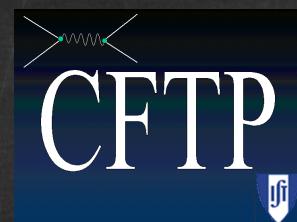


Constraining Dark Matter Properties with Fermi-LAT

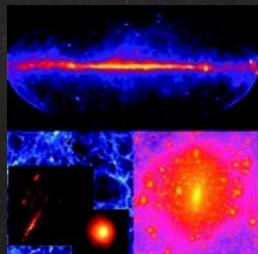
based on NB and S. Palomarez-Ruiz
arXiv:1006.0477

Nicolás BERNAL

Centro de Física Teórica de Partículas
Instituto Superior Técnico, Lisboa



Montpellier, July 26, 2010



IDM 2010
8th International Workshop on
Identification of Dark Matter
University of Montpellier 2
26-30 July 2010
www.lpta.univ-montp2.fr/idm2010



Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

- * The gamma-ray synchrotron signal lies at radio frequencies (at least for typical WIMP DM masses) \longrightarrow irrelevant

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

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

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

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

* Gamma-rays from Inverse Compton Scattering:

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

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

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

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

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

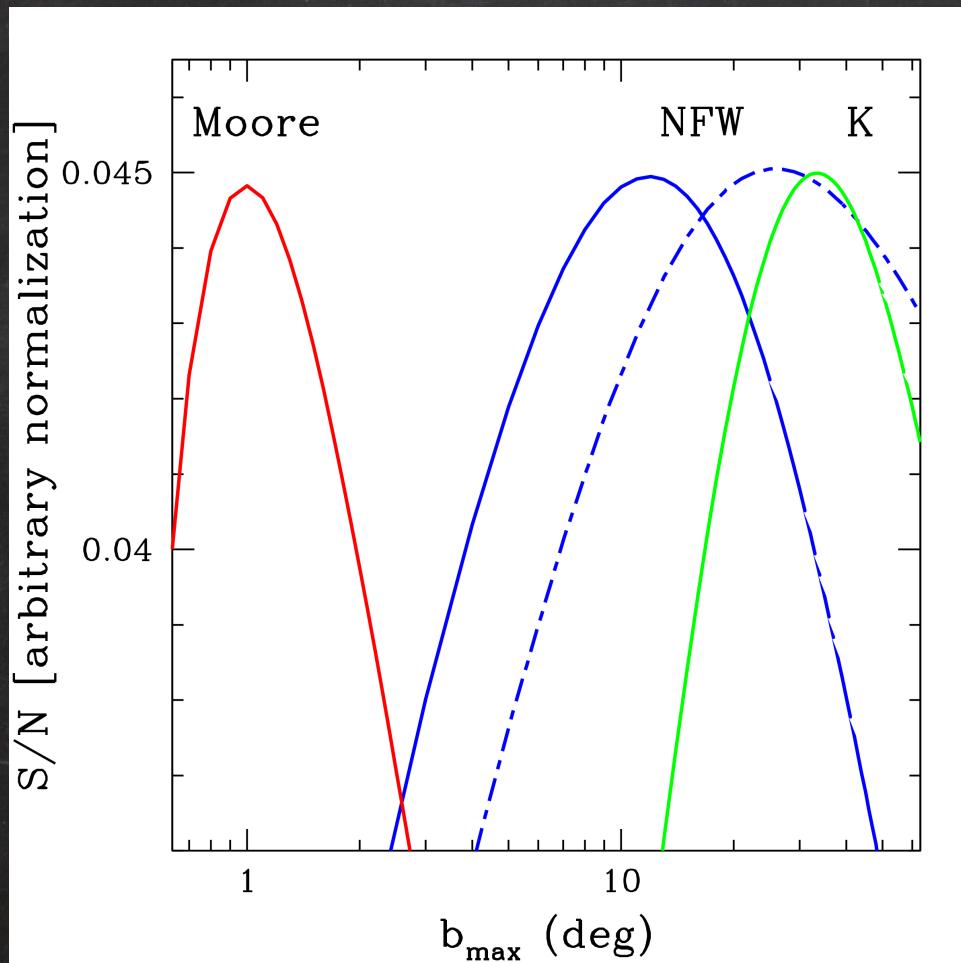
- Superposition of 3 blackbody spectra:
 - SL ($T=0.3$ eV), IR ($T=3.5$ meV), CMB ($T=2.7$ K)

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

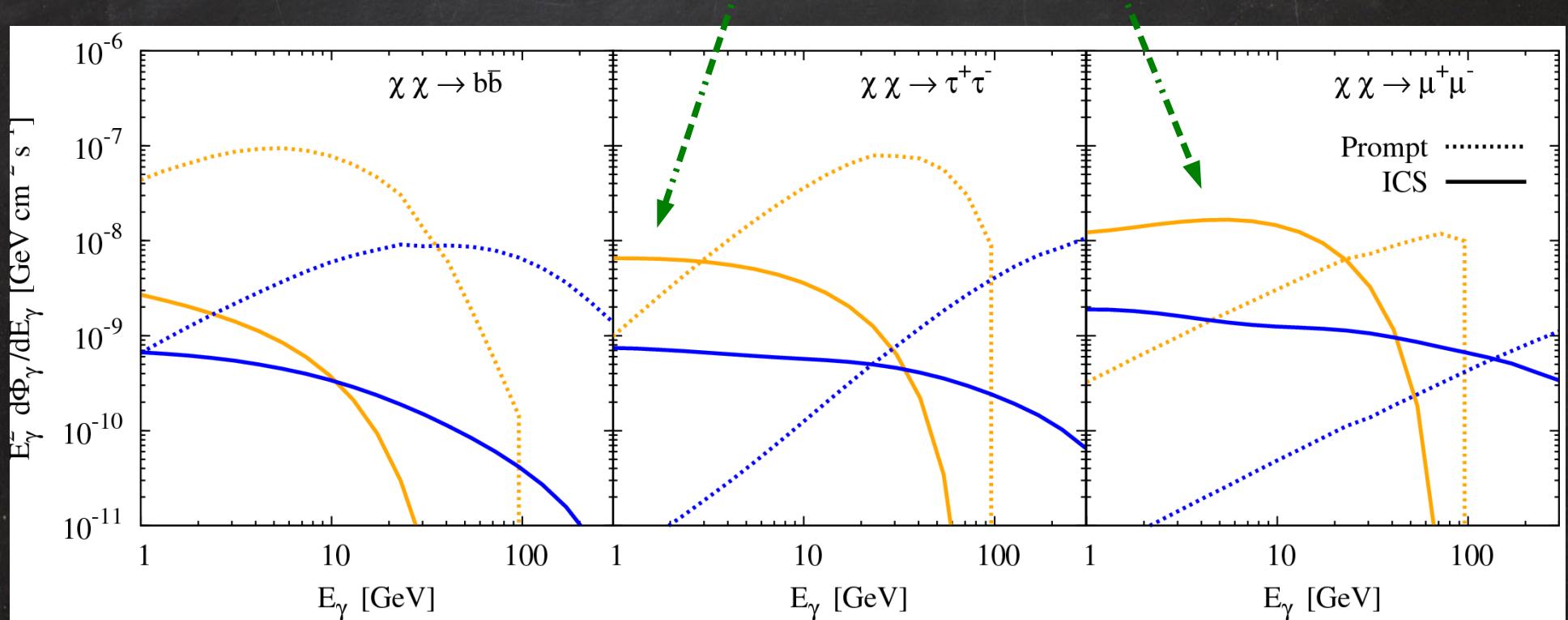


Our selection:
→ 10 degrees

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

Gamma-ray spectra from DM annihilation

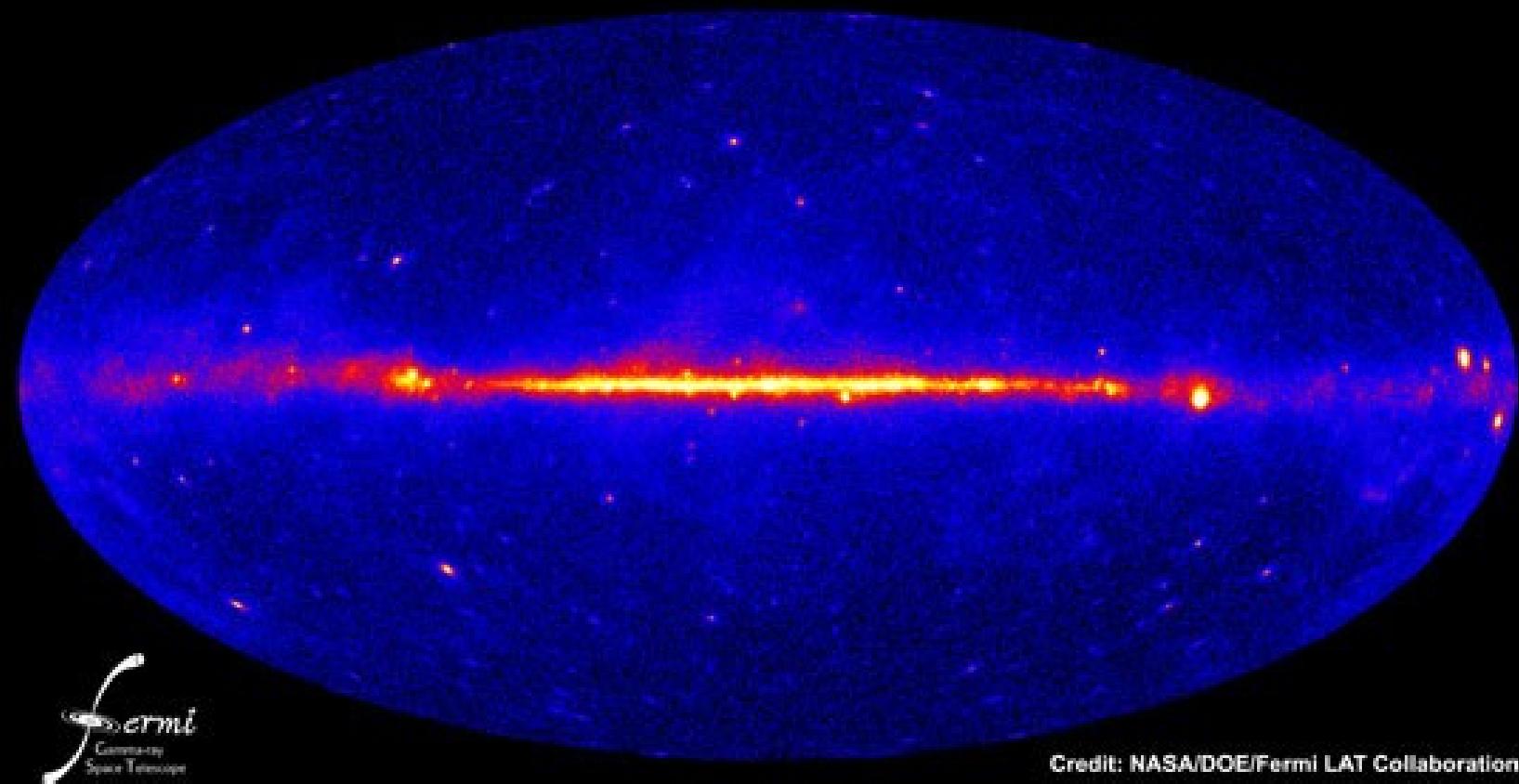
Important contribution from ICS at low energies!



NB and S Palomarez-Ruiz arXiv:1006.0477

Fermi-LAT sky map

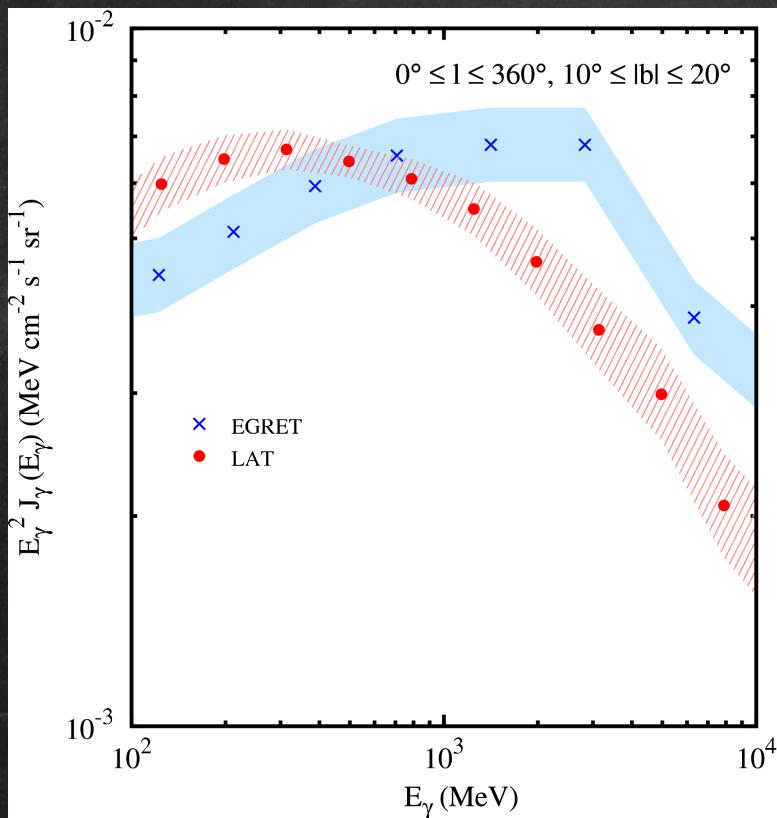
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Credit: NASA/DOE/Fermi LAT Collaboration

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

Galactic backgrounds: Diffuse emission



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

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

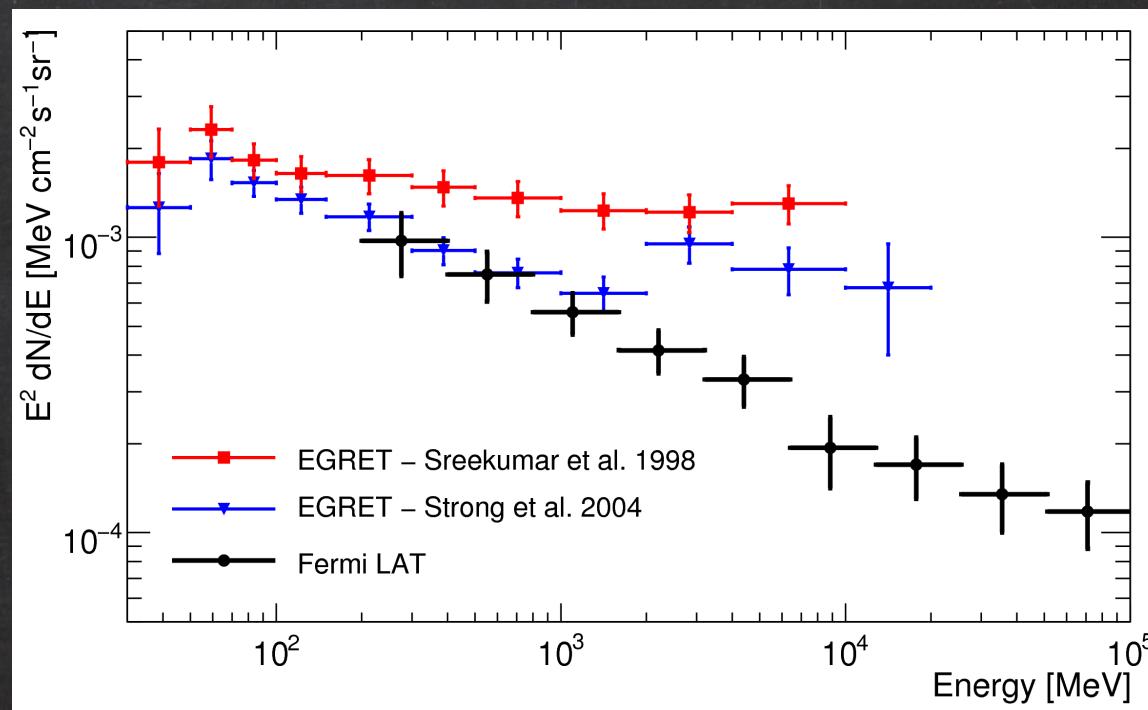
L Bergström, P Ullio and JH Buckley
Astropart. Phys. 9, 137, 1997

To fit EGRET at 1 GeV

→ $\alpha=2.6$

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

Galactic backgrounds: isotropic backg.

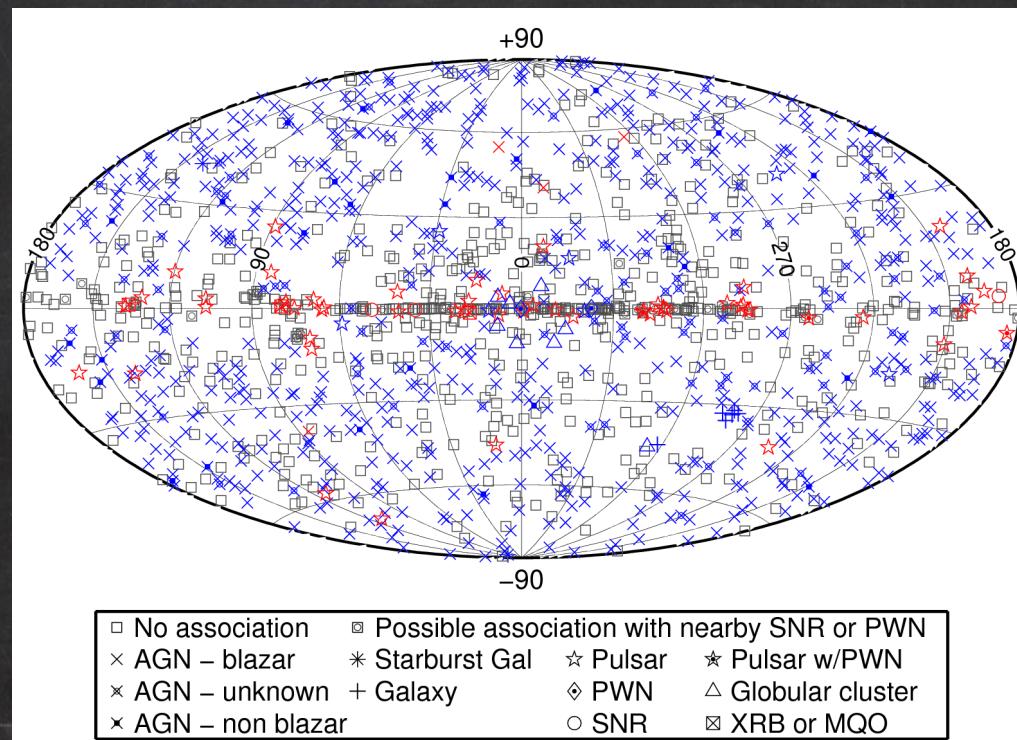


AA Abdo [Fermi-LAT Collaboration], Phys. Rev. Lett. 104, 101101, 2010

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

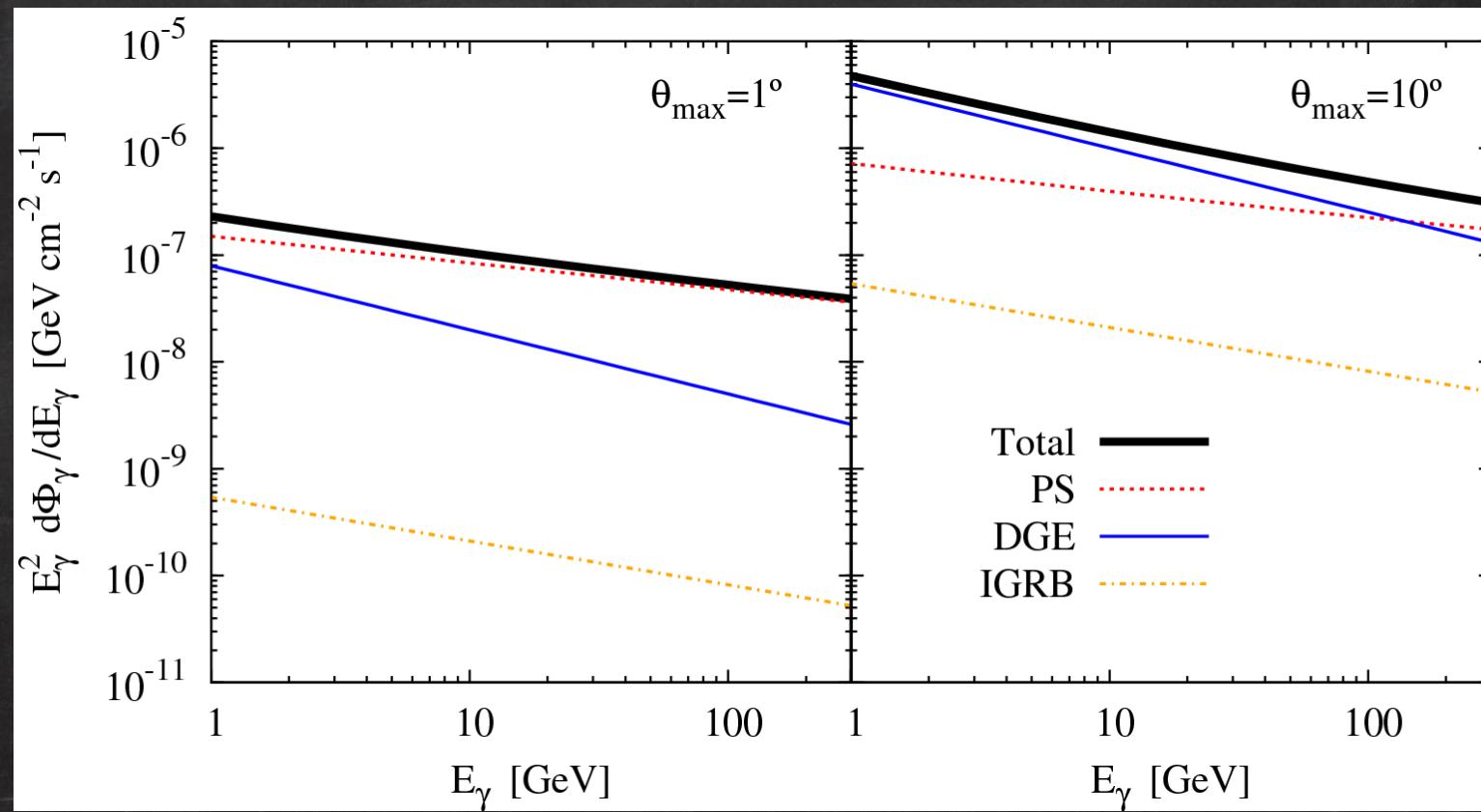
Galactic backgrounds: point sources

1451 point sources resolved at $> 4 \sigma$



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

Galactic backgrounds



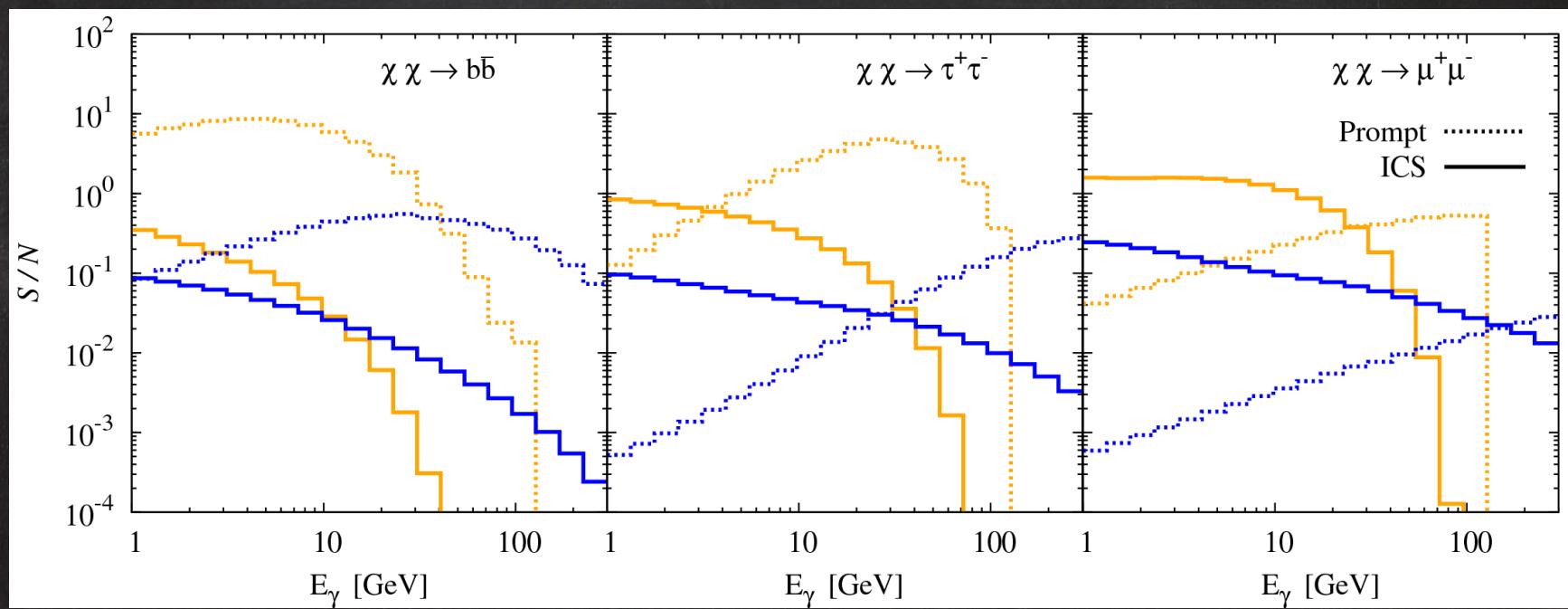
NB and S Palomares-Ruiz, arXiv:1006.0477

Significance of the signal: S/N

Prompt: dominant

Prompt: dominant high E
ICS: dominant low E

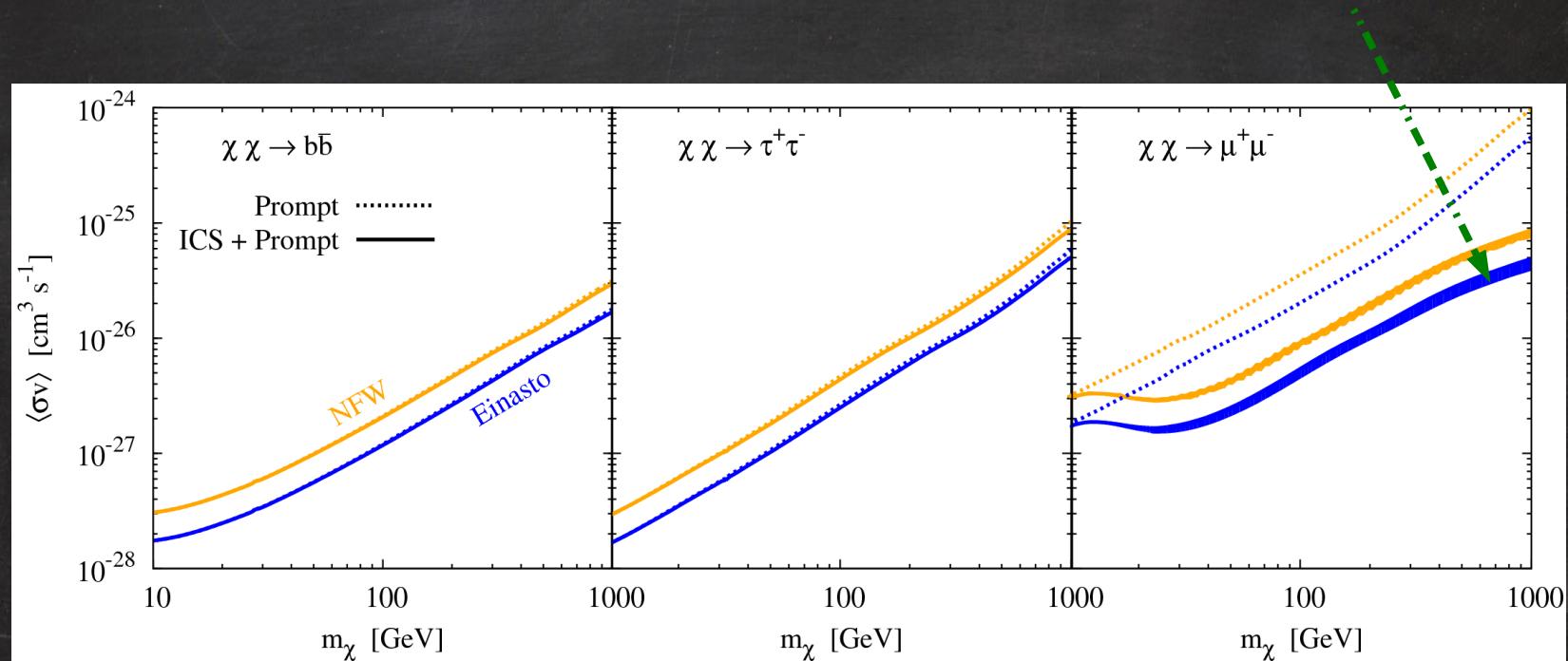
ICS: dominant



NB and S Palomares-Ruiz, arXiv:1006.0477

Fermi-LAT sensitivity to DM annihilations

Uncertainty on the propagation model

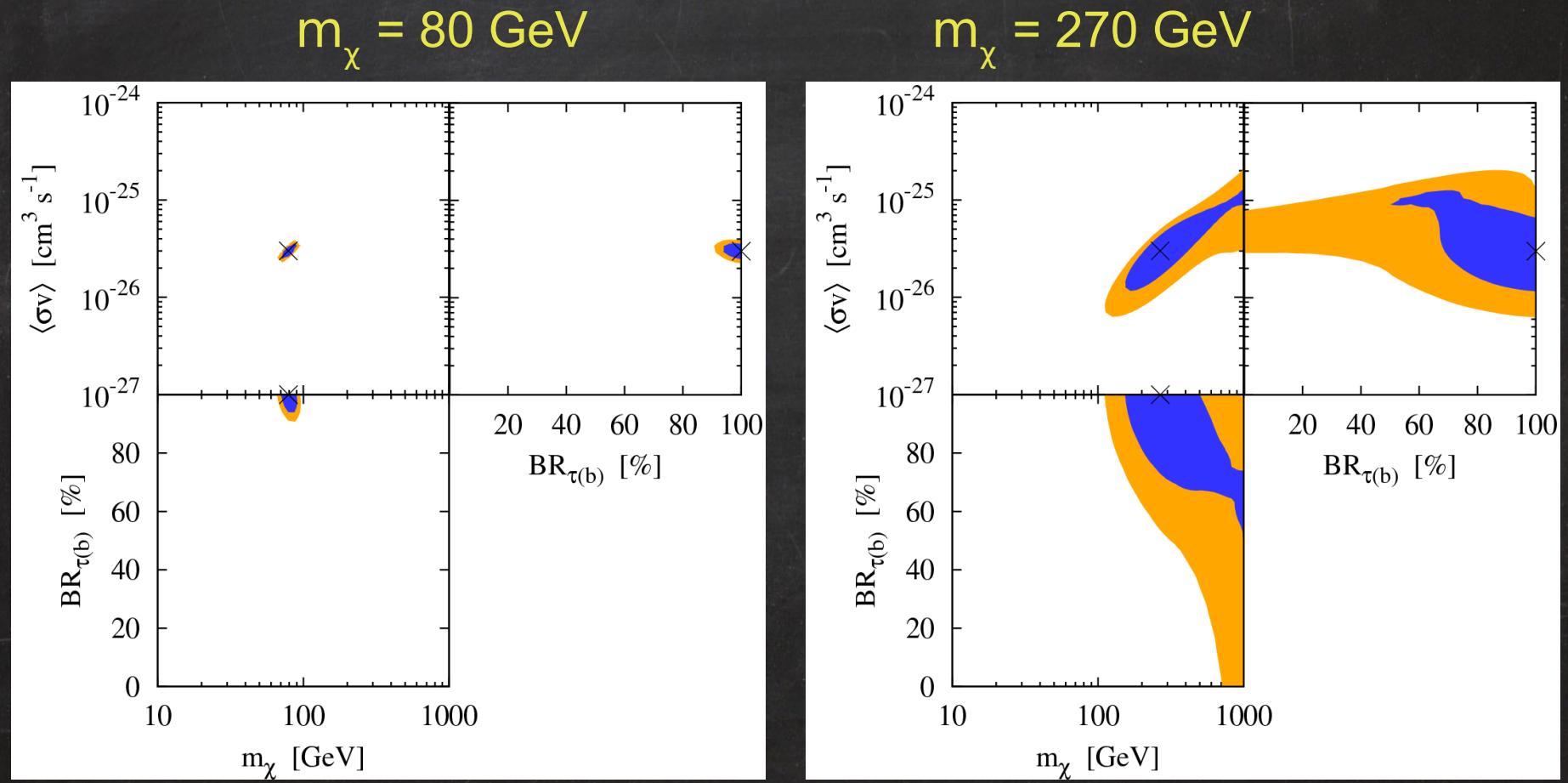


NB and S Palomares-Ruiz, arXiv:1006.0477

Constraining DM properties: default setup

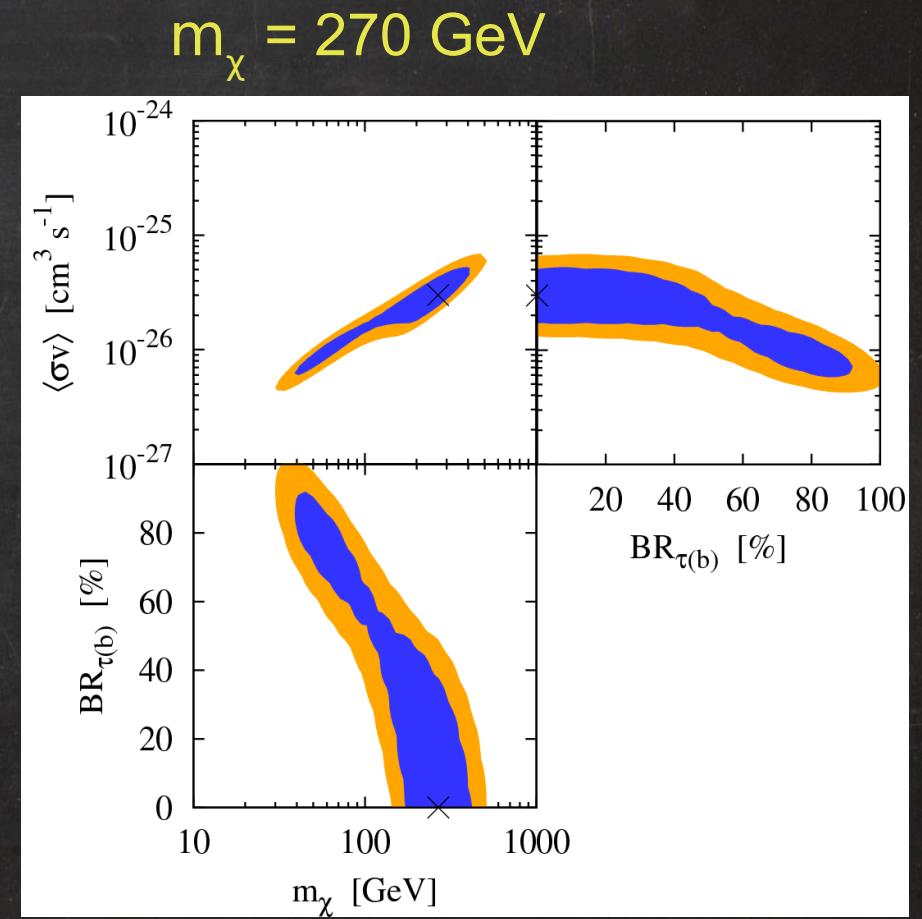
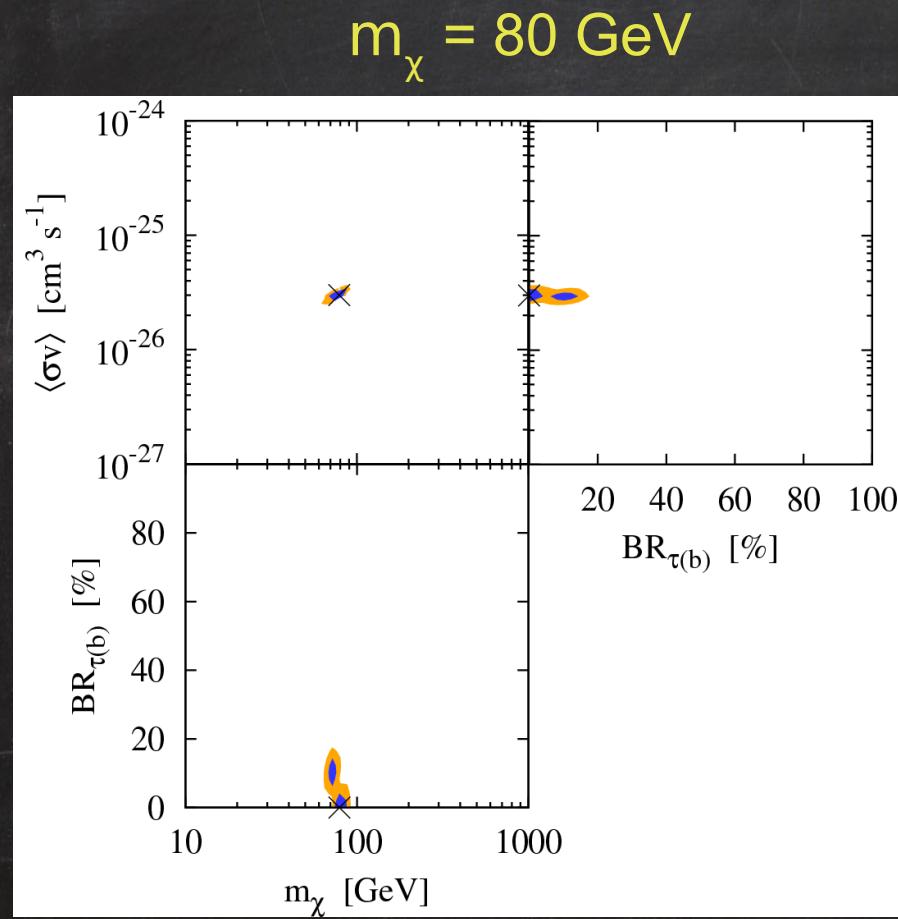
- * $\Theta_{\max} = 10^\circ$
- * DM profile: NFW
- * $\langle \sigma v \rangle = 3 \cdot 10^{-26} \text{ cm}^3 / \text{s}$
- * Propagation model: MED
- * “Real data”: $\tau^+ \tau^-$ pairs
- * Signal reconstructed with $\tau^+ \tau^-$ and bb pairs
- * Background perfectly known

Default setup



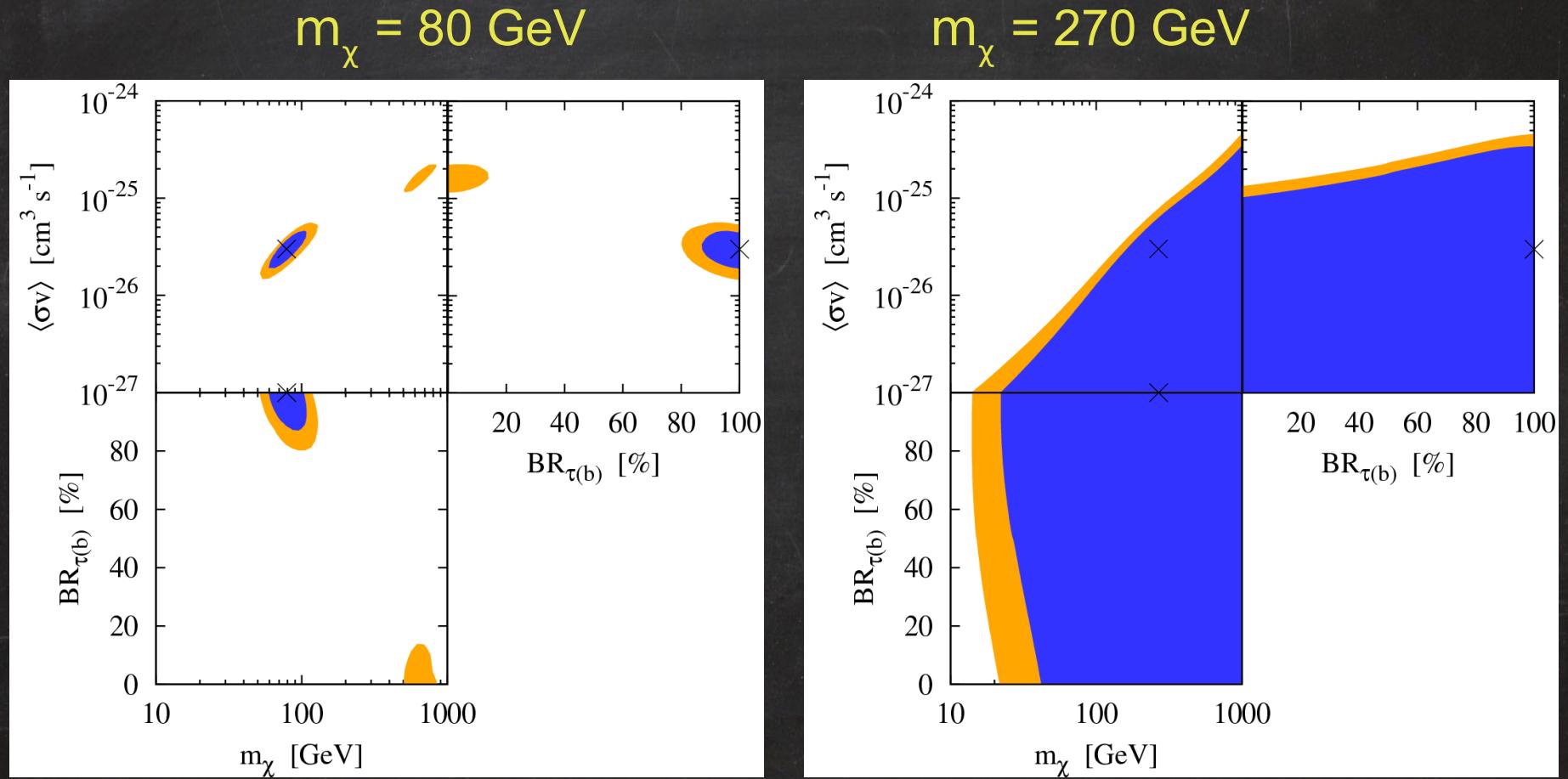
NB and S Palomares-Ruiz, arXiv:1006.0477

Data: bb



NB and S Palomares-Ruiz, arXiv:1006.0477

Observational region: 1° around the GC

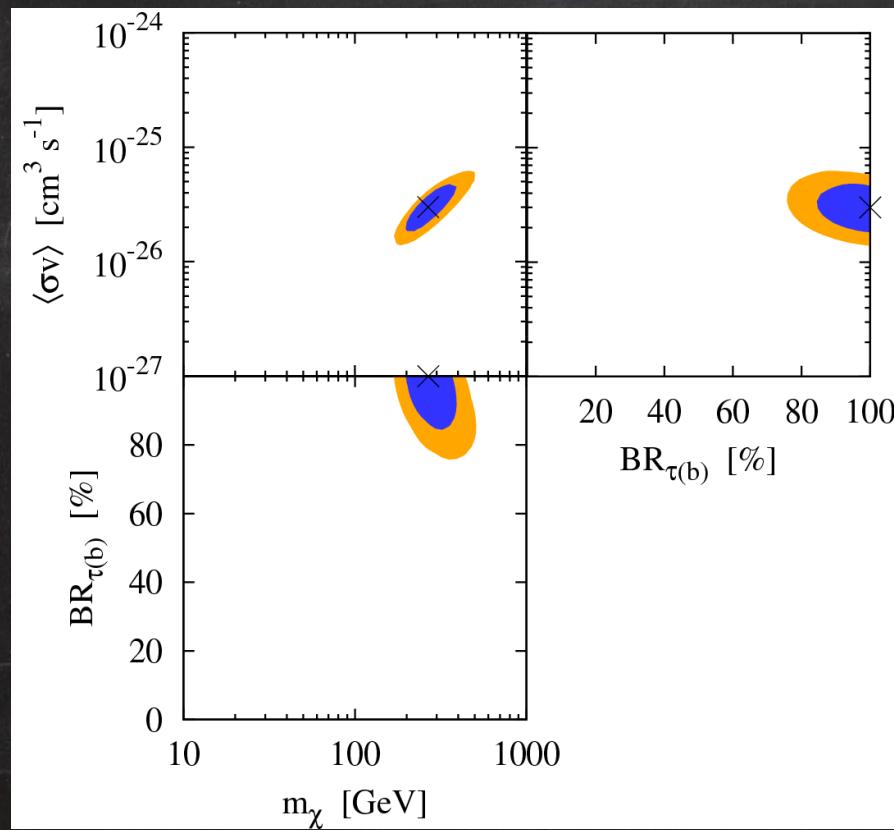


NB and S Palomares-Ruiz, arXiv:1006.0477

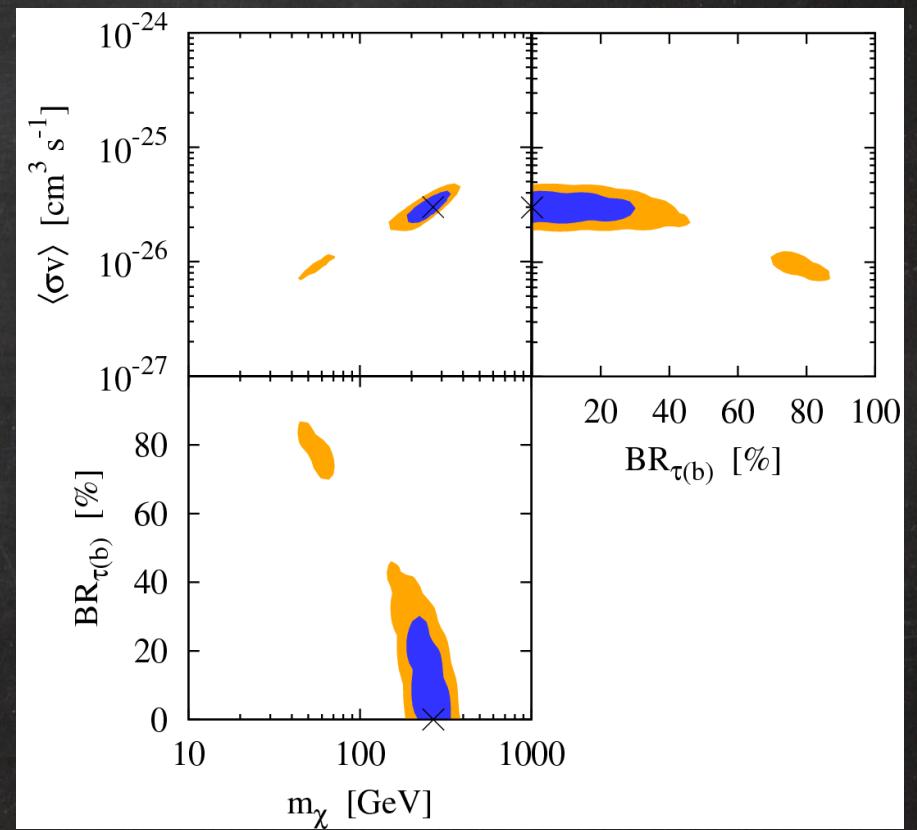
Einasto DM profile

$m = 270 \text{ GeV}$

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

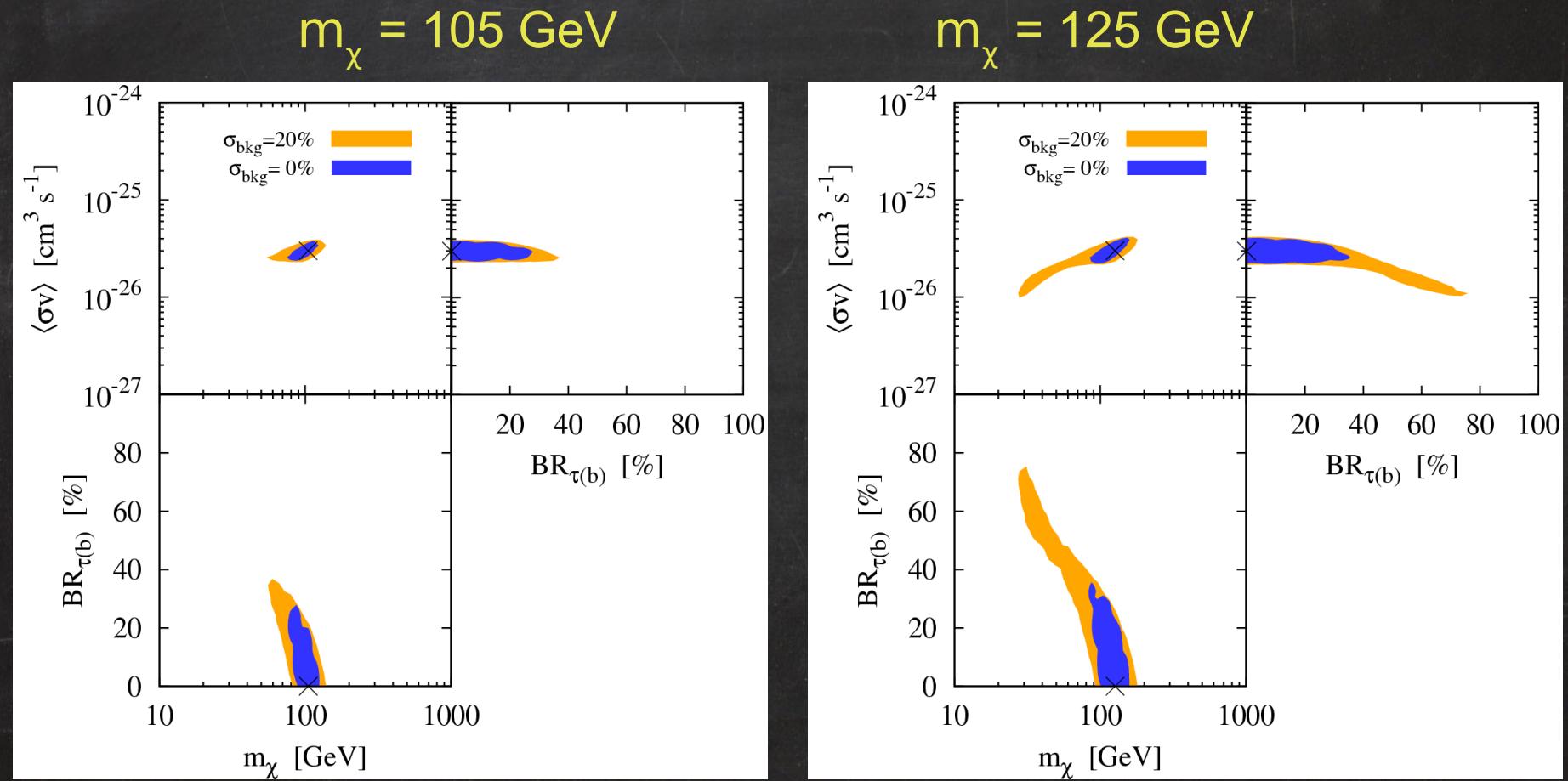


Data: bb



NB and S Palomares-Ruiz, arXiv:1006.0477

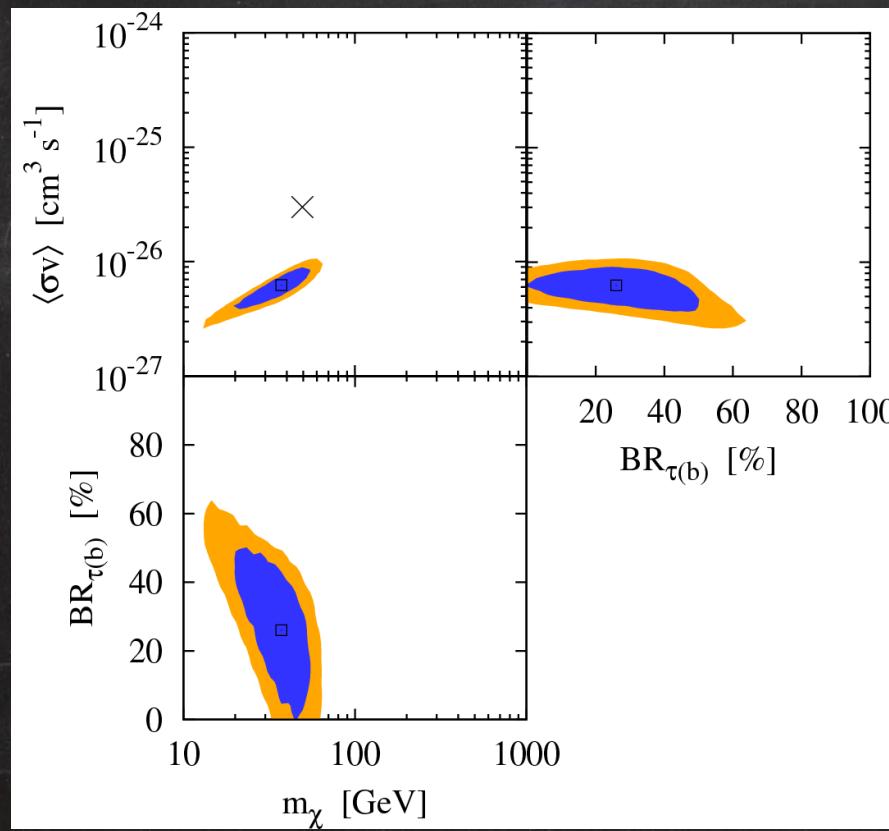
Data: bb Error background: 20%



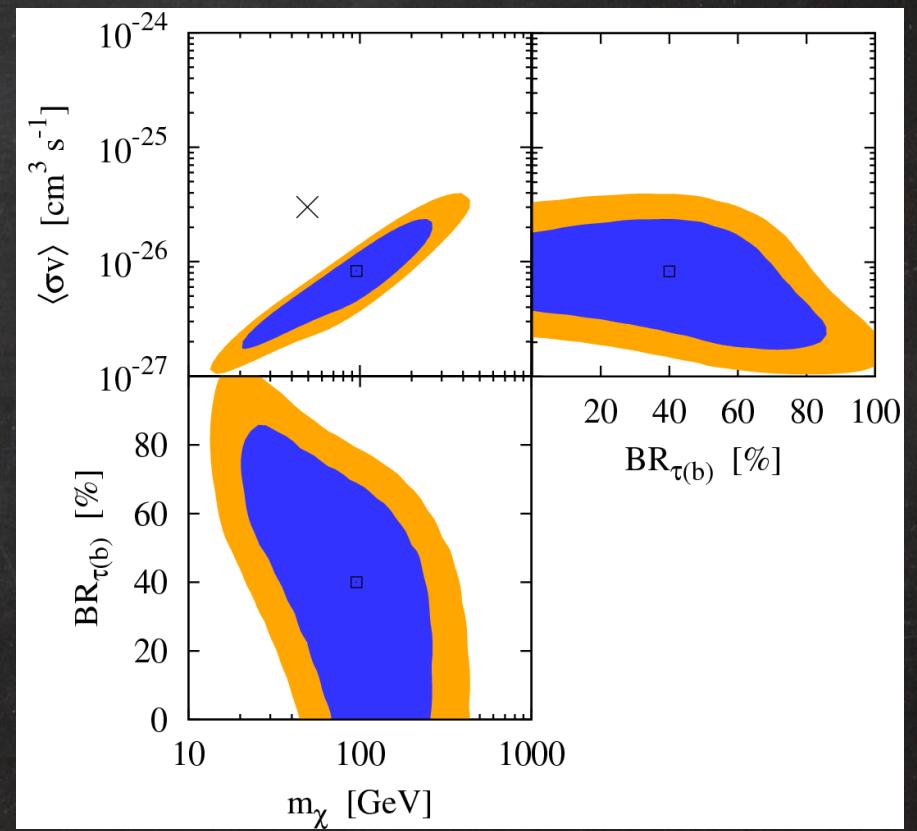
NB and S Palomares-Ruiz, arXiv:1006.0477

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

$m_\chi = 50 \text{ GeV}$



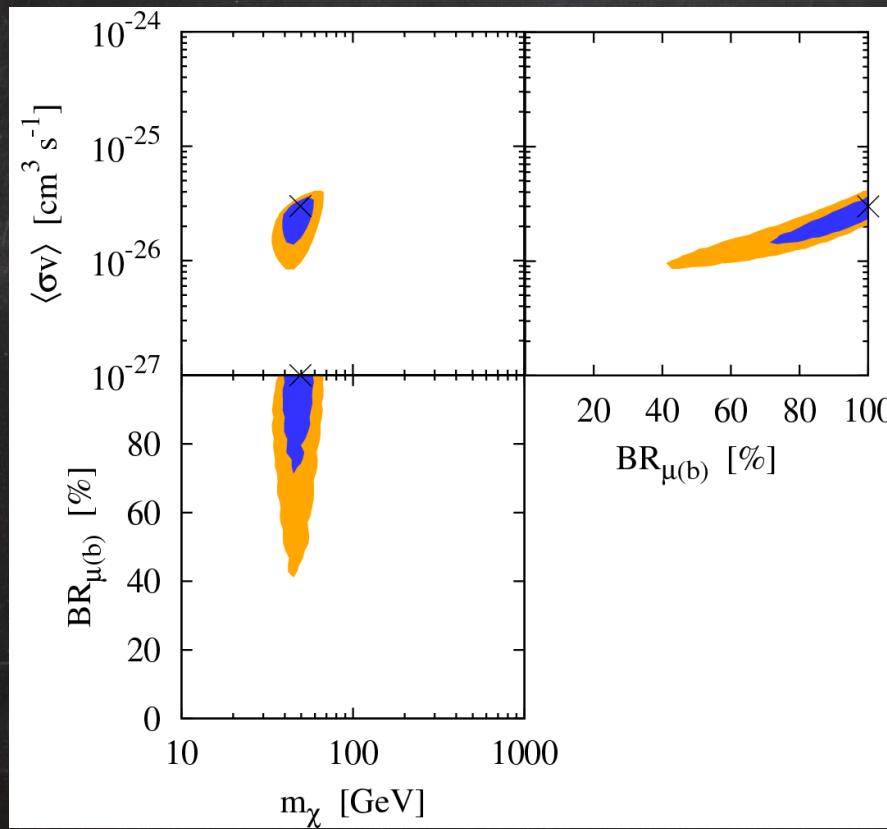
$m_\chi = 105 \text{ GeV}$



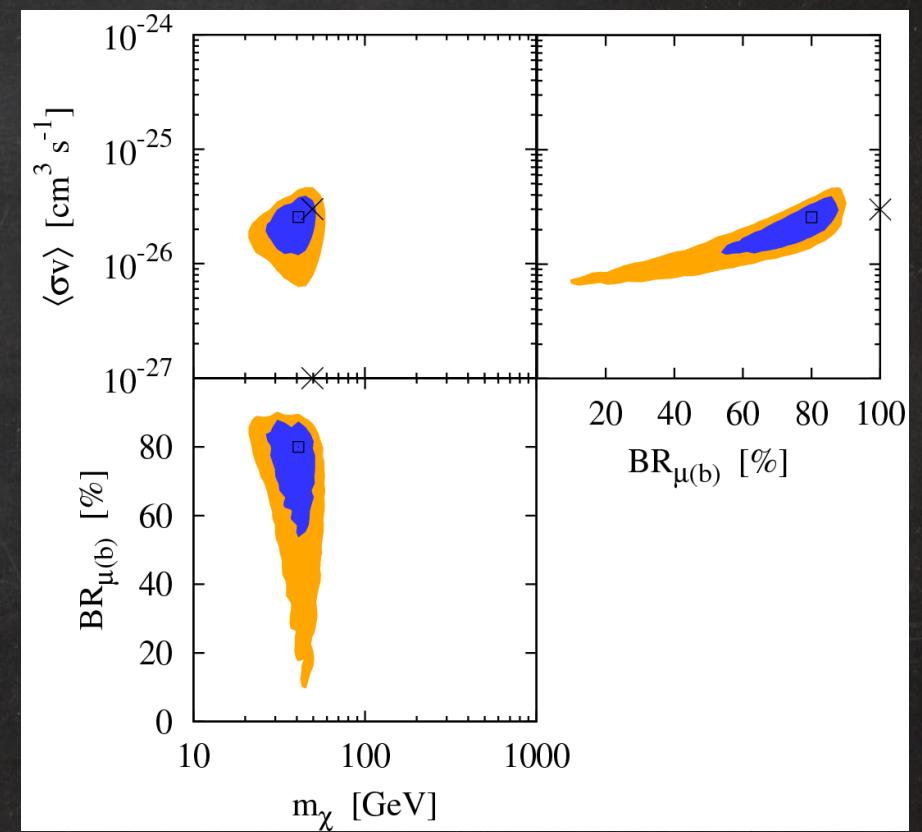
NB and S Palomares-Ruiz, arXiv:1006.0477

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

Reconstruction with ICS



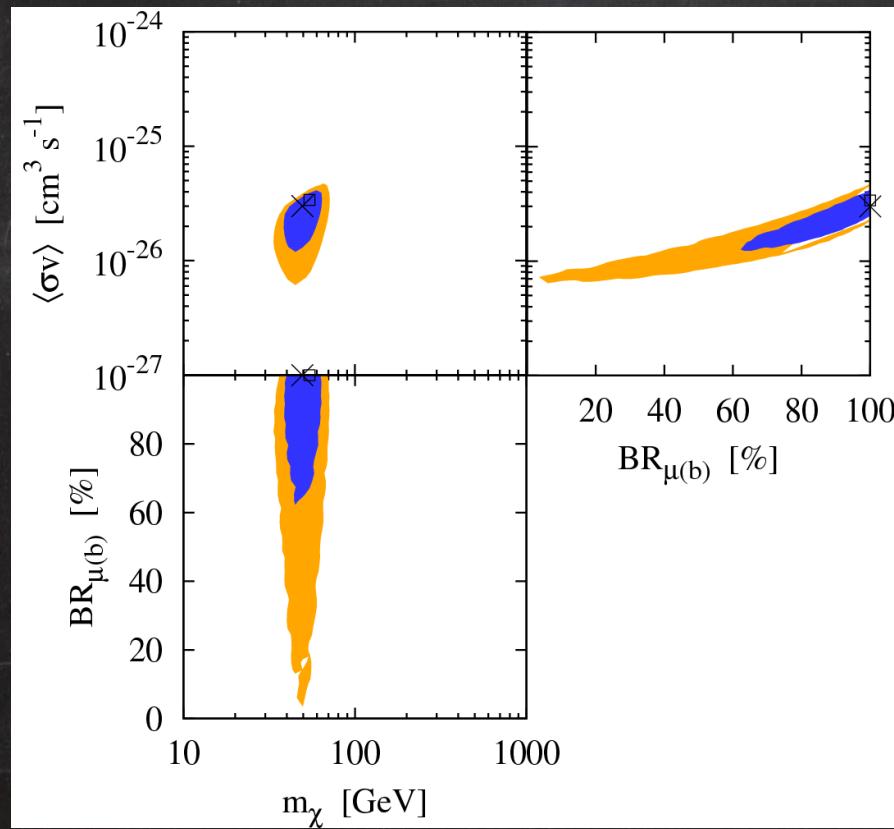
Reconstruction without ICS



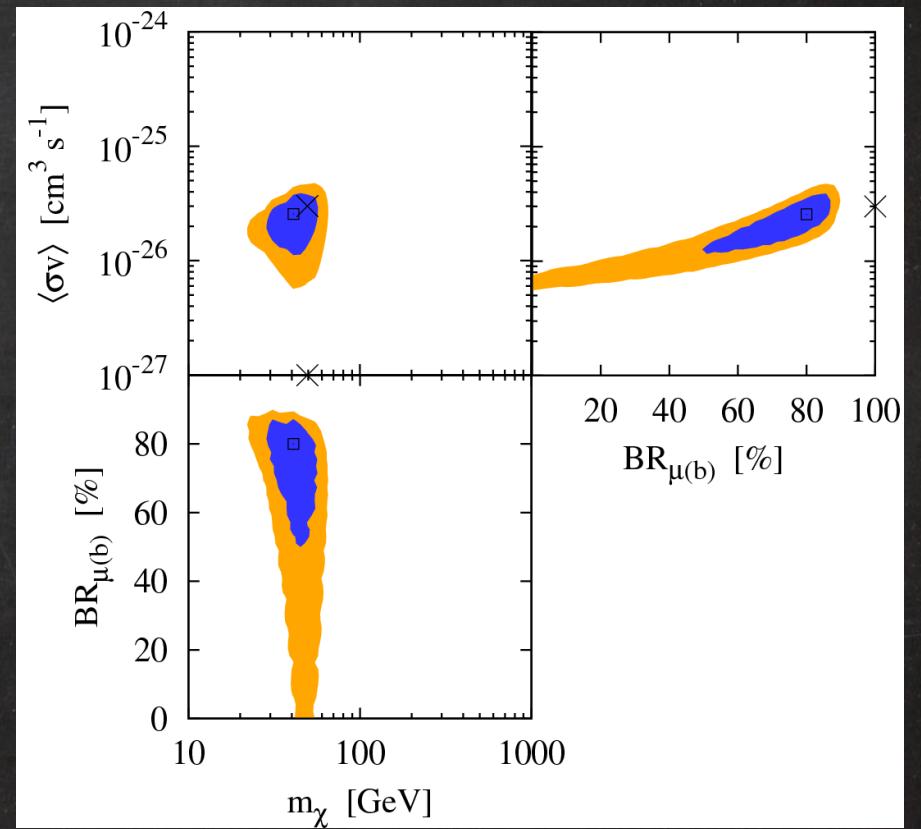
NB and S Palomares-Ruiz, arXiv:1006.0477

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

Reconstruction with ICS



Reconstruction 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 annihilations into hadronic channels, Fermi sensitivity is below the benchmark value for the annihilation cross section for thermal dark matter for $m_\chi < 1 \text{ TeV}$
- * We have also studied the dependence on different uncertainties and assumptions

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

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

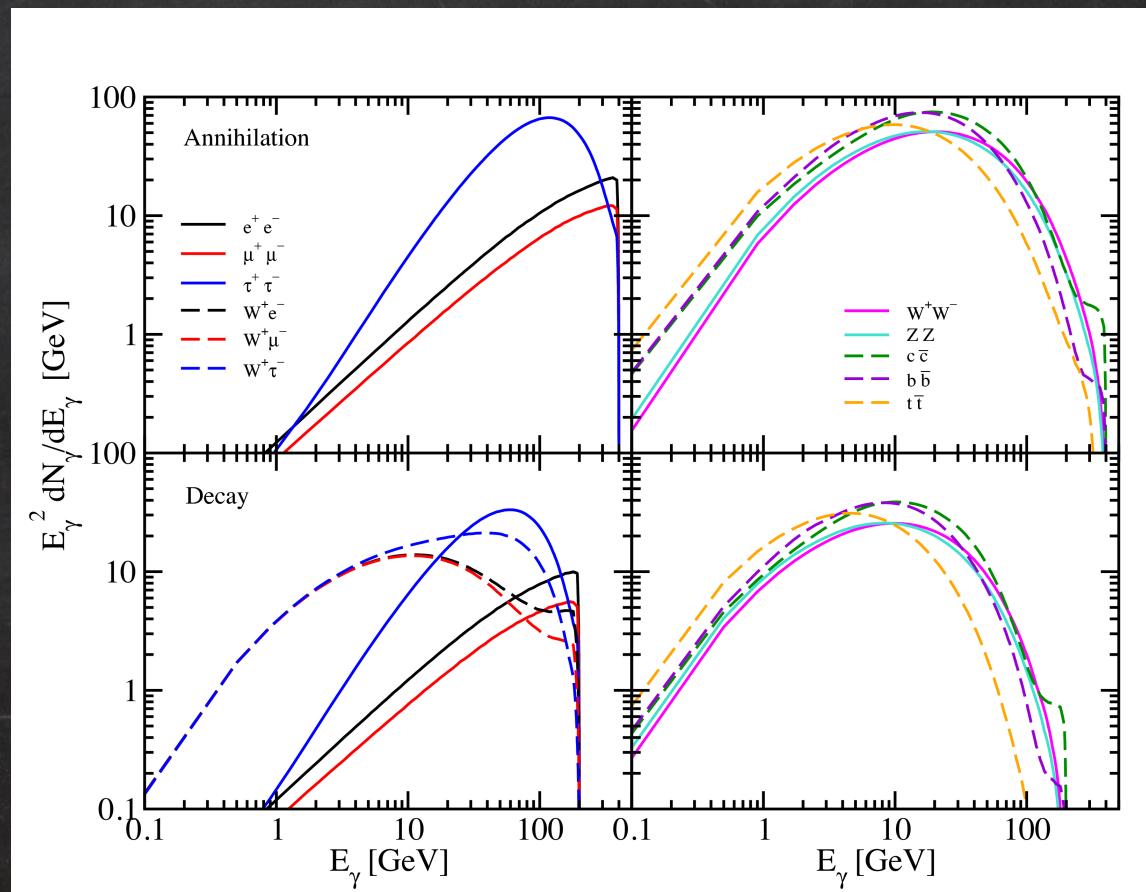
$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{prompt}}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_i \frac{dN_\gamma^i}{dE_\gamma} \text{BR}_i \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho(r(s, \Omega))^2 ds$$

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

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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Astro and Cosmo

DM halo profiles

From N-body simulations

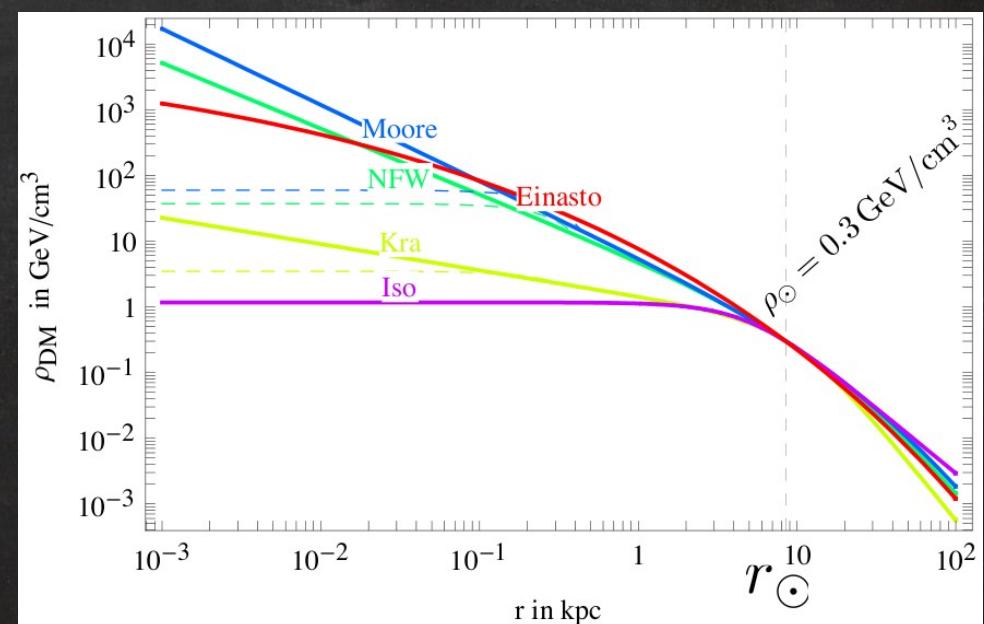
$$\rho(r) = \rho_\odot \frac{[1 + (R_\odot/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}{(r/R_\odot)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

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

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

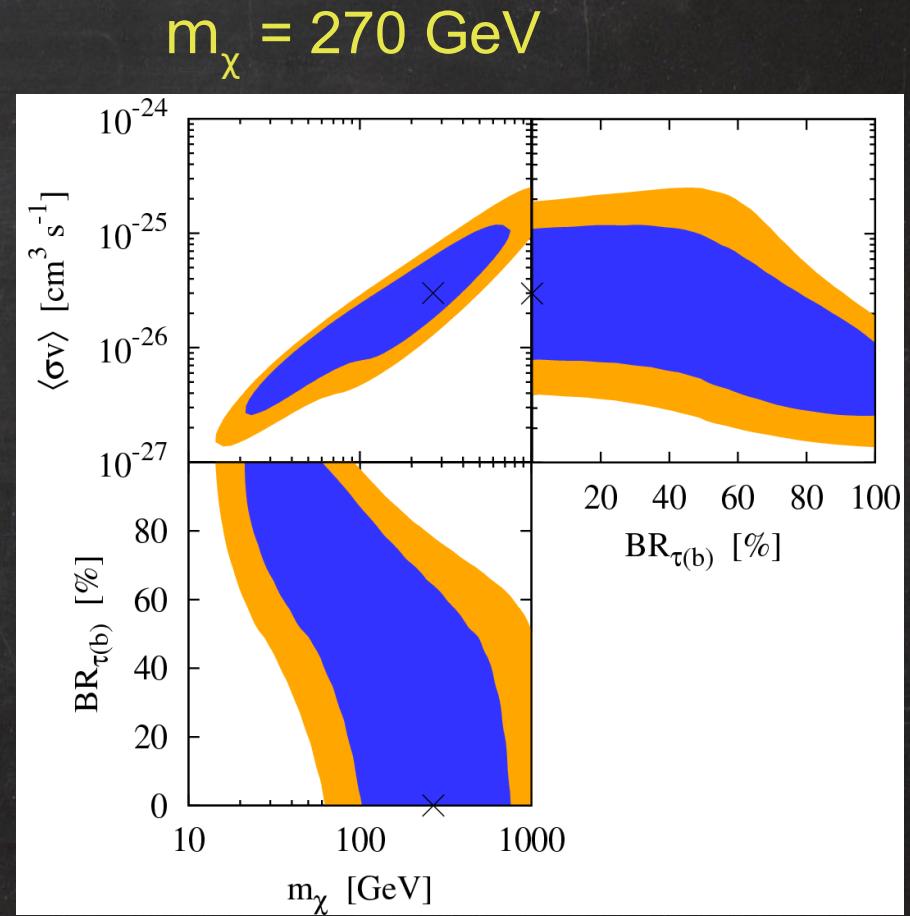
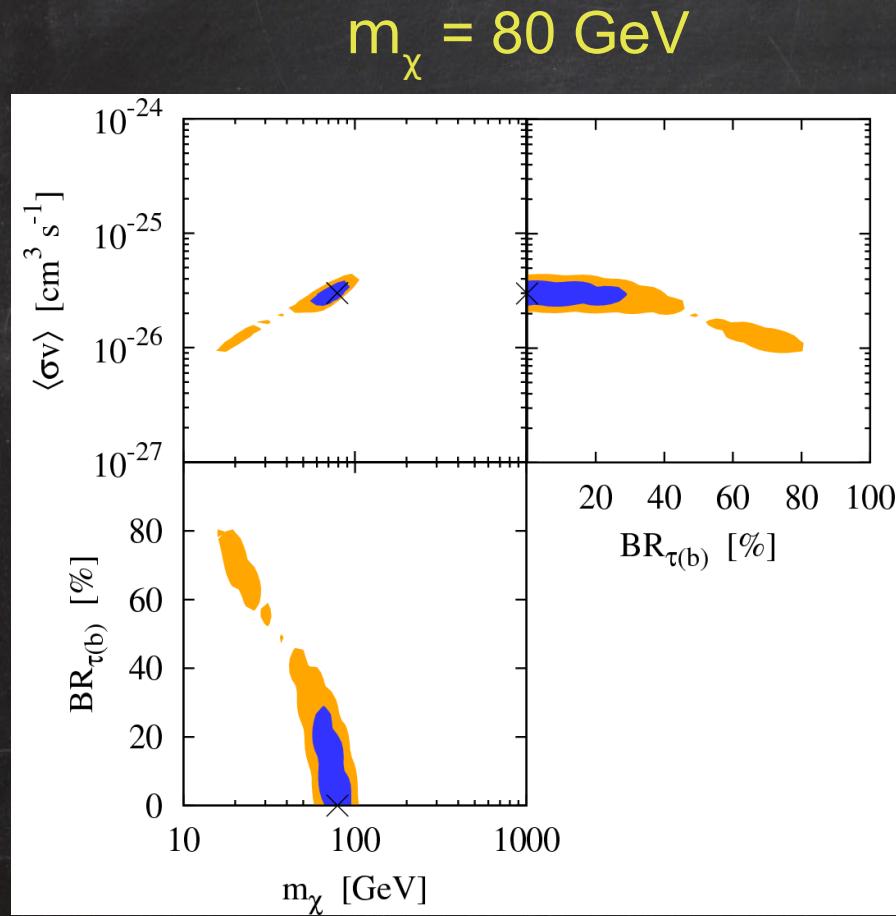
Einasto | $\alpha = 0.17$ $r_s = 20 \text{ kpc}$ $\rho_s = 0.06 \text{ GeV/cm}^3$

| 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 |



Observational region: 1° around the GC

Data: bb



NB and S Palomares-Ruiz, arXiv:1006.0477

Electron/Positron propagation in the halo

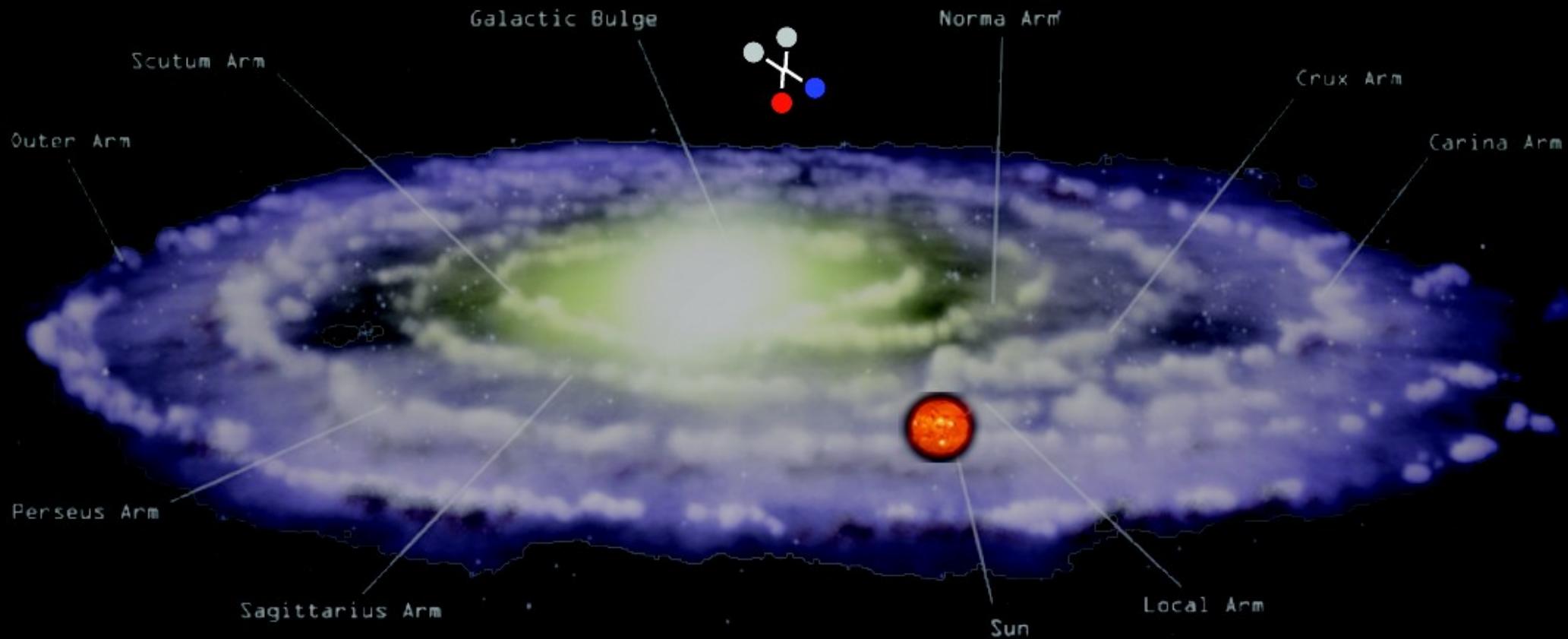
Three commonly used propagation models corresponding to the minimal, maximal and median primary *positron fluxes* that are compatible with the B/C data

| | 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 |

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

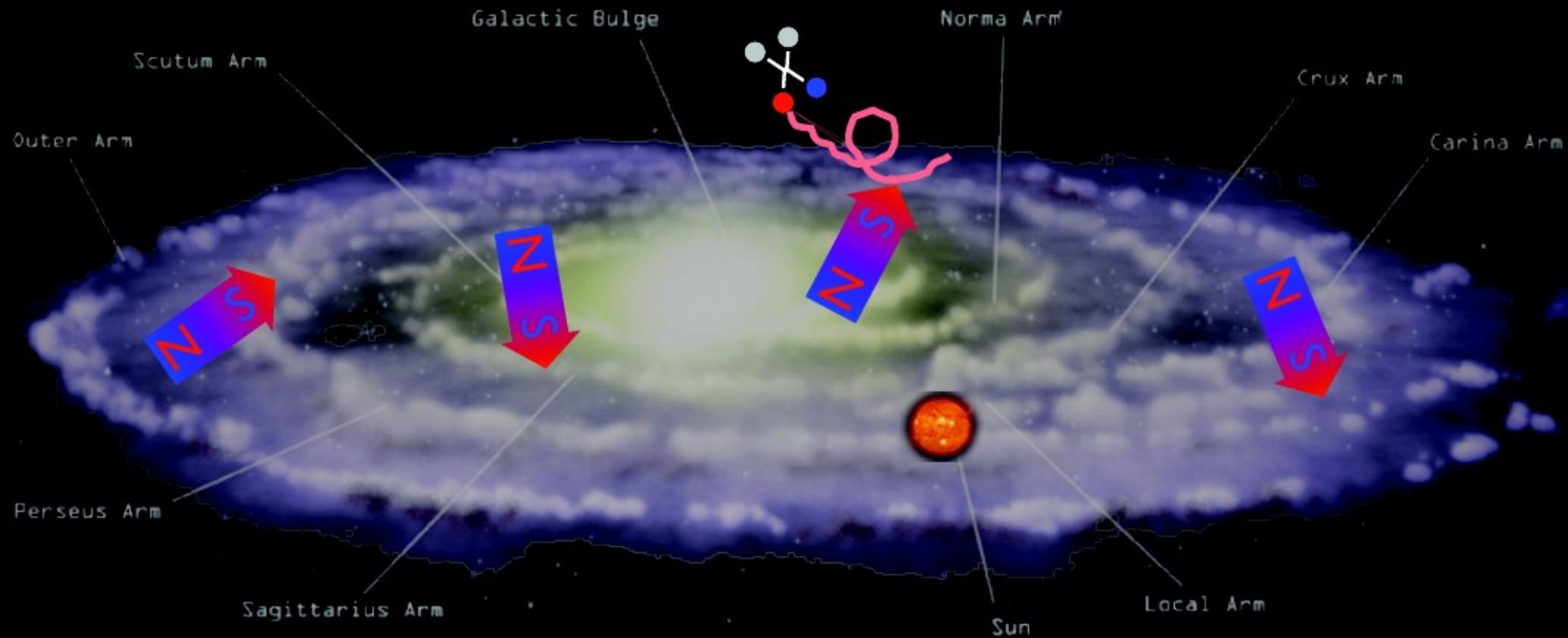
diffusion energy loss source

Electron/Positron propagation in the halo



Borrowed by M. Cirelli

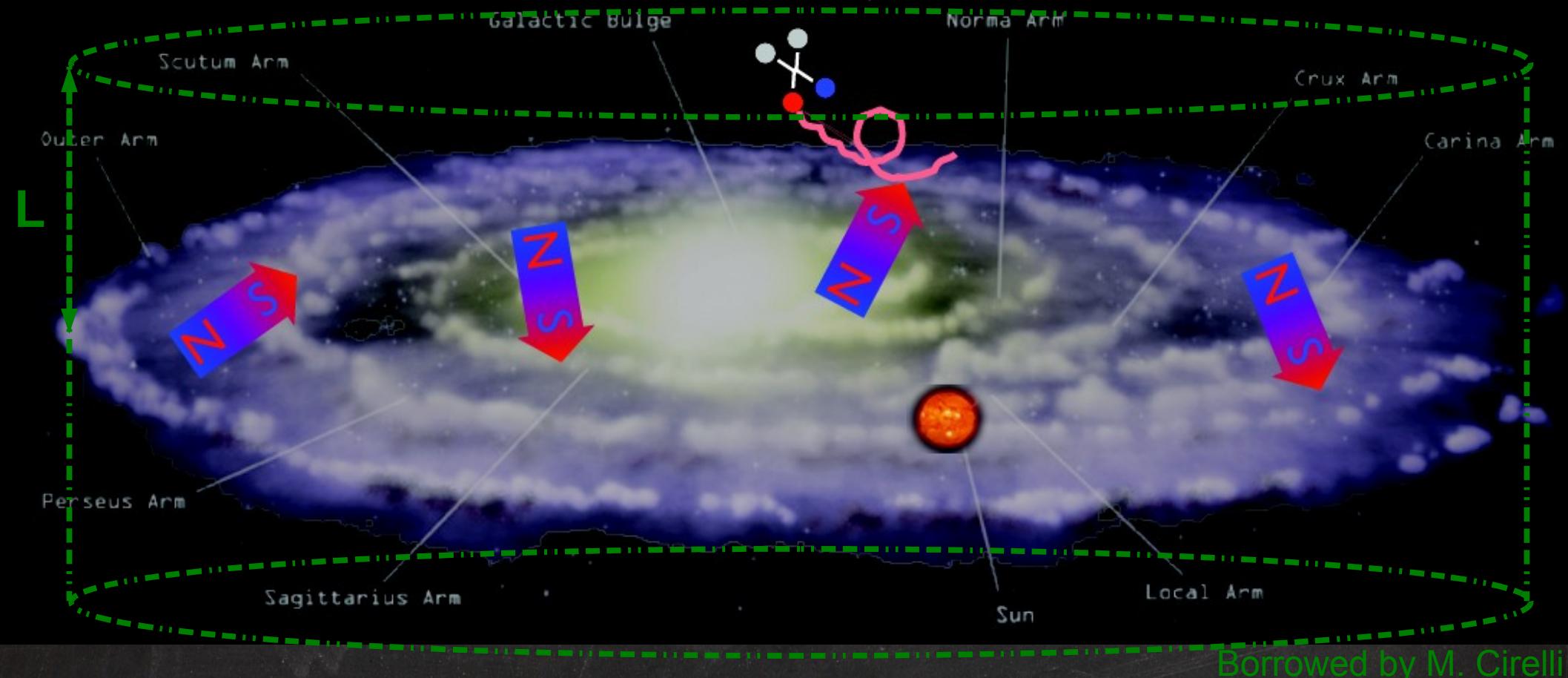
Electron/Positron propagation in the halo



Borrowed by M. Cirelli

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



Borrowed by M. Cirelli

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

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

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

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

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

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 |
|-----------|-------------|--------|