Small-Scale Dark Matter Clumps in the Galaxy

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DM clump analogue: self-gravitating cluster of stars

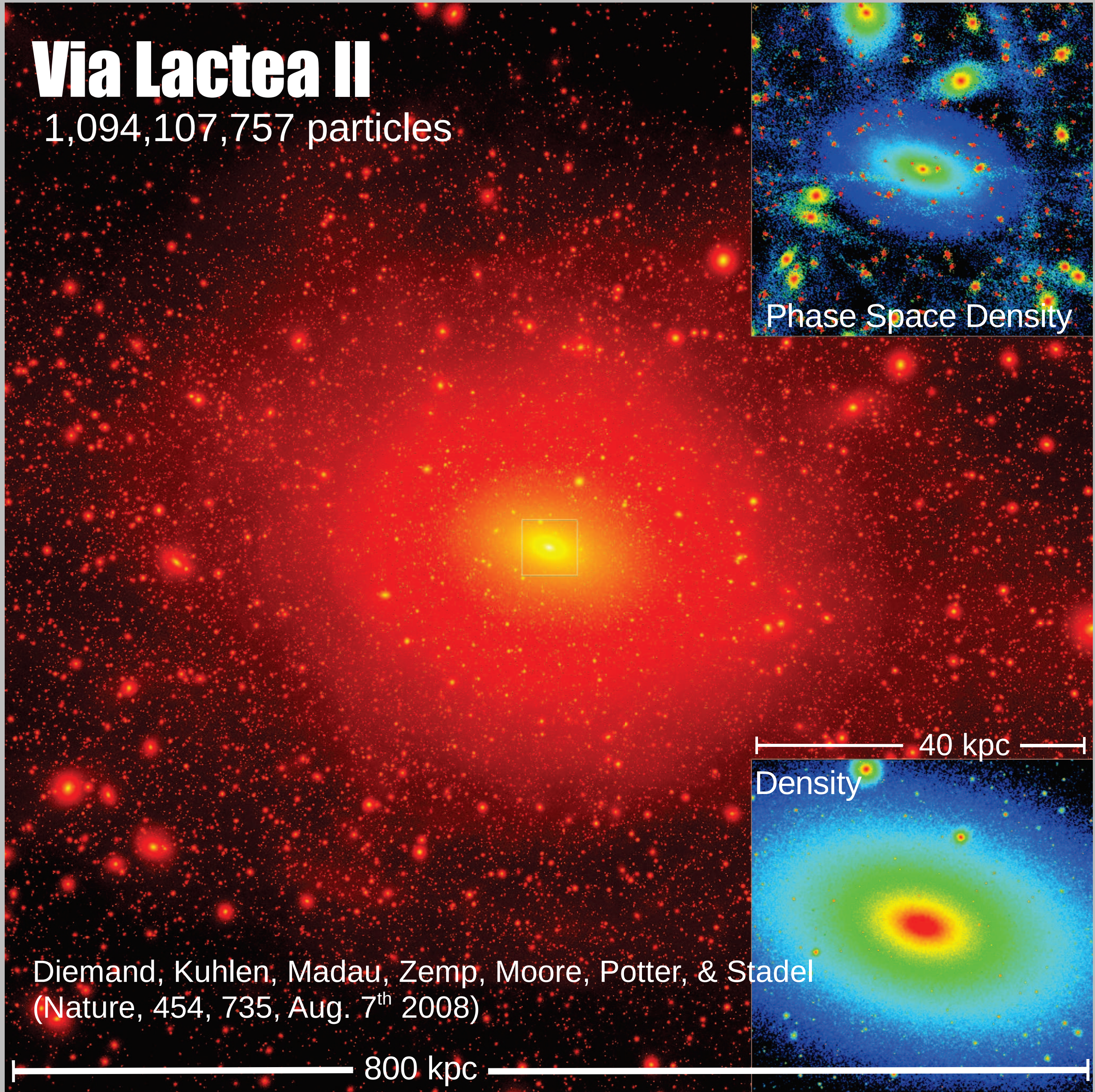
Hubble telescope view of Globular Cluster M 13

Large-scale DM clumps: numerical simulations of DM halos

Project Columbia supercomputer, NASA, **$2.34\,10^6$** particles

The Non-linear Regime: Numerical Simulations

One billion particles, one million cpu-hours

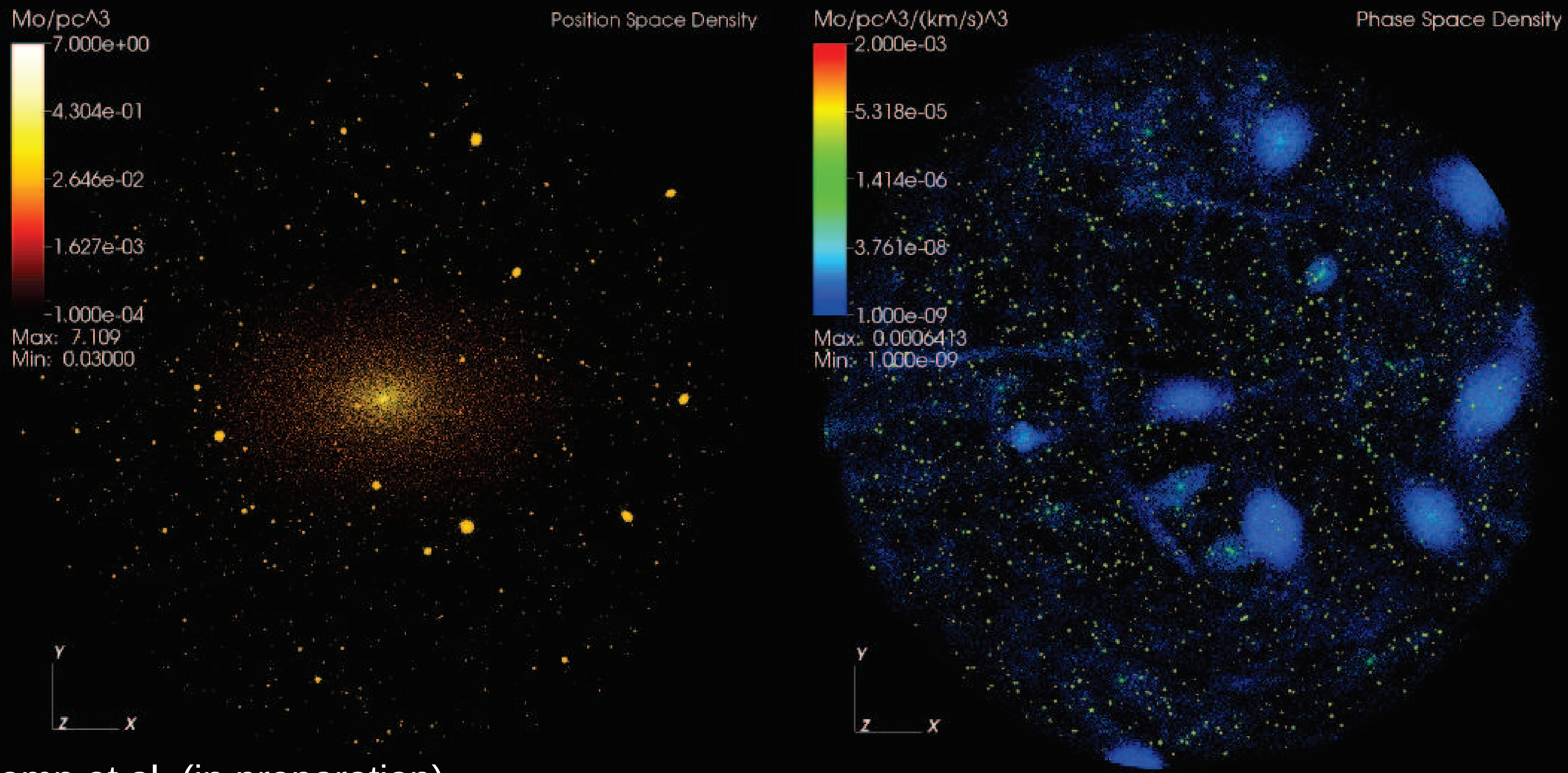


One million cpu-hours on ORNL's *Jaguar* Cray XT4

Produced 20 TB of data, the analysis is ongoing...

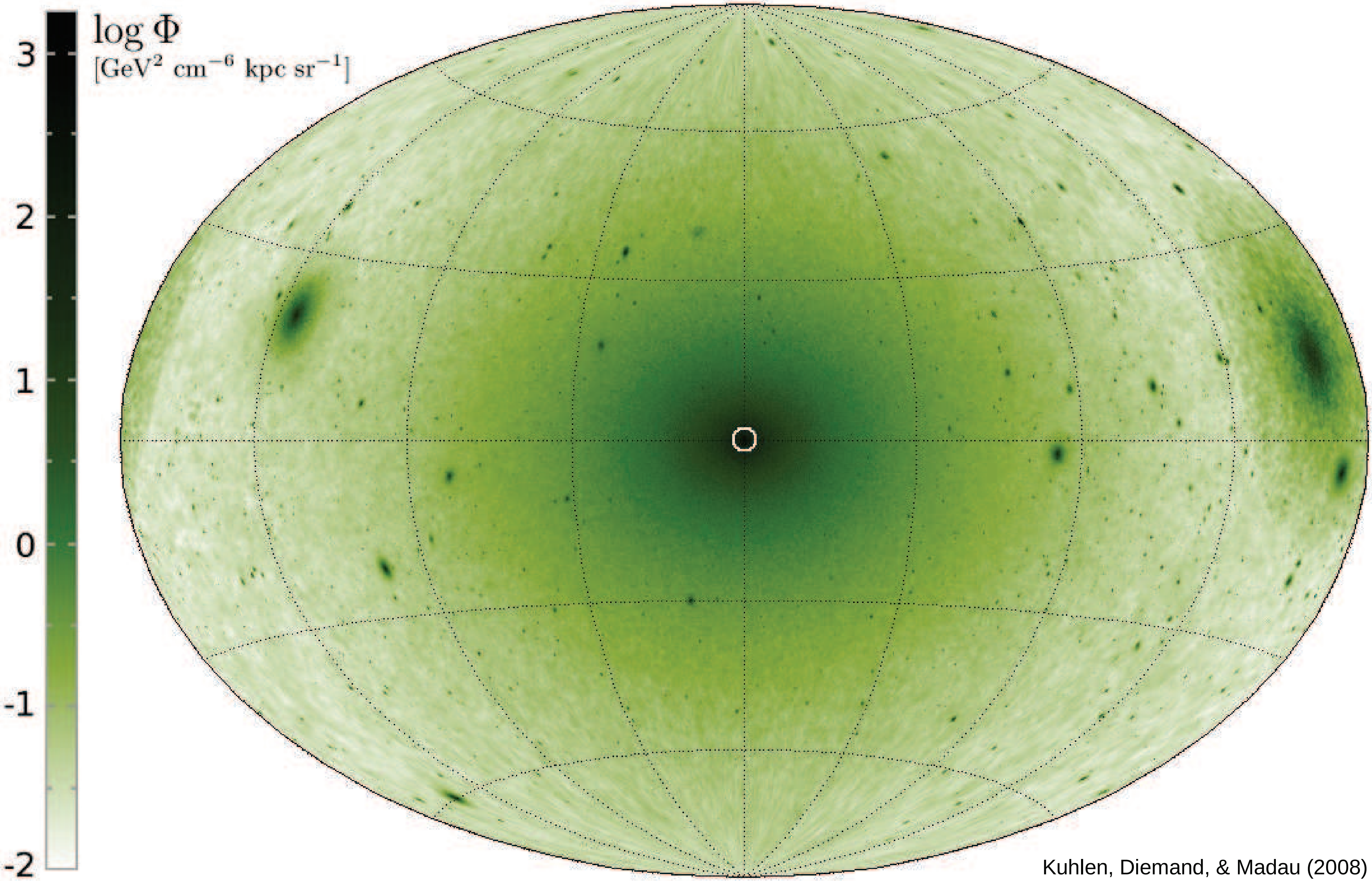
Via Lactea II – the inner 40 kpc

Whereas previous simulations were almost completely smooth in the central region, with VL-II we resolve lots of subhalos and tidal streams even down to 8 kpc.



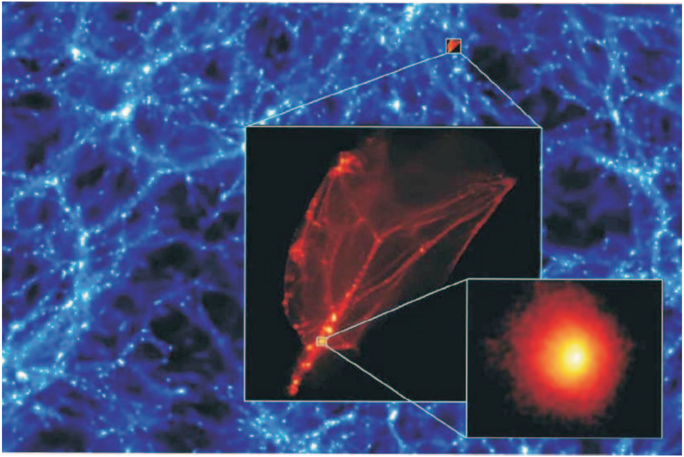
Zemp et al. (in preparation)

Simulated Dark Matter Annihilation Map



Kuhlen, Diemand, & Madau (2008)

Small-scale DM clumps: numerical simulations

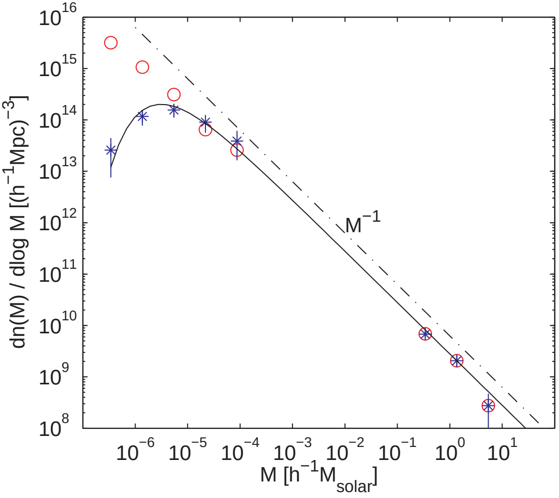


3 kpc 60 pc 0.024 pc

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

Diemand Moore & Stadel 05

Mass function of small scale DM clumps



Diemand Moore & Stadel 05

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*

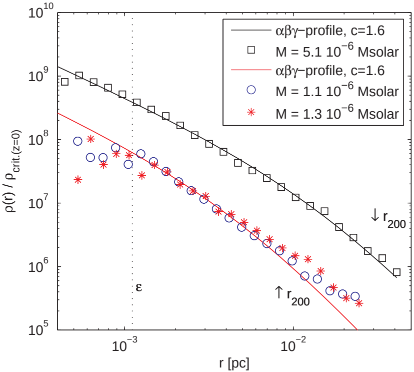
Cutoff of the clump mass spectrum by kinetic decoupling

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

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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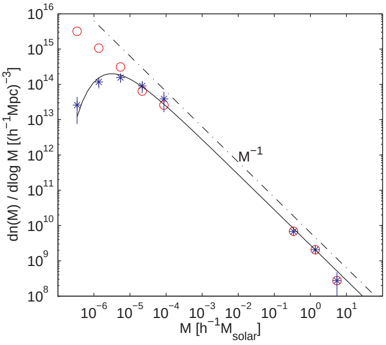


Diemand Moore & Stadel 05

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! $R_c/R = ?$

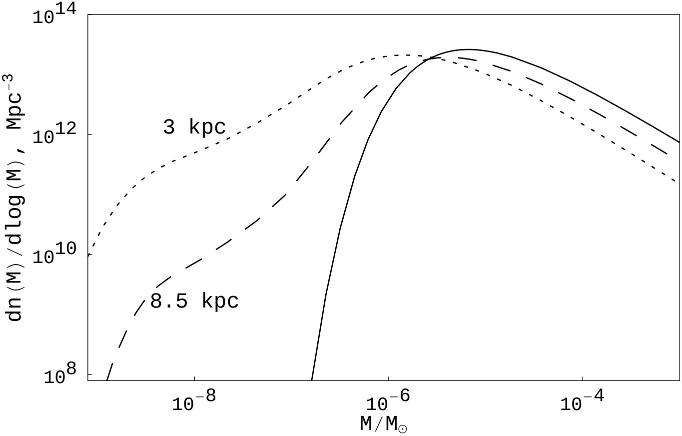
$R_c/R \simeq 1.8 \times 10^{-5}$ *Gurevich & Zybin 95*

$R_c/R \simeq 0.01$ *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



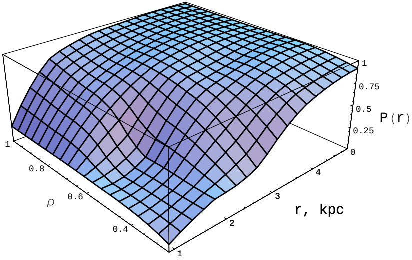
Numerically calculated modified mass function of clump remnants for galactocentric distances 3 and 8.5 kpc.

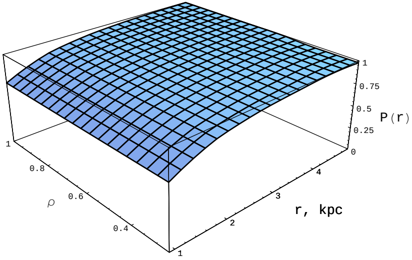
Solid curve is an initial mass function.

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**

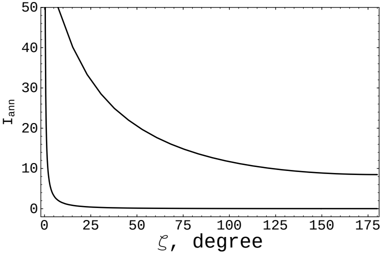
$$I_{\rm H} = \frac{\langle \sigma_{\rm ann} v \rangle}{2} \int_0^\pi d\zeta \sin\zeta \int_0^{r_{\rm max}(\zeta)} dr \frac{\rho_{\rm H}^2(l(\zeta, r))}{m_\chi^2}$$

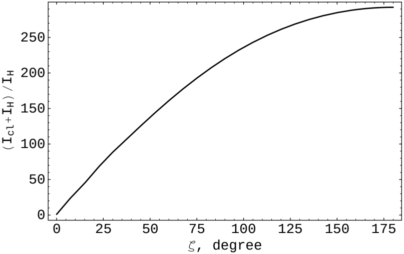
Amplification of annihilation signal (boost-factor) η

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

- 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 $M_{\min}$