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

Nicolás BERNAL
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Universität Bonn

Bethe Forum, November 17, 2011

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 – 'The WIMP Miracle'

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We assume a particle-physics model independent-framework:

→ generic WIMP with mass m_χ ,
annihilation cross-section $<\sigma v>$
and annihilating into a given 2 SM particles final state.

Detecting Dark Matter

* **Collider searches**
  Missing energy
  (Tevatron, LHC, ILC, CLIC...)

* **Direct detection**
  Nuclear recoil produced by DM elastic scattering
  (Xenon, CDMS, Edelweiss, DAMA/LIBRA, CoGent, CRESST...)

* **Indirect detecion**
  Observation of annihilation/decay products
  - Gamma-rays telescopes
    (Fermi, EGRET, Hess, Magic, Veritas...)

  - Antimatter experiments
    (Pamela, AMS-02, Heat, Bess...)

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

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Complementarity between different detection modes!

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Signal and backgrounds

Gamma-rays: general features

The differential intensity of the gamma-ray signal

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

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Gamma-rays: general features

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Prompt gamma-rays produced by annihilation of DM particles:

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

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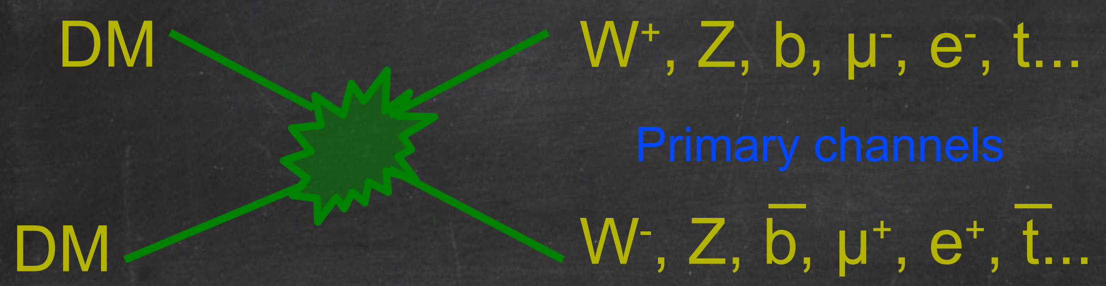
* Particle physics:

- 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-ray spectra from DM annihilation

We assume DM annihilates into 2 SM particles and use Pythia.



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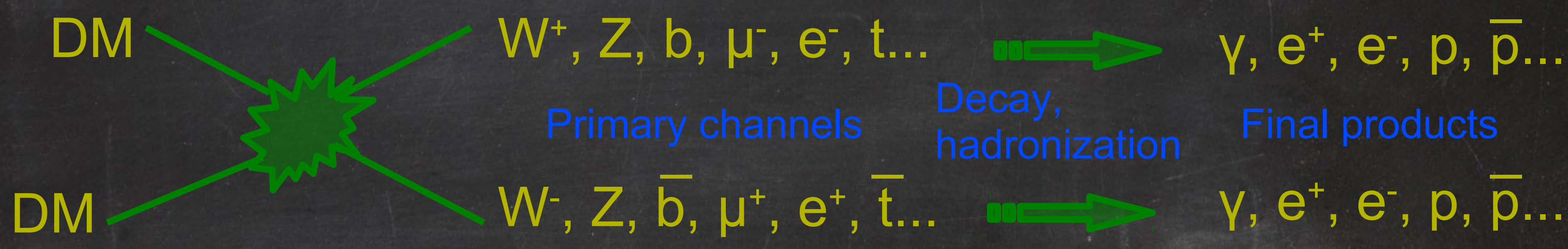
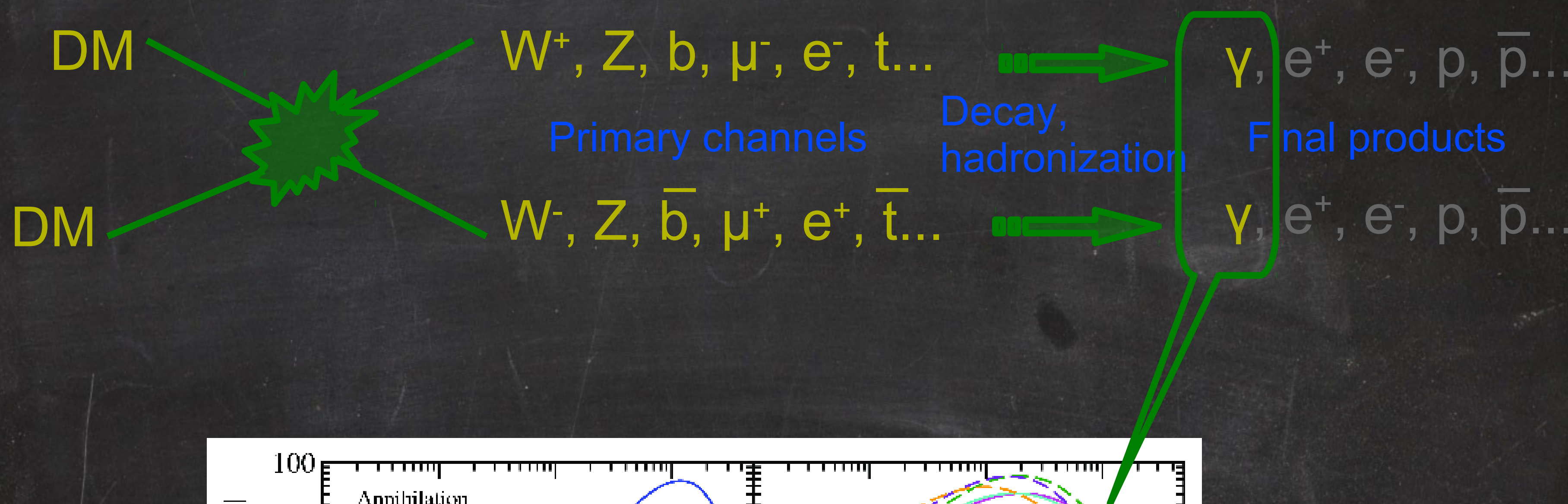
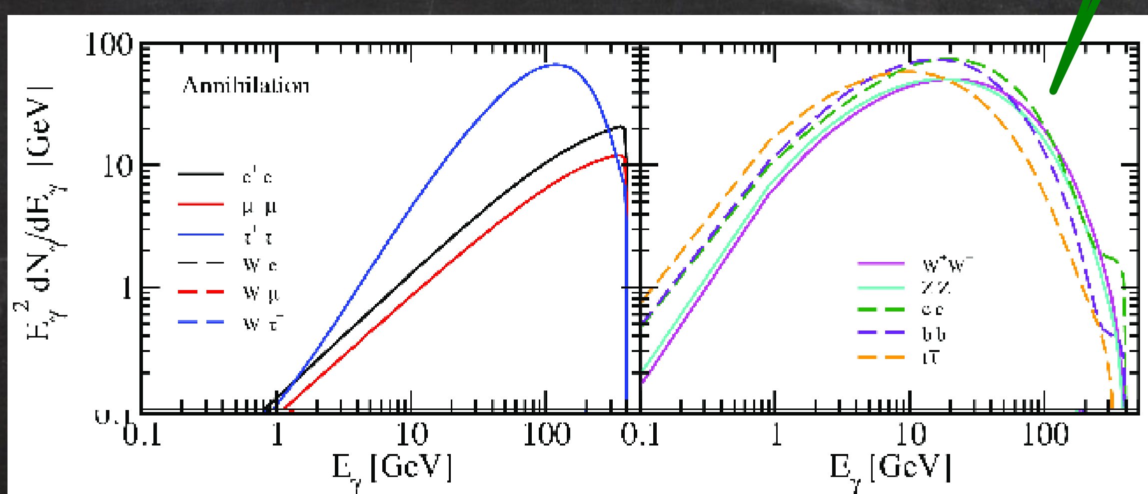


Gamma-ray spectra from DM annihilation

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



Hard channels



Soft channels

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

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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 the ROI

DM halo profiles

From N-body simulations

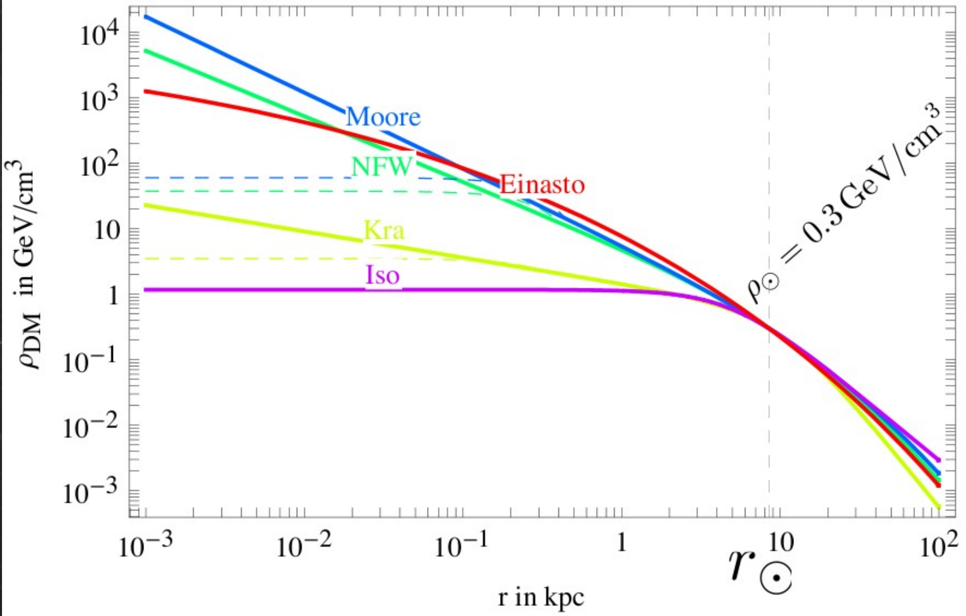
NFW profile (Via Lactea II)

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

Einasto profile (Aquarius)

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

Free parameters: ρ_0 , r_s ρ_0 , r_s and α



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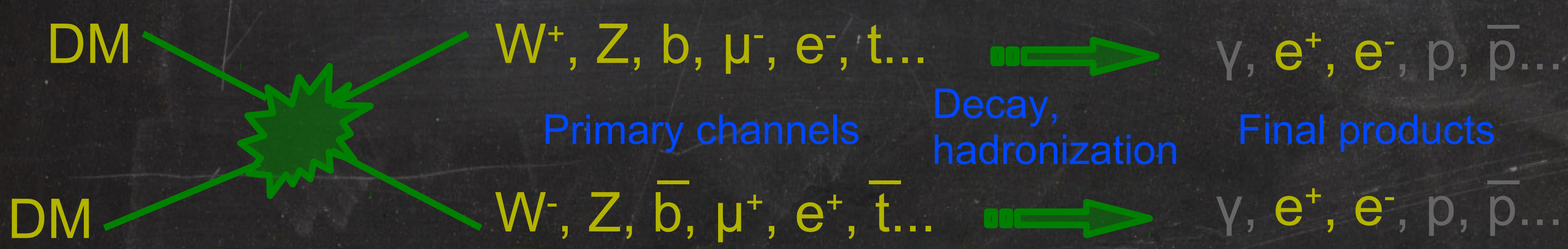
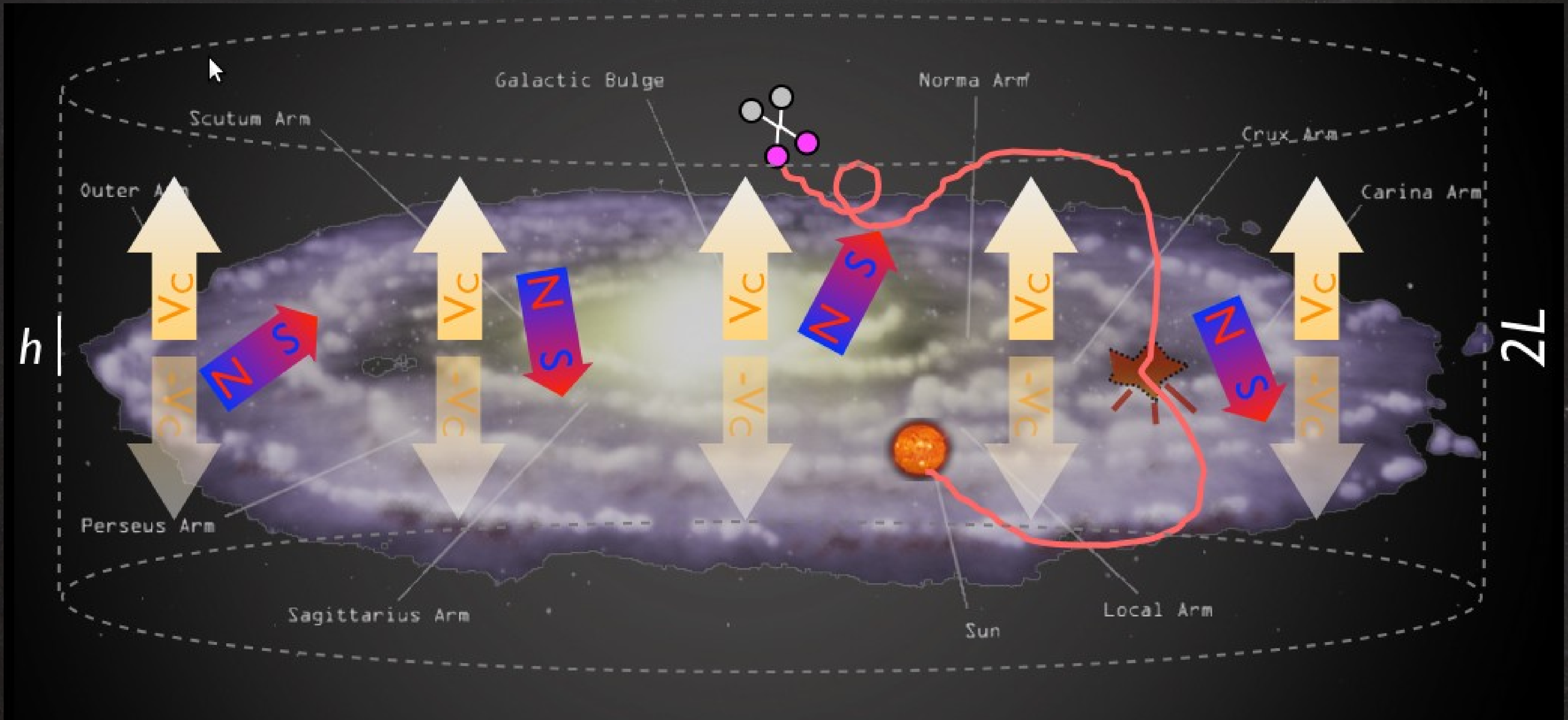
* Gamma-rays from Inverse Compton Scattering:

  - Electrons/Positrons propagate in the ISM



Gamma-rays: general features



$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

borrowed from M. Cirelli

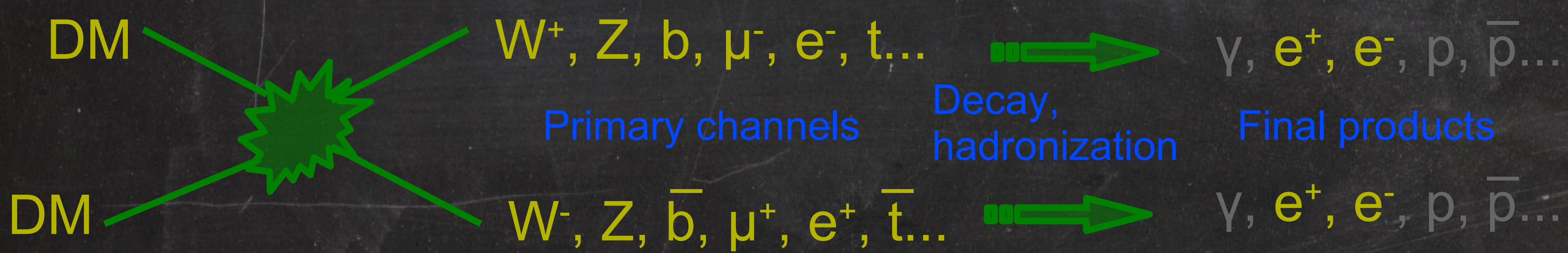
Gamma-rays: general features

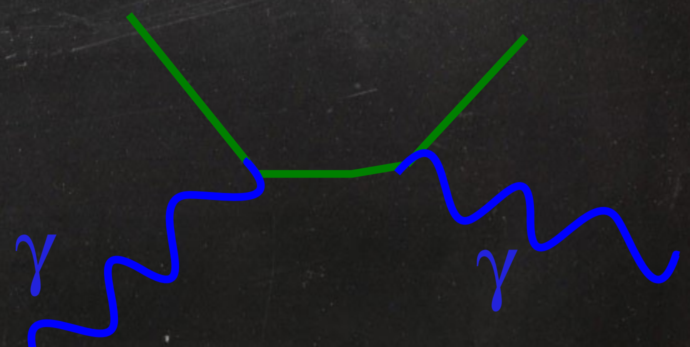
The differential intensity of the gamma-ray signal

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

* Gamma-rays from Inverse Compton Scattering:

- Gamma-rays production via ICS off the ambient photon background (CMB, Star light, IR...)





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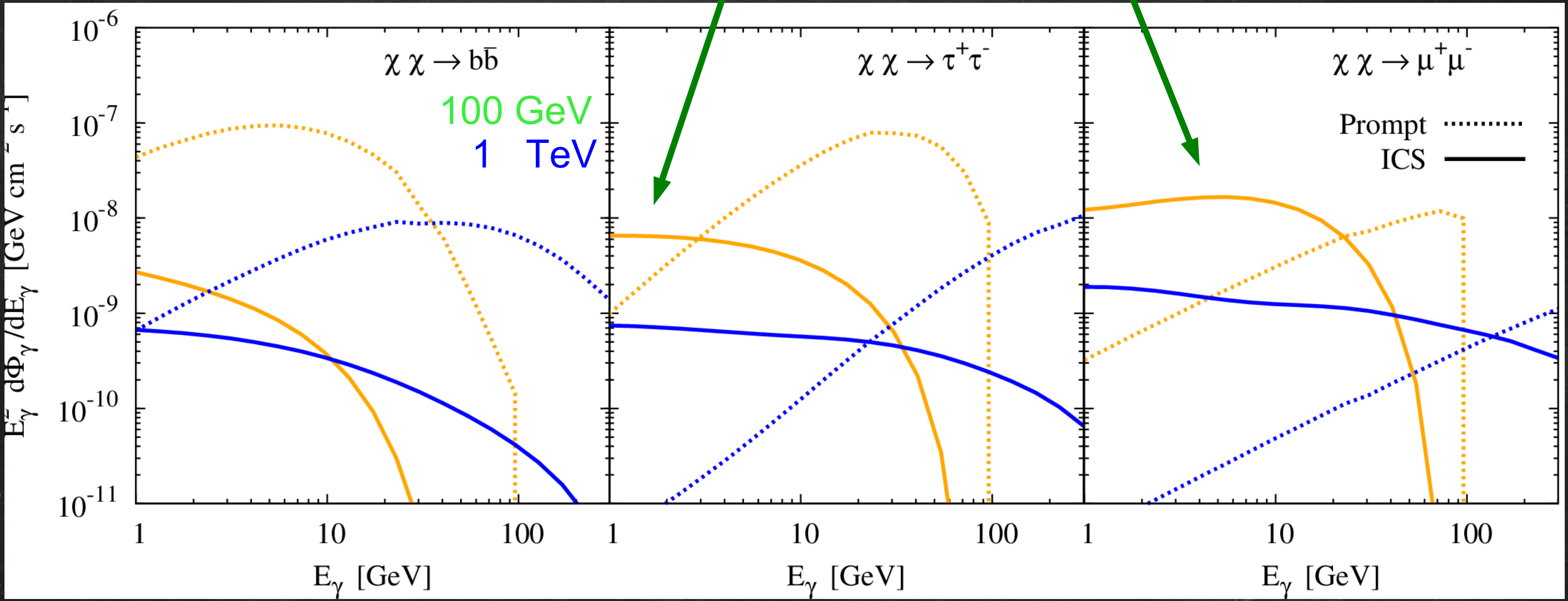
* Bremsstrahlung is due to particle interaction with the ISM, subdominant with respect to the prompt photons and ICS

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

Gamma-ray spectra from DM annihilation

Important contribution from ICS at low energies!



NB and S Palomarez-Ruiz arXiv:1006.0477

Instrument modelization

Fermi Science Tools (version v9r23p1)

Signal

* Compute the signal
* We generate photon events according
to the instrument response function: ***gtobssim***

Galactic backgrounds

* Diffuse galactic emission:

gll_iem_v02_P6_V11_DIFFUSE.fit (Recommended by the Fermi coll.)

  Pions decay

  Bremsstrahlung

  Inverse Compton scattering of CR

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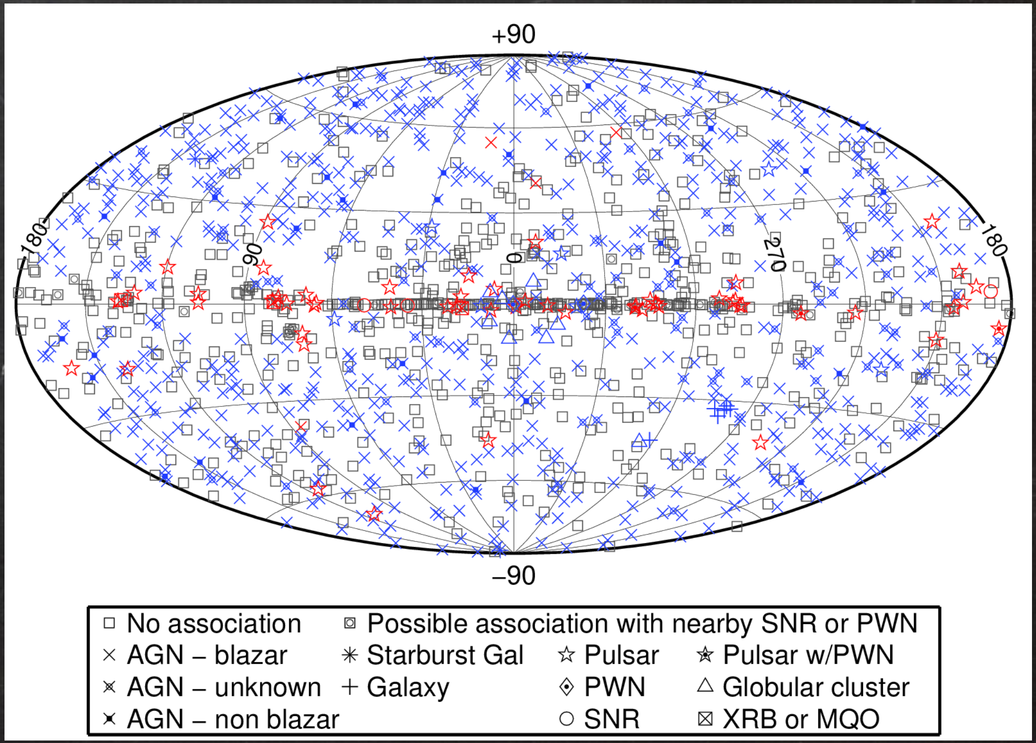
* Resolved point sources:
AA Abdo [Fermi-LAT Collaboration], Astrophys. J supp . 188:405, 2010

1451 point sources resolved at > 4 σ



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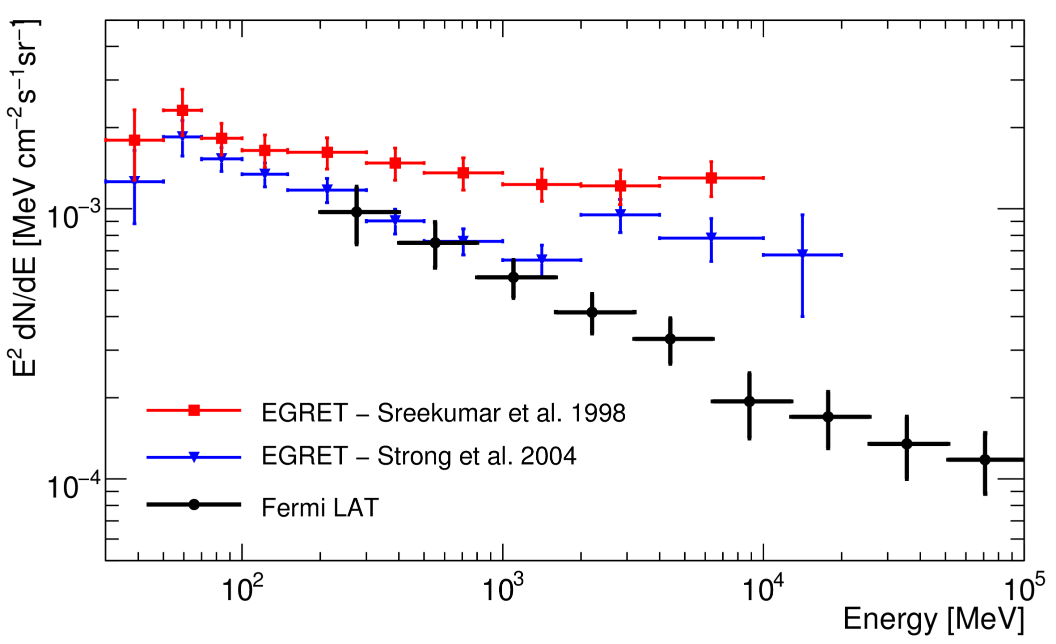
AA Abdo [Fermi-LAT Collaboration], Astrophys. J supp . 188:405, 2010

* Isotropic background:
AA Abdo [Fermi-LAT Collaboration], Phys. Rev. Lett. 104,101101, 2010
isotropic_iem_v02_P6_V11.txt



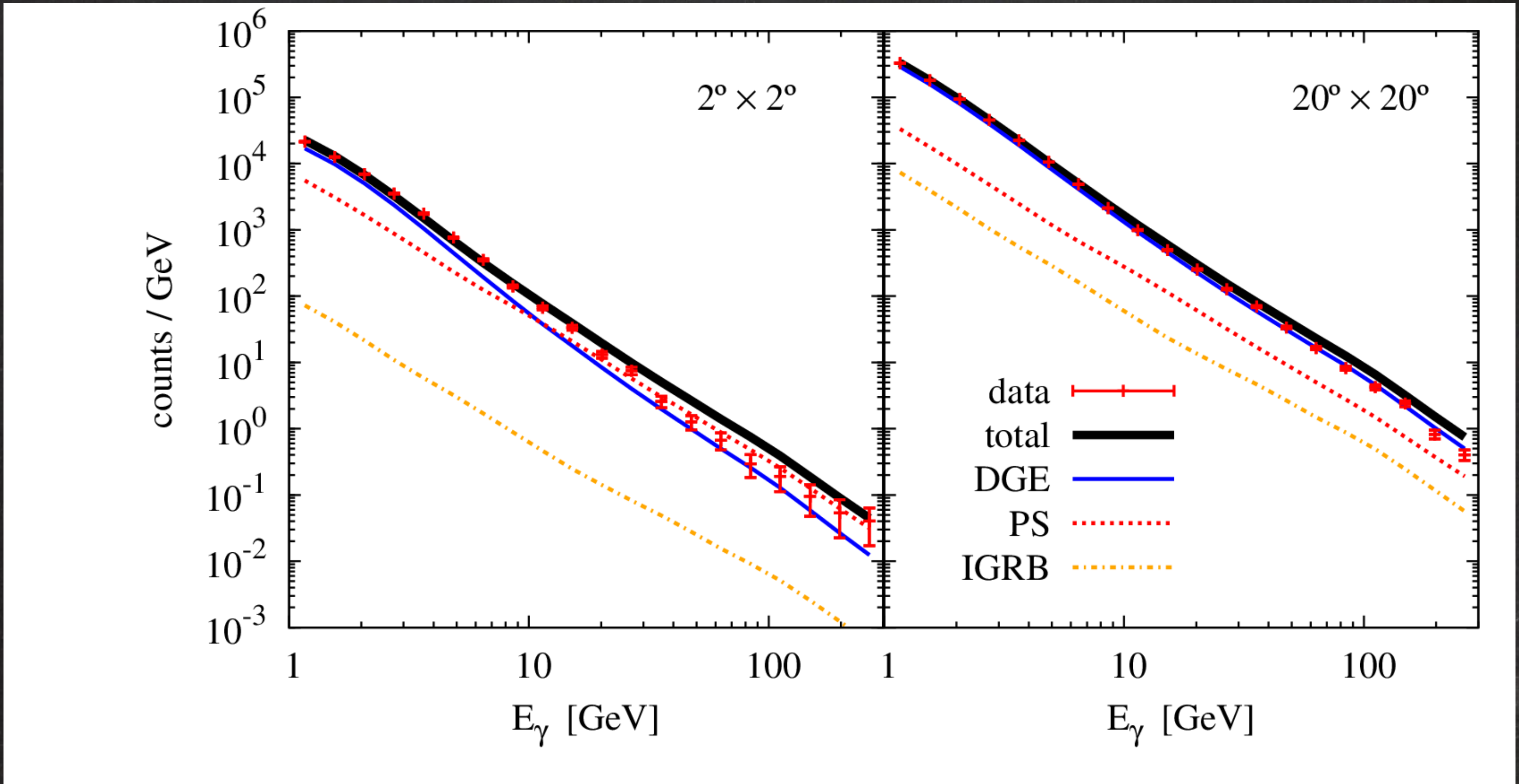
Instrument modelization

Fermi Science Tools (version v9r23p1)

Signal
* Compute the signal
* We generate photon events according to the instrument response function: ***gtobssim***

Background (data from Fermi-LAT)
* Download raw data
* Apply cuts on energy, position and time: ***gtselect*** + ***gtmktime***
  August 4, 2008 to July 12 2011
  20ºx20º centered in the GC (RA=266.46º, Dec=-28.97º)
* binned likelihood of the data: ***gtlike***
  (normalizations free)

Galactic backgrounds



NB and S Palomares-Ruiz, arXiv:1006.0477

Overview of the analysis

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

* We select an 'optimal' angular window

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

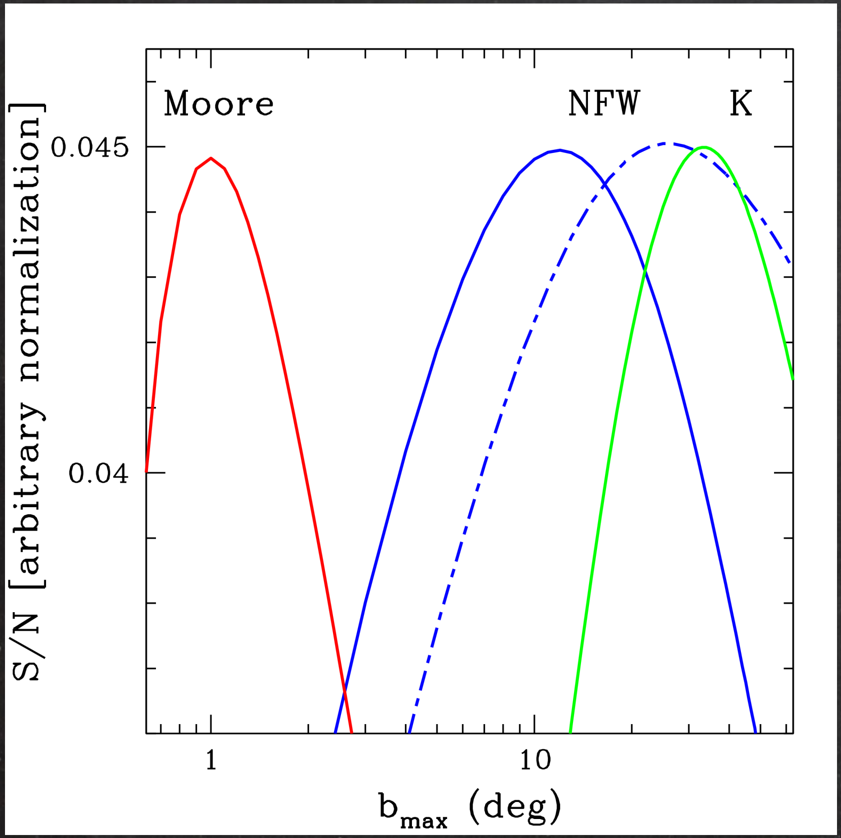
* We use the latest Fermi measurements for
  the background around the GC

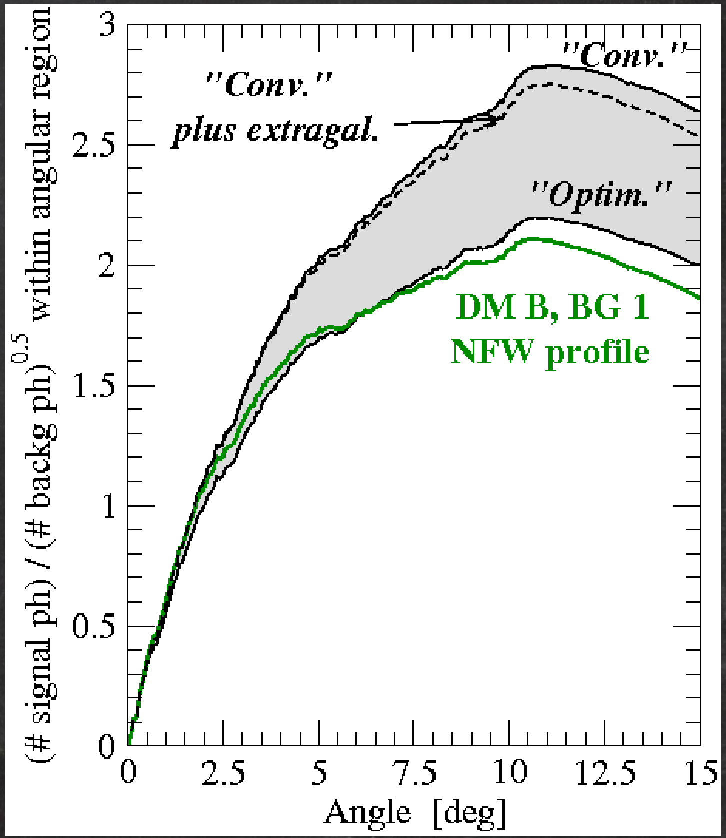
* We evaluate Fermi abilities to constrain DM properties:
  annihilation cross section, mass
  and dominant annihilation channels

* We evaluate Fermi abilities to constraint DM density profile

Optimal angular window

Significance of the signal: S/N





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

TE Jeltema and S Profumo
JCAP 0811:003, 2008

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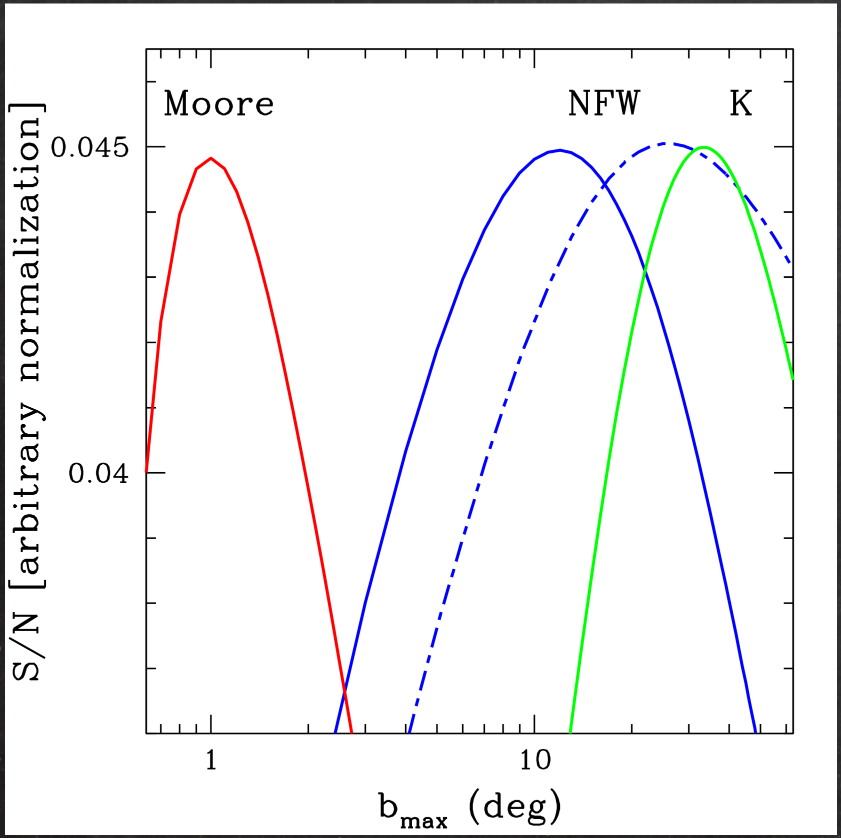

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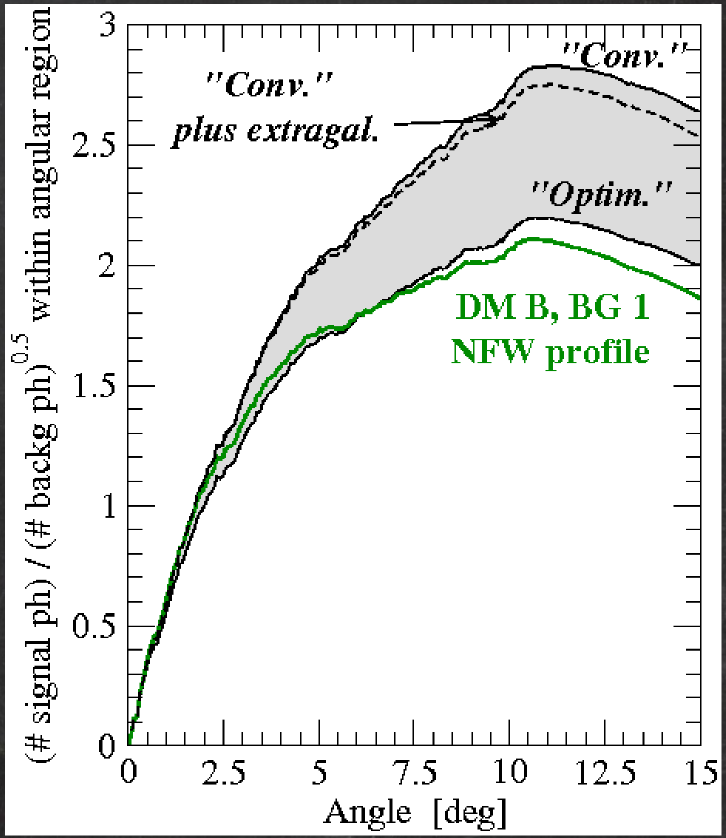


TE Jeltema and S Profumo
JCAP 0811:003, 2008

Our selection:
→ 10 degrees

Constraining DM properties

Constraining DM properties

* With Colliders

G. Polesello and D. R. Tovey, JHEP 05:071, 2004
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. Bélanger, 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 Detection

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
M. Drees, C.-L. Shan, JCAP 0806:012, 2008
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
J. Billard, F. Mayet, D. Santos Phys.Rev. D83 (2011) 075002...

* With Neutrinos from the Sun

J. Edsjö 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
A. Esmaili, Y. Farzan JCAP 1104 (2011) 007
C.R. Das, O. Mena, S. Palomarez-Ruiz, S. Pascoli arXiv:1110.5095...

* 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
S. Palomares-Ruiz and J. Siegal-Gaskins, JCAP 07:023, 2010
NB and S. Palomares-Ruiz, arXiv:1006.0477 and arXiv:1103.2377...

* With a Combination

NB, A. Goudelis, Y. Mambrini and C.Muñoz, JCAP 0901:046, 2009
G. Bertone, D. G. Cerdeño, M. Fornasa, R. R. Austri and R. Trotta, Phys. Rev. D82:055008, 2010
G. Bertone, D.G. Cerdeño, M. Fornasa, L. Pieri, R.Ruiz de Austri, R. Trotta arXiv:1111:2607...

Constraining DM properties: default setup

* 20º x 20º around the GC

* DM profile: NFW

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

* Propagation model: MED

* 5 years data taking

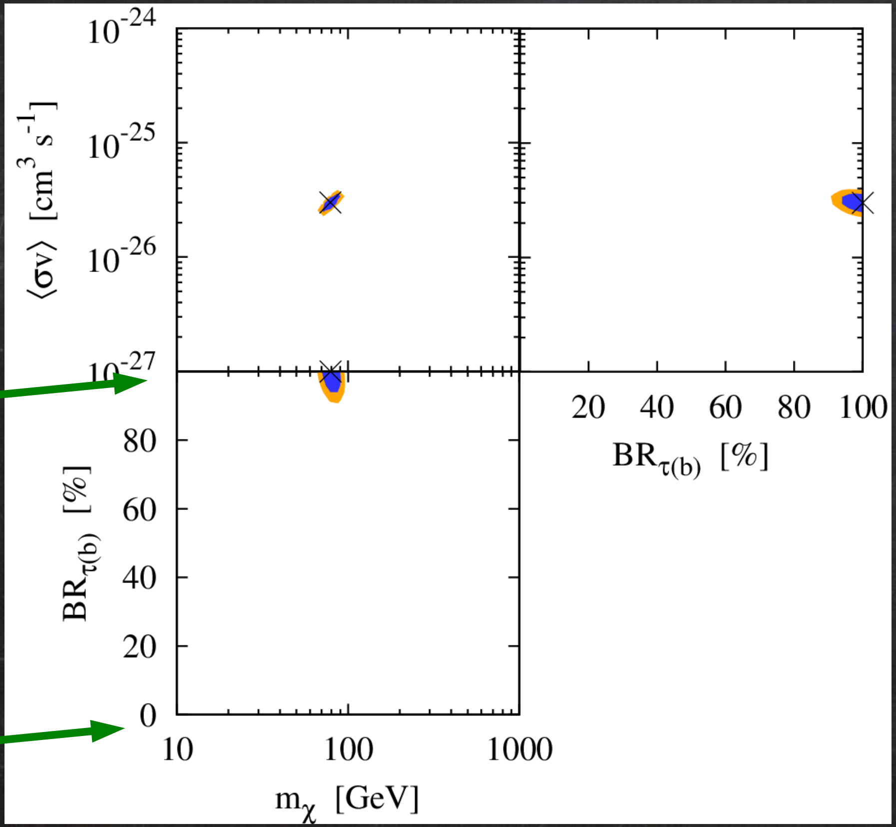
* “Real data”: $\tau^+ \tau^-$ pairs

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

* DM density profile known

Default setup

m_χ = 80 GeV



100% $\tau^+\tau^-$

100% $b\bar{b}$

NB and S Palomares-Ruiz, arXiv:1006.0477

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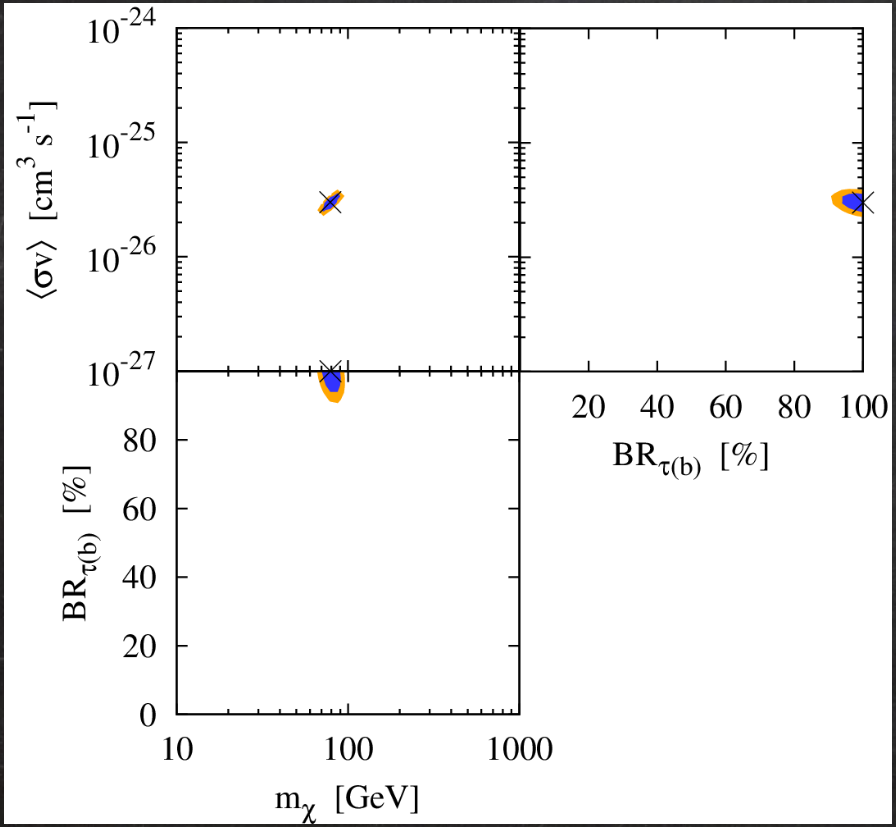
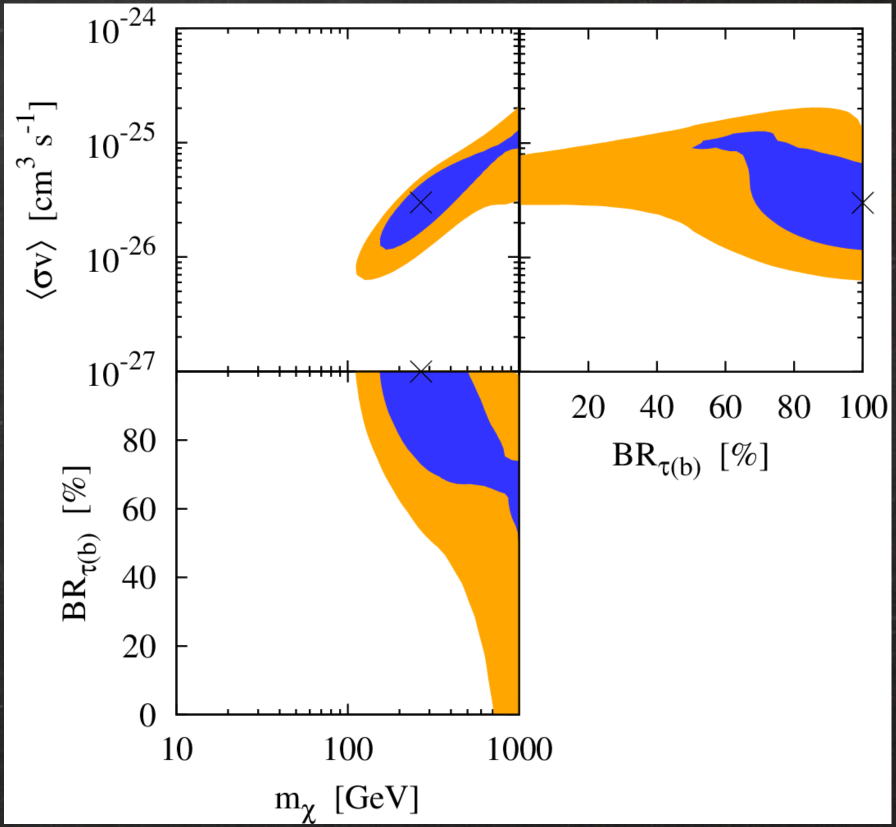


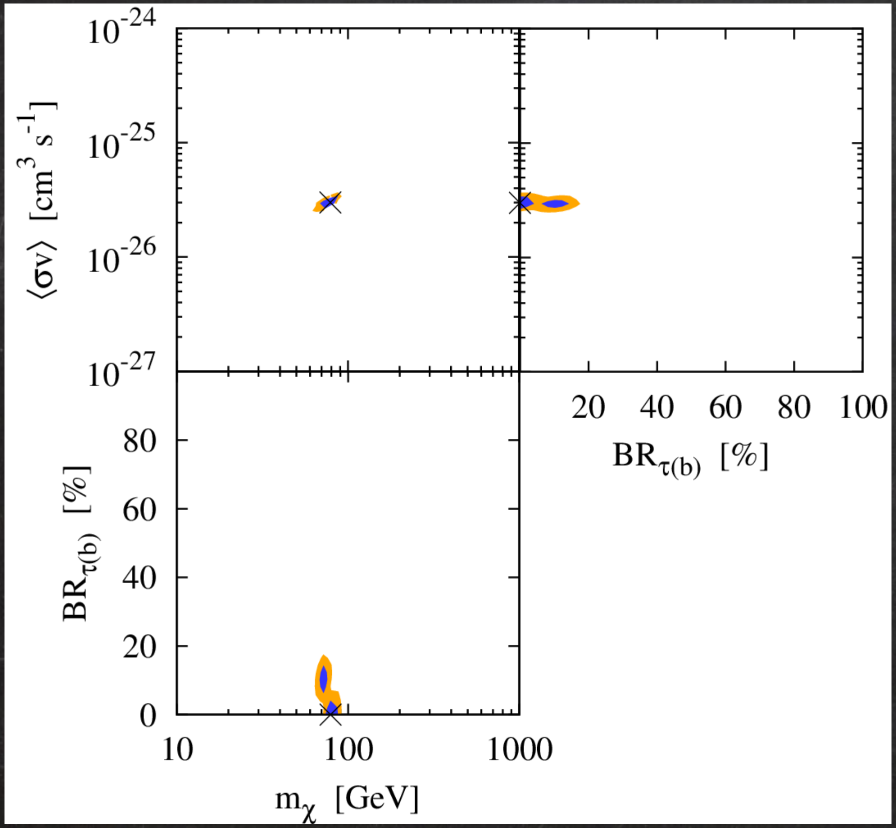
m_χ = 270 GeV



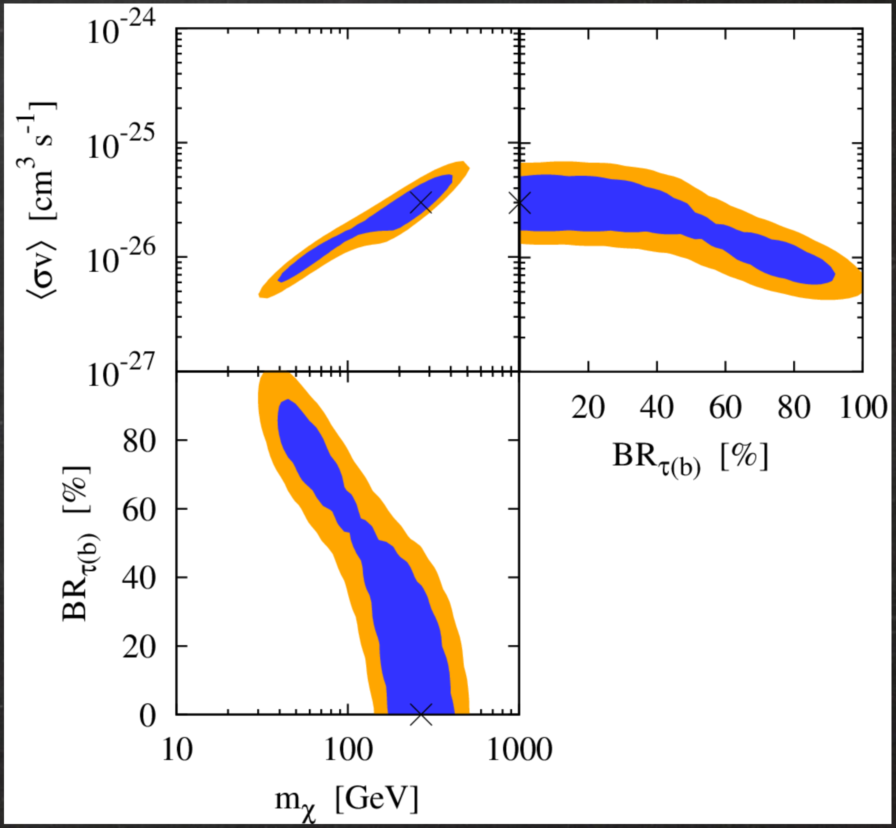
NB and S Palomares-Ruiz, arXiv:1006.0477

Data: bb

m_χ = 80 GeV



m_χ = 270 GeV

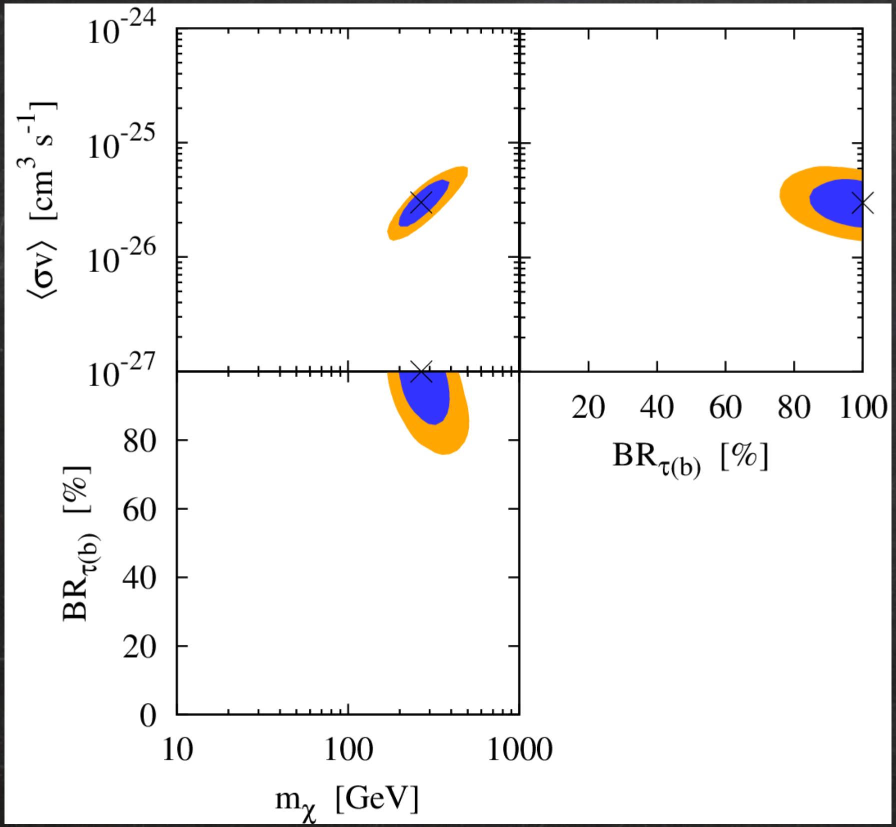


NB and S Palomares-Ruiz, arXiv:1006.0477

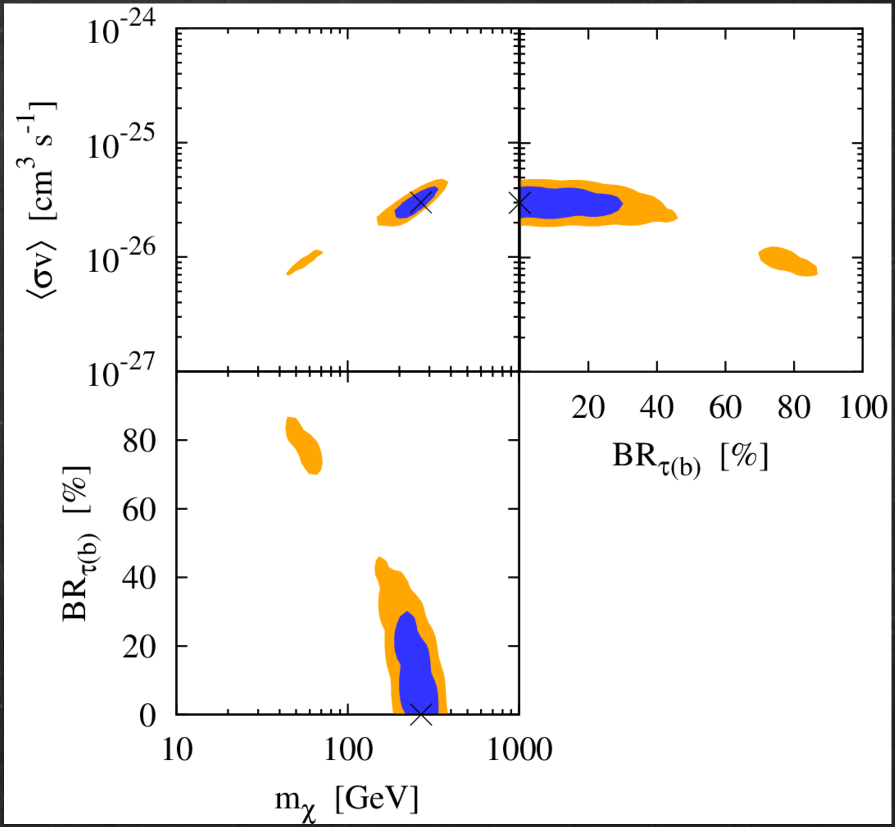
Dependence on the DM density profile

Einasto DM profile
m = 270 GeV

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



Data: bb

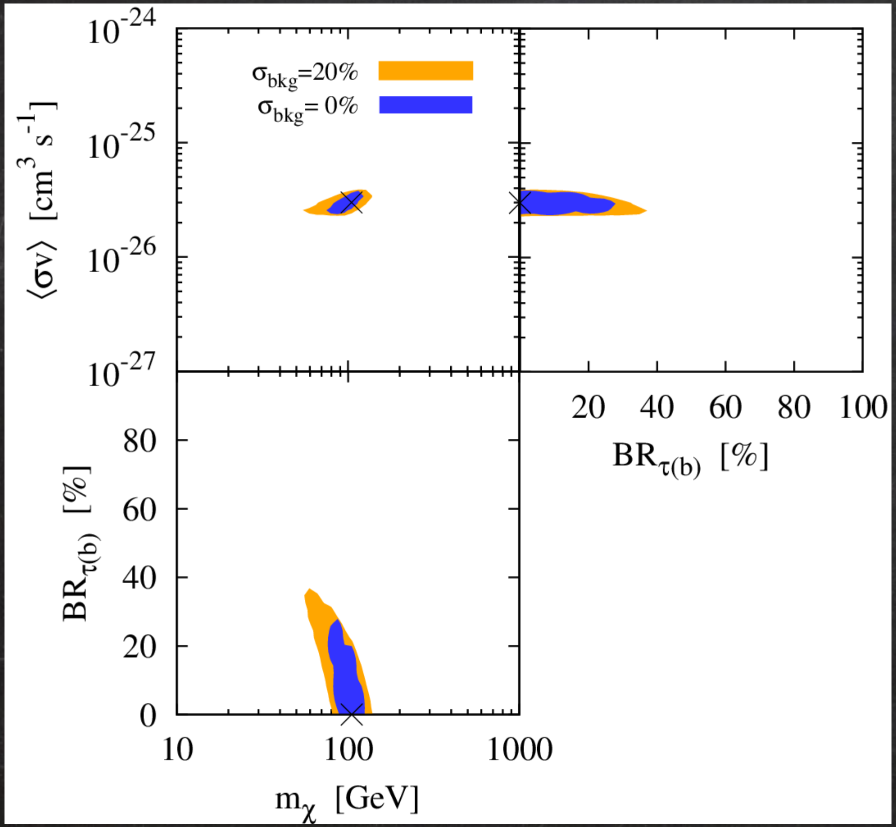


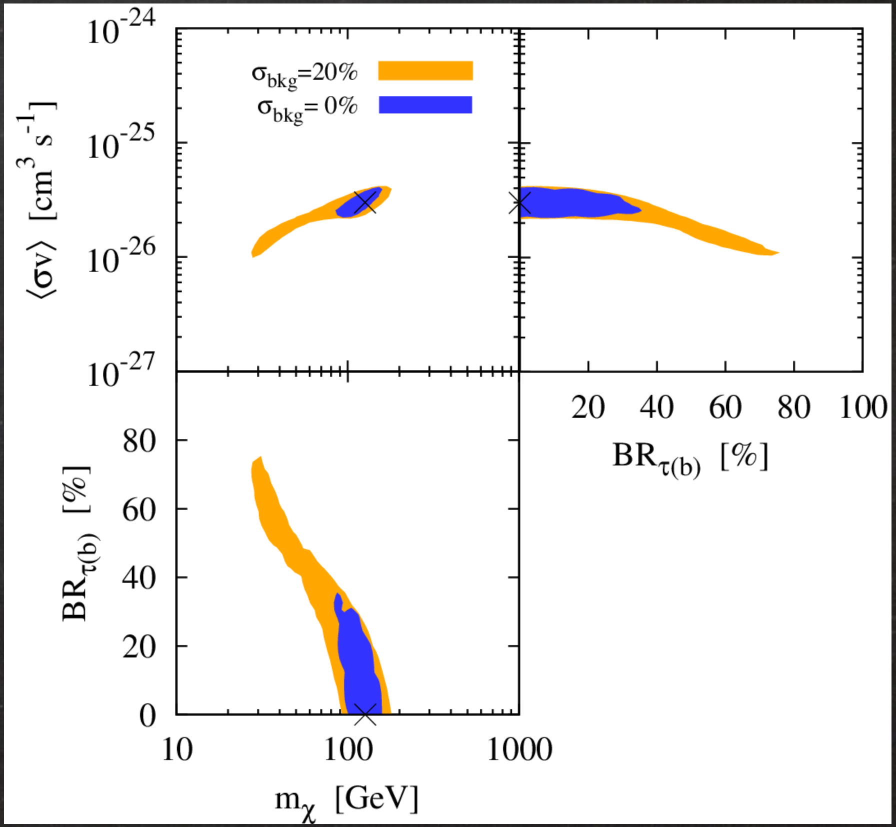
NB and S Palomares-Ruiz, arXiv:1006.0477

Dependence on systematic errors

Data: bb
Error background: 20%

m$_\chi$ = 105 GeV   m$_\chi$ = 125 GeV



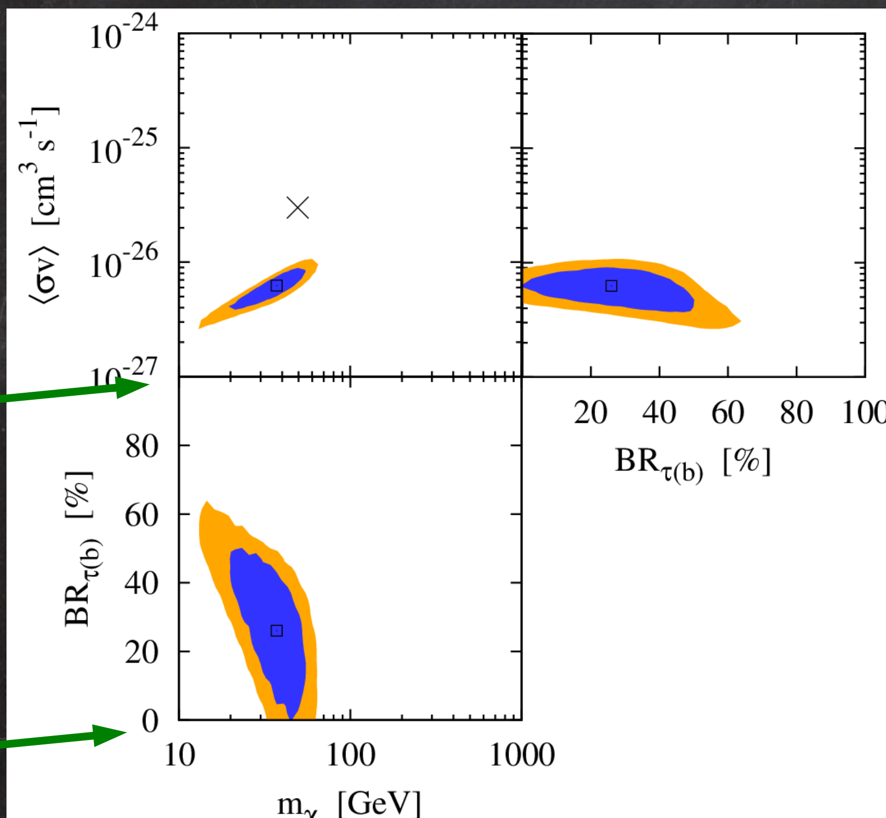


NB and S Palomares-Ruiz, arXiv:1006.0477

Dependence on the assumed DM model

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

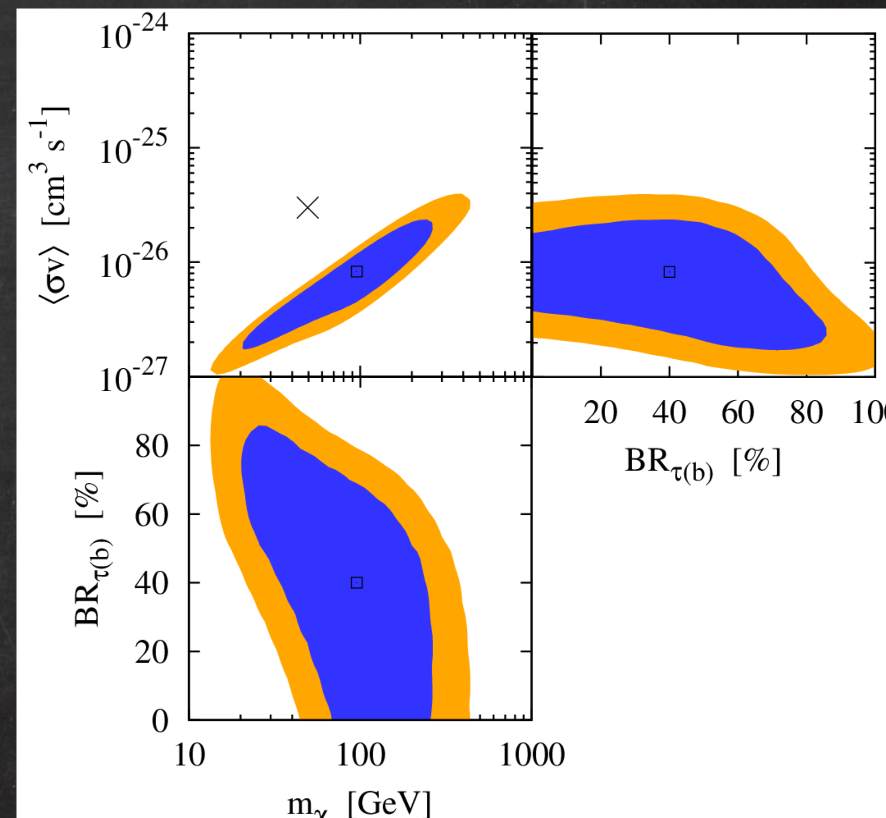
m_χ = 50 GeV



100% $\tau^+\tau^-$

100% $b\bar{b}$

m_χ = 105 GeV



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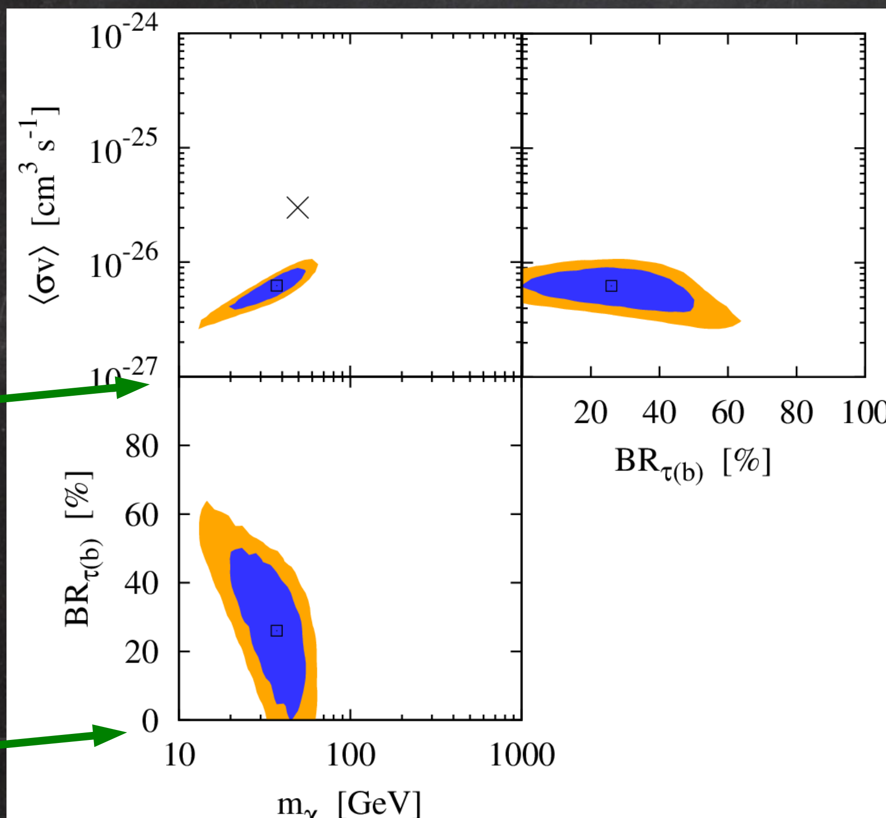
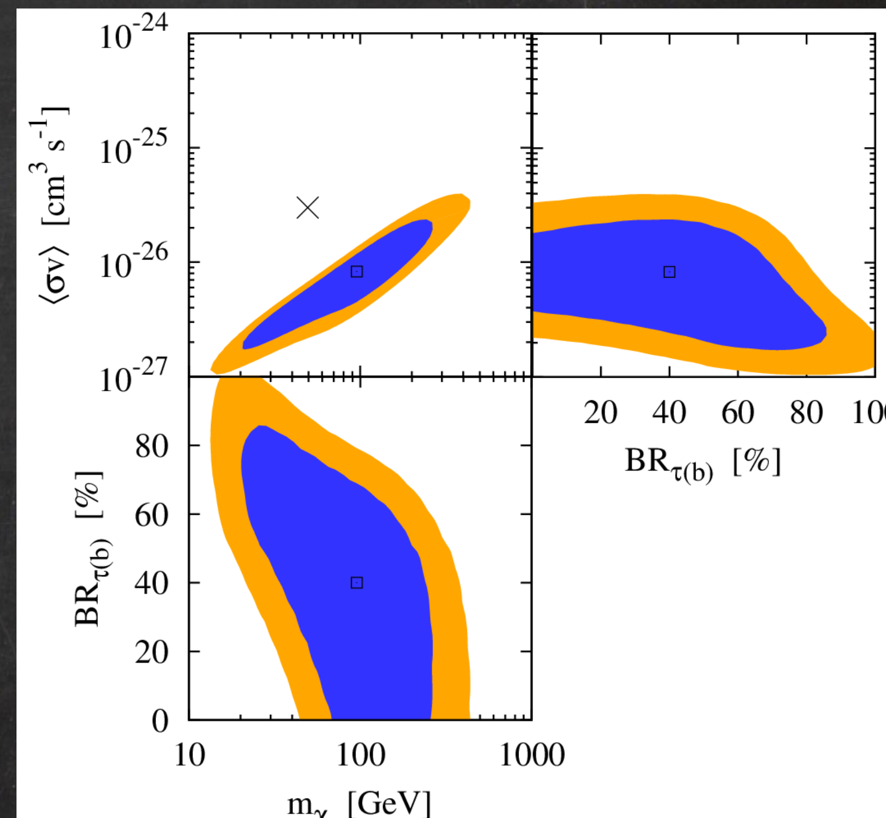


m_χ = 105 GeV



100% $\tau^+\tau^-$

100% $b\bar{b}$

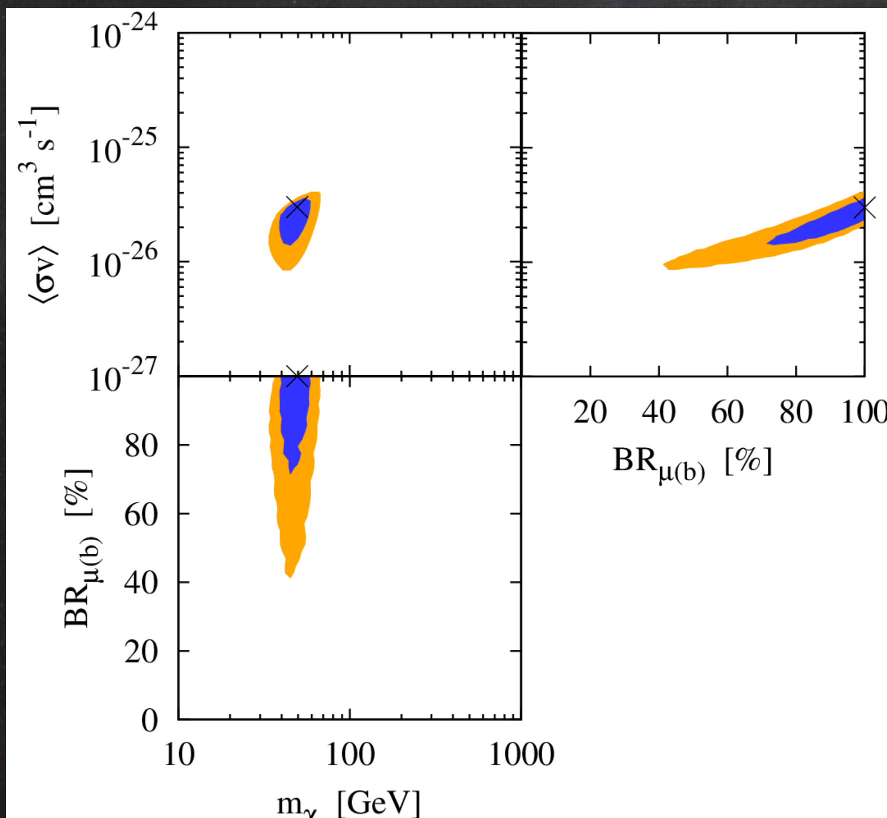
NB and S Palomares-Ruiz, arXiv:1006.0477

when taking into account the ICS to the γ spectrum, the annihilation channels cannot be generically classified as hard or soft

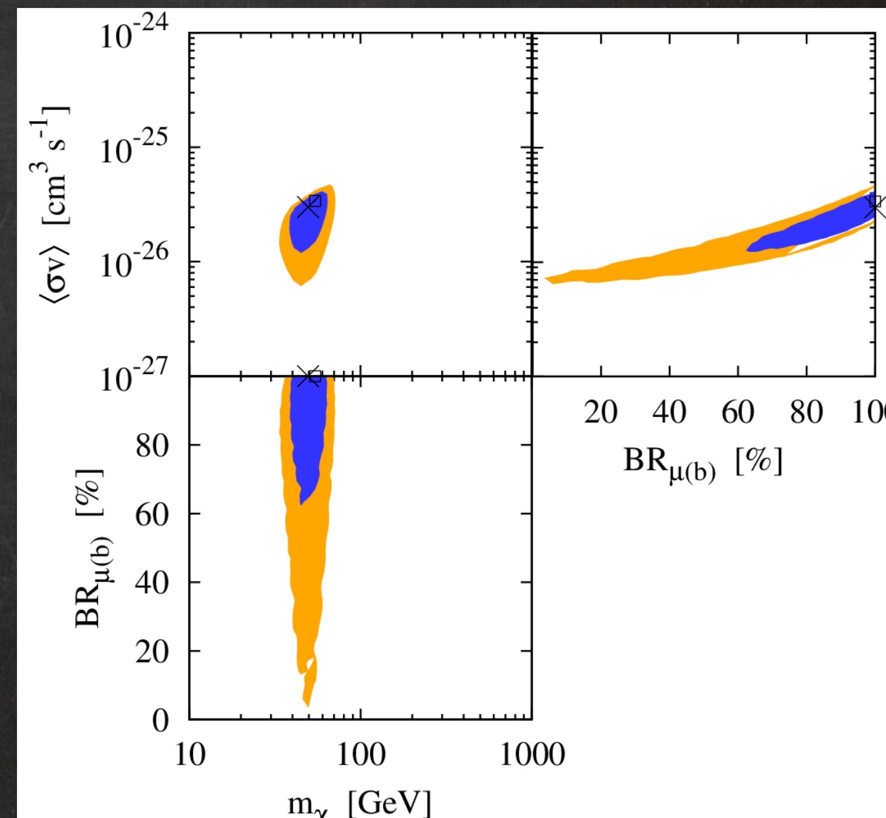
Dependence on the propagation model

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

MED with MED



MIN with MAX



NB and S Palomares-Ruiz, arXiv:1006.0477

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

* $\langle\sigma v\rangle = 3\ 10^{-26}$ cm^3 / s
  “Real data”: b b pairs

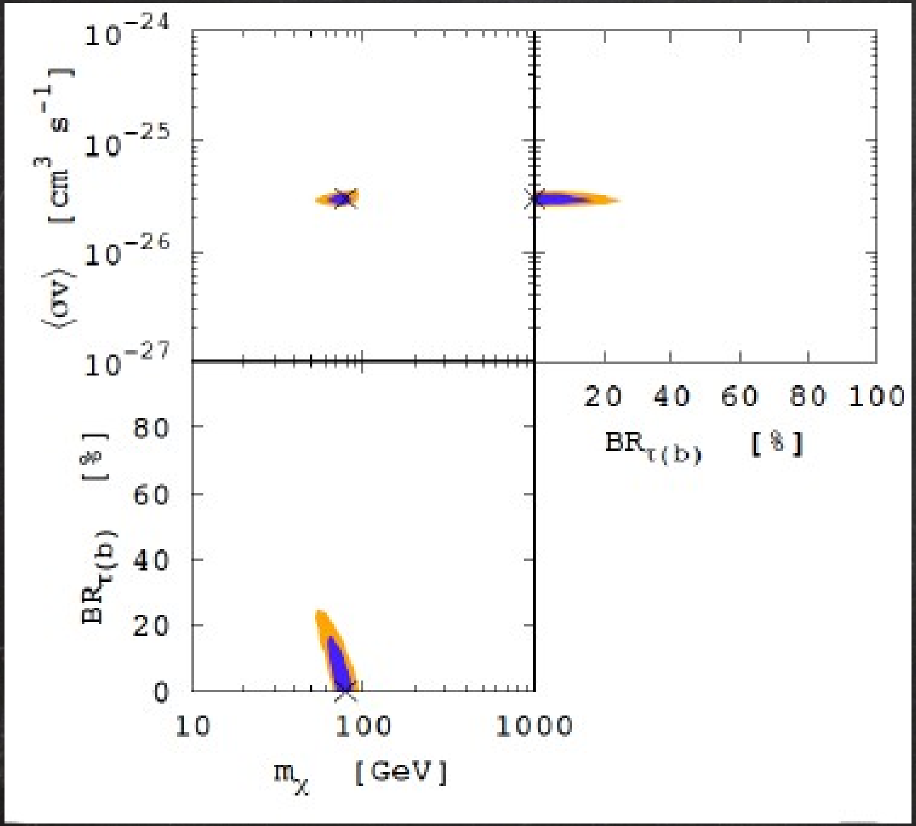
* DM profile: Einasto or NFW
  $\rho_0 = 0.4$ GeV/cm^3
  $R_0 = 8.3$ kpc
  $\alpha = 0.17$ $r_s = 20$ kpc

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

* Background error: statical + systematics (normalization)

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

DM properties...



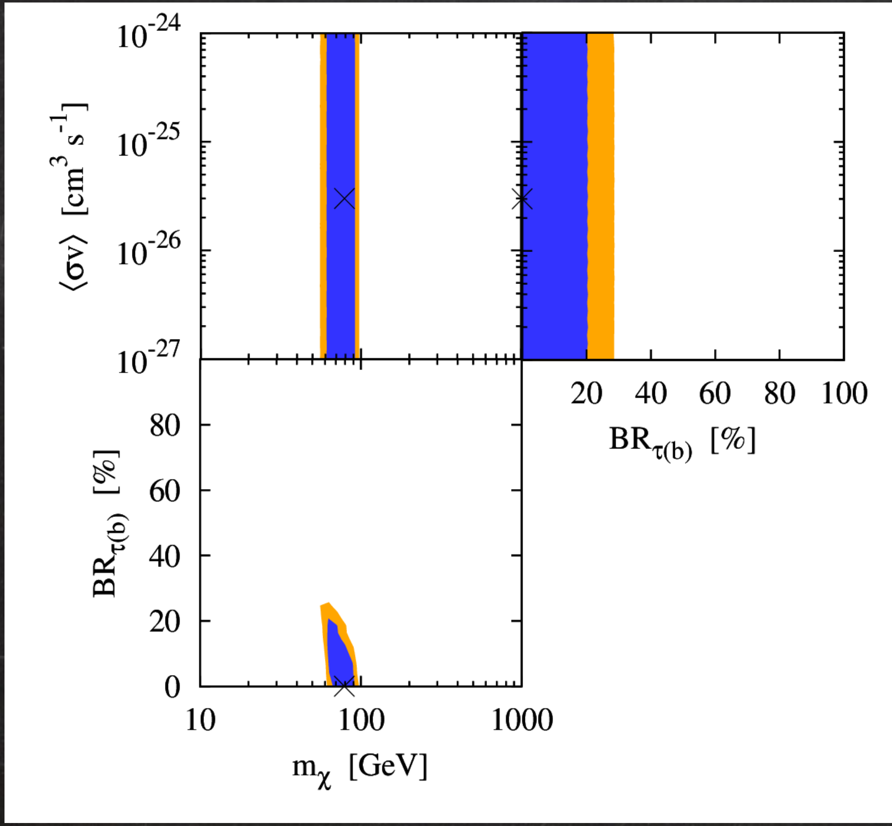
$$\rho(r) = \rho_\odot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - \left(\frac{R_\odot}{r_s}\right)^\alpha\right)\right]$$

ρ_0 , r_s and α

NB and S Palomares-Ruiz, arXiv:1006.0477

m_x = 80 GeV and Einasto DM profile unknown

DM properties...



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NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 80 GeV and Einasto
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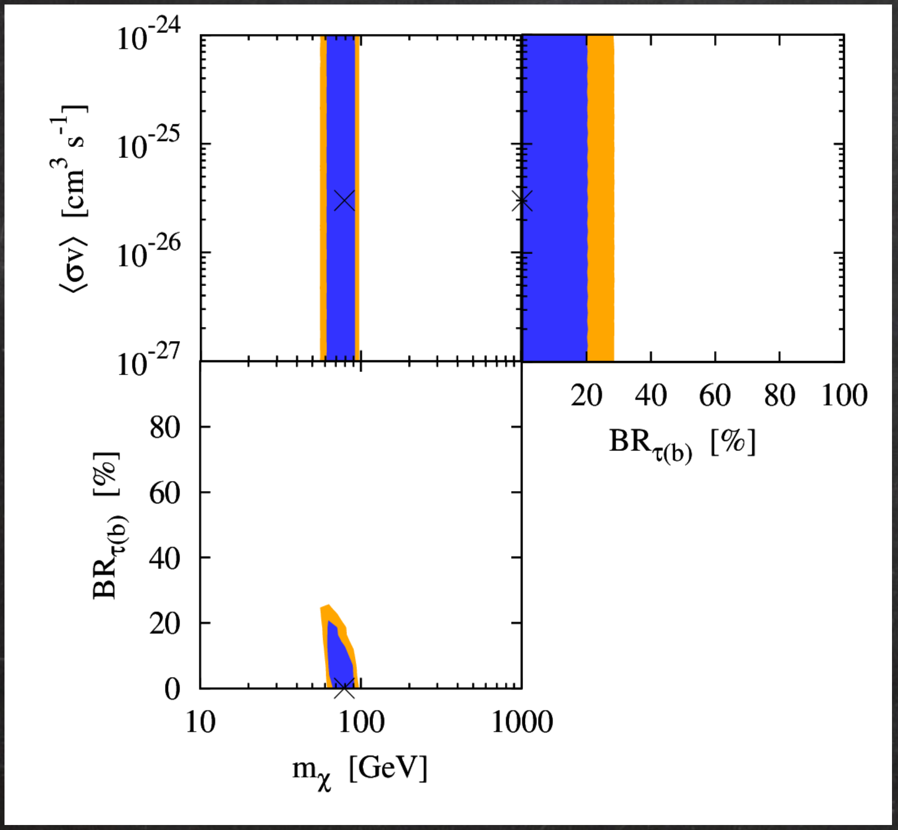
DM properties...



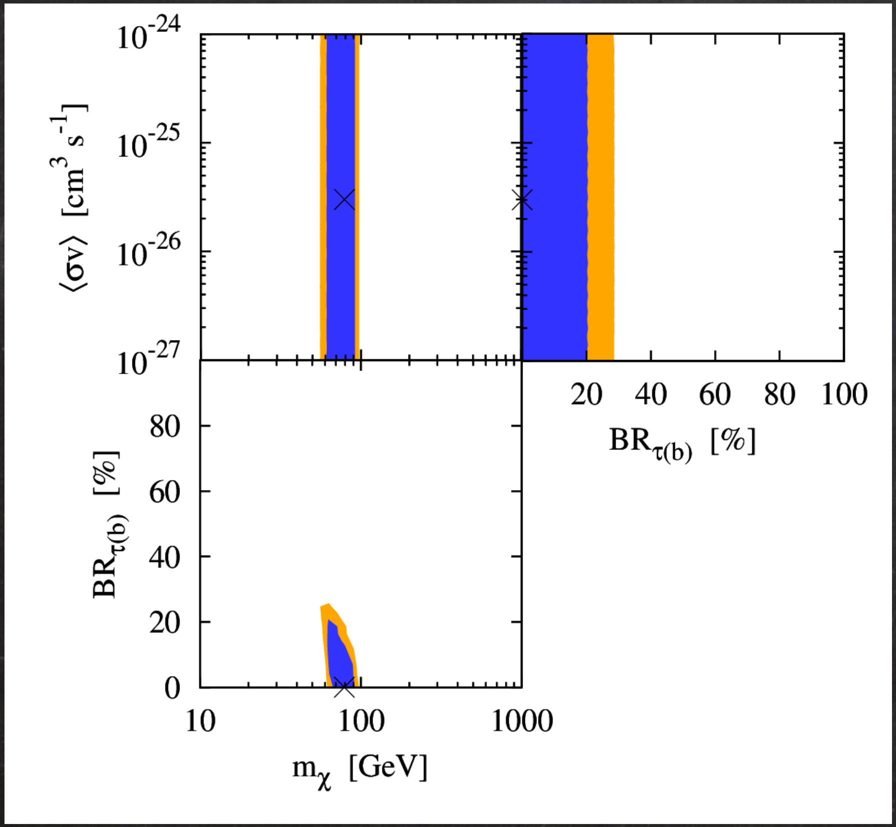
NB and S Palomares-Ruiz, arXiv:1103.2377

* Remember:
flux normalization
proportional to
<σv> and J(α, ρ_0, r_s)

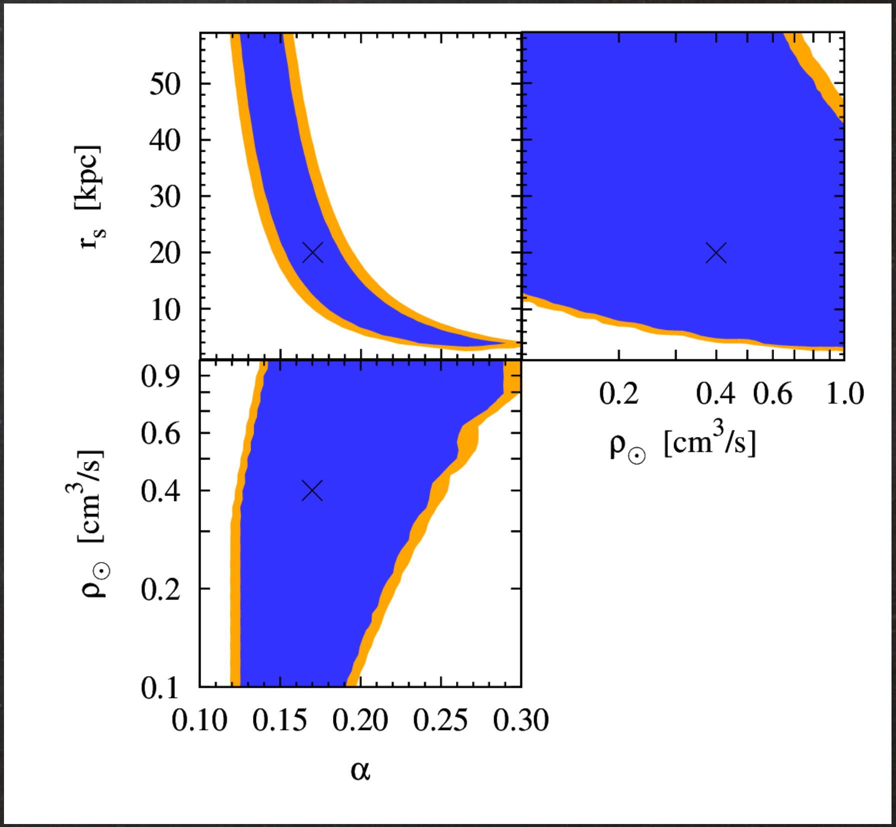
$$\overline{J}(\Omega) = \frac{1}{\Delta\Omega}\frac{1}{R_\odot\,\rho_\odot^2}\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \rho\big(r(s,\Omega)\big)^2\, ds$$

m_x = 80 GeV and Einasto
DM profile unknown

DM properties...



and DM density profile

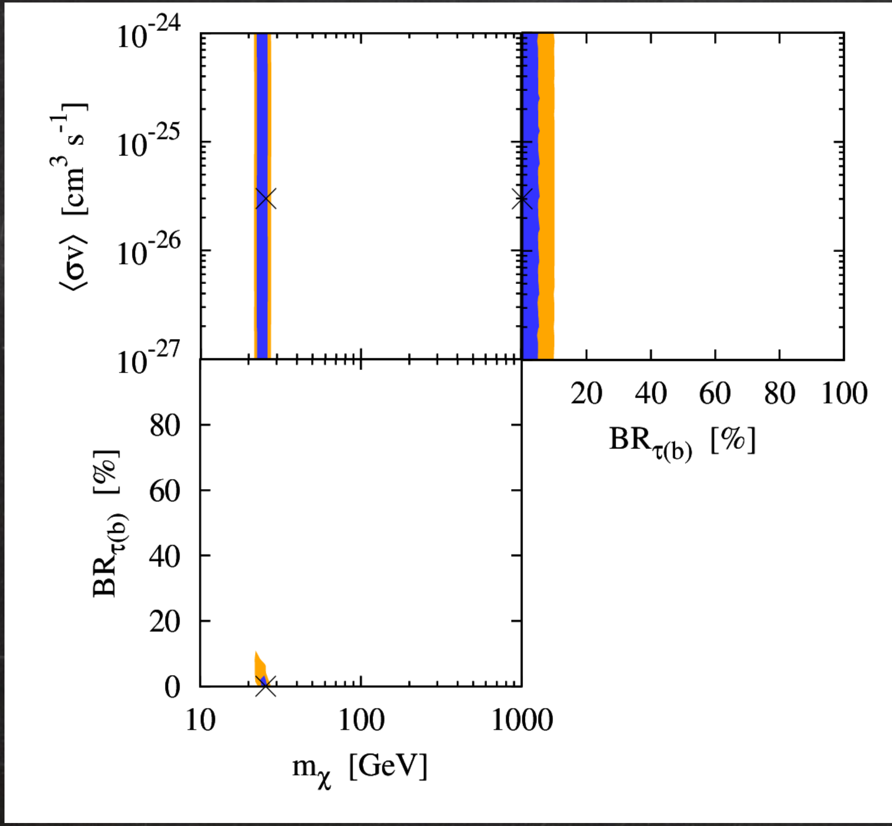


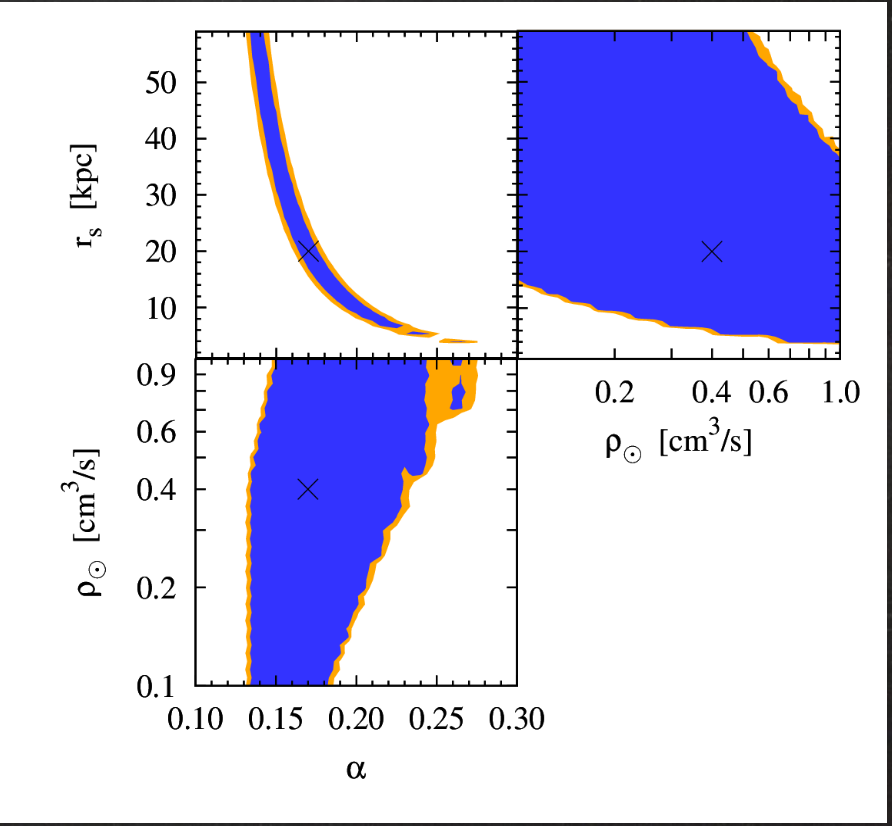
NB and S Palomares-Ruiz, arXiv:1103.2377

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

m_χ = 25 GeV and Einasto
DM profile unknown

DM properties... and DM density profile

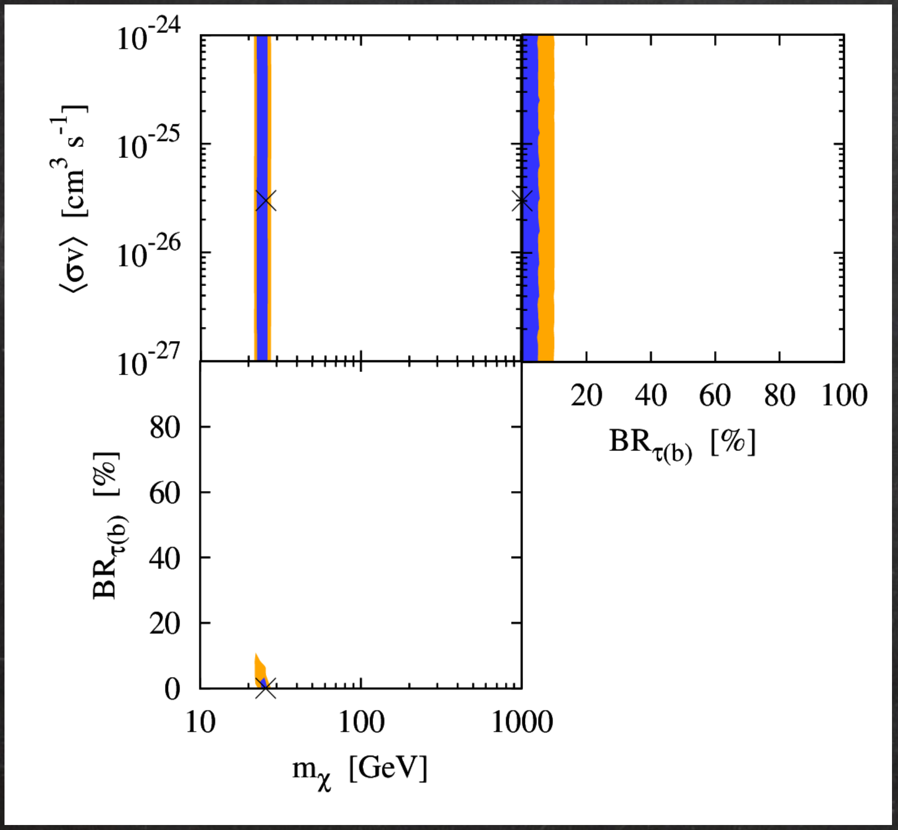


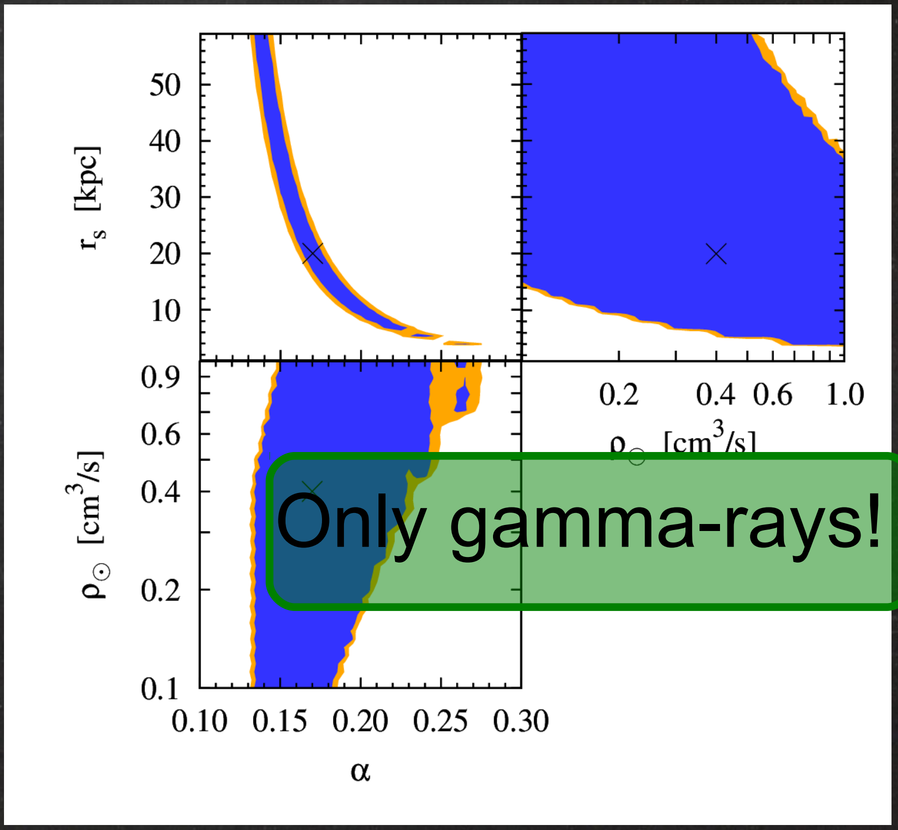


NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 25 GeV and Einasto
DM profile unknown

DM properties... and DM density profile





NB and S Palomares-Ruiz, arXiv:1103.2377

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

DM halo profiles

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

However...

Local DM density:

ρ_0= 0.39 ± 0.03 GeV/cm^3 (Catena & Ullio '09)
ρ_0= 0.40 ± 0.04 GeV/cm^3 (McMillan '11)

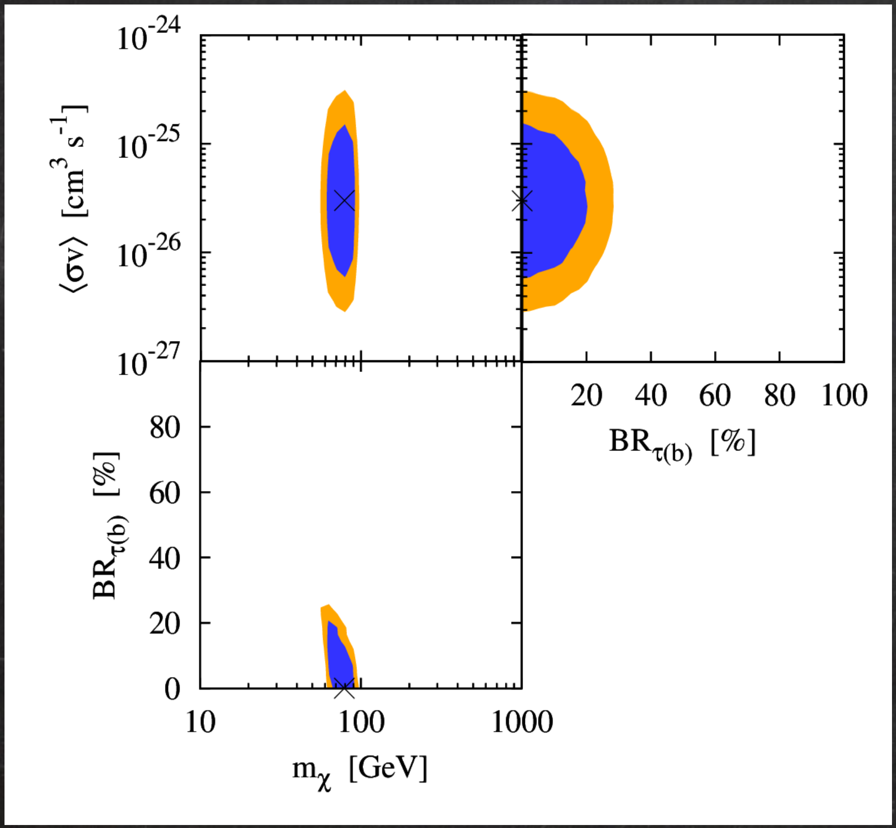
ρ_0 determined with an error of 50% or 10%

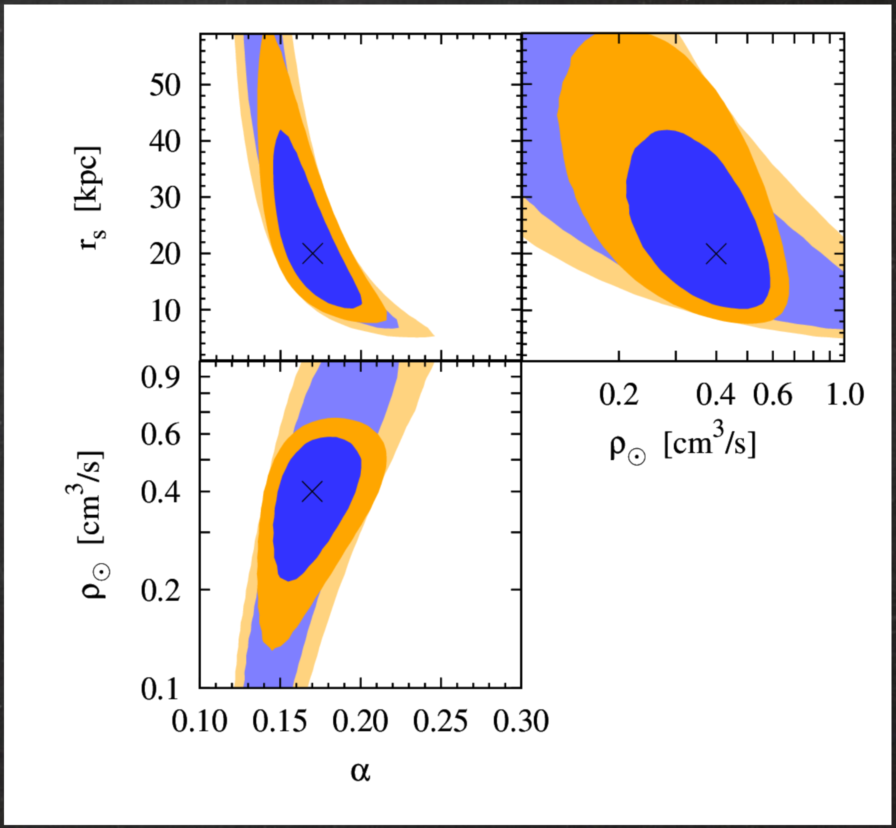
Annihilation cross section:

<σv> could be 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%

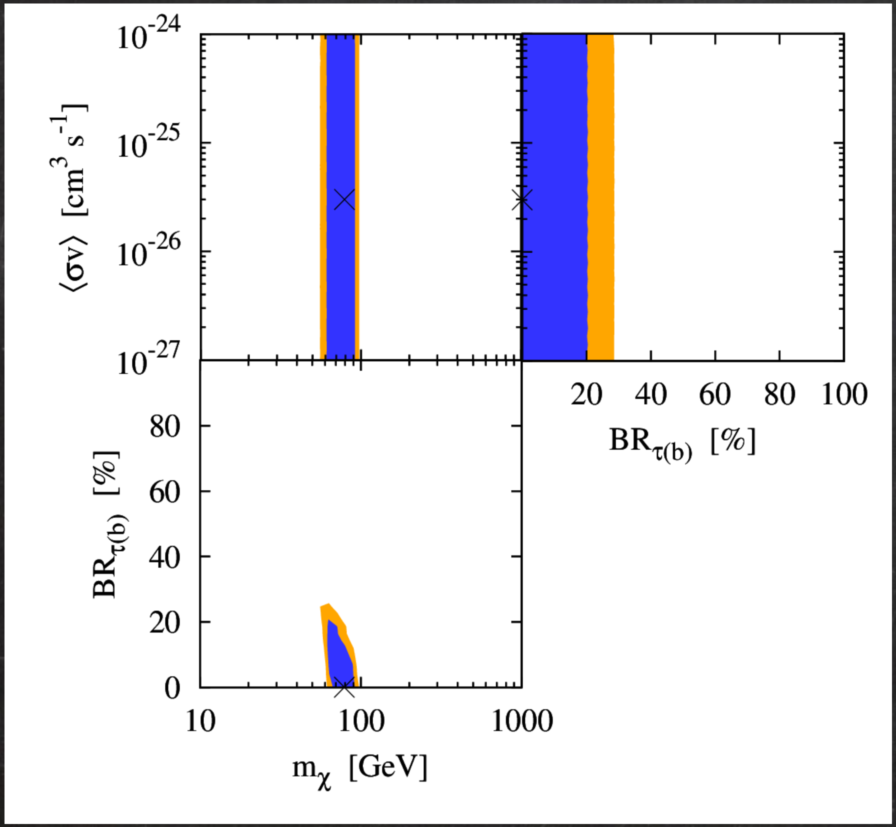


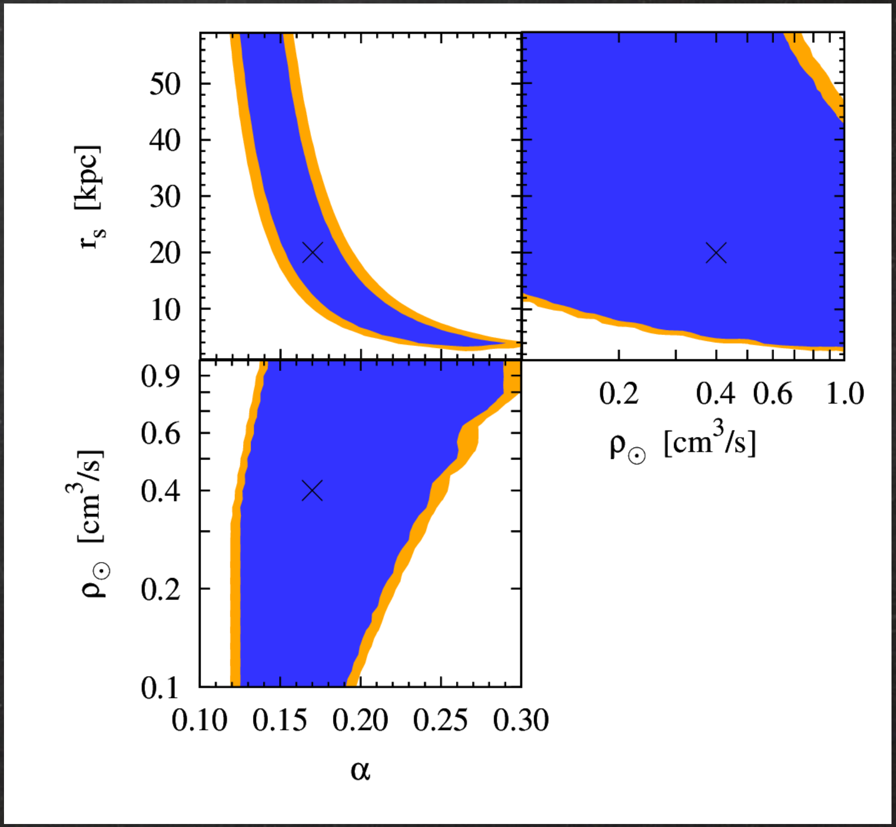


NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 80 GeV and Einasto

* Without priors

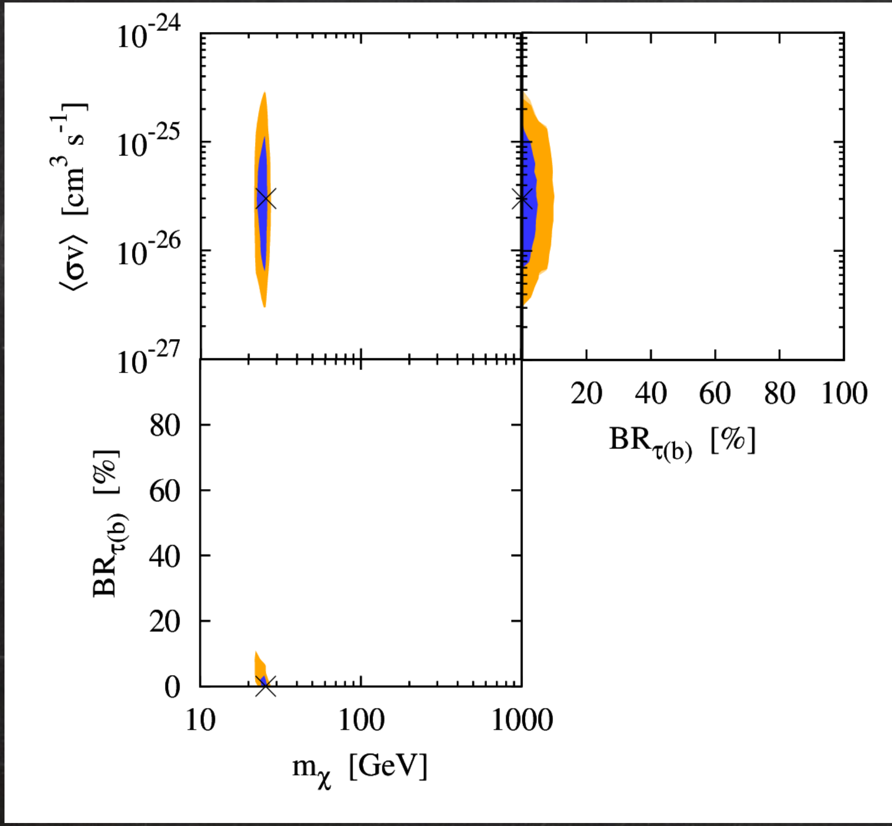


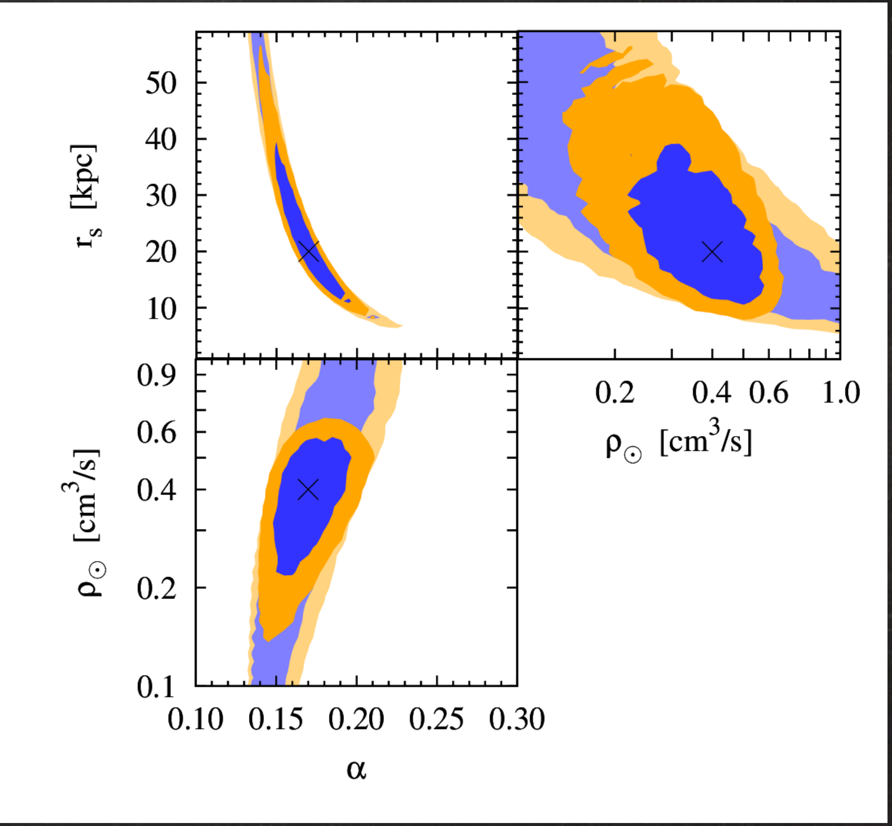


NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 25 GeV and Einasto

* <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

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}

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

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}

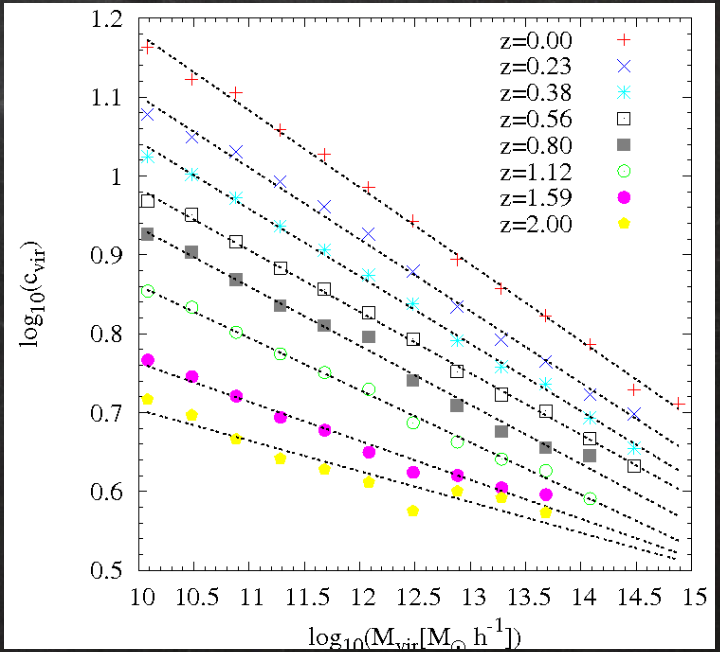
* Structural properties of DM halos depend on the halo mass

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

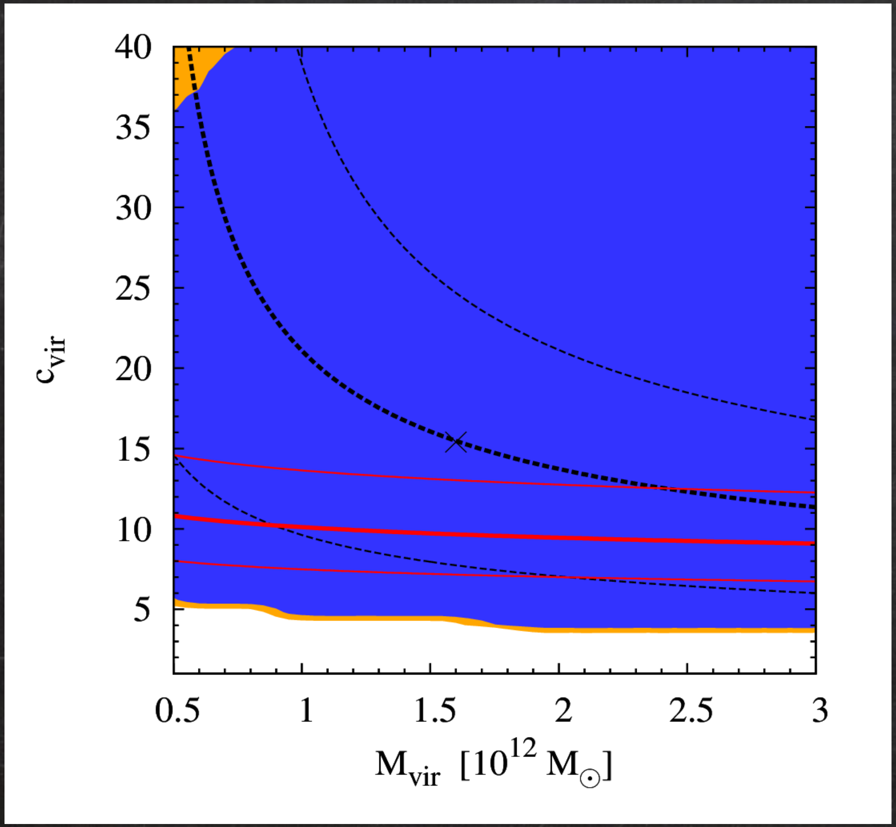
* $\rho_0 = 0.4$ GeV/cm^3 & $r_S = 20$ kpc → ($M_{vir} = 1.6\ 10^{12}\ M_\Theta$, $c_{vir} = 15.2$)
(PJ McMillan '11)

m_x = 25 GeV and NFW

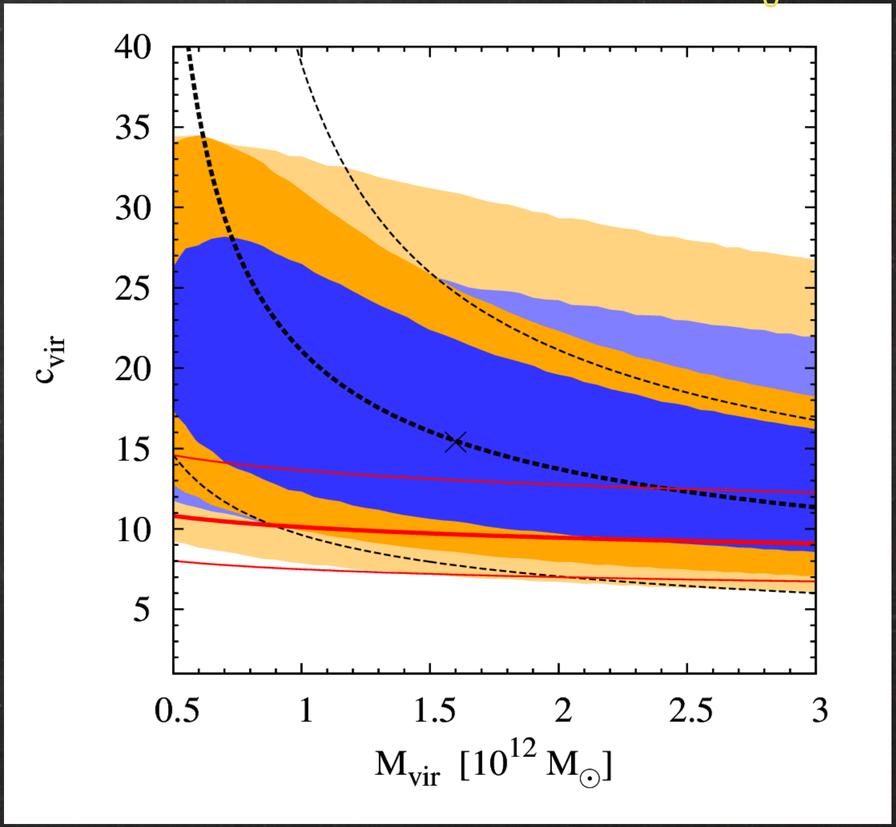
* ρ_0 = 0.4 GeV/cm^3 & r_S = 20 kpc → (M_{vir} = 1.6 10^{12} $M_\odot$, c_{vir} = 15.2)

(PJ McMillan '11)

No priors



Priors over <σv> and ρ_0



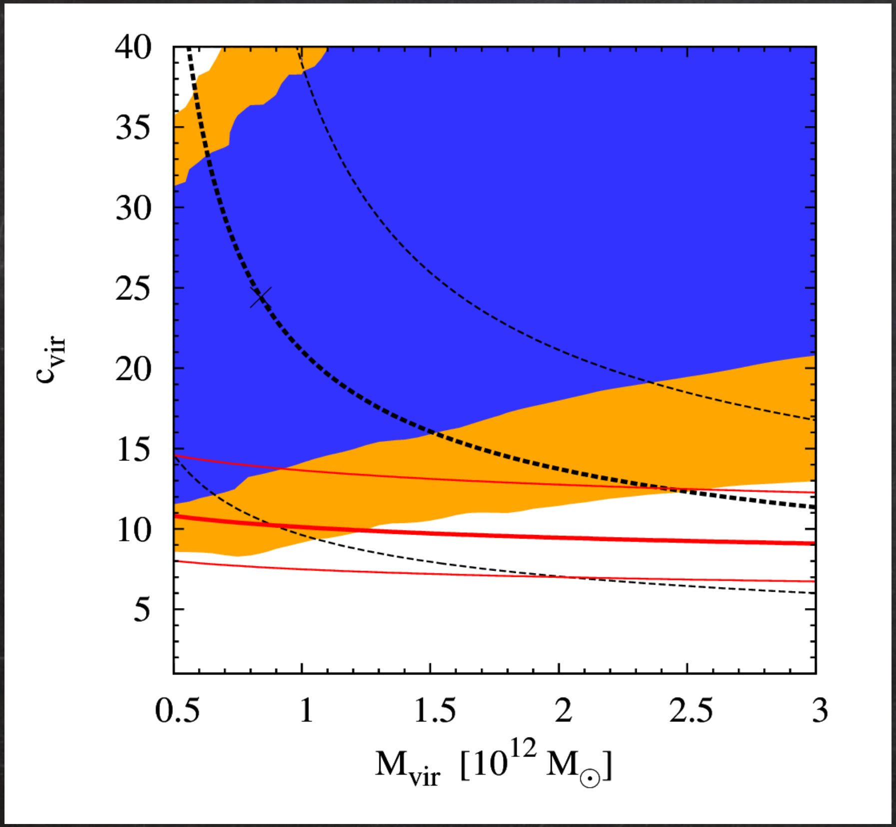
NB and S Palomares-Ruiz, arXiv:1103.2377

m_x = 25 GeV and NFW

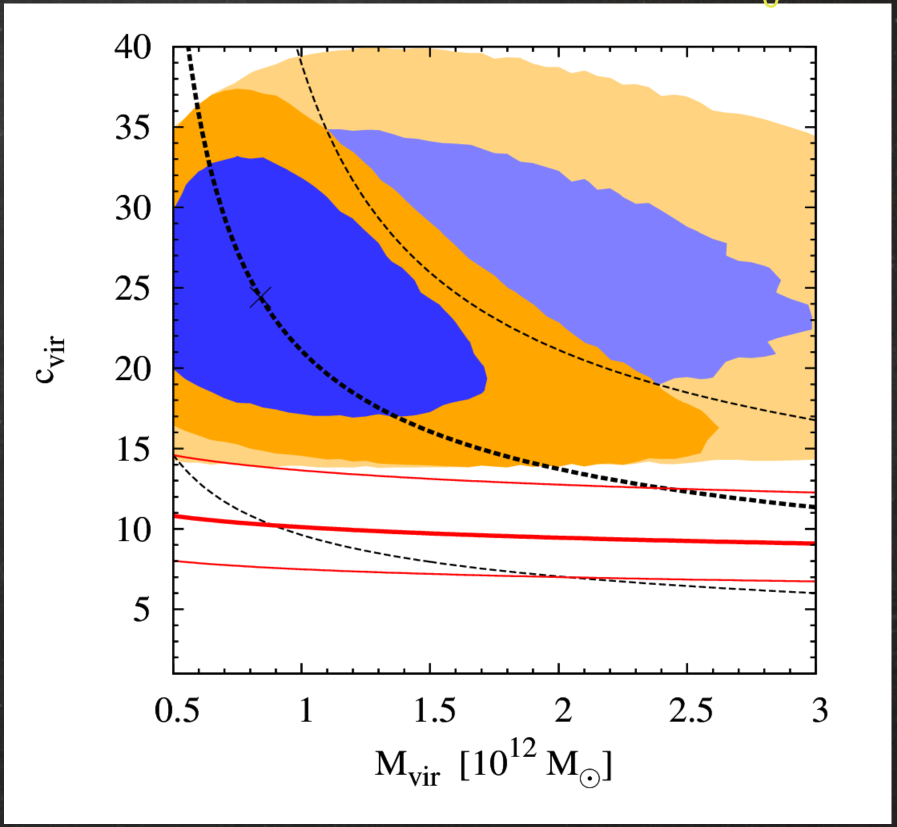
* M_{DM}(60 kpc) = 4 10^{11} M_Θ , ρ_0 = 0.4 GeV/cm^3 → r_S = 10 kpc

(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!

$R_0 = 7.2 \pm 0.3$ kpc (Bica *et al* '05)

$R_0 = 8.2 \pm 0.5$ kpc (Bovy *et al* '09)

$R_0 = 8.33 \pm 0.35$ kpc (Gillessen *et al* '08)

$R_0 = 8.4 \pm 0.6$ kpc (Reid *et al* '09)

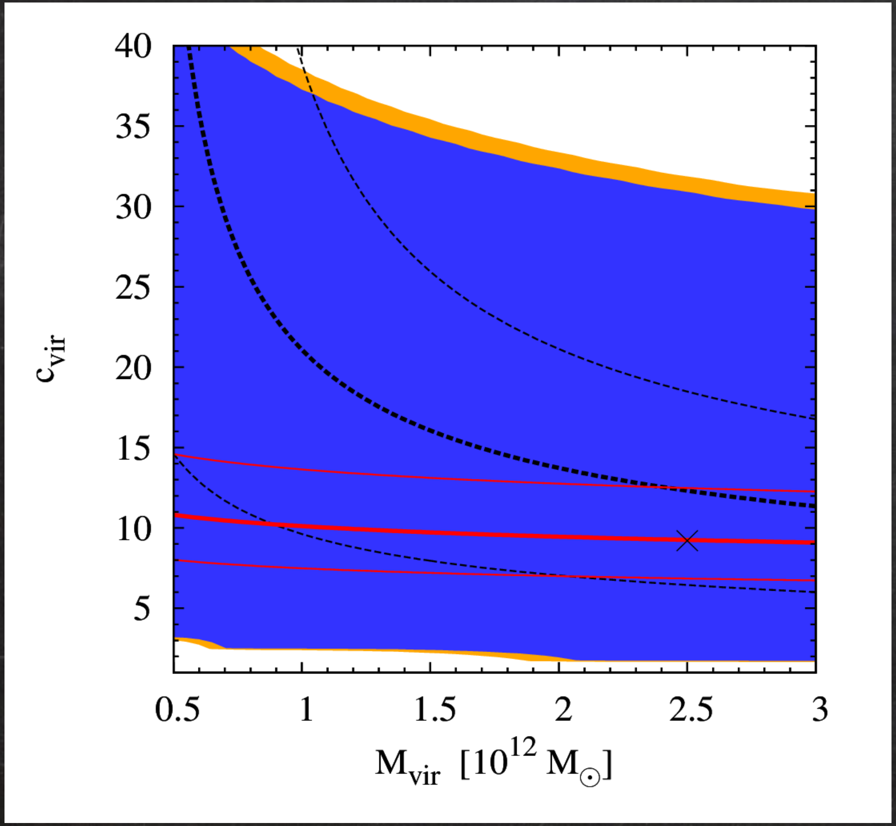
$R_0 = 8.7 \pm 0.5$ kpc (Vanhollebeke *et al* '09)...

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

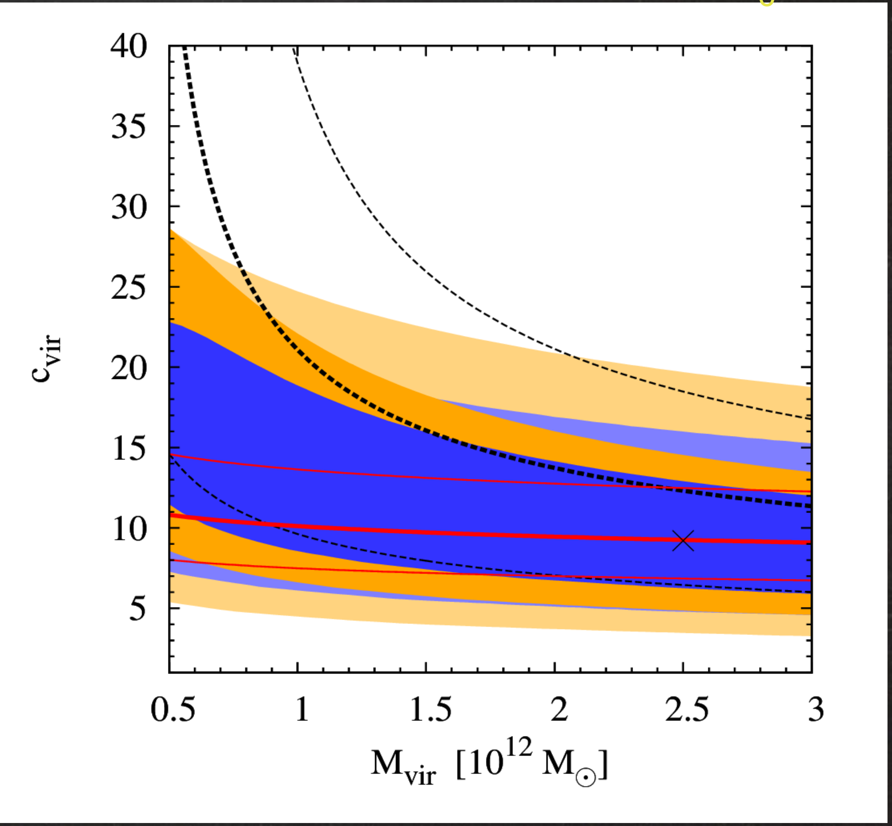
m_x = 25 GeV and NFW

* ρ_0 = 0.3 GeV/cm^3 → r_S = 38.6 kpc (${M_{vir}}$ = 2.5 10^{12} M_Θ , c_{vir} = 9.2)

No priors



Priors over <σv> and ρ_0



NB and S Palomares-Ruiz, arXiv:1103.2377

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

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

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

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

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

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

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

Local DM density:

ρ_0= 0.3 GeV/cm^3 it's usually assumed but...

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$\rho_0 = 0.32 \pm 0.07\ \mathrm{GeV/cm^3}$ (Strigari & Trotta '09)

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

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

$\rho_0 = 0.43 \pm 0.15\ \mathrm{GeV/cm^3}$ (Salucci *et al* '10)

$\rho_0 = 0.5 \pm 0.2\ \mathrm{GeV/cm^3}$ (Gates *et al* '95)

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