Lessons learned for high precision trackers for future space missions in light of the *Fermi* Large Area Telescope experience

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on behalf of the *Fermi*-LAT collaboration

Vertex 2015, Santa Fe NM

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Outline

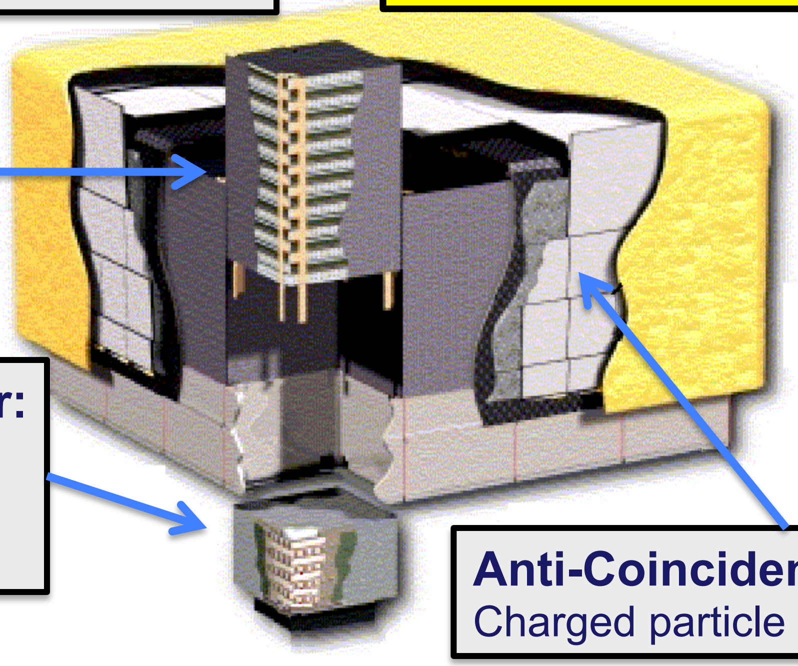
- The Silicon Tracker on the *Fermi* Large Area Telescope (*Fermi*-LAT)
  - See talk by Luca Baldini at Vertex 2013 for many more details about the *Fermi*-LAT Tracker construction and performance
- Context: γ-ray astronomy
- Looking forward: the next MeV to GeV γ-ray telescope
  - Science case
  - Design considerations
- Relevant lessons learned from the *Fermi*-LAT
- Summary
- Bonus Slides
  - State of the art: proposed mission concepts for γ-ray astronomy
  - *Fermi* sky-survey strategy, backgrounds

The *Fermi* Large Area Telescope

GBM (not pictured):
Covers entire un-occulted sky from 8 keV to 40 MeV

LAT: ~1m x 1.5m, 2800 kg

***Fermi*-LAT Collaboration:**
~400 Scientific Members, NASA / DOE & International Contributions



Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM v. hadron separation

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
With 2.4 sr field-of-view LAT sees whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

Atwood et al. 2009ApJ...697.1071A
Ackermann et al. 2012ApJS..203....4A
http://www-glast.stanford.edu/

Fermi design considerations, in pictures

Fermi spacecraft in payload fairing

Mission costs increase dramatically with payload size, mass and complexity

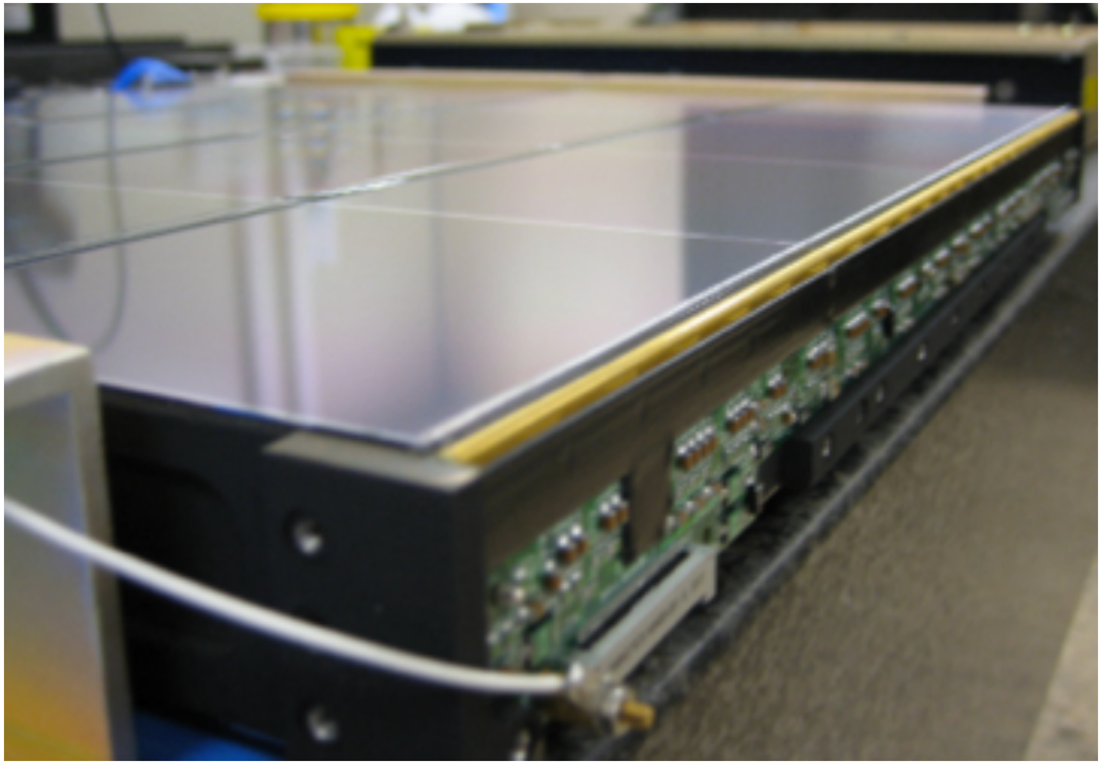
Launch: June 13th 2008

Instruments must survive launch, multiple years of operations in space

Power, heat dissipation, and data rate are more constrained than on ground

The *Fermi*-LAT tracker/ convertor

Tracker Bi-Layer, support structure and readout



Tracker tower (1 of 16)

Note the amount of non-sensor material (support structures, electronics) in addition to the Tungsten converters

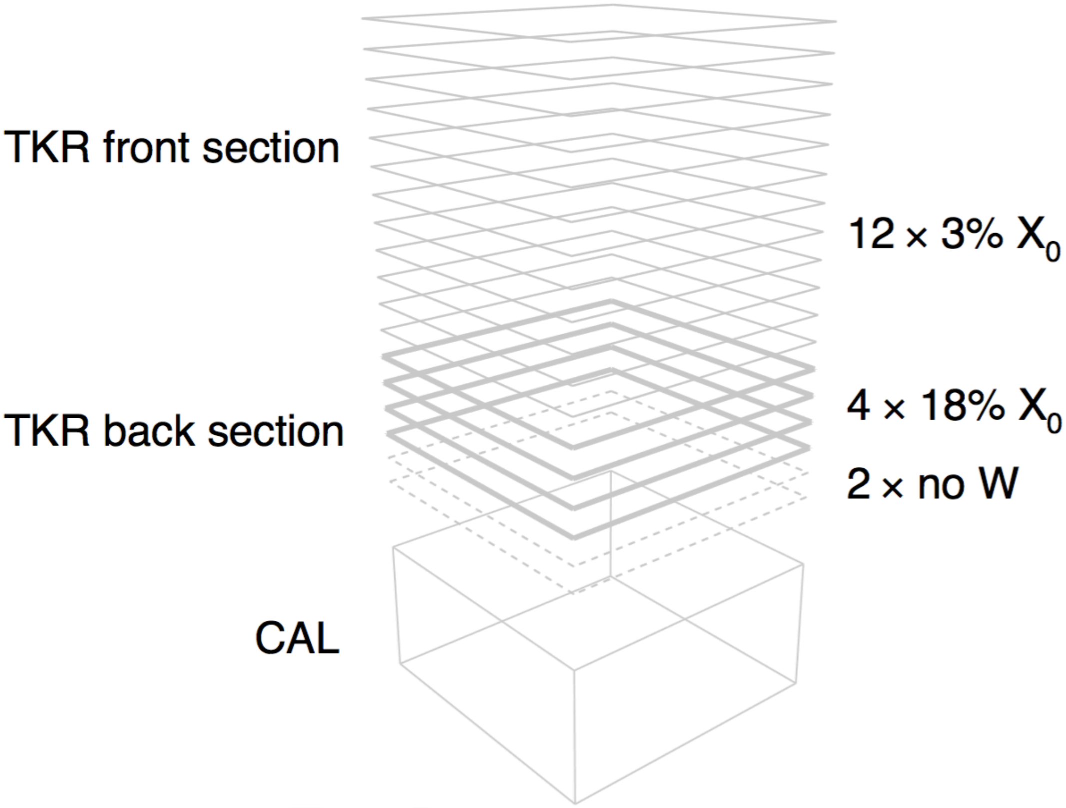
LAT tracker essentials

- 16 Modular towers
- 18 bi-layers, (x,y planes)

- 12 Layers thin (0.03 X_0) Tungsten
- 4 Layers thick (0.18 X_0) Tungsten
- 2 Layers no Tungsten

- Thickness: 400μm, Pitch 228 μm
- Point Resolution ~ pitch / sqrt(12)

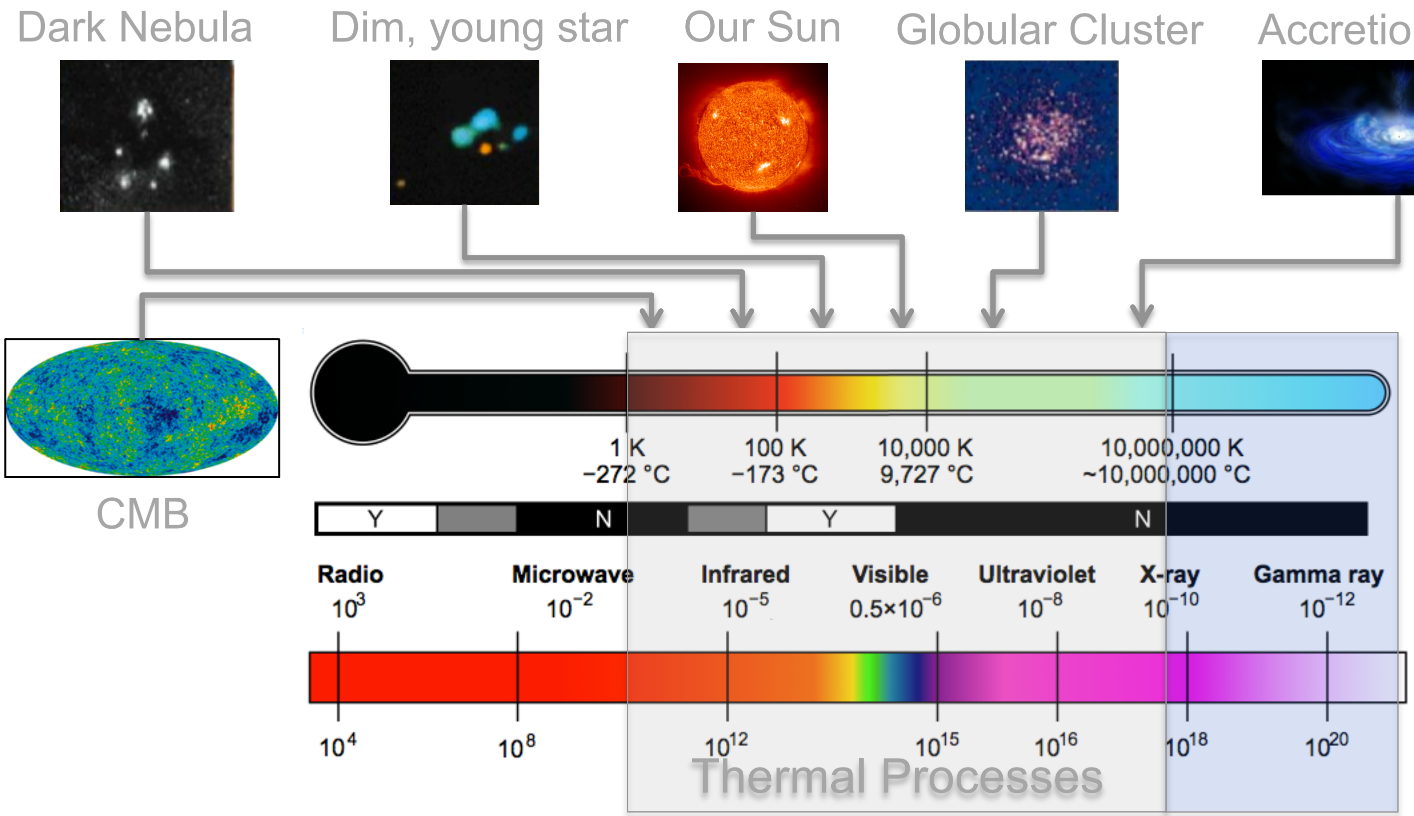
- Low power consumption
  - ≈ 200 μW/channel
  - LAT : 600W total
- Shaping time: 10μs
- Low noise occupancy
  - ≈ 1 noise hit per event in LAT
- Self-triggering (1.5 μs)
  - three x–y planes in a row
- Redundancy
  - 2 readout paths for all channels
- On-board zero suppression



No degradation of the excellent performance since launch!

GAMMA-RAY ASTRONOMY

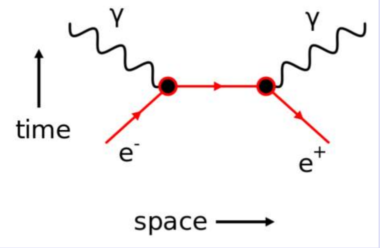
γ-rays Probe the Extreme, Non-Thermal, Universe



Energy & particle source

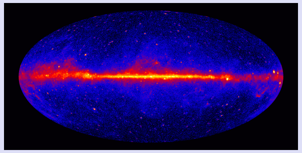
Acceleration mechanism

γ-ray production mechanism



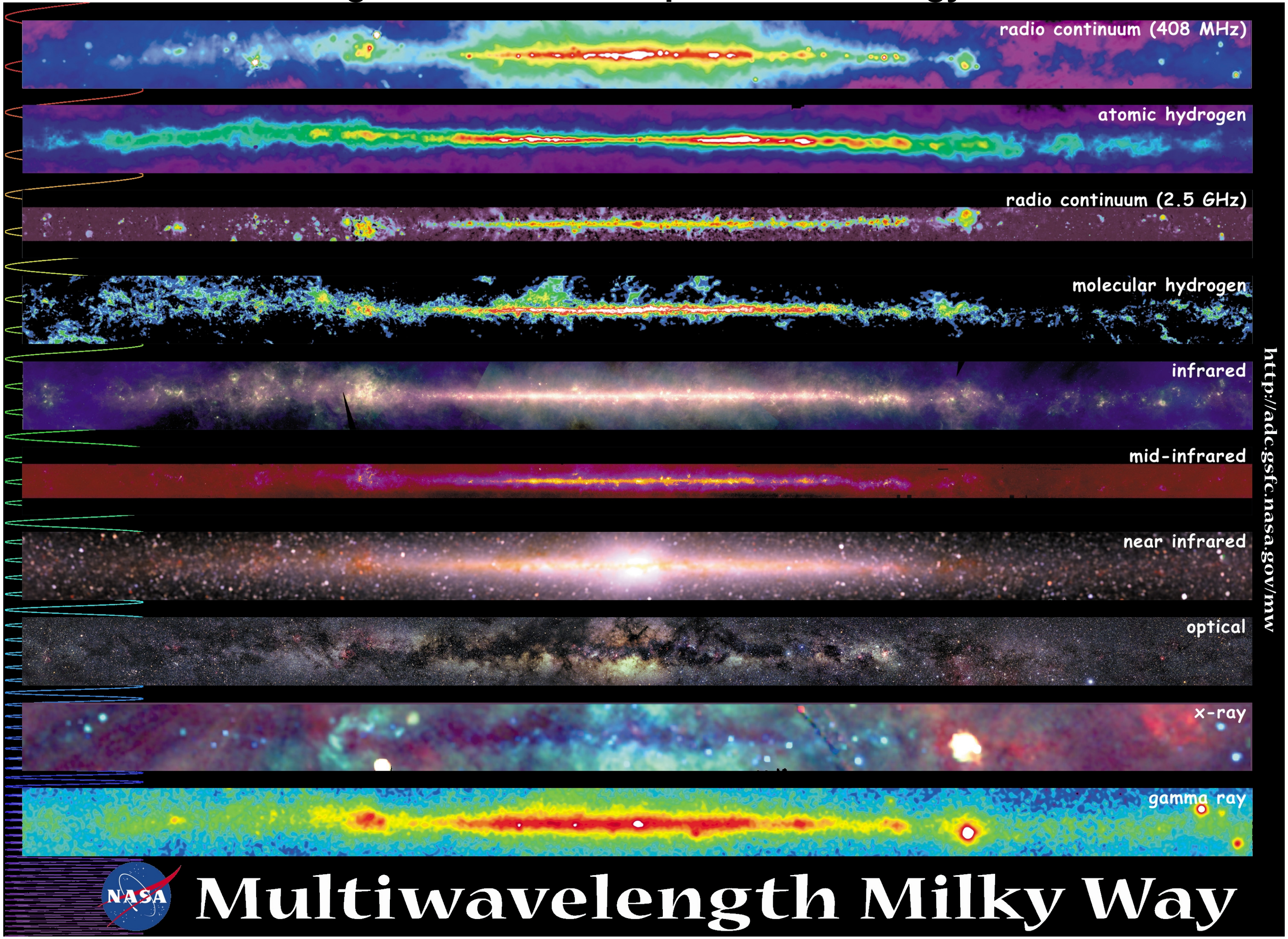
Foreground Effects

γ-ray sky



Multi-wavelength studies are crucial for Astronomy

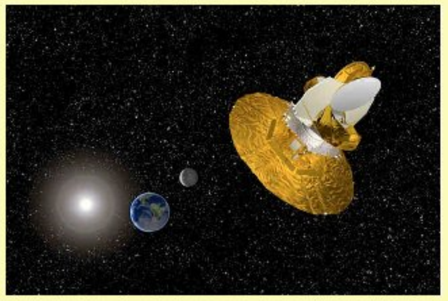
360° images of the Galactic plane in 11 energy bands



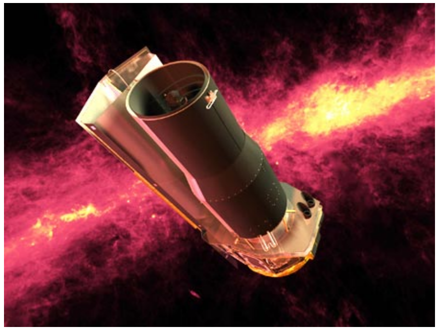
Higher Energy

Synergy with other instruments

Radio: pulsations, synchrotron emission, gas / dust maps, high resolution imaging of host galaxies…



Microwave: diffuse maps & morphology, host galaxy characteristics…

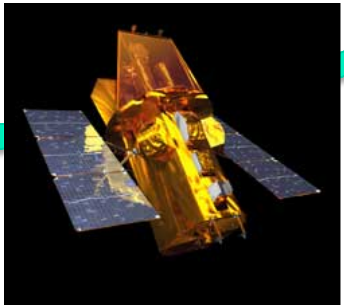


IR: gas/ dust maps, host galaxy characteristics

LAT Source Localization ~0.1°--0.01° comparable to the fields of view of many telescopes… Great for followups

Energy

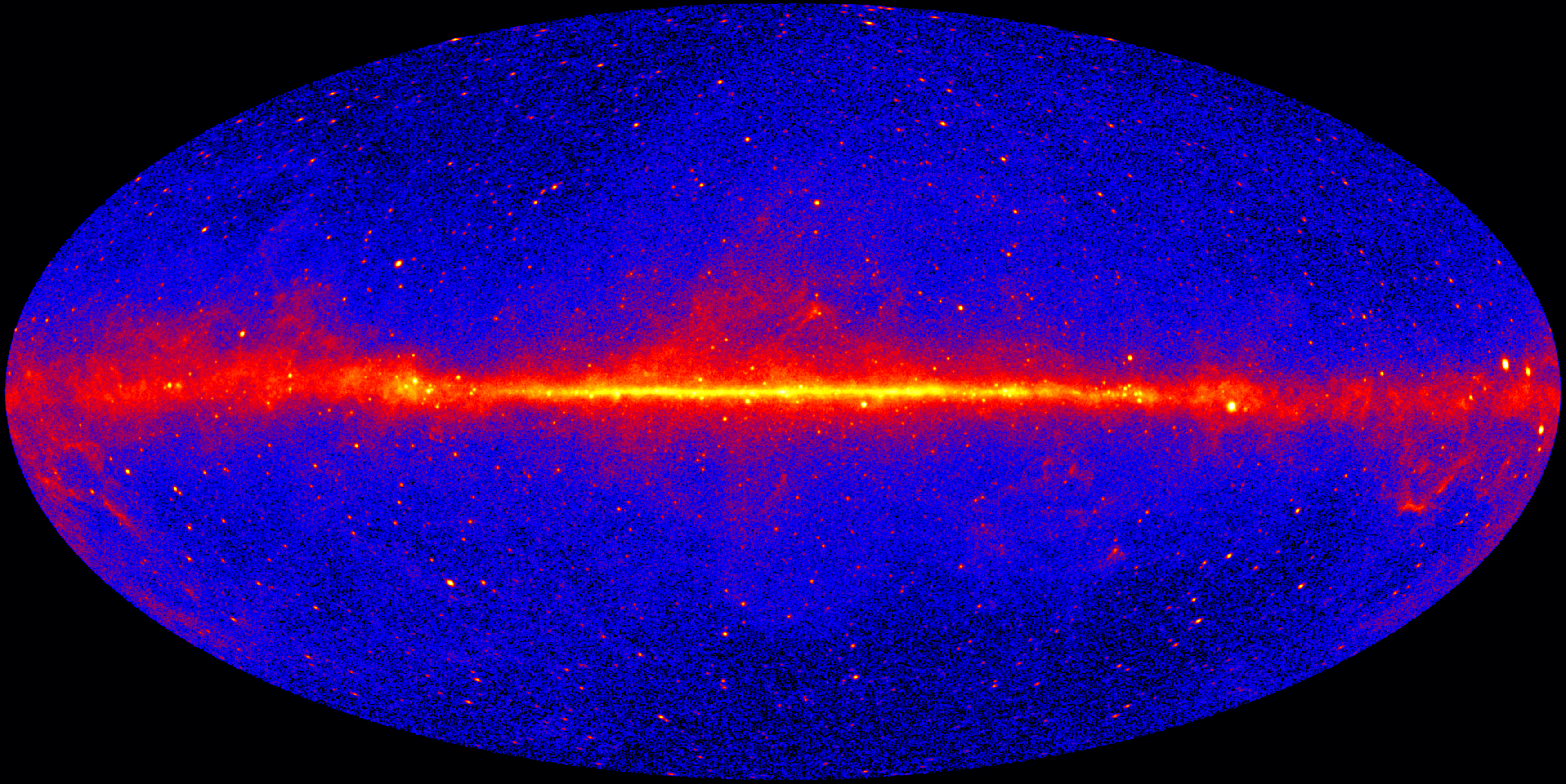
TeV: High-energy spectral breaks, supernovae morphology…



X-ray:
GRB afterglows, Galactic source morphology & pulsar association…

Optical:
GRB afterglows, AGN/ GRB redshifts, Dark Matter targets

Fermi γ-ray Sky

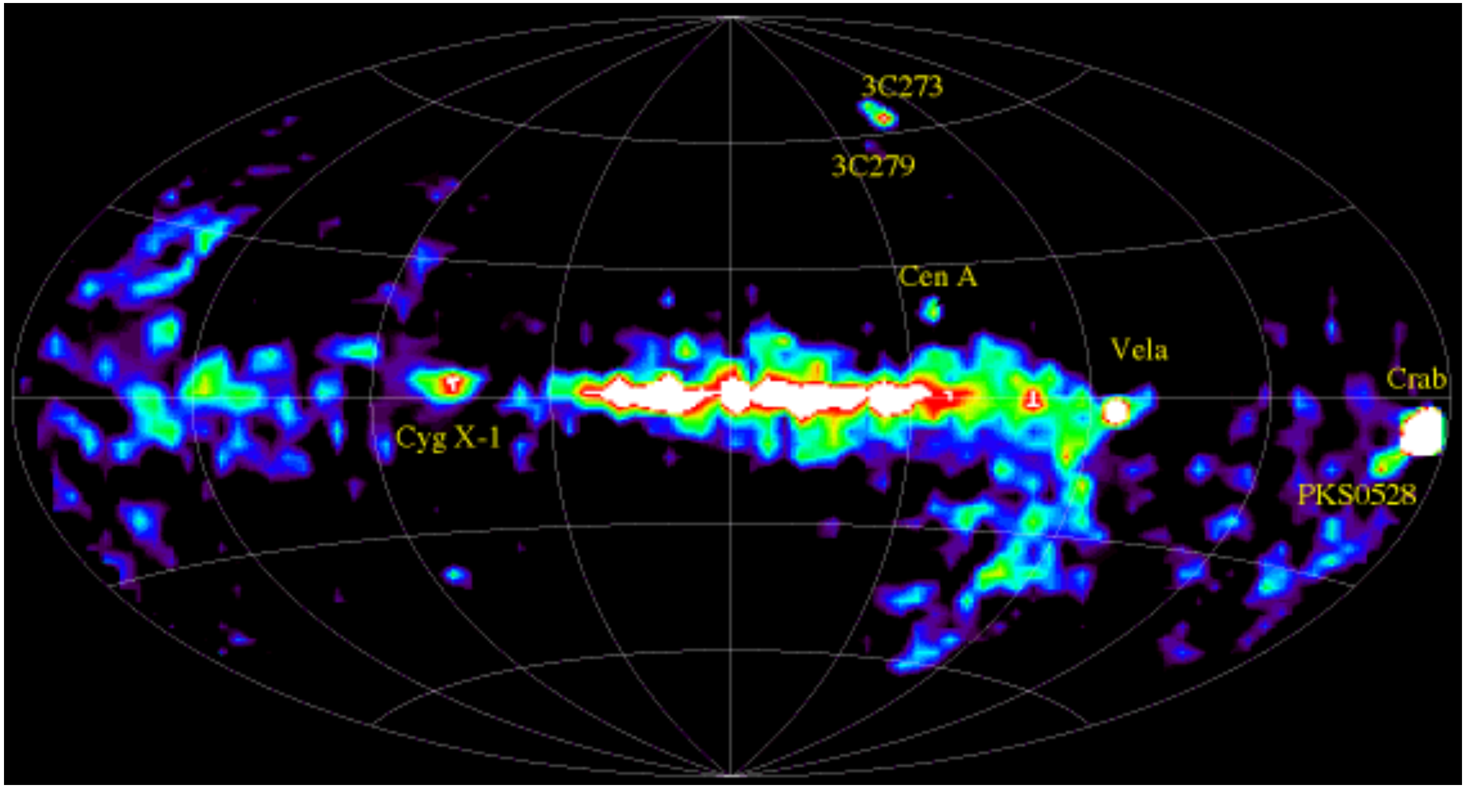


Fermi-LAT: 5 Year Sky,
Front-converting events > 1 GeV
All-sky map, exposure corrected,
Aitoff projection, Galactic coordinates

SCIENCE CASE FOR THE NEXT MEV TO GEV TELESCOPE

The under-explored MeV sky

COMPTEL Flux map: 1-30 MeV, full data set



CGRO Science Support Center

- COMPTEL catalog contains 32 steady sources[1], including a few such as "Extended emission from the HVC [high velocity cloud] complexes M and A area"

[1] Schoenfelder et al. (2000) [astro-ph/0002366]

Source sensitivities in the 100 keV to 100 MeV band

Point source sensitivity of X- and γ-ray telescopes

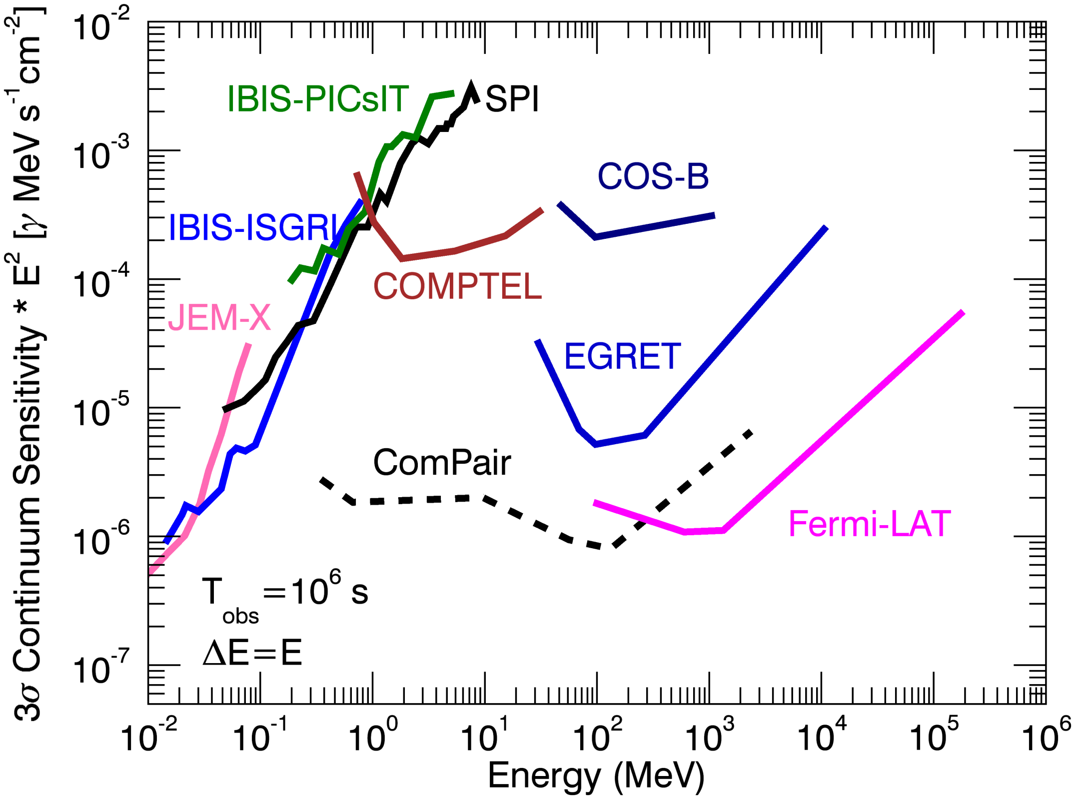
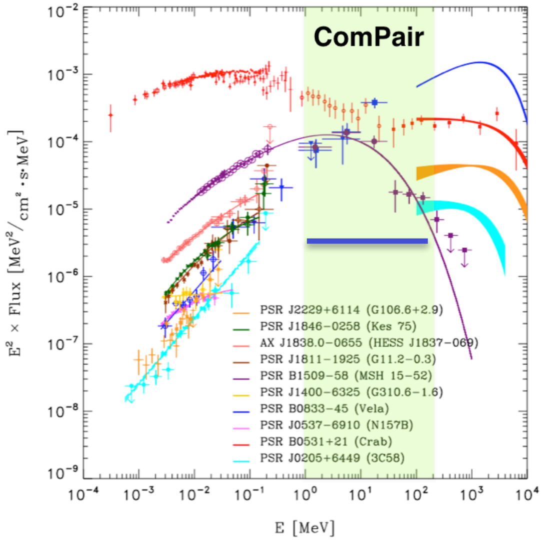


Figure courtesy of ComPair proposal team

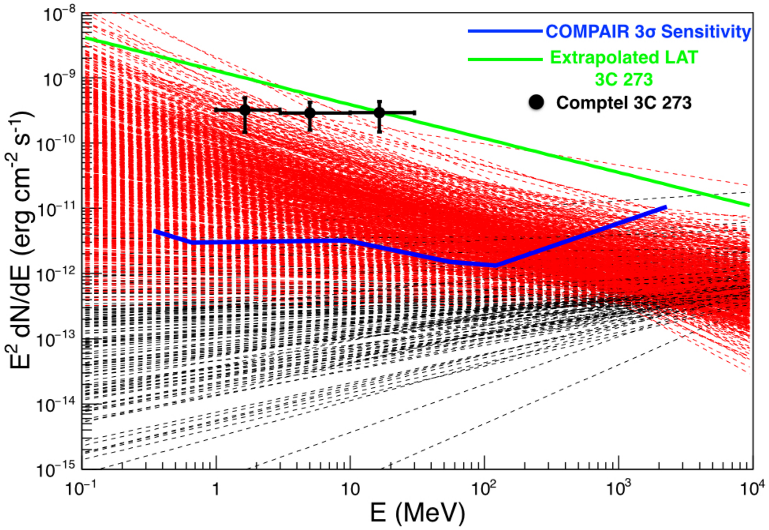
- COMPTEL point-source sensitivity is ~100 times worse than in adjacent energy bands
- Proposed mission concepts (e.g., ComPair, also see bonus slides) can achieve 100x improvement in much of the 100 keV to 100 MeV band

Guaranteed discoveries in the MeV band

Spectral Energy Distribution of Pulsars



Extrapolated fluxes of *Fermi*-LAT AGN



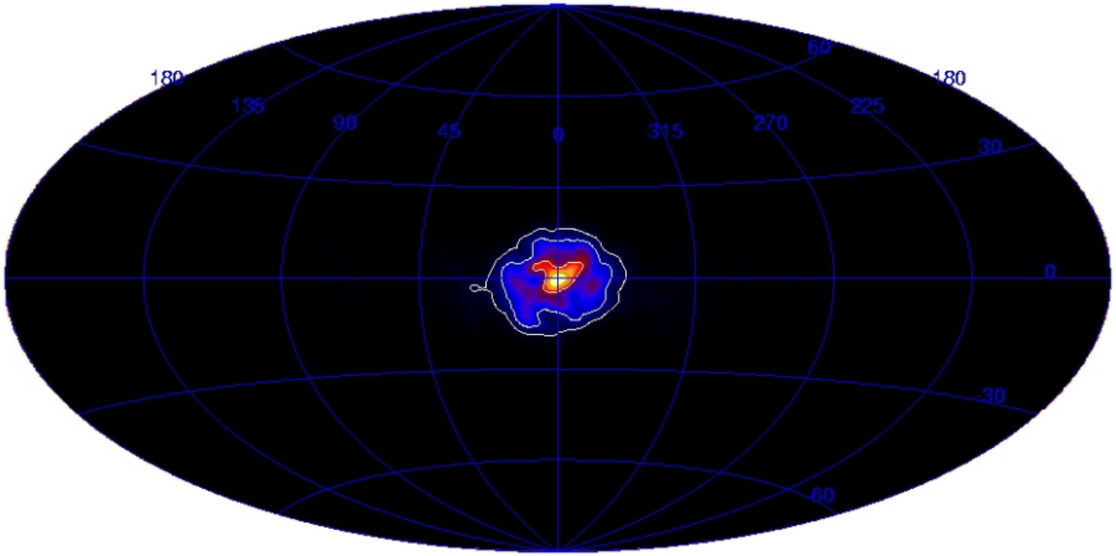
Figures courtesy of ComPair proposal team

- Extrapolations from adjacent energy bands suggest that any instrument with 1% COMPTEL sensitivity in the 1 to 100 MeV band should discover thousands of new sources
- Naïvely scaling prediction based on expanding the volume over which the instrument is sensitive to sources:
  - $N(>S) = N_0\, S^{-1.5} \rightarrow 32*(1/100)^{1.5} = 32000$ sources

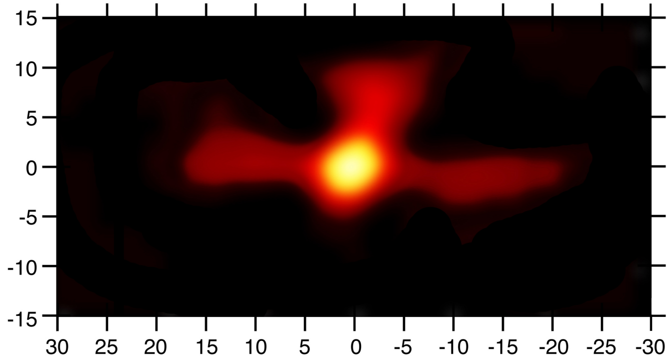
***Fermi*-LAT science can be extended and expanded in the MeV band**

511 keV line in the Galactic Center

INTEGRAL 511 keV all-sky map in Galactic coordinates



OSSE map of Galactic Center

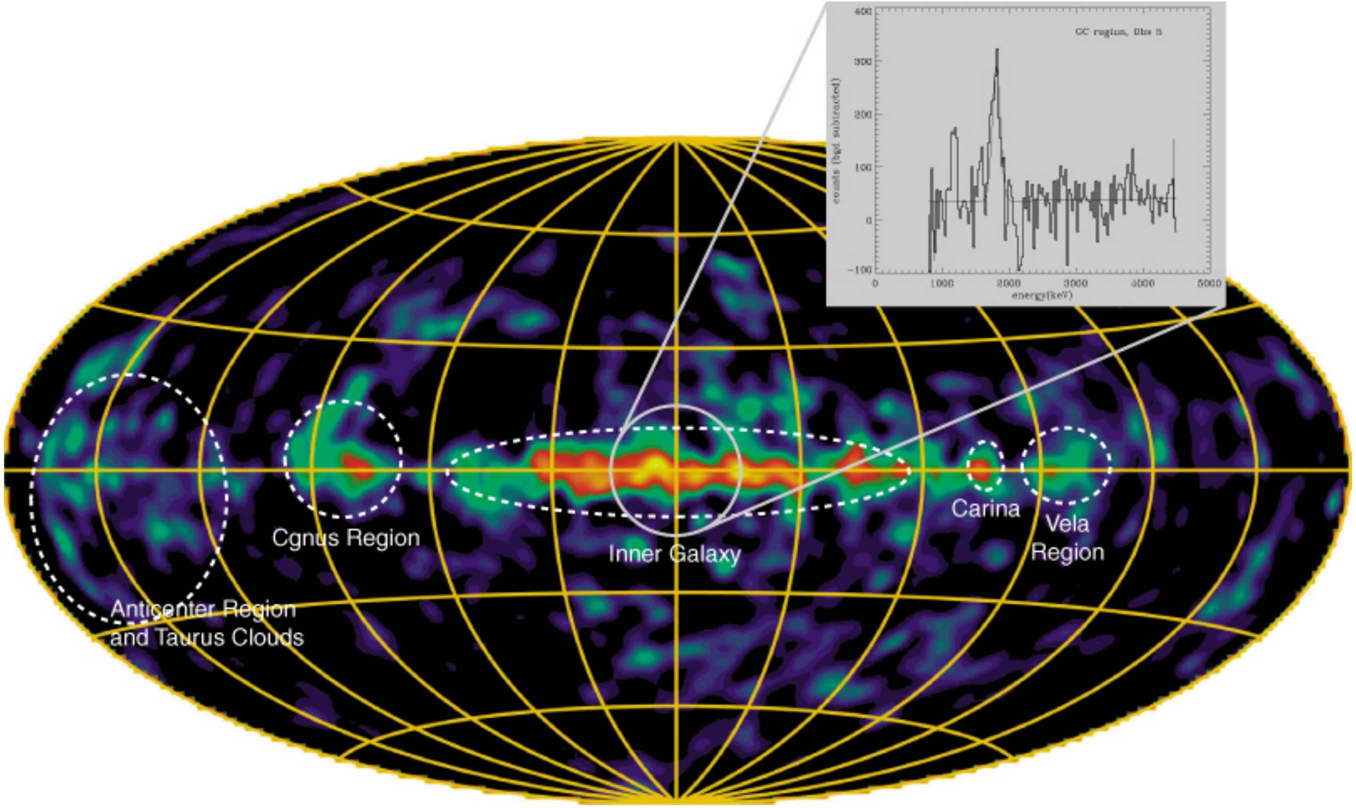


Figures courtesy of INTEGRAL and CGRO Science Support Centers

- 511 keV emission from the Galactic Center region is still not understood in complete detail
- Key question: what are the main sources of positrons in the inner Galaxy?
  - ~ 50% of emission is attributable to X-ray binary systems
  - Supernovae remnants also likely to contribute
  - Dark matter annihilation has been proposed as a contributor

Nuclear Lines, Tracers of Galactic Evolution

COMPTEL Map of the Milky Way at 1.8 MeV

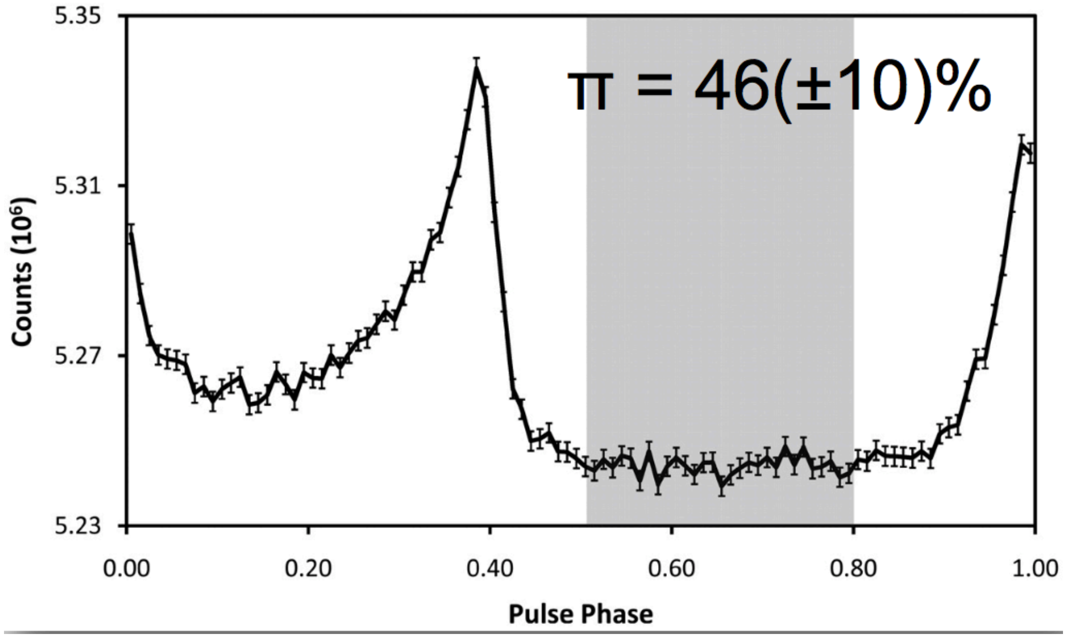


Figures courtesy of the CGRO Science Support Center

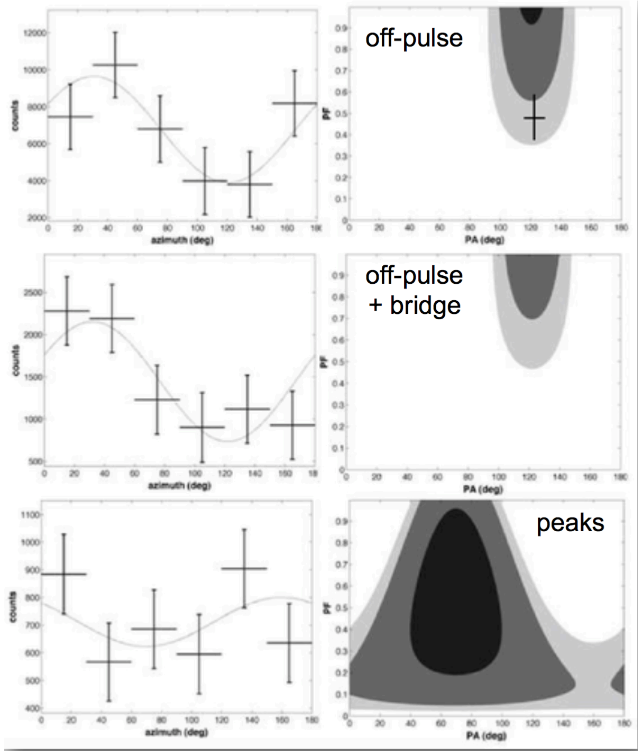
- Emission from heavy isotopes, e.g., ^{26}Al, traces nucleosynthesis in regions with massive young stars throughout the Milky Way
- Resolving multiple lines lets us map out the cycle of matter in the galaxy
- Resolving lines requires excellent energy resolution

Polarization, constraining non-thermal emission

Crab pulsar phaseogram (100 keV – 1 MeV)[1]



Crab polarization (200 - 800 keV)[2]



- Recall, γ-ray emission is non-thermal, ordered electro-magnetic fields play an important role in many non-thermal processes
- Polarization is an excellent probe of the nature of the γ-ray emission mechanism
- Passive material in the tracking volume compromises polarimetry

[1] Dean et al. 2008Sci...321.1183D [2] Forot et al. 2008 2008ApJ...688L..29F

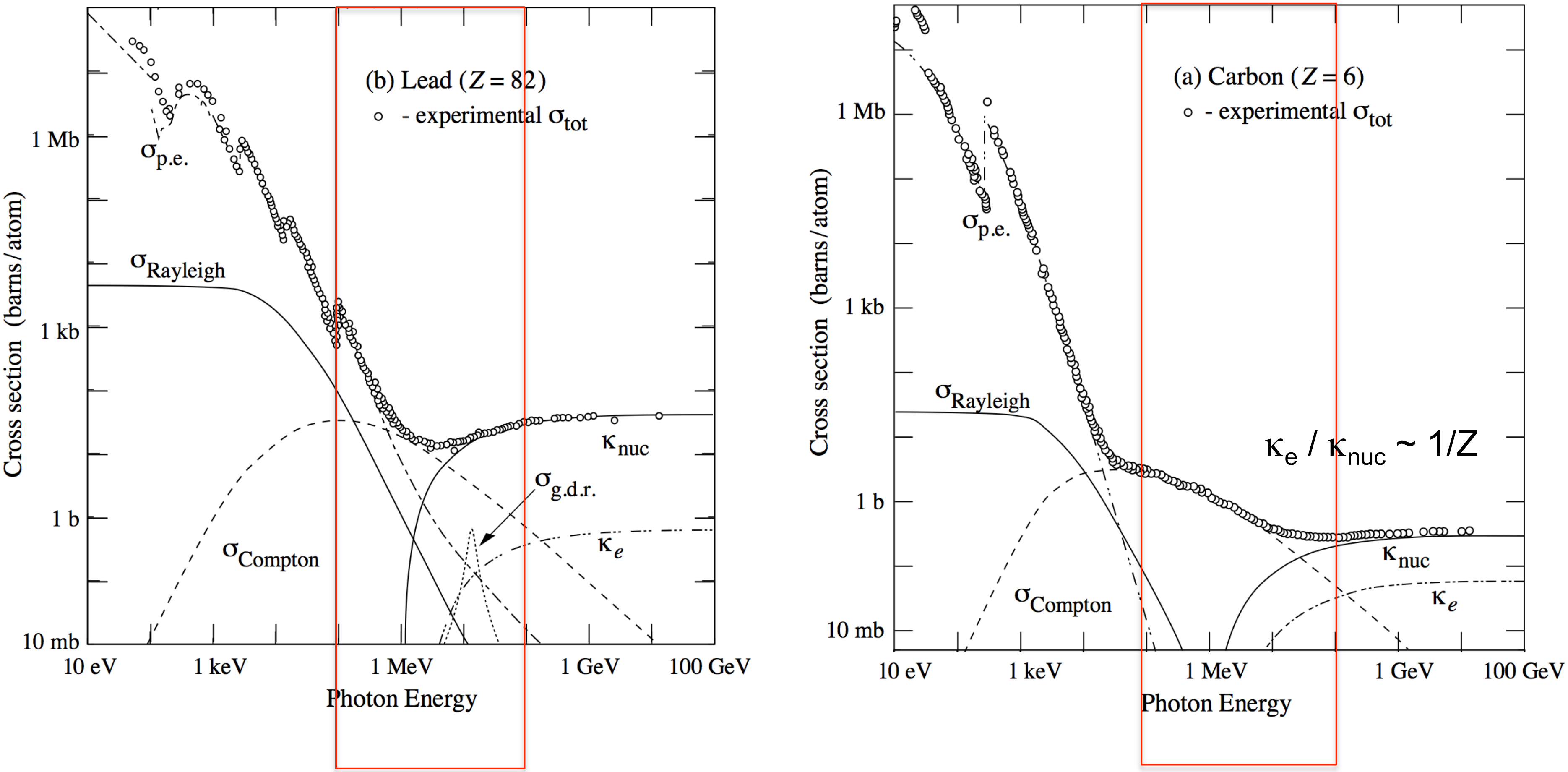
One-slide summary of MeV-GeV science

- Spectral Lines:
  - Trace nucleosynthesis in our Galaxy with nuclear lines
  - Trace e^+e^- (511 keV), π^0 decay / accelerated hadrons (68 MeV)
- Soft γ-ray sources that peak in the MeV-GeV band
  - Pulsars & other neutron stars, distant Active Galactic Nuclei (AGN), Gamma-ray bursts, γ-ray emission from solar flares
- Physics of neutron stars and black holes
  - Pulsar glitches, soft γ-ray repeater outbursts, magnetohydrodynamics of pulsars and black hole accretion disks
- Study transient phenomena
  - Varying / Flaring behavior in AGN, Pulsar Wind Nebulae
    - Polarization changes during flaring episodes constrain emission mechanisms
- Searches for low-mass Dark Matter (< 500 MeV)

DESIGN CONSIDERATIONS FOR THE NEXT MEV-GEV TELESCOPE

γ-ray interactions in the 100 keV to 100 MeV band

Interaction cross sections of γ rays with matter for various physical processes



$\kappa_e / \kappa_{nuc} \sim 1/Z$

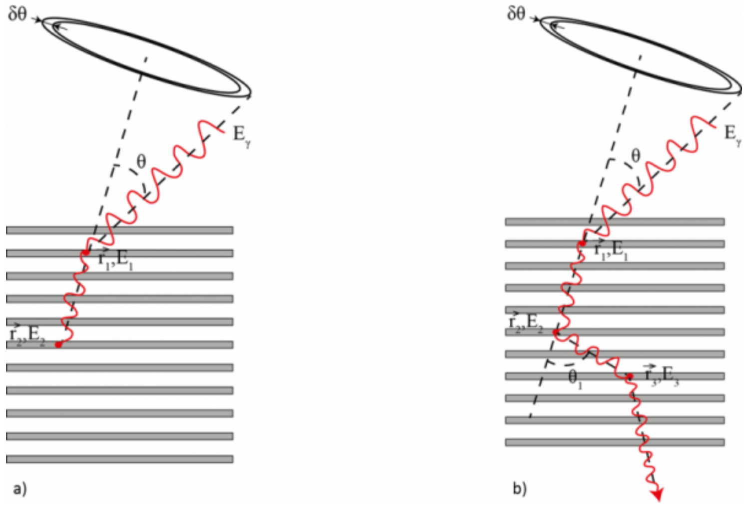
Compton / pair regime

Compton / pair regime

- This energy band is notoriously difficult, many competing mechanisms
- Choice of sensor material sets Compton / pair crossover energy

Compton & Pair-Conversion techniques

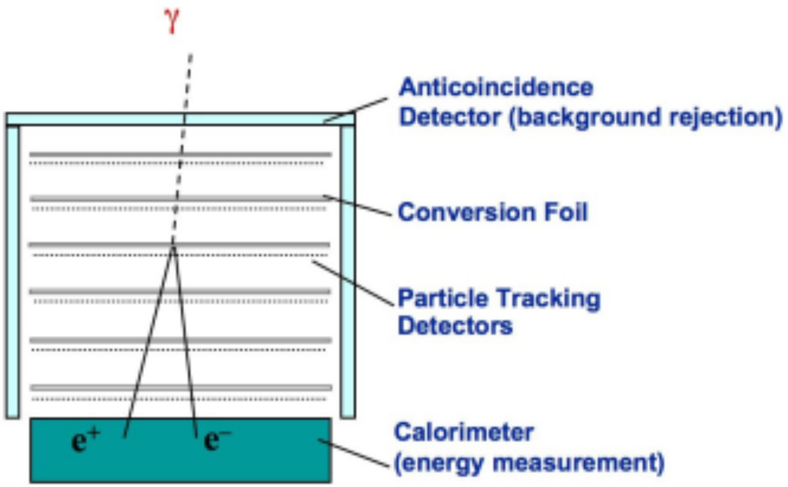
Compton Telescope



Scatter+absrotion

Three scatters

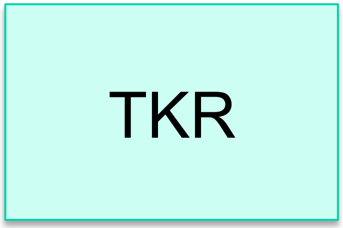
Pair-conversion Telescope



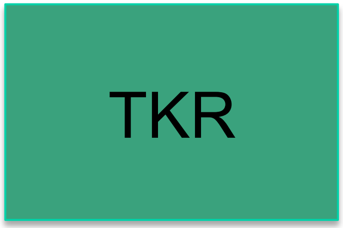
Compton telescope figure: UnivEarthS LabEX

- Compton:
  - Incoming γ ray energy estimated from energy depositions
  - Incoming γ ray direction lies on a ring (figure of merit: δθ)
- Pair-conversion:
  - Incoming γ ray energy estimated with calorimeter
  - Incoming γ ray direction from e^+e^- track directions (figure of merit: R_{68})
    - Point-spread function (PSF) 68% containment radius

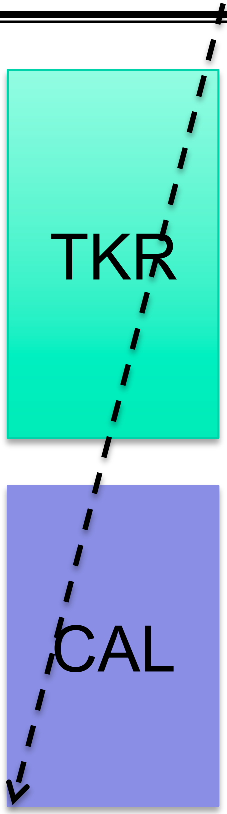
PSF (Resolution) v. Field of View and A_{eff} (Efficiency)



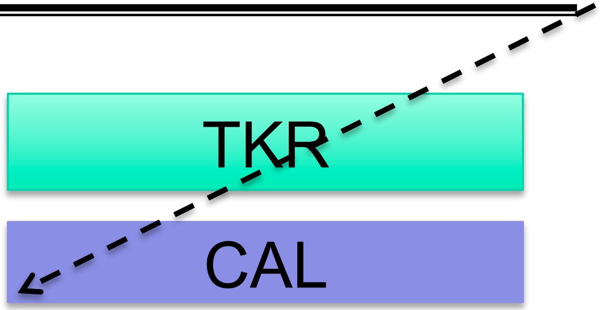
Low density:
Good PSF,
Poor A_{eff}



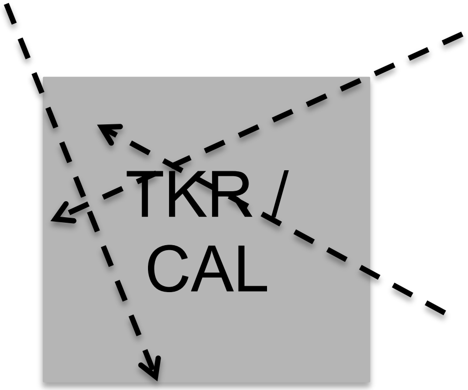
High density:
Poor PSF,
Good A_{eff}



Large Layer Spacing:
Good Resolution,
Poor FoV



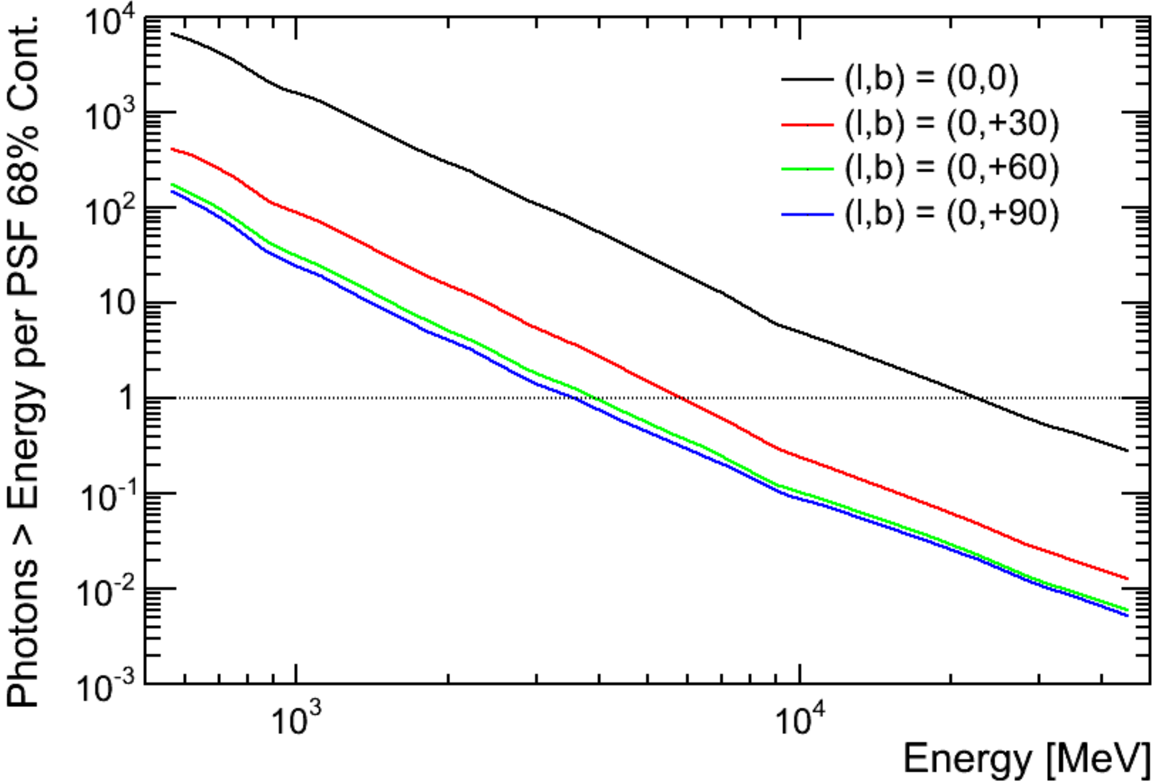
Small Layer Spacing:
Poor Resolution,
Good FoV



Is there a technology that allows monolithic design for > 2π field of view?

Optimizing PSF (Resolution) v. A_{eff} (Efficiency)

Celestial background photons above a given energy inside the PSF



Galactic plane

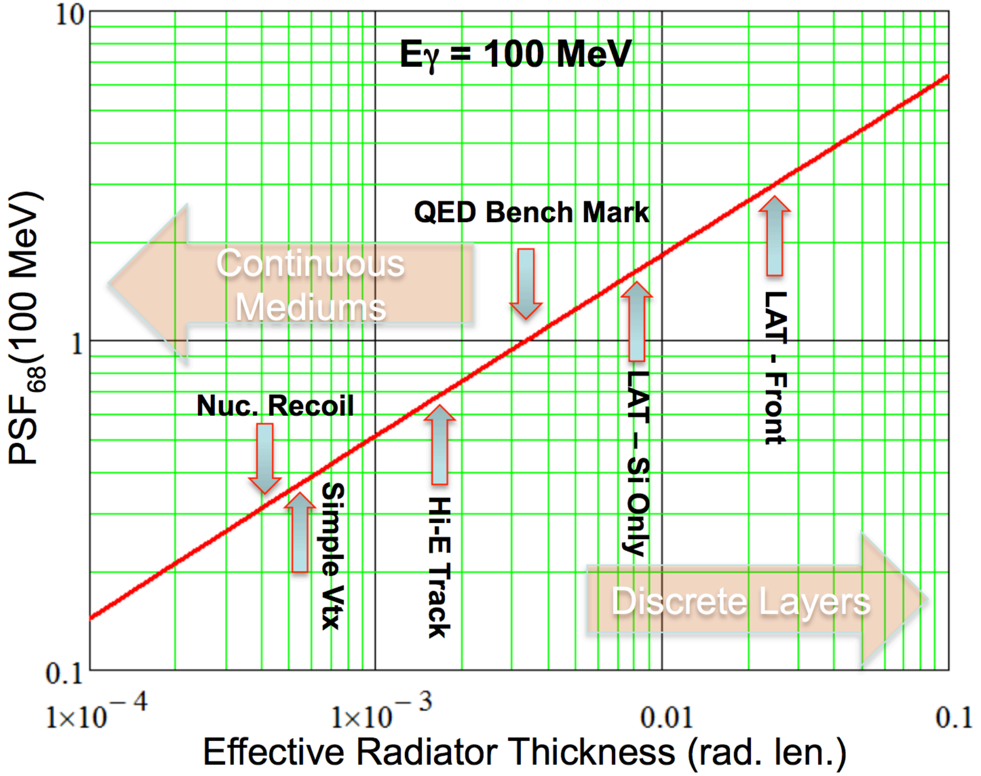
High Galactic latitudes

- Once we are signal limited, efficiency becomes more important that background rejection
  - Signal limited: expect < 1 background γ ray inside the PSF
  - Below 1 GeV, lots of background photons
    - we should favor spatial resolution over detection area to allow us to disentangle complex regions like the Galactic center

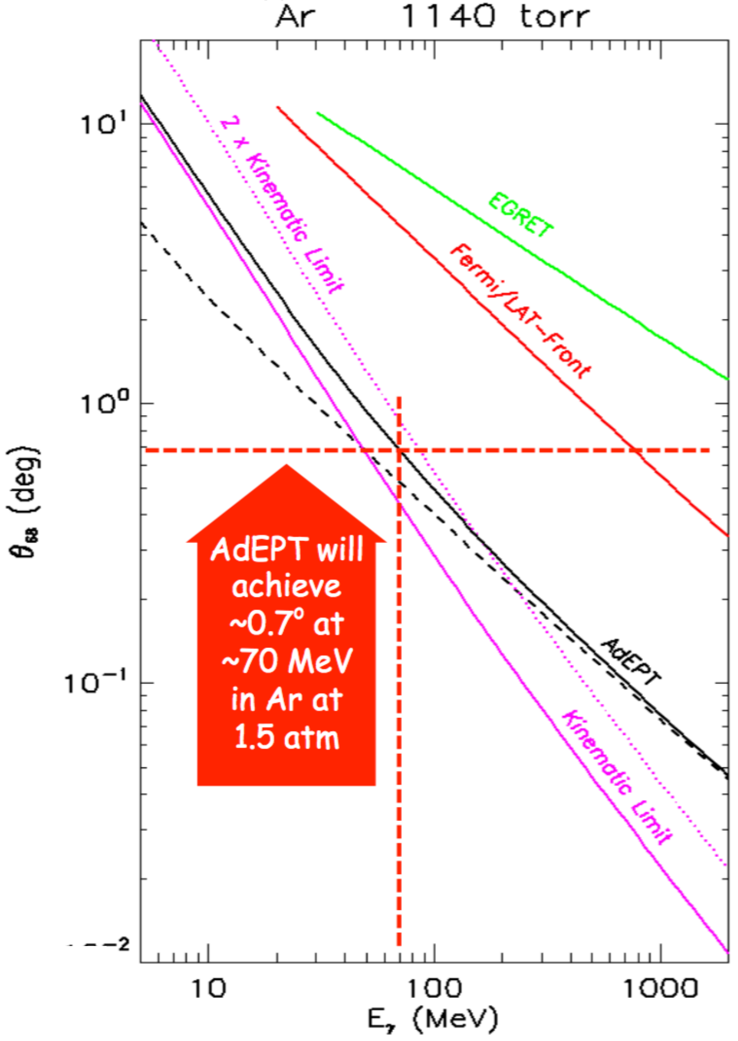
Point-spread function considerations

Right figure, AdEPT team

PSF at 100 MeV v. convertor thickness



PSF v. Energy for various instruments



AdEPT will achieve ~0.7° at ~70 MeV in Ar at 1.5 atm

Multiple-scatting dominates PSF

$$\Theta(E,X) := \frac{13.6\cdot\sqrt{X}(1.+.038\ln(X))\cdot\sqrt{2}\cdot 57.295}{.5\cdot E}$$

Ave Single Tkr Energy

Space Angle

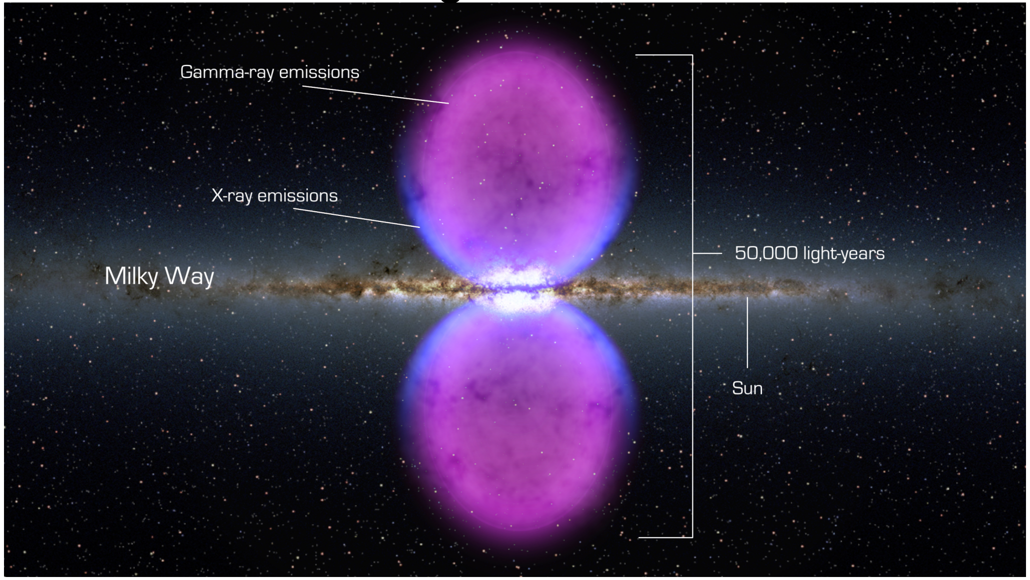
Wish list for next generation MeV-GeV telescope

- Improvement in γ-ray sensitivity (> 10x w.r.t. COMPTEL)
- Exceptional angular resolution for γ rays
  - (~0.2° or better at 1 GeV, < ~1.0° at 100 MeV)
- Very large field of view (≥ 2.5 sr)
- Polarization capability for both steady and transient sources
- Spectral resolution for nuclear lines, 511 keV line, π^0 decay feature
- Background reduction below level of the extragalactic background
- Fast trigger & alert capability for transient sources
- Design Constraints:
  - Size/ mass (< 5 m^3, 5000 kg)
  - Low-power (< ~kW total)
  - Low-bandwidth to ground (< ~50 GB / day)

LESSONS LEARNED FROM THE *FERMI*-LAT

Lesson 1: breadth of science

Schematic image of Fermi “bubbles”

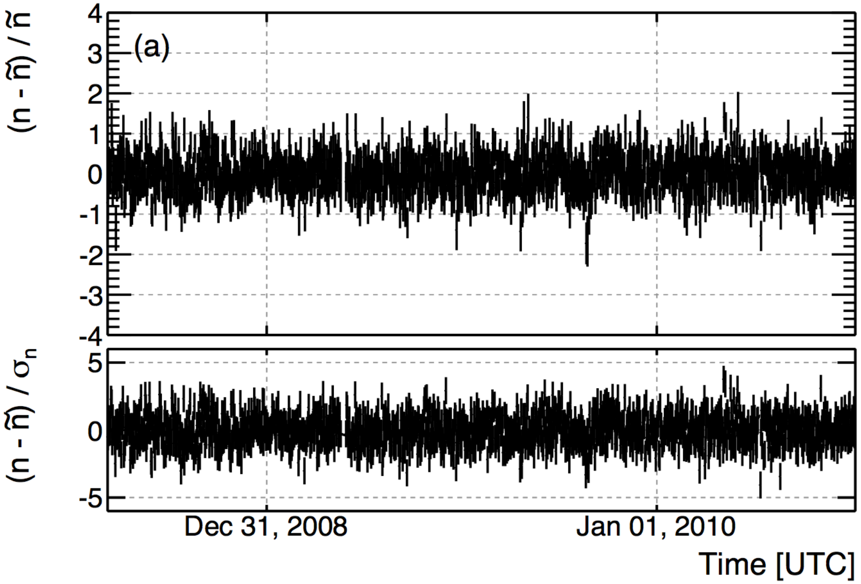


Science “*Fermi* pulsars” issue

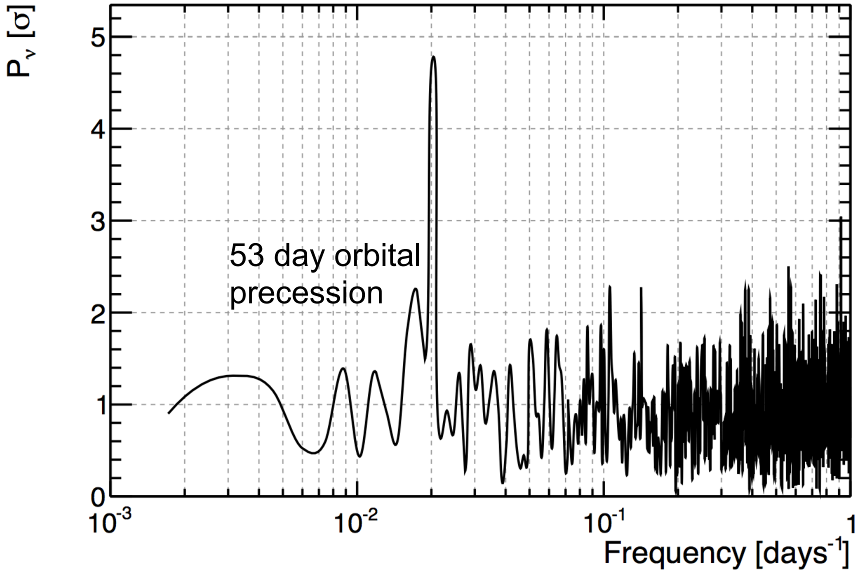
- Exploring a new energy band: optimize for the breadth of science
  - Top *Fermi* results were unpredicted and from many scientific areas
    - Fermi “bubbles”, millisecond γ-ray pulsars, Crab flares discoveries
    - New γ-ray source classes
    - Unresolved AGN account for most or all of isotropic backgrounds
  - Don’t push a single performance metric at the expense of others

Lesson 2, think carefully before making changes

Residuals from Vela pulsar flux measurement



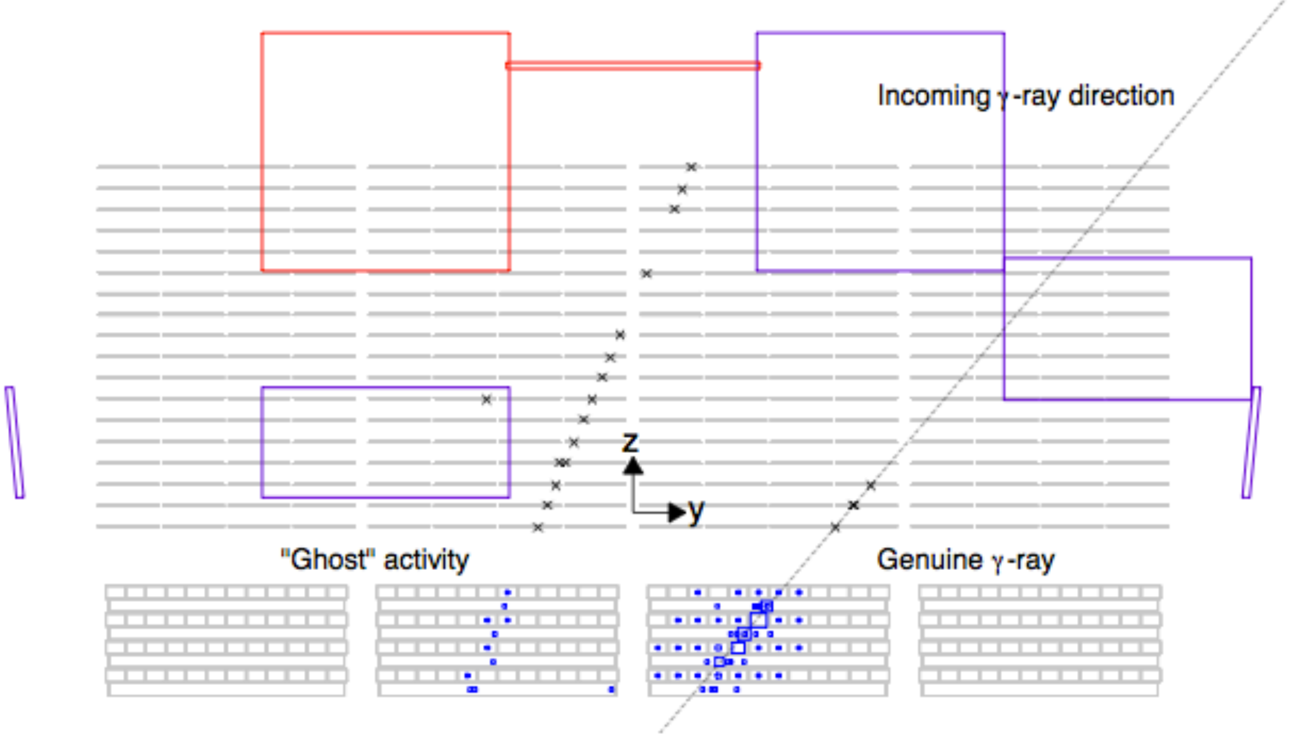
Fourier spectrum of residuals


53 day orbital precession

- For a sky-survey telescope instrumental stability is a huge benefit
  - LAT instrumental stability less than 2% effect on variability studies
  - This is small compared to unavoidable operational effects such as orbital precession, changing cosmic-ray rates, contamination from flaring sources
  - The LAT collaboration has chosen NOT to make configuration changes that would result in 1-2% efficiency improvements to ensure stability

Lesson 3, use flight data to optimize performance

Simulated 3 GeV γ-ray event with cyclic trigger event overlaid



- The low power budget and long shaping times of the LAT tracker make the LAT sensitive to pile-up signals from cosmic rays
- Redesigned the event reconstruction using GEANT simulations with overlaid cyclic trigger events ("Pass 8 event reconstruction")[1]
- > 25% improvement in sensitivity across the entire LAT energy band relative to "Pass 7", which used pre-launch event reconstruction

[1] Atwood et al. arXiv:1303.3514, see also this summary talk.

SUMMARY

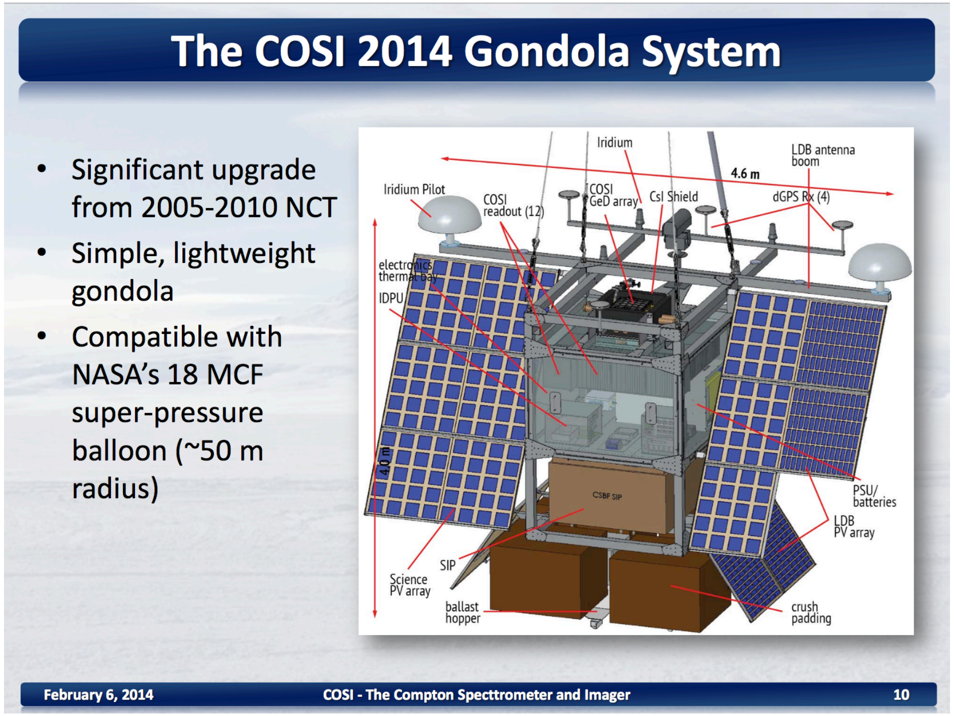
Summary

- The LAT Tracker has performed excellently from launch and continues to do so with minimal degradation
  - < 0.1% efficiency loss in Tracker (~ 1% / year light yield loss in CAL)
- *Fermi* shapes our understanding of the sky from ~100 MeV to 1 TeV
- Clear science case for a sky-survey instrument sensitive to the energy range just below the Fermi-LAT (100 keV to ~1 GeV)
  - Compton scattering: need energy and position resolution to constrain γ direction
  - Polarization: need vertex resolution near scattering/ conversion point
  - Line science: need energy resolution for spectrography
  - Wide field of view: γ-ray sky is variable
- Key lessons from the LAT Tracker's success:
  - Optimize design for broad scientific return
  - Think carefully before changing instrument configuration, performance stability is tremendously useful
  - Use flight data to optimize performance

BONUS SLIDES: STATE OF THE ART, PROPOSED MISSION CONCEPTS

Full presentations and details can be found at:
http://asd.gsfc.nasa.gov/conferences/future_gamma_obs/program/

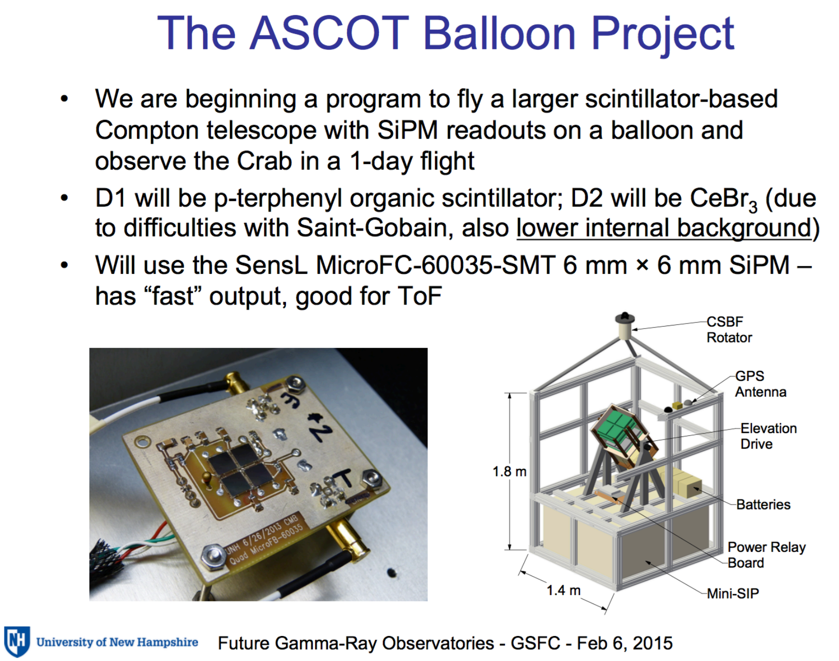
Compton telescope concepts



The COSI 2014 Gondola System

- Significant upgrade from 2005-2010 NCT
- Simple, lightweight gondola
- Compatible with NASA's 18 MCF super-pressure balloon (~50 m radius)

February 6, 2014 COSI - The Compton Spectrometer and Imager 10



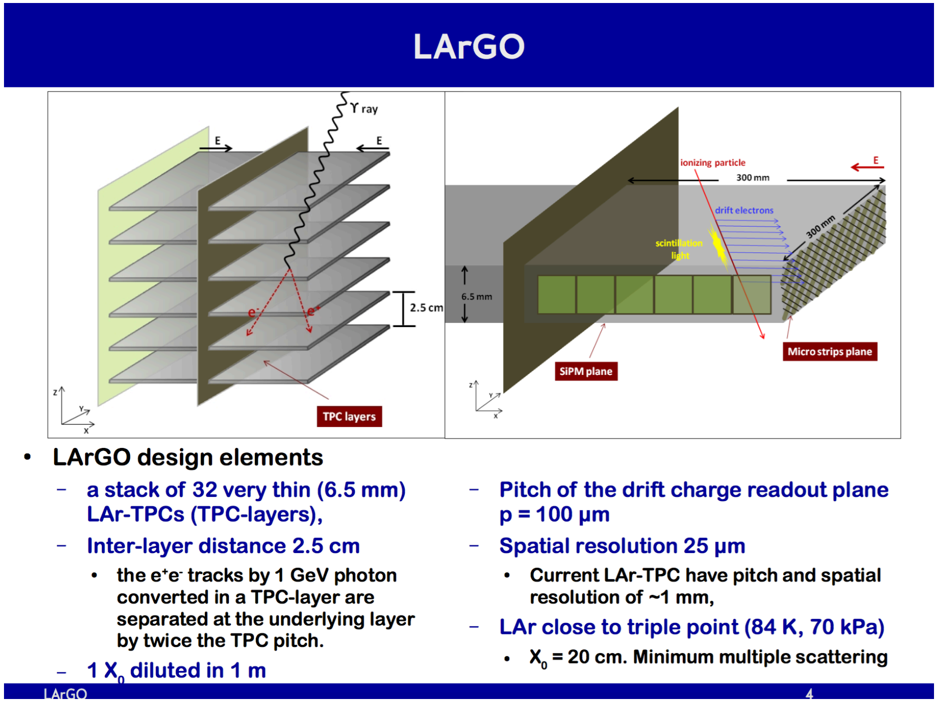
The ASCOT Balloon Project

- We are beginning a program to fly a larger scintillator-based Compton telescope with SiPM readouts on a balloon and observe the Crab in a 1-day flight
- D1 will be p-terphenyl organic scintillator; D2 will be $CeBr_3$ (due to difficulties with Saint-Gobain, also <u>lower internal background</u>)
- Will use the SensL MicroFC-60035-SMT 6 mm × 6 mm SiPM – has “fast” output, good for ToF

University of New Hampshire Future Gamma-Ray Observatories - GSFC - Feb 6, 2015

- These concepts are largely upgrades of COMPTEL that use position-sensitive semiconductor devices (Ge, Si, CdTe, CZT)
  - High-performance scintillators for improved energy resolution
  - SiPM-based readout of scintillation light
- Balloon flights of prototype modules

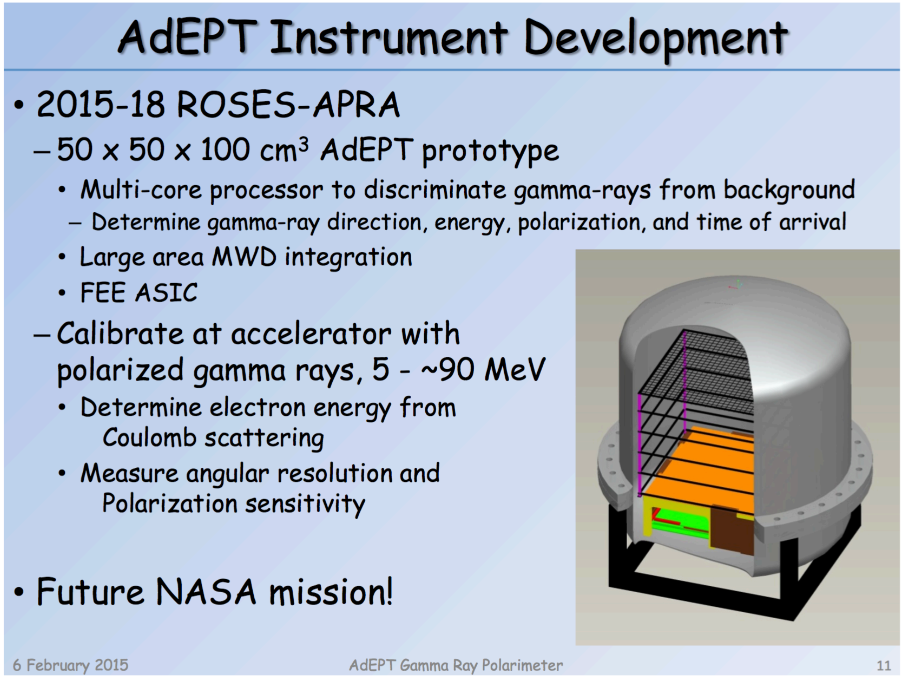
Drift chamber-based concepts



LArGO

- **LArGO design elements**
  - a stack of 32 very thin (6.5 mm) LAr-TPCs (TPC-layers),
  - Inter-layer distance 2.5 cm
    - the e^+e^- tracks by 1 GeV photon converted in a TPC-layer are separated at the underlying layer by twice the TPC pitch.
  - 1 X_0 diluted in 1 m
  - Pitch of the drift charge readout plane p = 100 µm
  - Spatial resolution 25 µm
    - Current LAr-TPC have pitch and spatial resolution of ~1 mm,
  - LAr close to triple point (84 K, 70 kPa)
    - X_0 = 20 cm. Minimum multiple scattering

LArGO 4



AdEPT Instrument Development

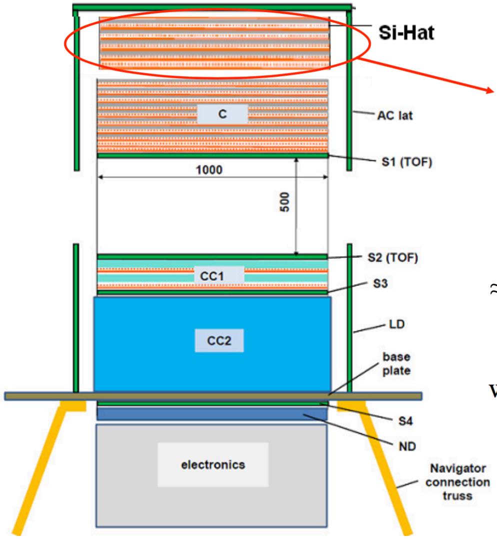
- 2015-18 ROSES-APRA
  - 50 x 50 x 100 cm^3 AdEPT prototype
    - Multi-core processor to discriminate gamma-rays from background
      - Determine gamma-ray direction, energy, polarization, and time of arrival
    - Large area MWD integration
    - FEE ASIC
  - Calibrate at accelerator with polarized gamma rays, 5 - ~90 MeV
    - Determine electron energy from Coulomb scattering
    - Measure angular resolution and Polarization sensitivity
- Future NASA mission!

6 February 2015 AdEPT Gamma Ray Polarimeter 11

- These designs optimize the amount of active to passive sensor material in the detector fiducial volume by using drift chamber technologies
  - LArGO: Liquid Argon. AdEPT: gas, HARPO: high-pressure gas
- Expect excellent performance for polarization
- Challenges arise for operation in space, must reject large induced backgrounds from pressure vessel
- AdEPT approved for balloon flight for prototype

“Fermi-Lite” concepts

Gamma 400

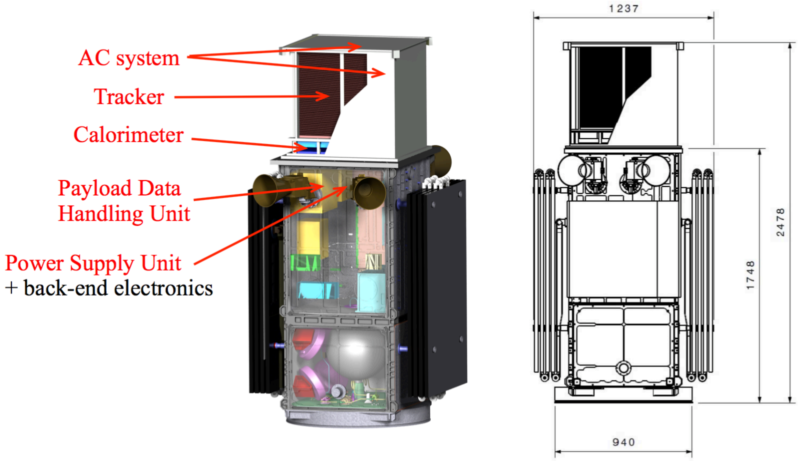


10-30 *x*-*y* Si-planes
(thickness: 0.5 mm)
+ electronics
no passive converter

≈ 10% X_0 of total conversion
additional ~400 cm^2 of A_{eff}
at E ~100 MeV
with ~1° of *PSF* at 100 MeV.

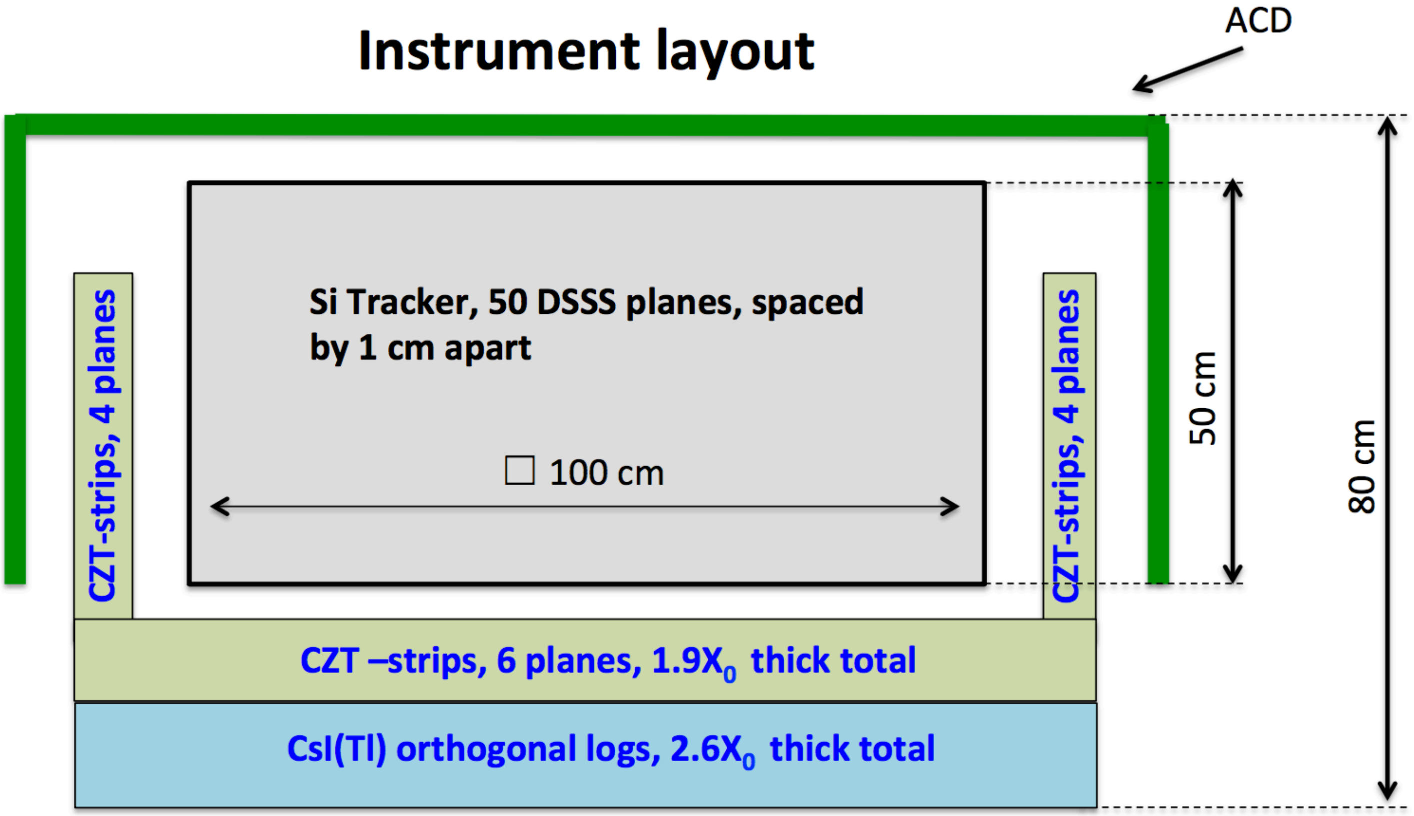
ASTROGAM Payload

- **ESA guidelines for the M4 Call interpreted at face value ⇒ ASTROGAM payload (single instrument) designed to be 300 kg**



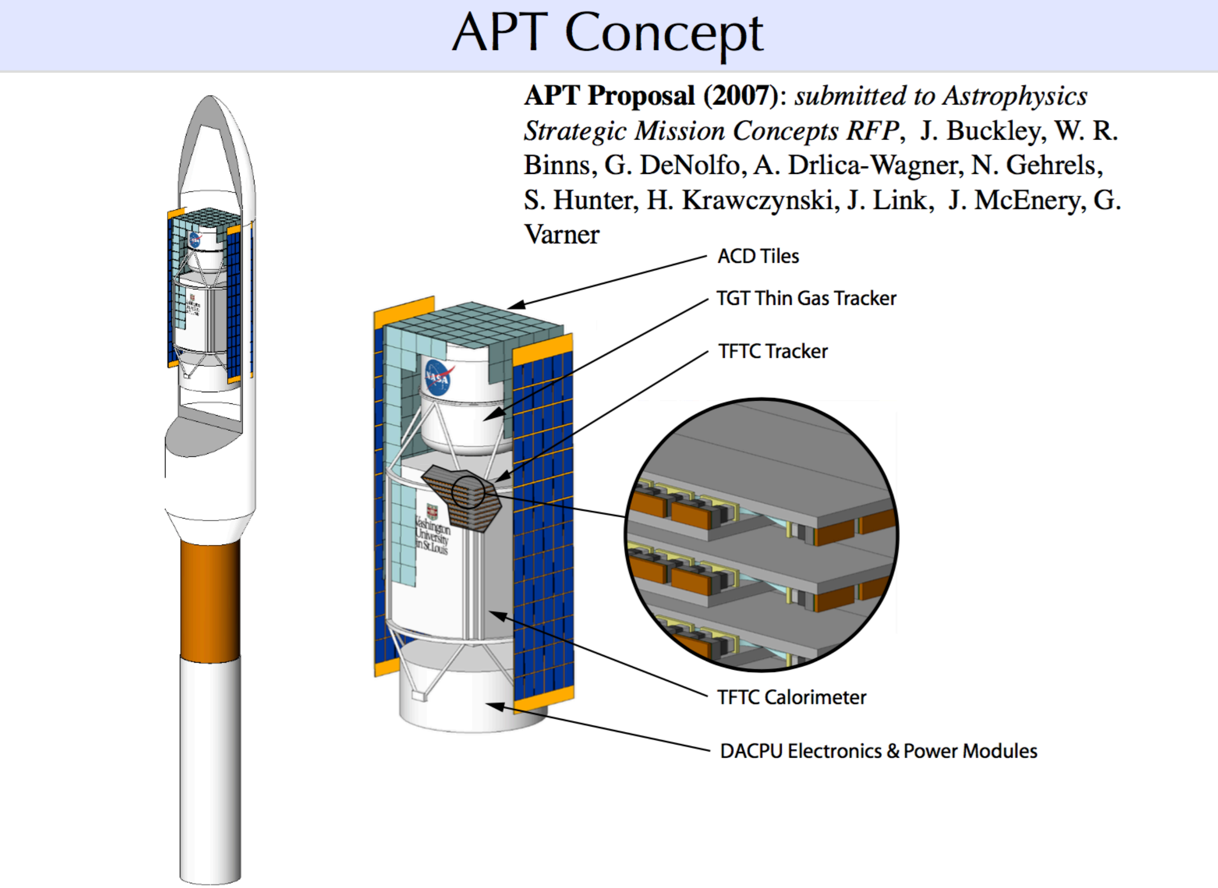
- These concepts are similar to *Fermi* with the Tungsten convertors removed
- Good PSF at 100 MeV
  - not quite as good as AdEPT, but larger A$_{eff}$, and simpler design
- Proposals to European Space Agency, also PANGU (China)

Compton / Pair-production concept (ComPair)



- Sensitivity to both Compton scattering and pair-conversions
- CZT strips surrounding Si Tracker to achieve full absorption of Compton scattered photon
- Proposal for balloon-flight prototype development

Advanced pair telescope concept



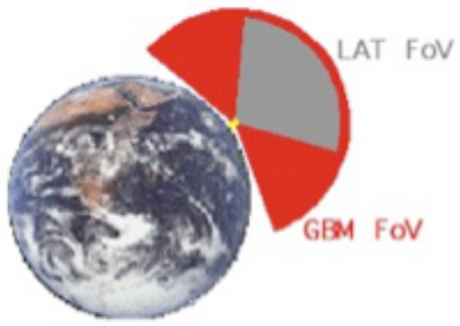
APT Concept

APT Proposal (2007): *submitted to Astrophysics Strategic Mission Concepts RFP*, J. Buckley, W. R. Binns, G. DeNolfo, A. Drlica-Wagner, N. Gehrels, S. Hunter, H. Krawczynski, J. Link, J. McEnery, G. Varner

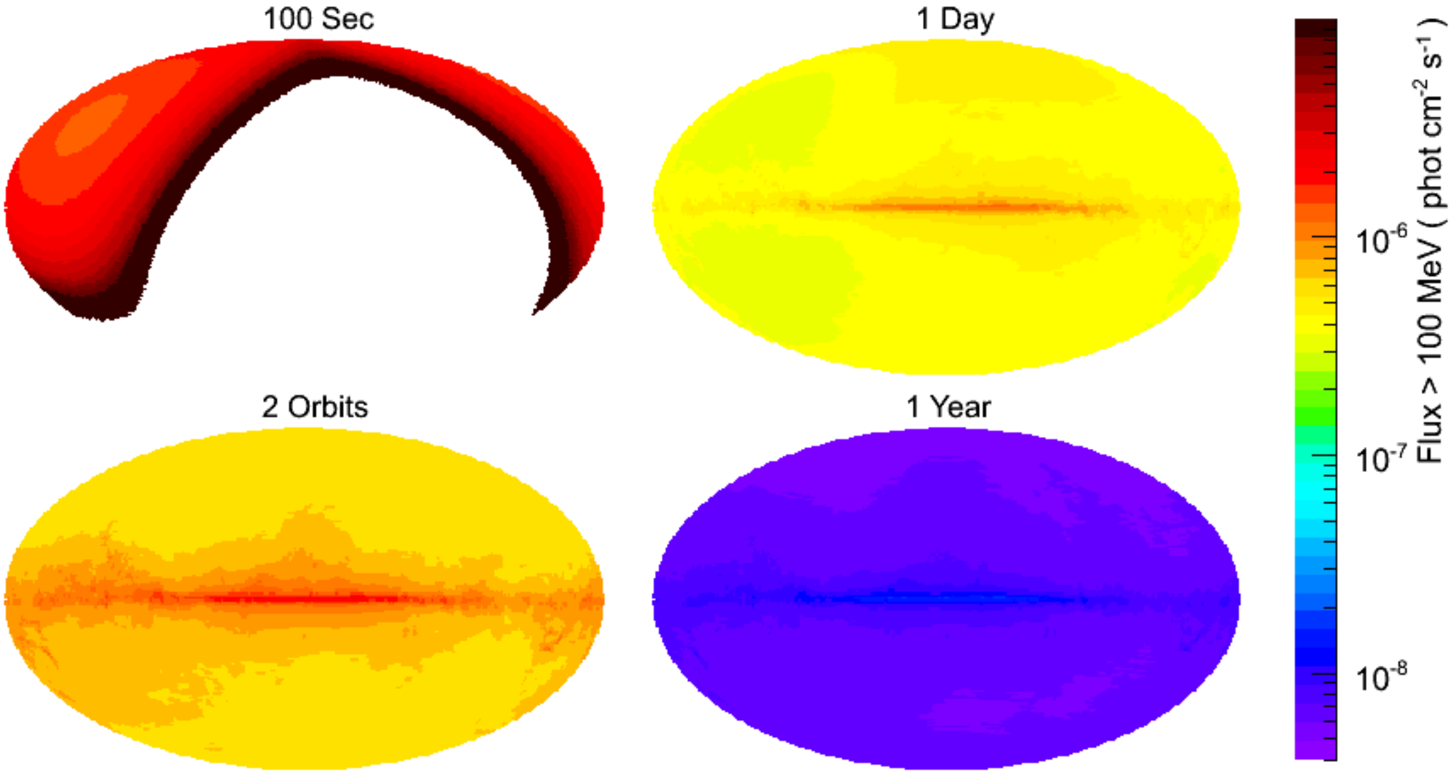
- Optimized for *Fermi*-LAT energy range, trades energy resolution for larger tracking volume and improved spatial resolution
- Aims for > 10x sensitivity improvement in GeV energy range

BONUS SLIDES: FERMI SKY-SURVEY STRATEGY, BACKGROUNDS

Fermi sky-survey mode



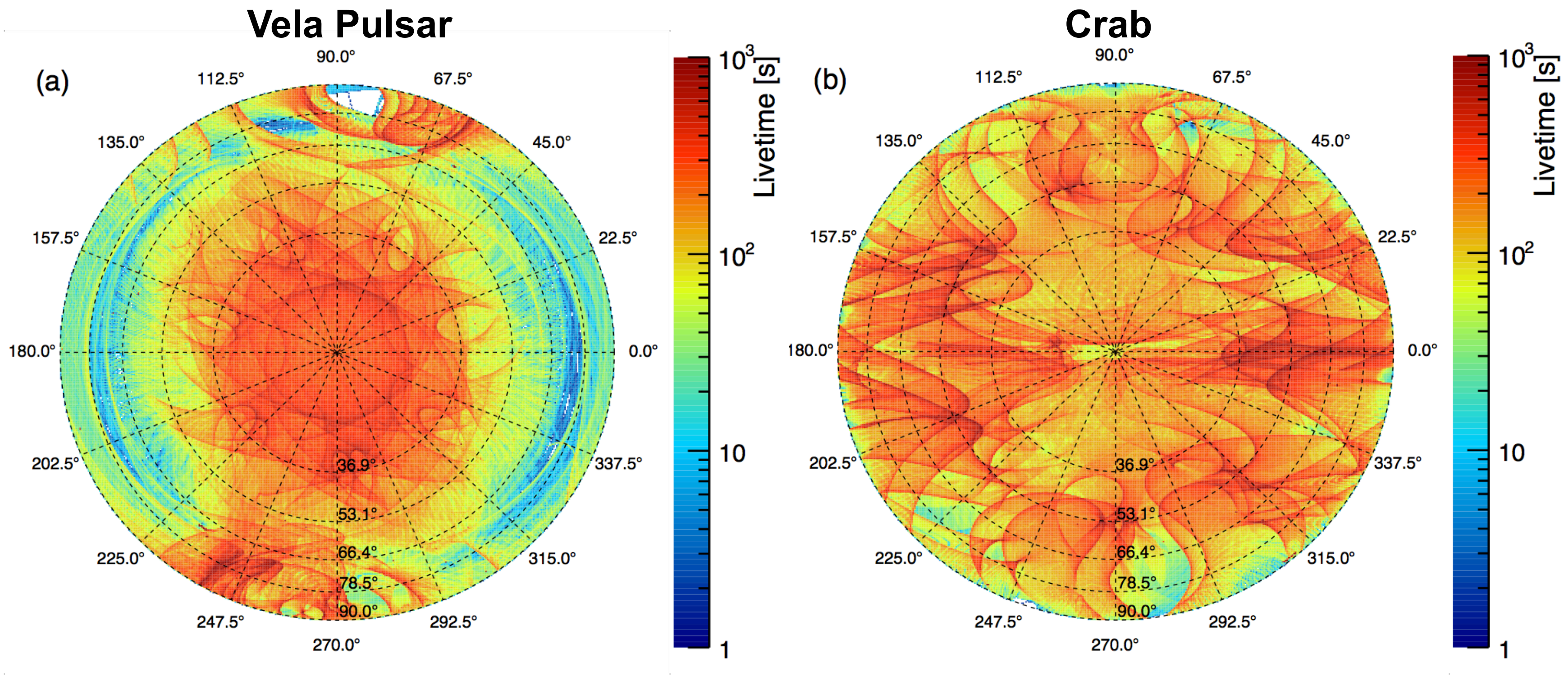
Huge field-of-view
LAT sees ~ 1/5 of the sky at any time
Some sensitivity out to 78° off-axis



Fermi spends every other orbit rocked either north or south.

3 hours to survey entire sky

Fermi epicycles: live time in instrument frame

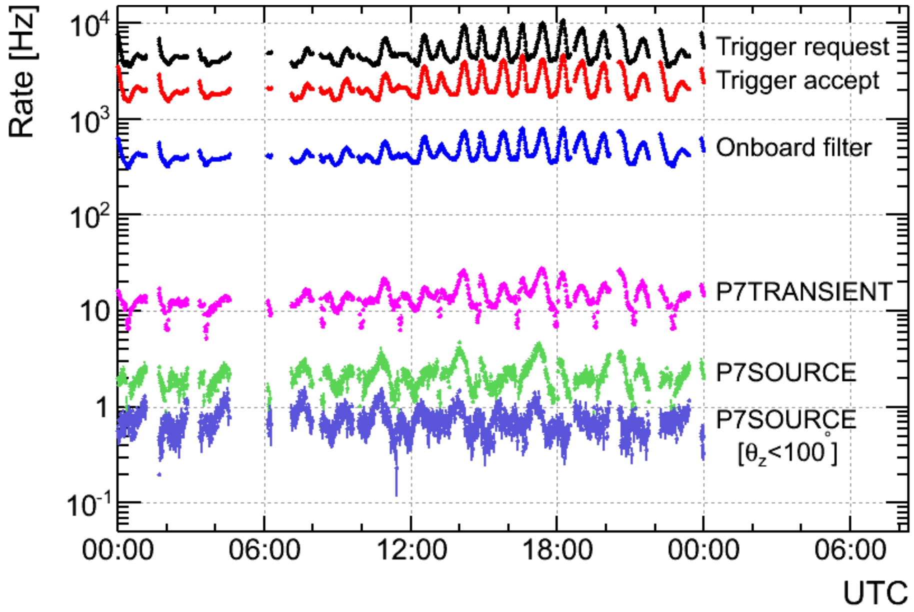


- Multiple cycles: 95 minutes orbital period, north and south rocking on alternate orbits, rolls to keep solar panels pointed at the sun, orbital plane precesses like a top with 54 day period
- Inaccuracies in instrument response modeling will induce artificial variability with corresponding periodicities

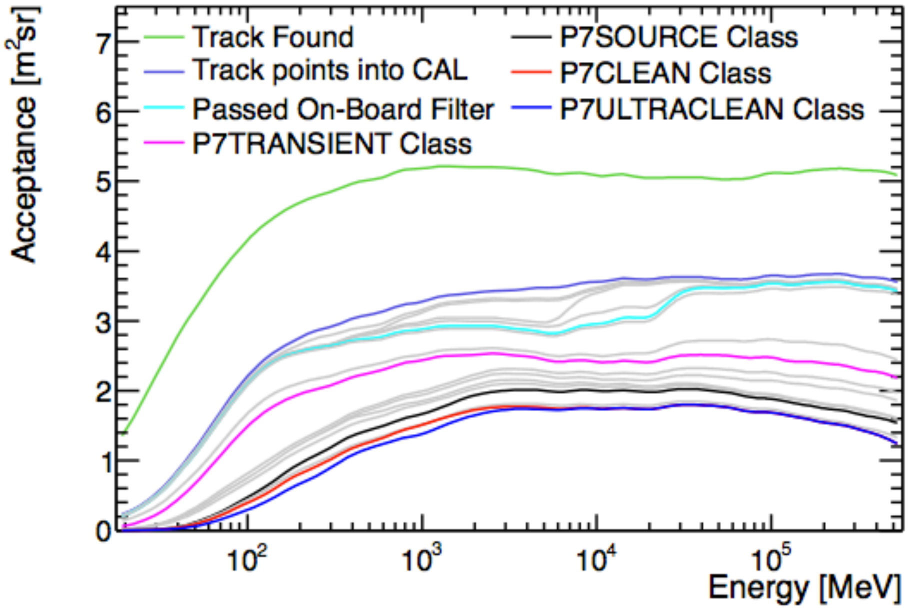
Astron. Picture of the Day: http://apod.nasa.gov/apod/ap120504.html
Animarted: https://www.youtube.com/watch?v=sw3WAcmfymM.

Particle rate reduction

Rate at various stages of data reduction

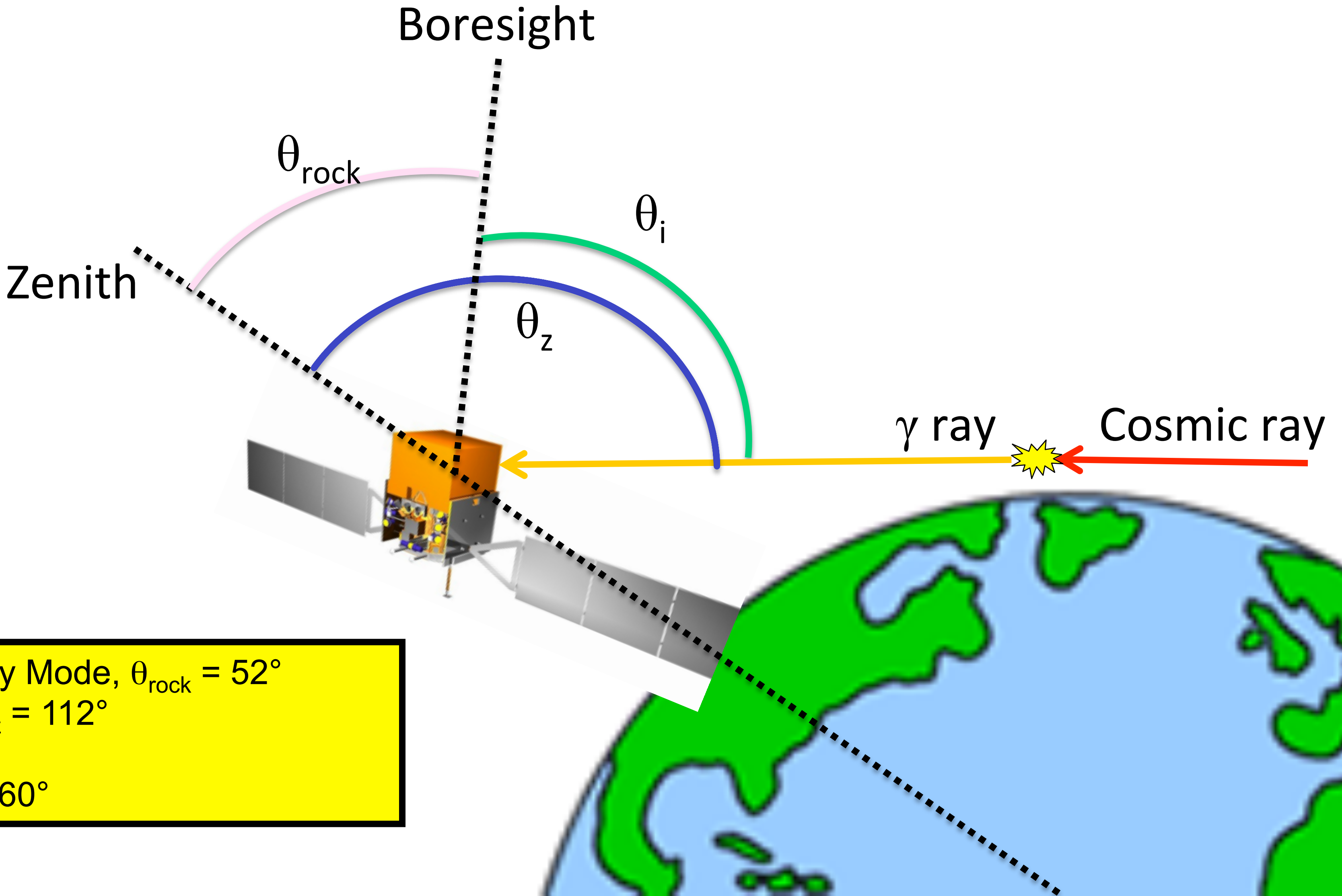


Acceptance at stages of data reduction



- Factor of > 10^5 in bkg. reduction is achieved in several stages
- About 50% γ-ray efficiency inside fiducial volume from 1-100 GeV

The Earth Limb: background & control sample



Sky Survey Mode, θ_{rock} = 52°
Limb at θ_{rz} = 112°

Limb: $\theta_i > 60°$