Nonthermal warm dark matter and the structure of galactic dark halos

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Main message of my poster

✓ We should care about

not only **the velocity dispersion** of the velocity distribution
of dark matter particles,
but also **the shape** of the velocity distribution function
of dark matter particles
for the formation of the galactic and subgalactic structures.

: pointed out in the linear perturbation theory by

Strigari, Kaplinghat and Bullock, astro-ph/0606281
Boyanovsky, astro-ph/0807.0646

Linearized Boltzmann-Vlasov equation in the matter-dominated era

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

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

Mode coupling between
(0th order) dark matter momentum (velocity) distribution
and
(1st order) perturbation Fourier mode.

$f(\vec{x},\vec{p},t) = f_0(p) + f_1(\vec{x},\vec{p},t) + \ldots$: the distribution function of dark matter particles

$\phi(\vec{x},t) = \phi_0(t) + \phi_1(\vec{x},t) + \ldots$: gravitational potential

The velocity dispersion of the velocity distribution of dark matter particles

➡ The free-streaming (cut-off) scale of the matter power spectrum

$$\lambda_{\mathrm{fs}} = \mathbf{1}\ \mathrm{Mpc}\left(\frac{\mathrm{keV}}{\mathbf{m_{DM}}}\right)\left(\frac{\langle \mathbf{P/T}\rangle}{\mathbf{3.15}}\right) \qquad \mathbf{k_{fs}} \equiv \left[\frac{\mathbf{3H_0^2\Omega_M}}{\mathbf{2\langle\tilde{V}^2\rangle(t_{eq})}}\right]^{\frac{1}{2}}$$

The shape of the velocity distribution function of dark matter particles

➡ The shape of the matter power spectrum
around the free-streaming (cut-off) scale

Does the above point have any impact on
the structure formation
at the galactic and subgalactic scales ?

We have performed
the cosmological N-body simulations
to answer this question.

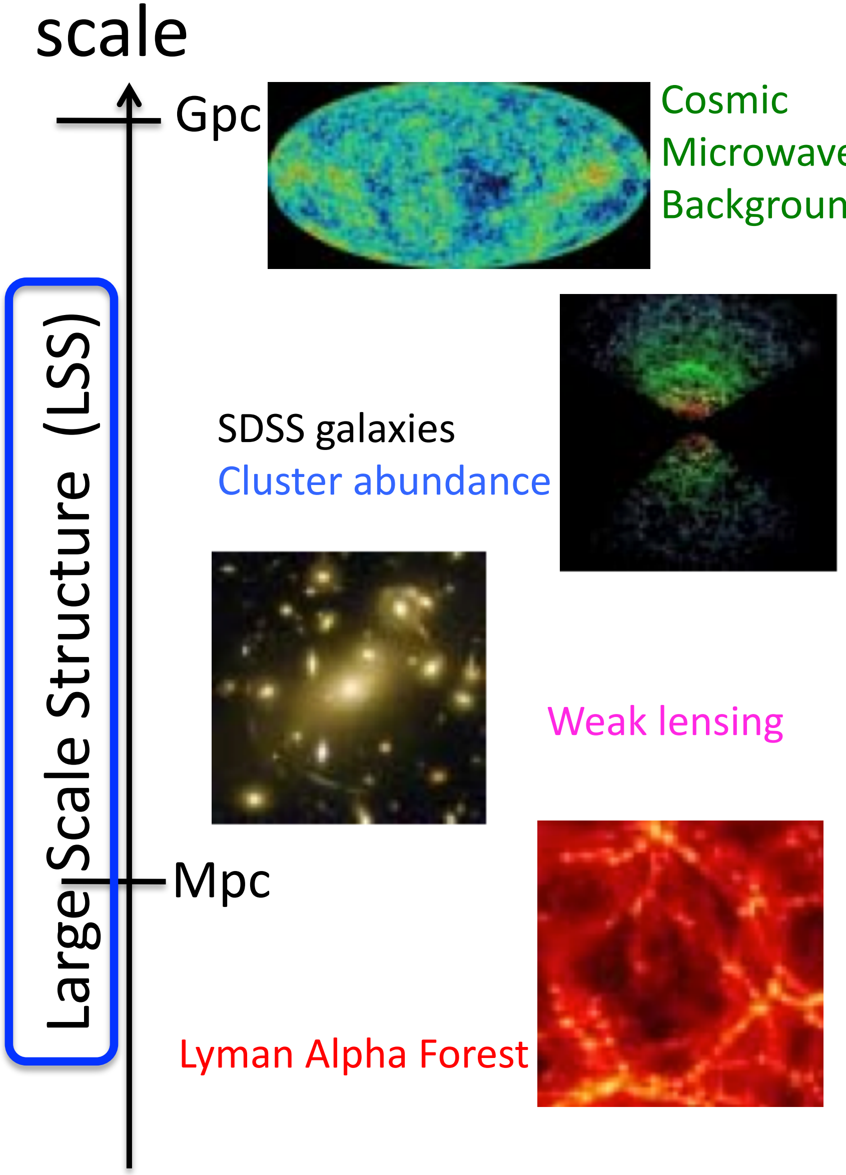
Motivation

- ✓ Warm dark matter (WDM) with a power spectrum truncated around the galactic scales is motivated from the viewpoint of both particle physics and astrophysics.
- ✓ Astrophysical observations imply that cold dark matter (CDM) models have problems at galactic scales. (‘small scale crisis’)
- ✓ Particle physics models predict promising WDM candidates.

Cold Dark Matter (CDM) and Large Scale Structure

CDM : Non-Relativistic @ decoupling

Standard assumption : ΛCDM cosmology



scale

Gpc

Cosmic Microwave Background

SDSS galaxies

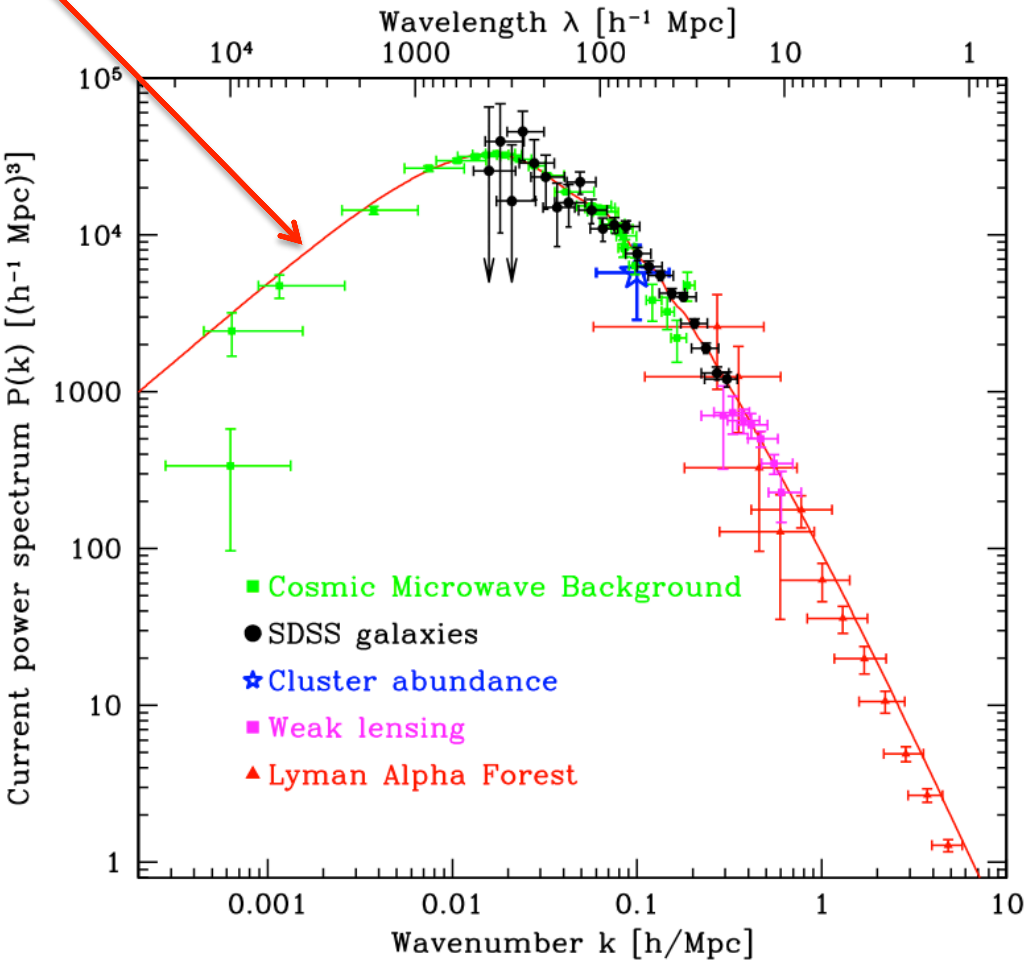
Cluster abundance

Weak lensing

Mpc

Lyman Alpha Forest

Large Scale Structure (LSS)



Tegmark et al. (2004)

CDM agrees with several observations of Large Scale Structure

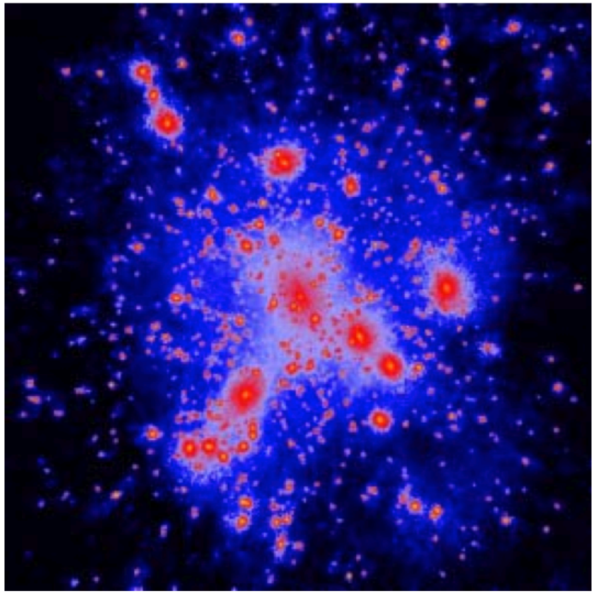
Cold Dark Matter (CDM) and Small Scale Structure

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

Small Scale Structure (SSS)

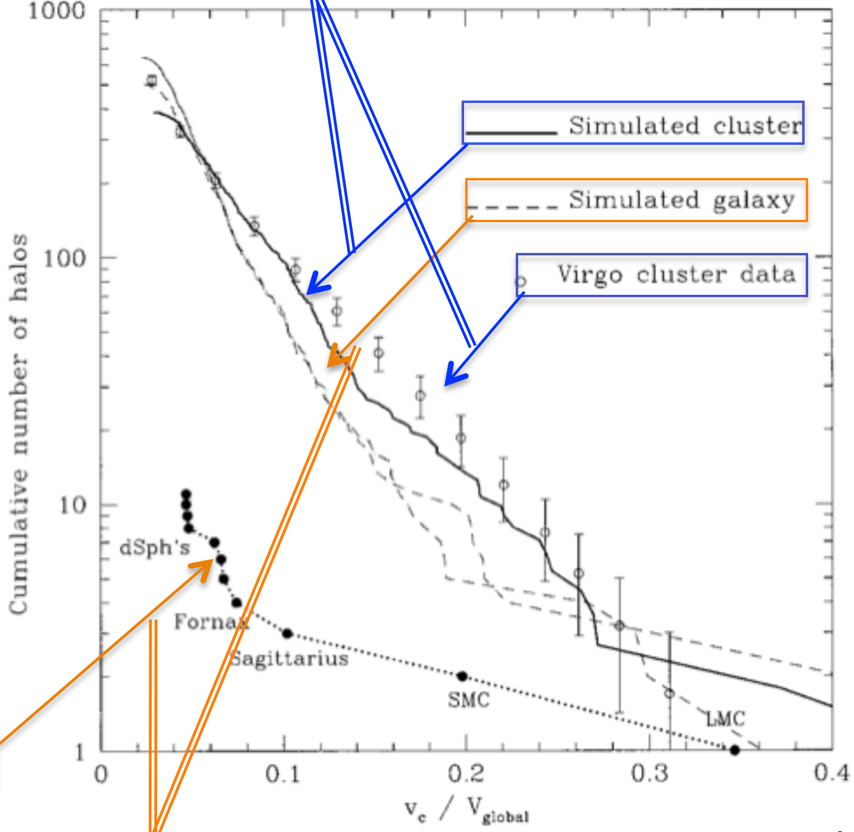
kpc

Missing satellite problem



Satellites within the Milky Way's halo

Agreement in LSS



Disagreement in SSS

circular velocity

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

Moore et (1999)

Cold Dark Matter (CDM) and Small Scale Structure

Small Scale Structure (SSS)

kpc

Cuspy halo ploblem

Density Profile

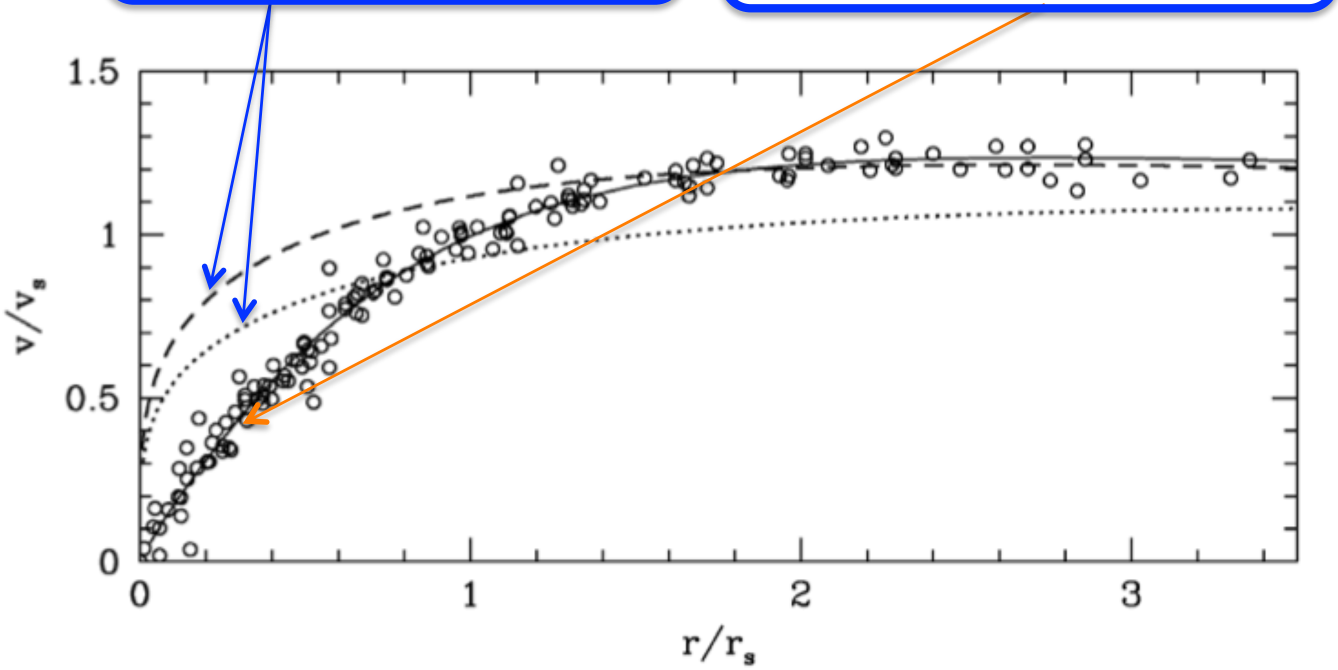
$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

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'**

Brief summary of particle physics WDM candidates and how they are produced

From the thermal bath

✓ Kinetic Decoupling (like SM neutrinos) light gravitino

T. Moroi, hep-ph/9503210 Bode, Ostriker and Turok, astro-ph/0010389

✓ Nonthermal process; decay, oscillation sterile neutrino

Kusenko, hep-ph/0906.2968

Out of the thermal bath

✓ Nonthermal process; decay

superWIMP : WIMP NLSP (stau) $\longrightarrow$ LSP (heavy gravitino)

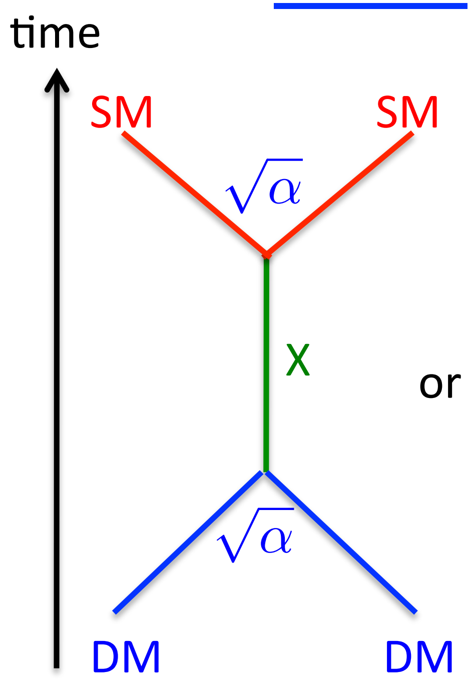
$$\rho_{\rm DM} = \frac{\mathbf{m}_{\mathbf{sWIMP}}}{\mathbf{m}_{\mathbf{WIMP}}}\rho_{\mathbf{WIMP}}$$

Feng, Rajaraman and Takayama, hep-ph/0302215

inflaton $\longrightarrow$ heavy gravitino

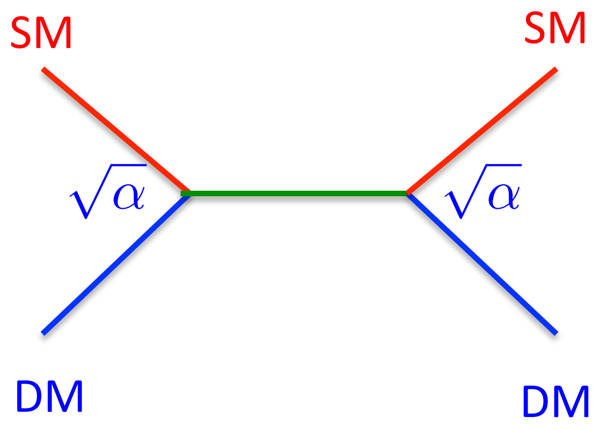
F. Takahashi, hep-ph/0705.0579

WIMP

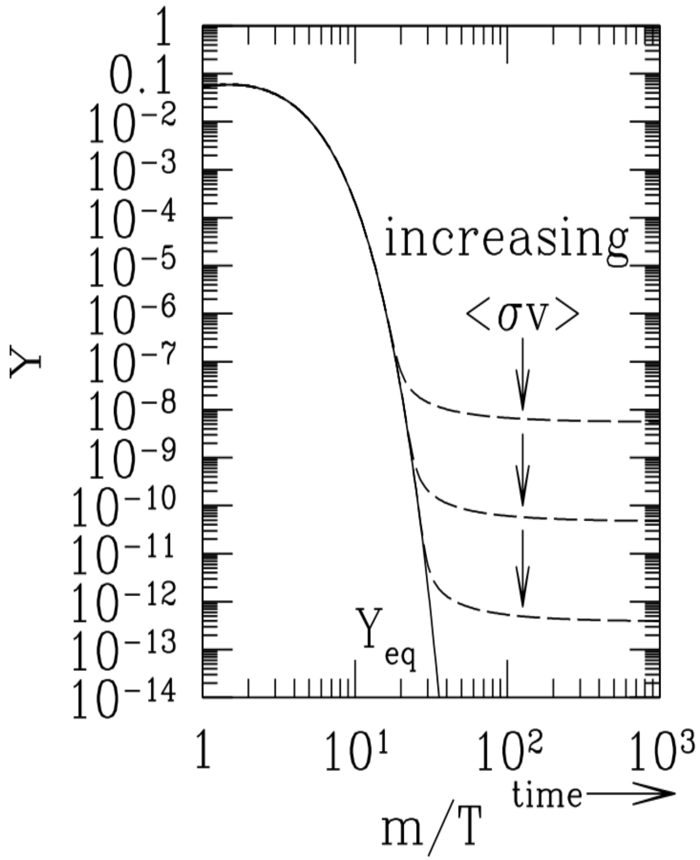


self-annihilation

or



freeze out



$$\Omega h^2 \approx \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle}.$$

$$\langle \sigma_{\mathbf{ann}} \mathbf{v} \rangle \sim \mathbf{10}^{-\mathbf{25}} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{\alpha}{\mathbf{10^{-2}}} \right)^{\mathbf{2}} \left(\frac{\mathbf{100GeV}}{\mathbf{m_X}} \right)^{\mathbf{2}}$$

➡ Electro Weak Scale(〜100GeV) WIMP naturally explains the relic abundance.

TeV scale SUSY & neutralino dark matter

Particle physics WDM candidates and brief summary of how they are produced

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Focus on

Out of the thermal bath

✓ Nonthermal process; decay

superWIMP : WIMP NLSP (stau) ⟶ LSP (heavy gravitino)

$$\rho_{\mathrm{DM}} = \frac{m_{\mathrm{sWIMP}}}{m_{\mathrm{WIMP}}} \rho_{\mathrm{WIMP}}$$

Feng, Rajaraman and Takayama, hep-ph/0302215

inflaton ⟶ heavy gravitino

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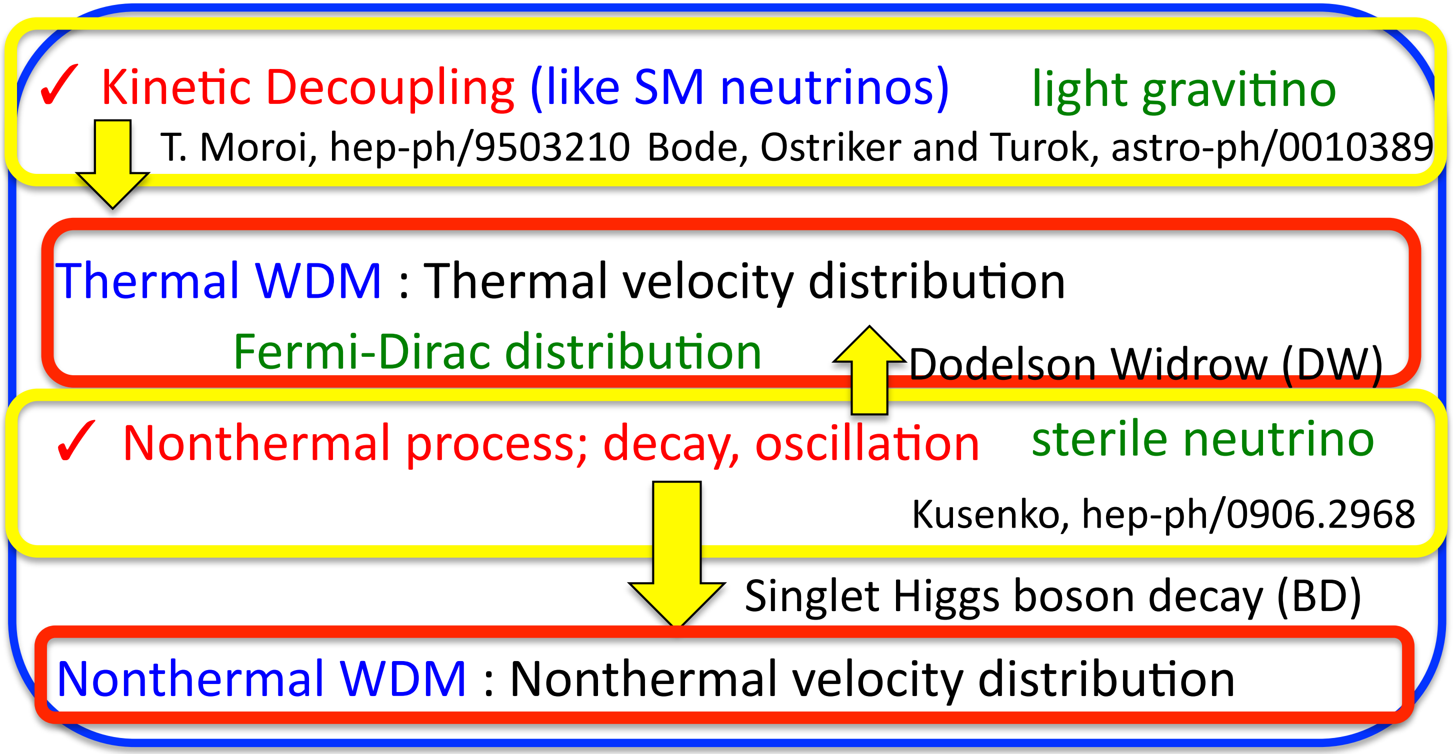
Particle physics WDM candidates and brief summary of how they are produced

From the thermal bath



✓ Kinetic Decoupling (like SM neutrinos) light gravitino

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Thermal WDM : Thermal velocity distribution

Fermi-Dirac distribution

Dodelson Widrow (DW)

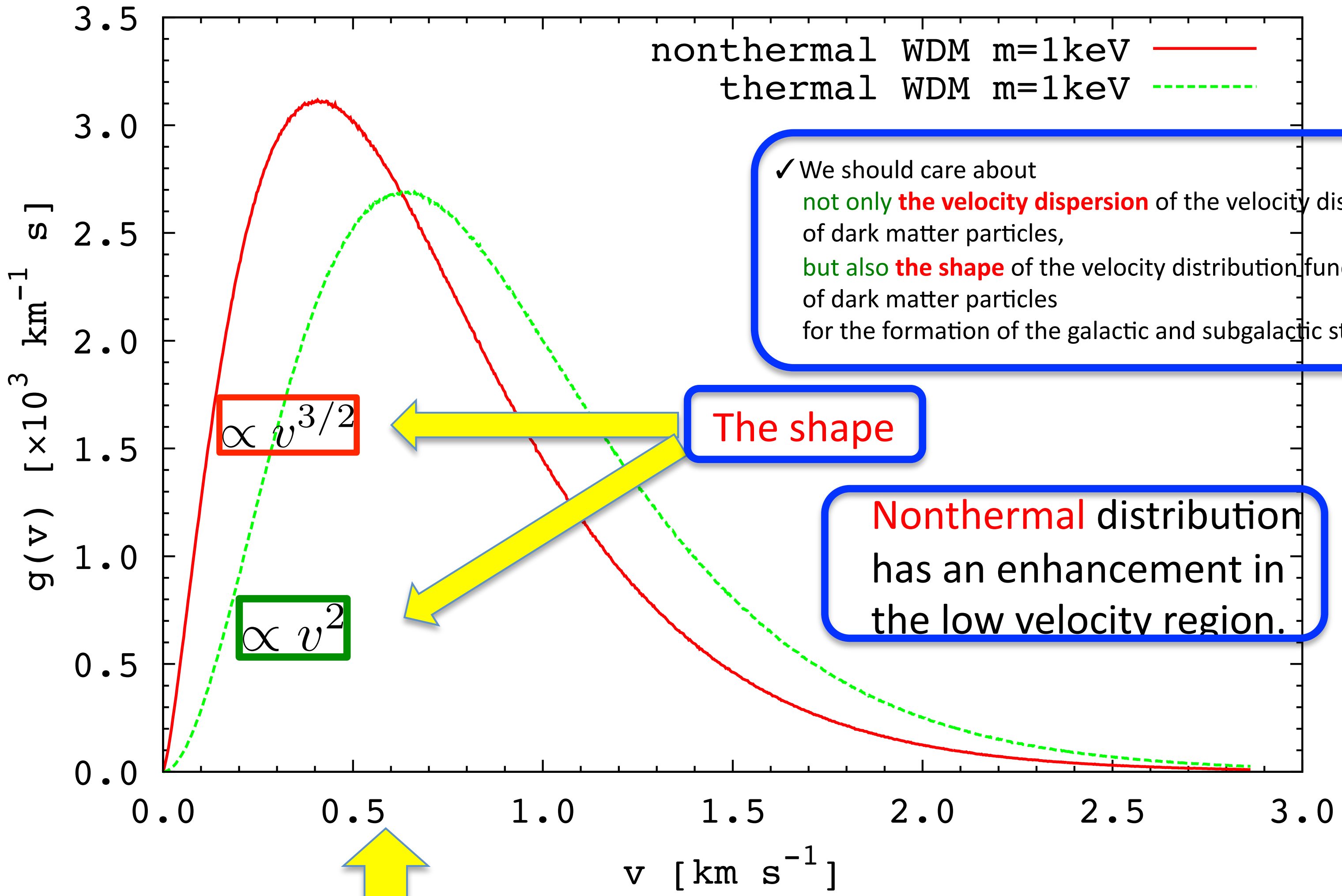
✓ Nonthermal process; decay, oscillation sterile neutrino

Kusenko, hep-ph/0906.2968

Singlet Higgs boson decay (BD)

Nonthermal WDM : Nonthermal velocity distribution

The velocity distributions at z=9 : themal v.s. nonthermal



$\propto v^{3/2}$

$\propto v^{2}$

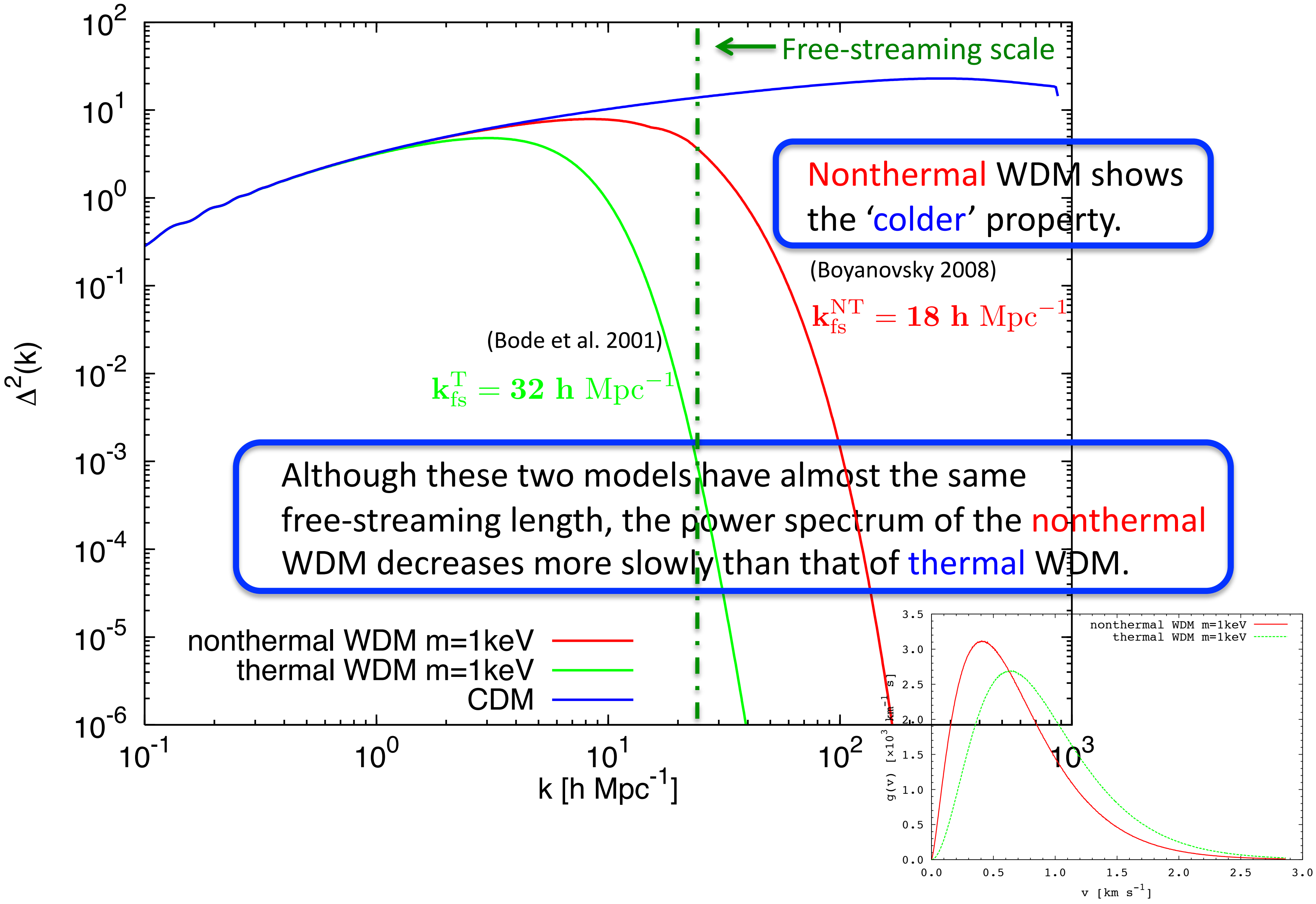
✓We should care about
not only **the velocity dispersion** of the velocity distribution of dark matter particles,
but also **the shape** of the velocity distribution function of dark matter particles
for the formation of the galactic and subgalactic structures.

The shape

Nonthermal distribution has an enhancement in the low velocity region.

The velocity dispersion

The linear power spectra at z=0 : themal v.s. nonthermal compared with CDM



← Free-streaming scale

Nonthermal WDM shows the ‘colder’ property.

(Boyanovsky 2008)

$\mathbf{k_{fs}^{NT} = 18\ h}\ \mathrm{Mpc}^{-1}$

(Bode et al. 2001)

$\mathbf{k_{fs}^{T} = 32\ h}\ \mathrm{Mpc}^{-1}$

Although these two models have almost the same free-streaming length, the power spectrum of the nonthermal WDM decreases more slowly than that of thermal WDM.

Parameters of our simulation

✓ Box Size : $\mathbf{10\ h^{-1}Mpc}$

✓ Number of Particles : $\mathbf{N = 256^3}$ (only Dark Matter)

✓ Cosmological parameters : WMAP5 (Komatsu et al. 2008)

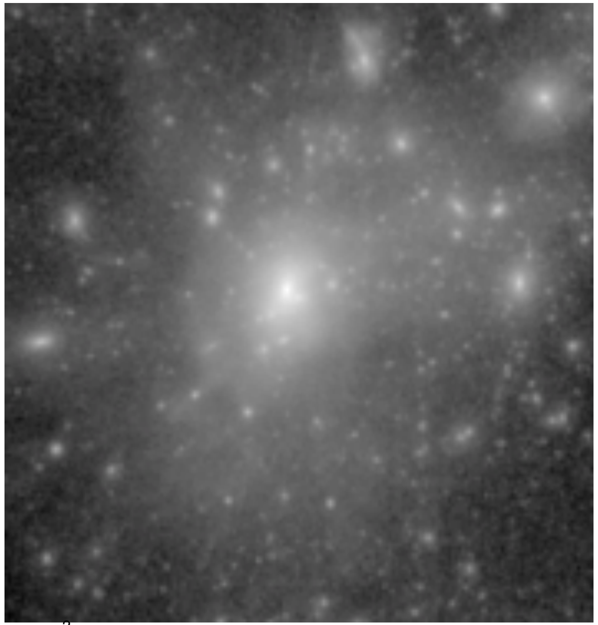
✓ Initial redshift z=9

✓ We can ignore the peculiar velocity of dark matter particles safely because the peculiar velocity has been already redshifted.

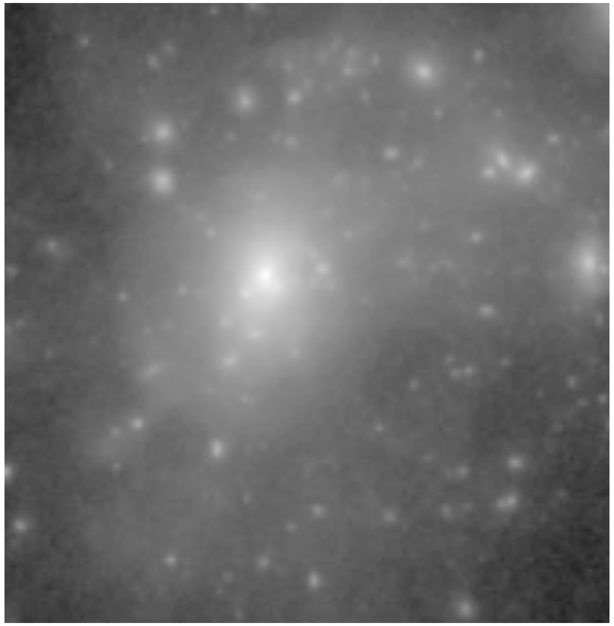
✓ The information of velocity distribution of dark matter particles are imprinted just in the power spectrum at such a low redshift.

Simulation results : the projected distribution of the substructures in a “Milky Way” halo at z=0

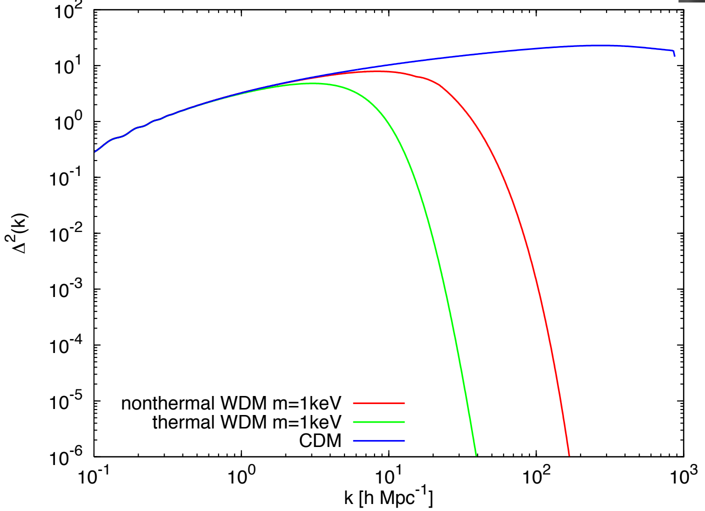
CDM



1 keV nonthermal WDM



1 keV thermal WDM

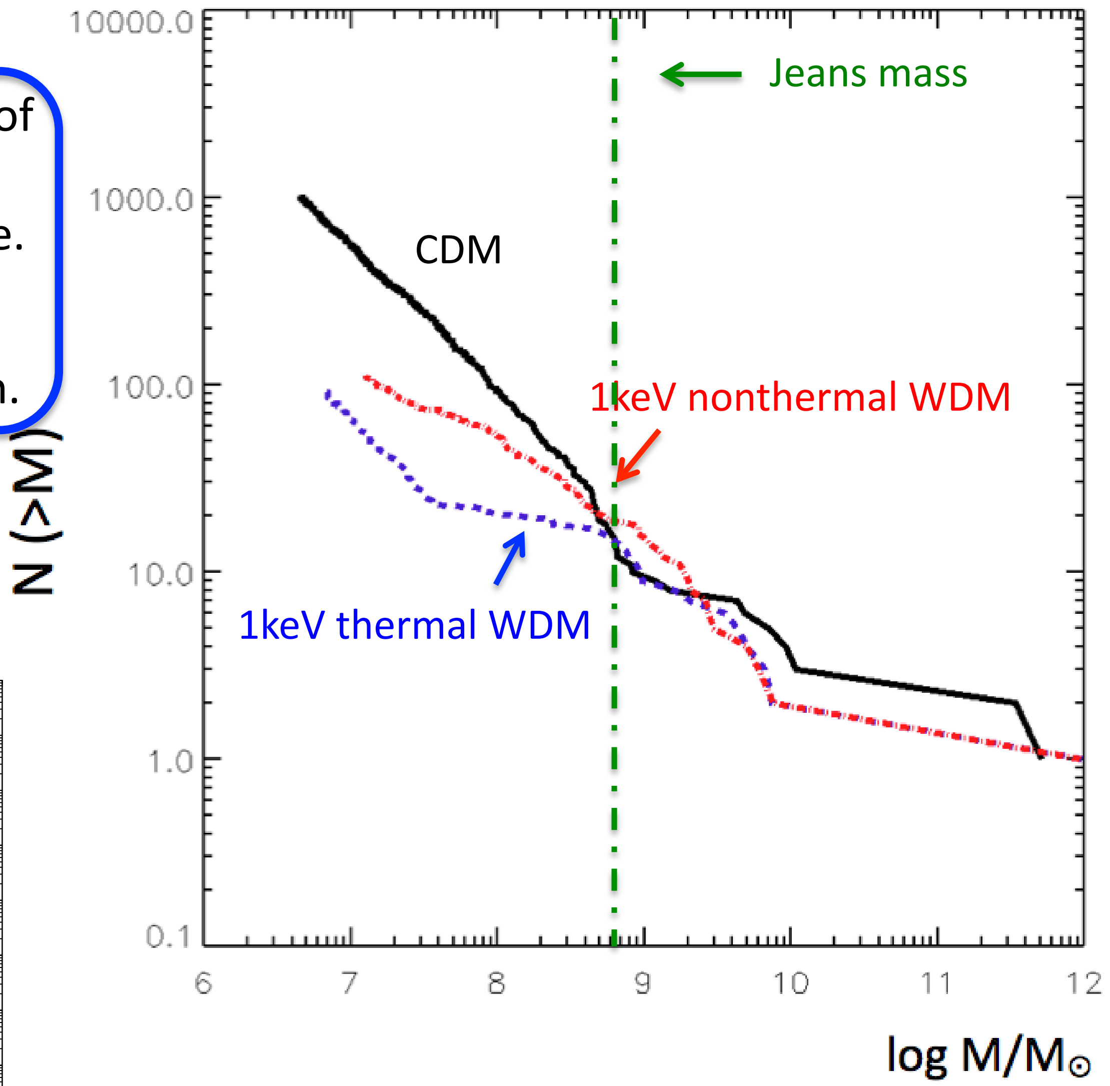


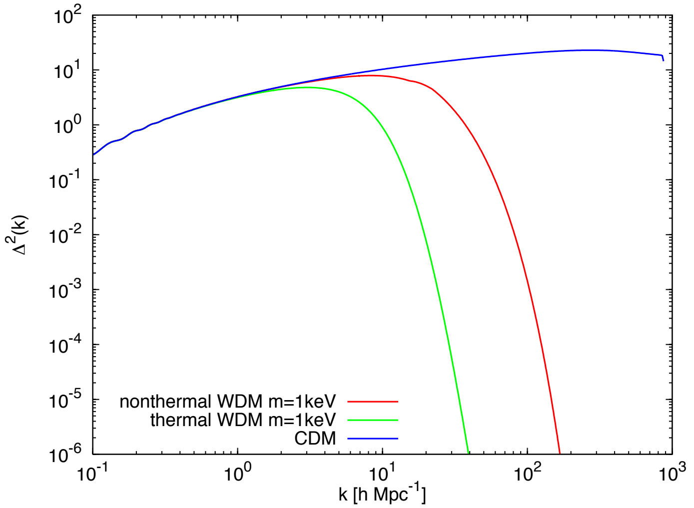
The ‘colder’ property of nonthermal WDM can be seen.

A.K. and Naoki Yoshida (in preparation)

Simulation results : the mass function of the subhalos in a “Milky Way” halo at z=0

- ✓ WDM suppress the formation of non-linear objects below the free-streaming scale.
- ✓ The ‘colder’ property of nonthermal WDM can be seen.

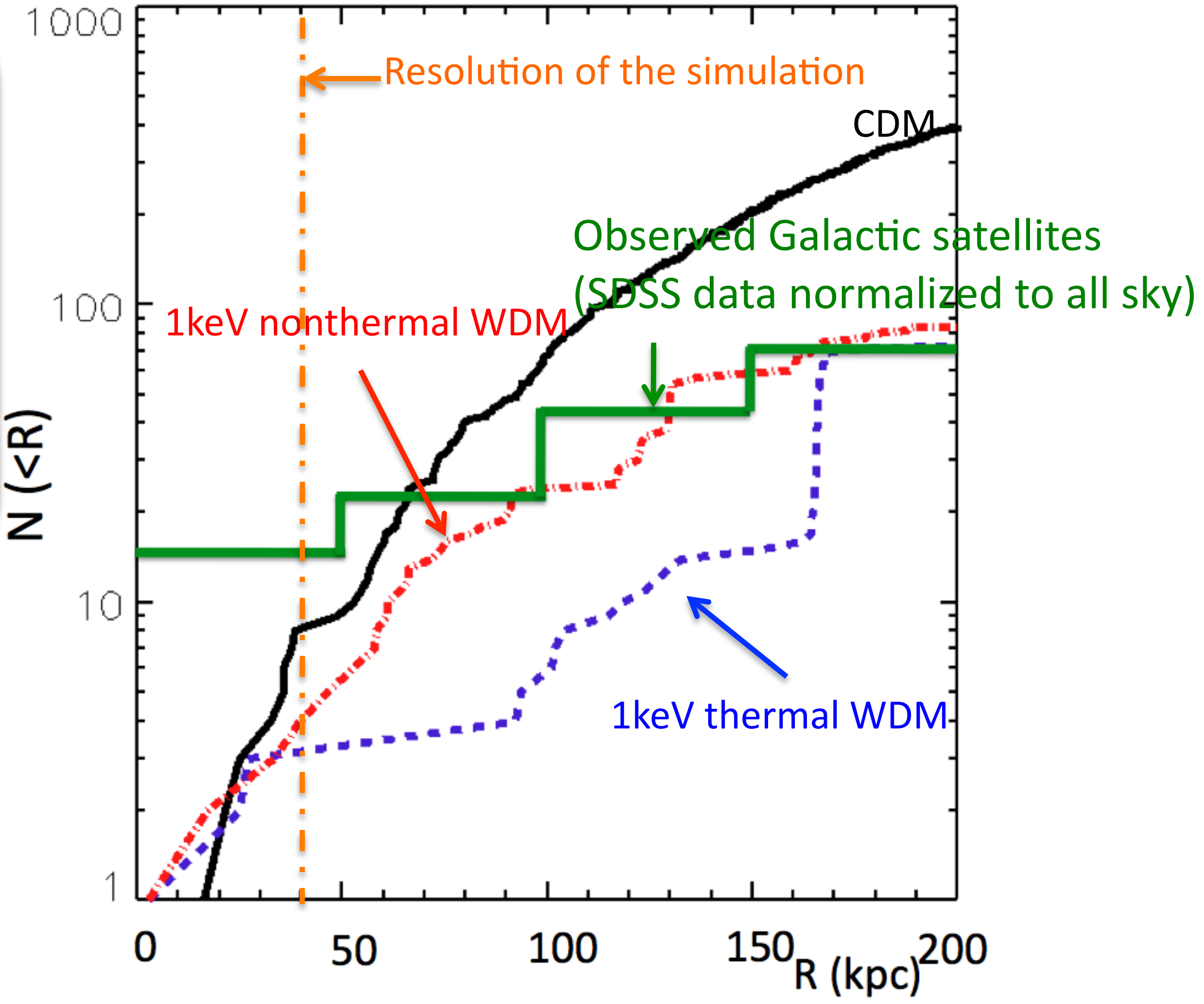


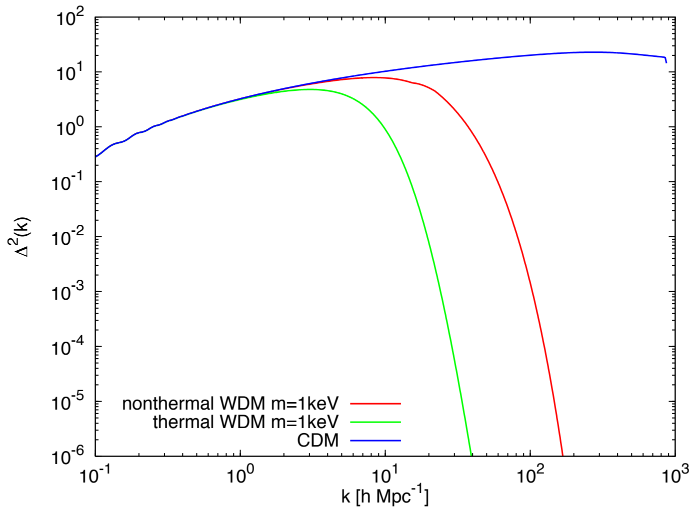


A.K. and Naoki Yoshida (in preparation)

Simulation results : the radial distribution of the subhalos in a "Milky Way" halo at z=0

- ✓ CDM overpredicts the abundance of the subhalos.
  This is an another realization of 'Missing satellites problem'.
- ✓ 1keV nonthermal WDM appears to reproduce the radial distribution of the observed satellites.





A.K. and Naoki Yoshida
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Summary and Conclusion

✓ We should care about
not only **the velocity dispersion** of the velocity distribution
of dark matter particles,
but also **the shape** of the velocity distribution function
of dark matter particles
for the formation of the galactic and subgalactic structures.

✓ The nonthermal velocity distribution skewed to low velocities
leads to a slower decrease of the power spectrum.
(‘Colder’ property of the nonthermal WDM)

✓ This ‘colder’ property of the nonthermal WDM
can be seen in richer galactic substructures.

✓ 1keV nonthermal WDM appears to reproduce the radial distribution of the
observed Milky Way satellites above the resolution of our simulation.

Difficulties of the WDM simulation

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

Difficulties of the WDM simulation

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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)

Difficulties of the WDM simulation

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Zel’dovich velo

Usual in

No!! Random

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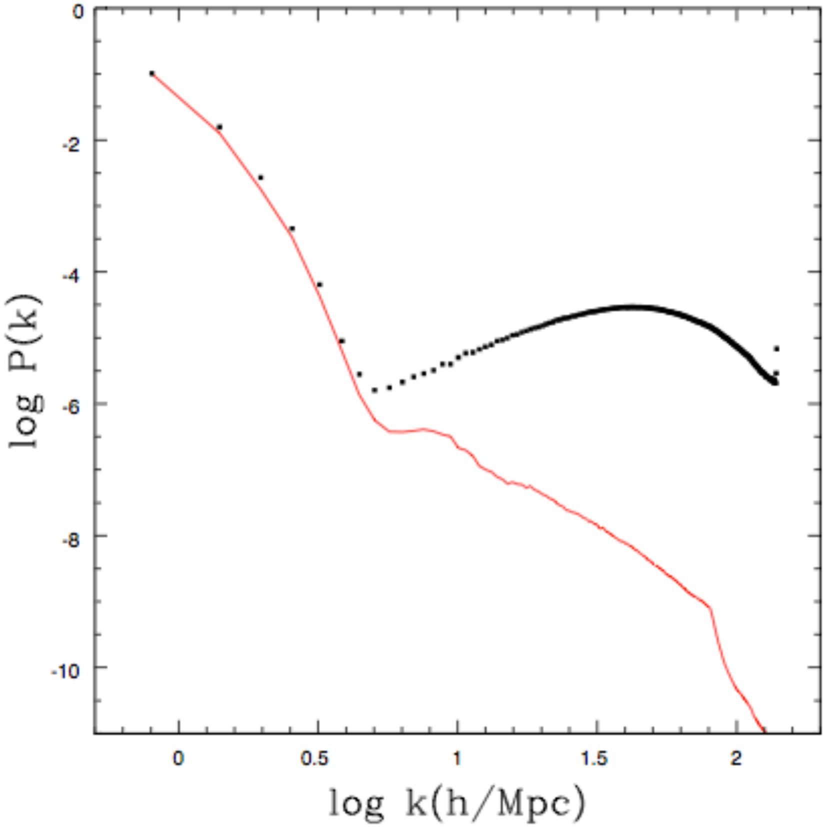
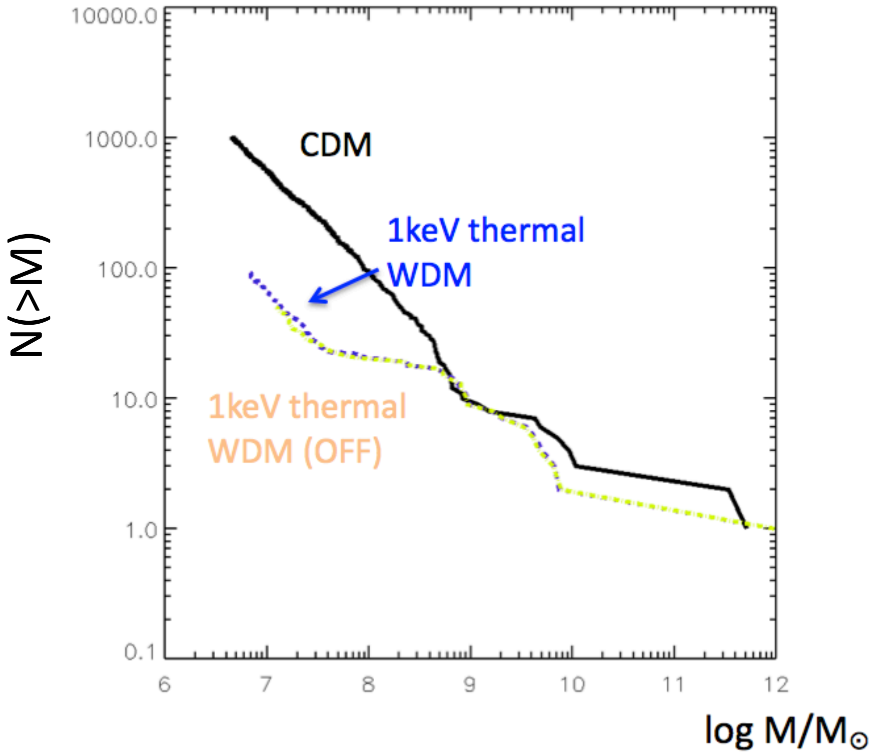
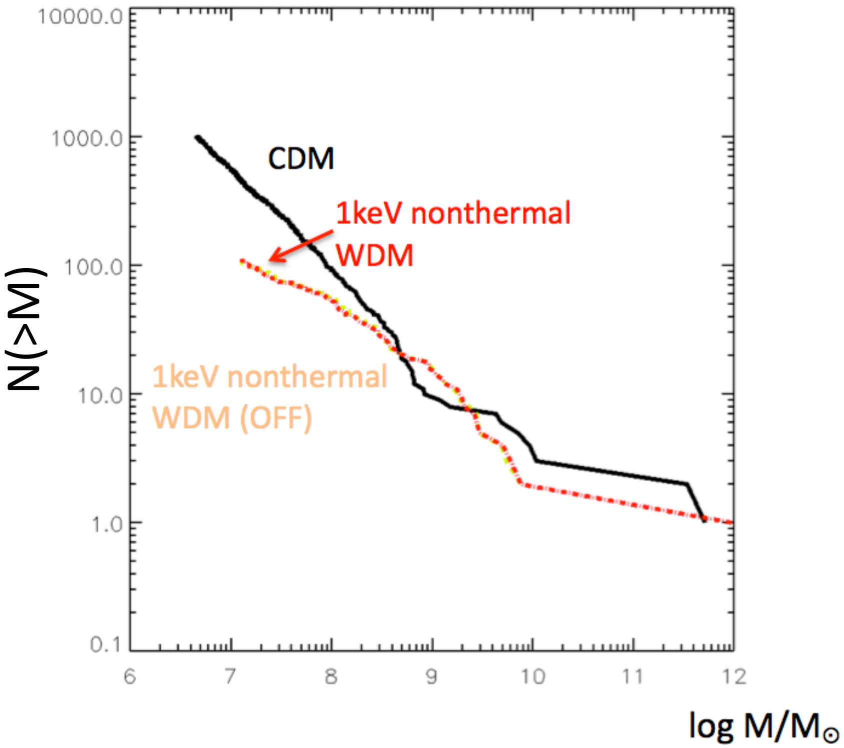


FIG. 1.— Comparison of the power spectra measured at $z = 40$ for the simulation started at $z = 40$ (solid line) and the one started at $z = 100$ (squares). The longest plotted wavelength is L_{box} while the highest frequency is $(2\pi/L_{box})\,256$.

Checking the convergence of our simulation :
the mass function of the subhalos in a "Milky Way" halo at z=0
with / without initial velocity





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