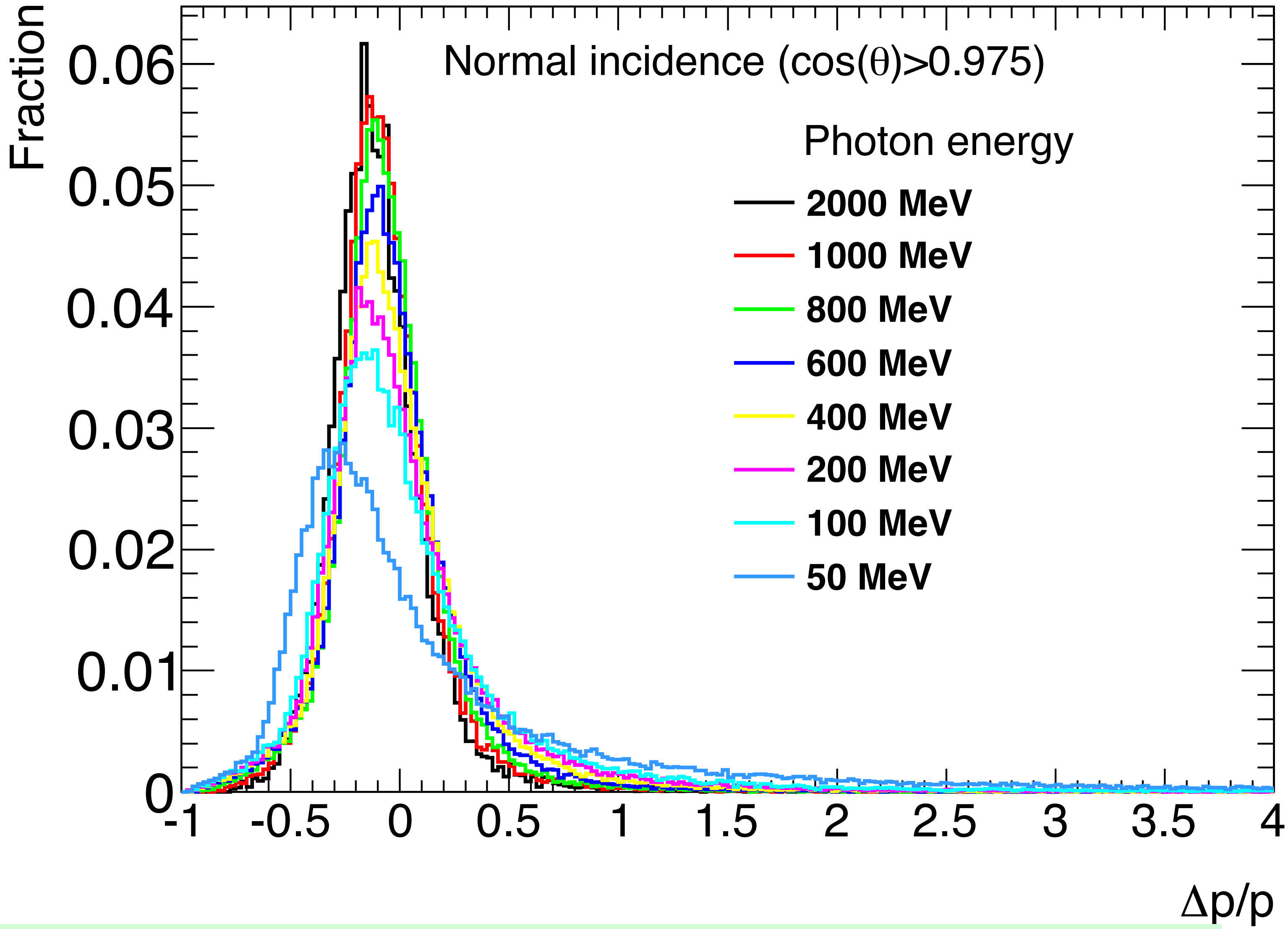


Large FOV for both tracks in target (limited energy measurement)

How about the energy measurement?

- Standard way is to use a calorimeter under the tracker
  - Eg. AGILE mini-calorimeter, CsI, 1.5X_0, 37.5x37.5x3 cm^3, ~30 kg total, ~20kg active
    - Limited energy resolution ~70% at 100 MeV because of leakage
    - For PANGU (50x50x3 cm^3) would need ~53 kg for calorimeter
  - Eg. GAMMA-LIGHT calorimeter (50x50x4.5 cm^3) $\Longrightarrow$ ~80 kg total
  - Calorimeter not optimal if payload < 100 kg
- The PANGU approach: magnetic spectrometer with permanent magnet
  - Magnet below the tracker-target (light-weight configuration)
    - Magnet can be independently optimized
    - But limited FOV
  - Complication
    - Need to minimize stray field and shield sensitive satellite equipment

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



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

PANGU v.s. Fermi

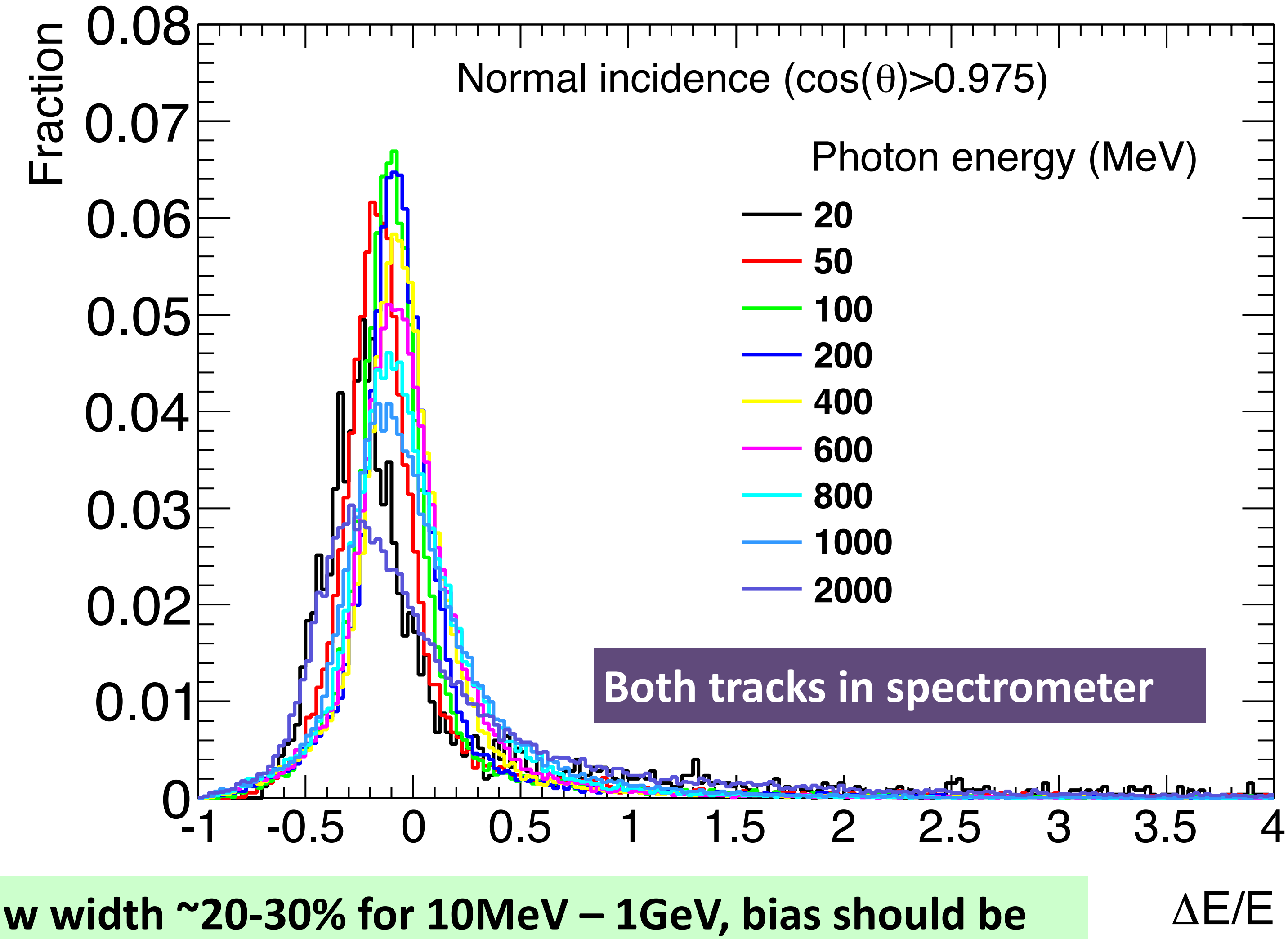
$~1 billion, 4,300 kg

30 MeV   300 MeV   3 GeV   30 GeV   300 GeV

30 MeV   300 MeV   3 GeV   30 GeV   300 GeV

~$100 million, ~300 kg (<100 kg payload)

Energy Resolution

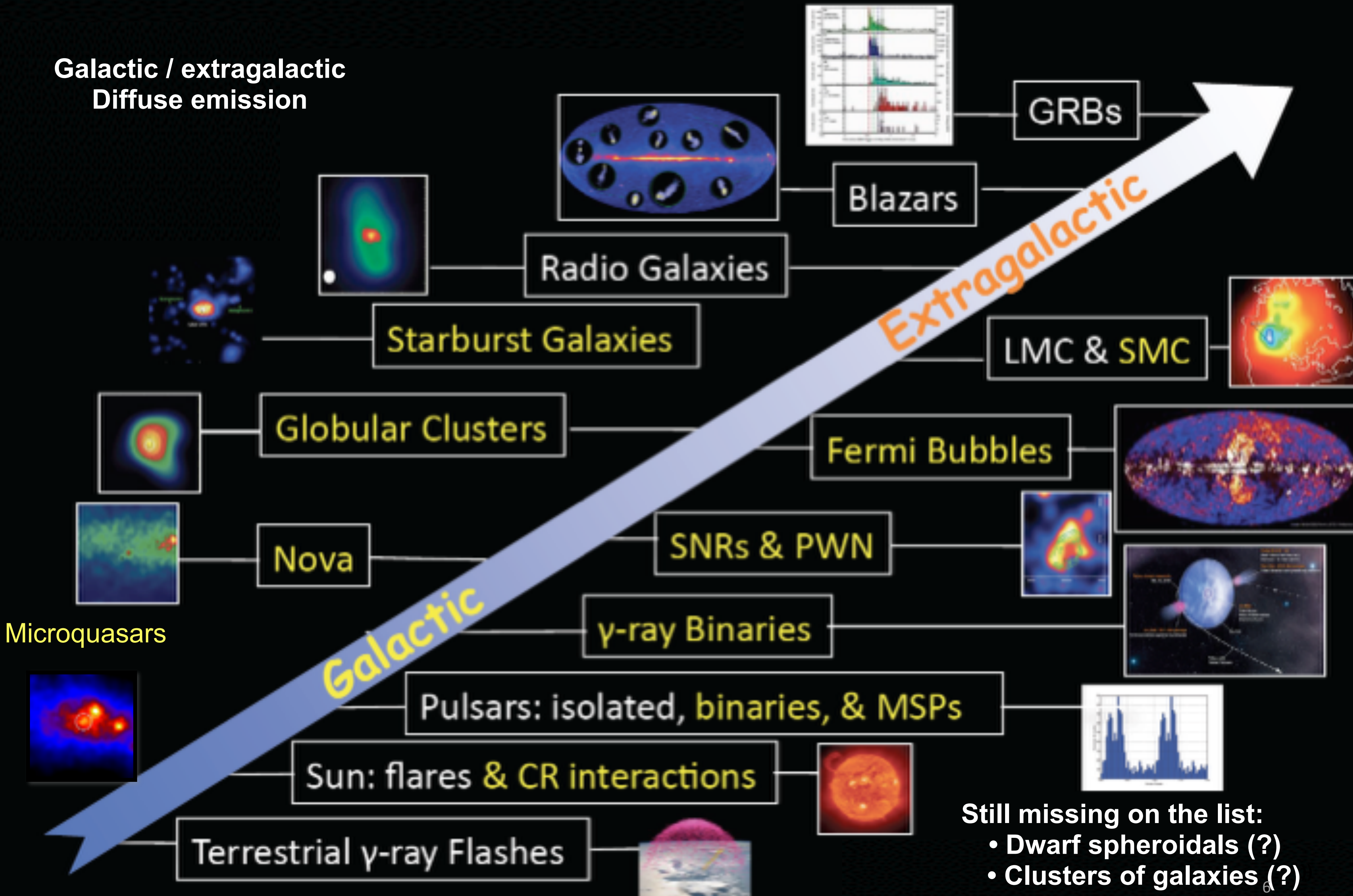


Raw width ~20-30% for 10MeV – 1GeV, bias should be corrected, e.g.. with energy measured in tracker

Scientific Objectives: highlights

- Precise mapping of the gamma-ray sky at sub-GeV with high angular resolution
- Origin and acceleration of high energy cosmic rays
- Indirect dark matter search
- First detection of sub-GeV polarization
- Full-sky monitoring of a variety of soft gamma-ray transients (GRB/AGN/Solar flare/Terrestrial)
- Synergic multi-wavelength campaign
- Lorentz invariance/Baryon asymmetry in early universe

The sub-GeV sky is rich!



Still missing on the list:

- **Dwarf spheroidals (?)**
- **Clusters of galaxies (?)**

Conclusions

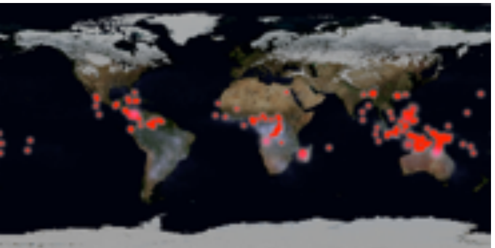
- **PANGU is an *unique and timely opportunity* for high energy astrophysics. It will resolve and monitoring the sub-GeV sky with unprecedented spatial resolution, separating diffuse gamma-ray emission from point sources**
  - **PANGU science is not “incremental science”, it will lead to fundamental discoveries and understanding.**
- **PANGU is synergic with DAMPE, HERD, CTA, Gamma-400 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**
  - **TRL6-7 for silicon tracker**
  - **TRL5 for scintillating fiber tracker**

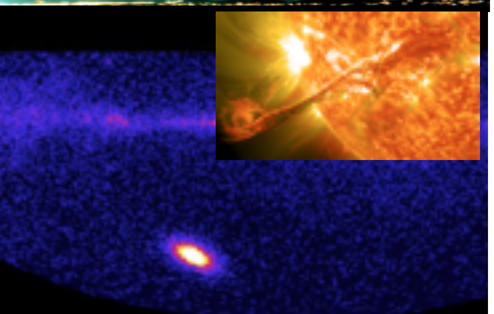
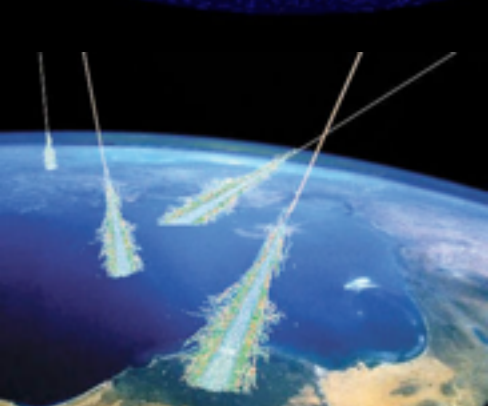
The idea is easy to scale up!

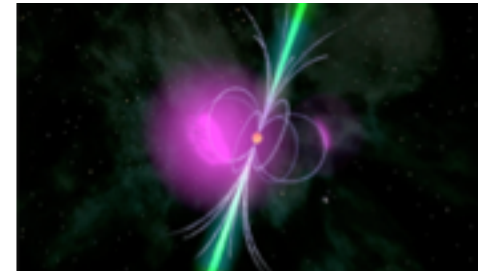
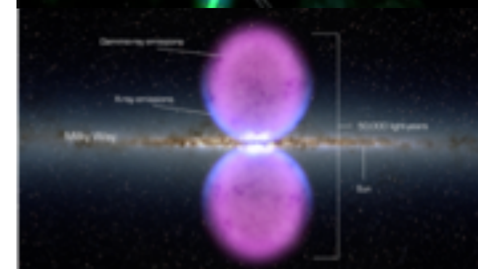
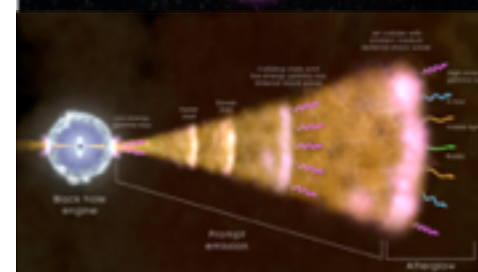
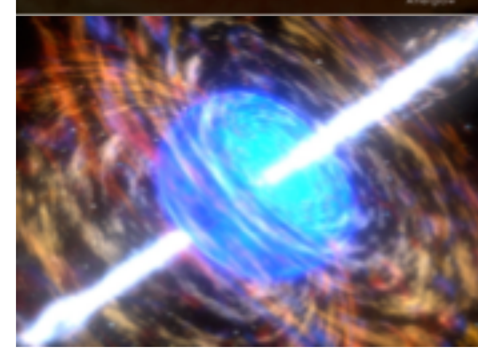
- Someday, 60 kg -> few tons, returns you a factor of ~100 better than Fermi at sub-GeV! Pushing the limit of GeV astronomy

That's exciting!

Thank You!



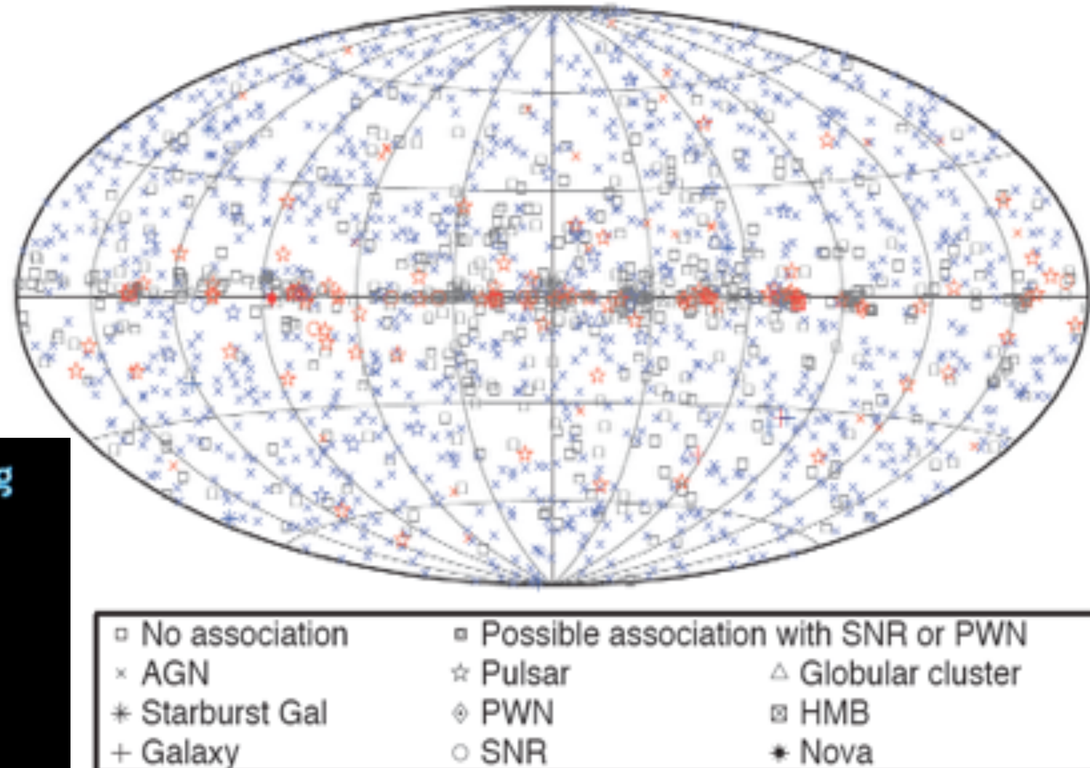
Welcome to join!

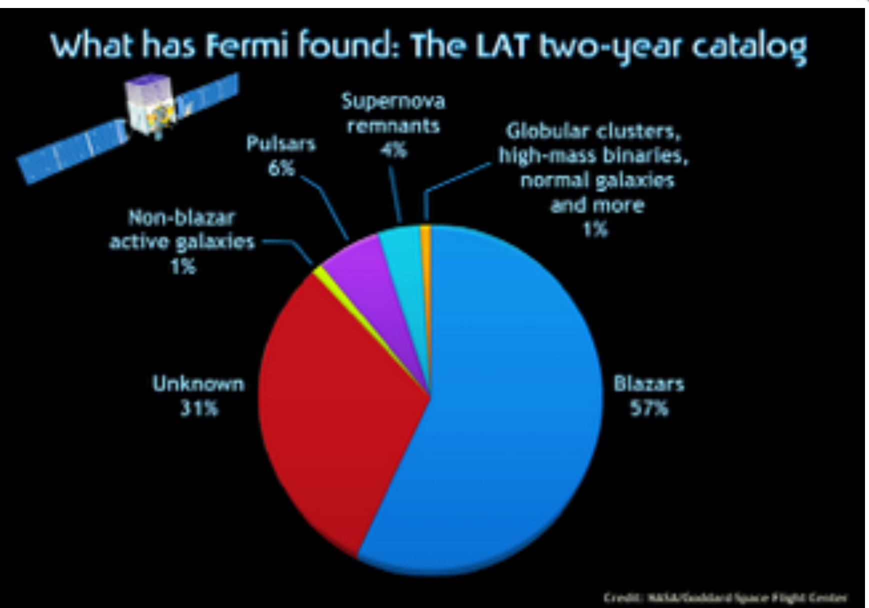
PANGU: All-sky explorer for the 10 MeV – 1 GeV Universe

A variety of sources, big discovery space!

PANGU is going to extend the spectrum of these sources to 10 MeV, and find new soft spectrum gamma-ray sources!

The Second Fermi LAT Catalog



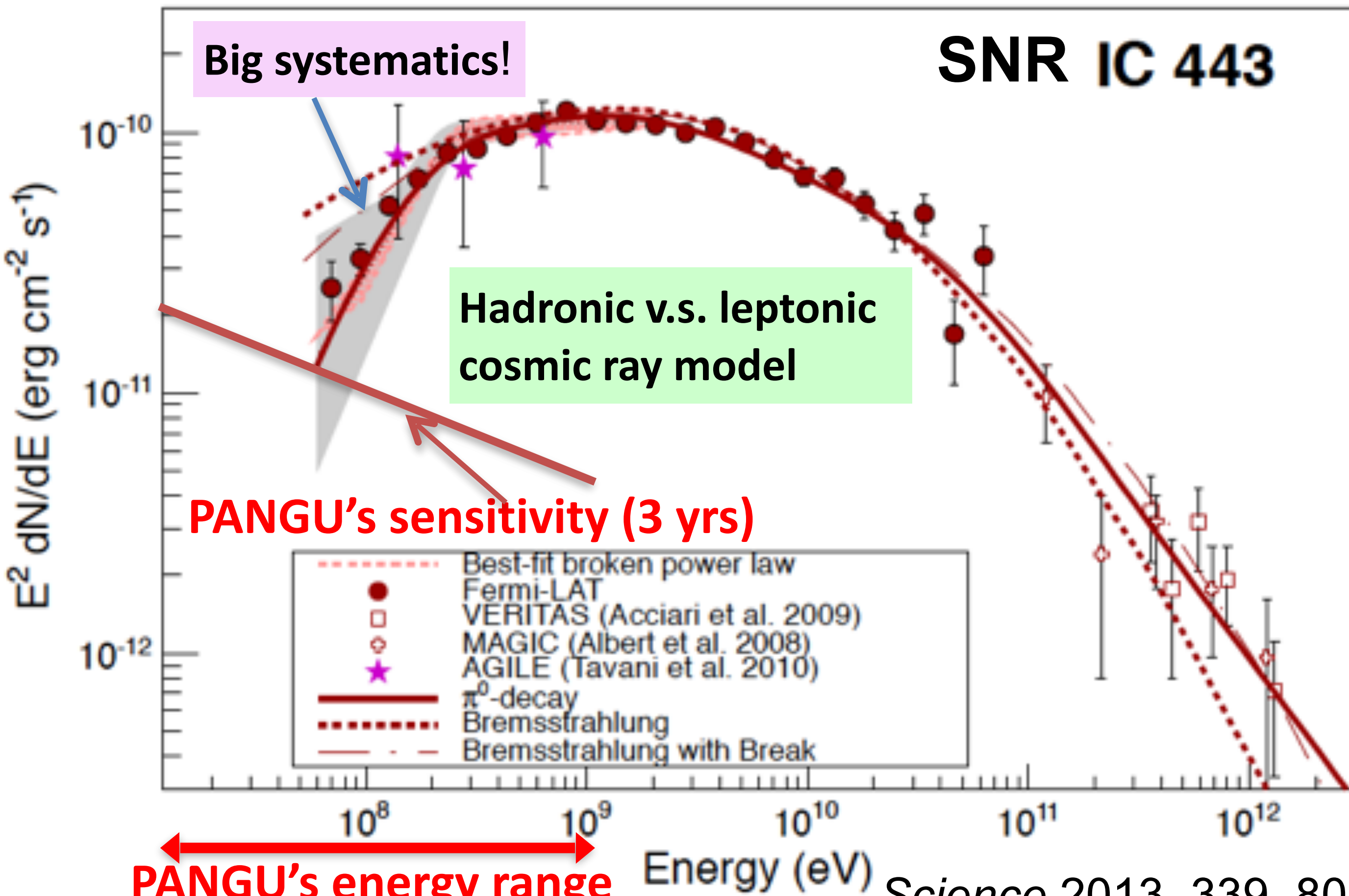


~1/3 are "unassociated" sources with unknown nature!

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

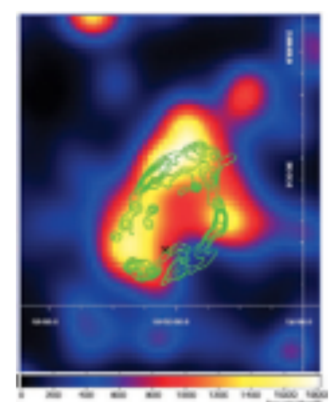
Supernovae Remnants and Particle Acceleration

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 ~5 times better PSF!**

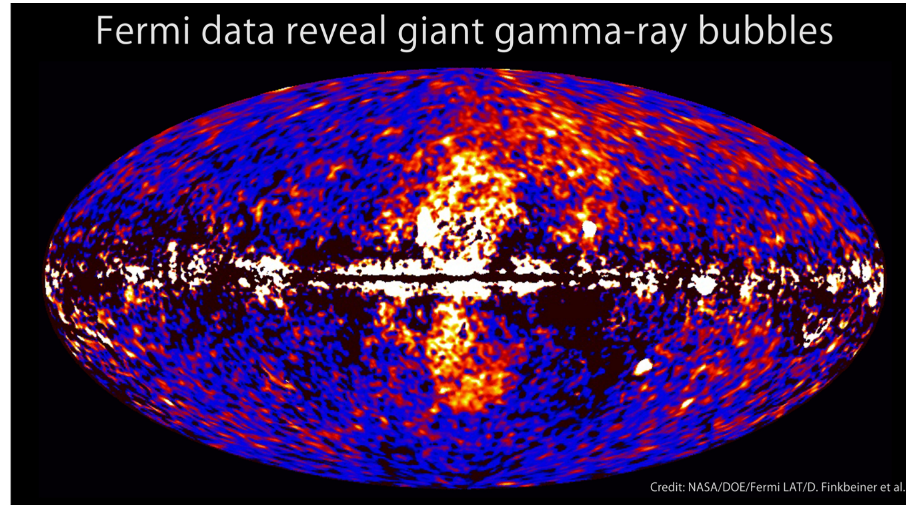


W44 Fermi

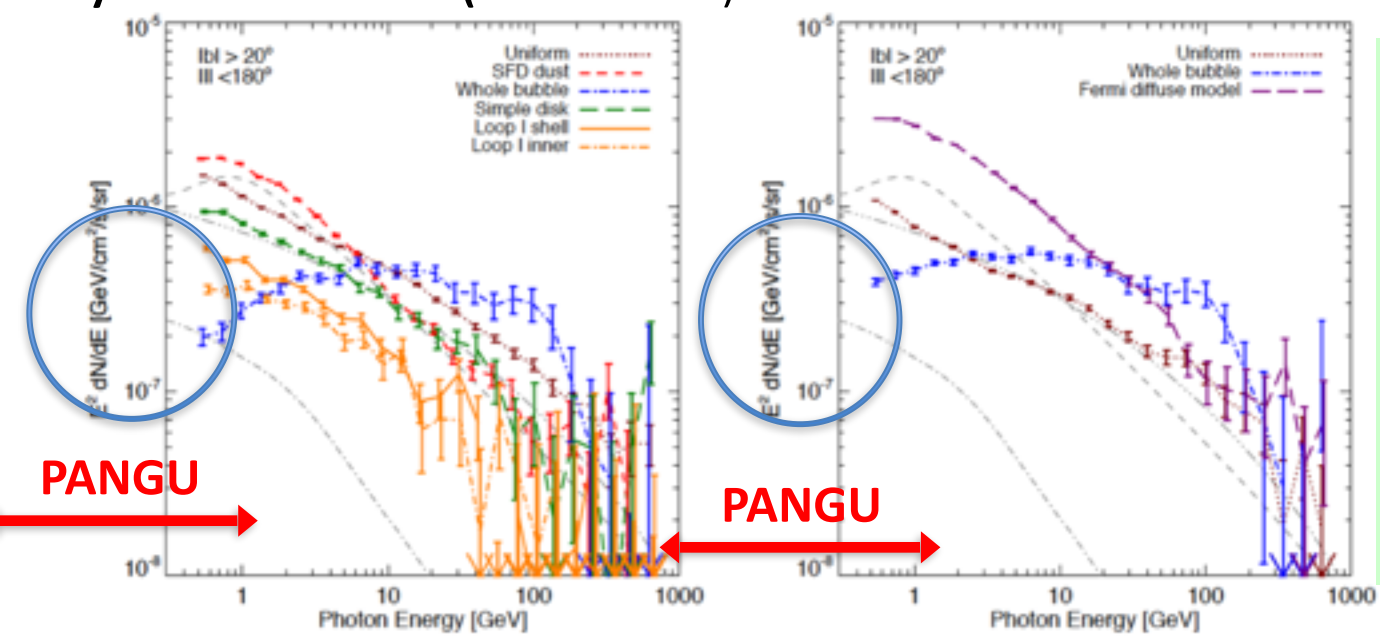
Fermi Bubbles --- Hadronic v.s. Leptonic

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**



Systematics limited (NOT counts!)

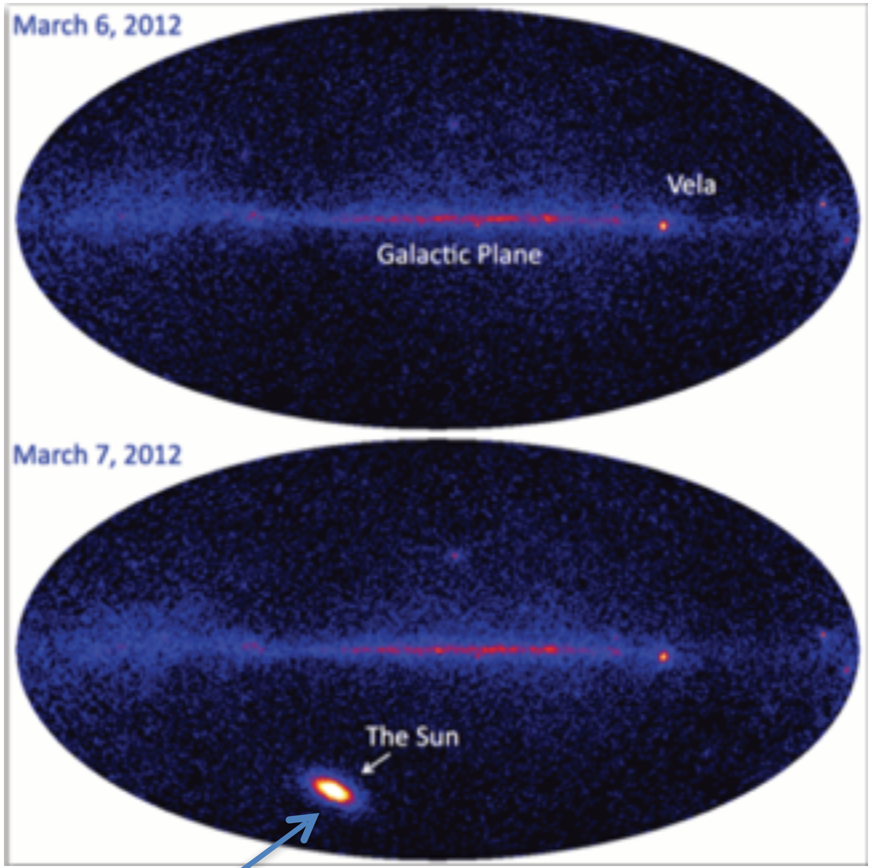


Measurement of < GeV cutoff is the key to infer the cosmic ray electron/ proton spectrum at low energy

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

Gamma-ray Emission from Solar Flares

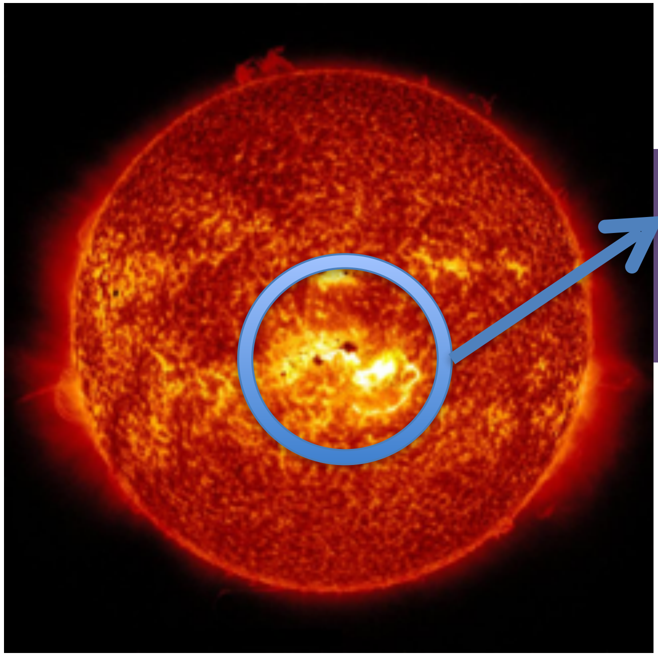
LAT 1 day all sky data >100 MeV



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

Bright solar flares have been detected by Fermi

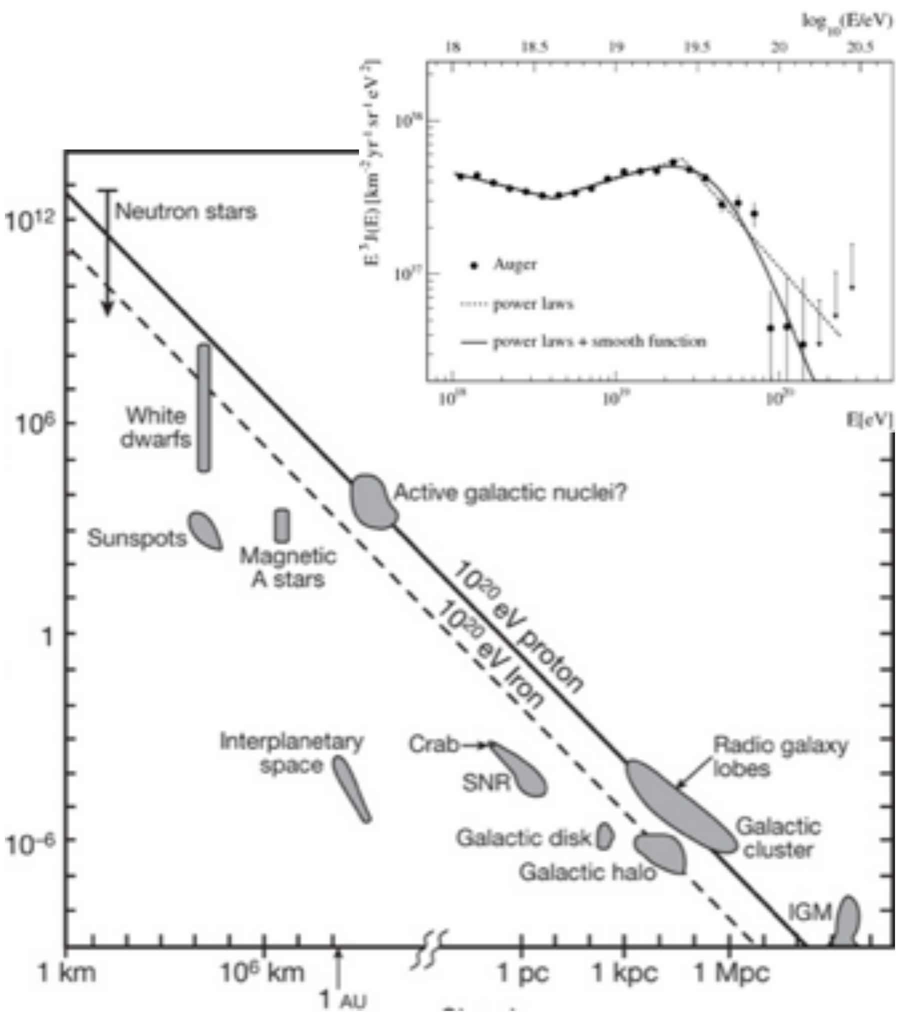
- **1000 time the flux of the steady Sun**
- **100 times the flux of Vela**
- **50 times the Crab flare**
- **High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours**
- **Softening of the spectrum with time**



PANGU can resolve the flare in γ-ray!

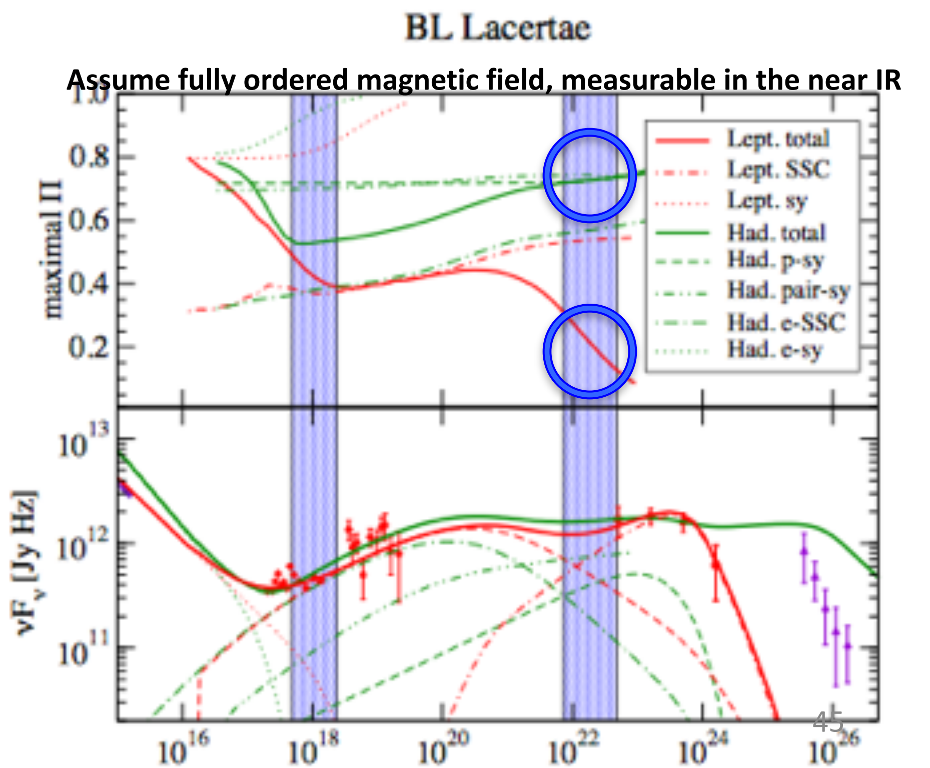
Blazars and Origin of the UHECRs

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 polarization in sub GeV range.**

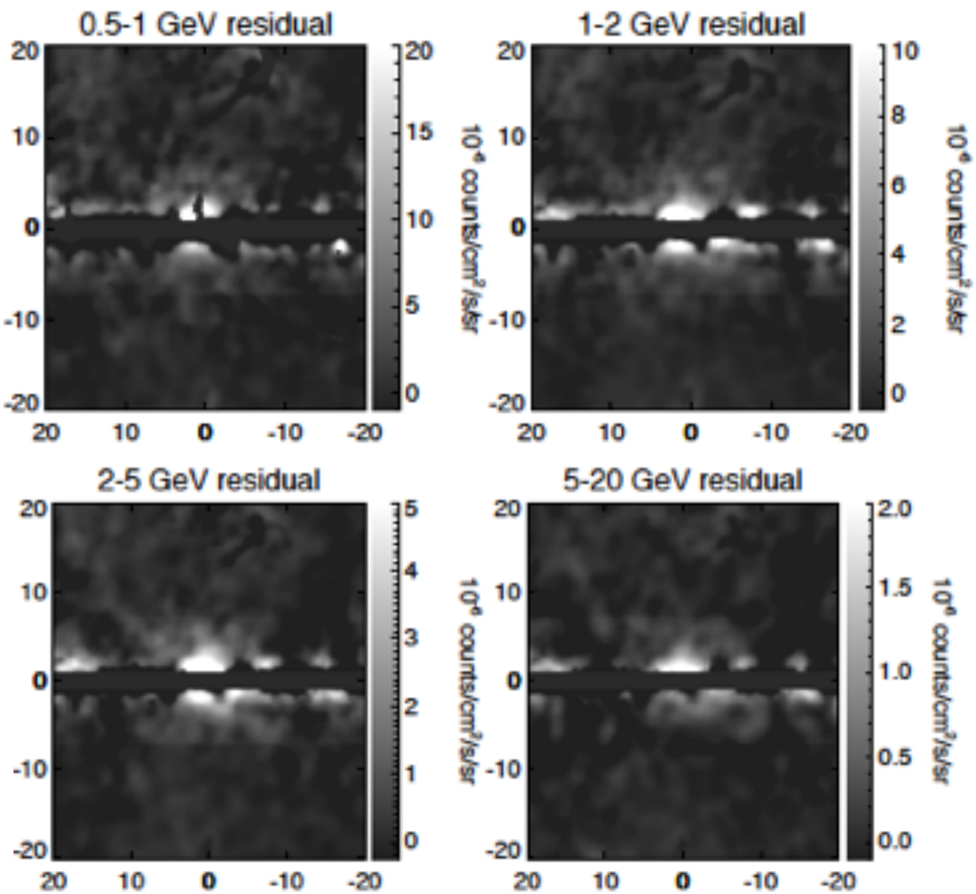
➠ PANGU observations of blazars flares



Zhang & Böttcher, 2013

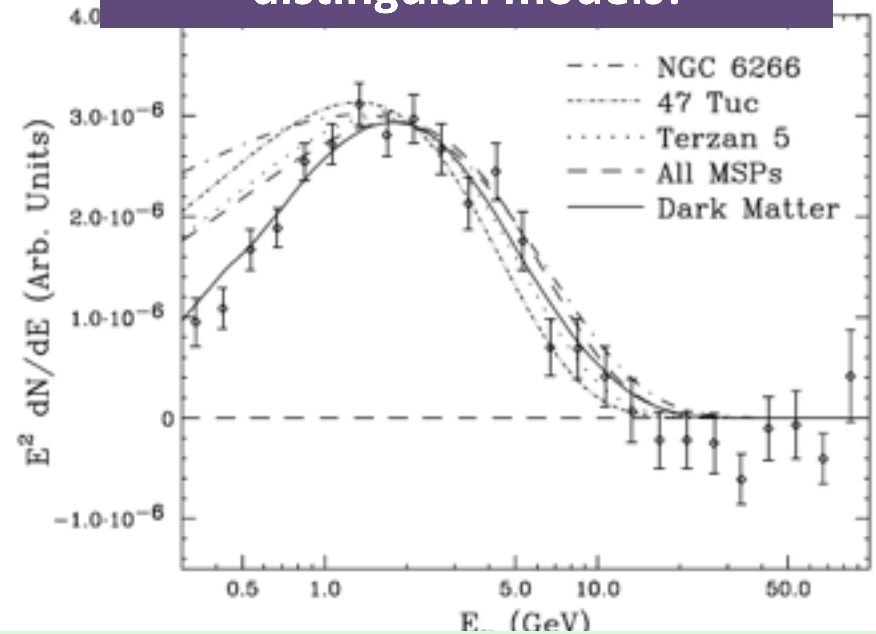
Are we seeing dark matter in gamma-ray from the Galactic center?

Are we seeing dark matter from the central of the Galaxy?



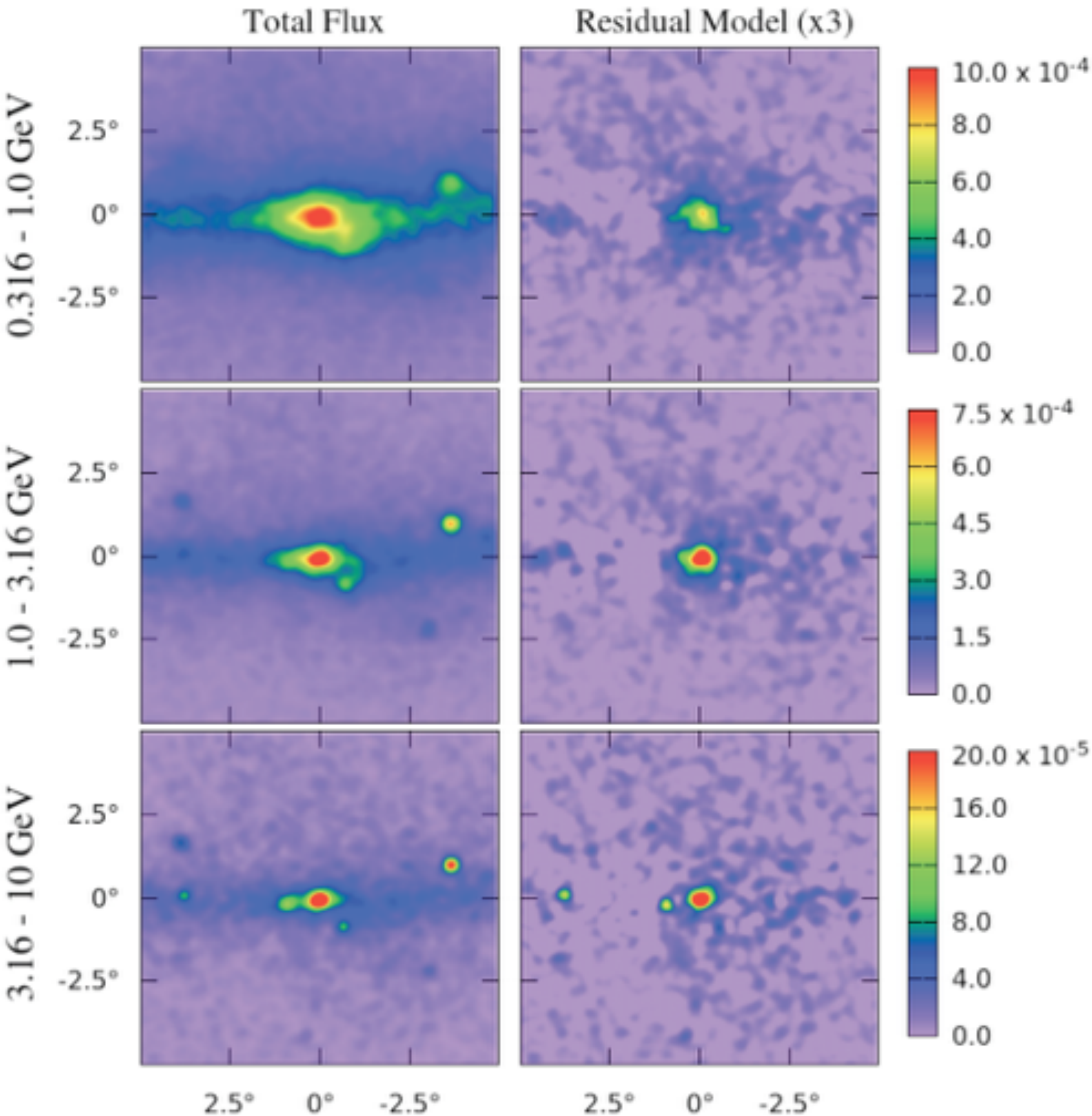
Daylan et al. (2014)

< GeV spectrum is key to distinguish models!



Fit well with 35 GeV DM WIMP -> bbar

Resolving the Galactic Center region in sub GeV gamma-rays: the central BH region, GeV and TeV sources, nebulae, compact sources, SNRs, and diffuse emission

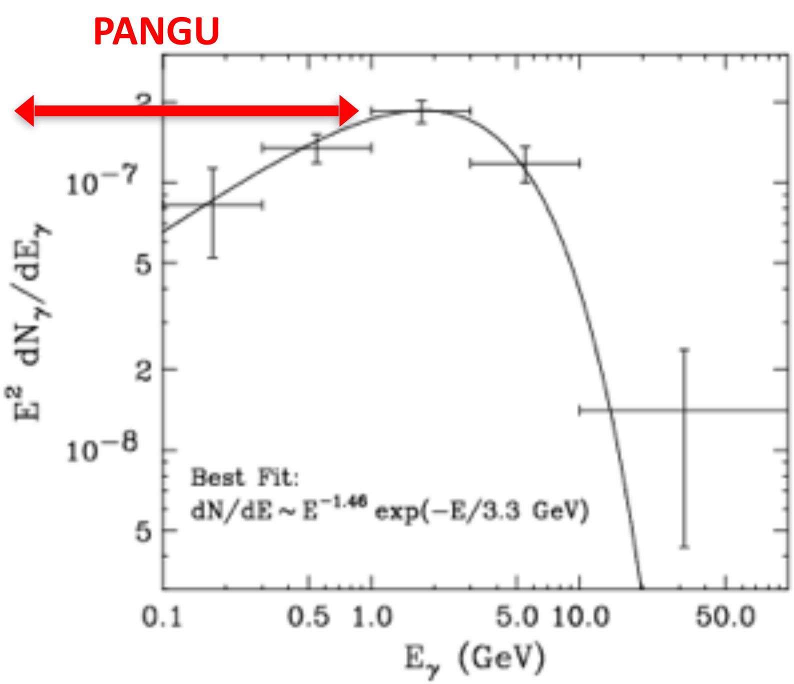


Total Flux
Residual Model (x3)
0.316 - 1.0 GeV
1.0 - 3.16 GeV
3.16 - 10 GeV
2.5°
0°
-2.5°
10.0 x 10^-4
8.0
6.0
4.0
2.0
0.0
7.5 x 10^-4
6.0
4.5
3.0
1.5
0.0
20.0 x 10^-5
16.0
12.0
8.0
4.0
0.0

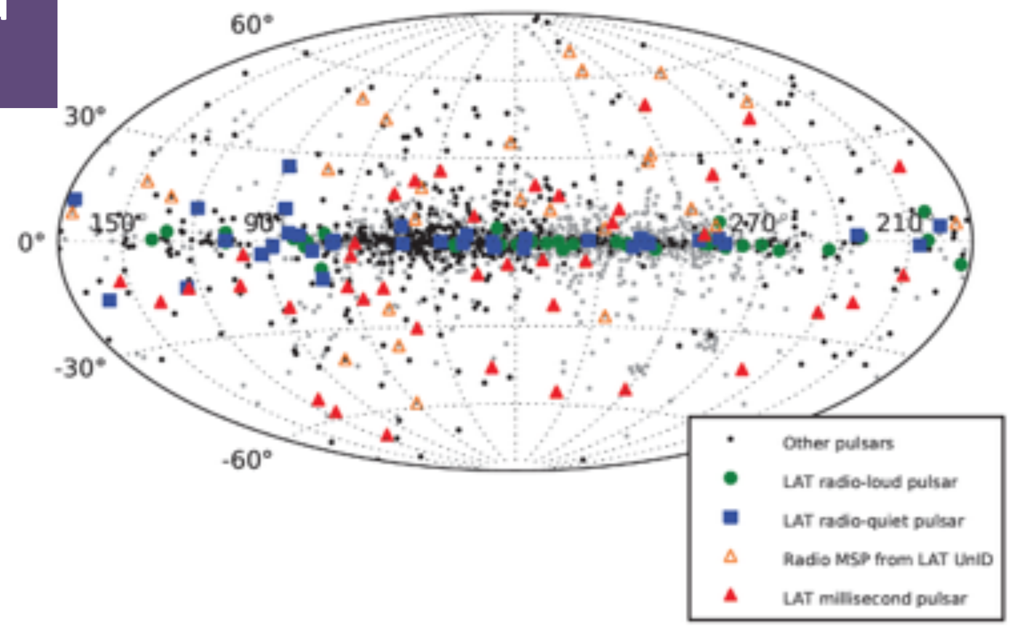
Pulsars: Ideal Targets for PANGU

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

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



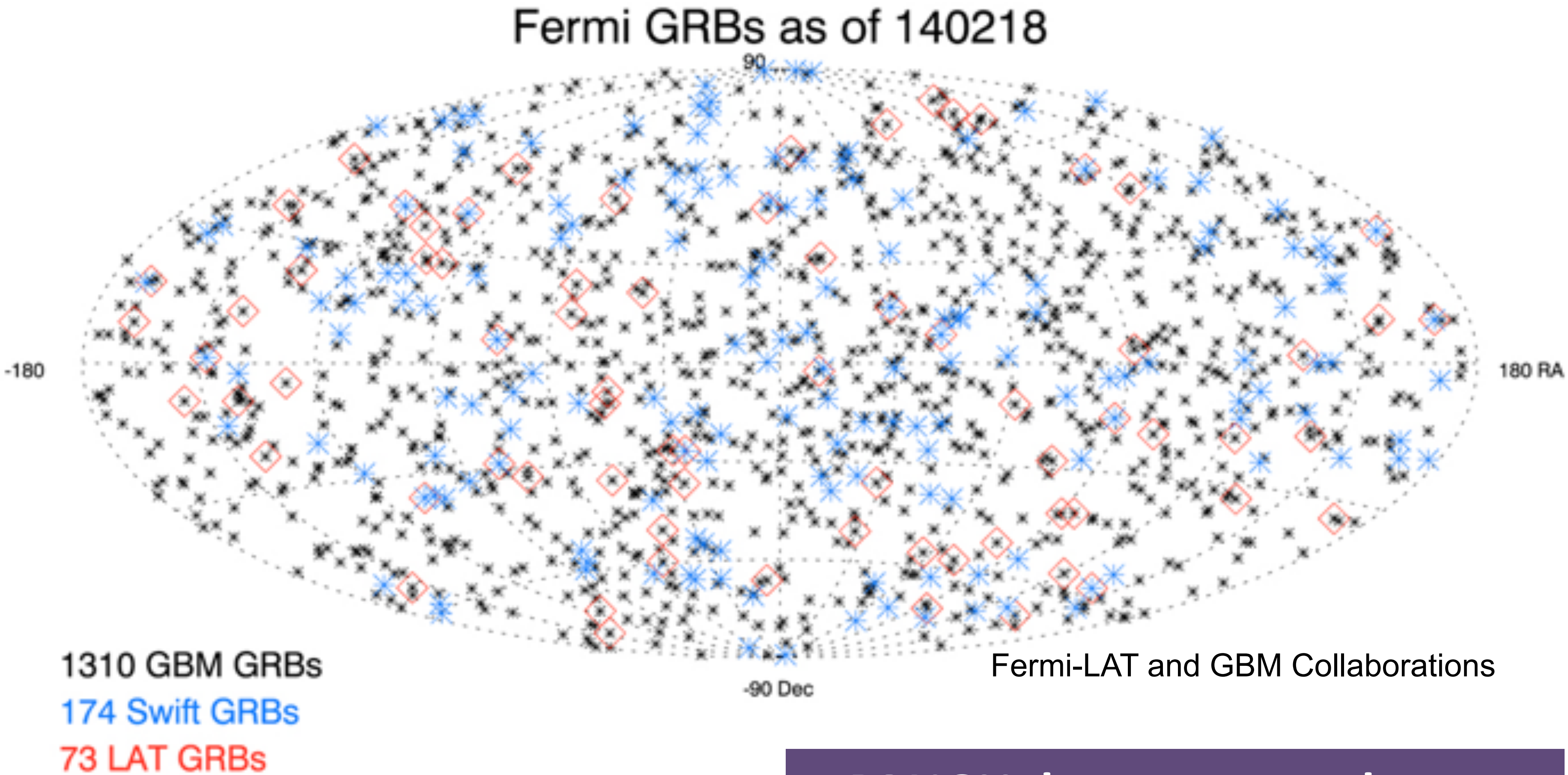
Example of MSP energy spectrum



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

PANGU is a GRB monitor



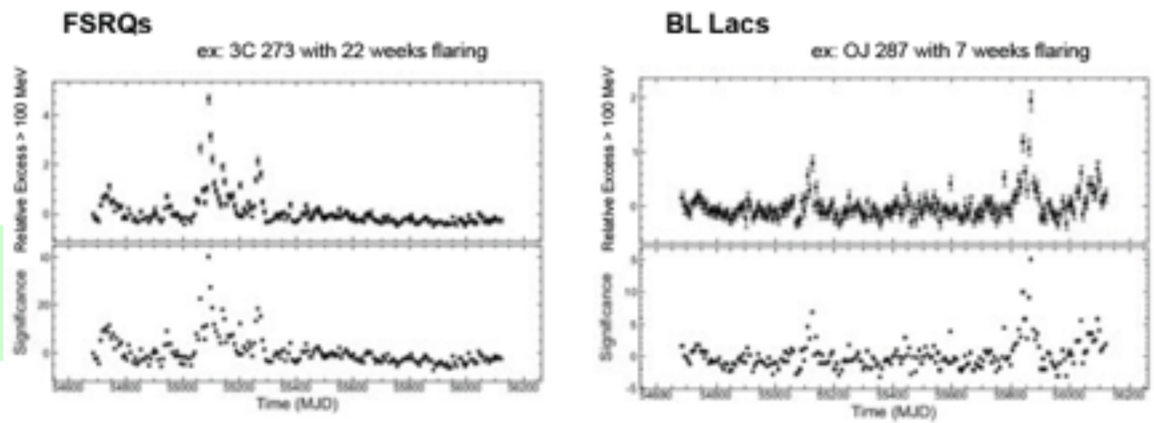
Fermi -> PANGU (2021)
Swift -> SVOM (2021)

PANGU: lower energy, better localization, larger field of view! (> tens of GRBs per year)

Why monitoring the sky with big FoV?

PANGU will continuous full-sky monitoring for the multi-wavelength community

Instantaneous access to lightcurve for any point in the sky



***Fermi*-LAT already found >200 flaring sources on weekly timescales.**

Variable source populations:

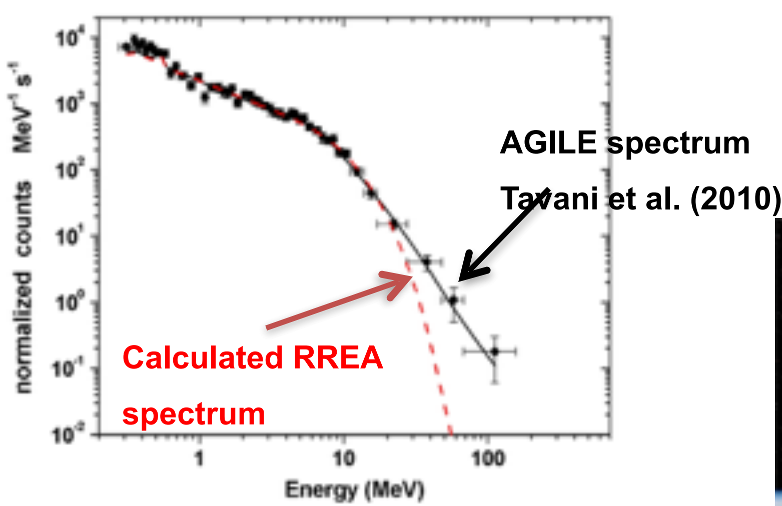
- **Characterize AGN populations properties**
- **New Galactic gamma-ray transient population: Novae**
- **Other Galactic sources expected with known binaries and AGN density.**

Earth Studies Objectives of PANGU: Terrestrial Gamma-ray Flashes

– TGFs are Intense (sub-)millisecond flashes of MeV gamma rays from thunderstorms
– Power in MeV flash comparable to power in lightning bolt
– Thunderstorms are most powerful natural terrestrial particle accelerator
• Accelerator at ~10-15 km altitude, accessible by aircraft

➠ PANGU will measure the >10 MeV spectrum with higher resolution imaging (better rejection of earth limb background).

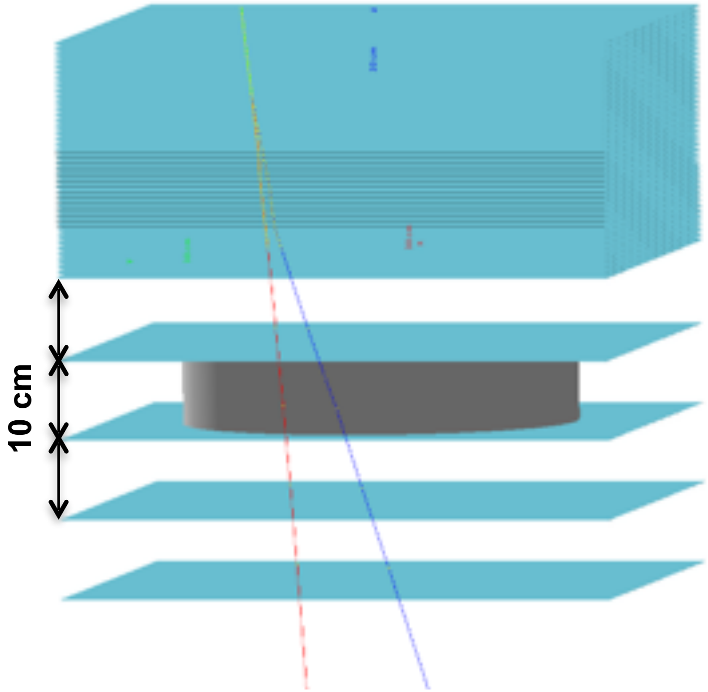
We plan to host a TGF archive which enables correlating high-energy TGFs with local and global meteorological data, unique data to atmospheric chemistry, local climate, and climate change Issues.



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

For p = 100-1000 MeV
$\Delta p/p$ ~30%-50% reachable
with B=0.1 T, L = 10 cm,
σ_x=70 μm, d = 10 cm



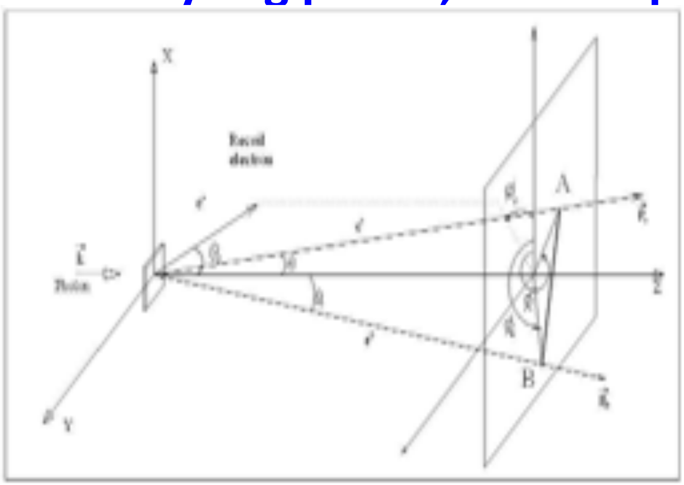
Permanent Magnet

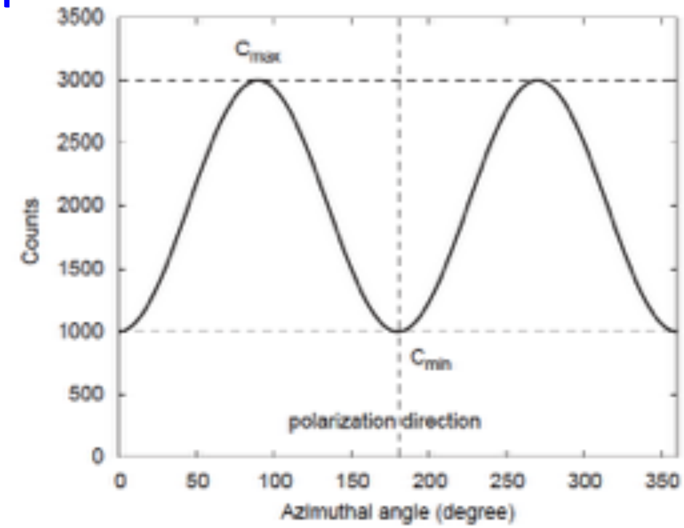
- Halbach array with NdFeB magnet
  - $B = B_0 V_f \ln(r_2/r_1)$
    - B_0 is the remnant field, assume 1.5 T (strongest available today)
    - V_f is the the filling factor, assume 0.9 – 0.95
    - r_1 is the inner radius, assume 25 cm
  - For B = 0.1 T, $r_2 = r_1 \exp(0.1/(1.5*0.9)) = 26.9$ cm
  - Magnet height 10 cm
    - For B = 0.1 T, magnet volume = $10 \times (26.9^2 - 25^2)\pi = 3098\ cm^3$
  - Density of magnet = 7.5 g/cm^3
    - Weight of magnet = 3098 x 0.0075 x 0.9 = 21 kg
  - It is possible to have 0.1 T with <30kg
- A square magnet (50 cm x 50 cm) would be heavier and less uniform
- Best to operate on low temperature, also fro SiPM

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, ~0.2 for pair production but kinematic dependent**



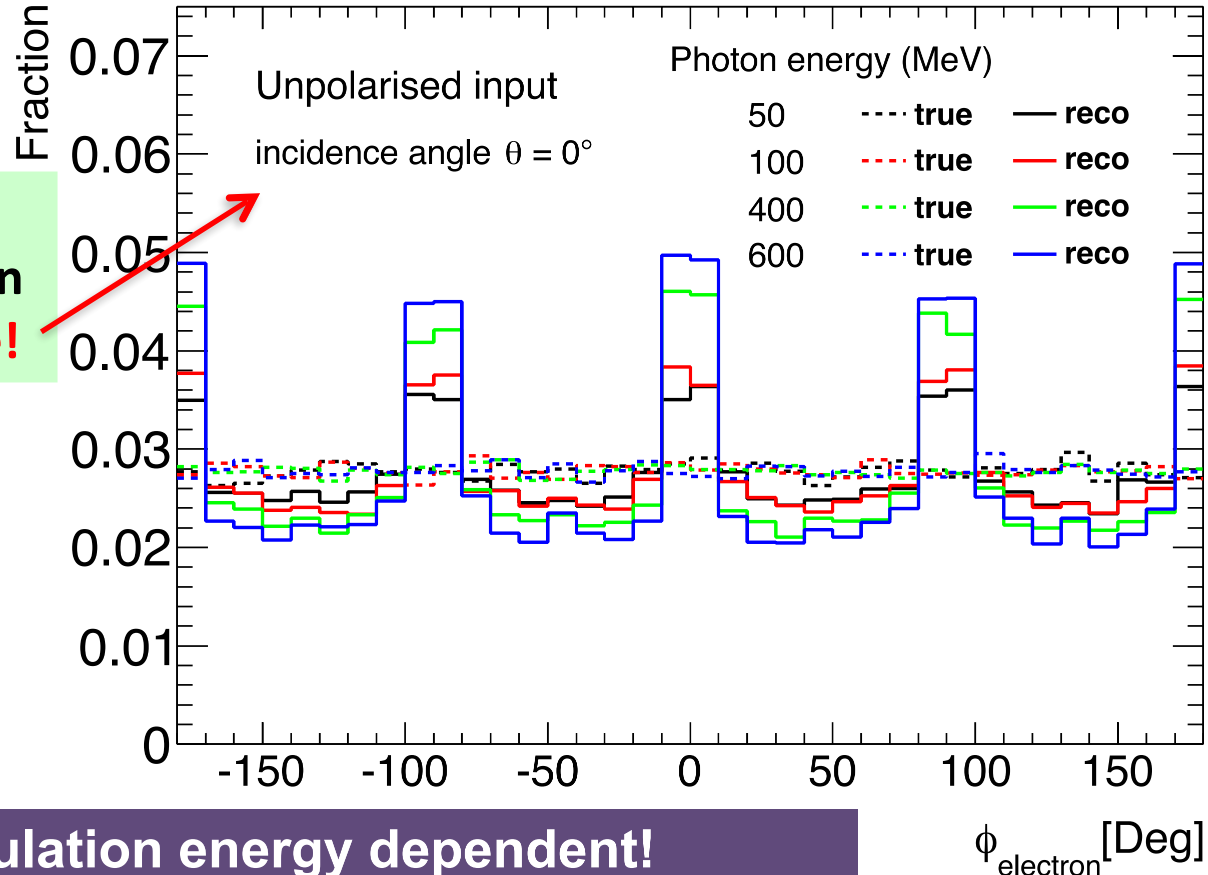


- **Keys to the measurement**
  - **Azimuthal angular resolution**
    - **transverse track length and multiple scattering**
  - **Intrinsic modulation of the detector!**

Detector Intrinsic Modulation

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

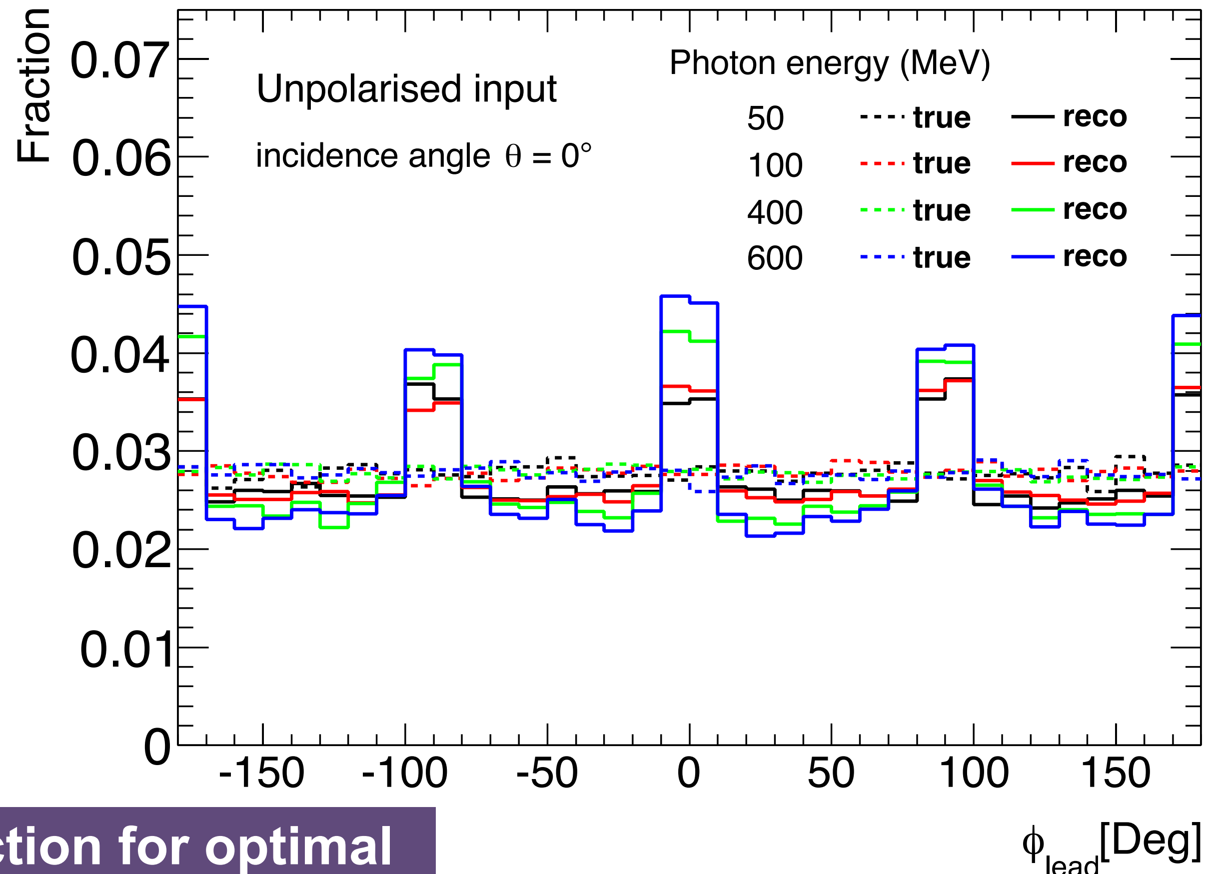
Intrinsic modulation is a function of photon direction
Best with normal incidence!



Intrinsic modulation energy dependent!
More important for higher energy because of smaller opening angle $\Longrightarrow$ shorter transverse track length

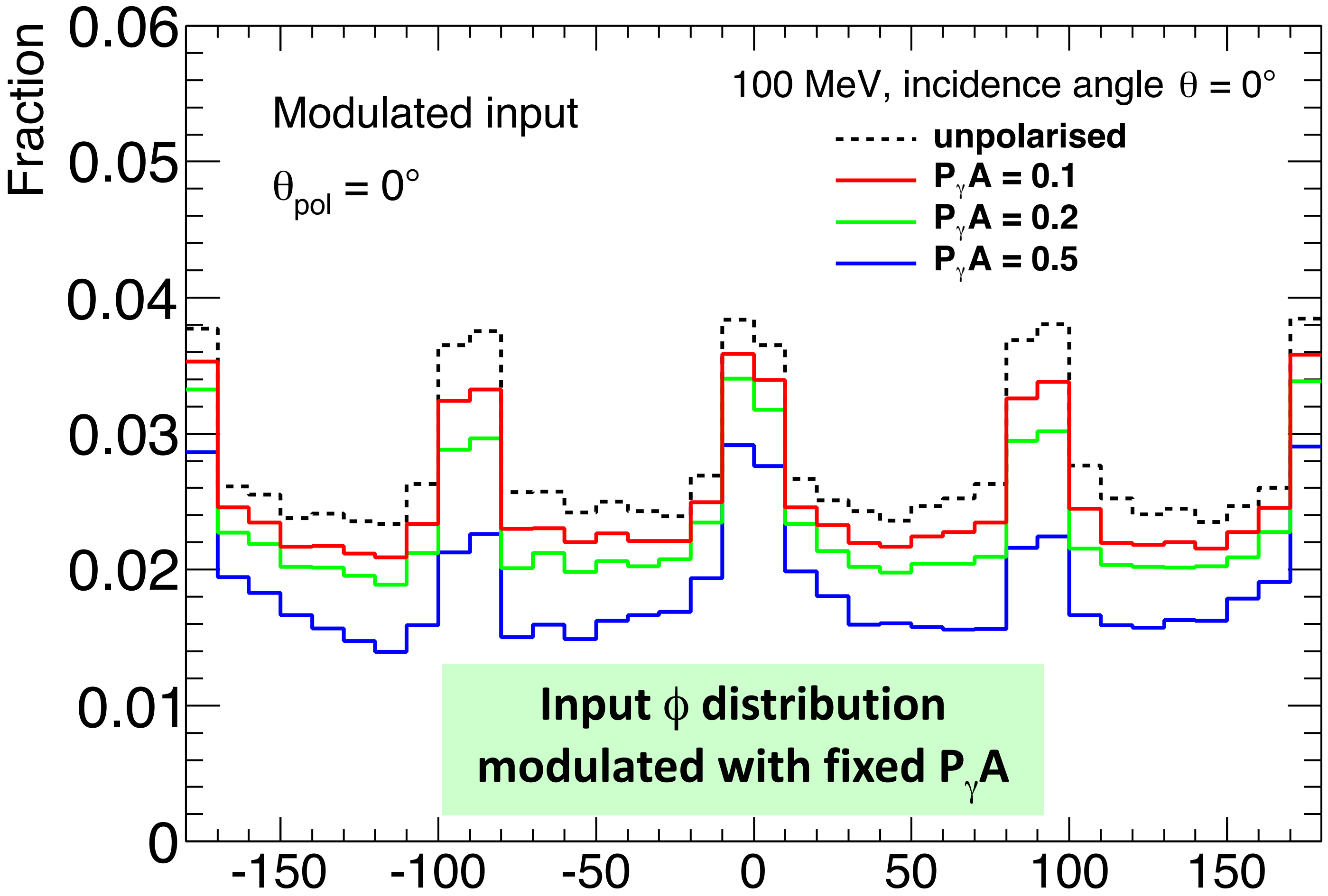
Intrinsic Modulation, Leading Track

- **Electron cannot be identified If no tracks reached spectrometer**
  - **Use leading track**



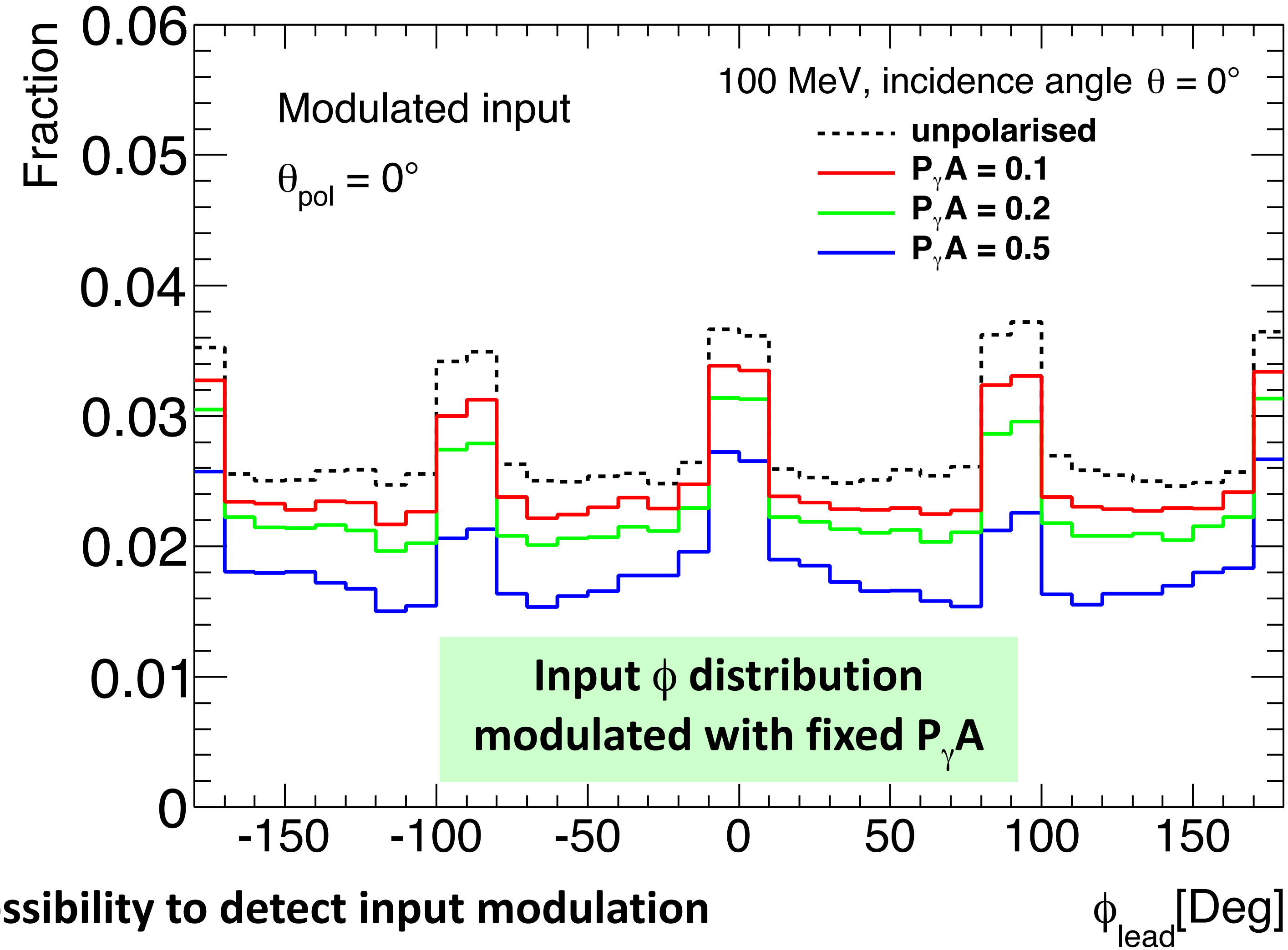
Variable and selection for optimal $P_\gamma A$ should be further studied

Input Modulation, Electron



- **Possibility to detect input modulation**
  - **Important to model intrinsic modulation!**
  - **Need reliable simulation code for polarised pair production**

Input Modulation, Leading Track



- **Possibility to detect input modulation**
  - **Important to model intrinsic modulation!**
  - **Need reliable simulation code for polarised pair production**

Angular resolution at ~100 MeV

NIMA 701, 225-230

- **Angular resolution contributions**
  - **Nuclear recoil introduce ~0.3° on angular resolution @100 MeV**
  - **Reconstruction of the pair (energy measurement)**
    - **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} = 0.35° @100 MeV, total material between 2 measurements should be less than 0.33% X_0!**
      - **310μm Si, 1.3mm fiber(polystyrene), 5.1cm Xe gas**
    - **Tracker nominal resolution: $\sqrt{2}\sigma_x/d$ = 0.9° for σ_x=70μm, d=6mm**
      - **Final resolution can approach $1.15\times\theta_{MS}$ when using many (~6) measurement points**