Scientific Optimization for Proposed MeV Gamma-Ray Instruments, Lessons Learned From the Fermi-LAT

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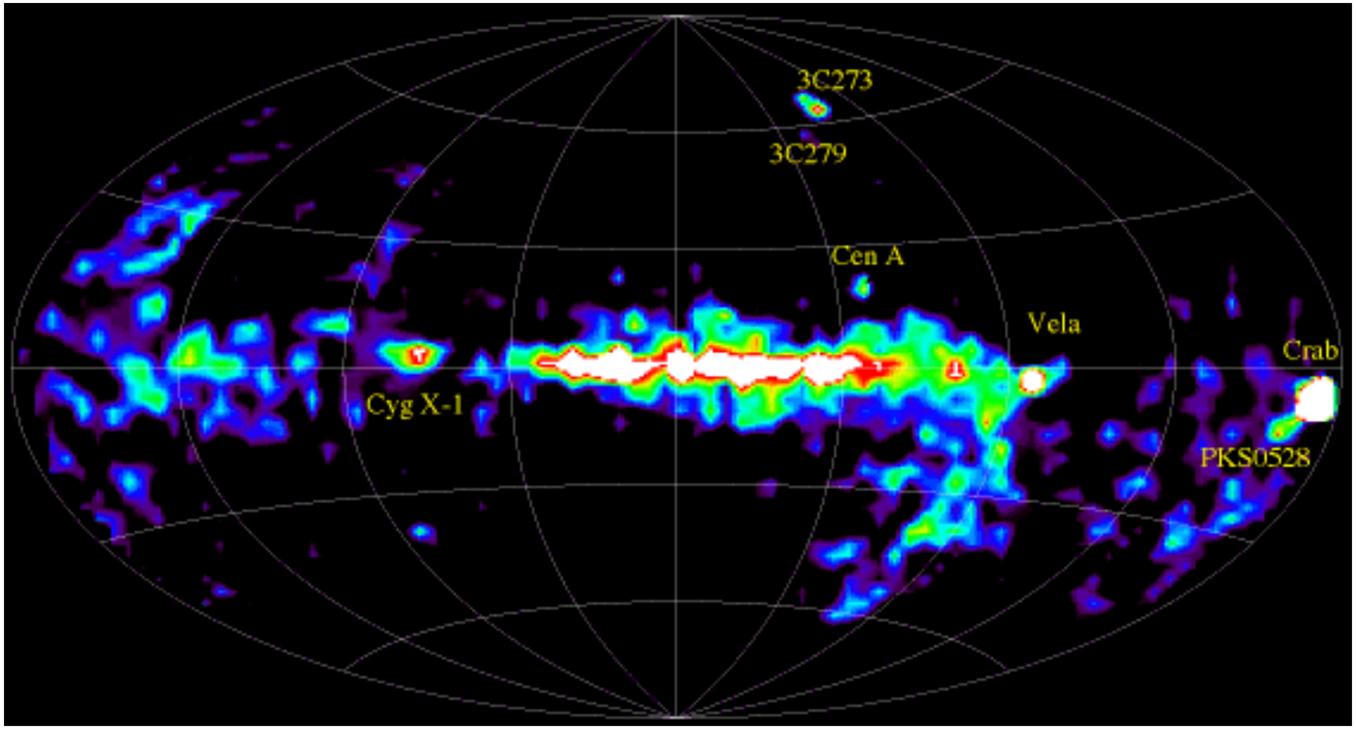
Outline

- Context: the under-explored MeV sky
  - State of the art: COMPTEL
  - Difficult energy band: Compton & pair-conversion techniques
- Key design choices and tradeoffs
  - Sensor Material: Compton v. pair-conversion
  - Effective area v. point-spread function
  - Detector Geometry

Context: the under-explored MeV Sky

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

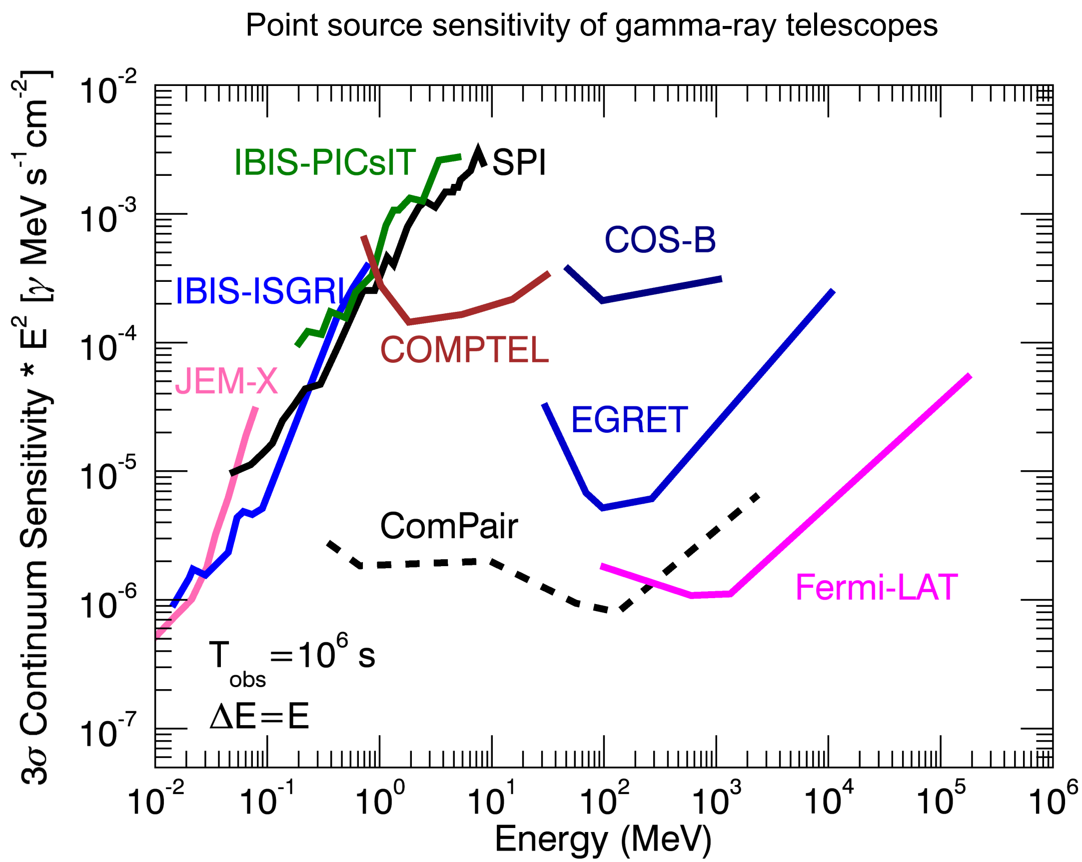


CGRO Science Support Center

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

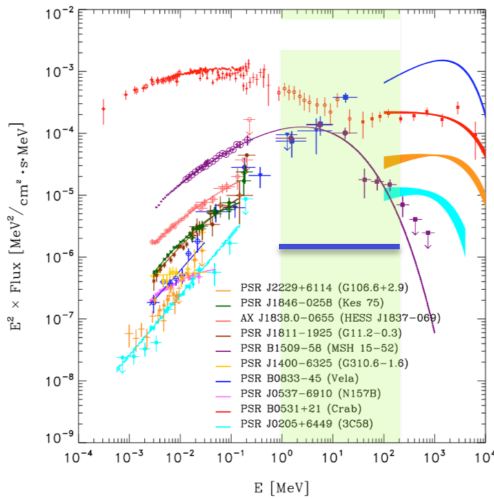
Source Sensitivity in the 100 keV to 100 MeV Band



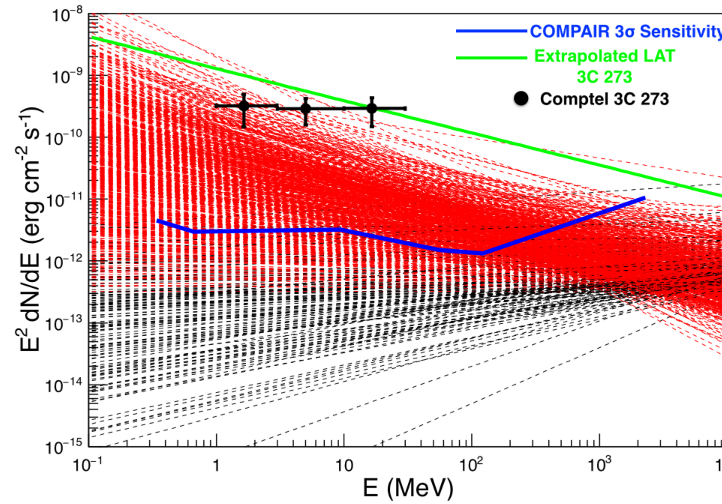
- COMPTEL point-source sensitivity is > 100x less than in adjacent energy bands
- Other mission concept studies give similar sensitivity to ComPair in some or all of the 100 keV to 100 MeV band

Guaranteed Discovery Potential

SEDs of Pulsars



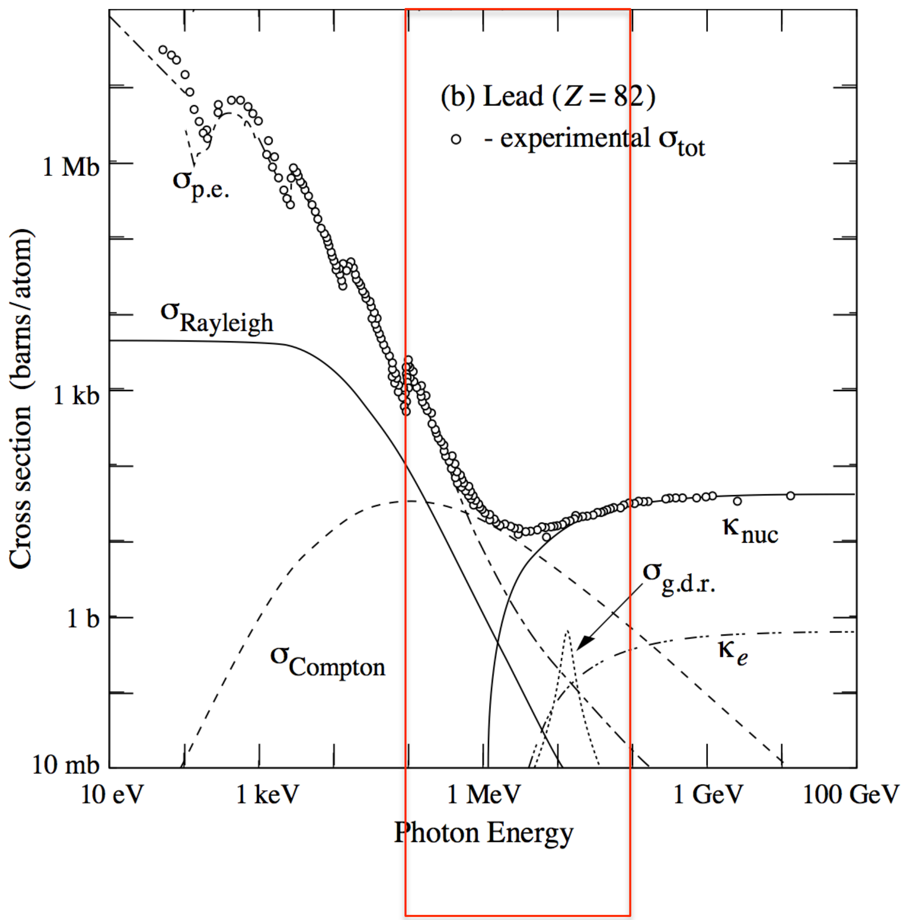
Extrapolated fluxes of *Fermi*-LAT AGN



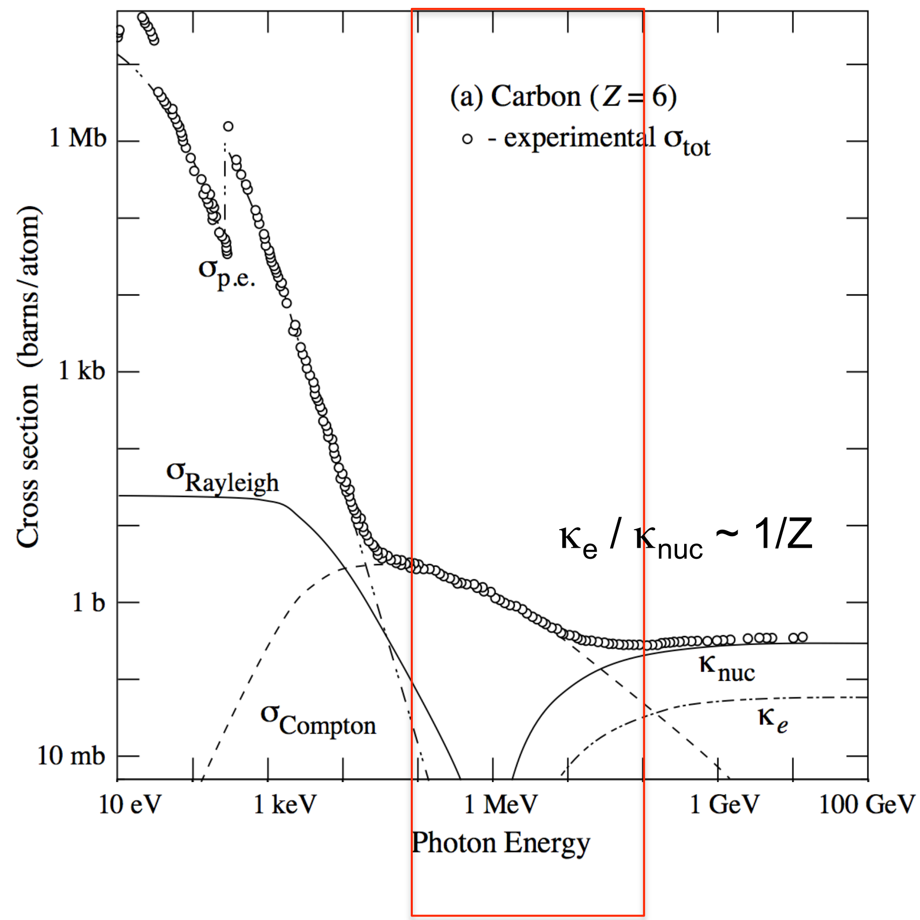
- Extrapolations from adjacent energy bands suggest that any instrument with 100X COMPTEL sensitivity in the 1 to 100 MeV band should discover thousands of new sources
- Naïvely scaling prediction based on expanding the volume over which we are sensitivity to sources:
  - $N(S) = N_0\, S^{1.5} \rightarrow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

γ-ray Interactions in the 100keV to 100MeV Band

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



Compton / pair regime

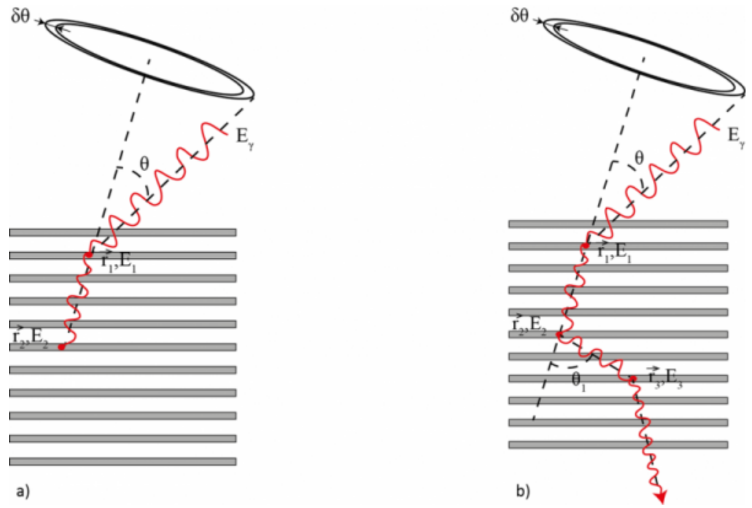


Compton / pair regime

- Choice of sensor material sets Compton / pair crossover energy

Compton & Pair-Conversion Techniques

Compton Telescope

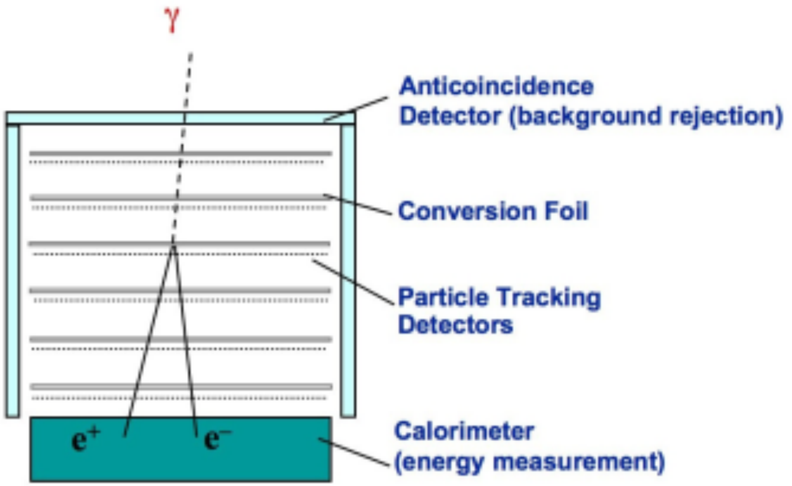


Scatter+absroption

Three scatters

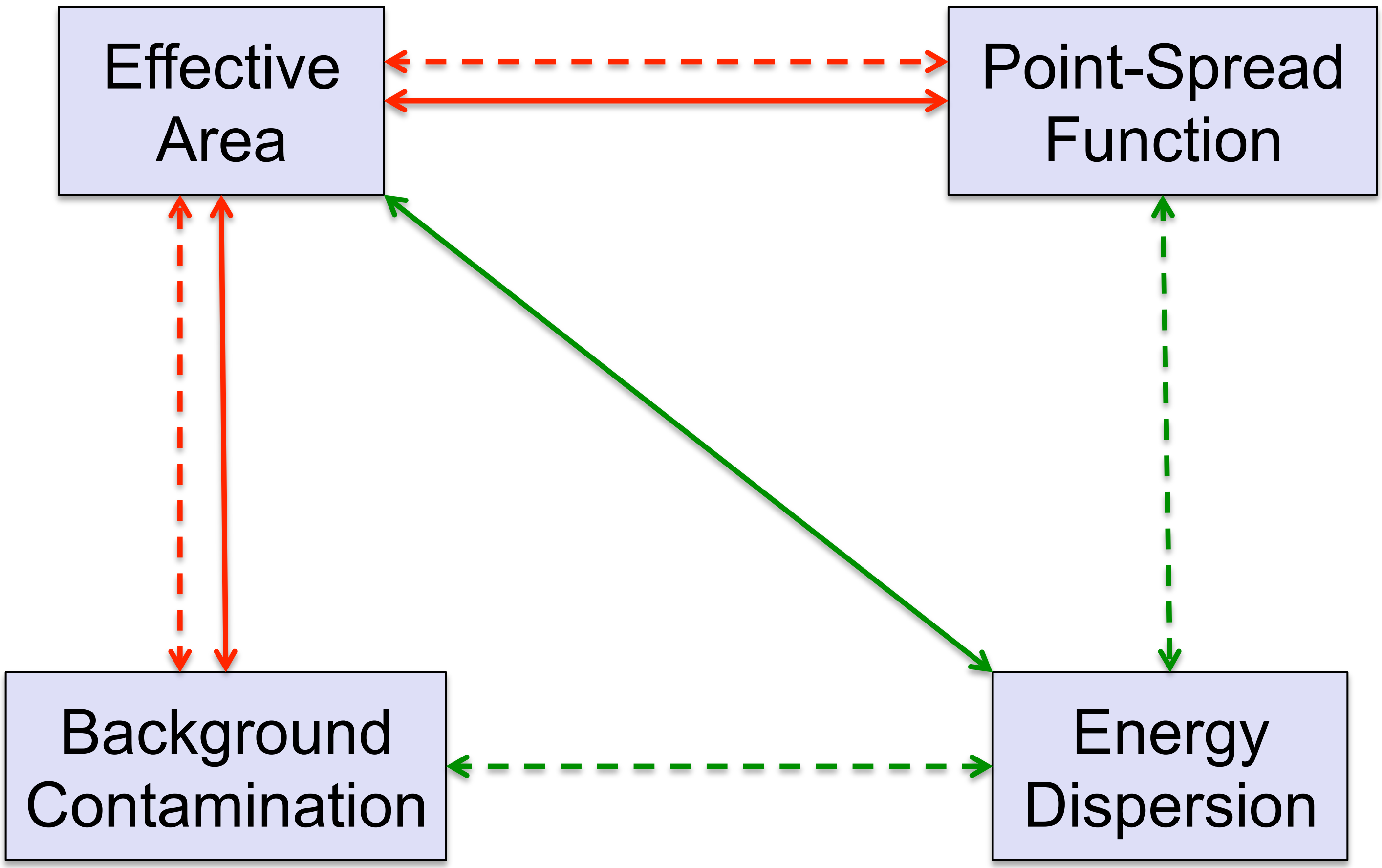
Image: http://www.univearths.fr/en/i5-gamma-ray-instrumentation-development

Pair-conversion Telescope



- 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})

Performance Parameters & Tradeoffs



Positive Correlation
Negative Correlation

Compton
Pair-conversion

Detector Material And Geometry Choices

- For a given total detector height, you can choose:
  - Sensor & convertor material
    - Density
    - Atomic number
    - Thickness per readout
  - Number of sensors => lever-arm / sensor
    - Sensor resolution => information per milli-X_0 (or per X_{Comp})
  - Geometry of convertor / sensor
    - Planar or 4π geometry

→ X_0 per readout
Pair v. Compton fraction
"Active" material fraction

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

$$X_{\text{Comp}}(E) = \frac{13.0 \text{ g cm}^{-2}\text{MeV}^{-1} A}{\log(2E/m_e c^2) + 1/2} E$$

X_0 / ρ values:
Si: 9.5 cm
Ge: 2.4 cm
CsI: 1.7 cm
W: 0.4 cm

Effective area versus Point-spread Function

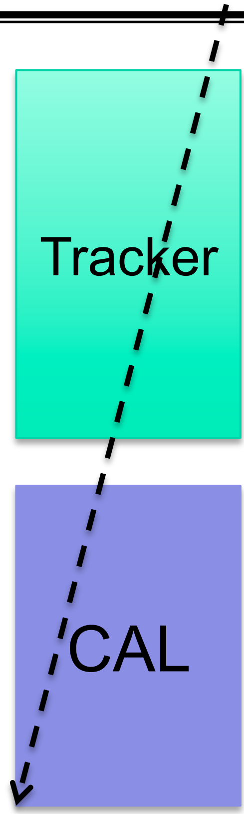
$$\theta_{\rm space}^{\rm rms} = \frac{\sqrt{2}\ 13.6\ \mathrm{MeVrad}}{E}\sqrt{x/X_0}[1+0.038\ln(x/X_0)].$$

For 100 MeV $e^{\pm}$: 0.006 X_0 => 1° of MCS

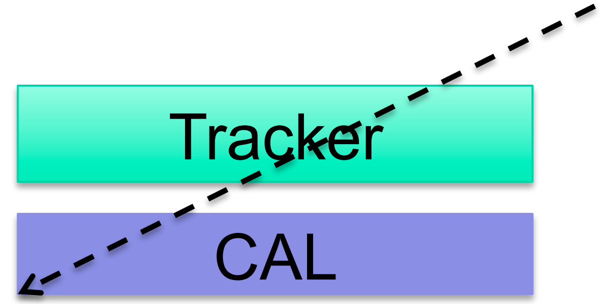
For 20 MeV $e^{\pm}$: 0.006 X_0 => 5° of MCS

- A key design choice is "information / mili-X_0"
  - Determines the point-spread function in the pair-conversion regime
    - Only the first hits contribute to direction measurement
  - This also determines the A_{eff} by fixing the total X_0 of the instrument.
    - The separation between readouts is limited by overall space constraints.
- Key design question:
  - How much information (positional accuracy * lever-arm * sqrt(N)) can we extract from the instrument before the particles are MCS dominated?

PSF & Energy Resolution vs. Field of View



Good Resolution,
Poor FoV



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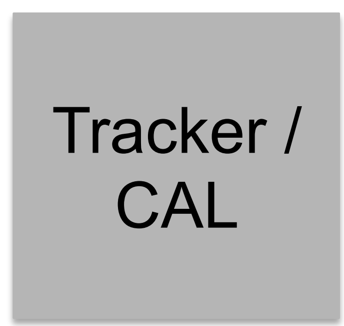

Is there a technology that allows monolithic design?

Assertion: Optimize for Breadth of Science

- The MeV sky is largely unexplored territory
  - We do not know which science topics will provide us with the most exciting surprises
  - We are guaranteed to see game-changing increases in the numbers of discovered sources in several source classes
  - *Fermi*-LAT has raised numerous scientific questions that can be investigated with data from the 100 keV to 100 MeV band
- ***Push each performance figure of merit to the point of diminishing returns, but no further***
- Broad science reach brings unexpected ancillary benefits
  - Large user community (higher chance serendipitous advances)
  - Cross-calibration (one person's background is another person signal)
  - Collaboration dynamics (everyone has a topic to call their own)