Structure Formation in Warm Dark Matter Models

6. June @ Meudon

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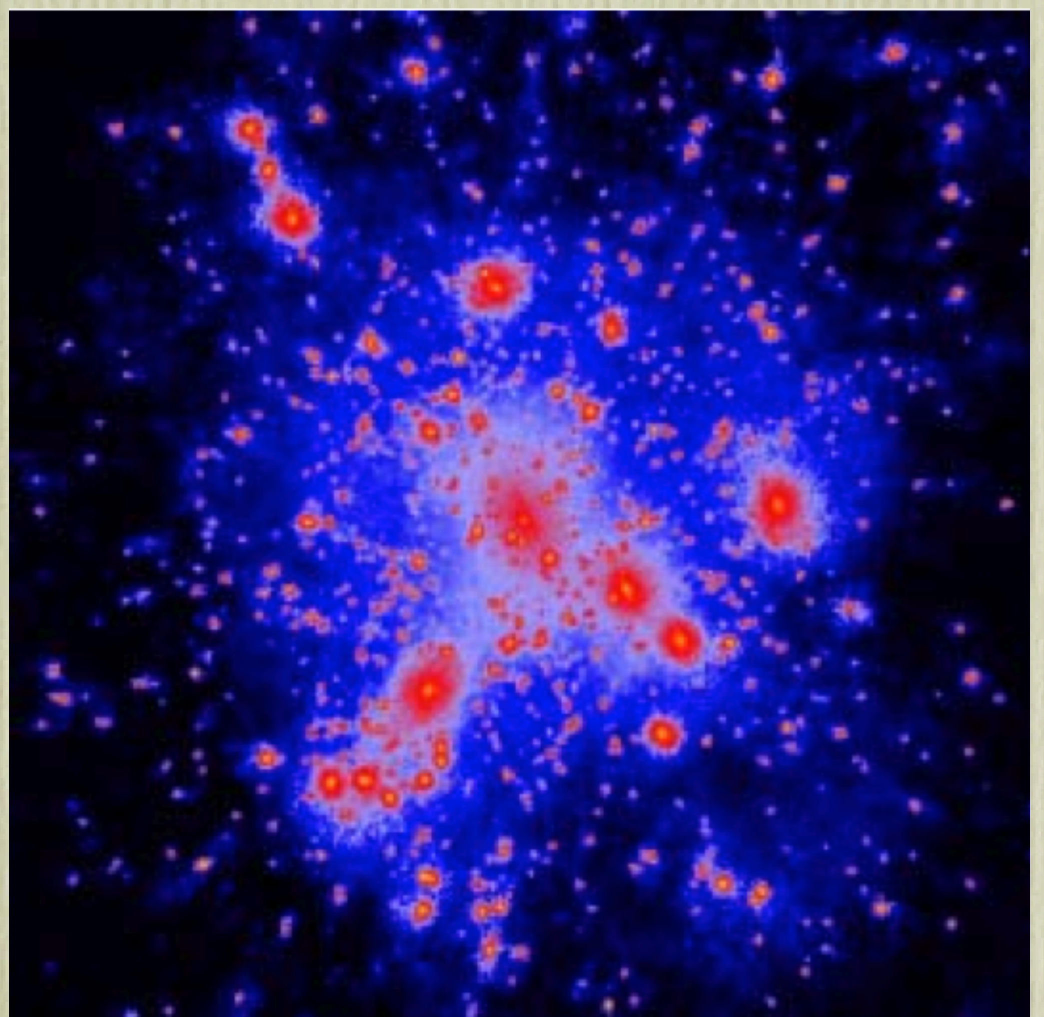
talk contents

1. wdm (warm dark matter) review in view of astrophysics
2. wdm scenarios in view of particle physics
3. ChaMP (chaged massive particles) as wdm
4. summary

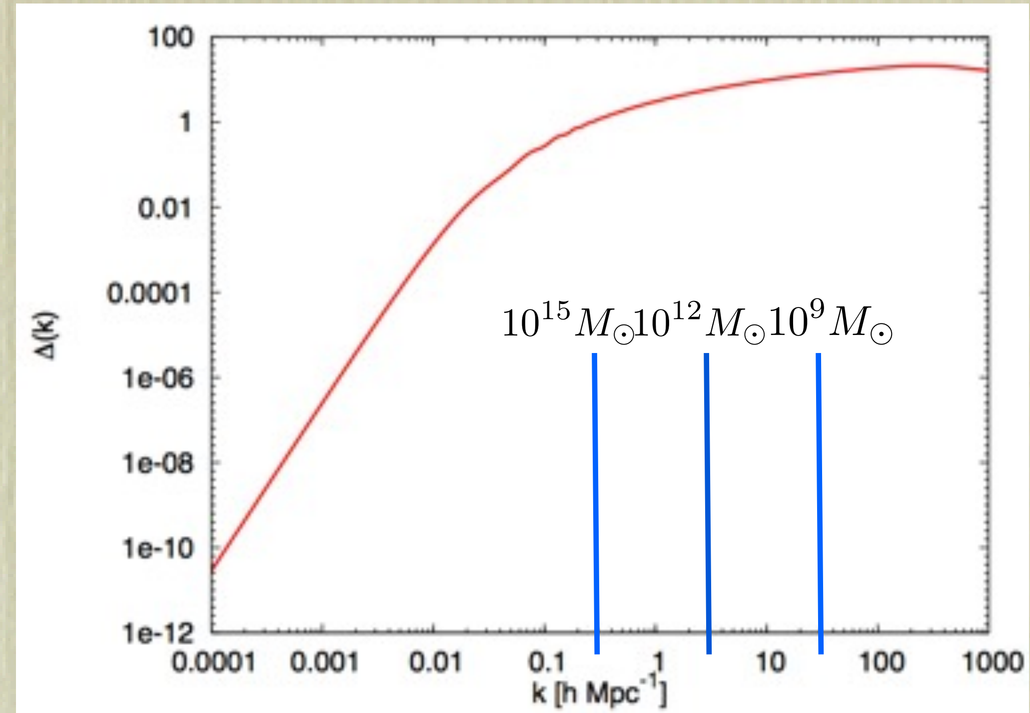
small scale crisis

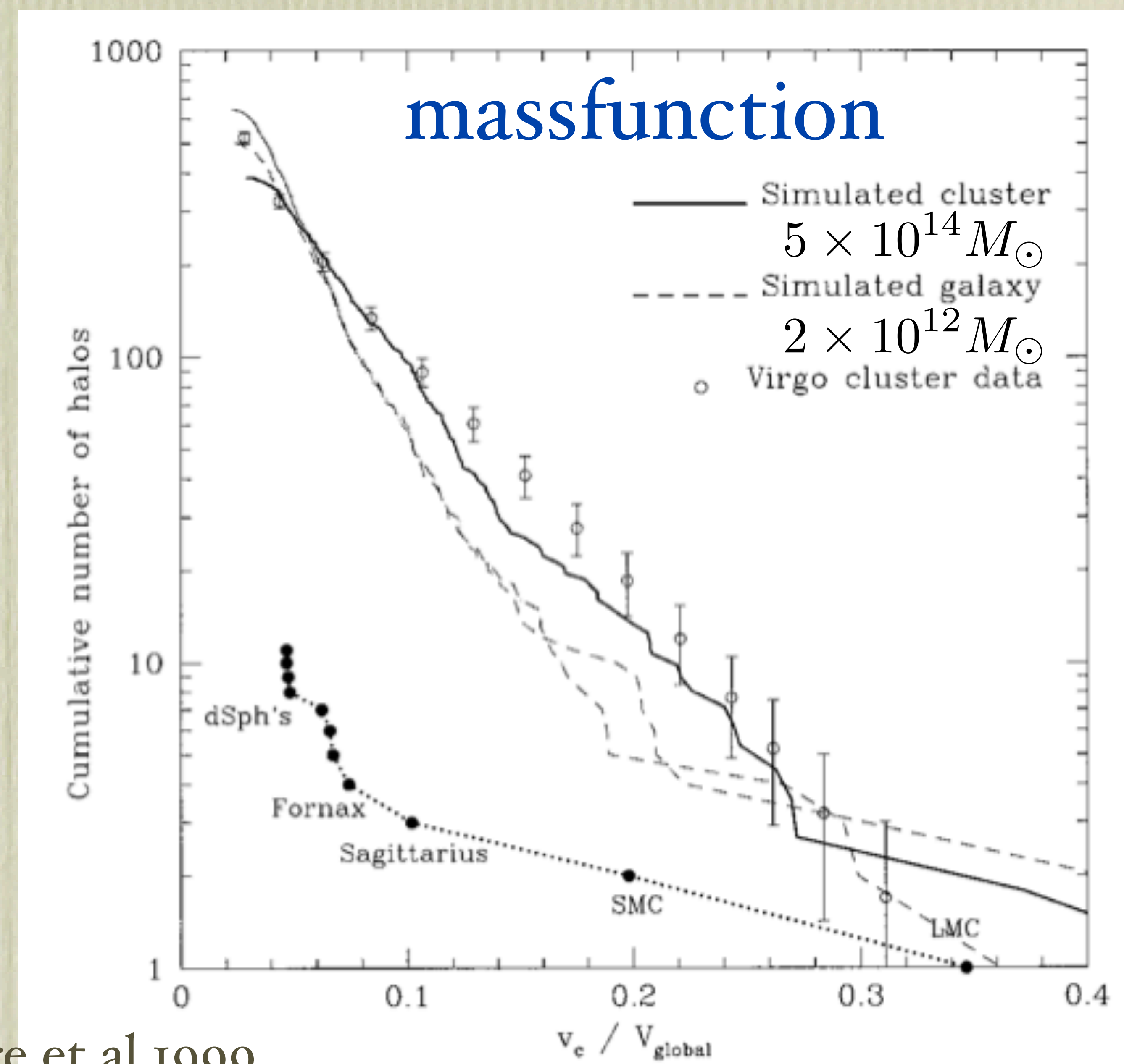
missing satellite problem



circular velocity

$$v_c = \sqrt{\frac{GM(<r)}{r}}$$





Moore et al 1999

small scale crisis

density profile

cuspy halo problem

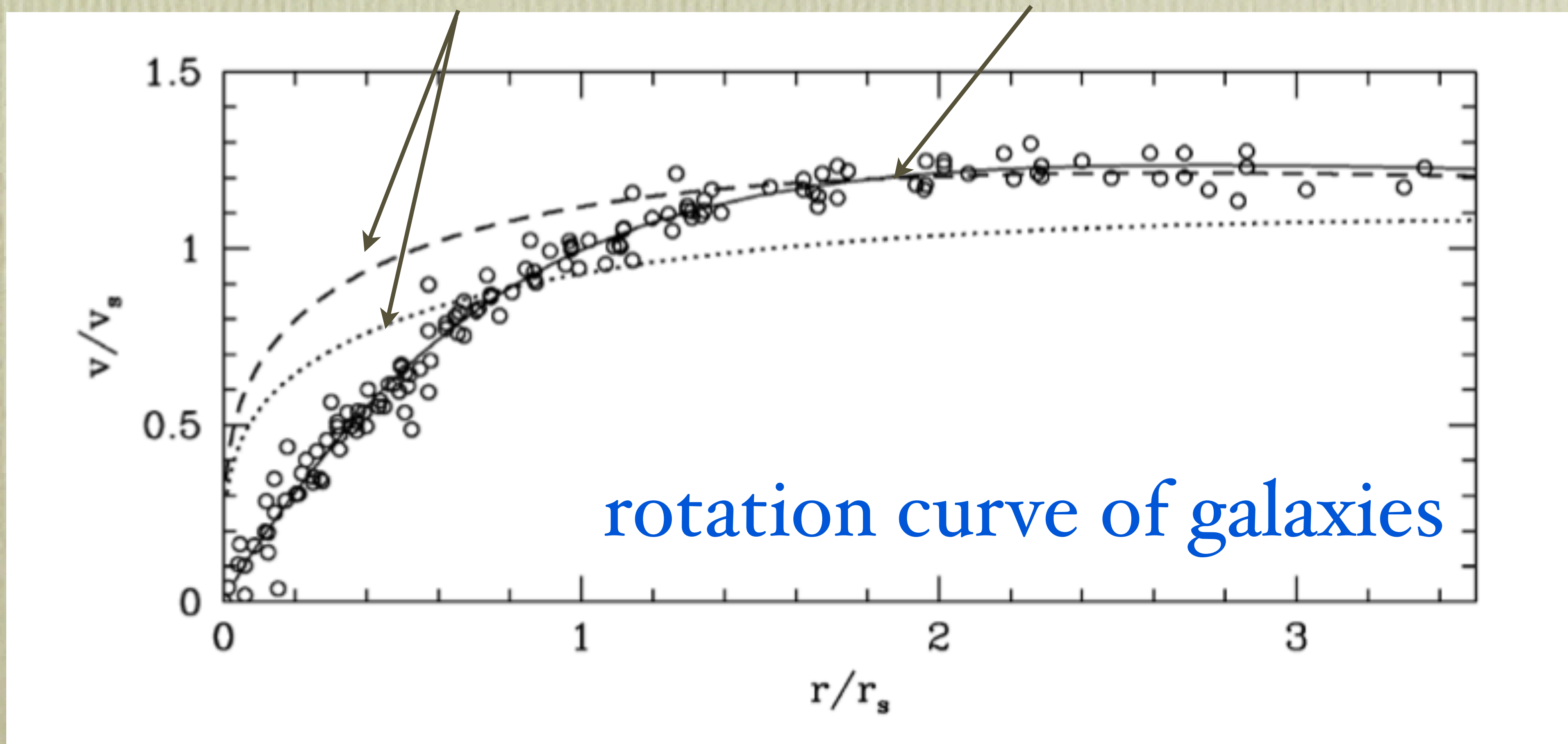
$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

circular velocity

$$v_c = \sqrt{\frac{GM(<r)}{r}}$$

simulation (NFW)
$\alpha = 1.5\ \beta = 3.0\ \gamma = 1.5$

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



rotation curve of galaxies

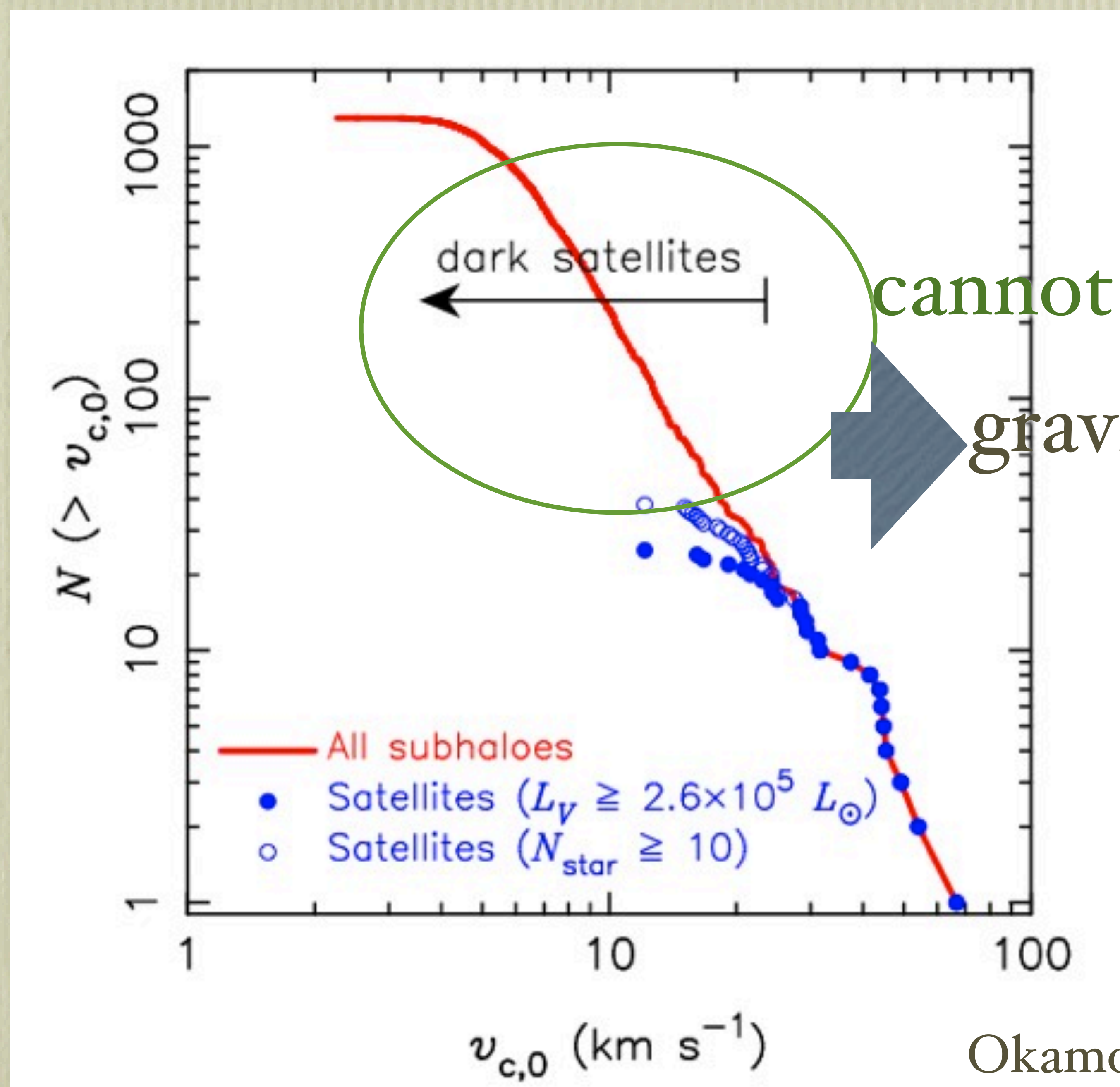
Moore et al 1999

small scale crisis now

baryon physics

missing satellite problem

reionization: supernovae explosion



cannot be seen

gravitational lensing

Hisano et al. 2006

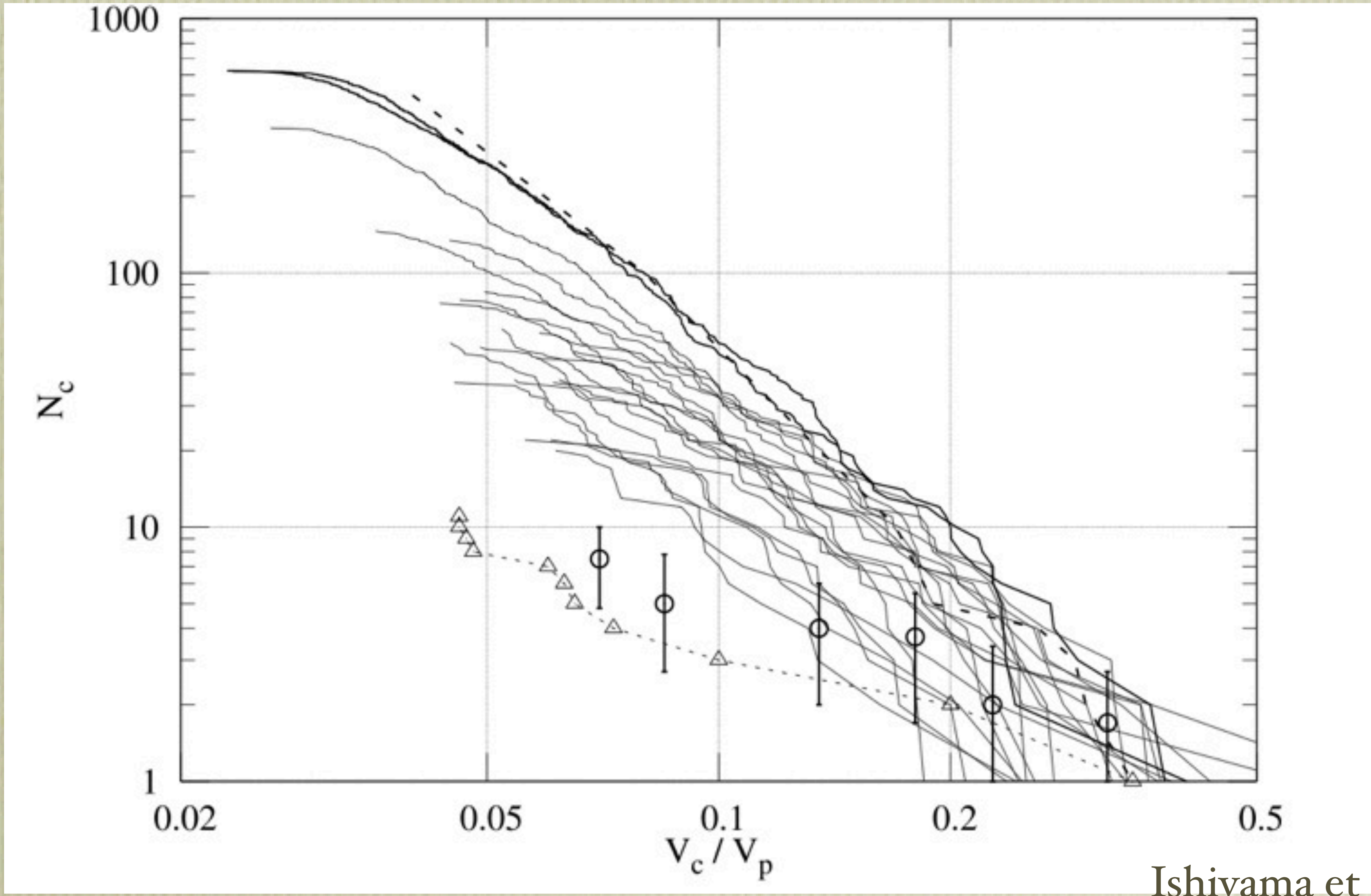
Okamoto, Frenck 2009

small scale crisis now

environment effect

missing satellite problem

large variance of subhalo abundance



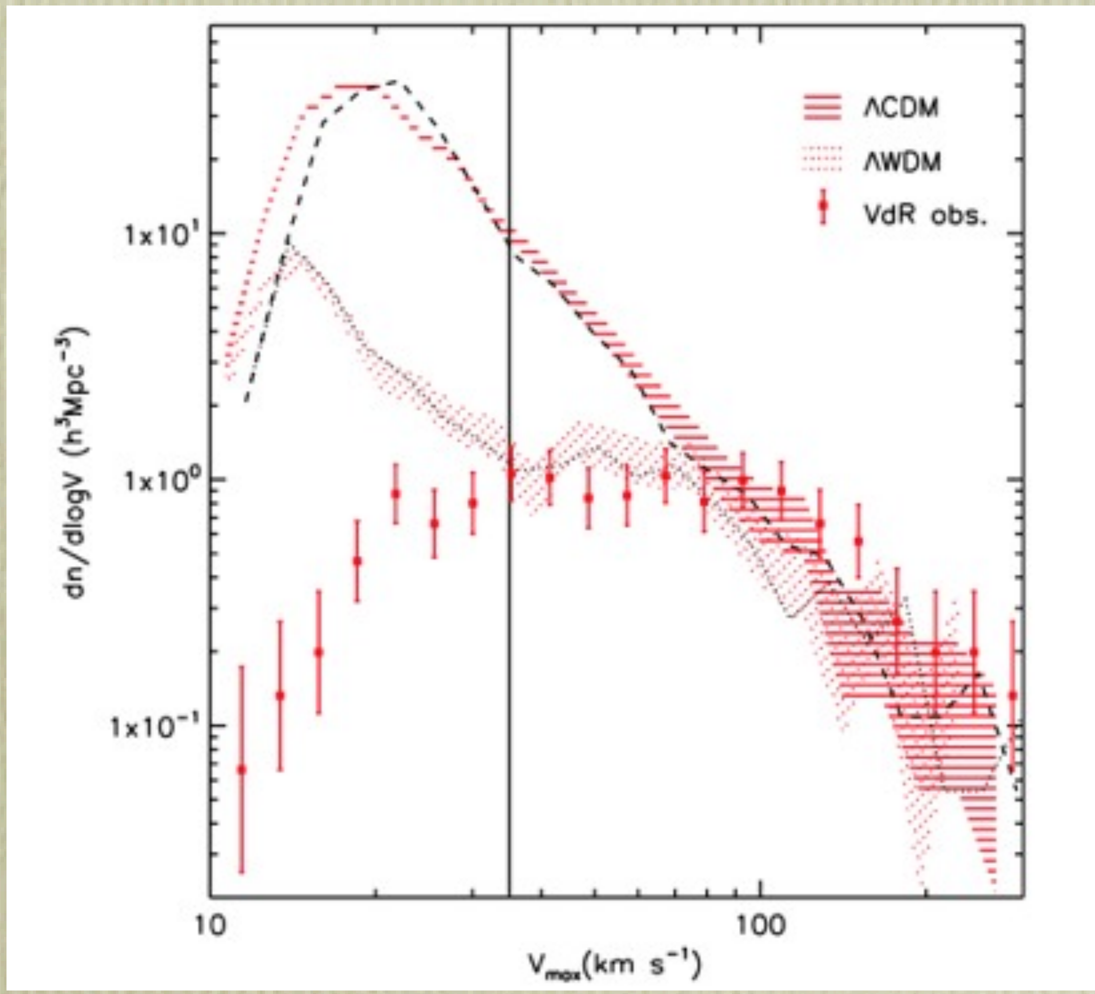
Ishiyama et al. 2008

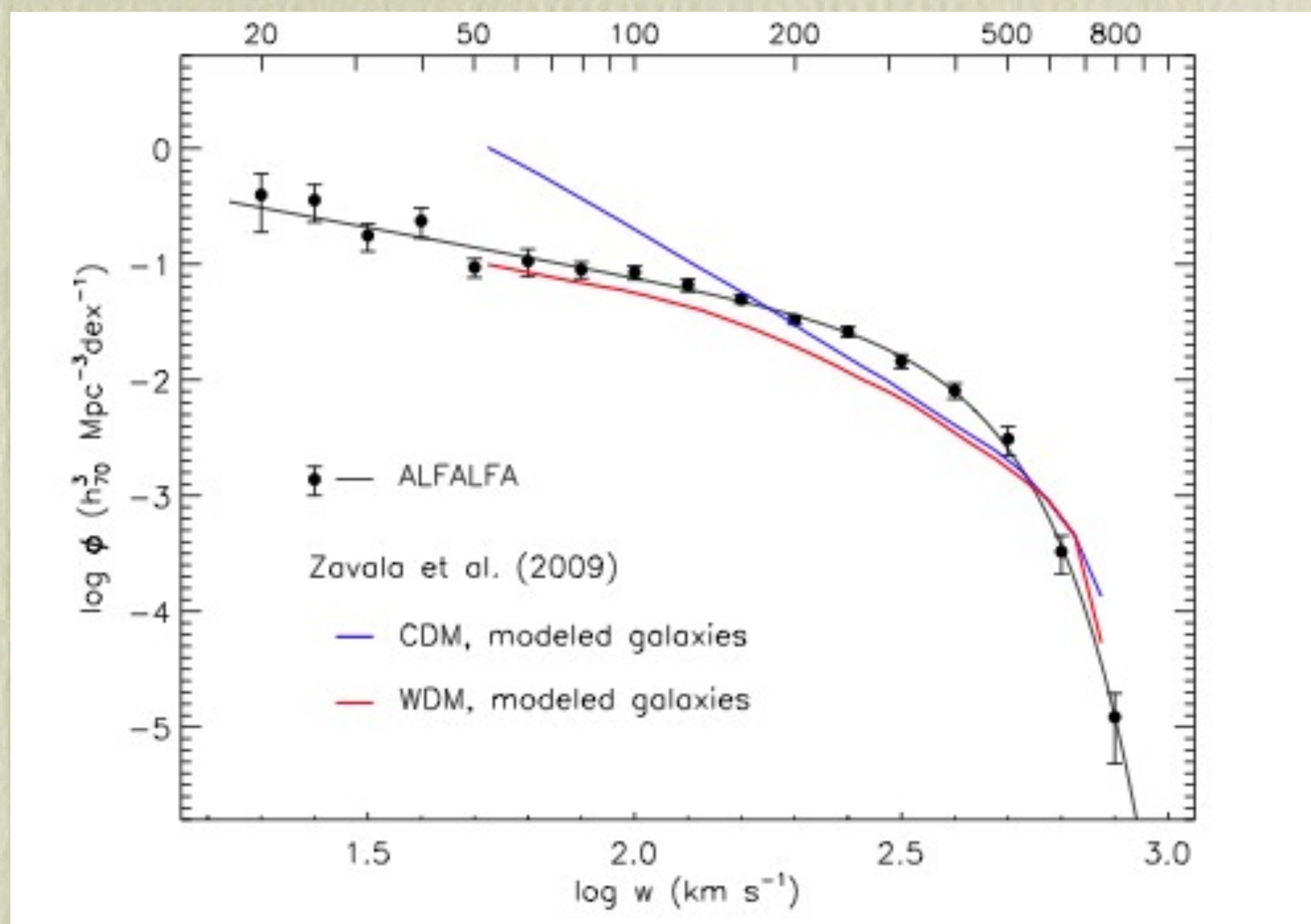
small scale crisis now

missing satellite problem

21cm observation with 20 cubic Mpc search region

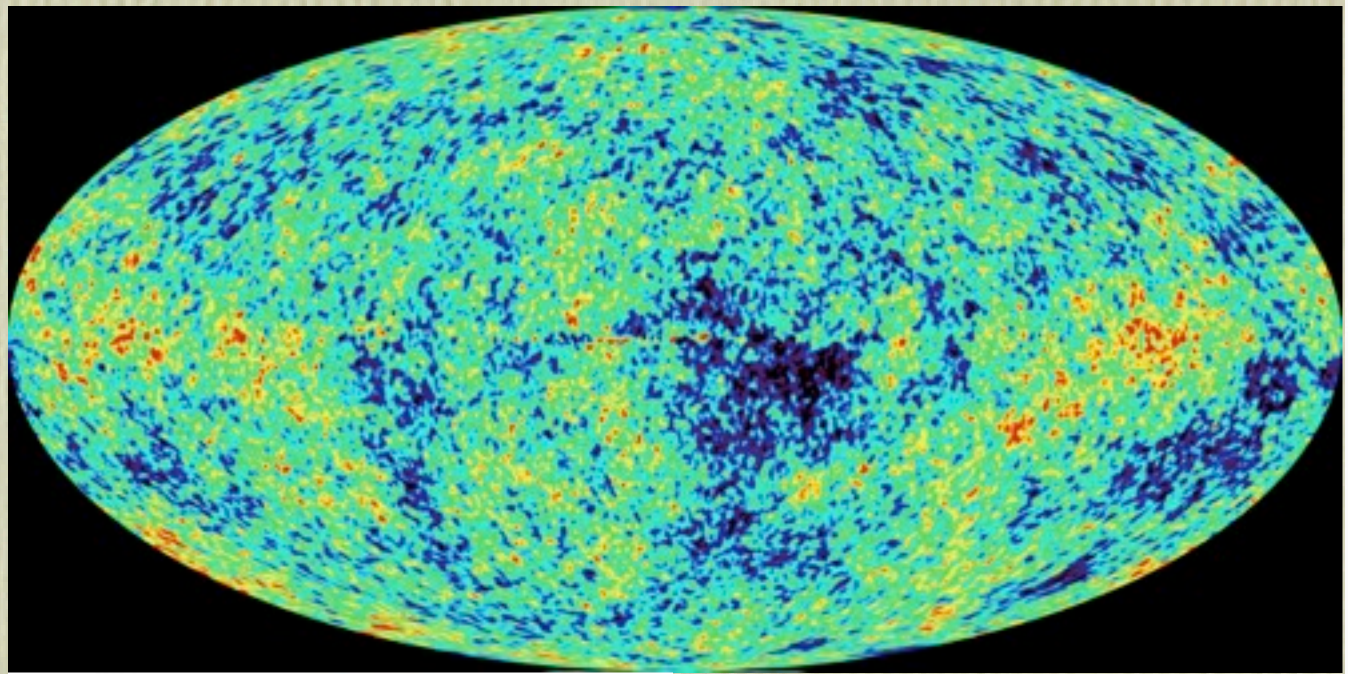
ALFALFA

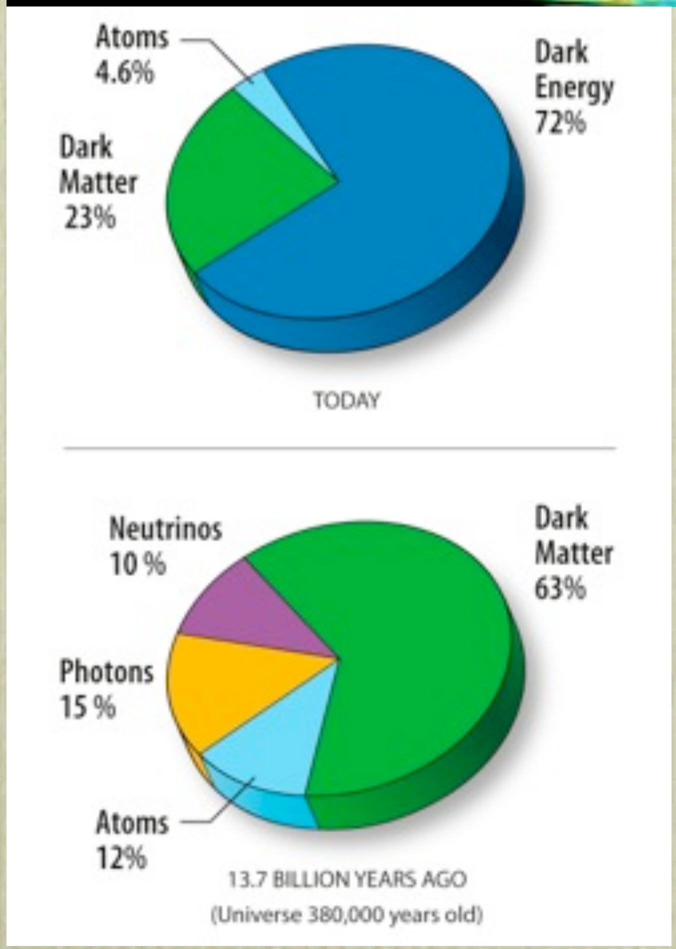




zavala et al. 2009

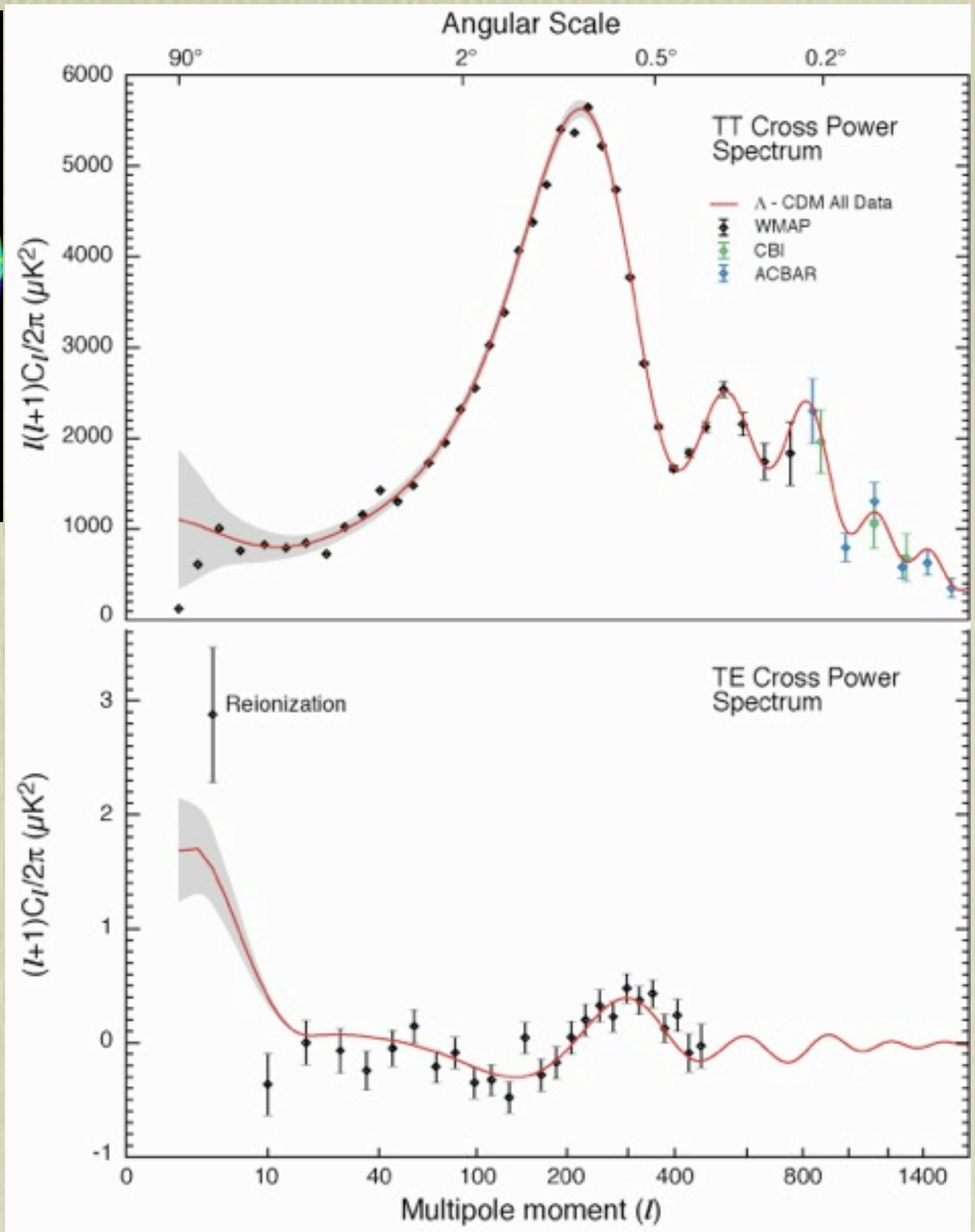
CMB anisotropy (it's miracle!!)





$$\frac{\Delta T}{T}(\mathbf{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\mathbf{n})$$

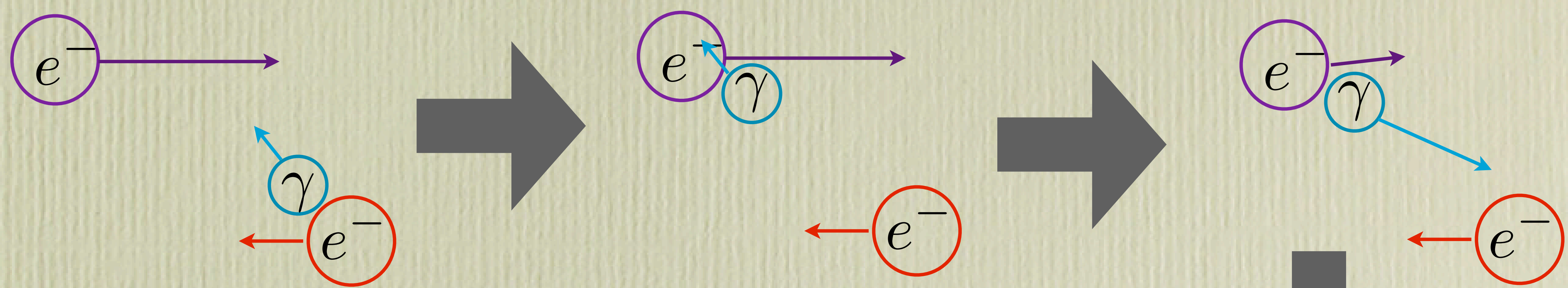
$$< a_{lm} a^*_{l'm'} >= \delta_{ll'} \delta_{mm'} C_l$$

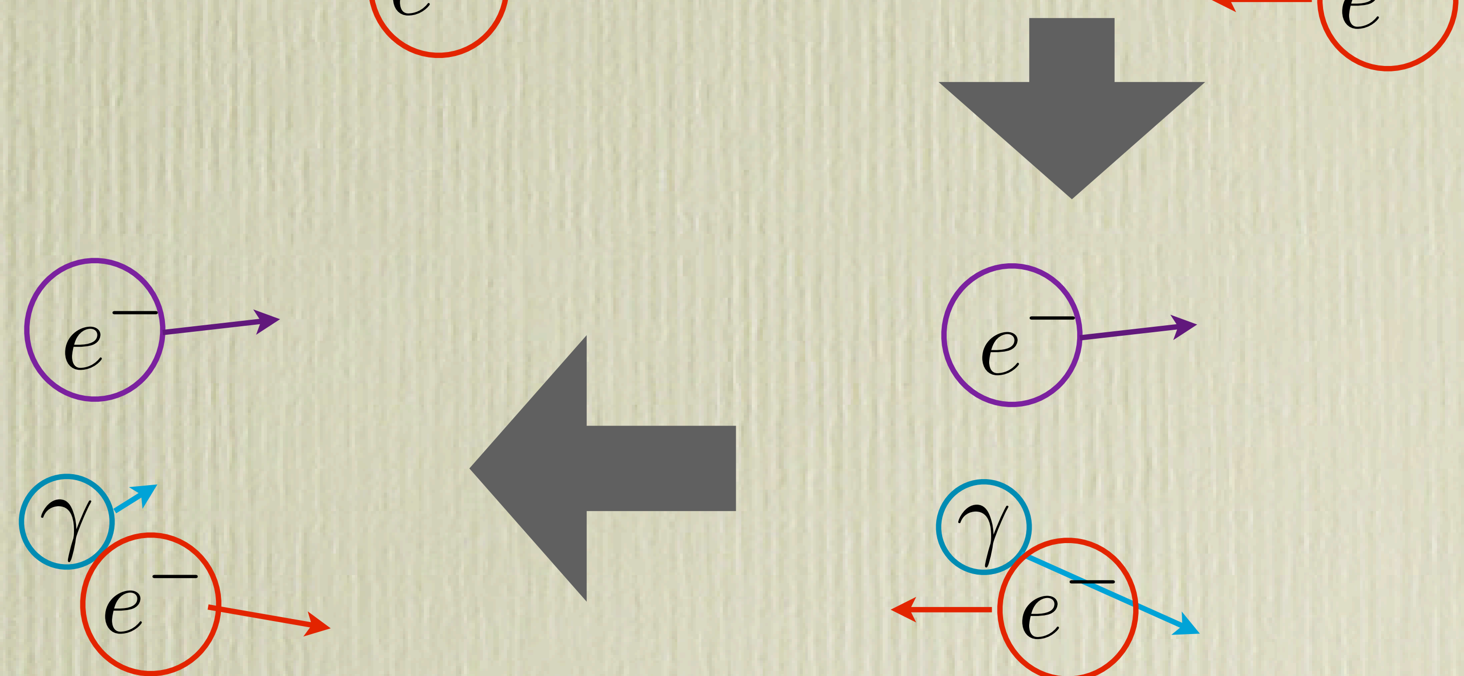


concordance ΛCDM cosmology

Silk damping

"collisional damping" ("Silk damping")





Thomson scattering diffuse photon and smooth out baryon anisotropy

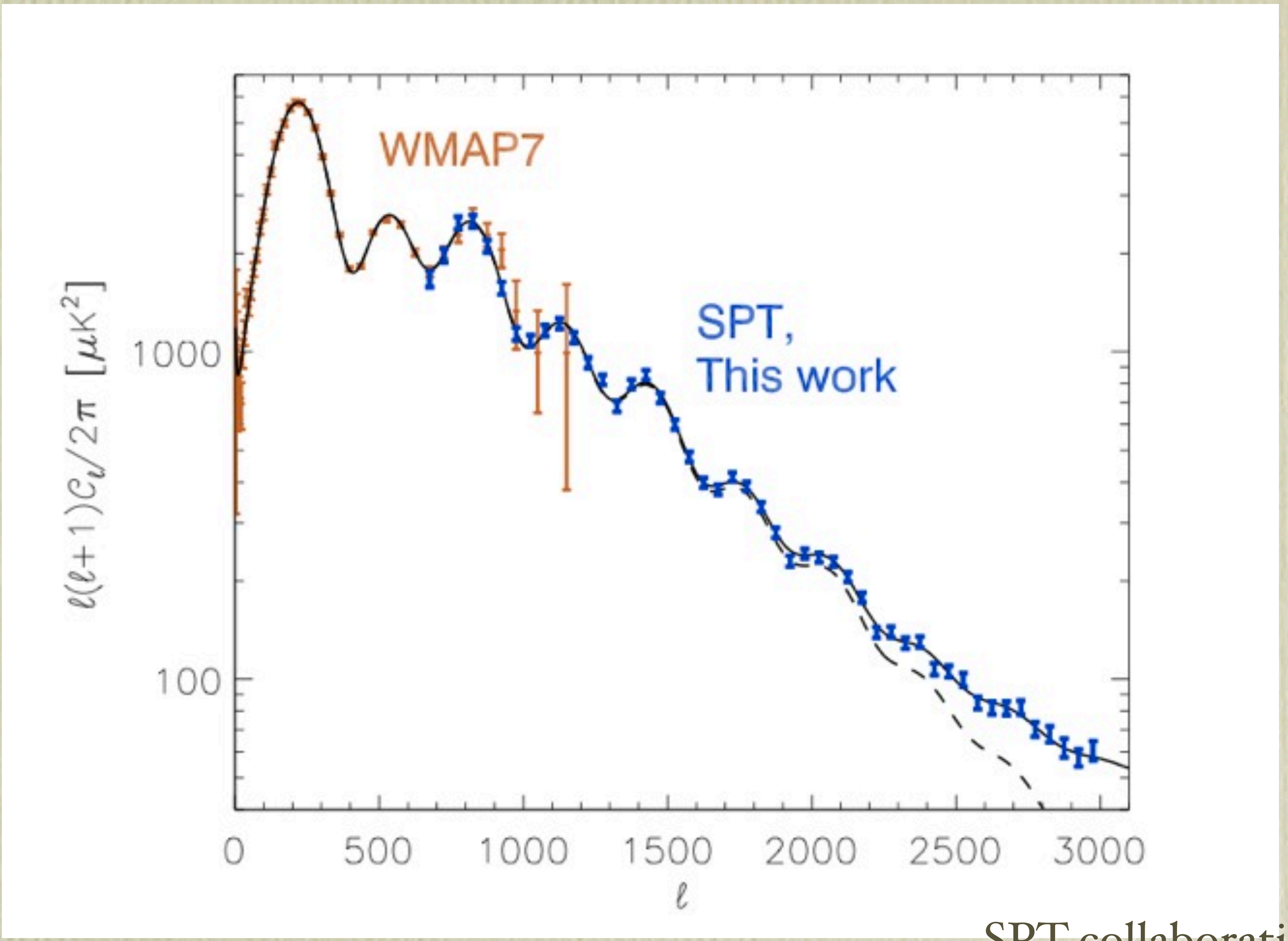
random walk

$$\Gamma \geq H \qquad \Gamma \sim \sigma n_e$$

$$\lambda_{\rm diff} \sim \lambda_{\rm fs}\sqrt{\sharp{\rm scat}}$$

$$\lambda_{\rm diff} \sim \frac{\eta}{\sqrt{\sigma n_e t}} \sim \sqrt{\frac{t}{\sigma n_e}} \qquad \longleftrightarrow \qquad \lambda_{\rm fs} \sim \sigma n_e \quad \sharp{\rm scat} \sim \frac{t}{\lambda_{\rm fs}}$$

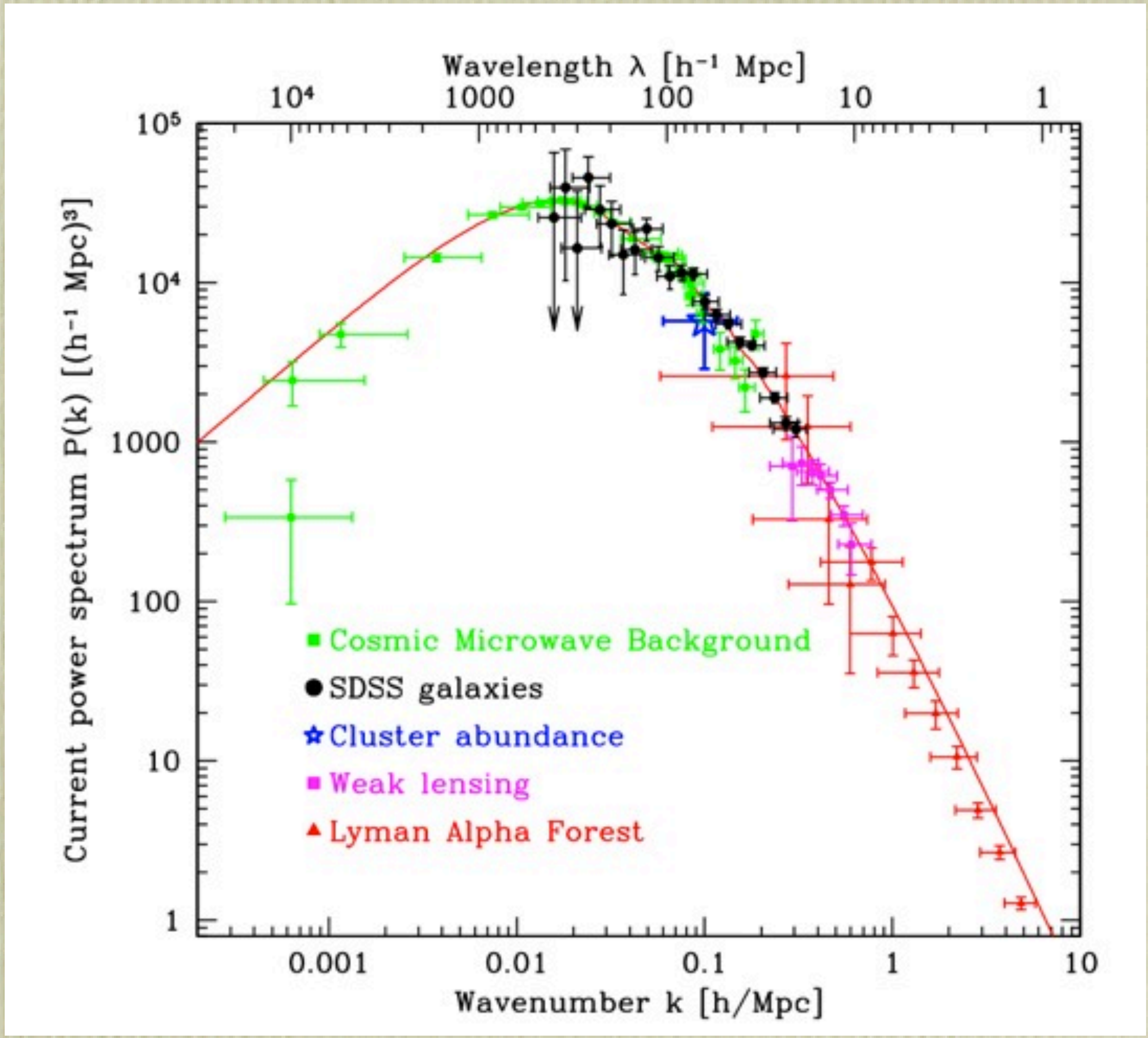
CMB anisotropy damping tale



SPT collaboration, 2011

Precise measurement of CMB anisotropy can't help

matter power spectrum



density perturbation

$$\delta(\mathbf{x}) \equiv \frac{\delta\rho}{\rho}(\mathbf{x}) = \int \frac{\mathrm{d}\mathbf{k}^3}{(2\pi)^3}\delta(\mathbf{k})e^{i\mathbf{k}\mathbf{x}}$$

$$< \delta(\mathbf{k})\delta^*(\mathbf{k}') >= (2\pi)^3\delta^3(\mathbf{k}-\mathbf{k}')\mathrm{P}(\mathbf{k})$$

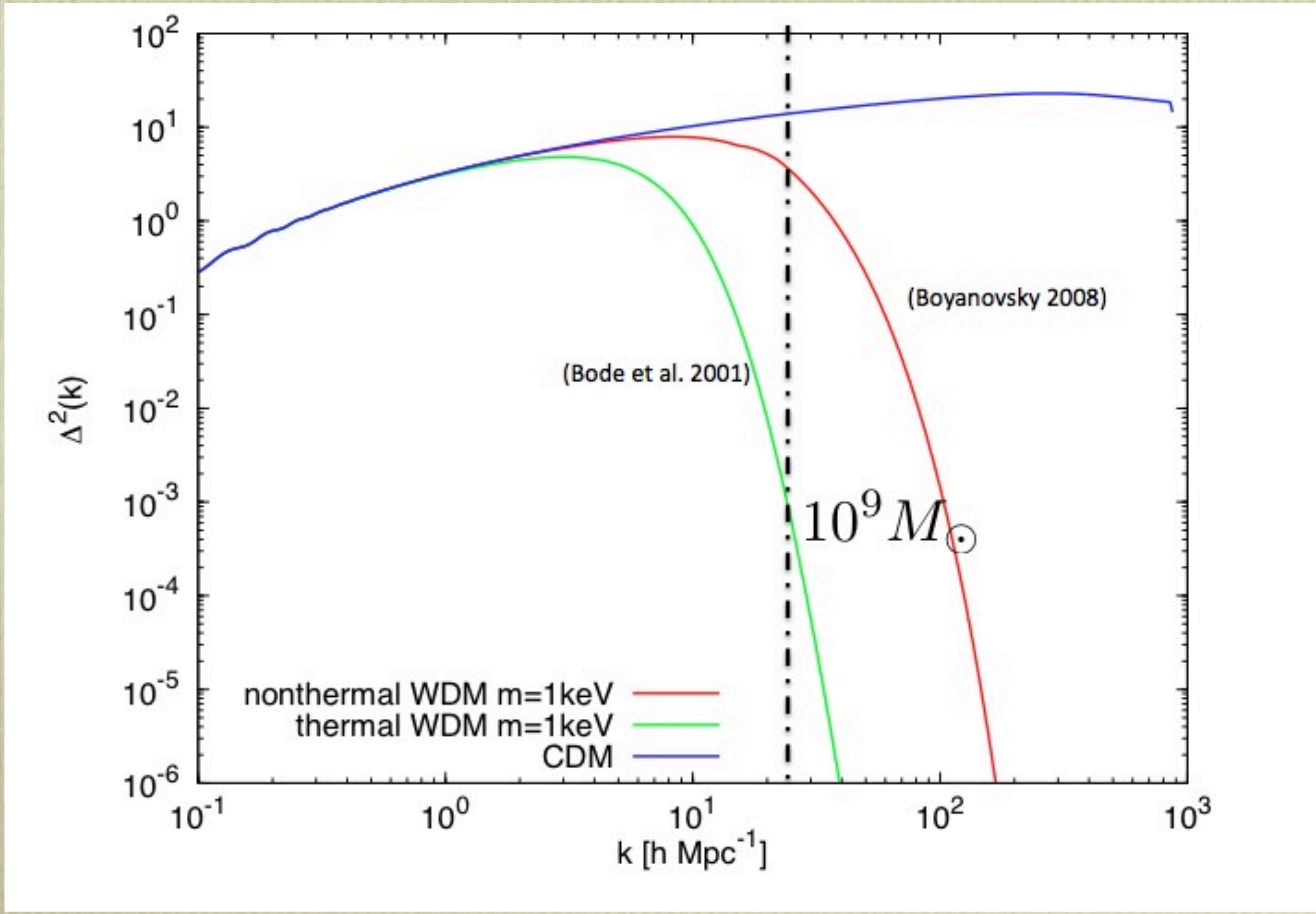
Tegmark et al. 2004

CMB anisotropy determines the matter power spectrum at Gpc scale

Warm dark matter as a solution

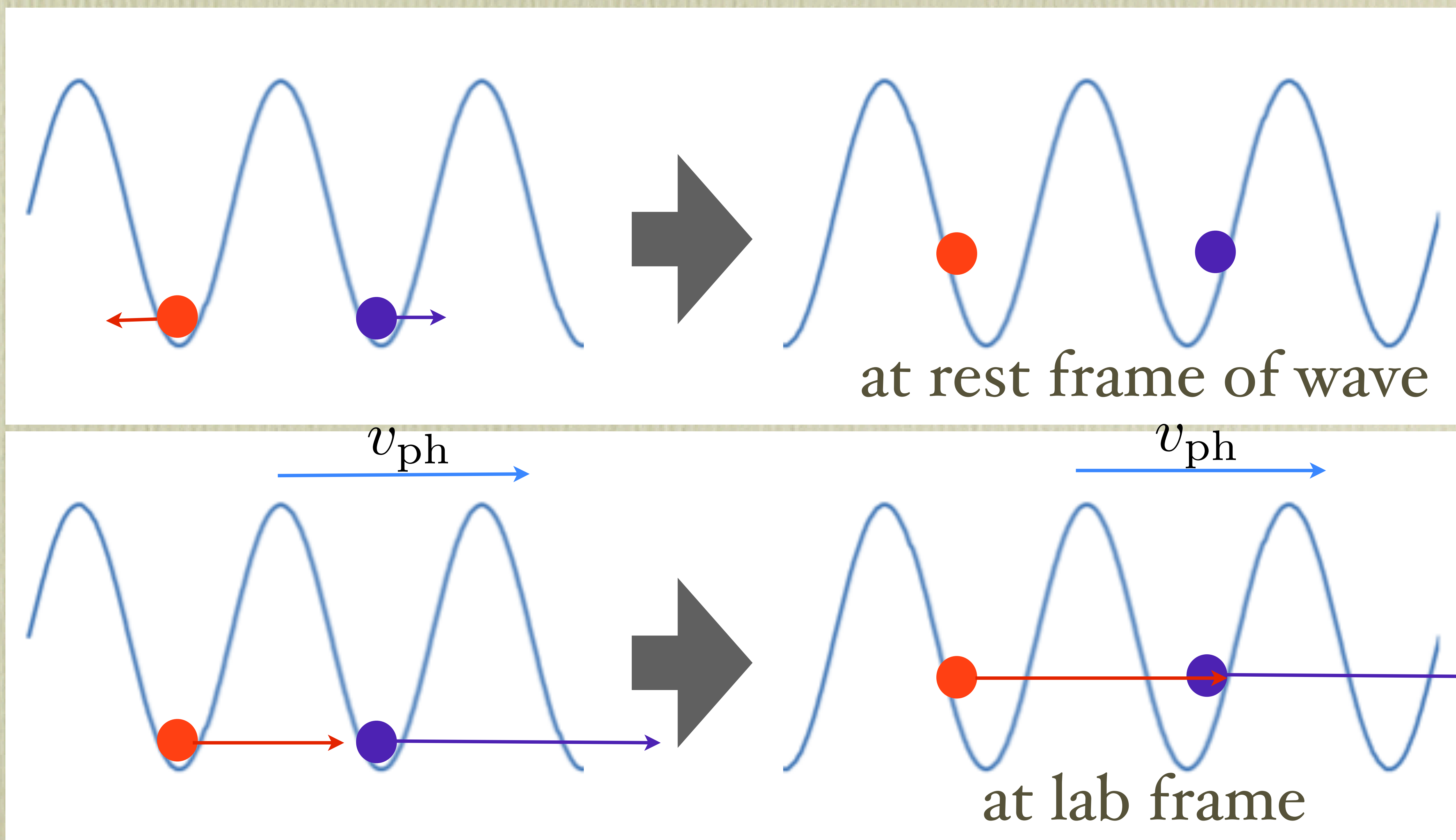
for $k > k_{\text{standard}}$

the amplitude of perturbation wave is dumped



CMB anisotropy dumping tale

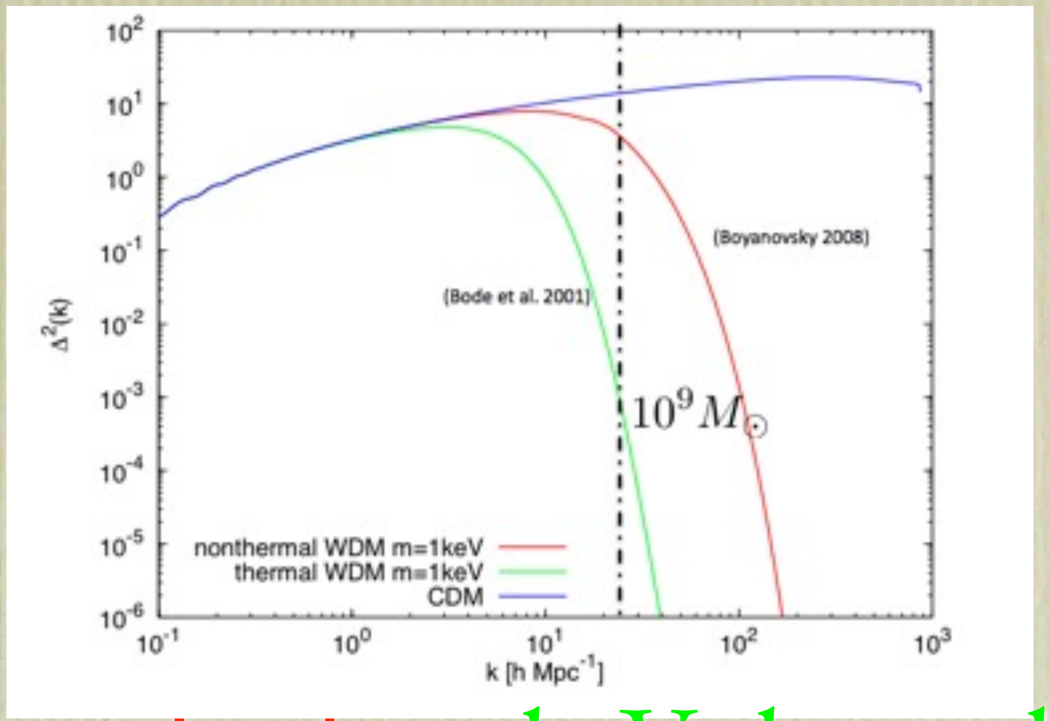
"collisionless damping" ("Landau damping")



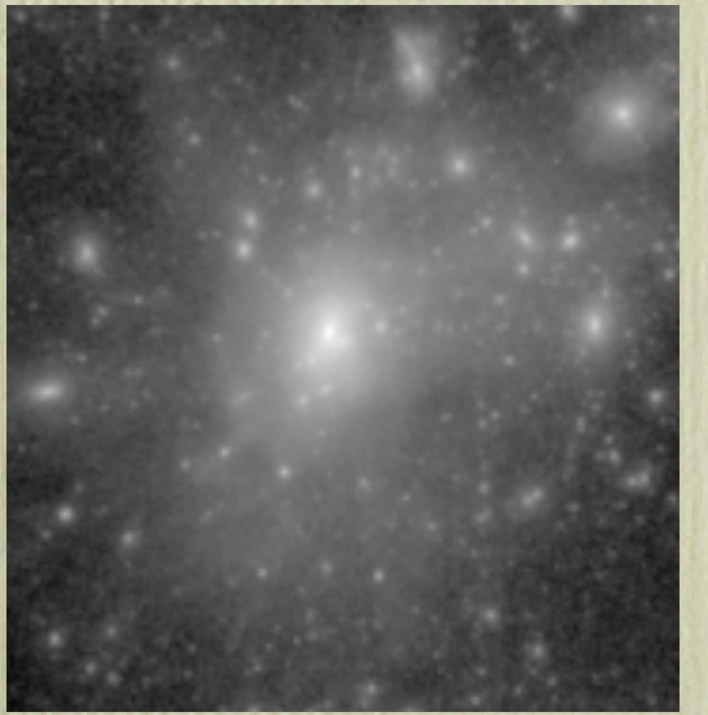
- gain energy
- lose energy

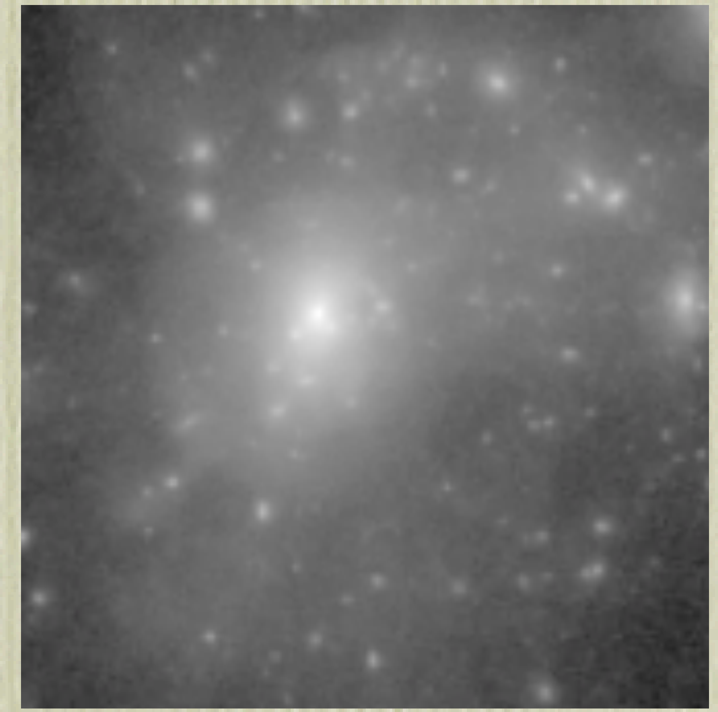
$$\mathrm{Im}(w) \propto \left.\frac{df_0(v)}{dv}\right|_{v=v_{ph}} \qquad v_{\rm ph} = \frac{w}{k}$$

simulation halo



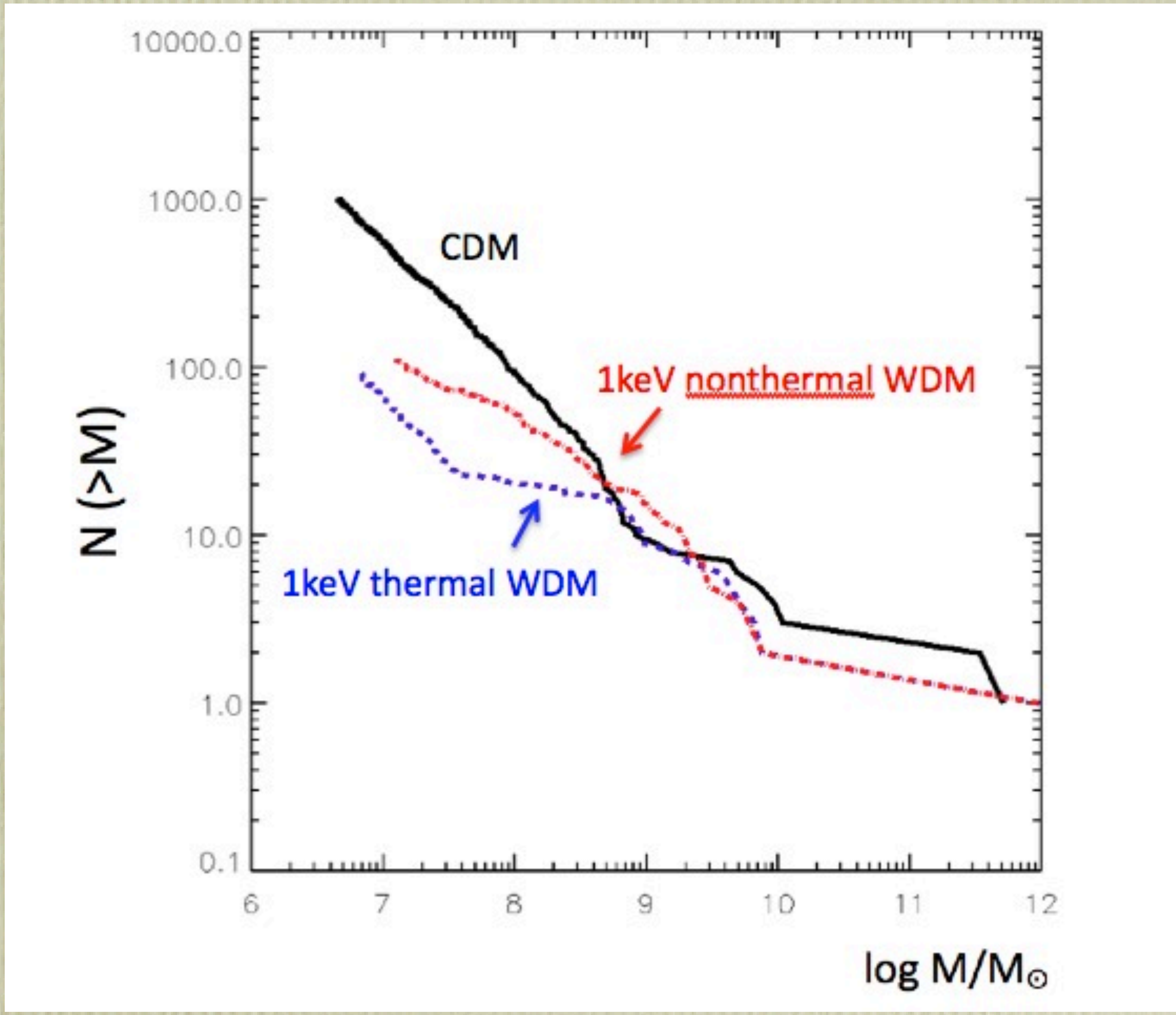
cdm　　1 keV nonthermal wdm　　1 keV thermal wdm

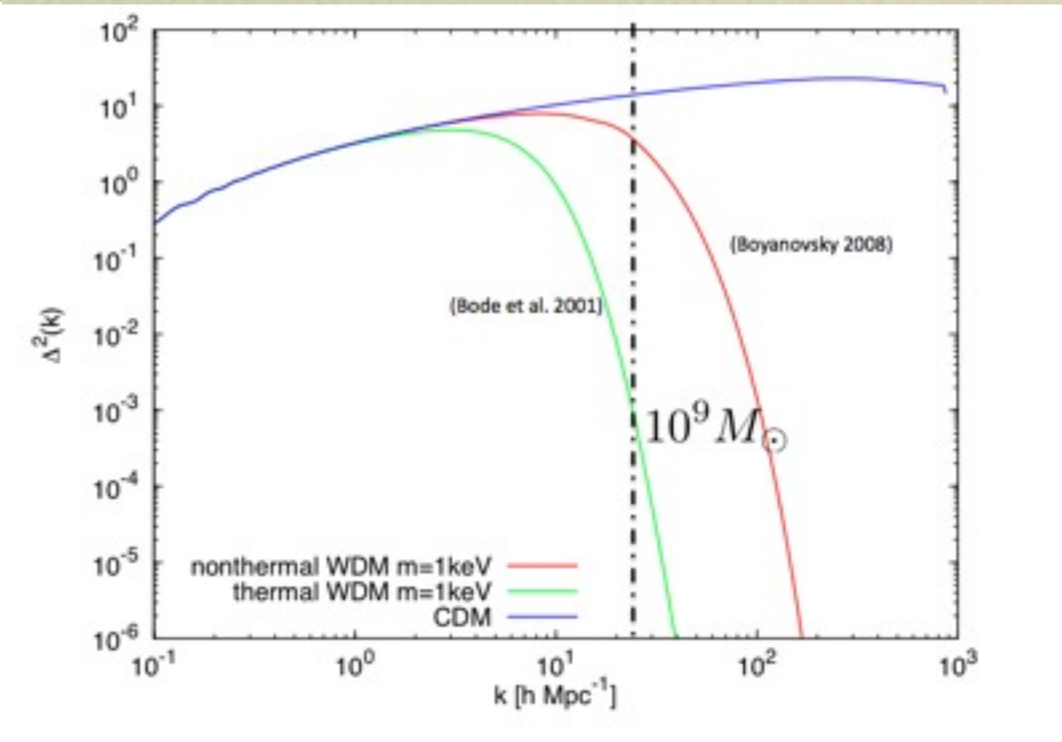




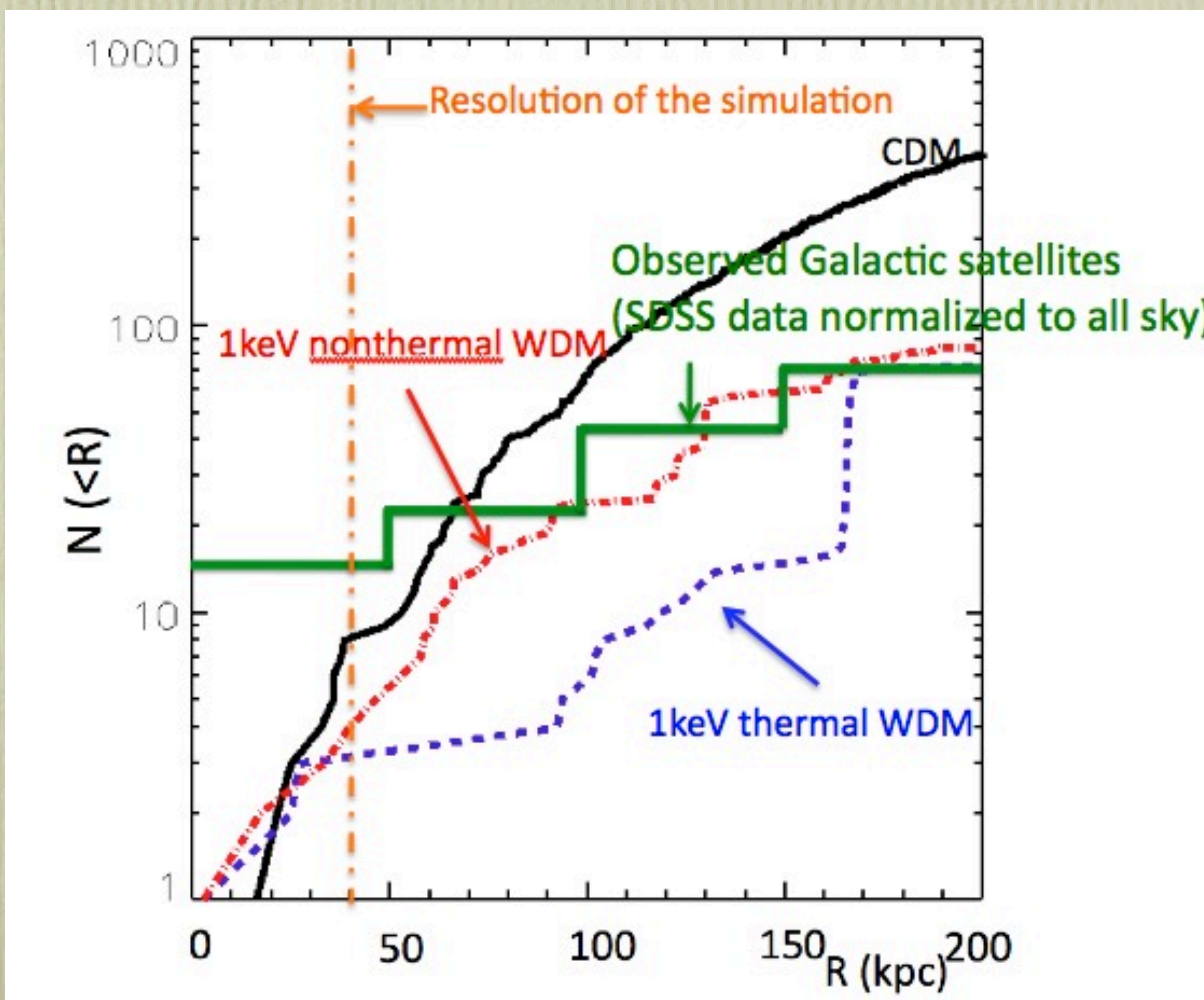
suppress substructure formation

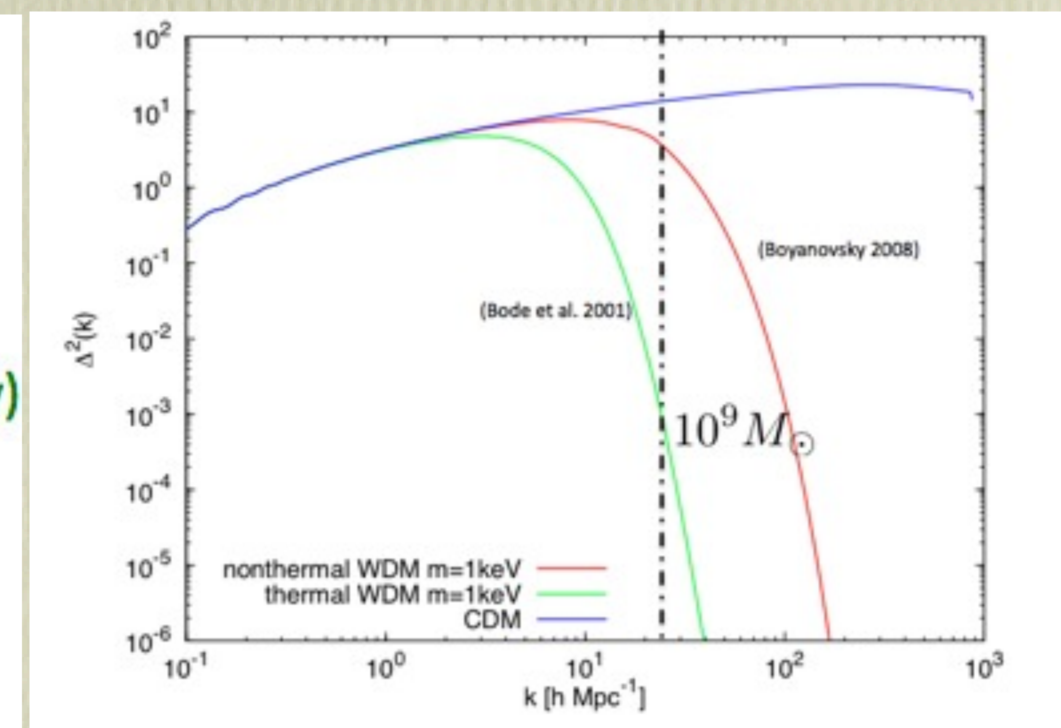
simulation mass function



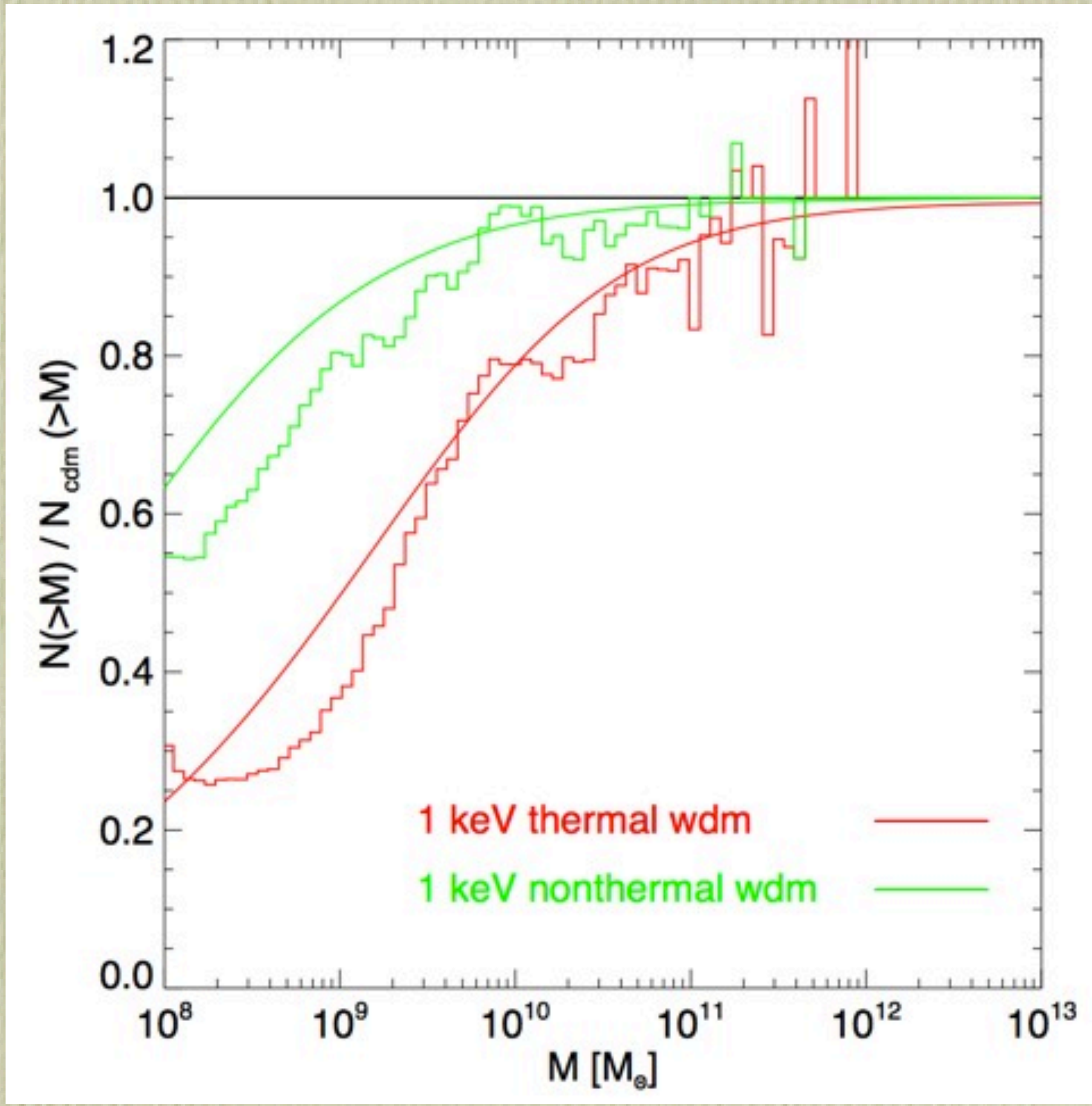


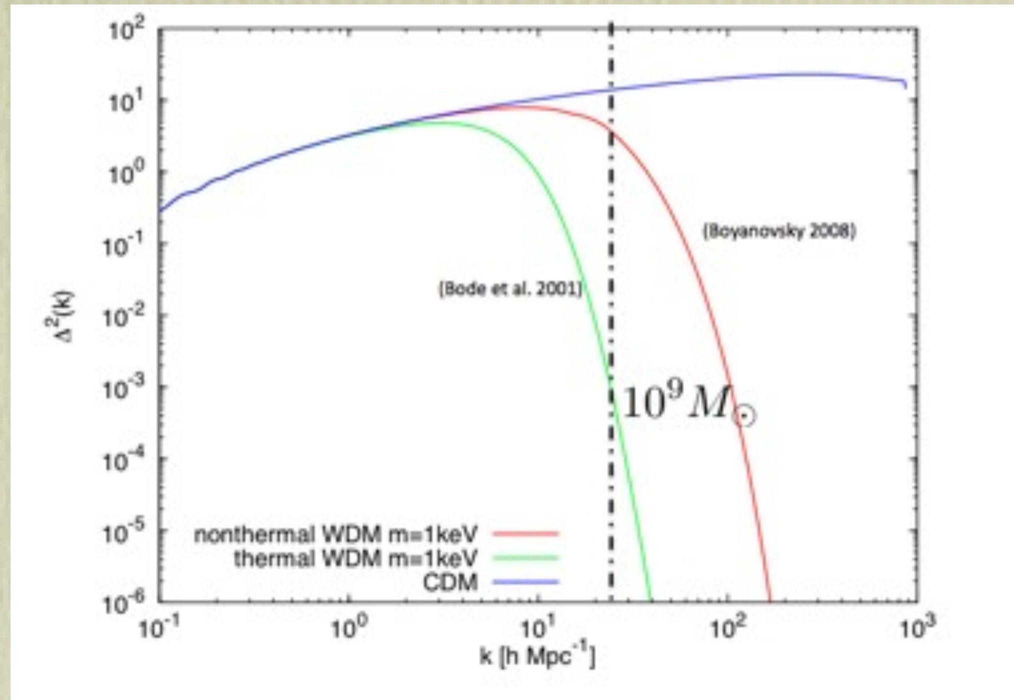
radial distribution of simulation Milky Way like halo





Press-Schechter prediction v.s. simulation





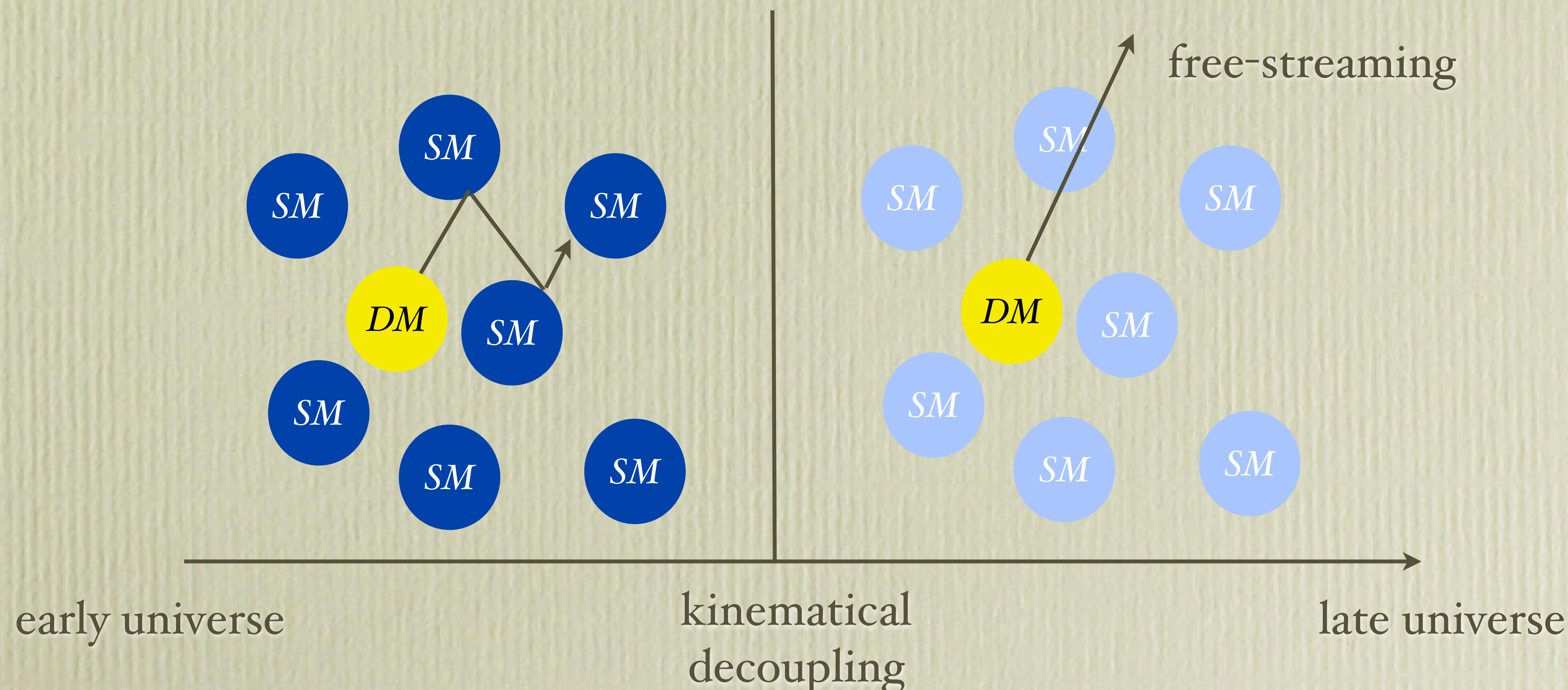
Press-Schechter prediction can reproduce simulation

particle physics scenarios of warm dark matter

1. twdm 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

$$f(q) \propto 1/(e^{q/T}+1)$$

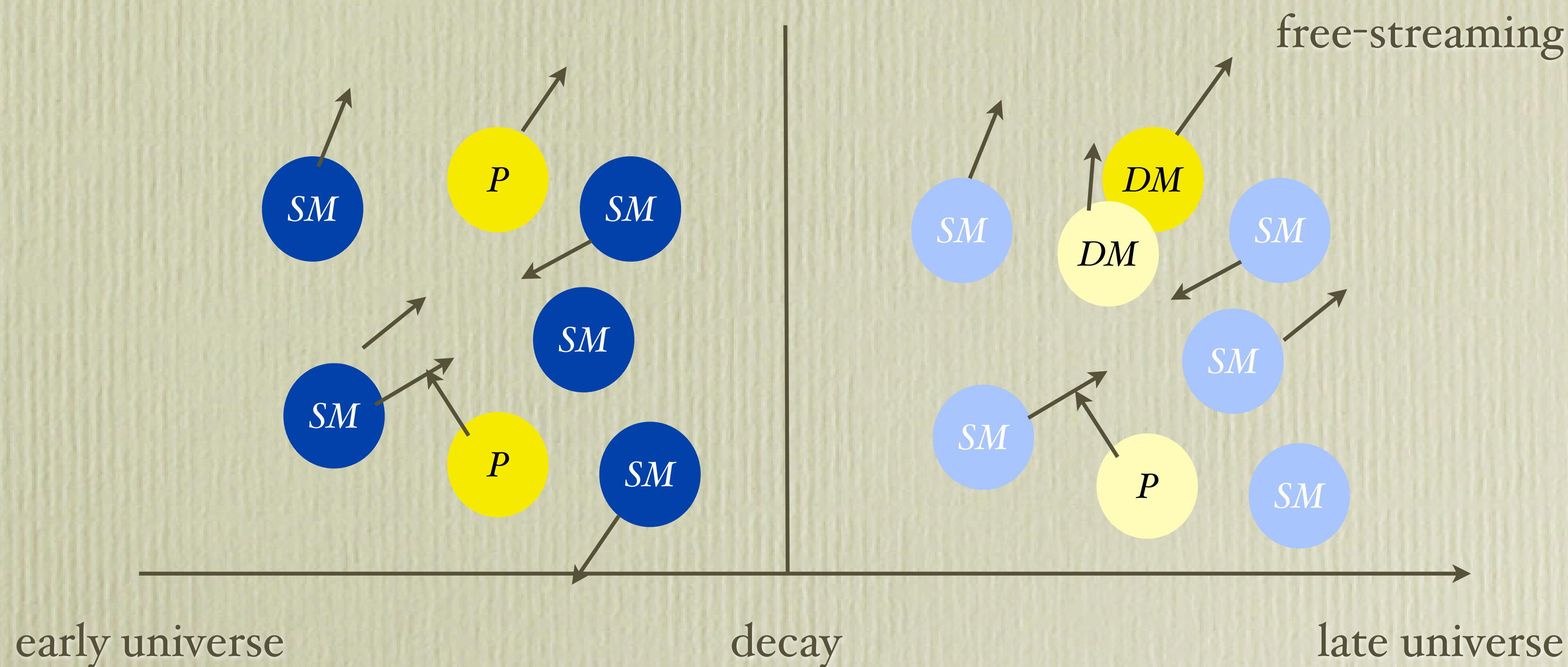
$$T = (10.75/g_*)^{1/3} T_\gamma$$

particle physics scenarios of warm dark matter

2. dwdm from thermal bath 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

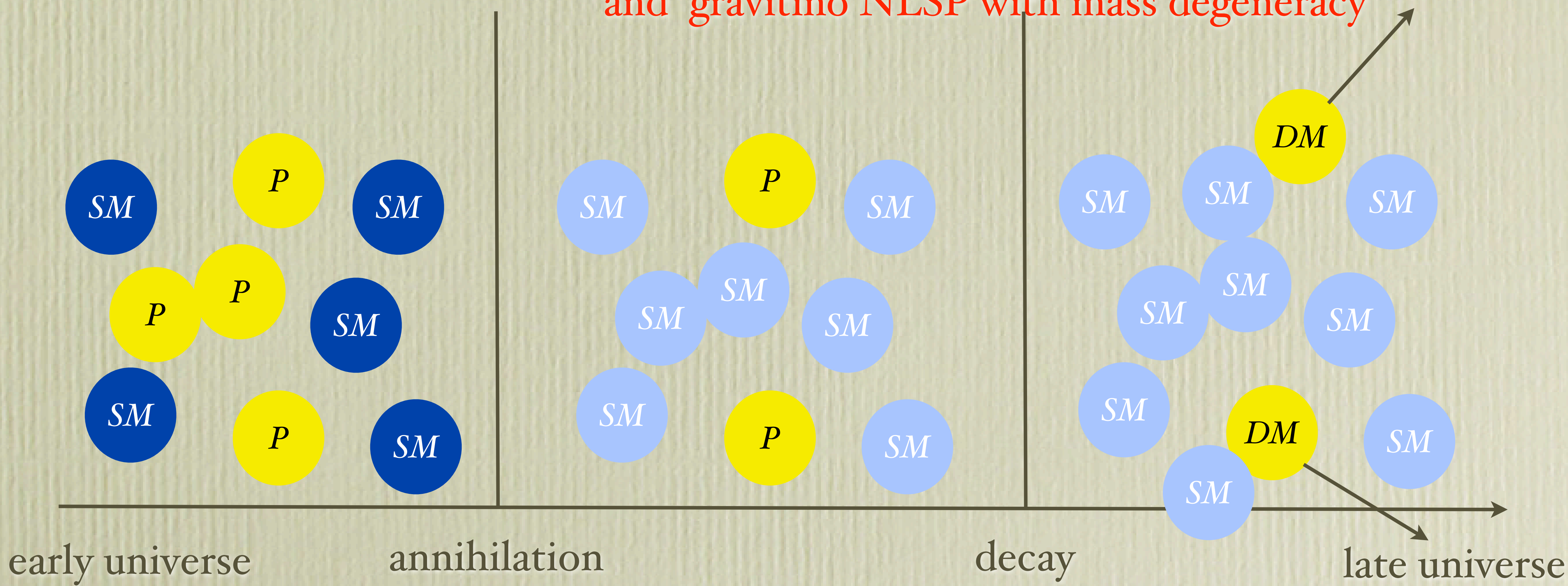
$$f(q) \propto (q/T)^{-0.5} e^{-q/T}$$
$$T = (10.75/g_*)^{1/3} T_\gamma$$

particle physics scenarios of warm dark matter

3. dwdm out of thermal bath   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

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

comparison between models

twdm e.g. gravitino

$$f(q) \propto 1/(e^{q/T}+1)$$

$$T = (10.75/g_*)^{1/3} T_\gamma$$

dwdm from thermal bath
e.g. sterile neutrino

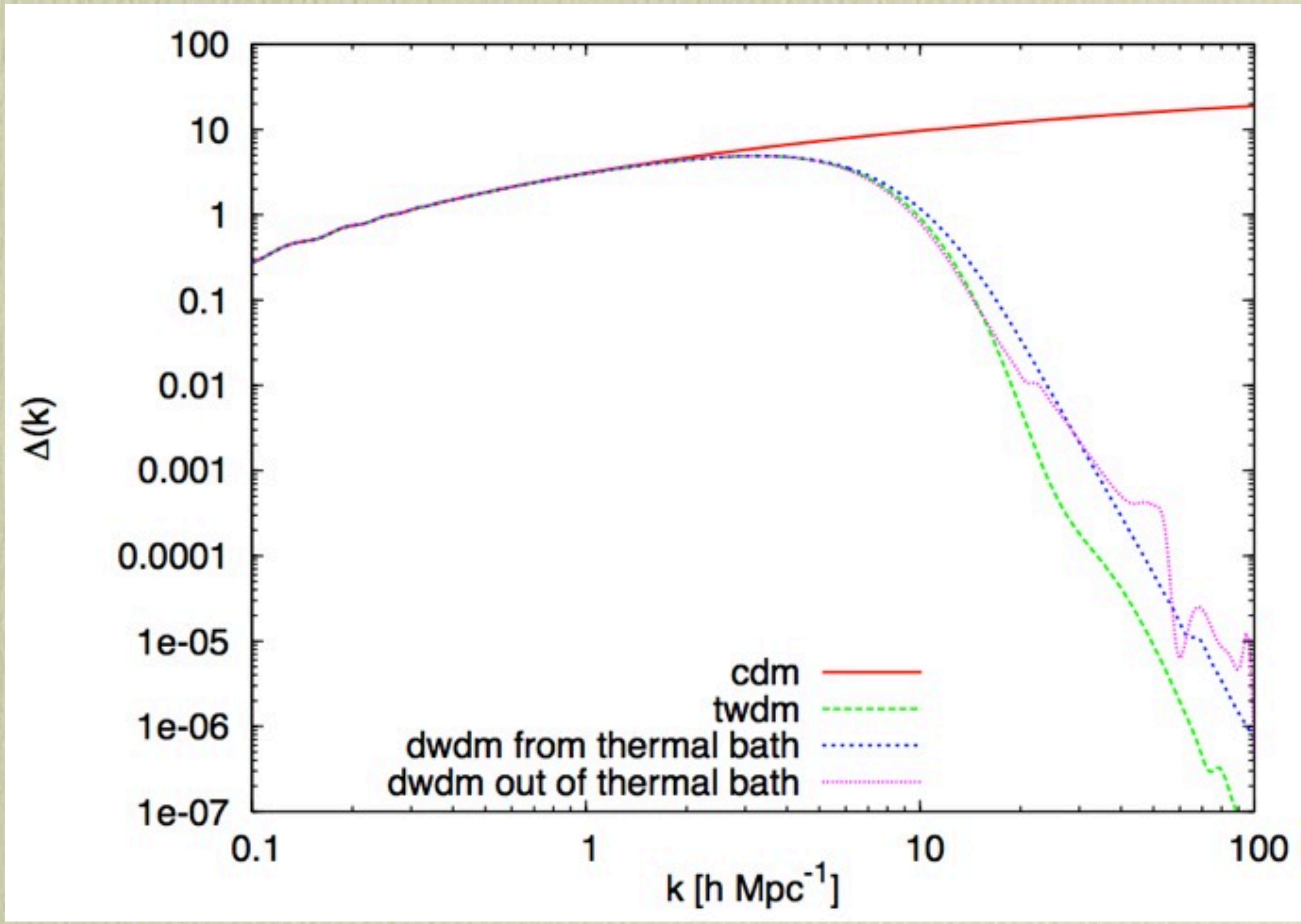
$$f(q) \propto (q/T)^{-0.5} e^{-q/T}$$

$$T = (10.75/g_*)^{1/3} T_\gamma$$

dwdm out of thermal bath
e.g. superWIMP

$$f(q) \propto (q/p_{\rm cm})^{-1} e^{-(q/p_{\rm cm})^2}$$

$$p_{\rm cm} = P_{cm} a_{\rm decay}$$



what's a good standard ?

Jeans scale at matter-radiation equality

$$k_{\text{standard}} = k_J|_{\text{eq}} \equiv \sqrt{\frac{4\pi\rho_{\text{crit}}\Omega_M}{< \mathbf{p}^2 > |_{\text{eq}}/m^2}} = \frac{\sqrt{3}}{\sqrt{2}\eta_{\text{NR}}}$$

$$\sim 30\ h\ \text{kpc}^{-1}$$

twdm e.g. gravitino

$$f(q) \propto 1/(e^{q/T} + 1)$$

$$T = (10.75/g_*)^{1/3} T_\gamma$$

dwdm from thermal bath e.g. sterile neutrino

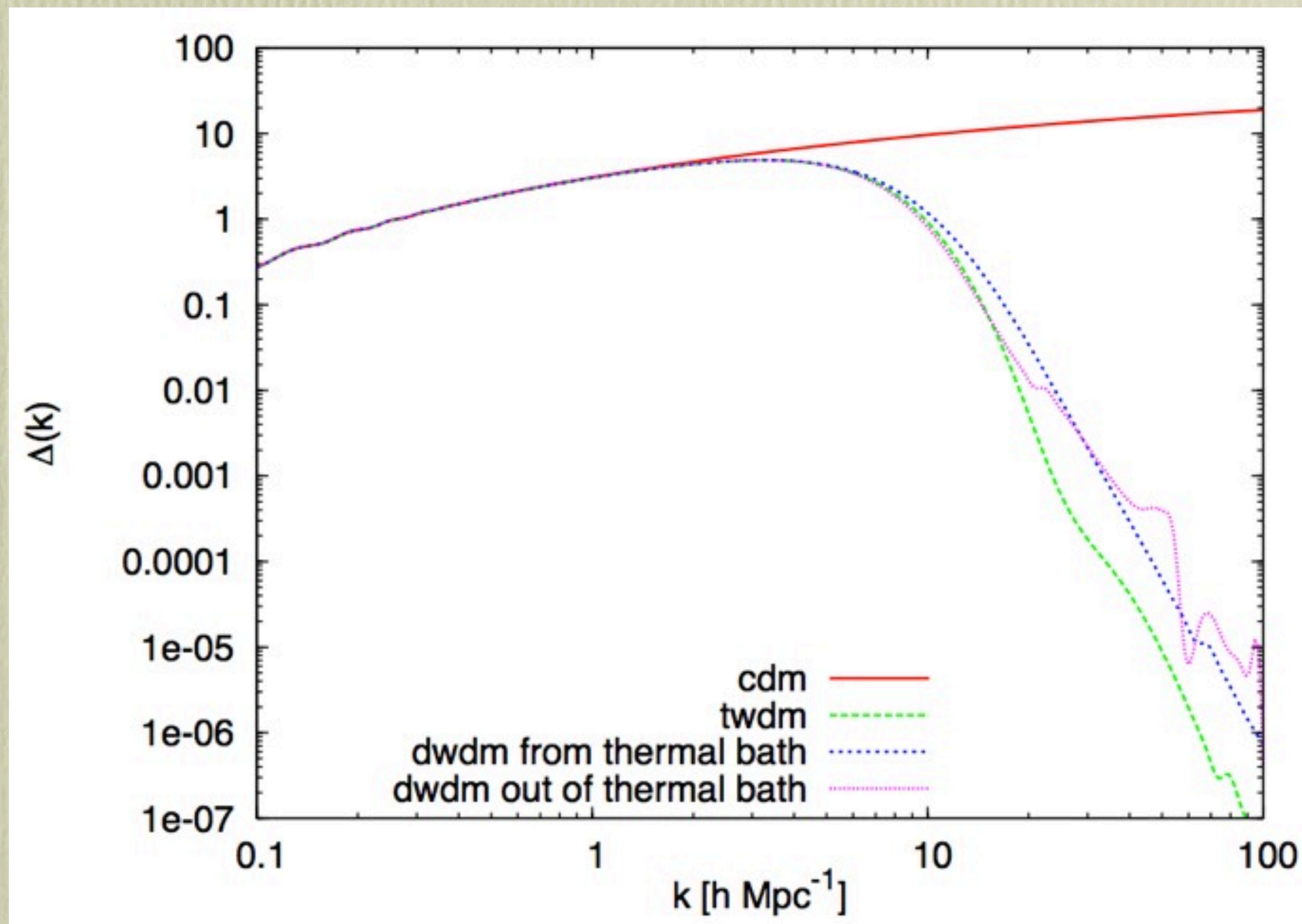
$$f(q) \propto (q/T)^{-0.5} e^{-q/T}$$

$$T = (10.75/g_*)^{1/3} T_\gamma$$

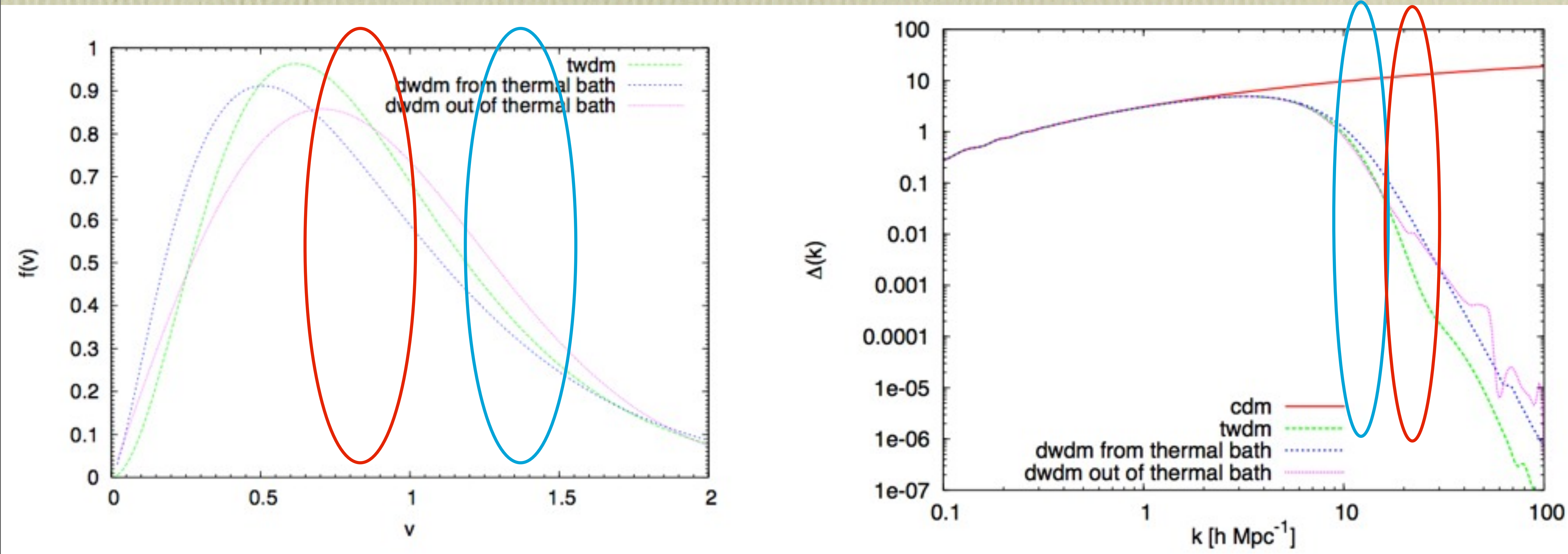
dwdm out of thermal bath e.g. superWIMP

$$f(q) \propto (q/p_{\text{cm}})^{-1} e^{-(q/p_{\text{cm}})^2}$$

$$p_{\text{cm}} = P_{cm} a_{\text{decay}}$$



relation between distribution functions and power spectra



normalized to

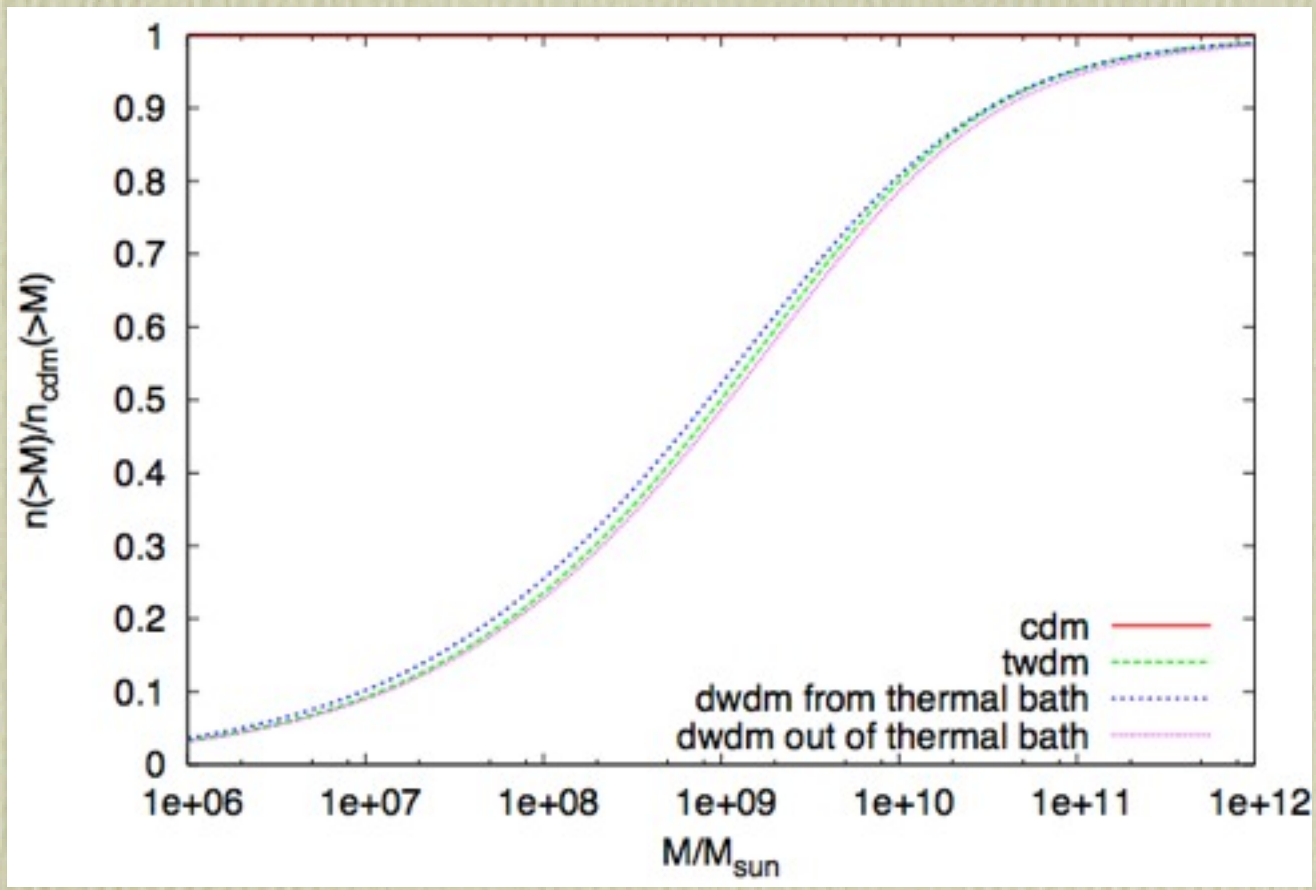
$$\int_0^\infty dv f(v) = 1$$ 0th moment: relic abundance

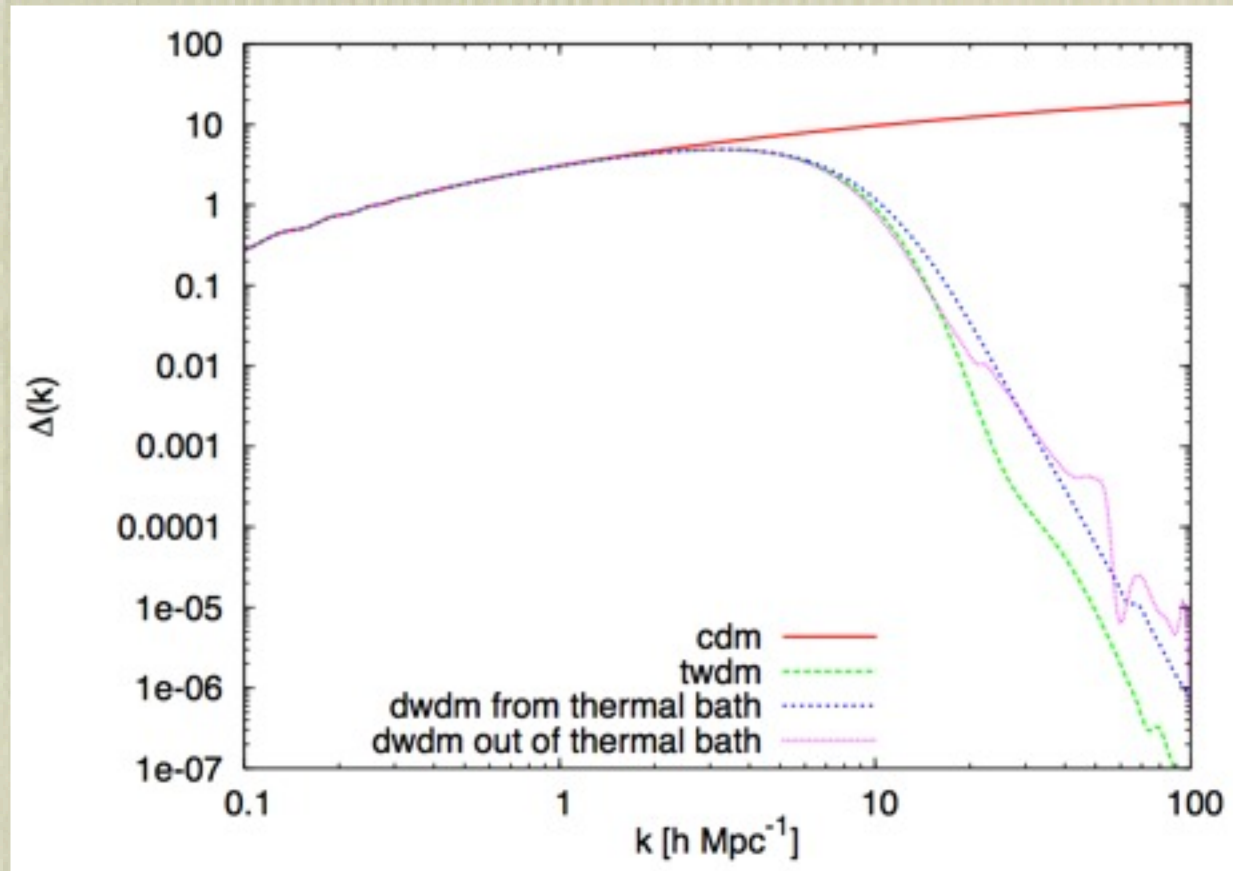
$$\int_0^\infty dv v^2 f(v) = 1$$ 2nd moment: Jeans length

low (high) momentum particle contributes to small (large) scale power spectrum

distinguish models ?

Press-Schechter prediction





non-linear growth forget the initial power spectrum

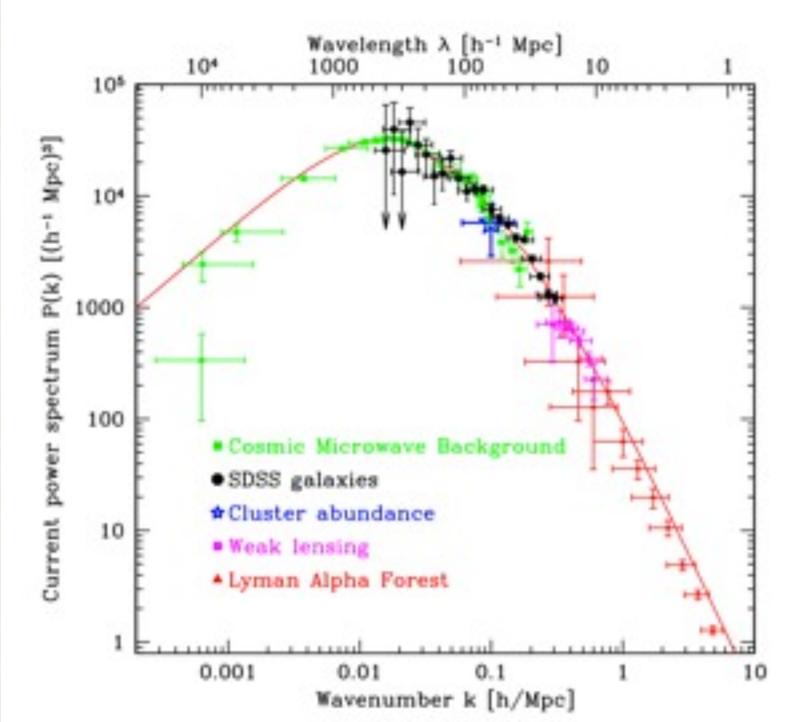
→ high-z !!

disguising dark matter as warm dark matter

ChaMP (Charged Massive Particles) 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 contradict Large Scale Structure of the Universe



➡ they should have proper life time

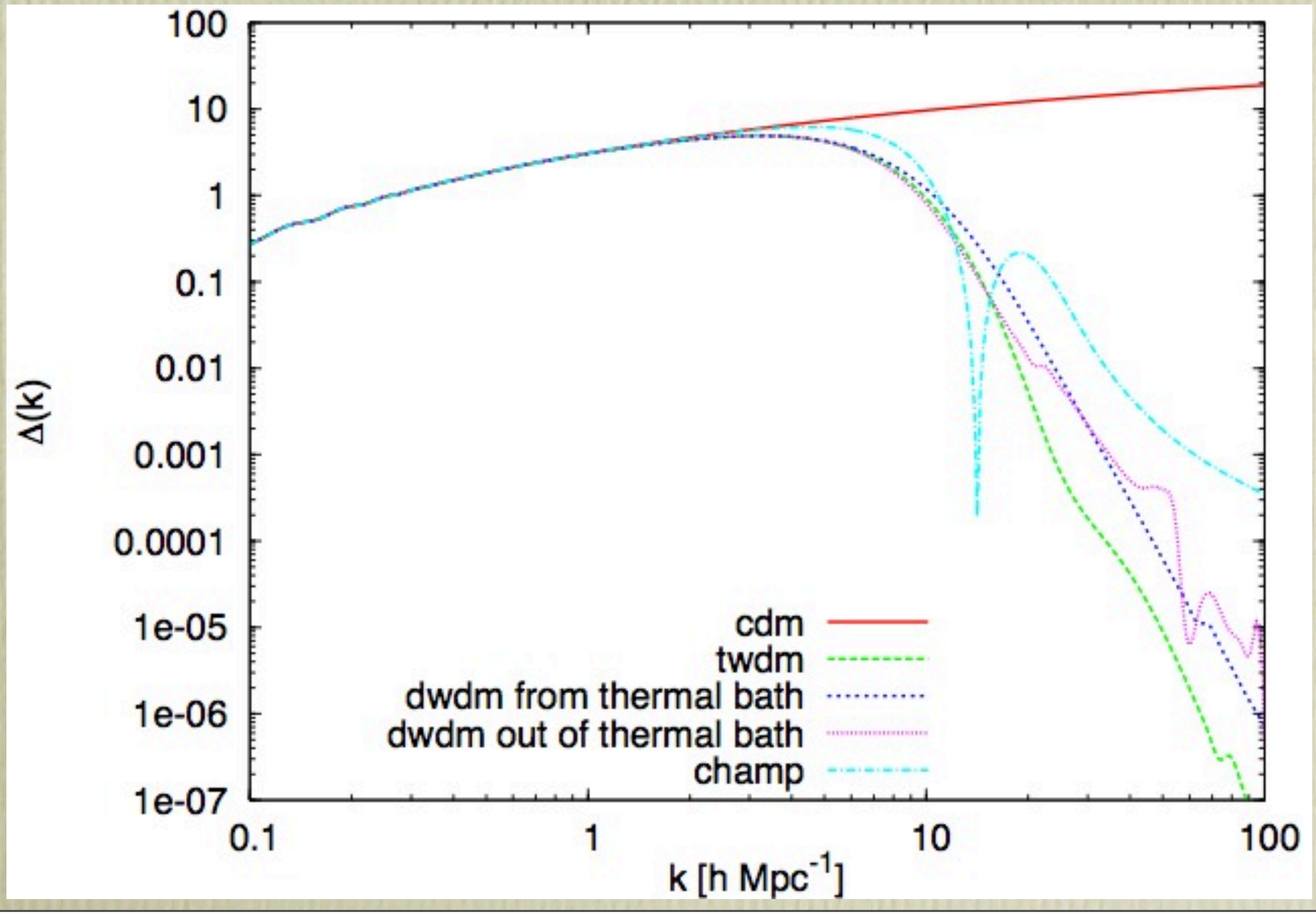
particle physics candidate: staus (superpartner of tau particle in SUSY theory) and gravitinos with mass degeneracy

disguising dark matter as warm dark matter

ChaMP (Charged Massive Particle)

$$k_{\rm standard} \simeq 10^4 \sqrt{\frac{s}{\tau_x}}\ h{\rm Mpc}^{-1}$$

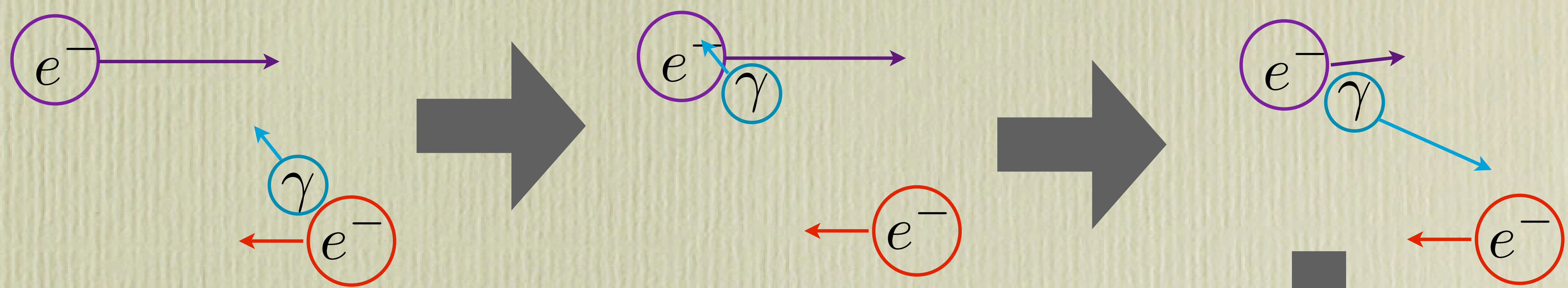
$$\tau_x \simeq 1\ \text{year}\ (\Gamma \simeq 10^{-32}\ \text{GeV})$$

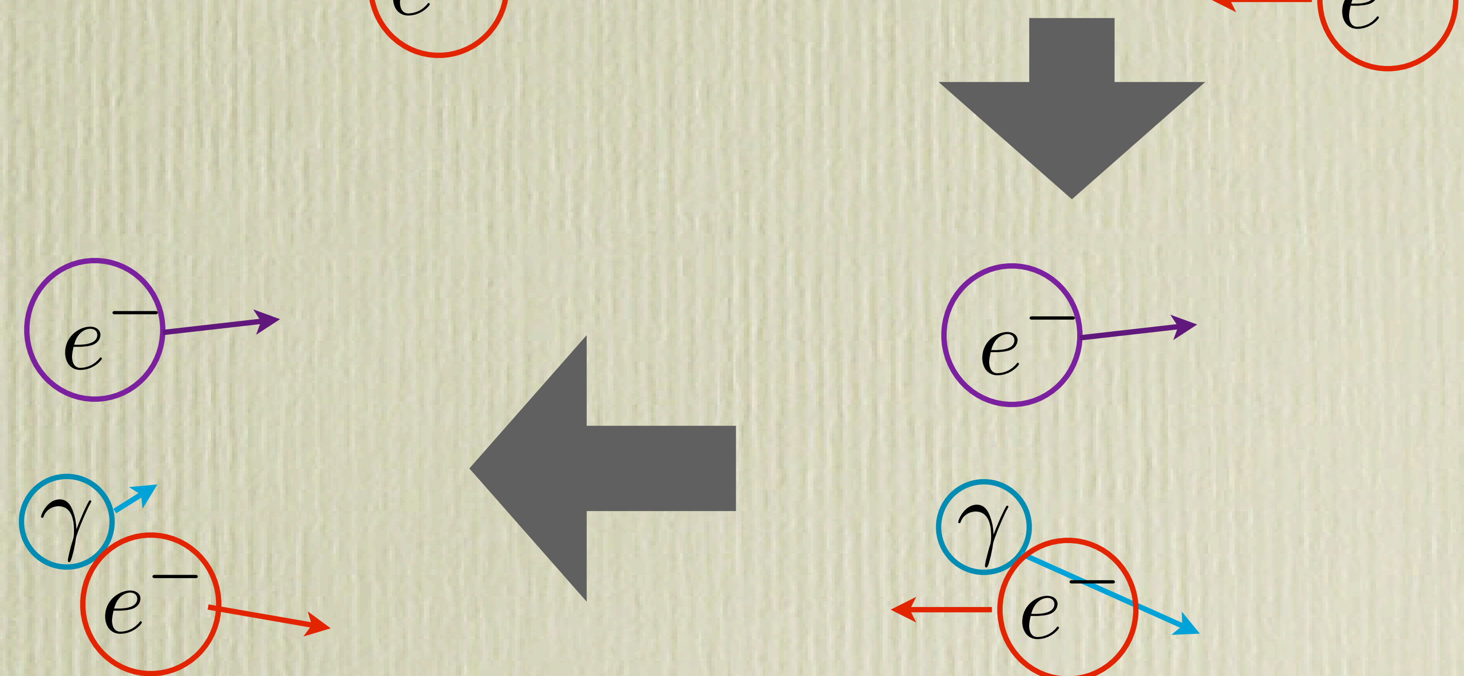


disguising dark matter as warm dark matter

"collisional damping" ("Silk damping")

$e \to$ ChaMP





Thomson scattering diffuse photon and smooth out baryon anisotropy

$$\Gamma \geq H \qquad \Gamma \sim \sigma n_e$$

$$\lambda_{\rm diff} \sim \frac{\eta}{\sqrt{\sigma n_e t}} \sim \sqrt{\frac{t}{\sigma n_e}}$$

$\longleftrightarrow$

random walk

$$\lambda_{\rm diff} \sim \lambda_{\rm fs}\sqrt{\sharp {\rm scat}}$$

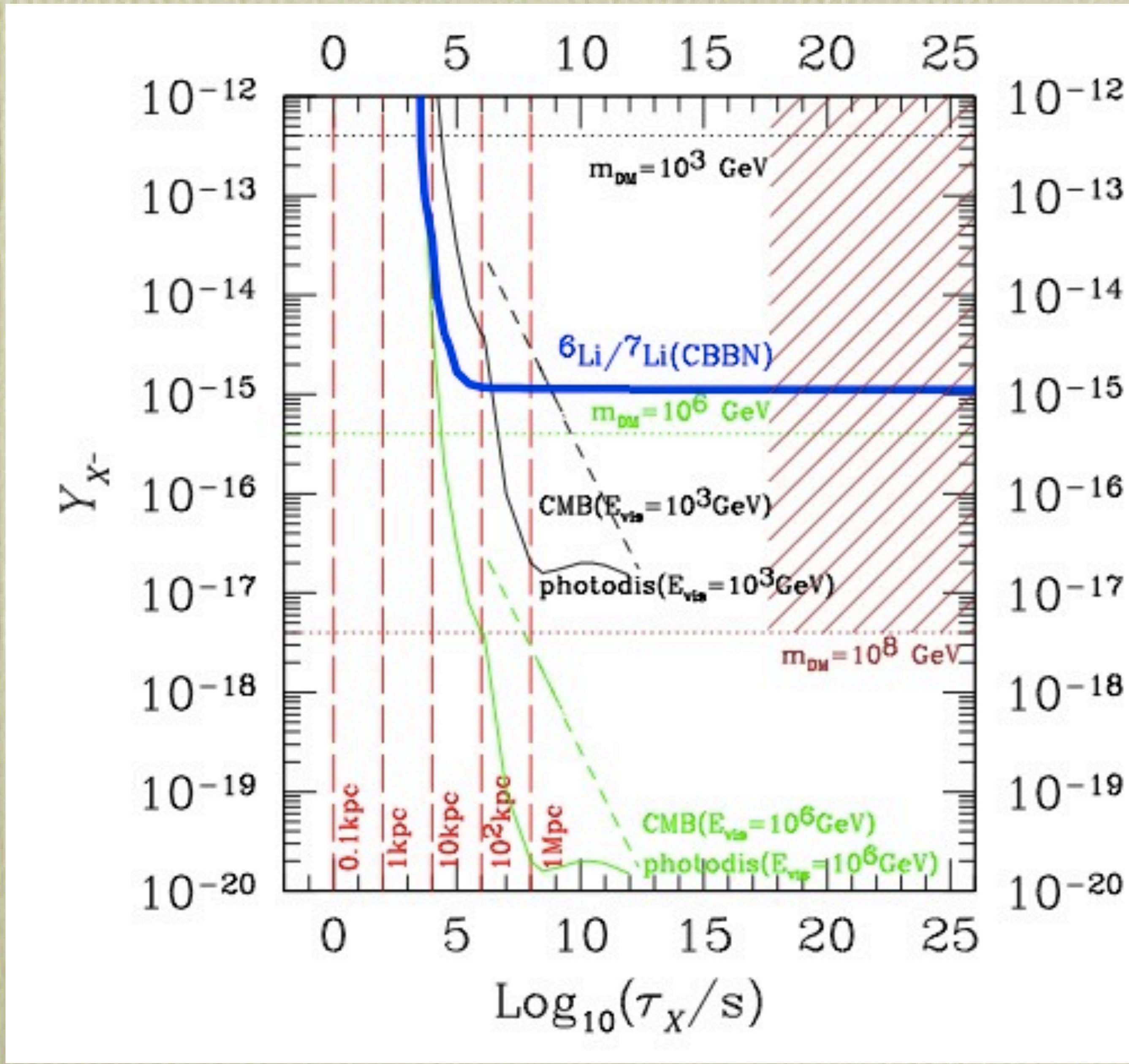
$$\lambda_{\rm fs} \sim \sigma n_e \quad \sharp{\rm scat} \sim \frac{t}{\lambda_{\rm fs}}$$

disguising dark matter as warm dark matter

ChaMP (Charged Massive Particle)

Kohri and Takahashi 2009

constraints on ChaMP



CBBN
: Catalyzed Big Bang Nucleosynthesis

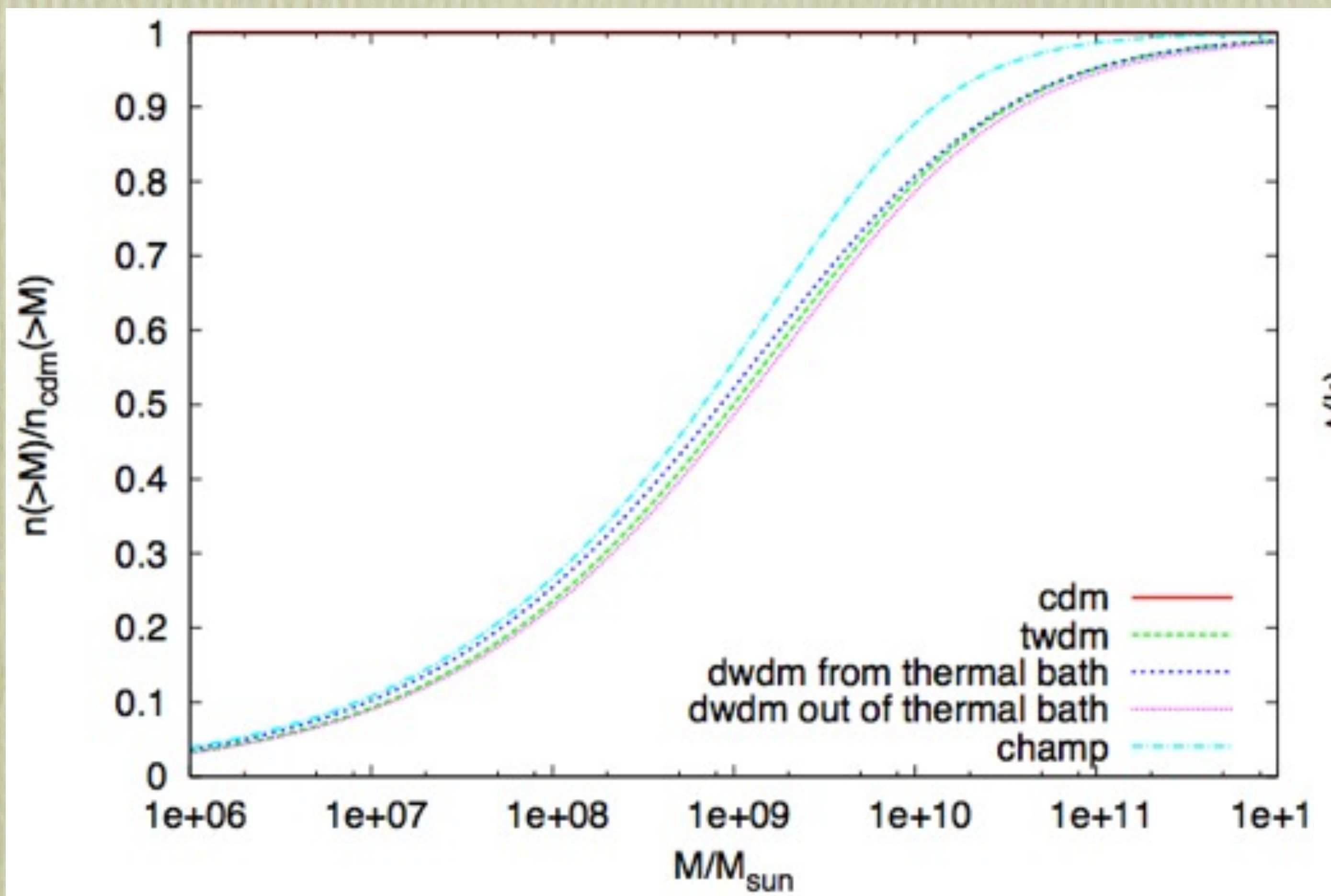
$$({}^4\mathrm{He}X^-) + \mathrm{D} \rightarrow {}^6\mathrm{Li} + X^-$$

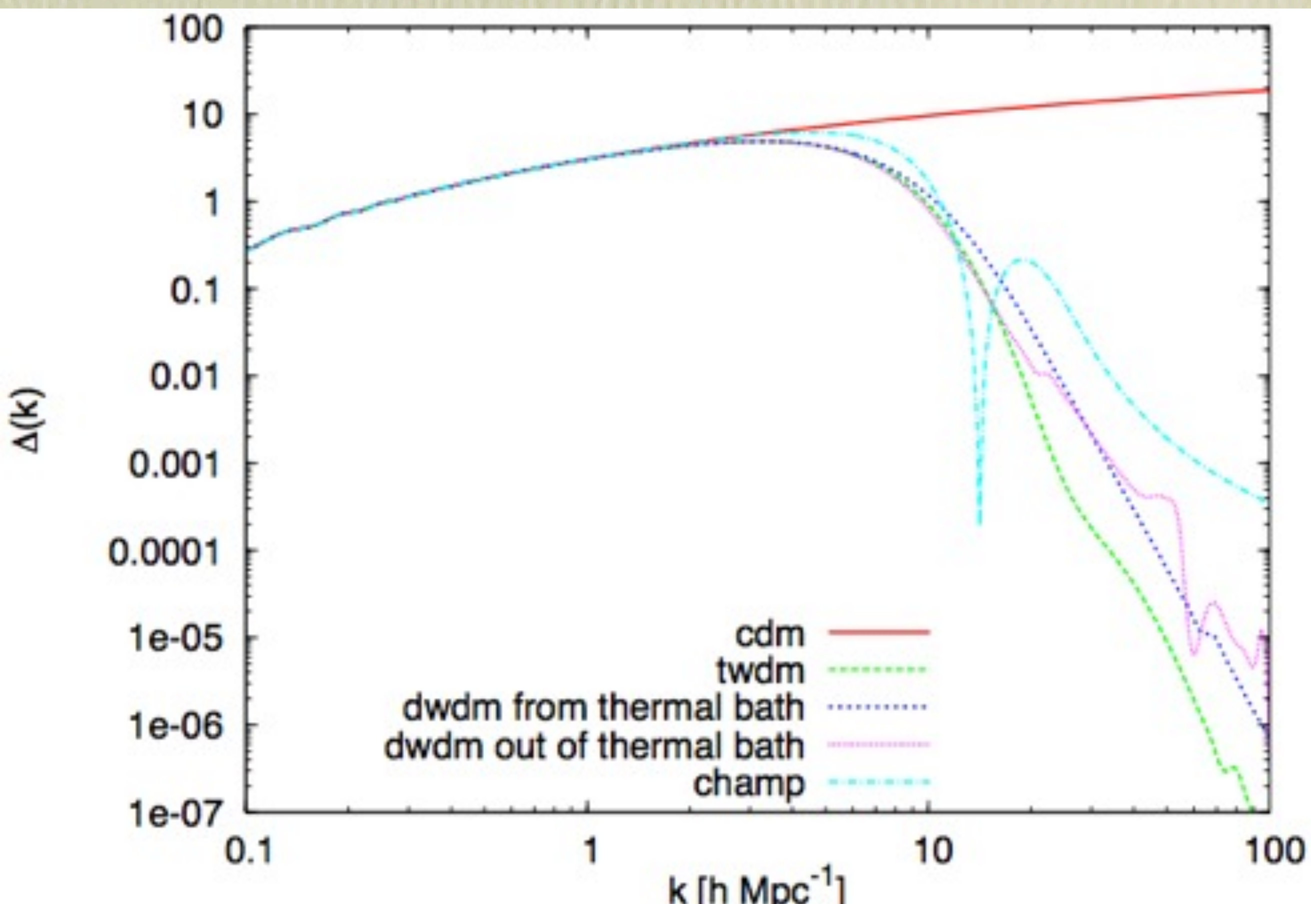
→ overproduction of ^{6}Li

distinguish champ ?

mass function : Press-Schechter

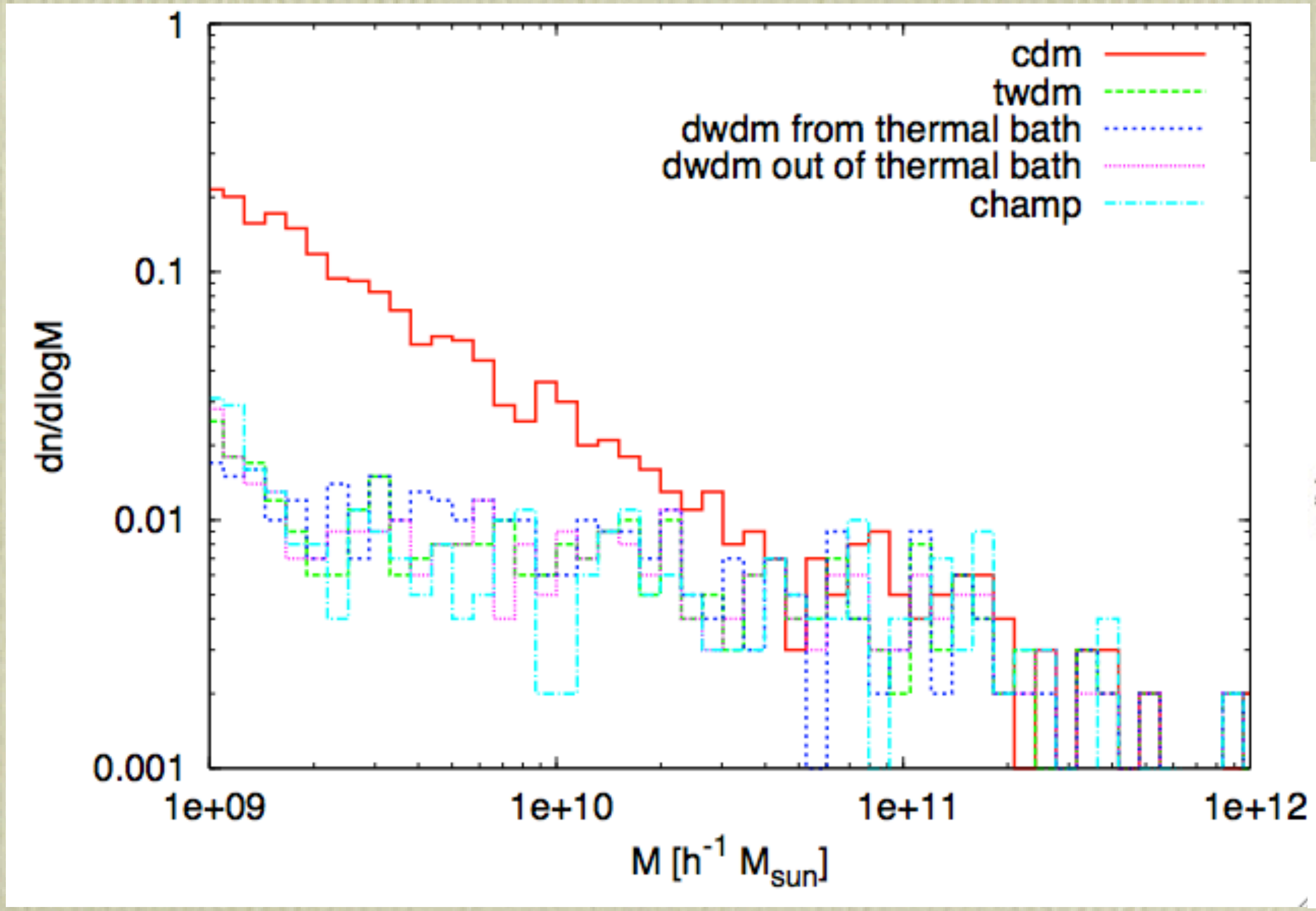
in collaboration with
Naoki Yoshida
Kazunori Kohri, Tomo Takahashi

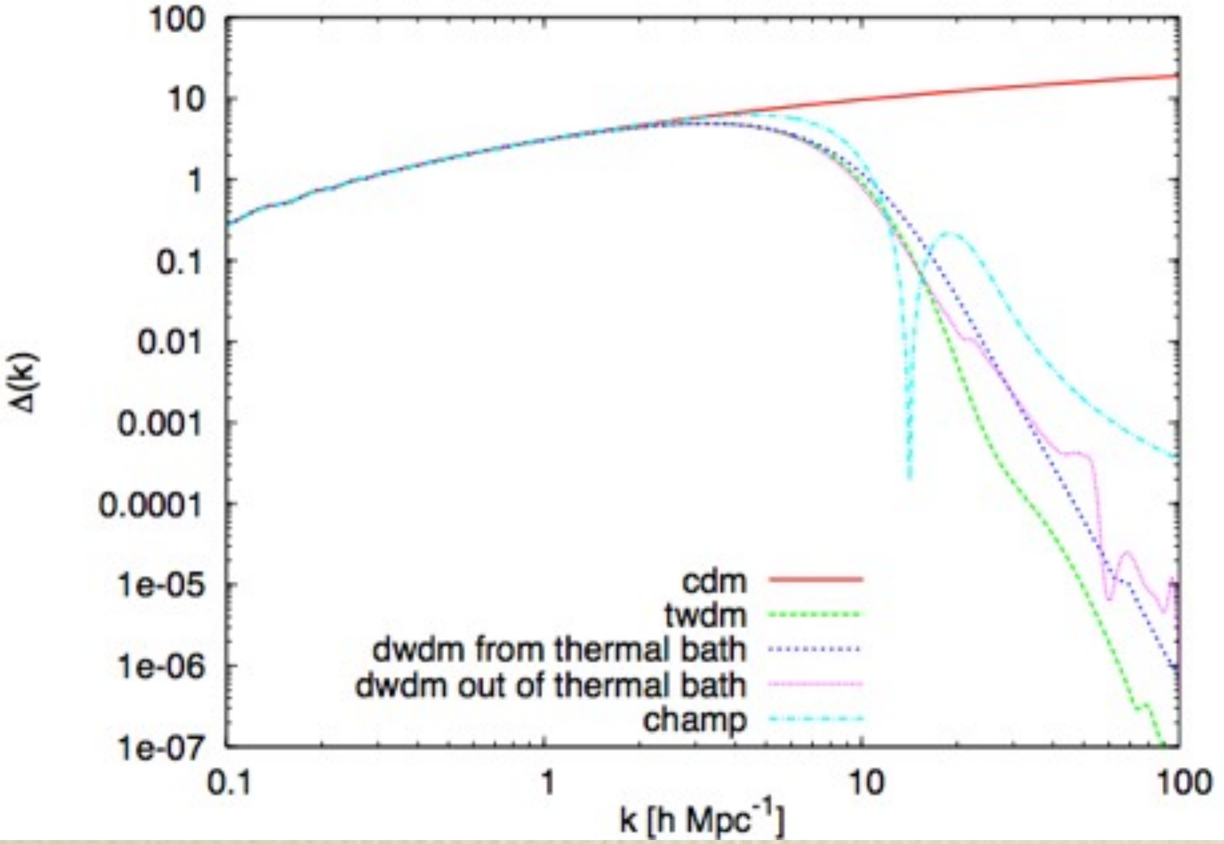




distinguish models ?

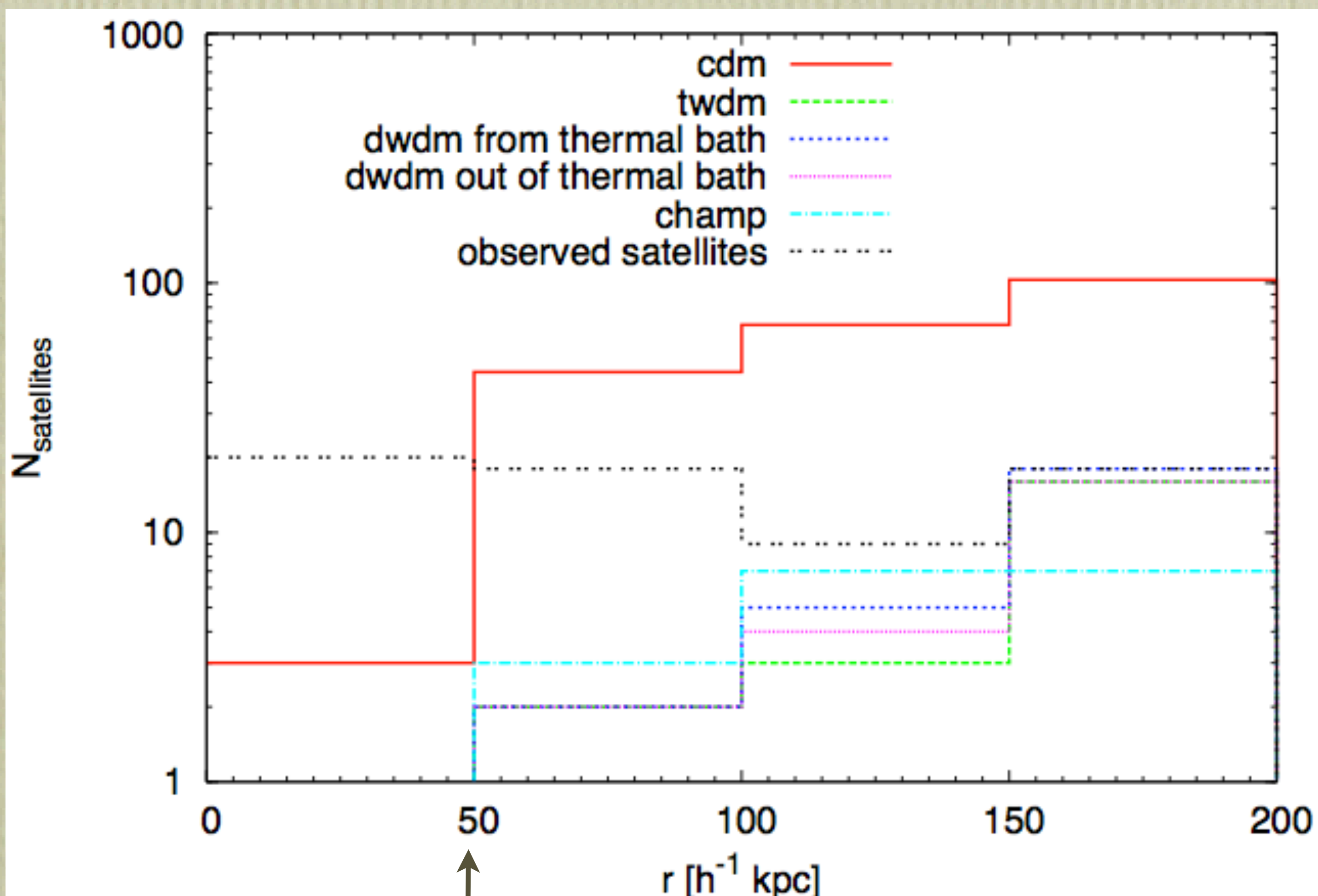
mass function : simulation

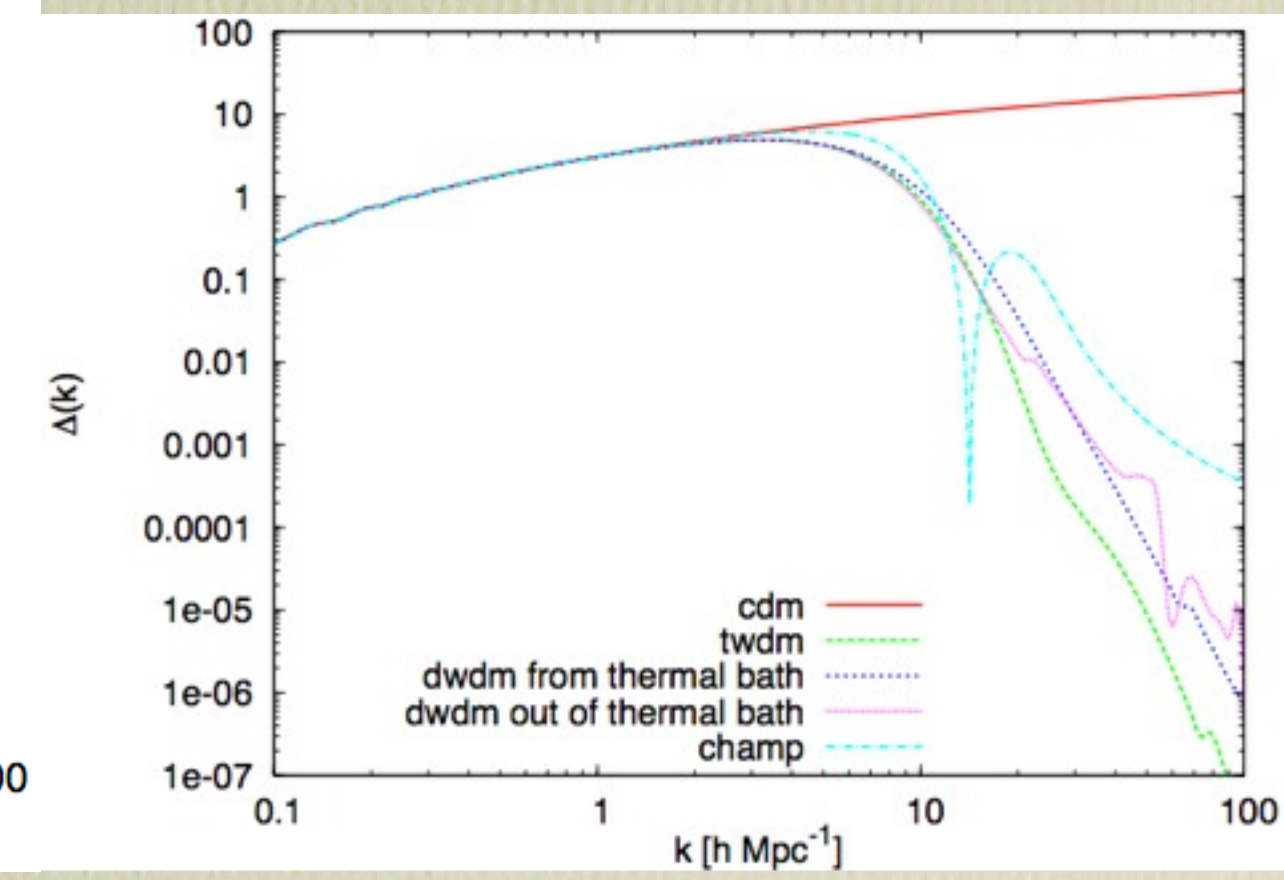




distinguish models ?

radial distribution of the subhalos in a "Milky Way" halo : simulation



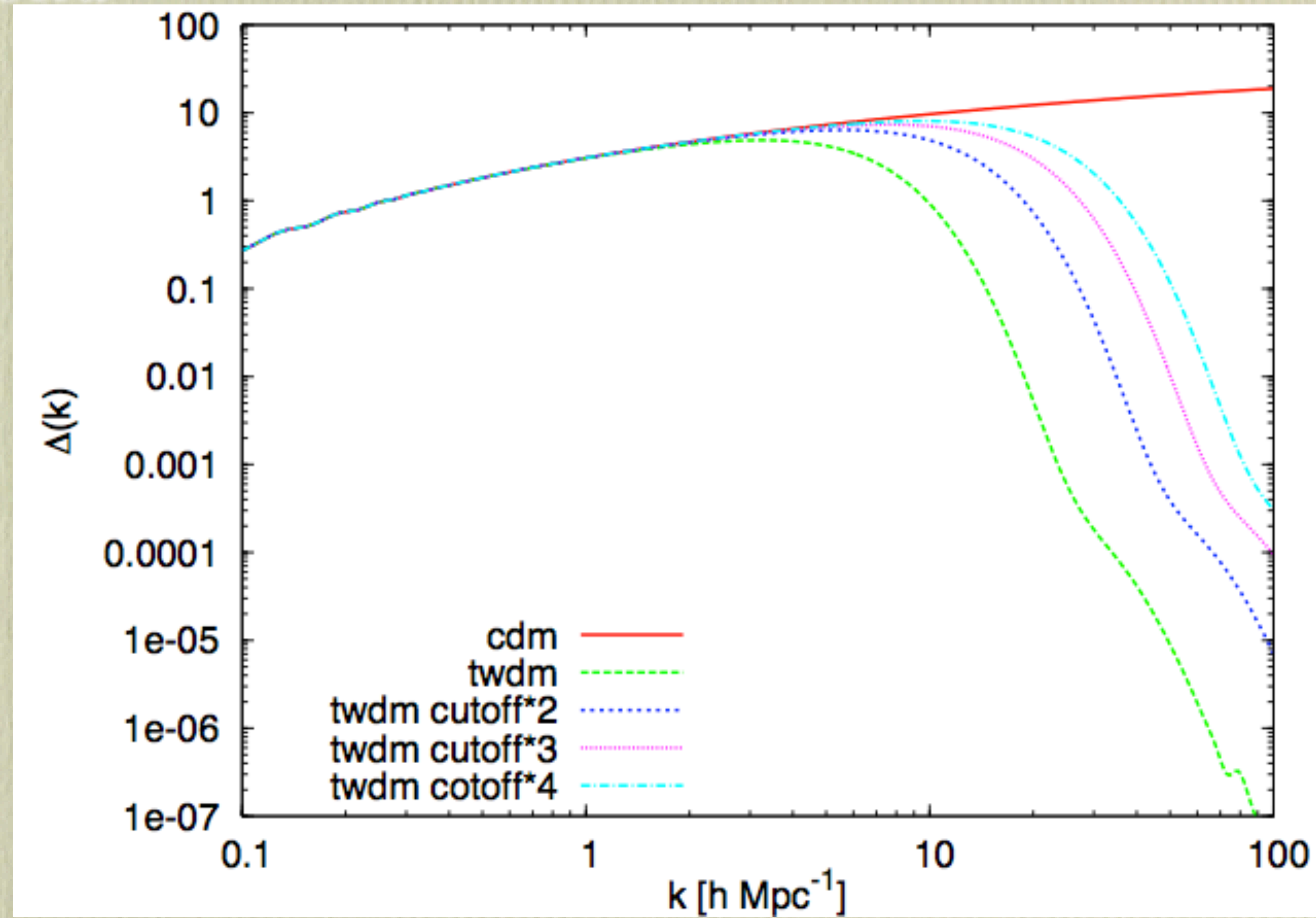


↑

resolution limit of simulation

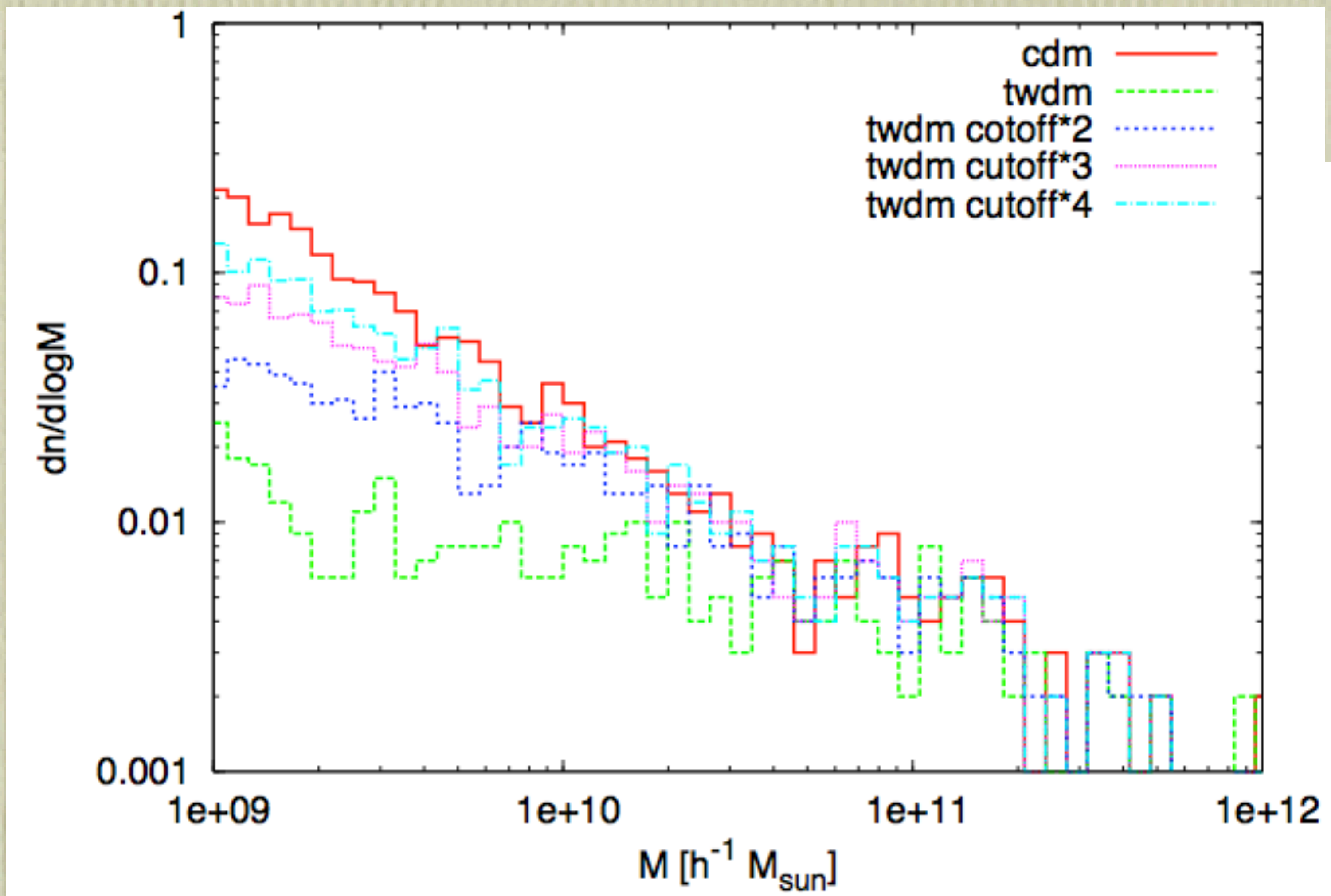
varying cutoff

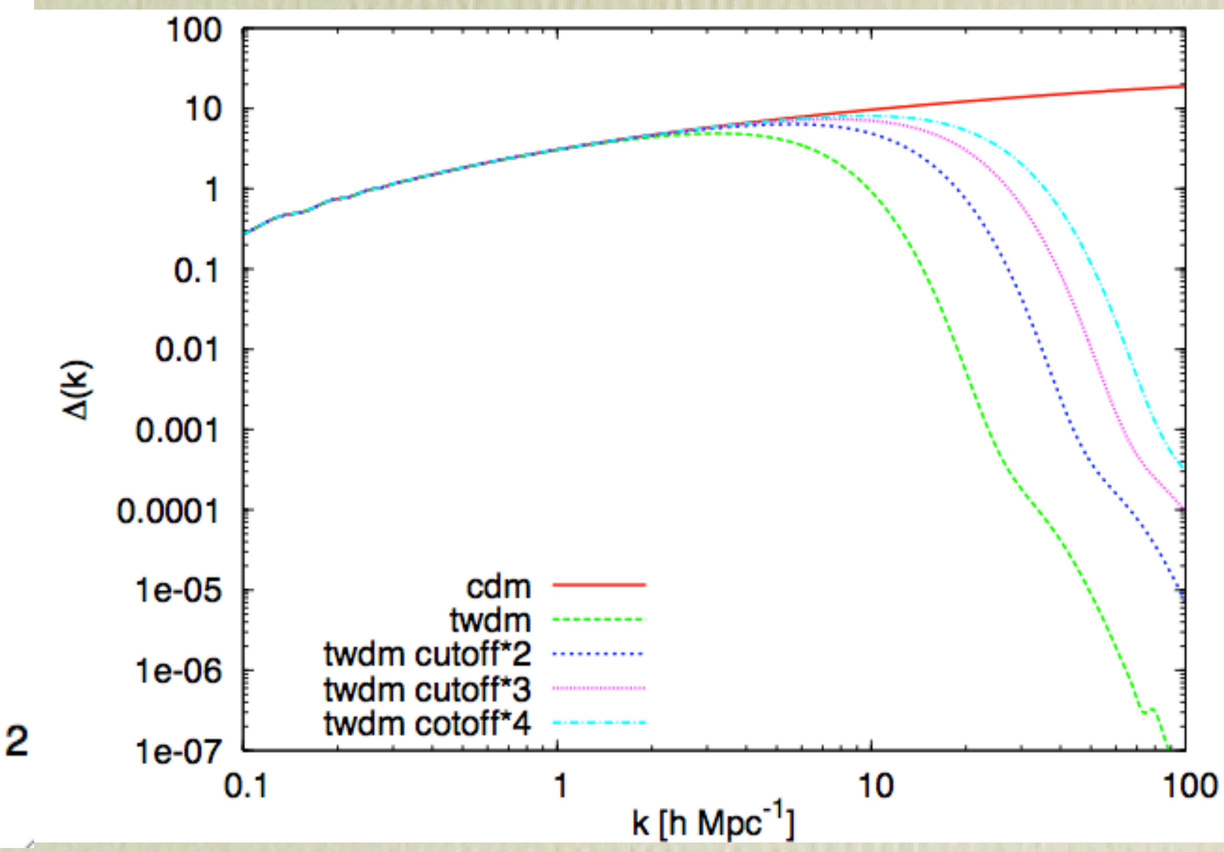
power spectra



varying cutoff

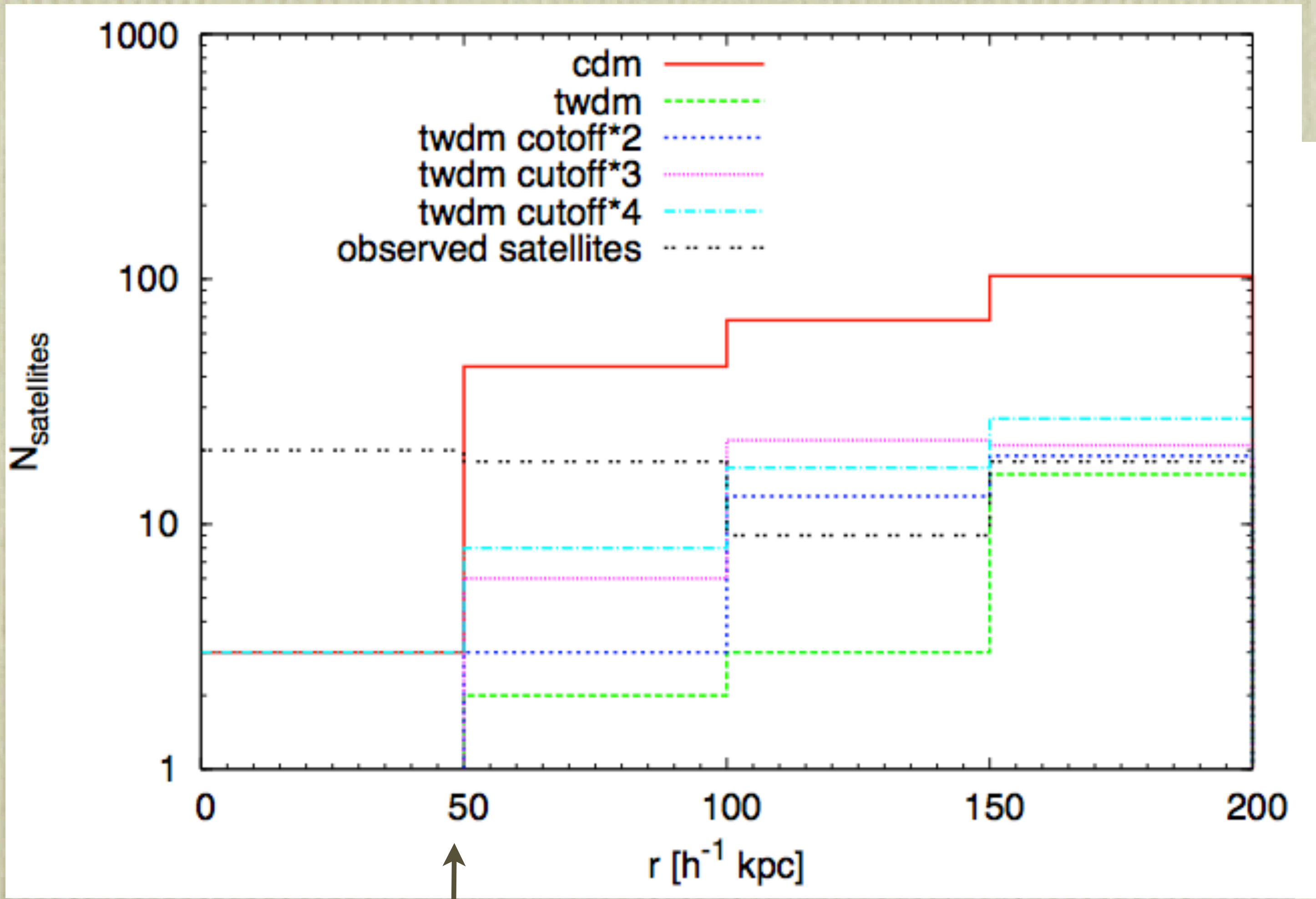
mass function : simulation

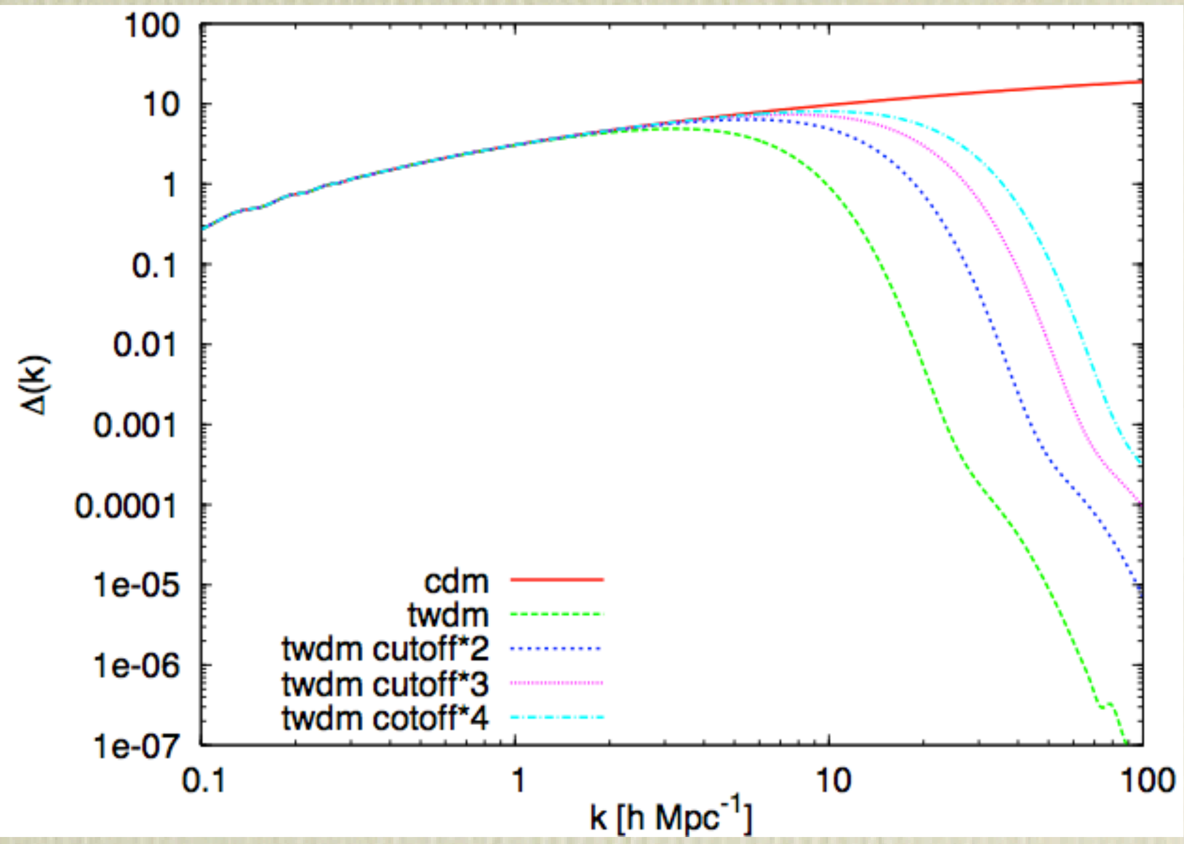




varying cutoff

radial distribution of the subhalos in a "Milky Way" halo : simulation





resolution limit of simulation

Summary and future prospects

Large Scale Structure of the Universe confirms ΛCDM cosmology

Small Scale Structure suffers from non-linear growth and baryon physics, so high redshift survey is promising
e.g. 21cm

Small Scale Crisis is apparent problem of ΛCDM cosmology and require better understanding of baryon physics or warm nature of dark matter

Future submillilensing survey may distinguish warm dark matter and baryon physics

Summary and future prospects

The standard of clustering property of warm dark matter is conformal time (horizon size) when warm dark matter become nonrelativistic

Warm dark matter models which have the same standard may not be distinguished by z=0 observation

ChaMP with life time about one year behave like warm dark matter

Thermally produced warm dark matter mass appears to be larger than 2 keV

Thank you for your attention