Destruction of dark matter clumps in Galaxy

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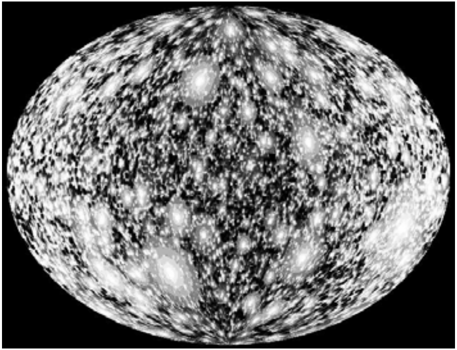
QUARKS – 2008

What happened to the central cores of tidally destructed dark matter clumps in the Galactic halo? We calculate the probability of surviving the remnants of dark matter clumps in the Galaxy by modelling the tidal destruction of the small-scale clumps. It is demonstrated that a substantial fraction of clump remnants may survive through the tidal destruction during the lifetime of the Galaxy if a radius of core is rather small. The resulting mass spectrum of survived clumps is extended down to the mass of the core of the cosmologically produced clumps with a minimal mass. Since annihilation signal is dominated by the dense part of the core, destruction of of the outer part of the clump affects relatively weakly annihilation rate and the survived dense remnants of tidally destructed clumps provides a large contribution to the annihilation signal in the Galaxy.

Gamma luminosity of Galaxy



$M_{min} = 10^5 - 10^8 M_\odot$ (Aloisio, Blasi & Olinto, 2002)

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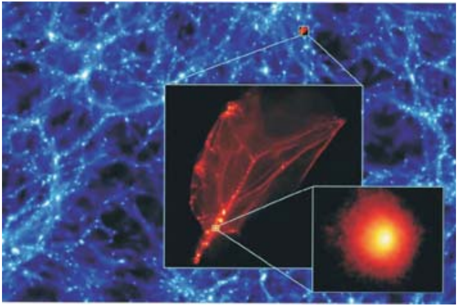
Minimum mass of clumps (the cutoff of the mass spectrum)

- $M_{\rm min} \sim 10^{-12} M_{\odot}$ (Zybin, Vysotsky, Gurevich, 1999)
- $M_{\rm min} \sim (10^{-7} - 10^{-6}) M_{\odot}$ (Schwarz, Hofmann, Stocker, 2001)
- $M_{\rm min} \sim 10^{-4} M_{\odot}$ (Loeb, Zaldarriaga, 2005)
- $M_{\rm min} \sim (10^{-5} - 10^{-4}) M_{\odot}$ (Bertschinger, 2006)

Kinetic decoupling $\frac{1}{\tau_{rel}} \simeq H(t)$

Numerical simulations

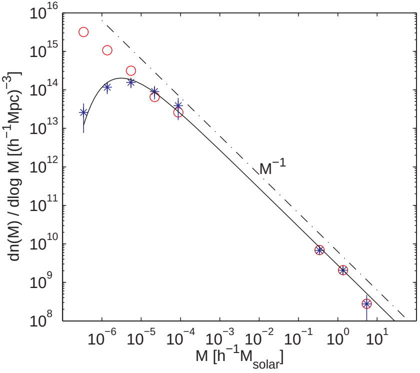


3 kpc 60 pc 0.024 pc

$N = 62 \cdot 10^6$, $m = 1.2 \cdot 10^{-10} M_\odot$, $z = 350 \rightarrow 26$

(Diemand, Moore, Stadel, 2005)

Mass function



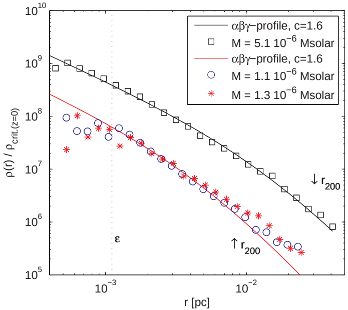
(Diemand, Moore, Stadel, 2005)

Clump structure

Density profile:

$$\rho_{\rm int}(r) = \begin{cases} \rho_c, & r < R_c; \\ \rho_c \left(\dfrac{r}{R_c}\right)^{-\beta}, & R_c < r < R; \\ 0, & r > R, \end{cases}$$

where $\beta \simeq 1.8$ (Gurevich, Zybin, 1988)



Core size $R_c/R \simeq 0.01$ (Moore et al., 2005)

Annihilation of DM in clumps

- **Rate of annihilation inside single clump**

  $\dot{N}_{\rm cl} = 4\pi \int\limits_0^\infty r^2 dr\, \rho^2_{\rm int}(r)\, m_\chi^{-2} \langle \sigma_{ann} v \rangle$

- **Observable signal**

$$I_{\rm cl} = \frac{\langle \sigma_{\rm ann} v \rangle}{4\pi} \int\limits_0^\pi d\zeta \sin\zeta \int\limits_0^{r_{\rm max}(\zeta)} \frac{2\pi r^2 dr}{r^2} \int\limits_{M_{\rm min}} dM \int dR\; n_{\rm cl}(l(\zeta, r), M, R)\, \dot{N}_{\rm cl}$$

- **Signal from diffuse DM**

$$I_{\rm hom} = \frac{\langle \sigma_{\rm ann} v \rangle}{2} \int\limits_0^\pi d\zeta \sin\zeta \int\limits_0^{r_{\rm max}(\zeta)} dr\, \frac{\rho^2_{\rm DM}(l(\zeta, r))}{m_\chi^2}$$

- Amplification of the signal

$$\eta = \frac{I_{\rm cl} + I_{\rm hom}}{I_{\rm hom}} \approx 1 + \xi S(x_c, \beta) \frac{\bar{\rho}_{\rm int}}{\tilde{\rho}_{\rm DM}}$$

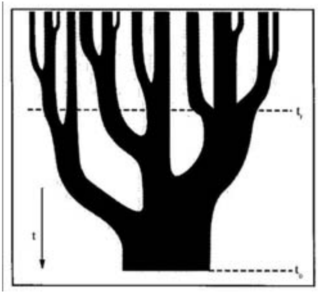
- Typical values:
  $S \simeq 5$
  $\tilde{\rho}_H \sim 0.3$ GeV cm^{-3}
  $\bar{\rho}_{\rm int} \sim 10^{-20}$ g cm^{-3}
  fraction of DM in the form of clumps - $\xi \sim 0.001$

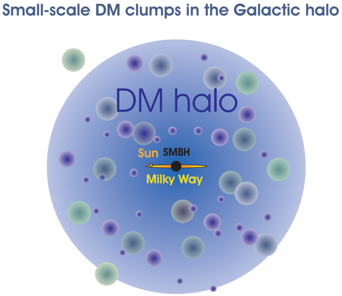
$$\boxed{\eta \sim 10^2}$$

Free (unconfined) clumps

$$\phi_{PS} dM = \left(\frac{2}{\pi}\right)^{1/2} \frac{\rho}{M} \frac{\delta_c}{D(t)\sigma_{\rm eq}^2} \frac{d\sigma_{\rm eq}}{\rm dM} \exp\left[\frac{-\delta_c^2}{2D(t)^2\sigma_{\rm eq}^2}\right] dM$$

(Press, Shechter, 1974)





- Criterium for destruction $\Delta E \geq |E| \sim GM^2/2R$
- Time of energy gain $T^{-1} = \dot{E}/|E|$
- Fraction of survived clumps e^{-J}, where

$$J \simeq \sum_{M_h} \frac{\Delta t}{T} \simeq \int_{t_1}^{t_f} \frac{dt_h}{T(\rho, \rho_h)} \simeq \gamma \frac{\rho_1 - \rho_f}{\rho} \simeq \gamma \frac{\rho_1}{\rho} \simeq \gamma \frac{t^2}{t_1^2}$$

- the sum is over intermediate hosts

- Mass function

$$\xi \frac{dM}{M} d\nu = dM\, d\nu \frac{e^{-\nu^2/2}}{\sqrt{2\pi}} \int_{t(\nu\sigma_{\rm eq})}^{t_0} dt_1 \left| \frac{\partial^2 F(M, t_1)}{\partial M\, \partial t_1} \right| e^{-J(t,t_1)}$$

$$\simeq \frac{\nu\, d\nu}{\sqrt{2\pi}} e^{-\nu^2/2} f_1(\gamma) \frac{d \log \sigma_{\rm eq}(M)}{dM} dM,$$

where

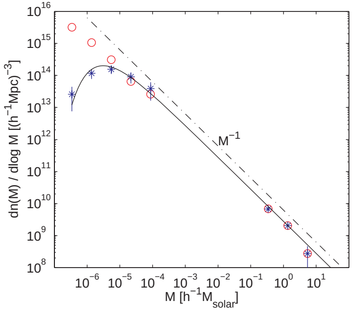
$$f_1(\gamma) = \frac{2[\Gamma(1/3) - \Gamma(1/3, \gamma)]}{3\sqrt{2\pi}\gamma^{1/3}}, \quad f_1(\gamma) \simeq 0.2\text{--}0.3 \;\; 14 < \gamma < 40$$

- Integral mass function and number density of clumps

$$\xi_{\rm int}\frac{dM}{M}\simeq 0.02(n+3)\,\frac{dM}{M}$$

$$n_{\rm cl}(M,R)d\ln Md\ln R=\frac{\rho_{\rm DM}(r_\odot)}{M}\xi(M,\nu)d\ln Md\nu$$

(Berezinsky, Dokuchaev, Eroshenko, 2003, 2006, 2008)



(Diemand, Moore, Stadel, 2005)

Destruction by disk

- Gravitational shocking (Ostriker, Spitzer, Chevalier, 1972):

$$\delta E = \frac{4g_m^2(\Delta z)^2 m}{v_{z,c}^2} A(a)$$

- Tidal forces: (Gnedin, Ostriker 1997, 1999), (Gnedin, Hernquist, Ostriker, 1999), (Gnedin, Lee, Ostriker, 1999), (Gnedin, 2003)
- $A(a)$ - adiabatic correction (Weinberg, 1994), (Gnedin, Ostriker 1999)
  $a = \omega\tau_d$, $A(a) = 1$ if $a \ll 1$ and $A(a) \ll 1$ if $a \gg 1$
  $A(a) = (1 + a^2)^{-3/2}$ (Gnedin, Ostriker 1999)
- isotropy halo model:

$$\rho(r) = 4\pi \int_{U(r)}^{0} dE \sqrt{2[E - U(r)]} f(E)$$

- exponential disk: $g_m(r) = 2\pi G\sigma_s(r), \quad \sigma_s(r) = \frac{M_d}{2\pi r_0^2} e^{-r/r_0}$

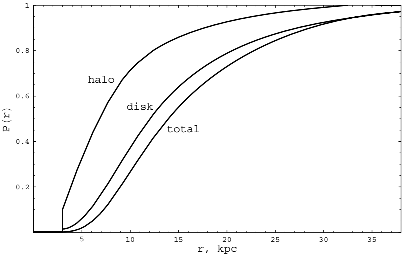
- Destruction by stars

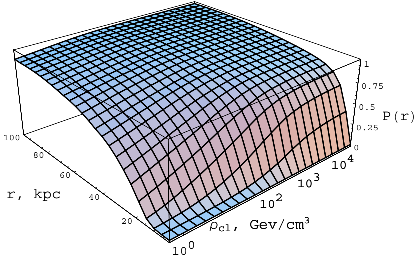
$$\Delta E = \frac{1}{2}\int d^3 r\, \rho(r)(v_z - \tilde{v}_z)^2$$

$$\dot{E} = \int_{l_*}^{\infty} 2\pi\, l v_{\rm rel}\, dl\, \Delta E(l)\, n_*, \quad t_*^{-1} = \pi l_*^2 v_{\rm rel} n_* + \frac{\dot{E}(l > l_*)}{|E|}$$

- Survival probability:

$$P(x,\alpha) = \frac{4\pi\sqrt{2}}{\tilde{\rho}(x)\sin\alpha}\int_0^1 dp \int_0^{\sin\alpha} d\cos\gamma \int_{\psi(x)}^1 d\varepsilon\,[\varepsilon - \psi(x)]^{1/2} F(\varepsilon) e^{-\Delta E/|E}$$

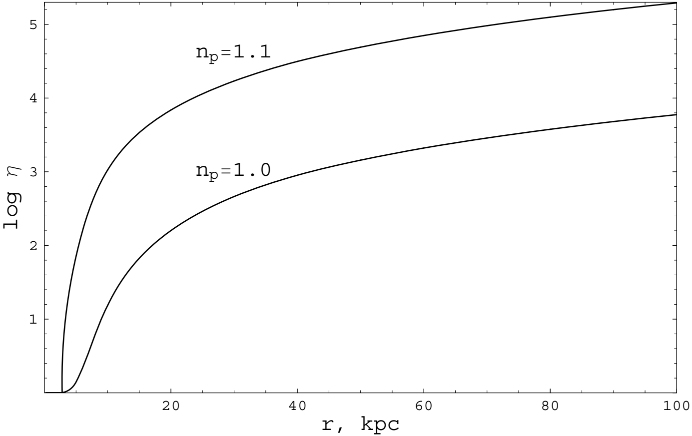




(Berezinsky, Dokuchaev, Eroshenko, 2006)

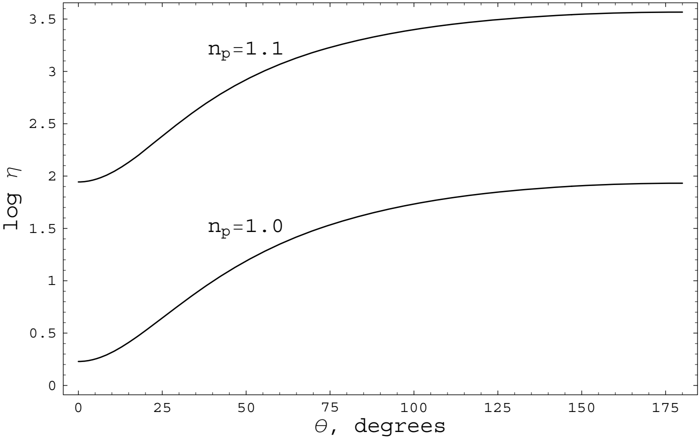
Left: Fraction of survived clumps with $M = 10^{-6} M_\odot$ and $\nu = 2$. Right: the same in dependence of clump density $\rho_{\rm cl}$ in GeV cm^{-3}.

Local amplification factor η



$\beta = 1.8$, $M_{\min} = 2 \cdot 10^{-8} M_{\odot}$, $n_p = 1.0$ and $n_p = 1.1$

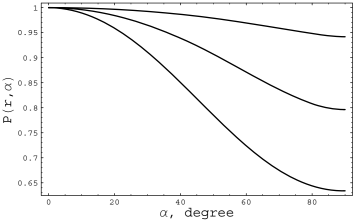
Boost factor η, integrated over line of sight

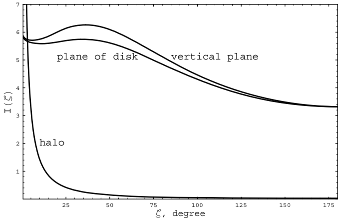


$\beta = 1.8$, $M_{\min} = 2 \cdot 10^{-8} M_{\odot}$, $n_p = 1.0$ and $n_p = 1.1$

Anisotropy

$\Delta\tilde{E} = 2g_m^2(\Delta z)^2/(v_{z,c}^2)$, $\quad v_{z,c} = J\sin\gamma/(mr_{\rm c})$, $\quad \Delta E/|E| = C/\sin^2\gamma$





(Berezinsky, Dokuchaev, Eroshenko, 2007)

Left: The normalized fractions of DM clumps in the halo $P(r,\alpha)$ which survive the tidal destruction by the stellar disk as a function of angle α between a radius-vector $\vec{r}$ and the disk polar axis. Radial distances from the Galactic center $r =$3, 8.5 and 20 kpc (from the bottom to the top). The curves must be multiplied by factors 0.04, 0.4 and 0.9 respectively. Right: The annihilation signal in the Galactic disk plane and in vertical plane as a function of the angle ζ between the line of observation and the direction to the Galactic center.

Remnants (cores) of clumps

- Simple criterium - $\sum_j (\Delta E)_j \sim |E|$
- Gradual mass loss $\rightarrow$ remnants. Core size $=$?
  $R_c/R \simeq 1.8 \times 10^{-5}$ (Gurevich, Zybin, 1995)
  $R_c/R \simeq 0.01$ (Diemand, Moore, Stadel, 2005)

$$\rho_{\rm int}(r) = \frac{3-\beta}{3}\,\bar{\rho}\left(\frac{r}{R}\right)^{-\beta}, \quad \dot{N} \propto \int_0^r 4\pi r^2 dr \rho_{\rm int}^2(r)$$

- Disk. Change of density and mass loss:

$$\delta\rho(r) = 2^{5/2}\pi \int_{-\delta\varepsilon}^{0} \sqrt{\varepsilon - \psi(r)}\, f_{\rm cl}(\varepsilon)\, d\varepsilon, \quad \delta M = -4\pi \int_0^R r^2 \delta\rho(r)\, dr$$

$$\left(\frac{\delta M}{M}\right)_d \simeq -0.13 Q_d \exp\left(-1.58 S_d^{1/2}\right)$$

$$Q_d = \frac{g_m^2}{2\pi v_{z,c}^2 G \bar{\rho}_i}, \quad S_d = \frac{4\pi}{3} G \bar{\rho}_i \tau_d^2$$

$$\frac{1}{\Delta T} \sum \left(\frac{\delta M}{M}\right)_d \simeq \frac{2}{T_t |\tilde{\phi}|} \int_{x_{min}}^{x_{max}} \left(\frac{\delta M}{M}\right)_d \frac{d\phi}{dx} dx$$

- Stars.

$$Q_s = \frac{Gm_*^2}{2\pi v_{\rm rel}^2 l^4 \bar{\rho}_i}, \quad S_s = \frac{4\pi}{3} G \bar{\rho}_i \tau_s^2$$

$$\frac{1}{M}\left(\frac{dM}{dt}\right)_s \simeq \frac{1}{2T_t\sqrt{2\pi G\rho_0}} \int_R^\infty 2\pi l\, dl \int_{x_{\rm min}}^{x_{\rm max}} \frac{ds\, n_*(s) v_{rel}}{\sqrt{\varepsilon - \psi(s) - y/s^2}} \left(\frac{\delta M}{M}\right)_s$$

- Number density of stars in the halo and bulge:

$$n_{h,*}(r) = (\rho_h/m_*)(r_\odot/r)^3$$

$m_* = 0.4\mathrm{M}_\odot$, $r_\odot = 8.5$ kpc, $\rho_h = 1.4 \times 10^{-5}\ \mathrm{M}_\odot/\mathrm{pc}^3$

(Bell et. al, 2007)

$$n_{b,*}(r) = (\rho_b/m_*) \exp\left[-(r/r_b)^{1.6}\right]$$

$\rho_b = 8\mathrm{M}_\odot/\mathrm{pc}^3$, $r_b = 1$ kpc (Launhardt, Zylka, Mezger, 2002)

- Isothermal density profile: $M(t) \propto R(t)$, $\bar{\rho}(t) \propto M(t)^{-2}$

$$\frac{dM}{dt} = \left(\frac{dM}{dt}\right)_d + \left(\frac{dM}{dt}\right)_s$$

$t_0 - t_G < t < t_0$

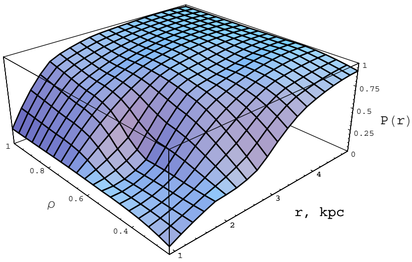
- Analytic approximation $A(a) = 0$:

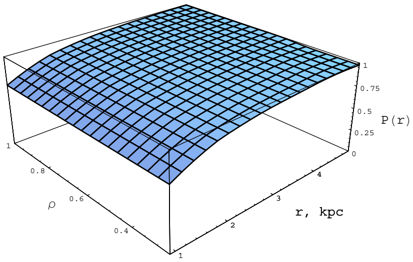
$$\frac{d\mu}{dt} = -\frac{\mu}{t_s} - \frac{\mu^3}{t_d}, \quad \mu \equiv M(t)/M_i$$

- Disk: $\mu(t) \equiv M(t)/M_i = (1 + t/t_\mathrm{d})^{-1/2}$
- Stars: $\mu(t) = \exp(-t/t_s)$
- Both:

$$\mu^2(t_0) = \frac{2t_d}{(2t_d + t_s)\exp(2t_0/t_s) - t_s}$$

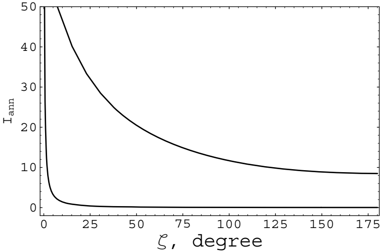
Numerical calculation

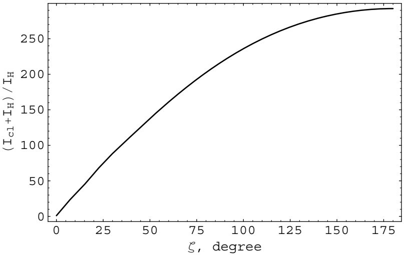




(Berezinsky, Dokuchaev, Eroshenko, 2008)

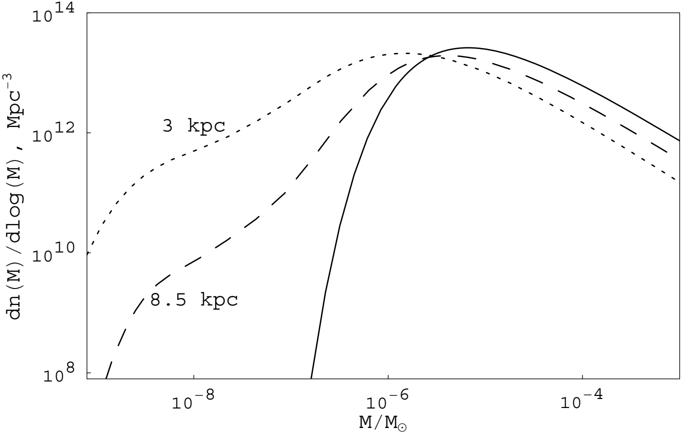
The survival probability $P(r, \rho)$ plotted as as a function of distance from the galactic center r and a mean internal clump density ρ in the cases $x_c =$0.1 and 0.05.





Left: The annihilation signal (upper curve) as a function of the angle ζ between the line of observation and the direction to the Galactic center.
Right: amplification of the signal $(I_{\rm cl} - I_{\rm H})/I_{\rm H}$.

Transformation of the mass function



Numerically calculated modified mass function of clump remnants for galactocentric distances 3 and 8.5 kpc. The solid curve shows the initial mass function.

Conclusion

Despite the small survival probability of clumps during early stage of hierarchial clustering, they provide the major contribution to the annihilation signal (in comparison with the unclumpy DM). The amplification (boost-factor) can reach 10^2 or even 10^3 depending on the initial perturbation spectrum and minimum mass of clumps. This boost-factor must be included in calculations of the annihilation signals. These remnants of DM clumps form the low-mass tail in the standard mass distribution of small-scale clumps extended much below $M_{\min}$ of the standard distribution. The numerical estimate of the boost-factor for DM particle annihilation inside clumps is very model-dependent. It depends on nature of DM particles and on their interaction with ambient plasma. Another parameter variation which affects strongly the boost-factor is the spectral index of density perturbation n_p.