Solving the Core-Cusp Problem of CDM Halos and the Origin of their Observational Laws

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Collaborators

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The Core-Cusp Problem in CDM Halos and Supernova Feedback

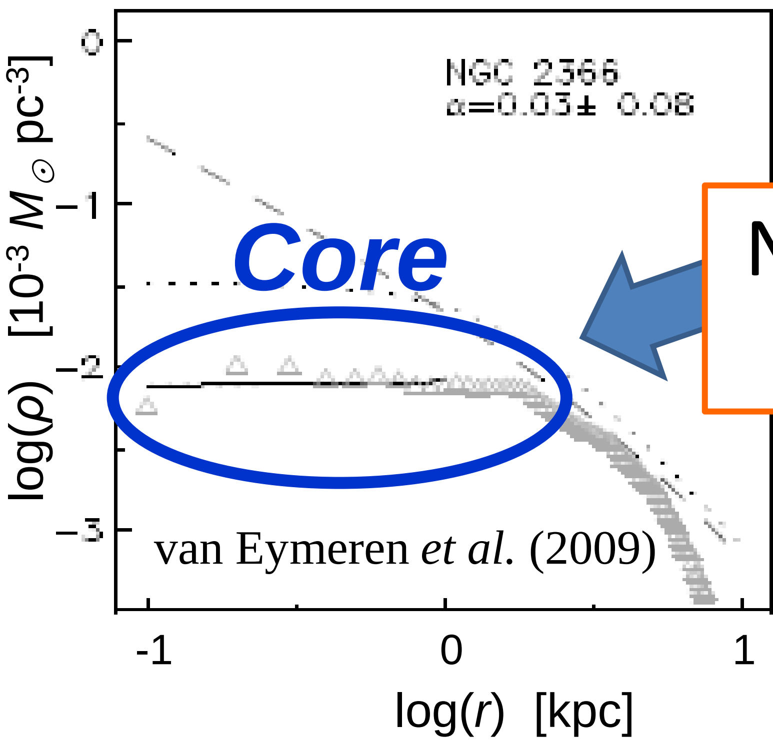
Ogiya and Mori, 2011, ApJ, 736, L2

Ogiya and Mori, 2012, arXiv: 1206.5412

Ogiya et al., 2013, ACS, 6(3), 58-70 (Japanese)

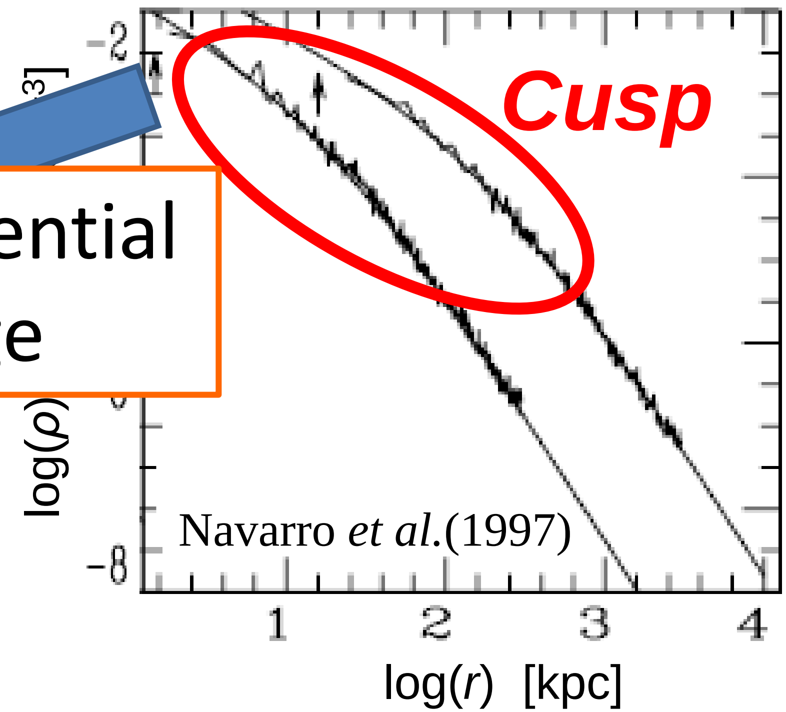
What is the Core-Cusp Problem?

Observation



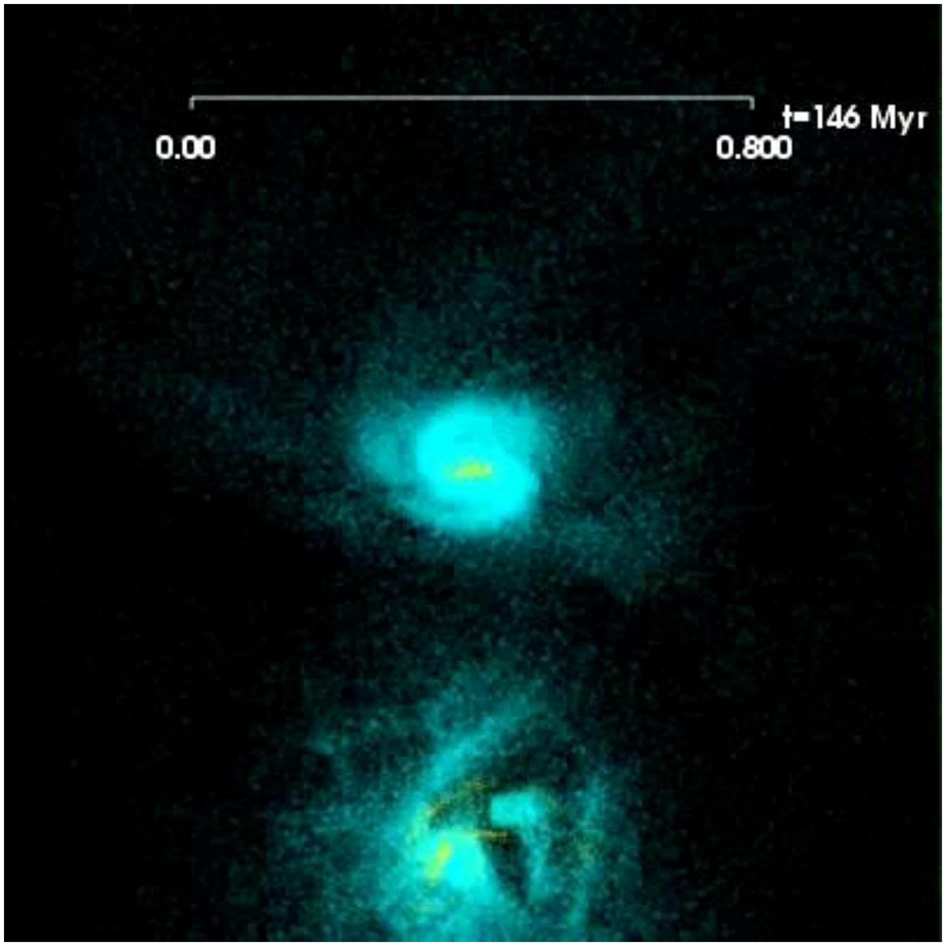
Need potential change

Theory (CDM)



Numerical simulation is a powerful tool!!

Supernova Feedback



Mashchenko et al. (2008)

- Gas Oscillation
  - Cosmoligical *N*-body+SPH simulation
    - Supernova feedback etc.
    - Blue: gas, Yellow: star
  - Gas
    - Blown out (expansion)
    - Fall back towards center
    - Repeat many times
- Gas Mass-Loss
  - Feedback → Galactic winds (e.g., Mori+ 1997, 1999; Mac Low & Ferrara 1999)

Motivation & Policy

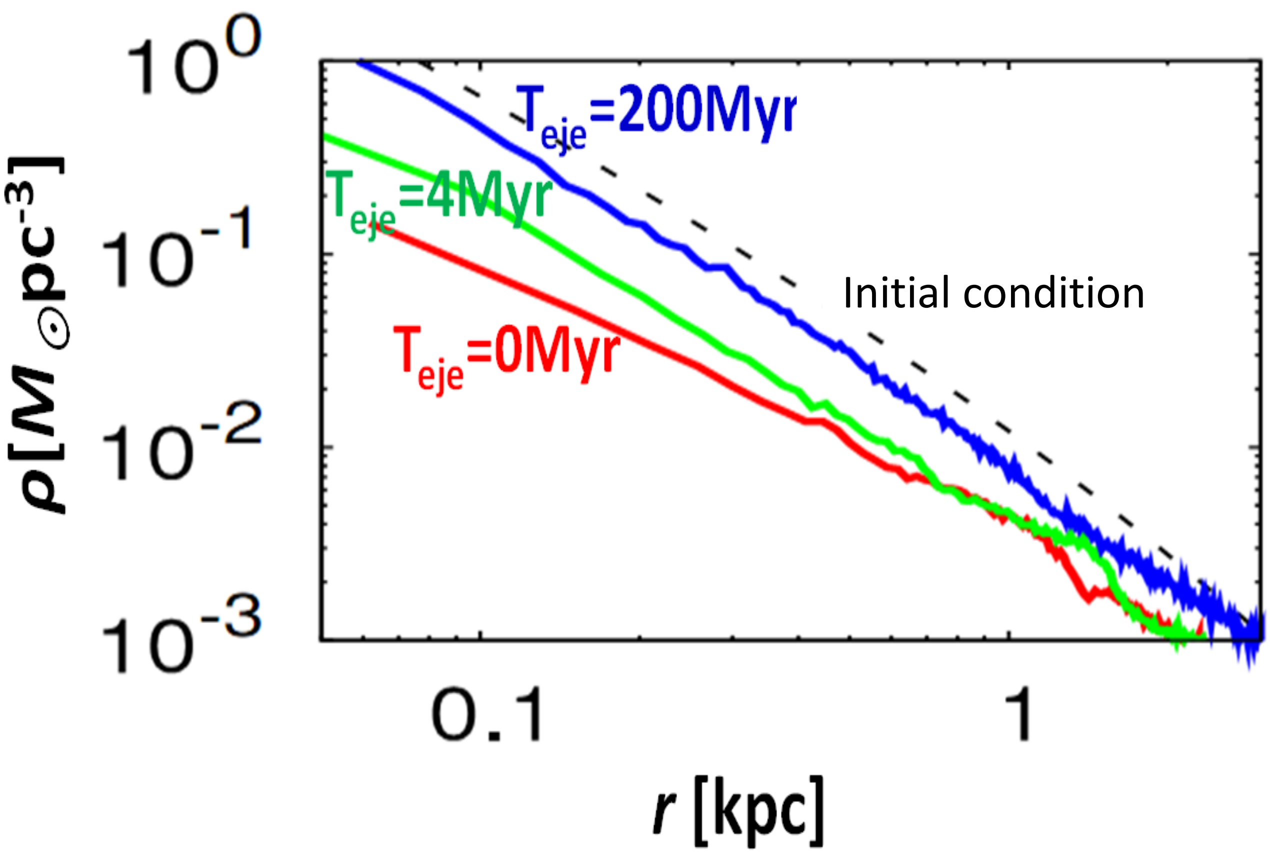
- Understanding the dynamical response of DM halos to Gas Mass-Loss/Oscillation
- Previous studies (e.g, Navarro et al. 1996; Pontzen & Governato 2012)
  - Poor authenticities of numerical simulations
  - Too complicated simulations

→ Constructing an analytical model

→ *N*-body simulations of idealized models with sufficient authenticities

Effects of Mass-Loss

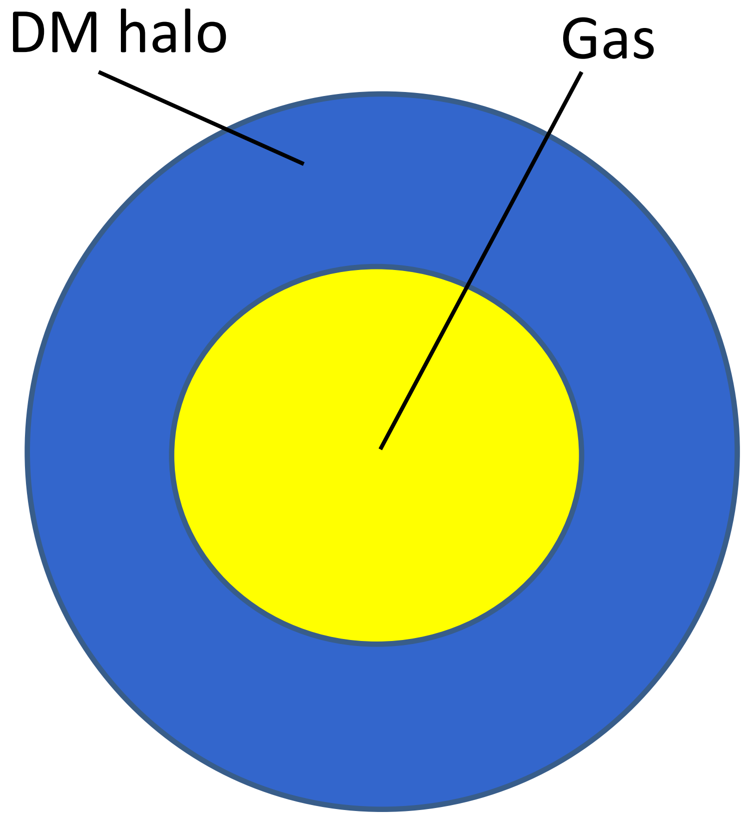
- The central cusp becomes flatter when mass-loss occur in a shorter timescale.
- But the central cusp still remains.
  - Counter-evidence against previous studies with poor authenticities



Performed on FIRST simulator and T2K-Tsukuba

GO & Mori, 2011, ApJ, 736, L2

Recurring Change in Potential



1) Gas heating by supernovae
2) Gas expansion
3) Energy loss by radiative cooling
4) Contraction towards the center
5) Ignition of star formation again

Repetition of these processes

Gas Oscillation

Change of potential ⇒ DM halo is affected gravitationally
⇒ Cusp-to-Core transformation?

Linear Analysis: Resonance Model

- Equilibrium system (0) + External force (ex) ⇒ Induced values (ind)
- Focus on the particle group with $\rho_0 = const.$, $v_0 = const.$
- External force :

$$-\frac{\partial \Phi_{\rm ex}}{\partial r} = \sum_n A_n \cos\left(kr - n\Omega t\right)$$

(A: strength, k: wavenumber, Ω: frequency)

Linearized continuity eq. and Euler eq.

$$\rho_{\rm ind}(t,r) = -\sum_n \frac{A_n \rho_0 k}{(n\Omega - kv_0)^2} \times \{\sin(kr - n\Omega t) - \sin(kr - kv_0 t) + (n\Omega - kv_0)t\cos(kr - kv_0 t)\}$$

$$v_{\rm ind}(t,r) = -\sum_n \frac{A_n}{n\Omega - kv_0}\{\sin(kr - n\Omega t) - \sin(kr - kv_0 t)\}$$

Resonance condition: $\boxed{n\Omega \sim kv_0}$

l'Hôpital's rule

$$\lim_{n\Omega \to kv_0} \rho_{{\rm ind},n} = \frac{A_n \rho_0 k}{2} t^2 \sin\left[k(r - v_0 t)\right] \qquad \lim_{n\Omega \to kv_0} v_{{\rm ind},n} = A_n t \cos\left[k(r - v_0 t)\right]$$

Prediction of Core Scale

Resonance condition

$$\boxed{T \approx t_d(r_{\rm core}) = \sqrt{\frac{3\pi}{32G\overline{\rho(r_{\rm core})}}}}$$

Resonance occurs when the condition is satisfied

⇒ Efficient energy transfer

⇒ System expands

⇒ Cusp-to-Core transformation

1. Mass profile of CDM halos

$$\rho(r) = \frac{\rho_0 R_{DM}^3}{r^\alpha (r + R_{DM})^{3-\alpha}}$$ (NFW: α=1)

$$T_{\rm c}^2 \equiv \frac{\pi^2}{8G} \frac{R_{\rm DM}^3 c^{3-\alpha} {}_2F_1[\alpha; -c]}{M_{\rm vir}}$$

F: Gauss's hyper-geometric function

$$\boxed{r_{\rm core} = R_{DM}\left(\frac{T}{T_c}\right)^{2/\alpha}}$$

2. Inversion procedure

$$\boxed{r_{\rm core} = t_{\rm d}^{-1}(T)}$$

Numerical Model

DM halo (*N*-body system):
NFW model (Navarro *et al.* 1997)

$$\rho(r) = \frac{\rho_0 R_{\mathrm{DM}}^3}{r(r+R_{\mathrm{DM}})^2}$$

Tree code developed for GPU clusters (GO+ 2013)

Baryon (external potential):
Hernquist potential (Hernquist 1990)

$$\Phi_b(r,t) = -\frac{GM_b}{r+R_b(t)}$$

$$R_{\mathrm{b}}(t) \propto \cos\left(2\pi t/T\right)$$

Property of DM halo

Number of particles N	16M, 128M
Softening parameter ε	0.004kpc
Virial mass of a DM halo M_{vir}	$10^9 M_\odot$
Virial radius of a DM halo R_{vir}	10kpc
Scale radius of a DM halo R_{DM}	2kpc
Total baryon mass $M_{\mathrm{b,tot}}$	$1.7\times10^8 M_\odot$

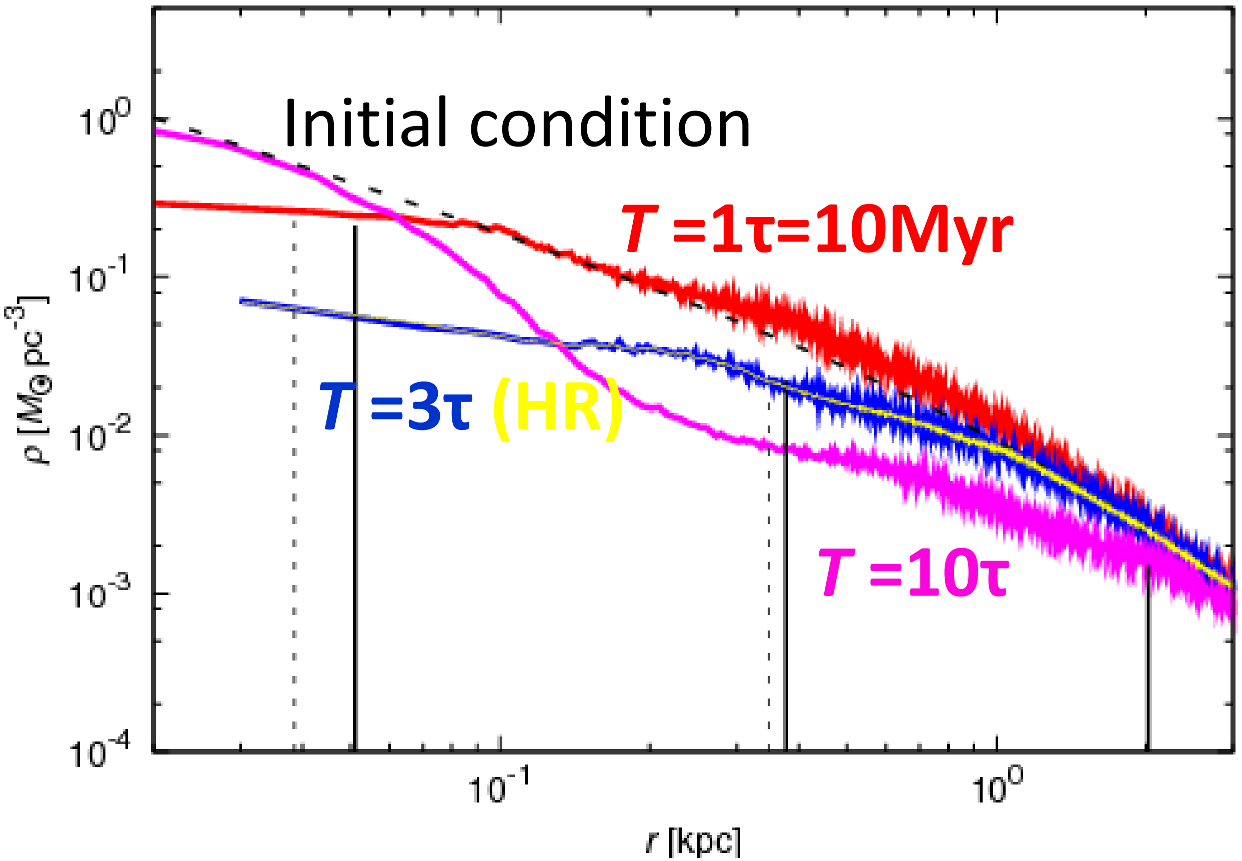
Oscillation period of the external force, T

$T = 1, 3, 10\ \tau$

$\tau \equiv 10\mathrm{Myr} \sim t_{\mathrm{d}}(0.2\mathrm{kpc})$

Density Profile

The cusp-to-core transformation and resultant core scale depend on the oscillation period of the external force, $\boldsymbol{T}$.



(after **10** cycles)

Prediction of Core Scale

Dashed

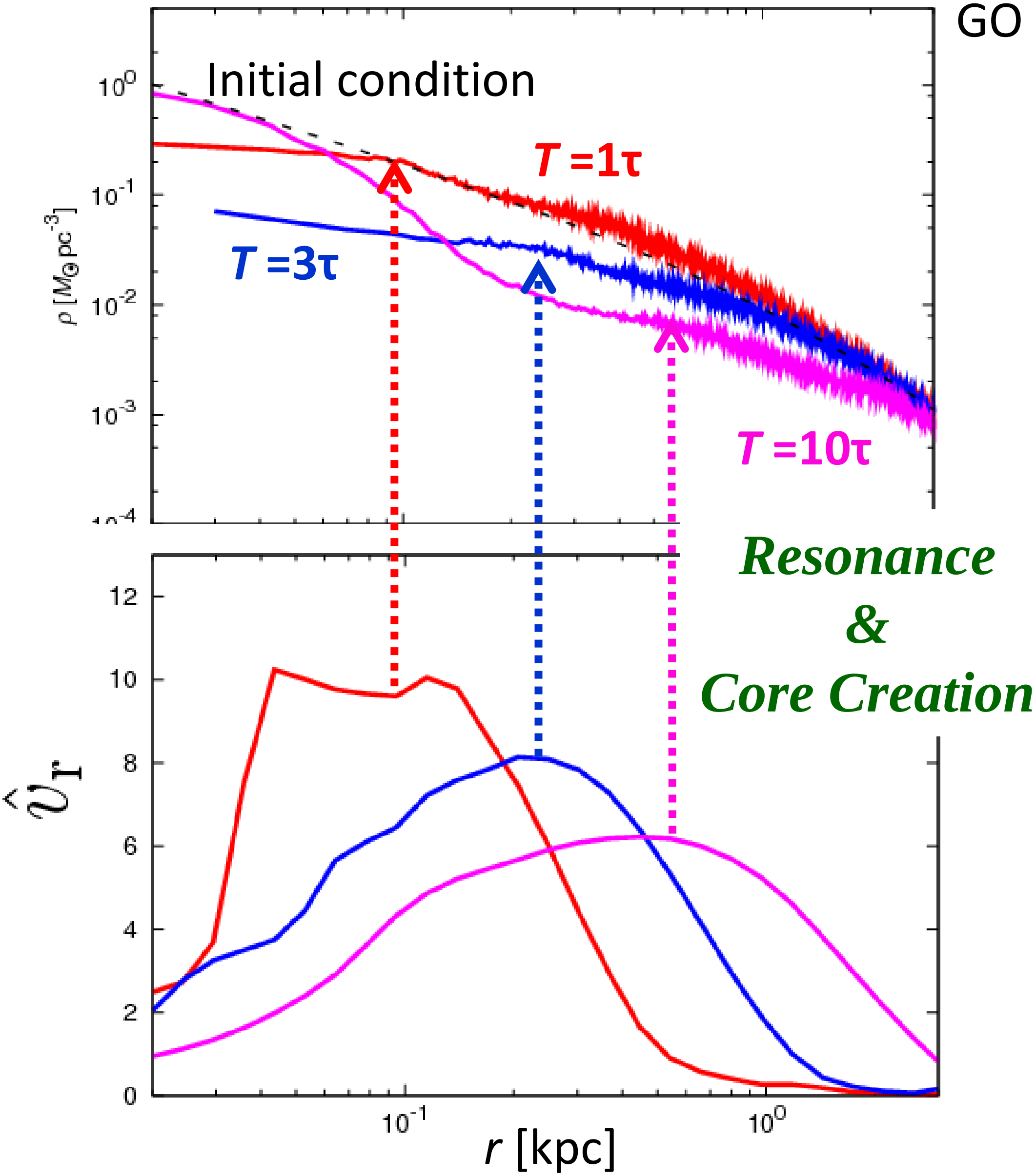
$$r_{\mathrm{core}} = R_{DM}\left(\frac{T}{T_c}\right)^{2/\alpha}$$

Solid

$$r_{\mathrm{core}} = t_{\mathrm{d}}^{-1}(T)$$

GO & Mori (2012)

Fourier Spectrum of Radial Velocity



GO & Mori (2012)

Density profiles of DM halos after 10 oscillation cycles

Fourier spectrum of radial velocity

$$v_r(t, r) \rightarrow \hat{v}_r(\omega, r)$$

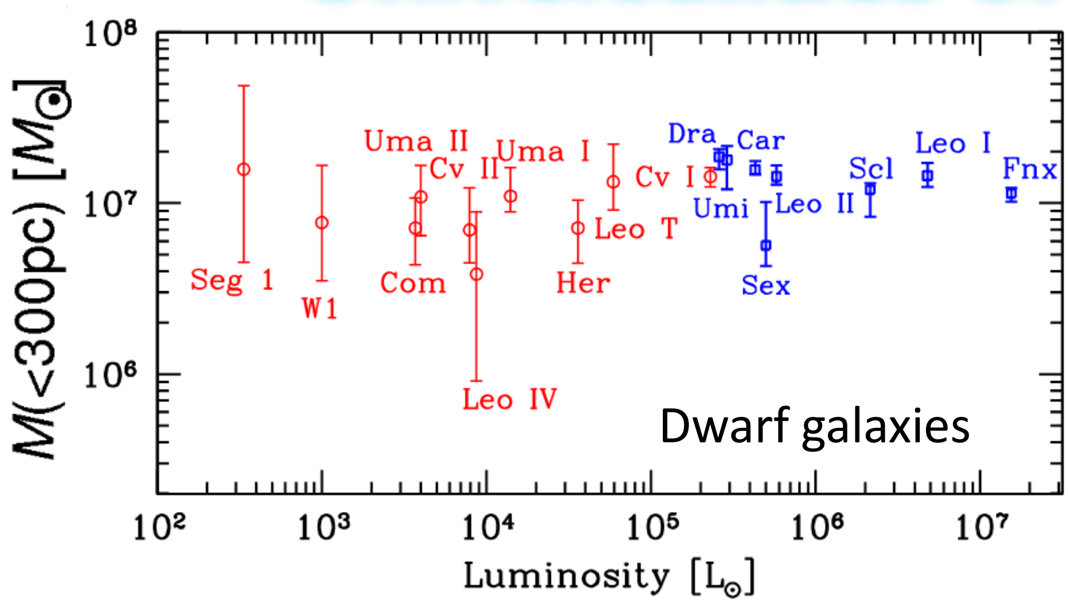
Peaks appear when $\omega = 2\pi/T$.

Each position of the peaks matches the core scale.

The Connection between the Cusp–to–Core Transformation and Observational Universalities of DM Halos

Ogiya et al., accepted for publication in MNRAS Letters

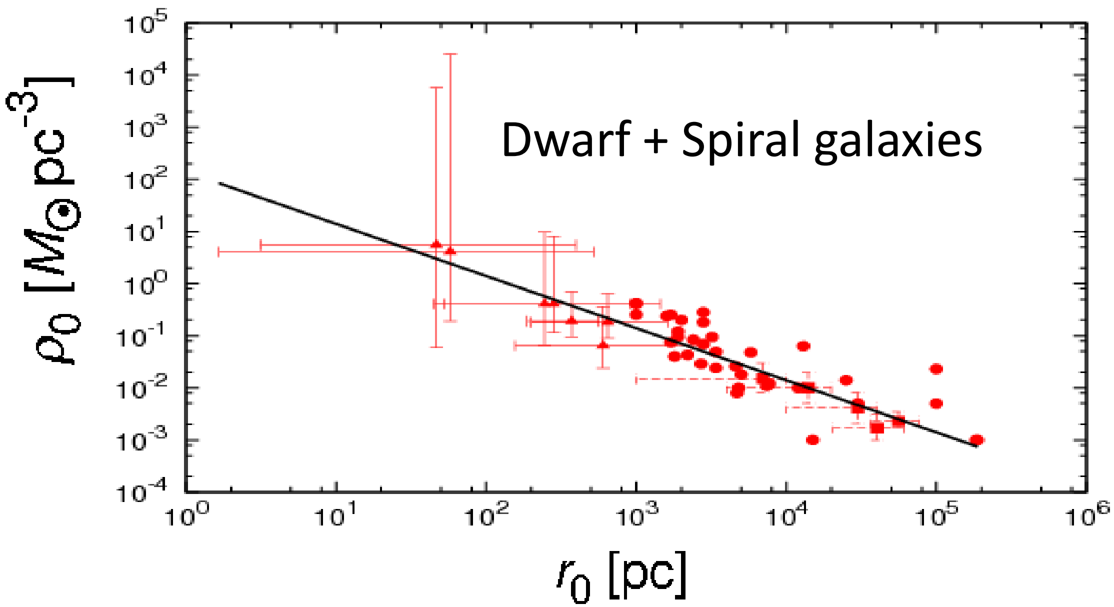
Universalities of DM Halos



- Strigari relation
  - $M(<300\mathrm{pc}) \sim 10^7 M_\odot$
  - Strigari et al. (2008)

    Cf. Walker et al. (2009);

    Hayashi & Chiba (2012)

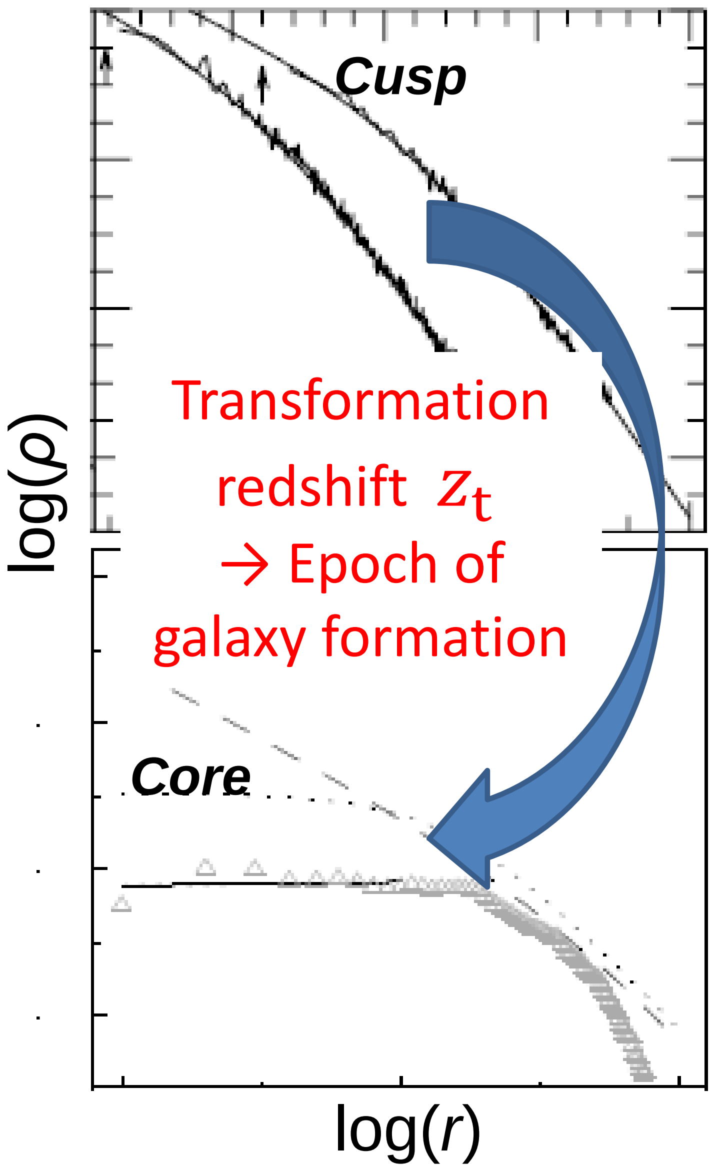


- $\mu_{0\mathrm{D}}$ relation
  - Central surface density, $\mu_{0\mathrm{D}} \equiv \rho_0 r_0 \sim 140\ M_\odot \mathrm{pc}^{-2}$
  - Kormendy & Freeman (2004)

    Cf. Donato et al. (2009);

    Salucci et al. (2012)

Assumption & Procedure



1. Halos form following an NFW profile with the $c(M_{200}, z)$ for given M_{200} and z

$\rightarrow \rho_s, r_s$

NFW profile

$$\rho(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2}$$

2. NFW halos are transformed into Burkert halos

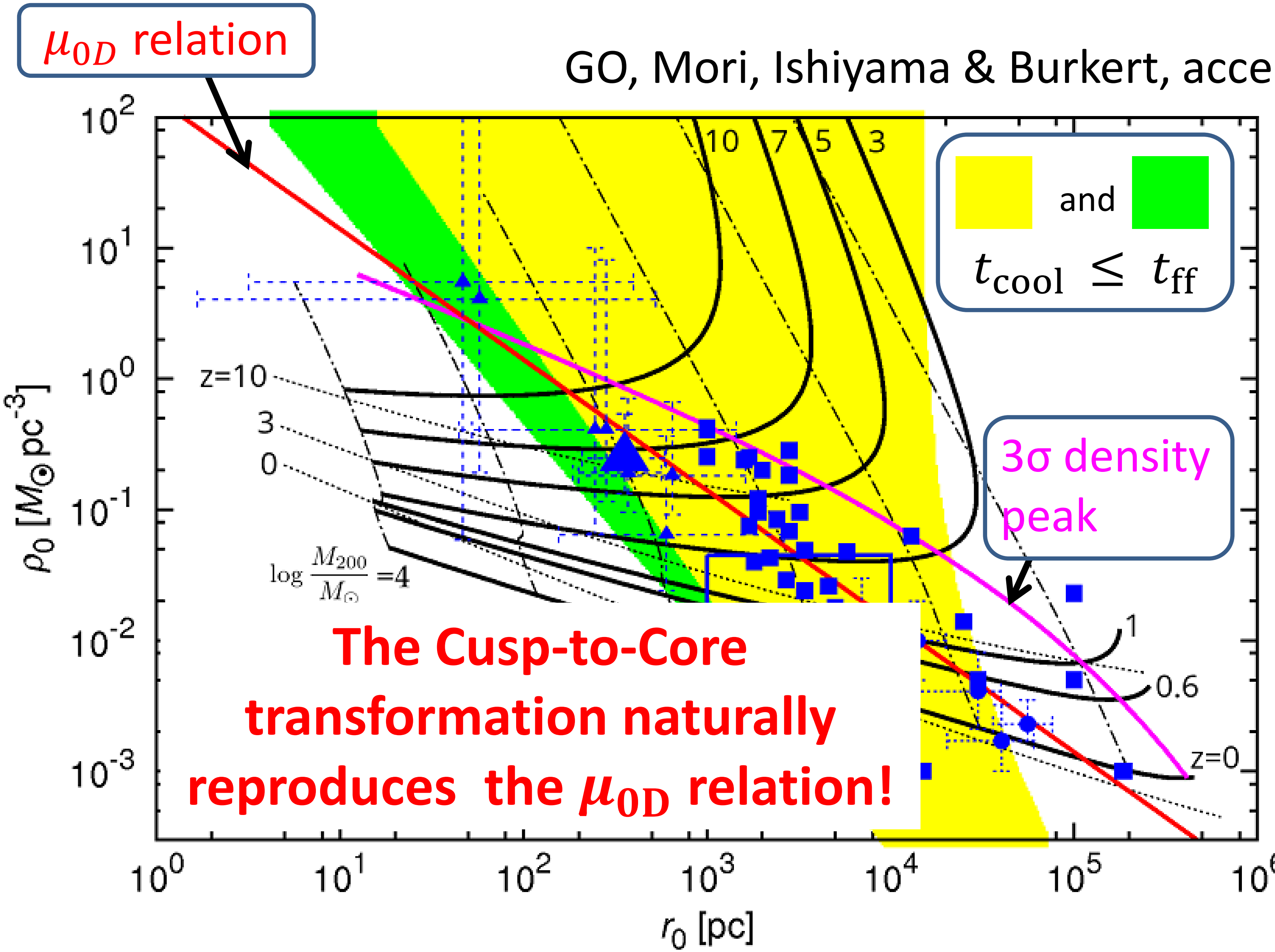
$\rightarrow \rho_0, r_0$

Burkert profile

$$\rho(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)}$$

Generation of the μ_{0D} Relation

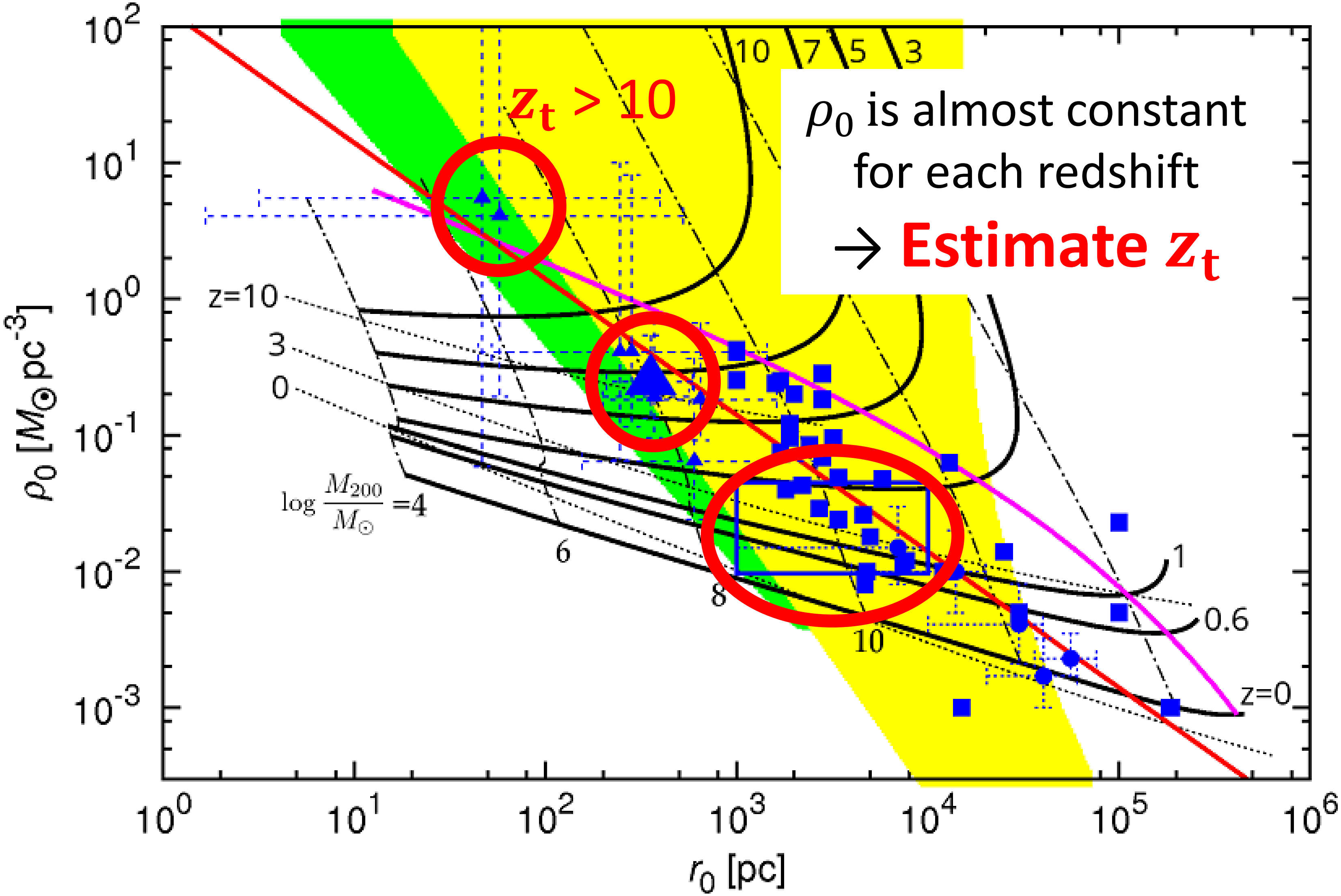
GO, Mori, Ishiyama & Burkert, accepted



The Cusp-to-Core transformation naturally reproduces the μ_{0D} relation!

Generation of the μ_{0D} Relation

GO, Mori, Ishiyama & Burkert, accepted



Summary

- Gas mass-loss is inefficient to flatten cusps.
- Resonances between DM particles and density waves of galactic gas plays a crucial role to flatten out the central cusp.
- Cusp-to-Core transformation naturally reproduces the $\mu_{0\mathrm{D}}$ relation.
  - Estimation of transformation redshift