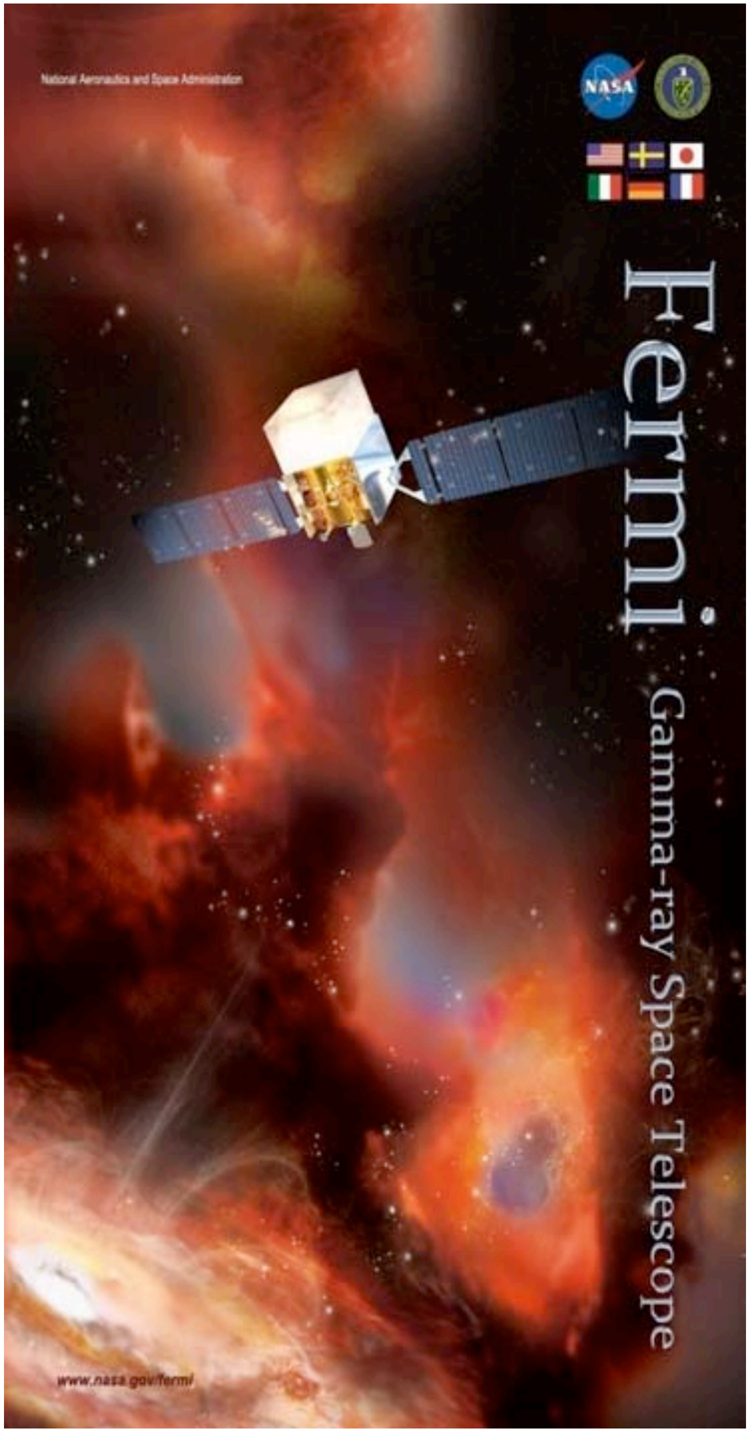


Constraints on Dark Matter with Fermi Observations of Dwarfs and Clusters

Tesla Jeltema
UC Santa Cruz
on behalf of the Fermi LAT Collaboration

Outline

- The Fermi Gamma-Ray Space Telescope

- Gamma rays from dark matter annihilation and Fermi searches

- Fermi-LAT preliminary 11 month results

    - dwarf and cluster observations

    - constraints on "standard" WIMP models

    - constraints on "PAMELA" models

Fermi Gamma-Ray Space Telescope

- Launched June 11, 2008

- Fermi-LAT began all-sky gamma-ray survey August 2008
  - 20 MeV to > 300 GeV
  - more 10x EGRET sensitivity

- Surveys the full sky every two orbits (3 hours)

Tesla Jeltema for the Fermi LAT Collaboration

LAT Collaboration

- France
  - CNRS/IN2P3, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

PI: Peter Michelson
(Stanford)

~400 Scientific Members (including 97 Affiliated Scientists, plus 71 Postdocs and 123 Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Project managed at SLAC.

The Fermi-LAT Basics

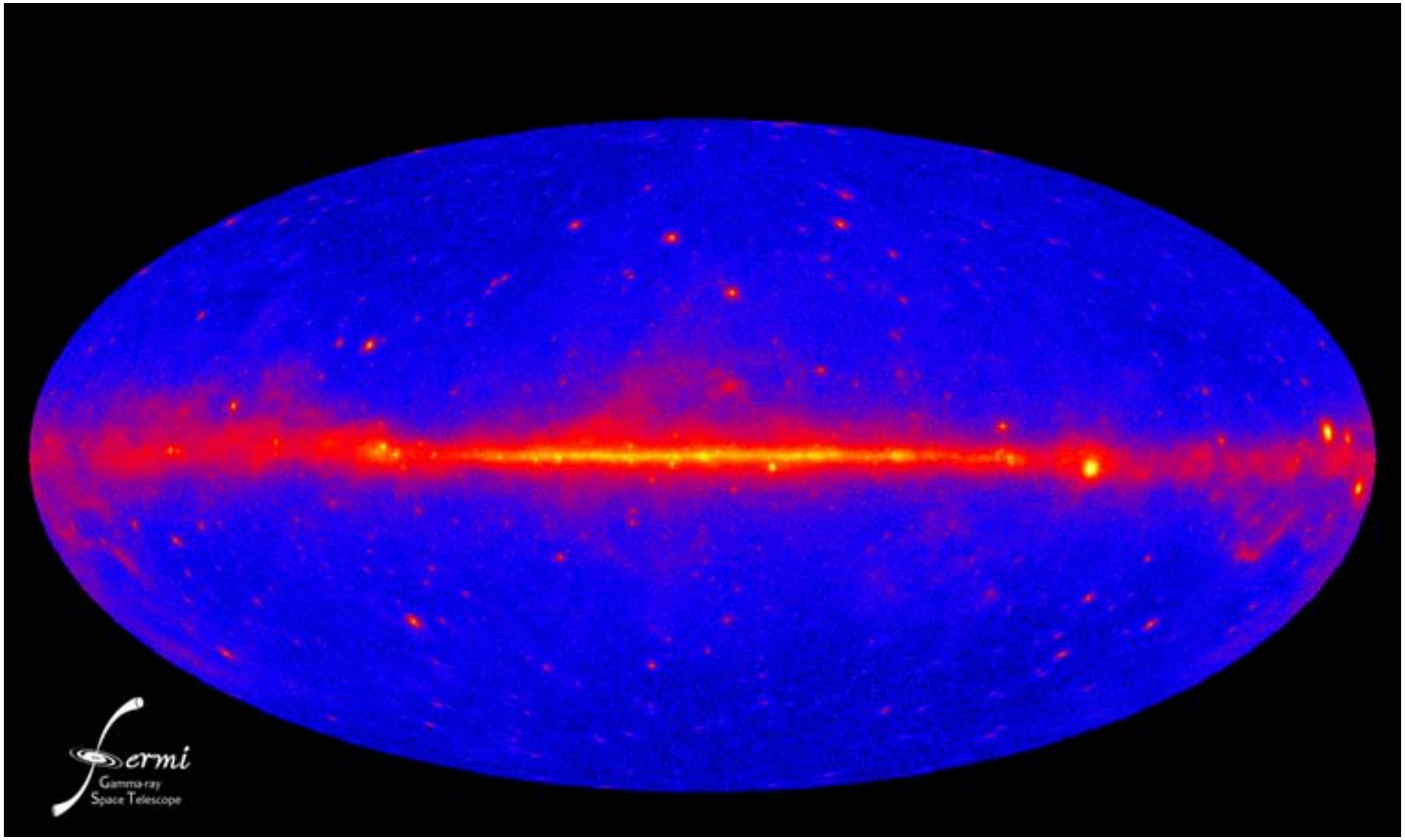
	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Eng. Rng. (GeV)	$A_{eff}\,\Omega$ (cm^2 sr)	# γ-rays
EGRET	**1991–00**	**5.8°**	**0.5°**	**0.03–10**	**750**	**1.4×10^6/yr**
AGILE	**2007–**	**4.7°**	**0.2°**	**0.03–50**	**1,500**	**4×10^6/yr**
***Fermi* LAT**	**2008–**	**3.5°**	**0.1°**	**0.02–300**	**25,000**	**1×10^8/yr**

- Broad science:

AGN, GRBs, Pulsars, SNRs, galactic and extragalactic diffuse emission, EBL, cosmic rays, indirect dark matter searches

Fermi-LAT 1 Year Sky Map

> 1000 gamma-ray sources



blazars, pulsars, binaries, globular clusters, starburst galaxies, SNR, radio galaxies, …

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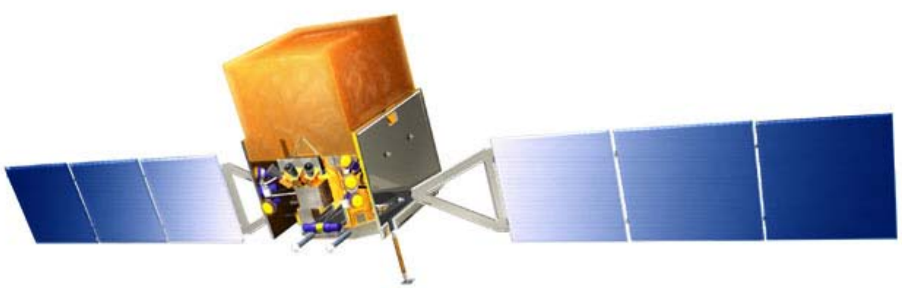
Searches for a Signal from Dark Matter with Fermi-LAT:

The First Year

(actually 11 months)



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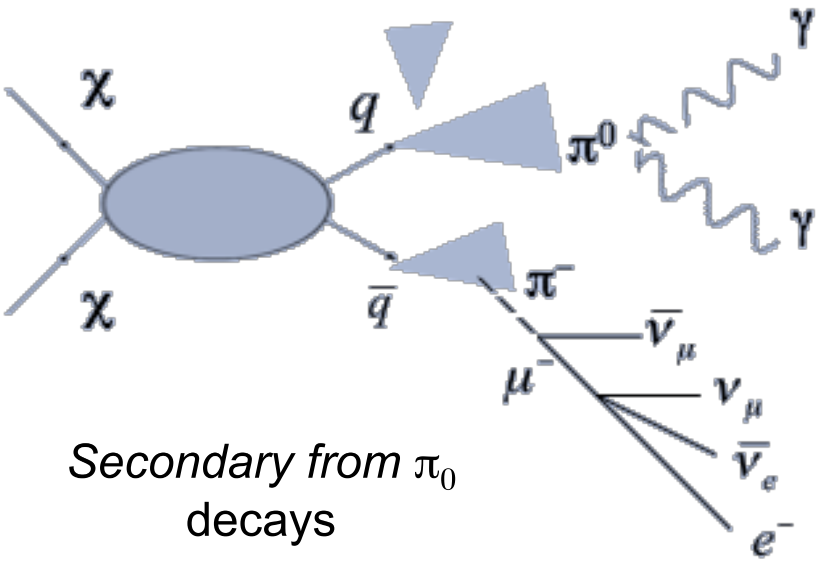
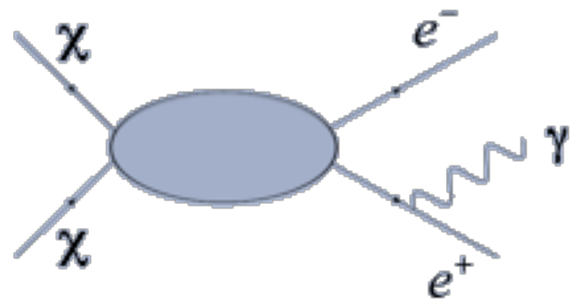
Gamma rays from Dark Matter Annihilation



Secondary from π_0 decays



Prompt lepton pair production

$$\Phi_{WIMP}(E,\Psi) = J(\Psi) \times \Phi^{PP}(E)$$

Astrophysical factor

$$J(\Psi) = \int_{l.o.s} dl(\Psi)\,\rho^2(l)$$

Particle physics factor

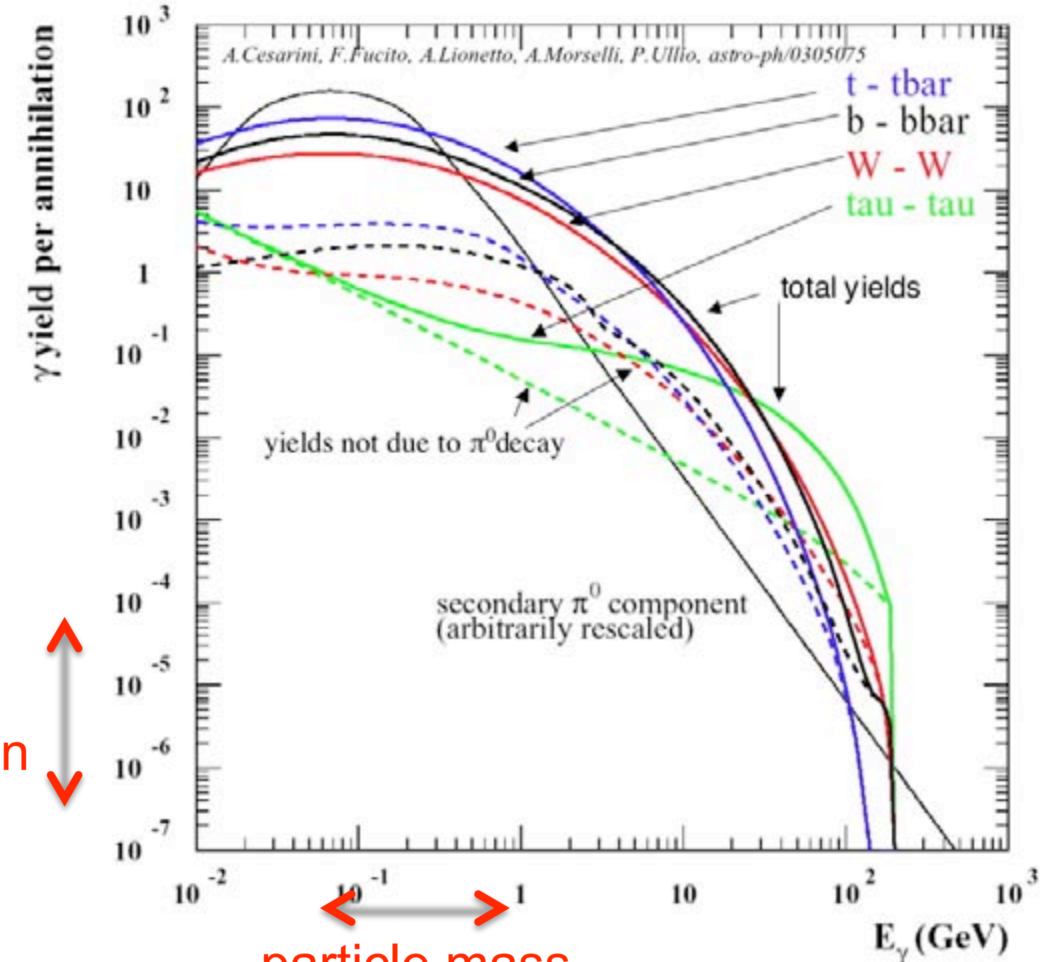
$$\Phi^{PP}(E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{m_{WIMP}^2} \sum_f \frac{dN_f}{dE} B_f$$

Gamma-ray Spectrum from WIMP annihilation

Gamma-ray yield for a 200 GeV WIMP

- cutoff at WIMP mass
- quark and gauge boson final states give similar spectra

DM density distribution
annihilation cross-section



particle mass
final state

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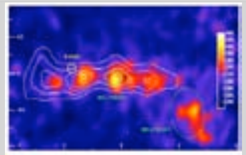
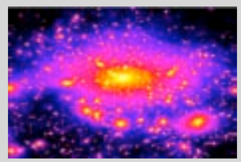
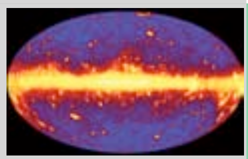
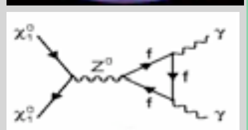
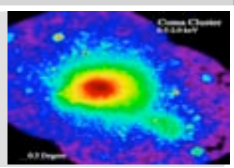
Fermi Dark Matter Searches

Several promising targets

Searches ongoing

Search Technique		**advantages**	**challenges**
Galactic center		Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos		Low background, Good source id	Low statistics
Milky Way halo		Large statistics	Galactic diffuse background
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics
Clusters of Galaxies		Low background, Good source id	Low statistics

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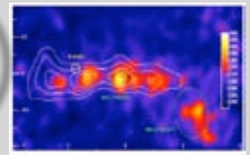
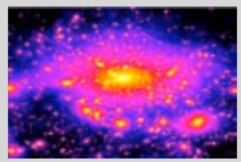
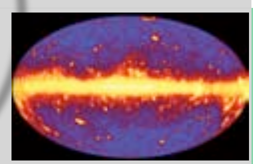
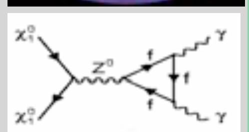
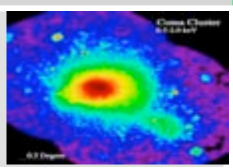
Fermi Dark Matter Searches

Require good knowledge of complicated diffuse backgrounds

Search Technique		advantages	challenges
Galactic center		Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos		Low background, Good source id	Low statistics
Milky Way halo		Large statistics	Galactic diffuse background
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics
Clusters of Galaxies		Low background, Good source id	Low statistics

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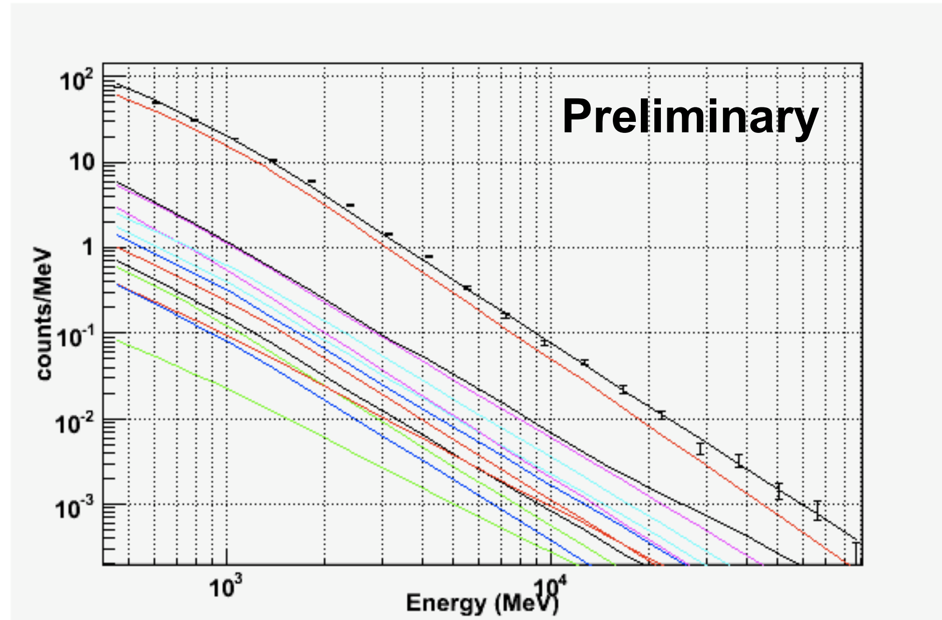
The Galactic Center

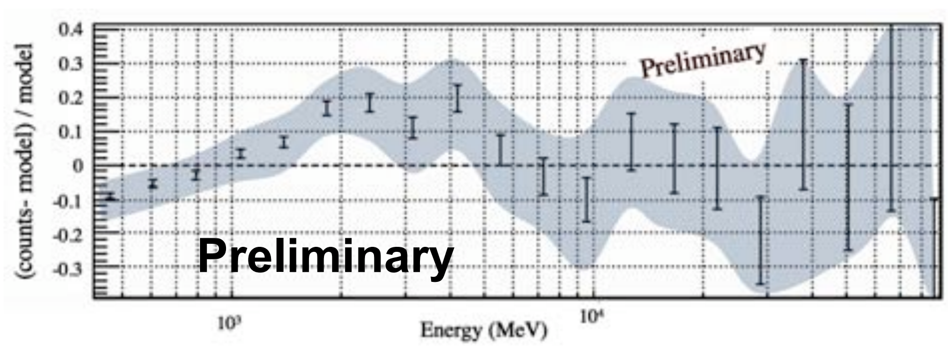
(see also S. Digel talk and V. Vitale poster, Fermi Symposium)

- Preliminary 11 month analysis of 7° region
  - GALPROP Galactic diffuse, isotropic diffuse, point sources

- Bulk of the emission is from detected sources and diffuse, particularly given systematics

- Galactic diffuse model is under active study





grey band: systematic uncertainty in effective area

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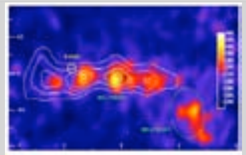
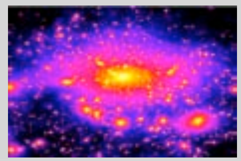
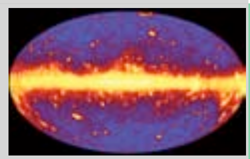
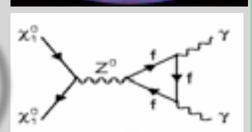
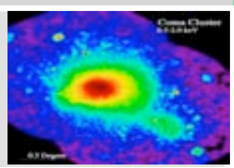
Fermi Dark Matter Searches

Search Technique	advantages	challenges
Galactic center 	Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos 	Low background, Good source id	Low statistics
Milky Way halo 	Large statistics	Galactic diffuse background
Extra-galactic 	Large Statistics	Astrophysics, galactic diffuse background
Spectral lines 	No astrophysical uncertainties, good source id	Low statistics
Clusters of Galaxies 	Low background, Good source id	Low statistics

Smoking gun, but signal small

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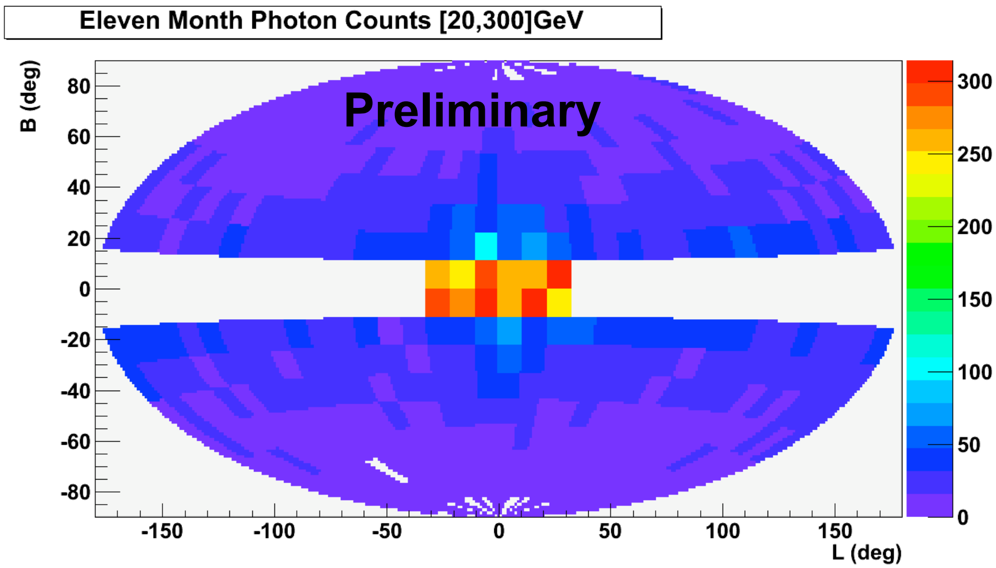
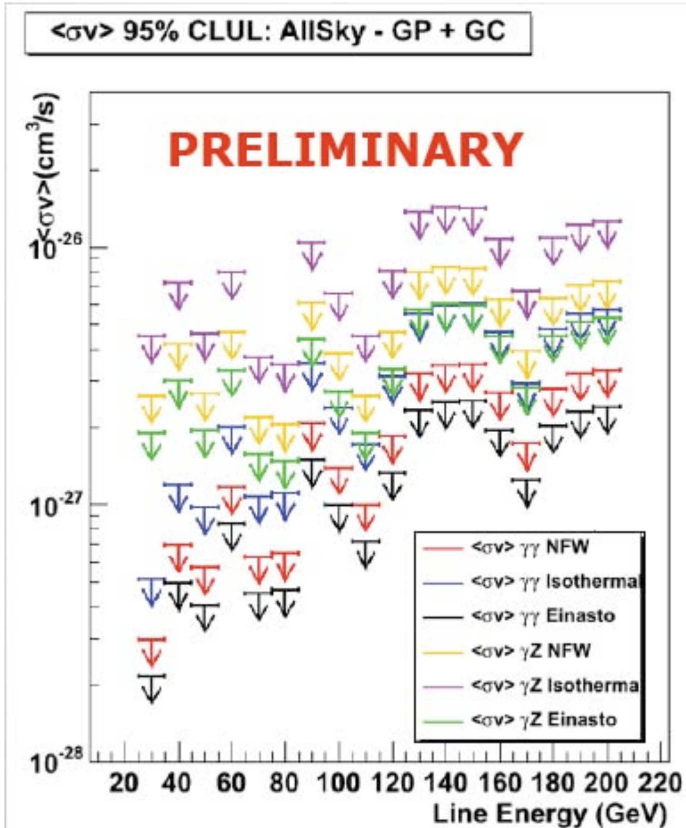
Line Search

(see also Y. Edmonds poster, Fermi Symposium)



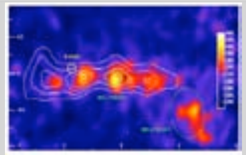
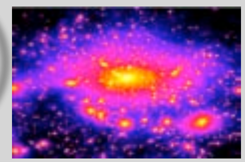
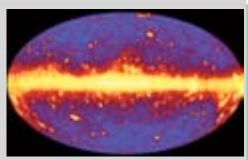
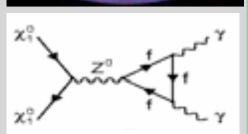
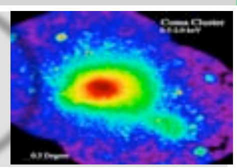


- Search for lines in 11 month data
  - |b| > 10° and 30° around GC
  - no detections
- 95% confidence level limits on line cross-sections ~10^{-27} cm^3 s^{-1}
- γZ constraint excludes wino LSP model of Kane et al. 2009

submitted to PRL

Tesla Jeltema for the Fermi LAT Collaboration

Fermi Dark Matter Searches

Search Technique		advantages	challenges
Galactic center		Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos		Low background, Good source id	Low statistics
Milky Way halo		Large statistics	Galactic diffuse background
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics
Clusters of Galaxies		Low background, Good source id	Low statistics

Dark matter dominated and in low background regions

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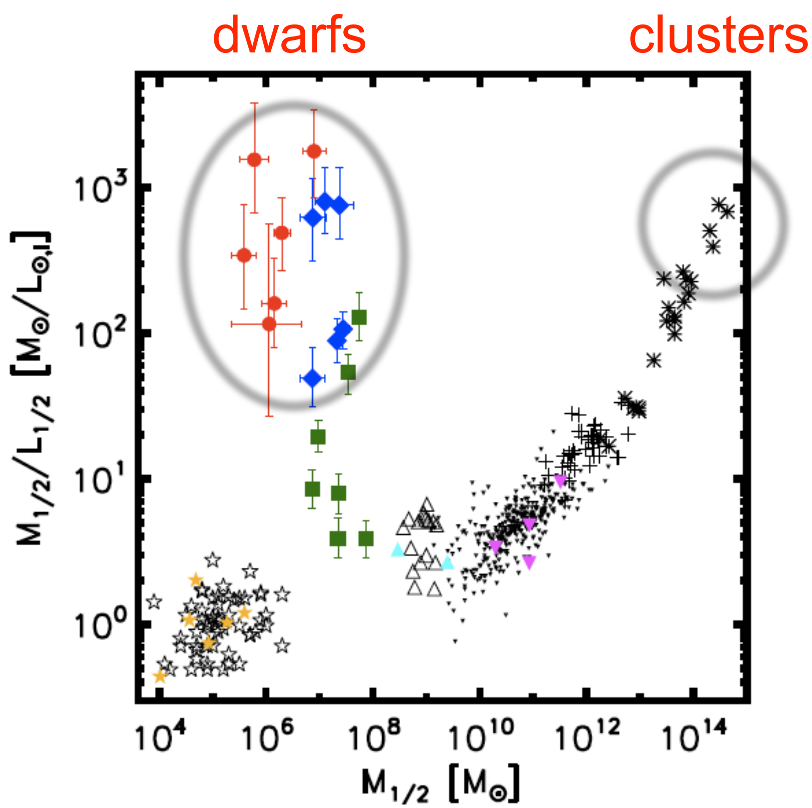
Dwarf Spherodial Galaxies

Local Group dwarf spheroidals are:

- ➢ nearby and very dark matter dominated
- ➢ most are expected to be free of other astrophysical gamma-ray sources
- ➢ SDSS has doubled the number of known dwarfs

Wolf et al. 2009



M/L at the half light radius

Galactic Substructure

(see also E. Bloom poster, Fermi Symposium)

Independent search for subhalos among unidentified Fermi sources:

- Search criteria: |b| > 10°, not variable, no ID at other wavelengths, spatially extended, DM-like spectrum

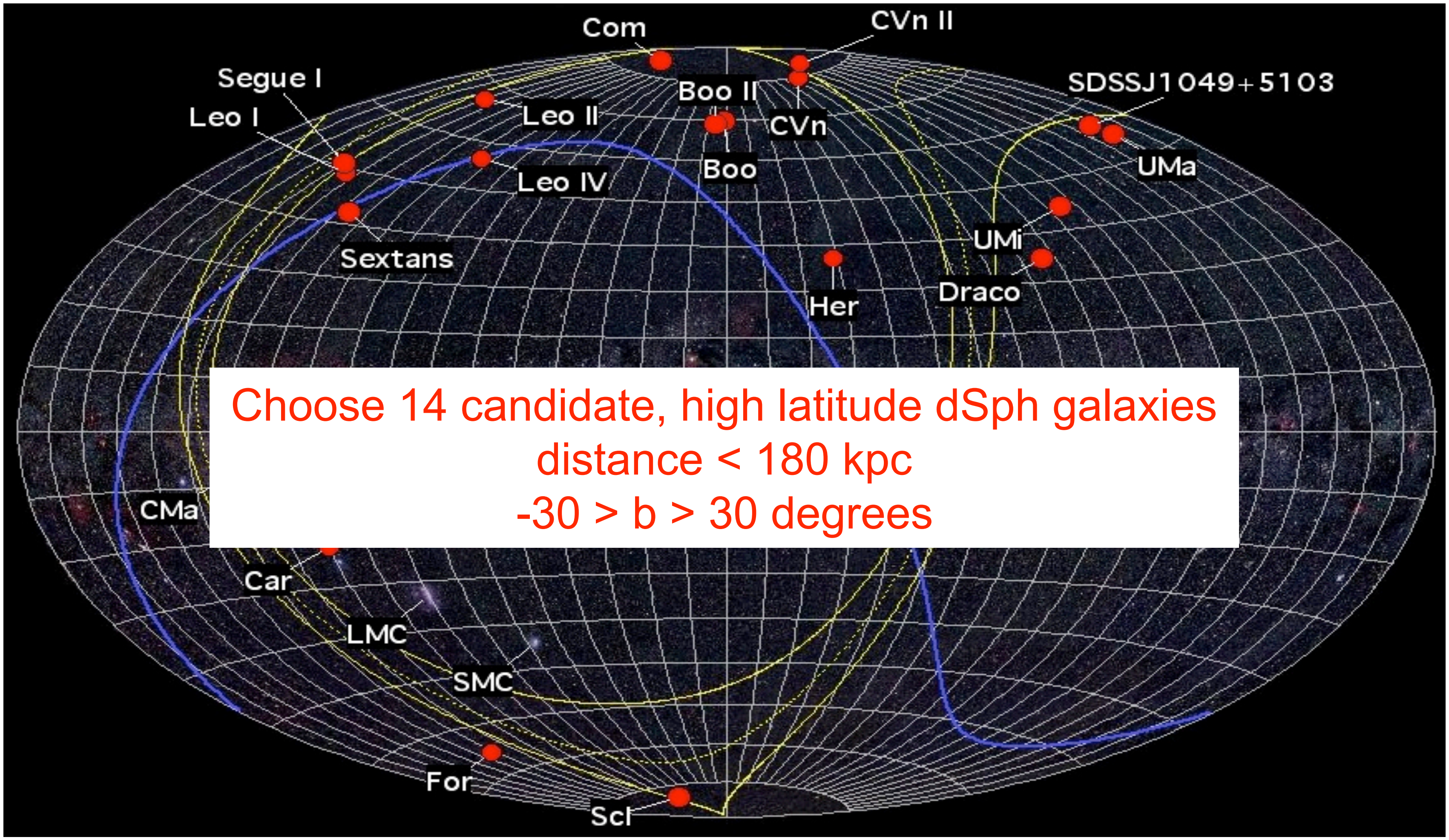
- No candidates meet all criteria > 5σ in 10 month data

- Consistent with predictions of Via Lactea II for 100 GeV WIMP with $\sigma v = 3 \times 10^{-26}$ cm^3 s^{-1}

➔ Here I will focus on known dwarfs detected in optical

Candidate Dwarf Spheroidals

(see also C. Farnier talk and P. Scott poster, Fermi Symposium)



Choose 14 candidate, high latitude dSph galaxies
distance < 180 kpc
-30 > b > 30 degrees

submitted to ApJ

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Fermi-LAT Data Analysis

- 11 months of data:
  - cuts to remove particle background and Earth's albedo
  - energy range 100 MeV to 50 GeV
  - 10 degree radius
  - binned analysis

- Backgrounds:
  - model galactic and isotropic diffuse
  - include point sources from Fermi-LAT catalog

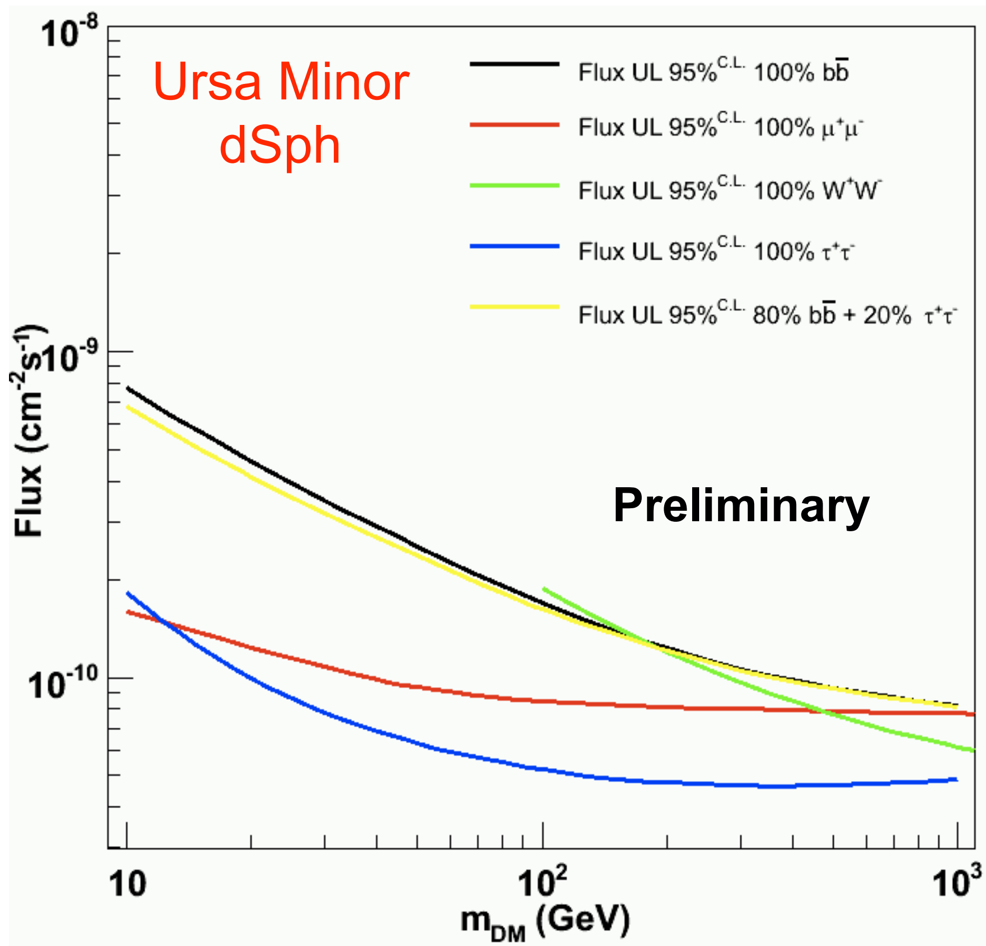
- Dwarfs modeled as point sources:
  - power law spectra with Γ = -1, -1.8, -2, -2.2, -2.4
  - dark matter annihilation with DMFIT (Jeltema & Profumo 2008)

No significant signal detected at the dwarf locations

Fermi-LAT Flux Upper Limits

Derive 95% confidence upper limits on the gamma-ray flux

- consider several final states and a grid of particle masses
- harder final states/ higher masses give lower flux limits
- bb, W^+W^-, and bb + $\tau^+\tau^-$ give similar results



Note: UMi gives among the best limits

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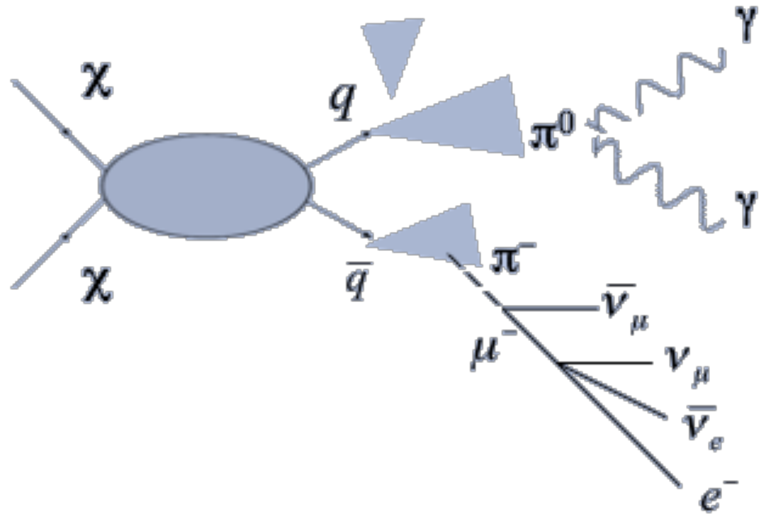
Dark Matter Density Profiles

Astrophysical factor derived from stellar kinematic data:

- assume an NFW profile (no substructure or Sommerfeld effects)
- maximum likelihood Markov chain fitting

Name	ρ_s $(10^8\ M_\odot\ kpc^{-3})$	r_s (kpc)	J^{NFW} $(10^{19}\ GeV^2\ cm^{-5})$
Ursa Major II	$1.43^{+3.37}_{-0.52}$	$0.13^{+0.10}_{-0.05}$	$0.58^{+0.91}_{-0.35}$
Coma Berenices	$0.84^{+2.98}_{-0.42}$	$0.11^{+0.11}_{-0.05}$	$0.16^{+0.22}_{-0.08}$
Bootes I	$0.89^{+2.34}_{-0.69}$	$0.18^{+0.19}_{-0.09}$	$0.16^{+0.35}_{-0.13}$
Ursa Minor	$0.44^{+1.04}_{-0.27}$	$0.48^{+0.38}_{-0.2}$	$0.64^{+0.25}_{-0.18}$
Sculptor	$0.21^{+0.32}_{-0.12}$	$0.70^{+0.57}_{-0.27}$	$0.24^{+0.06}_{-0.06}$
Draco	$0.19^{+0.14}_{-0.07}$	$1.84^{+1.0}_{-0.66}$	$1.20^{+0.31}_{-0.25}$
Sextans	$0.47^{+0.81}_{-0.30}$	$0.30^{+0.19}_{-0.11}$	$0.06^{+0.03}_{-0.02}$
Fornax	$0.36^{+0.69}_{-0.26}$	$0.43^{+0.36}_{-0.19}$	$0.06^{+0.03}_{-0.03}$

Constraints on “Standard” WIMP Models



(assume a b b final state)

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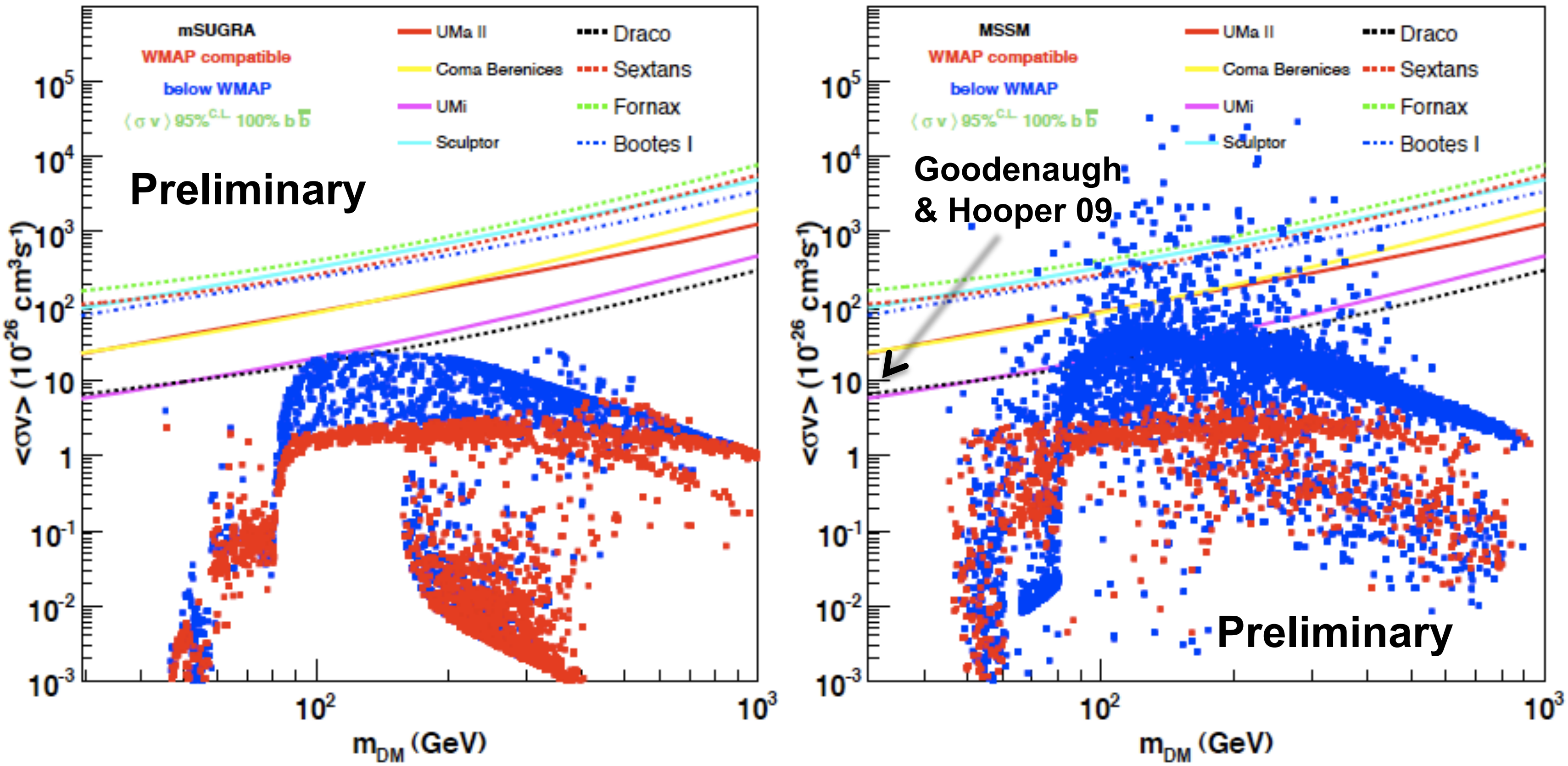
Annihilation Cross-Section Limits

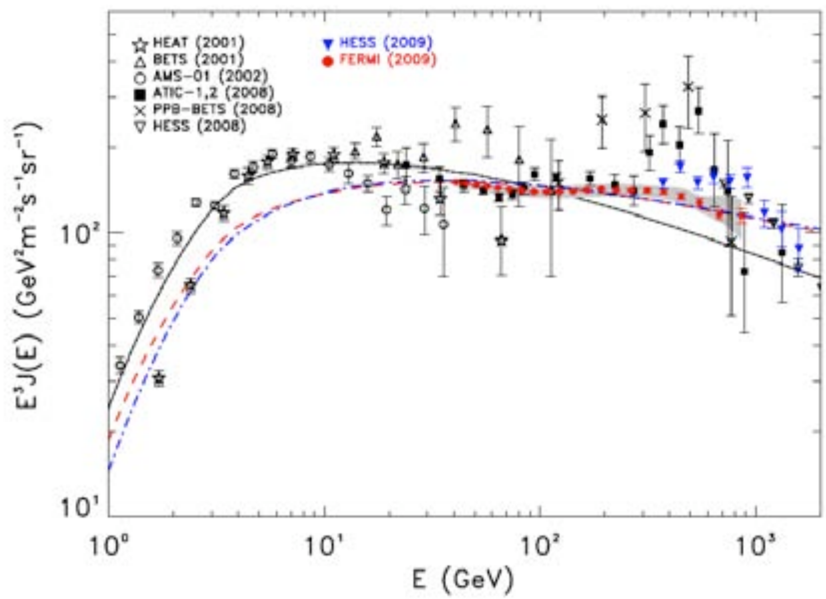
mSUGRA MSSM



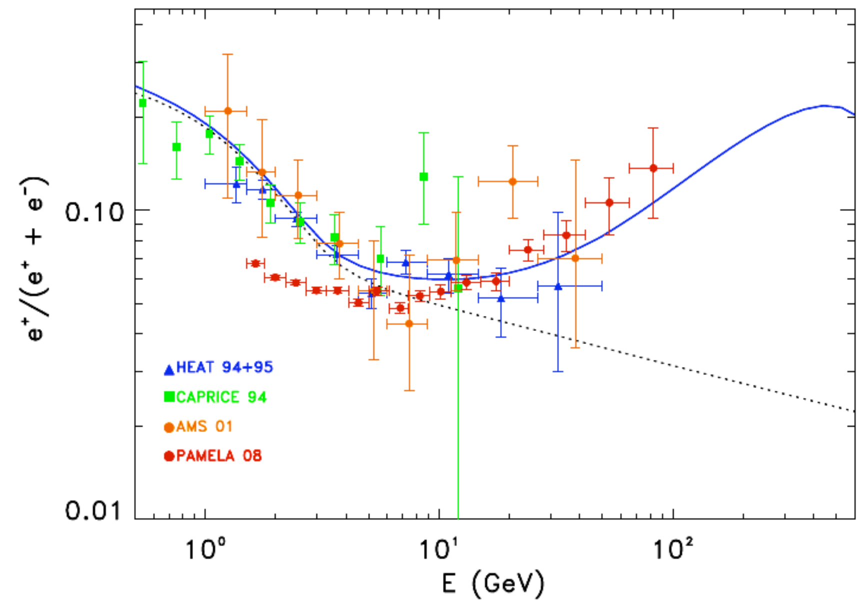
Exclude many MSSM models with low thermal relic densities.

- $\sigma v < 7 \times 10^{-26}$ at low mass
- no substructure or Sommerfeld boosts!

Constraints on Models Fitting Recent e^+ and e^- Measurements



$e^- + e^+$ spectrum



$e^+/(e^- + e^+)$ spectrum

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DM Annihilation Models Fitting the PAMELA Positron Excess

(while not violating other constraints)

➢ Leptonic final states with high particle masses (or annihilation to an intermediate which decays to leptons)

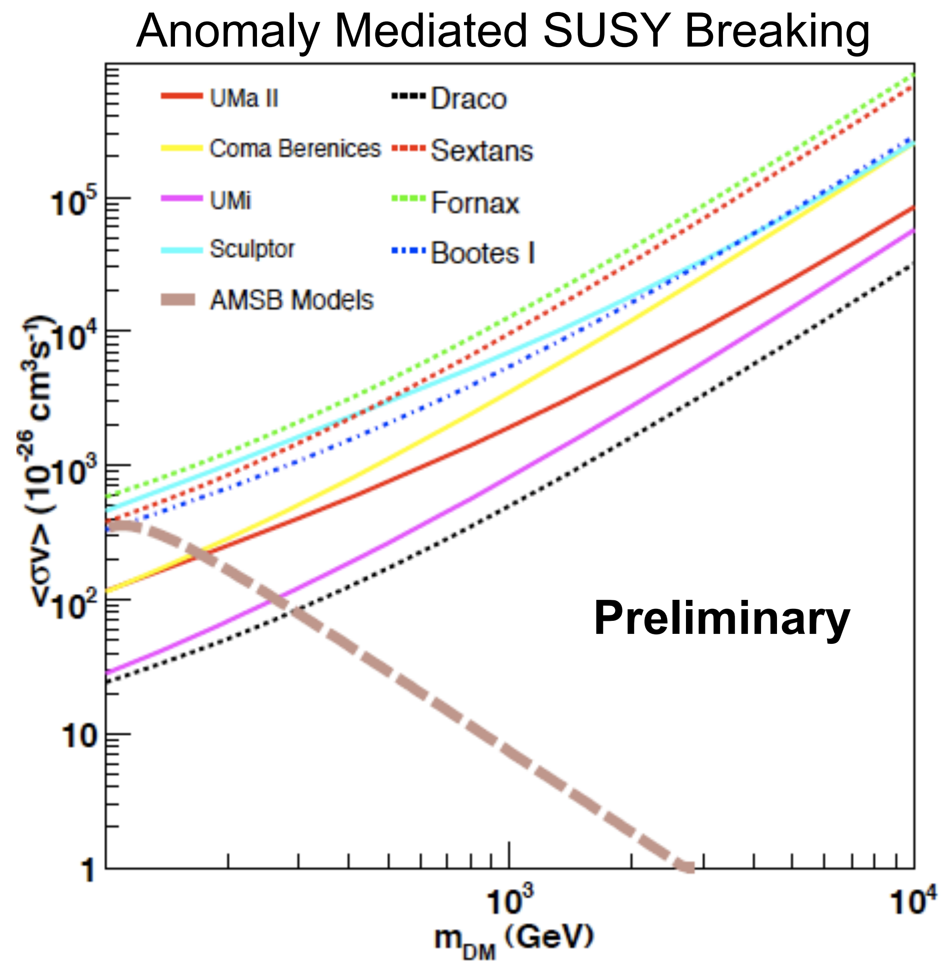
- We use a $\mu^+\mu^-$ final state as and example which fits well the PAMELA, Fermi, and HESS data

(Grasso et al. 2009, Bergstrom et al. 2009)

➢ Winos with mass ~ 200 GeV (Kane et al. 2009)

➢ Very high mass particle (> 10 TeV) annihilating to gauge bosons (Cirelli et al. 2009)

Annihilation Cross-Section Limits



Exclude AMSB models with mass < 300 GeV (i.e. Kane et al. 2009)

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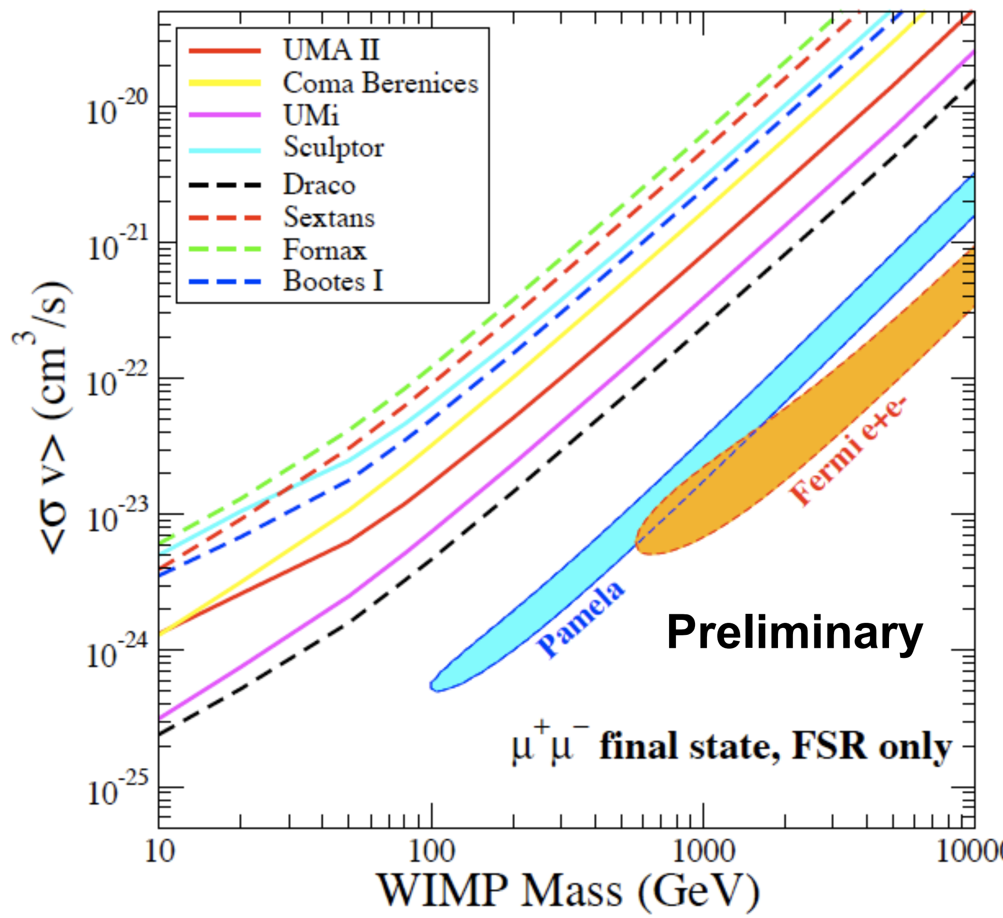
Annihilation Cross-Section Limits

Leptonic: $\mu^+\mu^-$ final state



(only includes final state gamma-ray radiation)

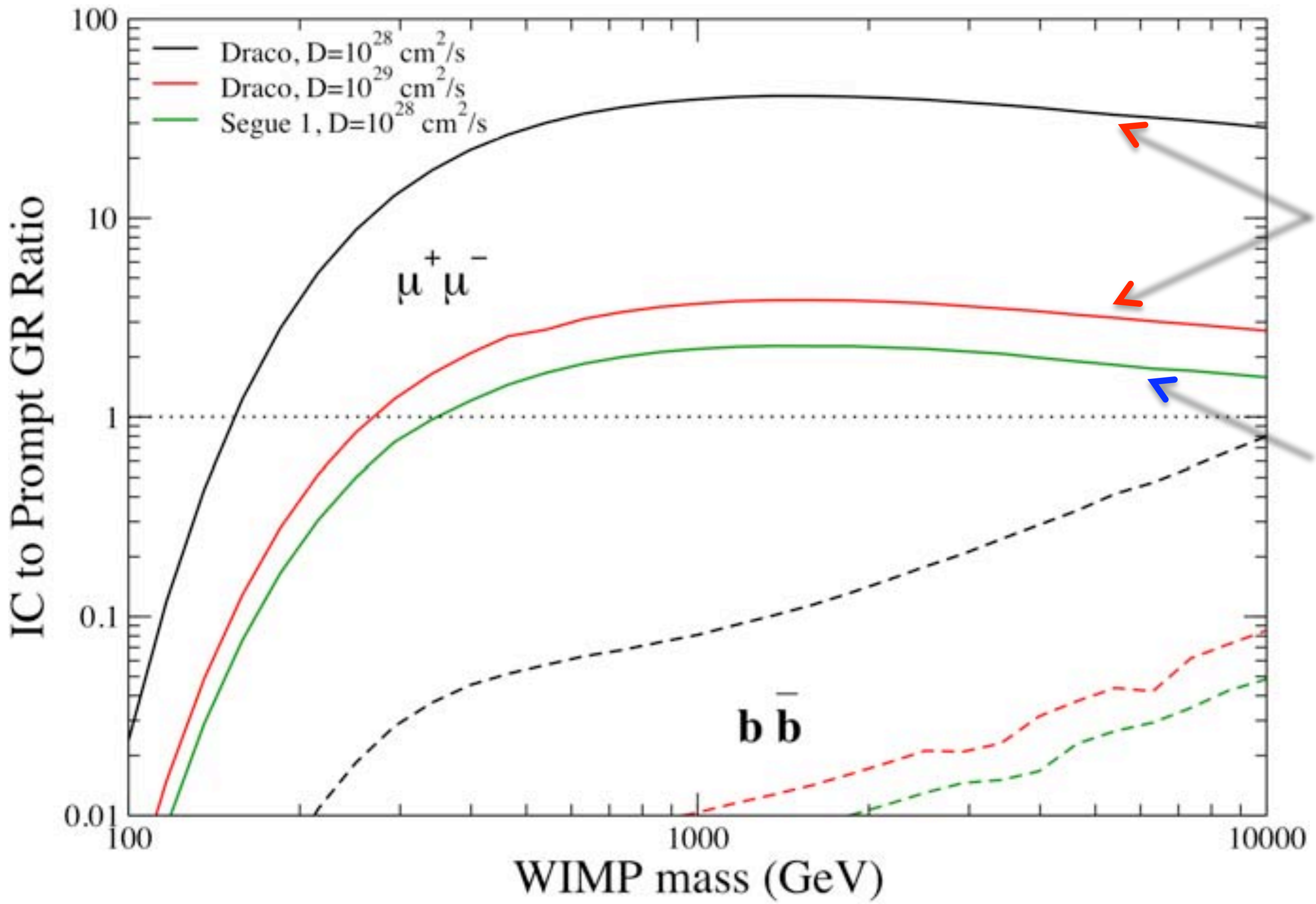
Inverse Compton Emission

- We expect significant IC gamma-ray emission for high mass WIMP models annihilating to leptonic final states.
- The IC flux depends strongly on the uncertain/ unknown diffusion of cosmic rays in dwarfs.
- We assume a simple diffusion model bounding what is found for the Milky Way

Note and foreshadowing of future slides:
For clusters, diffusion is not expected to be significant.

Inverse Compton Contribution

IC emission can dominate for leptonic final states at m > 300 GeV.

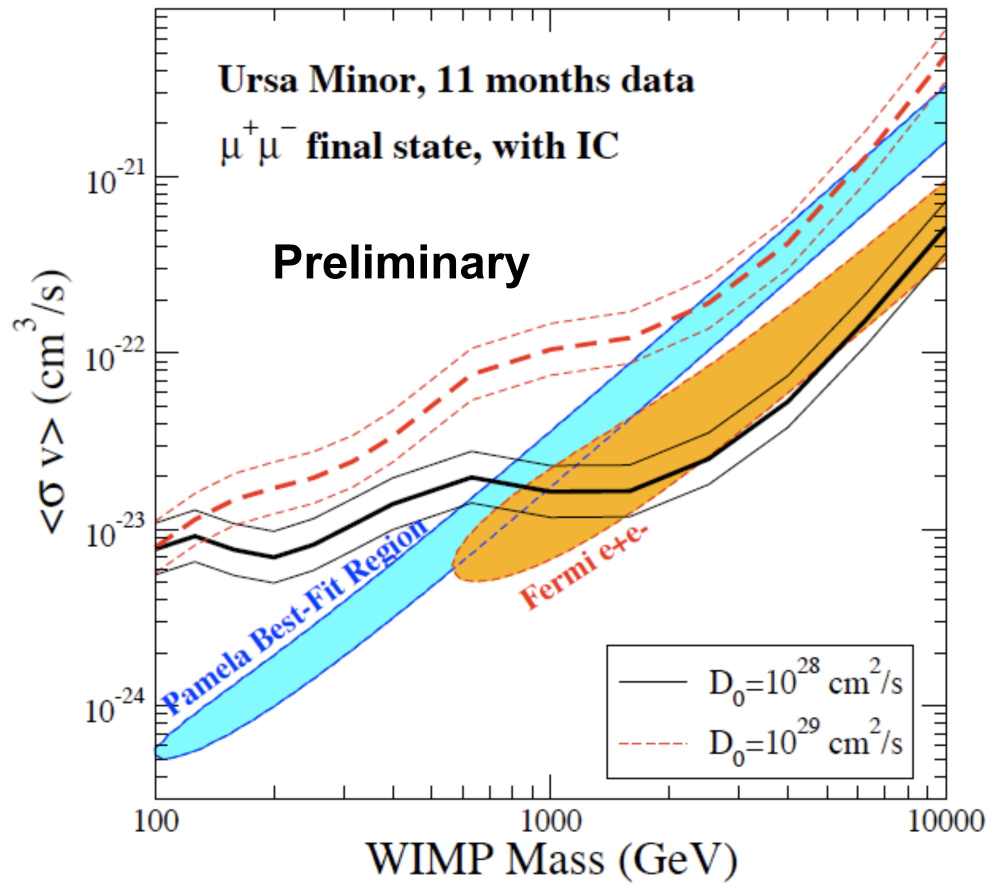


Draco:
variation in diffusion coeff. 10^{28} vs. 10^{29}

Segue 1:
diffusion more significant in small dwarfs

Constraints Including IC Emission

Combined constraints for FSR plus IC (D_0 = 10^{28} and 10^{29} cm^2/s).

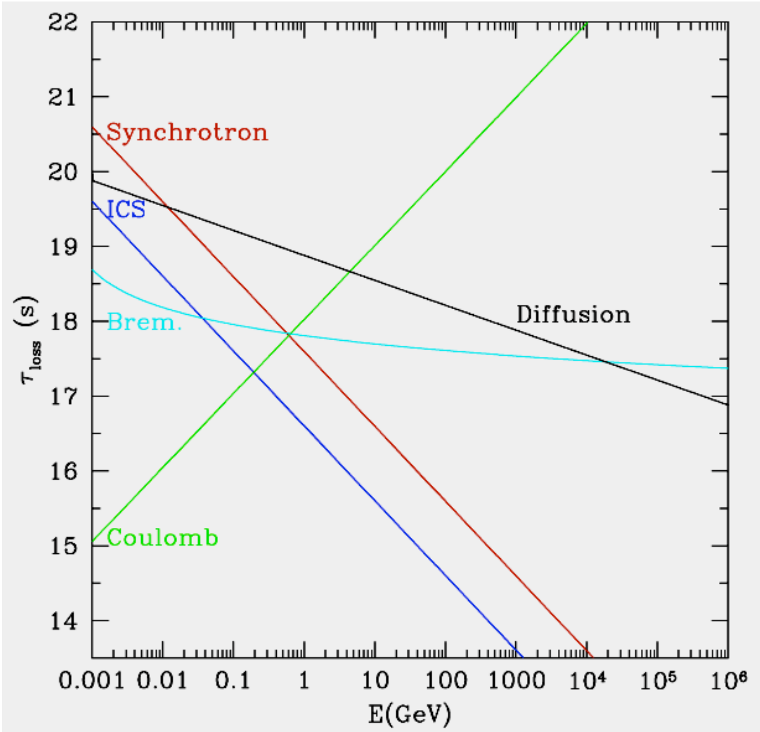


Depending on the diffusion model, we can limit high mass models

Comparison to Clusters of Galaxies

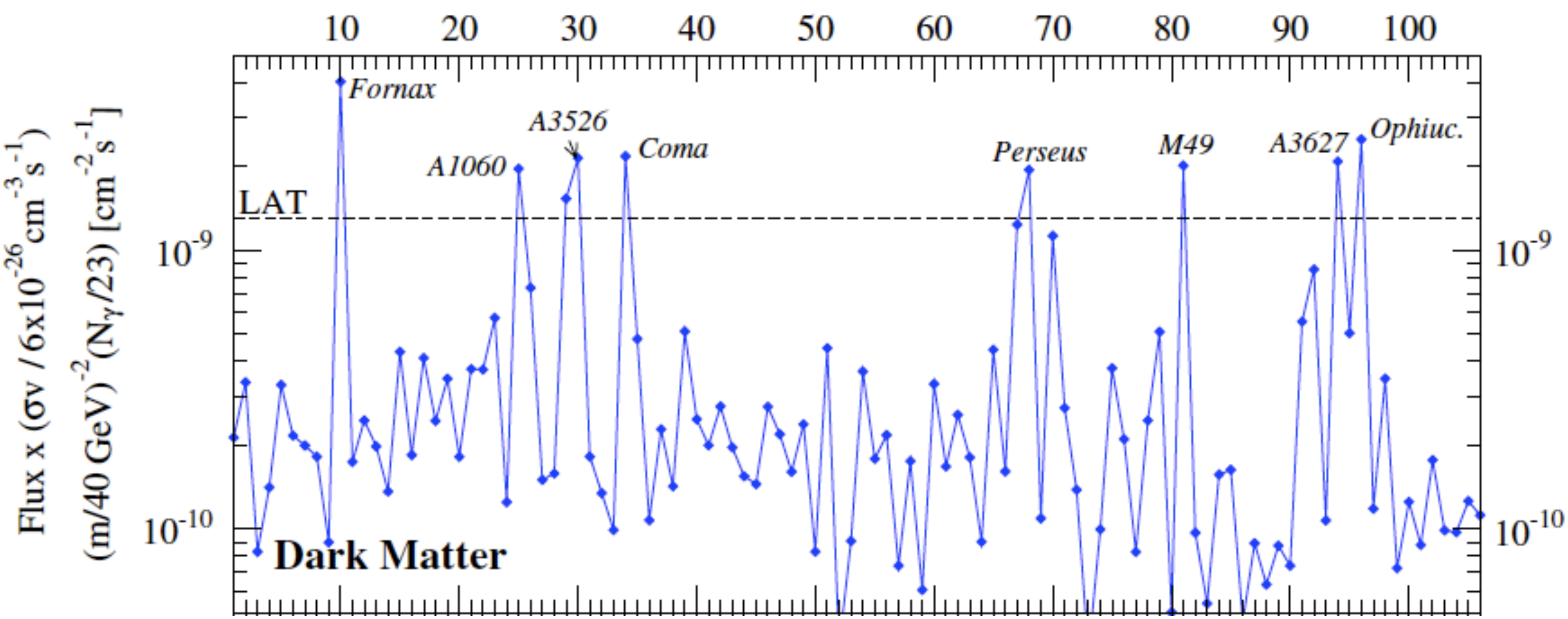
- Large DM densities and low backgrounds, like dwarfs (see Jeltema et al. 2009, Pinzke et al. 2009)

- For clusters, diffusion of e^+e^- not important
  - The energy loss timescale via IC scattering is much shorter than the diffusion time



Colafrancesco, Profumo, & Ullio 2007

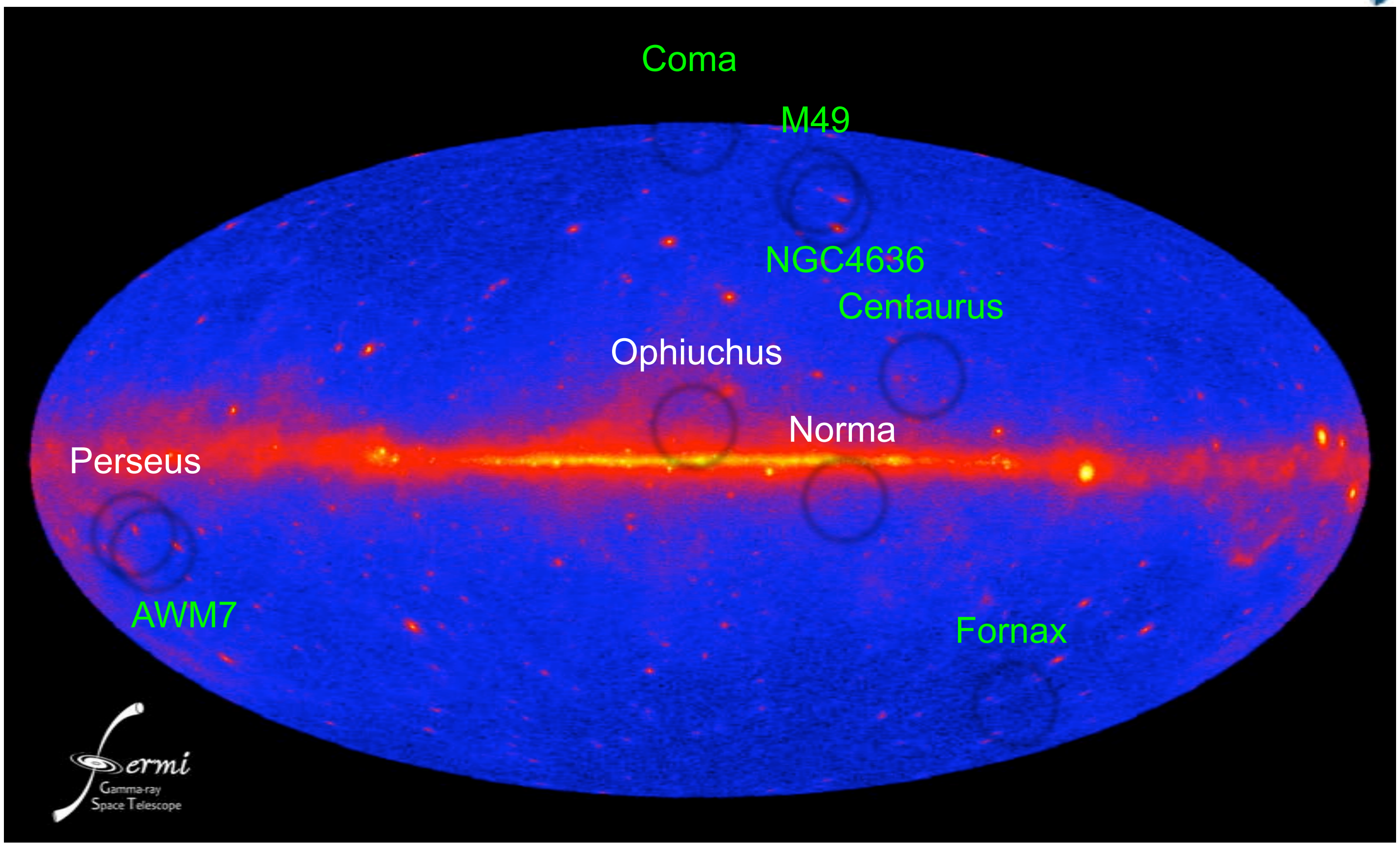
Best Candidate Clusters



(Jeltema, Kehayias, & Profumo 2009)

DM annihilation signal relatively higher for nearby groups compared to cosmic ray emission which favors X-ray bright clusters.

Cluster Sample



Brightest predicted clusters for dark matter annihilation (Jeltema, Kehayias, & Profumo 2009)

Cluster Sample

- Remove Perseus (centered on NGC1275) and Ophiuchus (near GC), and Norma (near Galactic plane)
- Final sample of 6 clusters

Cluster	RA	Dec.	z
AWM 7	43.6229	41.5781	0.0172
Fornax	54.6686	-35.3103	0.0046
M49	187.4437	7.9956	0.0033
NGC 4636	190.7084	2.6880	0.0031
Centaurus (A3526)	192.1995	-41.3087	0.0114
Coma	194.9468	27.9388	0.0231

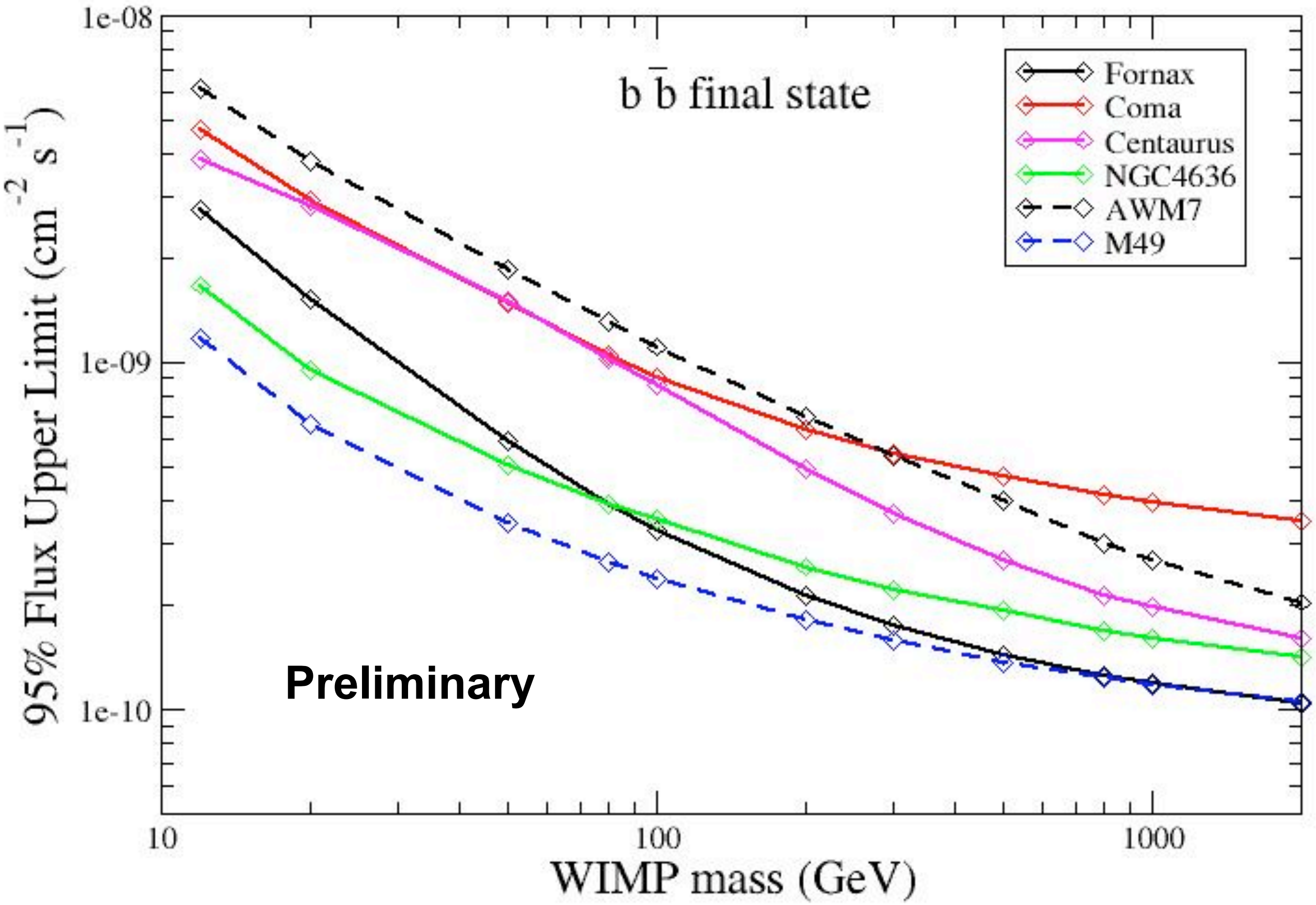
No significant signal detected in 11 months with Fermi

Cluster Modeling

- Density profiles based on X-ray data
  - Assume an NFW profile
  - Mass from Reiprich & Böhringer 2002 and c-M relation from Buote et al. 2007

- Vary contribution of substructure:
  - No substructure
  - Substructure on galaxy scales (dwarf galaxy or larger)
  - Substructure down to $M = 10^{-6}\ M_\odot$ and 20% of cluster mass

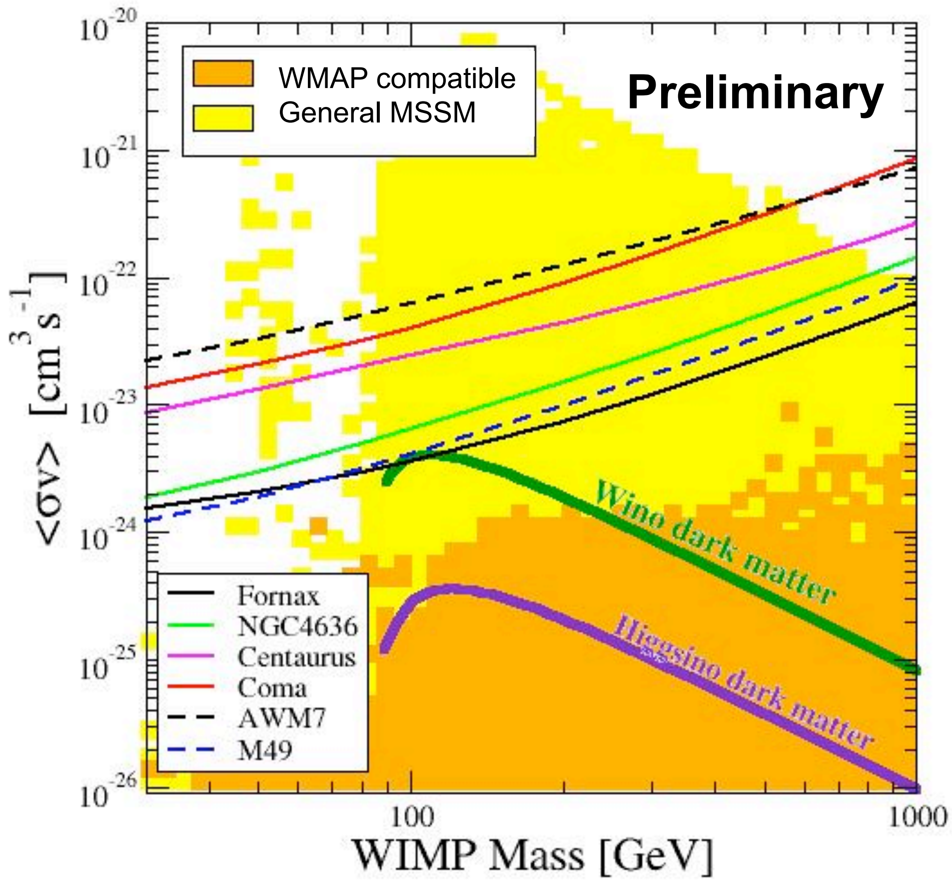
Flux Upper Limits



- 95% confidence level limits assuming a bb final state.

Constraints on "Standard" WIMP Models

All clusters, NFW only no substructure



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

- 95% confidence limits assuming a bb final state.
- Constraints are typically weaker than for dwarfs.

Constraints on "Standard" WIMP Models

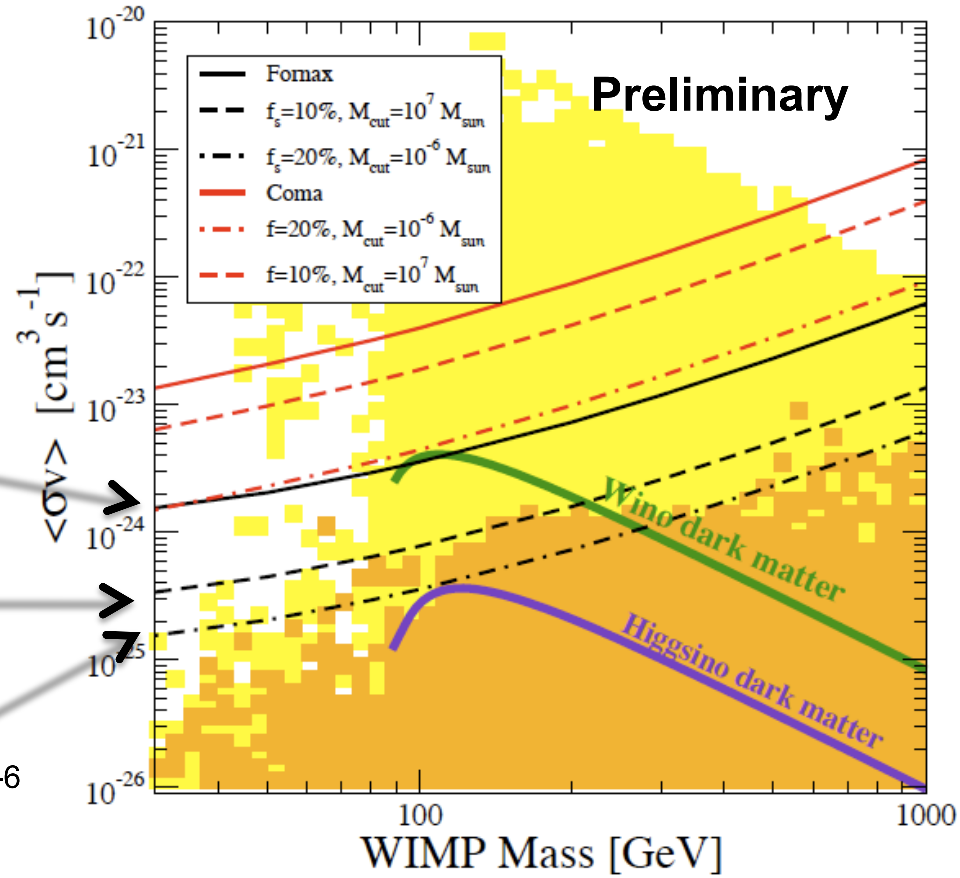
---- Fornax

---- Coma

no substructure

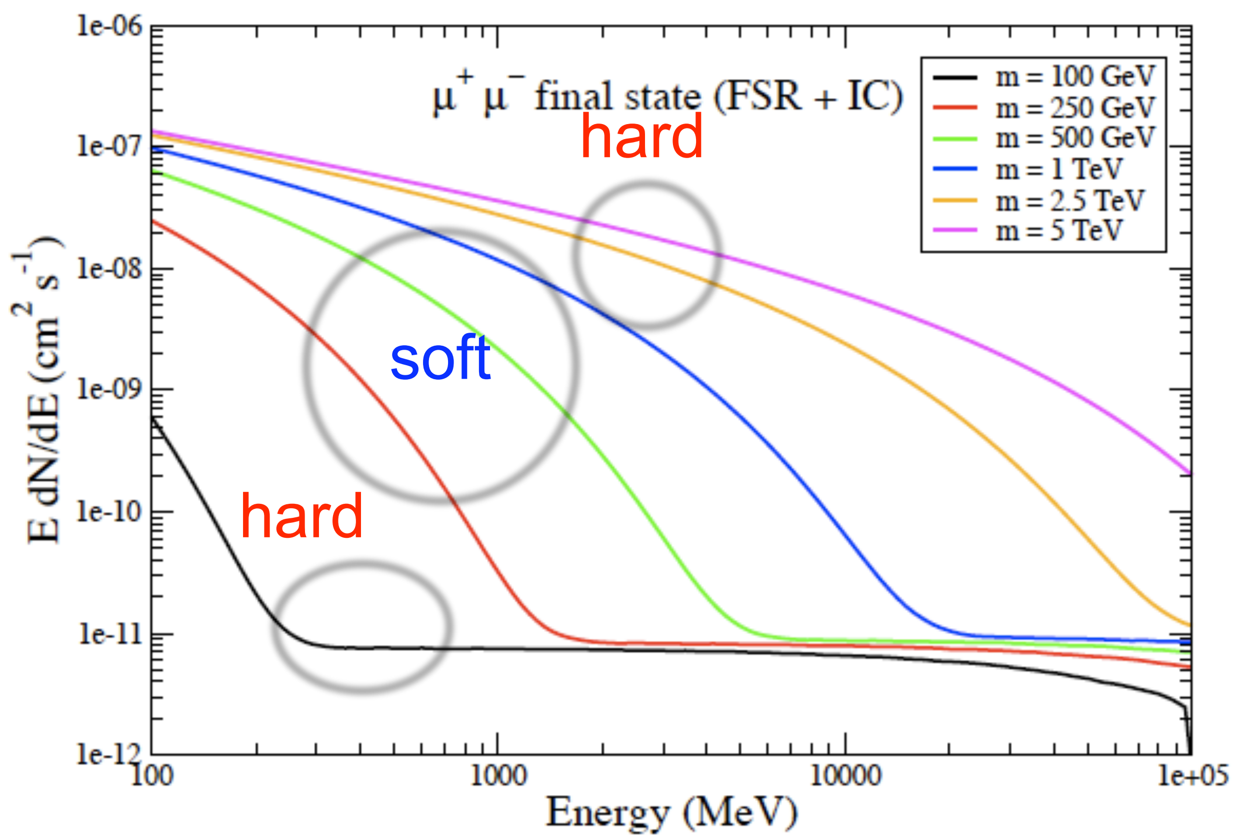
galaxies only

substructure with $M > 10^{-6}$



- 95% confidence limits assuming a bb final state.
- Constraints are typically weaker than for dwarfs.

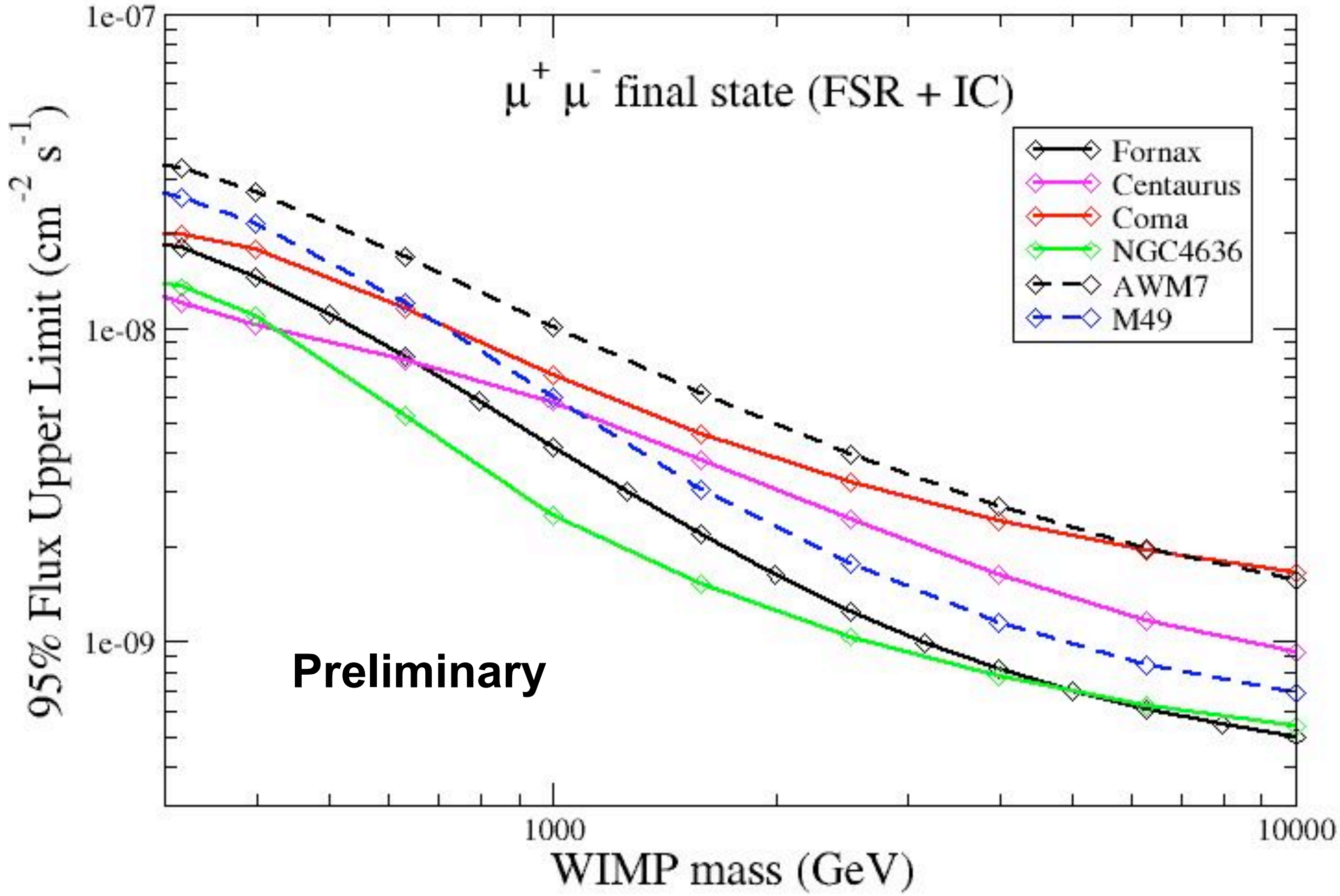
Gamma-Ray Spectrum for $\mu^+\mu^-$ Final State (FSR+IC)



IC emission dominates for masses greater than ~ 200 GeV

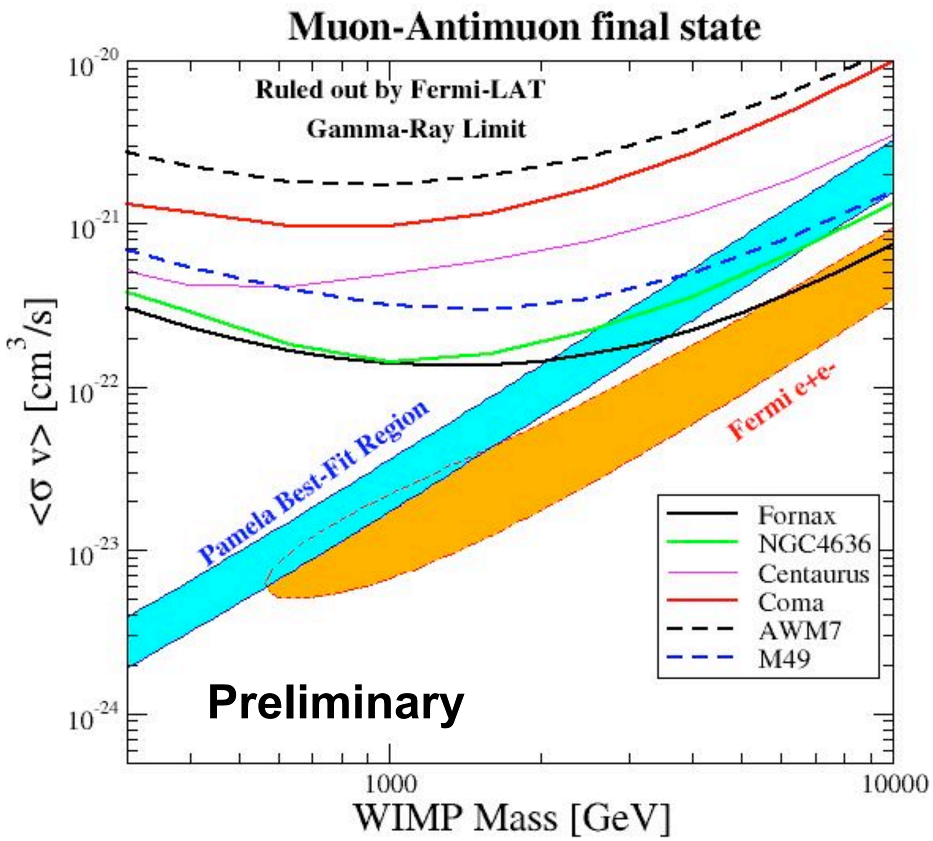
Tesla Jeltema for the Fermi LAT Collaboration

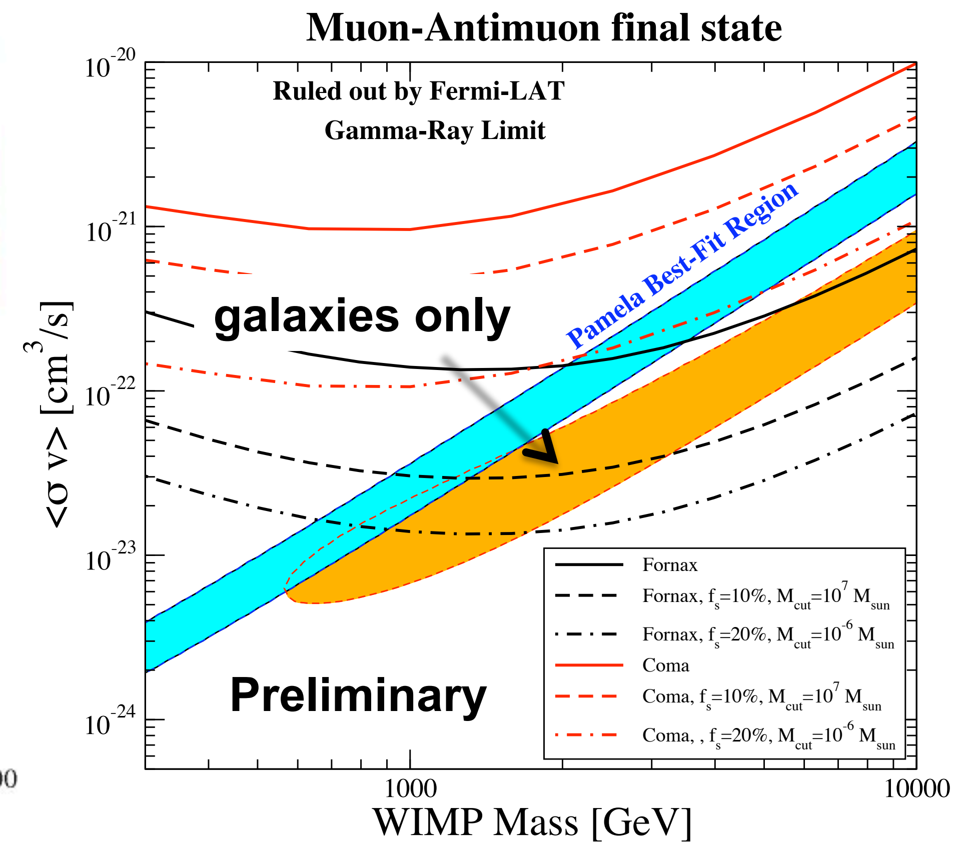
Flux Upper Limits



- 95% confidence level limits assuming a $\mu^+\mu^-$ final state.
- Shape is due to the varying IC spectrum

Constraints on "PAMELA" Models

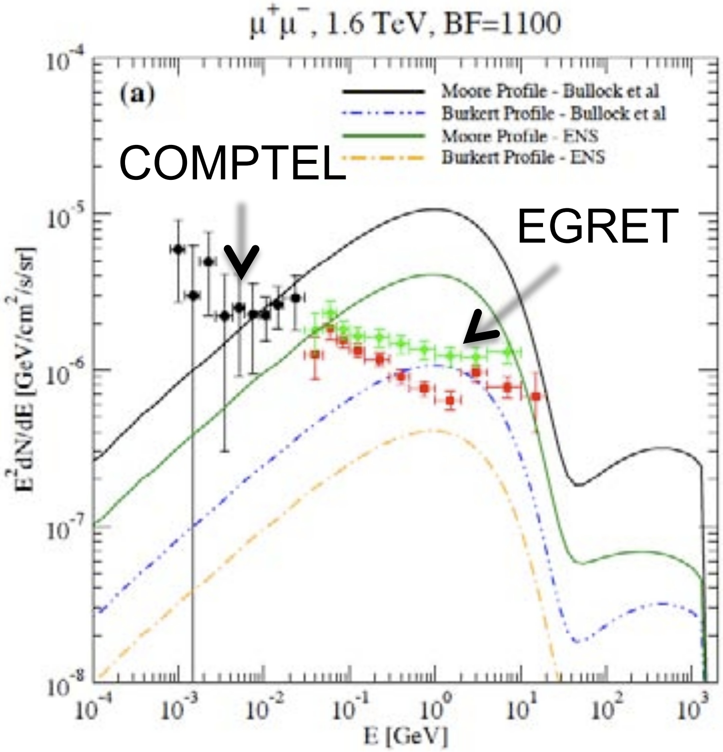


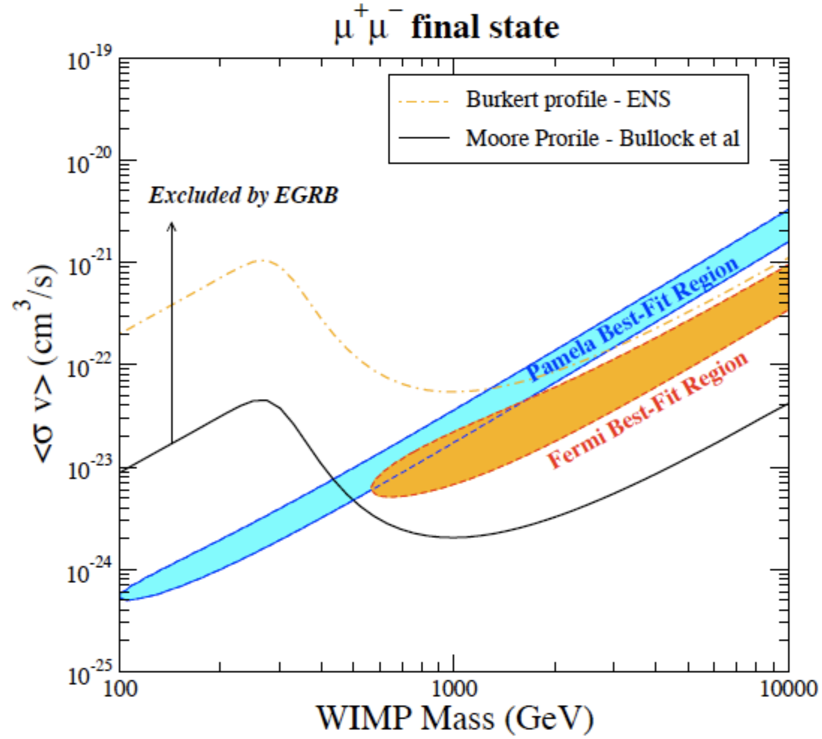


Exclude models fitting PAMELA data with mass > 1-2 TeV

Extragalactic Gamma-ray Background

(pre-Fermi: Profumo & Jeltema 2009)





EGRET: Sreekumar et al 1998, Strong et al 2004 COMPTEL: Kappadath et al 1996

- Conservatively assume IC emission from all halos cannot exceed total gamma-ray background.
- Again, exclude high mass "PAMELA" models

Update with Fermi coming soon! (see G. Zaharijas talk, TeV PA)

Conclusions

- Fermi-LAT provides a new window for indirect searches for dark matter.

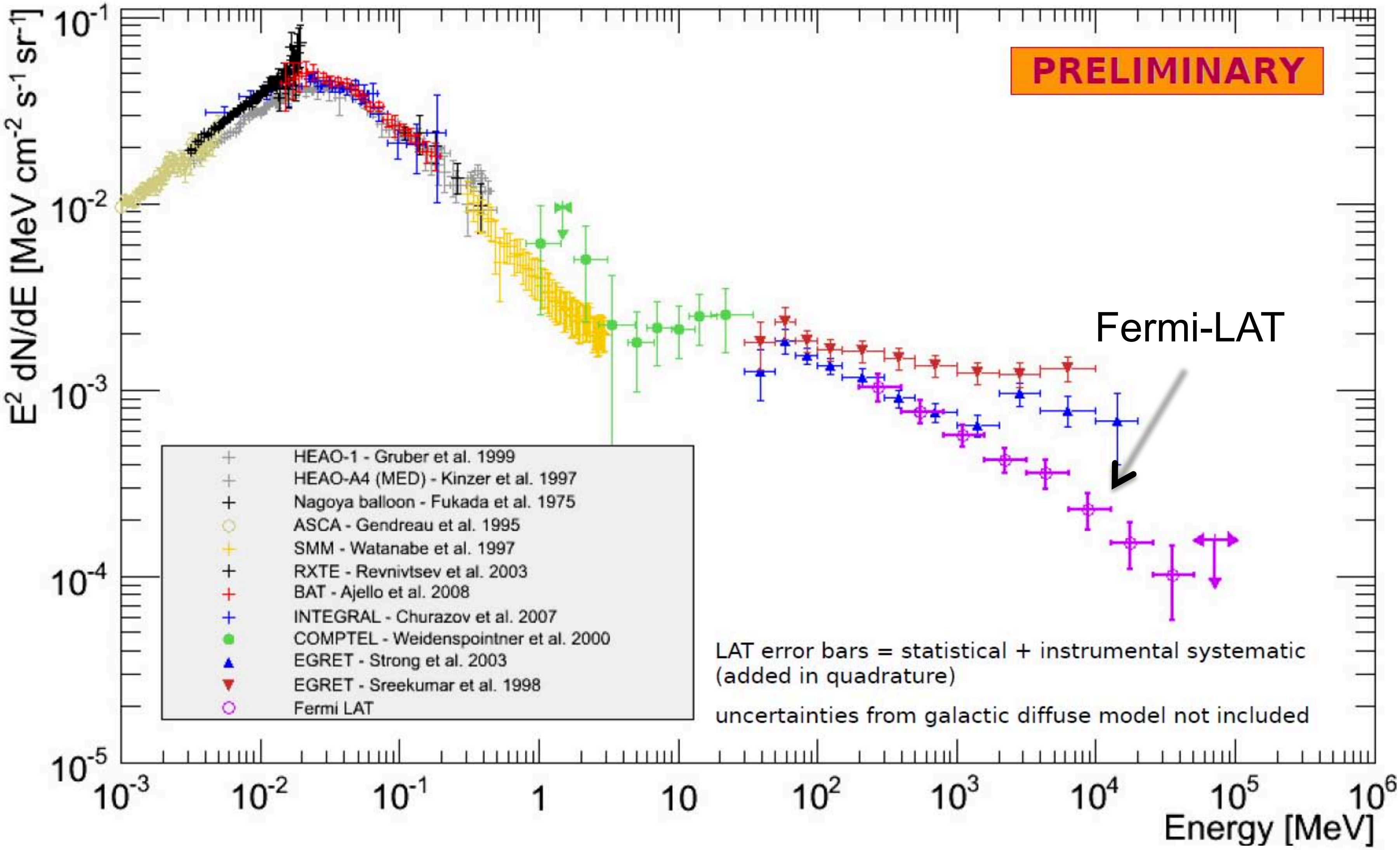
- No dwarf spheroidal galaxies or clusters detected in 11 months of data.

- Non-detection of dwarfs excludes AMSB models with mass < 300 GeV and low thermal relic density MSSM models

- Non-detection of clusters (and EGB) excludes models with mass > 1-2 TeV fitting the Pamela positron excess.

Backup Slides

Extragalactic Gamma-ray Background



Update with Fermi coming soon! (see G. Zaharijas talk, TeV PA)