High-energy cosmic-ray and gamma-ray detectors

An experimental overview

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Keywords and prospectives

- Cosmic rays, gamma rays, dark matter.
- High-energy (> 10 GeV).
  - Luckely, in real life, this effectively factors out much of the energy dependences.

1. Science objectives $\rightarrow$ requirements $\rightarrow$ instrument design.
2. Current instruments $\rightarrow$ limiting factors $\rightarrow$ how can we improve?
3. Current instruments $\rightarrow$ realistic improvement $\rightarrow$ science case?
4. New instrument concept $\rightarrow$ Science objectives?

- Slightly different questions and yet all legitimate and interesting.

Basic goal of the discussion
(One way to put it)

IRF	Cosmic-rays	Gamma-rays	DM
Acceptance	TBD	TBD	TBD
Field of view	TBD	TBD	TBD
Energy resolution	TBD	TBD	TBD
Point-spread function (PSF)	TBD	TBD	TBD

- Measure the relative importance of the different items in this table.
  - Not in abstract, but in connection with the science objectives.
- Some are easy.
  - e.g. the PSF for charged CR is not critical (a few deg is enough for large-scale anisotropy searches).
- Some are more subtle.
  - What is the best compromise between PSF and acceptance for a *realistic* high-energy gamma-ray detector?
- Impossible to optimize all the aspects at the same time, so need to make choices.

Basic formalism (1/2)

Trivial as it is, let's start from a short recap

- Source *brightness*:
  - Flux $\frac{dF}{dEdt}$ for point sources [$\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{GeV}^{-1}$];
  - Intensity $\frac{dJ}{dEdt}$ for isotropic sources [$\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}$].
- (Instantaneous) collecting power of the detector:
  - Effective area [m^2]: $\frac{dN}{dEdt} = A_{\mathrm{eff}} \times \frac{dF}{dEdt}$
    - This is a function of energy and incidence angle in the detector;
  - Acceptance (geometric factor) [m^2 sr]: $\frac{dN}{dEdt} = G \times \frac{dJ}{dEdt}$.
  - And also keep in mind that $\mathrm{FoV} = A_{\mathrm{eff}}^{\perp}/G$.
- Exposure—encapsulates the observing time $T_{\mathrm{obs}}$and link the brightness to the
  - Exposure [m^2 year]: $\mathcal{E}(E) = A_{\mathrm{eff}}(E) \times T_{\mathrm{obs}}$;
    - This is for one particular direction in the sky and involves the detailed observing profile of the instrument.
  - Exposure factor [m^2 sr year]: $\mathcal{E}_{\mathrm{f}}(E) = G(E) \times T_{\mathrm{obs}}$.
- If the sky exposure is uniform (*a la Fermi*) then $\mathcal{E}(E) \sim \frac{\mathcal{E}_{\mathrm{f}}(E)}{4\pi}$.
  - The entire LAT mission integrates $\mathcal{E} \sim 1\ \mathrm{m}^2$ sr and $\mathcal{E}_{\mathrm{f}} \sim 15\ \mathrm{m}^2$ sr (above ~ 10 GeV).

- Energy dispersion.
  - pdf of measuring an energy E' given a true energy E.
  - For any given (true) energy and incidence angle, this is a function.
  - Typically summarized by its width (energy resolution).
- Point-spread function.
  - pdf of measuring a direction v' given a true direction v.
  - If you assume azimuthal symmetry (around v) this is a function of a single variable (the space angle between the two directions);
  - i.e., conceptually similar to the energy dispersion, except for the fact that it is positive-definite.
  - Customarily measured by the 68% and 95% containment angles.
- Rigidity resolution and MDR
  - For magnetic spectrometers (up to what energy can we distinguish the sign of the charge).

Where do we stand?

Experiment	Peak G [m^2 sr]			$T_{\rm obs}$ [year]	$\sigma E/E$	
	$e^{\pm}$	γ	p		$e^{\pm}$, γ	p
Agile	–		–			
AMS-02		0.05		20	2% @ 50 GeV	?
ATIC		0.24		0.15		
CREAM	–	–	0.43	0.5		
Fermi	2.8 @ 50 GeV[1]	2.0 @ 10 GeV	–	10	5–15%	–
PaMeLa	0.00215	–	0.00215	7	5–10%	
CALET		0.12		5	2% @ 1 TeV	40% @ 1 TeV
DAMPE	0.3	0.2	0.2	3	1.5% @ 800 GeV	40% @ 800 GeV
Gamma-400		0.48 [2]		7	1% @ 10 GeV	–
Gamma-400 (CC[3])	3.4 @ 1 TeV		3.9 @ 1 TeV	7	2% @ 1 TeV	35% @ 1 TeV[4]
HERD		3		10	1% @ 100 GeV	30% @ 1 TeV

- Note that a fair comparison between so many different instrument is close to impossible.
  - (Take this numbers *cum grano salis*).
- And quite a few numbers are missing.

[1] The acceptance for $e^{\pm}$ @ 1 TeV is ~ 0.9 m^2 sr [PRD 82 092004 (2010)].
[2] [AIP Proc. 1516, 288-292 (2013)] quotes a FoV of 1.2 sr, which seems in contradiction with the drawing of the instrument.
[3] Alternative design including CALOCUBE.
[4] As good as 15% when exploiting a dual readout.

What next?

Not in the INFN sense, though the two are connected

- Science targets: cosmic/gamma rays and indirect dark matter searches.
- Energy range: above 10 GeV.
  - And no, we're not trying to go below 100 MeV at the same time.
- This is not linked, *a priori* to any of the projects being proposed for the near future.
  - Though we could conceivably provide inputs to such projects.
- And here are the three musketeers.

High-energy (above $\sim$ 10 GeV) space experiment

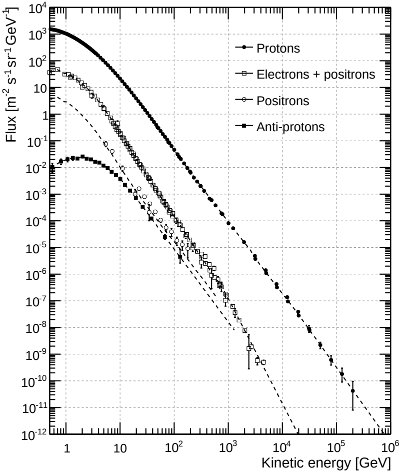
(1) Magnetic spectrometer (*a la* AMS-02)

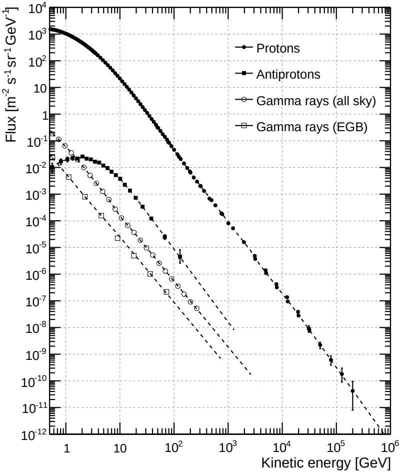
Calorimetric experiment

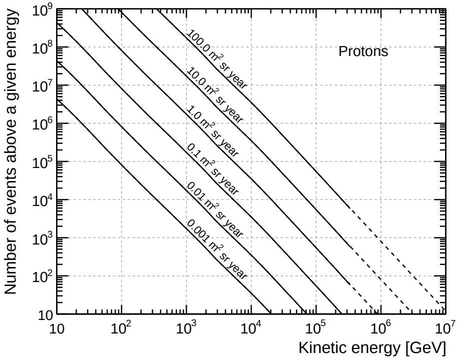
(2) Pair-conversion telescope (*a la* Fermi-LAT)

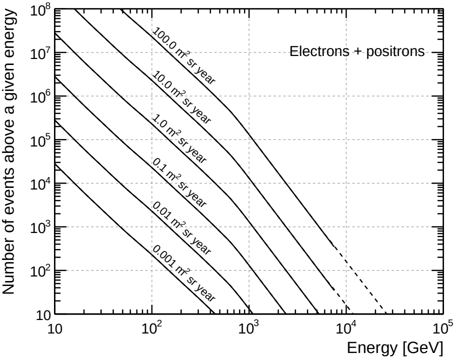
(3) CR calorimeter (*a la* CREAM/ATIC)

- Spectrometers discriminate the sign of the charge.
  - e.g., you get to measure positrons and antiprotons.
- Spectrometers can measure velocity and momentum.
  - e.g. you have access to CR isotopical composition.
- Calorimeters are relatively bigger.
  - Big magnets are heavy.
  - You can't really make a spectrometer as big as a purely calorimetric experiments with the same constraints.
- And a calorimeter vs. a pair-conversion telescope? Isn't it the same thing?
  - The pair-conversion telescope features a dedicated tracking stage.
  - You do get a much better PSF ($< 0.1^\circ$ vs. ~ 0.5–1°).
  - You also somewhat add complexity and reduce the FOV.

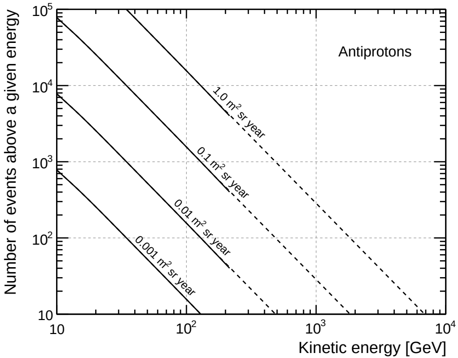

Flux [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
Kinetic energy [GeV]
Protons
Electrons + positrons
Positrons
Anti-protons

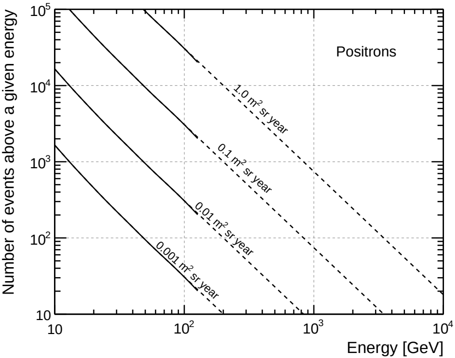

Flux [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
Kinetic energy [GeV]
Protons
Antiprotons
Gamma rays (all sky)
Gamma rays (EGB)





- Integral spectra from a weighted average of all the most recent available measurements.
  - And extrapolated (within reason) at high energy.
- For reference, our option (3) gives ~ 50 m^2 sr year in 10 years.

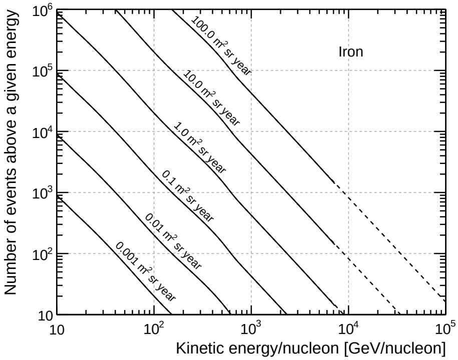


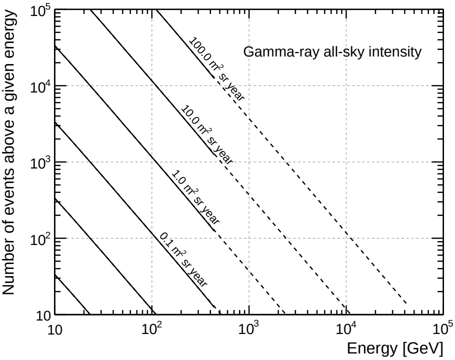


- Integral spectra from a weighted average of all the most recent available measurements.
  - And extrapolated (within reason) at high energy.
- For reference, our option (1) gives ~ 7.5 m^2 sr year in 10 years.
  - But statistics might not be the only issue, here.

Integral count spectra 3/3

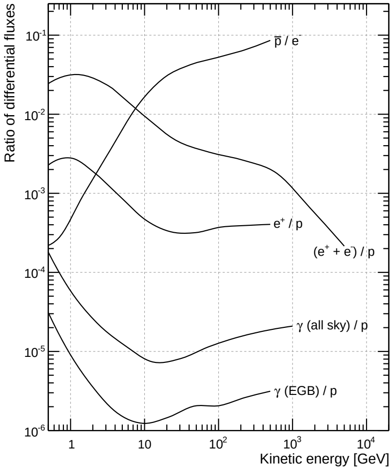
Nuclei and gamma rays



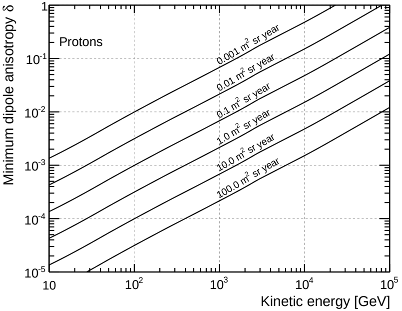


- Integral spectra from a weighted average of all the most recent available measurements.
  - And extrapolated (within reason) at high energy.
- And here we're back to the ~ 50 m^2 sr year in 10 years of (3).
  - Much more on gamma rays in the following.

The challenge of background rejection



- Statistics is not necessarily the only limiting factor.
  - e.g., electron/proton separation;
  - or charge confusion.

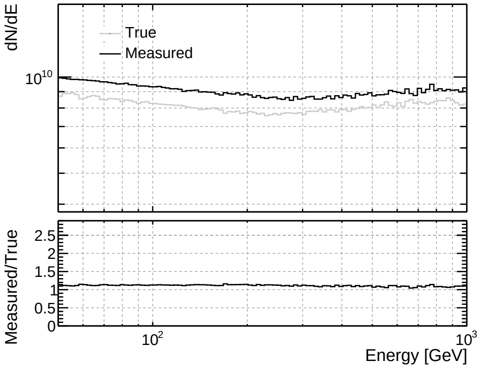


- Basic formalism for the minimum detectable integral dipole anisotropy:

$$\delta = \frac{\sqrt{2}n_\sigma}{\sqrt{N_{events}}}.$$

- And real life is more complicated, but this sets the stage for the discussion.

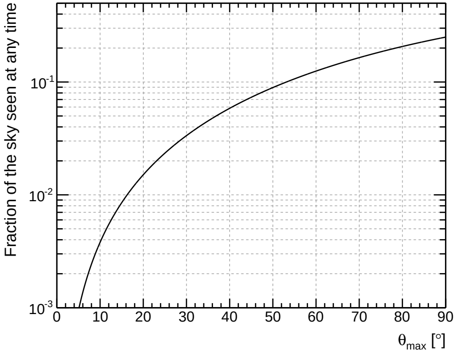
Charged CRs and energy resolution



- Illustrative exercise:
  - Take a proton spectrum *a la* Pamela—break at 230 GeV, index goes from -2.85 to -2.67.
  - Fold it with a 40% (gaussian) energy dispersion.
- You get a 10–15% $\sim$ rigid shift, but the break is still there.
- You don't need (nor you can achieve) a terrific energy resolution with hadrons.

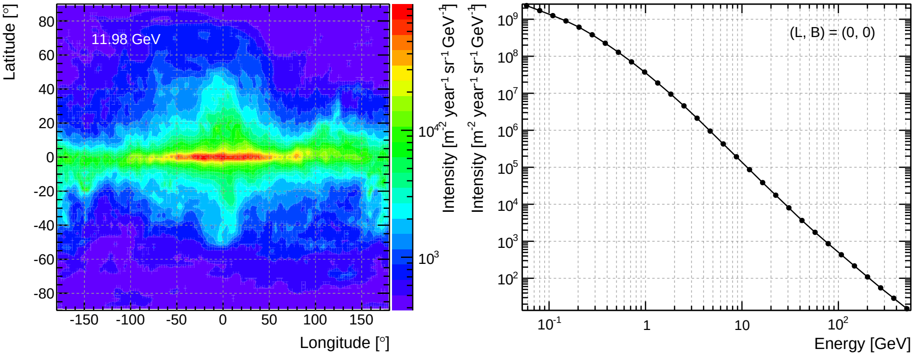
And the role of the observing strategy

This is really for gamma rays



- Naïve parameterization of the effective area.
- When the direction in the sky is important you get to choose:
  - do I accumulate exposure in one particular region or spread it out $\sim$ evenly across the sky?
  - (a.k.a. the *observing strategy*.)
- It could make a difference of factors!
  - Cannot discuss a gamma-ray instrument in abstract.

A close-up on the GDE



- 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?

A close-up on the GDE

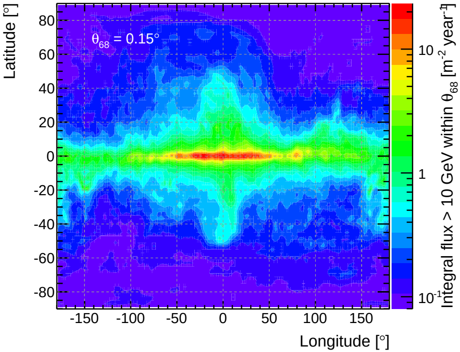
- Well... Take a patch of the sky subtending a solid angle equivalent to a circle with a radius of the PSF 68% containment:

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

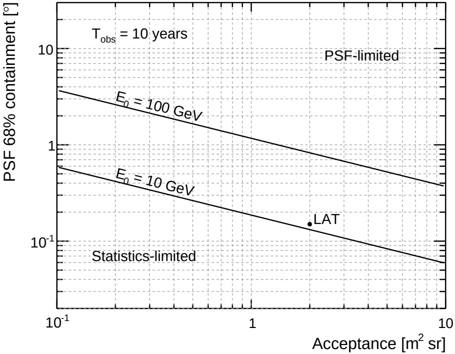
- Calculate the integral count spectrum above a given energy E_0 from such a patch:

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

- 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.

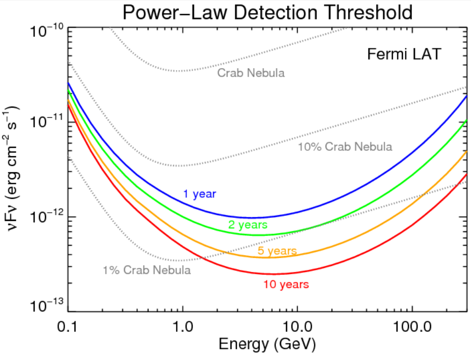


- Remember: 0.15° is representative of the high-energy PSF 68% containment of the LAT.
- And ~ 1 m^2 sr year is representative of the exposure accumulated by the LAT in the entire mission.
- The LAT limited by statistics (for the DGE) above 10 GeV.
  - A better PSF would not help.
  - Not even in the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



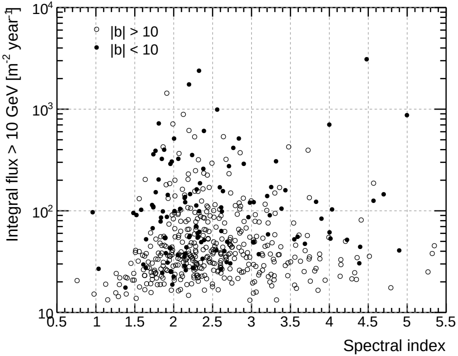
- Iso-sensitivity lines in the PSF-Acceptance phase space.
  - Galactic center, for a threshold energy of 10 and 100 GeV.

$$\theta_{68} = \left(\frac{4N_{\rm min}}{T_{\rm obs} \int_{E_0}^{\infty} I(E)dE} \right)^{\frac{1}{2}} G^{-\frac{1}{2}}$$



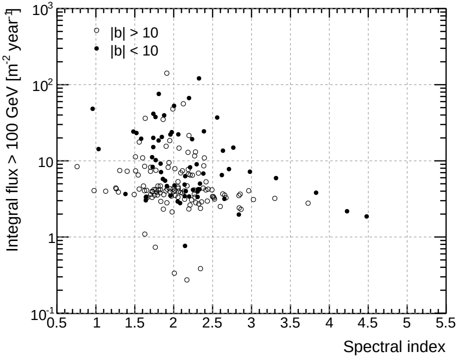
- Assume a plain power-law, scan the index and find the minimum normalization for which the source is detected.
  - Envelope of the power-laws plotted.
- Note the different scaling at low (background-dominated, $\propto \sqrt{T}$) and high (counting statistics dominated, $\propto T$) energy.
- Key is the scaling of the PSF with energy.
  - And again: at high energy the acceptance is the limiting factor.

And now (high-energy) point sources



- Compiled from the Fermi 1FHL (sources above 10 GeV).
  - 514 sources, with spectral properties.
- Keep in mind: ~ 1 m^2 sr year is representative of the exposure accumulated by the LAT in the entire mission.
  - Read on the *y*-axis $\sim$ the number of source photons detected by the LAT in the entire mission.
- Wondering what the brightest sources are? Crab, Vela-X, Mkn 421.

And now (high-energy) point sources



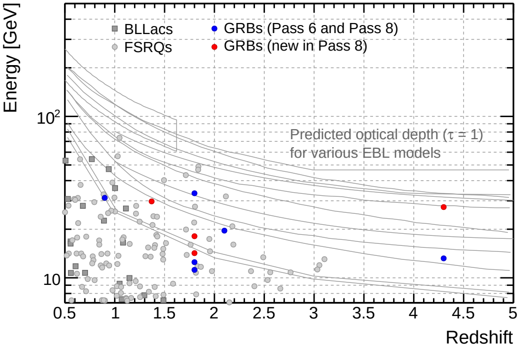
- Compiled from the Fermi 1FHL (sources above 10 GeV).
  - 514 sources, with spectral properties.
- Keep in mind: ~ 1 m^2 sr year is representative of the exposure accumulated by the LAT in the entire mission.
  - Read on the y-axis $\sim$ the number of source photons detected by the LAT in the entire mission.
- Wondering what the brightest sources are? Crab, Vela-X, Mkn 421.

What about source variability?

- The gamma-ray sky is highly variable.
  - Multi-wavelength studies need *simultaneous* data.
- A space-based, large-FOV instrument is key to complement what can be done from the ground with IACTs.
  - True!
- But keep in mind the previous slides.
  - With Fermi we are running at a rate $r \sim 10$ photons per year above 10 GeV for a reasonably bright source.
- This sets the minimum time scale T_v for detecting variability

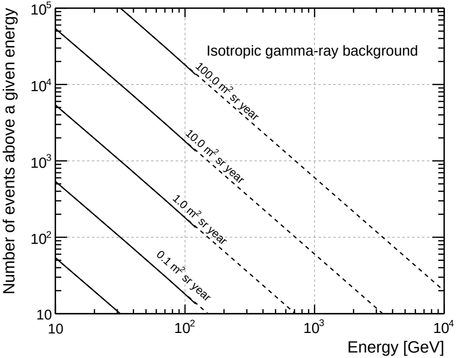
$$T_v > k/r$$

  typically with $k > 1$ (it depends on the flux enhancement).
  - We are talking about *months* in most of the times. Not days, not weeks.



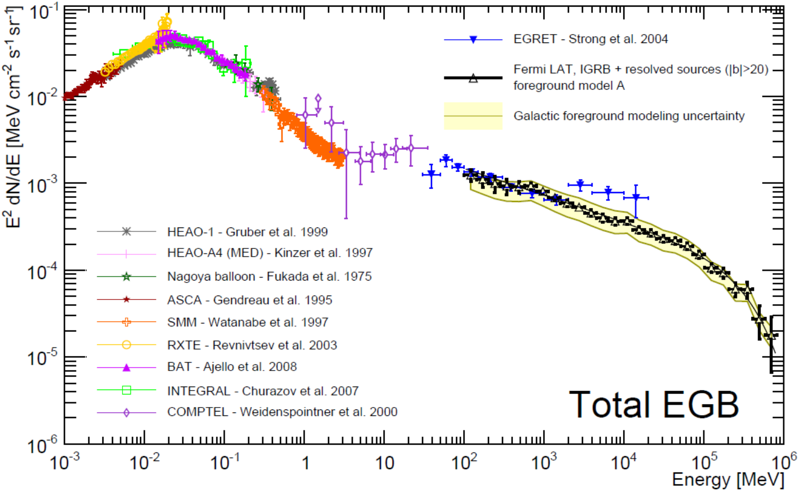
- This is a very LAT-centric plot, based on 35 bursts detected in the first three years of operation.
  - The 95 GeV photon from GRB130427A ($z = 0.34$) is probably worth mentioning.
- Bottom line: the LAT sees 2–3 photons *per year* above 10 GeV from GRBs.

The isotropic gamma-ray background



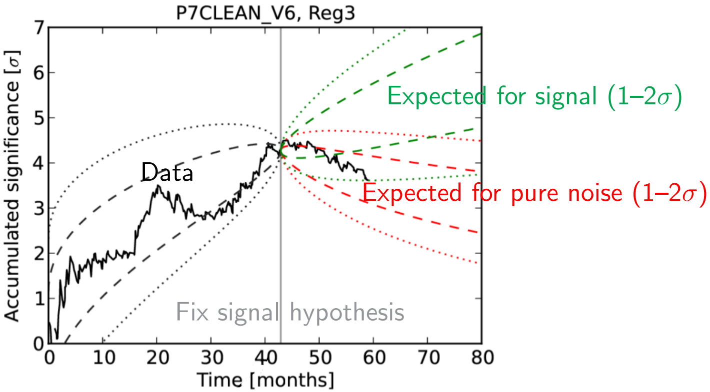
- The usual integral count spectrum.
- This is obtained extrapolating the LAT measurements between 200 MeV and 100 GeV.
- But...

The isotropic gamma-ray background
Presented by Keith Bechtol at the April APS meeting



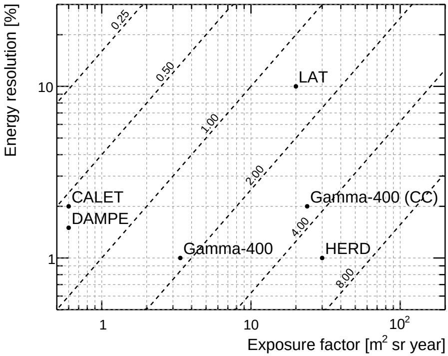
A gamma-ray line in the Galactic center?

Time evolution of the signal, see arXiv:1303.1798



- Weniger's updated results are consistent with the results from the recent LAT line-search paper.
  - Likely that the original putative line signal was a statistical fluctuation.
- More data and Pass 8 will hopefully give the final word.
  - (But this is not a LAT talk, so it's time to move on.)

Line search sensitivity

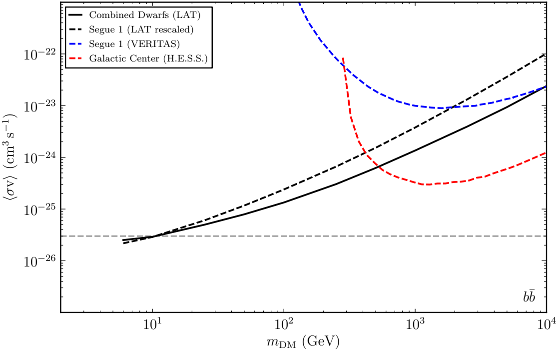


- The basic figure of merit Q is

$$Q = \frac{n_s}{\sqrt{n_b}} \propto \sqrt{\frac{\mathcal{E}_\mathrm{f}}{\sigma_E/E}}.$$

- Better energy resolution is good!
  - But only if you are not trading too much acceptance for that.

Dwarf spheroidal galaxies: a case study



- Customarily considered as the cleanest target for DM searches.
  - J-factors kinematically constrained within a factor of ~ 2.
  - Small astrophysical background.
  - Provide some of the most stringent limits on WIMP annihilation.
- Current IACTs rule at high WIMP masses.
  - The peak in the $E^2 dN/dE$ spectrum for the b-bbar channel is at about 5% of the WIMP mass
  - 500 GeV on this plot is really ~ 25 GeV in photon energy.

Sixth Symposium on Large TPCs for Low Energy Rare Event Detection IOP Publishing
Journal of Physics: Conference Series **460** (2013) 012015 doi:10.1088/1742-6596/460/1/012015

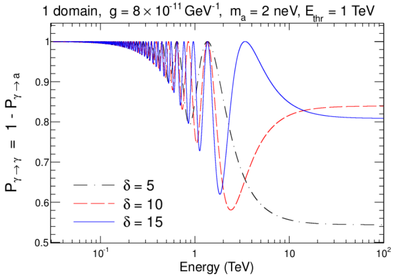


Figure 7. Spectral oscillation patterns in domains with coherent magnetic field and different ALP parameters (figure from [36]).

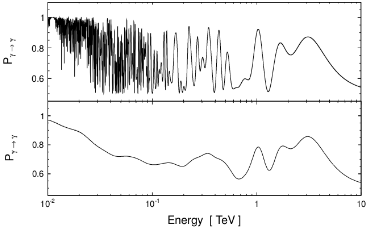


Figure 8. Example of ALP induced irregularity in the TeV range (top panel: Raw signal, bottom panel: Signal smeared with HESS resolution, figure from [38, 39]).

Tentative recap
And personal, too

- A large acceptance is key to most of the science targets.
  - This is especially true for gamma rays!
  - The gamma-ray sky is variable, but only with a high enough statistics.
- Any science case for the instrument design to be driven by the PSF?
  - Not for charged CR (we're interested in mid-to-large scale anisotropies at most).
  - And for gammas? Can we really exploit a sub-LAT PSF with the acceptance we can reasonably achieve?
- Energy resolution.
  - Not critical for hadrons, provided that it's decent.
  - Search for features in the CRE spectrum?
  - There is some possible discovery space in gamma rays: lines, axions.
- Basic question: spectrometer or calorimeter?
  - If we go with the latter, make it as big as possible.
- And synergies are important.
  - The gamma-ray community seems to think that the highest energy will be best served by CTA (and ground-based observatories) in the future.

(1) A magnetic spectrometer
a.k.a. AMS-03?

- Geometric factor: ~ 0.75 m^2 sr
  - Mind this will be heavy!
- Charge discrimination:
  - up to ~ 8 TeV for e^+/e^-;
  - up to ~ 800 GeV for $p/\bar{p}$.
- Isotopical composition.
- Point-spread function at the level of $\sim 0.5^\circ$.
- Measurement of Z for nuclei:
  - Something along the lines of $\Delta Z = 0.1 + 0.02Z$.
- Energy resolution:
  - EM showers: $\sim 10\%/\sqrt{E} \oplus 1\%$;
  - Hadronic showers: $\sim 40\%$.

(2) A pair-conversion telescope

- Geometric factor: ~ 1.5 m^2 sr
  - Similar (or slightly smaller) than Fermi.
- This would be optimized for the best PSF and energy resolution.
- Point-spread function at the level of $\sim 0.05^\circ$.
- Energy resolution:
  - EM showers: $\sim 10\%/\sqrt{E} \oplus 1\%$;
  - Hadronic showers: $\sim 40\%$.
- And we also assume a decent measurement of Z for nuclei.

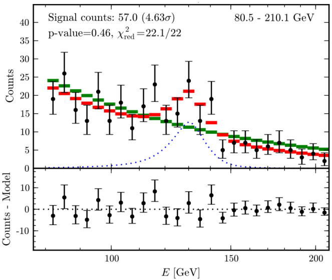
(3) A CR calorimeter

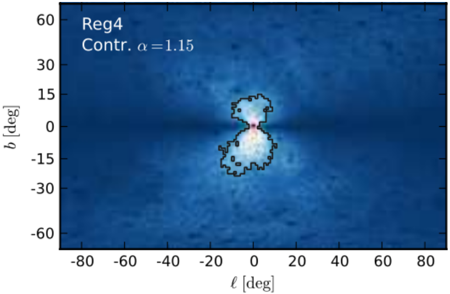
- Geometric factor: $\sim 5\ \mathrm{m}^2\ \mathrm{sr}$
- This would be optimized for the largest acceptance and for response to hadrons
- Point-spread function at the level of $\sim 1^\circ$.
- Energy resolution:
  - High-energy EM showers: $\sim 2\%$;
  - Hadronic showers: $\sim 15\%$.
- And again a measurement of Z for nuclei.
  - $\Delta Z = 0.05 + 0.014 * Z$

Spare slides

A gamma-ray line in the Galactic center?

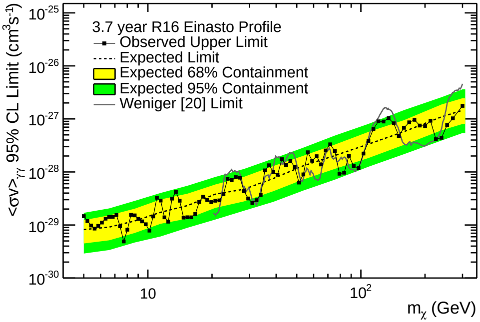
Weniger, JCAP **1208**, 007 (2012) and many others



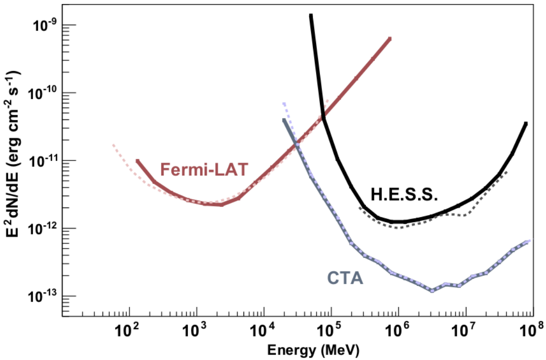


- Good example of a results based on Fermi data from outside the collaboration with a huge echo in the community.
- Triggered a large number of follow-up papers.
  - With the $\sim$ same feature found literally all over the place.

A gamma-ray line in the Galactic center?
arXiv:1305.5597

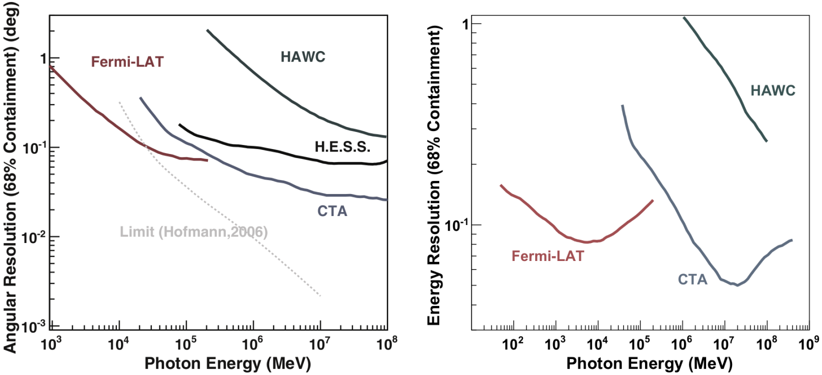


- Line-search paper published on PRD by the LAT collaboration.
- Broader scope, but addressing the question of the 130 GeV line.
  - Significance slightly lower with updated instrument calibration and better energy dispersion model.
  - Feature seems to be narrower than the energy resolution.
  - (Smaller) feature at the same E in the Earth limb control sample.
- Too early to draw any definitive conclusion with 3.7 years of data.



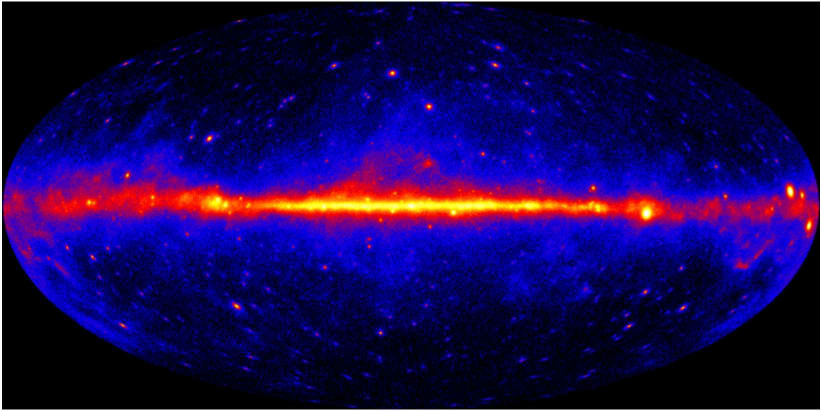
- Differential source sensitivity curves.
  - LAT: 10 years, high-latitude.
  - IACTs: 100 hours.
- The curve cross around $\sim$ 50 GeV.

SYNERGIES: CTA, LHAASO AND HAWK

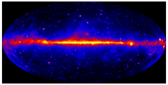
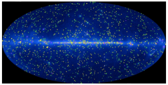


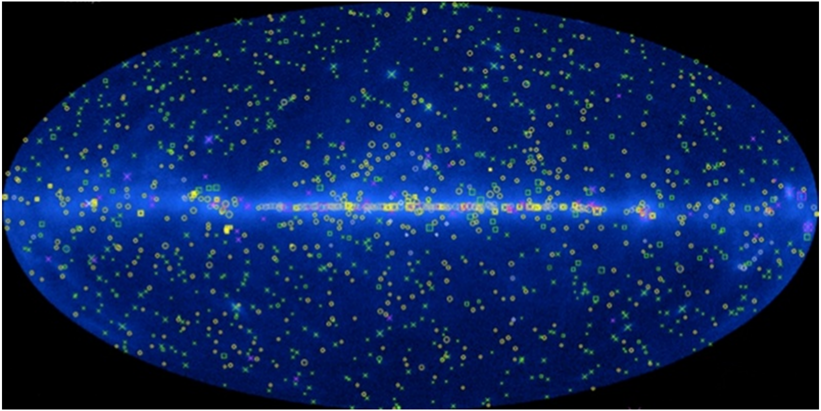
- Note LHAASO only appears in the title but we should keep an eye on it.

Dissecting gamma-ray sky



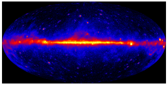
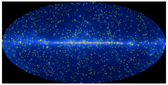
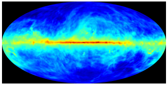
- The γ-ray sky:
  - Rate map (exposure corrected) of γ-candidates above 200 MeV collected during the first year of data taking.

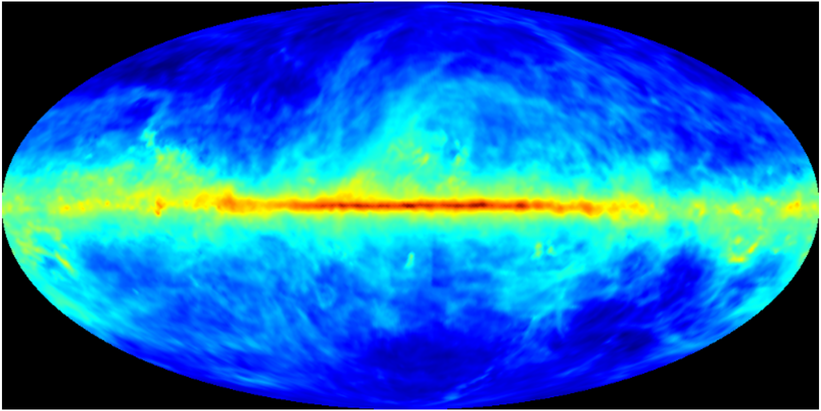
 = 



- Resolved point sources:
  - The catalogs are among the most important collaboration science products.

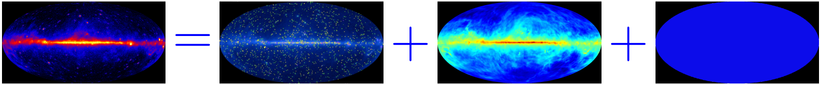
Dissecting gamma-ray sky

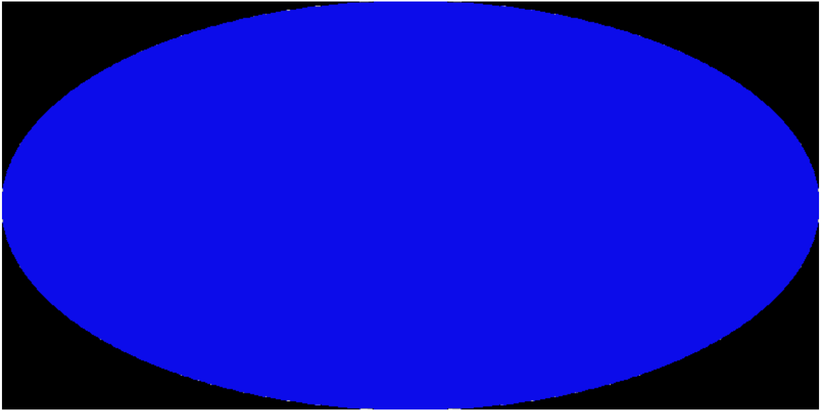
 =  + 



- Galactic diffuse radiation (accounts for the majority of photons):
  - Cosmic-ray interactions with the interstellar medium (synchrotron, inverse Compton, π^0 decay, bremsstrahlung).

Dissecting gamma-ray sky





- Isotropic diffuse emission:
  - Unresolved sources and truly diffuse (extragalactic) emission;
  - Residual cosmic-rays surviving background rejection filters.