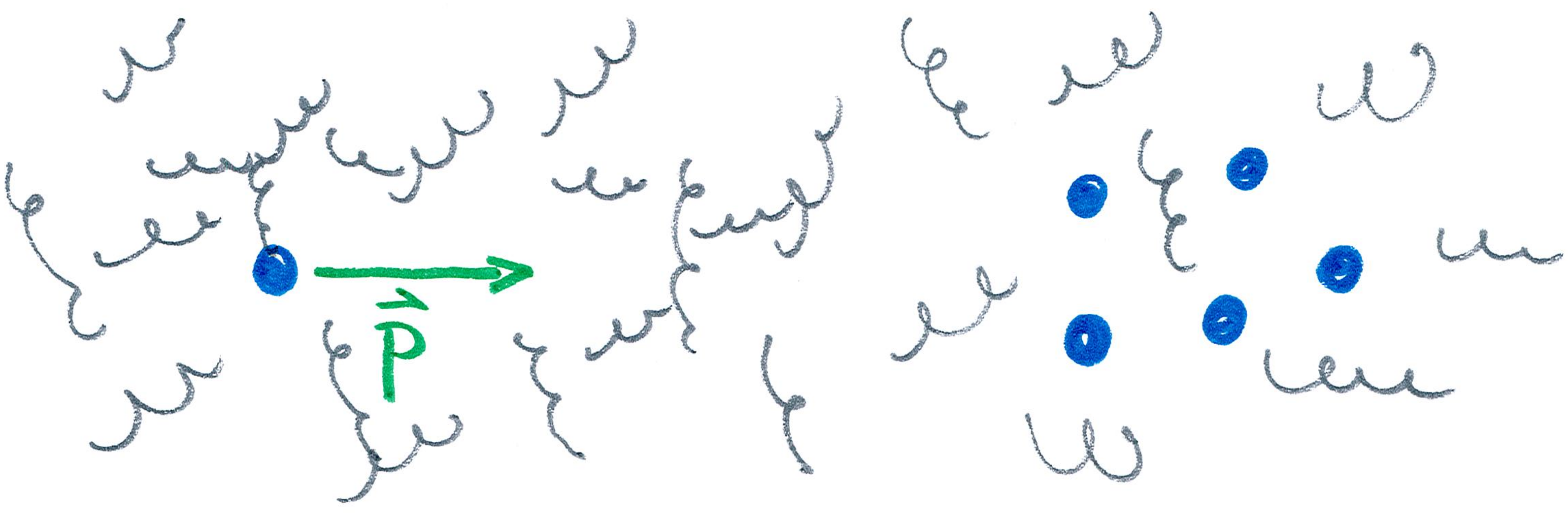
Large Scale Structure and Non-Abelian Dark Matter

Manuel Buen Abad (Boston)
Julien Lesgourgues (Aachen)
Gustavo Marques-Tavares (Stanford)
Martin Schmaltz (Boston)



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Outline

1. tension in ΛCDM between CMB fit and “direct” measurements

   H_0 and σ_8

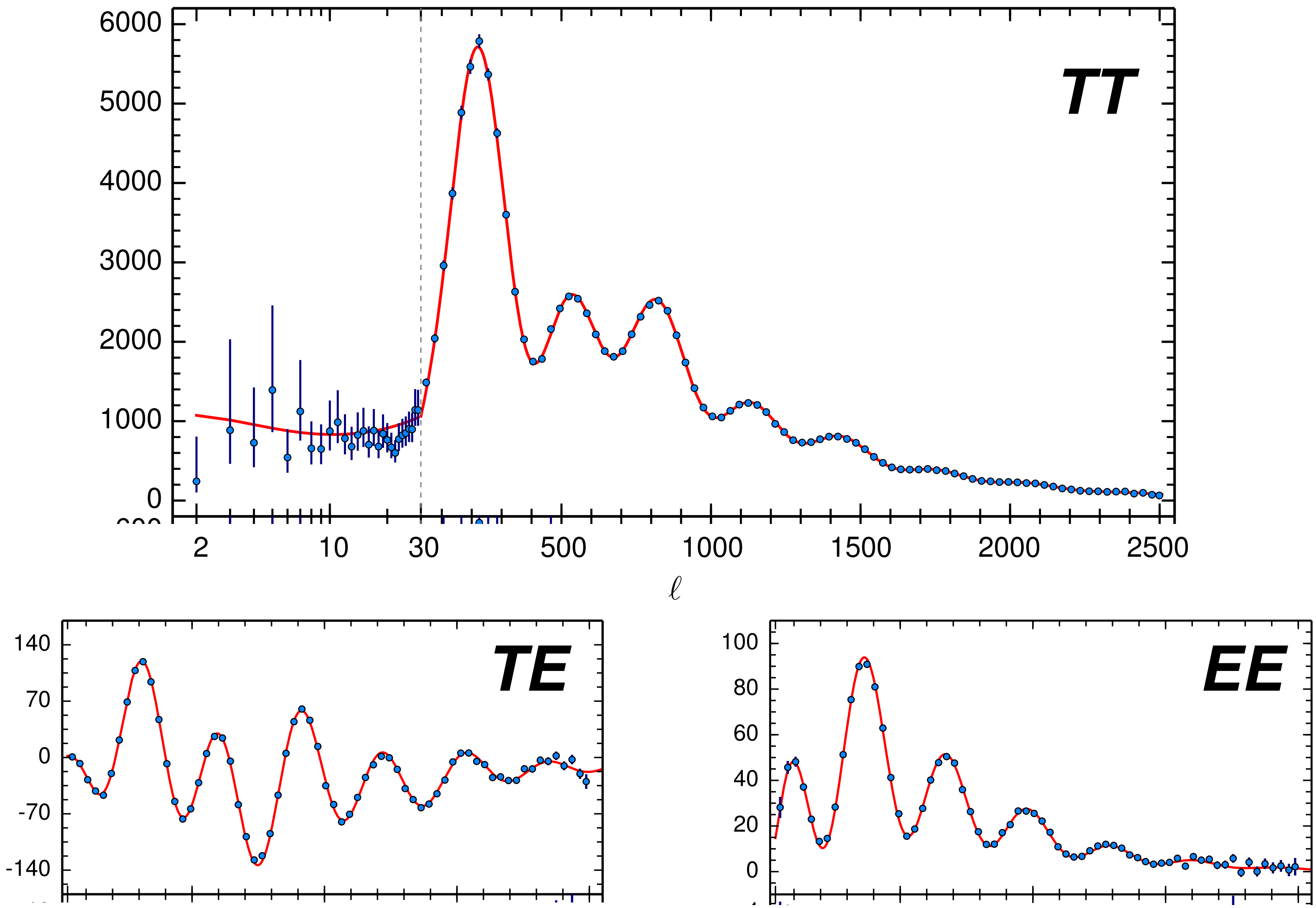
2. dark matter interacting with dark radiation model to the rescue

ΛCDM cosmic concordance model

Standard Model + collisionless dark matter
+ cosmological constant + “big bang”

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

Planck CMB

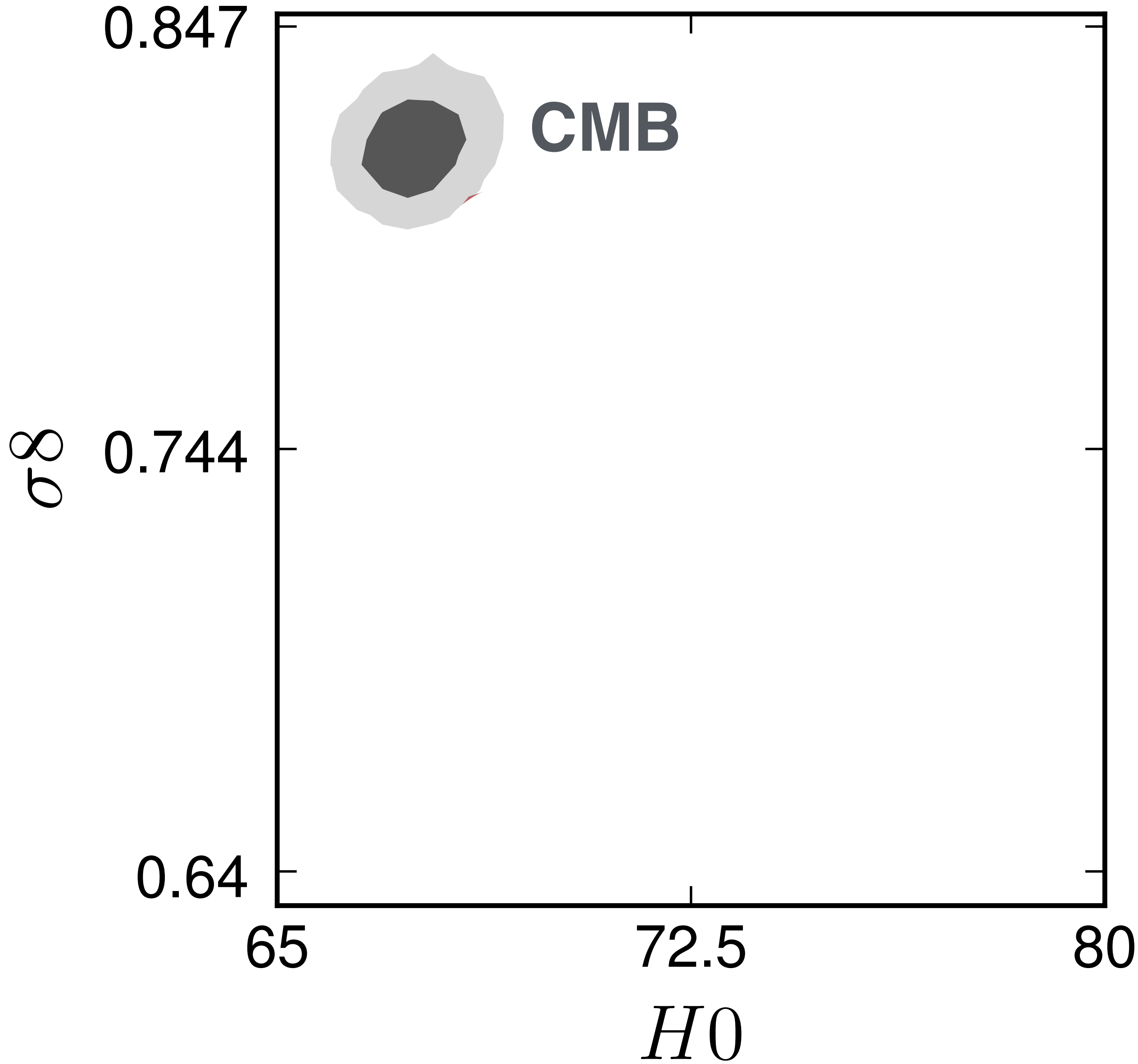

TT
6000
5000
4000
3000
2000
1000
0
2
10
30
500
1000
1500
2000
2500
ℓ
TE
140
70
0
-70
-140
EE
100
80
60
40
20
0

Planck CMB (TT,TE,EE,LowP)

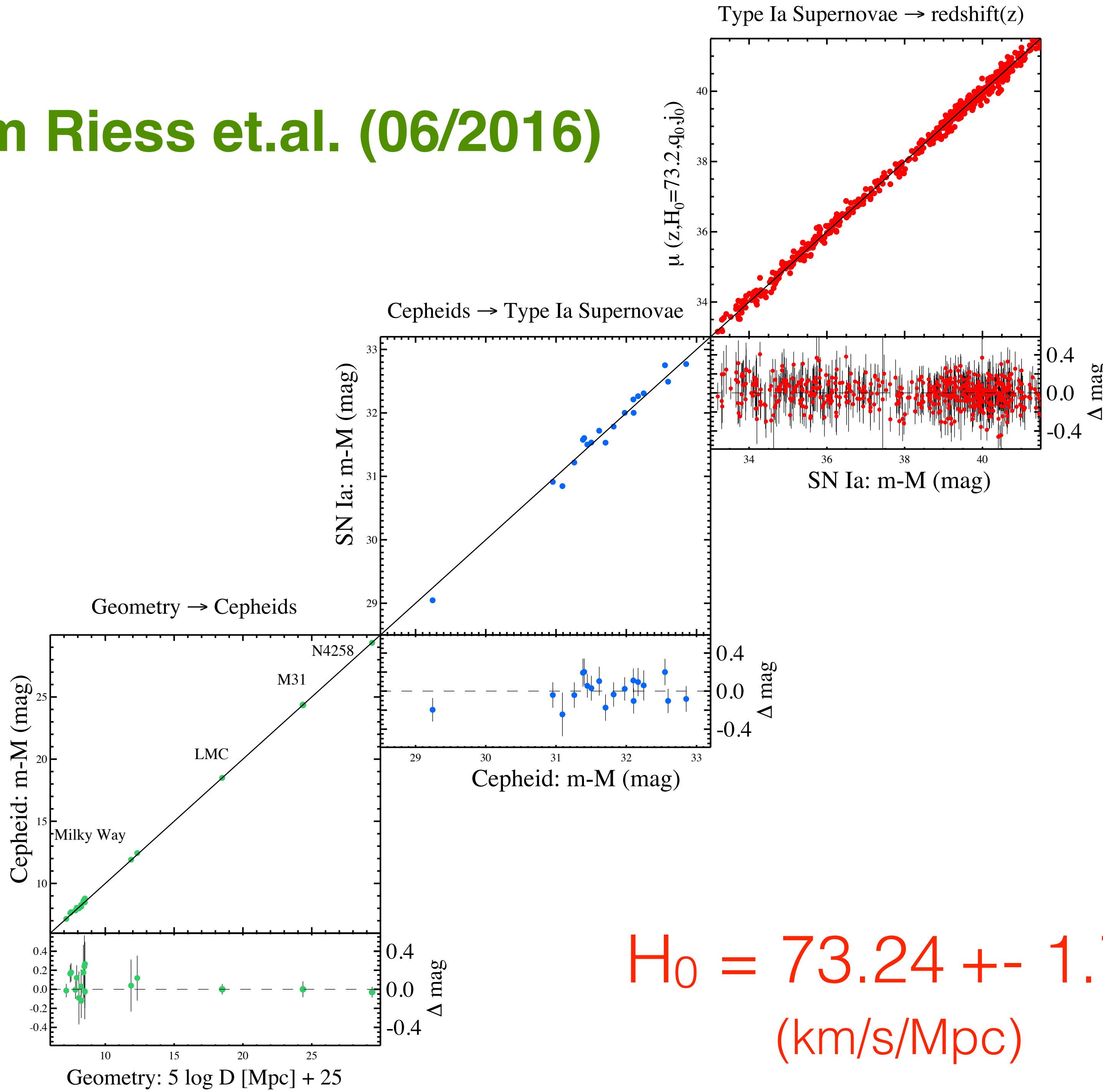
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013

ΛCDM

Poulin, Serpico, Lesgourgues
astro-ph/1606.02073



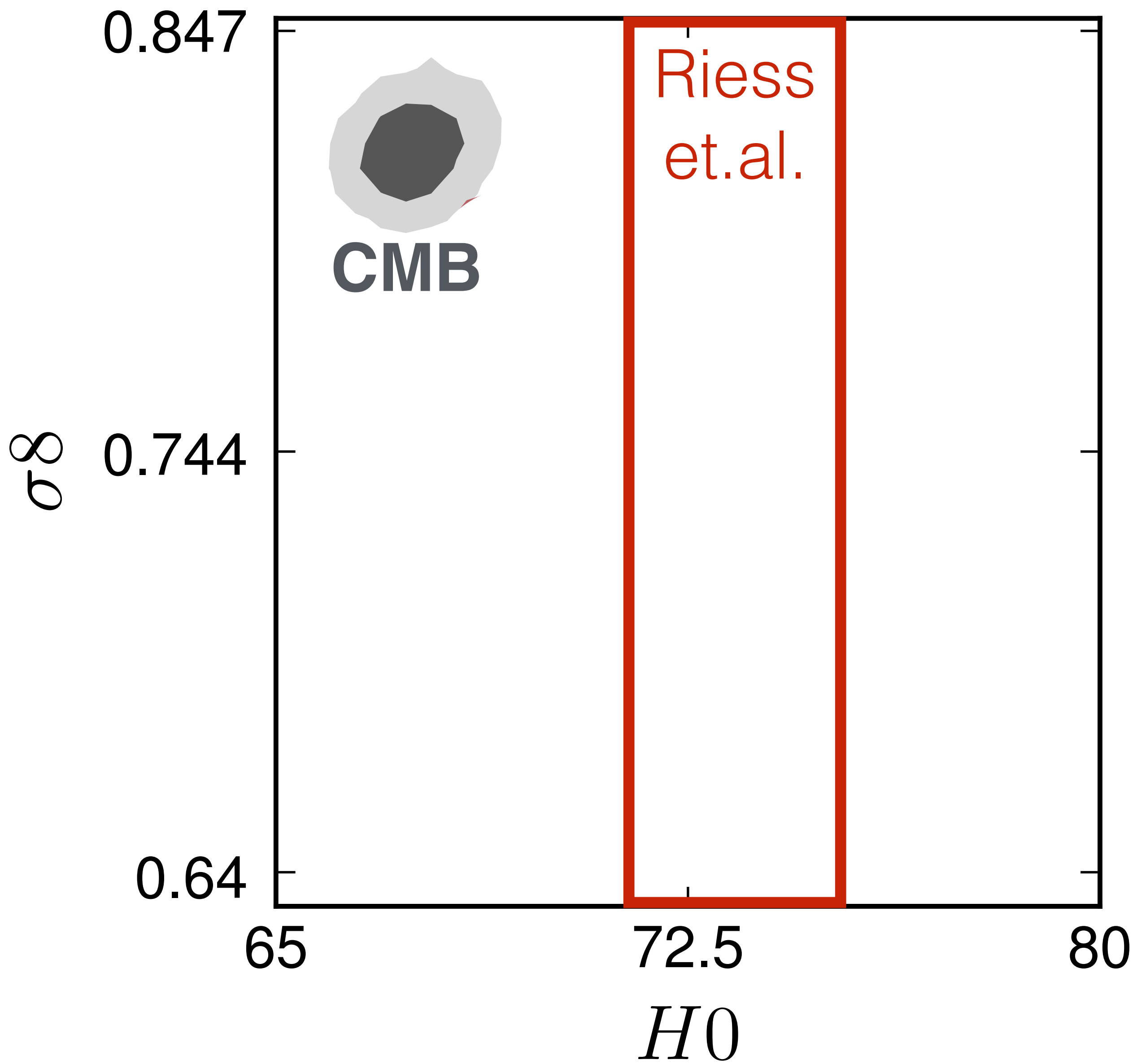
Adam Riess et.al. (06/2016)



$H_0 = 73.24 \pm 1.74$

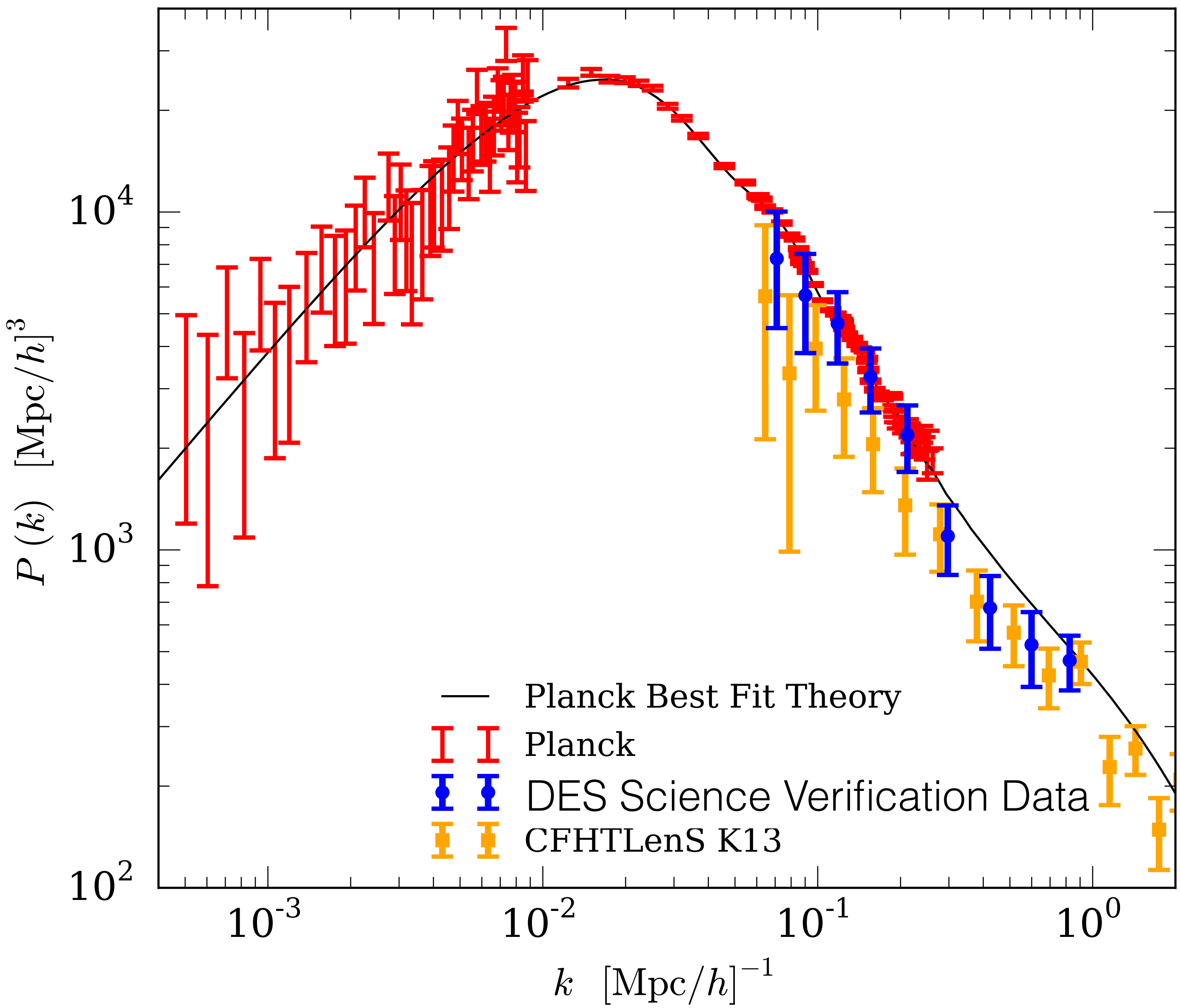
(km/s/Mpc)

ΛCDM

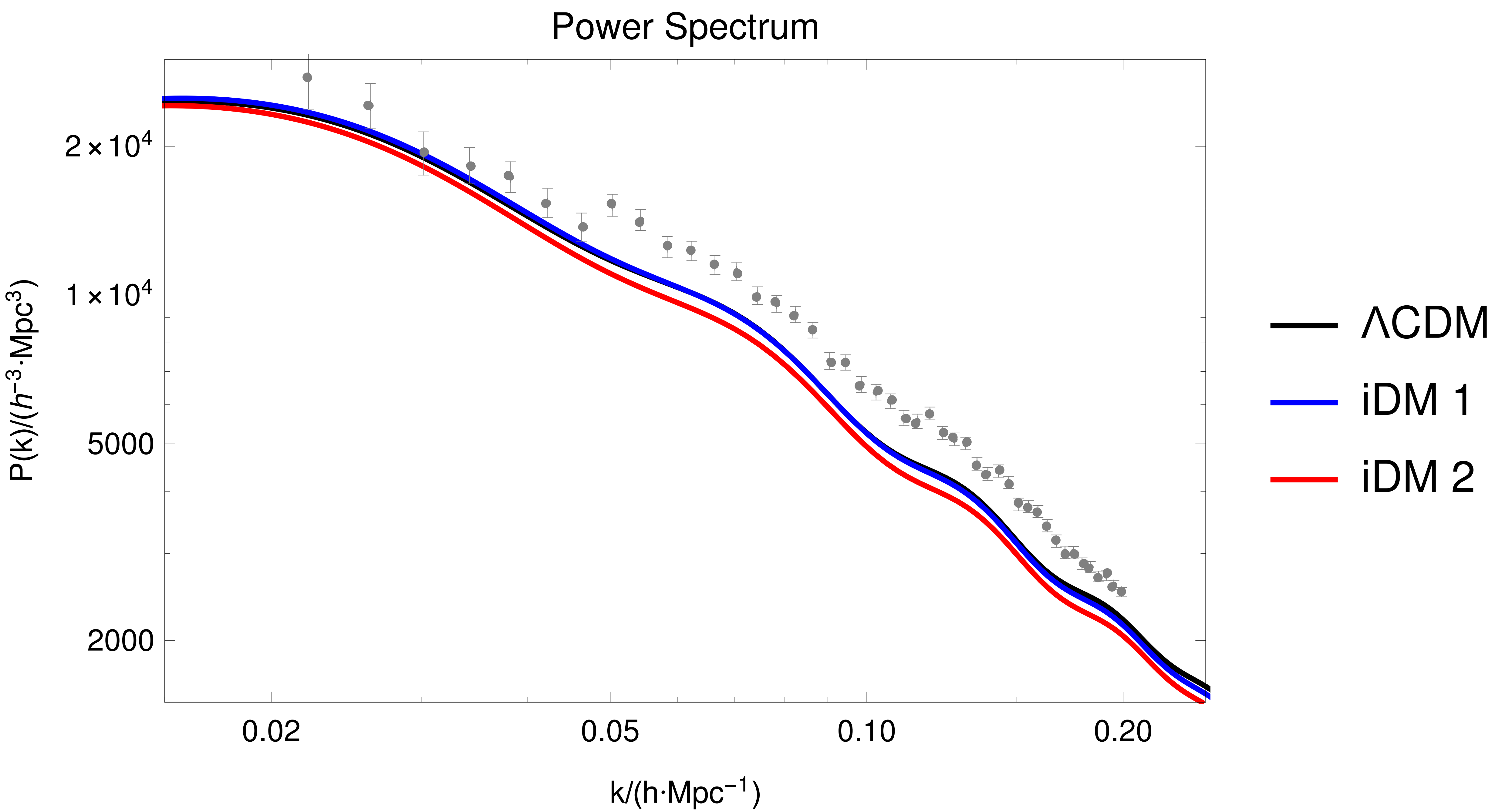


Matter Power Spectrum from weak lensing

DES astro-ph/150705552



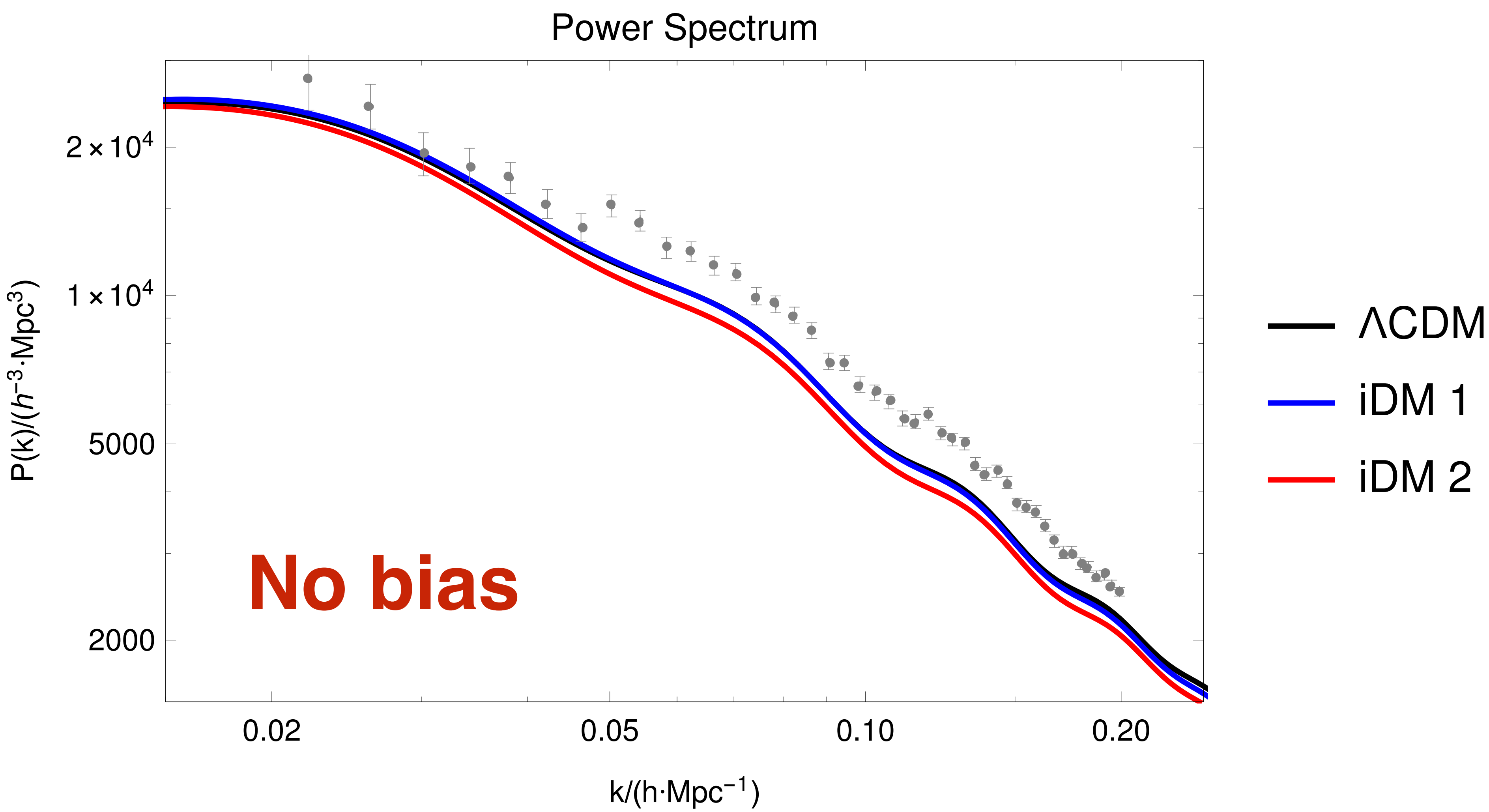
Galaxy Power Spectrum, SDSS-DR7, "straight up"



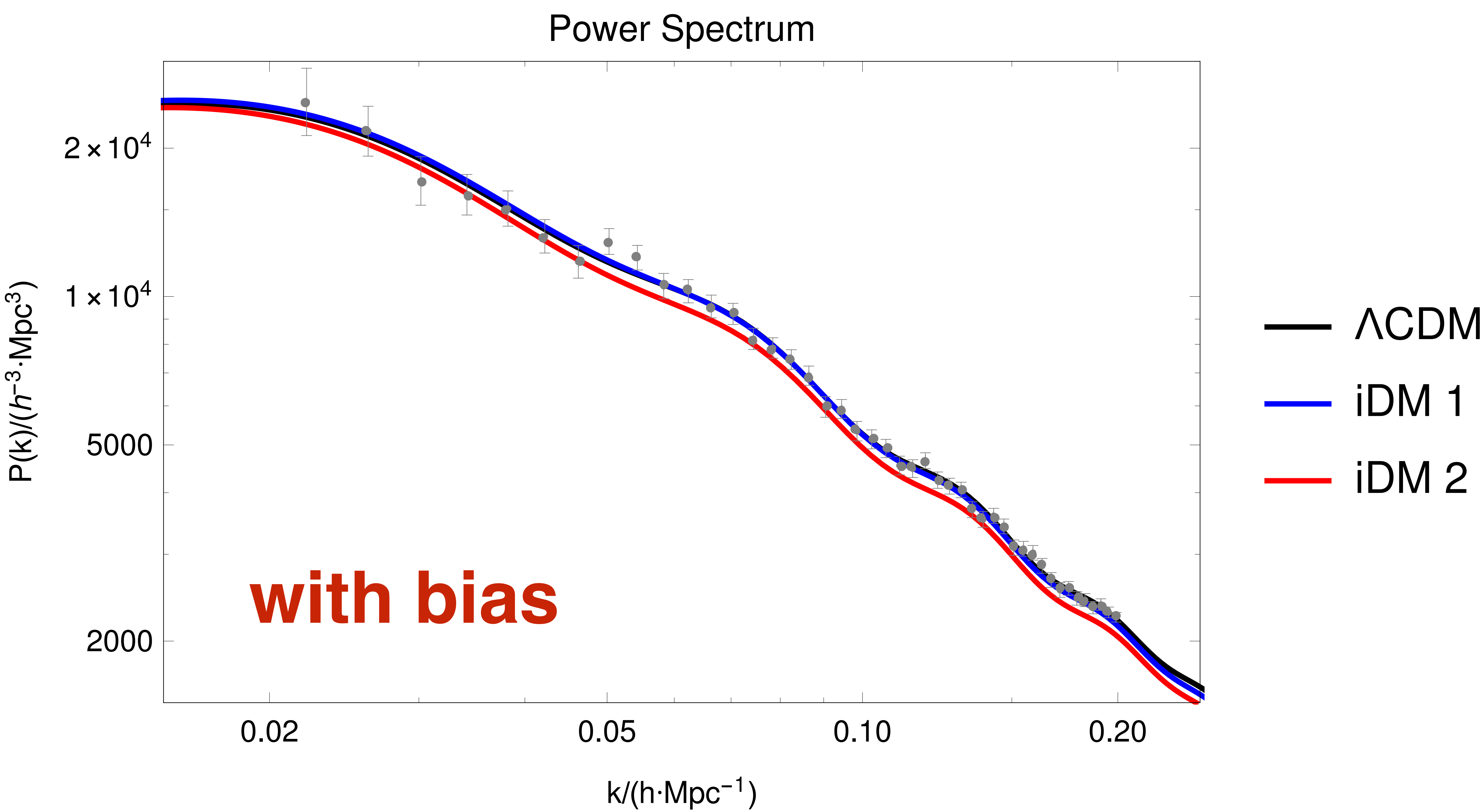
Galaxies don't track dark matter perfectly

"Galaxy bias"

$$P_{DM}(k) = P_{gal}(k)\,(a + b\,k + c\,k^2)$$

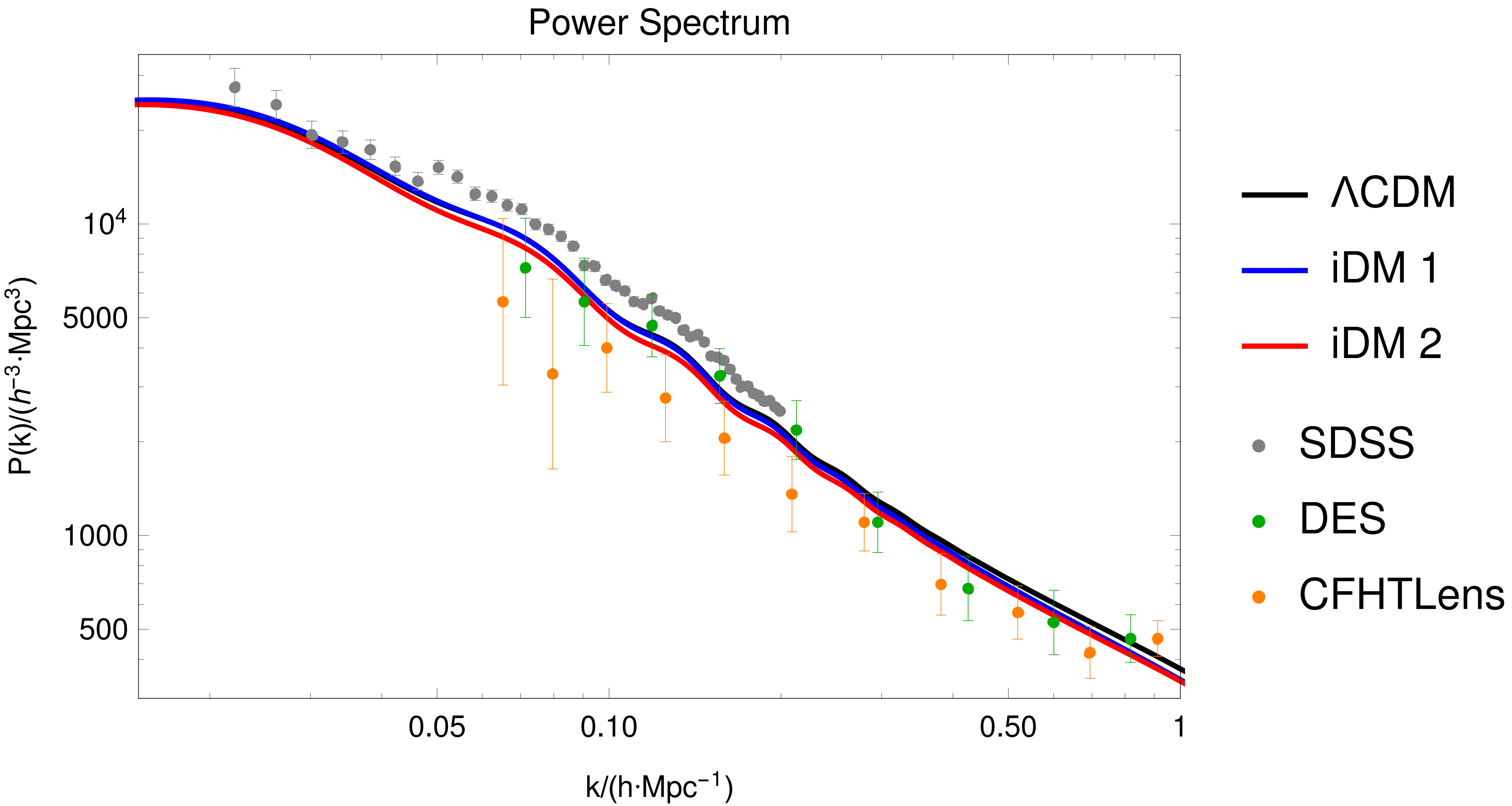


Galaxy Power Spectrum, SDSS-DR7

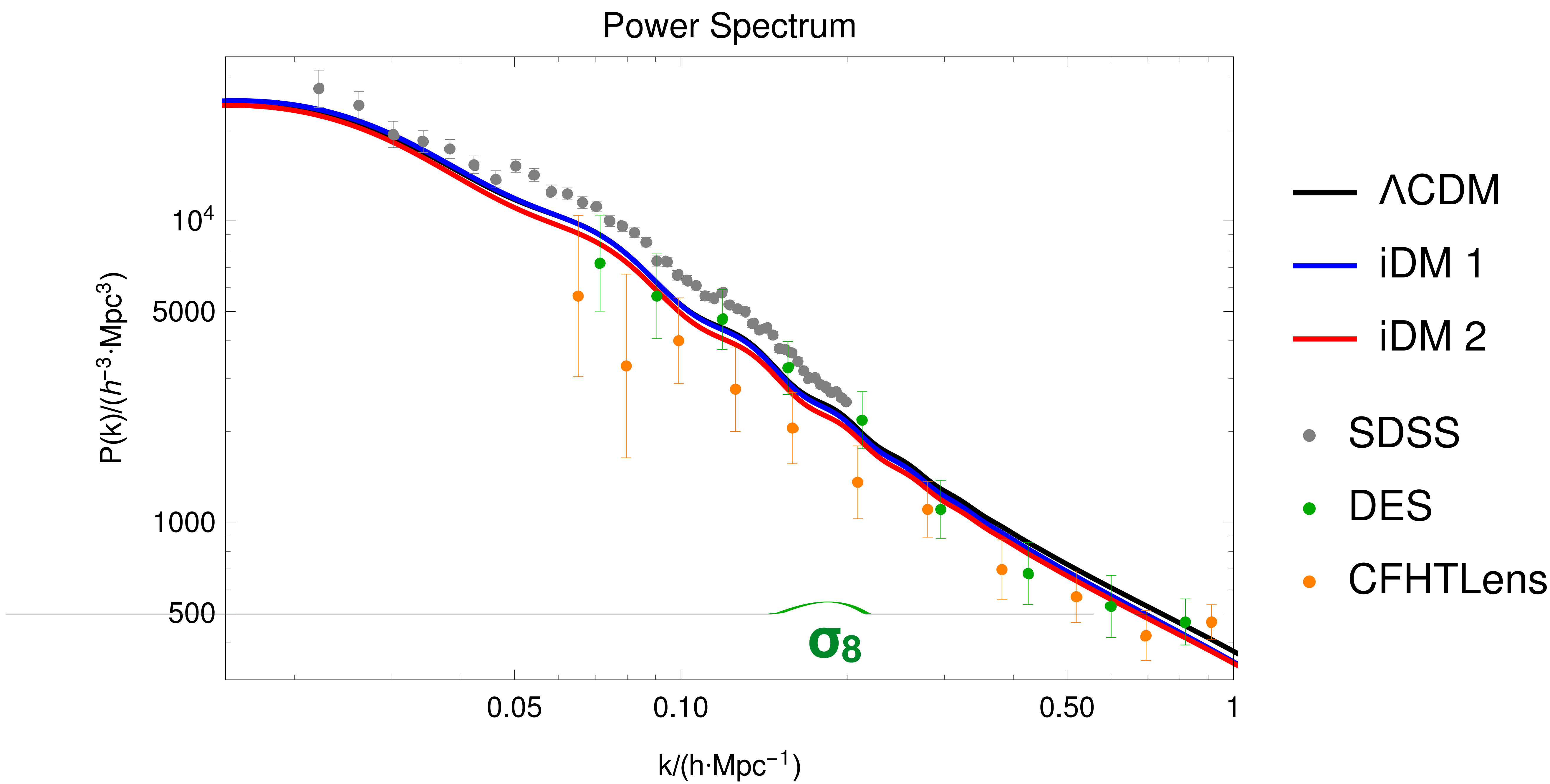


weak lensing: CFHTLens

DES (science verification 2015)



Planck lensing	0.815+-0.009	Planck CMB
Planck SZ	0.761+-0.012	0.831+-0.013
Lyman alpha	0.832+-0.017	

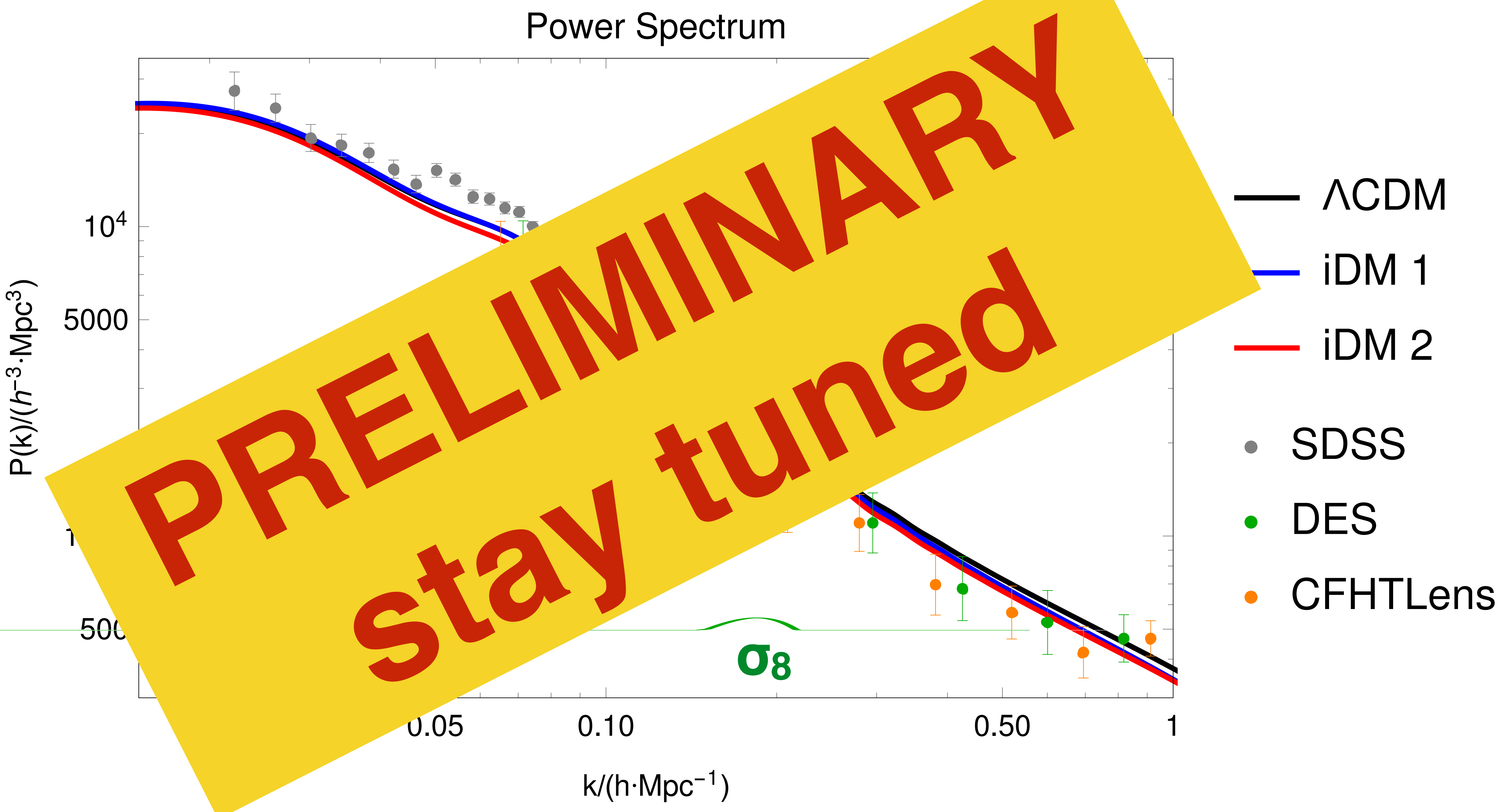


Planck lensing 0.815+-0.009

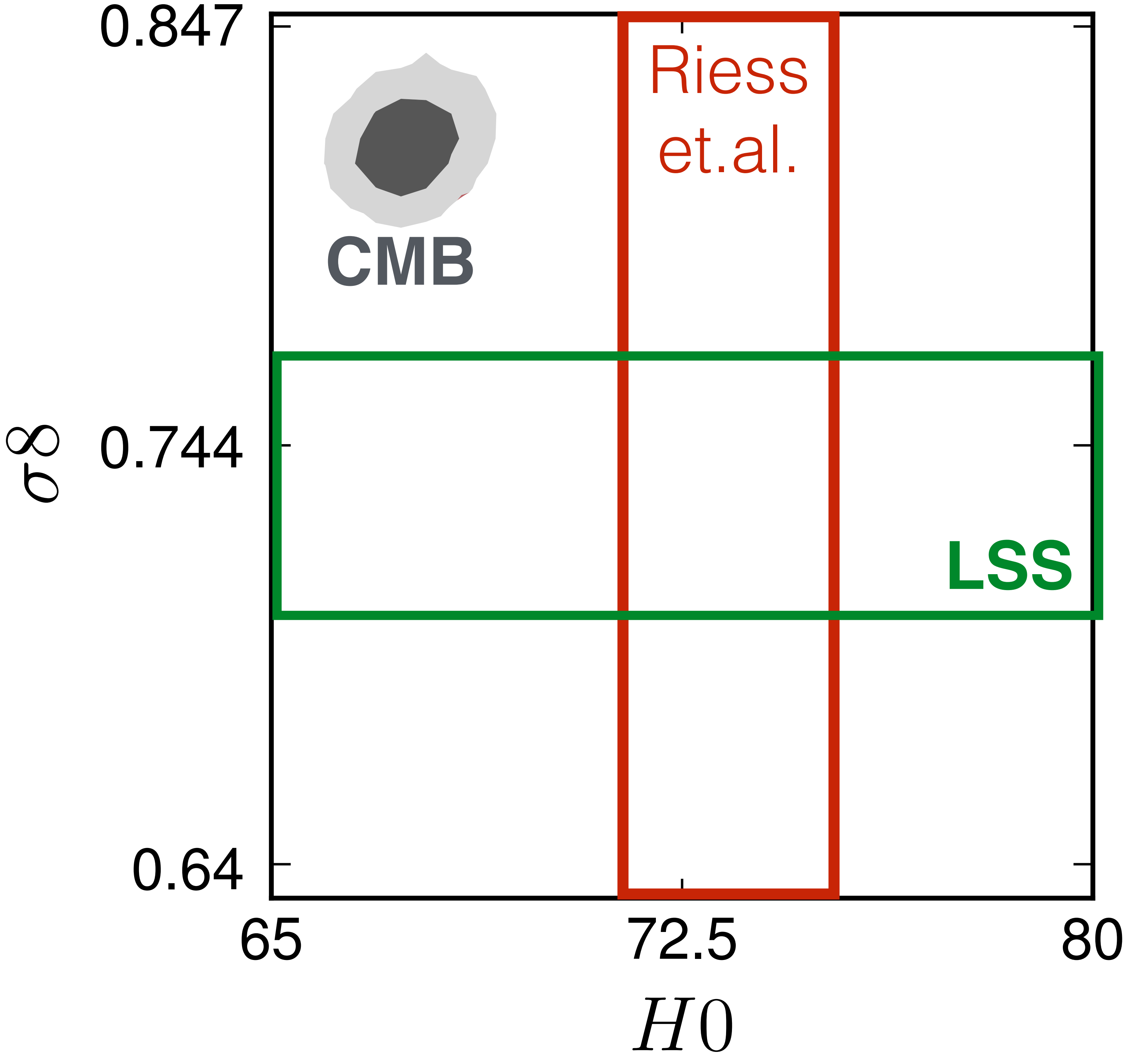
Planck SZ 0.761+-0.012

Lyman alpha 0.832+-0.017

Planck CMB 0.831+-0.013



ΛCDM



ΛCDM

Poulin, Serpico, Lesgourgues
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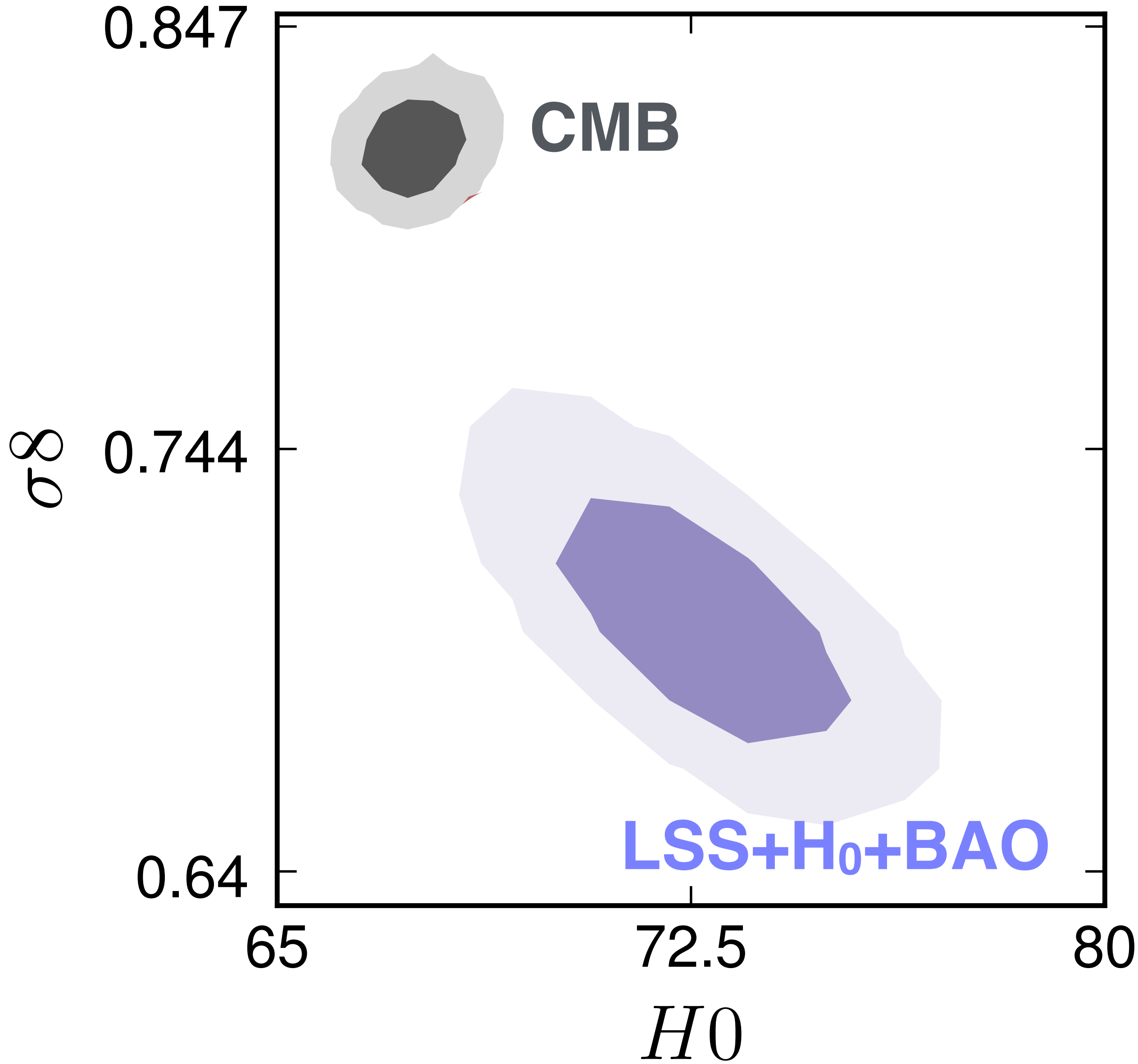
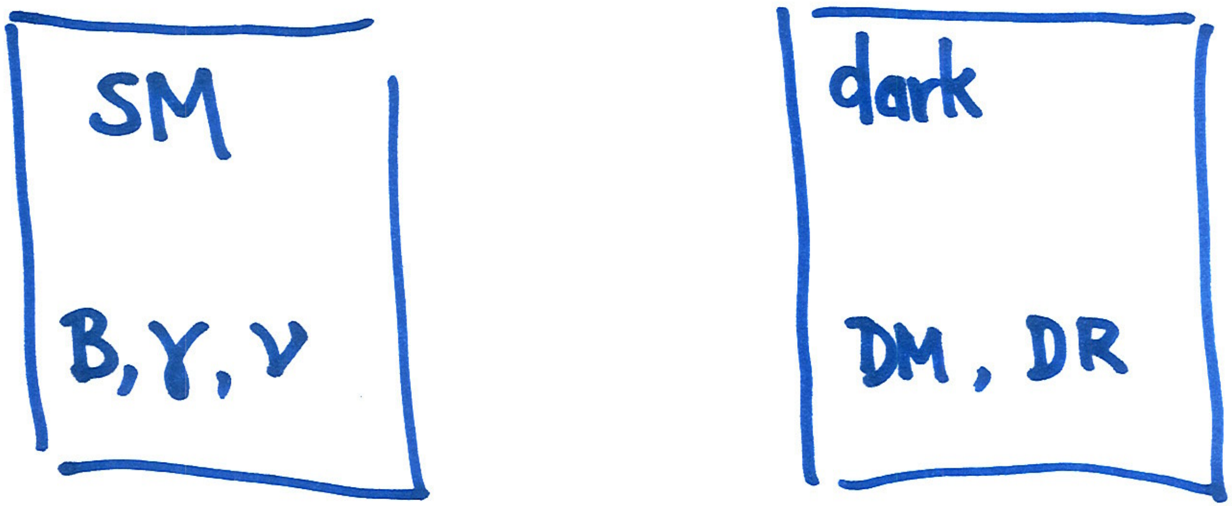


DM + DR model



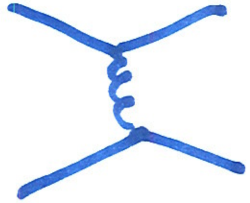
T_γ

$T_{DR} \lesssim T_\gamma$

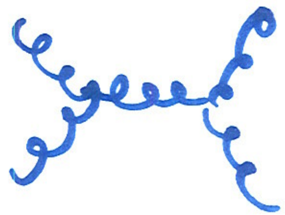
$M_{DM} \gg T_{DR}$ "cold"

example: non-Abelian dark sector

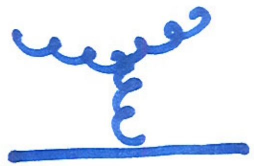
DM massive "dark quarks"



DR massless "dark gluons"

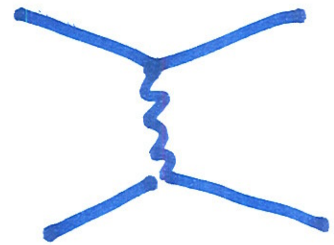


$g_D \sim 10^{-4} \Rightarrow$ "Λ"$_{QCD} \ll T_{DR}$

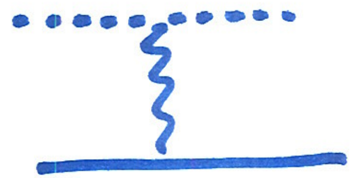


example: Abelian dark sector

DM massive "dark leptons"

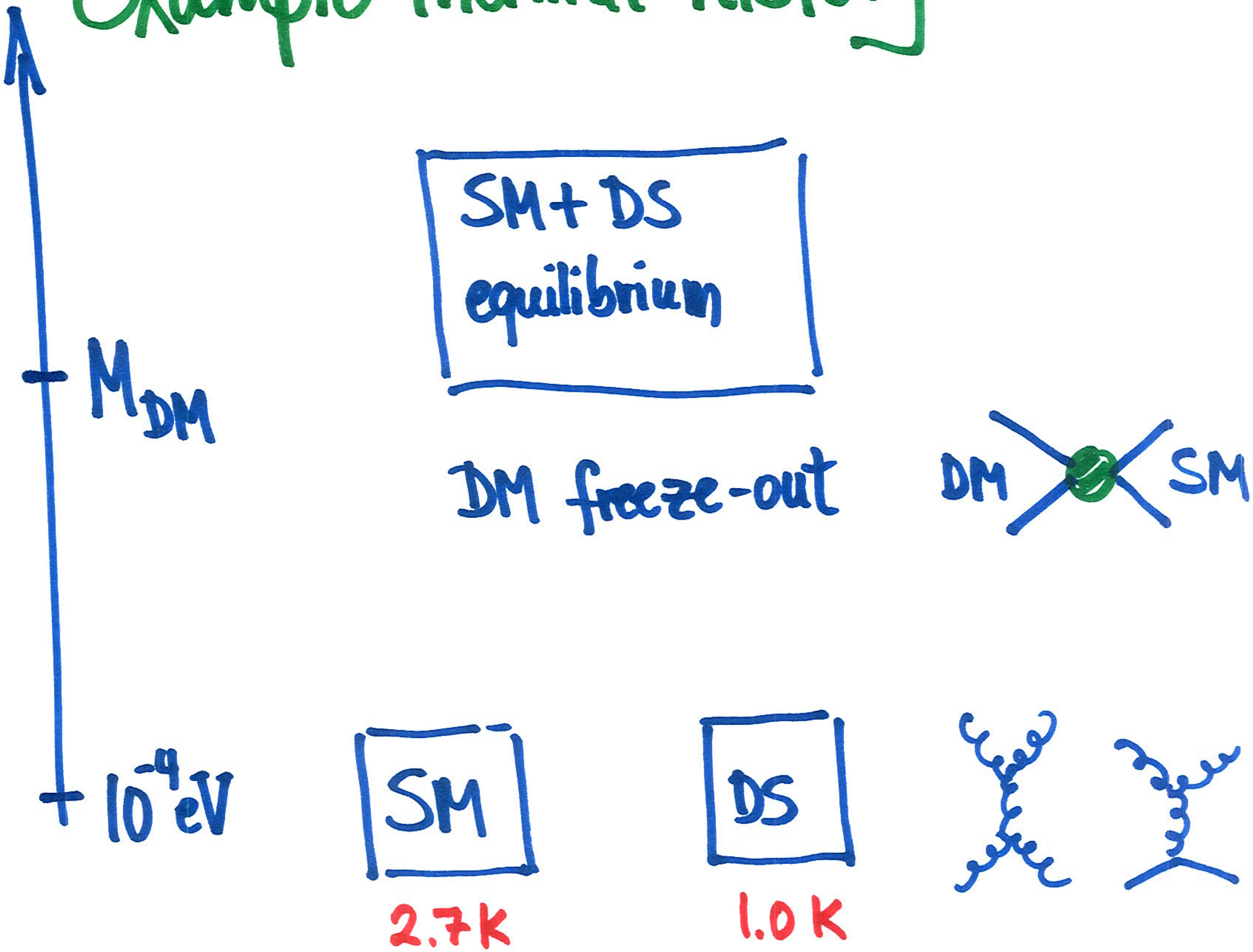


DR massless "dark photon + leptons"



$g_D \sim 10^{-4}$

example thermal history



What are important new effects ?

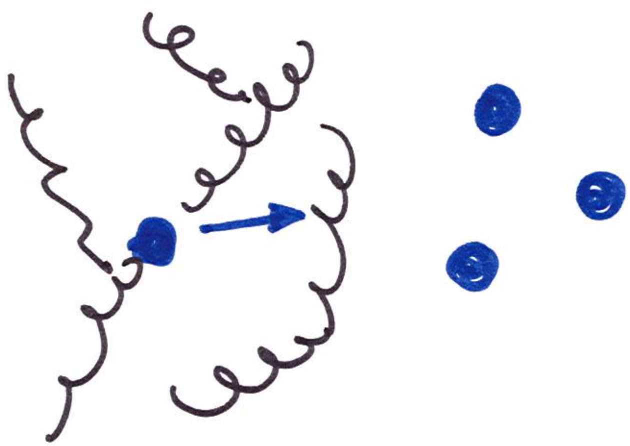
- energy density in dark radiation $\Rightarrow \Delta N_{eff}$
- DM-DR coupling $\Longrightarrow$ large scale structure

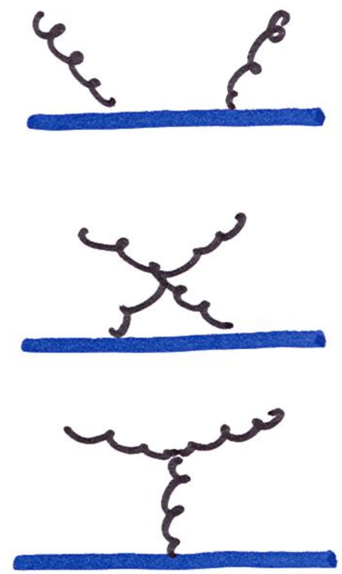
energy density in dark gluons

$$\rho_g \sim (N^2-1)\, T_g{}^4 = (N^2-1) \underbrace{\frac{T_g{}^4}{T_\nu{}^4}}\, T_\nu{}^4$$

$$\equiv \Delta N_{eff} \sim \begin{cases} \dfrac{N^2-1}{16.4} \\ \text{free parameter} \end{cases}$$

DM-DR interactions and large scale structure





Momentum transfer rate

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

"drag"

Debye cutoff

momentum transfer rate

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

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

linear perturbations in fluids

δ density pert.

θ velocity pert.

⋮

DM, DR, SM

↓

γ, ν, B

linear perturbations

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

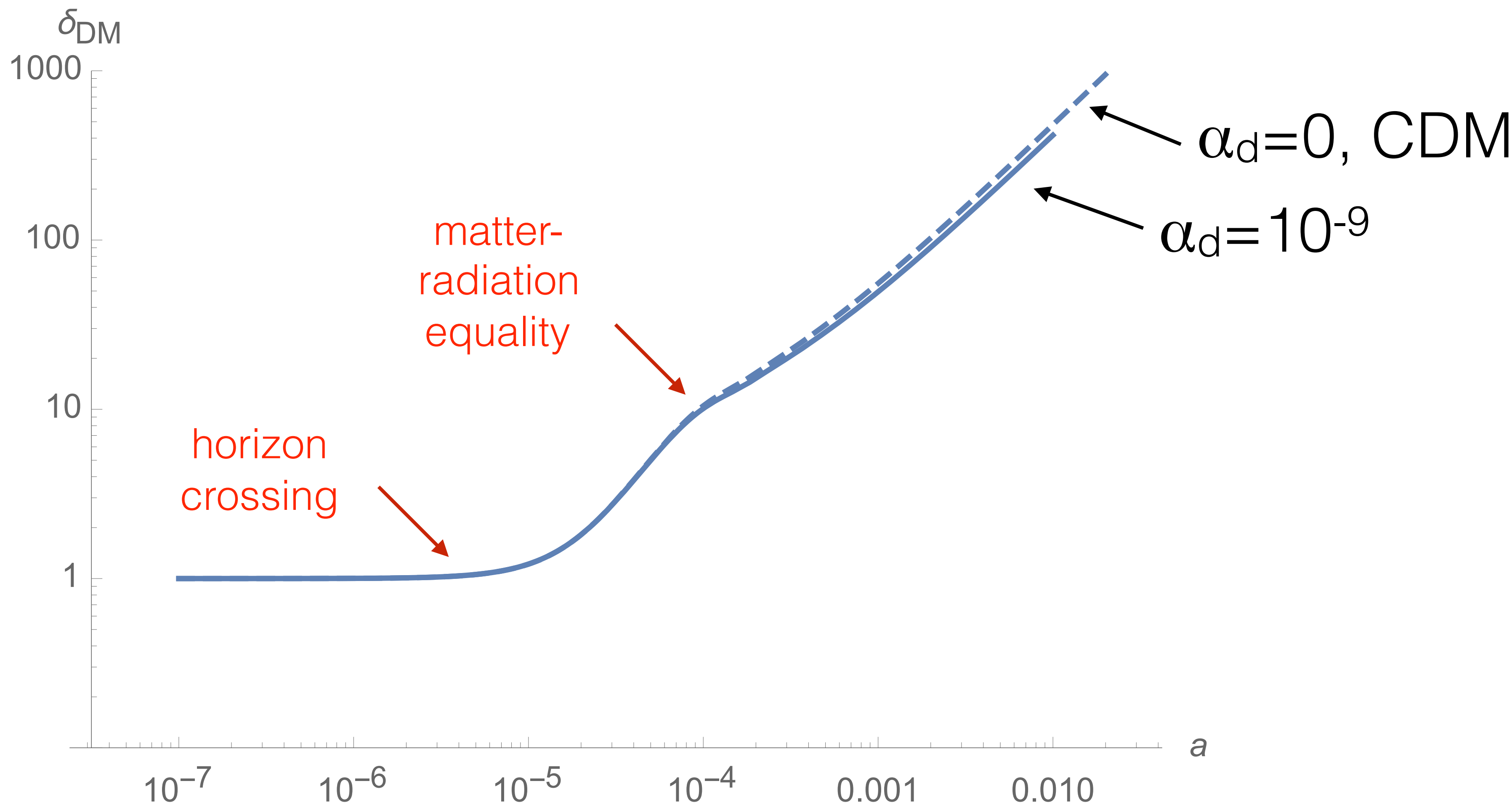
$$\dot{\theta}_{DM} = -\frac{\dot{a}}{a}\theta_{DM} + a\boldsymbol{\Gamma}_{\mathbf{p}}(\theta_{DR} - \theta_{DM}) + k^2\psi$$

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

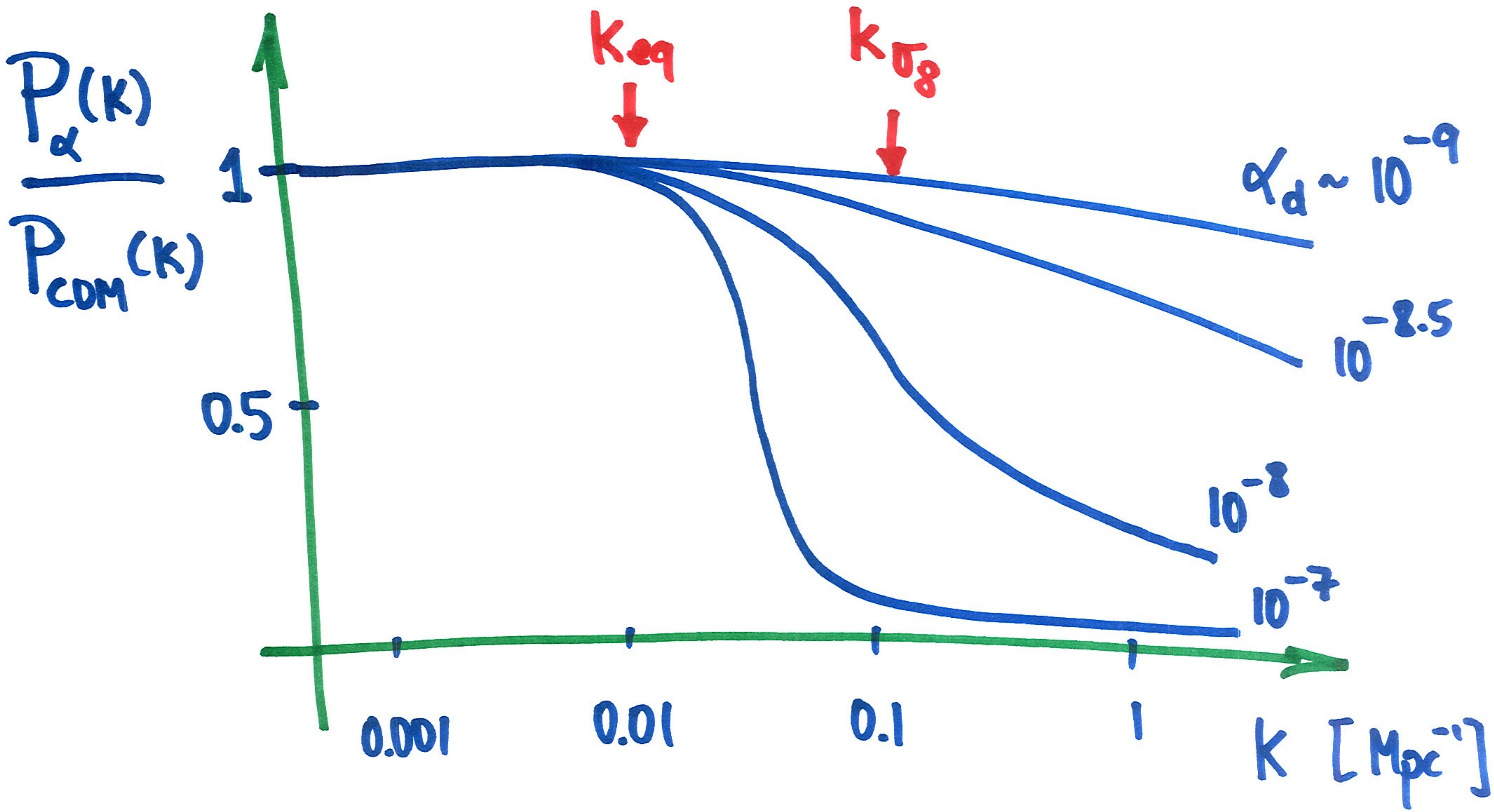
$$\dot{\theta}_{DR} = k^2\frac{\delta_{DR}}{4} + k^2\psi + \frac{3}{4}\frac{\rho_{DM}}{\rho_{DR}}a\boldsymbol{\Gamma}_{\mathbf{p}}(\theta_{DM} - \theta_{DR})$$

growth of perturbations

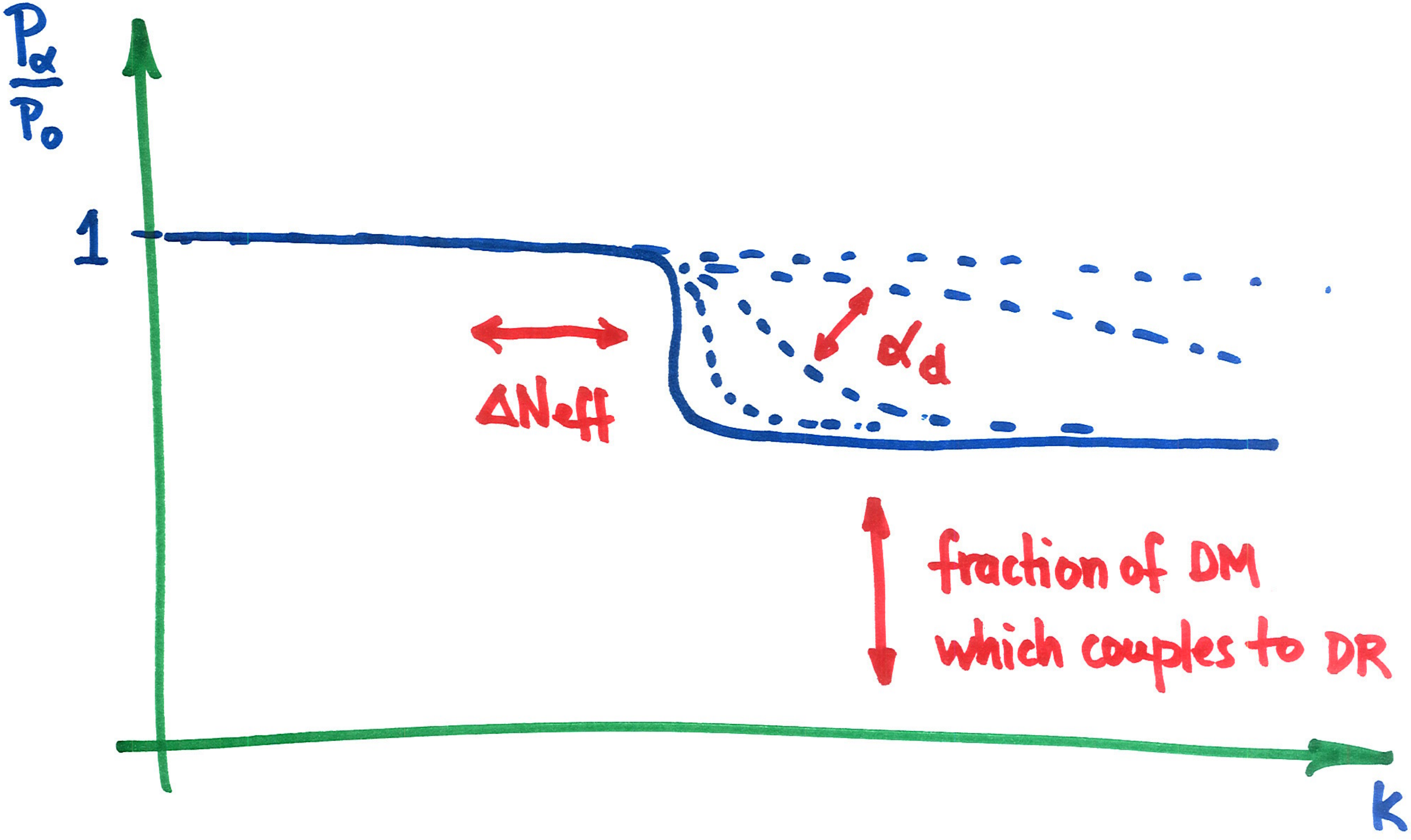
k=0.2 Mpc^{-1}



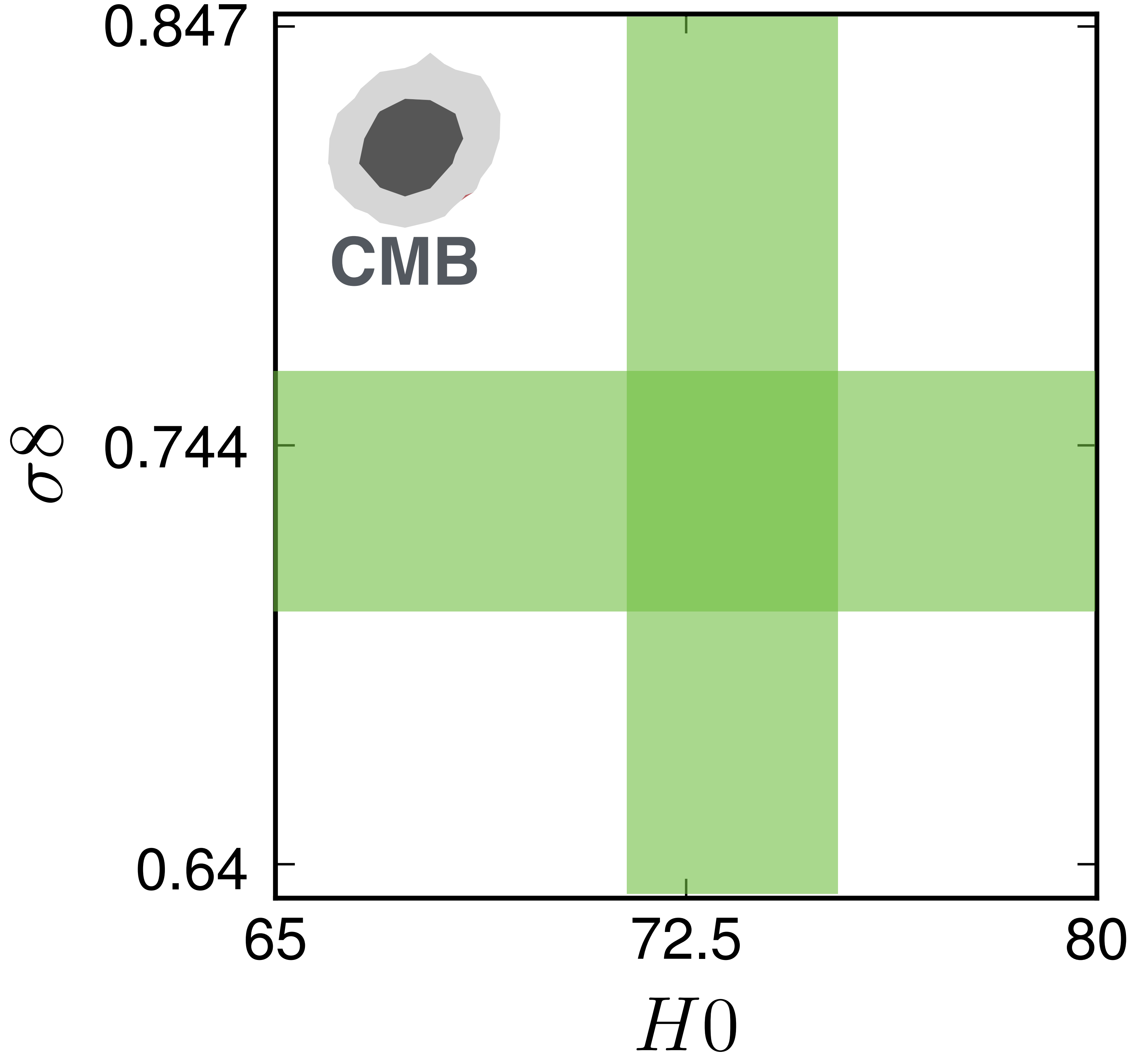
Matter power spectrum compared to CDM

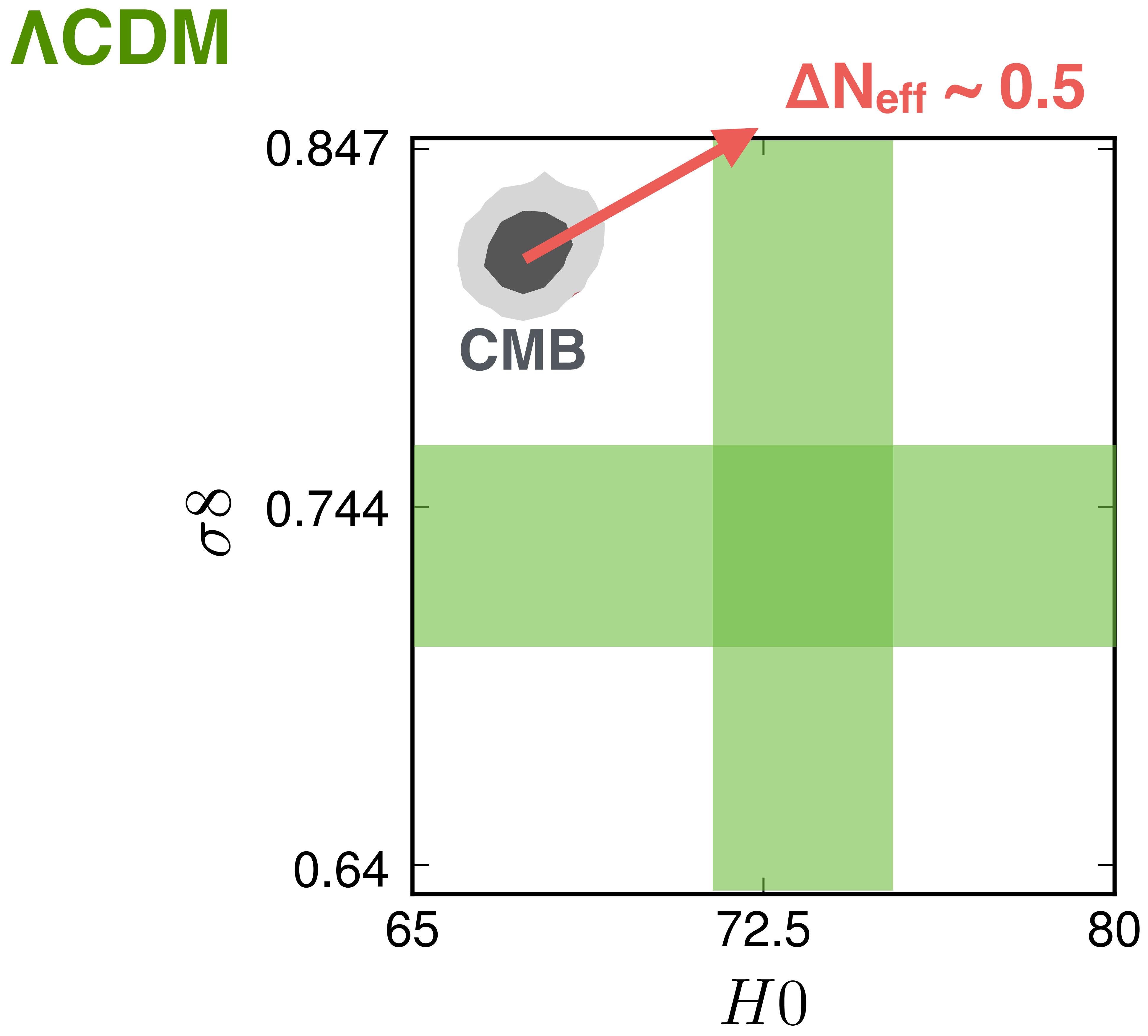


parameter dependence



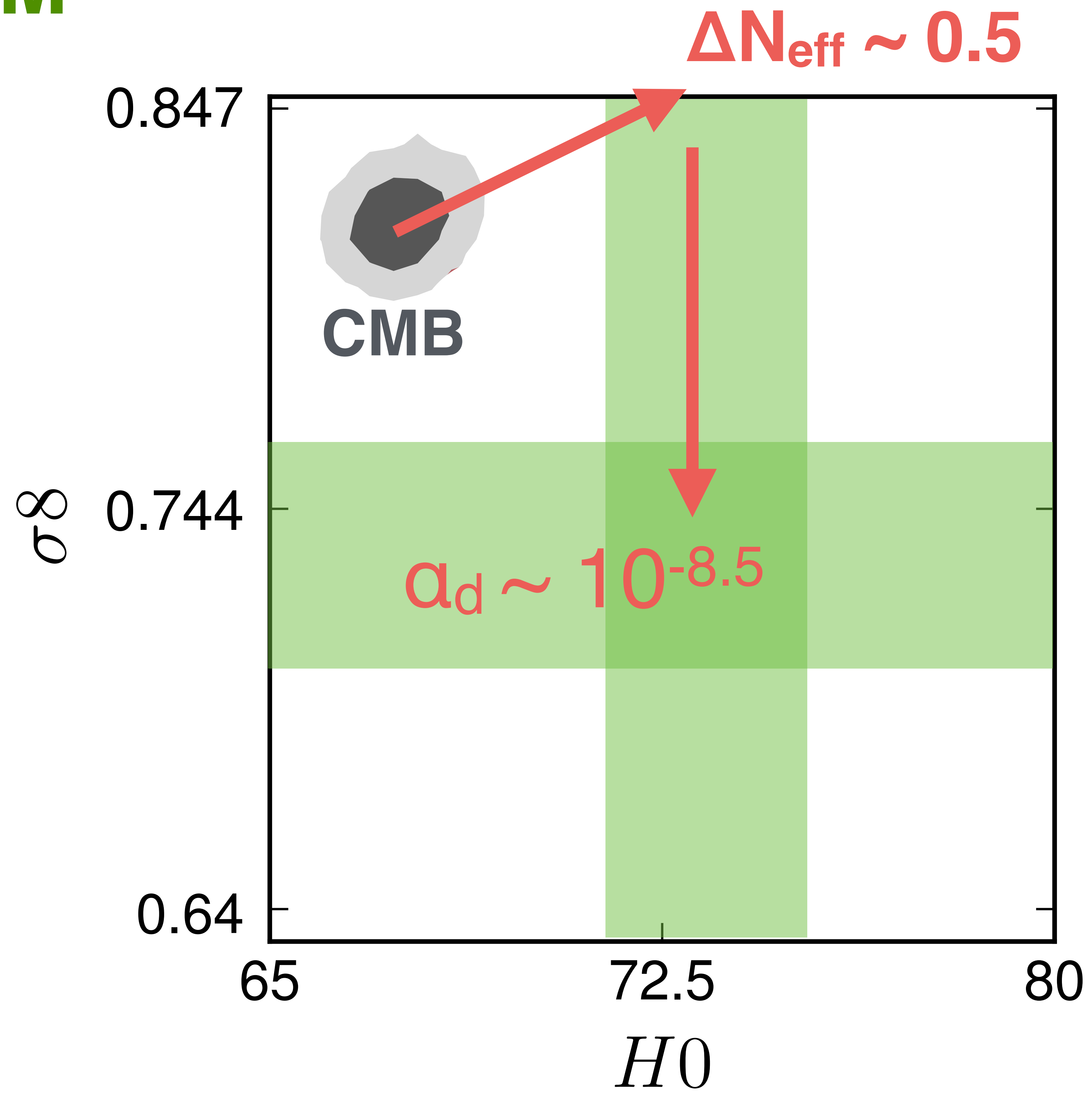
ΛCDM

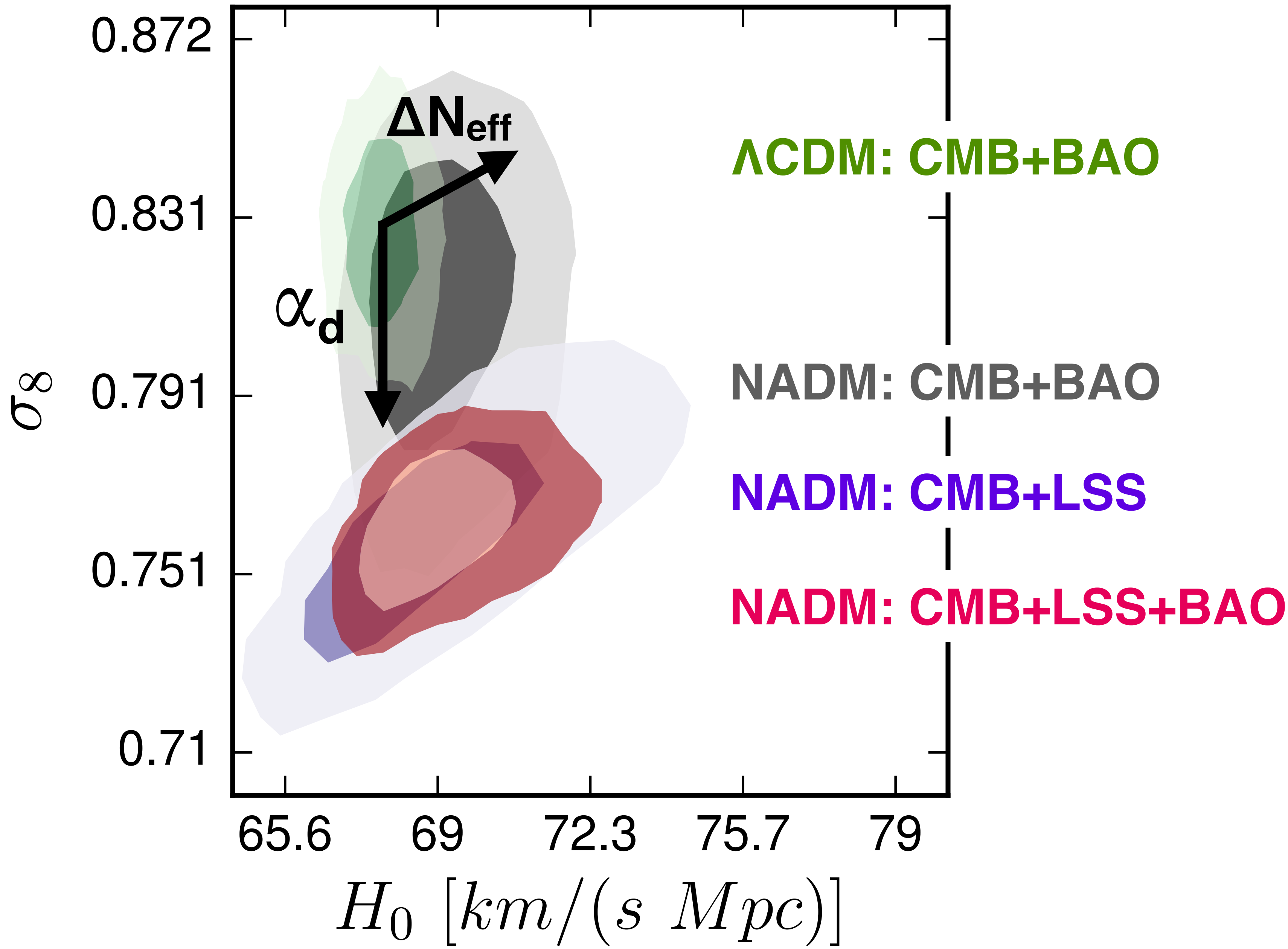




ΛCDM
ΔNeff ~ 0.5
0.847
0.744
0.64
CMB
σ8
65
72.5
80
H0

ΛCDM





0.872
0.831
0.791
0.751
0.71
65.6
69
72.3
75.7
79
σ_8
$H_0\ [km/(s\ Mpc)]$
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 - test: $p=0.002$ ($>3\sigma$)

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

back up!

Parameter	CMB+BAO	CMB+LSS	CMB+BAO +LSS	CMB+BAO +LSS+H_0
$100\omega_b$	$2.236^{+0.024}_{-0.026}$	$2.219^{+0.029}_{-0.041}$	$2.220^{+0.021}_{-0.025}$	$2.234^{+0.025}_{-0.026}$
$\omega_{\rm dm}$	$0.1244^{+0.0021}_{-0.0040}$	$0.1256^{+0.0034}_{-0.0047}$	$0.1249^{+0.0023}_{-0.0049}$	$0.1274^{+0.0040}_{-0.0060}$
$\Delta N_{\rm fluid}$	< 0.58	< 0.71	< 0.67	< 0.59
$10^7\Gamma_0$ [Mpc^{-1}]	< 1.54	$1.74^{+0.57}_{-0.55}$	$1.65^{+0.42}_{-0.44}$	$1.69^{+0.43}_{-0.48}$
H_0 [km/(s Mpc)]	$69.1^{+0.8}_{-1.3}$	$69.0^{+1.4}_{-2.4}$	$69.1^{+0.8}_{-1.5}$	$70.2^{+1.3}_{-1.6}$
$10^9 A_s$	$2.220^{+0.079}_{-0.081}$	$2.205^{+0.063}_{-0.076}$	$2.205^{+0.063}_{-0.069}$	$2.217^{+0.062}_{-0.070}$
n_s	$0.9709^{+0.0048}_{-0.0053}$	$0.9762^{+0.0070}_{-0.0081}$	$0.9736^{+0.0051}_{-0.0055}$	$0.9796^{+0.0049}_{-0.0053}$
$\tau_{\rm reio}$	$0.084^{+0.018}_{-0.019}$	$0.078^{+0.016}_{-0.019}$	$0.079^{+0.015}_{-0.015}$	$0.082^{+0.014}_{-0.016}$
$\Omega_{\rm m}$	$0.3088^{+0.0082}_{-0.0083}$	$0.3130^{+0.019}_{-0.018}$	$0.3097^{+0.0085}_{-0.0083}$	$0.3052^{+0.0080}_{-0.0083}$
σ_8	$0.811^{+0.026}_{-0.019}$	$0.760^{+0.017}_{-0.019}$	$0.762^{+0.011}_{-0.011}$	$0.766^{+0.011}_{-0.011}$
$\Delta\chi^2$ / ΛCDM	0	-9.6	-11.4	-12.7

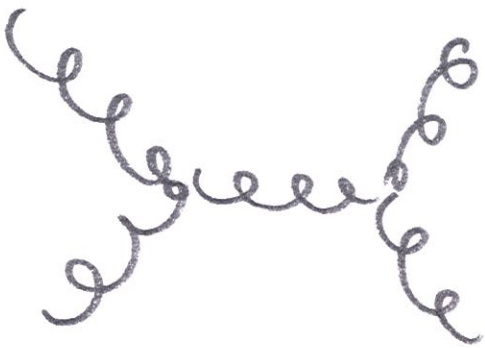
- **CMB**: we use the Planck 2015 TT + low-ℓ likelihood from Ref. [26].

- **BAO**: we use measurements of $D_V/r_{\rm drag}$ at $z = 0.106$ by 6dFGS [27], at $z = 0.15$ by SDSS-MGS [28], at $z = 0.32$ by BOSS- LOWZ [29], and anisotropic BAO measurements at $z = 0.57$ by BOSS-CMASS-DR11 [29].

- **LSS**: we use three probes of Large Scale Structure: the Planck 2015 lensing likelihood [30], the constraint $\sigma_8(\Omega_m/0.27)^{0.46} = 0.774 \pm 0.040$ (68%CL) derived from the weak lensing survey CFHTLenS [31], and the constraint $\sigma_8(\Omega_m/0.27)^{0.30} = 0.782 \pm 0.010$ (68%CL) from Planck SZ cluster mass function [32]. The latter con-

- **H_0**: we occasionally also use the constraint $H_0 = 73.8 \pm 2.4$ km/s/Mpc (68%CL) from Riess et al. [16]. Direct measurements of the local Hubble rate by e.g. [16, 17] have

difference between ν's and dark gluons

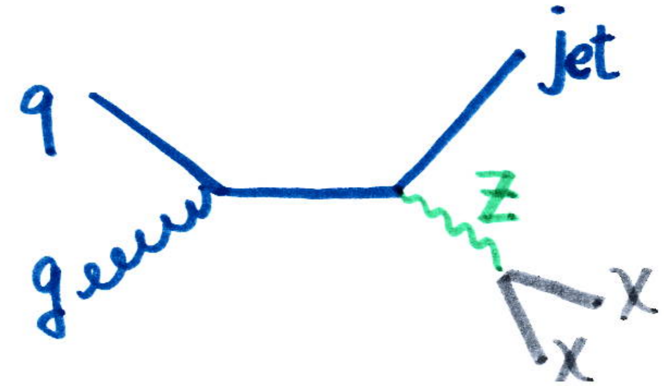


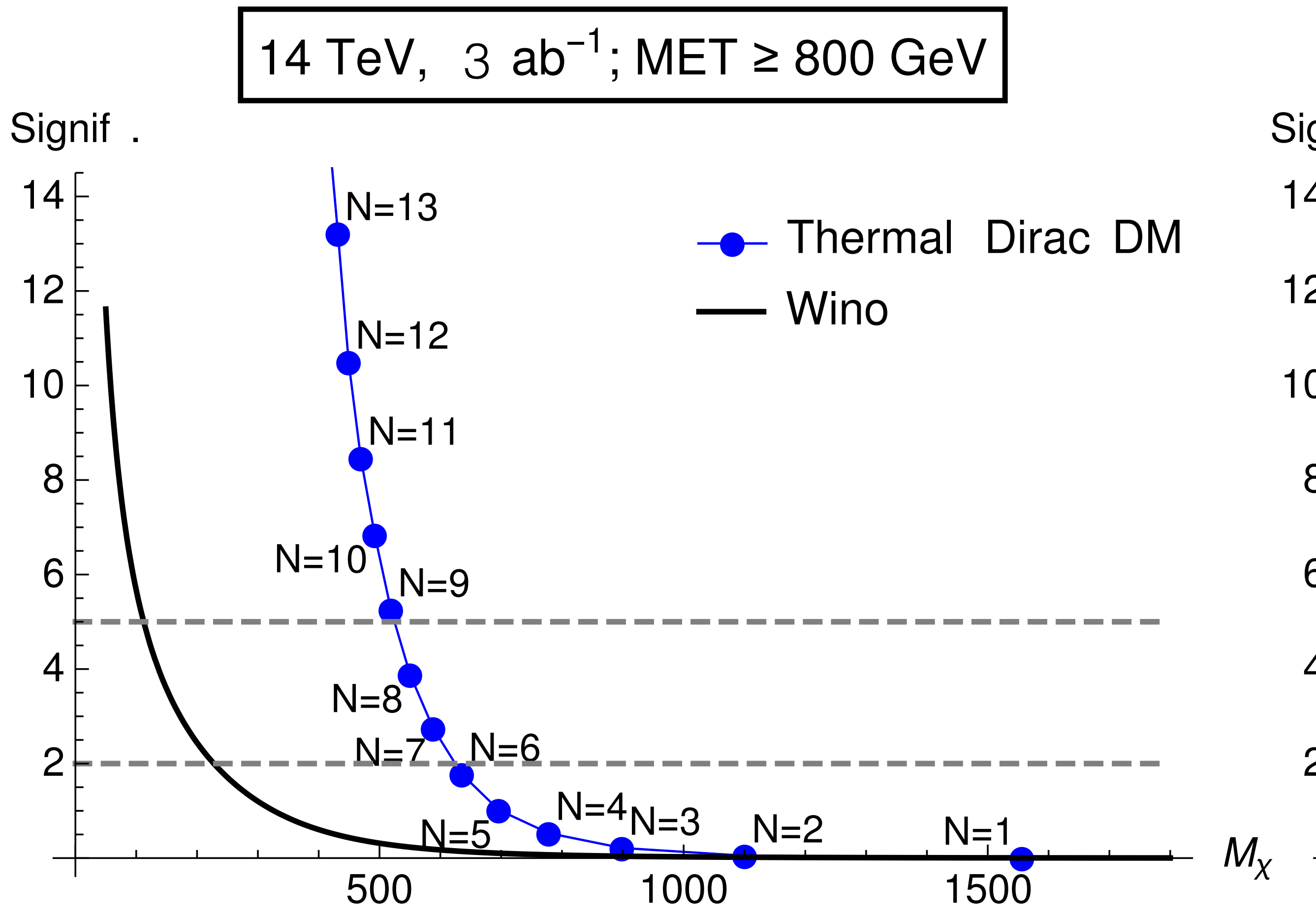
rate $\Gamma \gg H$

dark gluons do not free-stream → "perfect fluid"

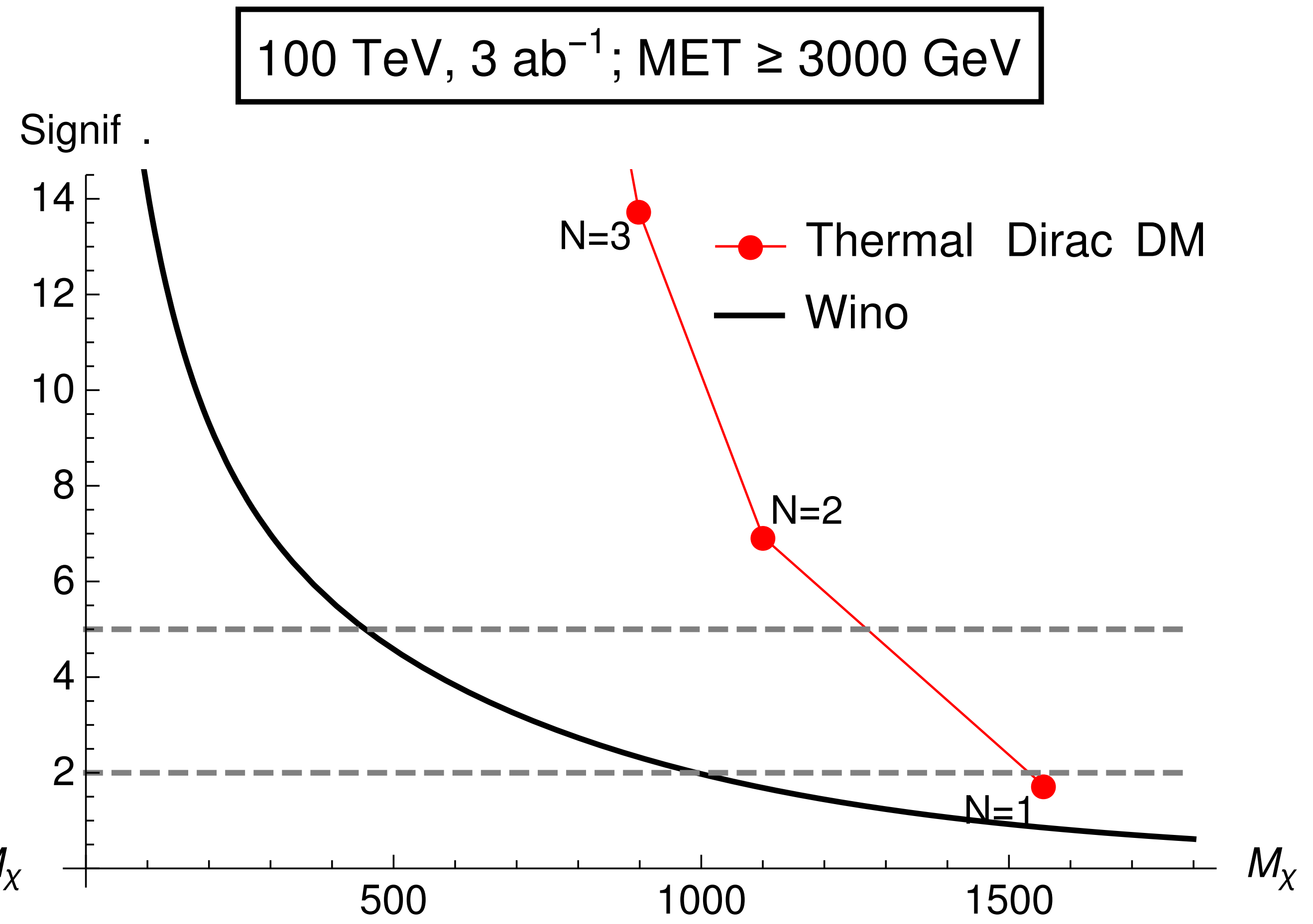
- phase shift of CMB peaks

Colliders: mono-jets





HL-LHC



100 TeV