Fermi Gamma-ray Space Telescope

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

Gabrijela Zaharijas
(ICTP&INFN Trieste)

A. Cuoco, J. Conrad, Z. Yang

for the Fermi-LAT collaboration

ICTP The Abdus Salam International Centre for Theoretical Physics
INFN Istituto Nazionale di Fisica Nucleare
Oskar Klein centre

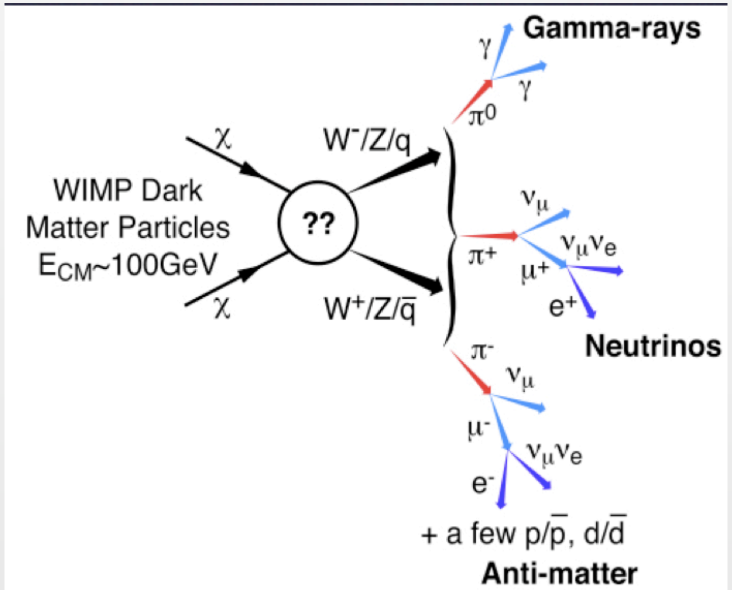
WIMP DM

P. Lipari's talk

While it is convincingly demonstrated from many experiments that DM makes up ~22% of energy density of the Universe, there are many candidates.

DM origin connected to the weak scale (hierarchy)? -> WIMPs:

A stable particle with a weak-scale mass, $M_\chi \sim M_Z$, which interacts with weak like interactions ($\sim G_F$) with the SM particles will be produced and freeze-out in the early universe with an observed thermal relic density!



$$\Omega_\chi h^2 \sim 0.1\ (3\ 10^{-26}\ \mathrm{cm^3 s^{-1}} / \langle \sigma v_{fo} \rangle)$$

Its relic density is determined by the very same annihilation processes we can use to detect it!

DM in γ rays

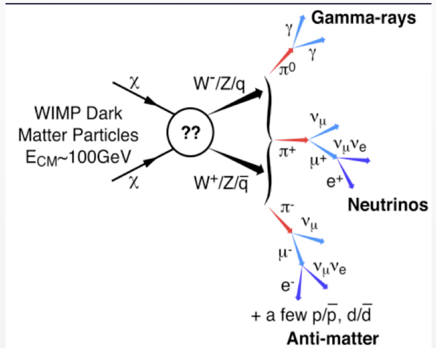
Gamma Ray Flux

(measured by Fermi-LAT)

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

Particle Physics

(photons per annihilation)

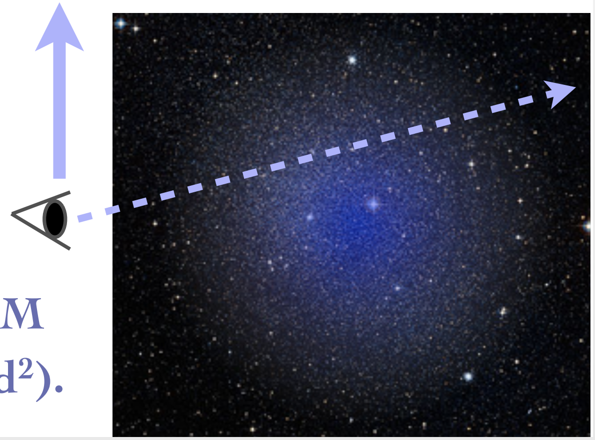


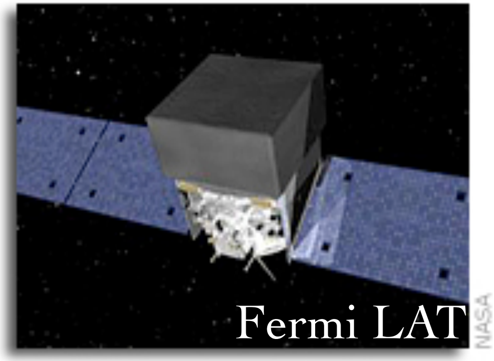
x

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

Dark Matter Distribution

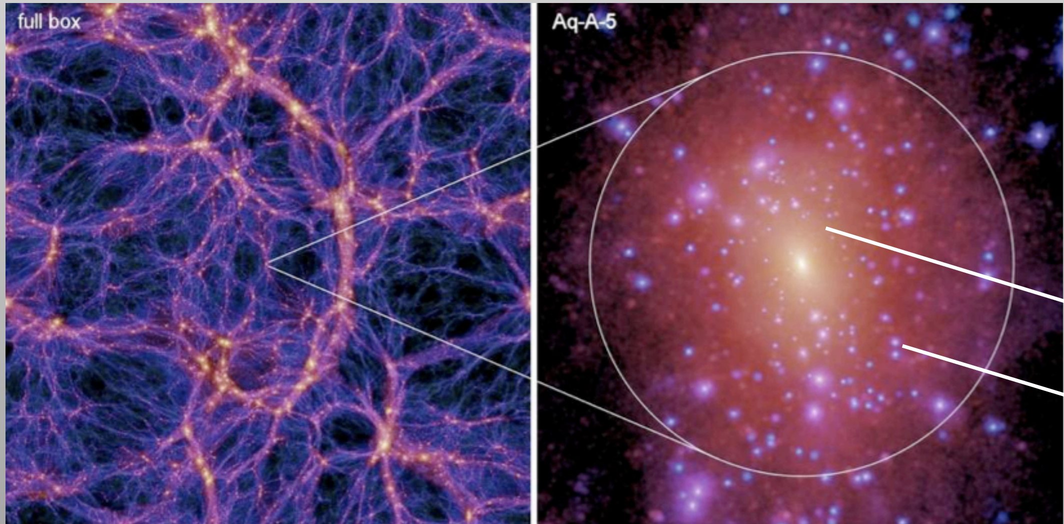
(line-of-sight integral)





Good targets: enhanced DM density (ρ^2) + close by ($1/d^2$).

DM in γ rays: morphology



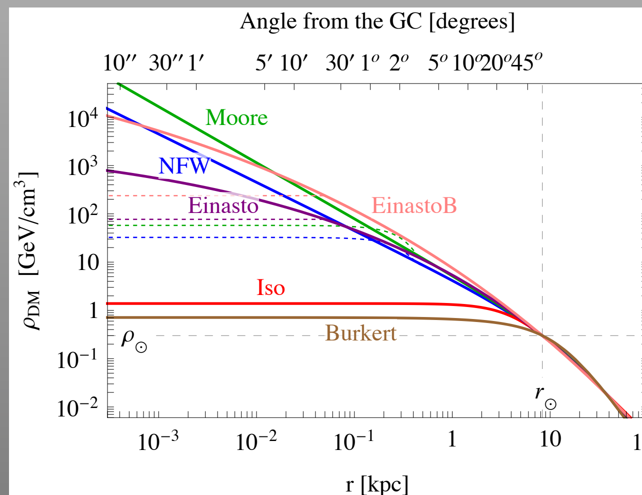
[Springel, V. et al, MNRAS, 2008.]

N-body simulations find *cuspy DM profiles* in smooth halos, and numerous subhalos population.

This talk

Maja's talk!

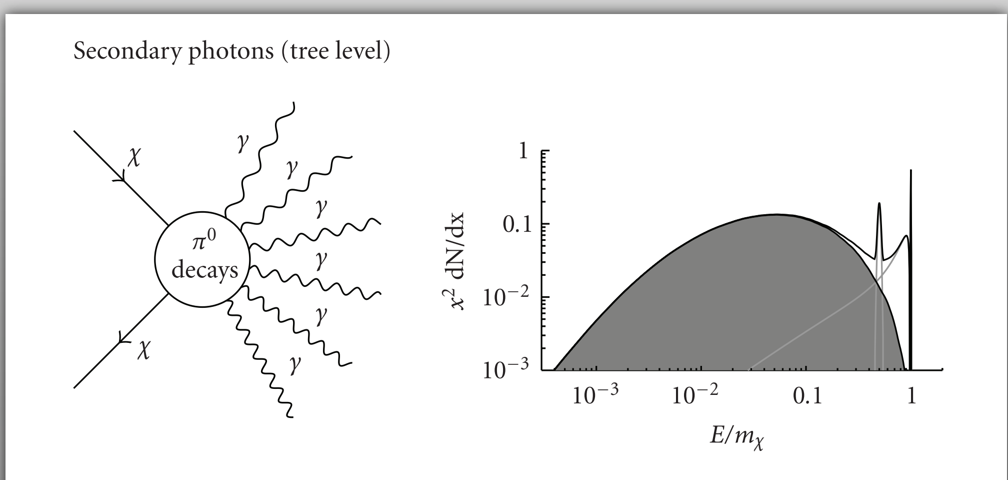
In our Galaxy, ϱ_{Sun}=0.43±0.15 GeV cm^{-3} (Salucci et al. 2010.); *NFW/Einasto profiles* found in simulations while *cored profiles* agree more with observations and some simulations which include baryons.



[Cirelli, M. et al. JCAP, 2011.]

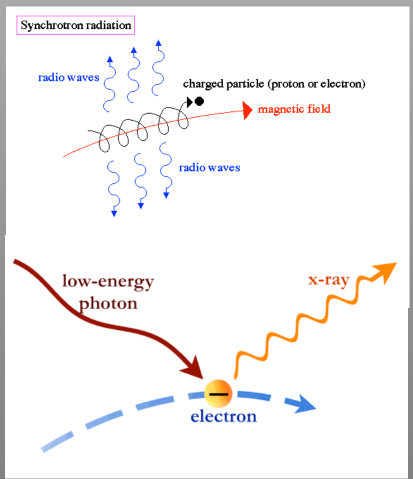
DM in γ rays: spectra

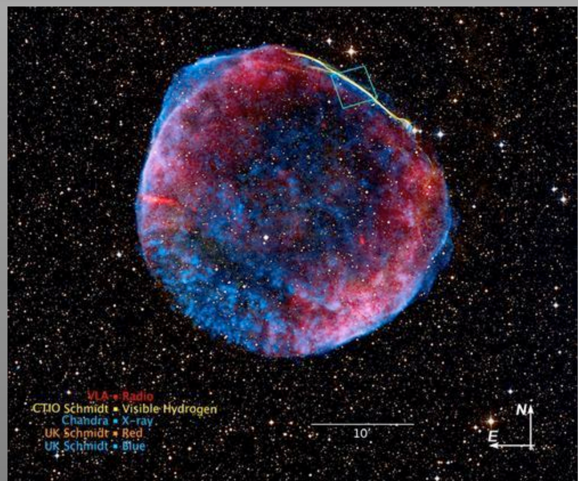
This talk



[M. Kuhlen, AA, 162083]

- for DM annihilation channels to gauge bosons and/or quarks/tau: annihilation products hadronize producing π^0 which then decays to gammas.
  most likely scenario; morphology follows that of a DM distribution.

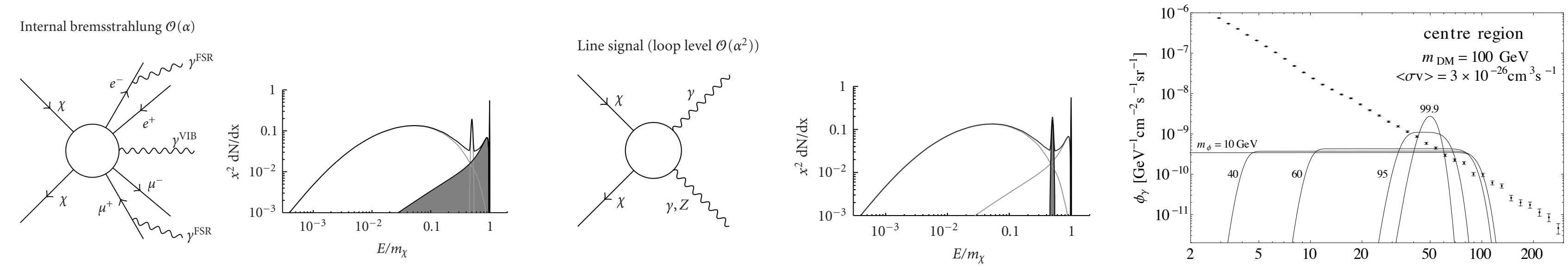




- for DM annihilation channels to leptons: gammas are produced in electron radiative losses: morphology correlates with ambient backgrounds and fields.

DM in γ rays: spectra

P. Lipari's talk

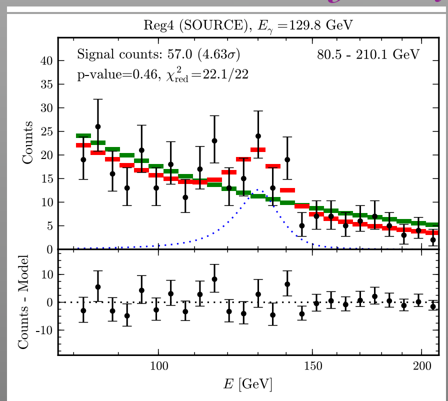


[M. Kuhlen, AA, 162083]

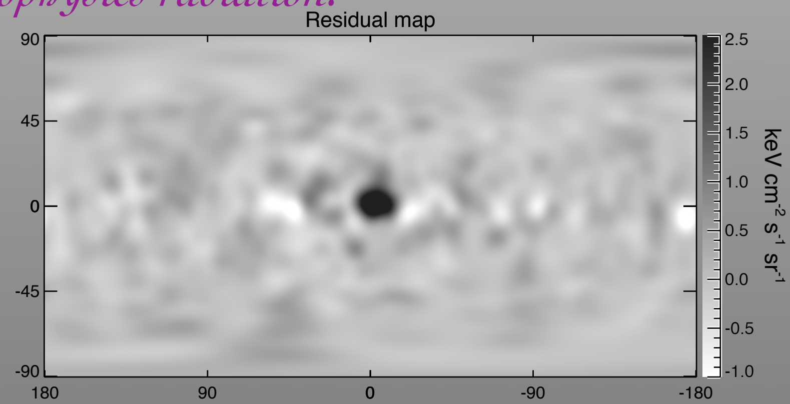
[A. Ibarra et al., 2012]

- 'Feature-full' (hard or line shaped) emission (photons from Final State Particles (FSR) or internal states (VIB) and annihilation to a γ-ray line (two photons/Zγ) through loop processes); or box shaped emission, to four photos via an intermediate state. *low signals but easier to distinguish from astrophysics radiation.*

Claims of a tentative detection of such signature ~130 GeV, in the vicinity of the GC; Fermi LAT analysis in progress.

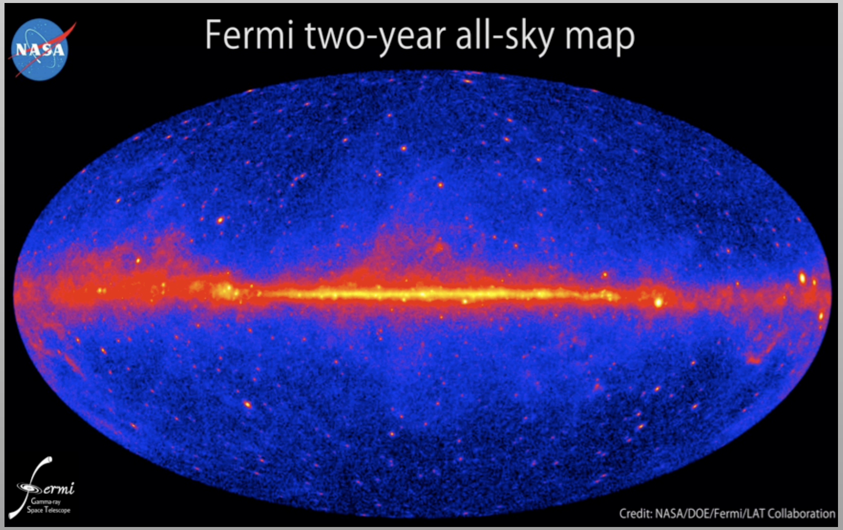


[C.Weniger, 1204.2797]



[Su and Finkbeiner, 1206.1616]

The Fermi sky

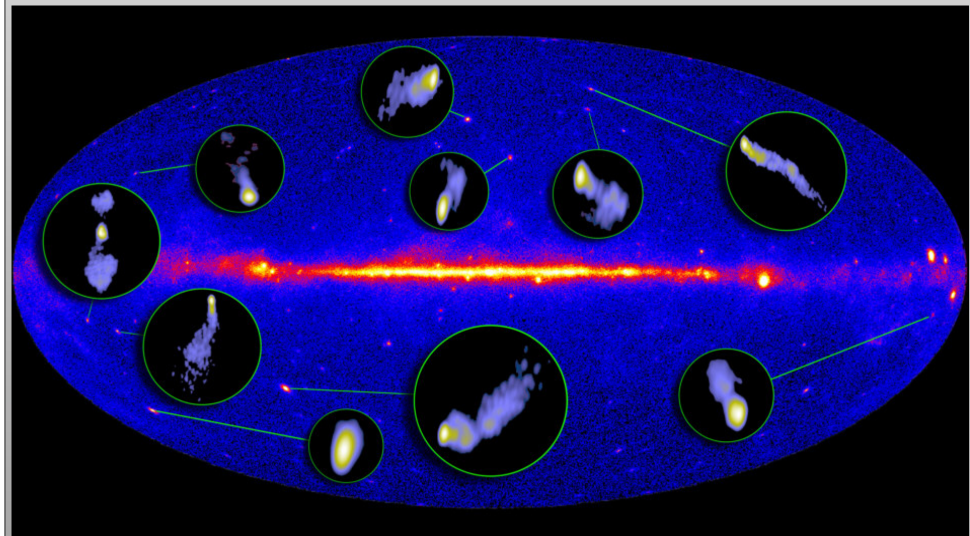
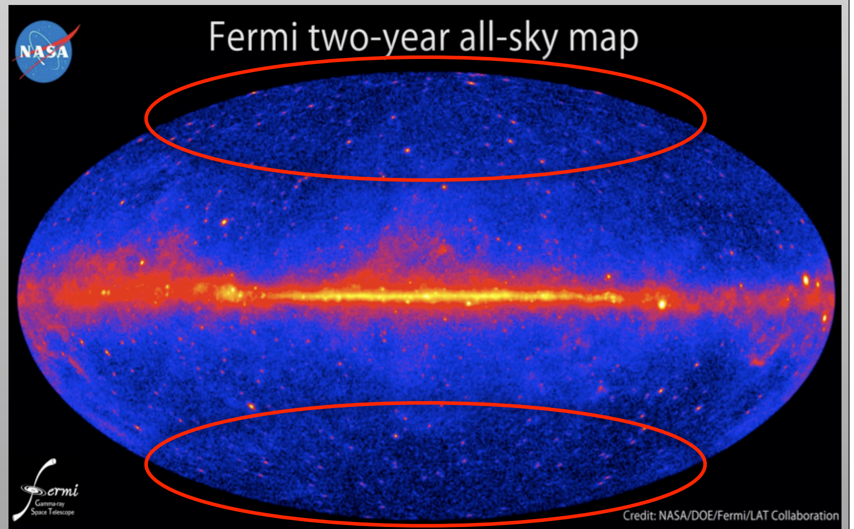


★ *Diffuse emission: Majority (~90%) of LAT photons. Diffuse emission* was measured for the first time with this satellite at energies >~ 10 GeV.

This talk

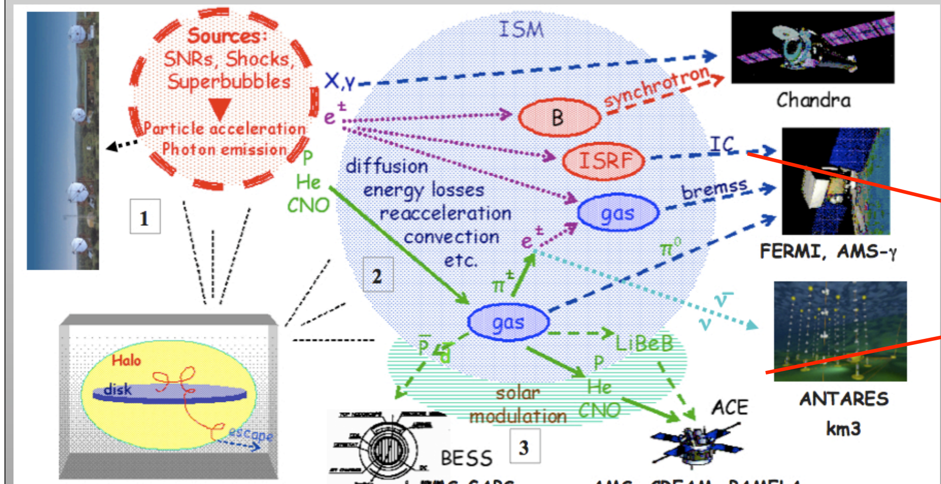
★ Point sources: 1888 sources in 2FGL (AGNs, pulsars, SNR, ...)

Diffuse emission

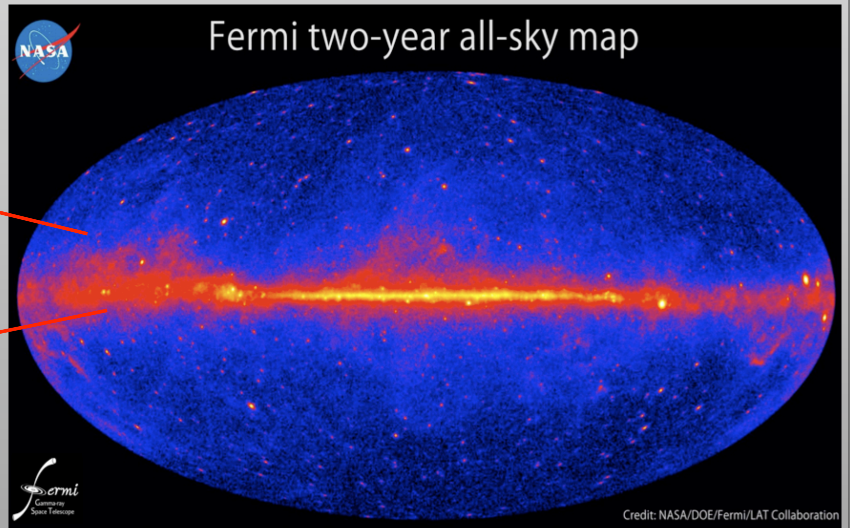
 

Two components:
Isotropic: high latitude emission, due to e.g. unresolved energetic extragalactic sources.

Diffuse emission



Adapted from Moskalenko et al. (2004)



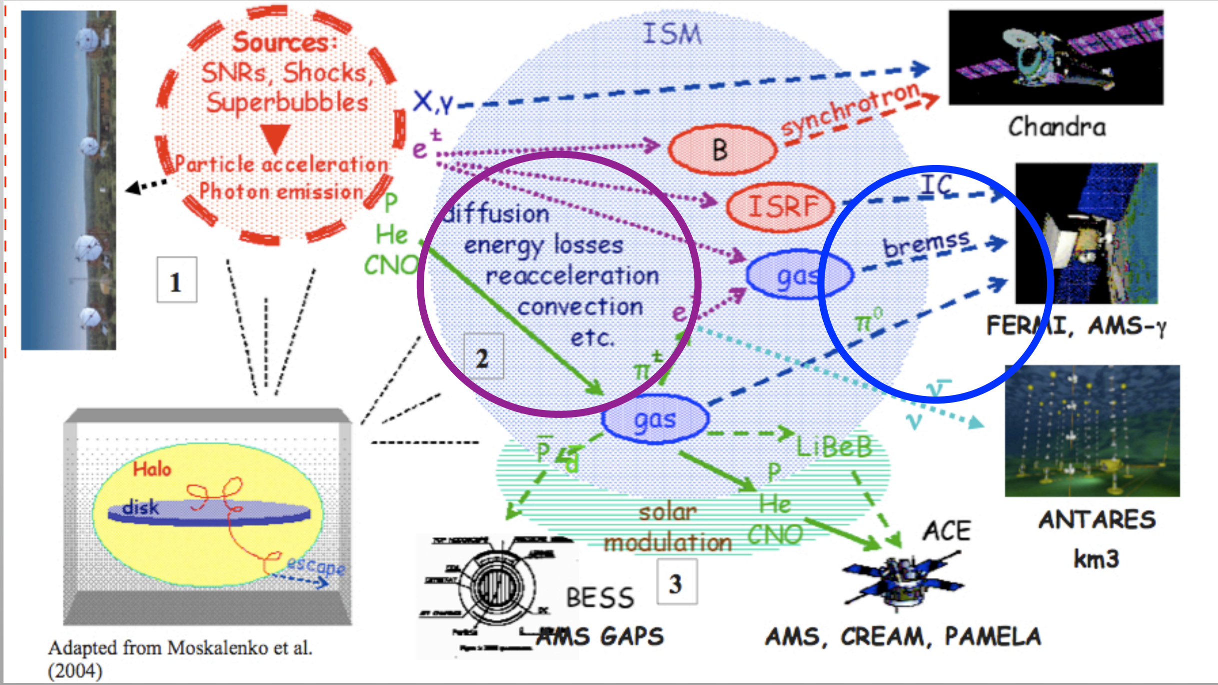
Two components:

Galactic: interaction of CR e/p/nuclei with interstellar medium and fields.

Galactic diffuse emission: γ-rays

E. Orlando's
P. Blasi's talks

distribution of CR sources in the disk and their energy injection spectrum



γ rays in the Fermi-LAT energy range:

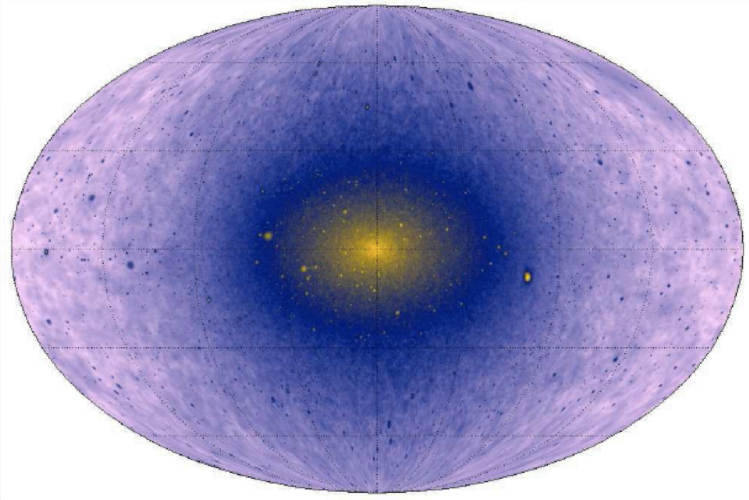
- *π^0 decay* produced by *CRp* scattering on the *interstellar gas*.
- Inverse Compton scattering of *CRe* on *interstellar radiation field*,
- bremsstrahlung from *CRe* scattering on the *interstellar gas*.

γ ray emission correlates spatially with the gas and ISRF distribution and depends on spatial and energy distribution of interstellar CR.

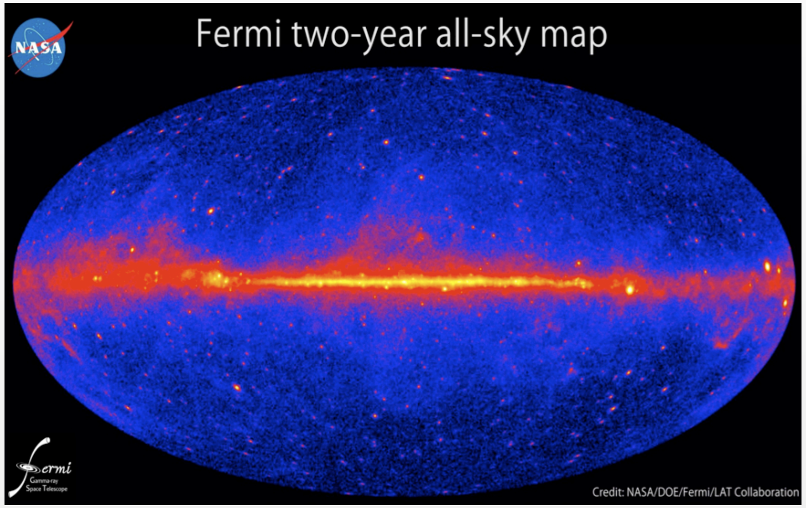
We use an 'effective' theory as implemented in GALPROP.

MW halo as a DM target

Predicted DM gamma ray signal.



Diemand et. al, APJ, 2006.



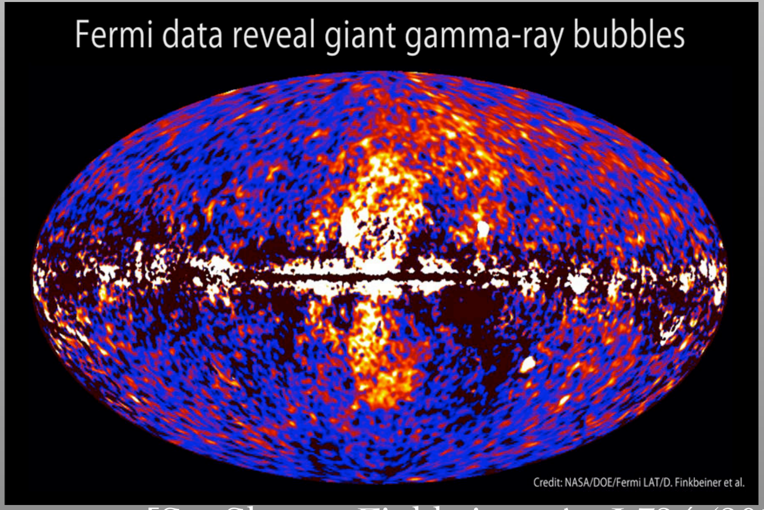
DM signal expected to be high (Sun is 'only' ~8 kpc away from the GC + DM content of the Milky Way is high!)
but, diffuse emission presents strong background + there are no smoking guns in this analysis!

→ standard astrophysical emission expected to correlate with the gas and radiation field content.
→ naive estimates S/N for DM searches optimal ~10 deg away from the Galactic plane

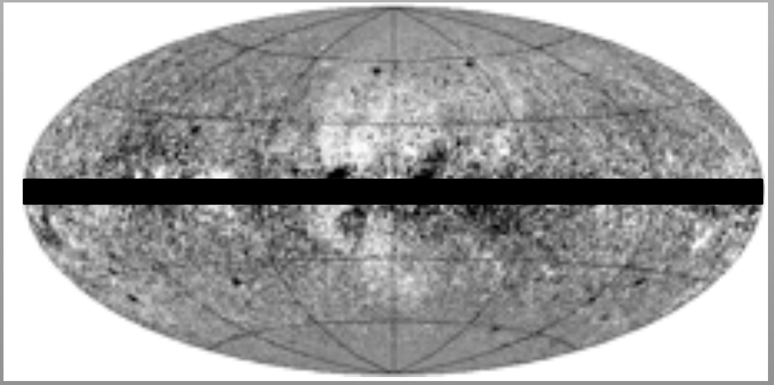
However Fermi-LAT revealed extended structures in the γ-ray diffuse emission:

- *Fermi bubbles*: a lobe like emission in the region of the Galactic Center
- Loop-1 (discovered previously in radio)

Residuals (data-modeling):



[Su, Slatyer, Finkbeiner, ApJ 724 (2010)]



[Casandjian, FS (2009)]

Because of a substantial uncertainty in diffuse modeling and degeneracies with DM signal, we set DM limits rather than look for its signatures.

Data set and Region of interest

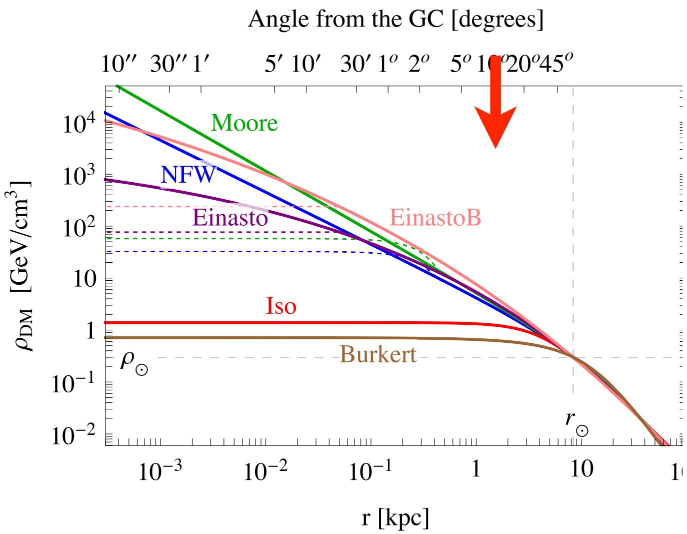
Data set: 24 months data, p7 clean event selection in the 1-100 (400) GeV energy range.

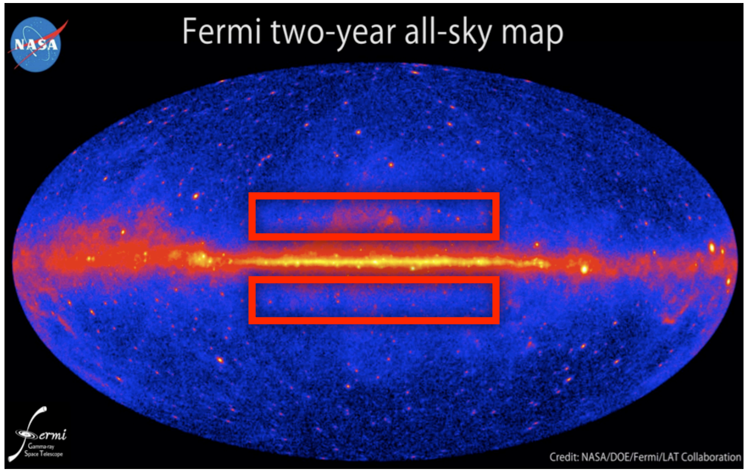
ROI: 5° <|b|<15° and |l|<80°.

This way we:

1 - *minimize DM profile uncertainty* (which is the highest in the Galactic Center region)

2 - *limit astrophysical uncertainty* by masking out the Galactic plane, *cutting-out high latitude emission from* Fermi lobes/Loop I





DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.

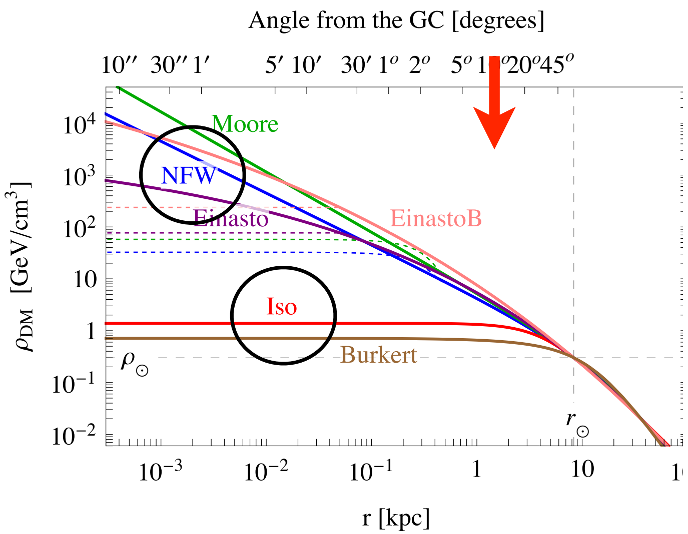
Two DM density profiles:

i) NFW and

ii) Isothermal DM profiles.

$$\text{NFW}: \quad \rho(r) = \rho_0 \left(1+\frac{R_S}{R_0}\right)^2 \frac{1}{\frac{r}{R_S}\left(1+\frac{r}{R_0}\right)^2}$$

$$\text{Isothermal}: \quad \rho(r) = \rho_0 \frac{R_S^2+R_c^2}{r^2+R_c^2}.$$



ρ_0=0.43 GeV/cm^3,

R_c=20 kpc (NFW), 2.8 kpc (Iso)

In our ROI, at
5<b<15deg →r ~1 kpc
the two profiles are quite similar (advantage wrt the Galactic Center studies, for example)

DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.

Two DM density profiles:

i) annihilating ($\chi\chi \rightarrow$SM SM) characterized by annihilation cross section $\langle\sigma v\rangle$ and

ii) decaying ($\chi \rightarrow$SM SM) characterized by the life time τ.

DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.

Three DM annihilation/decay channels:

i) $\chi\chi/\chi \rightarrow bb$

ii) $\chi\chi/\chi \rightarrow \mu\mu$

iii) $\chi\chi/\chi \rightarrow \tau\tau$

DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.

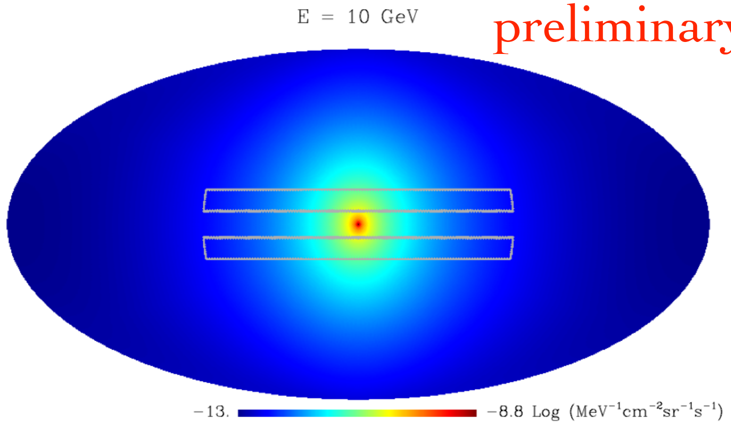
Three DM annihilation/decay channels:

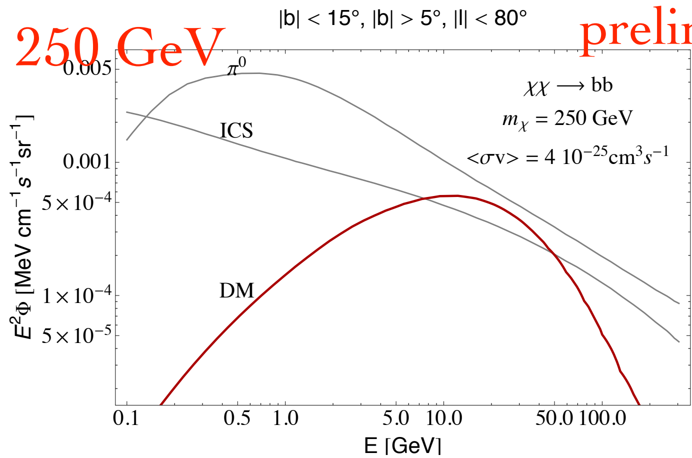
i) χχ/χ→bb

ii) χχ/χ→μμ

iii) χχ/χ→ττ

i) χχ/χ→bb→ qq… → π^0…→ photons





DM models

We test a set of 12 DM benchmark cases, in the mass range 5 GeV-10 TeV.

Three DM annihilation/decay channels:

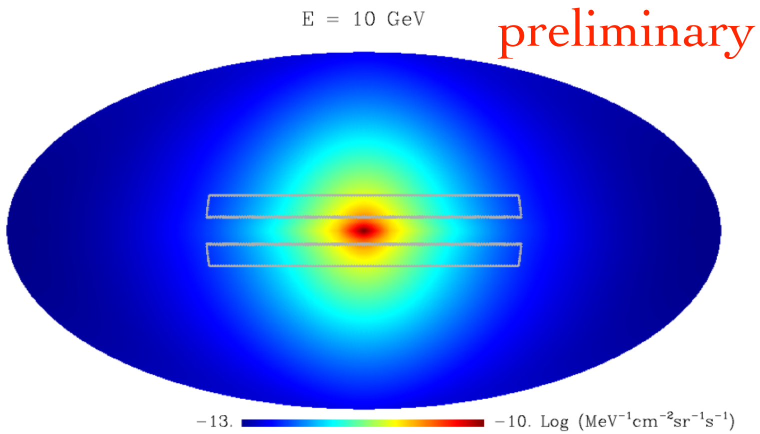
i) $\chi\chi/\chi \rightarrow bb$

ii) $\chi\chi/\chi \rightarrow \mu\mu$

iii) $\chi\chi/\chi \rightarrow \tau\tau$

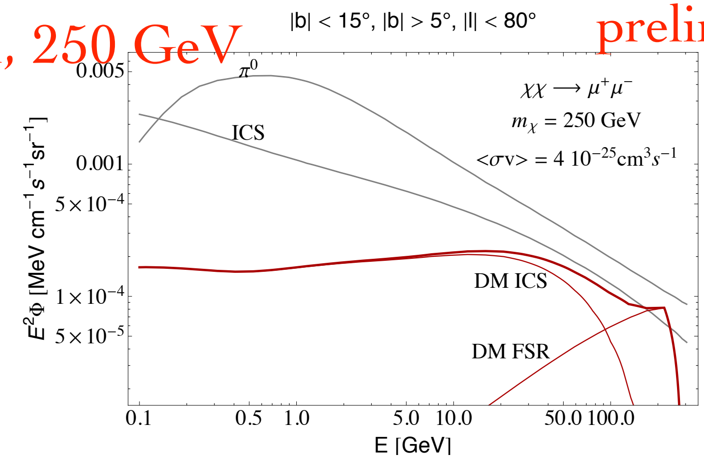
ii) $\chi\chi/\chi \rightarrow \mu\mu(\tau\tau) \rightarrow ee... \rightarrow$ photons radiated from final and internal states

$\rightarrow$ radiative photons (IC in interactions with ambient ISRF)



preliminary

μμ, 250 GeV



preliminary

When electrons are produced in DM annihilation/decay they were *propagated with the GALPROP code*, with propagation parameters consistent with the one used to model astrophysical diffuse emission.

Method 1

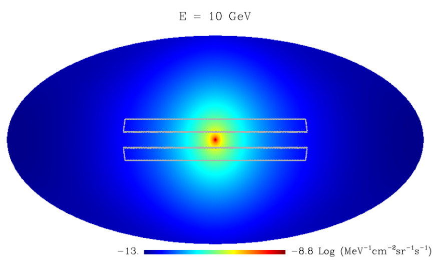
conservative 'no-background' limits:

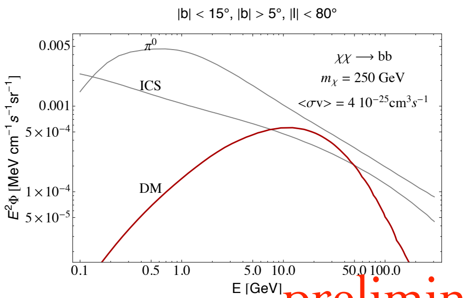
These limits do not involve any modeling of the astrophysical background, and are robust to that class of uncertainties (i.e. they are *conservative*).

The expected counts from DM, (n_{DM}) are compared with the observed counts (n_{data}) and the upper limits at 3(5) sigmas is set from the requirement:

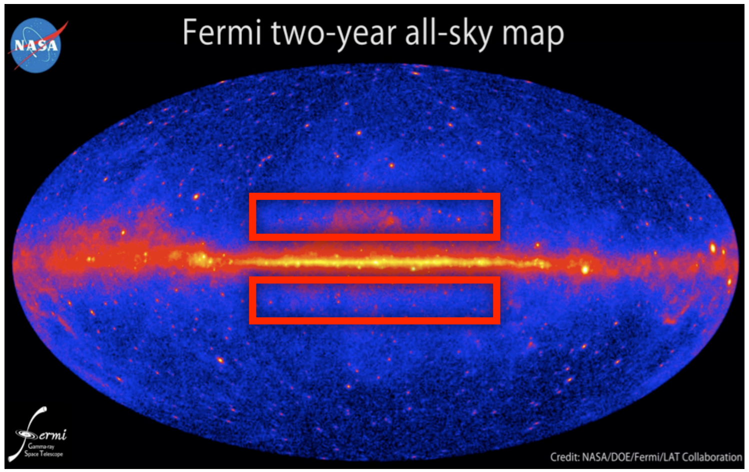
$n_{DM} - 3(5)\sqrt{n_{DM}} > n_{data}$,

in at least one energy bin.





preliminary

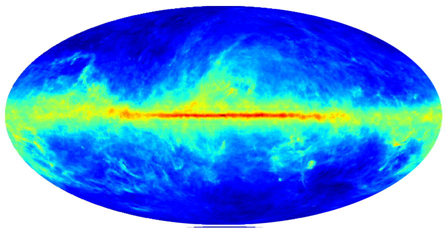


Method II

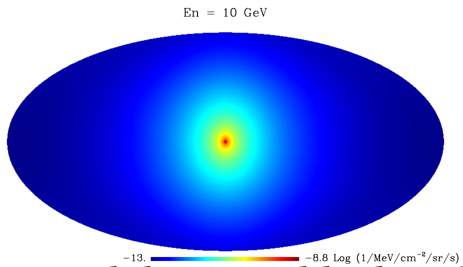
Limits derived with modeling the astrophysical signal:

To take into account uncertainties in the diffusion modeling we *model together standard and DM induced diffuse emission.*

Why is that important? Significant degeneracy among the two signals.



standard astrophysical emission



DM annihilating to bb chanel

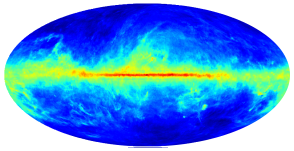
We demonstrate a method in which we use the gamma ray data to determine the best fit astrophysical and DM parameters. We then turn the problem around and use this machinery to set DM limits.

Note here that due to our limited ROI derived astrophysical parameters are only effective, because we do not fit the full sky (work in progress).

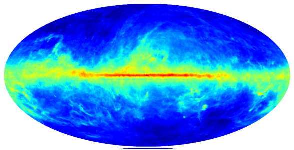
Fitting procedure: linear parameters

For each set of *parameters which enter a CR propagation equation* (size of the diffusion zone, diffusion index, etc) we produce *the three components of the Galactic diffuse emission.*

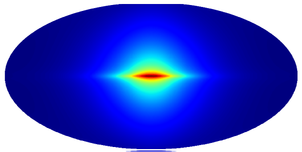
π^0 decay



bremss



IC

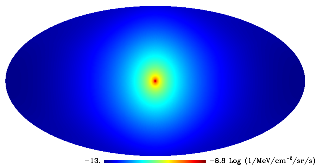


ADD an isotropic map (to mimic isotropic extra Galactic contribution)

isotropic

AND a DM map, for a fixed mass and particle physics benchmark case:

dark matter



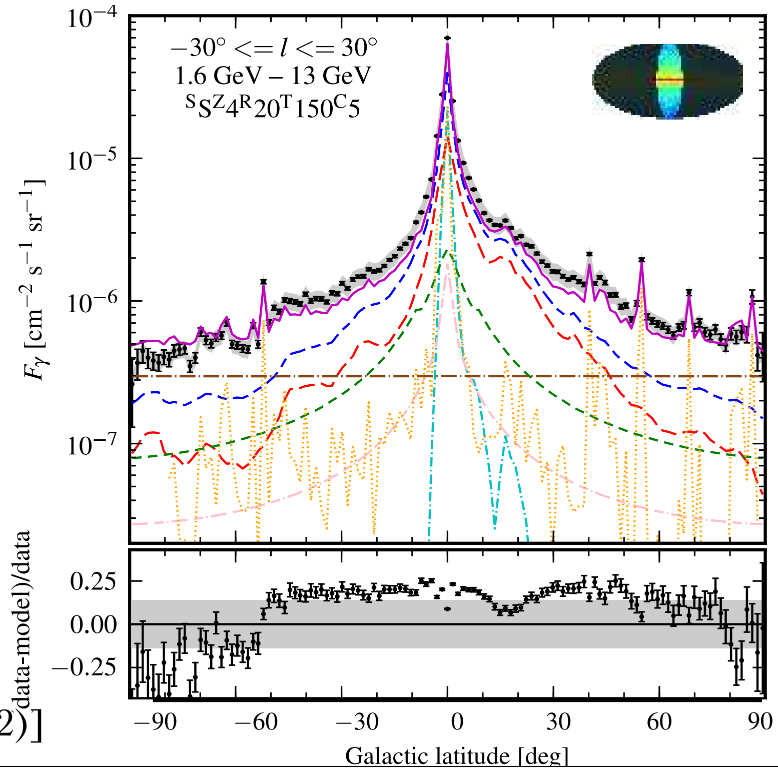
We *fit these templates to the data,* leaving their overall normalizations as a free (linear!) parameters of a fit (incorporating both morphology and spectra).

Fitting procedure: non-linear parameters

However, to take into account uncertainties in the diffusion modeling we repeat this procedure *over a grid of astrophysical models*.

In particular, we scan over CR parameters which are *degenerate* with a DM signal:
1- *height of the diffusive zone* (2<z<15 kpc;
with rest of parameters fixed by the CR data and B/C ratio)

A larger halo gives a broader latitude distribution → degenerate with DM contribution.



[Ackermann et al., ApJ (2012)]

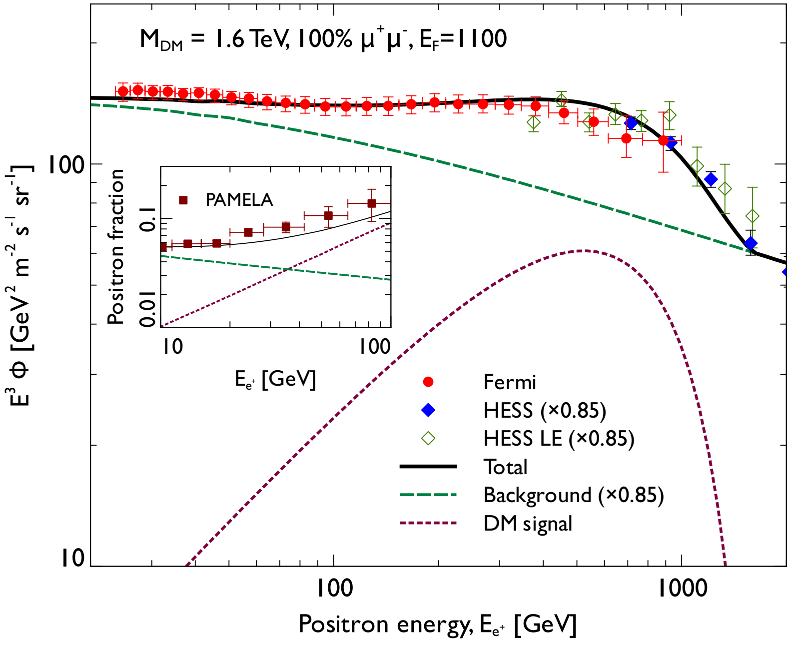
Fitting procedure: non-linear parameters

However, to take into account uncertainties in the diffusion modeling we repeat this procedure *over a grid of astrophysical models*.

In particular, we scan over parameters which are *degenerate* with a DM signal:
2- *electron injection index* (1.8<eI<2.9)

Harder electron injection spectrum → harder gamma-ray emission → can be confused with a DM contribution (if DM too produces electrons).

Bergström, Edsjö & Zaharijas 2009



Fitting procedure: non-linear parameters

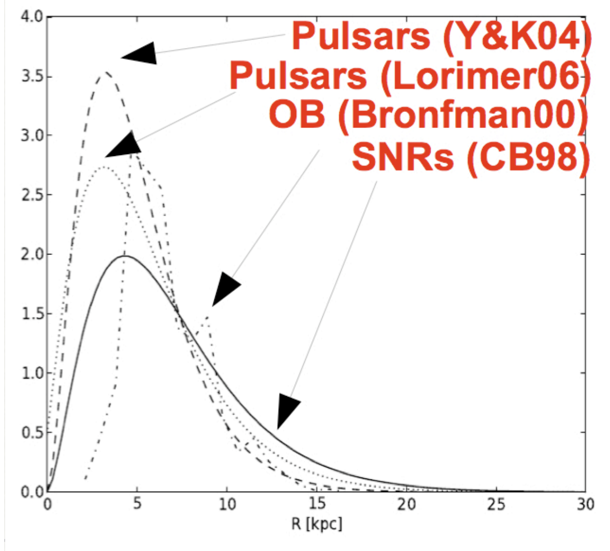
However, to take into account uncertainties in the diffusion modeling we repeat this procedure *over a grid of astrophysical models*.

In particular, we scan over parameters which are degenerate with a DM signal:
3- different choice for the gas maps: dust to gas ratio (0.0120<d2HI<0.0170)

Underestimating gas content in some regions of the Galaxy can also be compensated by DM.

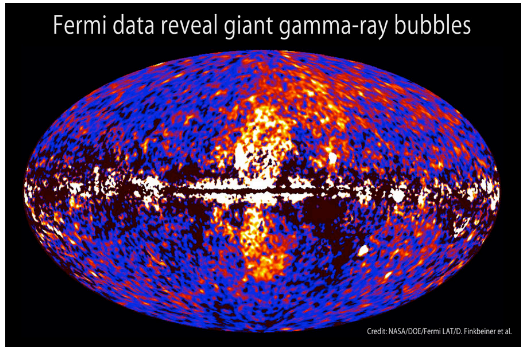
Radial distribution of CR sources (additional linear parameters)

CR source distribution is obtained from observation of SNR or its tracers. *Large observational bias towards the Galactic Center* → source distribution in that region degenerate with a DM contribution.



We produce template maps for a CR source distribution, which is a step function in radial bins. We then fit these radial bins to the data and determine *the distribution of CR consistently with the other parameters!*

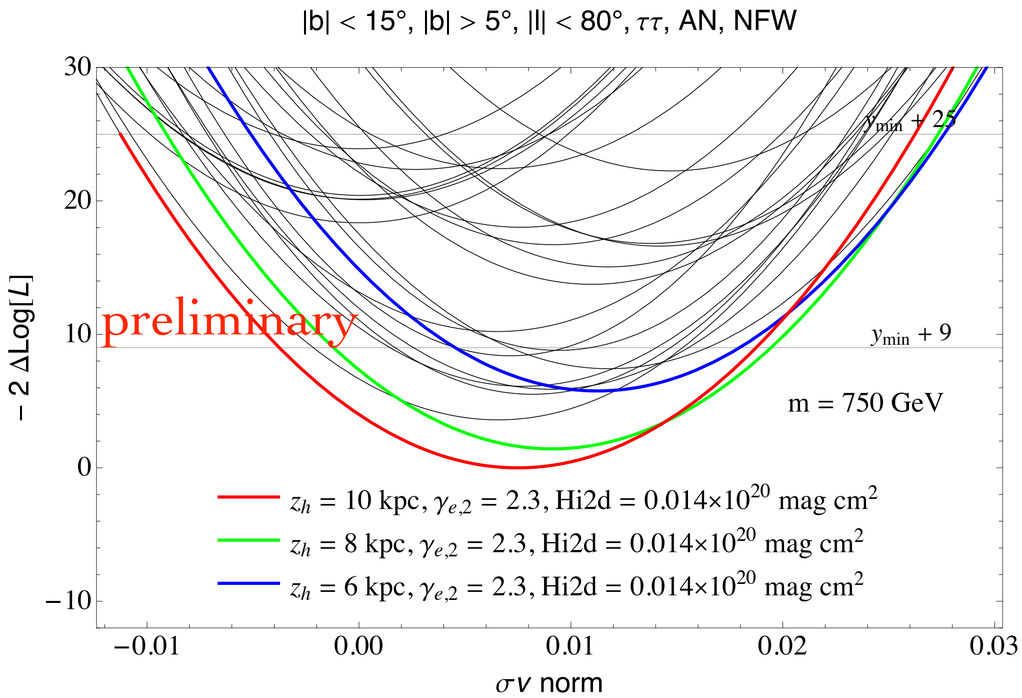
In addition we constrain astrophysical sources to be zero within 3 kpc from the GC region to stay conservative, given the complicated region.



Profile likelihood method

The profile likelihood method is used to combine all the models on a grid, and to derive the DM limits marginalized over the astrophysical uncertainties.

LogLikelihood vs DM normalization (σv)
for a *fixed* DM model and a mass:



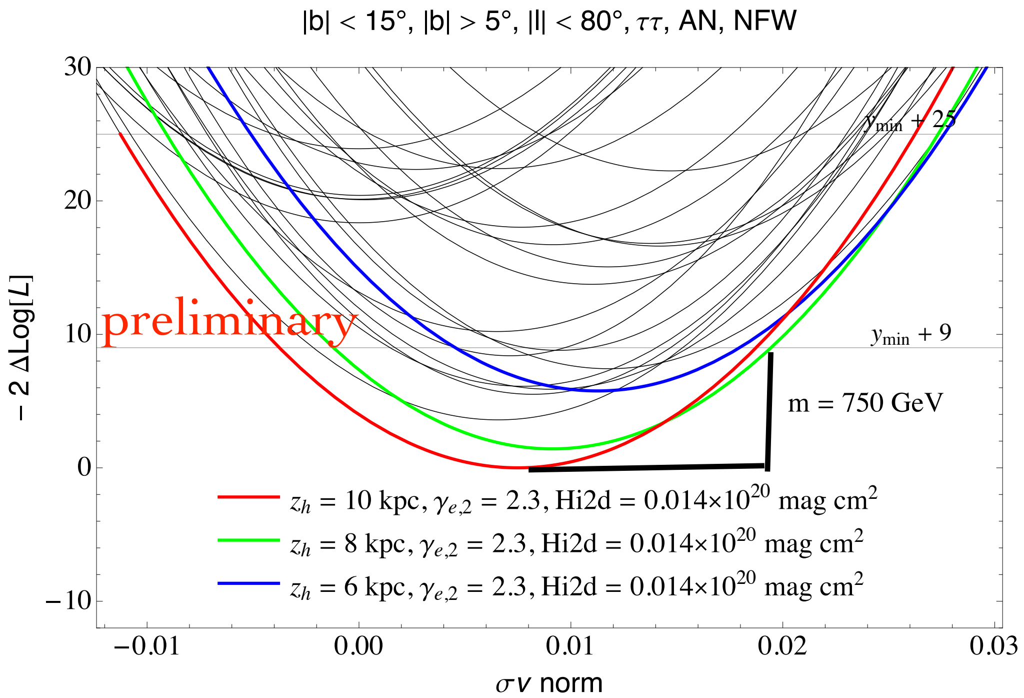
Different curves correspond to *different sets of non-linear parameters* - *different grid points!*

For each DM normalization then, the best fit linear parameters are found, and the overall likelihood of the model.

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

Profile likelihood method

LogLikelihood vs DM normalization (σv) for a *fixed* DM model and a mass:

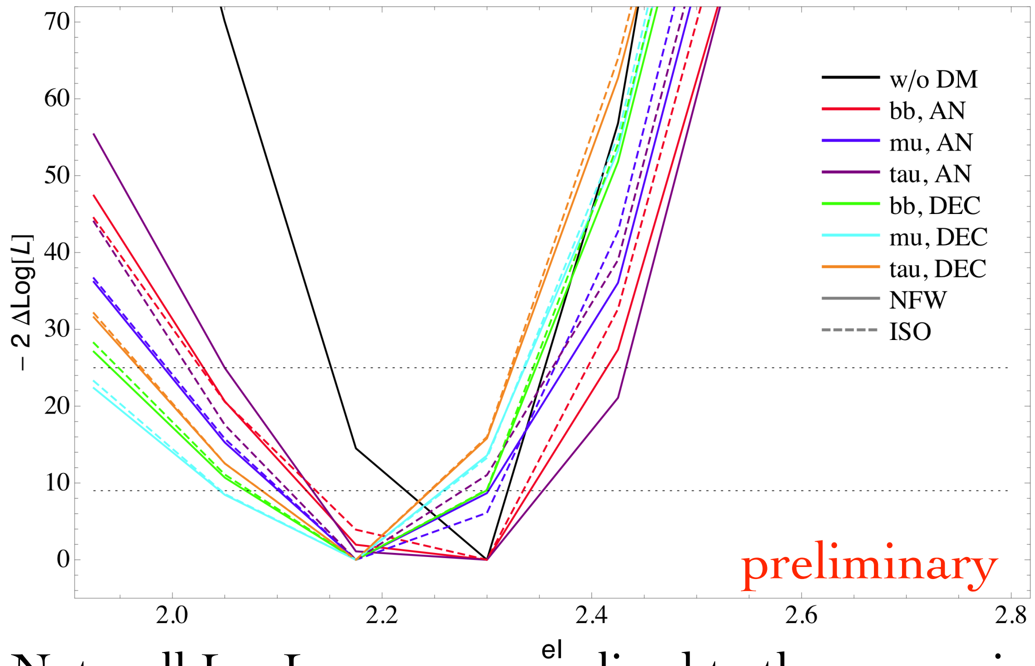


The envelope of all LogL curves represents the final profile likelihood over which we set limits.

Minima of LogL functions is *well populated*, making it possible to set 3(5)σ DM limits marginalizing over *many astro models* which are within 3 (5)σ within the minimum!

Results

The profile likelihood method can be used also to determine other parameters.



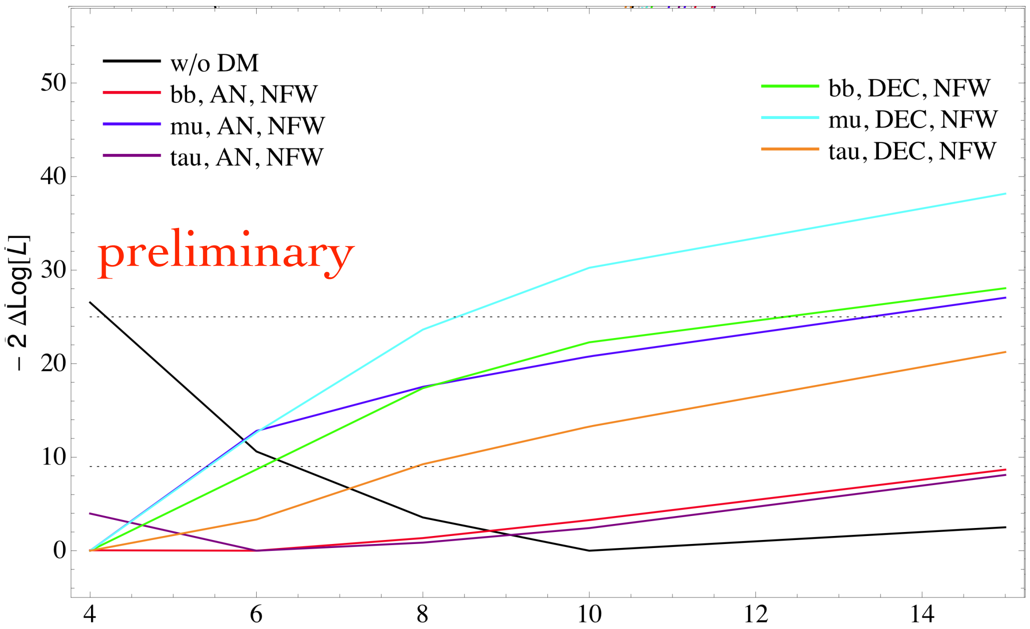
Profiles over single CR parameters show that many models are within 3 (5)σ of the minimum:
All models with
1.9<eI<2.5,
0.0120<HI2d<0.0160,
4<z<15
populate the minimum.

Note: all LogLs are renormalized to the same minimum.

In other words, *DM limits are not set based on a single diffuse model, but most of the models within working framework are within 3(5) σ of the minimum, and are thereby marginalized over to define the 3(5) σ DM limits.*

Results

The profile likelihood method can be used also to determine other parameters.



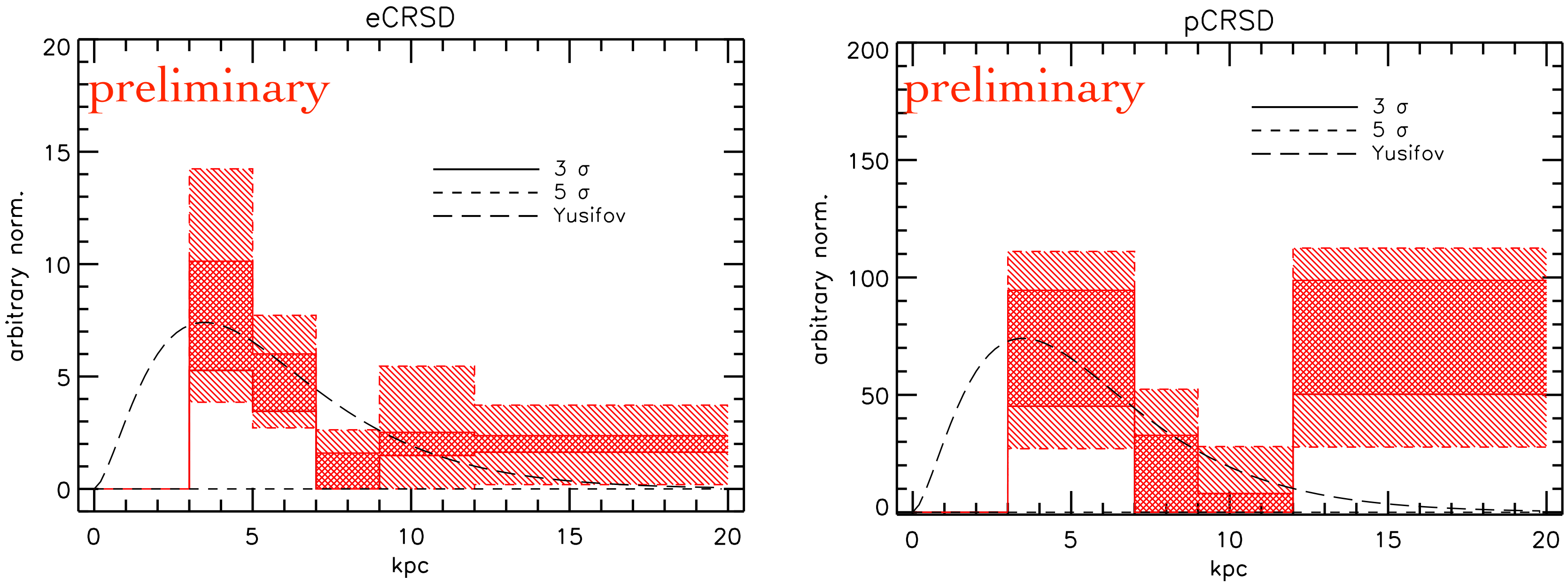
Profiles over single CR parameters show that many models are within 3 (5)σ of the minimum:
All models with
1.9<eI<2.5,
0.0120<HI2d<0.0160,
4<z<15
populate the minimum.

Note: all LogLs are renormalized to the same minimum.

In other words, *DM limits are not set based on a single diffuse model, but most of the models within working framework are within 3(5) σ of the minimum, and are thereby marginalized over to define the 3(5) σ DM limits.*

Results

Distribution of CR electrons and of CR protons, obtained in the fit.

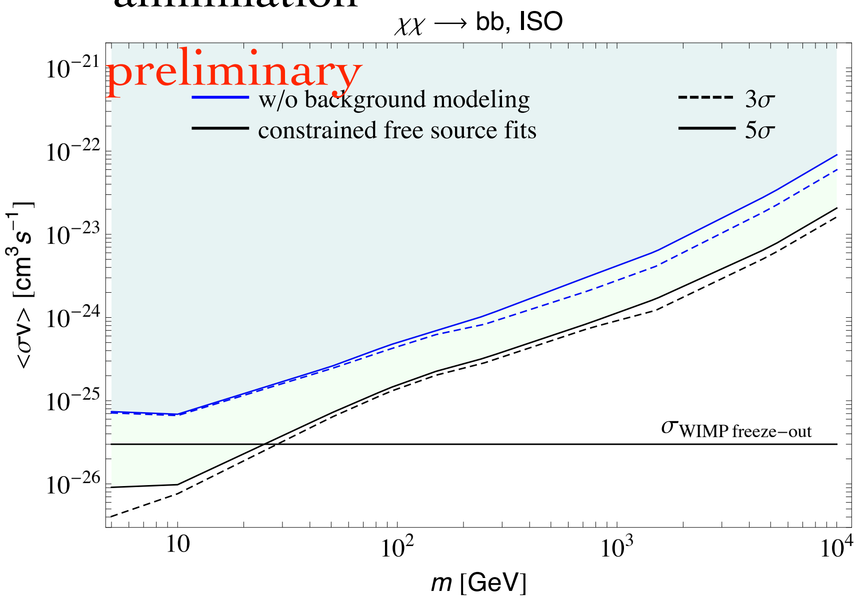


Matches a standard CR source distribution (Yus) at R>3 kpc.

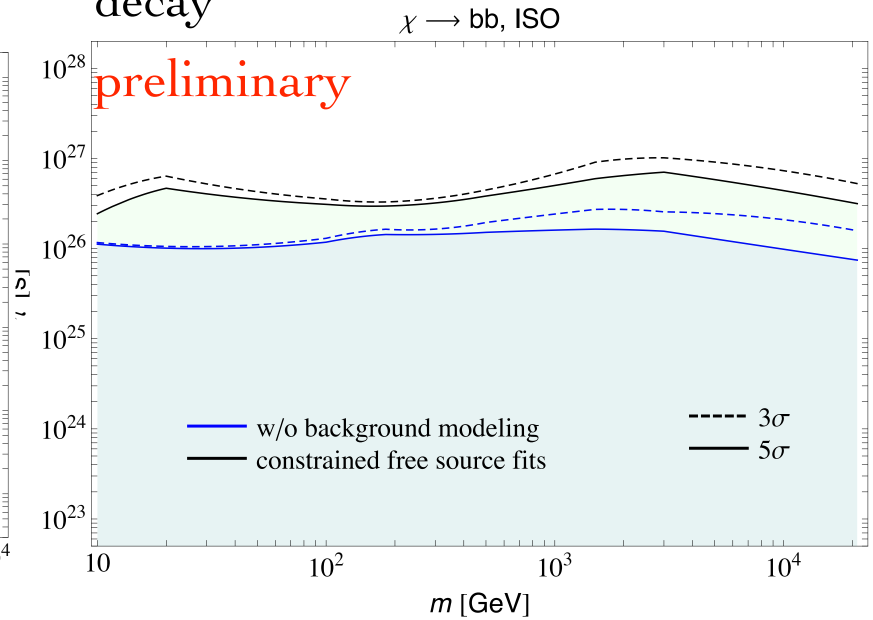
However, to get more conservative DM constraints *we set the distribution of CRe and CRp to zero in the inner 3 kpc. I.e. we force DM to make up all the sources in the central parts of the Galaxy, and model and subtract only emission R>3 kpc.*

DM limits: b ̄b channel

annihilation



decay



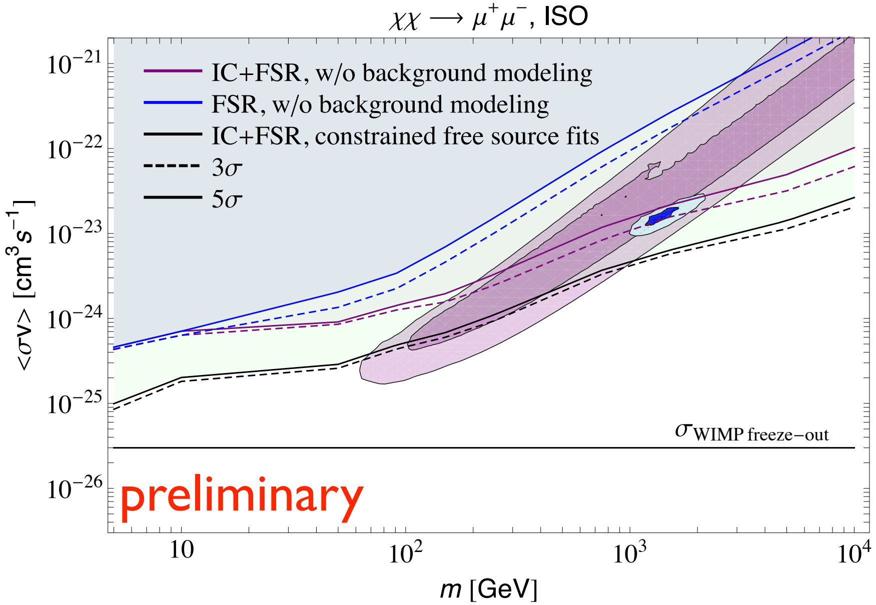
Blue: "no-background limits".

Black: limits obtained by marginalization over the CR source distribution, diffusive halo height and electron injection index, gas to dust ratio, *in which CR sources are held to zero in the inner 3 kpc*.

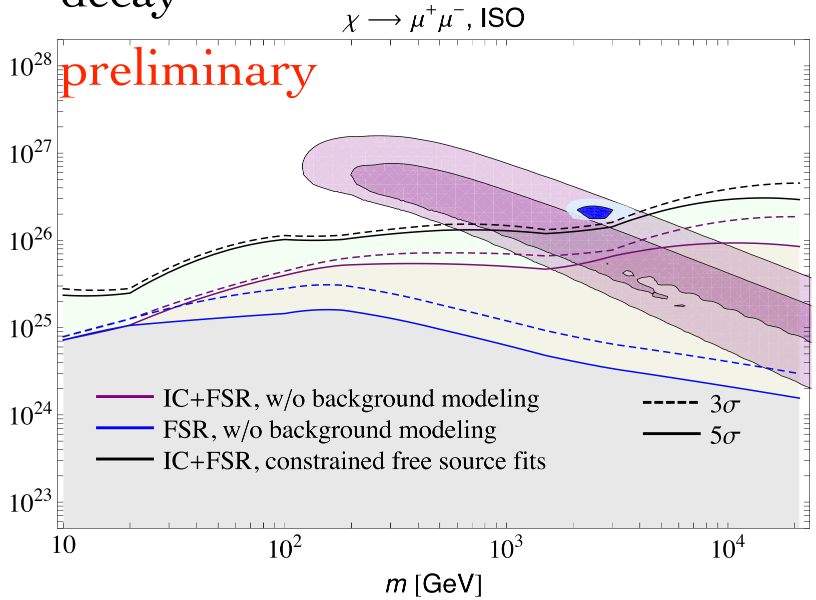
Limits with *NFW* profile (not shown) are only slightly better.

DM limits: μ+μ-channel

annihilation



decay



Blue: here we used only photons produced by muons to set "no-background limits" ('FSR only').

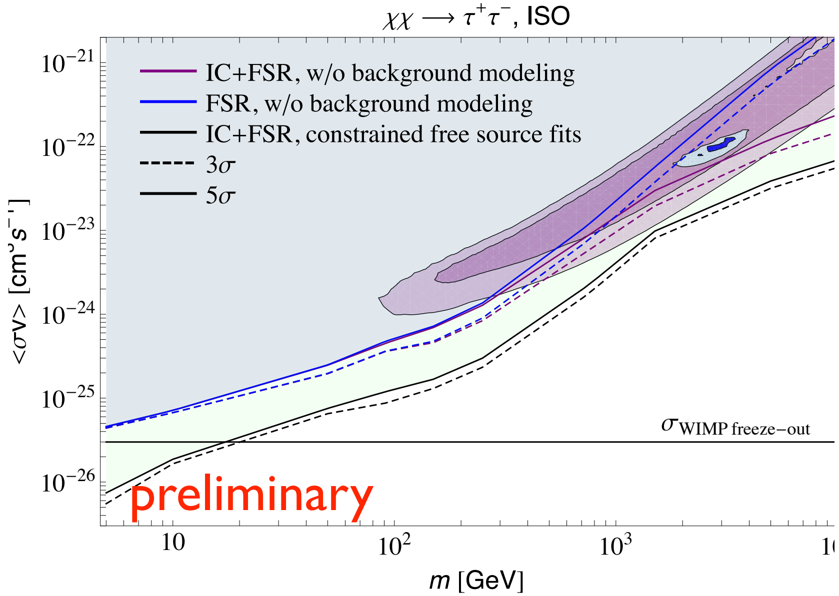
Violet: "no-background limits" FSR+IC

Black: limits from profile likelihood and *CR sources set to zero in the inner 3 kpc*.

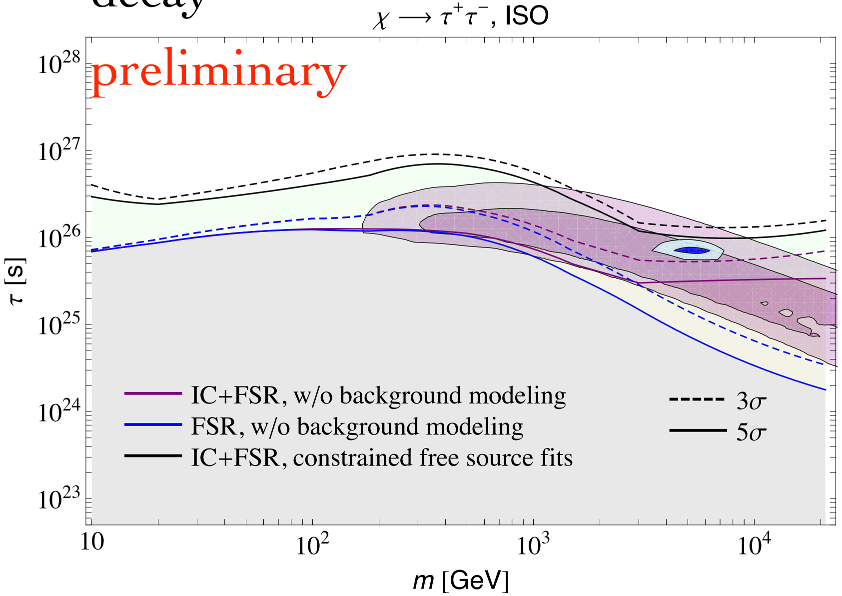
DM interpretation of PAMELA/Fermi CR anomalies strongly disfavored (for annihilating DM)

Limits: τ+τ−channel

annihilation



decay



Blue: here we used only photons produced by muons to set "no-background limits" ('FSR only').

Violet: "no-background limits" FSR+IC

Black: limits from profile likelihood and *CR sources set to zero in the inner 3 kpc.*

DM interpretation of PAMELA/Fermi CR anomalies strongly disfavored (for annihilating DM)

Summary

We test the LAT data for a contribution from the DM signal *in our Galaxy* and derive upper limits on DM self-annihilation cross section and decay time.

We make several conservative choices in the analysis:
- we consider *intermediate latitudes* where uncertainty due to the profile is smaller.
- we model and subtract *astrophysical signal only at >3 kpc from the GC*, which is relatively well modeled (compared to inner Galaxy).

We derive *competitive DM limits* and *demonstrate a method* which can be used to study diffuse emission.

The limits can be improved by using *complementary constraints on CR propagation parameters* (as AMS02, Planck, Lofar, etc.), *models for Galactic structures* (i.e. Fermi Bubbles) and *complementary constraints on the Galactic DM distribution*... work in progress.

Extra Slides

Parameter	Value					
Halo Height z_h(kpc)	2	4	6	8	10	15
Diffusion Coefficient D_0 (cm^{2}s^{-1})	2.7×10^{28}	5.3×10^{28}	7.1×10^{28}	8.3×10^{28}	9.4×10^{28}	1.0×10^{29}
Diffusion Index δ	0.33	0.33	0.33	0.33	0.33	0.33
Alfven Velocity v_A (km s^{-1})	35.0	33.5	31.1	29.5	28.6	26.3
Nucleon Injection Index (Low) $\gamma_{p,1}$	1.86	1.88	1.90	1.92	1.94	1.96
Nucleon Injection Index (High) $\gamma_{p,2}$	2.39	2.39	2.39	2.39	2.39	2.39
Nucleon break rigidity $\rho_{br,p}$(GV)	11.5	11.5	11.5	11.5	11.5	11.5

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
Linear Parameters	**Symbol**	**Range of variation**
eCRSD and pCRSD coefficients	c_i^e,c_i^p	0,+∞
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

[a]The parameters D_0, δ, v_A, $\gamma_{p,1}$, $\gamma_{p,1}$, $\rho_{br,p}$ are varied together with z_h as indicated in Table I.

Additional checks:

Parameter	$\|\delta\sigma/\sigma\|$ [%], $b\bar{b}$	$\|\delta\sigma/\sigma\|$ [%], $\mu^+\mu^-$
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]
HI2d [0.0110, **0.0140**; 0.0170]	[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**; Yus]	[**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]

To asses the impact of the *remaining CR parameters* we varied them *one at a time* and checked the variation of the DM limits for some DM mass and channel.
The results confirm that the *electron spectrum* and the *CR Source Distribution* have the major impact, while the other parameters have a subdominant effect on DM limits.