Searches for WIMP dark matter with the Fermi LAT

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for the Fermi-LAT collaboration

- WIMPs? ~weak scale (M_Z) mass particle interacting ~weakly (G_F).

- "a simple, elegant, compelling explanation for a complex physical phenomenon"

  - WIMP miracle: in the simple picture of 'thermal decoupling' $\Omega_{DM} \sim \sigma^{-1}$ (independent of DM mass)!

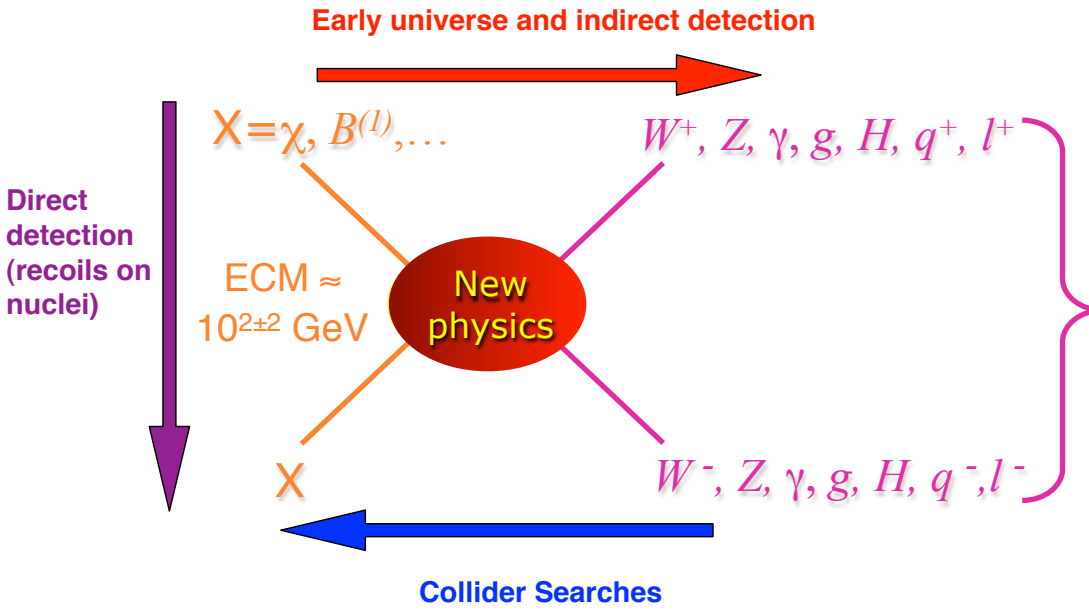
  - DM with a mass ~M_Z forms structures in a way confirmed by observations (true for $m_{DM} >\sim$ 1 MeV).

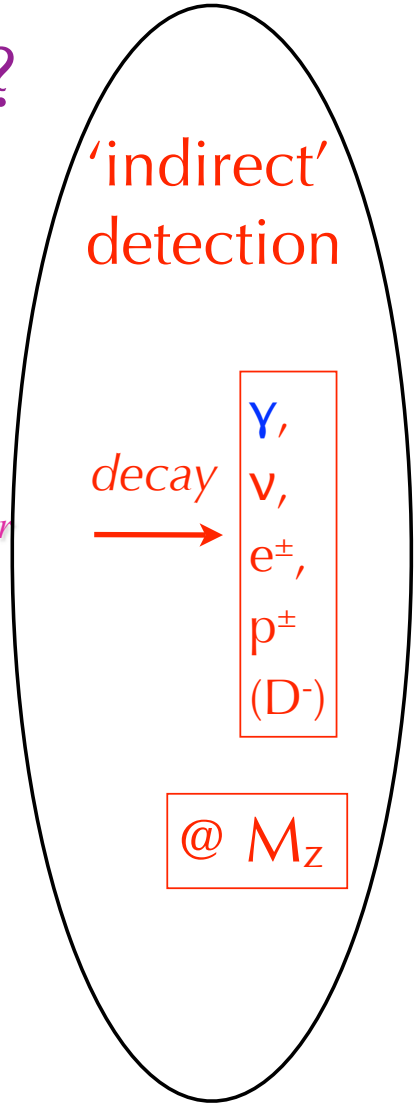
  - as a bonus, any theory which attempts to explain the origin of EW mass, generally introduces new stable EW mass particles.

(NB: "For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."
- Tommy Gold)

[taken from R. Kolb's talk, VEU2012]

• How to test the WIMP hypothesis?



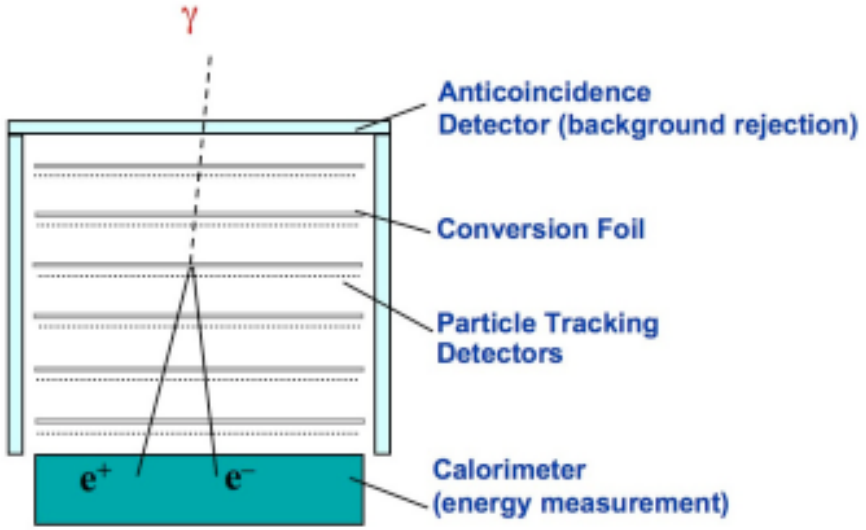


In the Early Universe: DM kept in equilibrium w SM by self-annihilations (σ).

Today, DM expected to annihilate with the same σ, in places where its density is enhanced!

in astrophysical systems - *remotely*

The instrument



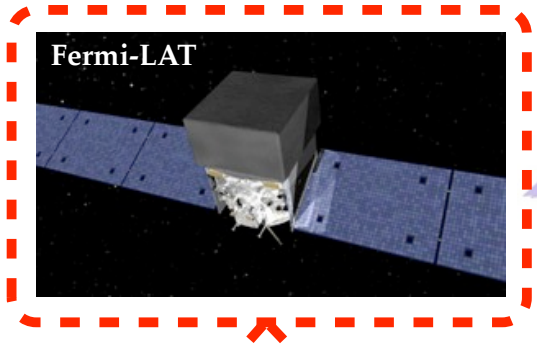
The Fermi LAT is a e+e− **pair-conversion telescope**; individual γ rays convert to e+e− pairs, whose tracks and deposited energy are recorded by the instrument. NOTE: it can detect BOTH gammas AND electrons.

Fermi LAT Collaboration: ~ 400 Scientific Members, NASA / DOE & International Contributions (Sweden, France, INFN, Italy; ...).

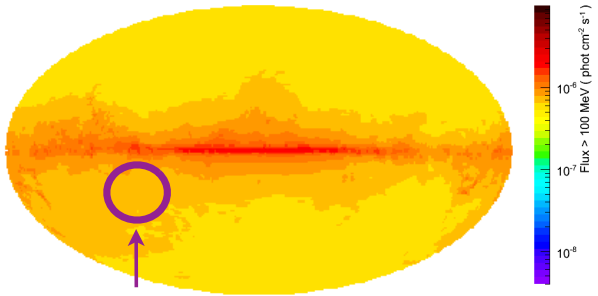
Data made public within 24 hours (http://fermi.gsfc.nasa.gov/ssc/).

Key features

Large field of view: 20% of the sky at any instant!

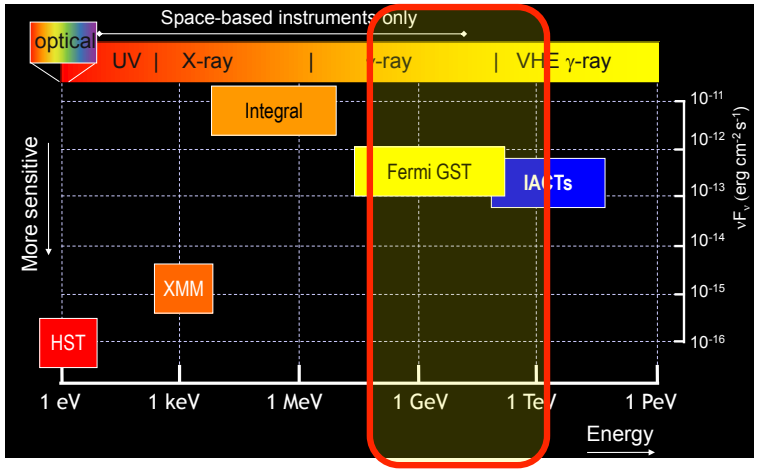


Every ~3 Hours



ground based gamma ray telescopes are pointing, ~few degree field of view.

Energy range: 20 MeV to >300 GeV (~Mz, ideally suited for WIMP searches).



WIMP Mass Range

Good angular resolution ~ 0.1 deg; and charged particle vs gamma separation...

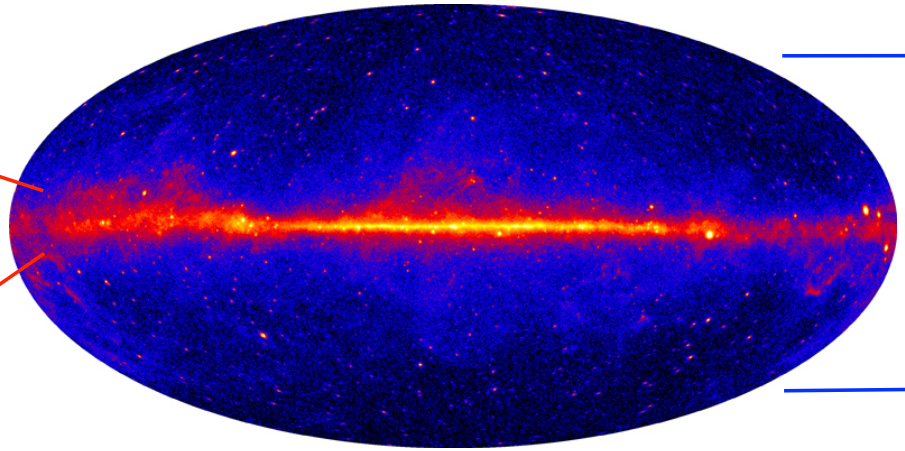
(http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm)

Science

1) Diffuse emission: ~90% LAT photons.

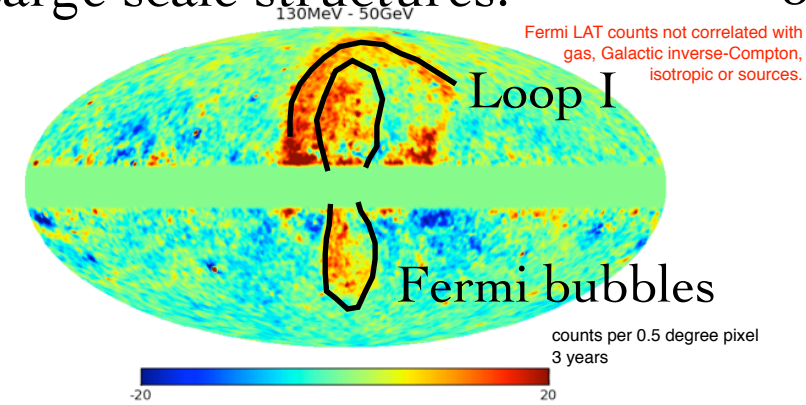
Fermi LAT three year sky map.

Galactic emission: **Charged CR** interact with the **interstellar medium** (gas, star light, ...)->γ



extra-Galactic: (high latitude, 'isotropic' emission). Made up by e.g. sources too faint to be resolved individually.

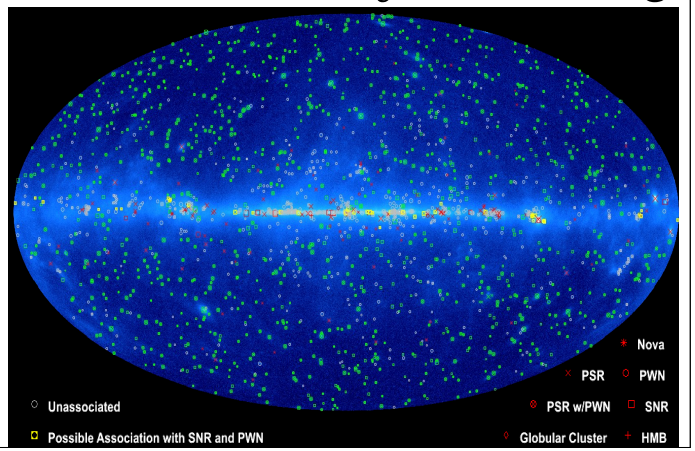
2) Large scale structures:



Fermi LAT counts not correlated with gas, Galactic inverse-Compton, isotropic or sources.

[Casandjian, Gamma2012]

3) ~1900 sources in the 2 year catalog



• What are we after?

gamma ray spectral flux

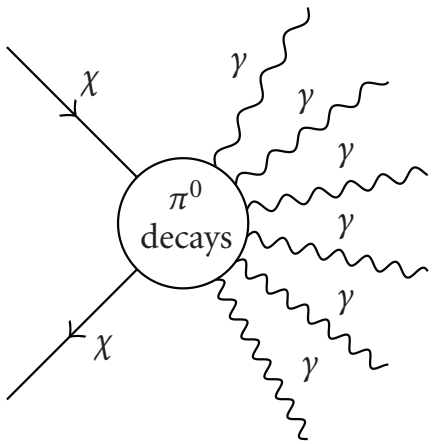
DM annihilation cross section, mass, branching ratios...

Integral of DM density SQUARED along line of site; 'J factor'

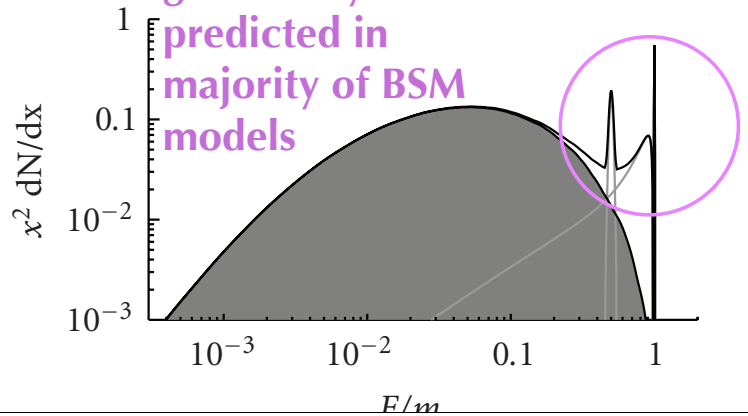
DM signal = particle physics X DM clustering

Particle physics part:

Secondary photons (tree level)



featureless spectra generically predicted in majority of BSM models

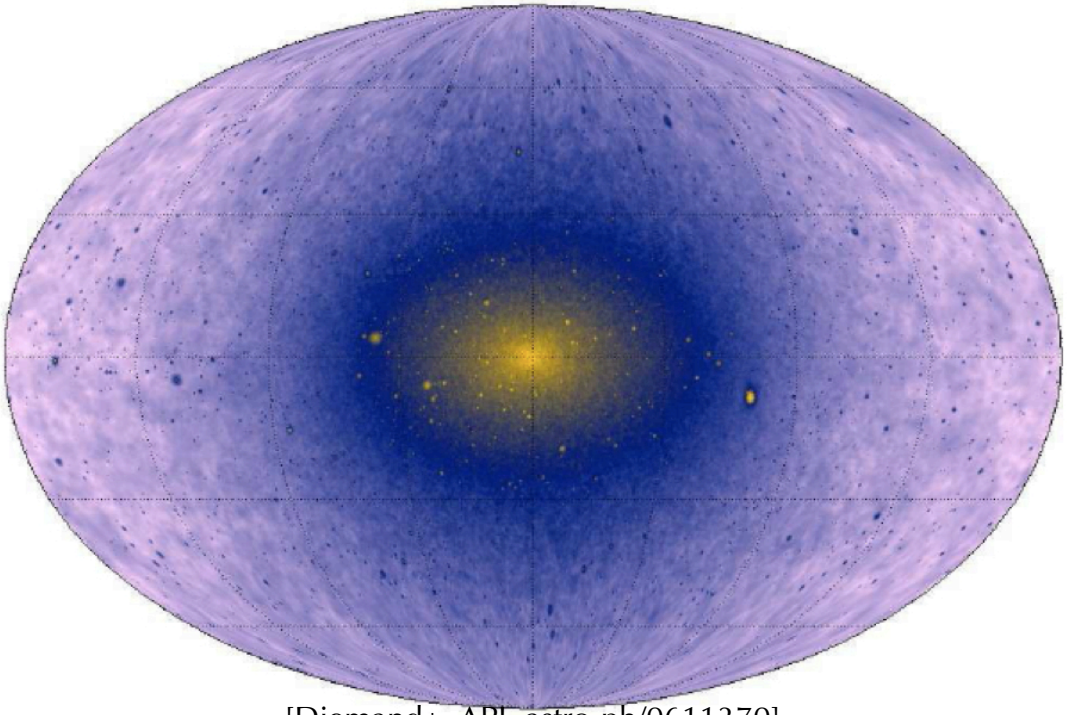


or characteristic hard/line like spectrum produced in loop processes or three body decays. (see A. Ibarra's talk)

• Where to look for DM gamma ray signals?

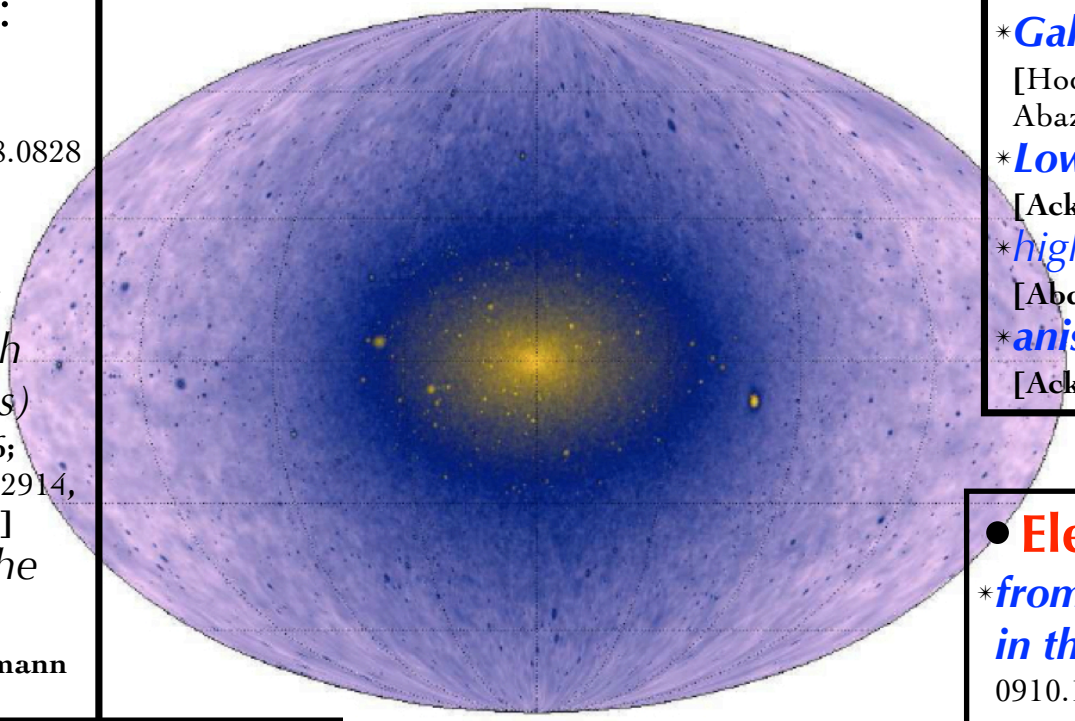
- γ propagate in a straight line, unaffected by Galaxy → DM clustering map (N-body simulations) is a good guide of observational targets.

Milky Way halo



[Diemand+, APJ, astro-ph/0611370]

- Fermi LAT has rich DM search program, on various scales! (with gammas AND electrons)



- Point sources:
  - ***dark satellites*** [**Ackermann+, 1201.2691;**Hooper+,1208.0828 Zechlin+,1210.3852...]
  - ***dwarf spheroidal Galaxies*** *(smallest resolved halos with stellar components)* [**Ackermann+,1108.3546;** Geringer-Sameth+, 1108.2914, **Mazziotta+,1203.6731...]**
  - ***Galaxy clusters*** *(the largest halos)* [Han+1207.6749, **Ackermann +,1002.2239]**

- Spectral search:
  - *all sky search for a* ***line emission*** [Weniger+, 1204.2797, **Ackermann+, 1001.4836&1205.2739...]**

- Diffuse emission:
  - ***Galactic Center*** *region* [Hooper+,1110.0006 ; Abazajian+, 1207.6047 ...]
  - ***Low Galactic latitudes*** **[Ackermann+,1205.6474]**
  - *high latitudes* **[Abdo+,1002.3603]**
  - ***anisotropies*** **[Ackermann+,1202.2856]**

- **Electrons**:
  - ***from DM annihilation in the Sun*** [Schuster+, 0910.1839; **Ajello+, 1107.4272]**
  - ***local electron ANISOTROPY*** **[Abdo+, 1008.5119]**

- However, what we measure does not look anything like it --- astrophysical processes present significant background for DM searches.
- Fermi LAT has rich DM search program, on various scales!

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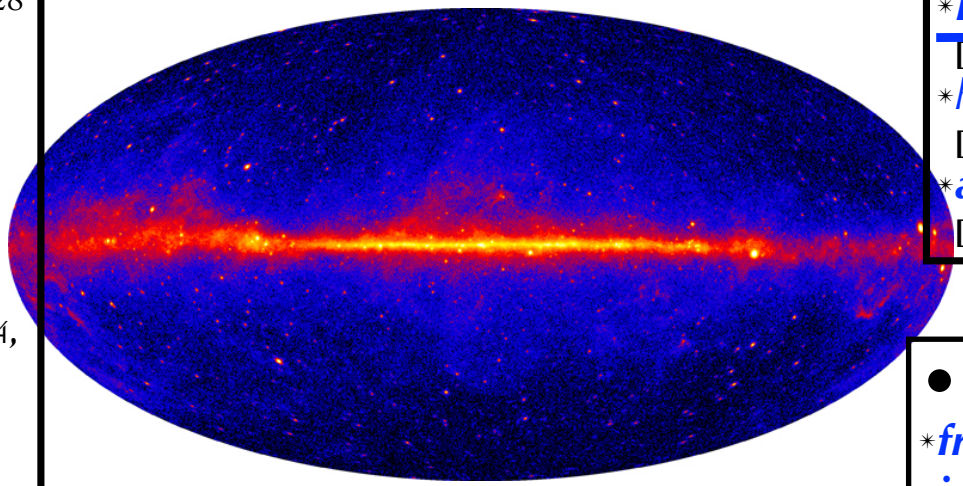

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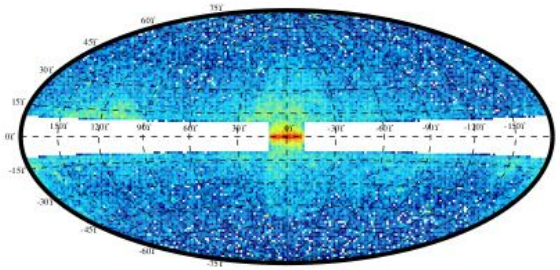
Spectral line search

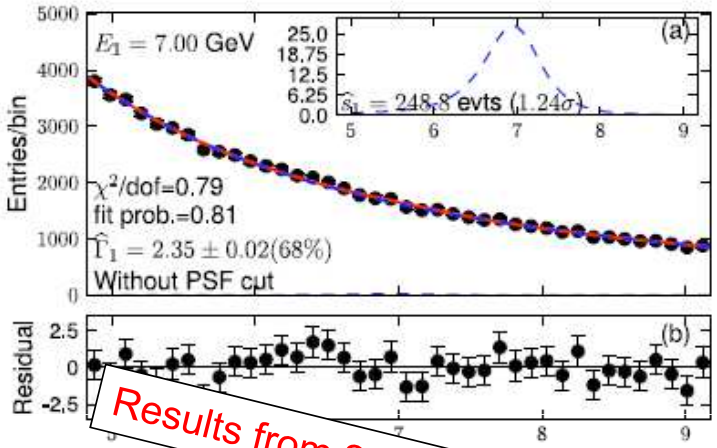
Advantage: sharp, distinct feature
Disadvantage: generally predicted counts low (however, see talk by A. Ibarra!)

Sliding window technique: model bkg as single power law and model energy dispersion from simulation ('line like' excess).

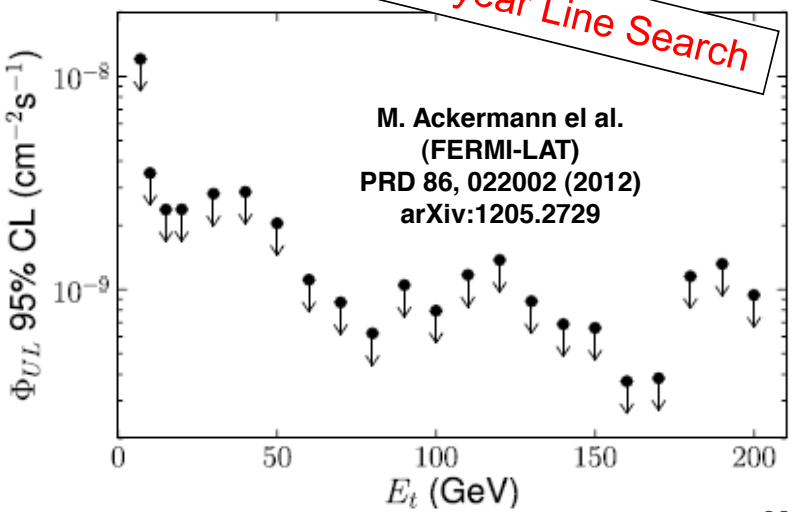
2 yr analysis Fermi LAT looked at the whole sky data and found no evidence of a line.



$|b| > 10^\circ$ plus $|\ell|, |b| < 10^\circ$



Results from 2 year Line Search



Spectral line search

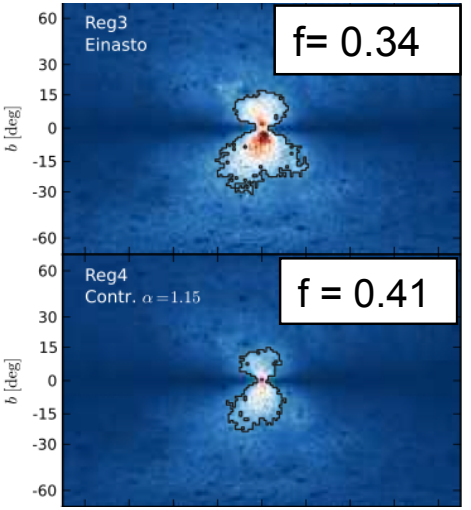
Weniger+ 2012: Evidence for a narrow spectral feature in 3.5 yr data near 130 GeV in **optimized ROIs** near the Galactic center.

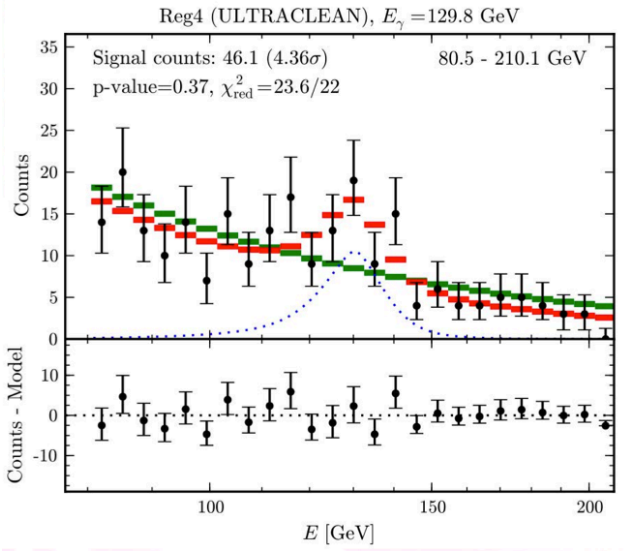
- Signal is particularly strong in 2 out of 5 test regions with

S/N> 30%-60%, with ~>4σ.

- Some indication of double line (111 &130 GeV), Su+, 2012 (1206.1616).

Exciting: 100+ papers since; line-like signature considered a smoking gun of DM!



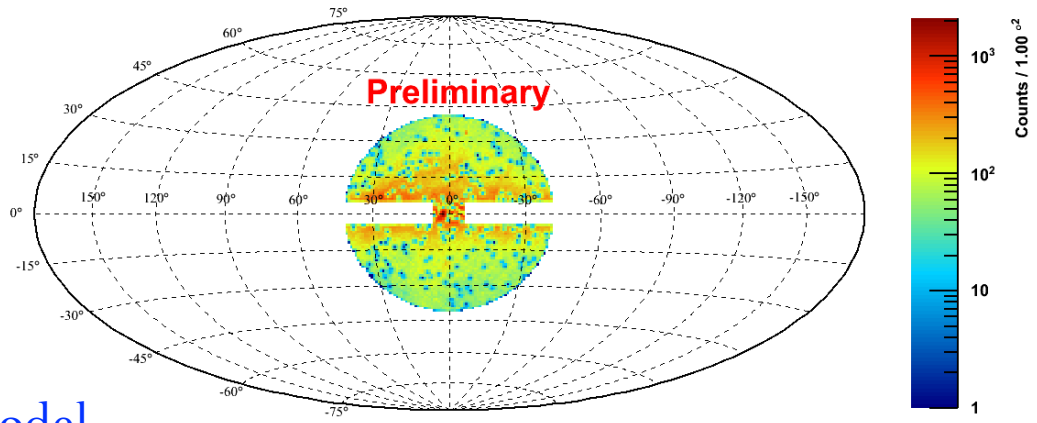


C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797

Spectral line search

Fermi LAT's 4yr line search:

1) Optimize ROI: comparing the signal expected from WIMPs, assuming a specific density profile and expected backgrounds.



2) Improved Energy Resolution Model

Previously modeled line with a triple Gaussian fit ("1D PDF").

However PDF weighted for observing profile varies moderately with declination.

-> use a "2D PDF": add a 2nd dimension to line model: PE.

Increases statistical power by ~15%.

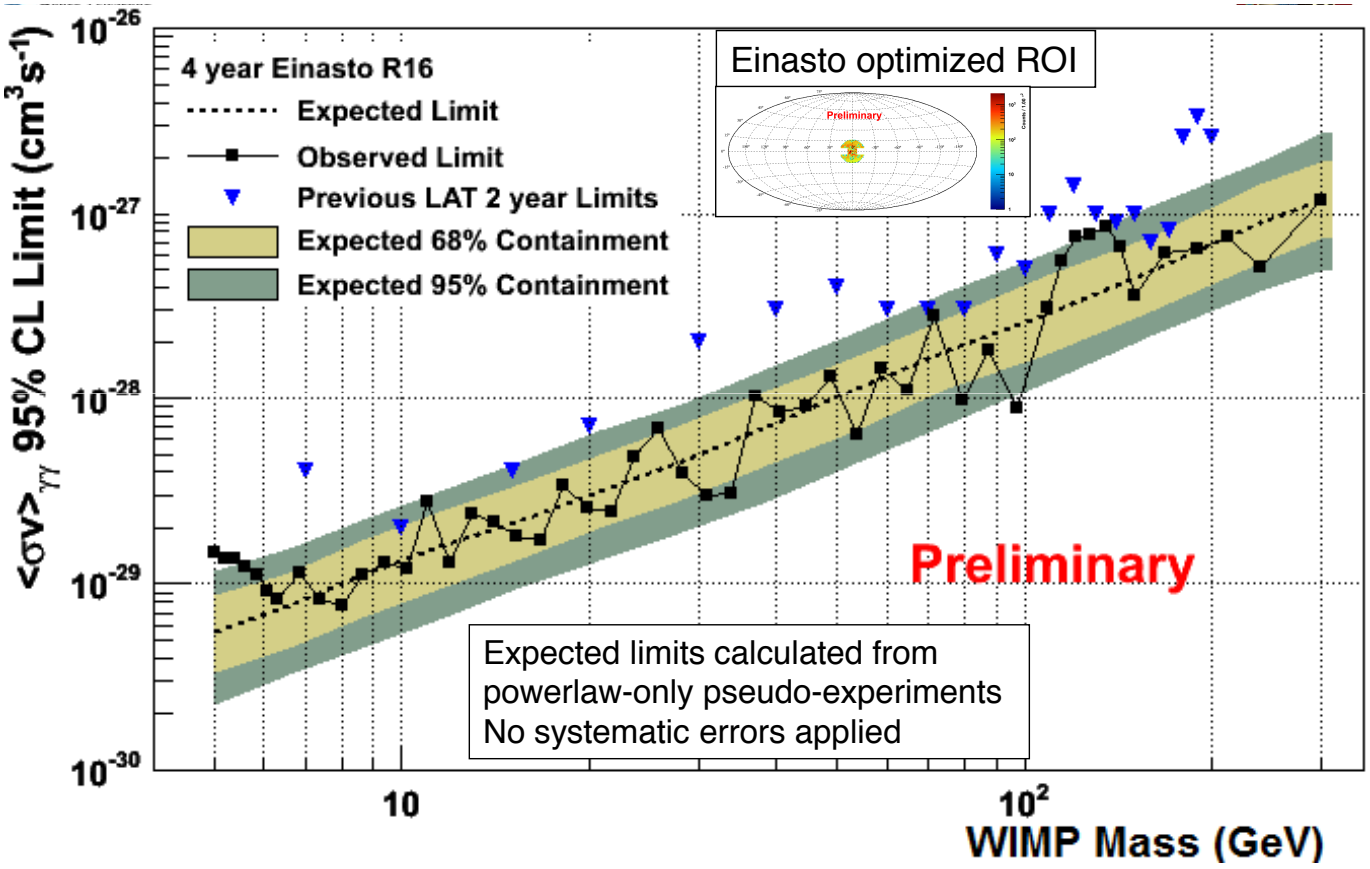
3) Data Reprocessing with Updated Calibrations

Corrects for loss in calorimeter light yield because of radiation damage (~4% in mission to date). This corresponds to a ~5% change in the energy scale at 130 GeV ->135 GeV.

Spectral line search

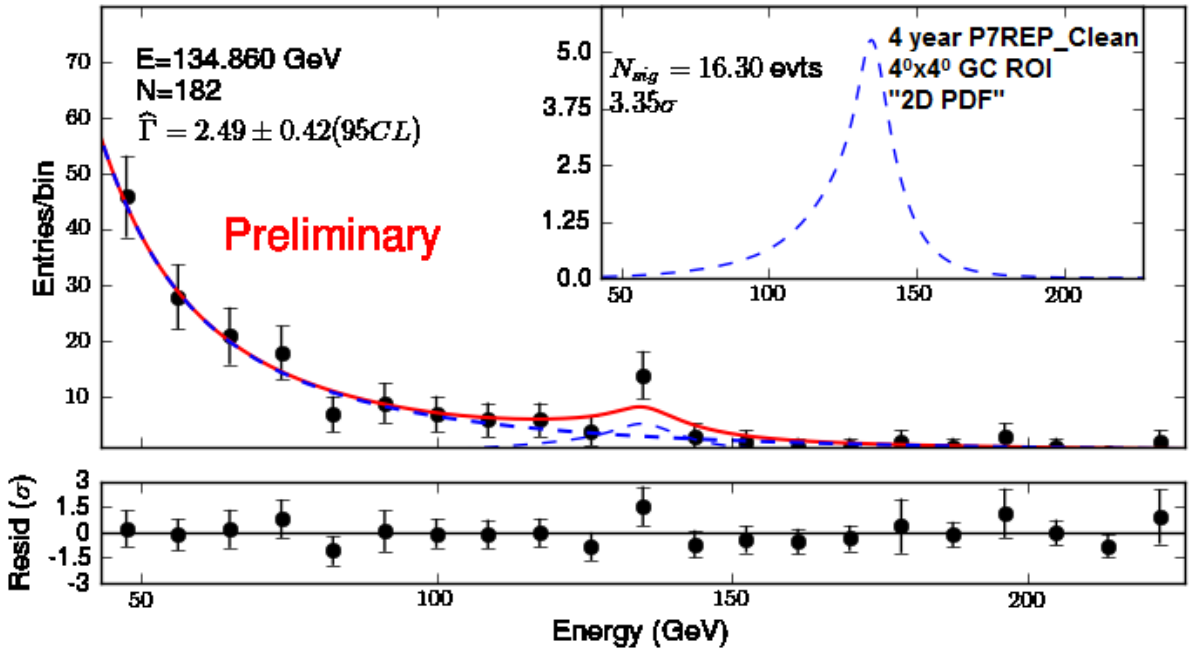
No signal found in a blind search.

95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ Upper Limit for the Einasto optimized ROI R16



Spectral line search

Exploring the tentative signal at 135 GeV.



4.01σ (local) 1D fit at 130 GeV with 4 year un-reprocessed data; 4°x4°GC ROI and 1D PDF

3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data; 4°x4°GC ROI, 2D PDF

<2σ global significance after trials factor

Spectral line search

Control Sample critical for this search, to test instrumental response.

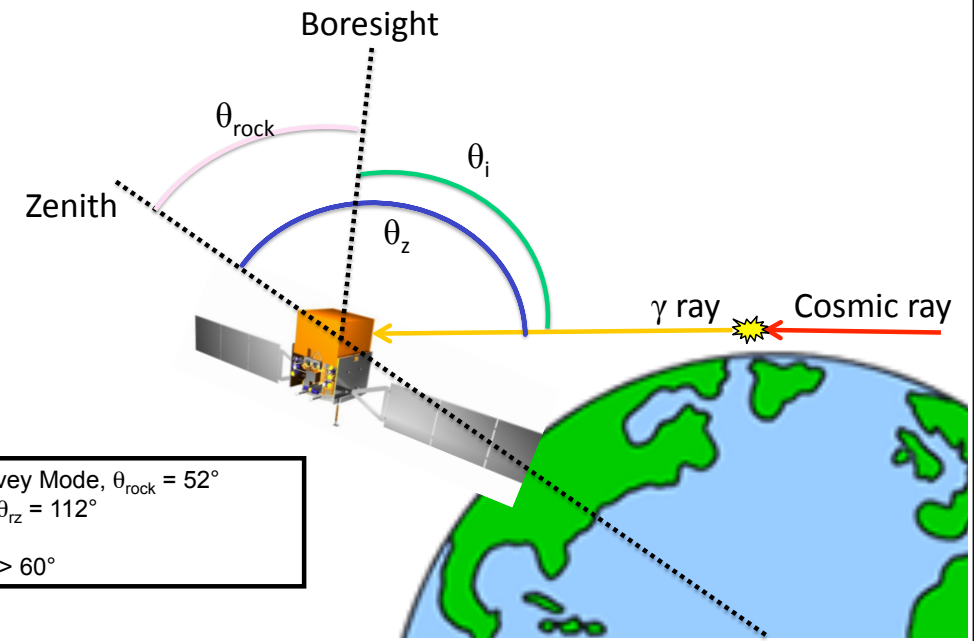
The Earth Limb:

gamma rays from CR interactions in the atmosphere -> expected to be a smooth power-law

Line-like feature in the limb at 135 GeV, ~2.2σ,

S/N_{limb} ~15%, while S/N_{GC} ~30% - 66%.

Possibly linked to a dip in the efficiency of the event cuts, just below 130 GeV (at ~115 GeV).



Spectral line search

Near term prospects:

Fermi LAT: improved event analysis (pass8) and weekly limb observations.

Call for white papers on possible modifications to the observing strategy.

HESS 2: 50 hours of GC observation enough to rule out signature or confirm it at 5 sigma (if systematics are under control); Observations start in March 2013.

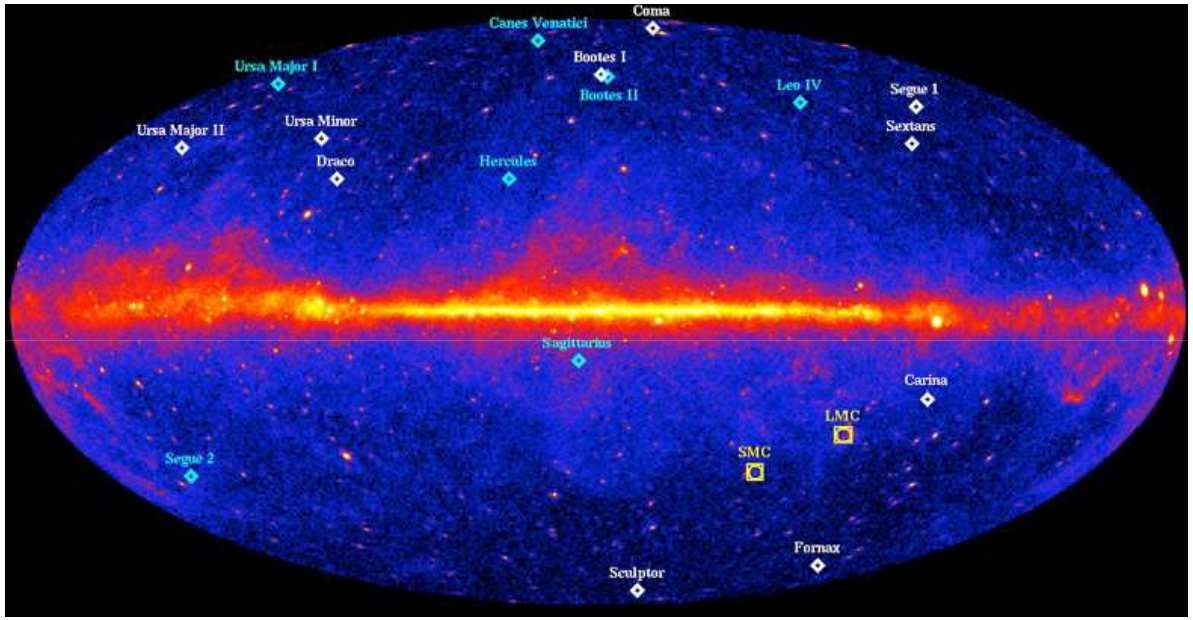
More details:

E. Charles @ Closing in on DM: http://indico.cern.ch/conferenceTimeTable.py?confId=197862#20130128

or A. Albert @ http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2012/program/fri/AAlbert.pdf

Dwarf spheroidal galaxies

- Dark-matter dominated objects:
- 100 - 1000 times more dark than visible matter
- Multi-wavelength observations show no basis for astrophysical gamma-ray production.



No evidence for a gamma ray signal from these objects yet.

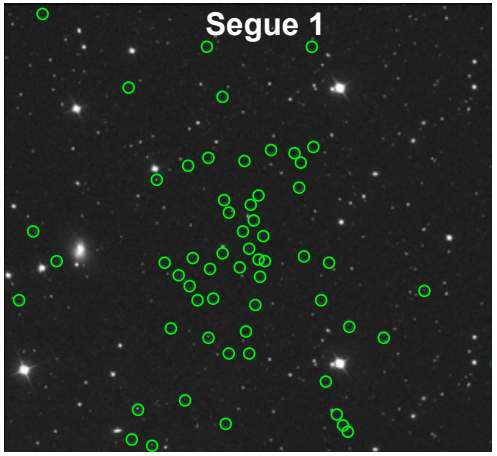
Dwarf spheroidal galaxies

The biggest uncertainty: **dark matter content!**

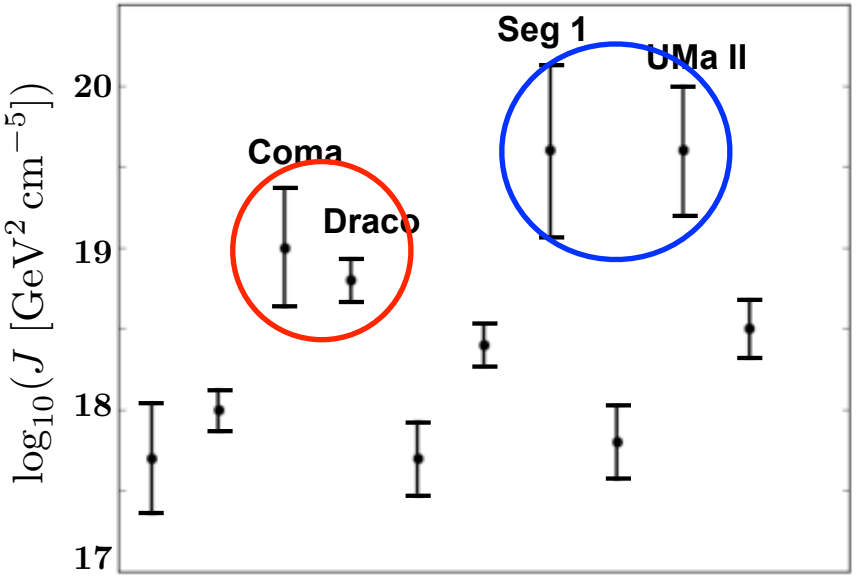
Determined from stellar velocity dispersion

– Classical dwarfs: thousand stars

– Ultra-faint dwarfs: <~ 100 stars



• Fit stellar velocity distribution of each dwarf (assuming an NFW profile) and calculate the **J-factors** by integrating out to a radius of 0.5 deg.

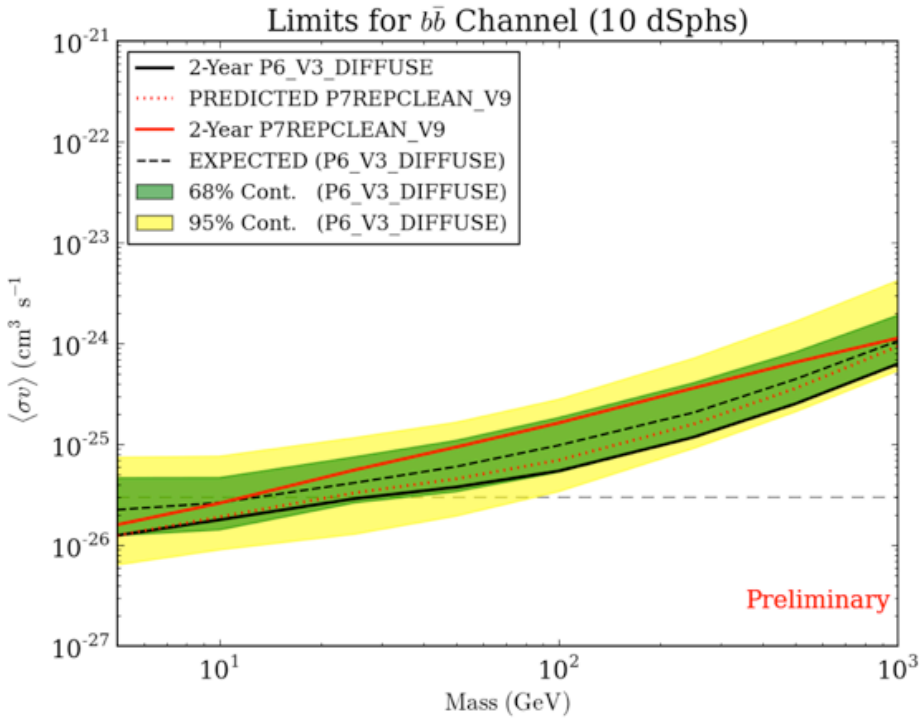


Dwarf spheroidal galaxies

Constraints:

- 10 dwarf galaxies
- 200 MeV-100 GeV gamma rays
- 2 years data, p6_v3_diffuse
- **Include the J-factor uncertainty as a nuisance parameter in the joint likelihood.**

Constrains the conventional thermal relic cross section for a WIMP mass <30 GeV annihilating to bb and $\tau^+\tau^-$.



Update the analysis with the new reprocessed data → lead to a statistical reshuffling of gamma-ray-classified events and higher limits.

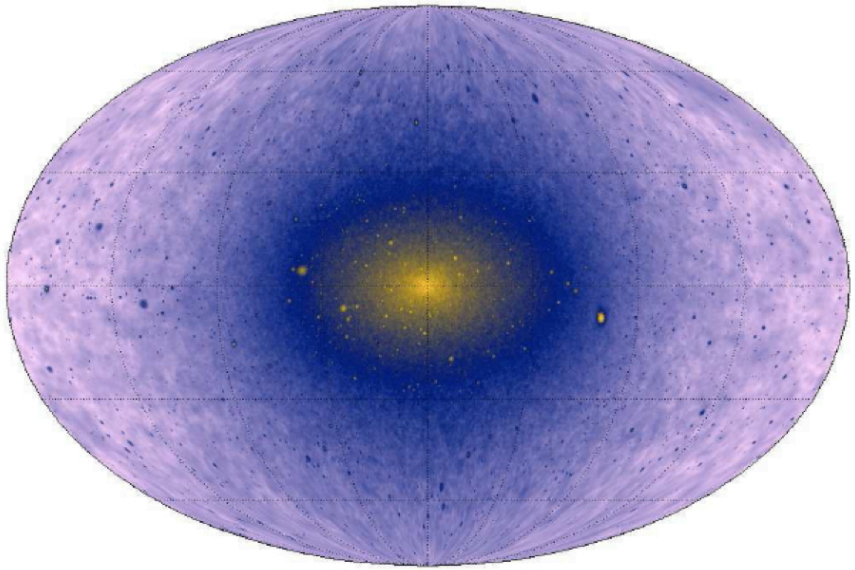
Both sets of limits lie within the 68% containment region of a statistical sample.

MW halo as a DM target

- DM annihilation signal is expected to be high in the inner regions of our halo
  - Sun is 'only' ~8 kpc away from the GC
  - DM content of the Milky Way is high

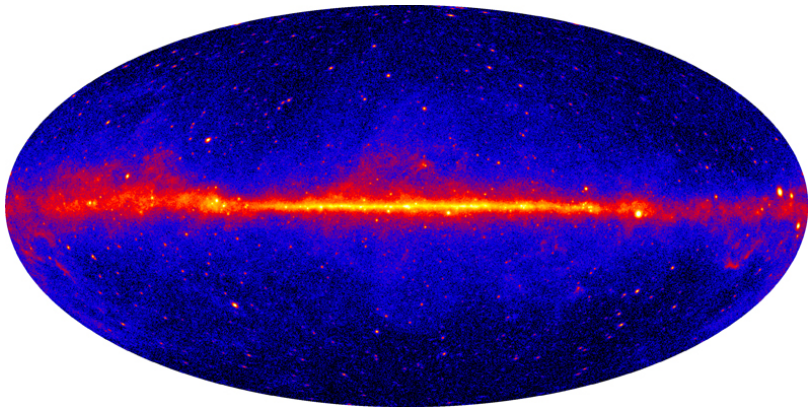
~ 'opposite' to previous cases: strong signal predicted in generic DM models but astrophysical bckgds high.

Predicted DM signal



Diemand et. al, APJ, 2006.

Fermi sky map - three year data.

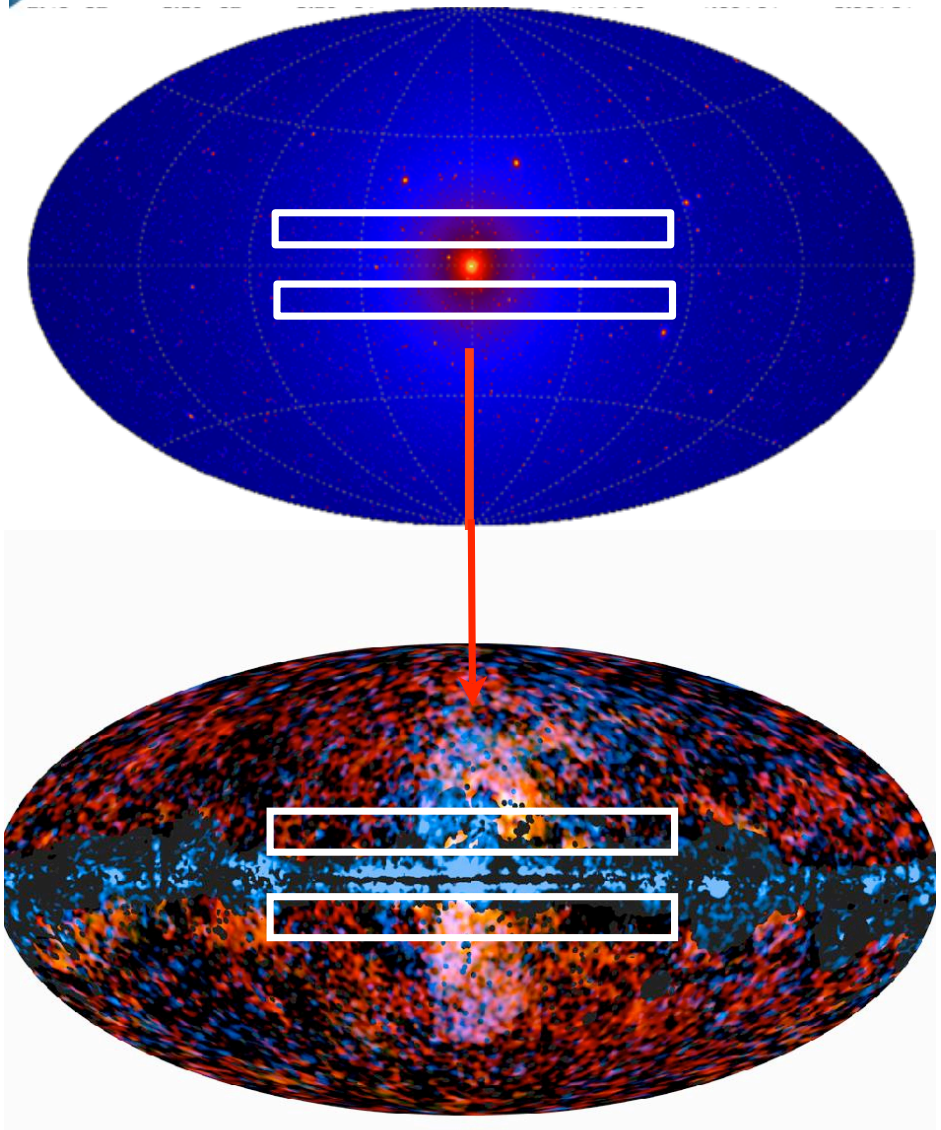


MW halo as a DM target

2 year p7v7 data

1-100 GeV

Analyze bands 5° -15° off the plane to minimize uncertainties.



- Two methods:

1. More conservative - Assume all emission from dark matter (no astrophysical model) [Papucci+, arXiv: 0912.0742 Cirelli+, arXiv:0912.0663]
2. More accurate - Fit dark matter source and astrophysical emission simultaneously and marginalize over astrophysical uncertainties. **[Ackermann+, arXiv:1205.6474]**

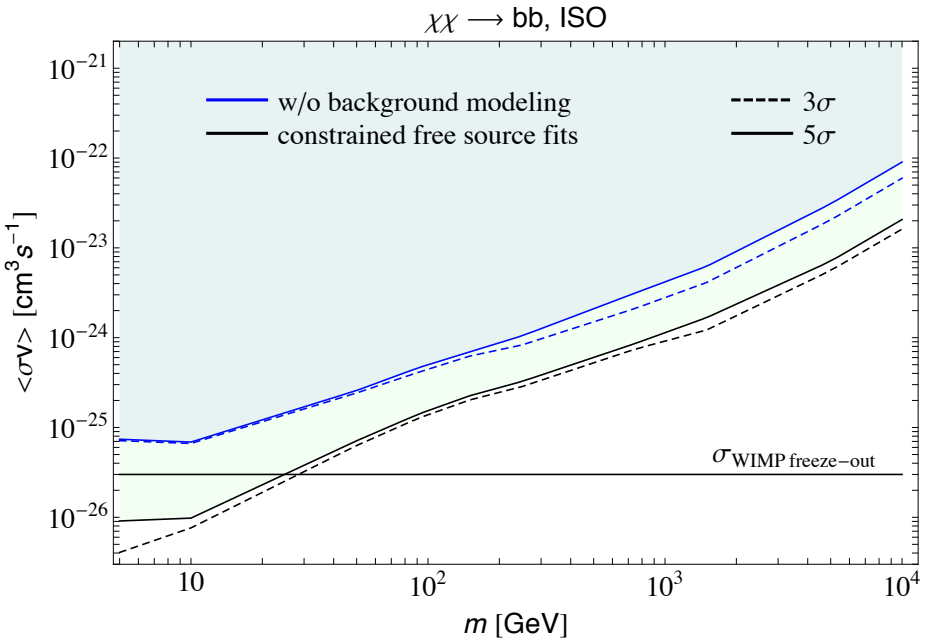
MW halo as a DM target

Limits on DM annihilation cross section, obtained after marginalization over a large set of astrophysical parameters together with DM component.

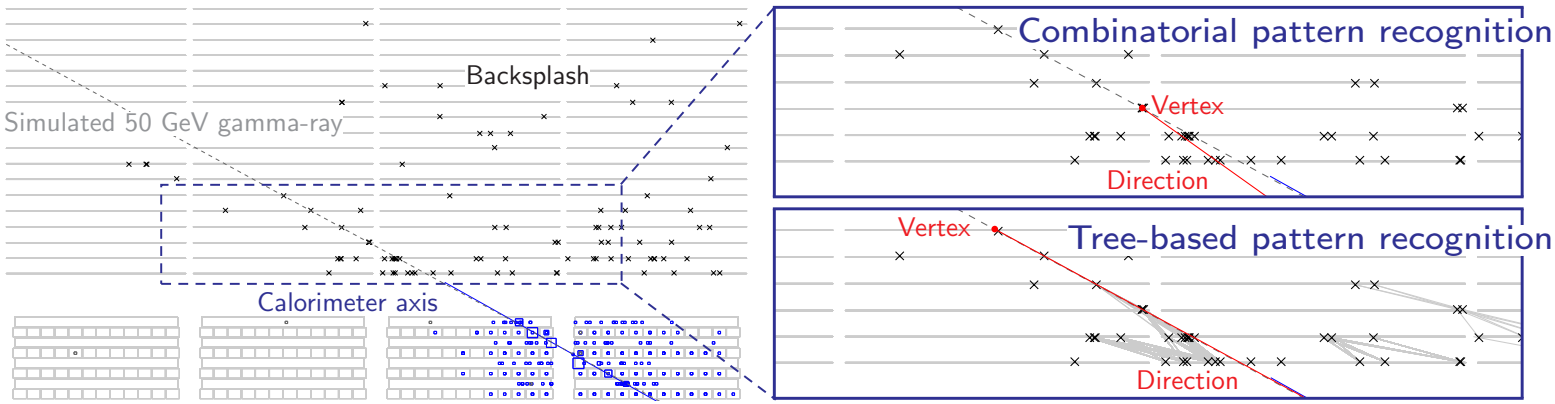
for ISOthermal DM profile and bbar channel (generic for most of particle physics models).

- Blue: limits obtained without any modeling of conventional astrophysical emission.
- generic WIMP models constrained below ~20 GeV.

Remaining uncertainty on the DM distribution in the Galaxy! follow up work.



Future: pass8



Pass 8 will approach the full scientific potential of the LAT. Lower backgrounds and better control over the systematic uncertainties.

* Extension of the energy reach:
* Better high-energy Point Spread Function.
* substantial effective area increase above 20 GeV (recover calorimeter-only events).

Summary

Fermi is in its 4 year in orbit:

– wealth of scientific results!

– data are public and largely used by the community.

– starting to constrain generic WIMP models for low mass WIMPS.

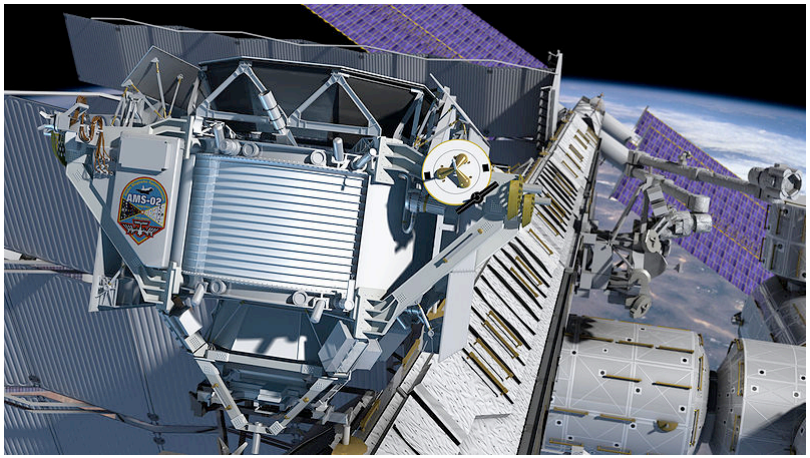
The best is yet to come:

– better understanding of the instrument

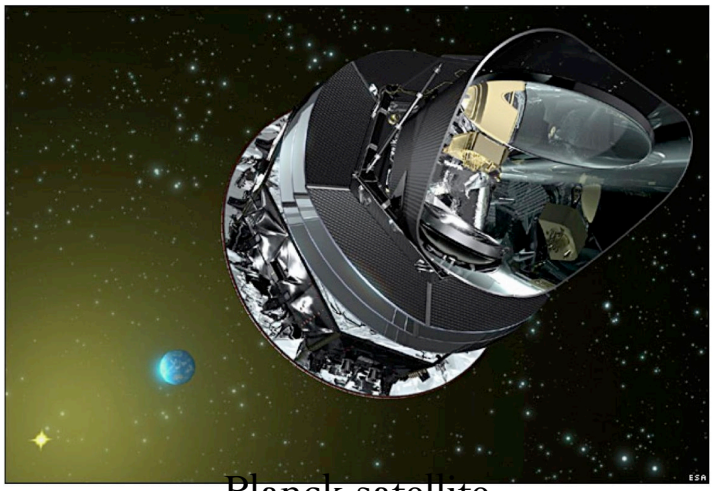
– better understanding of the astrophysics

- 2800 sources expected by 5 years of the LAT; high energy follow ups by ACTs and low energy instruments (Xray, radio); +...
- DM clustering properties from current optical and weak lensing surveys.
- AMS02 and Planck in orbit!

–> **great time for High energy astrophysics! AND by the end of Fermi's life (2018?) we might know what particles DM is made of.**



AMS 02 on ISS

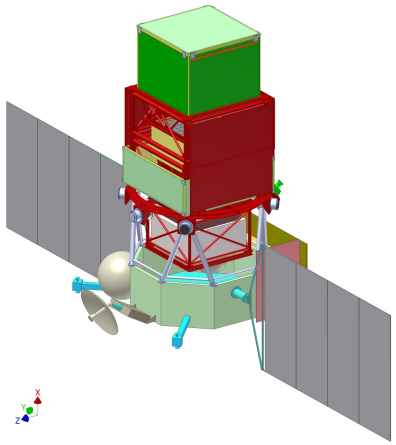


Planck satellite

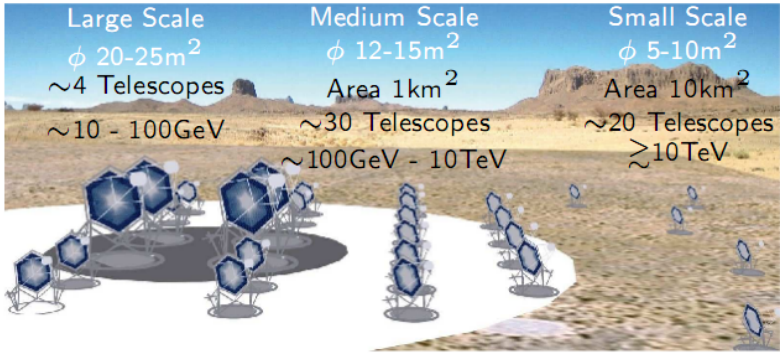
Future: next generation gamma ray experiments

The best is yet to come
– CTA: a ~km2 array of ACTs
– Gamma-400: Uses technology similar to Fermi LAT, but will have better angular and energy resolution and wider energy coverage.

launch planned for 2018.



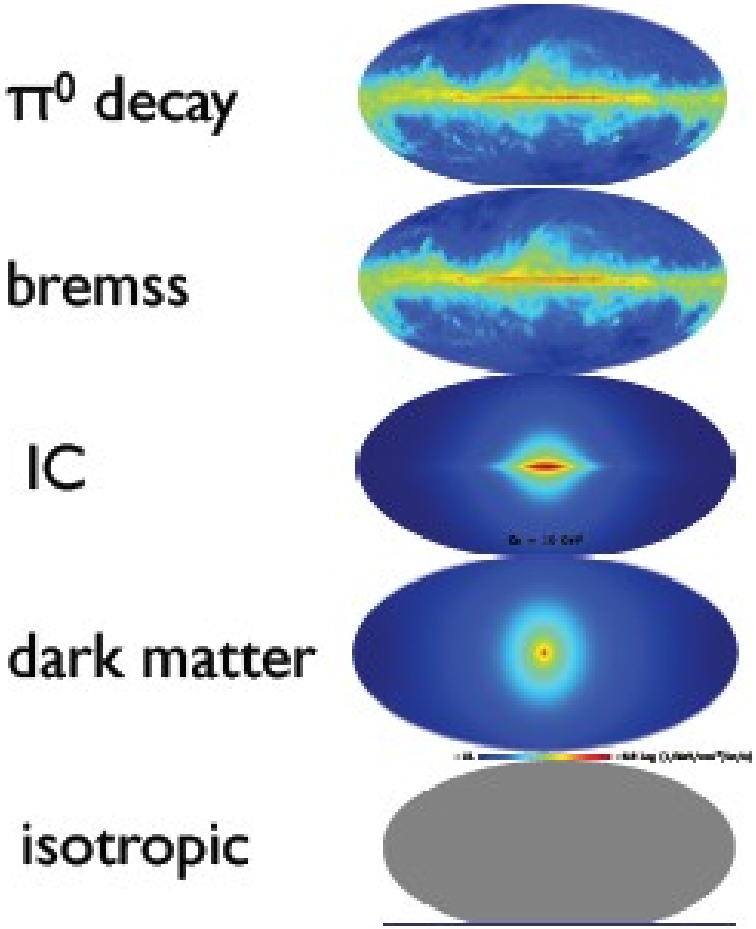
currently in design phase foreseen to be operative a few years from now.



Extra slides

Method II

- Distribution of CR sources is uncertain
  - to be conservative in deriving the DM constraints, set ALL CR sources to zero in the central 3 kpc.
- Allow several CR parameters to vary on a grid
  - for each point on a grid FIT the three components of emission TOGETHER with DM to the data
  - perform fits both in MORPHOLOGY and SPECTRA
- Combine these fits using the profile likelihood method
  - **derive DM limits marginalized over astrophysical uncertainties.**



Dwarf spheroidal galaxies

* Include statistical uncertainties from stellar kinematic data.

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

$$L(D\,|\,\mathbf{p_m},\{\mathbf{p_k}\}) = \prod_k L_k^{\rm LAT}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

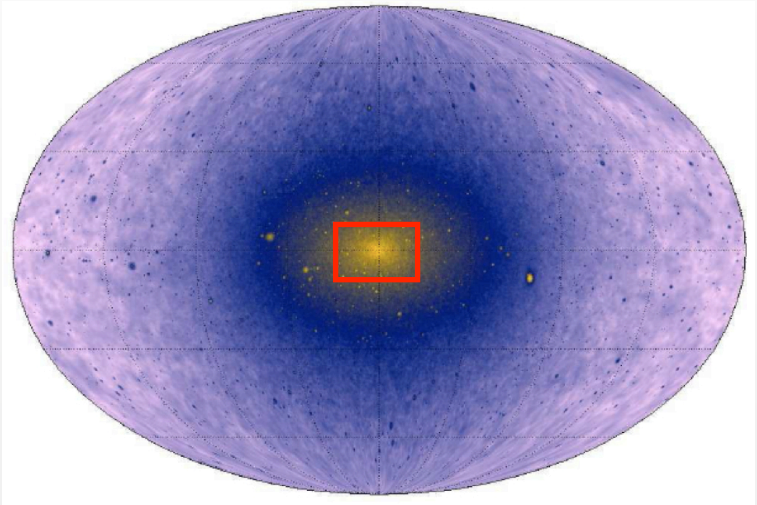
Shared by all dwarfs
(dark matter particle parameters)

Fit for each dwarf
(background sources)

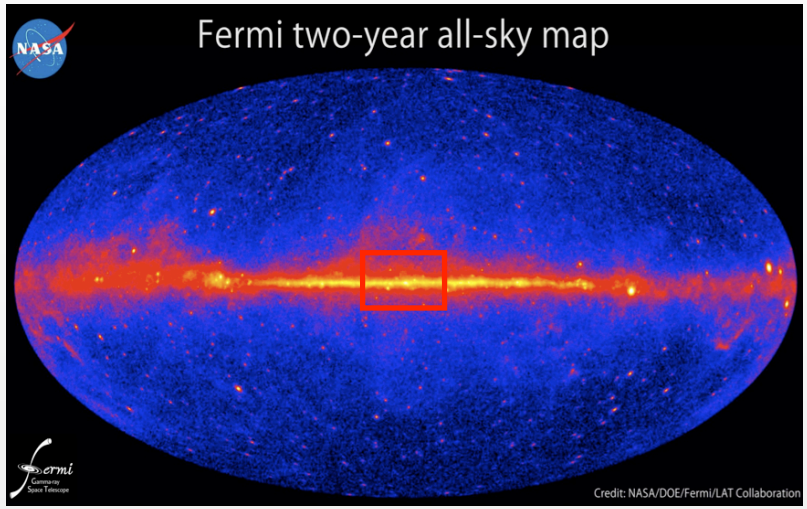
Uncertainty in J-factor

The Galactic center region

Predicted DM gamma ray signal.

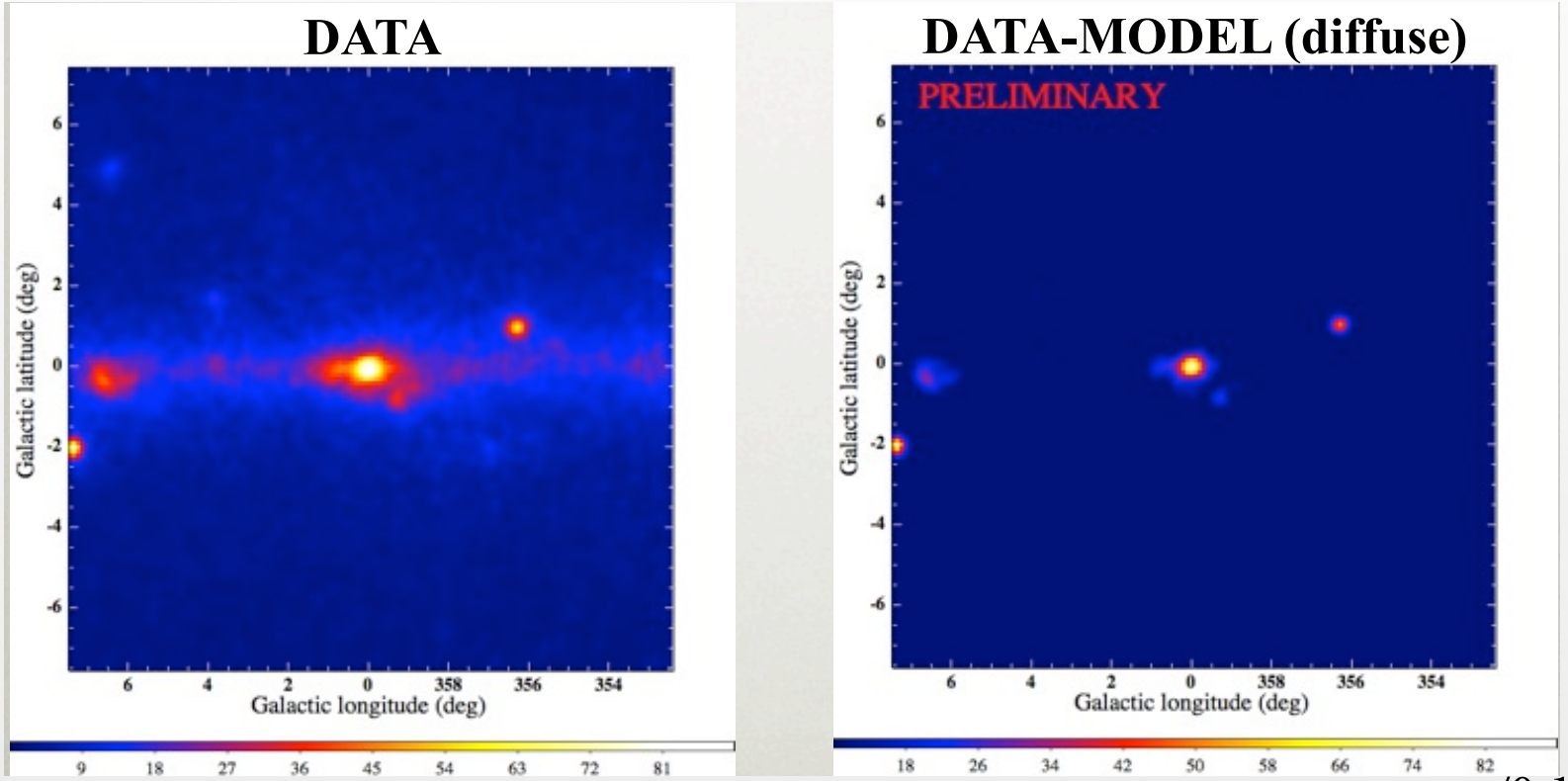


Diemand et. al, APJ, 2006.



Signal expectation potentially the highest ($\sim\rho^2/d^2$)
but astro background emission harder to model: strong interplay between *diffuse emission* and *numerous point sources*!

Modeling of the GC region

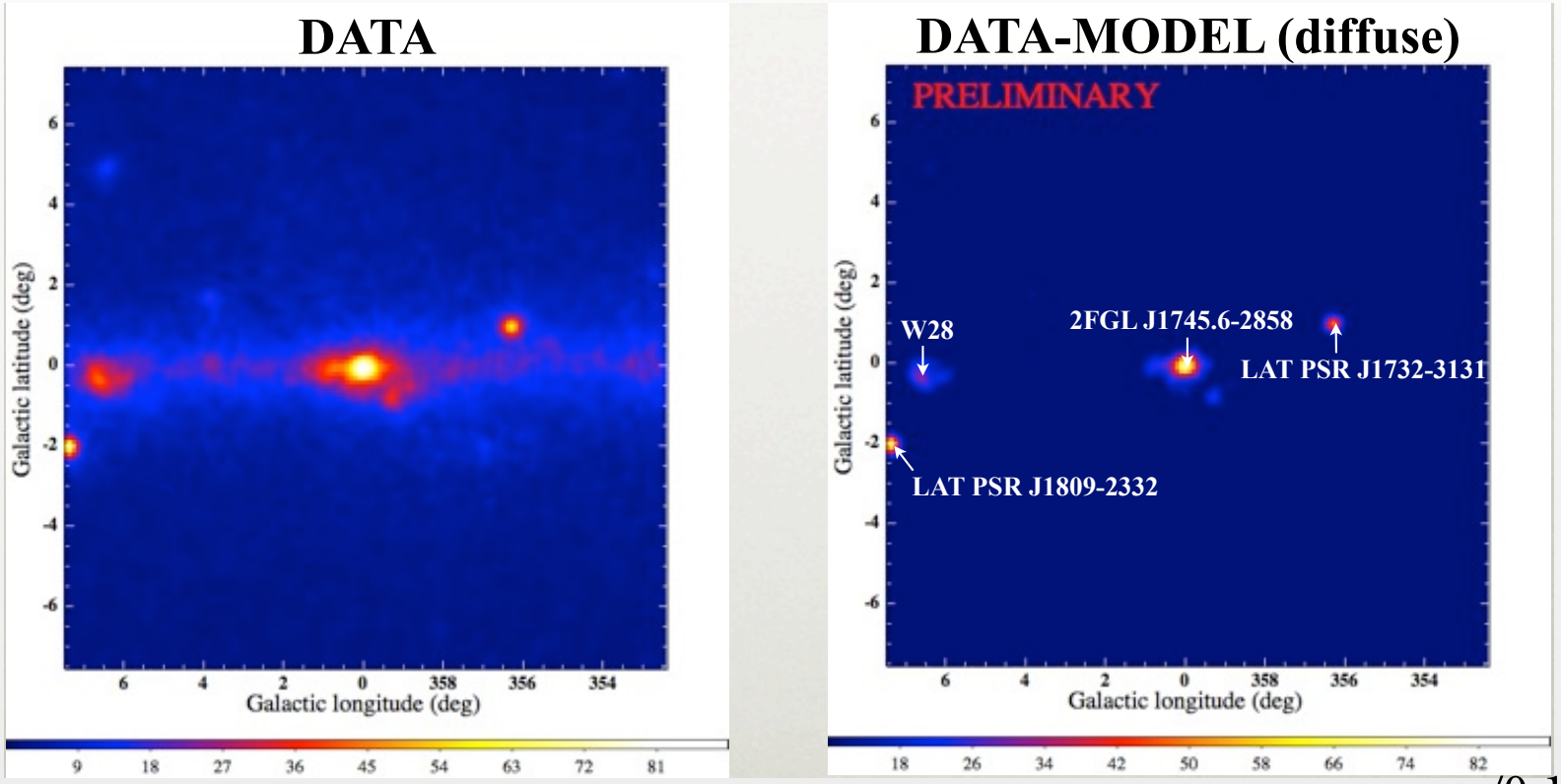


counts/0.1 deg^2

[S. Murgia, UCLA DM 2012]

data: 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT), ROI: 15x15 deg.
diffuse emission model: all sky GALPROP model tuned to the inner galaxy.

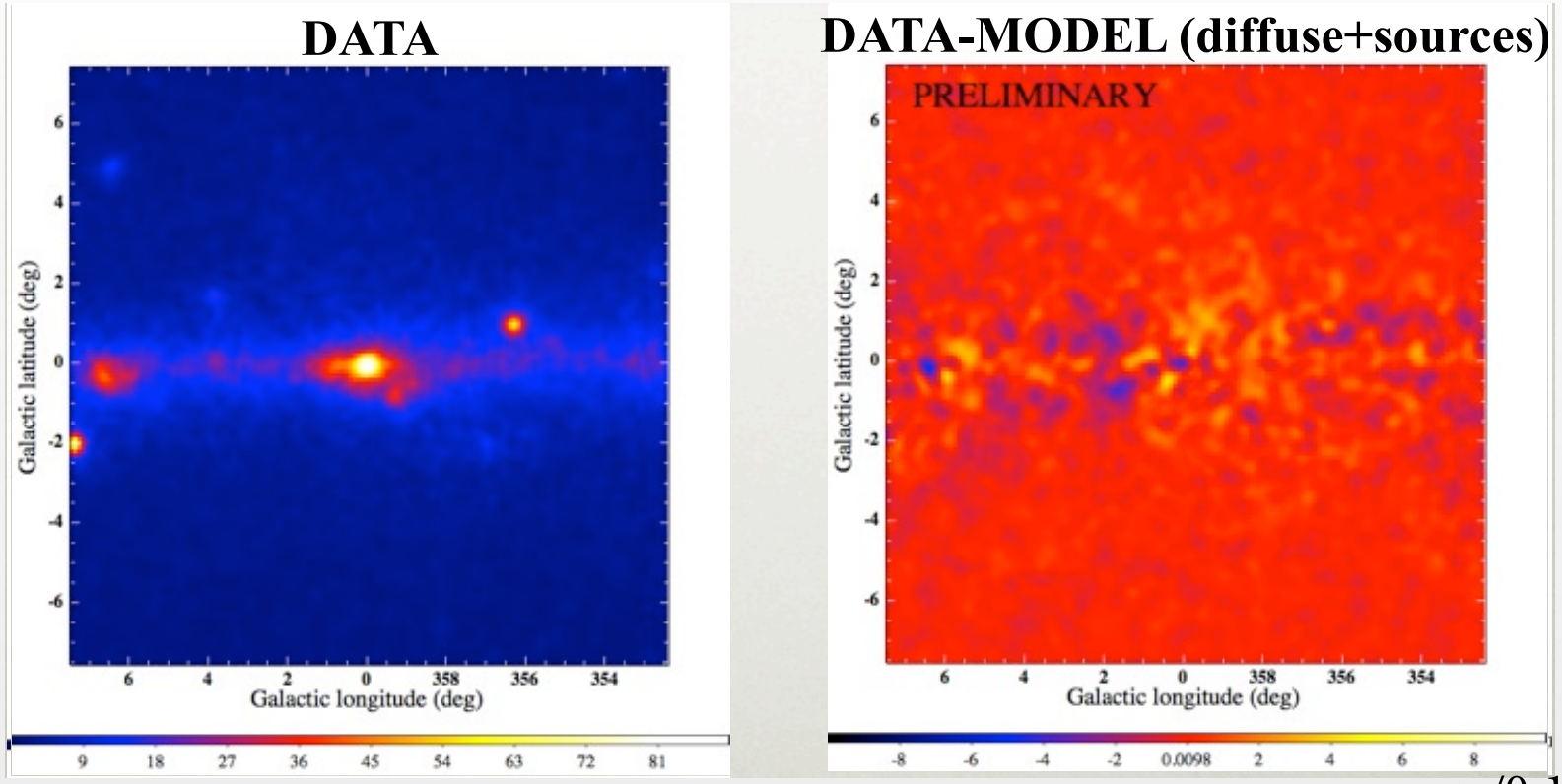
Modeling of the GC region



[S. Murgia, UCLA DM 2012]

Bright excesses after subtracting diffuse emission model are consistent with known sources.

Modeling of the GC region



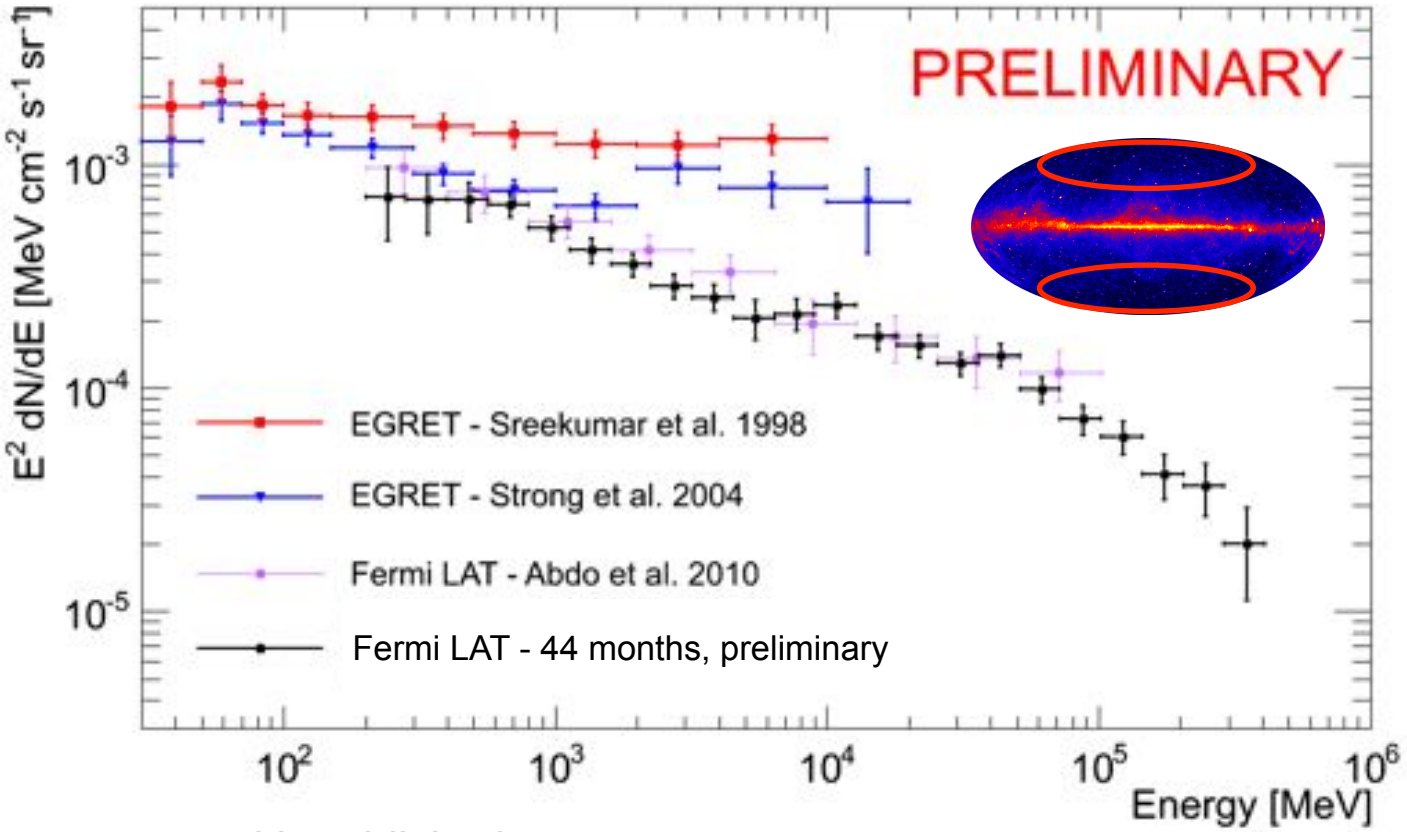
counts/0.1 deg^2

[S. Murgia, UCLA DM 2012]

Diffuse emission and point sources account for most of the emission observed in the region. Paper being finalized within collaboration.

Extra-Galactic sky

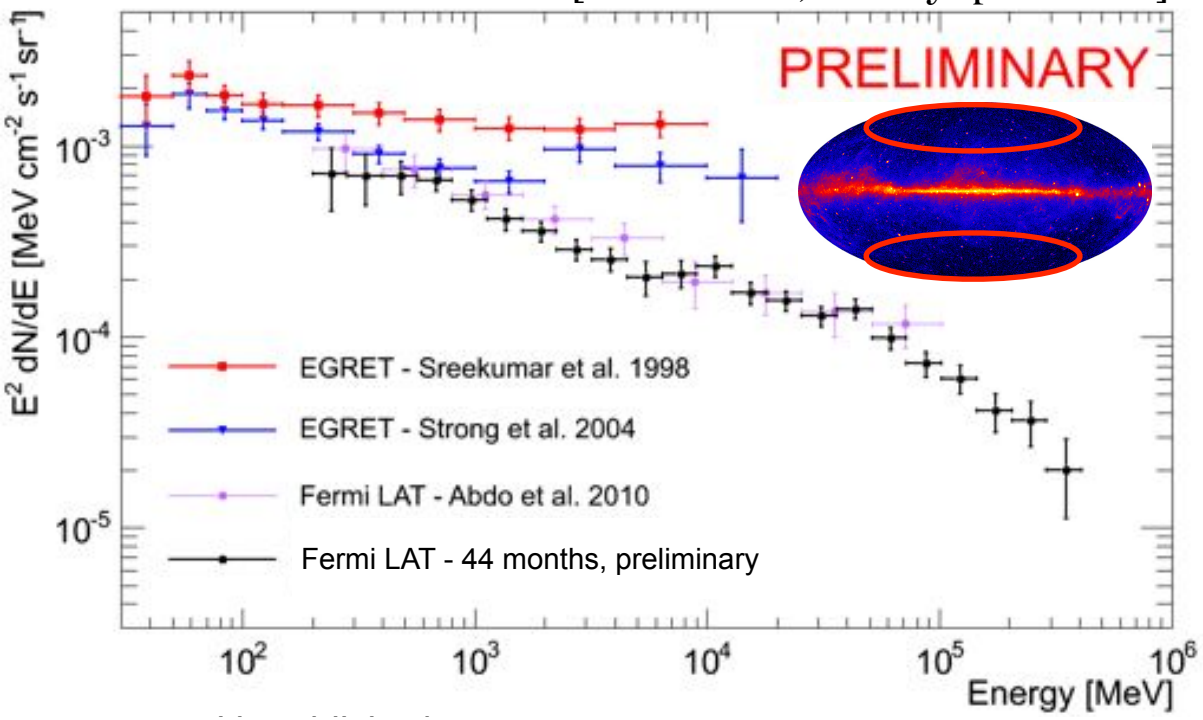
Spectrum of the isotropic diffuse emission (supposedly of an extraGalactic origin) has recently been measured to high energies <~400 GeV.



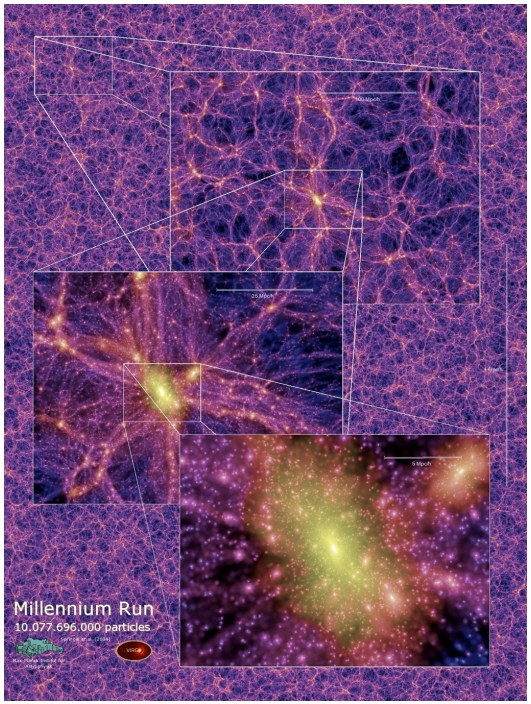
Extra-Galactic sky

Contributions from many source classes
– Normal galaxies (radio and star-forming)
– Active galactic nuclei (FSRQ & BL LACs)
– Dark matter?

[M. Ackermann, Fermi symposium 2012]

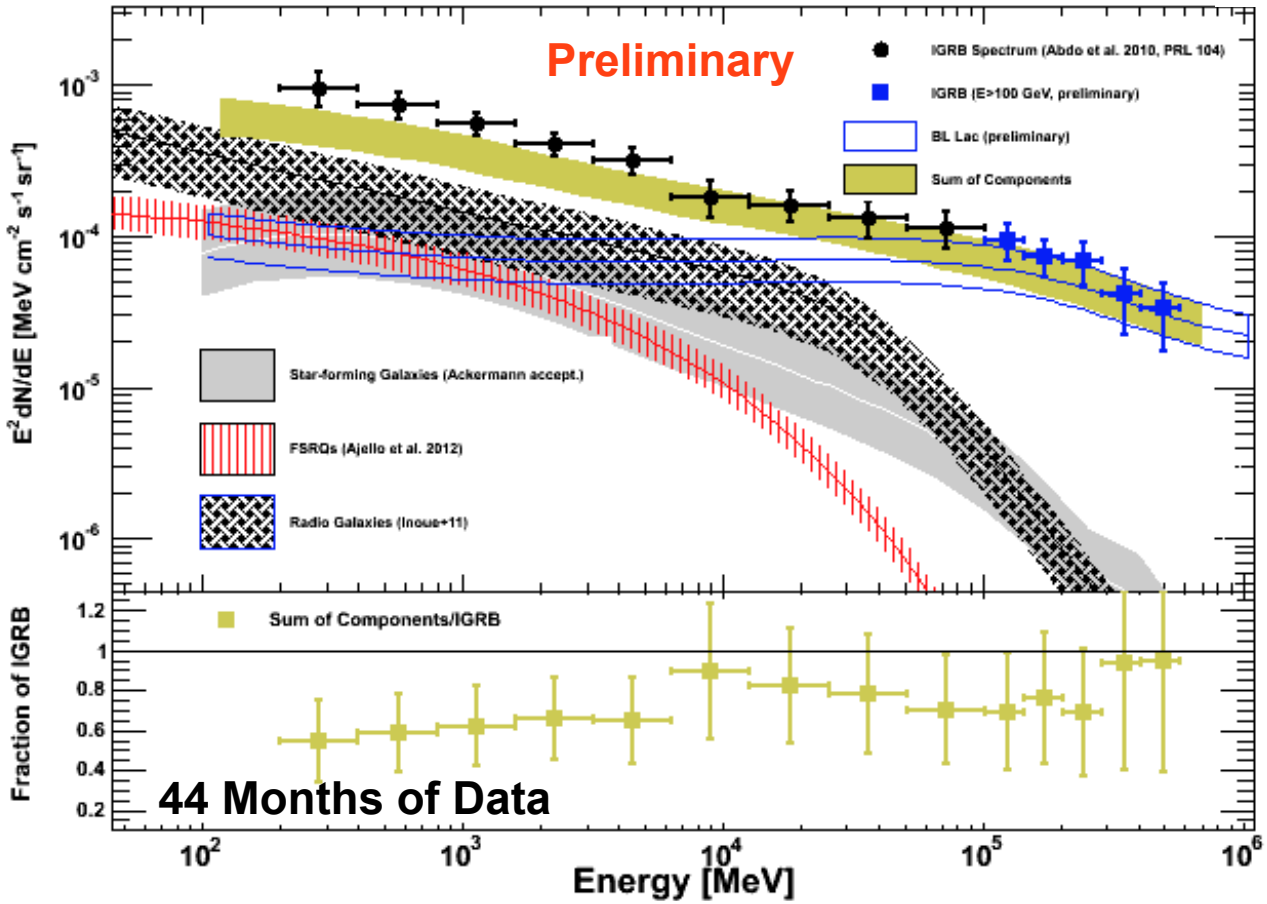


Dark matter annihilation in all halos at all red-shifts should contribute, too.



Extra-Galactic sky

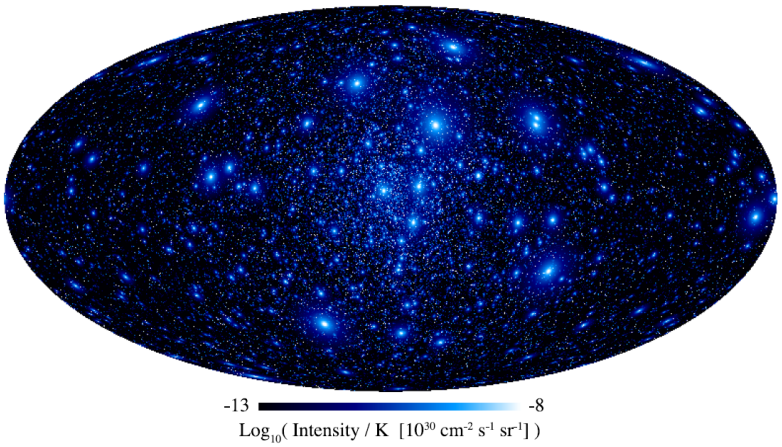
Fermi measured from the first time >500 sources above 10 GeV!
enough source classes to have good statistical sample and study their bulk properties!



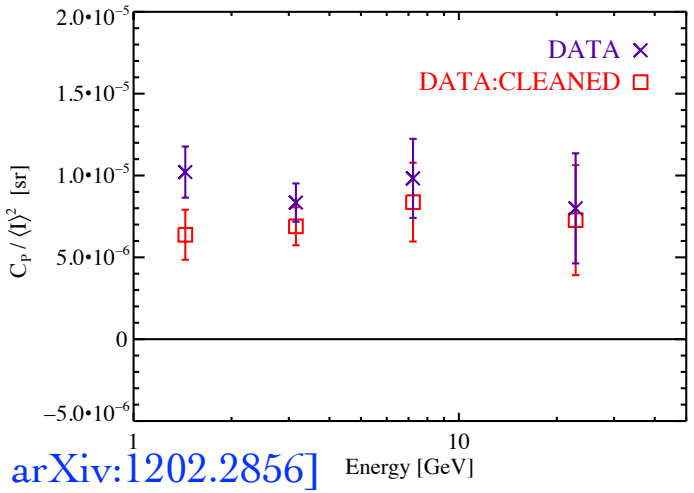
Extra-Galactic sky

Isotropic spectrum flux can be used to constrain the total extragalactic DM signal (summed over all DM halos and red shifts). -- work in progress.

However one can use an additional handle: **small angular scale fluctuations in the diffuse gamma-ray background** -> measured for the first time with the Fermi LAT!



Fluctuation anisotropy energy spectrum

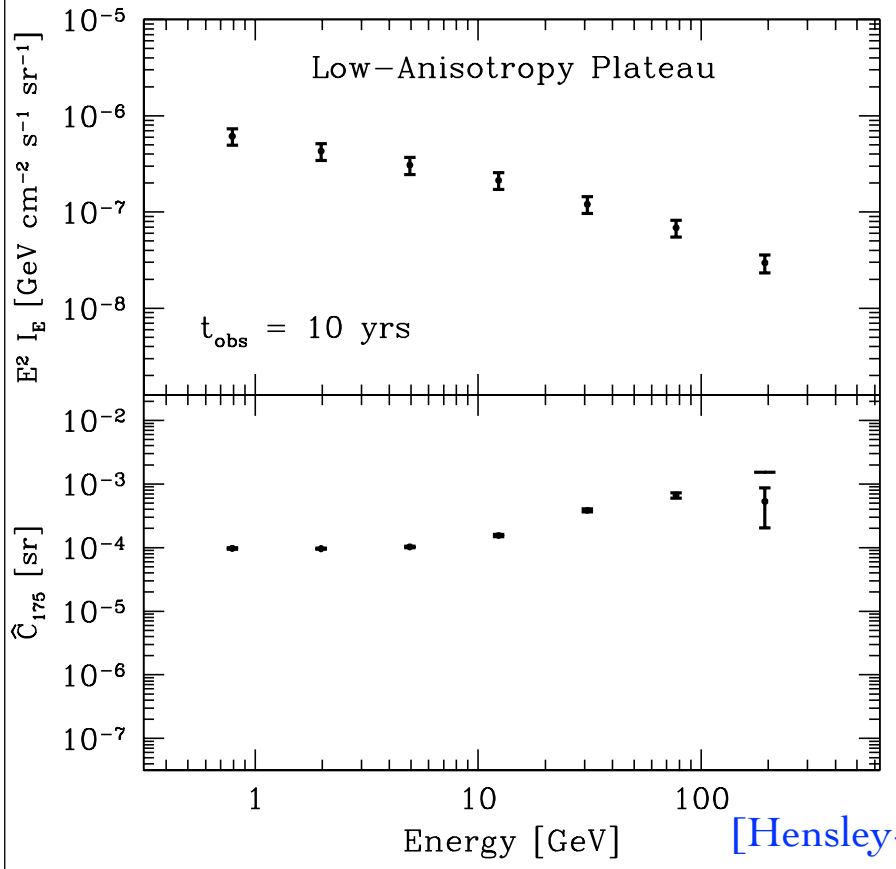


[Ackermann+, arXiv:1202.2856]

Extra-Galactic sky

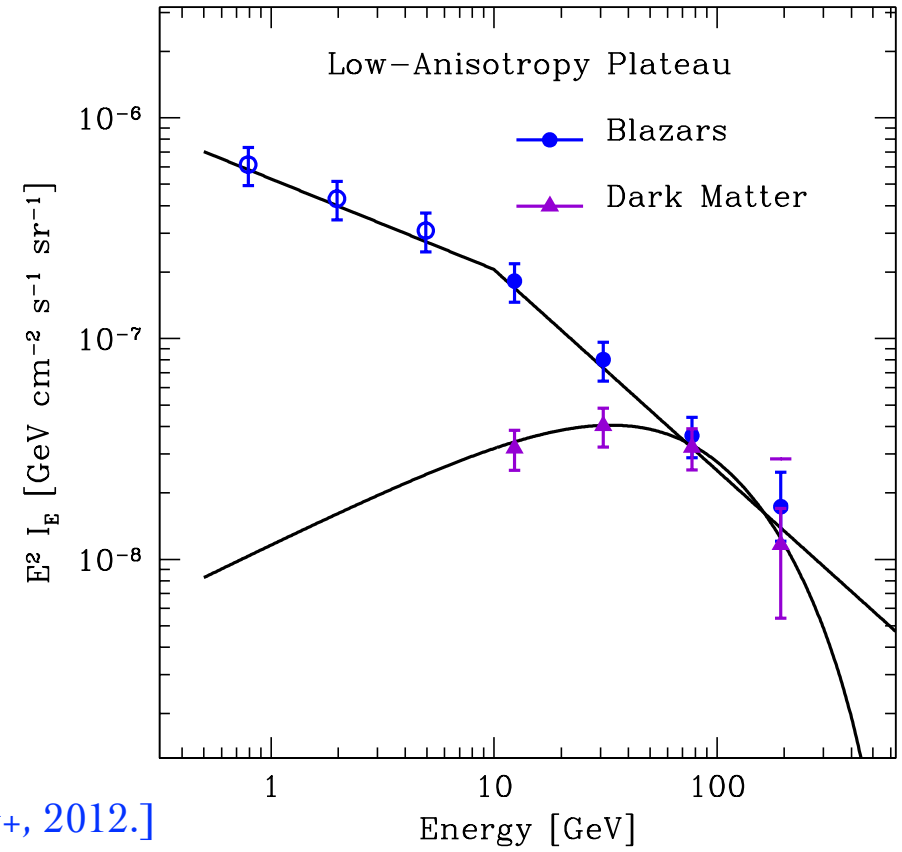
or, one case use BOTH intensity spectrum and the anisotropy spectrum to RECONSTRUCT the components of the energy spectrum.

Example observed intensity spectrum and anisotropy energy spectrum



[Hensley+, 2012.]

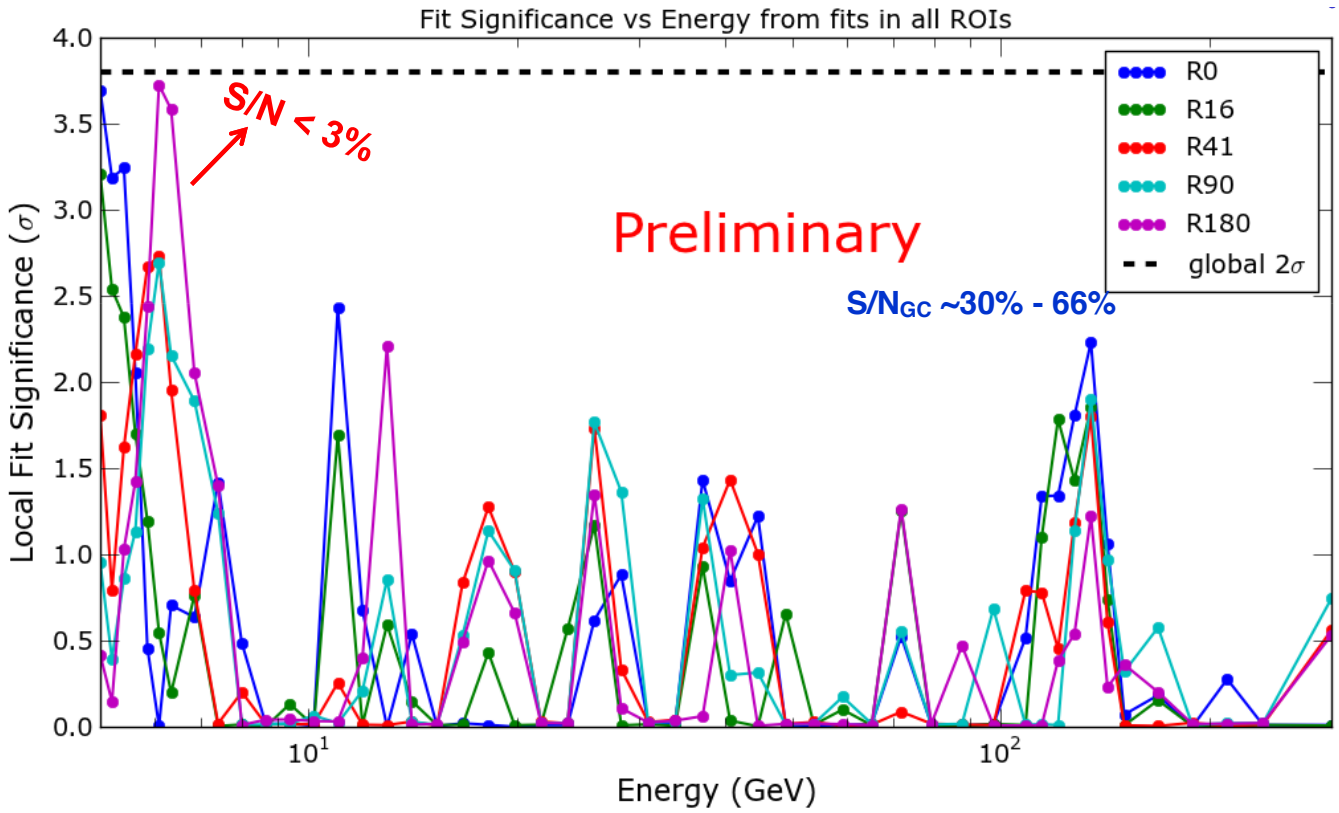
Decomposed energy spectra



Spectral line search

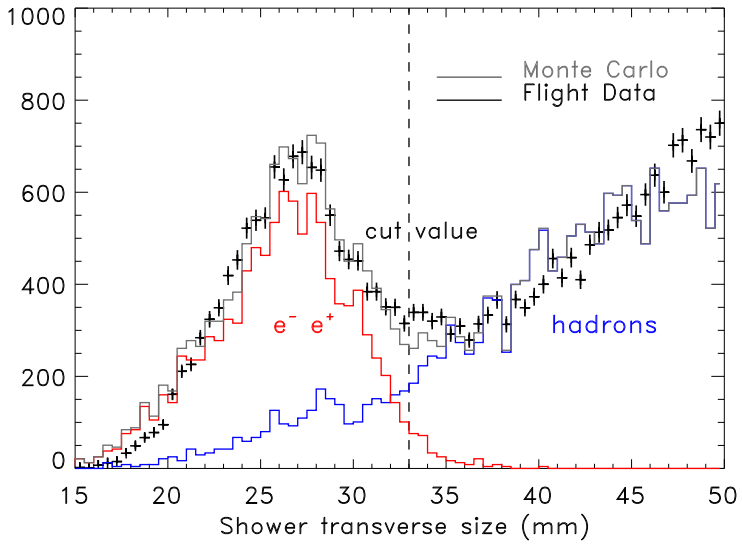
No signal found in a blind search.

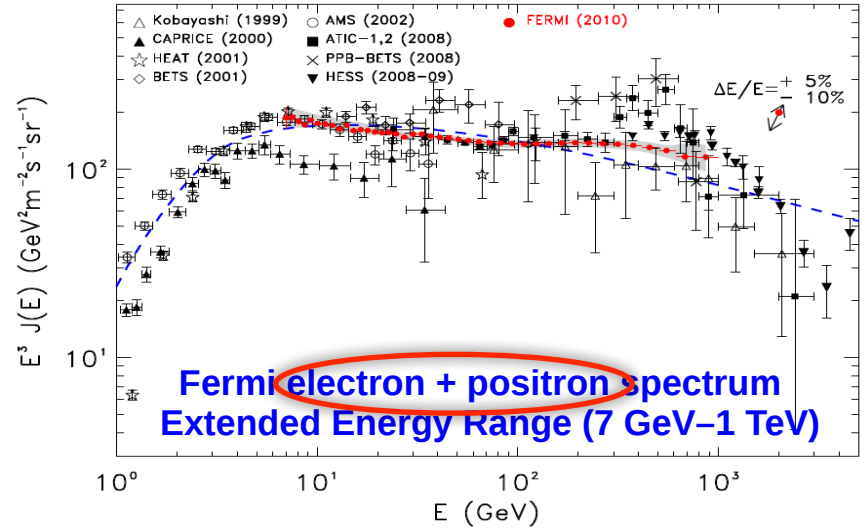
The huge statistics at low energies -> small uncertainties in the collecting area can produce statistical significant spectral features.



Science

3) Cosmic ray electrons/positrons.



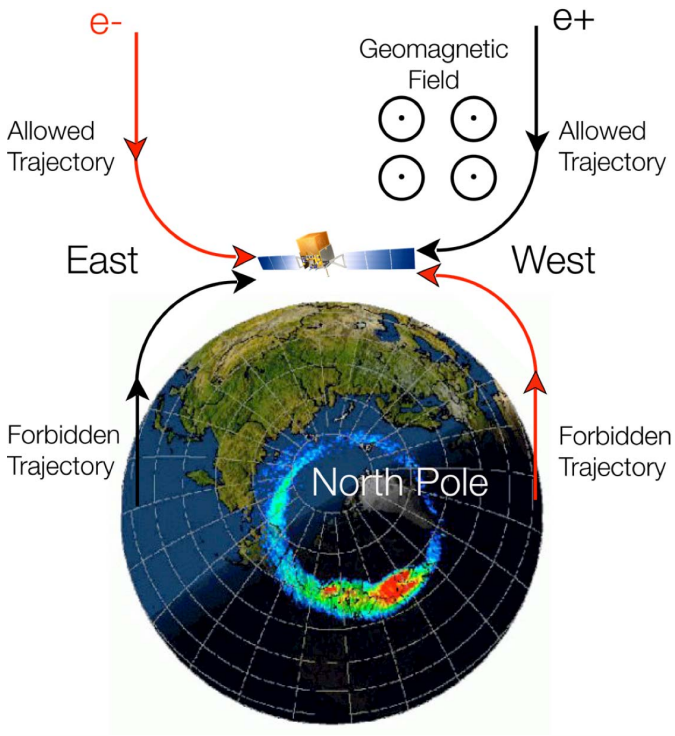


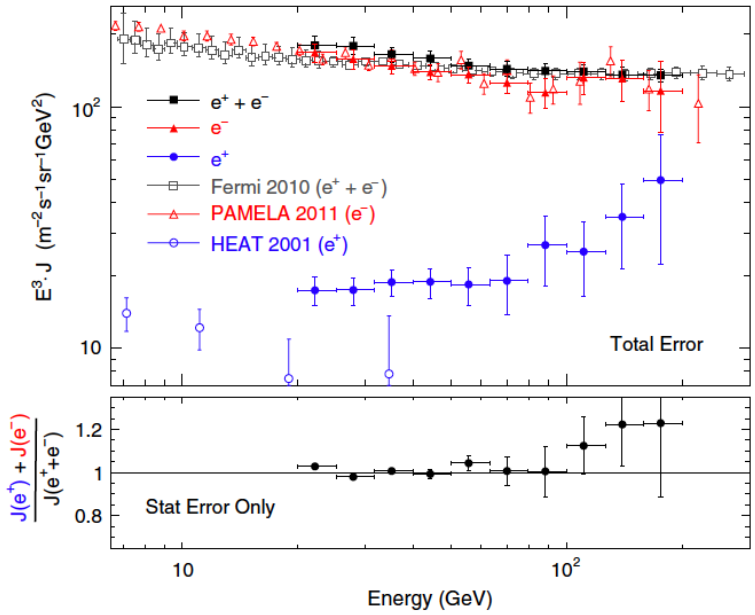
Ackermann, M. et al., Phys. Rev. D 82, 092004 (2010)

Since it records electromagnetic cascades, the LAT is also by its nature a detector for electrons and positrons.

Science

3) Cosmic ray electrons/positrons.



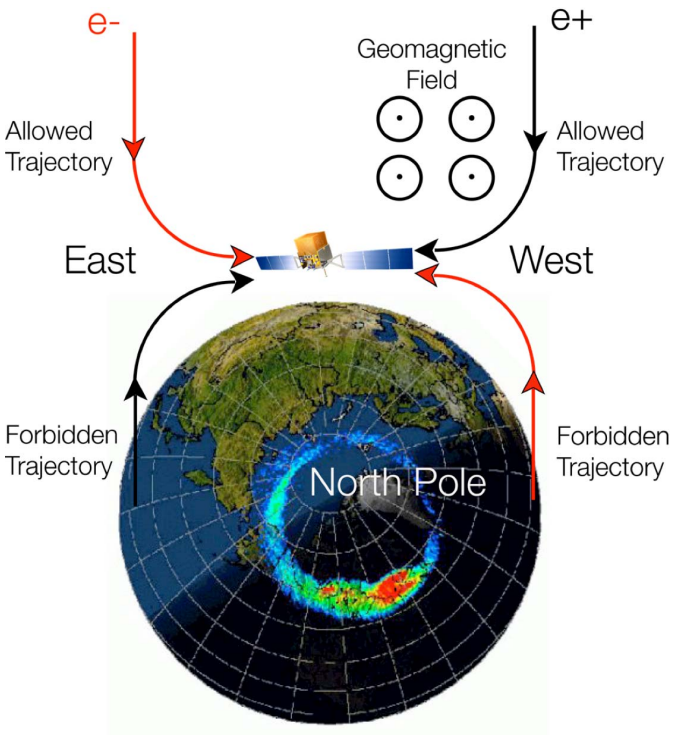


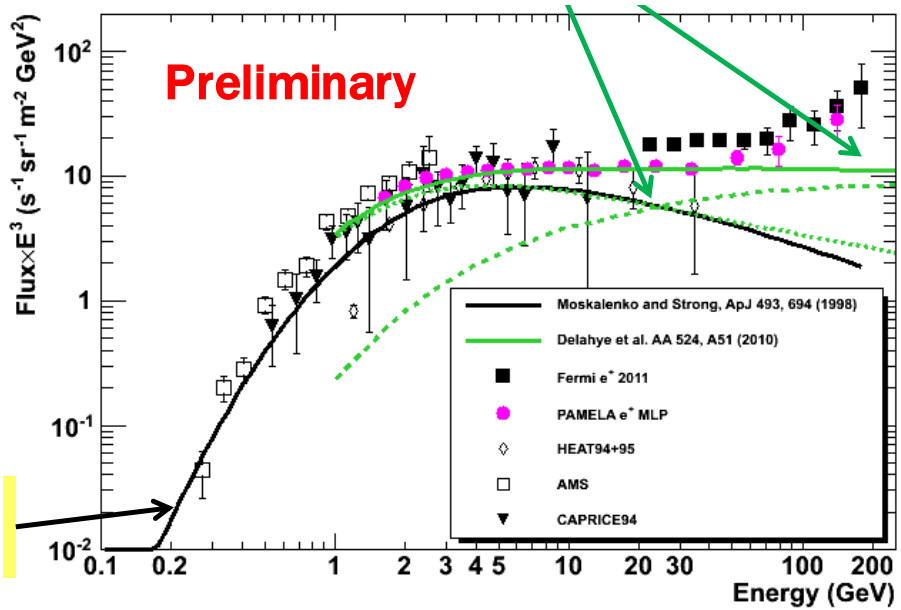
[Ackermann+, 2011, PRL 108, 011103.]

Recent search used Earth's shadow to measure independently electron AND positron spectra (note: Fermi does not carry a magnet!).
confirm PAMELA finding of an increasing positron fraction.

Science

3) Cosmic ray electrons/positrons.



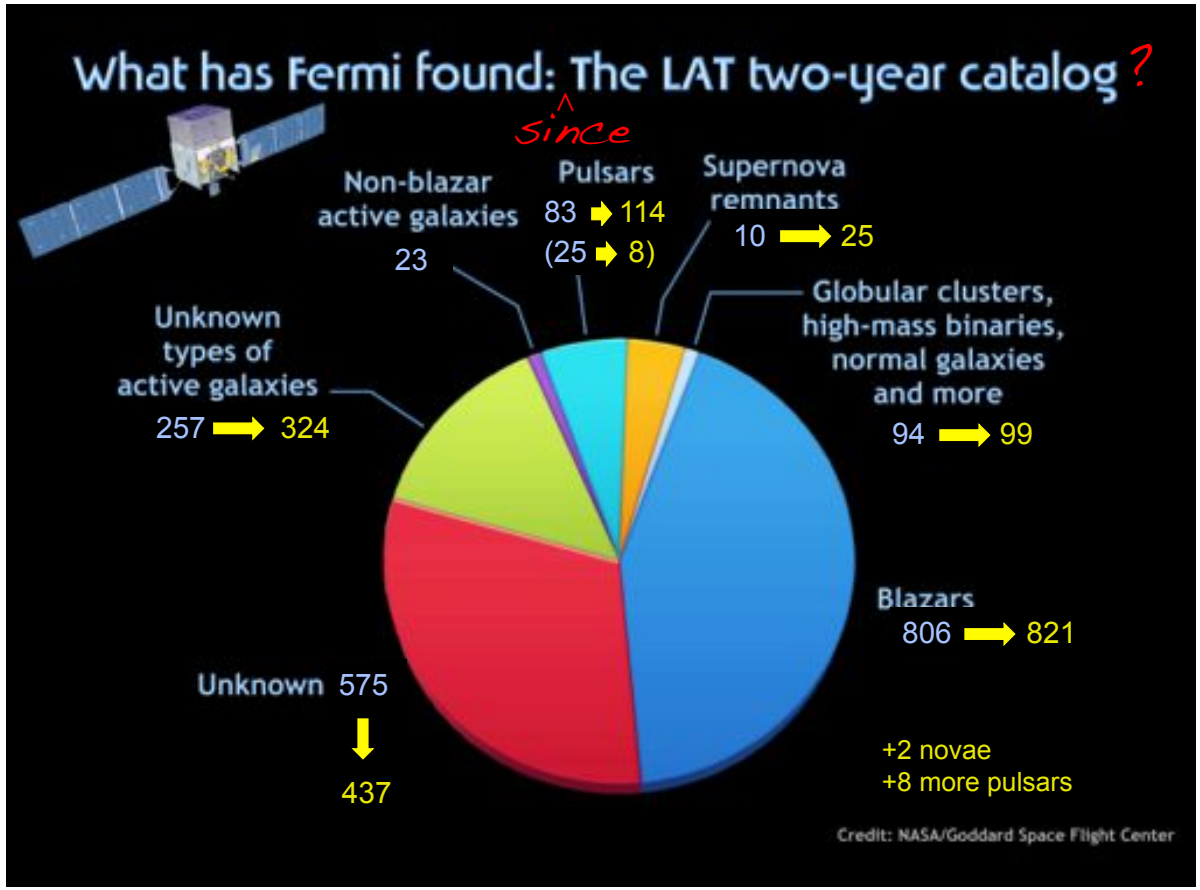


[M. Boezio, UCLA 2012.]

Recent search used Earth's shadow to measure independently electron AND positron spectra (note: Fermi does not carry a magnet!).
confirm PAMELA finding of an increasing positron fraction.

Science

2) Point sources:~1900 sources in the 2FGL.

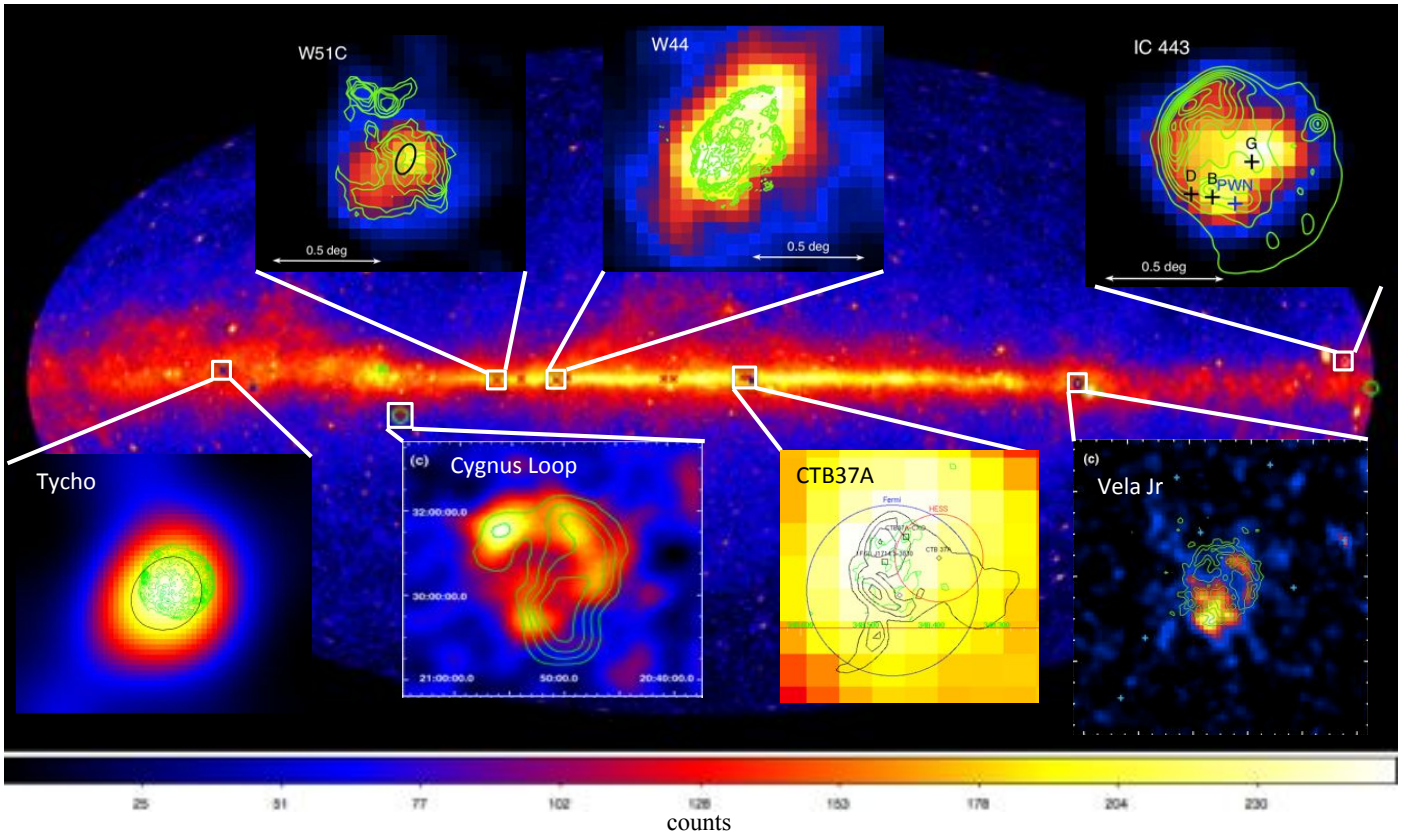


[E. Ferrara, Fermi Symposium 2012]

Science

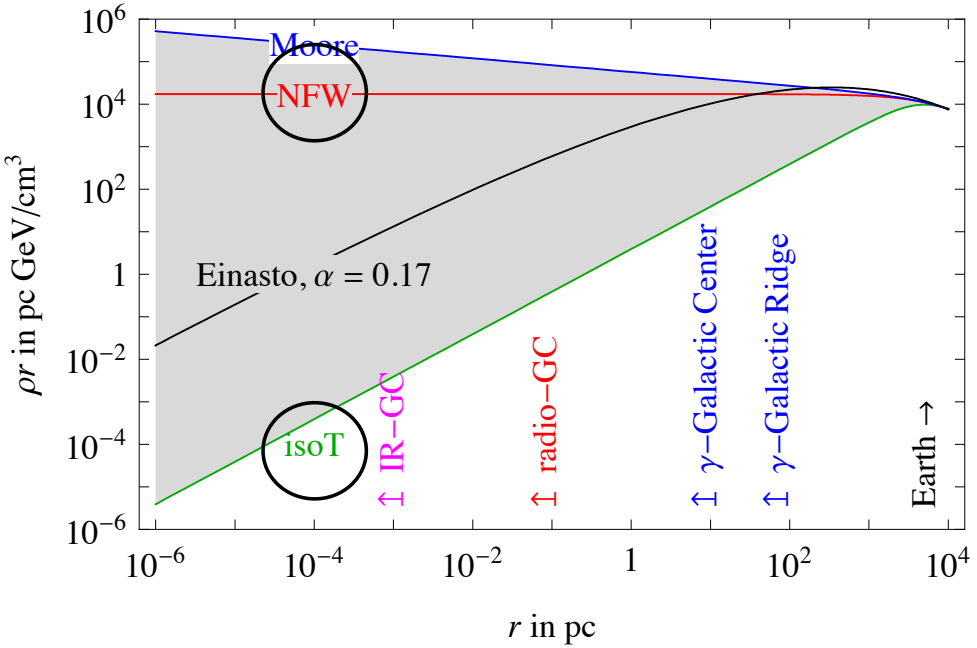
1. Point sources:
2. Diffuse emission
3. Cosmic ray electrons/positrons
4. ...

13 identified SNRs, including - 9 interacting - 4 young SNRs + 43 2FGL candidates
first fermi catalog of SNRs



DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.
Two DM density profiles:
i) NFW and
ii) Isothermal DM profiles.



$$\text{NFW:}\quad \rho(r) = \rho_0 \left(1+\frac{R_S}{R_0}\right)^2 \frac{1}{\frac{r}{R_S}\left(1+\frac{r}{R_0}\right)^2}$$

$$\text{Isothermal:}\quad \rho(r) = \rho_0 \frac{R_S^2+R_c^2}{r^2+R_c^2}.$$

ρ_0=0.43 GeV/cm^3,
R_c=20 kpc (NFW), 2.8 kpc (Iso)

In our ROI, at
5<b<15deg →r ~1 kpc
the two profiles are quite similar
(advantage to Galactic Center studies, for example)

DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.
Two DM density profiles:

i) annihilating ($\chi\chi \rightarrow$ SM SM) characterized by annihilation cross section $\langle \sigma v \rangle$ and

ii) decaying ($\chi \rightarrow$ SM SM) characterized by the life time τ.

DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.
Three DM annihilation/decay channels:

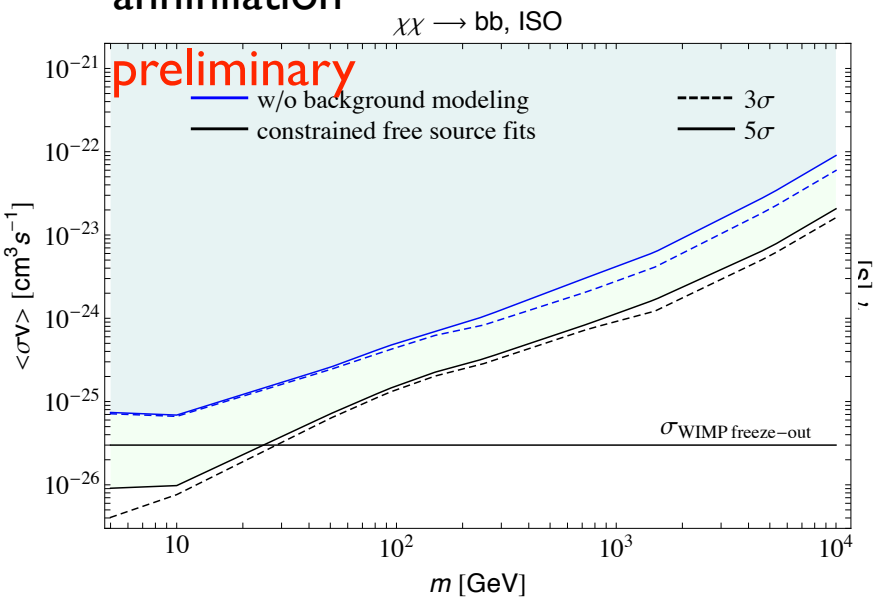
i) $\chi\chi/\chi \rightarrow b\bar{b}$

ii) $\chi\chi/\chi \rightarrow \mu\mu$

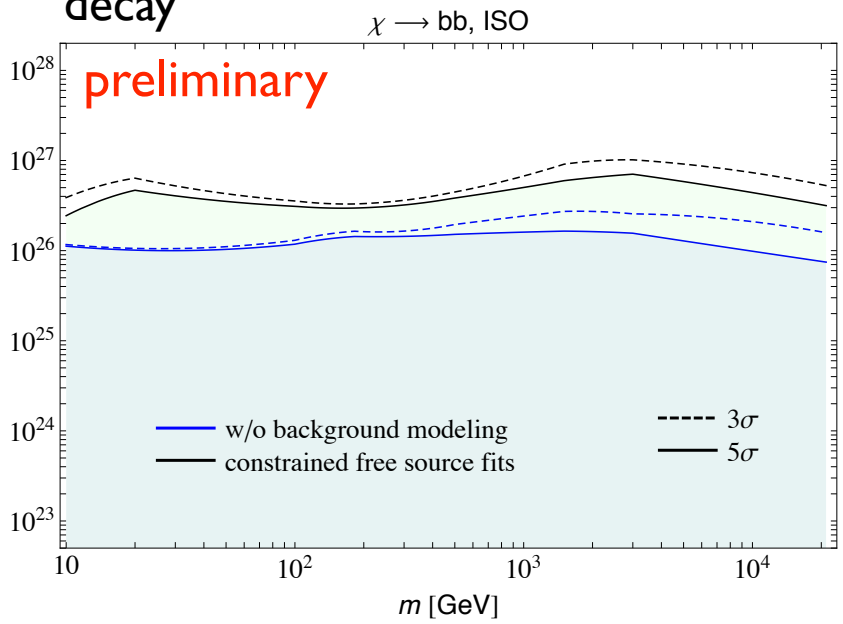
iii) $\chi\chi/\chi \rightarrow \tau\tau$

Results: $\bar{b}b$ channel

annihilation



decay



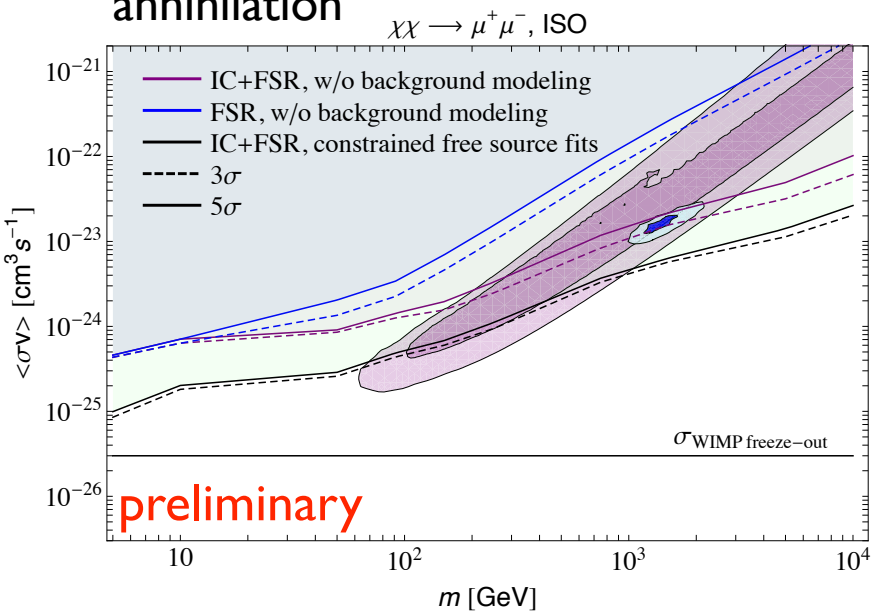
Blue: "no-background limits".

Black: limits obtained by marginalization over the CR source distribution, diffusive halo height and electron injection index, gas to dust ratio, *in which CR sources are held to zero in the inner 3 kpc.*

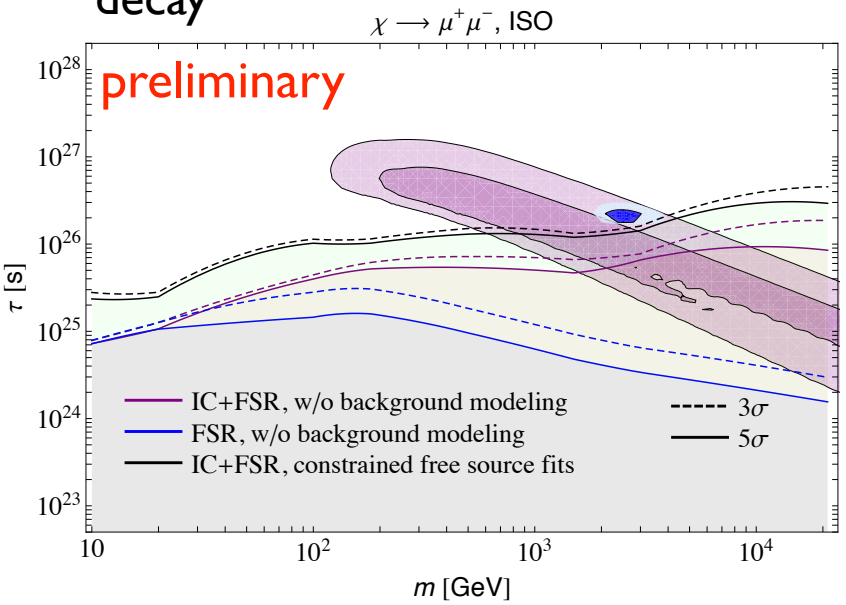
Limits with *NFW* profile (not shown) are only slightly better.

Limits: μ+μ−channel

annihilation



decay



Blue: here we used only photons produced by muons to set "no-background limits" ('FSR only').

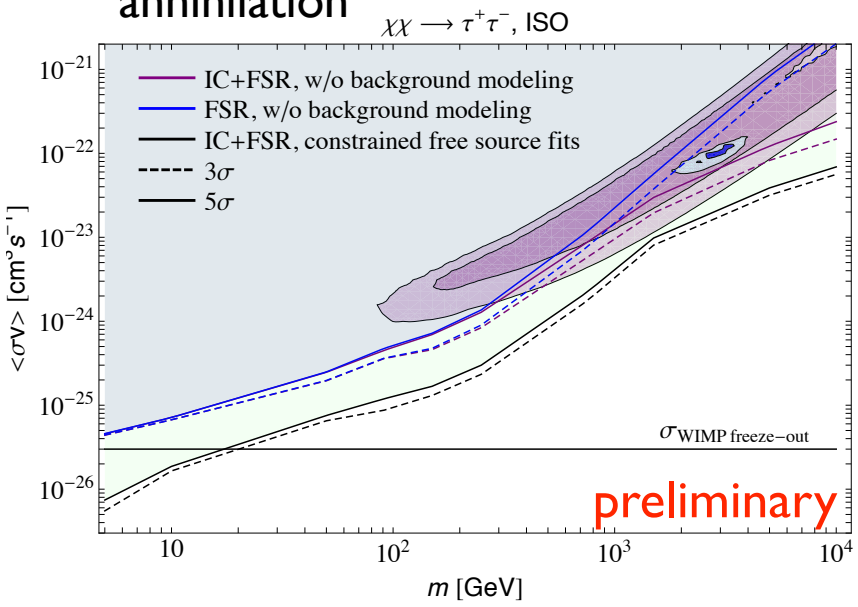
Violet: "no-background limits" FSR+IC

Black: limits from profile likelihood and *CR sources set to zero in the inner 3 kpc.*

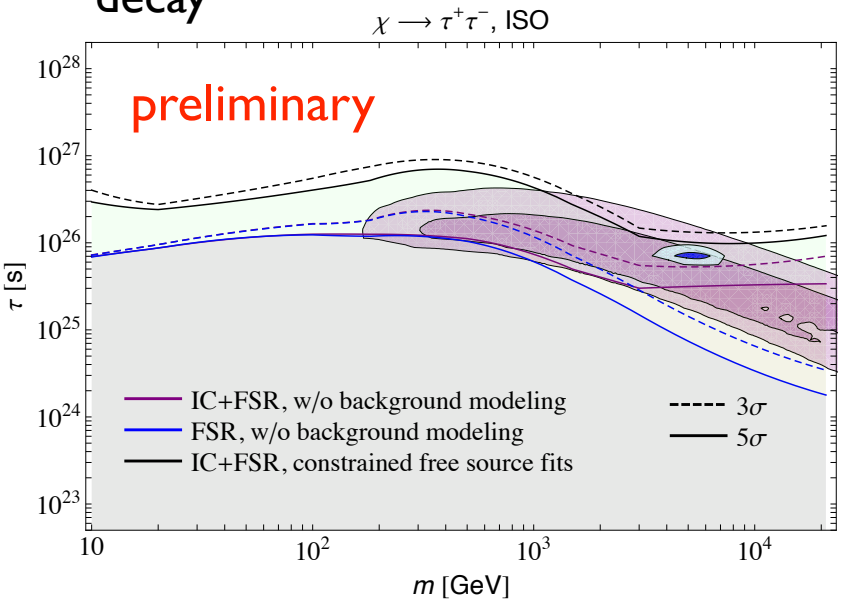
DM interpretation of PAMELA/Fermi CR anomalies strongly disfavored (for annihilating DM).

Limits: τ+τ−channel

annihilation



decay



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