DIFFUSE γ RAY CONSTRAINTS ON ANNIHILATING OR DECAYING DM AFTER FERMI

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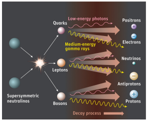
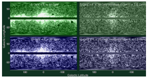
UNIVERSITÀ DEGLI STUDI DE L'AQUILA & UNIVERSITÉ PARIS 7

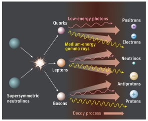
21$^{\text{th}}$ July 2010, Institut d'Astrophysique de Paris (IAP)

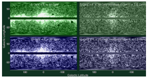
arXiv:0912.0663 in collaboration with M. Cirelli and P.D. Serpico





- Dark Matter Indirect Detection with γ rays
  - Inverse Compton γ rays
  - Prompt γ rays





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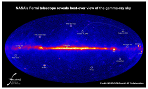
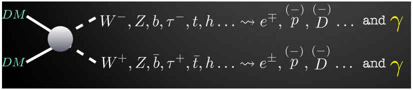


- Constraints on Annihilating or Decaying Dark Matter by using the diffuse γ rays measured by the FERMI satellite

Indirect Detection (γ Ray Constraints)



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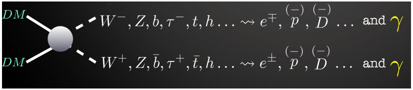

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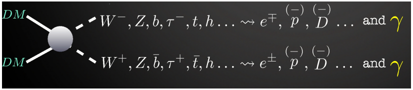

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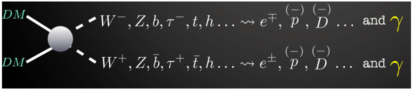

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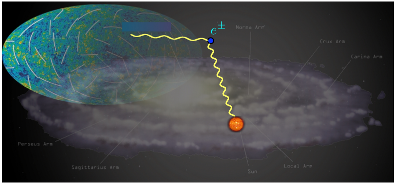
3. γ rays from the Inverse Compton Scattering (ICS) of the e^+e^-, produced by DM annihilations/decays in the Galactic Halo (GH), with the ISRF photons



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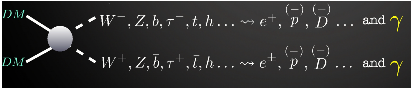

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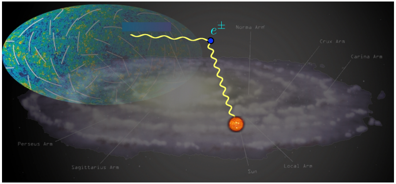
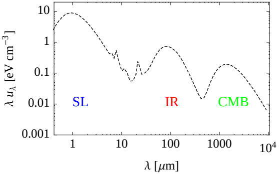
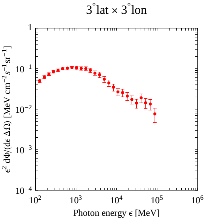
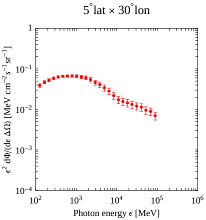


ISRF from GC





Talk by S. Digel



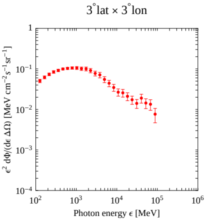
Talk by S. Digel

Fermi Data (FermiSymposium)

2 regions that surround the GC

- 3^o latitude $\times$ 3^o longitude
- 5^o latitude $\times$ 30^o longitude

Diffuse γ Ray Emission (Fermi Data Points)



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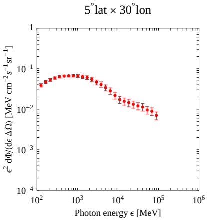

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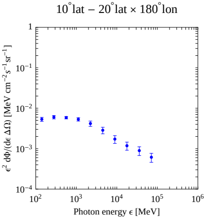
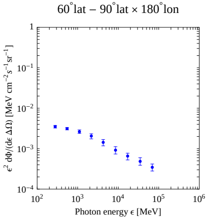


Talk by T. Porter



Talk by M. Ackerman

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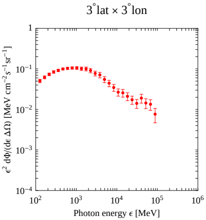

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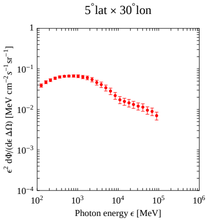

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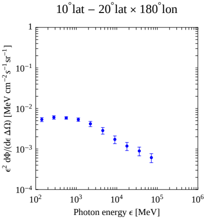

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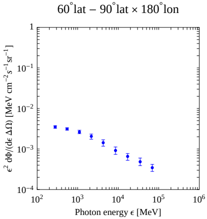

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The DM signals do not exceed more than 3σ the data

ICS Fluxes at Earth from DM Ann/Dec

$$\frac{d\Phi}{d\epsilon} = \frac{1}{\epsilon}\int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} ds\, \frac{j_{\text{tot}}(\epsilon, r(s))}{4\pi}$$

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$$j_{\mathrm{p}\gamma}(\epsilon, r) = \epsilon\, Q_\gamma(\epsilon, r)$$

DM Annihilation

$$Q_\gamma^{\mathrm{ann}}(\epsilon, r) = \frac{1}{2}\langle\sigma v\rangle\, n_\chi^2(r)\, \frac{dN_\gamma^{\mathrm{ann}}}{d\epsilon}(\epsilon)$$

DM Decay

$$Q_\gamma^{\mathrm{dec}}(\epsilon, r) = \Gamma_{\mathrm{dec}}\, n_\chi(r)\, \frac{dN_\gamma^{\mathrm{dec}}}{d\epsilon}(\epsilon)$$

$dN_\gamma/d\epsilon$ computed by using the PYTHIA MonteCarlo code

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$$j_{\text{IC}}(\epsilon, r) = 2\int_{m_{\text{e}}}^{m_\chi} dE_{\text{e}}\, \mathcal{P}(\epsilon, E_{\text{e}}, r)\, n_{\text{e}}(E_{\text{e}}, r)$$

Differential Power

The derivation is straightforward in terms of the well-known IC kinematics

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Differential Power

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Electrons Number Density

The derivation can be done by solving the diffusion-loss equation

Derivation of the Electrons Number Density

$$\underbrace{-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D\frac{\partial f}{\partial r}\right]}_{\text{diffusion}} + \underbrace{v\frac{\partial f}{\partial r}}_{\text{advection}} \underbrace{-\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 v)p\frac{\partial f}{\partial p}}_{\text{convection}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left[\dot{p}p^2 f\right]}_{\text{radiative losses}} = \underbrace{\frac{Q_e(E,r)}{4\pi p^2}}_{\text{source}}$$

$f = n_{\rm e}(E_{\rm e}, r)/(4\pi p^2)$ with p electron momentum

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Fermi Regions

Big Regions of the sky, well outside the GC

$$\theta = 1^o \Rightarrow \lambda^o = r_\odot \theta \simeq 0.15 \text{ kpc}$$

1. 0.45 kpc $\times$ 0.45 kpc
2. 0.74 kpc $\times$ 4.44 kpc
3. 1.48 kpc - 2.96 kpc $\times$ 26.65 kpc
4. 8.88 kpc - 13.33 kpc $\times$ 26.65 kpc

Derivation of the Electrons Number Density

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Derivation of the Electrons Number Density

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- Approximation for the inner part of our Galaxy ($\tau_{\mathrm{diff}} \sim \tau_{\mathrm{rad}}$)
  True outside the Galactic Plane ($\tau_{\mathrm{diff}} \gg \tau_{\mathrm{rad}}$)

Derivation of the Electrons Number Density

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- Approximation for the inner part of our Galaxy ($\tau_{\mathrm{diff}} \sim \tau_{\mathrm{rad}}$) True outside the Galactic Plane ($\tau_{\mathrm{diff}} \gg \tau_{\mathrm{rad}}$)
- Turn out to be dominated by the ICS radiative process

Derivation of the Electrons Number Density

$$n_e(E_e, r) = \frac{1}{b_{tot}(E_e, r)} \int_{E_e}^{m_\chi} d\tilde{E}_e \, Q_e(\tilde{E}_e, r)$$

Derivation of the Electrons Number Density

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DM Annihilation

$$Q_e^{ann}(E_e, r) = \frac{1}{2} \langle \sigma v \rangle \, n_\chi^2(r) \, \frac{dN_e^{ann}}{dE_e}(E_e)$$

- $\langle \sigma v \rangle$: Annihilation cross section
- $n_\chi = \rho / m_\chi$: DM number density
- dN_e^{ann}/dE_e: Electron spectrum produced by DM annihilation

DM Decay

$$Q_e^{dec}(E_e, r) = \Gamma_{dec} \, n_\chi(r) \, \frac{dN_e^{dec}}{dE_e}(E_e)$$

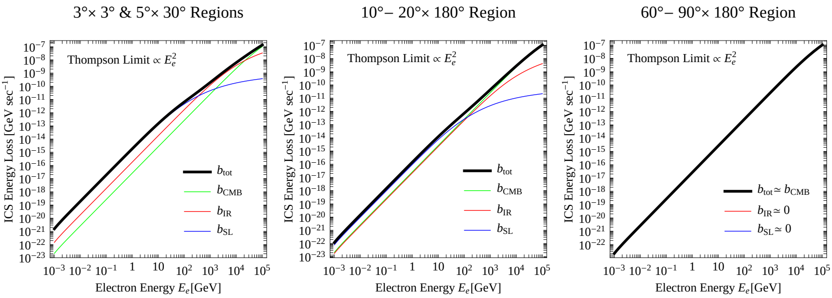
- $\Gamma_{dec} = 1/\tau_{dec}$: Decay rate
- $n_\chi = \rho / m_\chi$: DM number density
- dN_e^{dec}/dE_e: Electron spectrum produced by DM decay

dN_e/dE_e computed by using the PYTHIA MonteCarlo code

$$n_e^i(E_e, r) \simeq \frac{1}{b^i_{tot}(E_e)} \int_{E_e}^{m_\chi} d\tilde{E}_e \, Q_e(\tilde{E}_e, r)$$

Constant b_{tot} over each of the observation regions that we consider

$$b_{tot}(E_e, r) \simeq b^i_{tot}(E_e)$$



ICS Fluxes at Earth from DM Ann/Dec

$$\frac{d\Phi_i}{d\epsilon\,\Delta\Omega} = \begin{cases} \bar{J}_i^{\rm ann}\,\frac{1}{2}\,\frac{\langle\sigma v\rangle}{4\pi}\,\frac{\rho_\odot^2}{m_\chi^2}\,r_\odot\left[\left.\frac{dN_i^{\rm ann}}{d\epsilon}\right|_{\rm IC} + \left.\frac{dN^{\rm ann}}{d\epsilon}\right|_{\rm p\gamma}\right] & \text{(annihilation)} \\ \bar{J}_i^{\rm dec}\,\frac{\Gamma_{\rm dec}}{4\pi}\,\frac{\rho_\odot}{m_\chi}\,r_\odot\left[\left.\frac{dN_i^{\rm dec}}{d\epsilon}\right|_{\rm IC} + \left.\frac{dN^{\rm dec}}{d\epsilon}\right|_{\rm p\gamma}\right] & \text{(decay)} \end{cases}$$

$$\left.\frac{dN_i^{\rm ann/dec}}{d\epsilon}\right|_{\rm IC} = \frac{2}{\epsilon}\int_{m_{\rm e}}^{m_\chi} dE_{\rm e}\,\frac{\mathcal{P}_i(E_{\rm e},\epsilon)}{b_{\rm tot}^i(E_{\rm e})}\int_{E_{\rm e}}^{m_\chi} d\tilde{E}_{\rm e}\,\frac{dN_{\rm e}^{\rm ann/dec}}{d\tilde{E}_{\rm e}}, \qquad \left.\frac{dN^{\rm ann/dec}}{d\epsilon}\right|_{\rm p\gamma} = \frac{dN_\gamma^{\rm ann/dec}}{d\epsilon}.$$

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$$\left.\frac{dN_i^{\rm ann/dec}}{d\epsilon}\right|_{\rm IC} = \frac{2}{\epsilon} \int_{m_e}^{m_\chi} dE_e\, \frac{\mathcal{P}_i(E_e, \epsilon)}{b^i_{\rm tot}(E_e)} \int_{E_e}^{m_\chi} d\tilde{E}_e\, \frac{dN_e^{\rm ann/dec}}{d\tilde{E}_e}, \qquad \left.\frac{dN^{\rm ann/dec}}{d\epsilon}\right|_{\rm p\gamma} = \frac{dN_\gamma^{\rm ann/dec}}{d\epsilon}.$$

Annihilation Scenario

$$\bar{J}_i^{\rm ann} = \int \frac{ds}{r_\odot} \frac{\rho^2[r(s,b,l)]}{\rho_\odot^2}$$

$b \longrightarrow$ Galactic latitude
$l \longrightarrow$ Galactic longitude

Decay Scenario

$$\bar{J}_i^{\rm dec} = \int \frac{ds}{r_\odot} \frac{\rho[r(s,b,l)]}{\rho_\odot}$$

$b \longrightarrow$ Galactic latitude
$l \longrightarrow$ Galactic longitude

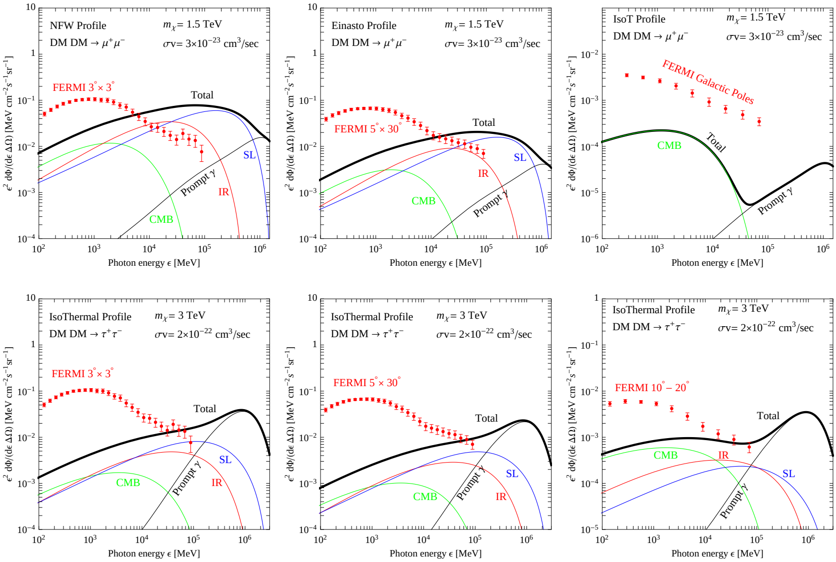
Boost Factors in our Regions

Region	latitude b & longitude l	$\bar{J}_i^{\rm ann}$ IsoT	$\bar{J}_i^{\rm ann}$ NFW	$\bar{J}_i^{\rm ann}$ Einasto	$\bar{J}_i^{\rm dec}$ IsoT	$\bar{J}_i^{\rm dec}$ NFW	$\bar{J}_i^{\rm dec}$ Einasto
'3×3'	$0.25^\circ < \|b\| < 2.75^\circ$ $357.25^\circ < l < 359.75^\circ$ $0.25^\circ < l < 2.75^\circ$	35.1	325	595	8.20	14.6	18.5
'5×30'	$0.25^\circ < \|b\| < 4.75^\circ$ $330.25^\circ < l < 359.75^\circ$ $0.25^\circ < l < 29.75^\circ$	20.9	51.1	85.9	6.56	7.53	8.72
'10−20'	$10^\circ < \|b\| < 20^\circ$ $0^\circ < l < 360^\circ$	3.35	3.46	4.23	2.45	2.38	2.47
'Gal Poles'	$60^\circ < \|b\| < 90^\circ$ $0^\circ < l < 360^\circ$	0.92	0.96	0.94	1.74	1.69	1.67

In the DM annihilation scenario the signals from the inner part of our Galaxy are boosted compare to the decay one

More competitive γ ray constraints in the DM annihilation scenario

Summary & Results (DM Annihilation)



Draw the Exclusion Lines $\langle\sigma_{\mathrm{ann}} v\rangle/m_\chi$ Plane

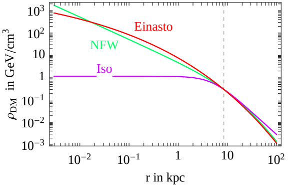
Recent Numerical Simulations (Einasto profile):

$$\rho_{\rm Ein}(r) = \rho_s \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right], \quad \alpha = 0.17.$$

Previously standard choices (NFW & IsoT):

$$\rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}, \quad \rho_{\rm isoT}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

DM halo model	r_s in kpc	ρ_s in GeV/cm^3
NFW	20.0	0.26
Einasto	21.8	0.05
Isothermal	3.20	2.31



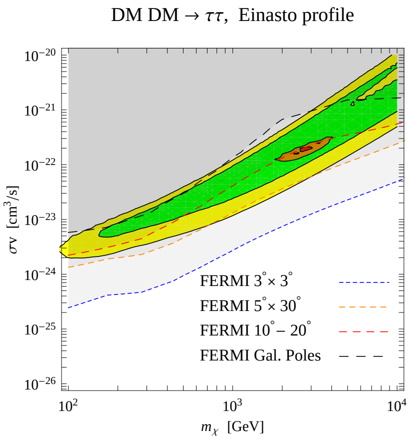
Draw the Exclusion Lines $\langle \sigma_{\mathrm{ann}} v \rangle / m_\chi$ Plane

- Consider a Benchmark DM Halo profile

- Calculate the ICS signal and the prompt signal in each given primary annihilation channel spanning the DM mass in a range between 100 GeV up to 10 TeV

Draw the Exclusion Lines $\langle \sigma_{\rm ann} v \rangle / m_\chi$ Plane

- Consider a Benchmark DM Halo profile
- Calculate the ICS signal and the prompt signal in each given primary annihilation channel spanning the DM mass in a range between 100 GeV up to 10 TeV
- Require that the DM signals do not exceed more than 3σ the FERMI experimental data



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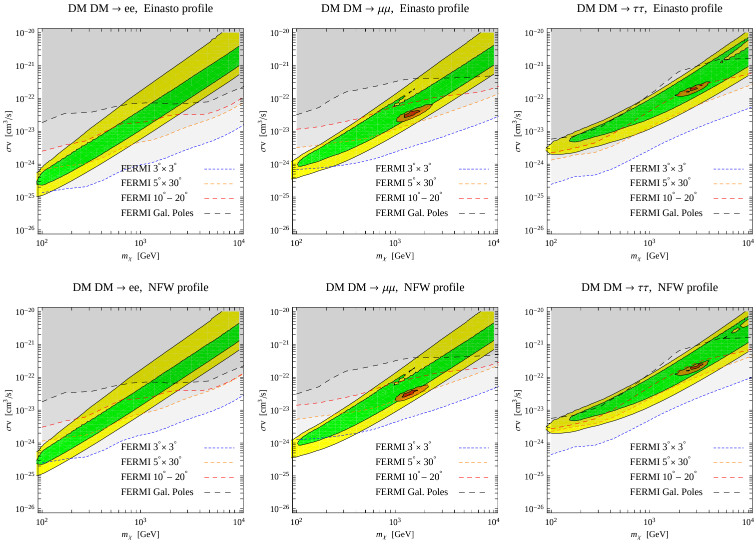
The PAMELA allowed region (green 95% C.L. and yellow 99.999% C.L.)

FERMI + HESS + PAMELA allowed region (red 95% C.L. and orange 99.999% C.L.)

are completely excluded by the IC + Prompt γ constraints !!!

IC + Prompt γ Constraints (DM Annihilation)



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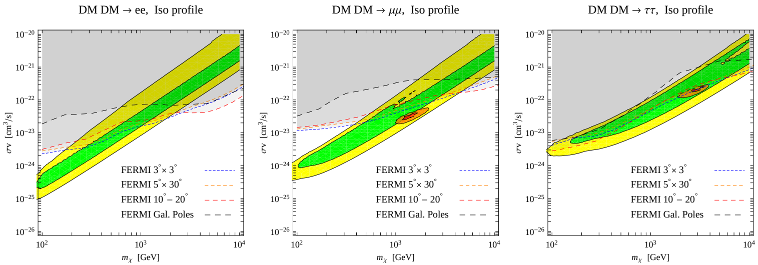

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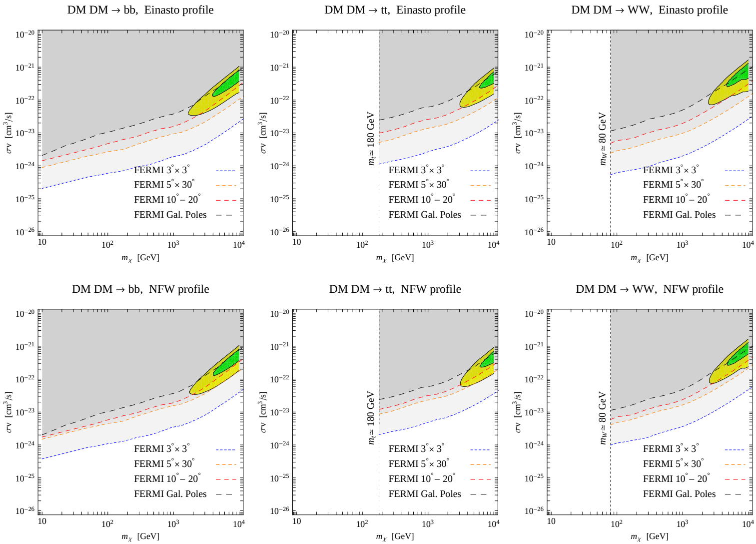
For the smooth isothermal profile, regions of the parameters space seem to be reopened.

The FERMI + HESS + PAMELA allowed region in the case of annihilation into muons is not excluded yet

Hadronic Mode Constraints



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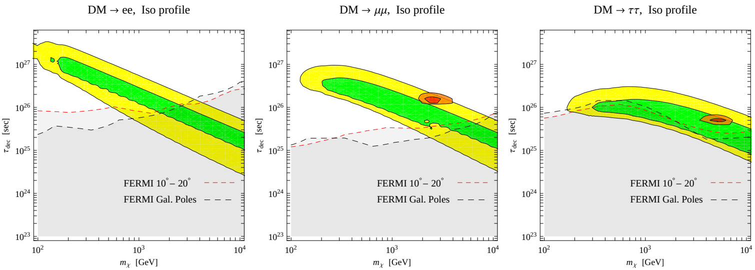
Draw the Exclusion Lines $\tau_{\rm dec}/m_\chi$ Plane

Draw the Exclusion Lines τ_{dec}/m_χ Plane

- IC + Prompt γ Constraints from our Galaxy



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The exclusion lines lie below the FERMI+HESS+PAMELA allowed region

The constraints from our Galaxy are not so strong

Draw the Exclusion Lines $\tau_{\rm dec}/m_\chi$ Plane

- IC + Prompt γ Constraints from the residual "Isotropic radiation"

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$$\frac{d\Phi^{\rm dec}_{\rm cosm}}{d\epsilon} = \Gamma_{\rm dec}\frac{\Omega_\chi \rho_{\rm c,0}}{m_\chi}\frac{1}{H_0}\int_0^\infty dz \frac{e^{-\tau(\epsilon,z)}}{\sqrt{\Omega_{\rm M}(1+z)^3+\Omega_\Lambda}}\left[\left.\frac{dN^{\rm dec}}{d\epsilon}\right|_{\rm IC} + \left.\frac{dN^{\rm dec}}{d\epsilon}\right|_{\rm p\gamma}\right]$$

Draw the Exclusion Lines $\tau_{\rm dec}/m_\chi$ Plane

- IC + Prompt γ Constraints from the residual "Isotropic radiation"

$$\frac{d\Phi^{\rm dec}_{\rm isotropic}}{d\epsilon} = \frac{d\Phi^{\rm dec}_{\rm cosm}}{d\epsilon} + 4\pi \frac{d\Phi^{\rm dec}_{\rm halo}}{d\epsilon\, d\Omega}\bigg|_{\rm Anti-GC}$$

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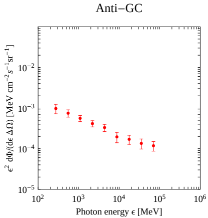

Talk by M. Ackerman, FermiSymposium

The "Isotropic Signal" does not exceed more than 3σ the FERMI data in the Anti-GC

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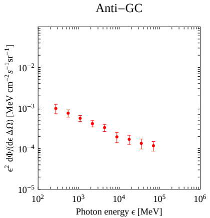

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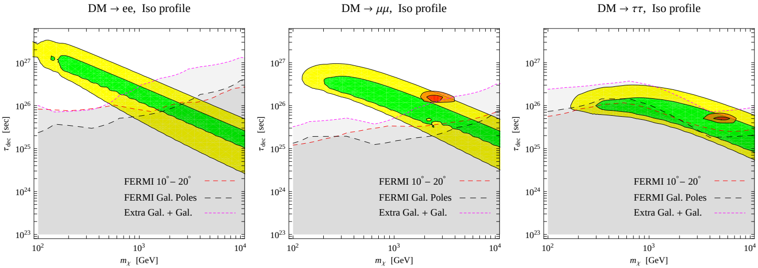
Annihilation Scenario

- Stronger dependence on the angular distance from the GC is introduced in the galactic flux (no longer "Isotropic signal")
- Dependence on the DM profiles and the clumpiness of DM halos is introduced in the cosmological flux (strong dependence on $M^{\rm Halo}_{\rm min}$, $c_{\rm vir}$)

see e.g. Zaharijas et al. JCAP 1004:014,2010

IC + Prompt γ Constraints (DM Decay)



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The residual "Isotropic radiation" measured by FERMI imposes the strongest contraints

It excludes the decay explanation of the FERMI+HESS+PAMELA anomalies for the $\tau\tau$ channel and starts to exclude the decay explanation for the $\mu\mu$ channel

Conclusions

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Leptonic Annihilation modes:

- For the NFW or Einasto profiles, the current data exclude not only DM scenarios explaining the FERMI+HESS+PAMELA allowed regions, but also PAMELA regions alone to hight confidence level
- For "cored" profiles, regions of the parameters space seem to be reopened (The annihilation into muons is not excluded yet)

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Tensions with other Constraints:

- Constraints from Synchrotron radiation (Bertone et al. arXiv:0811.3744)
- Constraints from Ionization and Heating of the InterGalactic Medium

(Cirelli, Iocco, Panci arXiv:0907.0719), (Huetsi et al. arXiv:0906.4550), (Galli et al. arXiv:0905.0003)