Non-Abelian dark matter and large scale structure

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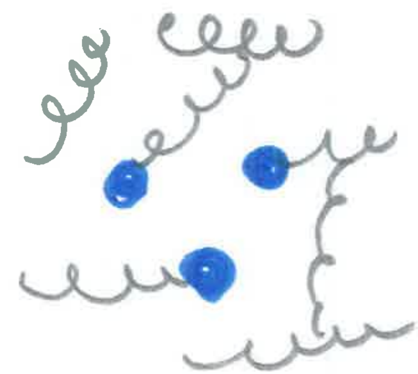
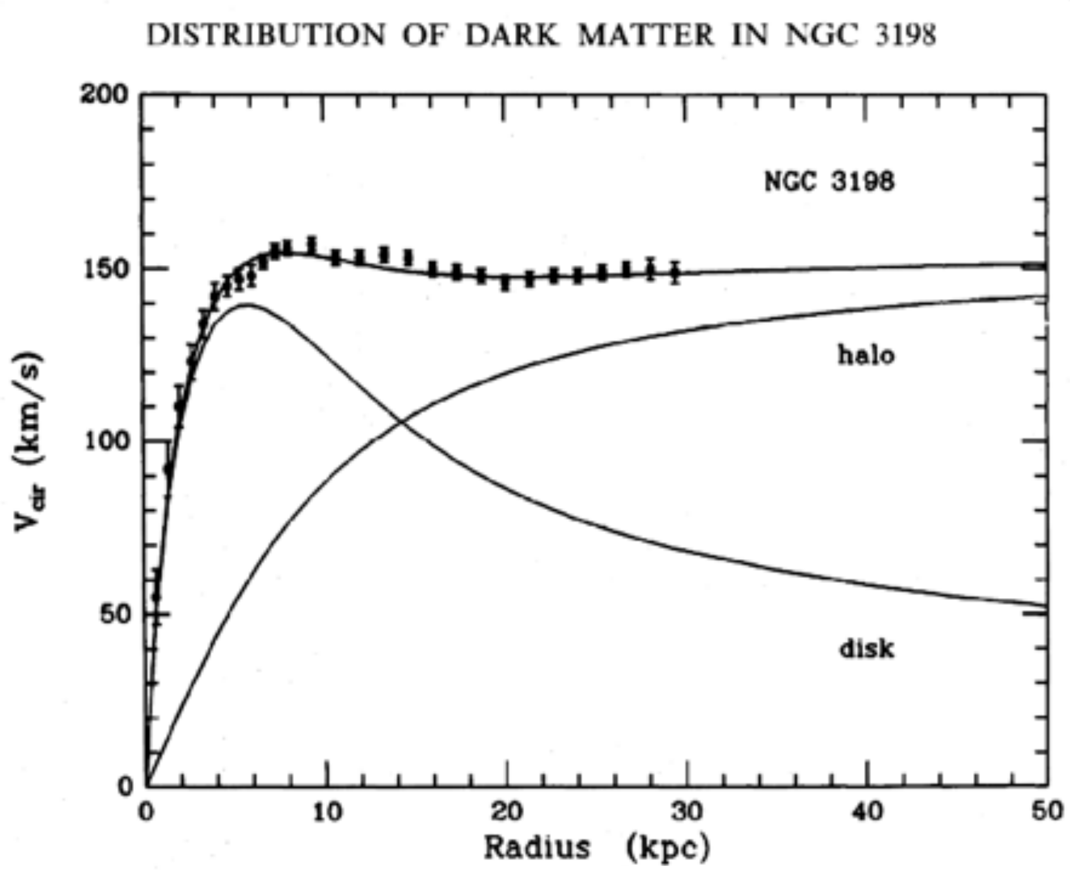
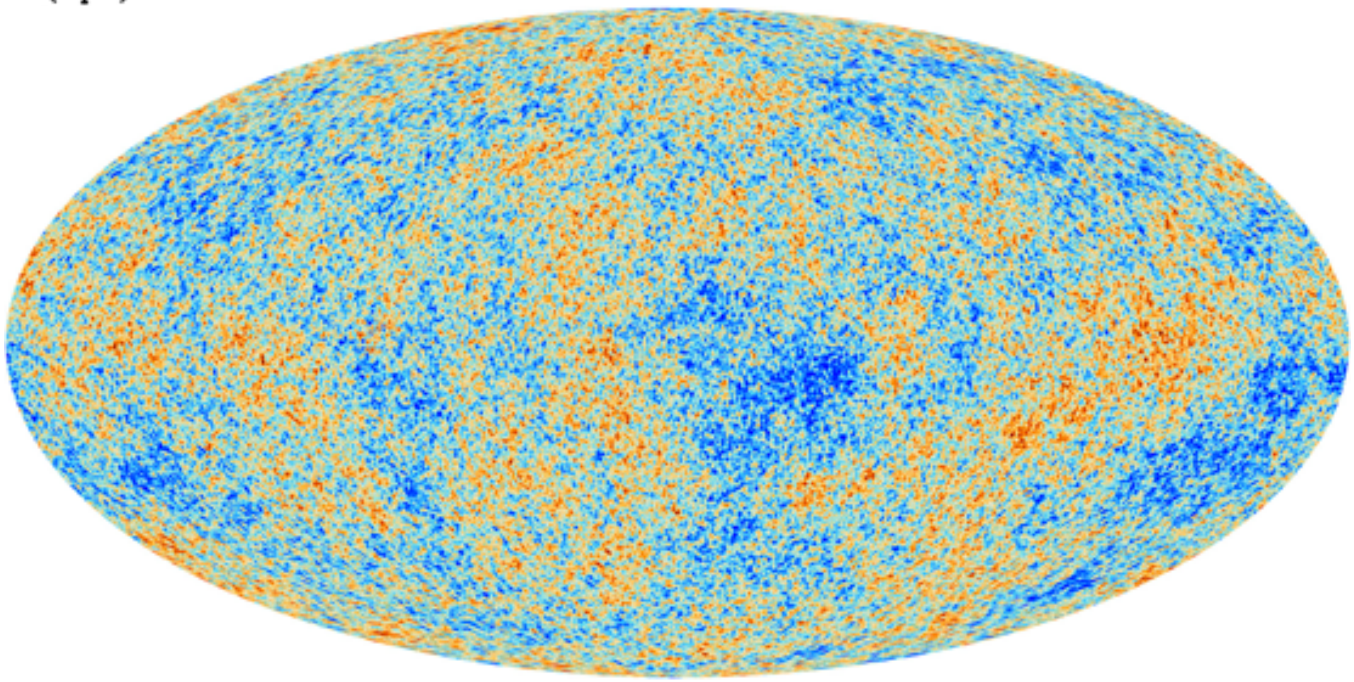


1505.03542
1507.04351

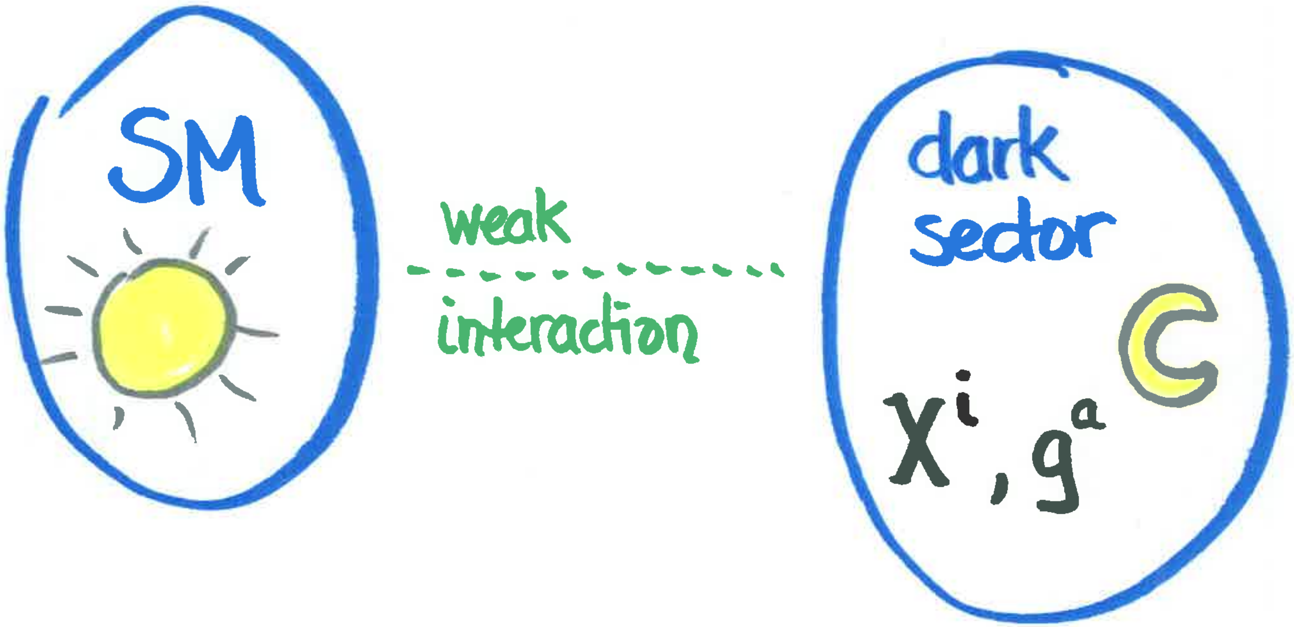
....

Dark matter evidence





Dark matter with multiplicity



$i = 1 \ldots N$

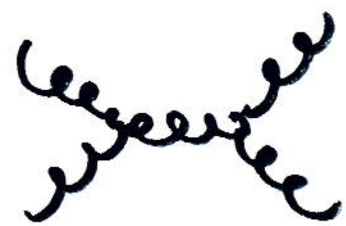
$a = 1 \ldots N^2 - 1$

$\alpha_d \sim 10^{-8}$

What is different?

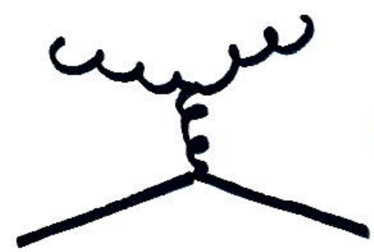
1. χ^i $\quad i=1\ldots N$ $\quad$ LHC, 100 TeV

2. g^a dark radiation



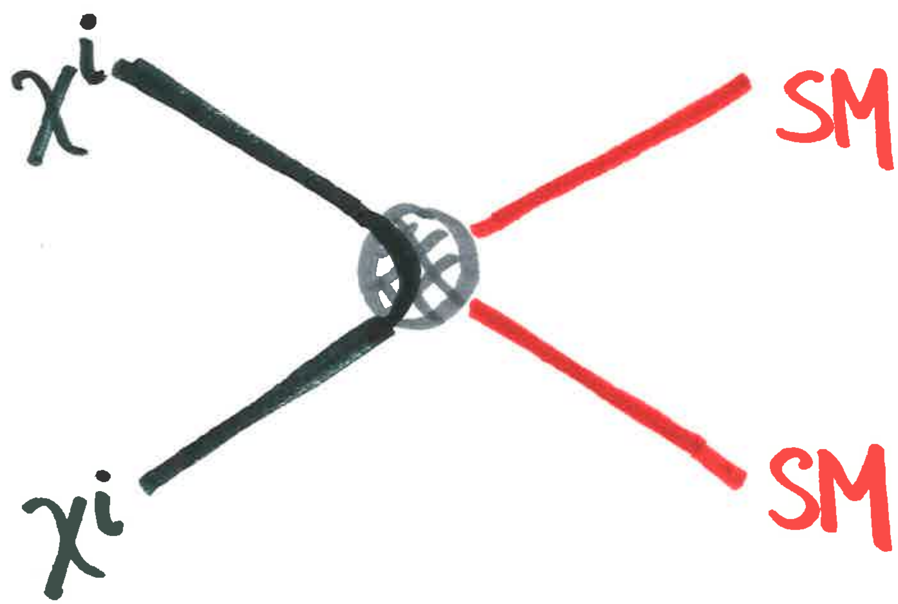
$N<4$

3. DM couples to radiation

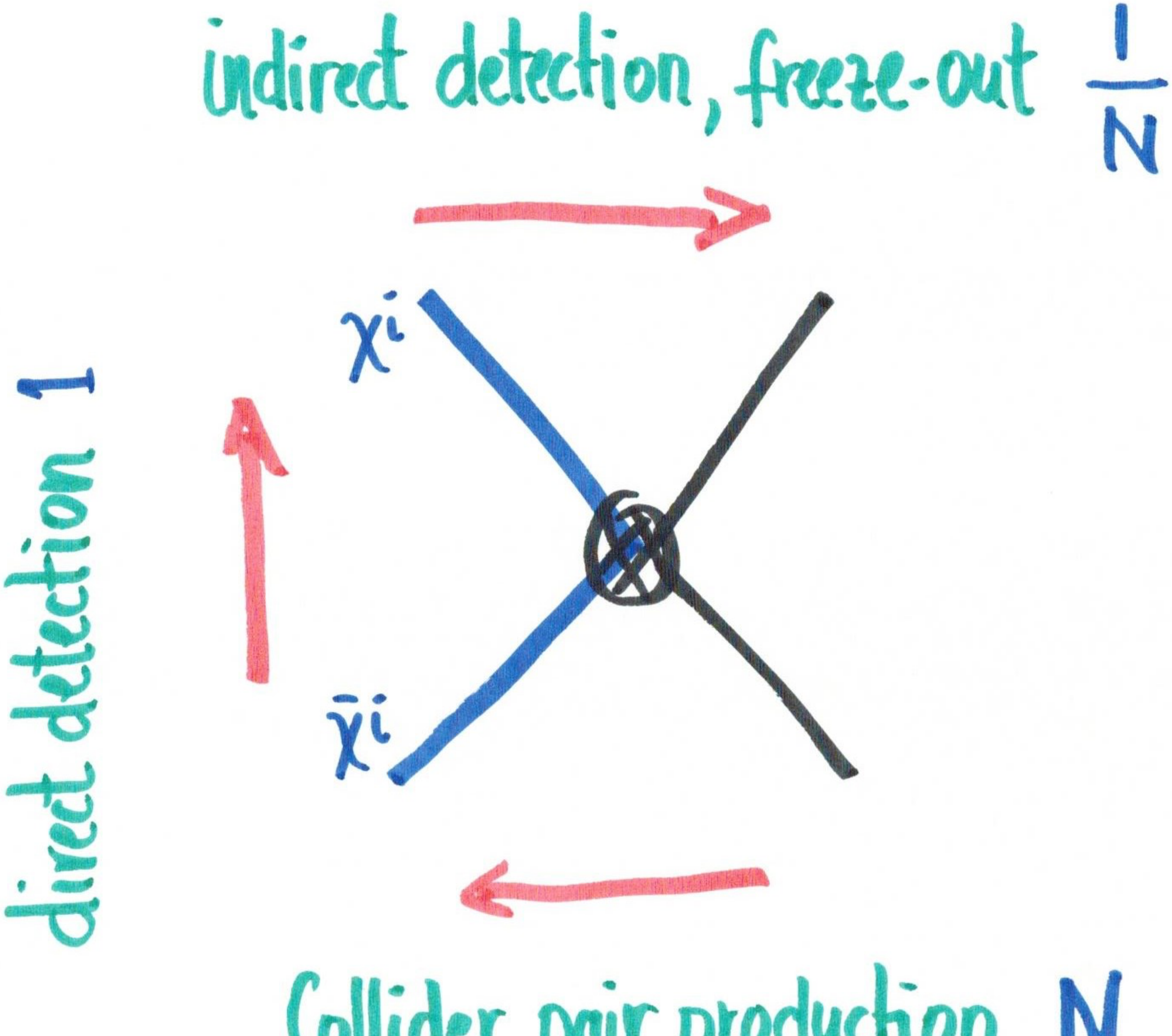


$\alpha_d<10^{-8}$

1. dark matter multiplicity



same dark color!


indirect detection, freeze-out
1/N
χ^i
χ̄^i
direct detection
1
Collider pair production
N

Example: Multiple "winos"

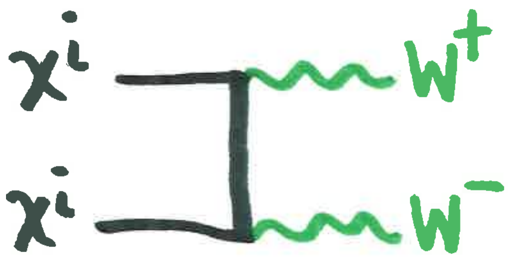
$SU(2)_W$ triplet $\longrightarrow$ $\left.\begin{array}{l}\chi^{\pm i} \text{ ——} \\ \chi^{0 i} \text{ ——}\end{array}\right\}$ 160 MeV

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

χ^{0i} = dark matter

DM abundance

$$\Omega_{DM} \sim 1/\langle \sigma v \rangle$$

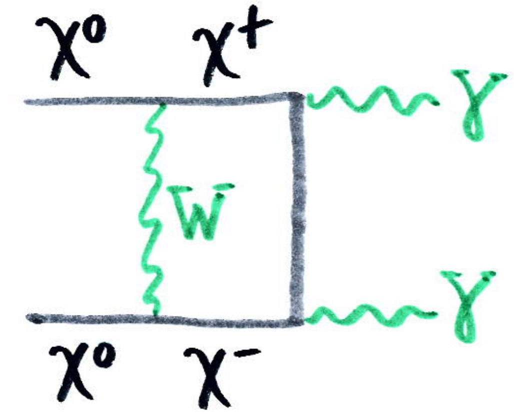


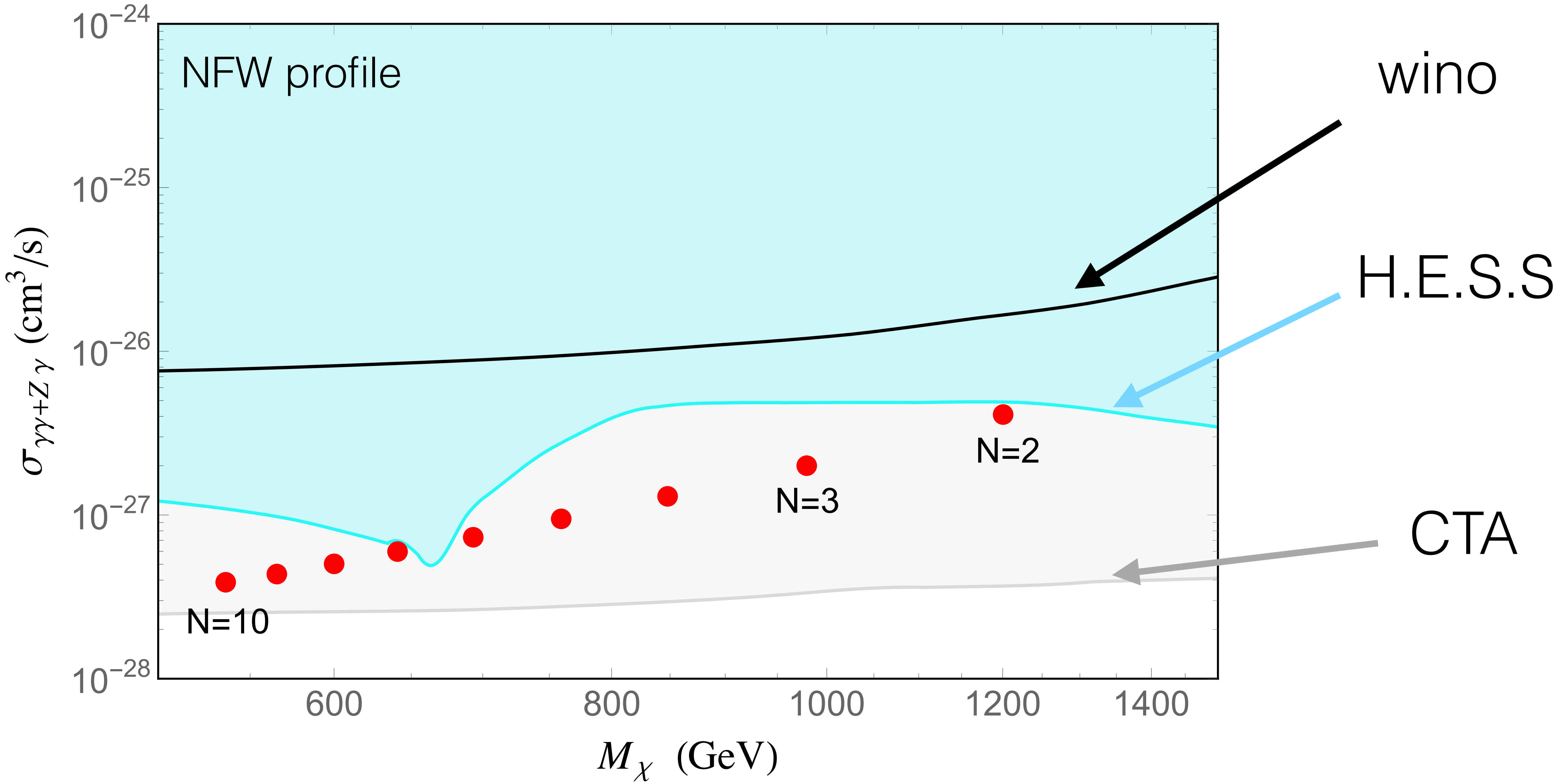
$$\langle \sigma v \rangle \sim \frac{1}{2N} \frac{\alpha_W^2}{M_\chi^2}$$

Dirac Color

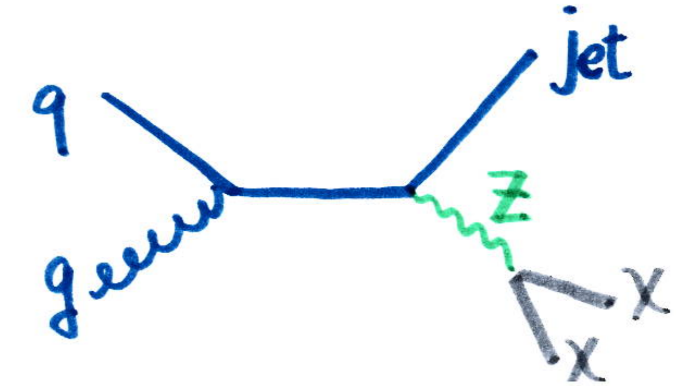
$$\Longrightarrow \quad M_\chi = M_\chi^{N=1} / \sqrt{2N}$$

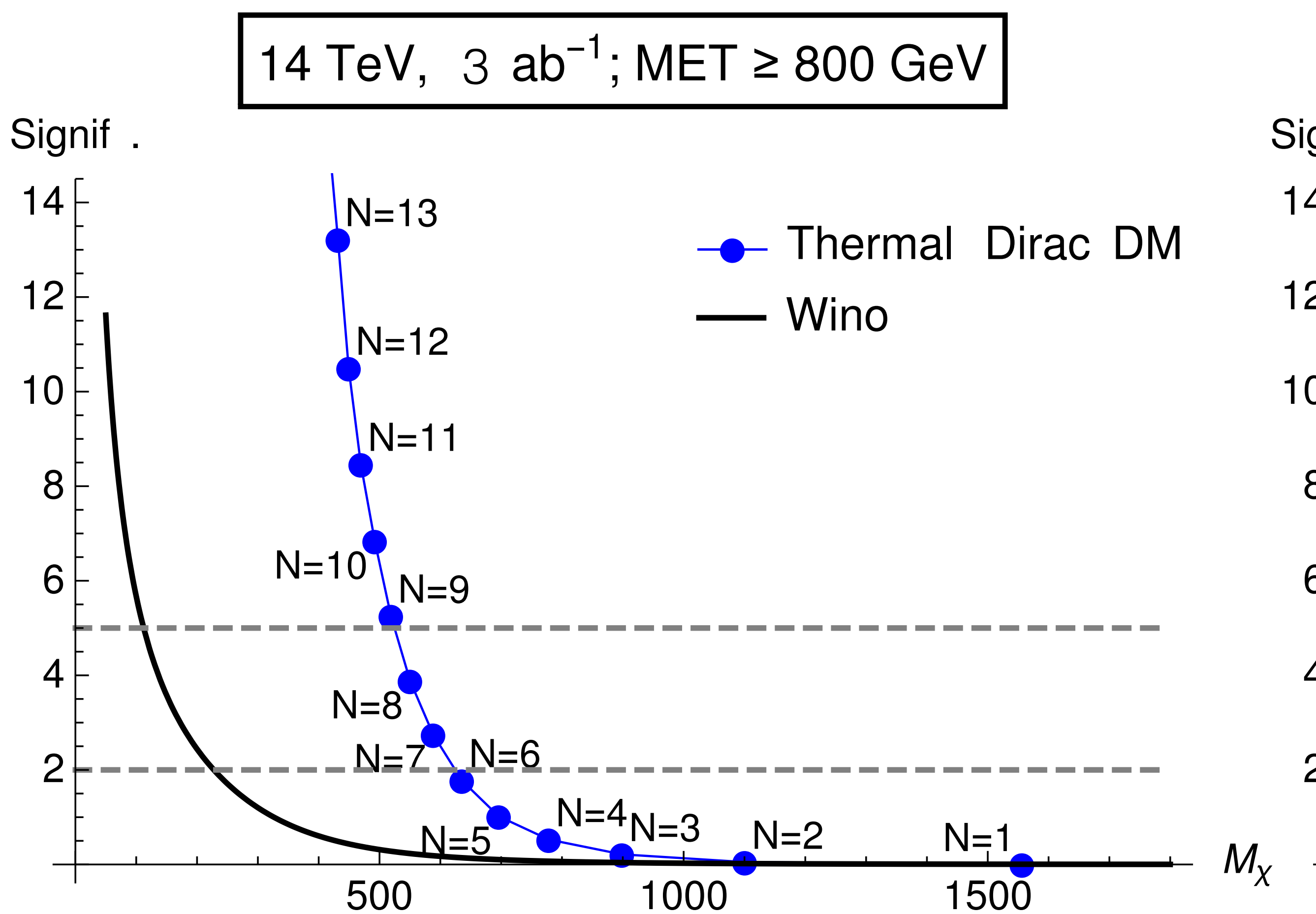
Indirect detection



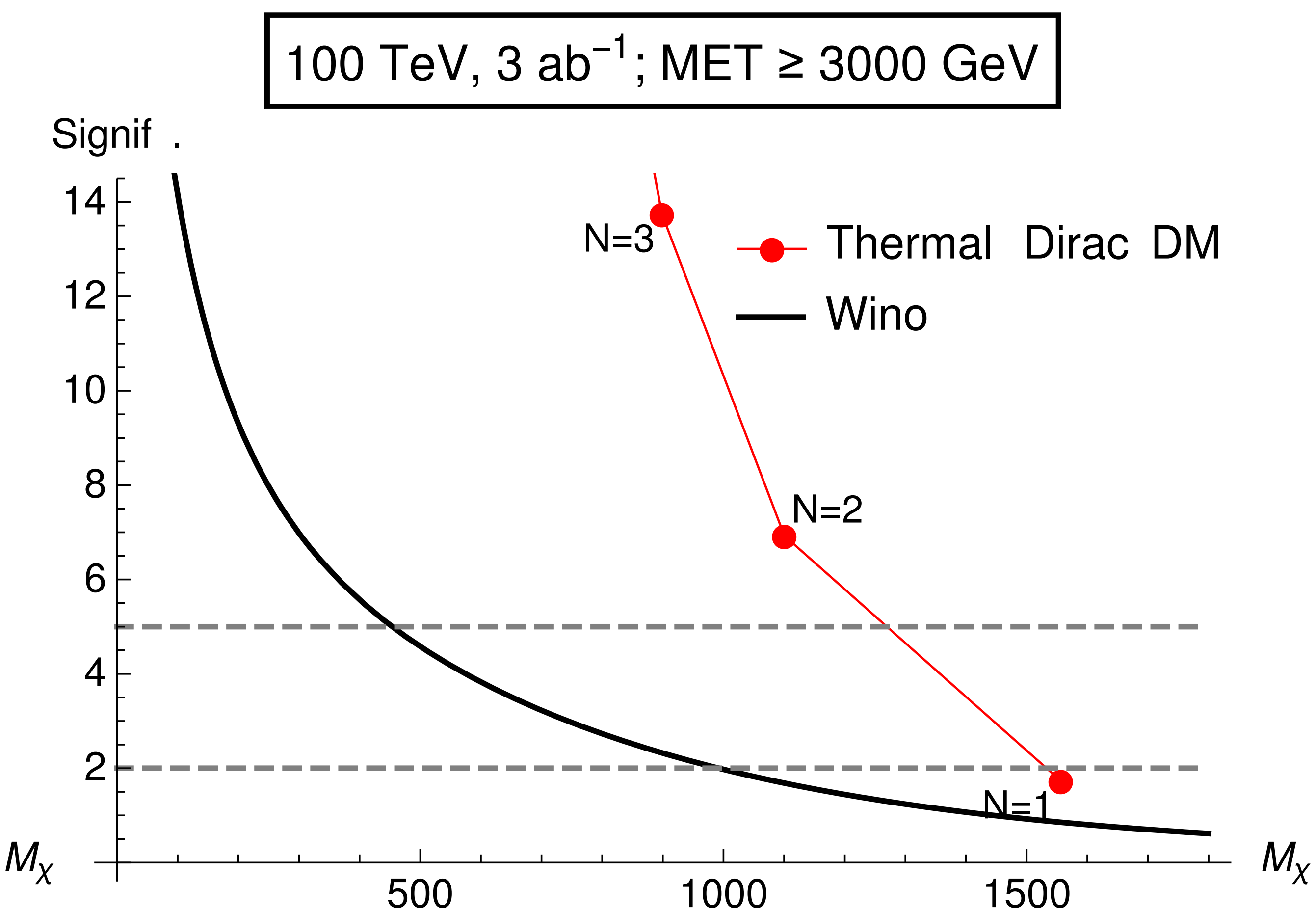


Colliders: mono-jets





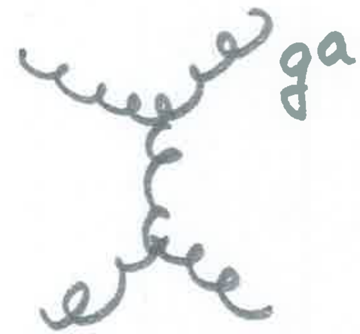
HL-LHC



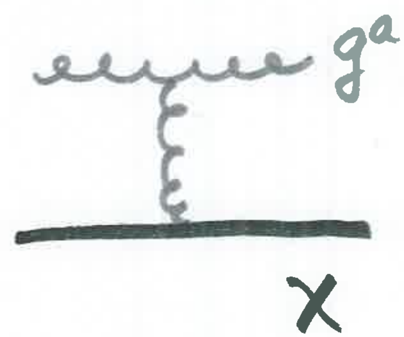
100 TeV

Cosmology

2. dark gluons



3. dark matter drag & large scale structure



Cosmology primer

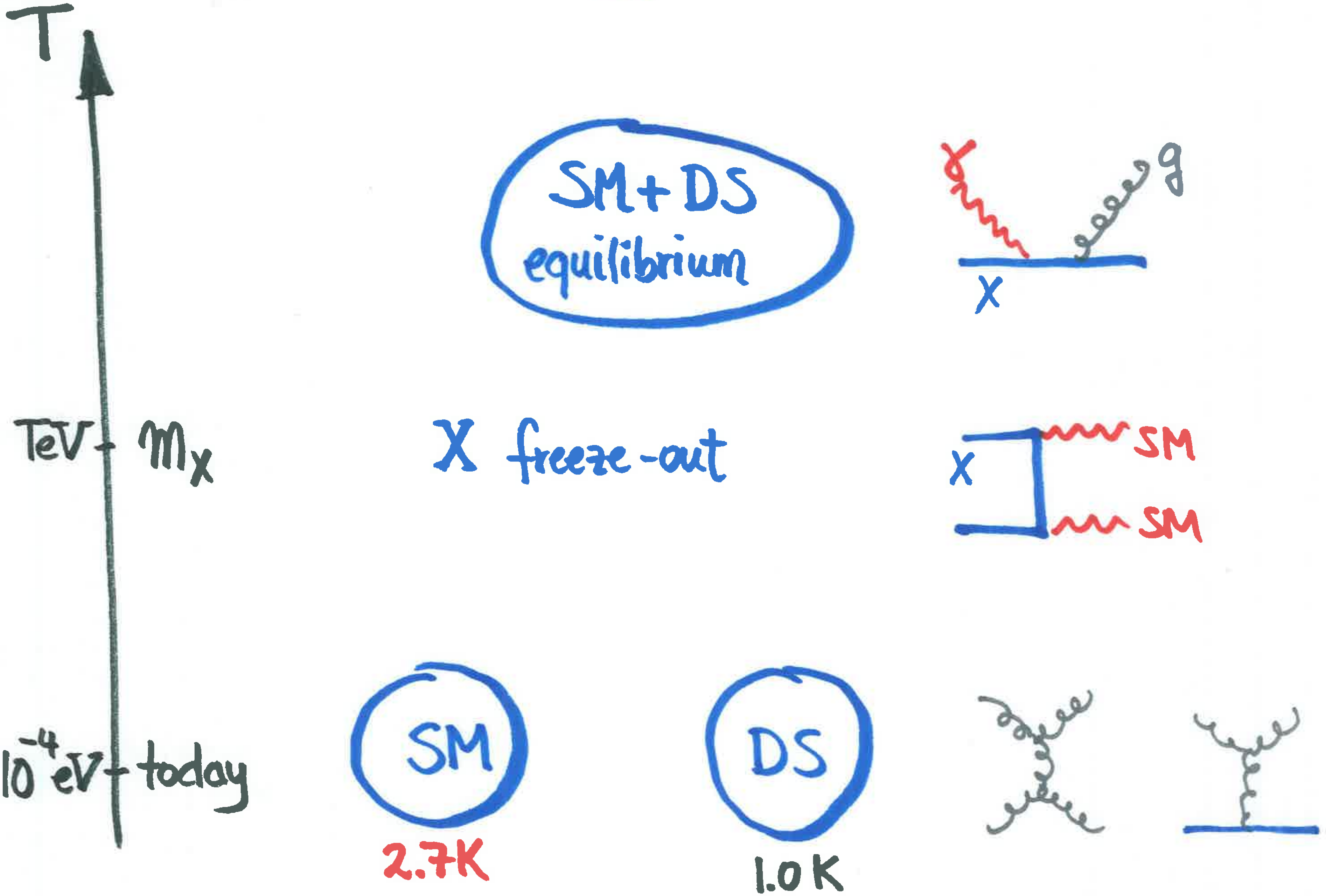
to determine if a process is important compare:

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

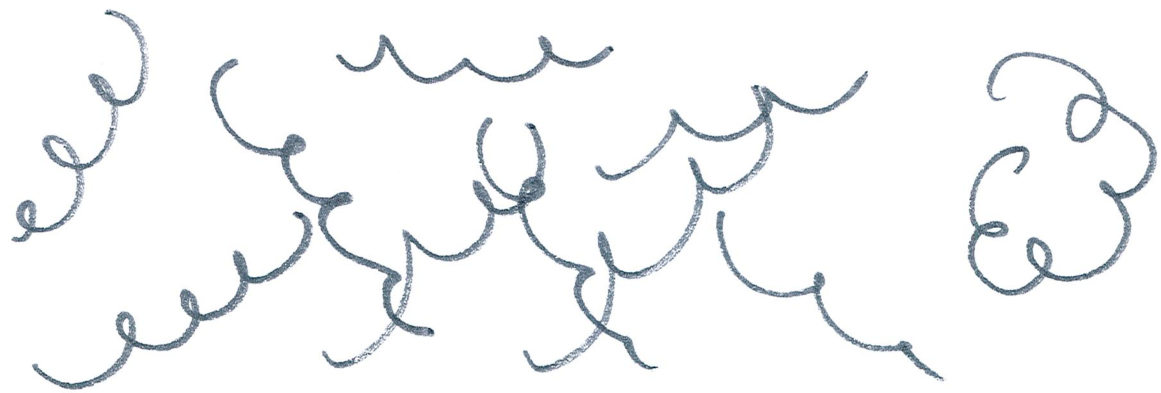
$$\uparrow \qquad\qquad\qquad \uparrow$$

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

Thermal history



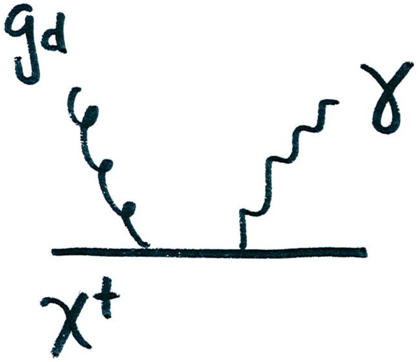
2. dark gluons



radiation : massless, weakly coupled

$\Lambda_{\text{"QCD"}} \lll\lll \text{Hubble}$

are dark gluons in equilibrium? ($T \sim m_\chi$)

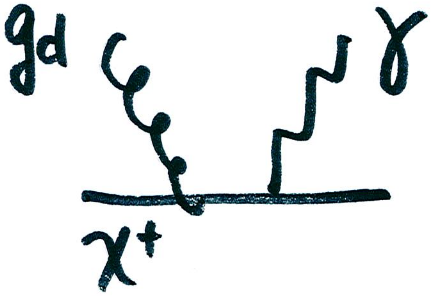


$$\Gamma \sim n_\chi \langle \sigma v \rangle \sim T^3 \, \frac{\alpha_d \alpha_{em}}{T^2}$$

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

$$\Gamma > H \Rightarrow \alpha_d > \frac{1}{\alpha_{em}} \frac{m_\chi}{M_{pl}} \approx \underline{10^{-13}}$$

gluons in equilibrium @ 10 GeV ?



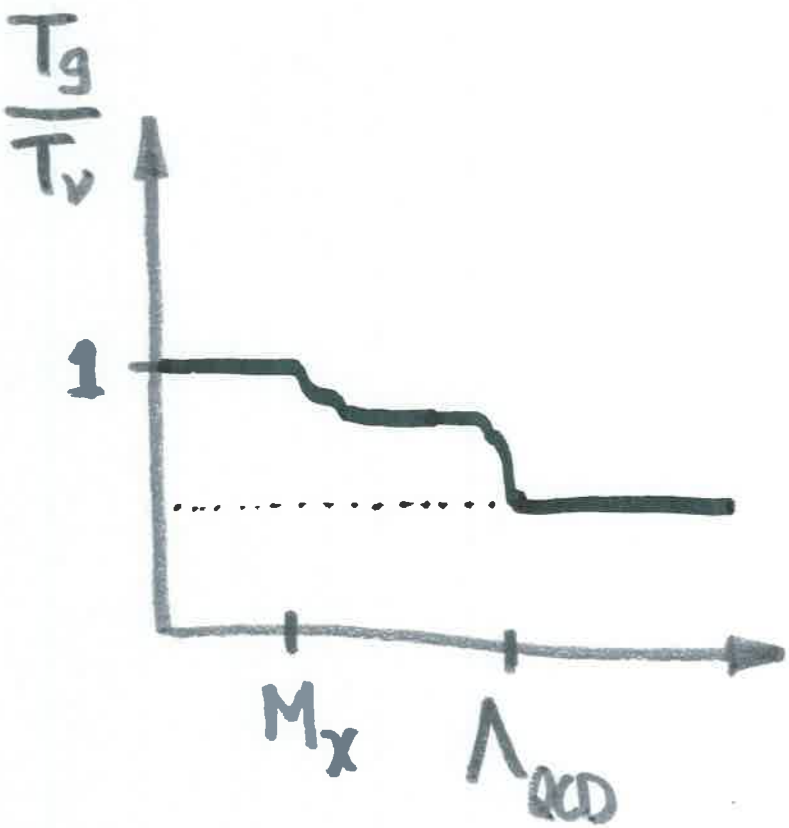
$$\Gamma \sim n_\chi \langle \sigma v \rangle \sim 10^{-11}\, T^3 \, \frac{\alpha_d \alpha_{em}}{M_\chi^2}$$

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

$$\Gamma > H \Rightarrow \alpha_d > 1$$ $\Rightarrow$ decoupled

after dark gluon decoupling ...

energydensity ?



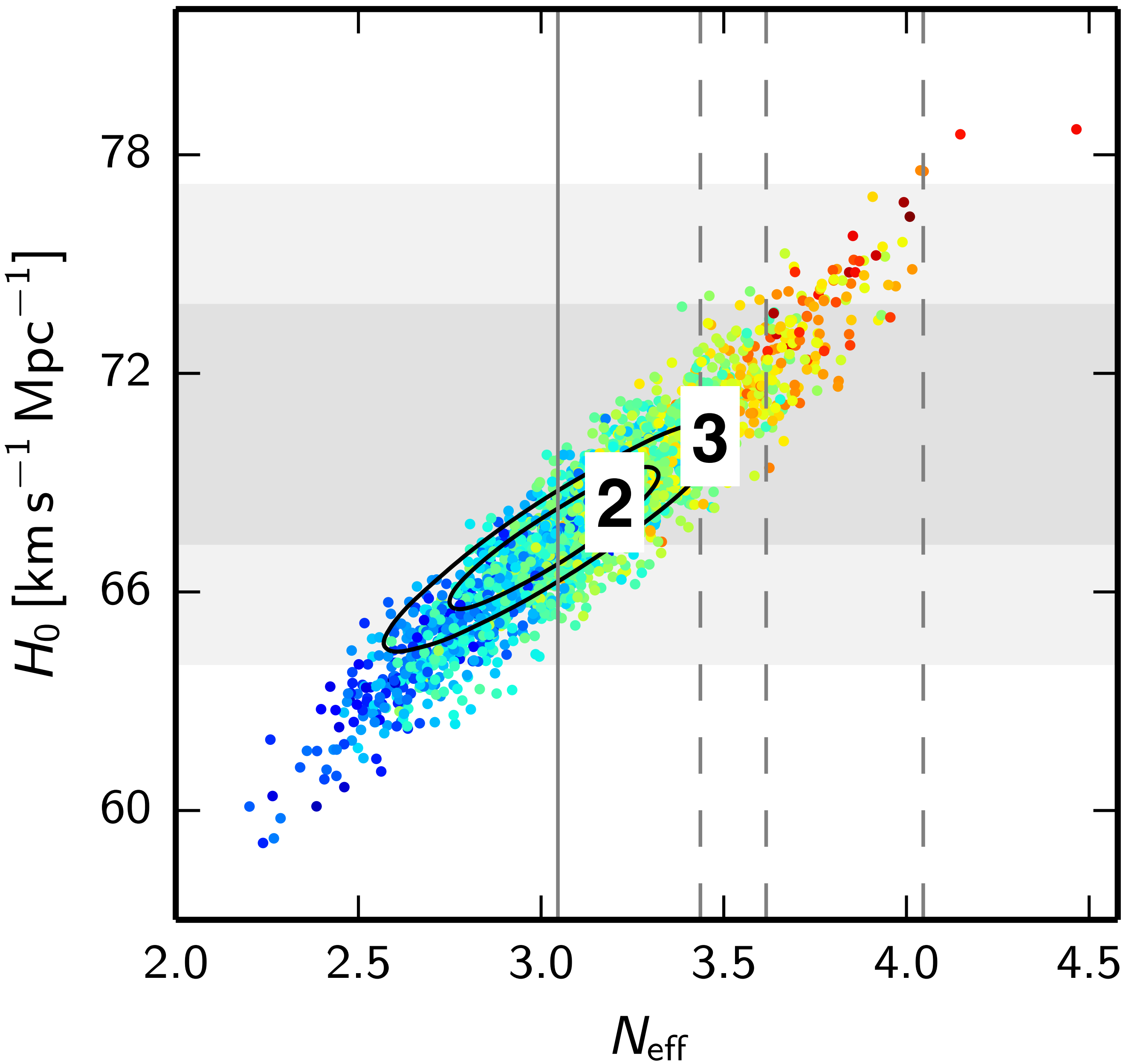
$$\rho_g \sim (N^2-1)\, T_g^4$$

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

$$\equiv \Delta N_{eff} \sim \frac{N^2-1}{16.4}$$

CMB: N=2,3

CMB and N_{eff}



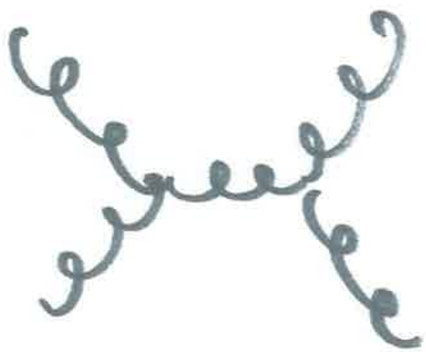
$N_{eff} = 3.13 \pm 0.32$ *Planck* TT+lowP

Planck Collaboration; arXiv:1502.01589

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

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

important difference to ν's : g selfinteractions



rate $\Gamma \sim \alpha_d^2 T \gg H$

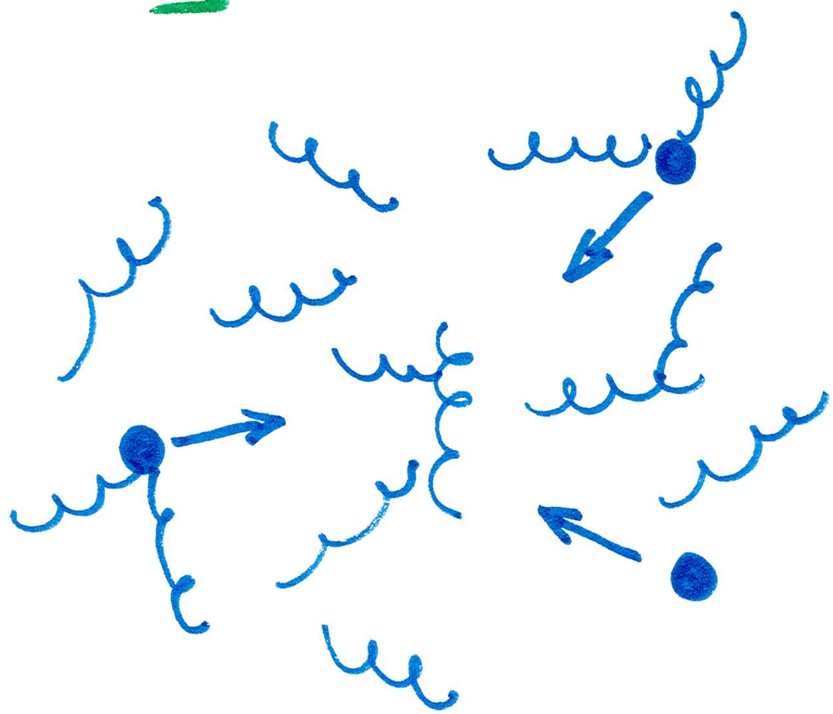
dark gluons do not free-stream → "perfect fluid"

CMB can distinguish !

2. dark radiation summary

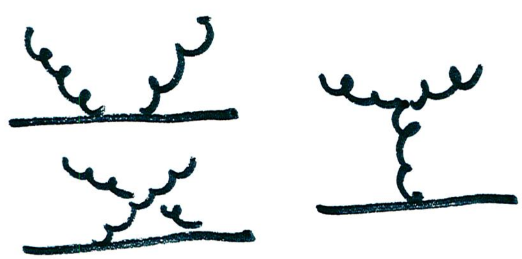
- perfect fluid for $10^{-13} < \alpha_d < 10^{-2}$, $T \sim 1K$
- $\Delta N_{eff} < 0.5 \implies N = 2, 3$
- Planck can distinguish $\left\{ \begin{array}{l} \text{perfect} \\ \text{free-streaming} \end{array} \right.$

3. DM-DR interactions and large scale structure

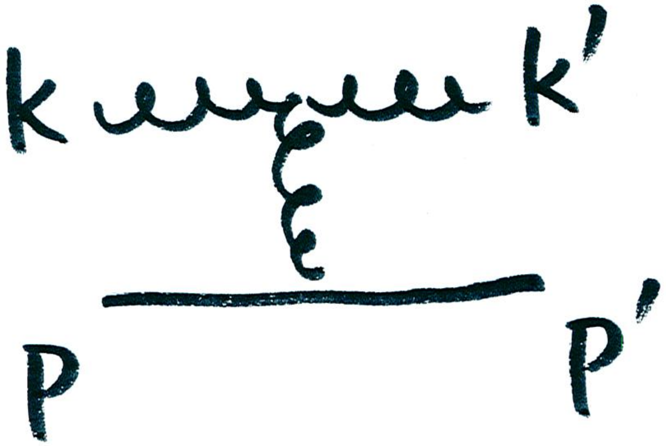


is DM coupled to DR fluid?

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



DM–DR coupling



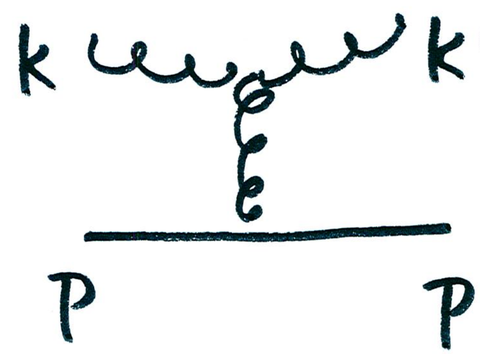
$$n\langle\sigma v\rangle \approx$$

$$\underbrace{\int d^3k\, f(k,T)}_{n} \quad \underbrace{\int d^3k'\, d^3p'\, \delta^4(\Sigma p)\, \frac{\cdots}{(k-k')^4}}_{\sigma v}$$

IR + collinear divergent

$$\left.\begin{array}{l}\text{Soft}\\ \text{Collinear}\end{array}\right\}\ \text{scatters matter very little}$$

weigh by momentum transfer



$$\dot{\vec{P}} \sim \int d^3k \, f(k,T) \int d^3k' \, d^3p' \, \delta^4 \, |M|^2 \, (\vec{p}\,' - \vec{p})$$

$$\sim -\Gamma_p \, \vec{P}$$

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

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

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

linear perturbations in fluids

δ density pert.

θ velocity pert.

$\vdots$

DM, DR, SM

$\downarrow$

γ, ν, B

linear perturbations

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

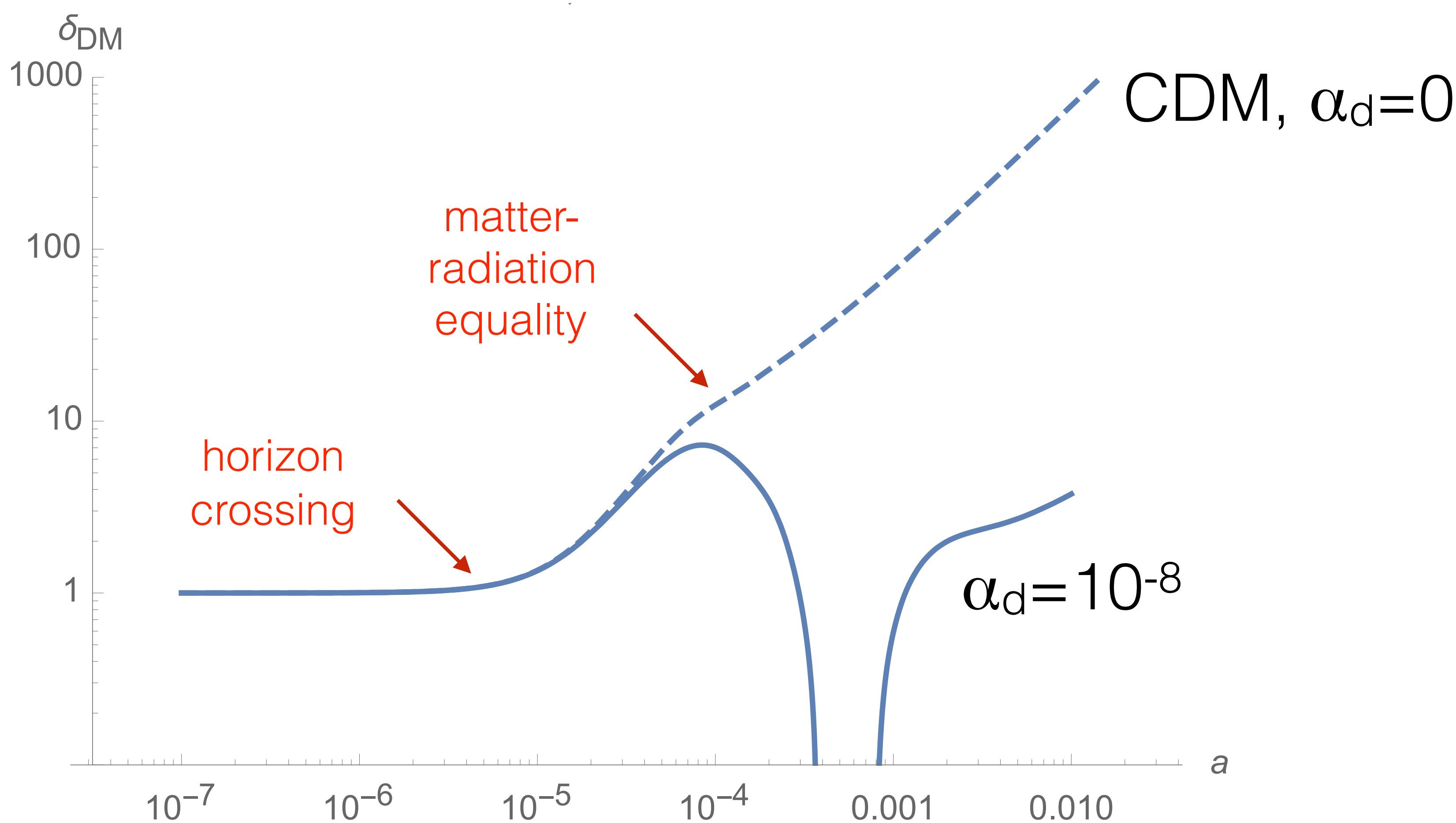
$$\dot{\theta}_{DM} = -\frac{\dot{a}}{a}\theta_{DM} + a\mathbf{\Gamma}_{\mathbf{p}}(\theta_{DR} - \theta_{DM}) + k^2\psi$$

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

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

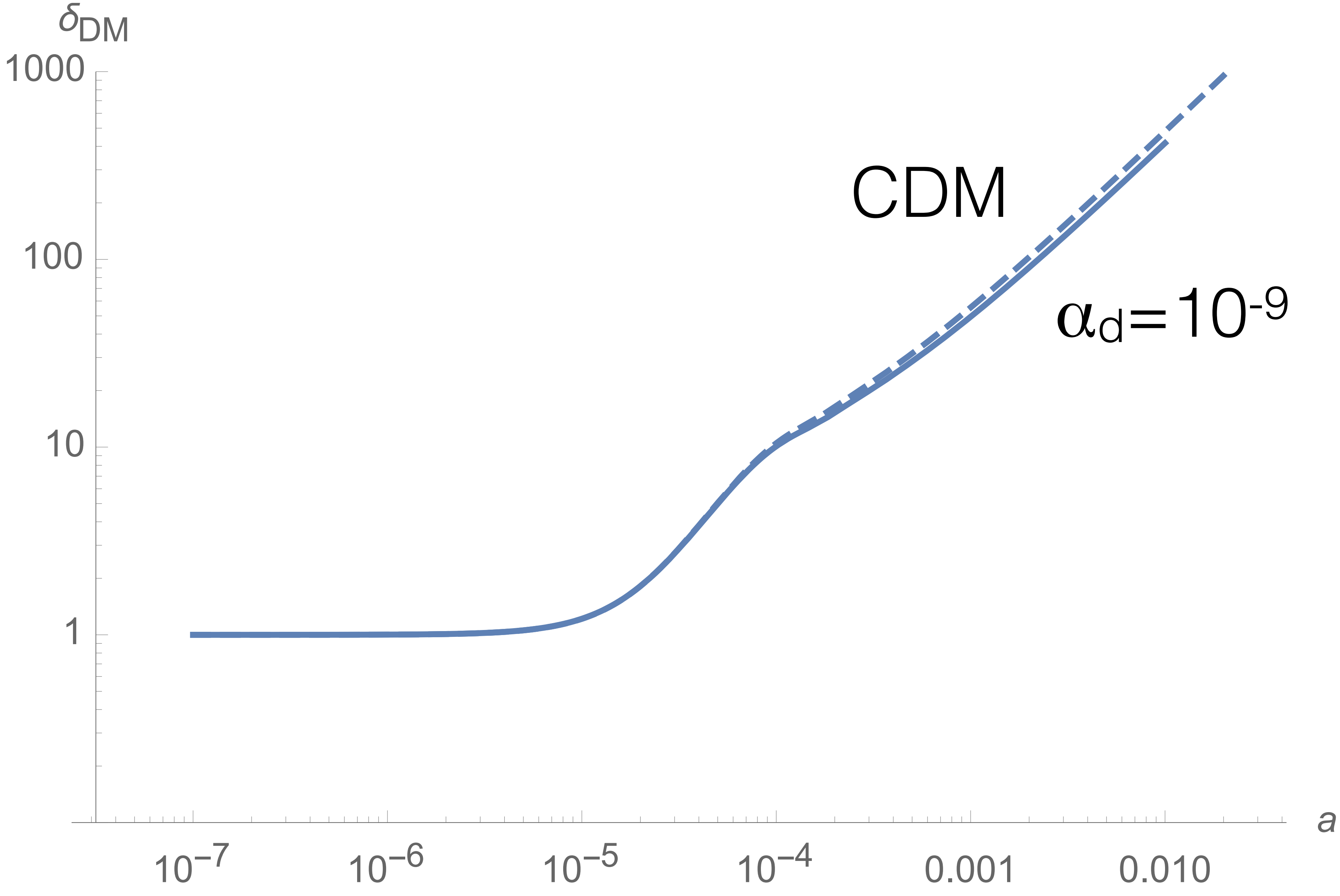
growth of perturbations

k=0.2 Mpc^{-1}

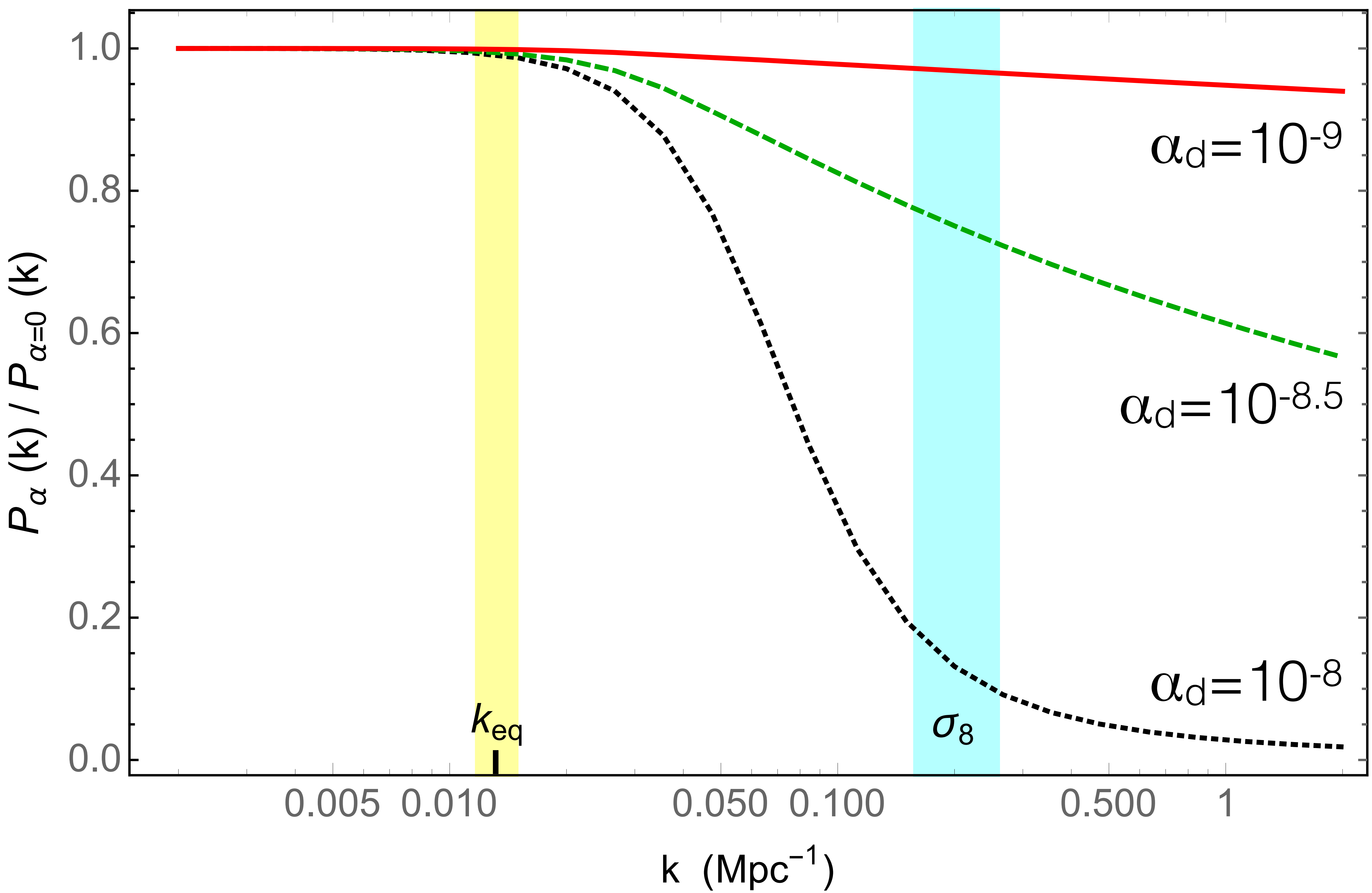


growth of perturbations

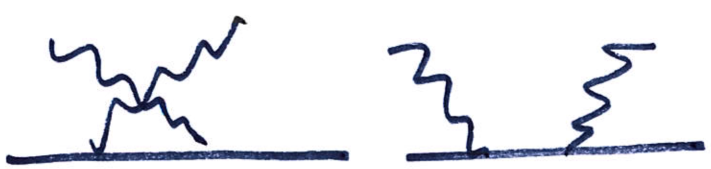
$k=0.2\ \mathrm{Mpc}^{-1}$



power spectrum change

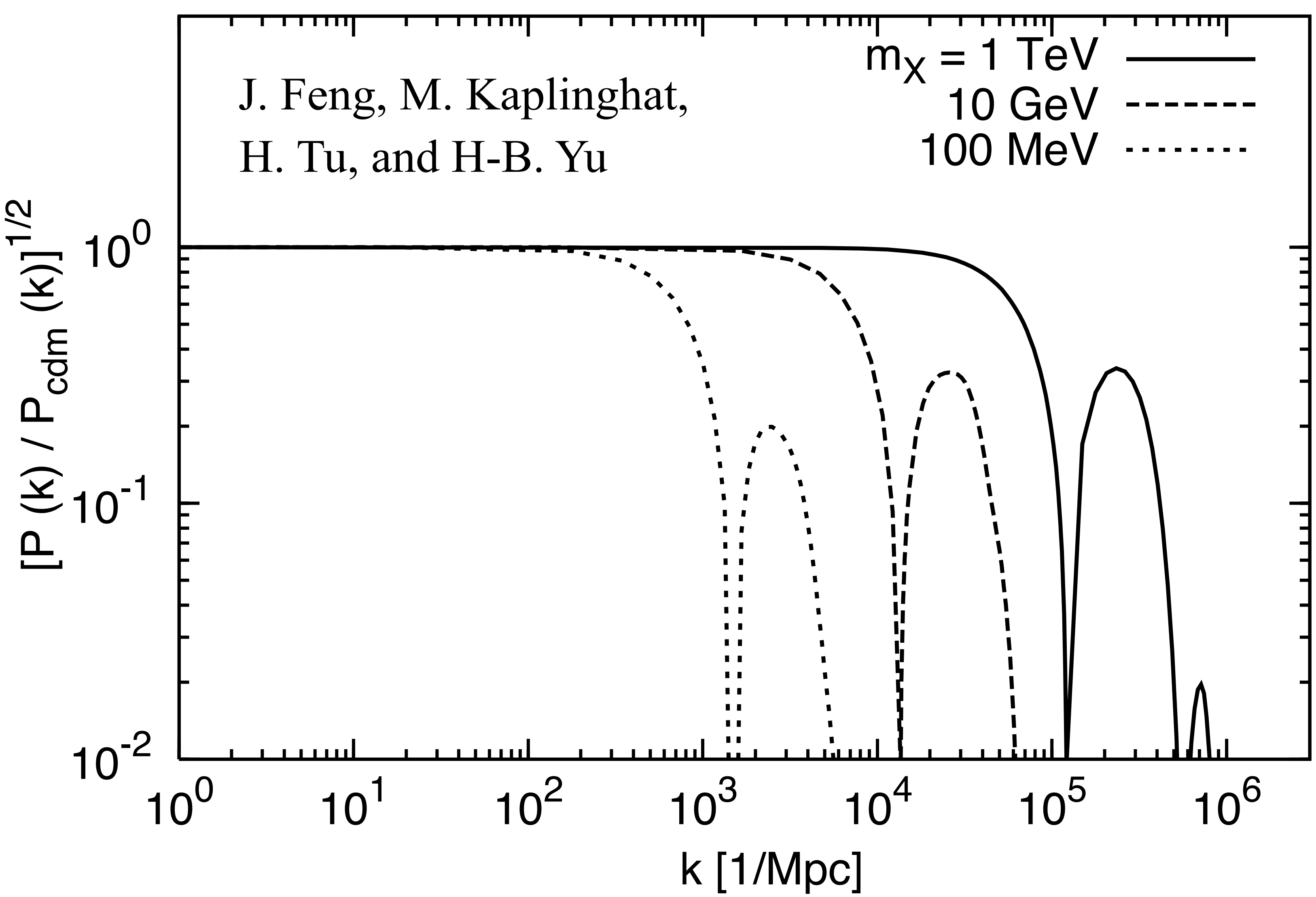


dark U(1) - compton scattering



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

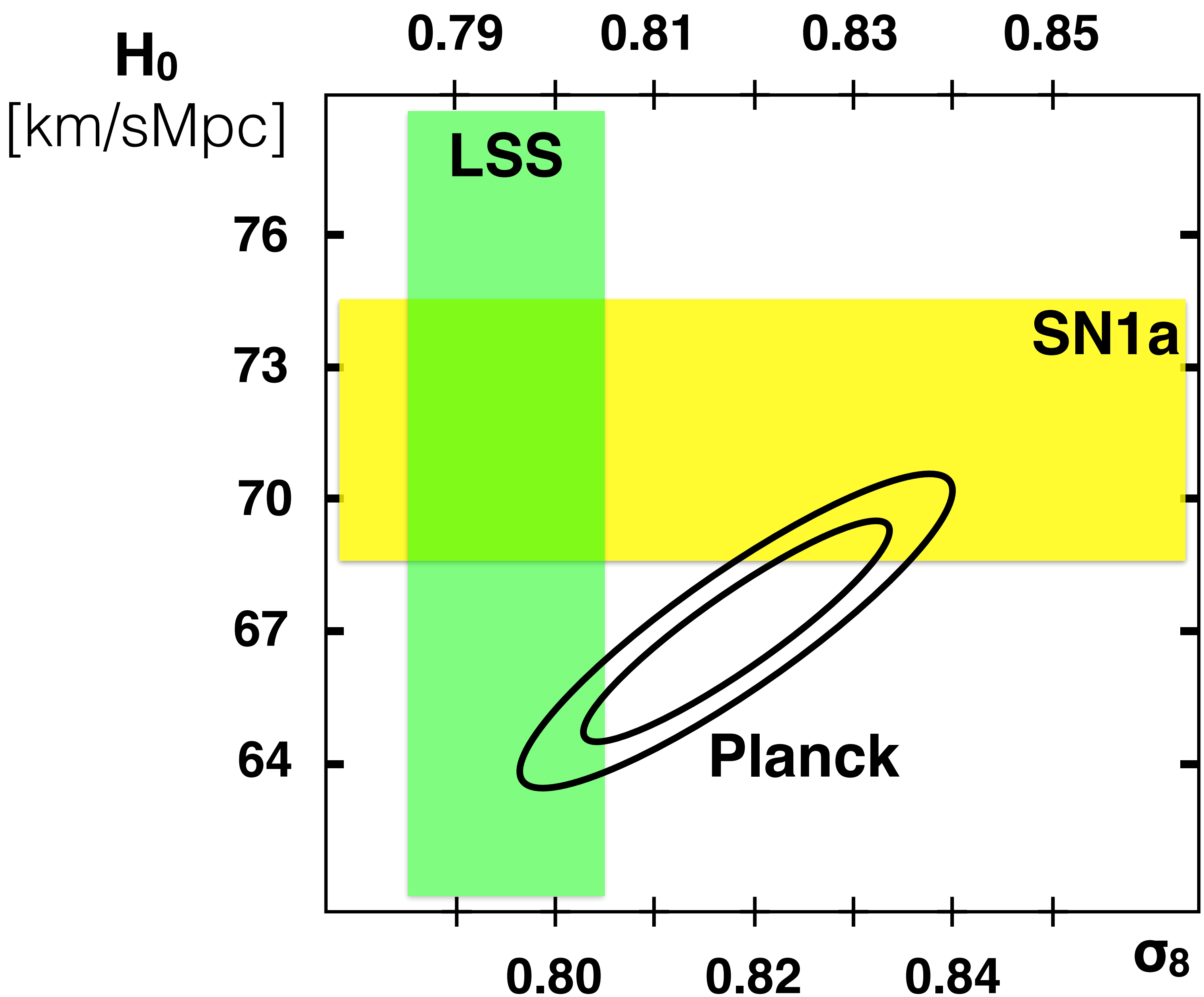
$$H \sim \frac{T^2}{M_{pl}}$$



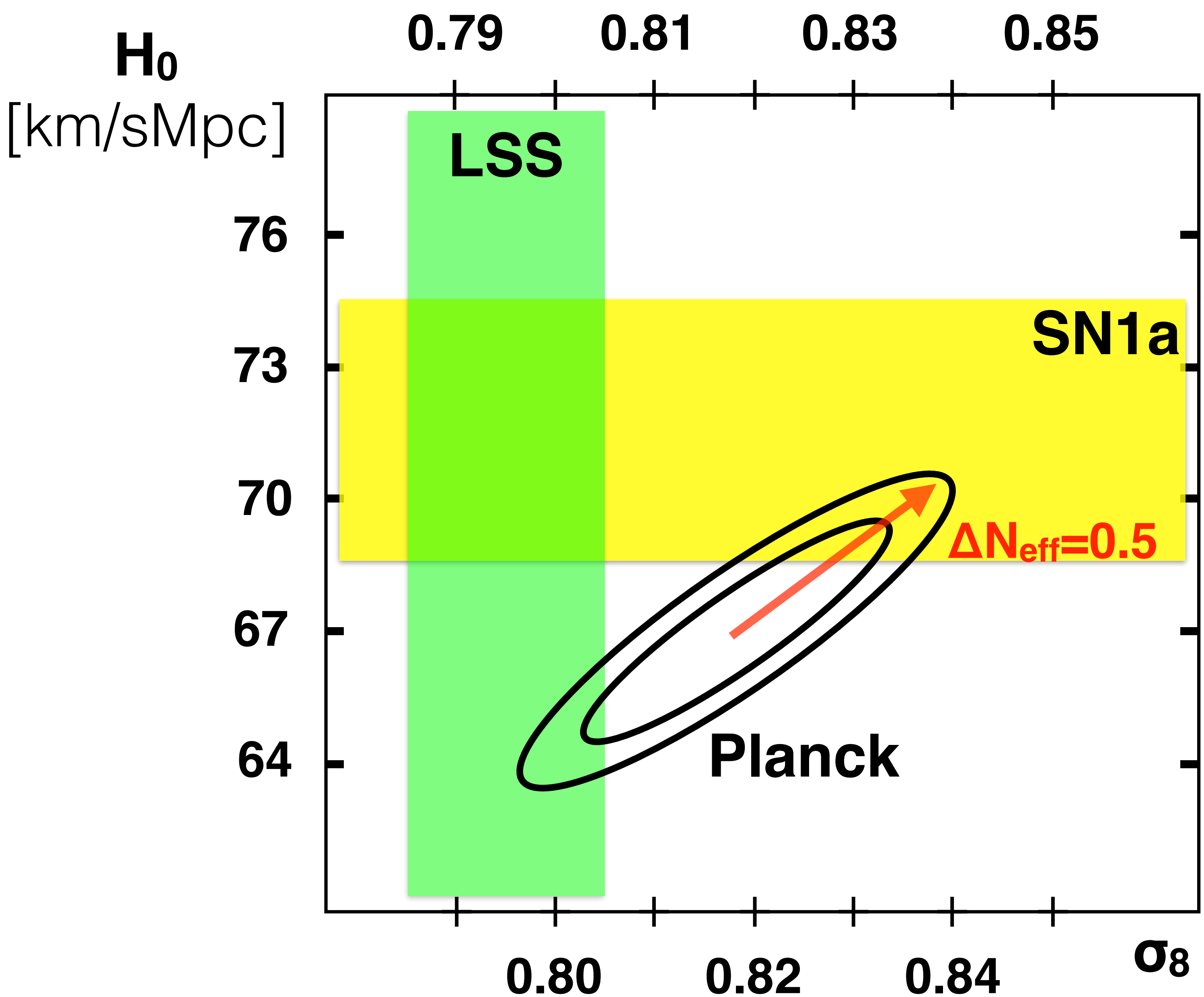
tension in precision data

	σ_8		H_0 $[{}^{km}/_{s\,Mpc}]$	
		ΛCDM		
Planck CMB:	0.831 ± 0.013		67.6 ± 0.6	Planck
Planck lensing:	0.802 ± 0.012		70.6 ± 3.3	SN1a
		"direct"		
LSS combine:	0.795 ± 0.009		73.9 ± 2.7	

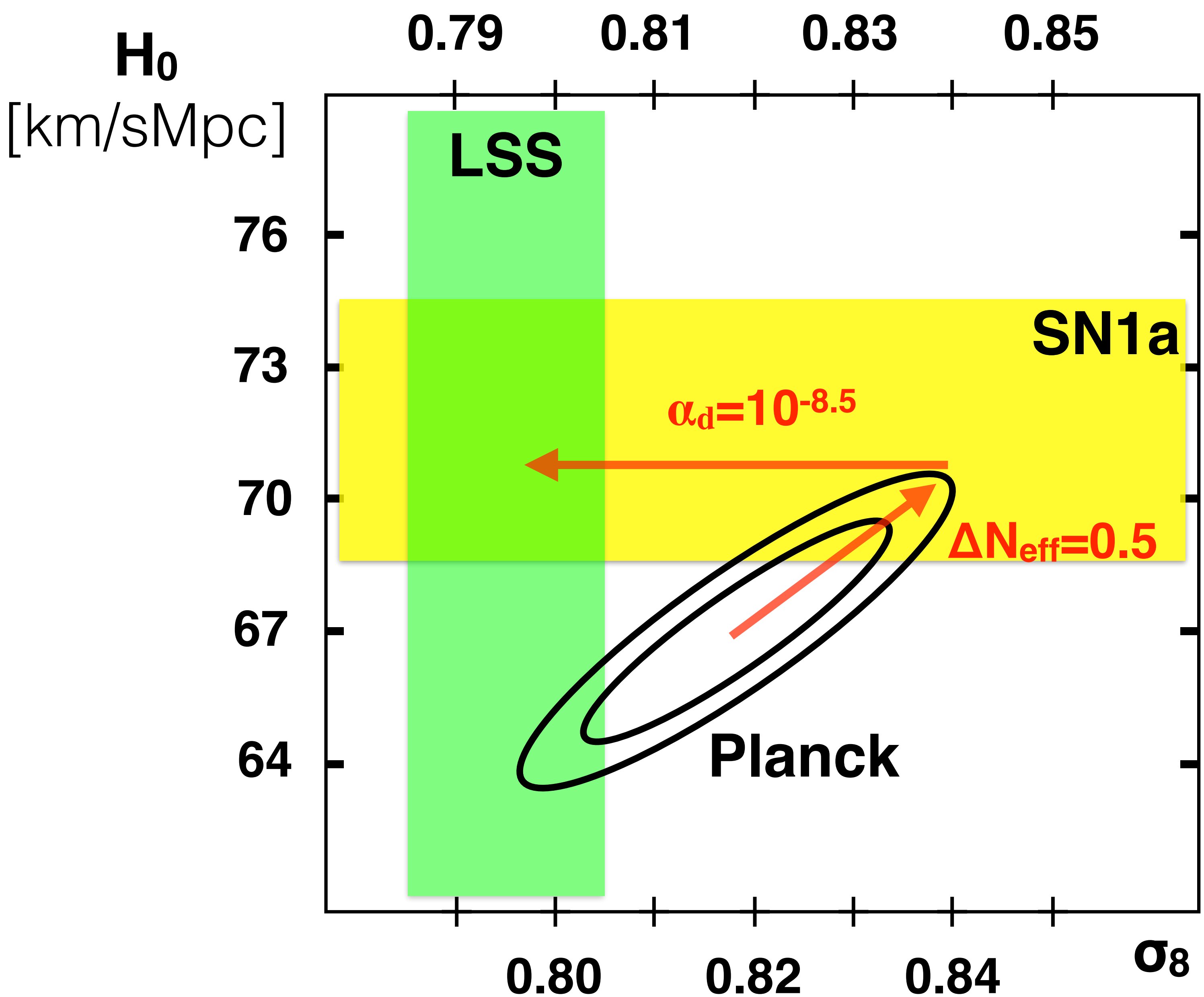
[1409.2769]



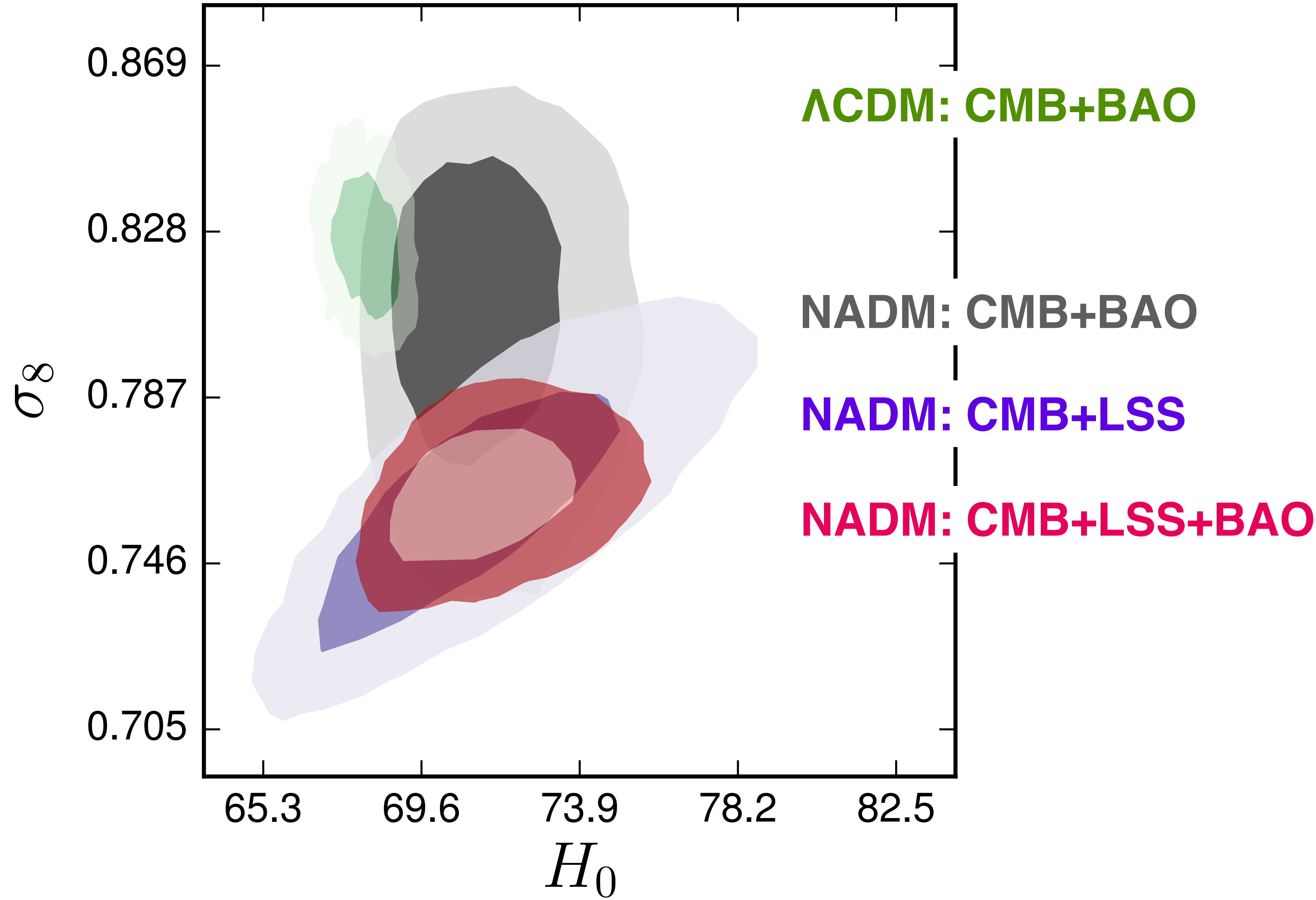
H0
[km/sMpc]
0.79
0.81
0.83
0.85
LSS
76
SN1a
73
70
67
64
Planck
0.80
0.82
0.84
σ8



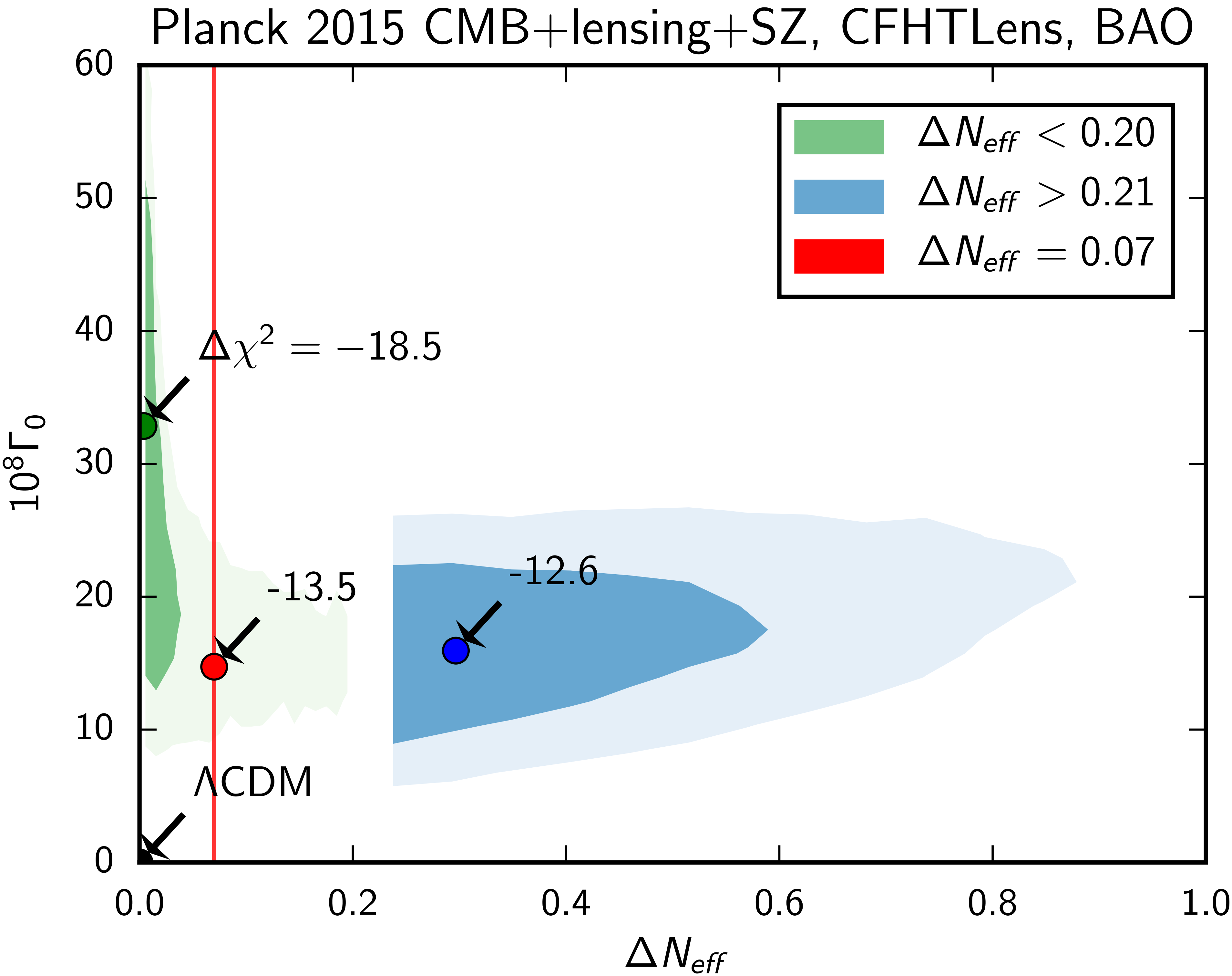
H0 [km/sMpc]
0.79
0.81
0.83
0.85
LSS
76
SN1a
73
70
ΔNeff=0.5
67
Planck
64
0.80
0.82
0.84
σ8



H0
[km/sMpc]
0.79
0.81
0.83
0.85
LSS
76
73
70
67
64
SN1a
αd=10-8.5
ΔNeff=0.5
Planck
0.80
0.82
0.84
σ8



ΛCDM: CMB+BAO
NADM: CMB+BAO
NADM: CMB+LSS
NADM: CMB+LSS+BAO
0.869
0.828
0.787
0.746
0.705
σ_8
65.3
69.6
73.9
78.2
82.5
H_0

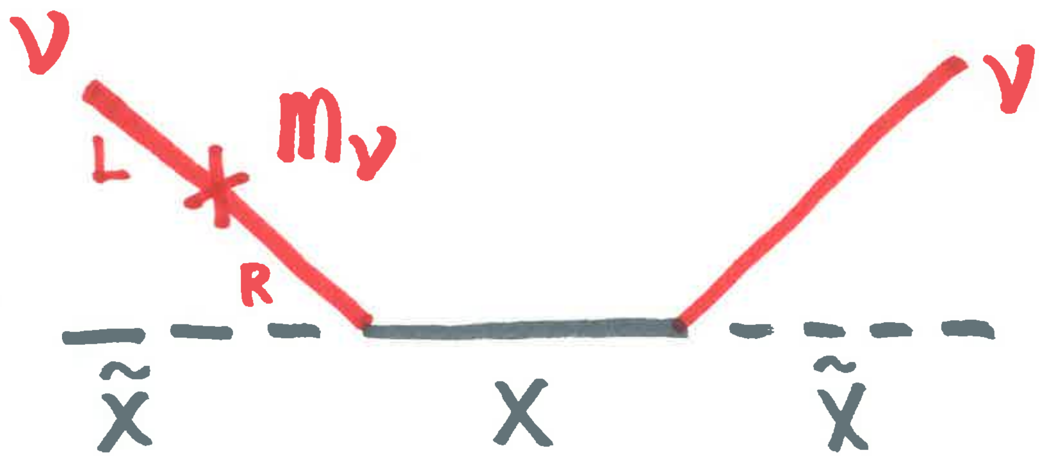


Planck 2015 CMB+lensing+SZ, CFHTLens, BAO
$\Delta N_{eff} < 0.20$
$\Delta N_{eff} > 0.21$
$\Delta N_{eff} = 0.07$
$\Delta\chi^2 = -18.5$
-13.5
-12.6
ΛCDM
$10^8\Gamma_0$
ΔN_{eff}
0
10
20
30
40
50
60
0.0
0.2
0.4
0.6
0.8
1.0

Summary: 3 stories

1. dark matter multiplicity → N-factors
2. self-interacting radiation ΔN_{eff} , 
3. LSS prefers DM drag $> 3\sigma$

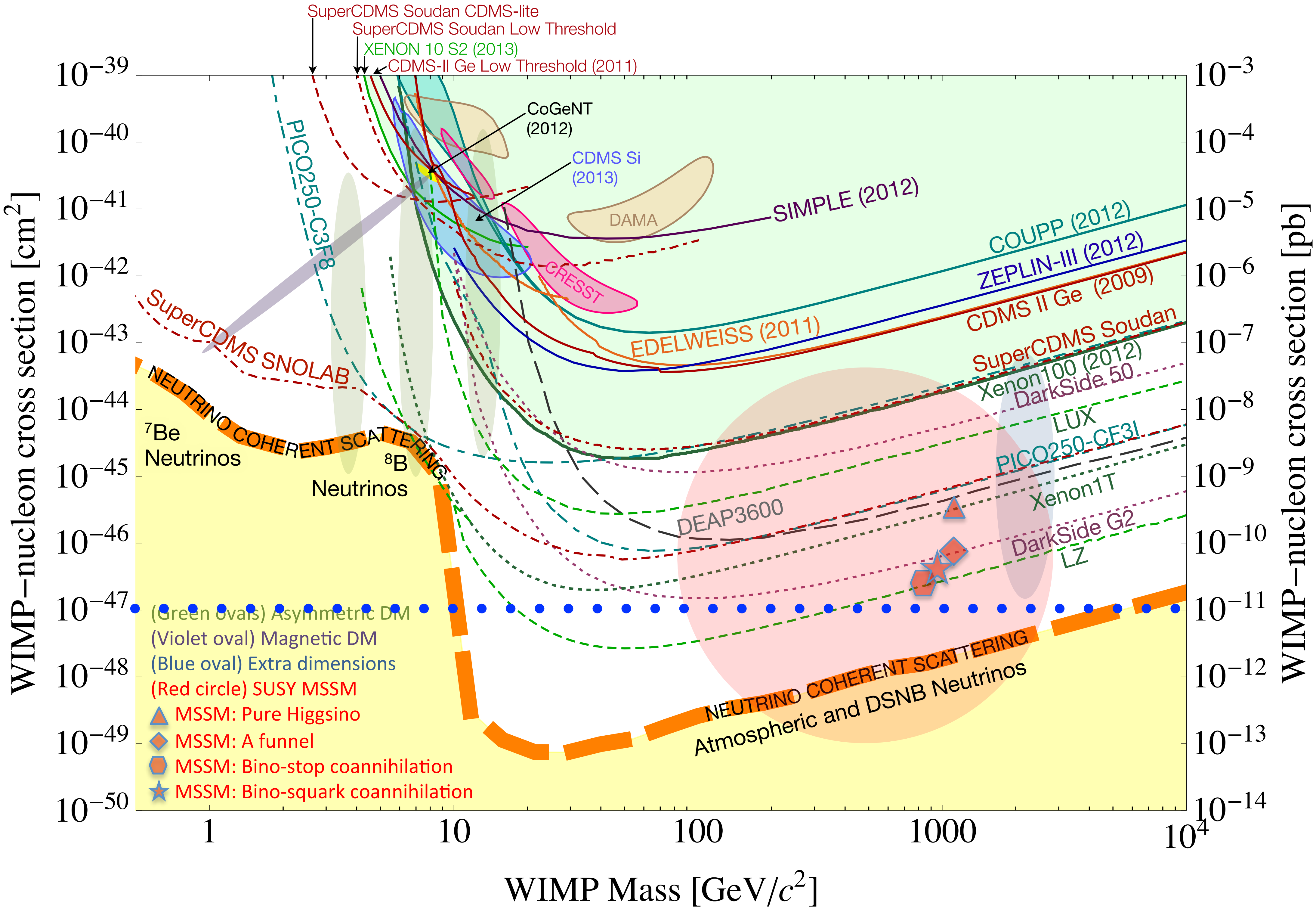
dark matter-neutrino "drag"?



$$\sim \left(\frac{m_\nu}{M_X}\right)^2 \alpha^2 \; \frac{T_\nu^2}{M_X}$$

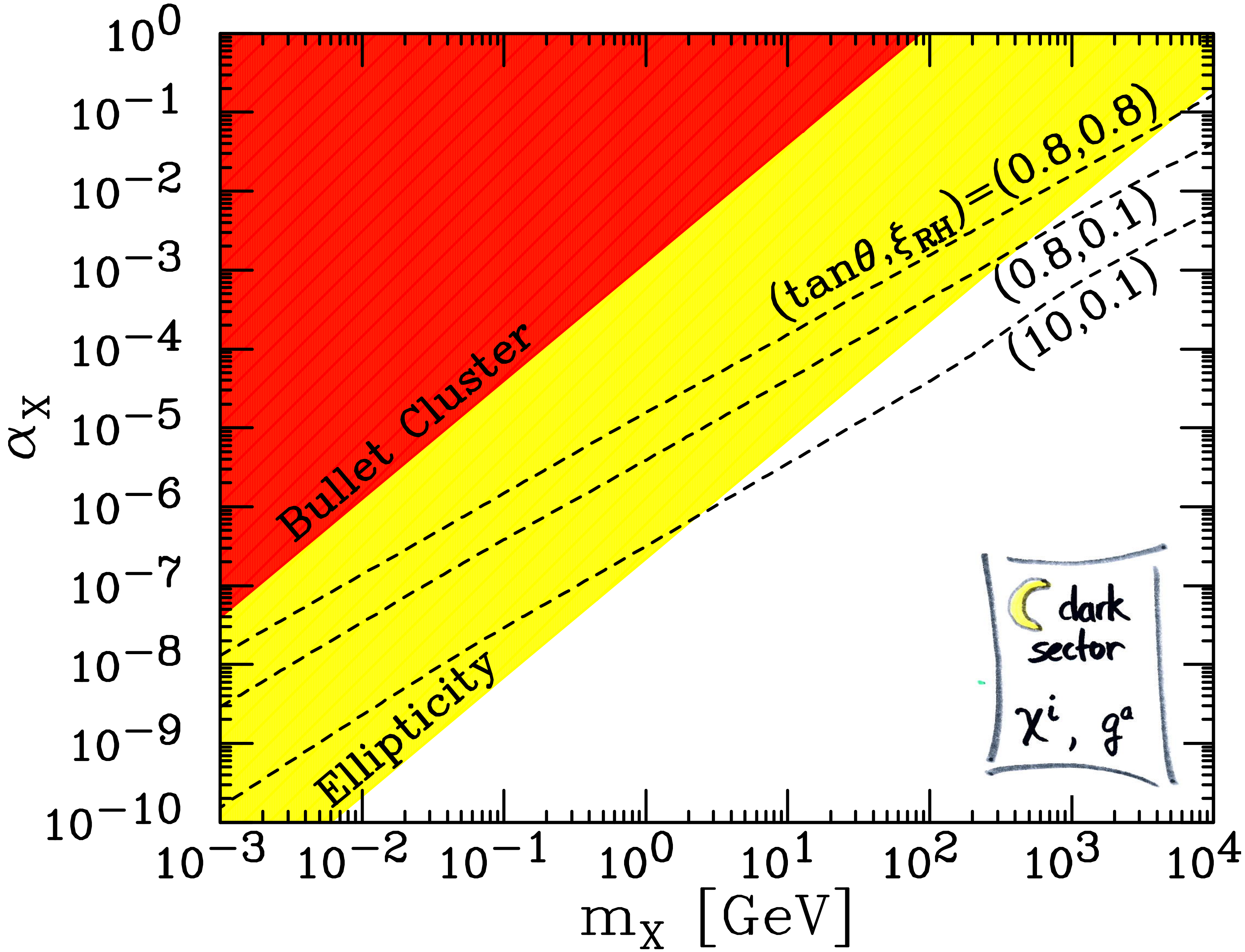
back up!

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



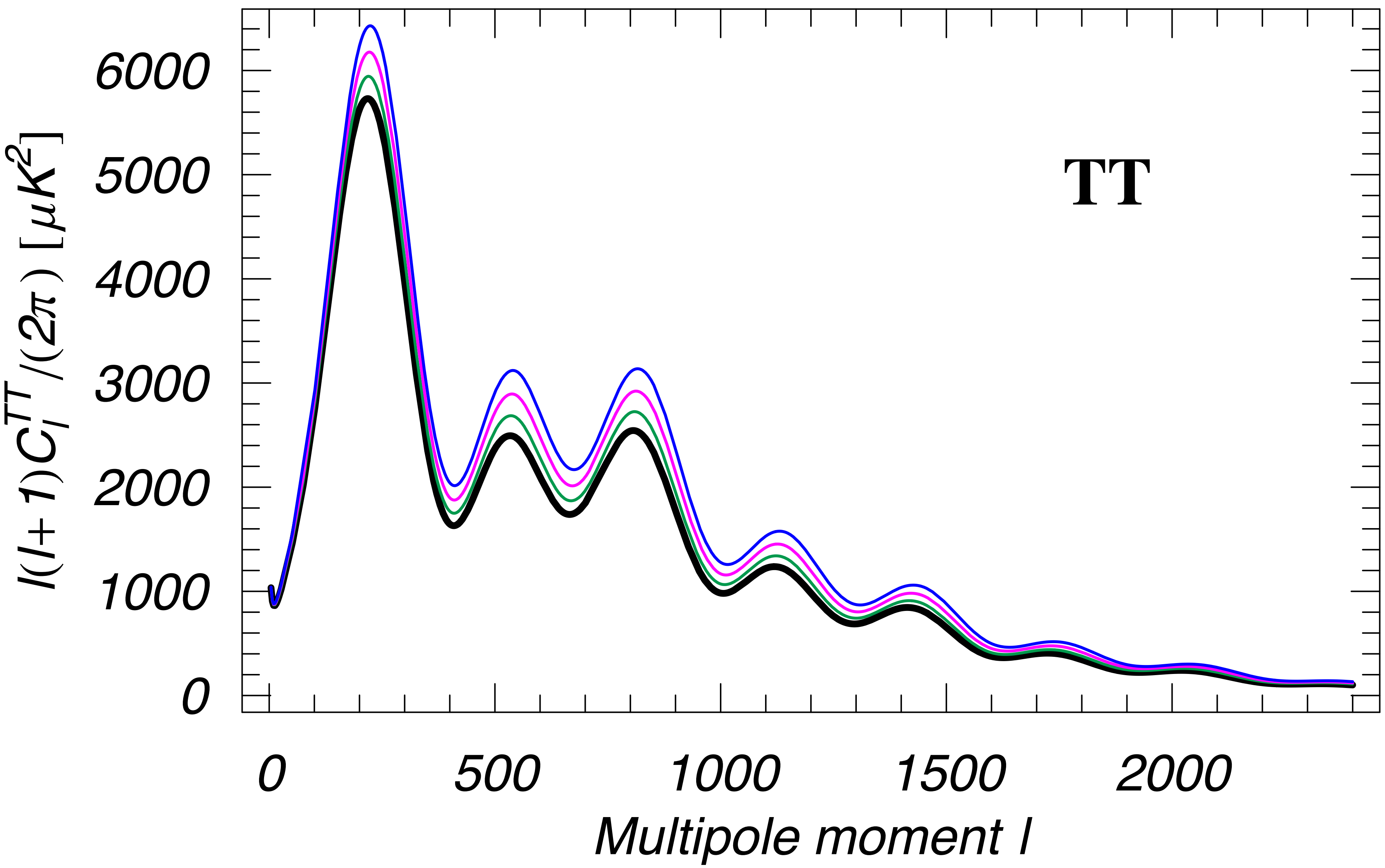
Snowmass CF1 Summary: WIMP Dark Matter Direct Detection arxiv:1310.8327

interacting dark matter bounds



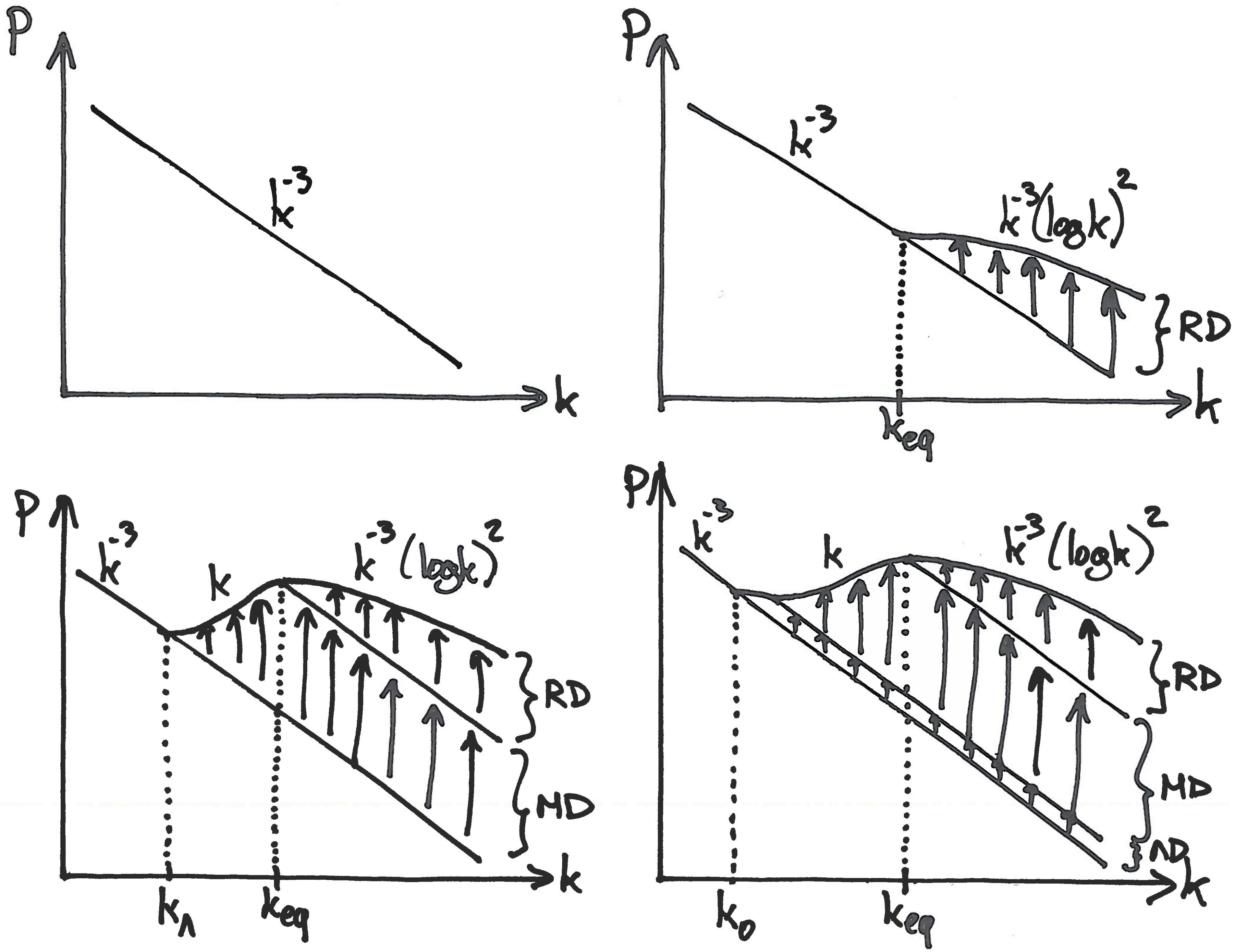
J. Feng, M. Kaplinghat, H. Tu, and H-B. Yu; JCAP 0907 (2009) 004 (arXiv:0905.3039)

CMB and free-streaming ν's



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

ΛCDM growth of perturbations



Julien Lesgourgues, TASI 2012