Next generation space experiments for TeV-PeV energies

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What's This?

- (partial) summary of a mini-workshop (2 days, 10 people invited , +local participants) in Pisa, 8-9 May 2014;
- organized BEFORE the WhatNext era;
- experimentalists (AMS, Fermi) and theroreticians for a joint discussion on
  - *"Physics Cases and Technical Solutions for a Next Generation Space Experiment after AMS and Fermi"*

Current issues in CR propagation

- Several important observables in the field of CR are well described by simple models of propagation and acceleration
- Yet there are some tensions with experimental data:
  - p/He ratio: He spectrum seems to be harder than protons, at least for energies <10TeV : *hardly explainable in terms of Fermi acceleration*
  - CR spectrum hardening: p and He spectra seem to harden at ~250 GeV , which requires a spectral break at these energies
  - anisotropy: models with index $\delta > 0.5$ predict an anisotropy larger than what observed in the 1-100 TeV range
  - γ-ray gradient: the measured diffuse γ-ray emission galactocentric gradient is flatter than predictions

The role of Space Detectors

- Necessity of a new generation of experiments in the TeV-PeV range
- This energy range can (and should) be covered by ground-based telescopes
- But space-based experiments can detect the *primary* CR component (i.e. before interacting with atmosphere) → sensitive to nuclear composition
- An additional bonus of space experiments is the possibility of measuring the charge sign→ access to anti-particles
- Limits: dimensions, mass, cost !

Recent, present and future Space (and Balloon) Detectors

Experiment	Geometrical Acceptance (m^2sr)			$\sigma E/E$		
	e	γ	p	e, γ	p	
ATIC	0.24	0.24	0.24	2% @ ?	-	balloon
CREAM	-	-	0.43	-	45% @ 100 TeV	
AMS02	0.05	0.05	0.02-0.25(*)	2% @200GeV	-	space
Fermi	2	2	-	5-15 %	-	
Pamela	0.0022	0.0022	-	5-10 %	-	
CALET	0.12	0.12	-	2% @ 1TeV	40% @ 1TeV	near future
DAMPE	0.2	0.2	-	1.5% @ 800 GeV	40% @ 800 GeV	
ISS CREAM	-	-	0.43	-	45% @ 100 TeV	
Gamma400	3	1	3	2% @ 1 TeV	35% @ 1 TeV	medium term
HERD	3	?	3	1% @ 1TeV	30% @ 10 TeV	
AMS03 (**)	0.75	0.75	?	2% @ 1 TeV	?	

(*) full span - inner only (**) to be intended as *"generic magnetic spectrometer"*

- Note that a fair comparison among so many different instruments is close to impossible
  - take these numbers *cum grano salis*

Space Detectors

- Energy range: E>10GeV
  - not trying to do E=100 MeV at the same time!
- Space experiments can be classified as

1. Magnetic spectrometers (*à la* AMS02)
2. Pair-conversion telescopes (*à la* Fermi)
3. Cosmic Ray calorimeters (*à la* CREAM or ATIC, but also ISS-CREAM, CALET, DAMPE, ...), that can be specialized on hadrons or on em-showers
   - with possible combinations of the techniques

Space Detectors

- *Spectrometers* : momentum and charge sign
  - **access to anti-particles (positrons, antiprotons, ...)**
  - access to CR isotopical composition (in principle)
  - BUT... magnet is heavy (permanent) or hard to operate (superconducting) → some R&D in progress
- *Pair-conversion telescope : gamma physics*
  - **dedicated tracking stage (>1X_0) in which γ->e^+e^-**
  - excellent Point Spread Function (PSF = angular resolution)
  - BUT ... adds some complexity: impact on Field Of View and Energy resolution
- *Calorimeters* : $e^\pm$, p, nuclei (Z measurement)
  - **maximum acceptance**
  - reach of high energies (~ PeV) for hadrons
  - precise (large statistics) measurement of e^++e^- flux

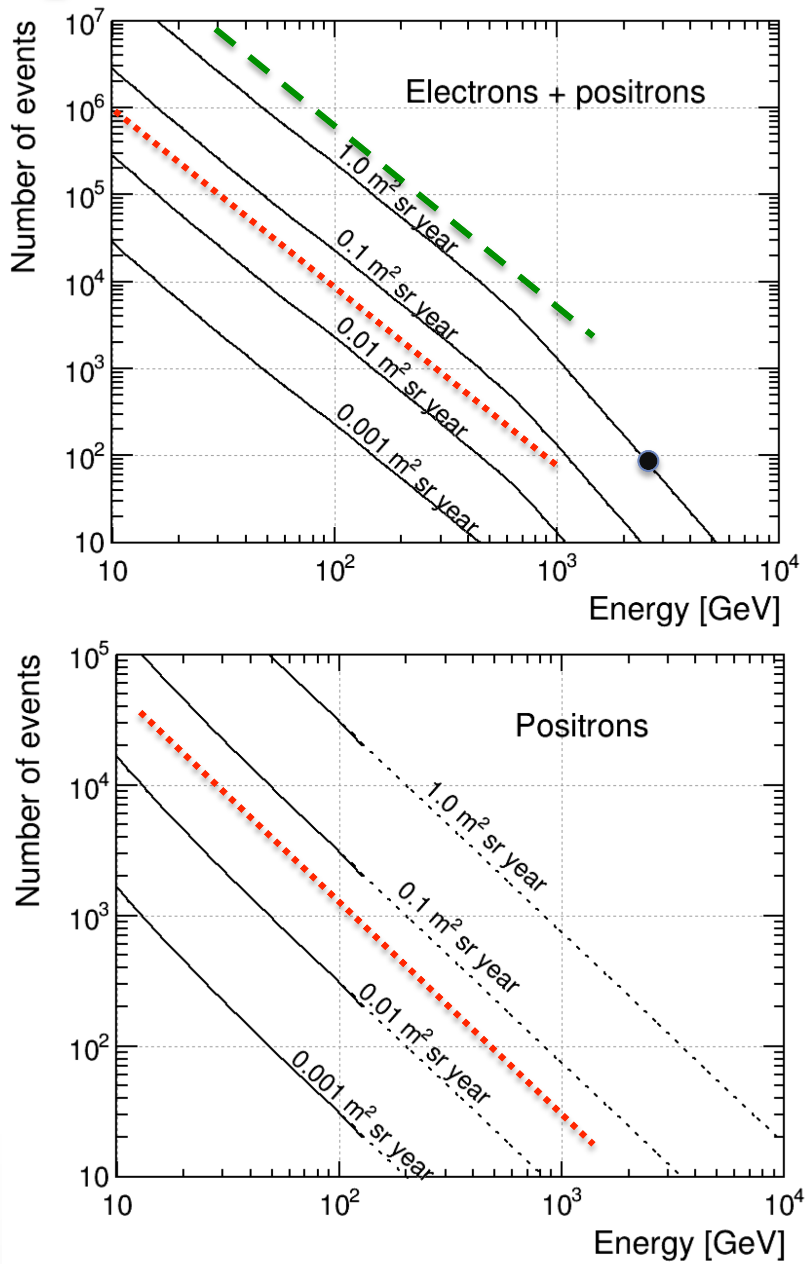
Statistics vs Acceptance

Geometrical Acceptance:

Fermi - - - -

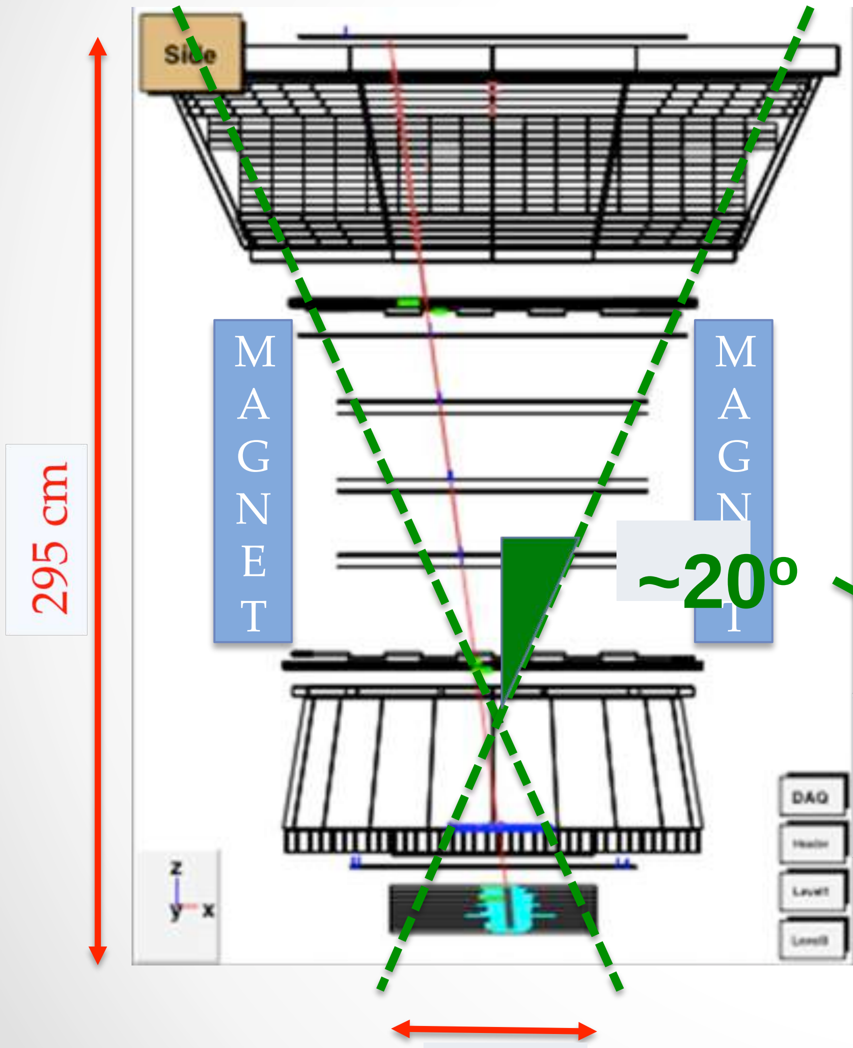
AMS02 ....

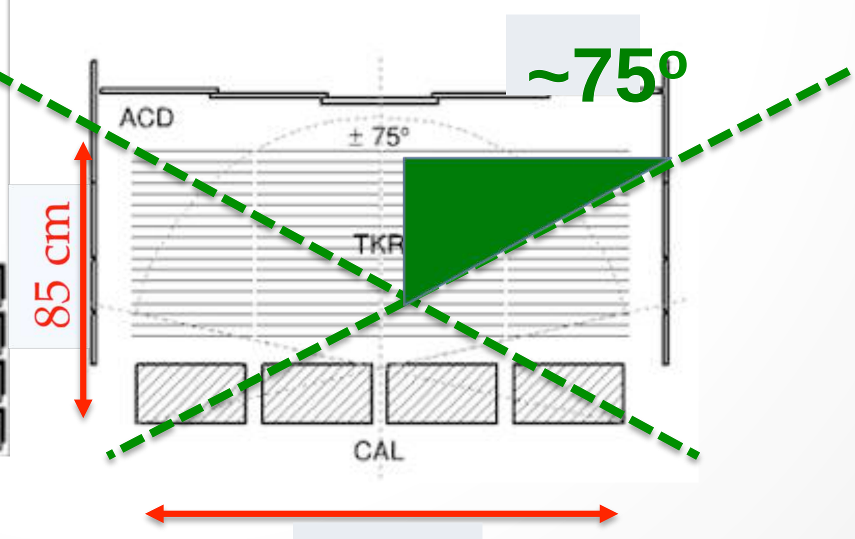
- The CR flux rapidly decreases with energy (~E^{-3})
- For an Acceptance of ***1m² sr year*** → at most ***100 e⁺+e⁻ events*** per year are expected at ***E~2-3 TeV***
- A magnetic spectrometer is limited by the Field Of View (see next slide)



Comparison AMS02-Fermi

- The 2 detectors in scale
- Fermi maximizes acceptance (Fermi-LAT)
- AMS02 FoV limited by magnet
- Fermi FoV limited by tracker





Next generation experiments

- Under some "reasonable" assumptions (no time to detail them here) possible figures for a next generation experiment are:

	$\Delta E/E$ em (asymprotic)	$\Delta E/E$ had (asymptotic)	Charge Discrimination	PSF (*degrees*)	acceptance ($m^2 sr$)
Magnetic Detector	2%	40%	up to 5.6 TeV (e^+) up to 1.5 TeV ($\bar{p}$)	0.5	0.71
γ telescope	2%	40%	-	0.05	2.5
Calorimeter	1%	20%	-	0.5	6

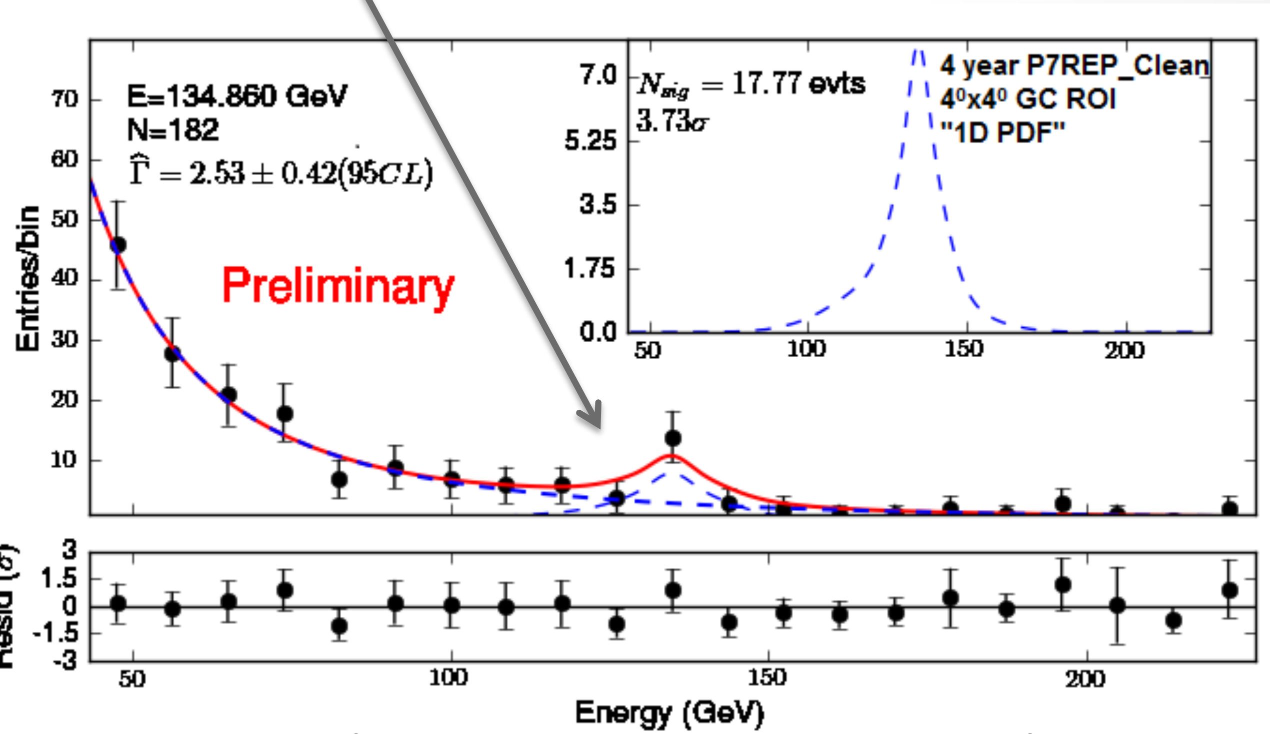
- Question: how much you can give up in statistics in order to gain in anti-particle identification (Magnet) or γ pointing capability (γ-converter)?

Example: Sensitivity to Gamma line

- Annihilation of a Dark Matter particle in a photon pair results in a distinct "line" in the photon spectrum
- The "*Quality of the line*" is:

$$Q = \frac{n_s}{\sqrt{n_b}}$$

- n_b proportional to the Energy Resolution ΔE (ΔE>bin width)



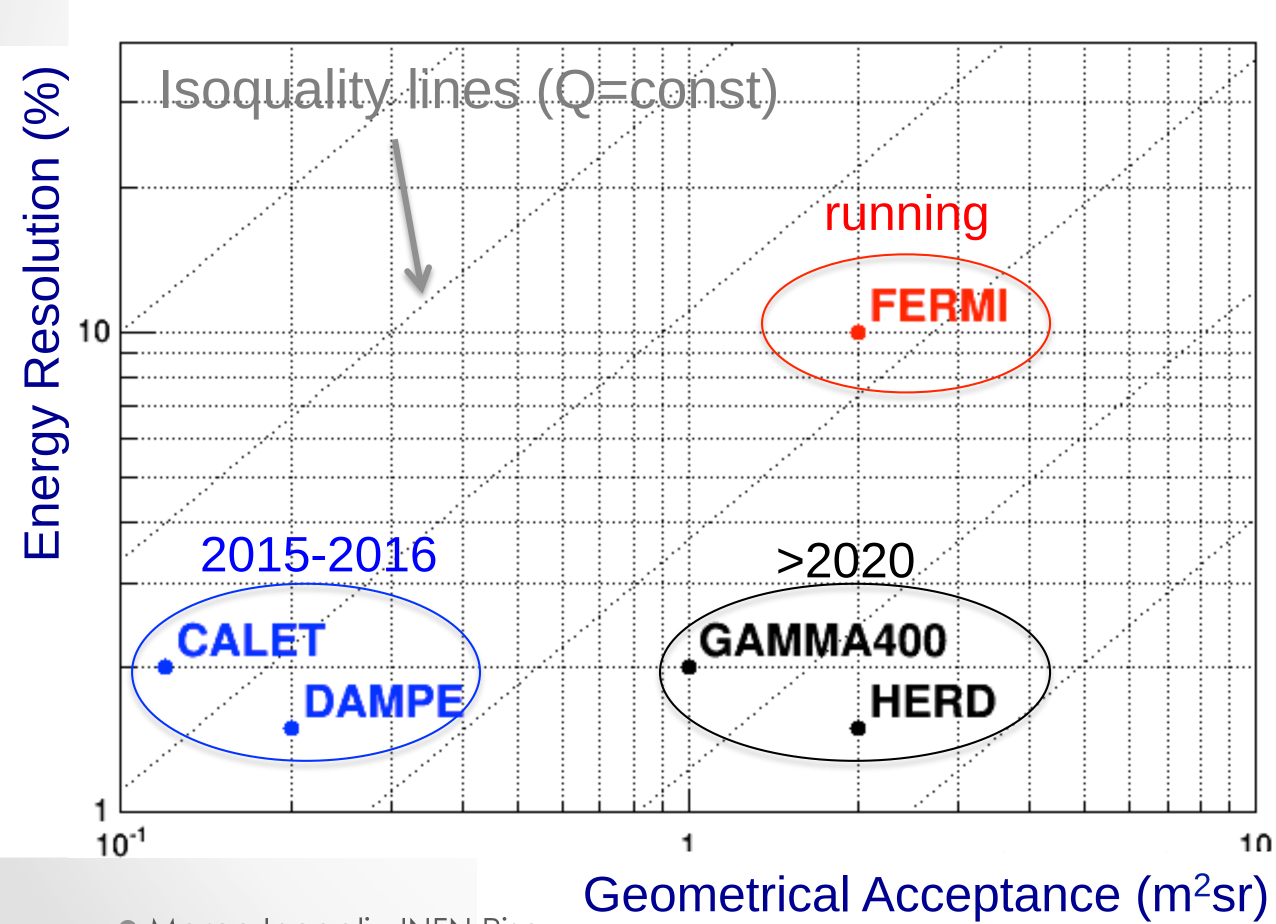
- Both n_s and n_b are proportional to the Geometrical Acceptance *A*

Sensitivity to Gamma line

$$Q = \frac{n_s}{\sqrt{n_b}} \propto \sqrt{\frac{A}{\Delta E / E}}$$

Acceptance

Energy Resolution



The message:

energy resolution is good ... if you are not trading too much acceptance for it!

NOTE: the parameters used for future detectors should only be taken as ***order of magnitude***!

And what about the systematics

- Three main *general* sources (I will not discuss terms like *Z* identification, trigger, ... as they are too much experiment-related):

1. Systematic error on the **geometrical acceptance**

$$\frac{\Delta J}{J} = -\frac{\Delta G}{G}$$

G = Geometrical Acceptance

2. Systematic error on **energy resolution**

$$\frac{\Delta J}{J} \sim \left(\frac{\Delta E}{E}\right)^2$$

$\Delta E/E$ = Energy Resolution

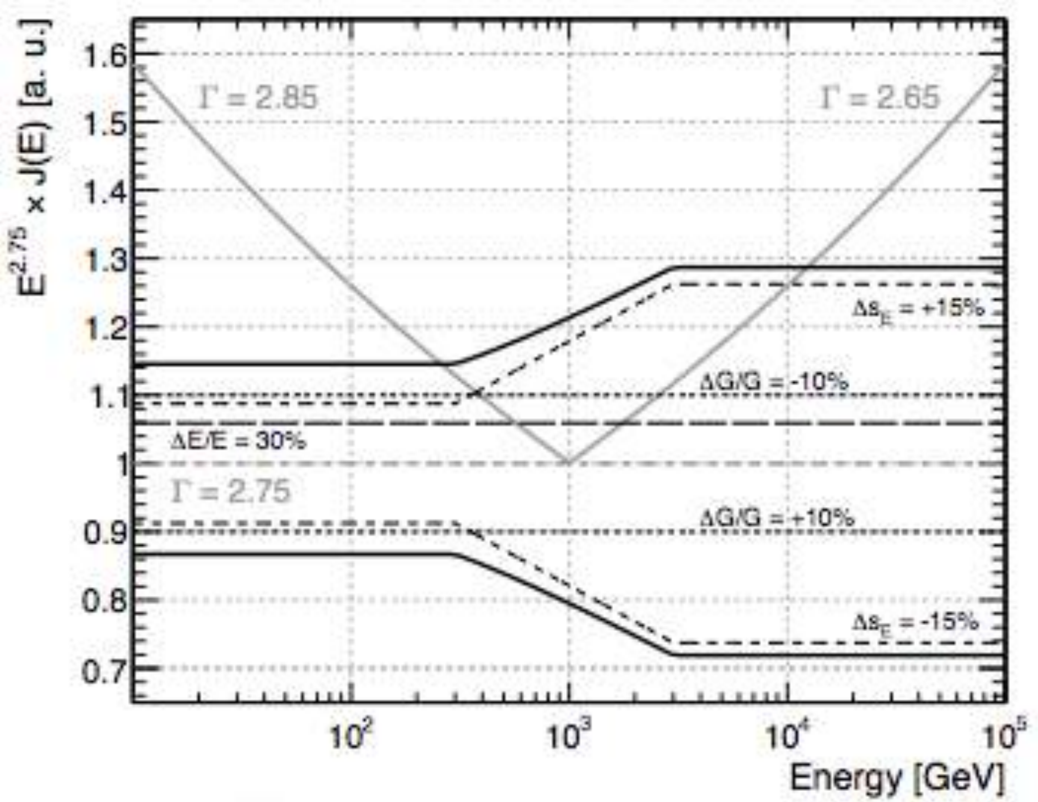
3. Systematic error on absolute **energy scale**

$$\frac{\Delta J}{J} = (\Gamma - 1)\frac{\Delta s_E}{s_E}$$

Δs_E = shift on asolute Energy Scale

Putting all together

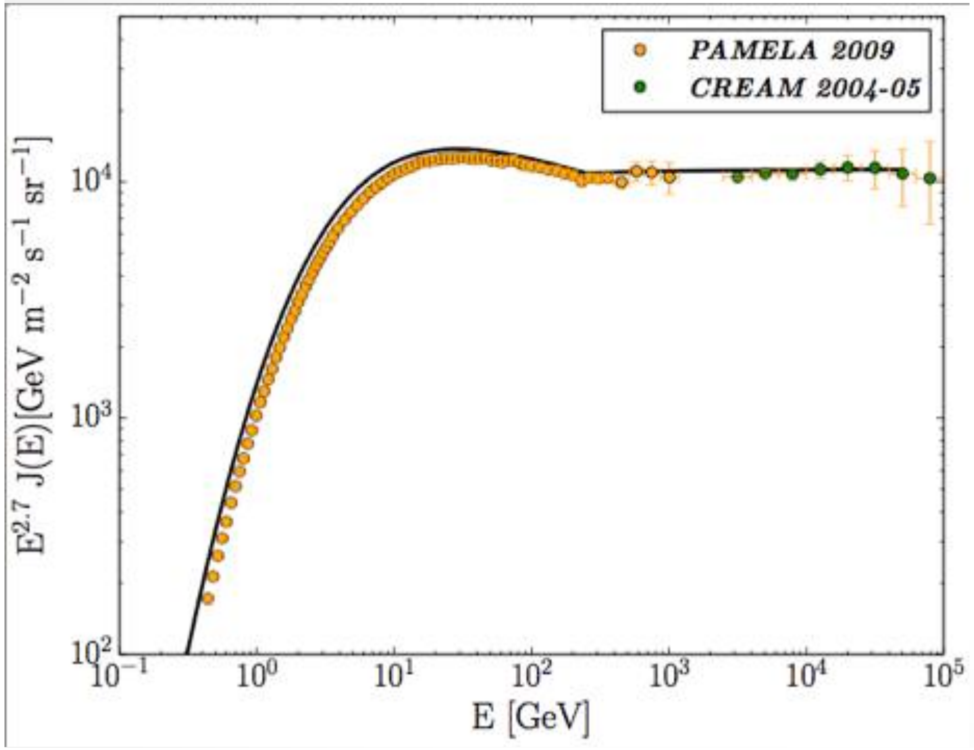
- Assumptions:
  - $\Delta G/G=10\%$
  - $\Delta E/E = 30\%$
  - $\Delta s_E = 5\% \to 15\%$
- Spectral deformations are bracketed by the solid line
- Grey lines represent a power spectrum with a break ($\Delta\Gamma$~0.2) at 1 Tev

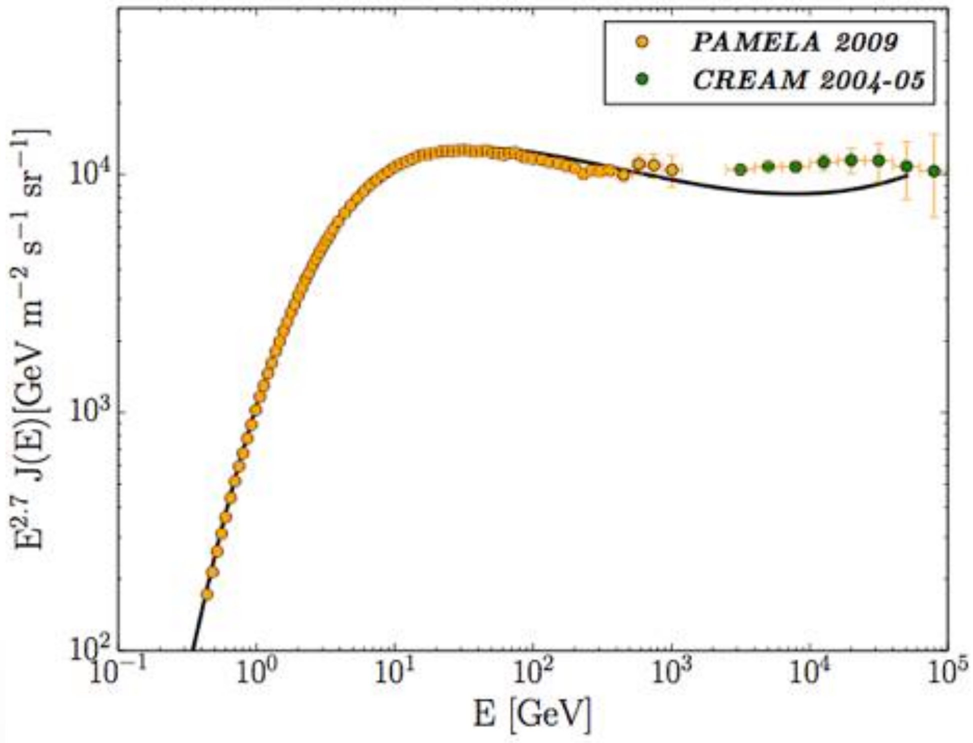


- The break is visible, provided the measurement extends up to >20TeV (in this case the grey line "sticks out" of the systematic limit)

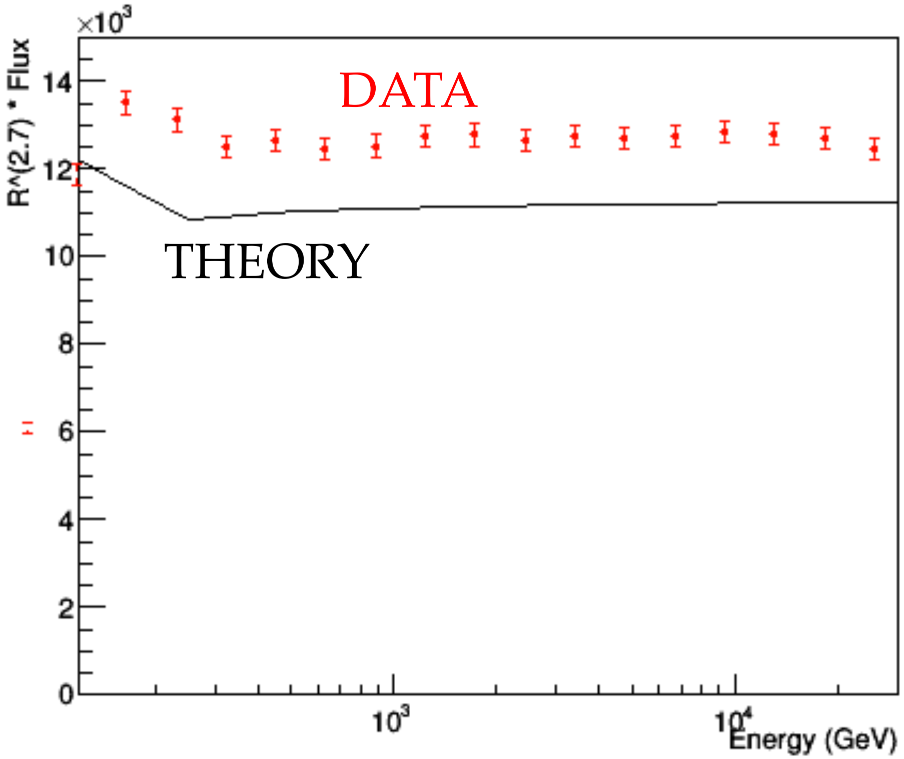
Example:
break in proton spectrum

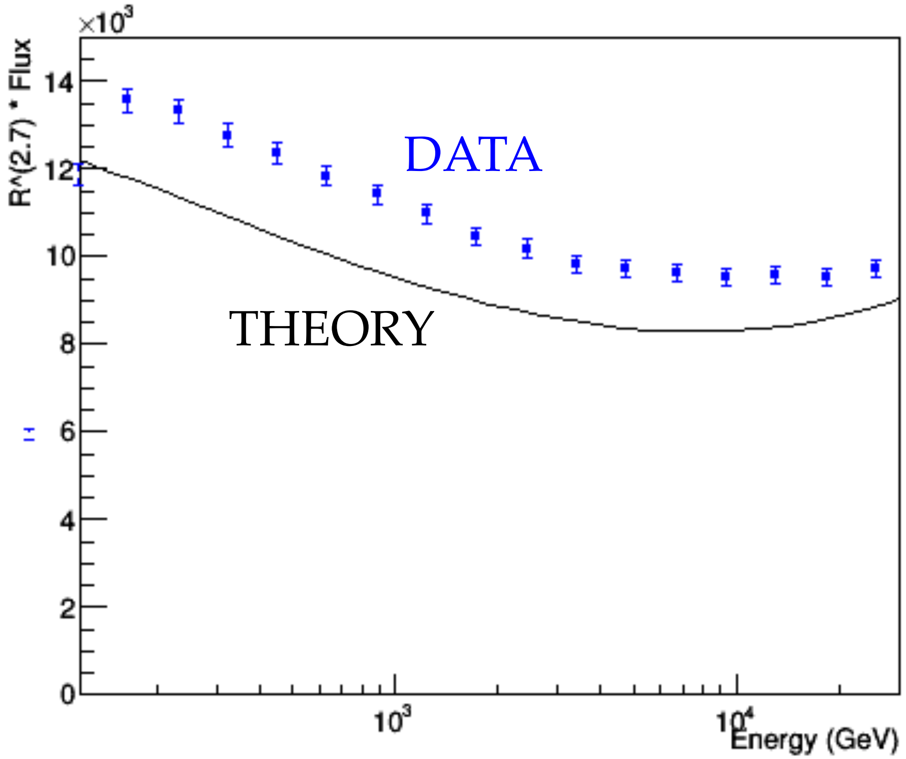
- Two possible models which "describe" the data
- How well are the spectral features visible if one assumes an energy resolution $\Delta E/E=40\%$ (but a *correct energy scale*)?





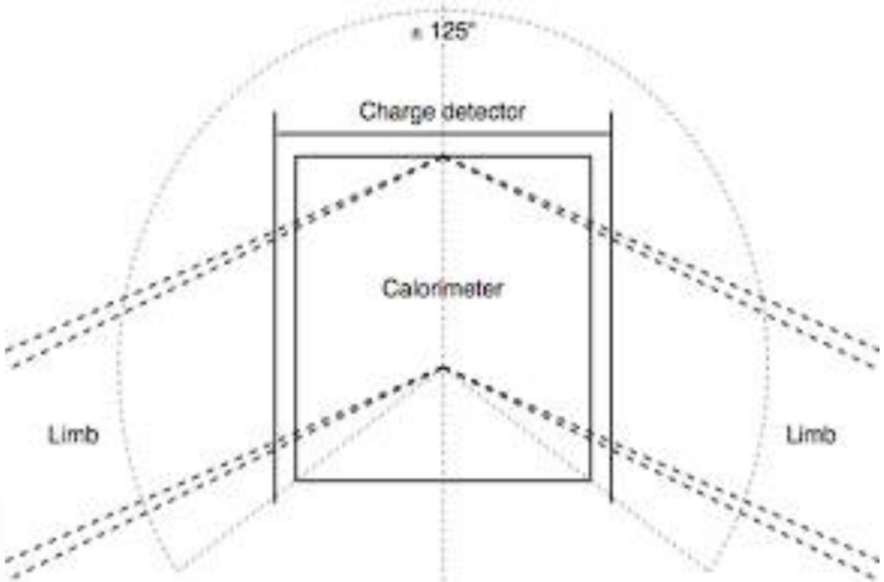
- Pseudo-experiments with an effective geometrical acceptance of 1m^{2}sr (*effective = multiplied by selection efficiency*) and 3 years of data taking
- For an (arbitrary) systematic of 2% flat in energy and a *ΔE/E=40%*, the break can be observed, but an <u>unfolding is necessary</u> to have the correct spectrum





Absolute energy scale

- However the most dangerous systematic is the absolute energy scale (not considered before!)
- Any possibility of calibrating in space?
- Earth limb: highest high-energy γ-ray source in *Low Earth Orbit (LEO)*
  - o with $5 m^2 sr$ a few thousand atmospheric γ-rays per year above 1 TeV
  - o x100 the celestial intensity
  - o ~1° wide at ~110°
  - o inelasticity factor k~0.16



Requirements for Next Generation Space Experiments

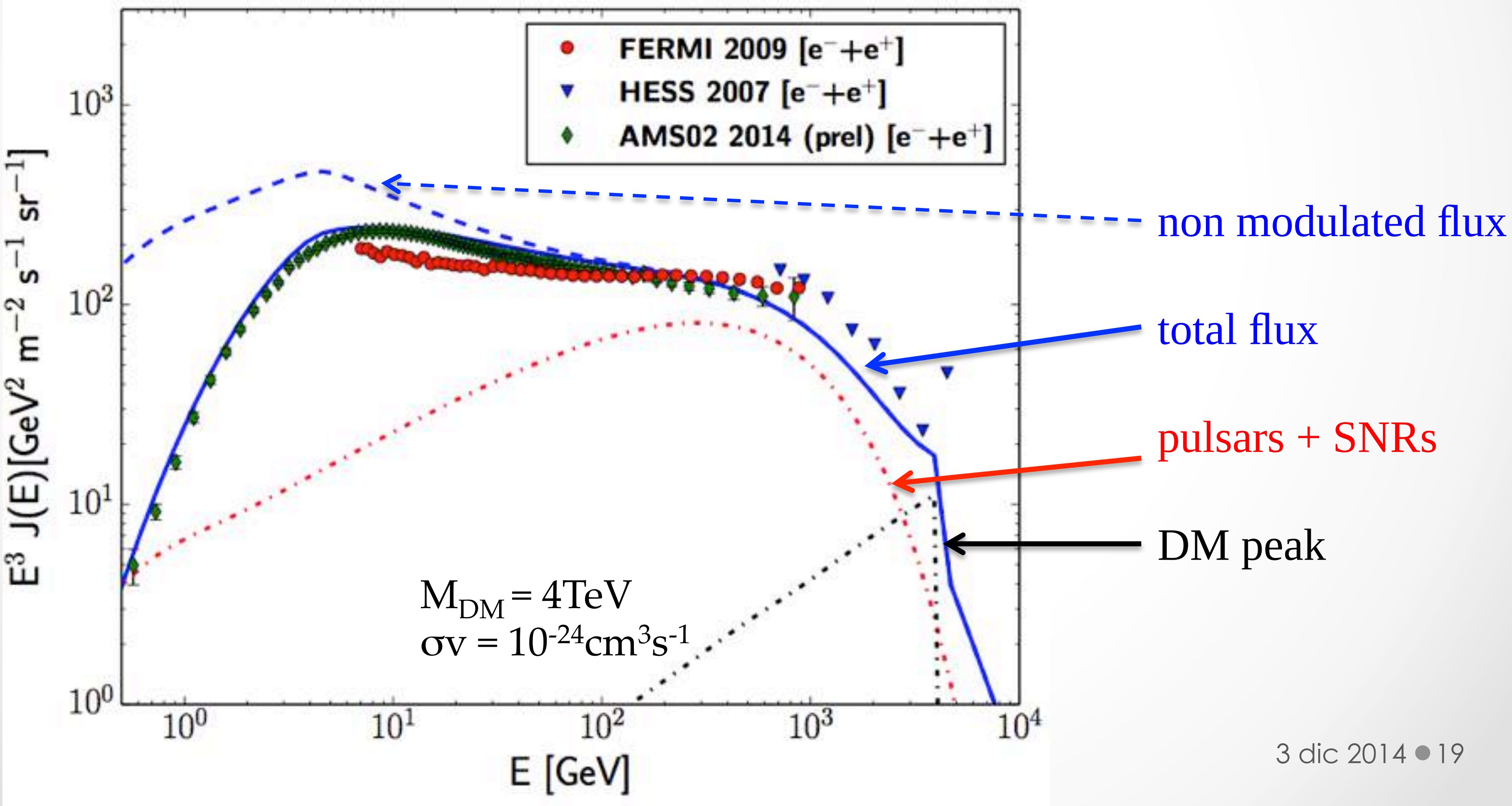
- The basic requirements for a *Next Generation Space Experiment* are:
  - maximal geometrical acceptance
  - identification of nuclei (Z) and electrons
  - capability of measuring hadron energy

  } **LARGE ACCEPTANCE CALORIMETER**

- What physics are we excluding, by giving up on the presence of a *γ-converter* or a *magnet*?
- Example: what about Dark Matter?
  - need access to anti-particle? → magnet
  - need analysis of γ-line or Diffuse Galactic Emission (DGE)? → γ-converter

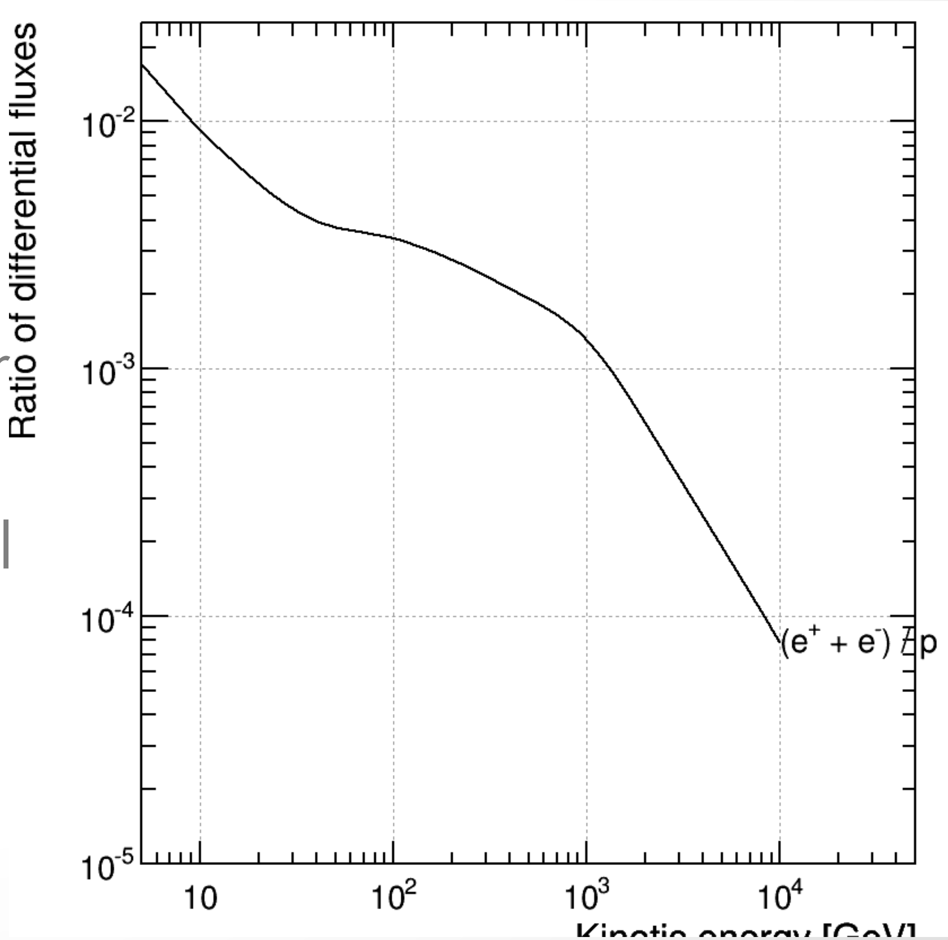
DM in e^++e^- (all electrons)

- Can DM be observed in the total flux (no charge sign)?
- Model of $\chi\chi \rightarrow l^+l^- \rightarrow e^+e^-X$ (*democratic leptons*) with a sharp decrease of the $e^\pm$ flux at M_χ

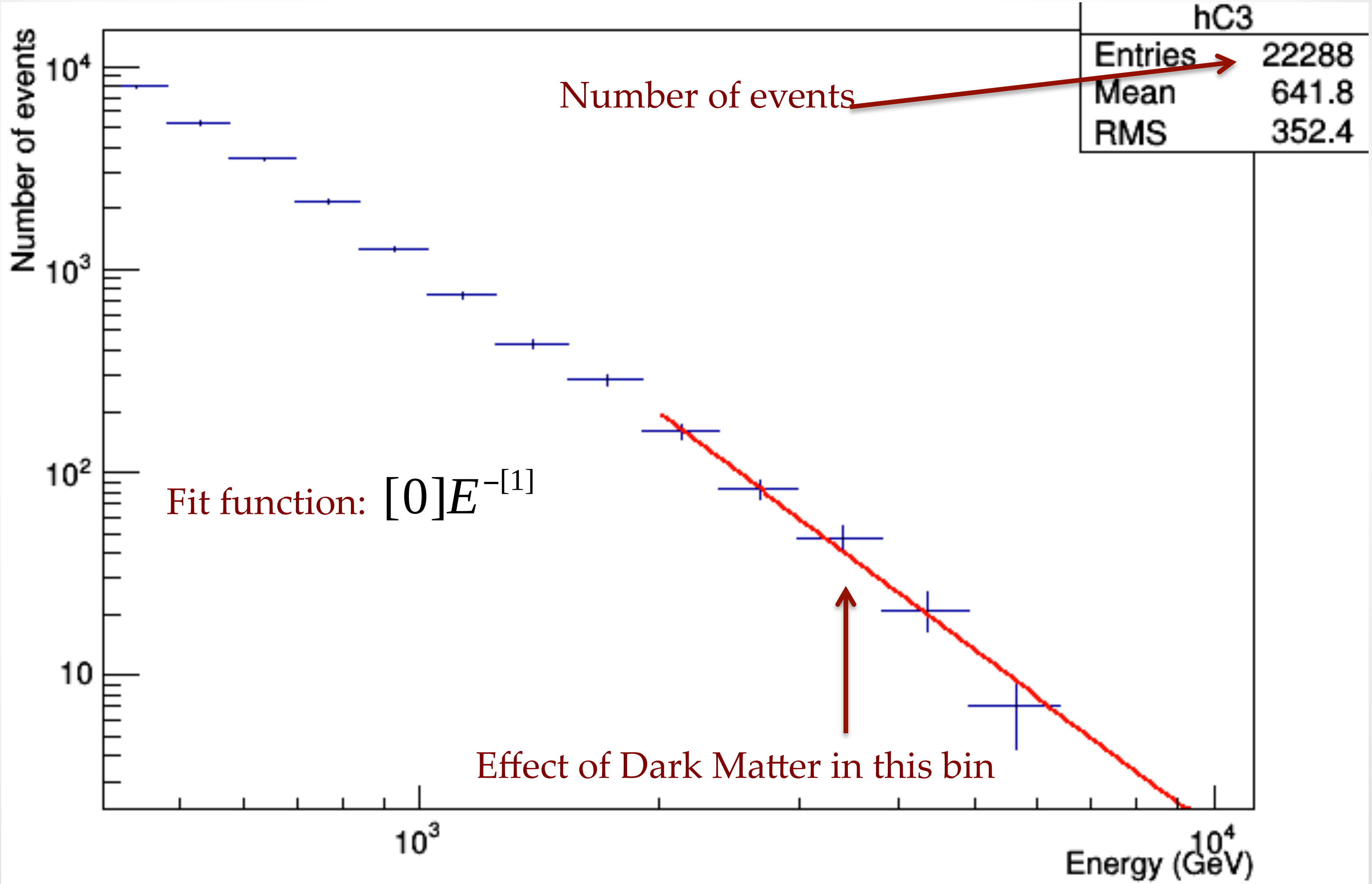


Generation of pseudo-experiments

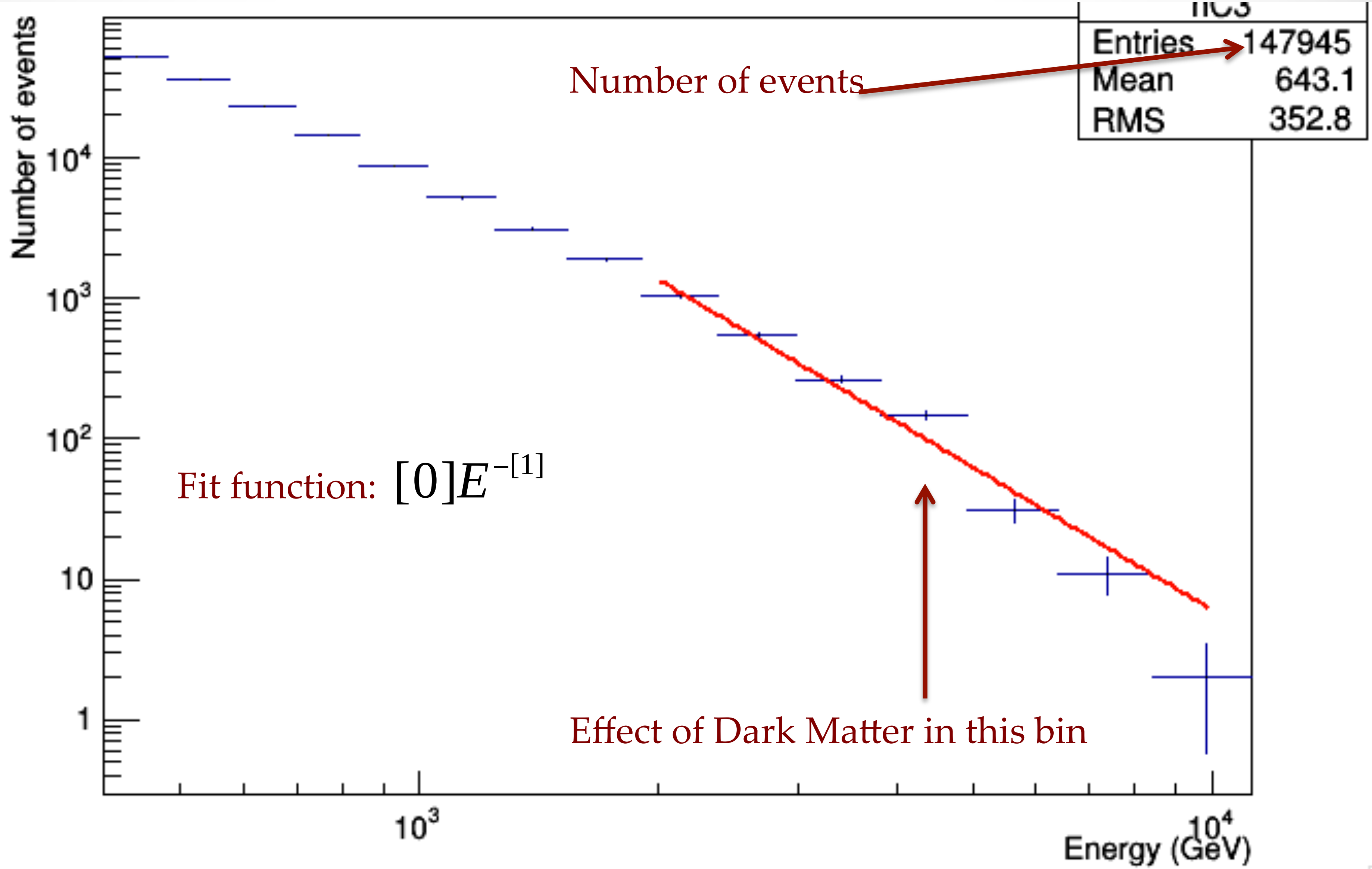
- Simulating N years of data (1 year = $2*10^7$sec) with N=3-5
- *Effective geometrical acceptance* A of $1m^2sr$ - $5m^2sr$
- The most critical assumpions are:
  - o protons have all been removed
  - o signal efficiency is flat over the whole range
- These assumptions are critical as the ep ratio rapidly decrease above 1 TeV



A = 1 m^2sr - T = 3 years

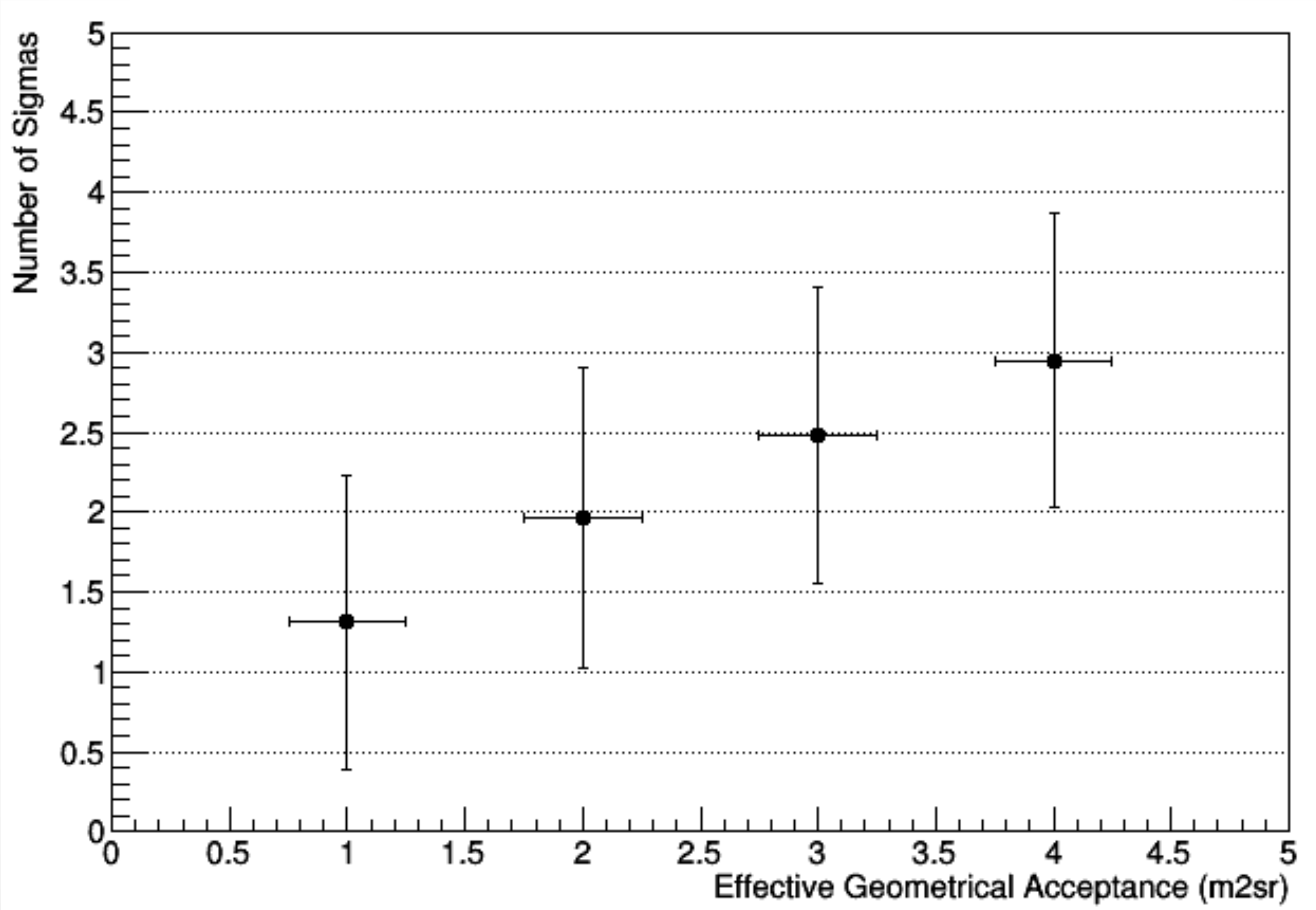


A = 4 m^2sr - T = 5 years



DM->e^++e^- in calorimeter experiment

- From this simple simulation, a 3σ effect is observed in 5 years ($5*2*10^7$ sec) with A=F*ε~4m^2sr



Magnet only : anti-protons

- the maximum rigidity accessible for anti-particles is limited by the *charge discrimination capability (CC)*
- CC depends on the antiparticle/particle ratio (r) and on the Maximum Detectable Rigidity (MDR)
- For a detector with an MDR = 6.7 TeV (a possible AMS03), and some *reasonable assumptions*, the anti-particle rigidity is limited to a fraction f_{CC} of R_{MDR} as from the following table:

r	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
f_{CC}	0.83	0.45	0.33	0.27	0.23
R_{CC} (TeV)	5.63	3.07	2.25	1.82	1.53

↑ anti-protons

Magnet only : isotopes

- Isotopes are identified by a combined measurement of
  - rigidity R (energy resolution is too poor)
  - velocity β, with TOF or Cherenkov techniques

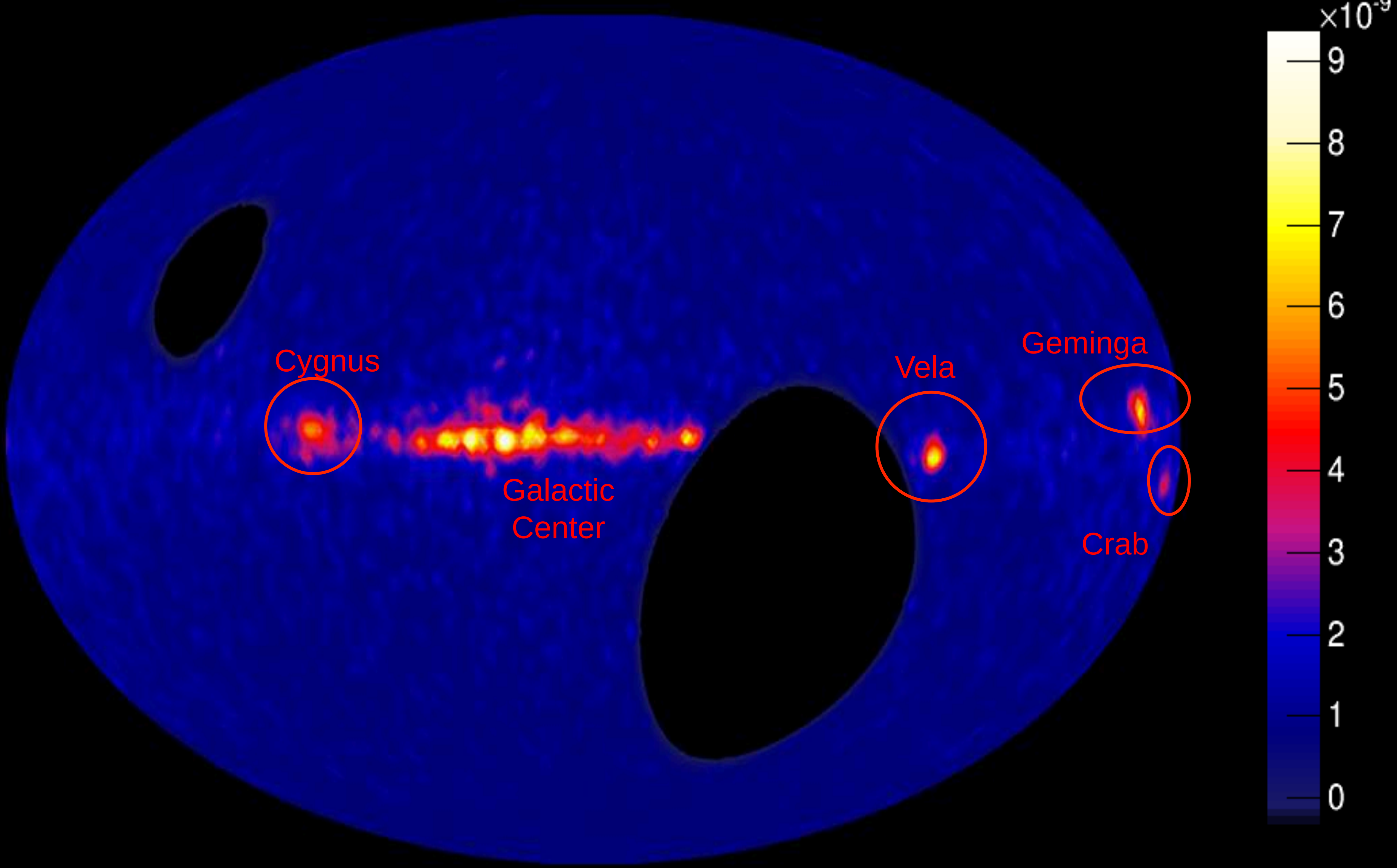
$$A = \frac{RZe}{m_n c\beta\gamma} \qquad \left(\frac{\delta A}{A}\right)^2 = \left(\gamma^2 \frac{\delta\beta}{\beta}\right)^2 + \left(\frac{\delta R}{R}\right)^2$$

- Due to the γ^2 term, assuming a per mill resolution on β (RICH) *A* can be measured up to ~10 GeV/n
- with TOF the limit is ~1 GeV (~1% resolution)
- *δR/R* must be ≤0.1 to have *δA*≤1 for A=10 (Beryllium)

Gamma-converter ?

- The main advantage of a γ-converter detector is a better PSF, useful to study point sources
- With the advent of CTA, which can reach energies down to few tens of GeV with their large telescopes, it is not clear the physics case which justifies such a technical choice
- By looking at LAT data, also the analyses of Diffuse Galactic Emission or Dwarf Galaxies are *limited by statistics, and not by PSF*
- Calorimeters can measure the photon axis better than 1° at energies ~20-30 GeV and above; is this enough?

AMS-ECAL sky map

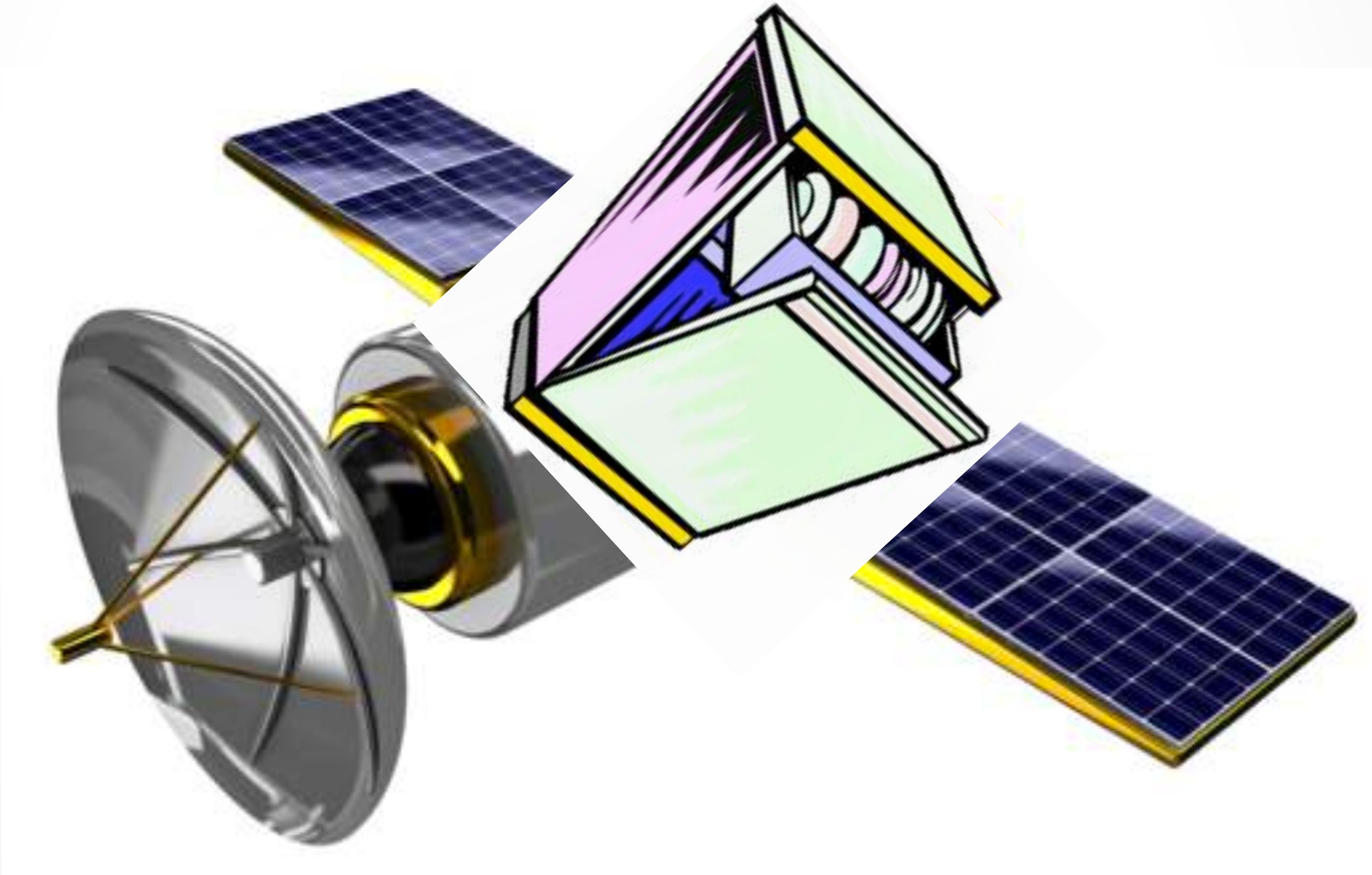


$E_\gamma > 5$ GeV

Flux 1°x1° pixels (photons $cm^{-2}s$)

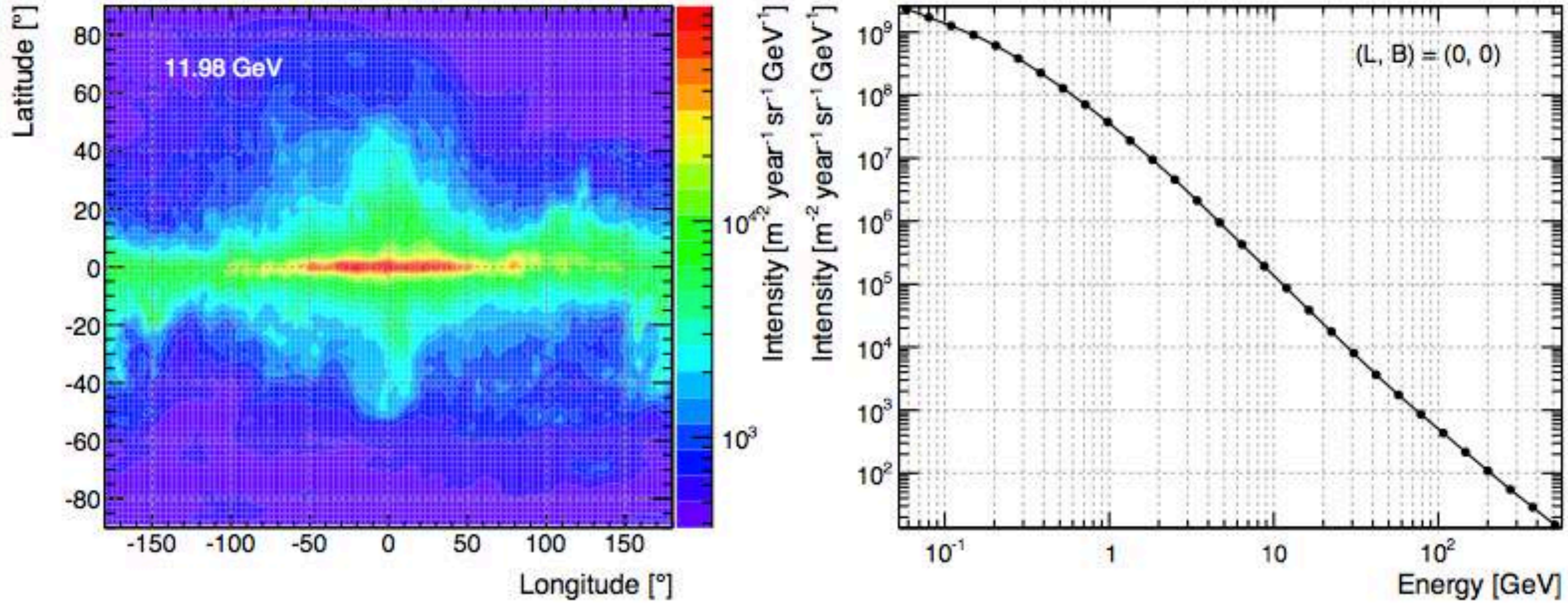
Conclusion or *Ode to the Dishwasher*

- Go for the largest and heaviest object you can build: a *Dishwasher in Space*!



Spare Slides

Diffuse Galactic Emission – 1/3



- Prospects for studying the high-energy DGE:
  - arguably, an instrument with a much better PSF than Fermi (e.g., Gamma-400) will do much better in mapping out the details.
- The DGE is a foreground for *all* the gamma-ray analyses!
  - Improving here, would be just terrific.
- How do I quantify it all?

Diffuse Galactic Emission – 2/3

- Well... Take a patch of the sky subtending a solid angle equivalent to a circle with a radius of the PSF 68% containment:

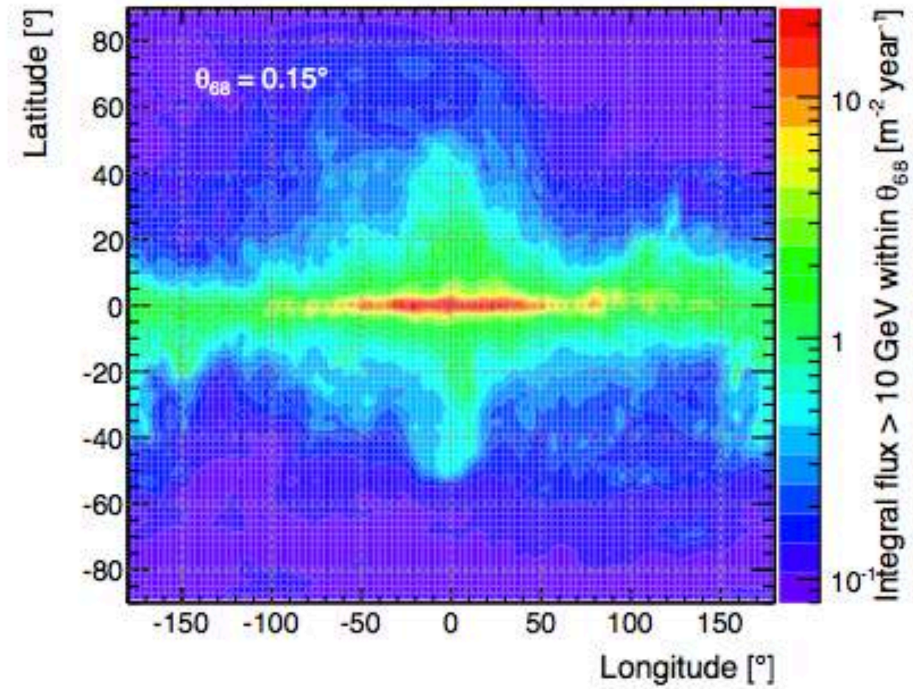
$$\Delta\Omega(E) = 2\pi\,[1 - \cos\theta_{68}(E)] \sim \pi\theta_{68}^2(E)$$

- Calculate the integral count spectrum above a given energy E_0 from such a patch:

$$n_{68}(E_0) = \int_{E_0}^{\infty} J_{DGE}(E)\mathcal{E}(E)\Delta\Omega(E)dE$$

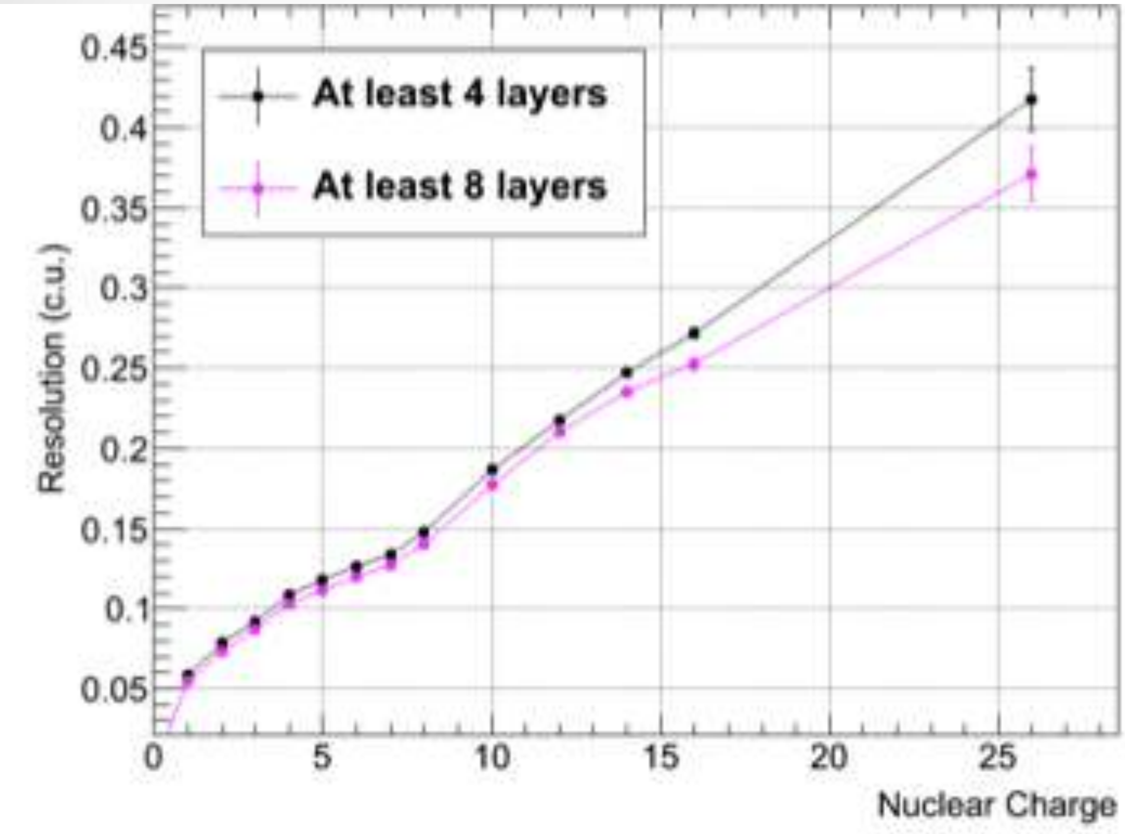
- And I argue that when this number is less than, say, ~ 10 you are not really resolving the sub-PSF details of the DGE anymore.
- This is really a complicate interplay of the PSF *and* the acceptance (again).
  - Any attempt of discussing IRFs (PSF or energy resolution) with no explicit reference to the detector acceptance is at least misleading.
- Ok, now we can play this game for all directions in the sky.

Diffuse Galactic Emission – 3/3

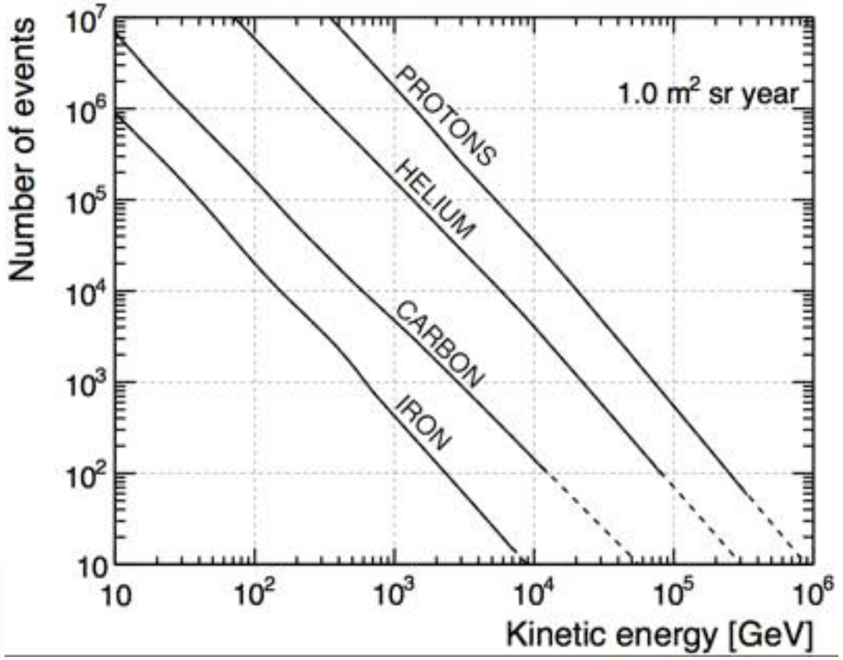


- Remember: 0.15° is representative of the high-energy PSF 68% containment of the LAT.
- And ~ 1 m^2 sr year is representative of the exposure accumulated by the LAT in the entire mission.
- The LAT limited by statistics (for the DGE) above 10 GeV.
  - A better PSF would not help.
  - Not even in the Galactic center.

Z resolution



- Z identification of nuclei is not too hard, provided statistics is sufficient
- Low dependence on momentum: relativistic rise of Bethe-Block distribution



- Typical Z resolution of Silicon layers:

$$\Delta Z = 0.014 \cdot Z + 0.036$$

Heavy DM in anti-protons

- Is a DM anti-p signal at ~1TeV "reasonable"?
- It requires M_{DM}>10TeV and a substantial boost factor