Investigating Dark Matter with the Fermi Large Area Telescope

Simona Murgia, SLAC-KIPAC
representing the Fermi-LAT Collaboration

Fermi Gamma-ray Space Telescope

SLAC NATIONAL ACCELERATOR LABORATORY

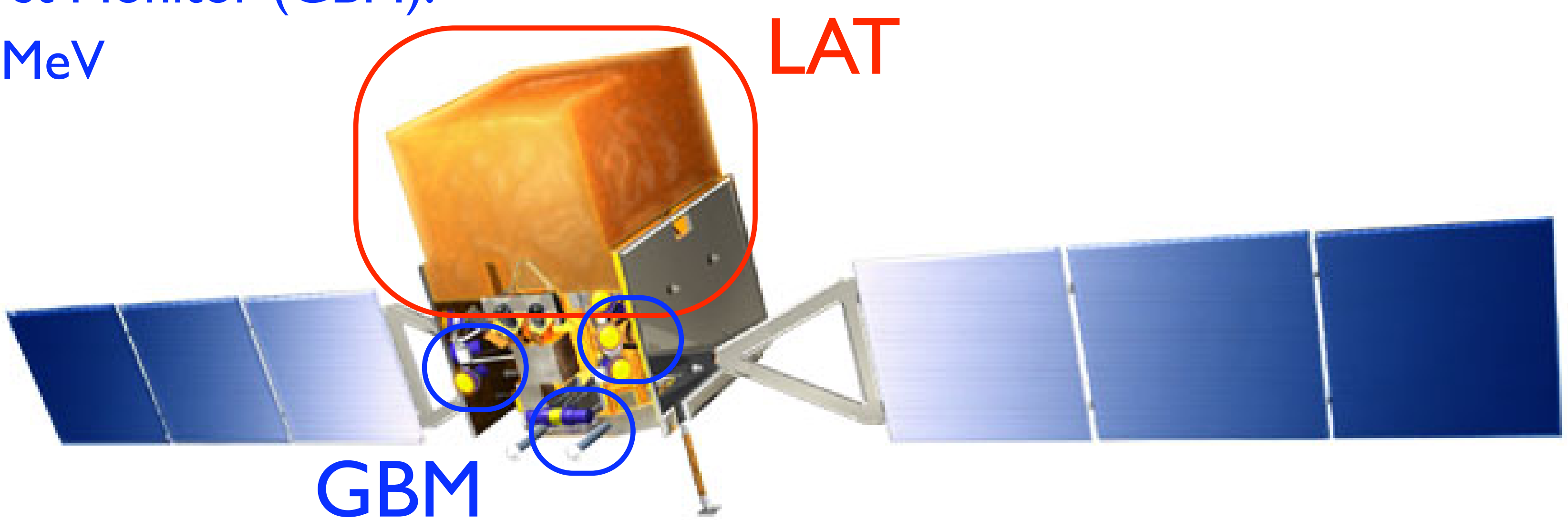
TeV Particle Astrophysics 2010
19-23 July 2010 - Paris

The Observatory

- Observe the gamma-ray sky in the 20 MeV to >300 GeV (LAT) energy range with unprecedented sensitivity
- Two instruments:

Large Area Telescope (LAT):
20 MeV - >300 GeV

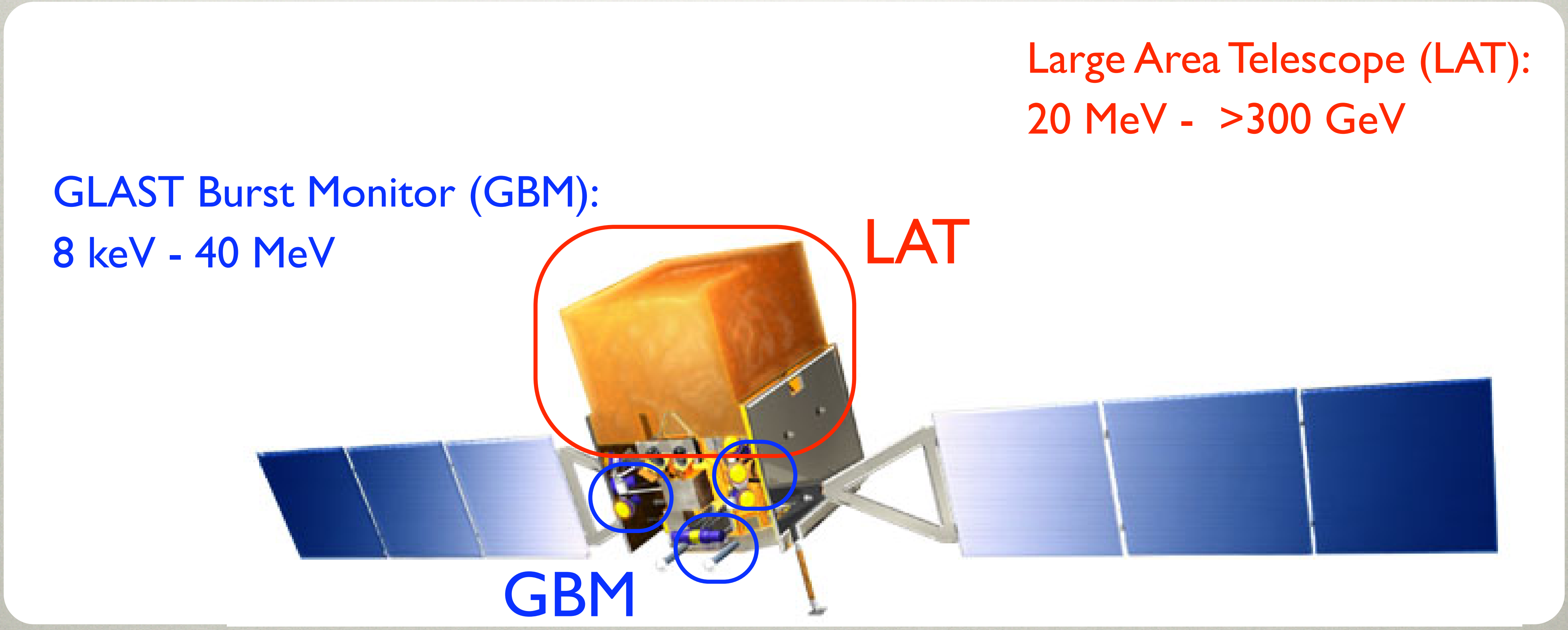
GLAST Burst Monitor (GBM):
8 keV - 40 MeV



The Observatory

- Observe the gamma-ray sky in the 20 MeV to >300 GeV (LAT) energy range with unprecedented sensitivity
- Two instruments:

➡ Great instrument to probe WIMP dark matter!
(and more, e.g. axions, not discussed in this talk...)



The Launch

- Fermi was launched by NASA on June 11, 2008 from Cape Canaveral
- Launch vehicle: Delta II heavy launch vehicle
- Orbit: 565 km, 25.6° inclination, circular
- The LAT observes the entire sky every ~3 hrs (2 orbits)
- Design life: 5 years (10 year goal)

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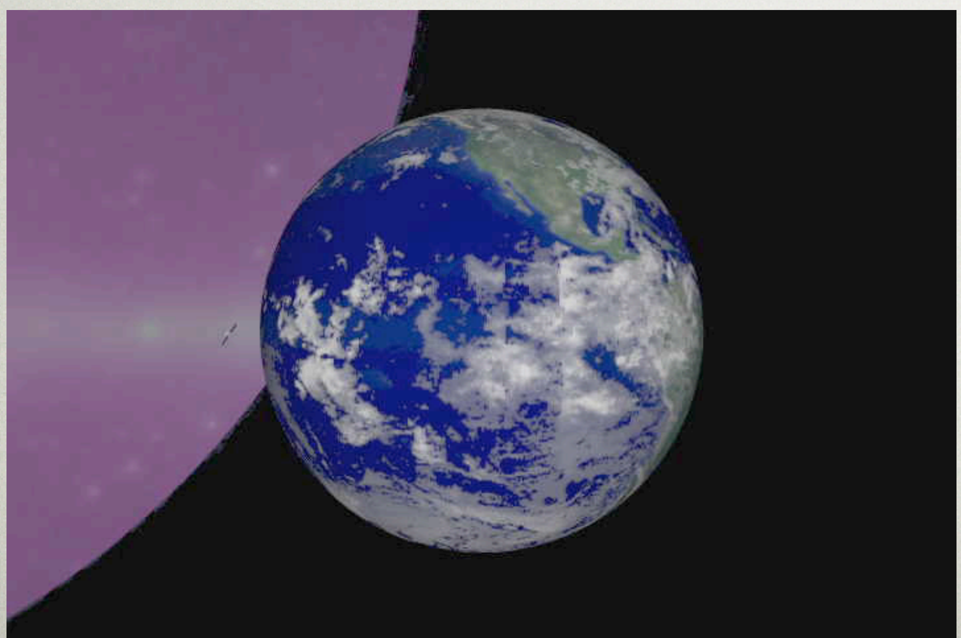
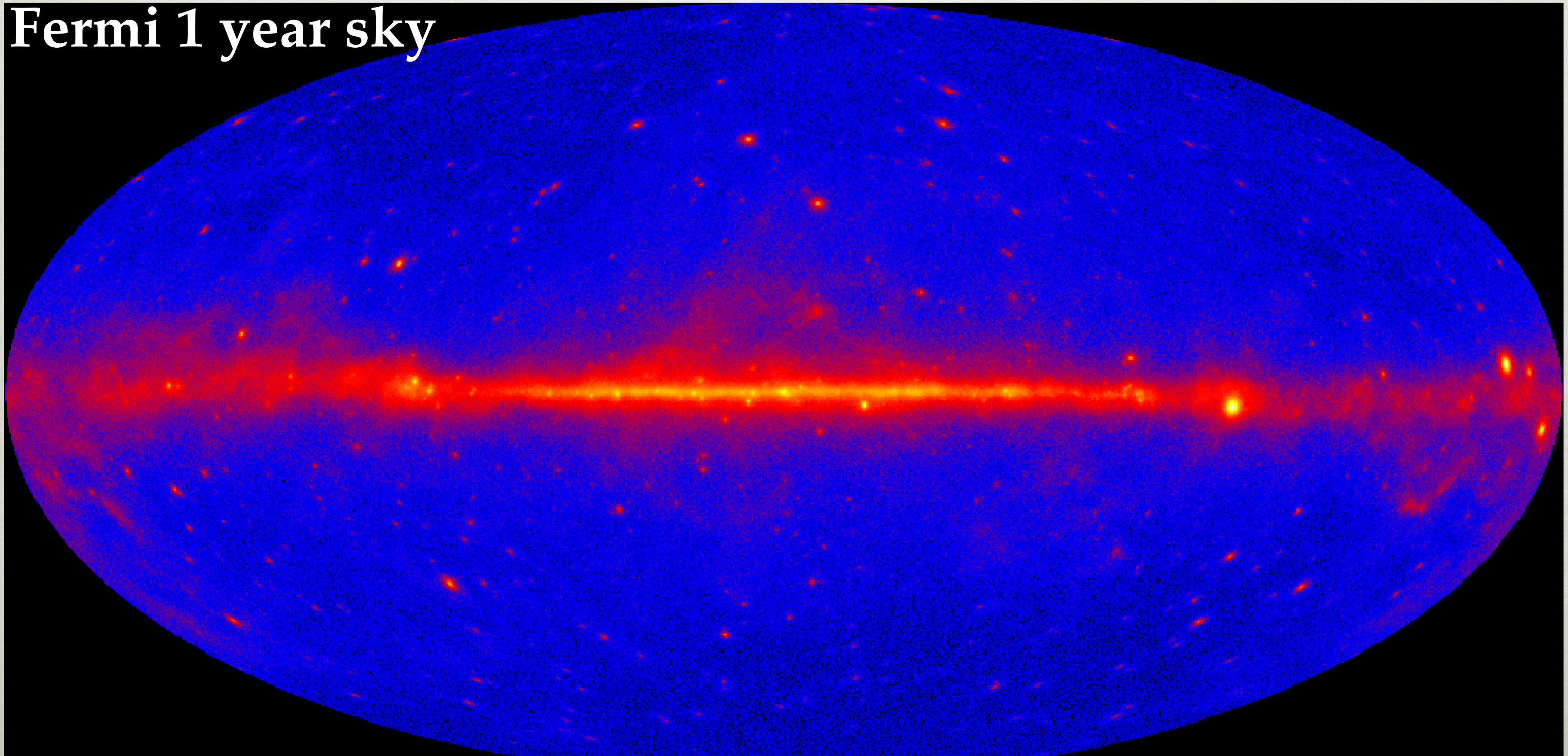


The Fermi Sky

- 1451 sources in First Fermi LAT source catalog (11 months)
- 241 sources show evidence of variability
- 57% of the sources are associated positionally, mostly with blazars and pulsars
- Small number of other classes of sources: XRB, PWN, SNR, starburst galaxies, globular clusters, radio galaxies, Seyferts



Annihilation Signal

particle physics

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

DM distribution

For DM decay:

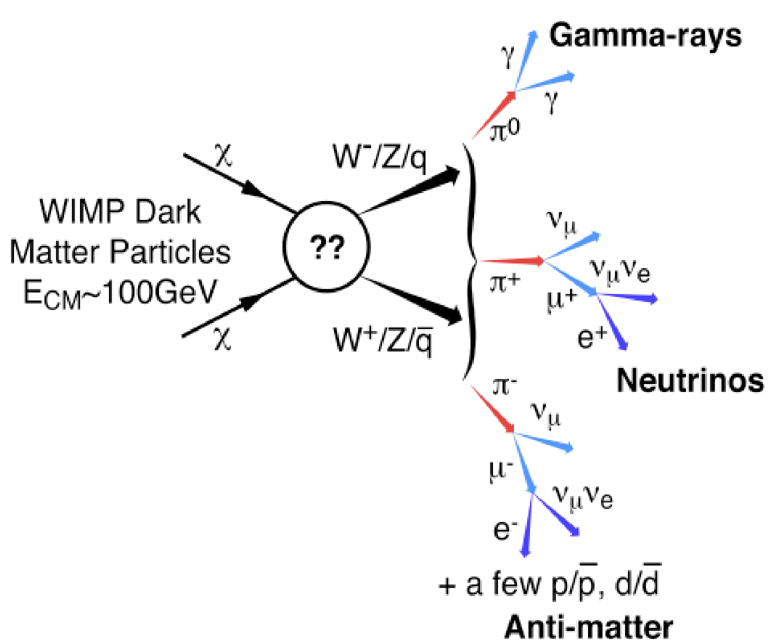
- $<\sigma_{ann}v>/2m^2_{\mathrm{WIMP}} \rightarrow 1/\tau m_{\mathrm{WIMP}}$
- $\rho^2 \rightarrow \rho$

WIMP Dark Matter Spectrum

- Several theoretical models have been proposed that predict the existence of WIMPs (Weakly Interacting Massive Particle) that are excellent DM candidates
- In addition to photons, with Fermi we can also probe electron+positron final states

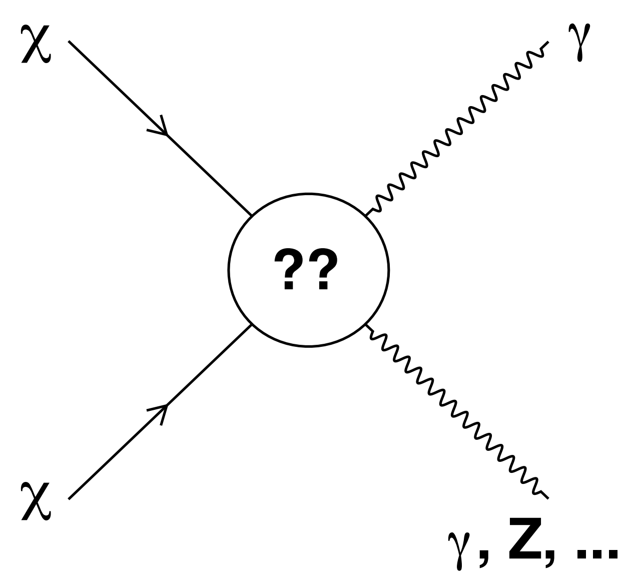
Continuum spectrum with cutoff at M_{DM}

Annihilation (or decay) into γ



Spectral line

Prompt annihilation into γγ, γZ, γH^0...
(also prompt decay into photons)



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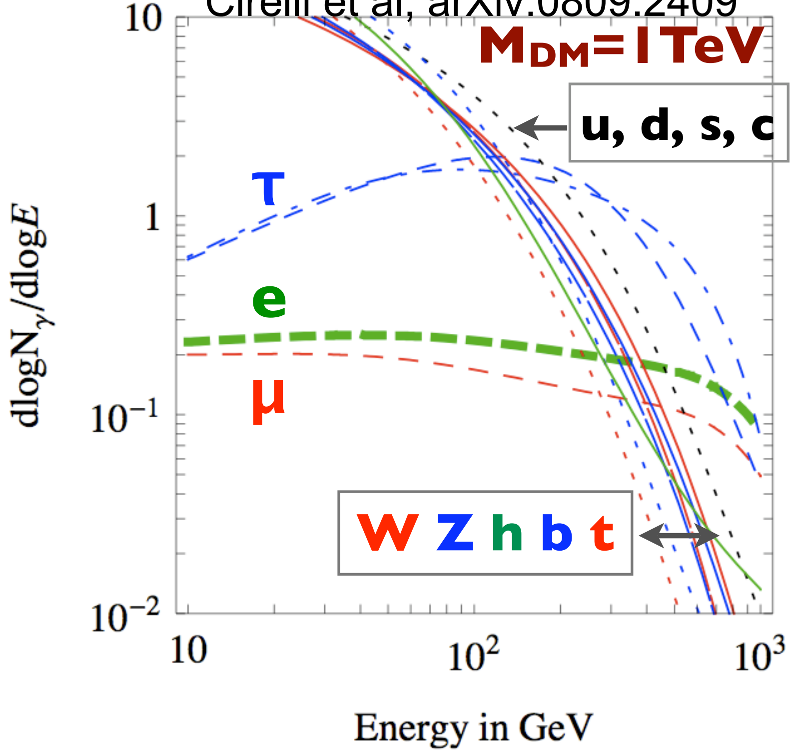
Cirelli et al, arXiv:0809.2409



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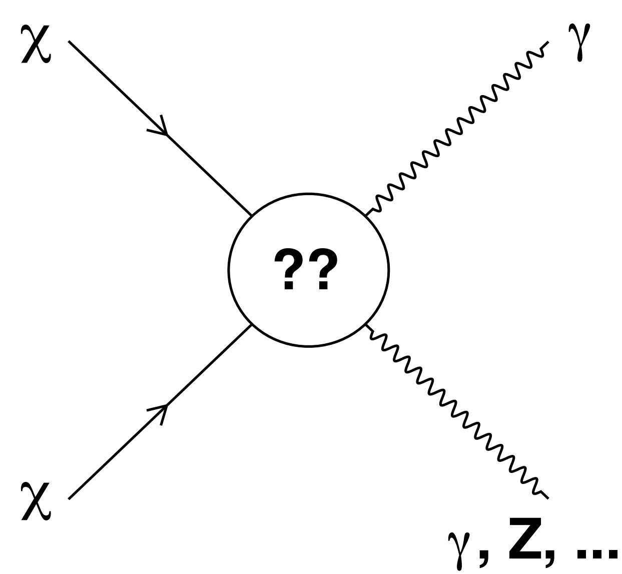

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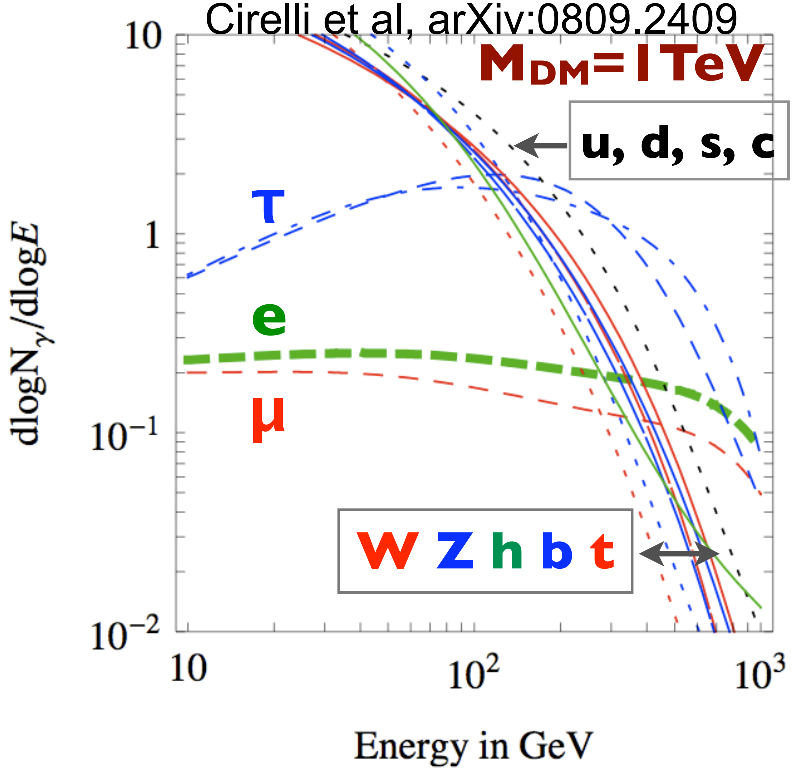


Spectral line

Prompt annihilation into γγ, γZ, γH^0...
(also prompt decay into photons)

Generally suppressed (10^{-1}-10^{-4}), but enhanced in some models

For γγ final state:

$$E_\gamma = M_{DM}$$

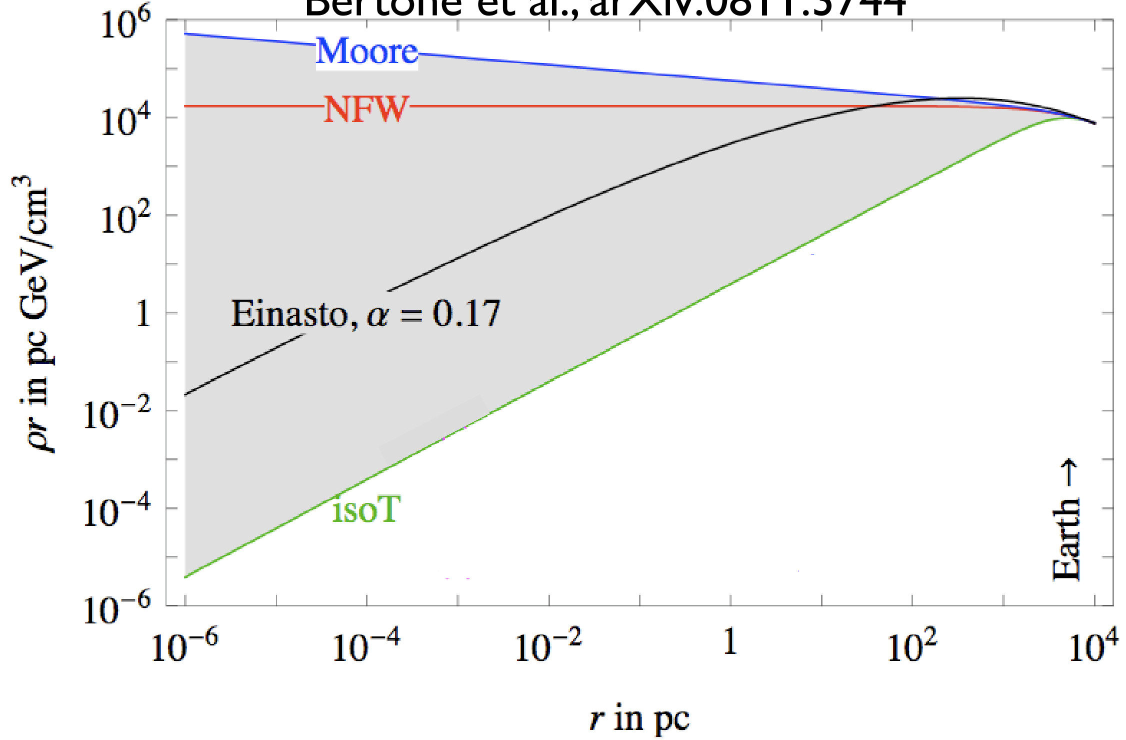
For γX final state:

$$E_\gamma = M_{DM} - \frac{M_X^2}{4M_{DM}}$$

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

Bertone et al., arXiv:0811.3744



NFW profile

Navarro, Frenk, and White 1997

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

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

$$a_0 = 20\ \mathrm{kpc},\ r_0 = 8.5\ \mathrm{kpc}$$

✓ Via Lactea II (Diemand et al 2008) predicts a cuspier profile, $\rho(r) \propto r^{-1.2}$

✓ Aquarius (Springel et al 2008) predicts a shallower than r^{-1} innermost profile

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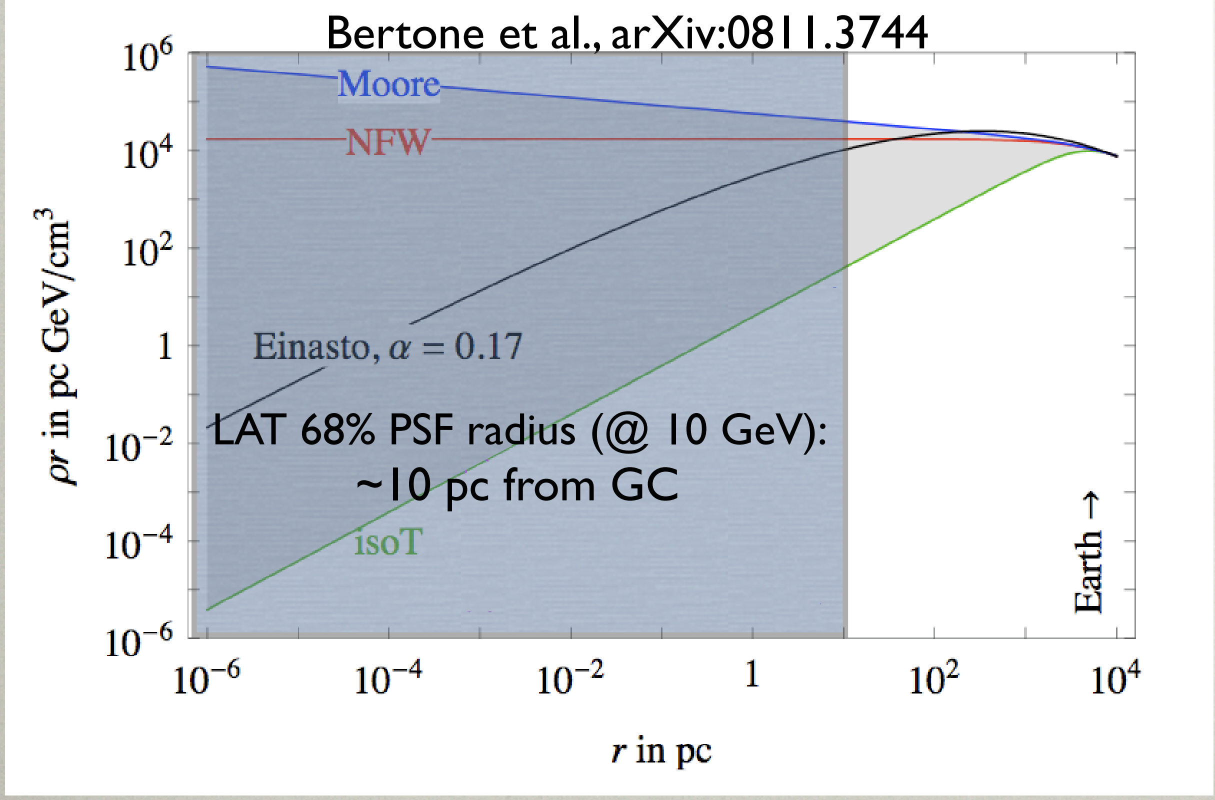

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Search Strategies

Galactic center:

Good statistics but source confusion/diffuse background

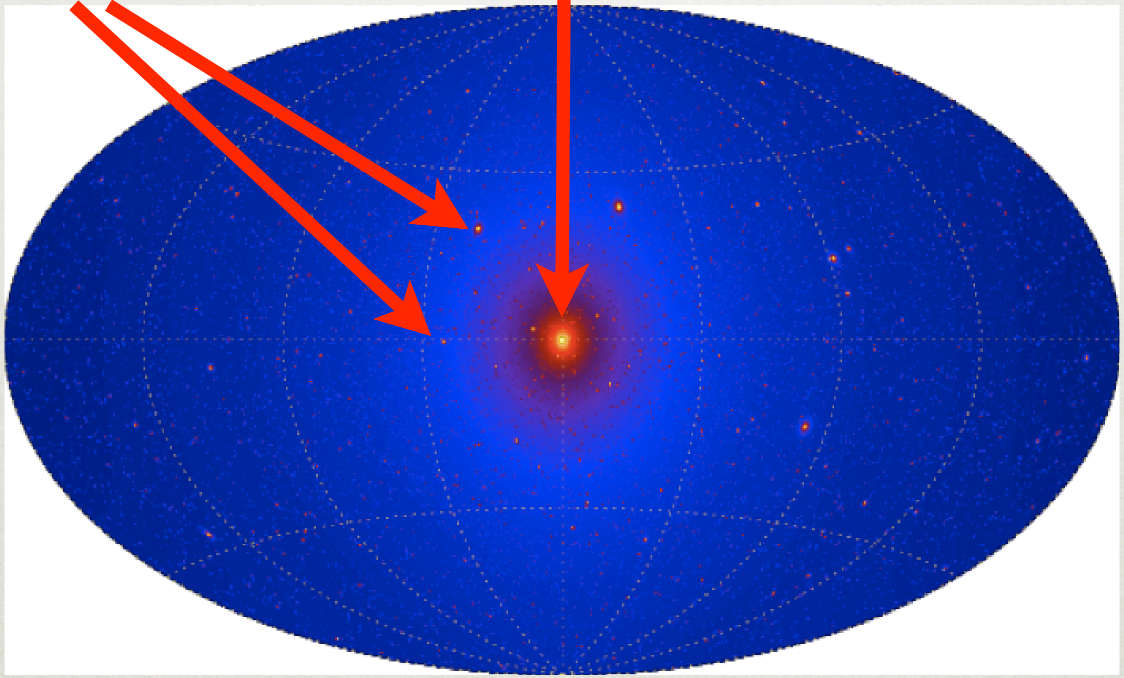
Satellites:

Low background and good source ID, but low statistics

Milky Way halo:

Large statistics but diffuse background

All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)



And electrons!

Spectral lines:

No astrophysical uncertainties, good source ID, but low statistics

Galaxy clusters:

Low background but low statistics

Extragalactic:

Large statistics, but astrophysics, Galactic diffuse background

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

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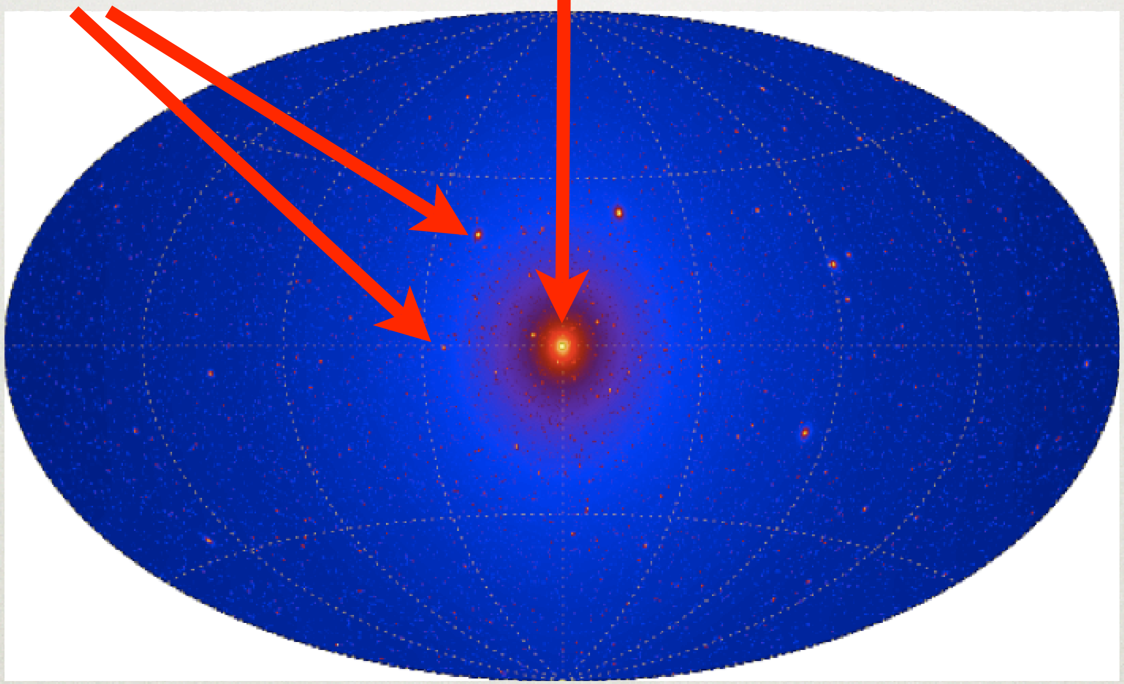

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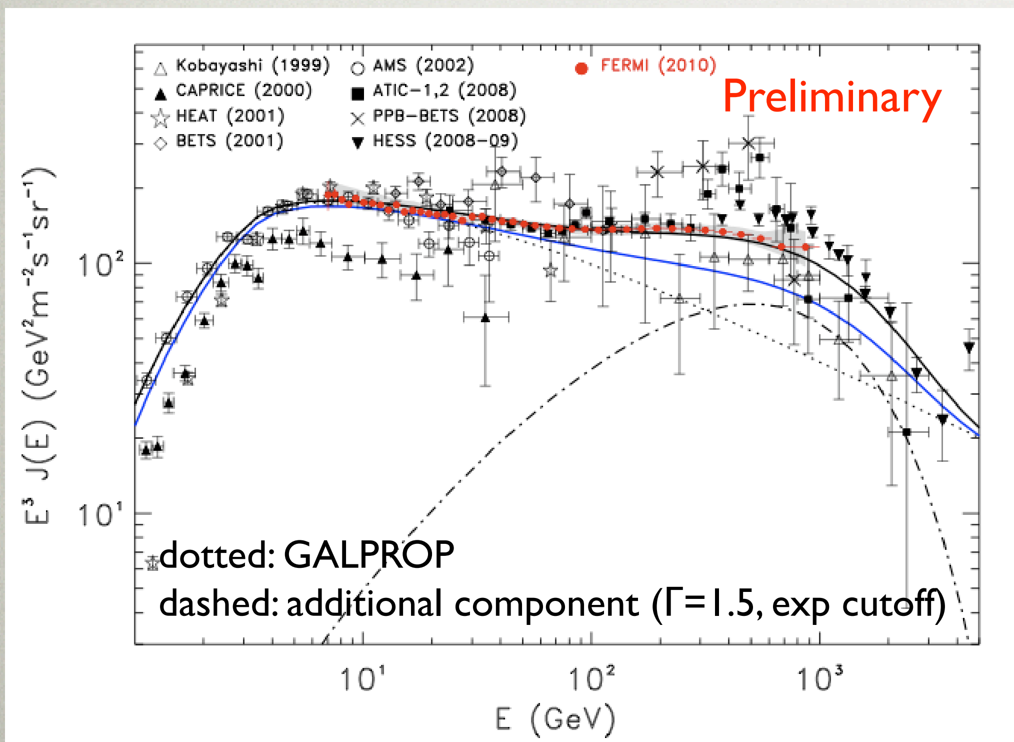
Hints from Space?

- Tantalizing signals from space could be interpreted as dark matter annihilation/ decay (e.g. PAMELA positron fraction, ATIC (and PPB-BETS) electron spectrum, EGRET GeV excess, WMAP haze, etc.)

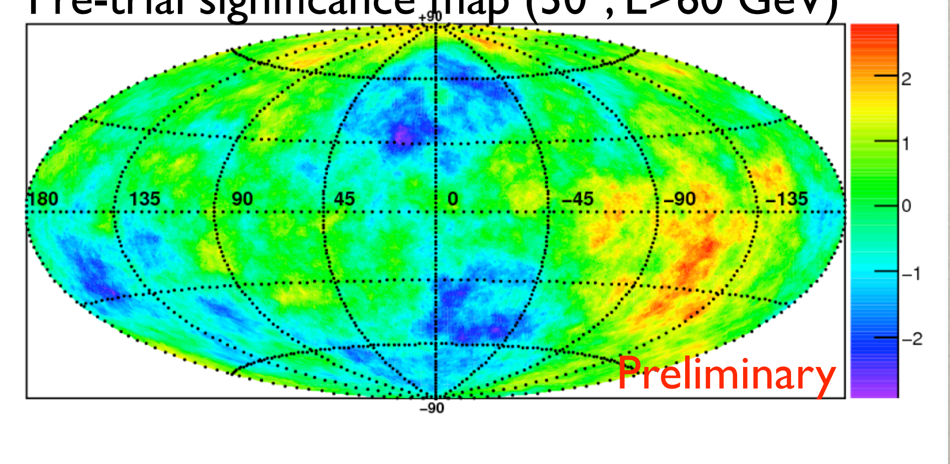
➡ Significant impact of Fermi on some of these claims with photons (more later) and also with electrons:

✓ No significant anisotropies were found in Fermi electron data (angular scales from 10° to 90°)

✓ However upper limits on dipole anisotropy cannot yet rule out individual pulsar/DM interpretation of PAMELA and Fermi e^+e^- data



Pre-trial significance map (30°, E>60 GeV)



Search for DM in the GC

Steep DM profiles ⇒ Expect large DM annihilation/decay signal from the GC!

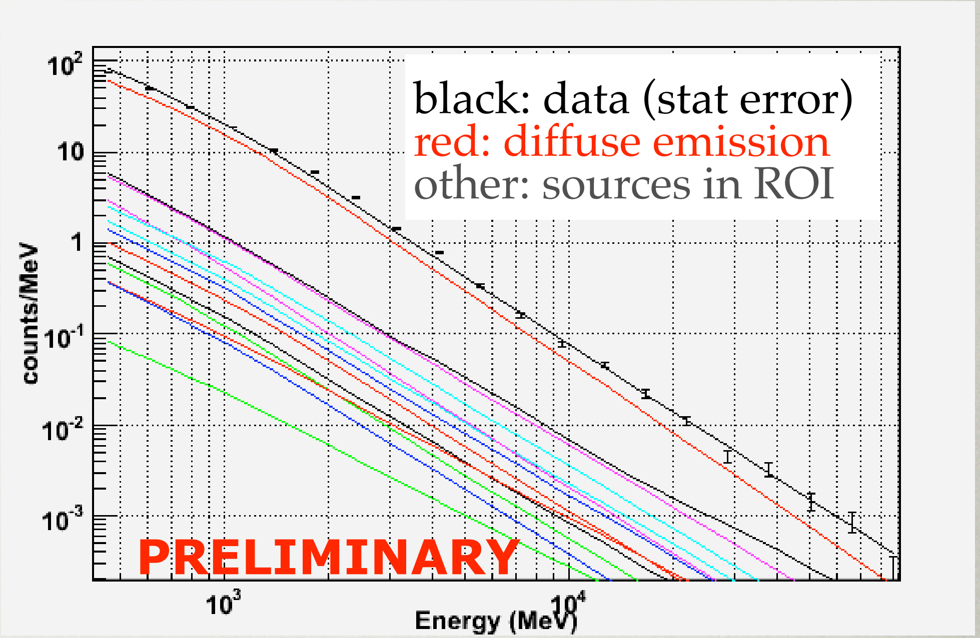
Good understanding of the astrophysical background is crucial to extract a potential DM signal from this complicated region of the sky:

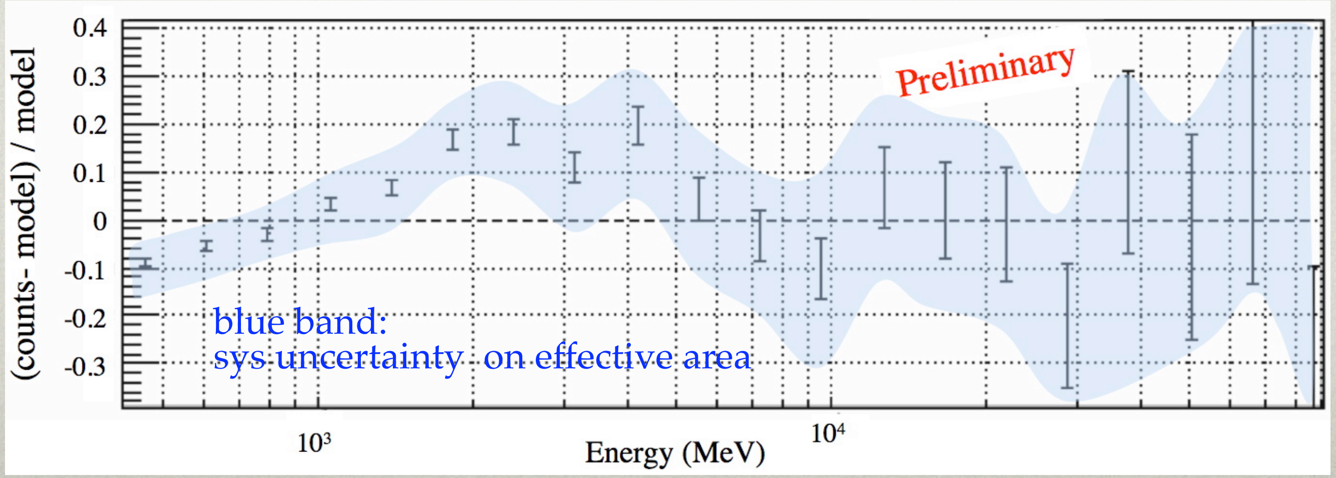
- source confusion: energetic sources near to or in the line of sight of the GC
- diffuse emission modeling: uncertainties in the integration over the line of sight in the direction of the GC, very difficult to model

Search for DM in the GC

- <u>Preliminary analysis of a 7° x7° region centered at the GC:</u>
  - Analysis of 11 months of data. Select events with energy >400 MeV and converting in the front section of the tracker (narrower PSF)
  - <u>Model</u>: galactic diffuse (GALPROP) and isotropic emission. Point sources in the region (from Fermi 1 year catalog)

➡ Model generally reproduces data well within uncertainties. The model somewhat under-predicts the data in the few GeV range.





Search for DM in the GC

- ➡ Any attempt to disentangle a potential dark matter signal from the galactic center region requires a detailed understanding of the conventional astrophysics and instrumental effects.

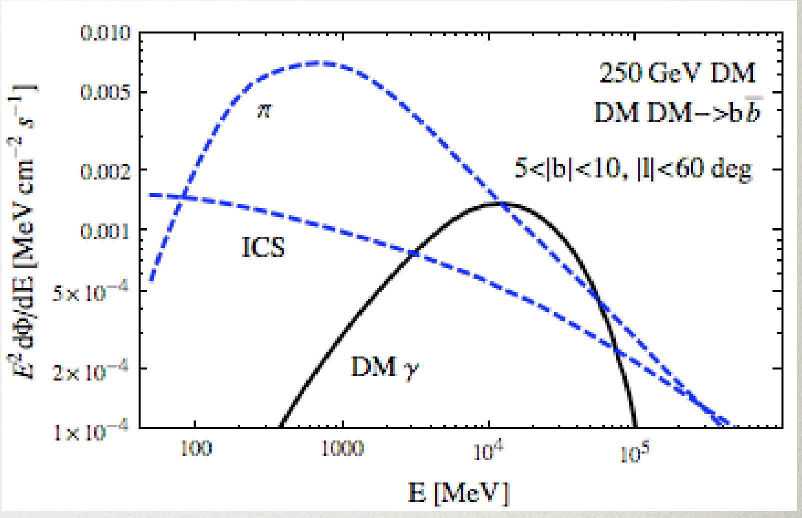
- More prosaic explanations must be ruled out before invoking a contribution from dark matter if an excess is found (e.g. modeling of the diffuse emission, unresolved sources, uncertainties in the effective area.)

- Dark matter constraints have been derived with conservative assumptions (shown at TeVPA 2009) however they can significantly improve only with better understanding of the background and detector response.

➡ More on the GC in Beatriz Canadas' talk on Wednesday (Session: Indirects DM Searches with Photons I)

Galactic Halo

- Look for a signal from the entire halo:
  - advantage: lots of statistics
  - (big) challenge: large background from Galactic diffuse emission and large uncertainties in its modeling
- Exploit both spectral and spatial information to differentiate DM from astrophysical background

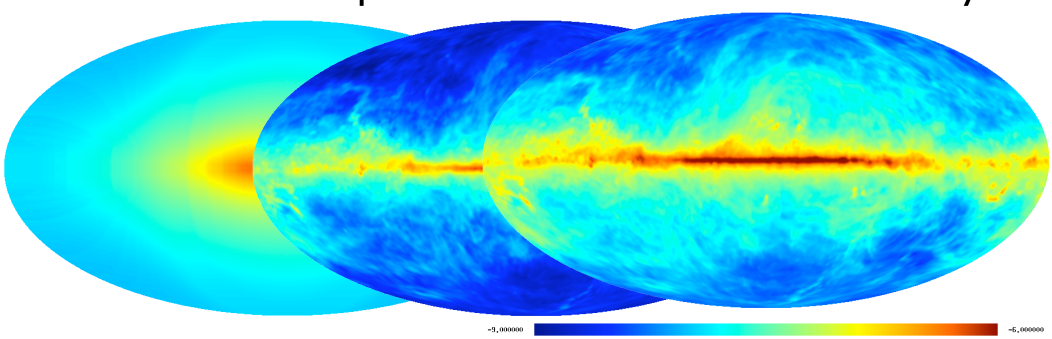


Galactic diffuse emission

(CR interactions with the interstellar medium)

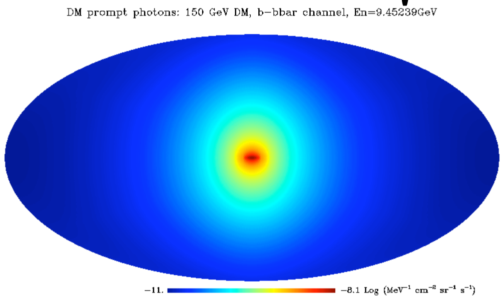
Inverse Compton

π^0-decay

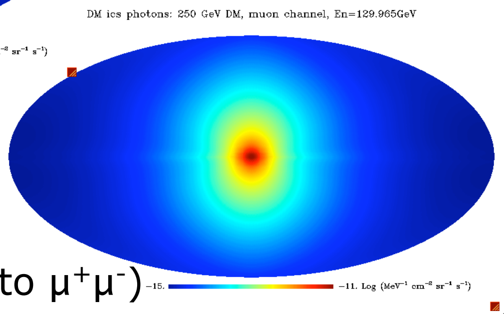


Bremsstrahlung

DM γ emission



Prompt
(DM annihilation into b-bbar)



Inverse Compton
(DM annihilation into $\mu^+\mu^-$)

Galactic Halo

- Analysis in progress to account for systematic uncertainties in the Galactic diffuse emission:
  - Generate a large number of background models with GALPROP to systematically sample all possible background models allowed by local cosmic ray data
  - Provides a priori prediction for the background, i.e. independent of the photon data

➡ WORK IN PROGRESS

- Preliminary DM constraints have been obtained by considering one GALPROP model as the benchmark (among a set of models that have overall good agreement with Fermi LAT data and are consistent with CR data)

- The constraints are very sensitive to the choice of the Galactic diffuse model. Conservative assumptions have been made on some parameters that strongly affect the limits (CR source distribution, propagation parameters)

  ➡ Much more on diffuse emission in Troy Porter's talk on Tuesday morning and Jean-Marc Casandjian's talk on Wednesday (Session: High Energy Astrophysics I)

Galactic Halo: Results

- Data: 21 months of data in the 0.8-100 GeV energy range. The data selection includes additional cuts compared to standard LAT analyses to remove residual charged particle contamination (same selection used for the LAT EGB paper)
  (The contribution from the galactic disk ($-5^{\circ} < b < 10^{\circ}$) and point sources is not included)
- Perform a binned (spatially and in energy) likelihood fit over the unmasked sky by including a dark matter component to the fit and by varying its normalization and the normalization of all other model components:
  Galactic diffuse emission: templates for IC, π^0 decay, and brem contribution from GALPROP;
  isotropic diffuse emission; residual point source contribution
- The DM upper limits are determined by the 3σ CL on the best fit normalization of the DM component

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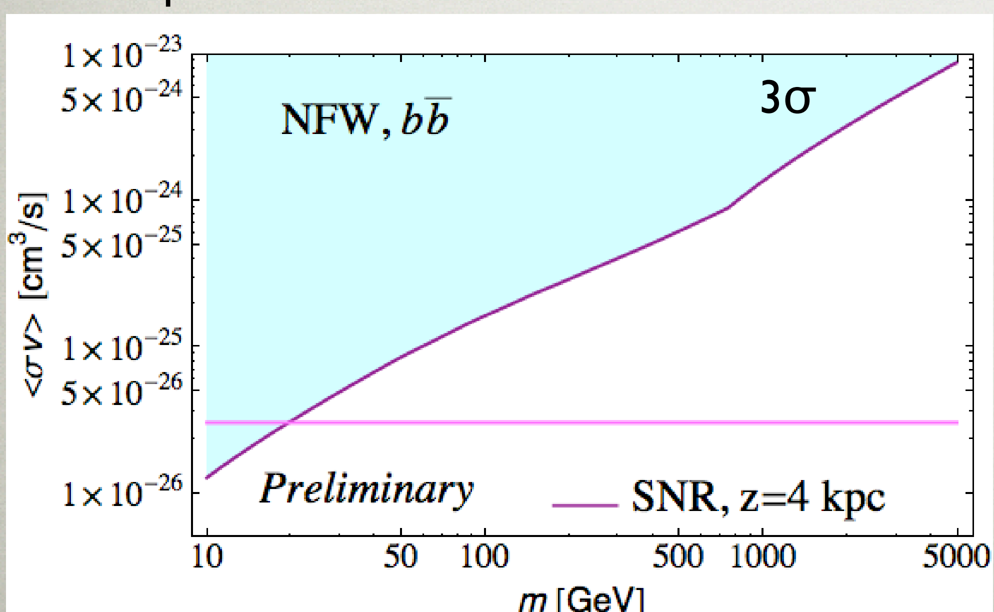

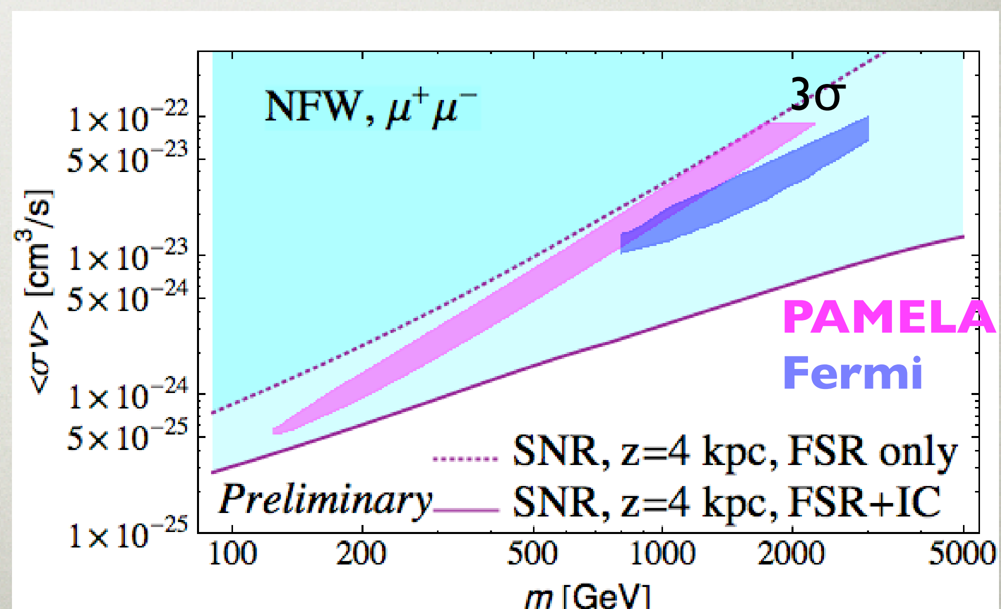

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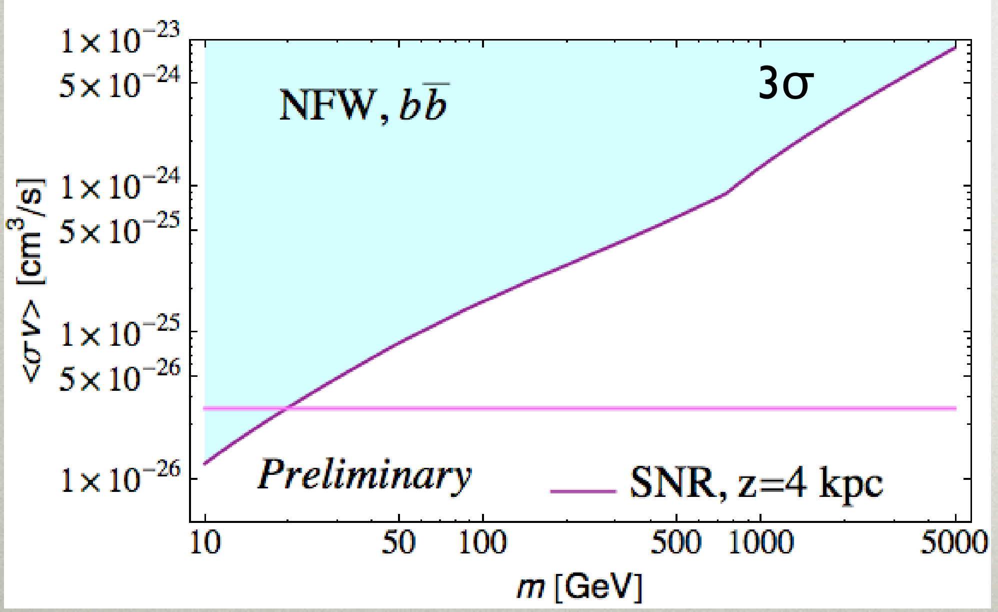
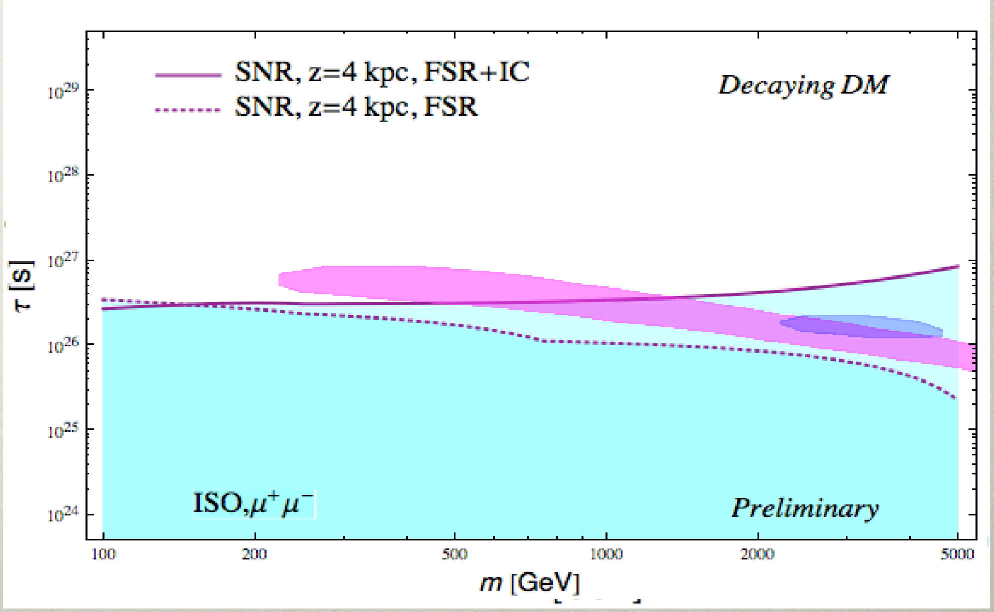


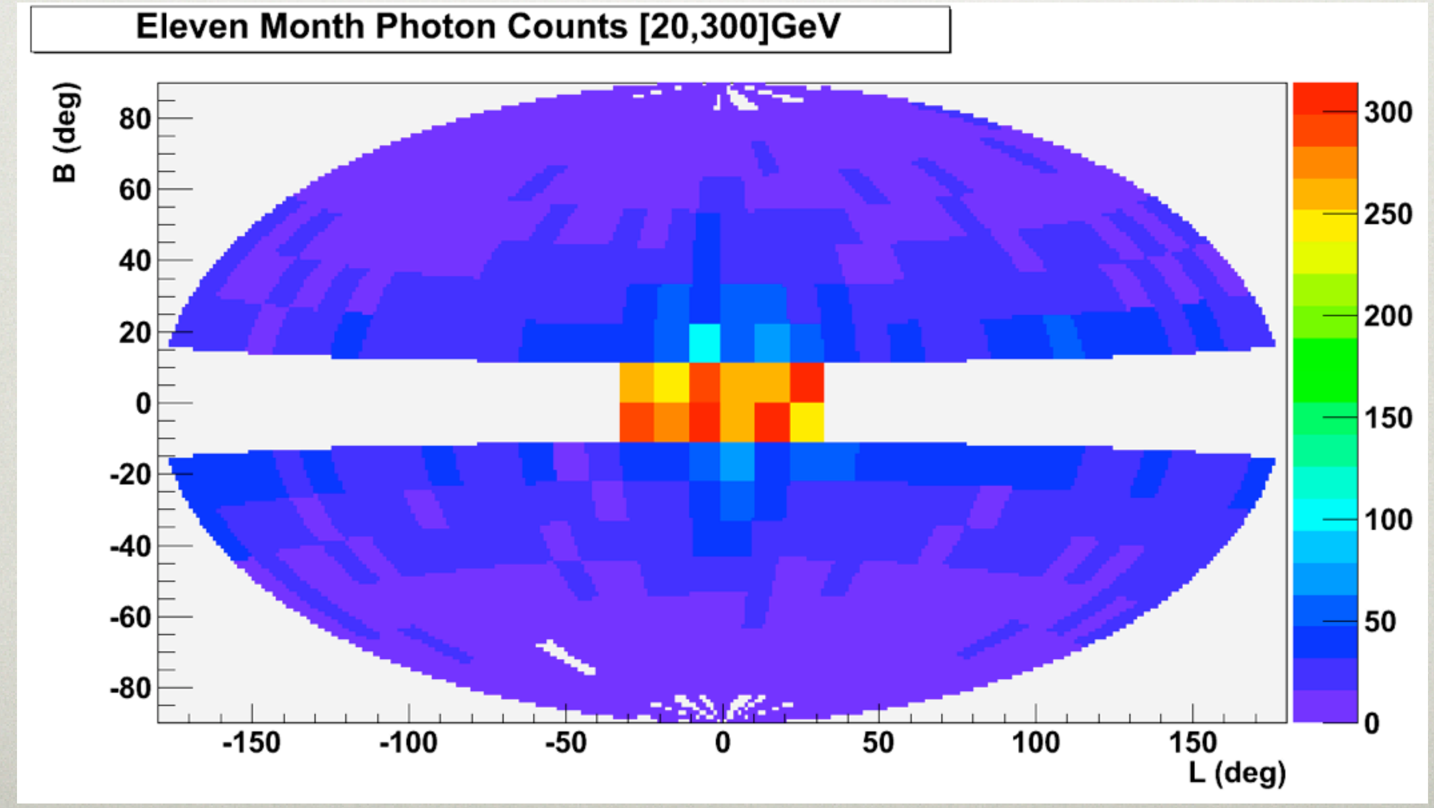


Phys. Rev. Lett.**104**, 091302 (2010)

arXiv preprint: 1001.4836

Search for Spectral Lines

- Smoking gun signal of dark matter
- Search for lines in the first 11 months of Fermi data in the 30-200 GeV energy range
- Search region
  - $|b|>10°$ and $20° \times 20°$ around galactic center
- Remove point sources (for $|b|>1°$). <u>The data selection includes additional cuts compared to standard LAT analyses to remove residual charged particle contamination.</u>

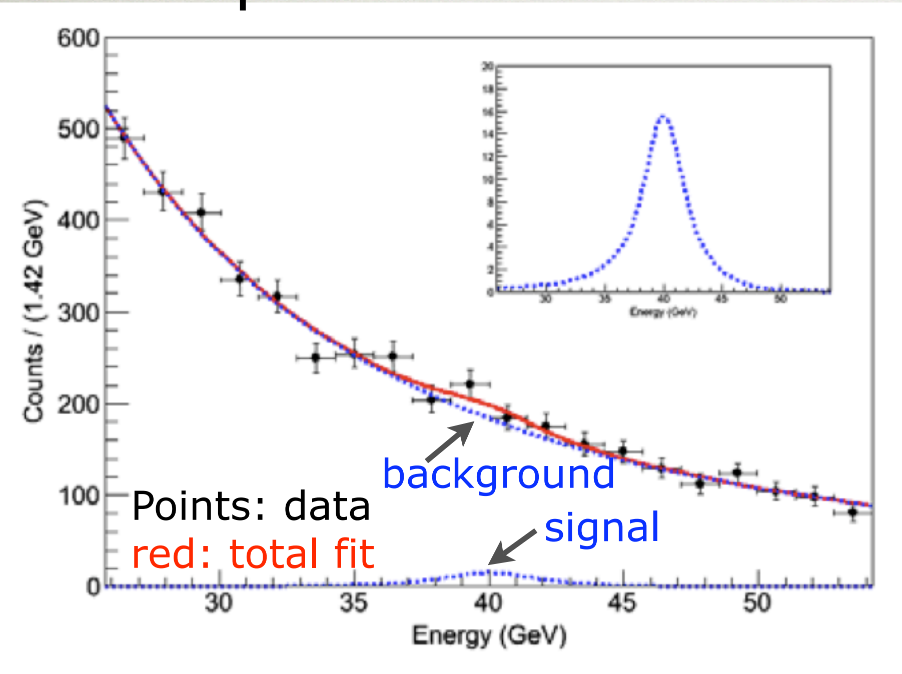


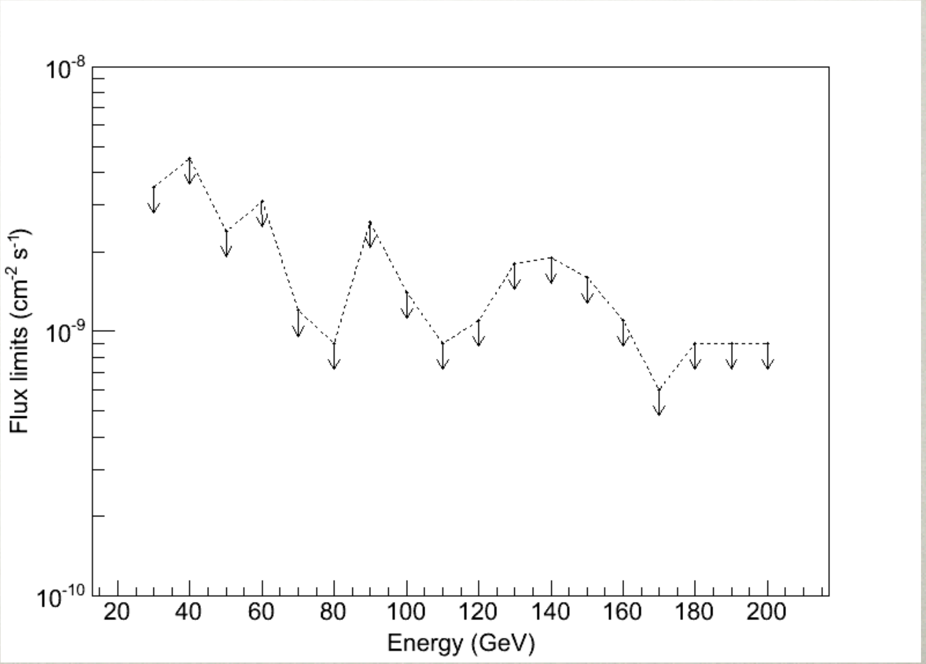
Search for Spectral Lines

- The signal is the LAT line response function. The background is modeled by a power-law function and determined by the fit $\Rightarrow$ No astrophysical uncertainties.
- <u>Optimal energy resolution and calibration very important for this analysis - resolution ~ 10% at 100 GeV</u>

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

Example fit for a 40 GeV line





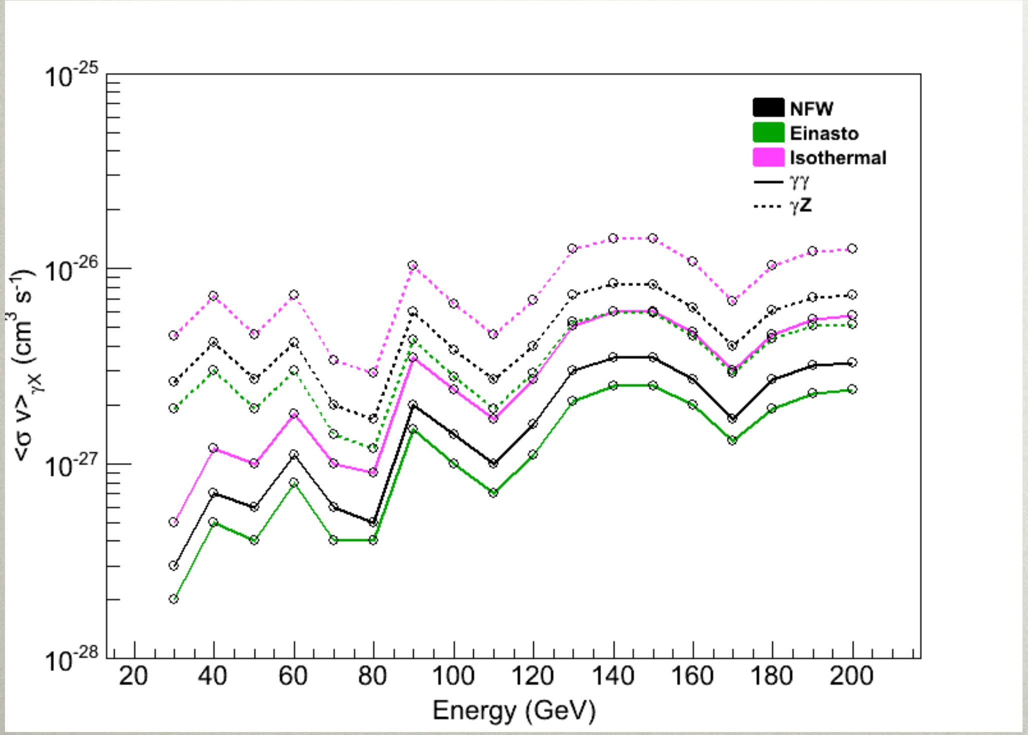
Search for Spectral Lines

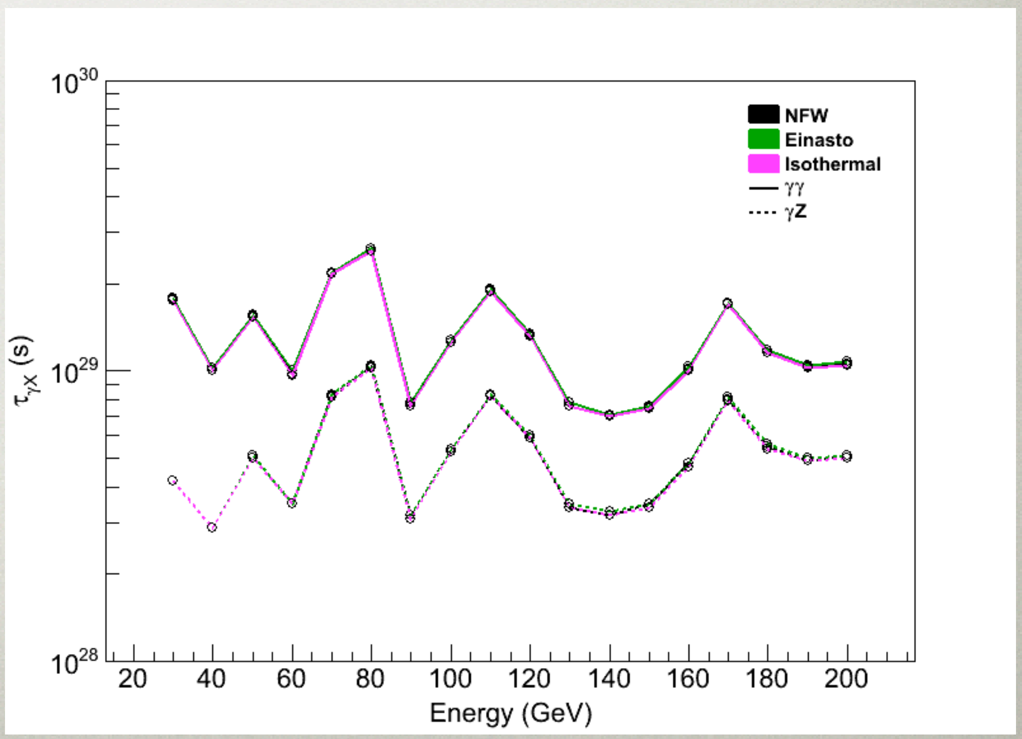
- With assumptions on the dark matter density distribution, we extract constraints on the dark matter annihilation cross-section (or lifetime for decaying dark matter)

✓ Limits on $\langle\sigma v\rangle$ are too weak (by O(1) or more) to constrain a typical thermal WIMP

✓ Limits constrain theories with non-thermally produced WIMPs. E.g. : Wino LSP (Kane 2009) predicts a γZ line with $\langle\sigma_{ann}v\rangle \sim 1.4 \times 10^{-26}$ cm^3s^{-1} and is disfavored by a factor of 2-5

✓ Lifetime limits constrain some gravitino decay models with $\tau < 10^{29}$s (expected lifetimes: 10^{23}-10^{37}s for $m_{3/2} \sim 100$ GeV)



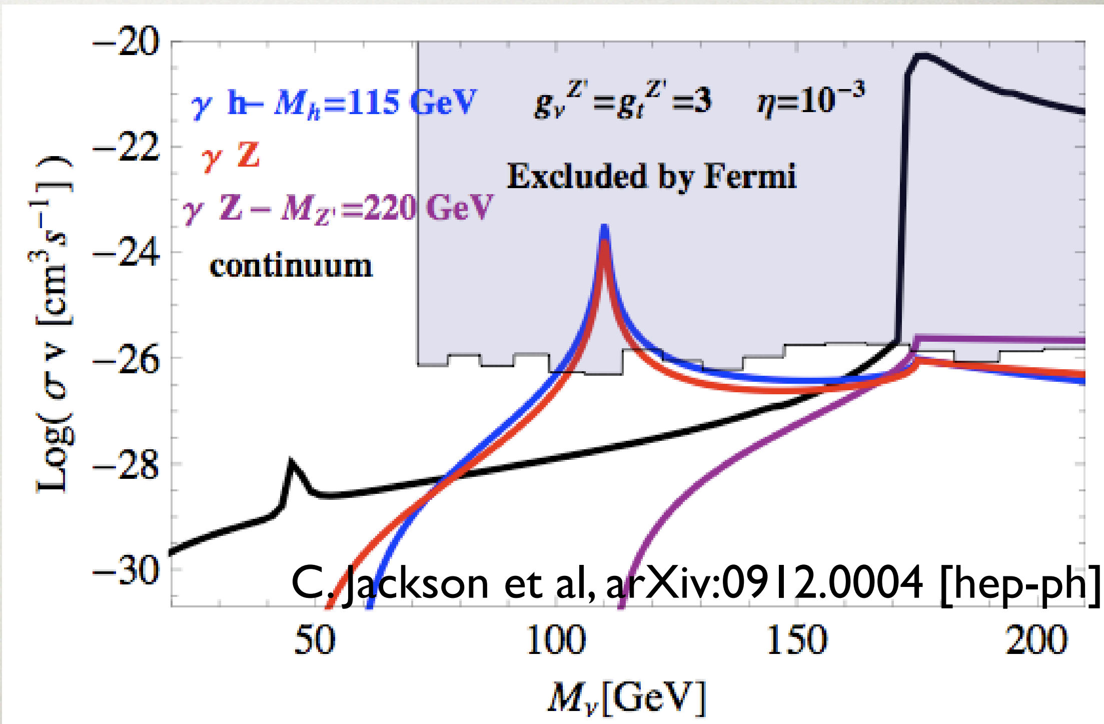


Search for Spectral Lines

- With assumptions on the dark matter density distribution, we extract constraints on the dark matter annihilation cross-section (or lifetime for decaying dark matter)

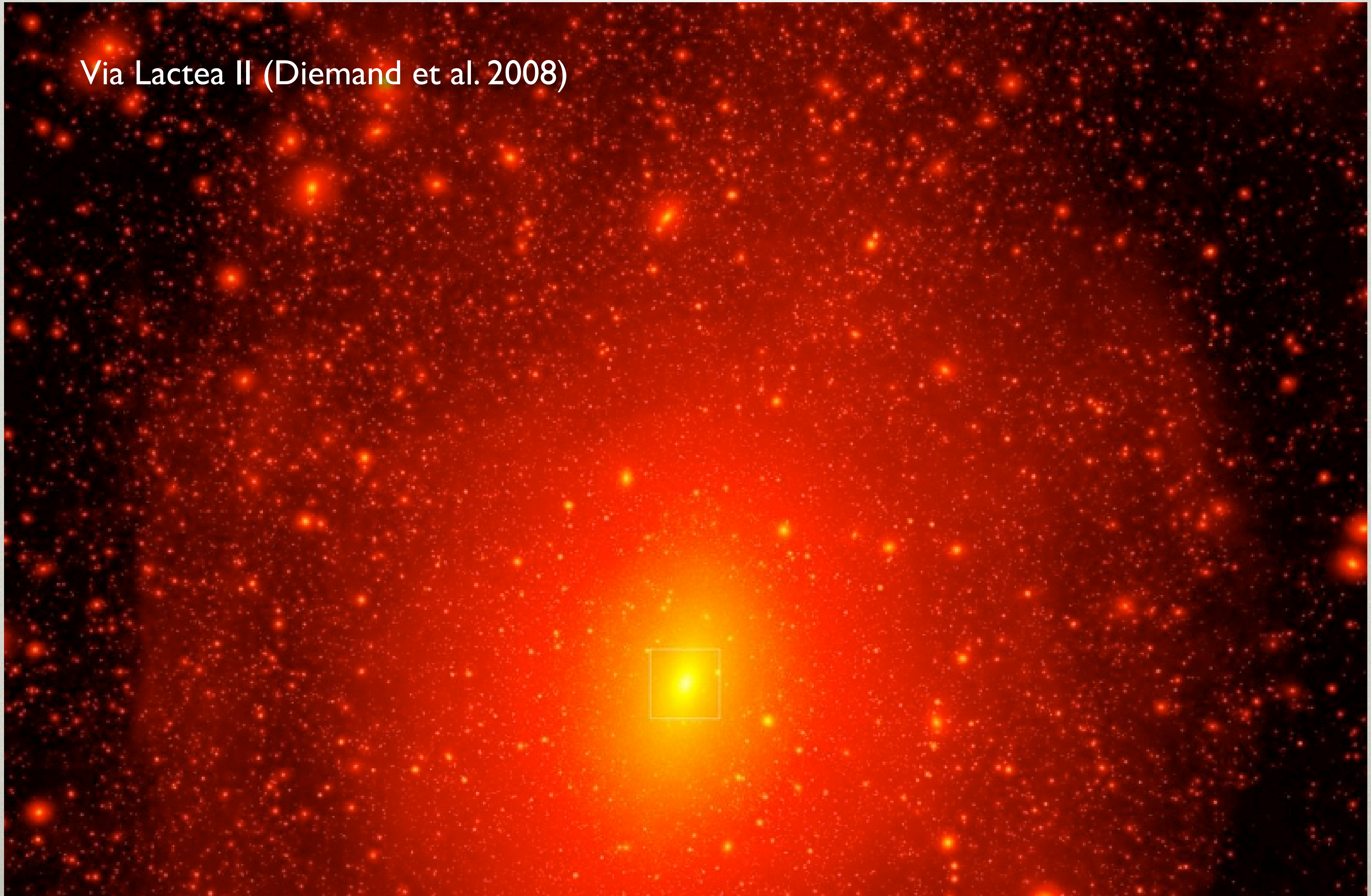
✓ Constraints have also been placed on recently-proposed models that predict WIMPs annihilating into γ +Higgs.

Higgs in space!



C. Jackson et al, arXiv:0912.0004 [hep-ph]

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.
  - Some of these satellites could be within a few kpc from the Sun (N-body simulations). Their extension could be resolved by the LAT
  - All sky search for promising candidates with the LAT

- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation. 25 have been discovered so far, many more are predicted.
  - Most are expected to be free from other astrophysical gamma ray sources and have low content in dust/gas, very few stars (Segue 1 might have 65 stars associated with it, M. Geha's talk at TeVPA 2009)
  - Given the distances and the LAT PSF, most are expected to appear as point sources
  - Select most promising candidates for observations

Search for DM Satellites

- **Search criteria:**
  - More than 10° from the galactic plane
  - No appreciable counterpart at other wavelengths
  - Emission constant in time (1 week interval)
  - Spatially extended
  - Spectrum determined by DM (both b-bbar and $\mu^+\mu^-$ spectra are tested vs a (soft) power law hypothesis)
- Search for sources (>5σ significance) passing these criteria in the 200 MeV to 300 GeV energy range.

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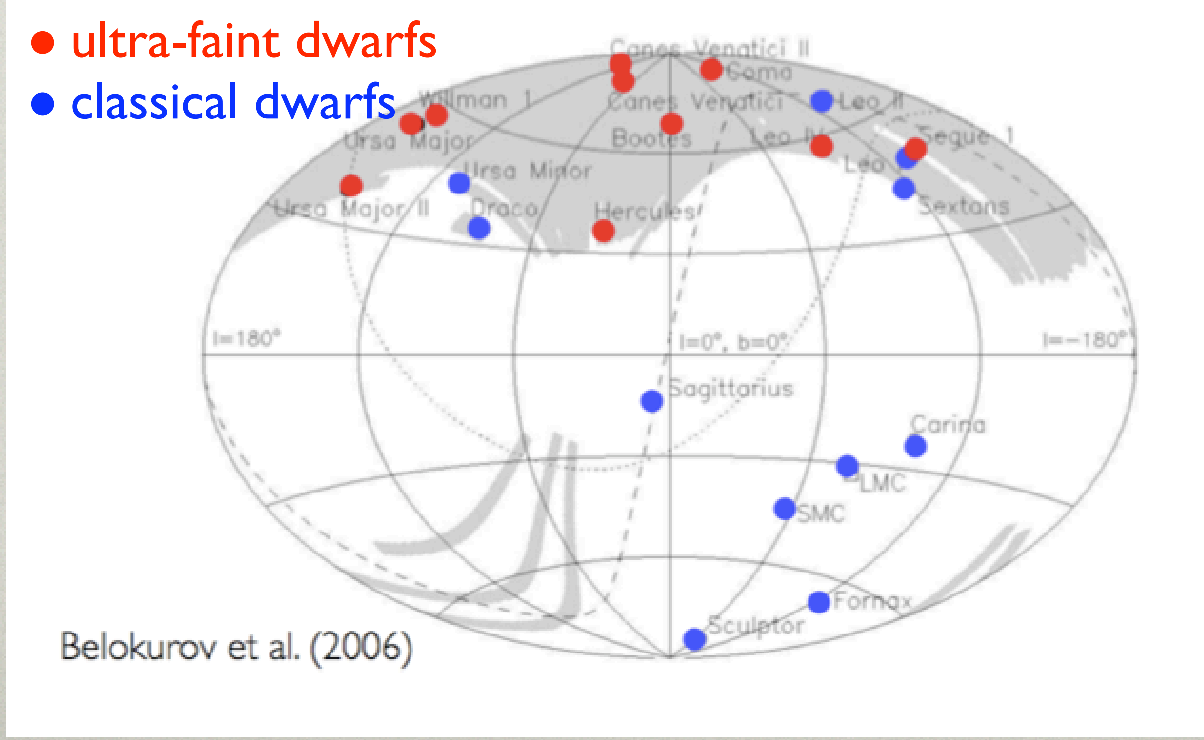
➡ No DM satellite candidates are found in 10 months of data (PRELIMINARY)

✓ Consistent with result of sensitivity study based on Via Lactea II predictions for a 100 GeV WIMP annihilating into b-bbar, $\langle\sigma v\rangle=3\times10^{-26}$ cm^3 s^{-1}
(Astrophys. J. 718, 899 (2010), e-print: arXiv:1006.1628)

✓ Work is ongoing to evaluate the sensitivity for other models

Search for DM in dSph

- Select promising dSph based on proximity (less than 180 kpc from the Sun), more than 30° from the Galactic plane, stellar kinematic data.
- Very large M/L ratio: 10 to ~> 1000 (M/L ~ 10 for Milky Way galaxy)
- More promising targets could be discovered by current and upcoming experiments (SDSS, DES, PanSTARRS, ...)



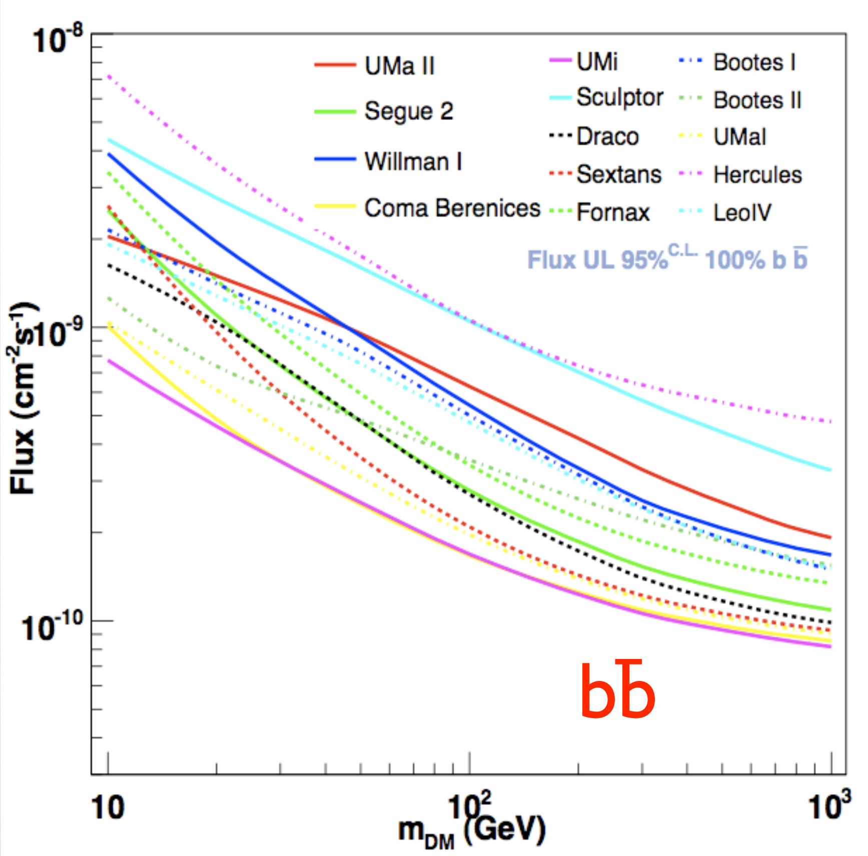
Ursa Major II
Segue 2
Willman 1
Coma Berenices
Bootes II
Bootes I
Ursa Minor
Sculptor
Draco
Sextans
Ursa Major I
Hercules
Fornax
Leo IV

Search for DM in dSph

- Energy ranges considered in the search: 100 MeV to 100 GeV
- Background: point sources+diffuse Galactic and isotropic emission

➡ No detection by Fermi with 11 months of data.

- Determine 95% flux upper limits for several possible annihilation final states
- Combine with the DM density inferred from the stellar data to extract constraints on <$\sigma_{ann}v$> vs WIMP mass for a subset of 8 dSph (based on stellar kinematic data)
- Stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)



Results with 11 months of data published in Astrophys. J. 712, 147 (2010)

Search for DM in dSph

- Energy ranges considered in the search: 100 MeV to 100 GeV
- Background: point sources+diffuse Galactic and isotropic emission

➡ No detection by Fermi with 11 months of data.

- Determine 95% flux upper limits for several possible annihilation final states
- Combine with the DM density inferred from the stellar data to extract constraints on $<\sigma_{ann}v>$ vs WIMP mass for a subset of 8 dSph (based on stellar kinematic data)
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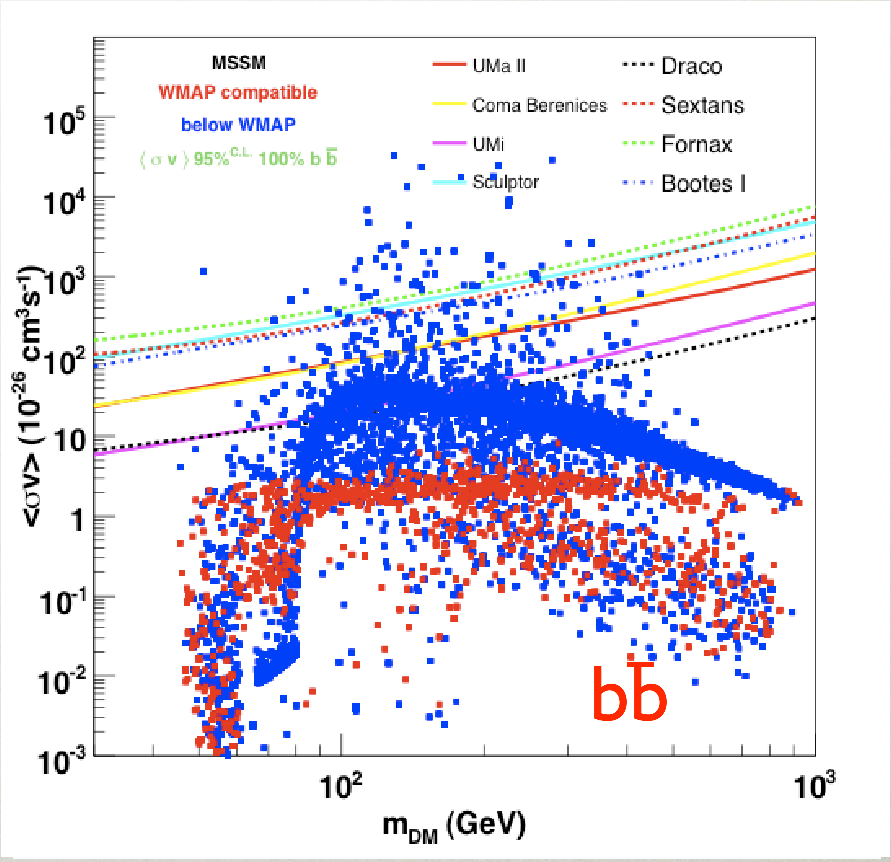


Results with 11 months of data published in Astrophys. J. 712, 147 (2010)

Search for DM in dSph

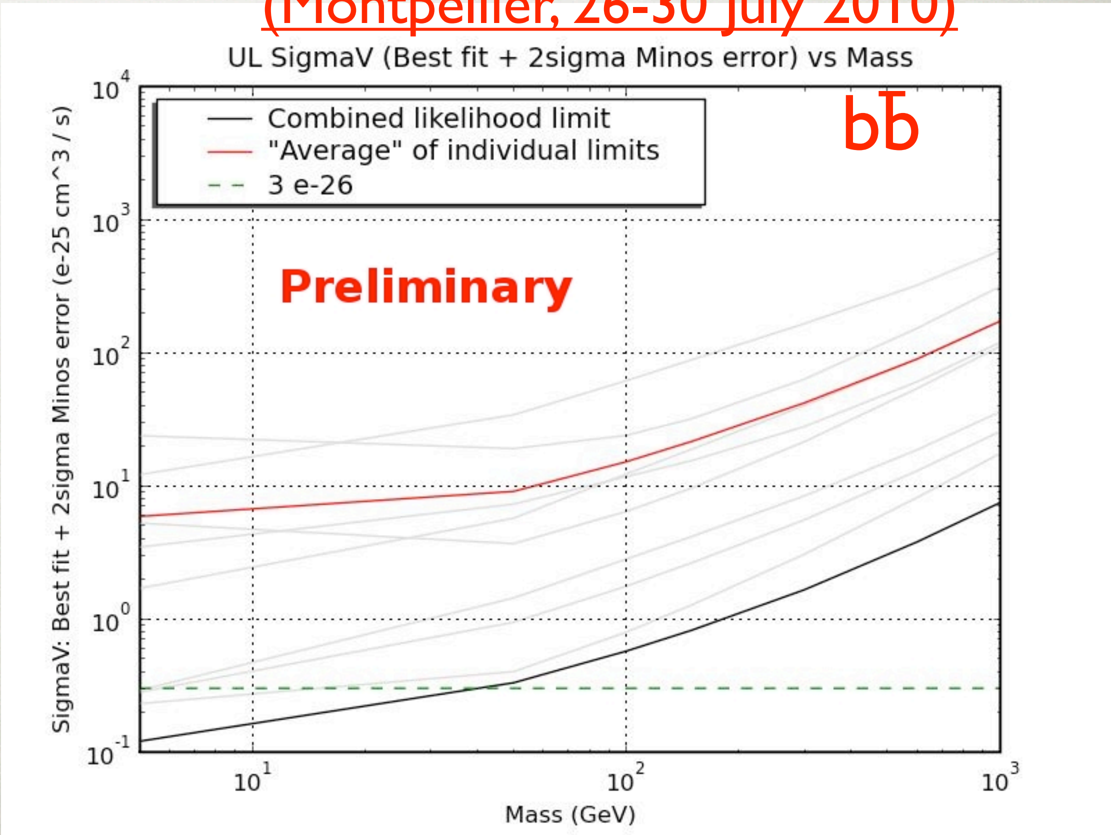
- Energy ranges considered in the search: 200 MeV to 100 GeV
- Background: point sources+diffuse Galactic and isotropic emission

➡ No detection by Fermi with 21 months of data

Maja Llena Garde's talk at IDM 2010 (Montpellier, 26-30 July 2010)

➡ Combined analysis of 8 dSph

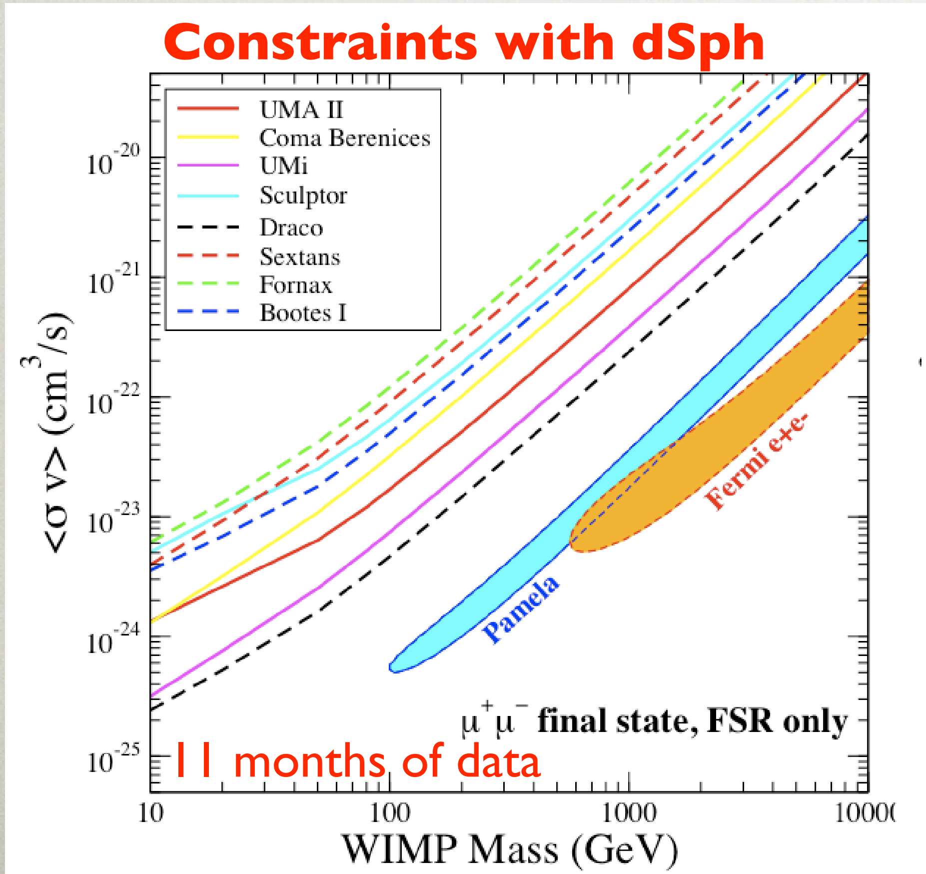
✓ Exclusion region cutting into interesting parameter space!

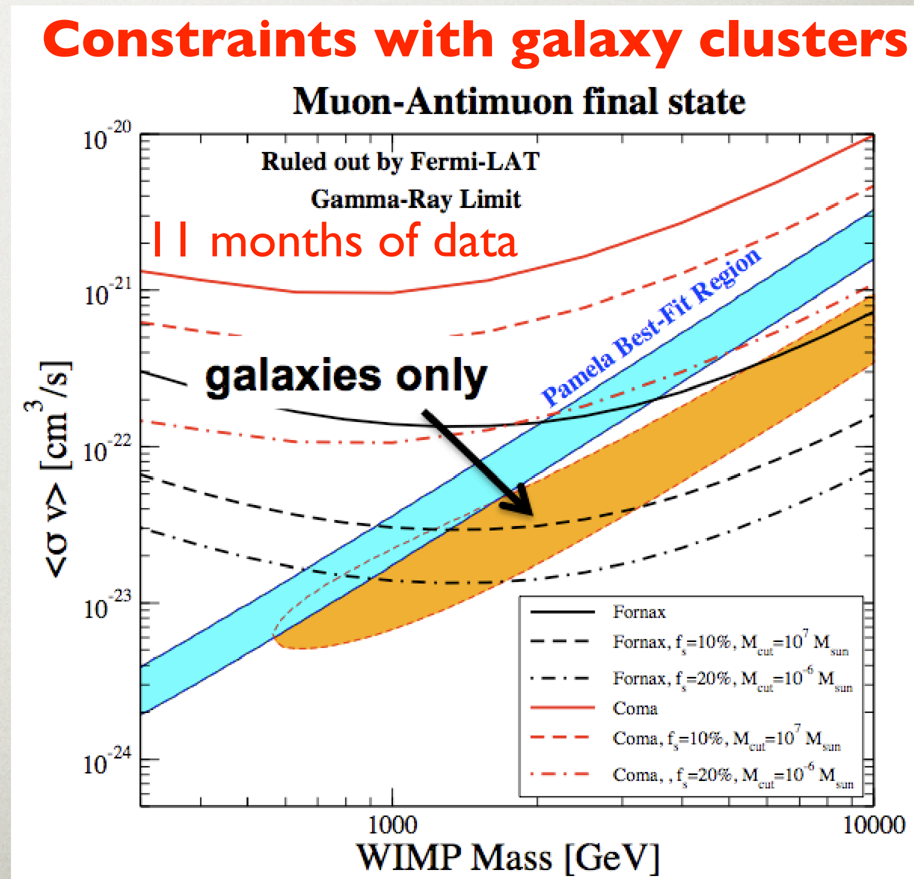


Search for DM in Galaxy Clusters

JCAP 1005:025,2010
arXiv preprint: 1002.2239

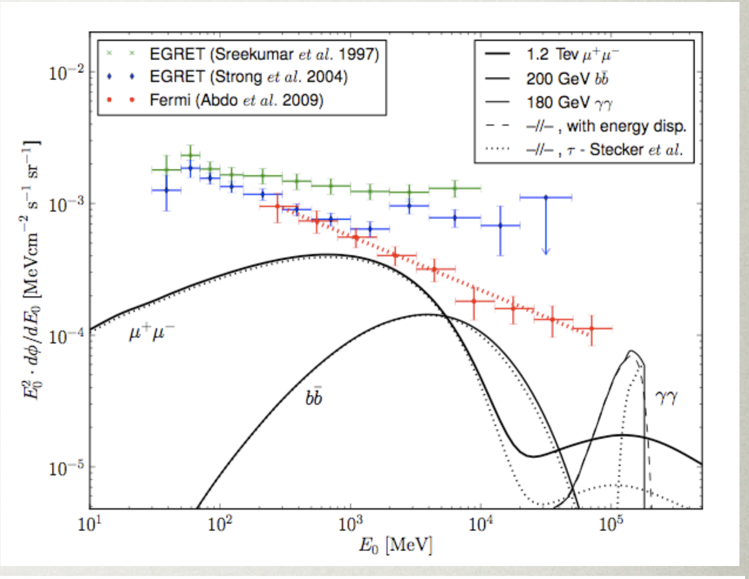
- ✓ Strong constraints on leptophilic DM models can be derived with Fermi non-detection of galaxy clusters (11 months of data) when the IC contribution off the CMB of secondary electrons from DM annihilation is included in the signal
- ✓ Constraints for a b-bbar final state are weaker than or comparable to (depending on the assumption on substructures) the ones obtained with dSph

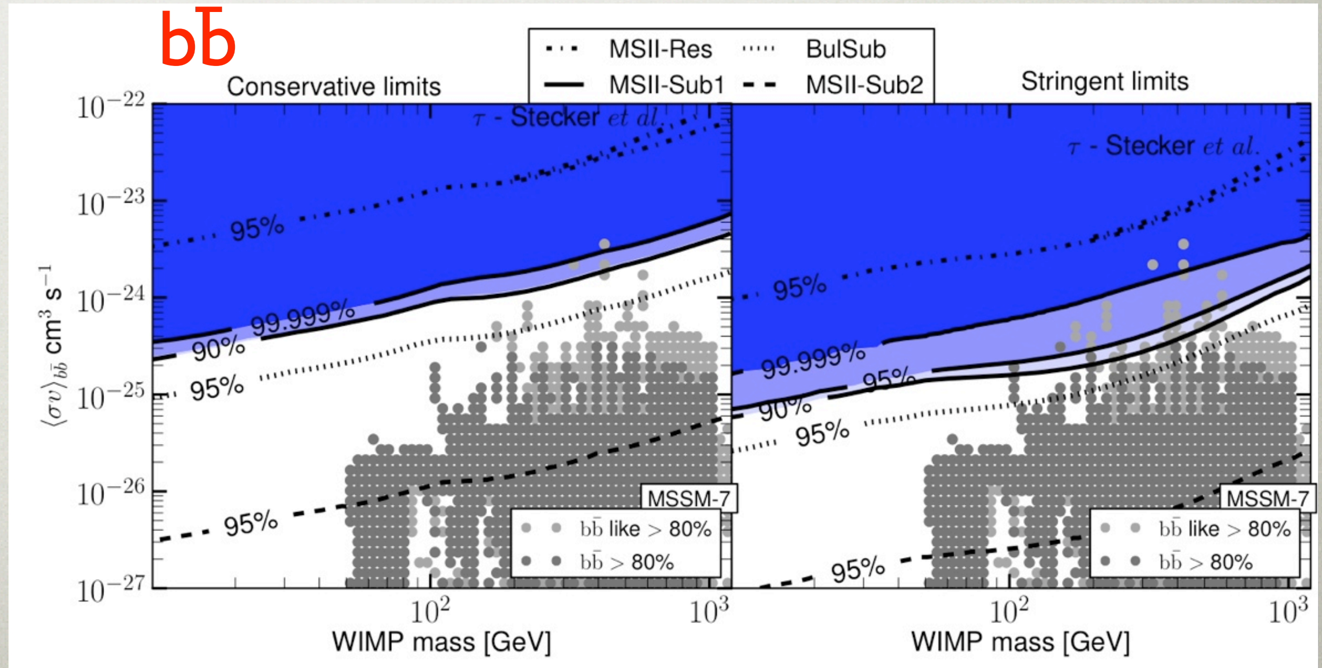




Cosmological DM

- Search for a DM annihilation signal from all halos at all redshifts
- Limits based on Fermi's measurement of the isotropic diffuse gamma-ray emission
- ➡ Limits can be very constraining for many interesting DM models, however the uncertainties on the evolution of the DM structure are large.





JCAP 1004:014,2010

arXiv preprint: 1002.4415

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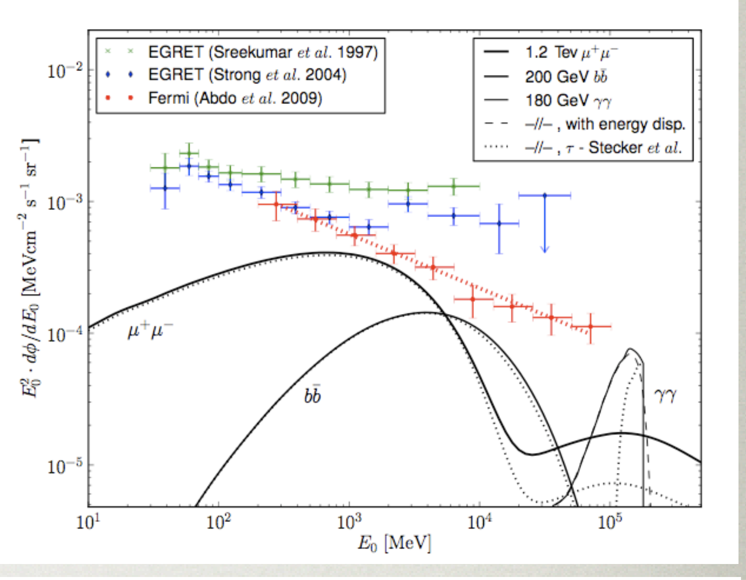

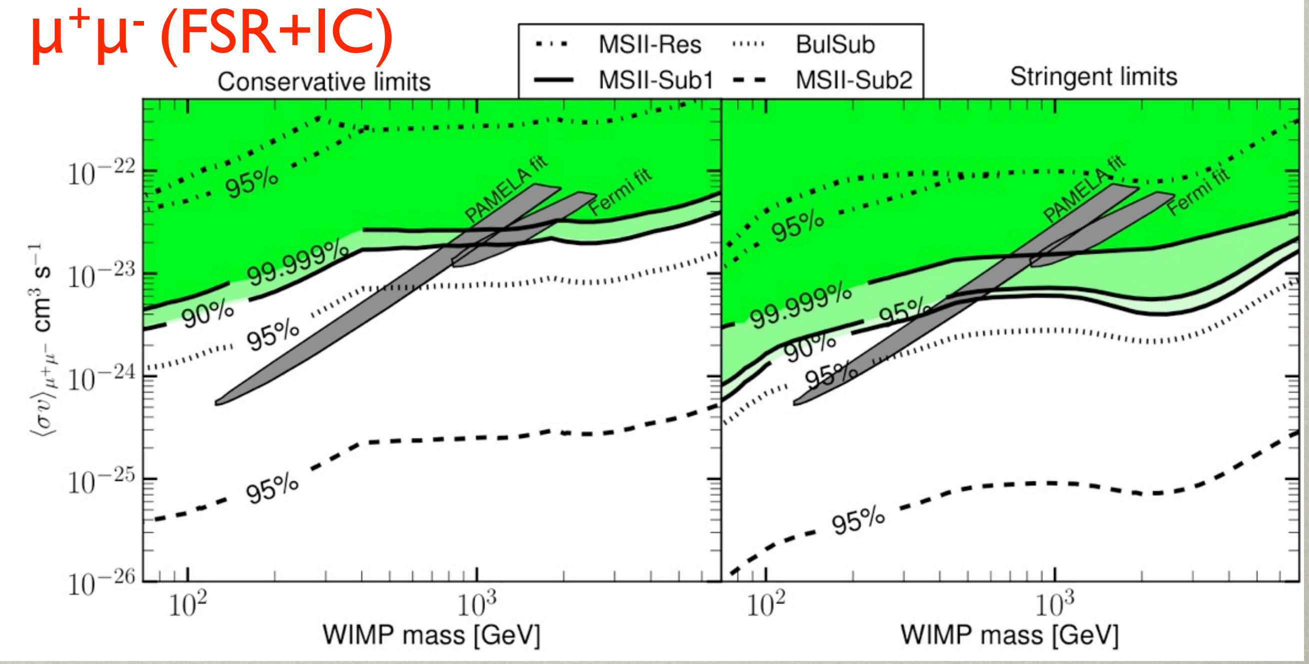

JCAP 1004:014,2010

arXiv preprint: 1002.4415

Conclusions/Outlook

- No discovery... however promising constraints on the nature of DM have been placed in particular for theories invoked to explain CR data (PAMELA and Fermi) in terms of DM annihilation.

- Outlook:

➡ Our knowledge of the astrophysical background is uncertain. This is currently a big limitation in particular for the Galactic center and the Galactic halo which otherwise have huge potential in terms of discovery or setting constraints. It requires a dedicated effort.

In addition, better understanding of the dark matter density distribution is essential in interpreting observations.

More improvements are anticipated with better understanding of the detector response.

Some analyses will further benefit from multi-wavelength observations (e.g. dSph and DM satellites.) And if a signal is observed elsewhere (e.g. LHC) it's likely to make our job easier!

➡ <u>Fermi is a 5 to 10 year mission: there is much more to come!</u>