The Abdus Salam
International Centre for Theoretical Physics

United Nations
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IAEA
International Atomic Energy Agency

2246-13

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Dark matter searches with Fermi

Vincenzo VITALE
Universita' di Roma 2
Italy

Dark Matter Searches with Fermi

Abel 1689. Credit: NASA, ESA, E. Jullo (Jet Propulsion Laboratory), P. Natarajan (Yale University), and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille, CNRS, France)

Vincenzo Vitale for the Fermi-LAT Collaboration
INFN Roma Tor Vergata

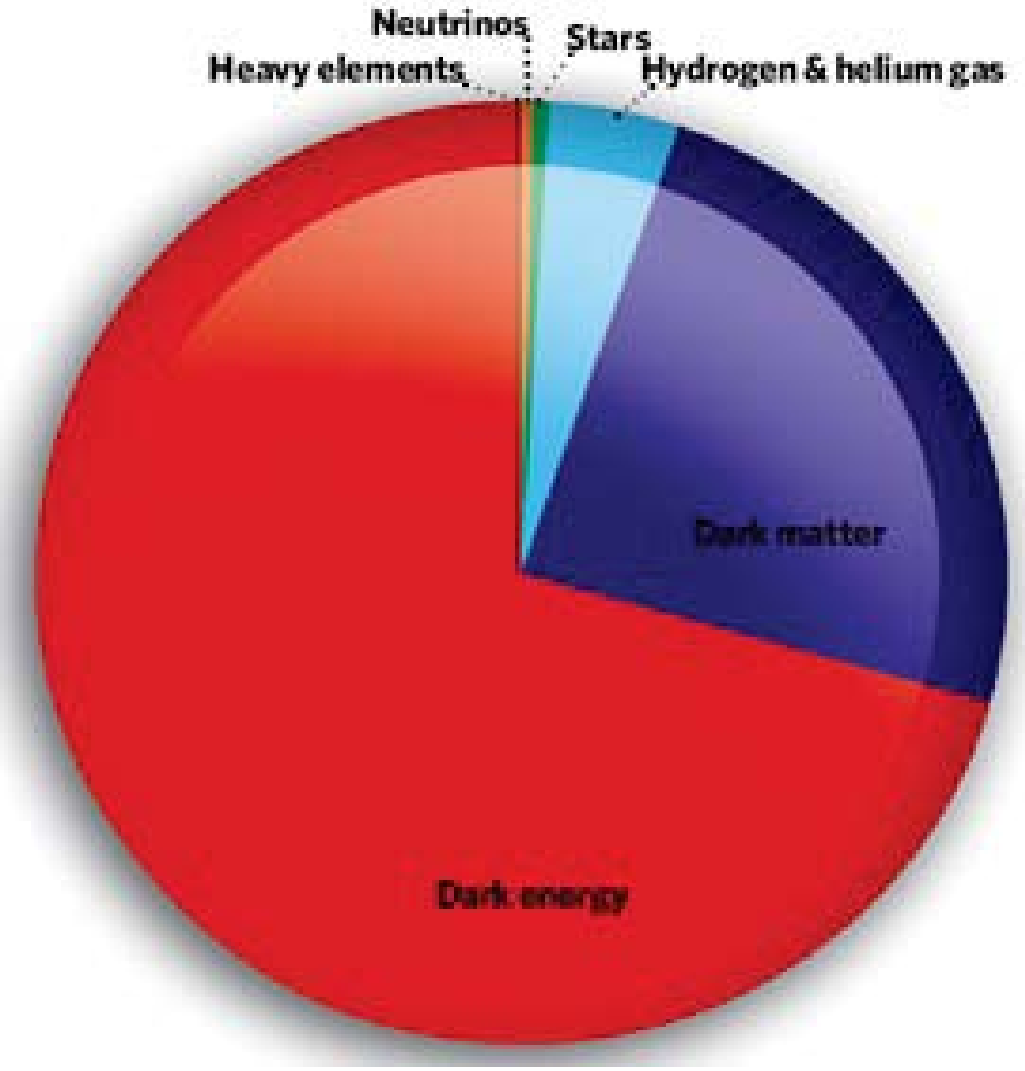
I -Testing the WIMP Hypothesis with Indirect Searches in Gamma Rays

WIMPS
Fluxes
Spectra
DM Distribution

Vincenzo Vitale, NUSKY 2011, ICPT Trieste, Italy

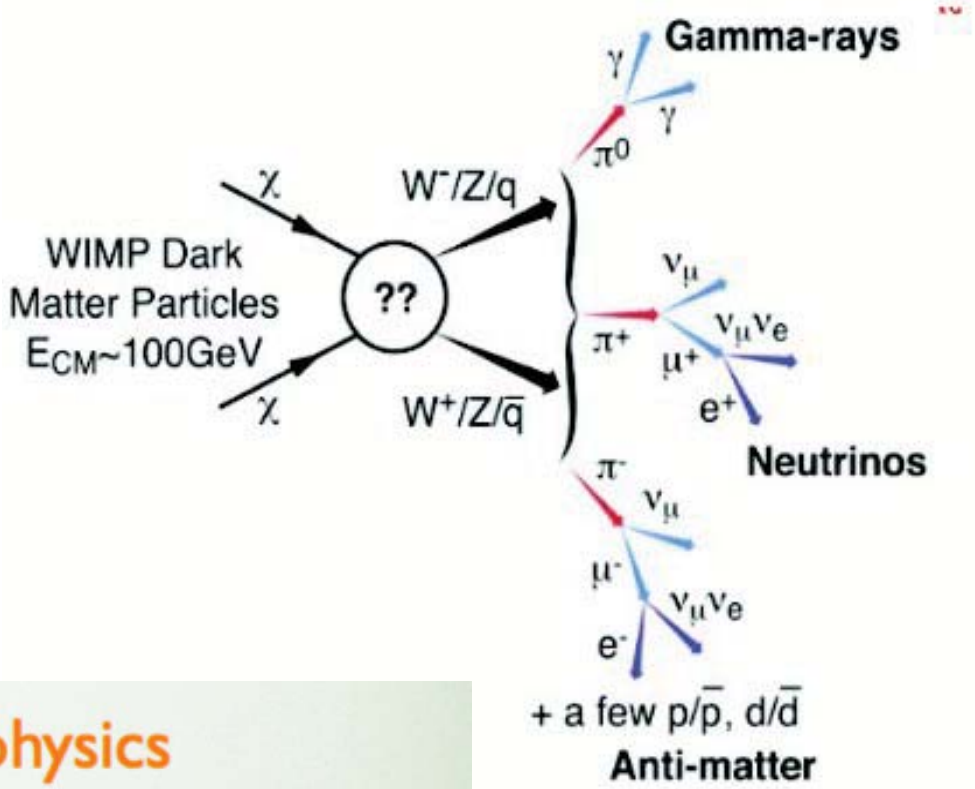
The WIMP hypothesis

- Dark Matter **required** by LambdaCDM Cosmology, Grav. Lensing, Cel. Dynamics
- **Beyond Standard Model physics** required
- **"natural" candidates at the weak scale** in several theories models (Super-symmetry, Universal Extra Dimensions, etc.), among others
- **WIMPs**, with EW properties, typical mass ~ 100 GeV and relic density thermally produced with cross-section $\langle\sigma v\rangle \sim 3\times10^{-26}$ $cm^3 s$



Indirect Dark Matter Fluxes

- DM particles annihilation or decay allow us to perform **Indirect Searches** in neutral and charged channels
- The neutral ones have (i) simpler propagation, (ii) **both spectral and spatial signatures**
- Expected flux typically factorized as Particle Physics factor and DM density distribution



particle physics

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

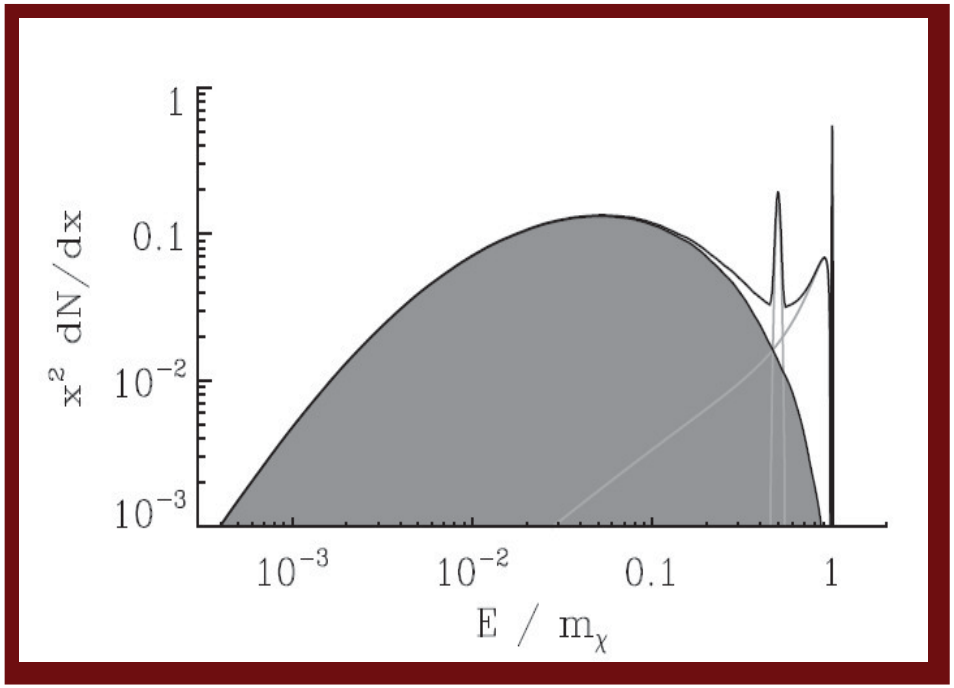
DM distribution

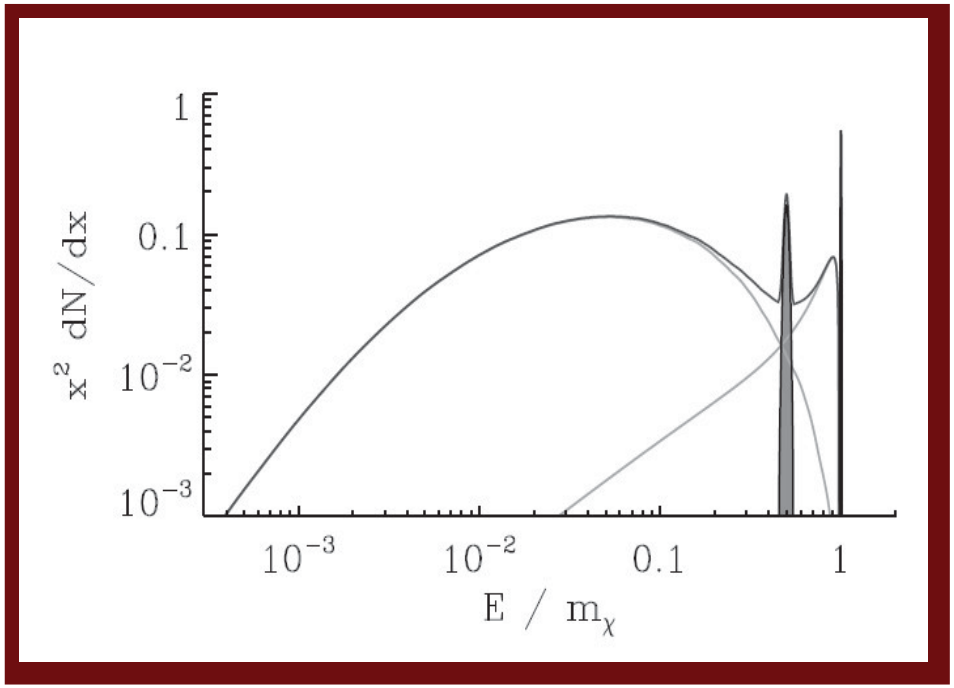
Here only annihilation considered

Gamma-ray Emission Spectra

- Choice of the particle physics model fixes final states and spectrum
- In general no simple power law spectra
- b-bbar spetrum good proxy for hadronic channels (quarks and gauge bosons)
- Annihilation line *"smoking-gun"* signature, but O(10-3 / 10-4) suppressed

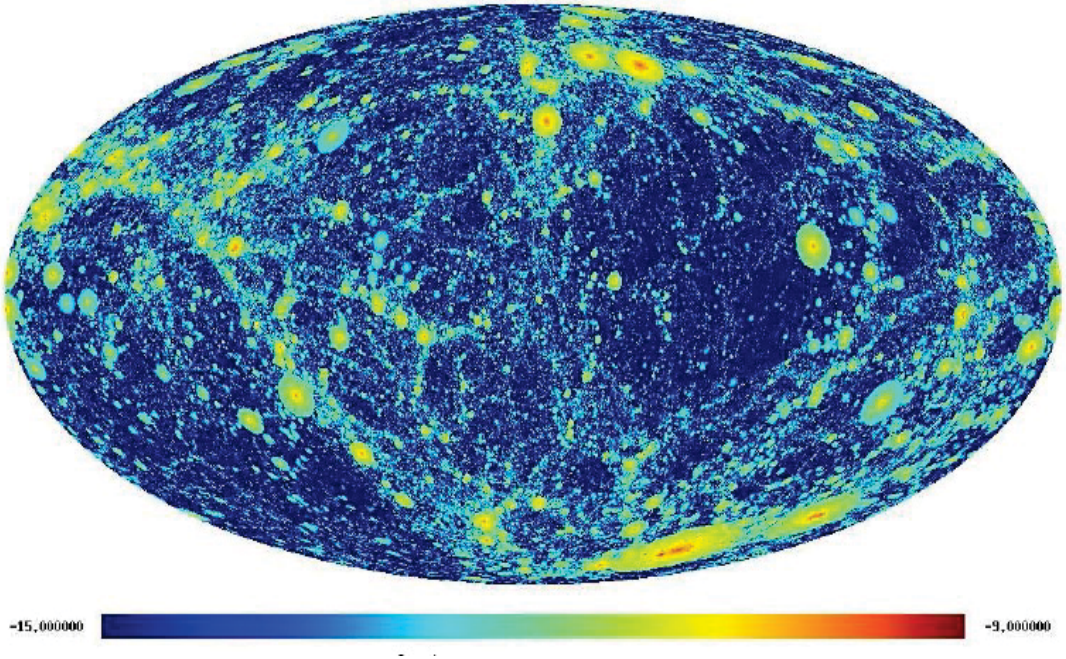
Figures: Michael Kuhlen, Adv. in Astron. 2010





Dark Matter Distribution

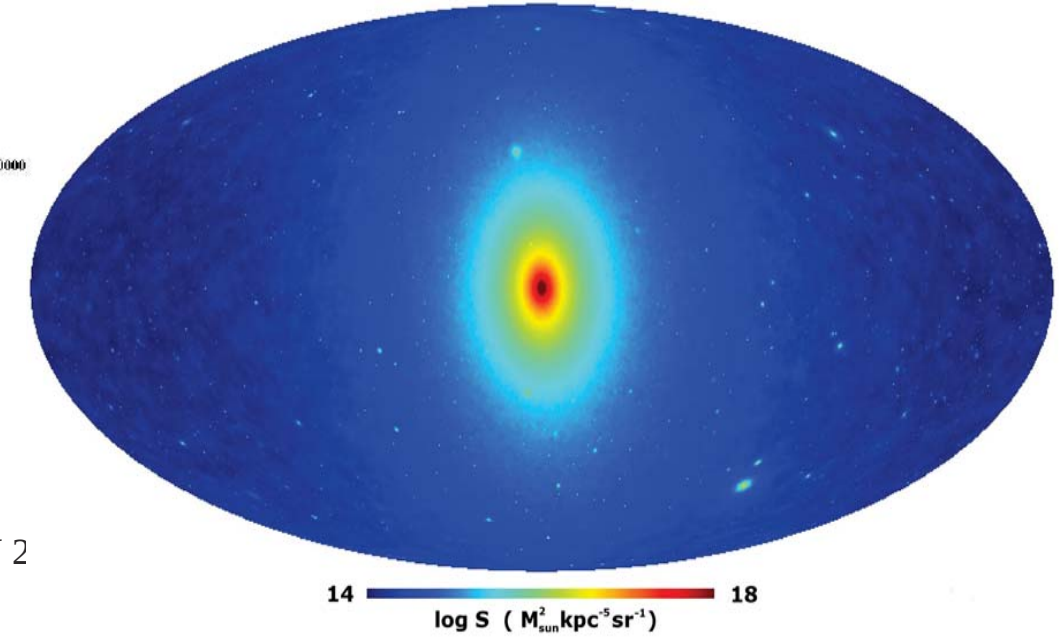
- Large **DM halos** with sub-structures and a possible central density cusps
- Milky Way embedded in a DM halo
- The MW DM halo foreseen to have several associated sub-structures...
- ... and web of extra-galactic DM structures foreseen by n-body simulations



Springel at al. NATURE 456, 44,
simulated gamma emission from annih. DM in the Milky Way

Gamma-ray emission in cm-2 s-1 from an annihilating DM particle with a mass of 200 GeV. Only halos and subhalos at z=0 of the Millennium-II N-body simulation are considered.

From Fornasa et al, 2011 in prep.

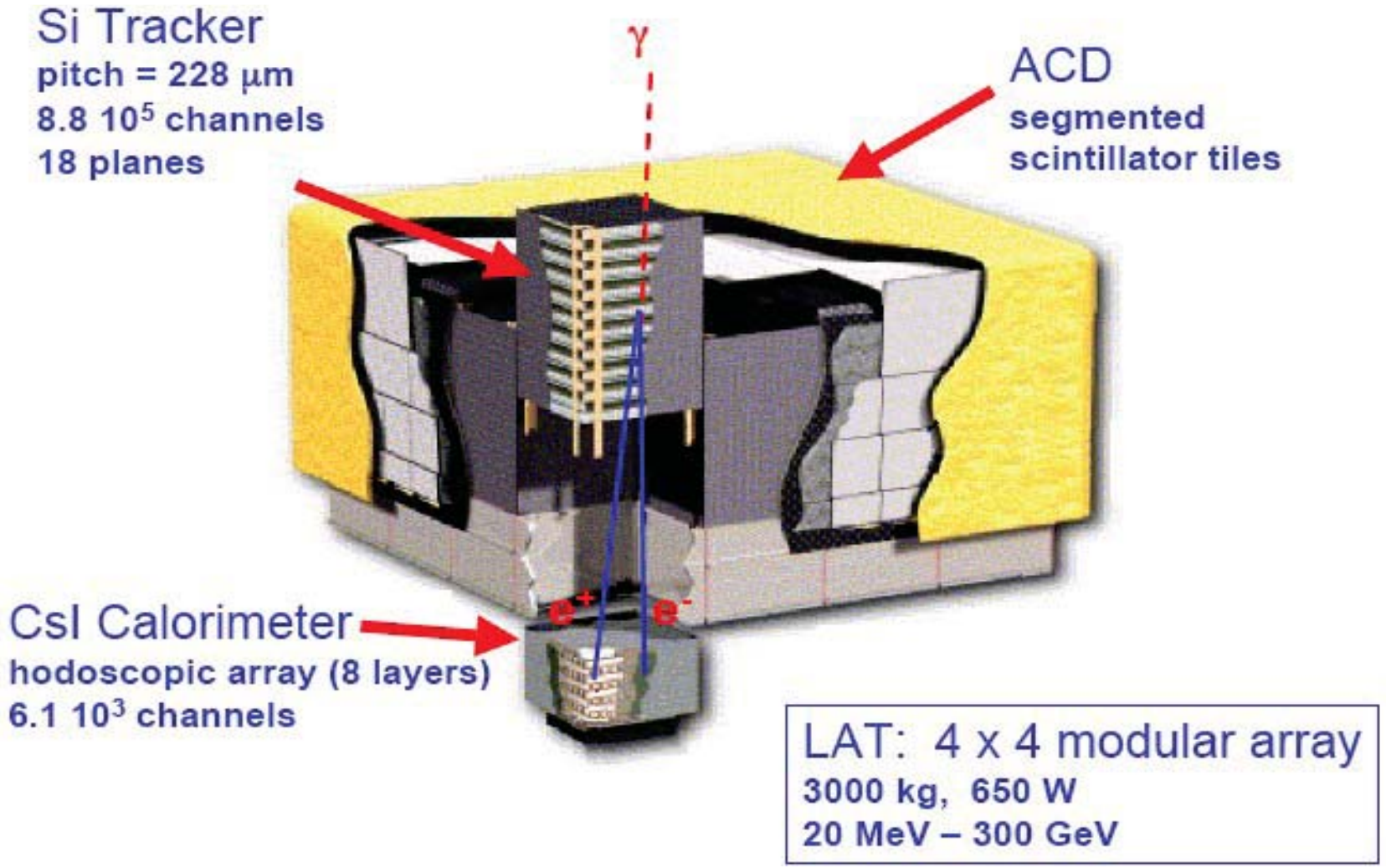


II -Experimental Techniques gamma rays from the space (and some charged particles)

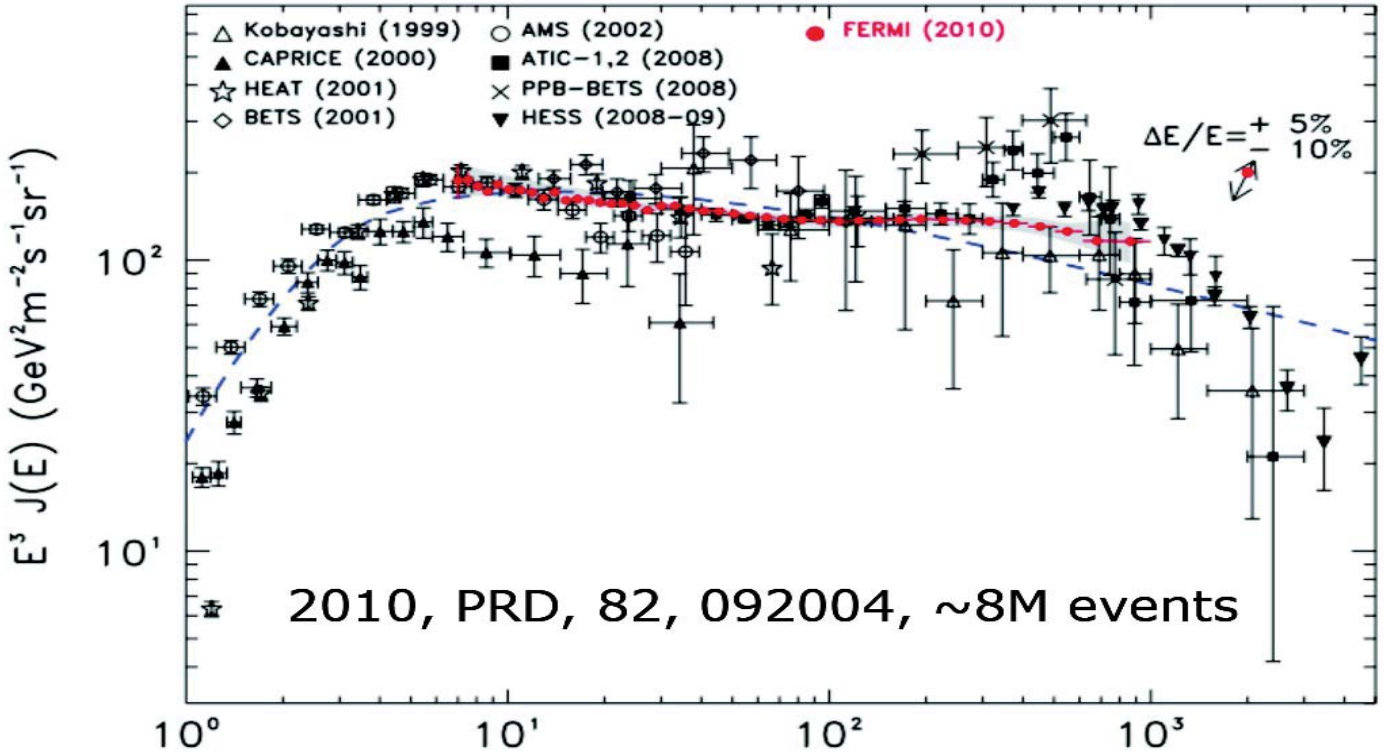
Gamma Rays from Space
Cosmic Rays with the LAT
Backup slides
Electron anisotropies

Gamma Rays from Space

The Large Area Telescope

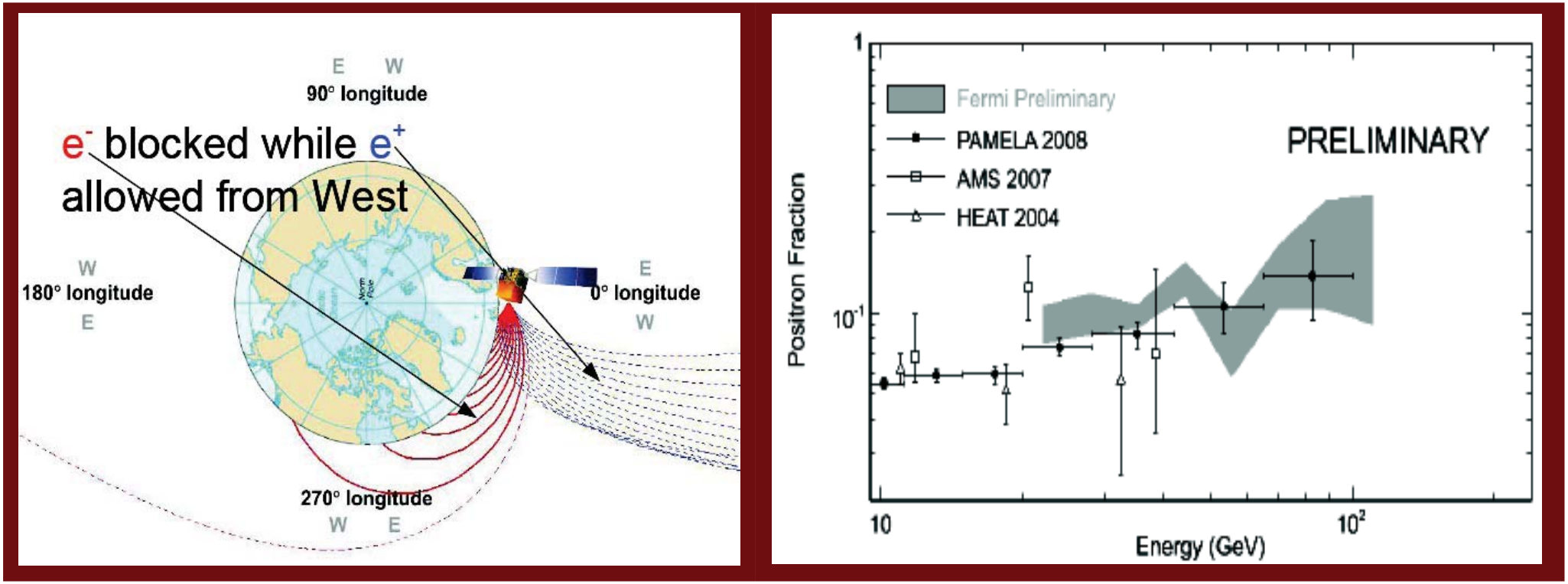


Charged Cosmic Rays electrons



- Spectrometers (PAMELA, AMS2) vs **Calorimeters** (ATIC, FERMI, IACTs)
- Statistics driven by ~size (acceptance), integrated livetime
- Inclusive spectrum e+ e- spectrum is hard with no strong features (a TeV cutoff seen by HESS)
- CRE Anisotropies (Fermi) exclude single local astrophysical source (no dipole, but leave room for DM)

Charged Cosmic Rays (II)



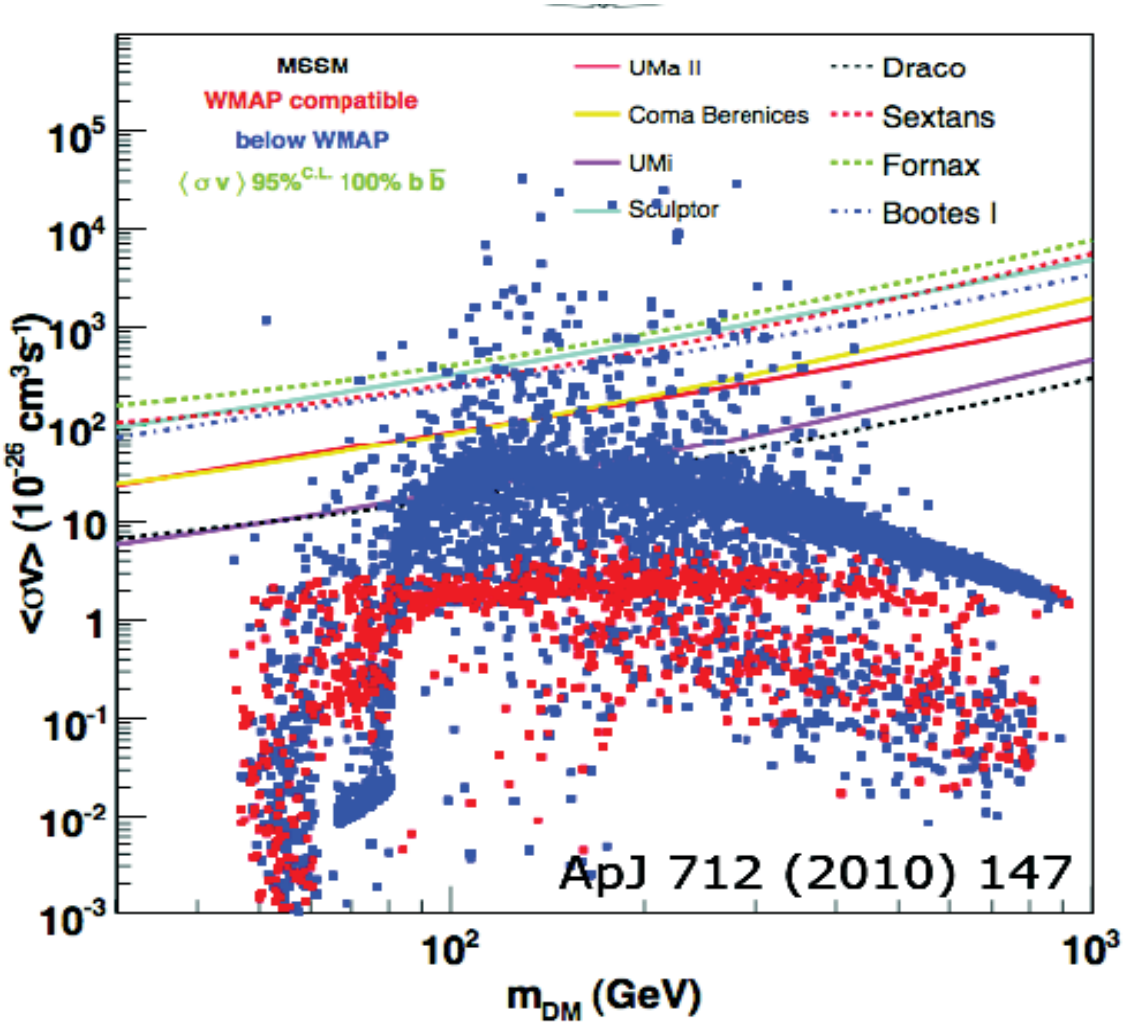
- The Fermi-LAT measured the cosmic-ray positron and electron spectra separately, between 20 – 130 GeV, using the Earth's magnetic field as a charge discriminator
- The two independent methods of background subtraction, Fit-Based and MC-Based, produce consistent results
- The observed positron fraction is **consistent with** the one measured by **PAMELA** (e.g. rising and at odd with standard production of secondariesand anti-proton spectrum)

III – Current Fermi/LAT Results

Point Sources
Extended Sources
Diffuse Emission
(backup slides)
Unidentified Sources
The Galactic Halo

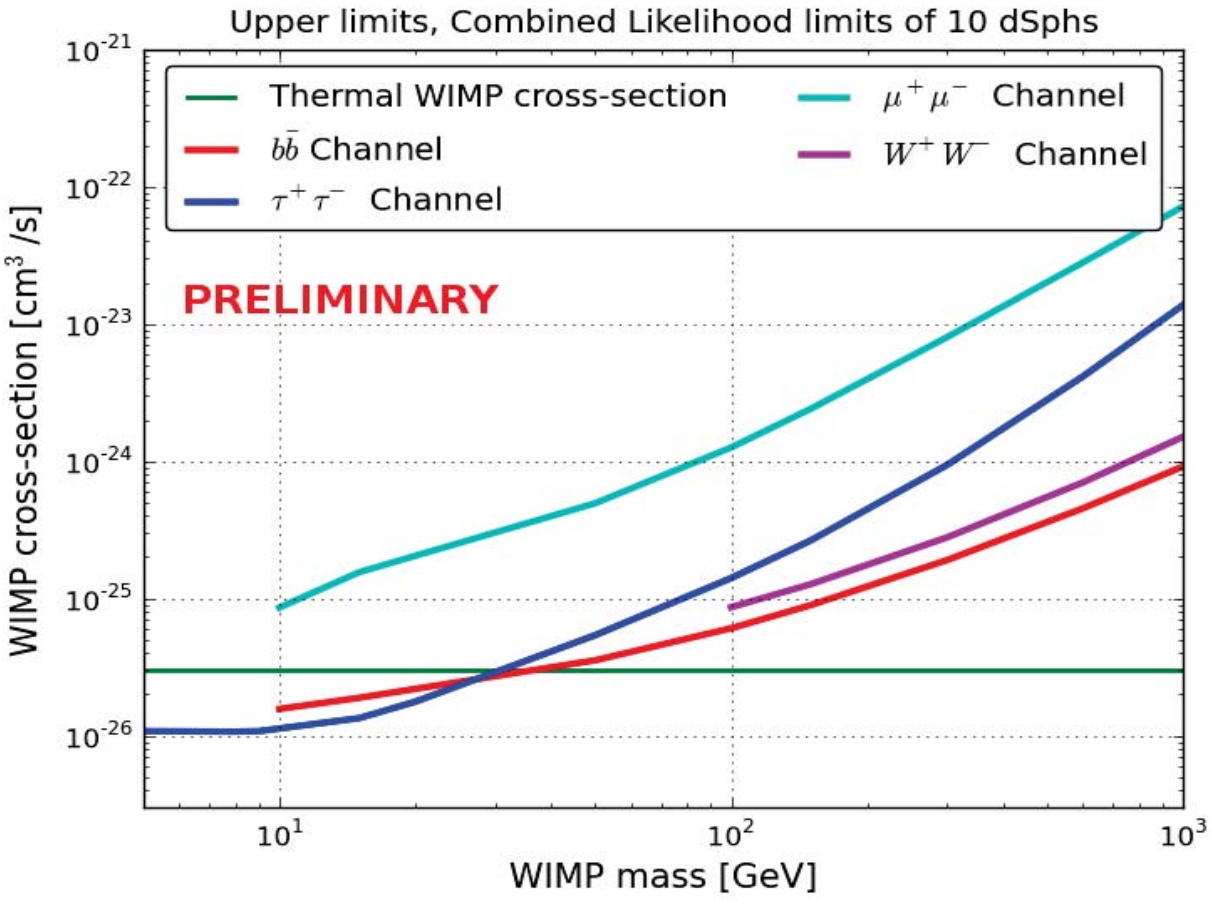
Dwarf Spheroidal Galaxies

- dSph are DM dominated systems (M/L up to 100-1000).
- Many dSphs closer than 100 kpc to the Galactic Centre.
- **Cleanest known target**
- Foreseen gamma-ray flux from DM dependent on the DM distribution
- U.L. on DM annihilation
- Previous results already close to cross-sections foreseen by some minimal super-symmetric extension of the Standard Model

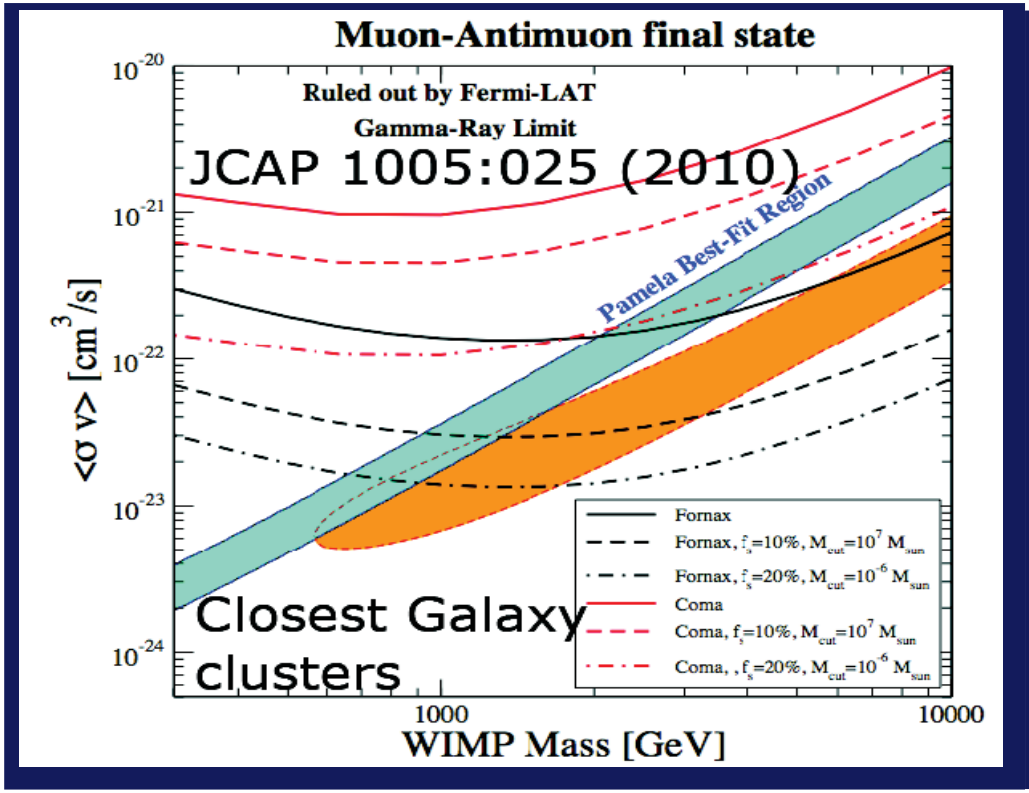


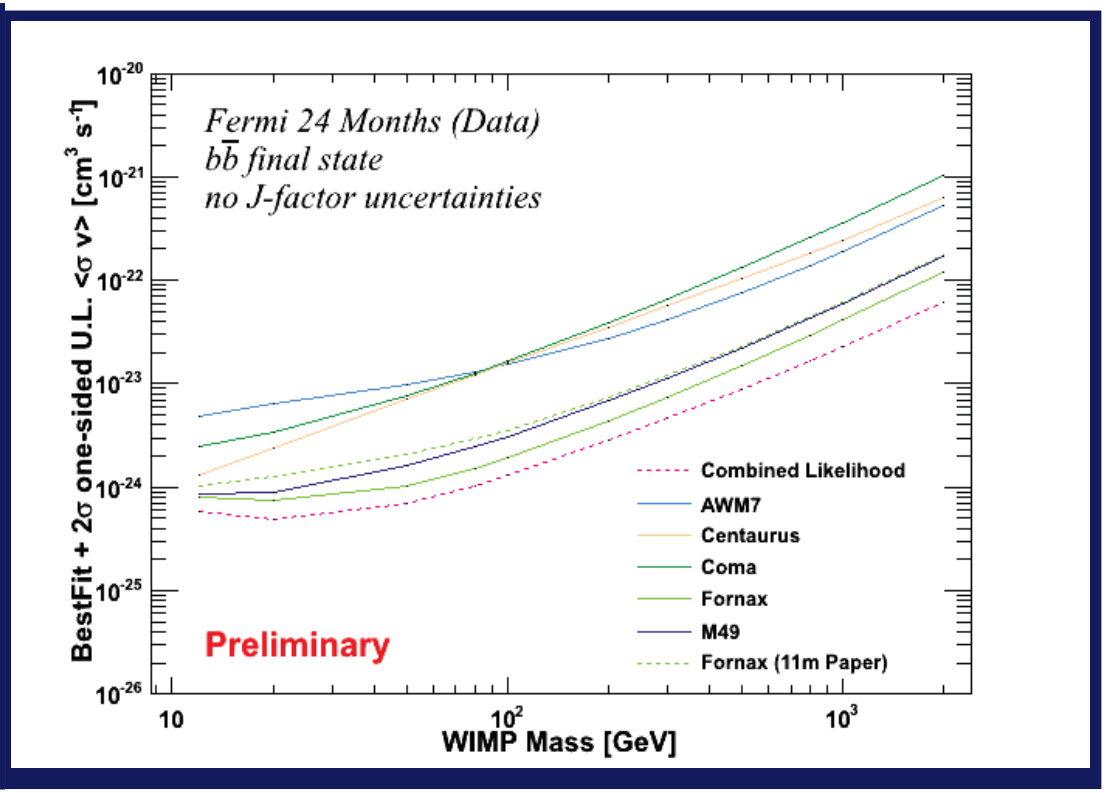
Dwarf Spheroidal Galaxies

- **Combined likelihood approach** within ST to derive combined upper limits for 10 dSphs.
- The dSphs are first individually fitted and then added to the combined fit, where the DM is fitted as a common parameter. Backgrounds and surrounding sources are fitted individually within the combined fit.
- **J-factor uncertainties** included
- The limits cut into the thermal WIMP regime for: bb and τ+τ- channels for WIMP < 30 GeV



Galaxy Clusters

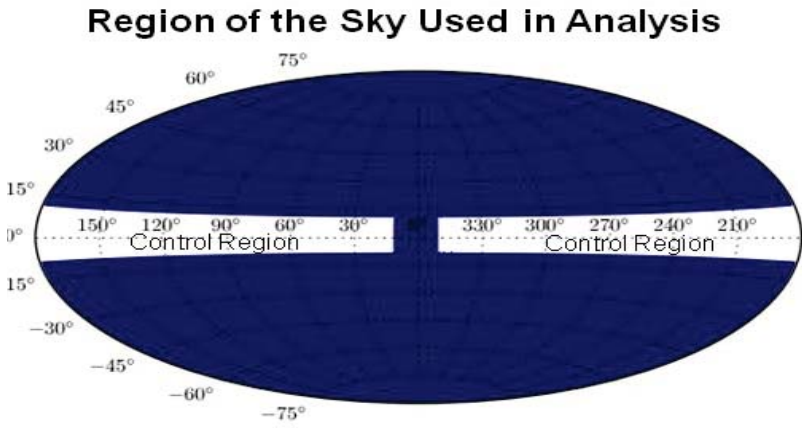


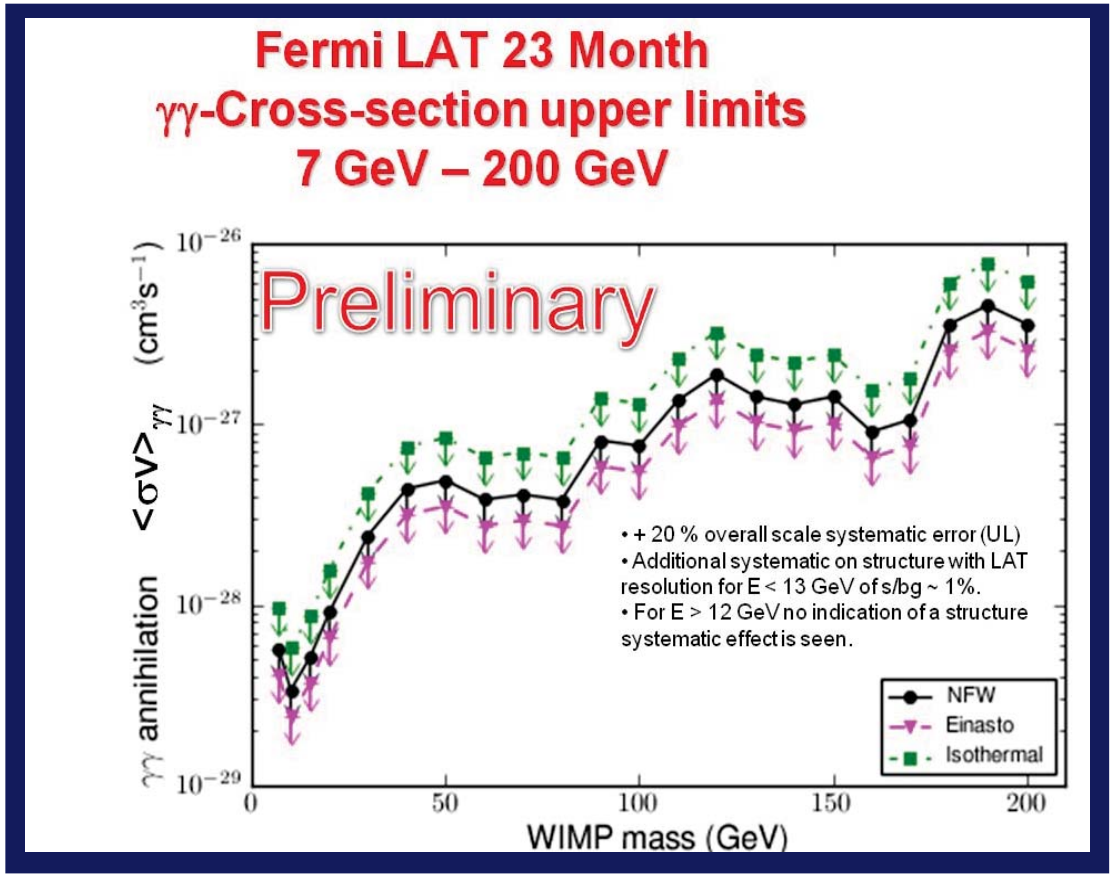


- U.L. on **DM annihilation or decay** (decay limits not shown here)
- Previous results **results disfavor lepto-philic DM** from CRE excesses
- New Combined likelihood analysis
- Energy between 200 MeV - 100 GeV (20 energy bins), P6v11 IRFs.
- All 1FGL sources within circle 15 degrees considered (fit of normalization parameter for those within 5 deg
- Uncertainties in the J-factors NOT included

All-Sky Line Search

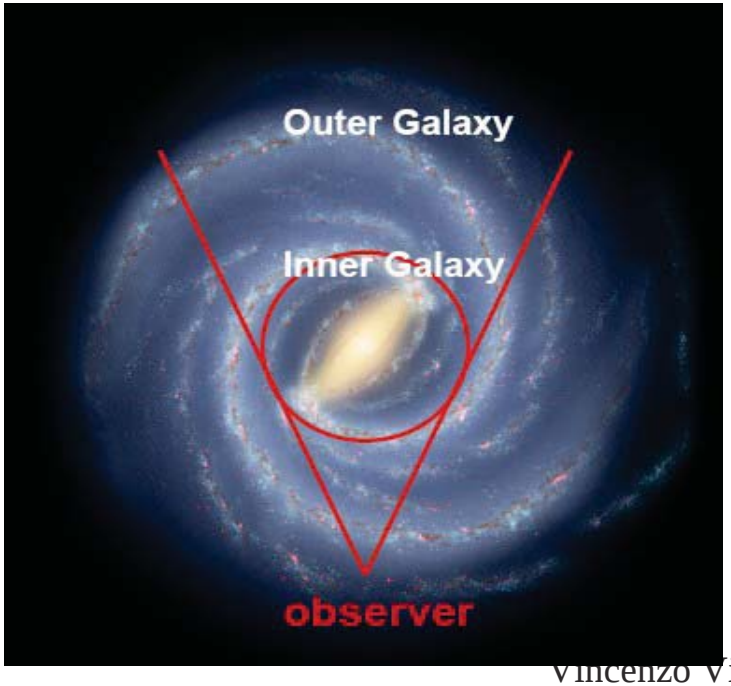
- Data extracted from a large fraction of the sky, the galactic plane used as control region
- No line feature detected from 7 to 200 GeV
- Spurious effects (CTBCORE) in the Pass 6v3 solved with the new Pass 7
- U.L. Constrain some scenarios (Higgs in space, some Gravitino decay, npn thermal WIMPs)

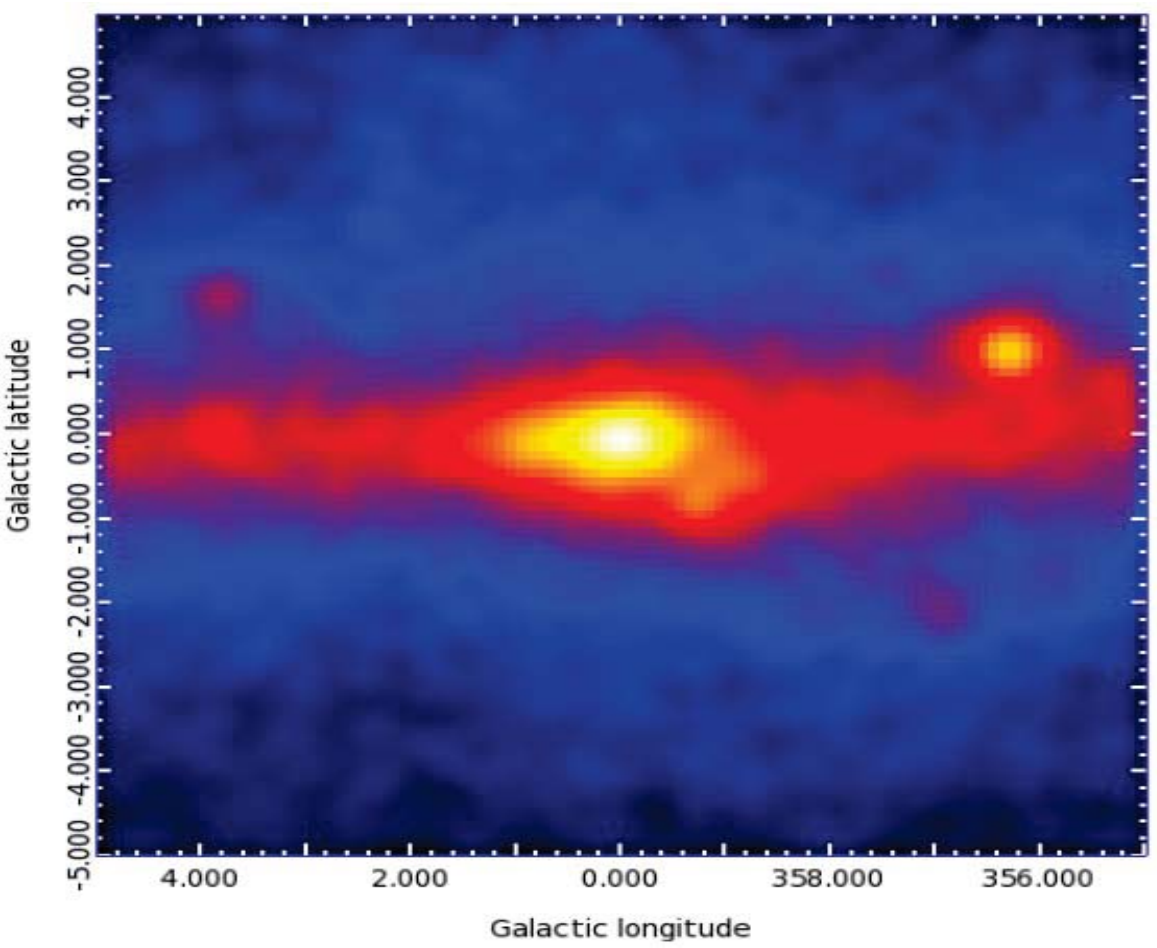




The Inner Galaxy

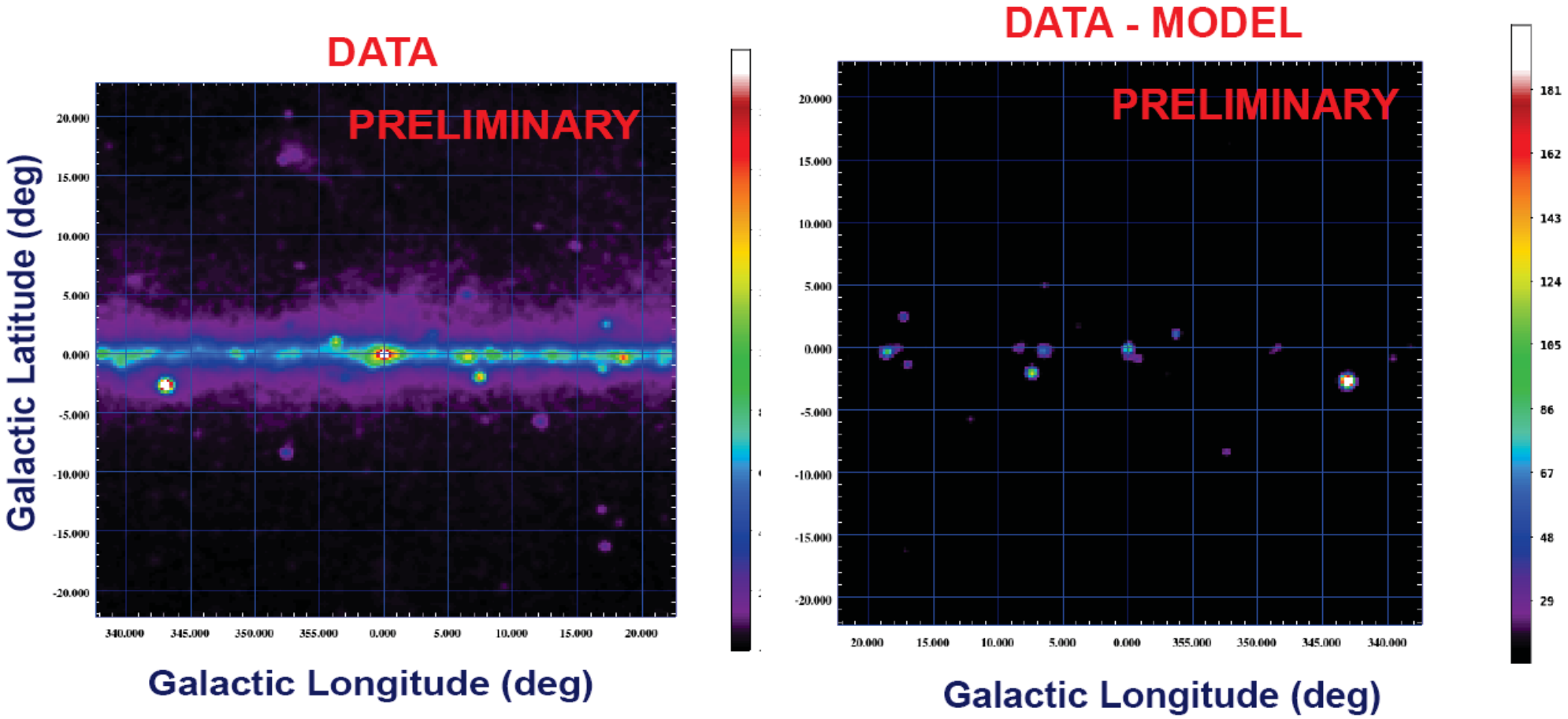
- The Milky Way centre *might* be (according to N-body simulations) the **brightest dark matter gamma-ray source**
- The region hosts a large number of sources (and possibly many unresolved ones)
- Diffuse gamma emission from interaction of cosmic rays with the interstellar gas and radiation fields: **(i) Inverse Compton**; (ii) Bremmstrahlung; **(iii) neutral pions decay**
- Diffuse emission coming from the from: (1) Outer galaxy, (2)True inner galaxy; (3) possible unresolved sources





The Inner Galaxy (II)

- Currently work in progress for modelling the the diffuse emission in the Inner Galaxy region (45X45deg) with physically-motivated model based on GALPROP
- In the residual emission (data – diffuse model) maps the bright known sources are visible
- Work in progress to characterise the low-level residual structures and point sources
- Possible to find combination of diffuse model + sources that describe the innermost region with relatively flat residuals
- Forthcoming paper(s) will describe the method and results in detail



III – Anisotropies in the Diffuse Emission

Angular Power Spectrum
The Analysis Results
(backup slides)
Measurement of the IGRB
Milky Way Lobes/Bubbles
Intensity Maps
APS from Sources

Angular Power Spectrum (APS)

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

L.Knox
1995PhRvD..52.4307K

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

$$\delta C_\ell^{\rm s} = \sqrt{\frac{2}{(2\ell+1)\,\Delta\ell\, f_{\rm sky}}} \left(C_\ell^{\rm s} + \frac{C_{\rm N}}{W_\ell^2} \right)$$

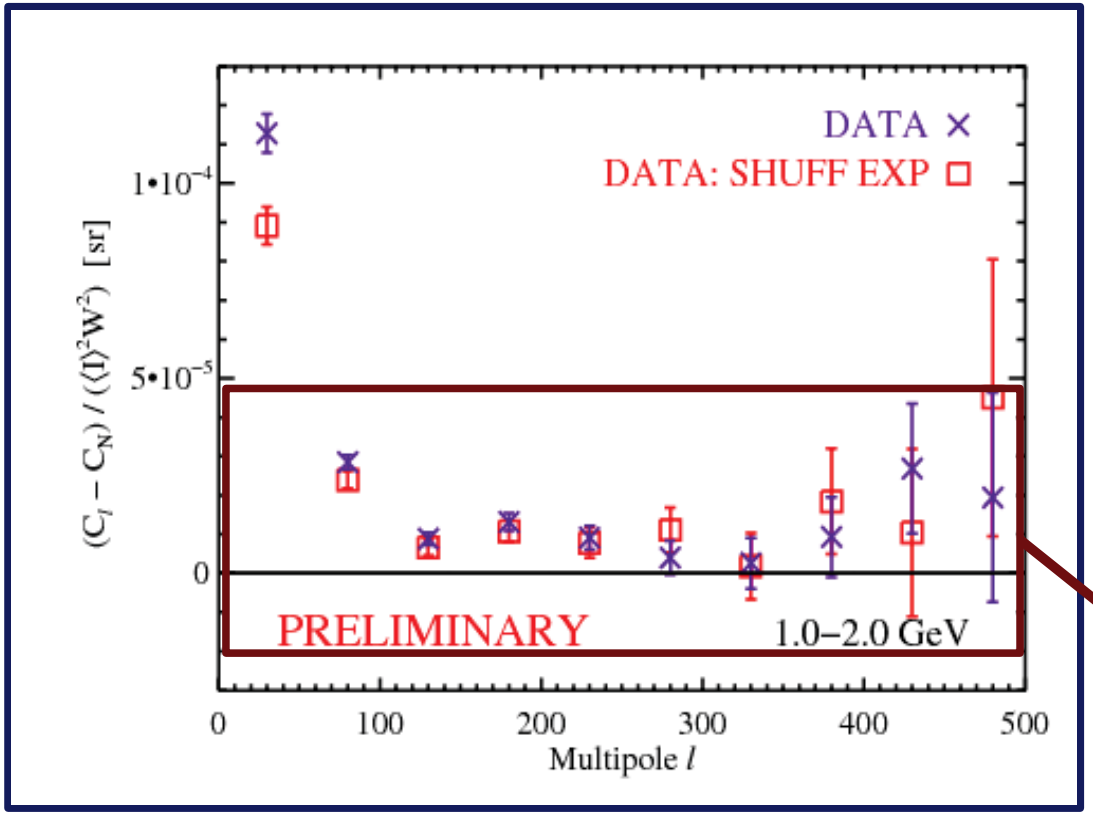
- A diffuse background can be built by the sum of a **large number of un-resolved faint sources** (possibly **DM Halos and sub-structures**, for example)
- Fluctuations from source populations can be identified, if different from the Poisson noise ones;
- the energy-dependence of the anisotropy can reveal/constrain multiple population
- Diffuse emission fluctuations can be studied with spher. harmonics expansions
- **C_l = intensity APS** : indicates dimensionful amplitude of anisotropy
- **C_l / $< I >^2$ = fluctuation APS**: dimensionless, independent of intensity normalization,

with **f_{sky}** = un-masked fraction of the sky, **W_l**=window function; **Δl** =multipole bin, **C_n** = noise angular power;

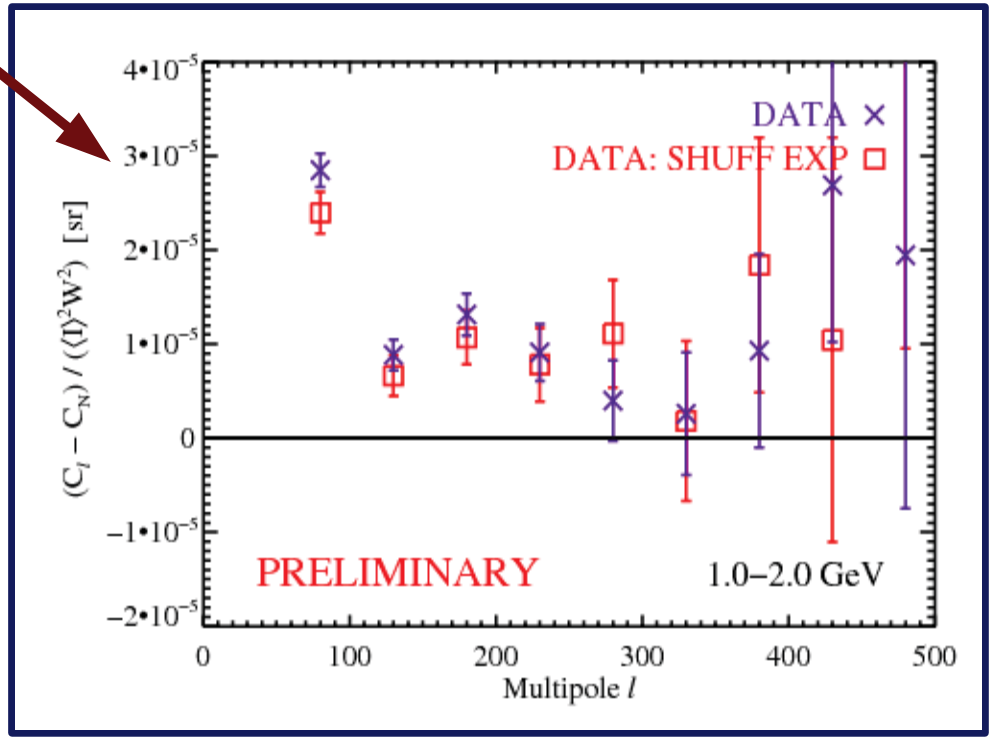
Studying Anisotropy in the IRGB

- **Fermi/LAT** all-sky observations from the first 22 months of operation
- The APS of the data are obtained from binned **Intensity maps**;
- **HEALPix** (Gorski et al 2005) used;
- Known sources and Galactic diff. em. minimized with **masking**;
- In the main analysis branch gtools were used for the exposure maps calc.
- An independent method (**Shuffling**) used to cross-check the exposure calculation effects;
- APS of real data and detailed **all-sky simulations** have been obtained and compared;
- A **Foreground Cleaning** has been used to estimate the possible effects of residual Galactic diffuse emission

APS of the Data

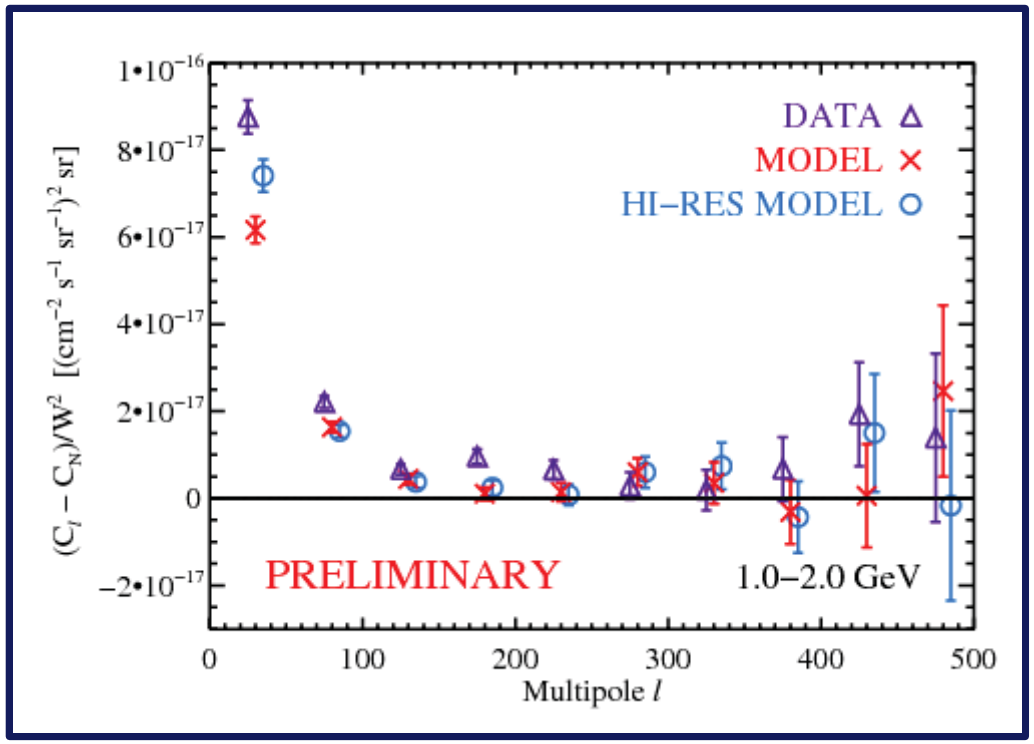


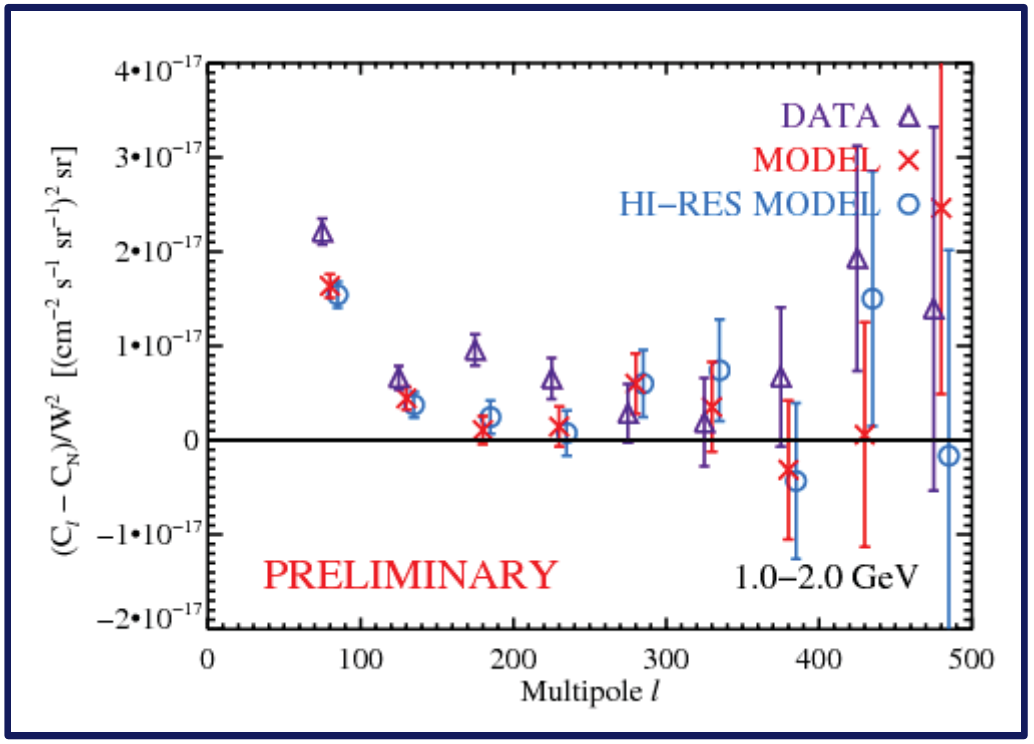
- For multipoles < 100 excess of angular power likely coming from the Galactic diffuse background
- For multipoles > 150 an excess of angular power is detected



measurement uncertainties: indicate 1-sigma statistical uncertainty, systematic uncertainty not included

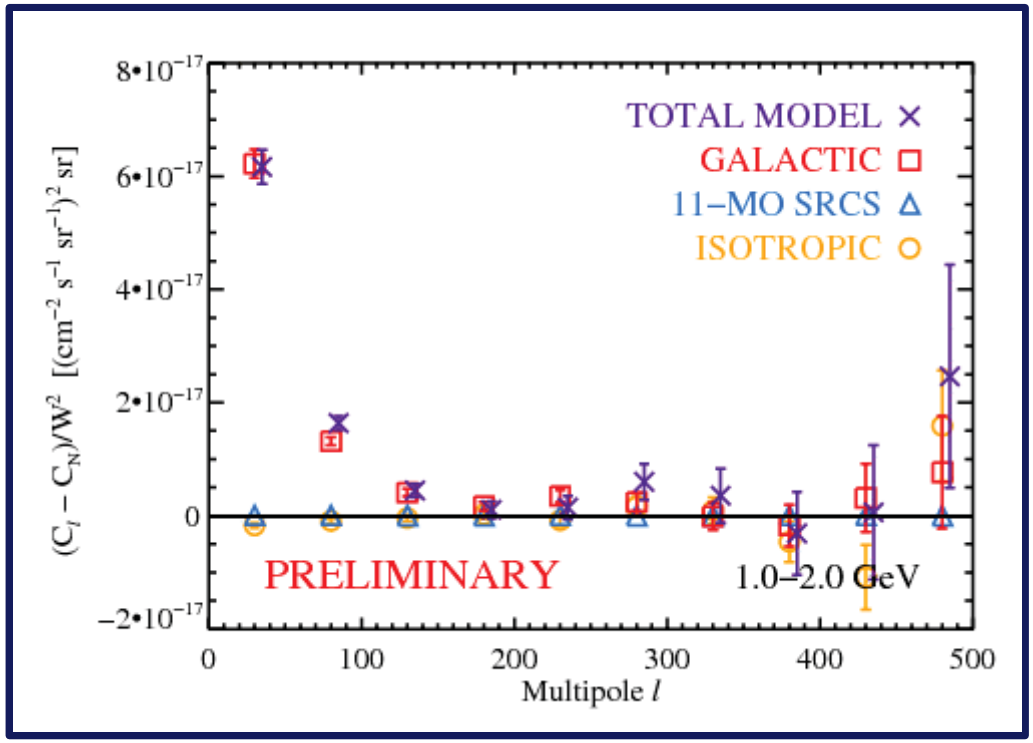
Simulated Sky Comparison (i)

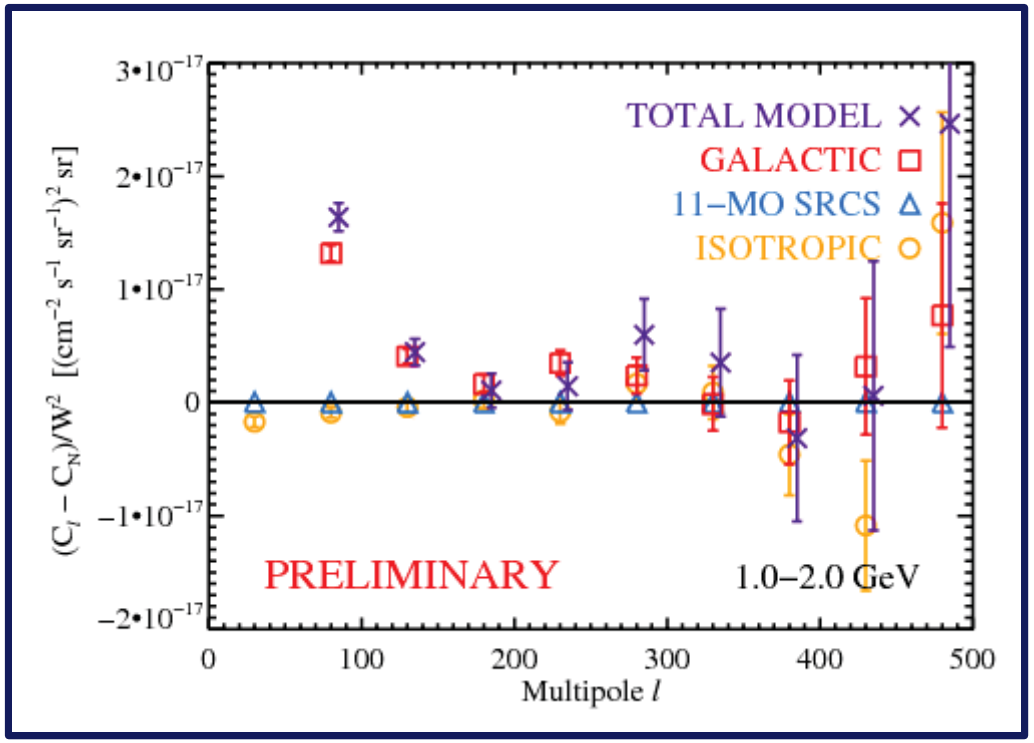




- All-sky simulations APS compared to real data ones
- Simulated: 1FGL sources (1451), Galactic diffuse emission (the standard gll_iem_v02.fit at 0.5deg resolution and a version at 0.125deg resolution), Isotropic diffuse emission;
- Other energy bins in backup slides

Simulated Sky Comparison(ii)





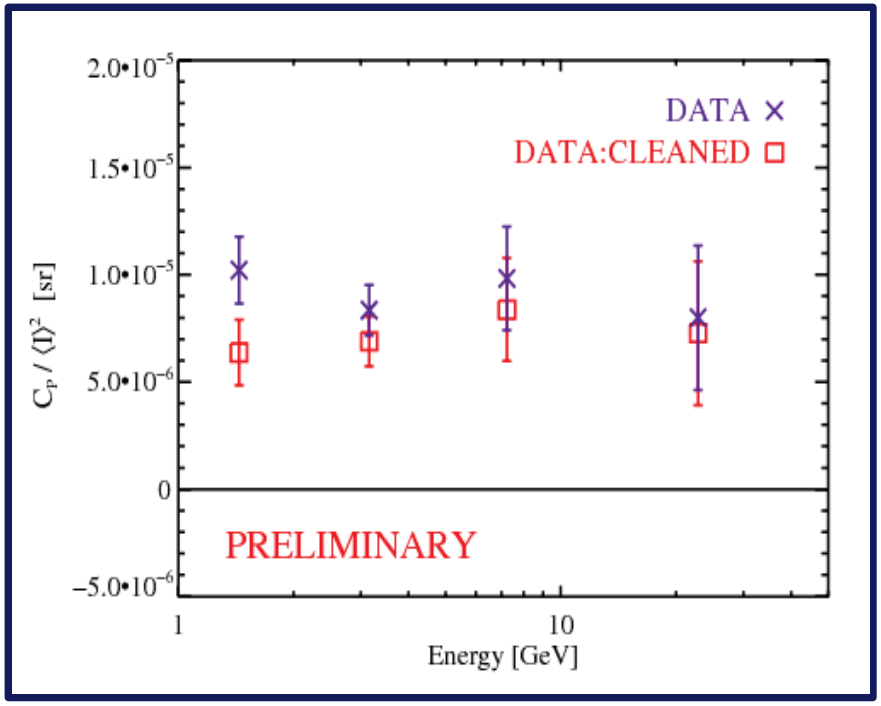
- Galactic diff. Model shows low multipole (l<100) excess
- Isotropic diffuse and sources follow expected behaviour
- Other energy bins in backup slides

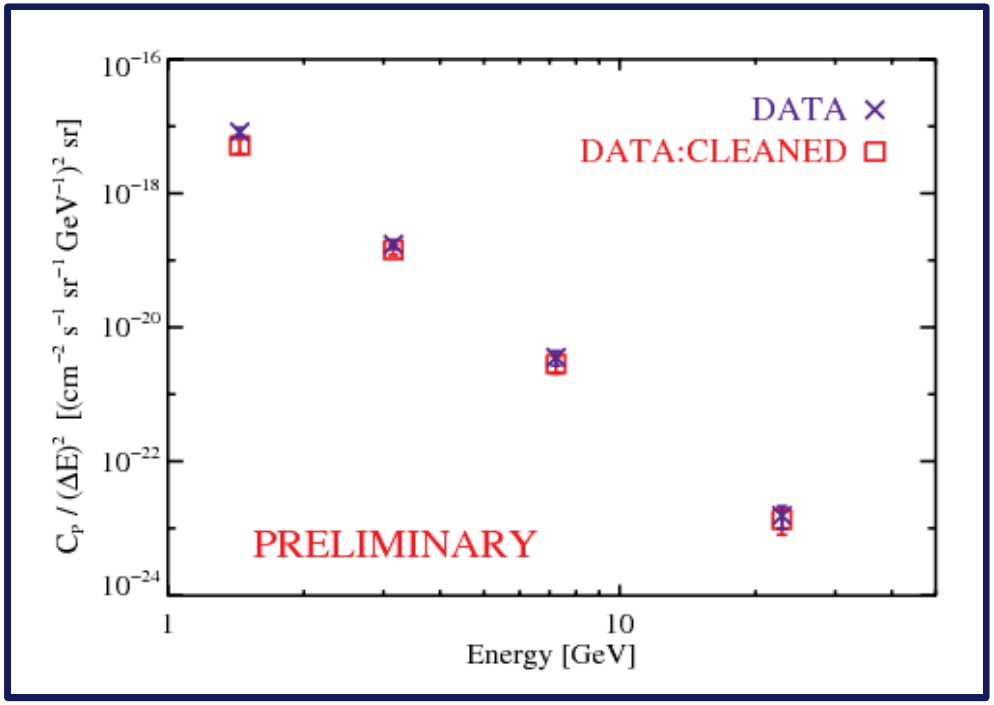
Angular Power in the Data

$E_{\rm min}$ [GeV]	$E_{\rm max}$ [GeV]	$C_{\rm P}$ $[({\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1})^2\ {\rm sr}]$	Significance	$C_{\rm P}/\langle I\rangle^2$ $[10^{-6}\ {\rm sr}]$
1.04	1.99	$7.39 \pm 1.14 \times 10^{-18}$	6.5σ	10.2 ± 1.6
1.99	5.00	$1.57 \pm 0.22 \times 10^{-18}$	7.2σ	8.35 ± 1.17
5.00	10.4	$1.06 \pm 0.26 \times 10^{-19}$	4.1σ	9.83 ± 2.42
10.4	50.0	$2.44 \pm 0.92 \times 10^{-20}$	2.7σ	8.00 ± 3.37

- Angular power detect with high significance up to 10GeV, and with a lower one at larger energies;
- Fluctuation angular power of 10^{-5} sr in the range predicted for astrophysical source classes and some DM scenarios

Energy Dependence of APS





- Fluctuation anisotropy energy spectrum consistent with no energy dependence and contributed by one or more source classes providing same fractional intensity contribution at all energies
- Intensity anisotropy energy spectrum consistent with one or more source classes with photon index -2.40+-0.07 (such as FSRQs and BL Lacs)

V – Conclusions

- Fermi and Pamela provide coherent observational picture
- Fermi and IACT complementary in energy range
- Neutrino initial results important for a comprehensive observational program

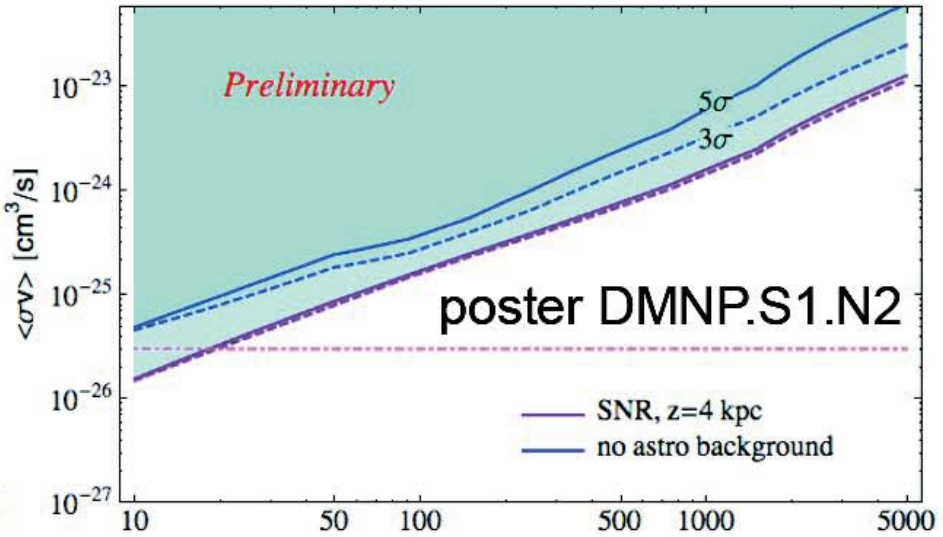
- Only upper limits so-far
- Point sources cleanest target
- Fermi limits from dwarfs scratching WIMP benchmark thermal cross section at ~10 GeV
- All sky (EGB, line, anisotropies) accessible to Fermi only
- Extended regions (halo, Inner Galaxy) promising but hard
- Diffuse emission is the maximal uncertainty, needed input from Fermi and other missions to improve modeling

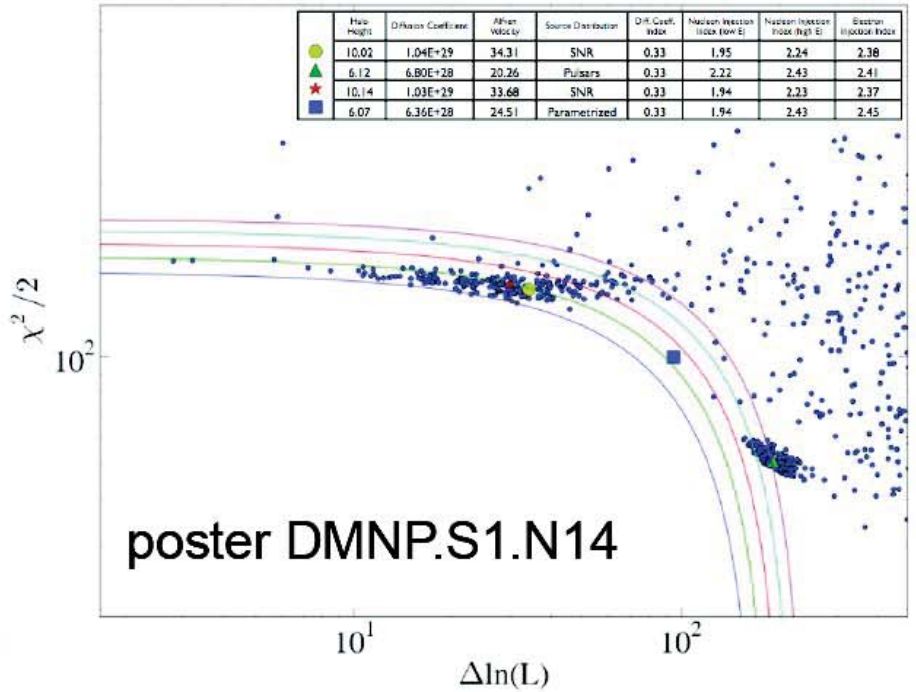
- Wealth of results from Indirect Dark Matter searches
- Gamma-ray results disfavor lepto-philic DM for CRE excesses
- Hints from direct or accelerator searches reduce models phase space for cross-checks

Backup Slides

Fermi updates on Galactic Halo

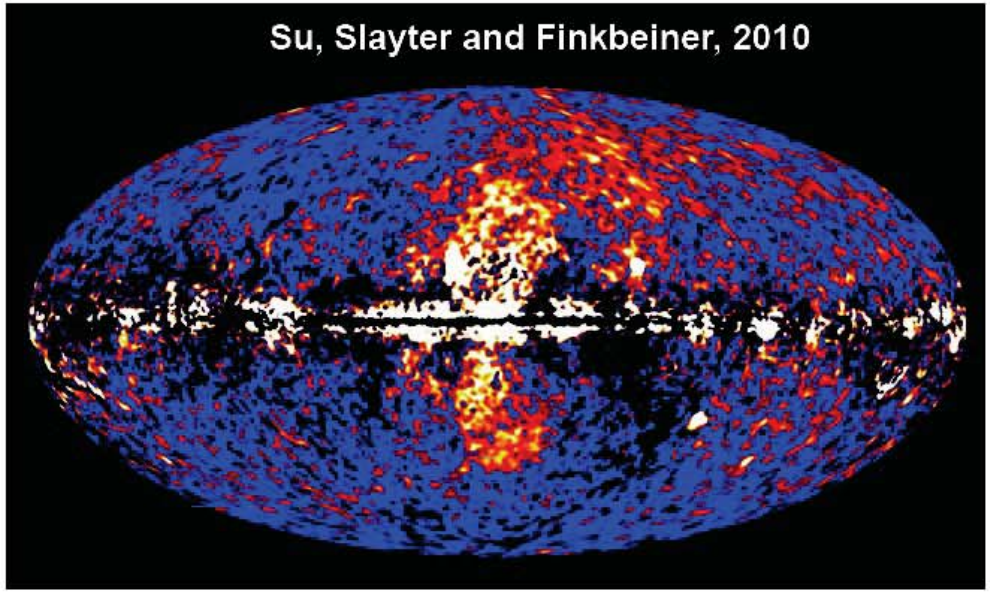
- Exploits both spectral and spatial information
  - Data binned in E and angle
- Large residuals in the fit favor a DM component
  - scan model parameters of diffuse emission that affect more significantly DM limits
  - Compute limits assuming all diffuse emission is DM
- Simultaneously fit CR and gamma-ray data scanning full phase space of CR models

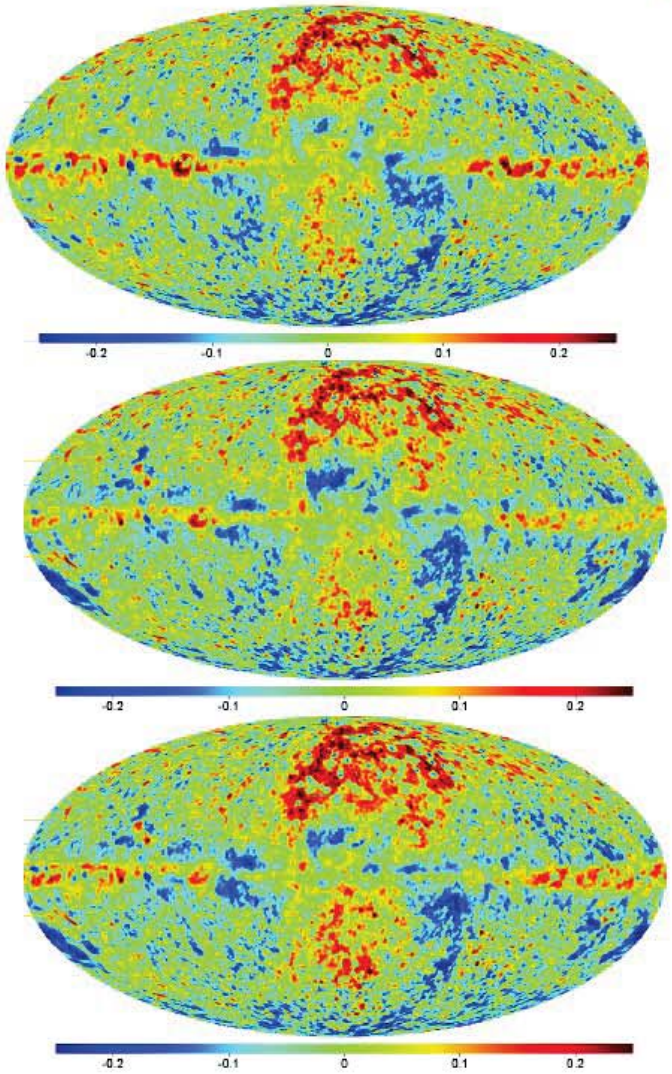




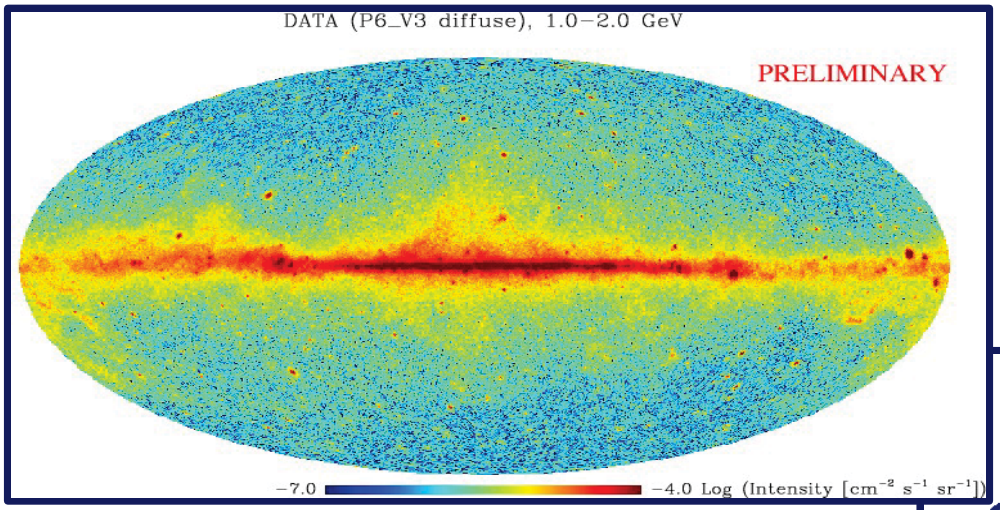
Challenge with Halo Analysis

- Residual maps from a selection of GALPROP models show considerable large scale structures
  - Fermi lobes, Loop I, bubbles … see talk by JM Casandjian



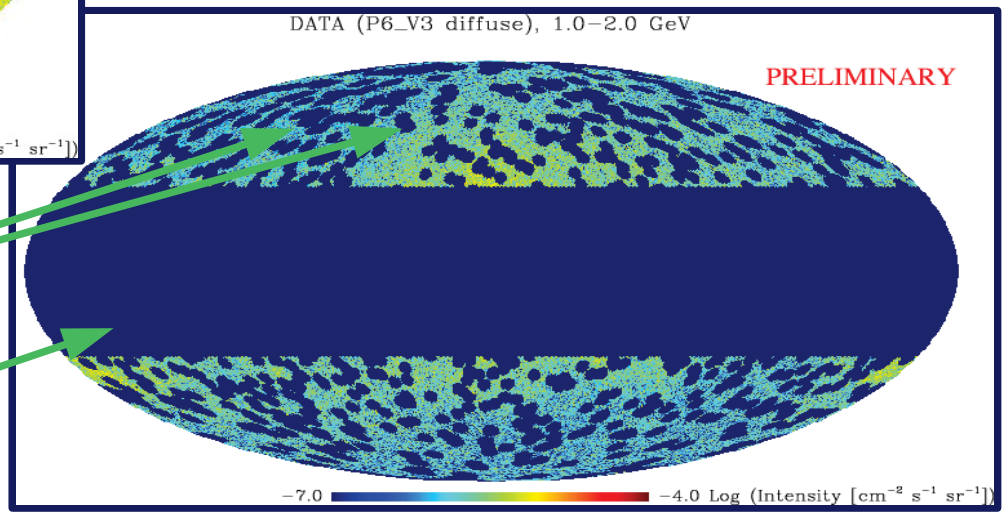


Data Intensity Maps



Counts Map (1-2GeV)

Masked Counts Map



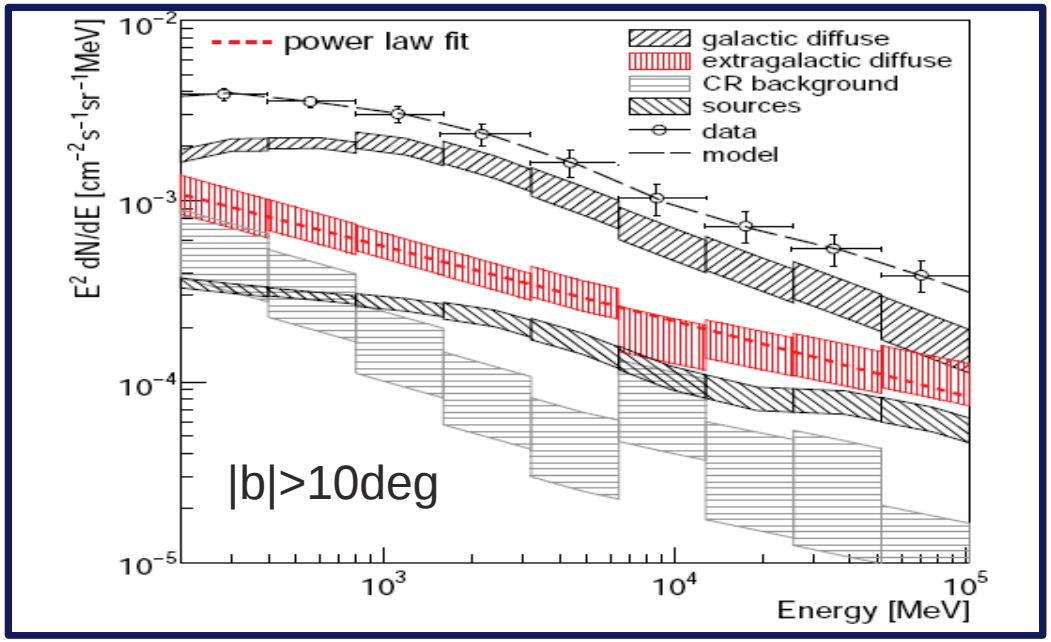
Sources Masking

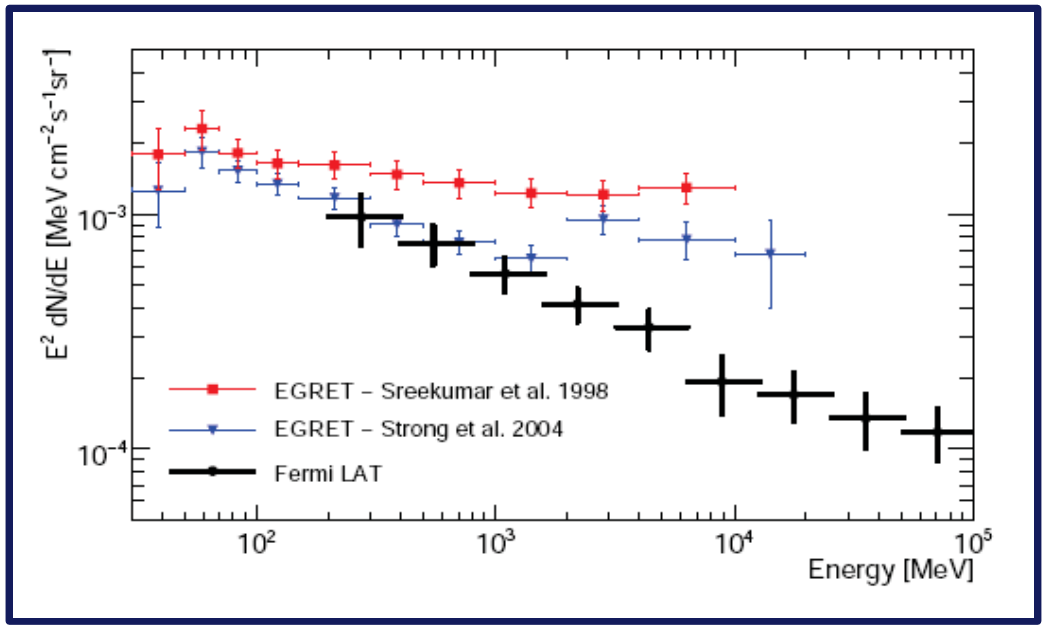
Galactic Plane Masking

- **22 months** of data, diffuse class events
- energy from **1 to 50 GeV, 4 energy bins** for APS calculation
- **Masking** of 11-month catalog sources (2deg radius) and |b| < 30 deg diffuse emission
- front- and back-converting events: processed separately through angular power spectrum calculation, then results are combined by weighted average

Measurement of the IGRB

- Galactic Diffuse Emission component
- Extra-Galactic Diffuse Emission component, with photon index -2.40+-0.05 and I(E>0.1GeV) = (1.03+-0.17)X 10^{-5} cm^{-2} s^{-1} sr^{-1}
- Residual Charged Cosmic Rays component
- Guaranteed contributions to IGRB: blazars, star forming galaxies, milli-second pulsars
- Possible contributions: Dark matter structures, etc

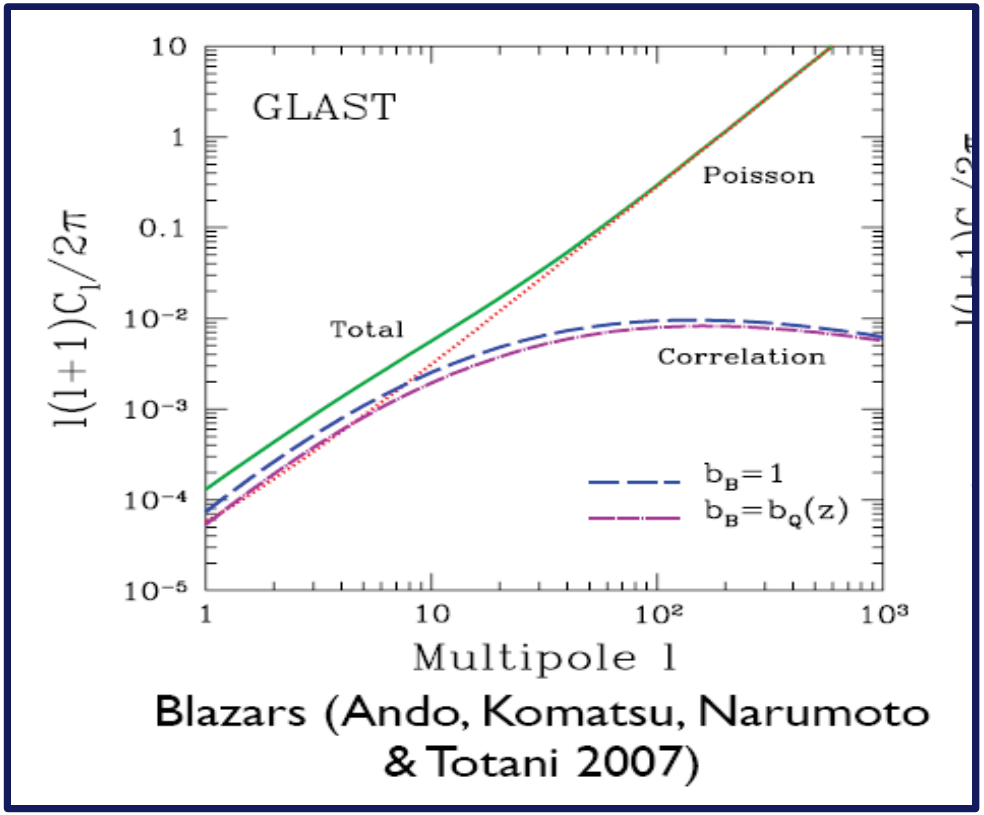




2010PhRvL.104j1101A

APS from Sources

- The Poisson angular power arises from un-clustered point sources and takes the same value at all multipoles
- The APS of many gamma-ray source pop. are dominated by the Poisson components for multipoles l>10
- The measured one is ~ 1e-5 sr, then within the range predicted for some astrophysical source classes and some dark matter scenarios
- Other source popolations APS in the backup



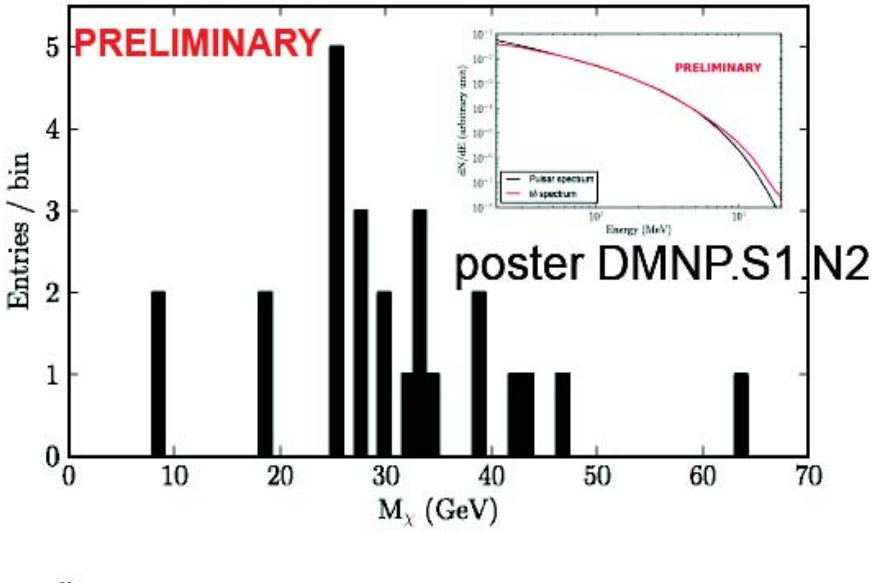
Blazars (Ando, Komatsu, Narumoto & Totani 2007)

predicted fluctuation angular power $C_\ell/\langle I\rangle^2$ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2

Fermi updates on sources

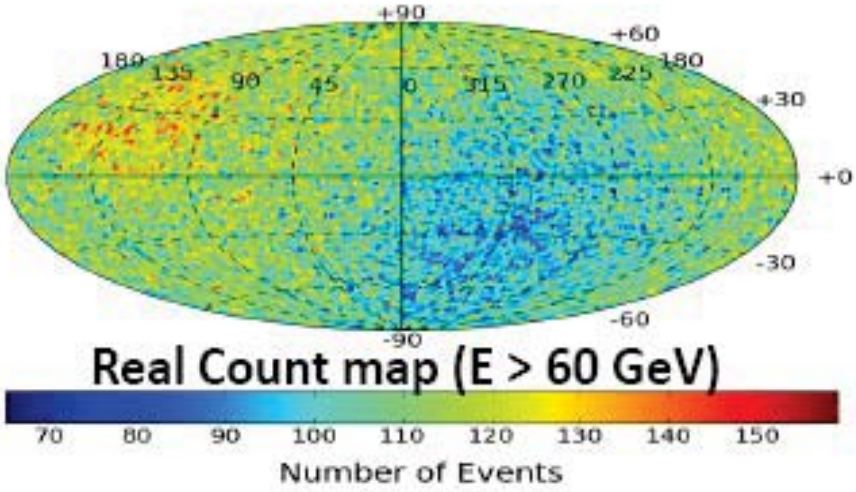
- No DM satellites found in 1 year of data when requiring
  - Spectrum inconsistent with conventional power law
  - source extension (almost all pulsars pass simple spectral tests)

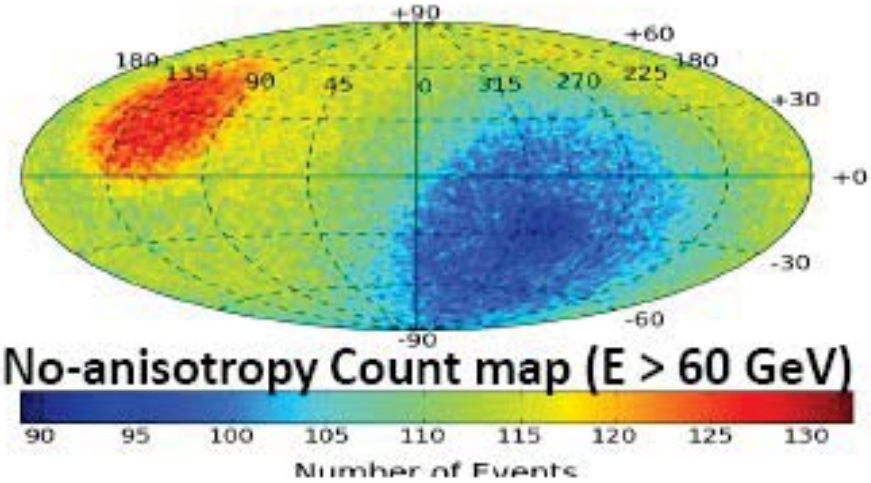


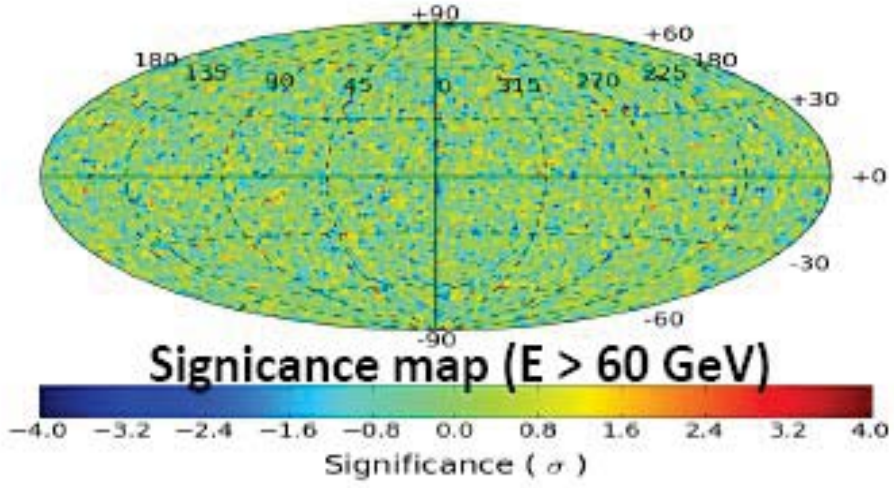
poster DMNP.S1.N2

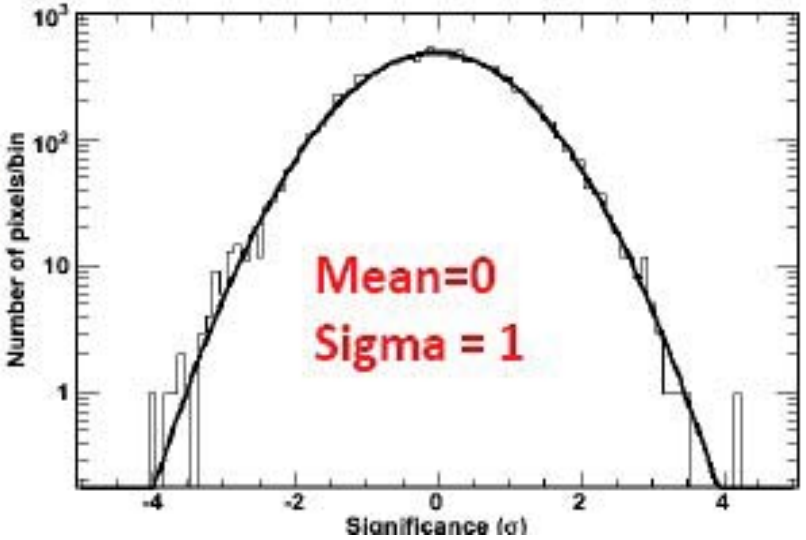
Search for CRE anisotropy

- **The arrival directions of events from the whole sky were searched for anisotropies in Galactic coordinates**
  - **Healpix pixelization scheme (12288 pixels, ≈3deg^2) used for the skymaps**









Significance skymaps

A pre-trials significance map produced by a bin to bin comparison of the no-CRE-anisotropy to the actual skymap:

- **Integration radius 10°, 30°, 60° and 90° and Energy>60GeV**
- **Because of the large number of trials (from ≈100 trials at 90° up to ≈ 5000 at 10° integration angular radius) all the observed fluctuations are *post-trials insignificant***