Cosmological boost factor for dark matter annihilation at redshifts of z=10-100 using the power spectrum approach

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RT & Kohri（2021）PRD

Introduction to Cosmological reionization

- UV radiation from first stars ionized intergalactic medium (IGM)

  this process began at z=10-20 and ended at z=6

  (e.g., Creig & Mesinger 2017)

- High energy photons or particles ($e^{\pm}, q, \bar{q}$, etc) might be produced

  by dark matter (DM) annihilation

  → affect the reionization process (e.g., Valdes+ 2013; Liu+ 2016; Hiroshima+ 2021)

Annihilation rate ∝ (DM density)^2

we calculate this quantity using N-body simulations at z=10-100

Cosmological boost factor

DM mass density

$$\rho_{\mathrm{DM}}(\vec{r}, z) = \bar{\rho}_{\mathrm{DM}}(z)\left\{1 + \delta_{\mathrm{DM}}(\vec{r}, z)\right\}$$

mean

density contrast

collision rate of DM particles ∝ (DM density)^2

$$\langle \rho^2_{\mathrm{DM}}(\vec{r}, z)\rangle = \bar{\rho}^2_{\mathrm{DM}}(z)\left\{1 + \langle \delta^2_{\mathrm{DM}}(\vec{r}, z)\rangle\right\}$$

$$= \bar{\rho}^2_{\mathrm{DM}}(z)\, B(z)$$

boost factor

How to calculate B(z) ?

1. Halo model approach
2. Power spectrum approach

both approaches give a consistent B(z) at z=0-6

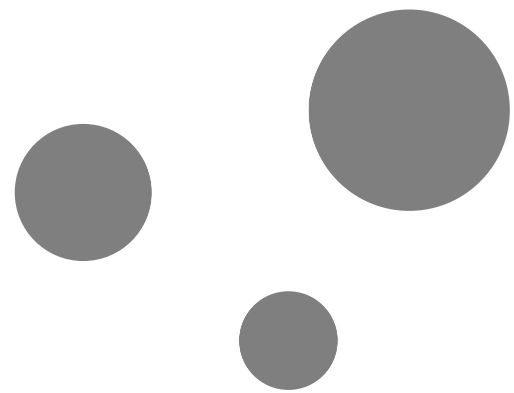
（The Fermi LAT collaboration 2015）

1. Halo model approach （e.g., Ullio+ 2002; Cirelli+ 2011; Valdes+ 2013; Evoli+ 2014; Ando+ 2019）

DM annihilation is enhanced at central/dense regions of halos

B(z) is obtained using the following model ingredients

- Halo density profile
- Halo mass function



model uncertainties:

subhalo（or sub-subhalo）mass function, ellipticity, central density profile

2. Power spectrum approach (Serpico+ 2012; Seffusatti+ 2014)

Boost factor

$$B(z) = 1 + \langle \delta^2_{\rm DM}(\vec{r}; z) \rangle$$
$$= 1 + \int_0^\infty d\ln k \, \underline{\Delta^2(k; z)}$$

dimensionless matter power spectrum

$$\Delta^2(k; z) = \frac{k^3}{2\pi^2} P(k; z)$$

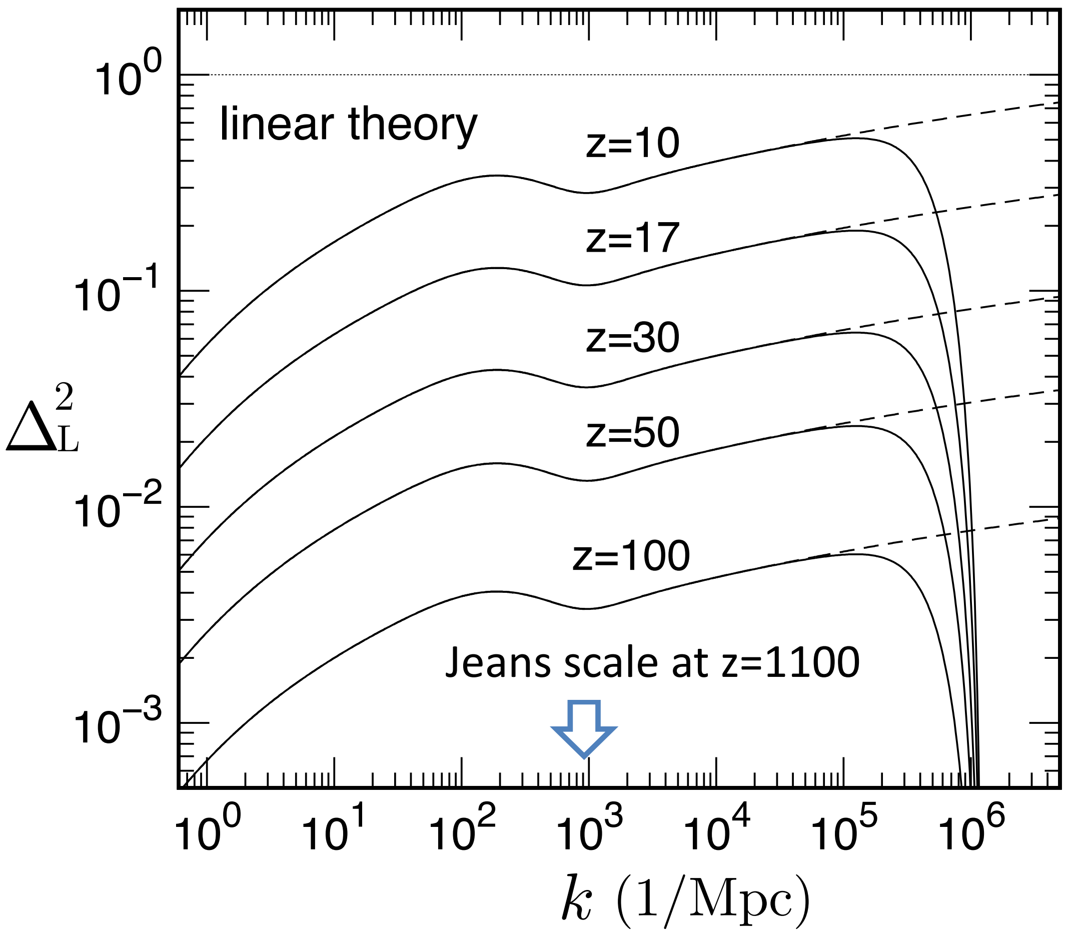
- linear Δ^2 is obtained using the linear perturbation theory
- non-linear Δ^2 is obtained using DM N-body simulations

Linear power spectrum

transfer function （Yamamoto, Sugiyama & Sato 1998）

with free-streaming（FS）damping of DM particles at $k_{\rm fs} = 10^6\ {\rm Mpc}^{-1}$

（Green, Hoffmann & Schwarz 2004）



Planck2016 flat ΛCDM

solid line : linear theory

dashed line : linear theory w/o FS damping

Non-linear evolution of power spectrum

dark-matter-only simulations with N-body code GreeM

（Ishiyama+ 2009）

number of particles: 5120^3

side length of simulation boxes: 1kpc, 10kpc, 100kpc, 1Mpc & 10Mpc

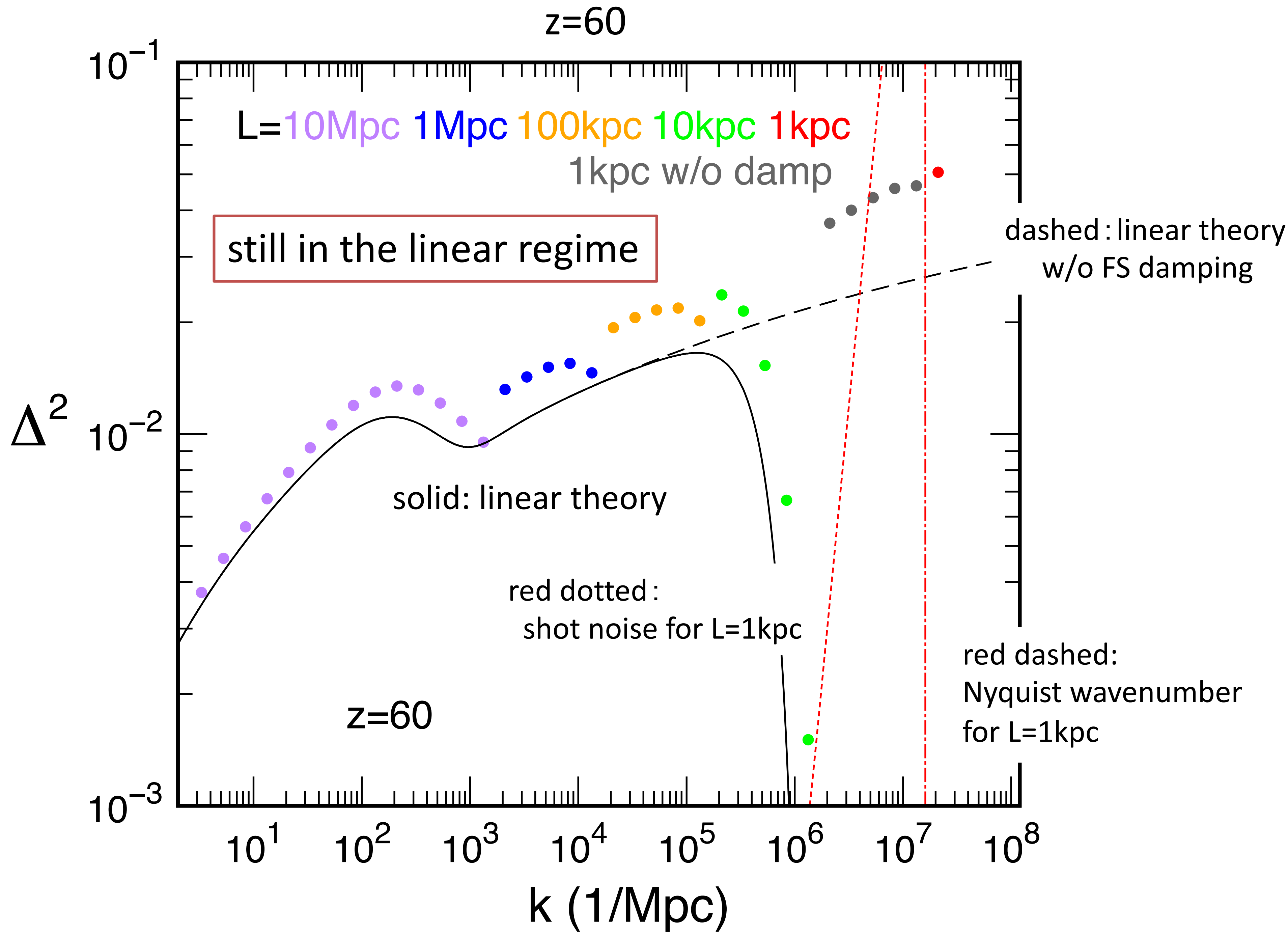
→ covering a wide range of scales

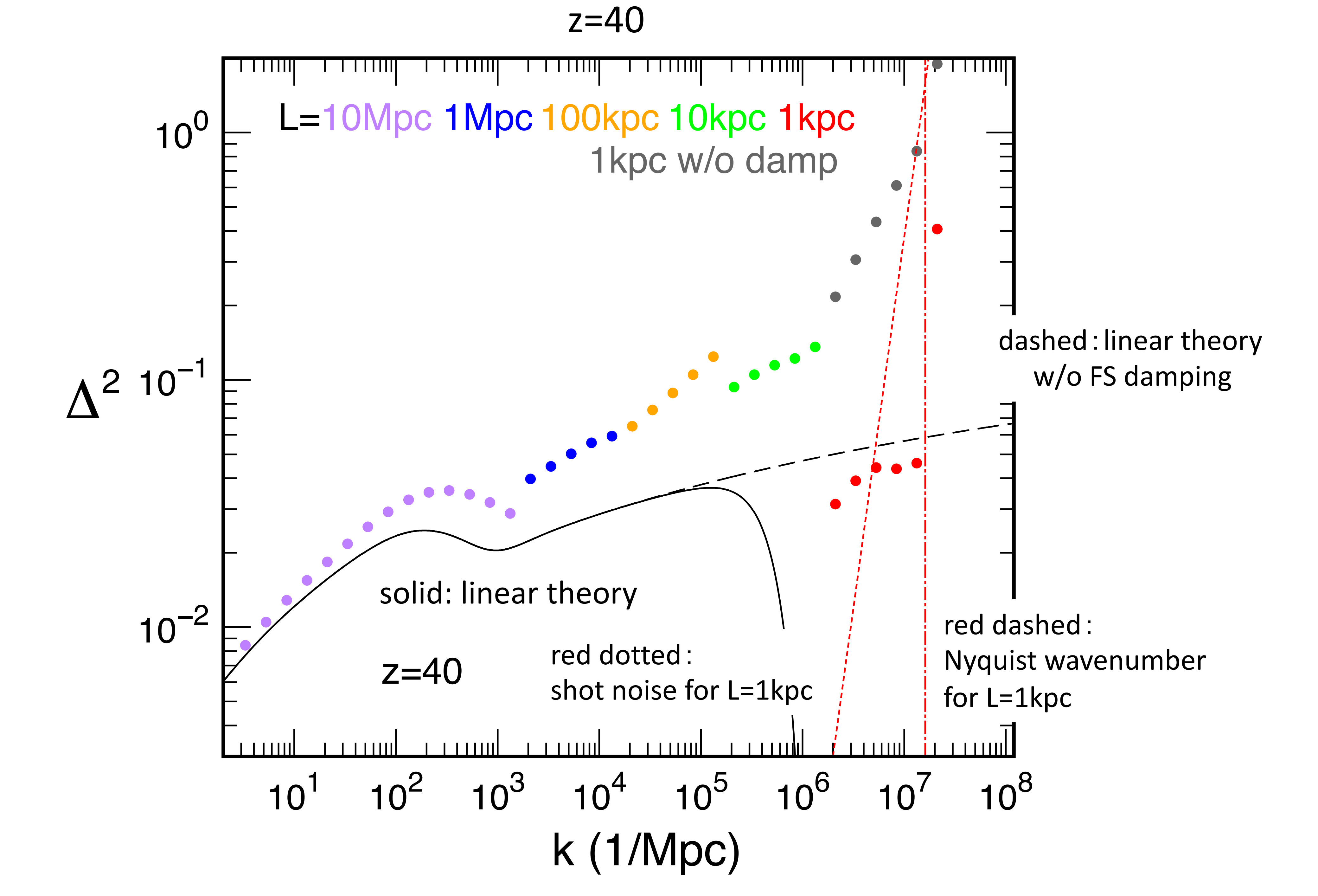
$$k = 1\,\mathrm{Mpc}^{-1} - 2\times 10^7\,\mathrm{Mpc}^{-1}$$

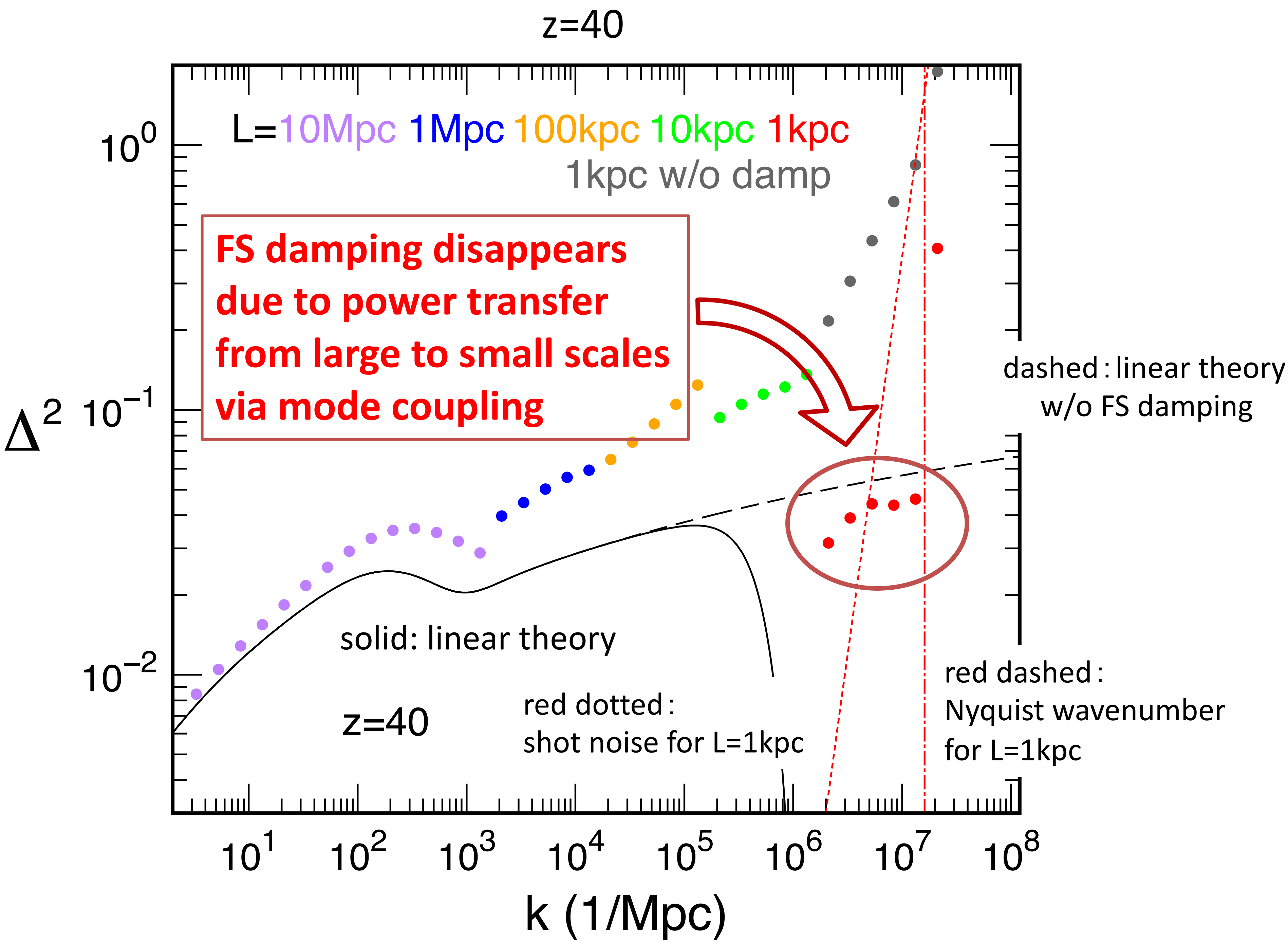
（Nyquist wavenumber for L=1kpc）

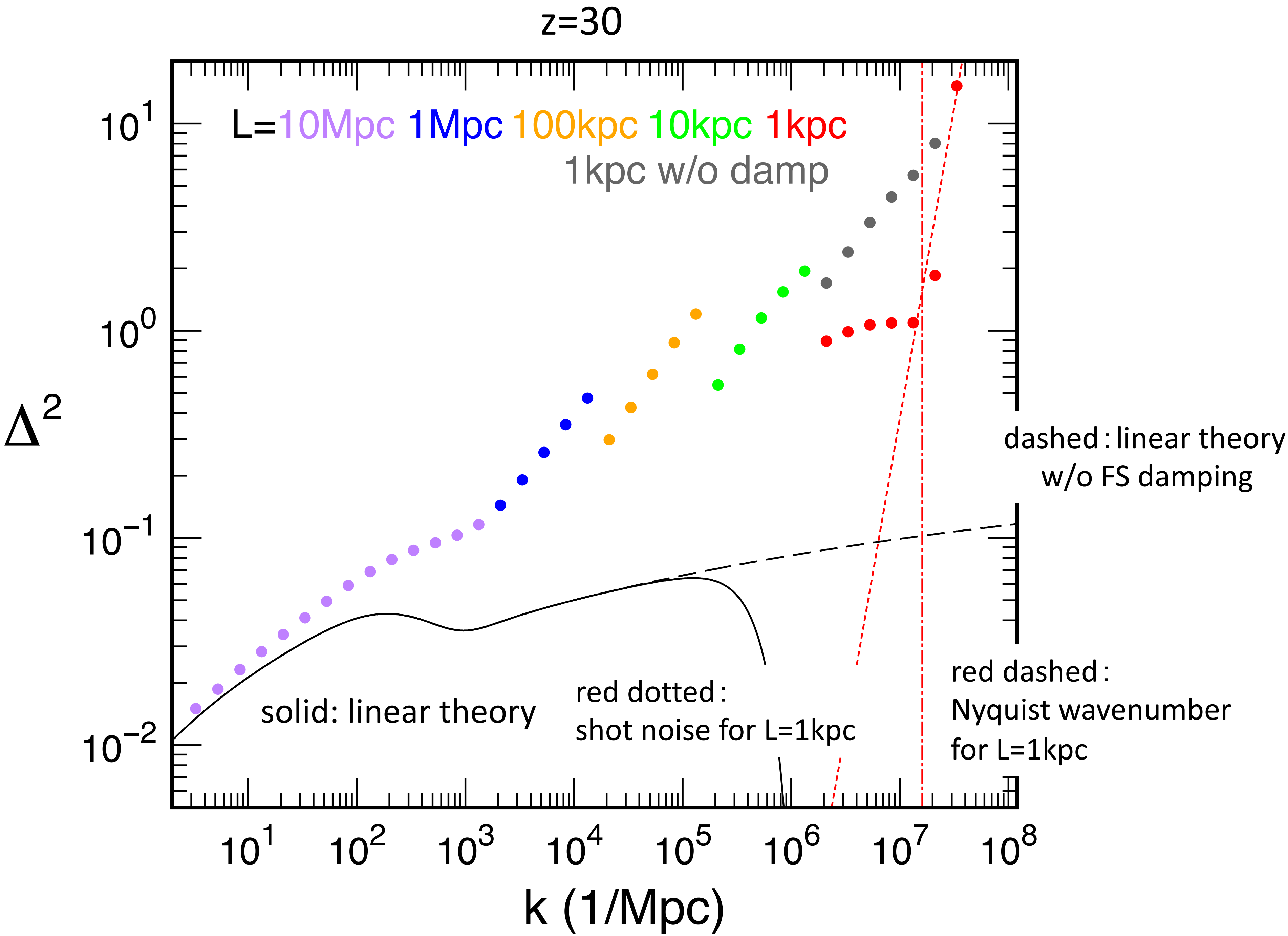
Initial redshift z=400

output redshifts z=100, 60, 50, 40, 30, 23, 17 & 10

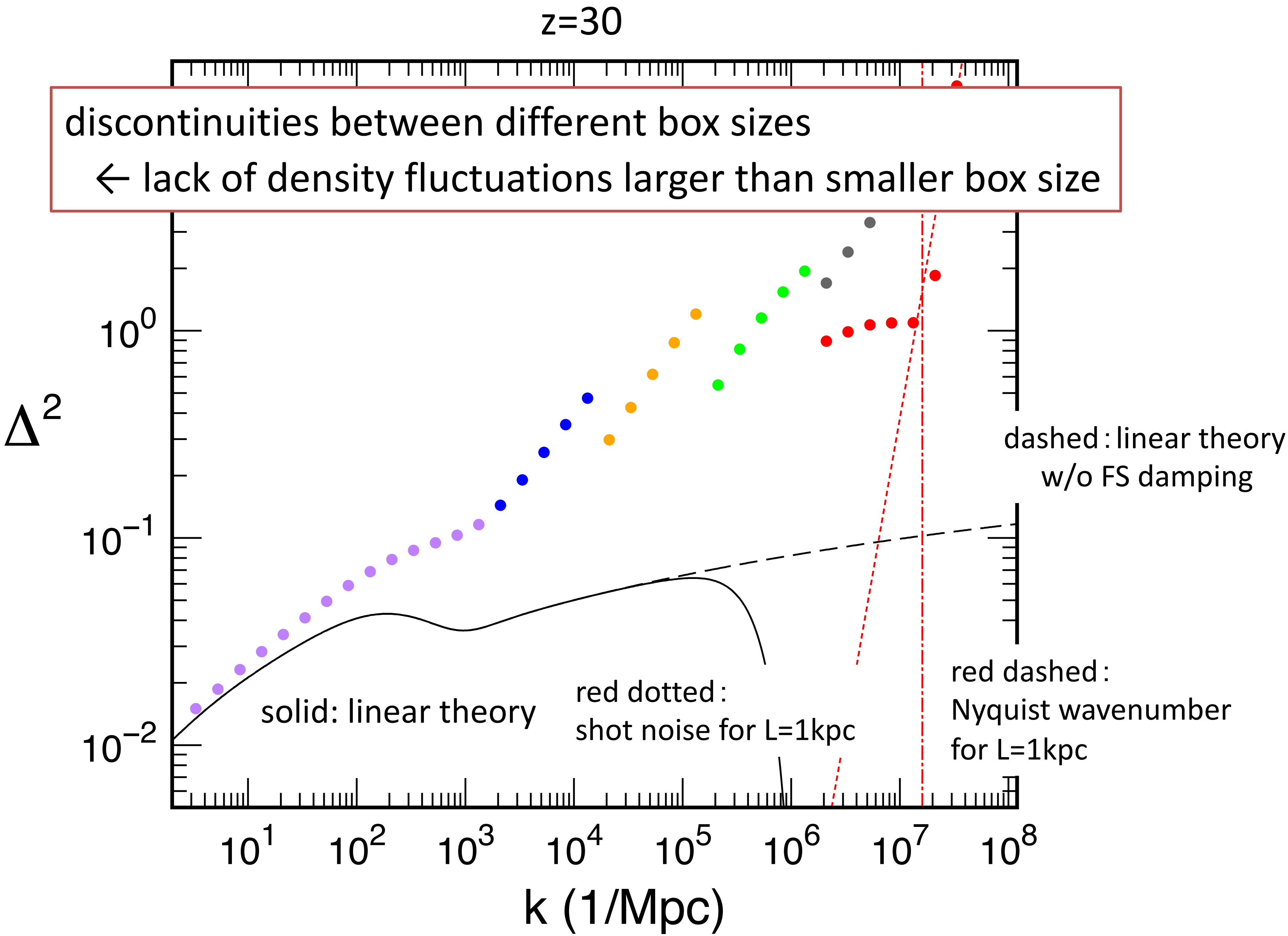

z=60
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
still in the linear regime
dashed : linear theory
w/o FS damping
solid: linear theory
red dotted :
shot noise for L=1kpc
red dashed:
Nyquist wavenumber
for L=1kpc
z=60
Δ²
10⁻¹
10⁻²
10⁻³
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
k (1/Mpc)


z=40
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
dashed : linear theory
w/o FS damping
solid: linear theory
z=40
red dotted :
shot noise for L=1kpc
red dashed :
Nyquist wavenumber
for L=1kpc
Δ^2
10^0
10^{-1}
10^{-2}
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
k (1/Mpc)

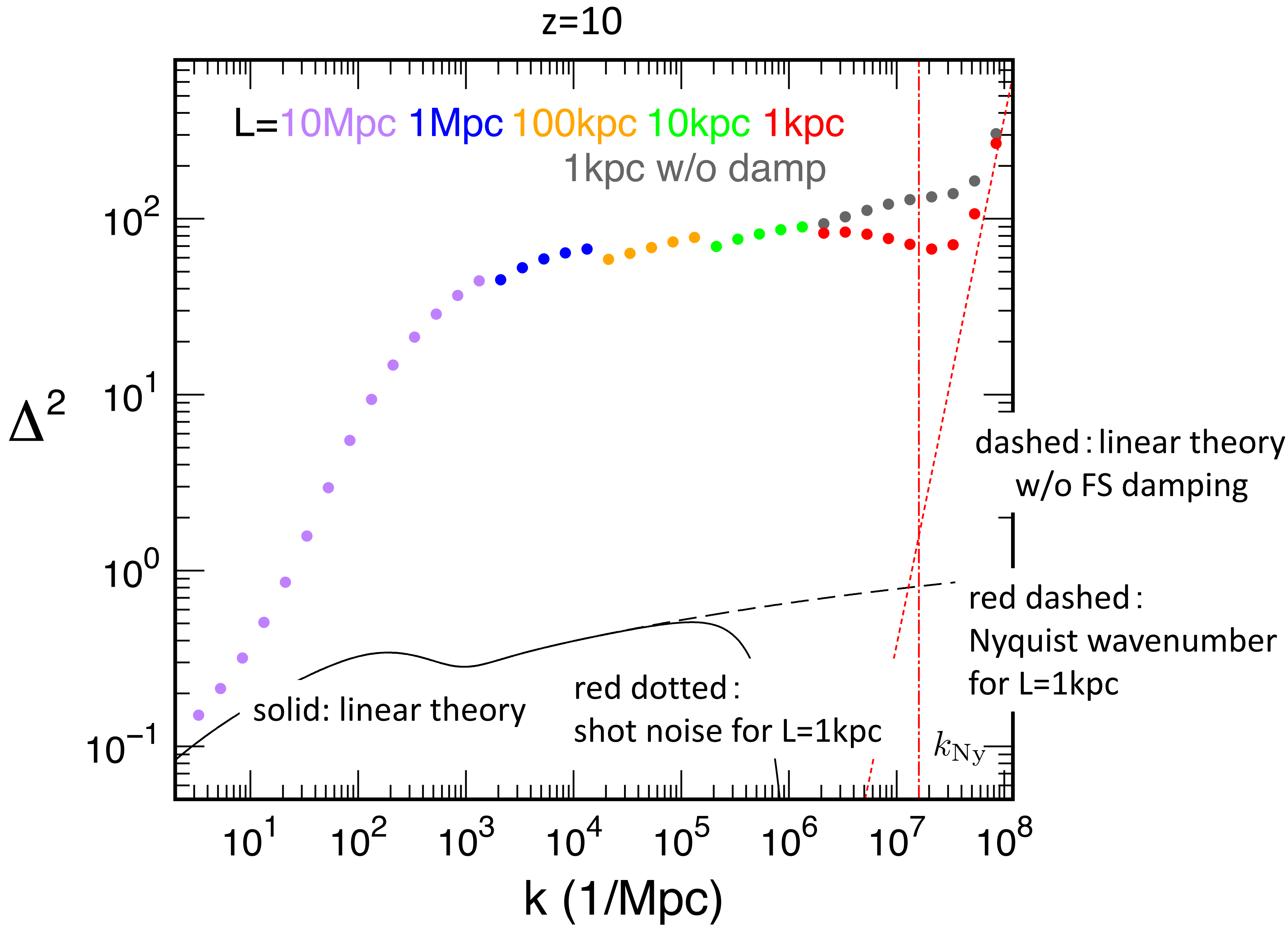

z=40
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
FS damping disappears due to power transfer from large to small scales via mode coupling
dashed : linear theory w/o FS damping
solid: linear theory
z=40
red dotted : shot noise for L=1kpc
red dashed : Nyquist wavenumber for L=1kpc
Δ^2
10^0
10^{-1}
10^{-2}
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
k (1/Mpc)



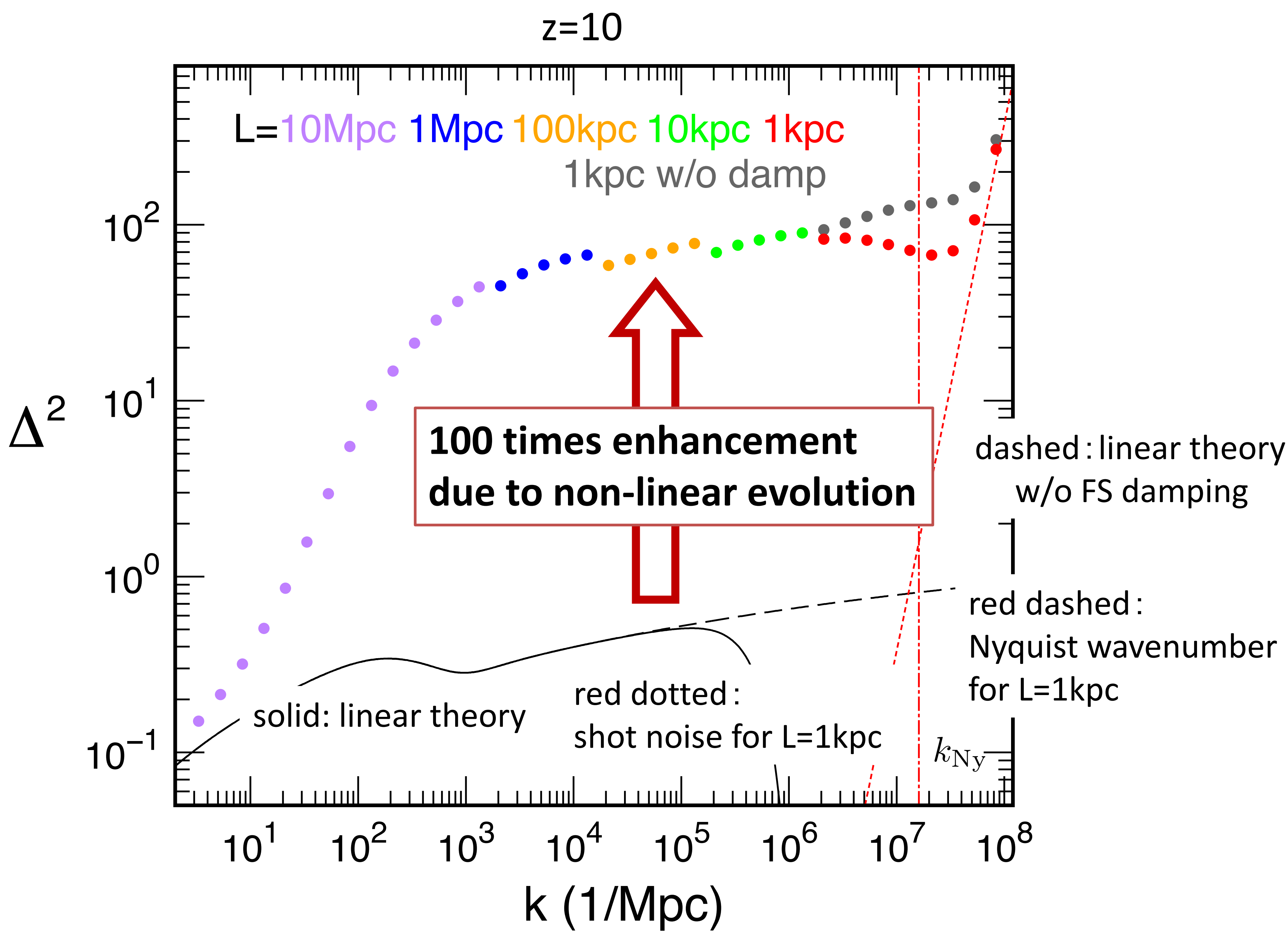
z=30
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
dashed : linear theory
w/o FS damping
solid: linear theory
red dotted :
shot noise for L=1kpc
red dashed :
Nyquist wavenumber
for L=1kpc
Δ²
k (1/Mpc)



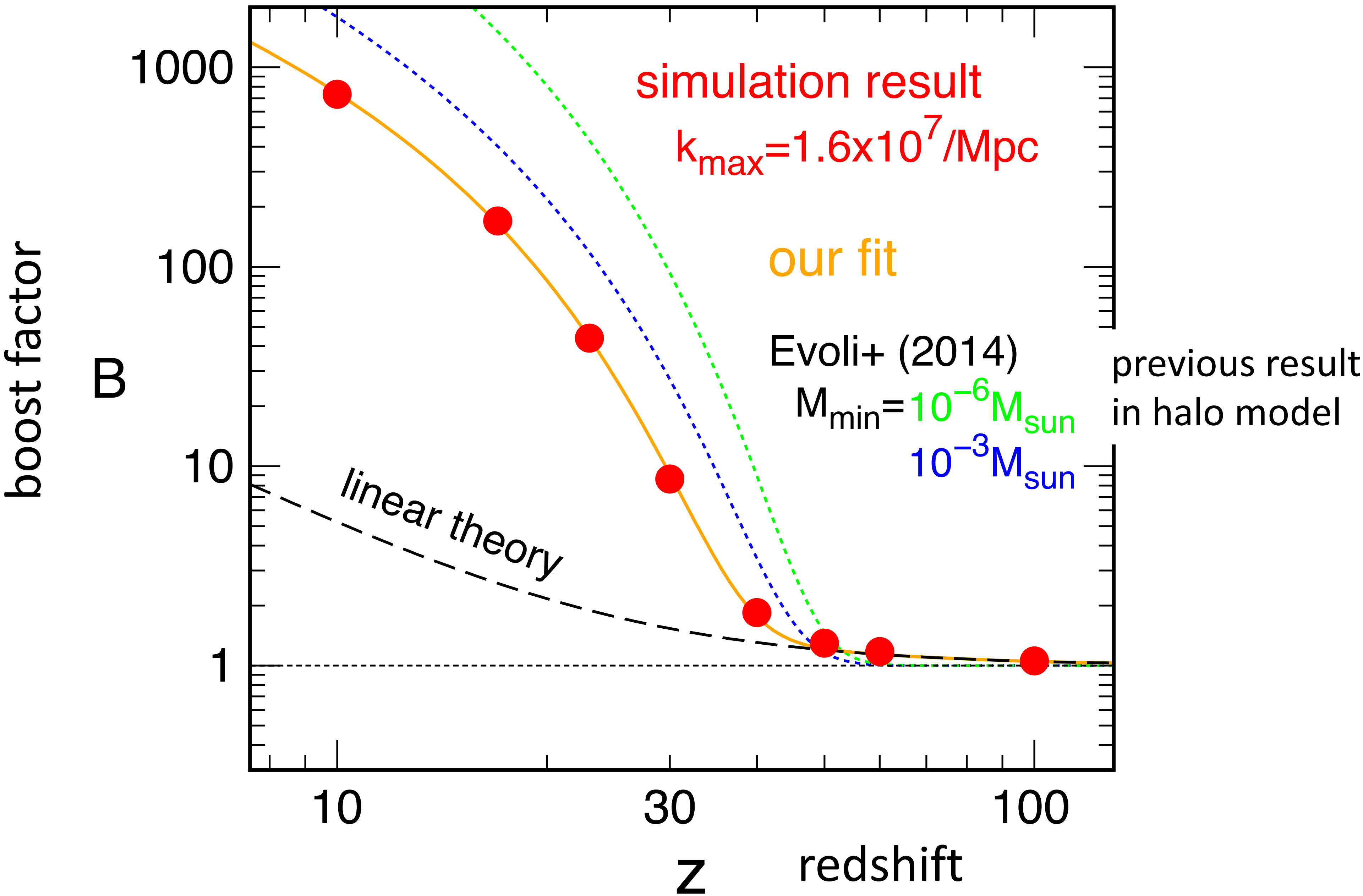
z=30
discontinuities between different box sizes
← lack of density fluctuations larger than smaller box size
dashed : linear theory w/o FS damping
solid: linear theory
red dotted : shot noise for L=1kpc
red dashed : Nyquist wavenumber for L=1kpc
Δ^2
10^0
10^{-1}
10^{-2}
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
k (1/Mpc)



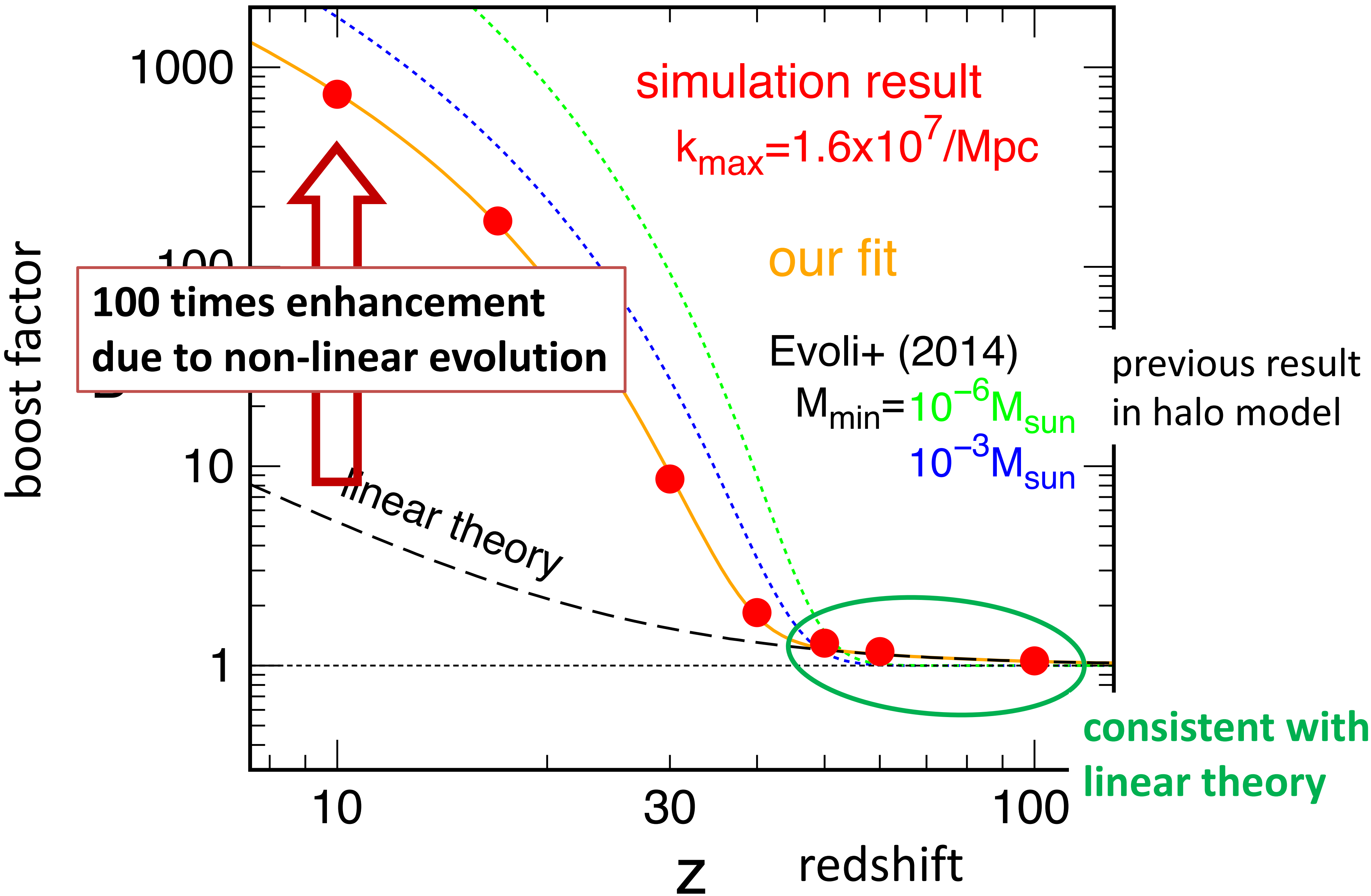
z=10
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
Δ^2
10^2
10^1
10^0
10^{-1}
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
k (1/Mpc)
dashed : linear theory
w/o FS damping
red dashed :
Nyquist wavenumber
for L=1kpc
$k_{\rm Ny}$
solid: linear theory
red dotted :
shot noise for L=1kpc



z=10
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
100 times enhancement due to non-linear evolution
dashed : linear theory w/o FS damping
red dashed : Nyquist wavenumber for L=1kpc
red dotted : shot noise for L=1kpc
solid: linear theory
$k_{\rm Ny}$
Δ^2
k (1/Mpc)
10^{-1}
10^0
10^1
10^2
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8



simulation result
kmax=1.6x10^7/Mpc
our fit
Evoli+ (2014)
Mmin=10^-6Msun
10^-3Msun
previous result
in halo model
linear theory
boost factor
B
1000
100
10
1
10
30
100
z
redshift



boost factor
1000
100
10
1
10
30
100
z
redshift
simulation result
k_max=1.6x10^7/Mpc
our fit
Evoli+ (2014)
M_min=10^-6 M_sun
10^-3 M_sun
previous result
in halo model
linear theory
100 times enhancement
due to non-linear evolution
consistent with
linear theory

Summary

- **Cosmological boost factor at z=10-100 is obtained** following non-linear gravitational evolution of DM density fluctuations with N-body sims

  see also Hiroshima+（2021）for practical application of our B(z)

- Our B(z) is consistent with linear theory prediction at z>50, but it is strongly enhanced at z<40

- **free-streaming damping still remains at z>50, but it disappears at z<40 due to power transfer from large to small scale** (via mode coupling)

- Our simulation does not include density fluctuations smaller than $\approx 0.4\ \mathrm{Mpc}$, therefore **our B(z) is lower bound**

TABLE I. Summary of our N-body simulations: the side length of cubic simulation box L, the number of particles N_p, the minimum wave number $2\pi/L$, the particle Nyquist wave number $k_{\rm Ny} \equiv (\pi/L)N_p^{1/3}$, and the N-body particle mass m_p. Values in parentheses indicate differing values for the low-resolution runs.

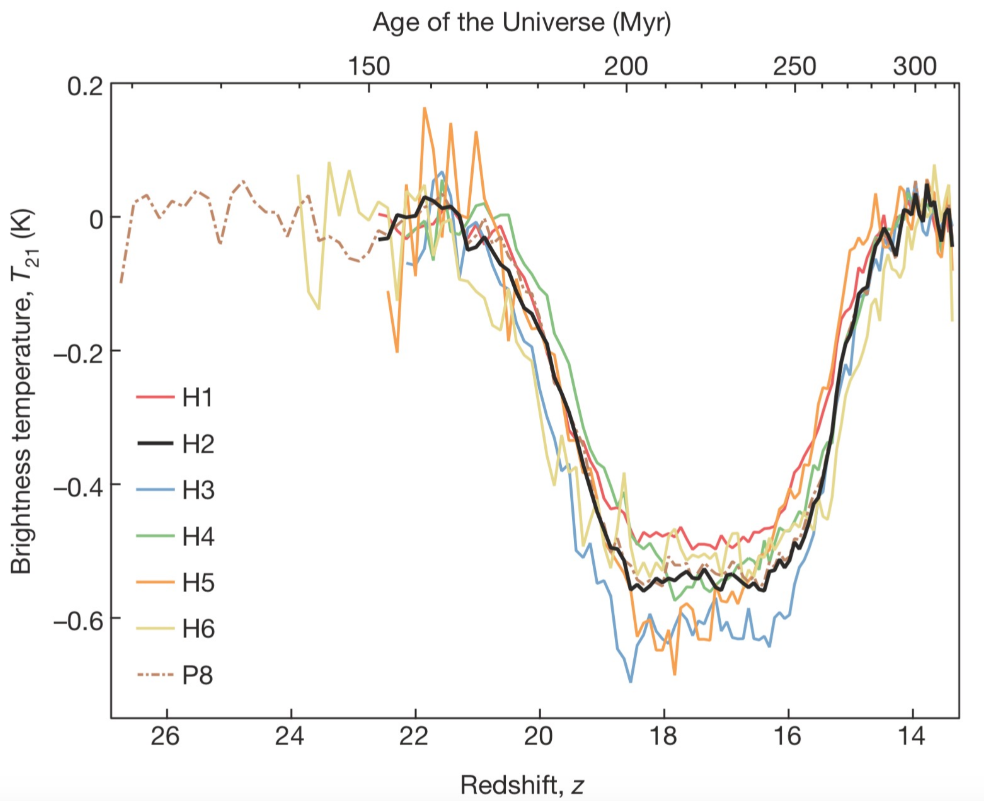
L	N_p	$2\pi/L$ [Mpc^{-1}]	$k_{\rm Ny}$ [Mpc^{-1}]	$m_p [M_\odot]$
10 Mpc	5120^3 (2560^3)	0.63	1.6×10^3 (800)	29 (230)
1 Mpc	5120^3 (2560^3)	6.3	1.6×10^4 (8.0×10^3)	2.9×10^{-2} (0.23)
100 kpc	5120^3 (2560^3)	63	1.6×10^5 (8.0×10^4)	2.9×10^{-5} (2.3×10^{-4})
10 kpc	5120^3 (2560^3)	630	1.6×10^6 (8.0×10^5)	2.9×10^{-8} (2.3×10^{-7})
1 kpc	5120^3 (2560^3)	6.3×10^3	1.6×10^7 (8.0×10^6)	2.9×10^{-11} (2.3×10^{-10})

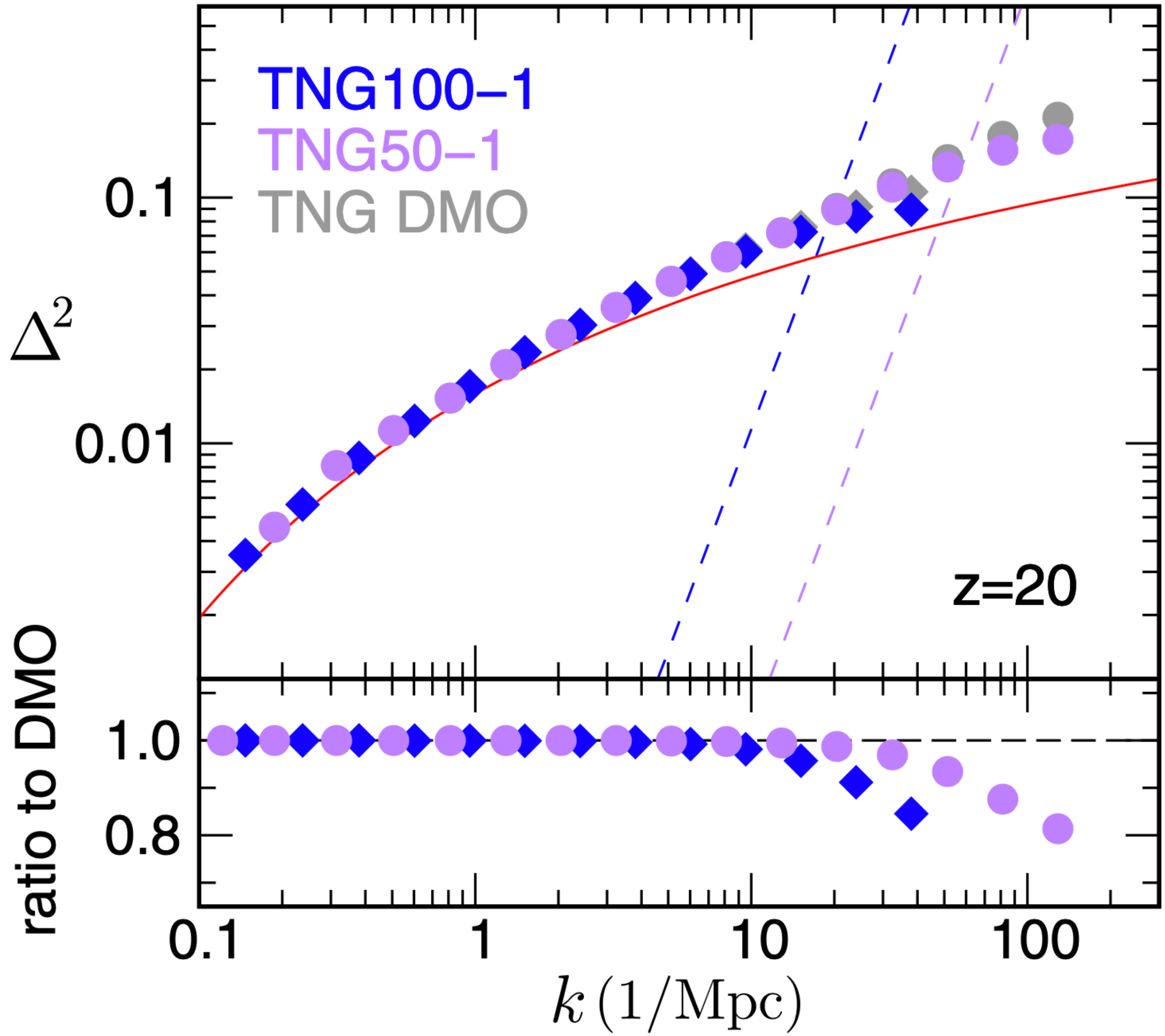
Introduction to Cosmological reionization

EDGES reported a detection of HI 21cm absorption at z=17

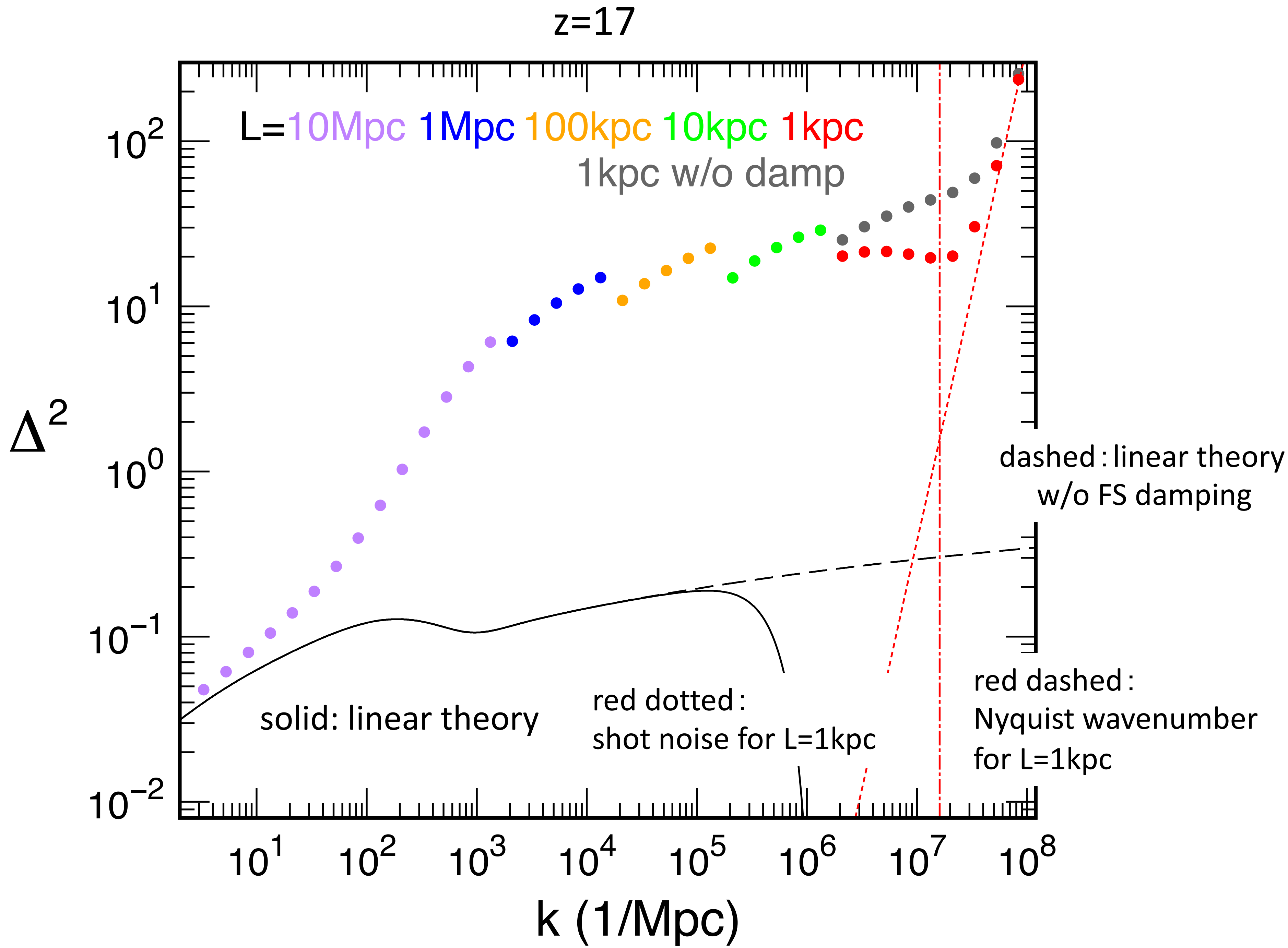
（Bowman+ 2018, Nature）

⇒ constrain (or exclude) heating of IGM by DM annihilation



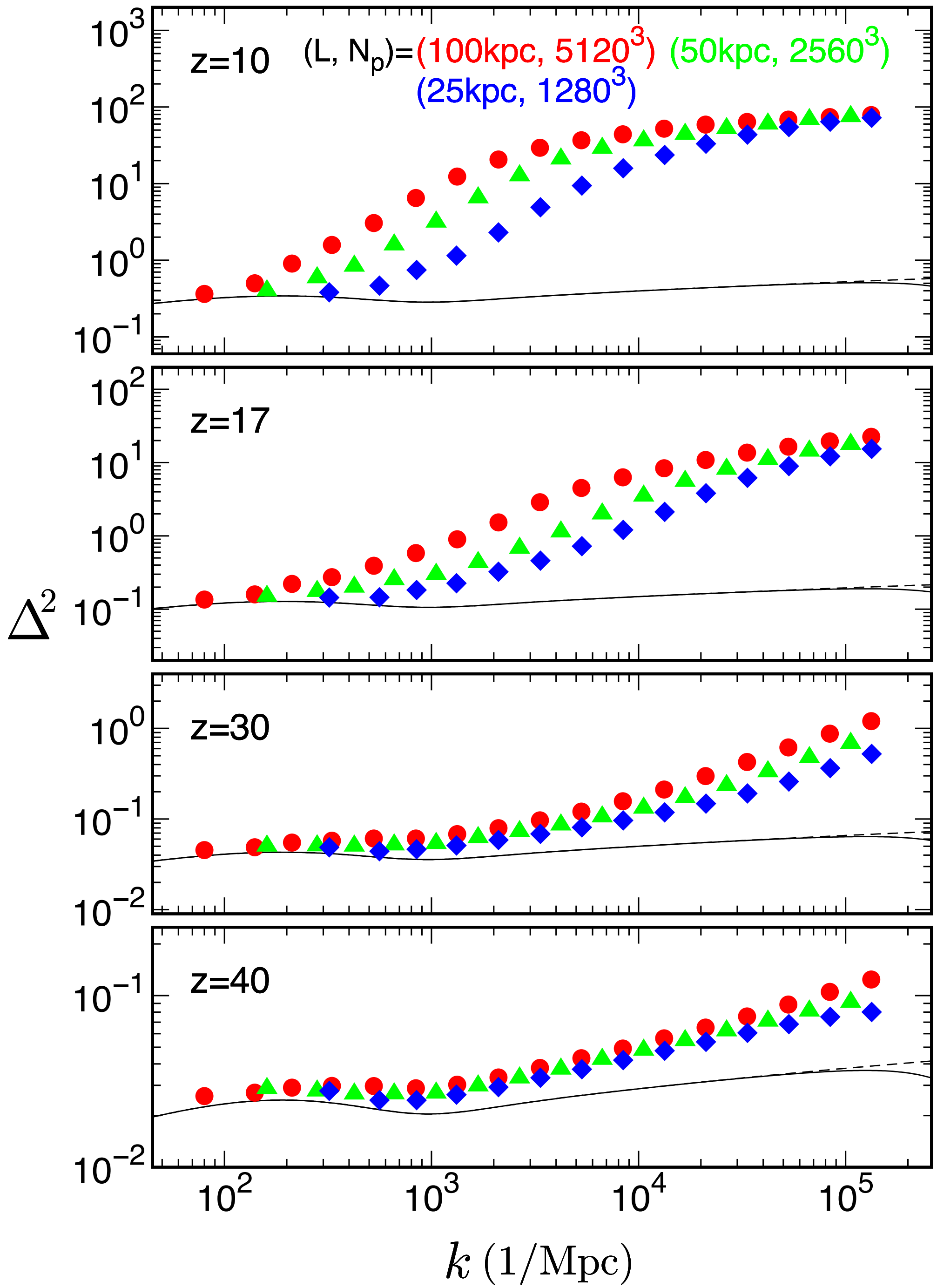


TNG100–1
TNG50–1
TNG DMO
0.1
0.01
Δ^2
z=20
ratio to DMO
1.0
0.8
0.1
1
10
100
$k\,(1/\mathrm{Mpc})$


z=17
L=10Mpc 1Mpc 100kpc 10kpc 1kpc
1kpc w/o damp
dashed : linear theory w/o FS damping
solid: linear theory
red dotted : shot noise for L=1kpc
red dashed : Nyquist wavenumber for L=1kpc
Δ²
k (1/Mpc)

イントロダクション：宇宙再イオン化

- 初代星からの紫外線による中性水素ガスのイオン化
- 赤方偏移 z=10-20 程度から始まり、z=6 には終了（e.g., 天文学辞典）
- 暗黒物質の対消滅により生ずる粒子（光子、電子・陽電子等）が宇宙再イオン化へ及ぼす可能性を考える　（Sekiguchi+ in preparation）
- 対消滅率は暗黒物質密度の2乗に比例するため、この物理量を求める



解像度は固定

ボックス長のみ変化