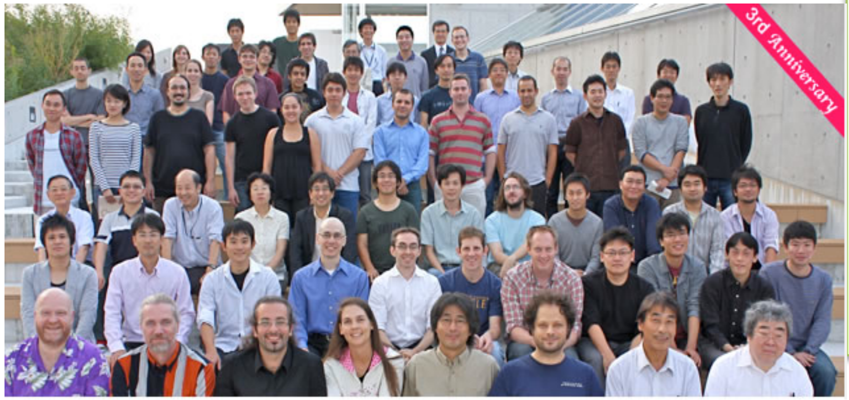
keV-mass sterile neutrino dark matter and the structure of galactic halos



Ayuki Kamada , Japan

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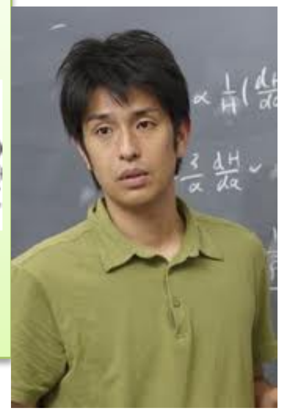
In collaboration with Naoki Yoshida



Big Earthquake hit Japan 11 March

Big Earthquake hit Japan 11 March

NOT RADIATION-DOMINANT PLEASE BELIEVE IN OUR POWER

CONTENTS

1. Cold Dark Matter(CDM)

   v.s.

   Warm Dark Matter(WDM)
2. Sterile Neutrino as WDM
3. Small Scale Structure Formation

   with

   Non-themal Sterile Neutrino
4. Conclusion and prospects

Cold Dark Matter

v.s.

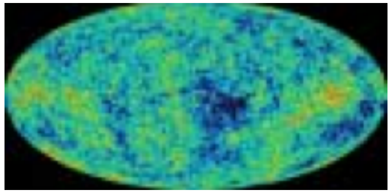
Warm Dark Matter

Cold Dark Matter(CDM) and Large Scale Structure

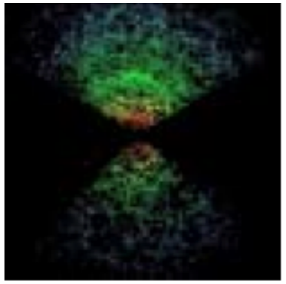
CDM : Non-Relativistic @ decoupling
Standard assumption : ΛCDM cosmology

scale

Gpc



Cosmic Microwave Background



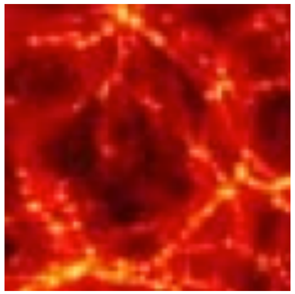
SDSS galaxies
Cluster abundance

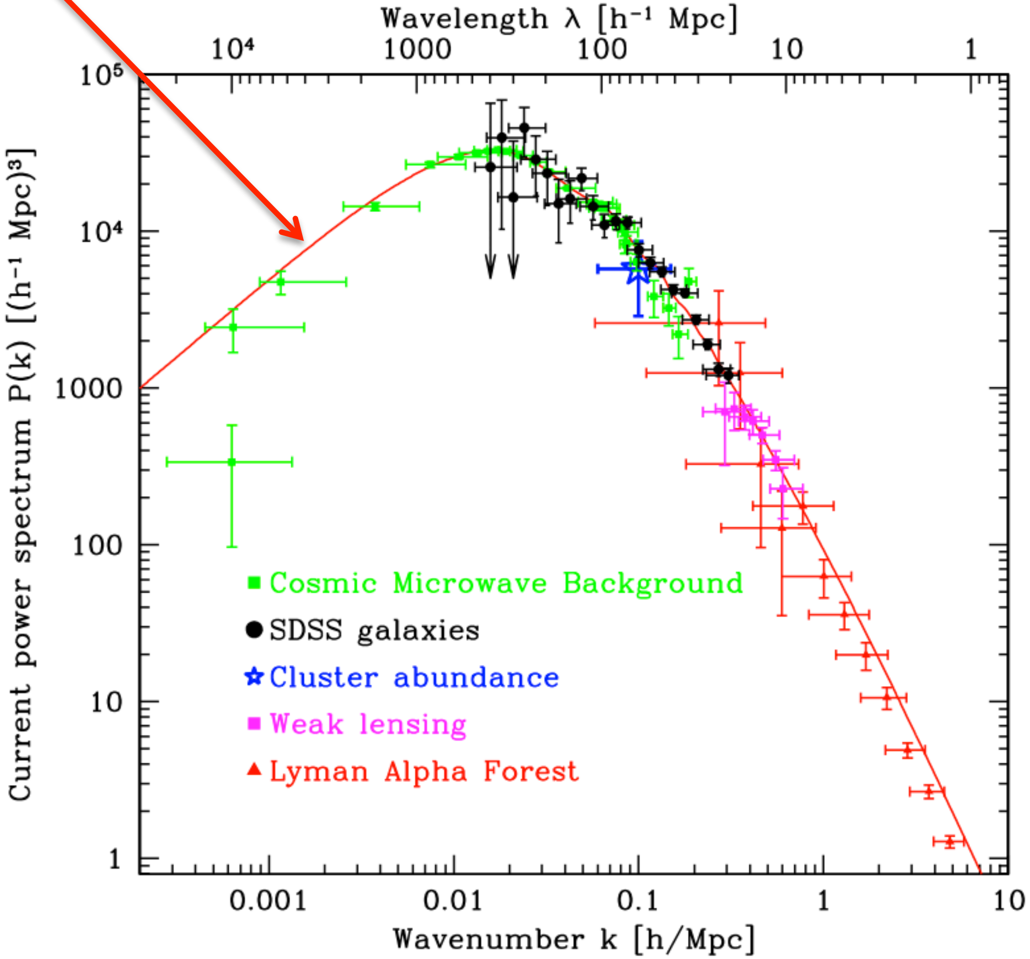
Weak lensing

Large Scale Structure (LSS)

Mpc

Lyman Alpha Forest





Tegmark et al. (2004)

CDM agrees with several observations of Large Scale Structure

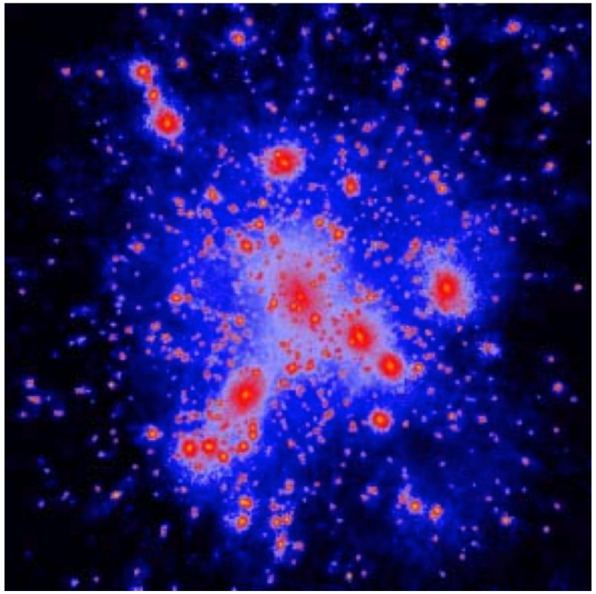
Cold Dark Matter(CDM) and Small Scale Structure

However…, **CDM** disagrees with several observations of Small Scale Structure

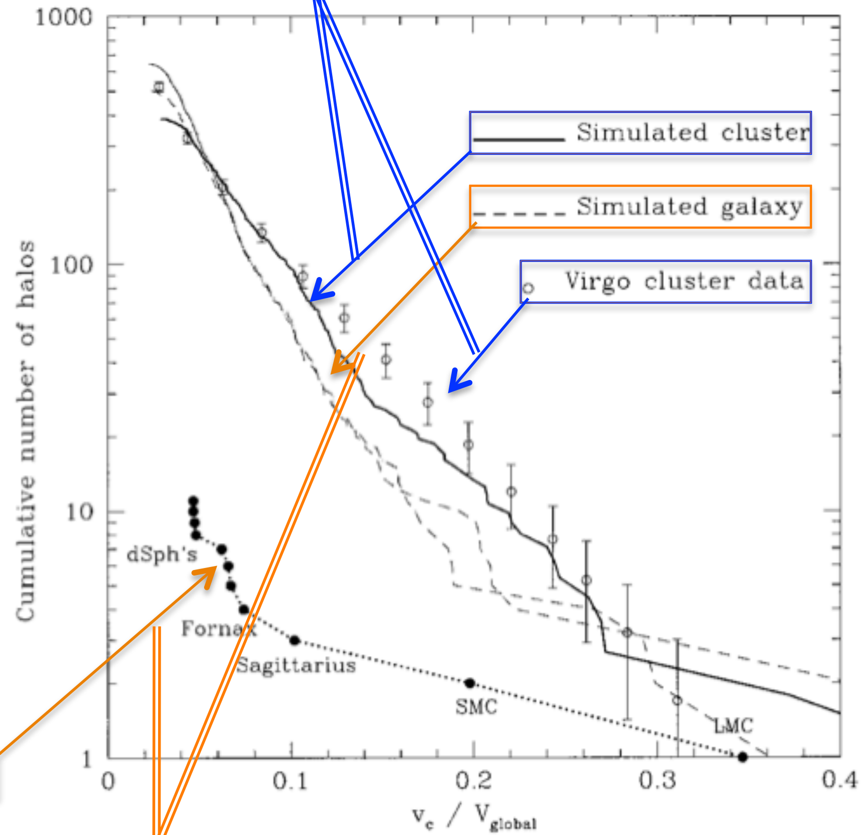
Small Scale Structure (SSS)

kpc

Missing Satellite Problem



Agreement in LSS



Satellites within the Milky Way's halo

Disagreement in SSS

Moore et (1999)

circular velocity

$$v = \sqrt{\frac{Gm}{r}}$$

Cold Dark Matter(CDM) and Small Scale Structure

Small Scale Structure (SSS)

kpc

Cuspy Halo Problem

Density Profile

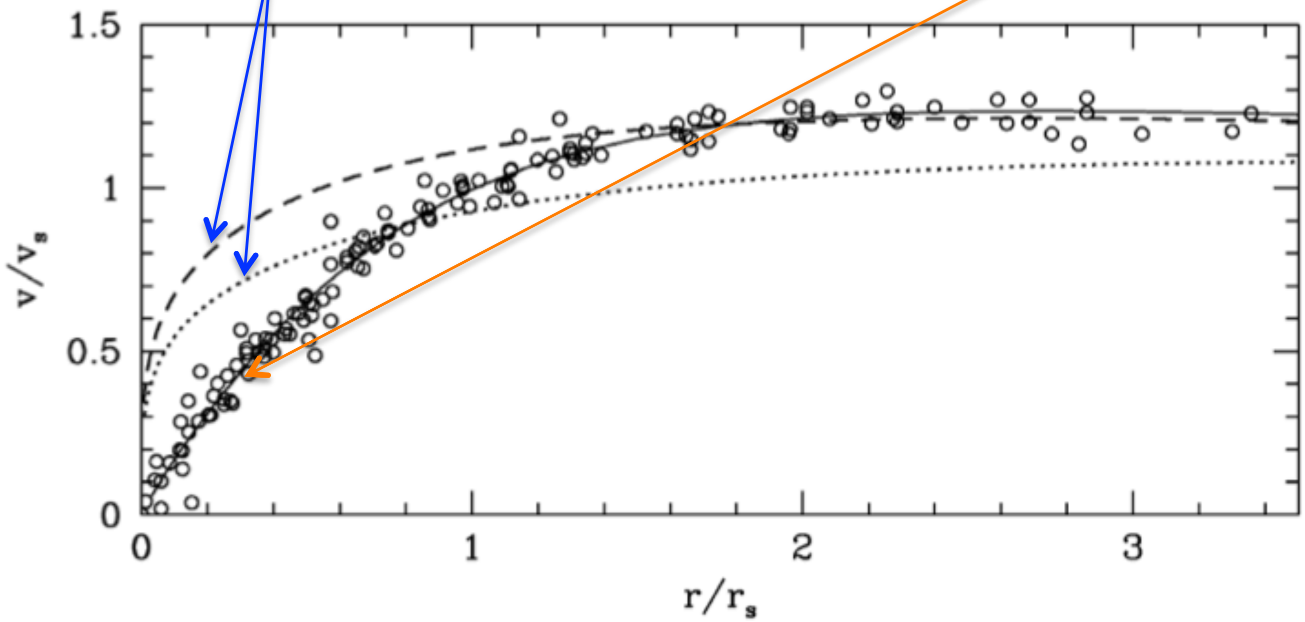
$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Simulated Profile

$\alpha = 1.5\ \beta = 3.0\ \gamma = 1.5$

Observed Profile

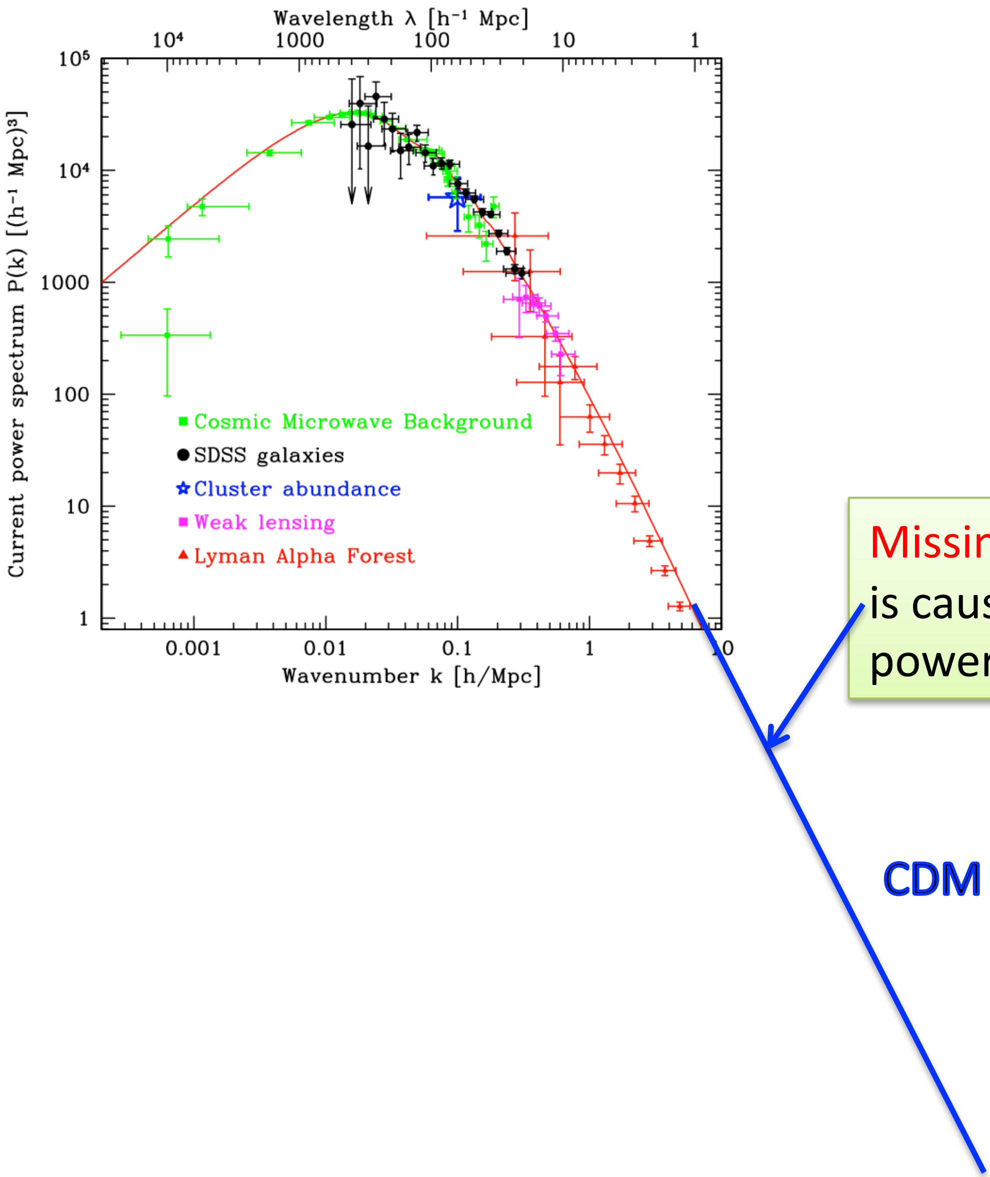
$\alpha = 2.0\ \beta = 3.0\ \gamma = 0.0$



Moore et (1999)

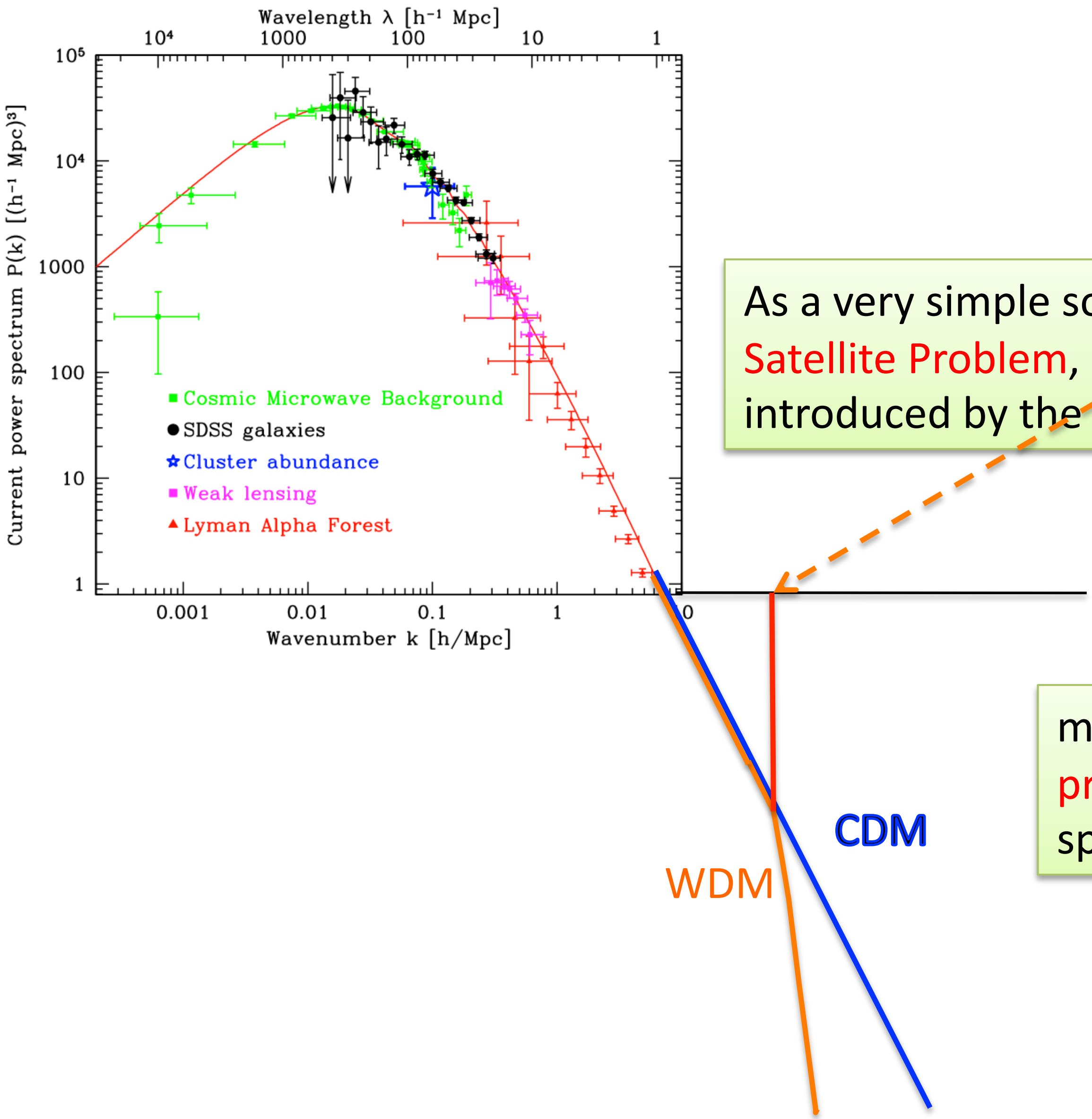
These disagreements in SSS are called **Small Scale Crisis**

How can we resolve the Small Scale Crisis?



Missing Satellite Problem
is caused by such a scale-independent power spectrum with **CDM**

How can we resolve the Small Scale Crisis?



As a very simple solution for Missing Satellite Problem, a cut-off scale may be introduced by the property of **Dark Matter**

WDM

may resolve the Cuspy Halo problem by its large phase space density

Linear Perturbation Theory

Boltzmann equation of Collision-less Dark Matter in Matter-Dominated era

$$\frac{\partial}{\partial t} f + \frac{\vec{p}}{a^2 m} \vec{\nabla}_{\vec{x}} f - m \vec{\nabla}_{\vec{x}} \phi \cdot \vec{\nabla}_{\vec{p}} f = 0$$

$$\Delta_{\vec{x}} \phi = \frac{4\pi G m}{a} \int \frac{d^3 p}{(2\pi)^3} f$$

Expanding around the homogeneous isotropic solution,

$$f(\vec{x}, \vec{p}, t) = f_0(p) + f_1(\vec{x}, \vec{p}, t) + \ldots$$

$$\phi(\vec{x}, t) = \phi_0(t) + \phi(\vec{x}, t) + \ldots$$

We get

$$\frac{\partial}{\partial t} f_1 + \frac{\vec{p}}{a^2 m} \vec{\nabla}_{\vec{x}} f_1 - m \vec{\nabla}_{\vec{x}} \phi_1 \cdot \vec{\nabla}_{\vec{p}} f_0 = 0$$

$$\Delta_{\vec{x}} \phi_1 = \frac{4\pi G m}{a} \int \frac{d^3 p}{(2\pi)^3} f_1$$

Mode coupling between
dark matter
momentum distribution
and
perturbation Fourier mode.

Linear Perturbation Theory

Integrating out momentum,

$$\frac{d^2}{dt^2}\tilde{\delta} + 2H\frac{d}{dt}\tilde{\delta} - (4\pi G\bar{\rho} - c_s^2\frac{\vec{k}^2}{a^2})\tilde{\delta} = 0$$

$$\tilde{\delta} \equiv \frac{\tilde{\delta\rho}}{\bar{\rho}}$$

Energy density perturbation

We get Jeans scale $k_J \equiv a\frac{(4\pi G\bar{\rho})^{\frac{1}{2}}}{c_s}$:k-dependent

from momentum distribution of Dark Matter

Note

Evolution of perturbation depend not only on Jeans scale(free steaming scale), but also on shape of dark matter momentum distribution

Sterile Neutrino

as

Warm Dark Matter

Motivation

-Astrophysics:
WDMs are solutions to
-overproduction of satellite galaxies
['missing satellites' problem]
-smooth cores of DM-dominated dwarf spheroidal
satellite (dSphs) galaxies

-Elementary Particle Physics:
sterile right-handed neutrinos are
the minimal extensions of Standard Model (SM)
to produce the left-handed neutrino mass
(by see-saw mechanism)
and Baryon assymetnry

Neutrino Hamiltonian

$$\mathscr{H}(p,T) = \begin{matrix} \\ \nu_a \\ \nu_s \end{matrix} \begin{matrix} \nu_a & \nu_s \\ \left(\begin{matrix} p + V(T) \\ y < H > \end{matrix}\right. & \left.\begin{matrix} y < H > \\ \sqrt{p^2 + M^2} \end{matrix}\right) \end{matrix}$$

$V(T)$: thermal potential

$< H >$: SM Higgs VEV $\sim$ 100GeV

↓ diagonalize!

$$U = \begin{matrix} \\ \nu \\ N \end{matrix} \begin{matrix} \nu_a & \nu_s \\ \left(\begin{matrix} \cos\theta \\ \sin\theta \end{matrix}\right. & \left.\begin{matrix} -\sin\theta \\ \cos\theta \end{matrix}\right) \end{matrix}$$

$$\mathscr{H}(p,T) = \frac{1}{2}[p + V(T) + \sqrt{p^2 + M^2}] \begin{matrix} \\ \nu \\ N \end{matrix} \begin{matrix} \nu & N \\ \left(\begin{matrix} 1 \\ 0 \end{matrix}\right. & \left.\begin{matrix} 0 \\ 1 \end{matrix}\right) \end{matrix} +$$

$$\frac{1}{2}\sqrt{[p + V(T) + \sqrt{p^2 + M^2}]^2 + 4[y < H >]^2} \begin{matrix} \\ \nu \\ N \end{matrix} \begin{matrix} \nu & N \\ \left(\begin{matrix} -1 \\ 0 \end{matrix}\right. & \left.\begin{matrix} 0 \\ 1 \end{matrix}\right) \end{matrix}$$

Neutrino Hamiltonian

$$\begin{cases} \text{p=0} \\ \text{V(T)=0} \\ \text{M} \gg y < H > \end{cases}$$

$$\downarrow$$

$$\mathscr{M} = \begin{matrix} & \nu & N \\ \begin{matrix} \nu \\ N \end{matrix} & \multicolumn{2}{c}{\begin{pmatrix} -\frac{[y<H>]^2}{M} & 0 \\ 0 & M \end{pmatrix}} \end{matrix} \qquad \theta = \frac{y < H >}{M}$$

'Super heavy' right-handed neutrino ⟷ 'Ultra light' left-handed neutrino

$$m_N \sim M \sim 10^{15}\text{GeV} \qquad y \sim 1 \qquad m_\nu \sim 10^{-2}\text{eV}$$

$$\theta \sim 10^{-13}$$

Sterile Neutrino

Can it be a (Cold) Dark Matter?
It cannot be. Because it's too massive and it interacts with SM particles too strongly (y∼1) , it has been produced in the heat bath and decayed in the very early Universe.

And, CDM is not what we are interested in.

We are interested in WDM, the mass of which is a few keV !

→ $y \sim 10^{-10}$

↙

Very Weakly interacting with SM particles

↓

Sterile Neutrino is Good Candidate of WDM !!

Production Mechanism

How 'sterile' neutrino was produced

↓ in the thermal history ?

Three 'Non-thermal' production mechanisms are considered.

1. Dodelsen & Widrow (DW) Mechanism :
via non-resonant neutrino oscillation

2. Shi & Fuller (SF) Mechanism :
via resonant neutrino oscillation

3. Singlet Higgs Decay :
via Singlet Higgs decay to sterile neutrino

DW Mechanism

via non-resonant neutrino oscillation

$$\text{heat bath} \rightarrow \nu_a \rightarrow \nu/N \rightarrow \nu_s$$

Thermal Production

Rate: $\Gamma \simeq \frac{7\pi}{24} G_F^2 T^4 p$

Oscillation

$$\begin{cases} p \gg M, V(T), y < H > \\ V(T) = c\Gamma, \quad c = \frac{4\sin^2 2\theta_W}{15\alpha} \end{cases}$$

Second Order Perturbation in heat bath $V(T) \propto G_F^2$

$$\mathscr{H}(p,T) = p + \begin{matrix} \\ \nu_a \\ \nu_s \end{matrix} \begin{matrix} \nu_a & \nu_s \\ \left(\begin{matrix} V(T) \\ y < H > \end{matrix} \right. & \left. \begin{matrix} y < H > \\ M^2/2p \end{matrix} \right) \end{matrix}$$

Mixing Angle: $\sin^2 2\theta = \frac{[y < H >]^2}{[y < H >]^2 + [V(T)/M + M/2]^2}$

S.Dodelson and L.M.Widrow, arXiv:astro-ph/9303287

SF Mechanism

via resonant neutrino oscillation

Assuming the lepton asymmetry

↓

First order perturbation is non-zero in heat bath !! $V(T) \propto G_F$
V(T) can be positive/negative large value.

↓

Mixing angle can be large.

X.Shi and G.M. Fuller, arXiv:astro-ph/9904041

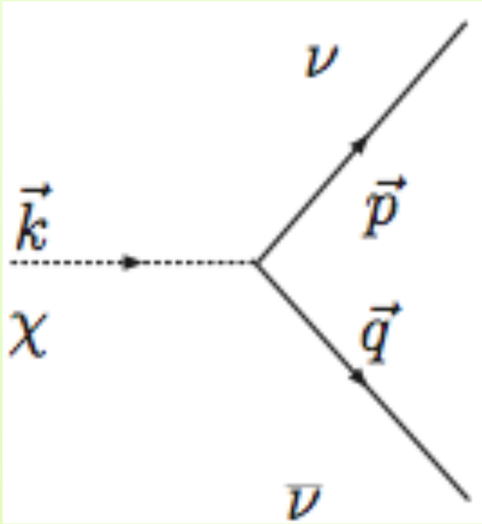
Singlet Higgs Decay

via Singlet Higgs decay to sterile neutrino

We introduce further a singlet Higgs to SM.
Its VEV (assuming ～100GeV) gives the mass (～a few keV) via Yukawa coupling ($Y \sim 10^{-8}$) to the added sterile right-handed neutrino.

↓

Thermal Singlet Higgs decays to sterile neutrino



D.Boyanovsky, arXiv:astro-ph/0807.0646

Small Scale Structure Formation
with
Sterile Neutrino

Distribution Function of Sterile Neutrino Produced In Each Mechanism

1. DW Mechanism → thermal distribution with suppression factor

$$f_0[y] = \frac{\beta}{e^y + 1}$$

(2. SF Mechanism → non-thermal distribution)

We simulate this one

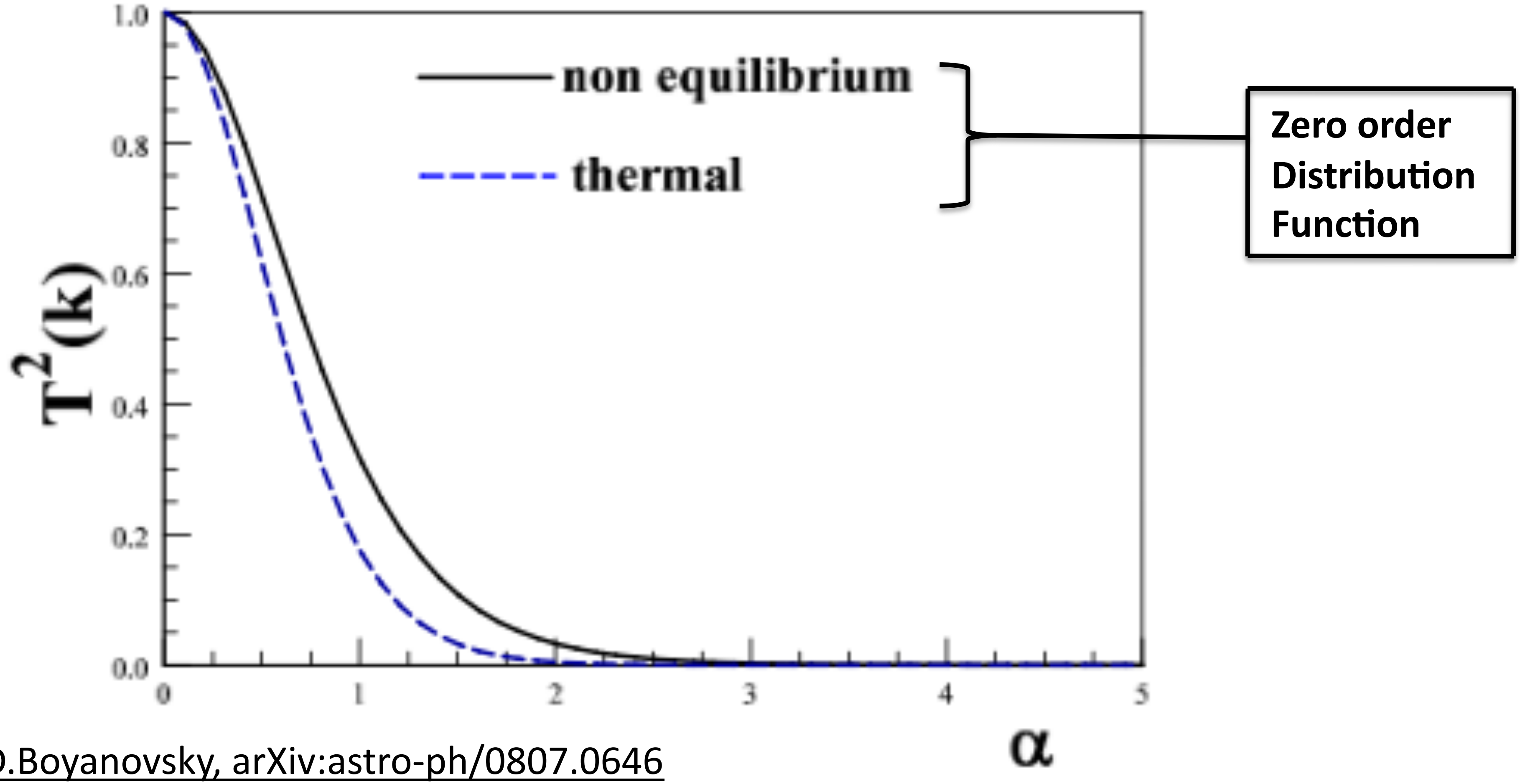
3. Singlet Higgs Decay → non-thermal distribution

$$f_0[y] \propto \frac{1}{y^{\frac{1}{2}}}$$

Extend to
Stau (NLSP) -> gravitino
Inflaton/moduli -> gravitino

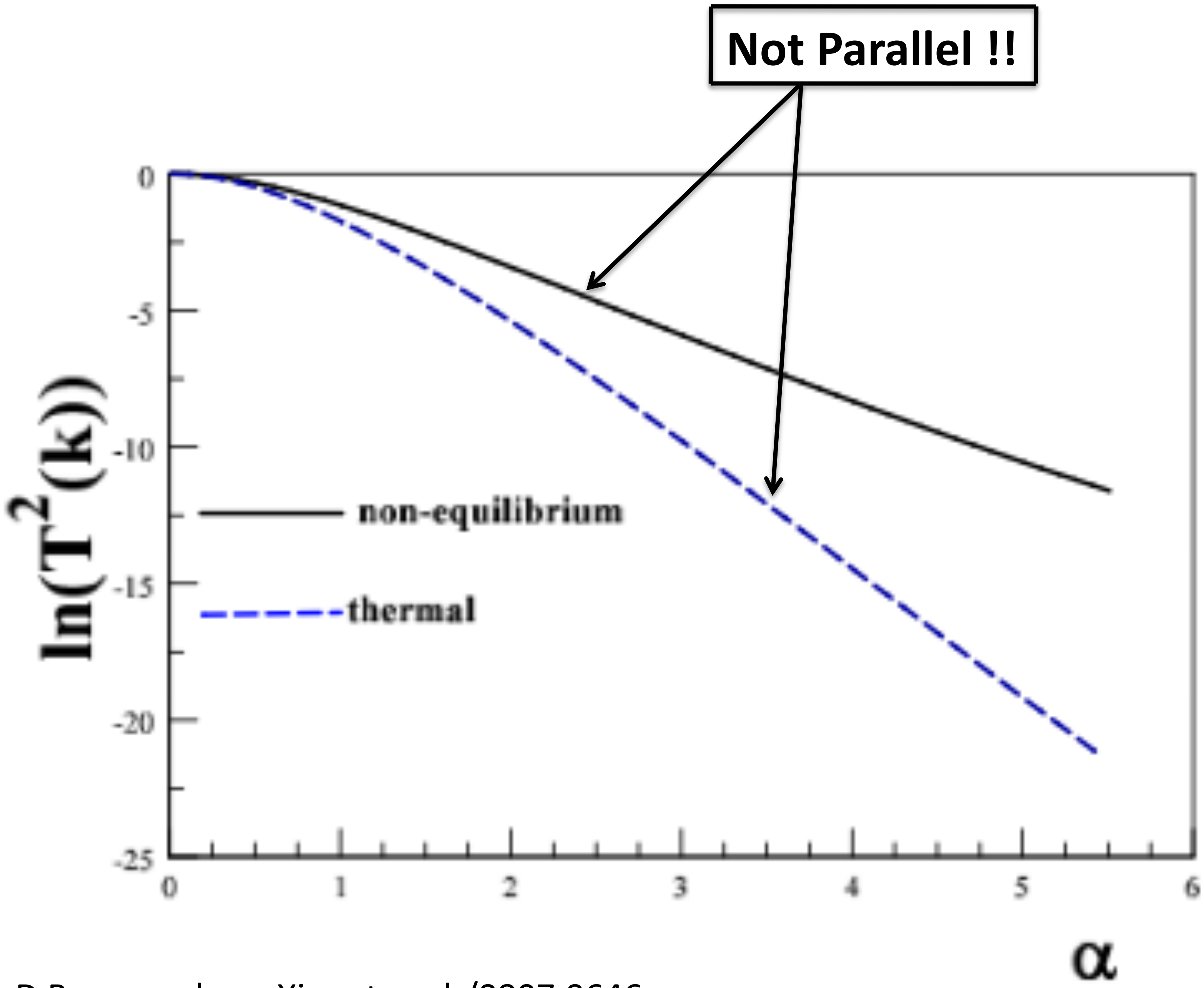
$$y = \frac{p_f(t)}{T(t)} = \frac{p}{T} \qquad p_f(t) = \frac{p}{a(t)} : \text{physical momentum}$$

Transfer Function $T(k)$



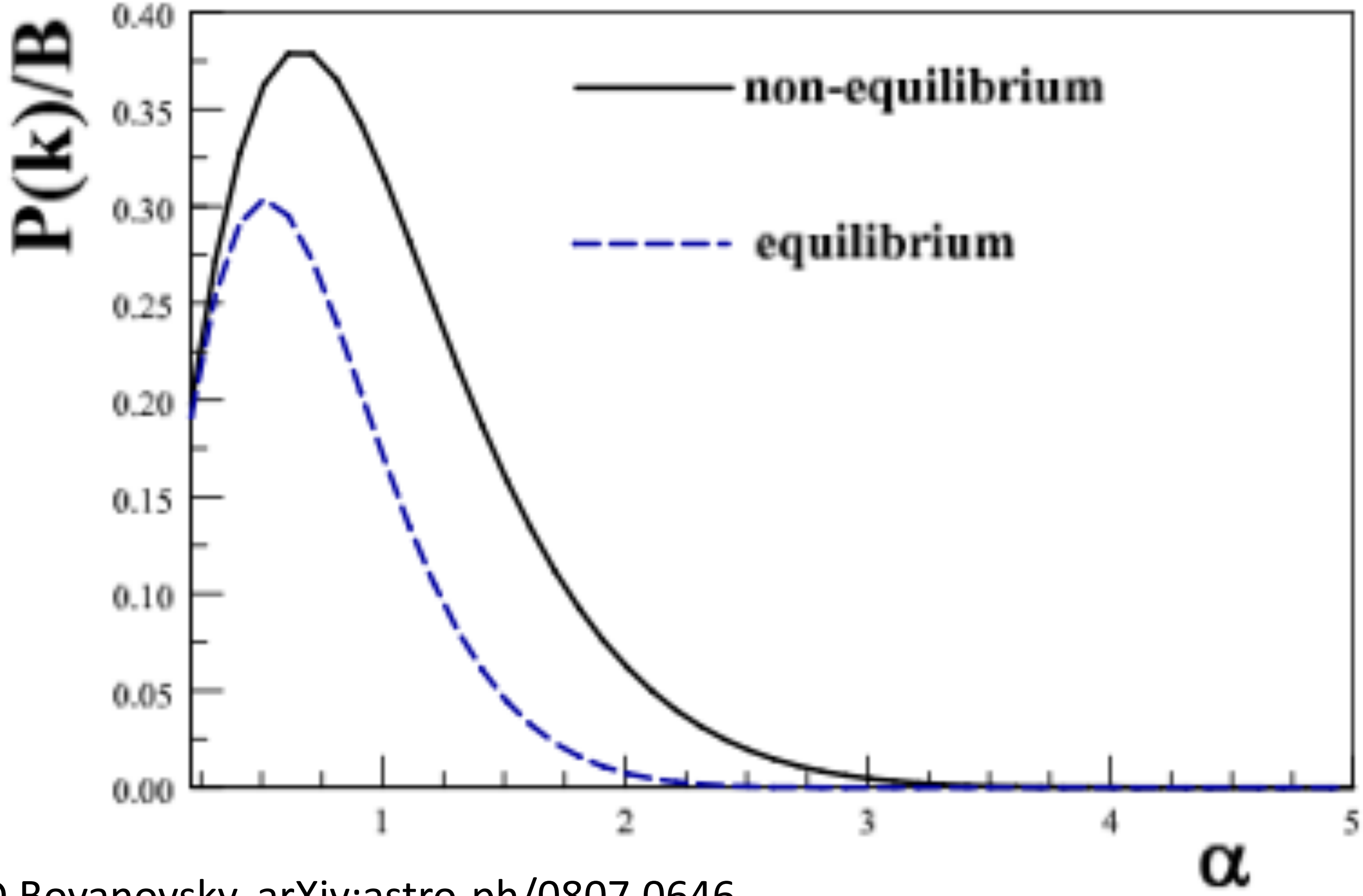
D.Boyanovsky, arXiv:astro-ph/0807.0646

$$\alpha = \left(\frac{6}{\bar{y}^2}\right)^{\frac{1}{2}} \frac{k}{k_{fs}(t_{eq})} \qquad \bar{y}^2 = \int_0^\infty dy y^4 \tilde{f}_0(y) \qquad \tilde{f}_0(y) = \frac{f_0(y)}{\int_0^\infty dy y^2 f_0(y)}$$



D.Boyanovsky, arXiv:astro-ph/0807.0646

Power Spectrum

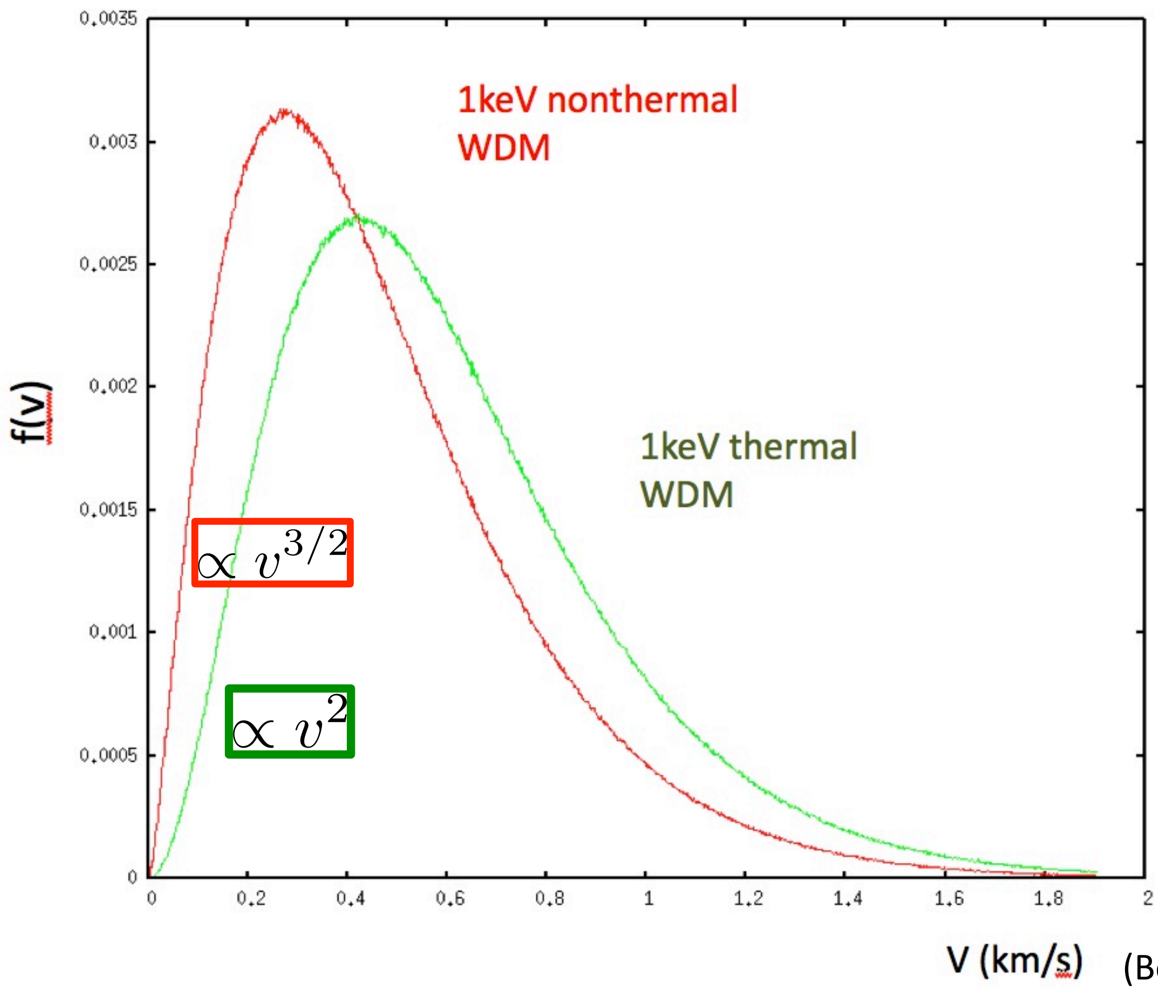


D.Boyanovsky, arXiv:astro-ph/0807.0646

$$P(k) = B\alpha^{n_s} T^2(k)$$

Linear Perturbation Theory

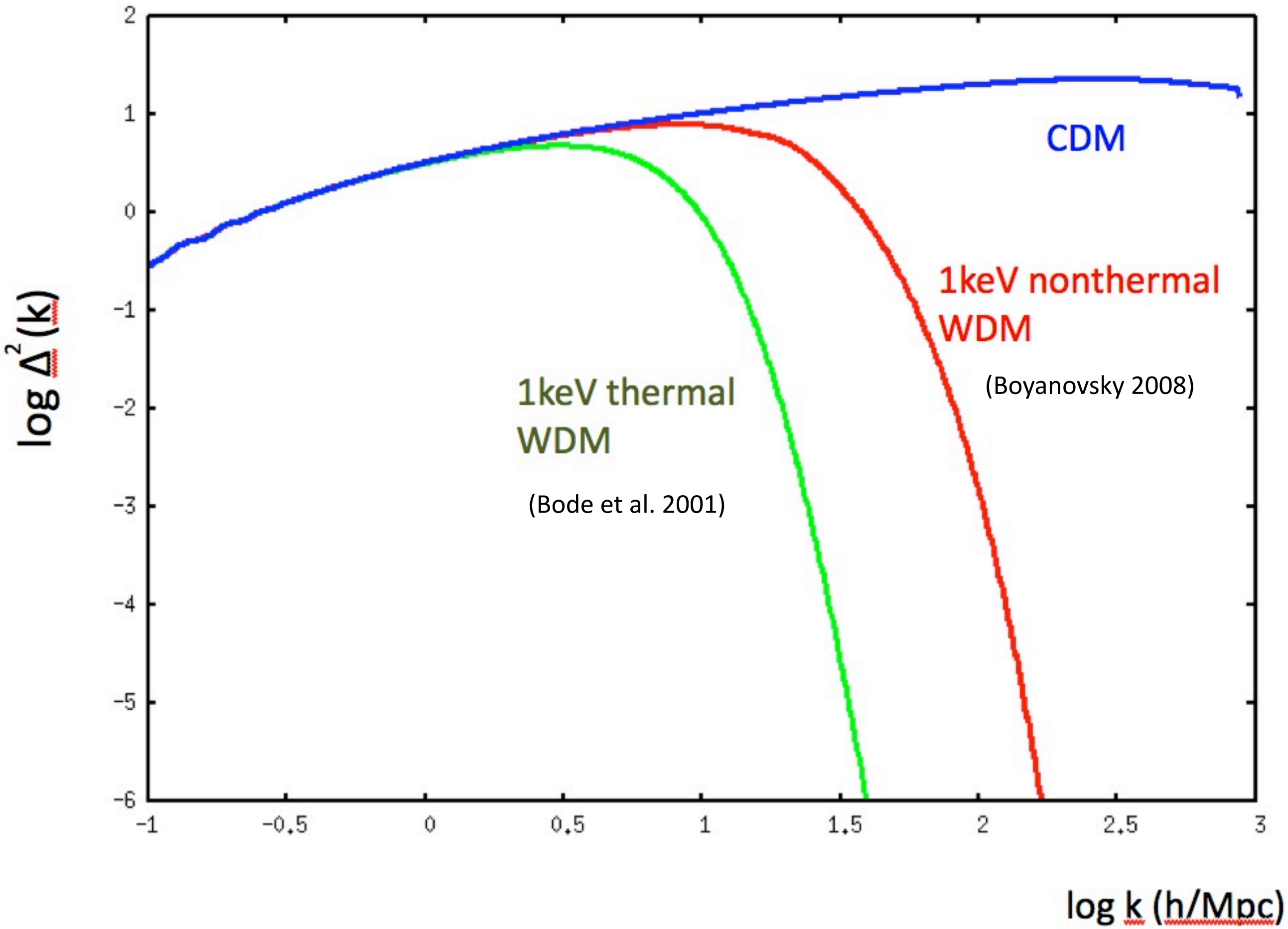
Velocity Distribution @ z=9



(Boyanovsky 2008)

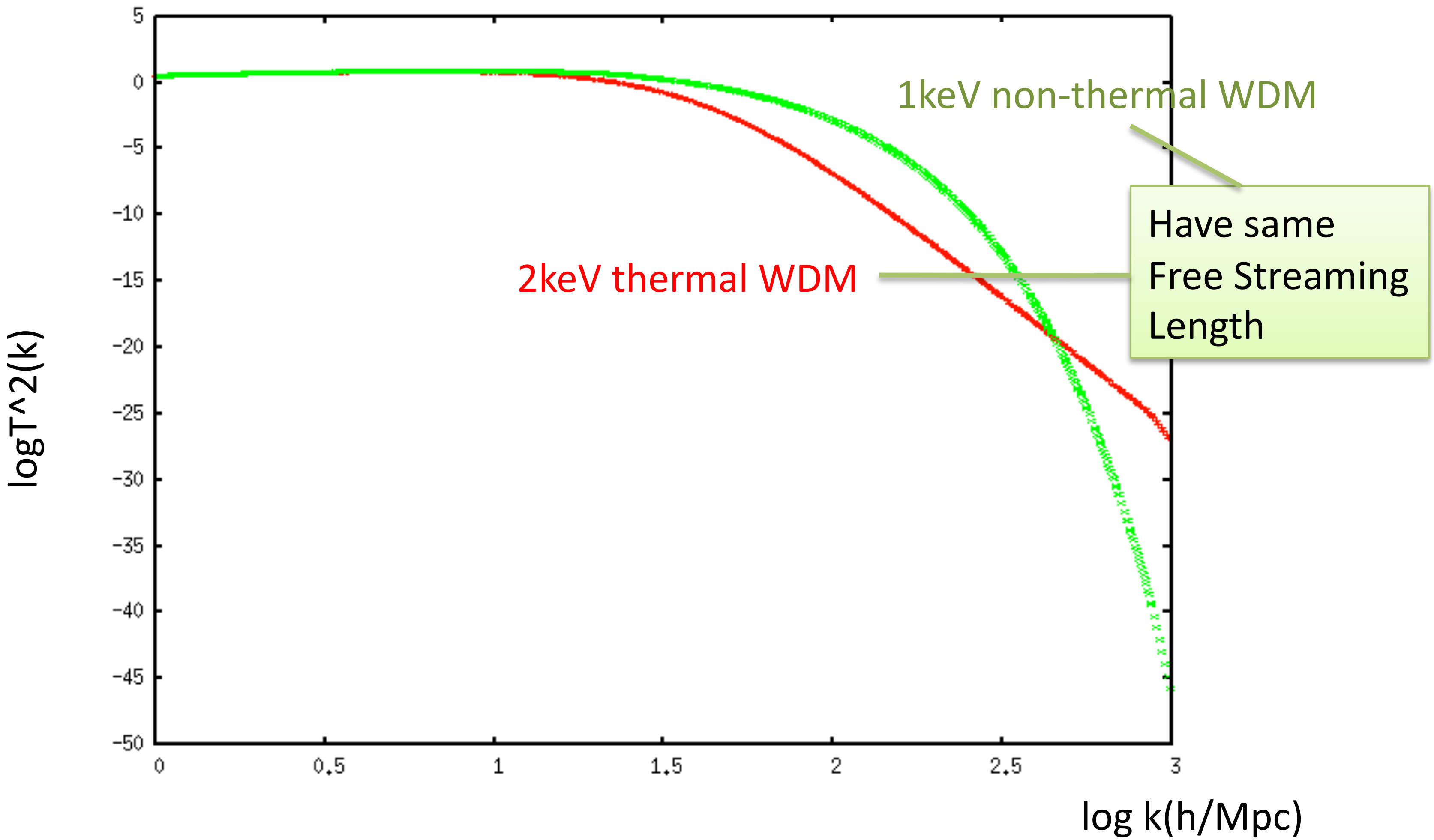
Linear Power Spectrum

Linear Power Spectrum @z=0



Linear Power Spectrum

Difference of Transfer Function @z=0



Simulation Method

In simulating the WDM, we have one big problem :
How do we include the peculiar velocity ?

Zel'dovich velocity + Random velocity ?

Usual initial condition of N-body simulation

Simulation Method

In simulating the WDM, we have one big problem :
How do we include the peculiar velocity ?

Zel'dovich velocity + Random velocity ?

Usual initial condition of N-body simulation

No!! Random velocity would result in artificial small scale structure

(Colin et al. 2007)

Simulation Method

In simulating t

How do we in

Zel'dovich vel

No!! Random

cale structure

et al. 2007)

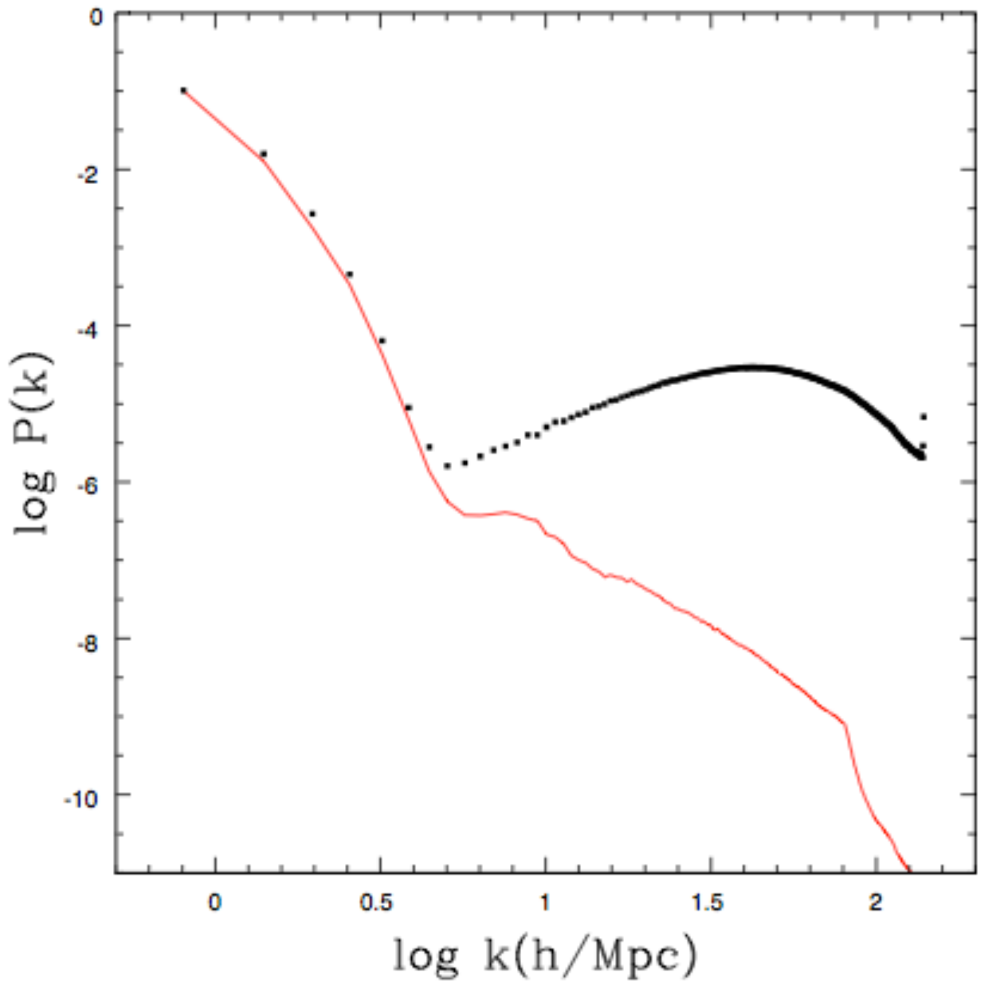


FIG. 1.— Comparison of the power spectra measured at $z = 40$ for the simulation started at $z = 40$ (solid line) and the one started at $z = 100$ (squares). The longest plotted wavelength is L_{box} while the highest frequency is $(2\pi/L_{box})\,256$.

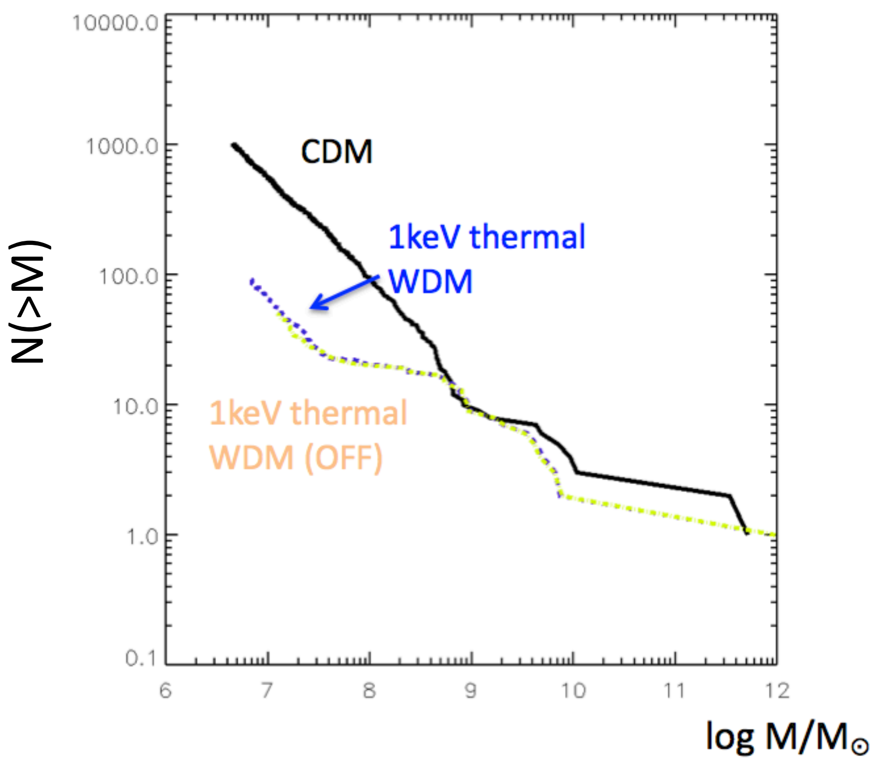
Simulation Method

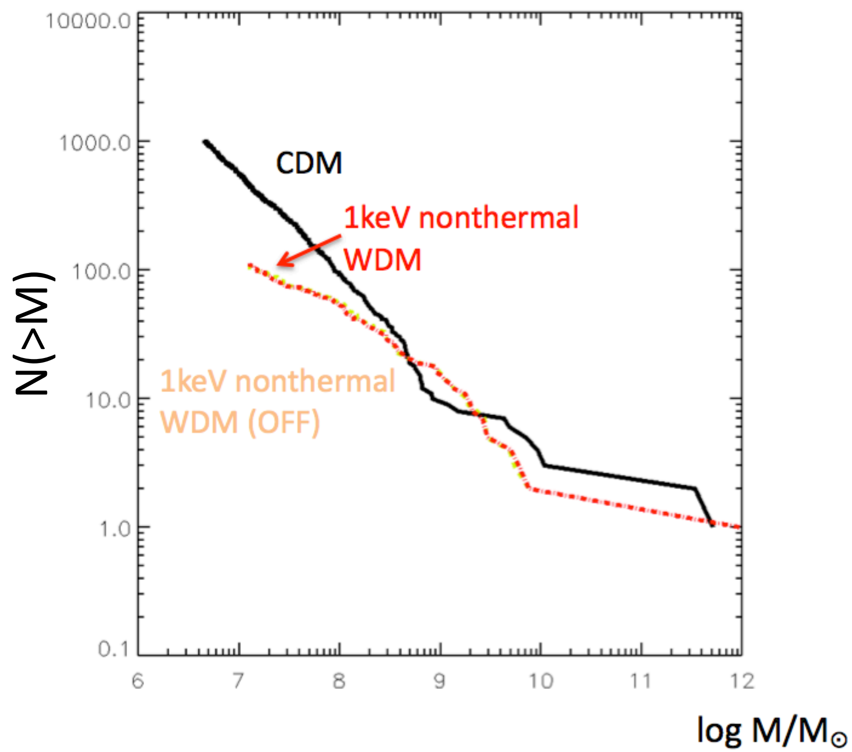
Our Simulation Parameters;

Box Size : 10 Mpc/h^3
Number of Particles : 512^3 (only Dark Matter)
Initial z=9
Random velocity : on / off
Cosmological parameters : WMAP5(Komatsu et al. 2008)

Simulation Result

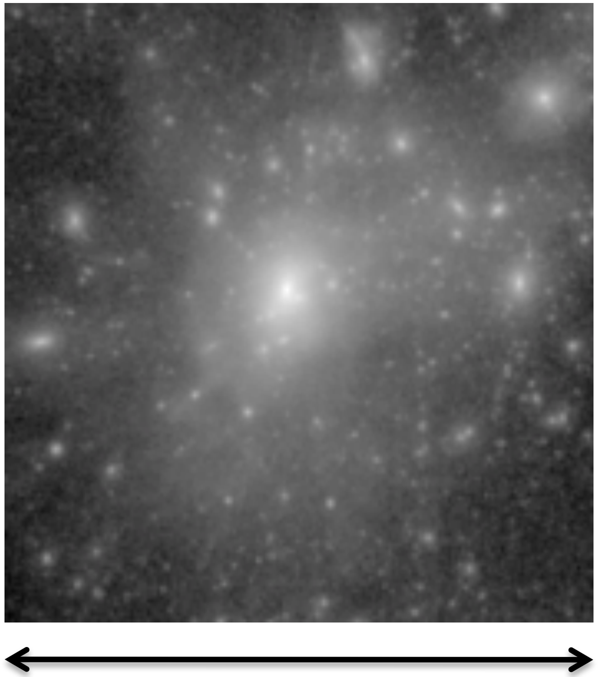
Mass Function of Milky Way like halo





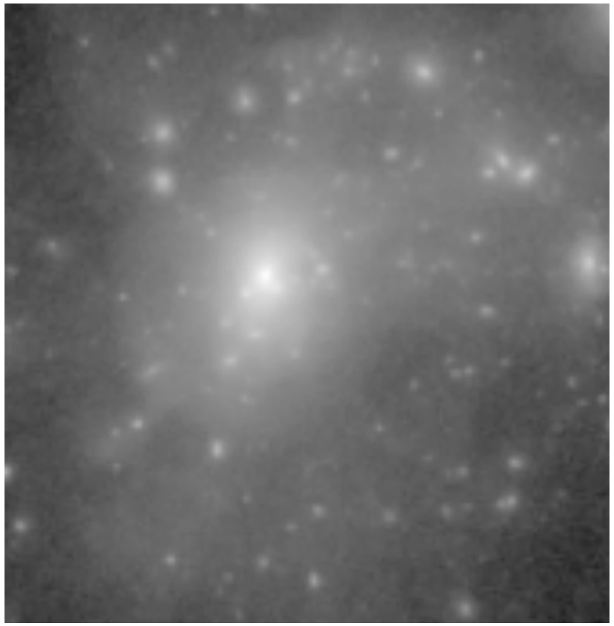
A.K. and Naoki Yoshida (in preparation)

Simulation Result

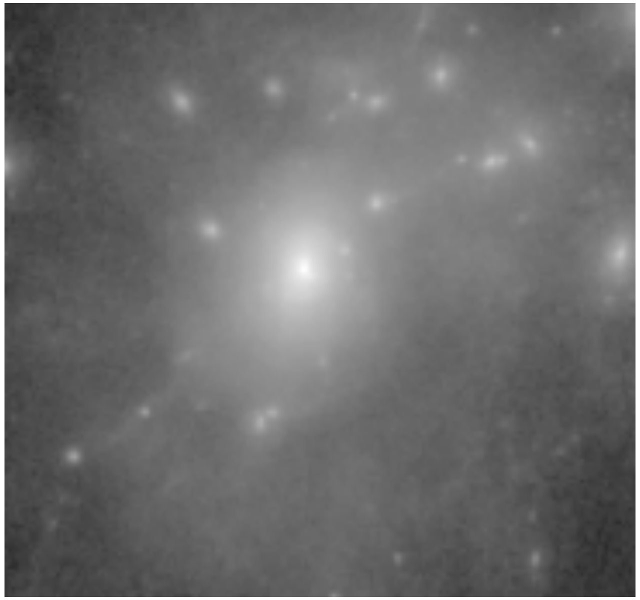


100 kpc

CDM



1keV nonthermal WDM

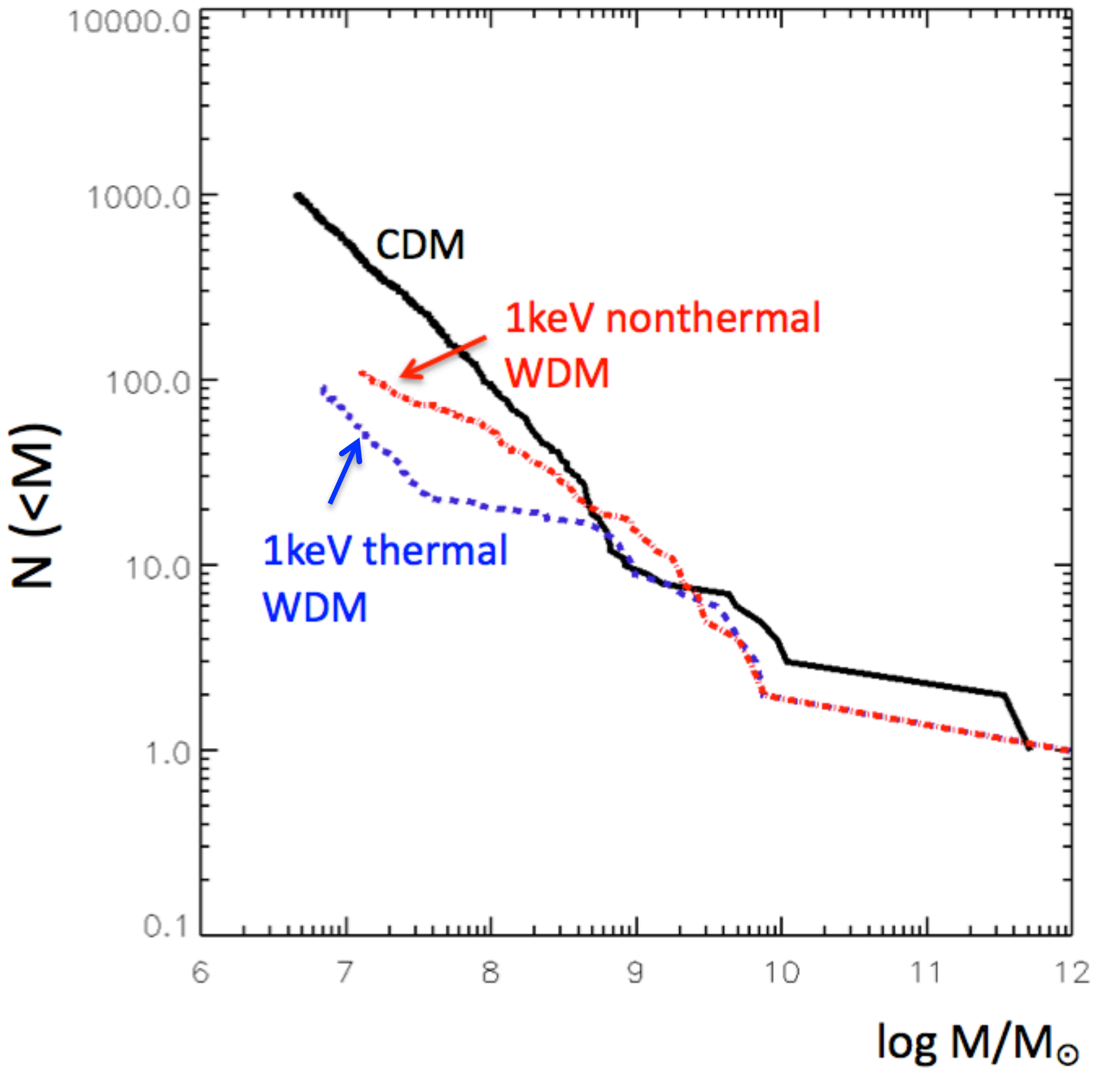


1keV thermal WDM

A.K. and Naoki Yoshida (in preparation)

Simulation Result

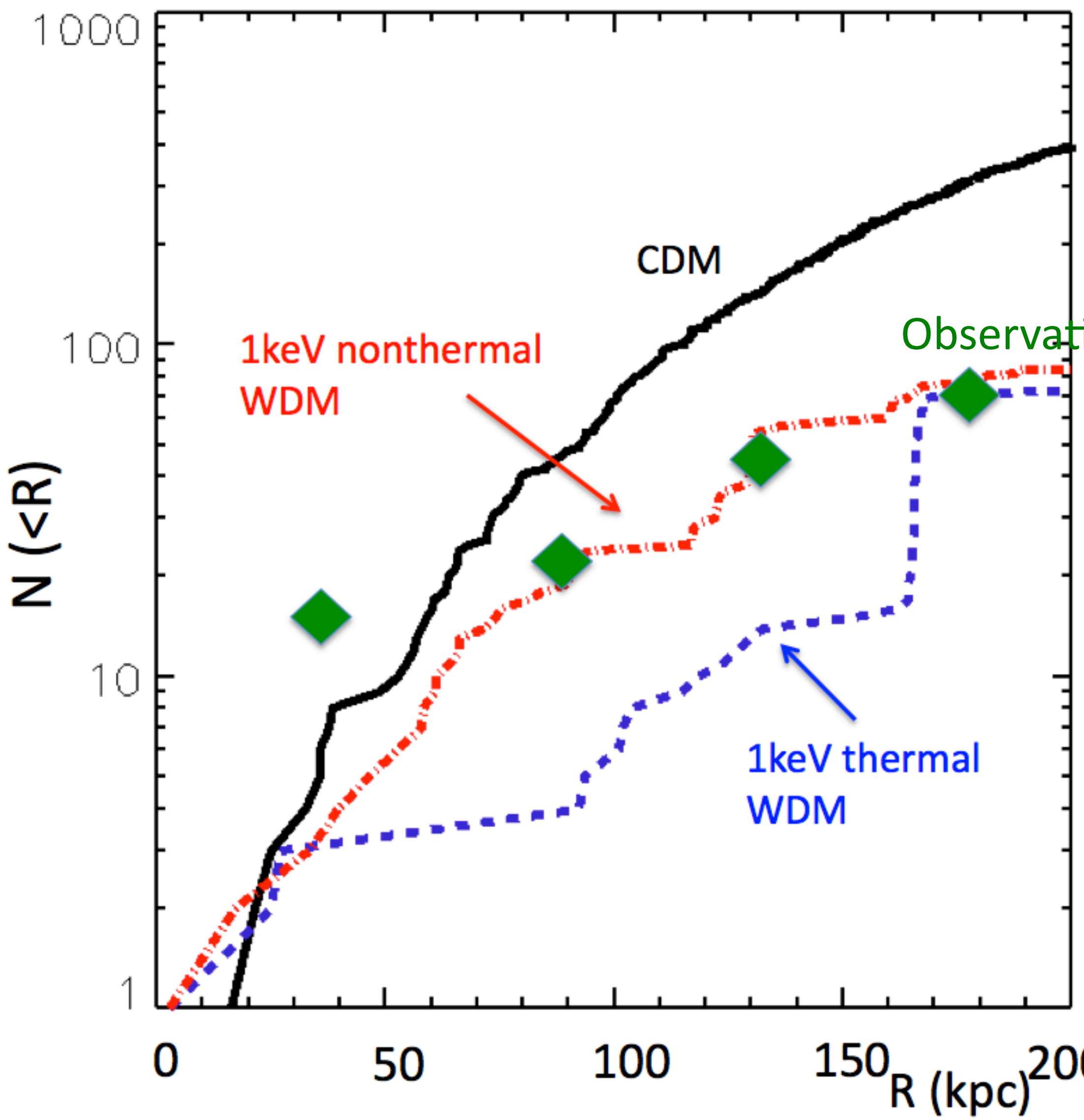
Subhalo Mass Function



A.K. and Naoki Yoshida (in preparation)

Simulation Result

Radial Distribution in Milky Way



A.K. and Naoki Yoshida
(in preparation)

Conclusion and Prospect

Conclusion and Prospect

- There are several motivations for WDM in both Astrophysics and Particle Physics

- Not only velocity(momentum) dispersion(scale) but also shape of velocity(momentum) distribution is important for Small Scale Structure

- We simulate the WDM model produced via non-thermal process and find a possibility that 1-keV non-thermal Sterile Neutrino may resolve Small Scale Crisis

- Non-thermally produced DM has very interesting possibilities and needs more study varying the parameters

Thank you !!

Welcome Suggestions and Comments !!