Constraining Dark Matter Properties and the Milky Way Dark Matter Density Profile with Fermi-LAT

based on NB and S. Palomares-Ruiz
arXiv:1006.0477
arXiv:1103.2377

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Universität Bonn

sur le PONT d'Avignon, April 21, 2011

Constraining DM properties

* With Colliders

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N. M. Nojiri, G. Polesello and D. R. Tovey, JHEP 03:063, 2006
E. A. Baltz, M. Battaglia, M. E. Peskin and T. Wizansky, Phys. Rev. D74:103521, 2006
G. Belanger, O. Kitter, S. Kraml, H. U. Martyn and A. Pukhov, Phys. Rev. D78:015011, 2008
R. L. Arnowitt, B. Dutta, A. Gurrola, T. Kamon, A. Krislock and D. Toback, Phys. Rev. Lett. 100:231802, 2008
B. Altunkaynak, M. Holmes and B. D. Nelson, JHEP 10:013, 2008

* With Direct Detecion

A. M. Green, JCAP 0708:022, 2007 and JCAP 0807:005, 2008
G. Bertone, D. G. Cerdeño, J. I. Collar and B. C. Odom, Phys. Rev. Lett. 99:151301, 2007
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L. E. Strigari and R. Trotta, JCAP 0911:019, 2009
A. H. G. Peter, Phys. Rev. D81:087301, 2010
Y.-T. Chou and C.-L. Shan, JCAP 1008:014, 2010

* With Neutrinos from the Sun

J. Edsjo and P. Gondolo, Phys. Lett. B357:595, 1995
M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, Nucl. Phys. B727:99, 2005
O. Mena, S. Palomares-Ruiz and S. Pascoli, Phys. Lett. B664:92, 2008

* With Gamma-Rays

S. Dodelson, D. Hooper and P. D. Serpico, Phys. Rev. D77:063512, 2008
T. E. Jeltema and S. Profumo, JCAP 0811:003, 2008
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NB and S. Palomares-Ruiz, arXiv:1006.0477 and arXiv:1103.2377

* With a Combination

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G. Bertone, D. G. Cerdeño, M. Fornasa, R. R. Austri and R. Trotta, Phys. Rev. D82:055008, 2010

Gamma-rays: general features

The differential intensity of the gamma-ray signal

Prompt gamma-rays produced by annihilation of DM particles:

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{\text{prompt}}(E_\gamma, \Delta\Omega) = R_\odot\, \rho_\odot^2\, \overline{J}(\Omega)\, \frac{\Delta\Omega}{4\,\pi}\, \frac{\langle\sigma v\rangle}{2\, m_\chi^2} \sum_i \mathrm{BR}_i\, \frac{dN_\gamma^i}{dE_\gamma}\,,$$

Gamma-rays: general features

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* Particle physics:

- m_x dark matter mass
- <σv> thermally averaged annihilation cross section
- Br_i branching ratio into photons for the i-th annihilation channel
- dN/dE differential gamma ray yield of SM particles into photons

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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* Astrophysics:

$$\overline{J}(\Omega) = \frac{1}{\Delta\Omega}\,\frac{1}{R_\odot\,\rho_\odot^2}\int_{\Delta\Omega} d\Omega\int_{\rm los}\rho\big(r(s,\Omega)\big)^2\,ds$$

- $\rho(r)$ dark matter density profile
- ρ_0 local DM density
- R_0 distance Sun – galactic center
- $\Delta\Omega$ solid angle of observation

DM halo profiles

From N-body simulations

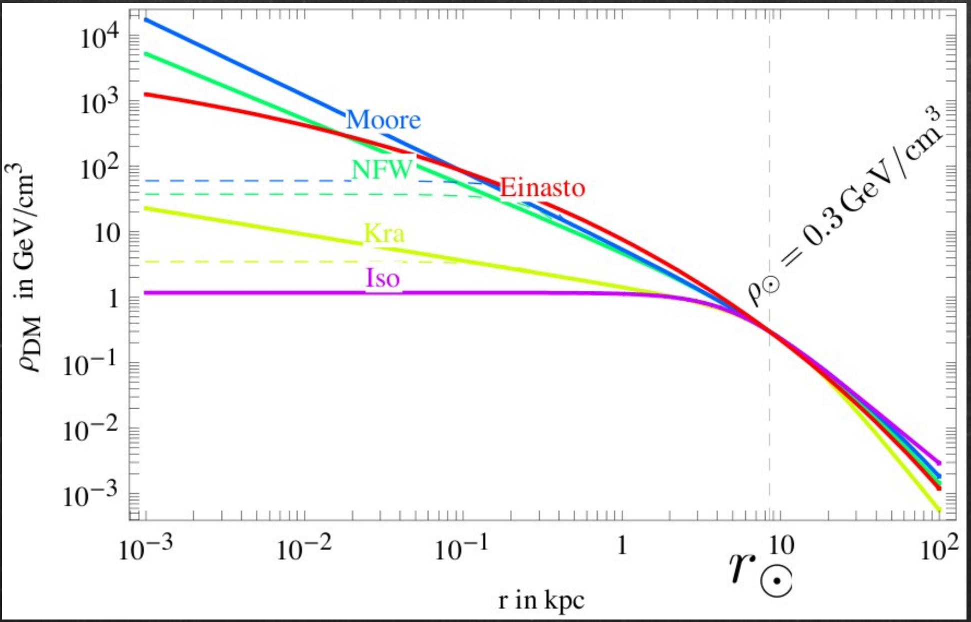
NFW profile

$$\rho(r) = \rho_\odot \frac{(R_\odot/r_s)\,[1+(R_\odot/r_s)]^2}{(r/r_s)\,[1+(r/r_s)]^2}$$

Einasto profile

$$\rho(r) = \rho_\odot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - \left(\frac{R_\odot}{r_s}\right)^\alpha\right)\right]$$

Free parameters: ρ_0 , r_s | ρ_0 , r_s and α



Galactic backgrounds

* Diffuse galactic emission:
GALPROP v54: 'conventional' model
    Pions decay
    Bremsstrahlung
    Inverse Compton scattering of CR

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

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

* Statistical error
* Systematical error $\sigma_{sys} = 3\ \sigma_{stat}$
AA Abdo [Fermi-LAT Collaboration], Phys. Rev. Lett. 104,101101, 2010

Constraining DM properties and the DM density profile

Default setup

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

* 10 concentric 1º x 1º angular bins around the GC

* 5 years data taking

* DM profile: Einasto or NFW

* $\langle\sigma v\rangle = 3\ 10^{-26}\ \ cm^3 / s$
* $R_0 = 8.3$ kpc
* $\rho_0 = 0.4\ GeV/cm^3$
* $\alpha = 0.17 \quad r_s = 20$ kpc

See talk by Catena

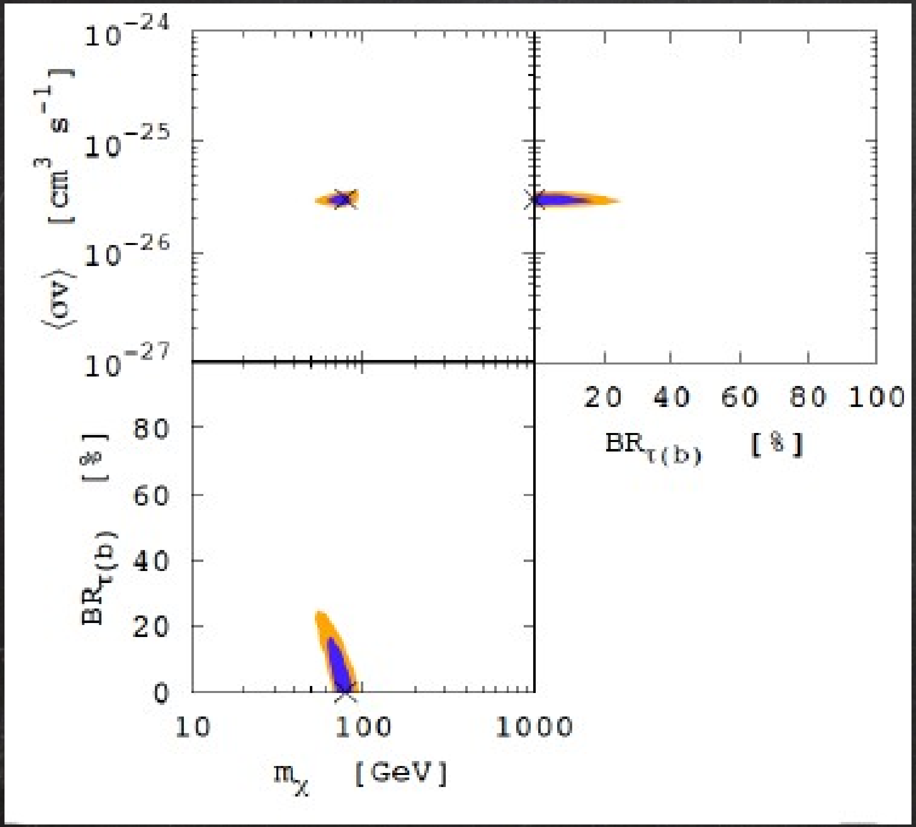
* "Real data": b b pairs

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

* Background error: statical + systematics

m_χ = 80 GeV and Einasto assuming a known DM profile!

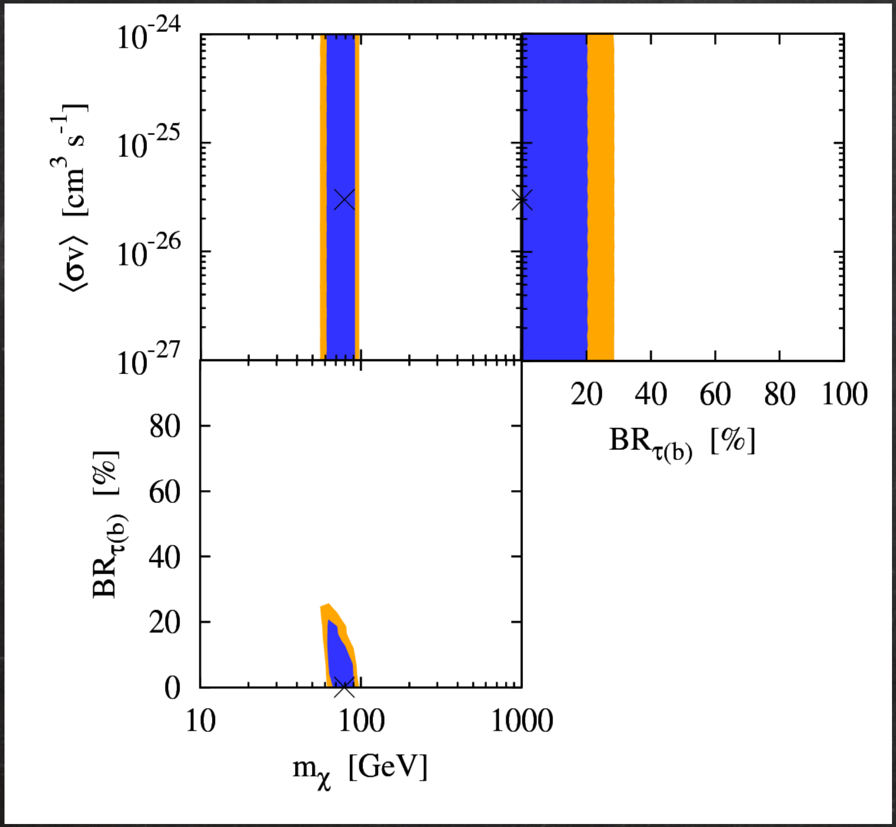
DM properties...



NB and S Palomares-Ruiz, arXiv:1006.0477

m_x = 80 GeV and Einasto DM profile unknown

DM properties...



NB and S Palomares-Ruiz, arXiv:1103.2377

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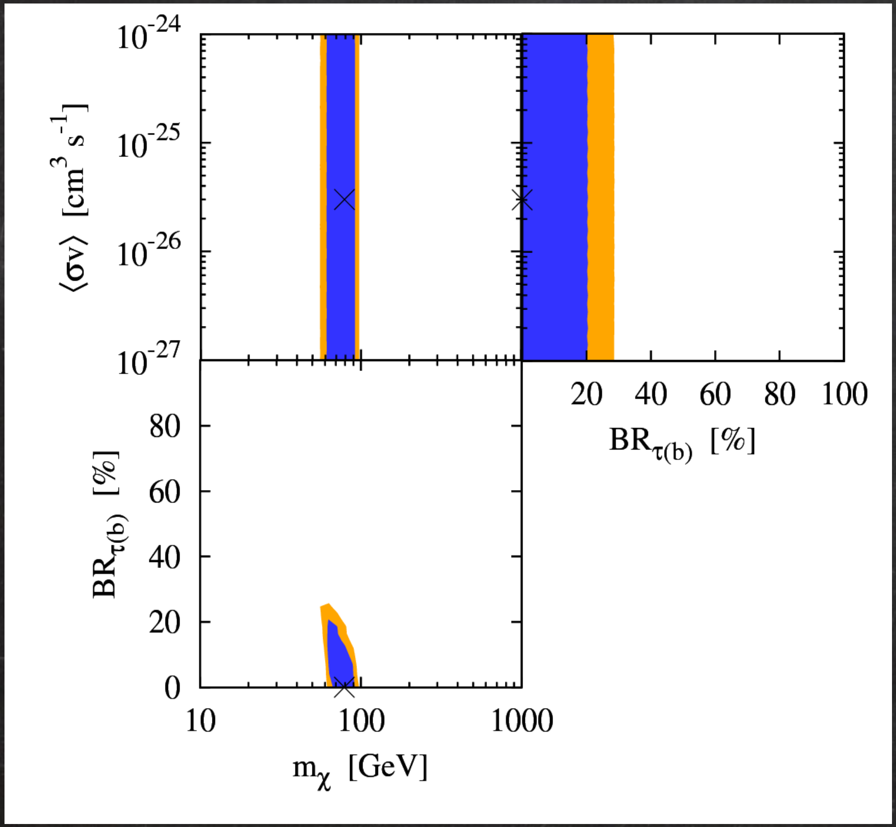
DM profile unknown

DM properties...

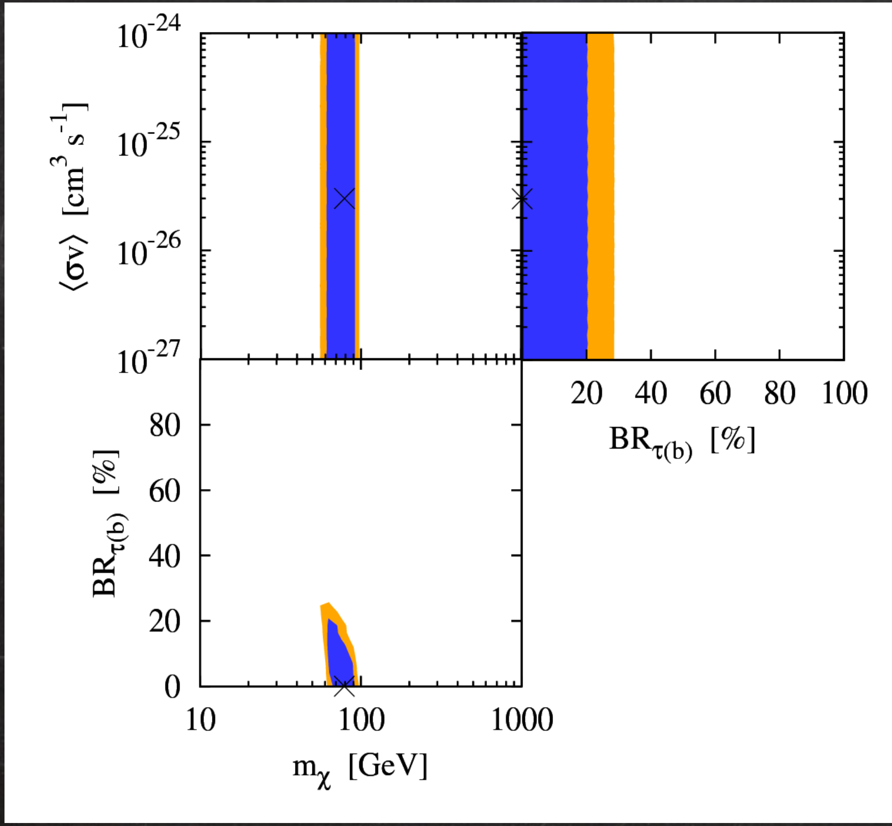


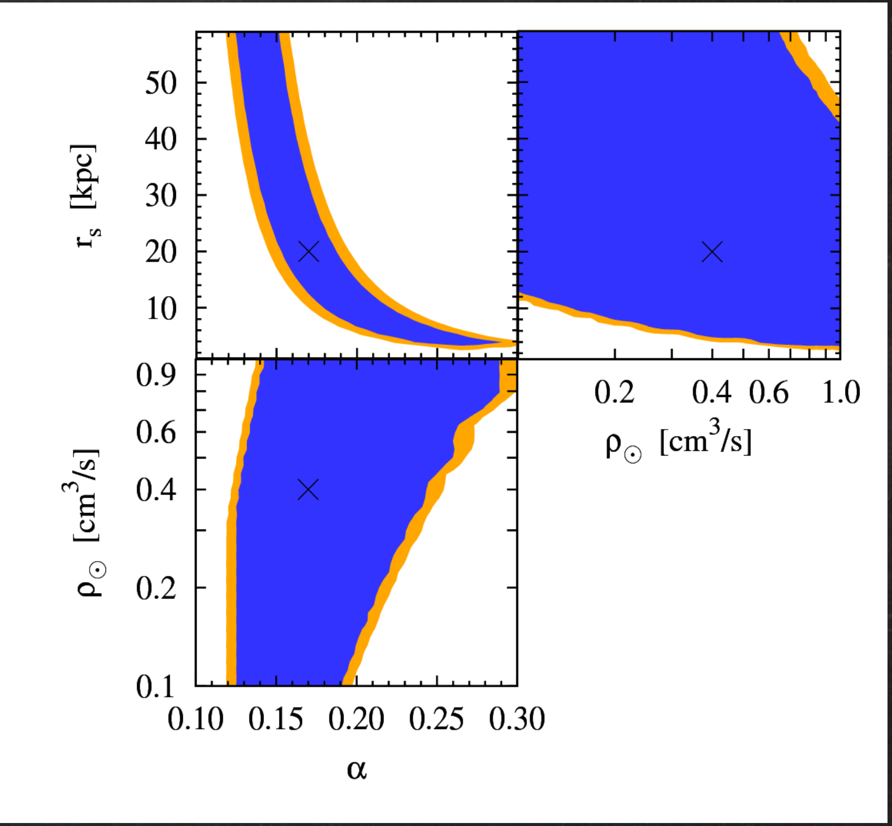
* Remember:
flux normalization
proportional to
<σv> and $J(\alpha, \rho_0, r_s)$

NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 80 GeV and Einasto
DM profile unknown

DM properties... and DM density profile



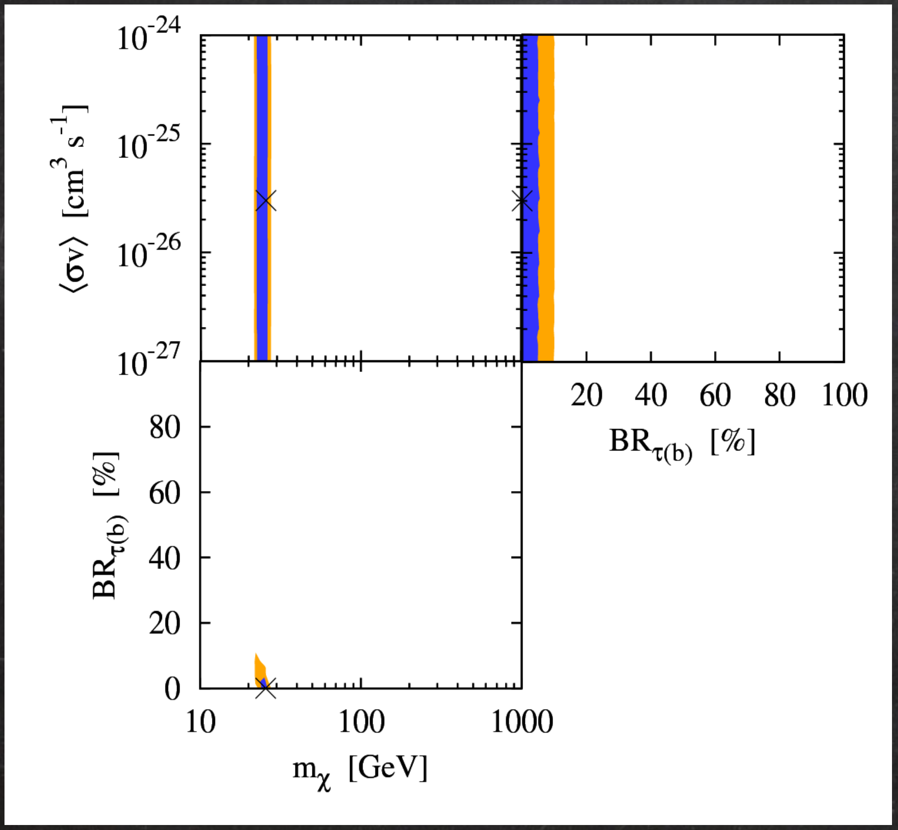


NB and S Palomares-Ruiz, arXiv:1103.2377

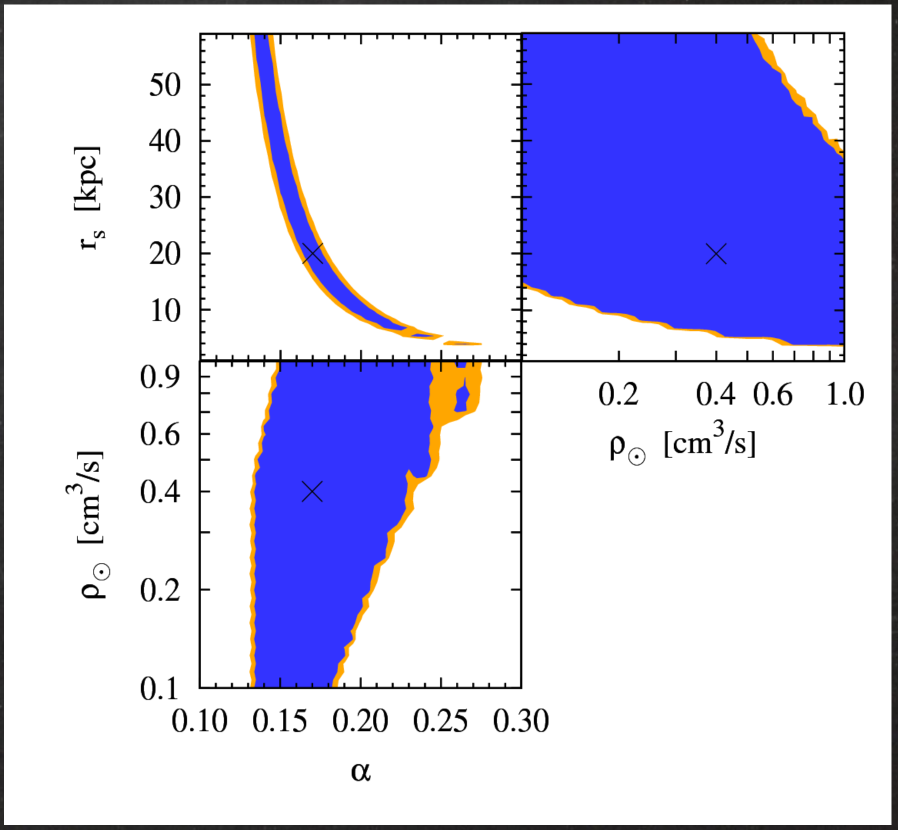
$$\rho(r) = \rho_{\odot} \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - \left(\frac{R_{\odot}}{r_s}\right)^{\alpha}\right)\right]$$

m_x = 25 GeV and Einasto DM profile unknown

DM properties...



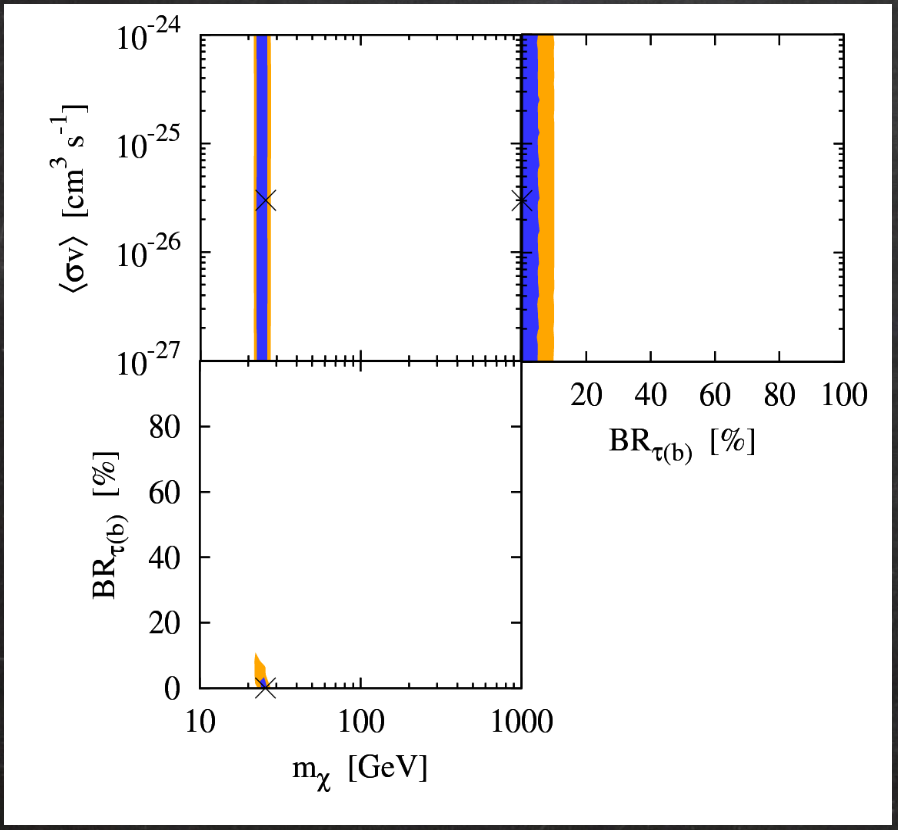
and DM density profile



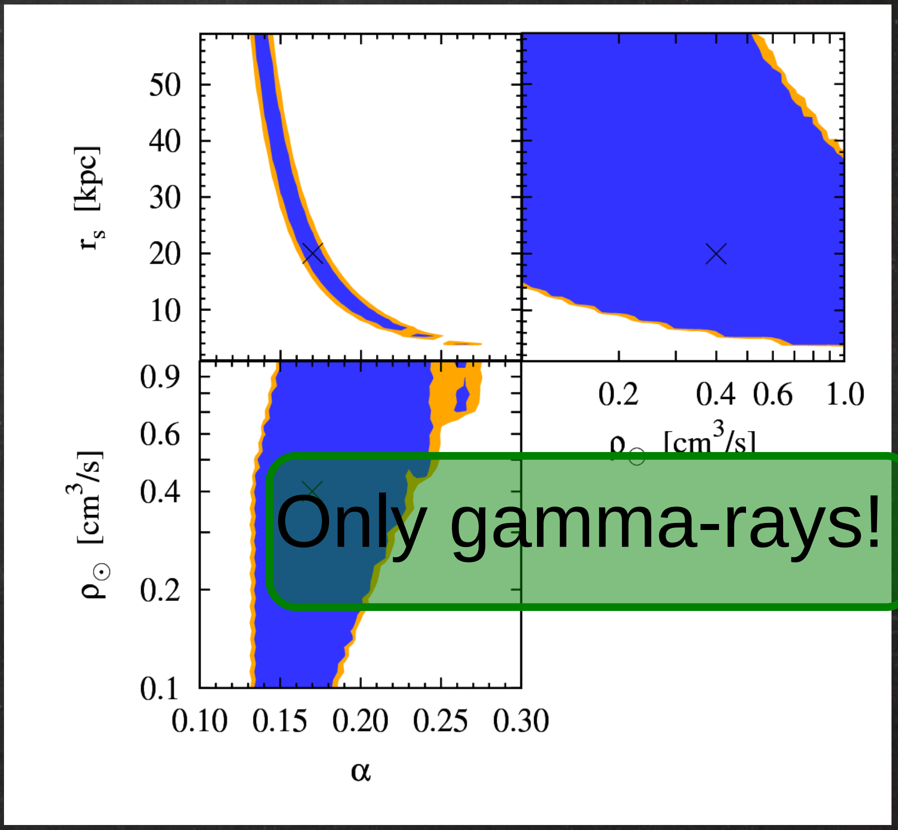
NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 25 GeV and Einasto
DM profile unknown

DM properties...



and DM density profile



Only gamma-rays!

NB and S Palomares-Ruiz, arXiv:1103.2377

Constraining DM properties and the DM density profile, assuming information on ρ_0 and $\langle\sigma v\rangle$

DM halo profiles

So far, we have shown results by just using gamma-rays observations

However...

Local DM density:

$\rho_0 = 0.39 \pm 0.03$ GeV/cm^3 (Catena & Ullio '09)

$\rho_0 = 0.40 \pm 0.04$ GeV/cm^3 (McMillan '11)

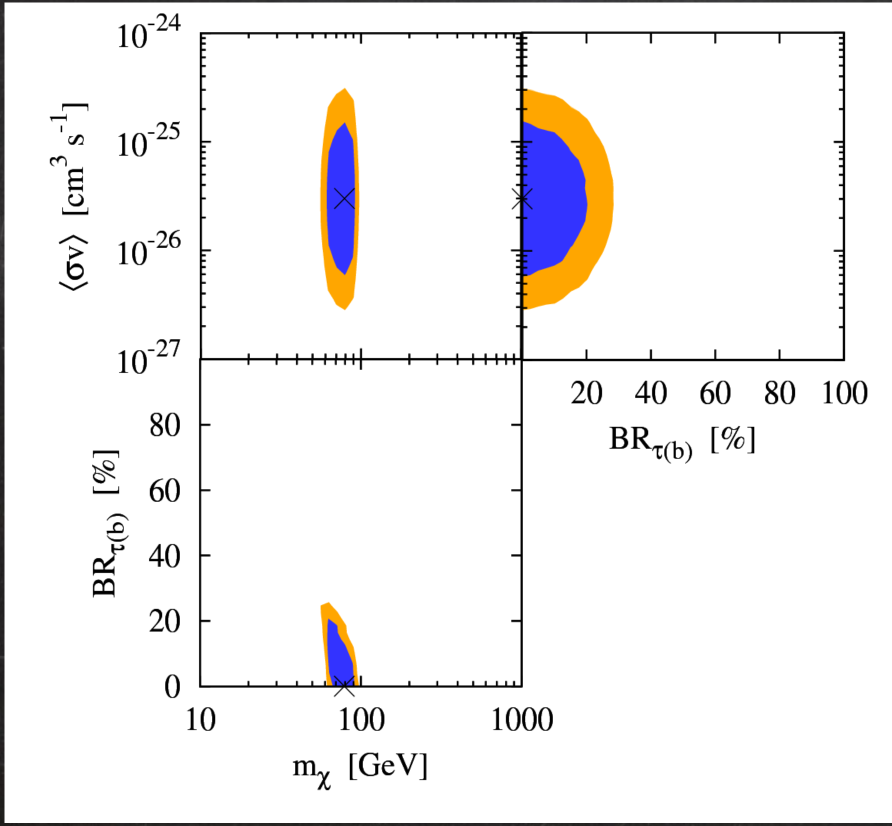
ρ_0 determined with an error of 50% or 10%

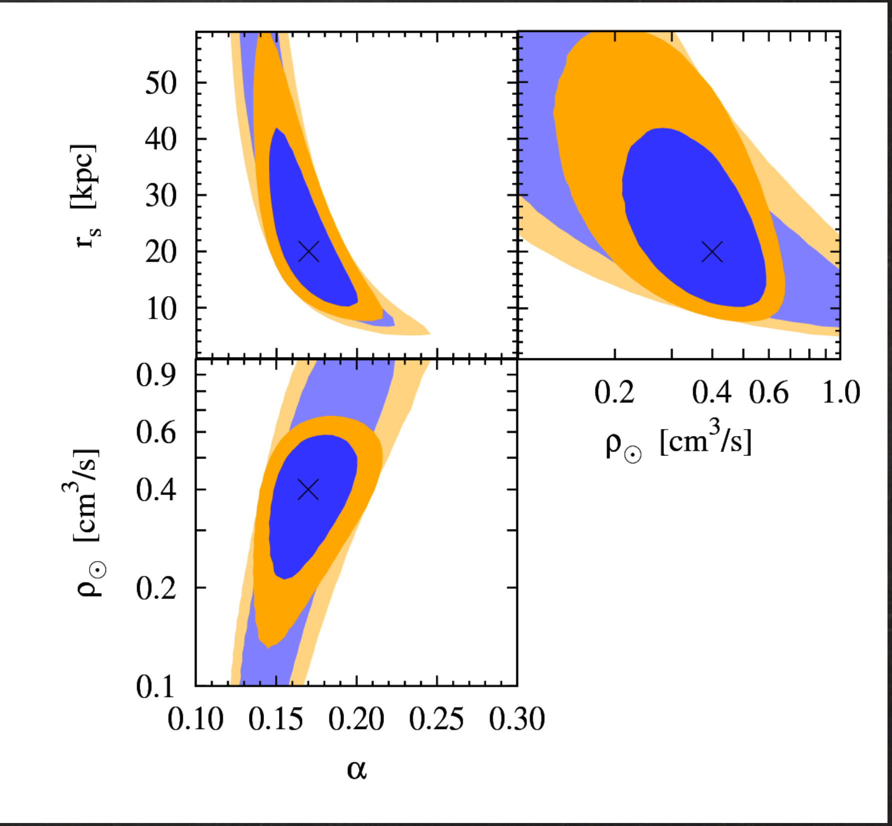
Annihilation cross section:

$\langle\sigma v\rangle$ is determined within
an order of magnitude at 3σ (Baltz *et al* '06)

m_x = 80 GeV and Einasto

* <σv> is determined within an order of magnitude at 3σ
* ρ_0 determined with an error of 50% or 10%

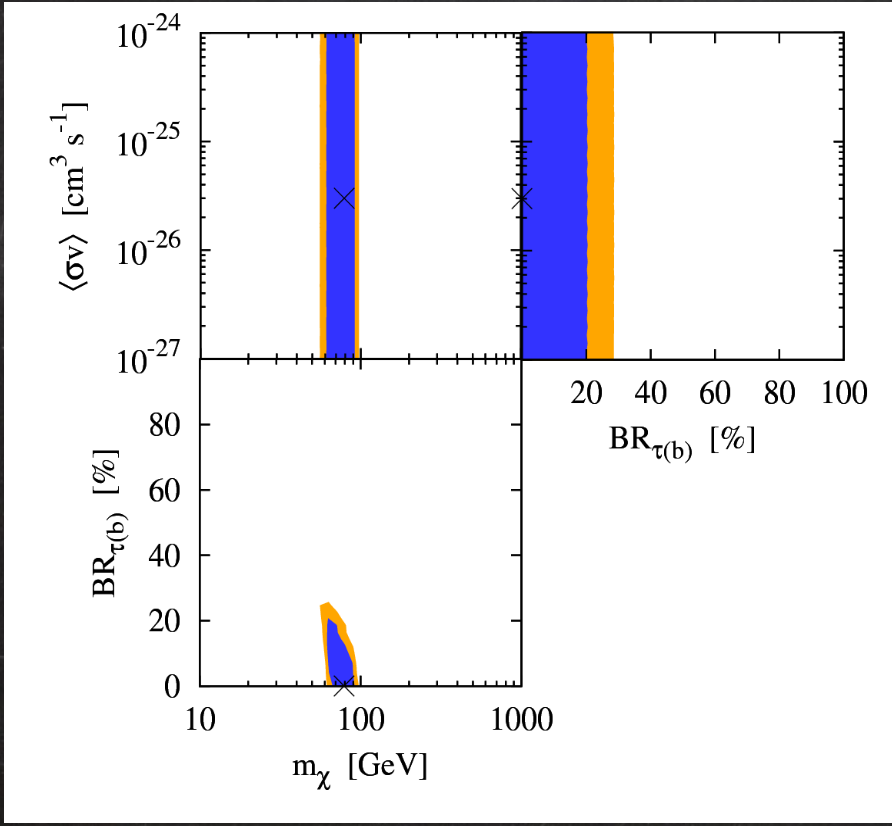


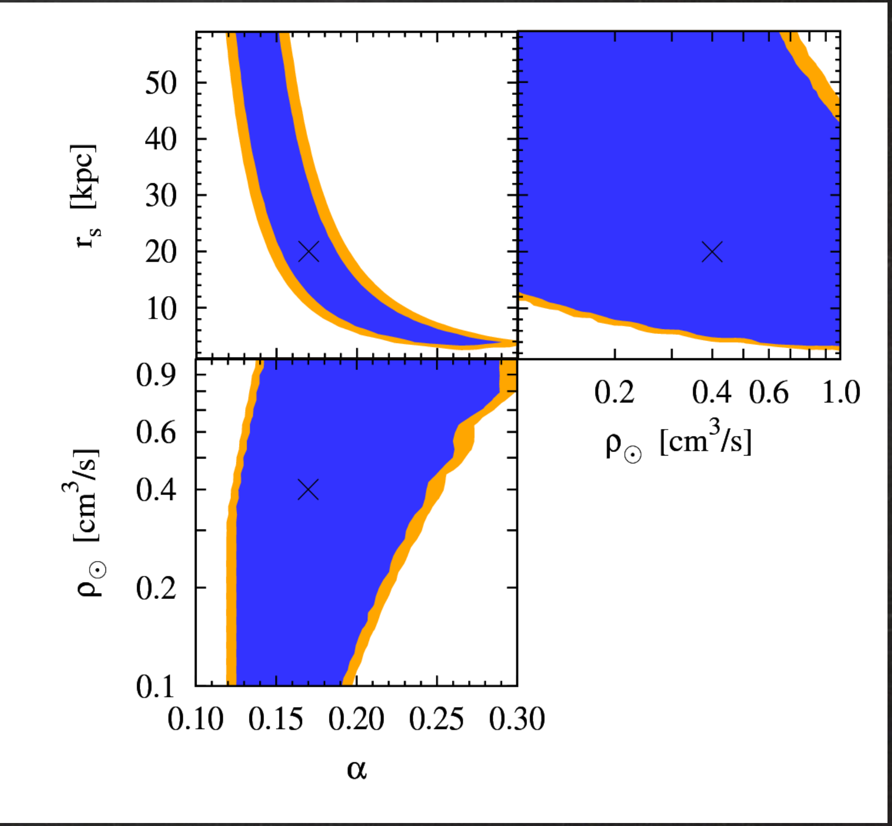


NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 80 GeV and Einasto

* Without priors





NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 25 GeV and Einasto

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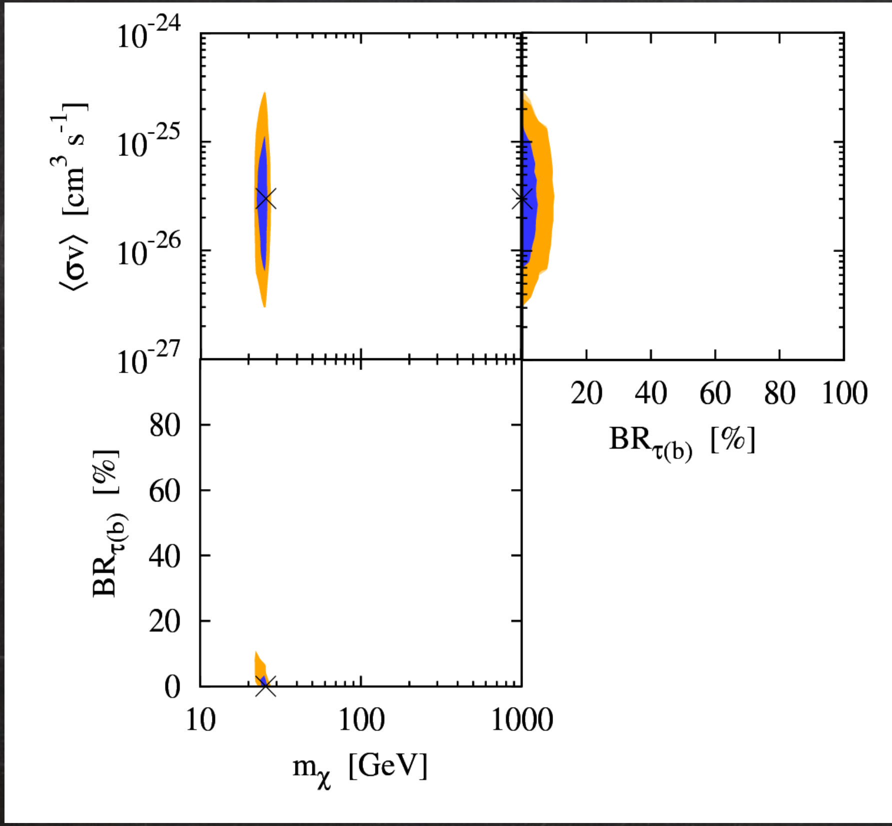
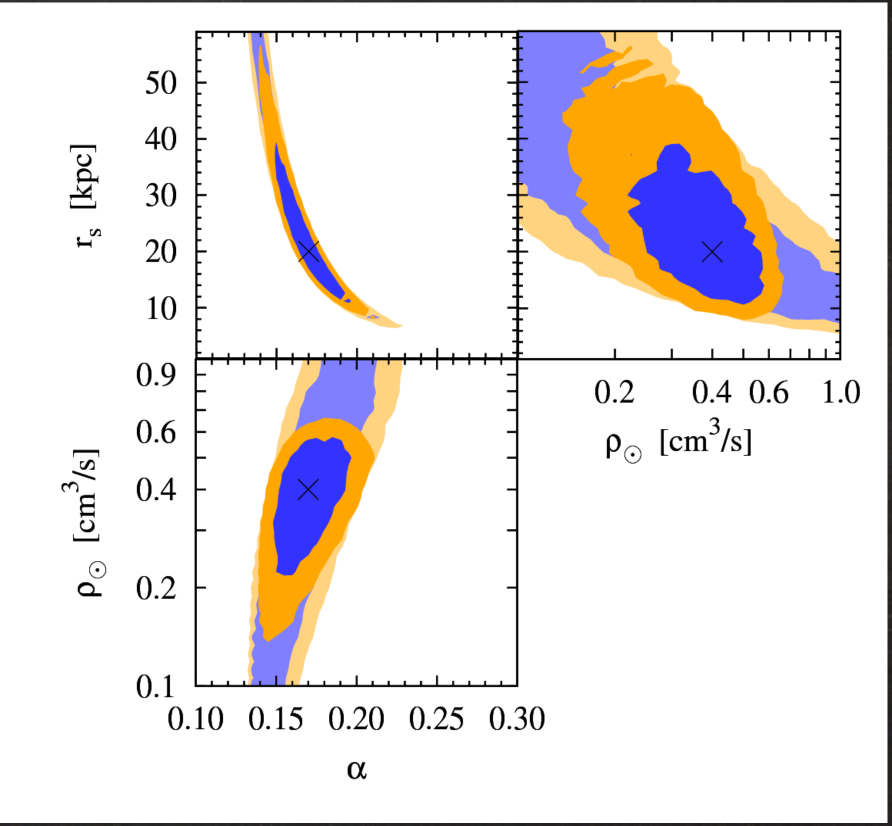




NB and S Palomares-Ruiz, arXiv:1103.2377

Constraining DM properties and the DM density profile: comparison with N-body simulations

Comparison with simulations

* We consider the NFW density profile
  determined by the parameters ρ_0 and r_s

* It's convenient to rewrite these parameters using
  the virial mass M_{vir} and the concentration parameter c_{vir}

Comparison with simulations

* We consider the NFW density profile determined by the parameters ρ_0 and r_s

* It's convenient to rewrite these parameters using the virial mass M_{vir} and the concentration parameter c_{vir}

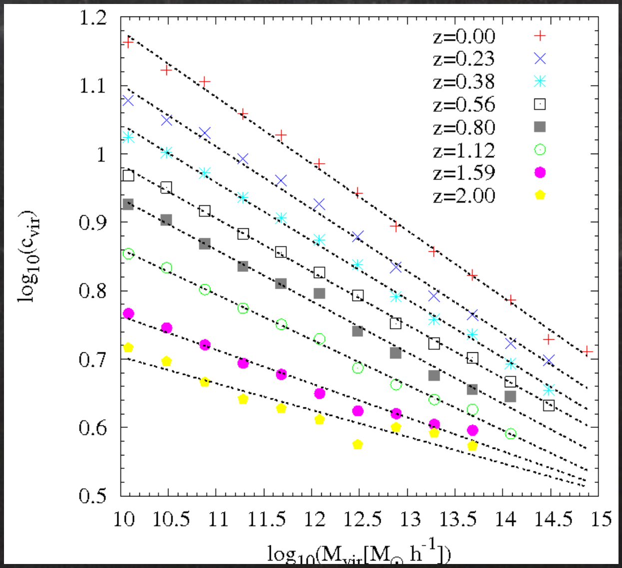
* Structural properties of DM halos depend on the halo mass

At z=0 and for relaxed halos:

$$c_{\rm vir} = 10^{2.155}\left(\frac{M_{\rm vir}}{h^{-1}{\rm M}_\odot}\right)^{-0.097}$$

This eq. Represents the mean concentration for a given M_{vir}

→ MW could be a quite atypical galaxy!!



Muñoz-Cuartas *et al* '10

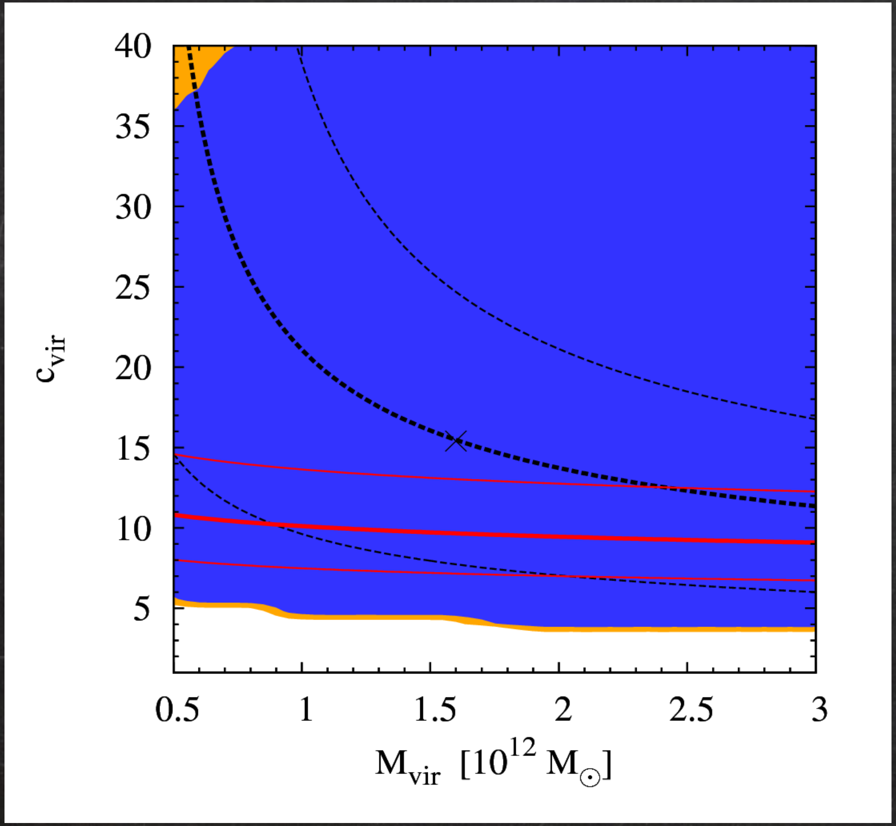
m_x = 25 GeV and NFW

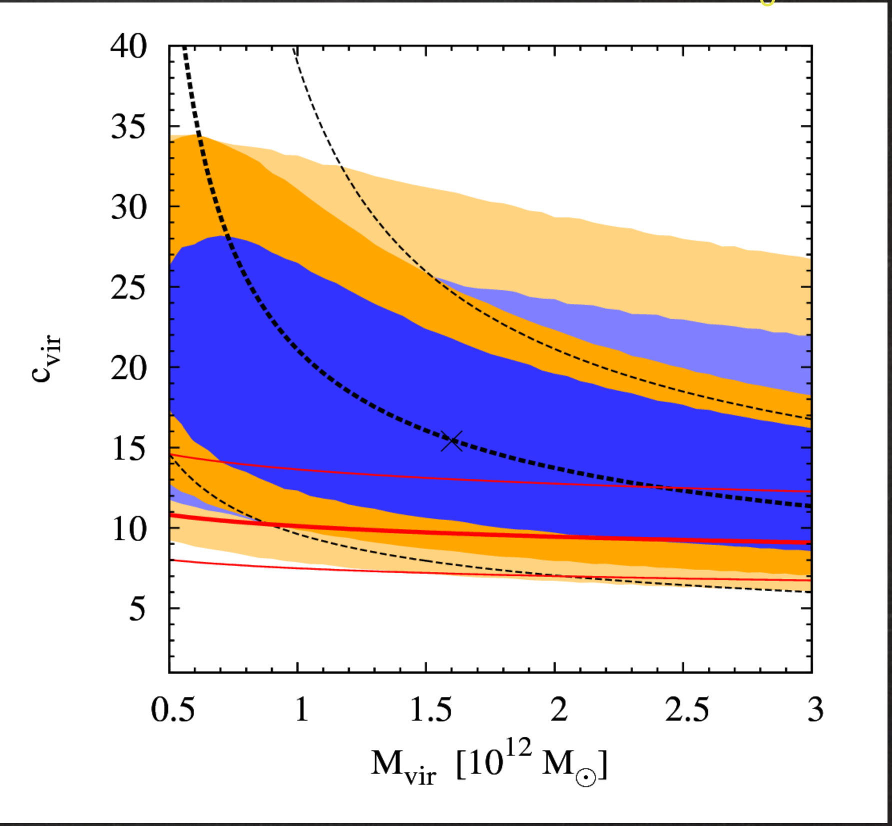
* ρ_0 = 0.4 GeV/cm^3 & r_S = 20 kpc → (M_{vir} = 1.6 10^{12} M_Θ , c_{vir} = 15.2)

(PJ McMillan '11)

No priors

Priors over <σv> and ρ_0





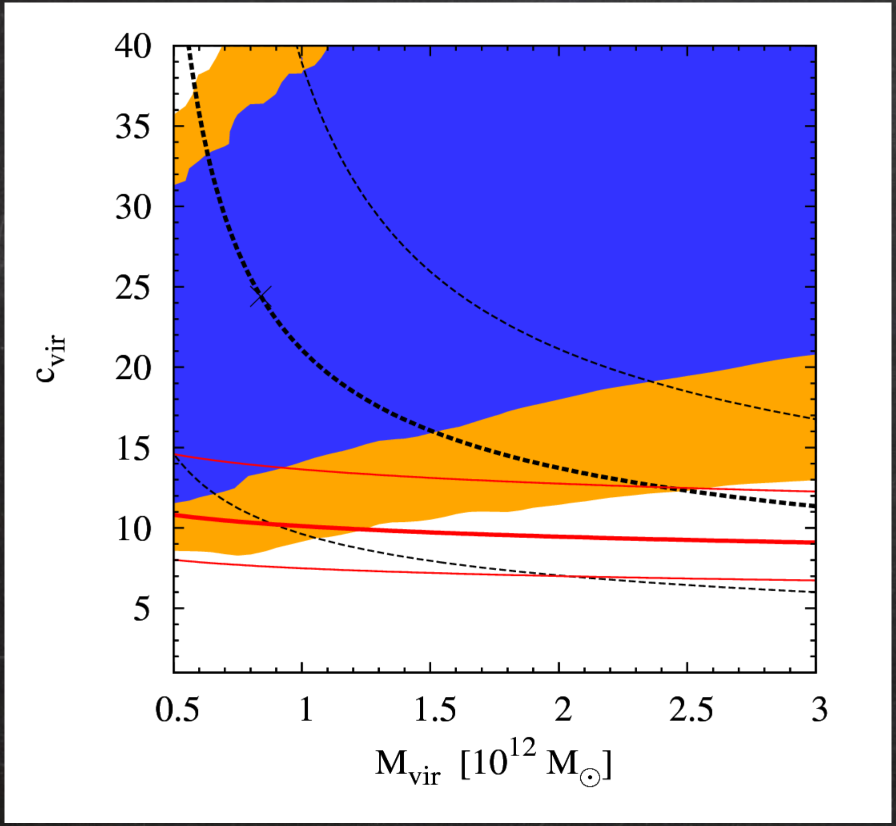
NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 25 GeV and NFW

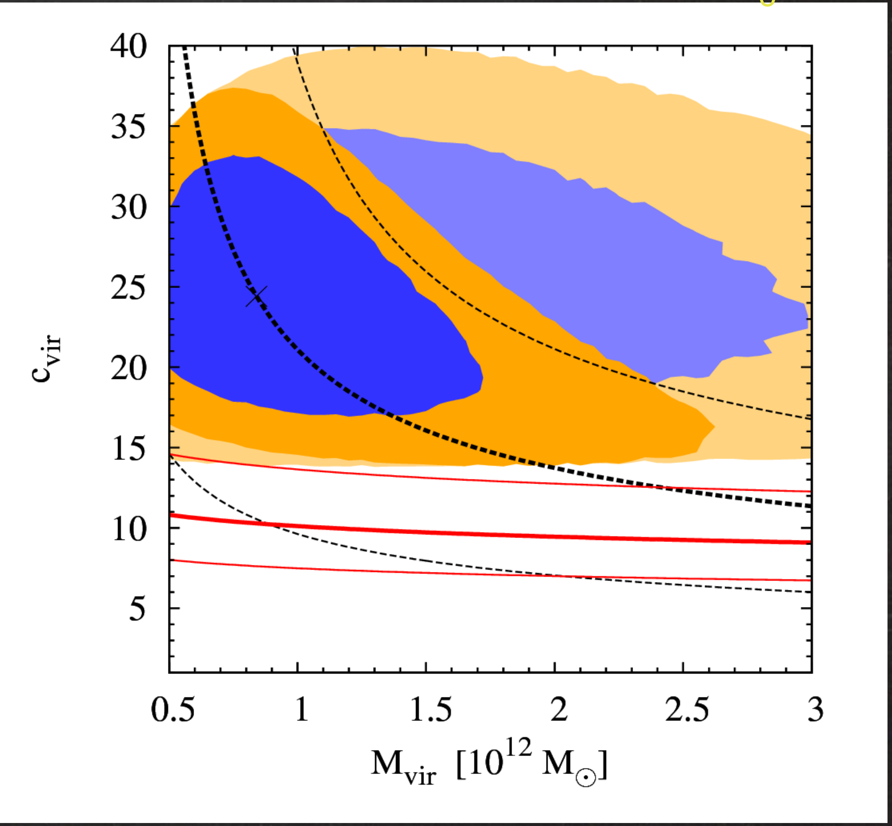
* M_{DM}(60 kpc) = 4 10^{11} $M_\odot$, ρ_0 = 0.4 GeV/cm^3 → r_S = 10 kpc

(SDSS Collab. Xue et al '08)

No priors



Priors over <σv> and ρ_0



NB and S Palomares-Ruiz, arXiv:1103.2377

Conclusions

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

* Conversely, gamma-ray searches could also be used to learn about the structure of the Milky Way DM halo

* We have studied the effect of astrophysical uncertainties on the determination of some DM particle properties

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

* we also consider the improvement in these results when external information on $\langle\sigma v\rangle$ and ρ_0 is included

DM halo profiles

From N-body simulations

NFW profile

$$\rho(r) = \rho_\odot \frac{(R_\odot/r_s)\,[1+(R_\odot/r_s)]^2}{(r/r_s)\,[1+(r/r_s)]^2}$$

Einasto profile

$$\rho(r) = \rho_\odot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - \left(\frac{R_\odot}{r_s}\right)^\alpha\right)\right]$$

Distance Sun - GC

R_0= 8.5 kpc old recommendation by the International Astronomical Union '86!

R_0= 7.2 ± 0.3 kpc (Bica *et al* '05)
R_0= 8.2 ± 0.5 kpc (Bovy *et al* '09)
R_0= 8.33 ± 0.35 kpc (Gillessen *et al* '08)
R_0= 8.4 ± 0.6 kpc (Reid *et al* '09)
R_0= 8.7 ± 0.5 kpc (Vanhollebeke *et al* '09)...

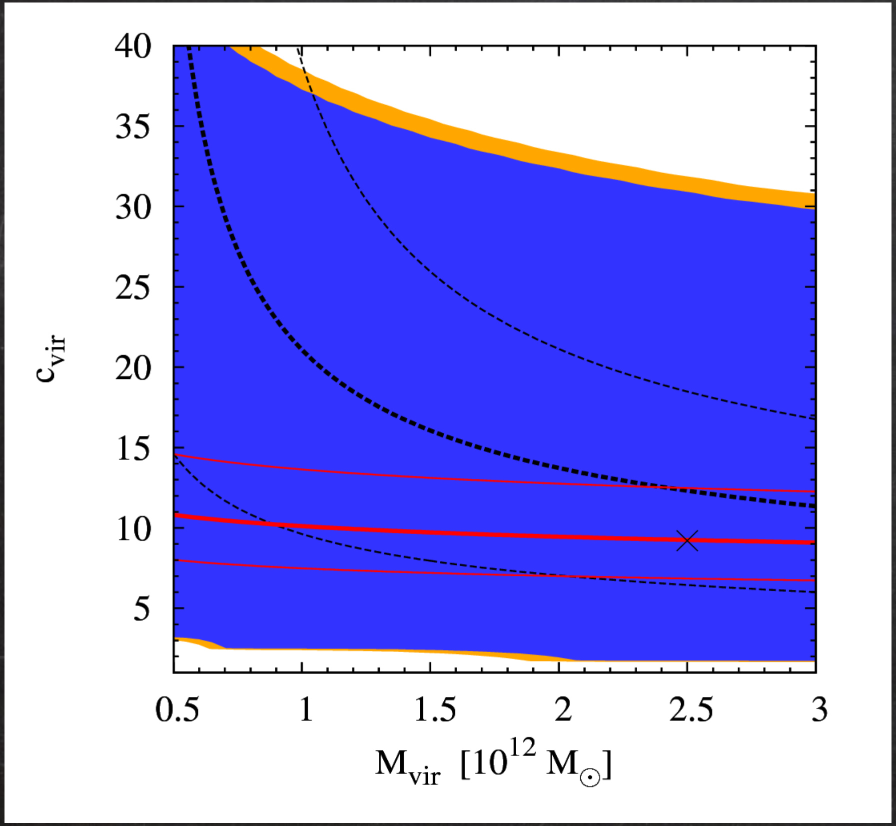
→ we are assuming R_0= 8.3 kpc as our default value

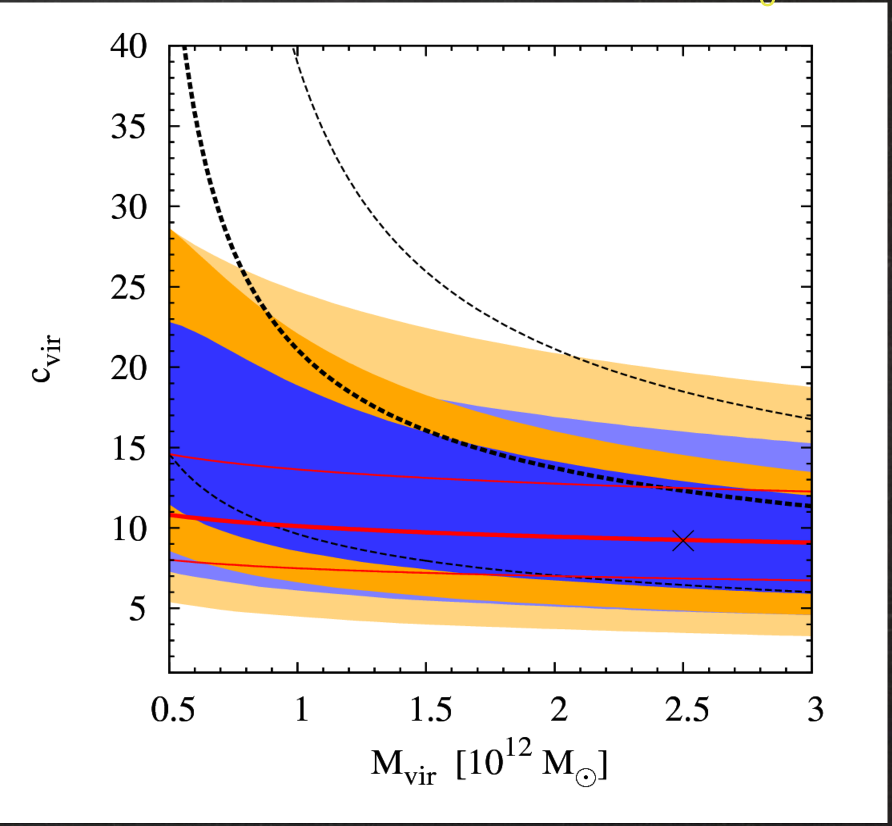
m_x = 25 GeV and NFW

* ρ_0 = 0.3 GeV/cm^3 → r_S = 38.6 kpc (M$_{vir}$ = 2.5 10^{12} M$_\odot$, c$_{vir}$ = 9.2)

No priors

Priors over <σv> and ρ_0





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Comparison with simulations

* We consider the NFW density profile determined by the parameters ρ_0 and r_s

* It's convenient to rewrite these parameters using the virial mass M_{vir} and the concentration parameter c_{vir}

$$R_{\rm vir} = \left[\frac{3\, M_{\rm vir}}{4\pi\, \Delta_{\rm vir}\, \rho_{\rm crit}}\right]^{1/3}$$

$$\Delta_{\rm vir} = 18\pi^2 + 82\,(\Omega_{\rm m} - 1) - 39\,(\Omega_{\rm m} - 1)^2$$

$$c_{\rm vir} \equiv \frac{R_{\rm vir}}{r_s}$$

Statistical method

$$\chi^2(\theta) = \sum_{j=1}^{10} \sum_{i=1}^{20} \frac{\left(S_{ij}(\theta) - S_{ij}^{\rm th}(\theta^0)\right)^2}{(\sigma_{\rm stat})_{ij}^2 + (\sigma_{\rm sys})_{ij}^2} \,,$$

$$(\sigma_{\rm stat})_{ij}^2 = S_{ij}^{\rm th}(\theta^0) + B_{ij} \,,$$

$$\sigma_{\rm sys} = 3\,\sigma_{\rm stat}$$

$$\chi^2_{\rm prior}(\theta) = \sum_{j=1}^{10} \sum_{i=1}^{20} \frac{\left(S_{ij}(\theta) - S_{ij}^{\rm th}(\theta^0)\right)^2}{(\sigma_{\rm stat})_{ij}^2 + (\sigma_{\rm sys})_{ij}^2} + \left(\frac{\rho_\odot - \rho_\odot^0}{\sigma_{\rho_\odot}}\right)^2 + \left(\frac{\log\langle\sigma v\rangle - \log\langle\sigma v\rangle^0}{\sigma_{\log\langle\sigma v\rangle}}\right)^2$$

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Local DM density:

$\rho_0 = 0.3\ \mathrm{GeV/cm^3}$ it's usually assumed but...

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ρ_0= 0.43 ± 0.15 GeV/cm^3 (Salucci *et al* '10)

ρ_0= 0.5 ± 0.2 GeV/cm^3 (Gates *et al* '95)

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