Investigating Dark Matter with the Fermi Large Area Telescope

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representing the Fermi-LAT Collaboration

Fermi Gamma-ray Space Telescope

SLAC NATIONAL ACCELERATOR LABORATORY

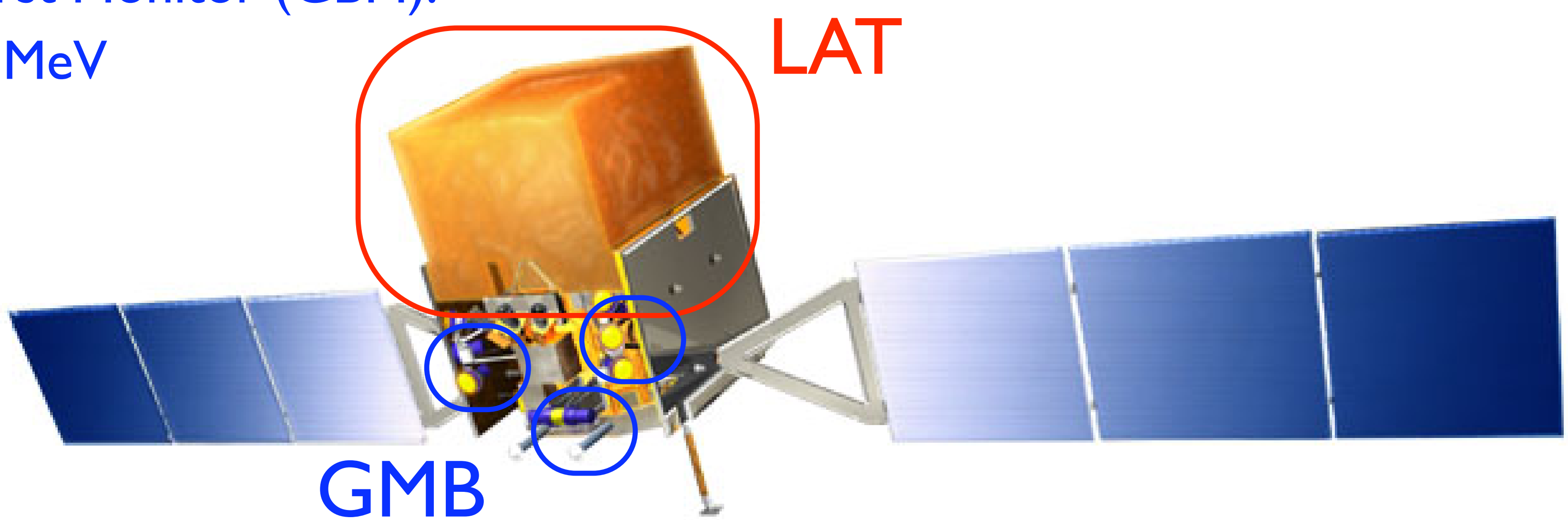
The Dark Matter Connection: Theory and Experiment
GGI - Florence, 17-21 May 2010

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...)

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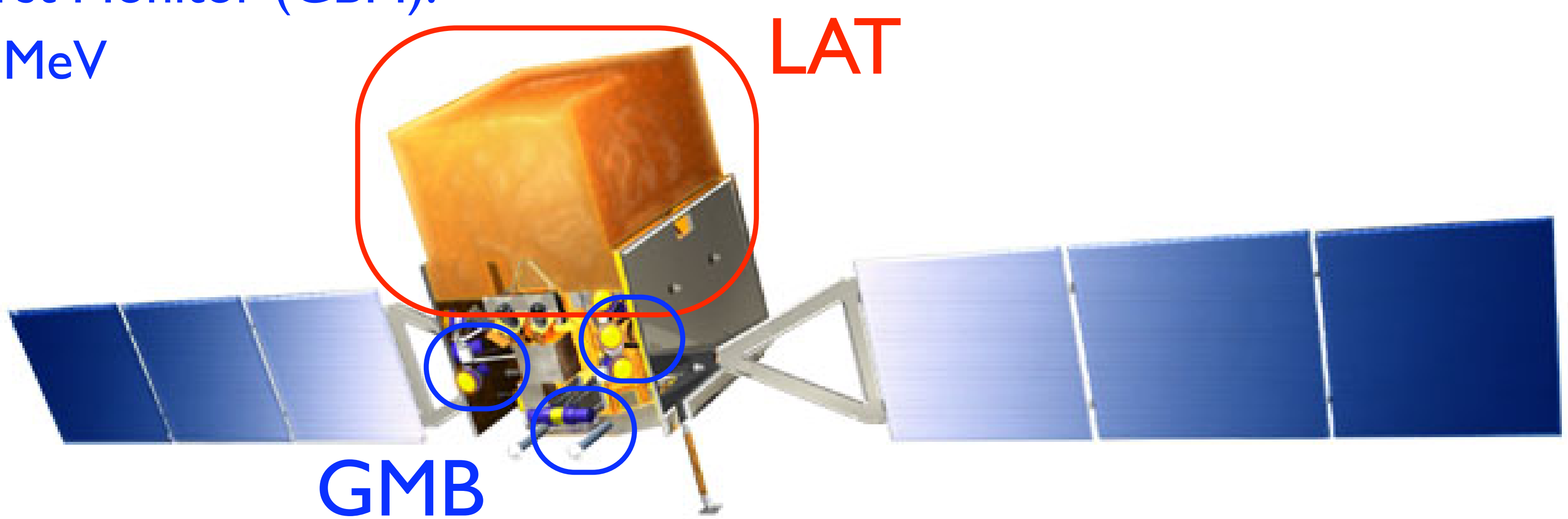

The Launch

- 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 (min)

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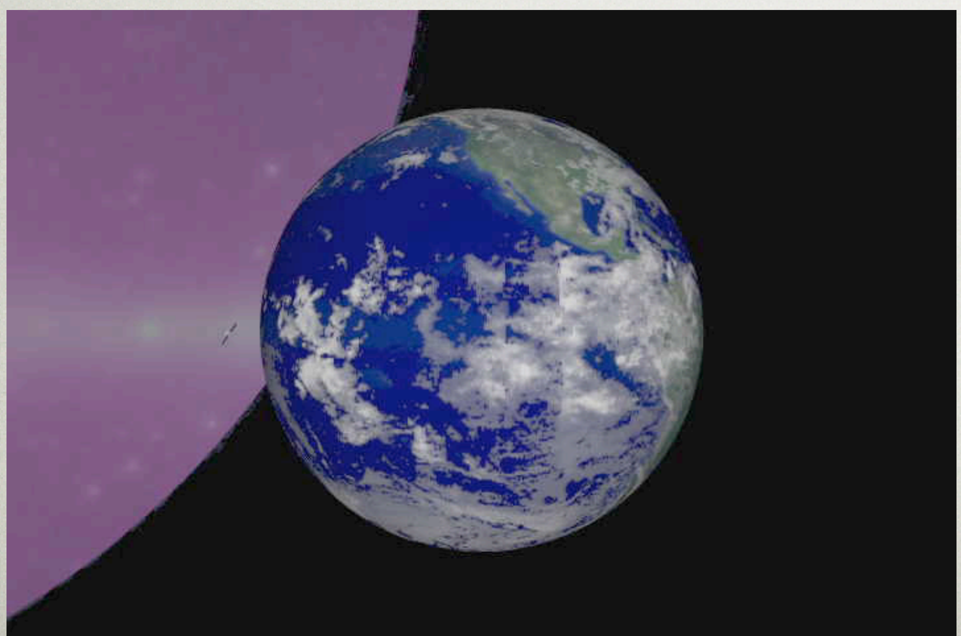
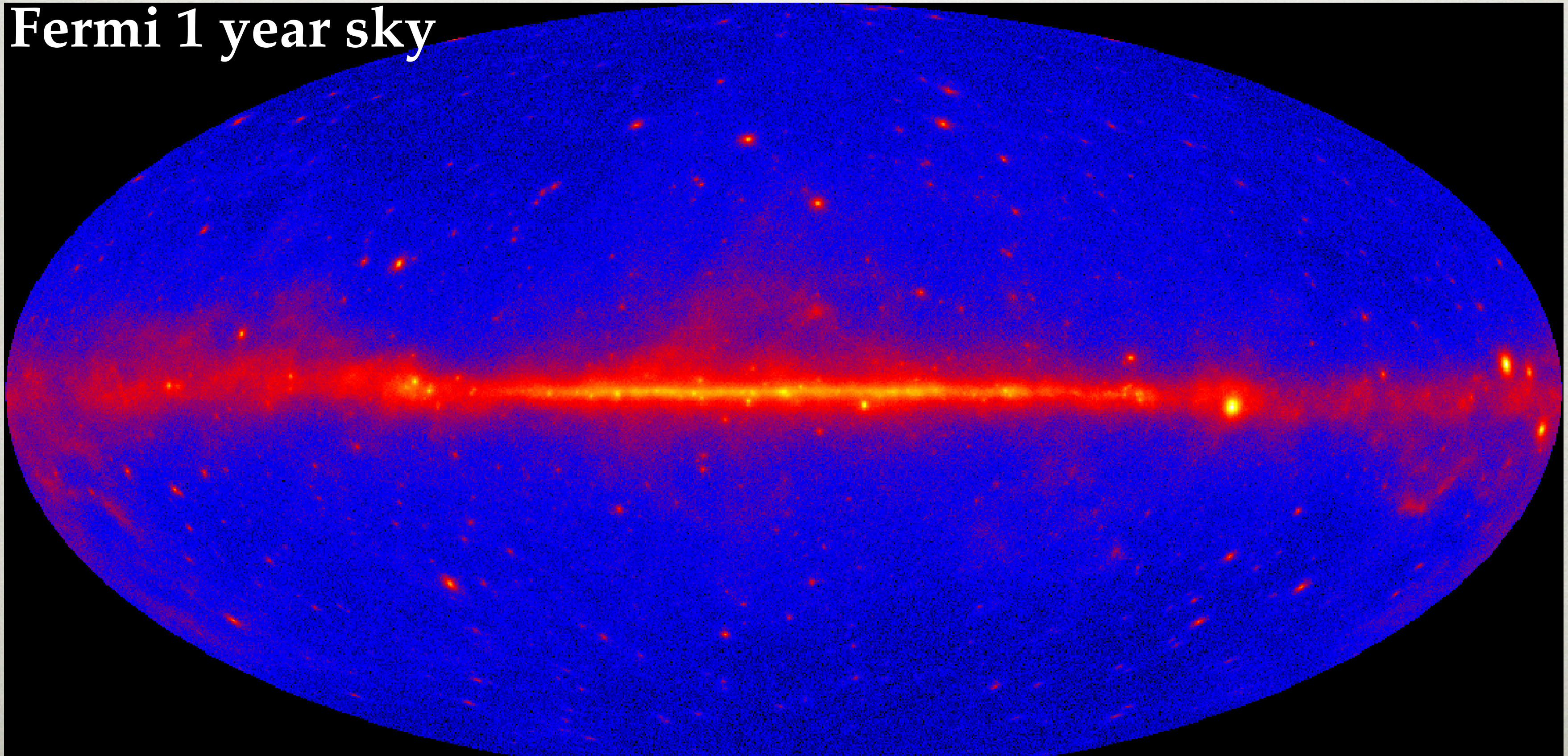


The Fermi Sky

- 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

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

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

DM distribution

For DM decay:

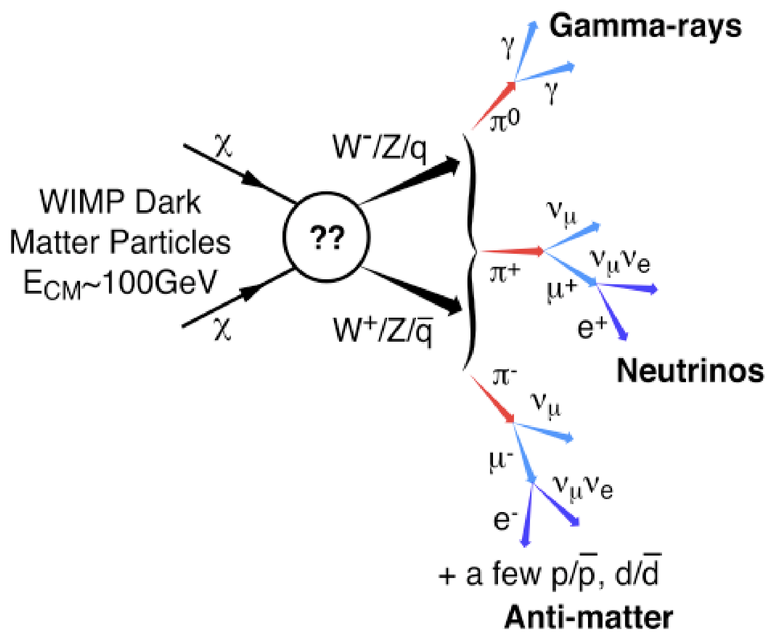
- $<\sigma_{ann}v>/2m^2_{WIMP} \rightarrow 1/\tau m_{WIMP}$
- $\rho^2 \rightarrow \rho$

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

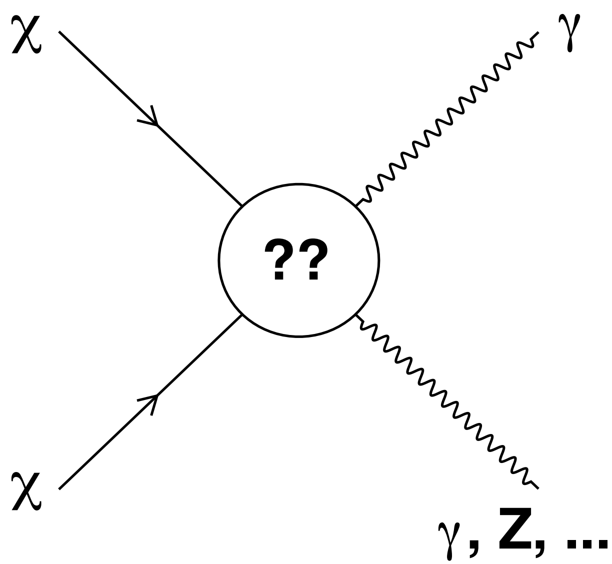
Continuum spectrum with cutoff at M_{DM}

Annihilation (or decay) into γ



Spectral line

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



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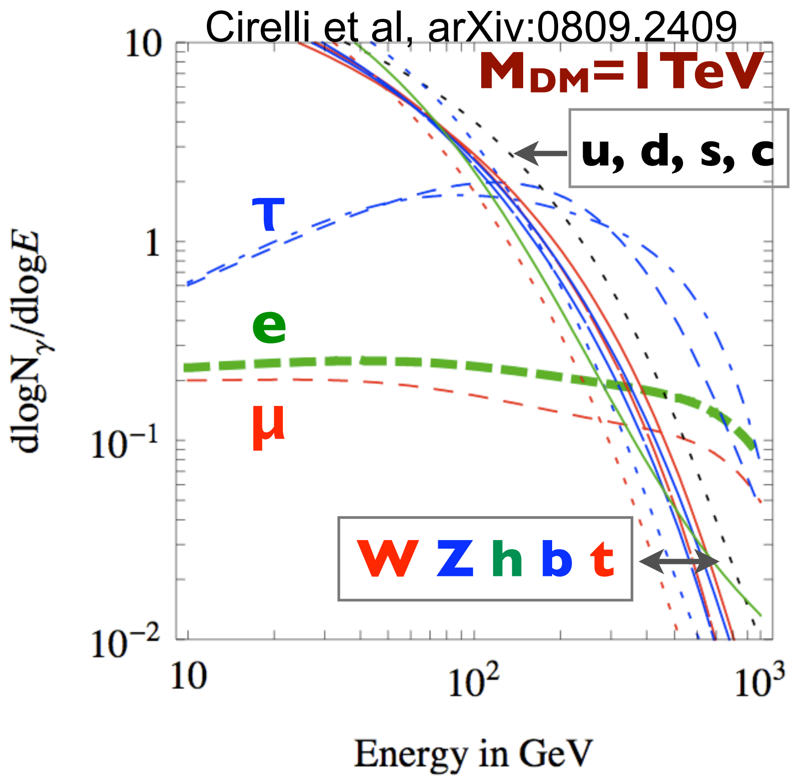

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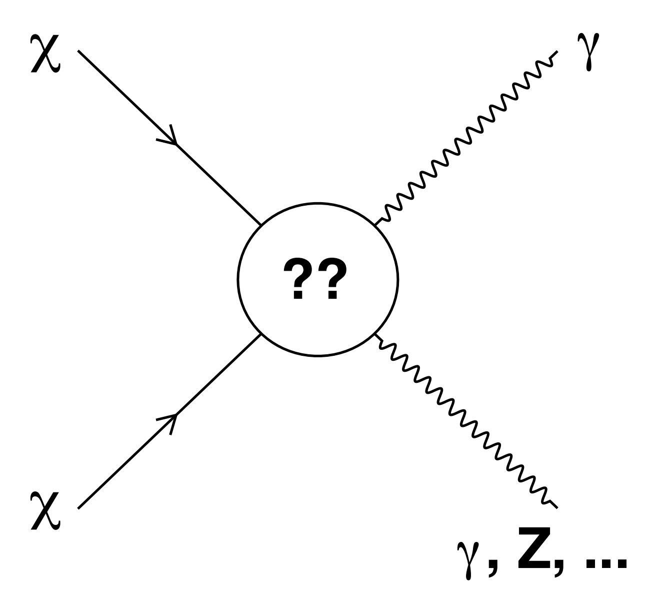

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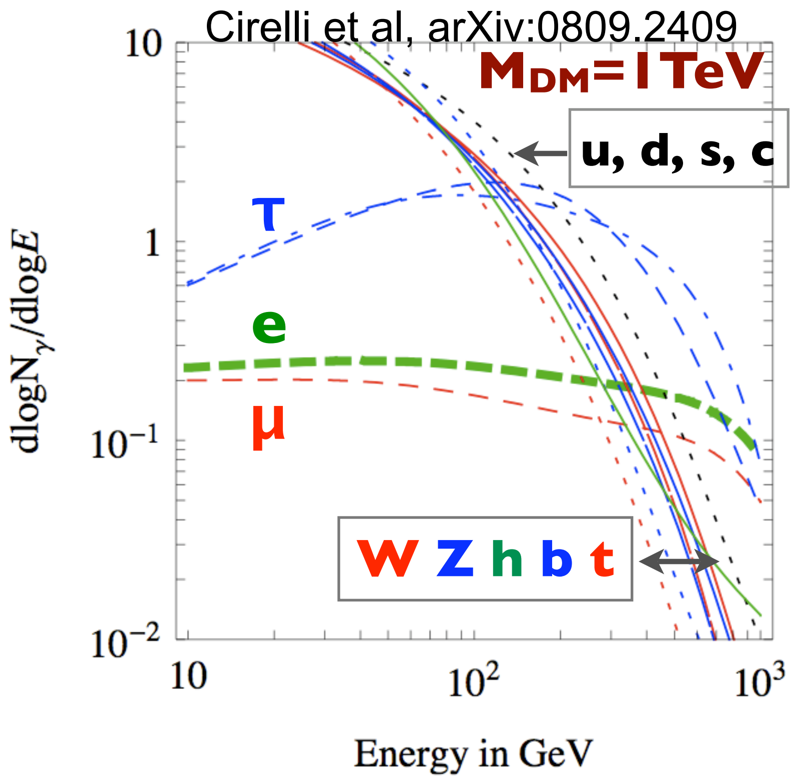


Spectral line

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:

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

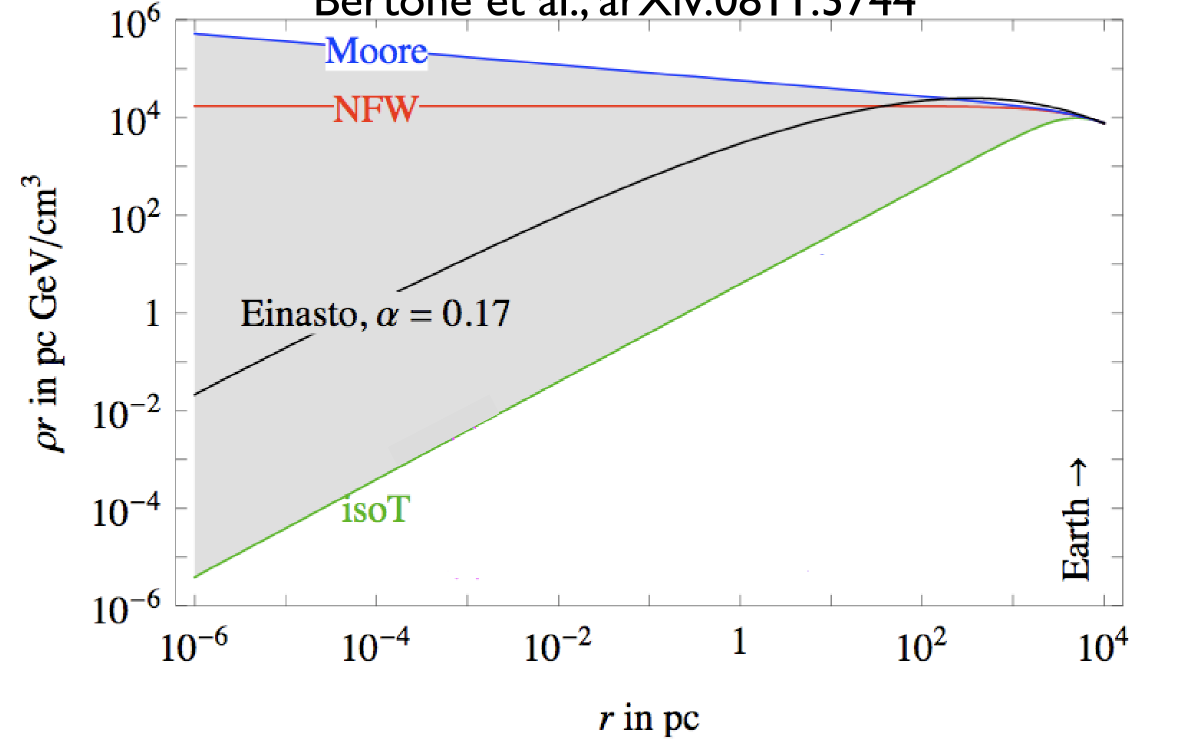
For γX final state:

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

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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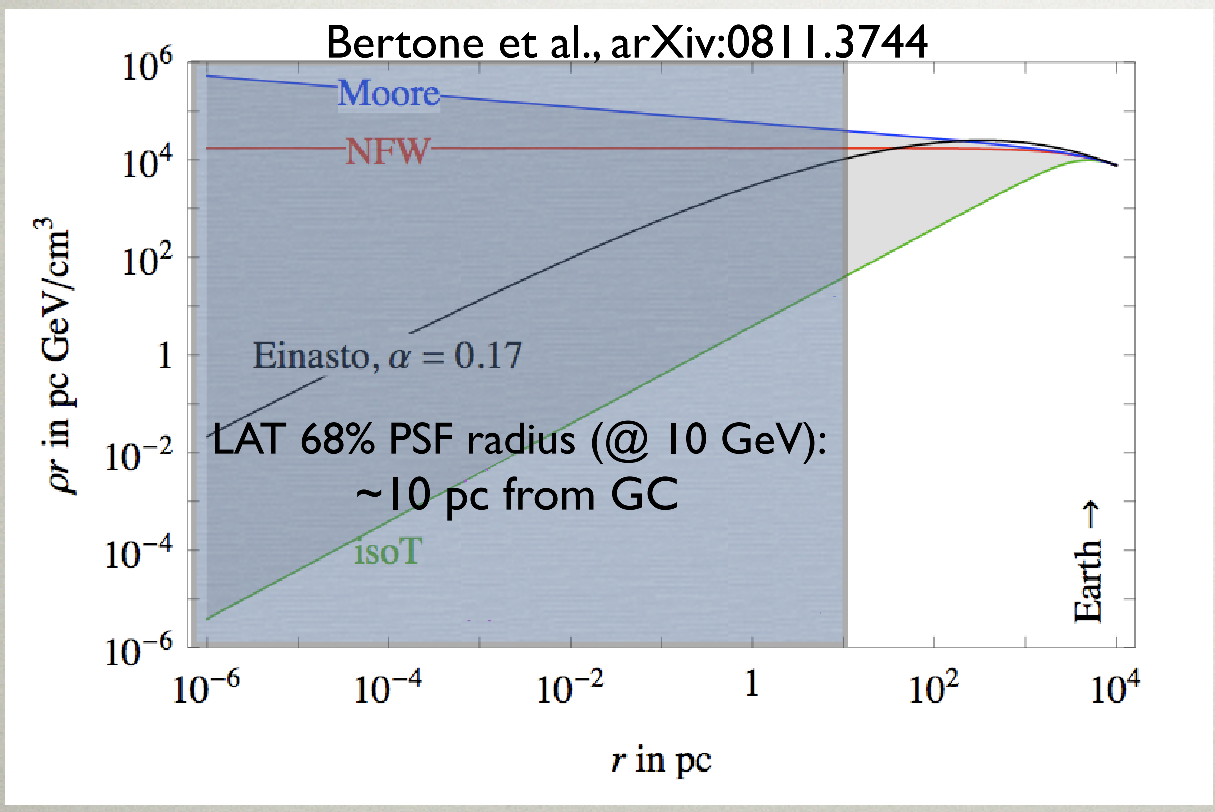

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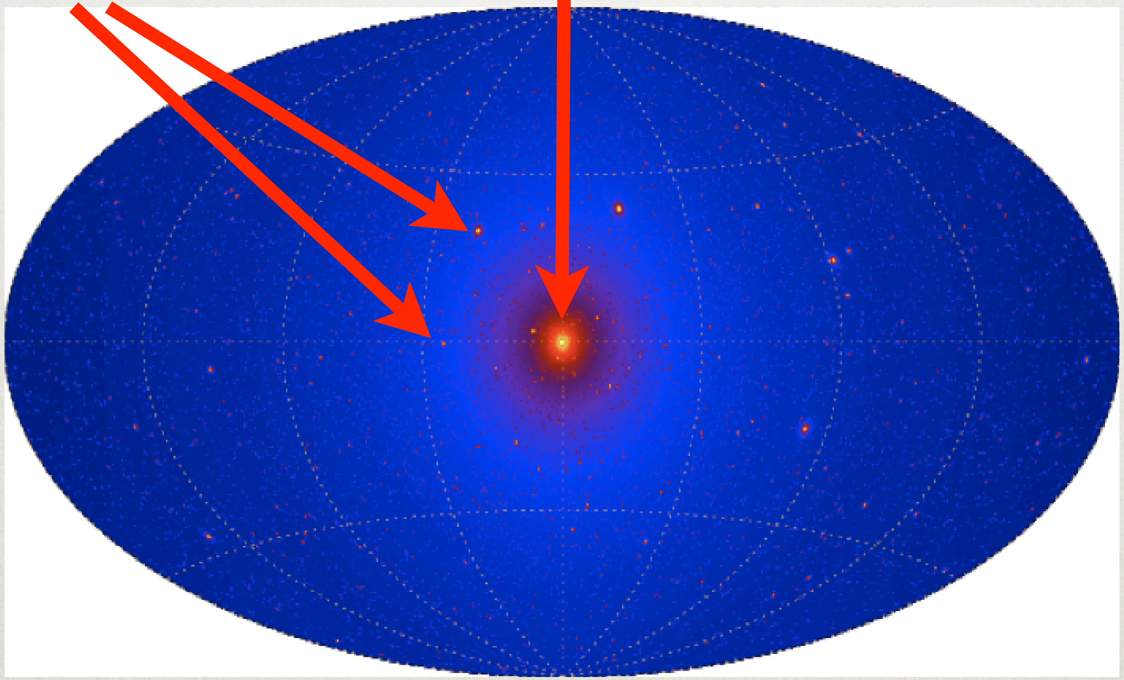
Search Strategies

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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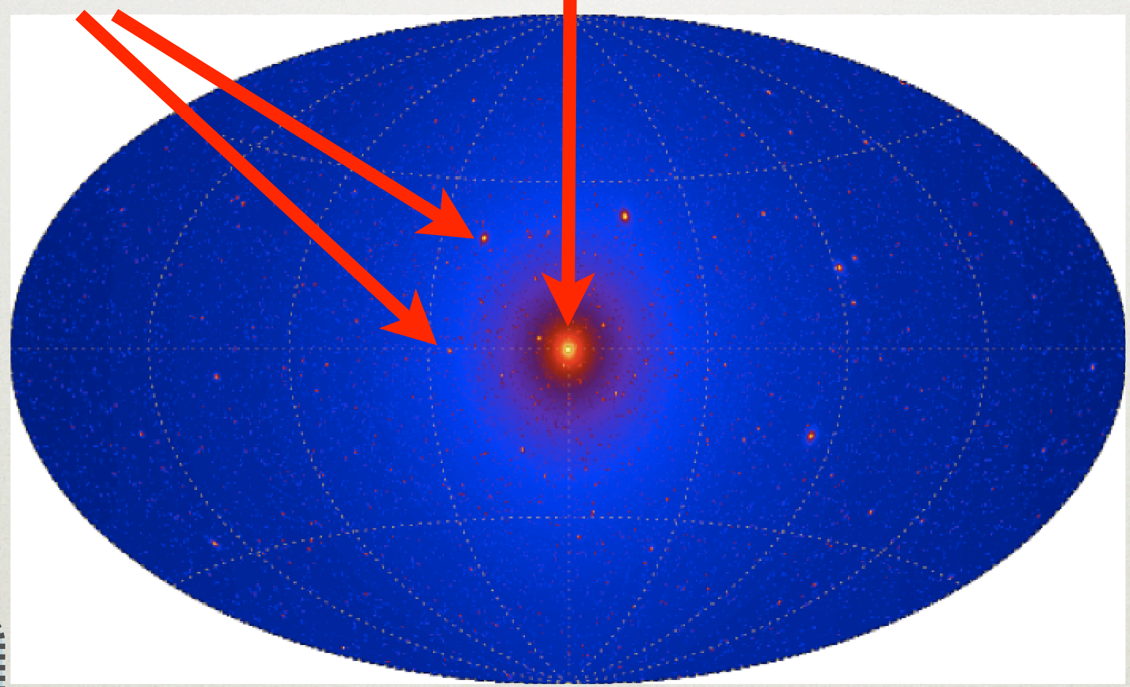

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Search for DM in the GC

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:

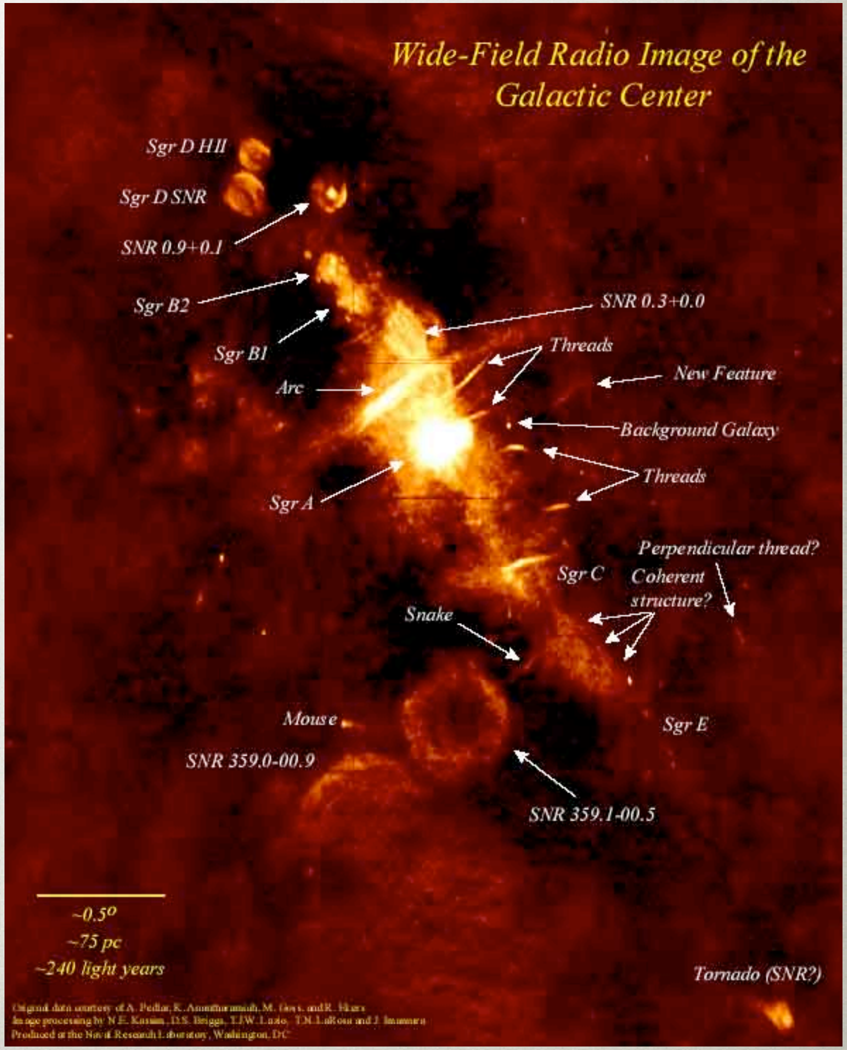
- source confusion: energetic sources near to or in the line of sight of the GC
- diffuse emission modeling: uncertainties in the integration over the line of sight in the direction of the GC, very difficult to model

Fermi Galactic Center Source

- Fermi's year 1 catalog source closest to the galactic center:

  1FGL J1745.6–2900
  Location: l, b = 359.941°, -0.051°
  (95% confinement radius: 1.1′)

- 25 formal associations based on position (1 pulsar wind nebula, 1 supernova remnant, 2 TeV sources, 4 low mass X-ray binaries, etc.)
- Future analyses based on spectral and timing information might narrow down the possibilities



Fermi Galactic Center Source

La Rosa et al 90 cm radio map

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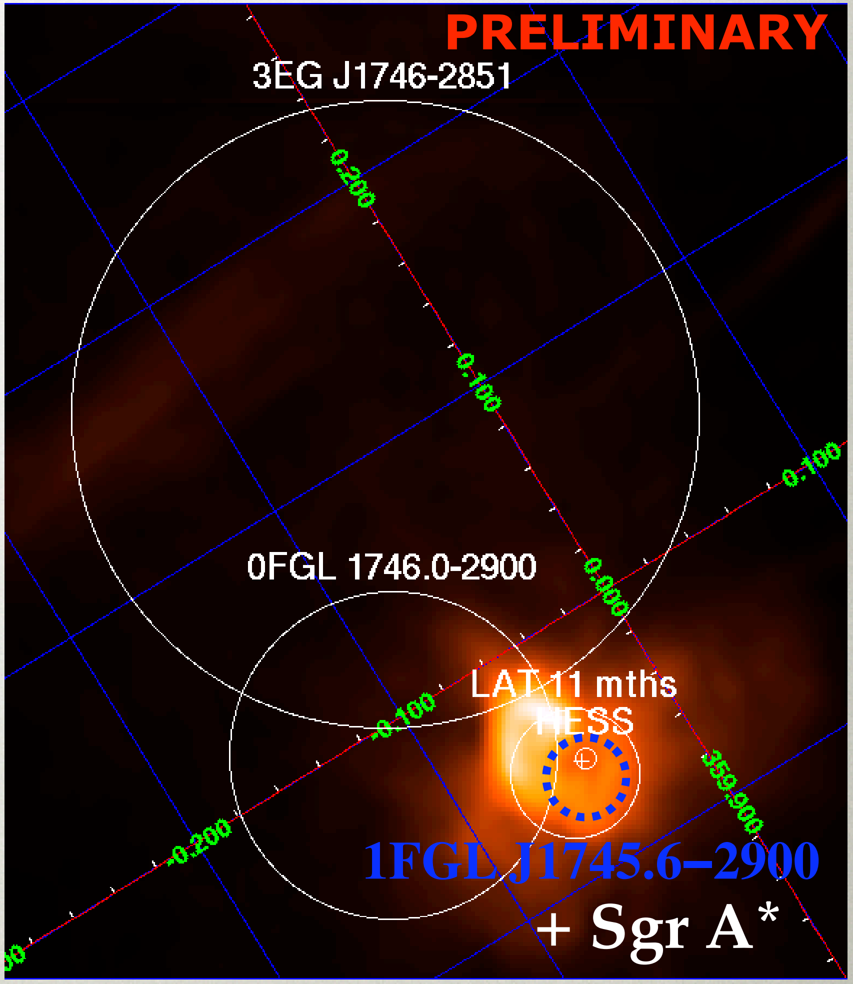
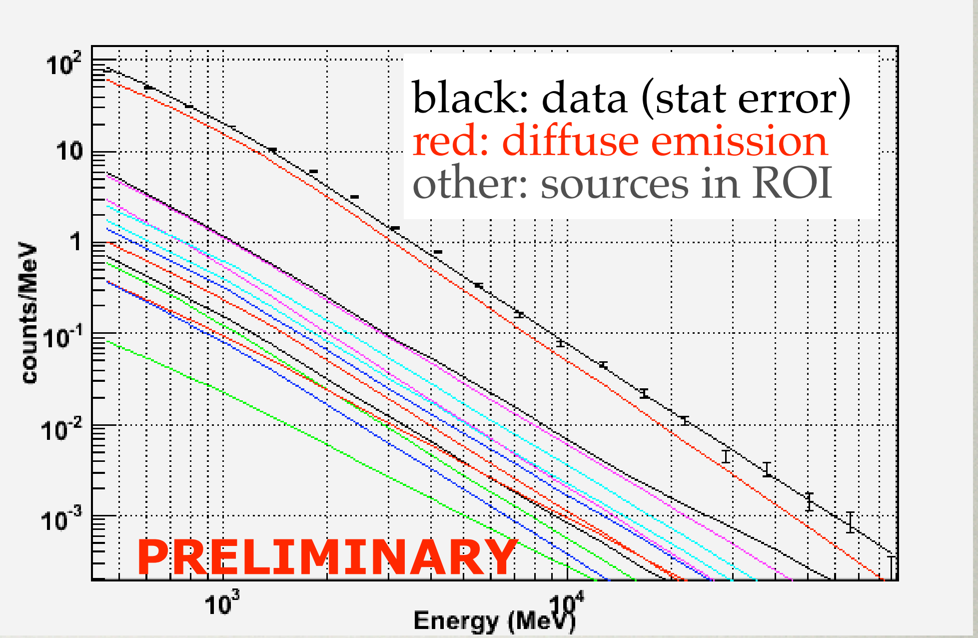
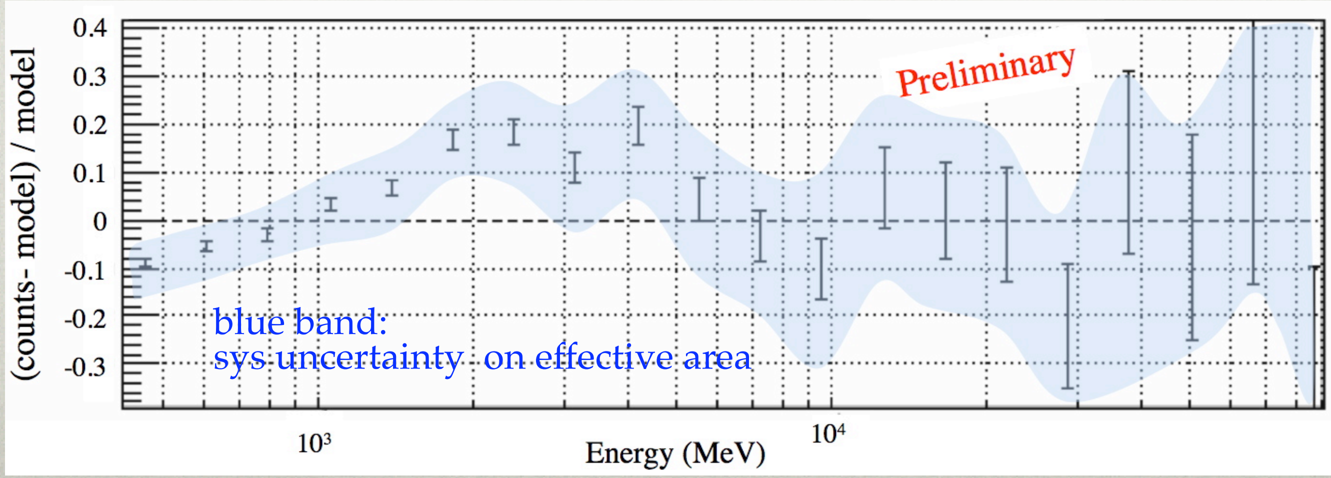


Search for DM in the GC

- Preliminary analysis of a 7° x7° region centered at the GC:
  - Analysis of 11 months of data with energy >400 MeV, front-converting events
  - Model: 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 (spatial residuals under investigation)





Search for DM in the GC

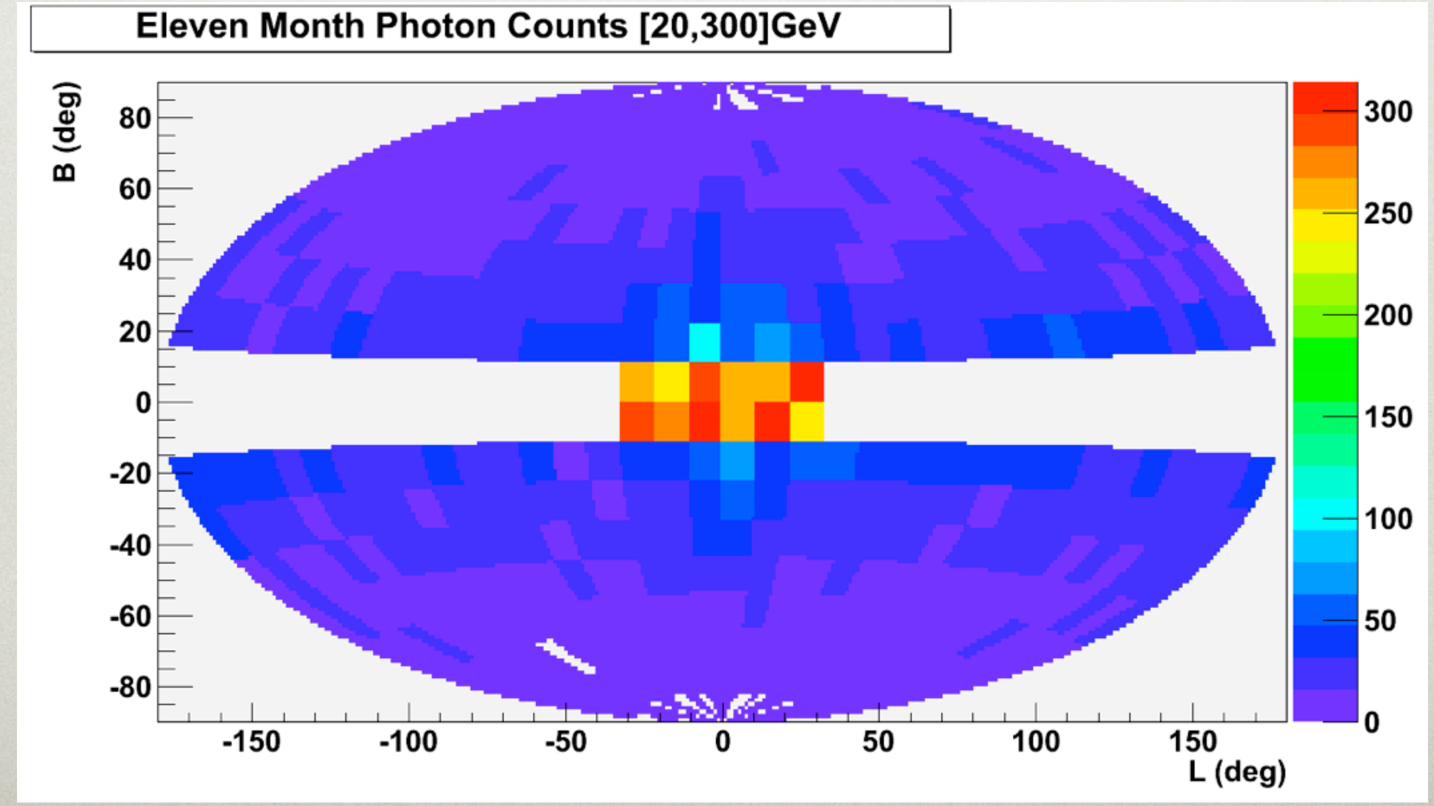
- ➡ Any attempt to disentangle a potential dark matter signal from the galactic center region requires a detailed understanding of the conventional astrophysics
- More prosaic explanations must be ruled out before invoking a contribution from dark matter if an excess is found (e.g. modeling of the diffuse emission, unresolved sources, ...)
- Analysis in progress to derive updated constraints on the annihilation cross section

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

arXiv preprint: 1001.4836

Search for Spectral Lines

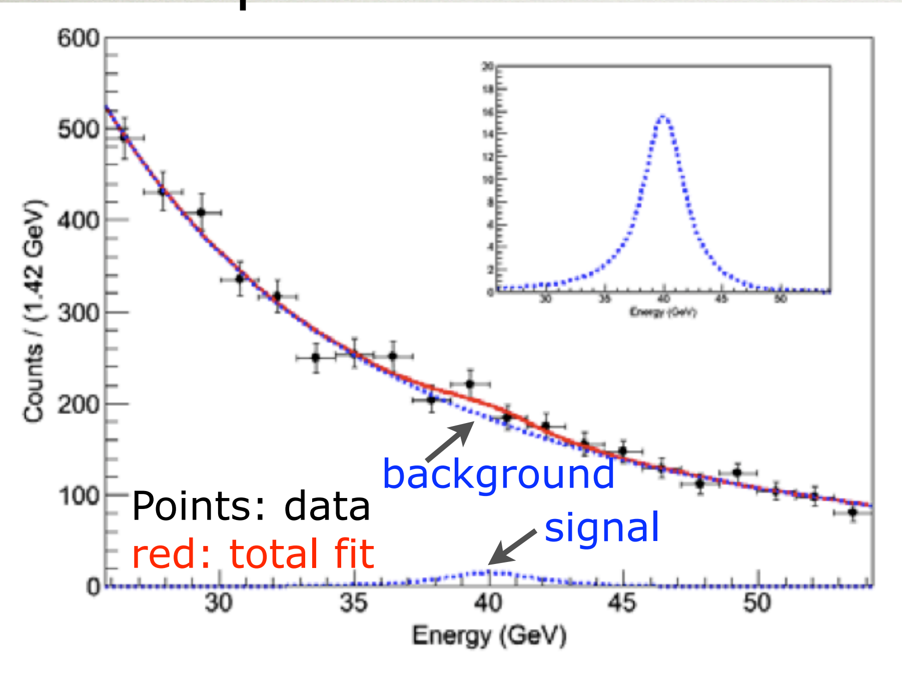
- Smoking gun signal of dark matter
- Search for lines in the first 11 months of Fermi data in the 30-200 GeV energy range
- Search region
  - $|b|>10°$ and $20° \times 20°$ around galactic center
- Remove point sources (for $|b|>1°$). <u>The data selection includes additional cuts compared to standard 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 ⇒ No astrophysical uncertainties.
- Optimal energy resolution and calibration very important for this analysis - resolution ~ 10% at 100 GeV

Example fit for a 40 GeV line



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

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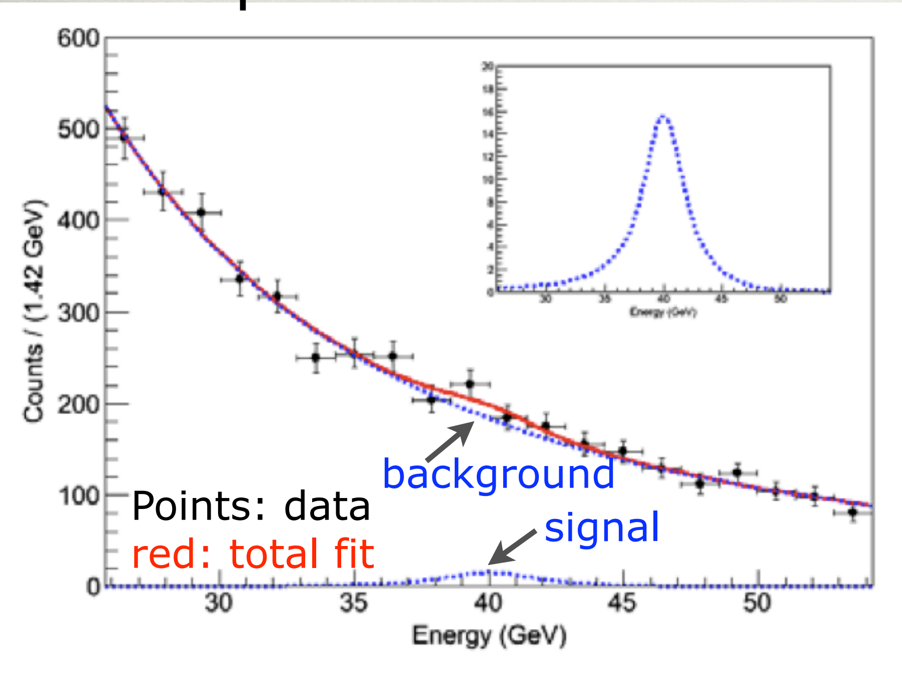
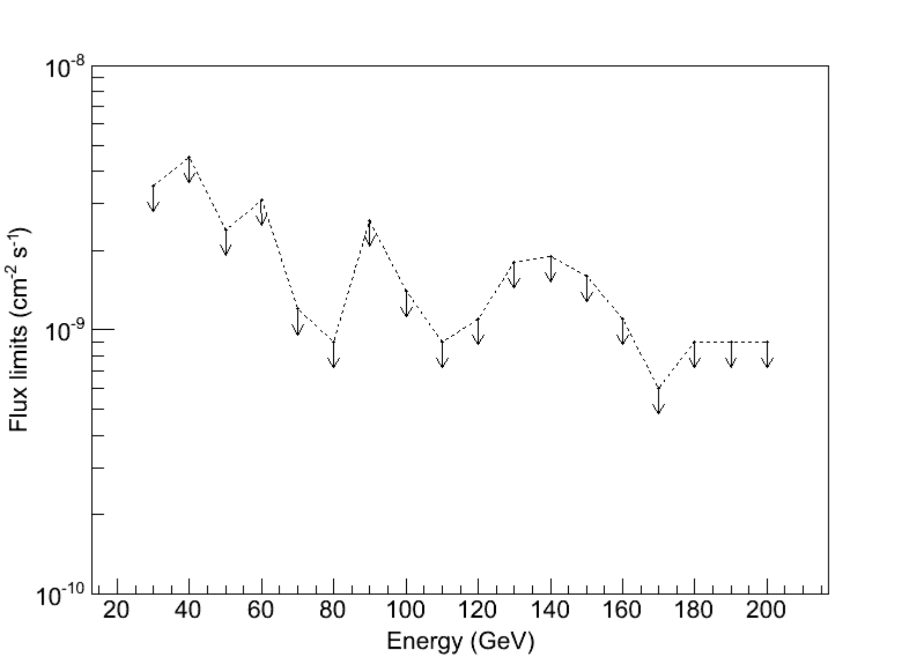
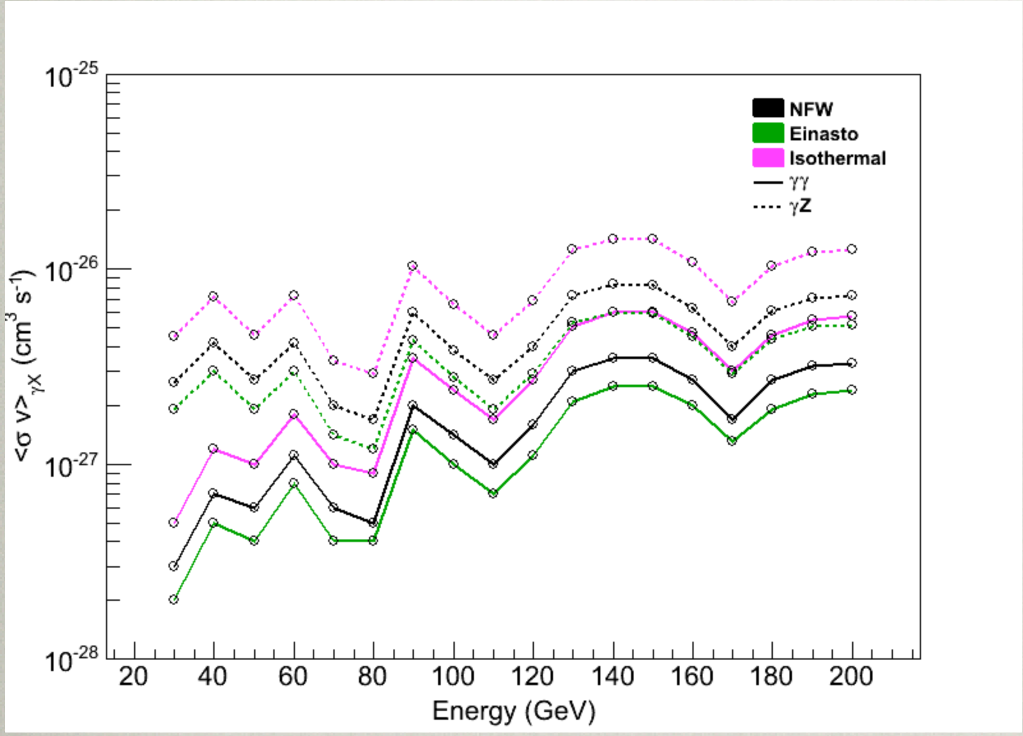
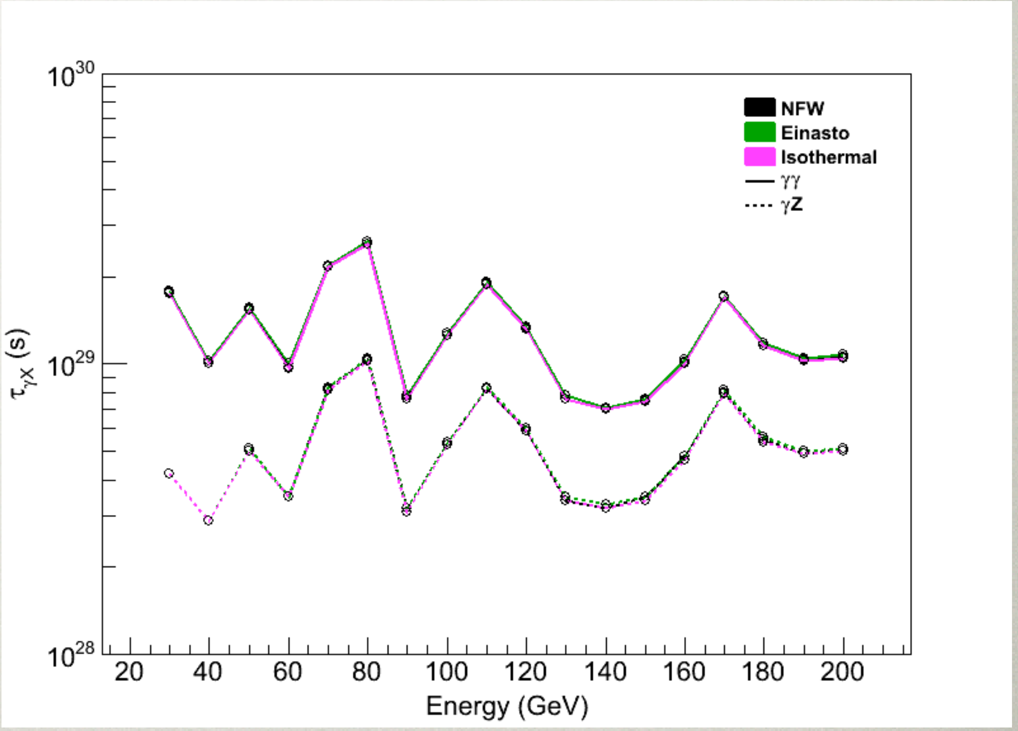




Search for Spectral Lines

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





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

  ✓ However, theories with non-thermally produced WIMPs (consistent with the observed relic density) can predict large annihilation cross section and have been invoked to partially explain cosmic ray data as the by-product of dark matter annihilation.
  E.g. Wino LSP (Kane 2009) predicts a γZ line with $\langle\sigma_{ann}v\rangle \sim 1.4\times10^{-26}$ $cm^3 s^{-1}$. Fermi's constraints disfavor this model 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 $m_{3/2}\sim100$ GeV)

Search for Spectral Lines

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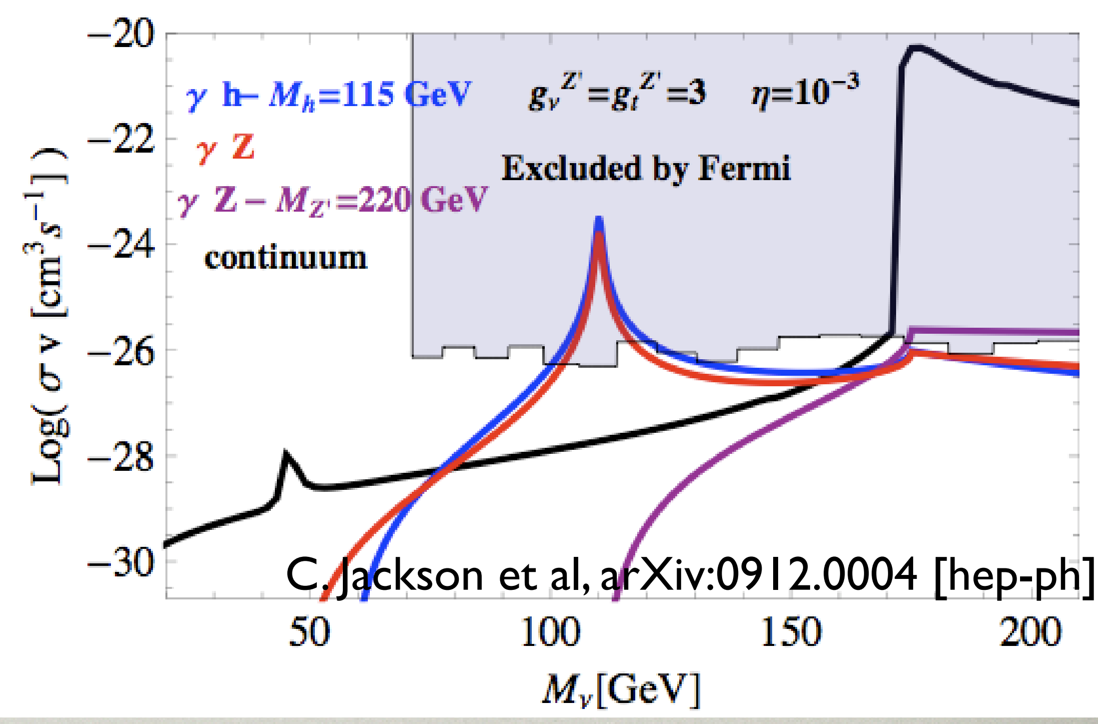
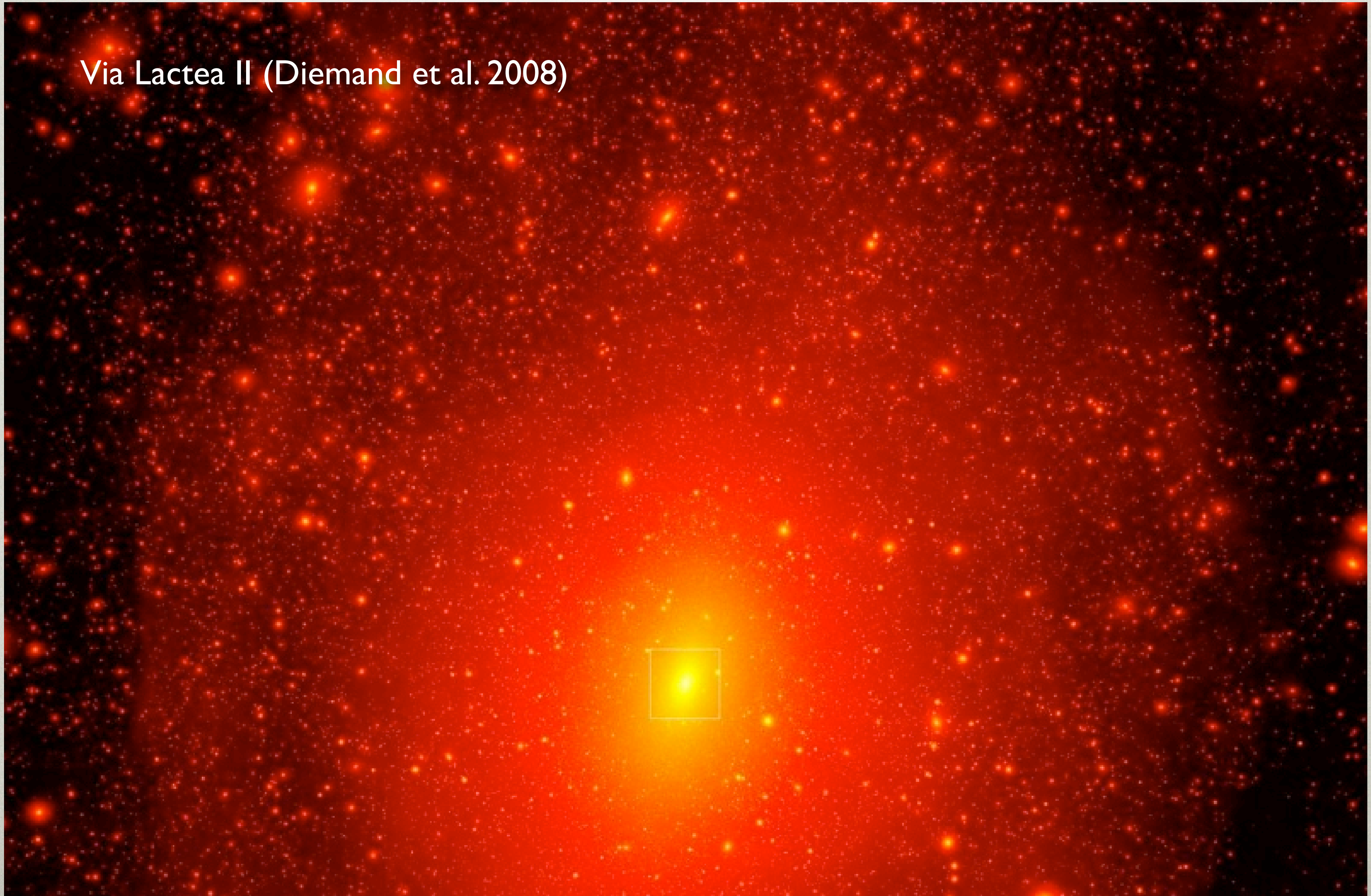
Higgs in space!

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



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, Geha & Simon 2009)
  - Given the distance 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: ~1° average radial extension for nearby, detectable clumps
  - Spectrum determined by DM (both b-bbar and $\mu^+\mu^-$ spectra are tested vs a (soft) power law hypothesis)

- Blind analysis: finalize selection method with 3 months of data and apply to 10 months
- Search for sources (>5σ significance) passing these criteria in the 200 MeV to 300 GeV energy range.
- Background: point sources+diffuse Galactic and isotropic emission

Search for DM Satellites

PRELIMINARY

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

✓ Consistent with result of sensitivity study based on Via Lactea II predictions for the DM distribution for a generic 100 GeV WIMP annihilating into b-bbar, $<\sigma v>=3x10^{-26}$ cm^3 s^{-1} (paper in preparation)

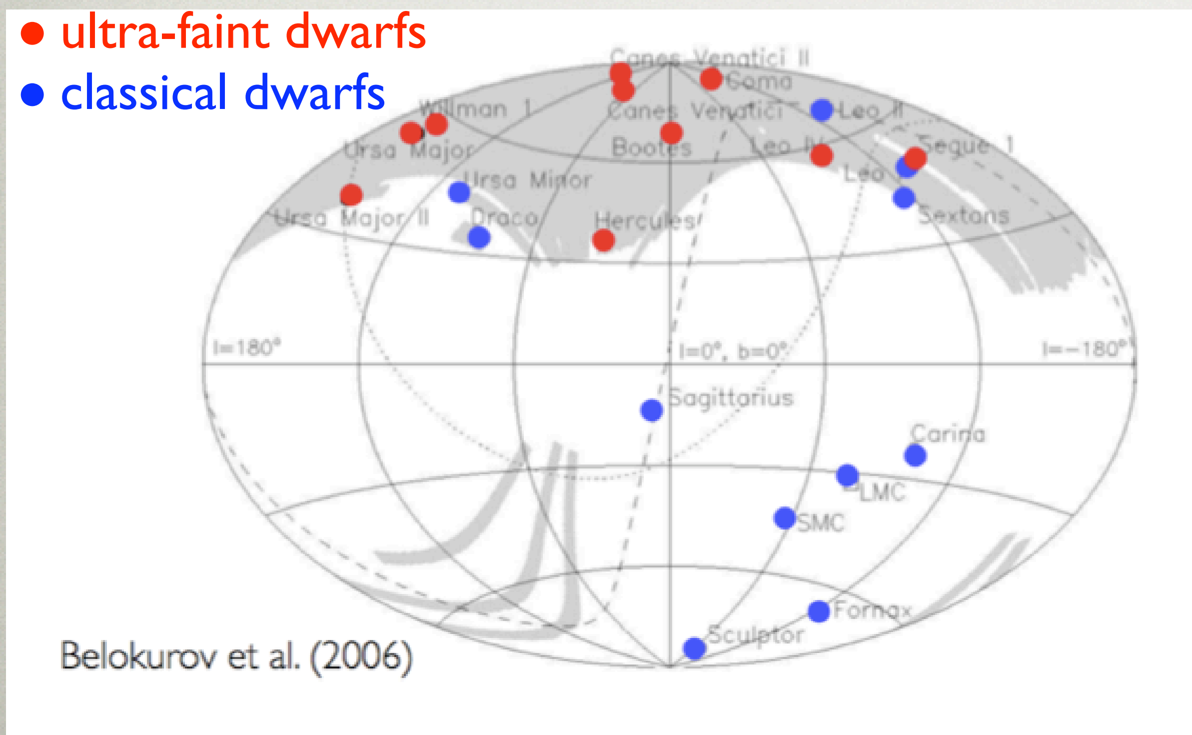
✓ Work is ongoing to evaluate the sensitivity for other models

Astrophys. J. **712**, 147 (2010)

arXiv preprint: 1001.4531

SEARCH FOR DM IN DSPH

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



Belokurov et al. (2006)

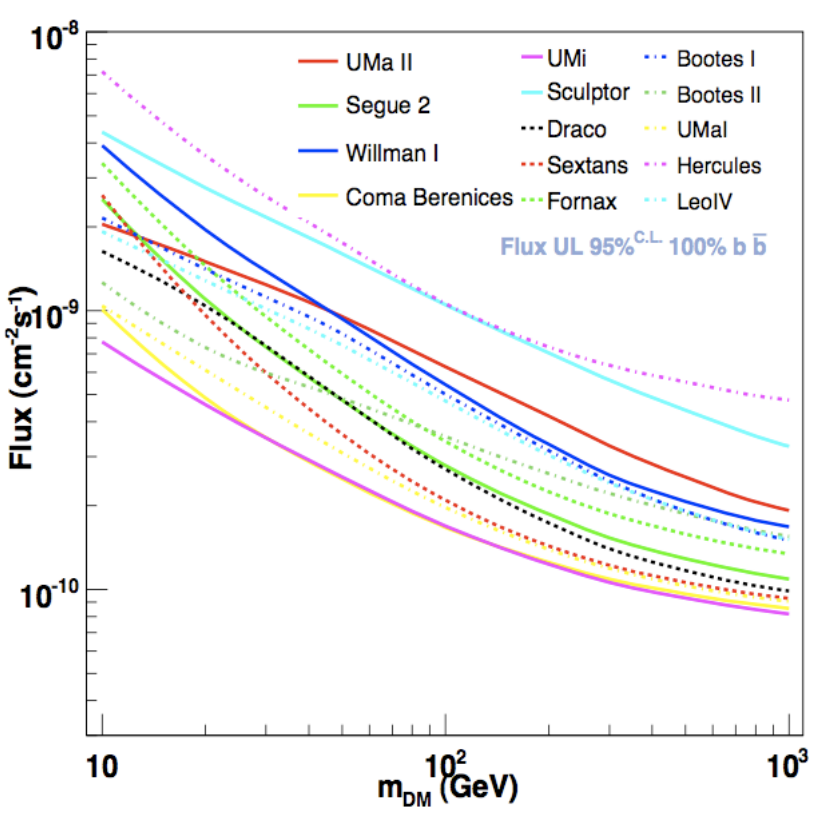
Distance: ~30 to 160 kpc

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 50 GeV
- Background: point sources+diffuse Galactic and isotropic emission

➡ No detection by Fermi with 11 months of data. 95% flux upper limits are placed for several possible annihilation final states.

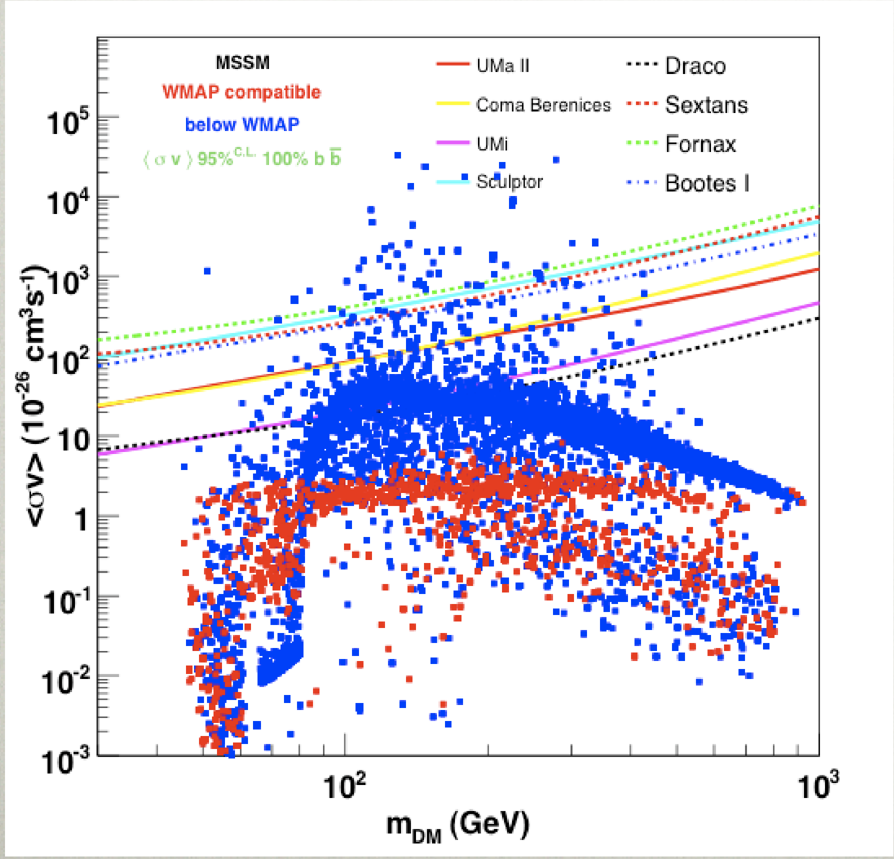


- Flux upper limits are combined with the DM density inferred by the stellar data(*) for a subset of 8 dSph (based on quality of stellar data) to extract constraints on $<\sigma_{ann}v>$ vs WIMP mass for specific DM models

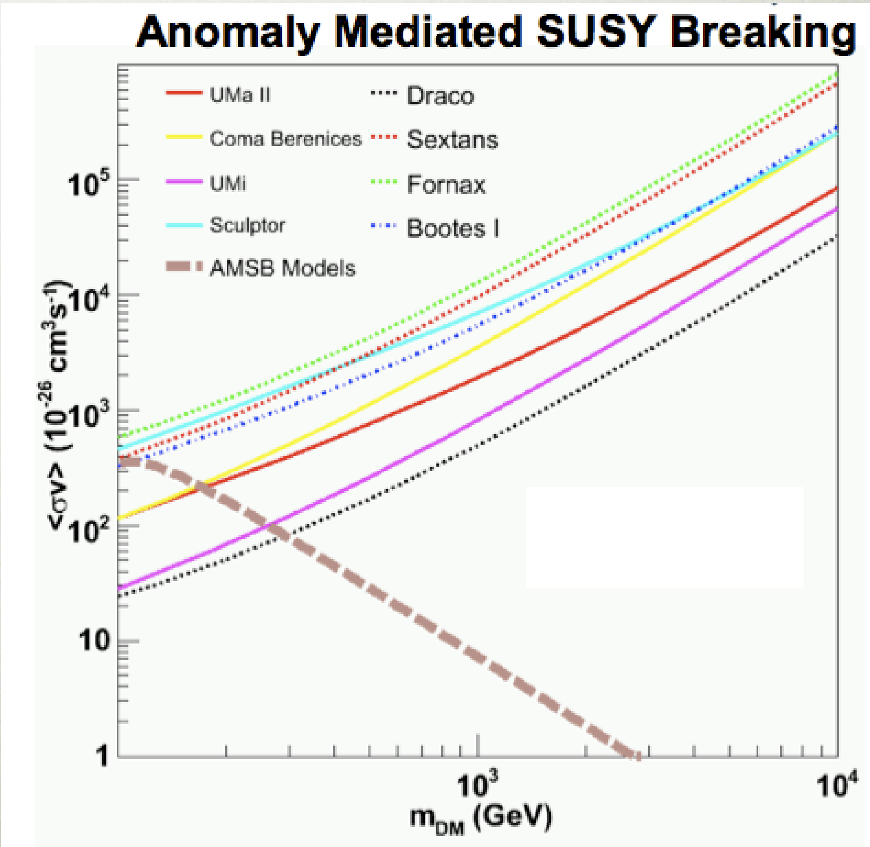
(*) stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)

Search for DM in dSph

- ✓ Exclusion regions cutting into interesting parameter space for some WIMP models

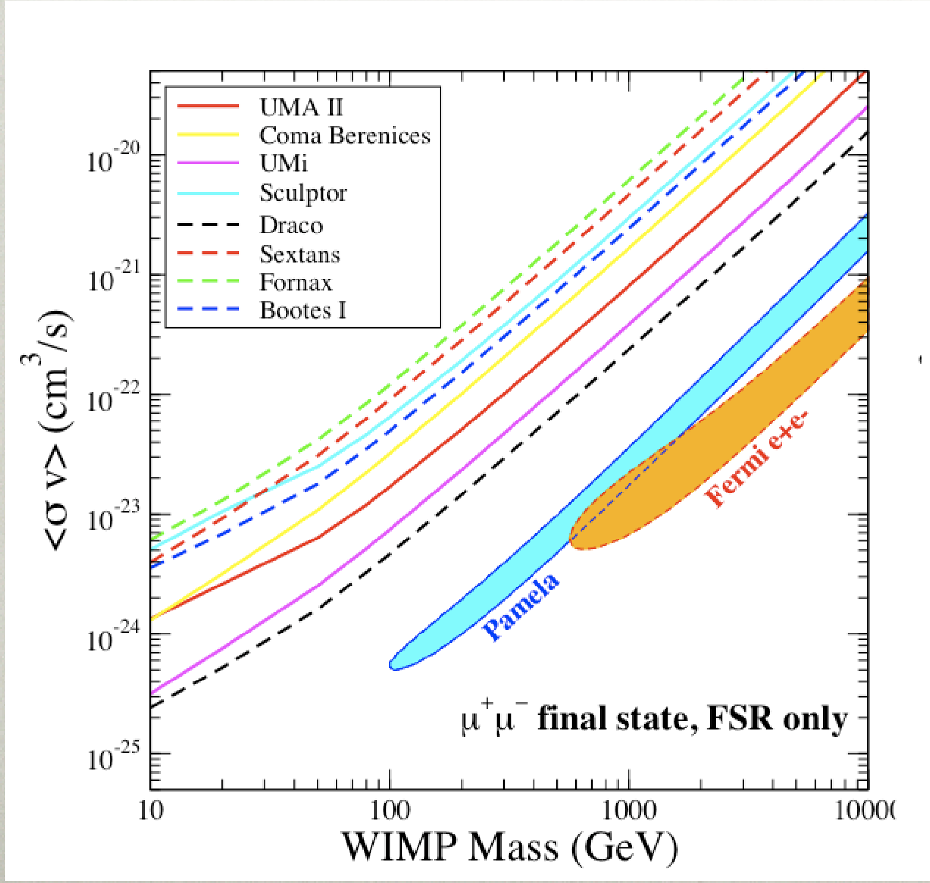


Limits disfavor Wino LSP with M=180 GeV



Search for DM in dSph

- ✓ WIMPs with large annihilation cross-sections into leptonic final states have been invoked to partially explain cosmic-ray data as the by-product of dark matter annihilation

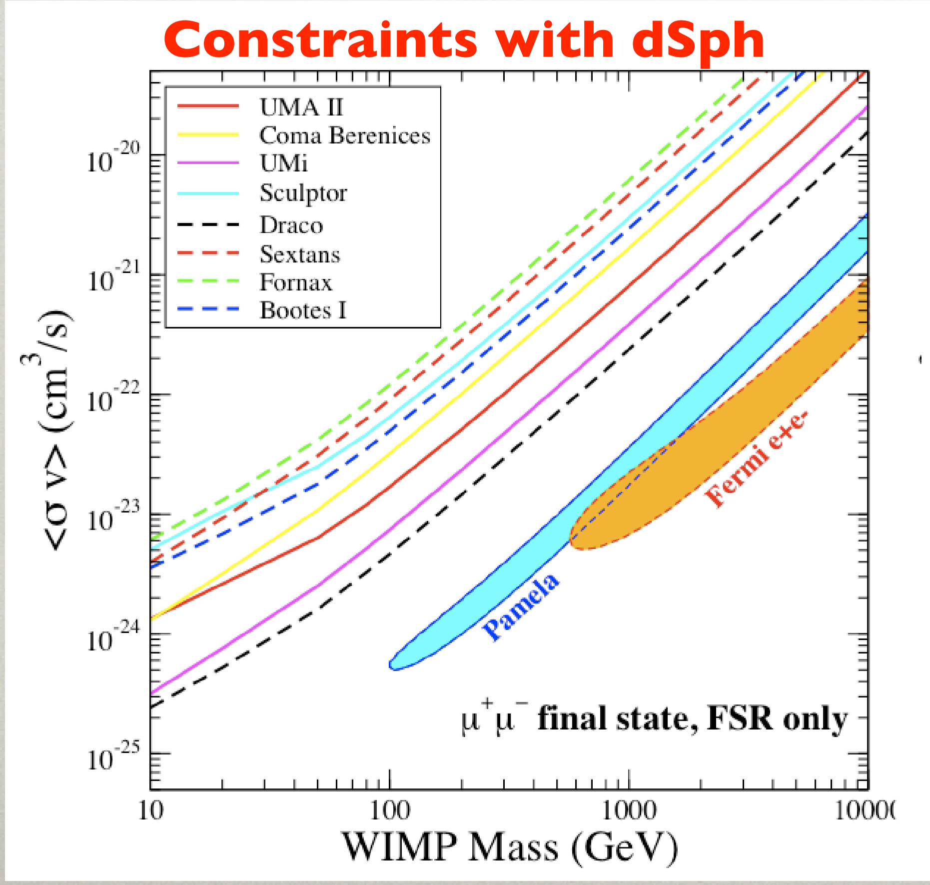


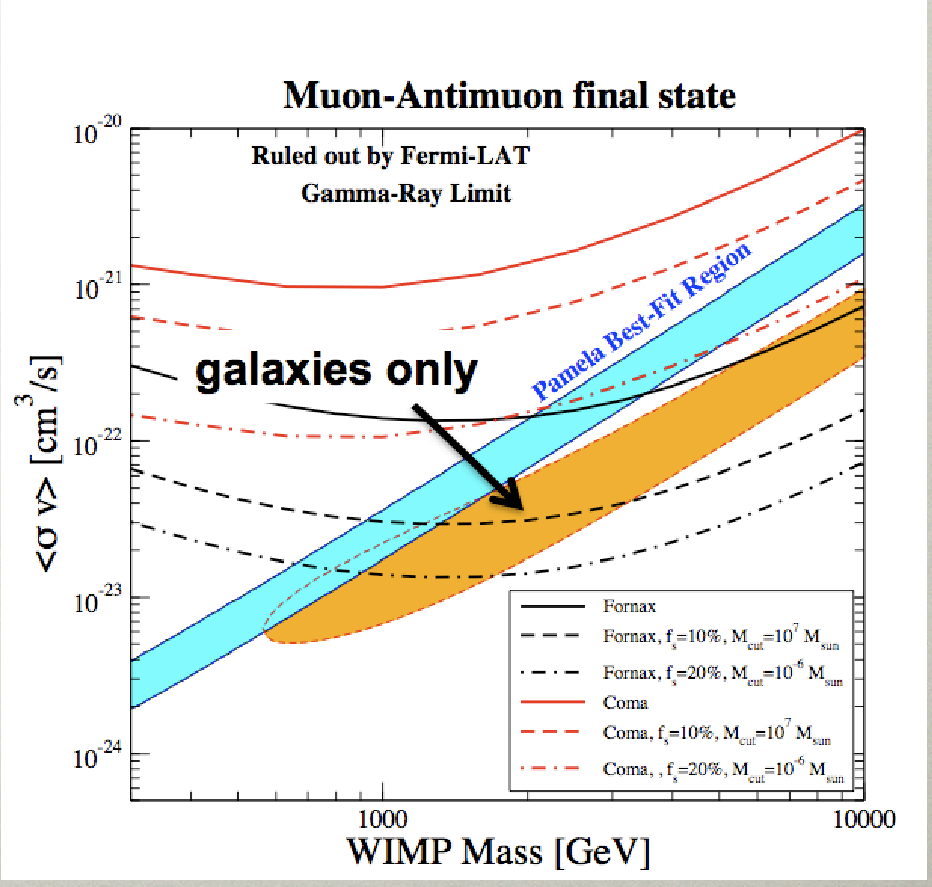
Accepted for publication JCAP

arXiv preprint: 1002.2239

Search for DM in Galaxy Clusters

- ✓ Stronger constraints on leptophilic DM models can be derived with Fermi non-detection of galaxy clusters (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



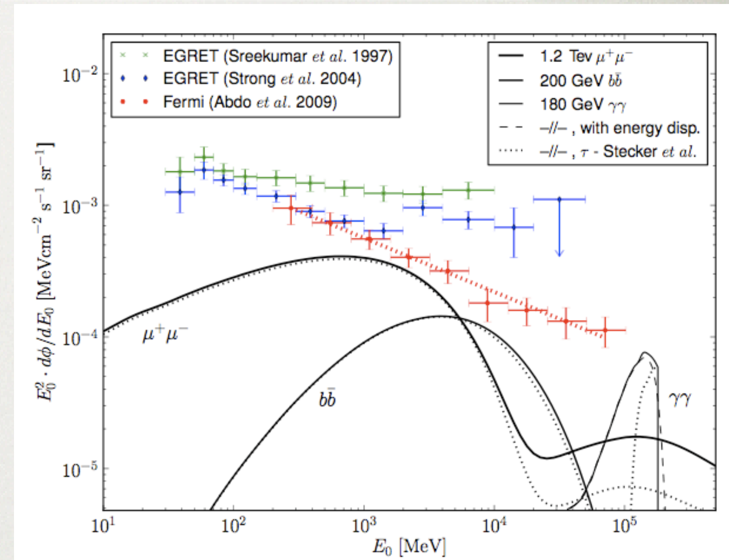


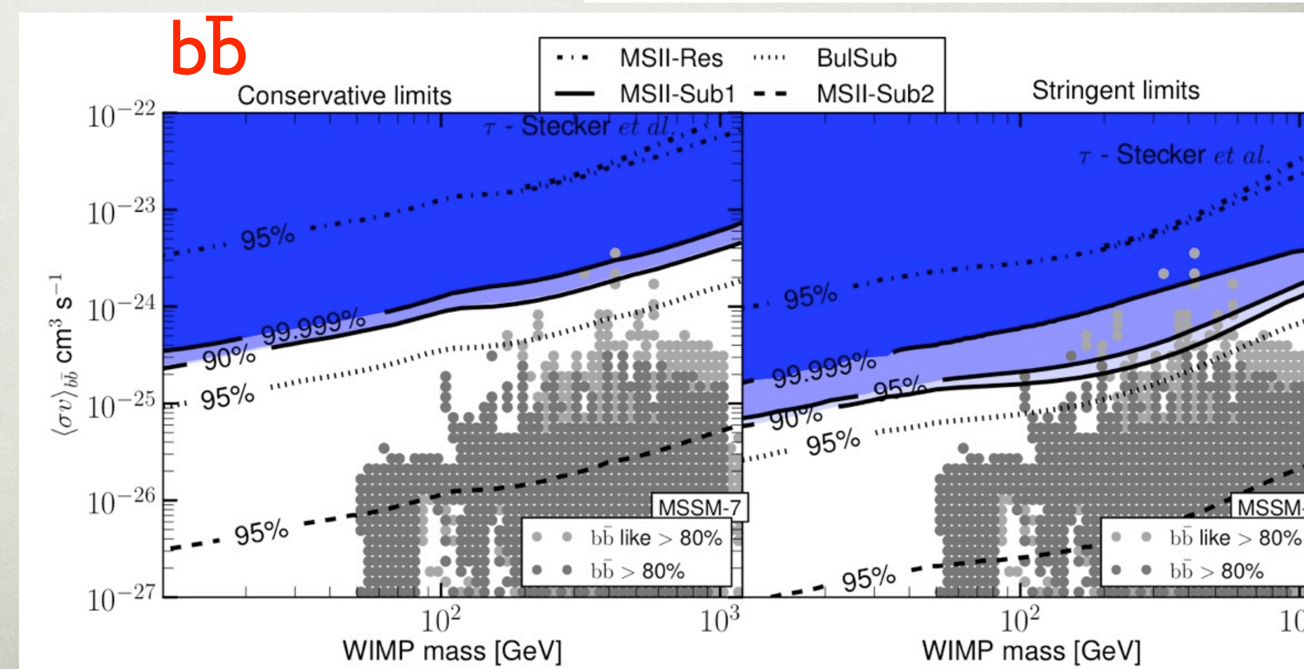
JCAP 1004:014,2010.

arXiv preprint: 1002.4415

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.





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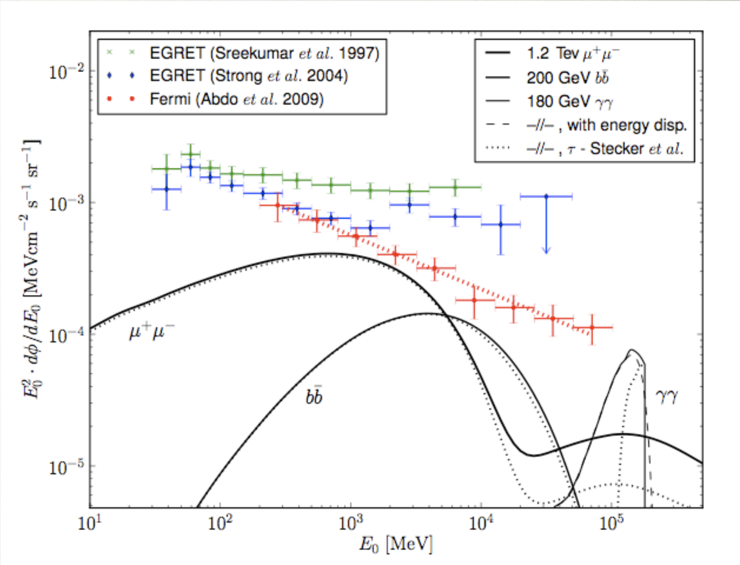

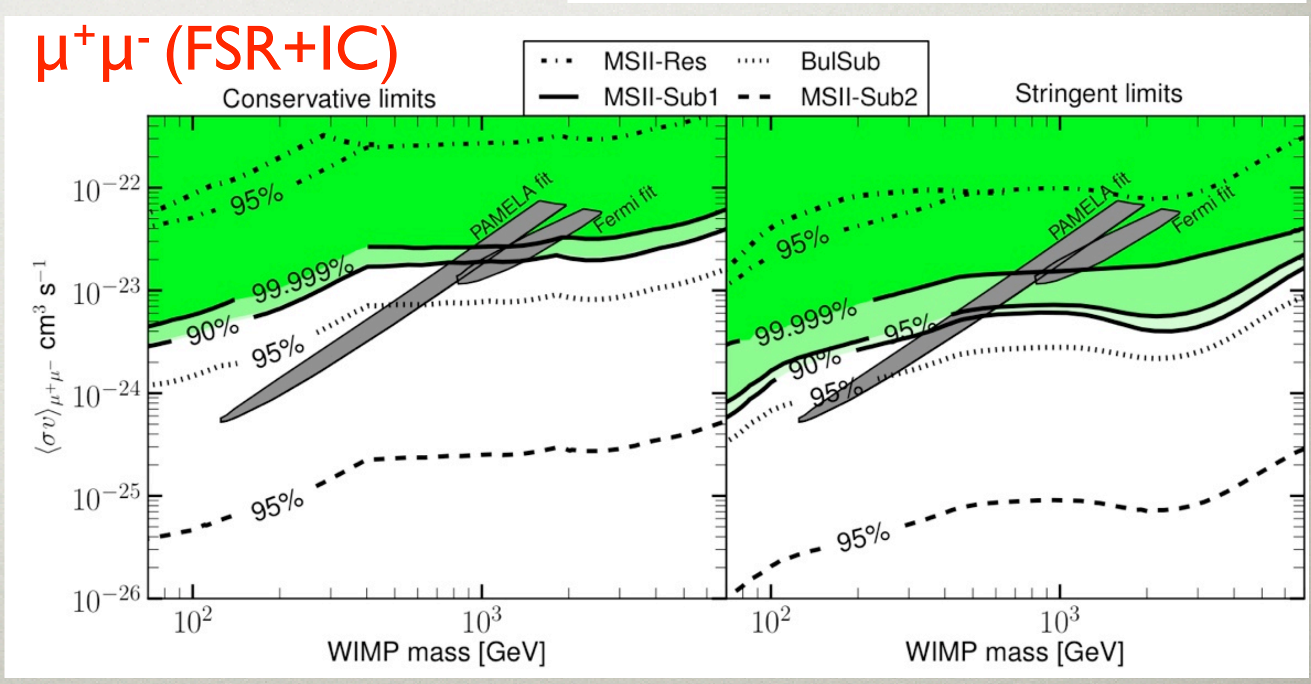

Conclusions

- No discovery... however:
- Promising constraints on the nature of DM have been placed

  The constraints are particularly strong for theories that predict the existence of WIMPs annihilating with large cross sections, some of which have been invoked to partially explain cosmic-ray data as the by-product of dark matter annihilation.

- Our knowledge of the astrophysical background is uncertain and initial discrepancies between data and preliminary background predictions should not be surprising. The gamma-ray sky is complex and Fermi's goal is to understand it better!

  ➡ Good understanding of the background is essential (and it should be achieved keeping in mind the risk of absorbing a potential signal into the background.) This will take time and it requires a dedicated effort, much like understanding the QCD background at the LHC, but with no control over the accelerator!

Outlook

- Many improvements are forseen:

In addition to increased statistics and better understanding of the astrophysical background:

- improving the instrumental background rejection (charged particle contamination in the LAT data is larger than predicted from pre-launch estimates)
- improving the acceptance below 200 MeV

will improve our ability to reliably extract a potential signal of new physics or set stronger constraints.

Further improvements are anticipated for analyses that benefits from multi-wavelength observations (for example Galactic Center, dwarf spheroidal galaxies and DM satellites). Of course, if a signal is observed elsewhere (e.g. LHC) it's likely to make our job easier

With Fermi we are exploring the unknown and it is very exciting!

➡ Fermi is a 5 to 10 year mission: we are just beginning!