The energy evolution of dark matter halos: how to fit observational data?

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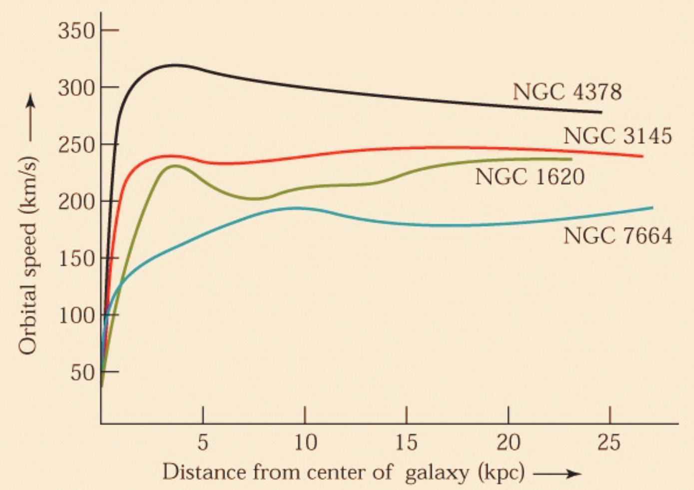
Dark matter. Discovery.



Density profiles. Theory.

Isothermal profile

$$\rho \sim r^{-2}$$

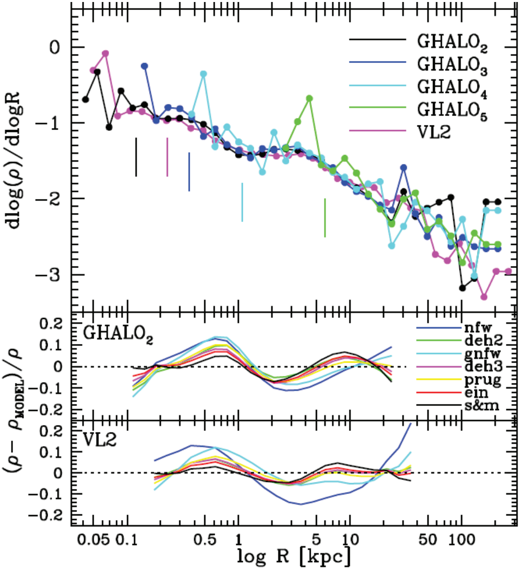
Navarro-Frenk-White profile

$$\rho_{NFW} = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

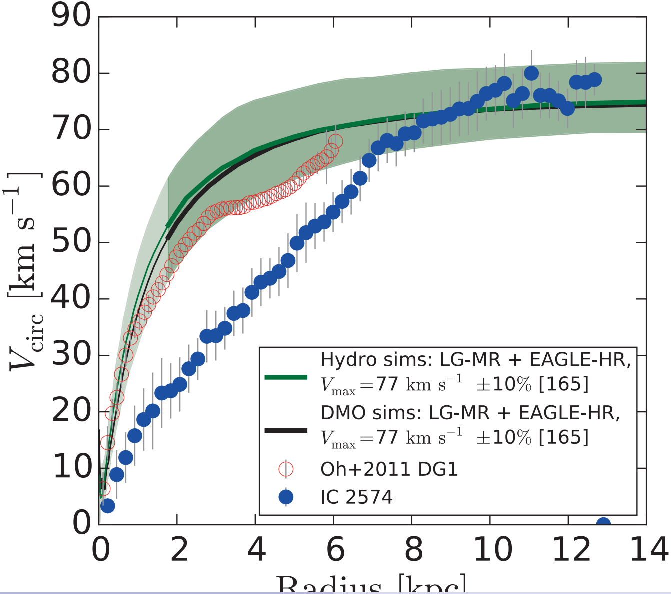
Einasto profile

$$\rho_{Ei} = \rho_s \exp\left\{-2n\left[\left(\frac{r}{r_s}\right)^{\frac{1}{n}} - 1\right]\right\}$$

Density profiles. N-body simulations (Stadel et al. 2009)



Simulations vs. observations (Oman et al. 2015)



Numerical effects

Relaxation time

$$\langle \Delta v \rangle \simeq 0 \qquad \langle \Delta v^2 \rangle \simeq \frac{8v^2 \ln \Lambda}{N(r)}$$

$$\tau_r = \frac{N(r)}{8 \ln \Lambda} \cdot \frac{r}{v}$$

(Power et. al. 2003) $t_0 \le 1.7\tau_r$
(Hayashi et al. 2003; Klypin et al. 2013) $t_0 \le 30\tau_r$

Fokker-Planck equation

Central profile $\rho \sim r^{-\beta}$

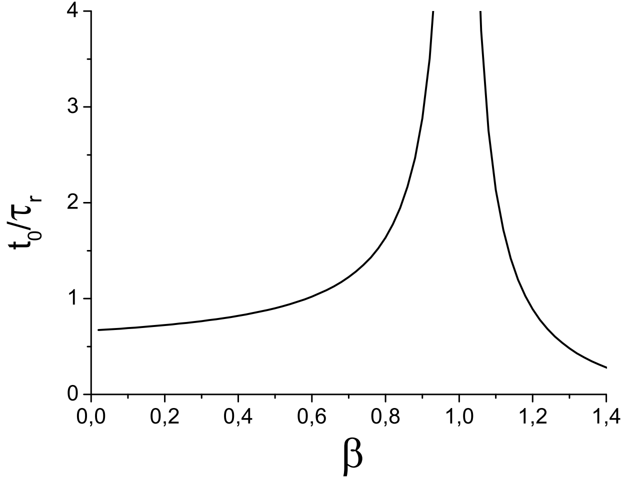
$$\frac{\partial n(p)}{\partial t} = \frac{\partial}{\partial p}\left\{\tilde{A}n(p) + \frac{\partial}{\partial p}[Bn(p)]\right\}$$

$$\tilde{A} = \frac{\langle \Delta p \rangle}{\delta t} = \mu \frac{\langle \Delta v \rangle}{\delta t} \qquad B = \frac{\langle \Delta p^2 \rangle}{2\delta t} = \frac{\mu^2}{2}\frac{\langle \Delta v^2 \rangle}{\delta t}$$

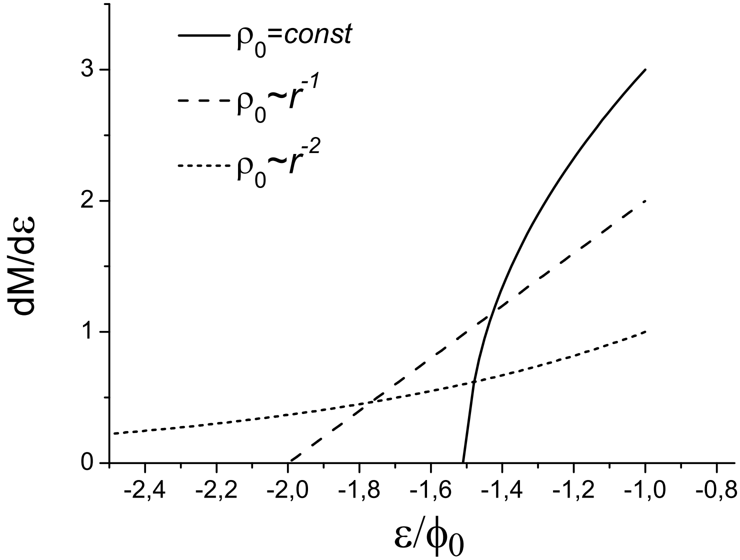
$$s = -\tilde{A}n(p) - \frac{\partial}{\partial p}[Bn(p)]$$

$$-s = \frac{dN(r)}{dt} = \frac{16(3-\beta)(1-\beta)}{(2-\beta)^2}\frac{\Phi \ln \Lambda}{r_b}\left(\frac{p}{\mu\Phi}\right)^{-\frac{\beta}{2-\beta}}$$

Profile evolution



The initial energy profiles $\left(\epsilon = \frac{v^2}{2} + \phi \qquad \phi_0 \equiv \frac{GM}{R}\right)$.



Moderate energy evolution

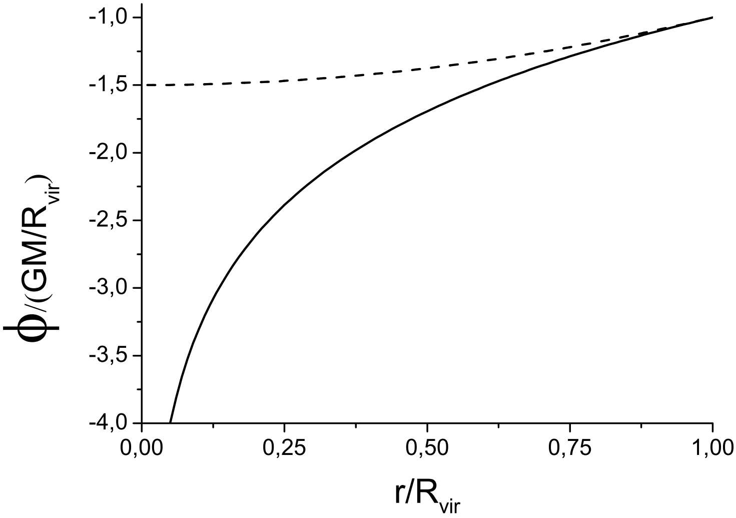
1) The final total specific energy ϵ_f of the majority of the particles differ from the initial ones ϵ_i no more than $c_{vir}/5$ times

$$\frac{\epsilon_f}{\epsilon_i} \le \frac{c_{vir}}{5} \qquad (1)$$

2)There can be particles that violate (1), but their total mass should be small with respect to the halo mass inside $r = \frac{2R_{vir}}{c_{vir}}$

$$M < \int\limits_0^{2R_{vir}/c_{vir}} dM_{\text{halo}} \qquad (2)$$

$\mathbf{r_0}$ is the largest distance that the particle can move away from the center



Calculations

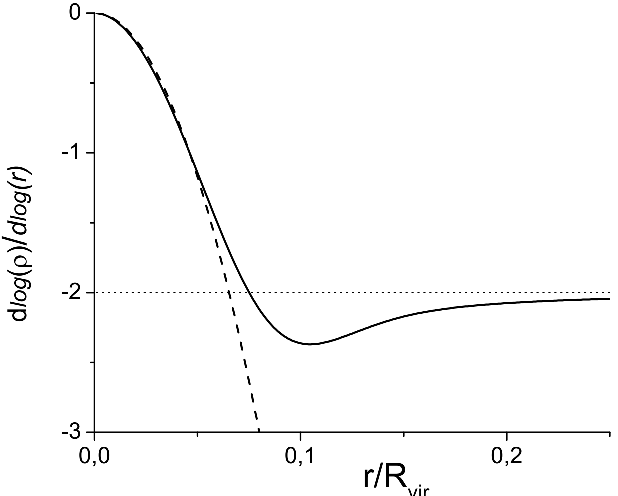
$$dm = f(r_0)\,\frac{2\mu}{\alpha^2}\exp\left(-\frac{\mu^2}{\alpha^2}\right)\,d\mu dr_0, \qquad \mu \equiv [\vec{v}\times\vec{r}]$$

$$D(x) \equiv e^{-x^2}\int_0^x e^{t^2}dt$$

$$r_c = \left\langle \frac{\alpha(r_0)}{\sqrt{2(\phi(r_0)-\phi(0))}} \right\rangle \simeq \frac{\langle\alpha(r_0)\rangle}{\sqrt{2|\phi(0)|}}$$

$$\boxed{\rho = \rho_c\frac{r_c}{r}\,D\left(\frac{r}{r_c}\right)} \qquad \rho_c = \frac{1}{2\pi r_c}\int_0^\infty \frac{f(r_0)dr_0}{\alpha(r_0)T(r_0)}$$

The model density profile with $r_c = 0.05R_{vir}$ and Einasto profile with $n = 0.5$ and $r_s = 0.017R_{vir}$ (dashed line).



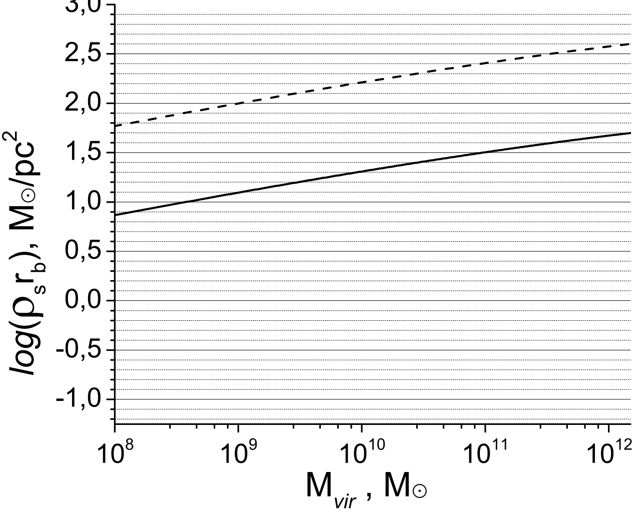
Consequences of the moderate energy evolution

1) The supposition that the energy exchange between the dark matter particles is small automatically leads to a cored Einasto-like density profile with $n \simeq 0.5$ in the halo center.(Astronomical Journal, 142, p. 15 (2011))

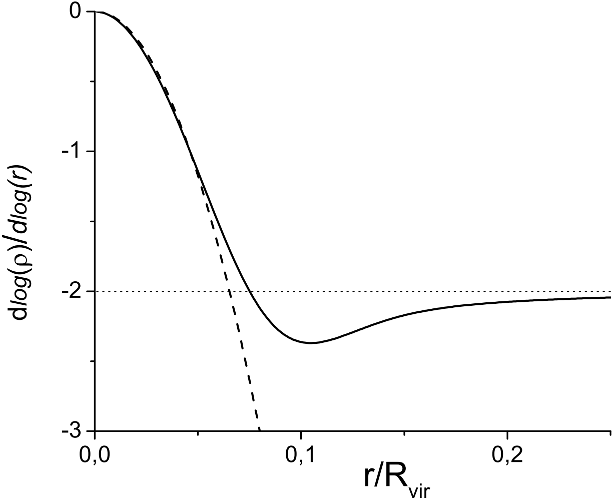
2) The presence of a typical region with $\rho \propto r^{-2}$ finds a natural explanation.

3) The moderate evolution scenario predicts the constancy of multiplication of the central density on the core radius $\rho_s r_s$. This result is also confirmed by observations (Kormendy & Freeman, 2004).

Dependence of $\log(\rho_s r_s)$ $(M_\odot/\text{pc}^2)$ on $\log(M_{vir}/M_\odot)$



So if the relaxation is not very violent



Clump destruction mechanisms

A WIMP of mass 100 GeV corresponds to minimal clumps $\sim 10^{-6} M_\odot$, $R_{vir} \sim 0.05$ pc. The average density $\bar\rho$ of the clump is $\bar\rho \cdot \frac{4}{3}\pi R_{vir}^3 = M_{vir}$. We will use the following designations: $m_6 = M_{vir}/10^{-6} M_\odot$, $r_6 = R_{vir}/0.05$ pc, $\bar\rho_6 = 1.9 \cdot 10^{-3}\ M_\odot/\mathrm{pc}^3$. For a clump with mass $M_{vir} = 10^{-6} M_\odot$, $m_6 = r_6 = \bar\rho_6 = 1$.

Collisions with stars

$$t_d \simeq \frac{17}{200} \frac{\sigma m_{cl} r_{cl}^2}{G m_*^2 n_* r_0^3}$$

where m_*, n_*, and σ_* are the average star mass, star number density and star velocity dispersion, respectively. The dispersion of clump velocities is σ_{cl}. $\sigma = \sqrt{\sigma_*^2 + \sigma_{cl}^2}$.

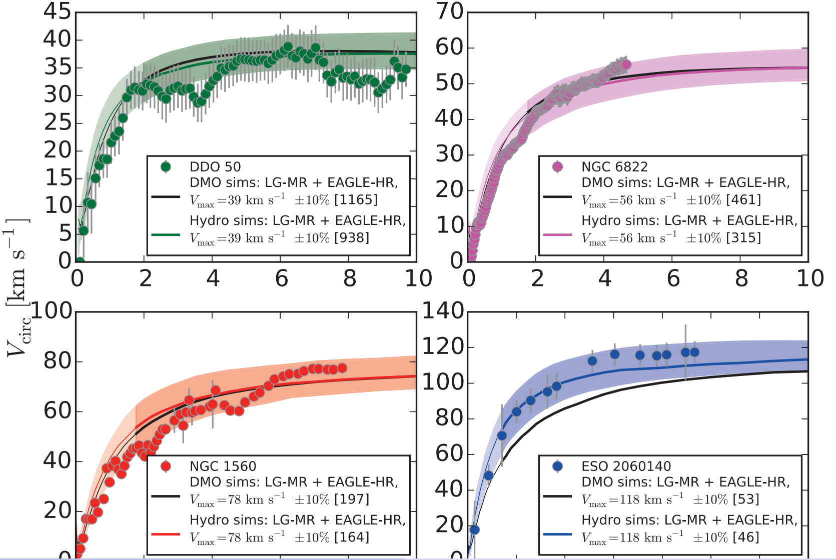
$$t_d \simeq (r/r_\odot)^3 m_6^{2/3} \cdot 8 \cdot 10^{10} \text{years}.$$

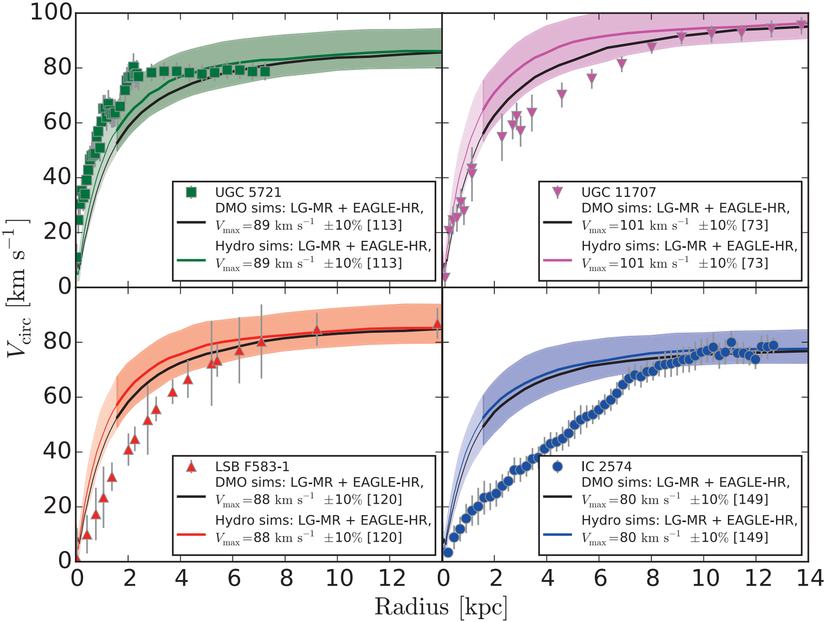
Destruction on the Milky Way disc $M_d = 8 \cdot 10^{10} M_\odot$.

$$N_d = \frac{3 r_d^4 v_\perp^2}{8 G M_d^2} \frac{m_{cl}}{r_{cl}^3} e^{2r/r_d}, \qquad r_d = 4.5\text{kpc} \tag{3}$$

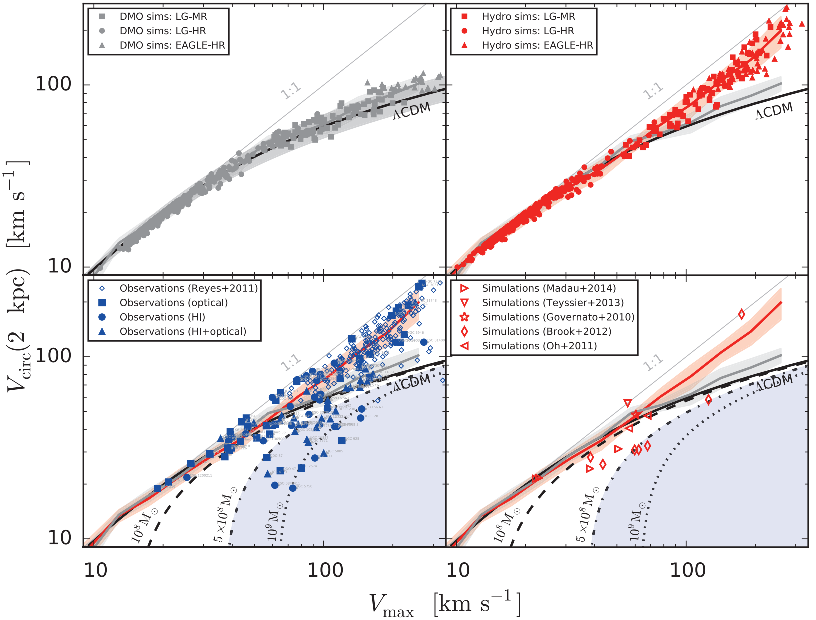
Destruction by the common gravitational field

$$k^2 \rho_{cl} < \bar{\rho}_p(r). \tag{4}$$


DDO 50
DMO sims: LG-MR + EAGLE-HR,
V_{max} = 39 km s^{-1} ±10% [1165]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} = 39 km s^{-1} ±10% [938]
NGC 6822
DMO sims: LG-MR + EAGLE-HR,
V_{max} = 56 km s^{-1} ±10% [461]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} = 56 km s^{-1} ±10% [315]
NGC 1560
DMO sims: LG-MR + EAGLE-HR,
V_{max} = 78 km s^{-1} ±10% [197]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} = 78 km s^{-1} ±10% [164]
ESO 2060140
DMO sims: LG-MR + EAGLE-HR,
V_{max} = 118 km s^{-1} ±10% [53]
Hydro sims: LG-MR + EAGLE-HR,
V_{max} = 118 km s^{-1} ±10% [46]
V_{circ} [km s^{-1}]



UGC 5721
DMO sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=89 km s^{-1} ±10% [113]
Hydro sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=89 km s^{-1} ±10% [113]
UGC 11707
DMO sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=101 km s^{-1} ±10% [73]
Hydro sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=101 km s^{-1} ±10% [73]
LSB F583-1
DMO sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=88 km s^{-1} ±10% [120]
Hydro sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=88 km s^{-1} ±10% [120]
IC 2574
DMO sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=80 km s^{-1} ±10% [149]
Hydro sims: LG-MR + EAGLE-HR,
$V_{\rm max}$=80 km s^{-1} ±10% [149]
$V_{\rm circ}$ [km s^{-1}]
Radius [kpc]


DMO sims: LG-MR
DMO sims: LG-HR
DMO sims: EAGLE-HR
Hydro sims: LG-MR
Hydro sims: LG-HR
Hydro sims: EAGLE-HR
Observations (Reyes+2011)
Observations (optical)
Observations (HI)
Observations (HI+optical)
Simulations (Madau+2014)
Simulations (Teyssier+2013)
Simulations (Governato+2010)
Simulations (Brook+2012)
Simulations (Oh+2011)
1:1
ΛCDM
$10^8 M_\odot$
$5\times10^8 M_\odot$
$10^9 M_\odot$
$V_{\rm circ}(2\ {\rm kpc})$ [km s^{-1}]
$V_{\rm max}$ [km s^{-1}]
10
100

Conclusion

1) The cusp persistently appearing in the N-body simulations can be a numerical effect.

2) The supposition that the energy exchange between the dark matter particles is small automatically leads to an Einasto-like density profile with $n \simeq 0.5$ in the halo centre.

3) The observed constancy of $\rho_s r_s$ multiplication and existence of a region with $\rho \propto r^{-2}$ find a natural explanation.

4) Cored clumps are significantly less firm than the standard cuspy ones. They should have been completely destroyed inside ~ 20 kpc from the Milky Way center. as well as in dwarf spheroidals. However, even under the most pessimistic assumption about the clump structure, the clumps should have survived in low-density cosmic structures.