γ-rays from Dark Matter annihilation in Galactic subhaloes

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Framework (Green et al., Diemand et al.)

- Galactic satellites are predicted by N-body simulations

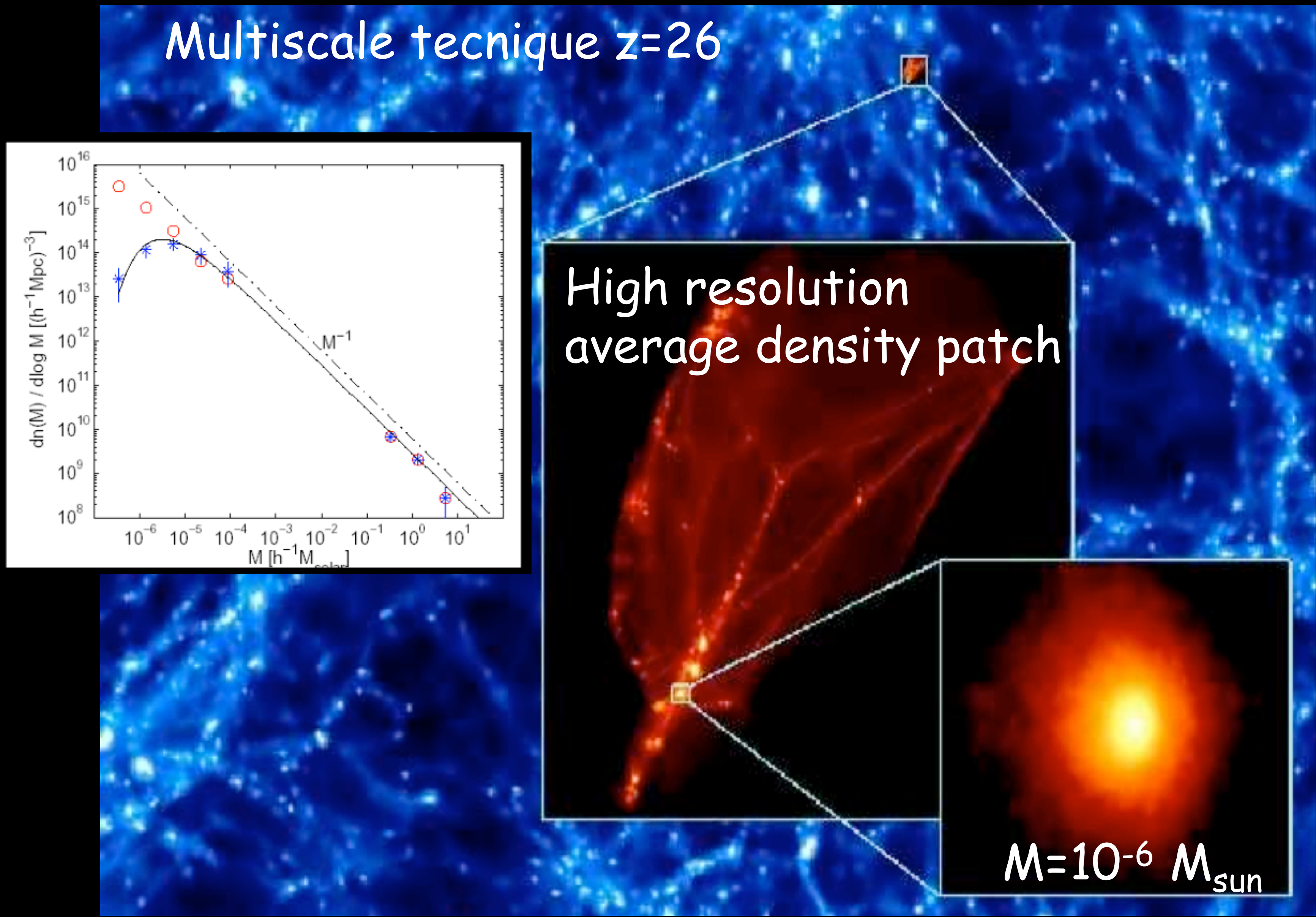
- If DM is a WIMP particle, the smaller haloes should be Earth-mass haloes

- About 10^{15} haloes should populate the Milky Way, with $dN/dM \sim M^{-2}$

- Their spatial distribution should trace the mass of the MW

- Their inner density should not be affected by their history and should follow the NFW profile

FRAMEWORK: Diemand, Moore, Stadel 2005



Assumptions

• Are there subhalos at all? None has seen them so far… assume YES, and include a tidal cut-off radius for their distribution in the MW

• Is DM a WIMP? assume YES

• Have all subhalos survived with invariate mass function till z=0? assume YES, without changing profile in the inner shells

• Which density profile for the MW? assume NFW

Project: exploring…

- … the concentration parameter of subhaloes

(Bullock, ENS, which extrapolation at low masses?
Did haloes evolve till present times or they froze to their formation epoch z_f- which extrapolation at low masses for z_f)

- … the effect of the initial conditions

(either assuming simplified average 1σ density peak rareness and extreme 5σ for low masses or deriving an analytical distribution of the σ–peak as a function of the halo mass)

- … the subhalo mass function

(assuming $dN_{sh}/dM_{sh} \sim M_{sh}^{-2}$, $M_{sh}^{-1.95}$, $M_{sh}^{-1.9}$)

Goal

• Detecting subhaloes: a multiwavelenght approach would be optimal.

✓ Use only γ-rays for the moment
✓ Work in progress: radio photons

Method

• Calculate numerically the diffuse contribution of the entire population of subhalos, for the different models explored
• MC simulate the closer and more brilliant subhalos, for the different models explored
• Compute detectability of both diffuse and resolved haloes with a GLAST-like satellite.

Indirect detection of γ-rays

$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

$$\Phi_{PP} = \frac{1}{4\pi}\frac{\sigma_{ann} v}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_f \frac{dN_f^\gamma}{dE_\gamma} BR_f$$

- distribution of DM along the l.o.s. λ:
MW smooth +
UNRESOLVED subhalos +
RESOLVED subhalos (ρ^2)

- geometry of the experiment ($\Delta\Omega$)

simplified expression: $\Phi_{COSMO} = \int_{\Delta\Omega,\lambda} \frac{\rho^2(r(\Delta\Omega,\lambda))}{\lambda^2} dV$

Indirect detection of γ-rays: $\Phi_{cosmology}$

MW smooth, RESOLVED subhalos

$$\Phi^{halo}_{COSMO}(M,c,r) = \iint_{\Delta\Omega} d\vartheta' d\varphi' \int_{l.o.s} d\lambda' \left[\frac{\rho^2_{DM}\left(M, c, r(\lambda, \lambda', \psi, \theta', \varphi')\right)}{\lambda^2} J(x,y,z;\lambda',\vartheta',\varphi') \right]$$

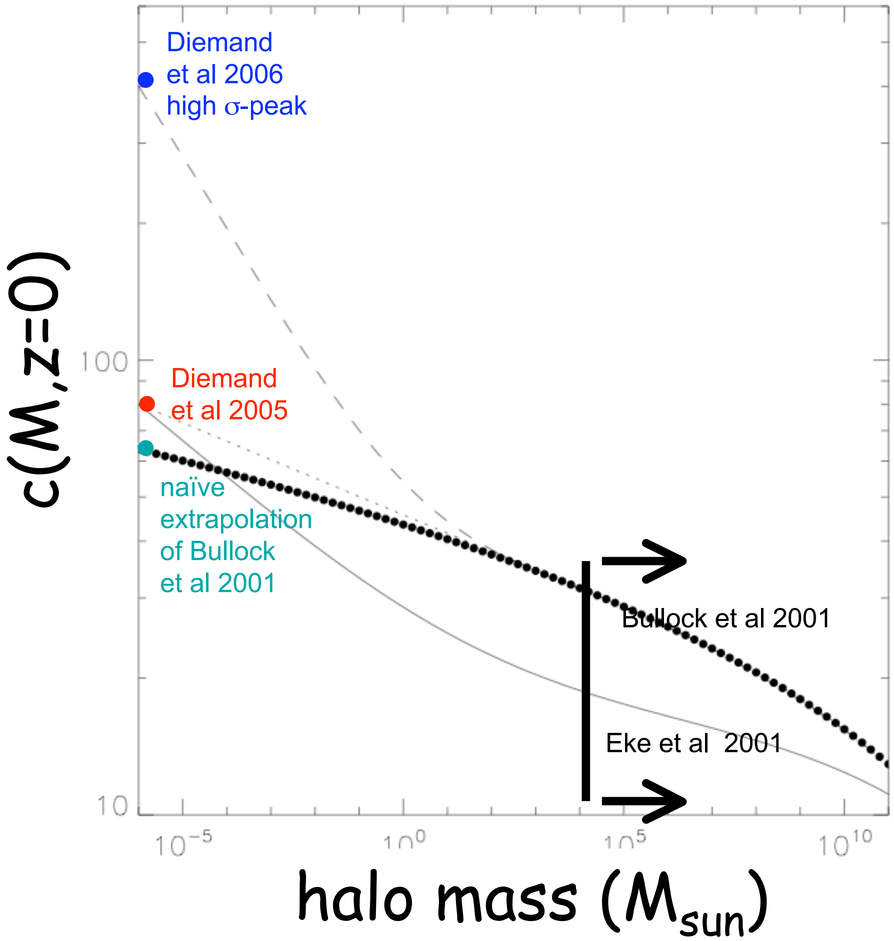
The DM density profile (here NFW) is a function of the halo mass, the concentration parameter and the radial distance from the halo center

UNRESOLVED subhalos

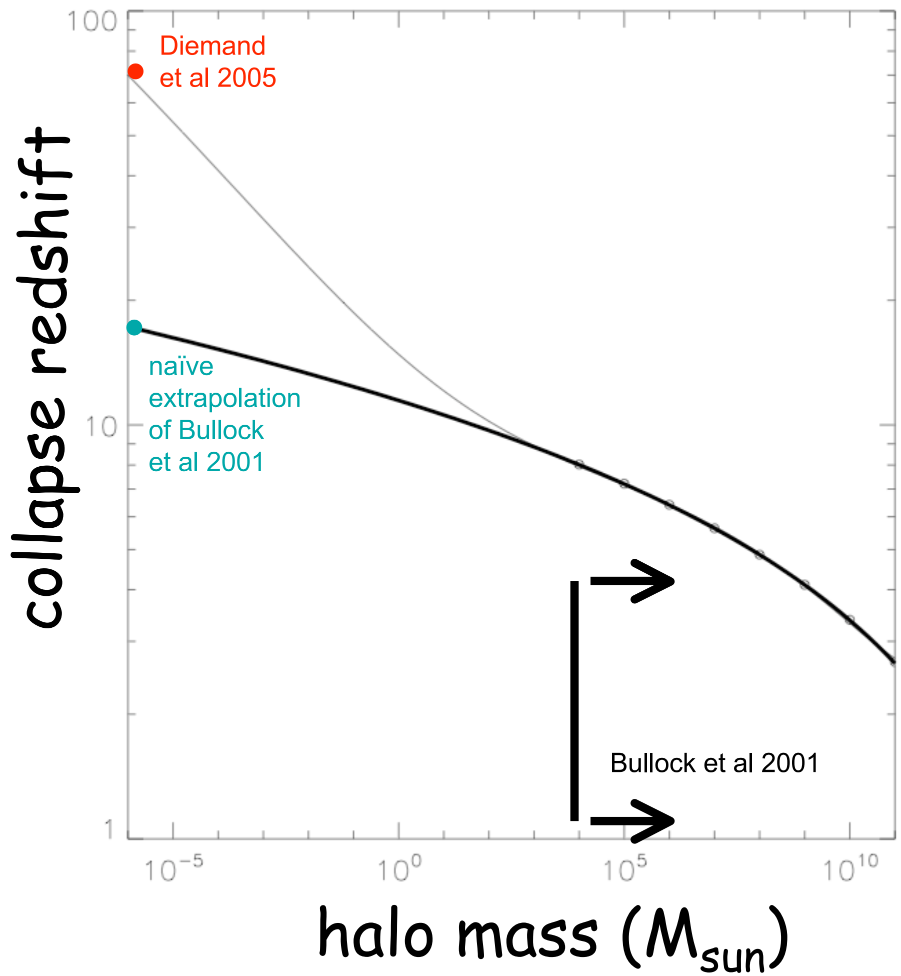
$$\Phi_{COSMO}(\psi,\Delta\Omega) = \int_M dM \int_c dc \iint_{\Delta\Omega} d\vartheta d\varphi \int_{l.o.s} d\lambda \Big[\rho_{sh}(M, R(R_{sun},\lambda,\psi,\vartheta,\varphi)) \cdot P(c) \cdot \Phi^{halo}_{COSMO}(M,c,r(\lambda,\lambda',\psi,\vartheta',\varphi')) \cdot J(x,y,z;\lambda,\vartheta,\varphi) \Big]$$

The single halo expression must be convolved with the subhalo mass and radial distribution function and with the concentration parameter distribution function

Subhalo concentration parameter: models



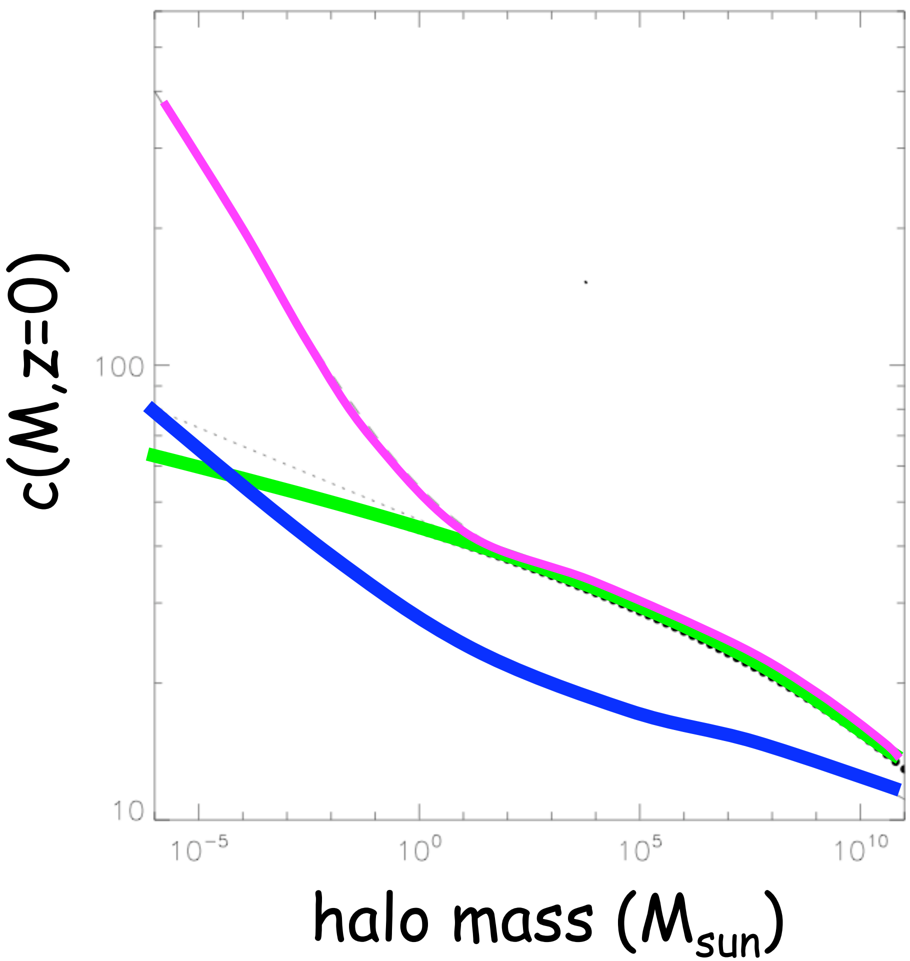
$c(M,z_c) = c\,(M,z=0)/(1+z_c)$



NB: these are average values!
a lognormal probability is assumed
everywhere in the analysis

L.Pieri, G. Bertone, E. Branchini, MNRAS in press, arXiv 0706.2101 [hereafter PBB07]

Subhalo concentration parameter: benchmarks



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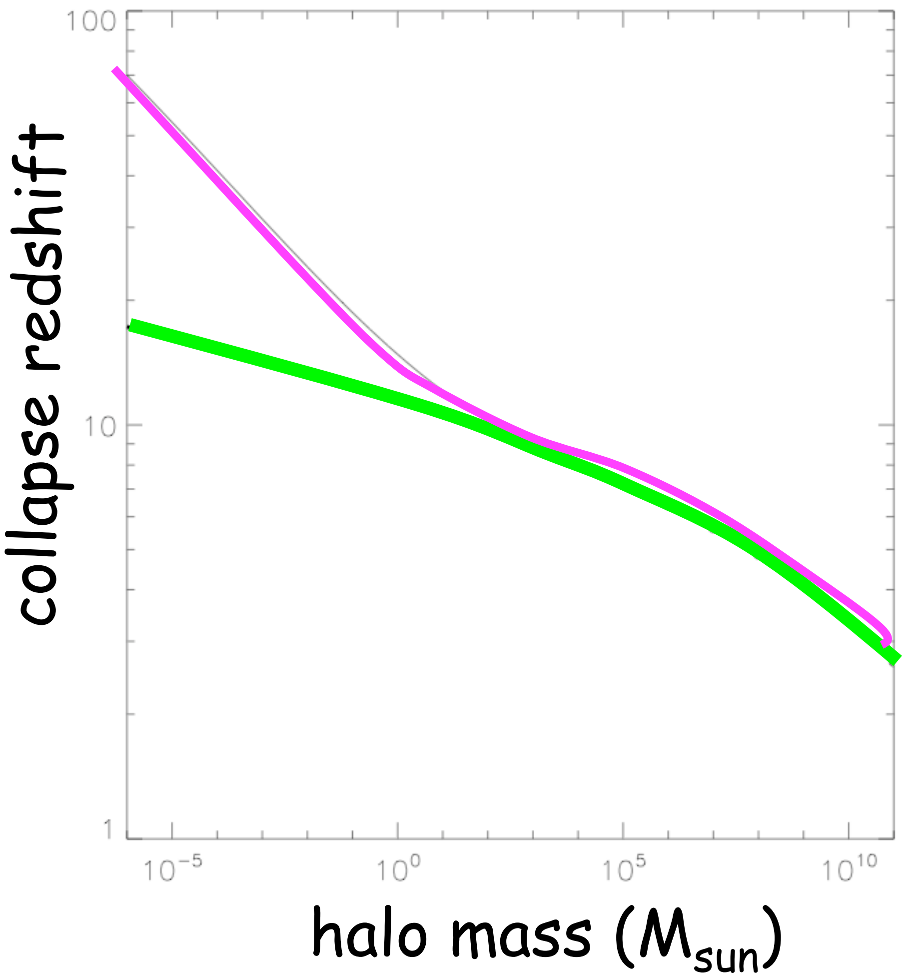

Model "1": exaggerated

Model "2": optimistic

Model "3": pessimistic

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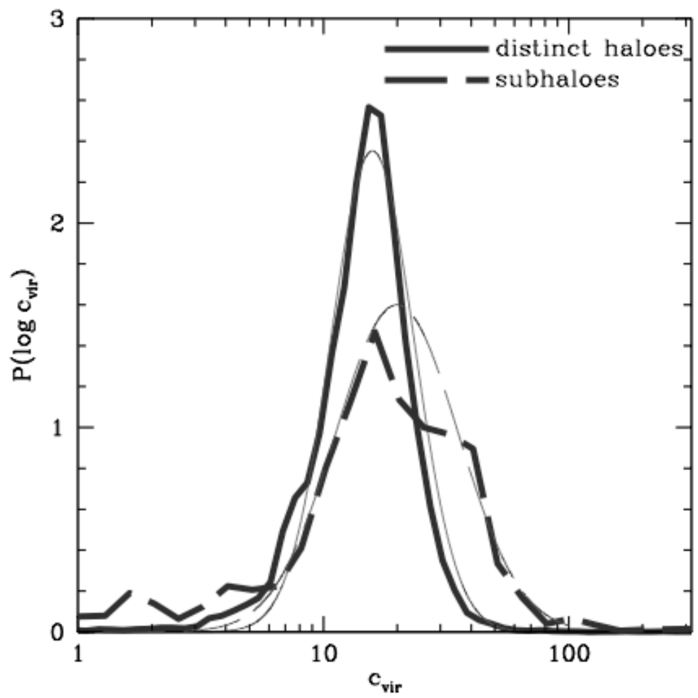
concentration parameter distribution

$P(c)$ from Bullock et al, 2001

Reflects the existence of different collapse redshifts



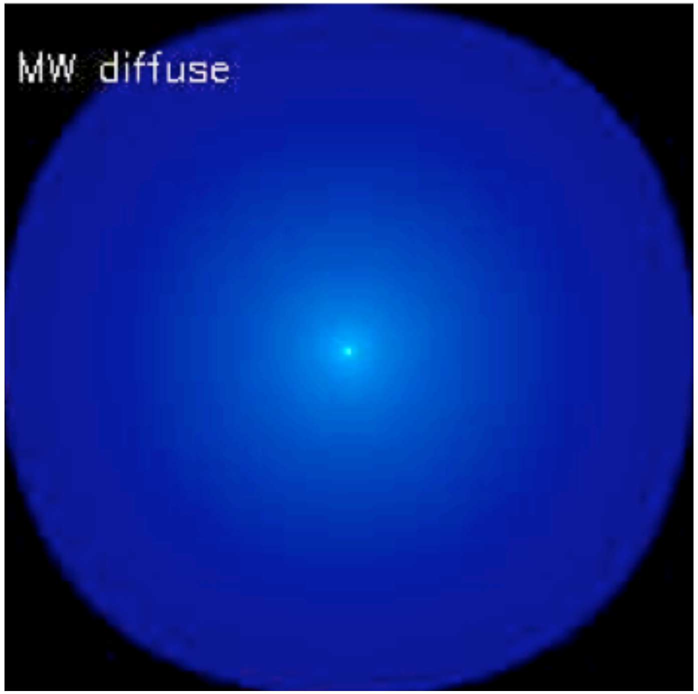
subhaloes number density

Tidal effects:
Roche criterion

$$\rho_{sh}(M,R) = A\frac{dN_{sh}}{dM}\frac{\theta(R - r_{min}(M))}{\frac{R}{r_s^{MW}}\left(1+\frac{R}{r_s^{MW}}\right)^2}$$

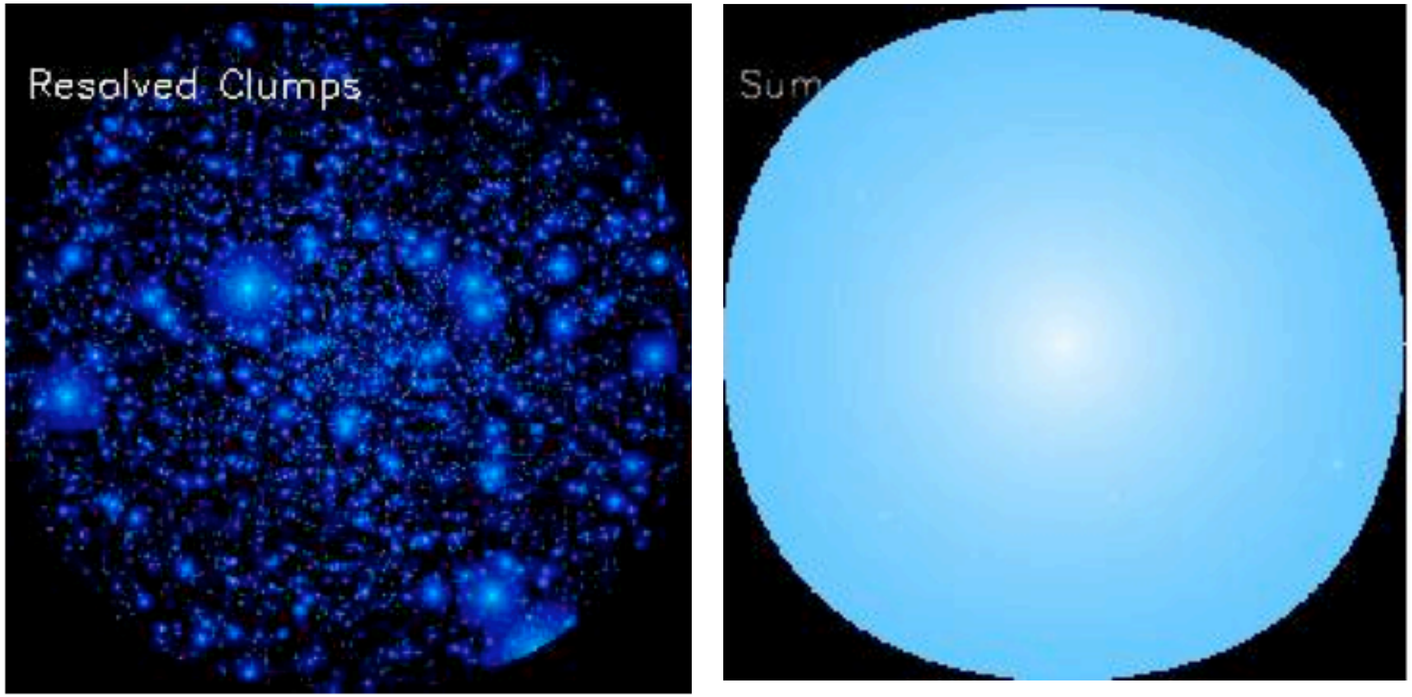
$$\frac{dN_{sh}}{dM} \propto M^{-\alpha} \qquad \alpha = 2, 1.95, 1.9$$

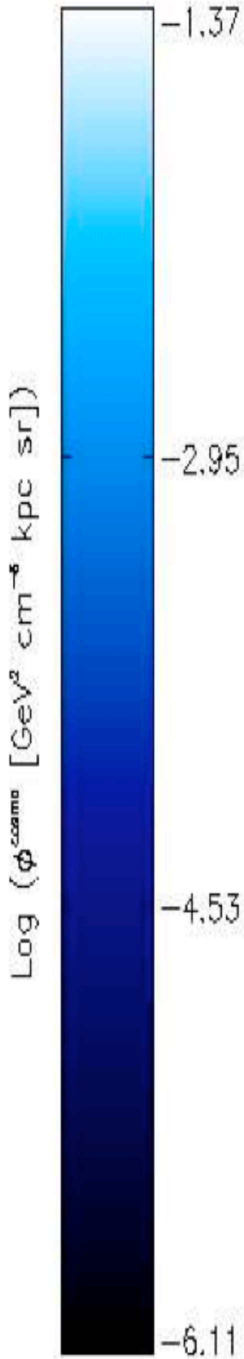
$$A \text{ t.c. } \int_{10^7 M_{sun}}^{10^{10} M_{sun}} M \cdot dM \int_0^{R_{vir}} dR 4\pi R^2 \rho_{sh}(M,R) = 0.1 M_{MW}$$



Contribution to $\Phi_{cosmology}$

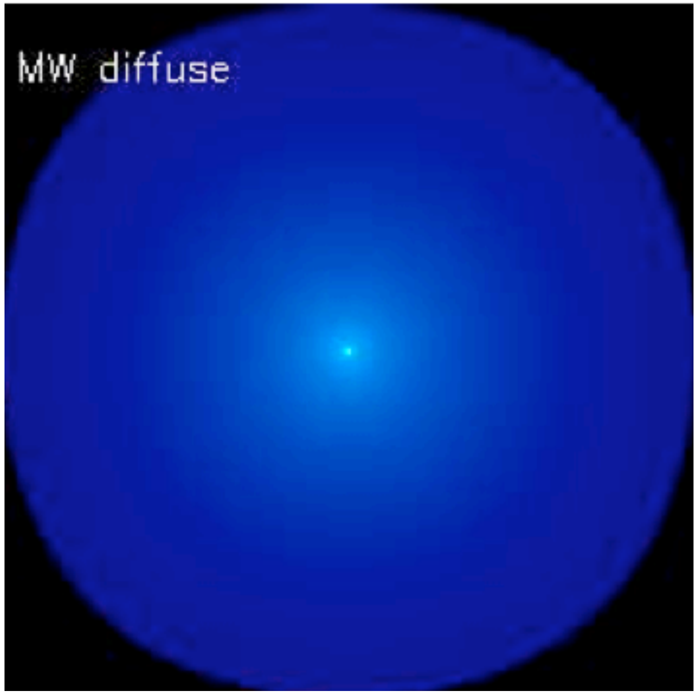
Model "1"

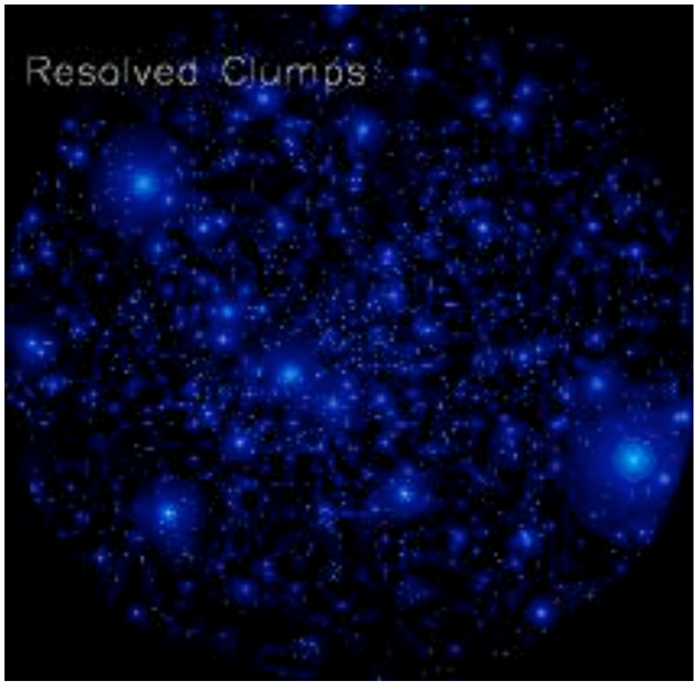


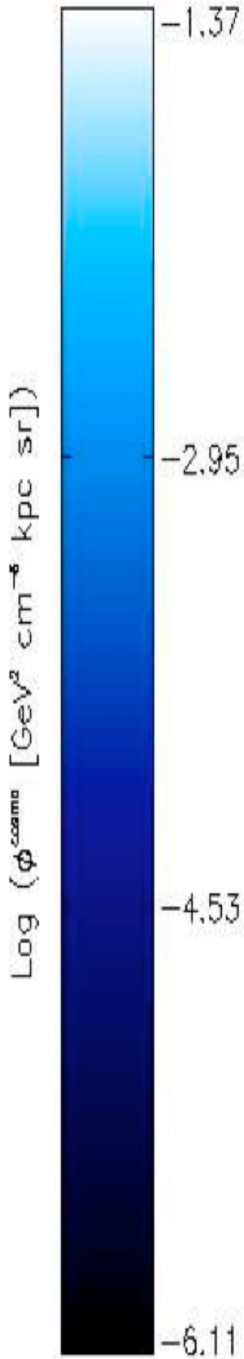


Contribution to $\Phi_{cosmology}$

Model "2"

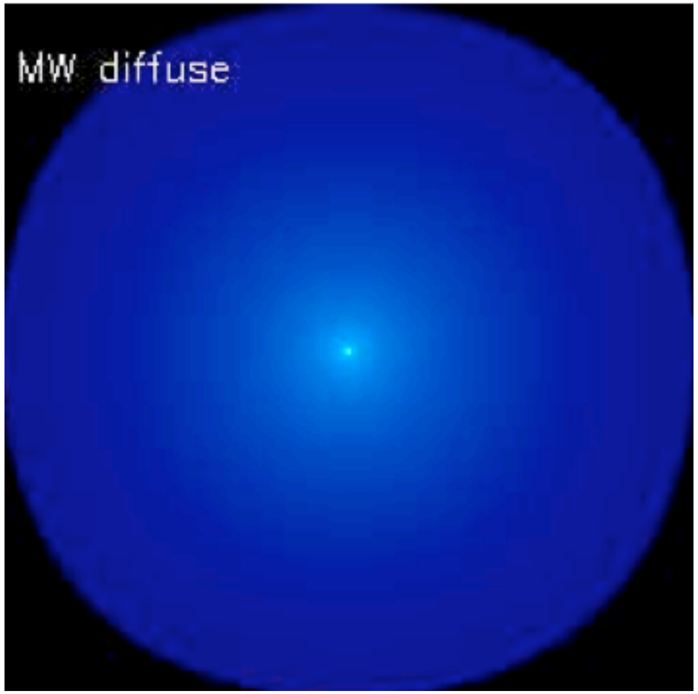


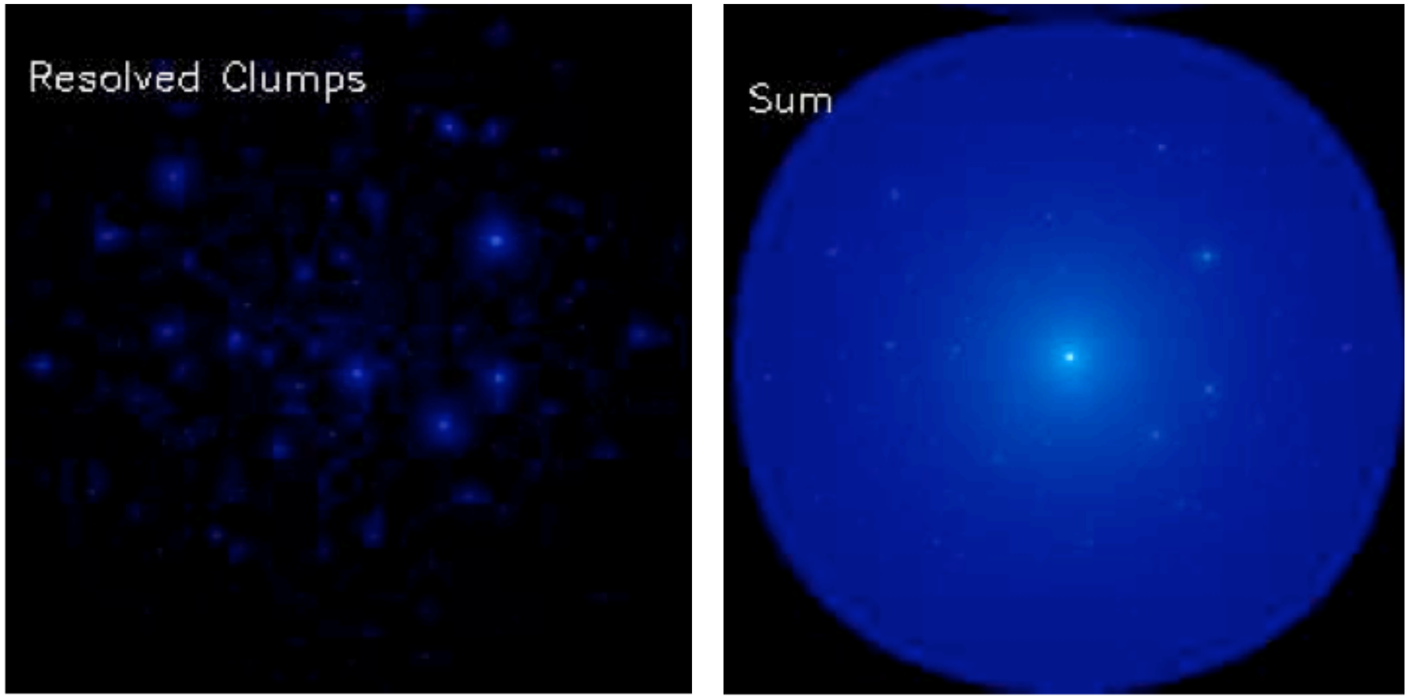


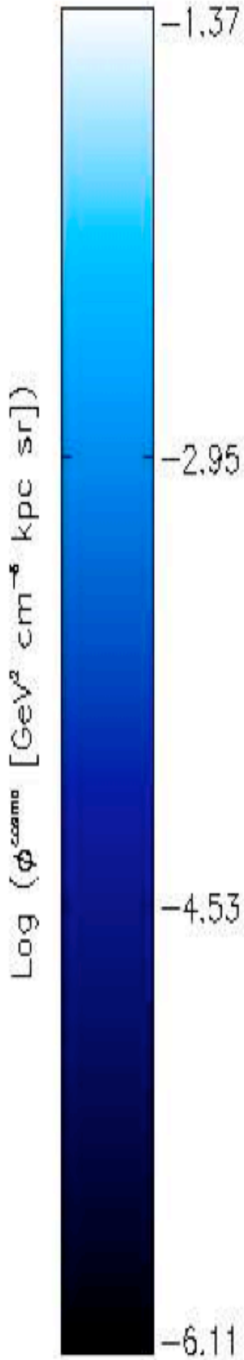


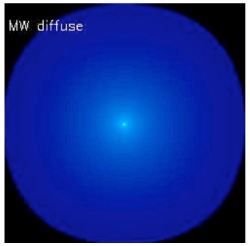
Contribution to $\Phi_{cosmology}$

Model "3"



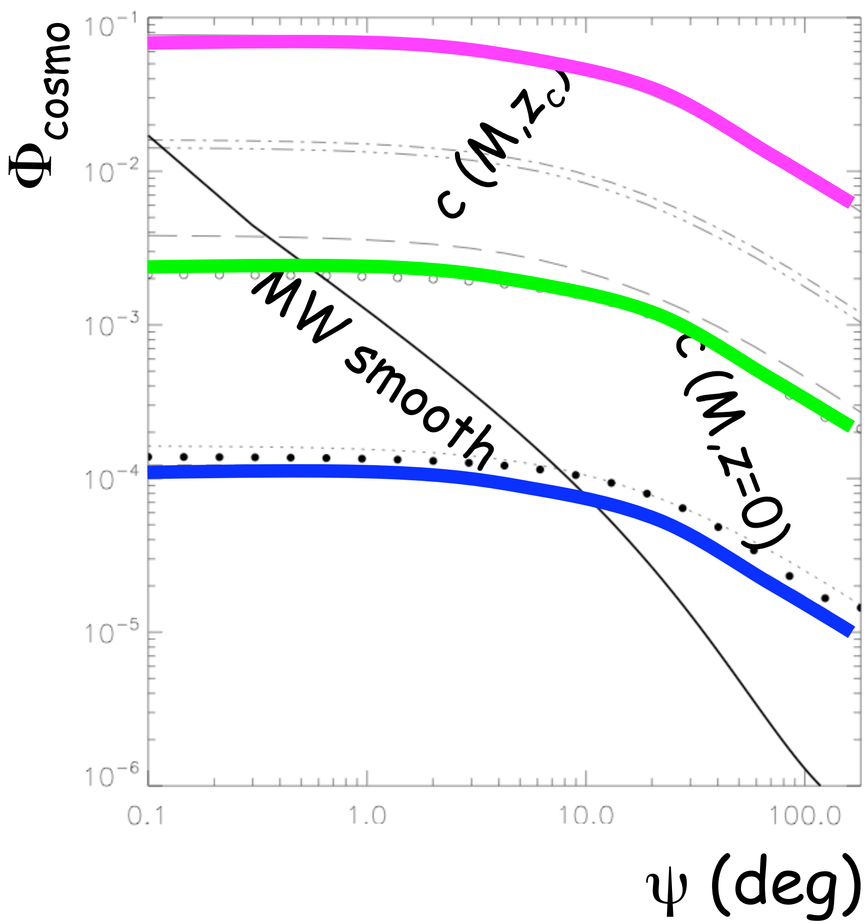




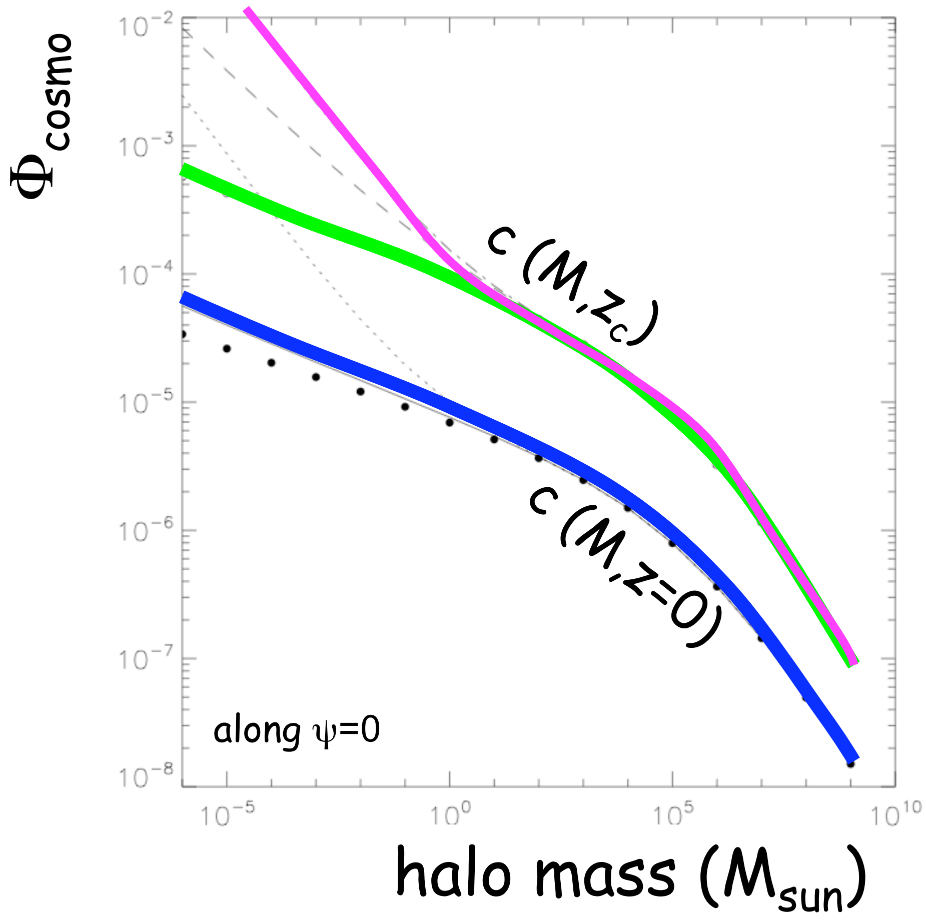


Results on subhalo models, smooth contribution the MILKY WAY case

Smooth Φ_{cosmo} VS ψ



Smooth Φ_{cosmo} VS halo mass



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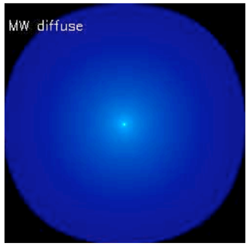

Results on subhalo models, boost factor

$$BF = \frac{\int_{Vol} \left(\rho^2_{05smoothMW} + \int_{\rho_{sh}, P(c)} \rho^2_{sh} dV dM dc \right) \cdot dV}{\int_{Vol} \rho^2_{smoothMW} dV}$$

Model “1”: 3300

Model “2”: 120

Model “3”: 6

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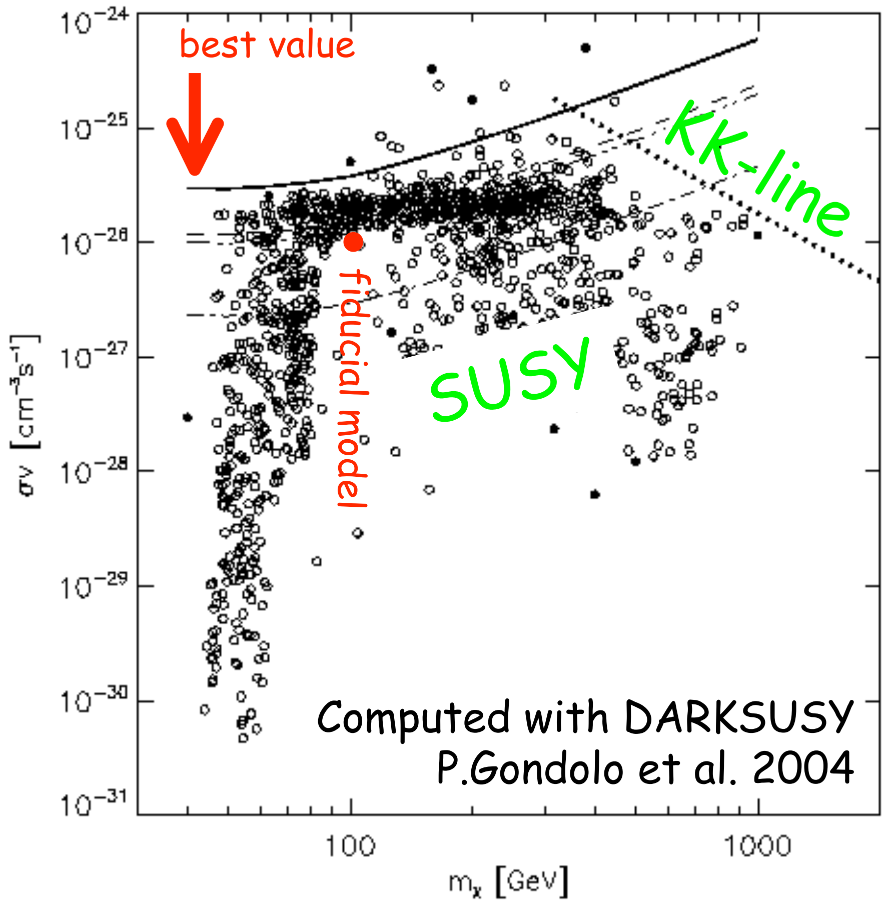
…and don't relax yet…

Remember that
indirect detection of γ-rays
depends on two (almost) independent terms

$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

Indirect detection of γ-rays: $\Phi_{\text{particle physics}}$

$$\Phi_{PP} = \frac{1}{4\pi} \frac{\sigma_{ann} v}{2 m_\chi^2} \int_{E_0}^{m_\chi} \sum_f \frac{dN_f^\gamma}{dE_\gamma} BR_f$$



Best value:

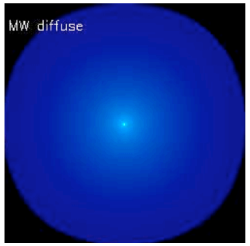
m_χ = 40 GeV

$\sigma_{ann} v = 3 \times 10^{-26}\ cm^3 s^{-1}$

Fiducial model:

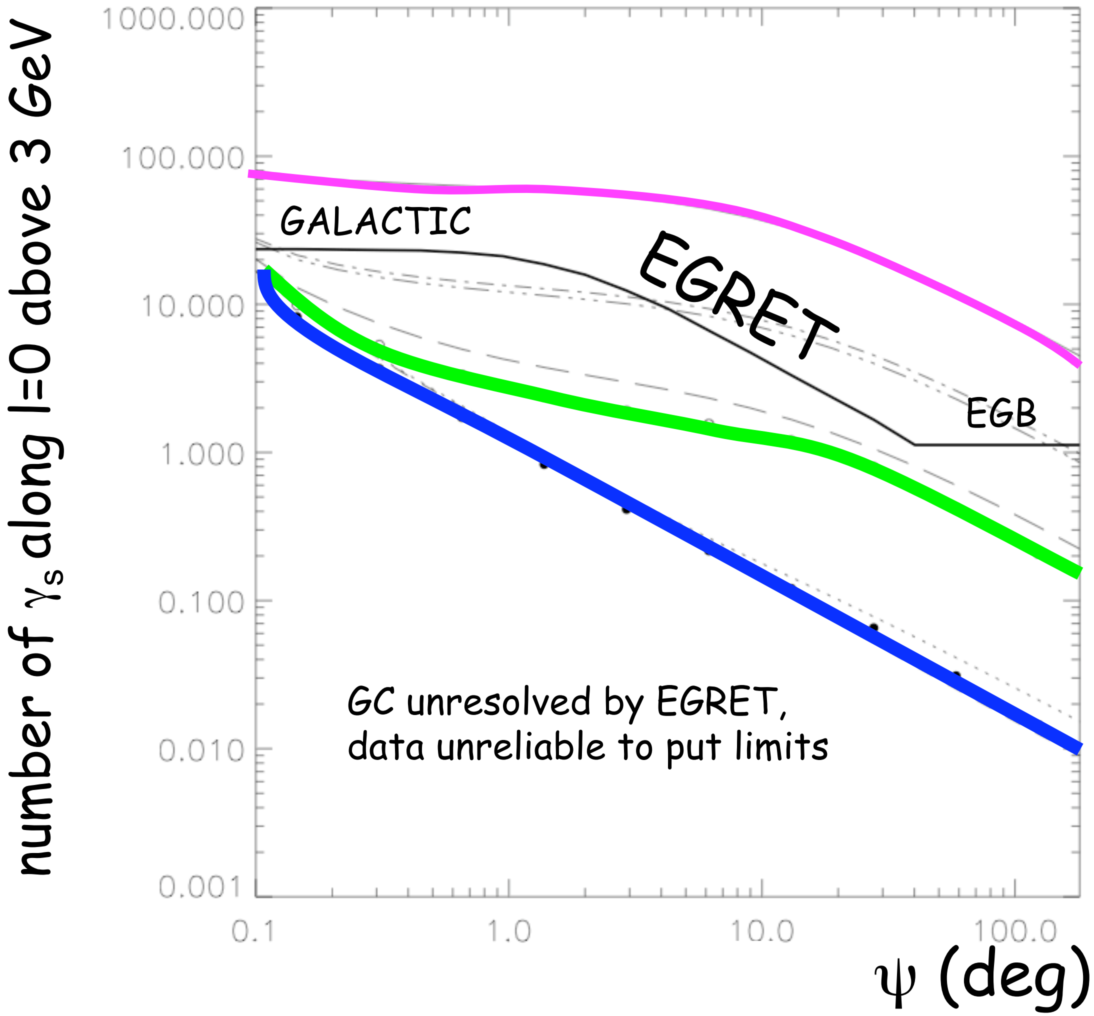
m_χ = 100 GeV

$\sigma_{ann} v = 10^{-26}\ cm^3 s^{-1}$



Results on subhalo models: number of expected photons

Best value PP, 1 year, $\Delta\Omega=10^{-5}$ sr (GLAST or ACT-like), E>3 GeV
(good compromise between angular resolution and signal to noise ratio)



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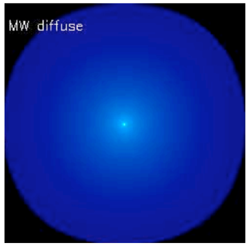
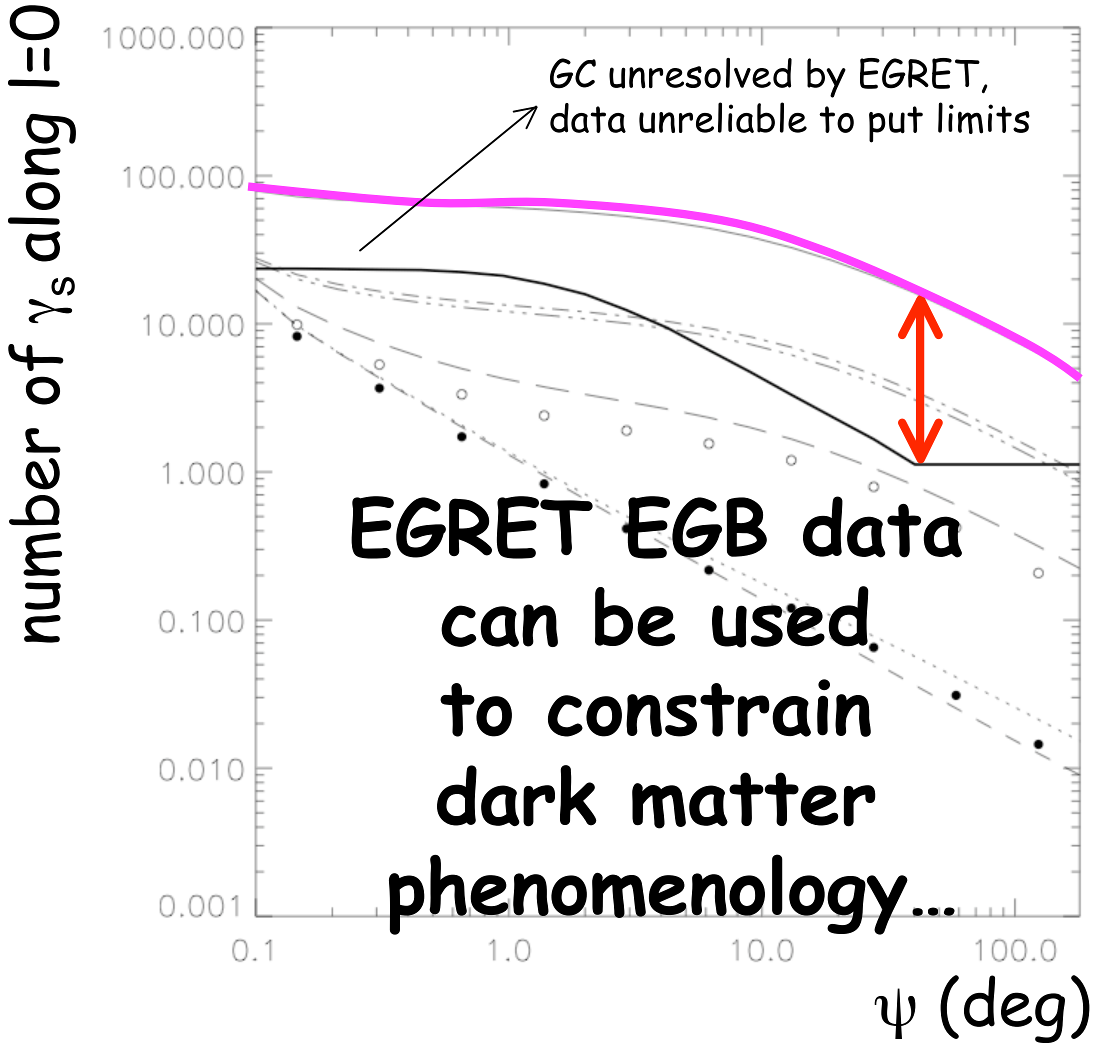


Results on subhalo models: constraints from EGRET data

All models exceeding the EGRET EGB data will be normalized to the EGRET value



EGRET EGB data can be used to constrain dark matter phenomenology...

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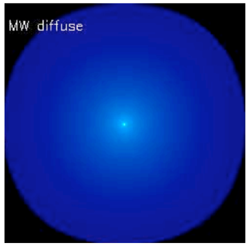
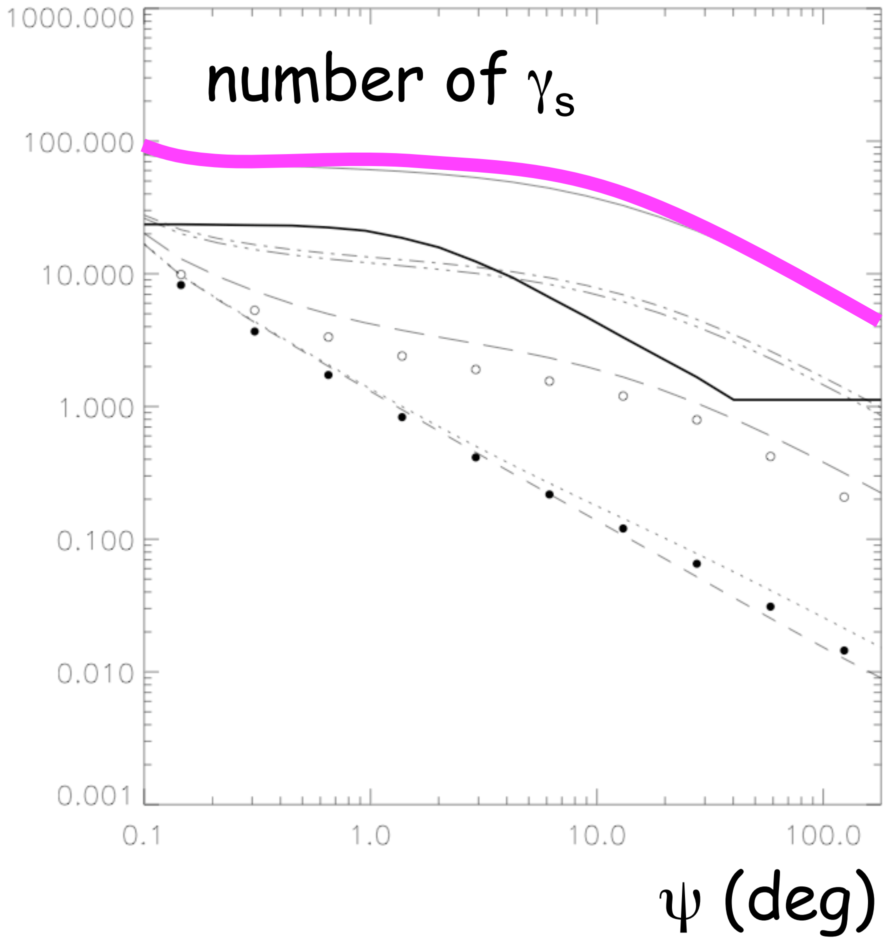
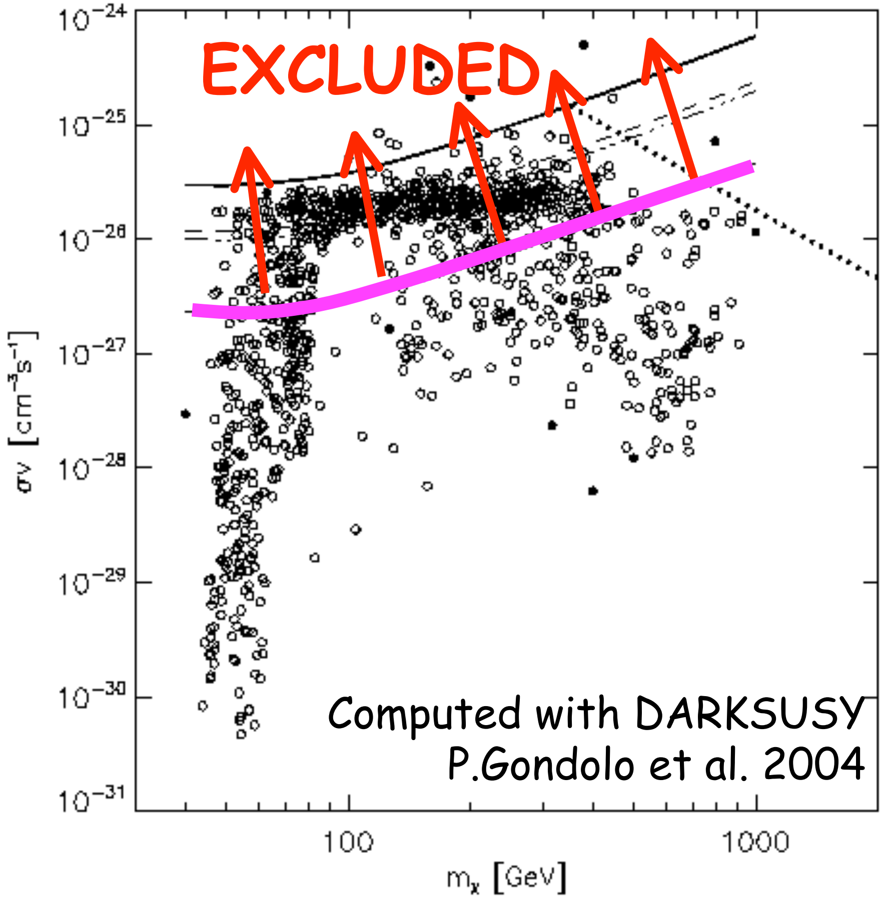
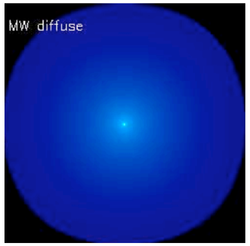


Constraints from EGRET





Φ_{cosmo} does not change, Φ_{PP} must be normalized

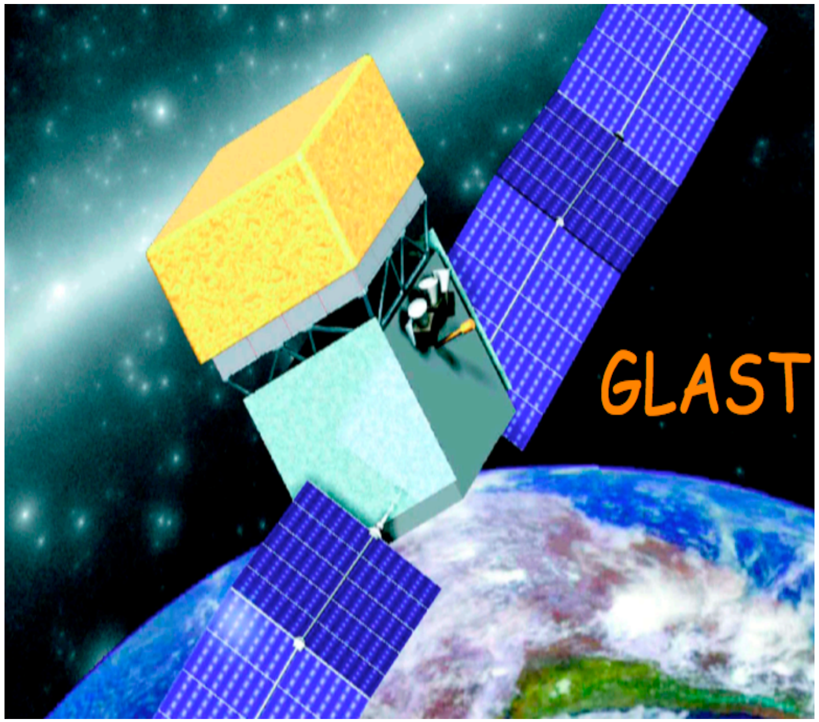


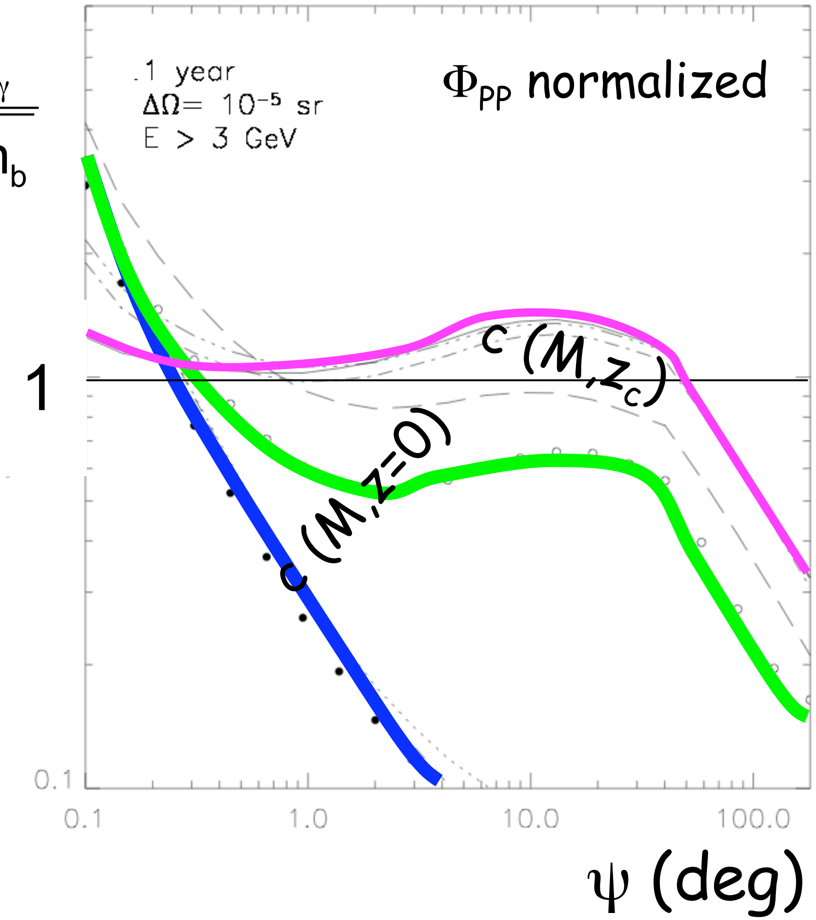
Experimental sensitivity for a GLAST-like observatory

Charged background free
A_{eff} = $10^4 cm^2$ always on-axis , independent on energy and incidence angle
Angular resolution 0.1°
ε_γ = 100 %, $\varepsilon_{\Delta\Omega}$ = 1
n_b extrapolated from EGRET

MW + subhalo smooth

$$\sigma = \frac{n_\gamma}{\sqrt{n_b}}$$





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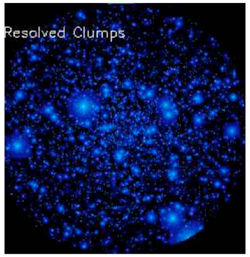
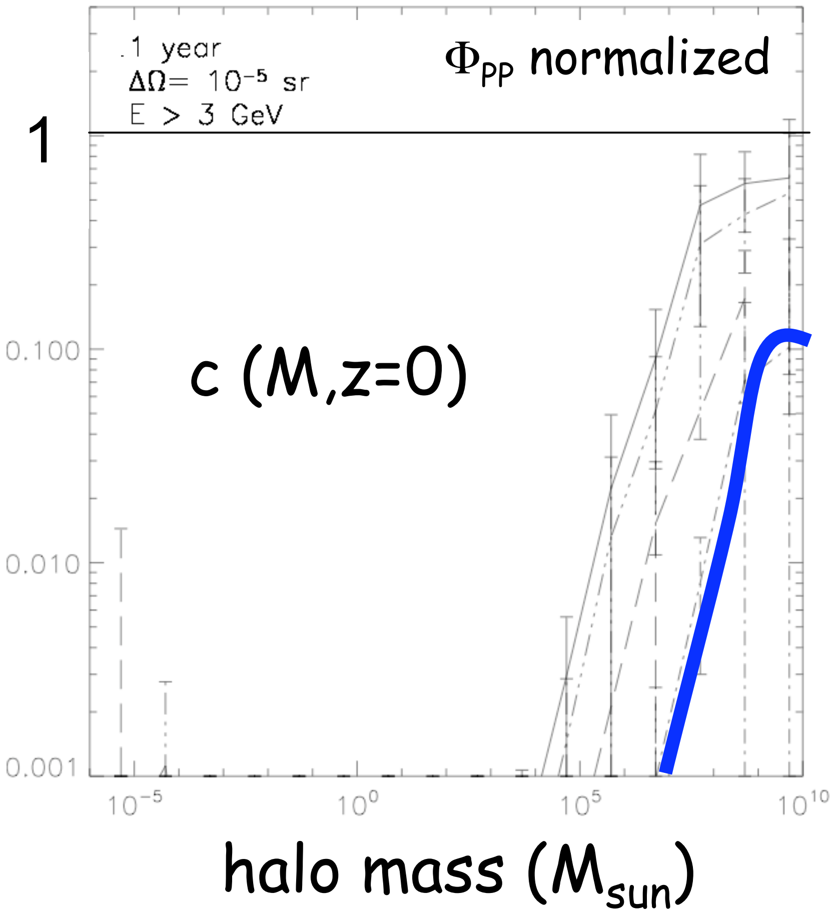
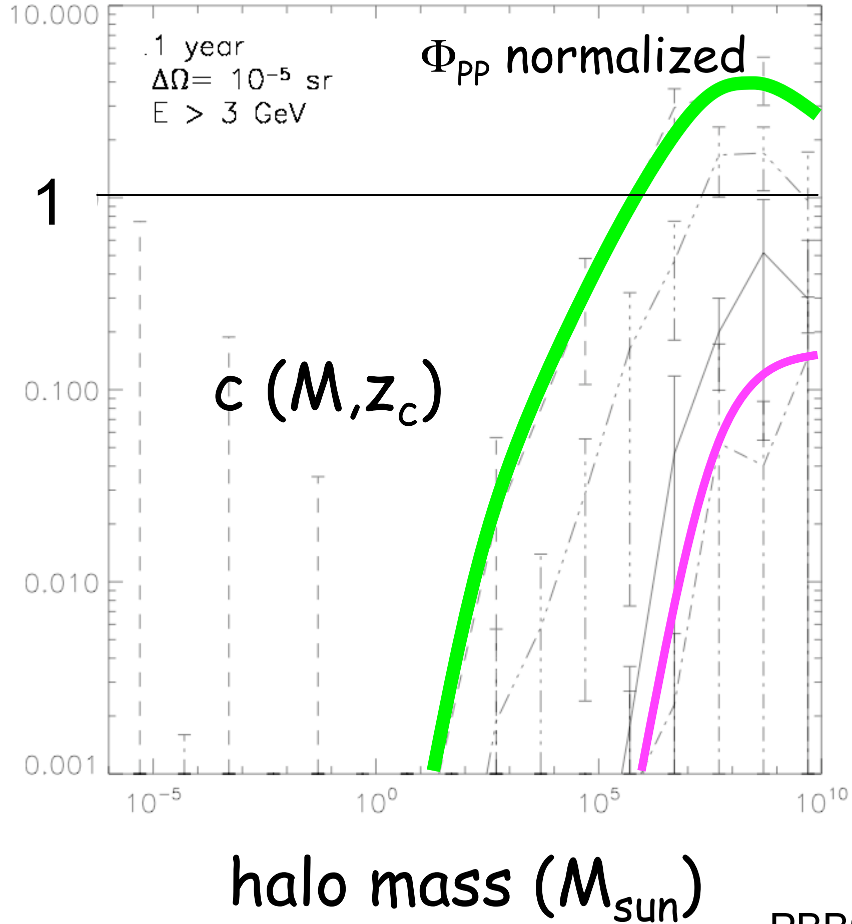


Experimental sensitivity for a GLAST-like observatory

Resolved halos

Number of haloes detectable at 5σ in 2.4 sr toward the GC





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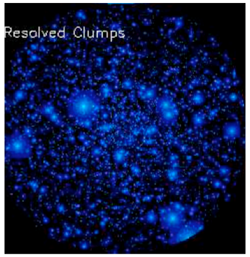

Experimental sensitivity for a GLAST-like observatory

Resolved halos, 2.4 sr f.o.v., different l.o.s.

	Number of detectable haloes ($\alpha = 1$)		
Model	$N_{GC}^{5\sigma}$	$N_{90}^{5\sigma}$	$N_{180}^{5\sigma}$
B_{ref,z_0}	0.65 ± 0.45*	0.85 ± 0.43	0.59 ± 0.30
B_{z_0}	0.65 ± 0.45	0.84 ± 0.43	0.59 ± 0.30
$B_{z_0,5\sigma}$	0.46 ± 0.34	0.60 ± 0.34	0.50 ± 0.27
B_{ref,z_c}	16.16 ± 2.60	23.24 ± 2.28	18.55 ± 1.72
B_{z_c}	1.74 ± 0.92	2.40 ± 0.82	2.15 ± 0.65
$B_{z_c,5\sigma}$	0.05 ± 0.05	0.07 ± 0.08	0.08 ± 0.08
ENS_{z_0}	0.06 ± 0.12	0.07 ± 0.10	0.04 ± 0.07
ENS_{z_c}	0.29 ± 0.40	0.49 ± 0.37	0.46 ± 0.30

There are 2 players: the EGRET extrapolated background and the number of subhaloes as a function of ψ

* Statistical error due to the average on the MC samples

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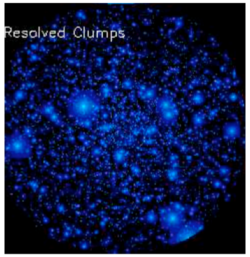
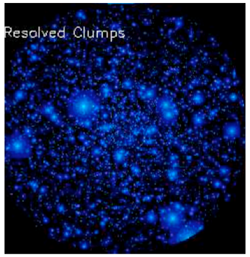


Experimental sensitivity for a GLAST-like observatory

Resolved halos, all sky survey, different α

Total number of detectable haloes			
Model	$N_{tot}^{5\sigma}$ ($\alpha = 1$)	$N_{tot}^{5\sigma}$ ($\alpha = 0.95$)	$N_{tot}^{5\sigma}$ ($\alpha = 0.9$)
B_{ref,z_0}	4.30 ± 4.00	3.62 ± 3.30	3.51 ± 2.11
B_{z_0}	4.26 ± 3.97	3.61 ± 3.30	3.50 ± 2.13
$B_{z_0,5\sigma}$	3.12 ± 3.09	3.30 ± 3.17	3.43 ± 2.04
B_{ref,z_c}	118.36 ± 24.96	132.89 ± 30.15	125.03 ± 20.06
B_{z_c}	12.53 ± 8.67	104.23 ± 24.78	119.04 ± 19.77
$B_{z_c,5\sigma}$	0.39 ± 0.56	10.55 ± 6.36	96.34 ± 18.66
ENS_{z_0}	0.33 ± 0.89	0.67 ± 1.58	0.34 ± 0.50
ENS_{z_c}	2.50 ± 4.48	23.43 ± 10.17	30.40 ± 10.31

There are 2 players: the intrinsic value of Φ_{COSMO} and the number of small mass halos (hence the reduced unresolved foreground and the effect of the EGRET EGB limit on Φ_{PP}) PBB07



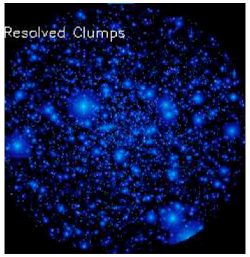
Experimental sensitivity for a GLAST-like observatory

The number of detectable halos over all-sky ranges from ~ 0 to ~ 130 (best value Φ_{PP})
(0 to $\lesssim$ 10 in fiducial model Φ_{PP})

No proper motion can be observed
The mass of detectable halos is > 10^5 M_{sun}

No proper motion can be observed

Is this result robust?



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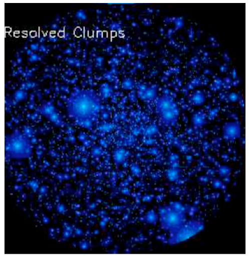
- concentration may depend on the initial conditions and on the distance from the GC
- subhaloes may contain sub-subhaloes
- ...



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Recent highlights on subhalo models (Diemand et al 2005)

✓ The mass of each progenitor accreted by the parent halo has a mass variance associated when it was a isolated halo.
The subhalo material is distributed according to this early σ-peak of the primordial density fluctuation field it belonged to:

$$n_{sh}(M,r,\nu) \propto \frac{dN_{sh}/dM}{\left(\frac{r}{r_\nu(M)}\right)^{\gamma}\left(1+\left(\frac{r}{r_\nu(M)}\right)^{\alpha}\right)^{\frac{\beta_\nu-\gamma}{\alpha}}}$$

$$r_\nu = r_s e^{\frac{\nu}{2}}$$

$$\beta_\nu = 3 + 0.26\nu^{1.6}$$

where ν is the number of σ-peaks.

✓ The concentration parameter inside each subhalo varies with ν :

$$c(\nu) = \nu c(\nu=1)$$

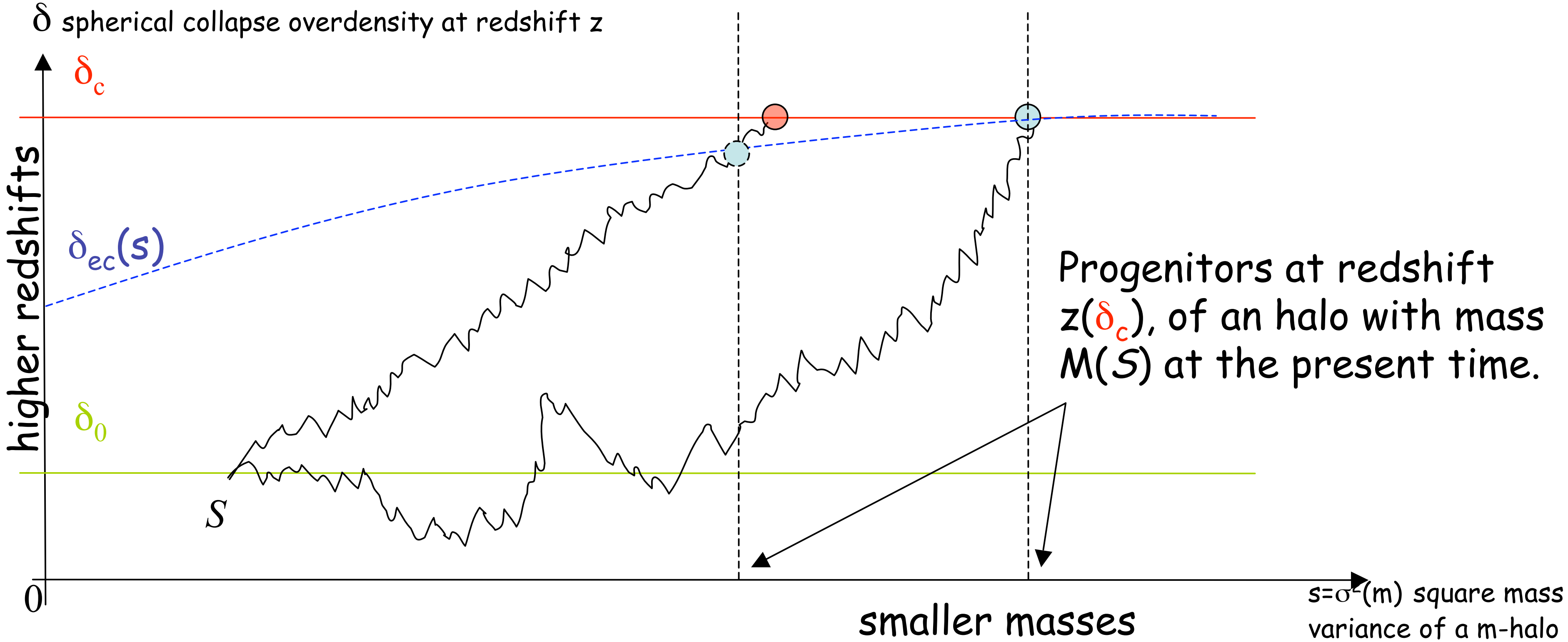
We need to determine $\nu(M)$

Conditional mass function of DM haloes (Lacey&Cole 1993)

$$f(s,\delta_c\,|\,S,\delta_0)ds = \frac{1}{\sqrt{2\pi}}\frac{\delta_c-\delta_0}{(s-S)^{3/2}}\exp\left(-\frac{(\delta_c-\delta_0)^2}{2(s-S)}\right)ds$$

fraction of mass belonging to haloes with mass ∈ [m,m+dm] at redshift z, which are progenitors of a halo of mass M at a later redshift z_0

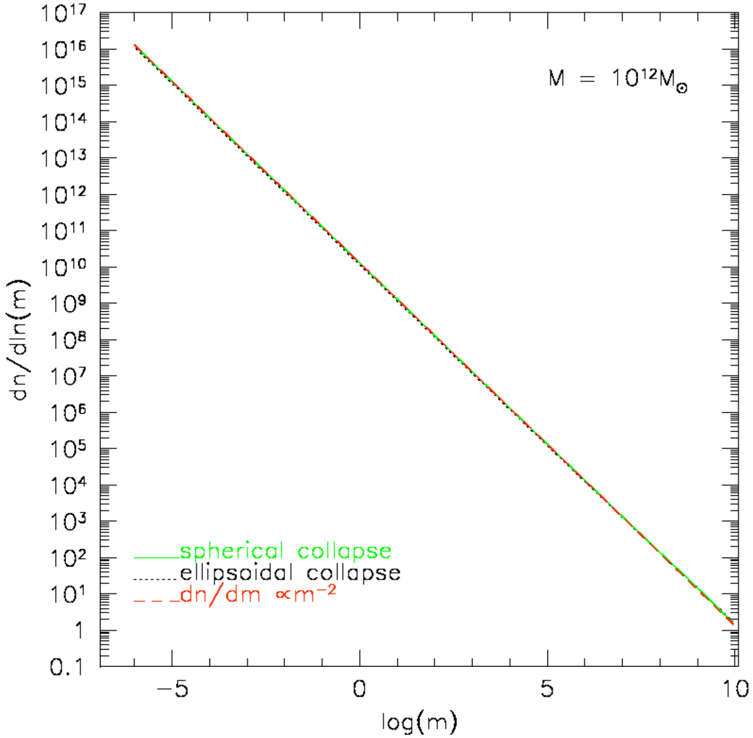
$$N(m,z\,|\,M,z_0)dm = \frac{M}{m}f(s,\delta_c\,|\,S,\delta_0)ds$$ number of progenitors at any given z

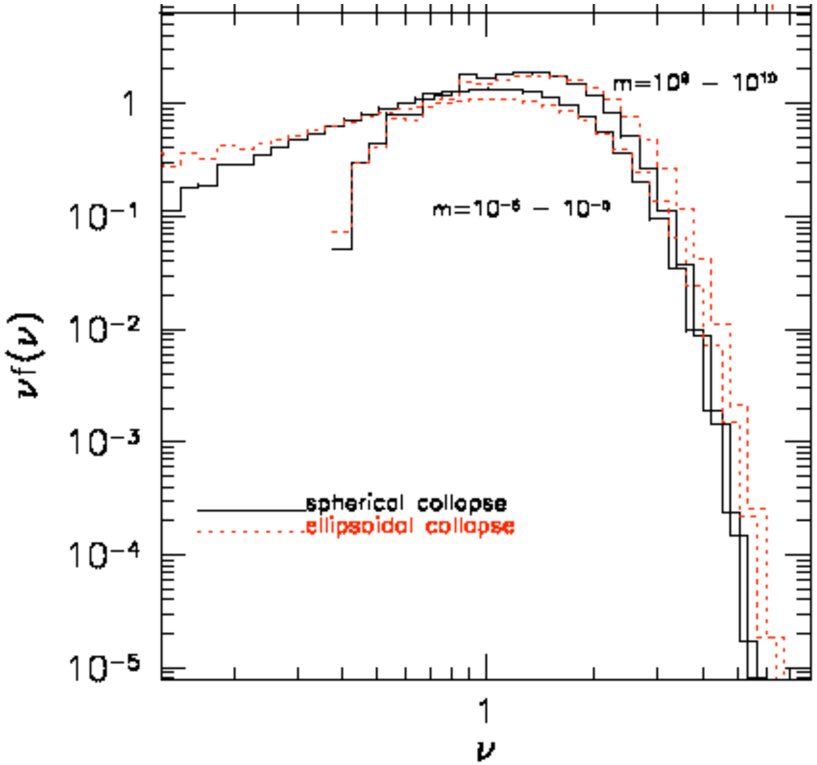


An analytical determination of the number of progenitors as a function of mass and redshift has been obtained, with $M \in [10^{-6}, 10^{10}] M_{sun}$

$$\frac{dN(m)}{dm} = \int_{\delta_0}^{\infty} \frac{M}{m} f(s, \delta_c \,|\, S, \delta_0) d\delta_c$$

$$\nu(M) = \frac{\delta_c^2}{s}$$

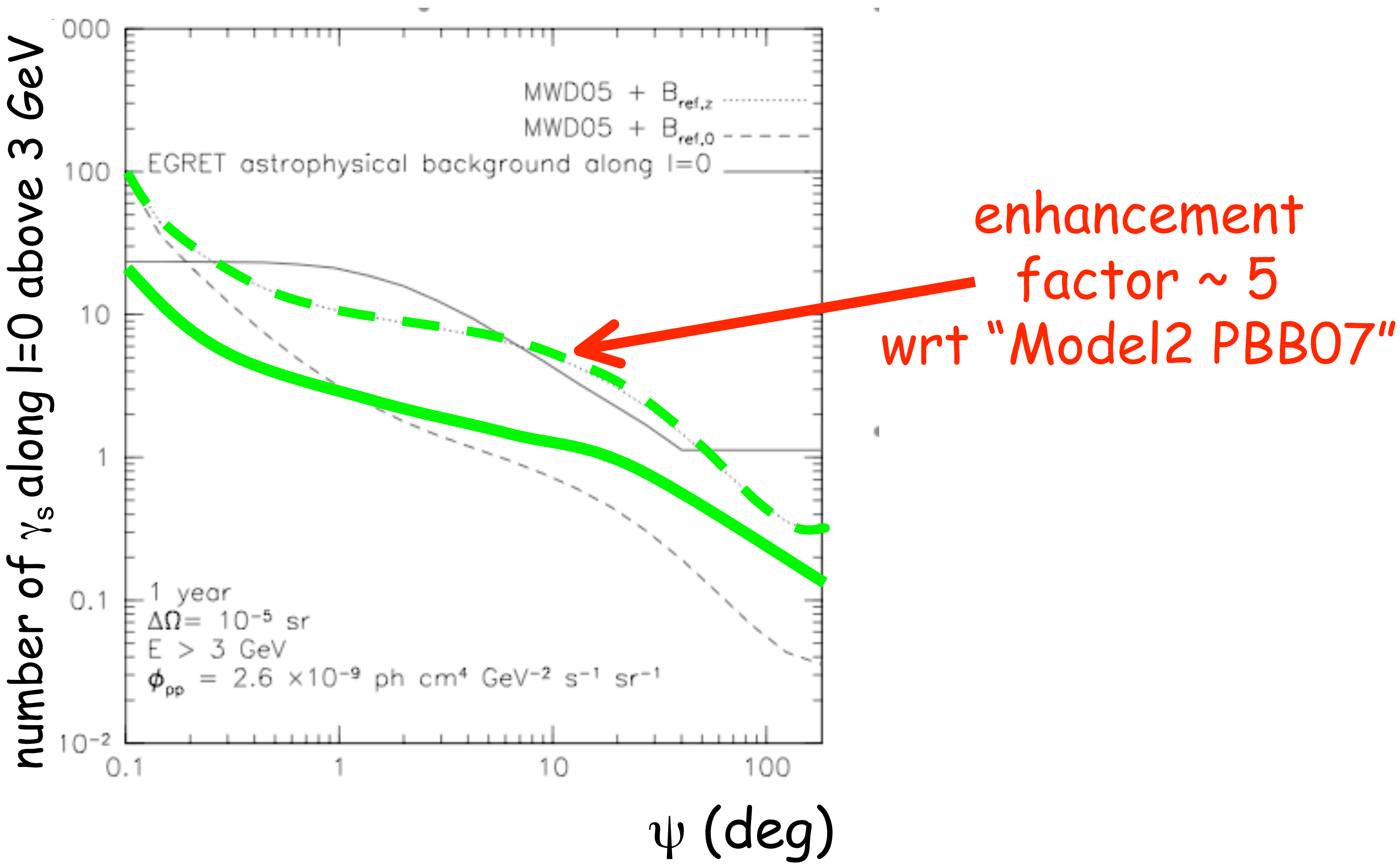




$$P(c) \rightarrow P(c(M))\, P(\nu(M))$$

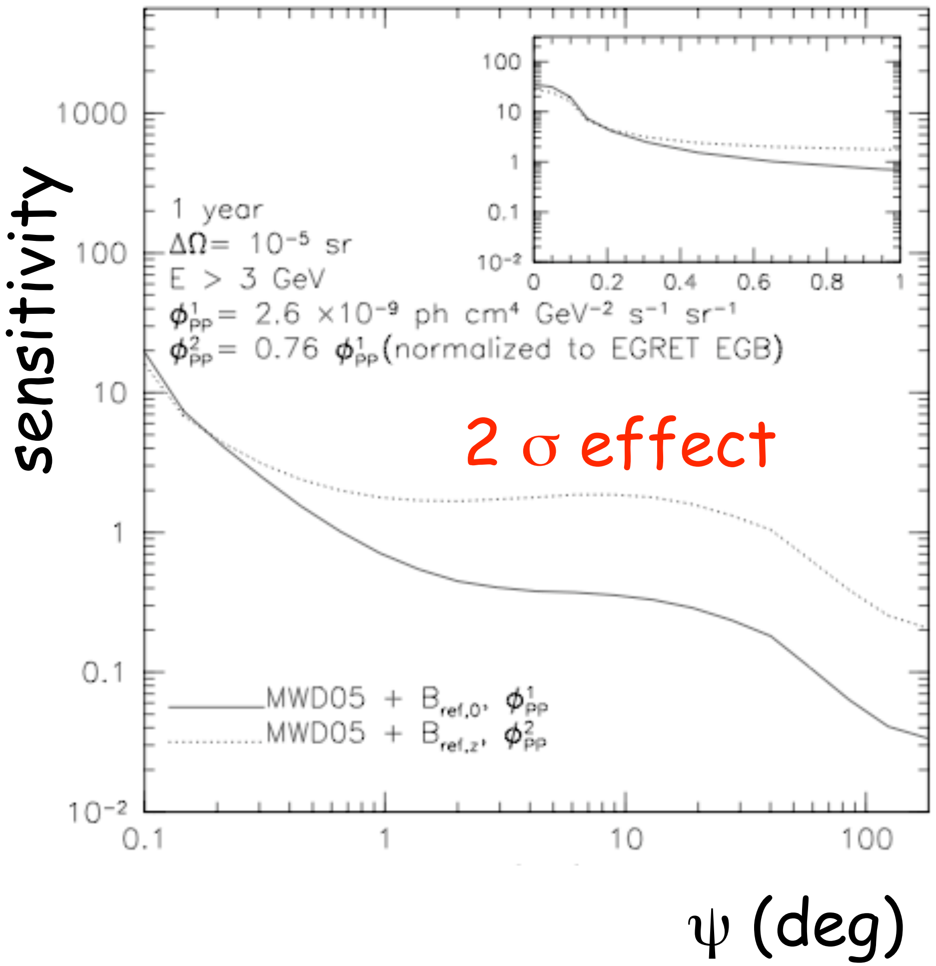
C. Giocoli, L. Pieri, G. Tormen, arXiv 0712.1476,MNRAS submitted, hereafter GPT07

Results on subhalo models : including the dependence of subhalo concentration parameter and distribution on the rarity of the density peak



GPT07

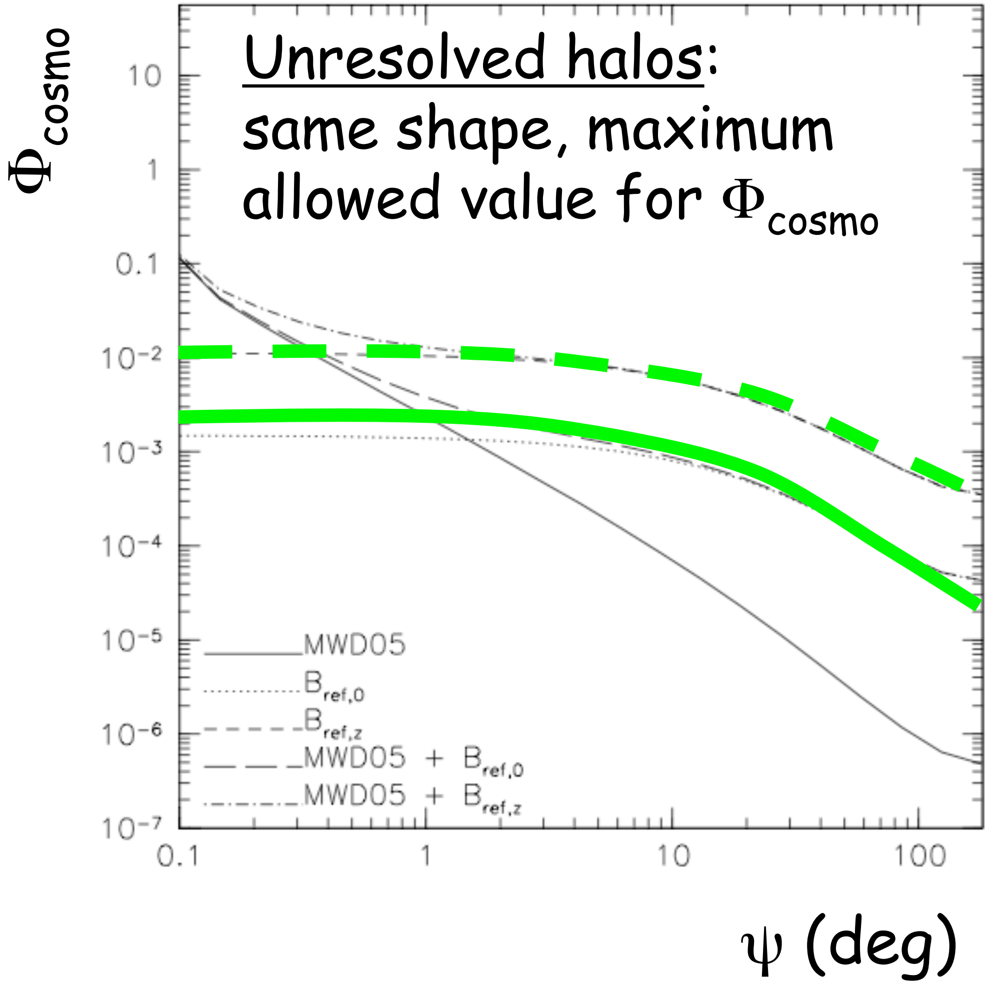
Results on subhalo models : including the dependence of subhalo concentration parameter and distribution on the rarity of the density peak



GC would be visible
as in PBB07
(but MW smooth halo
would be already enough
and the astrophysical
background is poorly known)

GPT07

Results on subhalo models : including the dependence of subhalo concentration parameter and distribution on the rarity of the density peak

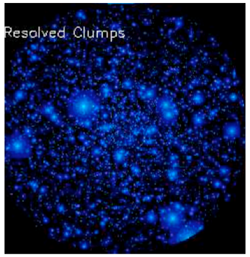


Resolved halos:
$P(\nu>1, r=r_{min}(M_h))$

- for high mass halos is not significant

- $N_h(\nu=2.4, r=r_{min}(10^{-6} M_{sun}))=1$ but $\nu=2.4$ is not enough for detection ($\nu=10$ is needed)

We don't expect a dramatic change on the number of detectable resolved halos



Experimental sensitivity for a GLAST-like observatory

The number of detectable halos over all-sky
ranges from ~ 0 to ~ 130 (best value Φ_{PP})
(0 to $\lesssim$ 10 in fiducial model Φ_{PP})

No proper motion can be observed
The mass of detectable halos
is > 10^5 M_{sun}

No proper motion can be observed

Is this result robust?

- concentration may depend on the initial conditions and on the distance from the GC

- subhaloes may contain sub-subhaloes

- ...

Results on subhalo models : including the possibility that subhaloes may contain sub-subhaloes

We have computed the BF due to subhaloes for DRACO

Model "1": 730 to 970

Model "2": 27 to 31

Model "3": 1.5 to 1.7

Different BF depend on the different determination of DRACO parameters (mass, density profile Lokas et al 2007, Gilmore et al 2007)

L. Pieri, A. Pizzella, E.M. Corsini, E. Dalla Bontà, F. Bertola MNRAS submitted, hereafter Petal07

Results on subhalo models : including the possibility that subhaloes may contain sub-subhaloes

BUT…

The same subhalo model must hold for the MW and for DRACO

↓

While computing the BF for DRACO, we HAVE TO take into consideration the EGRET EGB limit on the Milky Way, and the consequent reduction, or increment, of the allowed ϕ_{PP} value!

↓

Models with higher BF will have lower ϕ_{PP} and viceversa:

THE MAXIMUM EFFECT WILL BE THE SAME FOR ALL MODELS in the case of DRACO this is a factor ~ 1.5 on flux

Petal07

Conclusions

We filled the MW with a population of ~10^{16} subhalos, $dN/dM \propto M^{-2}$, $M^{-1.95}$, $M^{-1.9}$, assuming different models for the concentration of subhalos

The overall smooth γ-ray foreground provided by such a population of subhalos has been derived and compared with EGRET data on extragalactic γ-ray background. Models exceeding the EGRET data were normalized.

The GC could be detected, independenly on the existence of subhalos, but the astrophysical background is poorly known. The subhalo smooth foreground is not going to be detected with high sensitivity

The number of detectable haloes with a GLAST-like observatory is highly model-dependent (0 to ~ 130). In any case they would be massive subhalos ($M > 10^5 M_{sun}$) and no proper motion could be observed.

This results is not expected to change dramatically if rareness of density peaks is considered.

The effect of subhaloes inside subhaloes is work in progress.