Gas inflow and outflow に伴う dark matter haloのcusp-core遷移過程

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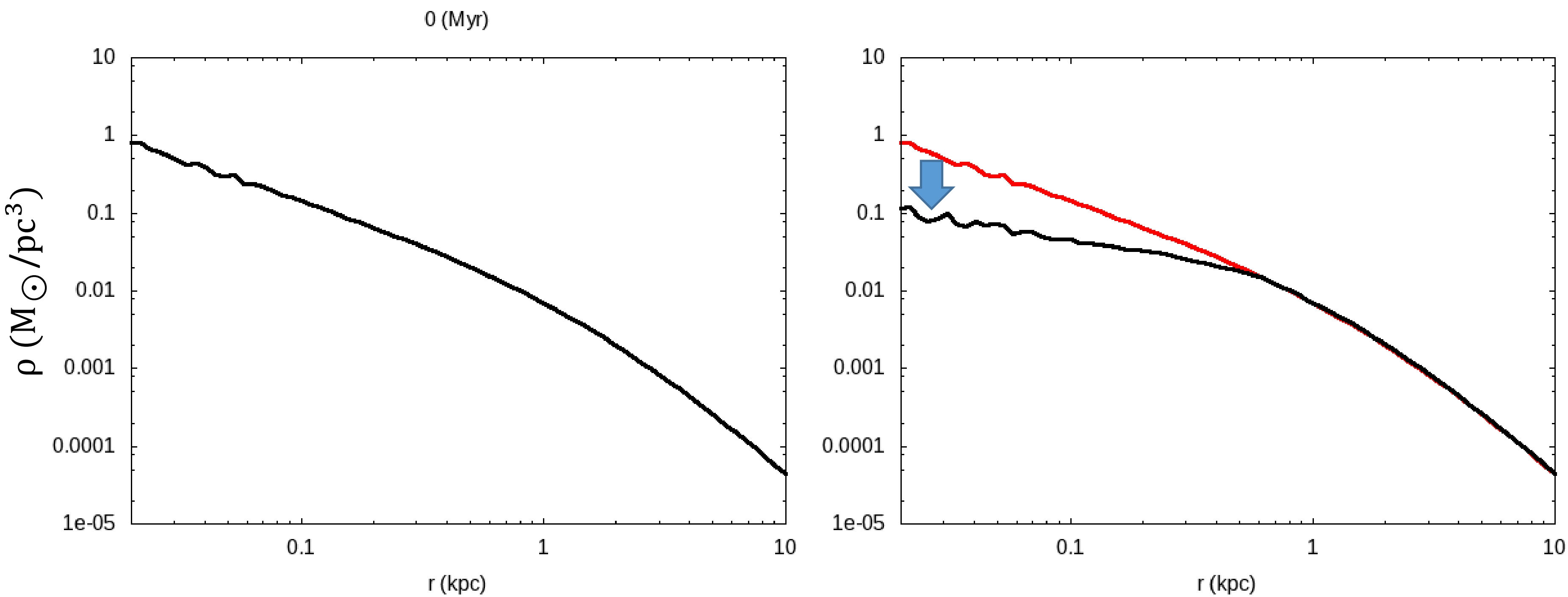
Galaxy-IGM workshops 2018, 8/8～10

Summary

- We suggest that star-forming galaxies with gas accretions and outflows are possibly on the sight of the cusp-core transition of DMH.

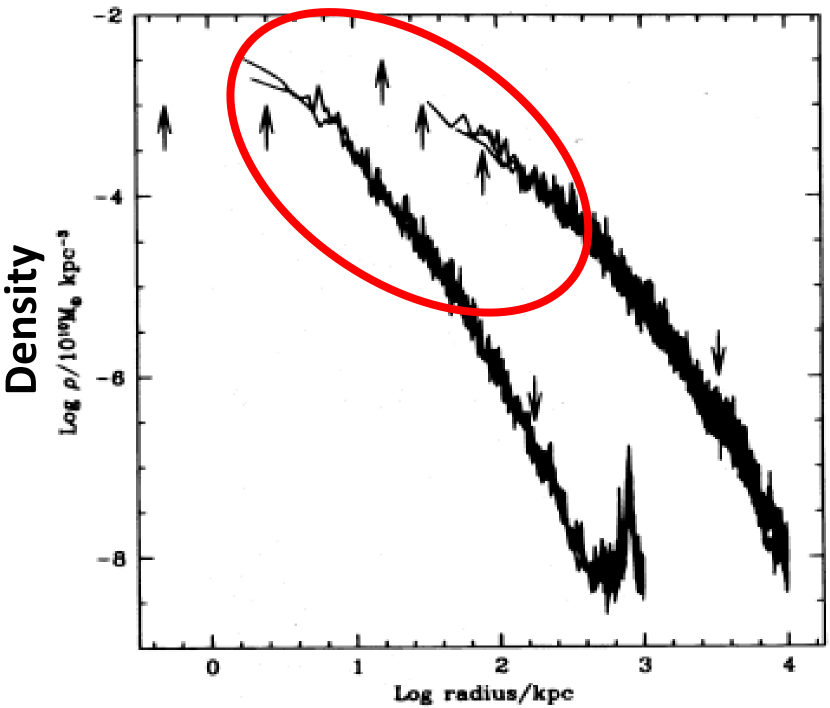


Introduction

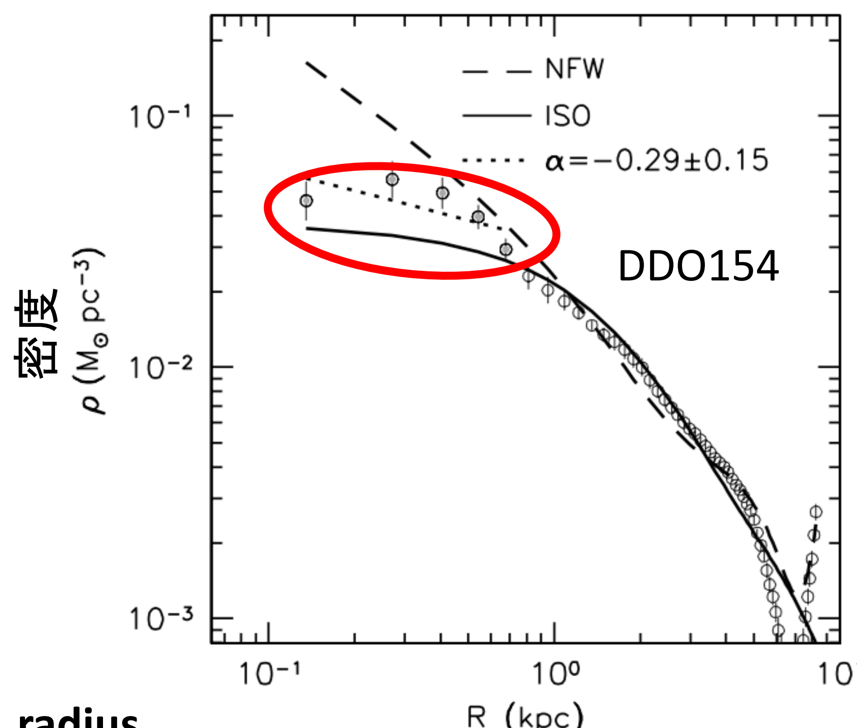
The Cusp-Core problem

Cosmological *N*-body simulations show that the density profile of dark matter halo (DMH) is diverge at the center. However, observed DMH in nearby dwarf galaxies has revealed almost constant density structures at their centers. (c.f. Burkert 1995)

cusp



core



radius

Navarro et al. (1996)

Oh et al. (2011)

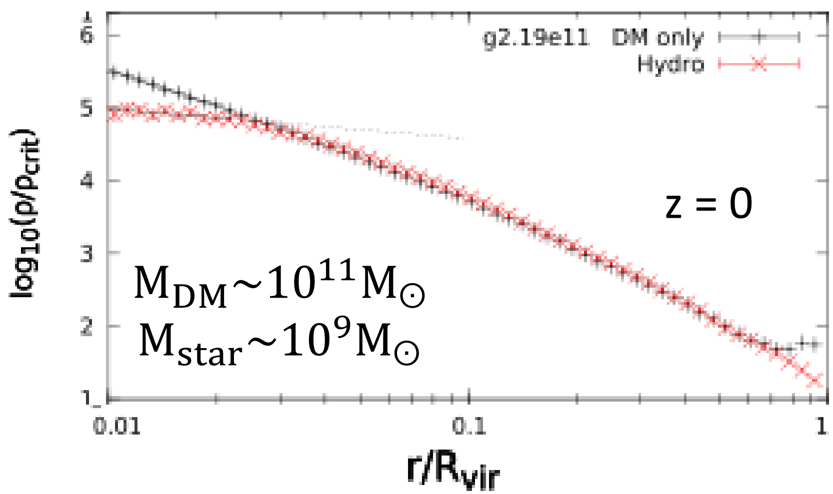
Cosmological hydro. simulation

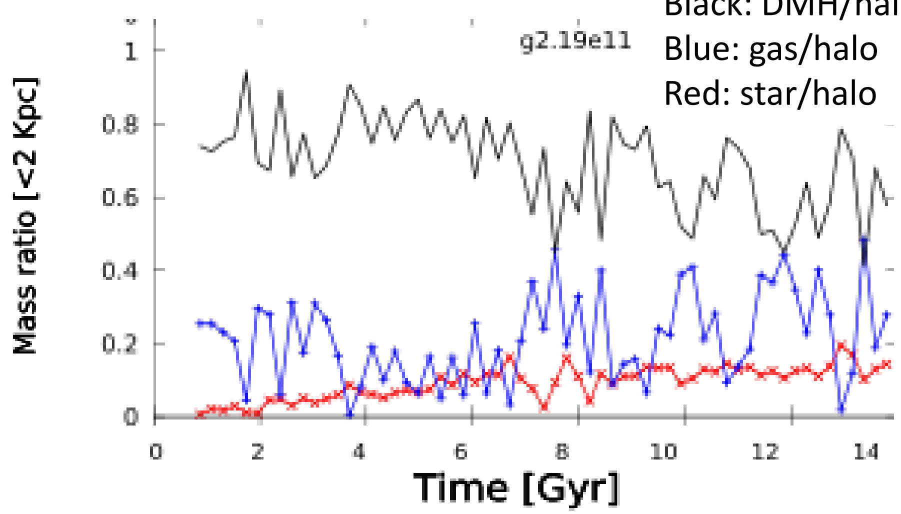
Edouard et al. 2016

N-body + SPH, zoom in simulation

Box size; $60^3\ h^{-1}$Mpc

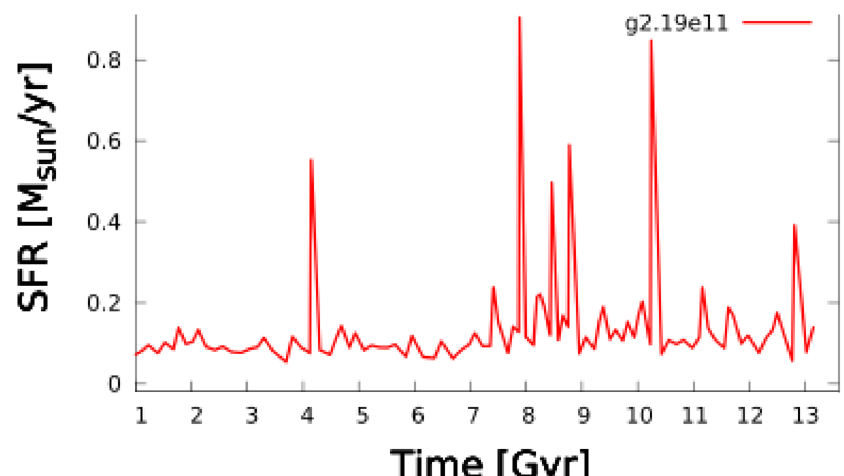
No. of particles n_{200}	No. of DM particles n_{DM}	No. of star particles n_{star}	DM particle mass m_{DM}	Virial mass $(M_{200}/M_\odot)$	Stellar mass $(M_{star}/M_\odot)$	$z = 0$ SFR $(M_\odot\ yr^{-1})$	Conv. rad.[a] (kpc)
920 447	557 247	113 958	2.169×10^5	1.31×10^{11}	9.27×10^8	8.2×10^{-2}	0.65





Black: DMH/halo
Blue: gas/halo
Red: star/halo

threshold of star forming
T<15,000 and $n>10.3cm^{-3}$



- DMH profile turns into core from cusp.
- Gas flows in and out recursively.
- Star formation is periodically.

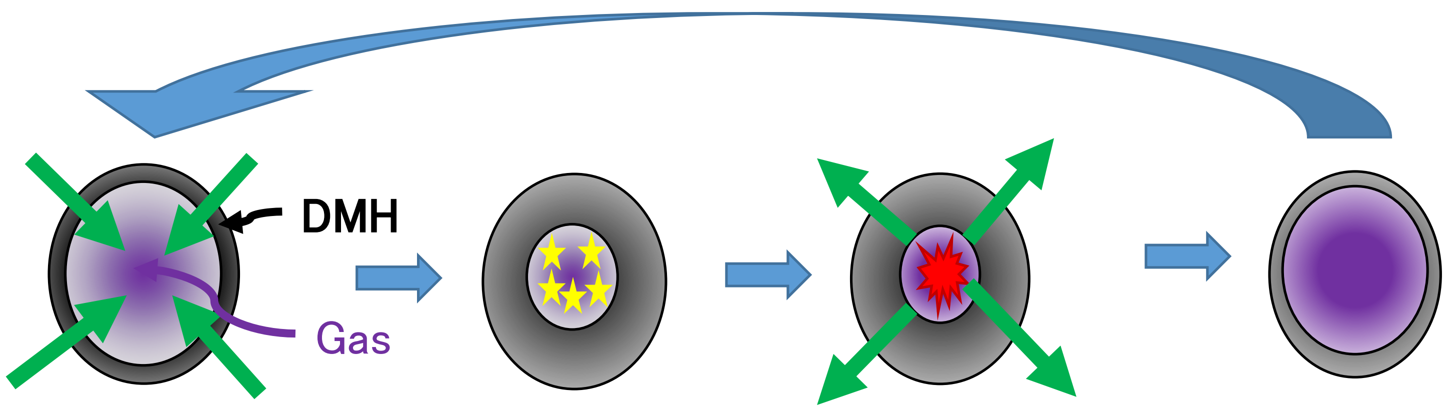
Model: recursive accretions and outflows

In our model, we consider recursive gas accretion and outflow driven by supernova (SN) feedback in starburst galaxies.

(Ogiya & Mori 2014a, b)

The galactic wind driven by supernova feedback expands into inter galactic space. The outflows loses energy by radiative cooling, and then falls back toward the galactic center. Subsequently, the starburst is enhanced again. This cycle of expansion and contraction of the interstellar gas leads to a recursive change in the gravitational potential.

Physical process



Gas accretion

Star formation

Gas outflow by SN

DMH density profile is changed by the Gas potential

Linear analysis

equation of motion of DMH particles $$\frac{\partial v_{ind}(r,t)}{\partial t} + v_0 \frac{\partial v_{ind}(r,t)}{\partial r} = -\frac{\partial \Phi_{ex}(r,t)}{\partial r}$$

v_0:initial speed

feedback from gas potential $$-\frac{\partial \Phi_{ex}(r,t)}{\partial r} = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} C_{n,m} \exp(\imath[mkr - n\Omega t])$$

Induced velocity of DMH particles by the forced gas oscillations

$$v_{ind}(r,t) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \frac{\imath C_{n,m}}{\boxed{mkv_0 - n\Omega}} \{\exp[\imath mk(r - v_0 t)] - \exp[\imath(mkr - n\Omega t)]\}$$

$C_{n,m}$:Amplitude, n, m:Fourier mode number , Ω:Angular frequency, k:wavenumber

- If v_0 satisfied the resonance condition $v_0 = \frac{n\Omega}{mk}$, v_{ind} takes the maximum.
- This increase of the kinetic energy of the DMH particles around the center of the DMH makes the cusp flatter.

Numerical simulation

Clutton-Brock (1972) , Clutton-Brock (1973) , Hernquist and Ostriker (1992)

<u>Self-Consistent Field (SCF) Method</u>

- basis expansion of density and potential by orthogonality basis function.
- free from the gravitational softening
- efficient computation on massively parallel computers by straightforward parallelization
- computational costs $\propto N \times (n_{max}+1) \times (l_{max}+1) \times (m_{max}+1)$;

N:Number of particles , n_{max} , l_{max} , m_{max} : number of expansion terms

Simulation model

Dark matter halo

$n_{max}=128$, $l_{max}=0$, $m_{max}=0$

- Created by MAGI (Miki and Umemura 2018)

$N = 16{,}777{,}216 \approx 10^7$ particles

NFW profile; Navarro et al. (1996)

Total DMH mass : $\mathrm{M_{DM}} = 10^9 \mathrm{M_\odot}$

Density profile : $\rho = \dfrac{\rho_s r_s^3}{r(r_s+r)^2}$

Scale density: ρ_s

Scale radius: $r_s = 2.0\mathrm{kpc}$

Gas distribution

Plummer profile; Plummer (1911)

$$\boldsymbol{a}(\boldsymbol{r}) = \frac{-GM_b r}{(r^2+r_b^2(t))^{3/2}} \frac{\boldsymbol{r}}{r}$$

Recursive change of the scale radius

Total gas mass: $\mathrm{M_b} = 0.01 M_{DM}$

Scale radius:

$$\mathrm{r_b} = 0.5[\mathrm{r_{b,max}} - \mathrm{r_{b,min}}] \times [1 + \cos(2\pi t/T + \varphi_0)] + \mathrm{r_{b,min}}$$

$\mathrm{r_{b,min}} = 0.04\mathrm{kpc}$, $\mathrm{r_{b,max}} = 10\mathrm{kpc}$

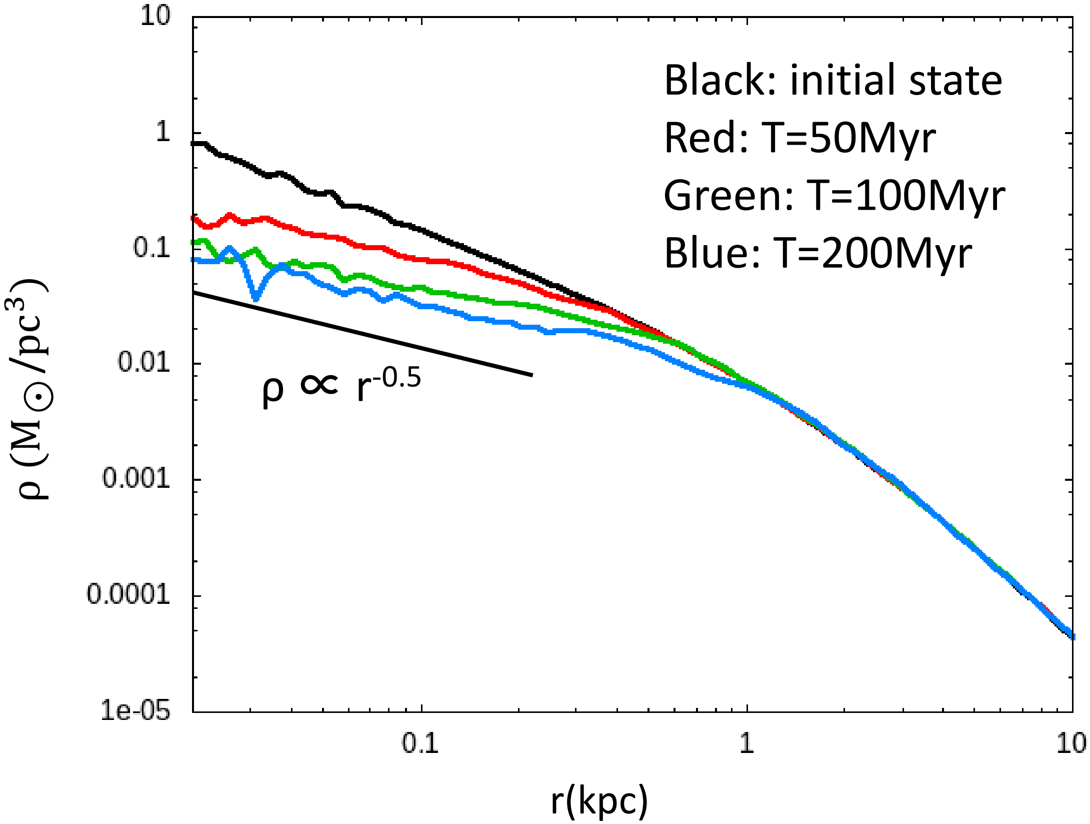
Recursive period :T

Oscillation 10 cycles

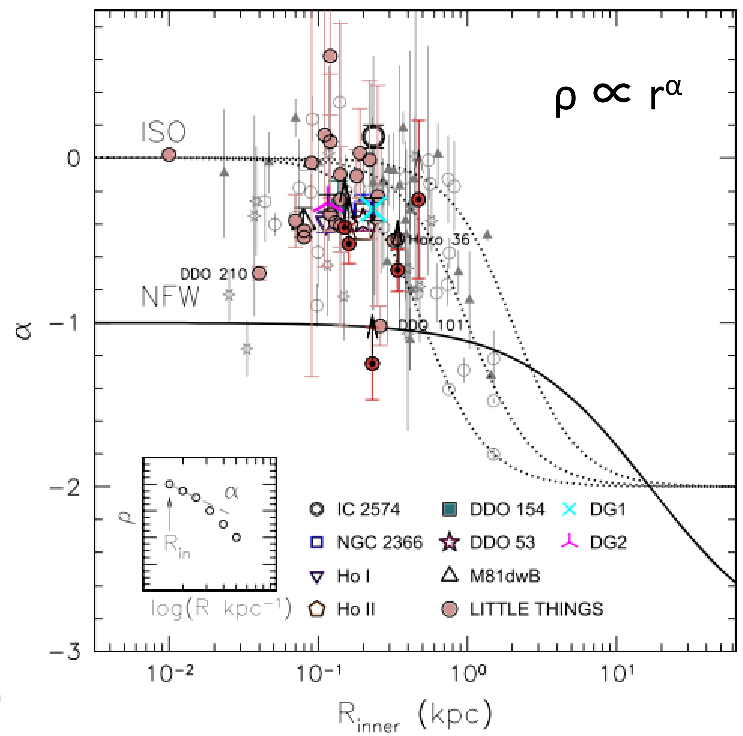
Results

Density profiles

quasi-equilibrium state using virial ratio



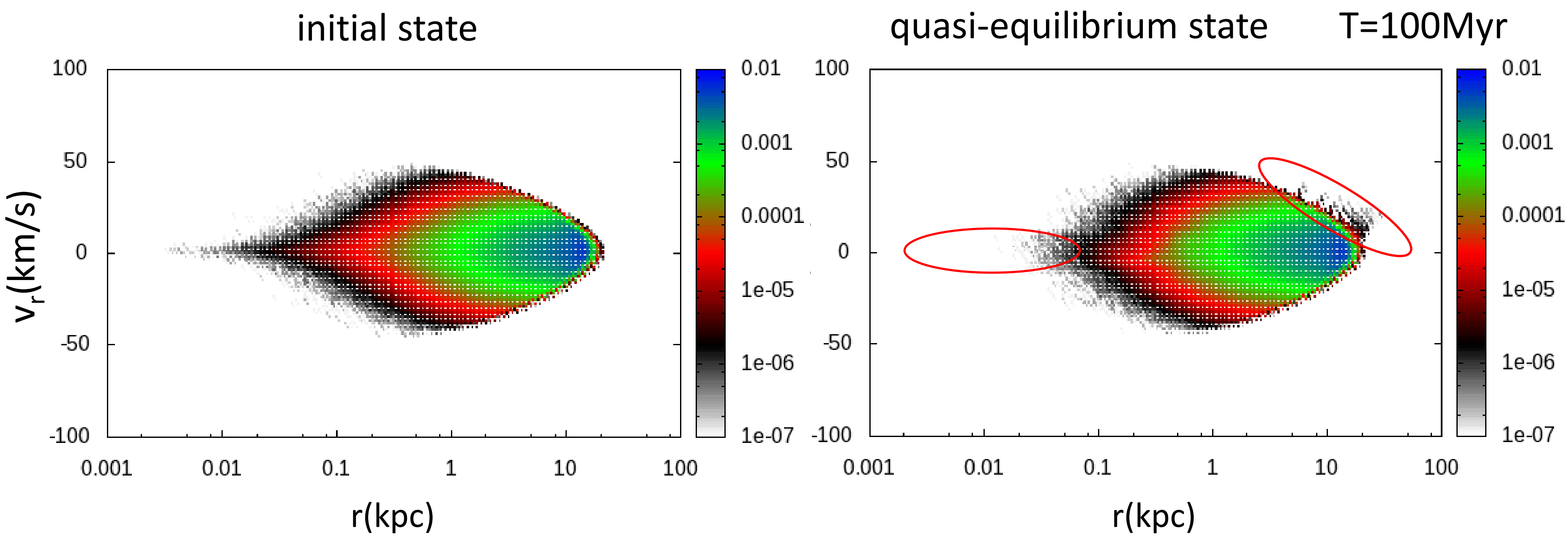
Observation of dwarf galaxies



Mean value: $\alpha = -0.34 \pm 0.24$

Oh et al. (2015)

Evolution of the phase space density



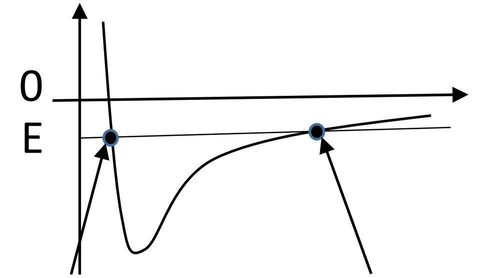
Escapers are less than 10^{-5} % of the total particles.

color label : Particles fraction

Eccentricity distributions

Eccentricity of DM particles derived by the effective potential.

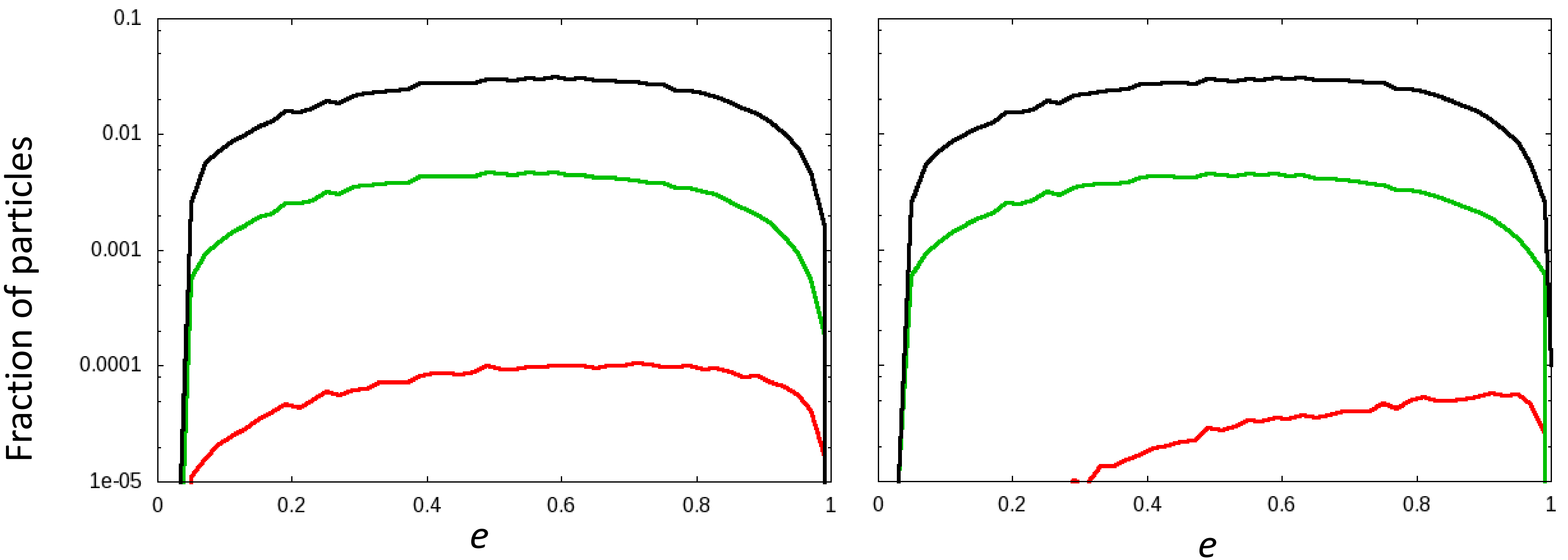
$$e = \frac{r_a - r_p}{r_a + r_p}$$



r_p: pericenter r_a: apocenter

initial state

quasi-equilibrium state T=100Myr



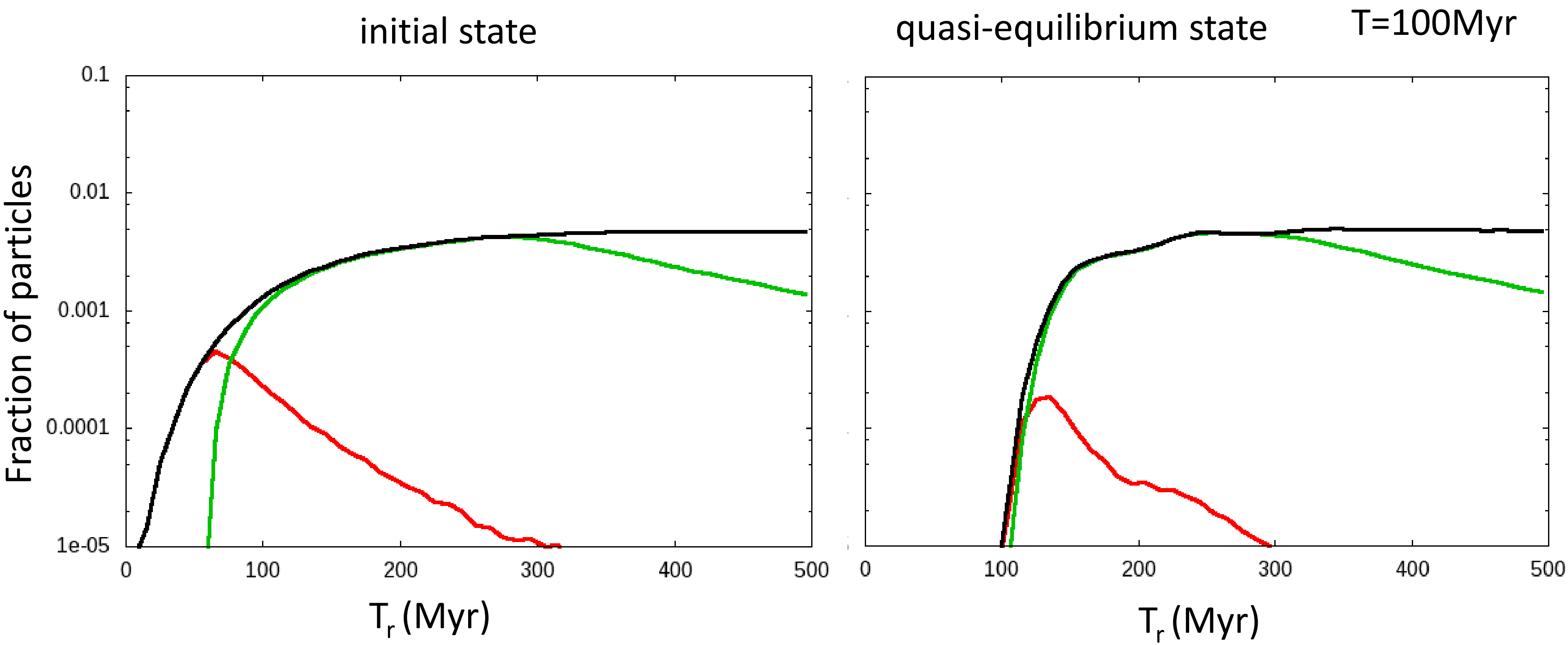
Red: r<0.2kpc

Green:0.2kpc<r<2kpc

Black: All particles

Radial period distributions

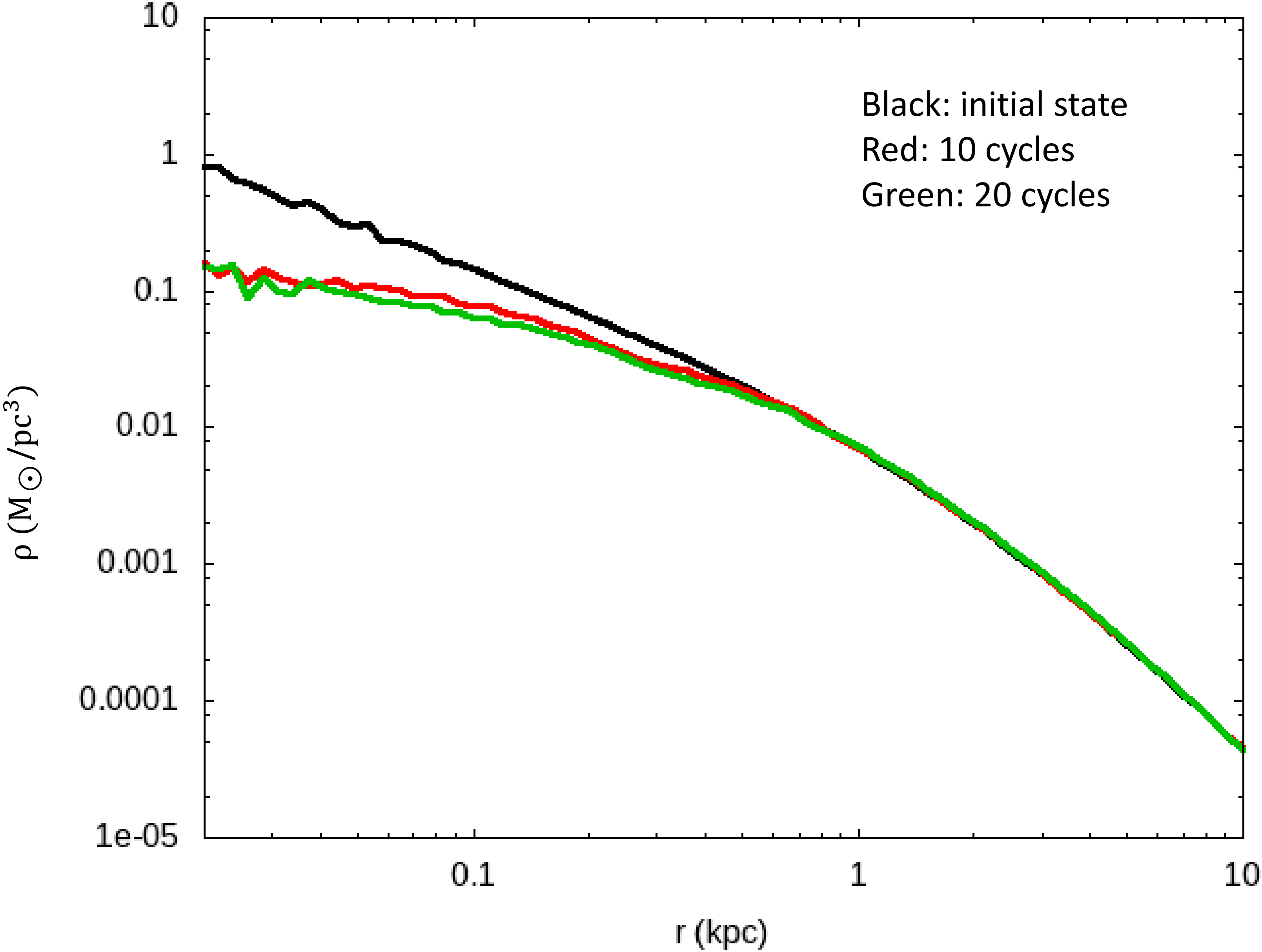
$$T_r = 2\int_{r_p}^{r_a} \frac{dr}{\sqrt{2[E-\Phi(r)] - L^2/r^2}}$$



Red: r<0.2kpc
Green:0.2kpc<r<2kpc
Black: All particles

Star forming state

T=100Myr



Summary

- We have investigated the dynamical response of the DMH due to the recursive change of the gas potential driven by the gas accretions and outflows in starburst galaxies.
- The resonance between the oscillation of the gas potential and the DM particle plays a vital role in the cusp-core transition.
- The resonant particles which effectively gained the radial velocity have the radially-enhanced orbit with the larger eccentricity.
- We suggest that star-forming galaxies with gas accretions and outflows are possibly on the sight of the cusp-core transition of DMH.