Latest Results on Dark Matter and New Physics Searches with Fermi

Simona Murgia, SLAC-KIPAC
on behalf of the Fermi-LAT Collaboration

TeV Particle Astrophysics 2009
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Fermi Gamma-ray Space Telescope

SLAC NATIONAL ACCELERATOR LABORATORY

DM and New Physics Searches with Fermi-LAT

- Fermi-LAT probes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity and it is also an excellent electron+positron detector
- Its great capabilities give us a unique perspective in investigating the existence of WIMPs indirectly, primarily through their annihilation or decay into photons and into electrons
- Indirect detection of a dark matter signal is complementary to direct detection and collider searches and provides invaluable information on the distribution of dark matter in space

➡ This talk: overview of recent results of dark matter and new physics searches after more than 1 year in orbit!

Annihilation Signal

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

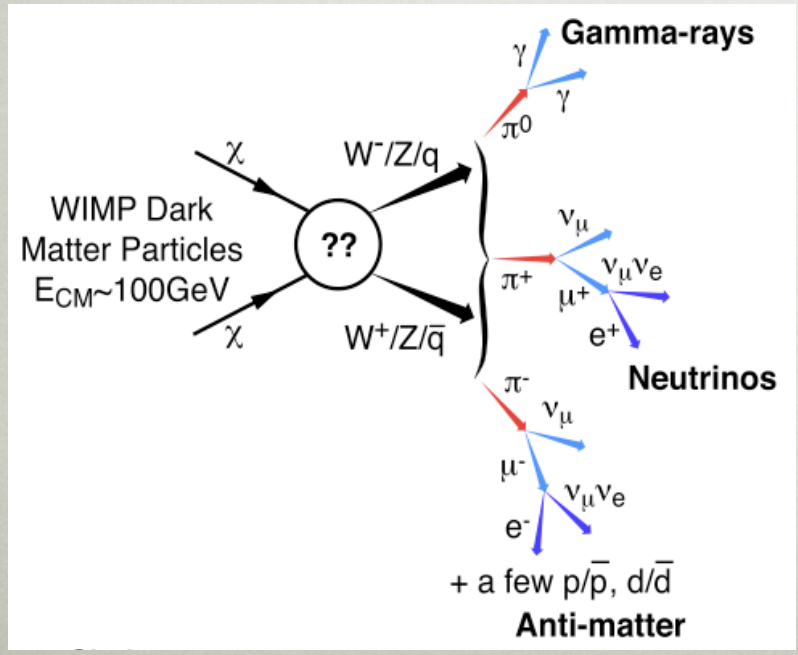
DM distribution

WIMP Signal

Continuum spectrum with cutoff at M_W

- For examples photons (or e^+e^-) from annihilation of neutralinos or KK dark matter

Neutralino annihilation into γ



Spectral line at M_W

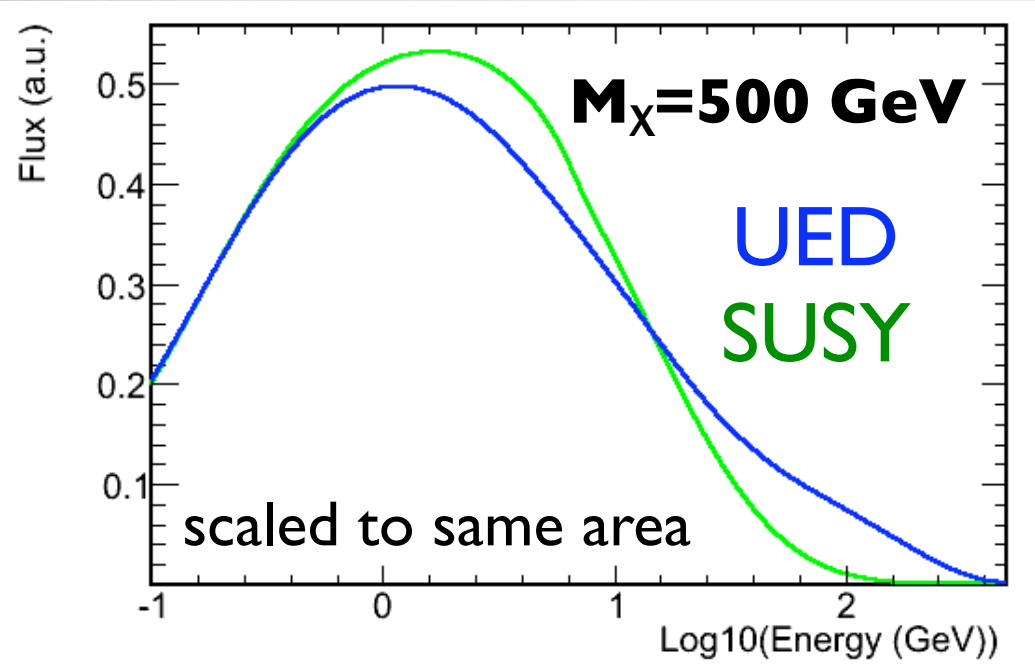
- Detection of prompt annihilation or decay into photons would provide a smoking gun signal for exotic physics
- Line signal can be strongly suppressed but enhancements are predicted in some models (e.g. gravitino decay)

UED vs SUSY

- Consider the photon spectrum from 500 GeV WIMP annihilation in SUSY and in UED:

  UED: photons mostly from lepton bremsstrahlung

  SUSY: photons mostly from b quark hadronization and then decay, energy spread through many final states lower photon energy. p-wave dominated cross-section yields lower photon fluxes for equal masses



➡ **Spectra can look very different in these scenarios**

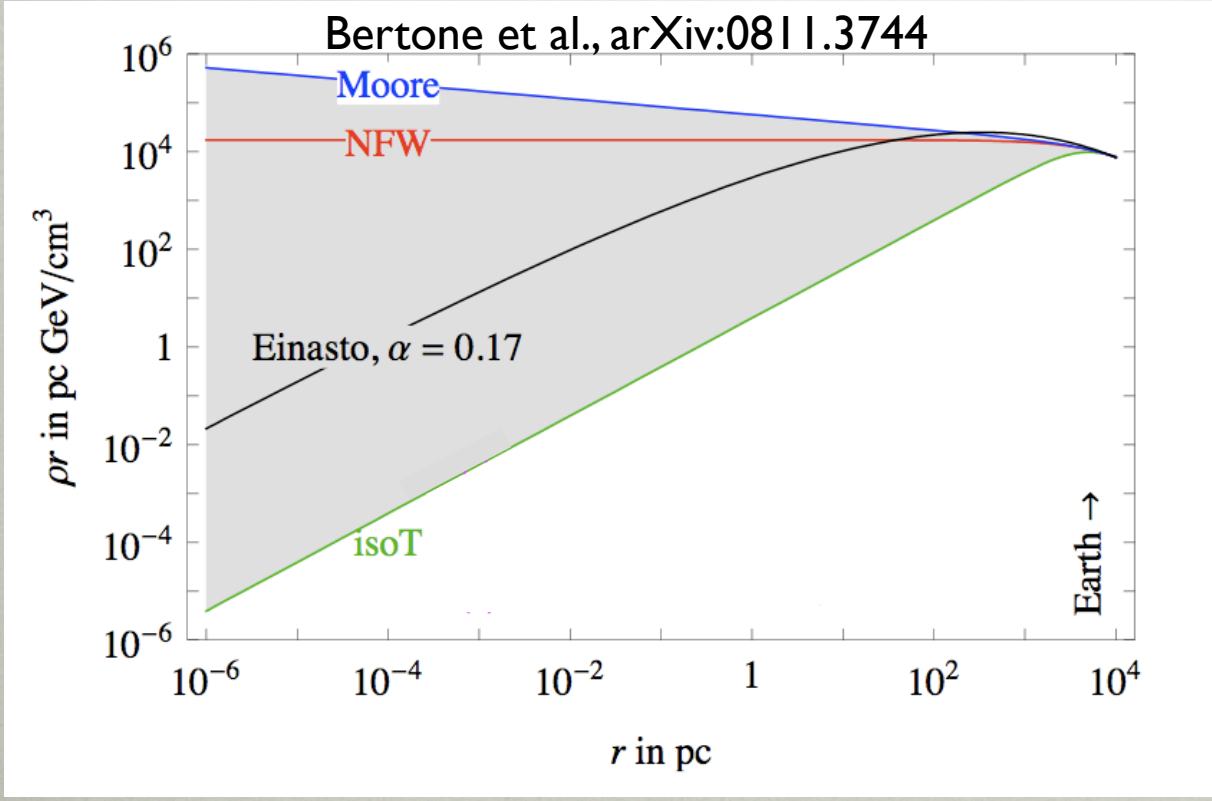
mSUGRA parameters:

$$m_0 = 500 \text{ GeV}$$
$$m_{1/2} = 1160 \text{ GeV}$$
$$A_0 = 0, \ \tan\beta = 10$$

Spectra generated with micromegas:
G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 174 (2006) 577; hep-ph/0405253
G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 149 (2002) 103; hep-ph/0112278

Dark Matter Distribution

- The dark matter annihilation (or decay) signal strongly depends on the dark matter distribution.
- Cuspier profiles and clumpiness of the dark matter halo can provide large boost factors



NFW profile

$$\rho(r) = \rho_0 \frac{r_0}{r} \frac{1 + (r_0/a_0)^2}{1 + (r/a_0)^2}$$

$$\rho_0 = 0.3 \text{ GeV/cm}^3$$

$$a_0 = 20 \text{ kpc}, \; r_0 = 8.5 \text{ kpc}$$

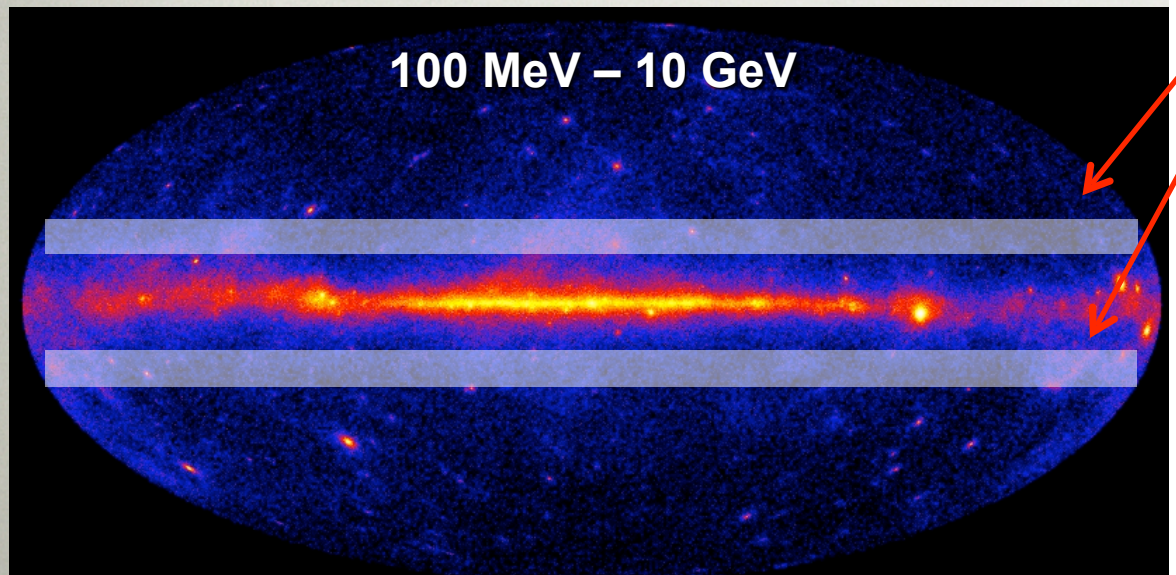
✓ Via Lactea II predicts a cuspier profile, $\rho(r) \propto r^{-1.2}$

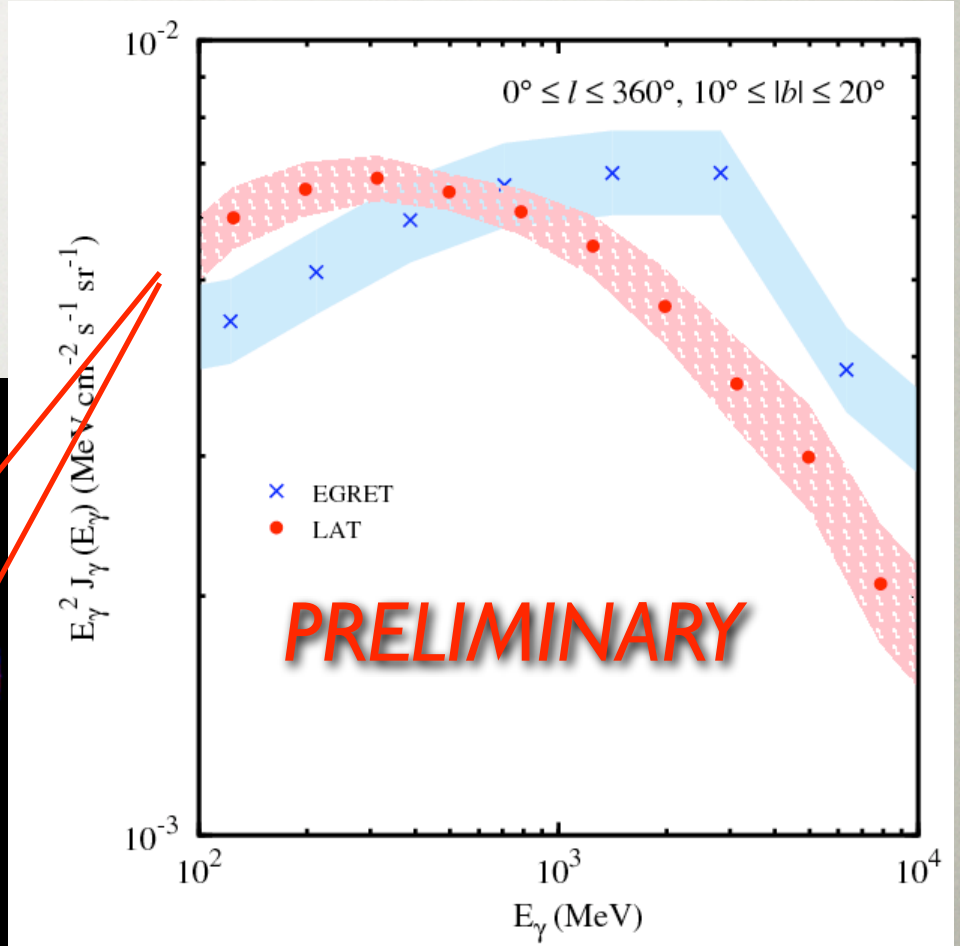
✓ Aquarius predicts a shallower than r^{-1} innermost profile

Galactic Diffuse Emission

- EGRET observed an all sky excess in the GeV range compared to predictions from cosmic ray propagation and γ ray production models consistent with local cosmic-ray nuclei and electron spectra
- <u>The data collected by the LAT from mid-August to end of December does not confirm the excess at intermediate latitudes</u>
- Sources are not subtracted (minor component)
  LAT error is systematic dominated
  (~10%, preliminary)

➡ Strongly constrains DM interpretations

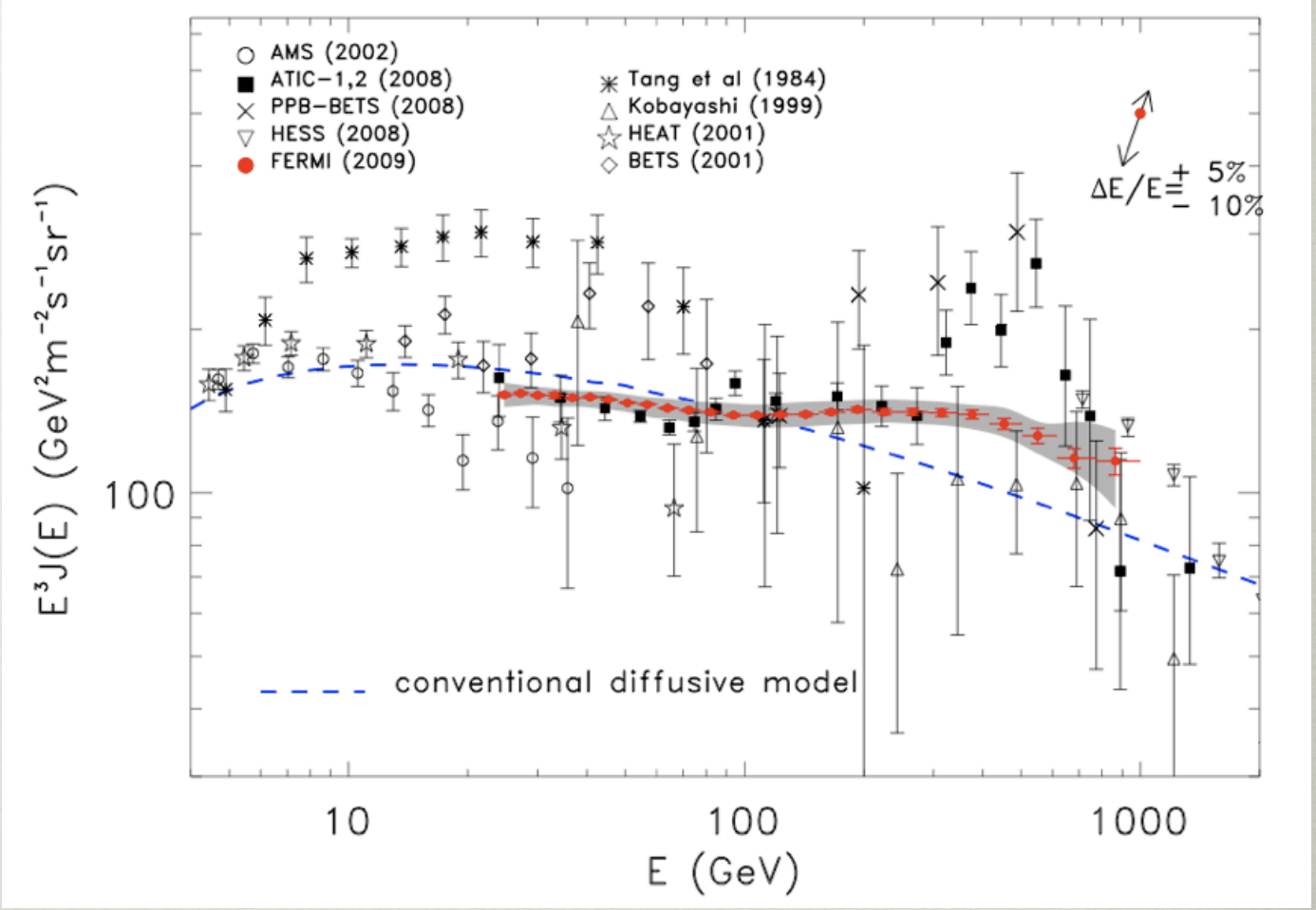




Fermi CRE Spectrum

Phys. Rev. Lett. 102, 181101 (2009)

- High statistics: ~4.5M events in 6 months
  - Errors dominated by systematic uncertainties
- Not compatible with the pre-Fermi data diffusive CR model ($E^{-3.3}$ whereas we measured $E^{-3.0}$)

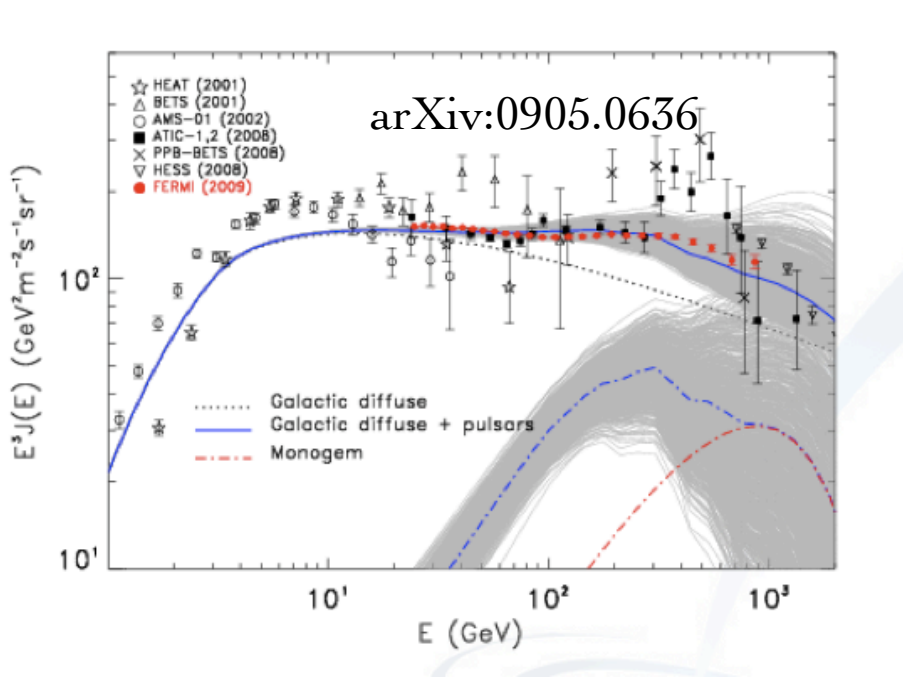


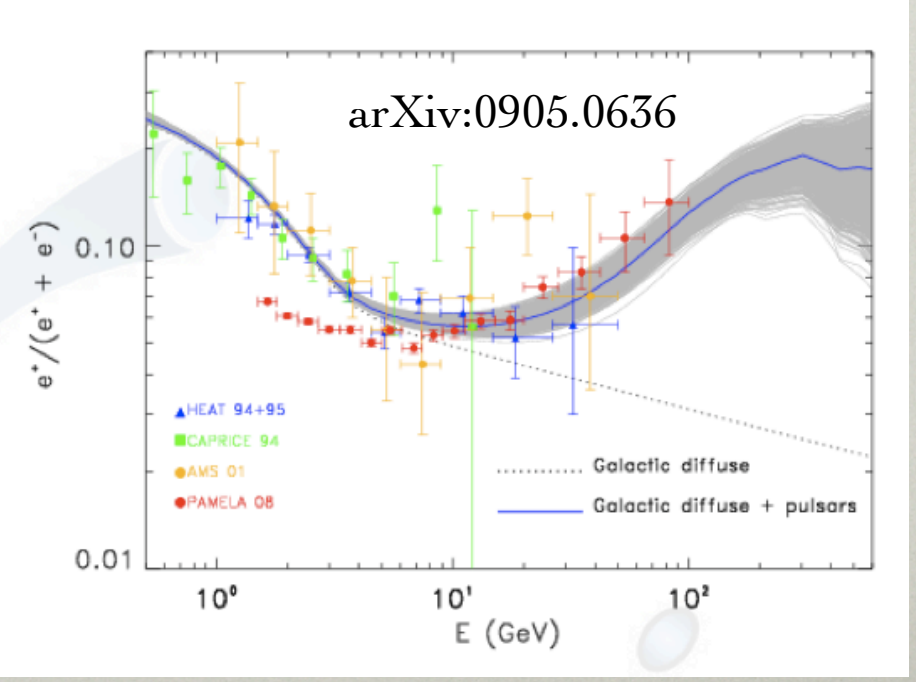
➡ No evidence of a prominent spectral feature

Nearby Pulsars & DM

- Consider contribution from suitable pulsar populations (from the ATNF catalog): nearby (within 3 kpc), mature but not too old (5×10^4 to 10^7 yr)
- Provides reasonable interpretation for Fermi, PAMELA and HESS data

➡ DM contribution is not required, however cannot be ruled out





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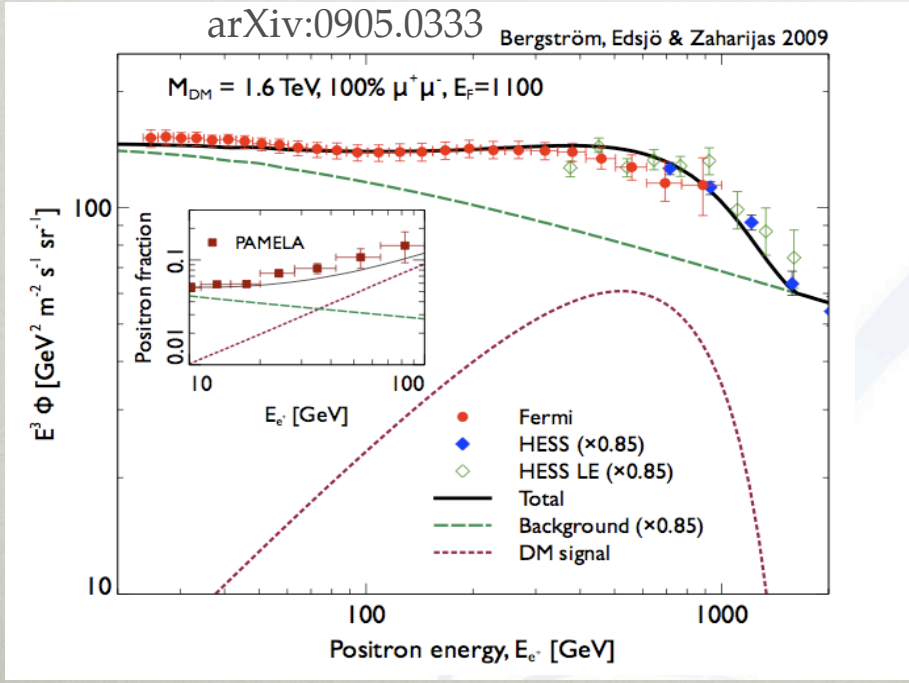
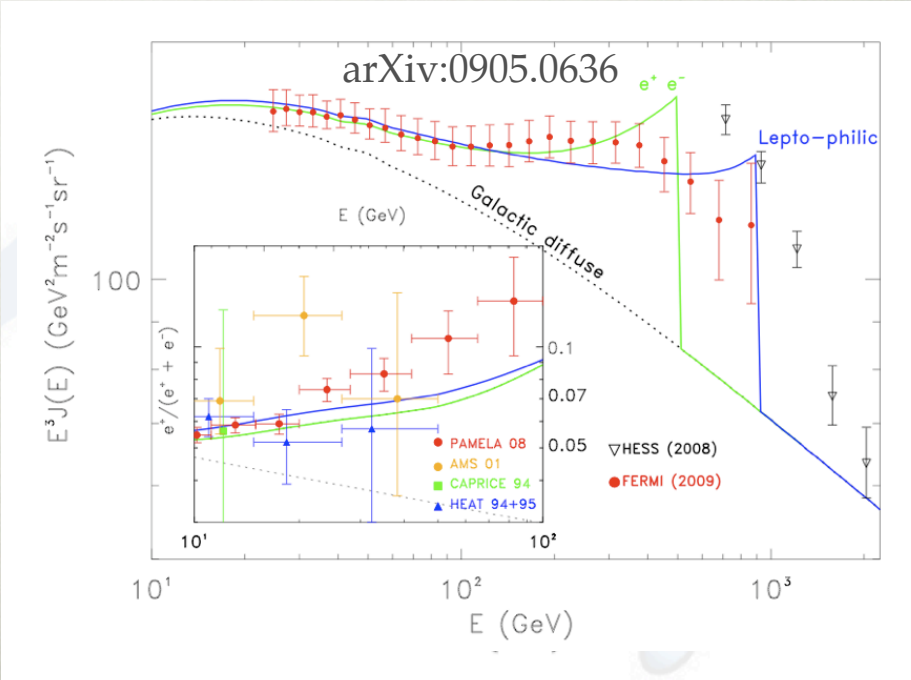
➡ Models that predict DM annihilation or decay into leptonic final states are strongly favored (do not overproduce antiprotons that would violate other measurements)



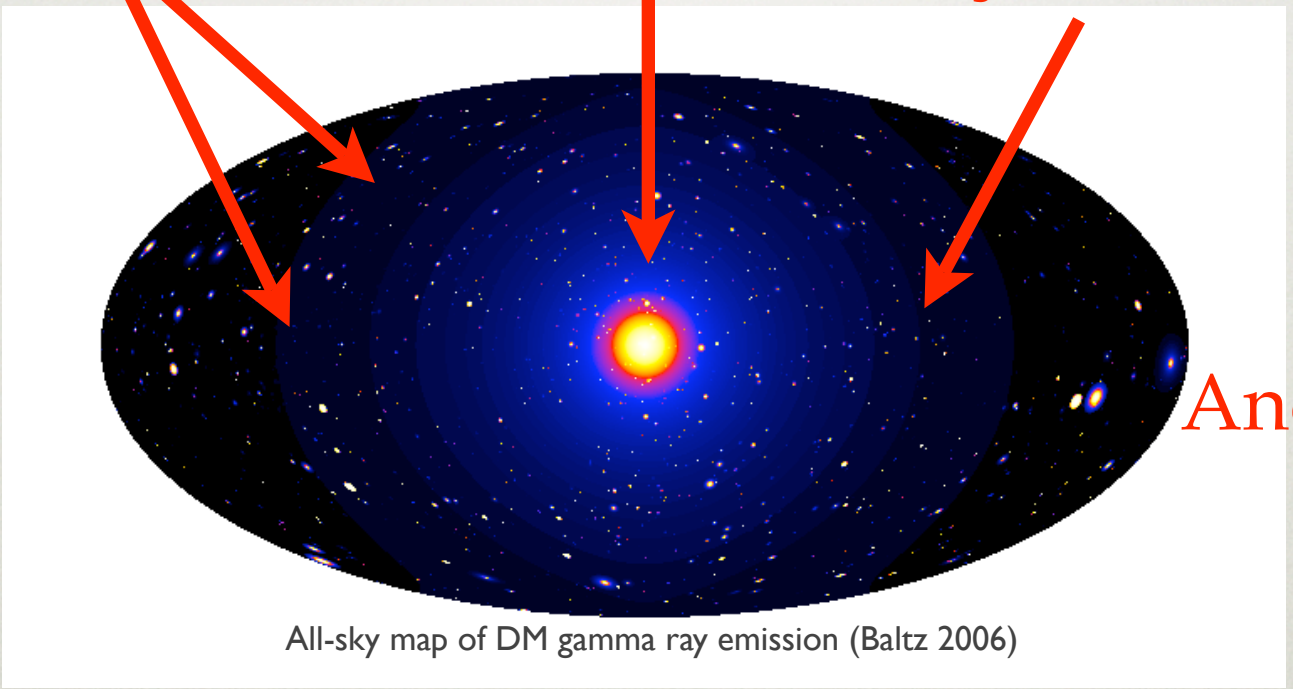


Search Strategies

Galactic center:
Good Statistics but source confusion/diffuse background

Satellites:
Low background and good source id, but low statistics, astrophysical background

Milky Way halo:
Large statistics but diffuse background


All-sky map of DM gamma ray emission (Baltz 2006)

And electrons!

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

DM Signal Assumptions

- The DM spectrum is the same everywhere (in the local Universe)! Uncertainties in the underlying particle physics model and DM distribution affect all of the DM searches. For model dependent results, for most Fermi analyses we have considered:
  - Two generic channels for the WIMP annihilation spectrum:
    - softer SUSY-like spectrum approximated by b-bbar
    - harder spectrum from leptonic final states: μ+μ- (final state radiation and, in some cases, Inverse Compton contribution to the photon yield are considered)
  - Assume NFW for the DM halo profile

Backgrounds

- Astrophysical background: photons from galactic diffuse emission (cosmic ray interaction with gas in the ISM and IRF), photons from the extra-galactic diffuse emission, point sources
  - Not the same for all analyses - depends on location in the sky
- Instrumental background: charged particles (protons, electrons, positrons) and some neutrons, Earth albedo photons. Rejected by on-board triggering+filtering and on the ground selection (only 1 in 10^5 survive)
  - To a good approximation is isotropic
  - In the analyses presented here, the cleanest photon sample is used (lowest residual background level)
  - To reduce Earth albedo, require zenith angles $< 105^o$

Search for DM in the GC

➡ N-body simulations predict steep DM profiles ⇒ Expect large DM annihilation/decay signal from the galactic center!

- <u>The best strategy is to use both spectral and spatial information to disentangle signal from background:</u>
  - A signal from WIMP annihilation is not expected to be well described by a (soft) power law and is predicted to be spatially extended.
- 0FGL J1746.0-2900 is the closest source to the GC in Fermi Bright Source List (>10 σ detection, first 3 months of data). Marginal variability is not confirmed with larger statistics

Source	l (°)	b (°)	θ_{95} (°)	Int.Flux(1<E<100GeV) $cm^{-2}s^{-1}$ 10^{-8}
0FGL J1732.8-3135	356.287	0.920	0.087	3.890±0.33
0FGL J1741.4-3046	357.959	-0.189	0.197	2.00±0.31
0FGL J1746.0-2900	359.988	-0.111	0.068	7.92±0.47

Search for DM in the GC

➡ However, good understanding of the astrophysical background is necessary to extract a potential signal from this complicated region of the sky:

- source confusion: energetic sources near to or in the line of sight of the GC
- diffuse emission modeling: uncertainties in the integration over the line of sight in the direction of the GC

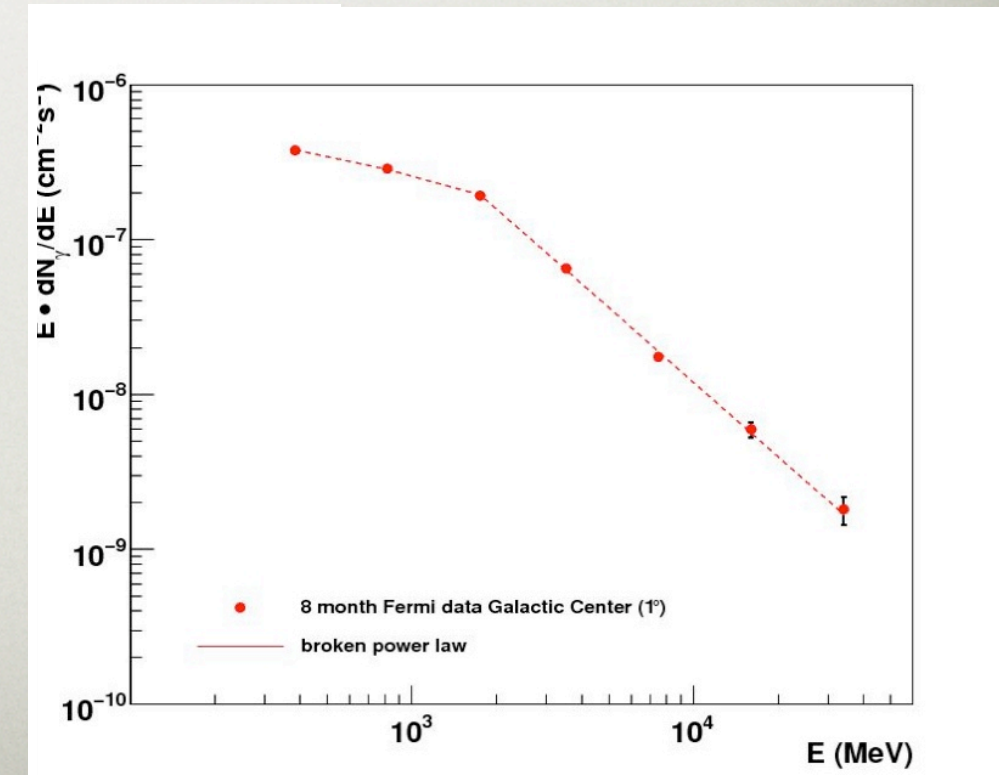
<u>Analyses that fully exploit the potential of the LAT data are ongoing. The results presented here are derived with a very conservative treatment of the GC region.</u>

Search for DM in the GC

- At this stage, a preliminary result has been obtained by considering the photon signal in a 1° region around the GC (RA = 266.46°, Dec = -28.97°). No attempt has been made to subtract the background in this region.
- Data: 8 months, 200 MeV to 40 GeV.
- Spectrum is well fitted by a broken power law (χ^2/dof = 0.87)

$\gamma_1 = -1.38 \pm 0.04$
$\gamma_2 = -2.60 \pm 0.05$
BreakValue = (1623± 107) MeV

Integral flux 100 MeV to 100 GeV:
$(1.22 \pm 0.02) \times 10^{-6}$ cm^{-2}s^{-1}



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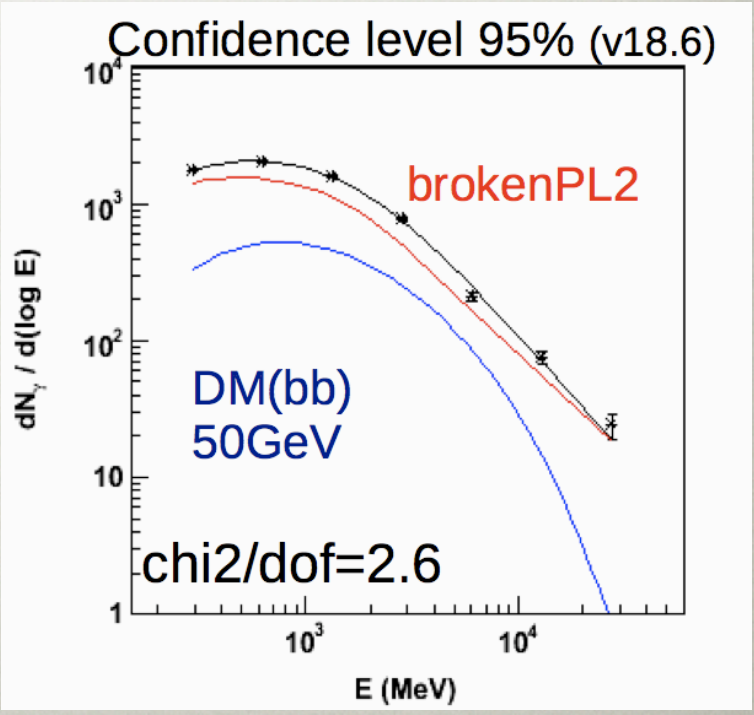
- Data: 8 months, 200 MeV to 40 GeV.
- Adding a generic WIMP component yields a worse fit (χ^2/dof = 66.5). Upper limits on flux, annihilation cross section are placed.



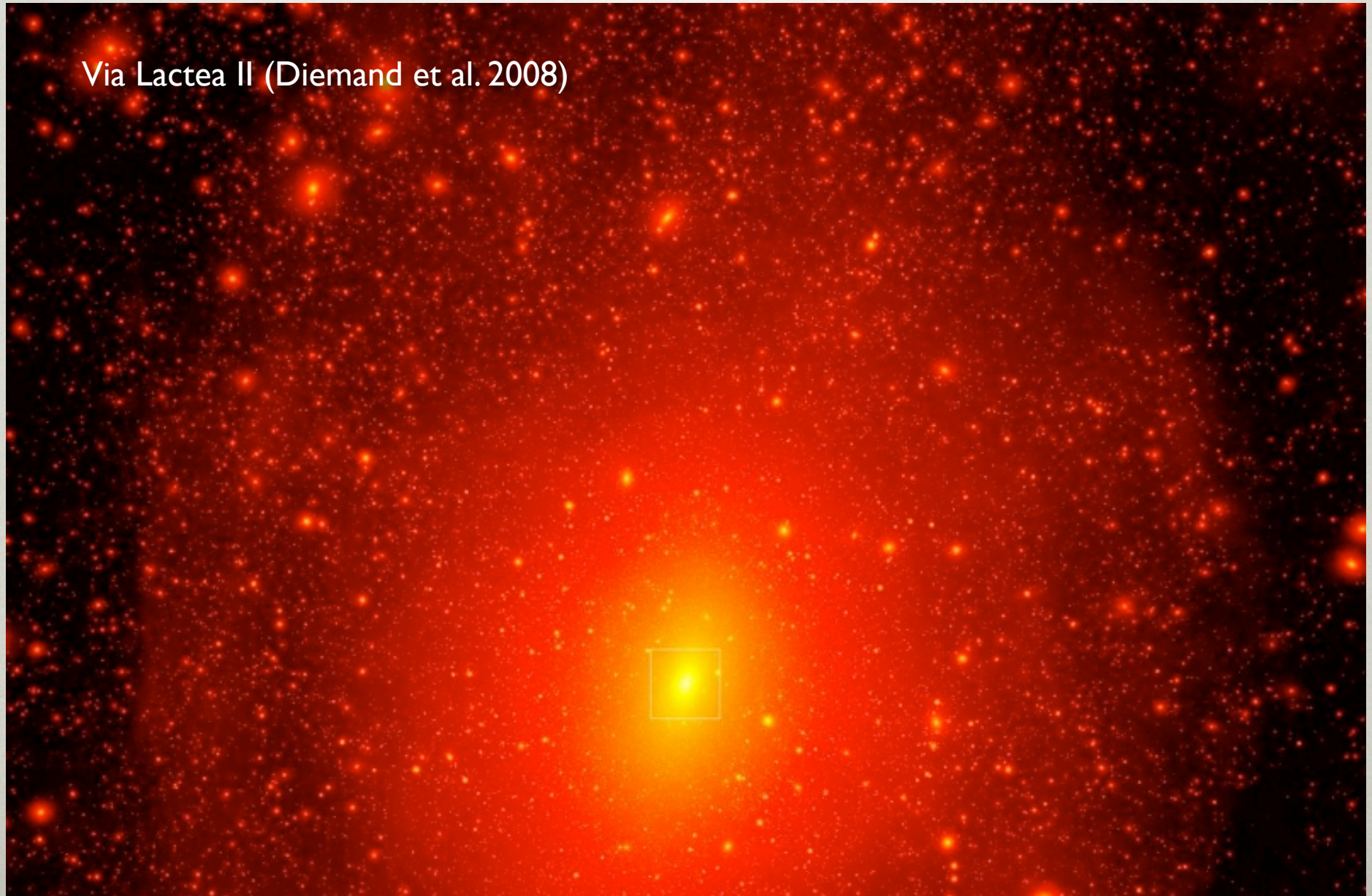
95% CL upper limit (100 MeV-50 GeV)

Flux: 2.43×10^{-7}cm^{-2}s^{-1}

$\langle\sigma v\rangle$: 3.98×10^{-25}cm^{3}s^{-1}

✱ C. Meurer's talk in parallel session 3 (Tuesday, July 14)

Search for DM Subhalos



Search for DM Subhalos

➡ DM substructures: very low background targets for DM searches

- Never before observed DM substructures (DM satellites):
  - Would significantly shine only in radiation produced by DM annihilation/decay.
  - Blind search for promising candidates in the Fermi sky
  - Some of these satellites could be within a few kpc from the Sun (N-body simulations). Their extension could be resolved by the LAT
- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation
  - Most are expected to be free from other astrophysical gamma ray sources and have low content in dust/gas, very few stars
  - Select most promising candidates
  - Given the distance and the LAT PSF, they are expected to appear pointlike

Search for DM Satellites

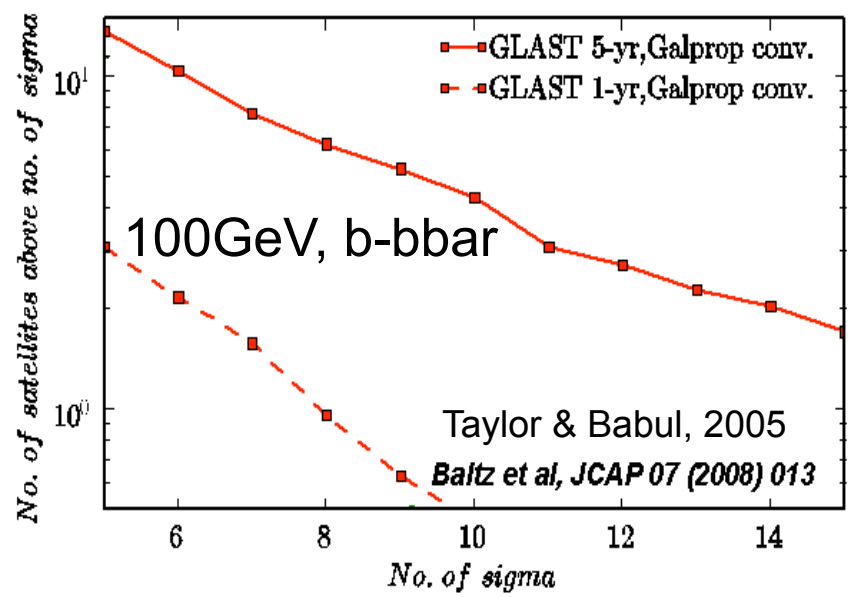
- Search criteria:
  - No appreciable counterpart at other wavelengths
  - Emission constant in time
  - Spatially extended (~1° average radial extension for nearby, detectable clumps)
  - Spectrum determined by DM
- Search for sources (>5σ significance) passing these criteria in the first 3 months of Fermi data in 200 MeV - 60 GeV energy range

Sensitivity study predicts ~ 1-3 detections/1 year

Via Lactea II and Aquarius

Model	VL2 5σ	Aq 5σ
40GeV, bb-bar	3.9+/-1.3	7.1+/-2.3
100GeV, W^+W^-	**1.3+/-0.9**	**2.9+/-1.2**

(Bertone et al., 2009, in preparation)



DM Satellite Candidate

- One source is found in the first 3 months of data which is:
  - Possibly extended (test NFW vs point-like hypothesis)
  - Possibly non-power law (test power-law vs WIMP b-bar spectrum)
  - Not variable (based on 1-week interval light curve)
  - No dSph counterpart
  - No molecular cloud counterpart
- Unfortunately, a closer inspection with 10 months of data reveals two nearby sources...

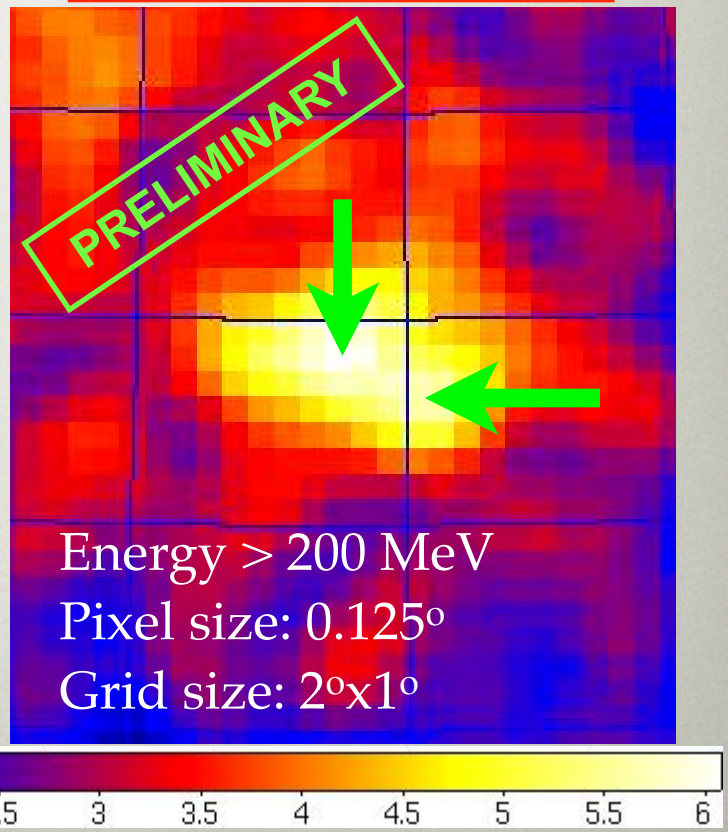
➡ No DM satellites are detected with 3 months of data

- Consistent with results of sensitivity study

☞ Results with 1 year of data coming soon!

✱ P. Wang's talk in parallel session 4 (Tuesday, July 14)

Smoothed Counts Map



Search for DM in dSph

- Select 10 most promising dSph based on proximity, stellar kinematic data: less that 150 kpc from the Sun, more than 30º from the galactic plane
- Not a final list! More promising targets could be discovered by current and upcoming experiments (SDSS, DES, PanSTARRS, ...)

Name	Distance (kpc)	year of discovery	M/L	l	b
Segue 1	23± 3	2007	1320 ± 2680	220.48	50.42
Ursa Major II	30± 5	2006	1722 ± 1226	152.46	37.44
Segue 2	35	2009	650^{+1300}_{-380}	149.4	-38.01
Willman 1	38± 7	2004	$\sim$500	158.57	56.78
Coma Berenices	44± 4	2006	448 ± 297	241.9	83.6
Usra Minor	66± 3	1954	275 ± 35	104.95	44.80
Sculptor	79± 4	1937	158 ± 33	287.15	-83.16
Draco	76± 5	1954	290 ± 60	86.37	34.72
Sextans	86± 4	1990	70 ± 10	243.4	42.2
Fornax	138± 8	1938	14.8 ± 8.3	237.1	-65.7

Search for DM in dSph

➡ No detection by Fermi with 9 months of data

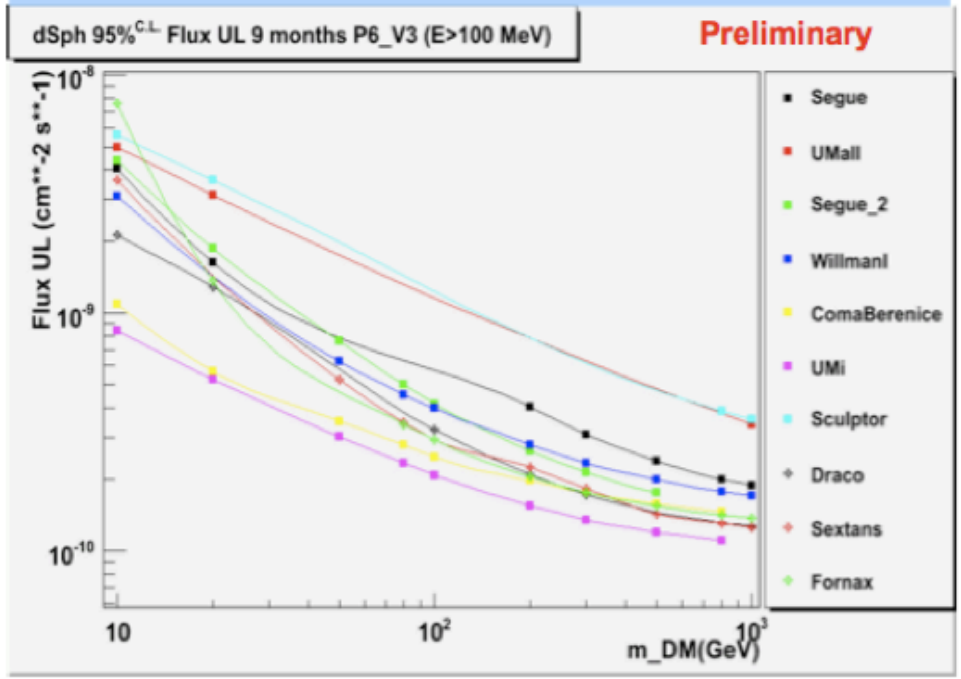
- 100 MeV to 50 GeV
- 10° region around location dSph.
- Background: point sources+diffuse galactic and isotropic emission

Flux upper limits assuming a point-like source at the dwarf location

power-law with fixed spectral index of γ = - 2

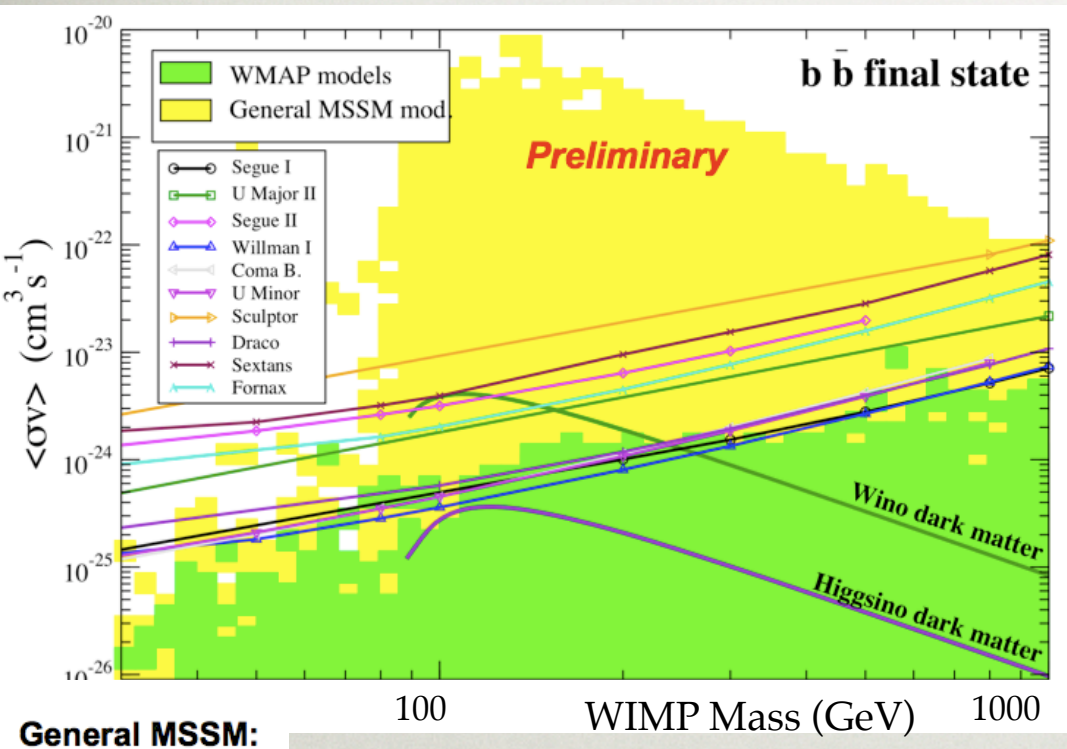
Name Preliminary	Flux UL (95%) $(E > 100\ MeV)$ $10^{-9}\ ph/cm^2/s$
Segue I	1.83
UMa II	4.60
Segue II	2.13
Willman I	2.12
Coma Berenice	0.97
UMi	0.72
Sculptor	4.79
Draco	1.16
Sextans	1.33
Fornax	1.67

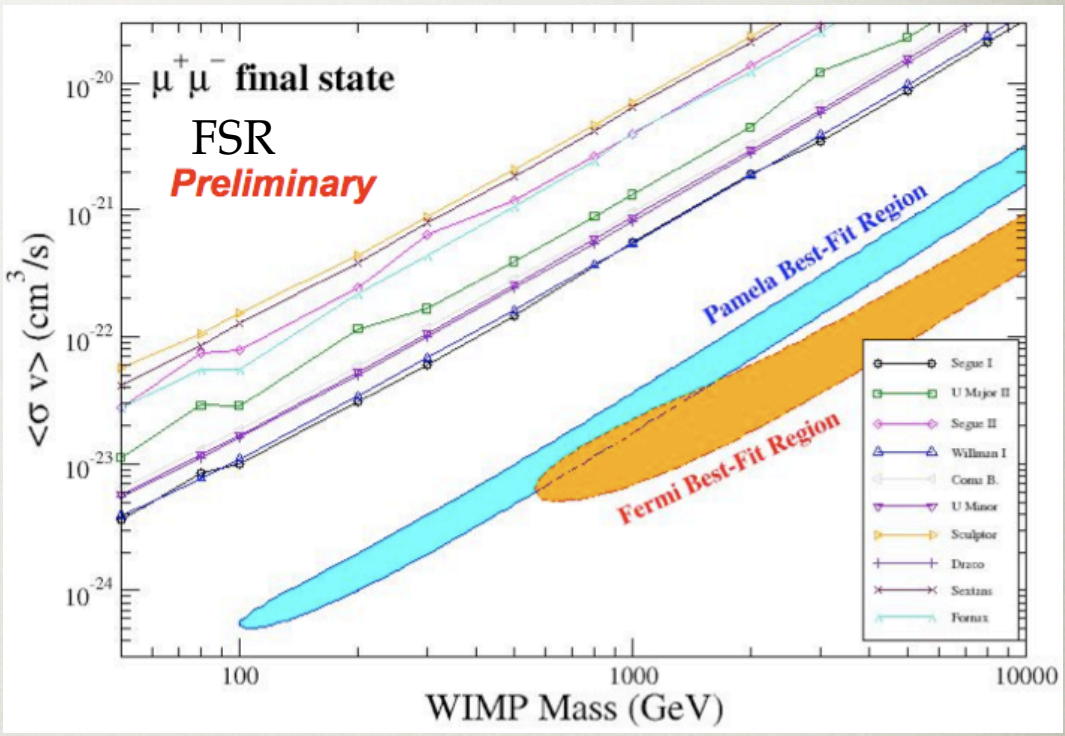
100% b-bbar DM annihilation



Search for DM in dSph

- Model dependent constraints:





General MSSM: includes temperature dependent resonance effects (Profumo 2005)

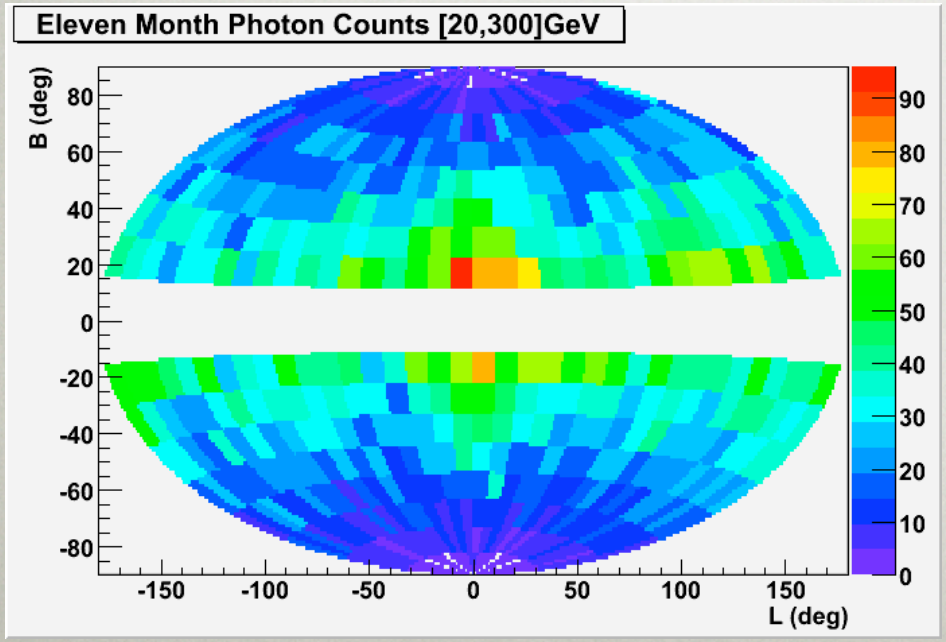
NFW, no substructures

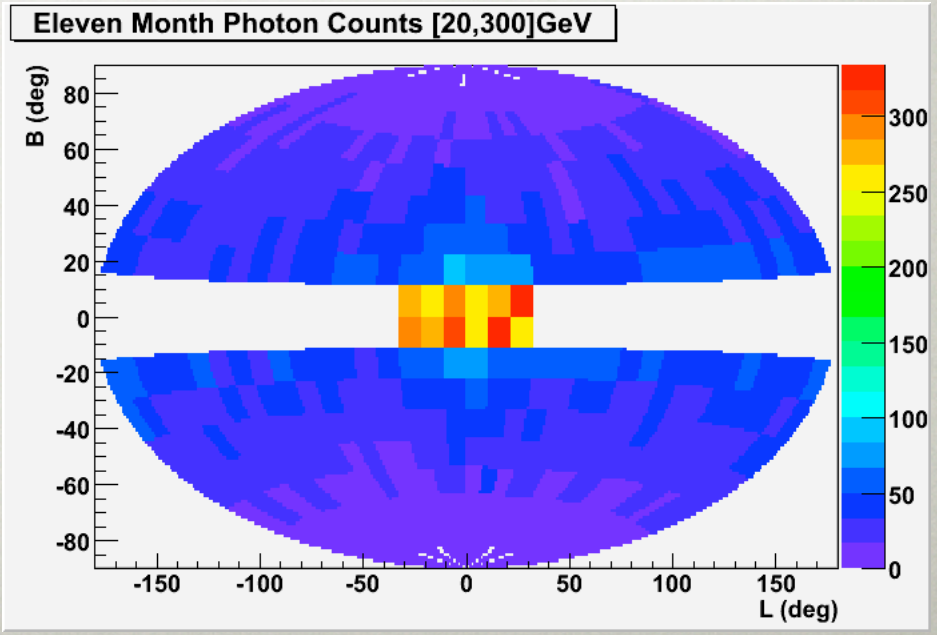
- T. Jeltema's talk in parallel session 3 (Tuesday, July 14)
- P. Scott's talk in parallel session 4 (Tuesday, July 14)

Search for Spectral Lines

➡ Smoking gun signal for exotic physics

- Search for lines in the first 11 months of Fermi data
- Search in two regions of the sky (to maximize signal):
  - $|b| > 10^o$
  - $|b| > 10^o$, keep 30° around galactic center
- Exclude point sources: remove 0.2^o radius around the source, PSF $= 0.1^o$ at 20 GeV

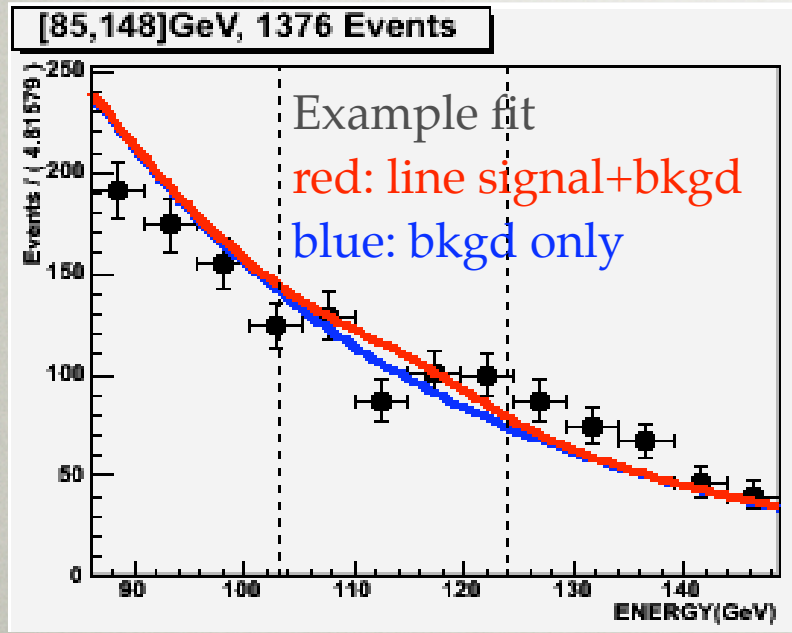


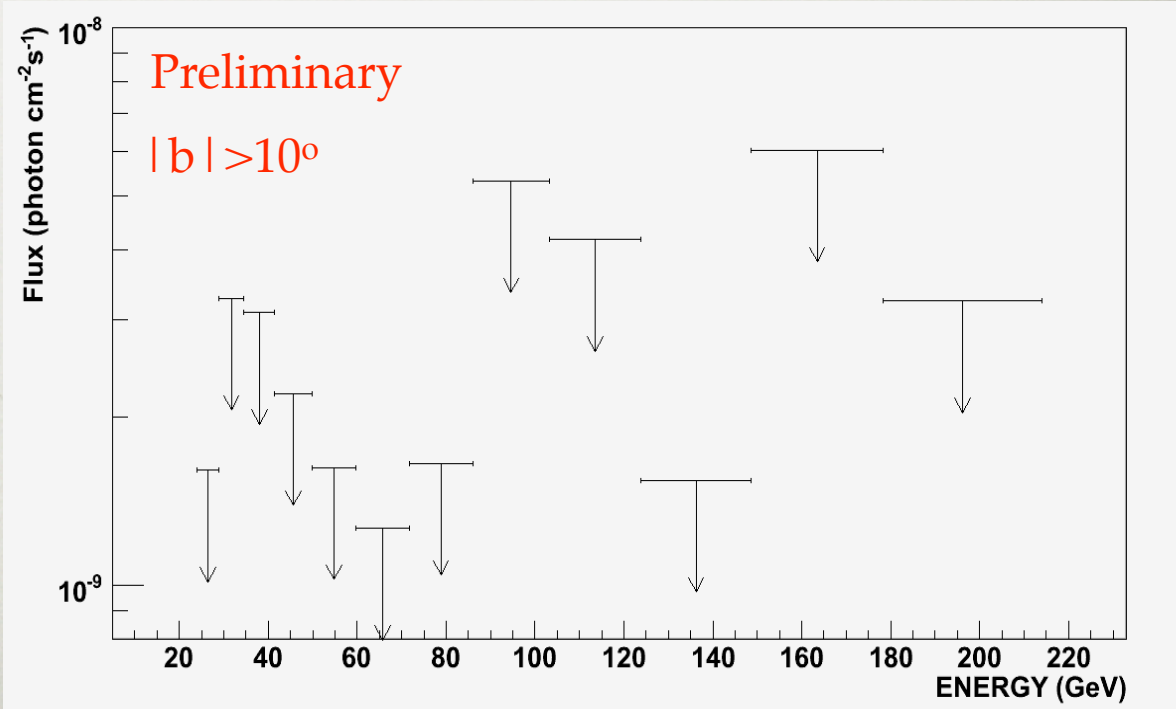


Search for Spectral Lines

- Look for a line signal in energy intervals in the 20-300 GeV range.
- The background is constrained by a fit to the side bins
- Optimal energy resolution and calibration very important for this analysis - resolution ~ 10% at 100 GeV

➡ No line detection, 95% CL flux upper limits are placed





✱ Y. Edmonds' talk in parallel session 1 (Monday, July 13)

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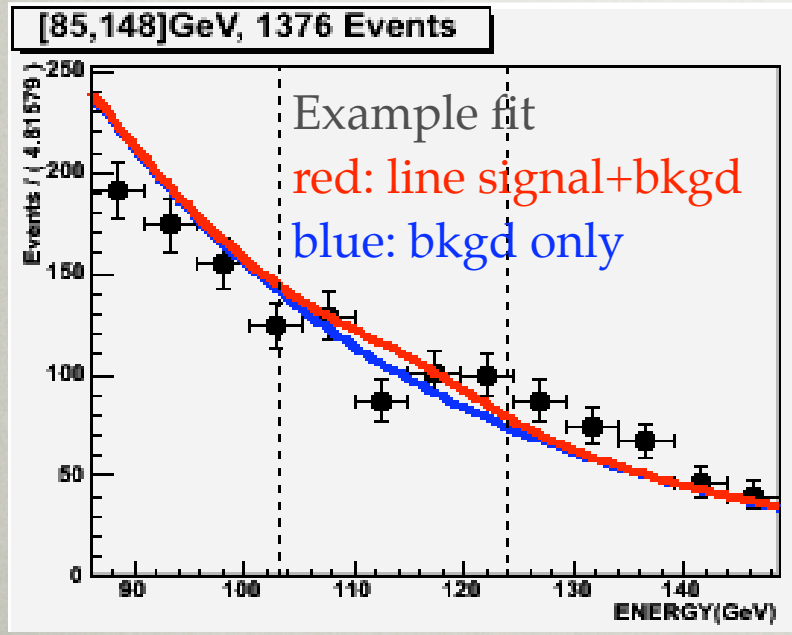

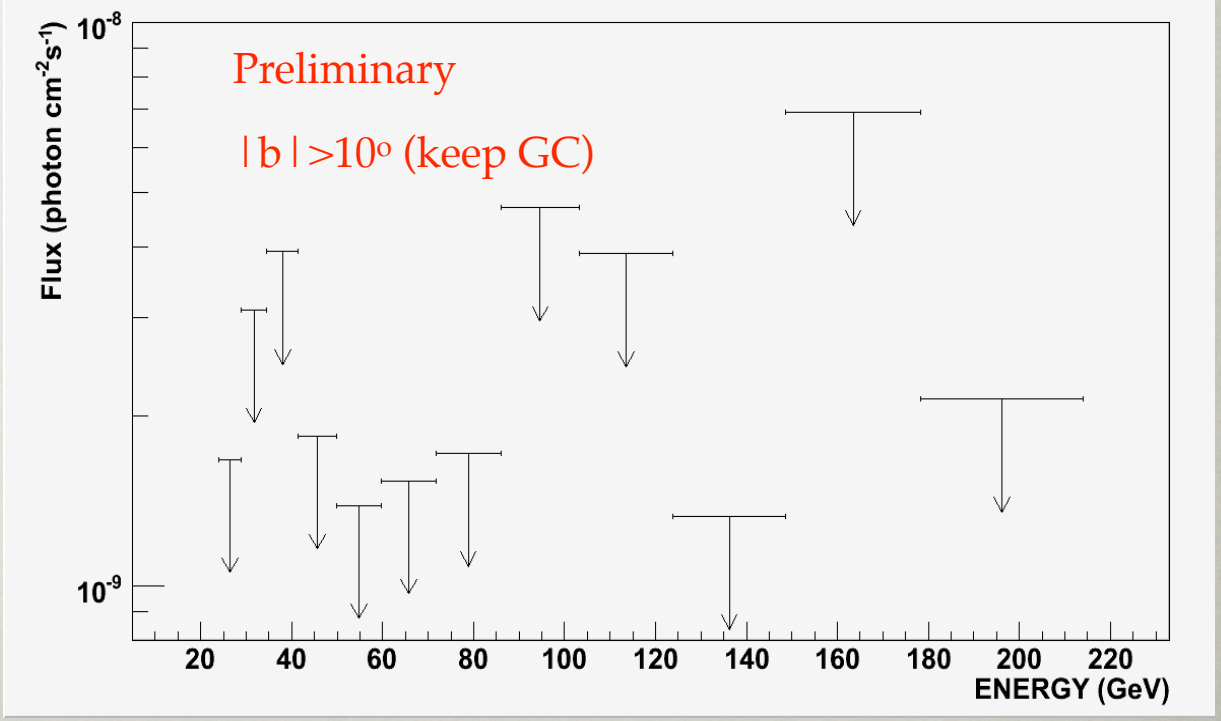

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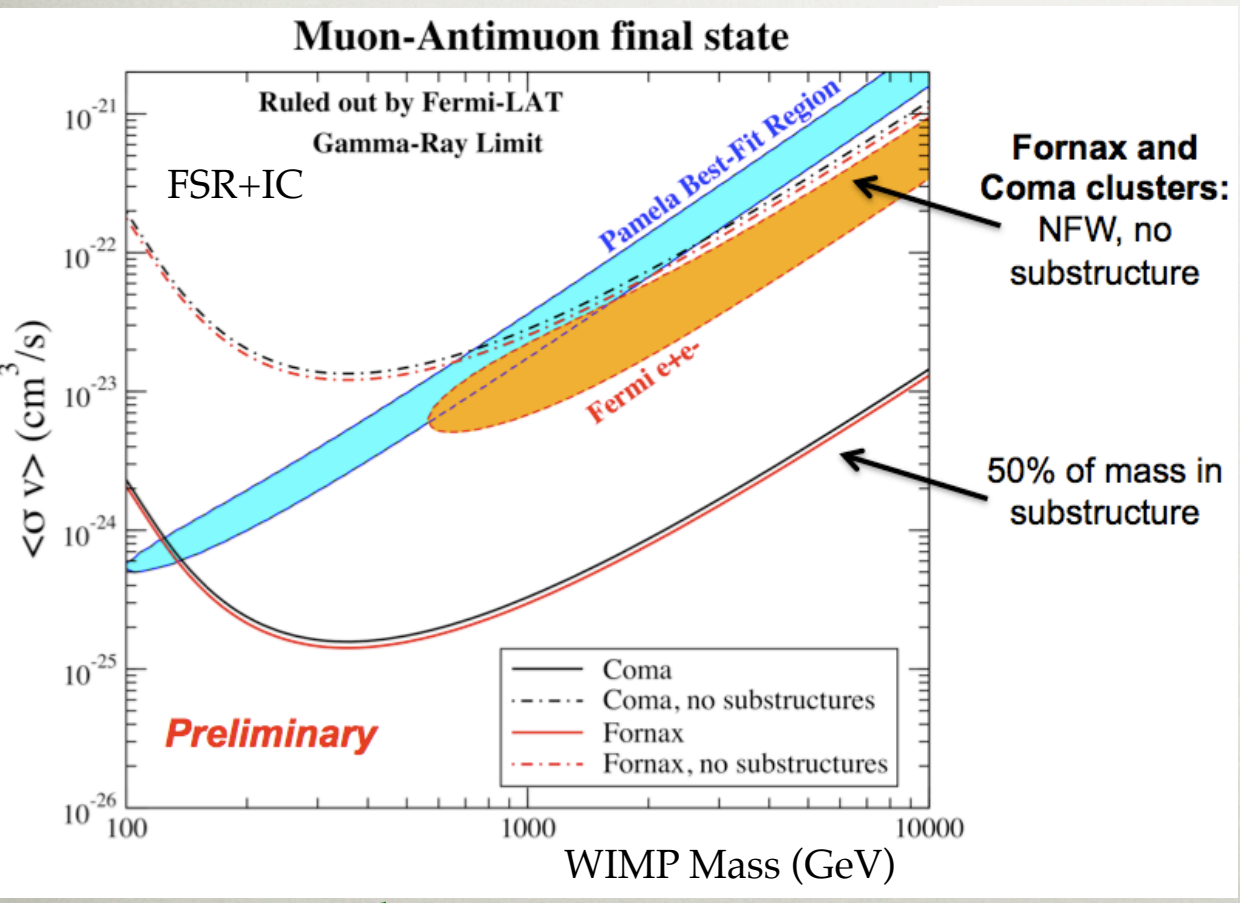
Search for DM in Galaxy Clusters

- Promising targets: large DM densities and low background

➡ Not detected by Fermi with 9 months of data



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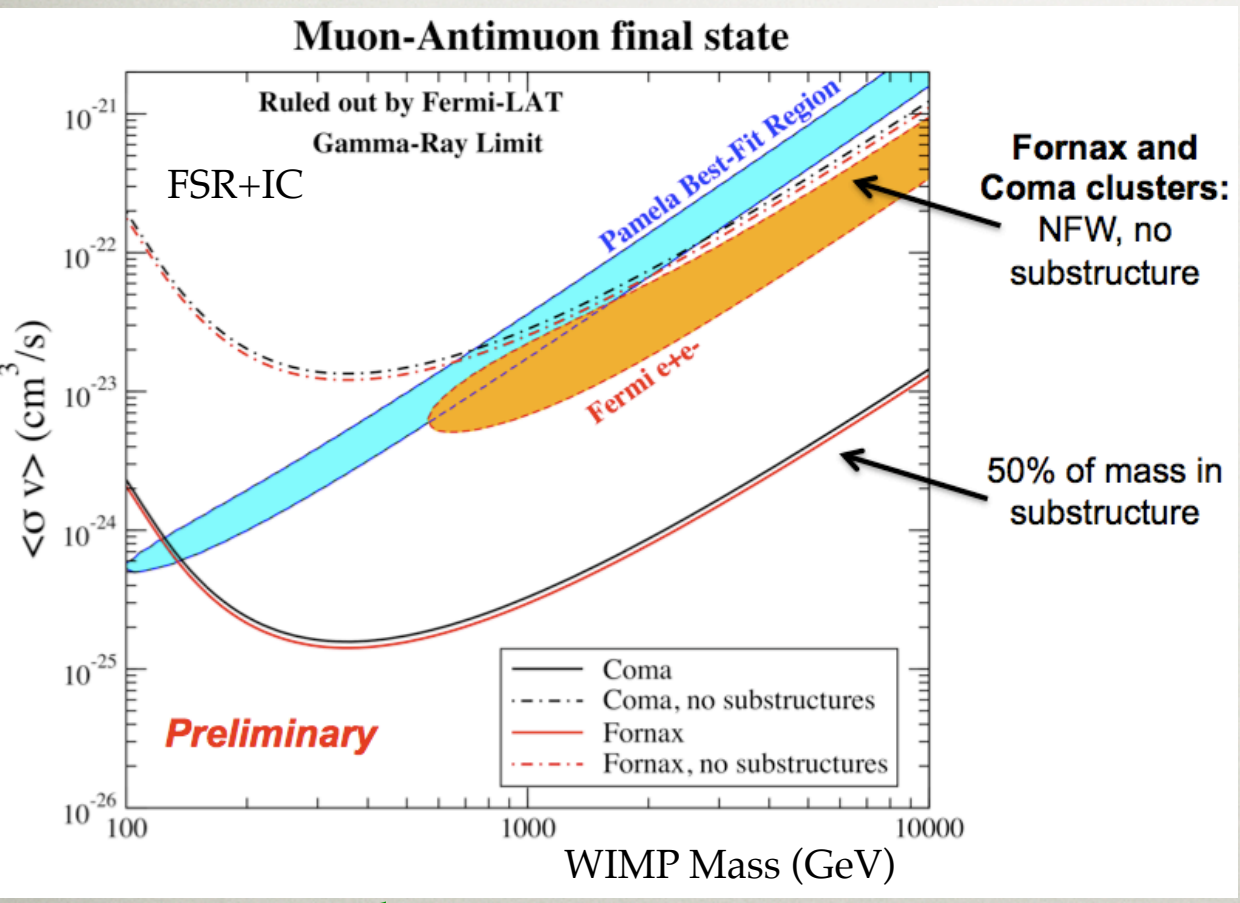

Constraints on ~TeV mass WIMPs annihilating into leptons with large cross-sections also from other observations, e.g.:

- ✓ WMAP constraints on reionization and heating of the intergalactic gas (Cirelli et al., arXiv:0907.0719)
- ✓ EGRET constraints on IC from CMB from DM annihilations in all halos at all redshifts (Profumo et al., arXiv:0906.0001)
- ✓ EGRET constraints on galaxy clusters (depends on substructure mass cutoff) (Pinzke et al., arXiv:0905.1948)

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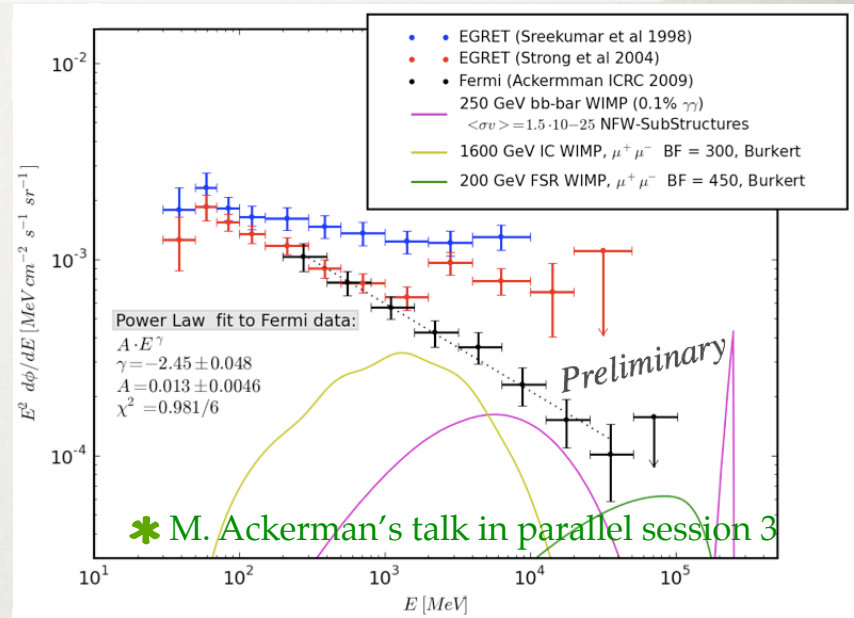
Cosmological DM

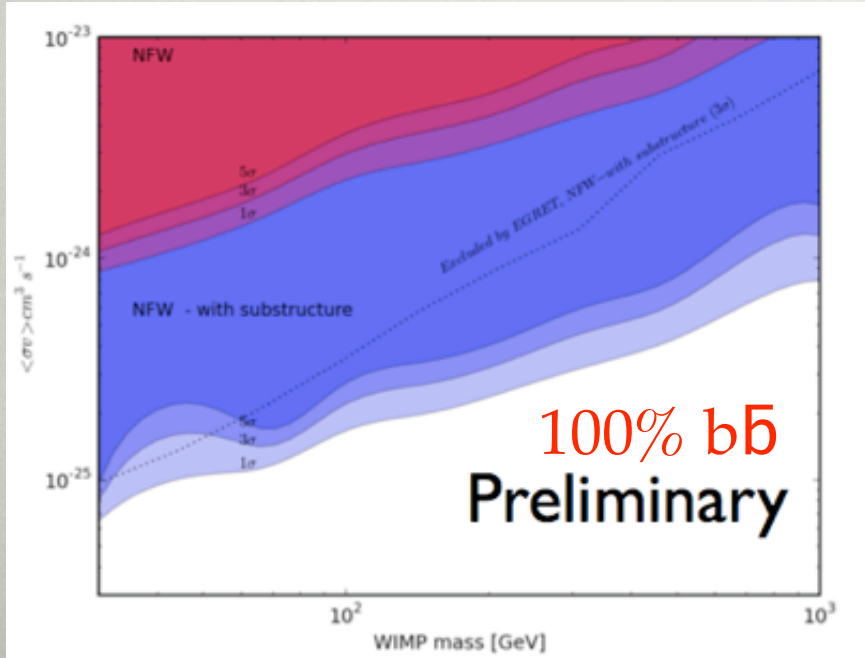
- Search for a DM annihilation signal in the EG emission
- Signal modeling:

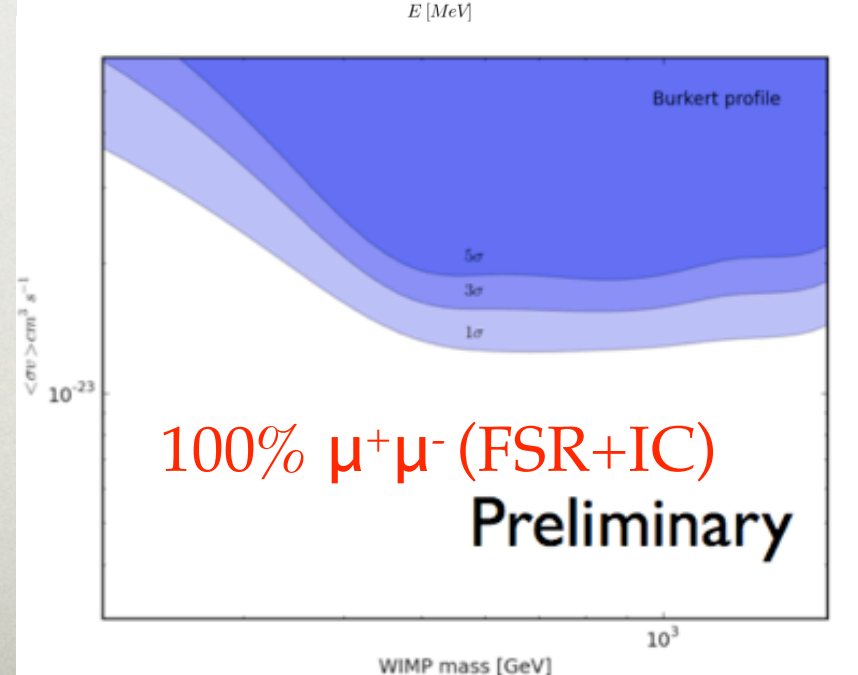
$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{M_\chi^2}\int dz\,(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0\,(1+z))}{dE}e^{-\tau(z,E_0)}$$

- Limits based on Fermi's measurement of the EG diffuse emission. No attempt to subtract astrophysical background.



✱ M. Ackerman's talk in parallel session 3





Conclusions/Outlook

- With the measurement of the galactic diffuse emission and the CR e+e- spectrum, the Fermi-LAT data have made significant impact in the dark matter interpretation of potential signals from other experiments
- Several promising search strategies are being pursued to search for DM with Fermi-LAT
- No signals have been detected... yet! Promising constraints on the nature of DM have been placed
- At this stage, DM substructures in the Milky Way halo are particularly good targets as they are largely background free.
- In addition to increased statistics, better understanding of the astrophysical and instrumental background will improve our ability to reliably extract a potential signal of new physics or set stronger constraints

➡ Updated results with 1 year of data will be released soon!