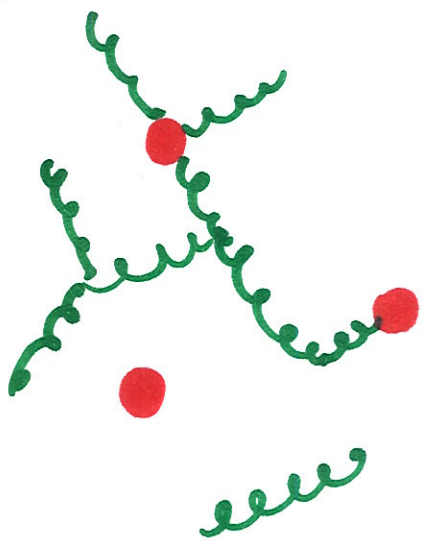
Cosmic Discordance &

Dark matter interacting with dark radiation

Schmaltz
Marques-Tavares
Lesgourgues

Buen-Abad
Kaplan
Weiner

1505.03542
1507.04351
...



1. tension between CMB and "direct" measurements of H_0, σ_8 in ΛCDM

2. model: DM interacting with DR

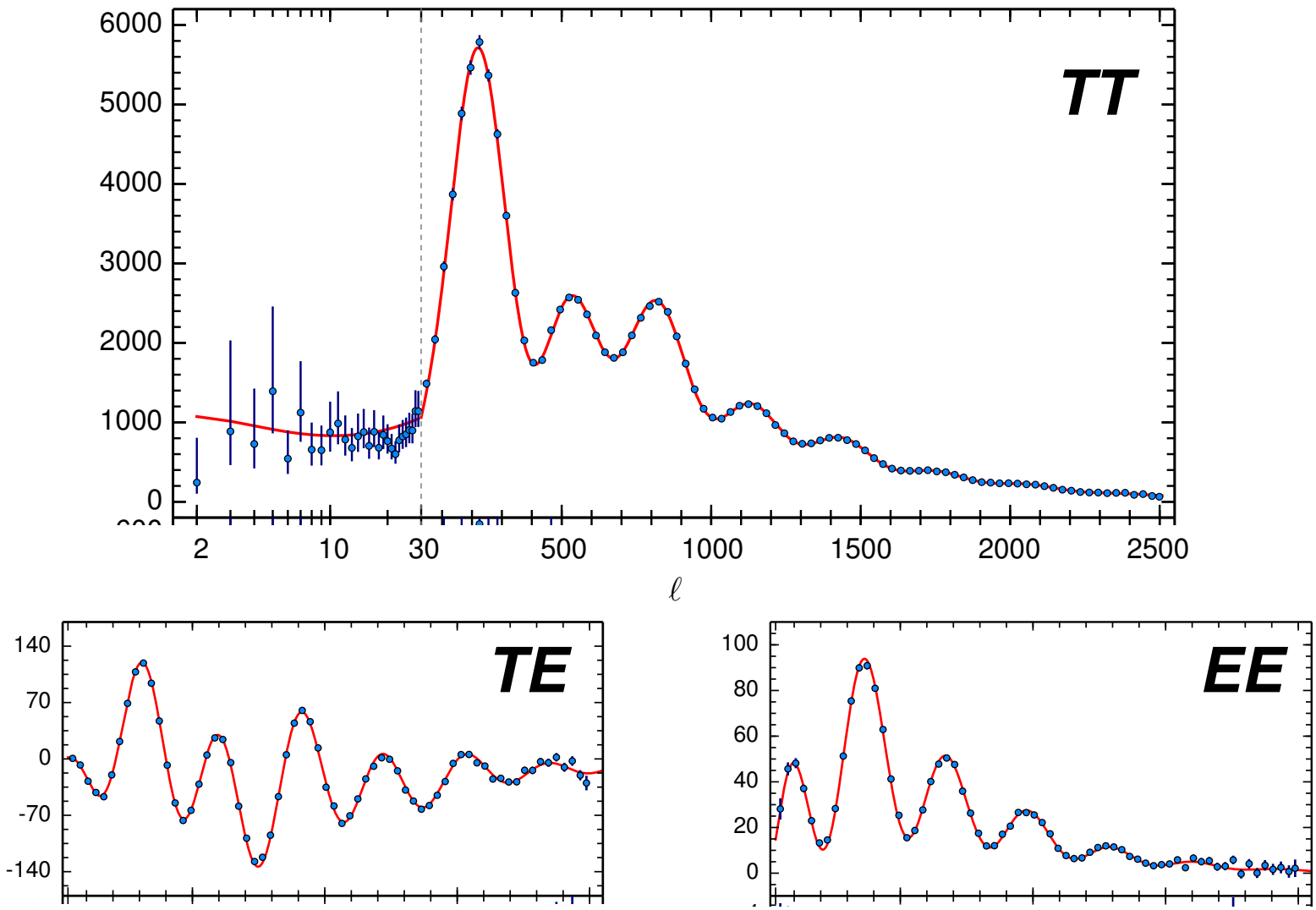
3. tension resolved ■

ΛCDM: cosmic concordance model

SM + collisionless cold DM + Λ + "big bang"

ω_{DM} $\omega_{Baryons}$ Ω_Λ A_s n_s τ_{reio}

Planck CMB

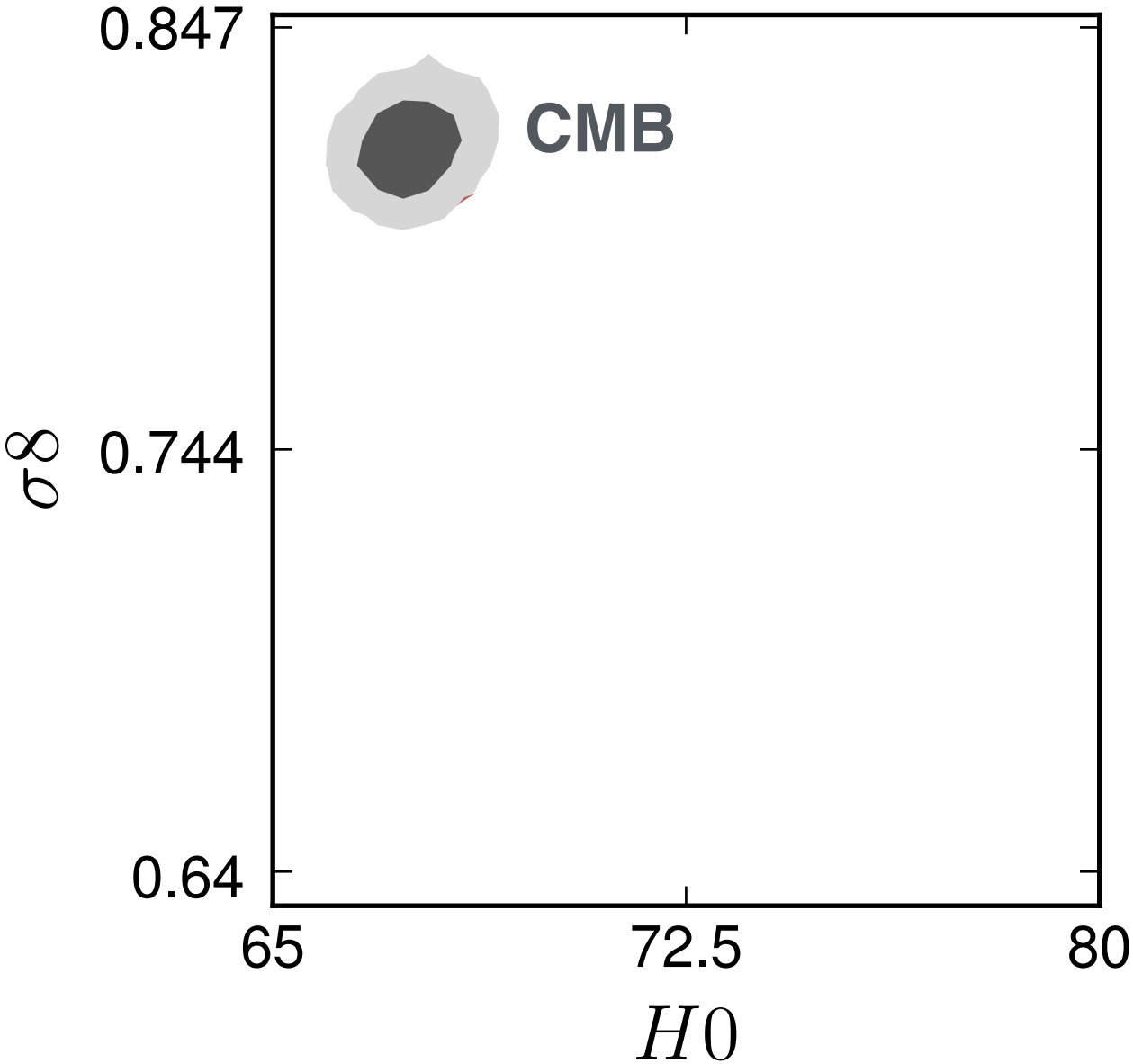

TT
6000
5000
4000
3000
2000
1000
0
2
10
30
500
1000
1500
2000
2500
ℓ
TE
140
70
0
-70
-140
EE
100
80
60
40
20
0

Planck CMB (TT,TE,EE,LowP)

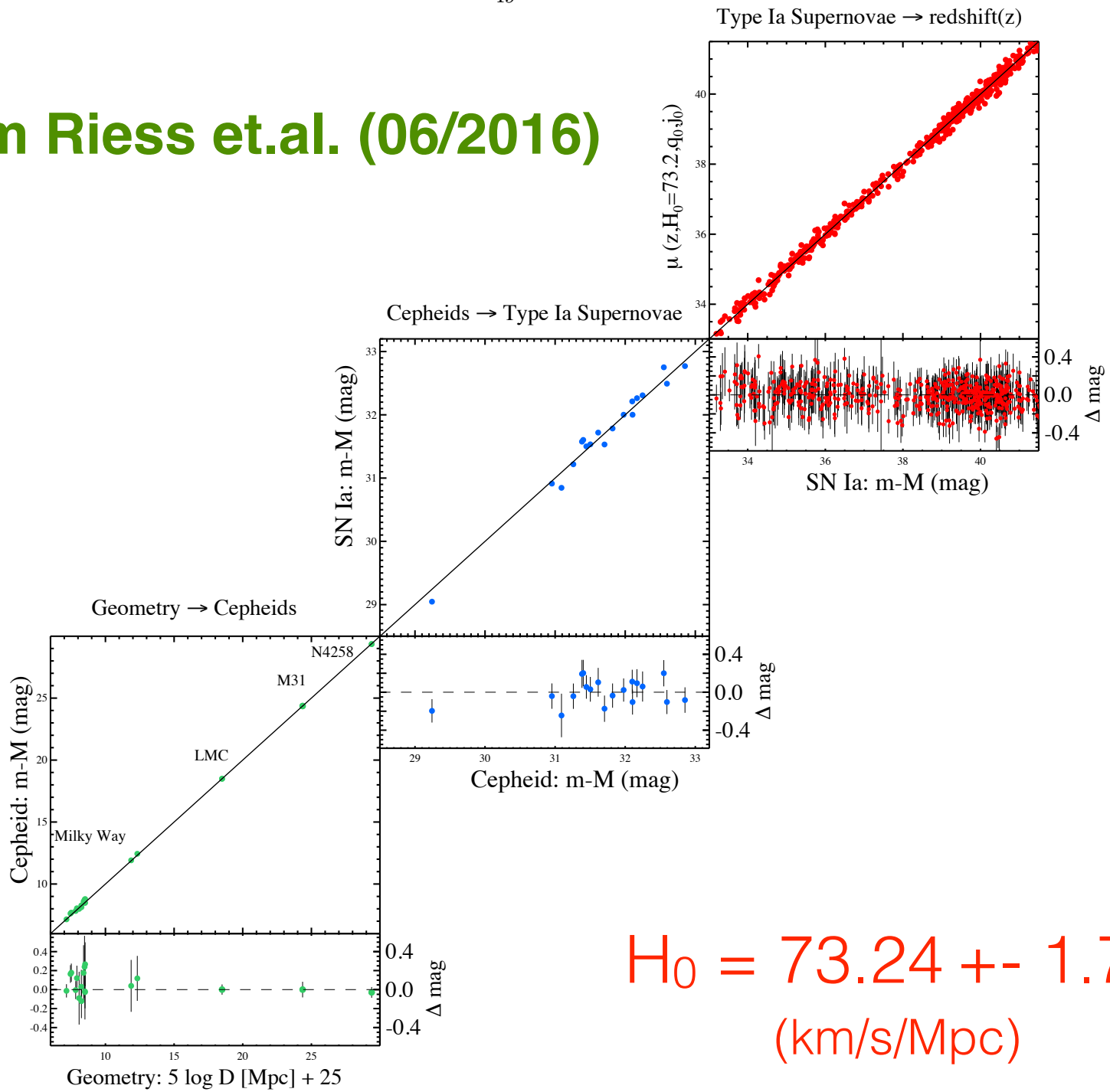
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013

ΛCDM

Poulin, Serpico, Lesgourgues
astro-ph/1606.02073



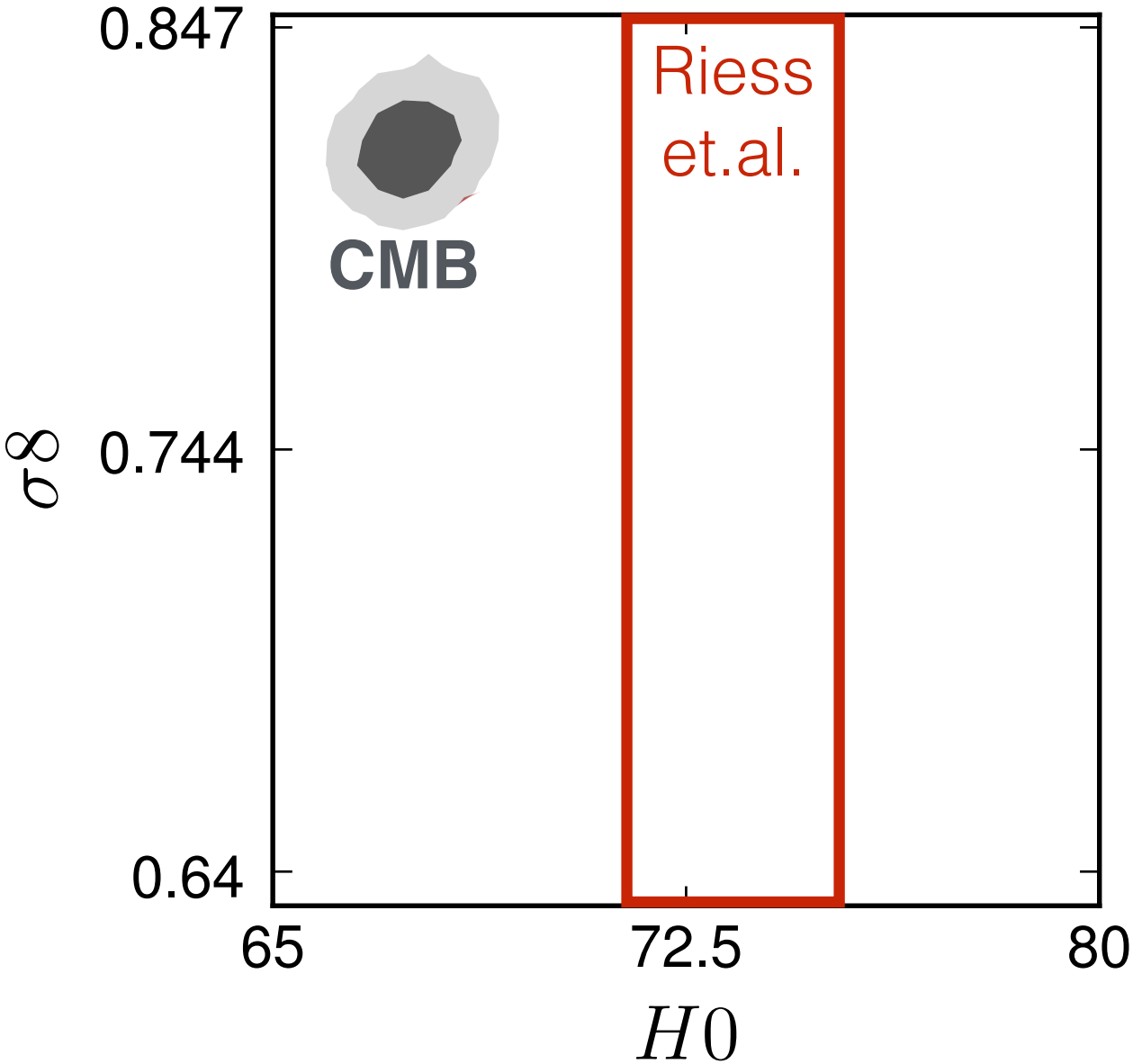
Adam Riess et.al. (06/2016)



H_0 = 73.24 +- 1.74

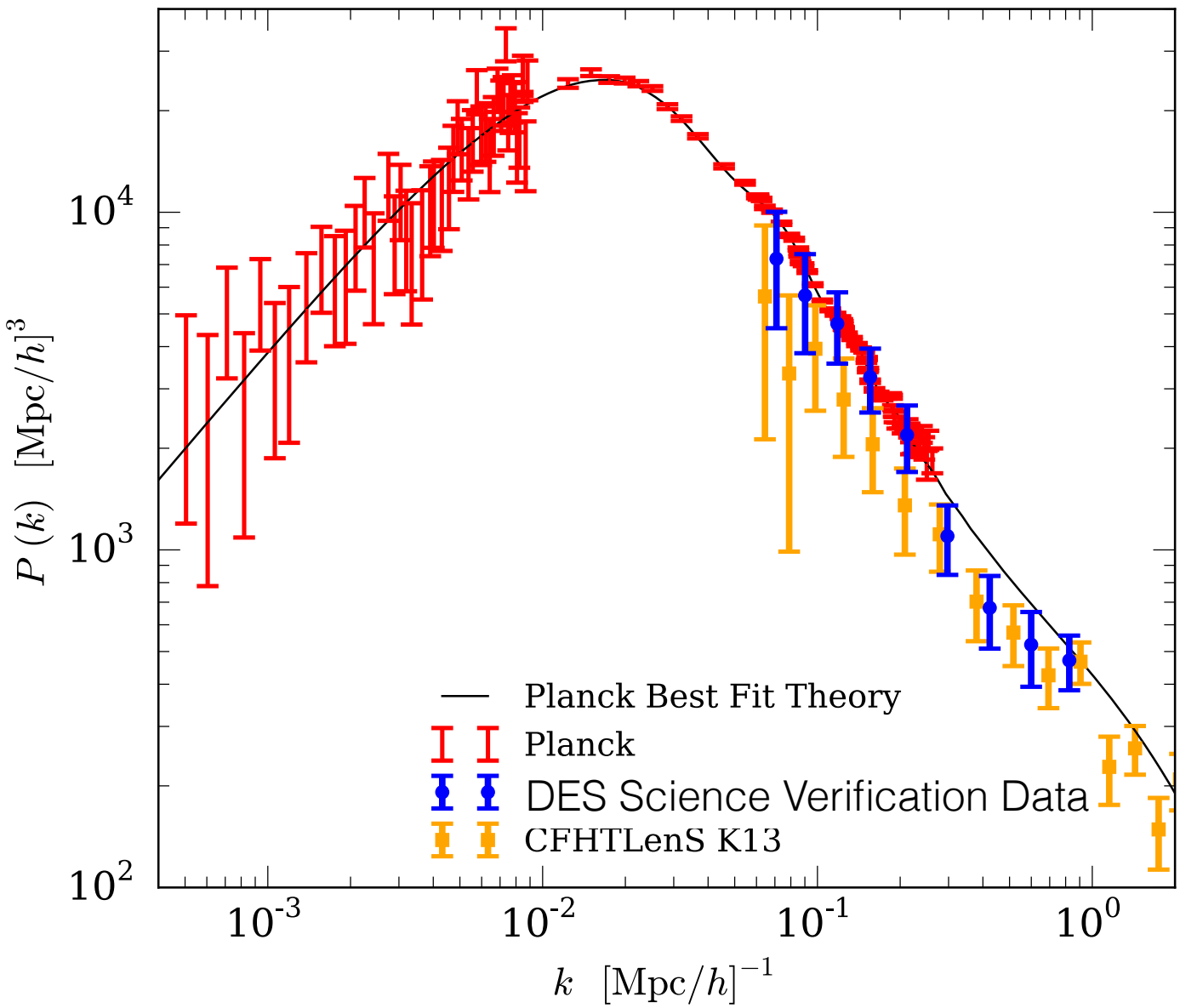
(km/s/Mpc)

ΛCDM

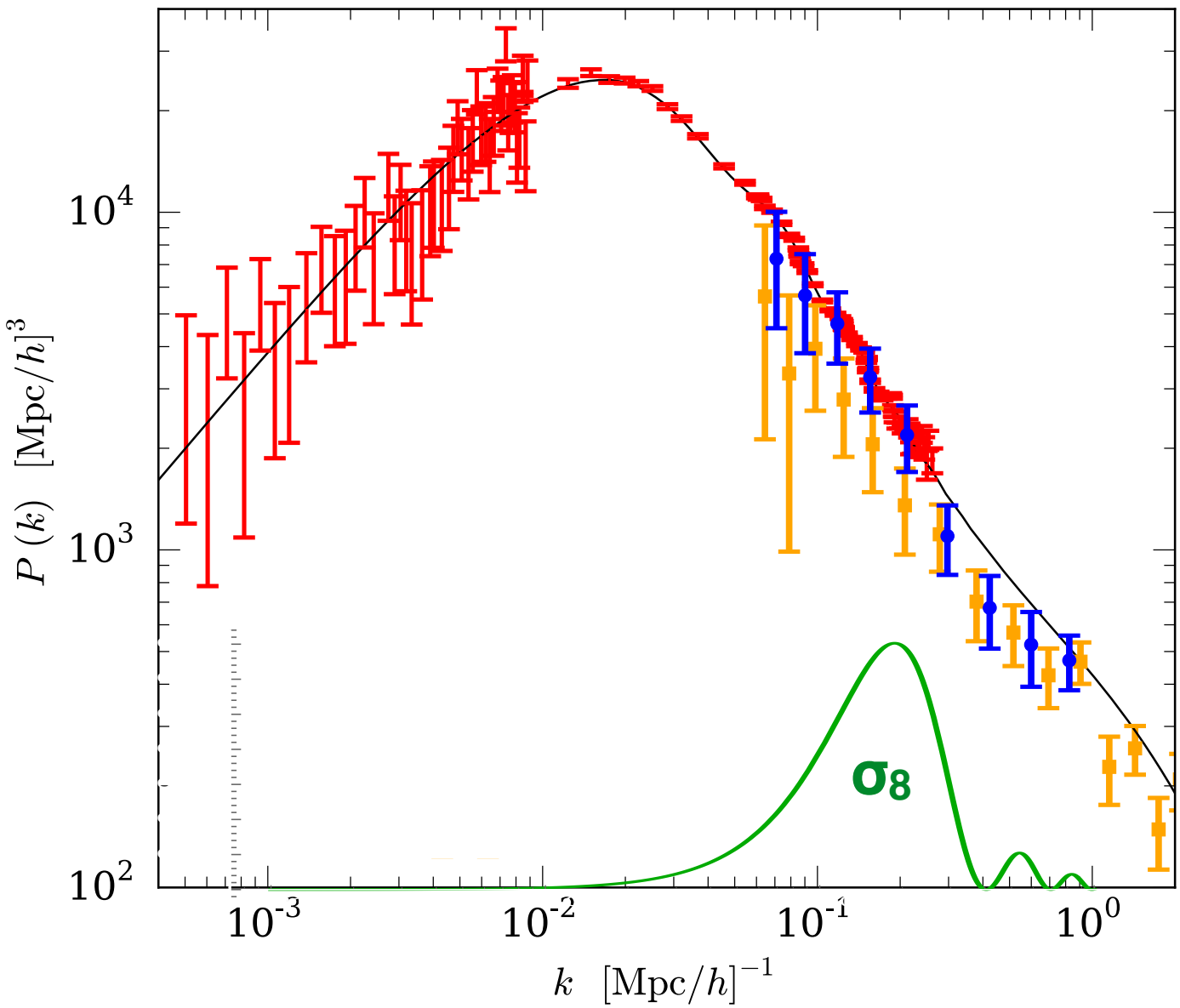


Matter Power Spectrum from weak lensing

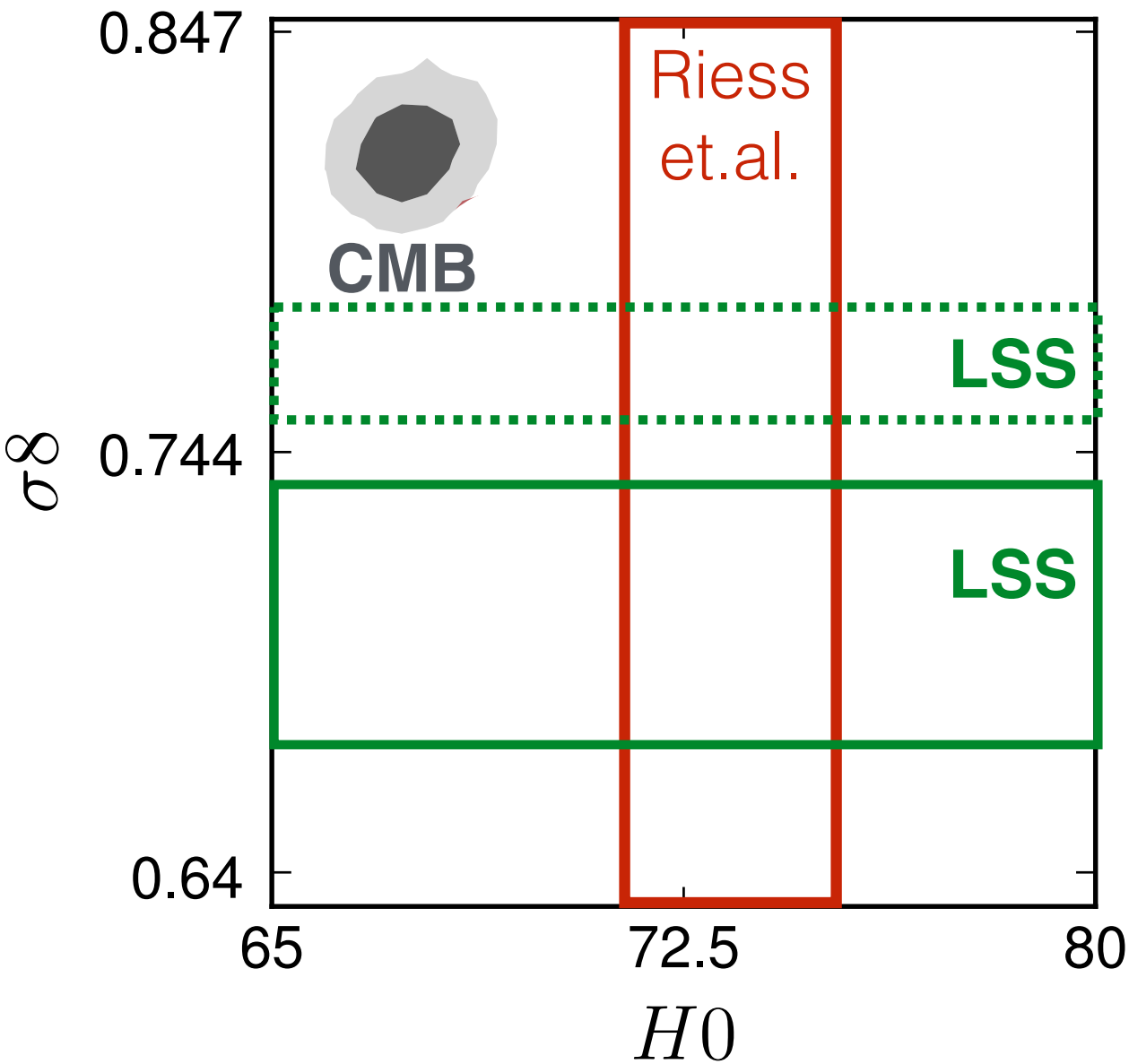
DES astro-ph/150705552



σ_8 from weak lensing



ΛCDM



ΛCDM

Poulin, Serpico, Lesgourgues
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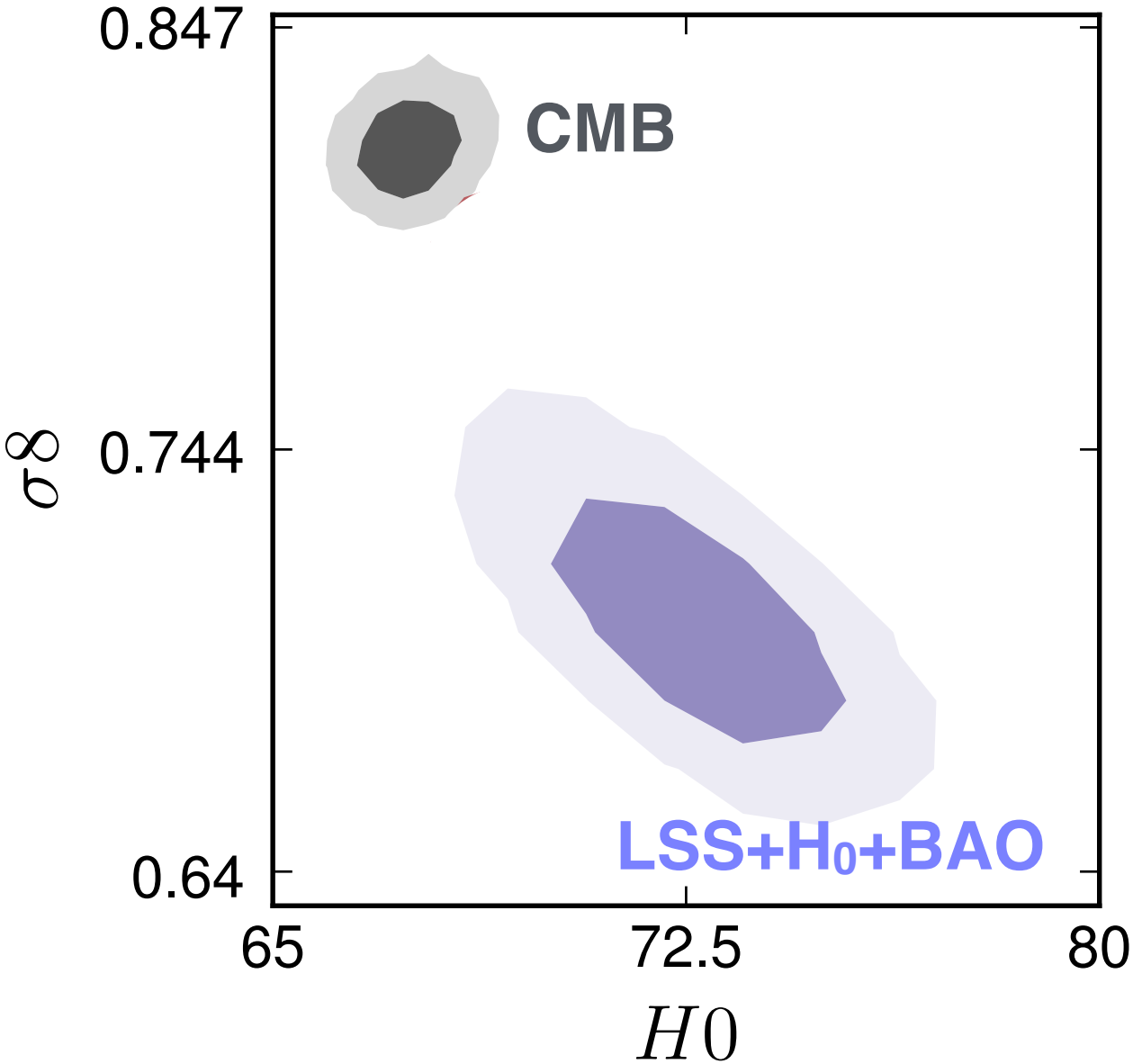
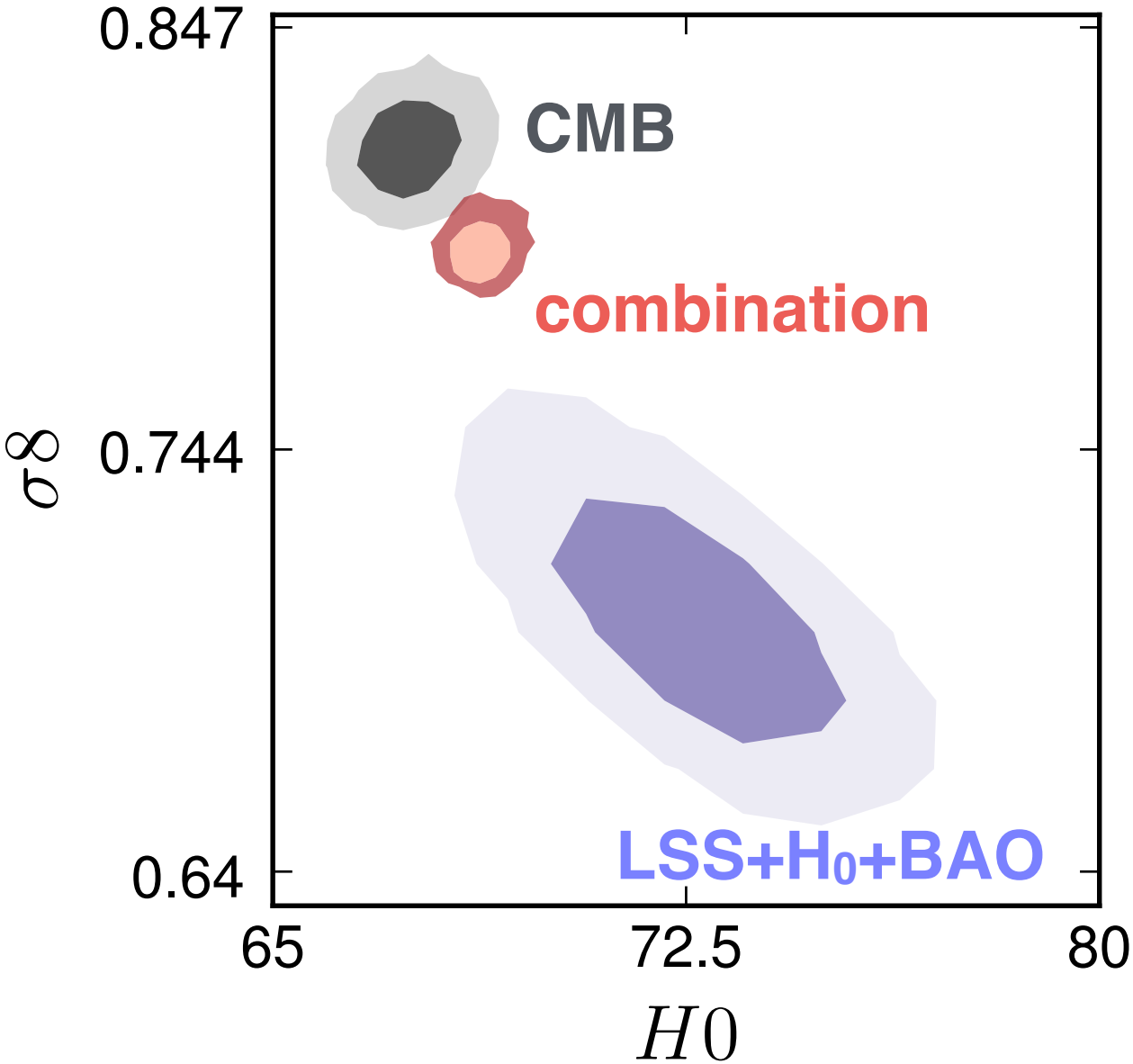


ΛCDM

Poulin, Serpico, Lesgourgues
astro-ph/1606.02073



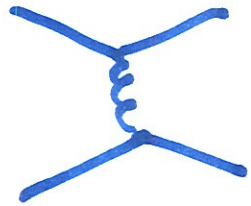
DM + DR model

SM	dark
B, γ, ν	DM, DR
T_γ	$T_{DR} \lesssim T_\gamma$

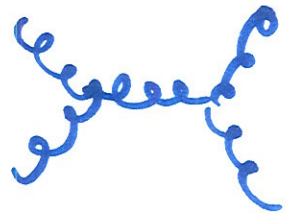
$M_{DM} \gg T_{DR}$ "cold"

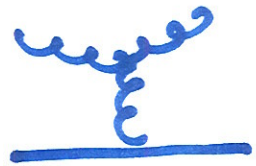
example: non-Abelian dark sector

DM massive "dark quarks"



DR massless "dark gluons"

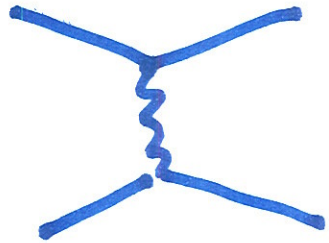




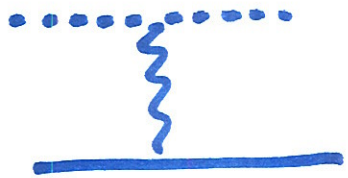
$$g_D \sim 10^{-4} \Rightarrow \text{"}\Lambda_{QCD}\text{"} \ll T_{DR}$$

example: Abelian dark sector

DM massive "dark leptons"

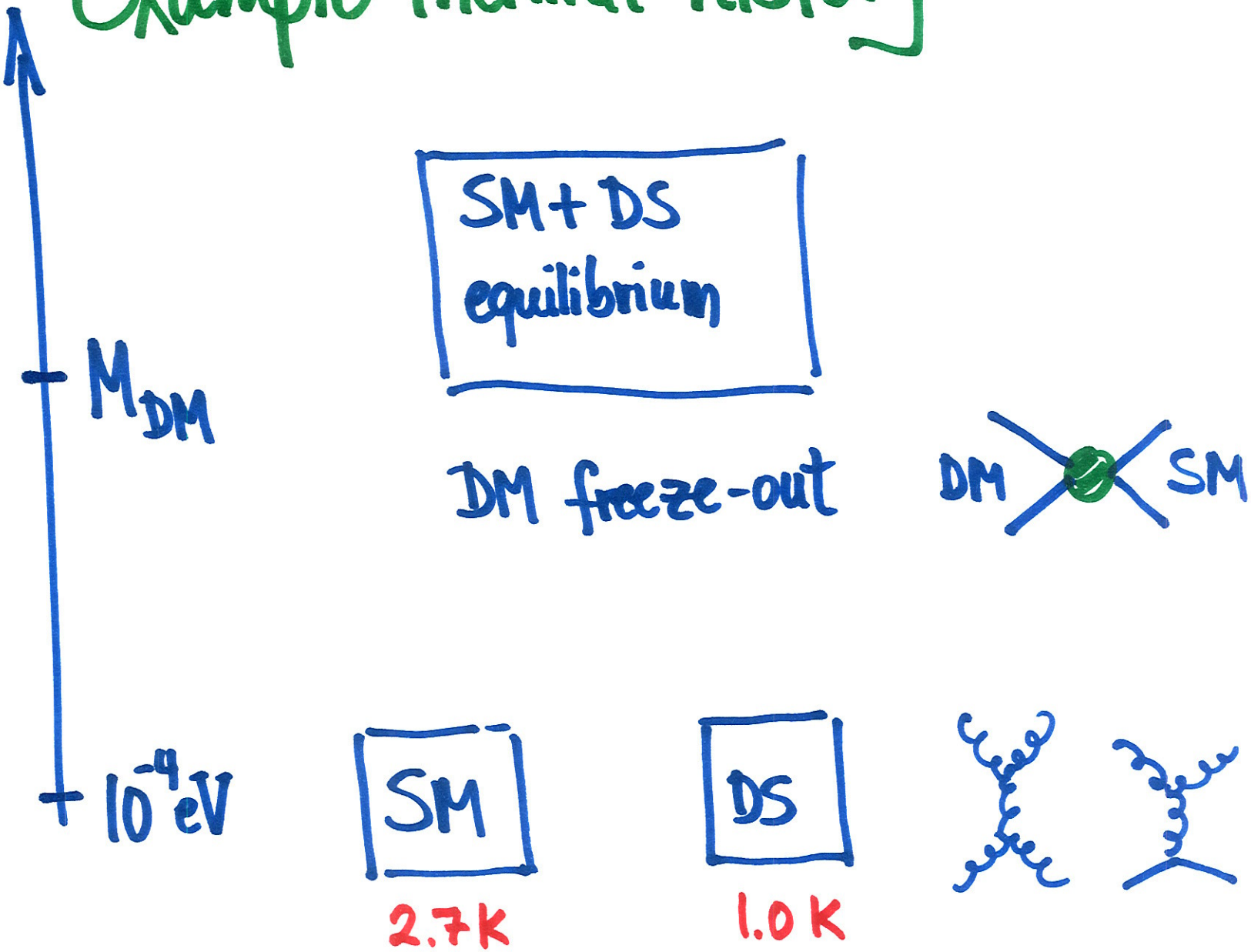


DR massless "dark photon + leptons"



$g_D \sim 10^{-4}$

example thermal history



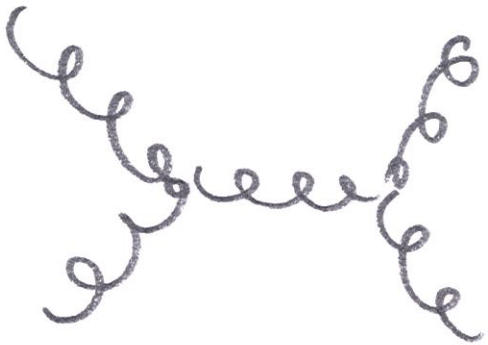
What are important new effects ?

- energy density in dark radiation $\Rightarrow \Delta N_{eff}$
- DM-DR coupling $\Longrightarrow$ large scale structure

energy density in dark gluons

$$\rho_g \sim (N^2-1)\, T_g^{\,4} = \underbrace{(N^2-1)\,\frac{T_g^{\,4}}{T_\nu^{\,4}}}_{\equiv\, \Delta N_{eff}\ \sim\ \begin{cases} \frac{N^2-1}{16.4} \\ \text{free parameter} \end{cases}}\, T_\nu^{\,4}$$

difference between ν's and dark gluons

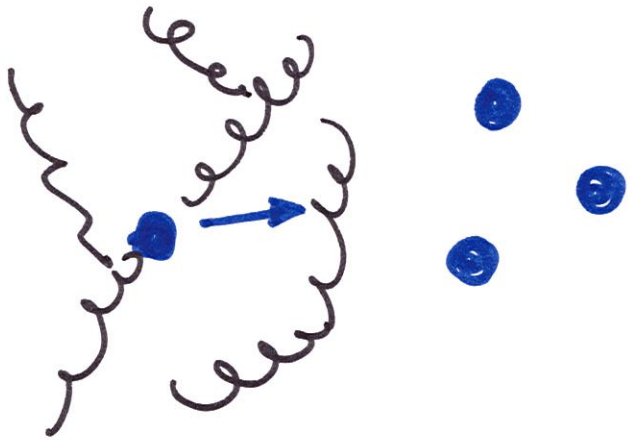


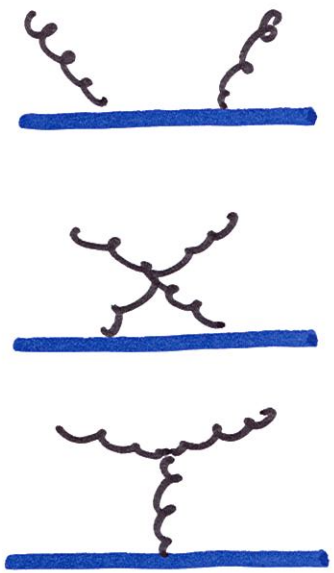
rate $\Gamma \gg H$

dark gluons do not free-stream $\longrightarrow$ "perfect fluid"

- phase shift of CMB peaks

DM-DR interactions and large scale structure





momentum transfer rate

$$\Gamma_p \equiv \frac{\dot{p}}{p} \sim \alpha_d^2 \log \frac{1}{\alpha_d} \frac{T_g^2}{M_\chi}$$

"drag"

Debye cutoff

momentum transfer rate

$$\Gamma_p \sim \alpha^2 \log\frac{1}{\alpha}\,\frac{T^2}{M_\chi} \quad \text{vs.} \quad H \sim \frac{T^2}{M_{pl}}$$

$\rightarrow$ $\alpha \sim 10^{-8}$ "interesting" throughout radiation domination.

linear perturbations in fluids

δ density pert.

θ velocity pert.

$\vdots$

DM, DR, SM

$\downarrow$

γ, ν, B

linear perturbations

$$\dot{\delta}_{DM} = -\theta_{DM} + 3\dot{\psi}$$

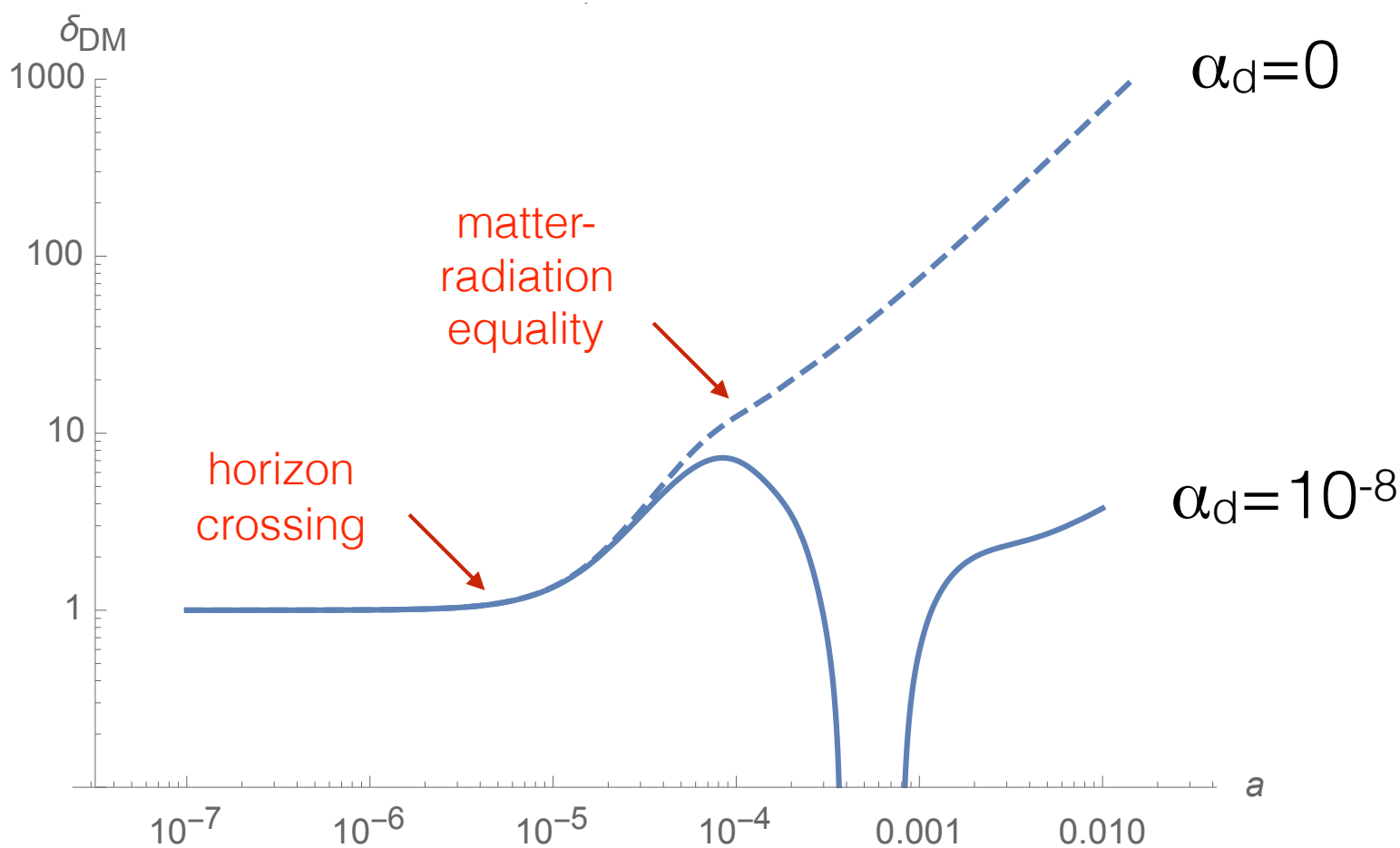
$$\dot{\theta}_{DM} = -\frac{\dot{a}}{a}\theta_{DM} + a\mathbf{\Gamma_p}(\theta_{DR} - \theta_{DM}) + k^2\psi$$

$$\dot{\delta}_{DR} = -\frac{4}{3}\theta_{DR} + 4\dot{\psi}$$

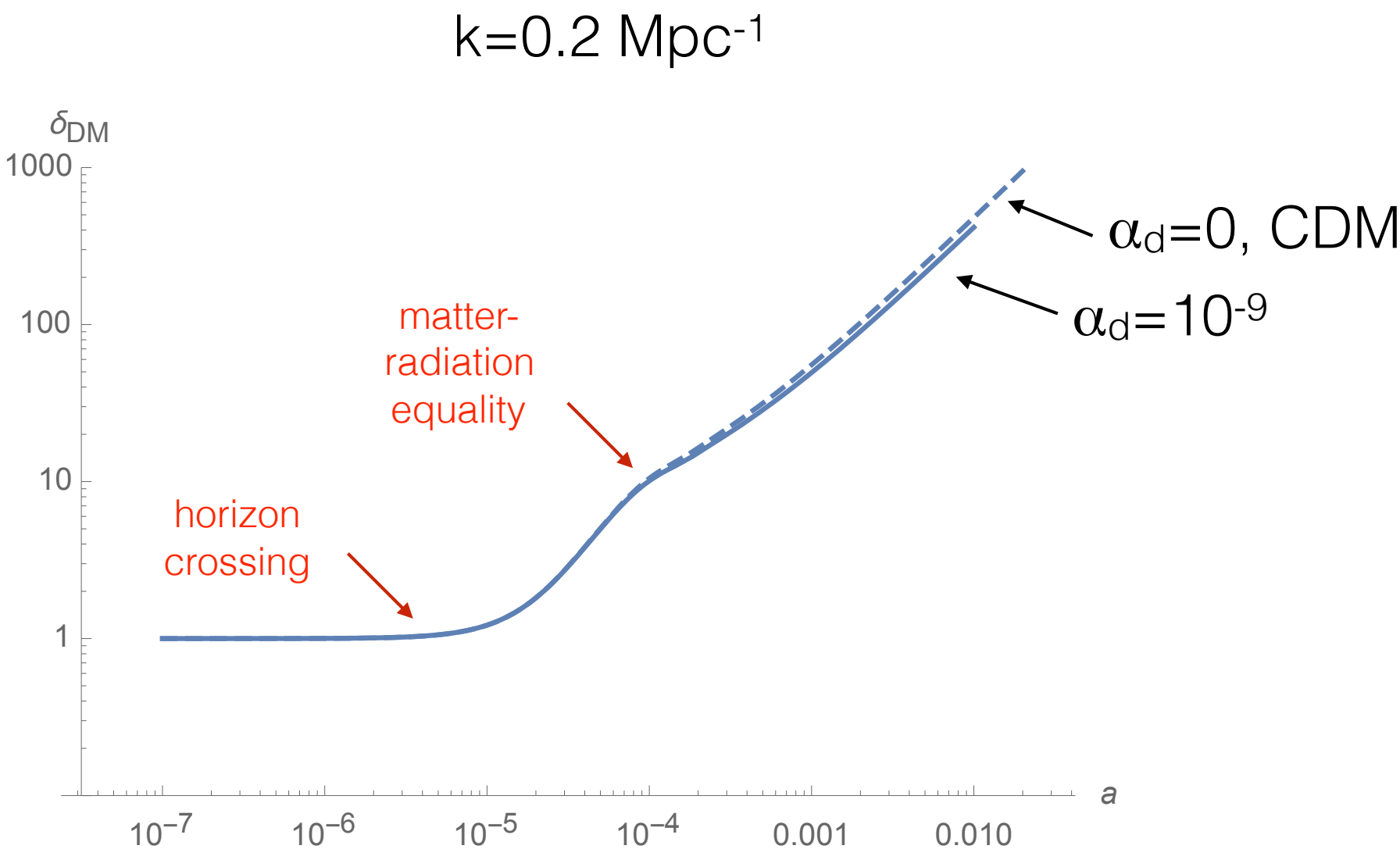
$$\dot{\theta}_{DR} = k^2\frac{\delta_{DR}}{4} + k^2\psi + \frac{3}{4}\frac{\rho_{DM}}{\rho_{DR}}a\mathbf{\Gamma_p}(\theta_{DM} - \theta_{DR})$$

growth of perturbations

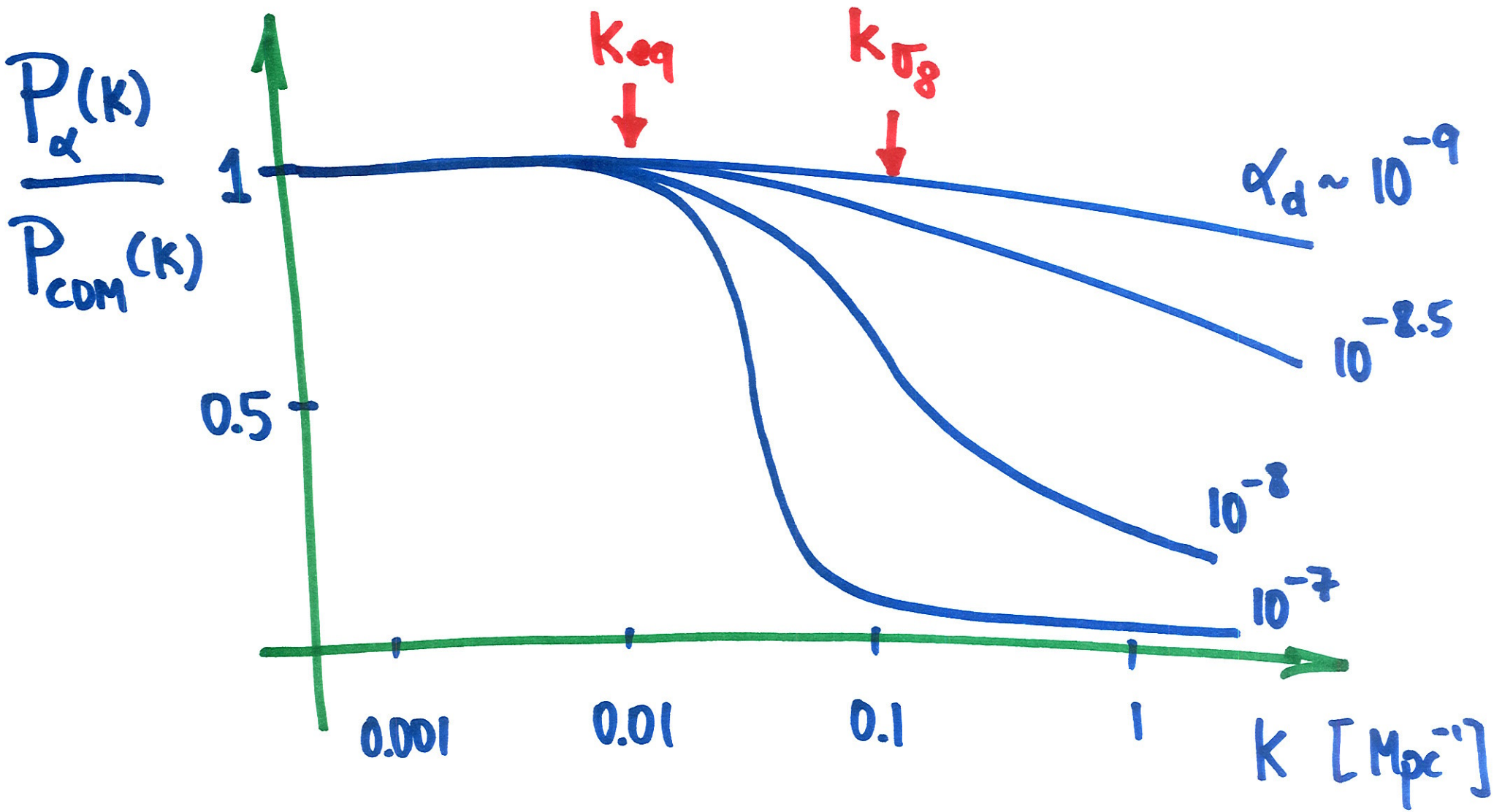
k=0.2 Mpc^{-1}



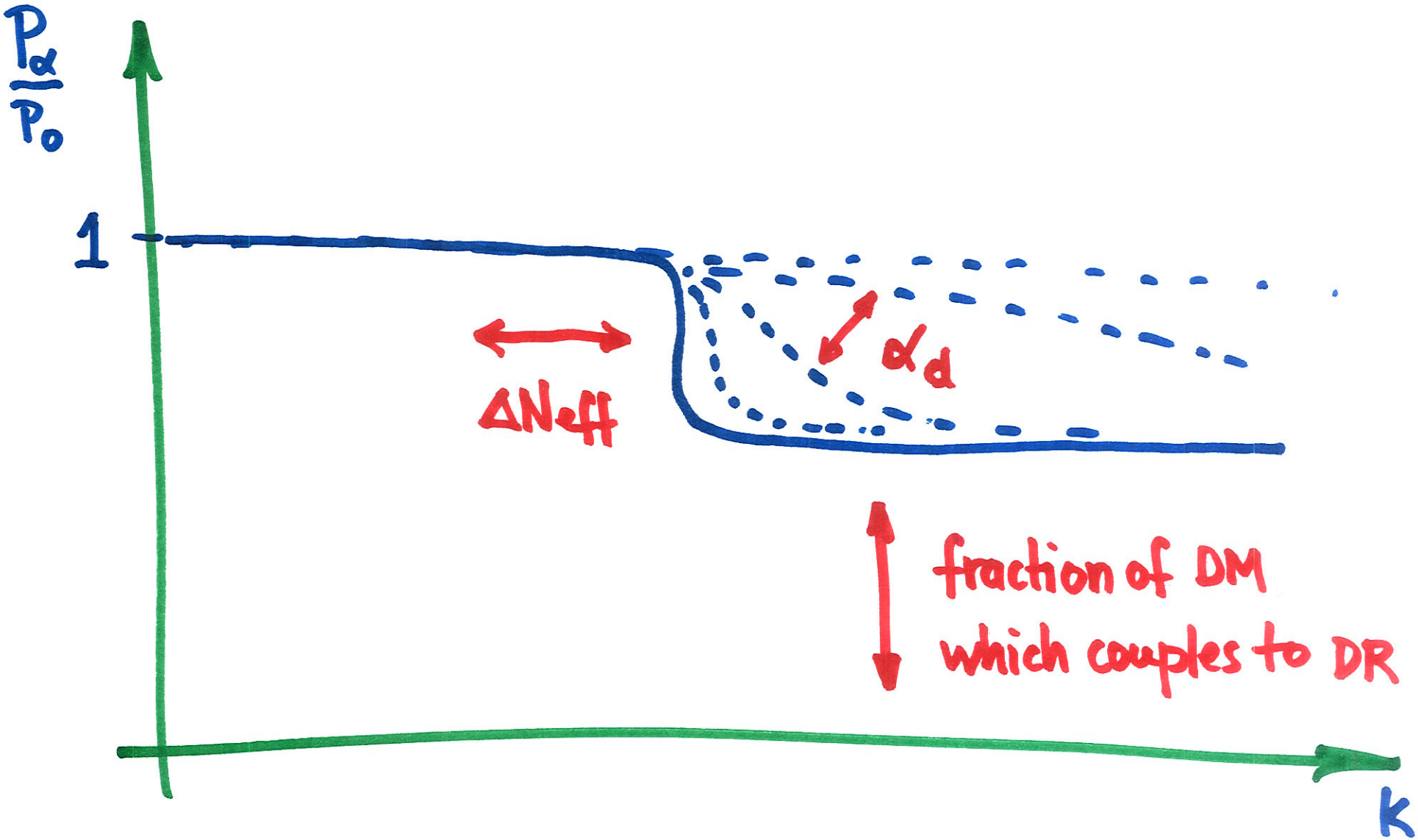
growth of perturbations



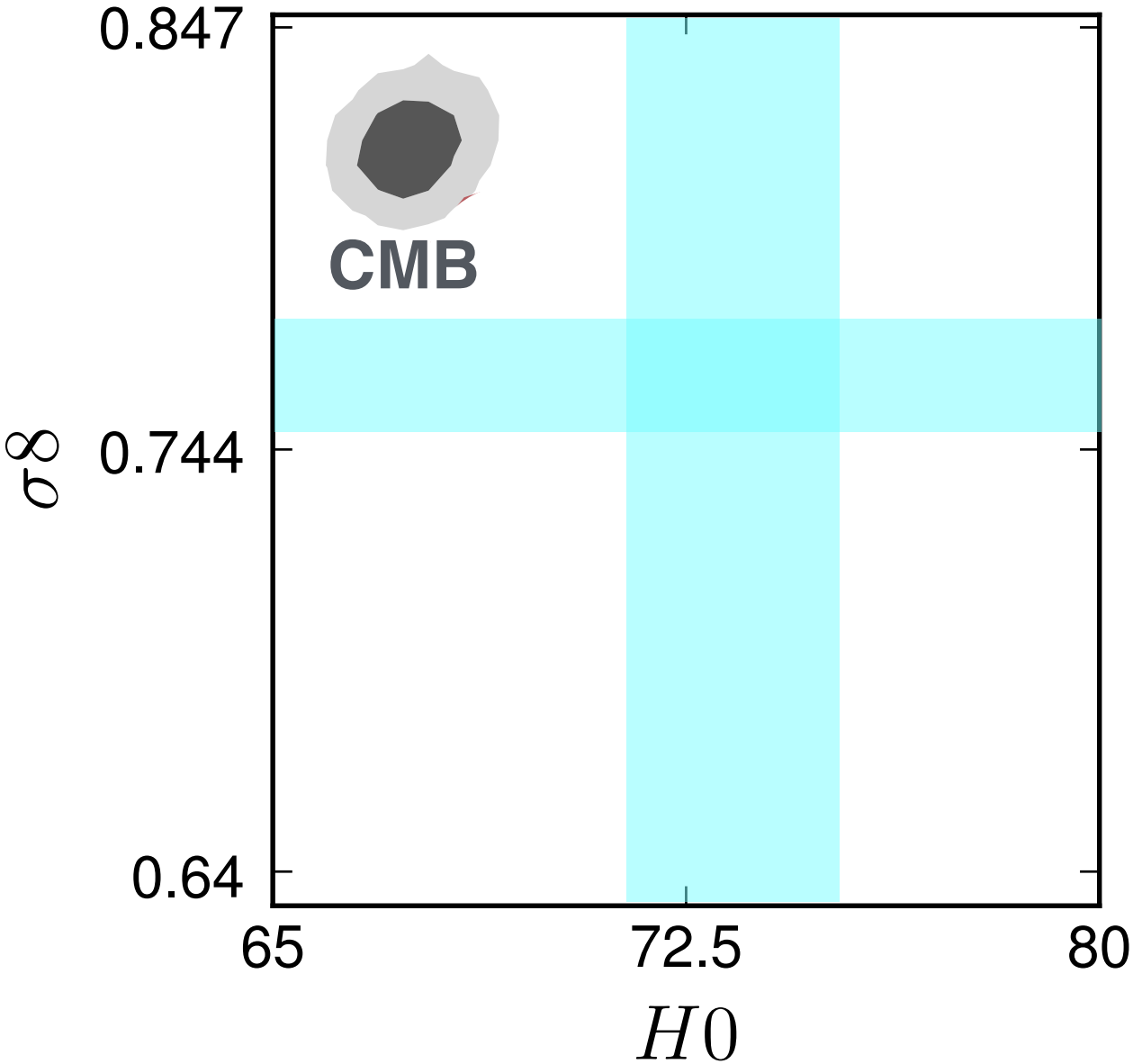
Matter power spectrum compared to CDM



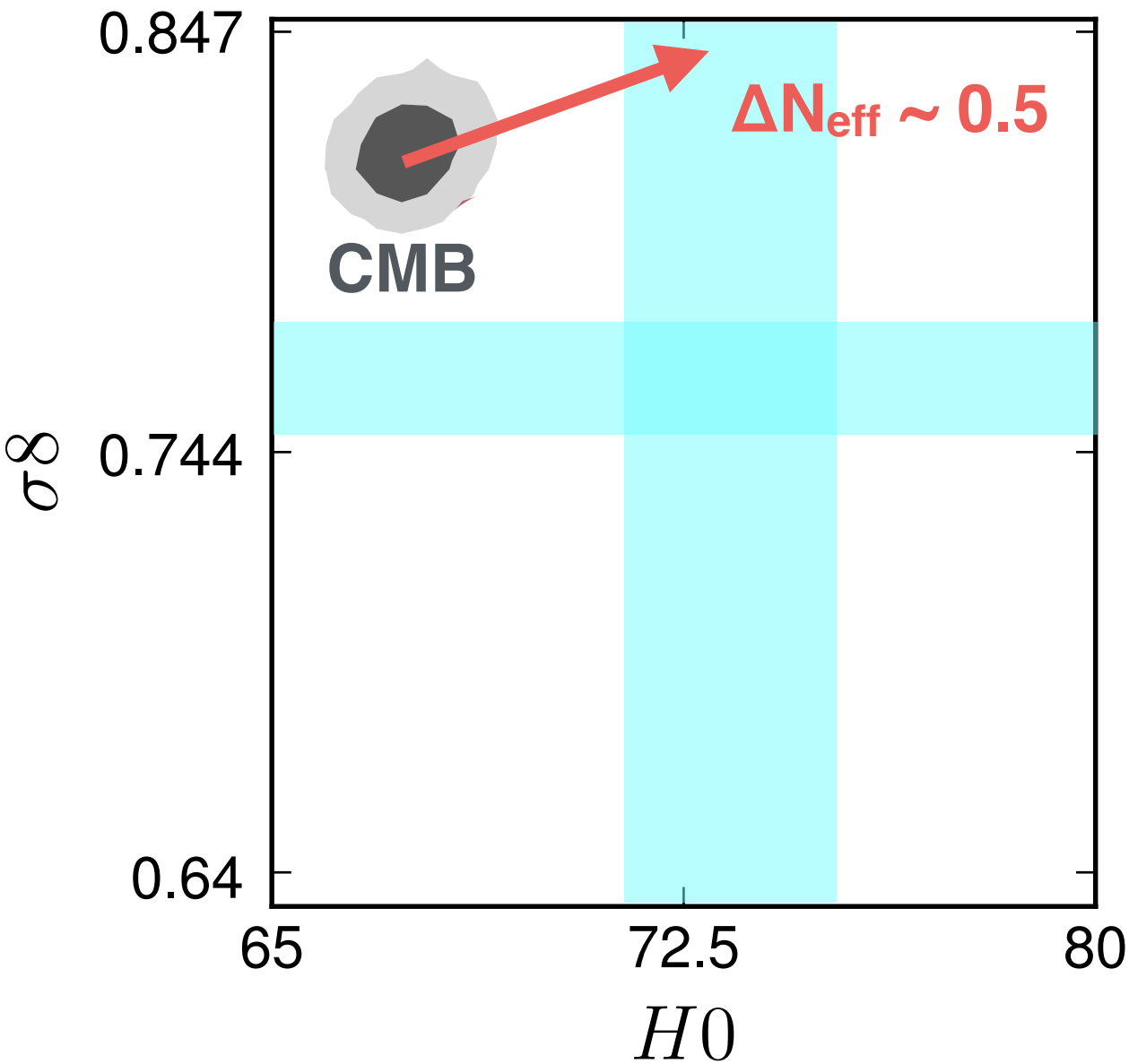
parameter dependence



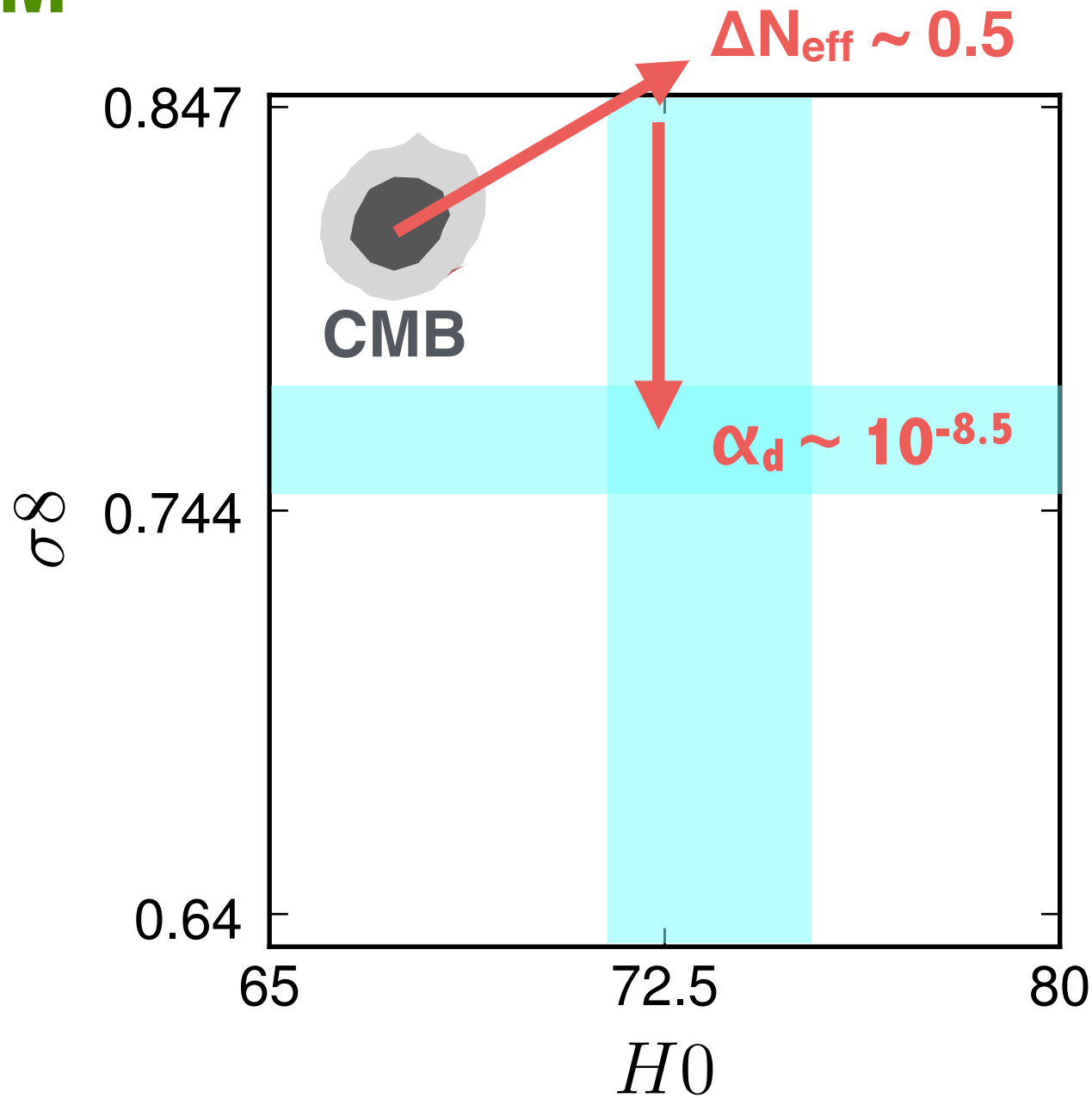
ΛCDM

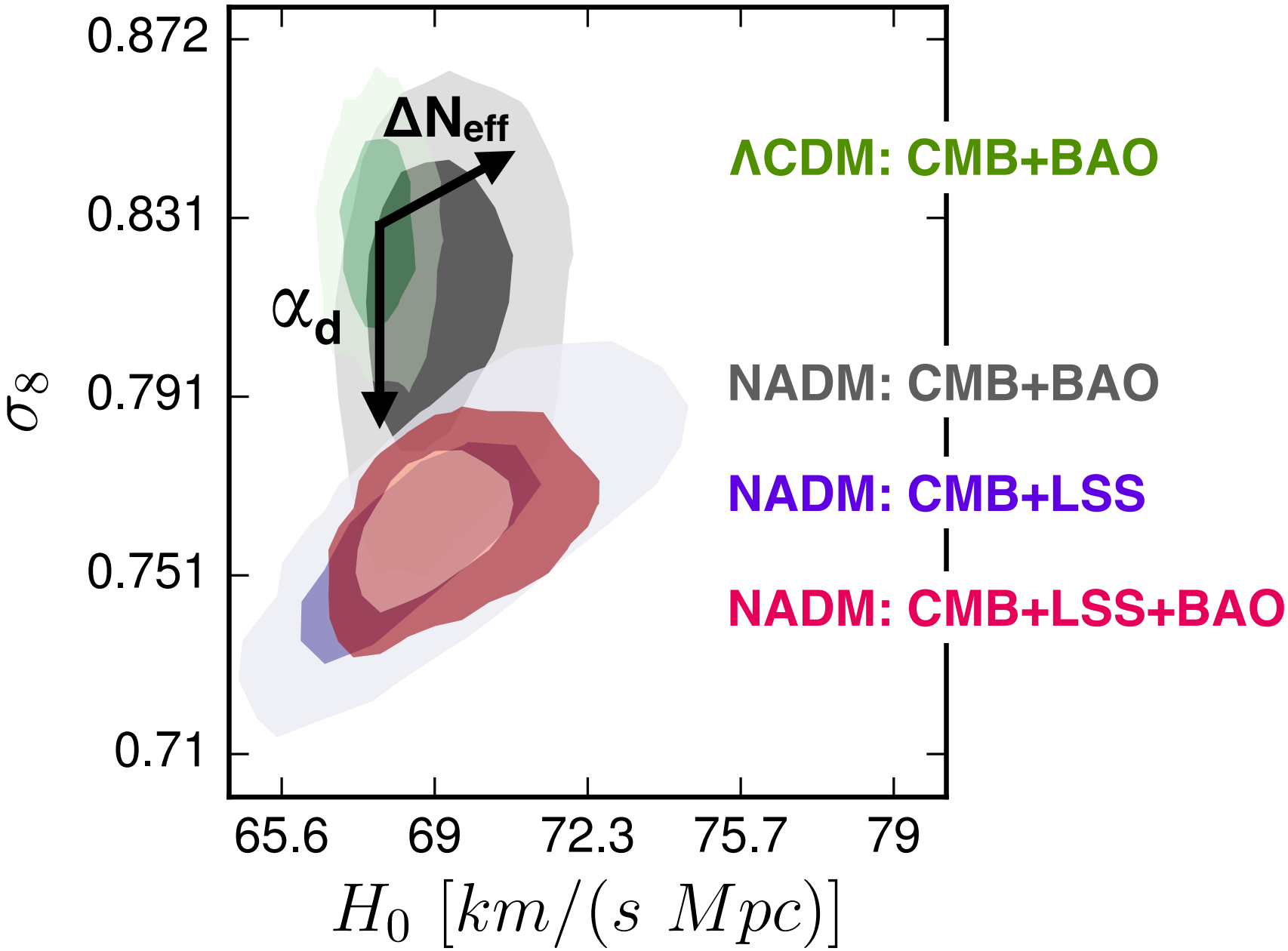


ΛCDM



ΛCDM




0.872
0.831
0.791
0.751
0.71
σ_8
65.6
69
72.3
75.7
79
H_0 $[km/(s\ Mpc)]$
ΔN_{eff}
α_d
ΛCDM: CMB+BAO
NADM: CMB+BAO
NADM: CMB+LSS
NADM: CMB+LSS+BAO

How well do we do?

$\Delta\chi^2 = -12.7$ with 2 new parameters

Fisher ***F****- test: p=0.002 (>3σ)

* used in archaic greek as the *digamma* letter

Summary

- dark radiation fixes H_0
-  $\sim \frac{T^2}{M}$ fixes σ_8