Recent Results on Dark Matter Searches with Fermi

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on behalf of the Fermi-LAT Collaboration

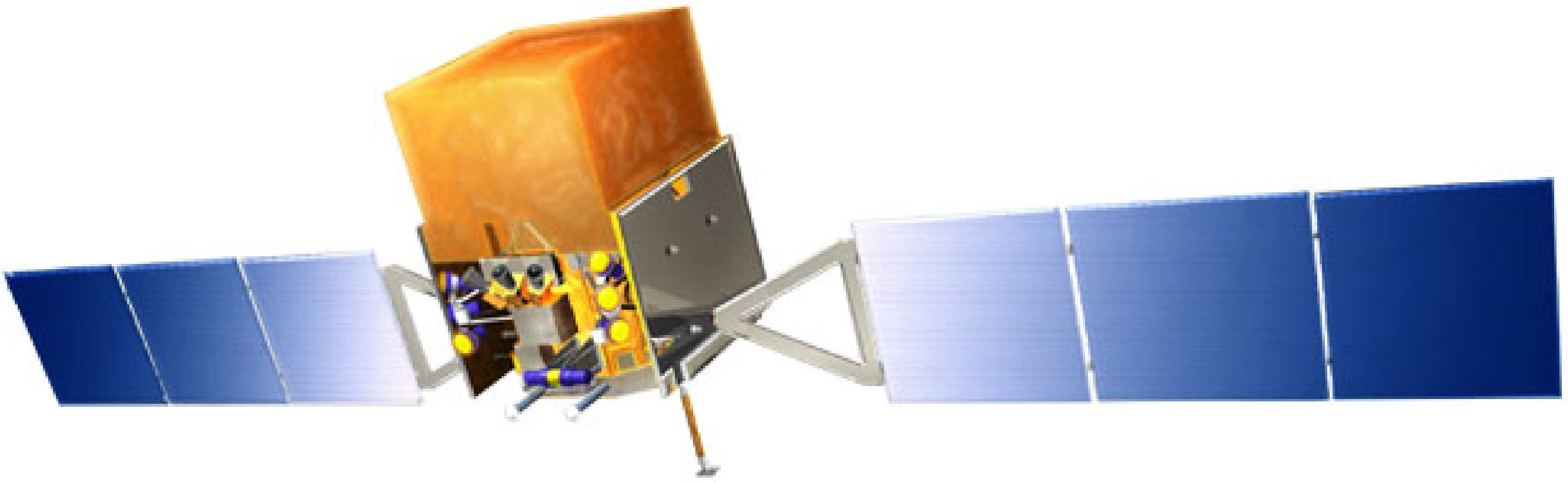
Fermi Gamma-ray Space Telescope

SLAC NATIONAL ACCELERATOR LABORATORY

KITP-UCSB
8 December 2009

The Observatory

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



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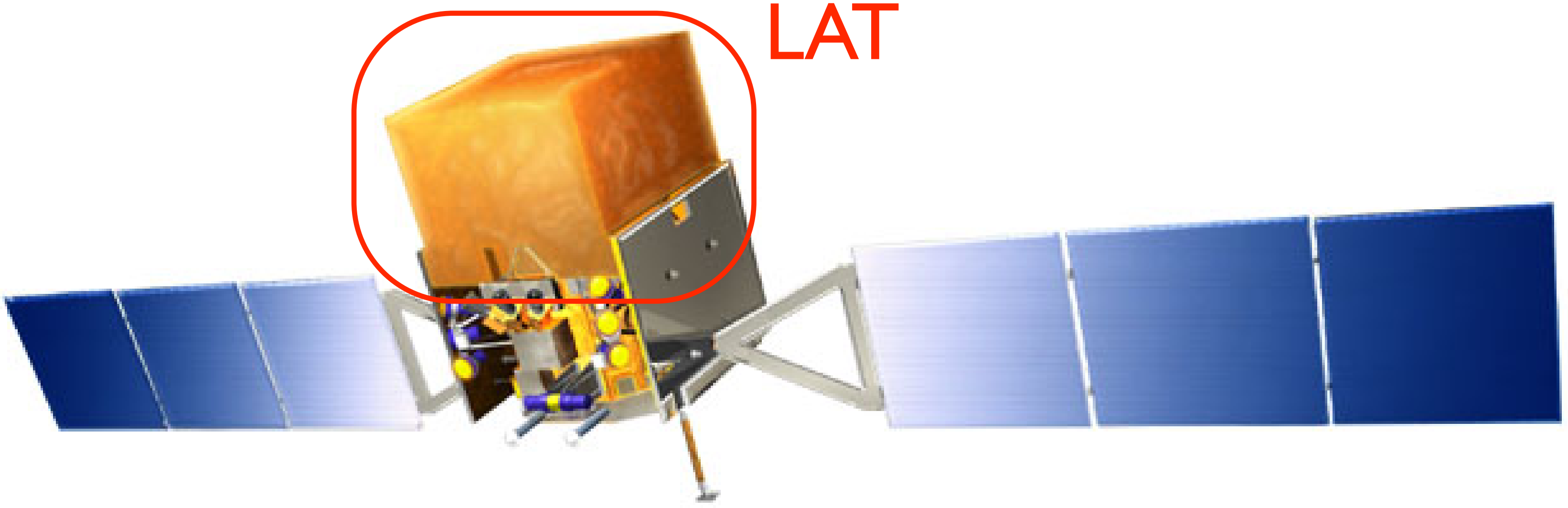
- Two instruments:

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



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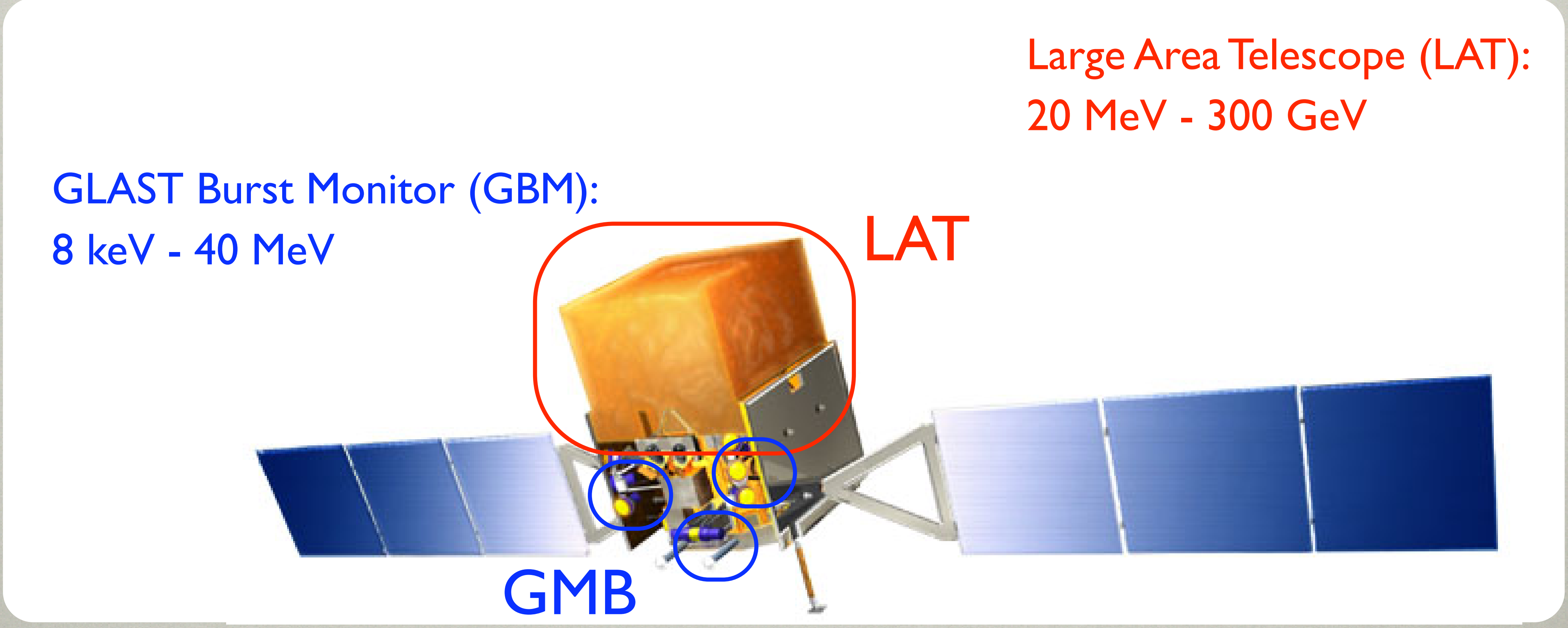


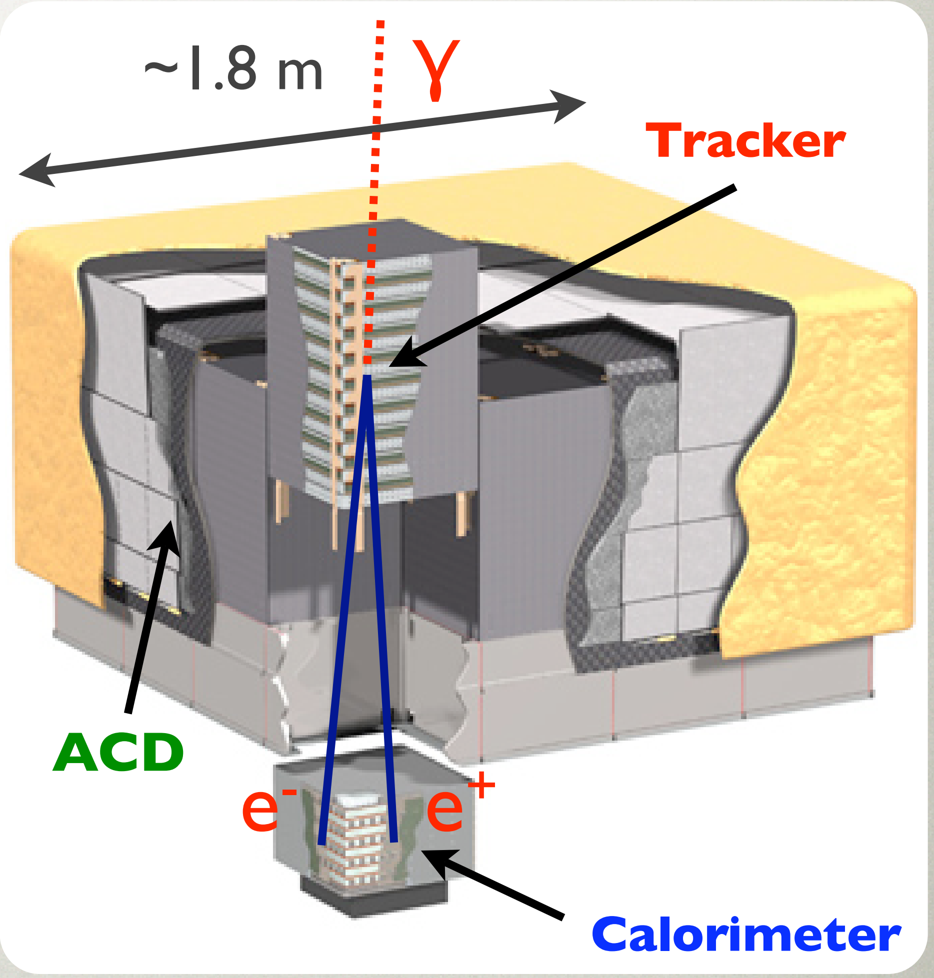
The LAT

Pair conversion telescope

Precision Si-strip Tracker:
precise measurement of photon direction, photon ID.
Si strip detectors, W conversion foils; 80 m^2 of Si active area. 1.5 radiation lengths on-axis.

Hodoscopic CsI Calorimeter:
measurement of photon energy, shower imaging.
Array of 1536 CsI(Tl) crystals in 8 layers. 8.6 radiation lengths on-axis.

Segmented Anti-Coincidence Detector (ACD):
charged particle veto (0.9997 average detection efficiency). Segmented design reduces self-veto at high energy.
89 plastic scintillator tiles and 8 ribbons.



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 orbit

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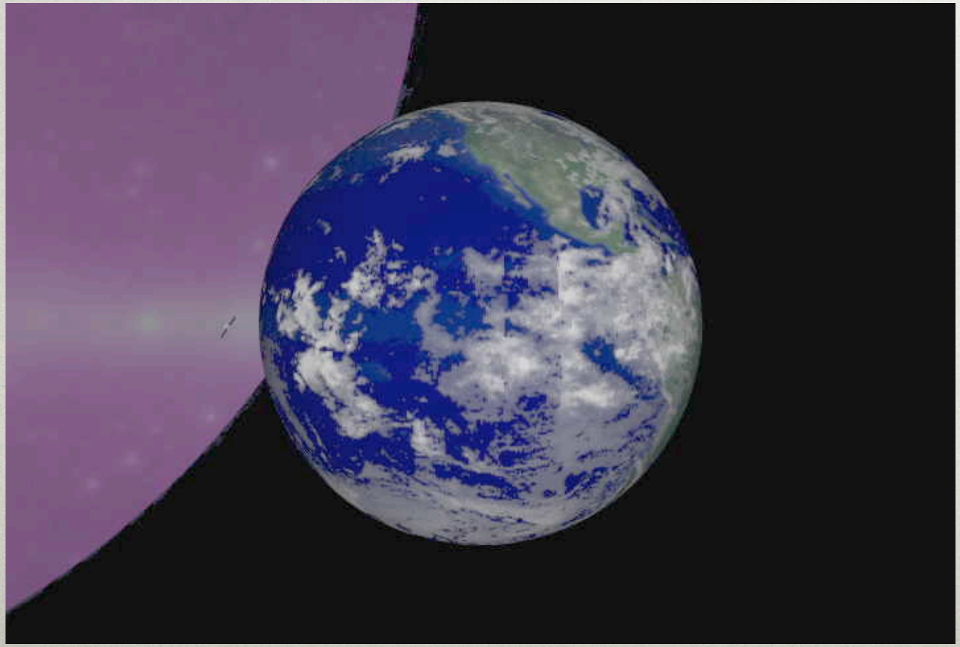
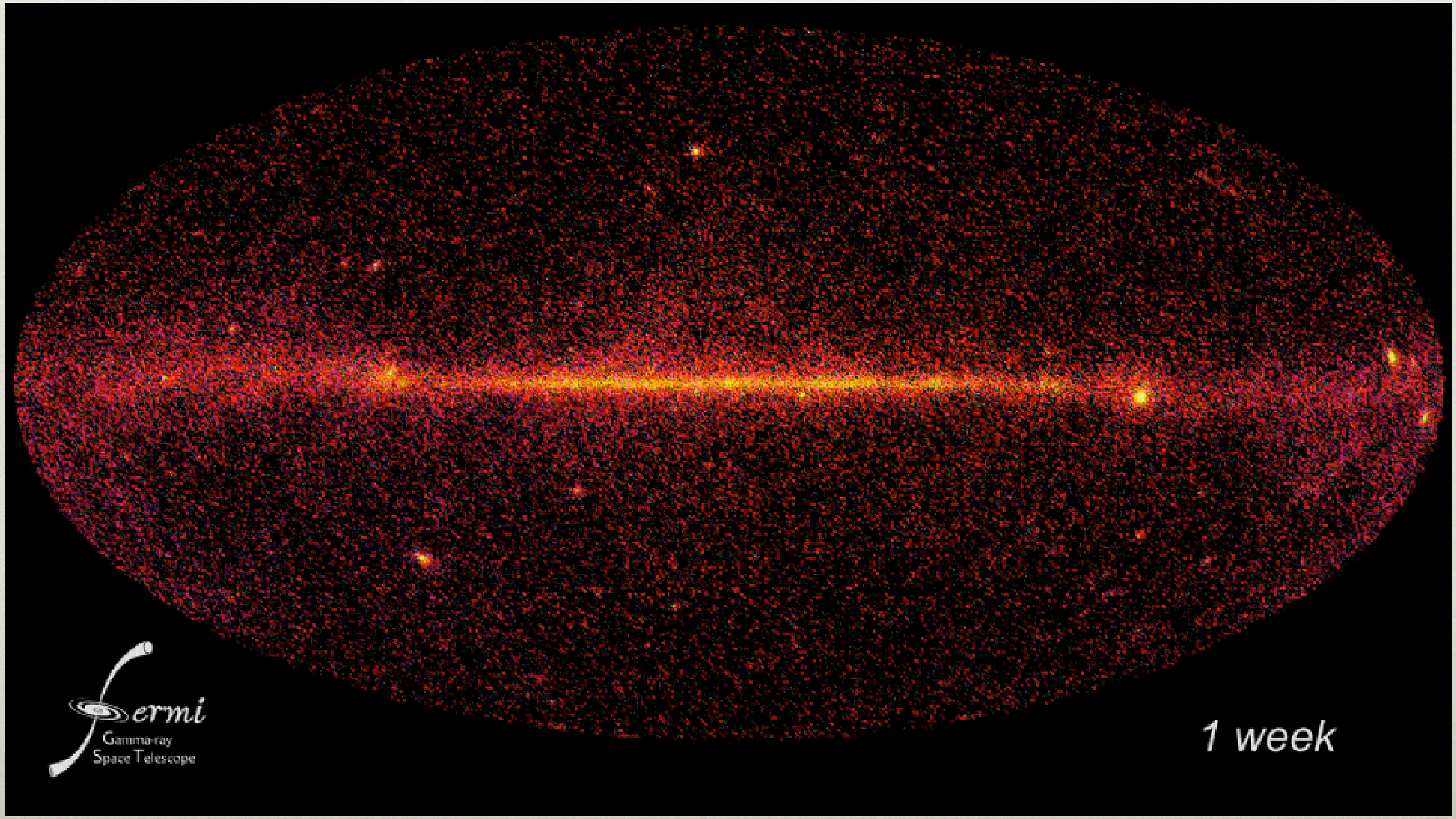
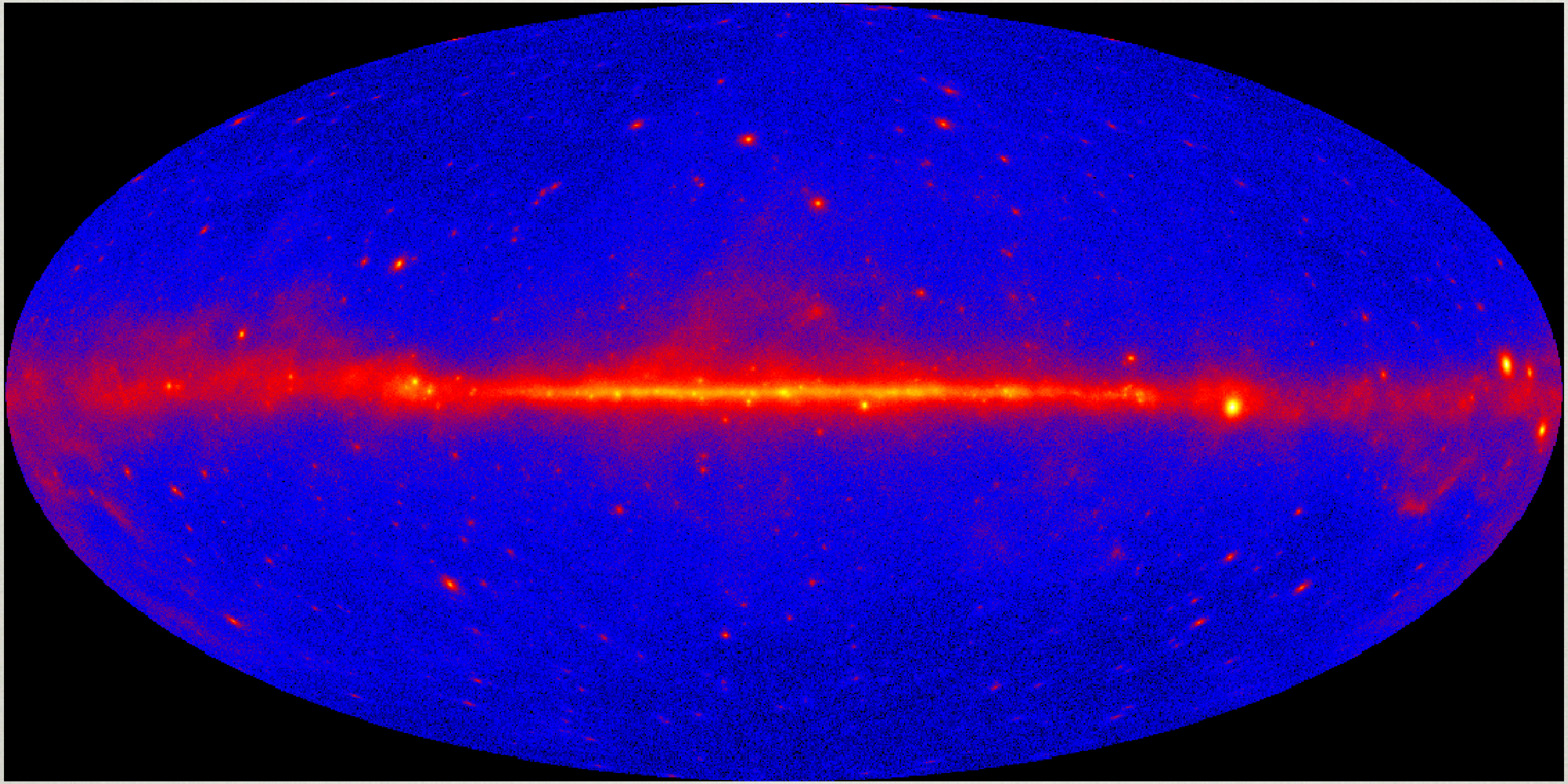


The Fermi Sky

- > 1000 sources in First Fermi LAT source catalog (available by the end of November)
- ~250 sources show evidence of variability
- Half 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

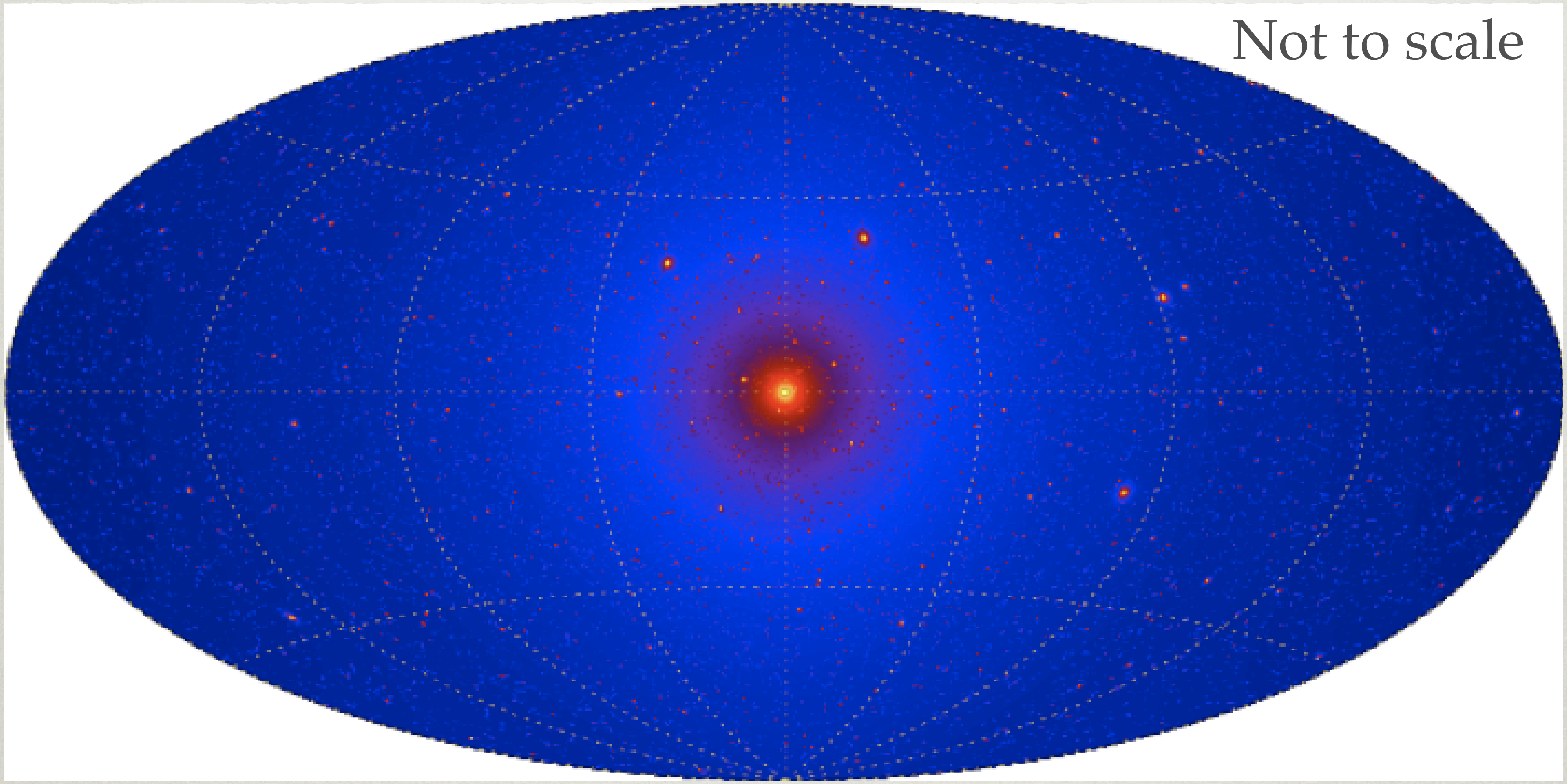


Fermi 1 year sky



Fermi's great capabilities give us a unique perspective in investigating the existence of dark matter particles indirectly, primarily through their annihilation or decay into photons and into electrons

Simulated sky map of γ-rays from DM annihilation



(Pieri et al, arXiv:0908.0195, based on Via Lactea II simulation)

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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

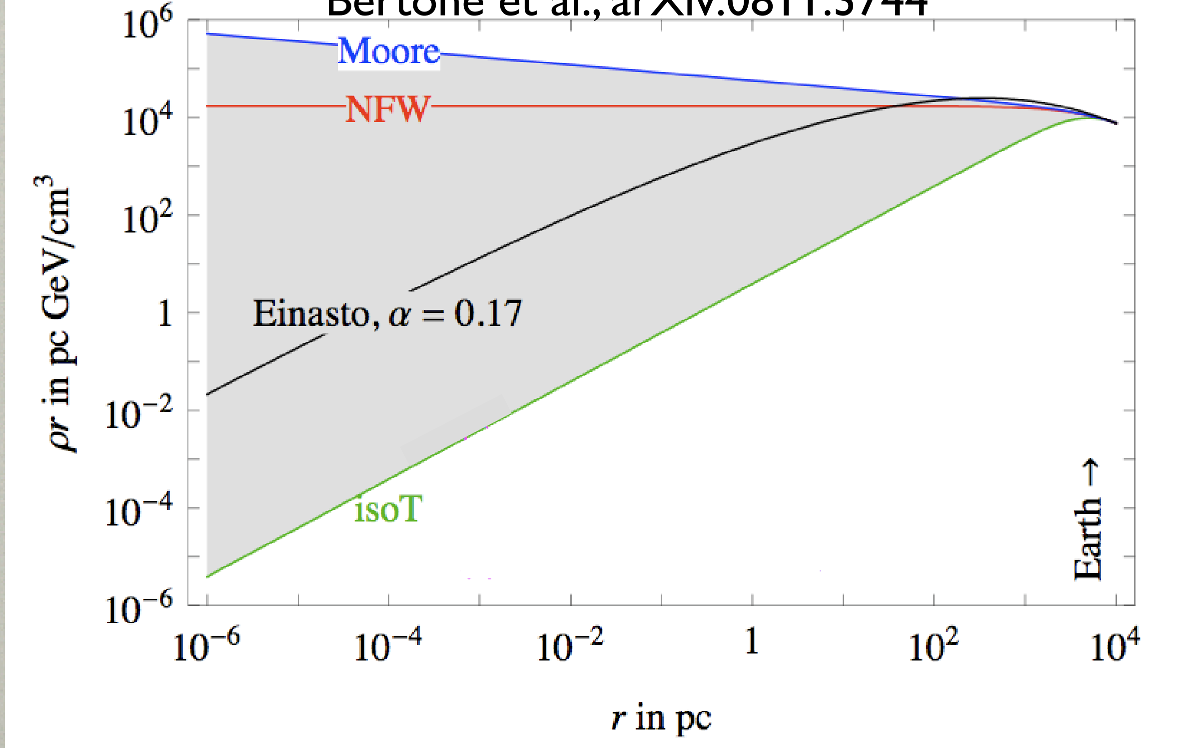
For DM decay:

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

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

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

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

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

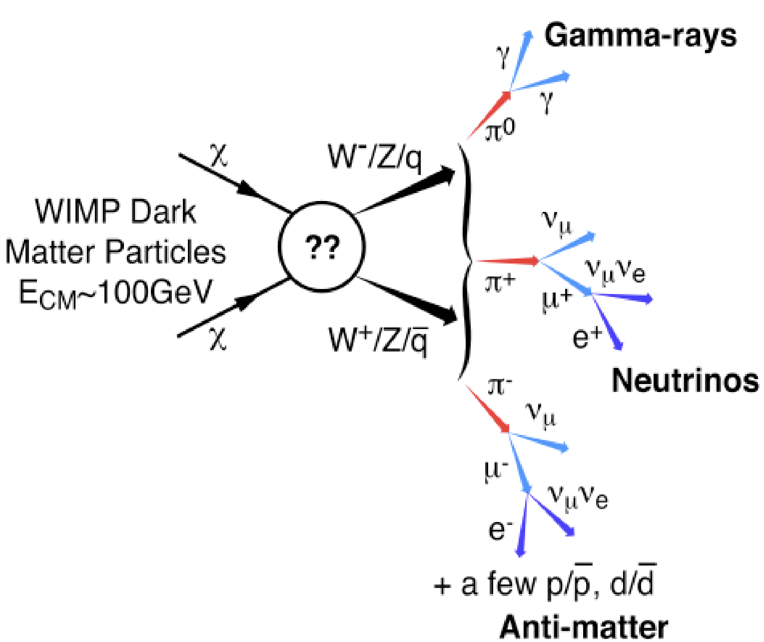
- ✓ Via Lactea II predicts a cuspier profile, $\rho(r) \propto r^{-1.2}$
- ✓ Aquarius predicts a shallower than r^{-1} innermost profile

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

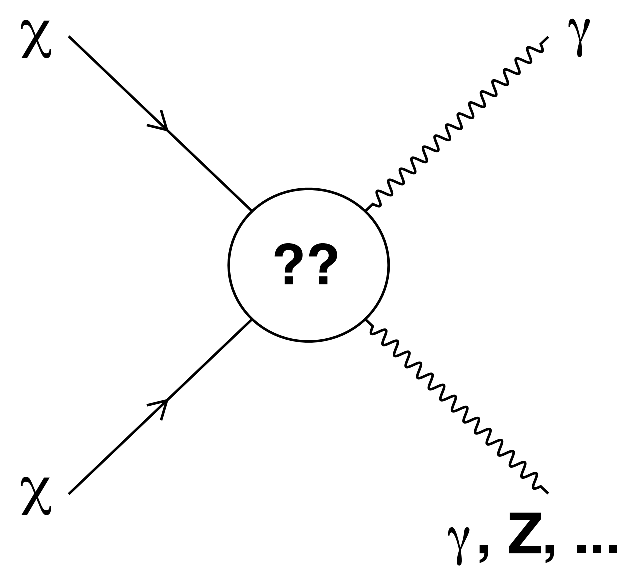
Continuum spectrum with cutoff at M_W

Annihilation (or decay) into γ



Spectral line at M_W

Prompt annihilation into $\gamma\gamma$, γZ, γH^0...
(also prompt decay into photons)

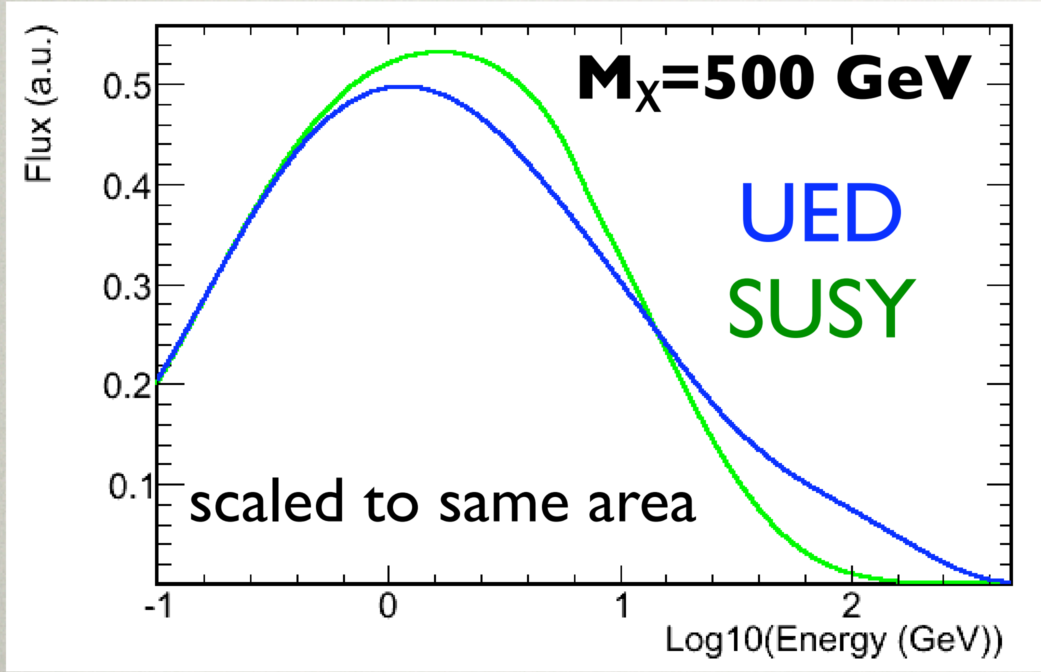


Two Examples

Example photon spectra 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



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

mSUGRA parameters:

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

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

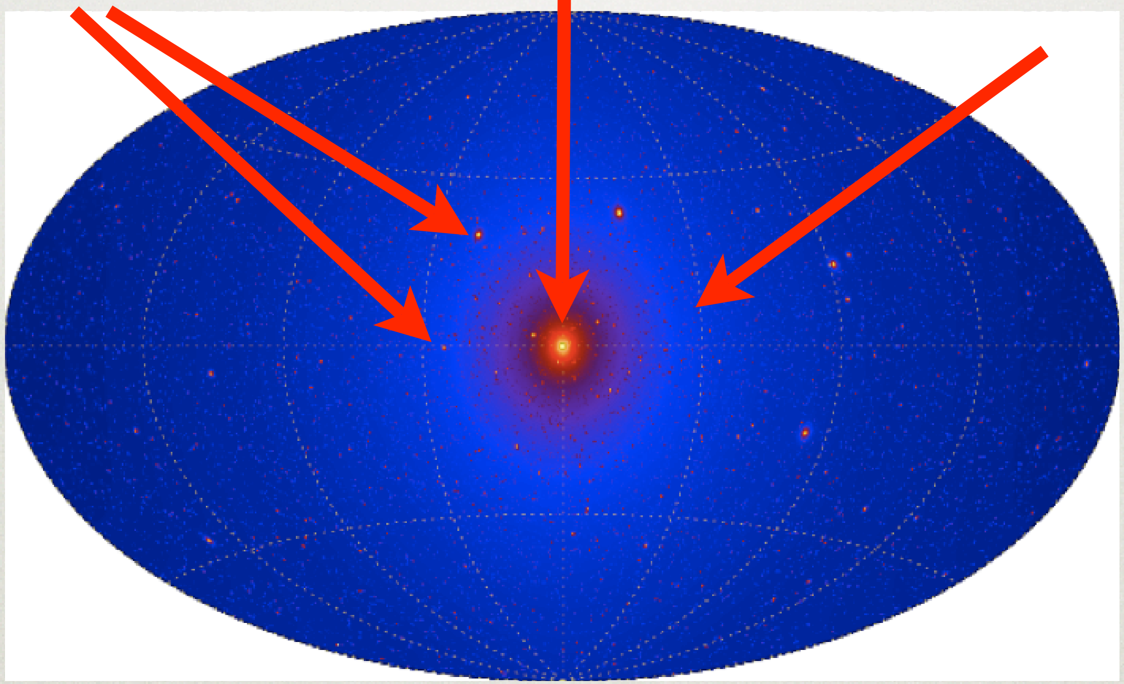
Search Strategies

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!

Anisotropies

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

Galaxy clusters:
Low background 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]

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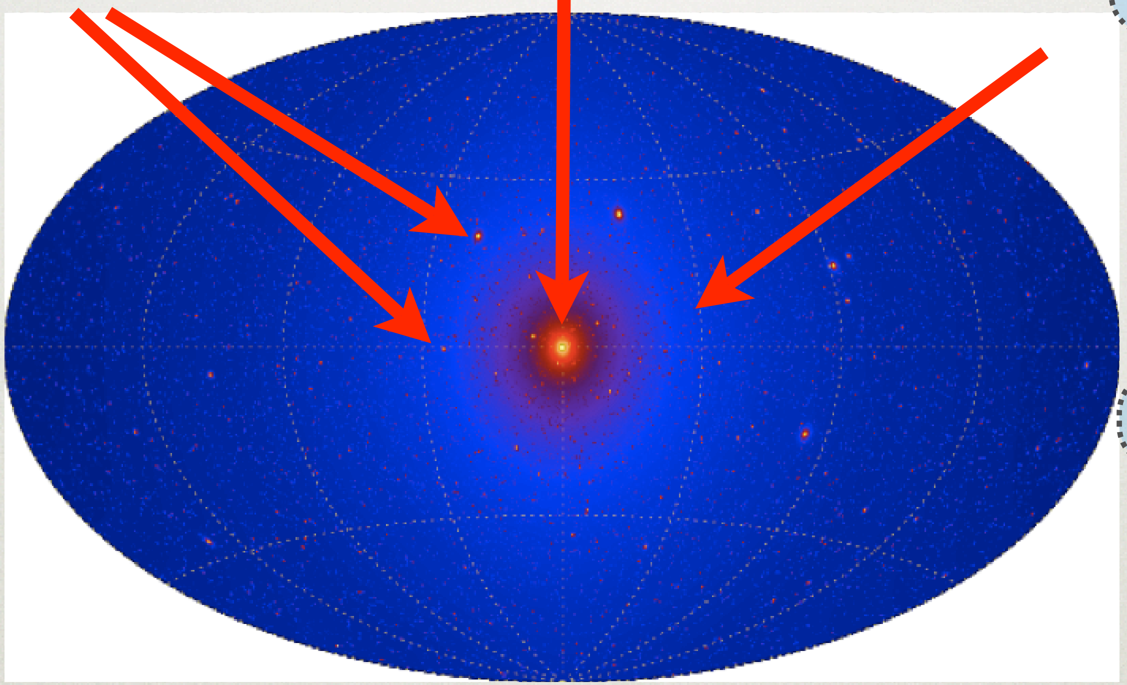

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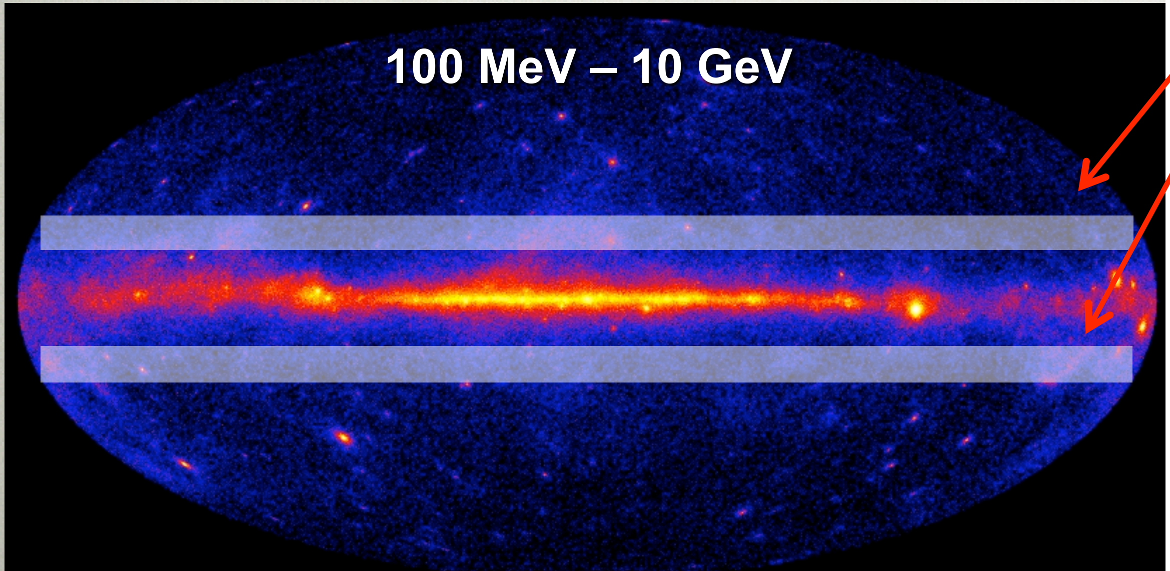
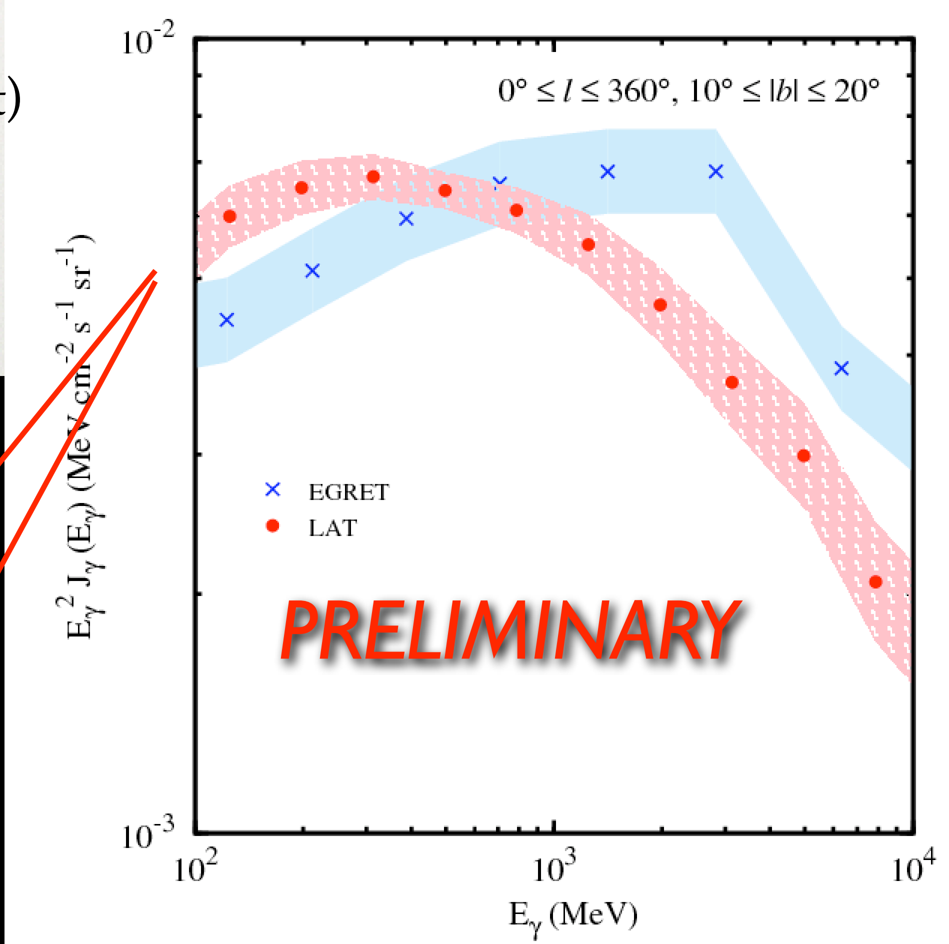
Galactic Diffuse Emission

- 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
- The data collected by the LAT from mid-August to end of December does not confirm the excess at intermediate latitudes
- Sources are not subtracted (minor component) LAT error is systematic dominated (~10%, preliminary)

➡ Strongly constrains DM interpretations

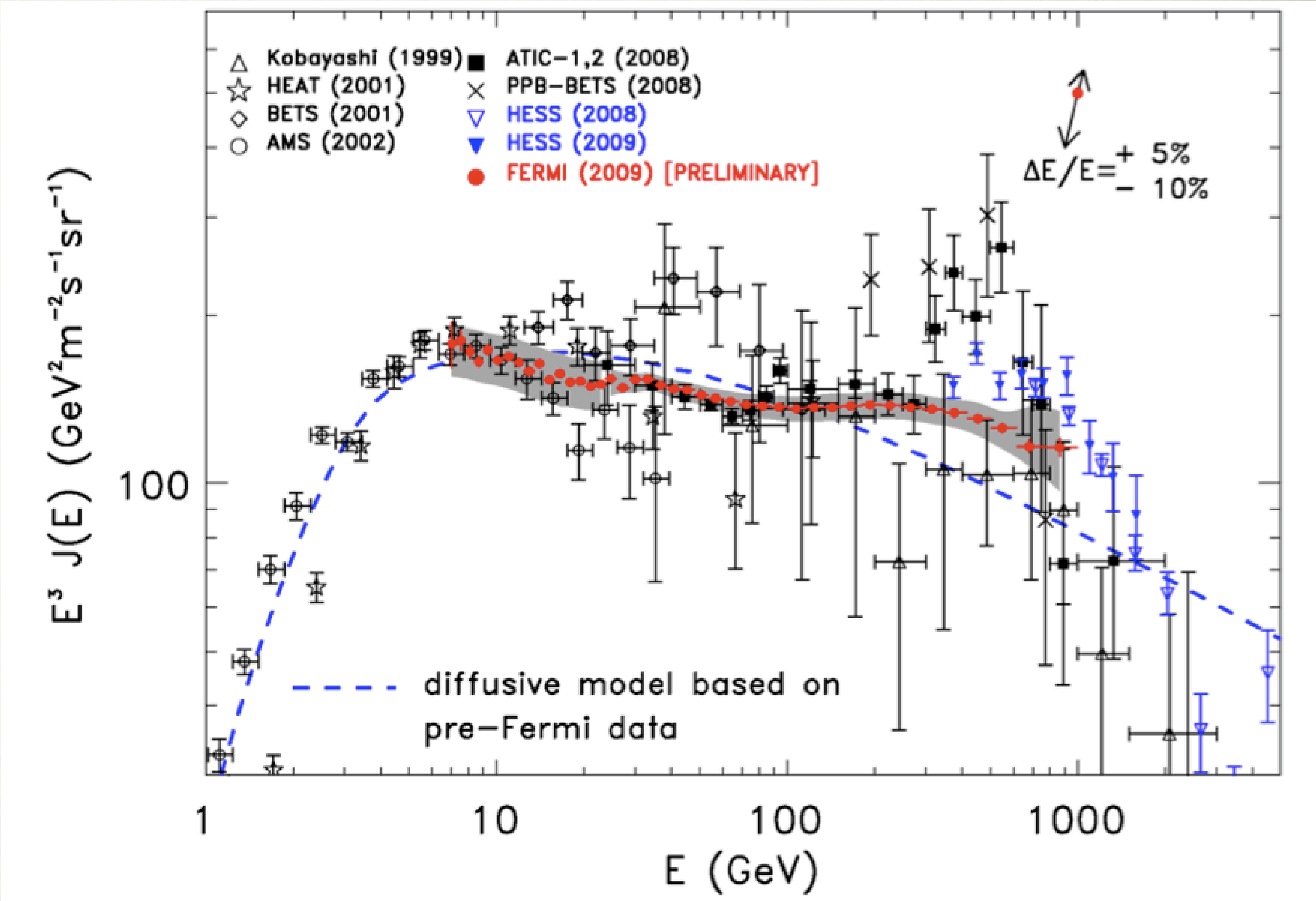




Fermi CRE Spectrum

New Fermi CRE spectrum, extends to lower energies

- High statistics: 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

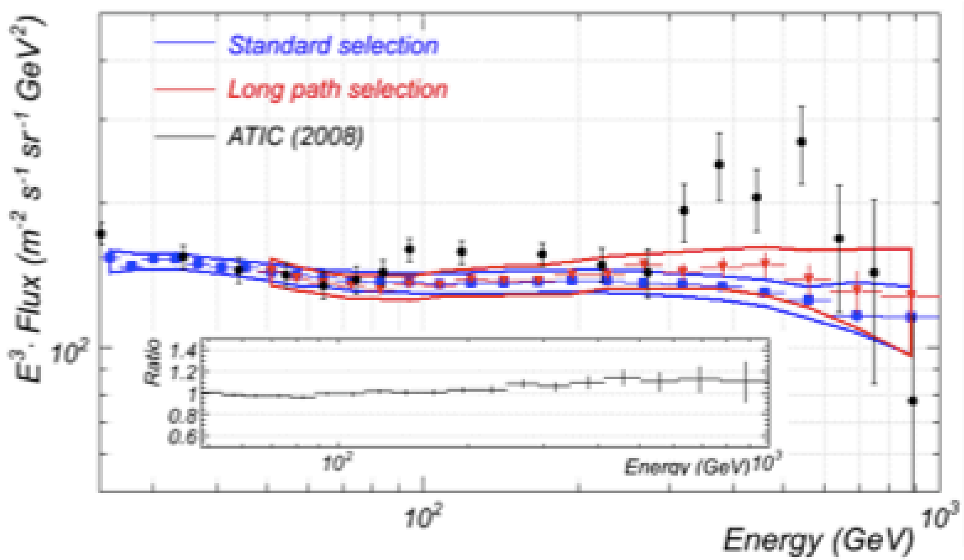


➡ Possible interpretations: revised diffusion model or extra component (astrophysical or DM)

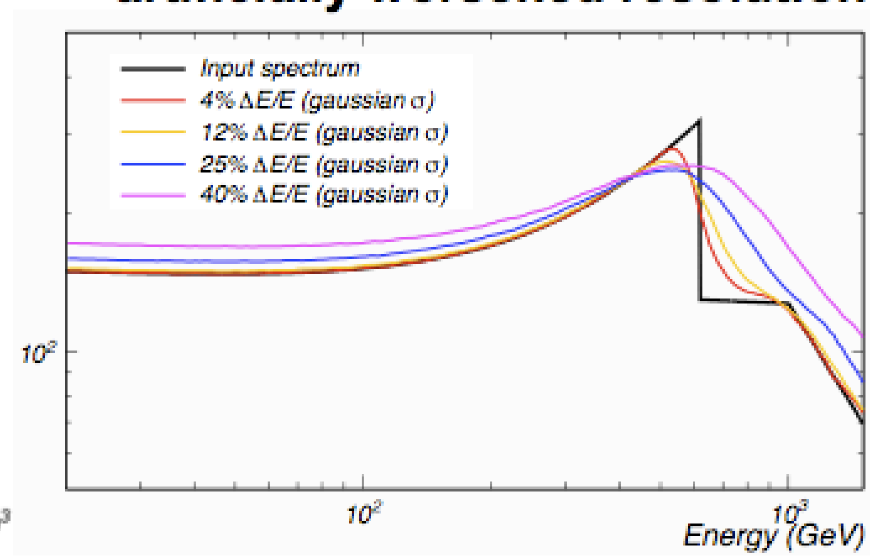
➡ DM contribution is not required, however cannot be ruled out

Comparison of standard and High-X0 spectra

- Consistent within their own systematics



- already demonstrated by simulation of LAT response to spectral features with artificially worsened resolution



➔ the LAT energy resolution is adequate to detect prominent spectral features

➔ the Fermi spectrum is NOT dependent on the energy resolution of the bulk of the events

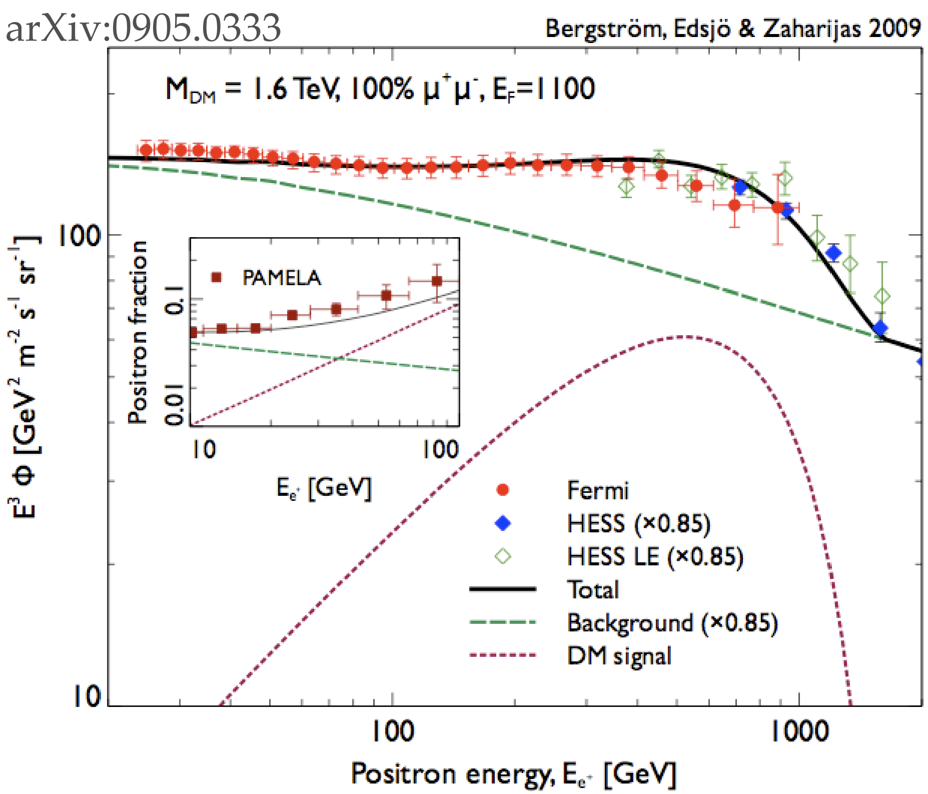
L. Latronico's talk, Fermi Symposium

Dark Matter Interpretation of CR Data

- DM models that predict annihilation or decay into leptonic final states are strongly favored (do not overproduce antiprotons that might violate other measurements)

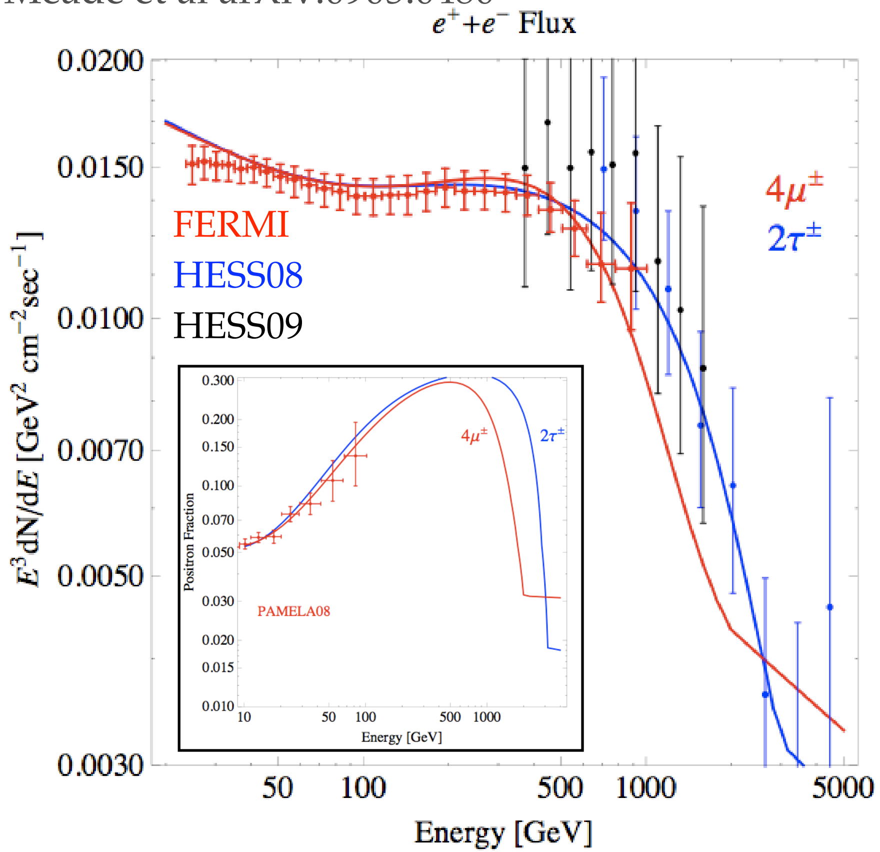
DM annihilation

arXiv:0905.0333



DM decay

Meade et al arXiv:0905.0480



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

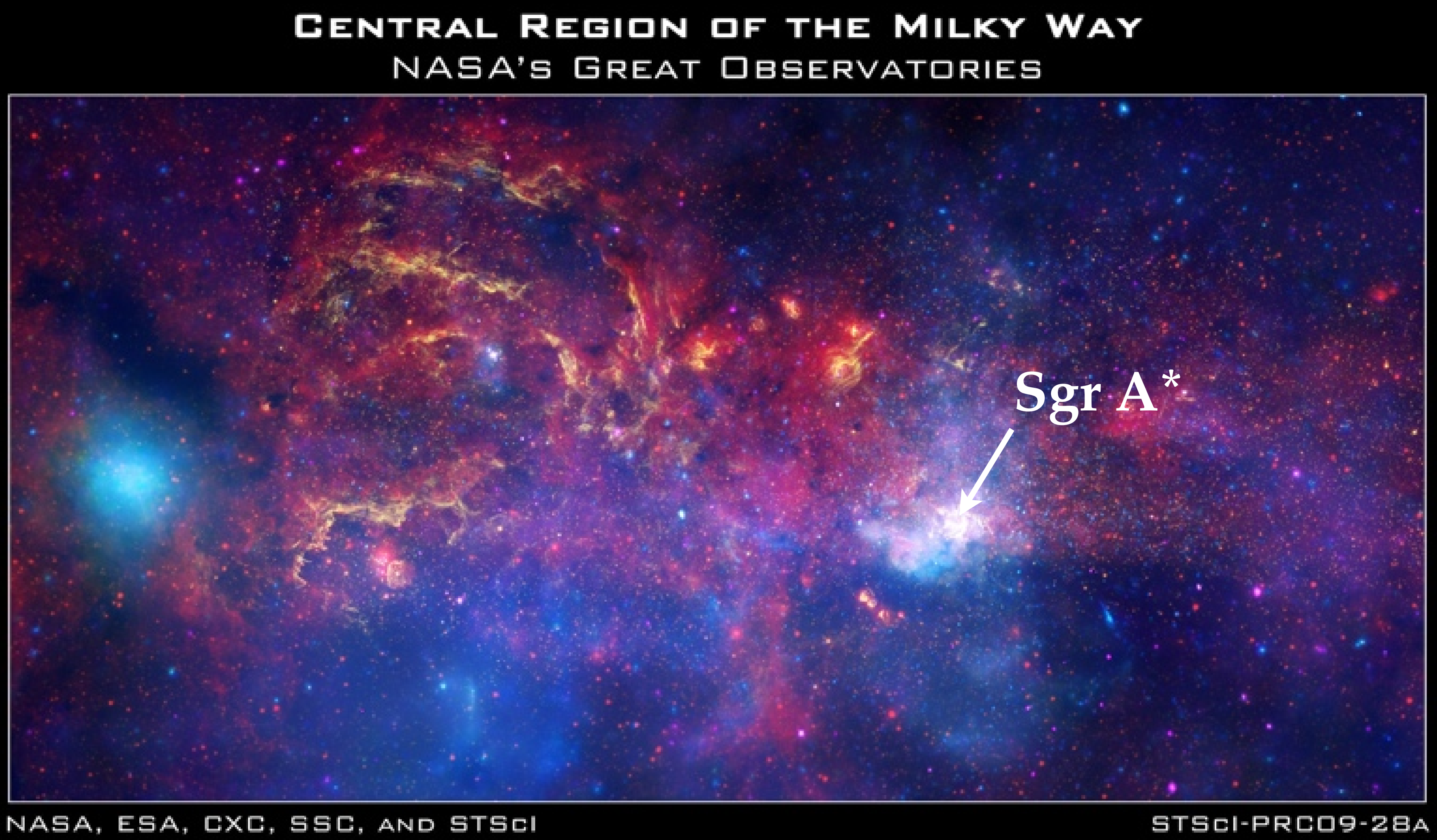


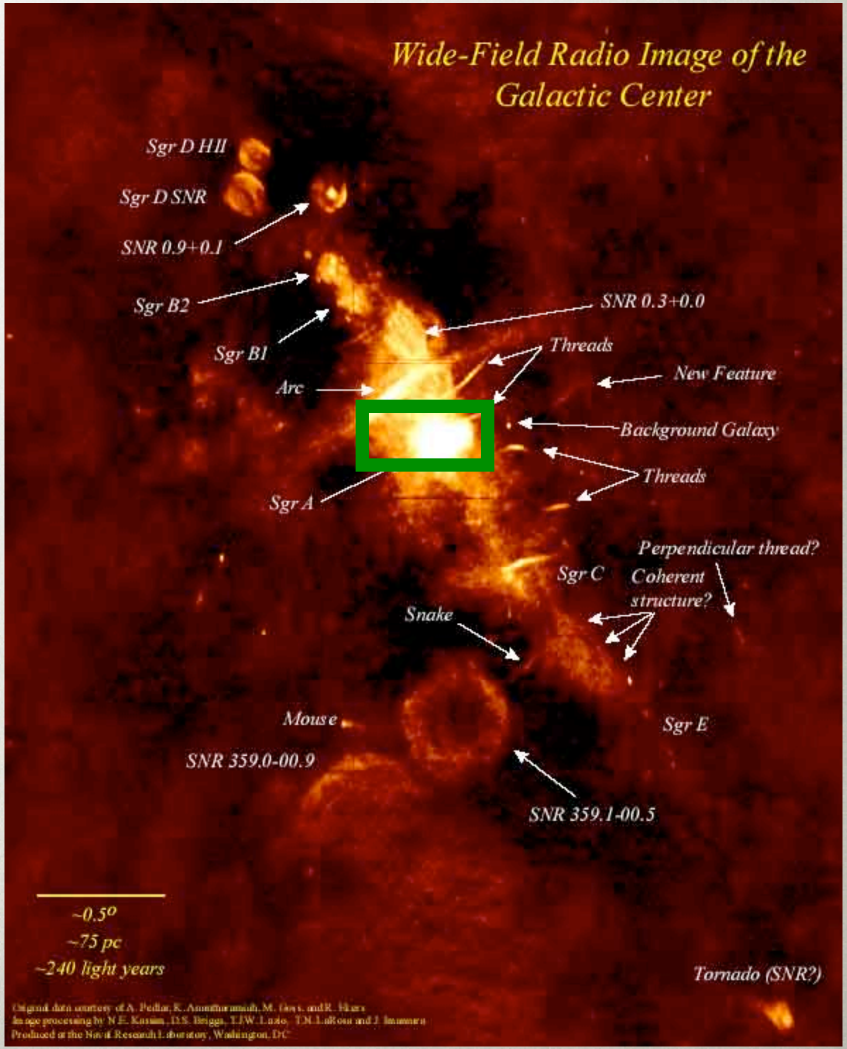
Image (width~0.5°) combines a near-infrared view from the Hubble Space Telescope (yellow), an infrared view from the Spitzer Space Telescope (red) and an X-ray view from the Chandra X-ray Observatory blue and violet) into one multi-wavelength picture.

Fermi Galactic Center Source

<u>Very crowded region of the sky!!</u>

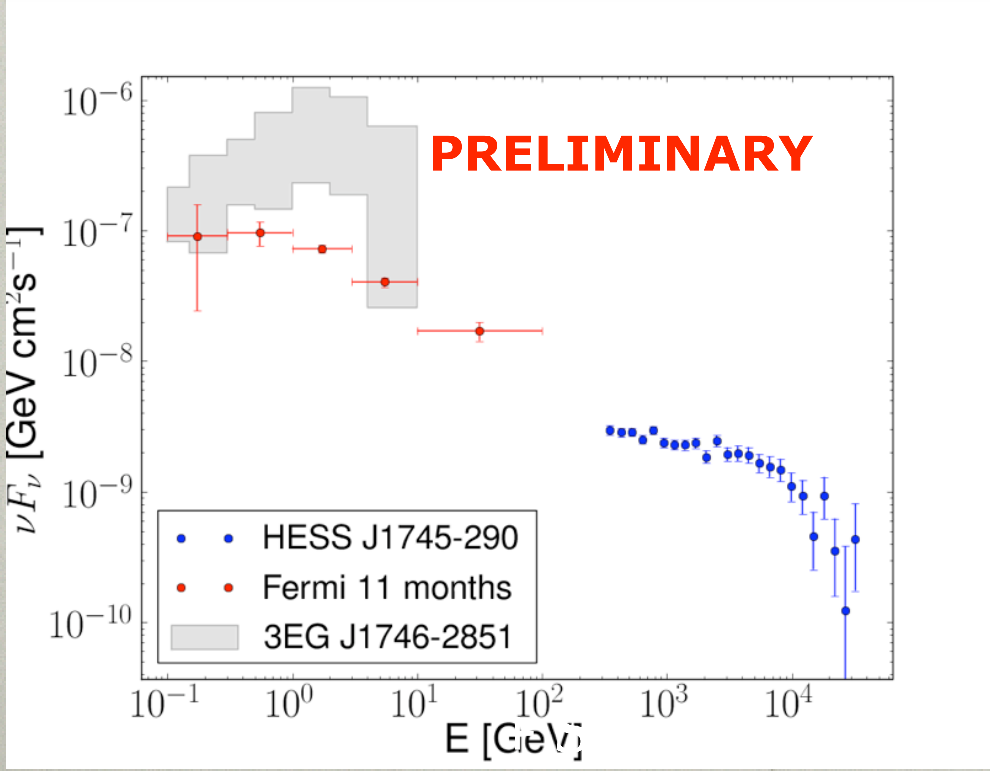
- 0FGL J1746.0-2900 is the closest source to the GC in Fermi Bright Source List (>10 σ detection, first 3 months of data).

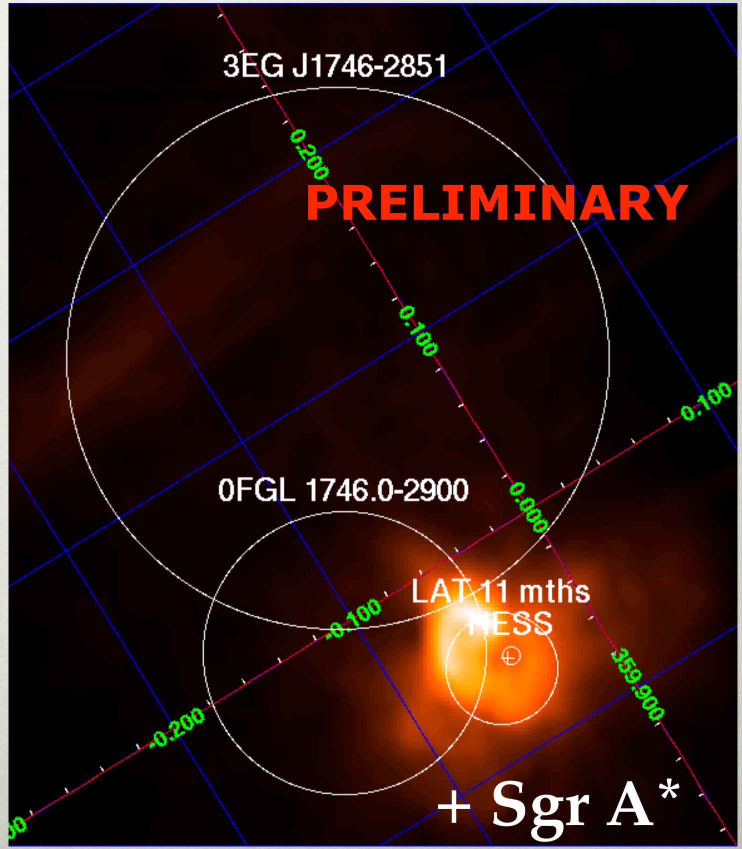
Source	l (°)	b (°)	θ_{95} (°)	Int.Flux(1<E<100GeV) $cm^{-2}s^{-1}$ 10^{-8}
0FGL J1732.8-3135	356.287	0.920	0.087	3.890±0.33
0FGL J1741.4-3046	357.959	-0.189	0.197	2.00±0.31
0FGL J1746.0-2900	359.988	-0.111	0.068	7.92±0.47



Fermi Galactic Center Source 11 Month Analysis

- Source location consistent with HESS source and Sgr A*. Sgr A East not excluded, but not favored.
- Marginal variability in BSL not confirmed with 11 month data
- 11 month flux significantly lower than EGRET analysis, harder spectrum
- Matching HESS Spectrum (single source hypothesis) requires either a high-energy break or a cutoff

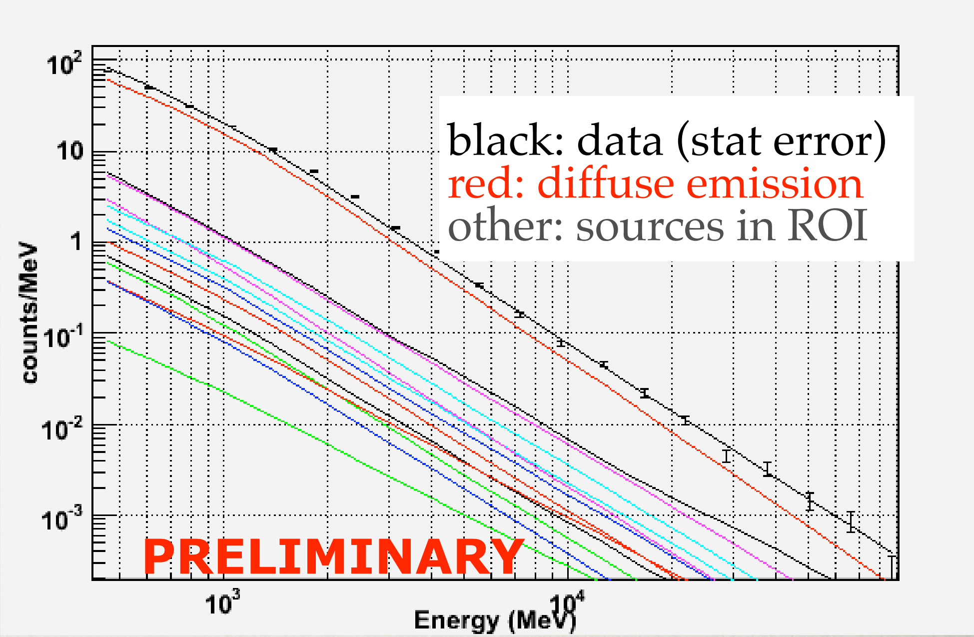


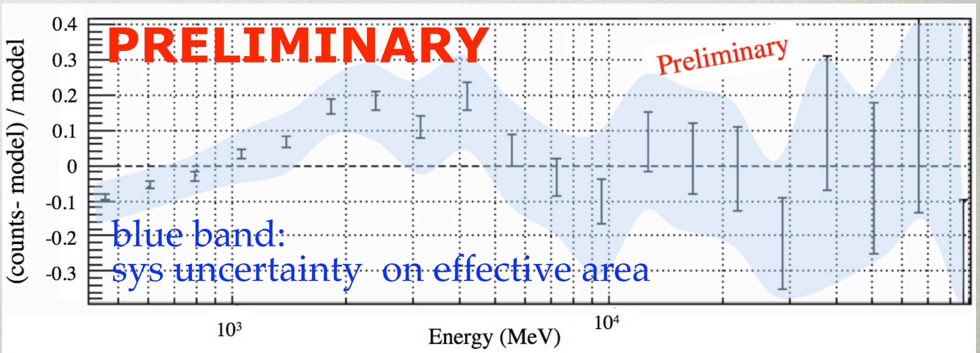


Search for DM in the GC

- Preliminary analysis of a 7° x7° region centered at the GC:
  - binned likelihood analysis of 11 months of data, >400 MeV, front-converting events
  - Model: galactic diffuse (GALPROP) and isotropic emission. Point sources in the region (from Fermi 1 year catalog, to be released)

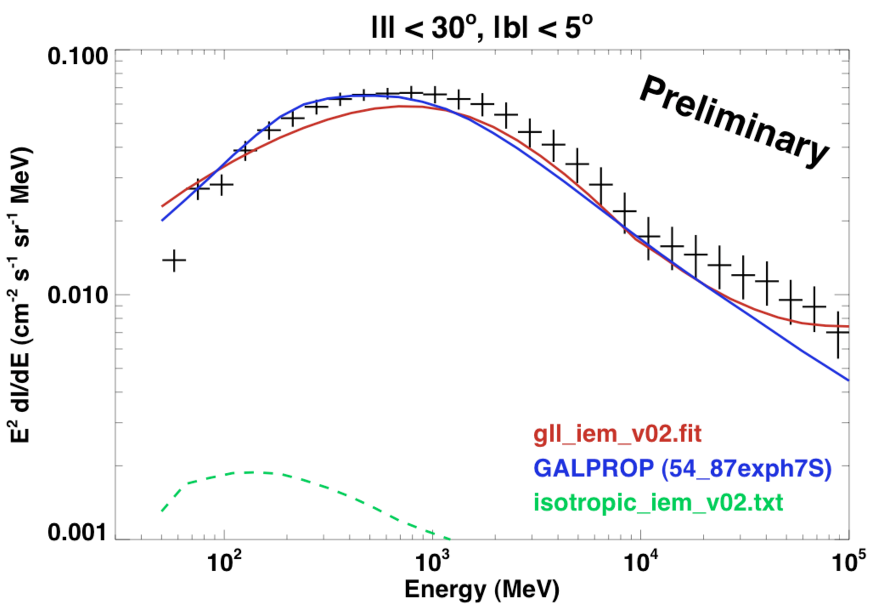
➡ Model generally reproduces data well within uncertainties. The model somewhat under-predicts the data in the few GeV range (spatial residuals under investigation)

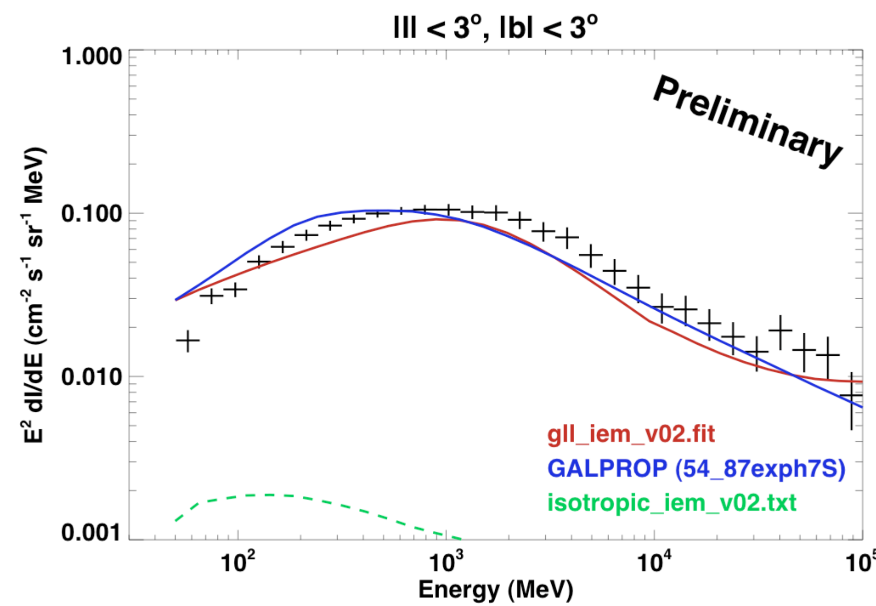




Spatial and Spectral Residuals

- The all-sky Galactic diffuse emission model released by the LAT team (red curve) somewhat under-predicts the sky intensity in the GC region



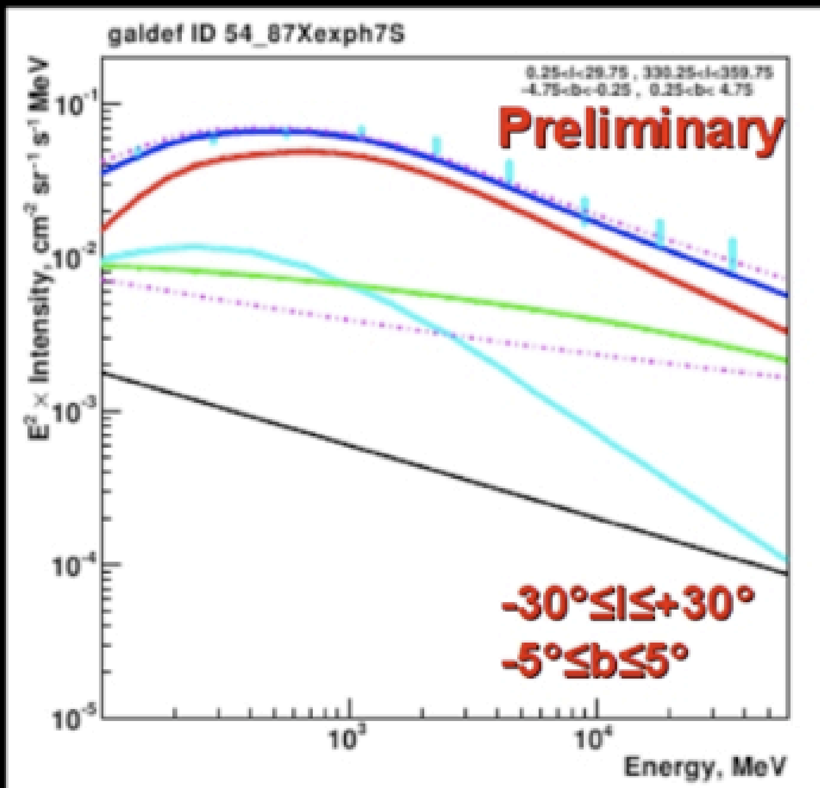


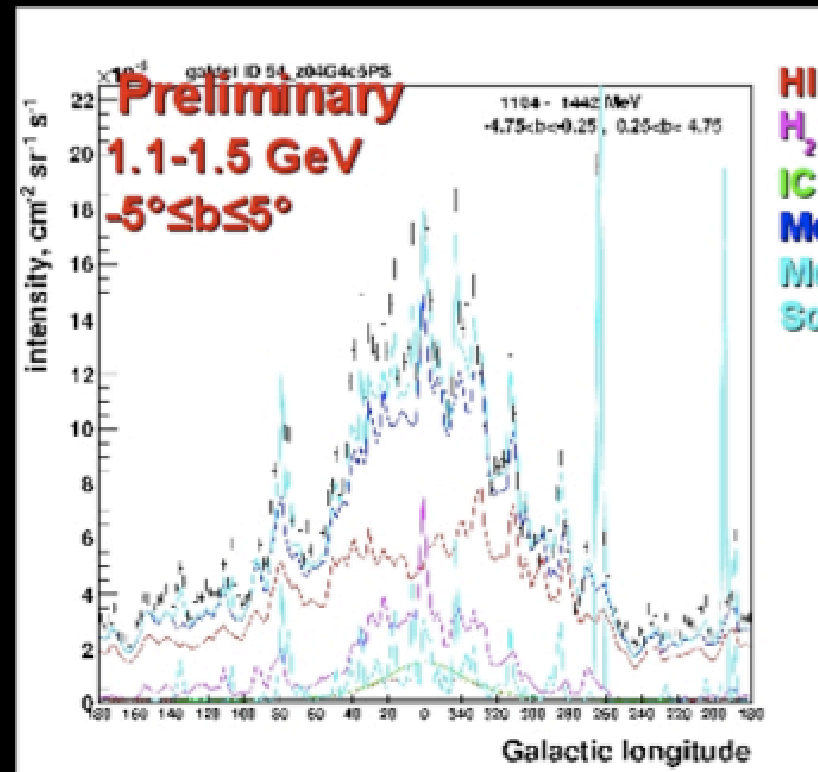
- Similar deviations are present in a GALPROP model calculation (blue) for the same region; N.B.: No point sources are included
- Deviations are greater than the systematic uncertainty but no dominant additional component needs to be invoked

S. Digel's talk, Fermi Symposium

Modelling the Inner Galaxy

Apply additional selection compared to the standard diffuse class to remove residual charged particle background, tune GALPROP





IC:
Total
OPT
IR
CMB

Brem
π^0-decay
Catalogue sources
Model total

Modified model = increased cosmic-ray intensities and corrections for residual gas → agreement with inner Galaxy is very good in spectrum and profile

T. Porter's talk, Fermi Symposium

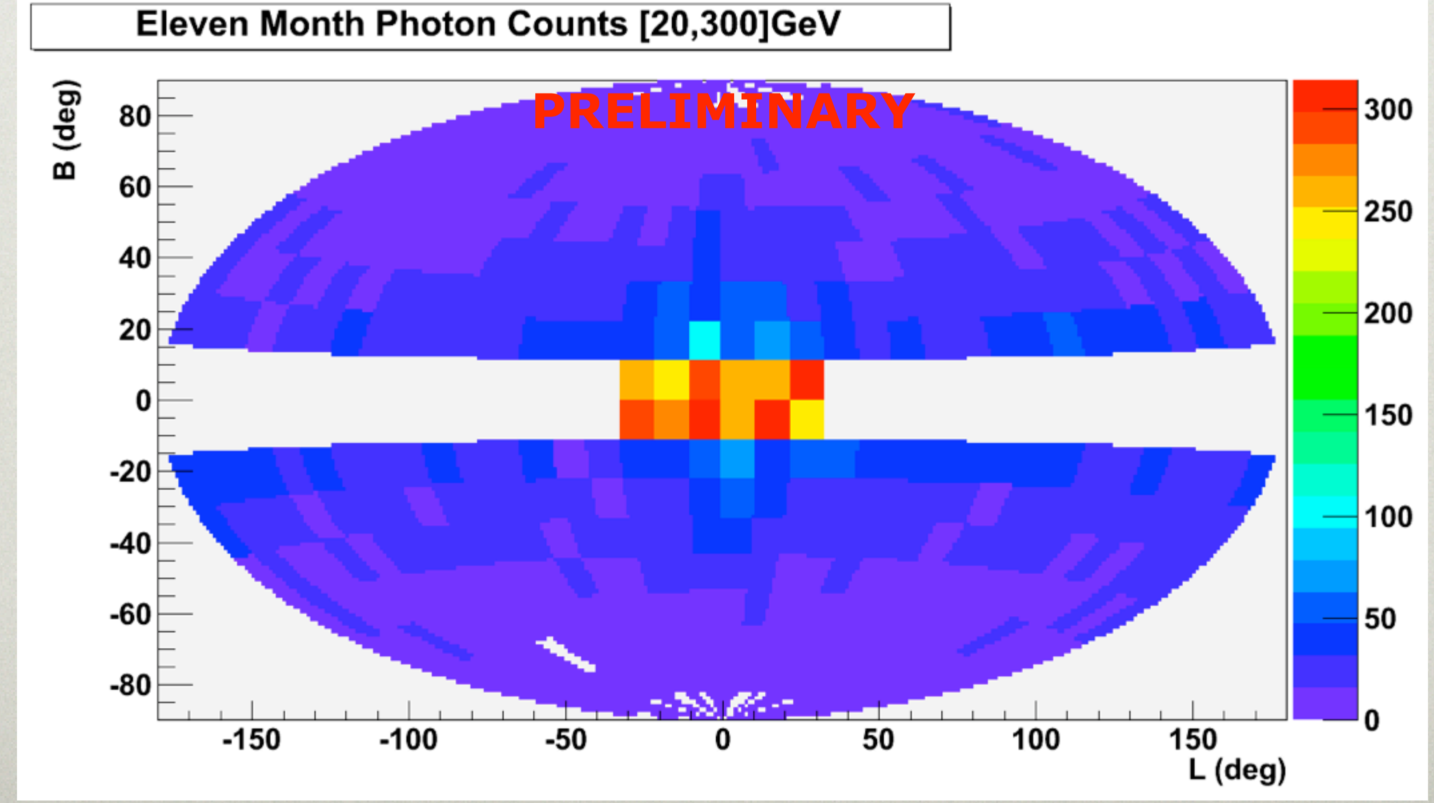
Search for DM in the GC

➡ 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 updated constraints on annihilation cross section

Search for Spectral Lines

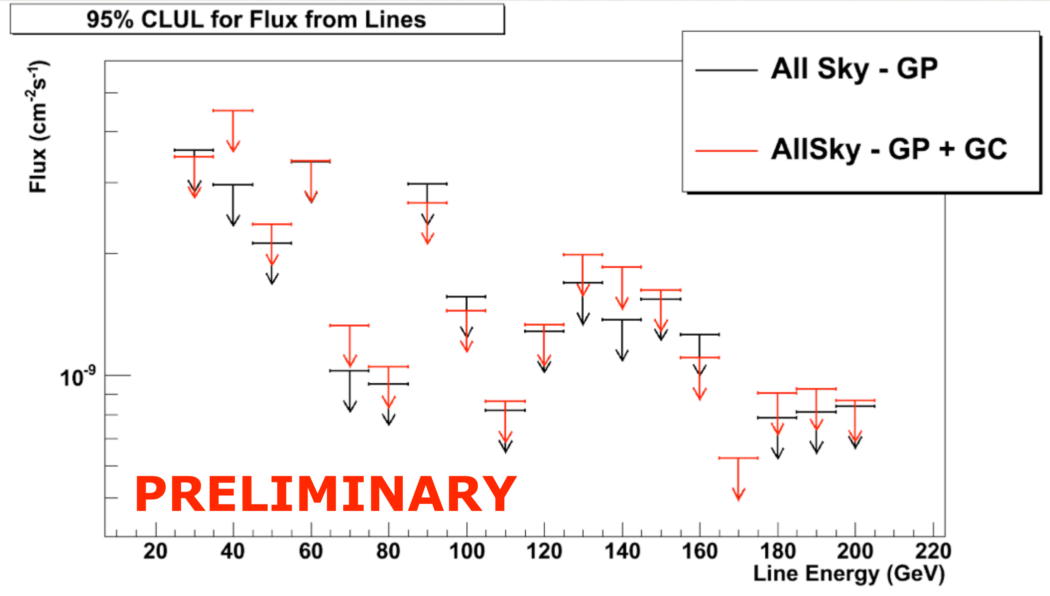
- Smoking gun signal of dark matter
- Search for lines in the first 11 months of Fermi data in the 30-200 GeV energy range
- Search region
  - |b|>10° and 30° around galactic center
- Remove point sources (for |b|>10°). The data selection includes additional cuts to remove residual charged particle contamination.



Search for Spectral Lines

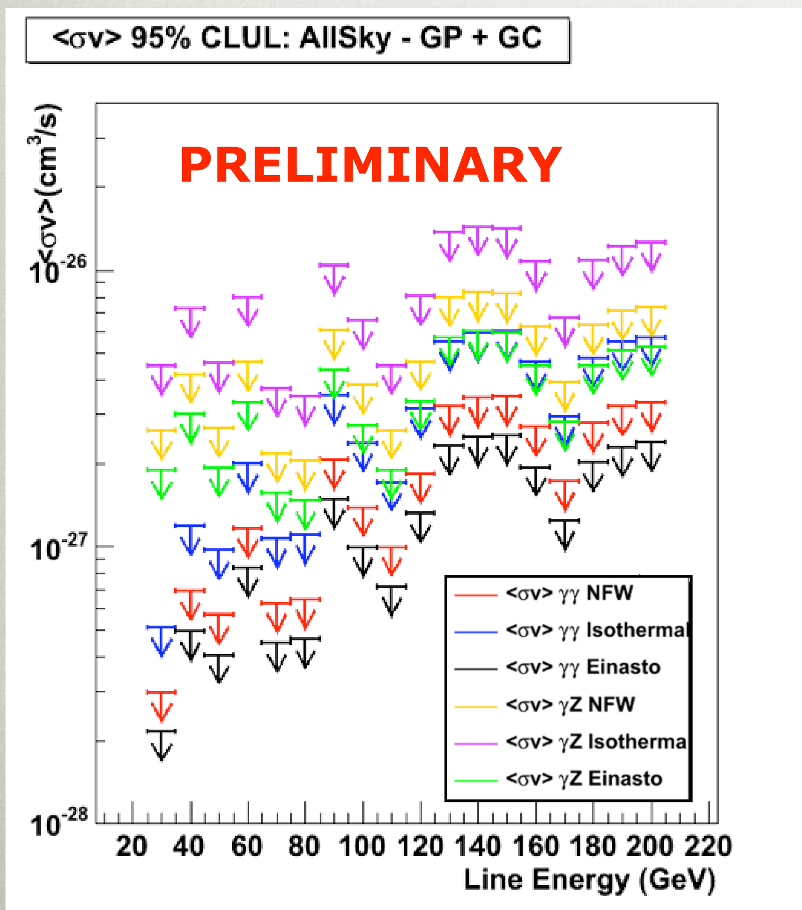
- Look for a line signal in energy intervals in the 30-200 GeV range.
- The signal is the LAT line response function. The background is modeled by a power law function and determined by the fit $\Rightarrow$ No astrophysical uncertainties.
- Optimal energy resolution and calibration very important for this analysis - resolution ~ 10% at 100 GeV

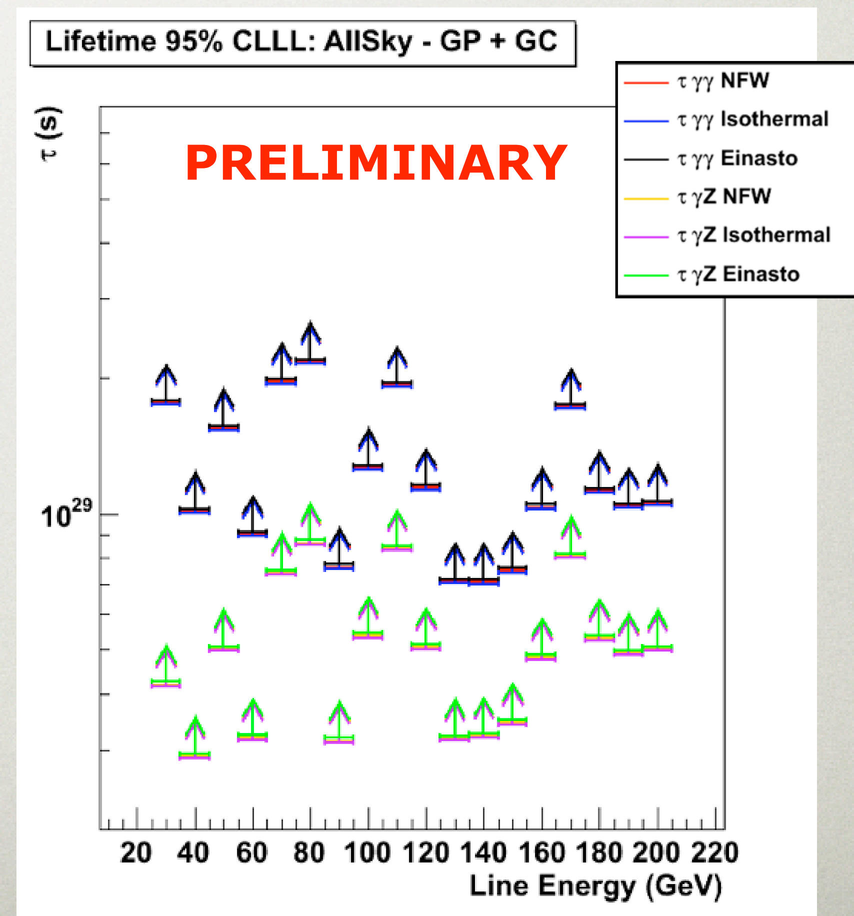
➡ No line detection, 95% CL flux upper limits are placed



Search for Spectral Lines

- For each energy (WIMP mass) the flux ULs are combined with the integral over the line of sight of the DM density² (or density) to extract UL (LL) on the annihilation cross section <σv> (or lifetime for decaying DM particles)

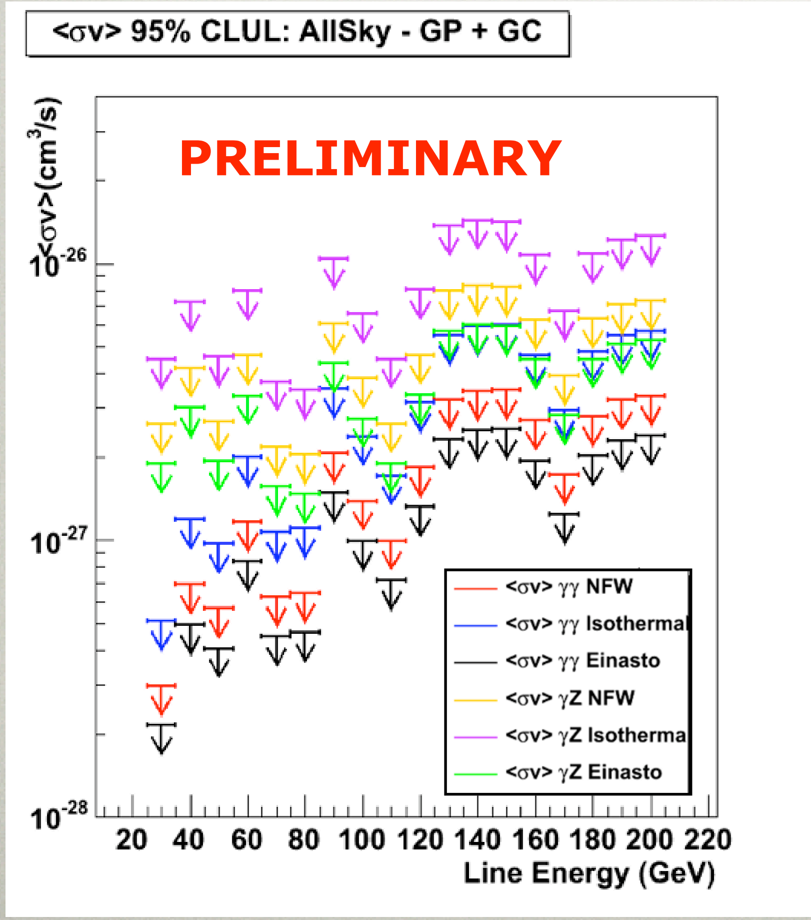


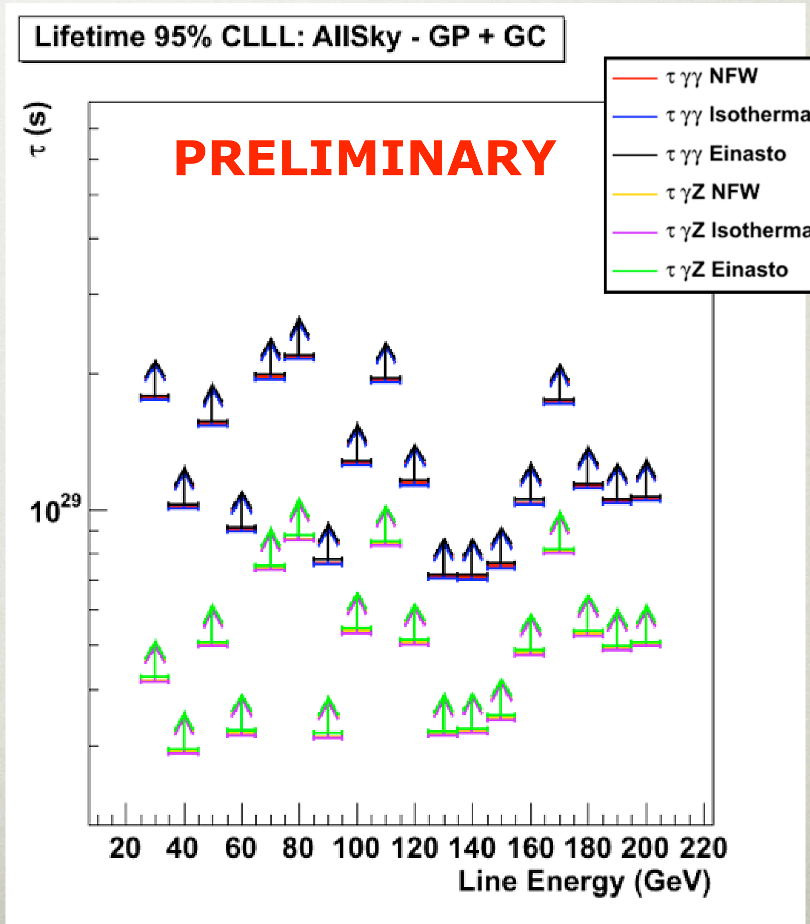


Search for Spectral Lines

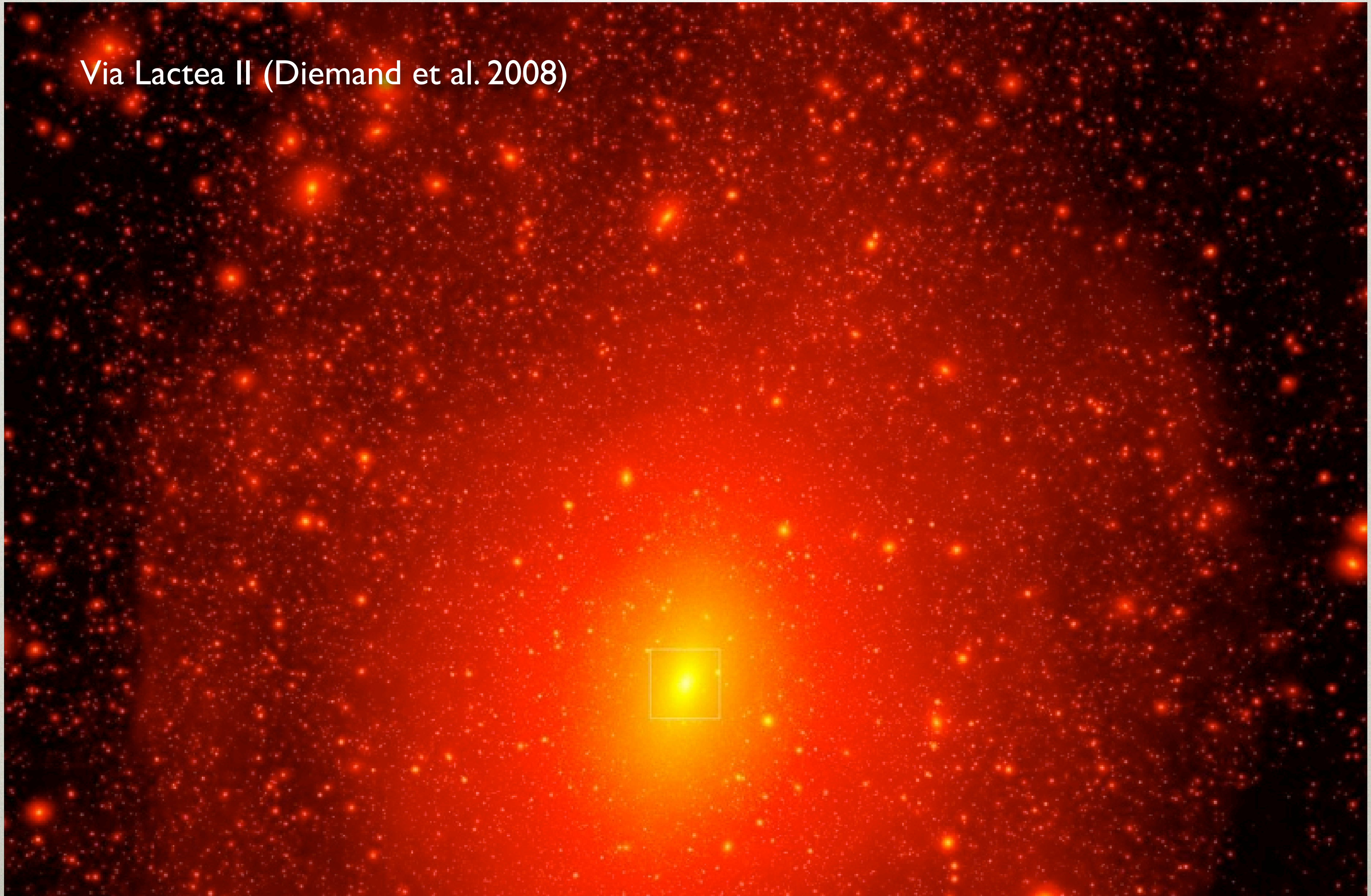
- ✓ Limits on <σv> are too weak (by O(1) or more) to constrain a typical thermal WIMP
- ✓ Some models predict large annihilation cross sections into lines:

Wino LSP (Kane 2009): γZ line has $\langle\sigma v\rangle \sim 1.4\times10^{-26}$ cm^3s^{-1} ⇒already disfavored by a factor of 2-5 depending on the halo profile





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, they are expected to appear as point sources
  - Select most promising candidates for observations

Search for DM Satellites

- **<u>Search criteria:</u>**
  - 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 FSR 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 100 MeV to 300 GeV energy range.
- Background: point sources+diffuse galactic and isotropic emission

Search for DM Satellites

4 sources above 5σ survive all criteria but the spectral requirement: their spectra do not favor the DM hypothesis.

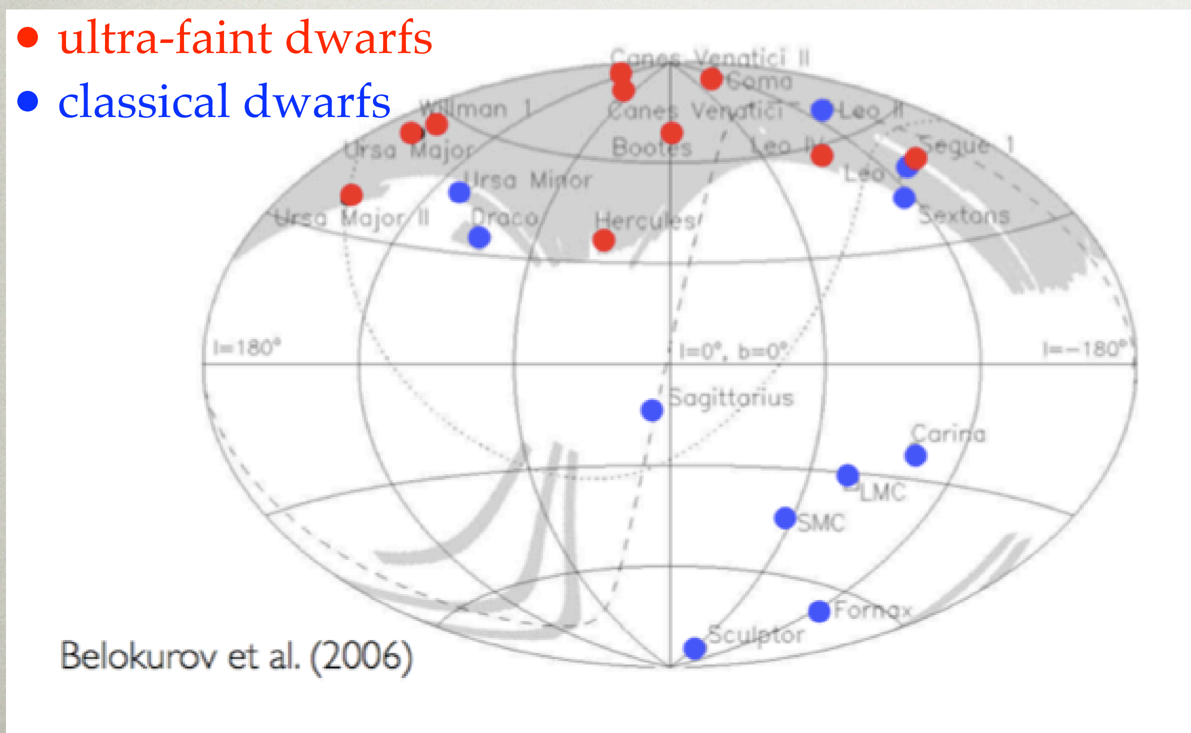
➡ No DM satellite candidates are found in 10 months of data

✓ Consistent with result of sensitivity study based on Via Lactea II predictions for the DM distribution for a 100 GeV WIMP annihilating into b-bbar, $\langle\sigma v\rangle = 3\times10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ (paper in preparation)

✓ Work is ongoing to evaluate the sensitivity for other models

Search for DM in dSph

- Select most promising dSph based on proximity, stellar kinematic data: less that 180 kpc from the Sun, more than 30º 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)



Distance: ~30 to 160 kpc

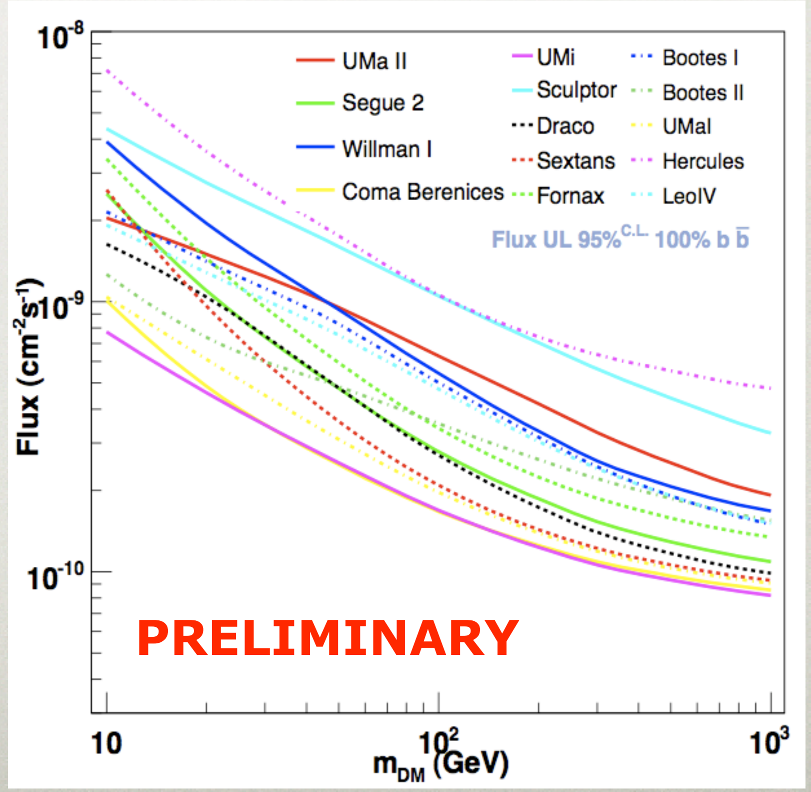
Ursa Major II
Segue 2
Willman 1
Coma Berenices
Bootes II
Bootes I
Ursa Minor
Sculptor
Draco
Sextans
Ursa Major I
Hercules
Fornax
Leo IV

Search for DM in dSph

- Energy ranges considered in the search: 100 MeV to 50 GeV
- 10^o region around location dSph.
- 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.

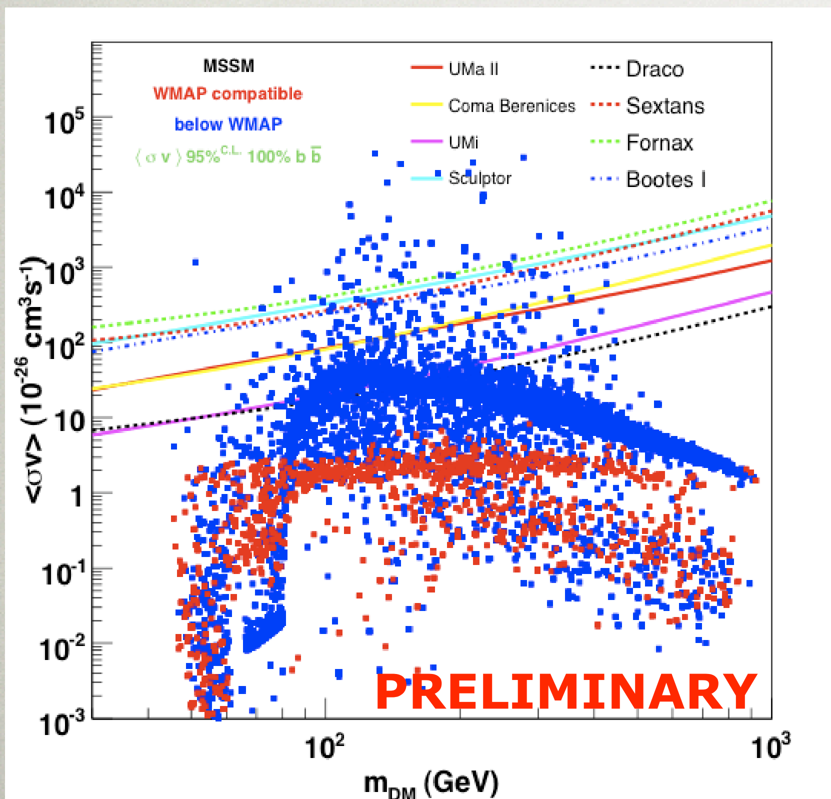
Upper limits assuming a b-bbar spectrum as a function of the WIMP mass

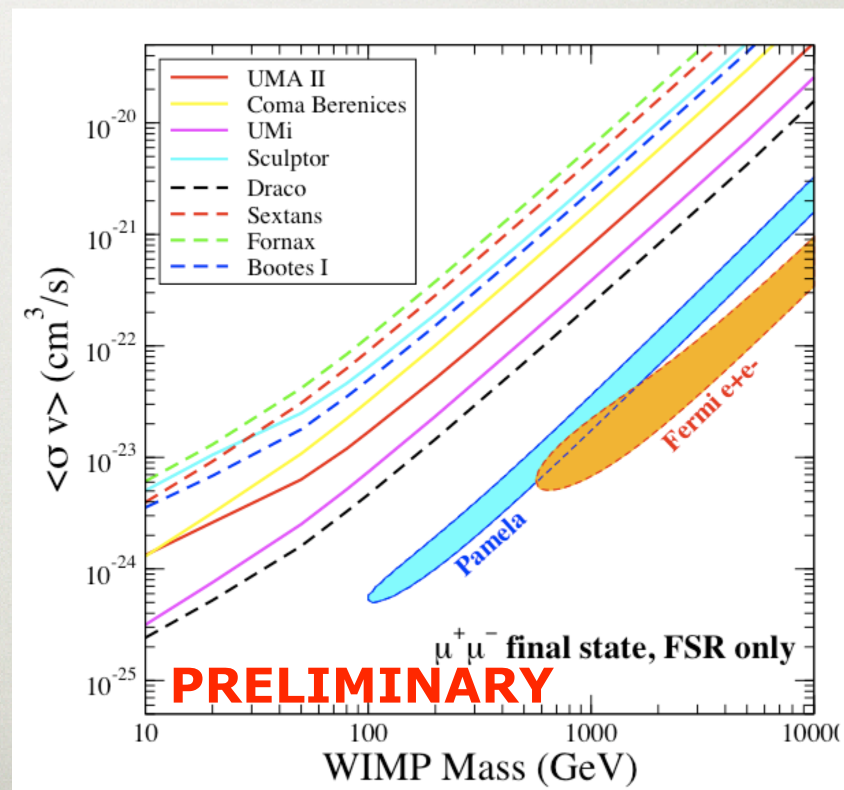


Search for DM in dSph

- 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 <σv> vs WIMP mass for specific DM models

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

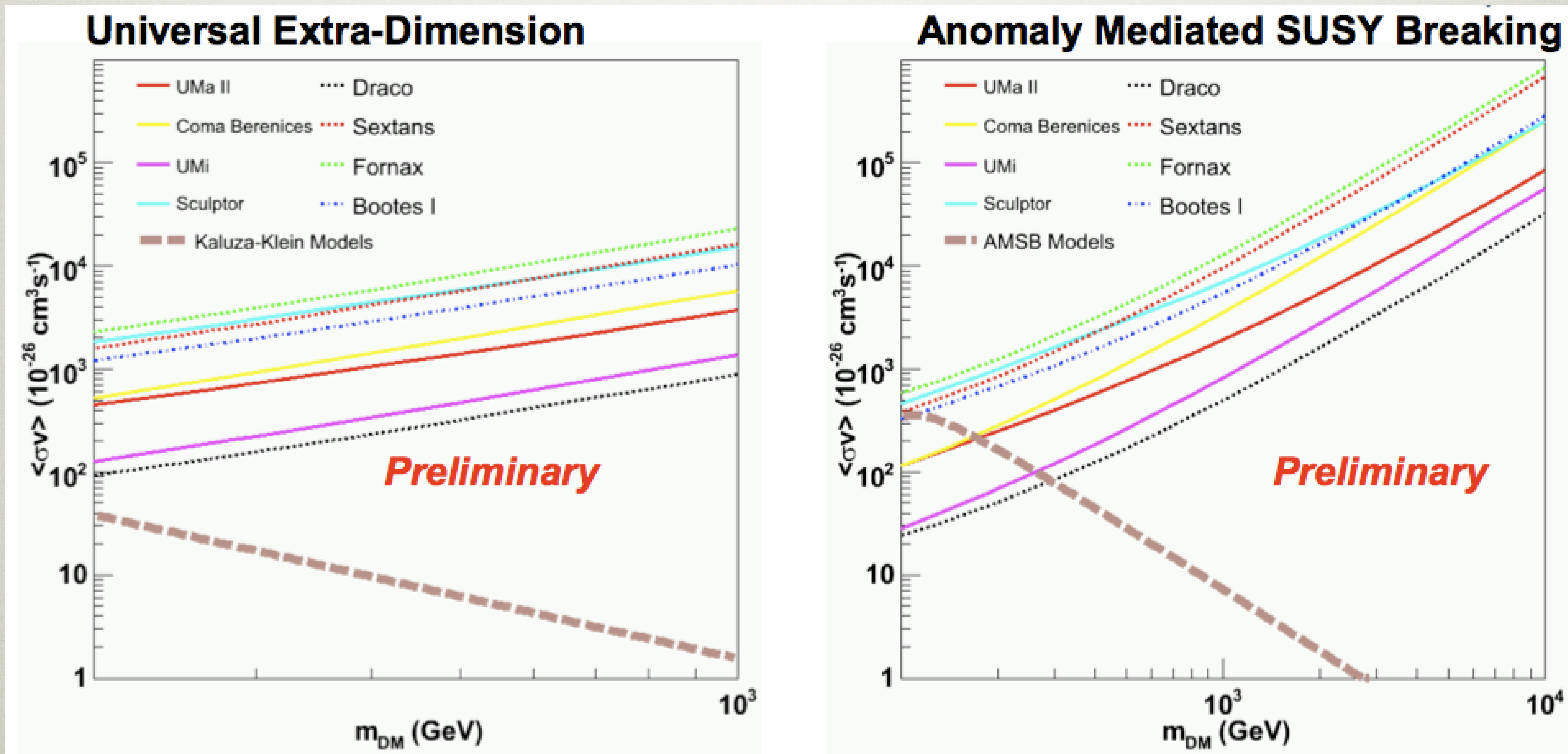




[*] stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)

Search for DM in dSph

- ✓ The data does not constrain UED models, however AMSB models with m_{WIMP}<300 GeV are already disfavored



Conclusions/Outlook

- No discovery....
- .... however promising constraints on the nature of DM have been placed
- 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
- Further improvements are anticipated for analysis that benefits from multi-wavelength observations (for example galactic center, dwarf spheroidal galaxies and DM satellites)