PANGU
盤古

A High Resolution Gamma-Ray Space Telescope

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for the PANGU Collaboration
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Second Workshop on a CAS-ESA Joint Scientific Space Mission
23-24 Sept. 2014, Copenhagen

* Presentation at this Workshop given by Dr. Shijun Lei of PMO

Overview

PANGU: PAir-productioN Gamma-ray Unit

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

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

Outline of the Presentation

- **The PANGU Collaboration**
- **Scientific Objectives**
- **Suggested Payload**
- **Mission Concept**
- **Potential Collaboration Projects**
- **Conclusions**

The PANGU Collaboration

- A growing international collaboration from China, Europe and US
  - 64 members from 21 Chinese institutes (including HK and Taiwan)
  - 18 members from 11 European institutes and 6 countries
    - Switzerland, Italy, Germany, France, Netherlands, Poland
  - 4 members from 4 US institutes

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

Chinese Collaborators (1)

1. Purple Mountain Observatory, CAS (12) (DAMPE, ASO-S)
   - 常进(Jin Chang, Chinese PI), 范一中(Yizhong Fang), 伍健(Jian Wu), 刘四明(Siming Liu), 吴雪峰(Xuefeng Wu), 张水乃(Shuinai Zhang), 董铁矿(Tiekuang Dong), 藏京京(Jingjing Zang), 韦大明(Daming Wei), 郭建华(Jianhua Guo), 冯磊(Lei Feng), 雷世俊(Shijun Lei)
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Chinese Collaborators (2)

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   – K.S. Cheng, P. Parkinson
13. National Tsing Hua University (2)
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Chinese Collaborators (3)

16. China University of Geosciences (1)
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20. Xiamen University (1)
    - 王俊峰 (Junfeng Wang)
21. Beijing Normal University (1)
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Supporter/advisory list:

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   - Roland Walter
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   - Giovanni Ambrosi, Bruna Bertucci, Gino Tosti
4. INFN Bari, Italy (2)
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   - Gabrijela Zaharijas
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12. Massachusetts Institute of Technology, U.S.A. (1)
    – Meng Su
13. University of Las Vegas, U.S.A. (1)
    – Bin Zhang
14. University of Massachusetts, U.S.A (1)
    – Daniel Wang
15. Purdue University, U.S.A (1)
    – Wei Cui

Supporter/advisory list:

- Lars Bergström (Stockholm University, OKC), Andrew Strong (MPA), Diego F. Torres (IEEC-CSIC), and many more!

Conference presentations of PANGU since first ESA-CAS workshop: strong interest from community

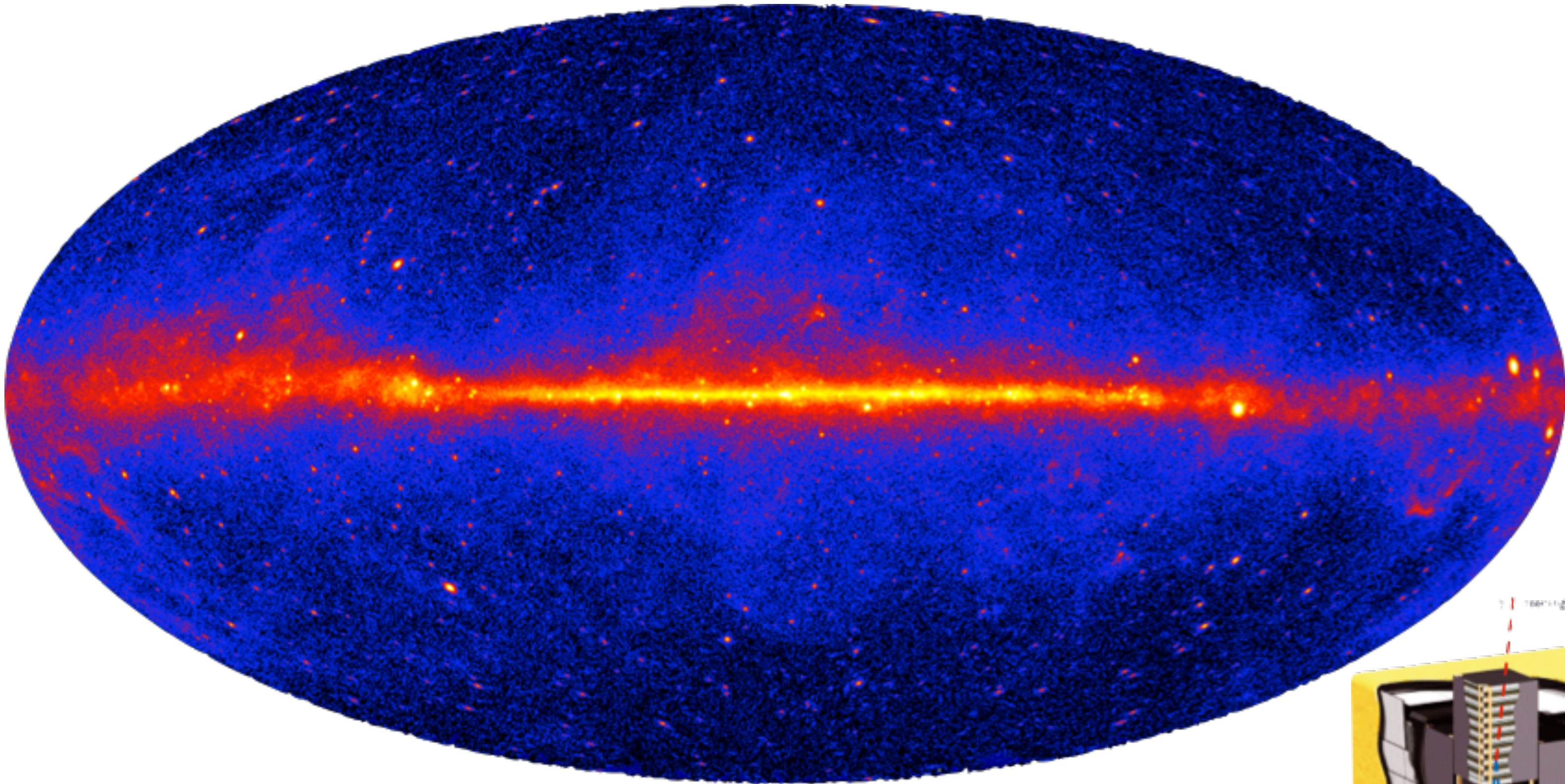
- **10th INTEGRAL Workshop**
- **SPIE Astronomical Telescopes + Instrumentation 2014**
- **International Conference on Particle Physics and Cosmology (COSMO-14)**
- **Debates on the Nature of Dark Matter (Sackler meeting 2014)**
- **High Energy Astrophysics Division 2014 Meeting**
- **Identification 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)**

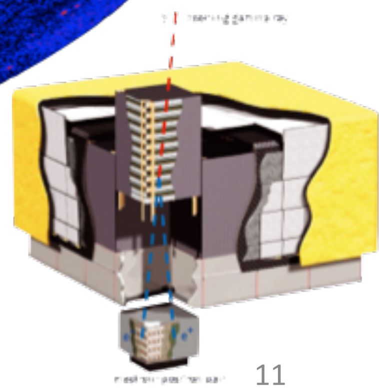
Fermi-LAT (2008-2018?)

(>1GeV)

~> 3000 gamma-ray sources

(~15 yrs after EGRET)





Space-borne gamma-ray instruments on the timescale of 2008+15 ~2020 (post-Fermi era)?

Sub-GeV is NOT improved by any future mission

- **Planned instruments focus on "high energy end" of cosmic-ray/ gamma-ray spectrum (DAMPE, HERD, Gamma-400)**
  - **~100 GeV (gamma-ray)**
  - **~TeV (electron)**
  - **~PeV (proton/nucleus)**

NO planned missions to improve ~<GeV observations, a poorly covered energy domain

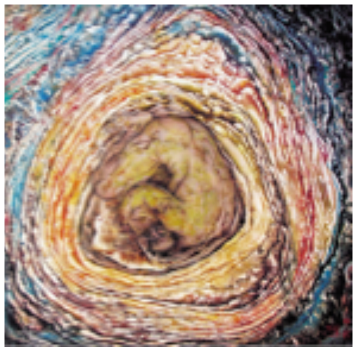
PANGU can fill this gap with a small mission!

What does PANGU mean to us?

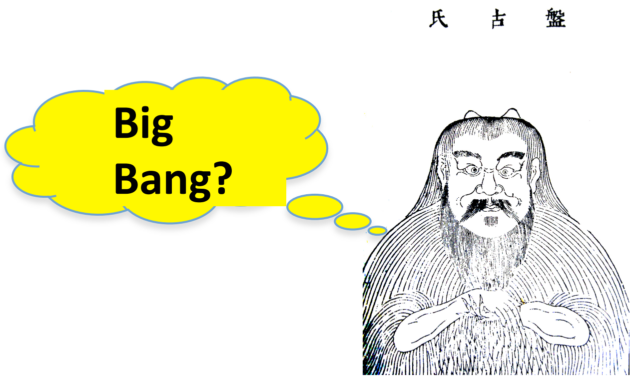
PAir productioN Gamma-ray Unit

PANoramic Gamma-ray Unit

Polarized ANd Gamma-ray Universe



PANGU SPIE proceeding:
Xin Wu et. al,
arXiv:1407.0710 [astro-ph.IM]



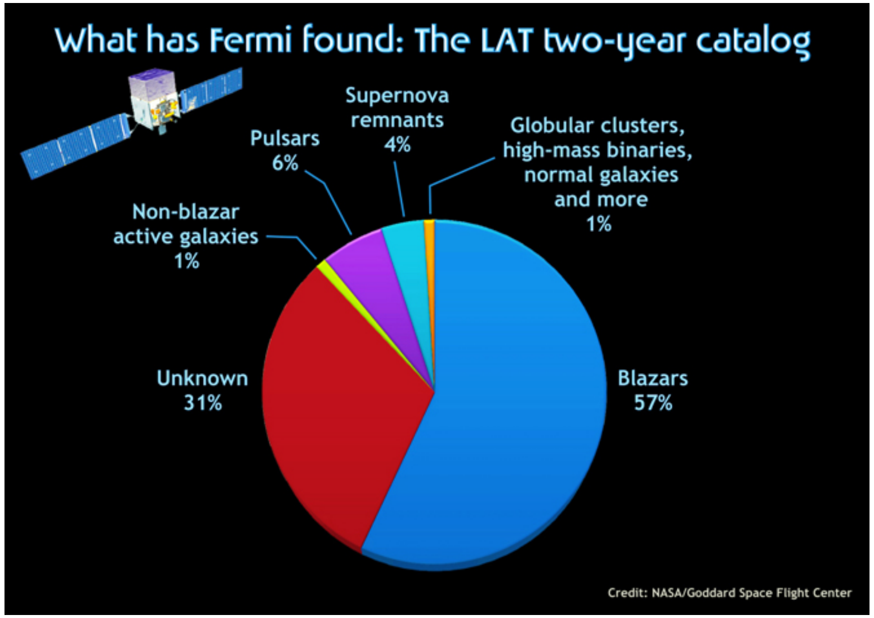
Scientific Objectives: Highlights

- Origin and acceleration of high energy cosmic rays
- Galactic and isotropic diffuse gamma-ray emission (Fermi Bubbles)
- Indirect dark matter search
- First detection of polarization at sub-GeV
- Full-sky monitoring of a variety of soft gamma-ray transients
- Baryon asymmetry in early universe / Lorentz invariance
- Solar flares / Terrestrial Gamma-Ray Flashes
- Synergic multi-energy campaign with future gamma-ray telescopes and other wavelength space/ground telescopes

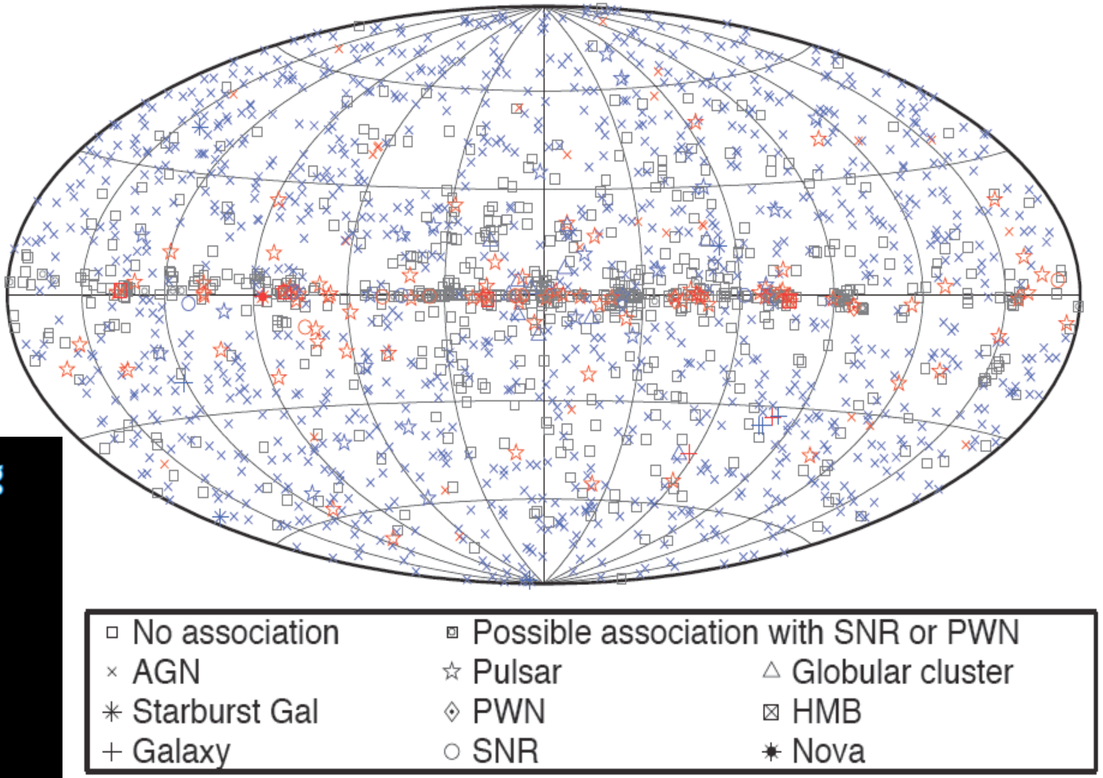
PANGU: All-sky explorer for the 10 MeV – 1 GeV Universe

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

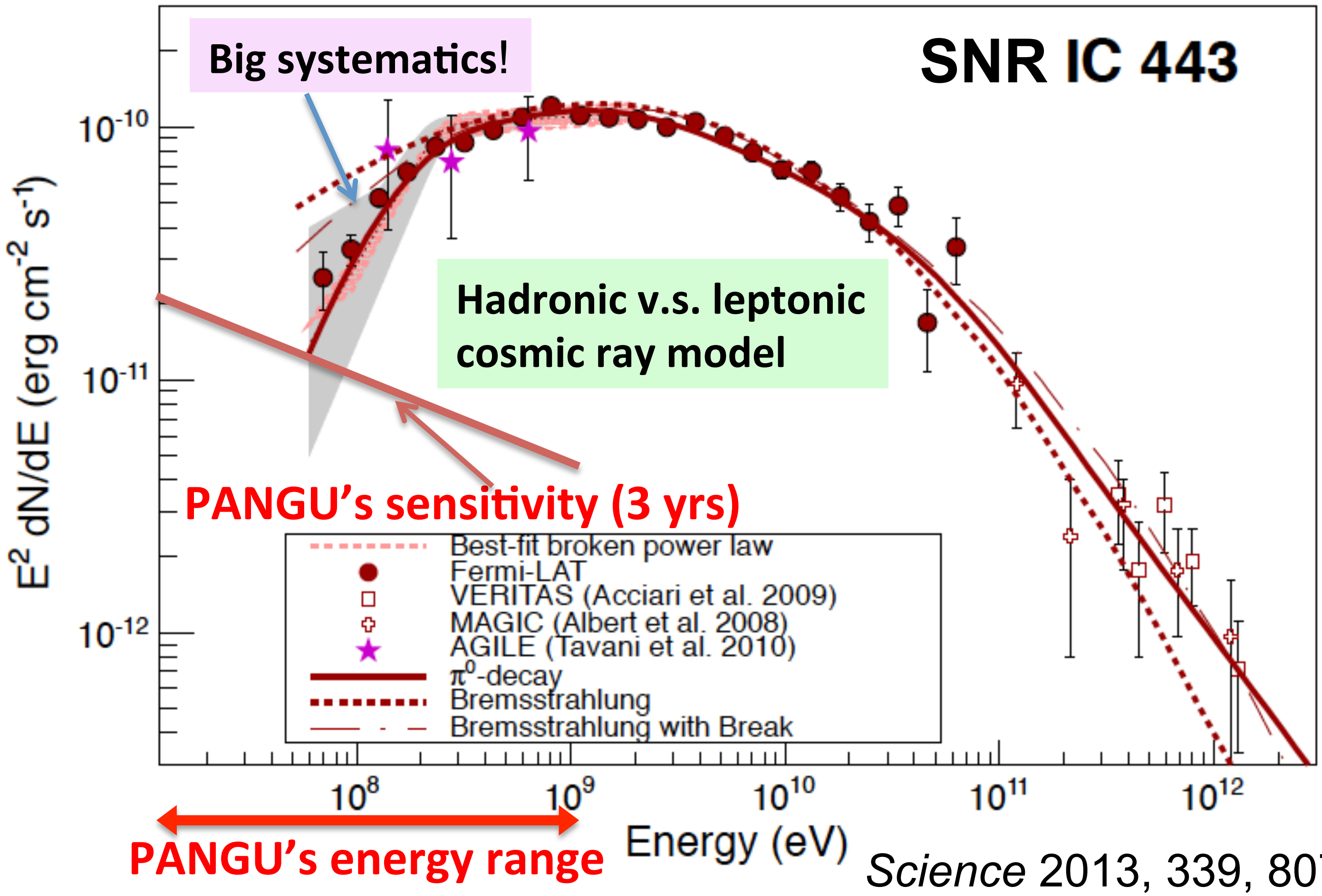


~1/3 are "unassociated" sources with unknown nature!

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

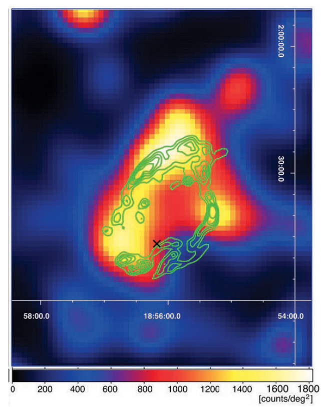
Supernovae Remnants and Particle Acceleration

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!**

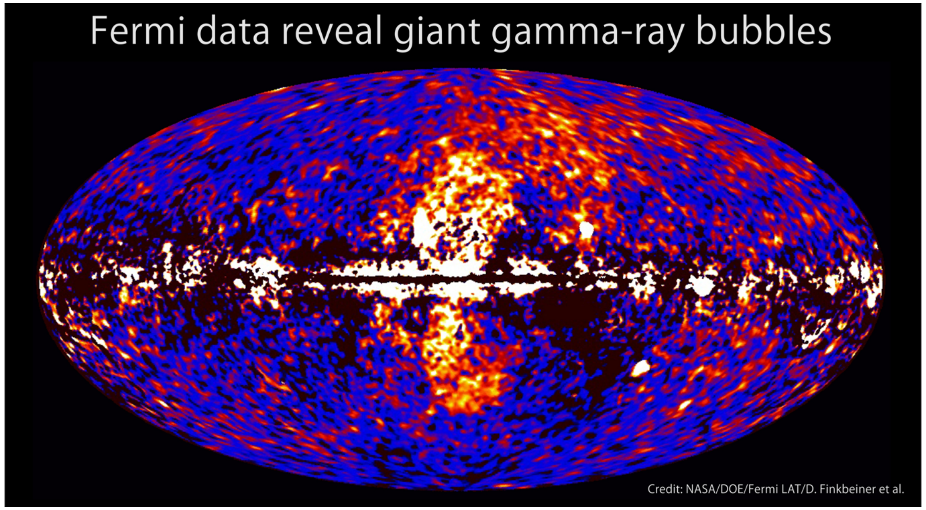


W44 Fermi

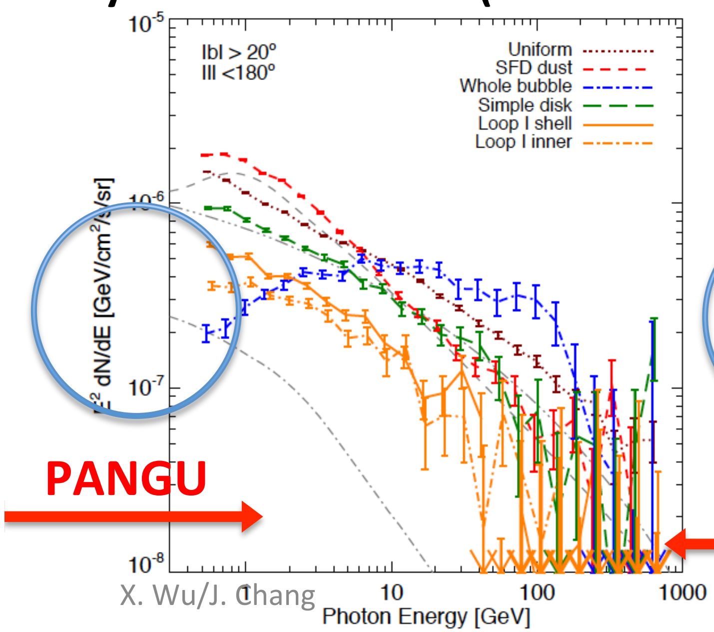
Fermi Bubbles --- Hadronic v.s. Leptonic

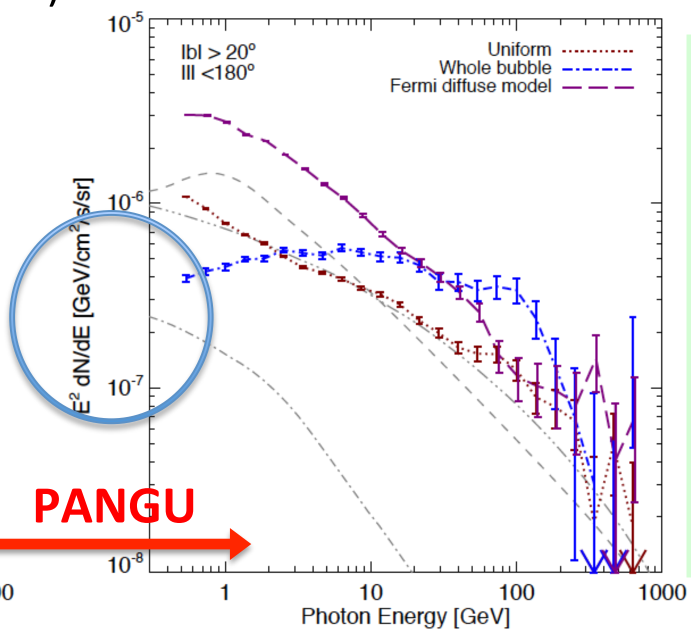
2014 Rossi Prize!

- **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!)

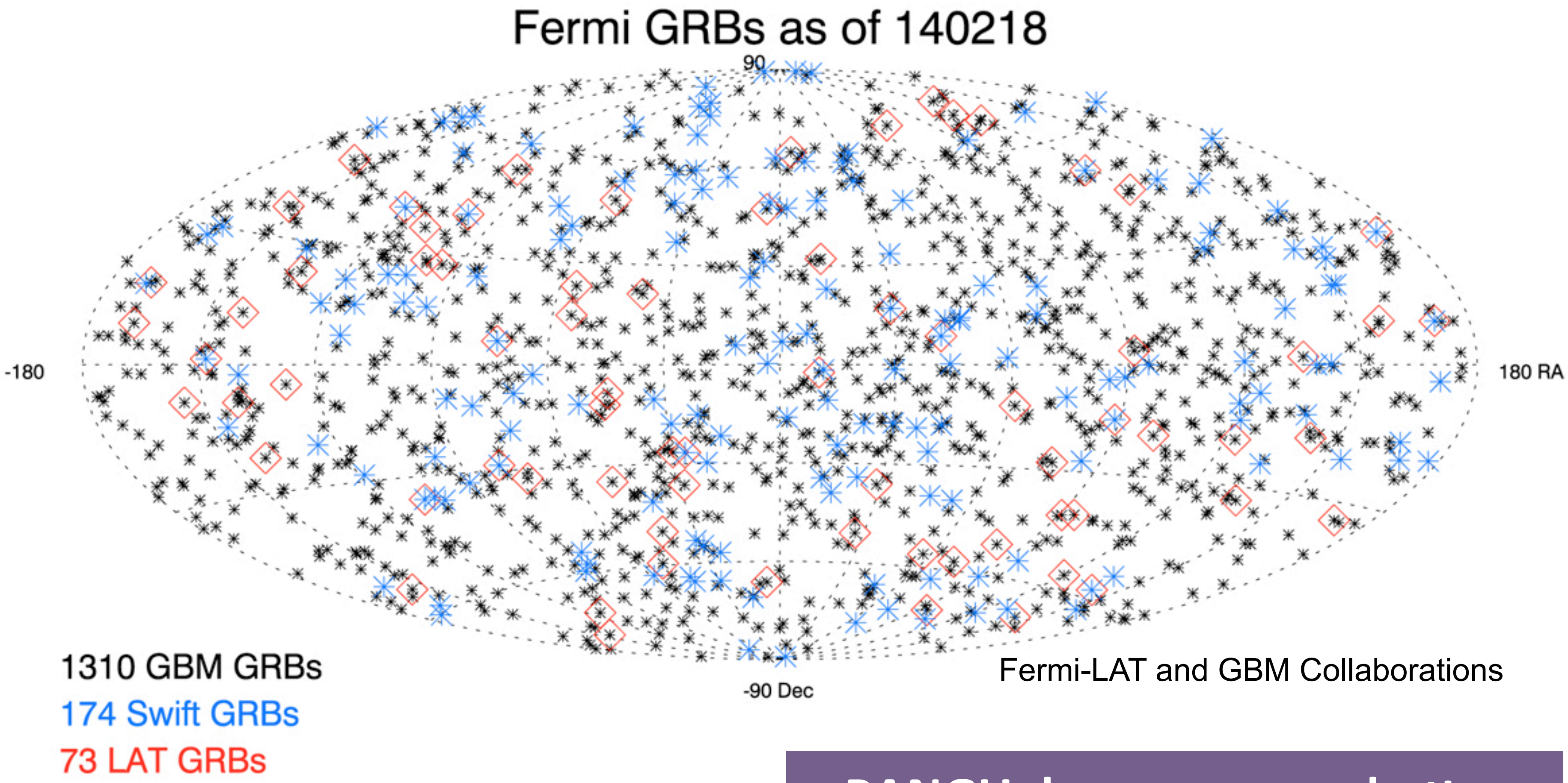




Measurement of < GeV cutoff is the key to infer the cosmic ray electron/proton spectrum at low energy

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

PANGU is a GRB Monitor

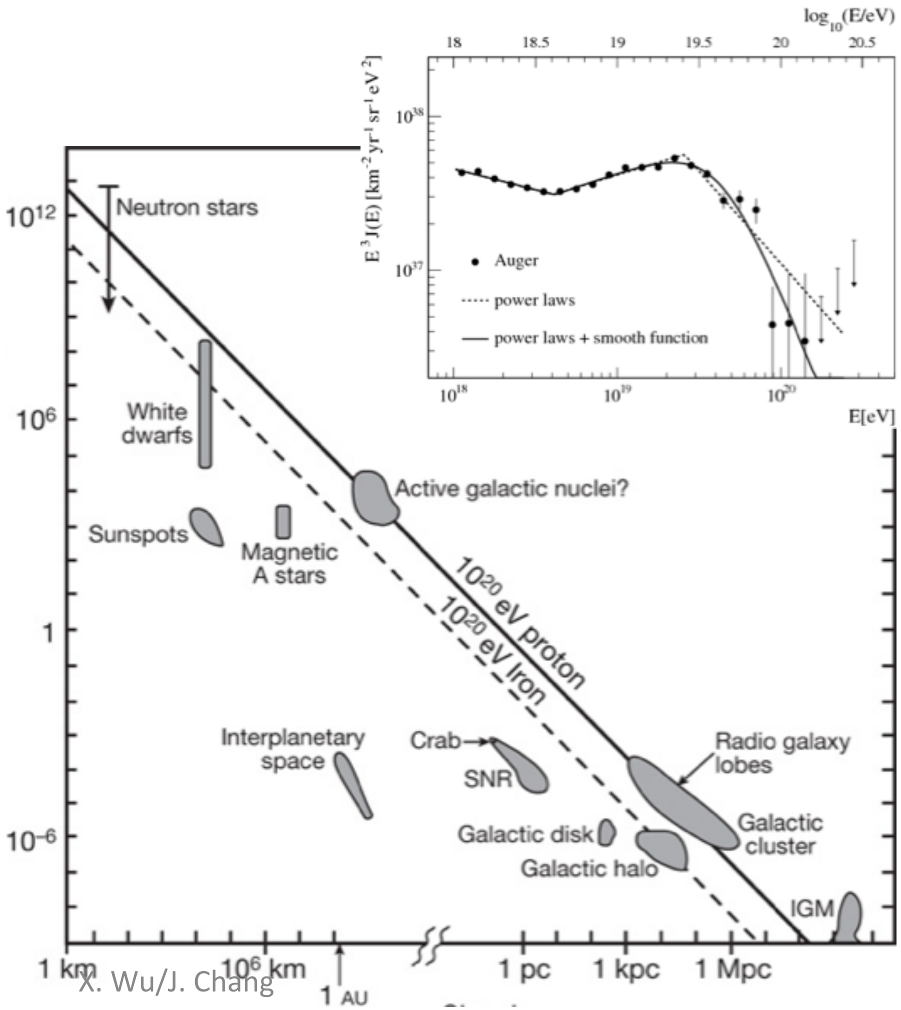


Fermi -> PANGU (2021)
Swift -> SVOM (2021)

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

Blazars and Origin of the UHECRs

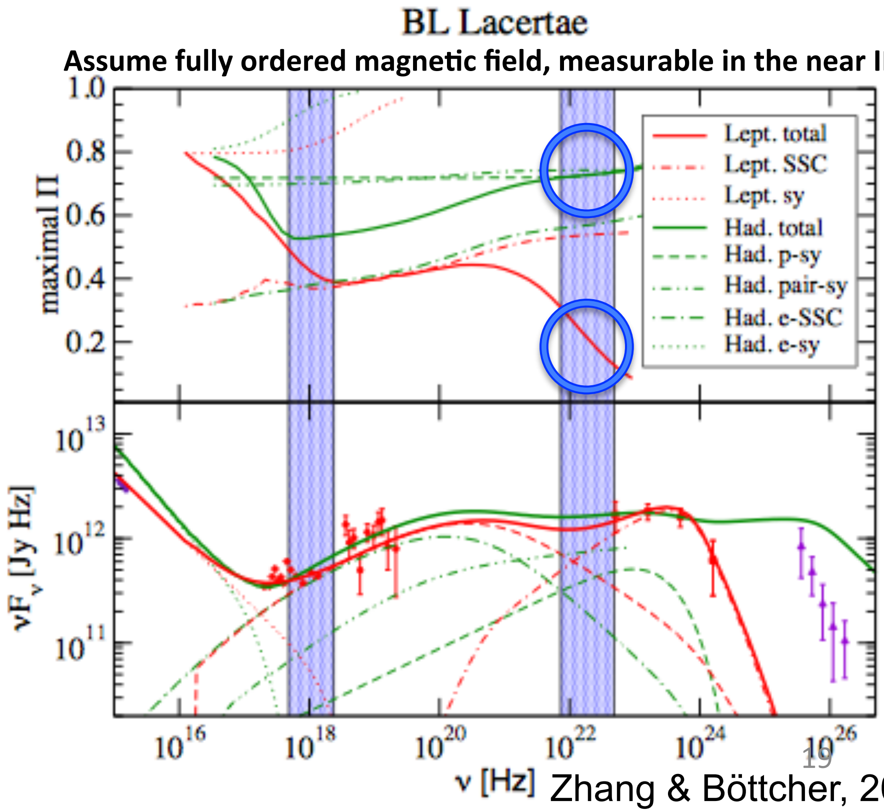
Standard hypothesis: shocks in hadronic jets of Active Galactic Nuclei



- **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

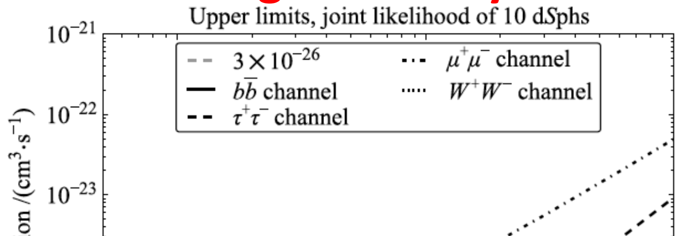
Assume fully ordered magnetic field, measurable in the near IR



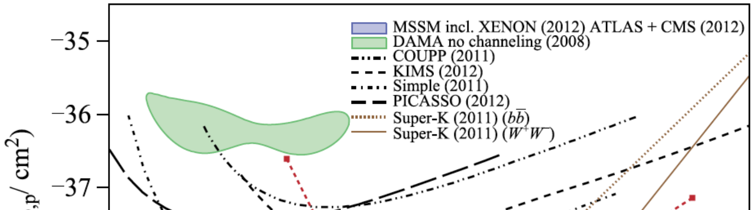
Zhang & Böttcher, 2013

Unique Rule in Low Mass Dark Matter Search

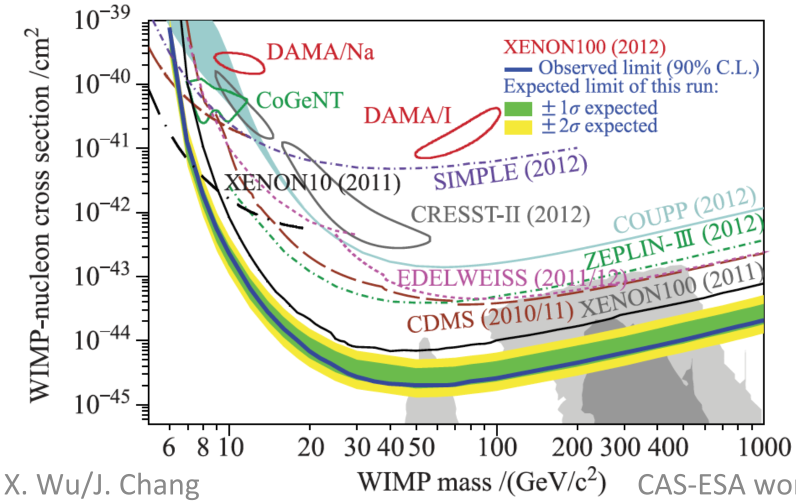
Fermi gamma-ray search

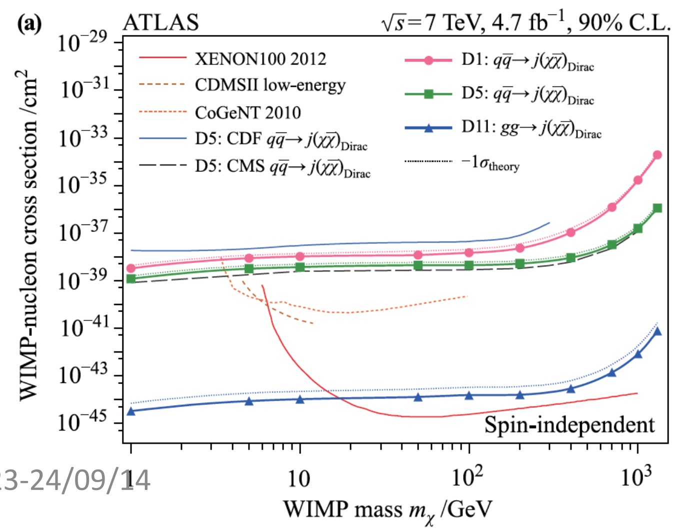


IceCube neutrino search



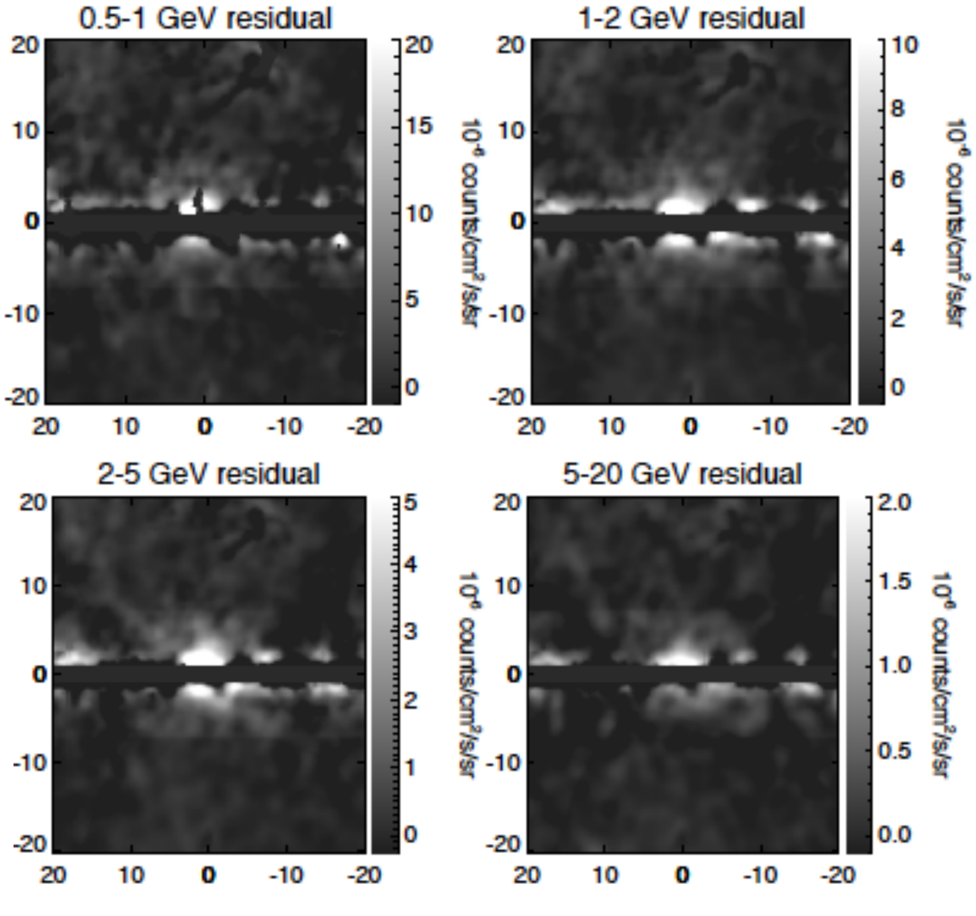
No missions are sensitive to PANGU's energy range --- unique in dark matter search, chance for discovery





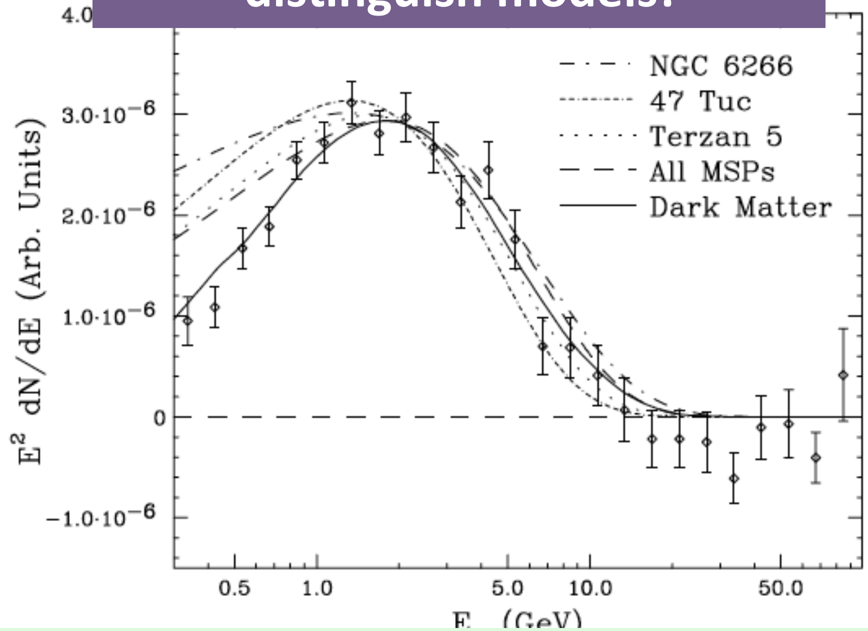
Search for Dark Matter Gamma-ray Signature from the Milky Way

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



Daylan et al. (2014)

< GeV spectrum is key to distinguish models!



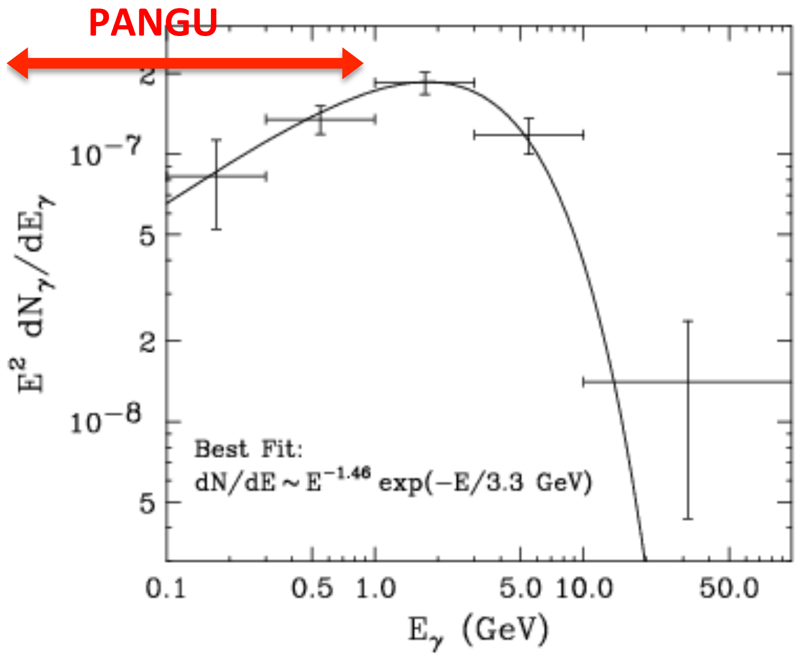
Fit well with 35 GeV DM WIMP -> bbar

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

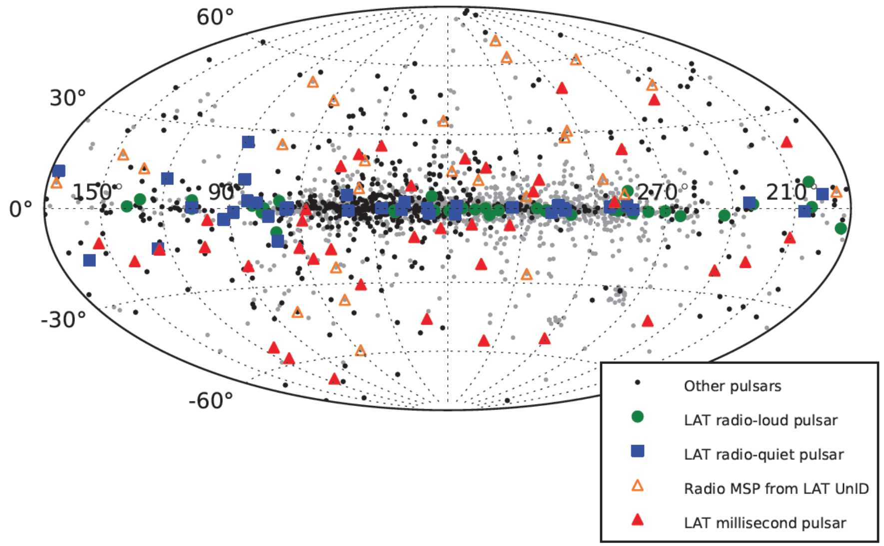
Pulsars: Ideal Targets for PANGU

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

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



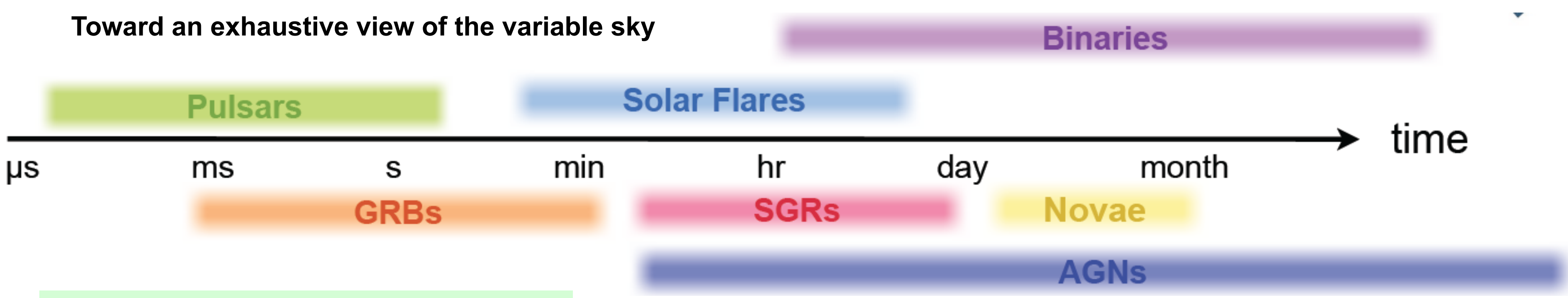
Example of MSP energy spectrum



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

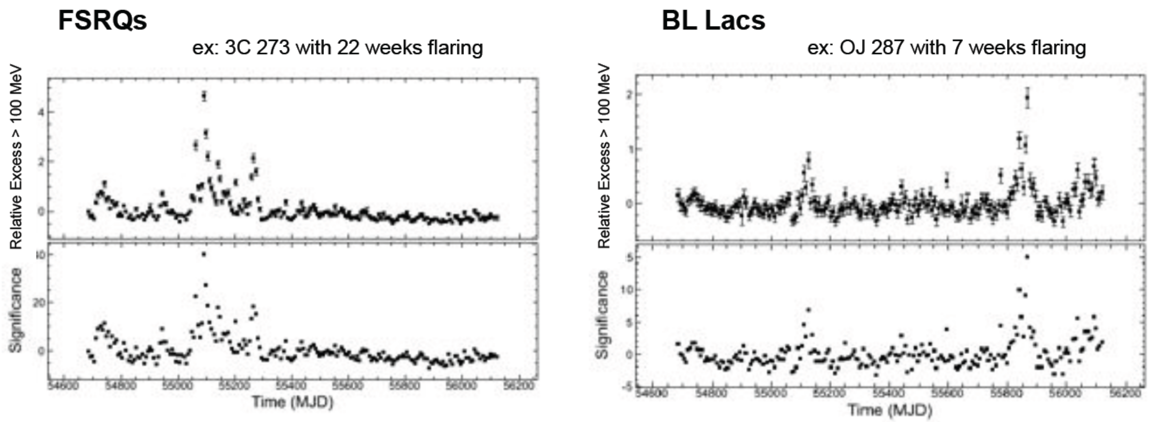
Gamma-ray observations can help to disentangle the geometry of pulsar magnetospheres and emission regions

Time Domain γ-ray Astronomy with Big FoV



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

Instantaneous access to lightcurve for any point in the sky



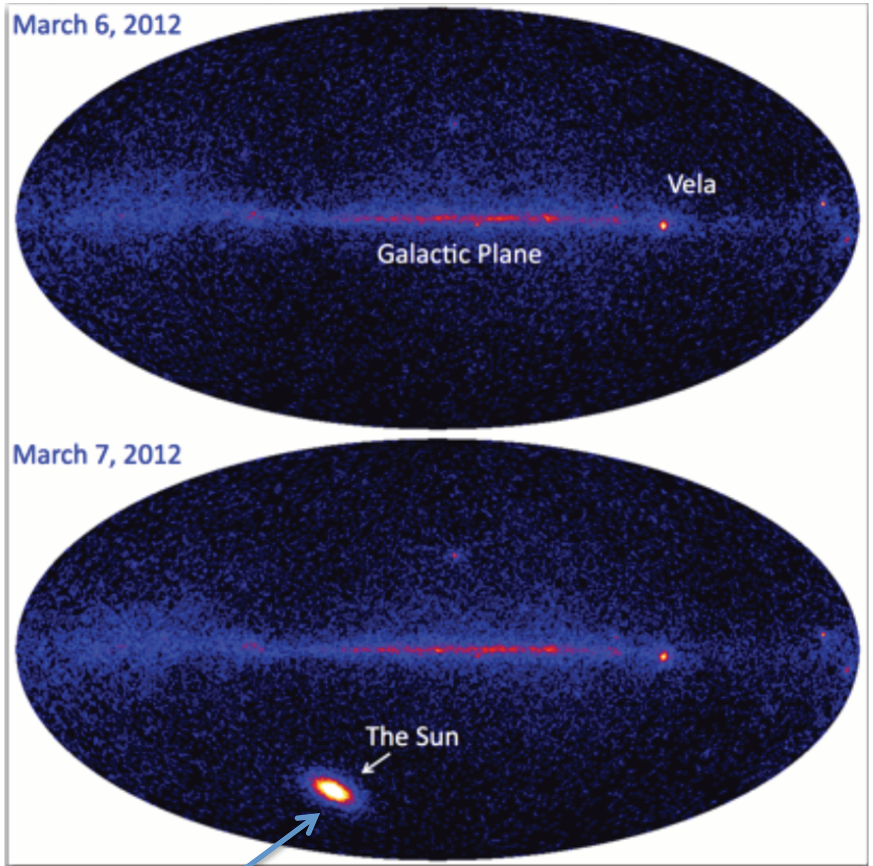
***Fermi*-LAT already found >200 flaring sources on weekly timescales.**

Variable source populations:

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

Gamma-ray Emission from Solar Flares

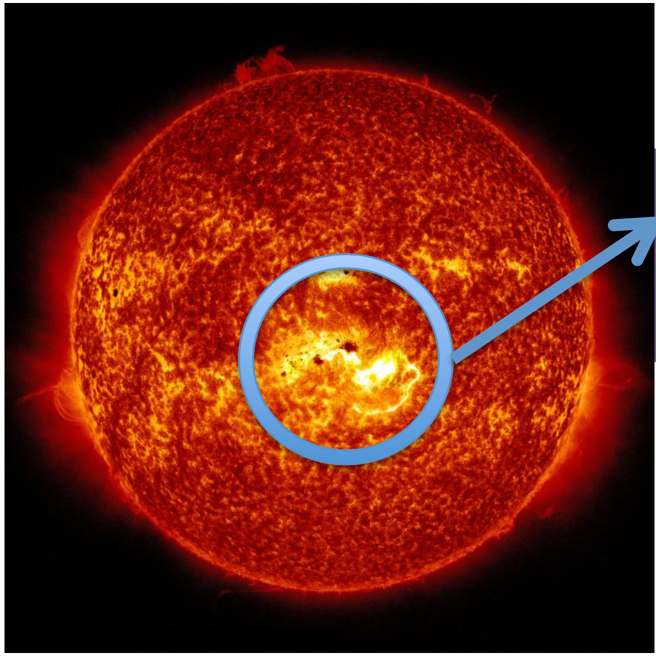
LAT 1 day all sky data >100 MeV



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

Bright solar flares have been detected by Fermi

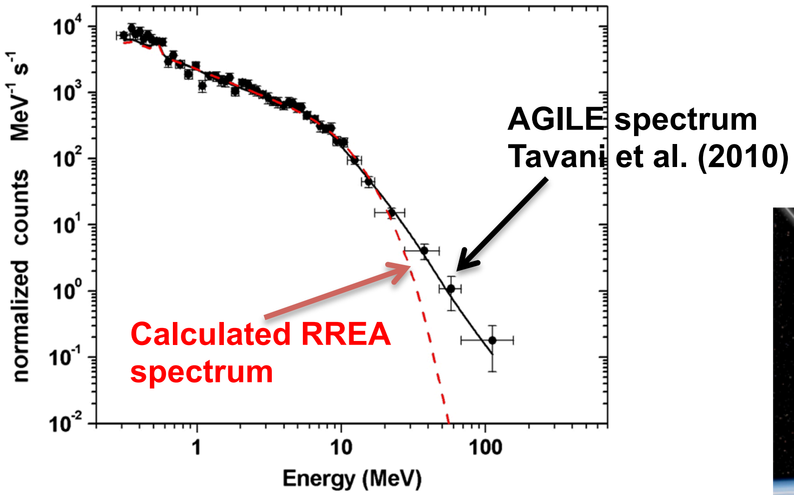
- **1000 time the flux of the steady Sun**
- **100 times the flux of Vela**
- **50 times the Crab flare**
- **High energy emission (>10 MeV, up to 4 GeV) lasts for ~20 hours**
- **Softening of the spectrum with time**



PANGU can resolve the flare in γ-ray!

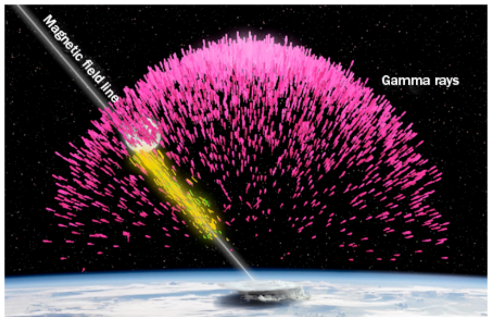
Earth Studies Objectives of PANGU: Terrestrial Gamma-ray Flashes

– 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



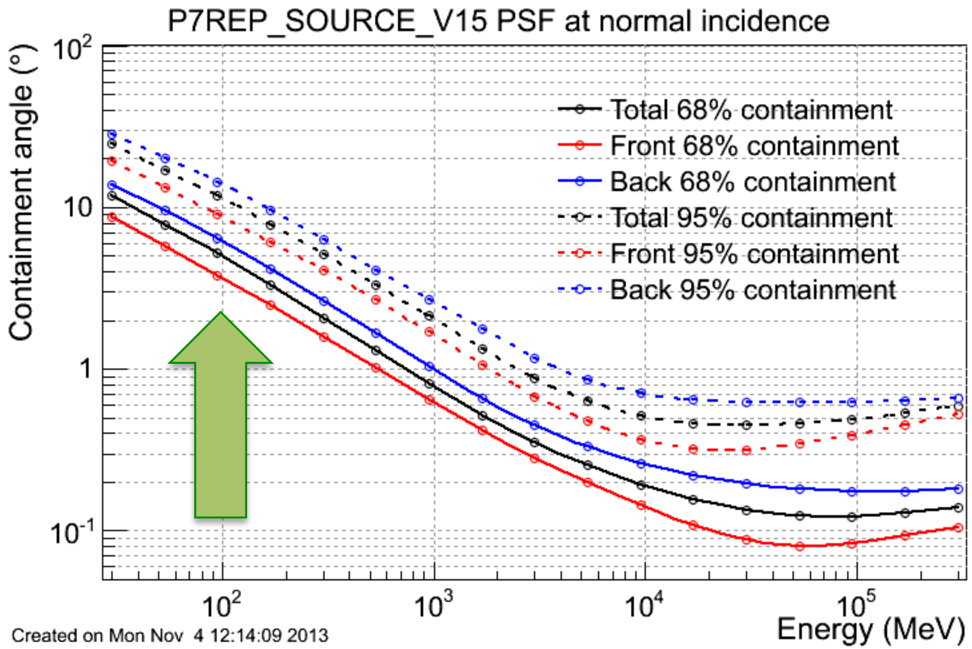
➡ PANGU will measure the >10 MeV spectrum with higher resolution imaging (better rejection of earth limb background).

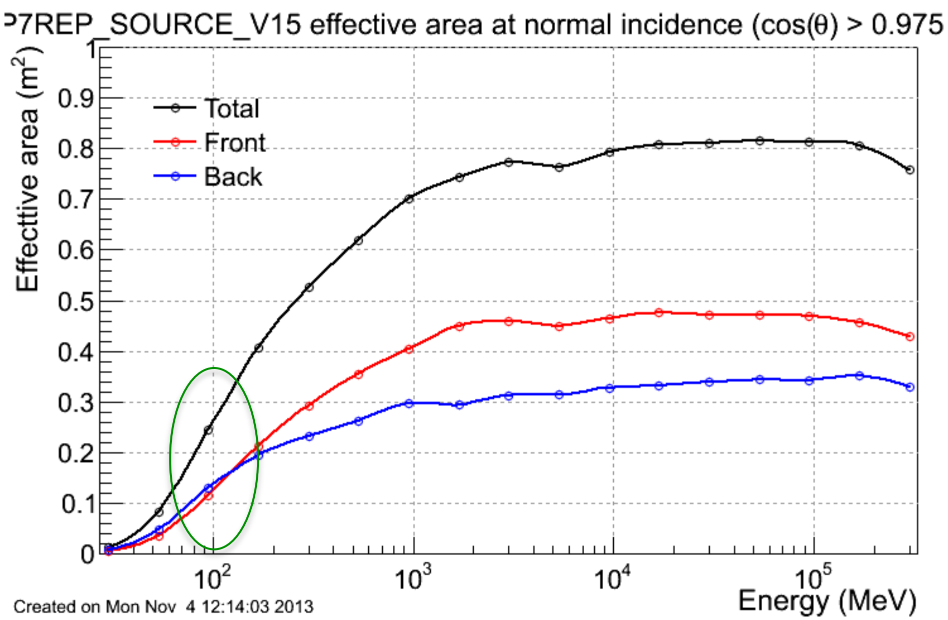
We plan to host a TGF archive which enables correlating high-energy TGFs with local and global meteorological data, unique data to atmospheric chemistry, local climate, and climate change Issues.



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**



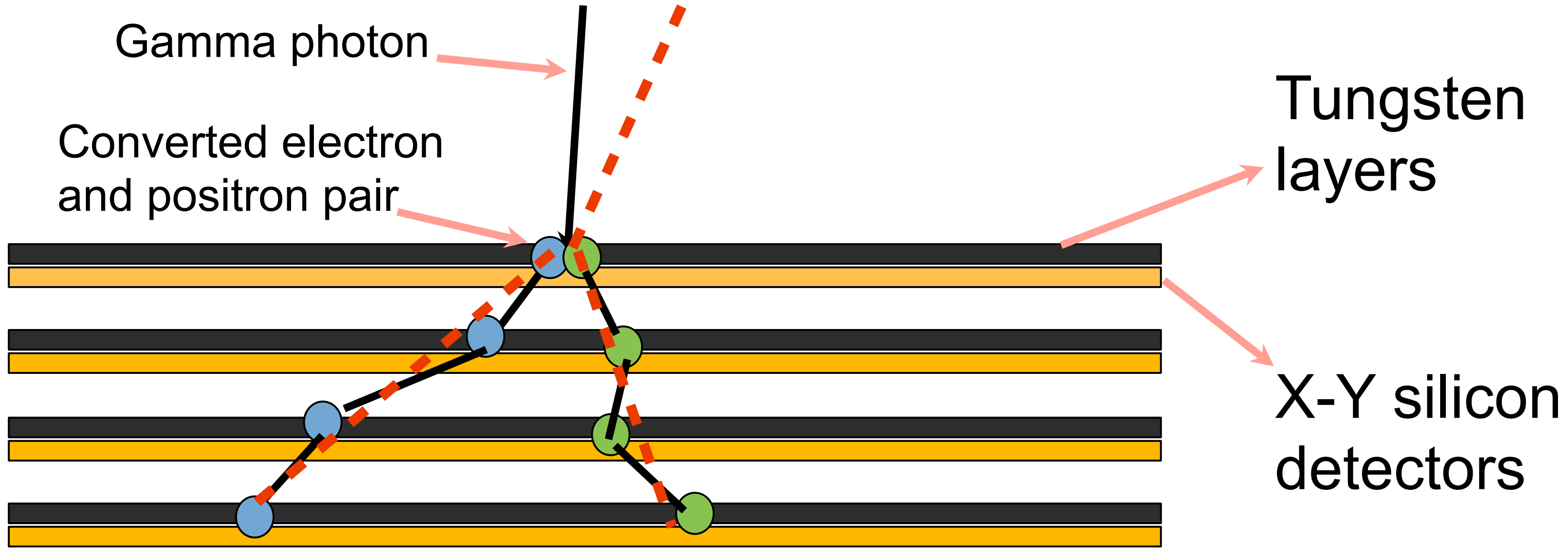


PSF 4°-6° @100 MeV

How to improve?

Detection principle:

How Fermi-LAT detects gamma-ray photons



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

-
-
-
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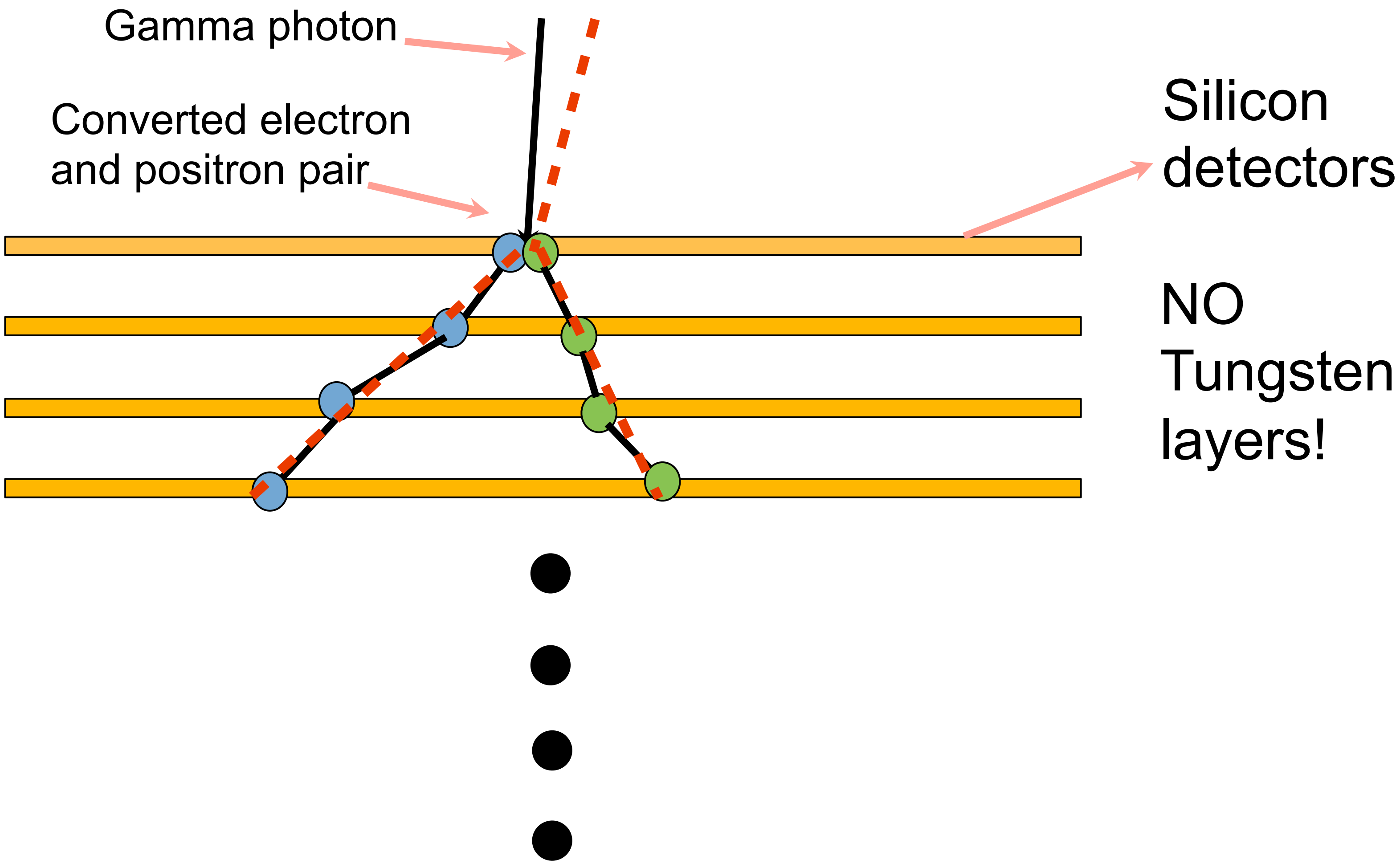
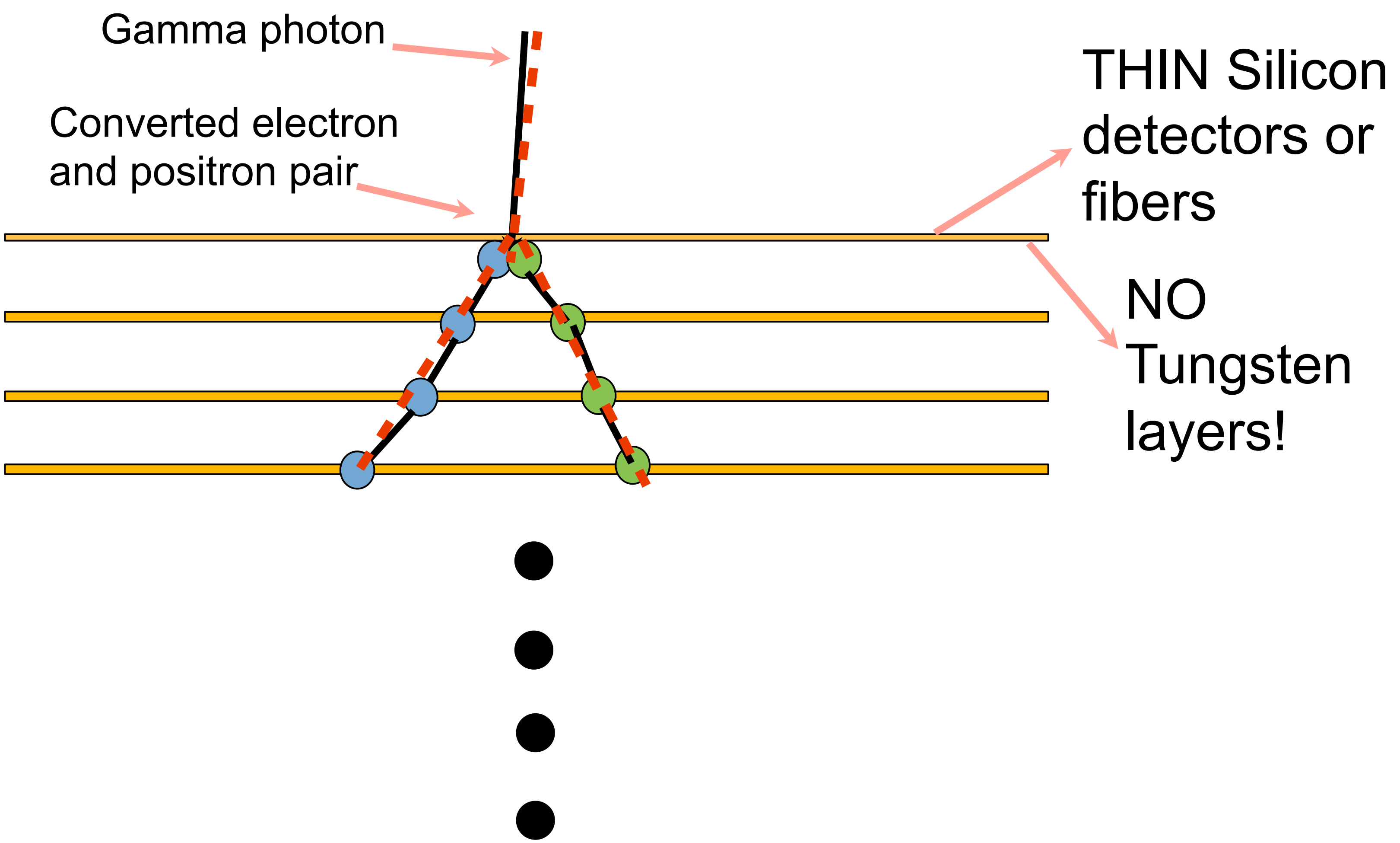
Detection principle:

How PANGU detects gamma-ray photons



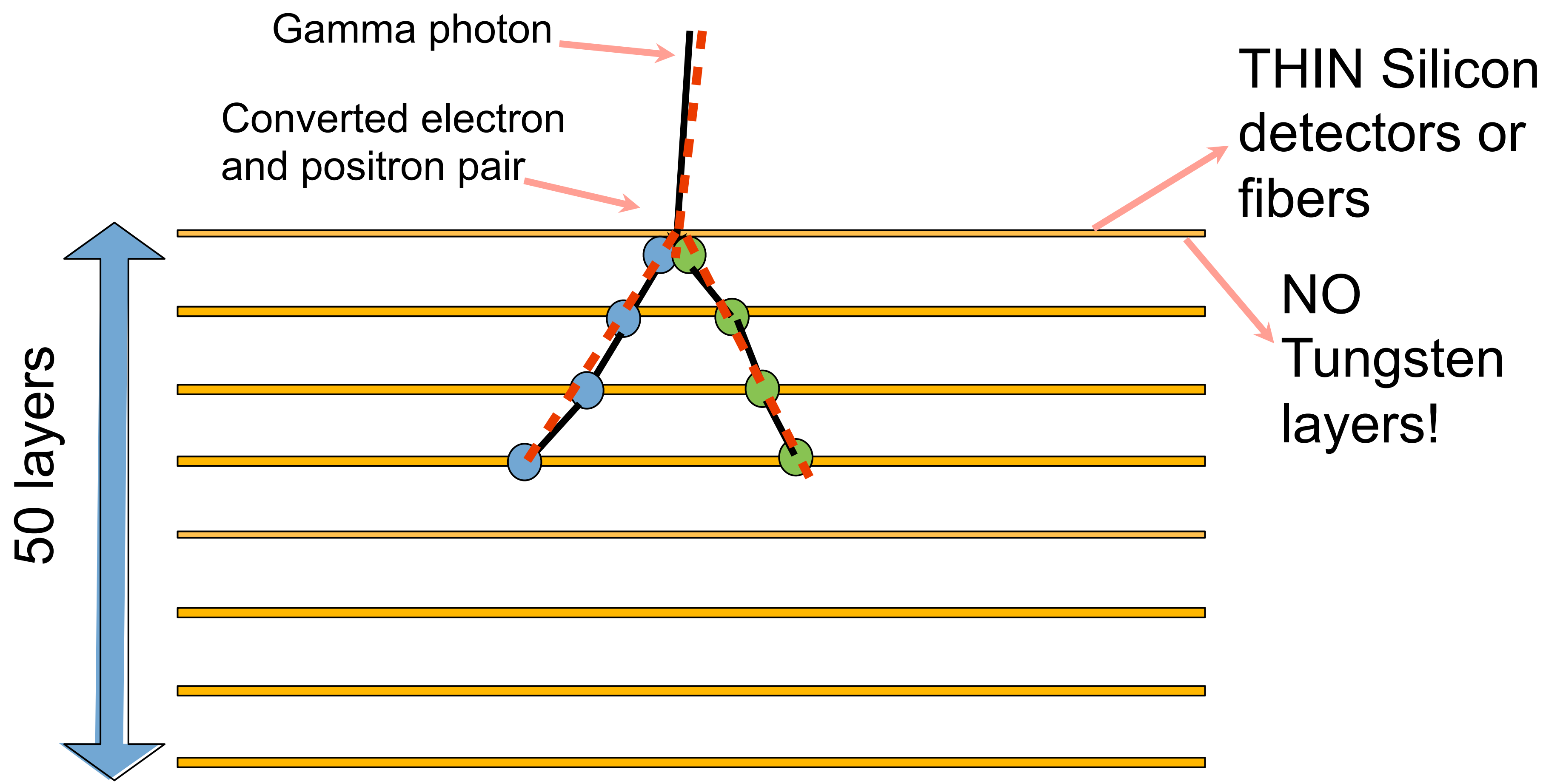
Detection principle:

How PANGU detects gamma-ray photons



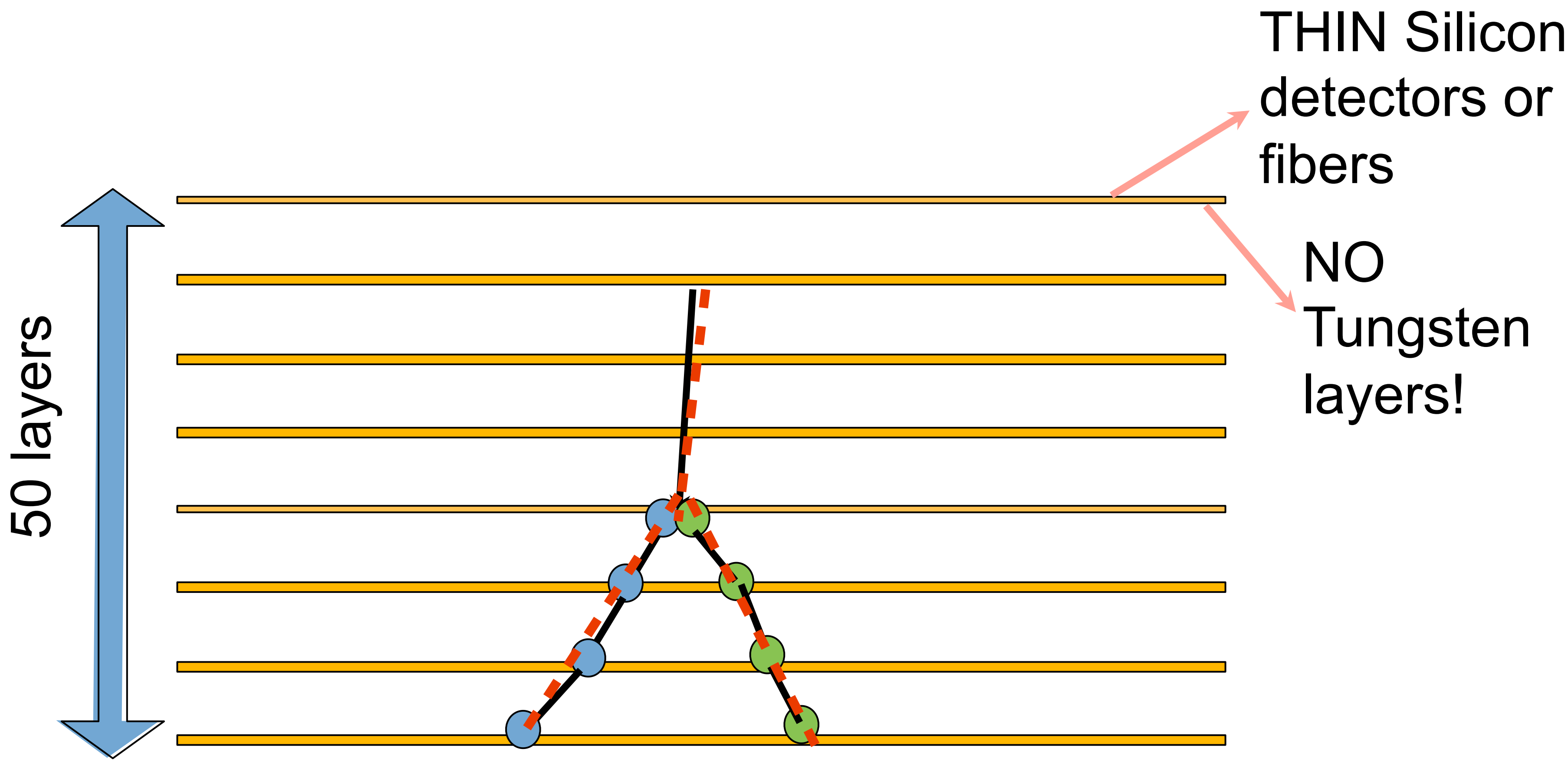
Detection principle:

How PANGU detects gamma-ray photons



Detection principle:

How PANGU detects gamma-ray photons



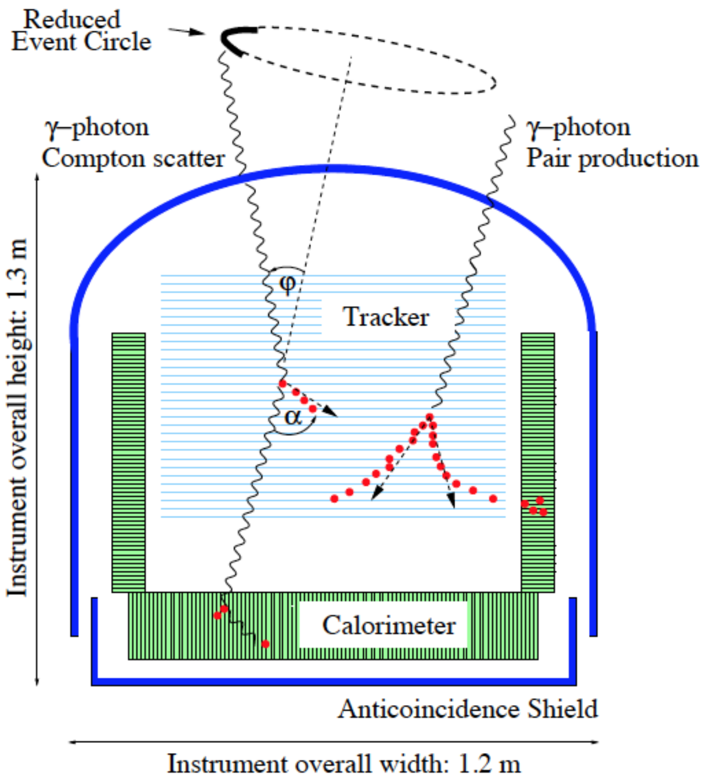
Possible Detector Concepts

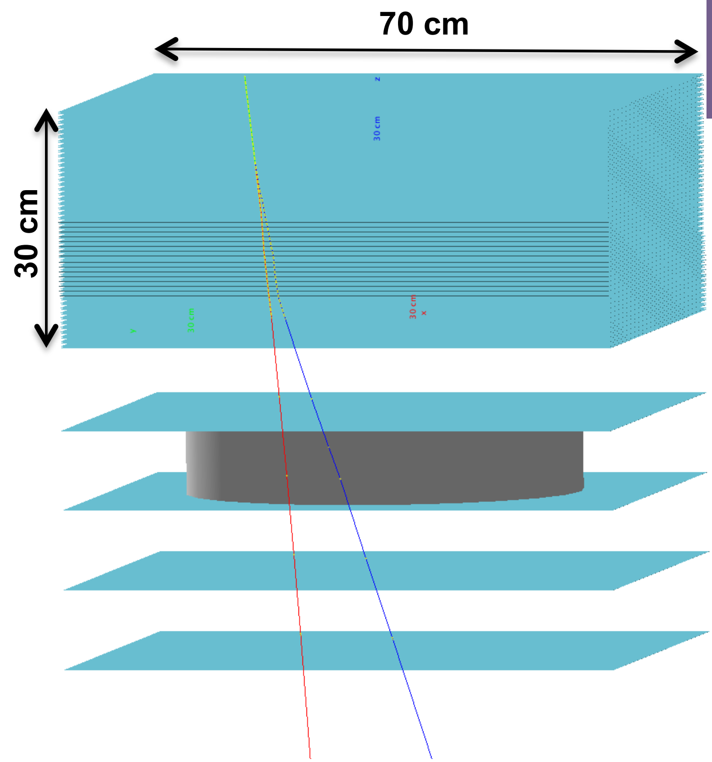
- To achieve $\lesssim 1°$ angular resolution passive material should be minimized and active detector should be thin or low density
  - To increase effective area (mass!) needs many layers or large volume
- Concepts for high resolution gamma pair telescope studied before
  - Low density gas TPC: *HARPO, AdEPT* (5-200 MeV), …
    - Potentially very good resolution
    - Need large pressure vessels (AdEPT: 6×1m^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-Si tracker or all-fiber light weight concept

Compton vs Pair Telescope

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

MEGA
~650 kg

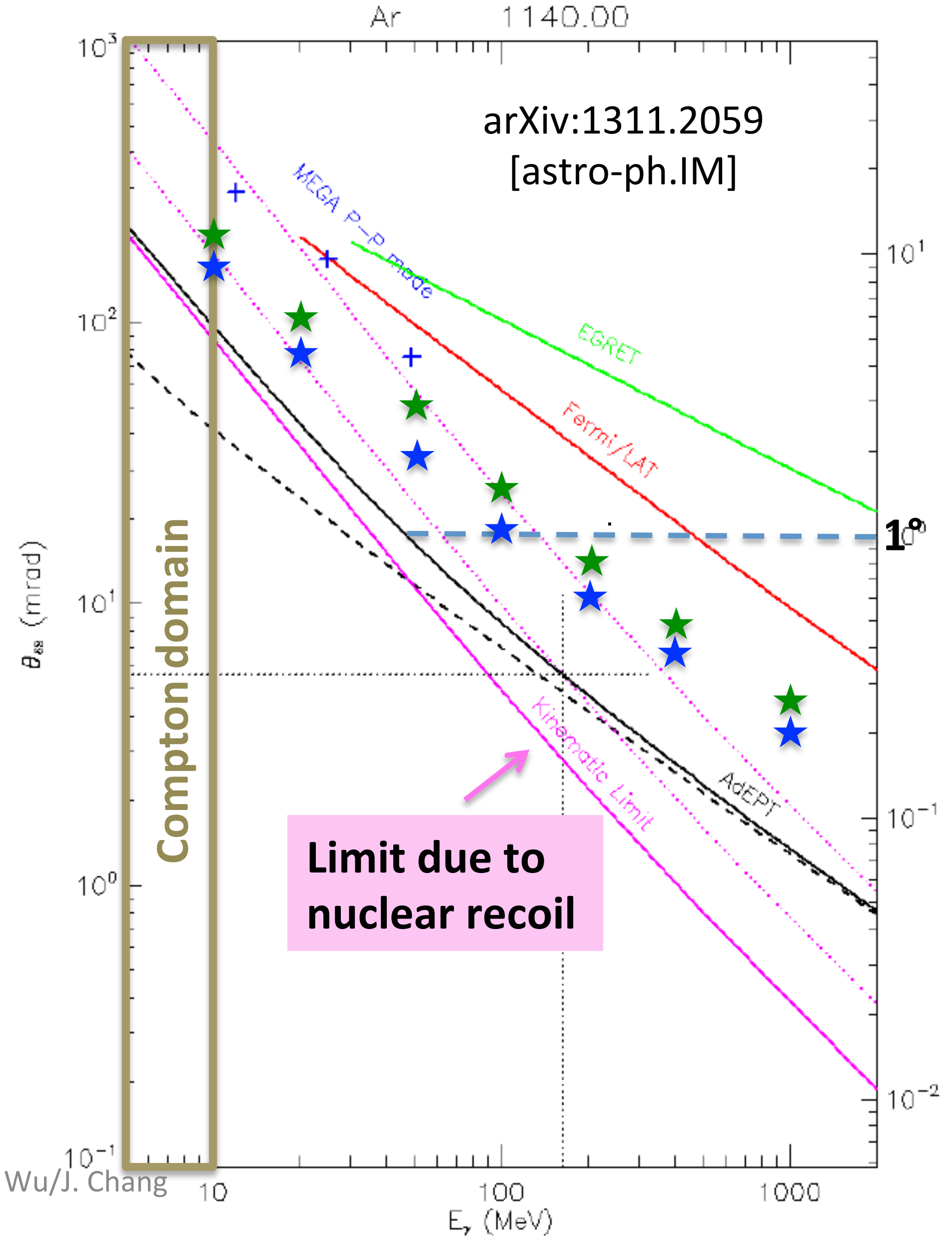




PANGU
<100 kg

- **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**

Angular resolution of pair telescopes



★ PANGU: both tracks in target

★ PANGU: both tracks in spectrometer

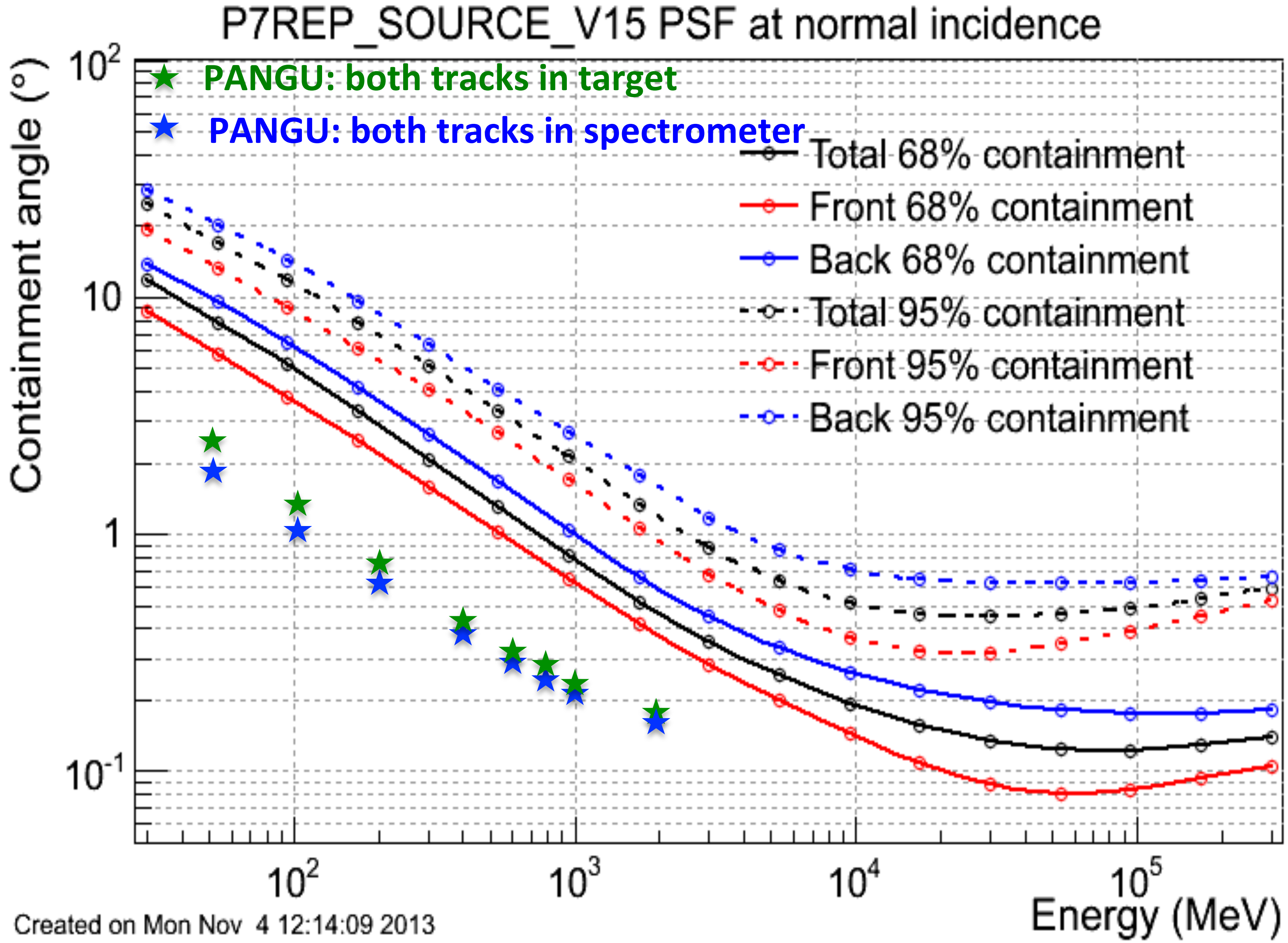
- Geant4 simulation with 150 μm thick single-sided Si detector, 242 μm pitch

  ⟹ position resolution ~70 μm
- Results are very preliminary

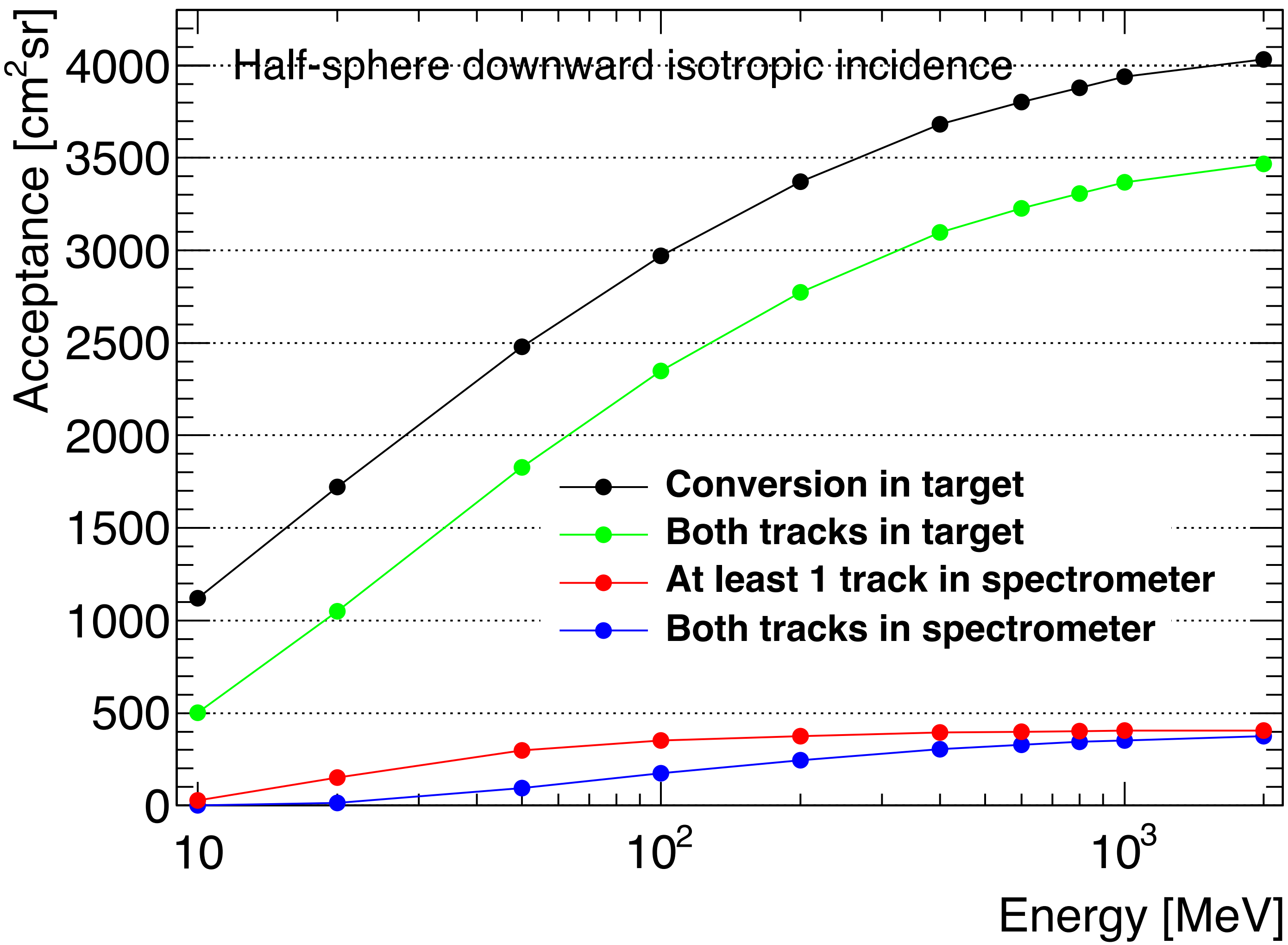
Very limited energy measurement if no tracks in spectrometer

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

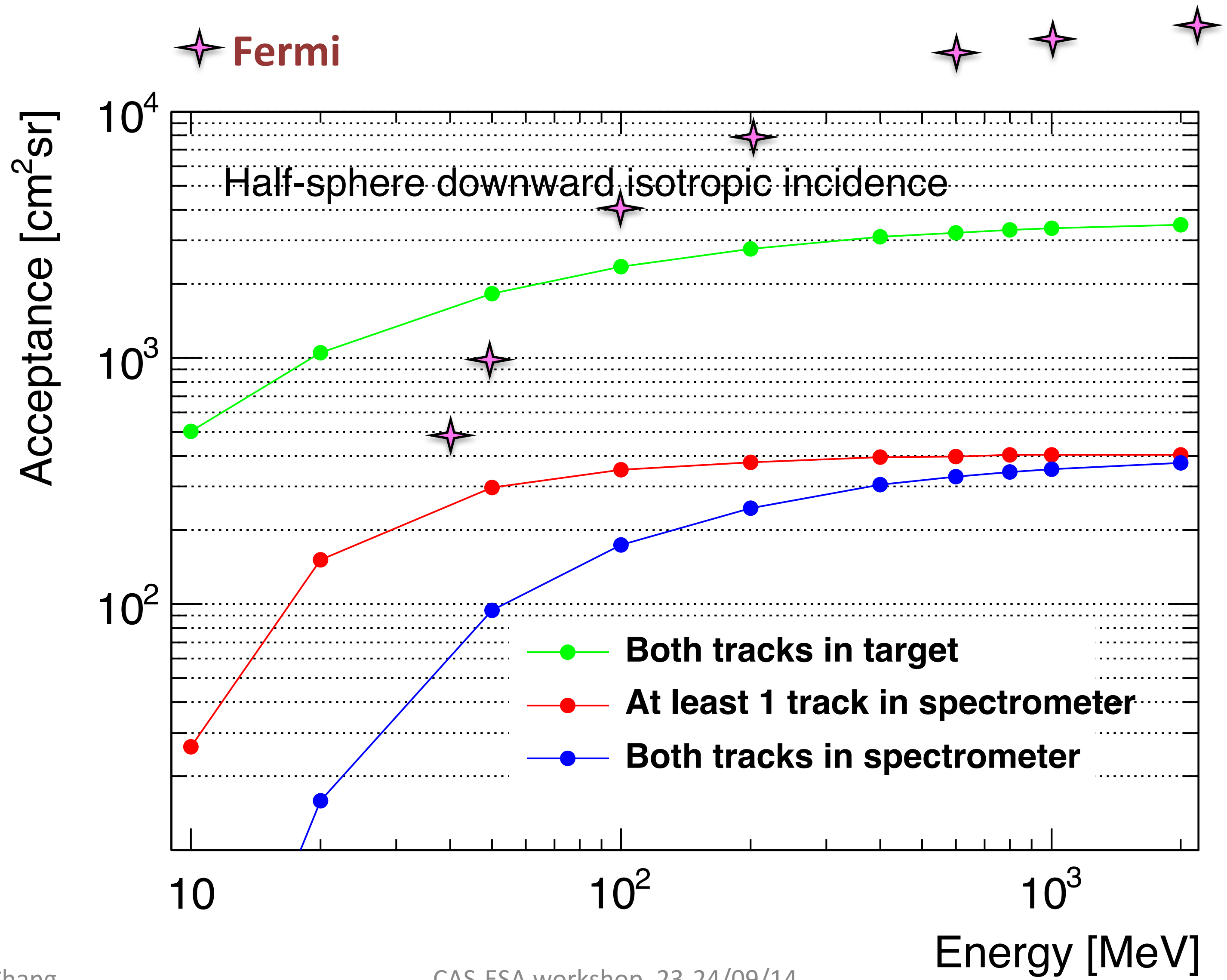
PSF Comparison with Fermi



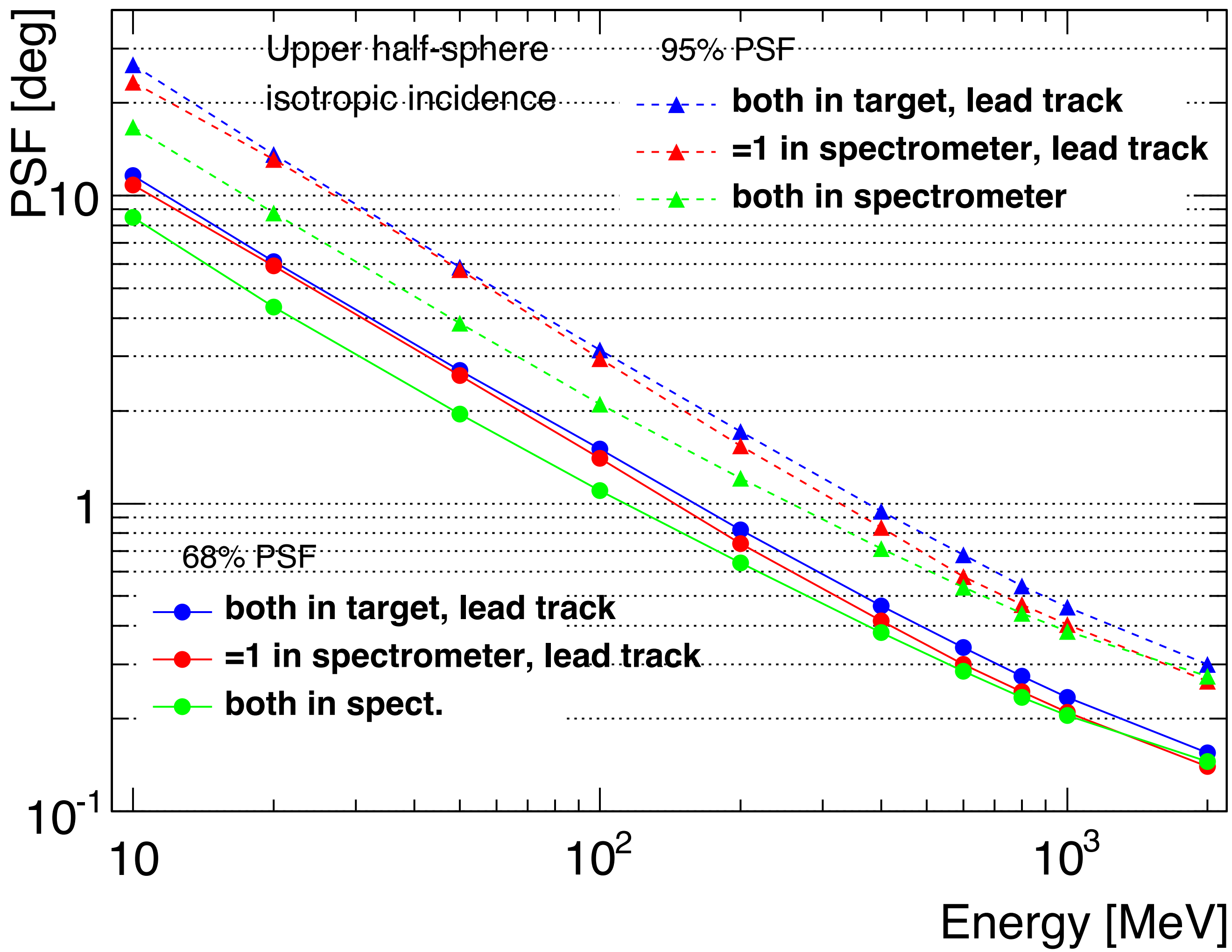
Acceptance


Half-sphere downward isotropic incidence
Acceptance [cm²sr]
4000
3500
3000
2500
2000
1500
1000
500
0
10
10²
10³
Energy [MeV]
Conversion in target
Both tracks in target
At least 1 track in spectrometer
Both tracks in spectrometer

Acceptance Compared to Fermi

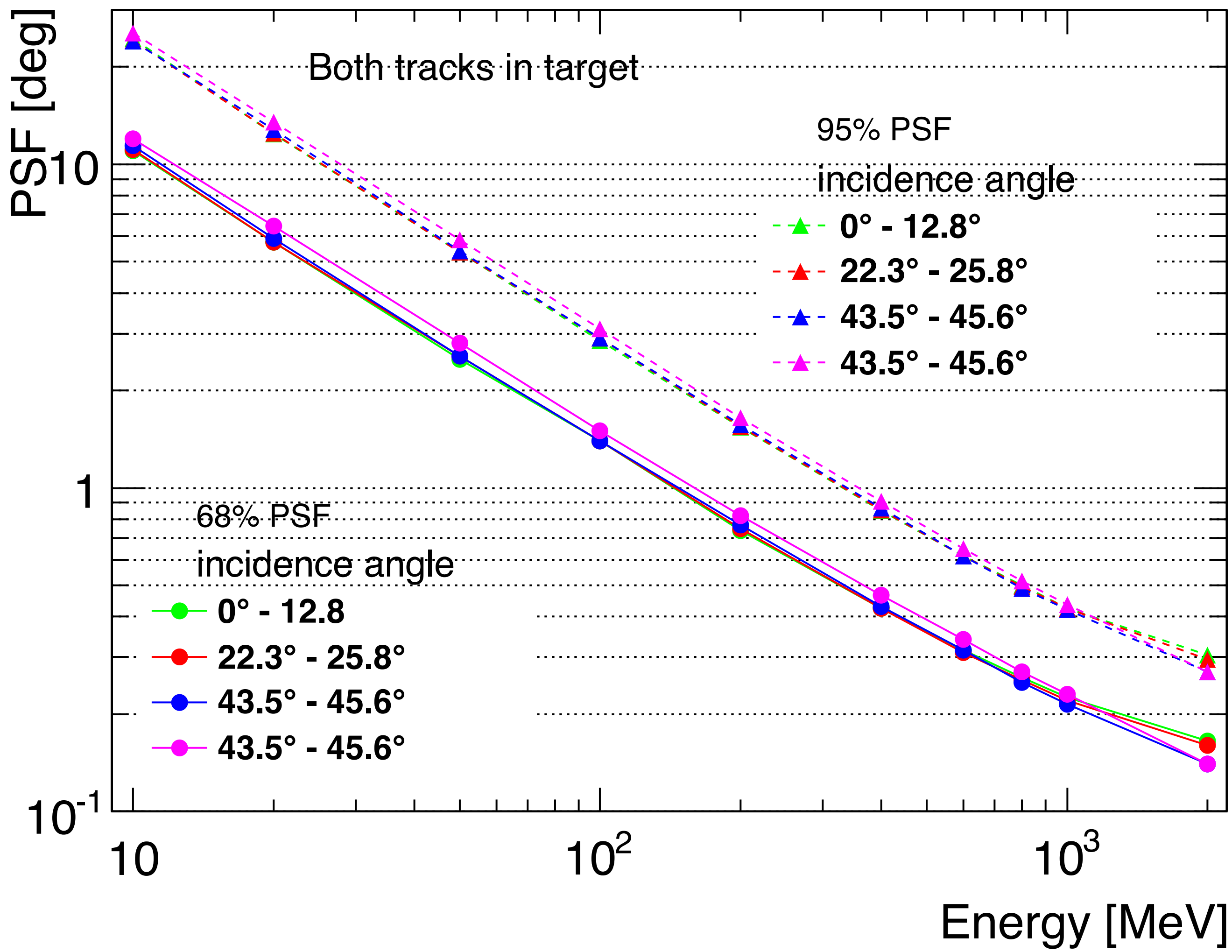


Point Spread Functions vs. Type



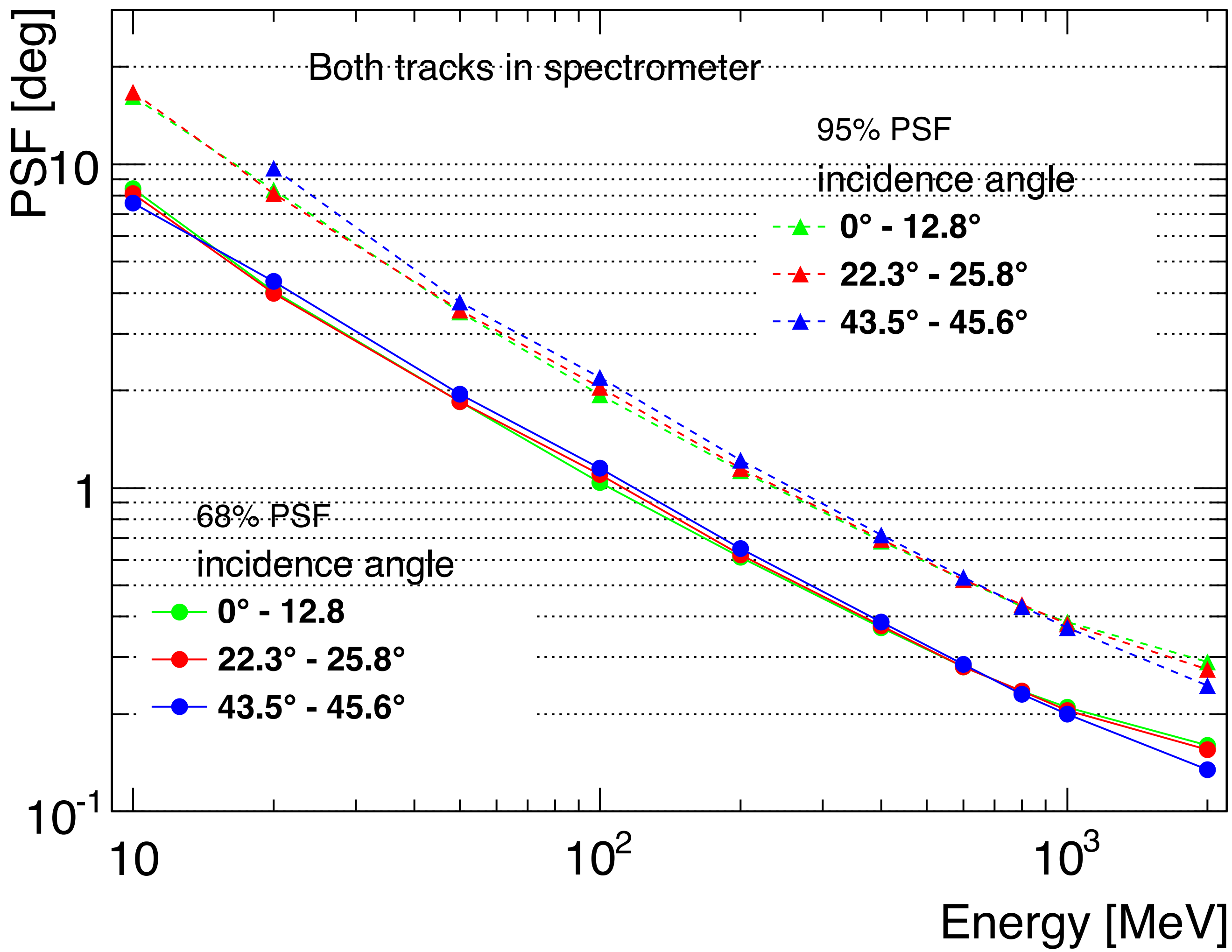
Averaging over all isotropic incidence angles within acceptance

Point Spread Functions vs Incidence



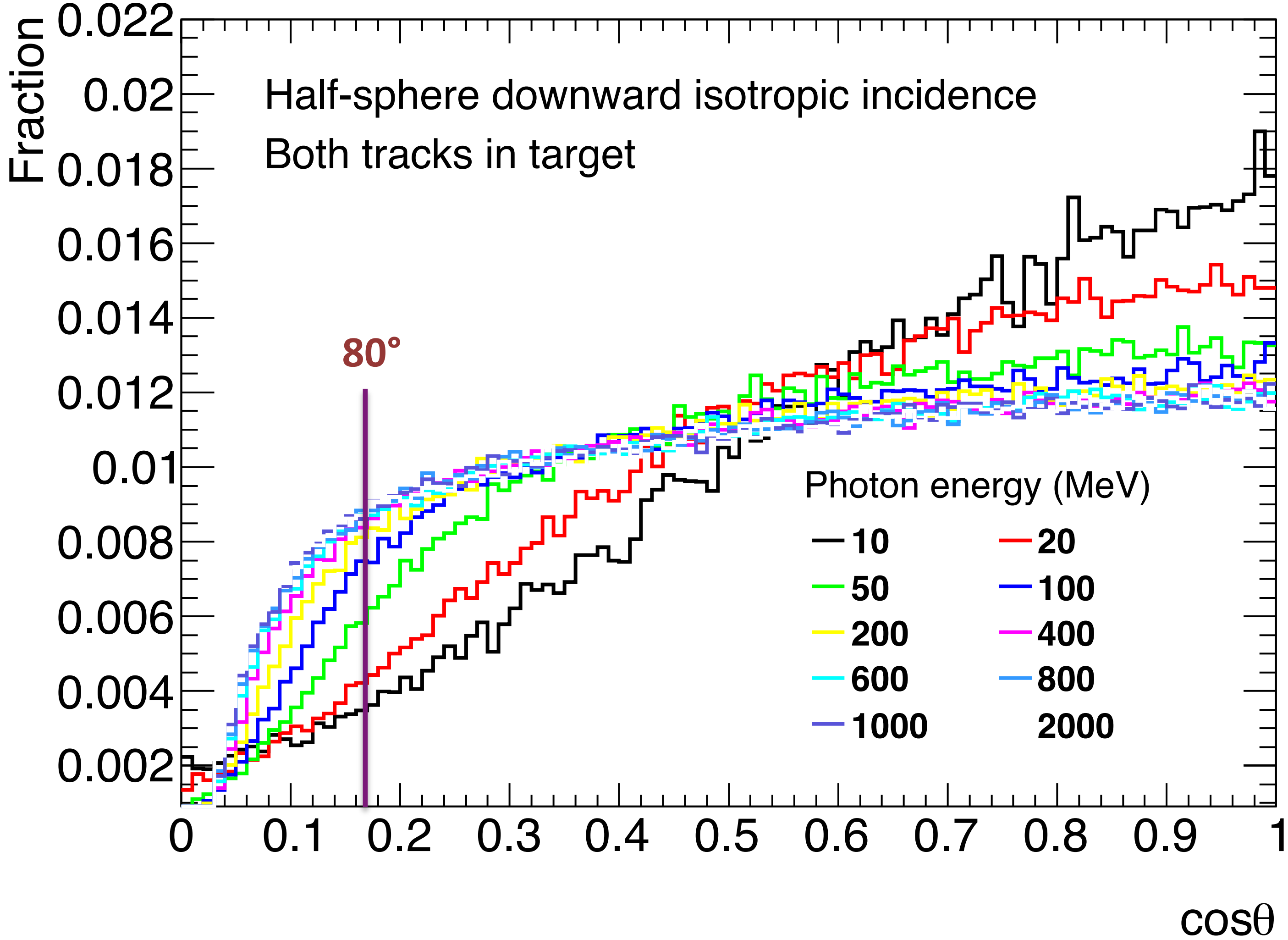
Both tracks in target

Point Spread Functions vs Incidence



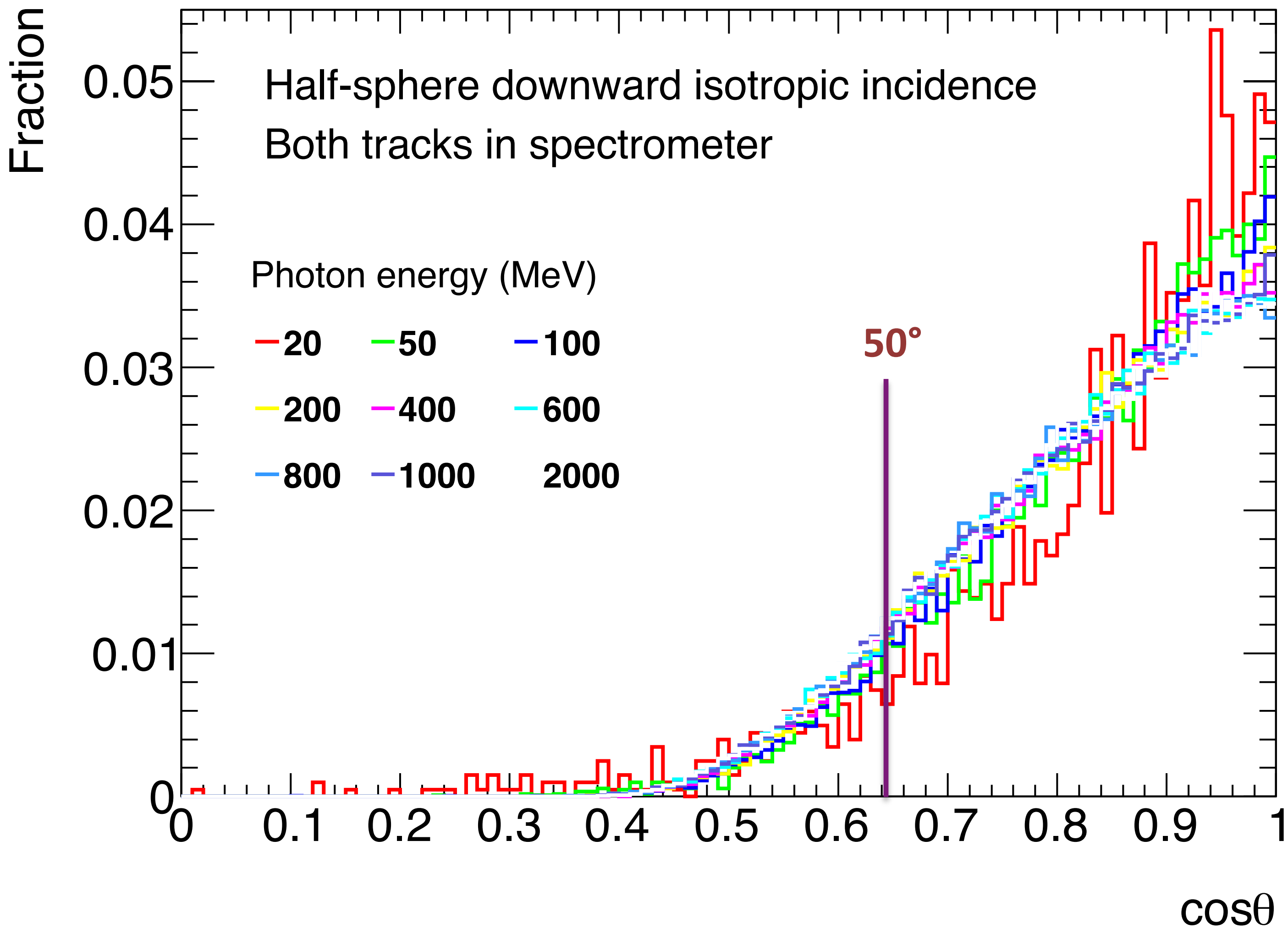
Both tracks in spectrometer

Angular Relative Acceptance



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

Angular Relative Effective Area



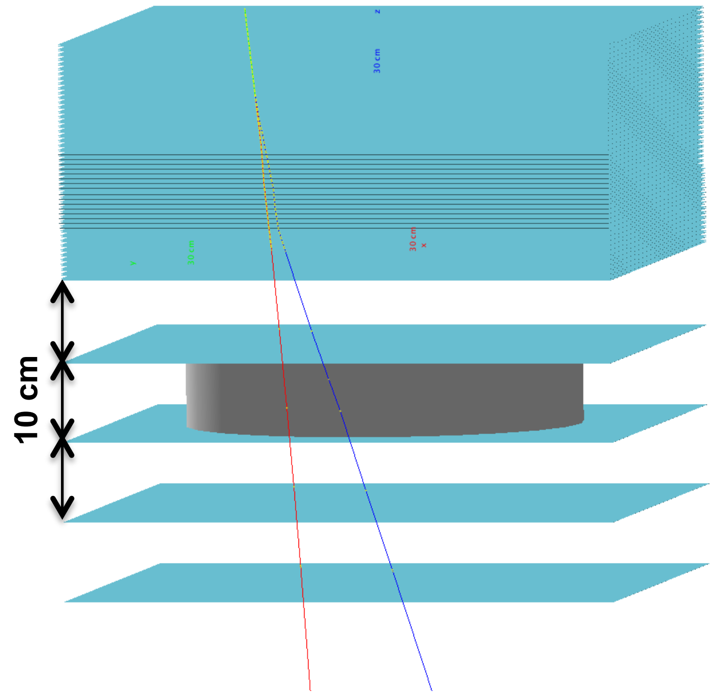
How about the energy measurement?

- 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

PANGU Magnetic Spectrometer

- **Momentum measurement through bending angle**
  - **θ = 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**

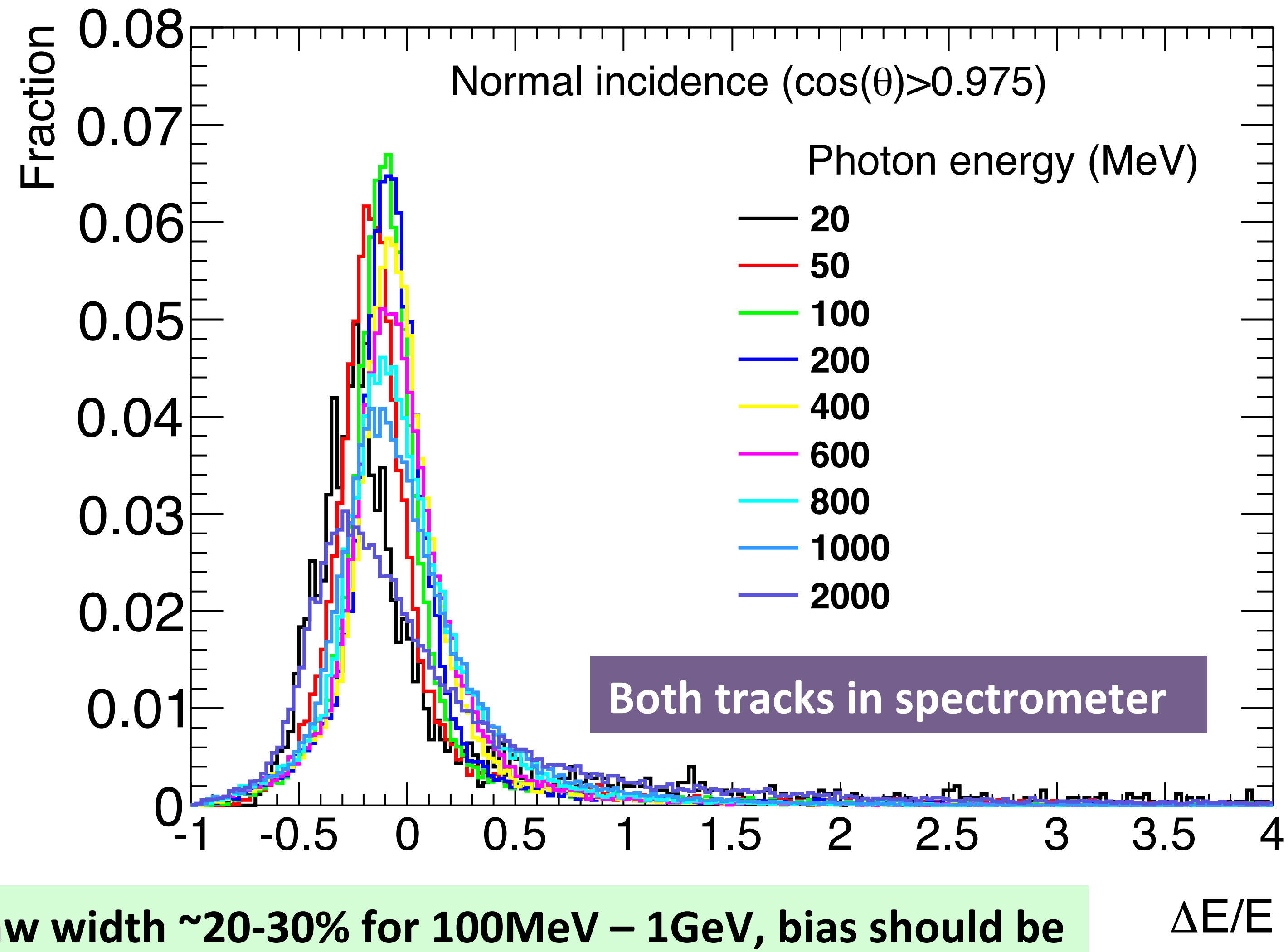
For p = 100-1000 MeV
Δp/p ~30%-50% reachable
with B=0.1 T, L = 10 cm,
σ_x=70 µm, d = 10 cm



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 = $10x(26.9^2-25^2)\pi = 3098\ cm^3$
  - 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

Energy Resolution



Raw width ~20-30% for 100MeV – 1GeV, bias should be corrected, eg. with energy measured in tracker

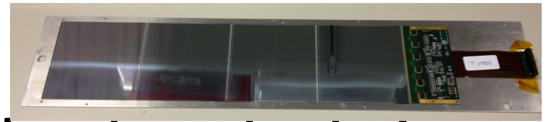
The Target-Tracker

- 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!

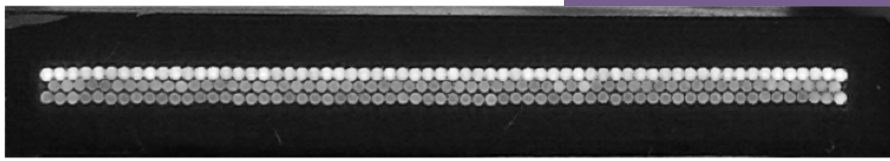
PANGU-Si vs PANGU-Fi

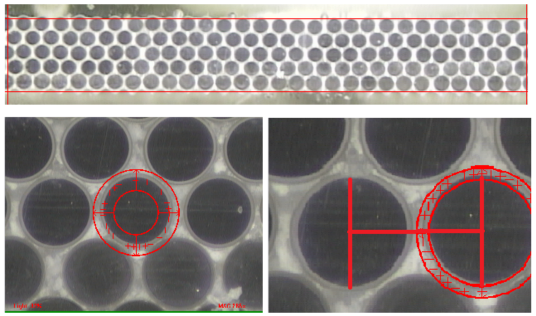
- **Silicon and fibers trackers are both viable technologies**
  - **Challenges are mainly engineering: optimal use of the limited weight (ultra-light module) and power budgets (low power ASICs)**
- **Silicon has been successfully used in similar space missions**
  - **Fermi, AGILE, Pamela, AMS-02, …**

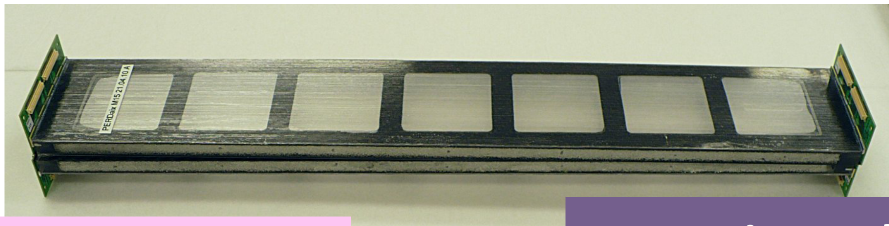


- **Fiber is cheaper, less fragile, more flexible geometry, but the technologies of scintillating photon detector (SiPM) and readout ASICs are newer**
  - **Recent developments in high energy physics, eg. LHCb, Mu3e, …**
    - **Also in space: balloon prototype PERDaix of PEBS**
  - **Position resolution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

Mu3e module







NIMA 628(2011)403

PERDaix module

X.

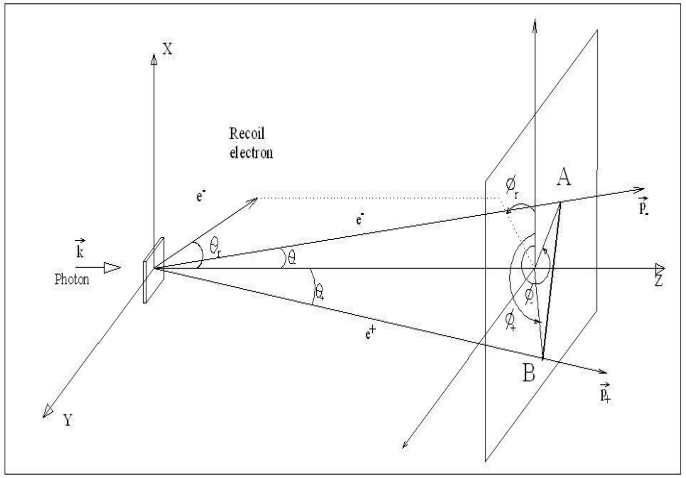
Power Consumption

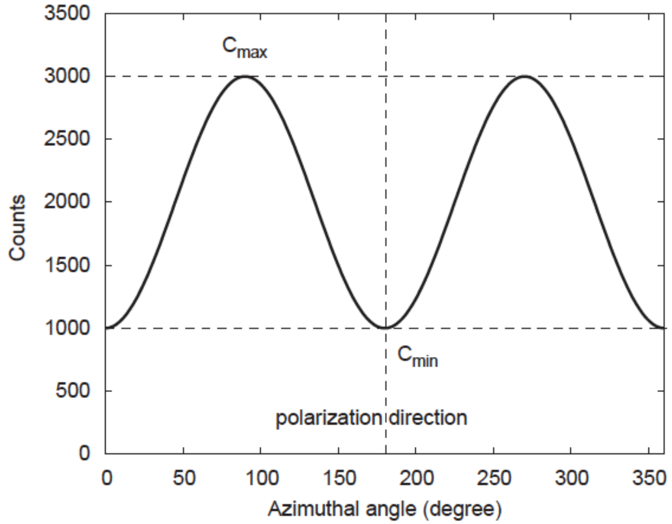
- **Total number of readout channels of 50 double-layers in the target + 6 layers in the lower tracker, with 250 µm readout pitch, is ~300k channels**
  - **Si strip detector pitch ~250µm, fibers can be readout by SiPM of 250 µm pitch**
- **Current Si readout ASIC consumes ~0.2mW/channel**
  - **Push 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**

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



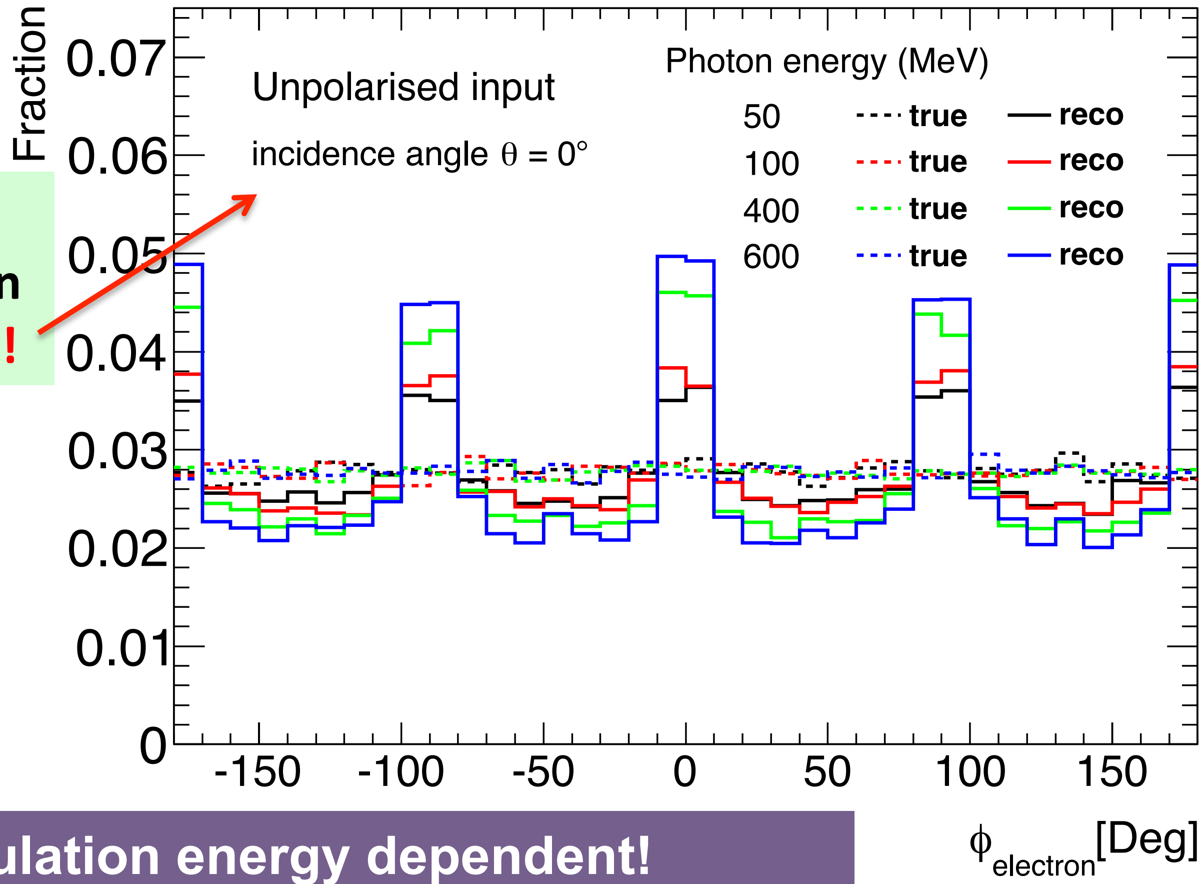


- Keys to the measurement
  - Azimuthal angular resolution
    - transverse track length and multiple scattering
  - Intrinsic modulation of the detector!

Detector Intrinsic Modulation

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

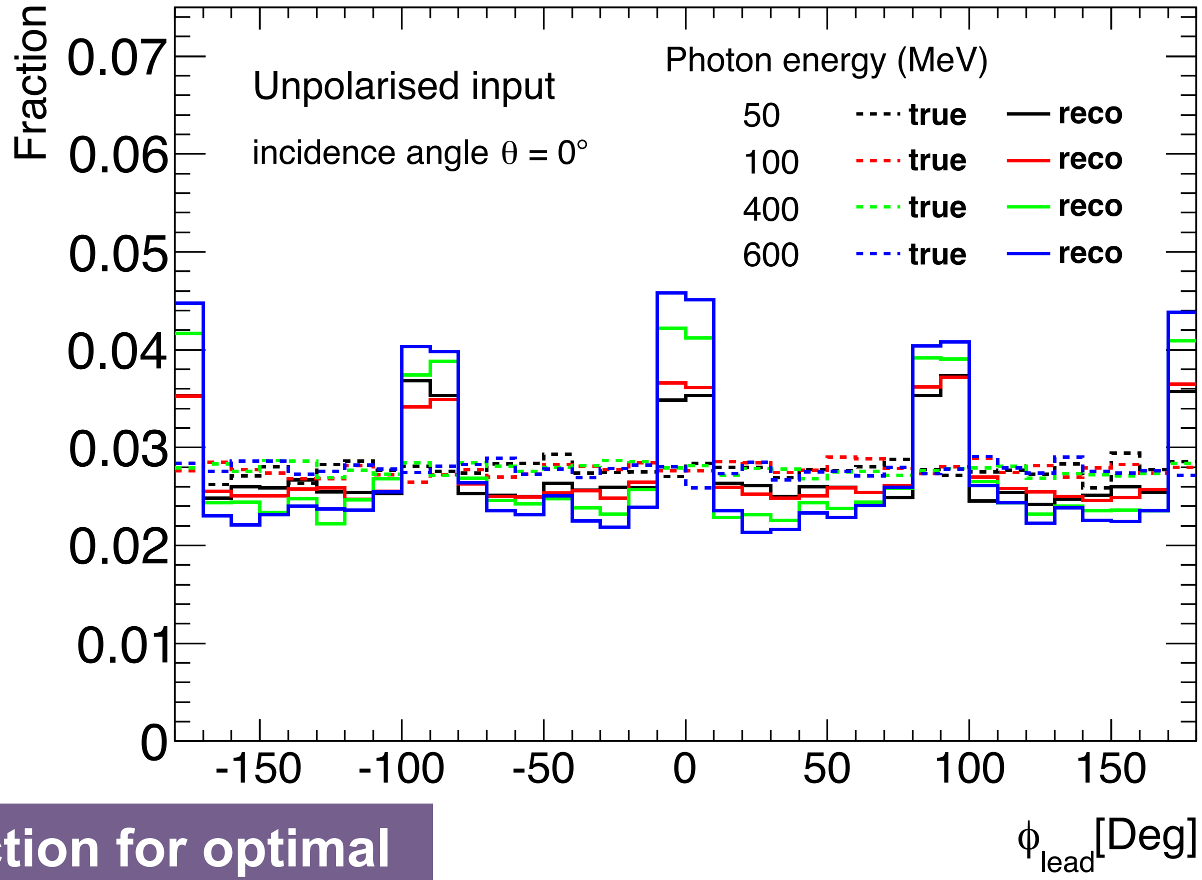
Intrinsic modulation is a function of photon direction
Best with normal incidence!



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

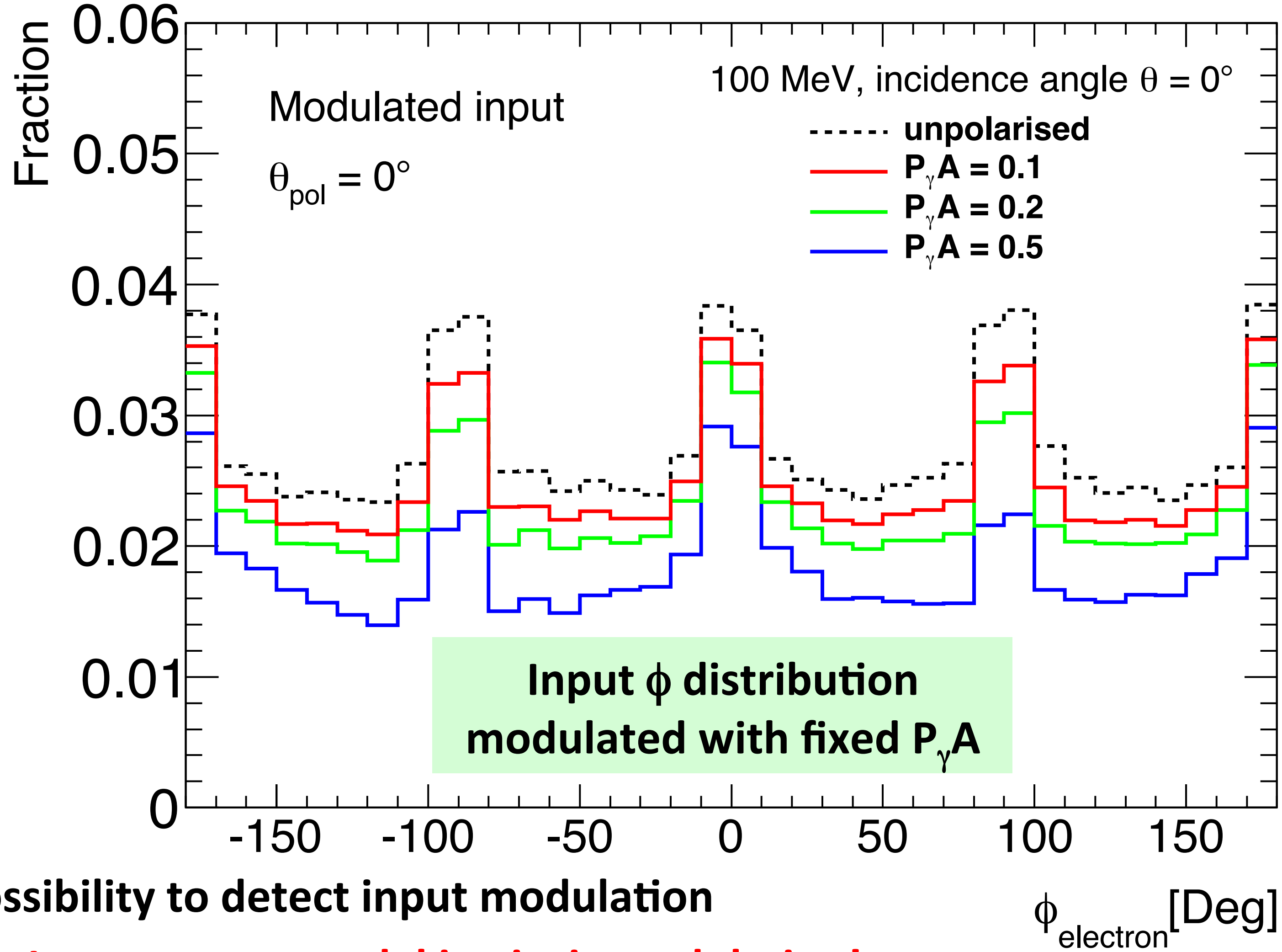
Intrinsic Modulation, Leading Track

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



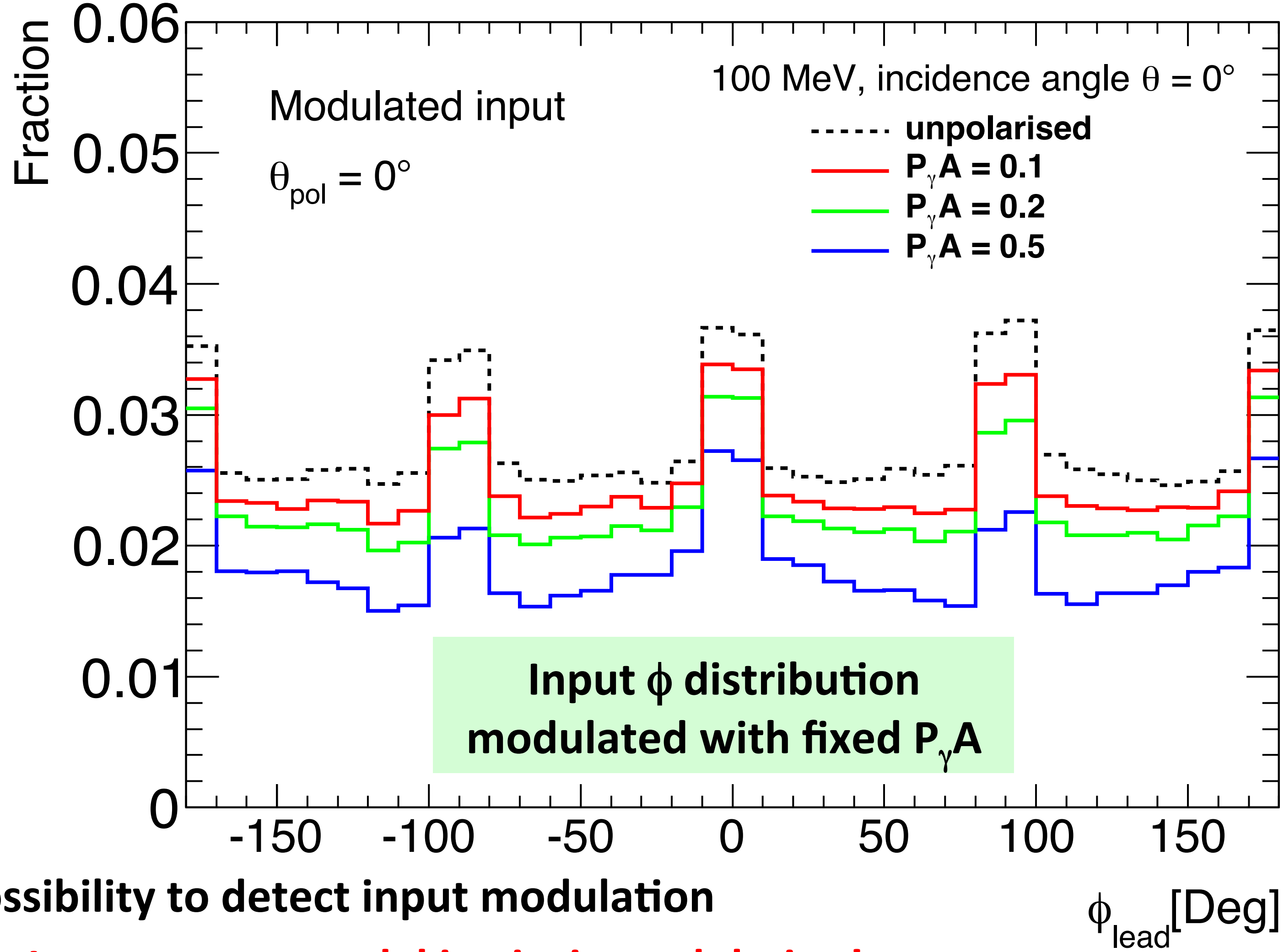
Variable and selection for optimal $P_\gamma A$ should be further studied

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**

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**

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 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**