Earth-size Dark Matter (micro) halos: Existence and Detectability

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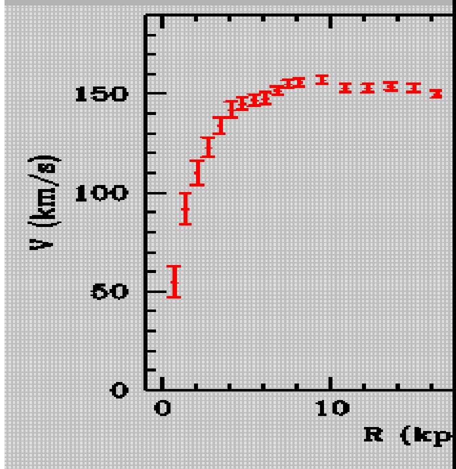
Obs. de la Cote d'Azur. Nice. Jan 25 2006

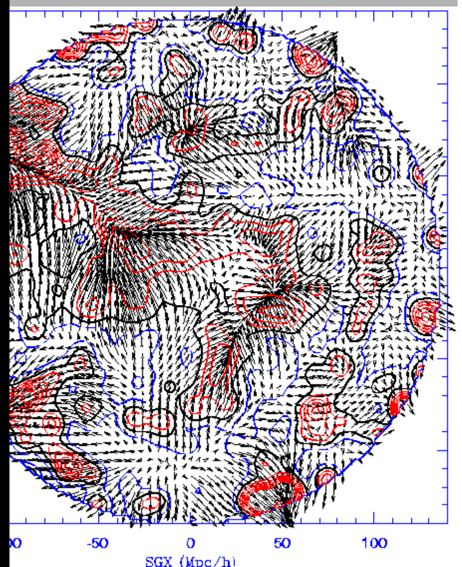
Dark Matter in the Universe

Galaxy Rotation C



Rubin e Ford (1

rent Large Scale Flows



ressler et al. (1987)

New Standard "Concordance" Cosmology:

$$\Omega_{Tot} = \Omega_{DM} + \Omega_b + \Omega_\gamma + \Omega_\nu + \Omega_\Lambda = 1.02 \pm 0.03$$

$$\Omega_b^{Nucl} \sim 0.04 \qquad \Omega_\gamma \sim \Omega_\nu \sim 10^{-5}$$

$$\Omega_\Lambda \sim 0.73$$

$$\Omega_{DM} \sim 0.23$$

M/L ~20 ~500

Scale (Mpc) ~0.1 ~60

Baryons Only

C

Nu

SUperSYmmetric Dark Matter 1

Looking for CDM candidates

SUperSYmmetry

New physics is likely at the alectroewak scale

Invariance of the theory under the exchange boson↔fermion

It is spontaneously broken at the electroweak scale (unknown breaking mechanism)

It introduces several new free parameters

In most supersymmetric models R-parity guarantees that the **L**ightest **S**upersymmetric **P**article is stable and weakly interacting (WIMP).

In most cases the **LSP** is a Majorana particle linear combination of Supersymmetric partners of the photon, Z° and the neutral Higgs bosons called

Neutralino $\chi = a_1 \tilde{B} + a_2 \tilde{W}^3 + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0$

Is the neutralino a good CDM candidate ?

SUperSYmmetric Dark Matter 2

- Neutralino is massive, stable and weakly interacting (WIMP).
- It is a thermal relic. $$\Omega_\chi = \frac{m_\chi n_\chi}{\rho_c} \sim \frac{6 \cdot 10^{-27}\,cm^3 s^{-1}}{<\sigma \cdot v>_{ann}}$$
- Its weak scale cross-section guarantees a significant contribution to the cosmological mass density. Indeed, $0.05 < \Omega_\chi < 0.3$ for a wide choice of susy parameters
- It freezes-out @ $T_f \sim m_\chi/25$. i.e. is non-relativistic at the decoupling and thus is "cold".
- Its mass is set by the electroweak scale. Current limits are

$$50\ GeV < m_\chi < 300\ TeV$$

Accelerator Searches → 50 GeV

Freeze-out + Cosmological DM density → 300 TeV

Neutralino is a good CDM candidate

Neutralinos searches

direct searches → χ elastic diffusion on nuclei (nucleus recoil energy)

indirect searches ($\chi\chi$ annihilation in high density regions) → neutrinos, antimatter, γ–rays

Gravitational instability in a cold, collisionless fluid leads to formation of virialized structures (halos) characterized by regions of enhanced density (cusps and caustics). We model the γ-ray emission from χ-annihilation within:

- <u>Central Regions of DM Halos</u> (MW, nearby galaxies
- <u>Sub-galactic DM Halos</u> and extragalactic signal)
- Galactic DM Caustics (Sergei's Talk)

γ–photons from neutralino annihilation

$$\frac{d\phi_\gamma(E,\psi,\Delta\theta)}{dE} = \frac{d\phi^{SUSY}}{dE}(E) \times \phi^{COSMO}(\psi,\Delta\theta)$$

$$\phi^{COSMO} = \int_{\Delta\Omega(\theta)} d\Omega \int_{l.o.s.} \rho_\chi^{\,2}(r(l,\psi))\,dl(\psi)$$

$$\frac{d\phi^{SUSY}}{dE} = \left[N_\gamma \cdot b_{Z\gamma}\,\delta\left(E - m_\chi\left(1 - \frac{m_Z^2}{4m_\chi^2}\right)\right) + N_\gamma \cdot b_{\gamma\gamma}\,\delta(E - m_\chi) + \sum_f \frac{dN_\gamma^f(E)}{dE} b_f \right] \cdot \frac{<\sigma v>_{ann}}{2 \cdot 4\pi \cdot m_\chi^2}$$

$\chi\chi \to Z\gamma$ → **Lines** ← $\chi\chi \to \gamma\gamma$

$b_{\gamma\gamma} \sim b_{Z\gamma} \sim 10^{-3}$

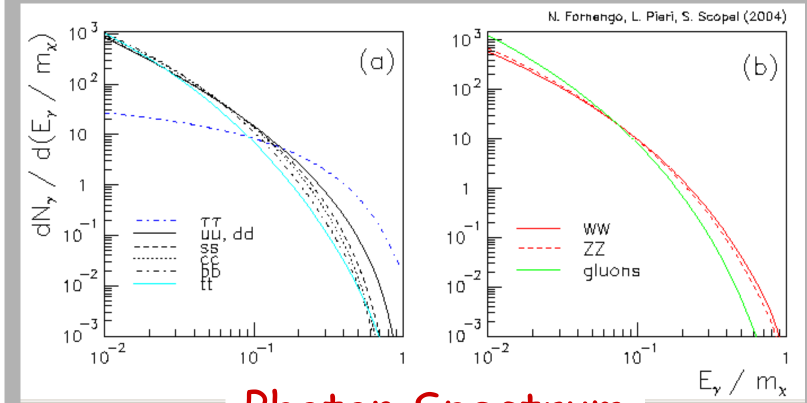
Continuum

1) Either fermions and gluons are produced directly from $\chi\chi$ annihilation or Higgs particles and gauge bosons decay into them

2) quarks and gluons hadronize…

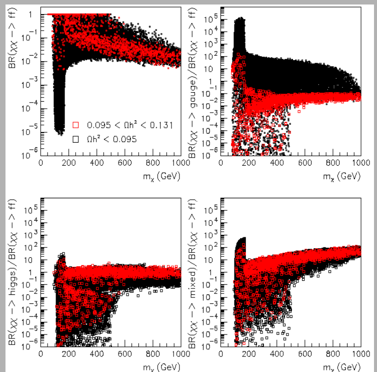
3) … π^0's decay into 2 photons

The supersymmetric factor ϕ^{SUSY}



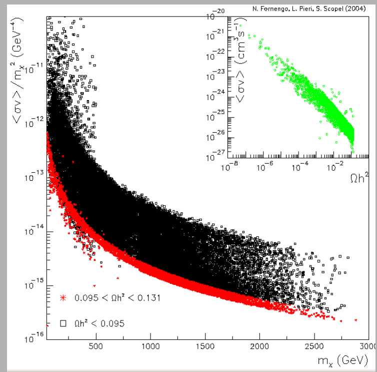
Photon Spectrum

×



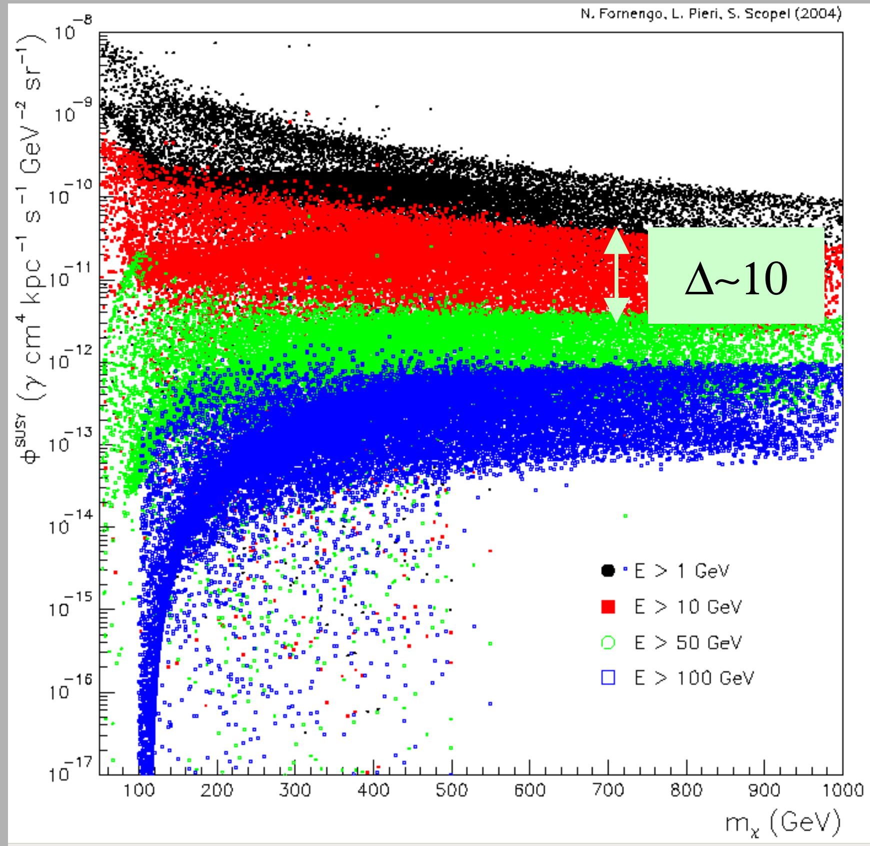
Branching Ratio

×



Cross Section

=



We use the implementation of a SUSY scheme directly at the EW scale, called eMSSM (effective Minimal SuperSymmetric Model). The number of parameters is restricted to those which shape the model at the EW scale

- 100 GeV $< |\mu|, M_2 <$ 6 TeV
- 90 GeV $< m_A <$ 1 TeV
- $M_1 = 5/3 \tan^2 \theta_W M_2$
- $-3 < A_{t,b,\tau}\, m_0 < 3$
- 100 GeV $< m_0 <$ 3 TeV
- $1 < \tan\beta < 50$

Modeling ϕ^{COSMO}: DM halo density profile 1

Is there a central "cusp" $\rho(r) \sim r^{-\alpha}$?

- Spatially resolved spectra of the diffuse hot gas of galaxies and clusters with Chandra give $\alpha = 1.25$ and $\alpha = 1.35$.
  Disturbed X-rays surface brightness clusters give $\alpha < 1$
- Radial mass profiles by intracluster medium density and temperature give $1 < \alpha < 2$
- Rotation curves of Low Surface Brightness galaxies give $\langle\alpha\rangle = 0.2$, but the distribution has tails at $\alpha = 2$
- Strong lensing and spectroscopic measurements of stellar dynamics of the brightest cluster galaxies give $\langle\alpha\rangle = 0.52 \pm 0.3$
- High resolution Hα rotation curves for dwarfs and LSB give $0 < \alpha < 1.2$
- Weak gravitational lensing of X-ray luminous clusters give $0.9 < \alpha < 1.6$
- Microlensing optical depth towards the MW Galactic Centre give $\alpha = 0.4$ (possibly due to halo-flattening)

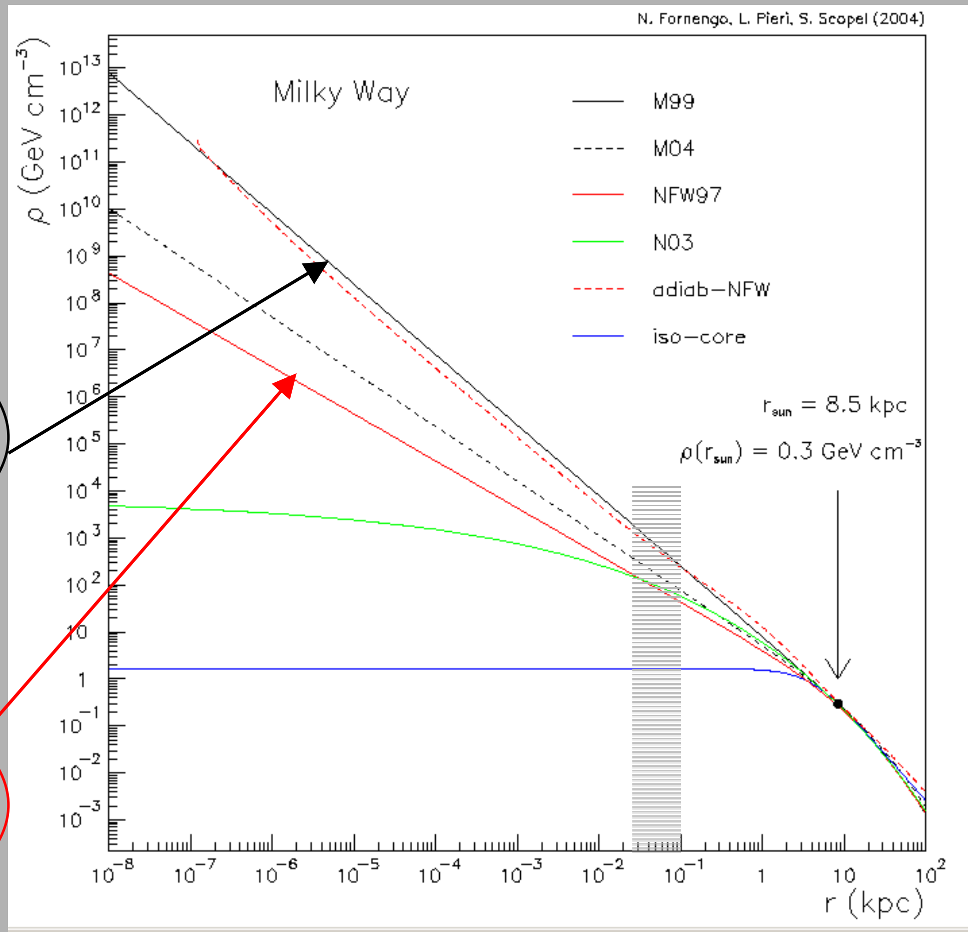
Weak constrains from current observations.

ϕ^{COSMO} and the halo density profile 2

Density profiles from N-body simulations

$$\rho_{M99}(r) = \frac{\rho_s^{M99}}{\left(\frac{r}{r_s^{M99}}\right)^{1.5} \cdot \left[1+\left(\frac{r}{r_s^{M99}}\right)^{3}\right]}$$

$$\rho_{NFW}(r) = \frac{\rho_s^{NFW}}{\left(\frac{r}{r_s^{NFW}}\right) \cdot \left[1+\left(\frac{r}{r_s^{NFW}}\right)\right]^2}$$



r_{min} ~ 10^{-8} kpc is given by the condition t_{ann} ~ t_{ff}, for the M99 profile

Annihilation time $t_{ann} \sim (\sigma_{ann} v n_\chi(r))^{-1}$

Free-Fall time $t_{ff} \sim (G_N \rho_G(r))^{-1/2}$

More Theoretical Uncertainties…

The presence of a Super Massive Black Hole may significantly modify ϕ^{COSMO}

-Adiabatic growth on a SMBH steepens the density profile. NFW→M99
(Ullio, Zhao & Kamionkowski 2001)
-Hierarchical build-up of SMBH results in a shallower profile $\rho(r)\sim r^{-0.5}$ within 10-100 pc (Merritt et al. 2002)

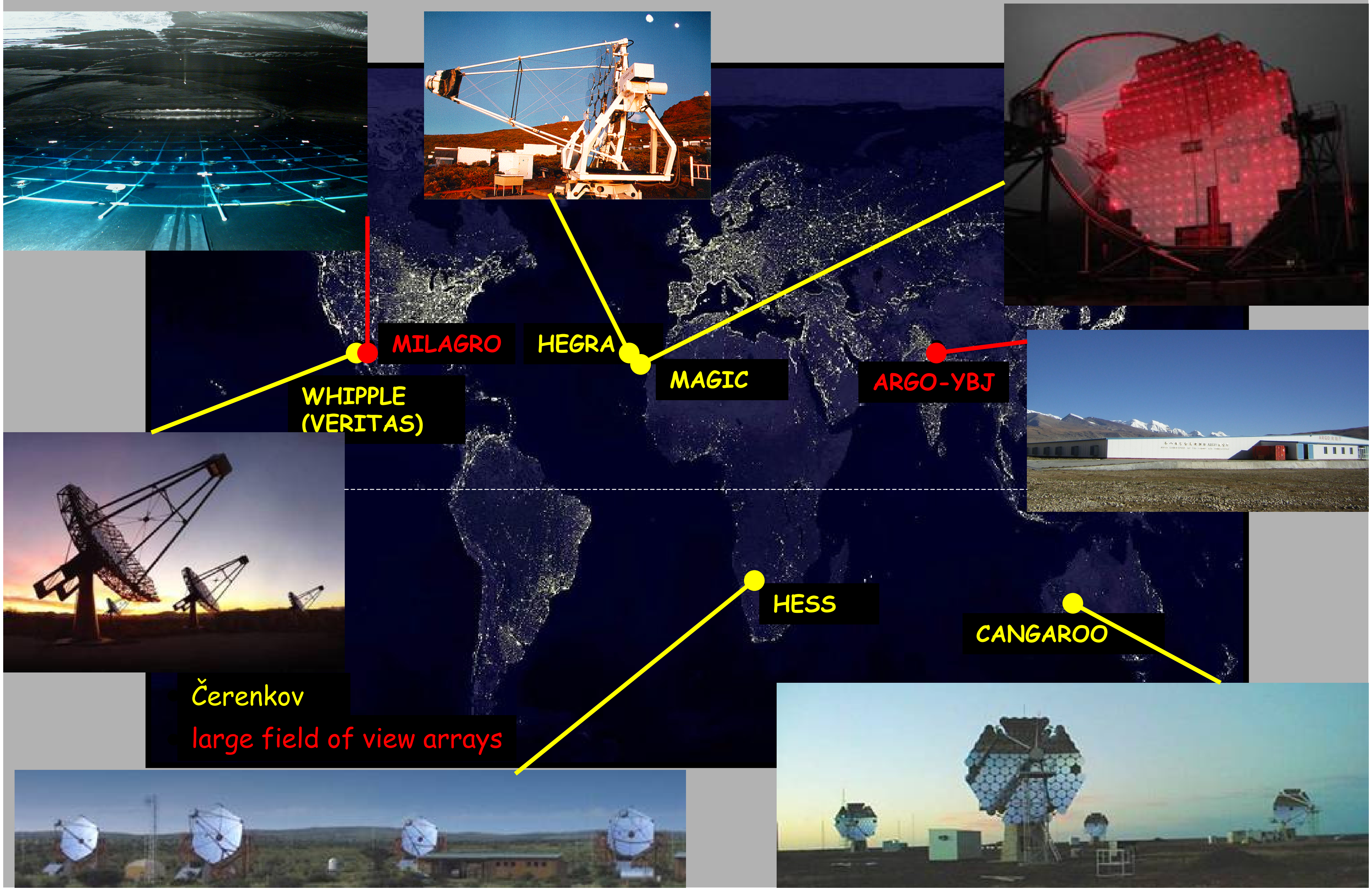
The baryon dominance in the central regions may also modify ϕ^{COSMO}

-Energy dissipation of the baryons results in a steep central profile in both baryon and DM density profiles $\rho(r)\sim r^{-1.6}$ ~ M99 profile
(Gnedin et al 2005)

-Interactions between DM and stars (kinetic heating, SMBH capture) decrease the DM density within 10-100 pc from the Galactic center
(Merritt 2004)

Best case scenario: M99 density profile
Worst case scenario: reduction of ϕ^{COSMO} by a factor 1-10 (w.r.t. NFW)

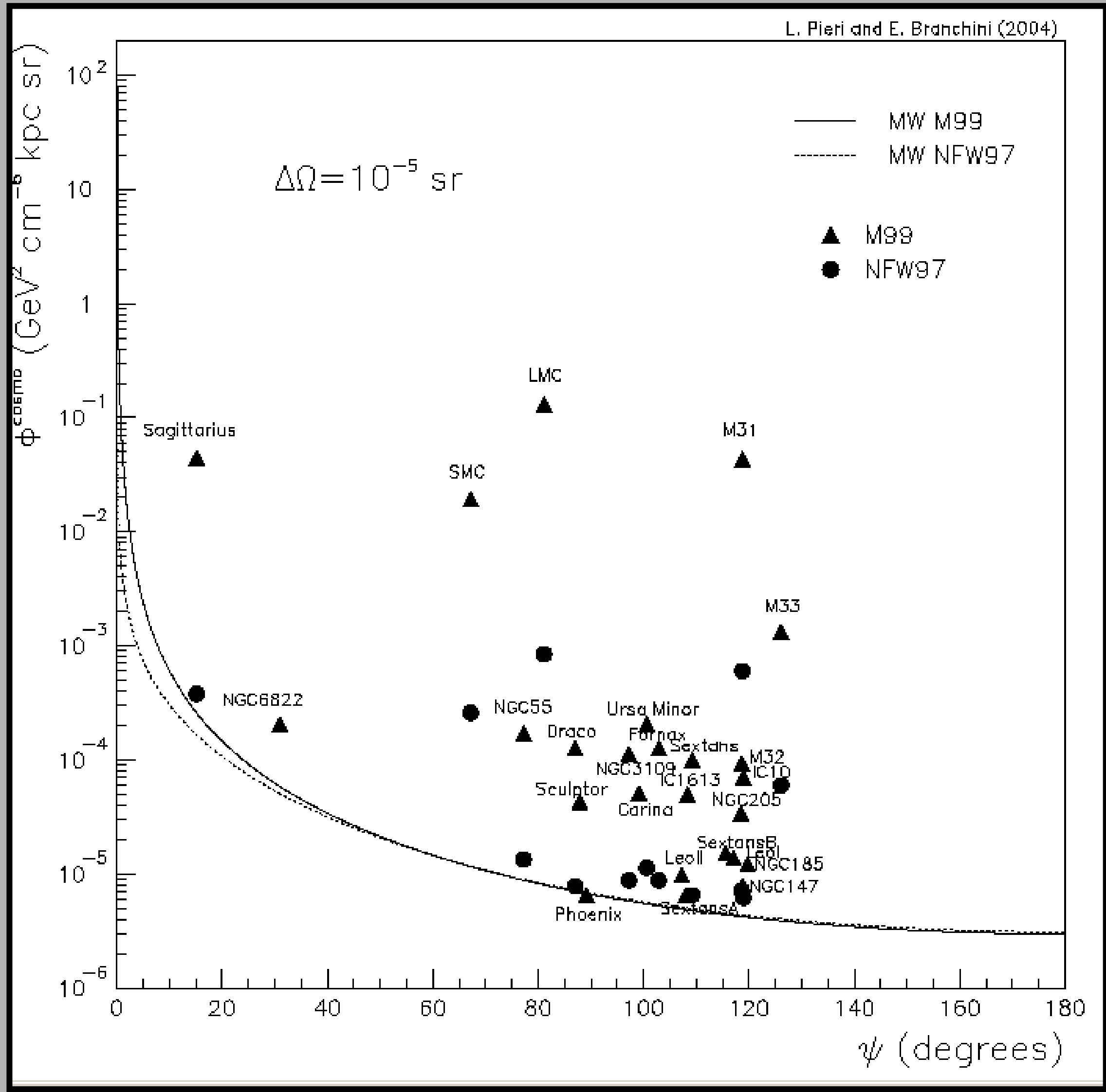
Ground-based γ-ray Observatories



Annihilation flux from different DM halo profiles

Several local galaxies shine above the Galactic foreground for both A NFW and a M99 profile.

Many nearby galaxies shine above the Galactic annihilation foreground.



L. Pieri & EB PRD 2004

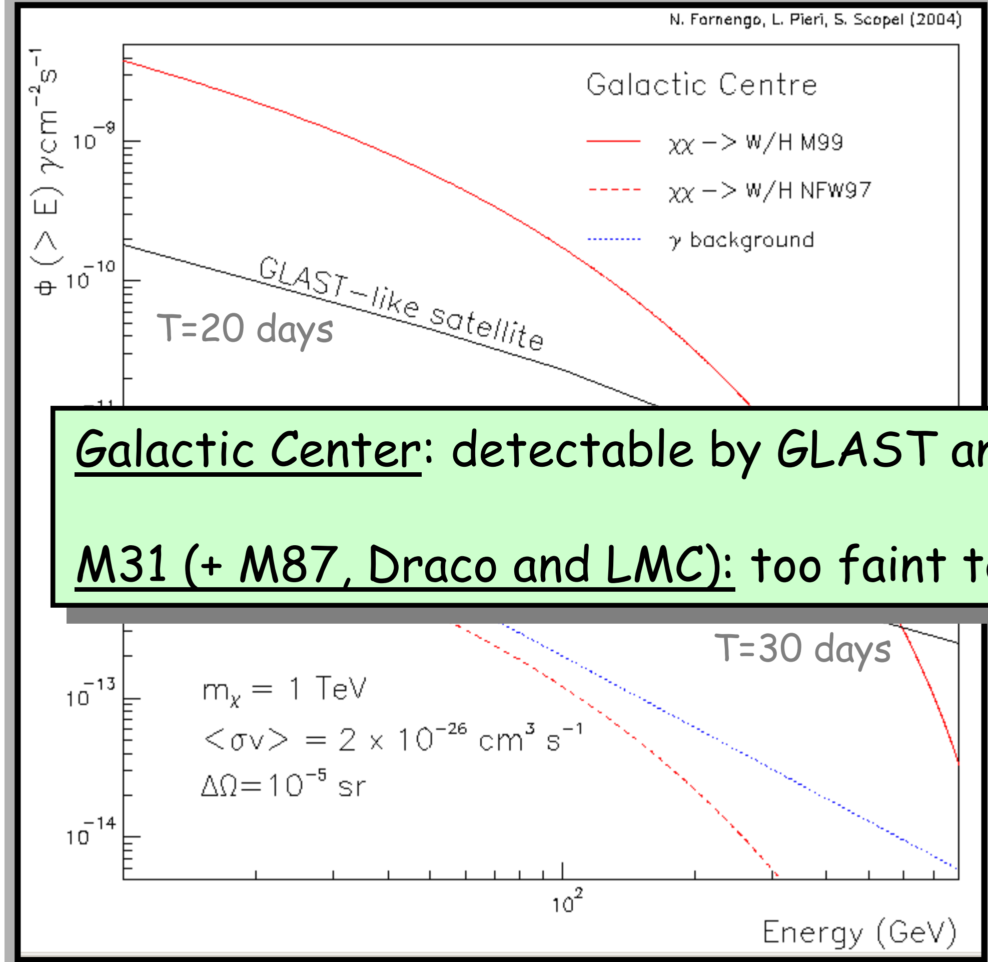
Experimental visibility of DM sources

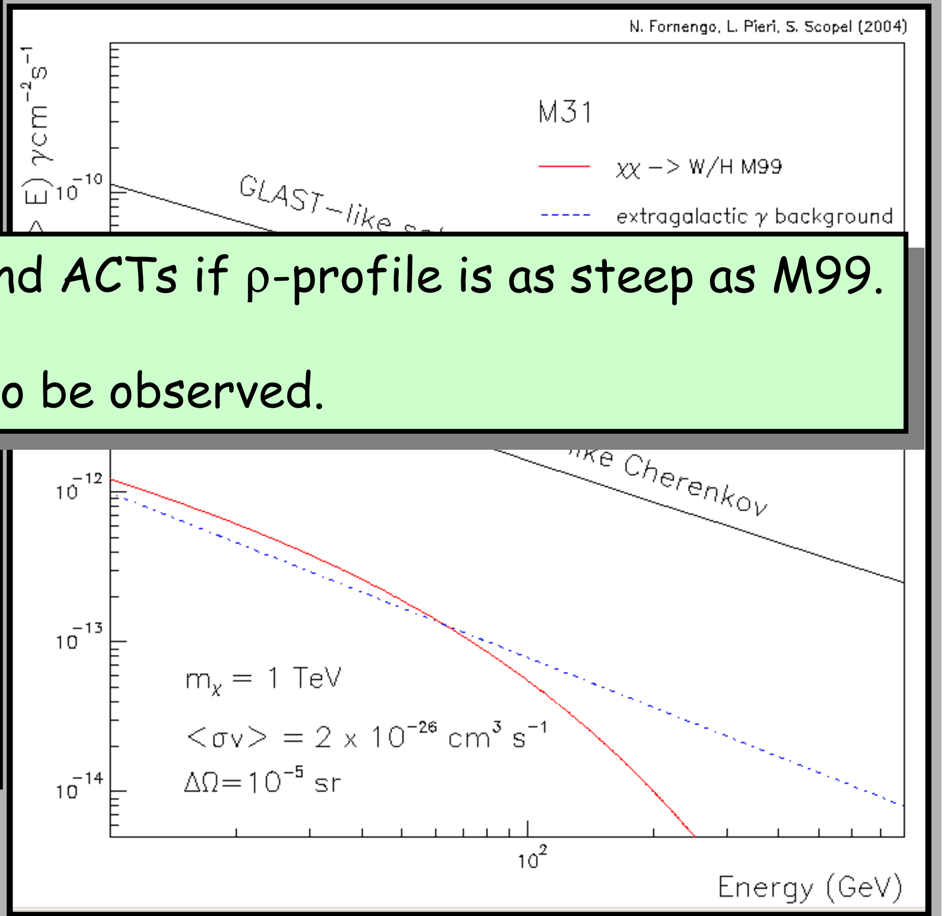
The sensitivity of the detector to point-like sources results from the ratio between the gamma flux from DM (unknown) and the fluctuation of the known n(h) + n(e) + n($\gamma_{diffuse}$) background

$$\frac{n_\gamma}{\sqrt{n_{bkg}}}(>E) \cong \sqrt{T_{obs} f(\delta)} \cdot \frac{0.7}{\sqrt{\Delta\Omega}} \cdot \frac{\int \varepsilon_\gamma A_\gamma^{eff} \varphi_\gamma^{DM} dE}{\sqrt{\int (1-\varepsilon_h) A_h^{eff} \varphi_h dE + \varepsilon_\gamma A_\gamma^{eff} \varphi_e dE + \varepsilon_\gamma A_\gamma^{eff} \varphi_\gamma^{diff} dE}}$$

	Čerenkov telescope	*Satellite*	*Air shower array*
effective area	~ $4 \cdot 10^8$ cm^2	~ 10^4 cm^2	~ 10^7 cm^2
γ-discrimination efficiency	$\varepsilon_\gamma = \varepsilon_h$ ~ 99%	ε_γ ~ 99% $\varepsilon_{charged}$ ~ 99.997%	$\varepsilon_\gamma = \varepsilon_h$ ~ 75%
angular resolution	~ 0.1° @100 GeV	~ 0.1° @1 GeV	~1° @100 GeV

Experimental Visibility

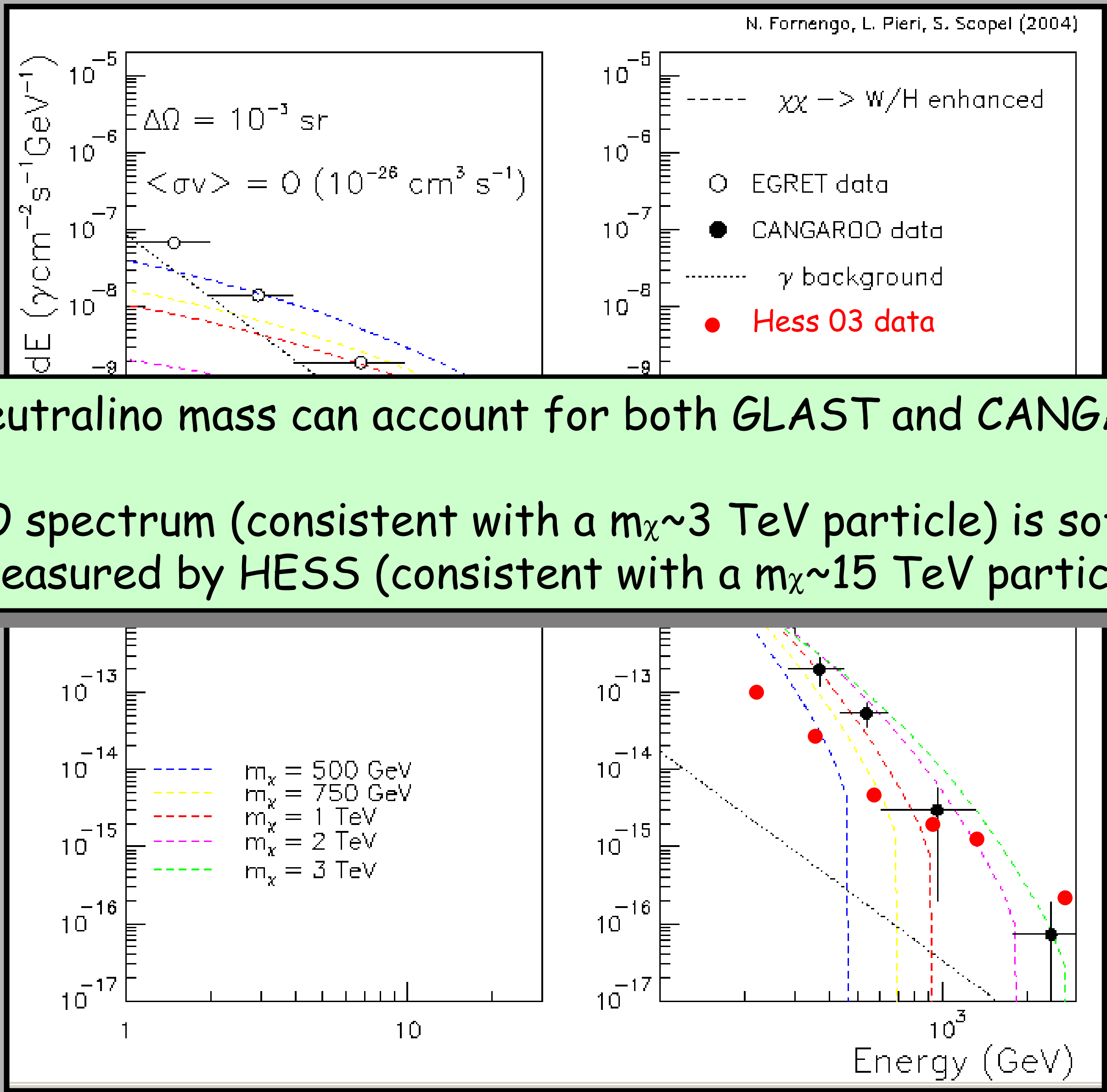




Galactic Center: detectable by GLAST and ACTs if ρ-profile is as steep as M99.

M31 (+ M87, Draco and LMC): too faint to be observed.

Have we already detected annihilation from the Galactic Center ?

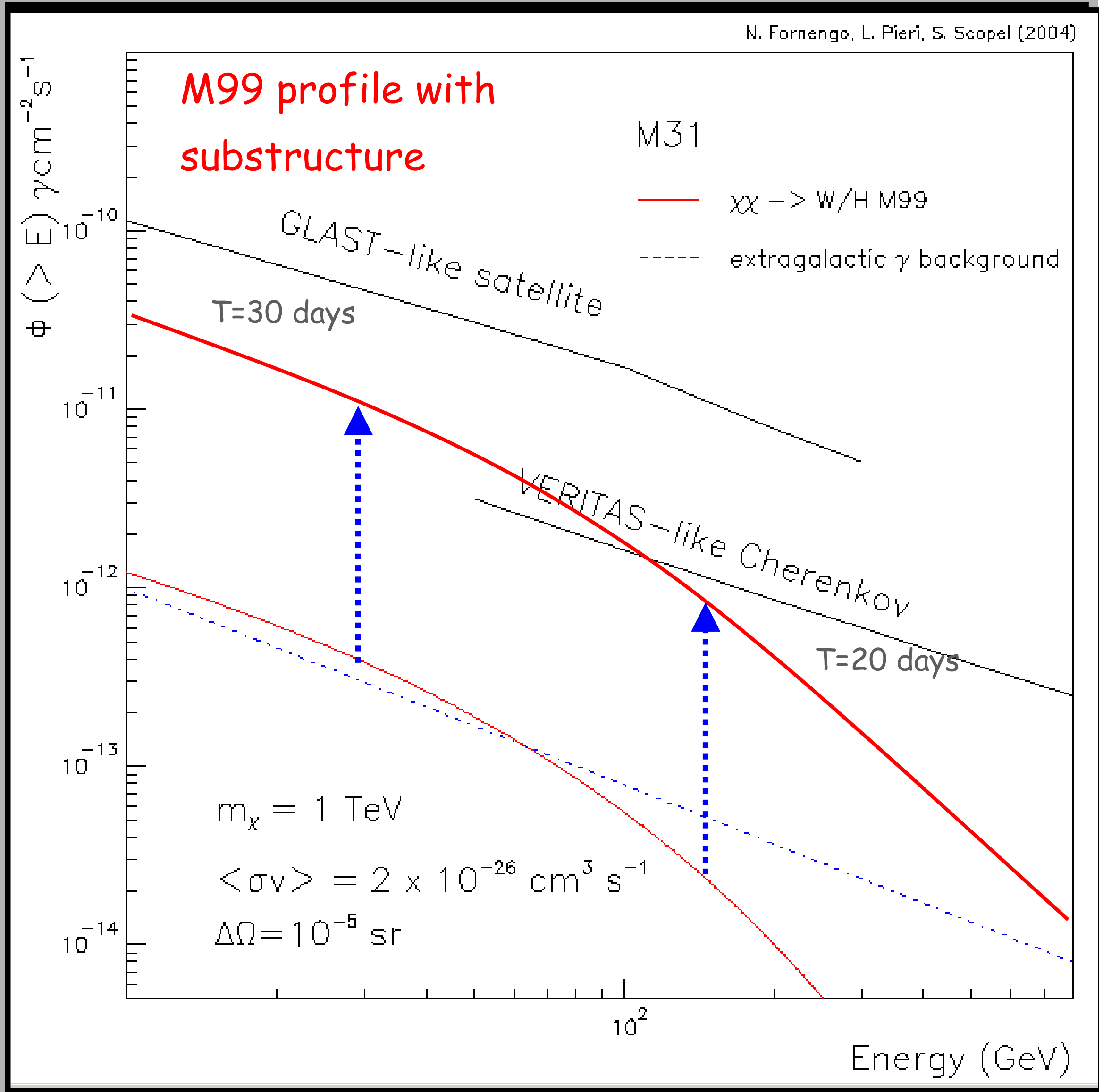


No single neutralino mass can account for both GLAST and CANGAROO data.

CANGAROO spectrum (consistent with a m_χ~3 TeV particle) is softer than that measured by HESS (consistent with a m_χ~15 TeV particle).

The effect of sub-galactic halos ($M_{SH} > 10^6\ M_{SUN}$)

In the hieararchical "bottom-up" structure formation scenario small virialized structured form first and then merge into larger systems. In a CDM Cosmology power on small scale is large enough to produce a wealth of sub-galactic halos that we do not actually observe ("*small scale CDM crisis*"). Some numerical experiments show that these small, dark Sub-haloes survive within their massive hosts. We have modelled the spatial distribution and mass function of this sub-halo population according to numerical experiments and have quantified their contribution to the annihilation flux



Influence of subhalos revised 1

What is the minimum mass of a virialized DM halos ? When do they form ? What are their typical size and density contrast ?

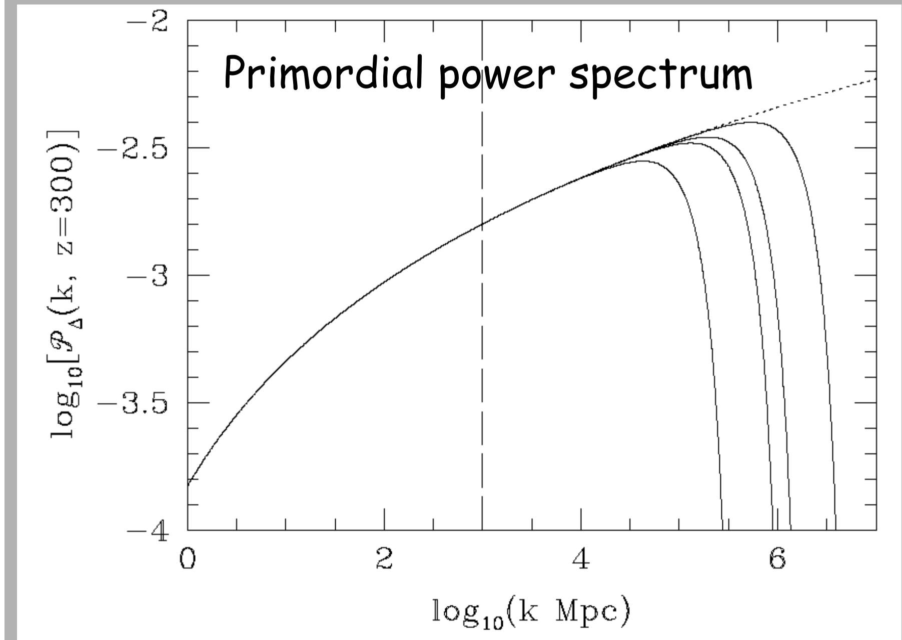
$$D(k) \equiv \frac{\Delta_{WIMP}(k,\eta)}{\Delta_{WIMP}(k,\eta_i)} = \left[1 - \frac{2}{3}\left(\frac{k}{k_{fs}}\right)^2\right] \exp\left[-\left(\frac{k}{k_{fs}}\right)^2 - \left(\frac{k}{k_d}\right)^2\right]$$

Free Streaming (k_{fs})

Collisional damping (k_d)

$$\frac{\delta\rho}{\rho} \equiv \Delta(k,z) = T_\Delta^{1/2}(k,z) D(k) \Delta(k,z_i)$$

$K_{fs}/k_d \sim 10^{-3}$ (@m_χ=100 GeV)



Typical first halos:

- $z_{nl} \sim 60 \pm 10$
- $M_{min} \sim 4.9 \times 10^{-6}\ M_{sun} \times (1/k\ \mathrm{pc})^3$
  $\sim 10^{-6}\ M_{sun} \times (m_\chi/100\ \mathrm{GeV})^{-1.5}$
- $R_{vir}(z=0)$=0.02 pc
- $\Delta_0\,(z=0)=(0.2 - 1.8) \times 10^6$

Z. Berezinsky, V. Dokouchaev, Y. Eroshenko 2005
A.M. Green, S. Hofmann, D. Schwartz 2005
A. Loeb, M. Zaldarriaga 2005

Influence of subhalos revised 2

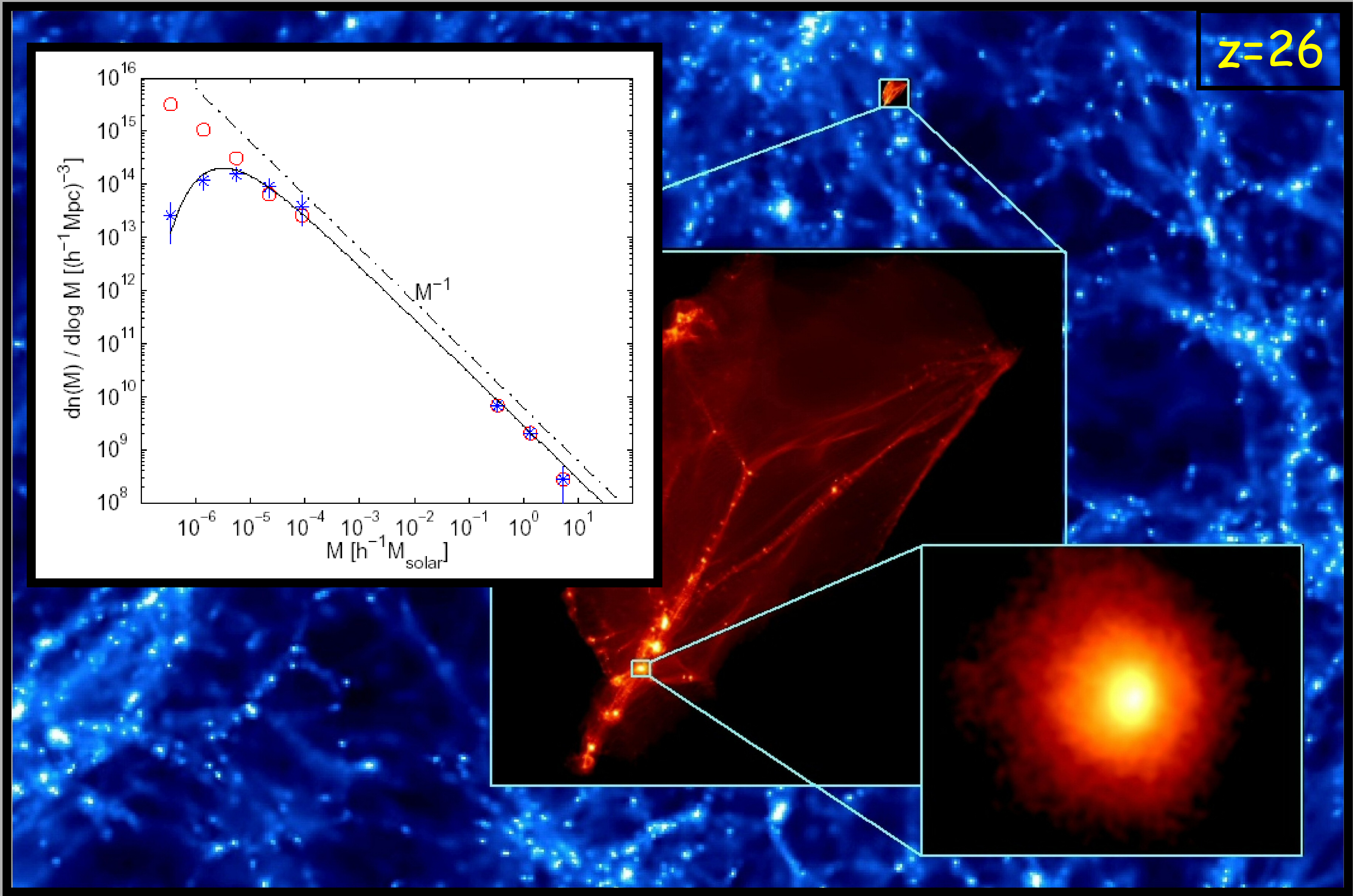
Do micro halos survive hierarhical clustering, interactions with galaxy tidal field and encounters with stars ? What fraction of their original mass is lost ? What is their final density profile ?

- Tidal shocks during halo merger history
- Tidal destruction by collective gravity filed of stars in the galactic disk
- Destruction by stellar enounters.

Z. Berezinsky, V. Dokouchaev, Y. Eroshenko	PRD	2003
Z. Berezinsky, V. Dokouchaev, Y. Eroshenko	astro-ph	2005
H. Zhao, J.E. Taylor, J. Silk, D. Hooper	astro-ph	2005

- Only 0.1-0.5 % of microhalos survive hierarchical clustering
- The fraction of sub-halos that survive encounters with stars strongly depends on the host properties (gravity field, stellar content) and on sub-halo's orbital parameter.
- In our galactic neighborhood most subhalos have lost a significant fraction of mass which is found in the form of 'microstream'

Influence of subhalos revised 2



J. Diemand, B. Moore and J. Stadel Nature 2005

Modeling subhalos

Sub-halo Mass Function

$$\frac{dN}{dM}dM \propto M^{-2}dM$$

Sub-halo NWF spatial distribution

$$f(r,M)dr \propto \frac{4\pi r^2 \theta(r - r_{Roche}(M))}{\left(\frac{r}{r_s^{MW}}\right)\left(1+\frac{r}{r_s^{MW}}\right)^2}dr$$

Sub-halo distribution

$$n(r,M)drdM = A\frac{dN}{dM}f(r,M)drdM$$

A (normalization): 10% of MW mass is in subhalos with M> 10^7 Msun

Consequences:

- ~50% of the MW mass in subhalos with M > 10^{-6} M_{sun}
- total number of Galactic subhalos is ~1.5 x 10^{16}
- sub-halos number density in the solar neighborhood ~ 100 pc^{-3}

Sub-halo NFW density profile

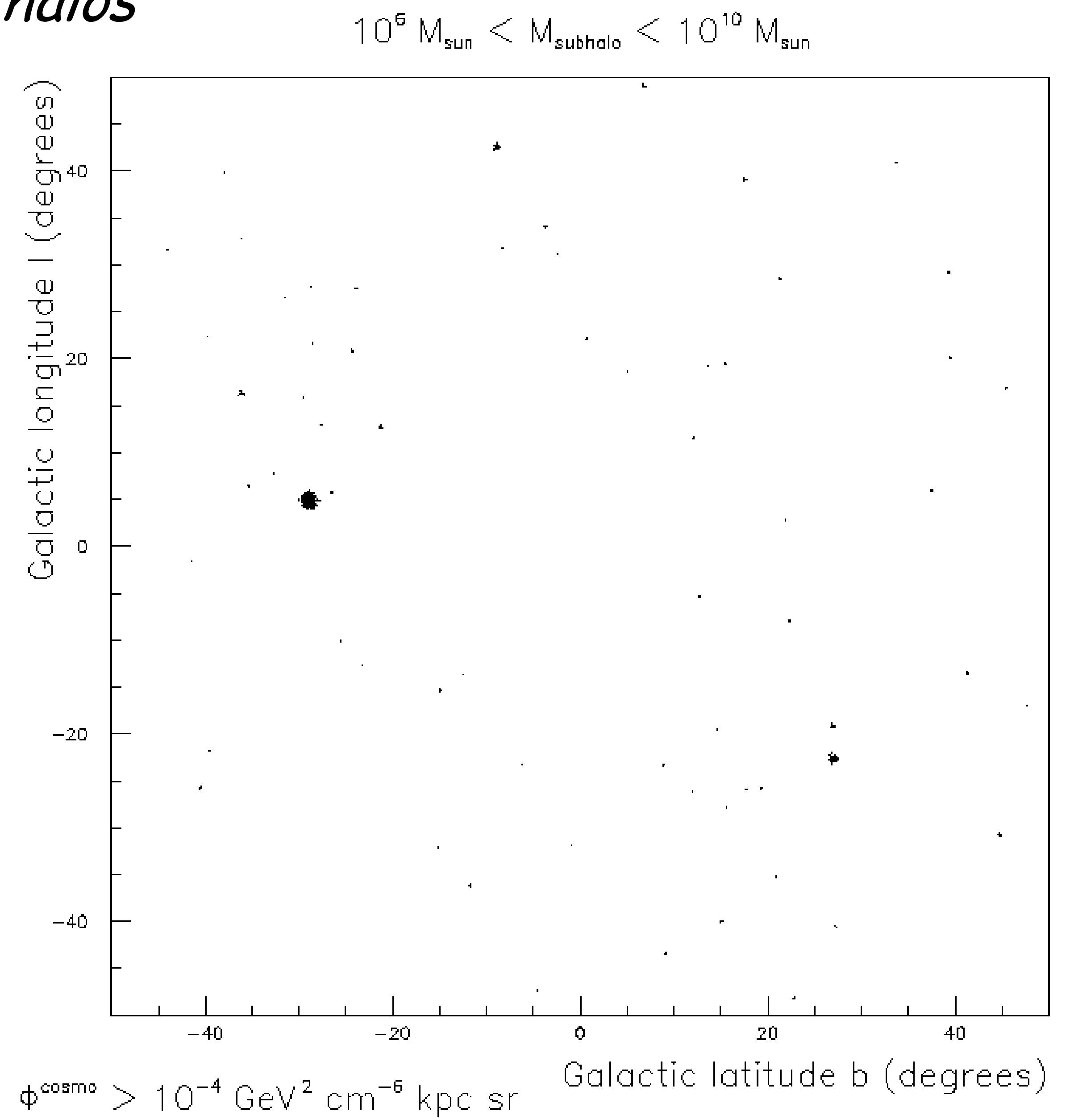
For M_{SH}=10^{-6} M_{sun}

- $R_{vir}(z=0)$=0.02 pc
- ρ_0~7 x 10^{-6} ρ_{crit} —> c^{NFW}_0 ~ 40

Lidia Pieri, EB and S. Hofmann PRL 2005

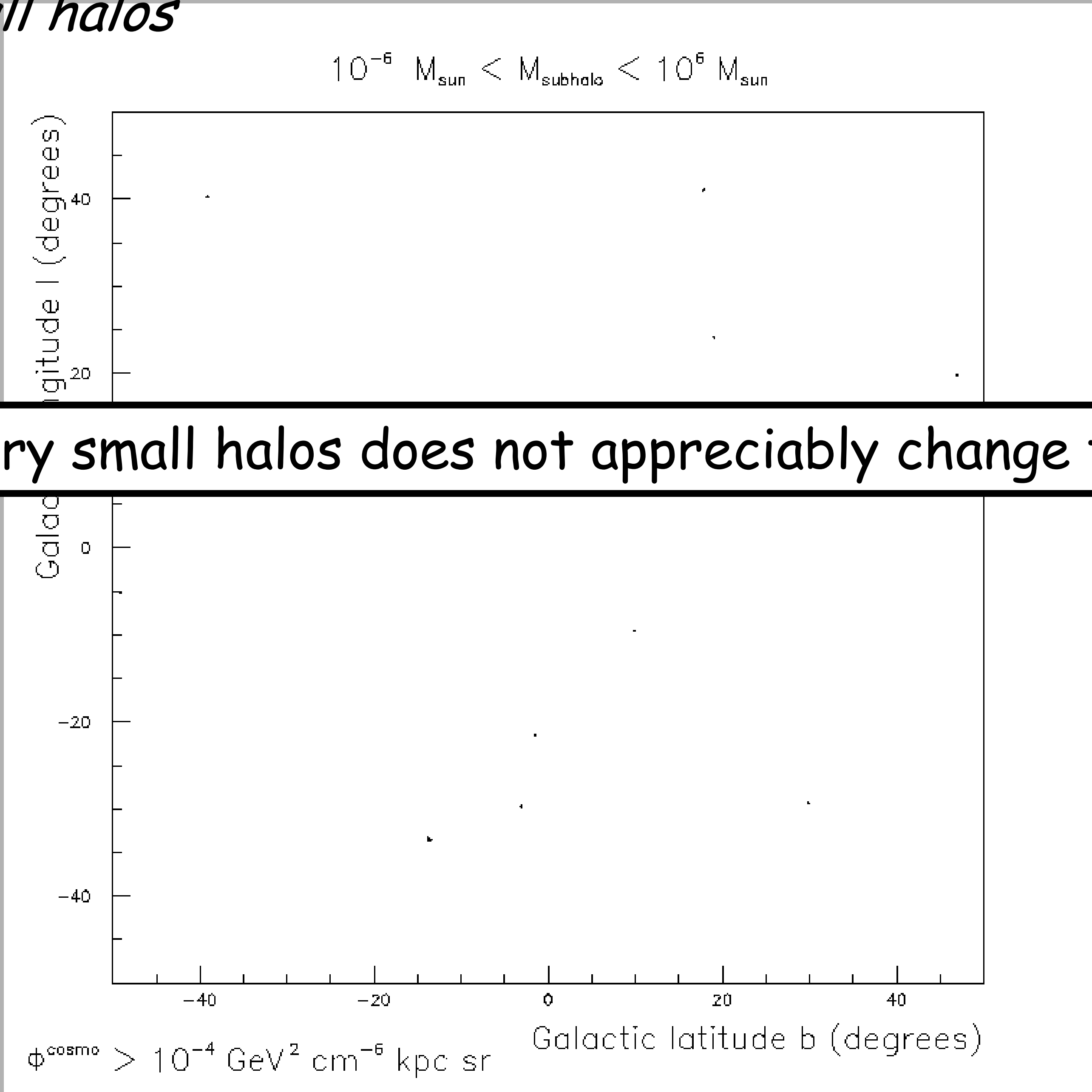
Lidia Pieri, EB, S. Hofmann PRL 2005

A subhalo sky:
the large halos



Lidia Pieri, EB and S. Hofmann 2005

A subhalo sky:
the small halos



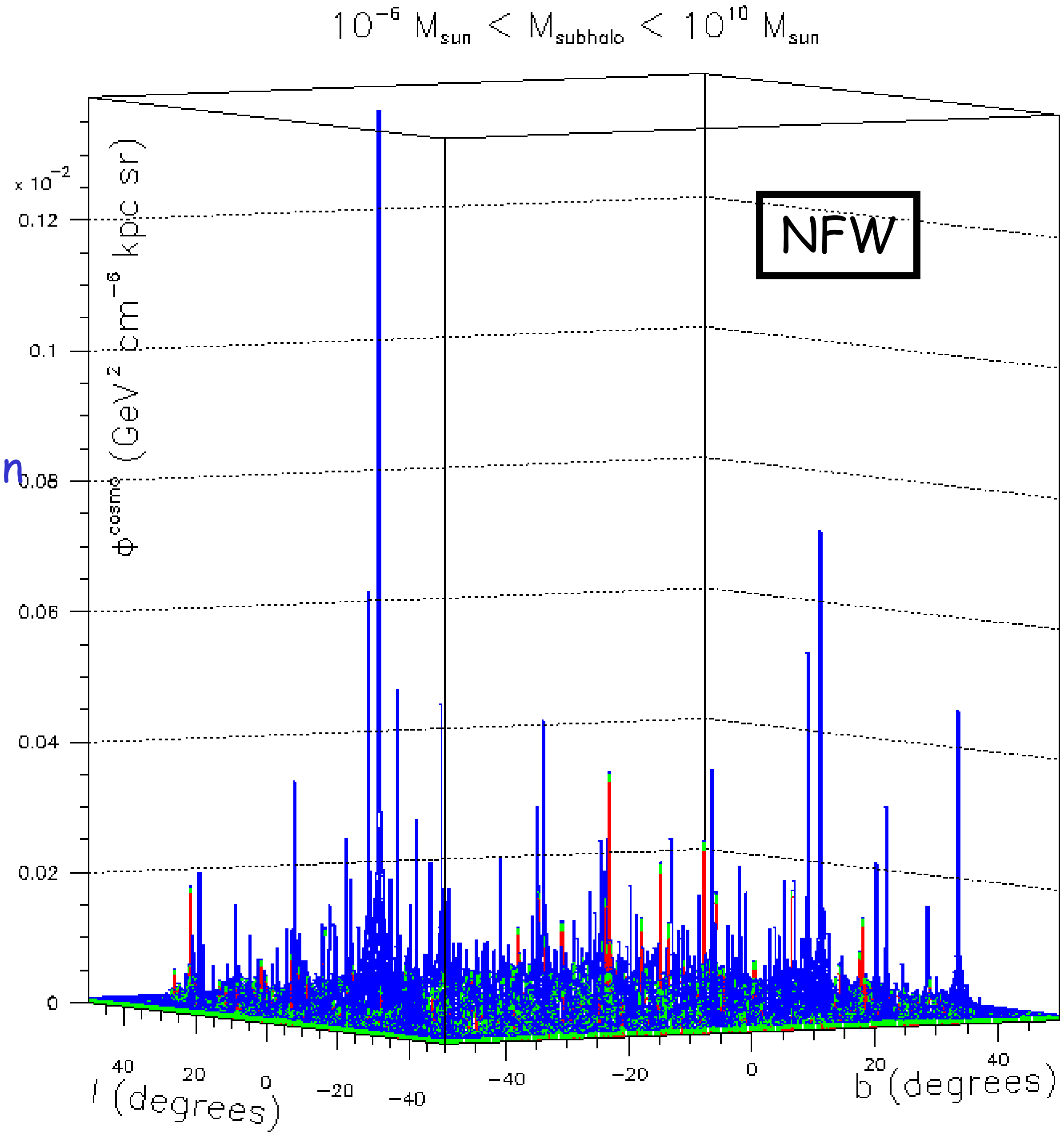
Adding very small halos does not appreciably change the result!

3D contribution
of the whole population
of subhalos

BLUE is the contribution
of large subhalos

GREEN is the
average contribution
of small subhalos

RED is the variance
contribution of small
subhalos

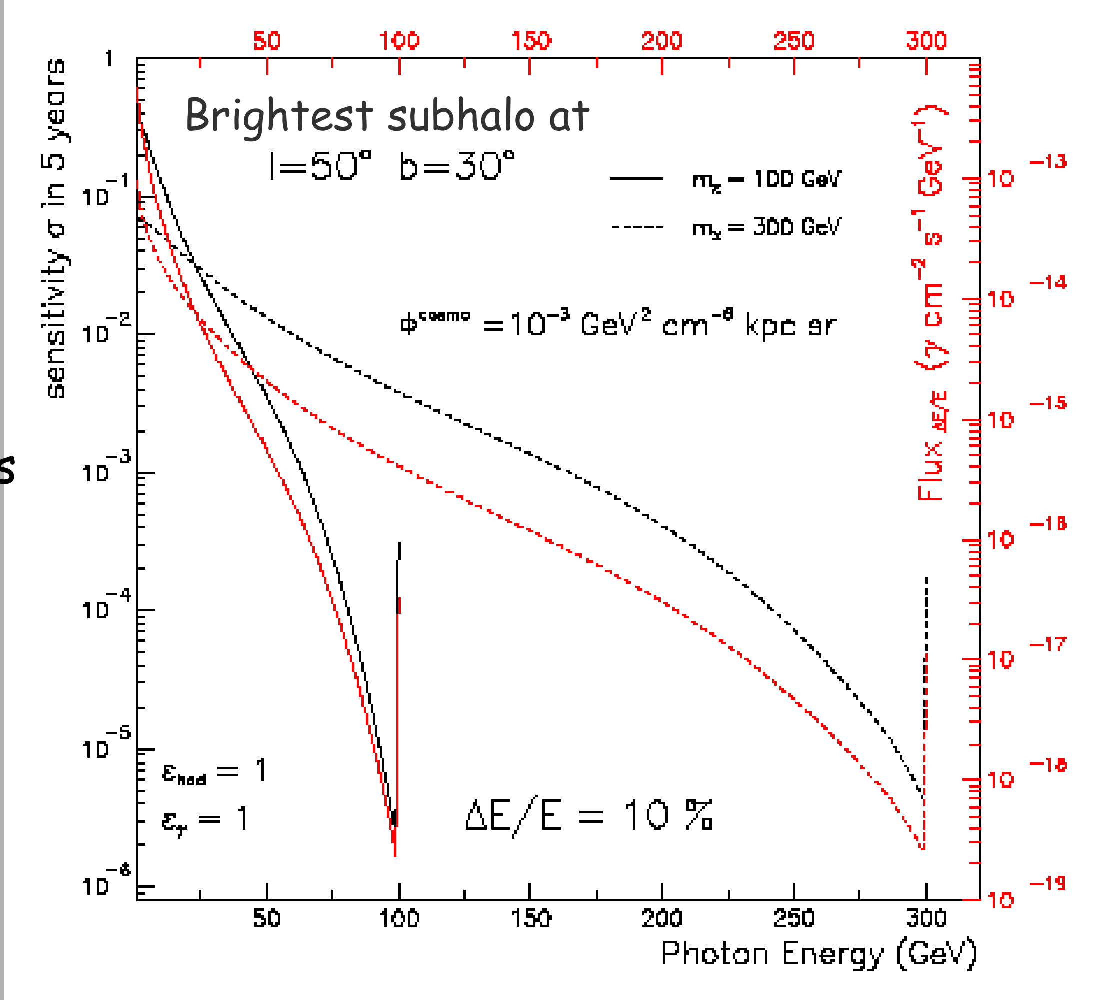


LP, E. Branchini and S. Hofmann 2005

Visibility of sub-galactic structures

The cross section for the neutralino annihilation can hardly exceed $\langle\sigma v\rangle_{ann} = 2\text{x}10^{-26}\ cm^3s^{-1}$

However, to detect the γ-lines one can take into account the energy resolution of next-generation experiments, such as GLAST.

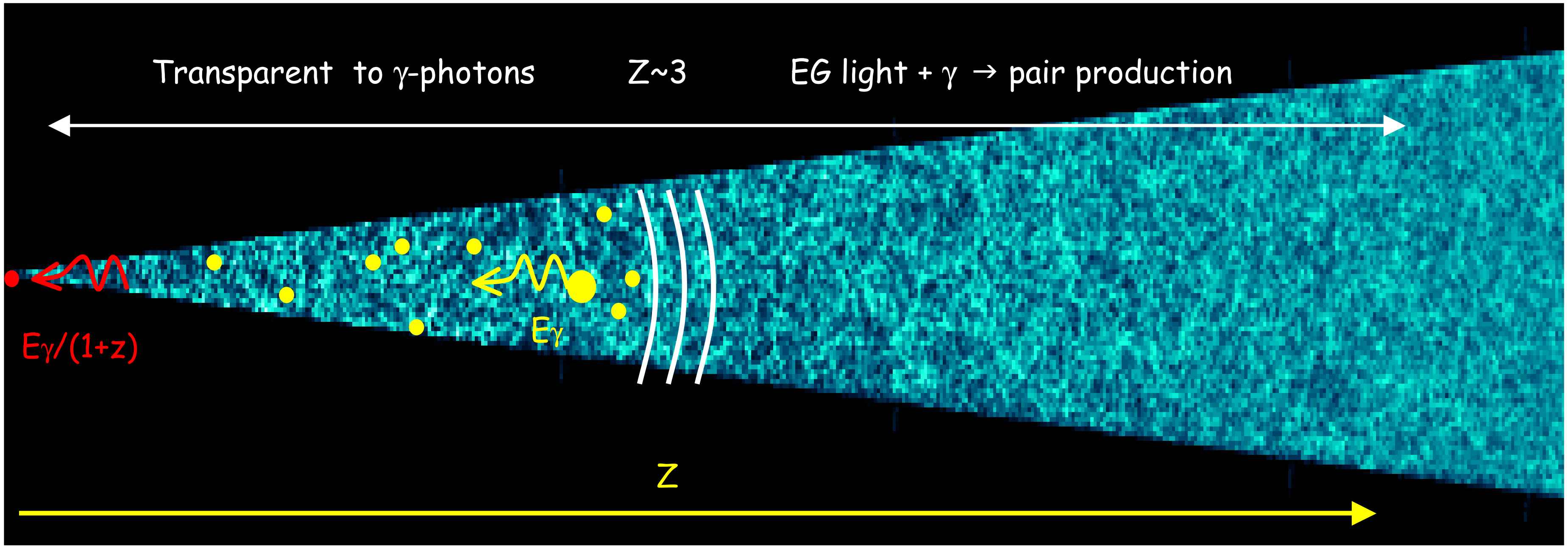


SIGNAL FROM MINIHALOS SEEMS TO BE TOO FAINT TO BE DETECTED

$\langle\sigma v\rangle_{ann} = 2\text{x}10^{-26}\ cm^3s^{-1}$
$\Phi^{COSMO}=10^{-3}\ GeV^2cm^{-6}\ kpc\ sr$
BR(γ-line)=10^{-3}

Lidia Pieri, EB, S. Hofmann PRL 2005

The integrated extragalactic flux



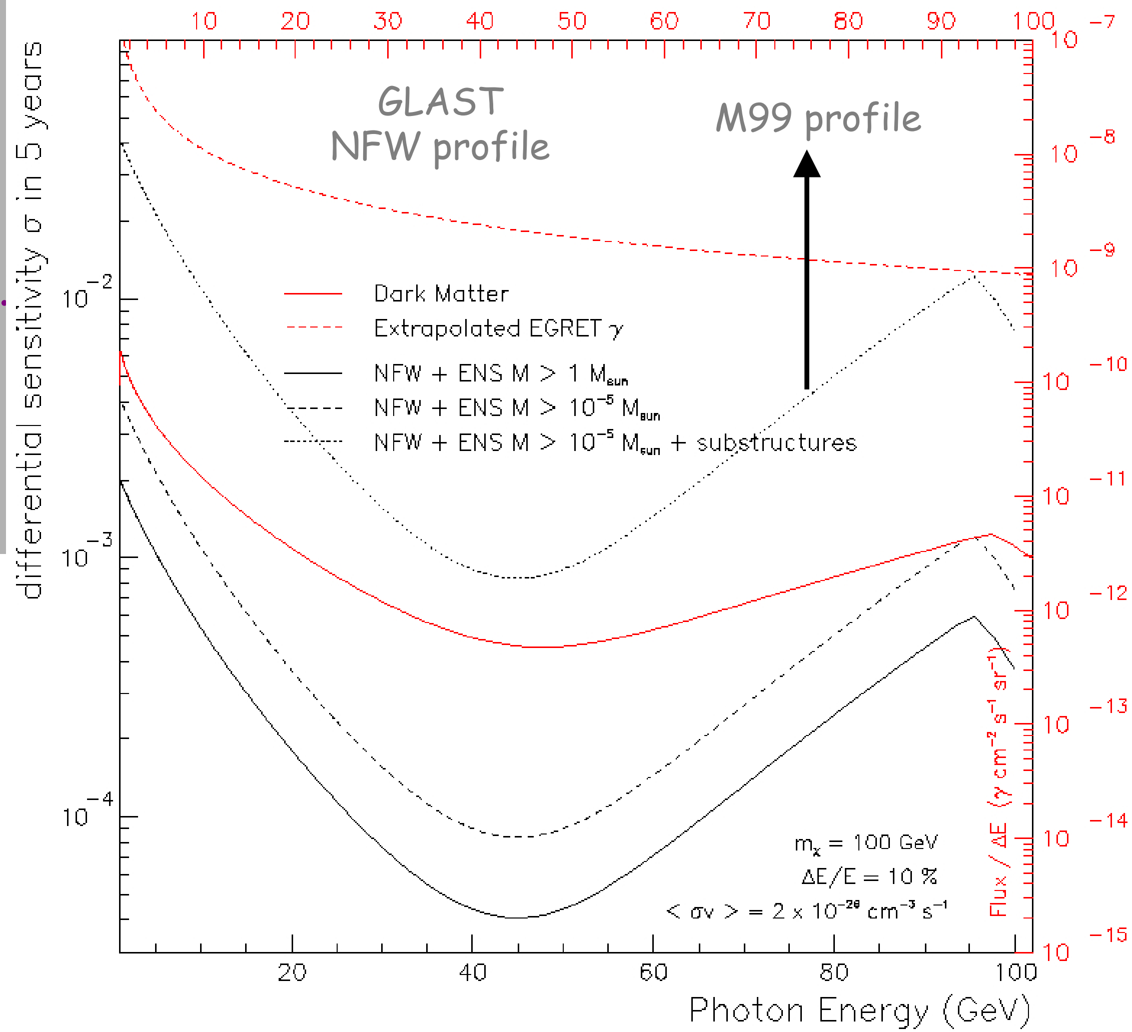
$$\frac{d\varphi_\gamma(E_{\gamma,0})}{dE} \propto \frac{<\sigma v>_{ann}}{m_\chi^2} \int_0^z \frac{dN_\gamma(E_0(1+z))}{dE} f(z) \int_{M_{min}}^{M_{Max}} \frac{dN_H}{dM_H}(M_H,z) \int_0^{R_{vir}} \rho(r,z,M_H) r^2 \, dr \, dM_H \, dz$$

Particle Physics   Geometry   Halo mass function   Halo density profile

Visibility of Extragalactic Flux

Cosmological redshift broadens the γ–annihilation line that could be observed using sensitive detectors with good energy resolution (e.g. GLAST $\Delta E/E=10\%$).

n.b. predictions are less sensitive to the halo density profile.



The extragalactic annihilation signal (both continuum and line emission) seems to be too faint to be detected by GLAST.
Better hope to detect the angular correlation of the signal (Ando, Komatsu 2006)

EB, L. Pieri and A. Nusser in prep

Conclusions and outlook

Even in more favourable theoretical scenarios detecting the annihilations flux off-Galactic Center is a rather challenging task.

Contrary to initial claims, the presence of substructures (both sub-galactic halos and dark matter caustics) does not increase the annihilation signal high enough to be detected by current and next generation γ-ray detectors.
Even in the best case scenarios, the number density of microhalos in the solar neighborhood is too small for indirect detection.

DM searches will benefit from many different observational constraints

-After recombination (t~100 Kyrs): CMB distortions (Padmanabhan & Finkbeiner 2005)

- Early Structure Formation (t~1 Gyrs): Reionization history (Loeb et al. 2005)

-Evolved Structures in the nearby universe (t~15 Gyrs).
  - High energy neutrinos from Sun and Earth (Desai et al. 2004)
  - High energy positrons near Earth (Coutou et al. 2002).
  - Microwave excess from Galactic center (*Synchrotron emission*) (Finkbeiner 2005)
  - Soft+Hard γ-rays from Galactic center (*high energy electrons inverse Compton scatter CMB and starlight photons*) (Strong et al 2004)

What about substructures ? Any dynamical signature ?