Challenges in Indirect Dark Matter Searches with gamma-rays

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ULB Brussels,
Nov. 22th 2013

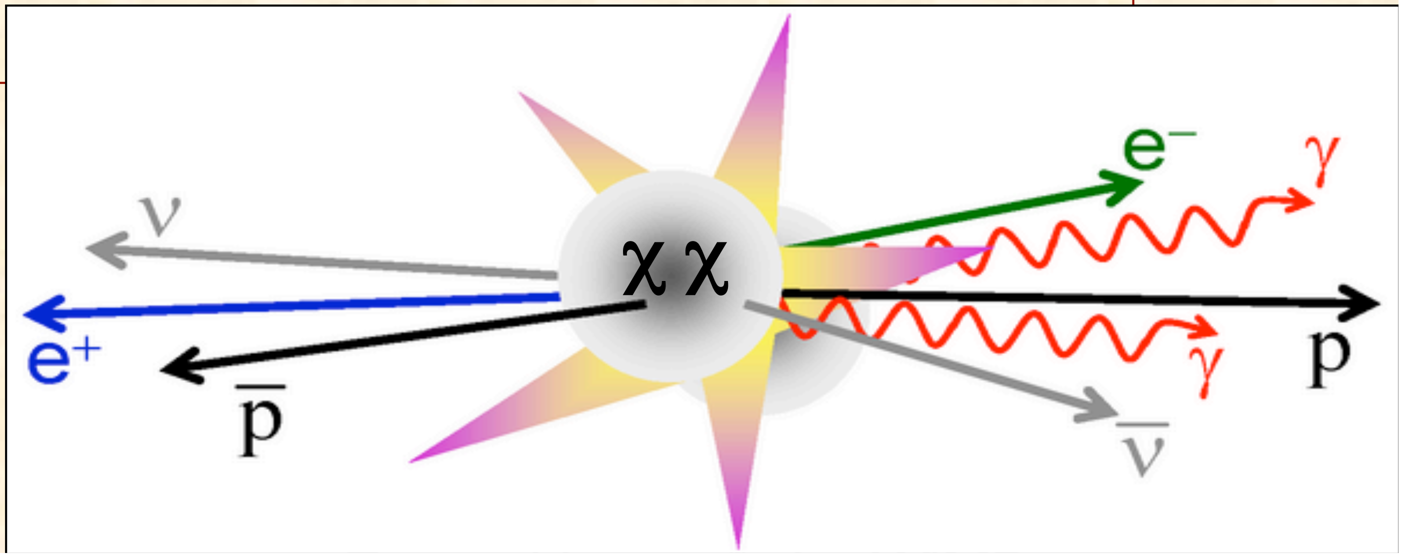
Four roads to Dark Matter

Indirect Detection of Dark Matter: the General Framework

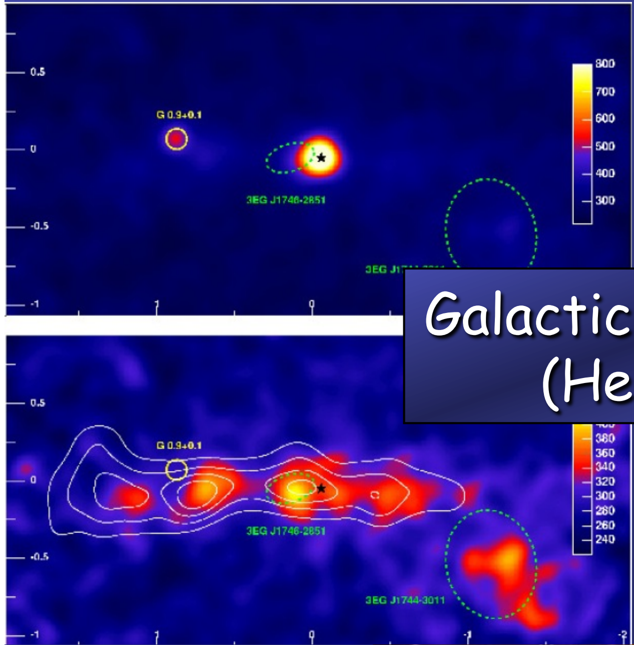
1) **WIMP Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons

2) **Fragmentation/Decay** Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays

3) **Synchrotron and Inverse Compton** Relativistic electrons up-scatter starlight to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields

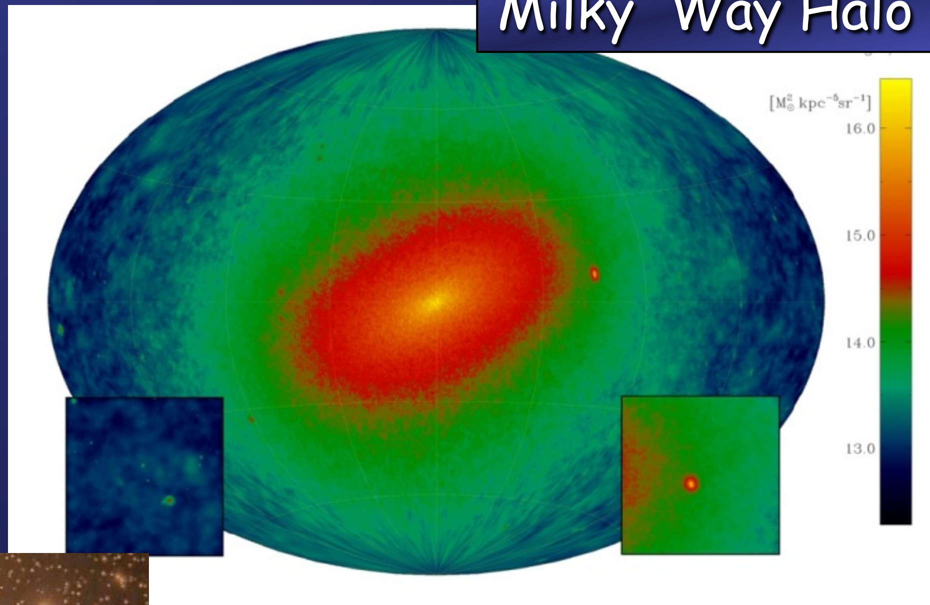


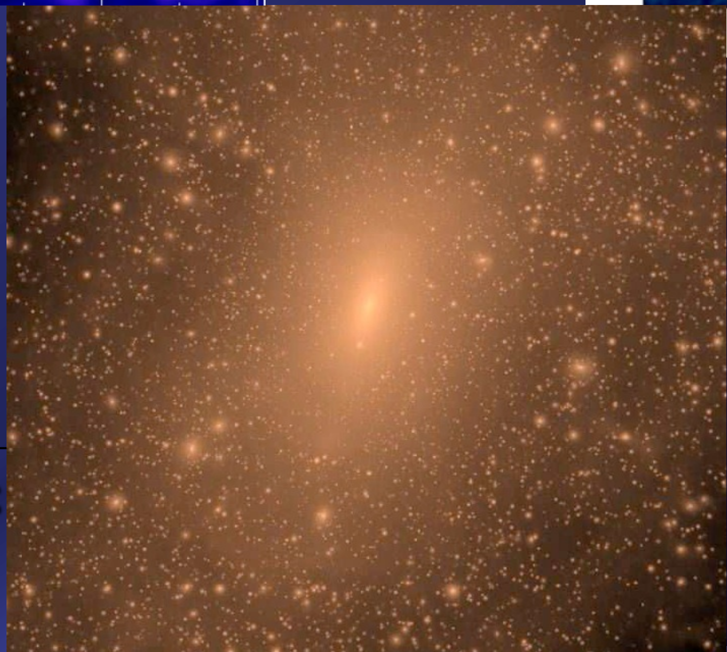
Where to look



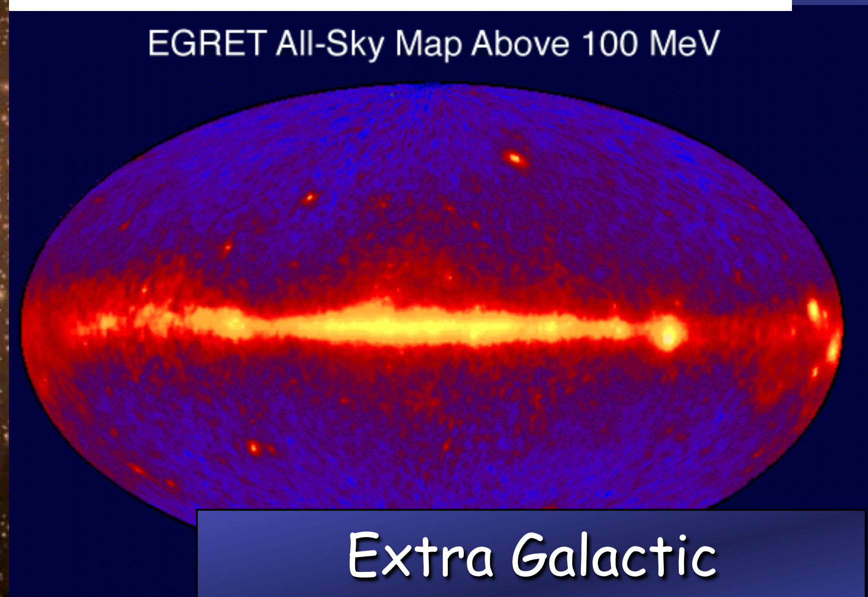
Galactic Center (Hess)

Milky Way Halo





DM Clumps: Via Lactea Simulation Diemand et al.



Extra Galactic Background

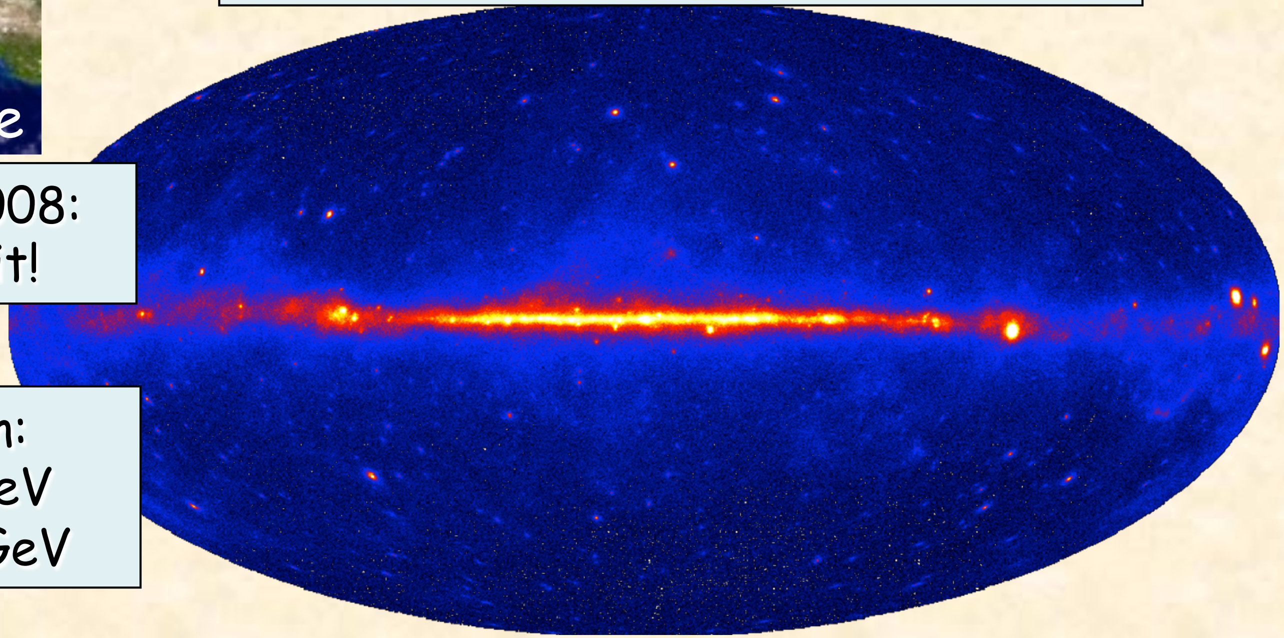
Indirect detection with gamma-rays: space based observations

Launched on 11th June 2008:
Already 5 yrs in orbit!

Good angular resolution:
better than 0.6° above 1 GeV
better than 0.1° above 10 GeV

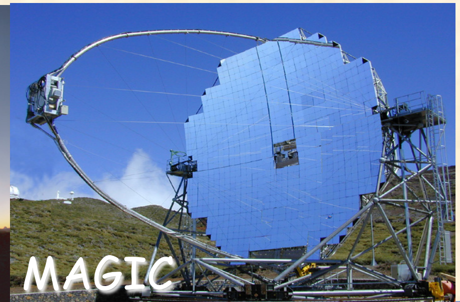
Effective Area:
Fermi: ~10000 cm2
EGRET: ~1000 cm2
→ ~one order of magnitude better statistic

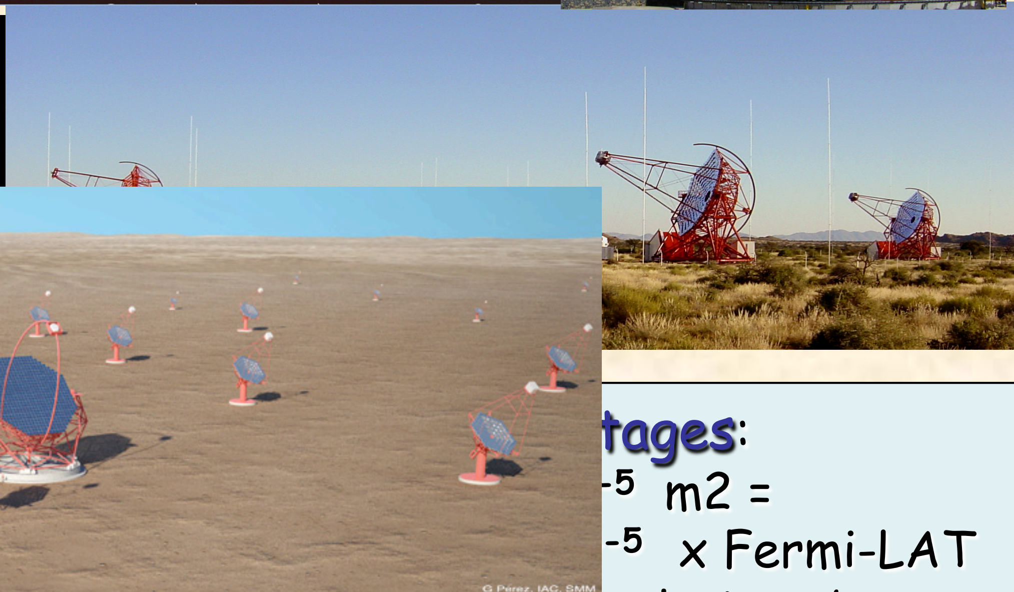
Fermi Gamma-Sky 30 MeV-300 GeV

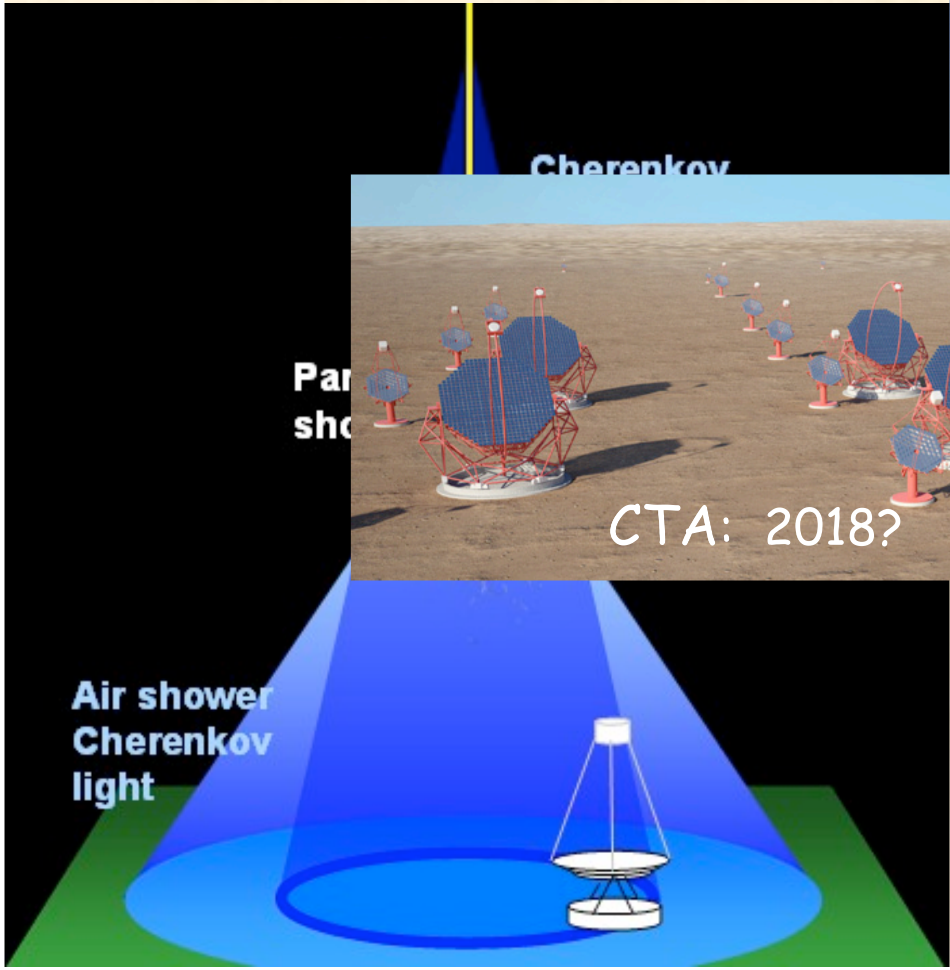


(2):ground based observations

Imaging Cherenkov Telescopes detect the showers produced by the gammas (and hadrons) interacting in the upper atmosphere







tages:

$^{-5}$ m2 =

$^{-5}$ x Fermi-LAT

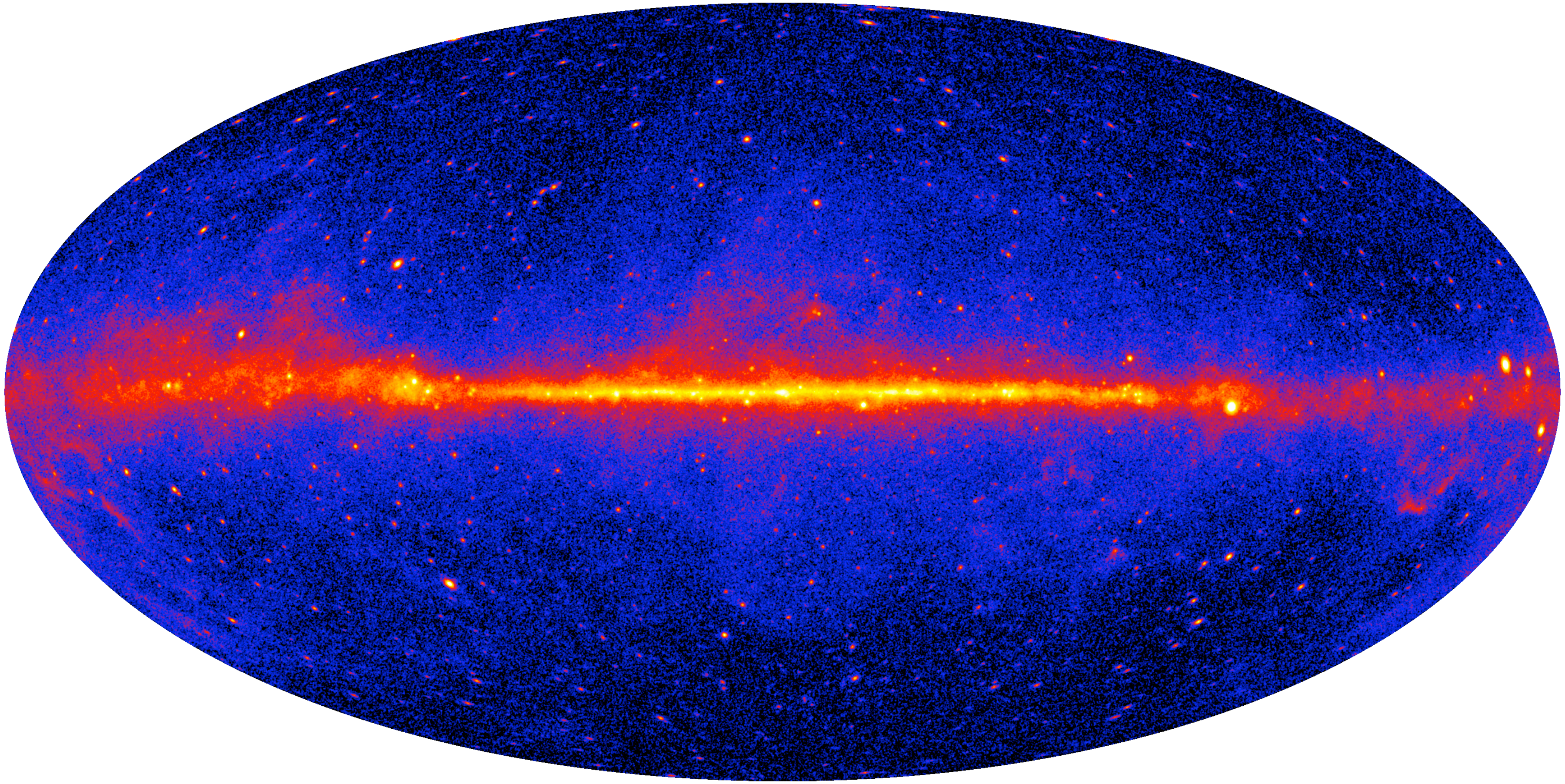
- Good Angular resolution: better than 0.1°

Drawbacks:

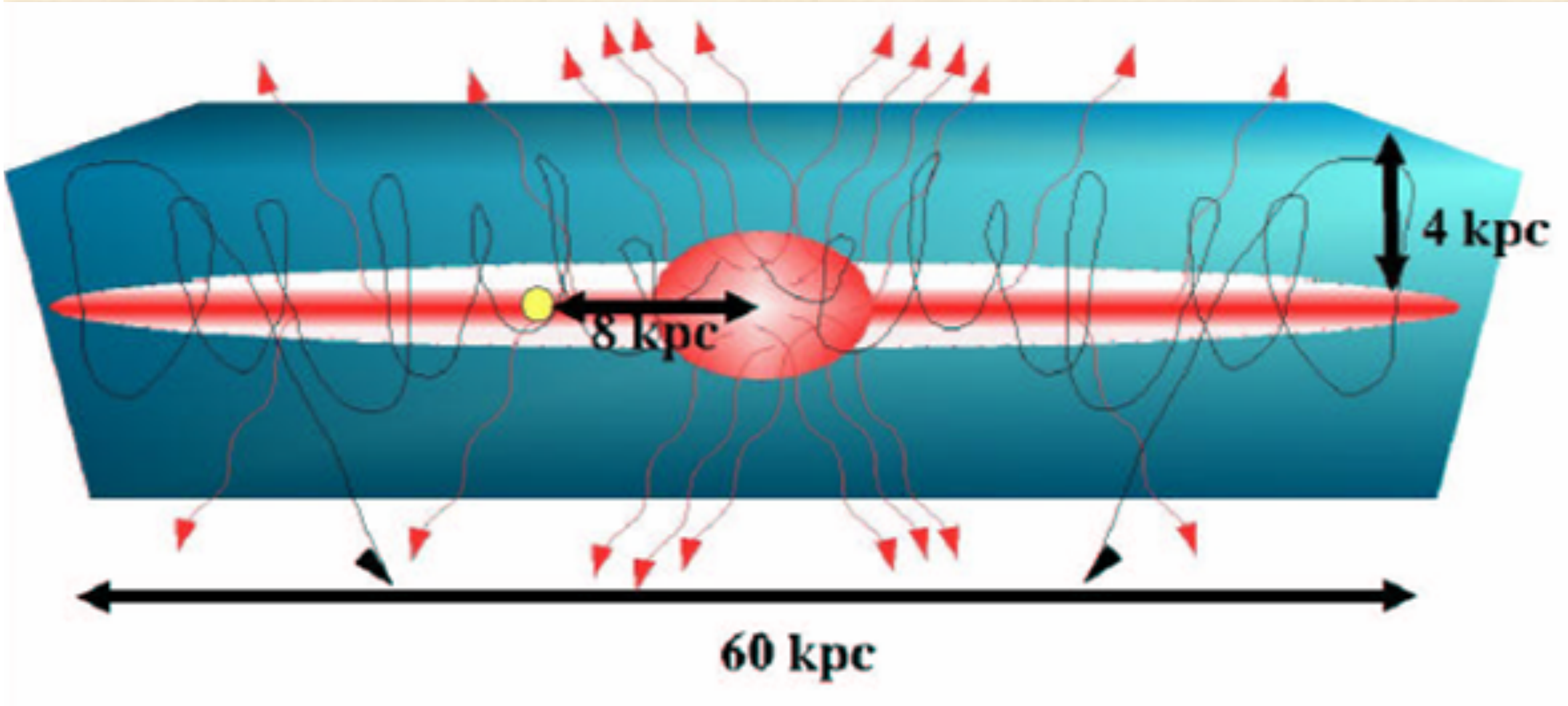
- Hadronic Background
- Narrow field of view: ~few degs
- High energy threshold: ~100 GeV

The Gamma Sky

Fermi Gamma-Sky, Front-only, >1 GeV (36 months, 3.39M events)



Propagation of CRs in the Galaxy



- Crude approximation in which CRs propagate in a slab containing the Galaxy, and escaping at the boundaries
- Described by a diffusion loss equation

Propagation of CRs in the Galaxy

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$

$$- \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

=0 Steady State Solution

Source Term:
Injection Spectrum

Diffusion

Energy Losses:
ICS and
Synchrotron

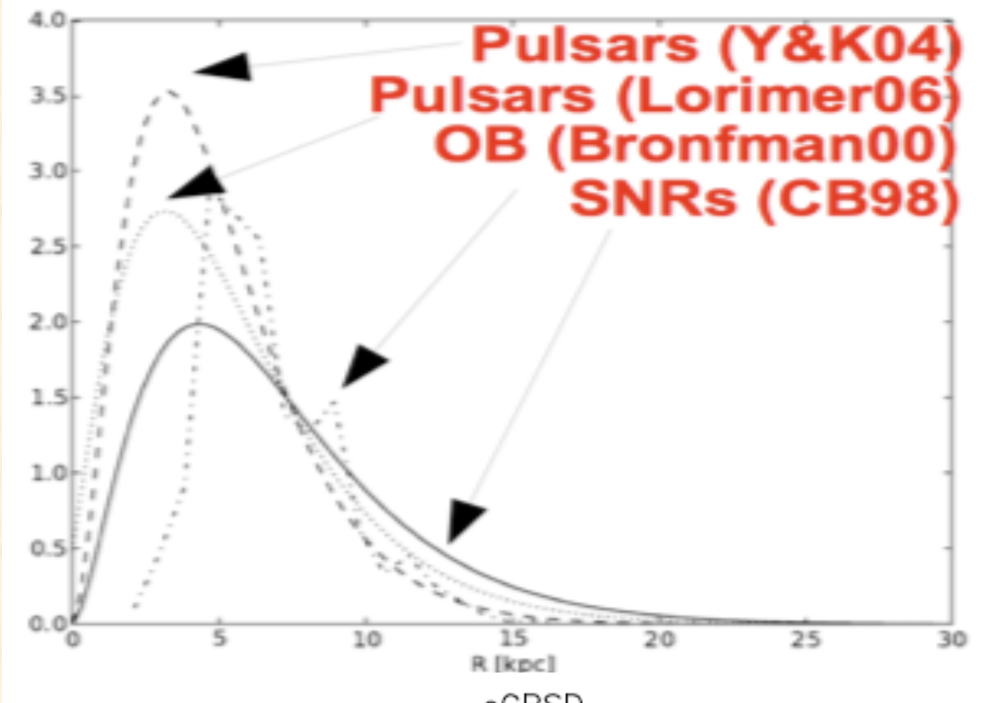
Reacceleration

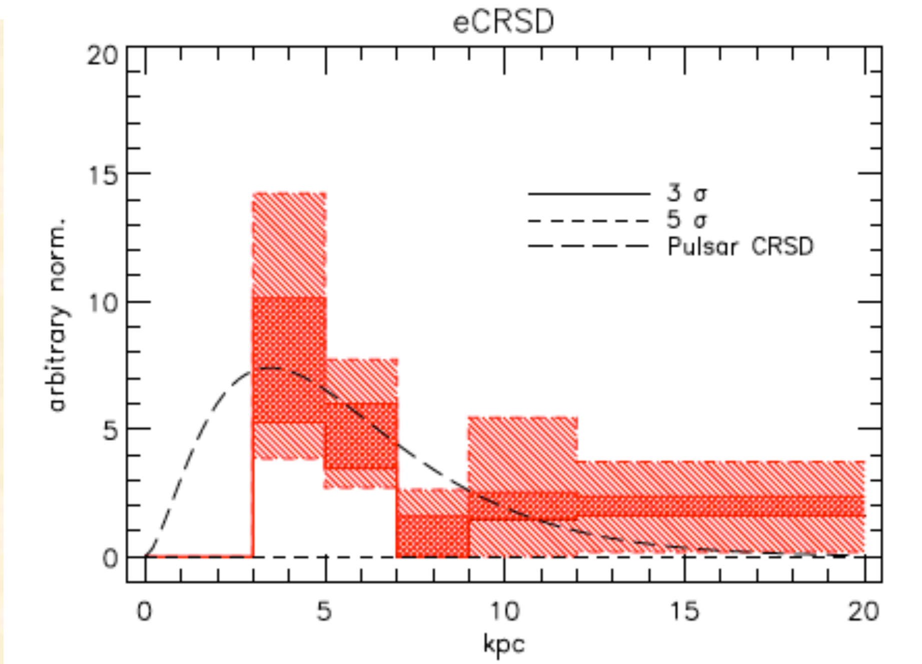
Fragmentation/Decay

Complementary and full numerical: **Galprop**, Moskalenko & Strong 98-08
Dragon Grasso, Maccione et al. 08

Radial distribution of CR sources

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

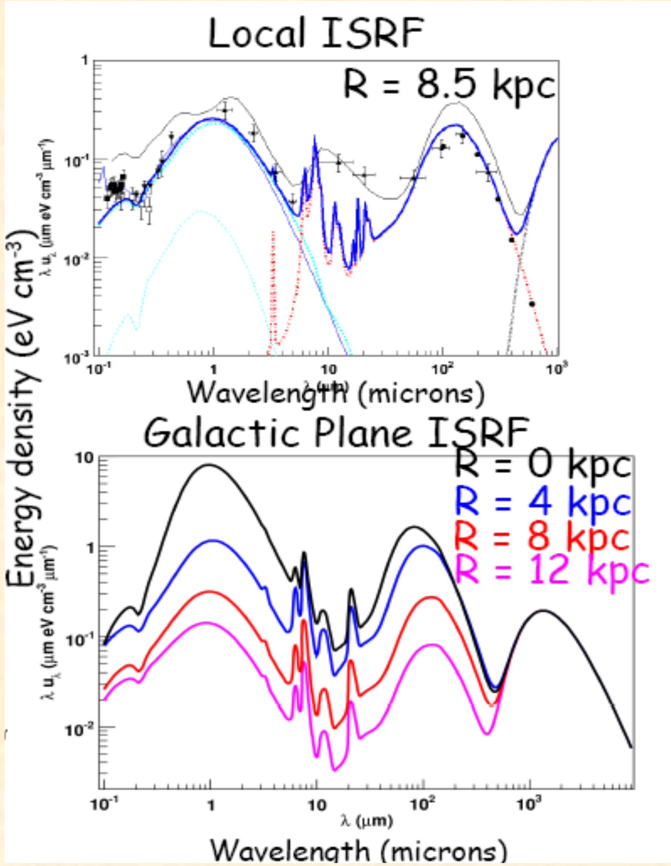




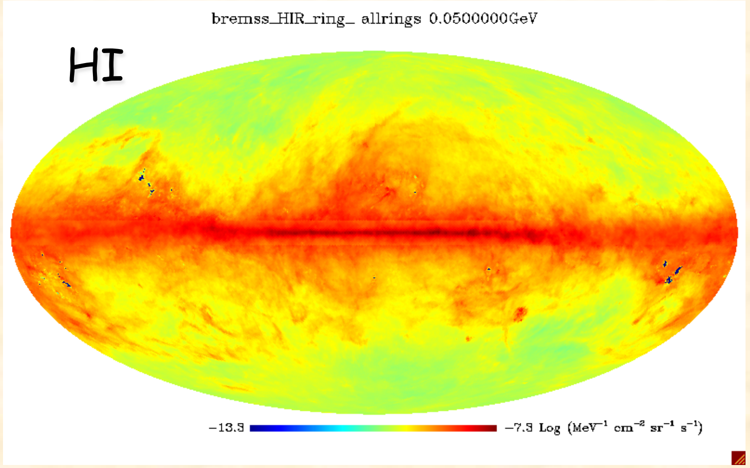
We use a parametric step-like CRSD.

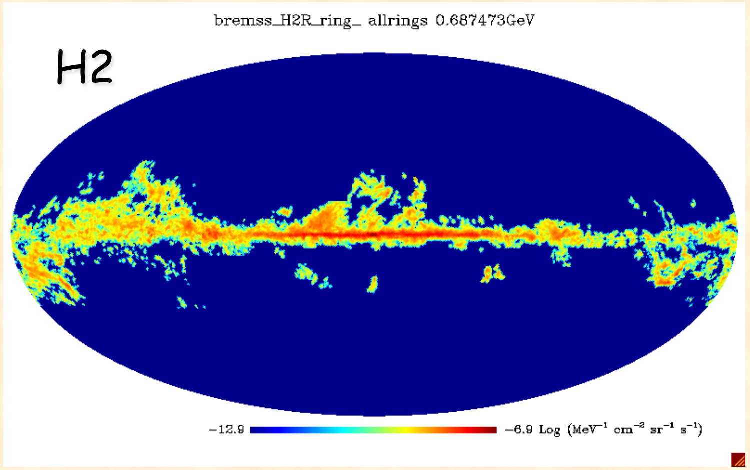
CR Targets: Gas and Radiation

Galactic ISRF



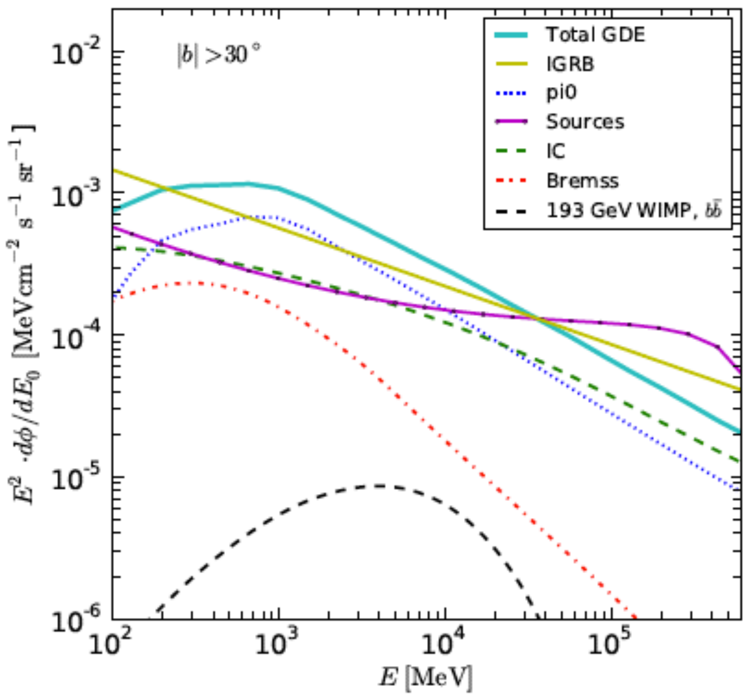
Synthetic model derived from dust infrared observations and stellar population synthesys





Quasi-3D distribution derived from 21cm surveys. Dark Gas from infrared observations

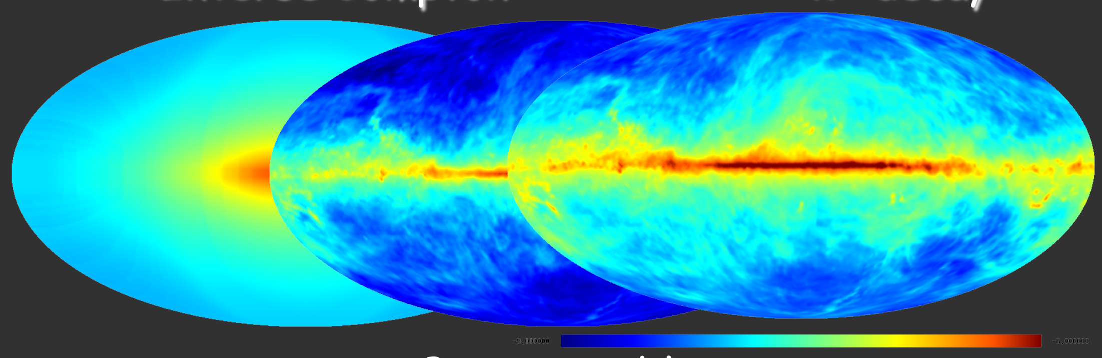
The Gamma Sky



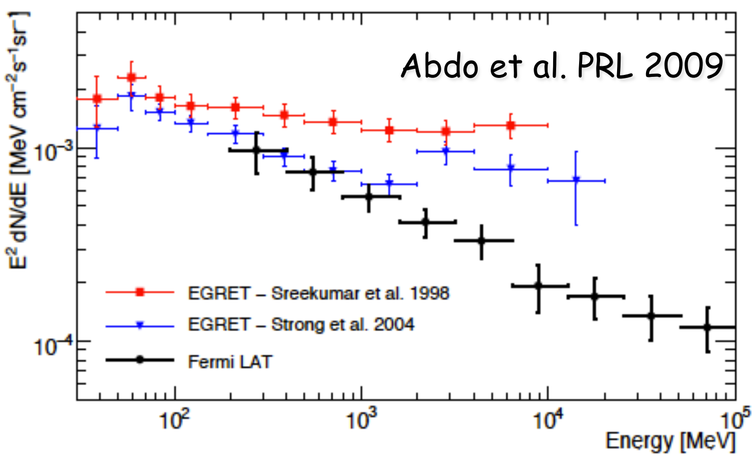
Galactic Contribution from:

1. Pion Decay
2. Inverse Compton
3. Electron Bremsstrahlung

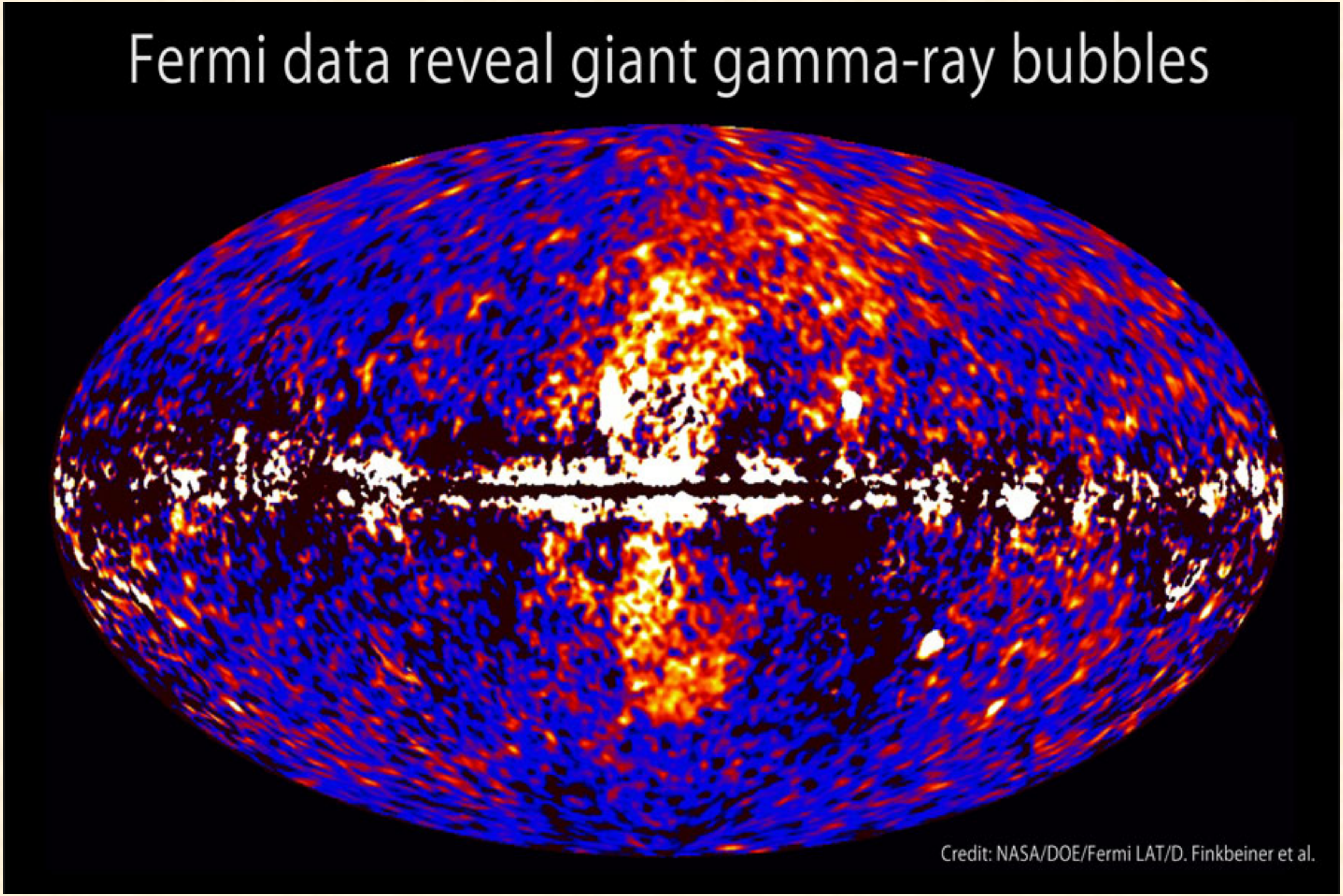
Galprop Foregrounds Model:



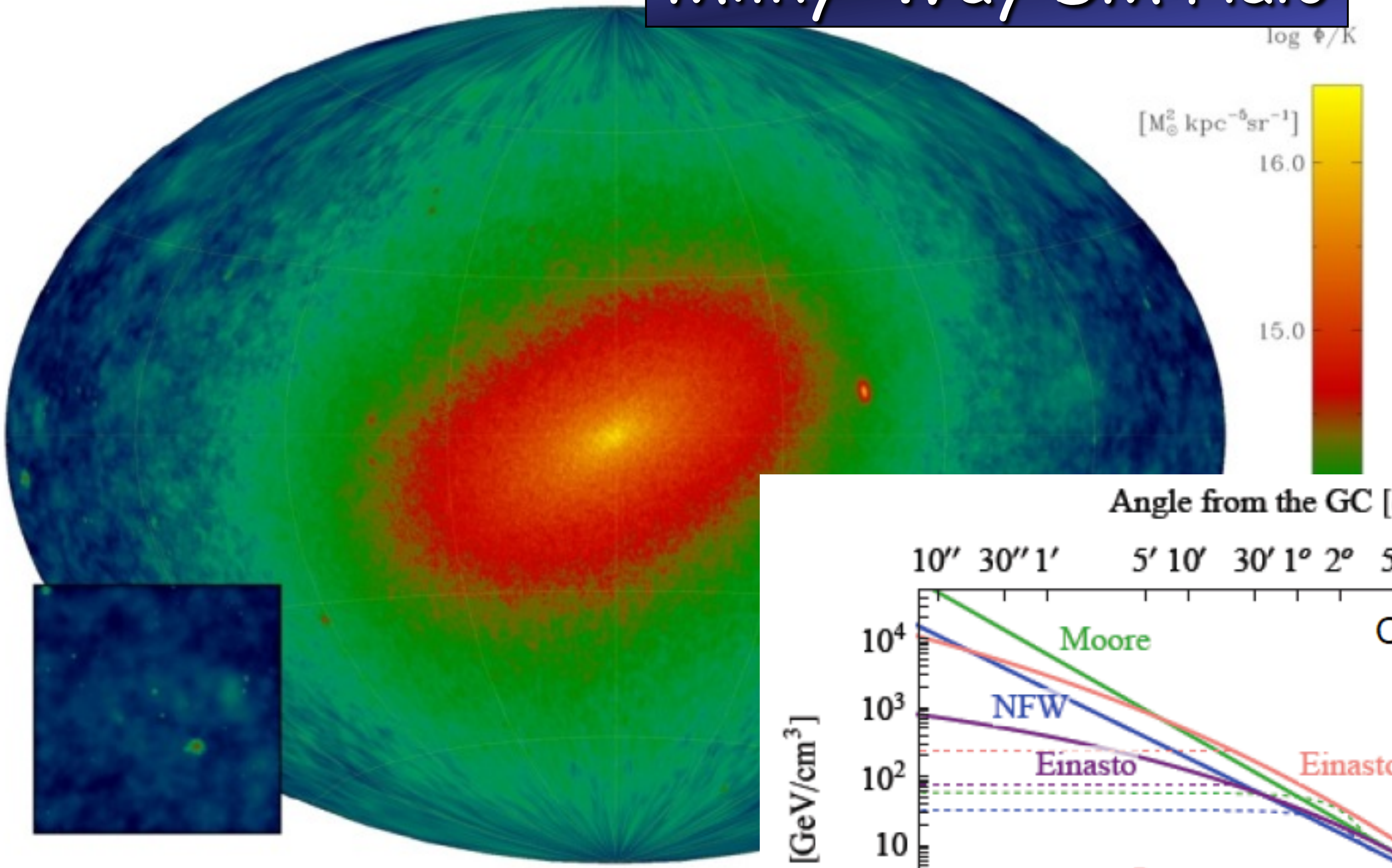
4. IGB

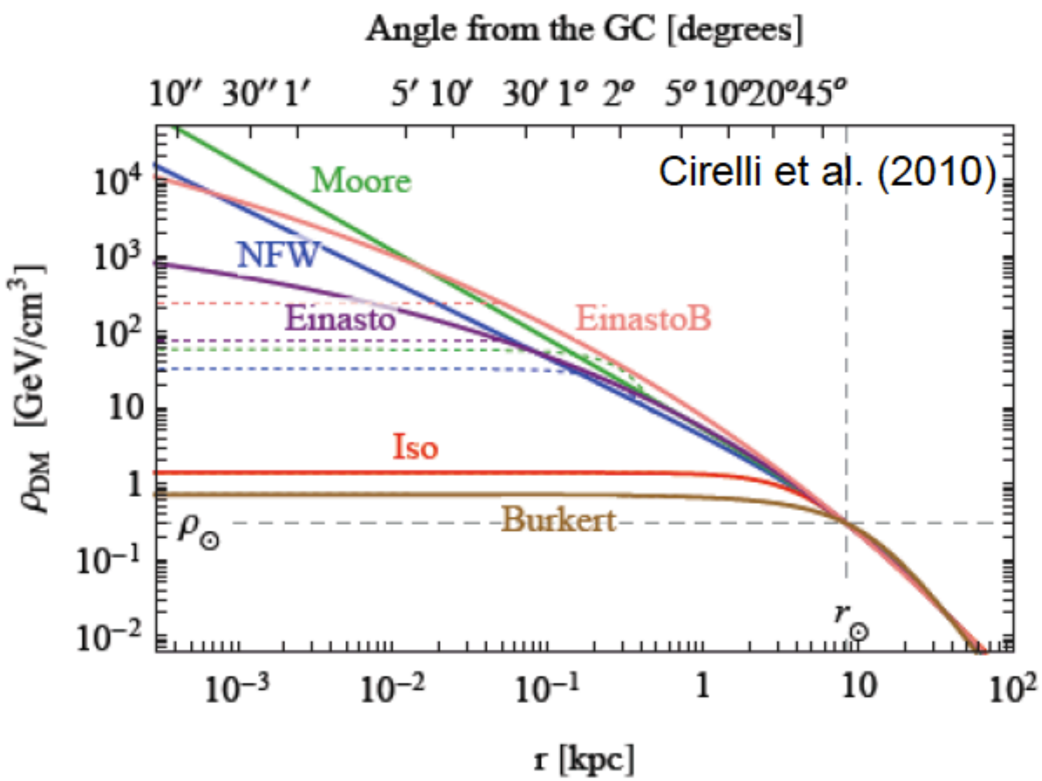


Lobes and Loops residuals



Milky Way DM Halo

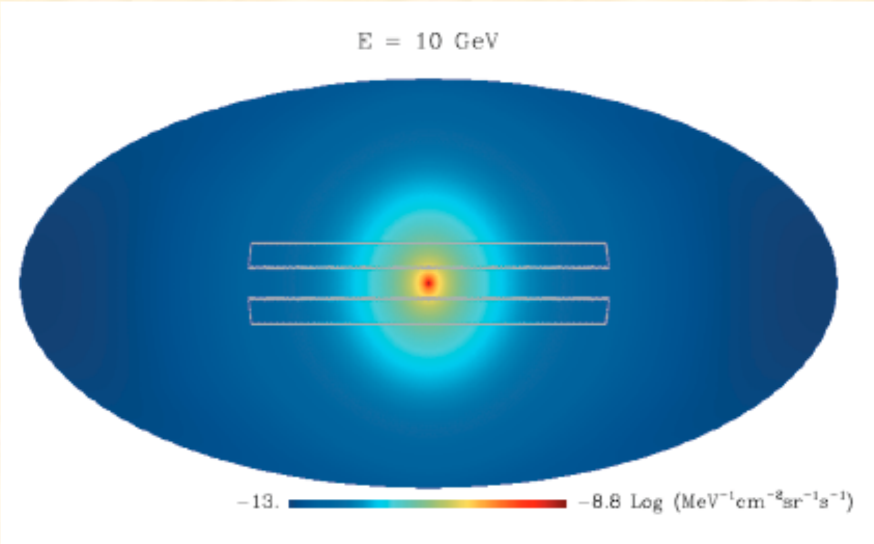


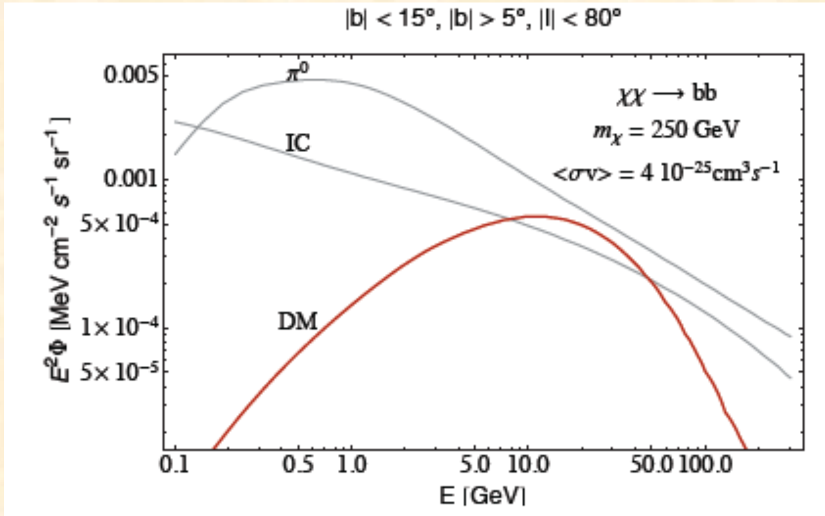


Different morphologies can be exploited to disentangle the DM signal from astrophysics

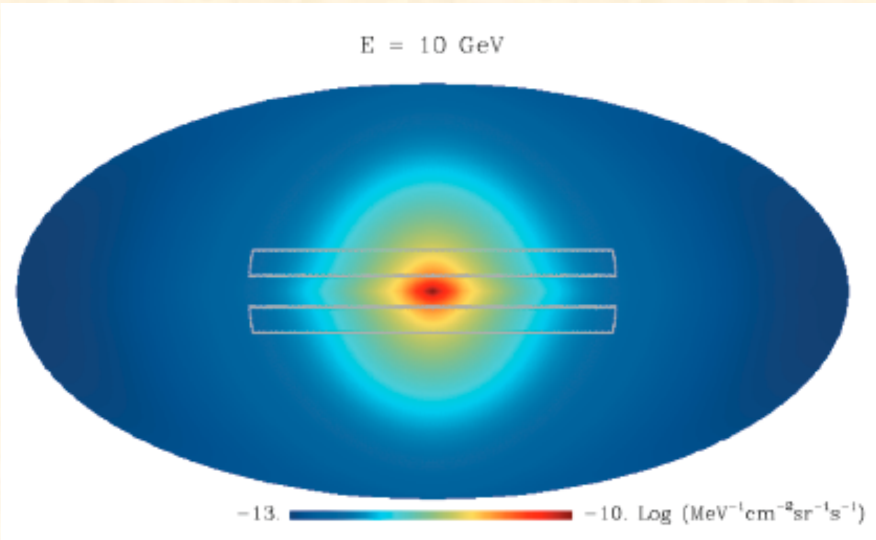
DM gamma components for ICS and FSR

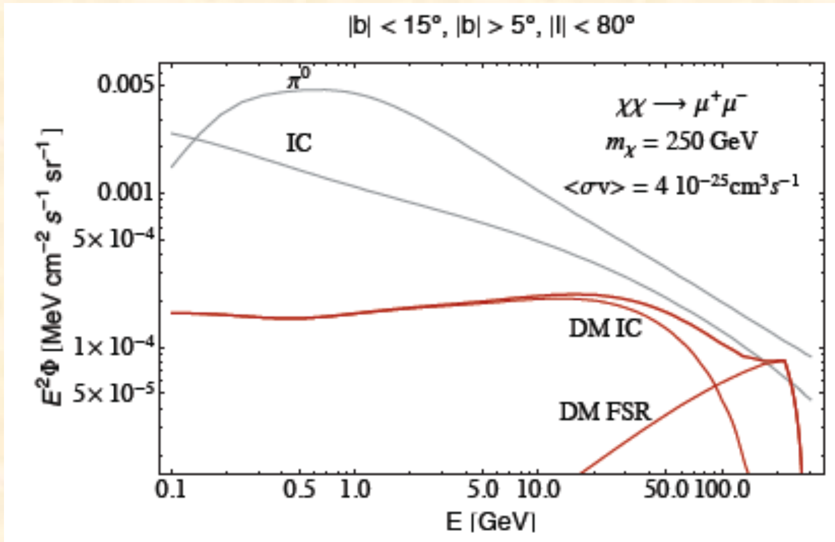
Final state radiation only (b-bar case): compact Haze morphology and peaked spectrum



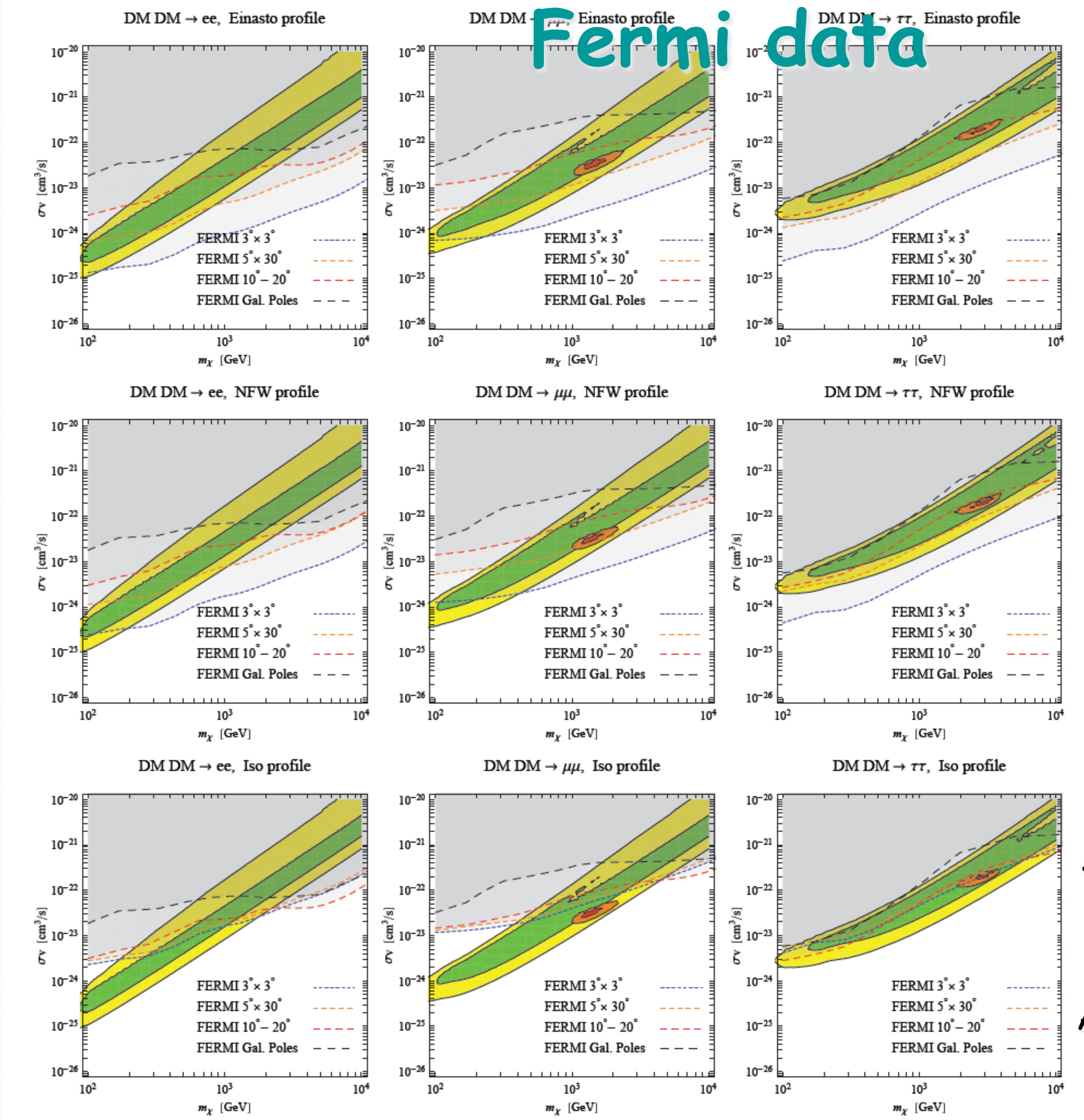


ICS +FSR (μ+μ- case): extended Haze morphology and hard spectrum





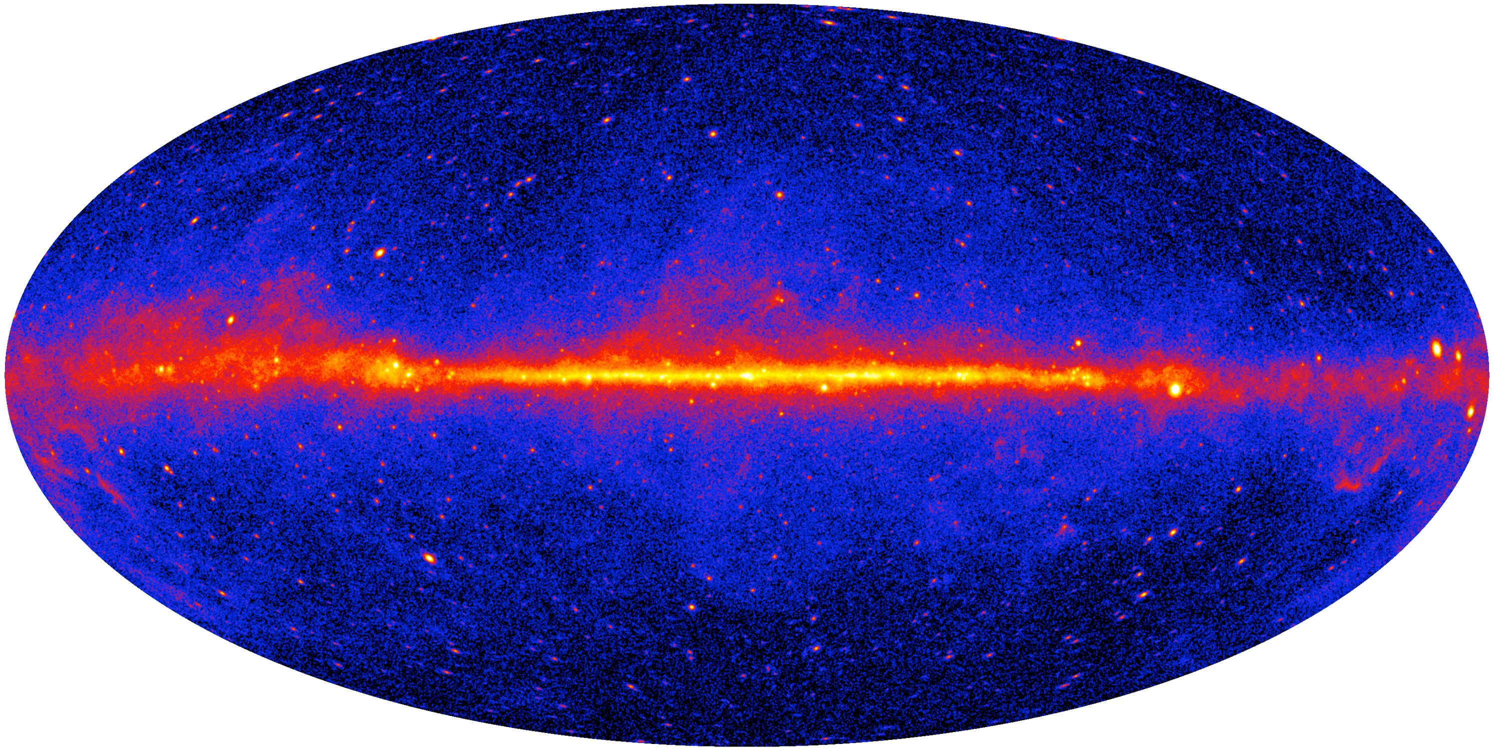
DM conservative constraints from ICS and Fermi data



M. Cirelli, P. Panci, P. D. Serpico, NPB 2010, arXiv: 0912.0663

G.Bertone, M.Cirelli, A.Strumia, M.Taoso, JCAP 2009, arXiv:0811.3744

Fermi sky-map, again



Looking at the map it is clear that the sky is not dominated by DM, but rather by the known astrophysical processes:
Can we take into account this fact and derive better limits?

Global fit of DM and background: Summary of the parameters of the model (I)

Parameter
v_A [30; **36**; 45] km s^{-1}
$\gamma_{p,1}$ [1.8; **1.9**; 2;]
$\gamma_{p,2}$ [2.35; **2.39**; 2.45]
$\rho_{br,p}$ [10; **11.5**; 12.5] GV
d2HI [0.0110, **0.0140**; 0.0170] 10^{-20} mag cm^2
$\gamma_{e,2}$ [2.0; **2.45**; 2.6]
(D_0, z_h) [**(5.0e28, 4)**; (7.1e28, 10)] cm^{2}s^{-1}
CRSD [**SNR**; Pulsar]
KRA($\delta = 0.5$); **KOL($\delta = 0.3$)**; PD($\delta = 0.6$)
V_c [**0**; 20] km s^{-1}
GMF [**Conf 1**, Conf 2]

$$D(\rho) = D_0(\rho/\rho_0)^{-\delta}$$

Diffusion coefficient as a power law in rigidity

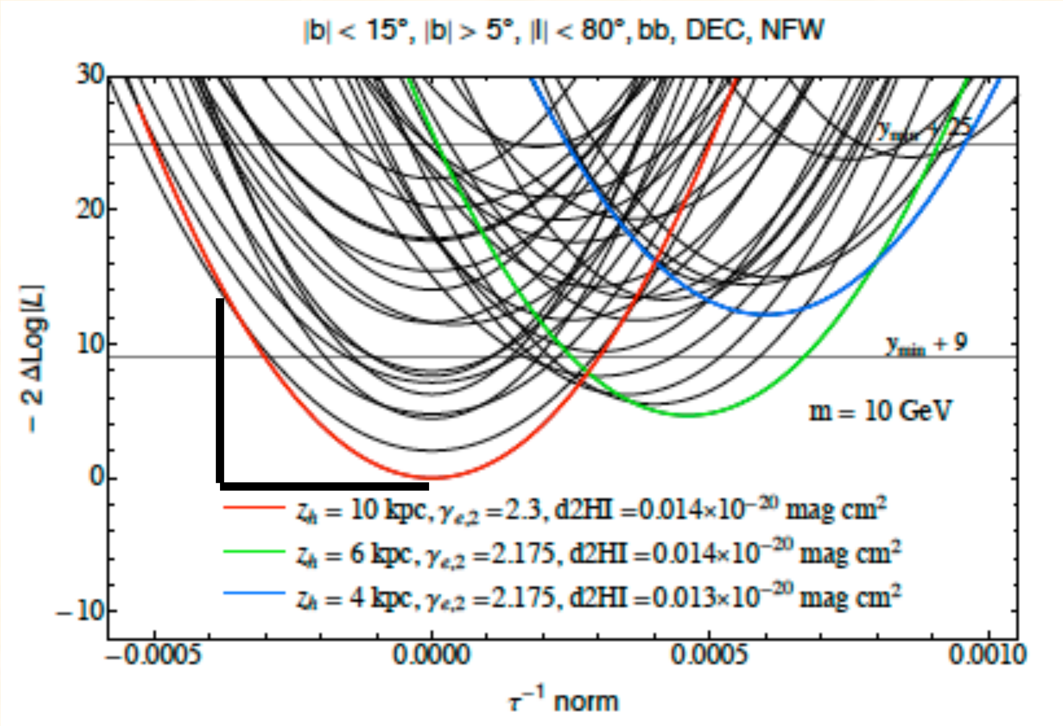
$$dq(p)/dp \propto p^{-\gamma}$$

Injection spectrum of nucleons and electrons as broken power laws in momentum

For the details check:
Ackermann et al [Fermi-Lat Coll.] ApJ 761 (2012) 91, Arxiv:1205.6474

Profile Likelihood Method

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



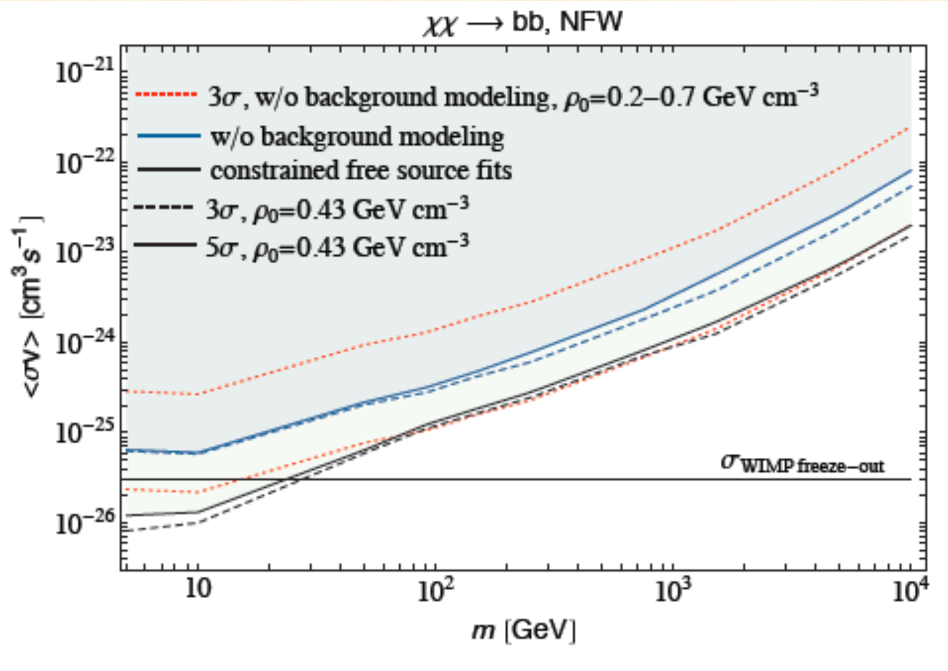
Different curves correspond to *different models from the grid*

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

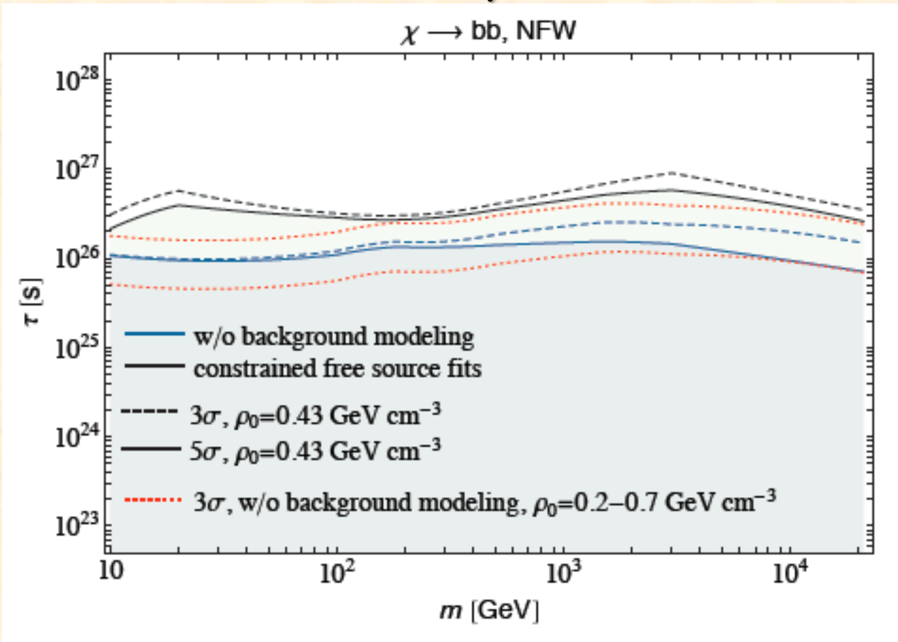
LogLikelihood vs DM normalization (σv) for a *fixed* DM model (channel and mass)

Constraints: bb channel

annihilation



decay

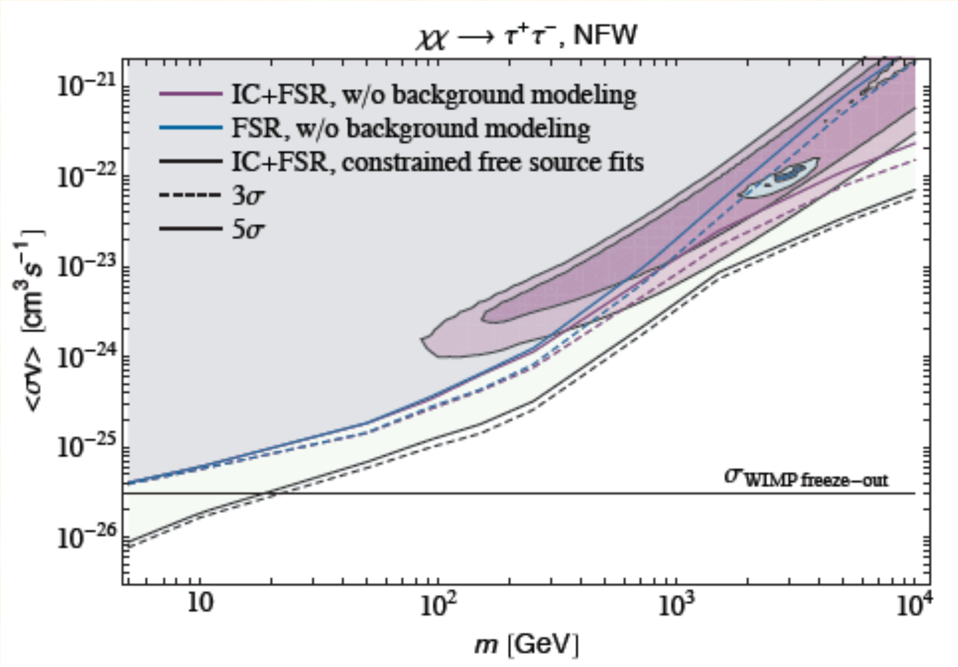


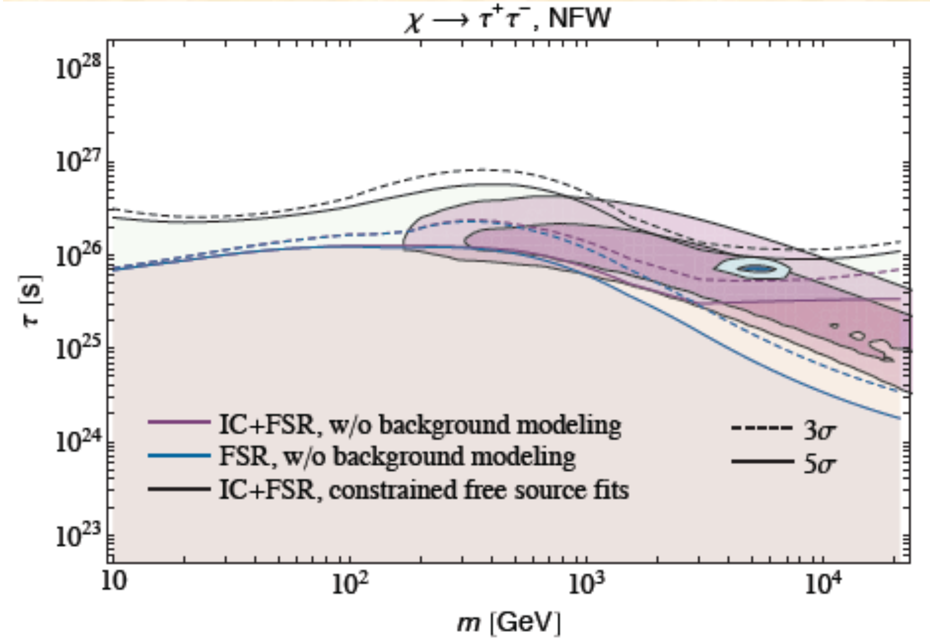
- Blue: “no-background limits”.
- Black: limits with modeling of the background, *in which CR sources are held to zero in the inner 3 kpc.*
- Red: shifting of the limits varying ρ_0 in the range 0.2-0-7 GeV/cm^{-3}
- Limits with *ISO* profile (not shown) are only slightly worst.

Constraints: τ+τ-channel

annihilation

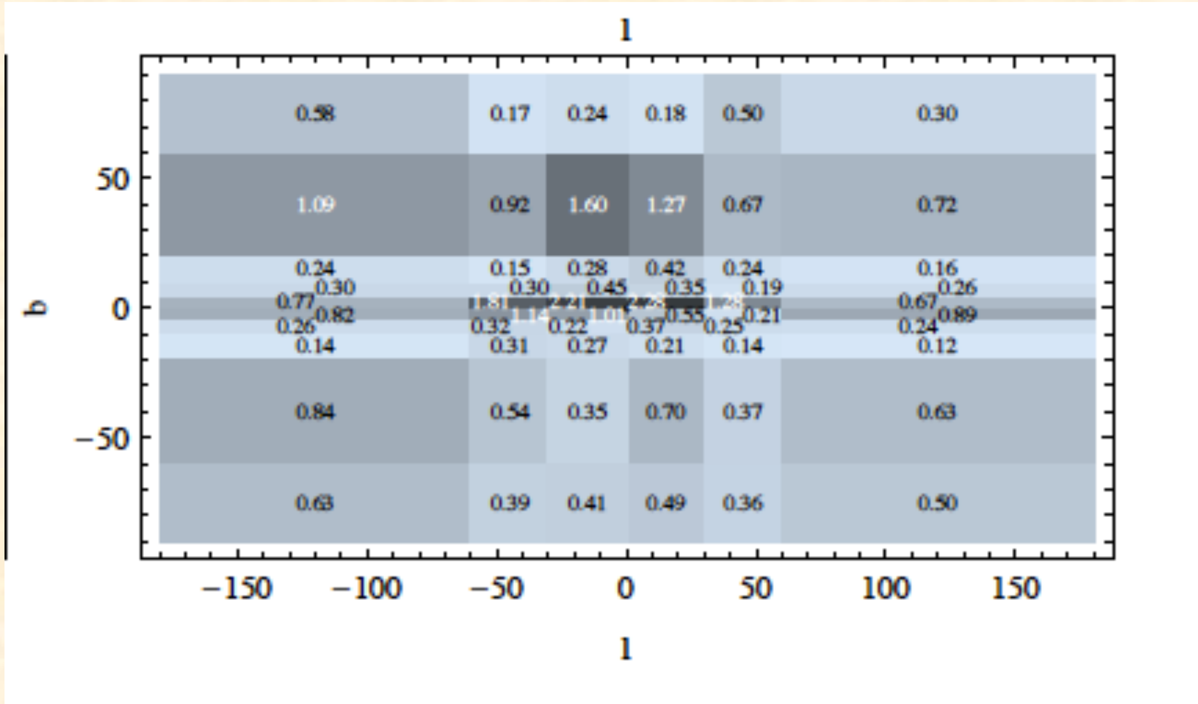
decay

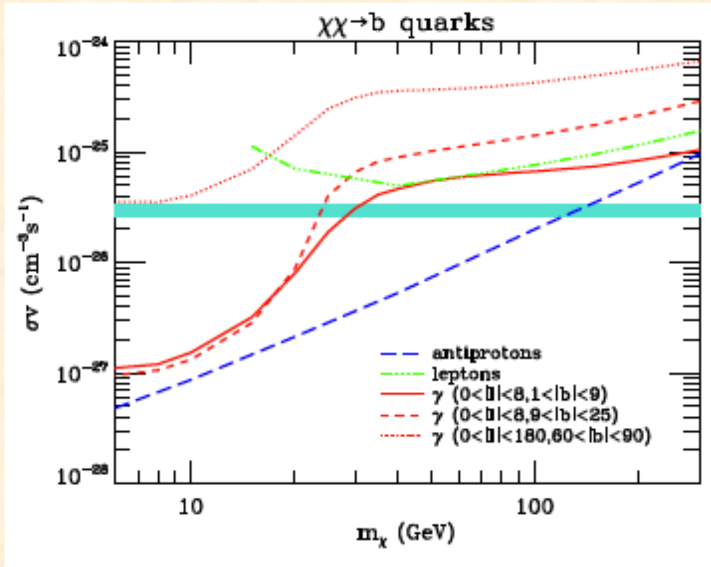




- Blue: here we used only photons produced by muons to set "no-background limits" ('FSR only').
- Violet: "no-background limits" FSR+IC
- Black: limits from profile likelihood and *CR sources set to zero in the inner 3 kpc.*
- *DM interpretation of PAMELA/Fermi CR anomalies strongly disfavored* (for annihilating DM).

Again the Galactic Halo

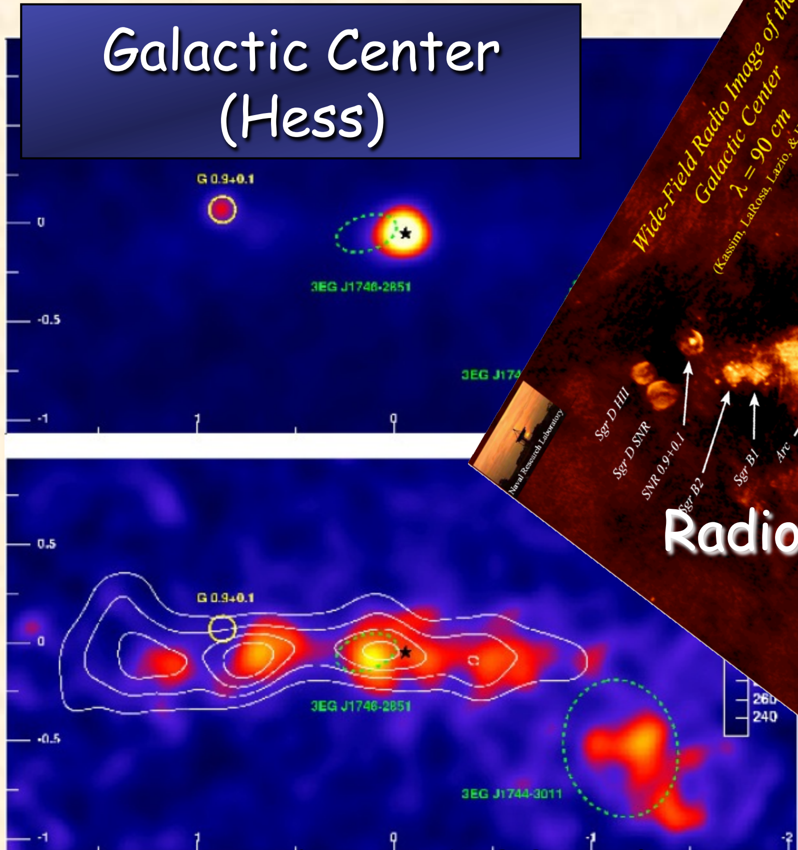


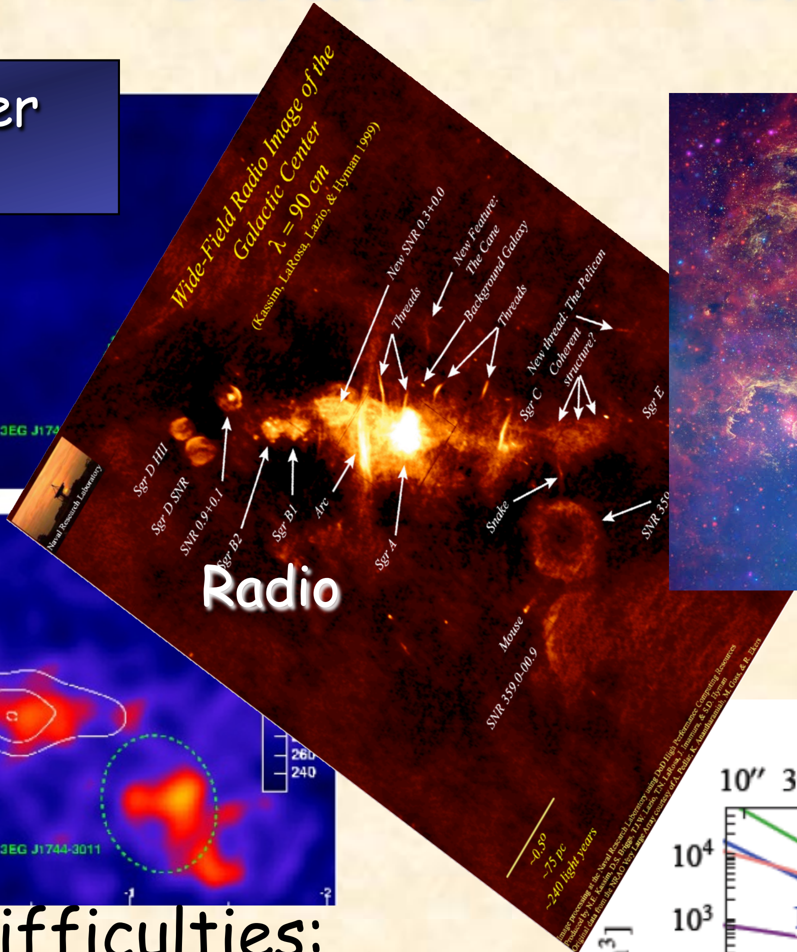


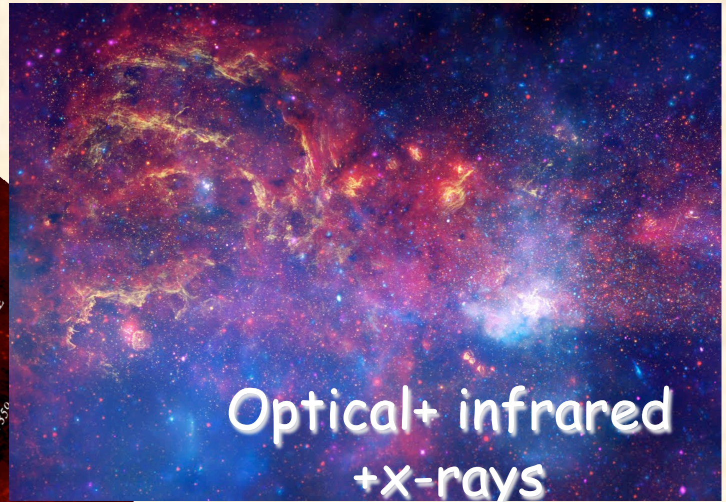
Tavakoli, Cholis, Evoli, Ullio, ArXiv:1308.4135

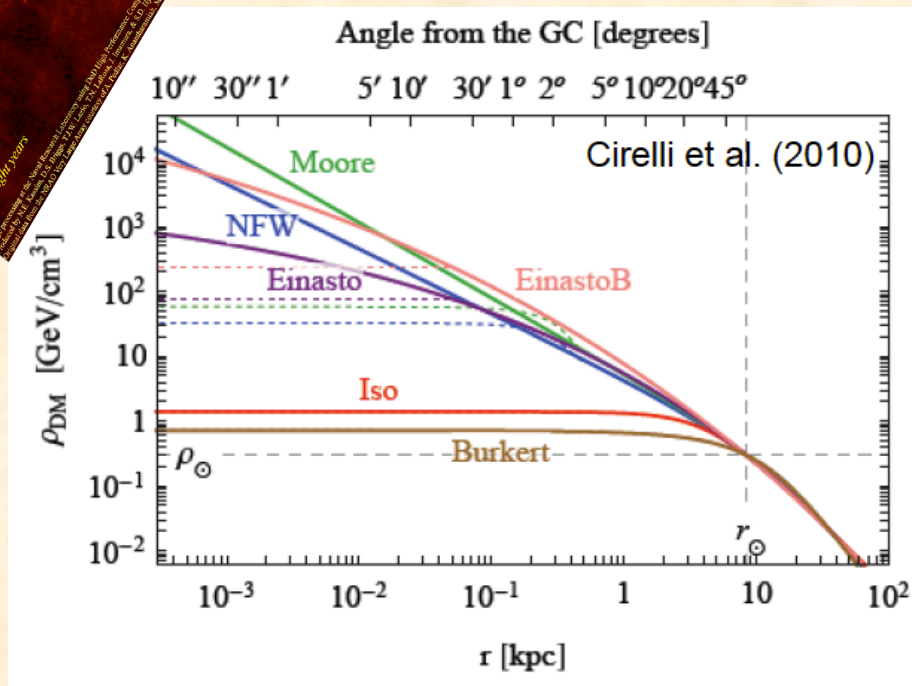
Tavakoli et al. also analyze the Galactic Halo and the all-sky diffuse emission taking into account uncertainties in the gas emissivities. A self-consistent framework is used to derive constraints from gamma-rays and charged particles.

Galactic Center





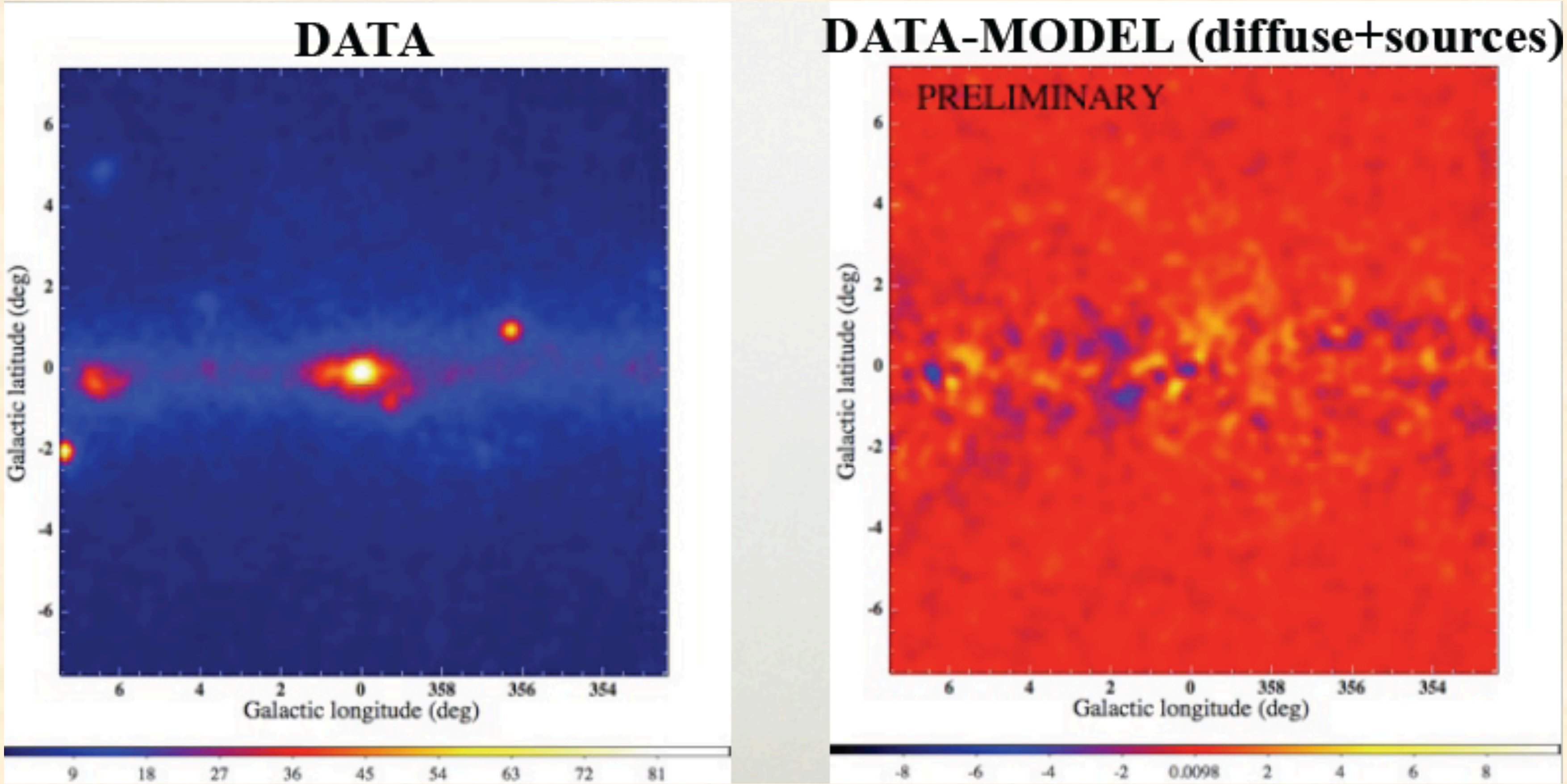




Further difficulties:

- Strong Background from the astrophysical point and diffuse sources in the GC
- Large Uncertainties in the DM profile
- Overall, however, the same methodology used for the Halo can be applied to the GC. Work in progress….

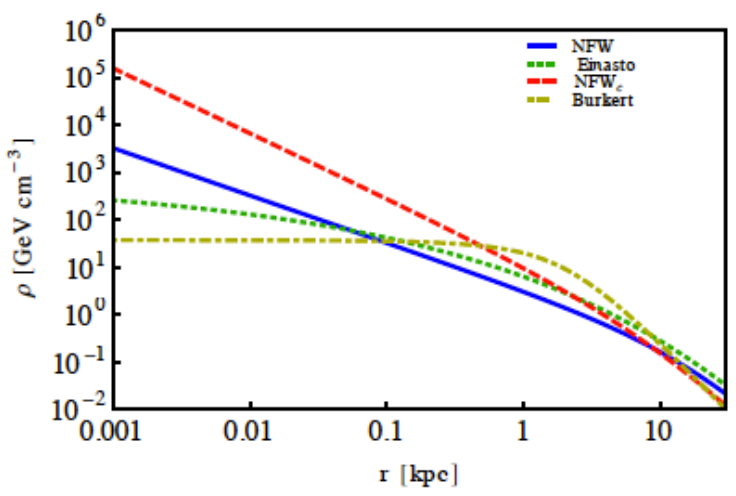
Galactic Center

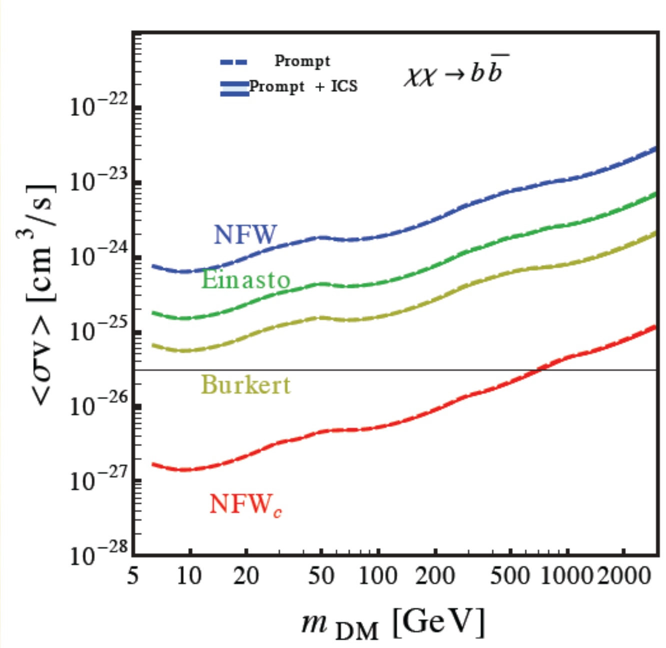


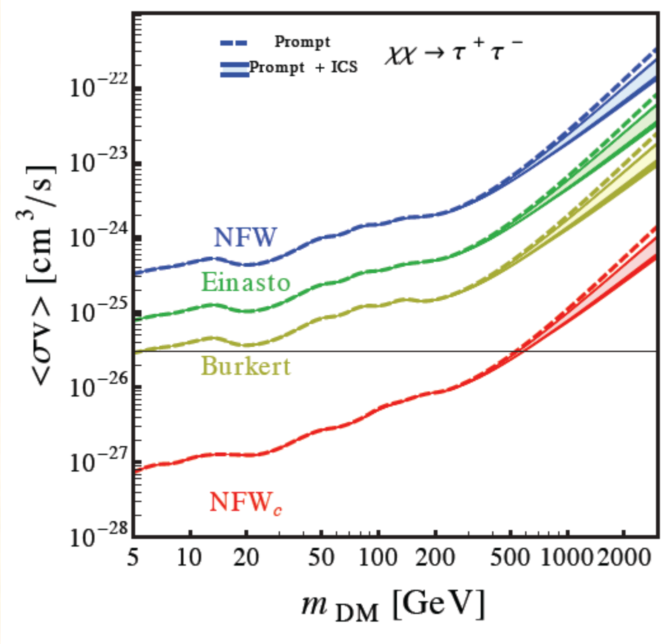
preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT)

Fermi-LAT analysis of the CG in progress:
See talk by Simona Murgia

Galactic Center: conservative limits



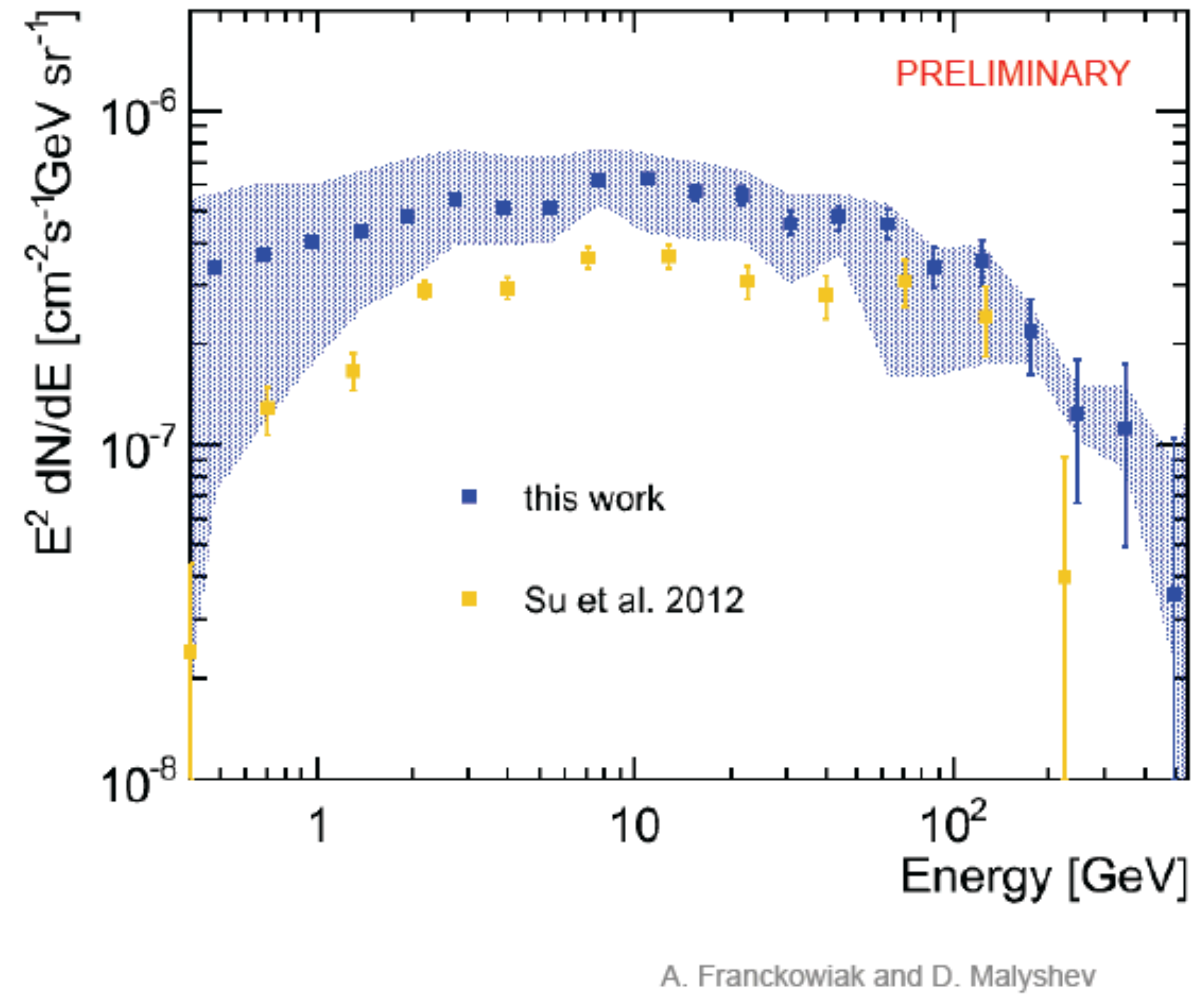




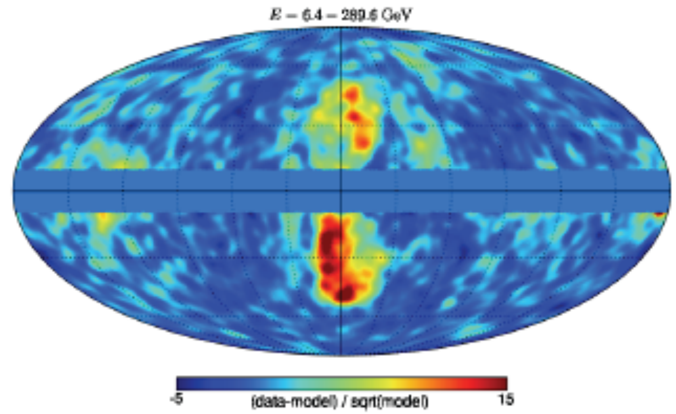
DM limits requiring that the DM signal does not exceed the observed emission are quite DM profile dependent.
The hypothesis of contracted NFW profile is in tension with the standard thermal relic expectation

Gomez-Vargas et al., arXiv:1308.3515, JCAP 2013

Spectrum of the Bubbles



Integrated residual map from 6.4 to 300 GeV

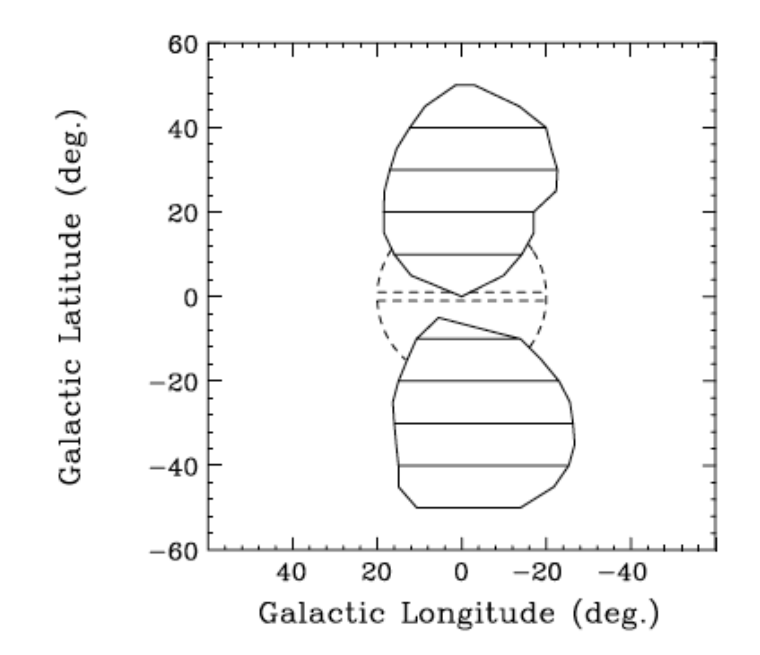


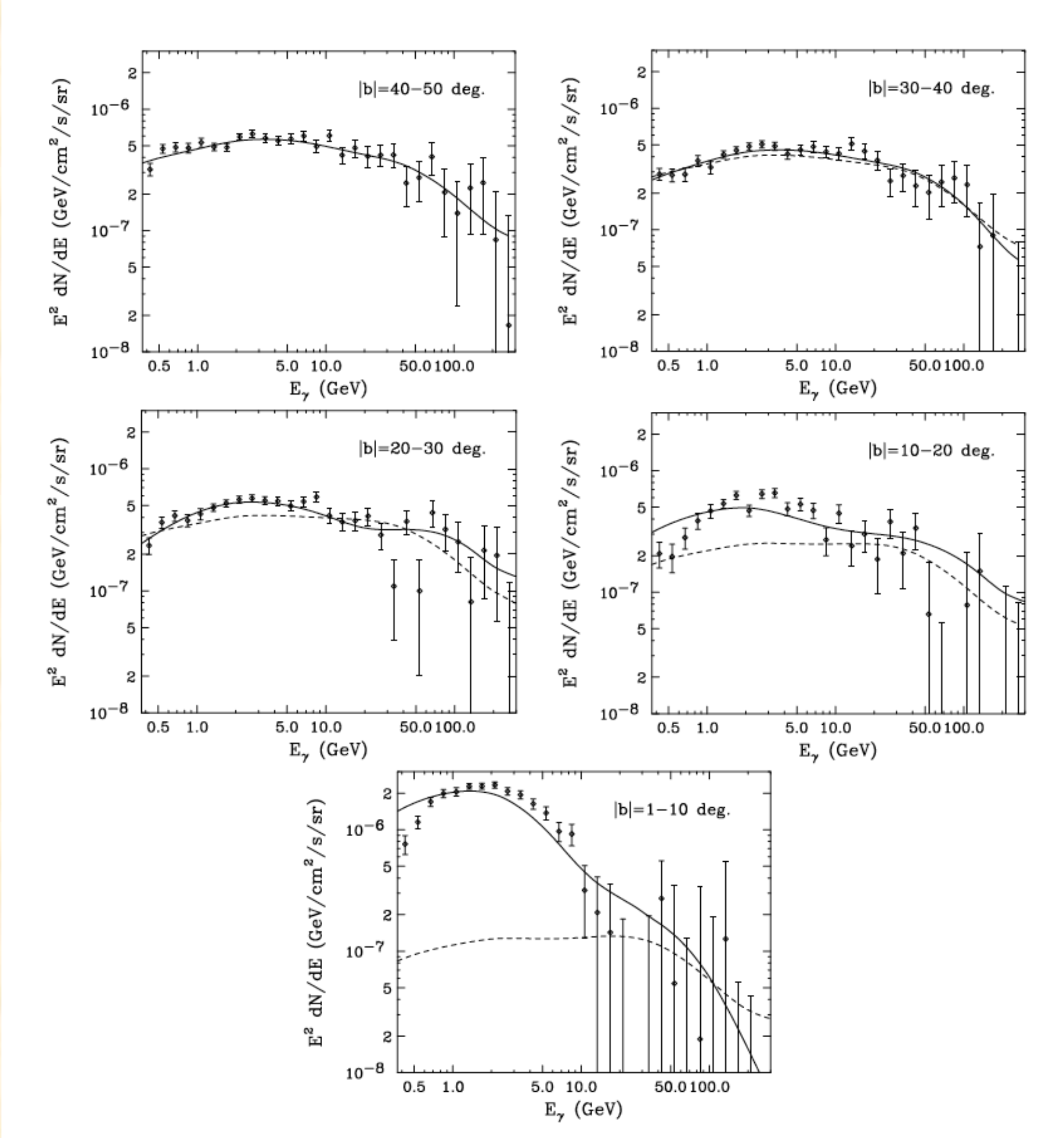
Large systematic uncertainties at low energies.

Softening above ~200GeV

A. Franckowiak and D. Malyshev, for the Fermi-LAT Collaboration ICRC 2013

Inner Galaxy Excess(?)



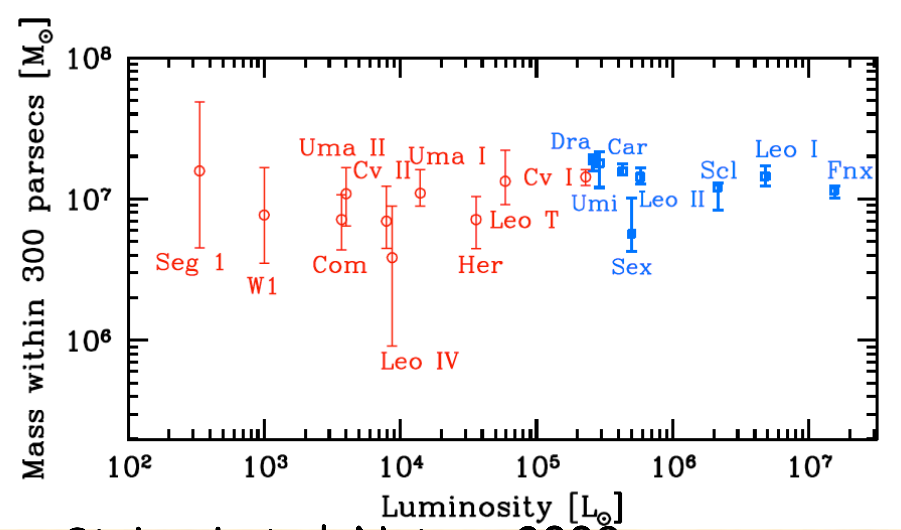


Hooper and Slatyer claim the Bubble spectrum has a "bump" in the region within 10 degrees from the GC.

Astrophysical backgrounds in this region are very complicate and need to be accounted carefully.

Hooper, Slatyer, 2013, ArXiv:1302.6589

Clean targets: Nearby Dwarfs Galaxies



Strigari et al. Nature 2009

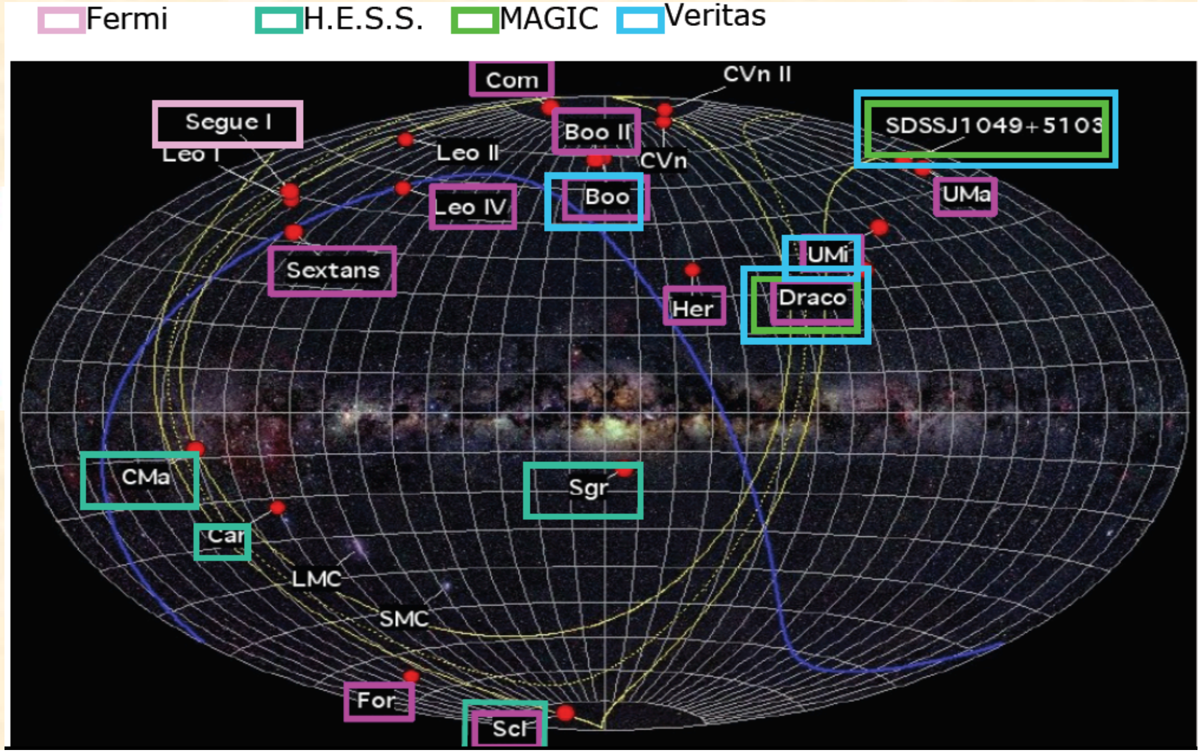
The faintest dwarfs detected have a mass to light ratio of more than 10^4: they are DM dominated system with very little astrophysical signal expected

J-factor

$$J(\psi) = \int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\, \rho_\chi^2(l)$$

J-factors (DM signal) and their uncertainties can be calculated from stellar kinematical data of the dwarfs

Dwarfs probed in gamma-rays



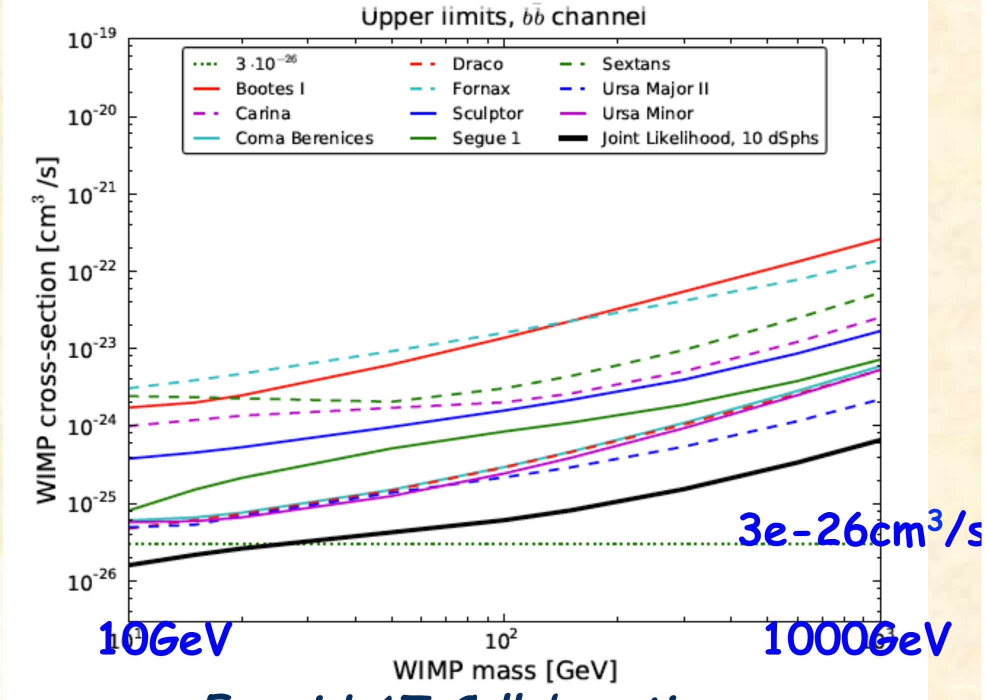
Novel constraints using a combined likelihood and including J-factor uncertainties

$$L(<\sigma_{ann}v>, m_{WIMP}; \vec{\Theta}) =$$
$$\prod_i^N L_i(<\sigma_{ann}v>, m_{WIMP}, J_i^m, C, b_i; \vec{\Theta}_i) \frac{1}{J_i^m \sigma_{J,i}\sqrt{2\pi}} e^{\frac{-(\ln(J_i^m) - J_i^{true})^2}{2\sigma_{J,i}^2}}$$

The method implements a product of likelihoods from the single dwarfs, instead of the usual multiple source stacking. The formalism also allows to take into account easily the J-factor uncertainties.

Including the J-factor uncertainties changes the constraint by roughly 40 %.

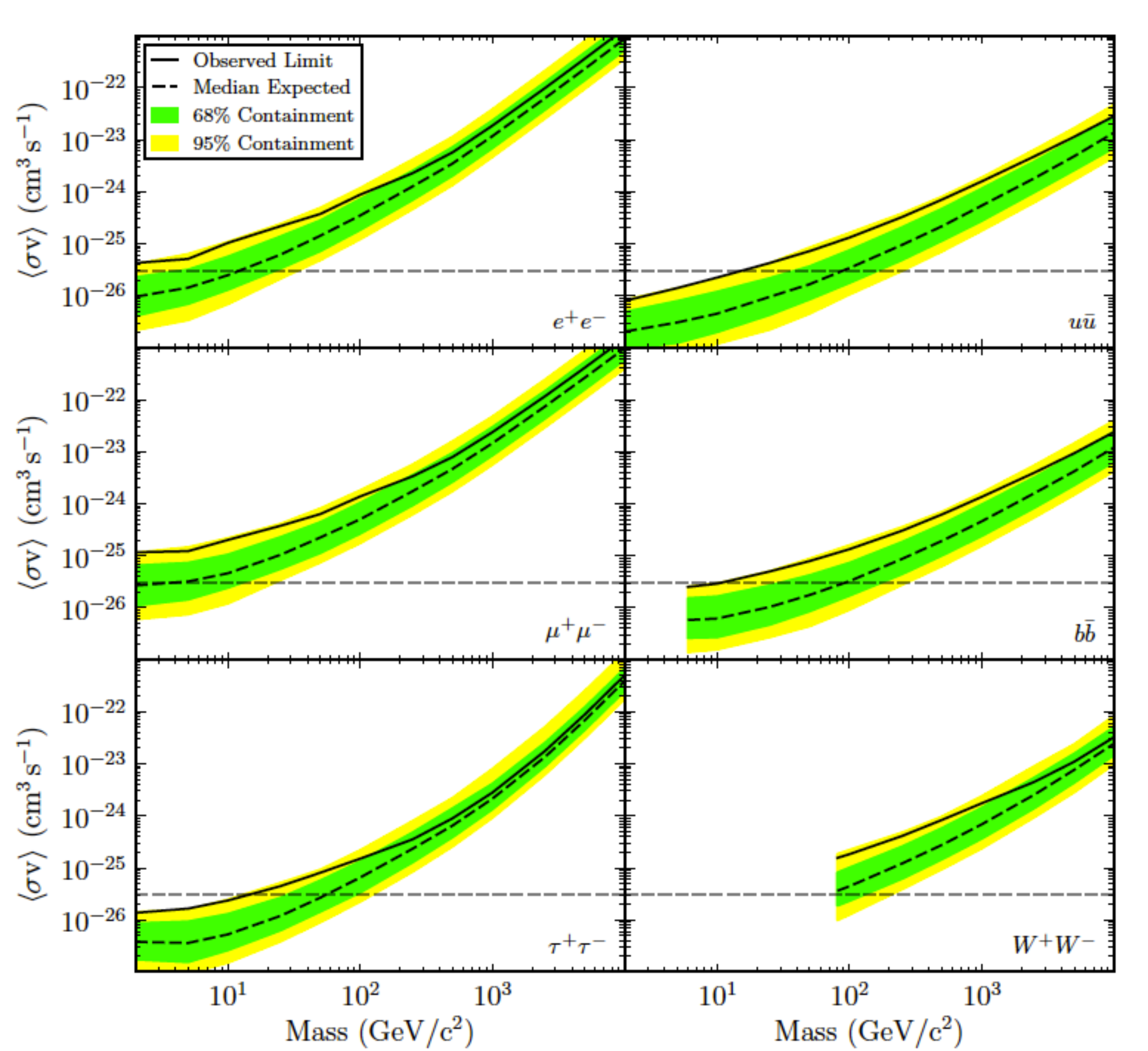
- J-factor uncertainties included



Fermi LAT Collaboration,

arXiv:1108.3546, PRL 2012

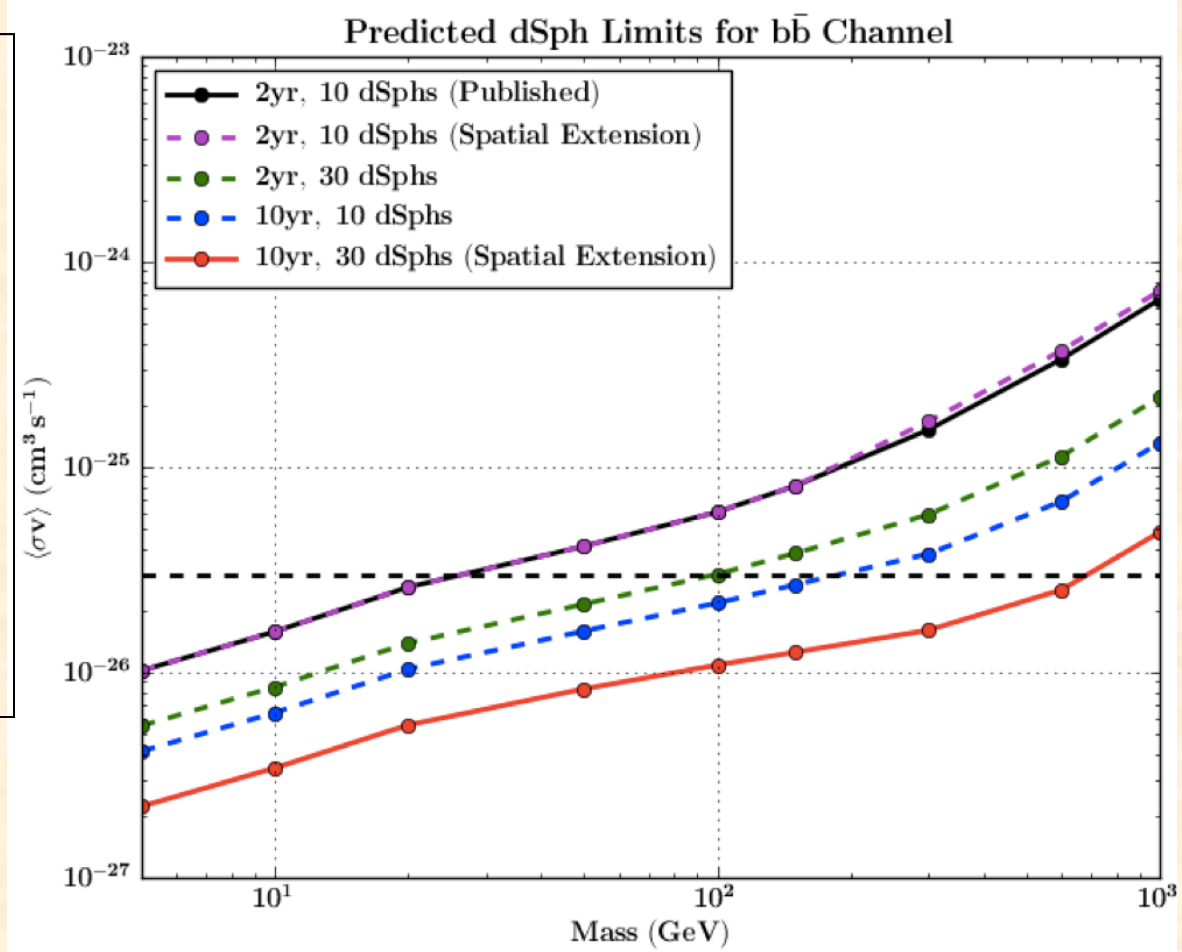
Updated constraints with 4 yrs p7 data



Fermi LAT Collaboration, arXiv:1310.0828, PRD 2013

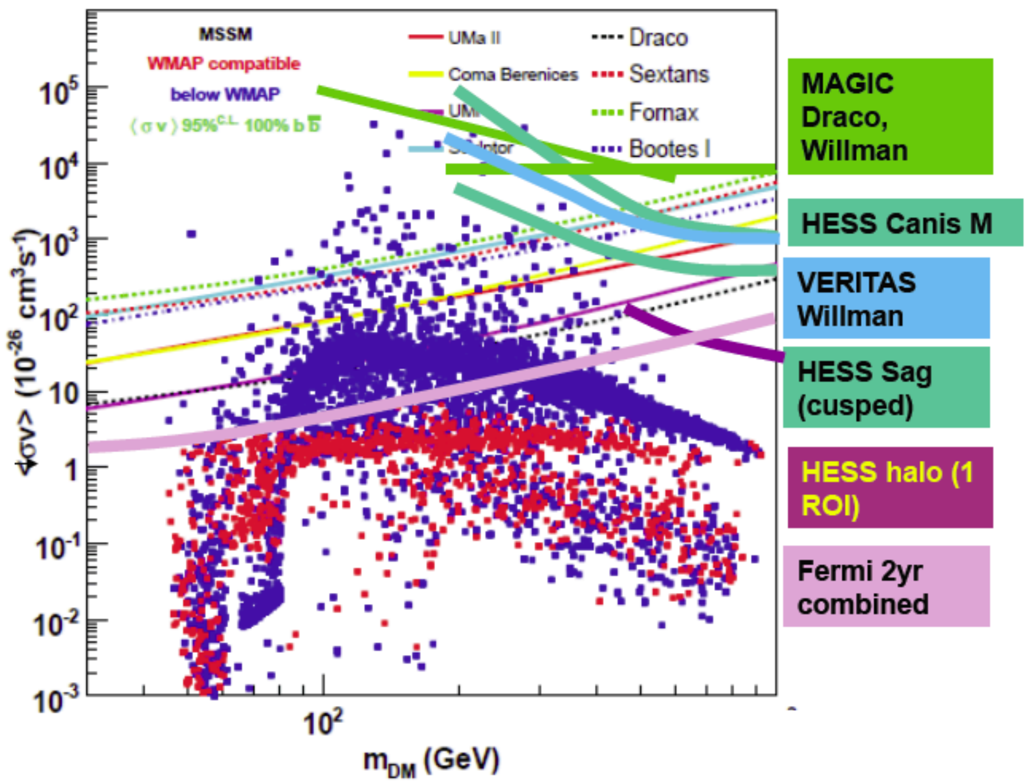
DM limit improvement estimate in 10 years with the composite likelihood approach (2008- 2018)

- 10 years of data instead of 2(5x)
- 30 dSphs (3x) (supposing that the new optical surveys will find new dSph)
- ~10% from spatial extension (source extension increases the signal region at high energy E > 10 GeV, M > 200 GeV)



- There are many assumptions in this prediction
- Doesn't deal with a possible detections.

Fermi and Cherenkov telescopes in comparison and some projection to the future



At the moment IACTs limits are competitive with Fermi only above ~1 TeV due to the IACTs' high energy threshold. This will be partly remedied with lower energy threshold instruments like CTA.

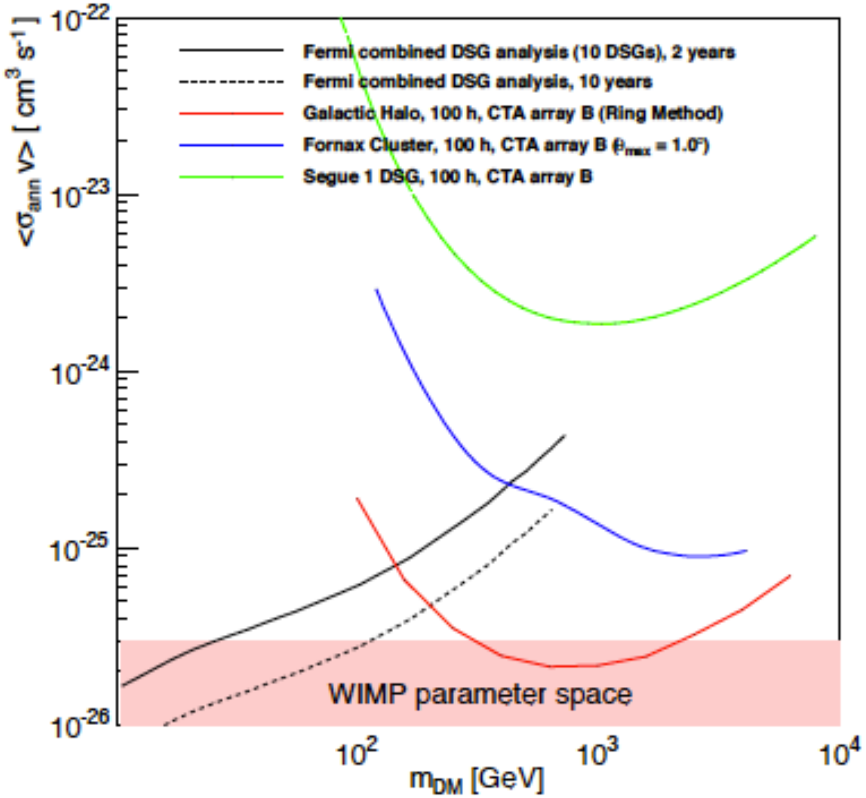
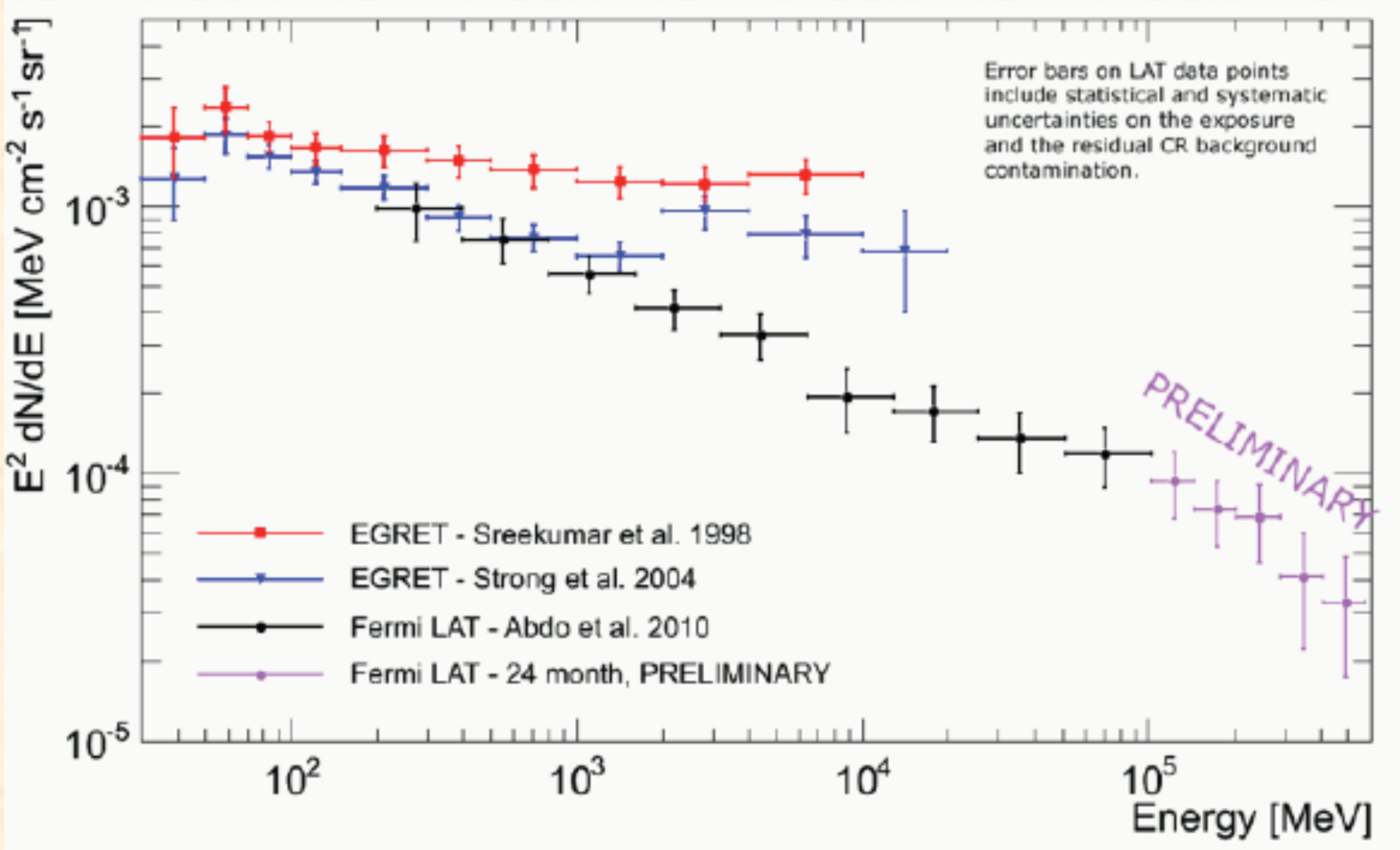


Figure adapted from: ***Fermi-LAT: Astrophys.J. 712:147-158,2010***

Courtesy of Jan Conrad

CTA: arXiv:1208.5356, Astropart.Phys. 43 (2013)

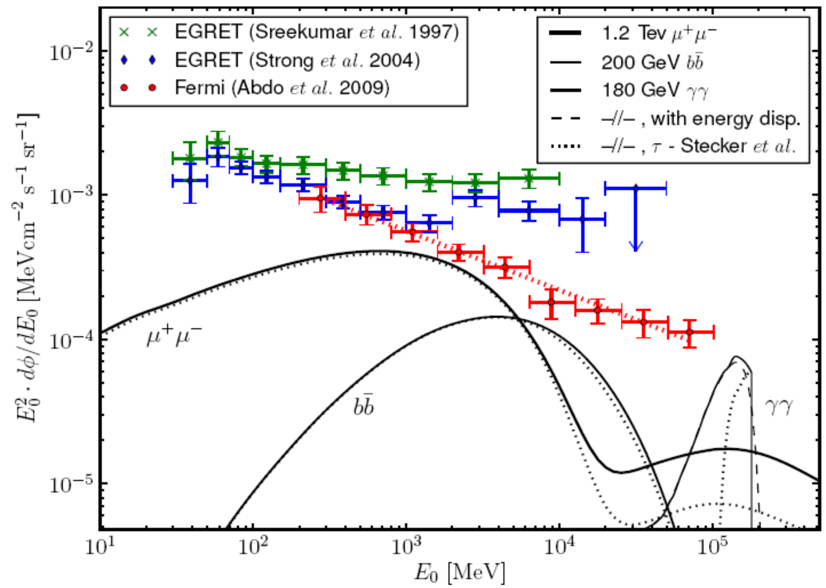
The Extra-Galactic Gamma-ray Background (EGB)



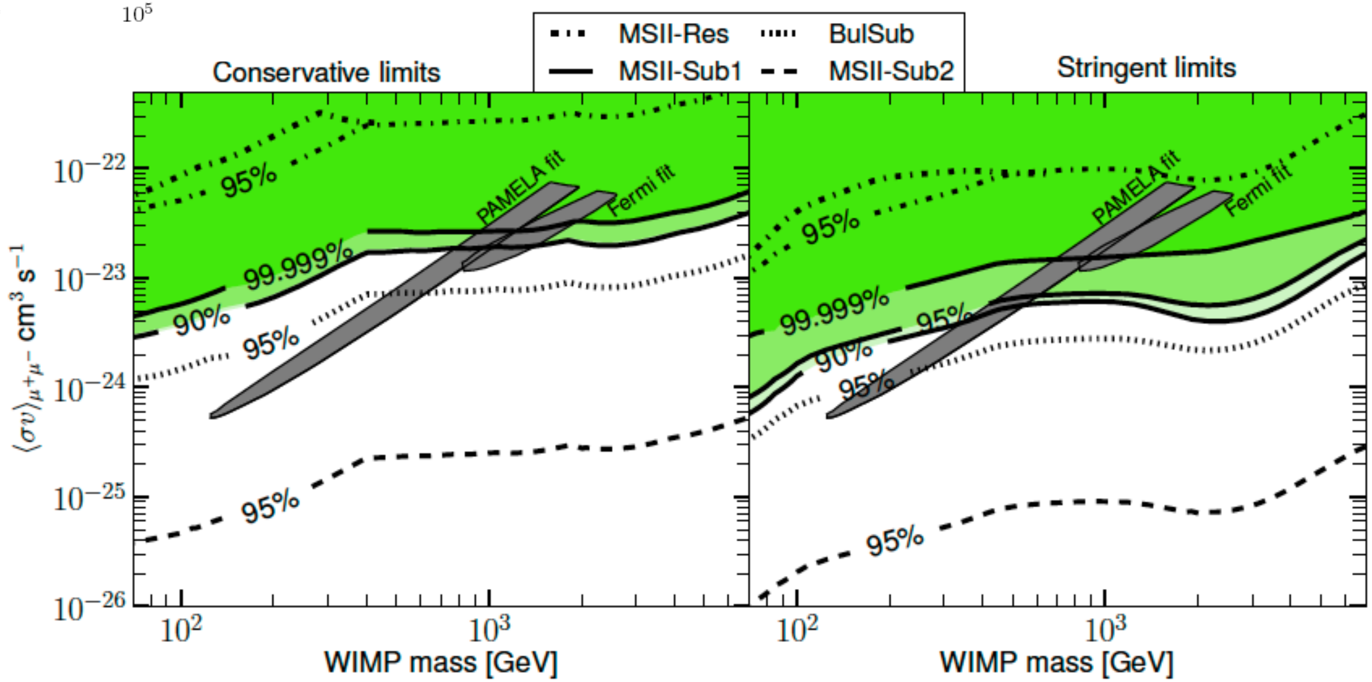
M.Ackermann, TeVPA2011, Stockholm

- Smooth spectrum for energies > 100 GeV
- Indications of spectral softening at high energies

Constraints from the Extra-Galactic Gamma-ray Background



- Potentially very constraining, but gives very model dependent limits due to large uncertainties in the predicted DM signal
- Better understanding of the DM clustering at small scales can help tight the uncertainties. (see e.g. Serpico et al. arXiv:1109.0095)



Abdo et al. (Fermi-LAT)JCAP 1004 (2010) 014

The origin of the EGB

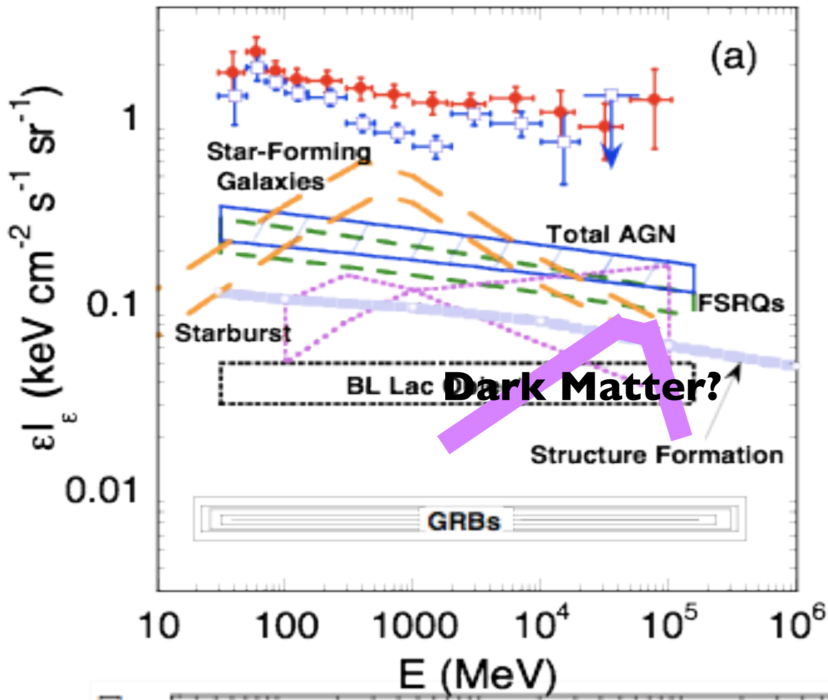
- many astrophysical sources are *guaranteed* to contribute, e.g.:
- blazars
- star-forming galaxies
- millisecond pulsars
- AGNs
- clusters of Galaxies
- clusters Shocks
- cascades from UHECRs

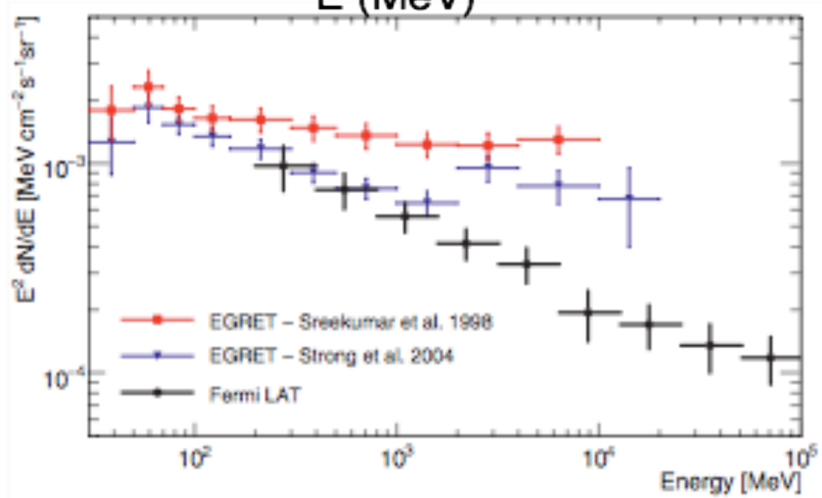
and…

- Dark matter(?)

- relatively featureless total EGB intensity spectrum → lack of spectral handles to ID individual components
- the amplitude and energy dependence of the anisotropy is a complementary tool to disentangle different contributions

Dermer 2007





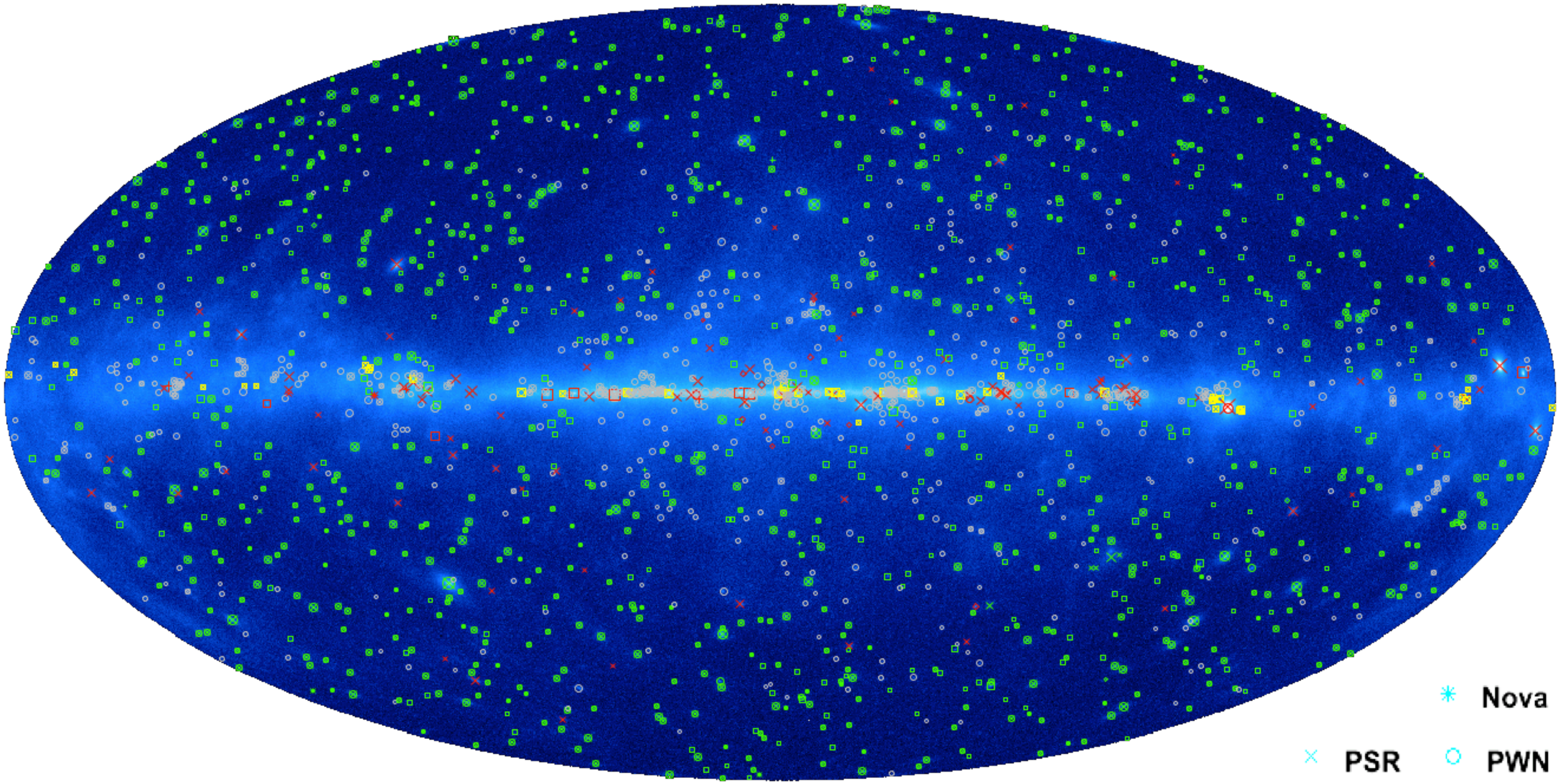
Abdo et al., PRL 104 (2010) 101101

Resolved Sources - 2FGL catalogue

AGN　AGN-Blazar
AGN-Non Blazar

~2000 sources

Galaxy　Starburst Galaxy
Radio Galaxy　Seyfert Galaxy

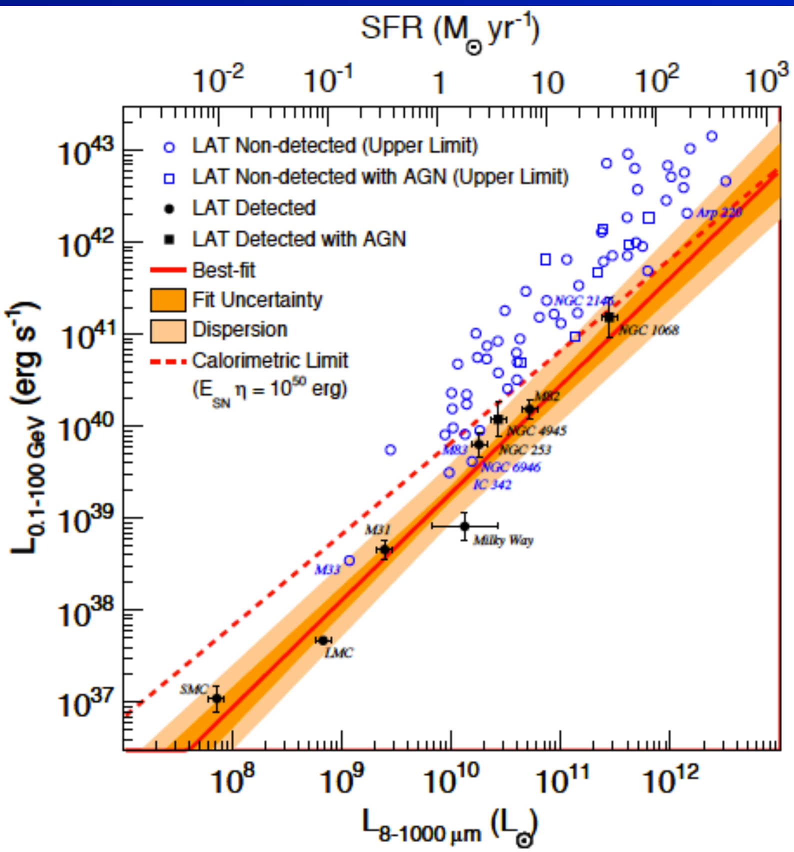


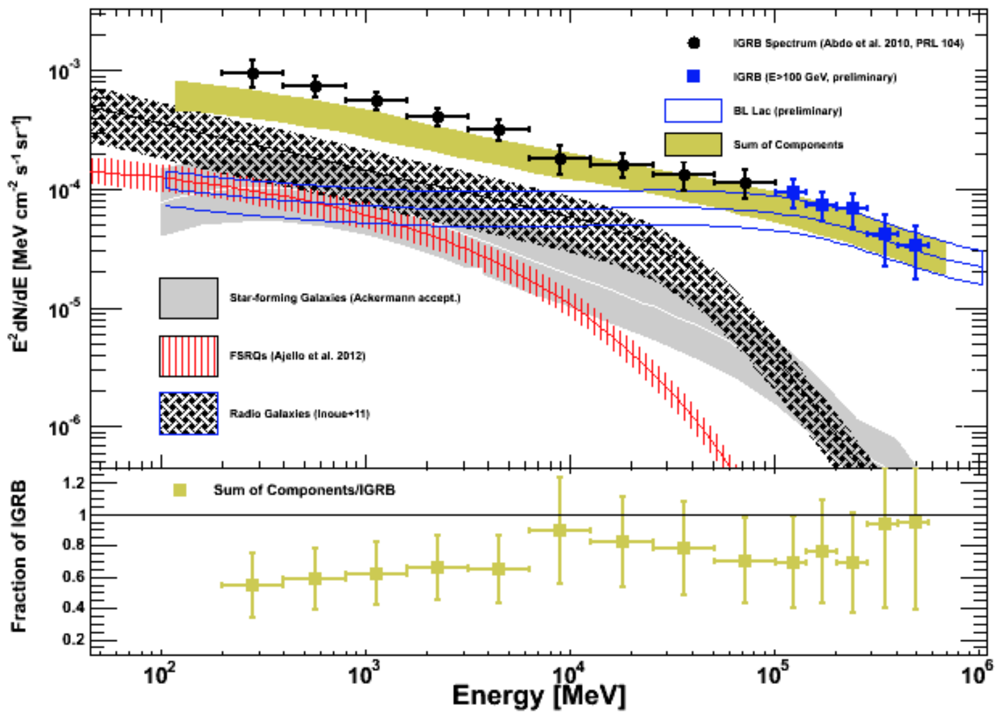
Nova
PSR　PWN
PSR w/PWN　SNR
Globular Cluster　HMB

Unassociated
Possible Association with SNR and PWN

Credit: Fermi Large Area Telescope Collaboration

EGB Status





As for the blazars, a luminosity function for normal galaxies can be built, but due to the very few galaxies detected (~10) a calibration on radio observation is required.

AGN contribution more unceratain. Overall the blazar-SFG-AGN model explain almost all the EGB.

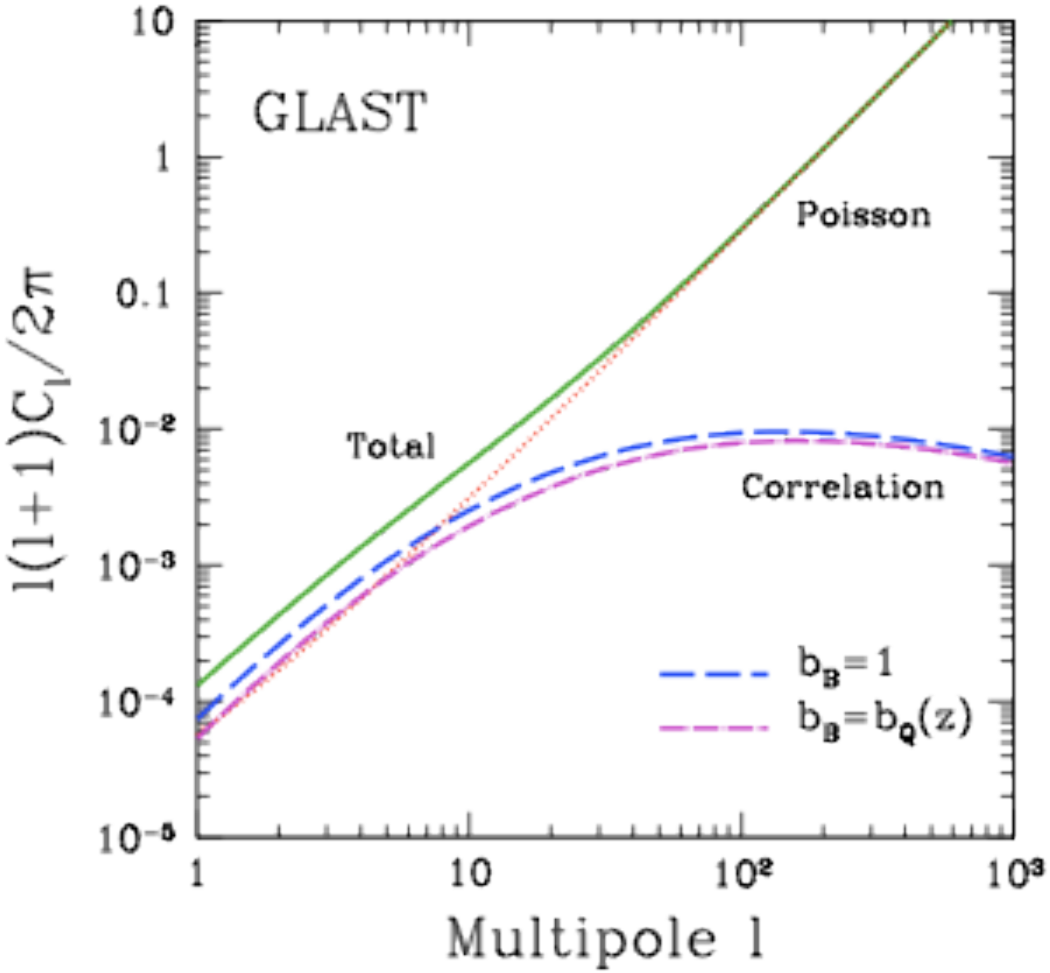
Fermi-LAT collaboration, Astrophys.J. (2012)

Angular power spectra of unresolved gamma-ray sources

- the angular power spectrum of many gamma-ray source classes is dominated by the Poisson (shot noise) component for multipoles greater than ~ 10
- Poisson angular power arises from unclustered point sources and takes the same value at all multipoles

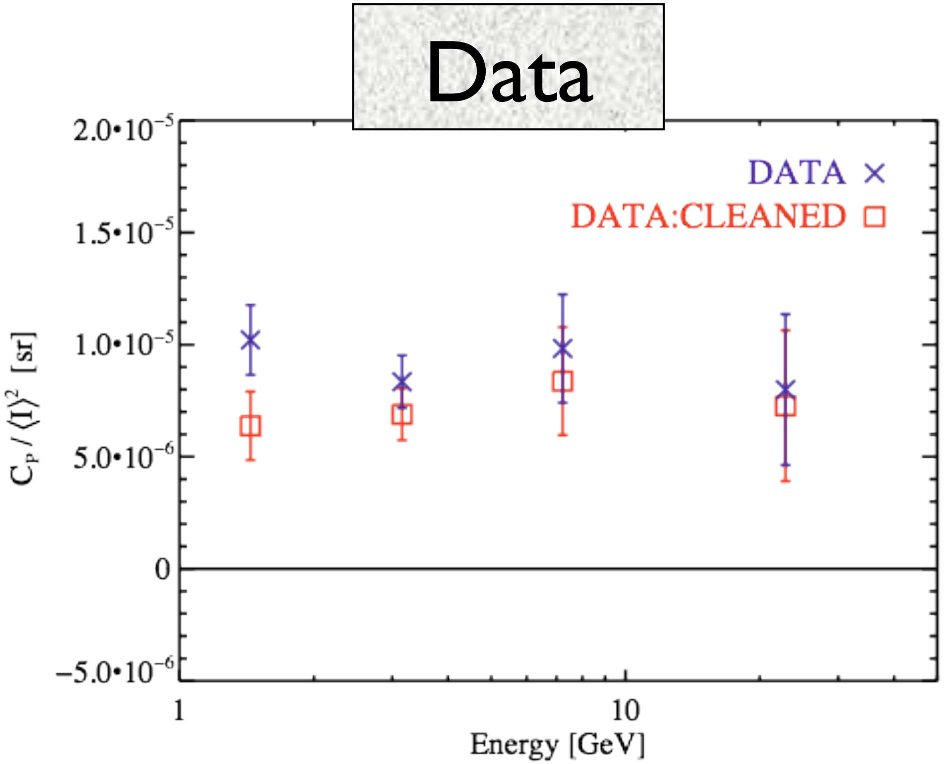
predicted fluctuation angular power $C_\ell/\langle I\rangle^2$[sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

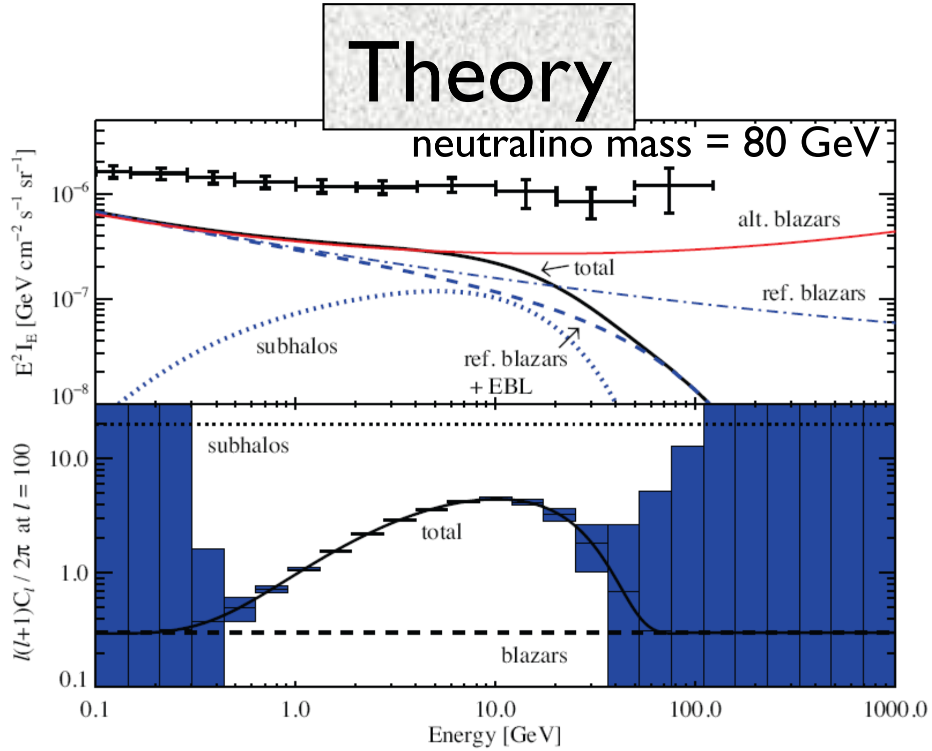
- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2



Blazars (Ando, Komatsu, Narumoto & Totani 2007)

Anisotropy Energy Spectrum: Data vs Theory

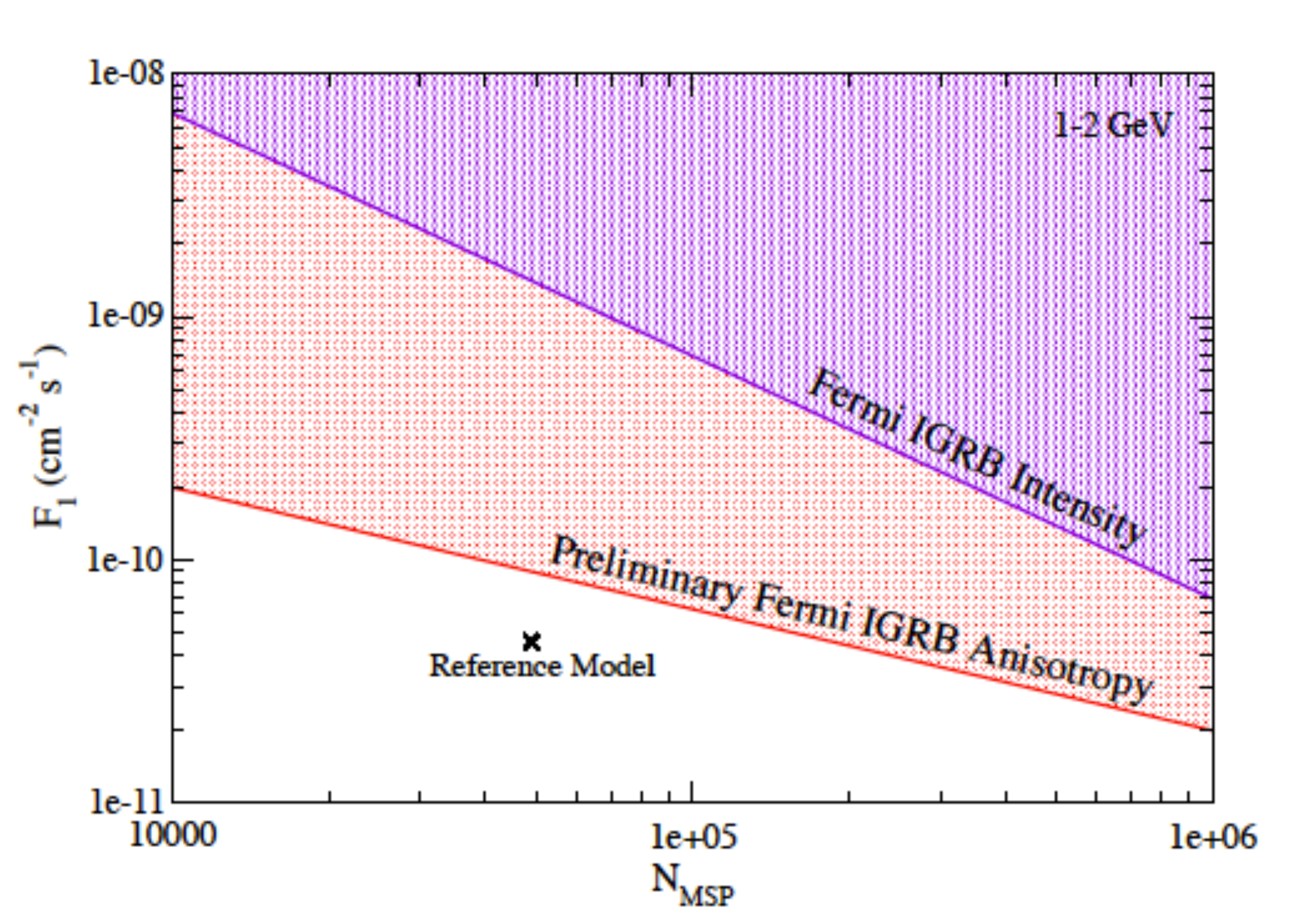




J. Siegal-Gaskins, V. Pavlidou, Phys.Rev.Lett. 102:241301,2009.

- No bump yet in the data…
- More statistics is needed to improve on the error bars and to increase the number of bins in energy. This will be provided by Fermi in the next few years.

Anisotropy Constraints on the Pulsar Contribution

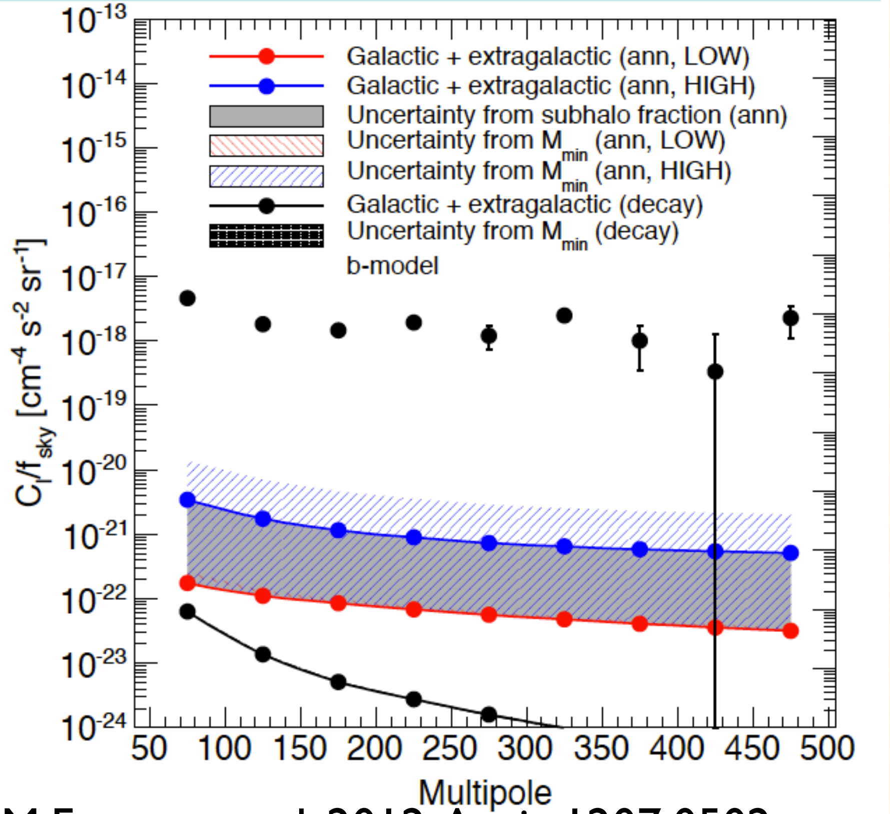


J. M. Siegal-Gaskins, R. Reesman, V. Pavlidou, S. Profumo, T.P. Walker, Mon.Not.Roy.Astron.Soc. 415 (2011) 1074S

- Constraints on the parameter space of Pulsars are ~1 order of magnitude stronger using anisotropy
- Reference models should be detectable/testable with a slight improvement in the anisotropy measurement

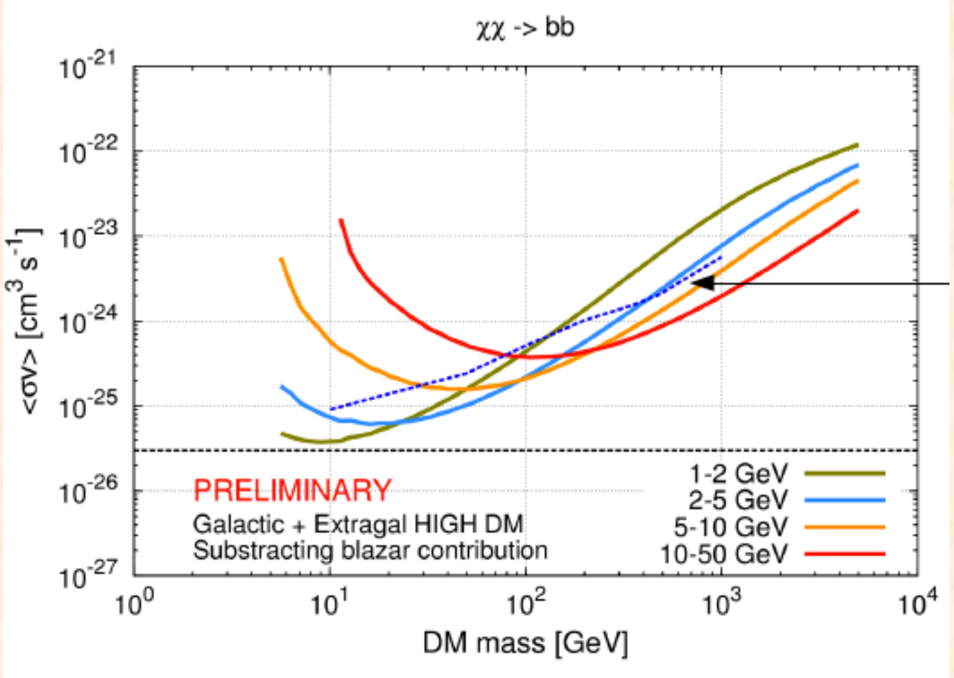
Anisotropy Constraints on the DM Contribution

M_χ=200 GeV, σv=3x10^{-26} cm^{3}s^{-1},
E=2–5 GeV



M.Fornasa et al. 2012, Arxiv:1207.0502

- Using theoretical prediction of the galactic and extragalactic DM anisotropy (from numerical simulation like Millennium or Aquarius) constraints on the DM component from anisotropy can be set.
- Joint **Multidark-Fermi** project ongoing.



- Interesting values of <σv> can be probed depending on the anisotropy properties of DM.

Gomes-Vargas et al. 2012 arXiv:1303.2154
Ando & Komatsu PRD 2013

Summary and Conclusions

- Indirect DM searches are typically characterized by low Signal/ Background ratio. Understanding and characterizing accurately the astrophysical backgrounds is thus crucial to improve the sensitivity to DM and to exclude false signals.
- Analysis of the galactic Halo and galactic Center is perhaps providing hints of a signal. But backgrounds need to be addressed carefully
- Dwarf galaxies limits are very competitive and expected to improve further in the next years.
- Anisotropy is helping in better constraining the extra-galactic emission (and the DM contribution)

Backup Slides

HALO

Global fit of DM and background: Summary of the parameters of the model (II)

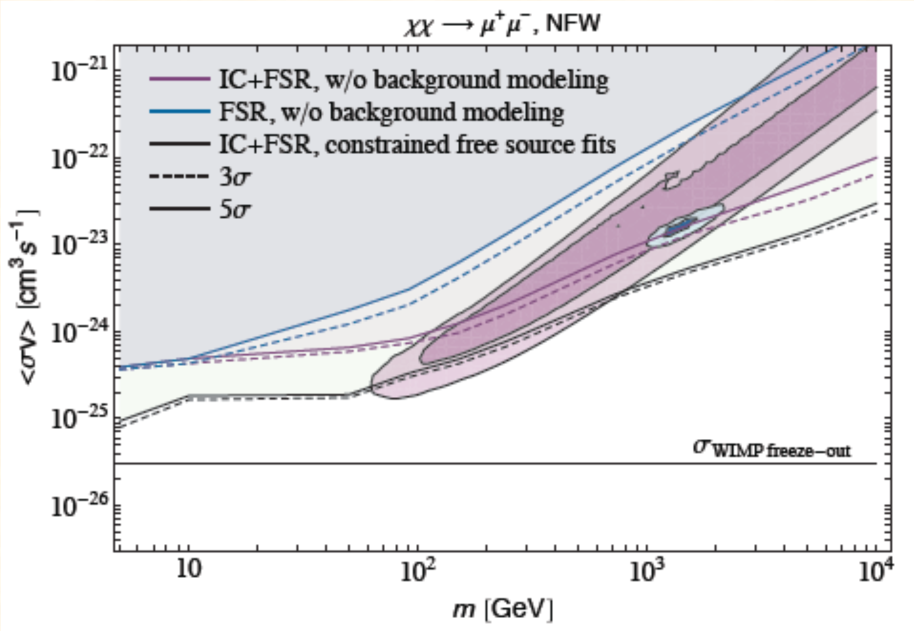
Non linear Parameters	Symbol	Grid values
index of the injection CRE spectrum	$\gamma_{e,2}$	1.925, 2.050, 2.175, 2.300, 2.425, 2.550, 2.675, 2.800
half height of the diffusive halo[a]	z_h	2, 4, 6, 8, 10, 15 kpc
dust to HI ratio	d2HI	(0.0120, 0.0130, 0.0140, 0.0150, 0.0160, 0.0170) $\times 10^{-20}$ mag cm^2
Linear Parameters	**Symbol**	**Range of variation**
eCRSD and pCRSD coefficients	c_i^e, c_i^p	$0, +\infty$
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

[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.

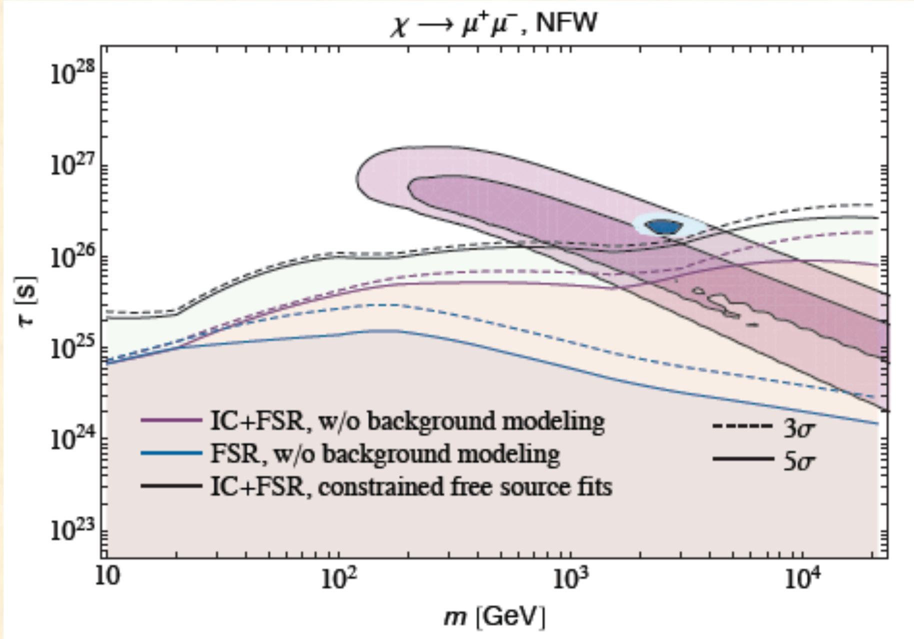
TABLE II: Summary table of the parameters varied in the fit. The top part of the table shows the non linear parameters and the grid values at which the likelihood is computed. The bottom part shows the linear parameters and the range of variation allowed in the fit. The coefficients of the CRSDs are forced to be positive, except $c_1^{e,p}$ and $c_2^{e,p}$ which are set to zero. The local X_{CO} ratio is restricted to vary in the range 0-50 $\times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, while $\alpha_{IGB,m}$ and α_χ are left free to assume both positive and negative values. See the text for more details.

Constraints: μ+μ-channel

annihilation



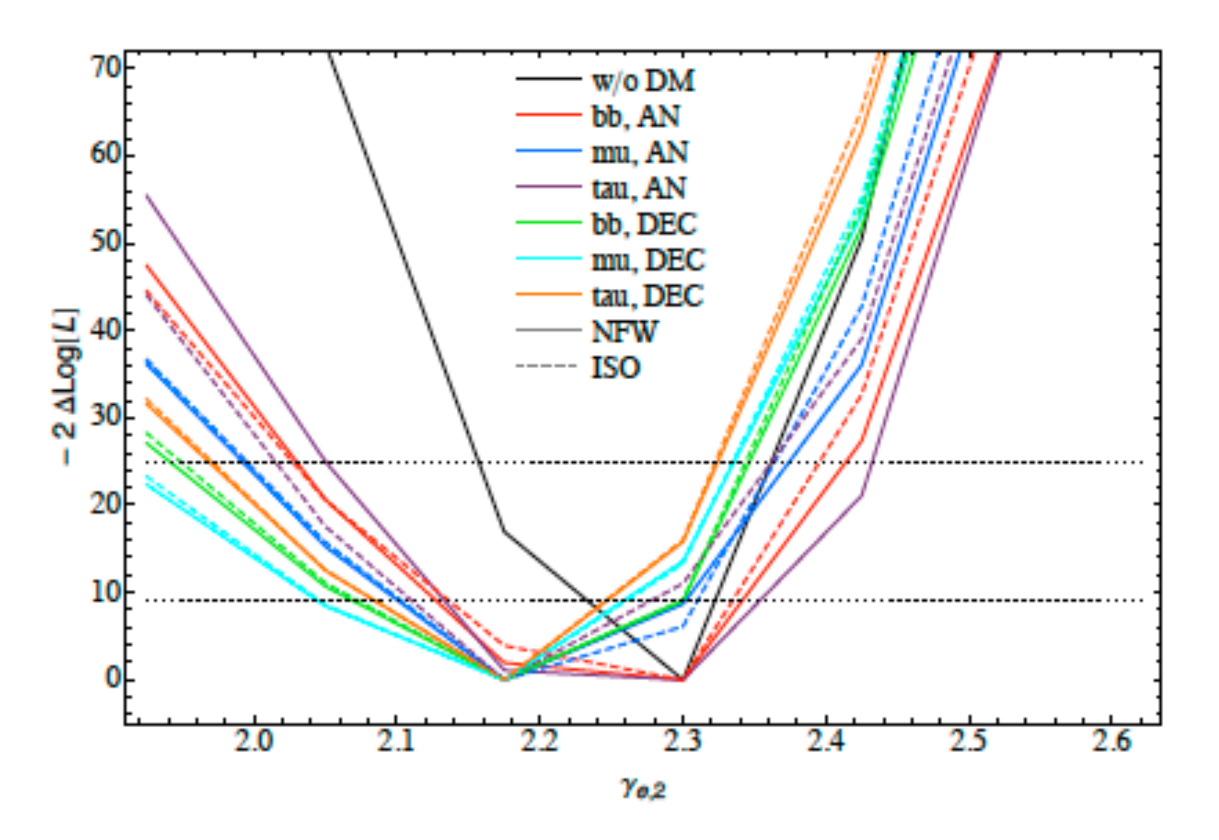
decay



- 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).

Further results: electron index

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



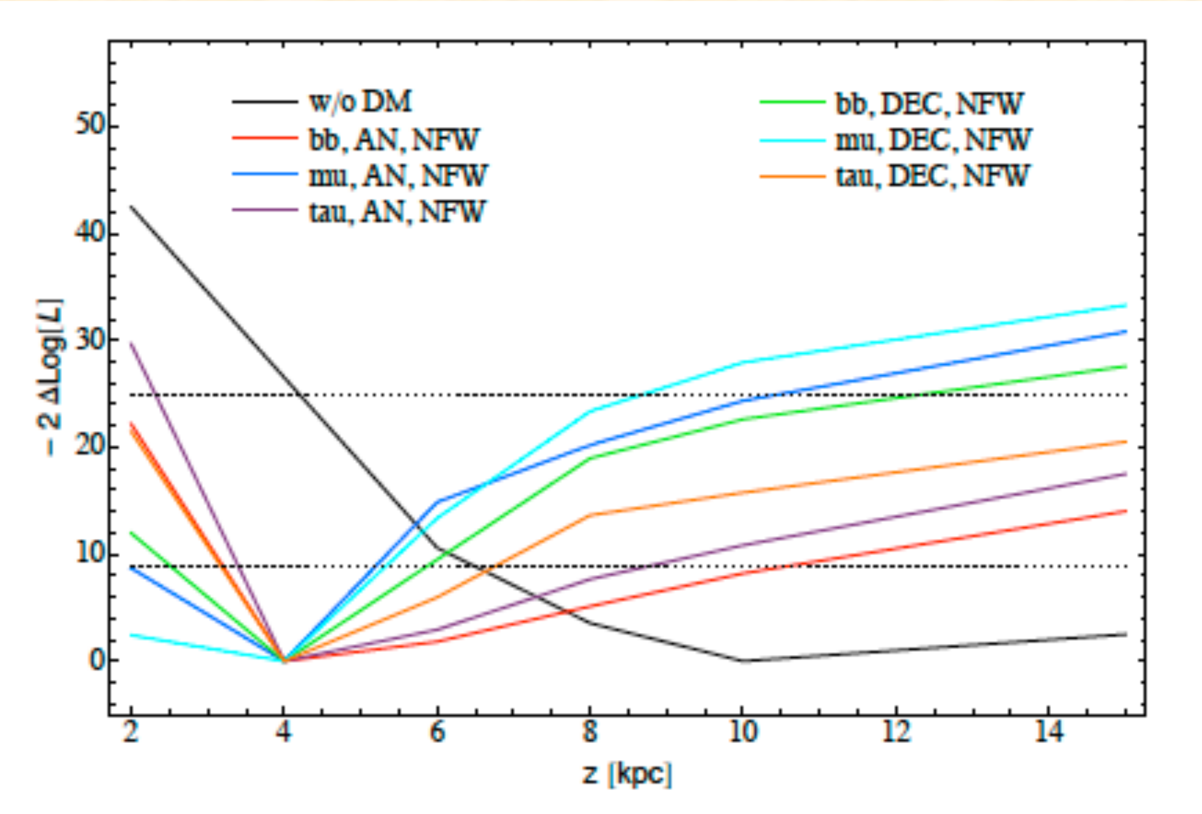
Using an extended energy range and full sky fitting, constraints can be likely improved.

The plot also show that the global minimum is poulated by many models: check against biased in our results.

Note: all LogLs are renormalized to the same minimum.

Further results: diffusive Halo height

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



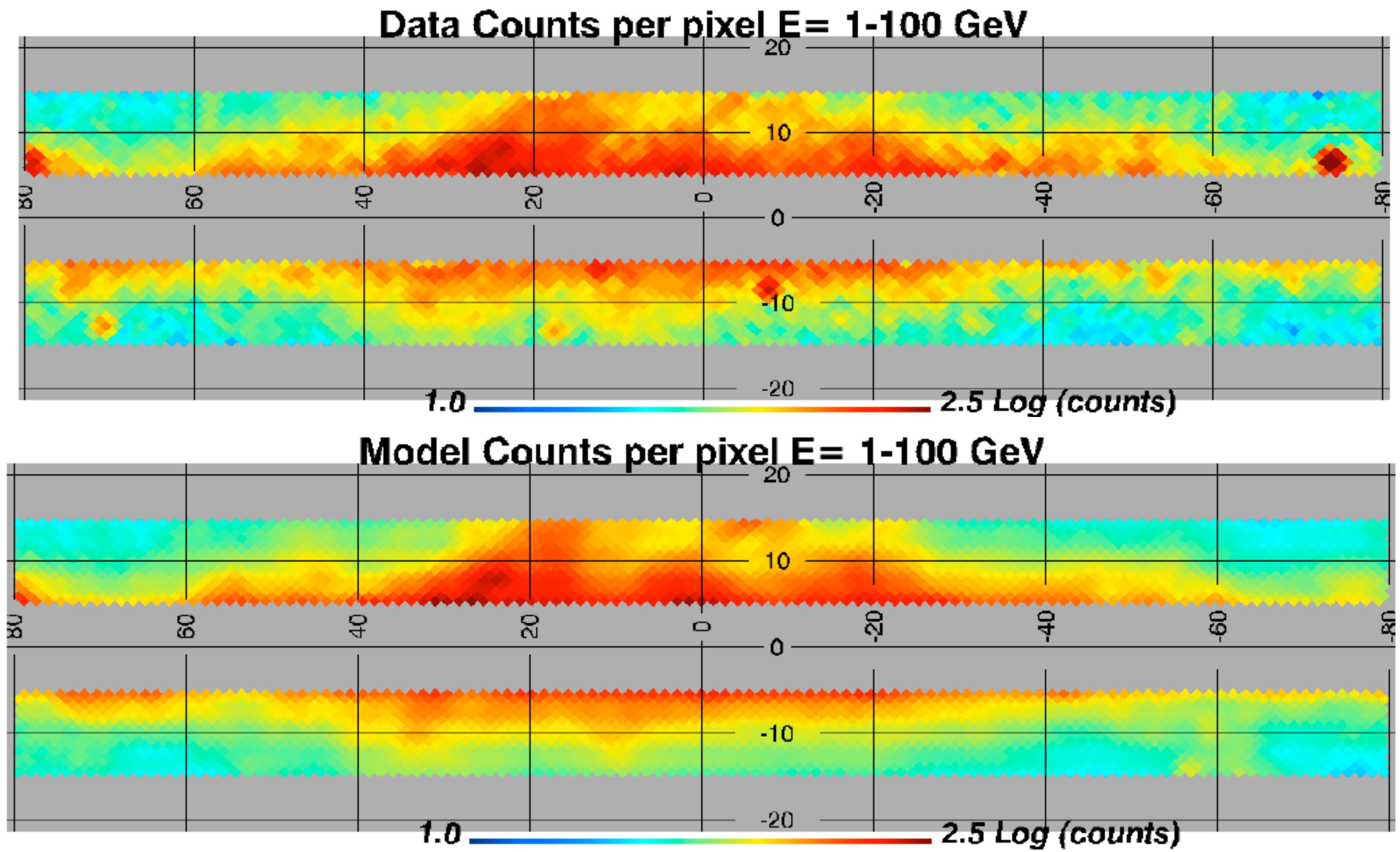
Using an extended energy range and full sky fitting, constraints can be likely improved.

The plot also show that the global minimum is poulated by many models: check against biased in our results.

Note: all LogLs are renormalized to the same minimum.

Halo of 4 kpc with DM?

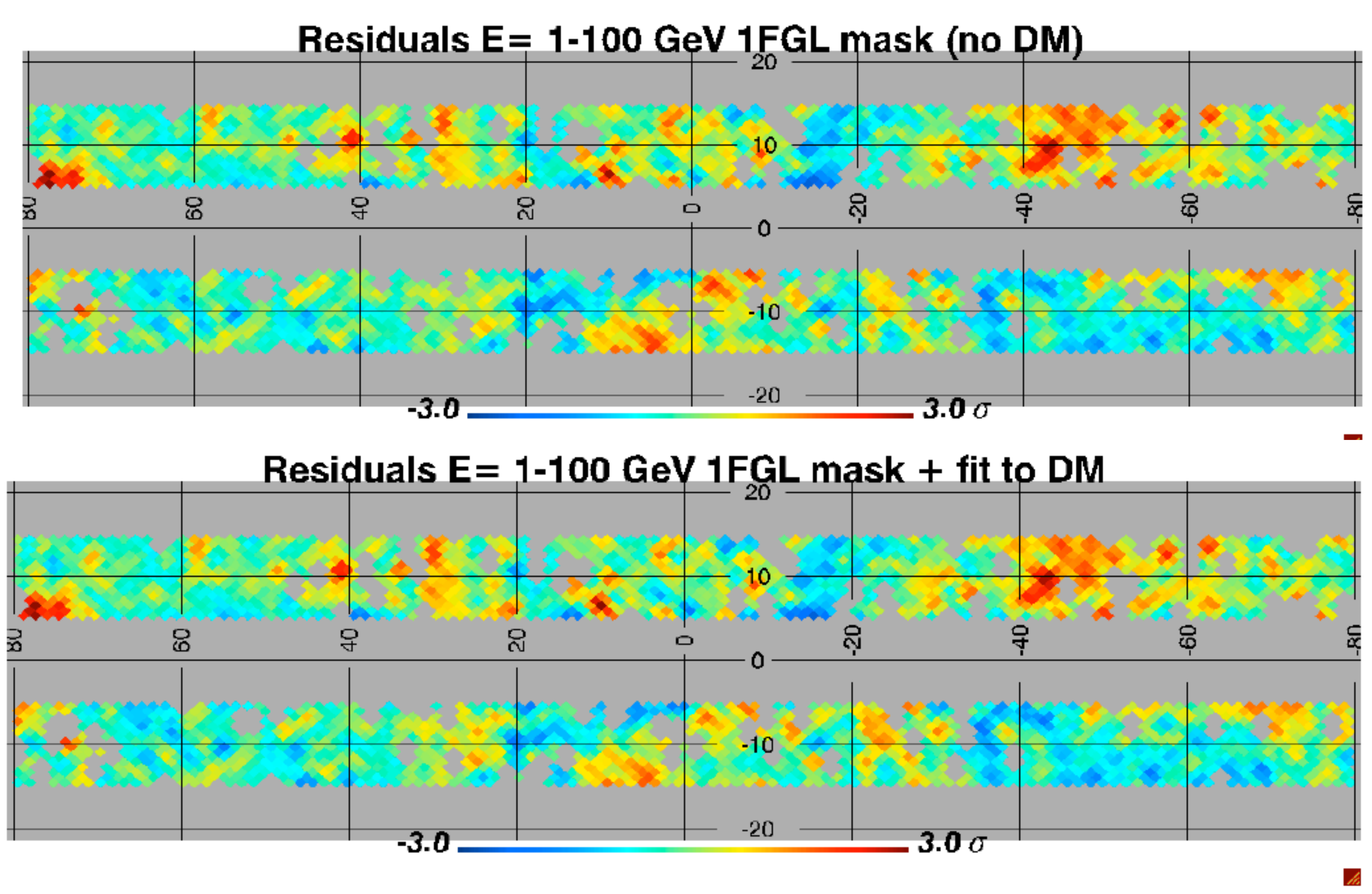
Counts in the ROI and best fit model



The Region of Interest (ROI) excludes

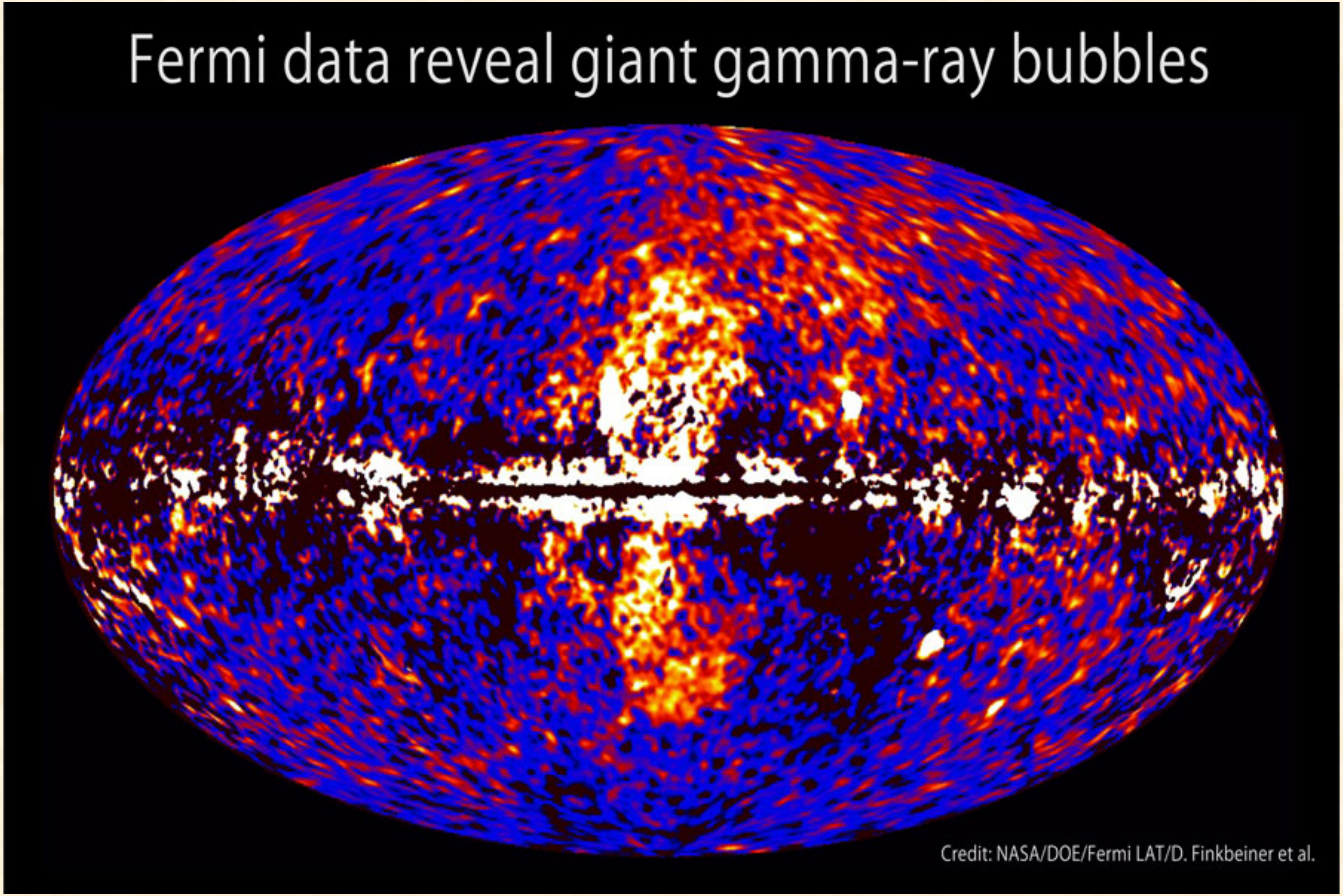
- the Galactic Plane (Inner Galaxy will be considered in another paper)
- the Outer Galaxy (no DM there), and
- the high latitudes (high pollution from the Lobes)

Residuals



Residuals are overall flat. Some feature remains due to the low latitude tips of the Lobes and Loop I

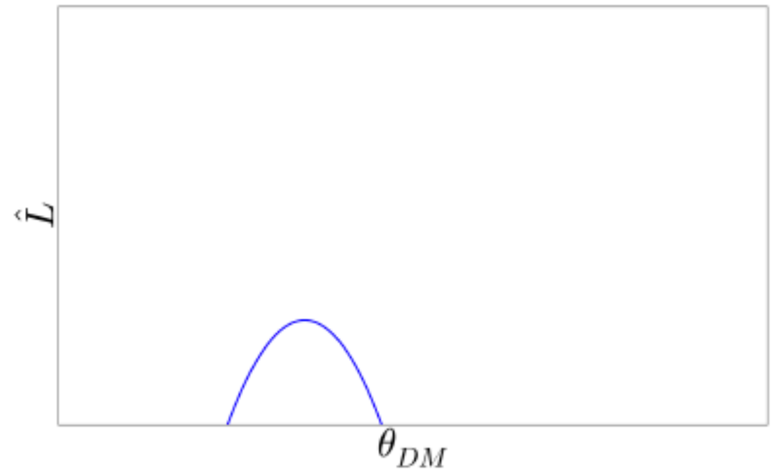
Lobes and Loops residuals



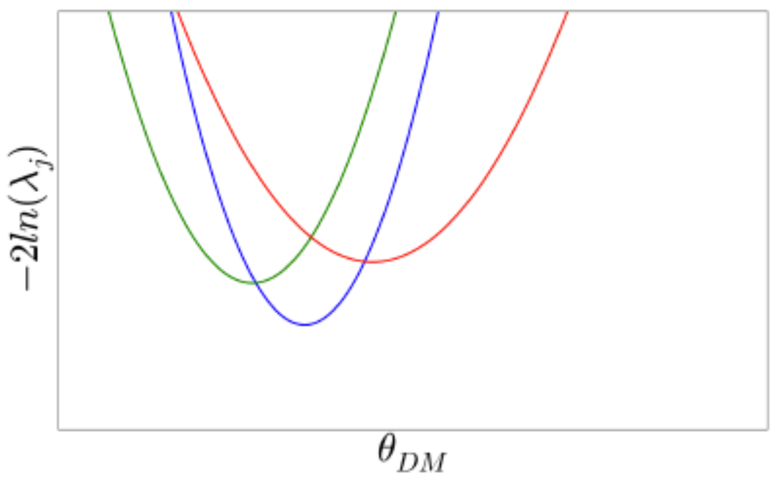
Profile Likelihood Method

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

Step 1: Derive the profile Likelihood for a given Galprop model marginalizing over the linear parameters



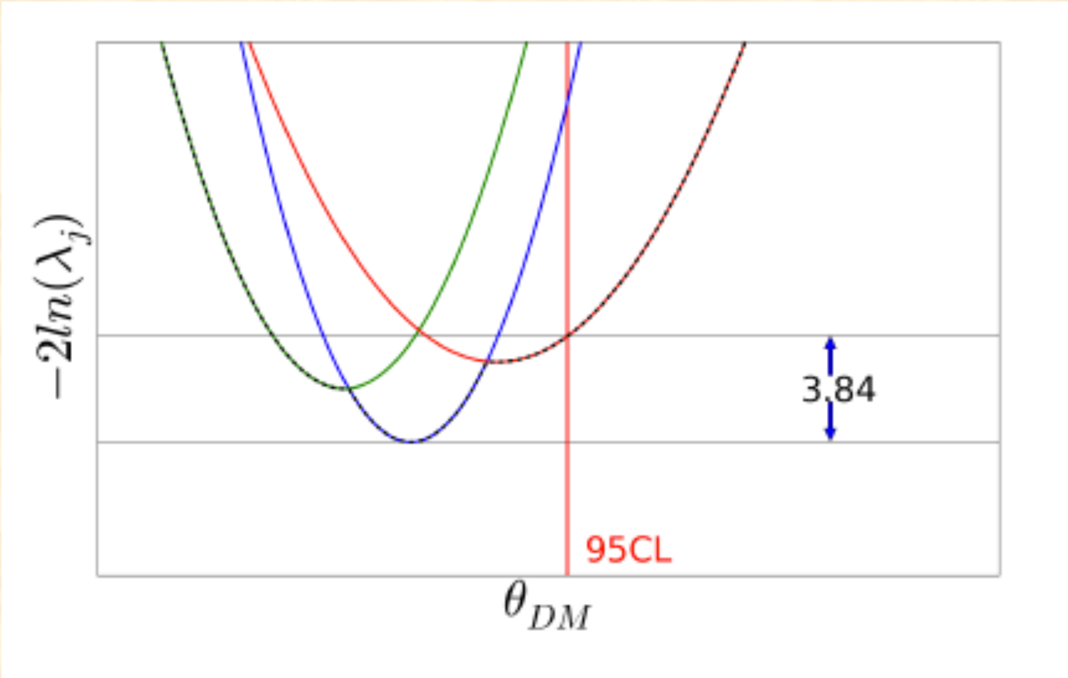
Step 2: Derive the profile likelihood for each galprop model (non linear parameter)



Profile Likelihood Method

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

Step 3: Build the "global" profile likelihood taking the global minimum for each value of DM normalization, i.e. the envelope of all the single likelihoods. Set intervals/constraints at a given confidence level.



Diffusion Parameters

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

TABLE I: CR diffusion parameters from [13] used in this work.

For each value of zh, the rest of diffusion/injection parameter are fixed via a fit to the local p spectrum and B/C ratio. Kolmogorov diffusion is assumed (but see also later).