Astroparticules et ciel gamma : Le Large Area Telescope à bord de l'observatoire *Fermi*

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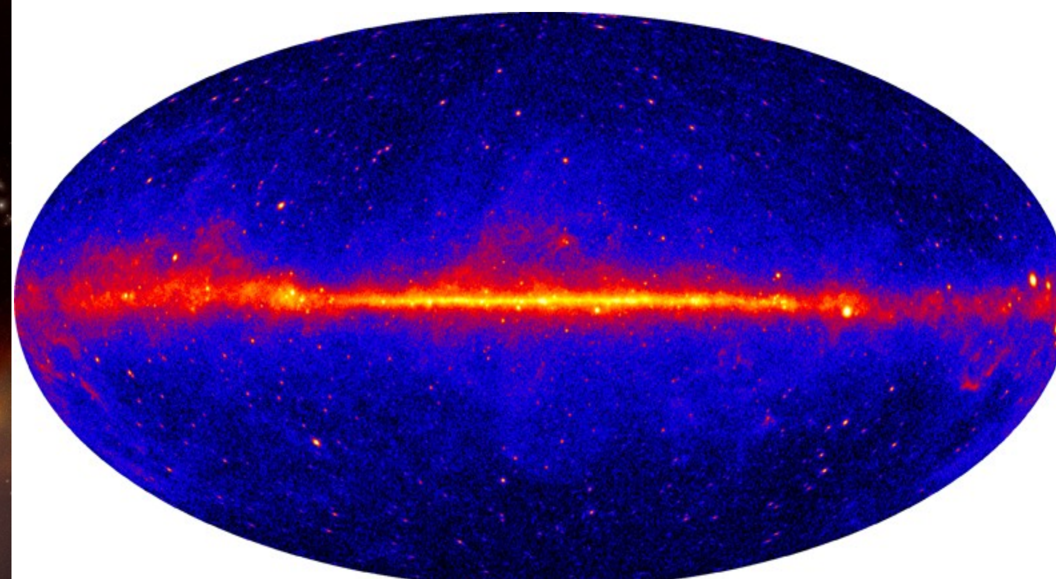


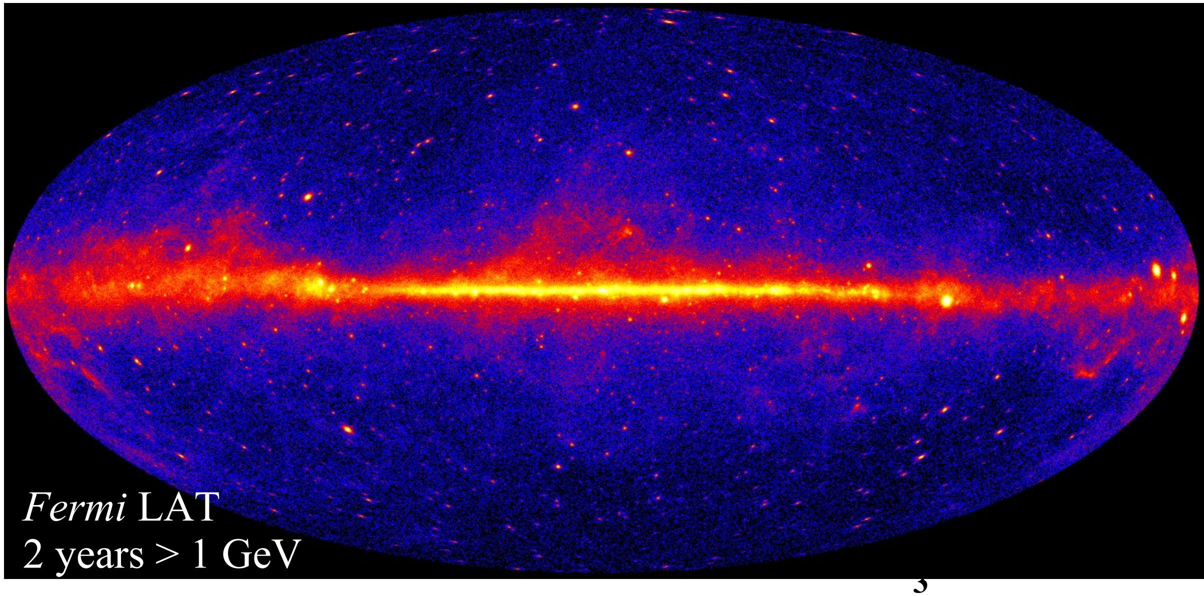
Séminaire LPC 30 mars 2012

Outline

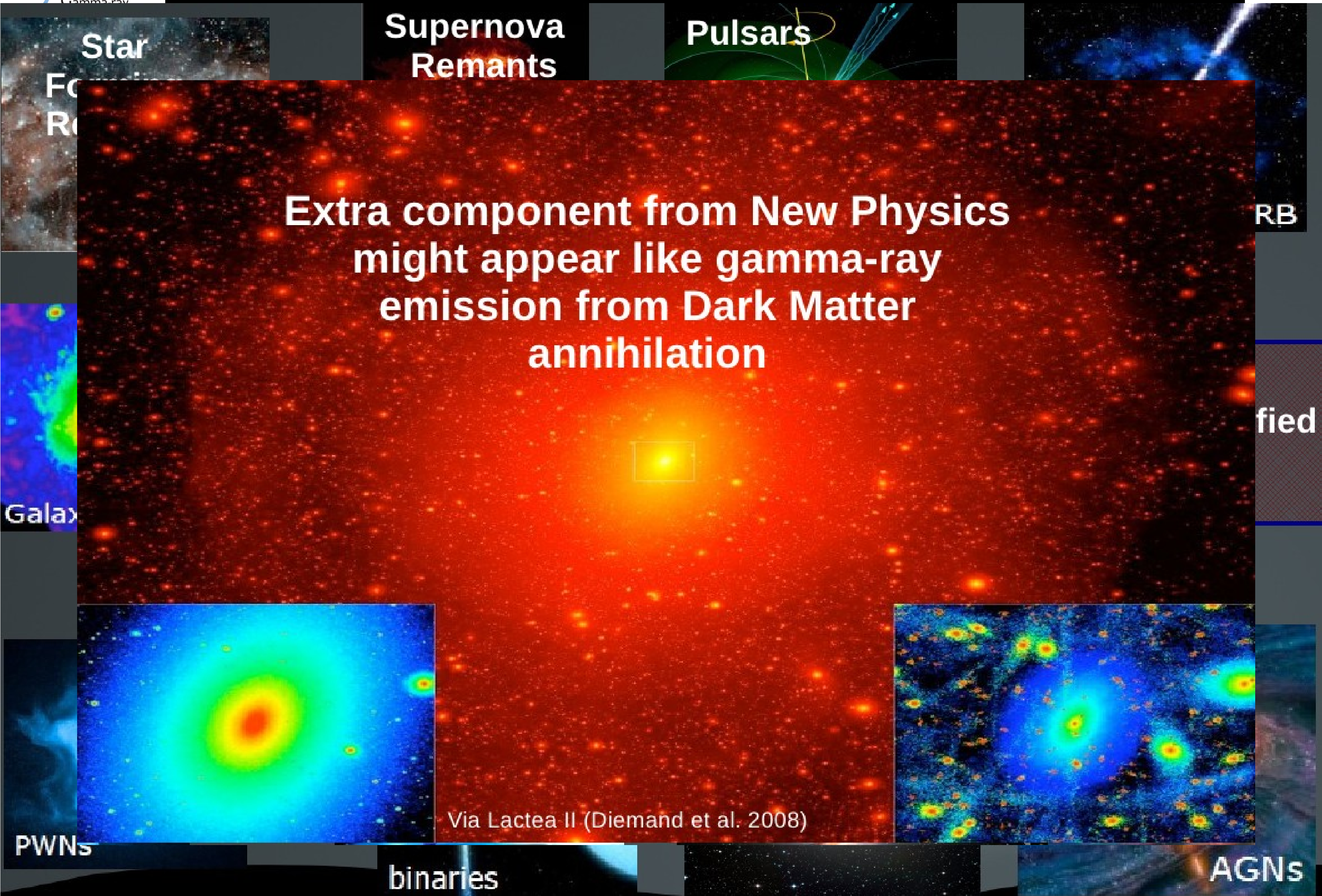
- Introductory remarks
- *Fermi* Mission, the LAT, and the analysis of its data
- A selection of Highlights related to Astroparticle Physics

Astroparticle Physics ?

- Astrophysics with particles ?
  - Yes for neutrinos and cosmic rays, possibly even gravitational waves
  - Not really photons, not even γ-rays..... or else astrophysics = astroparticle
- Astrophysics of particles ?
  - The study of/search for particles of astronomical origin : Yes
  - With a twist in the scope : not the study of the astrophysical sources themselves, but rather the questions of 'fundamental physics' that they lay open.
- Cross-Feeding with High-Energy Astrophysics (HEA) increasingly crucial (X-ray and beyond) : The phenomena of interest to astroparticle physics usually exhibit extreme behavior typical of HEA, and they usually arise in the midst of an important astrophysical foreground, that needs study/modeling
- Gamma Rays!
  - Easy to detect (think neutrinos/GW)
  - Produced by interactions of HE particles, not in thermal equilibrium, and thus trace the most violent processes in the Universe.
  - And of course they come straight to us, possibly attenuated but not deflected.



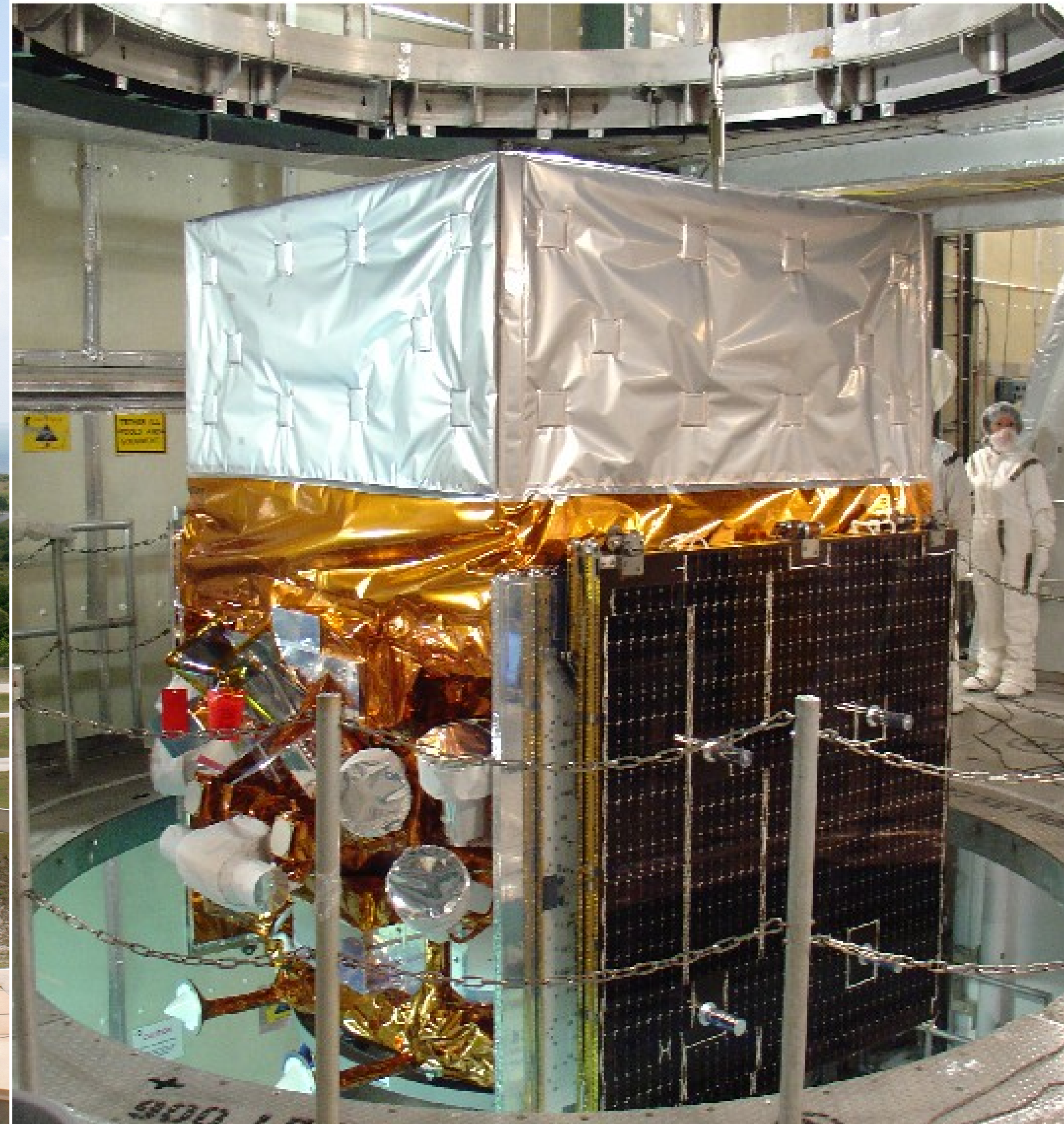
The GeV-TeV γ-ray sky : cosmic accelerators



The *Fermi* Observatory

Cape Canaveral

11 June 2008, 12:05PM EDT



Lifetime : 5 years (min)

Orbit : 565 km, 96'

Inclination : 25.6°

Fermi Observatory

LAT
Large Area Telescope
20 MeV to >300 GeV

All sky survey mode

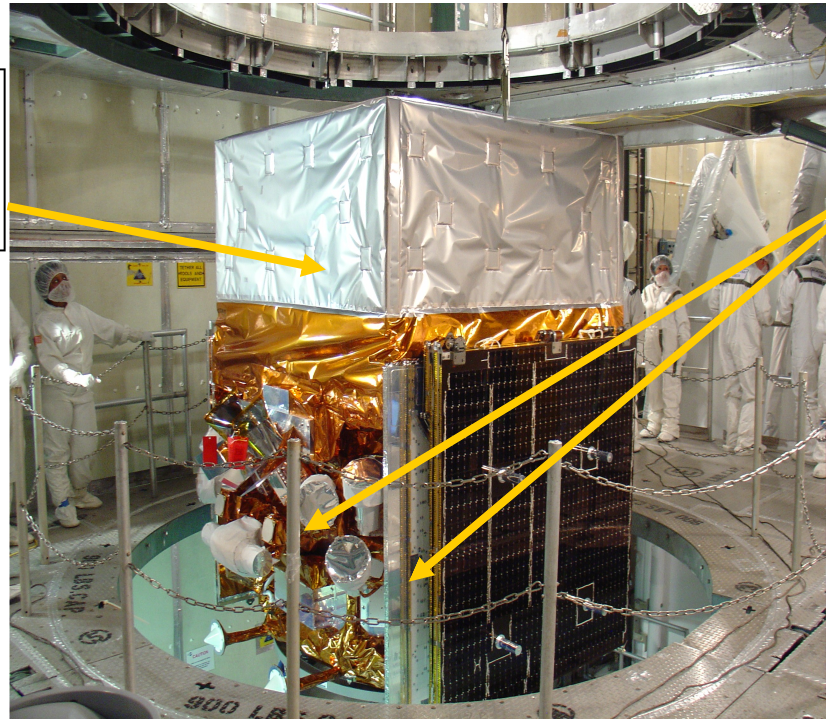
Re-pointing Capabilities

Autonomous

Rapid slew speed

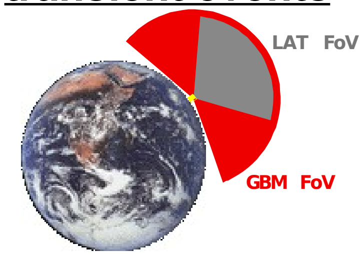
(75° in < 10 minutes)

25 μs deadtime



GBM
Gamma-ray Burst Monitor
NaI and BGO Detectors
8 keV - 30 MeV

correlative observations of <u>transient events</u>



KEY FEATURES

Huge field of view

LAT: 20% of the sky (~2.4 sr) at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.

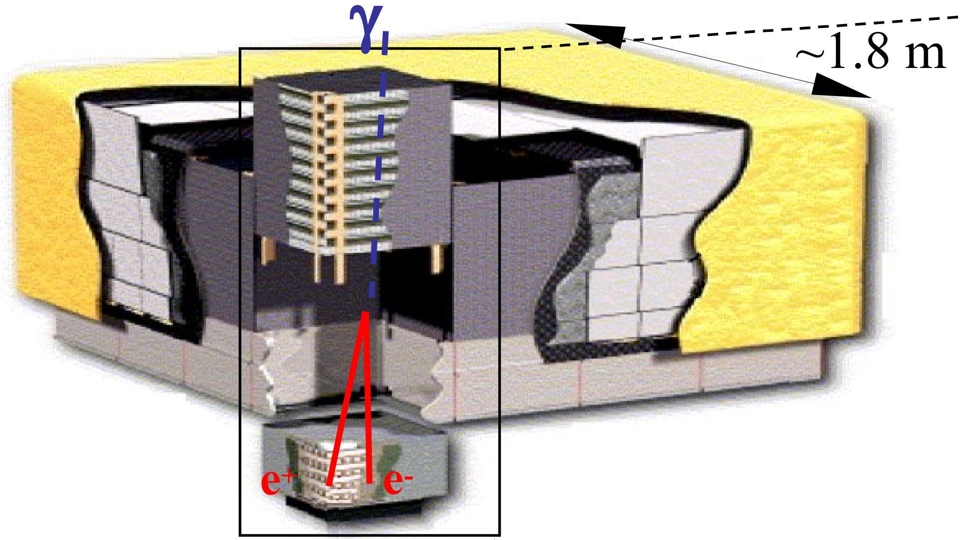
Huge energy range

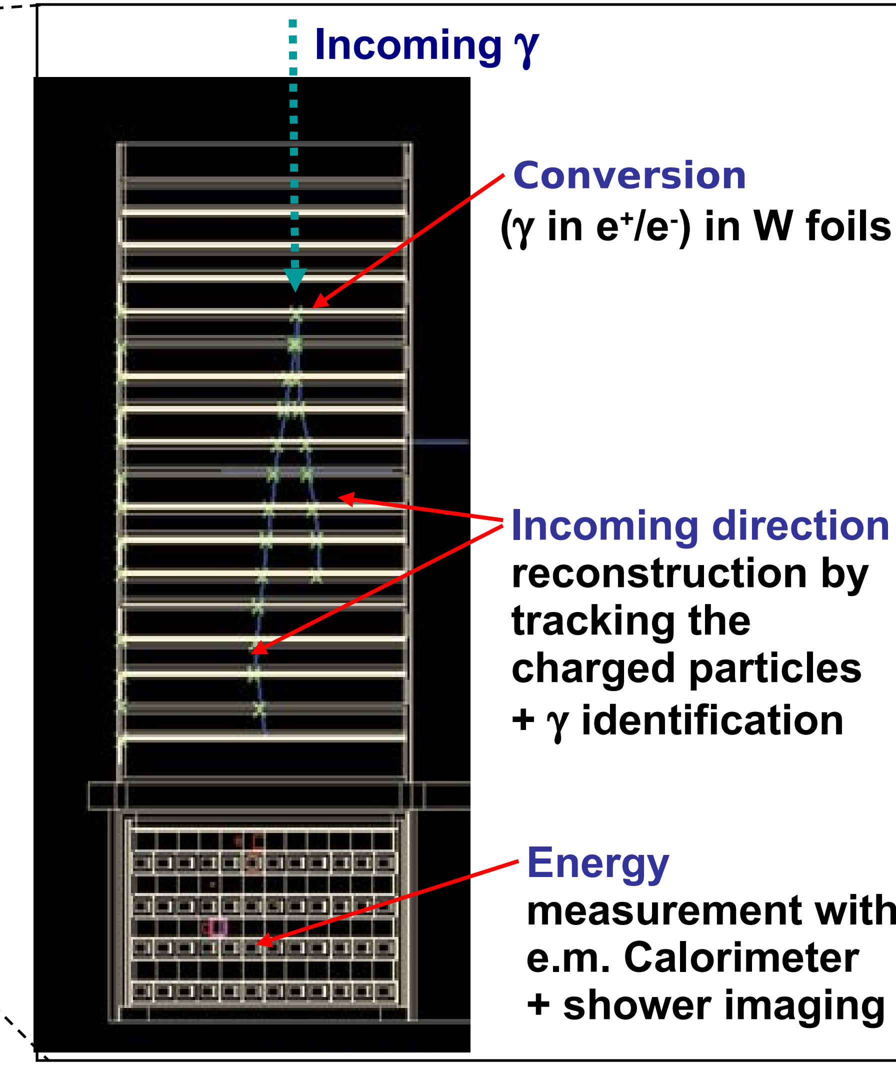
Total of >7 energy decades including largely unexplored band 10 GeV - 100 GeV. Currently no other telescope covering this energy range.

Great discovery potential

The LAT

A modular Pair Conversion Telescope (4x4 identical towers)





Precision Si-strip tracker :

Si-strip detector, W converter foils,
$80\ m^2$ of Si active area,
1.5 radiation lengths on-axis.

Hodoscopic CsI calorimeter :

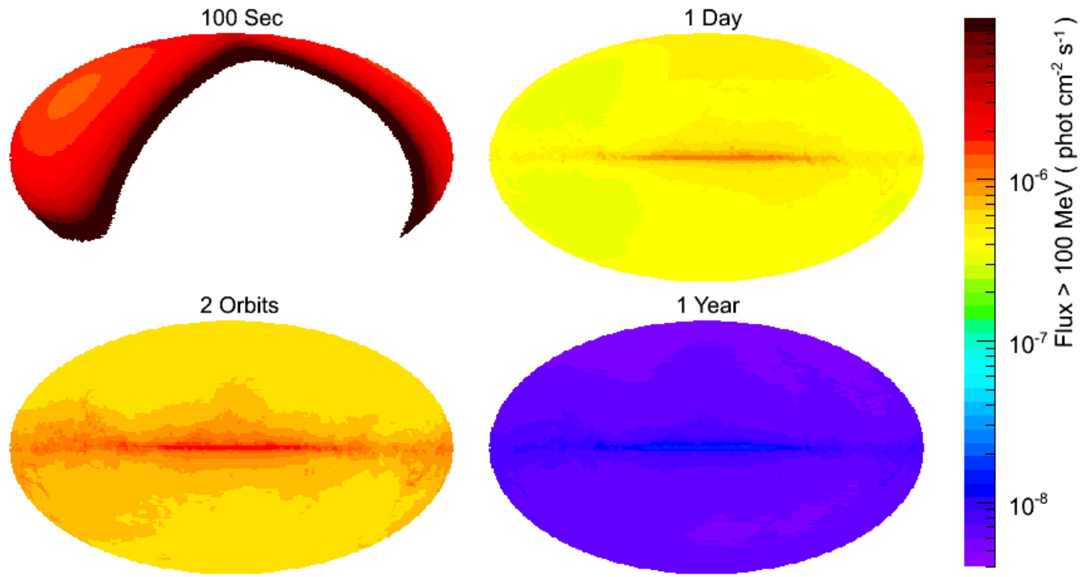
array of 1536 CsI(Tl) crystals in 8 layers.
8.6 radiation lengths on-axis.

Segmented Anti-Coincidence Detector :

89 plastic scintillator tiles and 8 ribbons.
charged particles veto (0.9997 average detection efficiency).

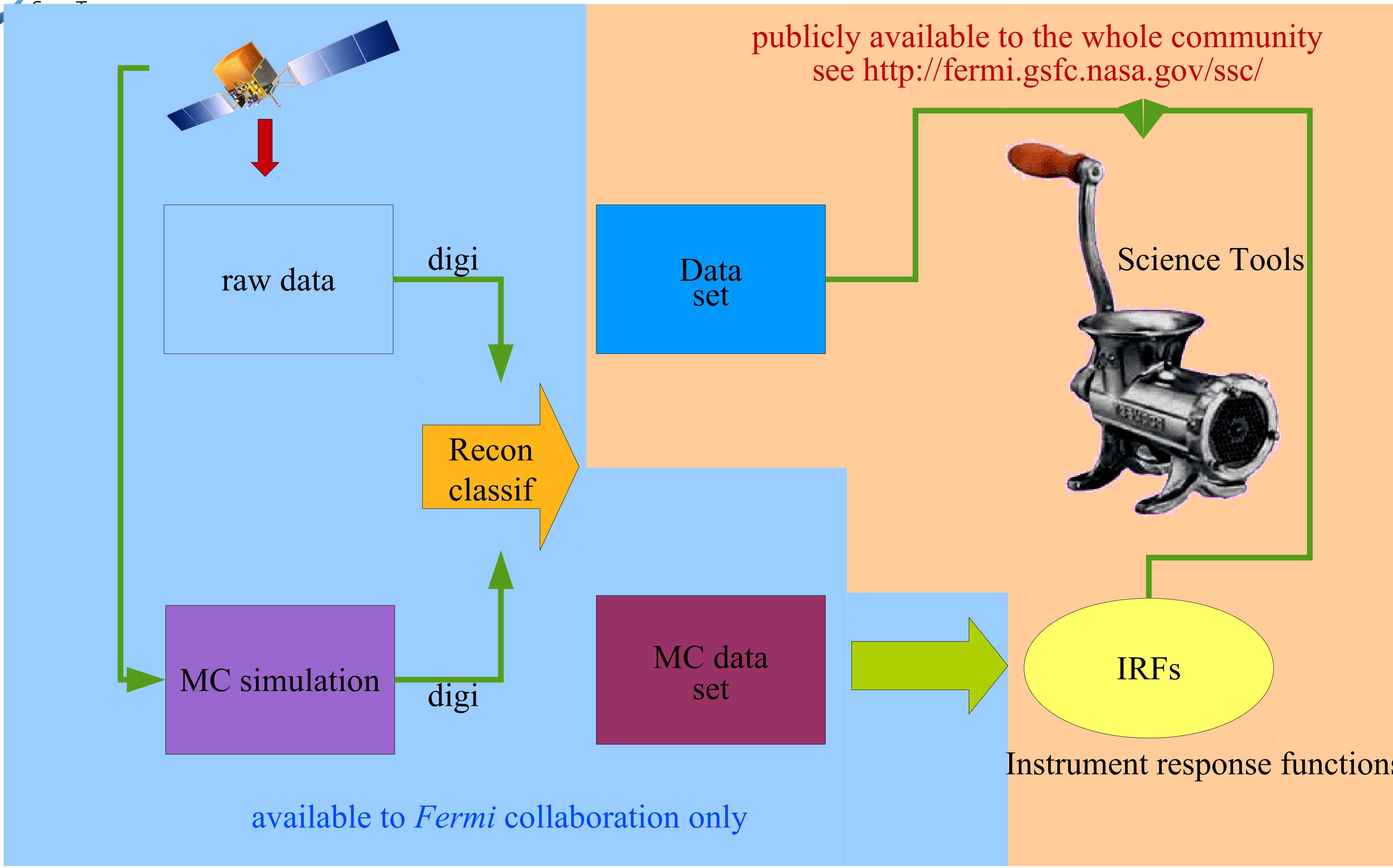
Observing strategy

- **standard sky survey → scans the whole sky every 2 orbits (3 h)**
  - observatory rocks by ±50º on alternate orbits
  - uniform exposure over time

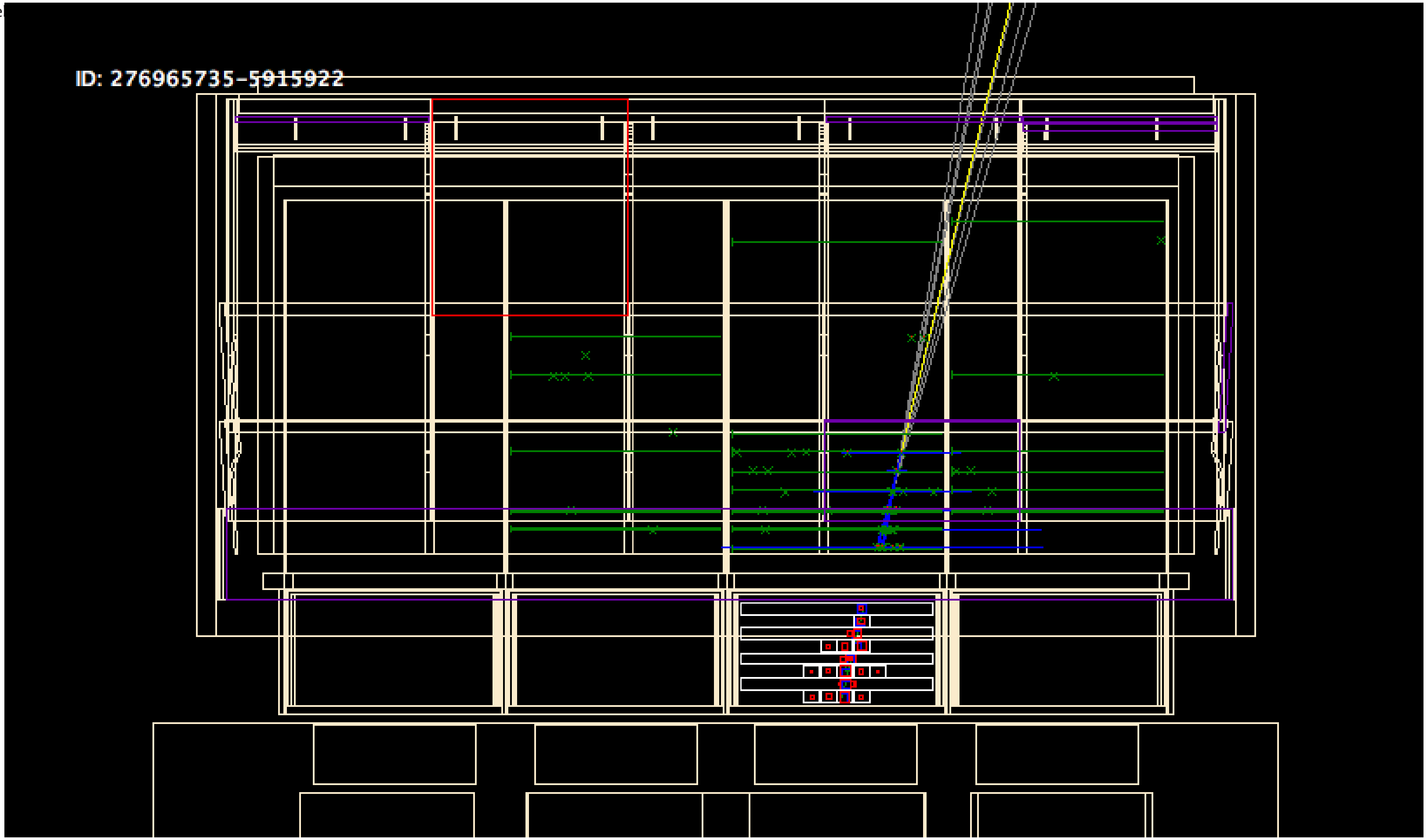


- **alternative observing modes:**
  - autonomous repointing of bursts (1-2 per month)
  - Target Of Opportunity (TOO)
  - <1% up to 2010, 6% in 2011

Fermi LAT data analysis: overview



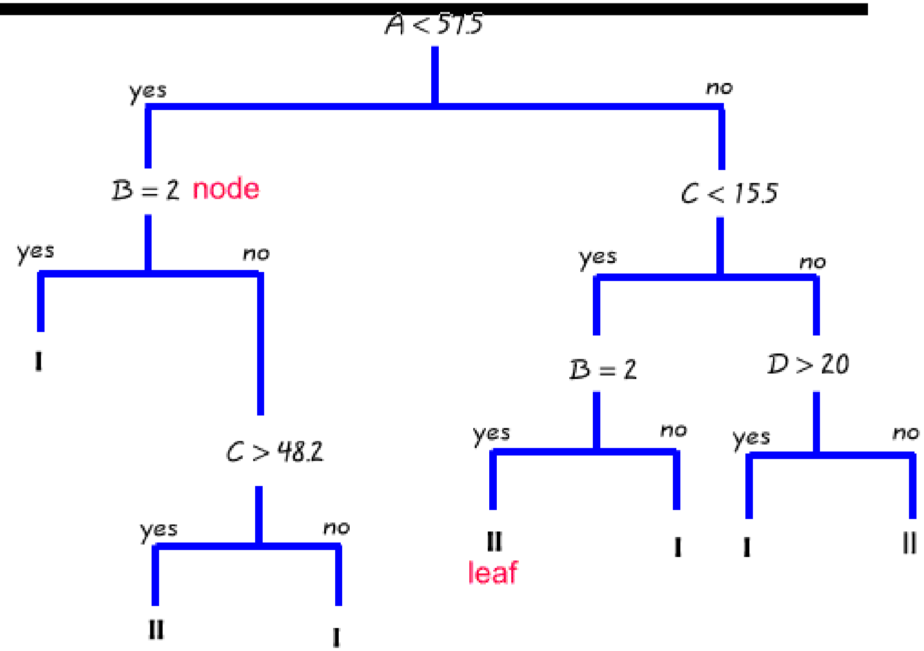
Tracking and energy reconstruction

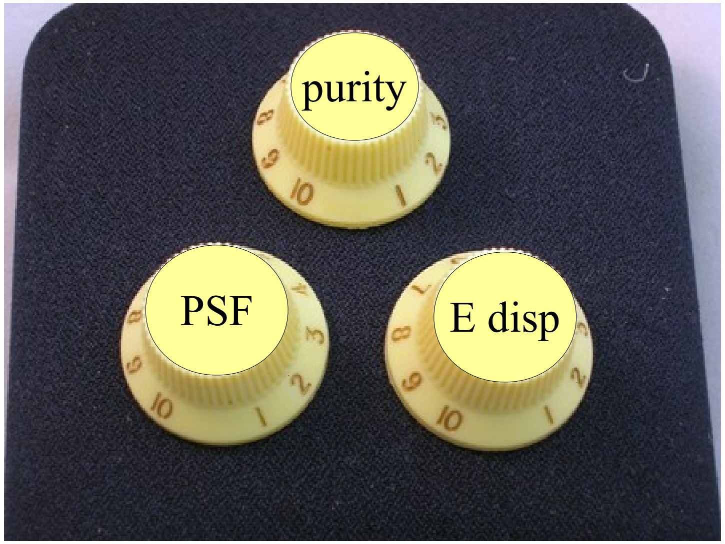


- **combines information from all subsystems**
- **multiple determinations for tracks/vertices and energy**

Event classification

- **based on huge MC simulations: cuts + classification trees**
- **assign to each event**
  - **best direction and energy**
  - **goodness factors**
    - **direction (PSF)**
    - **energy (dispersion)**
    - **gamma-probability (purity)**
- **define cuts which are used to produce datasets**
- **Data reduction :**
  - **~2.5 kHz onboard triggers**
  - **~500 Hz onboard filtered**
  - **~2 Hz of candidate photons**

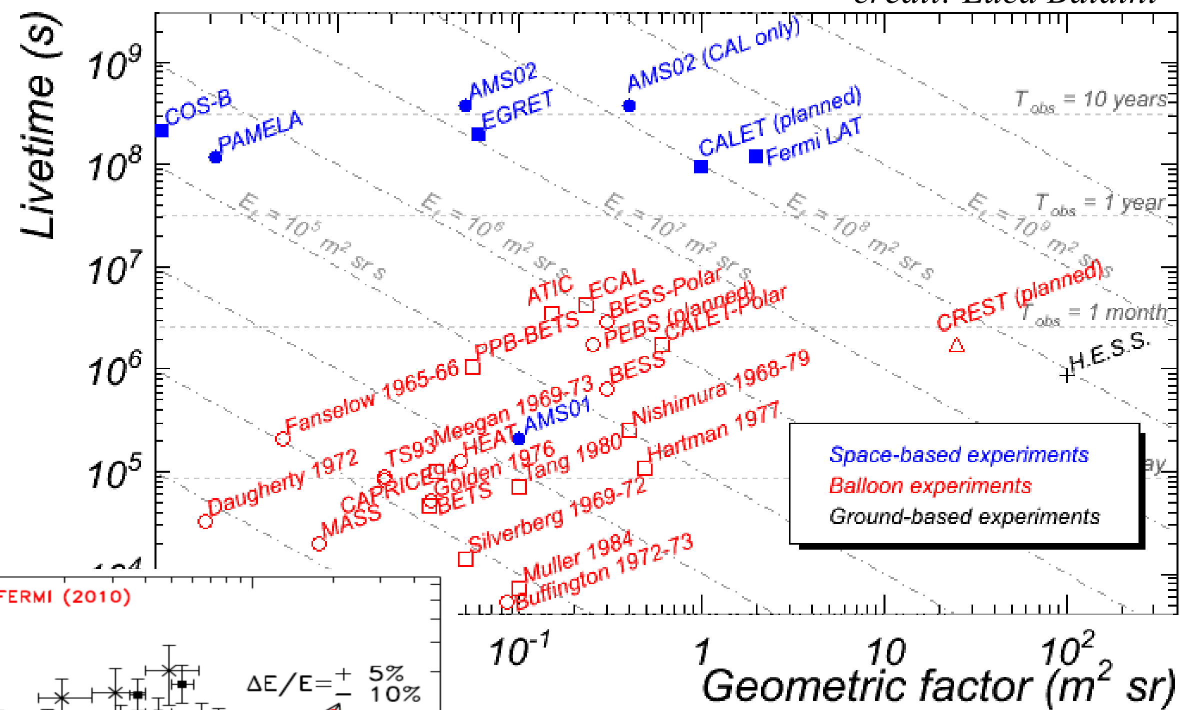


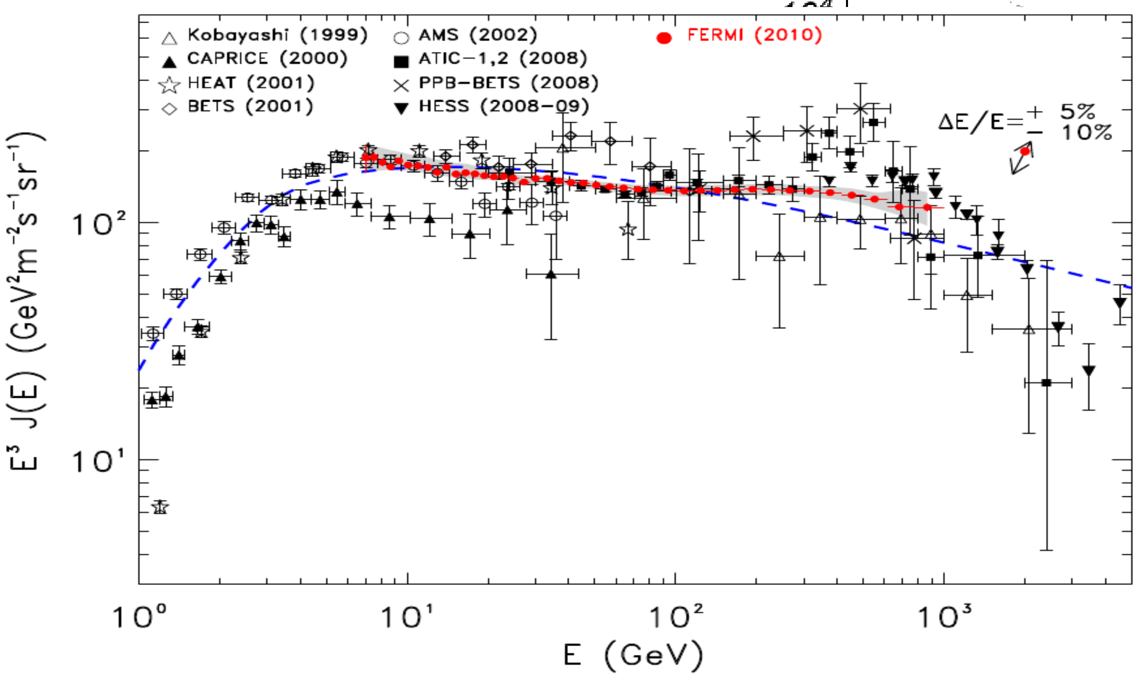


Not only gammas!

- ***Fermi* = electron telescope !**
  - **> 20 GeV, high-pass filter,**
  - **< 20 GeV diagnostic filter**
  - **recon identical to gammas, analogous event selection**
  - **no magnets for charge separation**
  - **large acceptance/ collection time**
- **proton analysis under way**

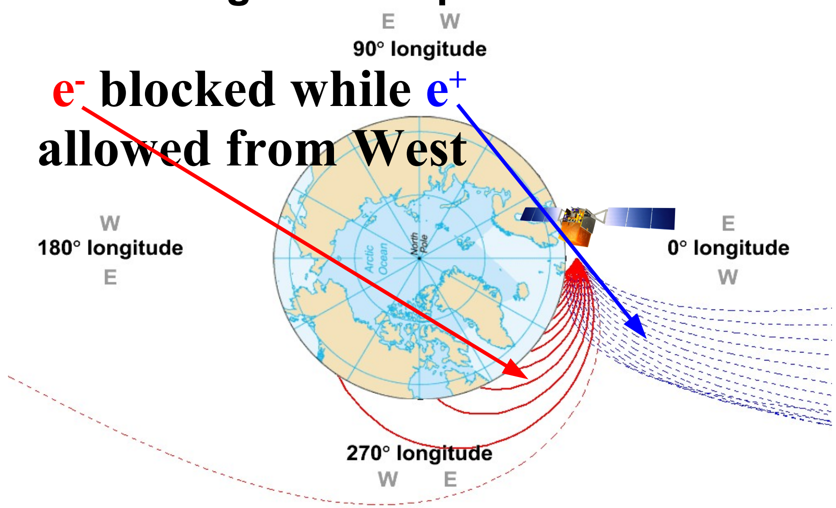
credit: Luca Baldini

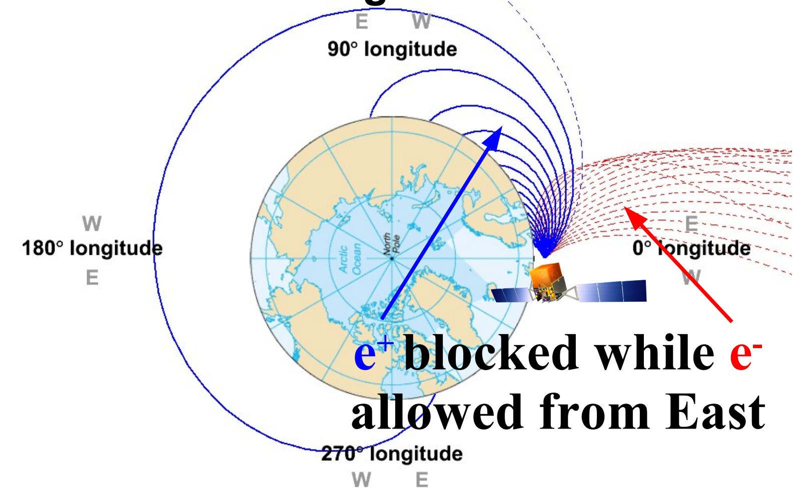




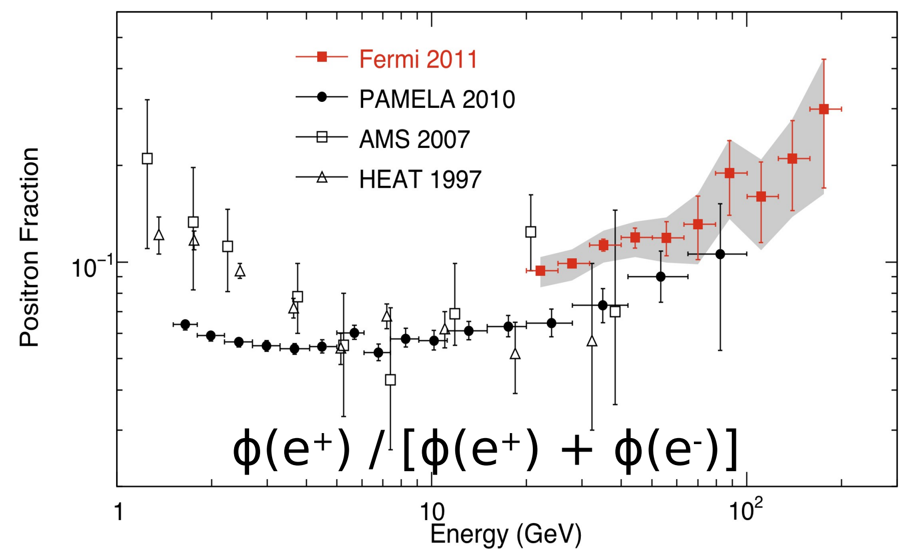
Fermi – LAT Positron fraction measurement

« Unfortunately », the LAT does not carry a magnet, therefore, we cannot discriminate the particle charge … except if we use the earth magnetic field to distinguish e+ from e- !





- Pure e+ region in the West and pure e- region in the East
- Regions vary with particle energy and spacecraft position
- To determine regions, use code by Smart and Shea, which numerically calculates particle's trajectory in geomagnetic field

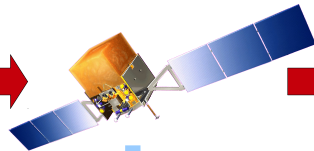


We find that the positron fraction increases with energy between 20 and 200 GeV, consistent with results reported by PAMELA.

Scientific analysis

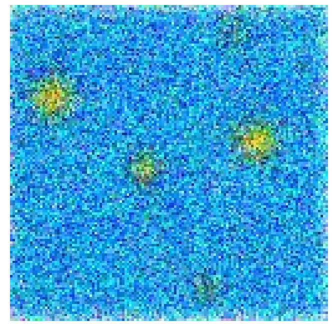
sky

ROI : region of interest



orbital history

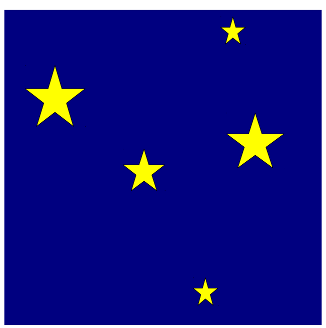
data counts



Binned or Unbinned Poisson Likelihood

- **Assumes a model**
- **Determine model parameters through best fit to the data**
- **Assess component/model significance**

model



SR : source region

IRFs

Model -predicted counts

$$\log \mathcal{L} = \sum n_j \log \theta_j - N_{\text{pred}}$$

$$N_{\text{pred}} = \int dt \int_{\varepsilon_{\min}}^{\varepsilon_{\max}} d\varepsilon' \int_{\Omega_{\text{roi}}} d\hat{p}' \, M(\varepsilon', \hat{p}', t)$$

$$\theta_j = \int dt \int_j d\varepsilon' d\hat{p}' \, M(\varepsilon', \hat{p}', t)$$

$$M(\varepsilon', \hat{p}', t) = \int_{\text{SR}} d\varepsilon d\hat{p} \, S(\varepsilon, \hat{p}) R(\varepsilon', \hat{p}'; \varepsilon, \hat{p}, t)$$

astro. pars. of interest hide here

IRFs

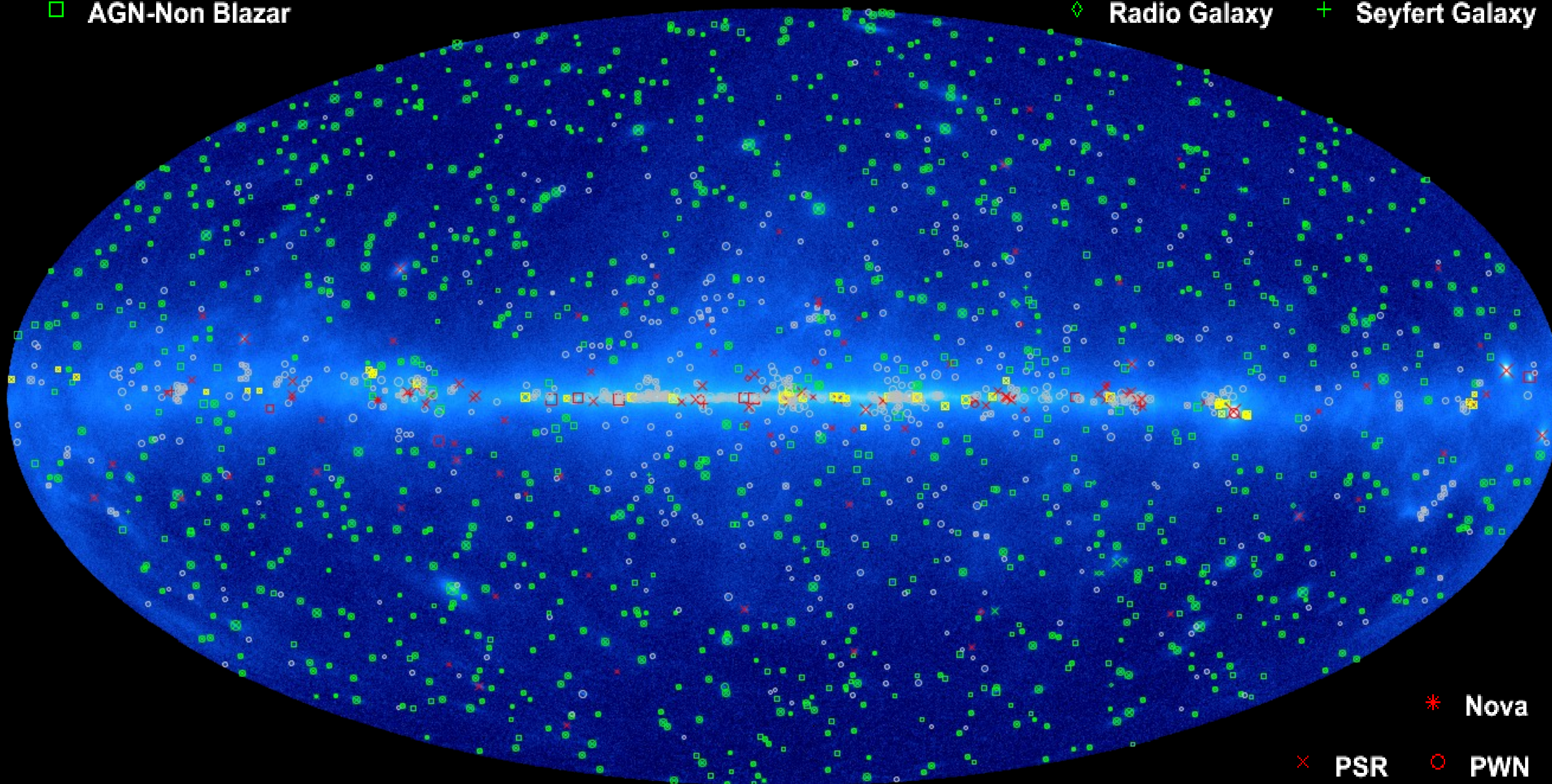
Fermi Large Area Telescope 2FGL catalog

AGN AGN-Blazar

AGN-Non Blazar

Galaxy Starburst Galaxy

Radio Galaxy Seyfert Galaxy



Nova

PSR PWN

Unassociated

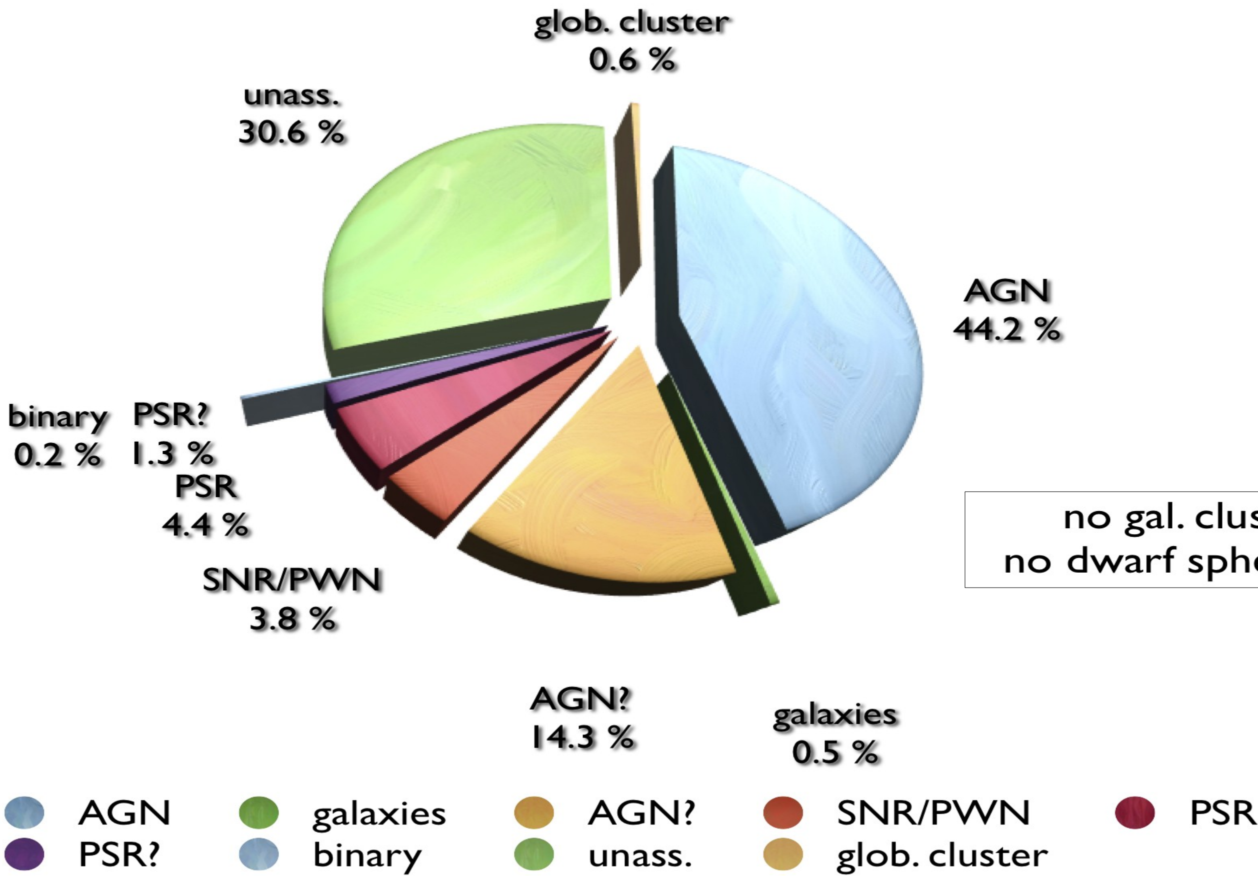
PSR w/PWN SNR

Possible Association with SNR and PWN

Globular Cluster HMB

Credit: Fermi Large Area Telescope Collaboration

The 2FGL Catalog: source classes



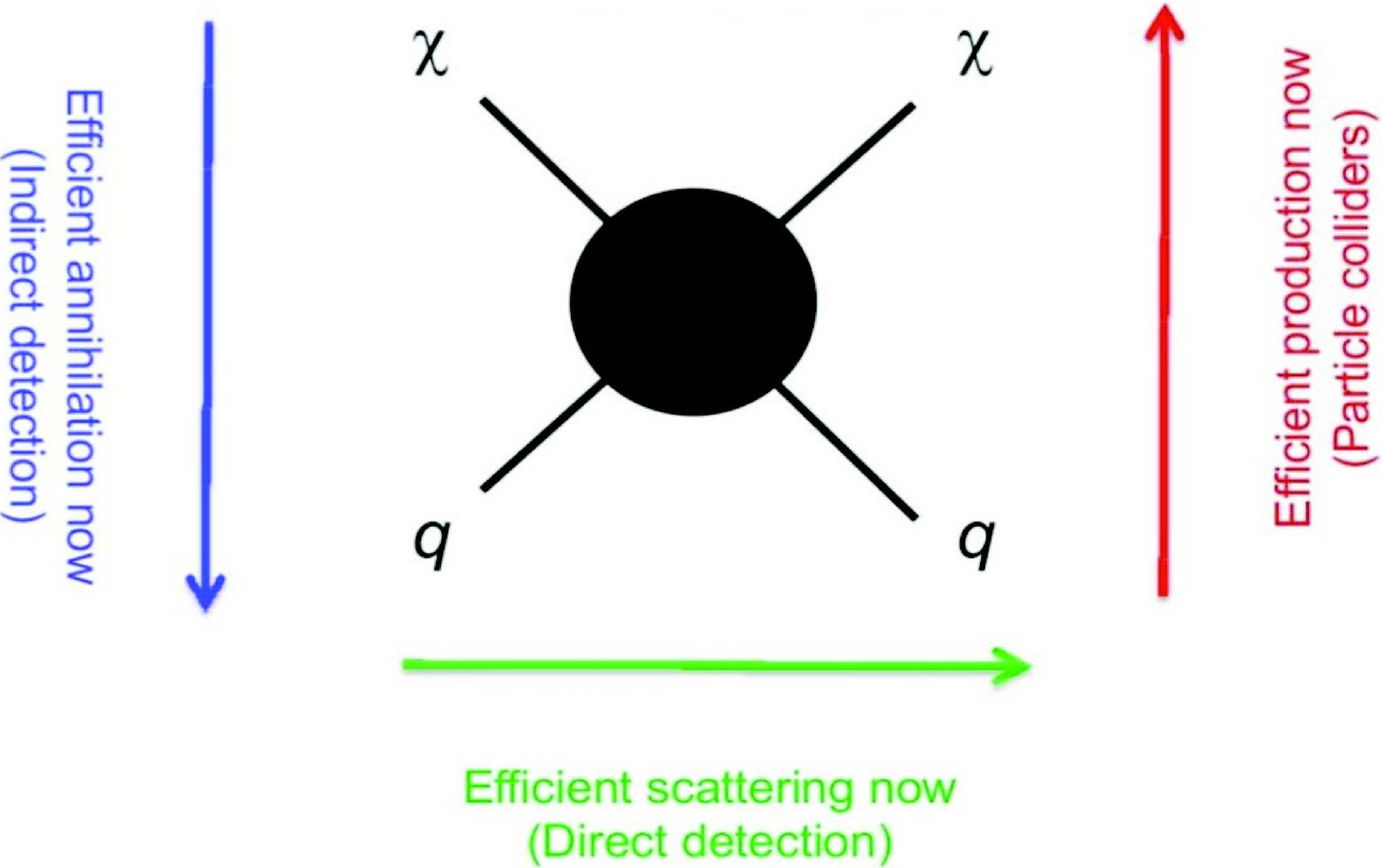
no gal. clusters
no dwarf spheroidals

- 1873 sources: 127 firmly identified, 1170 reliably associated
- http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/
  arXiv:1108.1435

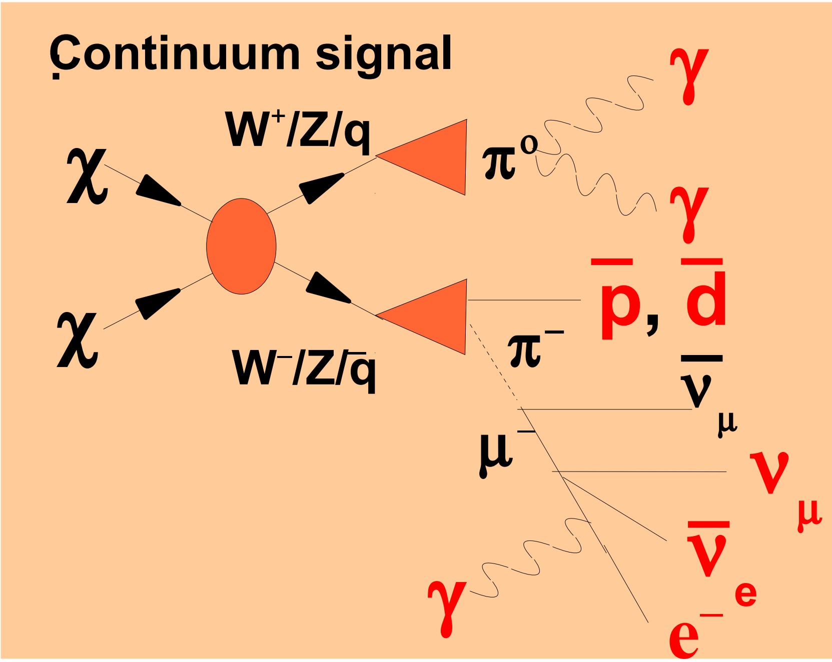
“Astroparticle” topics with the LAT

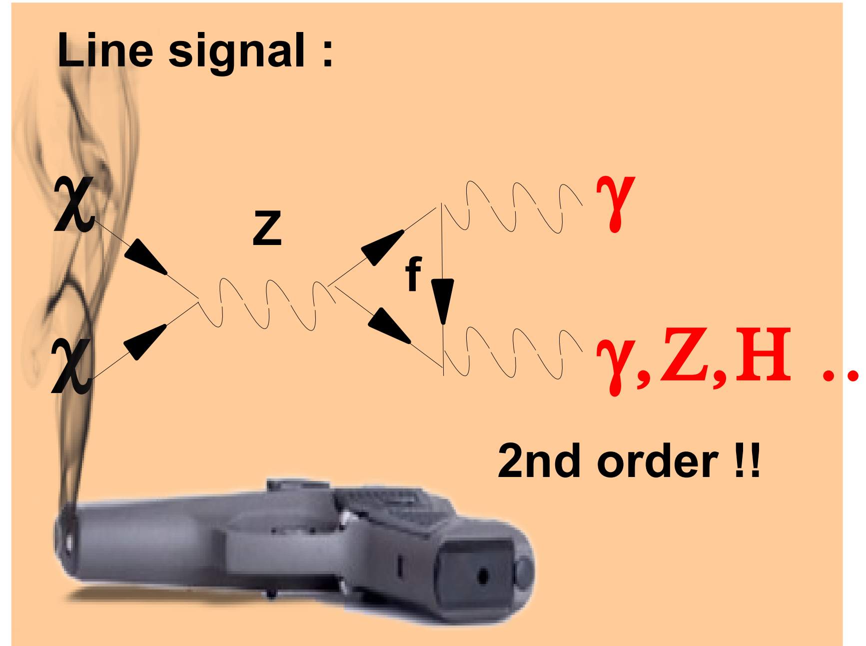
- WIMP searches
  - Dwarf spheroidals improved analysis
  - A word on the UED motivated LKP
- KK graviton γ-ray emissivity in neutron stars
- “Analysis R&D phase” : axion-like particle distortion of AGN spectra
- The cherry on the cake (sort of....) : Lorentz-invariance tests with GRBs

WIMP Dark Matter Searches



Indirect Detection of Dark Matter (WIMP)



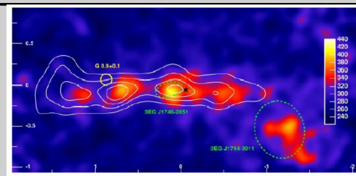
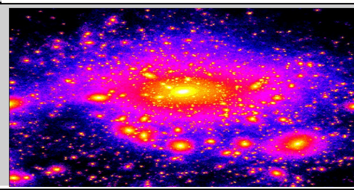
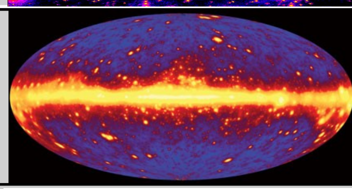
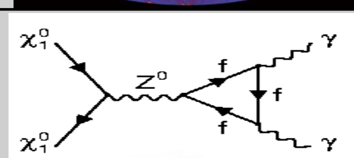
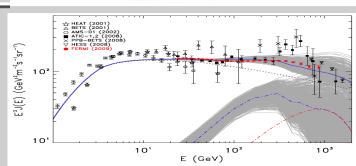


$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \underbrace{\frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_f \frac{dn_\gamma^f}{dE_\gamma} B_f}_{Particle\ Physics} \underbrace{\int_{\Delta\Omega} \int_{l.o.s} \rho^2(l)\ dl(\psi)\ d\Omega}_{Astrophysics}$$

DM distribution :
NFW, Moore, Isothermal, ...

J-factor

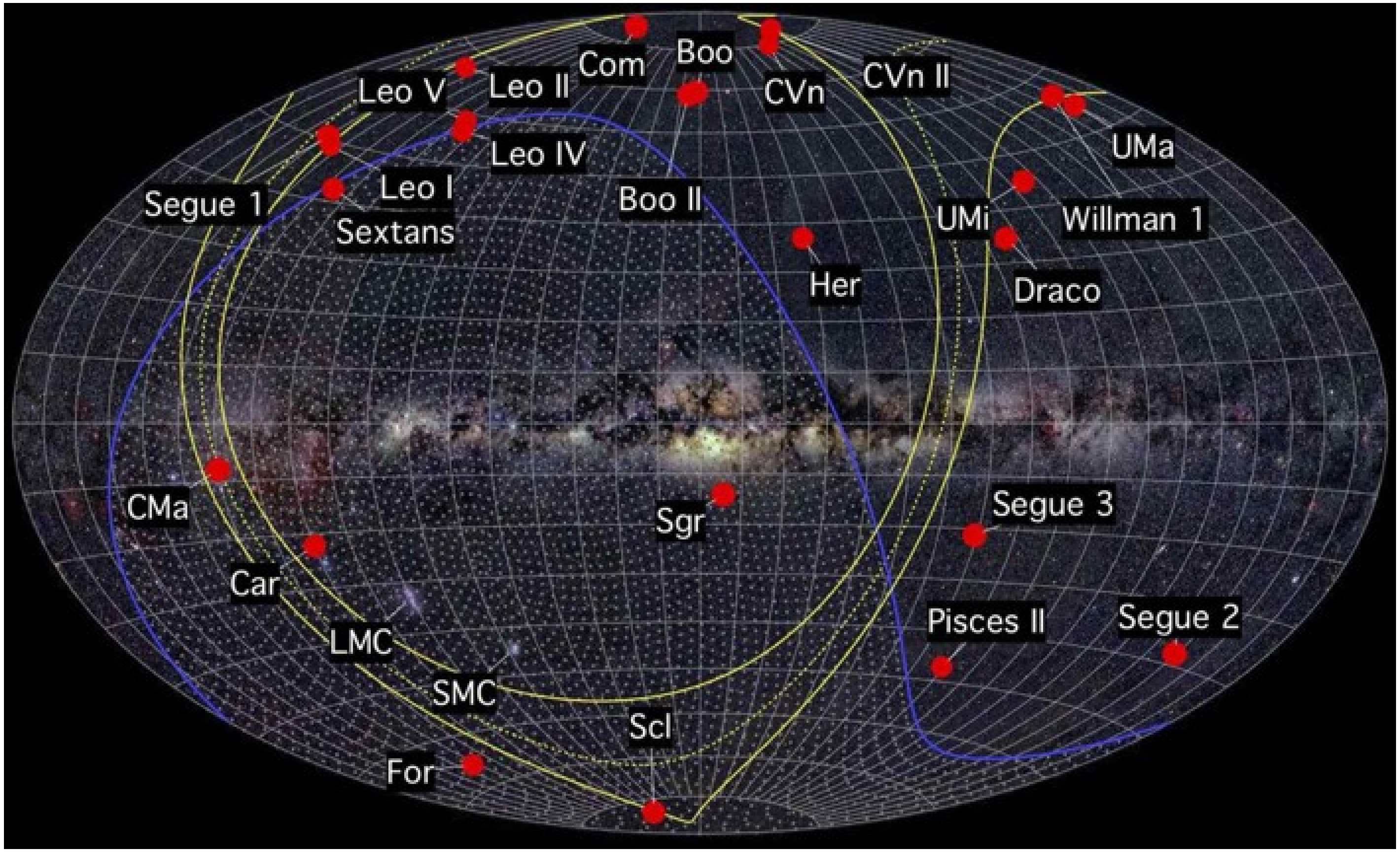
The LAT DM Hunting Targets

Search Technique		advantages	challenges
Galactic center		Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos, Point Sources		Low background, Good source id	Low statistics
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics
Cosmic-ray electrons		Experimental hints, large stat. + DM models discrimin.	Astrophysical background Diffusion models

Pre-launch sensitivities published in E.A. Baltz et al. JCAP07 (2008) 013

The Whole HEA is a Potential Background (but for the lines!)

Dwarf Spheroidal Galaxies



- **Roughly two dozen dwarf spheroidal satellite galaxies of the Milky Way**
- **Some of the most dark matter dominated objects in the Universe**
- **No astrophysical gamma-ray production expected**
- **Recent ultra-faint ones discovered by SDSS optical survey**

Dwarf combined Likelihood

PRL 107, 241302; arXiv:1108.3546

- Perform a combined analysis of multiple dwarf spheroidal galaxies
- Approximate integrated J-factor with 0.5 degrees as a point-source contribution at the location of each dwarf
- Include uncertainties in the integrated dark matter distributions from stellar kinematic data.
- Joint likelihood function:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

$$L(D\,|\,\underbrace{\mathbf{p_m}}_{\text{Shared by all dwarfs}},\underbrace{\{\mathbf{p_k}\}}_{\text{Fit for each dwarf}}) = \prod_k L_k^{\mathrm{LAT}}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \underbrace{\frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k}e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}}_{\text{Uncertainty in J-factor}}$$

Shared by all dwarfs (dark matter particle parameters)

Fit for each dwarf (background sources)

Uncertainty in J-factor

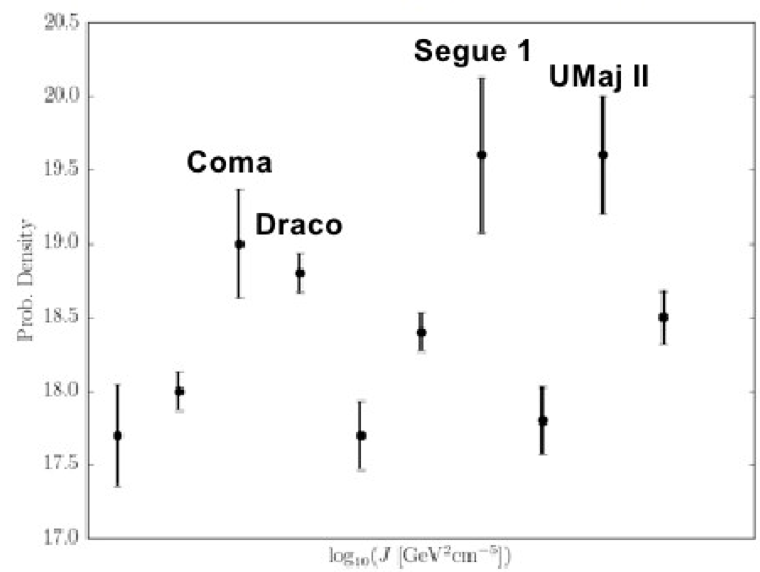
Computing the J-factor

PRL 107, 241302; arXiv:1108.3546

- **Dwarf dark matter content from the line-of-sight velocities of the member stars (e.g. Martinez et al. 2009)**
- **Mass within half-light radius of each dwarf is largely independent of assumptions on the cored or cuspy nature of the inner profile**
- **Calculate the total integrated J-factor within a cone with angular radius of 0.5 degrees (~ comparable to LAT angular resolution)**
- **The posterior distribution and likelihood function for J are well described by a log-normal function**
- **Some of the new ultra-faint dwarfs have the largest J-factors and the largest uncertainties**

Name	l (degree)	b (degree)	d (kpc)	$\overline{\log_{10}(J)}$ ($\log_{10}$[GeV^2 cm^{-5}])	σ	Reference
Bootes I	358.08	69.62	60	17.7	0.34	[1]
Carina	260.11	−22.22	101	18.0	0.13	[2]
Coma Berenices	241.9	83.6	44	19.0	0.37	[3]
Draco	86.37	34.72	80	18.8	0.13	[2]
Fornax	237.1	−65.7	138	17.7	0.23	[2]
Sculptor	287.15	−83.16	80	18.4	0.13	[2]
Segue 1	220.48	50.42	23	19.6	0.53	[4]
Sextans	243.4	42.2	86	17.8	0.23	[2]
Ursa Major II	152.46	37.44	32	19.6	0.40	[3]
Ursa Minor	104.95	44.80	66	18.5	0.18	[2]

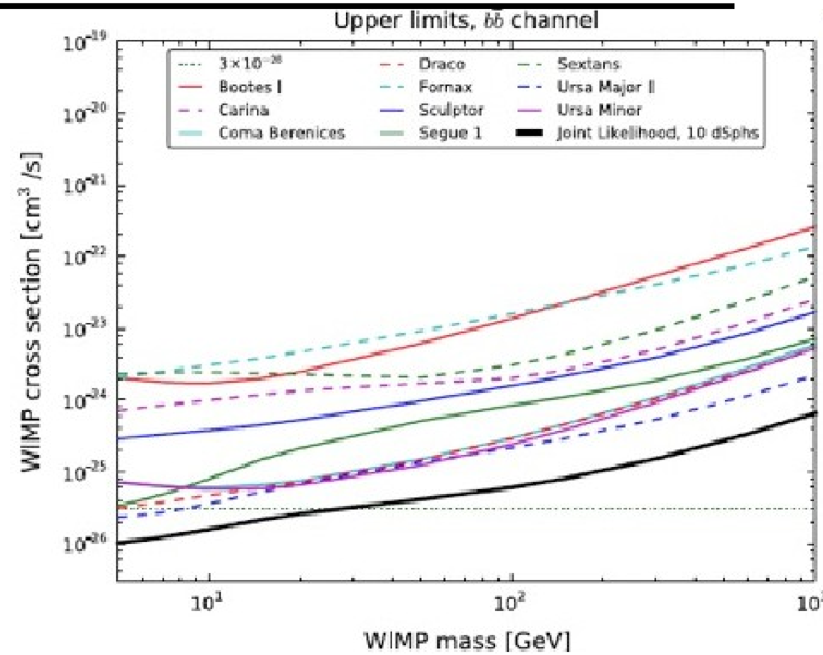
[1] S. E. Koposov *et al.*, Astrophys. J. **736**, 146 (2011).
[2] M. G. Walker *et al.*, Astrophys. J. **704**, 1274 (2009).
[3] J.D. Simon and M. Geha, Astrophys. J. **670**, 313 (2007).
[4] J.D. Simon *et al.*, Astrophys. J. **733**, 46 (2011).



Dwarf Spheroidal results

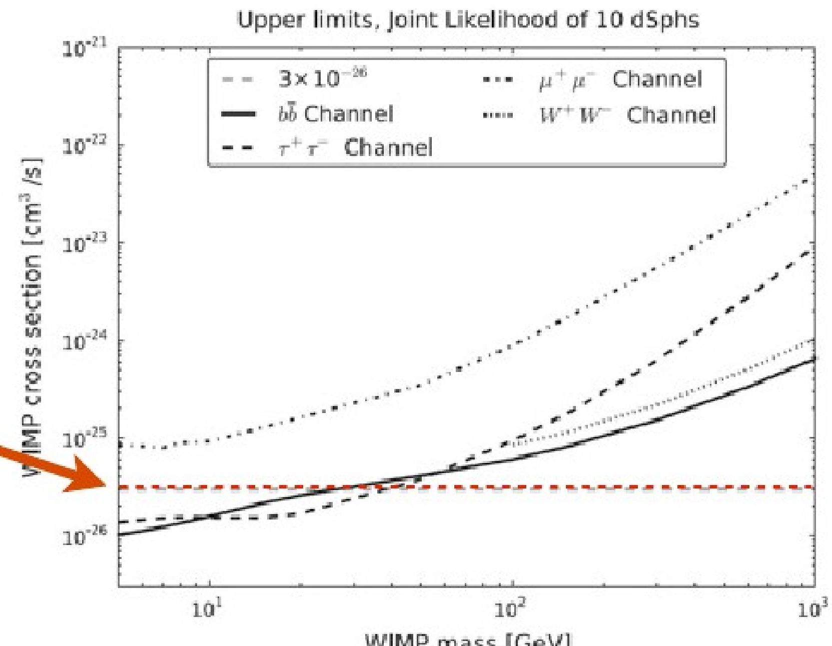
PRL 107, 241302; arXiv:1108.3546

- **Robust constraints come from a joint likelihood analysis of**
  - **10 dwarf galaxies**
  - **200 MeV - 100 GeV gamma-rays**
  - **2 years of data**
  - **4 annihilation channels**



- **Include uncertainties in the solid-angle-integrated J-factor**

- **Exclude the conventional thermal relic cross section for a WIMP with mass < 30 GeV annihilating to** $b\bar{b}$ **or** $\tau^+\tau^-$



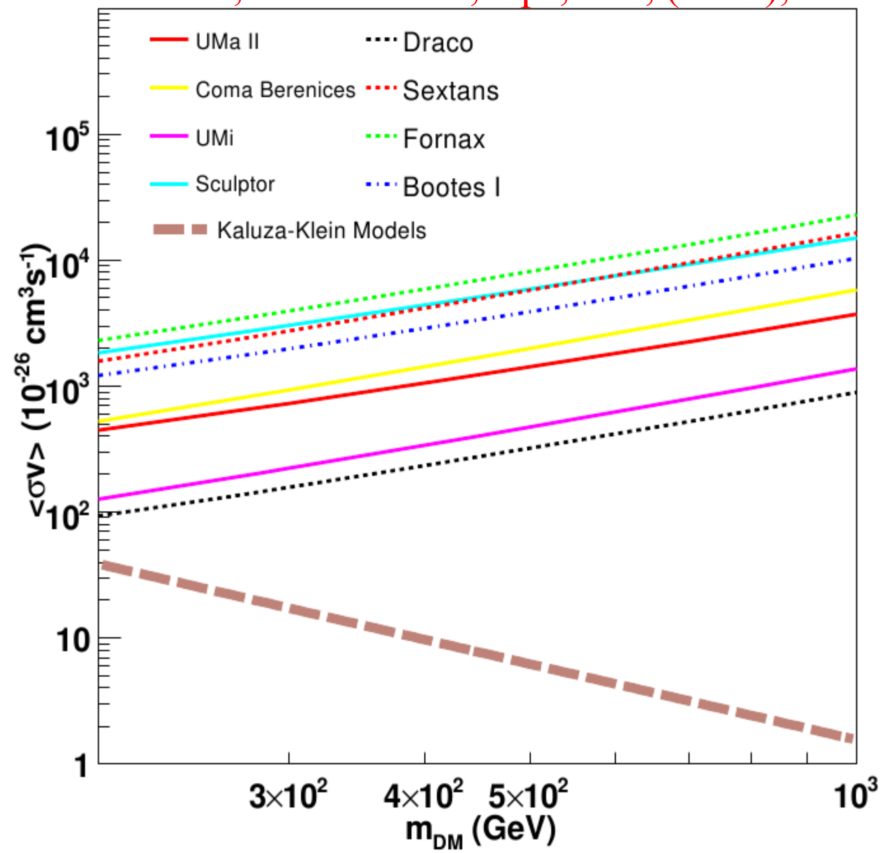
A word on UED motivated LKP

- UED : all the particles see the extra-dims.
- A LKP is stabilized with a residual symmetry, much like the LSP
  - Typically : the first mode of the B tower
  - Main differences are a higher expected mass range, and a large branching ratio into l+l- channels
- Servant&Tait(03) :

$$\langle \sigma v \rangle = \frac{95 g_1^4}{324 \pi m_{\rm LKP}^2} \simeq \frac{1.7 \times 10^{-26}\, {\rm cm}^3/{\rm s}}{(m_{\rm LKP}/{\rm TeV})^2}.$$

- ~60% br inclusive l+l-, ~36% in qqbar
  - We looked at the constraints from the latter

11 mths, P6v3Diffuse, ApJ, 712, (2010), 147



- The dominant lepton channel copiously produce electrons, with an expected sharp edge at the LKP mass. Difficult to extract from the overall spectrum....

"Astroparticle" topics with the LAT

- WIMP searches
  - Dwarf spheroidals improved analysis
  - A word on the UED motivated LKP

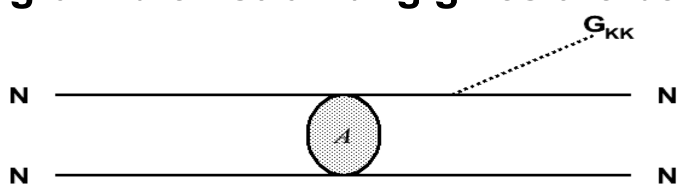
- KK graviton γ-ray emissivity in neutron stars

- "Analysis R&D phase" : axion-like particle distortion of AGN spectra

- The cherry on the cake (sort of....) : Lorentz-invariance tests with GRBs

Large Extra-Dimensions and Neutron Stars

- LED model proposed by Arkani-Hamed, Dimopoulos and Dvali (ADD-98) as a solution to the hierarchy problem : M_p>>TeV
  - Assume all fields but graviton propagate in a 4D "brane", and only graviton propagates in the "bulk" of dimension 4+n, with n extra-dims compactified on a torus (radius R)
  - Then the natural scale for gravity M_D verifies $M_P^2 = M_D^{n+2} R^n$. Setting $M_D \sim 1$ *TeV* yields :
    - n=1 : R~10^{11} km excluded long ago by Newton...
    - n=2 : R~0.5mm : realm of current pendulum experiments
    - n>3 : all bets are off (and n=6 is a sweet spot for a class of theorists...)
    - $M_D R \sim 10^{32/n}$ *hence "large" dimension :* $R >> M_D$ *for n reasonable n and* $M_D \sim$*TeV*
- Current Eöt-Wash group constraint : M_D>3.2 TeV at 95%CL for n=2
- Astrophysical constraints can be much larger (albeit with completely different systematics):
  - Compactification yields a tower of KK gravitons, much like the original KK theory.
  - These interact with matter fields and modify the energetics of stars/supernovae etc...
    - Nucleon-Nucleon gravi-bremstrahlung gives the best constraints



    - M_D>50 TeV from SN1987A (with T=30 MeV) (Barger et al. 99)
  - Then Hannestad&Raffelt (03) noted that KK gravitons thus produced in SN cores could be trapped by the newly-formed Neutron Star, and then slowly decay in pairs of γ-rays

ADD LED analysis with the LAT

Fermi LAT Collaboration, JCAP02(2012)012

- **Focus on 6 neutron stars, not in 1FGL, age < 2×10^{8} yr, d < 0.40 kpc, *B*surf < 3×10^{13} G, |*b*| > 15°**
- **Extend the Hannestad&Raffelt framework with a full MonteCarlo in order to derive the expected differential gamma-ray spectrum**
  - **Full account of NS age (exp. Decay from birth to present)**
  - **Modeling of attenuation in the magnetic field (dipole approx.)**

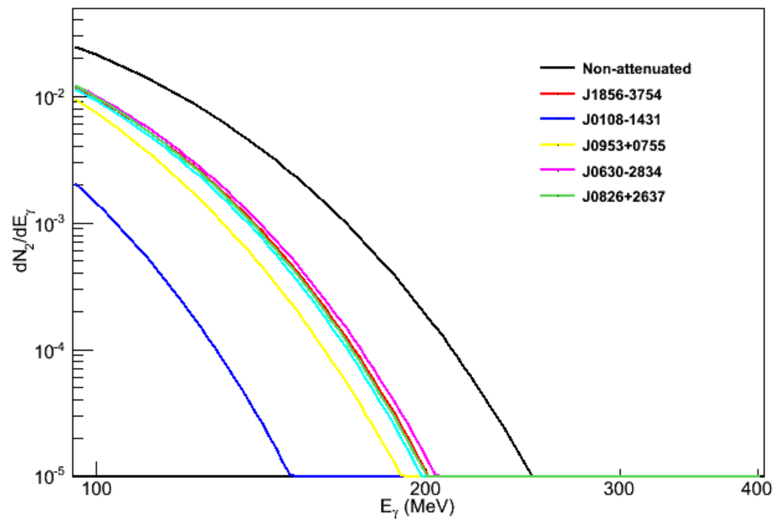
$$\frac{d\Phi_n}{dE} = k_n \left(\frac{d}{\mathrm{kpc}}\right)^{-2} R^n \frac{dN_n}{dE} \quad [\mathrm{cm^{-2}s^{-1}MeV^{-1}}]$$

$$k_n = \frac{1}{4\pi(3.086\times10^{21}\ \mathrm{cm/kpc})^2}(30\mathrm{MeV})^3$$

$$\times(3.17\times10^{-23}\ \mathrm{MeV^{-3}s^{-1}})\left(1.52033\times10^{14}\right)^n$$

$$\times N_{0,n} \times \frac{2}{3}$$

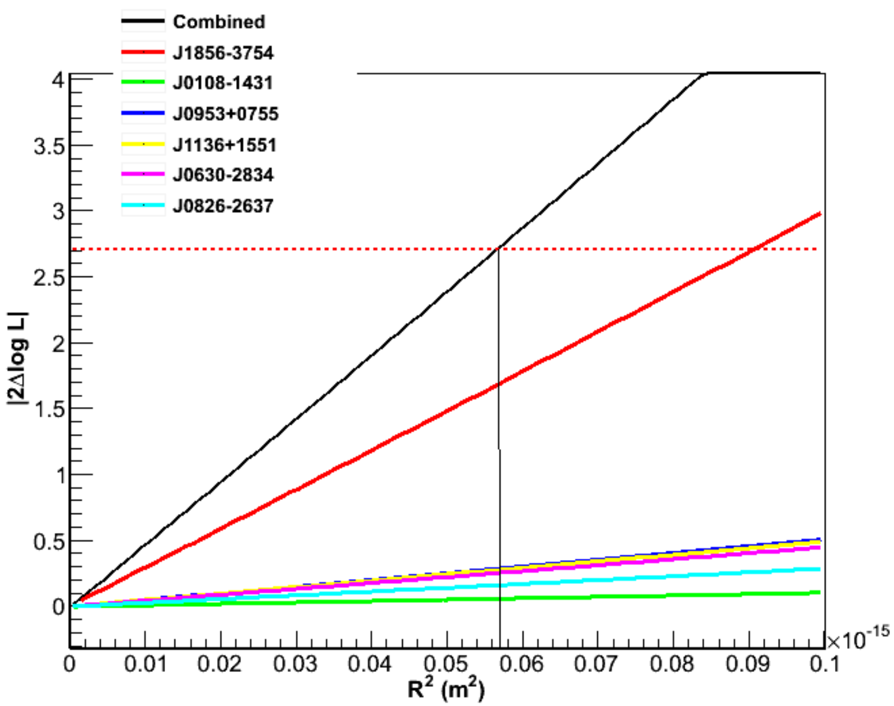
$$T = 30\ \mathrm{MeV}\ [\mathrm{supernova\ \ core\ temperature}]$$



- **For each n, fit this spectrum to the LAT data in each ROI, in 100-400 MeV**

ADD LED Search Interpretation and Conclusions

- **Again, a combined Likelihood can be considered to increase the statistical power : this time it is easy, just a sum of the Likelihood functions :**



Fermi LAT Collaboration, JCAP02(2012)012

n	Fermi -LAT TeV	DØ TeV	CDF TeV	LEP TeV	ATLAS TeV	CMS TeV
2	230	2.09	1.40	1.60	1.5	3.2
3	16	1.94	1.15	1.20	1.1	3.3
4	2.5	1.62	1.04	0.94	1.8	3.4
5	0.70	1.46	0.98	0.77	2.0	3.4
6	0.25	1.36	0.94	0.66	2.0	3.4
7	0.12	1.29	-	-		

95% CL lower limits on *MD* (TeV)

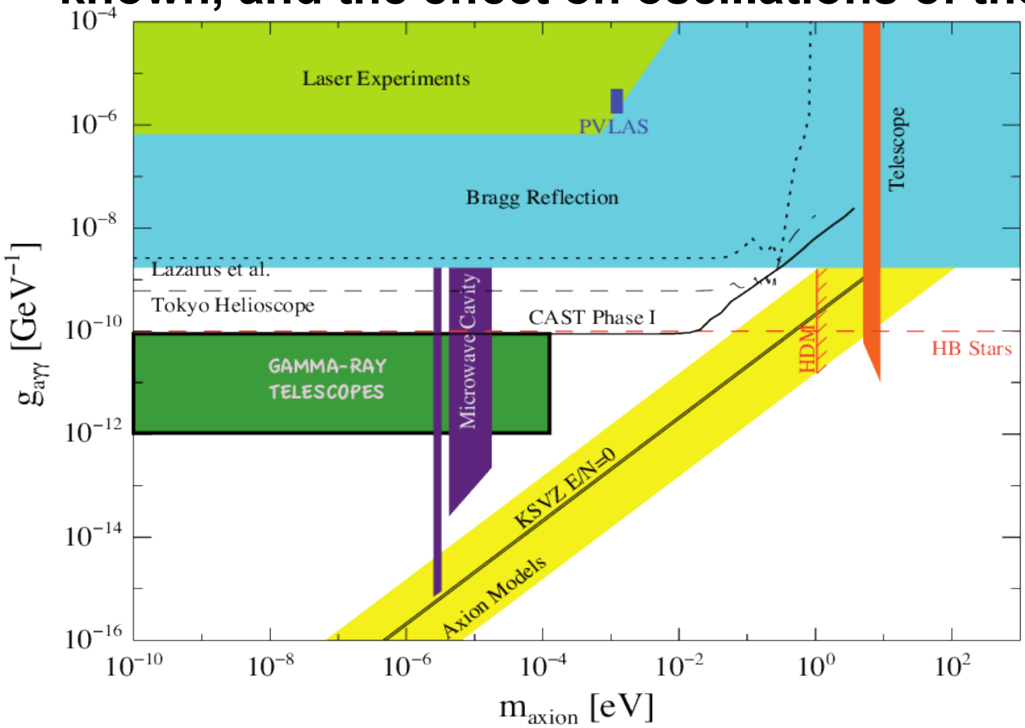
n=2 at 1TeV for toroidal compactification is ruled out

“Astroparticle” topics with the LAT

- WIMP searches
  - Dwarf spheroidals improved analysis
  - A word on the UED motivated LKP
- KK graviton γ-ray emissivity in neutron stars
- “Analysis R&D phase” : axion-like particle distortion of AGN spectra
- The cherry on the cake (sort of....) : Lorentz-invariance tests with GRBs

Axion & Axion-Like Particle Search

- **Axion and axion-like particles (ALP) are another class of very good DM candidates. Masses are <<eV though, and phenomenology is completely different.**
- **In the context of searches with the LAT, the strategy rests on distortion due to photon-alp oscillations during their travel through B_{AGN} and IGMF.**
- **Difficult analysis : AGN are not standard candles! B_{AGN} is not very well known, and the effect on oscillations of the 2 fields are non-trivial**



- **The combined Likelihood is likely to be key to the success of such an analysis**
- **Some sw development needed....**
- **But the parameter space covered by γ-ray experiments is exceedingly hard to cover with other techniques!**

“Astroparticle” topics with the LAT

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- The cherry on the cake (sort of....) : Lorentz-invariance tests with GRBs

Limits on Lorentz Invariance Violation

- **Heuristic modification of the photon dispersion relation :**
  - $c^2 P^2 = E^2 (1+ f(E/E_{QG}))$ E_{QG} : *effective LIV energy scale*
  - For $E \ll E_{QG}$: $c^2 P^2 = E^2 (1+ \alpha(E/E_{QG})^n + O(E/E_{QG})^{n+1})$ $\Longrightarrow$ $v=\delta E/\delta P \sim c (1+ \alpha(E/E_{QG})^n)$
    - n=1 or 2 in current studies
    - α is just a constant (can disappear in E_{QG}), but its sign matters a lot!
      - $\alpha<0$: subluminal regime (high energy photons arrive later)
      - $\alpha>0$: superluminal regime (high energy photons arrive earlier)

- **Simple case : n=1, $\alpha<0$:**
  - Consider a photon of energy E observed at t.
  - If it belongs to the GRB, at the very least it has been emitted *after* the trigger t0.
  - Thus the maximal time delay due to LIV is t-t0 : $\Delta t<t-t0$
  - With a distance estimate, this results in a "conservative" lower limit on E_{QG}
    - Independent of intrinsic time lags in GRBs
    - Subluminal regime is the crucial assumption (less conservative constraints still possible in superluminal regime)

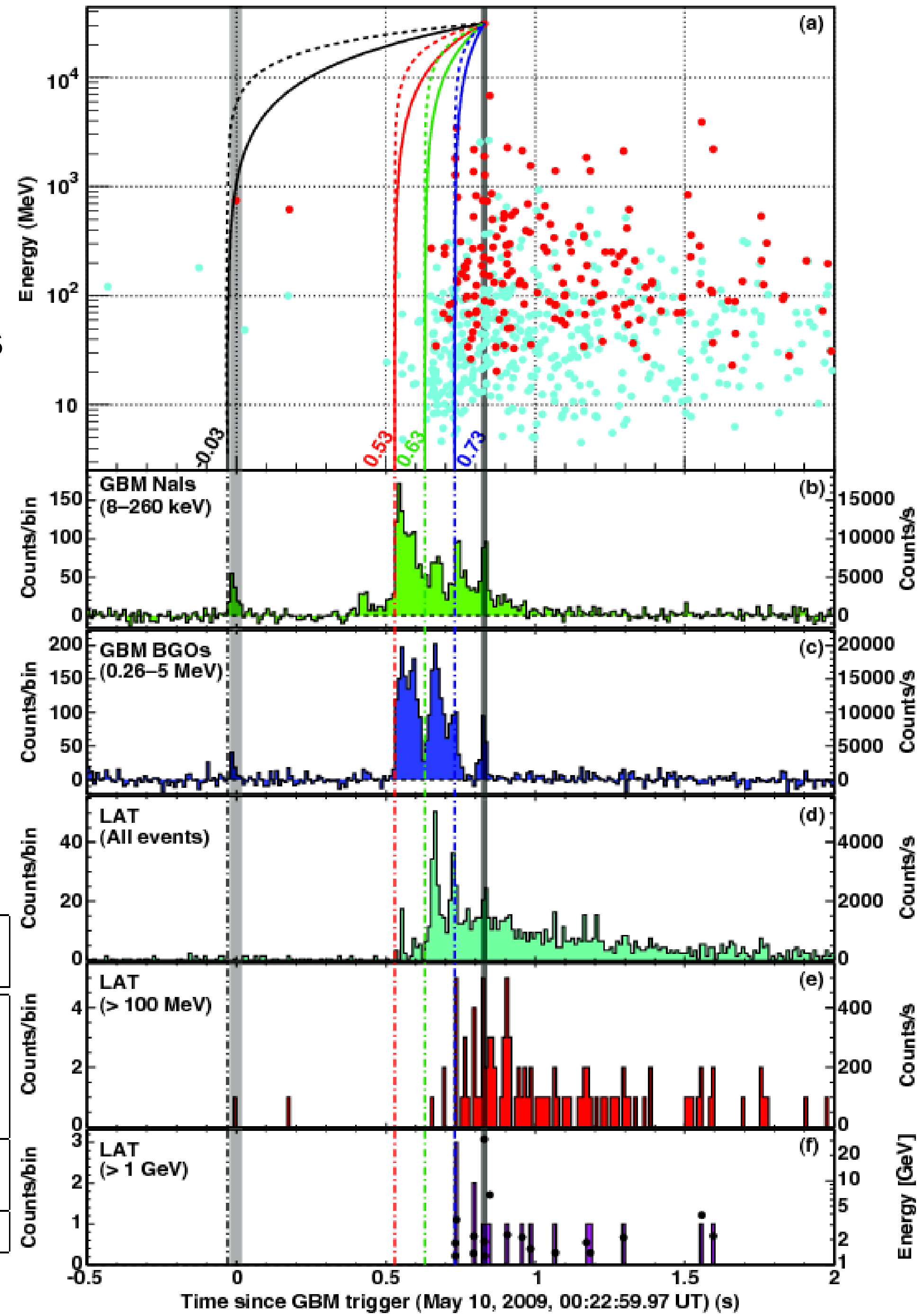
GRB 090510

- **A short bright burst with**
  - **A 31 GeV photon associated**
  - **redshift determination (z~0.9)**
- **allows to set new stringent lower limits on LIV effect in photon time arrival.**

$M_{QG} > 1.19 \times M_{Plank}$

- **If $M_{QG} \sim M_{Planck}$ is expected, *Fermi* starts to disfavor linear effect**
- **Abdo et al., Nature, 462, 331**

$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
-30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start of > 100 MeV emission	100	1	> 5.12
730	< 99	start of > 1 GeV emission	1000	1	> 10.0
—	< 10	association with < 1 MeV spike	0.1	± 1	> 102
—	< 19	if 0.75 GeV γ is from 1$^{\rm st}$ spike	0.1	± 1	> 1.33
$\left\lvert\frac{\Delta t}{\Delta E}\right\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	± 1	> 1.22



Conclusions

- Fermi is in its 4th year of observation.
  - Wealth of scientific results
  - The Fermi LAT (and GBM) data are public, and largely used by the community
  - No indication of early aging or significant decrease of data quality

- In 2013, a Senior Review Committee will decide to extend the 5 year nominal duration of the mission (up to a total of 10 years)

- Fermi has proved to be an excellent astro-particle observatory
  - Many effects in GeV range expected in the gamma-ray sky from models beyond the SM...
  - … because it is a remarkable HEA observatory!
  - And don't expect the next generation soon...

- Hopefully by the end of its life (2018?), we will know what lurks beyond the Standard Model, and what makes up the bulk of Dark Matter