Characteristic Mass of Dark Matter Haloes for the Cusp-Core Transition

Michi Shinozaki, Masao Mori and Yuka Kaneda
(University of Tsukuba)

Abstract

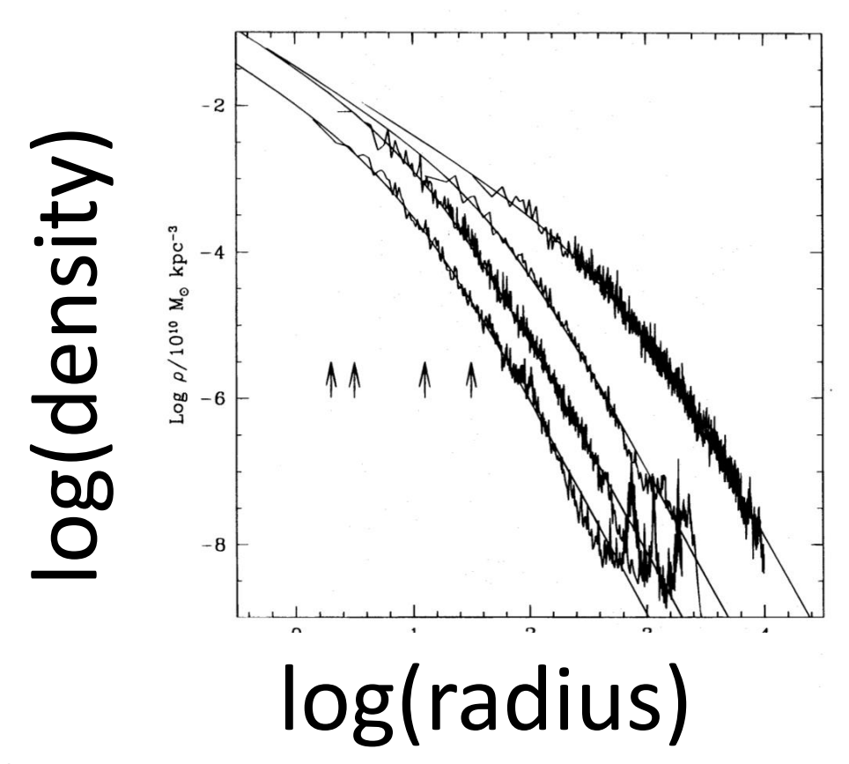
The dark matter haloes surrounding galaxies exhibit remarkable universal properties. Recently, Kaneda, Mori, and Otaki (2024) investigated the cusp-core problem of dark matter haloes by analysing their internal structures, derived from the ultra high resolution cosmological simulation by Ishiyama et al. (2021). The cusp-core problem refers to a discrepancy between theory and observation, wherein observations of dwarf galaxies often reveal flatter cores, despite simulations predicting a high density cusp at the centre. Their findings suggest that dark matter haloes associated with galaxies exceeding a mass of $10^{11} M_\odot$ generally exhibit a cusp structure, whereas less massive galaxies typically display a core structure. In this study, we present a model of the cusp-core transition in cold dark matter haloes, identifying the critical halo mass at which this transition occurs and examining the physical conditions under which supernova feedback primarily drives this transition.

Background: Ishiyama et al. 2021

Introduction

Cusp-core problem

- **CDM simulations: cusp**



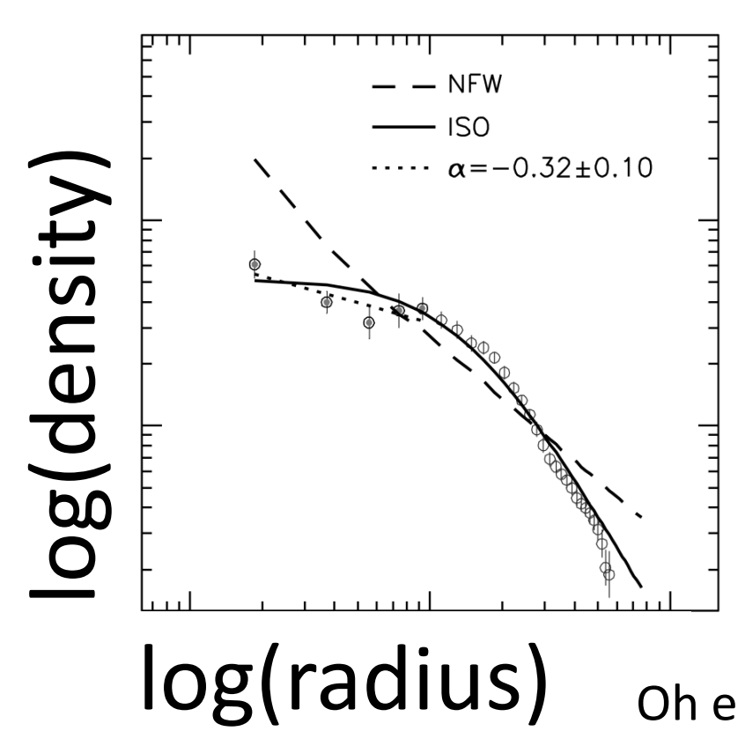
Navarro, Frenk & White(1996)

ex) NFW profile

$$\rho(r) = \frac{\rho_{\rm N} r_{\rm N}^3}{r(r+r_{\rm N})^2}$$

$r_{\rm N}$: scale radius, $\rho_{\rm N}$: scale density

- **dwarf galaxy observation: core**



Oh et al. (2011)

ex) Burkert profile

Burkert (1995)

$$\rho(r) = \frac{\rho_{\rm B} r_{\rm B}^3}{(r+r_{\rm B})(r^2+r_{\rm B}^2)}$$

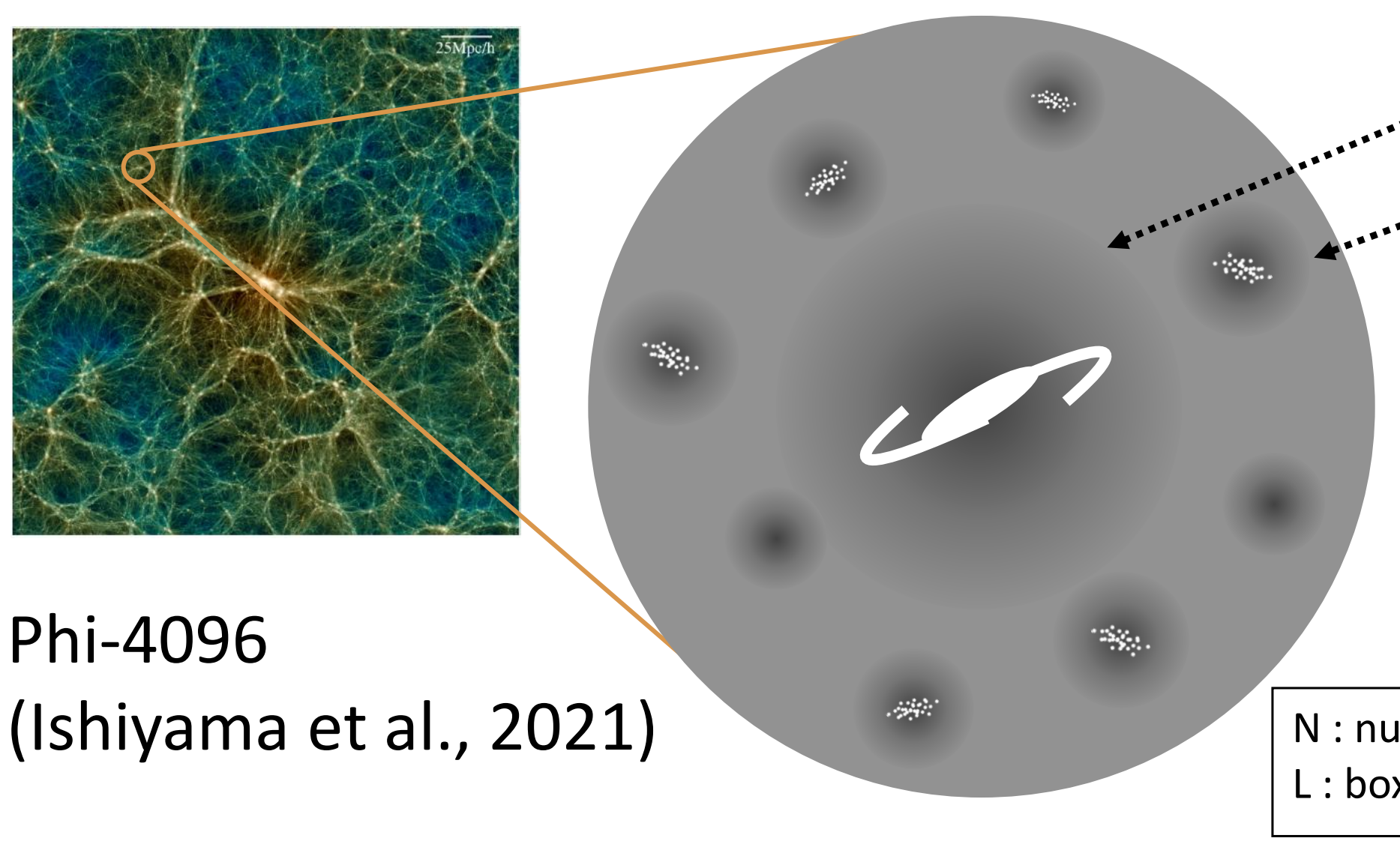
$r_{\rm B}$: core radius, $\rho_{\rm B}$: central density

Solutions

- Considering new candidates for dark matter particles that intrinsically produce cores
- Taking the effect of baryonic feedback processes into account in the CDM simulations to alter cusps to cores

Methods

Cosmological N-body simulation



Phi-4096
(Ishiyama et al., 2021)

27 Milky Way-like hosts

~300,000 Subhalos

$< 2r_{\rm vir,host}$ and $> 10^6 {\rm M}_\odot$

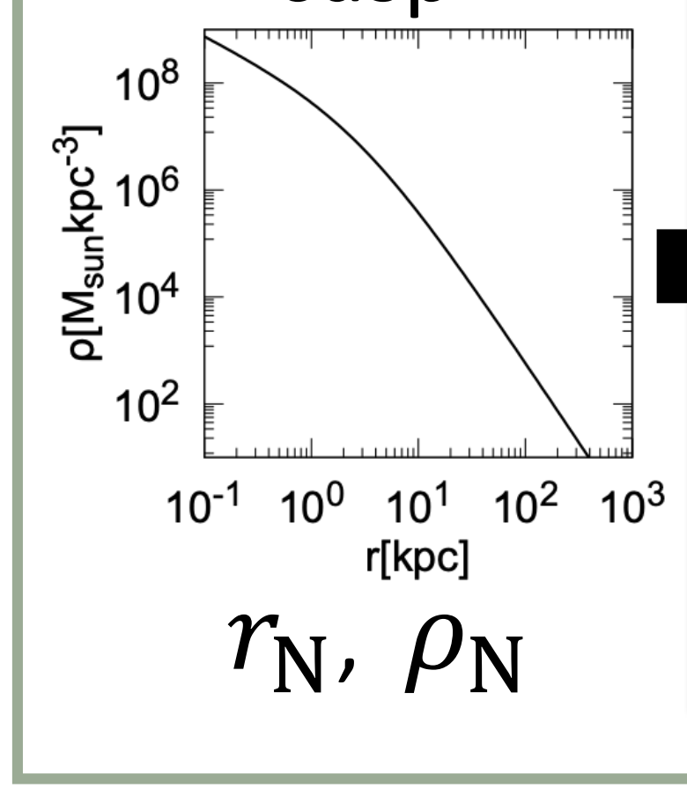
Properties of Phi-4096 ▼

Name	N	L $(h^{-1}{\rm Mpc})$	ε $(h^{-1}{\rm kpc})$	$m_{\rm p}$ $(h^{-1}M_\odot)$
Phi4096	4096^3	16.0	0.06	5.13×10^3

N : number of particle
L : box length
ϵ : softening length
m_p : particle mass resolution

Cusp-to-core transition model

cusp



$r_{\rm N}$, $\rho_{\rm N}$

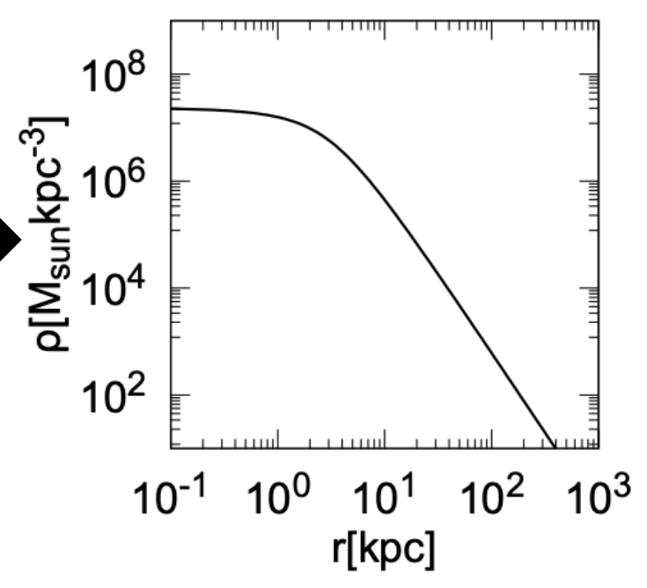
Transition model

1. only the inner region is affected
2. the total mass is conserved

$$r_{\rm B} = \eta(r_{\rm N}, \rho_{\rm N}) r_{\rm N}$$
$$\rho_{\rm B} = \xi(r_{\rm N}, \rho_{\rm N}) \rho_{\rm N}$$

uniquely determined

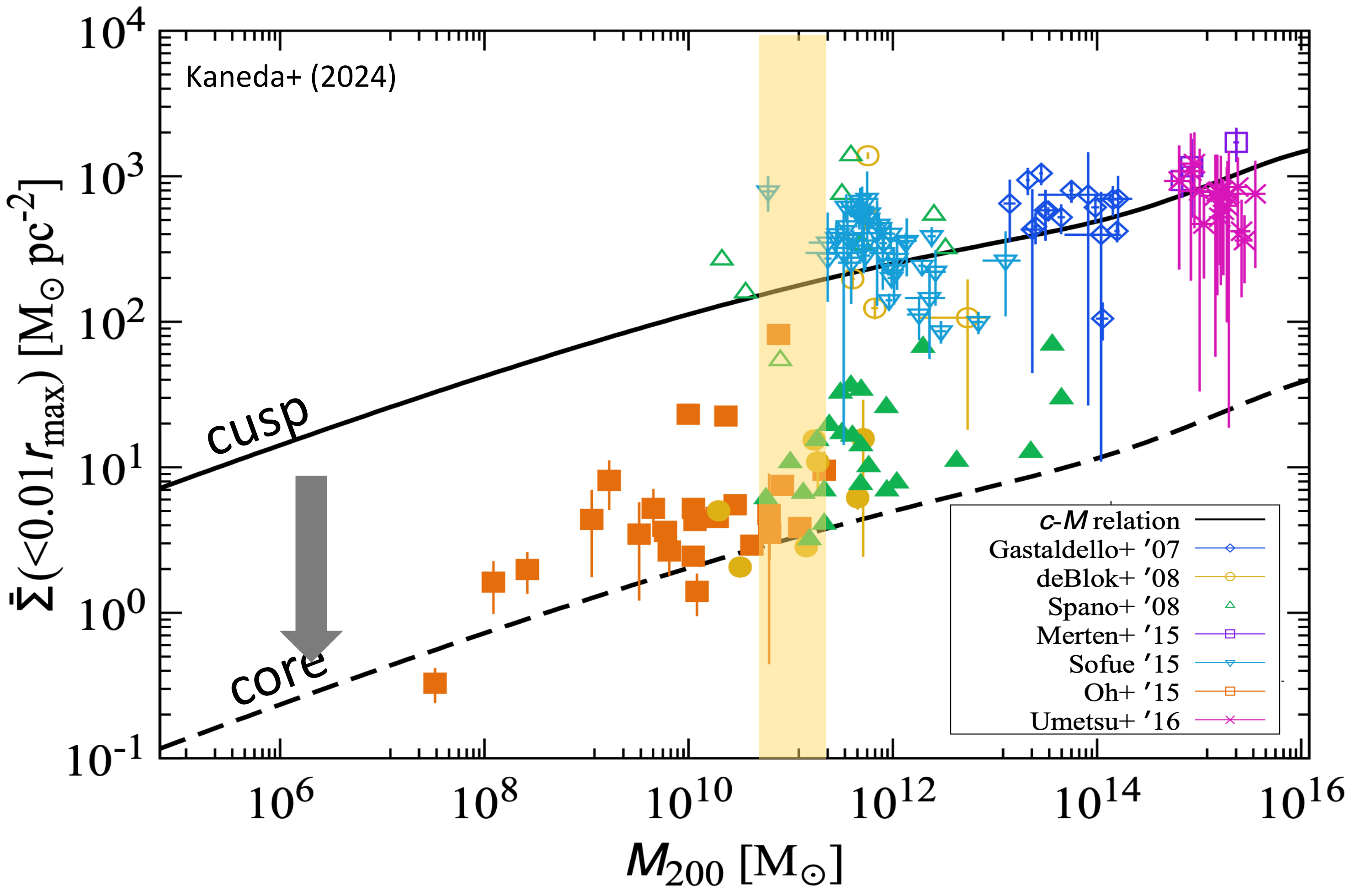
core



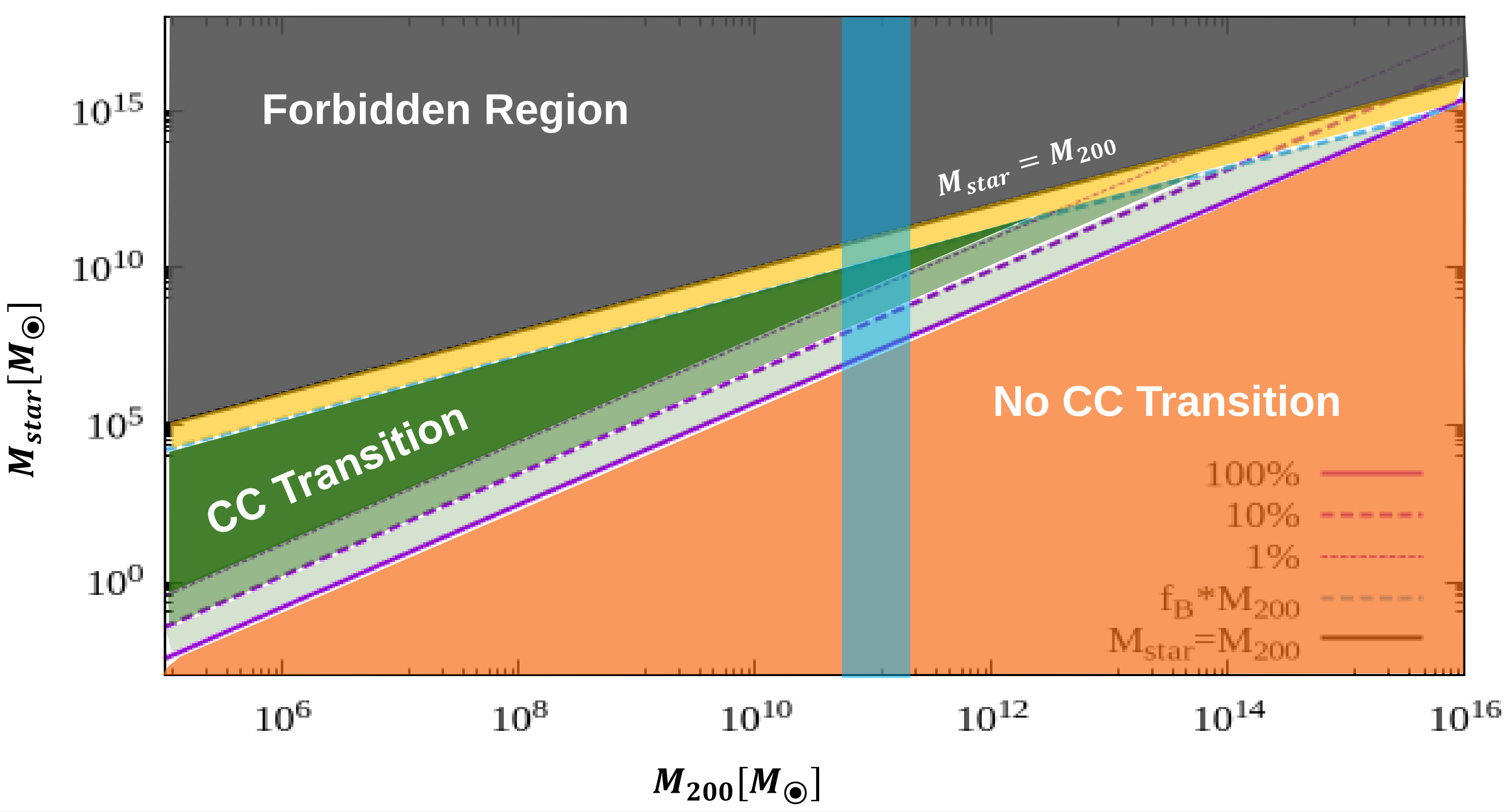
$r_{\rm B}$, $\rho_{\rm B}$

Results

Theoretical scaling relation with CC transition



Critical mass and SN energy transport efficiency



Physical conditions for the CC transition

$$\boldsymbol{M_* > M_{*,crit} = \frac{\Delta E}{\varepsilon\, \varepsilon_{51}\, f_{SN\,{\rm II}}}}$$

$\Delta E \equiv E_{BKT} - E_{NFW}$
E_{BKT} , E_{NFW} : *total energy*
ε : energy conversion efficiency
ε_{51} : SN II energy , 10^{51} *erg*
$f_{SN\,{\rm II}}$: Number of SN II per 1 $M_\odot$

- Chabrier's Initial Mass Function

$$f_{SN\,{\rm II}} = \int_{8\,M_\odot}^{100 M_\odot} \phi(m)dm \qquad \phi(m) \propto \begin{cases} exp\left[-\frac{(\log m - \log m_c)^2}{2\sigma^2}\right] & \text{for } m/M_\odot \le 1.0 \\ m^{-1.35\pm0.3} & \text{for } m/M_\odot > 1.0 \end{cases}$$

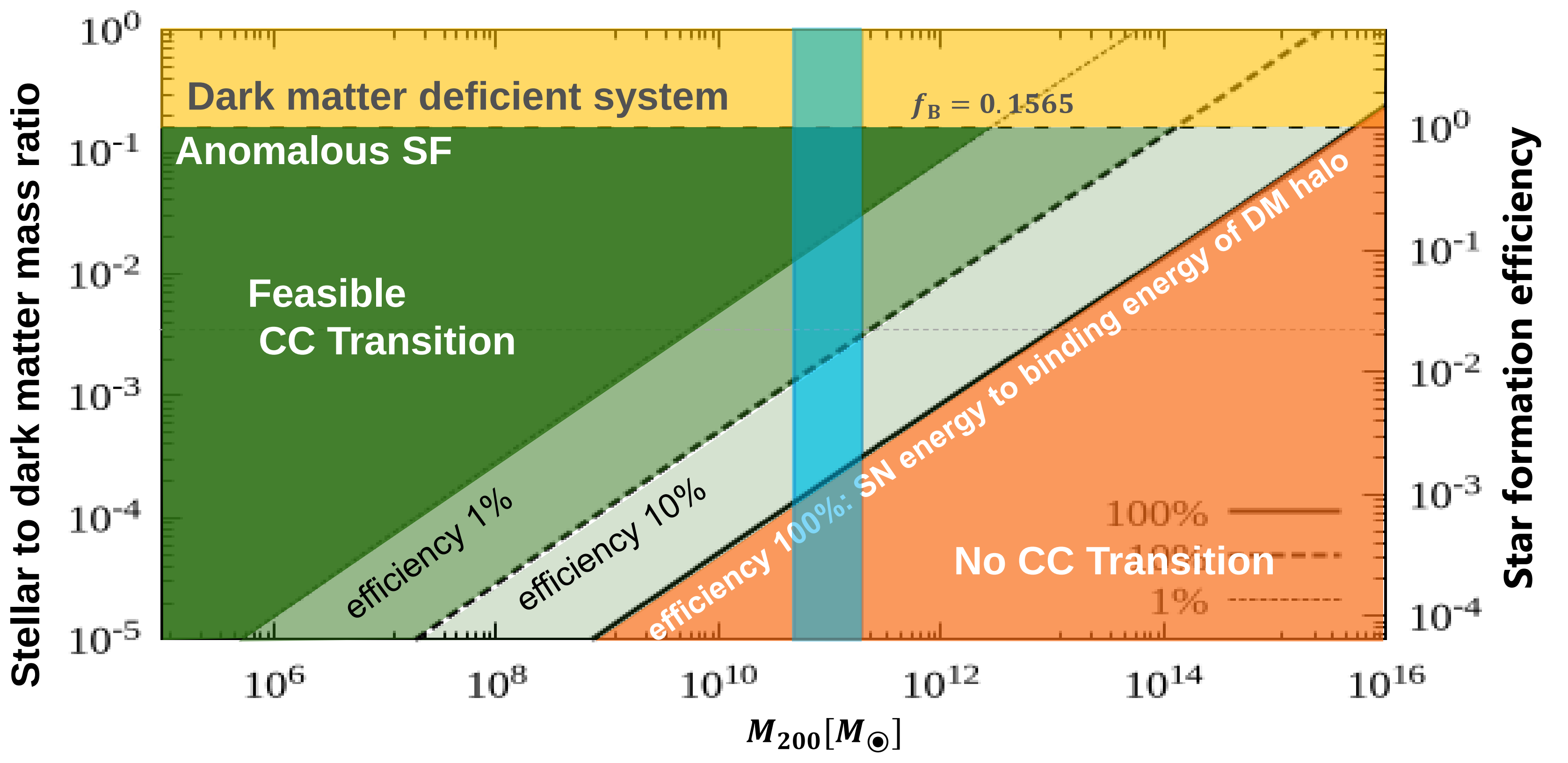
Chabrier+ (2005)

- Star Formation Efficiency

$$SFE = \frac{M_*}{f_B M_{200}}$$

$f_B = \Omega_B/\Omega_m = 0.1565$

Ω_B : *barion dencity parameter*
Ω_m : *mass dencity parameter*



Summary

- **The *c-M* relation is consistent with observations from dwarf galaxies to galaxy clusters.**
- **For cored haloes, a scaling relation based on the *c-M* relation and our cusp-to-core transition model is proposed.**
- **This scaling relation aligns well with observations, and the transition from cusp to core is suggested to occur at $M_{200} \sim 10^{11} M_\odot$.**
- **This critical mass depends on SF efficiency and the efficiency of SN feedback transfer to the binding energy of the DM halo.**

Refs: Burkert, 1995, ApJ, 447, L25; Ishiyama et al., 2021, ApJ, 506, 42; Kaneda, Mori & Otaki, 2024, PASJ, 76, 1026; Navarro, Frenk & White, 1996, ApJ, 462, 563; Oh et al., 2011, AJ, 142, 24