

*A thin detector as a high angular resolution gamma ray telescope (and polarimeter) in the MeV-TeV energy range*

*Towards a post-Fermi mission ?*

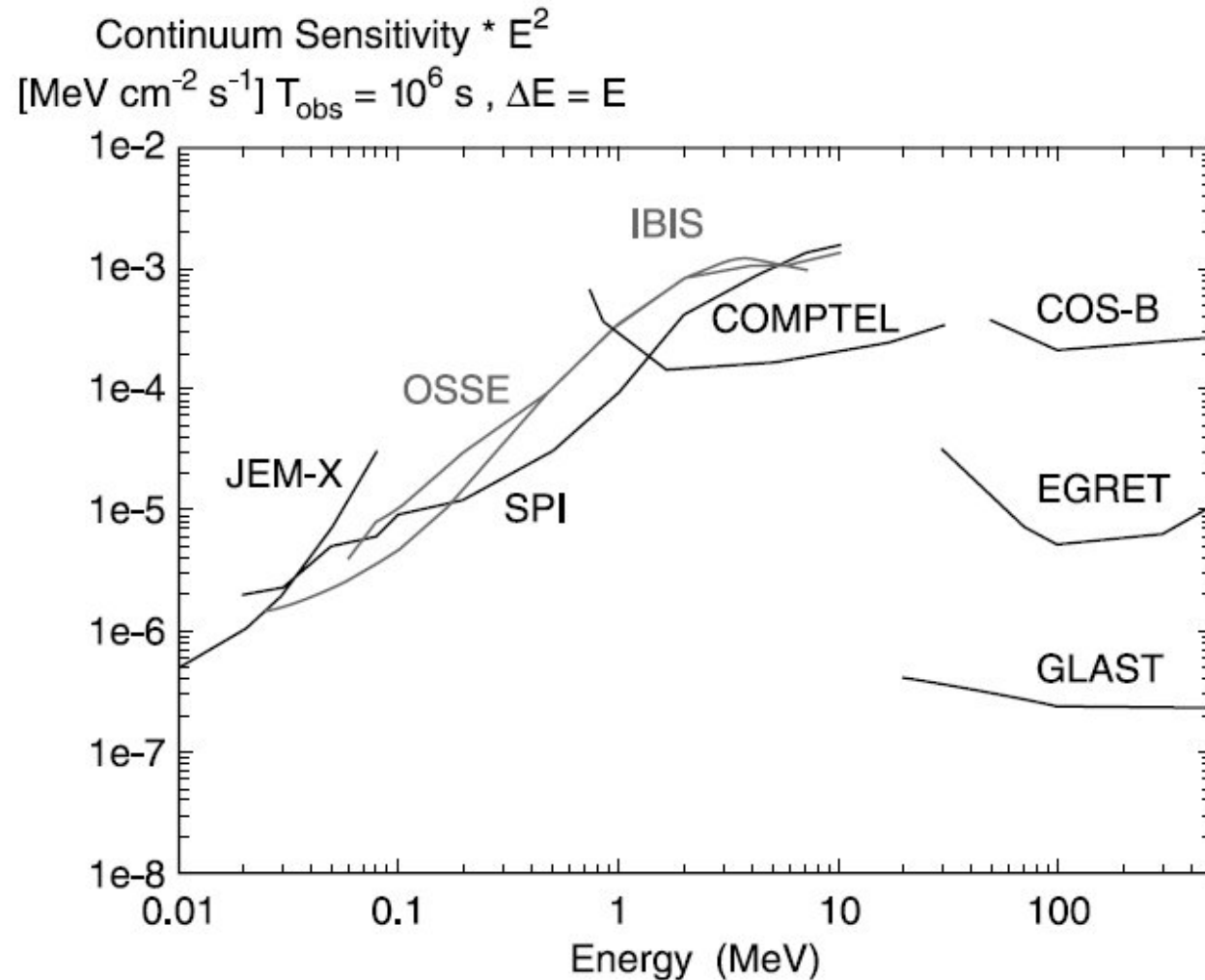
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LLR Ecole Polytechnique and CNRS/IN2P3

Gamma2012, Heidelberg, July 9-13 2012

## *Motivation 1 : fill the sensitivity gap ..*

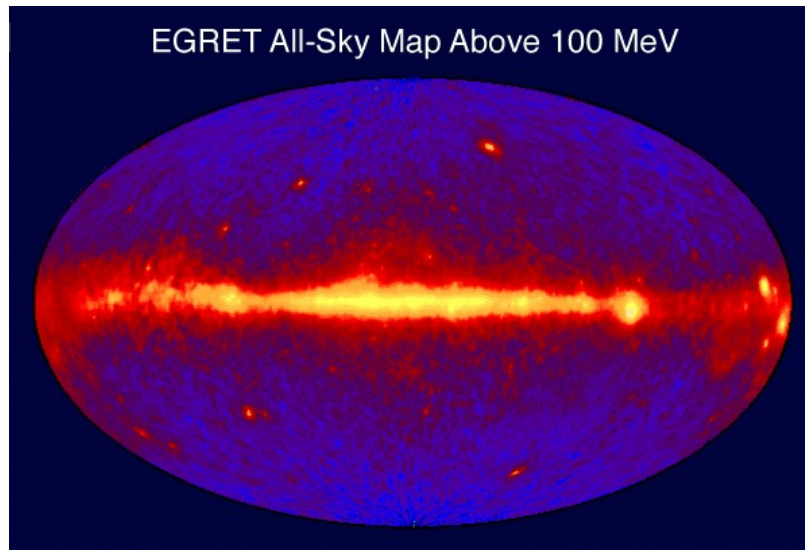
.. between Compton-based and  $e^+e^-$  pair based telescopes.



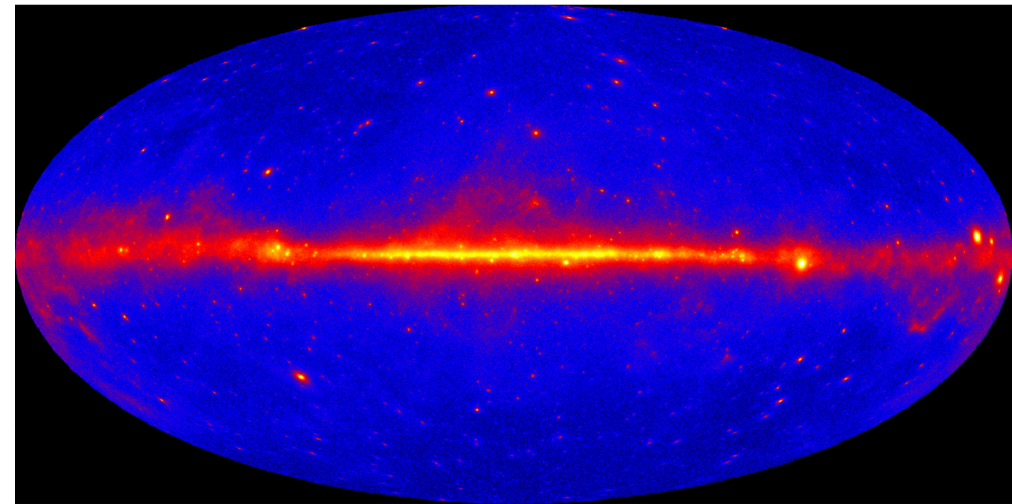
V. Schönfelder, New Astr. Rev. 48 (2004) 193

## *Motivation 2 : improve the PSF*

Especially in the crowded region, in the galactic plane



EGRET 9 years,  $E > 100\text{MeV}$



Fermi 2 years,  $E > 100\text{MeV}$

## *Thick / Thin detectors*

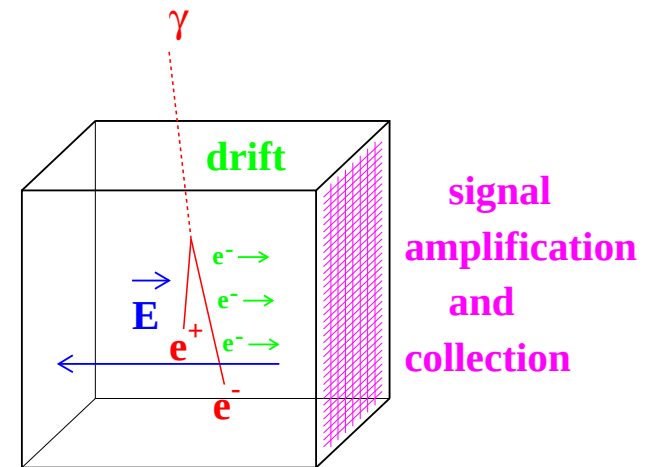
|                        | Thick                       | Thin                                      |                 |
|------------------------|-----------------------------|-------------------------------------------|-----------------|
| Conversion probability | $p \approx 1$               | $p \ll 1$                                 |                 |
| Effective area         | $\approx S \times \epsilon$ | $\approx \sigma \times M \times \epsilon$ |                 |
| Conversion processes   | compete                     | don't compete                             | with each other |

Compton scattering in low  $Z$  material not an issue.

# Time Projection Chamber

The TPC (D. R. Nygren 1974) : an example of thin detector.

- Homogeneous, fully sensitive medium
- Uniform  $\vec{E}$
- Liquid (Solid) ( $v_d = \mathcal{O}(\text{mm}/\mu\text{s})$ ), or gas with quencher ( $v_d = \mathcal{O}(\text{cm}/\mu\text{s})$ ).
- Diffusion  $\mathcal{O}(200\mu\text{m}/\sqrt{\text{cm}})$
- 3D imaging of the photon conversion
- Signal reading at endplane :  $2n$  ( $x, y$  strips) or  $n^2$  (pads) channels



Test parameters for this talk :

- Media : Ne, Ar, Xe
- Tracking length  $L = 30\text{cm}$  (gas,  $P = 1\text{bar}$  and  $P = 10\text{bar}$ ),  
 $L = 10\text{cm}$  (Liq / Sol),
  - unless  $X_0 < L$  (eg. : liq Xe : 3 cm in which case  $L = 3\text{cm}$  ).
- Longitudinal sampling  $l = 1\text{mm}$  ( $N = L/l$ ), spatial resolution 0.1mm

## *Angular resolution $\sigma_\theta$*

$$p_{\text{gamma}}^{\vec{}} = p_{e^+}^{\vec{}} + p_{e^-}^{\vec{}} + p_r^{\vec{}}$$

Several contributions :

- Track angular resolution
- Recoil momentum
  - nuclear  $\gamma Z \rightarrow e^+ e^- Z$  : unobserved
  - triplet  $\gamma e^- \rightarrow e^+ e^- e^-$  : observed
- Track energy (momentum) resolution

## *Track angular resolution $\sigma_\theta$*

- Computing angular resolution involves track and multiple scattering and detector spatial resolution ;
- At high track momentum  $p$ , detector spatial resolution dominates

$$\sigma_\theta \propto \frac{\sigma}{L\sqrt{N}}$$

- At low track momentum, multiple scattering dominates,

$$\sigma_\theta \propto \sigma^{1/4} l^{1/8} X_0^{-3/8} p^{-3/4}$$

( Fermi :  $\sigma_\theta \propto p^{-0.78}$  [arXiv :1206.1896v1](https://arxiv.org/abs/1206.1896v1) [[astro-ph.IM](#)])

- Limit between the two regimes is at momentum  $(p_0 = 13.6\text{MeV}/c)$

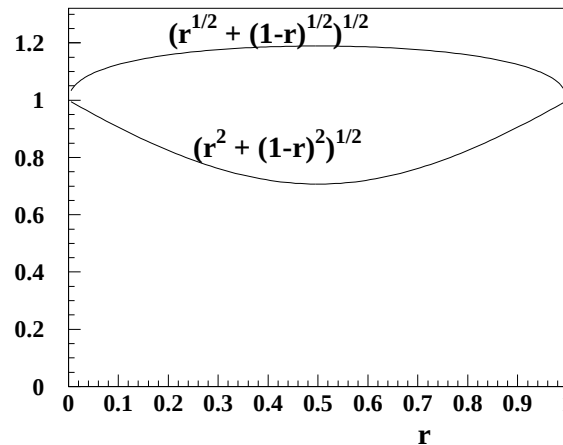
$$p_{lim} \propto \frac{p_0 L^2}{\sigma \sqrt{l} X_0}$$

R. L. Gluckstern, Nucl. Instrum. Meth. 24, 381 (1963).

# From track to photon angular resolution

- $E_\gamma = E_+ E_-$ ,  $\vec{p}_\gamma = \vec{p}_+ + \vec{p}_-$  neglecting recoil here ;
- $r$  energy fraction carried away by  $e^+$  ;  $r$  distribution approx. flat.  

$$\theta_\gamma = (r)\theta_{x+} + (1-r)\theta_{x-},$$



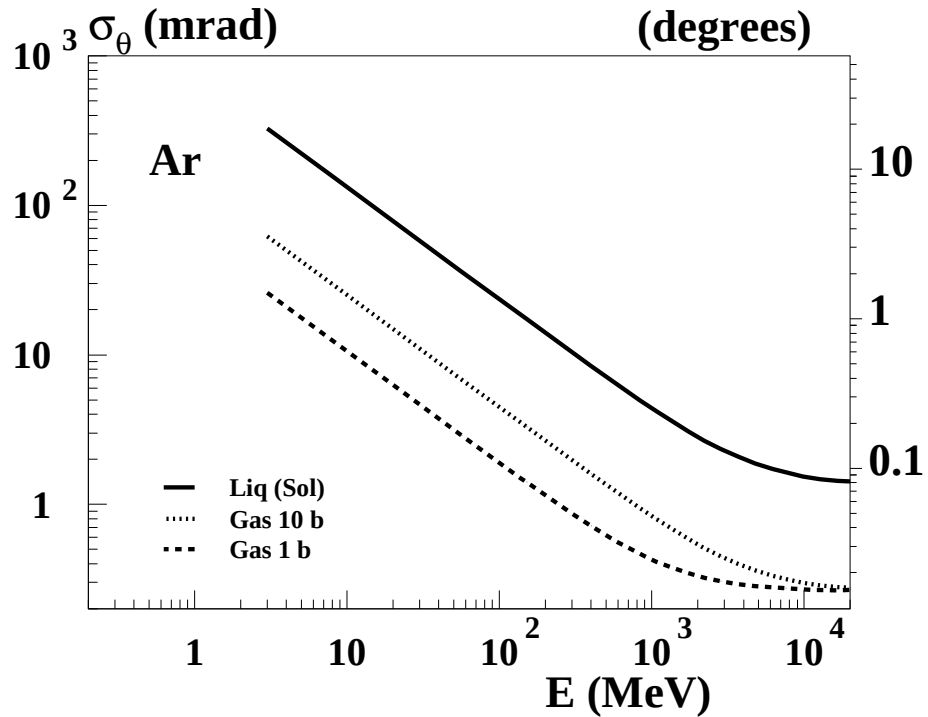
- multiple scattering dominated régime,  

$$\sigma_{\theta,\pm} = Ap^{-3/4} \qquad \sigma_{\theta,\gamma} = Ap^{-3/4} \sqrt{\sqrt{r} + \sqrt{1-r}}$$
- High energy régime :  

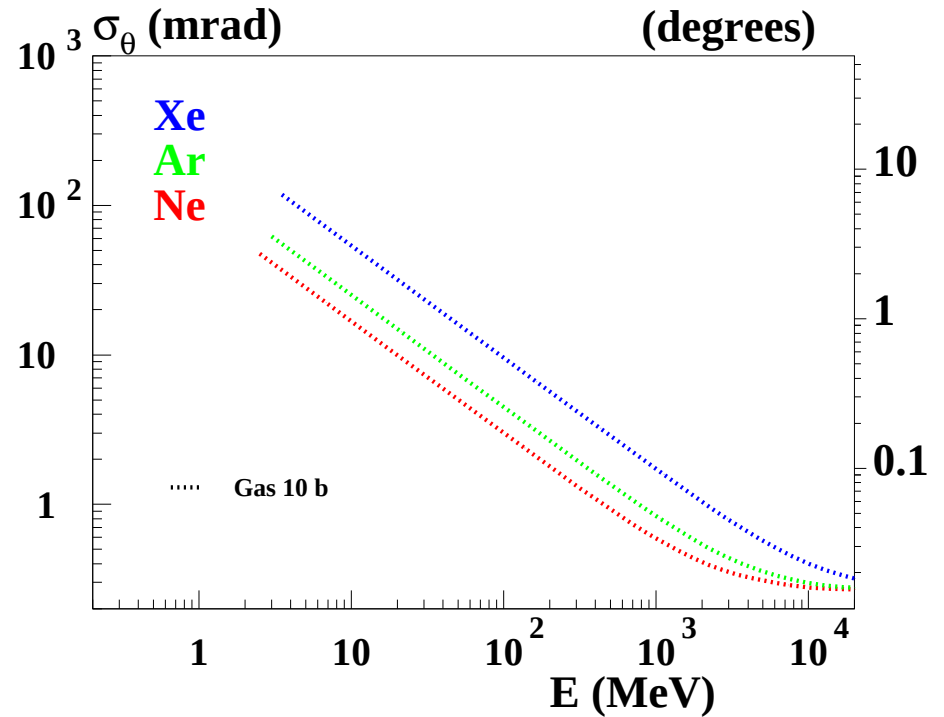
$$\sigma_{\theta,\pm} = B \qquad \sigma_{\theta,\gamma} = B \sqrt{r^2 + (1-r)^2}$$
- In the following I neglect these factors.



# Photon angular resolution

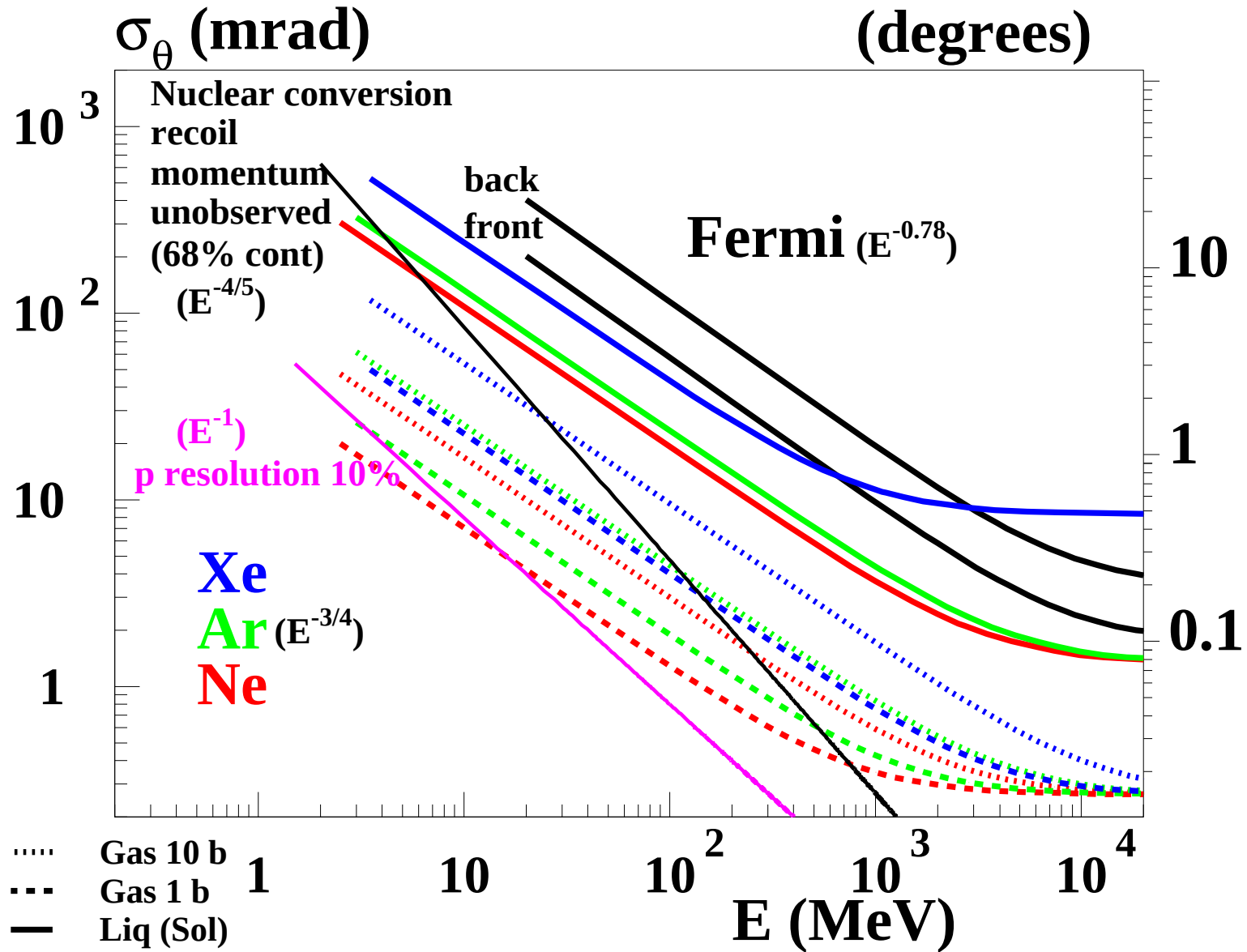


Variation with density



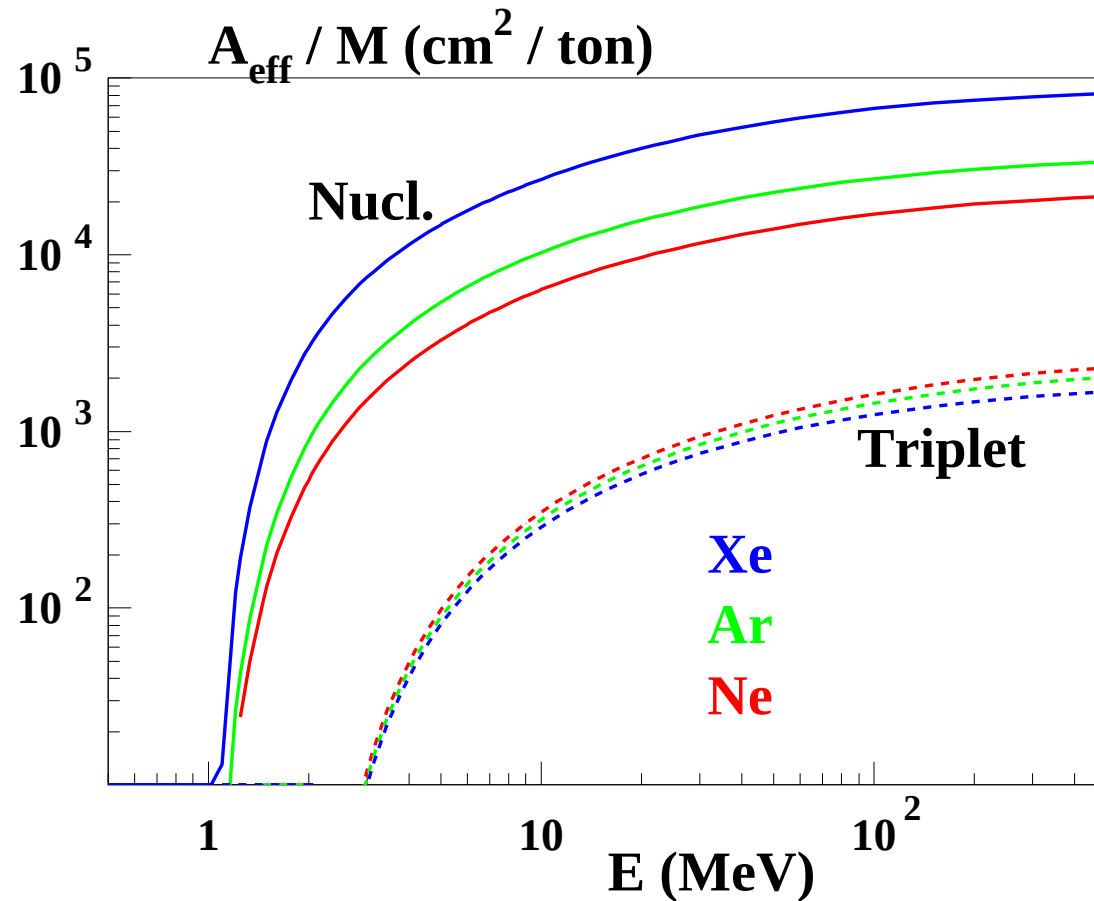
Variation with  $Z$

# Photon angular resolution



# Effective Area

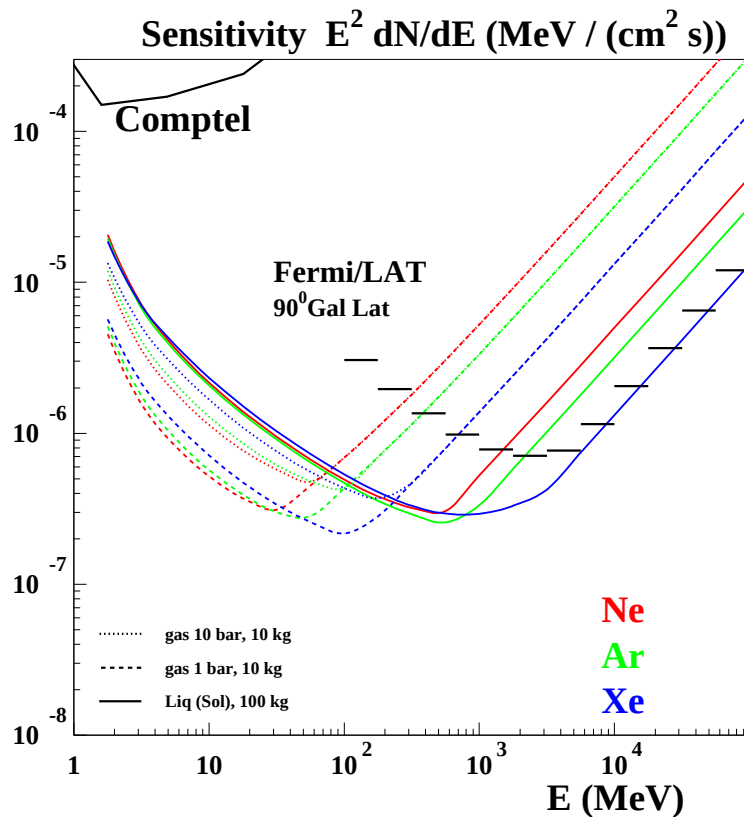
$$A_{eff} = \sigma \times M, \epsilon \approx 1 \text{ assumed.}$$



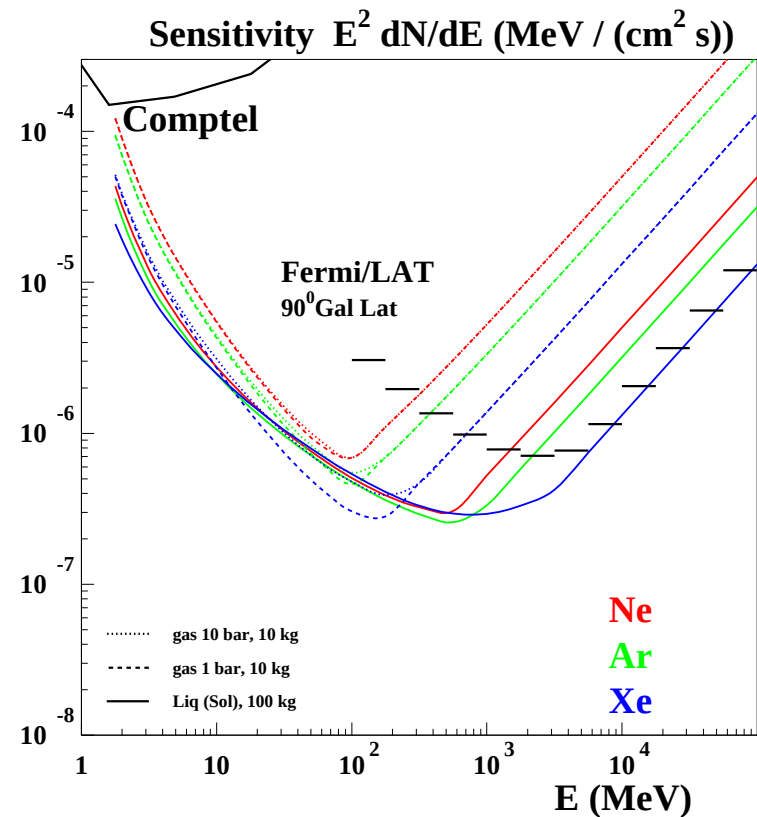
- nuclear  $\gamma Z \rightarrow e^+ e^- Z$
- triplet  $\gamma e^- \rightarrow e^+ e^- e^-$

# Differential sensitivity

- A la Fermi/LAT (4 energy bins/decade, 3 years, 5 sigma significance,  $\geq 10\gamma$ )
- High galactic latitude : extragalactic background Fermi P.R.L. 104, 101101 (2010)
- Liq/Sol 100 kg detector mass, gas 10 kg; exposure fraction 17 %



Neglect unmeasured recoil  $q$

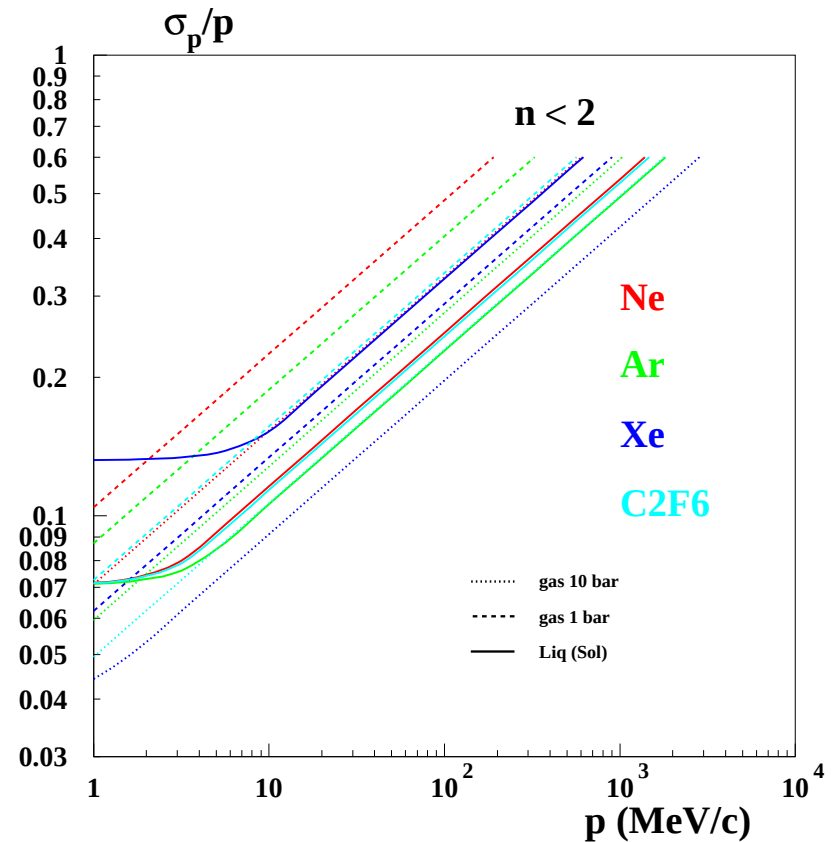


Includes unmeasured recoil  $q$

# *p from multiple measurement of multiple scattering*

- $\theta_0 \propto 1/p \Rightarrow p \propto 1/\theta_0$
- Optimization of step size.

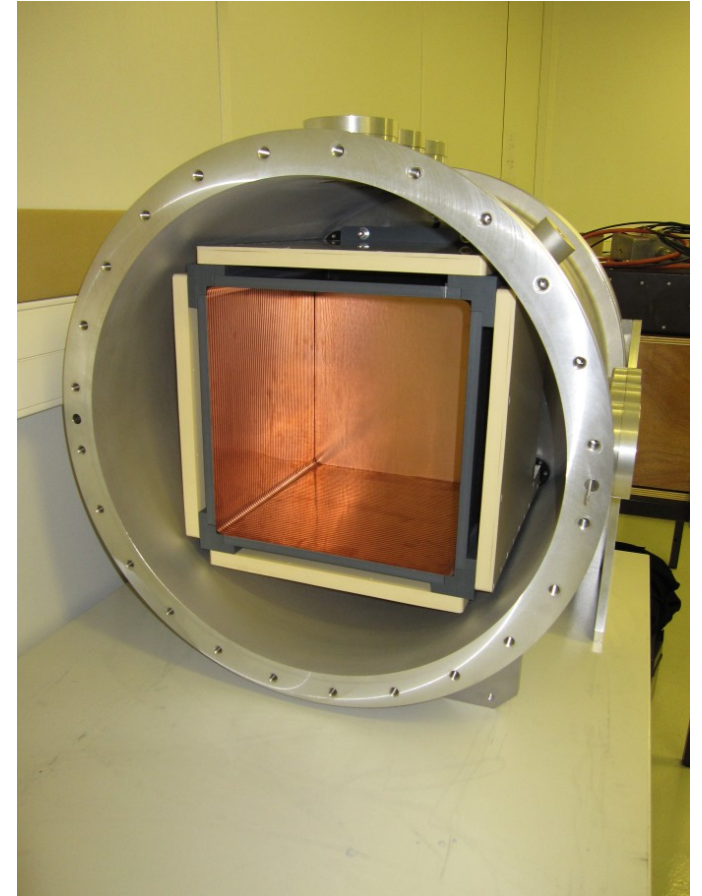
$$\frac{\sigma_p}{p} \propto \frac{1}{\sqrt{L}} \left[ \frac{p\sigma\sqrt{X_0}}{13.6\text{MeV}/c} \right]^{1/3}$$



- Needs additional  $p$  measurement above 100 MeV
  - A calorimeter? watch mission mass budget;
  - A magnetic spectrometer?

# *HARPO Project*

- Characterization of a TPC as  $\gamma$  telescope and polarimeter
- Measurement of triplet ( $\gamma e^- \rightarrow e^+ e^- e^-$ ) polarization asymmetry
- Demonstrator built,  $(30 \text{ cm})^3$ , 5 bar Ar-based gas.
- Being tested with cosmic rays
- Data taking with polarized  $\gamma$  beam being prepared, 2 – 76 MeV (NewSUBARU), 1.5 – 2.5 GeV SPring8, Japan



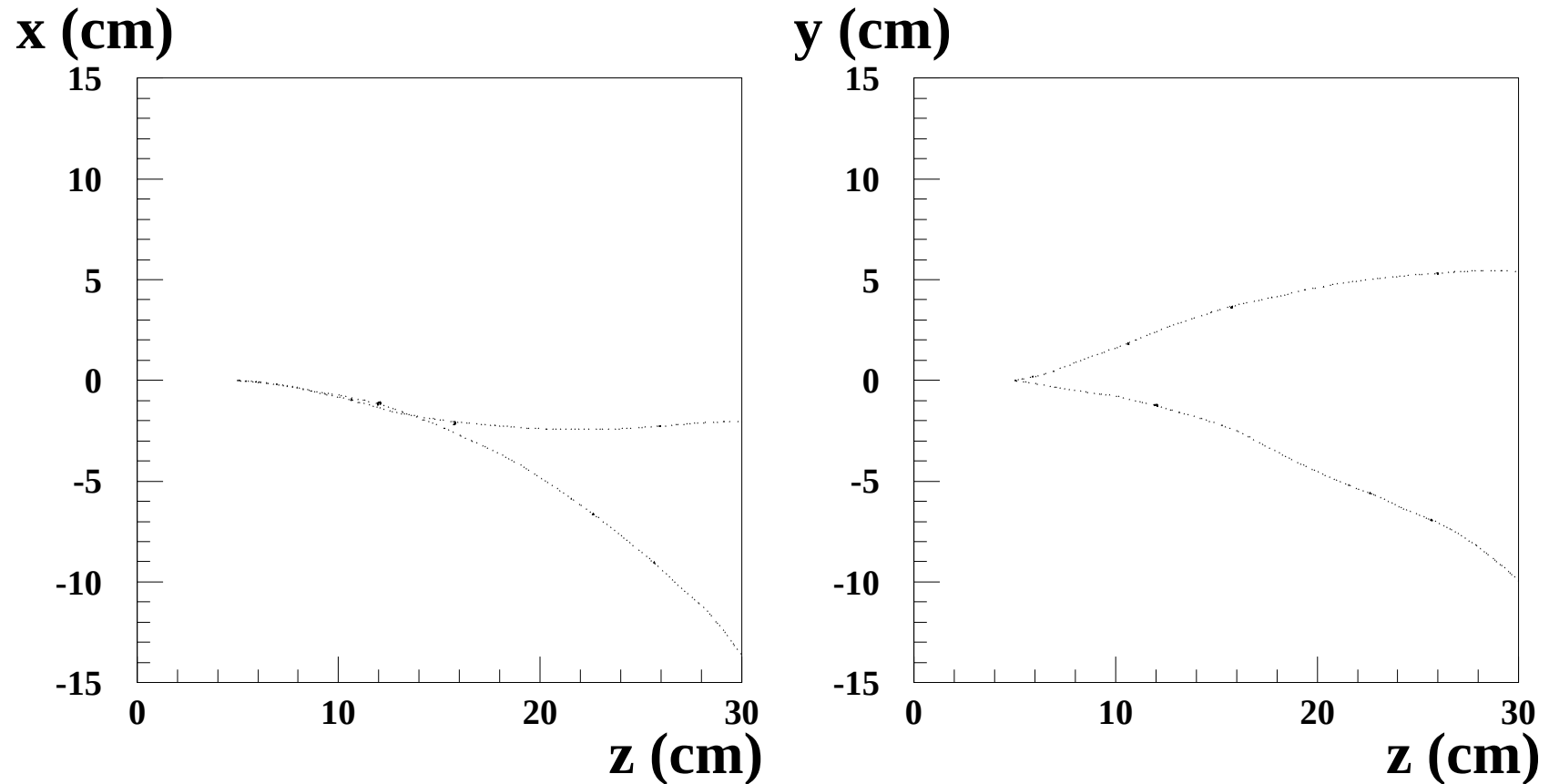
[arXiv :1203.5889v1](https://arxiv.org/abs/1203.5889v1) [astro-ph.IM]

# *Conclusion*

Thick → thin detector technology allows :

- Improvement of angular resolution → and of background rejection
  - $\gamma$  albedo easily rejected by detailed event imaging.
- $2\pi$  acceptance
- Increase of effective area / unit mass
- Impressive sensitivity improvement [MeV - GeV]
  - even for modest mass (gas 10 kg, liq/sol 100 kg).
- Track momentum measurement up to 100 MeV
  - Must be complemented at high energy
- Gas : Polarimetry by analysis of azimuthal angle of recoiling  $e^-$

*Thanks for your attention*



A 10 MeV  $\gamma$  converting into a  $(30\text{cm})^3$  5 bar Ar TPC.

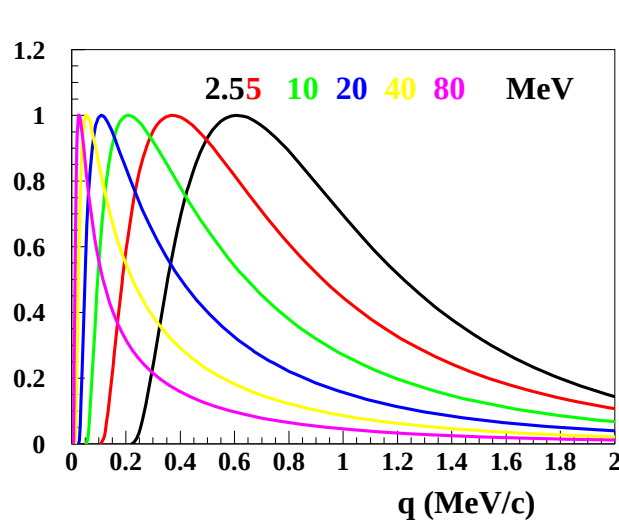
EGS5 simulation



# *Backup slides*

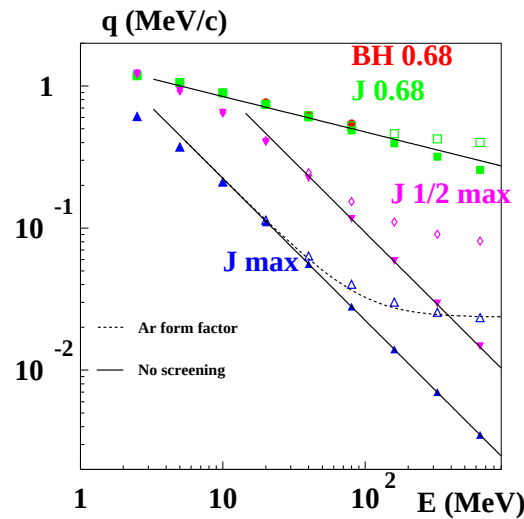
# Momentum of the recoiling particle

- Triplet :  $\gamma e^- \rightarrow (e^+ e^-) e^-$
- “Nuclear” :  $\gamma Z \rightarrow (e^+ e^-) Z$  :  $\vec{q}$  unmeasured.  
 $q$  said to be “typically 1 MeV/c”.



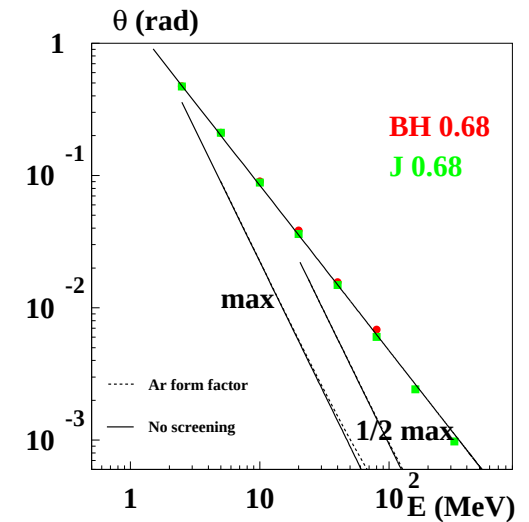
1d R. Jost Phys. Rev. 80, 189 (1950).

68 % containment  
 maximum  
 At half max

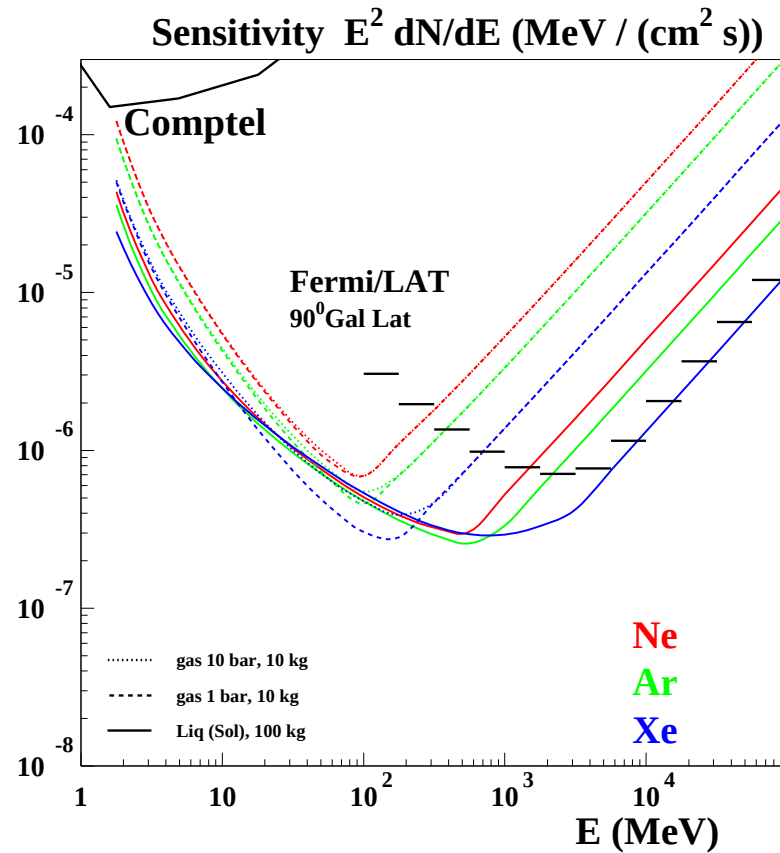


5d “The quantum theory of radiation”, W. Heitler, 1954.

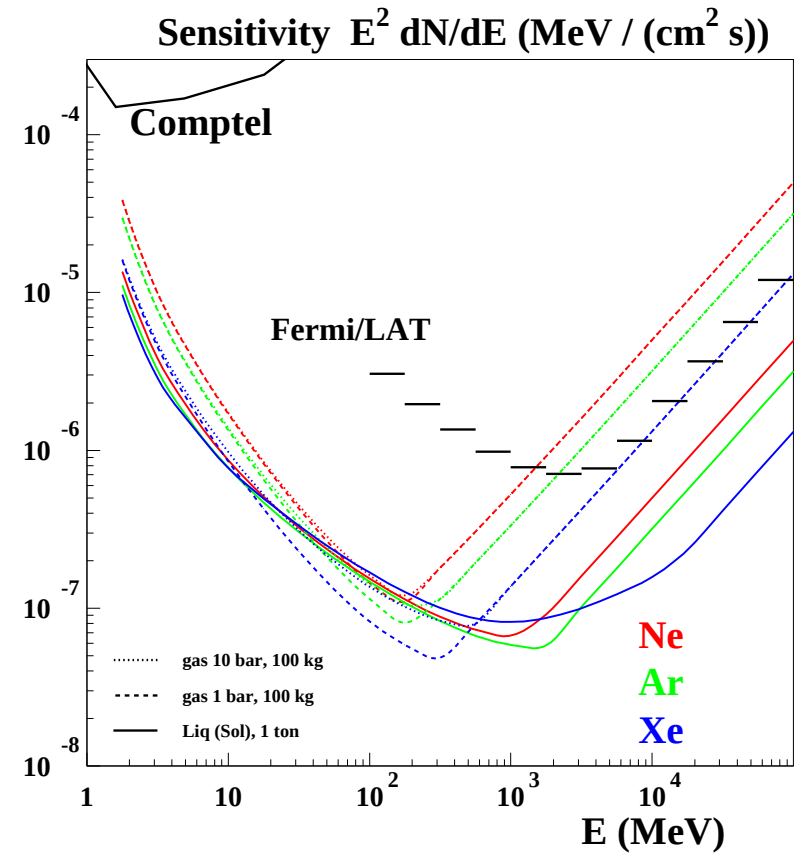
| $q$ (MeV/c)        | $\theta$           |
|--------------------|--------------------|
| $\propto E^{-1/4}$ | $\propto E^{-5/4}$ |
| $\propto 1/E$      | $\propto 1/E^2$    |
| $\propto 1/E$      | $\propto 1/E^2$    |



# *Sensitivity : effect of a factor $\times 10$ in mass*

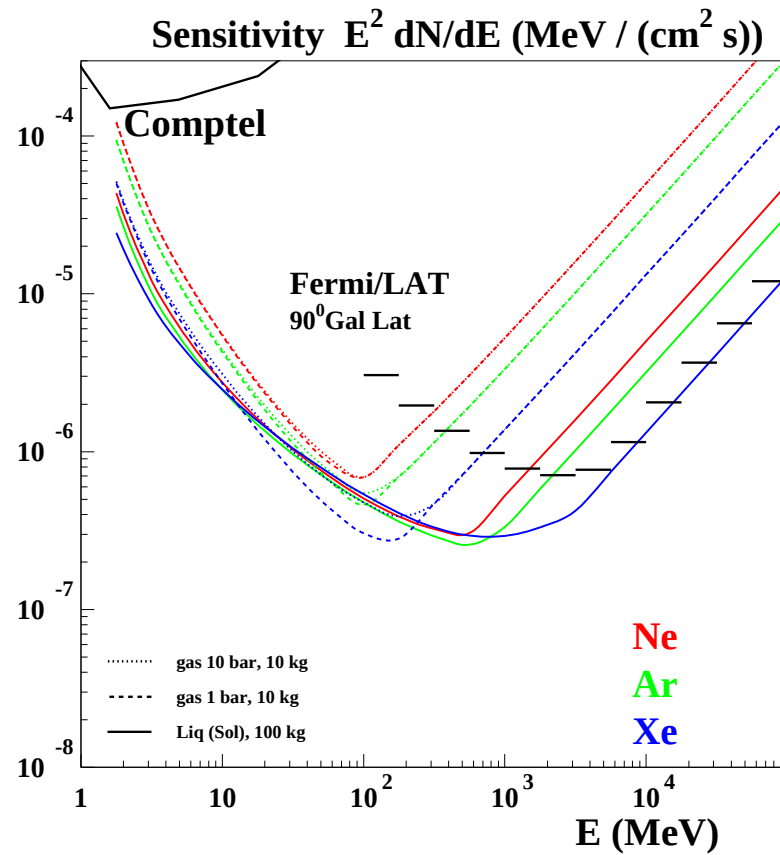


1

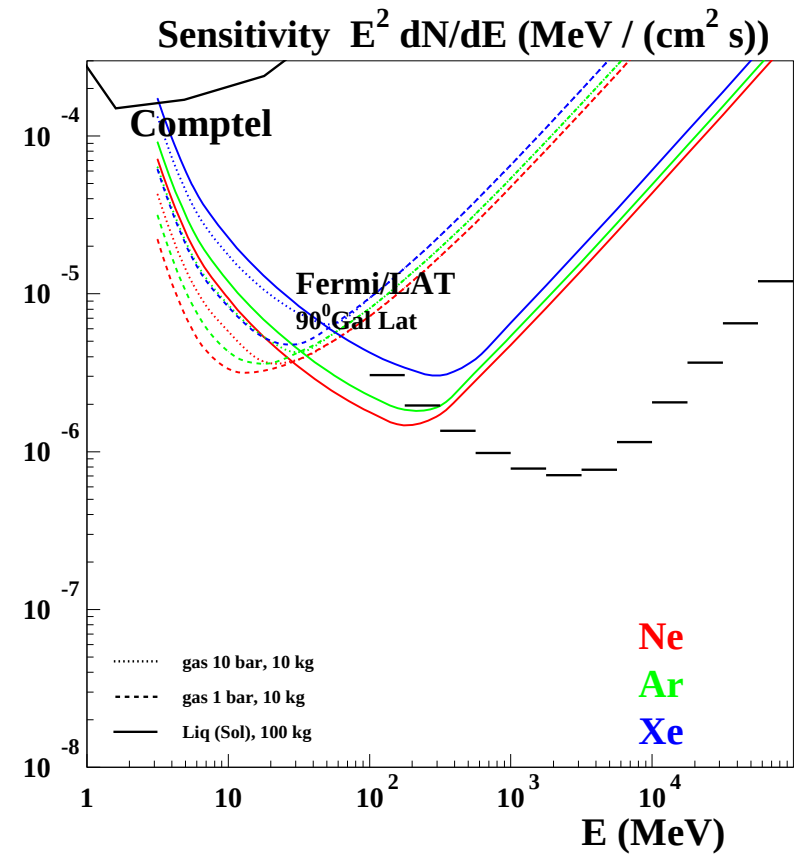


10

# *Sensitivity : Nuclear compared to triplet*



Nuclear



Triplet

# *Polarimetry in a nutshell*

Analysis of  $(1 + \mathcal{A}P \cos [2(\phi - \phi_0)])$  of  $\gamma$  conversion

- Compton ? Polarization asymmetry  $\mathcal{A} \propto 1/E$  😞
- Nuclear pair conversion ? multiple scattering ruins  $\phi$  measurement 😞
- Triplet pair conversion ?
  - recoil electron emitted at large angle
  - momentum typically sub-MeV/c
  - measurement possible in gas TPC
  - Crab :  $\sigma_P \approx 0.6/\sqrt{\text{year.kg}}$  in Ar
    - 3 years, 10 kg,  $\sigma_P \approx 10\%$

See eg, Poster by U. Menzler et al.

Polarization as a possible discriminant of high-energy gamma-ray production processes in AGN

# *Magnetic spectro in a nutshell*

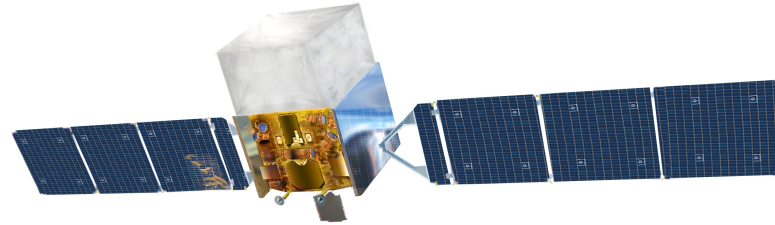
Curvature  $\rho \equiv 1/R = 0.3B/p_t$ , [T], [m], [GeV/c]

$$\frac{\sigma_\rho}{\rho} = \frac{\sigma}{L^2 0.3B} \sqrt{\frac{720}{N}}$$

- $B = 0.1 \text{ T}$
- $L = 1 \text{ m}$
- $d = 1 \text{ mm} \rightarrow N = 1000$
- $\sigma = 100 \mu\text{m}$

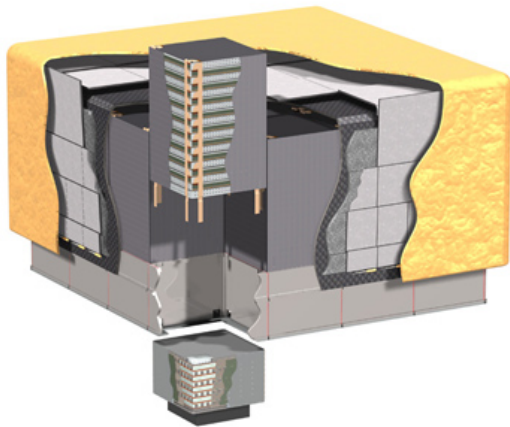
$$\frac{\sigma_\rho}{\rho} = 28\% \frac{p_T}{100 \text{ GeV}/c} \oplus C^{st}$$

# *GLAST / Fermi*



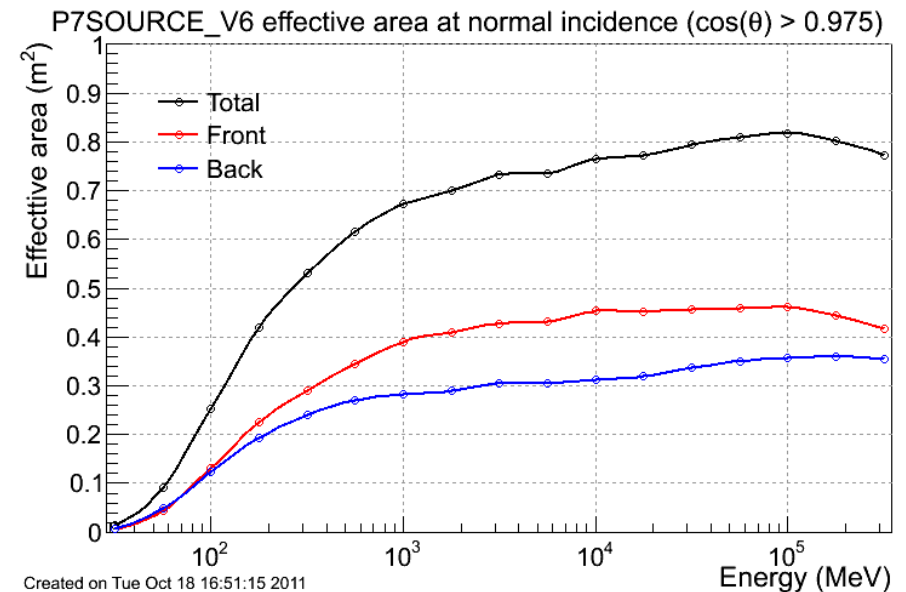
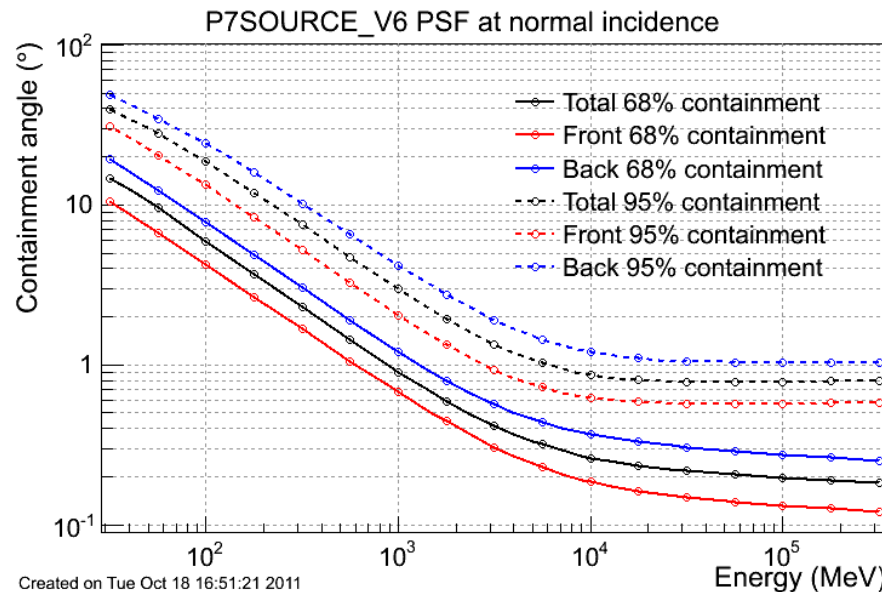
## Fermi LAT : 2008 – 2018

- Impressive harvest on vast programme :  
pulsars, active galactic nuclei (AGN), gamma-ray bursts (GRB), binary stars, supernova remnants  
...
- $E_\gamma$  range 20 MeV - 300 GeV
- 16-plane **Converter/Tracker W/Si** ( $1.1X_0$ )
- 8-layer CsI :TI **Calorimeter CsI :TI** ( $8.6X_0$ )
- Segmented scintillator cosmic-ray veto
- $1.8\text{m} \times 1.8\text{m} \times 0.7\text{m}$ , 2.8 ton.



# Fermi

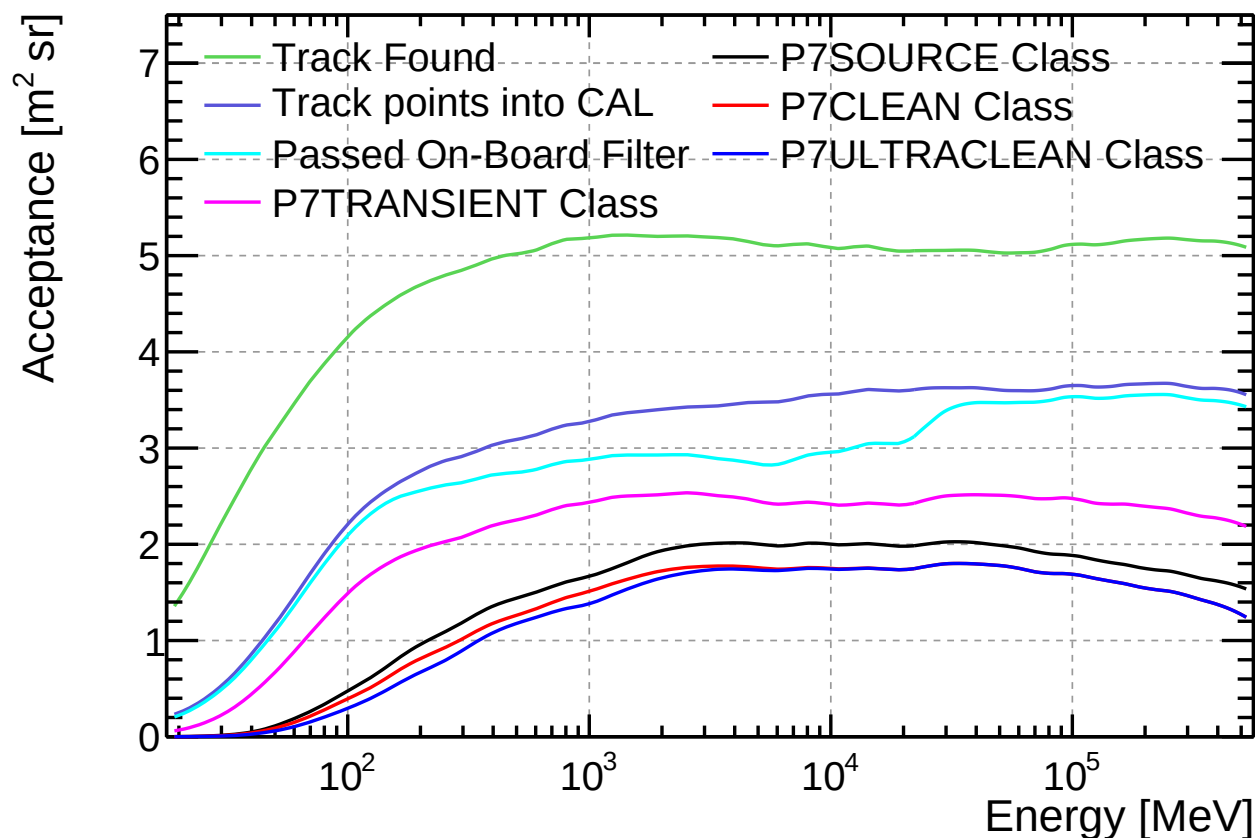
- Actually Fermi is publishing mostly in the range 0.1 – 300 GeV
- Effective area  $\approx 1 \text{ m}^2$  above 1 GeV



- Photon selection kills efficiency at low  $E$ 
  - Due to huge background at low  $E$
  - Due to larger angular resolution at low  $E$
- No polarimetry



# *Fermi/LAT $A_{eff}$*



Fermi/LAT  $A_{eff}$  integrated over the FOV as a function of energy at successive stages of the event filtering as estimated with simulated data.

[arXiv :1206.1896v1 \[astro-ph.IM\]](https://arxiv.org/abs/1206.1896v1)