Remnants of small-scale dark matter clumps

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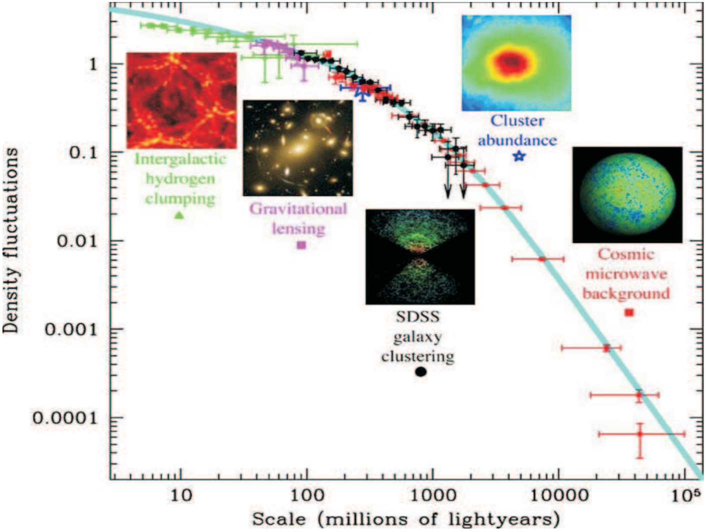
Main messages

- We calculate probability of surviving of remnants of dark matter clumps in the Galaxy by modelling the tidal destruction of small-scale clumps
- A substantial fraction of clump remnants may survive through the tidal destruction by stars during the lifetime of the Galaxy if the radius of a core is rather small
- Since annihilation signal is dominated by the dense part of the core, destruction of the outer part of the clump affects the annihilation rate relatively weakly, and the survived dense remnants of tidally destructed clumps provide a large contribution to the annihilation signal in the Galaxy

DM clumps from density fluctuations



Supposition: Harrison-Zel'dovich spectrum of initial density fluctuations

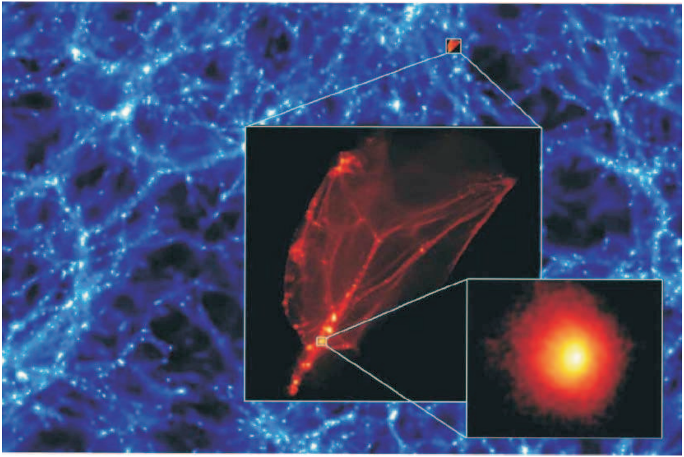
DM clump analogue: self-gravitating cluster of stars

Hubble telescope view of Globular Cluster M 13

Large-scale DM clumps: numerical simulations of DM halos

Project Columbia supercomputer, NASA, $\mathbf{2.34\,10^6}$ particles

Small-scale DM clumps: numerical simulations

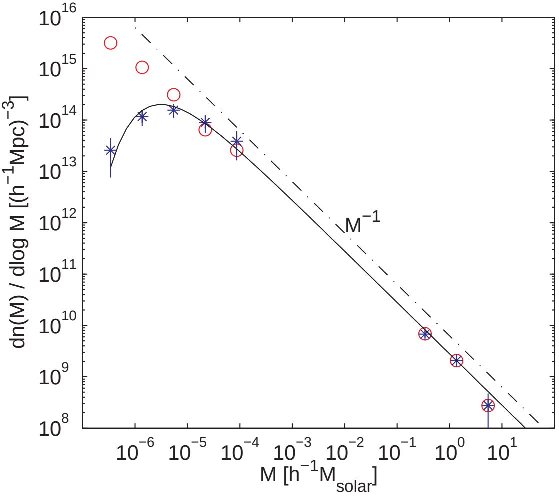


3 kpc 60 pc 0.024 pc

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

Diemand Moore & Stadel 05

Mass function of small scale DM clumps



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Cutoff of DM clump mass spectrum

SUSY neutralino DM particles with mass $\sim 10 - 100$ GeV

Minimum mass of DM clumps $M_{\min}$:

- $10^{-12}\,M_\odot$ — *Zybin Vysotsky & Gurevich 99*
- $10^{-7} - 10^{-6}\,M_\odot$ — *Schwarz Hofmann & Stocker 01*
- $10^{-8}\,M_\odot$ — *Brezinsky Dokuchaev & Eroshenko 03*
- $10^{-4}\,M_\odot$ — *Loeb & Zaldarriaga 05*
- $10^{-5} - 10^{-4}\,M_\odot$ — *Bertschinger 06*
- $10^{-6} - 10^{2}\,M_\odot$ — *Profumo Sigurdson & Kamionkowski 06*

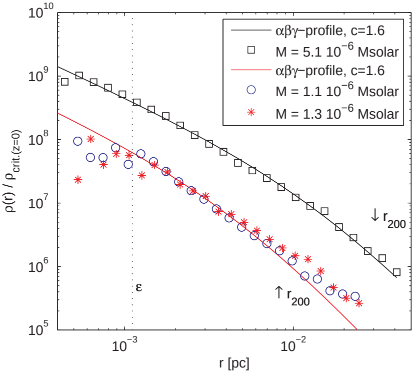
Cutoff of the clump mass spectrum by kinetic decoupling

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

Internal density profile of DM clump

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

$\beta \simeq 1.8$ *Gurevich & Zybin 88*



Core size $R_c/R \simeq 0.01$ *Moore et al 05*

Integral mass function and number density of clumps

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

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

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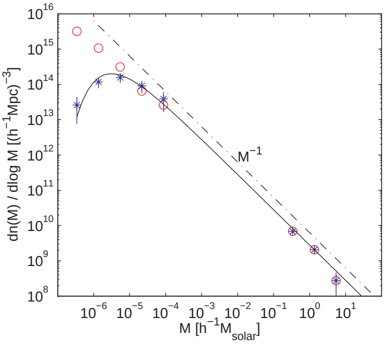


Diemand Moore & Stadel 05

Survival of clump remnants (cores)

Successive tidal stripping of clump during multiple encounters with stars, shell by shell, from the outer to inner ones: $1, \ldots, j, j+1 \ldots$

- Criterium for clump stripping $\sum_j (\Delta E)_j \sim |E_b|$
- Gradual mass loss shell by shell up to the core $\rightarrow$ remnant
- Radius of clump core is uncertain! $R_c/R = ?$

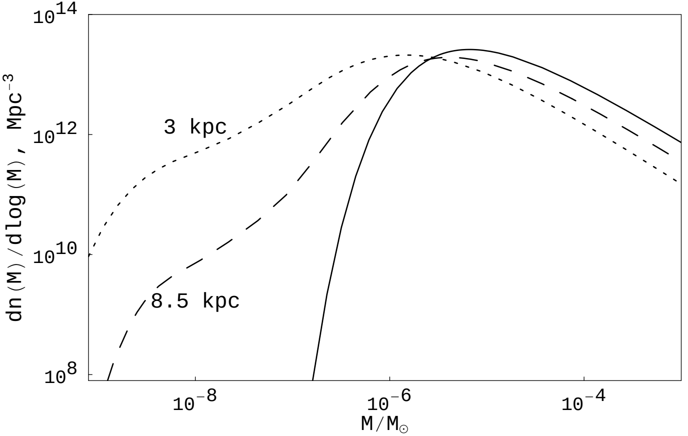
$R_c/R \simeq 1.8 \times 10^{-5}$ *Gurevich & Zybin 95*

$R_c/R \simeq 0.01$ *Diemand Moore & Stadel 05*

Central core dominates in annihilation rate at $\beta = 1.7 > 1.5\,!$

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

Transformation of the mass function



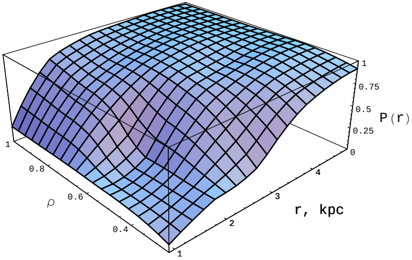
Numerically calculated modified mass function of clump remnants for galactocentric distances 3 and 8.5 kpc.

Solid curve is an initial mass function.

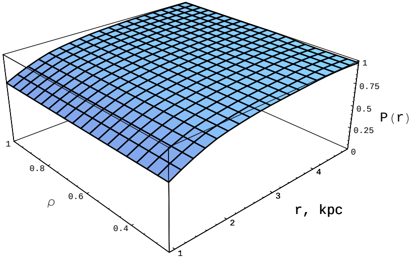
Probability of clump remnant survival

depending on the clump core radius $x_c = R_c/R$

$x_c = 0.1$



$x_c = 0.05$



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Survival probability $P(r, \rho)$ as a function of radial distance from the Galactic center r and a mean internal clump density ρ

Clump remnants mainly survived in the Galaxy, $P(r, \rho) \simeq 1$**, if** $x_c \leq 0.05$ **!**

Annihilation of DM in clumps

- **Annihilation in a single clump**

$$\dot{N}_{\rm cl} = 4\pi \int_0^\infty r^2 dr \rho_{\rm int}^2(r) m_\chi^{-2} \langle \sigma_{ann} v \rangle$$

- **Observed annihilation signal**

$$I_{\rm cl} = \frac{\langle \sigma_{\rm ann} v \rangle}{4\pi} \int_0^\pi d\zeta \sin\zeta \int_0^{r_{\rm max}(\zeta)} \frac{2\pi r^2 dr}{r^2} \int_{M_{\rm min}} dM \int dR \; n_{\rm cl}(l(\zeta, r), M, R) \dot{N}_{\rm cl}$$

- **Signal from diffuse DM in the Halo**

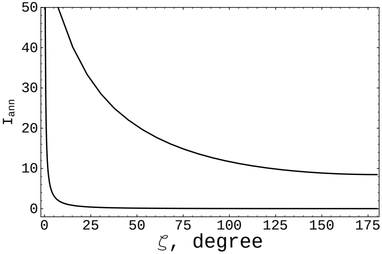
$$I_{\rm H} = \frac{\langle \sigma_{\rm ann} v \rangle}{2} \int_0^\pi d\zeta \sin\zeta \int_0^{r_{\rm max}(\zeta)} dr \frac{\rho_{\rm H}^2(l(\zeta, r))}{m_\chi^2}$$

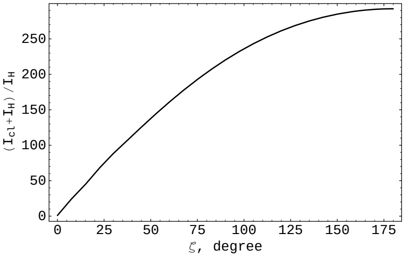
Amplification of annihilation signal (boost-factor) η

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

- Typical values:
  - Geometric factor $S \simeq 5$
  - Diffuse DM density in the Halo $\tilde{\rho}_{\rm H} \sim 0.3$ GeV cm^{-3}
  - Mean clump density $\bar{\rho}_{\rm cl} \sim 10^{-20}$ g cm^{-3}
- Mass fraction of DM clumps $\xi \sim 0.001$
- Boost-factor $\boxed{\eta \sim 10^2}$

Annihilation signal from the Galactic halo





- Left upper curve: annihilation signal as a function of the angle ζ between the line of observation and direction to the Galactic center
  Left bottom curve: the same for the Galactic halo without DM clumps
- Right: Amplification (boosting) of annihilation signal $\eta = (I_{\rm cl} + I_{\rm H})/I_{\rm H}$

Conclusions

- Despite the small survival probability of DM clumps during early stage of hierarchial clustering, they provide the major contribution to the annihilation signal in comparison with the diffuse unclumpy DM
- Central cores (remnants) of small-scale DM clumps may survive through the tidal destruction by stars
- Survival probability of remnants strongly depends on the radius of the clump central core R_c
- Annihilation amplification (boost-factor) $\eta \sim 10^2 - 10^3$ depends on the initial perturbation spectrum and minimum mass of clumps $M_{\rm min}$