Dark Matter constraint from the Fermi-LAT diffuse data

on behalf of the Fermi-LAT collaboration

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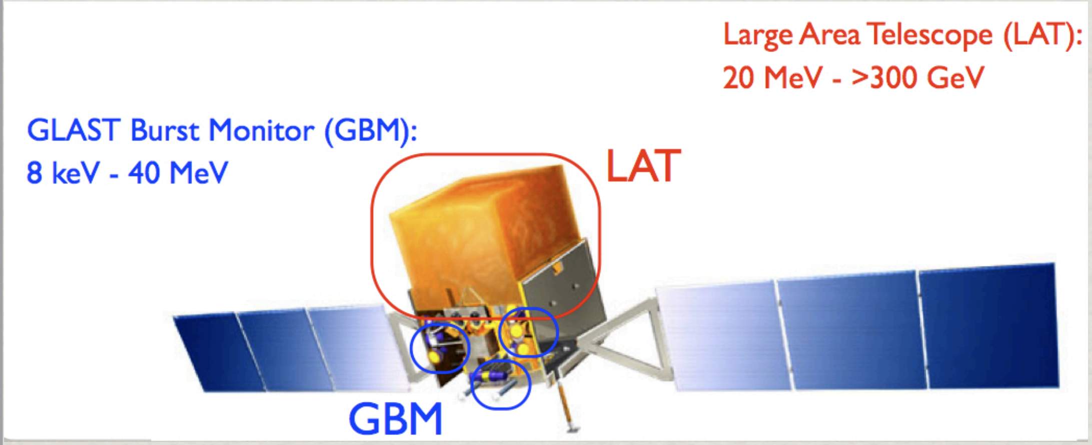
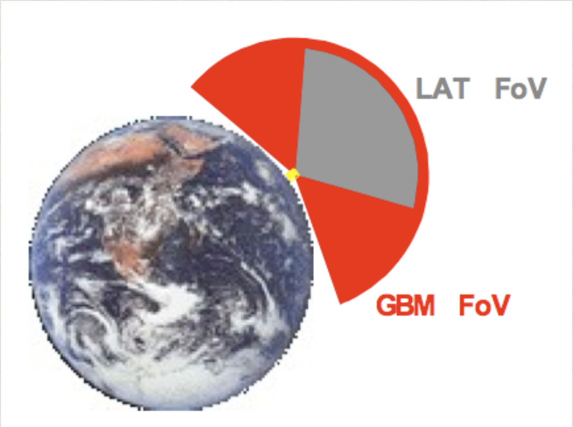
Fermi-LAT instrument: excellent in measuring the ***gamma ray diffuse emission***.

- Large field of view: 20% of the sky at any instant. In the survey mode exposes every part of the sky for ~30 min, every 3 hours.

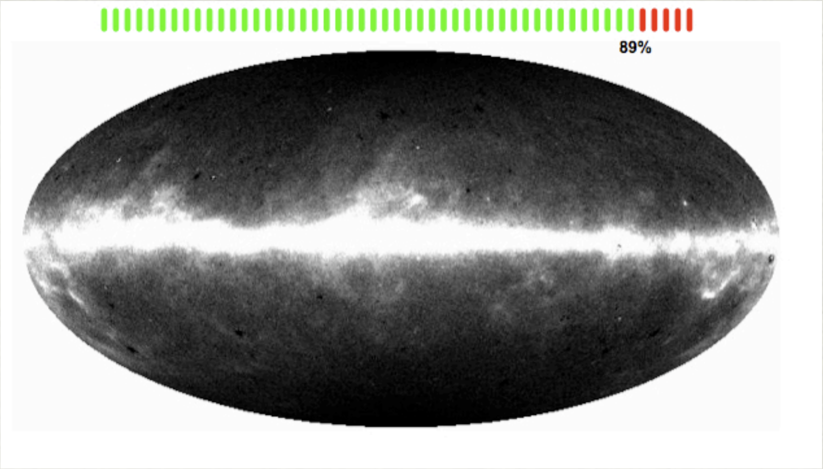
- Good charged particle discrimination, critical in separating gamma rays from the background cosmic rays.

Energy range: 20 MeV to >300 GeV (LAT), ***includes previously unexplored energy band 10-100 GeV.***





*Diffuse emission has high potential for DM searches -- contains information on the morphology as well as in the DM annihilation/decay spectral features.



LAT diffuse emission (point sources subtracted)
[J-M Casandjian, TeVPa2010]

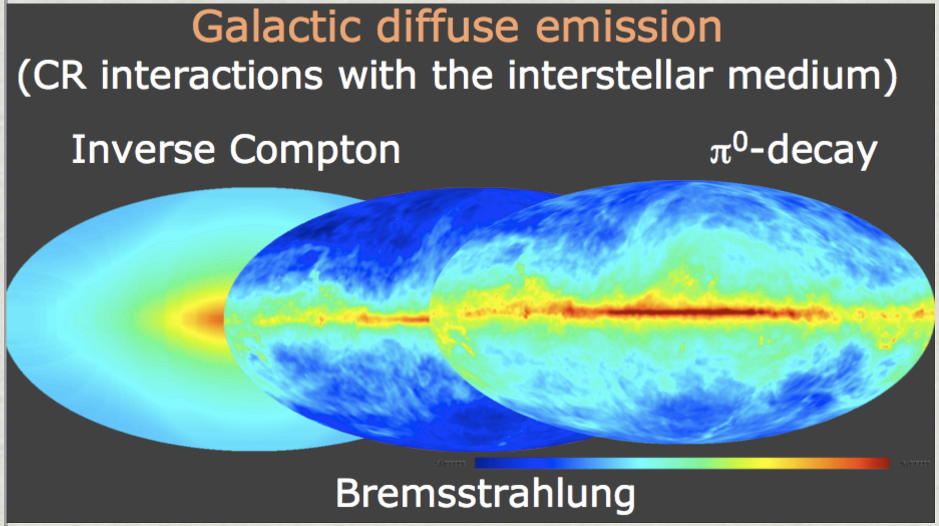
It has **good statistics** (~90% of LAT photons!), but signal of astrophysical origin (background!) is challenging to model and disentangle from DM signatures;

Diffuse DM analysis by the Fermi team:

- ***analysis of the Extragalactic (Isotropic) Signal, by using the intensity and spectral shape of the signal or angular anisotropies.***
- ***analysis of the diffuse emission in terms of DM signal from the Galactic DM halo.***

Galactic halo DM analysis

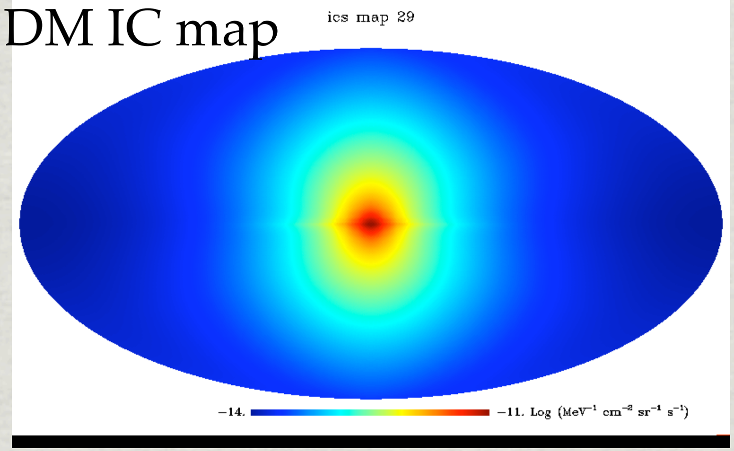
[Ongoing work - preliminary results]



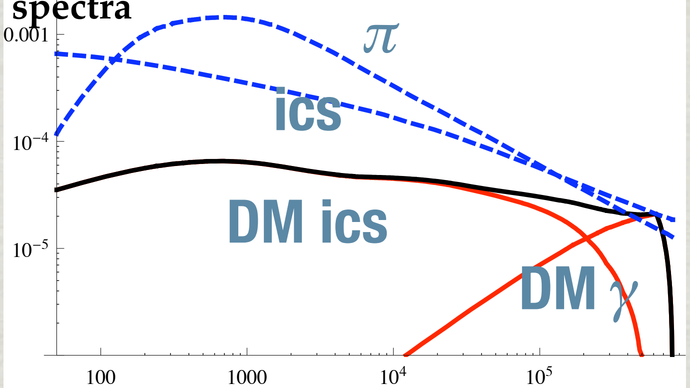
The full sky fit to the Galactic diffuse data can probe DM efficiently, ***by exploiting both, spatial and spectral information.***

However, to constrain the dark matter contribution, a rigorous understanding of the astrophysical signal is needed.

DM IC map



astrophysical and DM annihilation spectra



Astrophysical diffuse models

Galactic diffuse gamma rays are mainly produced through:

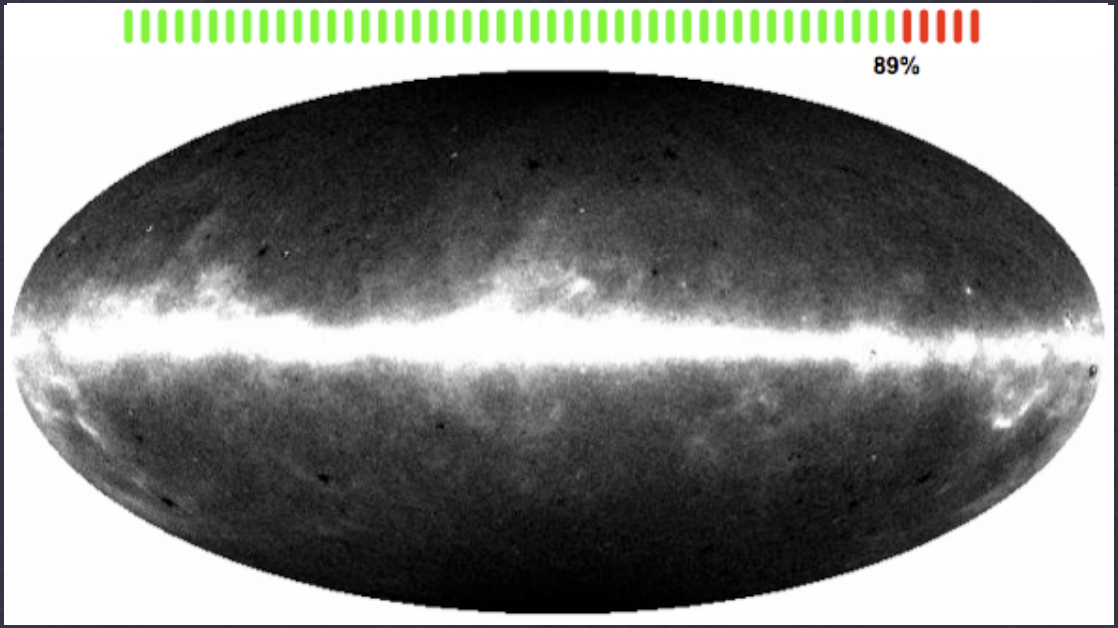
- Scattering of ***cosmic rays p and e*** off of the ***gas*** (***atomic, molecular and ionized hydrogen***) in the Galaxy:
  - pp$\rightarrow\pi^0\rightarrow\gamma\gamma$
  - bremsstrahlung of electrons
- and inverse Compton scatter of *electrons on ISRF, IR and CMB photons*
- GALPROP code is used to model this emission; it uses ***detailed gas and ISRF maps*** and ***calculates gamma ray emission for a specified CR source distribution and set of diffusion parameters***.

Astrophysical diffuse models

There is no one ‘best’ astrophysical model. Given the complexity of the problem there are many models which reproduce well the diffuse data.

Approach: ***For a different sets of reasonable initial assumptions on CR propagation and distributions, remaining astrophysical parameters are obtained in a fit to the cosmic ray and gamma ray data -> defines a set of astrophysical models all of which reproduce the data reasonably well.***

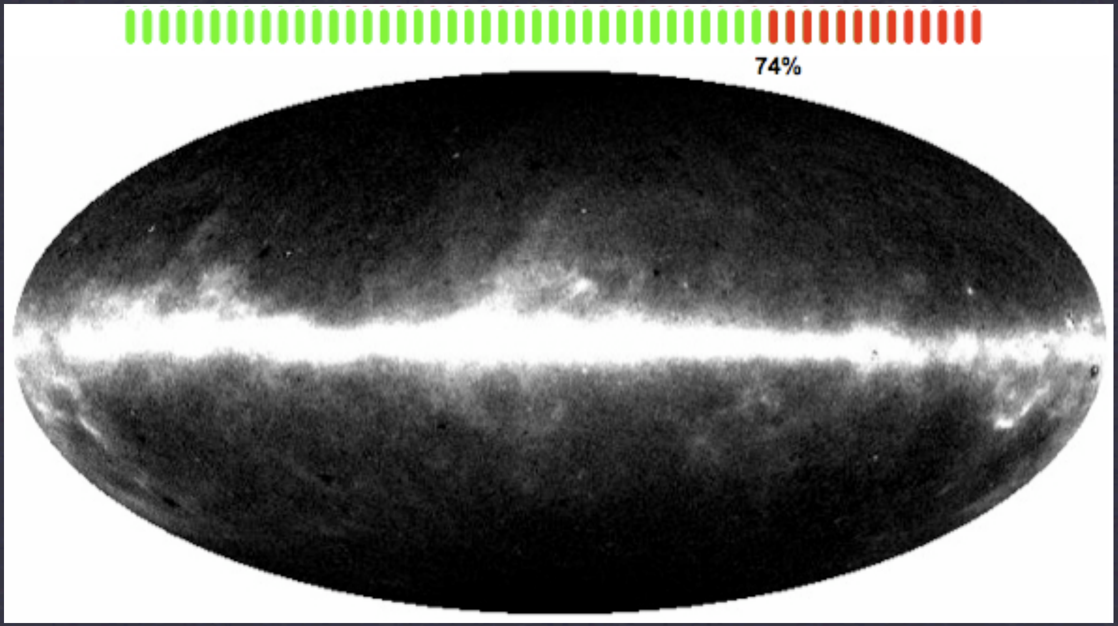
The fit to gamma ray data is obtained with a binned maximum likelihood tool GaRDiAn (uses both, energy and spatial bins).



[J-M Casandjian, TeVPa2010]

Diffuse model: linear templates

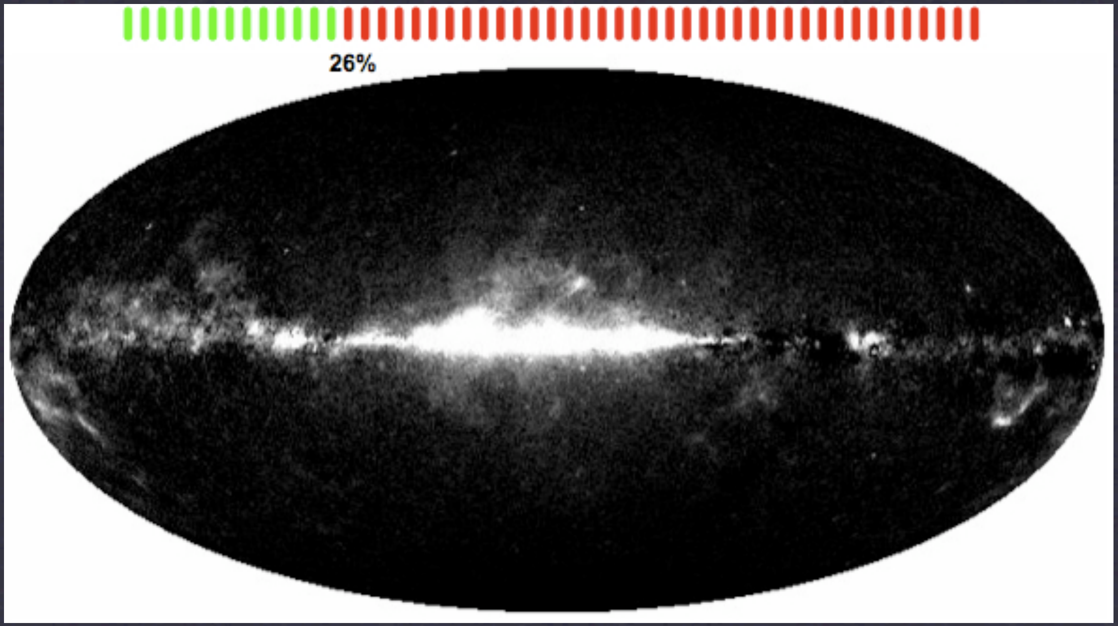
- All sky - point sources



[J-M Casandjian, TeVPa2010]

Diffuse model: linear templates

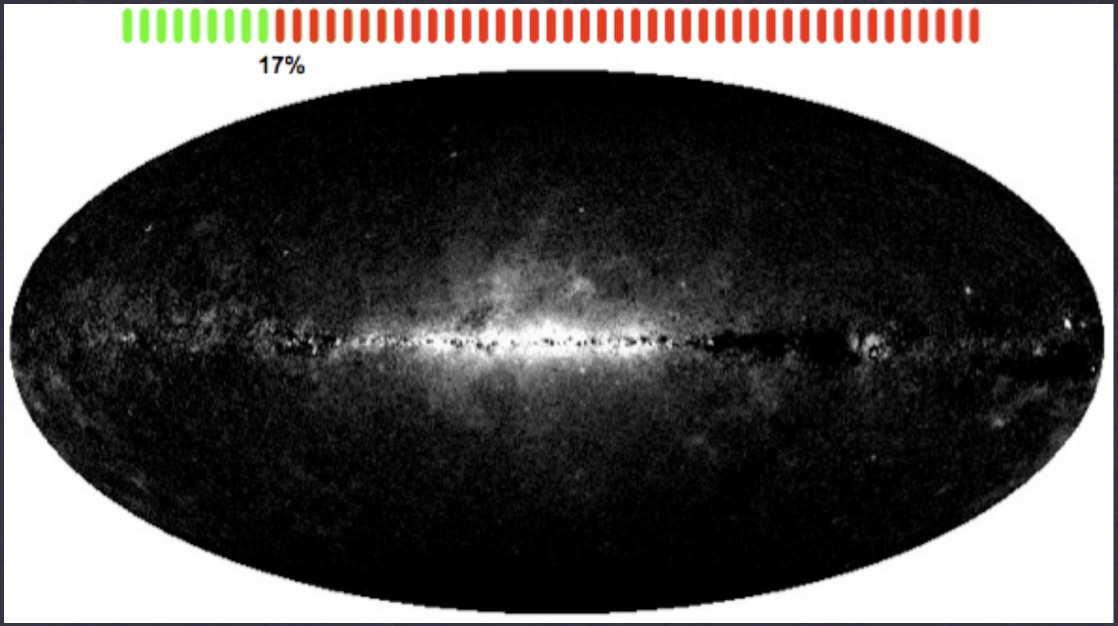
- All sky - point sources - isotropic (extra Galactic) component.



[J-M Casandjian, TeVPa2010]

Diffuse model: linear templates

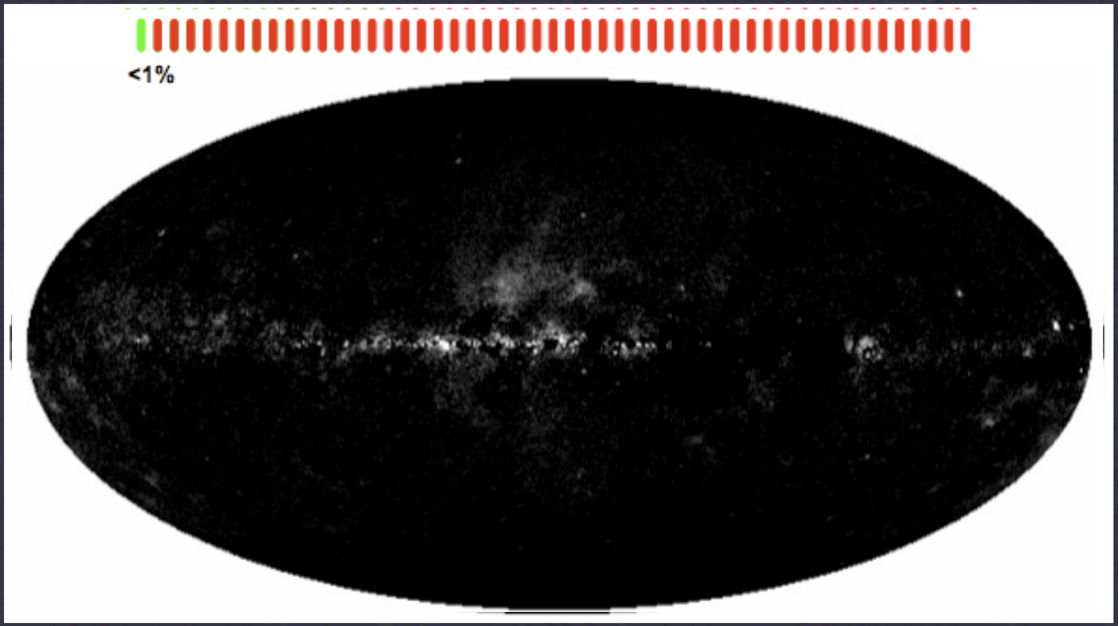
- All sky - point sources - isotropic (extra Galactic) component - HI (atomic) and HII (ionized hidrogen) template (~50% of emission!)



[J-M Casandjian, TeVPa2010]

Diffuse model: linear templates

- All sky - point sources - isotropic (extra Galactic) component - HI (atomic) and HII (ionized hidrogen) -H2 (molecular) template



Diffuse model: linear templates

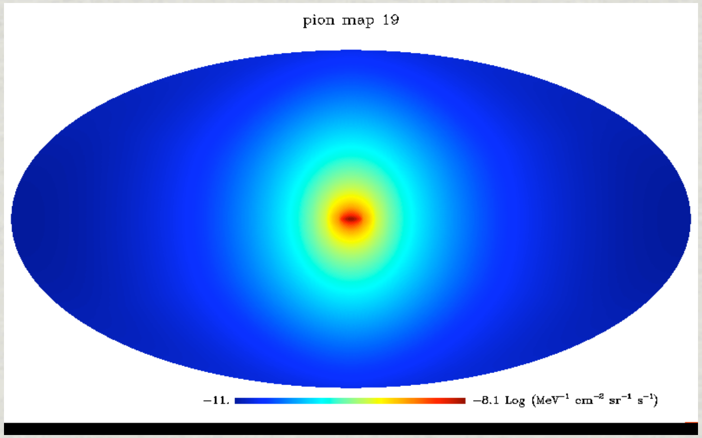
- All sky - point sources - isotropic (extra Galactic) component - HI (atomic) and HII (ionized hidrogen) -H2 (molecular) template - Inverse Compton.
- residuals <1 %; most of which correlates with the dark gas and is further subtracted.
- *-> by fitting separately various templates one can get a handle on observational uncertainties and infer properties of underlying CR source distribution and propagation.*

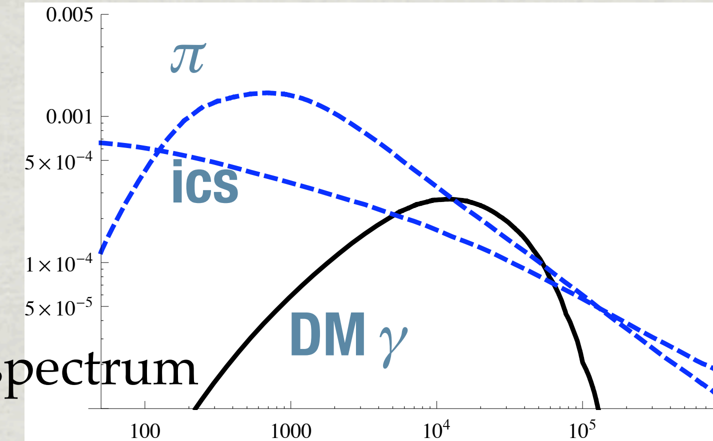
Dark Matter searches

- To set DM constraints, we use the same approach, by adding DM template sky maps to *a chosen astrophysical model*. DM maps are obtained with GALPROP code, with a set of propagation parameters consistent with the astrophysical model assumed.
- Data used are 21 months data, in which residual background suppression has been improved, while keeping most of the effective area (data clean set).
- The limits are set as the 3 sigma confidence level above the best fit normalization of the DM contribution.

DM maps and energy spectra considered:

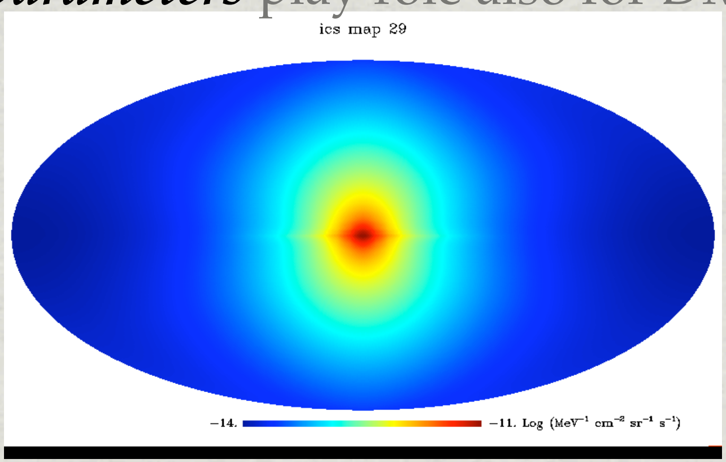
- ***only photons*** produced in DM annihilations (***'b-bbar' case***)

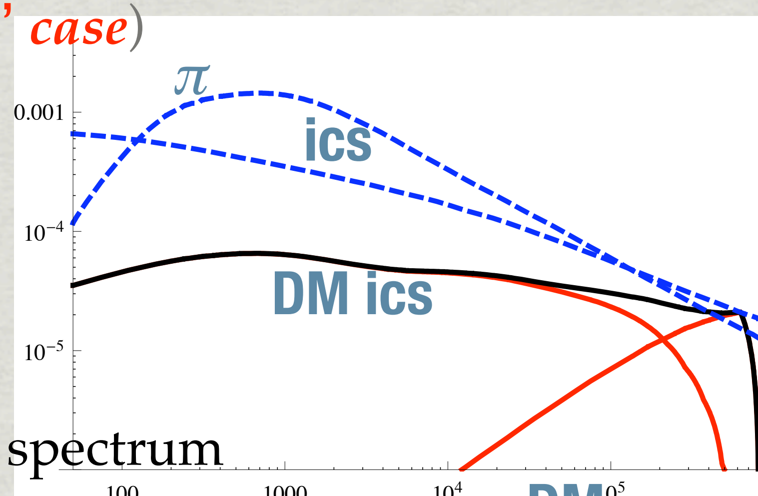




'peaked' spectrum

-***photons + electrons*** produced in DM annihilations, too: ***propagation parameters*** play role also for DM maps (***'μ' case***)





hard, -2 spectrum

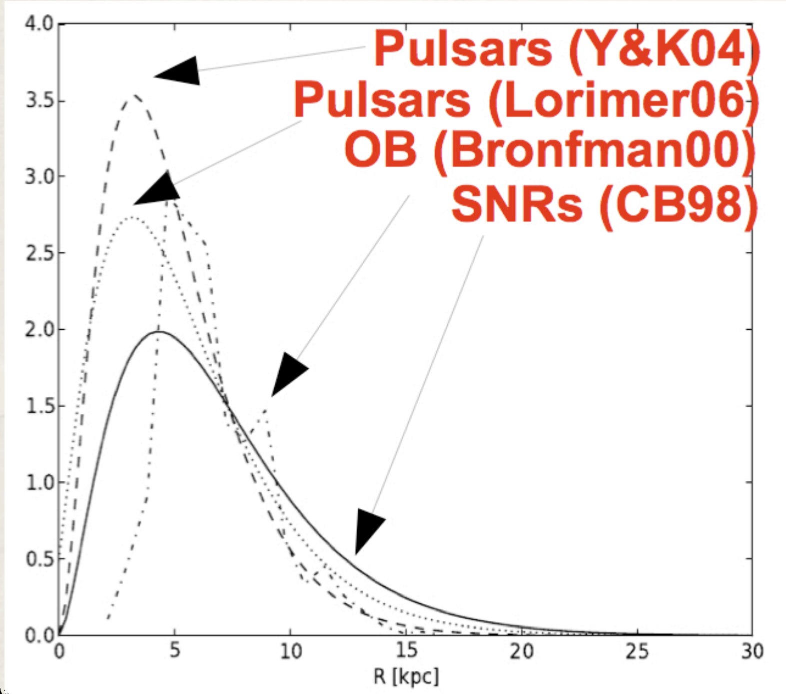
DM γ

Note: DM signal dominates in the Galactic Center region and has an extended latitude profile.

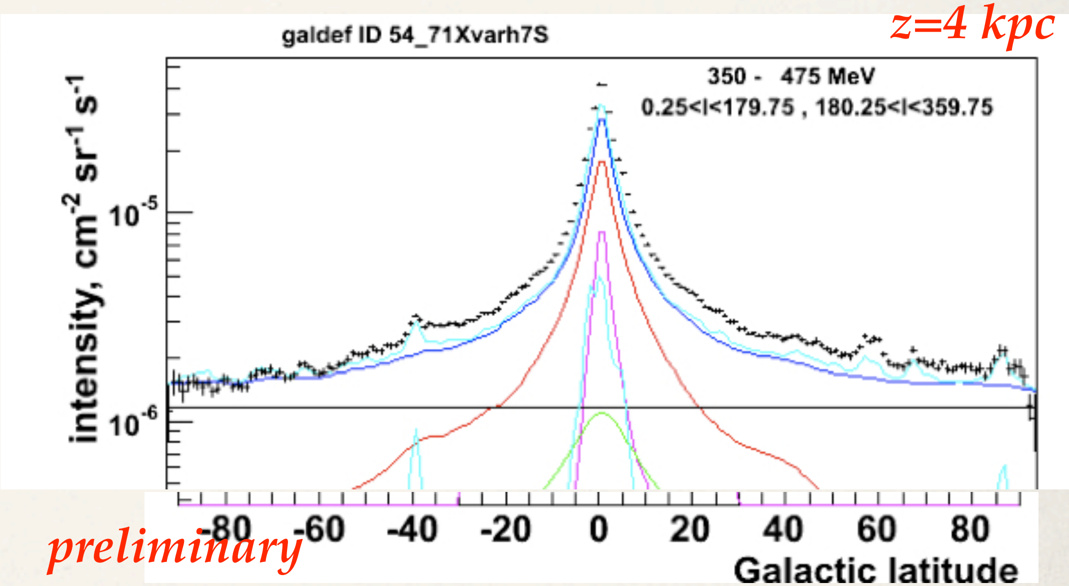
- Among all astrophysical models obtained as described we choose the one expected to give most conservative DM constraints. The two most critical parameters in this respect are *distributions of CR sources* and *diffusive halo size.*

Distributions of CR sources: chosen distribution is based on the observation of 46 SNR, (observational bias) has low gradient in the inner Galaxy and it underpredicts data there -> it gives one of the most conservative DM limits.

A larger halo gives a broader latitude distribution. *Small halo size underpredicts data in terms of the latitude profiles, making the DM limits weaker in that case.*



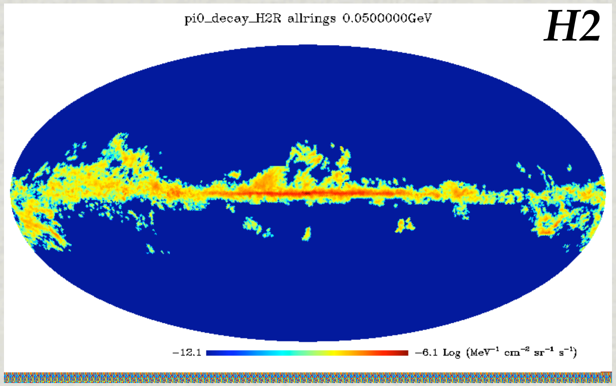
z=4 kpc

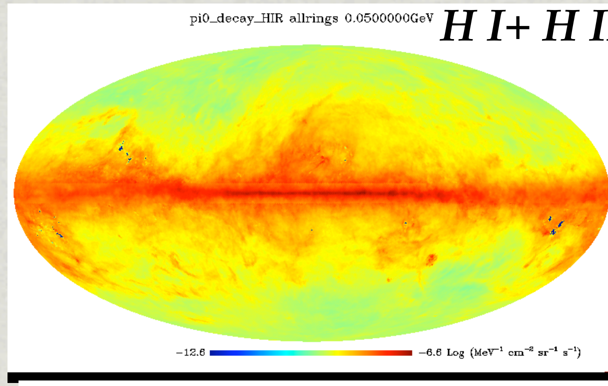


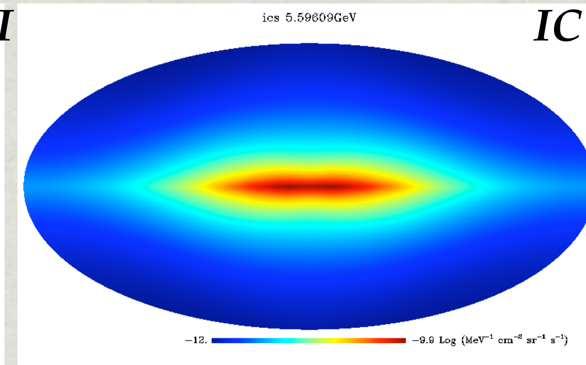
preliminary

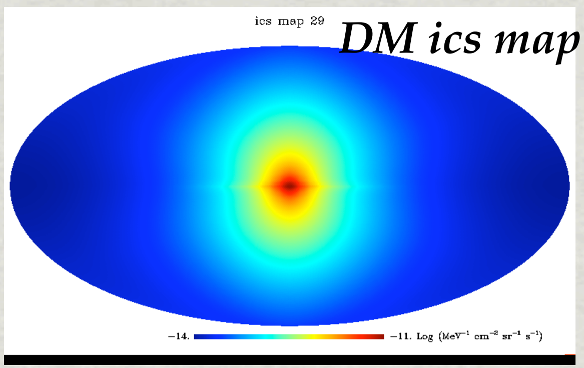
➔ *We consider a model with CR source distribution as determined by the direct observation of SNR and smaller halo size z=4 kpc, (with other parameters optimized to the CRE and Fermi data) to set the DM limits.*

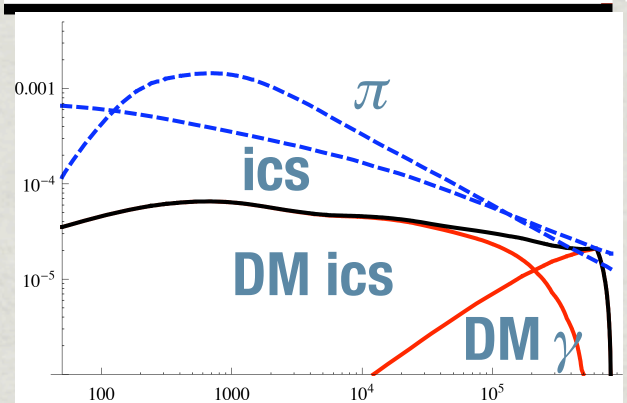
- Full sky fit is performed with the following free parameters: overall normalization of H2, HI, IC (3) and DM maps (1 or 2); normalization of the isotropic component (1) and residual contribution from point sources (1).

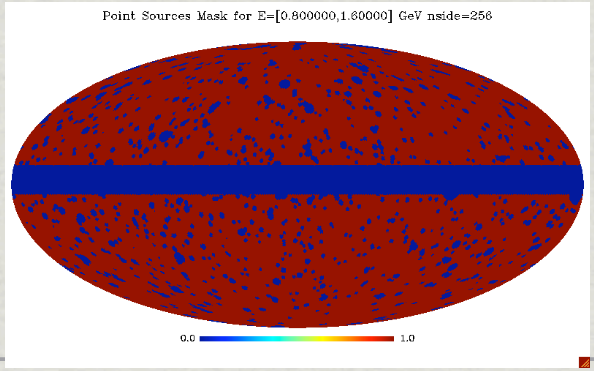




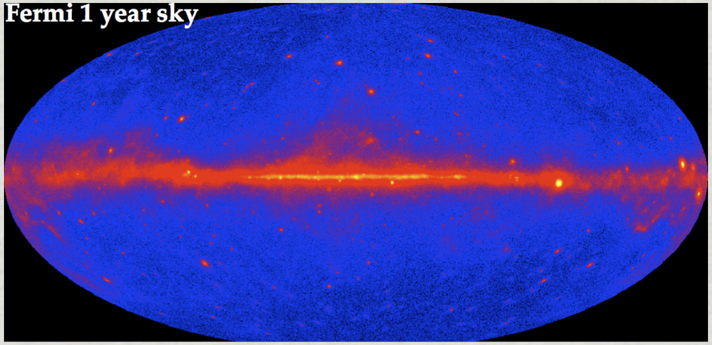




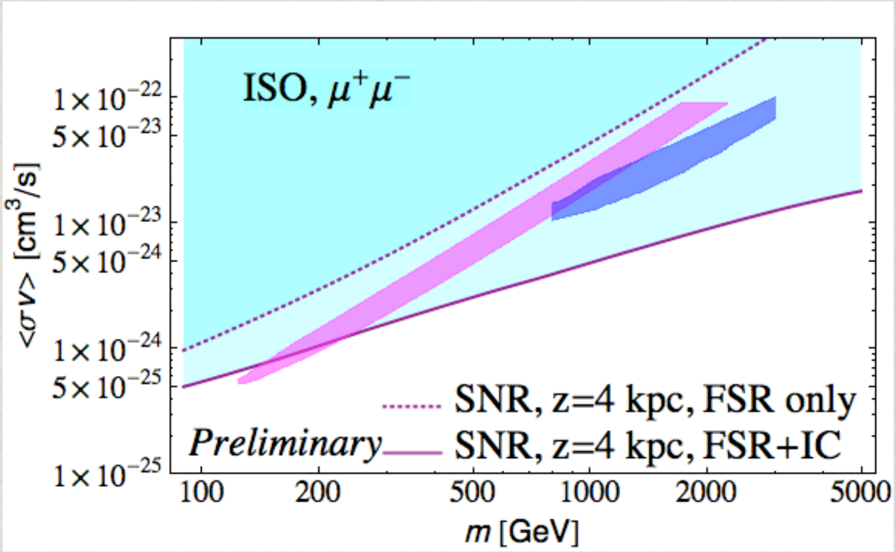


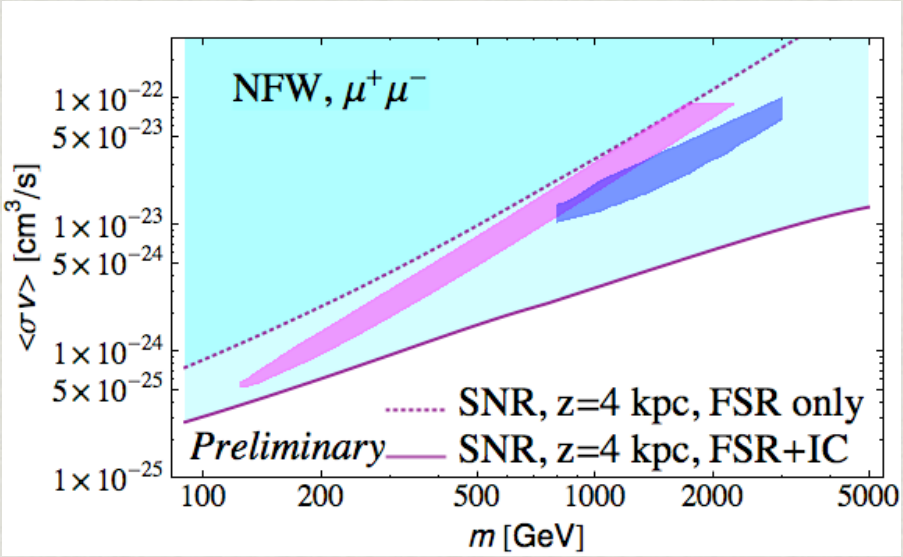


mask: point sources and the galactic plane ($-5<b<10$ deg):

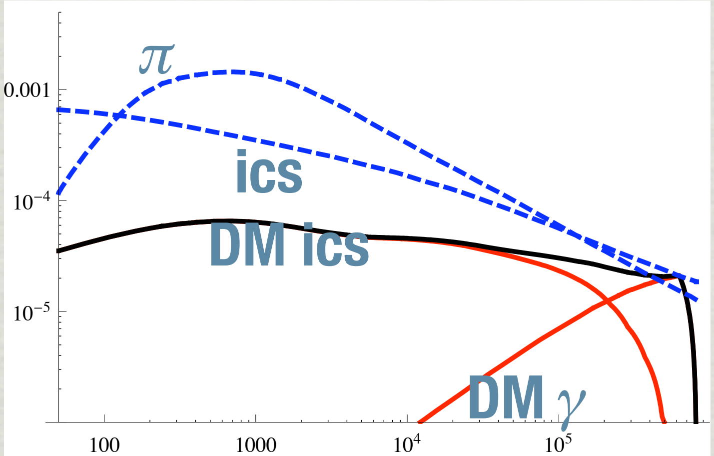


Exclusion plots, $\mu\mu$ channel



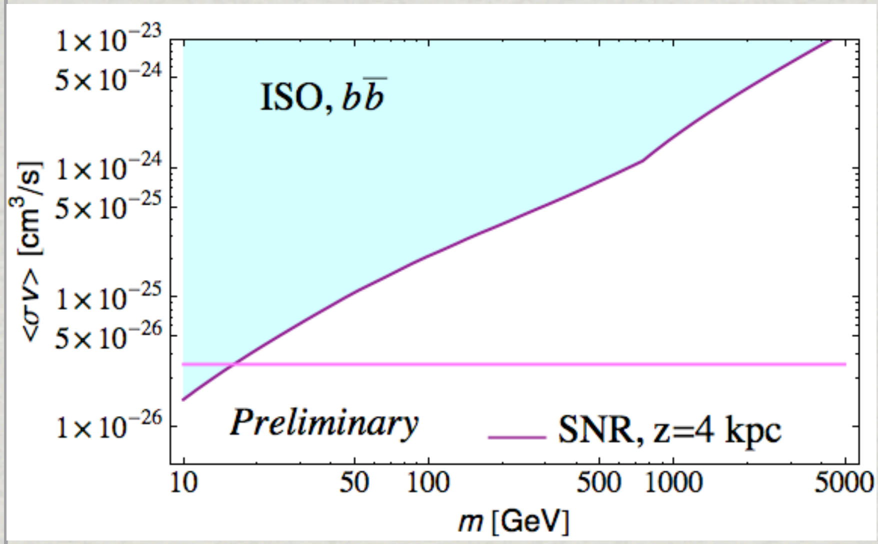


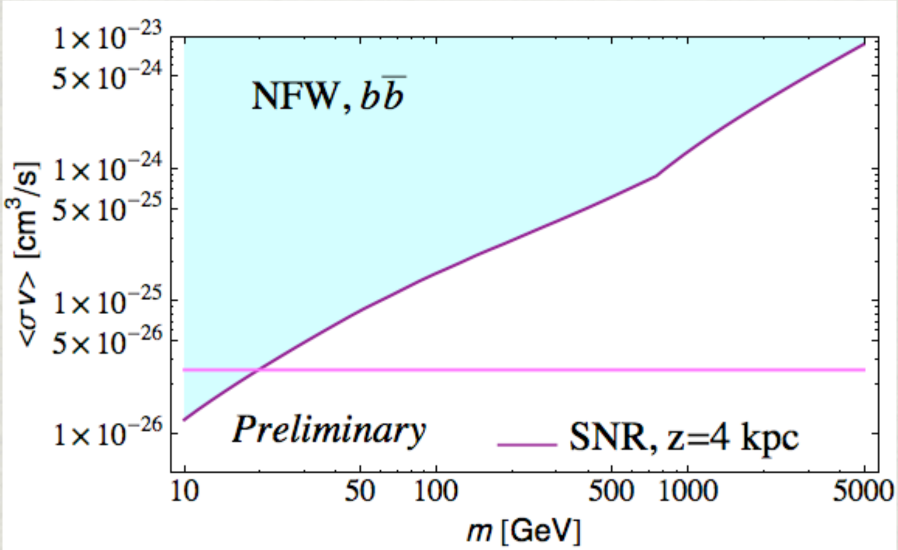
- *PAMELA (pink) and Fermi (Blue) regions are excluded when full DM spectrum (FSR+IC) is considered.*



- *Note: FSR-only limits are weak since the data only up to 100 GeV has been used (will improve when/if <~300 GeV data set is used).*

Exclusion plots, bb channel

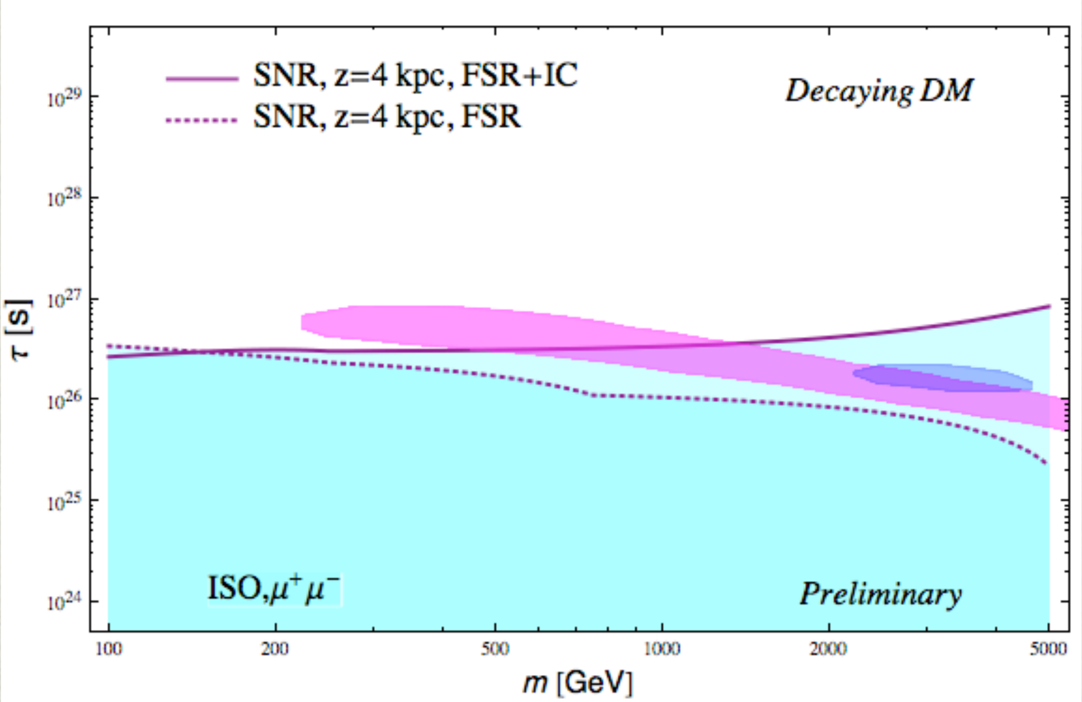




- *as expected, limits do not depend much on the DM profile assumed (given mostly by a sky region 10<|b|<20 deg).*

- *good constraining potential of this approach, freeze-out value reached for low masses. Limits are expected to improve significantly with a better understanding of the astrophysical model (most critically in the region of the Galactic Center).*

Exclusion plots, DM decay to $\mu\mu$ channel



- ***Also in the case of the decayibg DM, PAMELA (pink) and Fermi (Blue) regions are disfavored when full DM spectrum (FSR+IC) is considered.***

Quantifying systematics in modeling of diffuse emission

∗In the described approach DM limits are set within a given (conservative) astrophysical set-up.

∗The ***systematics uncertainty in a choice of an astrophysical set-up*** are hard to quantify since astrophysical maps depend on a ***large number of parameters in a non-linear way***.

∗A possible approach is to vary a number of astrophysical parameters (diffusion coefficient, alfven speed, electron and proton injection spectra... in addition to halo height and source distribution) and form a ***profile likelihood*** in a astro+DM fit to cosmic and gamma ray data. In this way, systematic uncertainties would be incorporated in the actual DM limits.

∗At present, due to the computational limitations and still large uncertainties in the modeling, specially in the galactic center region, this method cannot be fully exploited.
→ ***Ongoing effort within the Fermi-LAT collaboration.***

Profile likelihood

[B. Anderson, IDM2010]

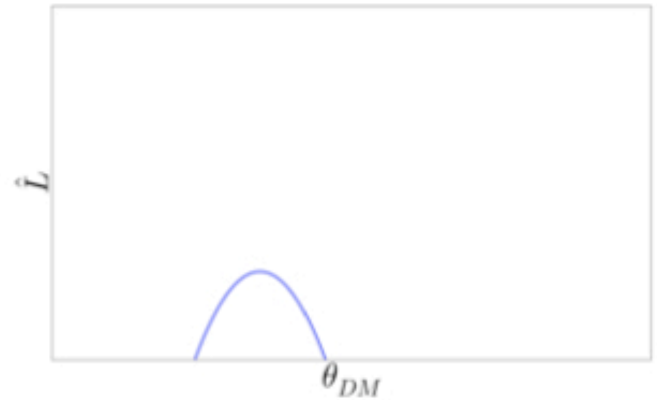
In Principle

Scanning the DM normalization, we smoothly transition between background models.

Step 1

For each GALPROP model, maximize $\hat{L}$ w.r.t. linear parameters, $\vec{\alpha}$, for each value of θ_{DM} (Flux Normalization).

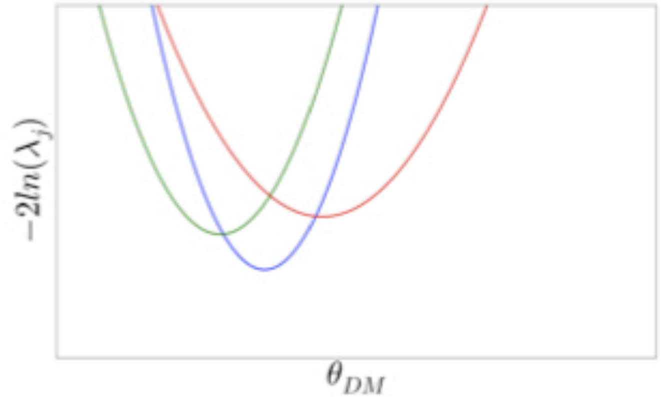
$\hat{L}_j(\theta_{DM}) = \prod_i P_{ij}(n_i; \vec{\alpha}_{max}, \theta_{DM})$



Step 2

Construct a test statistic for each diffuse model (different colors) using the best overall Likelihood and the CR fit probability.

$$\lambda_j(\theta_{DM}) = \frac{P_j^{CR}\hat{L}_j(\theta_{DM})}{(P_j^{CR}\hat{L}_j)_{best}}$$



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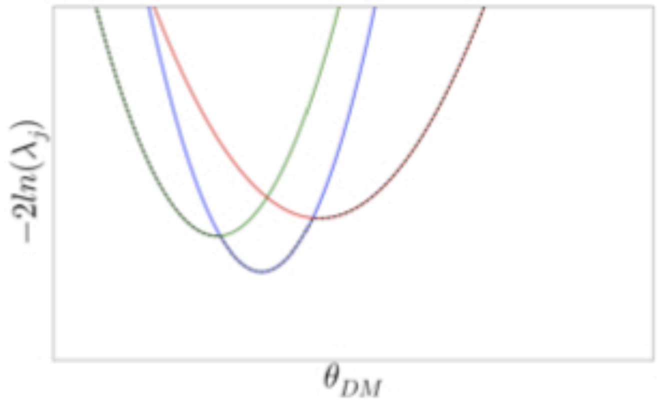
Scanning the DM normalization, we smoothly transition between background models.



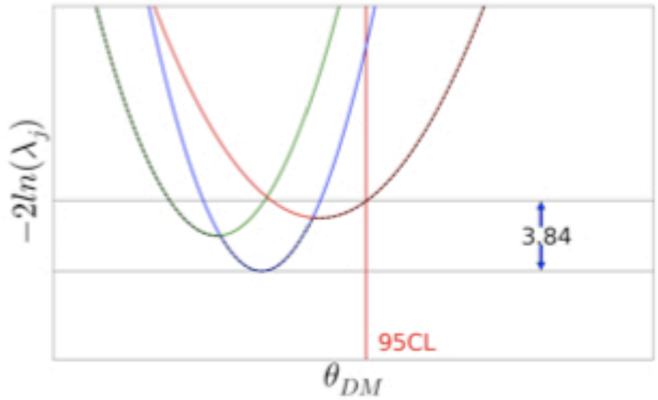
Step 3

The profile likelihood is the curve that follows the minimum of all GALPROP models.

$T_{chi^2}(\theta_{DM}) = -2ln\lambda_{j_{max}}(\theta_{DM})$

Step 4

Since $T_{chi^2}(\theta_{DM})$ behaves as a χ^2 with one d.o.f., we set the 95% confidence upper limit to where the profile likelihood rises by 3.84 above the absolute minimum.

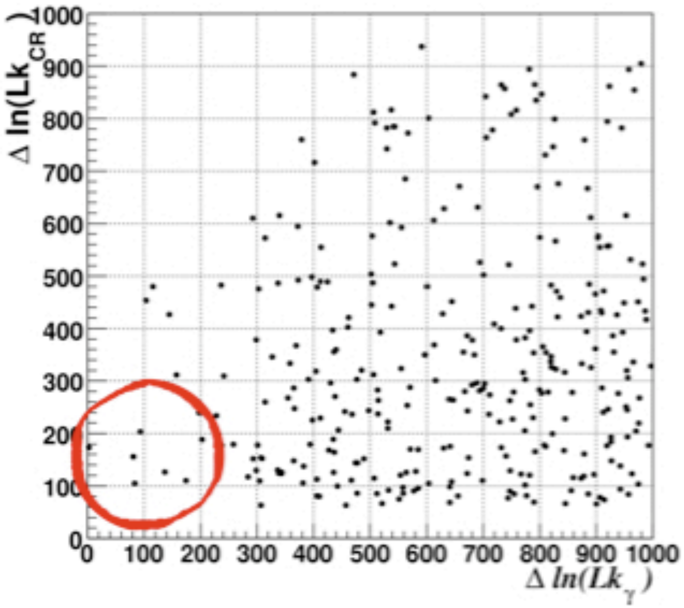


Profile likelihood

[B. Anderson, IDM2010]

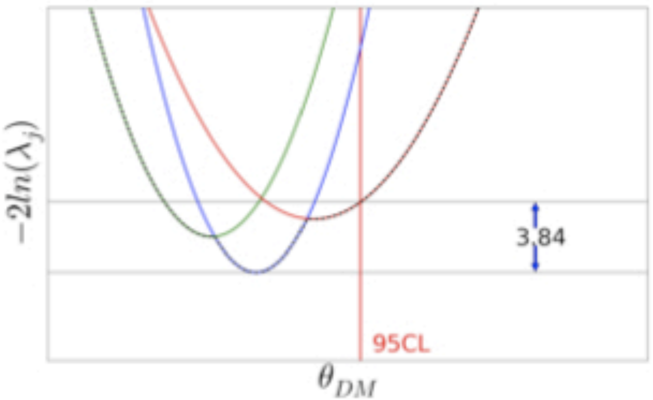
In Practice

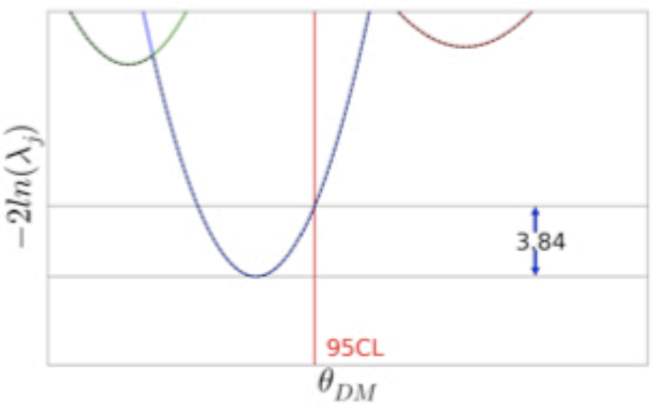
Sparse sampling means our limits all still come from a single model.



Sparse Sampling

Including χ^2 from the CR data in the Likelihood makes it difficult (naively sampling) to populate the region that satisfies both CR and gamma rays. This important region is currently dominated by a couple of models.





Outlook

•*Galactic halo DM limits: obtained in a full sky fit which exploits both, spatial and spectral information of DM and astrophysical signal. Limits presented are relative to the astrophysical model assumed: We use conservative set-up, CR source distribution as given by the direct observation of SNR, and a small halo size, z=4 kpc.*

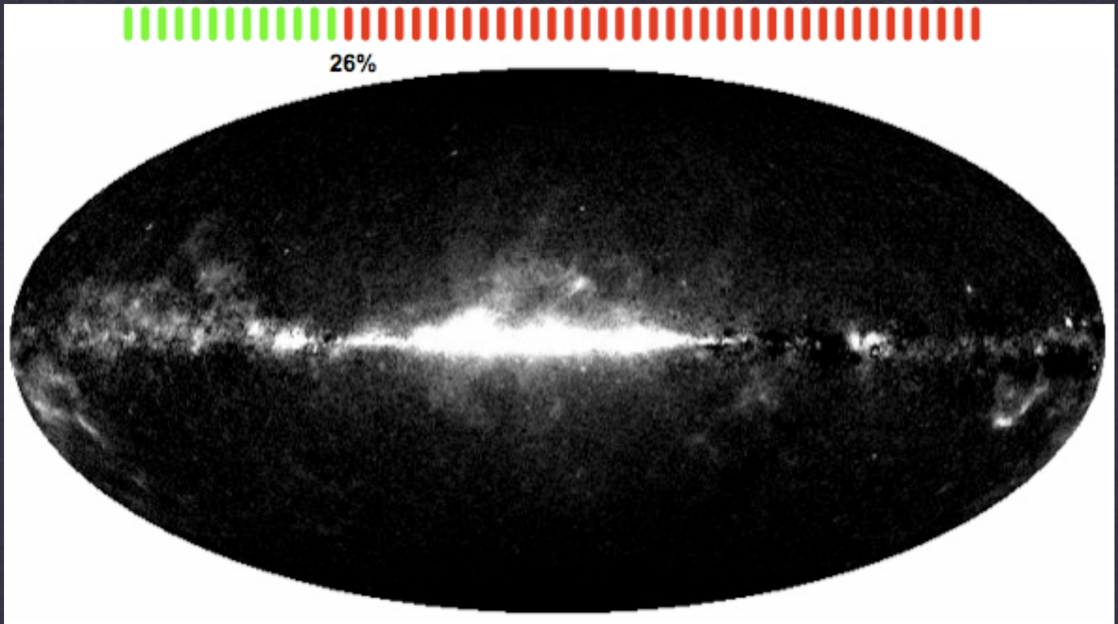
• *Present limits do not confirm the DM interpretation of the PAMELA/Fermi CR excesses, and reach the freeze-out cross section value for low masses.*

•*Ongoing effort to implement systematics due to the astrophysical modeling into DM limits (finer sampling of the diffuse models needed, at present).*

• *Future improvements: modeling of astrophysical background critical for DM searches in the diffuse signal. Near-term improvements include improved modeling of the Galactic diffuse emission in the inner Galaxy.*

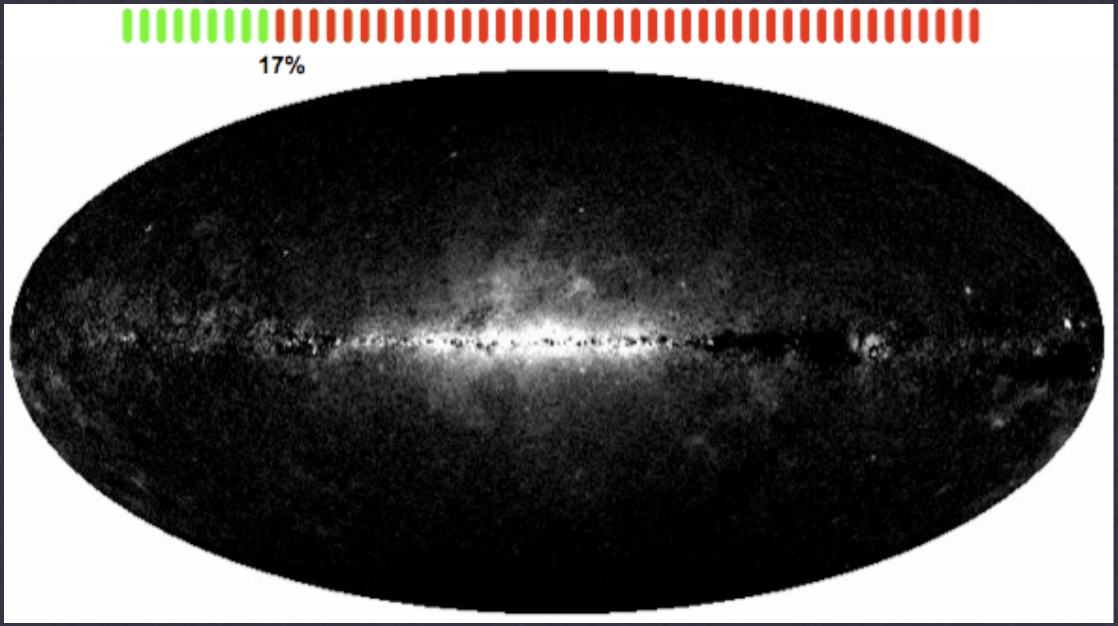
• *These are early attempts in DM searches, Fermi is a 5-10 year mission (+HESS-II, MAGIC-II, Planck, AMS-02, ...).*

extra slides



Diffuse model: linear template fitting approach

- All sky - point sources - isotropic (extra Galactic) component - HI and HII template
- H I (*atomic* H), traced by the 21 cm line; the column density of H I can be determined under the assumption on the the spin temperature T_s. H II (*ionized* hydrogen) is added to this map, based on pulsar dispersion measurements - (only 1% in density but important due to *the large scale hight* ~2kpc).



Diffuse model: linear template fitting approach

- All sky - point sources - isotropic (extra Galactic) component - HI and HII template -H2 template
- H_2 templates (*molecular* gas traced by the CO J=1→0 line,) -- depends on the assumption on the conversion factor $N_{H2}=X_{CO}(R)\ N_{CO}$

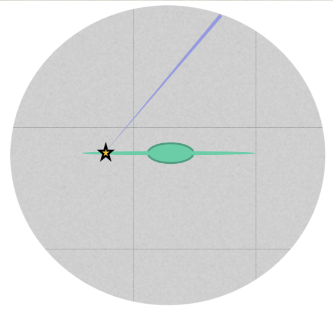
Current work on quantifying the effect of the astrophysical model choice

- Investigate many different diffuse models by varying 7 different parameters.

D0_xx Diffusion Coefficient 1e+27 -- 4e+29 cm^2 s
z_max Halo Height 1 -- 11 kpc
D_g_1 (2) Diffusion Index 0.33, 0.5
v_Alfven Alfven Velocity 0 -- 50 km s^-1
electron_g_1 Electron Injection Index 1.8 -- 2.5
nuc_g_1 Nucleon Injection Index 1.7 -- 2.6
nuc_g_2 Nucleon Injection Index (Above reference rigidity) 2.26, 2.43
source_model SNR Pulsars

Idea: to incorporate the uncertainty in the astrophysical model, by finding the best fit model to the gamma ray data (for a given DM contribution), and weighting it by the χ^2 of such model w.r.t. the CR data.

INDIRECT DARK MATTER DETECTION IN GAMMA RAYS



Bergstrom, L., talk at DM2010.

Advantage of gamma-rays: propagation not affected by the Galaxy.
*Can give a specific signature both in **spatial variation** (line-of-sight cone) and **spectral shape**.*

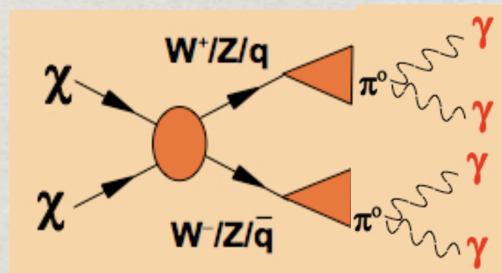
Flux of gamma rays produced in DM annihilations:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\pi}\boxed{\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}\cdot\boxed{\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\;\rho_\chi^2(l)}$$

- **<σv>,** *fixed by measured DM density today (for a thermally decoupled relic).*
- *dN/dE fixed by particle physics*
- *ρ - from N-body simulations;*

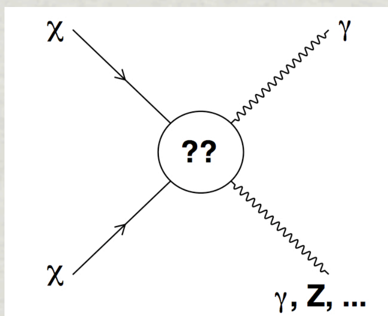
γ ray production channels

- **Prompt (direct) radiation:**
  - continuum spectra:



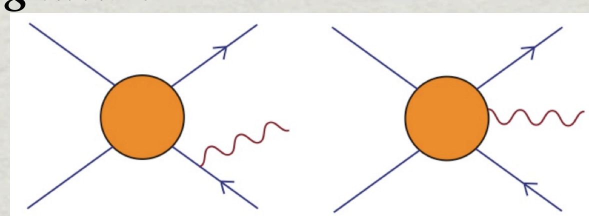
Dominant production for DM annihilating to quarks and gauge bosons (i.e. SUSY) .

  - line:



Loop suppressed, but unique, smoking gun, signature.

  - final state radiation:



- through **radiative processes**:

$$\chi\,\bar{\chi} \rightarrow \begin{cases} e^+\,e^- \\ l^+\,l^- \text{ or } \phi\,\phi \rightarrow \ldots + e^+\,e^- \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + e^\pm \end{cases}$$

ambient backgrounds and fields

Synchrotron, Inv. Compton, Bremstrahlung, Coulomb, Ionization → radio, IR, X-rays, γs

Important if there is a significant branching to leptons.