Recent results on dark matter search with the Fermi-LAT

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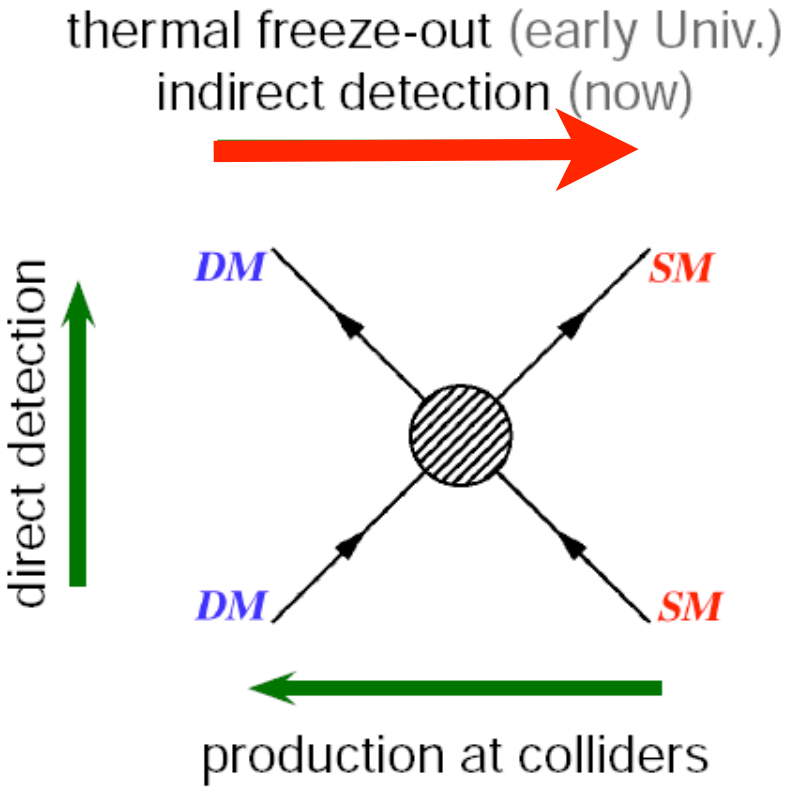
(ICTP & INFN Trieste)

On behalf of the Fermi LAT Collaboration

ICTP

INFN Istituto Nazionale di Fisica Nucleare

• How to **detect** WIMPs (other than gravitationally)



decay

γ,
ν,
$e^{\pm}$,
$p^{\pm}$
D^{-}

@ $\leq M_z$

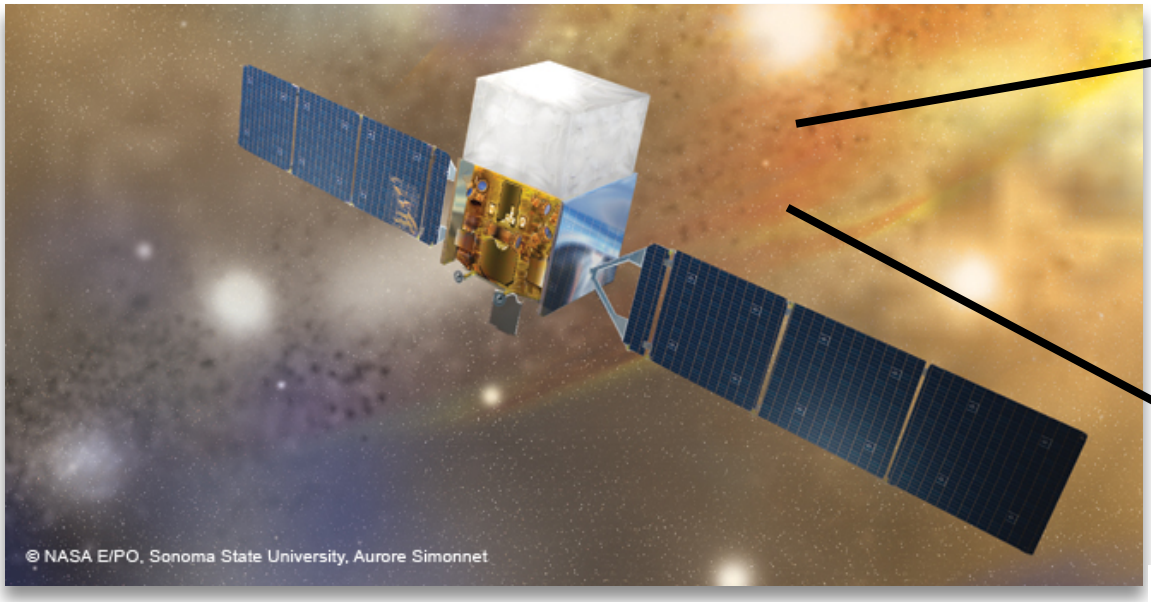
In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

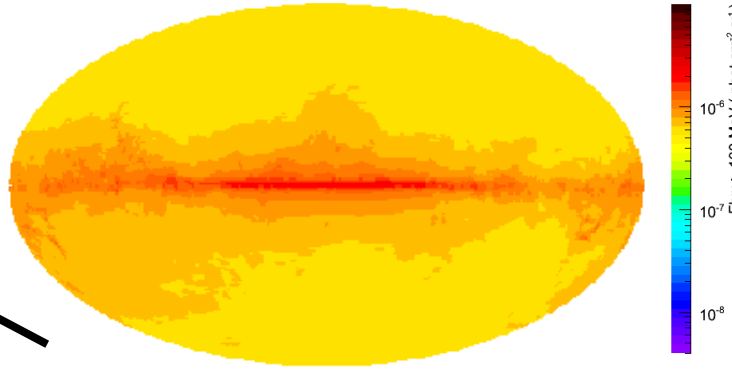
Today, DM expected to annihilate with the same $\langle \sigma v \rangle_{thermal}$*, in places where its density is enhanced!*

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

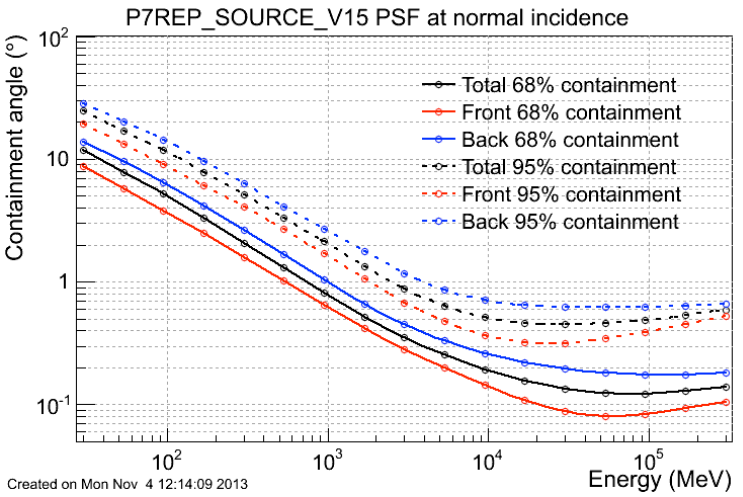
in astrophysical systems - *remotely*

Fermi LAT





energy range 20 MeV->300 GeV.



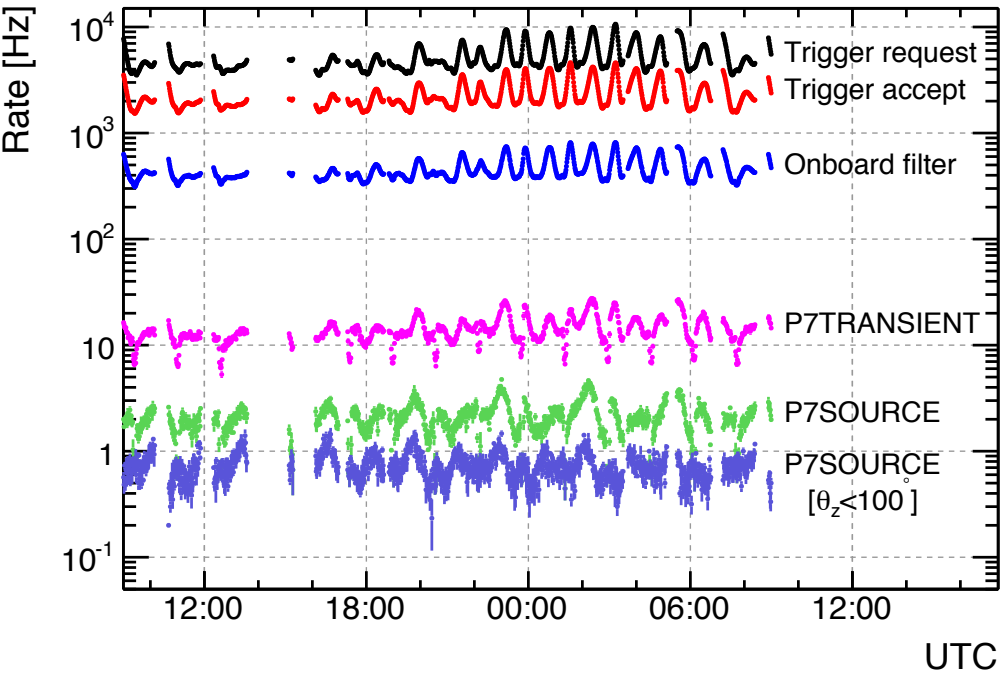
Launch June 11, 2008.

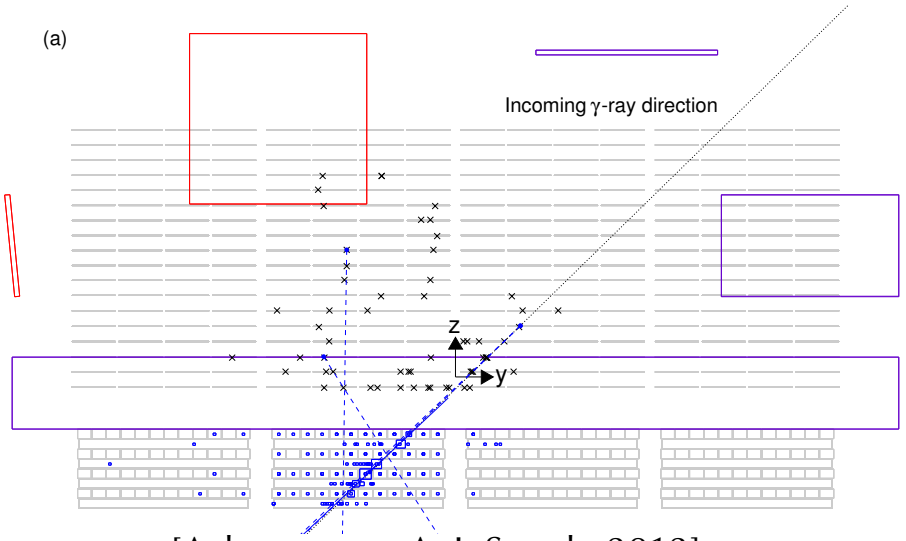
e+e- pair conversion instrument: **Si tracker**, **CsI calorimeter** & **anti-coincidence detector** (good gamma vs charged CR discrimination).

Data made **public** within 24 hours (http://fermi.gsfc.nasa.gov/ssc/).

more @L. Baldini's talk

DM search: challenges





[Ackermann+, ApJ. Suppl., 2012]

1) The flux of charged particles passing through the LAT is several thousand times larger than the γ-ray flux -> several stages of event selection are needed to purify the γ-ray content.

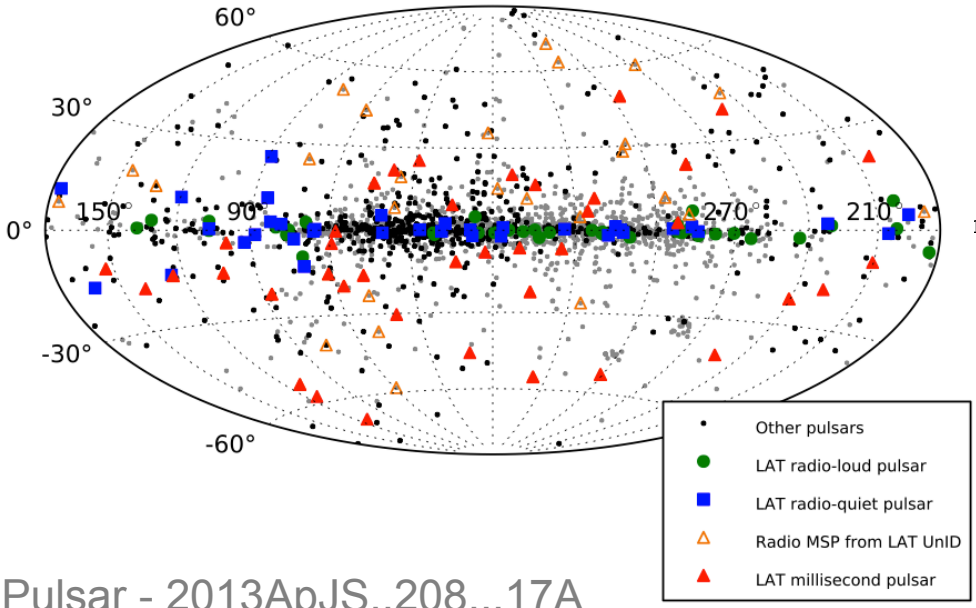
The event analysis requires knowledge of the LAT, the physics of particle interactions within its volumes, and of the particle backgrounds in the Fermi orbit.

DM search: challenges

2) Spiral Galaxies (as our own) are strong gamma-ray sources:
lots of interstellar gas which both leads to star production (CR sources) and makes target for CRs to produce gamma rays. -> **diffuse emission ~80% of the Fermi LAT photons.**

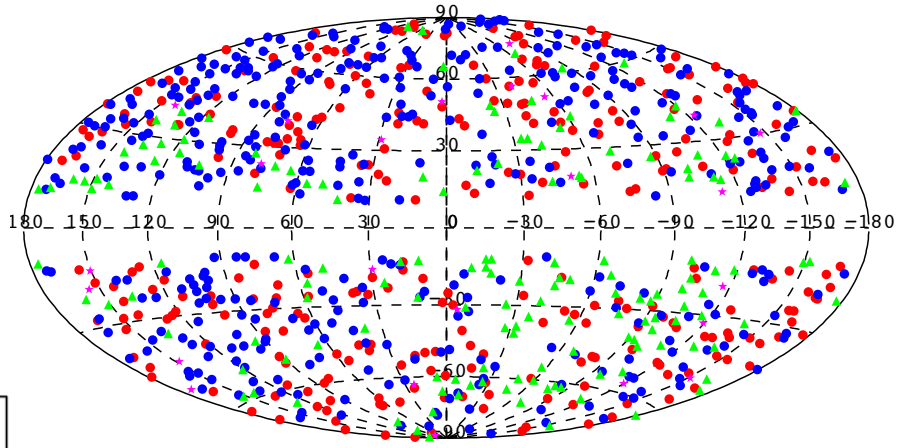
DM search: challenges

Galactic point sources



Pulsar - 2013ApJS..208...17A

Extragalactic point sources



Red: FSRQs, blue: BLLacs, green: AGN of unknown type.

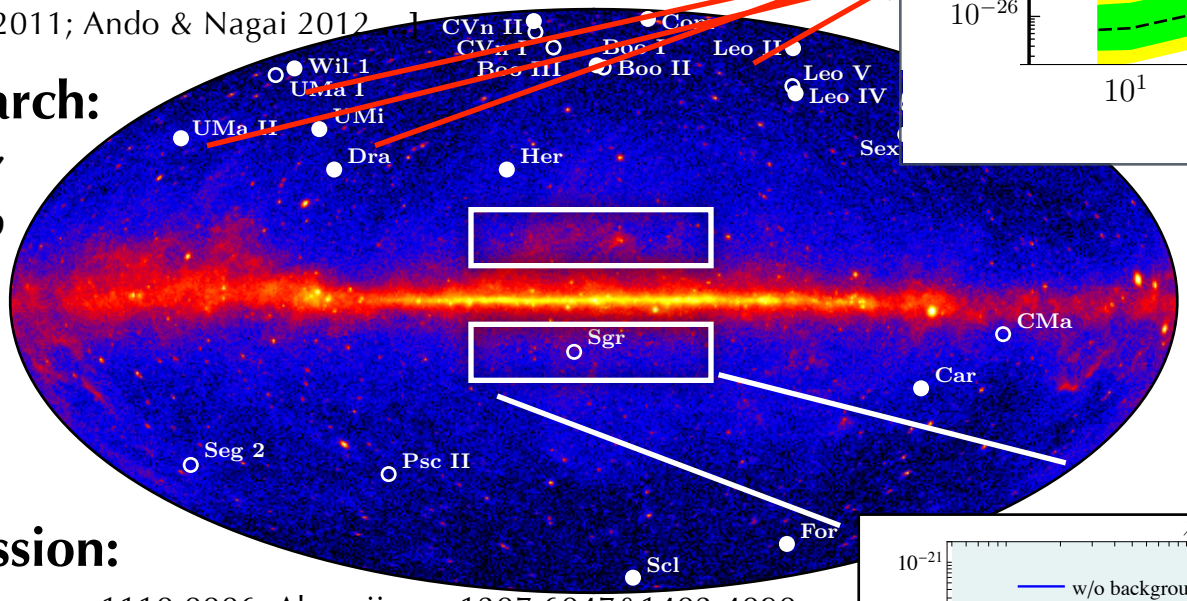
[Ackermann+, ApJ 2011]

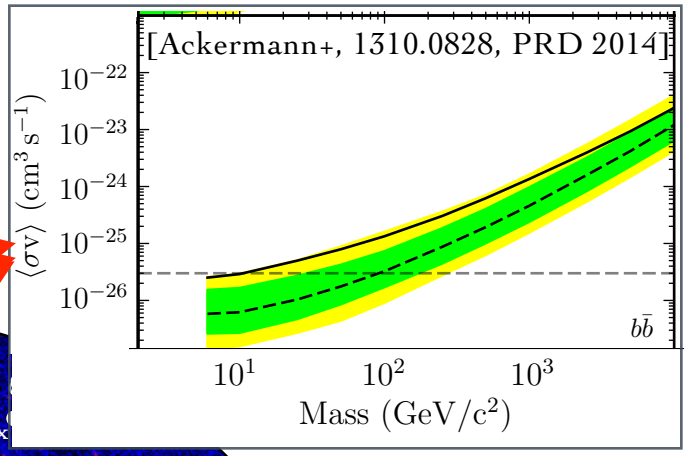
3) GeV gamma ray sky is a crowded place: ~2000 point sources in the 2FGL:
Galactic: ~100 pulsars
Extragalactic: ~800 AGNs
the point source contribution needs to be modeled and accounted for (both for resolved sources and unresolved counterparts).

Fermi LAT data used for a rich DM search program, on various scales!

- **Point sources:**
  - *dark satellites* **[Ackermann+,1201.2691;** Hooper+,1208.0828 Zechlin+, 1210.3852,...]
  - *dwarf spheroidal Galaxies* **[Ackermann+,1108.3546& 1310.0828;** Geringer-Sameth+, 1108.2914**, Mazziotta+,1203.6731, ...]**
  - *Galaxy clusters* [Han+1207.6749**, Ackermann+,1002.2239,** Sanchez-Conde et al. 2011; Ando & Nagai 2012 ...]

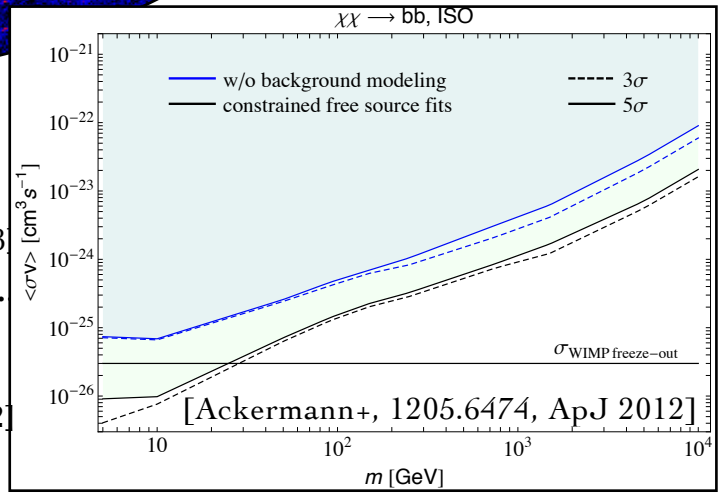
- **Spectral search:**
  [Weniger+, 1204.2797, **Ackermann+, 1001.4836&1205.2739 &1305.5597...]**



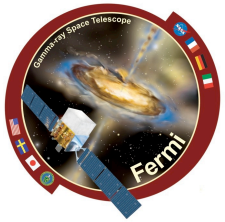


- **Diffuse emission:**
  - *Galactic Center* [Hooper+,1110.0006; Abazajian+, 1207.6047&1402.4090; Huang+, 1310.7609; Daylan+,1402.6703; **Gomez-Vargas+, 1308.3515**...]
  - *Low Galactic latitudes* **[Ackermann+,1205.6474, ...]**
  - **isotropic flux** **[Abdo+,1002.3603,** Bringmann+,1303.3284; Cholis+, 1312.0608
  - *angular anisotropies* **[Ackermann+,1202.2856; Gomez-Vargas+, 1303.2154, ..**

- **Electrons:**
  - *from DM annihilation in the Sun* [Schuster+, 0910.1839; **Ajello+,1107.4272]**
  - *local electron ANISOTROPY* **[Abdo+,1008.5119]**



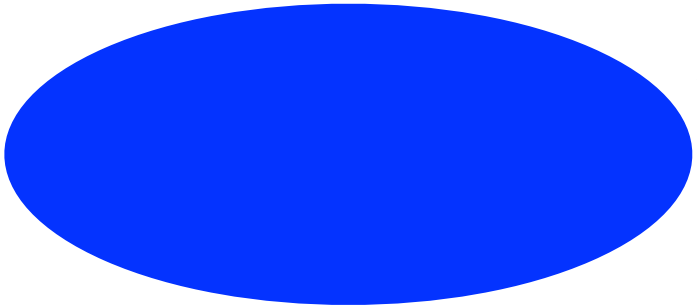
Outline



- Focus on the **newest** DM results from the Fermi team:
  - **Cosmological DM annihilations**:
  - **Low energy spectral line search** (A. Albert+,1406.3430, JCAP submitted)
  - new kid on the block: **Smith high-velocity cloud** (A. Drlica-Wagner+, 1405.1030, APJ accepted)

- Sneak-peak:
  - near future results: **DM annihilation in Galaxy Clusters** →**S. Zimmer's talk**
  - **Pass8**: →**L. Baldini's talk**

Isotropic emission: sources



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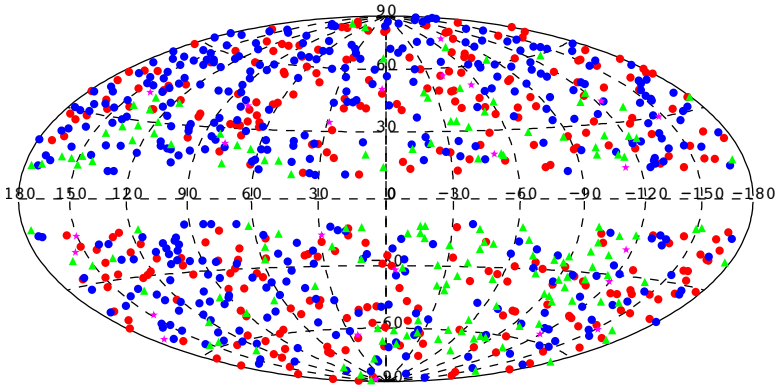
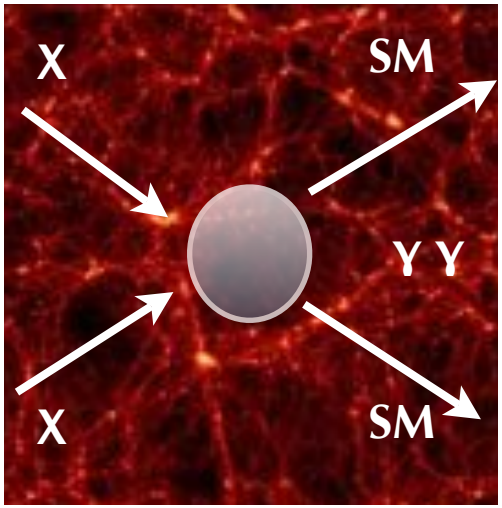


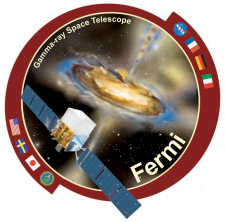
+ (...) +

- **Expect contribution from: *unresolved*** Blazars, Radio Galaxies, Star Forming Galaxies

- **... and WIMP annihilations (from all DM halos at all redshifts), if contributing to the gamma ray sky.**



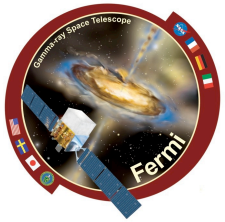
Cosmological DM annihilation



- **Challenges:**
  - **Estimate of the 'guaranteed' (astrophysical) contributions to the isotropic signal**
  - **Strength of the DM gamma ray signal: depends on DM *clustering* properties at *various (small!) scales***
  - **DM signal WITHIN our Galaxy: could it bias the measurement of the isotropic spectral flux?**

- **Two complementary approaches:**
  - **Isotropic spectral flux**: single power-law ->harder to interpret; BUT higher statistics-extended energy range
  - **angular anisotropy of high latitude emission**: harder measurement&smaller statistics, BUT better handle on the Galactic foregrounds (cut large scales), additional handle from cross correlations with galaxy surveys

Cosmological DM annihilation



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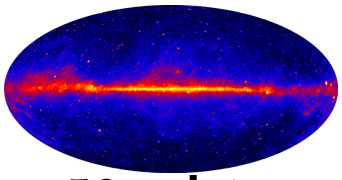
Isotropic flux: measurement

- **extended energy range:** 200 MeV - 100 GeV -> **100 MeV - 820 GeV.**
  - two custom event selections optimized for LOW (<13 GeV) and HIGH (>13 GeV) energies
  - detailed modeling of the Galactic Diffuse emission
  - Extensive detector-level simulations used for initial estimate of residual cosmic-ray background


50m data

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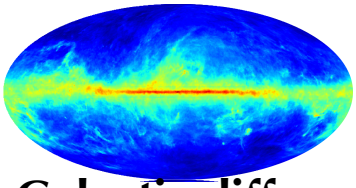
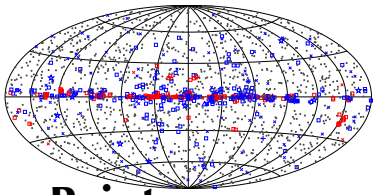
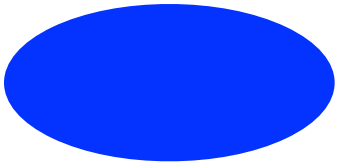

Galactic diffuse

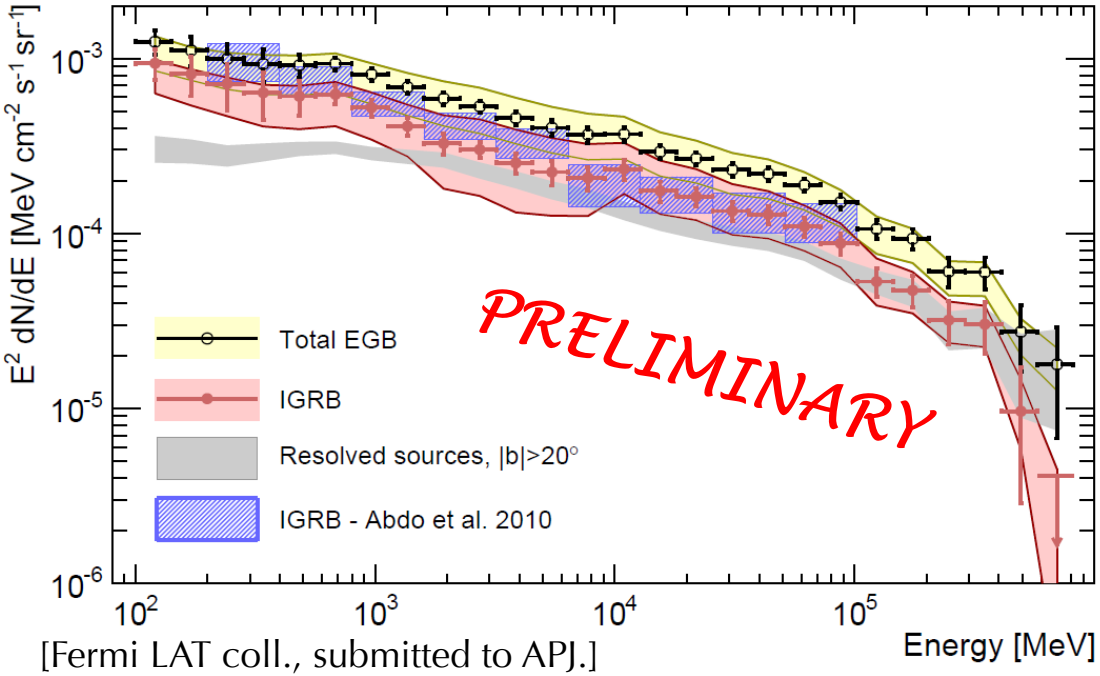
+


Point sources

+


Isotropic gamma rays+ residual charged CRs. IGRB: CR subtracted.

more @ M. Ackermann talk



[Fermi LAT coll., submitted to APJ.]

Isotropic emission: DM signal

- **Strength of the extragalactic signal:**

$$\frac{d\phi}{dE_0} = \frac{c\,\langle\sigma v\rangle(\Omega_{\rm DM}\rho_c)^2}{8\pi\, m_{DM}^2} \int dz \frac{e^{-\tau(E_0,z)}(1+z)^3\zeta(z)}{H(z)} \frac{dN}{dE}\Big|_{E=E_0(1+z)}$$

The 'flux multiplier' parametrizes DM clustering at all scales and is the main source of uncertainty. The smallest predicted halo scale ~$10^{-6}M_{sol}$ << what was traditionally measured in simulations or from observations.

Simulations do not resolve the whole hierarchy of structure formation...

an extrapolation of more than 10 orders of magnitude!

$10^{-9}, 10^{-6}\,h^{-1}\,M_\odot$?

Isotropic emission: DM signal

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Uncertainty in the signal translates to the uncertainty on constraints of DM cross section.

Simulations do not resolve the whole hierarchy of structure formation...

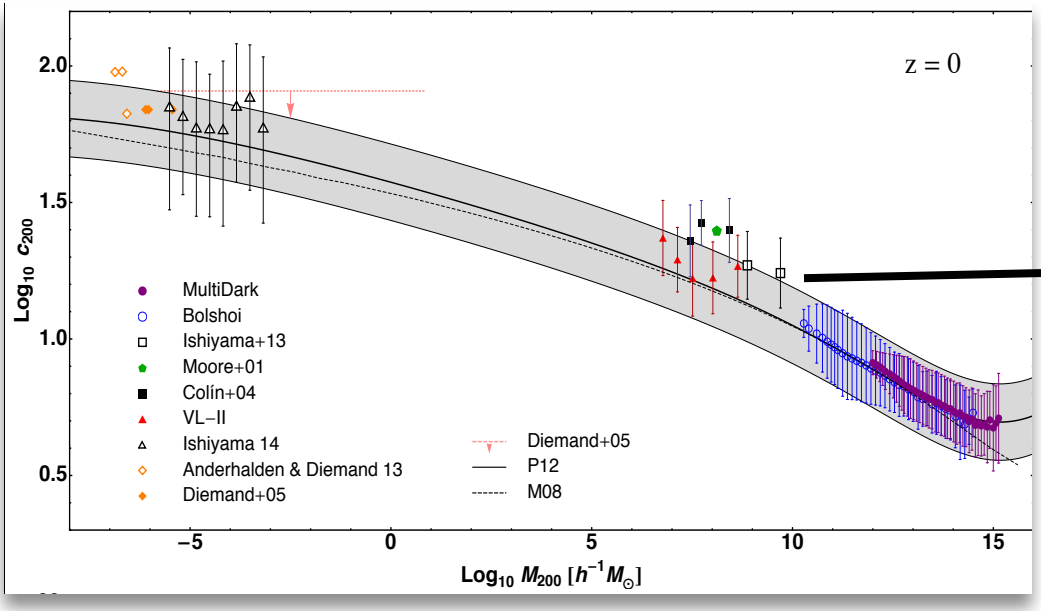
Isotropic emission: DM signal

Use Two approaches

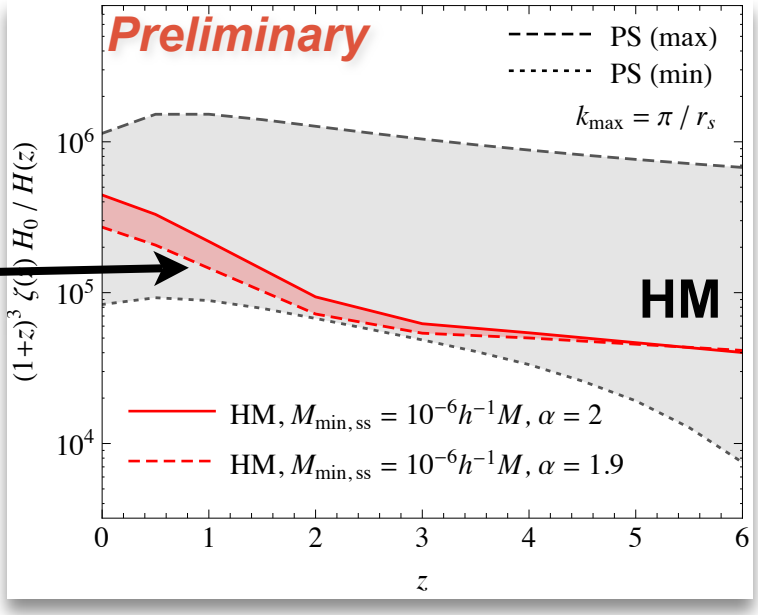
- **Flux multiplier** calculated in the **halo model** (**'real space' calculation; input: DM density distribution, concentration, mass number etc**)
- **improvement**: use the most up to date measurement of the 'concentration' parameter (measured now down to $\mathbf{10^{-6} M_{sol}}$ in dedicated simulations)

$$\zeta(z) = \mathrm{f}\ (\mathrm{dn/dM},\ \mathbf{c^3},\ \ldots)$$

concentration vs halo mass



Flux multiplier vs red shift



[Sanchez-Conde&Prada, MNRAS 2014]

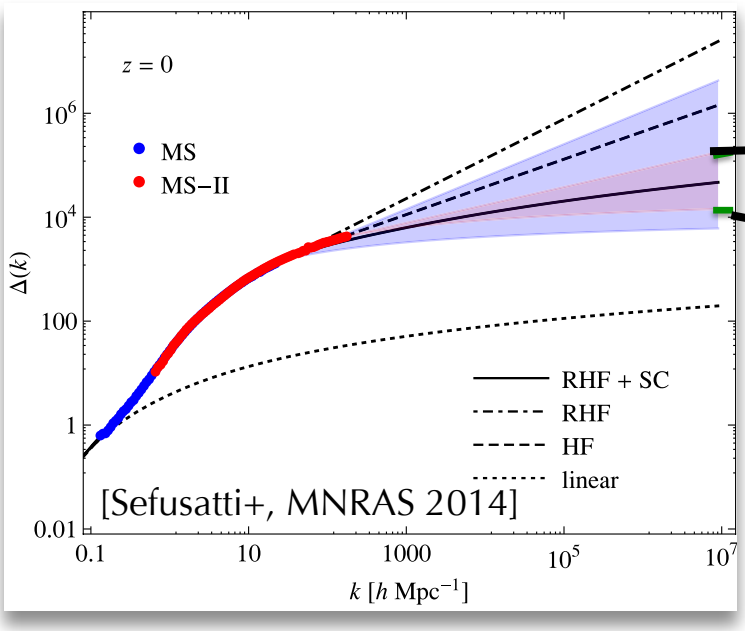
Isotropic emission: DM signal

Use Two approaches

- **the *uncertainty* on flux multiplier** calculated using **the matter power spectrum** measurement (**two point function of DM density field, in Fourier space**) - **need to extrapolate only one quantity directly measured in simulations.**

$$\zeta(z) \equiv \langle \delta^2(z) \rangle = \int^{k_{max}} \frac{d\,k}{k} \Delta_{NL}(k, z)$$

power spectrum vs scale



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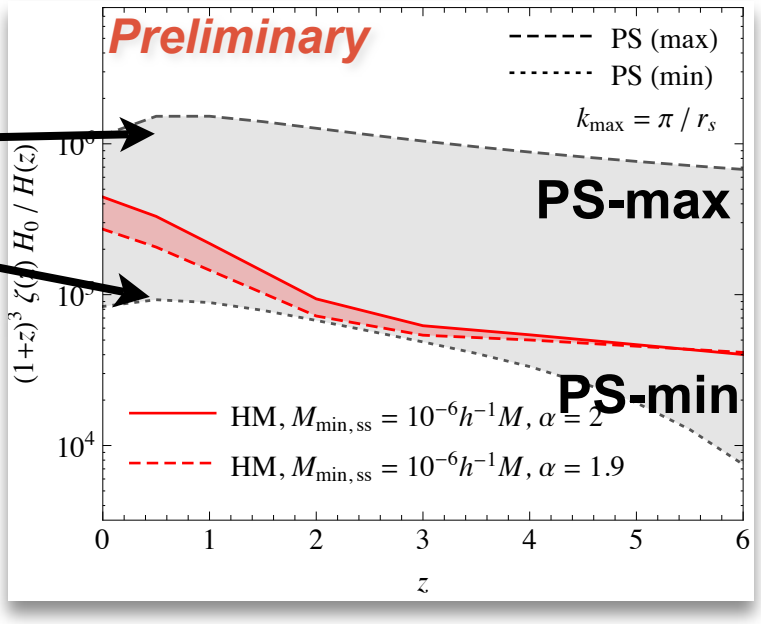

- **uncertainty reduced from 3 orders of magnitude in older works to <~20.**

Isotropic emission: DM signal

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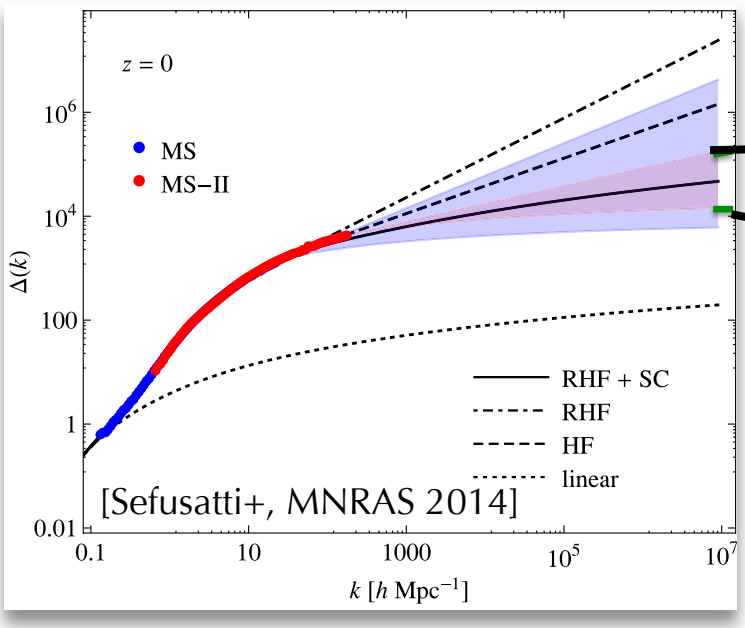

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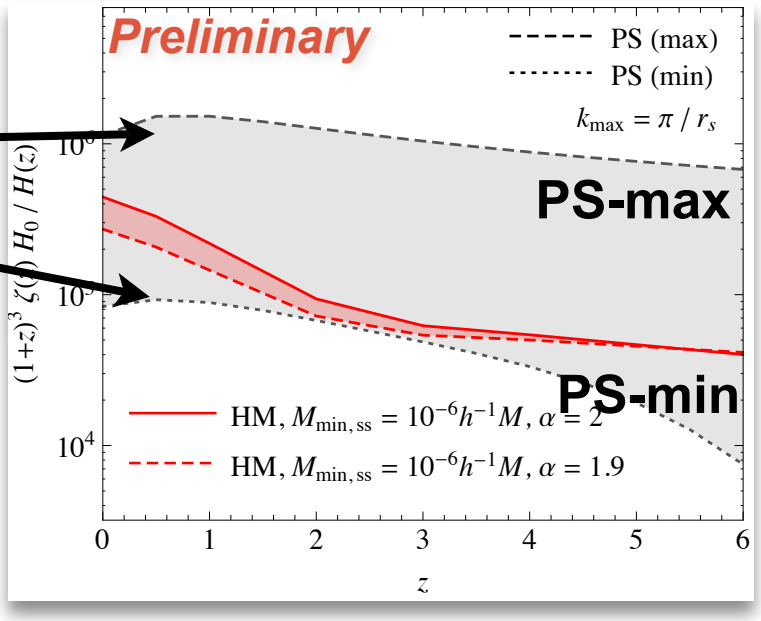
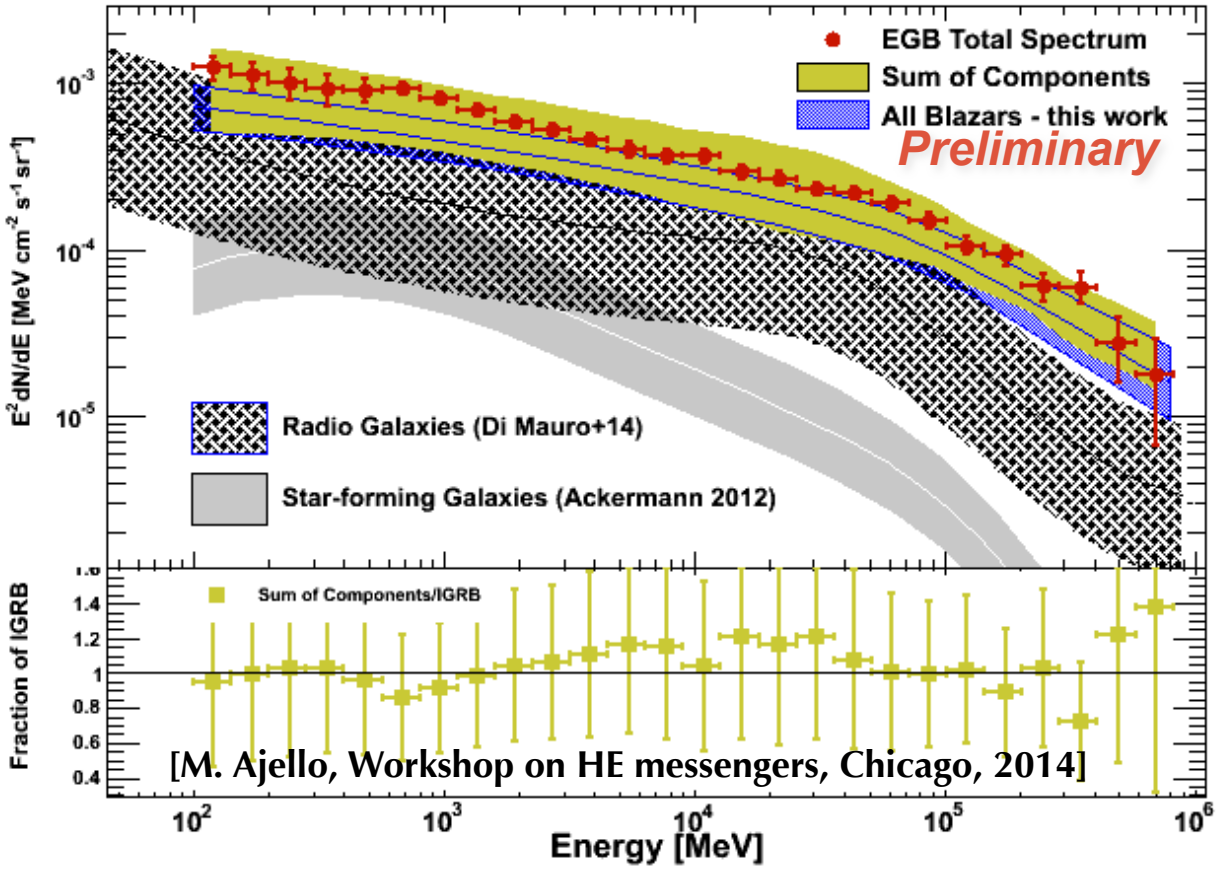


- **uncertainty reduced from 3 orders of magnitude in older works to <~20.**
- **+** add contribution from **Galactic subhalos**: i) **'benchmark'** calculated consistently as in the HM ***or*** ii) the '**MINminal'** contribution

Isotropic emission: 'guaranteed' contribution from unresolved gamma ray sources

- Active field of research currently updated using the IGRB extended energy range and 5 year source catalogs.
- **robust minimal** isotropic astrophysical contribution only from blazar population (at the ~15 % level of the signal <100 GeV [Abdo+, APJ 2010]).



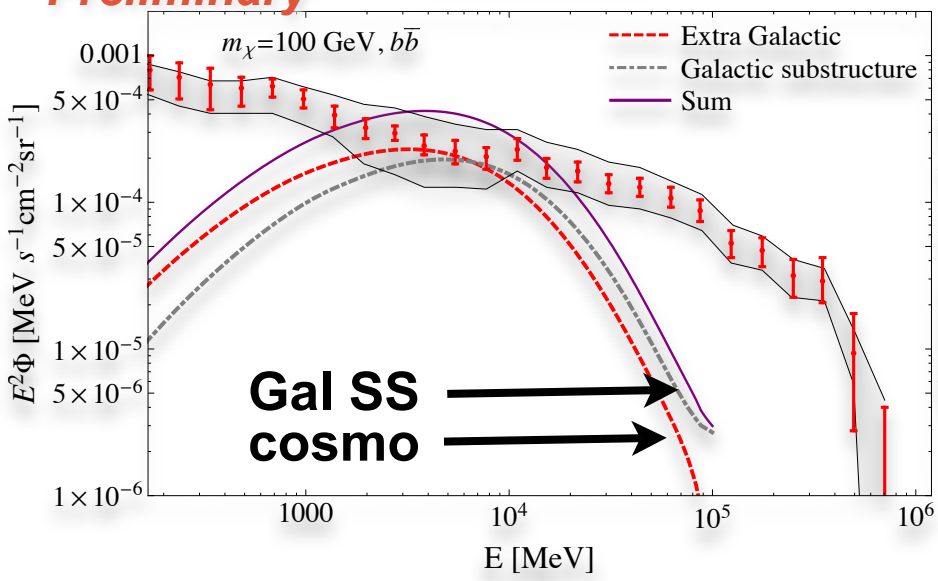
[M. Ajello, Workshop on HE messengers, Chicago, 2014]

Isotropic emission: DM limits

- in this work two types of limits: conservative and optimistic.
- the 'true' limits in-between

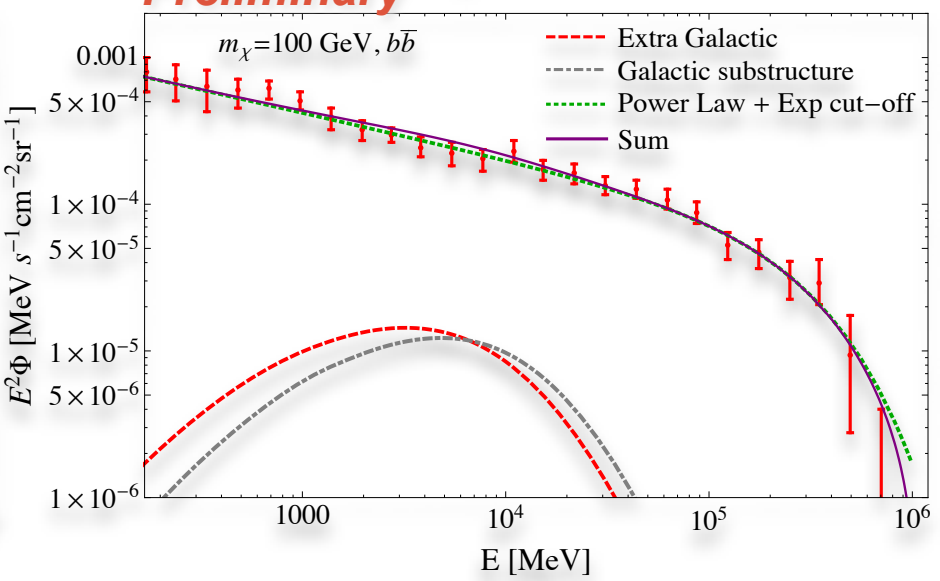
Preliminary

Conservative limits

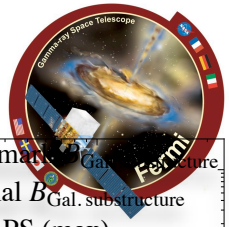


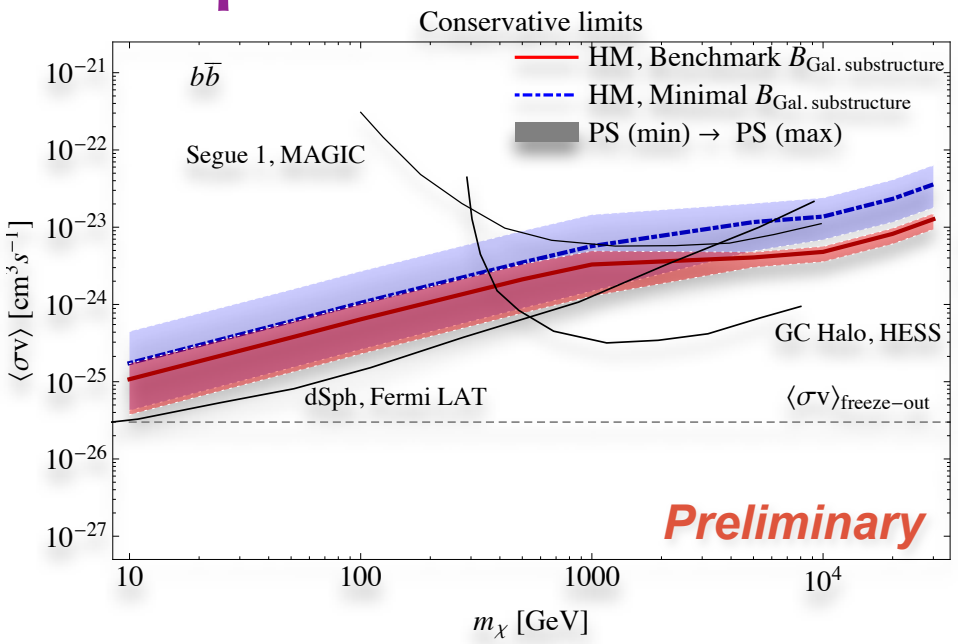
Preliminary

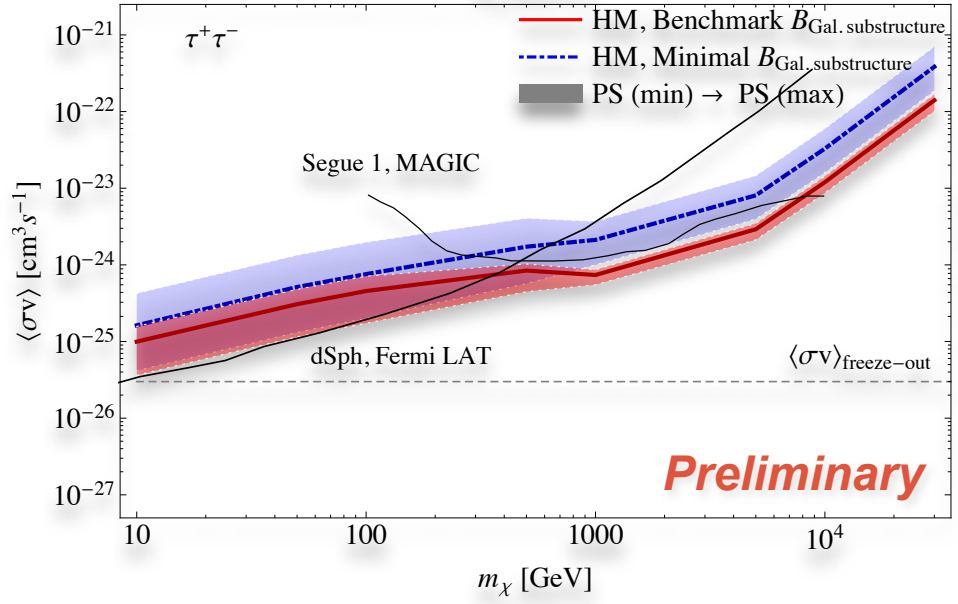
Optimistic limits

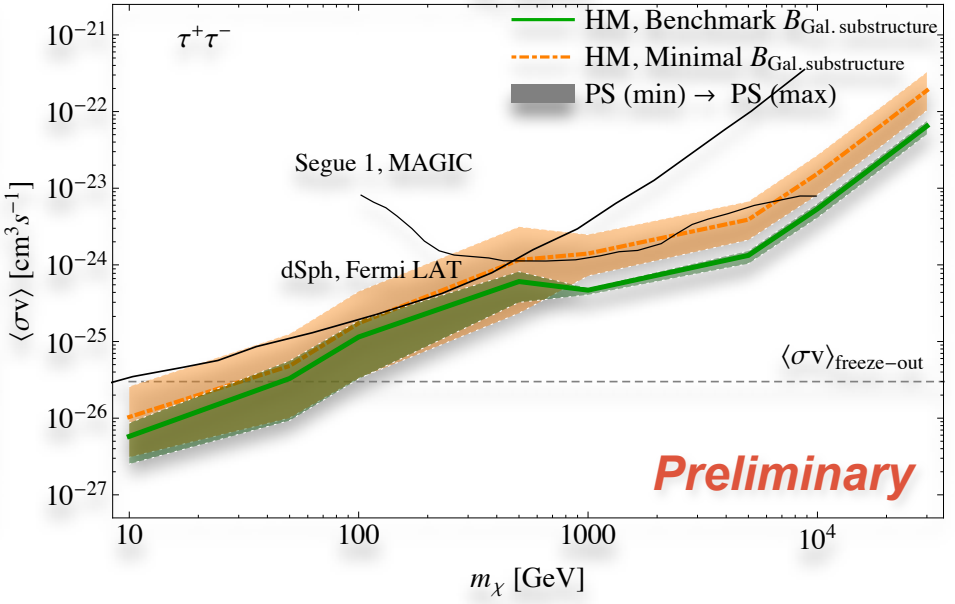


Isotropic emission: DM limits





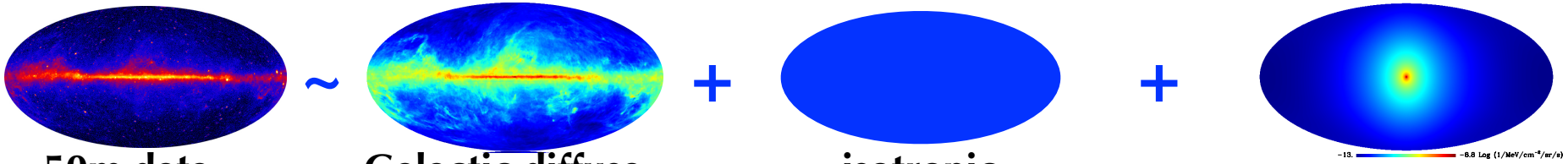


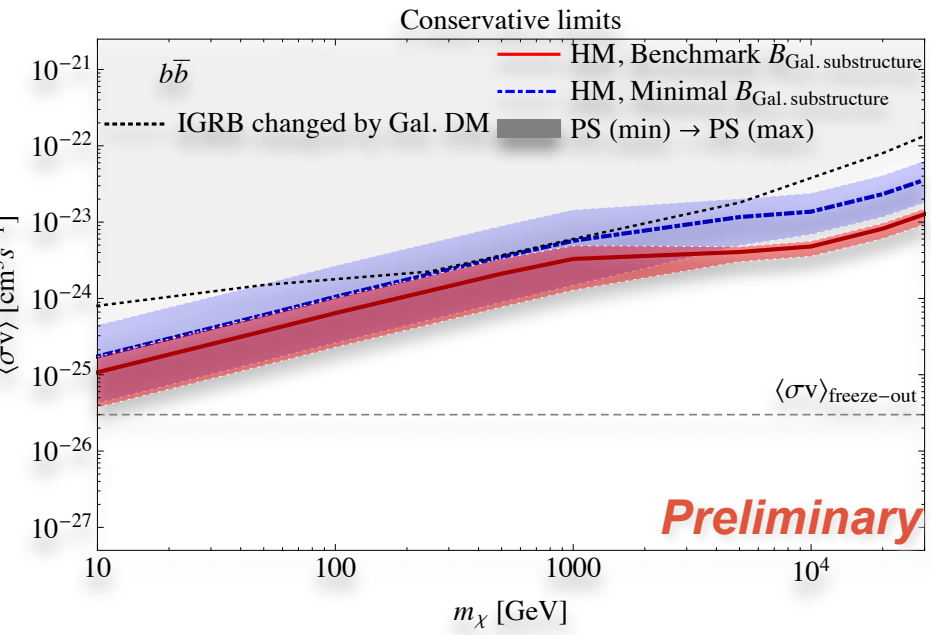


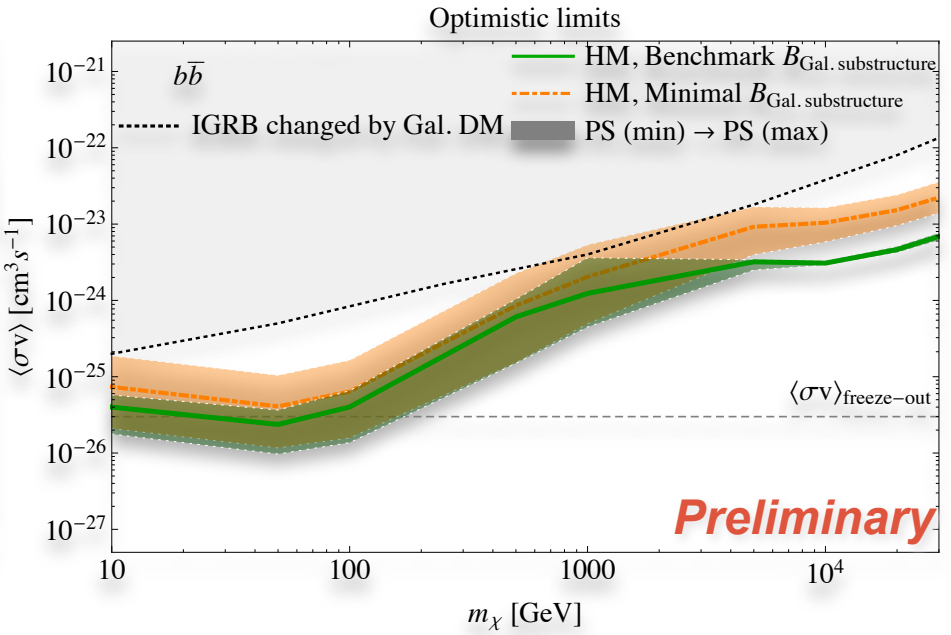
- **The strongest Fermi LAT limits in the >~5 TeV range. Good sensitivity to WIMPs in the 10-100 GeV.**

Isotropic emission: biases from the Galactic DM component

– explore at what level the DM Galactic smooth counterpart of the isotropic signal impacts the derivation of the IGRB spectrum



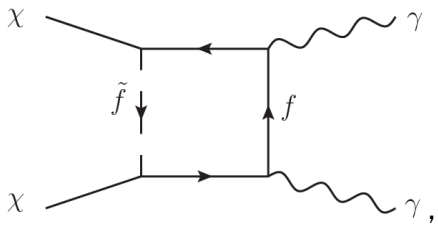


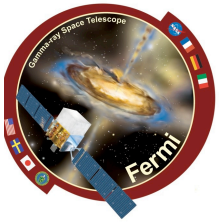


For the cross sections in the gray region DM Galactic smooth signal would significantly alter the IGRB spectrum: 2σ from its syst band (left) or 2σ departure wrt to the IGRB error-bars (right). For most of the exclusion band our procedure is self consistent.

The DM limits in the intersection region are conservative, as IGRB gets lower in the presence of the Galactic smooth component.

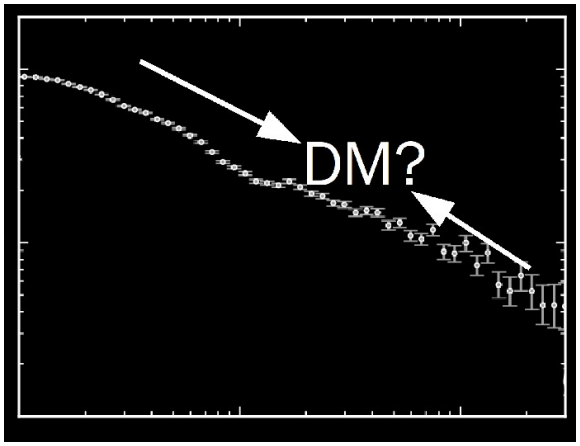
Low energy line search:





Line search basics:

$\chi\chi$ or $\chi \rightarrow \gamma X$ (X = γ, Z, H)
give monochromatic gamma signal
Advantage: sharp, distinct feature ("smoking gun")
Disadvantage: low predicted counts (loop-suppressed)



This project ([Albert+, 1406.3430; external authors: M. Grefe, C. Muñoz, C. Weniger]):
Search for DM lines from 100 MeV to 10 GeV, for annihilation ($\chi\chi \rightarrow \gamma\gamma$) and decay ($\Psi_{3/2} \rightarrow \nu\gamma$)
- previously unexplored region with the Fermi LAT
- in the case of decay, constrains models of Gravitino decay ($\Psi_{3/2} \rightarrow \nu\gamma$)

Challenge:
at low energies the statistical uncertainty gets very small (<1%) and the systematic uncertainties dominate - important to model them properly

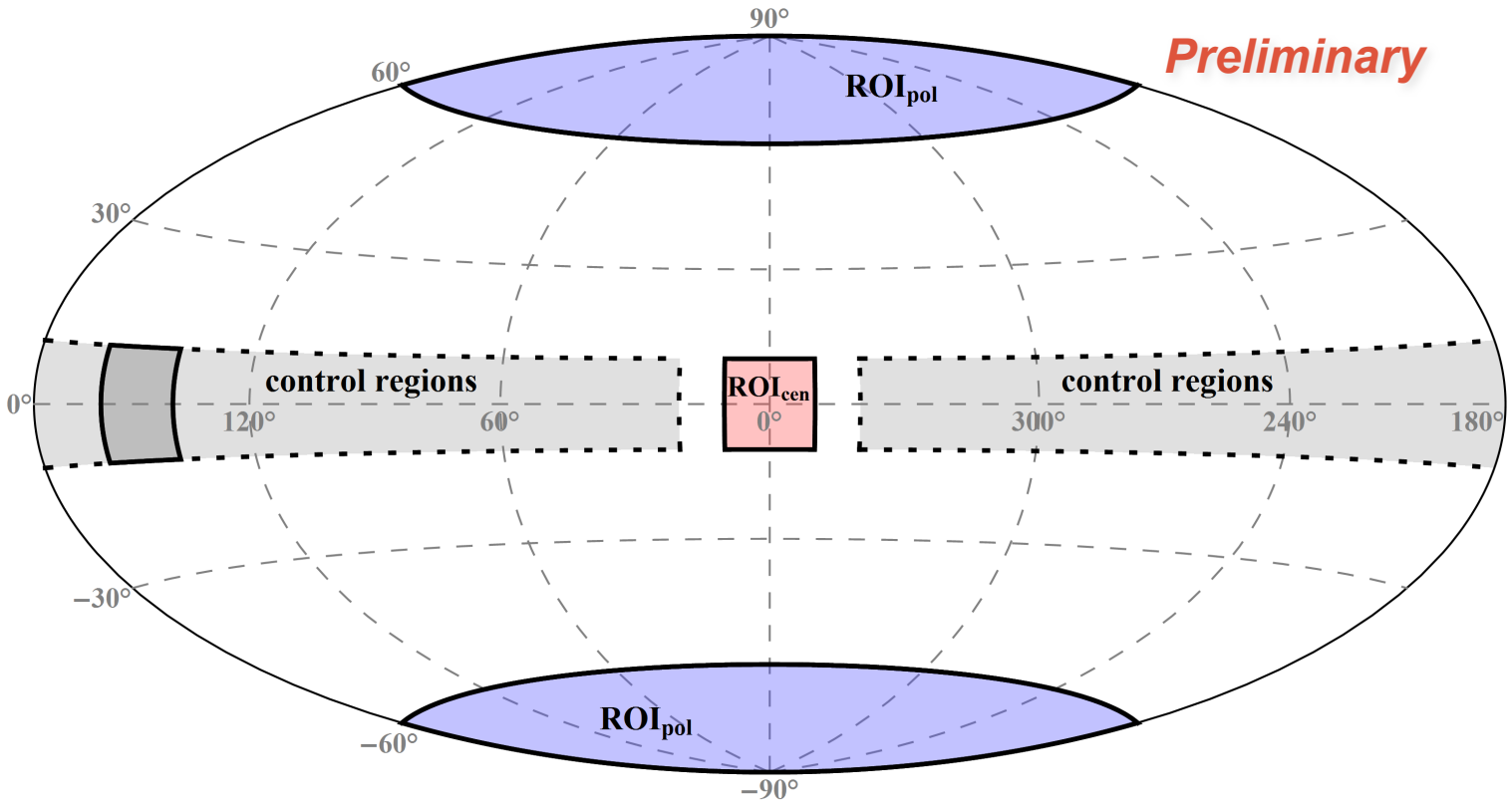
Data:
P7 REP Clean, ZA < 100°, 5.2 years
Fit for lines from 100 MeV to 10 GeV ($\pm 2\sigma_E$ windows -> 56.5 MeV to 11.5 GeV)

Low energy line search: region of interest

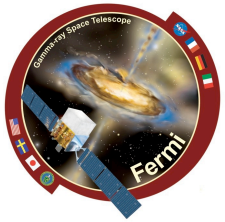
Use Einasto Profile (α=0.17, $\rho_\odot$=0.4 GeV/cm^3, $R_\odot$ = 8.5 kpc).

"ROI_{cen}" is the annihilation ROI; $|b| < 10°$, $|l| < 10°$

"ROI_{pol}" is the decay ROI ; $|b| > 60°$



Low energy line search: uncertainties



Focus on systematics which offsets the estimated number of signal events with respect to its true value

- Expect to scale linearly with the number of events in the ROI (δfsys)
- Express as uncertainty in terms of a fractional signal

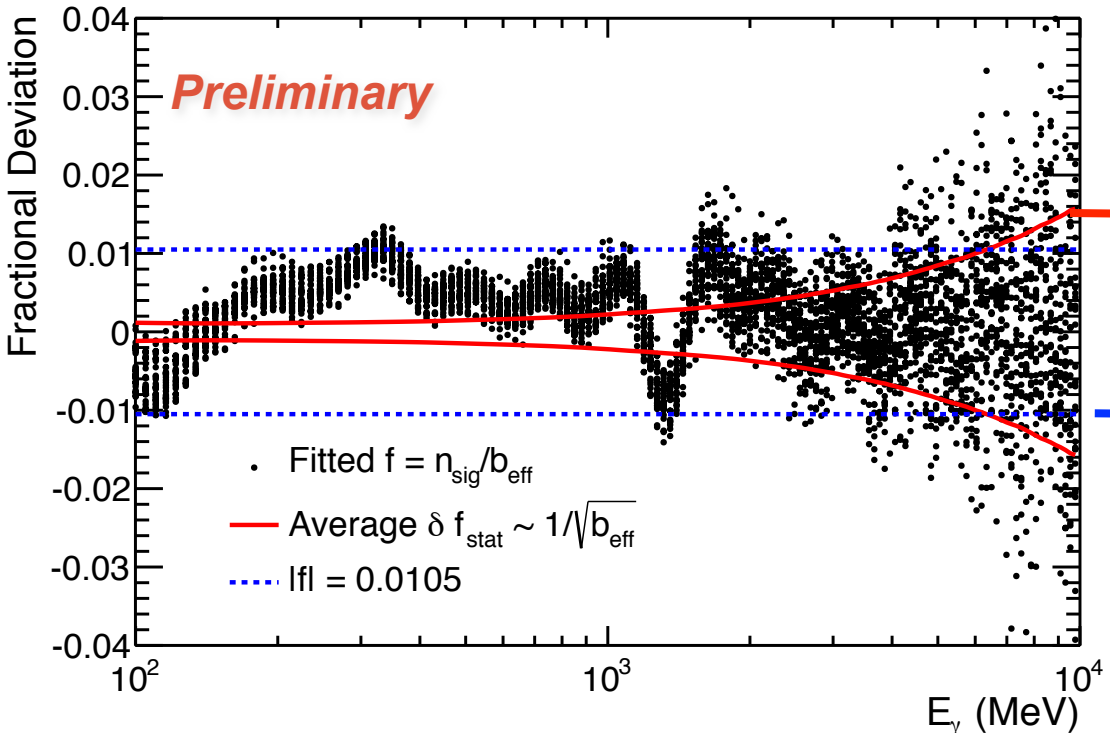
$$f \equiv n_{\rm sig}/b_{\rm eff}$$

Estimate δf_{sys} by fitting for lines in control regions

- Galactic Ridge ($|L|>10°$, 20°×20° squares along Galactic Plane)
- δf_{sys} from Bkg modelling, A_{eff}, and Sources

Below ~3 GeV our line search is systematics-limited

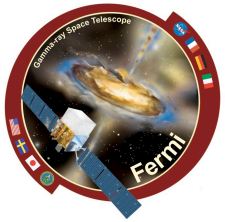
- Fractional statistical uncertainty is $\delta f_{stat} \sim 1/\sqrt{b_{eff}}$
- Compare to estimated systematic uncertainties ($\delta f_{sys} \leq 1\%$)



statistical uncertainty

chosen average syst uncertainty

Low energy line search: fitting method



Include nuisance parameter (n_{sys}) for systematically-induced line-like features:

- **only consider the true signal events to be those that remain after subtracting the expected systematic offset, $n_{sig}' = n_{sig} - n_{syst}$**
- **We add a Gaussian constraint on n_{sys} to the likelihood fit**

f_{sys} determined by control regions fits (i.e. off-center Galactic Ridge)

Similar technique used to incorporate J-factor systematic uncertainties in LAT Collaboration dSph analysis

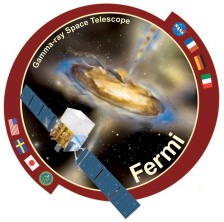
Can be applied whenever accounting for systematic uncertainties is important

- **the full likelihood function**

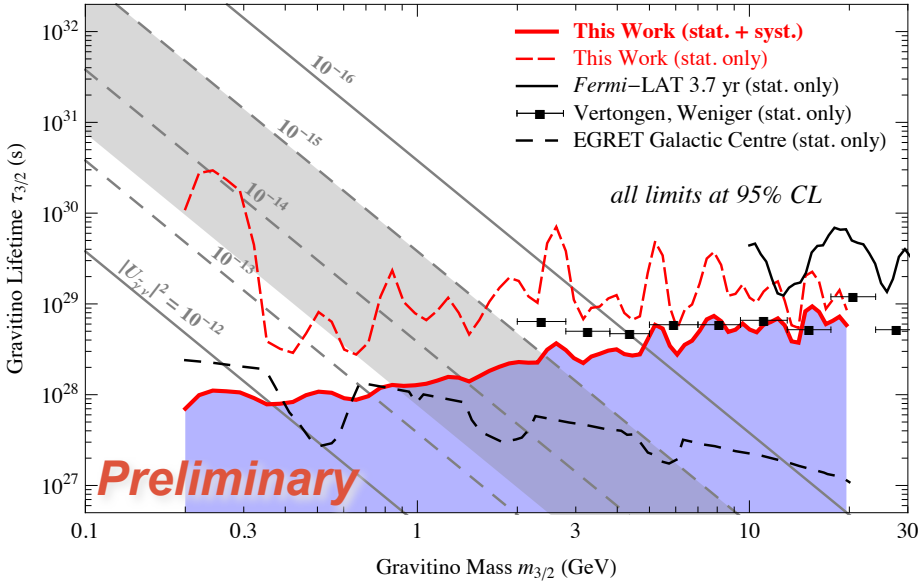
$$\mathcal{L}(\alpha, \Gamma, n_{\rm sig}, n_{\rm syst}) = P_{\mathcal{F}}(n_{\rm syst}, b_{\rm eff}) \prod_i P(c_i | \mu_i(\alpha, \Gamma, n_{\rm sig} + n_{\rm syst}))$$

$$P_{\mathcal{F}}(n_{\rm syst}, b_{\rm eff}) = \frac{1}{\sigma_{\rm syst}\sqrt{2\pi}} \exp\left(-\frac{(n_{\rm syst} - \mu_{\rm syst})^2}{2\sigma_{\rm syst}^2}\right) \qquad \sigma_{\rm syst} = \delta f_{\rm syst} b_{\rm eff}$$

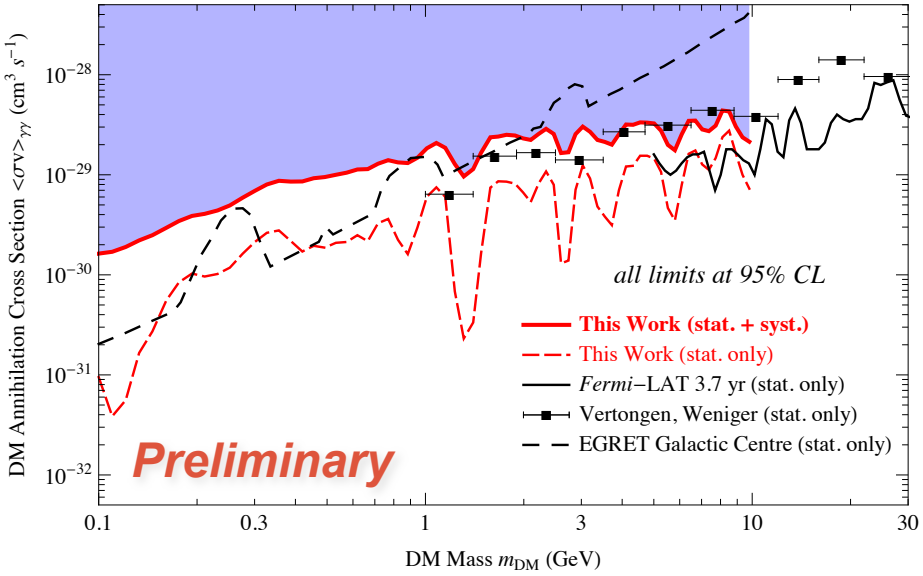
Low energy line search: limits



$\Psi_{3/2} \rightarrow \nu\gamma$



$XX \rightarrow \gamma\gamma$



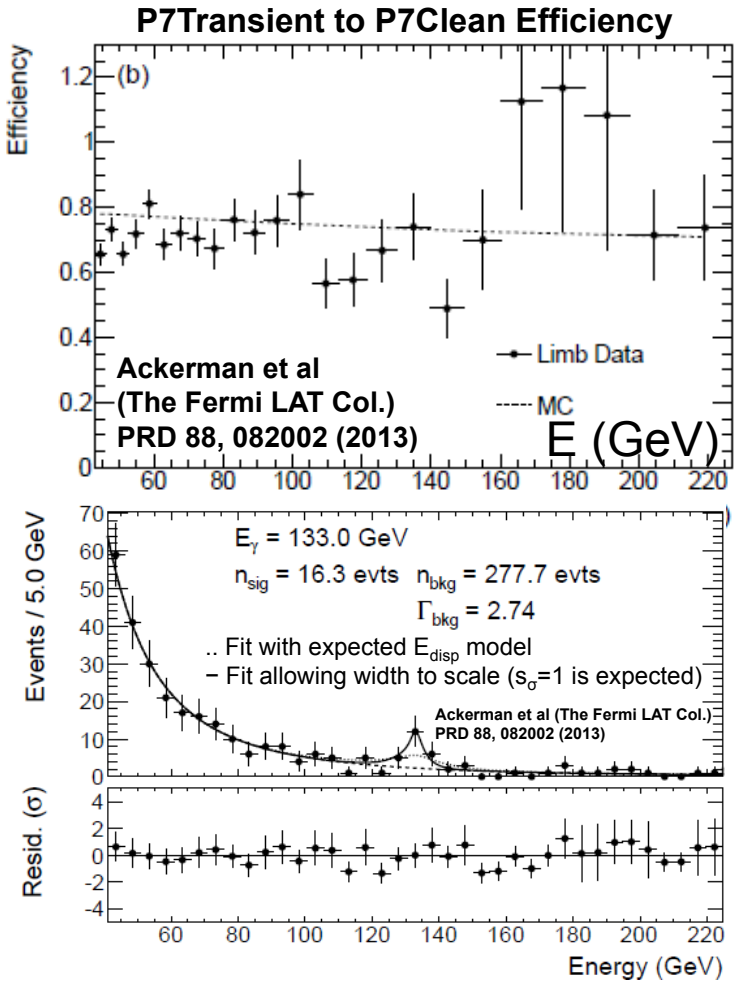
[Albert+, 1406.3430, JCAP submitted]

High energy line search: update

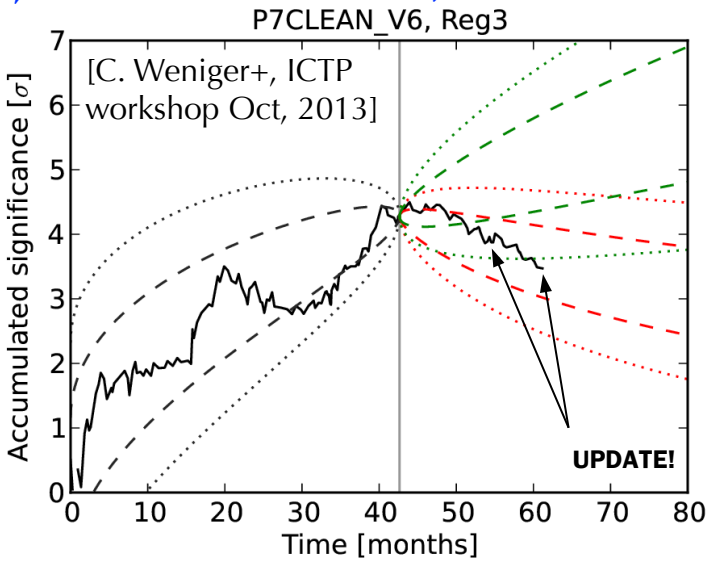
- this analysis statistics dominated.
- curious hint for a 133 GeV line being followed up by the LAT team and community

Weak line signal appears in the control sample (Earth limb ($|\theta r| < 52^0$)

- Not large enough to explain all the GC signal (f=0.14, in GC would be 0.8σ).



- Let width scale factor float in fit (while preserving shape)
- $s_\sigma = 0.32^{+0.22}_{-0.07}(95\%CL) \quad \Delta TS = 9.4$



→ Behaves like expected for a statistical fluke

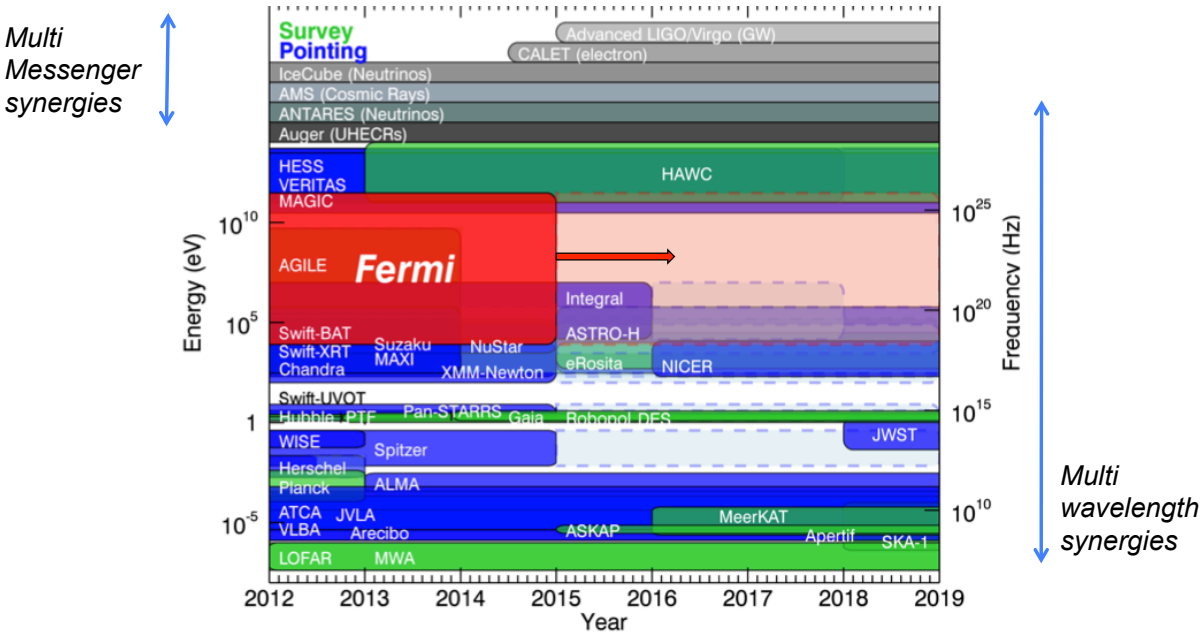
Since spring 2012, feature has decreased.

Bkg fluctuation?

- Decreasing with more data
- Much narrower than expected energy resolution

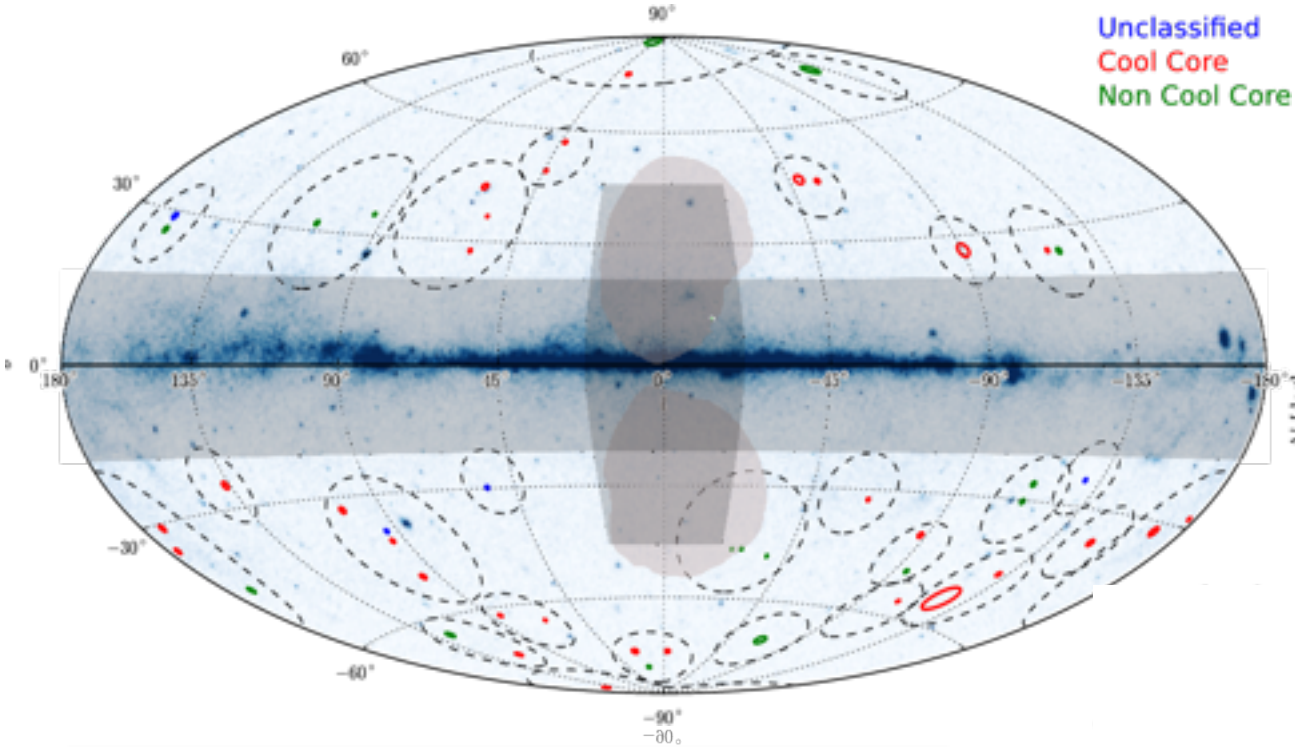
Summary:

- Search for gamma ray signatures of **cosmological DM annihilation** are being improved:
  - **better handle on DM clustering properties**
  - **extended energy range**
  - **consistency checks with Galactic DM component**
- **Low energy gamma ray line search** sets **robust** limits and utilizes a method of including systematic uncertainty in DM searches
- Traditional **sensitivity range to DM mass by Fermi LAT being expanded** both at the high and low mass ends.
- **Pass8** + **cont'd LAT operation through till 2016** will boost this trend and increase sensitivity to DM search (**L. Baldini's talk!**)



Extra Slides

Sneak Peak: Galaxy Clusters stacked analysis



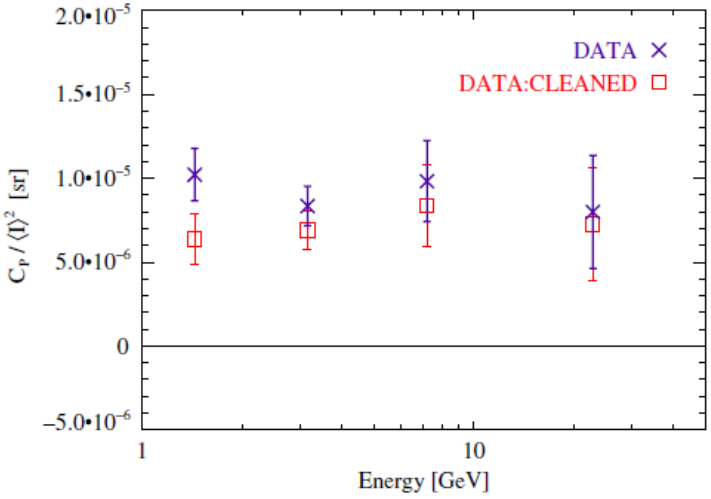
Galaxy Clusters: the biggest DM halos yet to form (contain hundreds of Galaxies).
Challenge: **DM clustering on small scales**, in Cluster substructure is the source of most of uncertainty.
Analysis:
5 year data analysis (500 MeV - 200 GeV), **34 Clusters**
stacked likelihood analysis, as the one used for the dwarf spheroidal galaxies
.... *more by Stephan!*

Isotropic emission: Angular Power Spectrum

- decompose an intensity map, with the sky direction, in spherical harmonics:
  - The APS is given by the coefficients

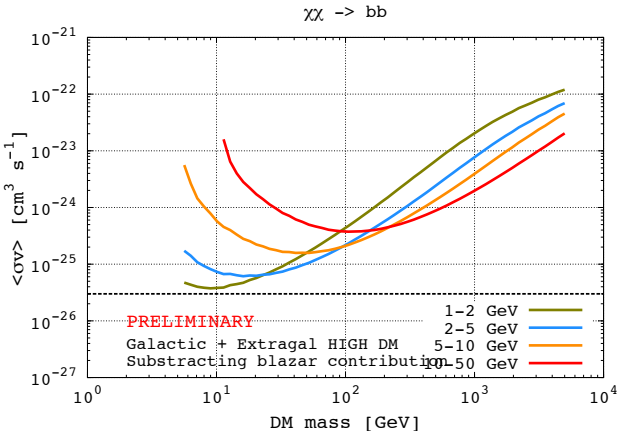
$$I(\Psi)=\sum_{lm} a_{lm} Y_{lm}(\Psi). \qquad C_l=\langle |a_{lm}|^2 \rangle$$

- 22m data analysis: APS detected with ~7sigma:
  - consistent with being mostly due to the blazar population
  - DM limits set: biggest uncertainty DM clustering properties at small scales
  - work in progress: updated APS measurement and DM limits. cross correlation with Galaxy catalogs
- important complementarity between angular anisotropy vs flux intensity DM search



Fermi-LAT collaboration, PRD. **85** 083007 (2012)

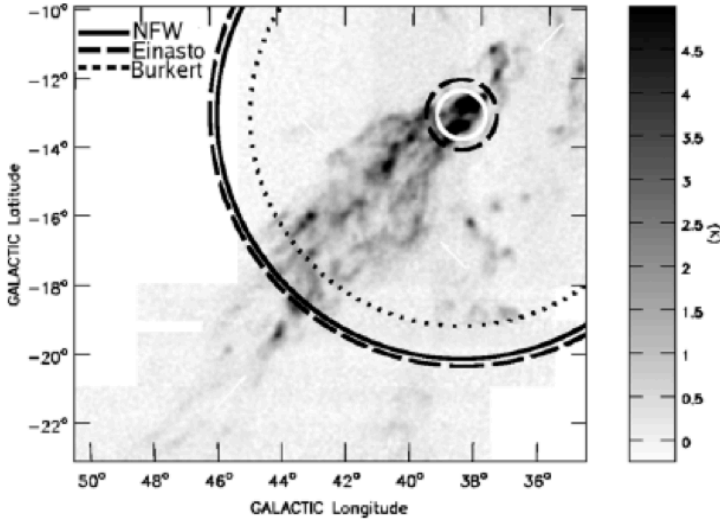
Constraints using 2-sigma upper limits on non-blazar anisotropy



[G. Gomez-Vargas, Anisotropy Workshop, Amsterdam, 2014]

Smith cloud:

- **Motivation:**
  - High Velocity Clouds of HI and HII gas (~$10^6 M_{sun}$)
    - Low galactic latitude, ~12.4Kpc
  - Trajectory suggest is passed through Galactic disk ~70Myear ago
  - Current bound state of gas suggest ~100/1000x DM halo to confine gas through Milky way passage
    - Large uncertainty in DM content

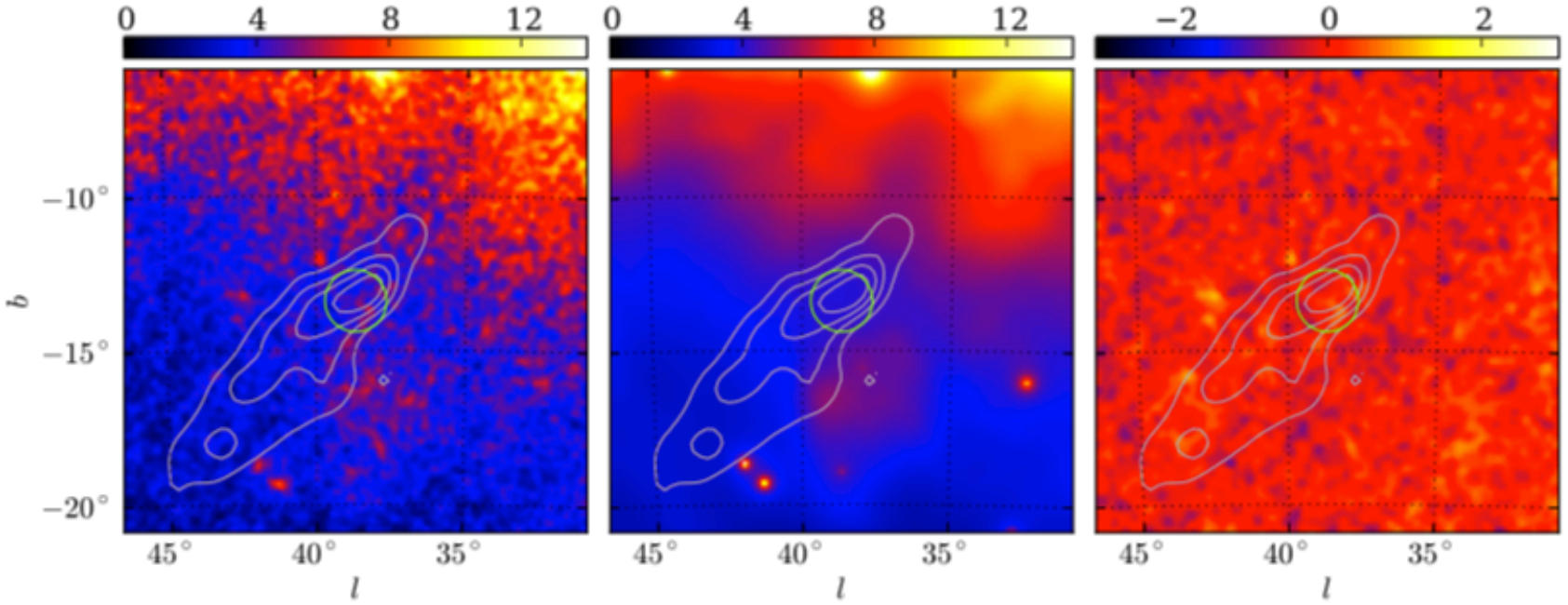


- **People:**
  - LAT Collaboration: Alex Drlica-Wagner, German Gomez Vargas, John Hewitt, Luigi Tibaldo
  - External authors: Tim Linden
- **Data:**
  - 5.2 years, Pass7 reprocessed data, need specific model of diffuse γ-rays

Smith cloud:

Challenge:

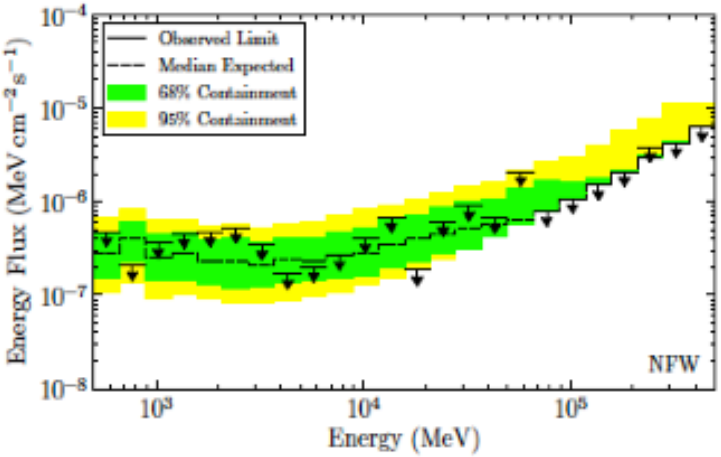
close to the Galactic plane (3kpc below the plane) - diffuse modeling critical

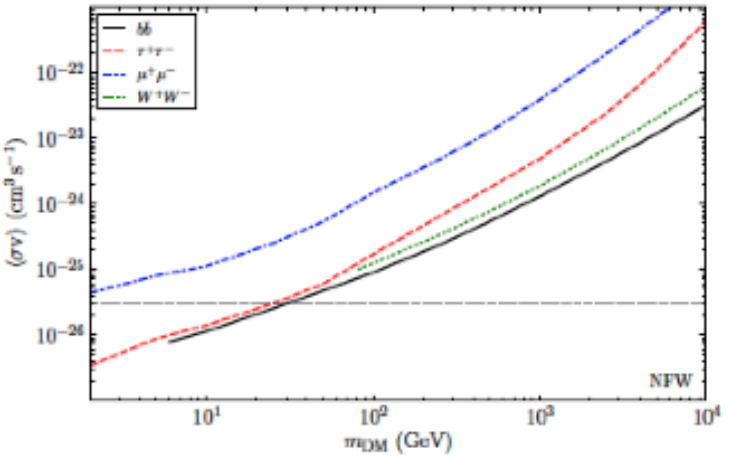


- Do not use standard diffuse model distributed for source analysis
- Build GALPROP templates of standard components of diffuse γ-rays using InfraRed observations of Smith Cloud

Smith cloud:

Drlica-Wagner, GAGV, J. Hewitt, T. Linden & L. Tibaldo
arXiv:1405.1030





- No very significant signal
  - TS ~4.7 for 5 GeV WIMP going to τ+τ-
- Constraints are highly dependent on the assumed DM profile
  - J-factors vary by a factor of ~40
- Uncertainty in the DM profile dominates over other systematic and statistical uncertainties

Drlica-Wagner, GAGV, J. Hewet, T. Linden & L. Tibaldo
arXiv:1405.1030