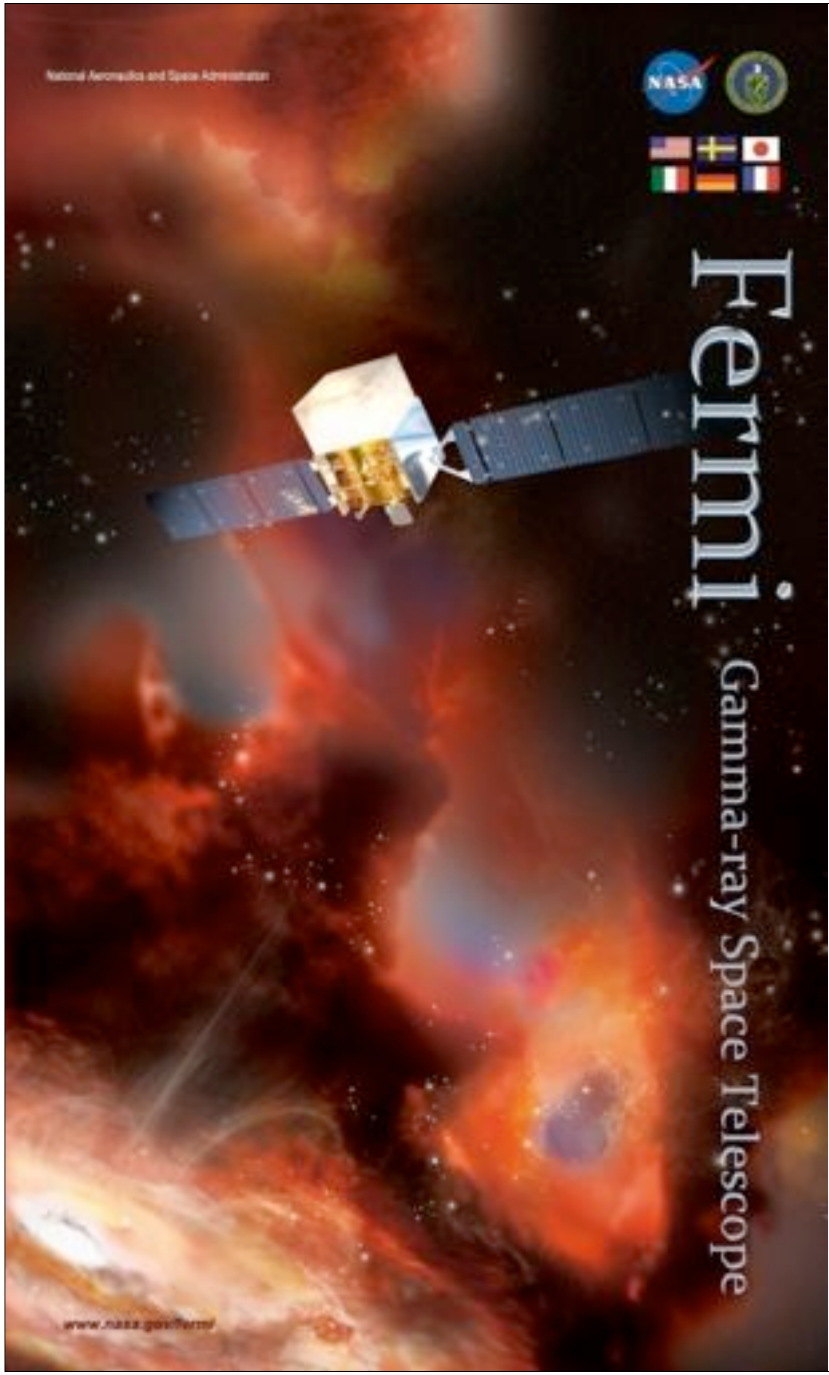

Constraints on dark matter annihilation and decay in the Milky Way halo

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On behalf of the Fermi LAT Collaboration

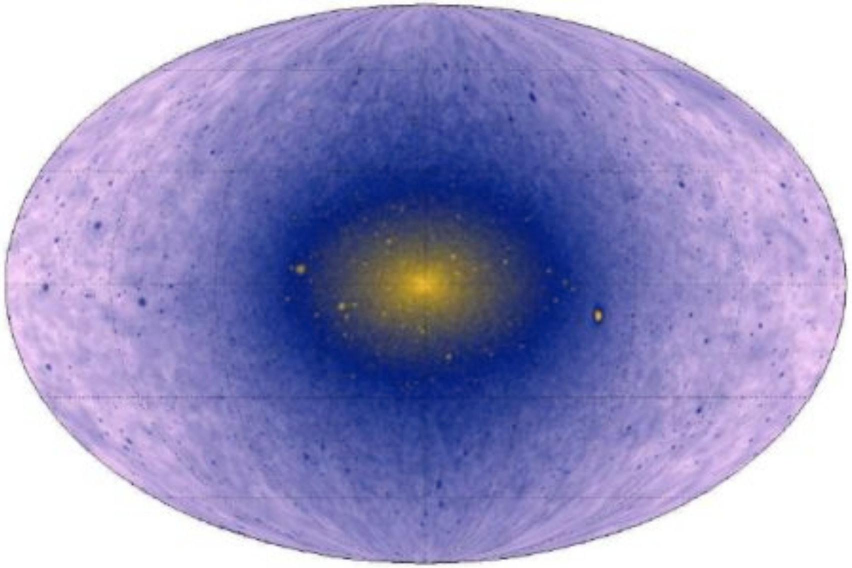
[Ackermann et al., Apj, 2012; 1205.6474]

WIMP annihilations

- Self annihilations of Weakly Interacting Massive Particles (WIMPs) expected to produce γ rays detectable by the Fermi LAT.

  → reviewed by L. Bergstrom and S. Profumo
- Focus on continuum emission from WIMP annihilations.
- Explore representative channels to follow phenomenological approach, independent of any specific Beyond the Standard Model physics

Predicted DM signal



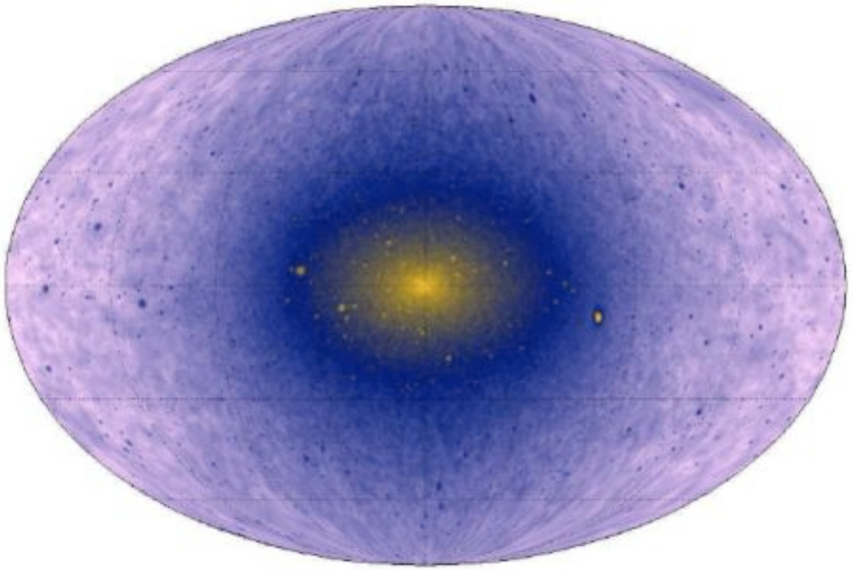
Diemand et. al, APJ, 2006.

MW halo as a DM target

- DM annihilation signal is expected to be high in the inner regions of our halo
  - Sun is 'only' ~8 kpc away from the GC
  - DM content of the Milky Way is high

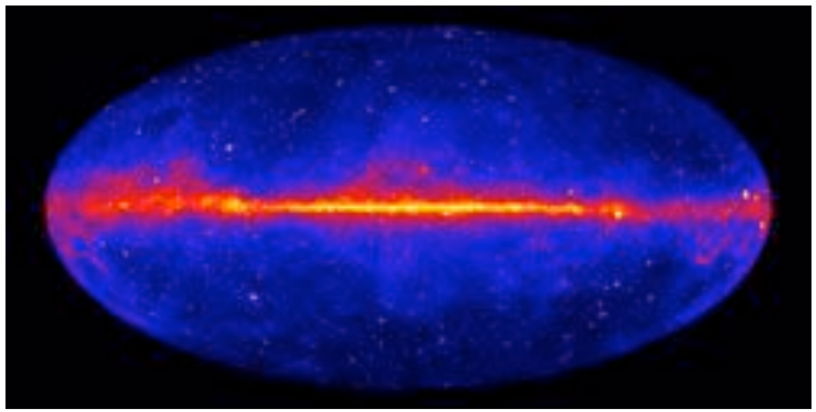
- However, diffuse gamma-ray emission presents strong background
  + there are no spectral or morphological smoking guns in this analysis!

Predicted DM signal



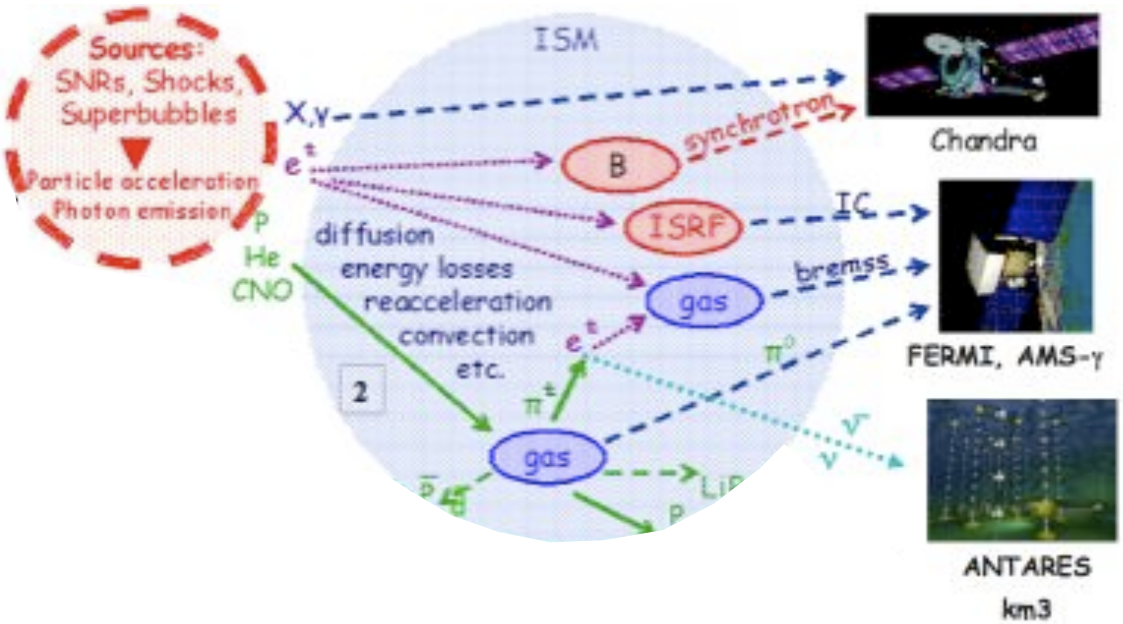
Diemand et. al, APJ, 2006.

Fermi sky map - three year data.



γ ray diffuse emission as measured by Fermi-LAT

- **Majority of the diffuse emission is due to CR interacting with the ISM**
  - **three component in the LAT energy range: Inverse Compton and bremssthralung emission from cosmic ray electrons and decay of pions (produced in CR proton scatterings with the gas).**
  - **many parameters needed to describe it: distribution of CR source, injection spectra, gas maps, CR propagation parameters...**



Adapted from Moskalenko et al. (2004)

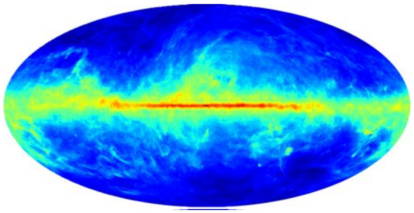
DM limits

Idea: fit the data in spatial and energy bins to break degeneracy among the two signals.

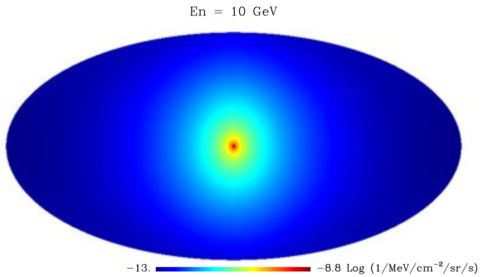
→ model simultaneously the conventional and DM induced diffuse emission while scanning over many parameters.

- **at this stage we set DM limits rather than look for its signatures**
  → conservative choices made.

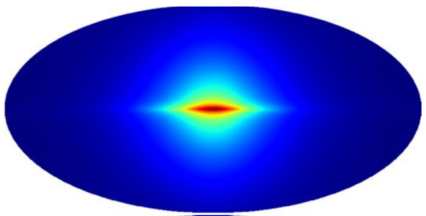
π^0, bremss



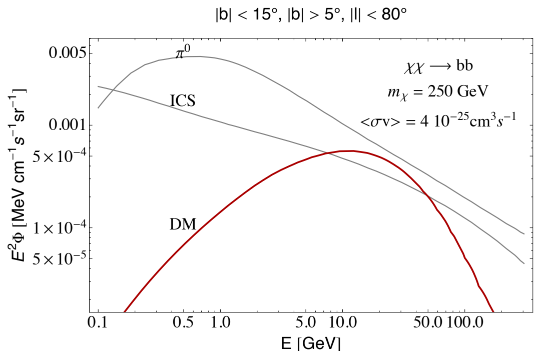
DM



IC



$E^2\ \Phi$



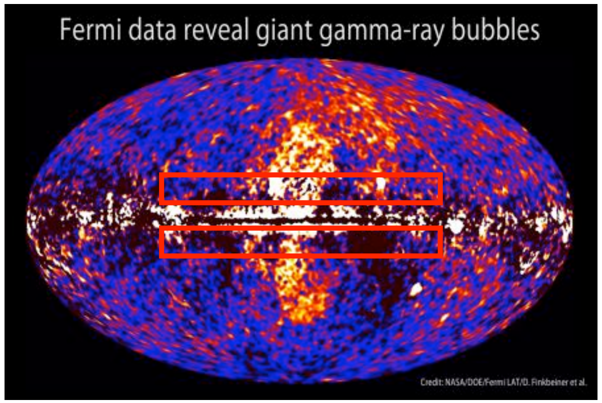
E [GeV]

1 100

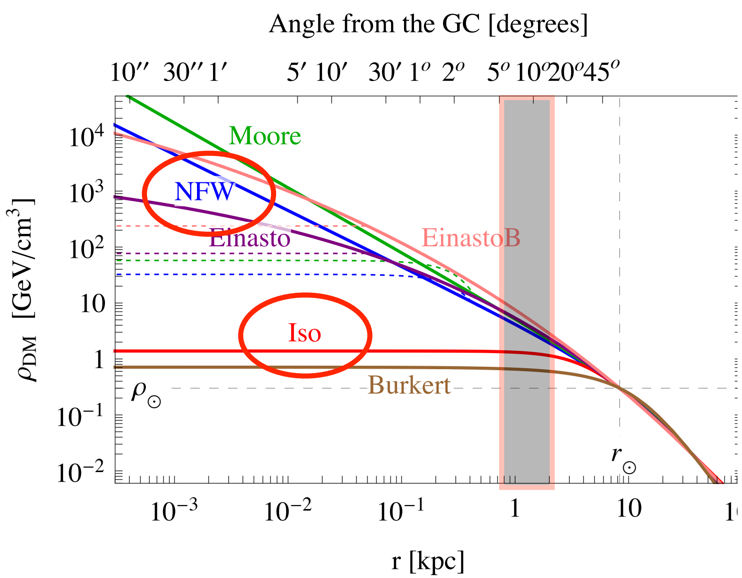
Data set and Region of interest

- **Astrophysical emission strong along the plane + Fermi LAT data revealed large scale structures at high latitudes (Fermi bubbles and Loop I)**
- **ROI: 5° <|b|<15° and |l|<80°:**
  1. **limit astrophysical uncertainty by masking out the Galactic plane and by cutting-out high latitude emission from Fermi lobes/Loop I**
  2. **minimize DM profile uncertainty (the highest at the Galactic Center region)**
- **24 months data, p7CLEAN_v6 event selection in the 1-100 (400) GeV energy range.**

Fermi bubbles



Su et al, 2010.
Talk by D. Finkbeiner & posters by A. Franckowiak, D. Malishev, M. Su.



Modeling

- **Signal and background modeling is based on a series of physically-motivated parametrized template maps of the diffuse emission derived with the GALPROP code.**

- **We sample a grid of nonlinear astrophysical parameters while fitting a set of linear parameters of the diffuse emission.**

  - **Non-linear (grid) parameters: chosen among the ones expected to be the most degenerate with DM component.**

Non linear Parameters	Symbol	
index of the injection CRE spectrum	$\gamma_{e,2}$	**1.925 - 2.8**
half height of the diffusive halo	z_h	**2 - 15 kpc**
dust to HI ratio	d2HI	**12-17 $\times 10^{17}$mag cm^2**

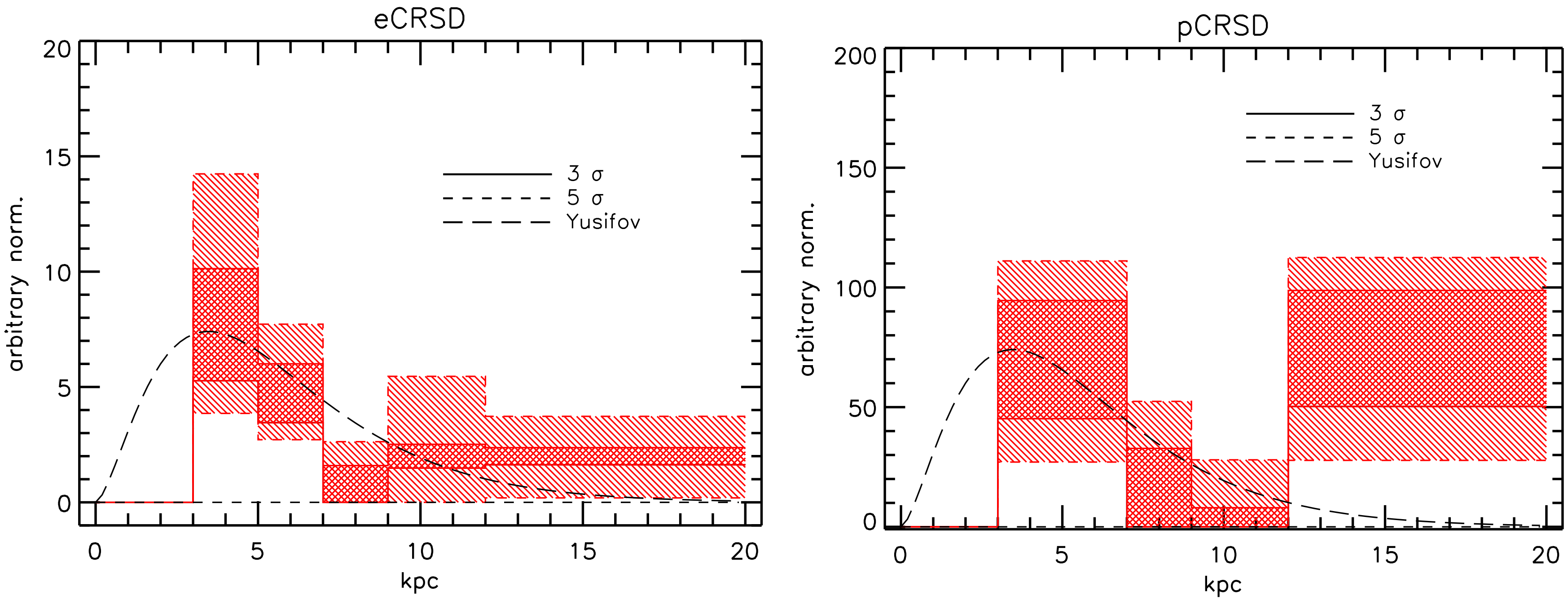
Modeling

- **For each grid model we produce template maps which are then rescaled by linear parameters in the fit. Template maps:**
  - **Galactic emission template maps (bremss, π^0, IC) produced assuming CR sources to be distributed as a step function in Galacto-centric rings**
    - **CR source distribution: poorly constrained in the inner Galaxy → CRe and CRp source distributions are free linear parameter in each ring**
  - **DM template maps**
  - **Isotropic (extra Galactic emission**

Linear Parameters	Symbol	
eCRSD and pCRSD coefficients	c_i^e, c_i^p	**7X2**
local H_2 to CO factor	X_{CO}^{loc}	**1**
IGB normalization in various energy bins	$\alpha_{IGB,m}$	**5**
DM normalization	α_χ	**1**

CR source distribution

- **In addition we impose a constraint: $c_i^e = c_i^p = 0$, for R<3 kpc.**
  - **determination of the source distribution is not reliable in the inner Galaxy region in this analysis due to the limited ROI and grid parameters.**



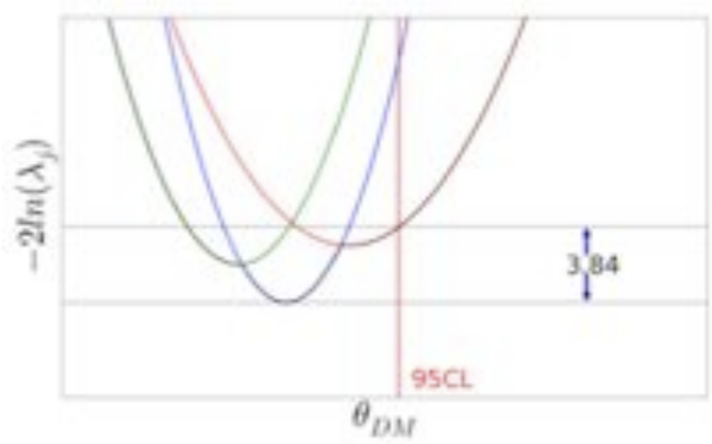
Fitting procedure

- Fits at different grid points are compared using the **profile likelihood method**.
  - for each grid point (different parabolas) we find a likelihood function L_k; maximized over all linear parameters α, for every value of the DM norm, θ_{DM}.
  - we construct test statistics (TS) wrt to the best overall likelihood
  - The profile likelihood is the curve that follows the minima of all grid/GALPROP models.
  - assuming it behaves as a χ^2 with one degree of freedom, we set the limits using the value of a DM normalization for which its value raises by 9/25 from the minimum.
    - Minima of LogL functions is well populated, making it possible to set 3(5)σ DM limits marginalizing over many astrophysical models.

LogLikelihood vs DM normalization for a fixed DM model and mass.

$$L_k(\theta_{DM}, \hat{\hat{\vec{\alpha}}}) = max_{\vec{\alpha}} \prod_i P_{ik}(n_i; \vec{\alpha}, \theta_{DM})$$

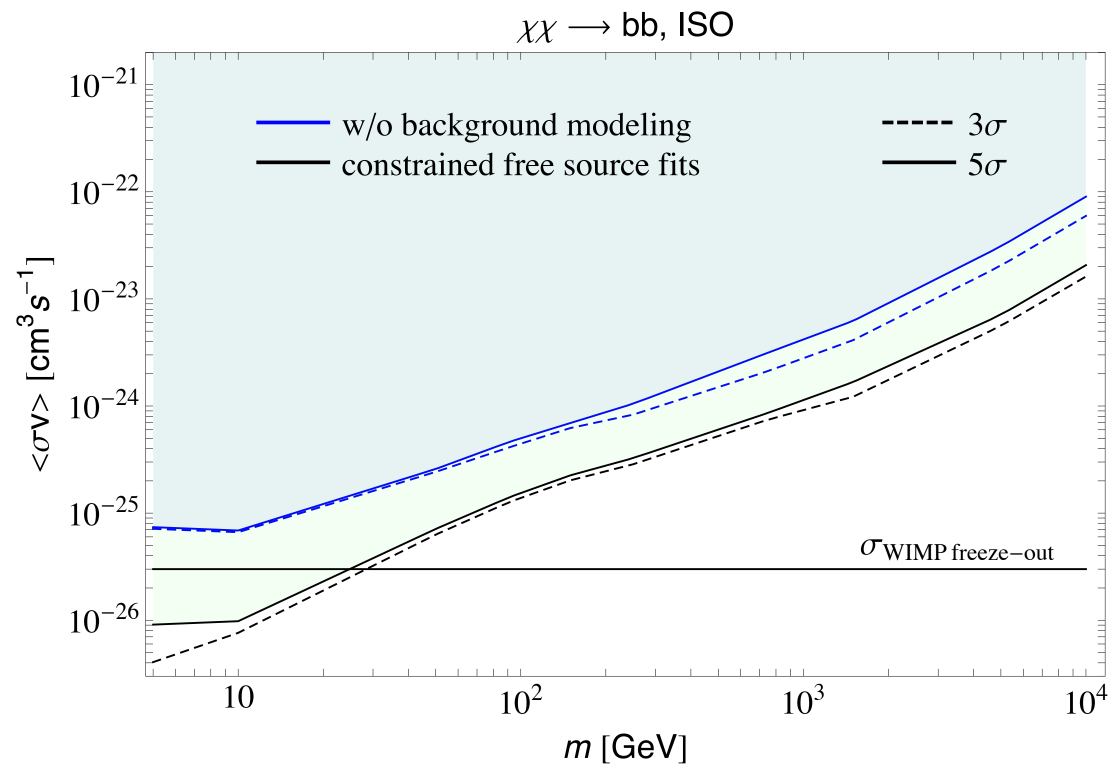
$$TS = 2\Delta \ln(\mathcal{L}/\mathcal{L}_0)$$



Results - DM limits

Limits on DM annihilation cross section, for ISOthermal DM profile and bbar channel (generic for most of particle physics models).

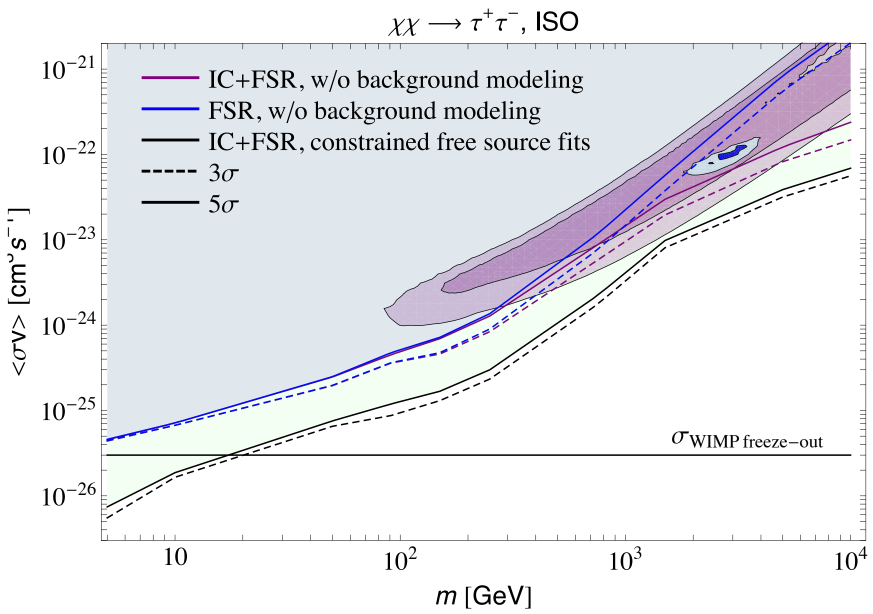
- **Blue: limits obtained without any modeling of conventional astrophysical emission.**
- **generic WIMP models constrained below ~20 GeV.**

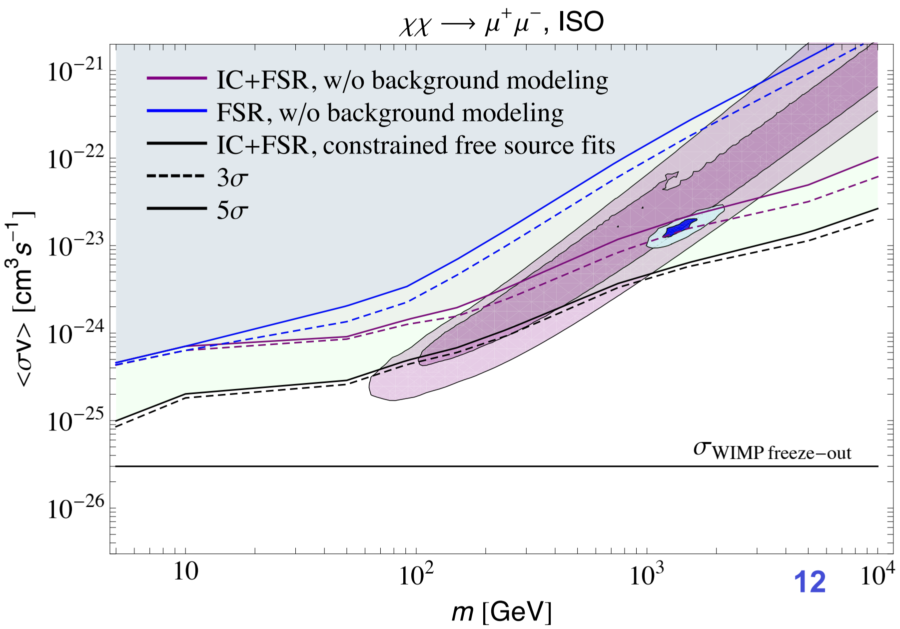


Results - DM limits

Limits on DM annihilation cross section, for ISOthermal DM profile.

- leptonic final states: purple lines: limits derived by modeling only the direct photon emission. Purple regions: fit to PAMELA and Fermi LAT electron/positron data, [Cirelli et al., Nucl. Phys. B, 2010]. -> covered in S. Profumo's talk.



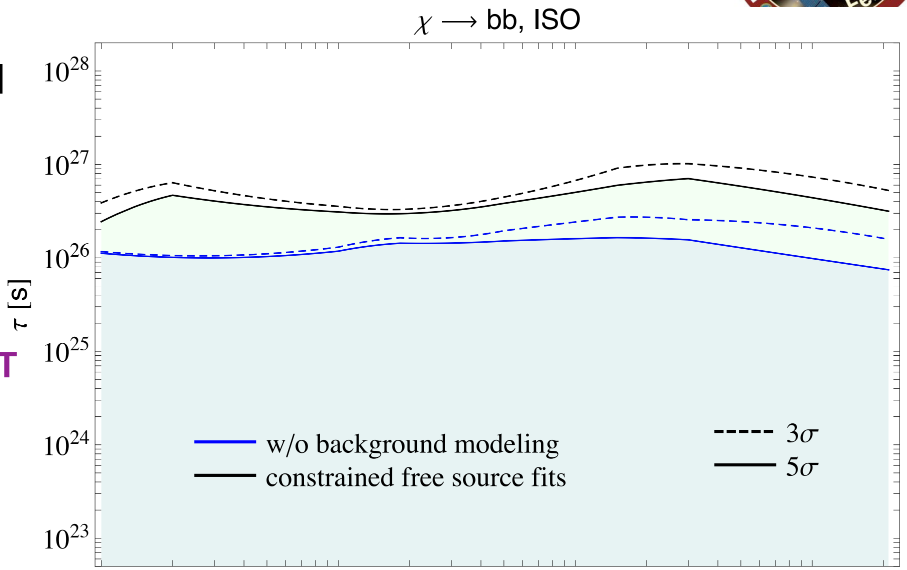


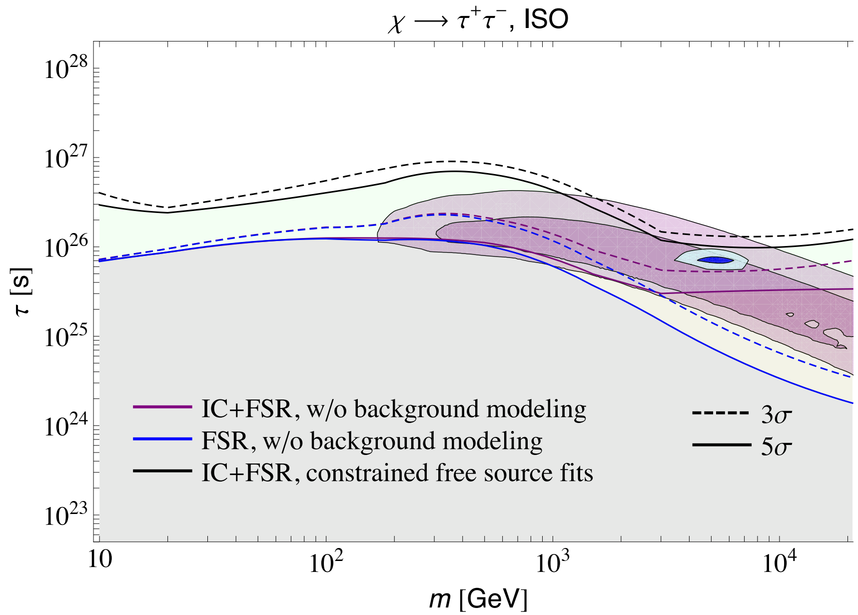
Results - DM limits

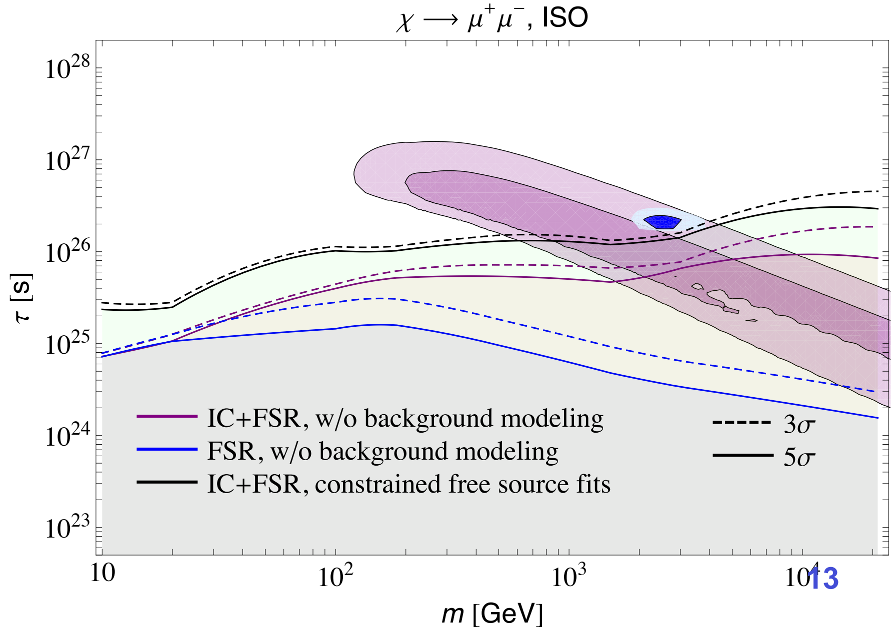
Limits on DM decay lifetime, for ISOthermal DM profile.

- Blue: "no-background limits".
- leptonic final states: purple lines: limits derived by modeling only the direct photon emission.

  Purple regions: fit to PAMELA and Fermi LAT electron/positron data, [Cirelli et al., 2010].







DM limits - additional uncertainties

- **Remaining parameters of the diffuse emission.**
  - Alfven speed, Galactic winds, ...
    - estimated to be at the level of 10%.
- **DM density profile and its overall normalization.**
  - sensitivity both on the DM density profile (probed)
  - and its overall normalization (factor of ~2).

Parameter	
v_A [30; **36**; 45] km s^{-1}	<~ 10%
$\gamma_{p,1}$ [1.8; **1.9**; 2;]	<~ 3%
$\gamma_{p,2}$ [2.35; **2.39**; 2.45]	<~ 3%
$\rho_{br,p}$ [10; **11.5**; 12.5] GV	<~ 2 %
d2HI [0.0110, **0.0140**; 0.0170] 10^{-20} mag cm^2	<~ 10 %

KRA($\delta = 0.5$); **KOL($\delta = 0.3$)**; PD($\delta = 0.6$)	[4.0; **0**; 3.0]	[1.0; **0**; 5]	<~ 5%
V_c [**0**; 20] km s^{-1}	[**0**; 6]	[**0**; 4]	<~ 6%
GMF [**Conf 1**, Conf 2]	[**0**; 3]	[**0**; 8]	<~ 10%

Summary

- **DM signal in our Galaxy high, but searches challenging due to bright diffuse emission signal degenerate with that of a DM.**
- **Several conservative choices in the analysis:**
  - **consider intermediate latitudes where uncertainty due to the profile is smaller.**
  - **model and subtract astrophysical signal only at >3 kpc from the GC, which is relatively well modeled (compared to inner Galaxy).**
- **Derived competitive DM limits (comparable to those of dwarf Galaxies & with different type of uncertainties) and demonstrated a method which could be used to study presence of additional components in the diffuse emission.**
- **To come: improved modeling of astrophysical mission (finer grid, more propagation models, Fermi bubbles) & inclusion of uncertainty in the DM density profile.**

BACKUP SLIDES

Full parameter tables

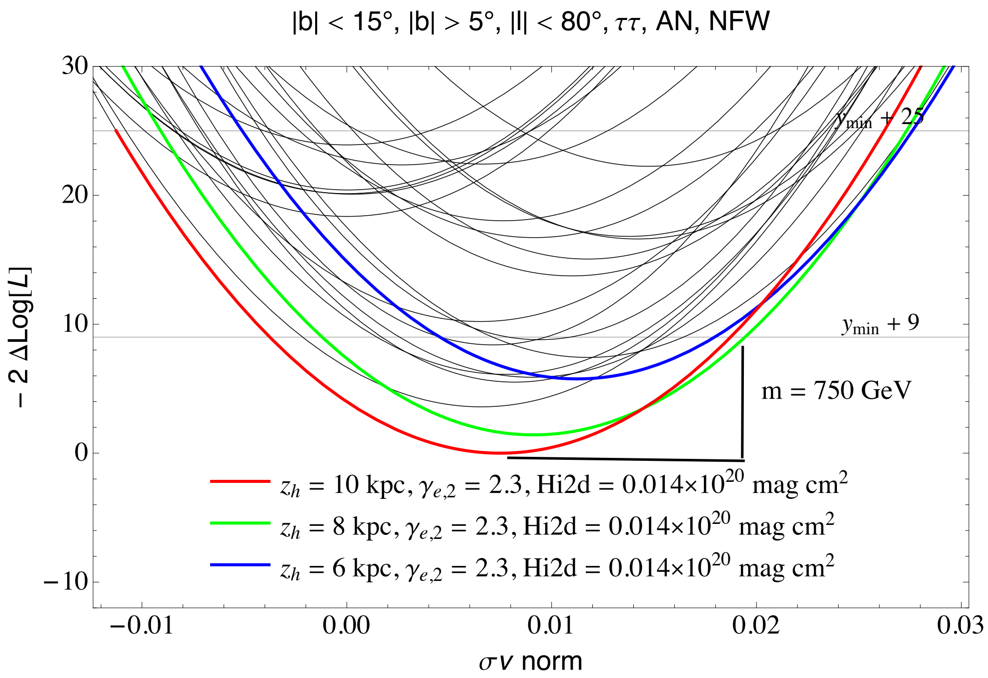
Non linear Parameters	Symbol	Grid values
index of the injection CRE spectrum	$\gamma_{e,2}$	1.925, 2.050, 2.175, 2.300, 2.425, 2.550, 2.675, 2.800
half height of the diffusive halo[a]	z_h	2, 4, 6, 8, 10, 15 kpc
dust to HI ratio	d2HI	(0.0120, 0.0130, 0.0140, 0.0150, 0.0160, 0.0170) $\times 10^{-20}$ mag cm^2

eCRSD and pCRSD coefficients	c_i^e,c_i^p	0,$+\infty$
local H_2 to CO factor	X_{CO}^{loc}	0-50 $\times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$
IGB normalization in various energy bins	$\alpha_{IGB,m}$	free
DM normalization	α_χ	free

Parameter	$\lvert\delta\sigma/\sigma\rvert$ [%], $b\bar{b}$	$\lvert\delta\sigma/\sigma\rvert$ [%], $\mu^+\mu^-$
v_A [30; **36**; 45] km s^{-1}	[6; **0**; 11]	[4.; **0**; 9]
$\gamma_{p,1}$ [1.8; **1.9**; 2;]	[1.0; **0**; 2.5]	[1.5; **0**; 2.0]
$\gamma_{p,2}$ [2.35; **2.39**; 2.45]	[2.5; **0**; 1.5]	[2.5; **0**; 1.5]
$\rho_{br,p}$ [10; **11.5**; 12.5] GV	[0.5; **0**; 1.0]	[0.9; **0**; 1.5]
d2HI [0.0110, **0.0140**; 0.0170] 10^{-20} mag cm^2	[3; **0**; 12]	[3;**0**; 9]
$\gamma_{e,2}$ [2.0; **2.45**; 2.6]	[17; **0**; 7]	[18; **0**; 5]
(D_0, z_h) [**(5.0e28, 4)**; (7.1e28, 10)] cm^{2}s^{-1}	[**0**; 10]	[**0**; 7]
CRSD [**SNR**; Pulsar]	[**0**; 61]	[**0**; 59]
KRA($\delta = 0.5$); **KOL($\delta = 0.3$)**; PD($\delta = 0.6$)	[4.0; **0**; 3.0]	[1.0; **0**; 5]
V_c [**0**; 20] km s^{-1}	[**0**; 6]	[**0**; 4]
GMF [**Conf 1**, Conf 2]	[**0**; 3]	[**0**; 8]

Profile likelihood method

- **Fits at different grid points are compared using the Profile likelihood method.**
  - **Minima of LogL functions is well populated, making it possible to set 3(5)σ DM limits marginalizing over many astro models.**
    - **The envelope of all LogL curves represents the final profile likelihood over which we set limits.**

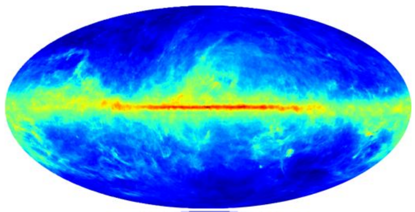


LogLikelihood vs DM normalization for a fixed DM model and mass.

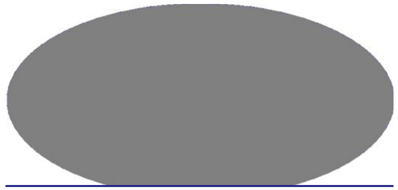
Fitting procedure - linear fits

- **For each DM model and each point on a grid we fit such whole sky maps to the data:**
  - **fitting components: three components of the astrophysical emission, dark matter maps and an isotropic map representing extragalactic emission.**
    - **We leave the overall normalizations (in each galactocentric ring) as a free parameters of a fit, incorporating both morphology and spectra.**

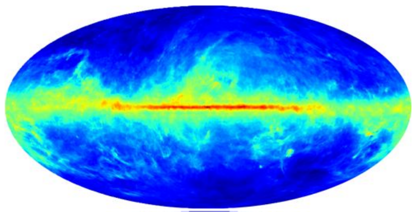
π^0 decay



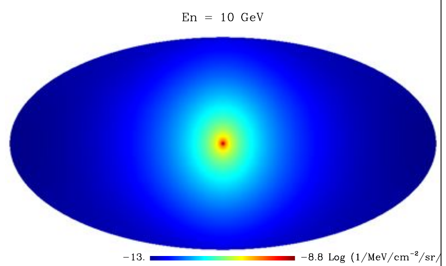
isotropic



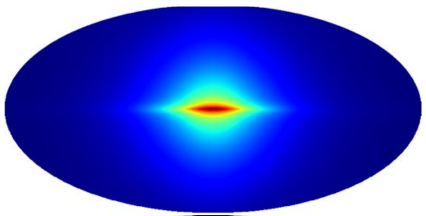
bremss



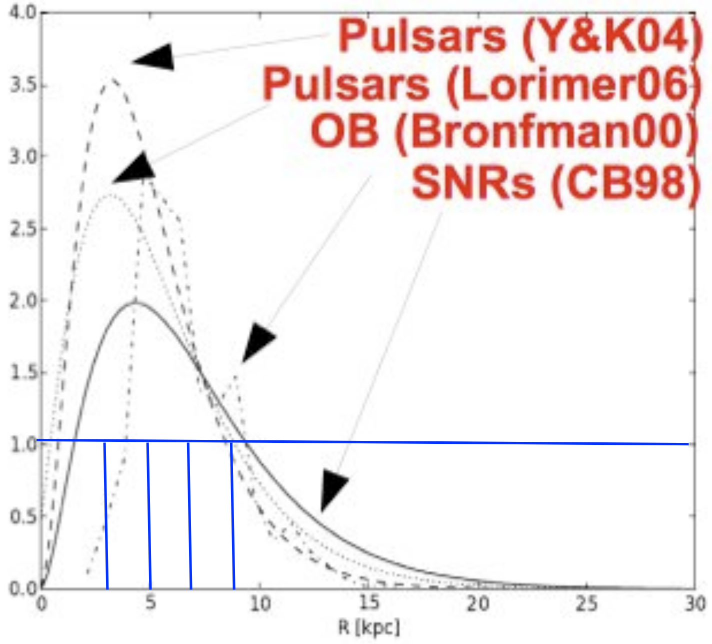
dark matter



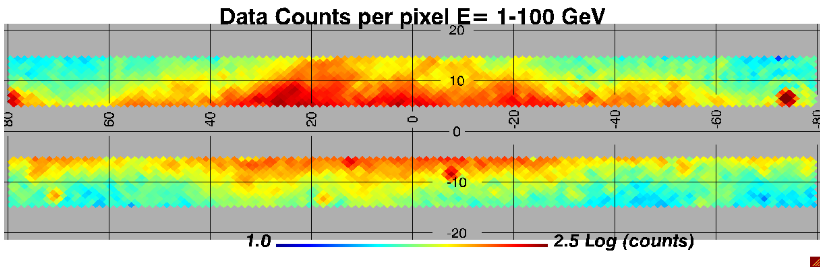
IC

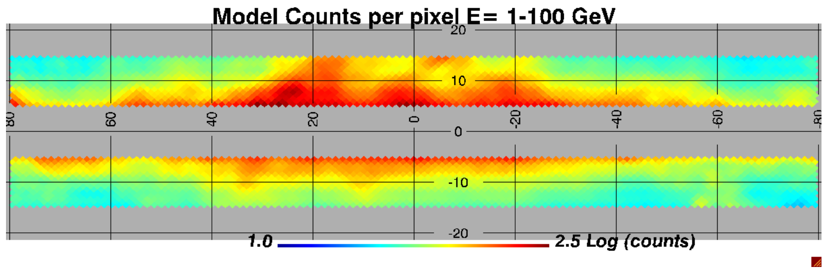


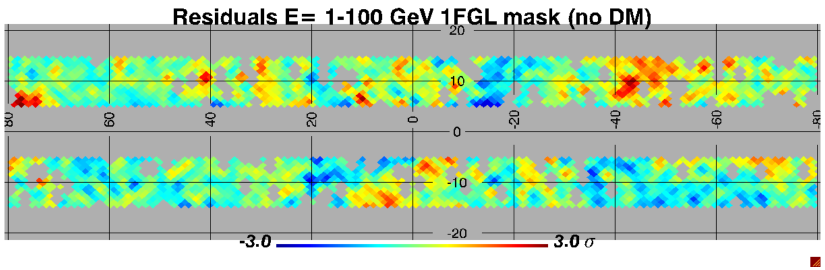
CR source distribution

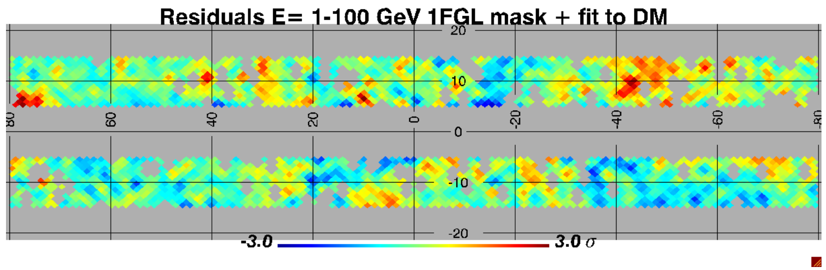


Residuals

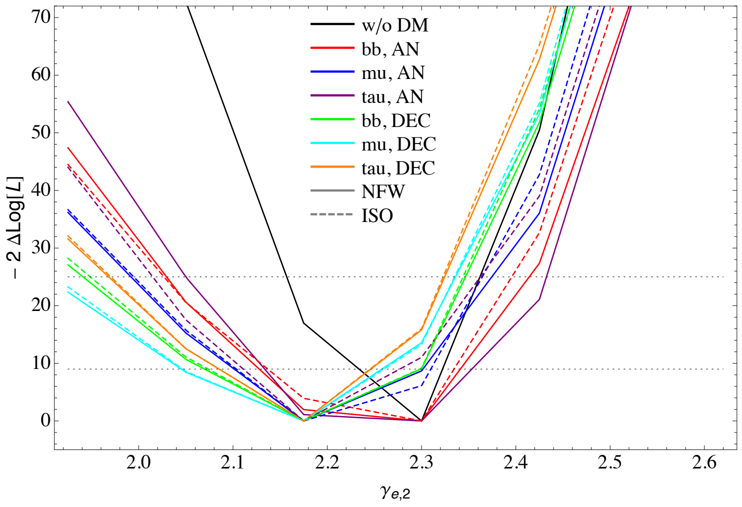

Data Counts per pixel E= 1-100 GeV
20
10
0
-10
-20
1.0
2.5 Log (counts)

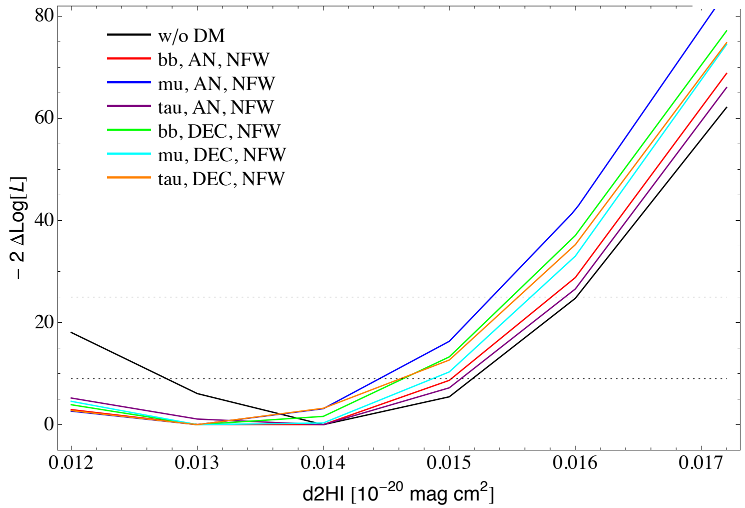

Model Counts per pixel E= 1-100 GeV
20
10
0
-10
-20
1.0
2.5 Log (counts)

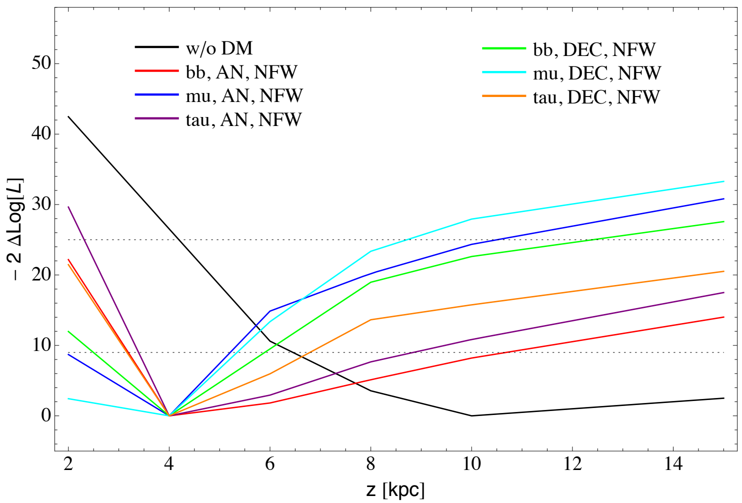

Residuals E= 1-100 GeV 1FGL mask (no DM)
20
10
0
-10
-20
-3.0
3.0 σ


Residuals E= 1-100 GeV 1FGL mask + fit to DM
20
10
0
-10
-20
-3.0
3.0 σ

Non linear parameters







$$
\begin{aligned}
I \;=\; \sum_i \Big\{ & c_i^p \left(H^i_{\pi^0} + \sum_j X^j_{\rm CO} H^{ij}_{2\,\pi^0}\right) + \\
& c_i^e \left(H^i_{\rm bremss} + \sum_j X^j_{\rm CO} H^{ij}_{2\,\rm bremss} + IC^i\right) \Big\} + \\
& \alpha_\chi \left(\chi_\gamma + \chi_{ic}\right) + \sum_m \alpha_{IGB,m}\, IGB^m .
\end{aligned}
$$