Constraints on WIMP annihilation for contracted Dark Matter in the inner Galaxy with the Fermi-LAT

Carlos Muñoz

Instituto de Física Teórica UAM-CSIC

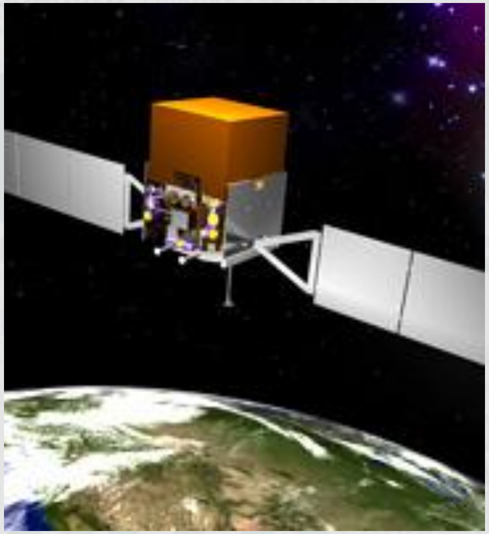
Universidad Autónoma de Madrid
Departamento de Física Teórica

MultiDark
Multimessenger Approach for Dark Matter Detection

DSU 2013, SISSA Trieste, October 14-17

By comparing theoretical predictions
with the gamma-ray emission observed by the Fermi LAT
from the region around the Galactic Center,

is it possible to derive stringent constraints on parameters
of generic dark matter (DM) candidates?



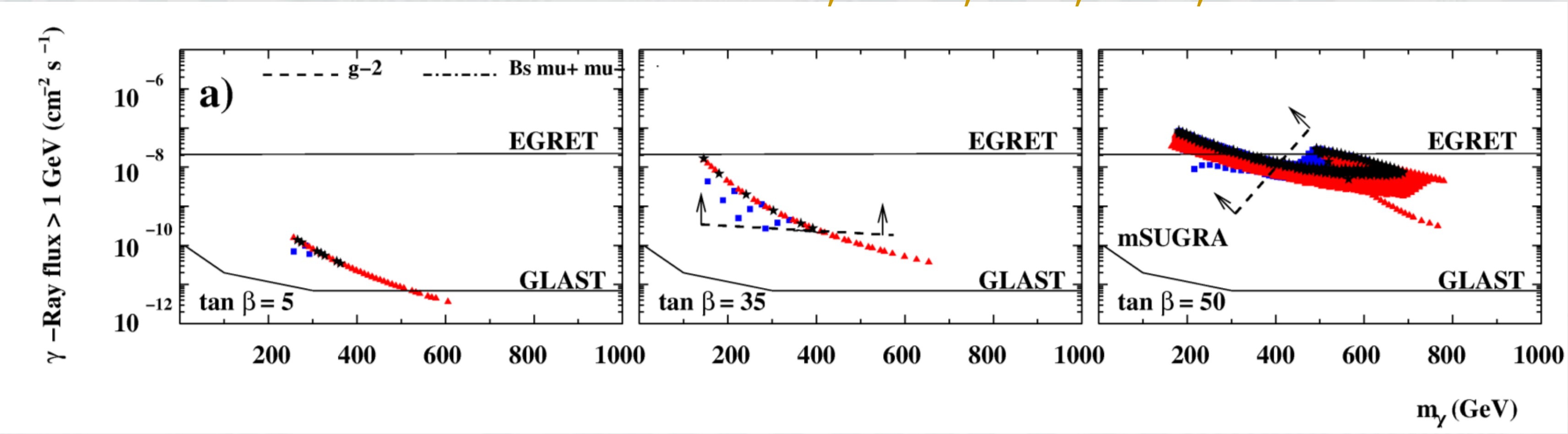
YES in the likely case that the collapse of baryons to the Galactic Center is accompanied by the contraction of the DM

Prada, Klypin, Flix Molina, Martinez, Simonneau, 0401512
Mambrini, Munoz, Nezri, Prada, 0506204

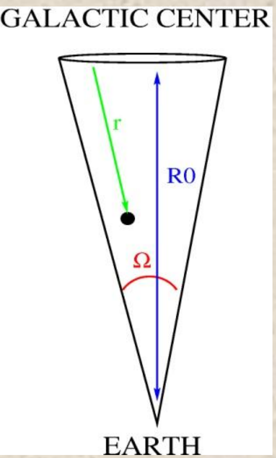
The behavior of NFW might be modified $\rho \longrightarrow 1/r$ making it steeper: $1/r^{\gamma}$

Constraining e.g. the SUSY parameter, as discussed in this old work:

Mambrini, Munoz, Nezri, Prada, 0506204



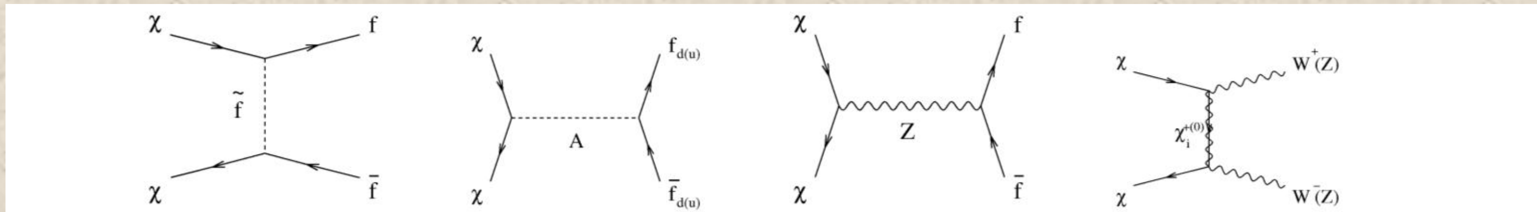
Theoretical Predictions



$$\phi \sim \left(\int_{\text{line of sight}} \rho^2 \, dr\right) \sigma_{ann} v / m^2$$

Astrophysics

Particle physics



Particle physics: $\propto \frac{m_\chi m_f}{m^2_{\tilde{f}}} Z^2_{11}$ $\quad \propto \frac{m^2_\chi}{m^2_A} \frac{Z_{11} Z_{13,14}}{m_W} m_{f_d} \tan\beta \left(\frac{m_{f_u}}{\tan\beta}\right)$ $\quad \propto \frac{m_f m_\chi}{m^2_Z} Z^2_{13,14}$ $\quad \propto \frac{[-Z_{14} V^*_{21} + \sqrt{2} Z_{12} V^*_{11}]^2 (-Z_{13} N^*_{31} + Z_{14} N^*_{41})^2}{1 + m^2_{\chi_i^{+(0)}}/m^2_\chi - m^2_{W(Z)}/m^2_\chi}$

Astrophysics: e.g. a **NFW profile** for our galaxy, has for small distances from the galactic center $\rho(r) \sim \rho_0 / r$

DARK MATTER DENSITY PROFILES

High-resolution N-body simulations of the gravitational collapse of a collisionless system of particles, suggest the existence of a universal DM density profile.

from micro-haloes to galaxy clusters

Using the parametrization:

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}},$$

where the density ρ_s and the radius r_s vary from halo to halo

- The NFW profile, with $(\alpha,\beta,\gamma)=(1,3,1)$, is the most widely used

Navarro, Frenk, White, 9508025, 9611107

$$\rho(r) = \frac{\rho_s}{(r/r_s)\,(1+r/r_s)^2}$$

Cuspy profile in the inner region ($\rho_h \longrightarrow 1/r$) implying a singularity towards the center

Einasto, 1968
Navarro et al., 0311231

- Another approximation is the so-called Einasto profile which seems to provide a better fit than NFW to numerical results

$$\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\},$$

Simulations now resolve the cusp down to radius of ~ 100 pc, thus there is less of extrapolation to the central region of ~ 1-10 pc, where most of the annihilation signal is expected to come from

However, these are DM-only simulations, but central regions of galaxies like the Milky Way are dominated by baryons

They might modify e.g. the behaviour of NFW $\rho \longrightarrow 1/r$ making it steeper

The baryons lose energy through radiative processes and fall into the central regions of a forming galaxy. Thus the resulting gravitational potential is deeper, and the DM must move closer to the center increasing its density

Zeldovich, Klypin, Khlopov, Chechetkin, 1980
Blumenthal, Faber, Flores, Primack, 1986
Gnedin, Kravtsov, Klypin, Nagai, 0406247

The effect seems to be confirmed by high-resolution hydrodynamic simulations that self-consistently include complex baryonic physics such as gas dissipation, star formation and supernova feedback

Gustafsson, Fairbairn, Sommmer-Larsen, 0608634
Colín, Valenzuela, Klypin, 0506627
Tissera, White, Pedrosa, Scannapieco, 0911.2316
O.Y. Gnedin, Ceverino, N.Y. Gnedin, Klypin, Kravtsov, Levine, Nagai, Yepes, 1108.5736

The effect of baryons in the distribution of dark matter

Assuming that the compression occurs adiabatically, one obtains:

$$M_i\,(r_i)\,r_i = M_f\,(r_f)\,r_f \quad , \quad M_f = M_{DM} + M_b$$

Mass profile of the galactic halo before the compression (obtained through N-body simulations)

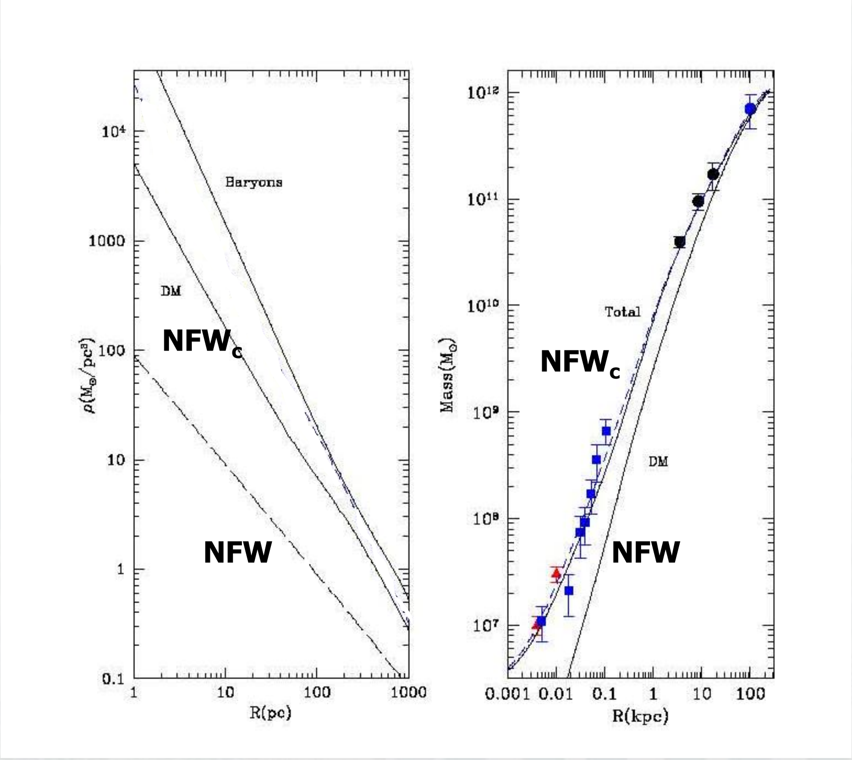
Baryonic composition of the Milky Way observed now

$$M_i = M_{DM}\,(\Omega_{DM} + \Omega_b)\,/\,\Omega_{DM}$$

The to be determined dark matter component of the halo today

Zeldovich, Klypin, Khlopov, Chechetkin, 1980
Blumenthal, Faber, Flores, Primack, 1986
Gnedin, Kravtsov, Klypin, Nagai, 0406247

From observational data of the Milky Way, the parameters of the DM profiles have been constrained



Prada, Klypin, Flix Molina, Martínez, Simonneau, astro-ph/0401512

Fitting the data with the power-law parametrization:

Cerdeño, Huh, Klypin, Mambrini, C.M., Peiró, Prada, Gómez-Vargas, Morselli, Sánchez-Conde arXiv:1308.3515

MultiDark + Fermi

$$\rho_{NFW}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \longrightarrow \rho_{NFWc}(r) = \frac{\rho_s}{(r/r_s)^{1.37}\,[1 + (r/r_s)^{0.76}]^{2.54}}$$

- in the inner region $\rho \rightarrow 1/r$ $\longrightarrow$ in the inner region $\rho \rightarrow 1/r^{1.37}$

Catena, Ullio, 0907.0018 $\longrightarrow$

Profile	α	β	γ	ρ_s [GeV cm^{-3}]	r_s [kpc]
NFW	1	3	1	0.21	23.8
NFW$_c$	0.76	3.3	1.37	0.35	18.5
Einasto	0.22	—	—	0.08	19.7

Caution:

Astrophysicists identified another process, which tends to decrease the DM density and flatten the DM cusp

Mashchenko, Couchman, Wadsley, 0605672, 0711.4803
Pontzen, Governato, Blumenthal, 1106.0499

The mechanism relies on numerous episodes of baryon infall followed by a strong burst of star formation, which expels the baryons producing at the end a significant decline of the DM density.

Cosmological simulations which implement this process show this result

Governato et al., 0911.2237
Maccio et al, 1111.5620

Whether the process happened in reality in the Milky Way is still unclear…

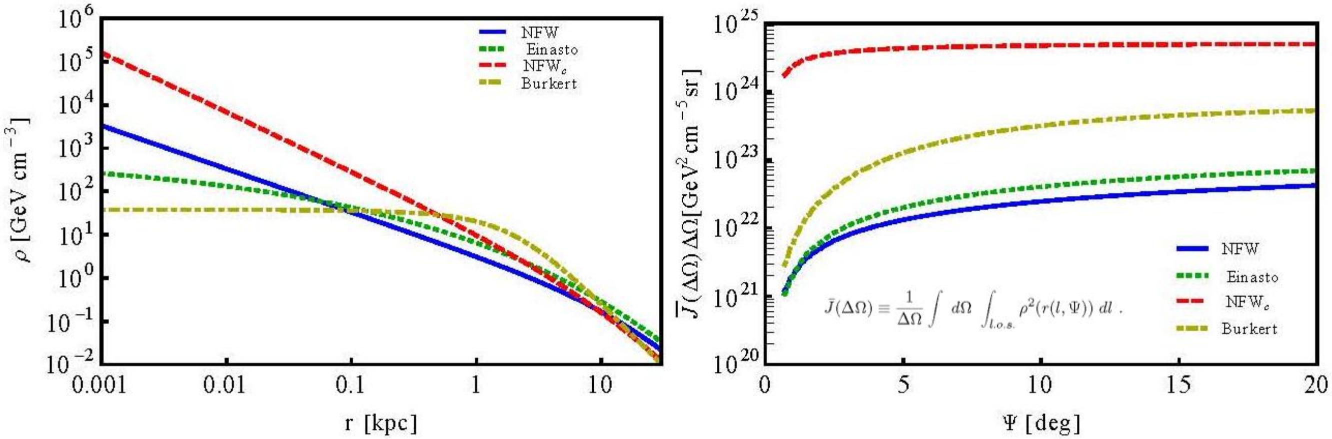


Figure 1: Left panel: DM density profiles used in this work, with the parameters given in Table 1. Right panel: The $\bar{J}(\Delta\Omega)\Delta\Omega$ quantity integrated on a ring with inner radius of 0.5 deg ($\sim$ 0.07 kpc) and external radius of Ψ ($R_\odot \tan\Psi$) for the DM density profiles given in Table 1. Blue (solid),

The theory

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{prompt} = \sum_i \frac{dN_\gamma^i}{dE_\gamma}\frac{\langle\sigma_i v\rangle}{8\pi m_{DM}^2}\bar{J}(\Delta\Omega)\Delta\Omega ,$$

to be compared with the observations

To set constraints we request that the expected DM signal does not exceed the observed flux (due to DM + astrophysical background)

No subtraction of any astrophysical background is made.
Very conservative analysis!

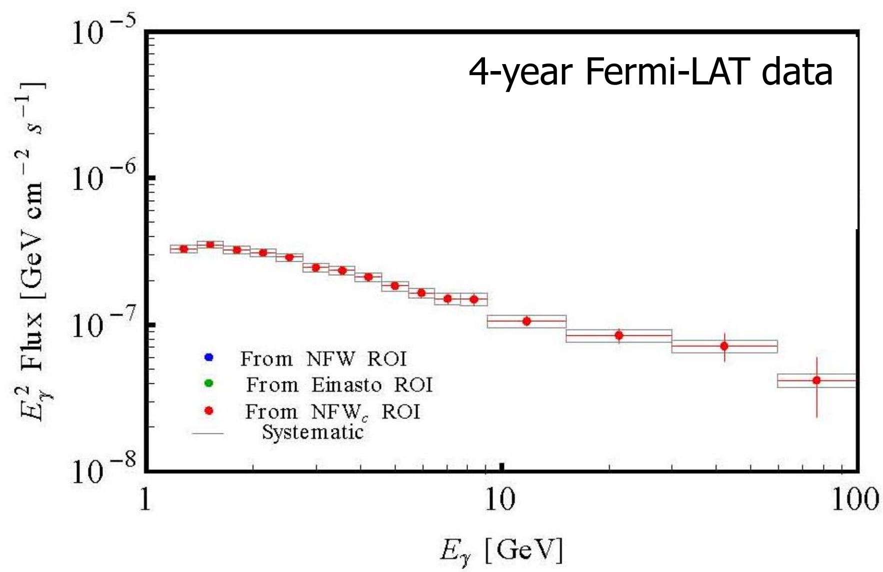


Figure 4: Energy spectrum extracted from Fermi-LAT data for the optimized regions that are shown in Figure 3. Data are shown as points and the vertical error bars represent the statistical errors. The latter are in many cases smaller than the point size. The boxes represent the systematic error in the Fermi-LAT effective area.

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Optimization of the region of interest for dark matter searches

In order to find the ROI that maximizes the S/N, we follow the next steps:

1. Maps of the quantity $\bar{J}(\Delta\Omega)\,\Delta\Omega$ for the three DM density profiles considered (i.e., Einasto,NFW and NFWc) are built, and used as the signal.
2. The noise is assumed to be the square root of the photon flux map, as measured by Fermi.
3. A mask is introduced to cover the GC and the Galactic plane, i.e., the most conflictive regions in the analysis.

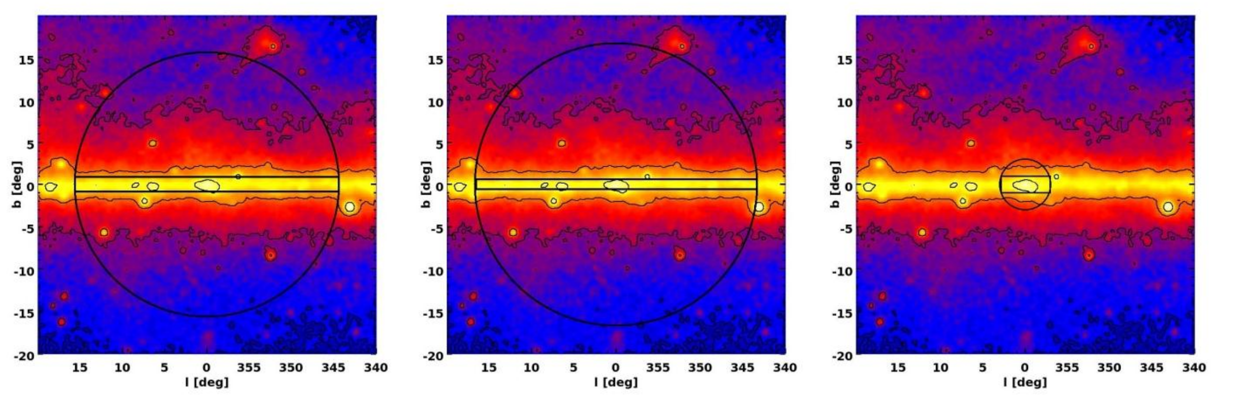

Figure 3: Maps of the observed flux by the Fermi-LAT in the energy range 1 − 100 GeV, in units of photons cm^{-2} s^{-1}, for the three DM profiles studied. From left to right: Einasto, NFW and NFW$_c$.

Profile	θ_2 [deg]	$\|b\|$ [deg]	$\Delta\Omega$ [sr]	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times 10^{22}$ GeV^2 cm^{-5} sr]	Flux (1 − 100 GeV) [$\times 10^{-7}$ cm^{-2}s^{-1}]
Einasto	15.6	0.7	0.217	5.1	31.4 ± 0.3
NFW	16.7	0.6	0.253	3.3	38.0 ± 0.3
NFW$_c$	3.0	1.0	0.005	86.8	2.2 ± 0.1

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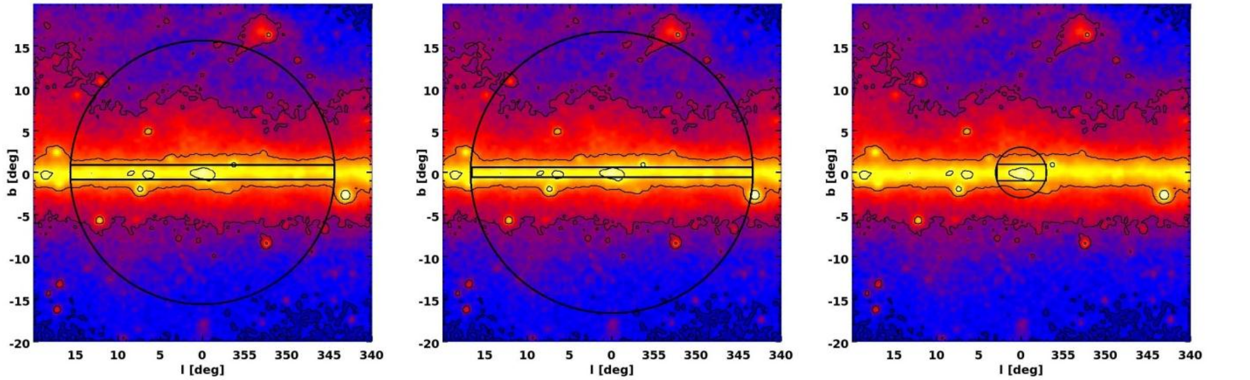

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Clearly, the NFW$_c$ ROI is the smallest one. This is because in the inner region of 5 deg, the J(ΔΩ) ΔΩ for NFW$_c$ becomes constant, whereas for the other two profiles this quantity becomes flat at larger radius. Therefore, by increasing the aperture above few degrees does not increase the S/N for the NFWc case

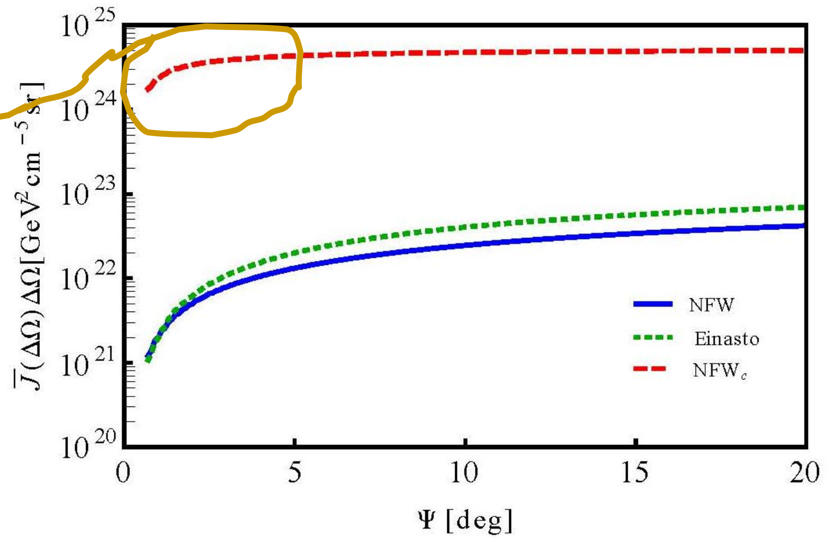


Figure 1: The $\bar{J}(\Delta\Omega)\Delta\Omega$ quantity integrated on a ring with inner radius of 0.5 degrees and external radius of Ψ degrees for the DM density profiles given in Table 1. Blue (solid), red (long-dashed) and green (short-dashed) lines correspond to NFW, NFW$_c$ and Einasto profiles, respectively. The three density profiles are compatible with current observational data.

Flux measurement

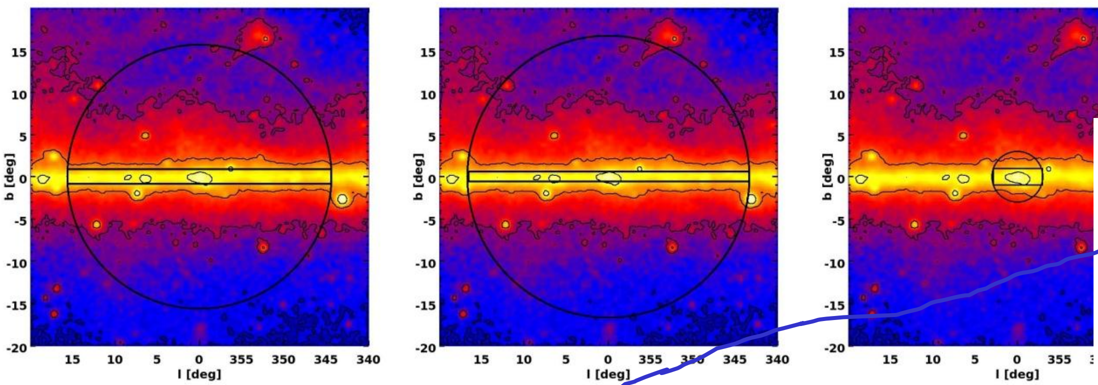


Figure 3: Maps of the observed flux by the Fermi-LAT in the energy range 1 – 100 GeV, in units of photons cm^{-2} s^{-1}, for the three DM profiles studied. From left to right: Einasto, NFW and NFW$_c$. I

Profile	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times 10^{22}$ GeV^2 cm^{-5} sr]	Flux (1 – 100 GeV) [$\times 10^{-7}$ cm^{-2}s^{-1}]
Einasto	5.1	31.4 ± 0.3
NFW	3.3	38.0 ± 0.3
NFW$_c$	86.8	2.2 ± 0.1

To set constraints we request that the DM-induced gamma ray flux does not exceed the observed flux upper limit

No subtraction of any astrophysical background is made

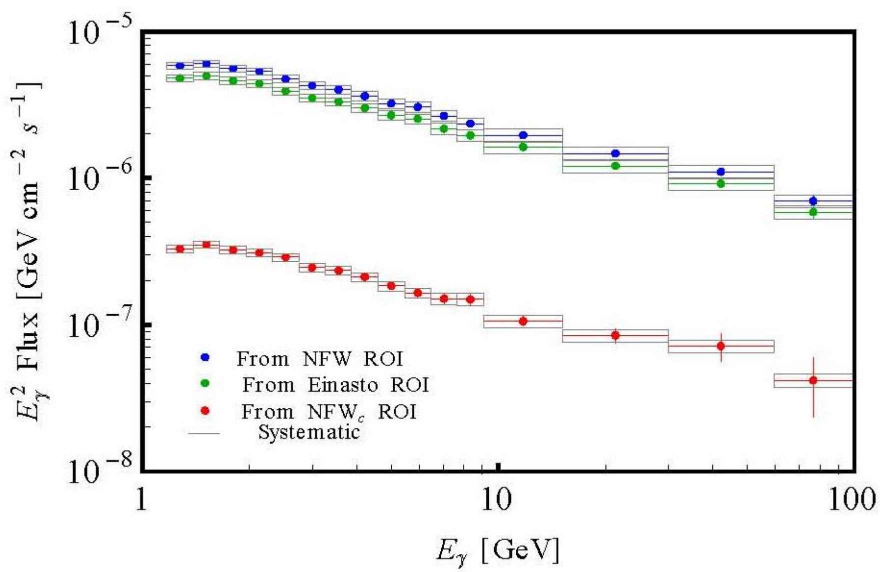


Figure 4: Energy spectrum extracted from Fermi-LAT data for the optimized regions that are shown in Figure 3. Data are shown as points and the vertical error bars represent the statistical errors. The latter are in many cases smaller than the point size. The boxes represent the systematic error in the Fermi-LAT effective area.

Carlos Muñoz
UAM & IFT

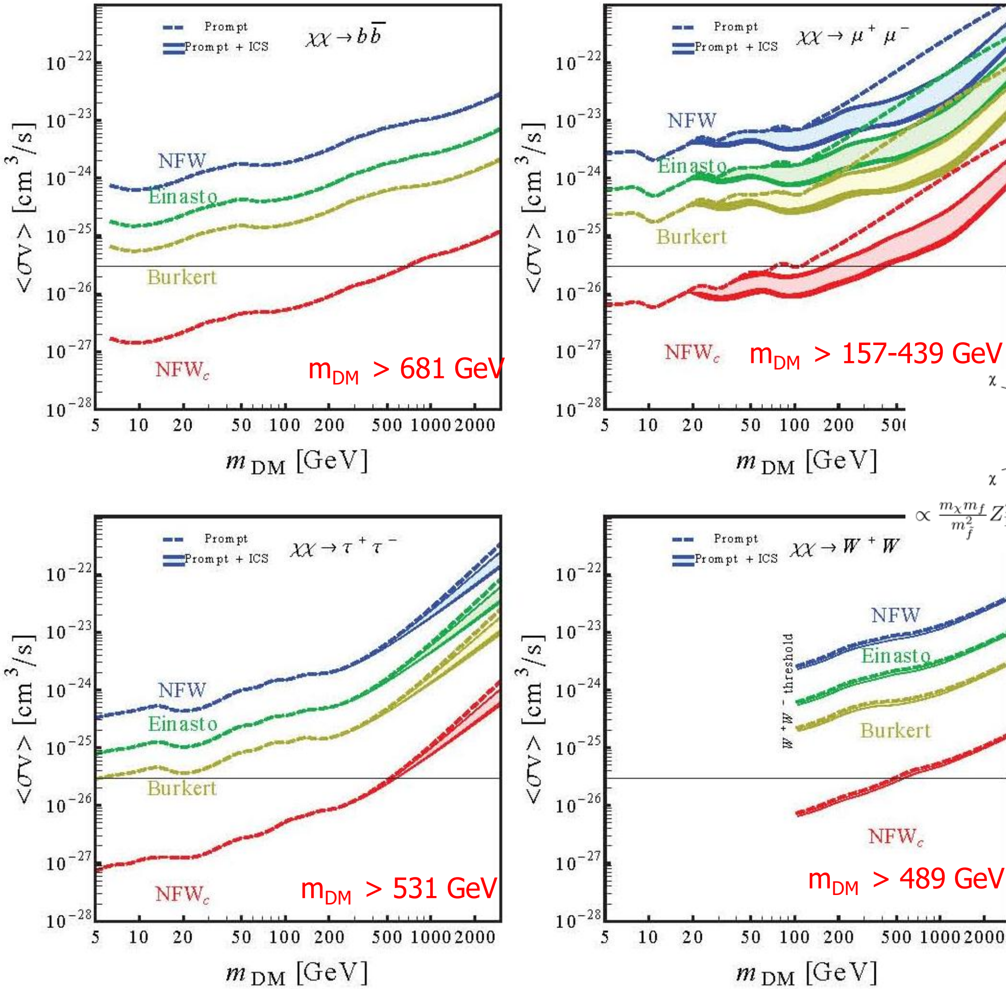
LIMITS ON THE DARK MATTER ANNIHILATION CROSS SECTION

Conservative approach:
Require that the integrated gamma-ray flux of the expected DM signal for each energy bin does not exceed the observed flux upper limit

No subtraction of any astrophysical background is made

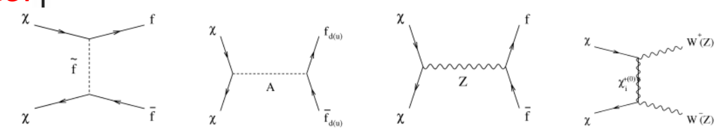
We use LAT data measured between August 4, 2008, and June 15, 2012

The upper limits on the annihilation cross section of DM particles obtained are two orders of magnitude stronger than withouth contraction



In general the final state will be a combination of the final states presented here

e.g., in SUSY, the neutralino annihilation modes are 70% bb - 30% $\tau\tau$ for a Bino DM, and 100% W^+W^- for a Wino DM



$\propto \frac{m_\chi m_f}{m_{\tilde{f}}^2} Z_{11}^2 \quad \propto \frac{m_\chi^2}{m_A^2}\frac{Z_{11}Z_{13,14}}{m_W} m_{f_d} \tan\beta(\frac{m_{f_u}}{\tan\beta}) \quad \propto \frac{m_f m_\chi}{m_Z^2} Z_{13,14}^2 \quad \propto \frac{[-Z_{14}V_{21}^* + \sqrt{2}Z_{12}V_{11}^*]^2(-Z_{13}N_{31}^* + Z_{14}N_{41}^*)^2}{1 + m^2_{\chi_i^{+(0)}}/m_\chi^2 - m^2_{W(Z)}/m_\chi^2}$

Also, the value of σv in the Galactic halo might be smaller than 3 x10^{-26} cm^3 s^{-1}

-e.g., in SUSY, in the early Universe coannihilation channels can also contribute to σv

-Also, DM particles whose annihilation in the Early Universe is dominated by velocity dependent contributions would have a smaller value of σv in the Galactic halo, where the DM velocity is much smaller, and can escape this constraint:

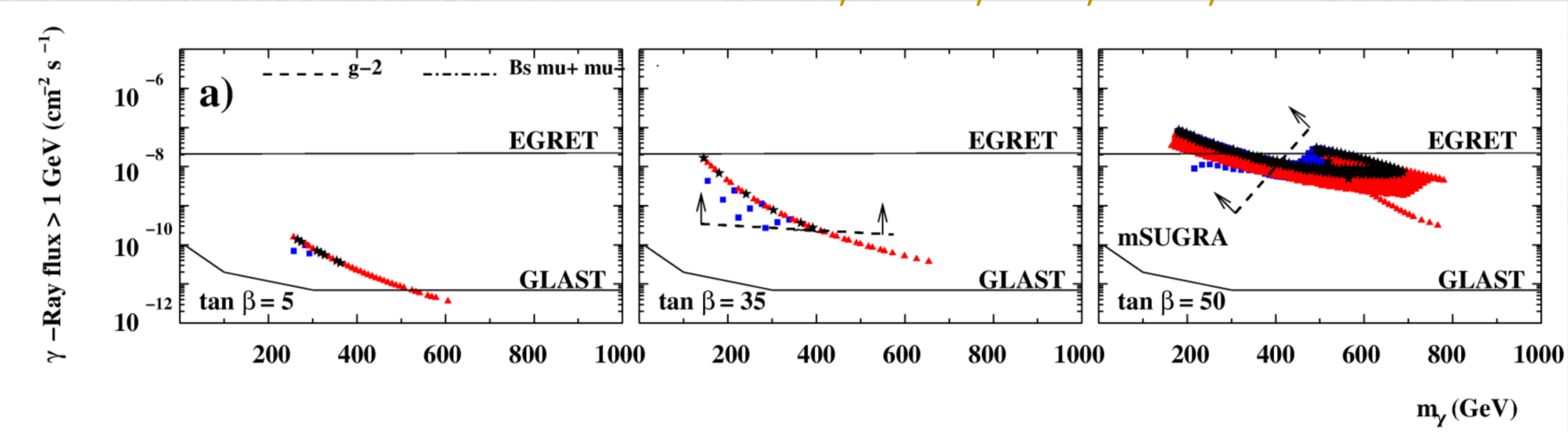
$$\Omega h^2 \approx 3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \langle \sigma v \rangle^{-1} \approx 0.1$$

In this sense, the results derived for pure annihilation channels can be interpreted as limiting cases which give an idea of what can happen in realistic scenarios

But still Fermi-LAT data imply that large regions of parameters of DM candidates are not compatible with compressed DM profiles

Work in progress,
Constraining the SUSY parameter space inspired by an old study of the MSSM:

Mambrini, Munoz, Nezri, Prada, 0506204



So we are now updating the neutralino MSSM case and studying the NMSSM, and the sneutrino in the extension of the NMSSM, Higgs portal models, ...

CONCLUSION

Fermi LAT data imply that large regions of parameters of DM candidates are not compatible with compressed DM density profiles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THE END