Constraining Dark Matter Properties with Fermi-LAT

based on NB and S. Palomarez-Ruiz
arXiv:1006.0477

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Instituto Superior Técnico, Lisboa

Bonn, July 12, 2010

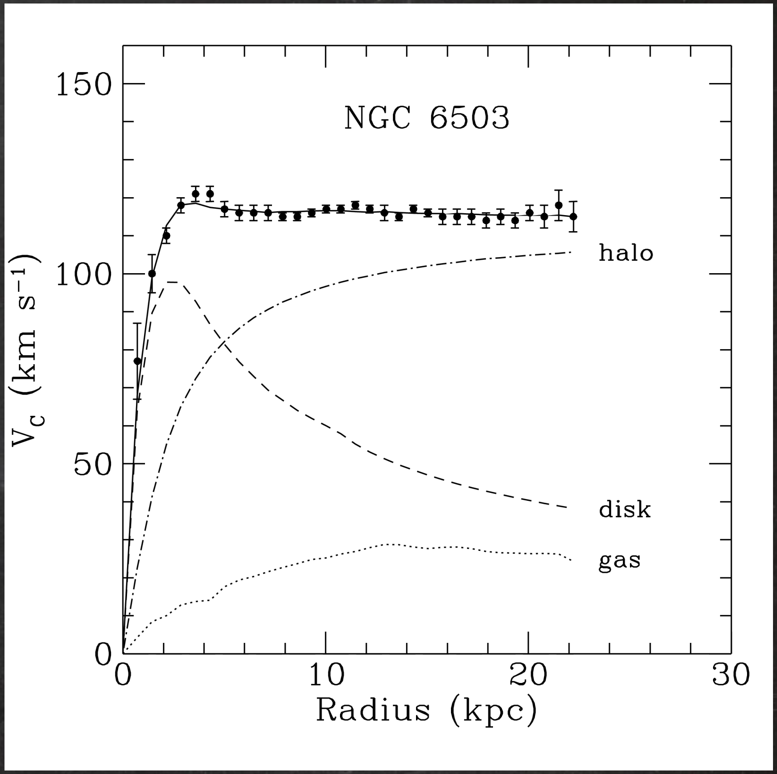
The evidence for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (missing force) at very different scales!

* **Galactic rotation curves**

$$v_c(r)^2 = \frac{2\, G_N\, M(r)}{r}$$

$v_c(r) \sim \text{const.}$ $\dashrightarrow$ $\rho(r) \sim r^{-2}$



Bergeman et al. MNRAS 249 (1991)

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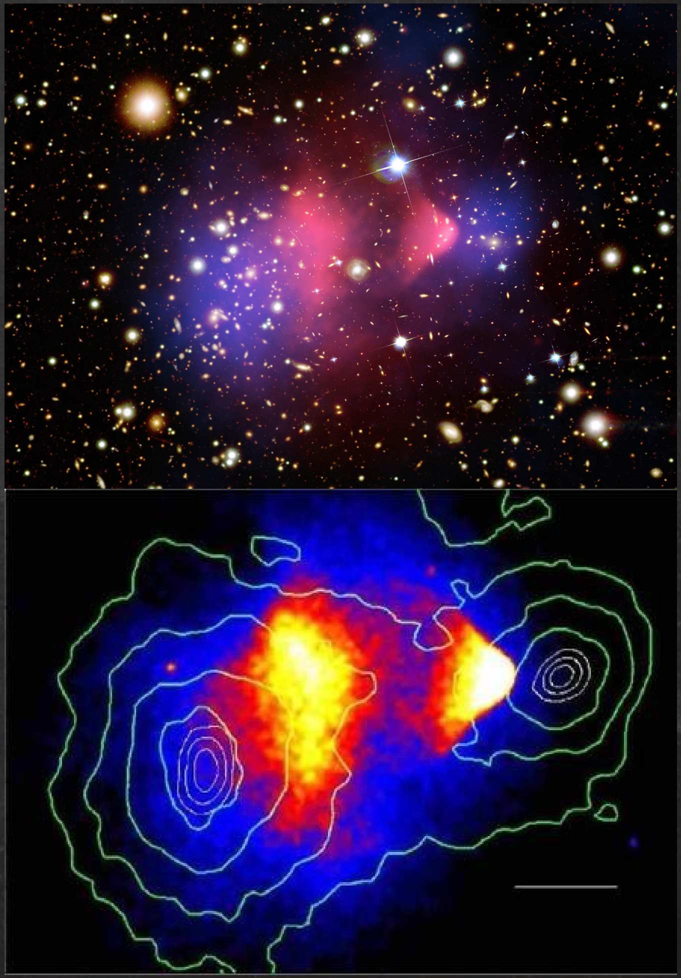
* **Galactic rotation curves**

* **Clusters of galaxies**
  - rotation curves
  - gravitational lensing
  - X-ray gas temperature



Bullet cluster

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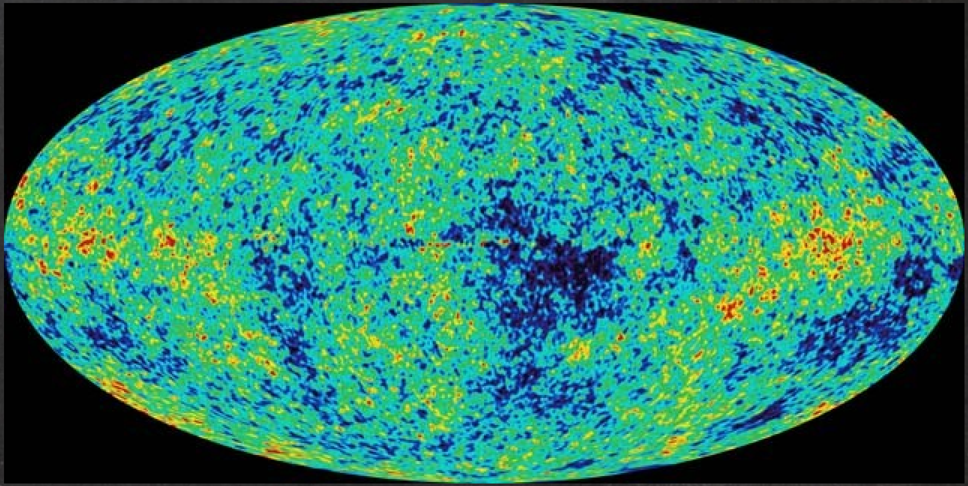
* **Galactic rotation curves**

* **Clusters of galaxies**

* **CMB anisotropies**

Ω_{DM}=0.101±0.06 (WMAP)



WMAP collaboration
Astrophys. J. Suppl. 180 (1009)

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* **Galactic rotation curves**

* **Clusters of galaxies**

* **CMB anisotropies**

DM is there
What is DM?

Weakly Interacting Massive Particles

There existe well-motivated theories beyond the SM, providing DM candidates at the EW scale:

* SUSY with *R-parity*: **LSP**
* Little Higgs with *T-parity*
* Extra dimensions with *K-parity*: **LKP**

Weak cross-sections gives rougly the right density for thermal WIMPs

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→ We assume a particle-physics model independent-framework: generic WIMP with mass m_χ and annihilation cross-section $\langle \sigma v \rangle$

Detecting Dark Matter

* **Collider searches**

  Missing energy

  (Tevatron, LHC, ILC, CLIC...)

* **Direct detection**

  Nuclear recoil produced by DM elastic scattering

  (Xenon, CMDS, Edelweiss...)

* **Indirect detecion**

  Observation of annihilation/decay products

  - Gamma-rays telescopes

    (Fermi, EGRET, Hess, Magic, Veritas...)

  - Antimatter experiments

    (Pamela, Heat, Bess...)

  - Neutrino detectors

    (IceCube, Antares, Amanda, Super-Kamiokande...)

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Current experiments

Fermi

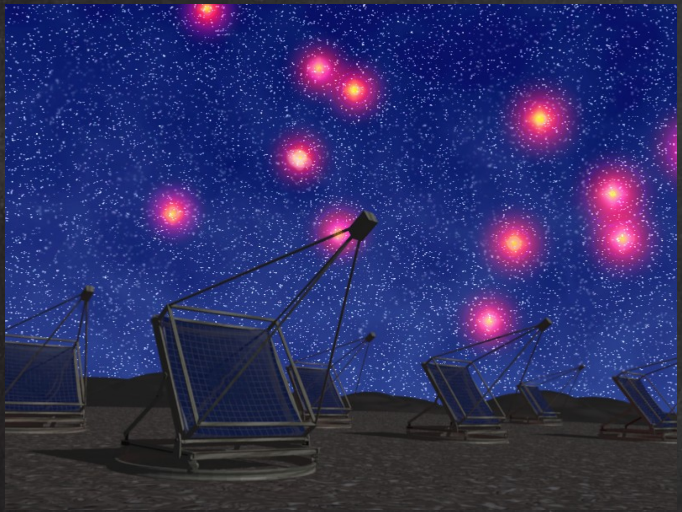
HESS

Veritas

Magic

Future experiments

CTA
(Cherenkov Telescope Array)



AGIS
(Advanced Gamma-ray Imaging System)

They foresee an improvement of about an order of magnitude in sensitivity and to extend the energy range of ACTs to lower and higher energies

Gamma-rays: general features

The differential intensity of the gamma-ray signal

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\Omega)=\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\rm prompt}(E_\gamma,\Delta\Omega)+\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\rm ICS}(E_\gamma,\Delta\Omega)+\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\rm synchrotron}(E_\gamma,\Delta\Omega)$$

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* The gamma-ray synchrotron signal lies at radio frecuencies (at least for typical WIMP DM masses) ----► irrelevant

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* Prompt gamma-rays produced by annihilation of DM particles:

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{prompt}}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2\,m_\chi^2}\sum_i \frac{dN_\gamma^i}{dE_\gamma}\,\text{BR}_i\,\frac{1}{4\,\pi}\int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho\big(r(s,\Omega)\big)^2\,ds$$

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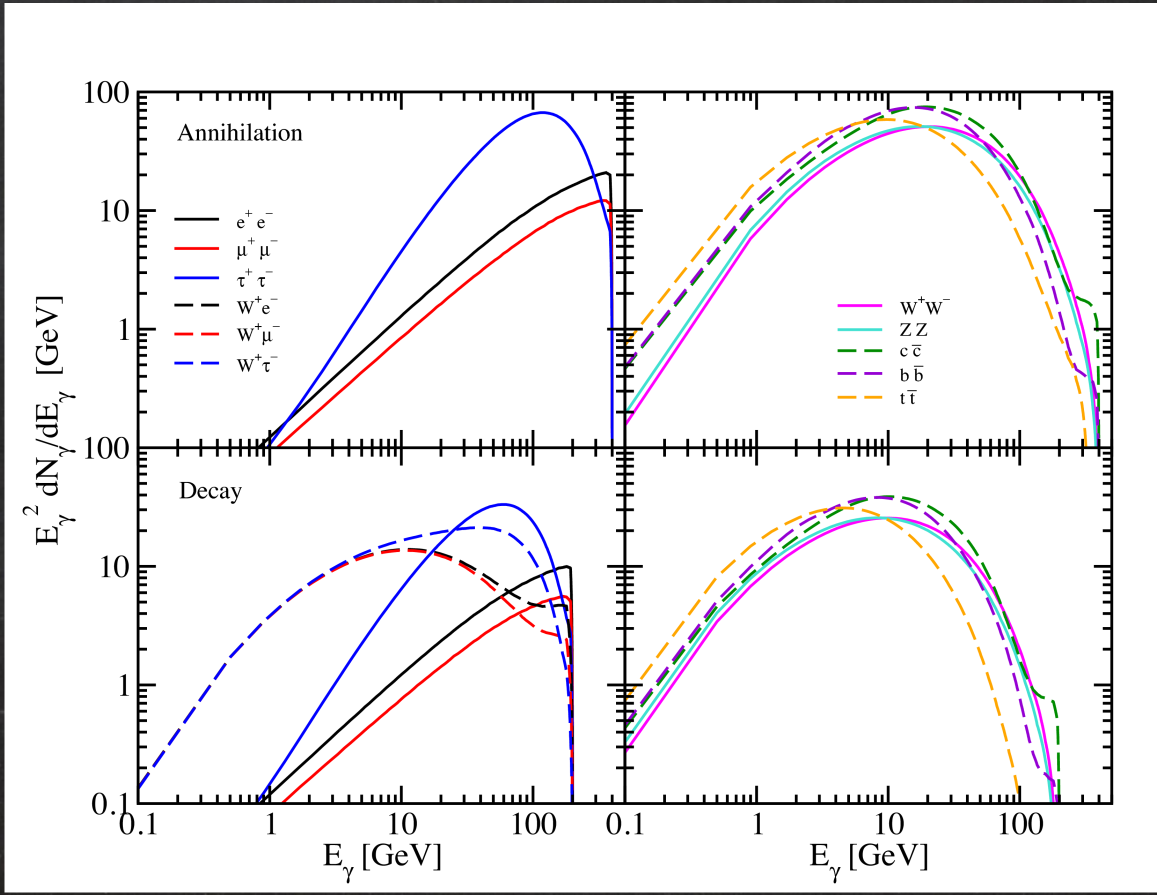
Particle P.

Gamma-ray spectra from DM annihilation

We assume DM annihilates into 2 SM particles and use Pythia.
Here only prompt photons are shown

Hard channels



Soft channels

S. Palomares-Ruiz & JM Siegal-Gaskins arXiv:1003.1142

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AstroP and Cosmo

DM halo profiles

From N-body simulations

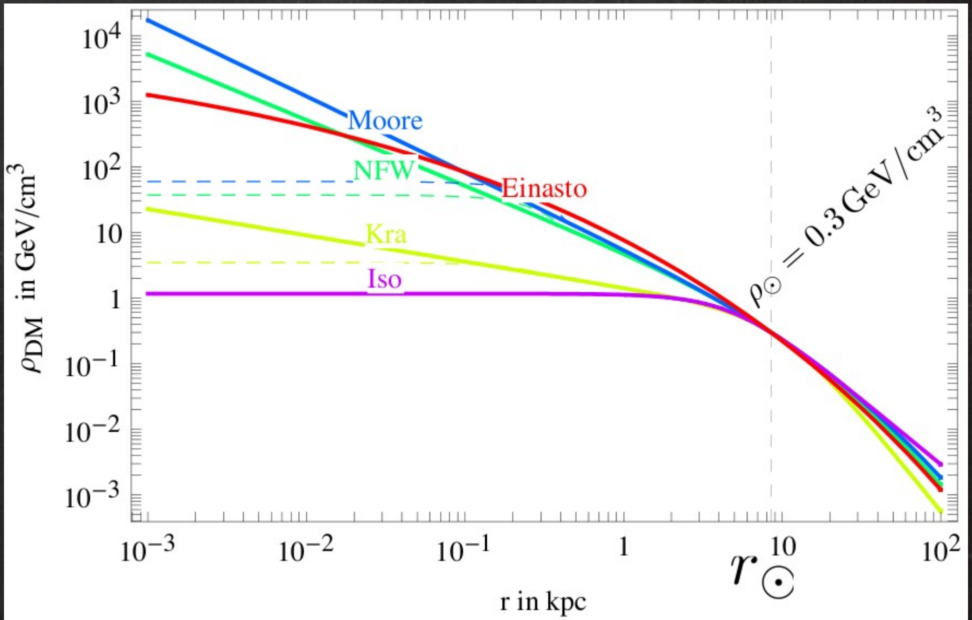
$$\rho(r) = \rho_\odot \frac{[1 + (R_\odot/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}{(r/R_\odot)^\gamma\,[1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

At small r: $\rho(r)=1/r^\gamma$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

$$\rho(r) = \rho_s \cdot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

Einasto | $\alpha = 0.17$ $r_s = 20\,\text{kpc}$ $\rho_s = 0.06\,\text{GeV/cm}^3$



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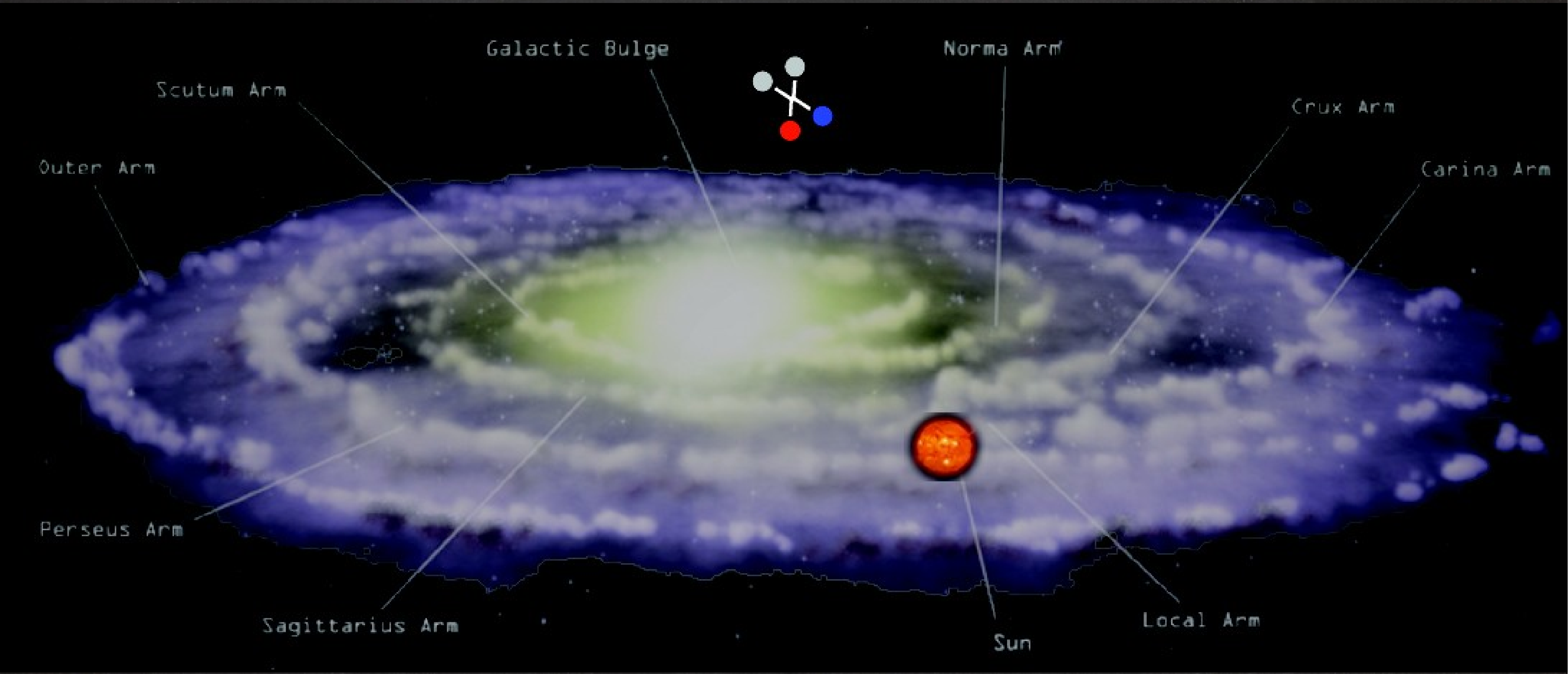
* Gamma-rays from Inverse Compton Scattering:

- Electrons/Positrons could propagate in the ISM
- Gamma-rays production via ICS off the ambient photon background

Electron/Positron propagation in the halo



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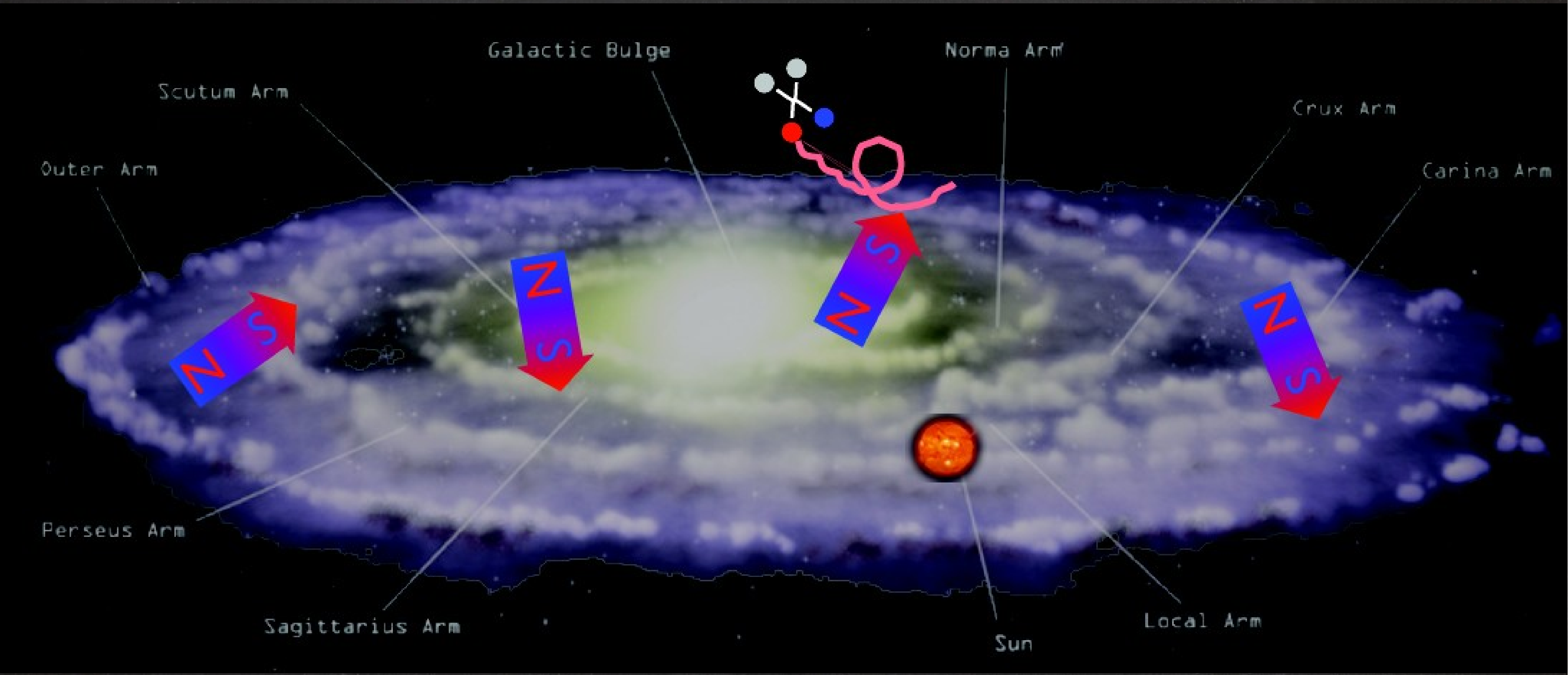
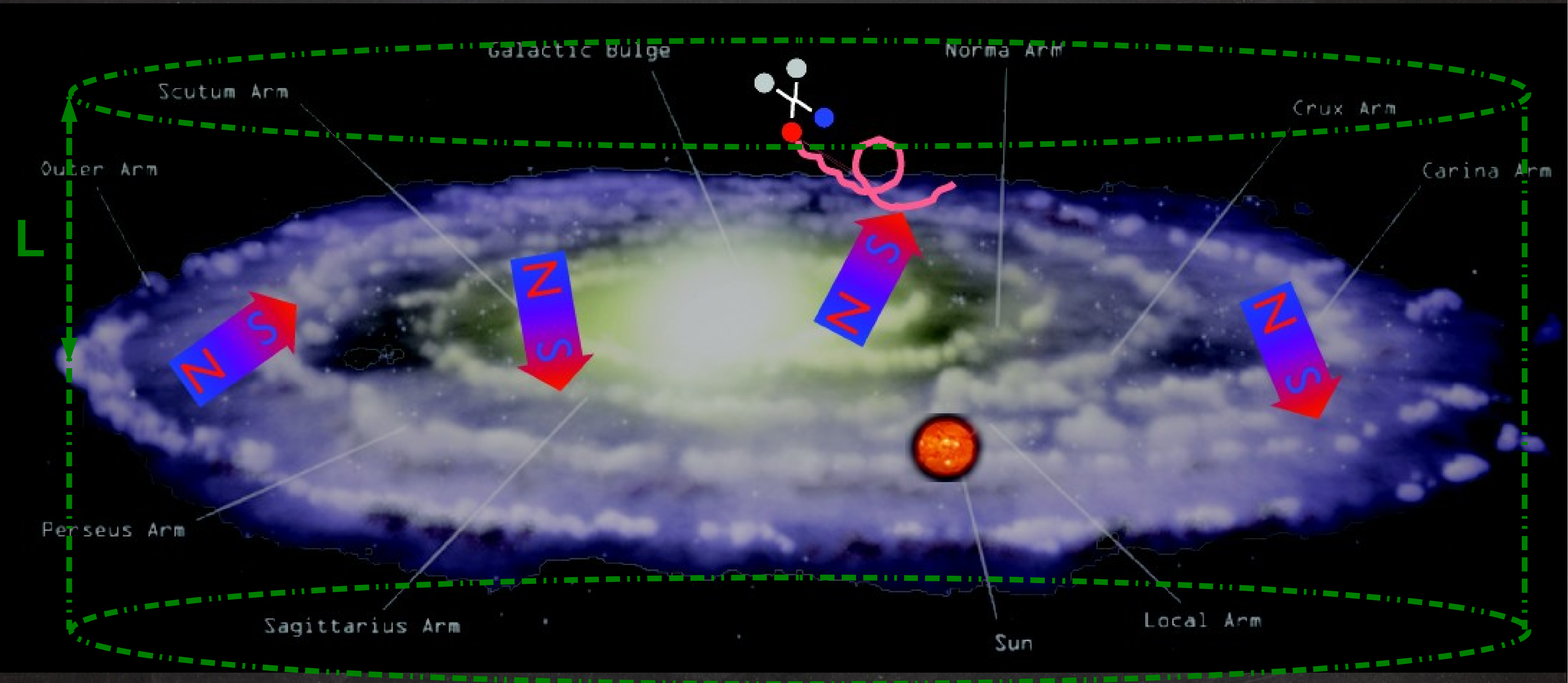


A plethora of tangled magnet fields, particles can jump to nearby field lines which will drastically alter their courses

→ Random walk

Electron/Positron propagation in the halo



$$\nabla\left(K(\vec{x},E)\,\nabla\frac{dn_e}{dE}(\vec{x},E)\right)+\frac{\partial}{\partial E}\left(b(\vec{x},E)\,\frac{dn_e}{dE}(\vec{x},E)\right)+Q(\vec{x},E)=0$$

diffusion energy loss source

Electron/Positron propagation in the halo

Three commonly used propagation models corresponding to the minimal, maximal and median primary *positron fluxes* that are compatible with the B/C data

	L [kpc]	K_0 [kpc^2/Myr]	α
MIN	1	0.00595	0.55
MED	4	0.0112	0.70
MAX	15	0.0765	0.46

$$\nabla\left(K(\vec{x},E)\,\nabla\frac{dn_e}{dE}(\vec{x},E)\right)+\frac{\partial}{\partial E}\left(b(\vec{x},E)\,\frac{dn_e}{dE}(\vec{x},E)\right)+Q(\vec{x},E)=0$$

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* Gamma-rays from Inverse Compton Scattering:
- Electrons/Positrons could propagate in the ISM
- Gamma-rays production via ICS off the ambient photon background

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\rm ICS}(E_\gamma,\Delta\Omega) = \frac{1}{E_\gamma}\frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\rm los} ds \int_{m_e}^{m_\chi} dE\,\mathcal{P}(E_\gamma,E)\,\frac{dn_e}{dE}(E, r_c(s,\Omega), z_c(s,\Omega))$$

Differential power emitted into photon of energy E_γ
by electrons/positrons of energy E

- Superposition of 3 blackbody spectra:
SL (T=0.3 eV), IR (T=3.5 meV), CMB (T=2.7 K)

Overview of the analysis

* We consider the energy range [1, 300] GeV

* We select an 'optimal' angular window

* We add the ICS contribution to the DM-induced gamma-ray spectrum: crucial for some cases

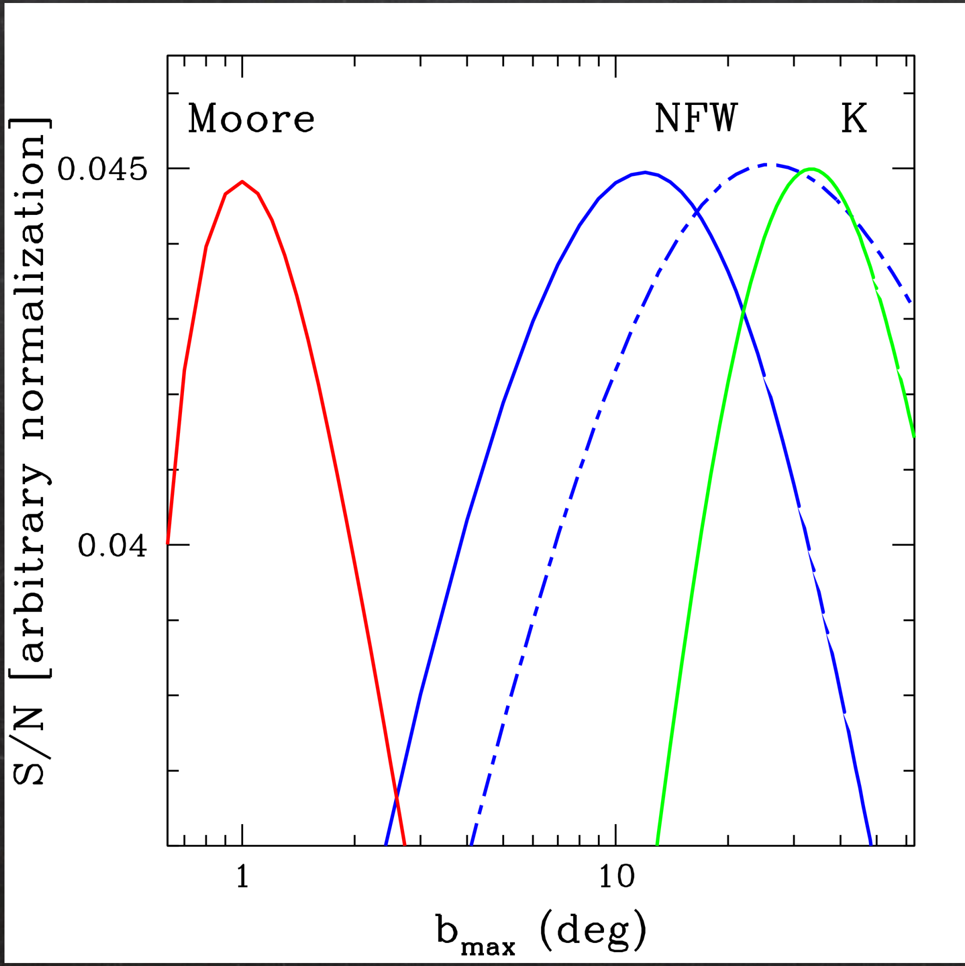
* We use the latest Fermi measurements for the background around the GC

* We evaluate Fermi sensitivity to DM annihilations

* We evaluate Fermi abilities to constrain DM properties: annihilation cross section, mass and dominant annihilation channels

Optimal angular window

Significance of the signal: S/N



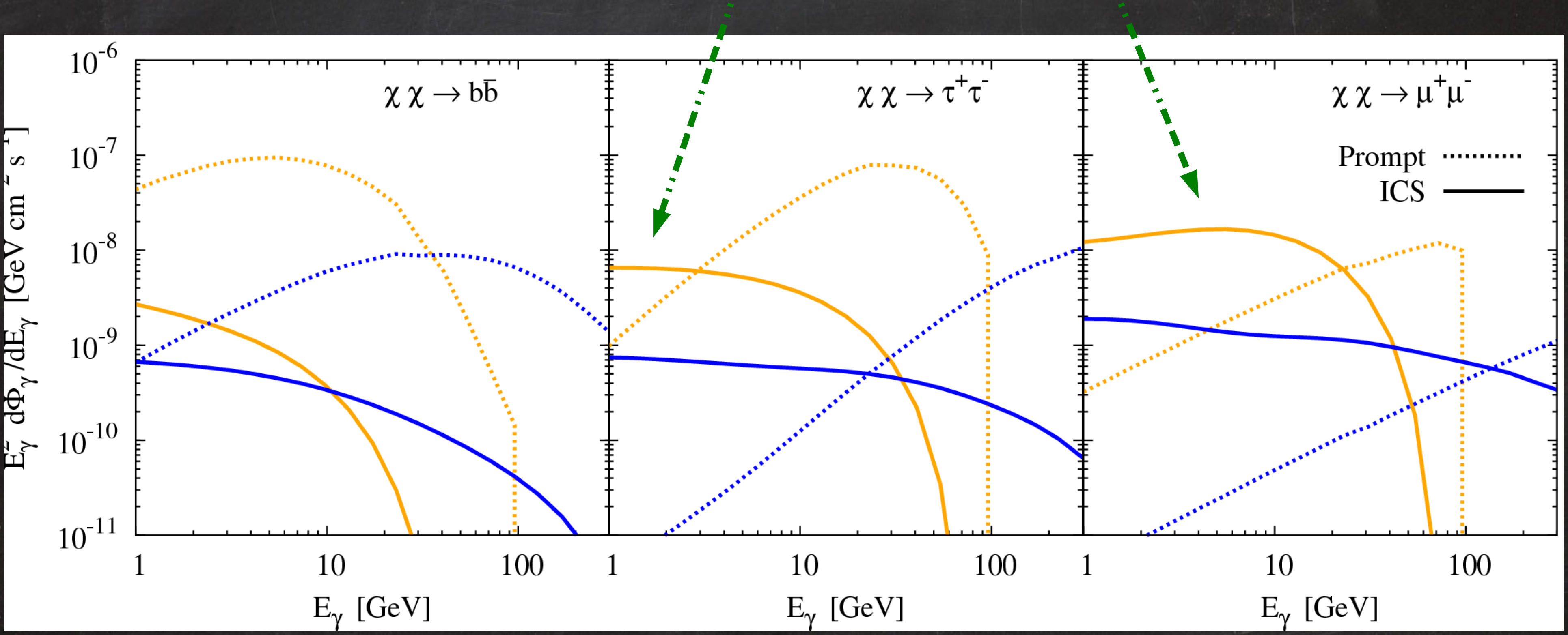
PD Serpico and G Zaharijas
Astropart. Phys. Rev. D 69 (2004)

Our selection:

10 degrees

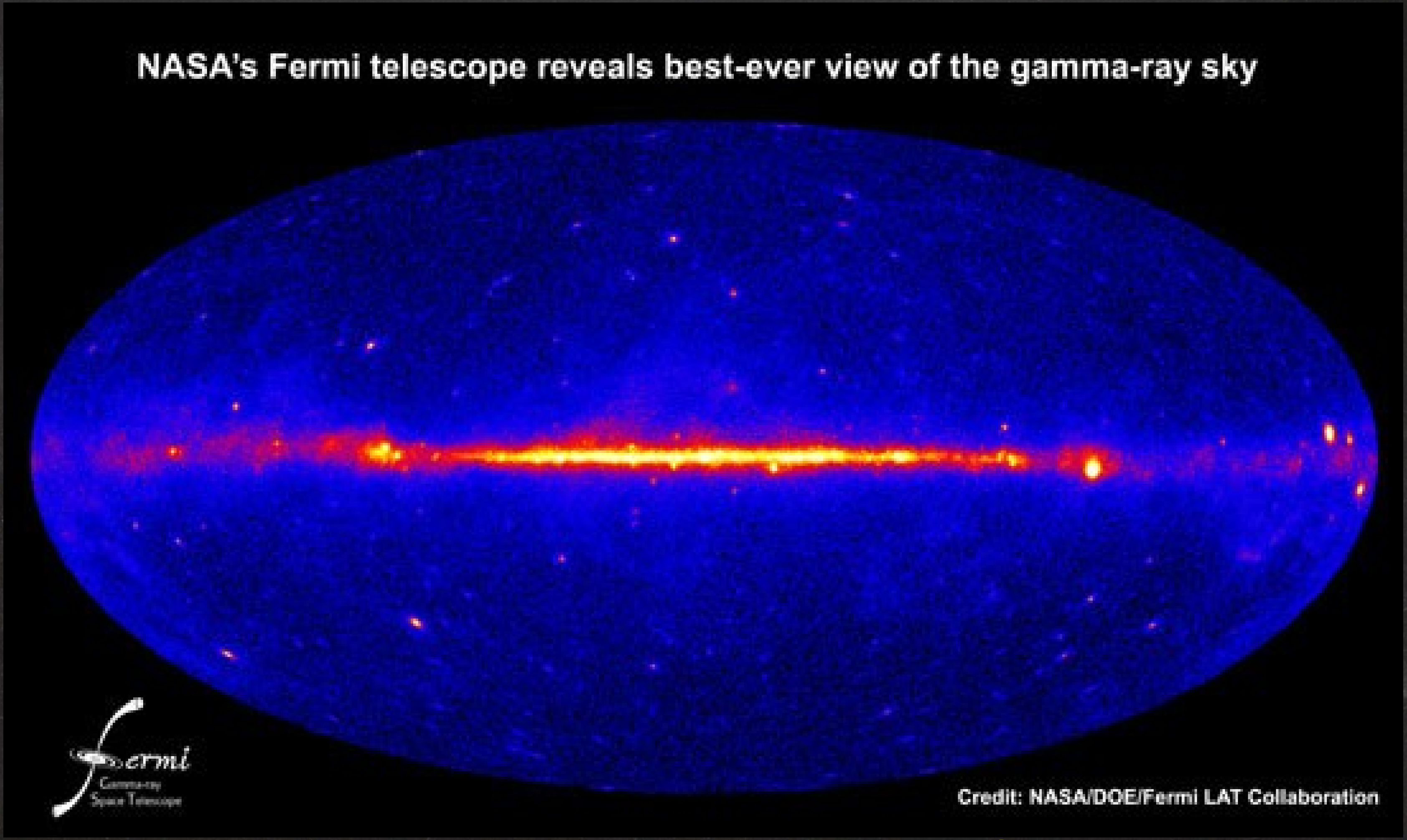
Gamma-ray spectra from DM annihilation

Important contribution from ICS at low energies!



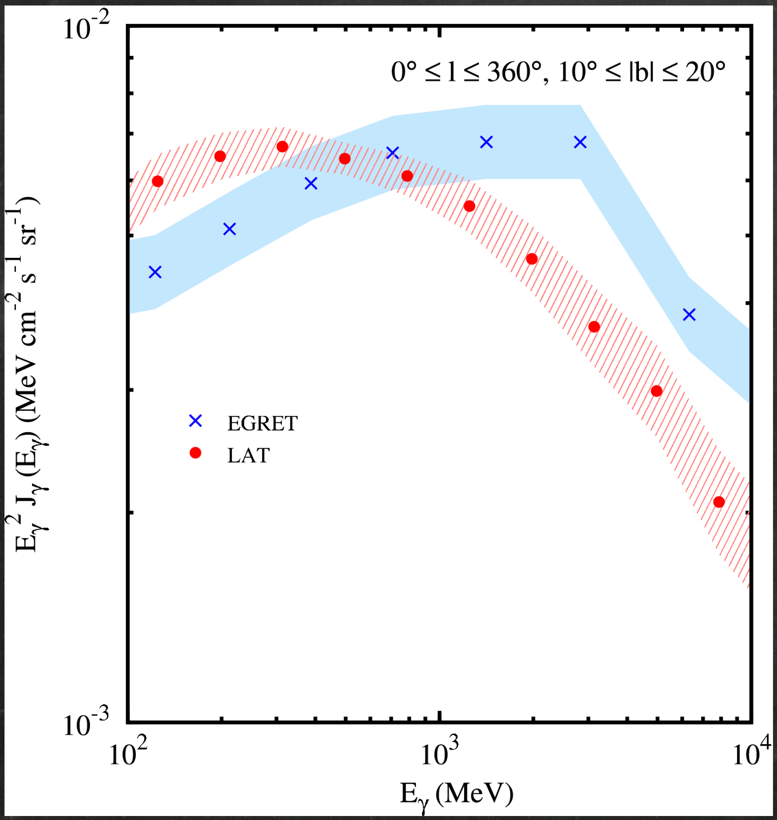
NB and S Palomarez-Ruiz arXiv:1006.0477

Fermi-LAT sky map



AA Abdo [Fermi-LAT collaboration], Astrophys. J. Supp. 188:405, 2010

Galactic backgrounds: Diffuse emission



AA Abdo [Fermi-LAT Collaboration]
Phys. Rev. Lett. 103, 251101, 2009

$$\left(\frac{d\Phi}{dE_\gamma}\right)_{\rm DGE}(E_\gamma, l, b) = N_0(l,b)\left(\frac{E_\gamma}{1\,\rm GeV}\right)^{-\alpha} 10^{-6}\,\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}$$

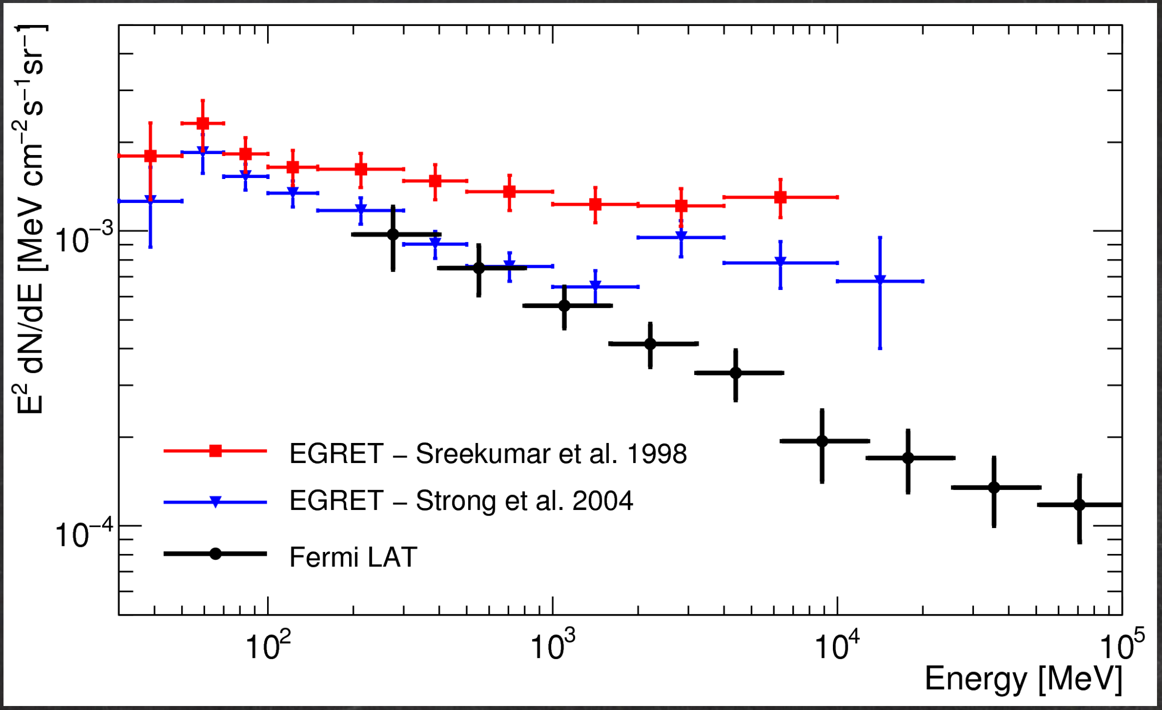
$$N_0(l,b) = \begin{cases} \left(\frac{85.5}{\sqrt{1+(l/35)^2}\sqrt{1+[b/(1.1+0.022\,|l|)]^2}} + 0.5\right) & |l| \ge 30° \\ \left(\frac{85.5}{\sqrt{1+(l/35)^2}\sqrt{1+[b/1.8]^2}} + 0.5\right) & |l| \le 30° \end{cases}$$

L Bergström, P Ullio and JH Bucley
Astropart. Phys. 9, 137, 1997

To fit EGRET at 1 GeV

→ α=2.6

Galactic backgrounds: isotropic backg.

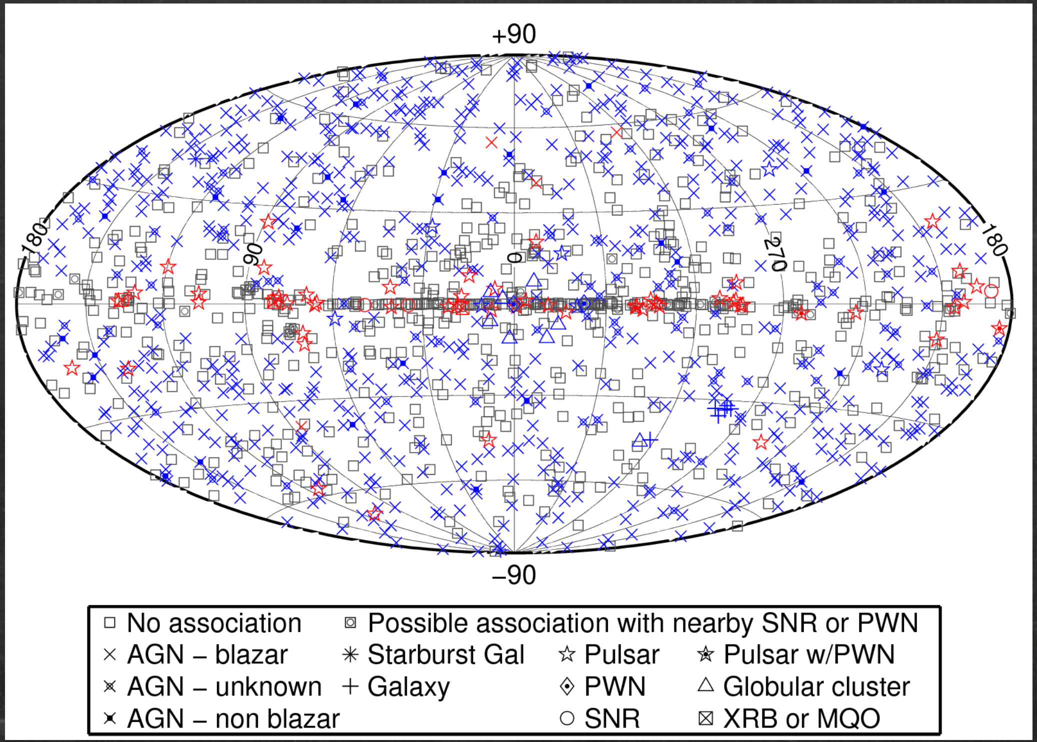


AA Abdo [Fermi-LAT Collaboration], Phys. Rev. Lett. 104,101101, 2010

$$\left(\frac{d\Phi}{dE_\gamma}\right)_{\rm IGRB}(E_\gamma) = 5.65\cdot 10^{-7}\cdot\left(\frac{E_\gamma}{\rm GeV}\right)^{-2.41}\quad {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Galactic backgrounds: point sources

1451 point sources resolved at > 4 σ



AA Abdo [Fermi-LAT Collaboration], Astrophys. J supp . 188:405, 2010

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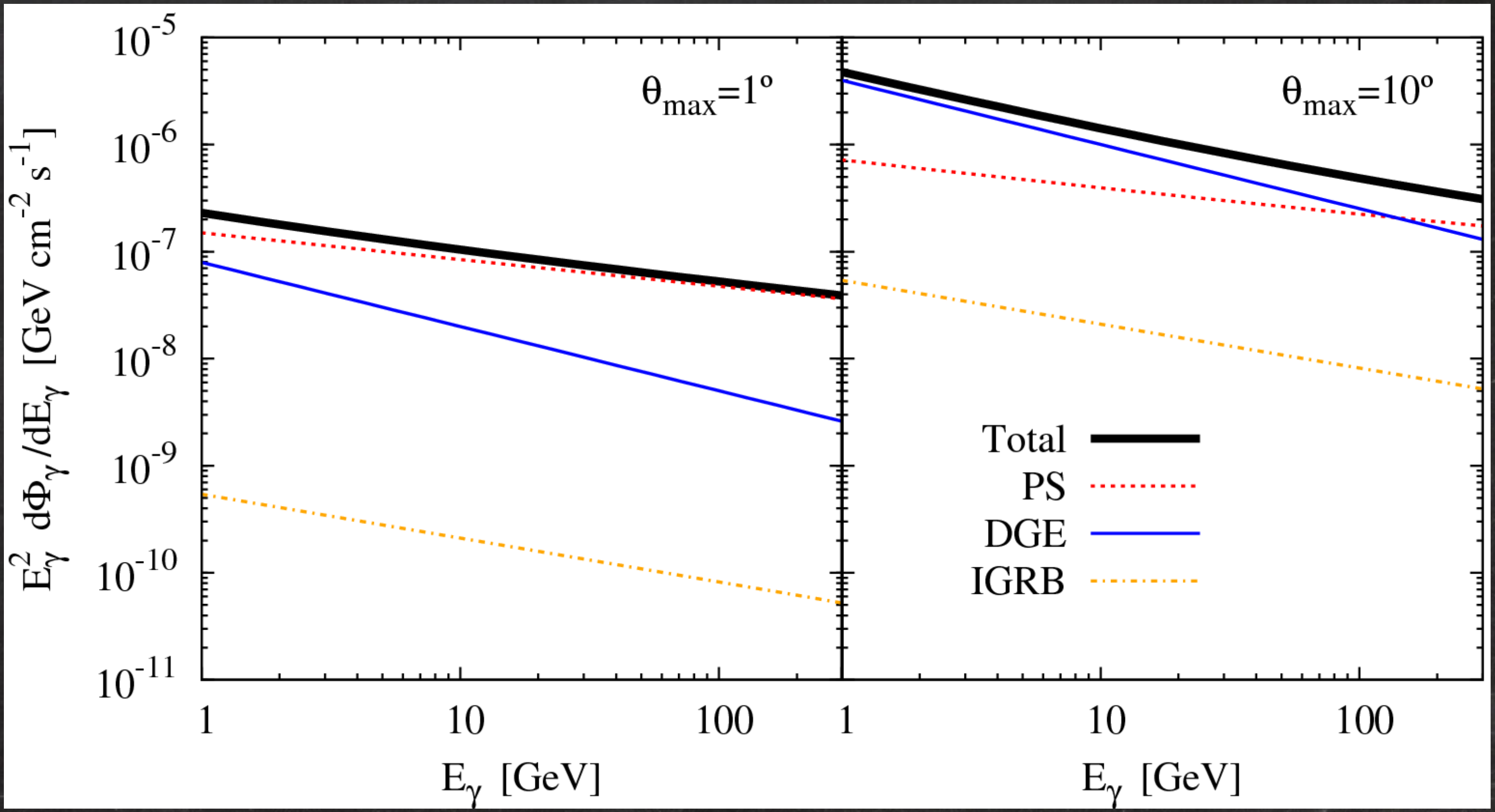


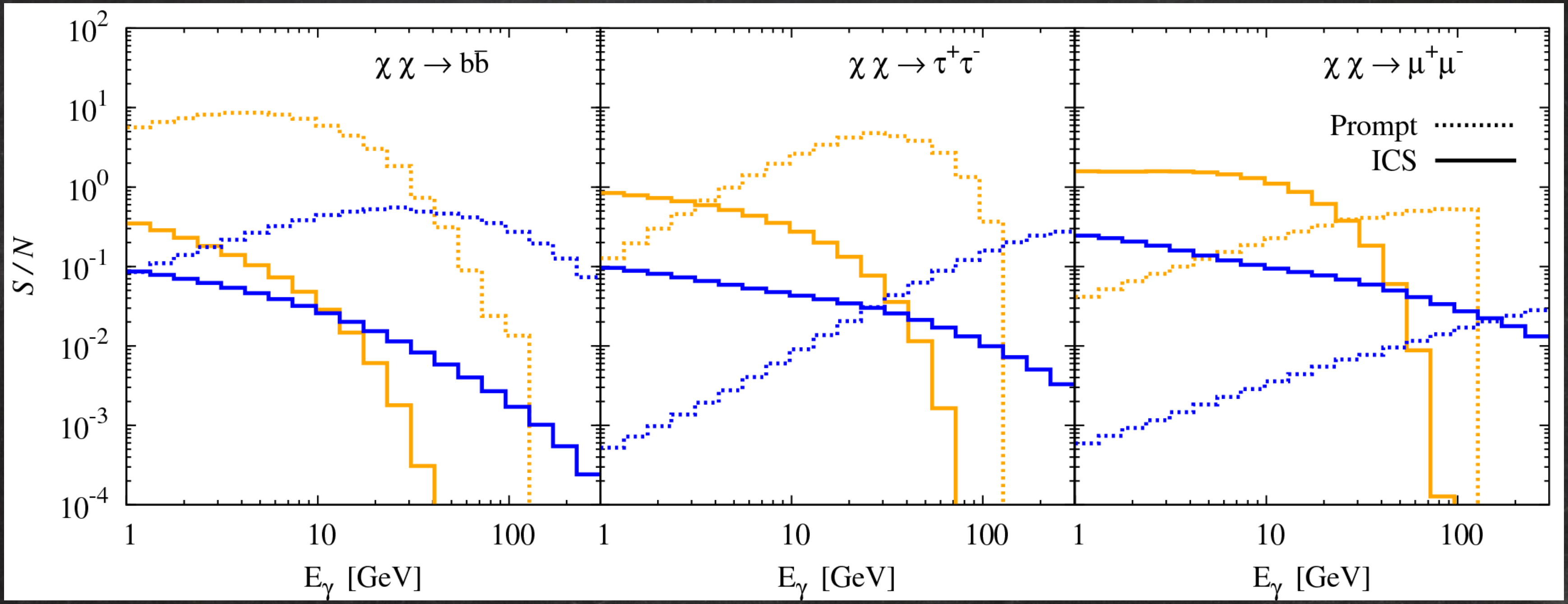
NB and S Palomares-Ruiz, arXiv:1006.0477

Significance of the signal: S/N

Prompt: dominant

Prompt: dominant high E
ICS: dominant low E

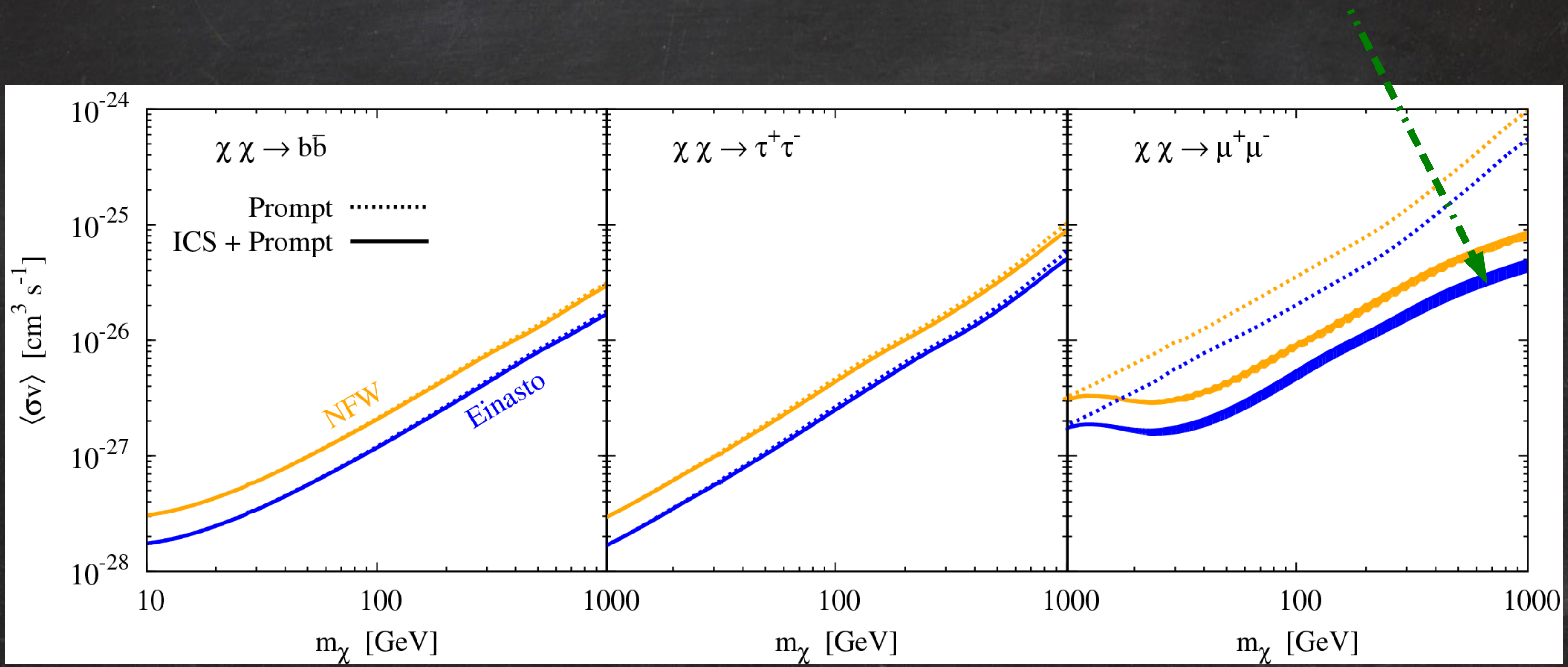
ICS: dominant



NB and S Palomares-Ruiz, arXiv:1006.0477

Fermi-LAT sensitivity to DM annihilations

Uncertanity on the propagation model



NB and S Palomares-Ruiz, arXiv:1006.0477

Constraining DM properties: default setup

* $\Theta_{max} = 10º$

* DM profile: NFW

* $<\sigma v> = 3\ 10^{-26}\ cm^3 / s$

* Propagation model: MED

* “Real data”: $\tau^+ \tau^-$ pairs

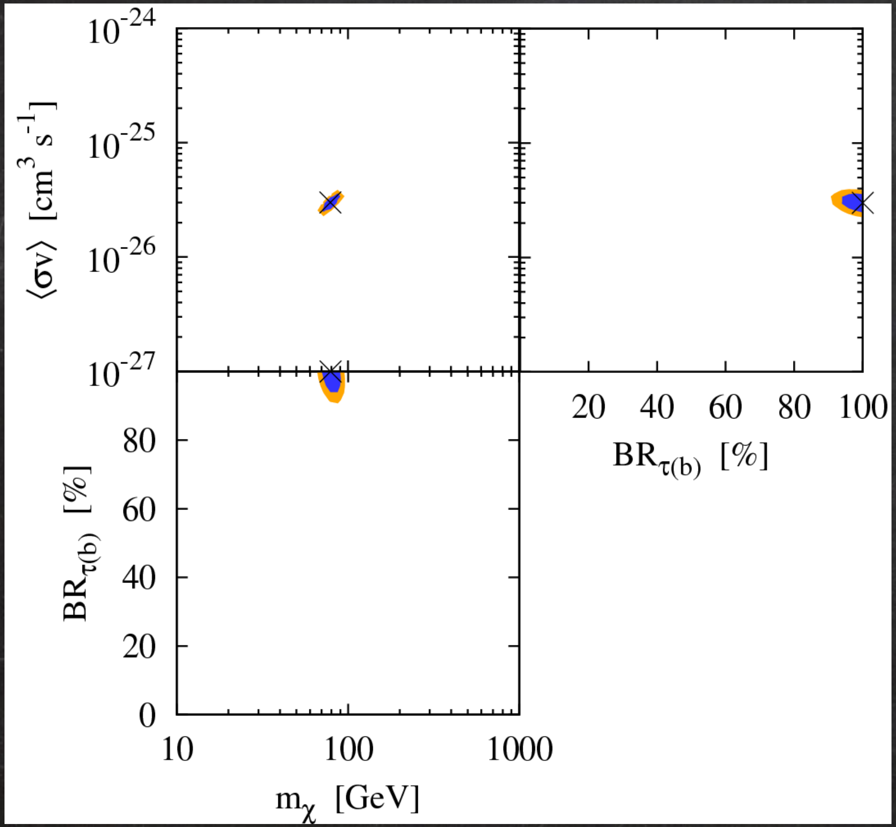
* Signal reconstructed with $\tau^+ \tau^-$ and bb pairs

* Background perfectly known

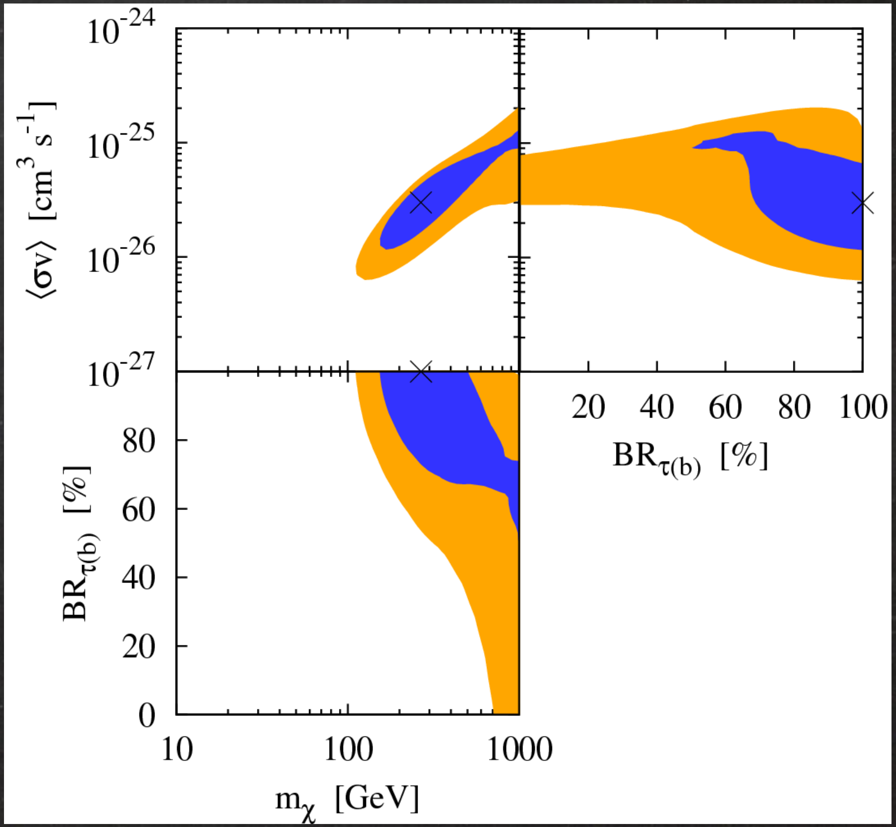
* t = 5 years of data taking

Default setup

m_χ = 80 GeV



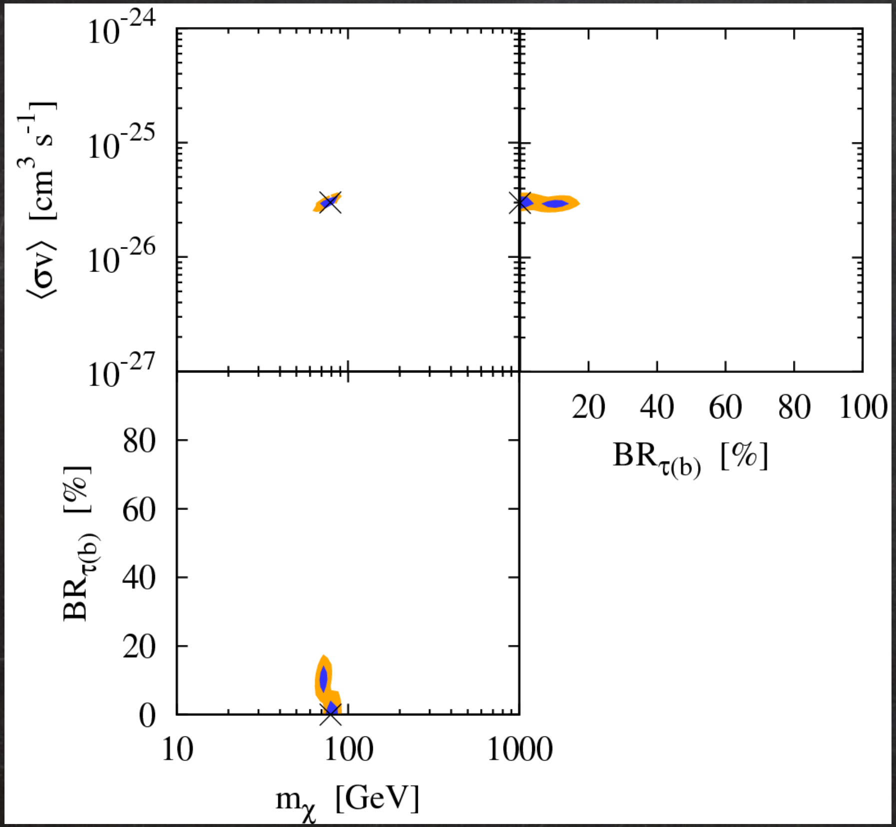
m_χ = 270 GeV



NB and S Palomares-Ruiz, arXiv:1006.0477

Data: bb

m_χ = 80 GeV



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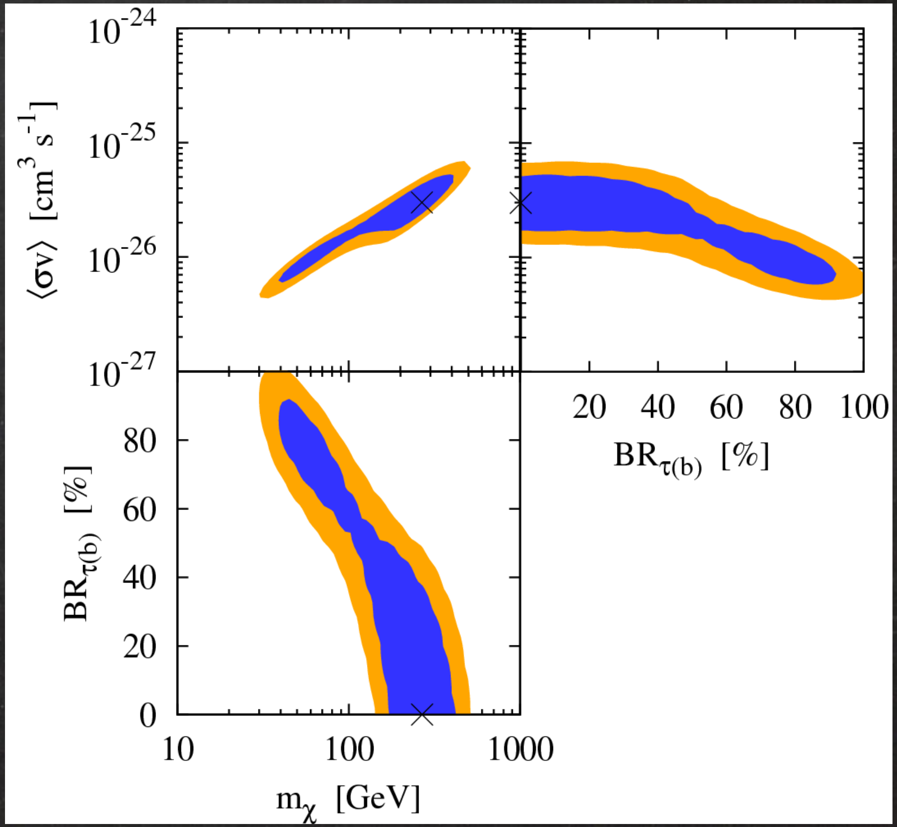
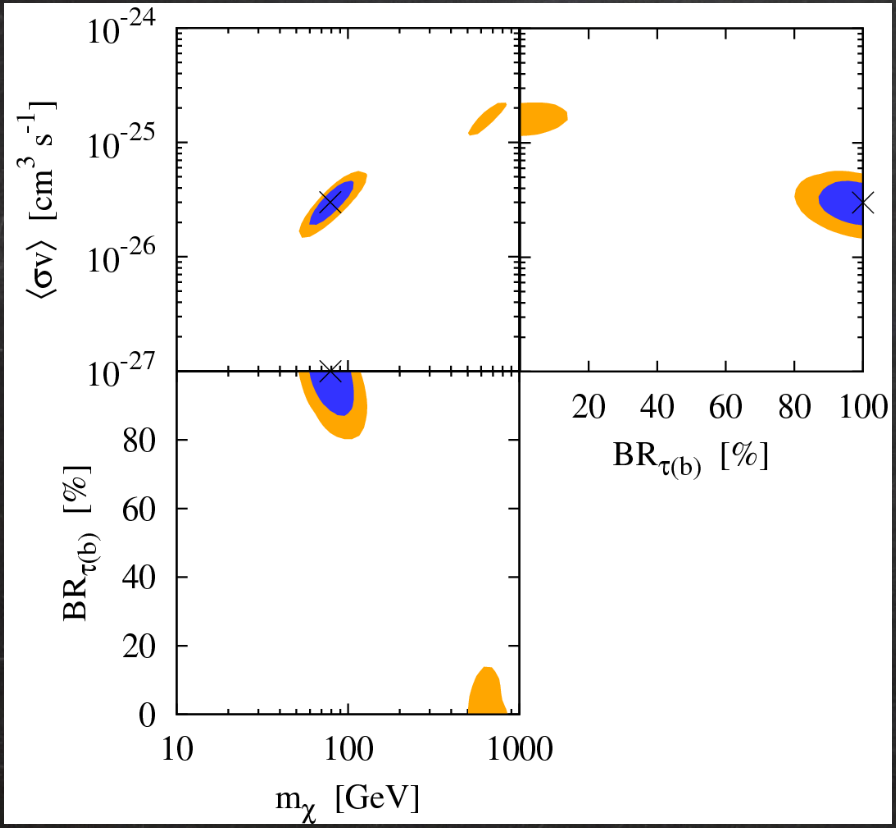


NB and S Palomares-Ruiz, arXiv:1006.0477

Dependence on the observational region

Observational region: 1º around the GC

m_χ = 80 GeV



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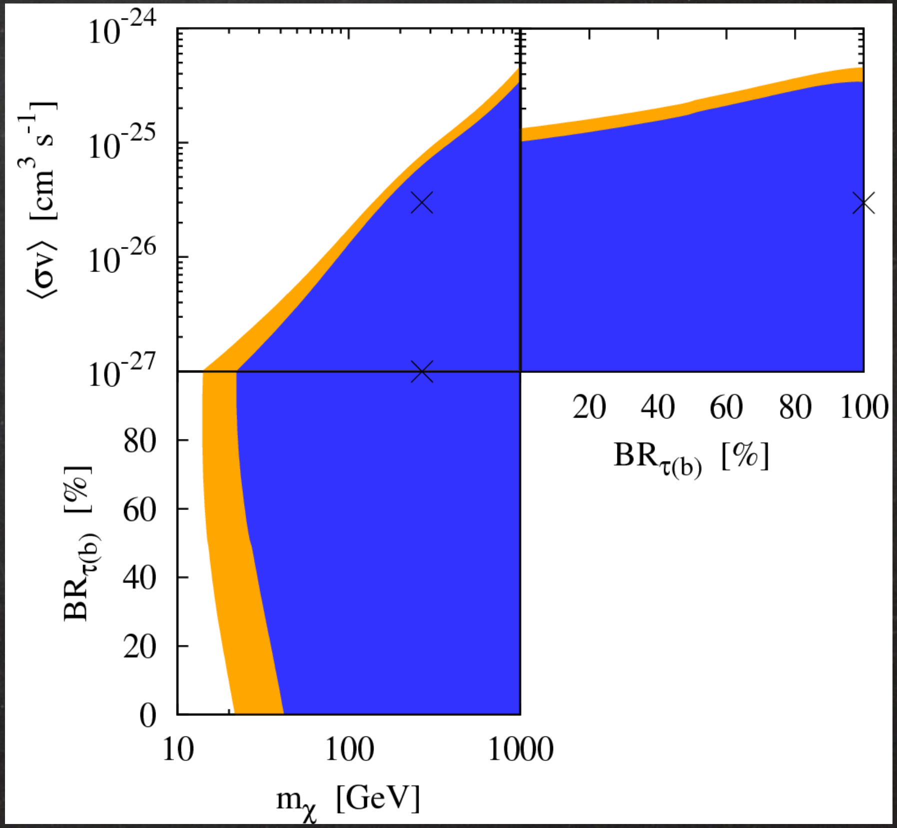

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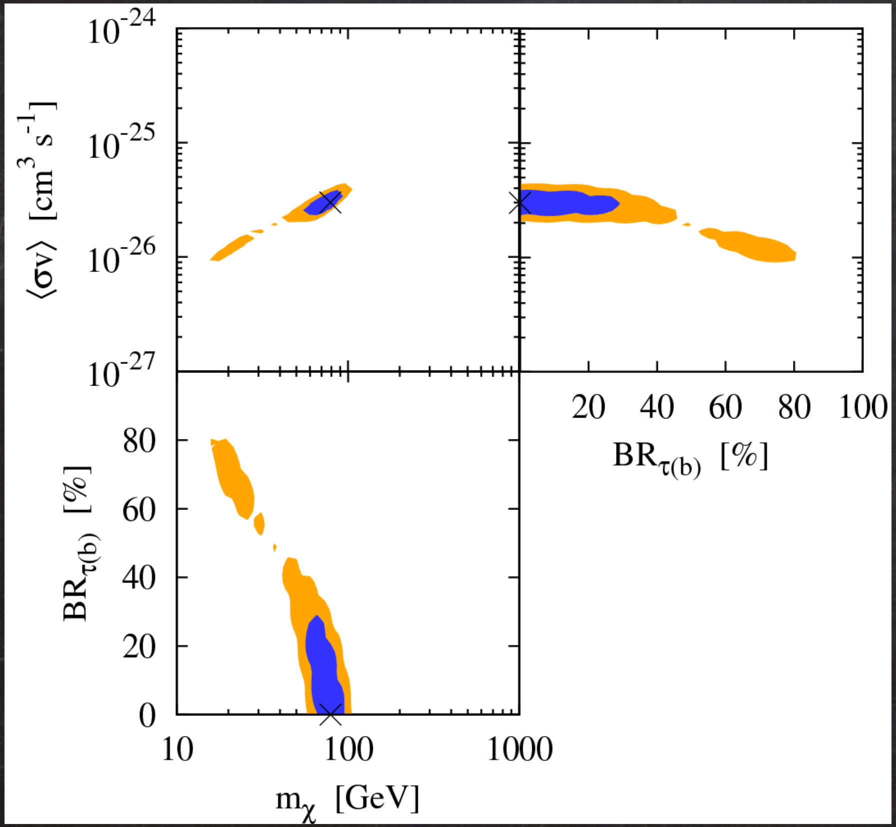

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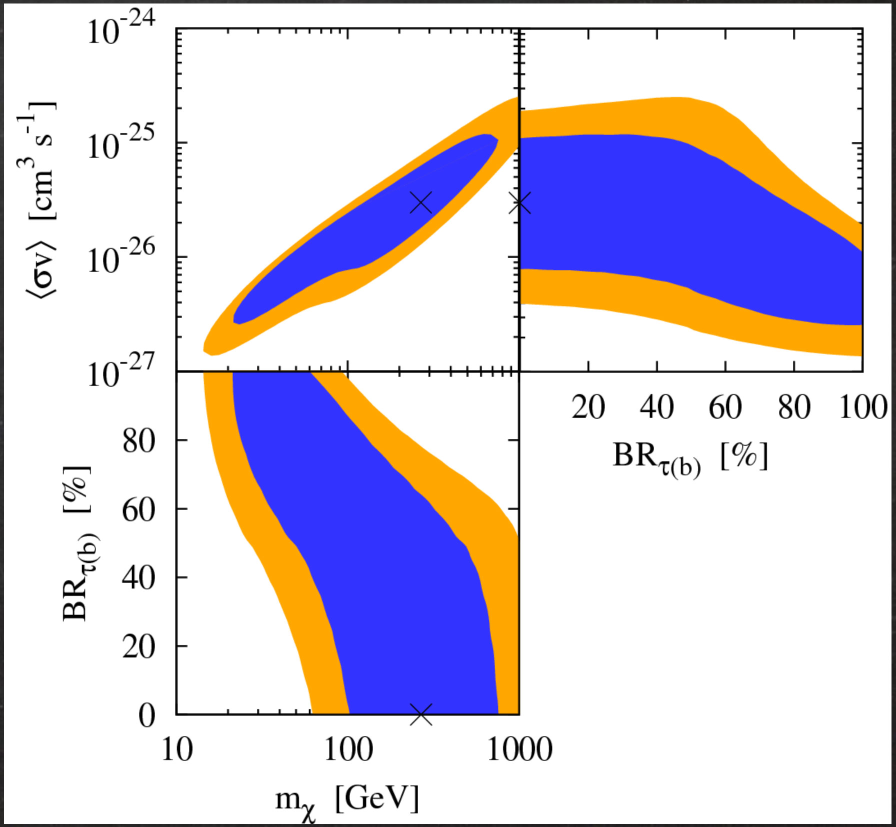
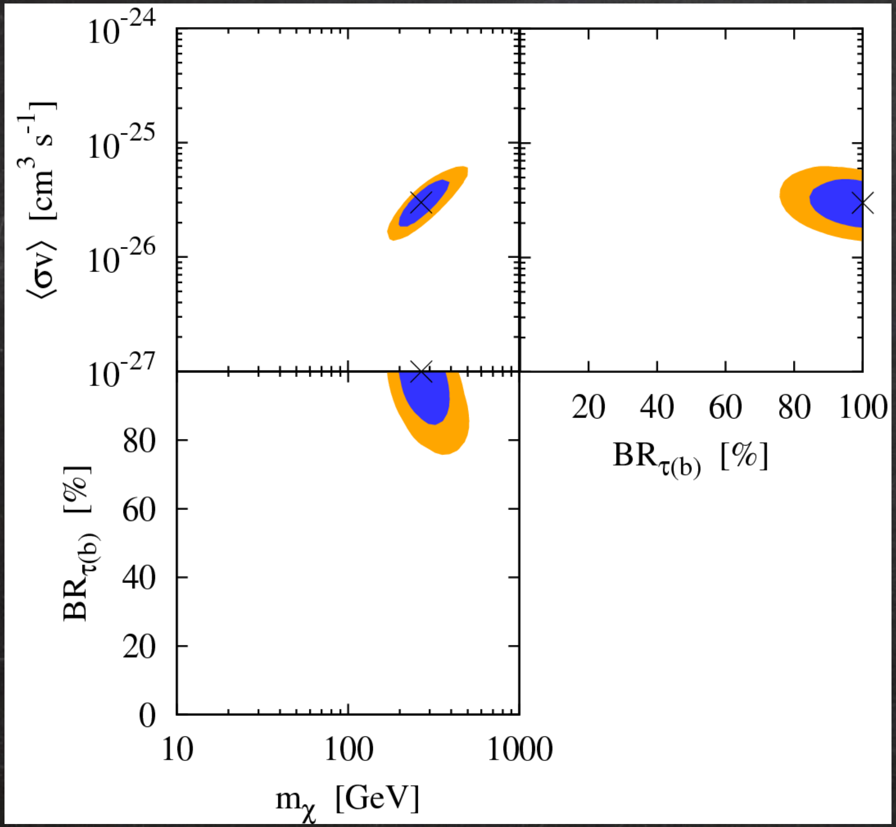


NB and S Palomares-Ruiz, arXiv:1006.0477

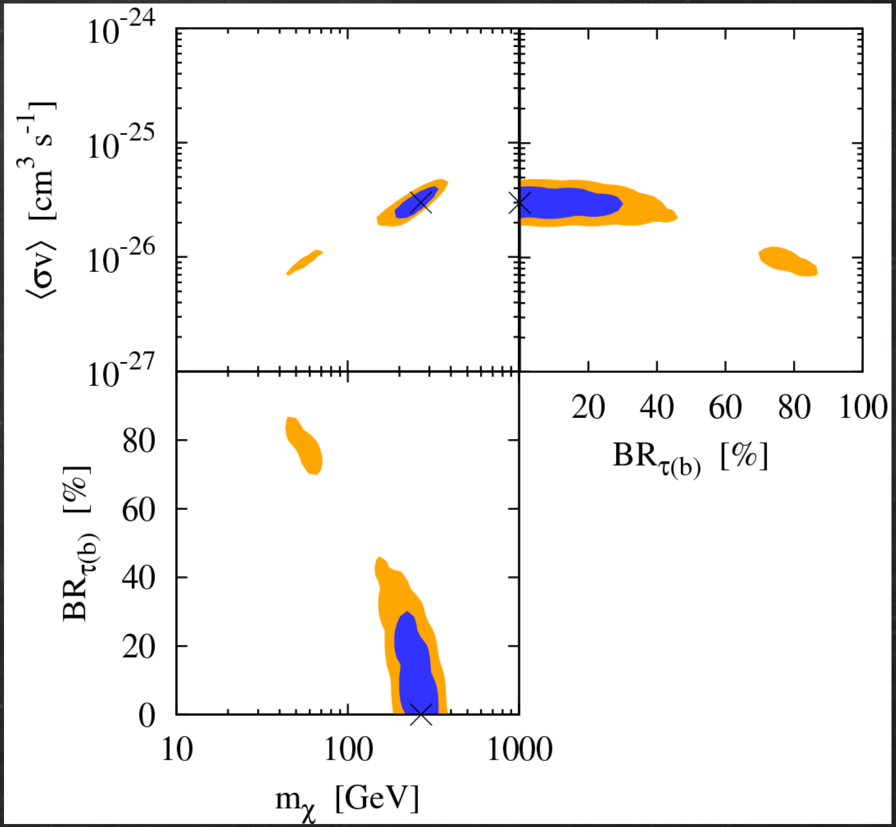
Dependence on the DM density profile

Einasto DM profile
m = 270 GeV

Data: $\tau^+ \tau^-$



Data: bb

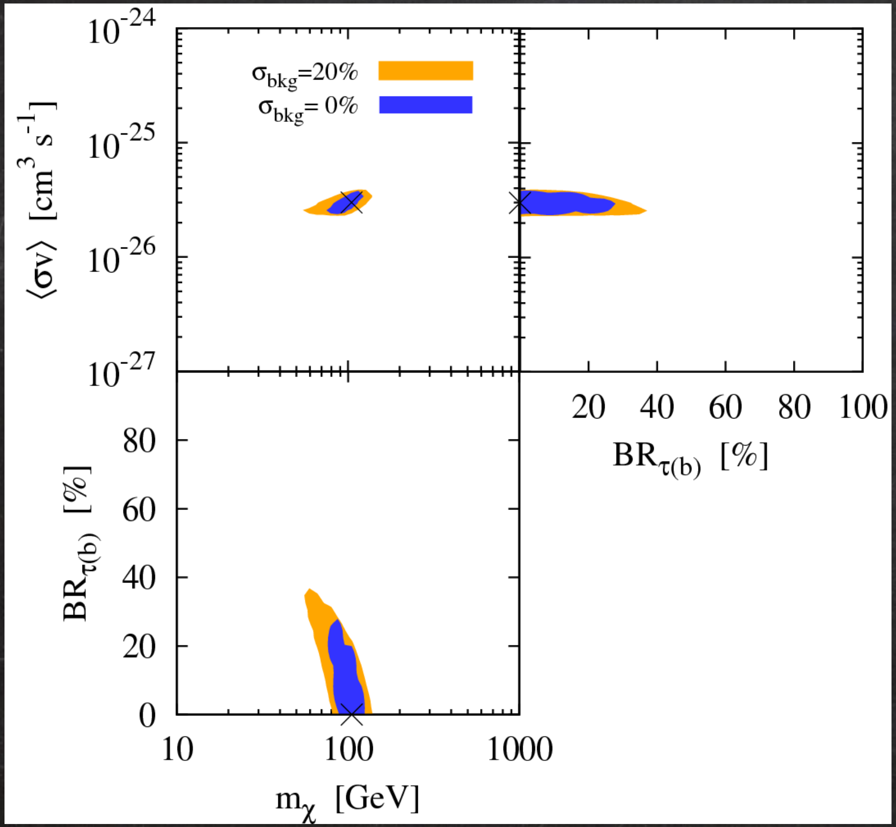


NB and S Palomares-Ruiz, arXiv:1006.0477

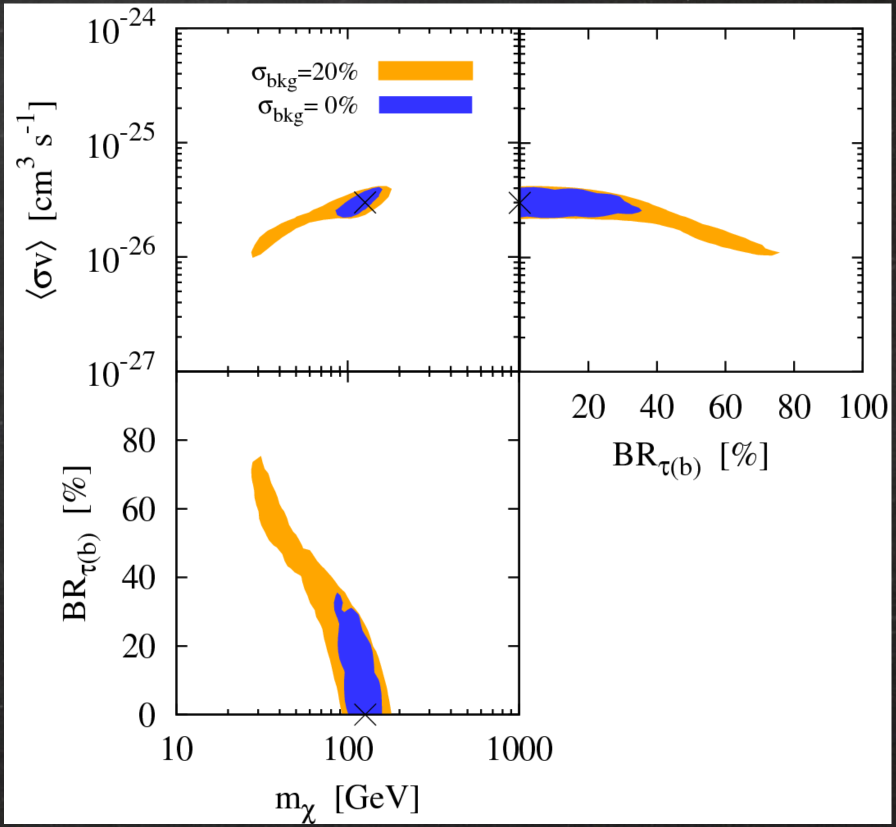
Dependence on systematic errors

Data: bb
Error background: 20%

m_χ = 105 GeV



m_χ = 125 GeV

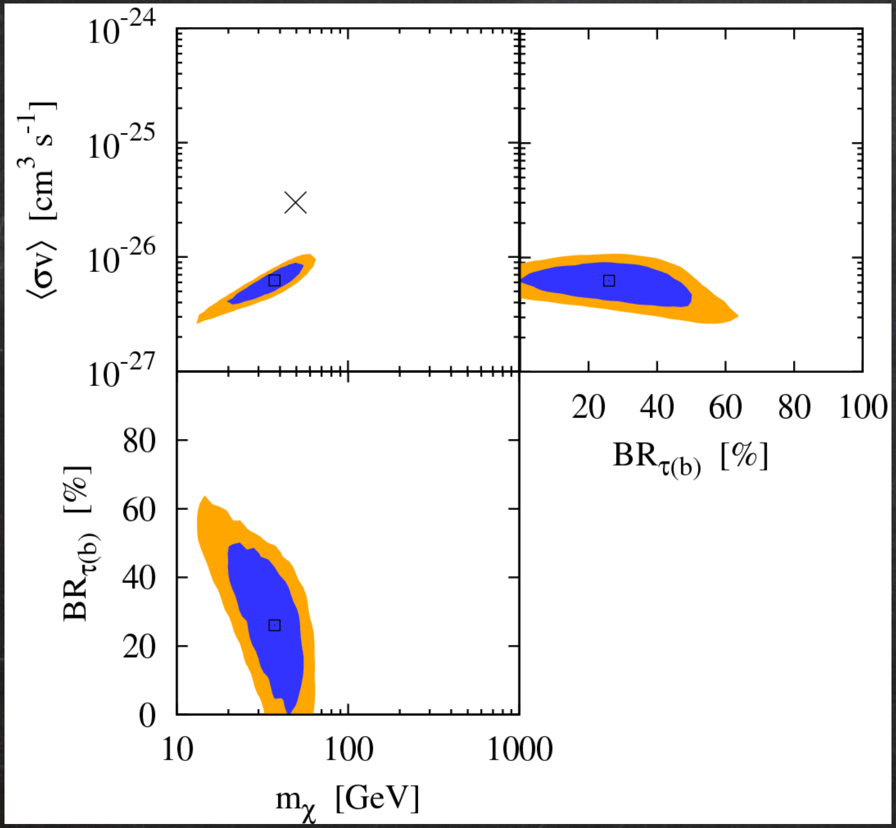


NB and S Palomares-Ruiz, arXiv:1006.0477

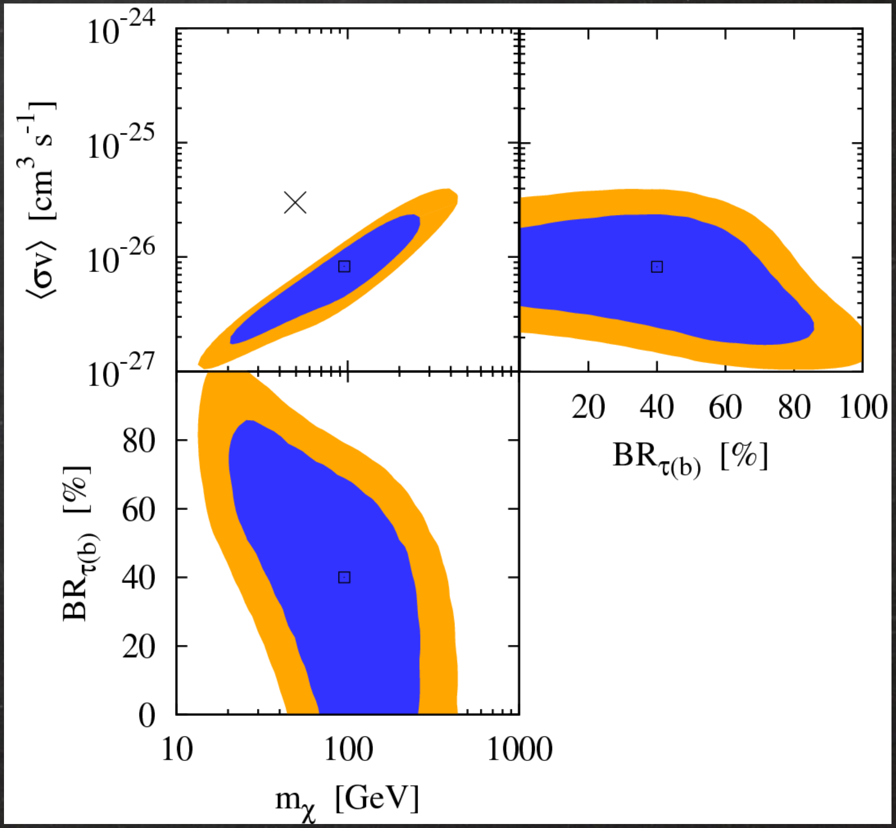
Dependence on the assumed DM model

Data: $\mu^+ \mu^-$

m_χ = 50 GeV



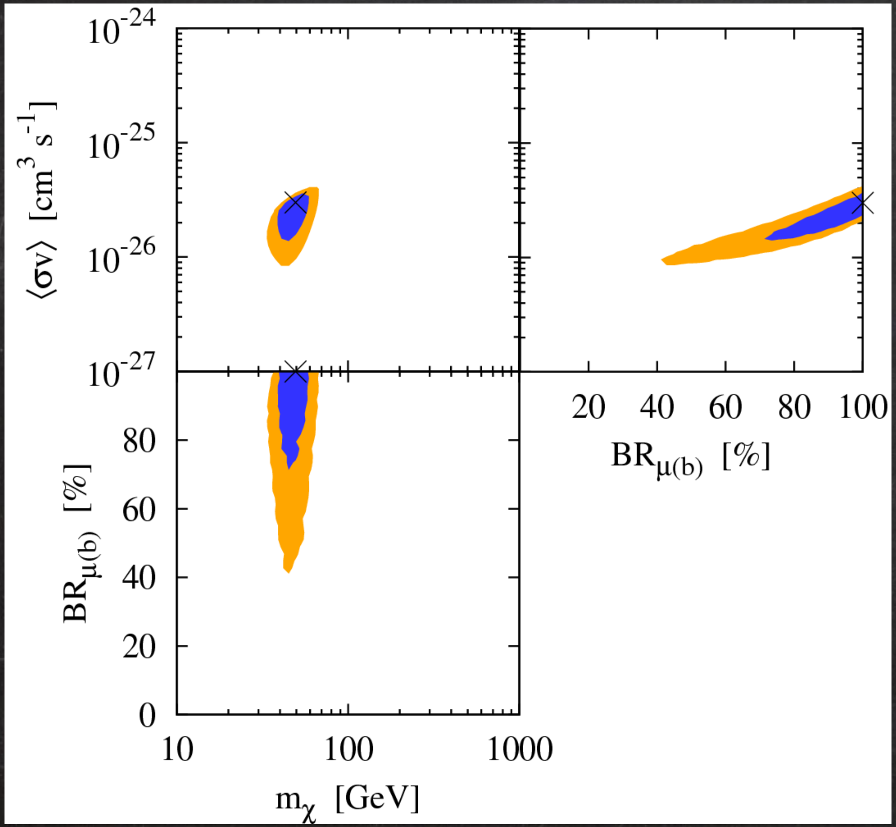
m_χ = 105 GeV



NB and S Palomares-Ruiz, arXiv:1006.0477

Data: $\mu^+ \mu^-$ Simulated: $\mu^+ \mu^-$ / bb
m= 50 GeV

With ICS in the data



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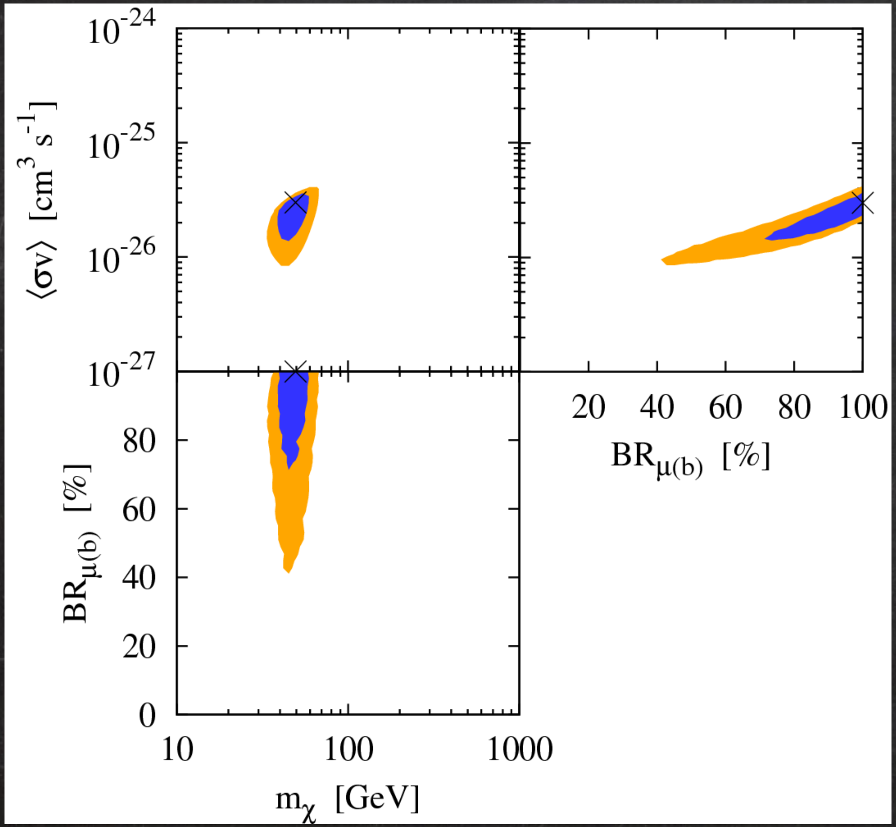
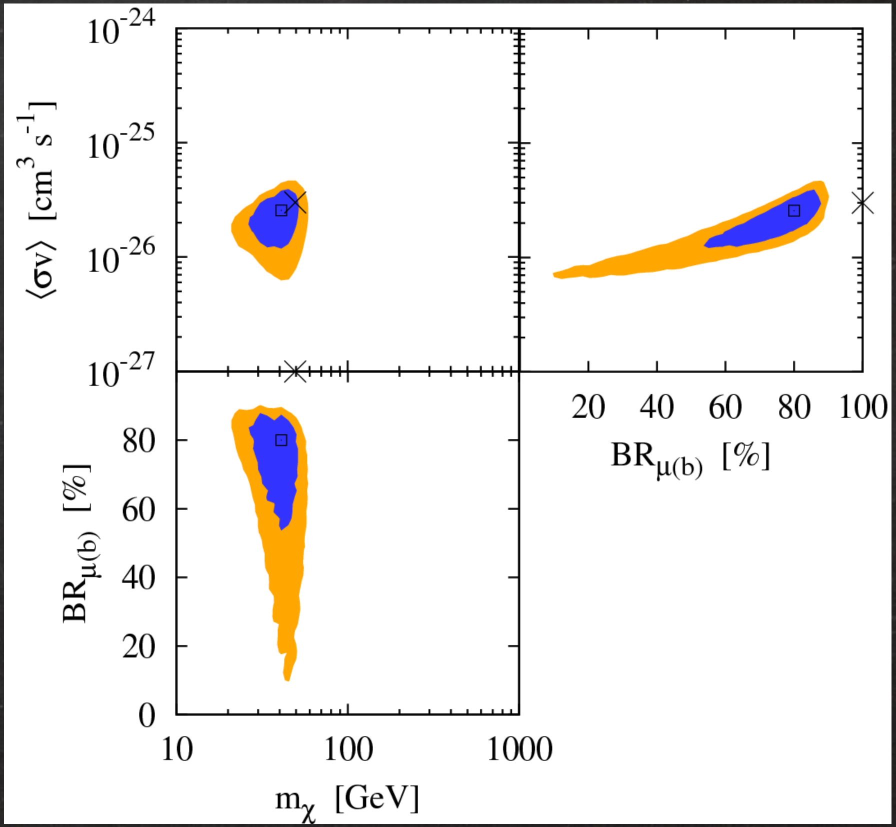
m= 50 GeV

With ICS in the data



Without ICS in the data

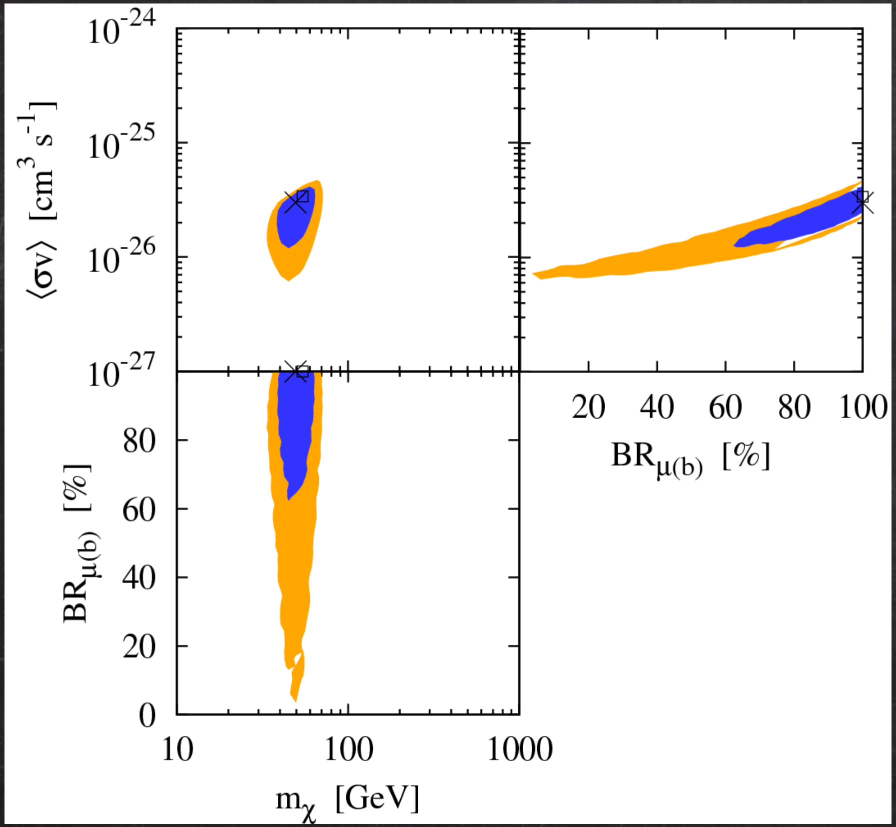


NB and S Palomares-Ruiz, arXiv:1006.0477

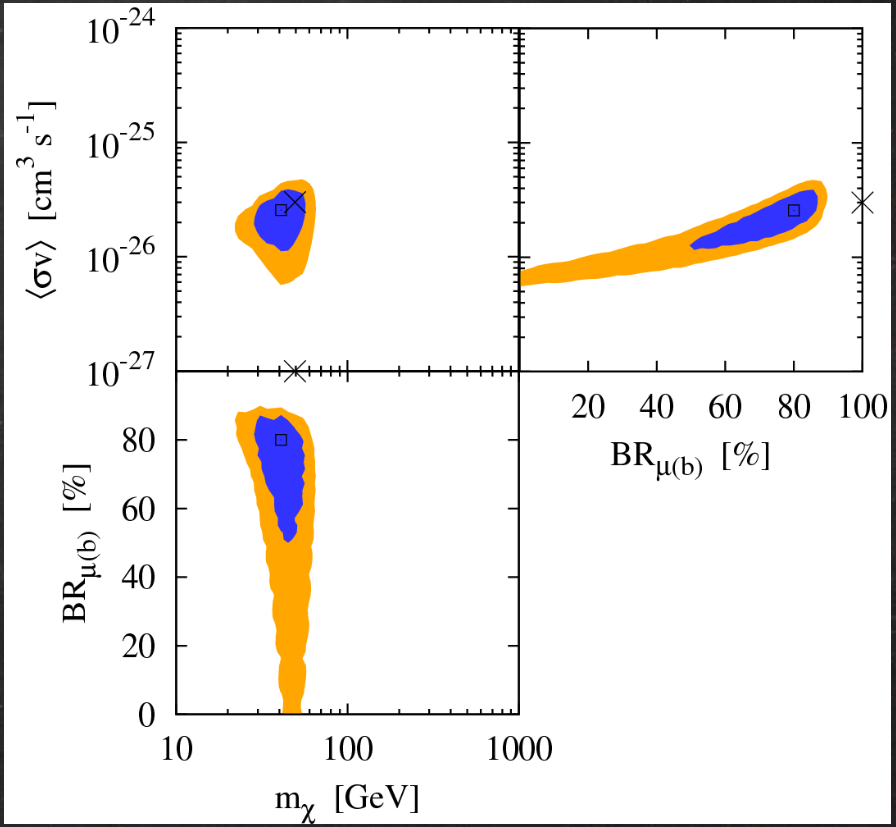
Dependence on the propagation model

Data: $\mu^+\mu^-$; MIN Simulated: $\mu^+\mu^-/bb$; MAX
m= 50 GeV

With ICS



Without ICS



NB and S Palomares-Ruiz, arXiv:1006.0477

Conclusions

* We have studied the abilities of Fermi-LAT, by using current and future observation of gamma-rays from the GC, to constrain some DM properties as annihilation cross section, mass and branching ratio into dominant annihilation channels

* We have included the ICS contribution to the signal spectra, which for some cases turns out to be crucial to get the correct results

* We have used the latest Fermi measurements to simulate the galactic backgrounds

* We have evaluated the sensitivity to DM annihilations: after 5 years and for annhihilations into hadronic channels, Fermi sensitivity is below the benchmark value for the annihilation cross section for thermal dark matter for $m_\chi < 1$ TeV

* We have also studied the dependence on different uncertainties and assumptions

Back up Slides

Electron/Positron propagation in the halo

Three commonly used propagation models corresponding to the minimal, maximal and median primary *positron fluxes* that are compatible with the B/C data

$$\frac{dn_{e^\pm}}{dE}(r_c, z_c, E) = \frac{\beta\,\langle\sigma v\rangle}{2}\left(\frac{\rho(r_c, z_c)}{m_\chi}\right)^2 \frac{E_0\,\tau_E}{E^2}\sum_i \mathrm{BR}_i \int_E^{m_\chi} \frac{dN^i_{e^\pm}}{dE_s}(E_s)\,\tilde{I}(\lambda_D, r_c, z_c)\,dE_s$$

I: all the dependence on the Astro and independent on Particle P.

$$\tilde{I}(\lambda_D, r_c, z_c) = \sum_{i,n=1}^{\infty} J_0\left(\frac{\alpha_i\,r_c}{R_{\rm gal}}\right)\varphi_n(z_c)\,\exp\left[-\left\{\left(\frac{n\,\pi}{2L}\right)^2 + \frac{\alpha_i^2}{R_{\rm gal}^2}\right\}\frac{\lambda_D^2}{4}\right] R_{i,n}(r_c, z_c)$$

Diffusion length: $\lambda_D^2(\epsilon,\, \epsilon_s) = 4\,K_0\,\tau_E\left(\frac{(E/E_0)^{\alpha-1} - (E_s/E_0)^{\alpha-1}}{1-\alpha}\right)$

Baltz & Edsjö Phys. Rev. D59 (1998)
Delahaye, Lineros, Donato & Fornengo Phys Rev. D77 (2008)

$$\nabla\left(K(\vec{x}, E)\,\nabla\frac{dn_e}{dE}(\vec{x}, E)\right) + \frac{\partial}{\partial E}\left(b(\vec{x}, E)\,\frac{dn_e}{dE}(\vec{x}, E)\right) + Q(\vec{x}, E) = 0$$

diffusion energy loss source