Dark Matter Halos in Warm Dark Matter Models

5. June @ Workshop CIAS Meudon 2013

Ayuki Kamada (Kavli IPMU, Univ. of Tokyo)

in collaboration with
Naoki Yoshida (Kavli IPMU, Univ. of Tokyo)
Kazunori Kohri (KEK)
Tomo Takahashi (Univ. of Saga)

Outline

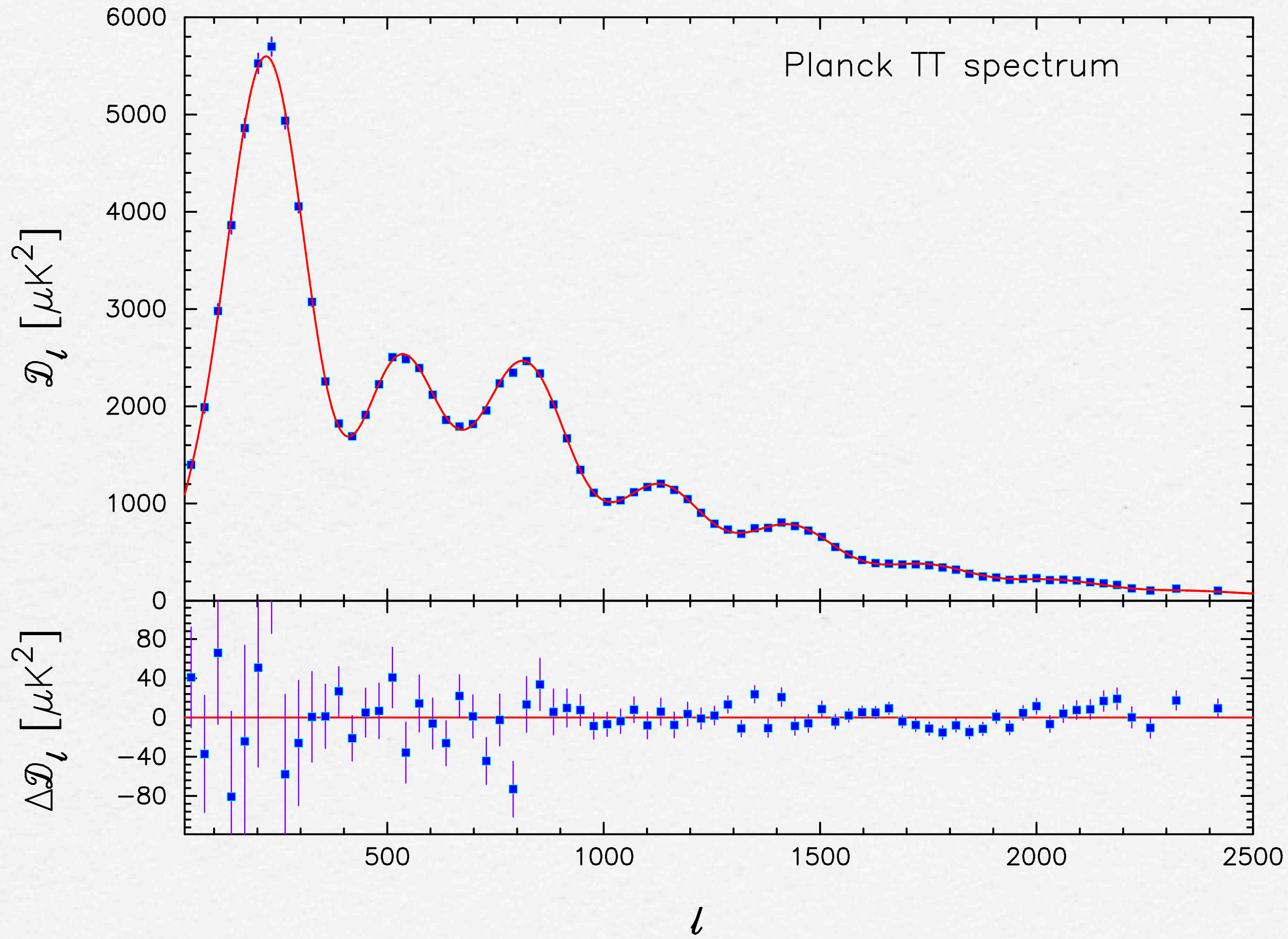
✓ Brief review of WDM (Warm Dark Matter)
  - astrophysics & particle physics aspects

✓ Linear evolution of the primordial matter density fluctuation in WDM models
  - introduce a cut-off scale, which characterizes the linear matter power spectra in different WDM models

✓ Structure formation in WDM models
  - discuss some difficulties in WDM simulations

based on **A. Kamada et al, JCAP (2013)**

Great success of ΛCDM in CMB

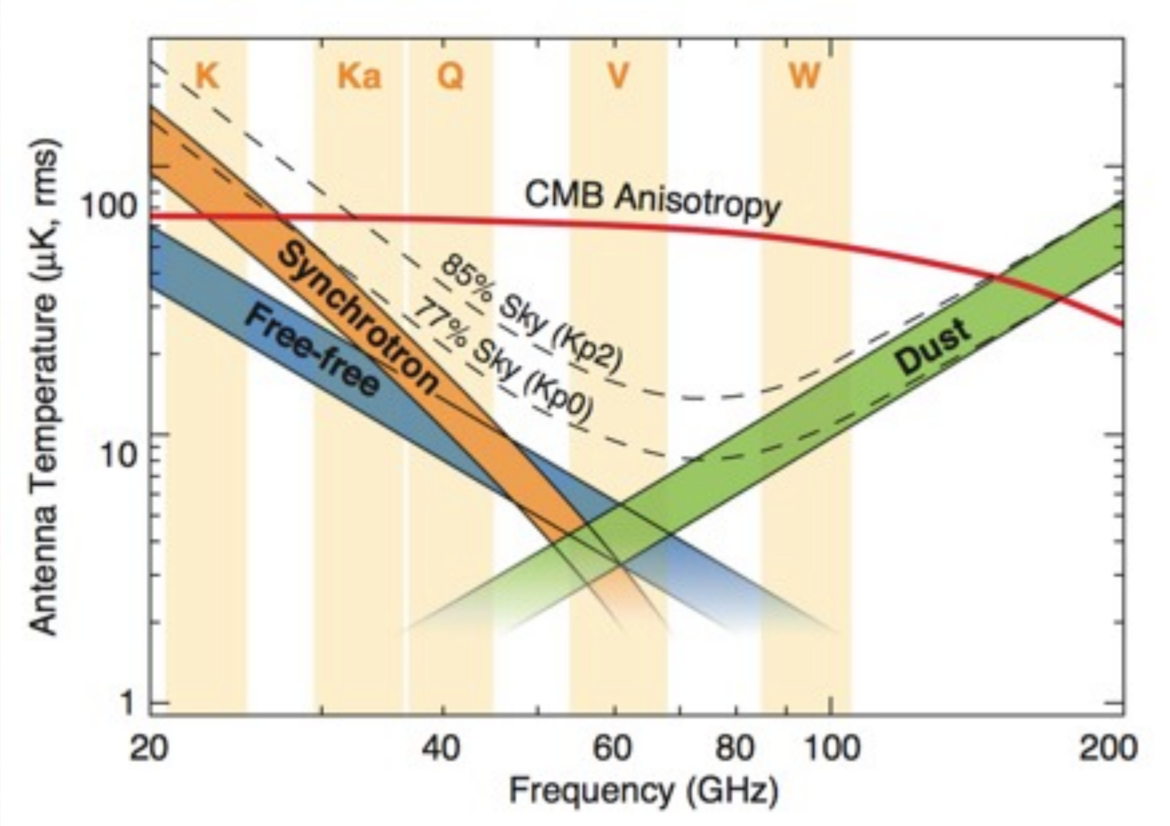


Planck 2013 results. XVI

	Planck	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

Now, cosmological parameters are determined at a percentage level!!

What makes CMB such a powerful tool?



web page of LAMBDA

✓Measurement

✓direct measurement
- (almost) foreground-free

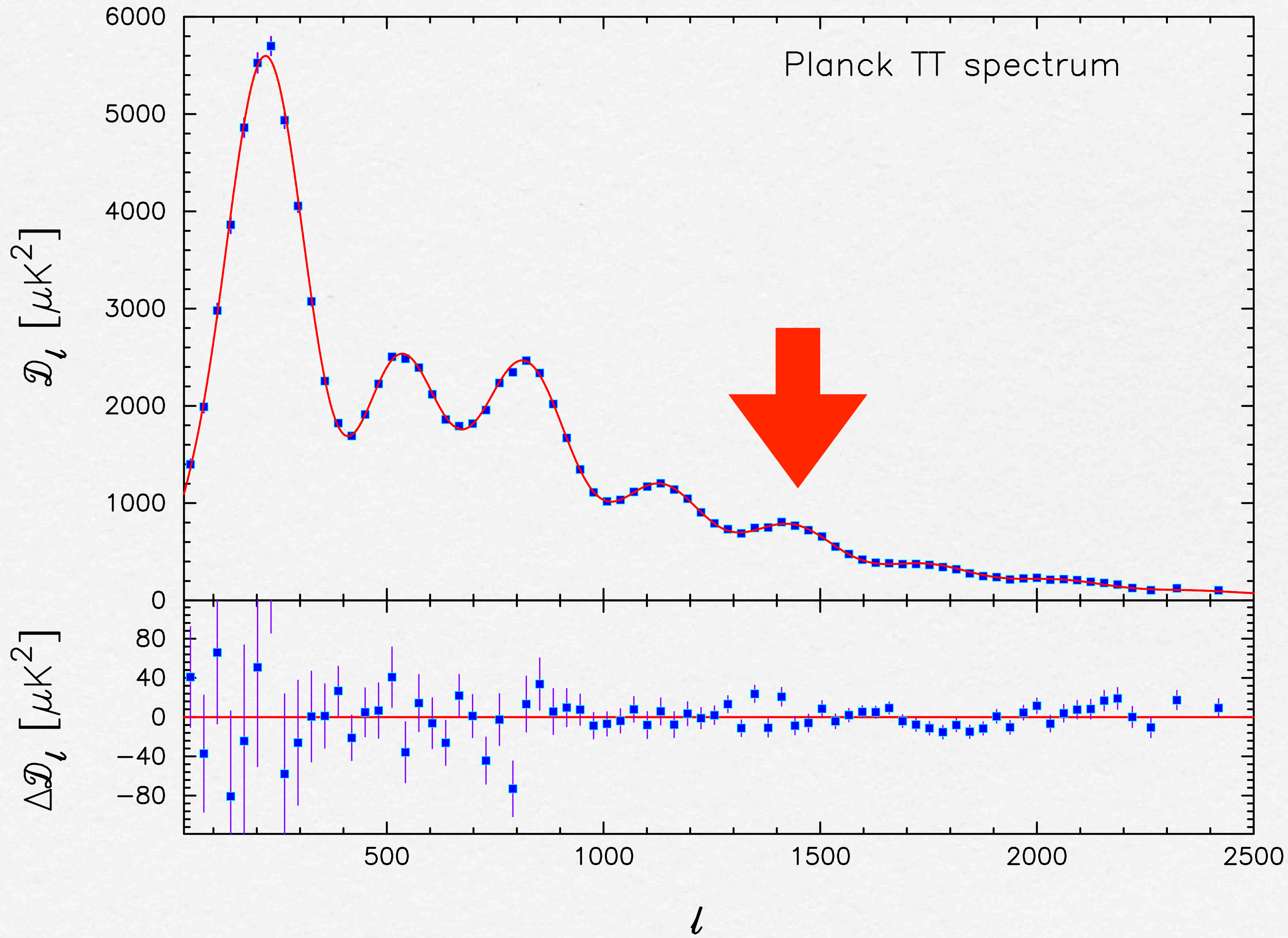
✓Theory

✓First principle calculation
- perturbation theory of General Relativity
(while gauge freedom is troublesome)

<- CMB comes from the early ($z \sim 1000$) Universe

Limitation of CMB - Silk damping

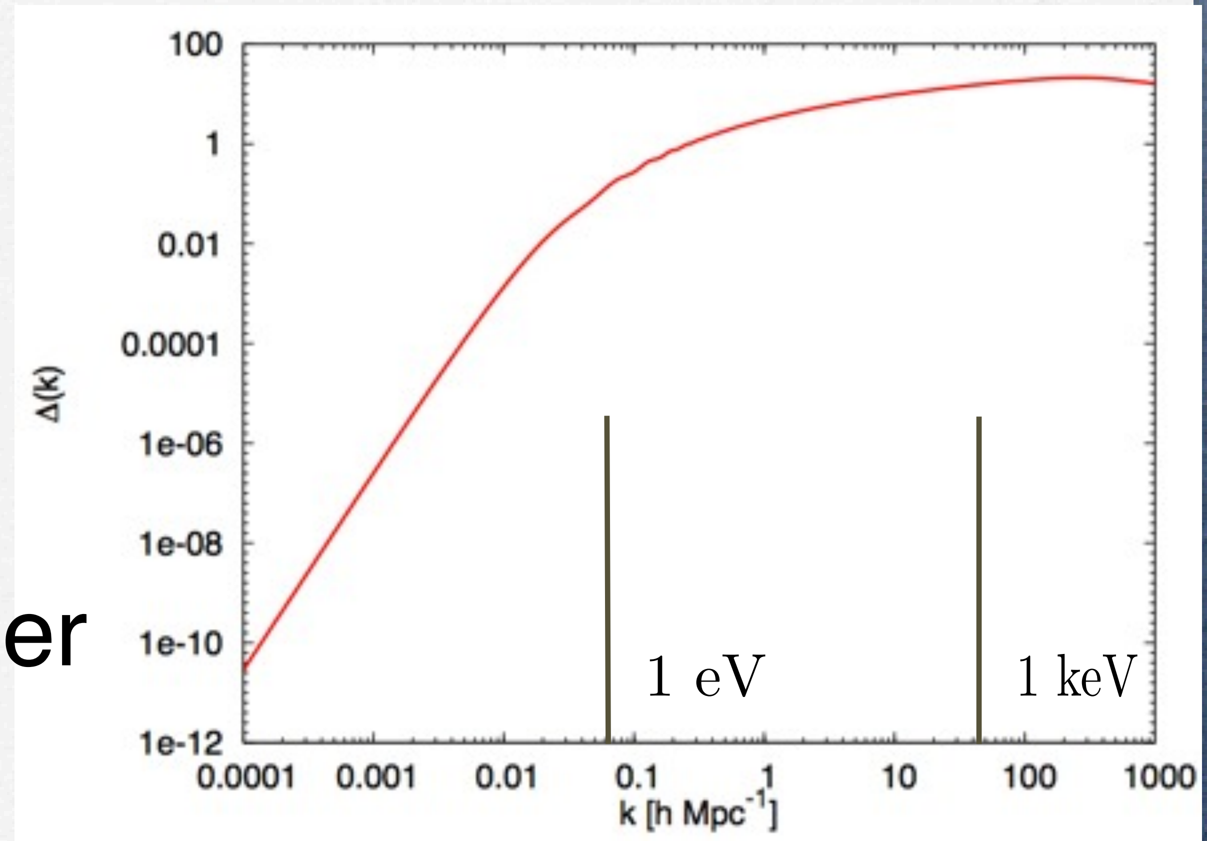
Around the epoch of recombination, baryons and photons drag each other through the Compton scattering
-> The primordial fluctuations of baryons and photons are erased



Limitation of CMB - Silk damping

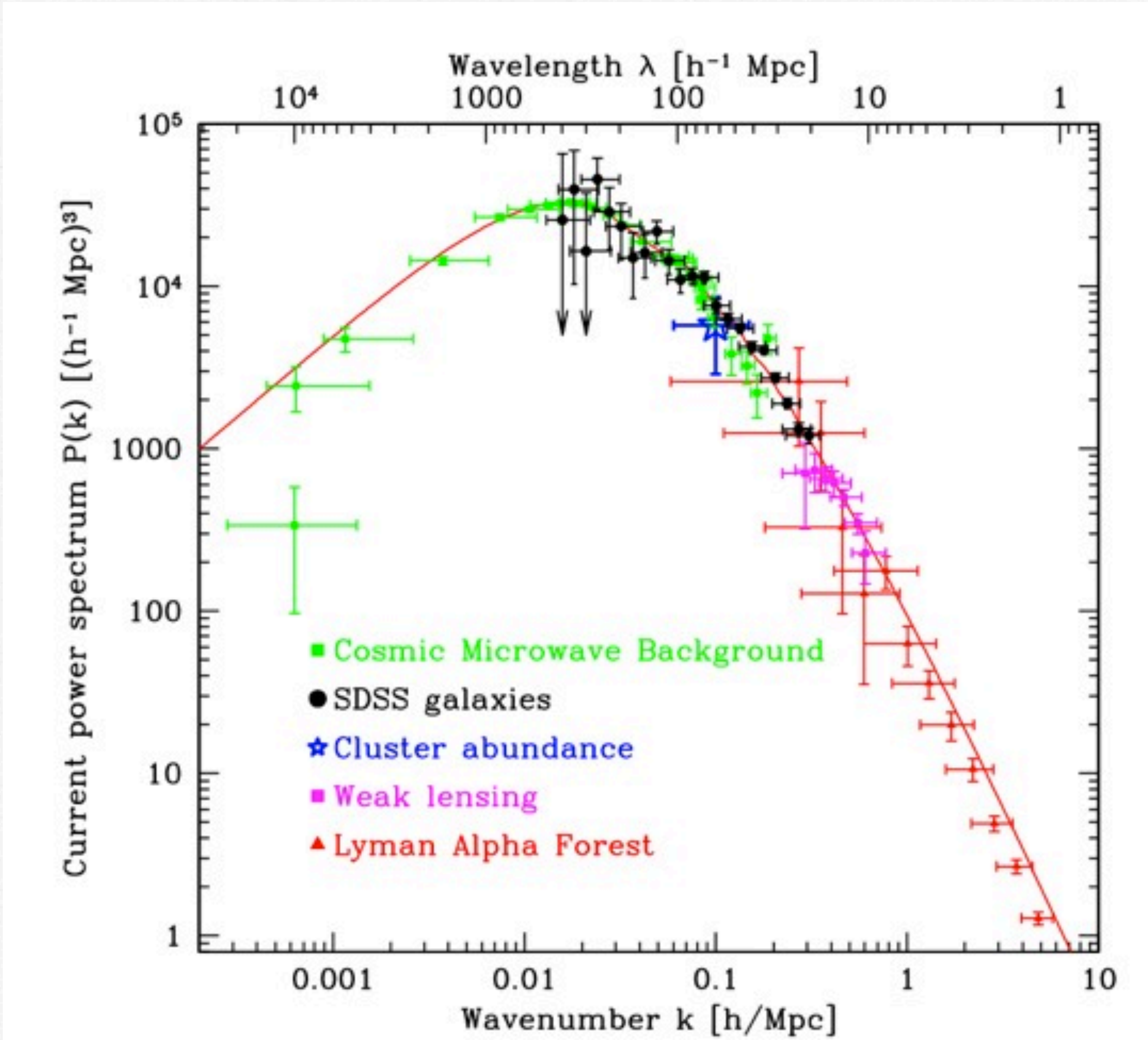
Silk damping makes the small-scale ($l>2000$ <-> $k>0.1$ Mpc^{-1}) matter fluctuations inaccessible

However, smaller-scale matter density fluctuations contains imprints of earlier Universe (e.g. $k\sim10$ Mpc^{-1} <-> $T\sim1$ keV) : hint of the nature of dark matter



-> Seek other probes than CMB

Matter power spectrum



Large-scale matter density fluctuations ($k<10\ Mpc^{-1}$) in ΛCDM cosmology are concordant with several observations.

Disadvantage in LSS observations

✓ Measurement

- ✓ indirect measurement
  - only luminous (low-redshift) objects can be observed
  -> selection bias

✓ Theory

- ✓ breakdown of perturbation theory for low red-shift and/or small-scale matter distributions
  -> large N-body simulations
- ✓ importance of galactic baryon physics
  -> large N-body+hydrodynamical simulations

evolution of density perturbation

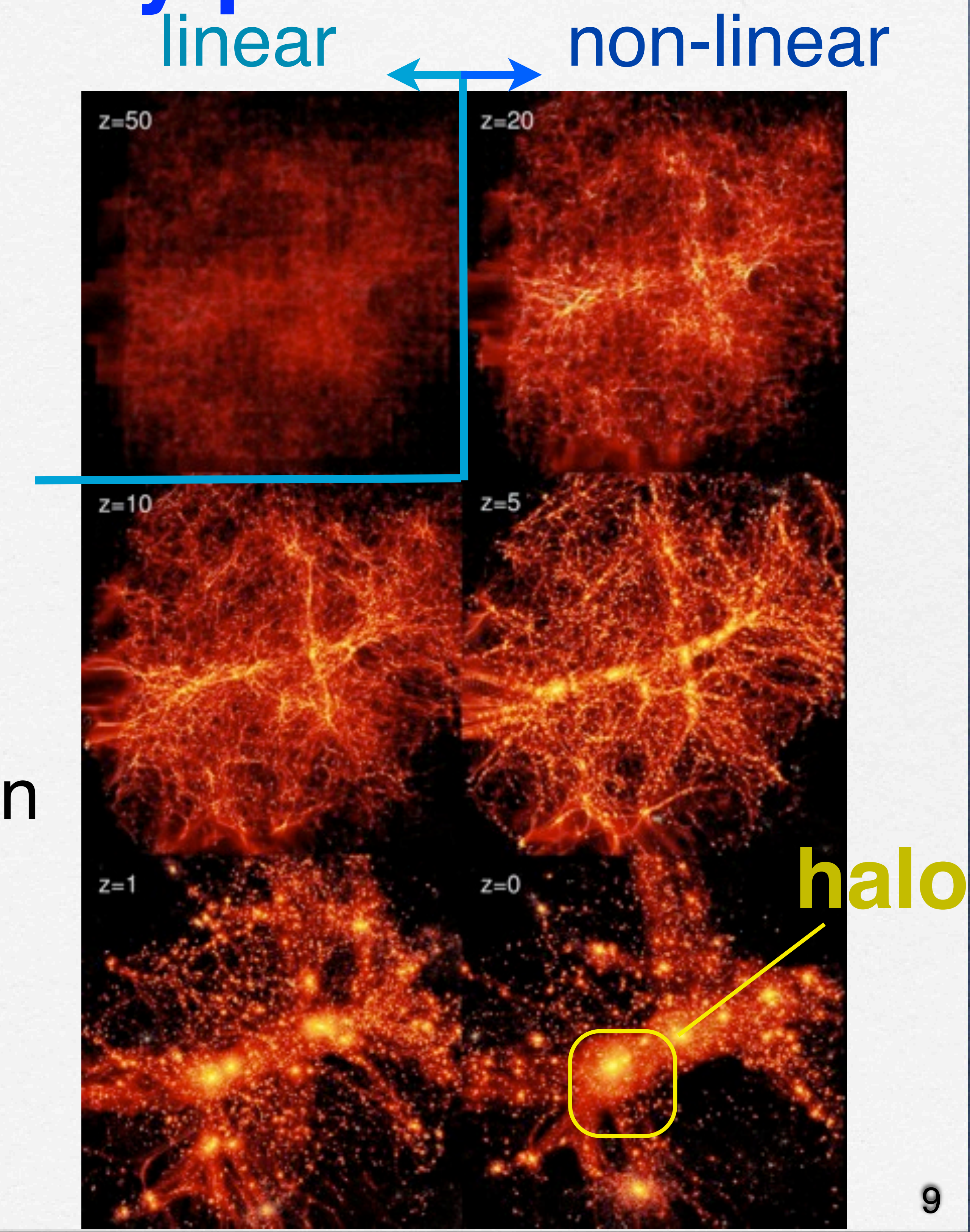
In the matter dominated era, density perturbation evolve in proportion to scale factor

$$\delta(t) \propto a$$

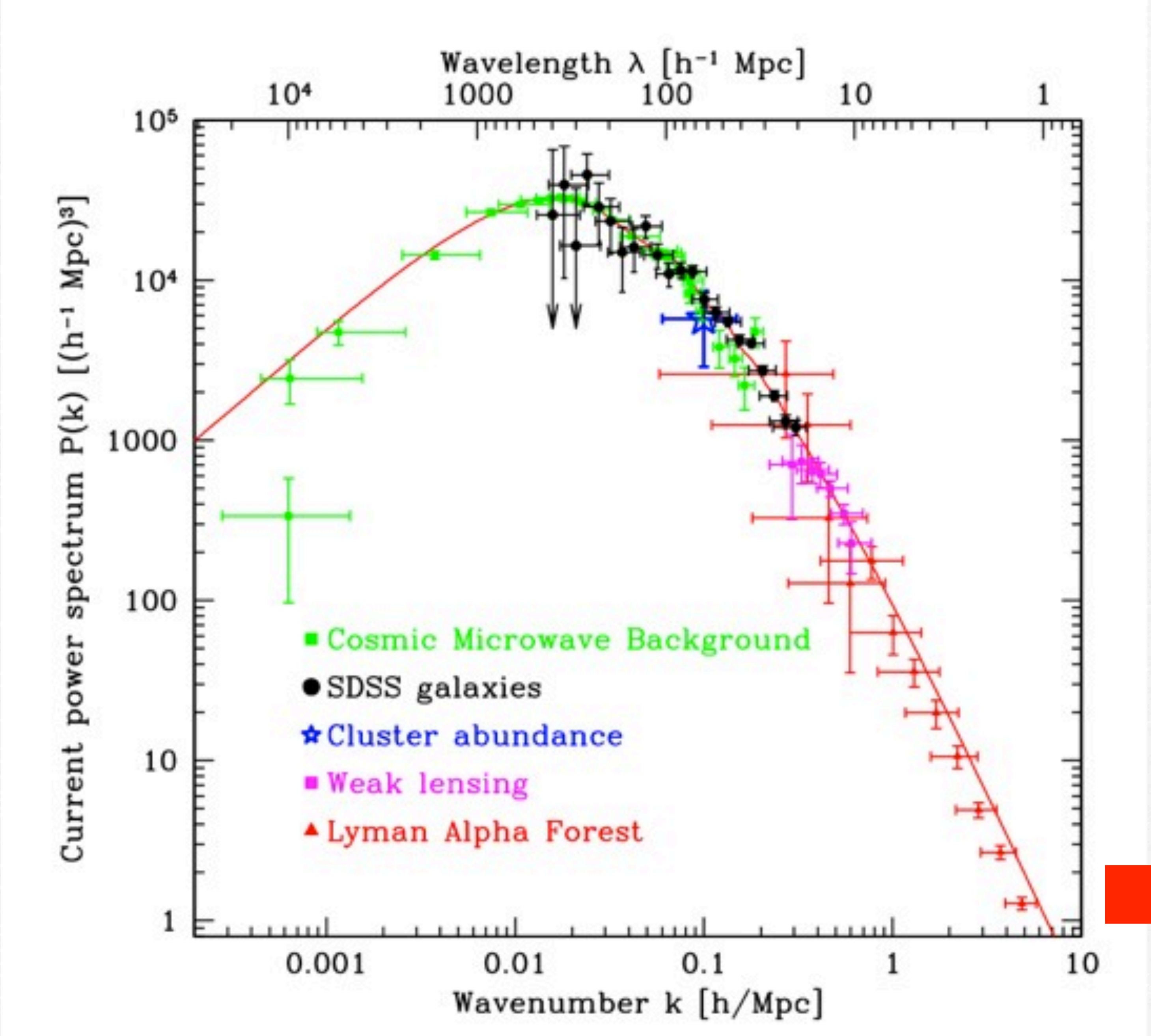
Then, density perturbation goes into non-linear evolution

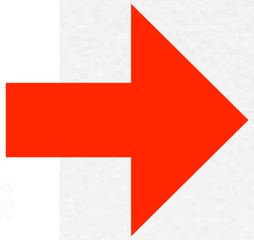
$$\delta(t) \gg 1$$

to form the structure of the Universe, which we observe now



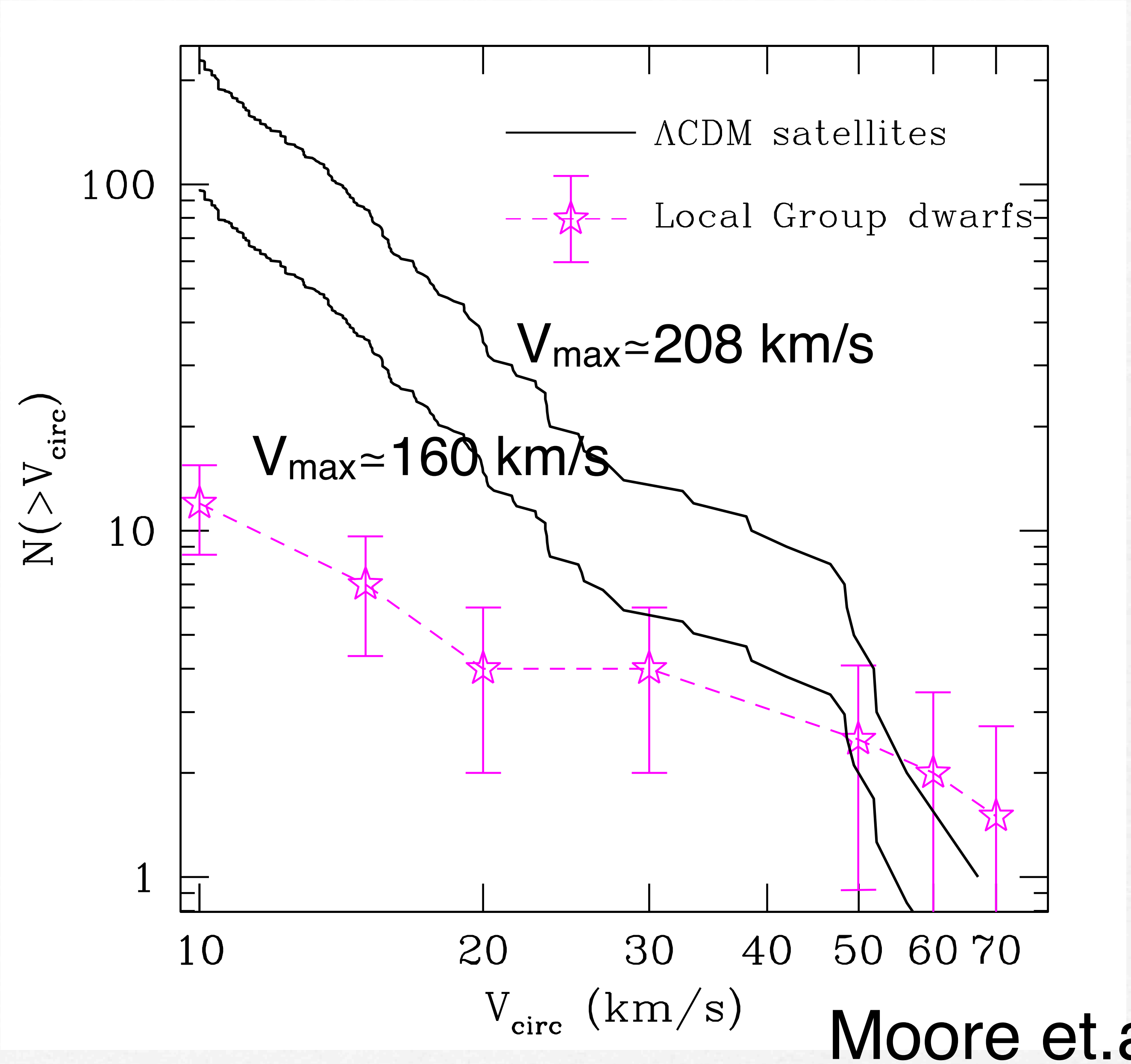
Smaller-scales





How about smaller-scale matter distribution?

Missing satellite problem

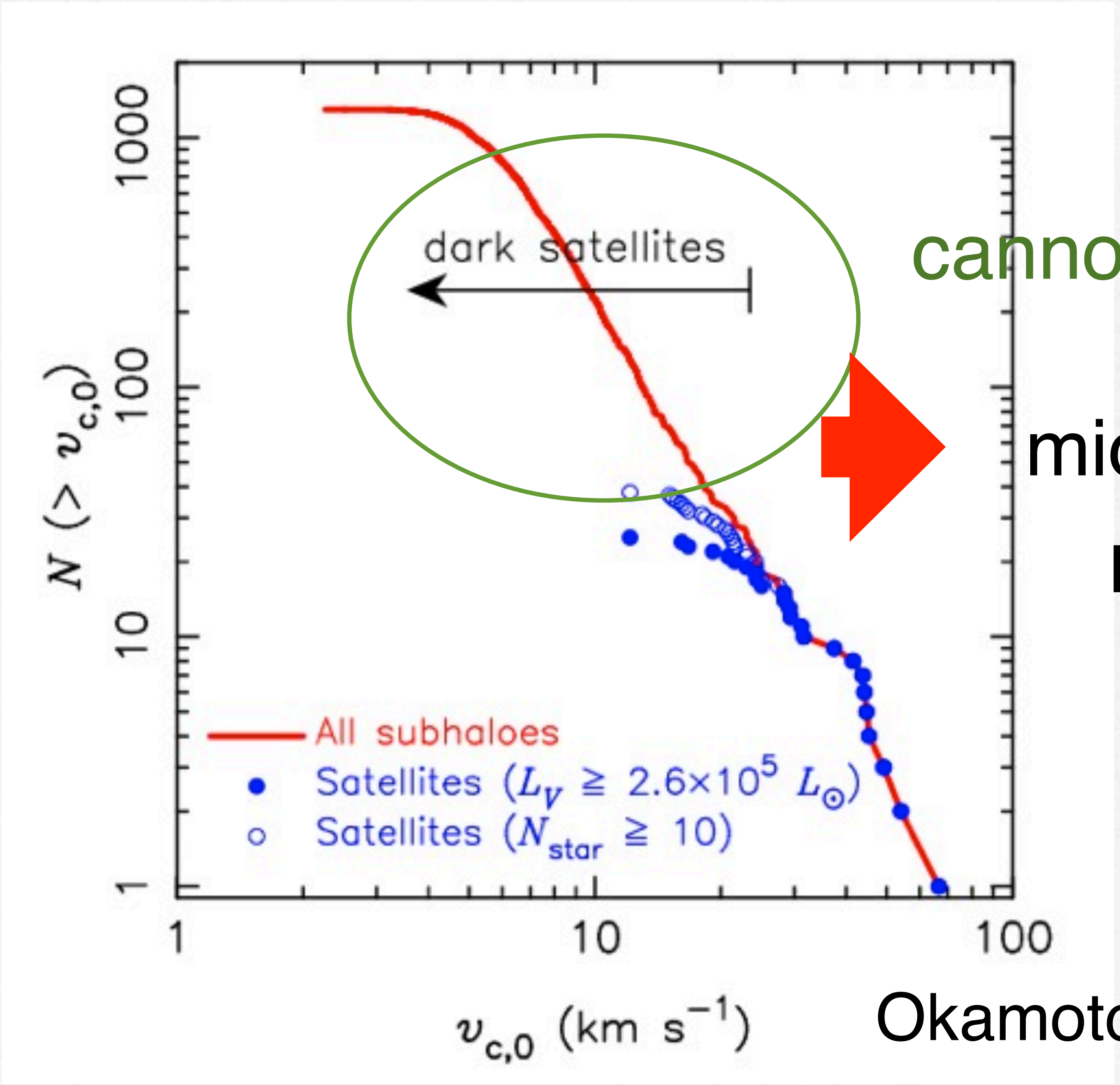


Moore et.al. 1999; Kravtsov 2009

The number of Observed satellites in the Milky Way are less than predicted in ΛCDM cosmology by a factor of ~10

One possible solution

baryonic physics - supernova explosion @ reionization



cannot be seen

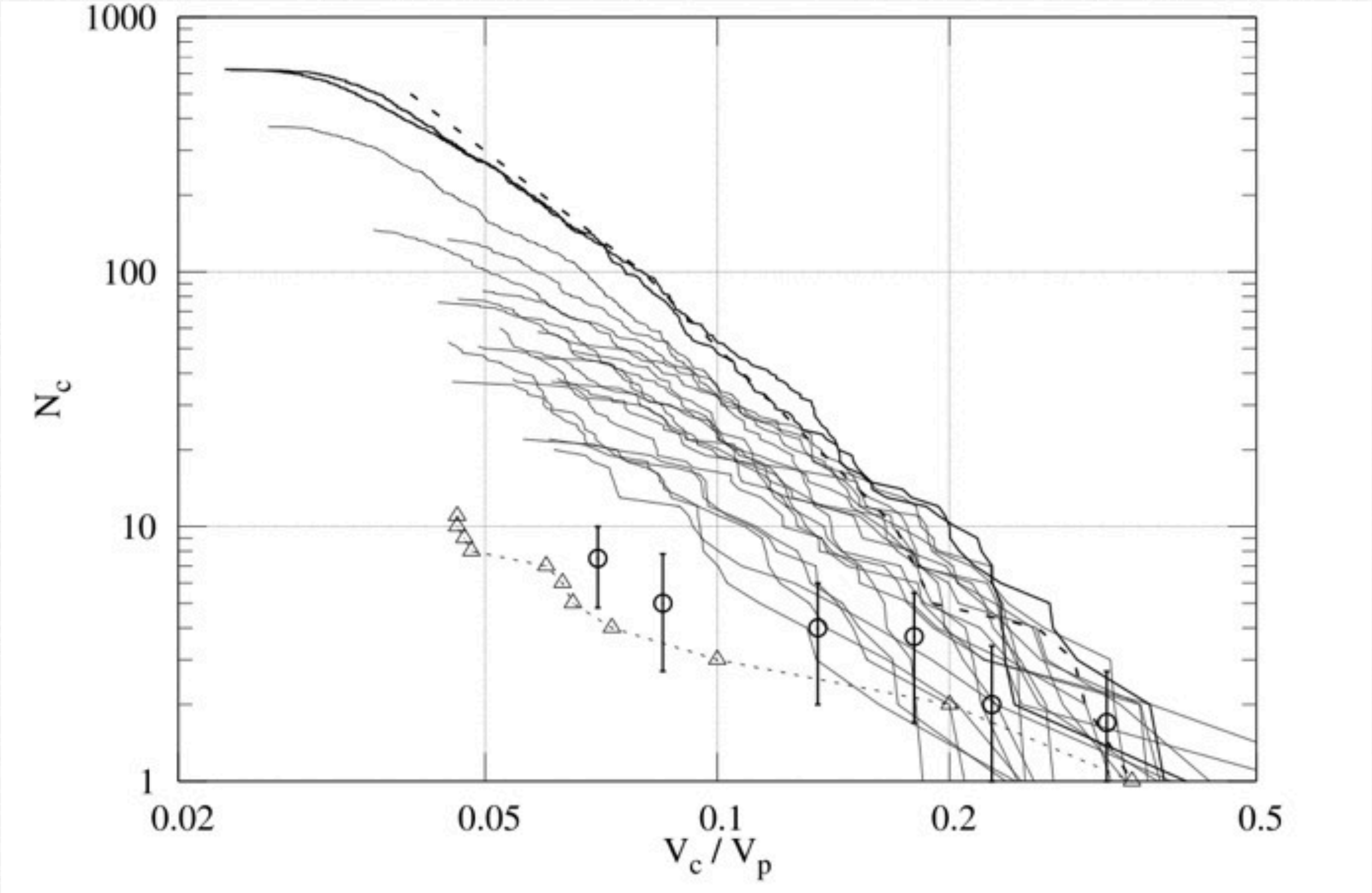
microlensing

Hisano et al. 2006

Okamoto, Frenck 2009

One possible solution

Cosmic variance - large variance of subhalo abundance



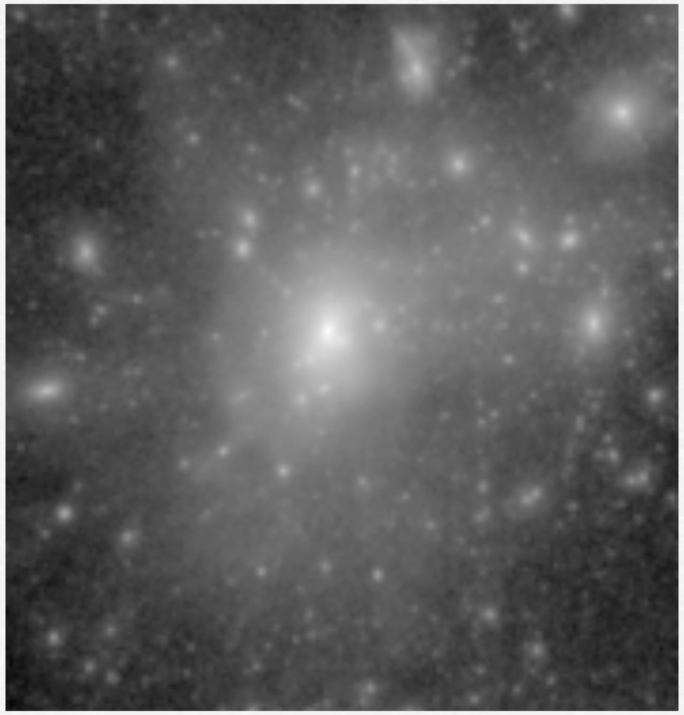
Ishiyama et al. 2008

One possible solution

Warm Dark Matter (WDM)
- Non-negligible velocity dispersion of WDM acts as an effective "pressure" of WDM fluids

-> The evolution of subgalactic-scale matter density fluctuations is suppressed

100 kpc



CDM

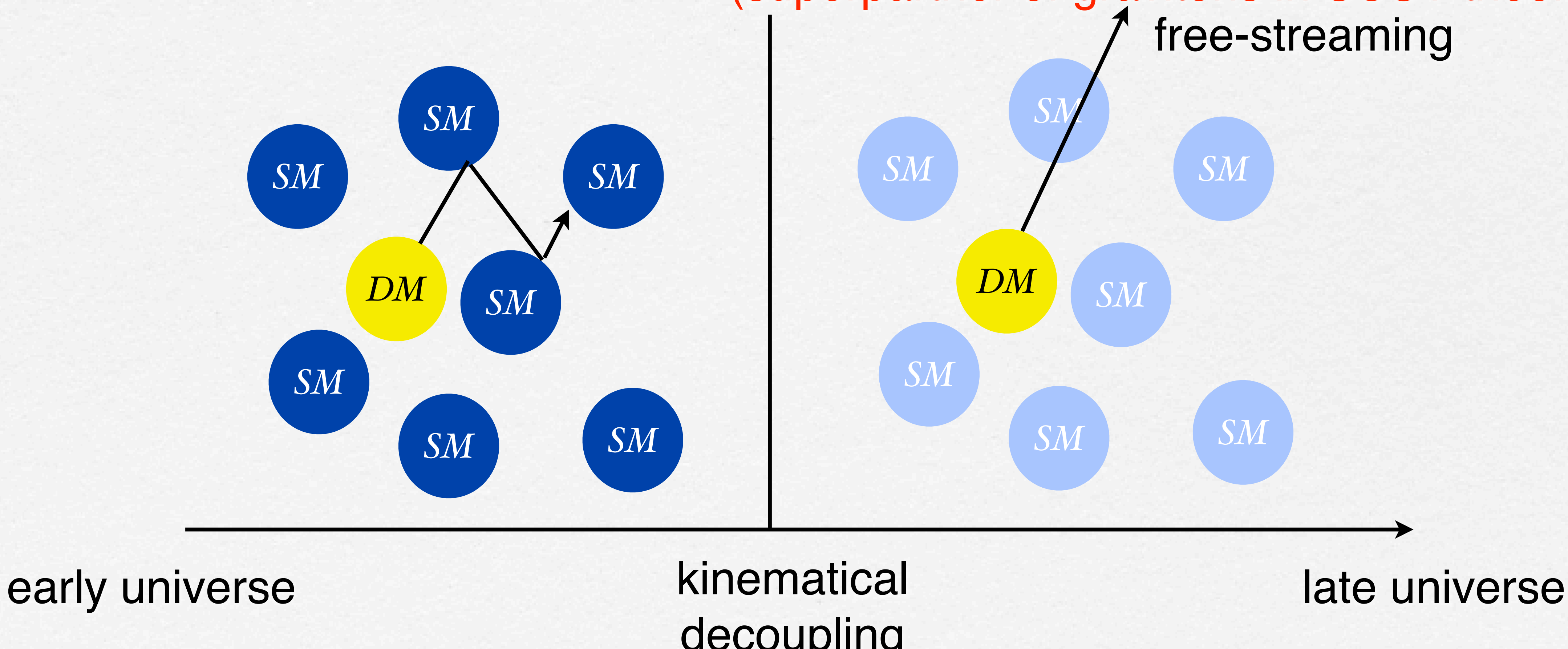
WDM

Particle Physics Scenarios of WDM

Thermal WDM   Bode et al. 2001

: DM particles are produced in the thermal bath and
are subsequently decoupled kinematically when they are relativistic
like SM left-handed neutrinos

particle physics candidate: light gravitinos
(superpartner of gravitons in SUSY theory)



➡ momentum (velocity) distribution $f(q) \propto 1/(e^{q/T}+1)$ $T = (10.75/g_*)^{1/3} T_\gamma$

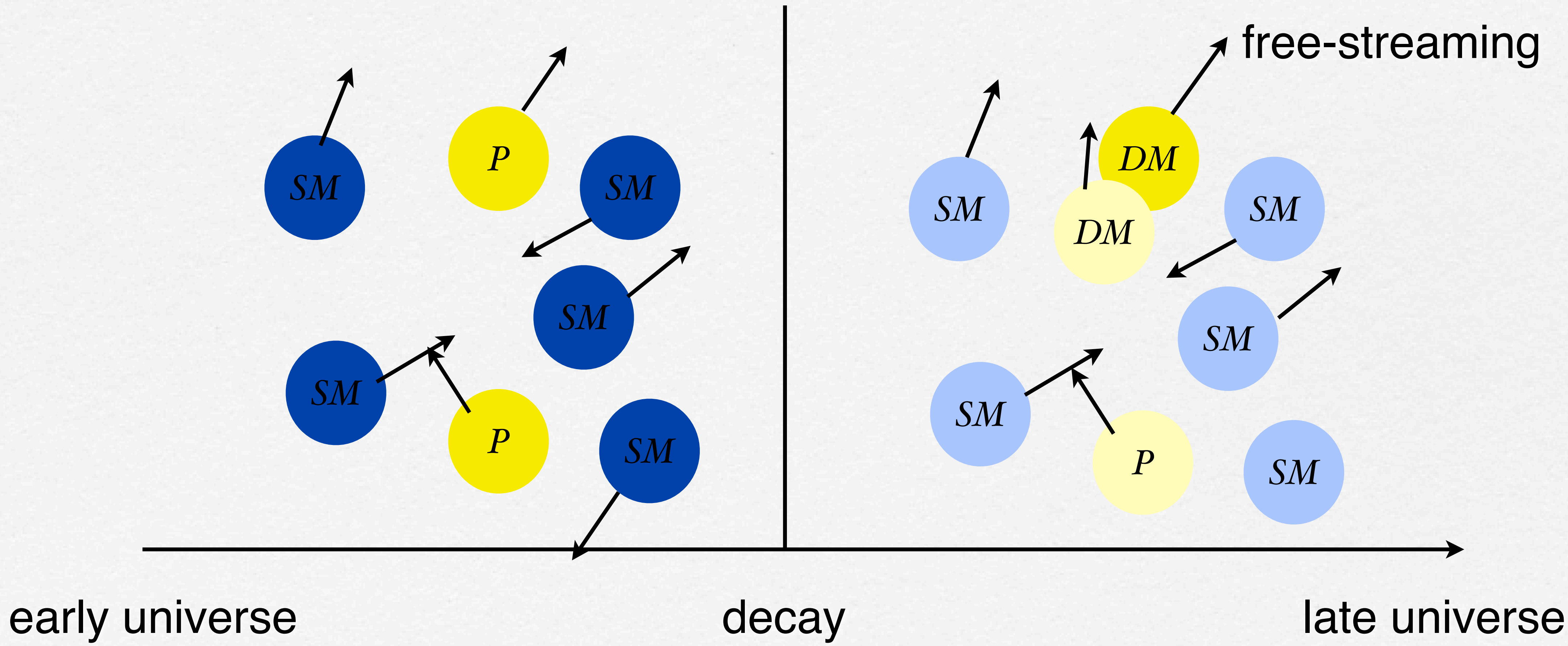
Particle Physics Scenarios of WDM

WDM produced by the thermal boson decay

Boyanovsky 2008

: unstable relativistic parent particles are produced in the thermal bath and gradually (out of equilibrium) decays into daughter particles (warm dark matter)

particle physics candidate: sterile neutrinos via decay of singlet Higgs



➡ momentum (velocity) distribution $f(q) \propto (q/T)^{-0.5} e^{-q/T}$ $T = (10.75/g_*)^{1/3} T_\gamma$

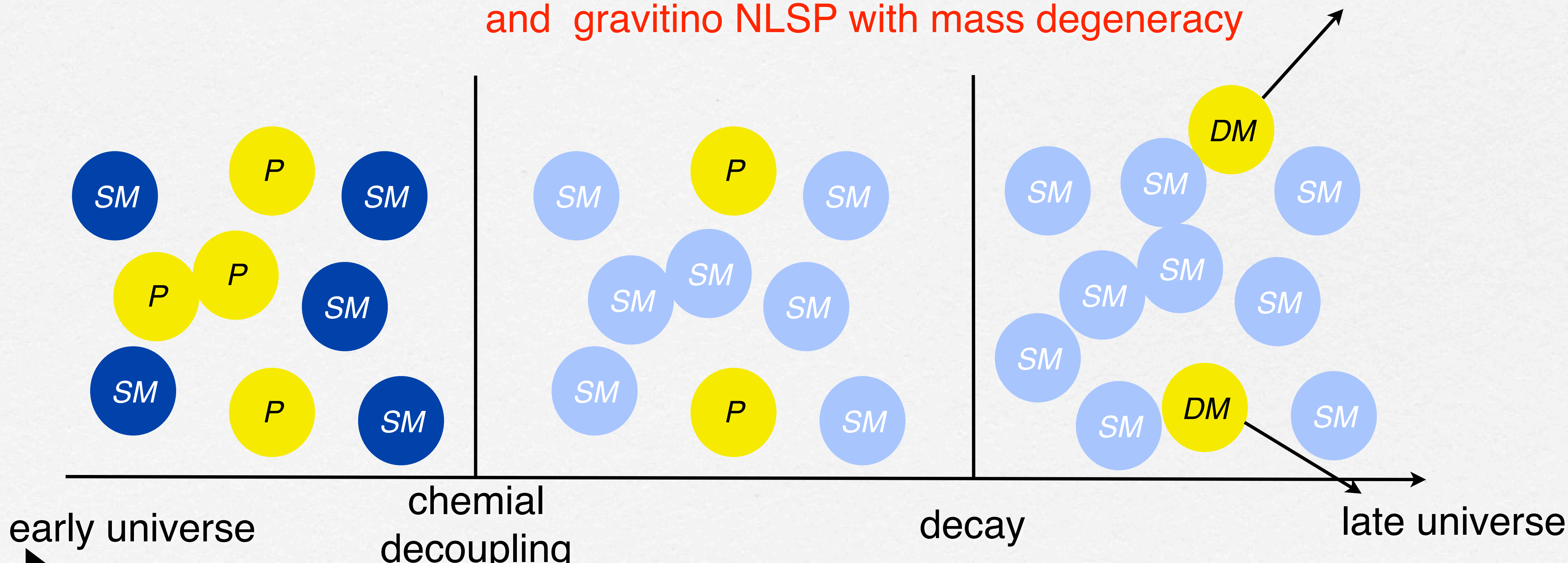
Particle Physics Scenarios of WDM

WDM produced by the non-relativistic particle decay

Kaplinghat 2005

: unstable but long-lived parent particles are produced in the thermal bath and become nonrelativistic and decoupled as usual WIMP scenario. Finally they decay into daughter particles (warm dark matter)

particle physics candidate: neutralino LSP (Lightest Supersymmetric Particle) and gravitino NLSP with mass degeneracy

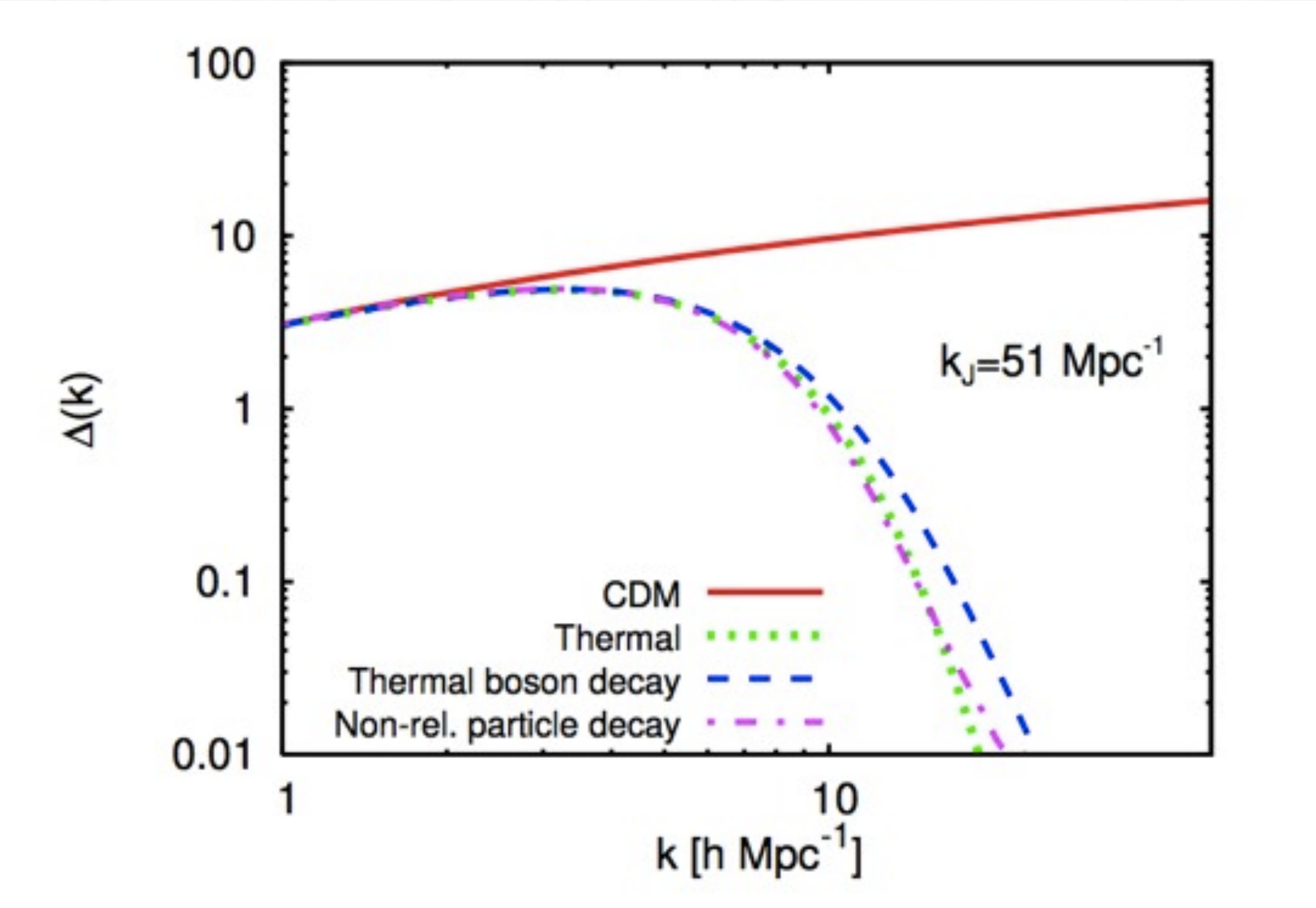


momentum (velocity) distribution $f(q) \propto (q/p_{\rm cm})^{-1} e^{-(q/p_{\rm cm})^2}$ $p_{\rm cm} = P_{cm} a_{\rm decay}$

Jeans scale at matter-radiation equality

$$k_{\mathrm{J}} = a\sqrt{\frac{4\pi G\rho_{\mathrm{M}}}{\sigma^2}}\Bigg|_{t=t_{\mathrm{eq}}}$$

σ^2 : mean square of the velocity of the dark matter particles



characterizes the linear matter power spectra in different WDM models

One possible solution

Long-Lived CHAMP (Charged Massive Particle)

Sigurdson and Kamionkowsky 2004

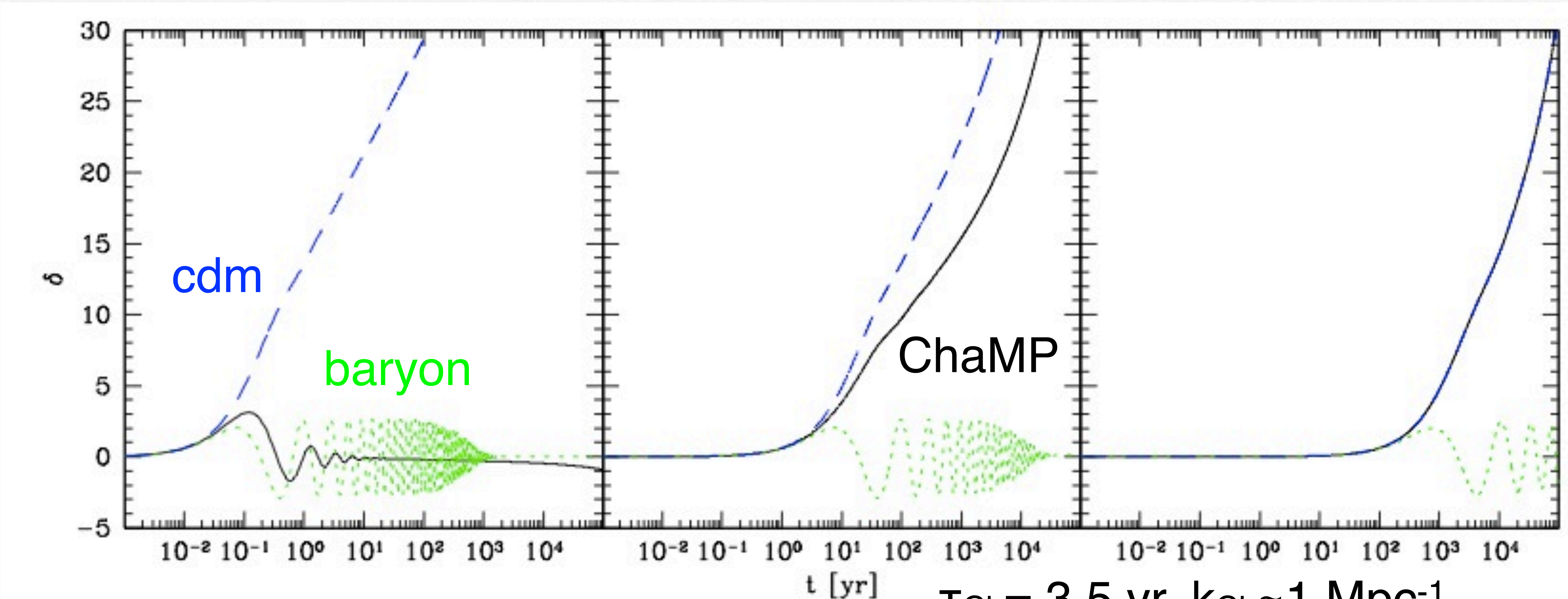
CHAMP have Electric-Magnetic charge and acoustically oscillate with baryons by photon pressure like proton

-> If they are stable or their life time is longer than the age of the Universe, they spoil success of ΛCDM cosmology in LSS of the Universe

-> they should have proper life time

particle physics candidate: staus (superpartner of tau particle in SUSY theory) and gravitinos with mass degeneracy

Long-Lived CHAMP

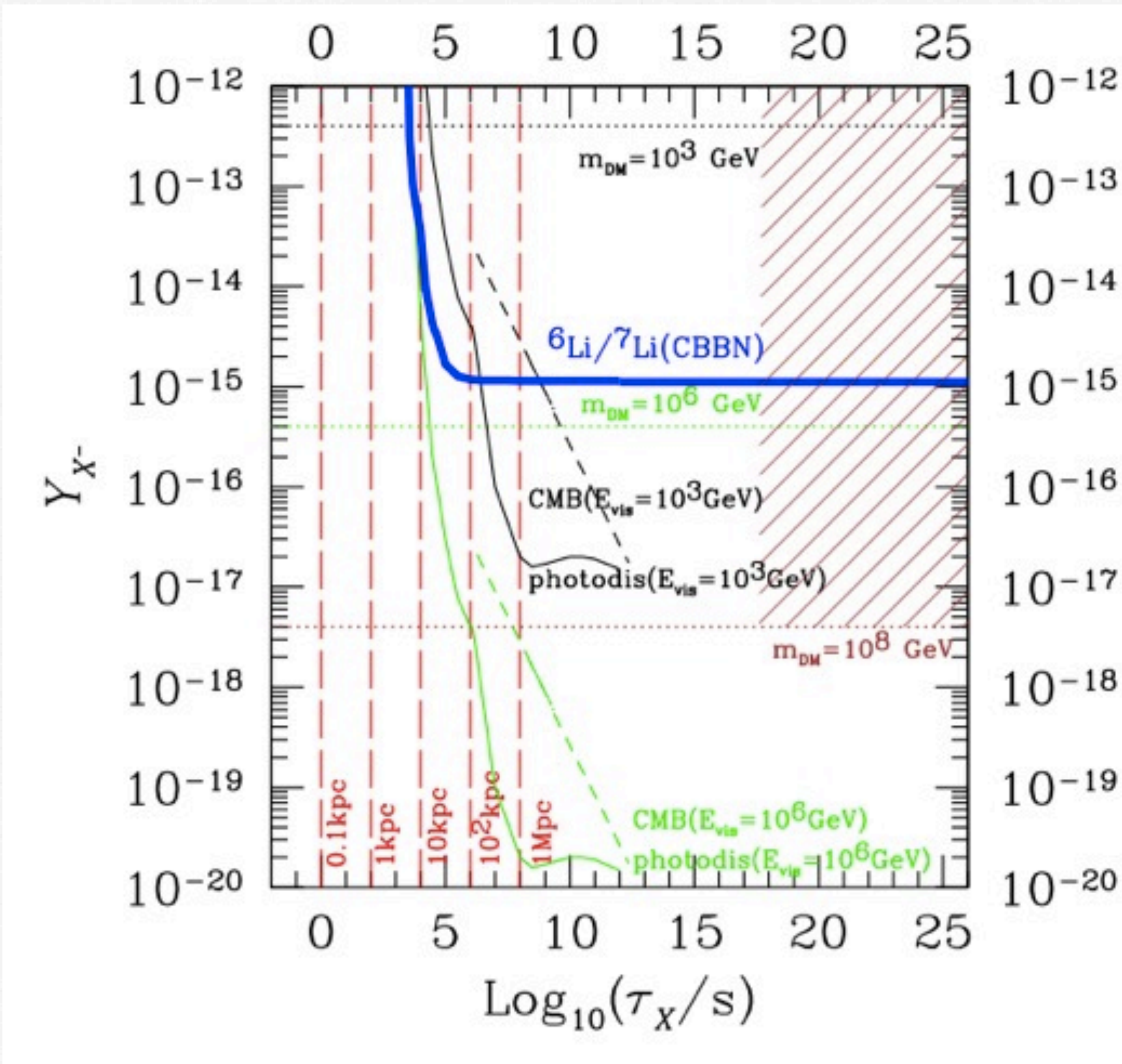


τ_{Ch}= 3.5 yr, $k_{Ch} \simeq 1$ Mpc^{-1}

Cut-off scale of matter power spectra is determined by the life time of CHAMP τ_{Ch}

$$k_{\rm Ch} = aH\big|_{t=\tau_{\rm Ch}}$$

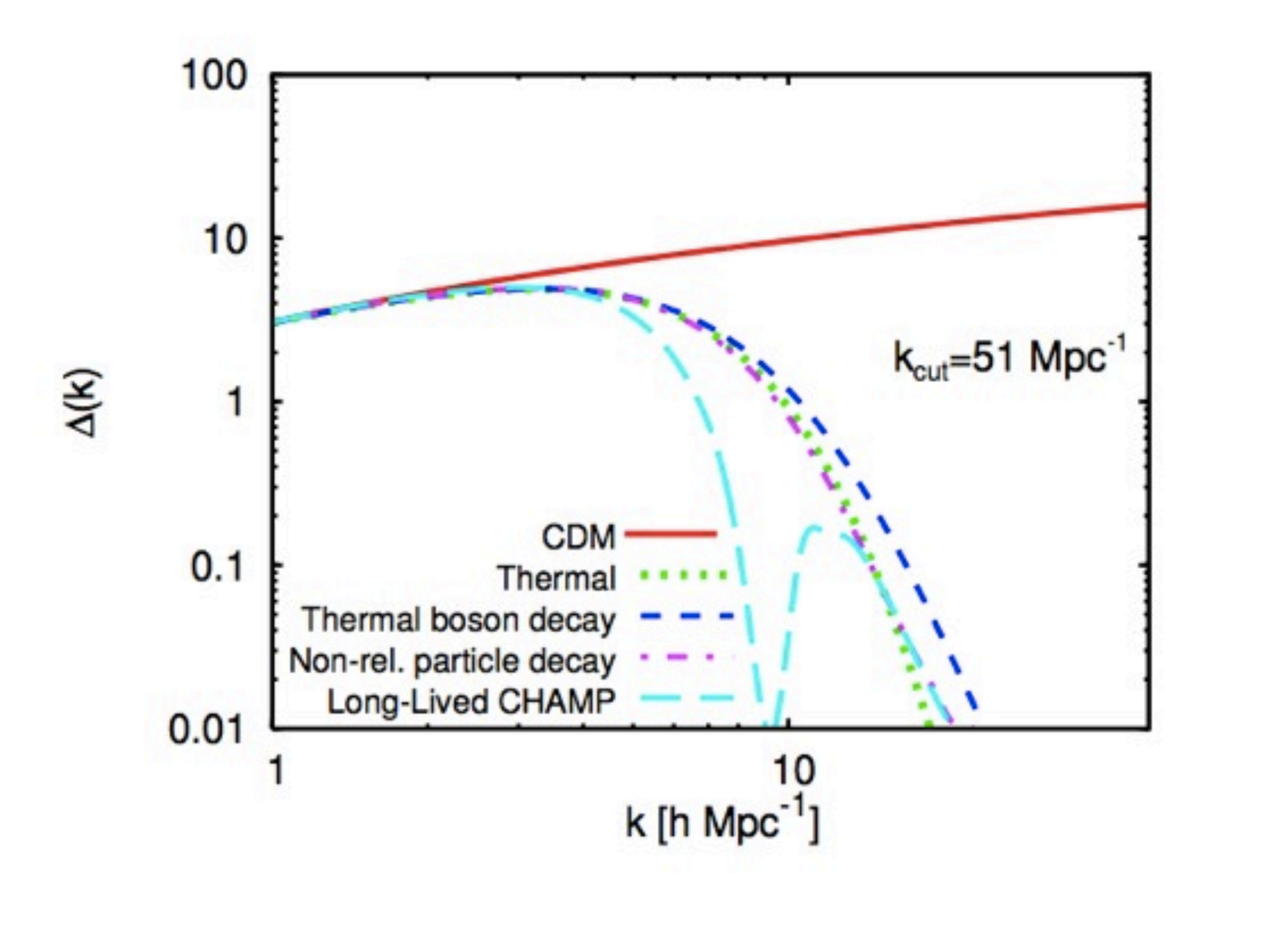
Constraint on Long-Lived CHAMP



Kohri and Takahashi, 2009

The mass of Long-Lived CHAMP should be large and degenerate with daughter DM particle

Linear matter power spectra



$$k_{\rm cut} \equiv k_{\rm J} \simeq 45\, k_{\rm Ch}$$

Linear matter power spectra with the same cut-off scale are similar in different models

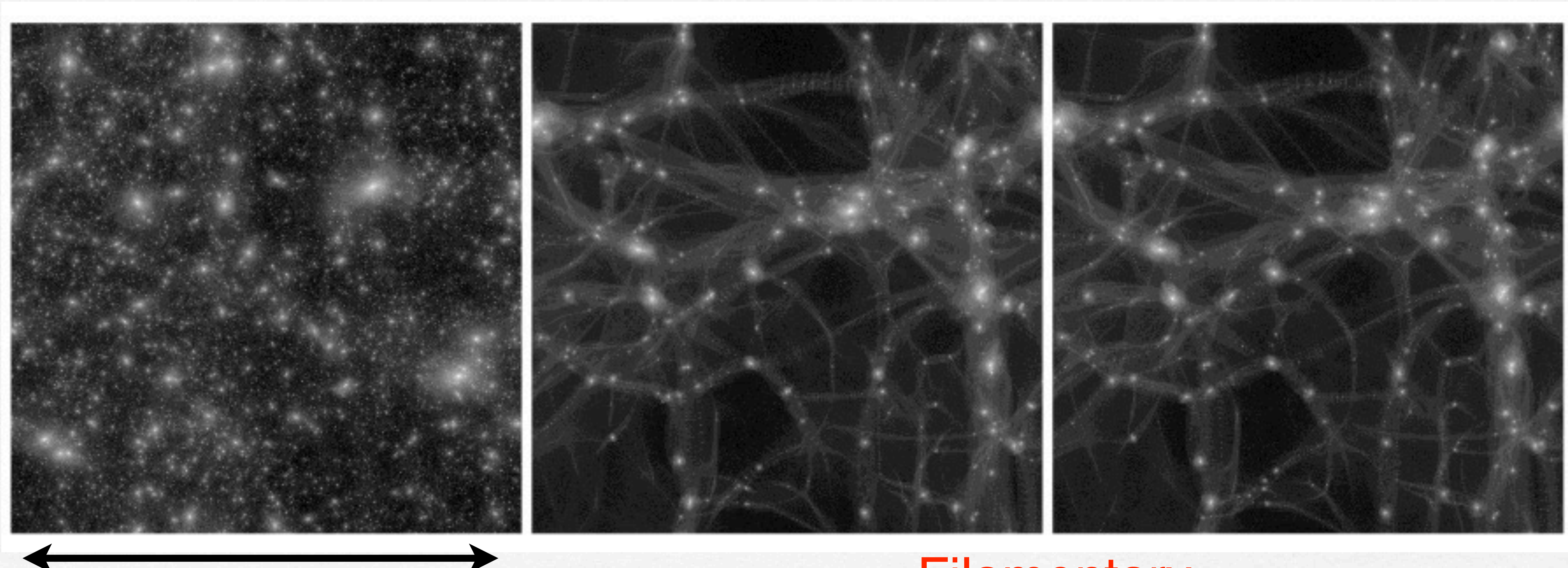
➡ How about the matter distribution after non-linear evolution?

Simulated matter distributions

CDM

Thermal WDM with $k_{cut} \simeq 51\ Mpc^{-1}$

Long-Lived CHAMP with $k_{cut} \simeq 51\ Mpc^{-1}$

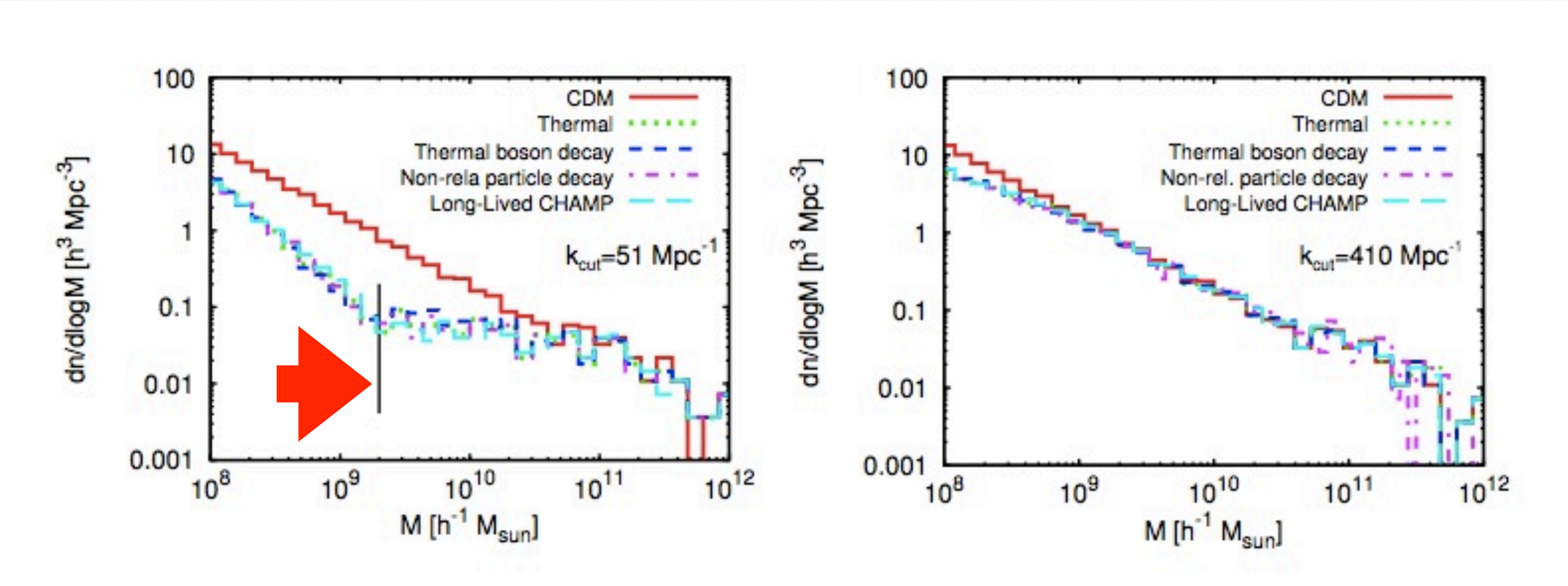


10 Mpc

Filamentary

Difficult to distinguish matter distribution in Thermal WDM and Lon-Lived CHAMP with the same cut-off

Simulated halo mass functions



$$M = \frac{4\pi\rho_{\rm M}}{3}\left(\frac{2\pi}{k_{\rm cut}}\right)^3 \simeq 2\times 10^9\, h^{-1}\, M_{\rm sun} \times \left(\frac{51\,{\rm Mpc}^{-1}}{k_{\rm cut}}\right)^3$$

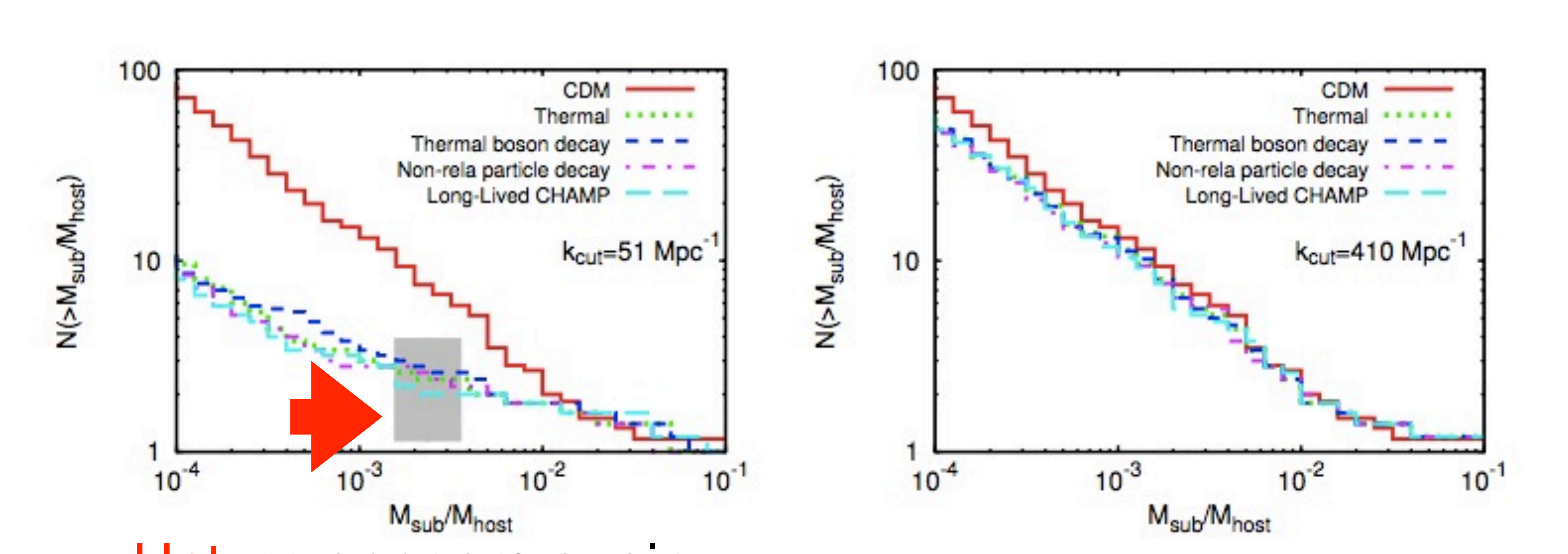
Upturn may be owing to the artificial objects due to the discreteness effect of the simulation

Wang and White 2007

Simulated subhalo mass functions

Pick up simulated Milky Way-size halos with

$$0.5 \times 10^{12}\, h^{-1}\, M_{\rm sun} < M_{\rm halo} < 1.5 \times 10^{12}\, h^{-1}\, M_{\rm sun}$$



Upturn appears again

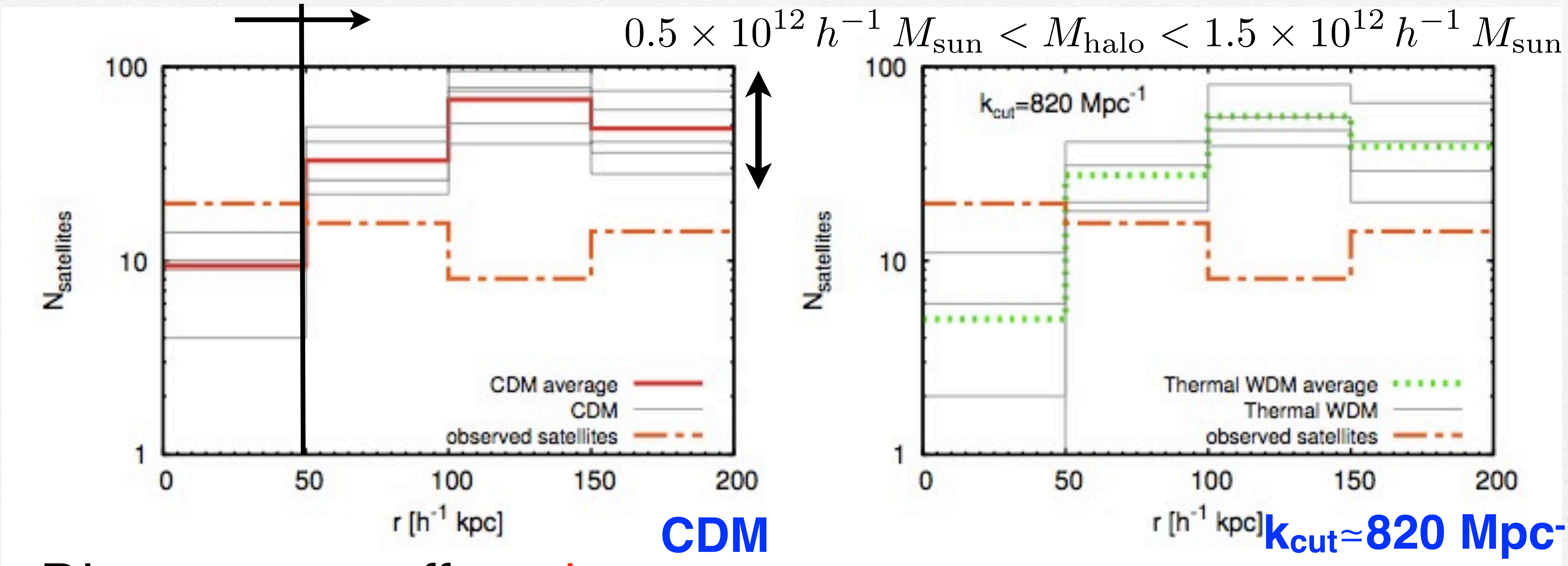
-> We should take care of artificial effect in discussing the missing satellite problem (below)

Radial profiles of simulated subhalos

resolution limit

different halos in the simulation

$0.5 \times 10^{12}\, h^{-1}\, M_{\rm sun} < M_{\rm halo} < 1.5 \times 10^{12}\, h^{-1}\, M_{\rm sun}$

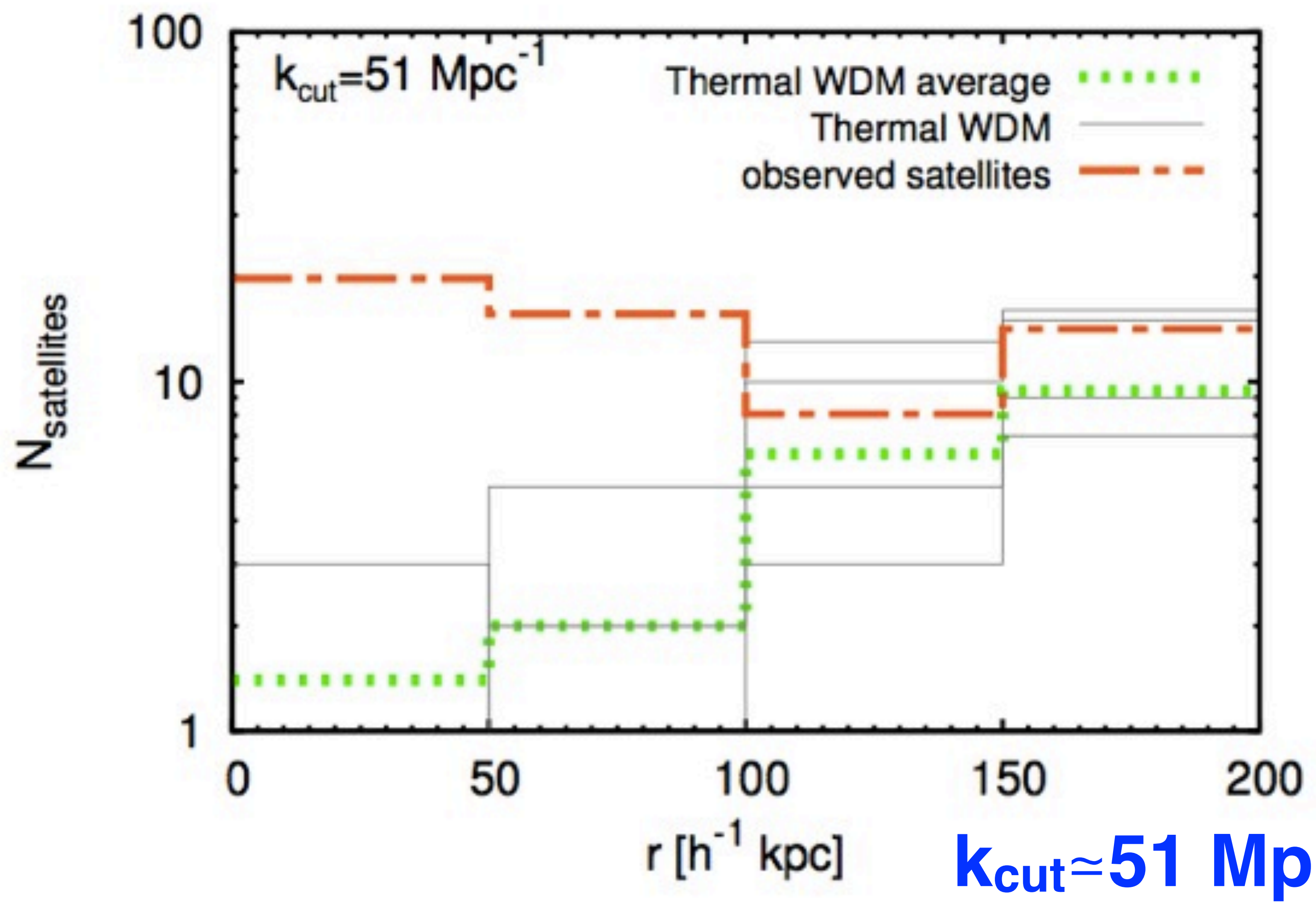


Discreteness effect does not matter

<- large cut-off scale

Predicted number of subhalos is larger than the number of Milky Way satellites (missing satellite problem)

Radial profiles of simulated subhalos

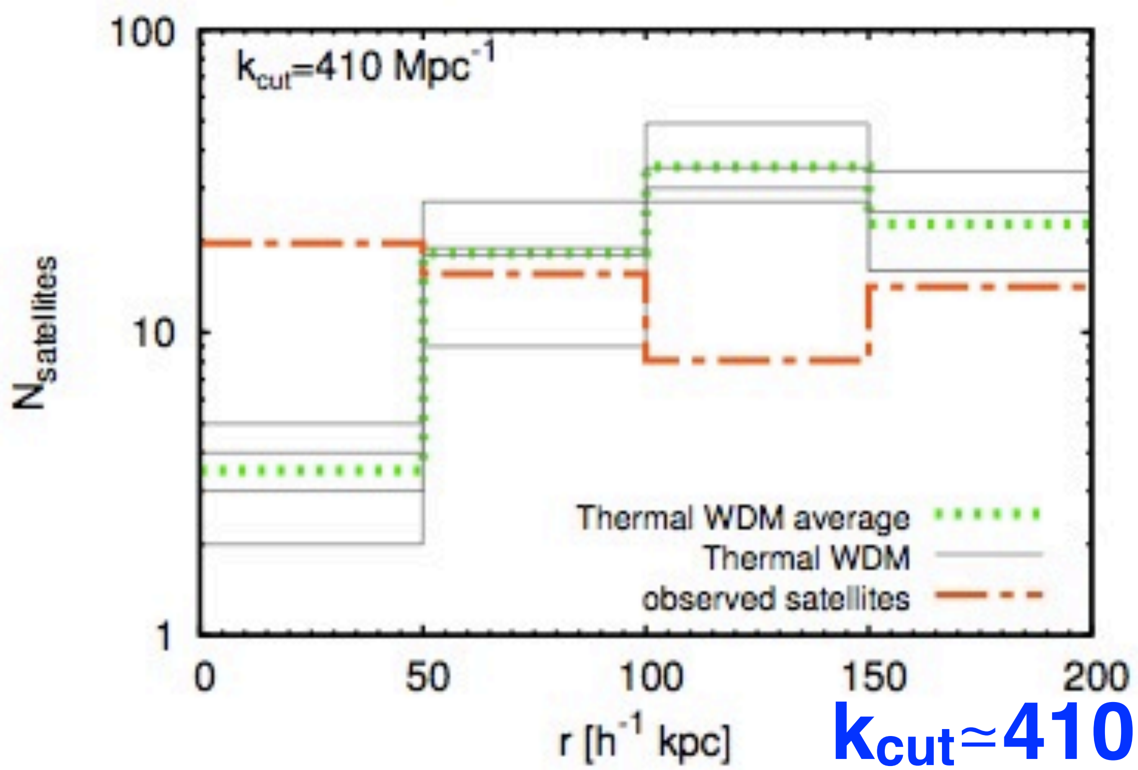


$k_{cut} \simeq 51$ Mpc^{-1}

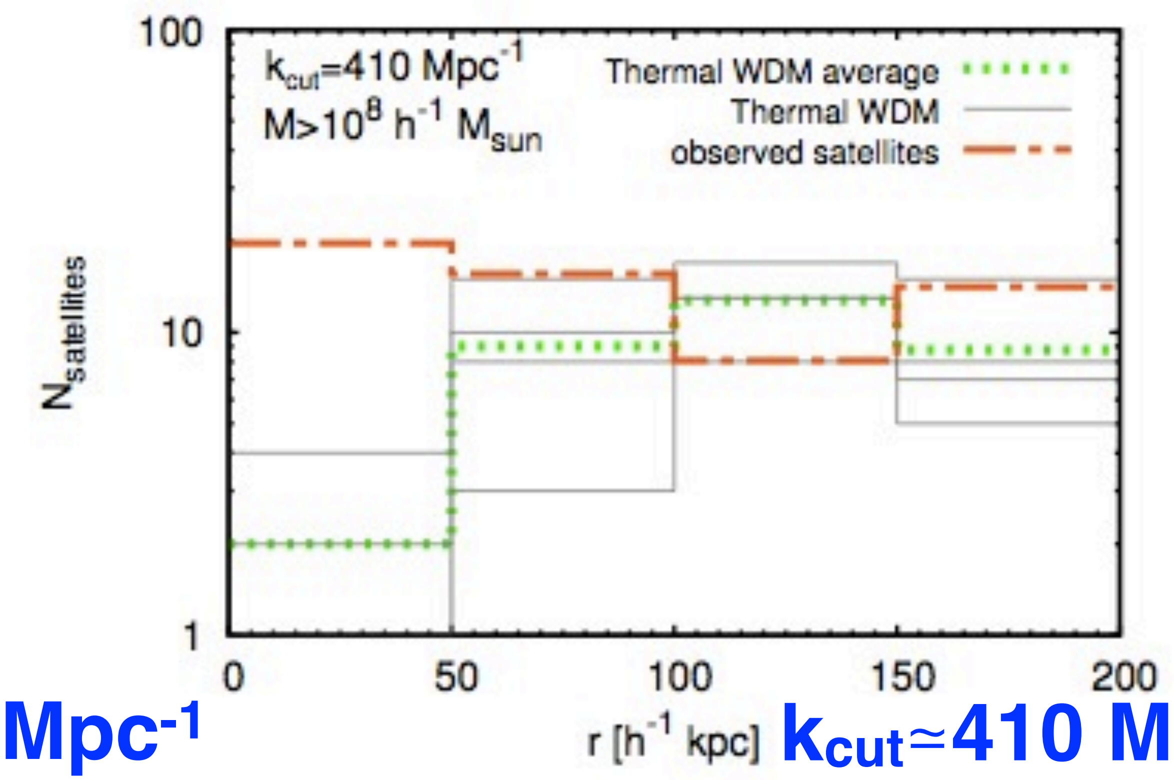
Predicted number of subhalos even with artificial objects is smaller than the number of Milky Way satellites

-> Thermal WDM model with $k_{cut} \simeq 51$ Mpc^{-1} is disfavored

Radial profiles of simulated subhalos



k_{cut}≃410 Mpc^{-1}
w/ artificial objects

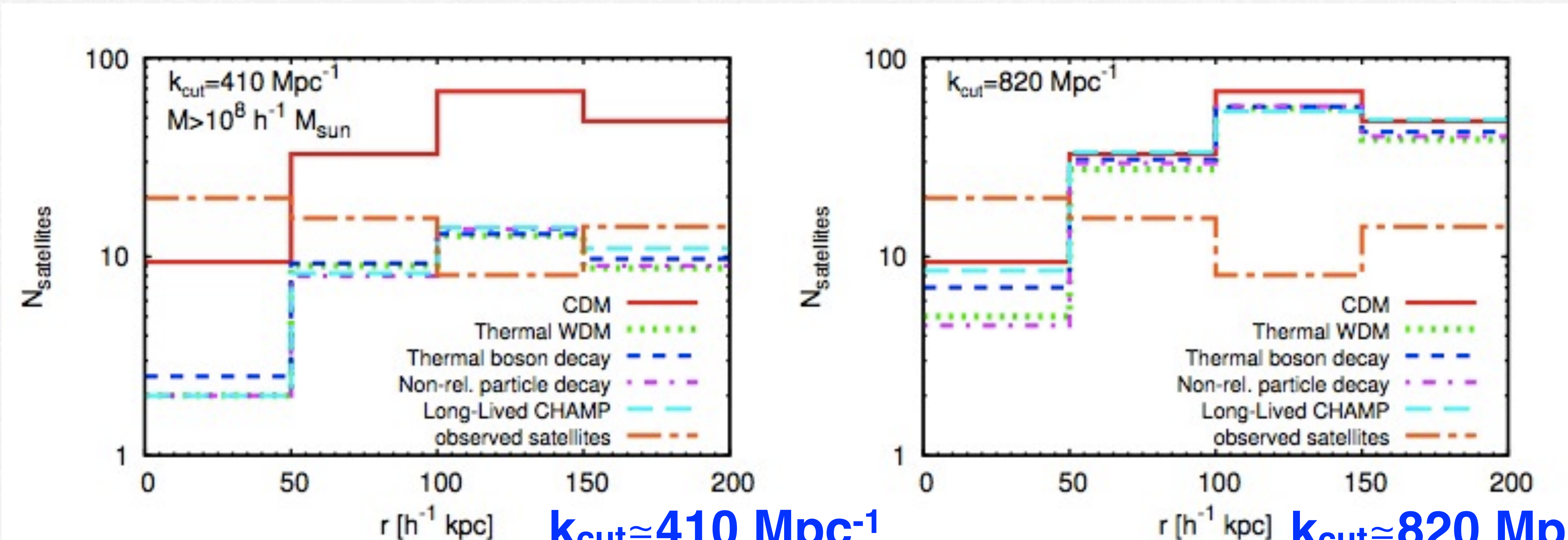


k_{cut}≃410 Mpc^{-1}
w/o artificial objects

Discarding small artificial sub-halos ($M_{\rm sub} < M_{\rm c} \simeq 10^8\, h^{-1}\, M_{\rm sun}$) reduces the subhalo abundance by a factor of ~2

Thermal WDM model with k_{cut}≃410 Mpc^{-1} appears to reproduce the observed distribution of satellites

Comparison between different models



$k_{cut} \simeq 410$ Mpc^{-1} **$k_{cut} \simeq 820$ Mpc^{-1}**

w/o artificial objects

The subhalo abundances are also well characterized by the cut-off scale k_{cut}

Conclusion

- ✓ WDM is expected to be one possible solution to the missing satellite problem
- ✓ Linear matter power spectra in different WDM models and Long-Lived CHAMP model are characterized by the cut-off scale k_{cut}, which is directly related to the particle physics model parameters
- ✓ Discreteness effect should be taken care of in WDM simulations
- ✓ k_{cut} also characterizes the non-linear structure of the Universe and models with $k_{cut} \simeq 50$-800 Mpc^{-1} can resolve the missing satellite problem