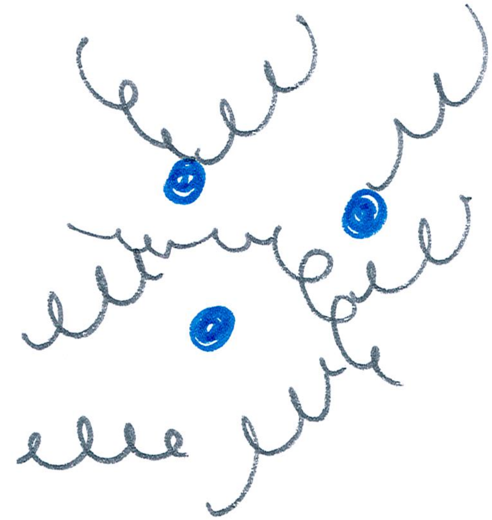
Non-Abelian dark matter & dark radiation



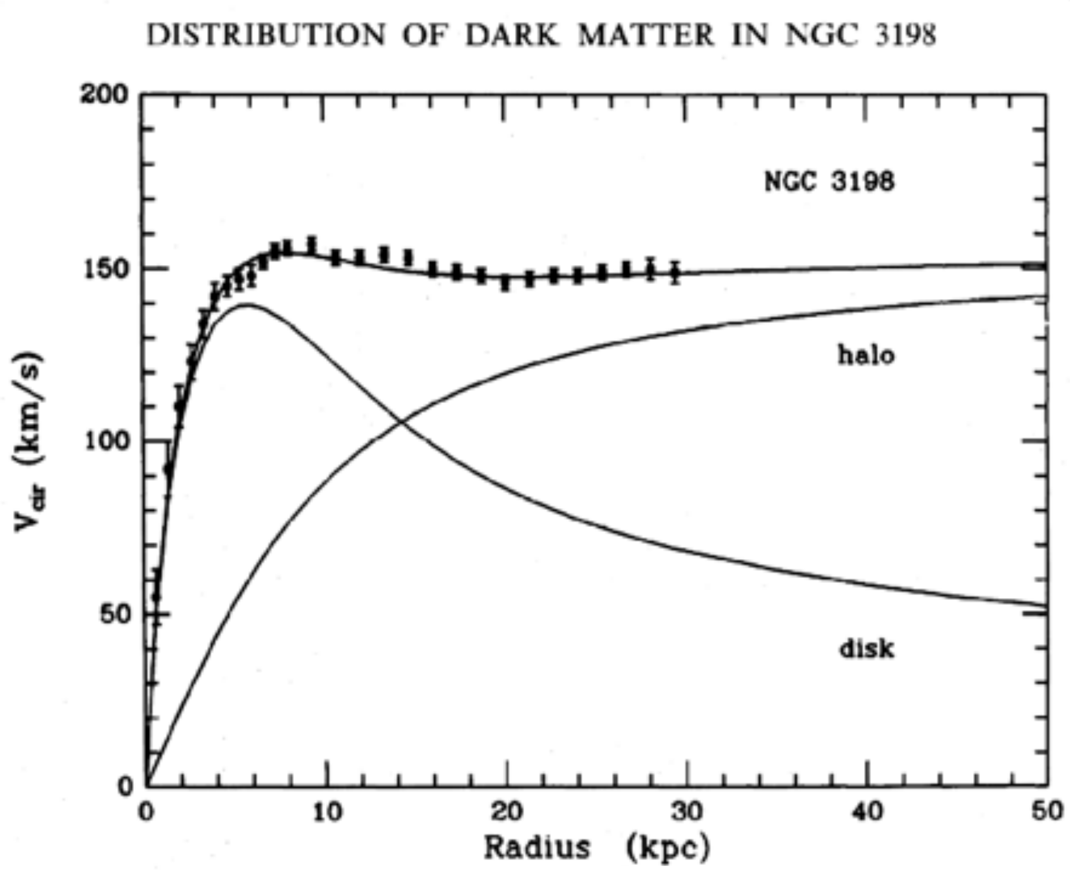
hep-ph 1505.XXXX

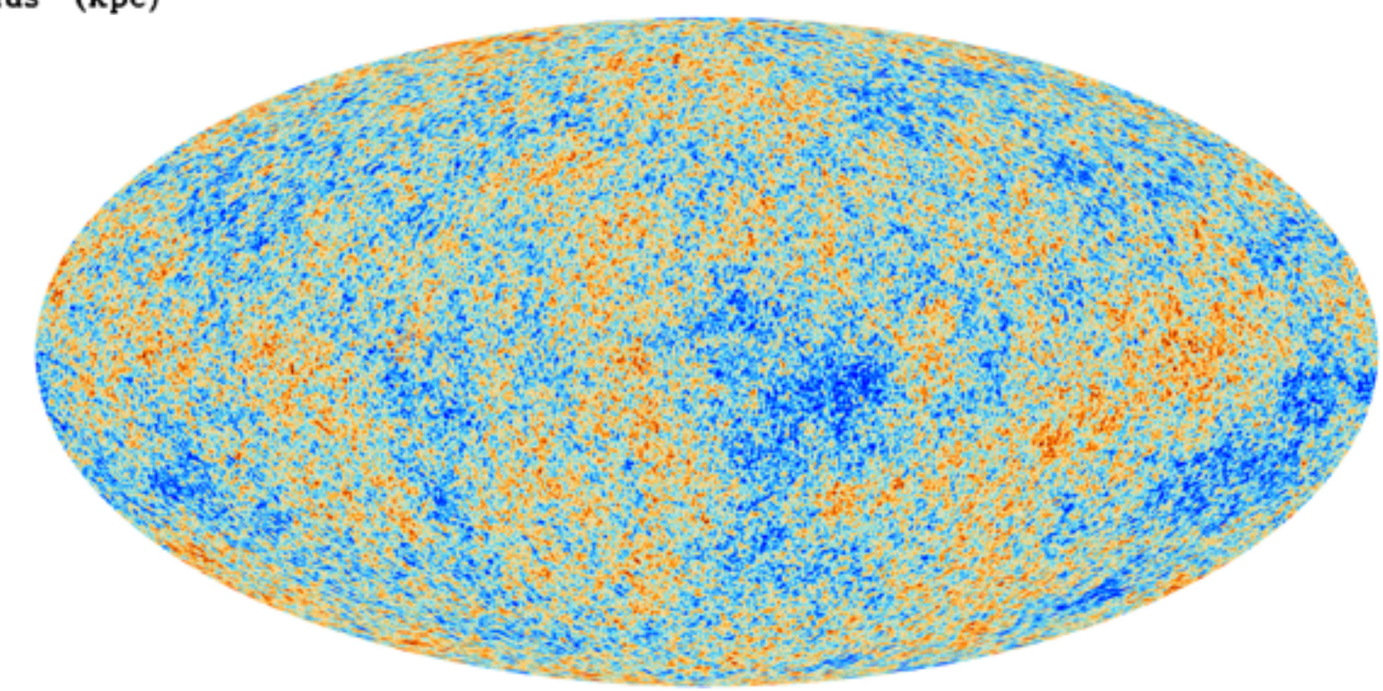
Manuel Buen-Abad

Gustavo Marques Tavares

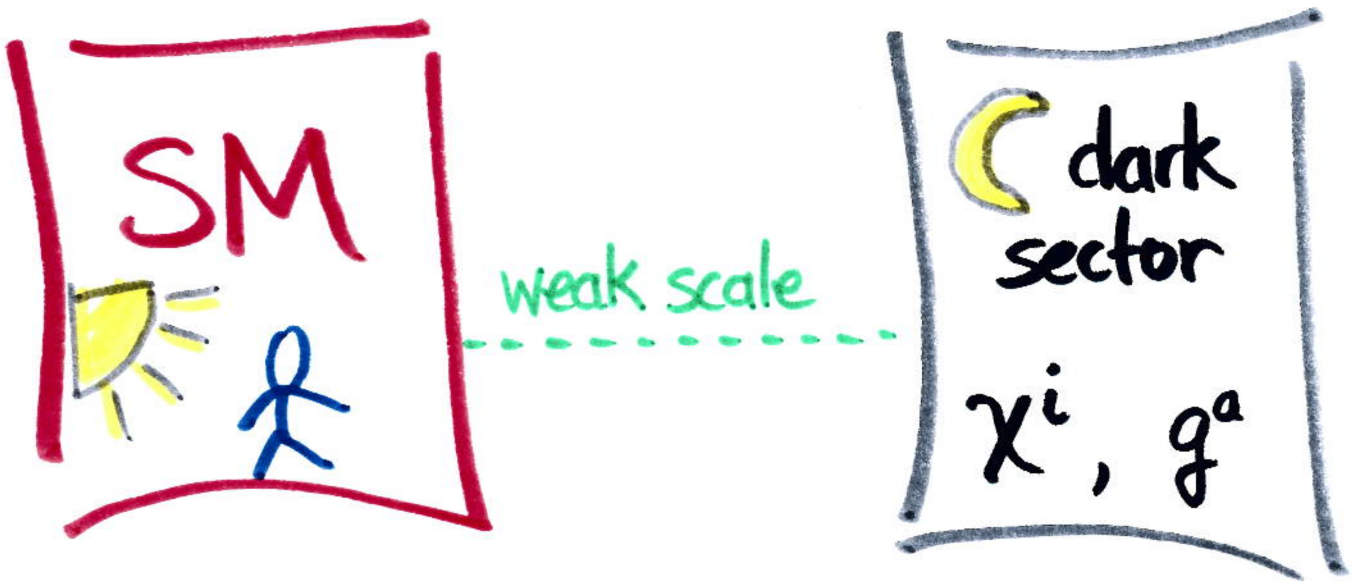
Martin Schmaltz

Dark matter evidence





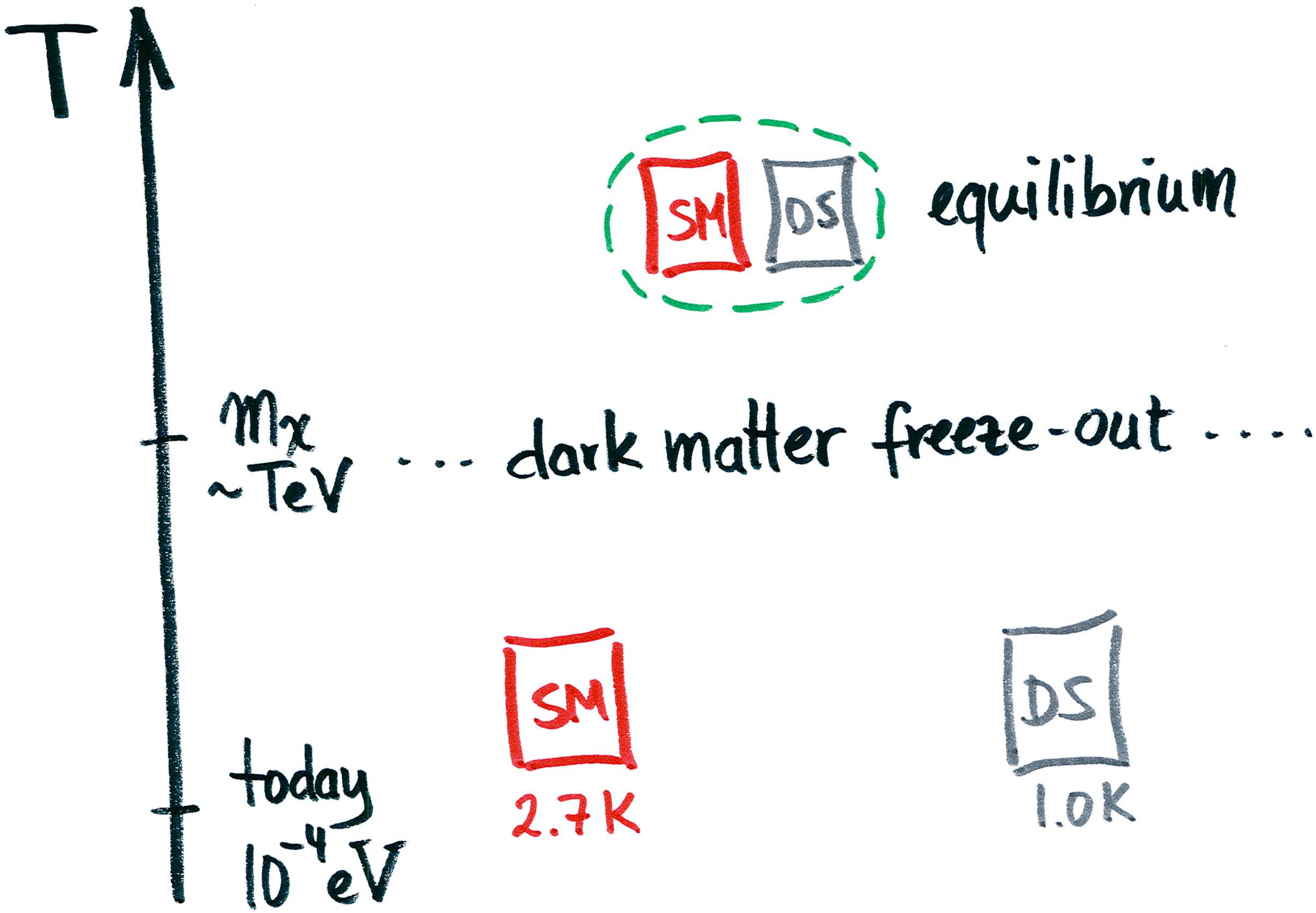
Non-Abelian dark sector



$SU(N)$: $i = 1 \ldots N$

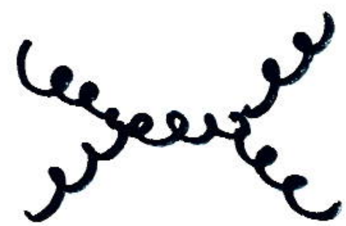
$a = 1 \ldots N^2 - 1$

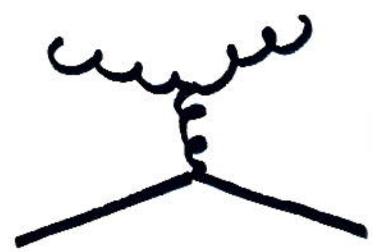
"A brief history of temperature"



What is different ?

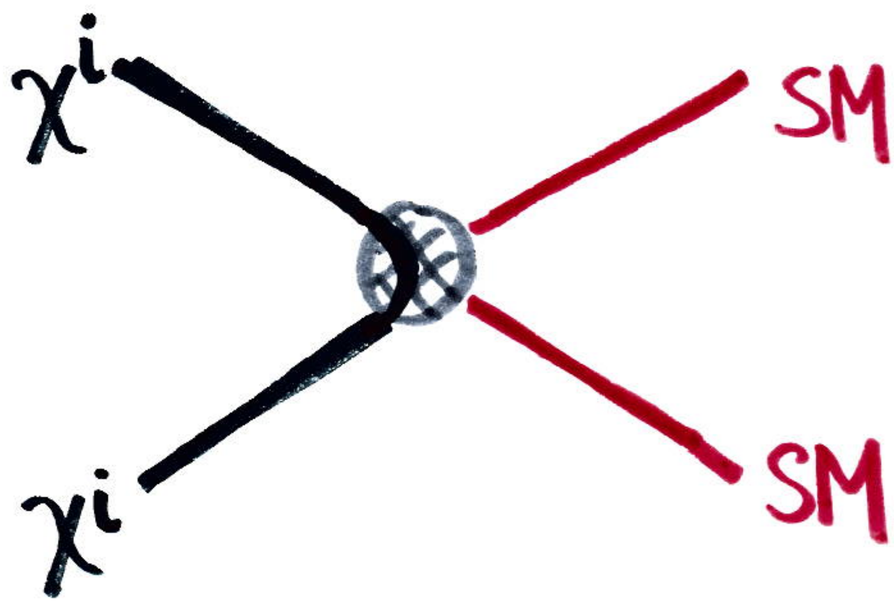
1. χ^i $\quad i=1\ldots N$ $\quad$ LHC, 100 TeV

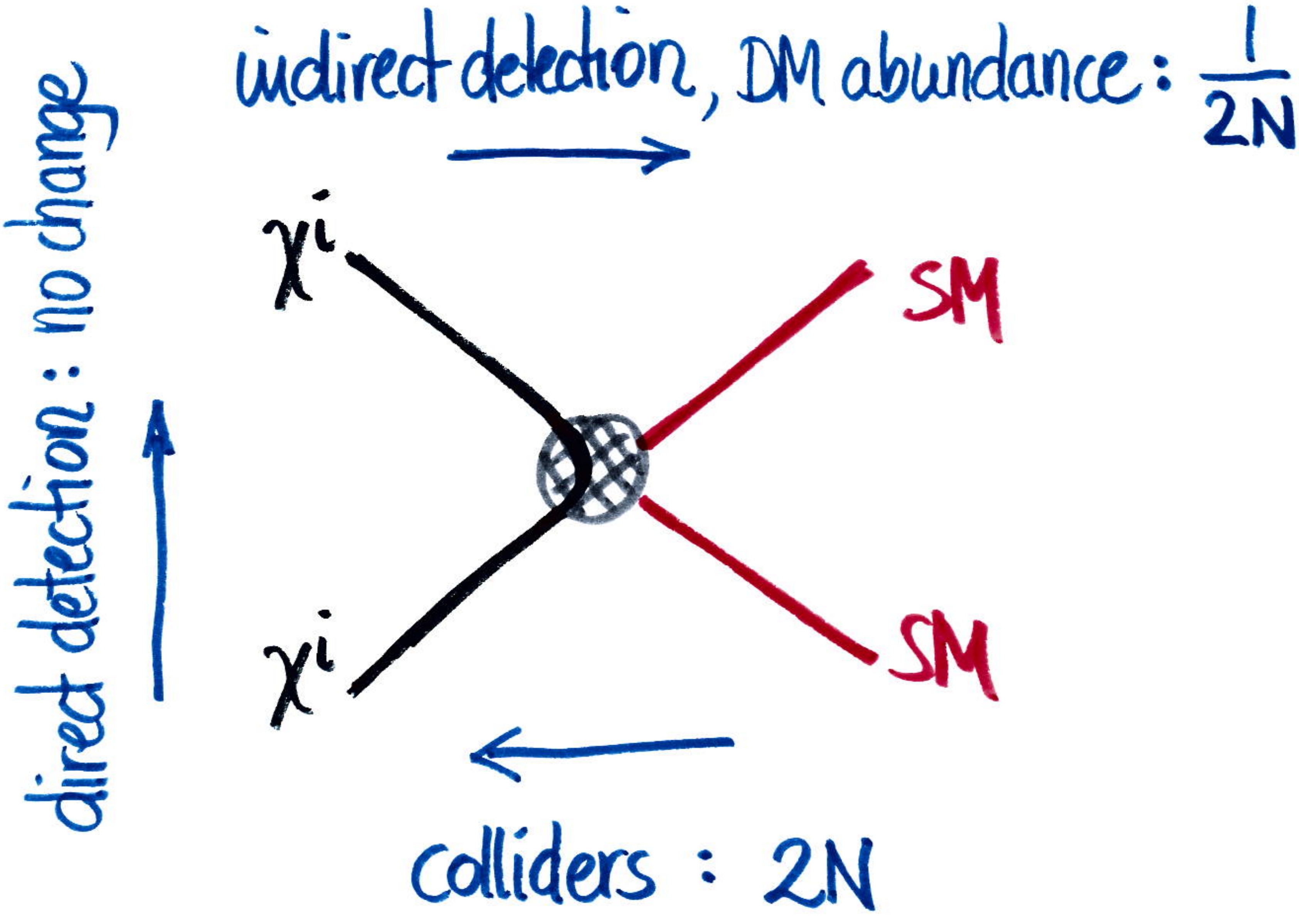
2. g^a dark radiation  $N<4$

3. DM couples to radiation  $\alpha_d < 10^{-8}$

1. dark matter multiplicity

same color!





indirect detection, DM abundance : $\frac{1}{2N}$
direct detection : no change
χ^i
χ^i
SM
SM
colliders : 2N

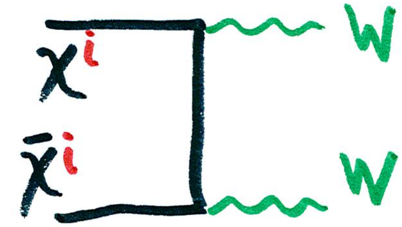
Example: multiple "winos"

$SU(2)_W$ triplet $\longrightarrow$ $\left.\begin{array}{l} \chi^{\pm i} \ \text{———} \\ \chi^{0 i} \ \text{———} \end{array}\right\}$ 160 MeV

~ TeV Dirac mass $\quad m \bar{\chi} \chi$

$\chi^{0 i}$ = dark matter

DM abundance

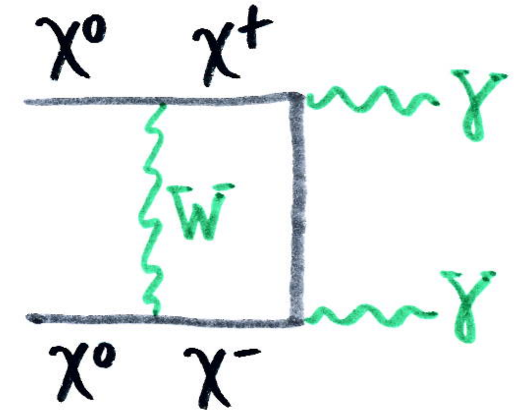


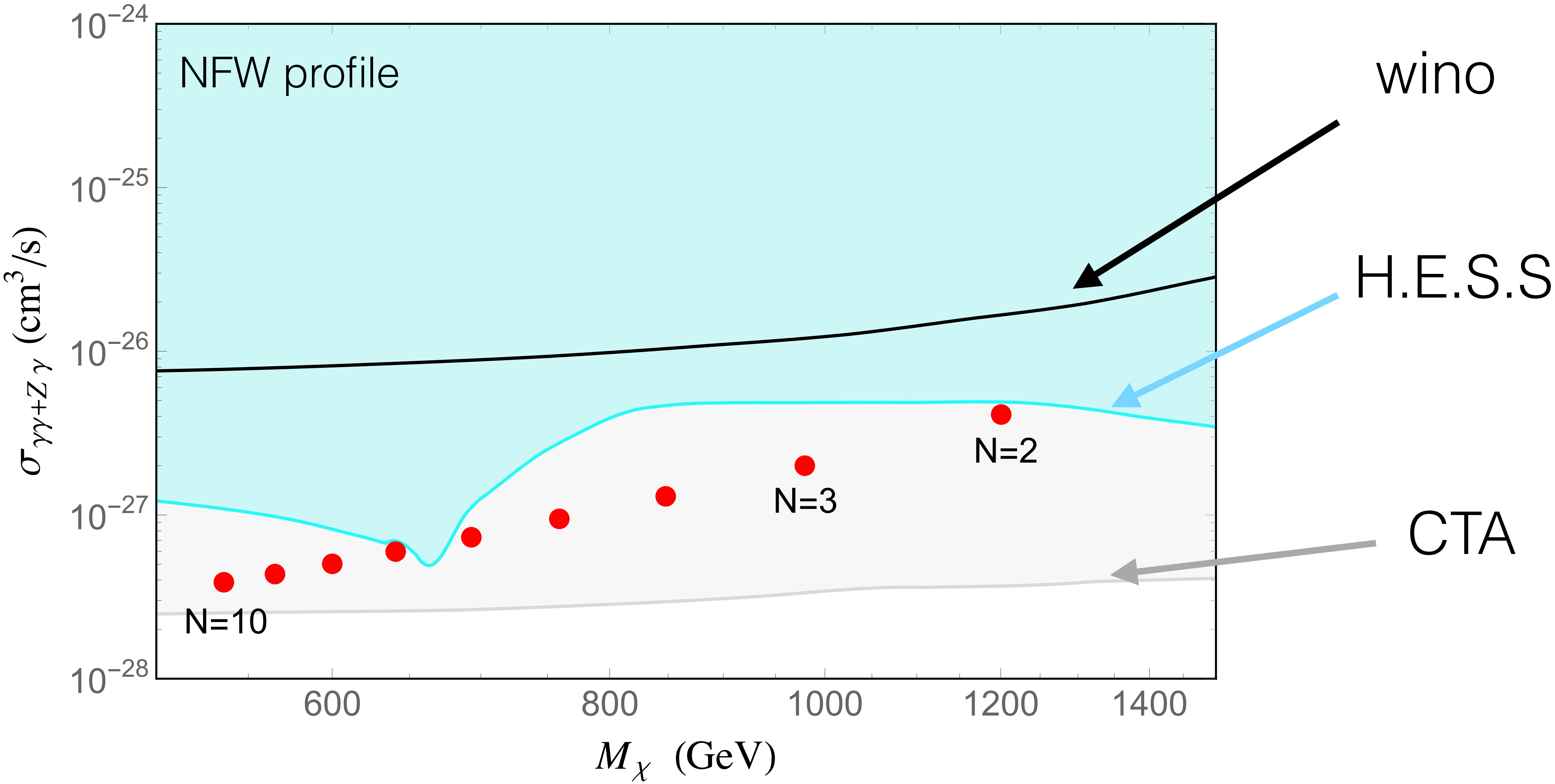
$$\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle} \qquad \langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_\chi^2} \frac{1}{2N}$$

$$\Rightarrow \quad M_\chi = M_{wino} / \sqrt{2N}$$

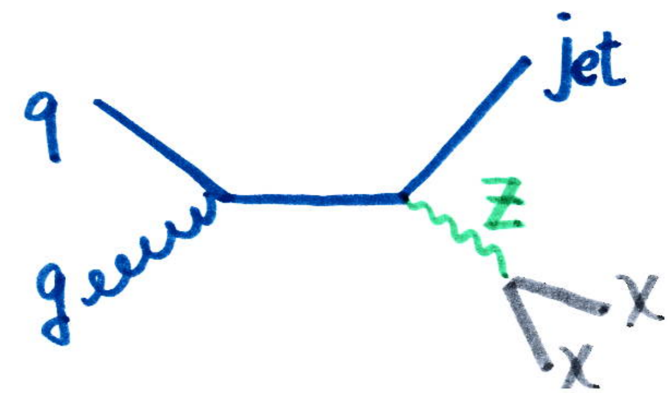
$N =$	1	2	3	4	...
M_χ [TeV]	2.4*	1.2	1.0	0.9	

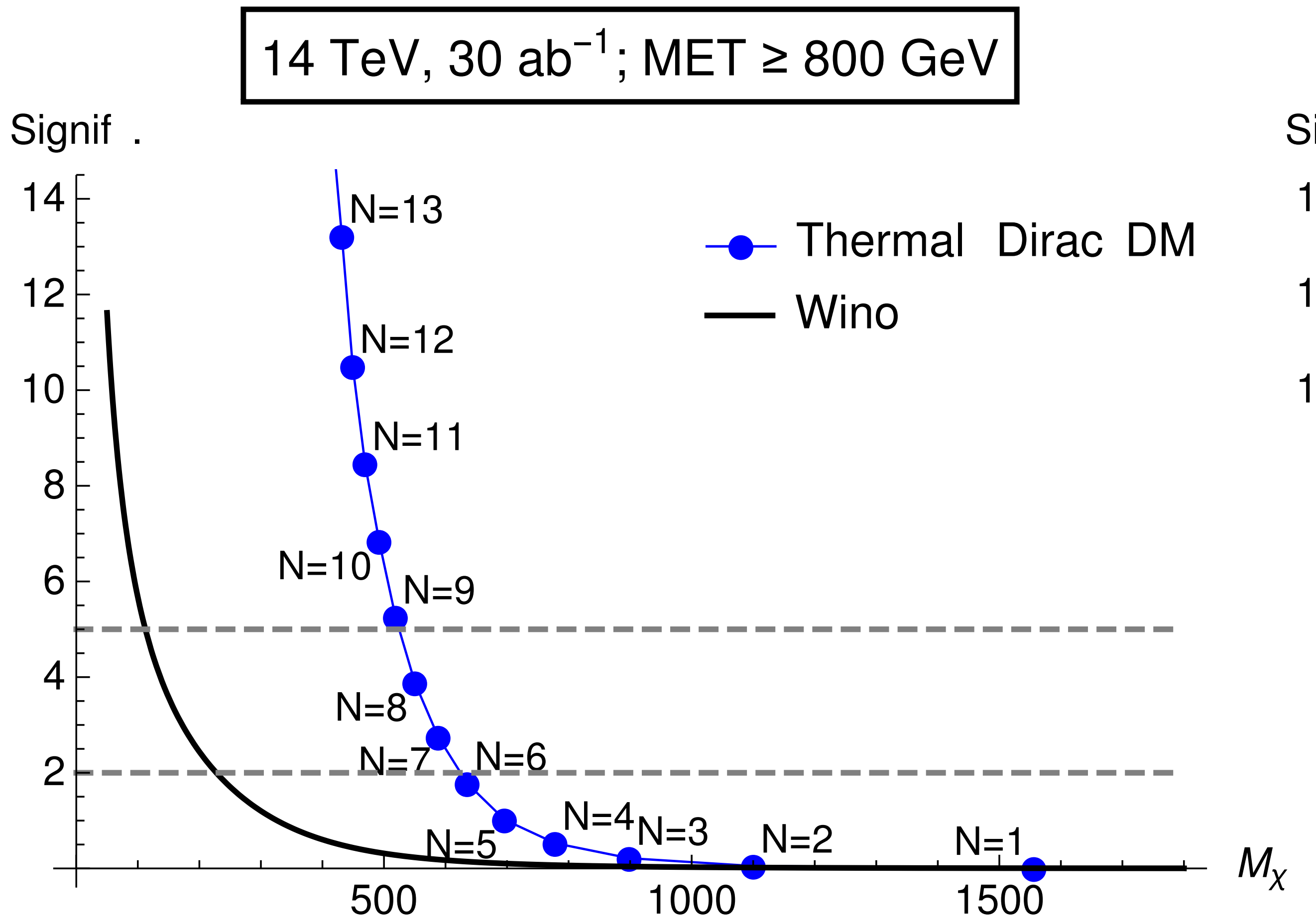
Indirect detection

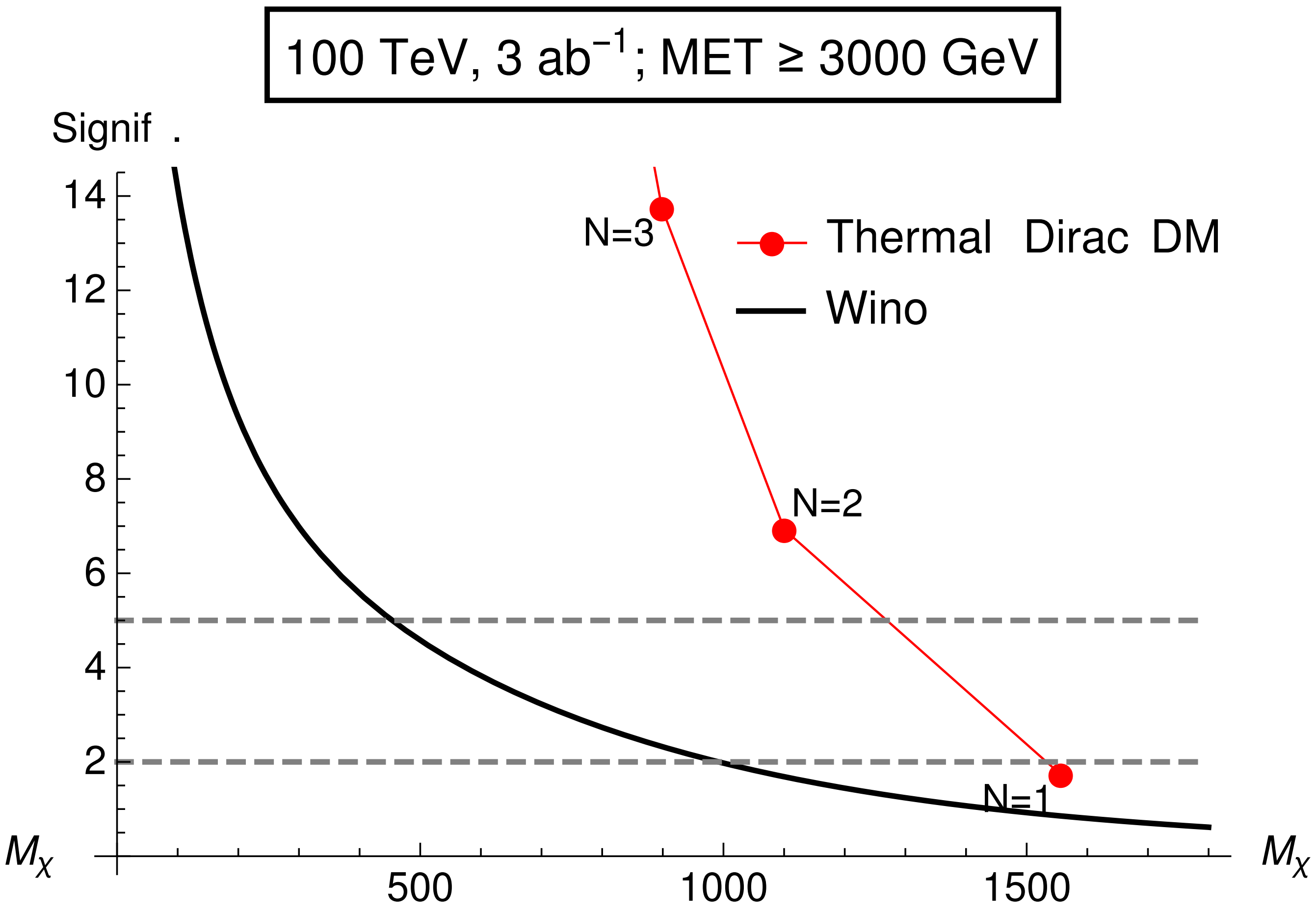




Colliders: mono-jets



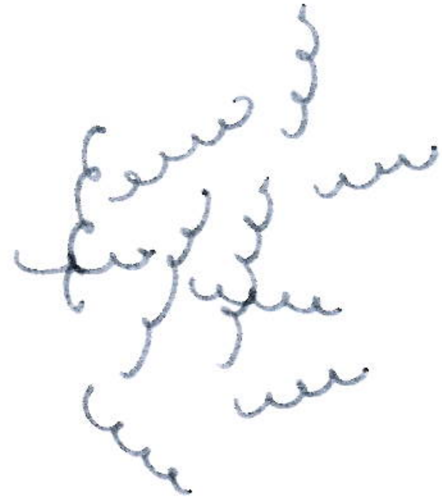




HL-LHC

100 TeV

2. dark gluons



no confinement $\Rightarrow \Lambda_d \ll 10^{-4}\,\mathrm{eV}$

$$\left(\mu/\Lambda\right)^{2b_0} = e^{1/\alpha_d}$$

$$\Rightarrow \alpha_d \lesssim 10^{-2}$$

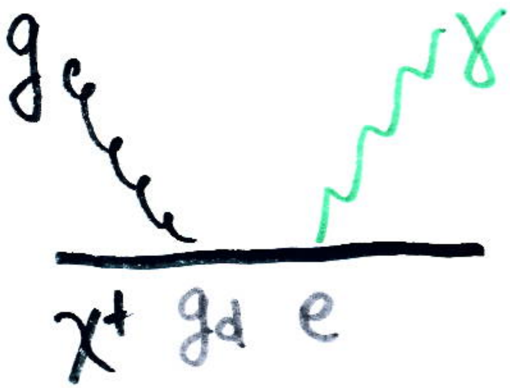
Cosmology for model builders

to decide if a process is important compare

$$\Gamma_{\text{process}} \quad \text{vs.} \quad H_{\text{ubble}}$$

$$n\langle \sigma v \rangle \qquad\qquad \frac{T^2}{M_{pl}}$$

Are dark gluons in thermal equil.?

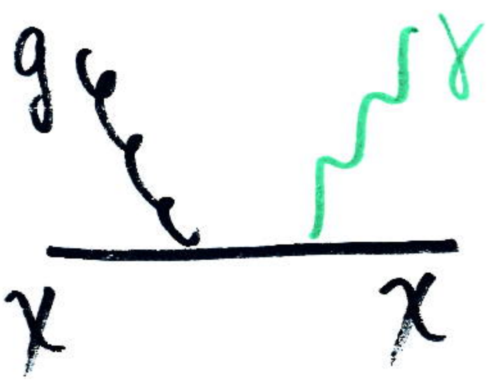


$$\Gamma \sim n_\chi \langle \sigma v \rangle \sim \frac{T^2}{M_{pl}}$$

$$\sim T^{\cancel{3}} \frac{\alpha_d \alpha_{em}}{\cancel{T^2}}$$

$\Longrightarrow$ Yes, if $\quad \alpha_d > \frac{1}{\alpha_{em}} \frac{T}{M_{pl}} \sim 10^{-13}$

gluons in equilibrium at 10 GeV ?



$$\Gamma \sim \overset{\sim e^{-T/M_\chi}}{n_\chi} \langle \sigma v \rangle \sim \frac{T^2}{M_{pl}}$$

$$\sim 10^{-11}\, T^3 \, \frac{\alpha_d \, \alpha_{em}}{M_\chi^2}$$

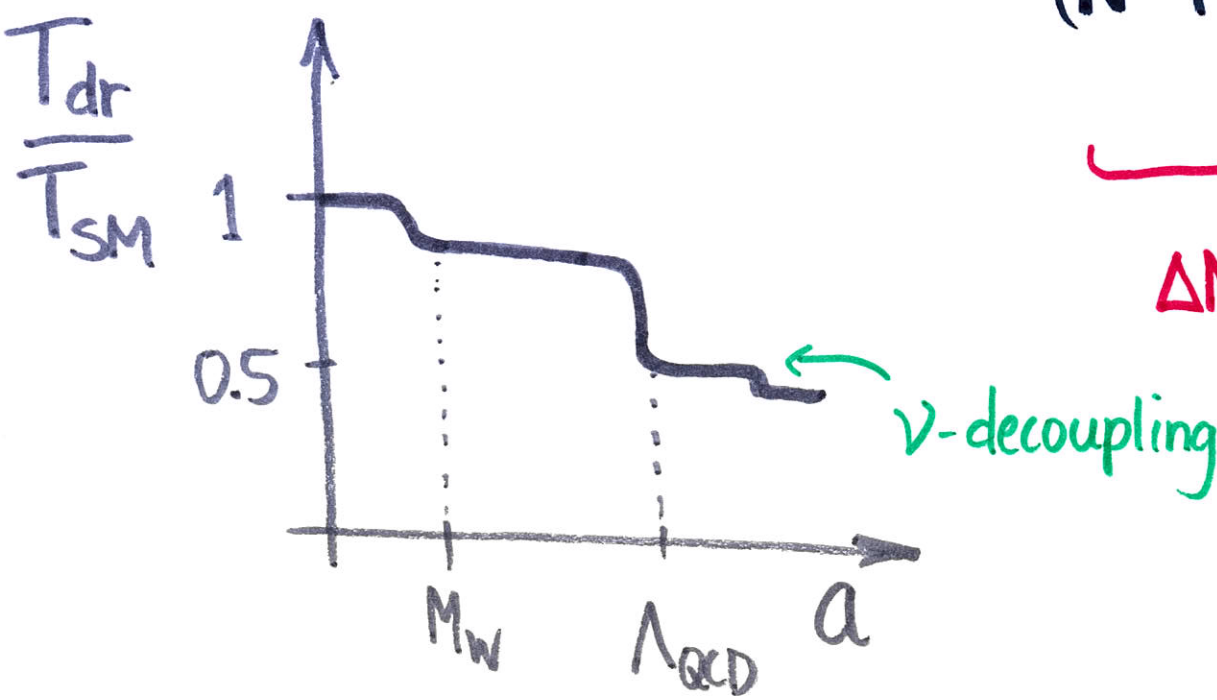
$\Rightarrow$ ~~Yes~~ No, if $\alpha_d > \dfrac{10^{11}}{\alpha_{em}} \dfrac{M_\chi^2}{T M_{pl}} \approx 1$

after dark radiation decoupling

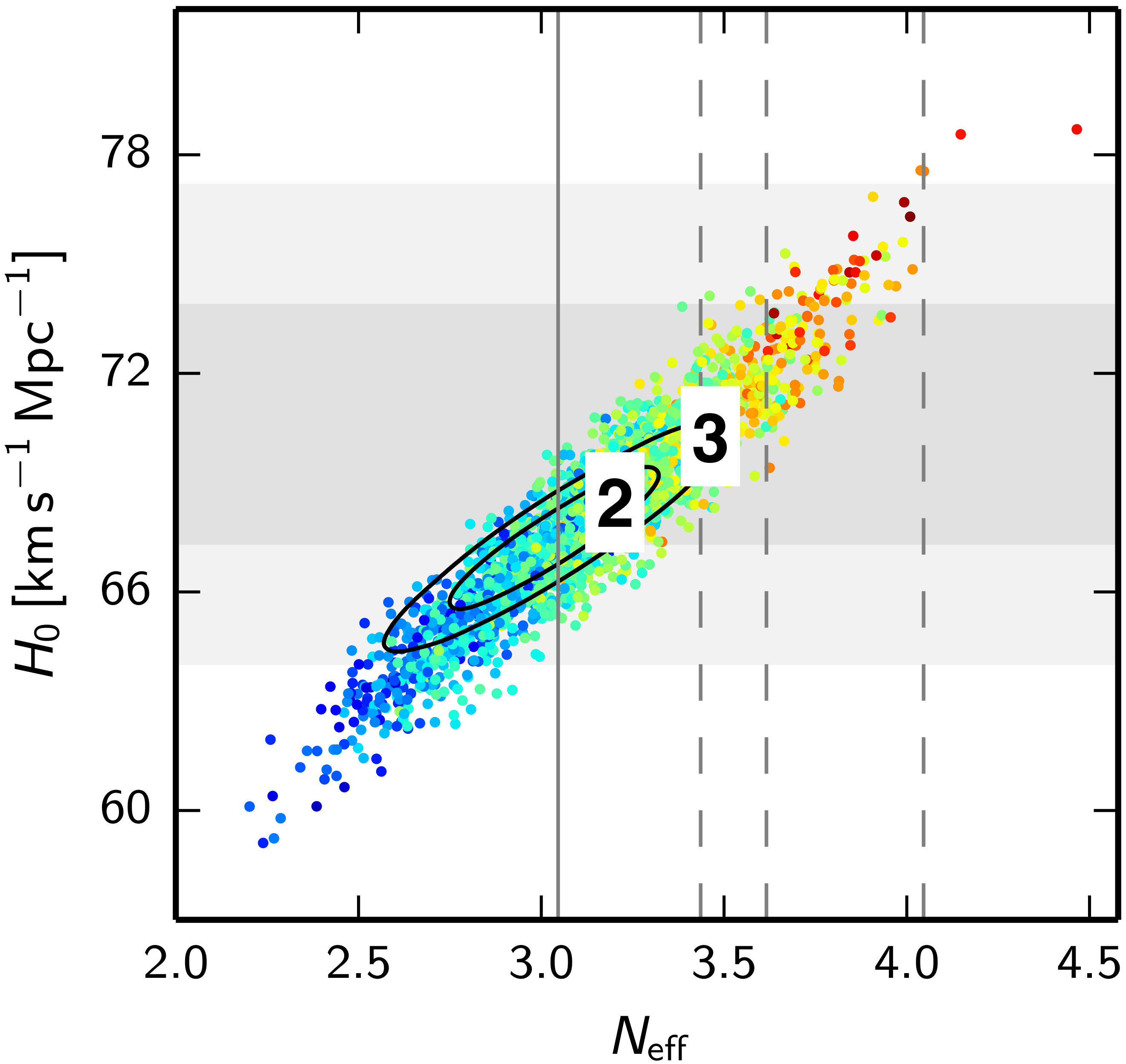
energy density?

$$\rho_{dr} \sim (N^2-1)\cdot 2 \cdot T_{dr}^4$$

$$= \underbrace{(N^2-1)\left(\frac{T_{dr}}{T_\nu}\right)^4}_{\Delta N_{eff} \approx \frac{N^2-1}{16}} 2\, T_\nu^4$$



CMB and N_{eff}



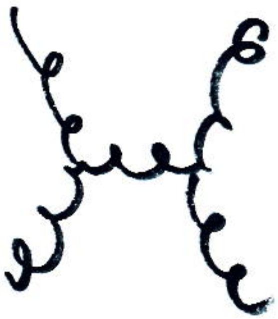
$N_{eff} = 3.13 \pm 0.32$ *Planck* TT+lowP

Planck Collaboration; arXiv:1502.01589

$\Delta N_{eff} < 0.5$ @ 95%

=> $N_{colors} = 2,3$

dark gluons are a perfect fluid



$$\Gamma \sim \alpha_d^2 T \quad \text{vs.} \quad \frac{T^2}{M_{pl}} \sim 10^{-27}\, T \quad (T = eV)$$

$\Longrightarrow$ no viscosity, anisotropic stress (ν, γ)

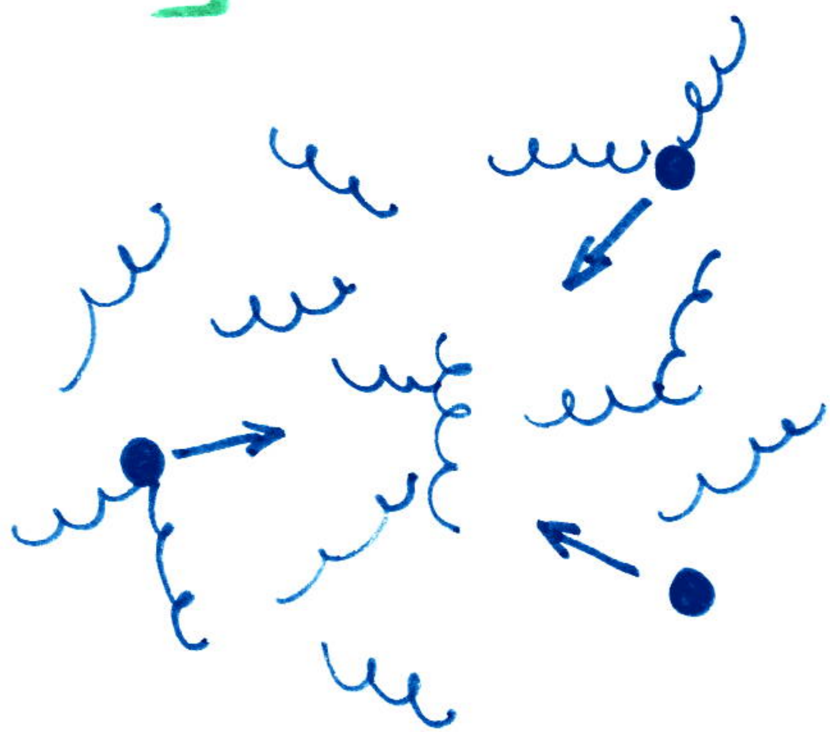
not free streaming

CMB will tell!

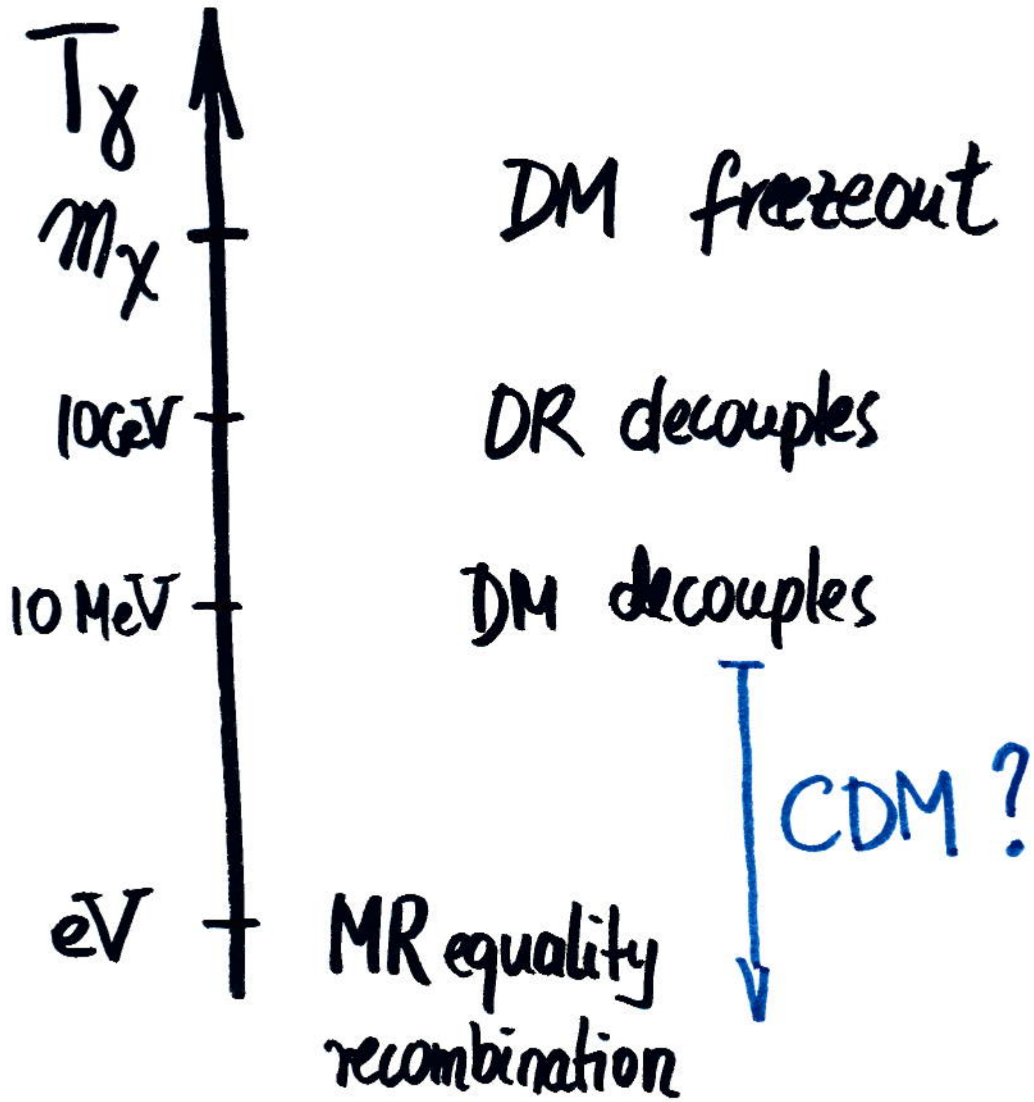
2. dark radiation summary

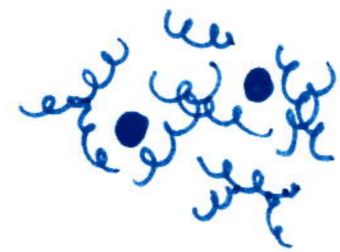
- perfect fluid for $10^{-13} < \alpha_d < 10^{-2}$, $T \sim 1K$
- $\Delta N_{eff} < 0.5 \implies N = 2, 3$
- Planck can distinguish $\begin{cases} \text{perfect} \\ \text{free-streaming} \end{cases}$

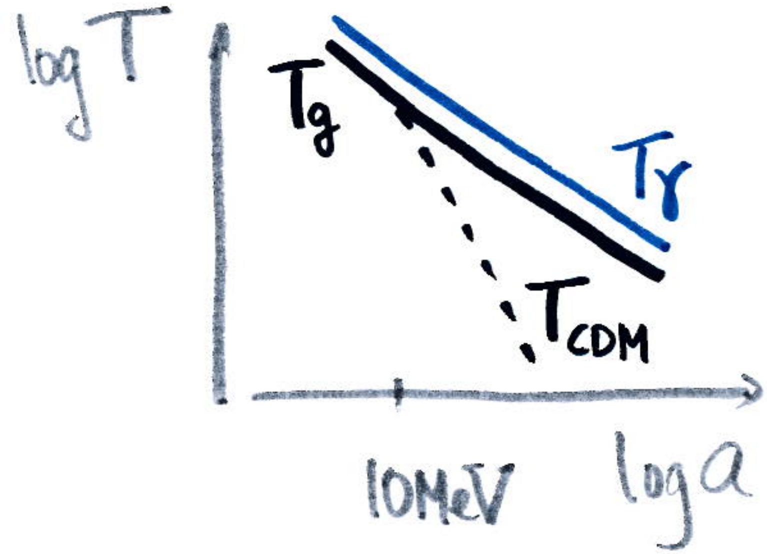
3. DM-DR interactions and large scale structure



a brief history of dark time

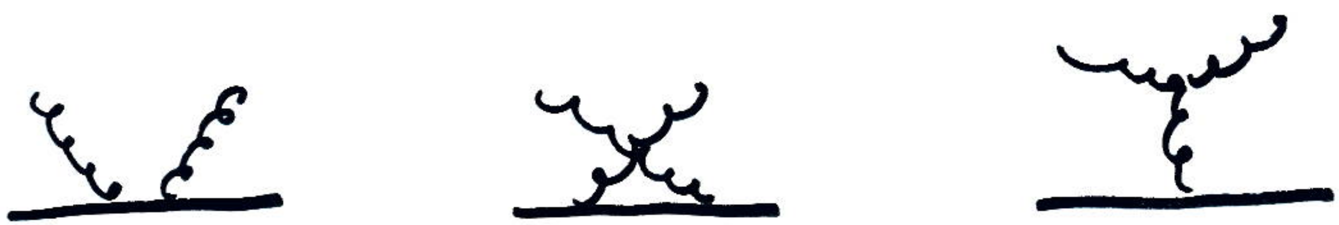




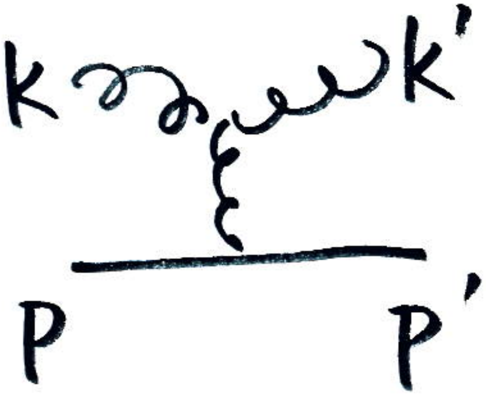


are DM & DR coupled ?

$$\underset{n\sigma v}{\Gamma} \sim H$$



DM DR coupling



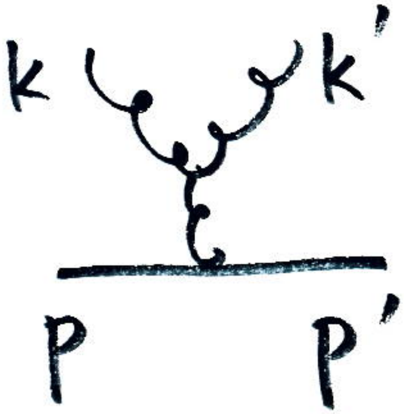
$$\langle \sigma v \rangle \approx$$

$$\int d^3k \int d^3p' \int d^3k' \, \delta^4(\Sigma p) \, \frac{1}{(k-k')^4} \, f(k,T)$$

$$= \infty$$

forward scatters
soft scatters

Energy transfer rate

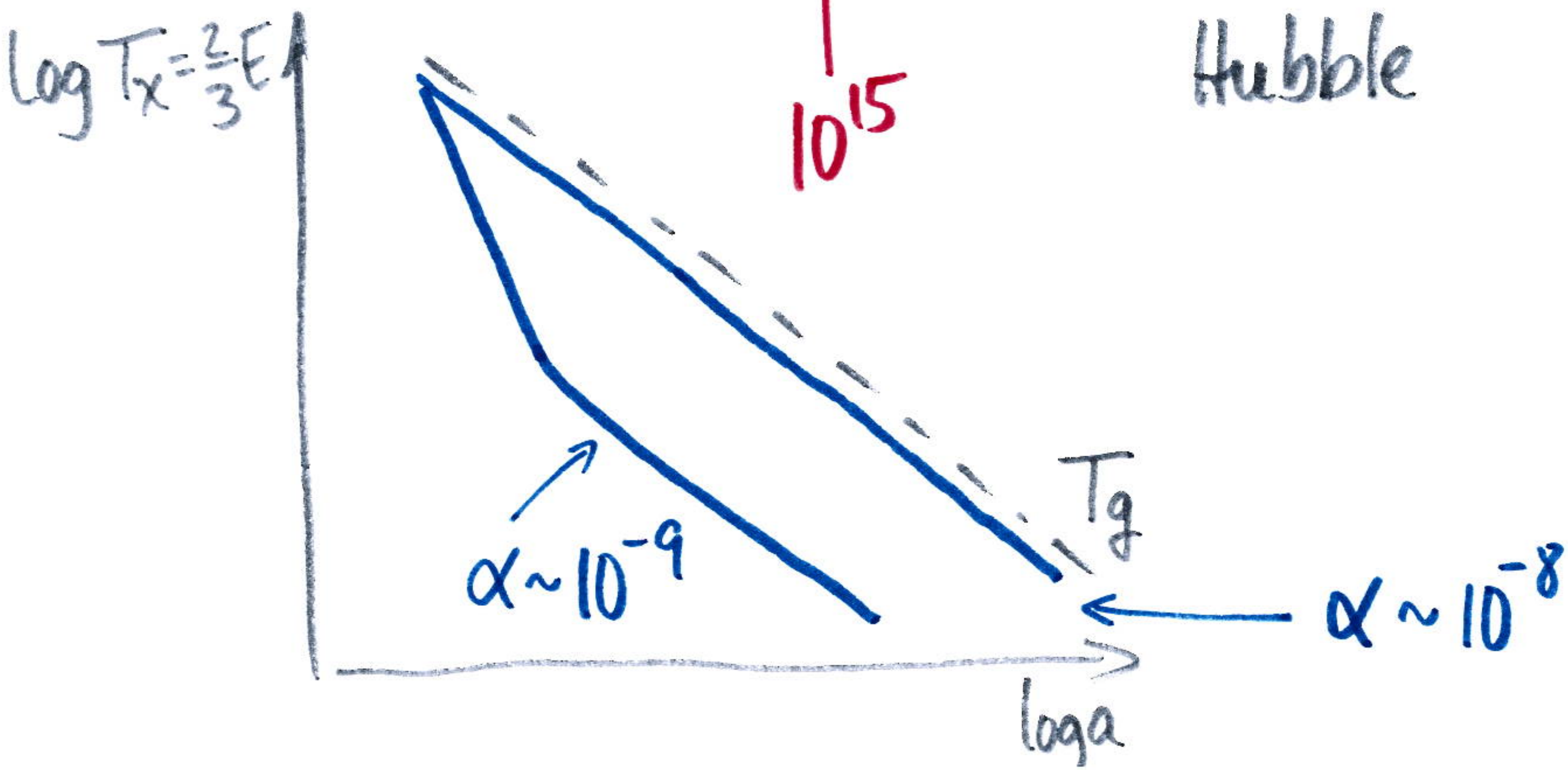


$$\Gamma_E \sim \frac{\dot{E}}{E} \sim \frac{\left\langle \sigma v \left(\frac{\vec{p}'^2}{2M} - \frac{\vec{p}^2}{2M} \right) \right\rangle}{E}$$

$$\sim \alpha_d^2 \log \frac{T^2}{\underbrace{\alpha}_{\text{Debye}} T^2} \, \frac{T^2}{M_X} \, \frac{T}{T_X}$$

Energy transfer rate & Hubble

$$\Gamma_E = \alpha^2 \log\frac{1}{\alpha}\, \underbrace{\frac{M_{pl}}{M_X}}_{10^{15}} \frac{T}{T_X} \underbrace{\frac{T^2}{M_{pl}}}_{\text{Hubble}}$$



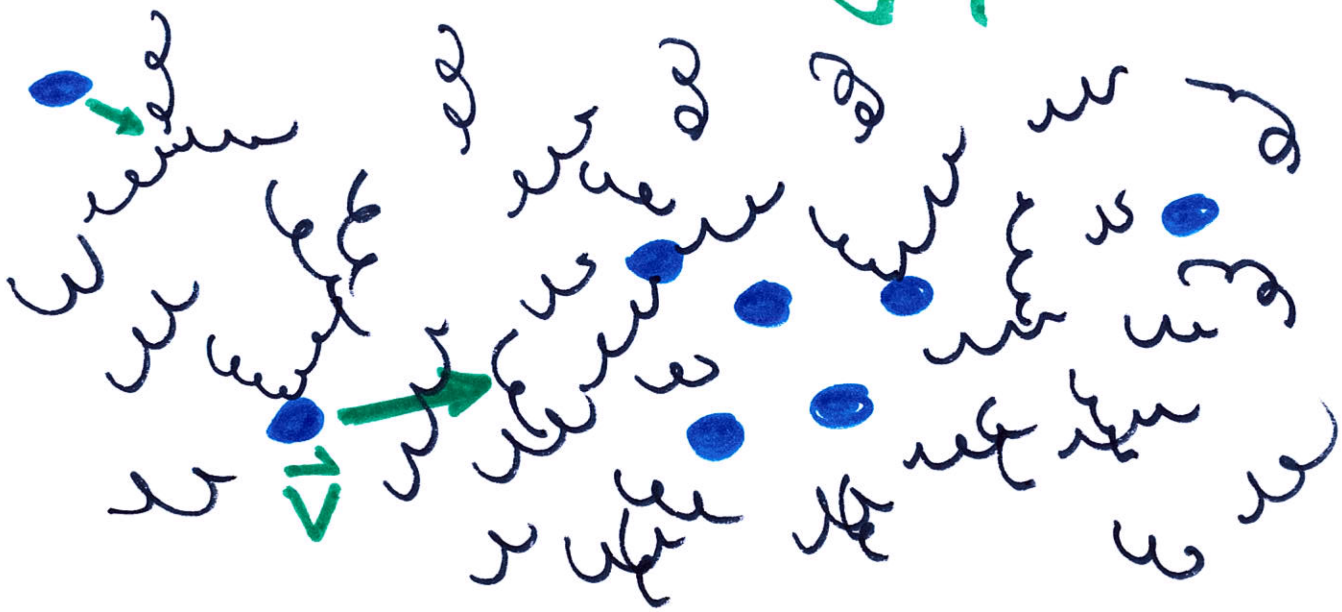
DM does not cool like

non-relativistic matter ~~CDM~~

$T_\chi \sim \epsilon T_g$ but $v_\chi \sim \sqrt{\frac{T_\chi}{M_\chi}} \ll 1.$

does this generate
an interesting signature
in large scale structure ?

growth of DM density perturbations



$$\Gamma_v \equiv \frac{\dot{v}}{v} \sim \alpha_d^2 \log\frac{1}{\alpha_d} \, \frac{T_g^2}{M_X}$$ friction

linear perturbations

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

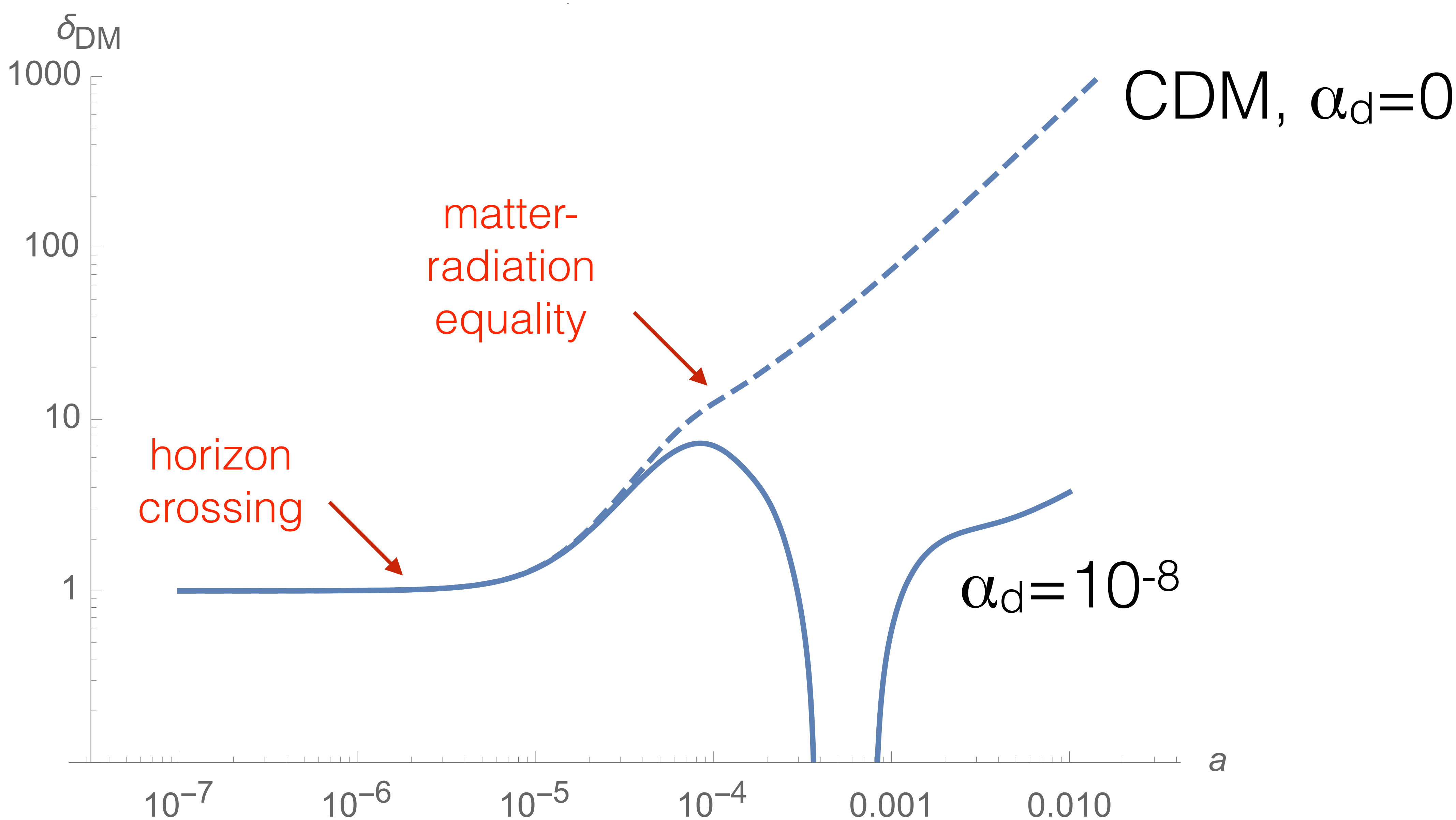
$$\dot{\theta}_{DM} = -\frac{\dot{a}}{a}\theta_{DM} + a\mathbf{\Gamma}_V(\theta_{DR} - \theta_{DM}) + k^2\psi$$

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

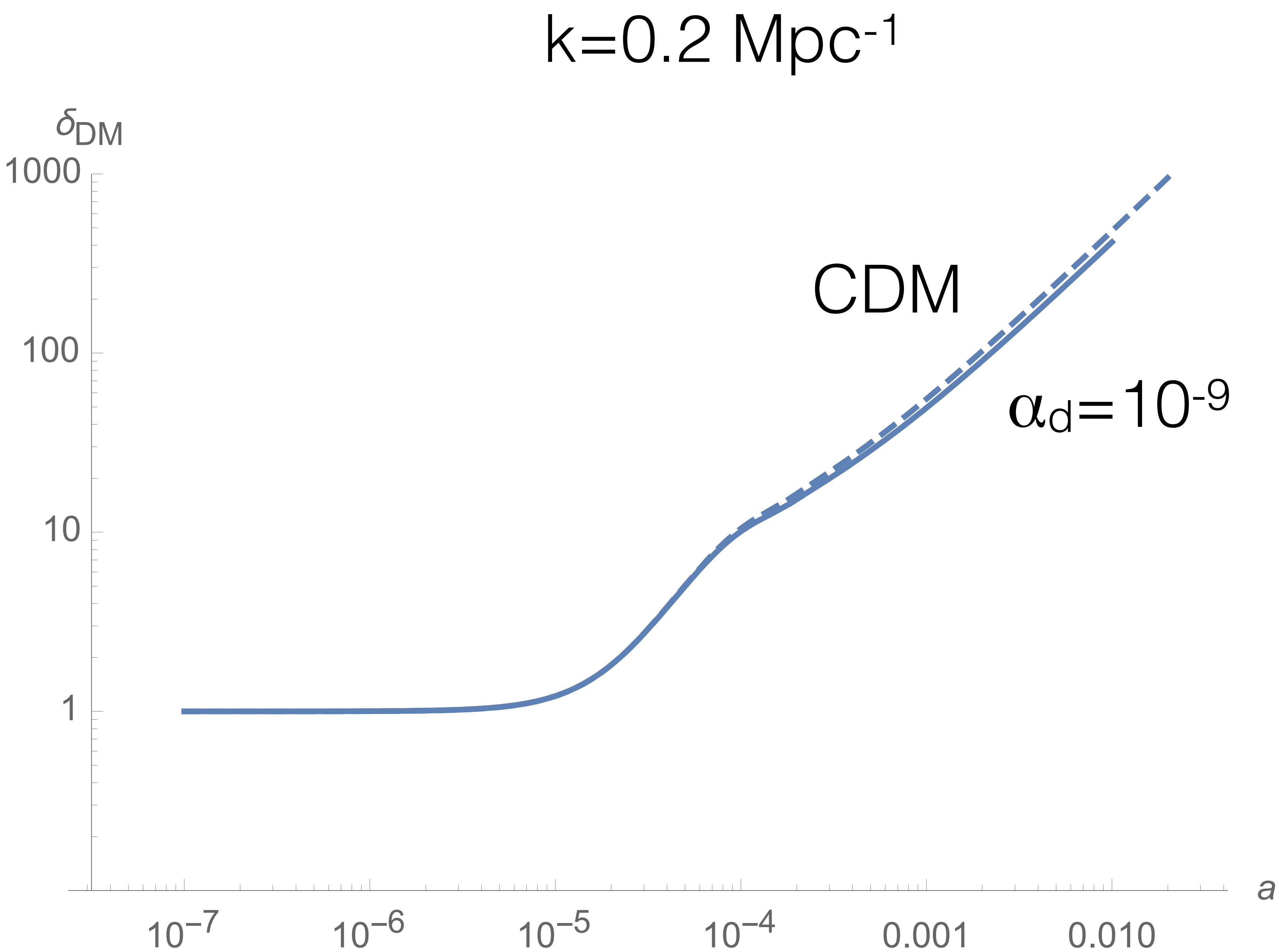
$$\dot{\theta}_{DR} = k^2\frac{\delta_{DR}}{4} + k^2\psi + \frac{3}{4}\frac{\rho_{DM}}{\rho_{DR}}a\mathbf{\Gamma}_V(\theta_{DM} - \theta_{DR})$$

growth of perturbations

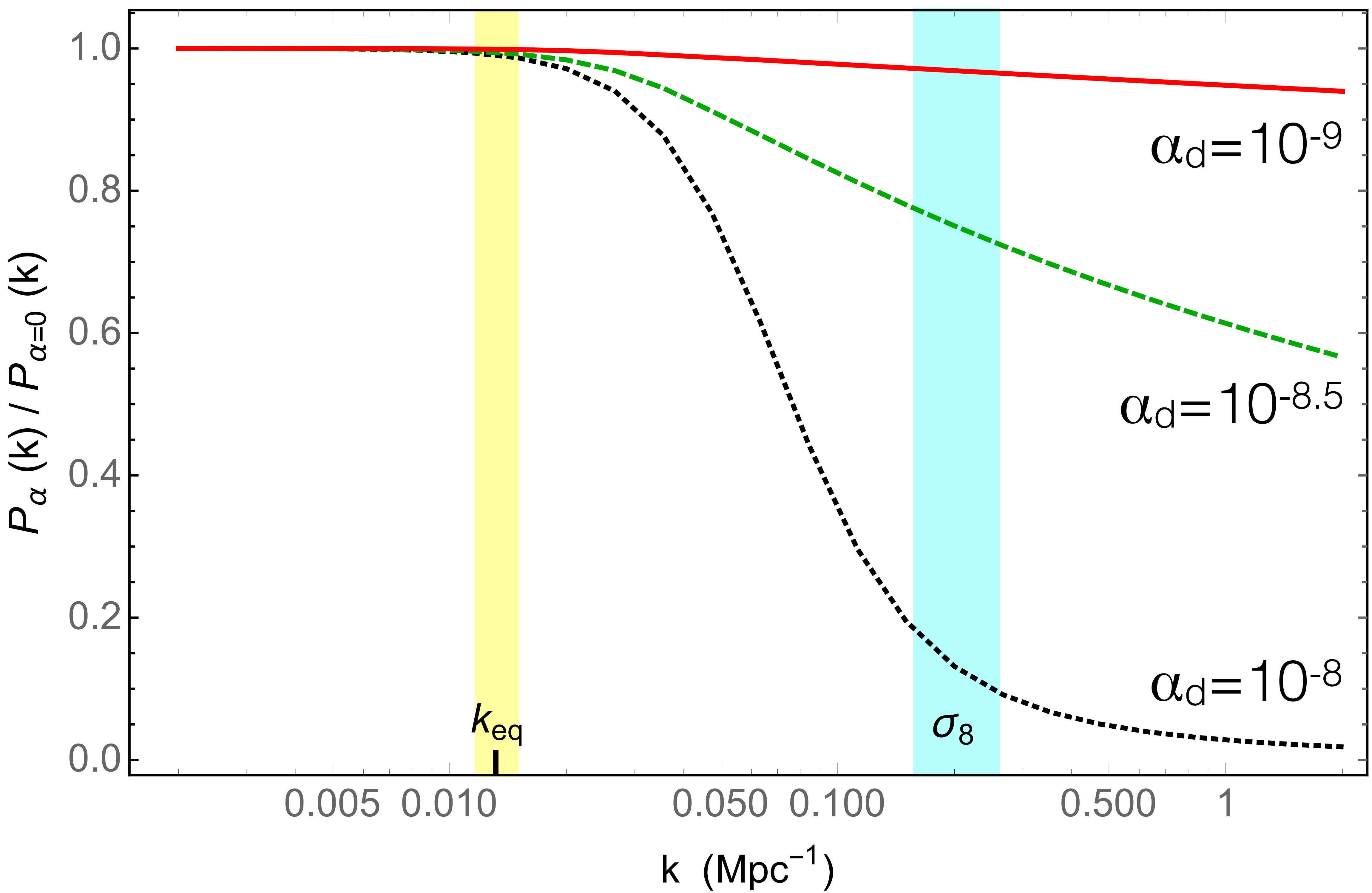
$k = 0.2\ \mathrm{Mpc}^{-1}$



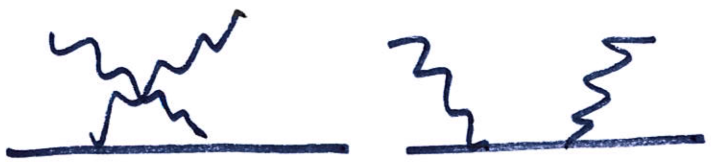
growth of perturbations



power spectrum change

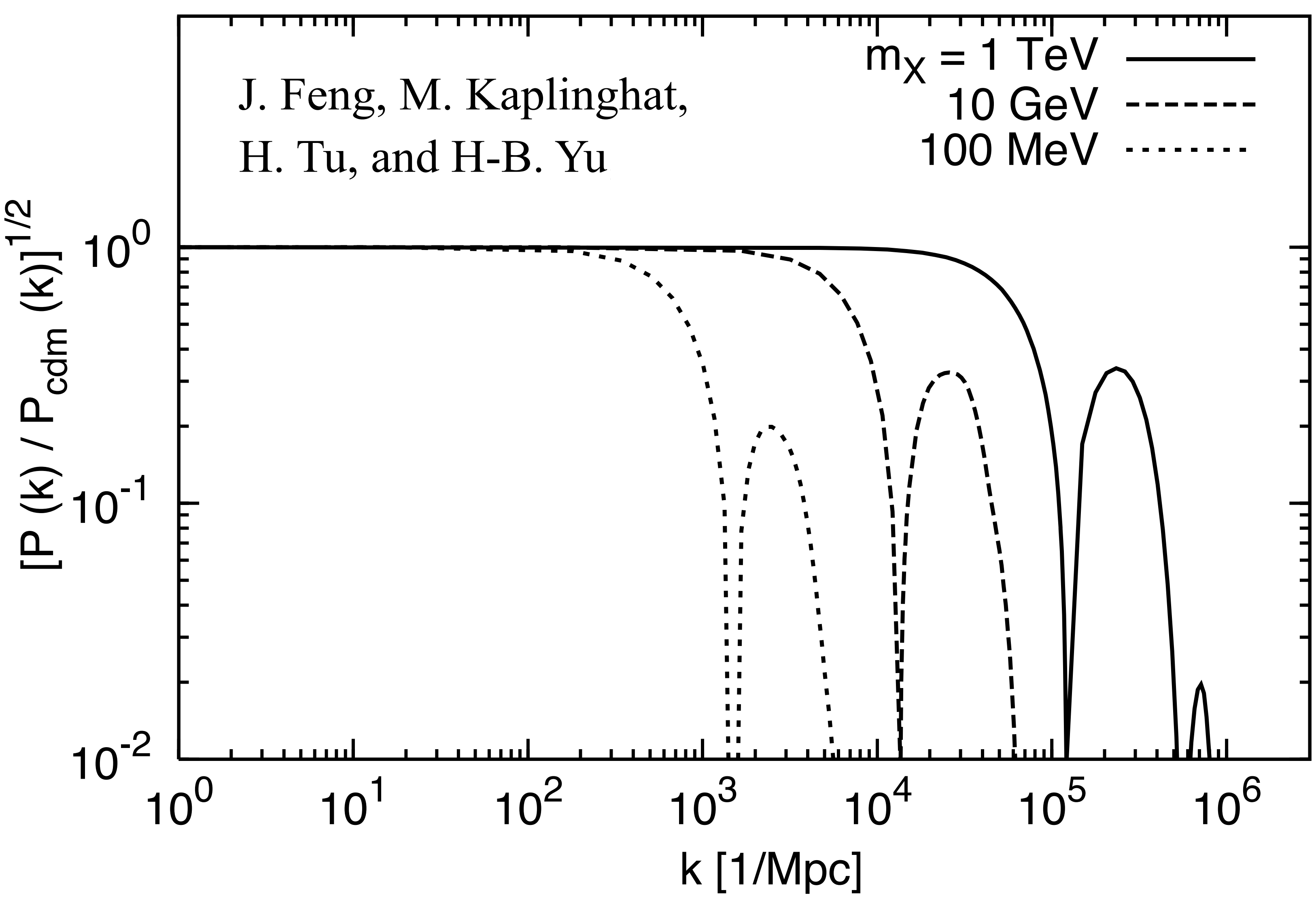


dark U(1) - compton scattering

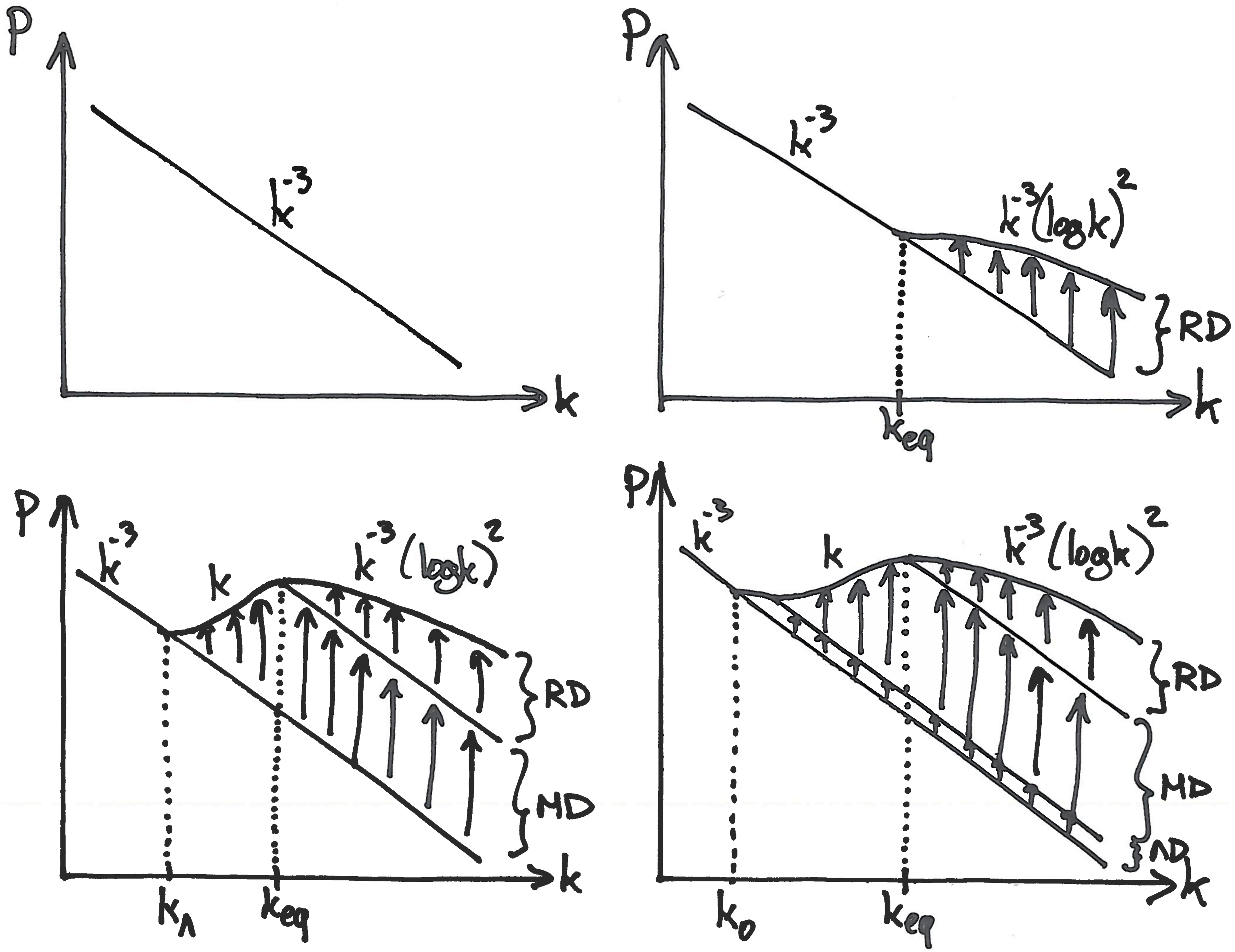


$$\Gamma_V \sim \alpha_d^2 \frac{T_d^4}{M_\chi^3}$$

$$H \sim \frac{T^2}{M_{pl}}$$



ΛCDM growth of perturbations



Julien Lesgourgues, TASI 2012

tension in the data ?

σ_8

Planck CMB: 0.831 ± 0.013

Planck lensing: 0.802 ± 0.012

LSS combine: 0.795 ± 0.009

(Battye, Charnock, Moss 1409.2769)

$H_0 \; \left[\frac{\text{km}}{\text{s Mpc}}\right]$

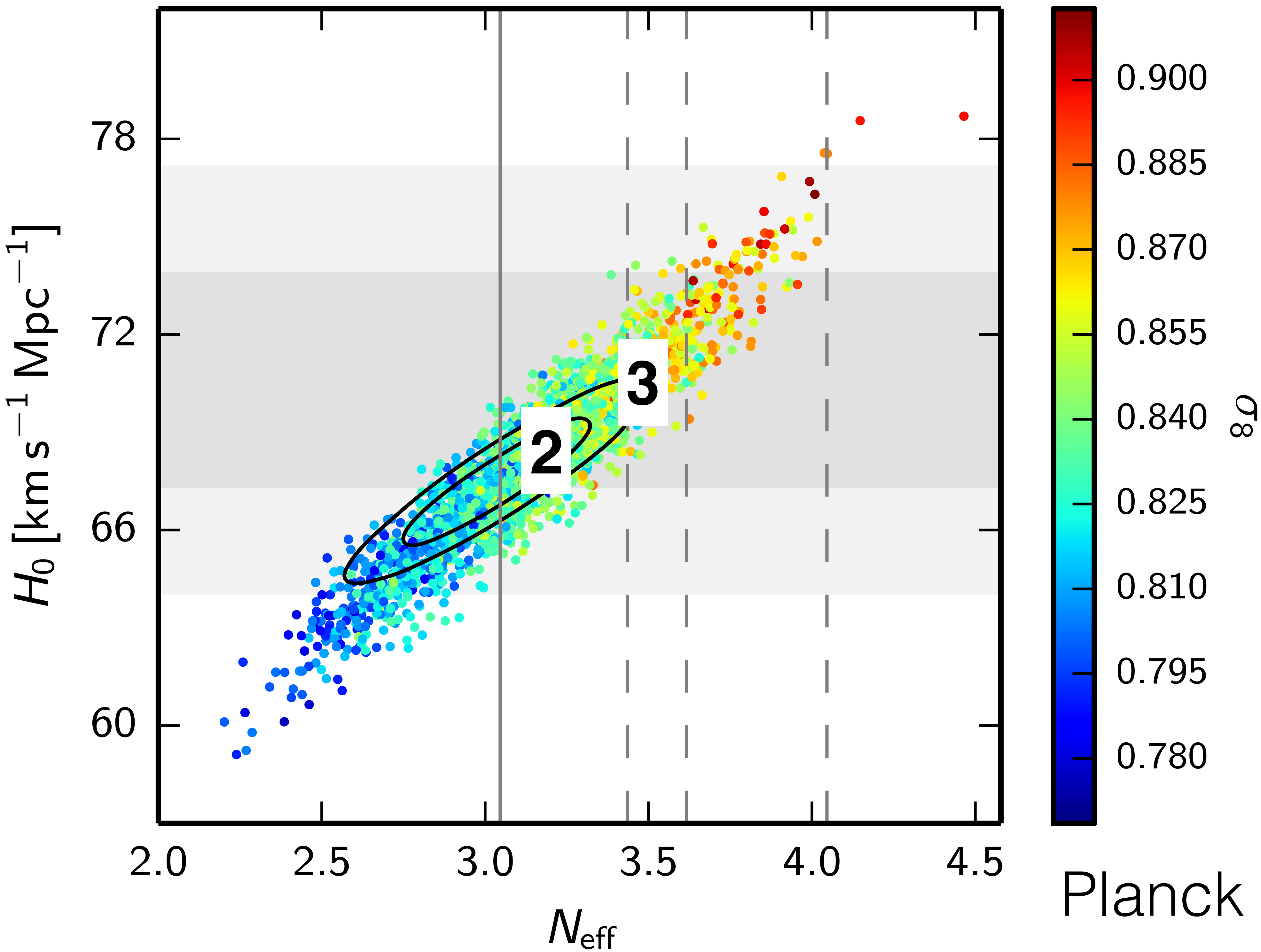
67.6 ± 0.6 Planck CMB

73.0 ± 2.4 SN1a

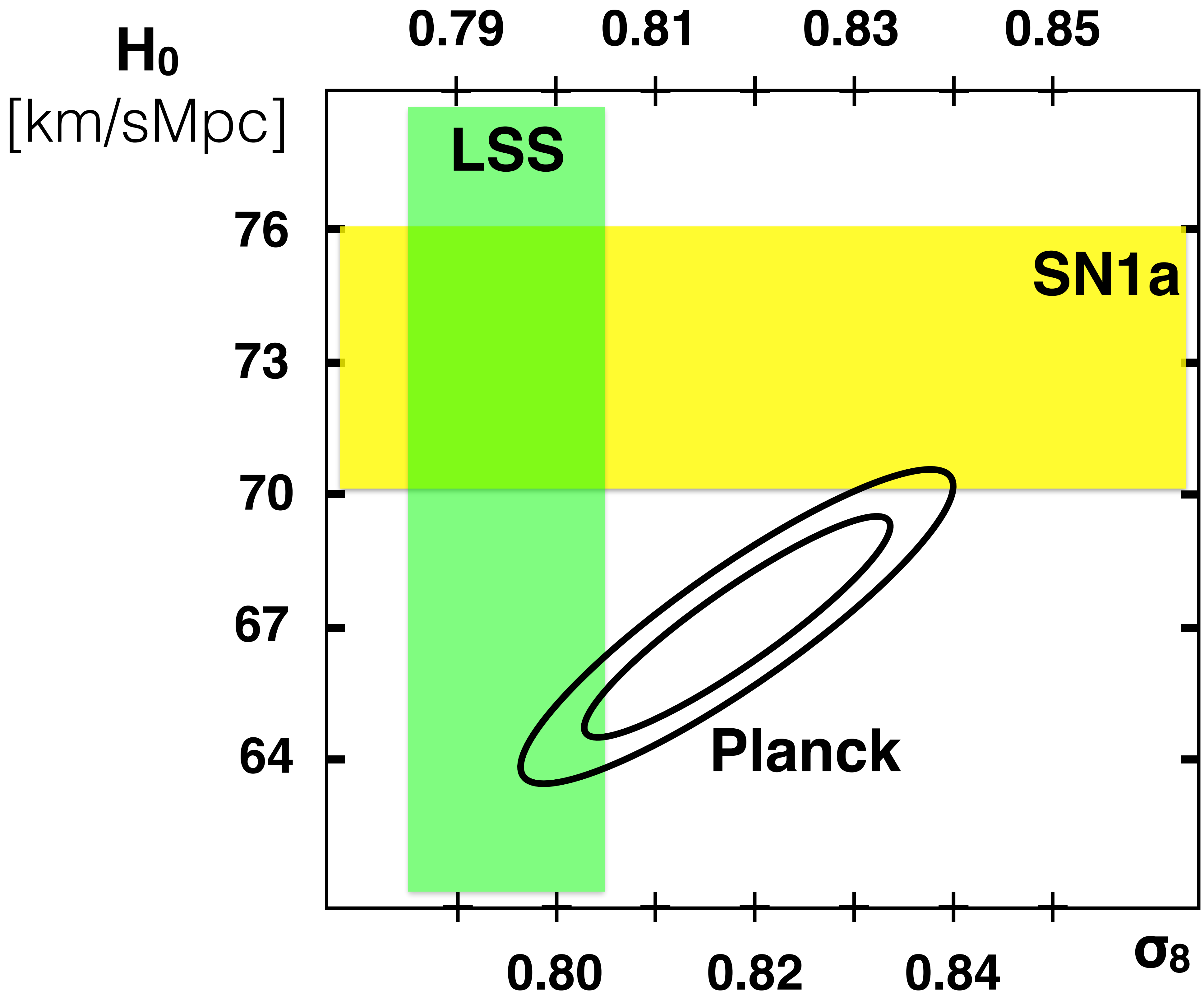
ΛCDM

"direct"

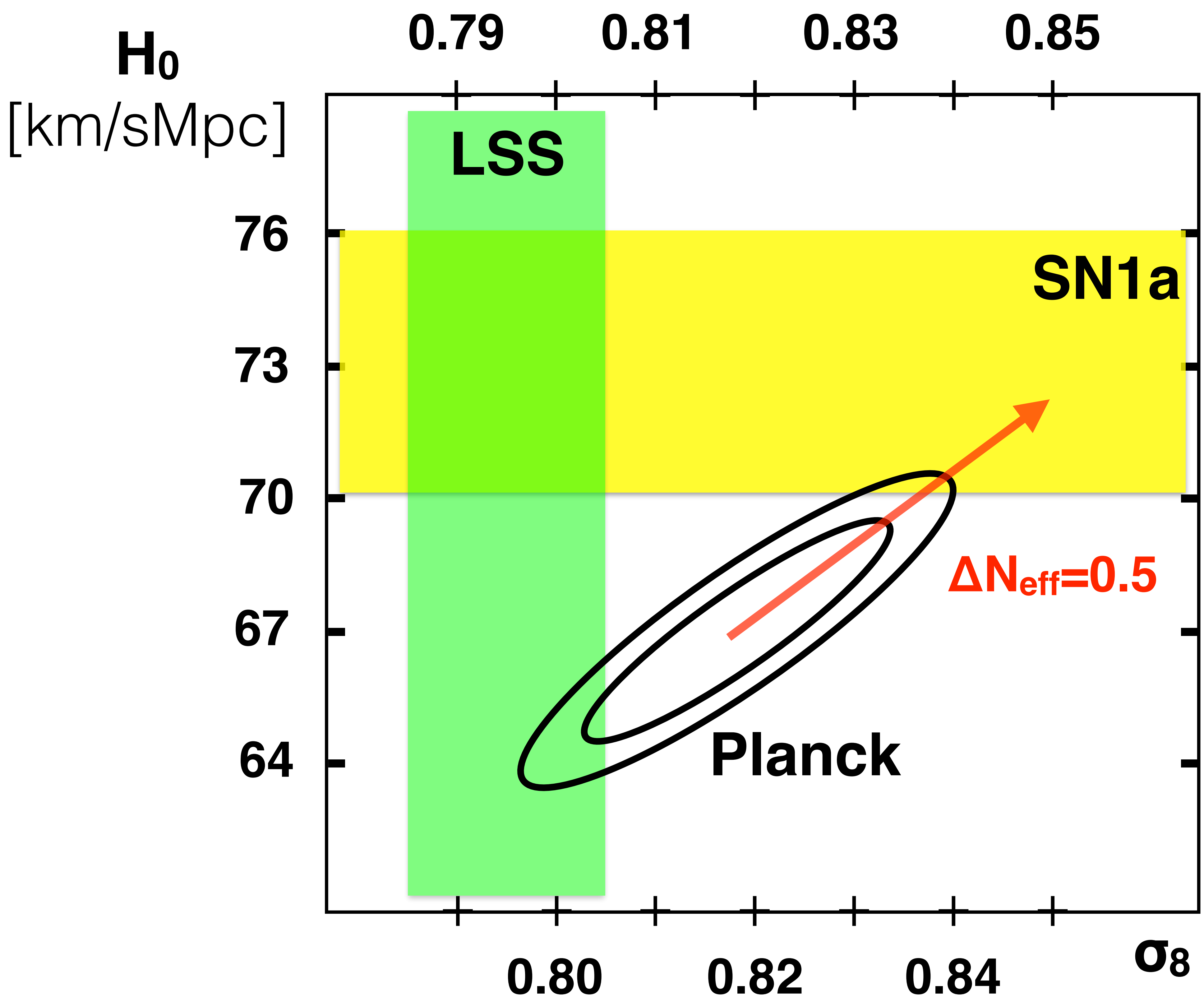
cosmic concordance



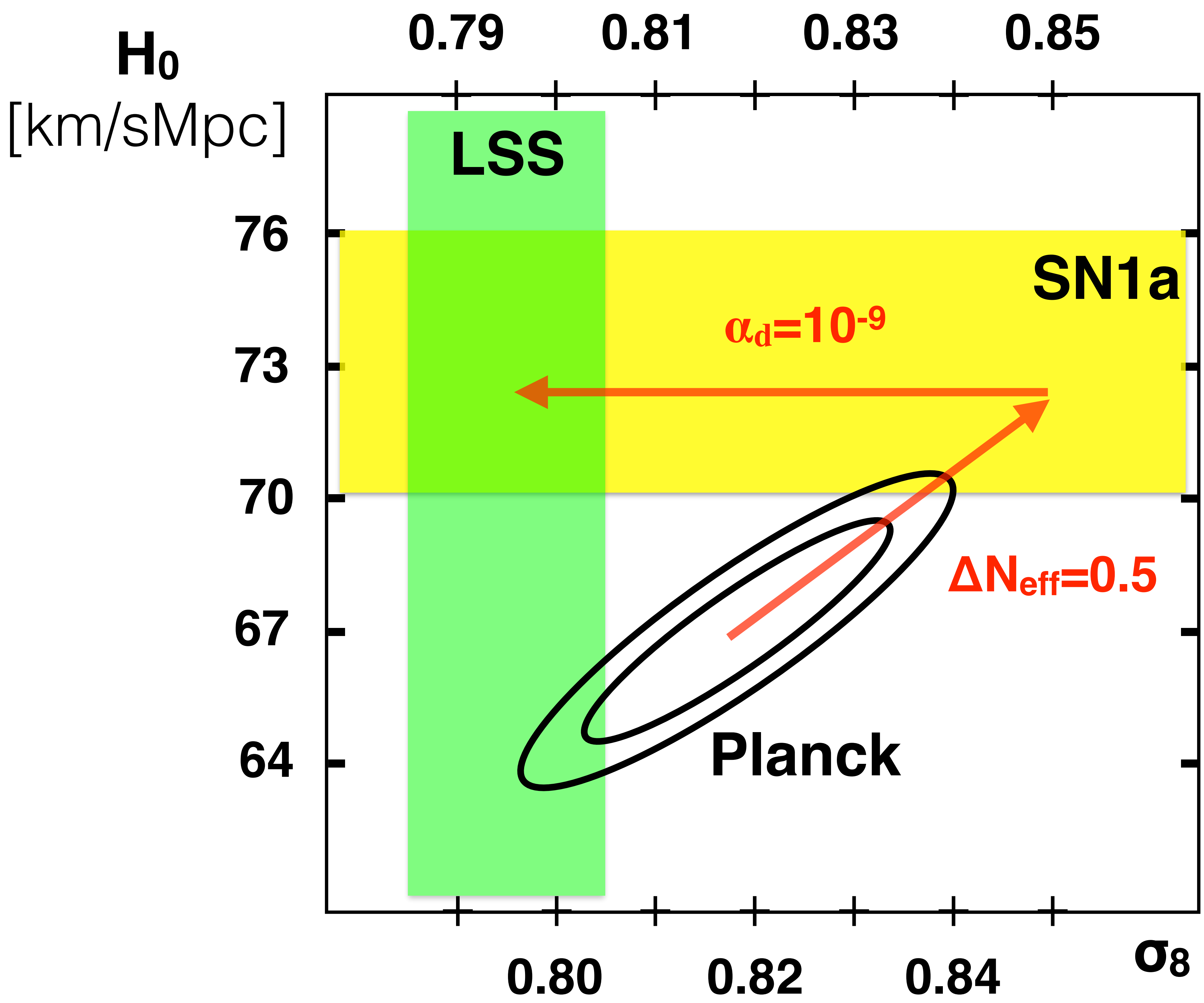
Planck 2015



H_0
[km/sMpc]
0.79
0.81
0.83
0.85
LSS
76
SN1a
73
70
67
64
Planck
0.80
0.82
0.84
σ_8

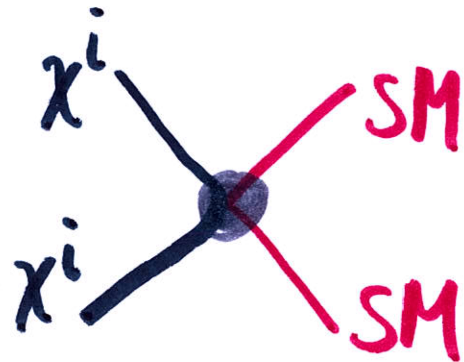


H0 [km/sMpc]
0.79
0.81
0.83
0.85
LSS
76
SN1a
73
70
ΔNeff=0.5
67
64
Planck
0.80
0.82
0.84
σ8



H_0
[km/sMpc]
0.79
0.81
0.83
0.85
LSS
76
SN1a
$\alpha_d=10^{-9}$
73
70
$\Delta N_{eff}=0.5$
67
64
Planck
0.80
0.82
0.84
σ_8

Conclusions?

1. multiplicity 

2. dark radiation  $N = 2, 3$

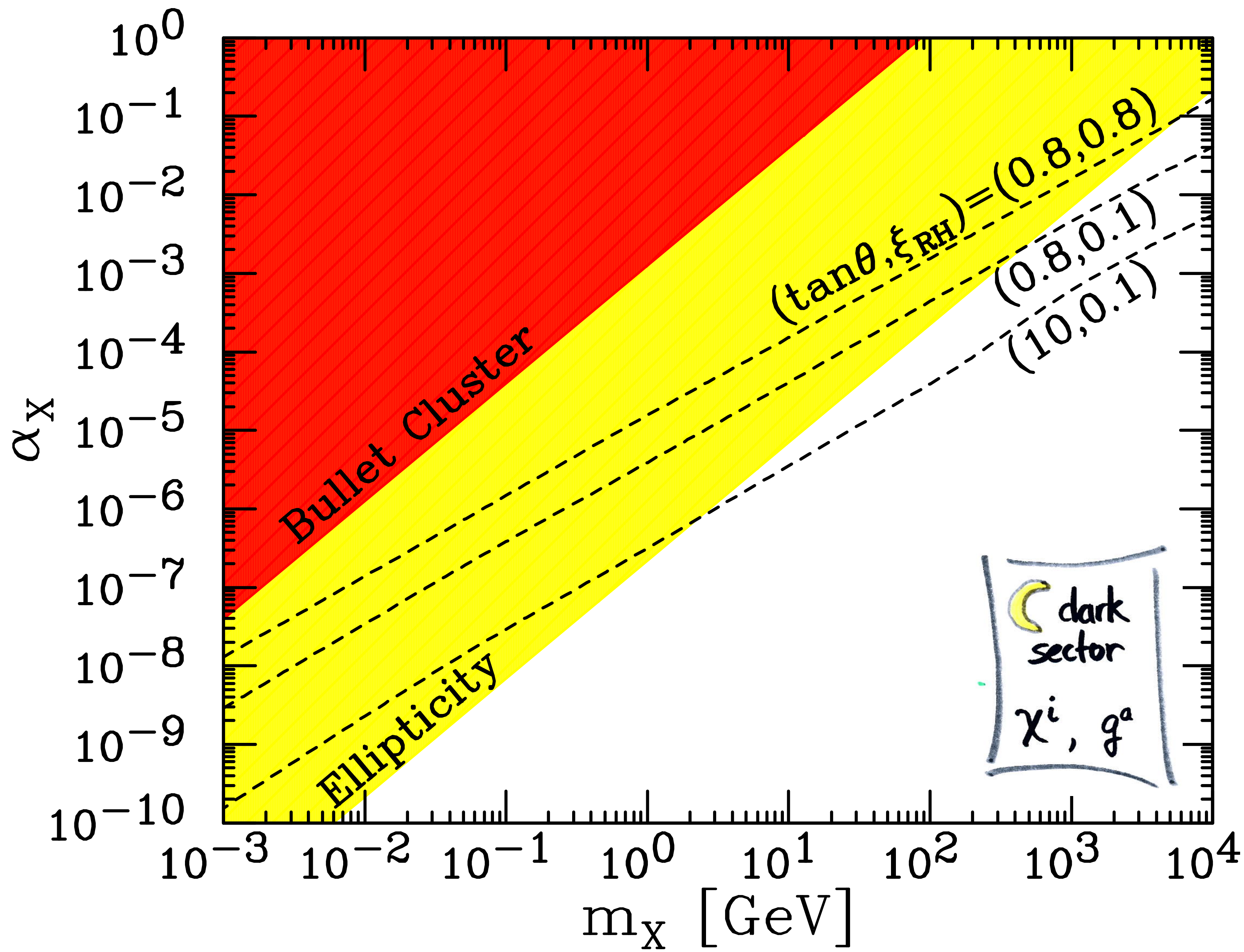
   H_0

3. DM-DR coupling  $\alpha_d \lesssim 10^{-9}$

   σ_8

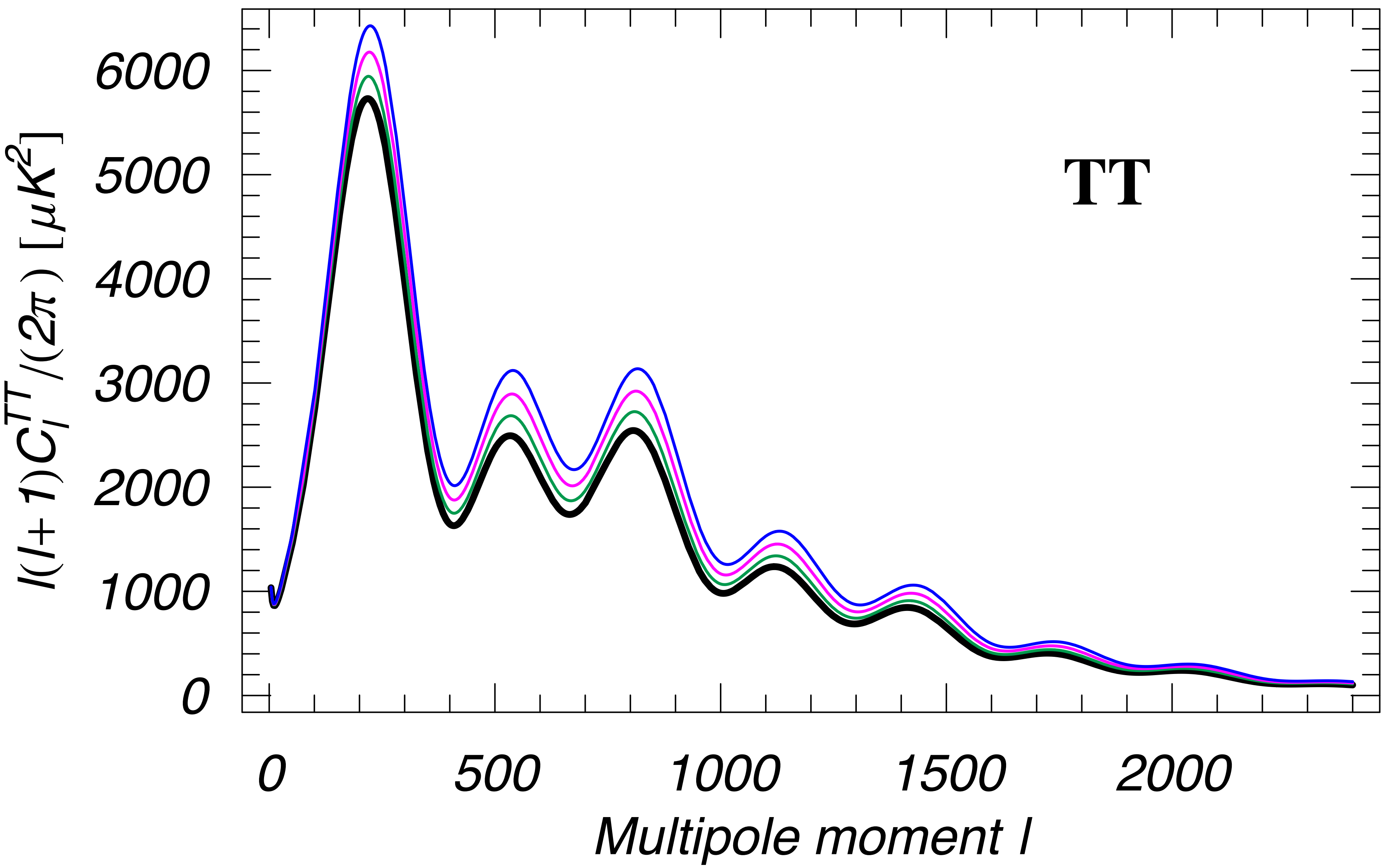
back up!

interacting dark matter bounds



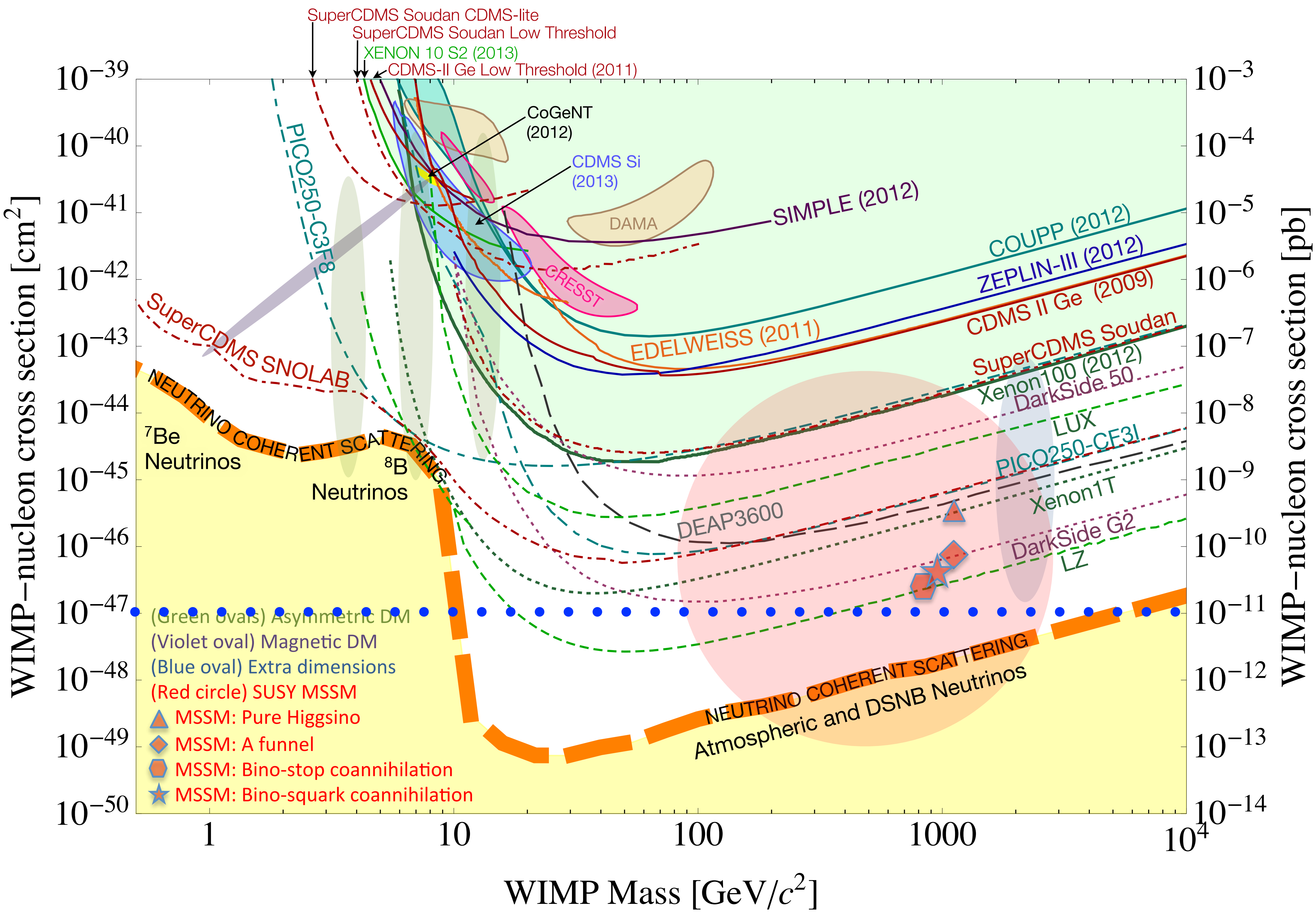
J. Feng, M. Kaplinghat, H. Tu, and H-B. Yu; JCAP 0907 (2009) 004 (arXiv:0905.3039)

CMB and free-streaming ν's



A.Friedland, K.M. Zurek and S. Bashinsky, arxiv:0704.3271

$$\sigma_{SI} = 1.3 \times 10^{-47}\ \mathrm{cm}^2$$



Snowmass CF1 Summary: WIMP Dark Matter Direct Detection arxiv:1310.8327