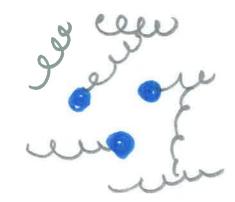
Non-Abelian dark matter and large scale structure

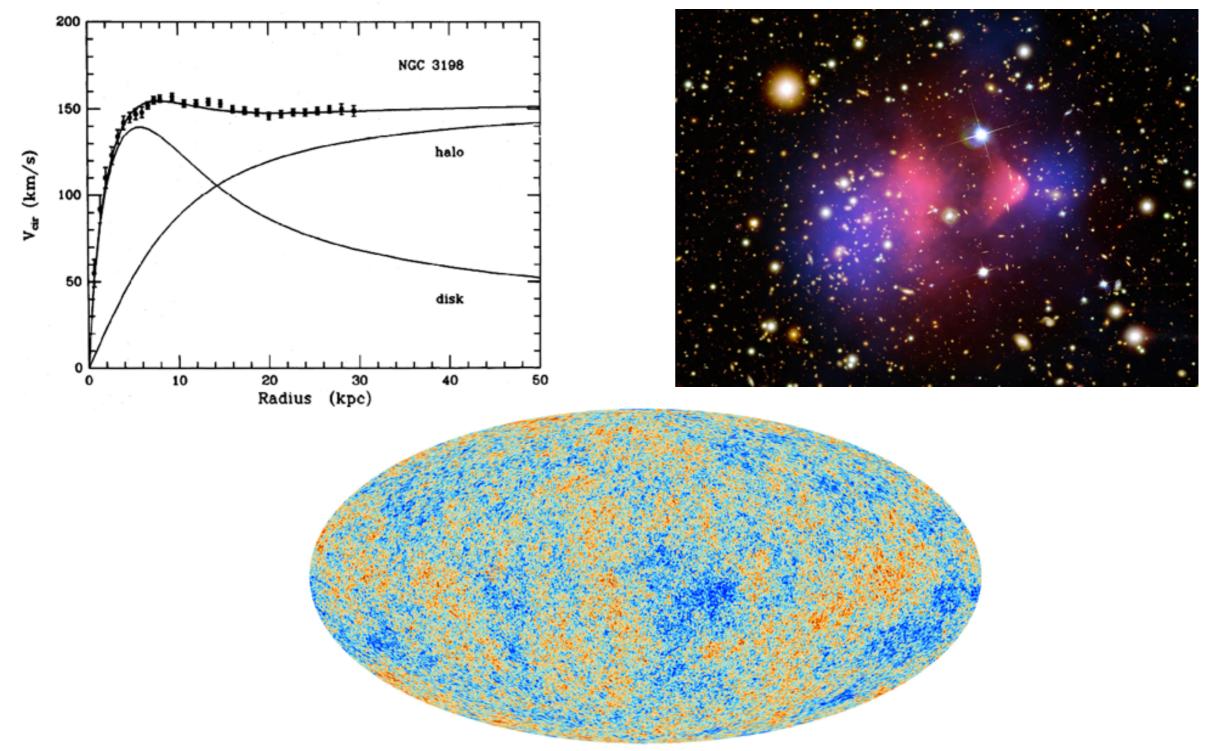
- M. Schmaltz (Boston U.)
- W. G. Marques-Tavares (Stanford) M. Buen-Abad (BU) J. Lesgourgues (Aachen)



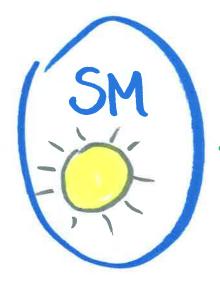
1505.03542

### Dark matter evidence

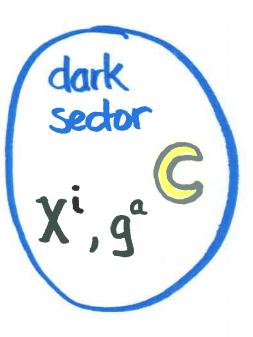
DISTRIBUTION OF DARK MATTER IN NGC 3198



# Dark matter with multiplicity



weak interaction



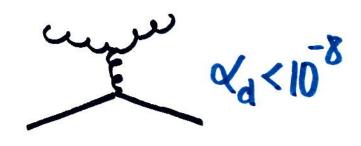
i=1...N  $a = 1...N^2 - 1$  $\propto_{\rm d} \sim 10^{-8}$ 

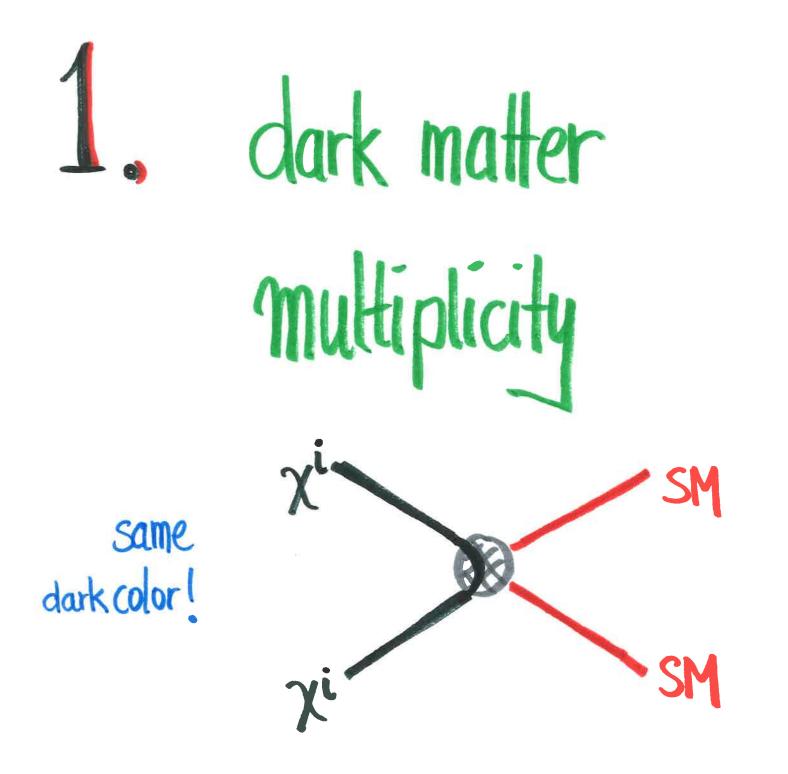
# What is different ?

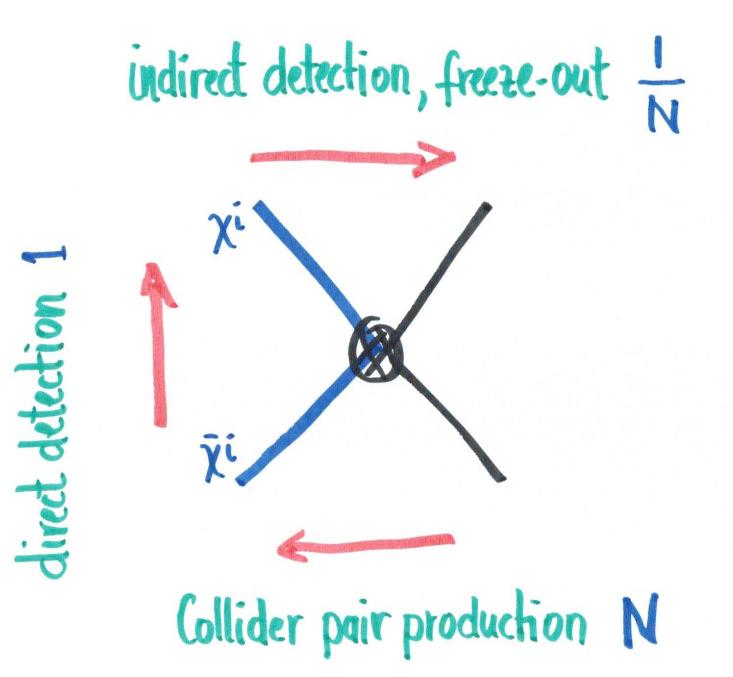
1.  $\chi^i$  i=1...N LHC, DO TEV

2. ga dark radiation (every N<4

3. DM couples to radiation where a < 10"



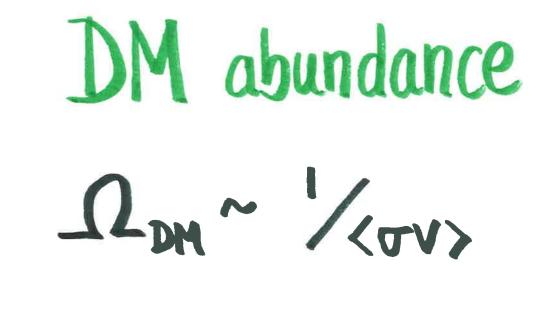




Example: Multiple "winos"  $SU(2)_{W}$  triplet  $\longrightarrow \chi^{\pm i} = \frac{\chi^{\pm i}}{\chi^{\circ i}} = \frac{160 \text{ MeV}}{160 \text{ MeV}}$ 

#### ~ TeV Dirac mass $M \bar{\chi} \chi$

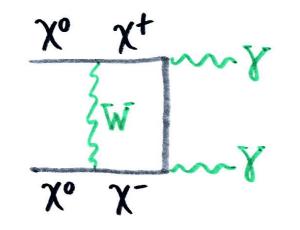
 $\chi^{oi} = \text{dark matter}$ 

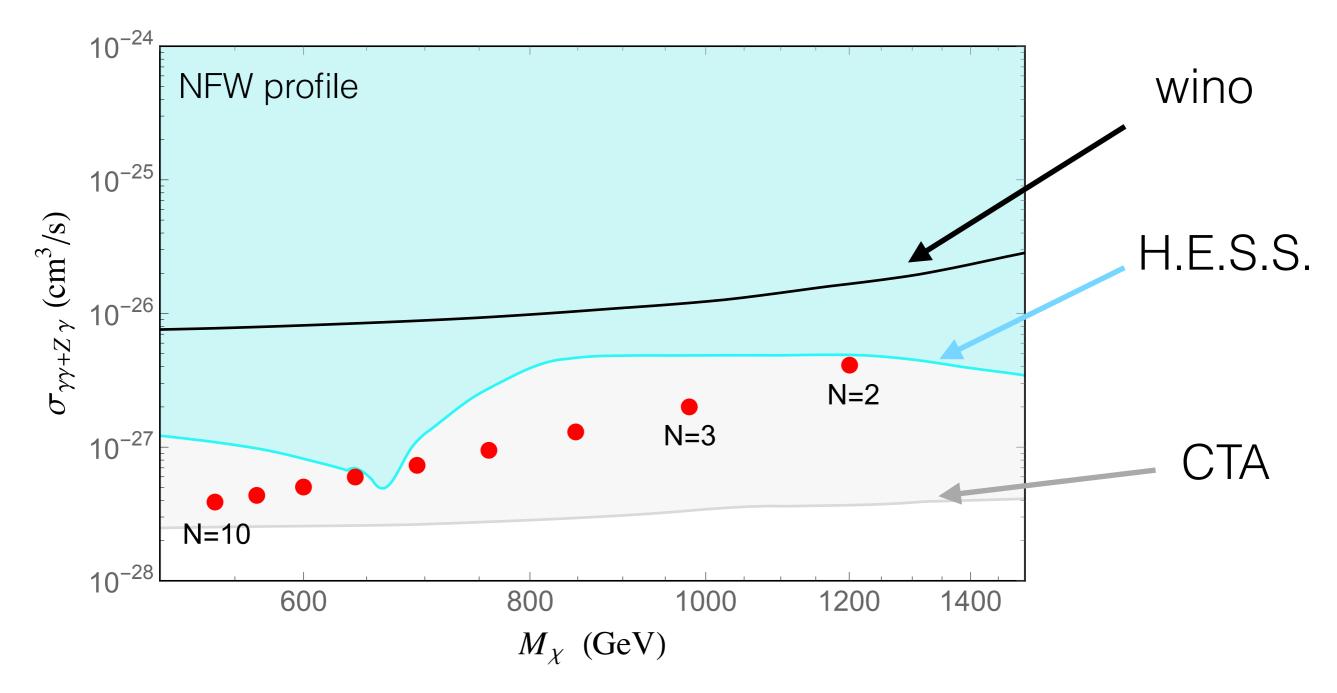


 $\chi^{i}$   $\chi^{i}$ 

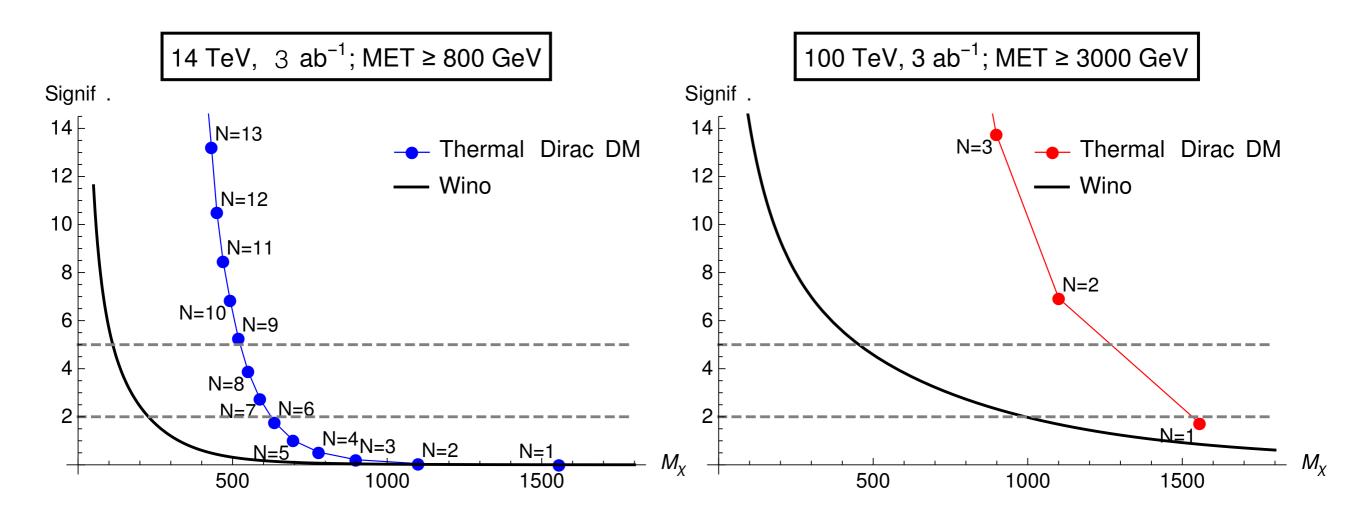
 $\implies M_{\chi} = M_{\chi}^{N=1} / \sqrt{2N}$ 

# Indirect detection





Colliders: mono-jets



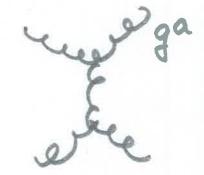
HL-LHC

100 TeV

jet



2. dark gluons



3. dark matter drag & large scale structure

### Cosmology primer to determine if a process is important (ompare : process Hubble VS. reger N<5v>

Thermal history SM+DS equilibrium X TeV Mx X freeze-out SM 10 eV today DS 2.7K 1.0 K

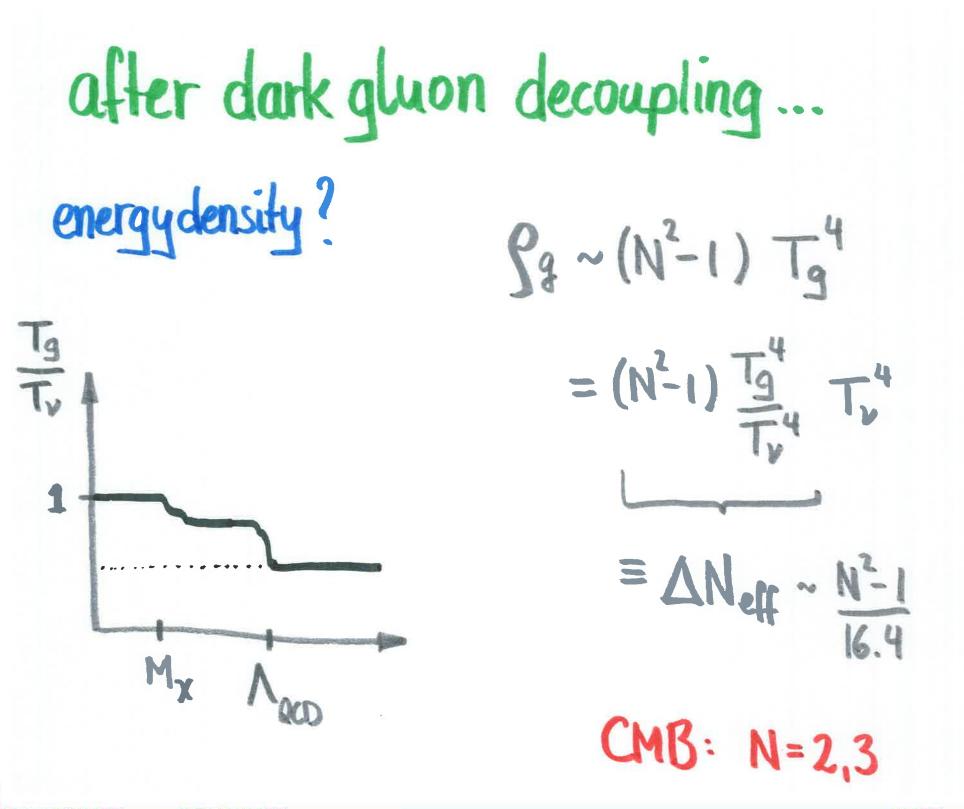




#### radiation: massless, weakly coupled $\Lambda_{aco}^{"} \ll Hubble$

are dark gluons in equilibrium?  $(T \sim m_{\chi})$  $\frac{v_{t}}{x^{t}}$   $\int -n_{\chi}\langle \overline{v} \rangle \sim T^{3} \frac{ddem}{T^{2}}$ H~T' Moe  $\Gamma > H \Rightarrow \alpha_d > \frac{1}{\alpha_{em}} \frac{m_x}{M_{pe}} \approx 10^{-5}$ 

gluons in equilibrium @ 10 Gev? [~ ηχ (σν)~ [0" τ3 dddem N<sup>2</sup> H~ I Mpe



would require the sta os by capture on tritium, for ized or additional pl speriment (Coccoret a Cosmological parameters but where the structure of the st Col<mark>l</mark>aboration: ). Unfortunately, for the mass Figure  $f e^{\frac{7}{4}} e^{\frac{4}{3}} p_{\gamma}$ . Shows by *Planck*, detection with the The numerical factors in this equation are included so that Neff Nem= 3 foi three stude 2 mode Advernes khat were the work P e diffiçult. posplaneknäilliborationalardi oppologias sogediction is actually  $N_{\rm eff} = 3.046$ , since neutrinos are not completely decoupled at electron-positron annihilation and are subsequently slightly heated (Mangano et al. 2002). In this section we focus on additional density from mass- $[km s^{-1} Mpc^{-1}]$ less particles. In addition to massless sterile neutrinos, a variety of other particles could contribute to  $N_{\rm eff}$ . We assume that the additional massless particles are produced well before recombi-72 nation, and neither interact nor decay, so that their energy den-site scales with the expansion excells like massless neutrinos. At relational  $\Delta V_{eff}$  = D could correspond to zeally thermal-ized sterile neutrino that decoupled at  $T \leq 100$  MeV; for ex- $\int$  les from *Planck* TT+lowP chains in the  $N_{\rm eff}$ coded by  $\sigma_8$ . The grey bands show the constraint 2 (30.6 ± 3.3) km s<sup>-1</sup>Mpc<sup>-1</sup> of Eq. (30). Note that higher ample any sterile neutrino with mixing angles large enough to provide a potential resolution of short baseline reactor neutring ings  $H_0$  into better consistency with direct measurements, out increases  $\sigma_8$ . Solid black contours show the constraints from Hation anomalies would most likely thermalize rapidly 66 early Universe. However, this solution to the neutrino oscillation *Planck* TT, TE, TE+lowP+BAO. Models with  $N_{\rm eff}$  < 3.046 (left Gniverse If the solid tentic l/line) require bhoten heating after neutrino decoupling or incomplete the mainzation. Dashed vertical lines correspond to specific fully-thermalized particle models, for exanomalies requires approximately 1 eV sterile neutrinos, rather than the massless case considered in this section; exploration of two parameters/<del>1/of</del> asi 2/m, is expired in Sect. 6.4.3 For eview of stende neutrinos see Abazapan eval. (2012). one additional massless loson that decoupled around the interast he beautinos ( $\Delta N_{\rm eff}$  1).S),  $\Delta h$  buoref finuton lation ( $\Delta N_{\rm eff} \approx 0.39$ ), or an additional sterile neutrino cotal relativistic Mare Amerally the additional radiation does not need to be fully thermalized, for example there are many possible models of non-thermal radiation production via particle decays (see e.g., that decoupled around the same time as the active neutrinos diation Hase kamp & Kersten 2013; Conlor & Marsh 2013). The adiation could also be produced at temperatures  $T \ge 10$  NeV, in which case typically  $\Delta N_{\text{eff}} < 1$  for each additional species, March 3, 15 3.5 2.5 2.0 3.0 3.5 4.0 4.5 A larger range of neutrino masses was found by Beutler et al. since heating by photon production at muon annihilation (at  $T \approx 100$  MeV) decreases the fractional importance of the ad-(2014) using a combination of RSD, BAO, and weak lensditional component at the later times relevant for the CMB. For ing metration. The tension between the RSD results and particles produced at  $T \gg 100$  MeV the density would be dibase ACDM was subsequently reduced following the analysis luted even more by numerous phase transitions and particle anniof Samushia et al. (2014), as shown in Fig. 17. Galaxy weak hilations, and give  $\Delta N_{\rm eff} \ll 1$ . Furthermore, if the particle is not lensing and some cluster constraints remain in tension with base fermionic, the factors entering the entropy conservation equation

> Another way of potentially improving neutrino mass constraints is to use measurements of the Ly $\alpha$  flux power spectrum

problems in Sect. 6.4.4.

 $\Lambda$ CDM, and we discuss possible neutrino resolutions of these

fractional values of  $\Delta N_{\text{eff}}$ . For example Weinberg (2013) considers the case of a thermalized massless boson, which contributes  $\Delta N_{\text{eff}} = 4/7 \approx 0.57$  if it decouples in the range 0.5 MeV < T < 100 MeV like the poutrinos, or  $\Delta N_{\pi} \approx 0.20$  if it decouples at

are different, and even thermalized particles could give specific

### important difference to v's : 9 selfinteractions

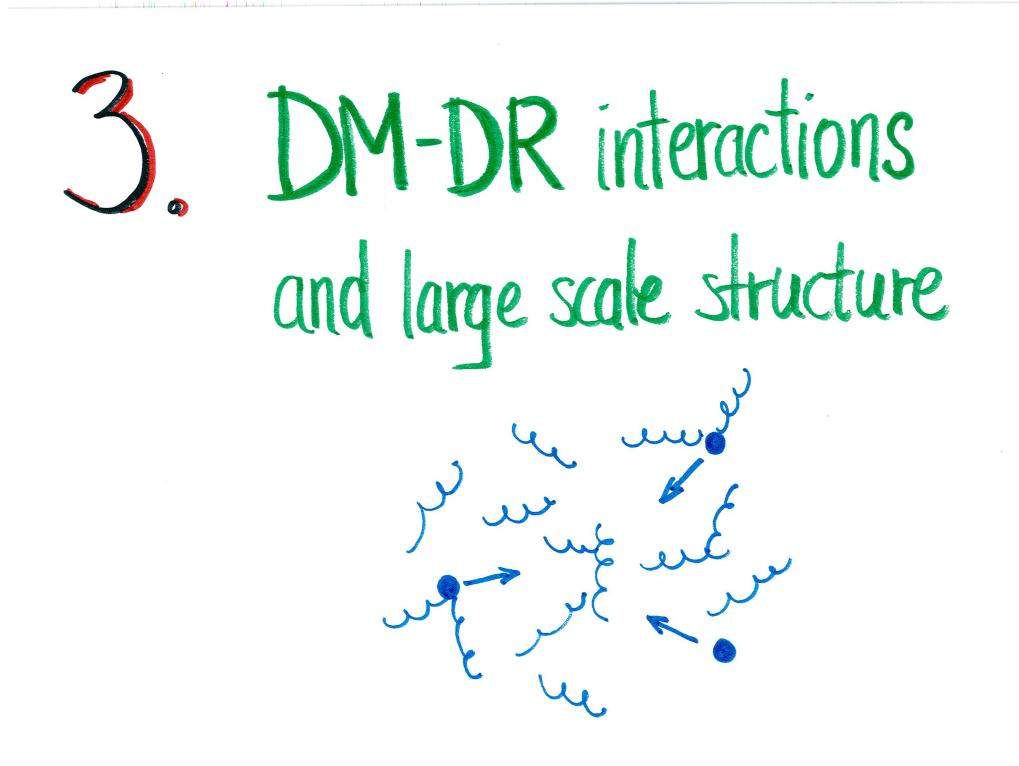


dark gluons do not free-stream ---- "perfect fluid "

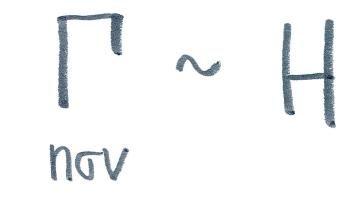
CMB can distinguish!

# 2. dark radiation summary

- perfect fluid for 10<sup>-13</sup>< d\_< 10<sup>-2</sup>, T~1K
- $\Delta Neff < 0.5 \implies N = 2,3$
- Planck can distinguish [ perfect free-streaming



# is DM coupled to DR fluid?



te p and

DM-DR coupling Kurrer K  $N\langle \sigma v \rangle \approx$  $\int d^{3}k f(k,T) \int d^{3}k' d^{3}p' \int (zp) \frac{1}{(k-k')^{4}}$ IR+collinear divergent

# Soft ] scatters matter very little

weigh by momentum transfer kunnerk' P P'

 $\vec{P} \sim \left( d^3 k f(k,T) \int d^3 k' d^3 p' \int M \left[ M \right]^2 (\vec{p}' - \vec{p}) \right]$  $\sim - \Gamma_p \vec{p}$ 

# Momentum transfer rate $\Gamma_{p} = \frac{P}{P} \sim \alpha_{d}^{2} \log \frac{1}{\sqrt{d}} \frac{T_{g}}{M_{\chi}}$ drag Debye cutoff

# Momentum transfer rate

 $\Gamma_{\rm P} \sim \alpha^2 \log \frac{1}{2} \frac{T^2}{M_{\rm X}}$  vs.  $H \sim \frac{T^2}{M_{\rm Pl}}$ 

-- X~10" interesting" Hroughout radiation domination

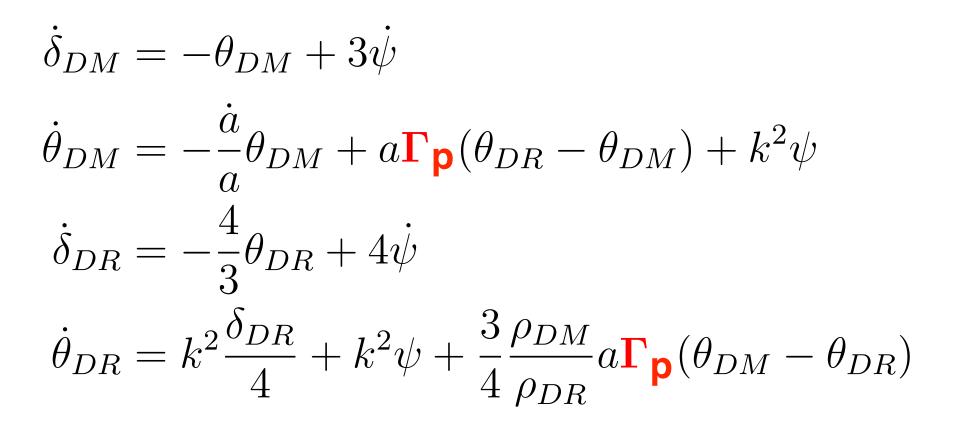
# linear perturbations in fluids

S density pert. O velocity pert.

DM, DR, SM V V, V, B

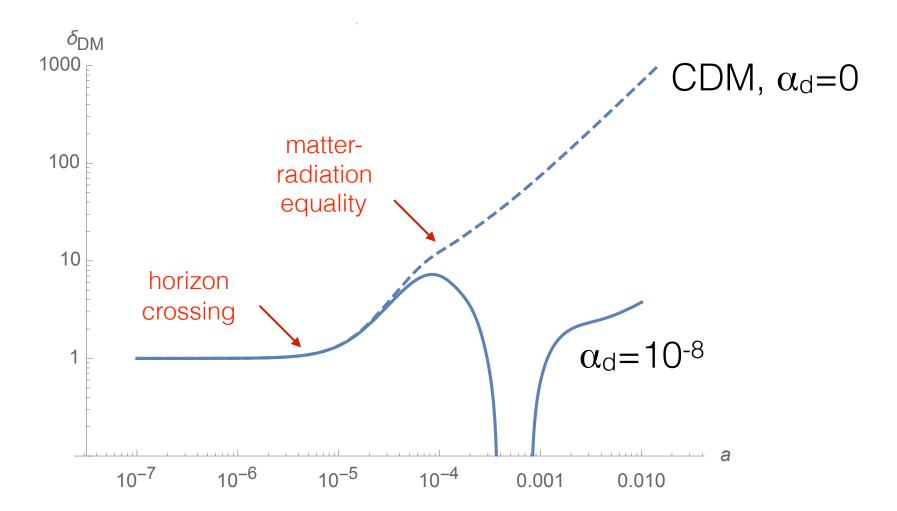
- •
- 2

#### linear perturbations



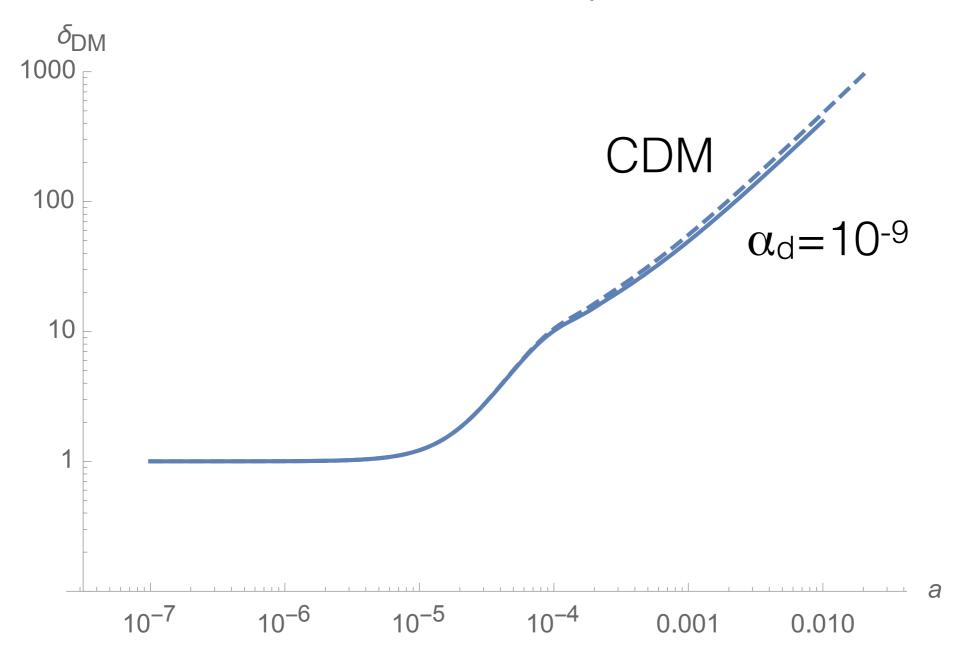
#### growth of perturbations

k=0.2 Mpc<sup>-1</sup>

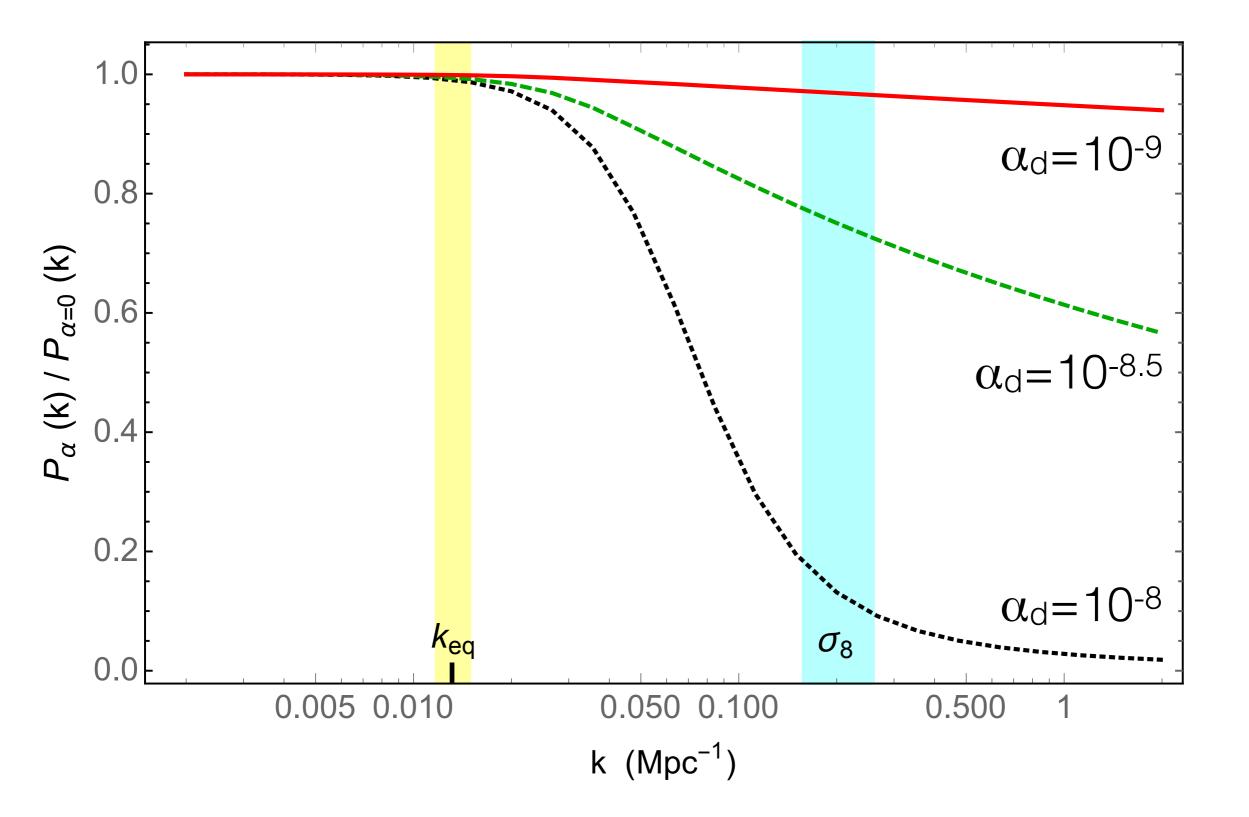


# growth of perturbations

k=0.2 Mpc<sup>-1</sup>



#### power spectrum change



 $10^{-3}$ 10-2 10-1 10<sup>0</sup>  $10^2 \text{ m}^3 \text{GeV}^4$ 10<sup>1</sup>  $m_x$  [GeV]  $m_x = 1$  TeV -FIG. 1: Alternal MegKanslinghat,  $\alpha_X$ ,  $\alpha_X$  plane, 10 GeV  $m_X$ -is-the ma ed regionender the Haru) and H. Ryhere sactoris U(he) ENASSION the starkic mart con roken Shidden with WMAyrsten indications with WMAyrsten smologian (the charting) consisters, with, WMAR Orbsults, 0.1, h? dashetl), free  $_{\rm H}) = (\sqrt{3/5}, 0.5), d(d/3/2), ions), a(e0, dis favorashbar), constraint starburthe, Builder$ gions arentus ationed (dardoned) and ftom other Badlelligtister abgelaationsa lark red Tabel Bullet Benster and tellingticity and statist area derived in Section ister and ellipticity constraints are derived in Secs. VIII and VII, respectivel of the parameter space of these models are excluded because t eter space of these condicts with extra to estimate the predicted minimum flict with observation, we analyze the kinetic decoupling of hidder tion, we 19 abjzed file kunet is the soupling with the part charge data and the and the source betweek that with the anti-here and here an dark matter interacts For they concord find weathing the the the the twinter the the twinter twitter twinter twinter twinter twinter twinter t For the case of  $\tilde{\tau}^h$  dark on anter, through the weak the desk  $\tilde{\tau}^h_{\rm m}$  atter  $\tilde{\tau}^h_{\rm e}$  in but also the not only through the weak sr  $\tilde{\sigma}^h \tilde{v}^h \tilde{v}^h$ Tuesday, March 3, 15  $\tilde{\tau}^h \gamma^h \leftrightarrow \tilde{\tau}^h \gamma^h$ . SASTIVE will suppressed them Feraltures, the this mapping is weather the process  $\tilde{\tau}^h \gamma^h \leftrightarrow \tilde{\tau}^h \gamma^h$ . SASTIVE will suppress the this mapping the the process  $\tilde{\tau}^h \gamma^h \leftrightarrow \tilde{\tau}^h \gamma^h$ .

 $10^{10}$   $10^{-3}$   $10^{-2}$   $10^{-1}$   $10^{-1}$ 

10

Bullet Clus

Ellipticity0-9

 $\overset{
m \varkappa}{_{\rm V}} 10^{-5}$ 

 $M_{DM_{10}}^{30}$ 

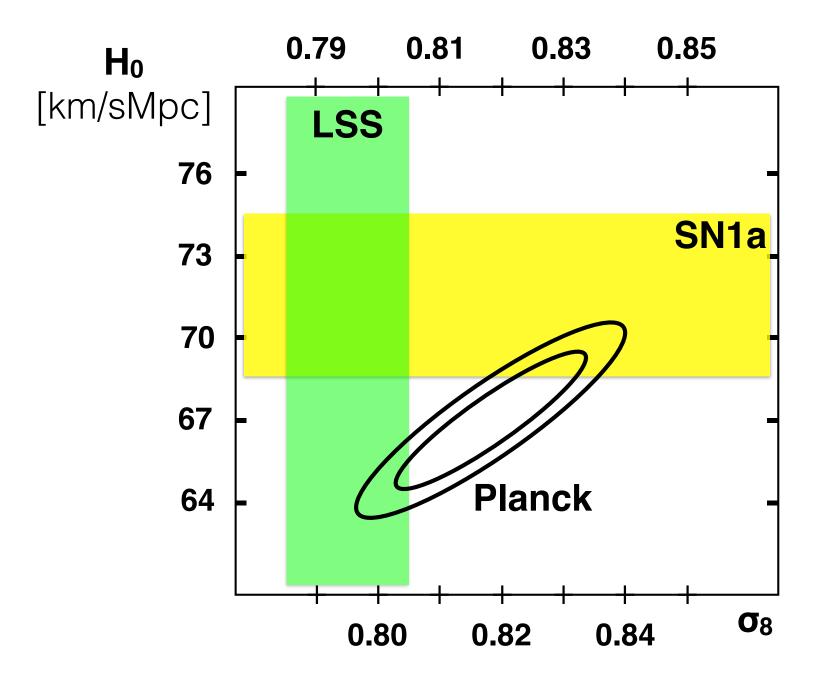
 $10^{-10}$ 

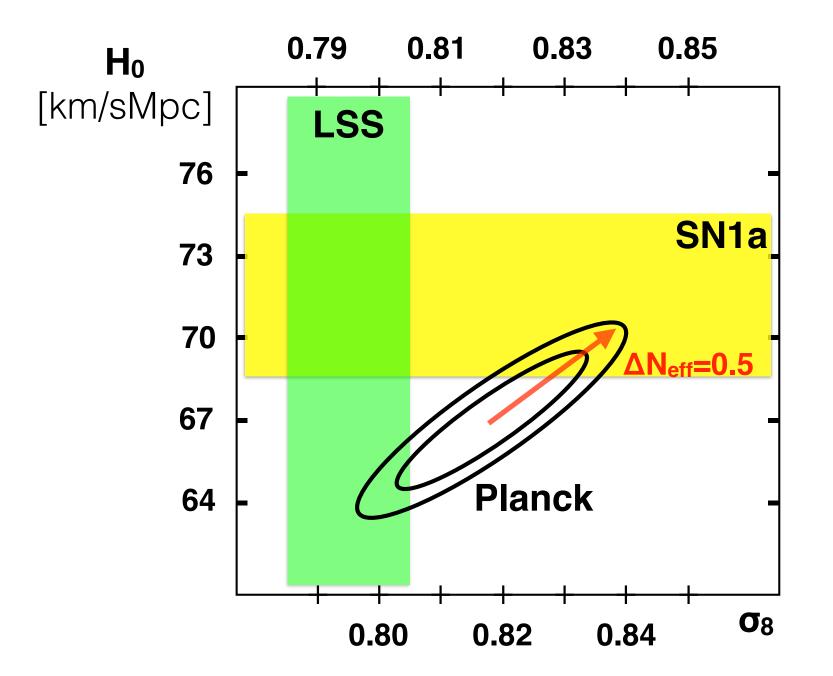
dark U(1) $\alpha \frac{27}{10}$ 

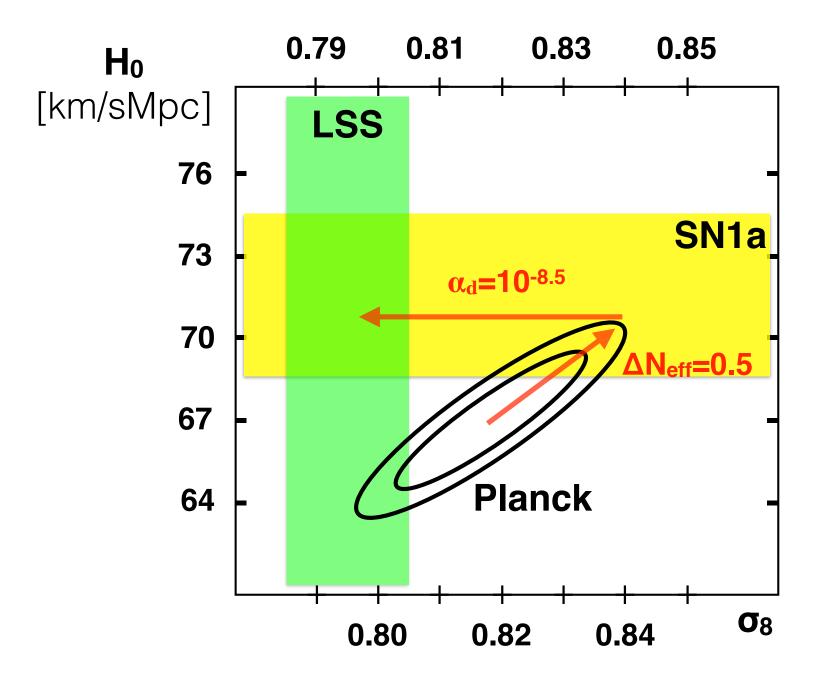
<sub>10</sub>-6

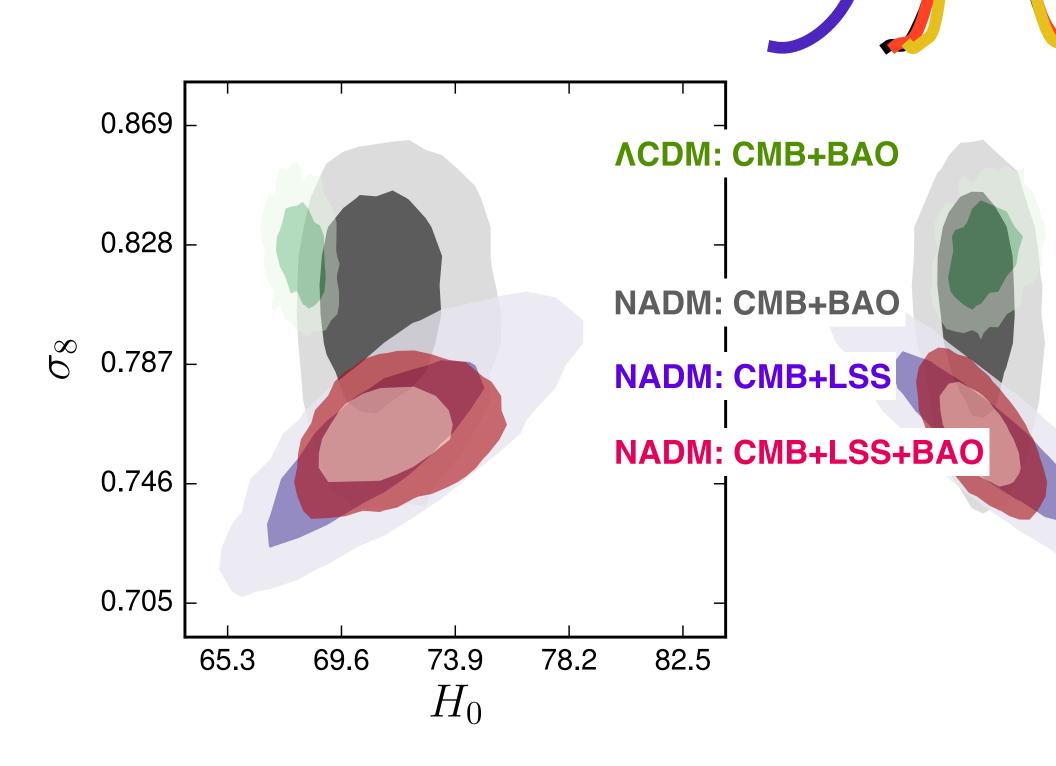
1 dreating/ a large quilitative difference between this case and the

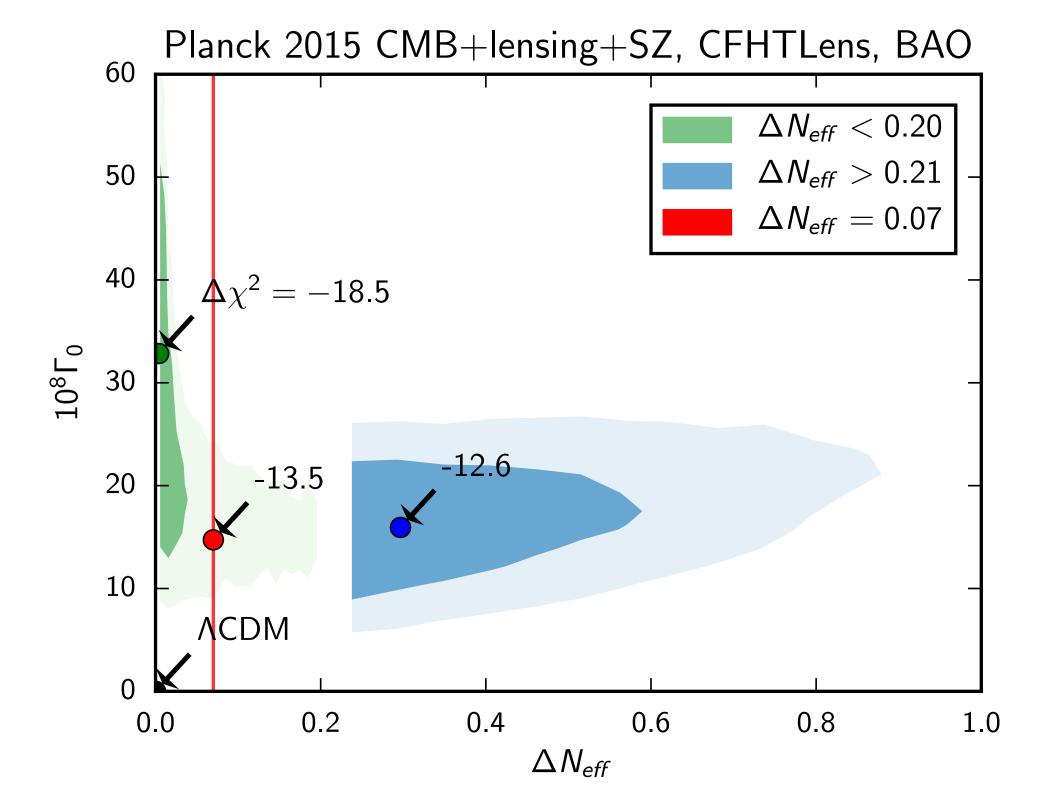
## tension in precision data T<sub>x</sub> H. [km/sMpc] **ACDM** Planck CMB: 0.831 ± 0.013 - 67.6 ± 0.6 Planck Planck lensing: $0.802 \pm 0.012 \times 70.6 \pm 3.3$ "direct" LSS combine: $0.795 \pm 0.009$ ~ 73.9 ± 2.7 SN1a [1409.2769]







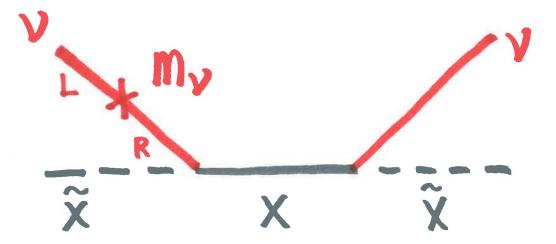




# Summary: 3 stories

- 1. dark matter multiplicity -> N-factors
- 2. self-interacting radiation ANeff, Sue
- 3. LSS prefers DM drag >35

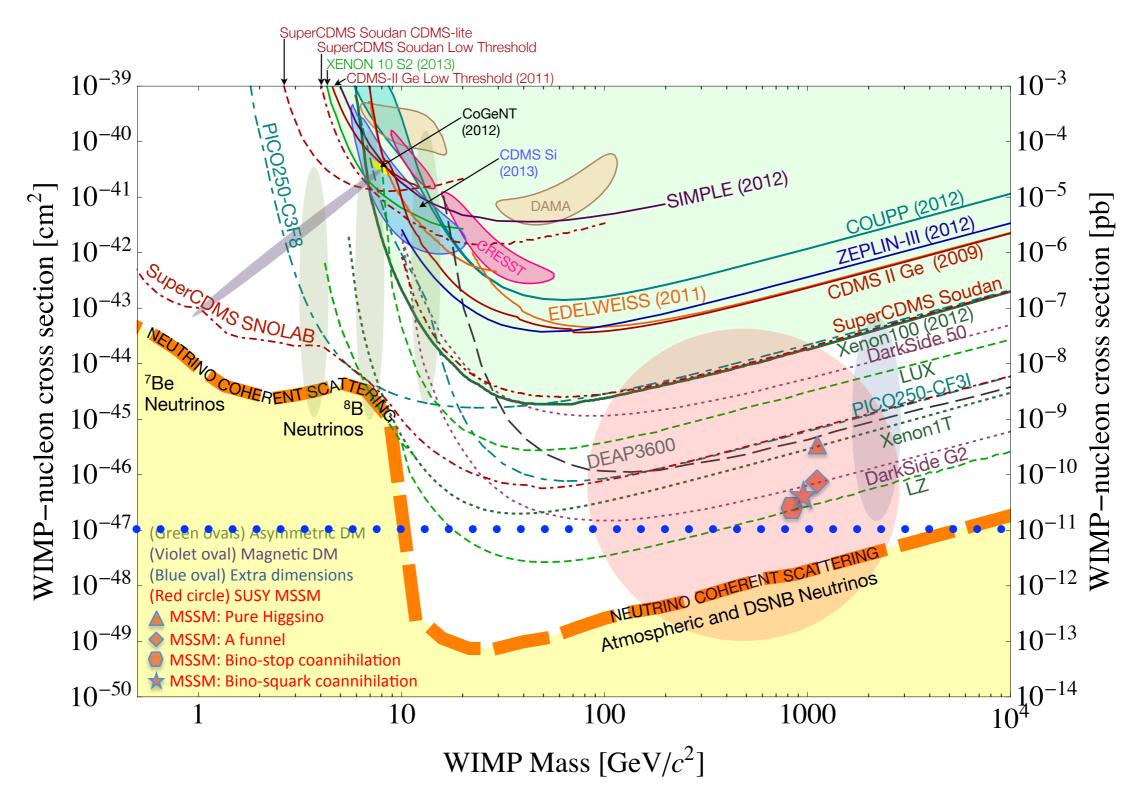
# dark matter-neutrino "drag"?



$$\sim \left(\frac{m_v}{M_x}\right)^2 \alpha^2 \frac{T_v^2}{M_x}$$

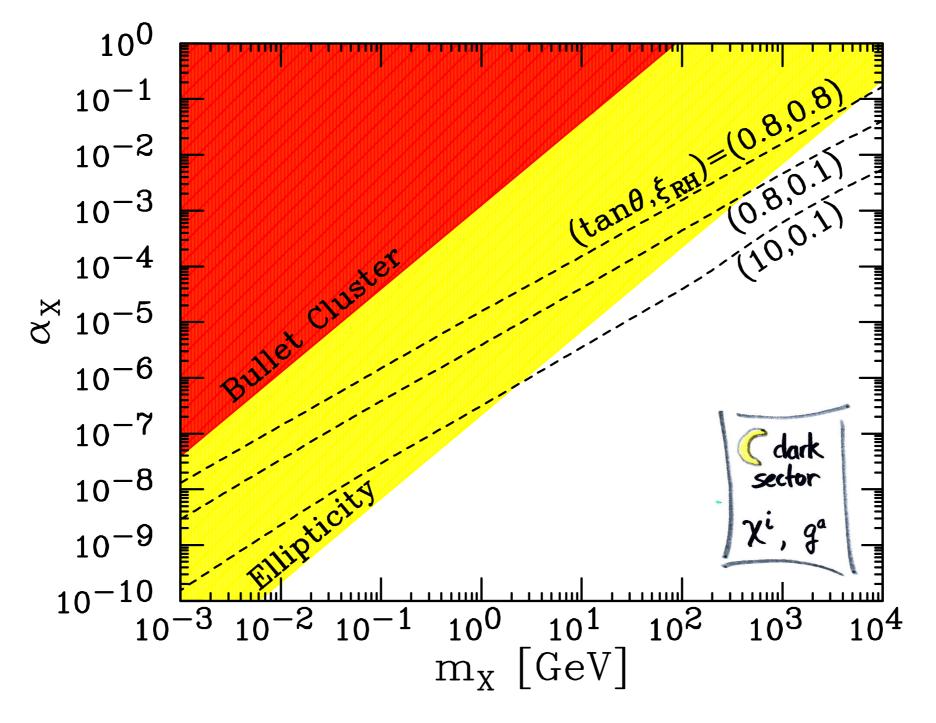
back up!

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



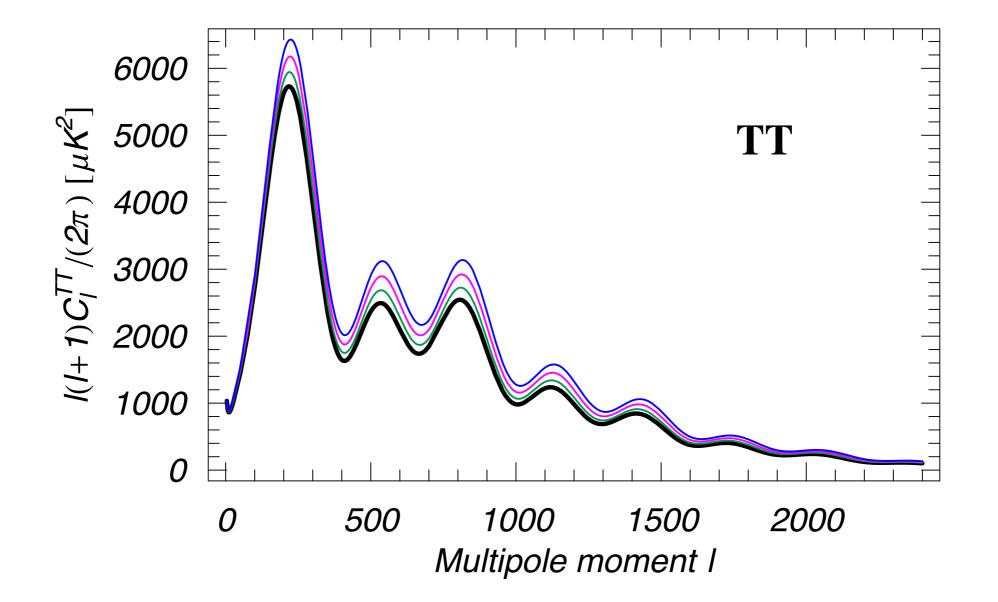
Snowmass CF1 Summary: WIMP Dark Matter Direct Detection arxiv:1310.8327

### interacting dark matter bounds



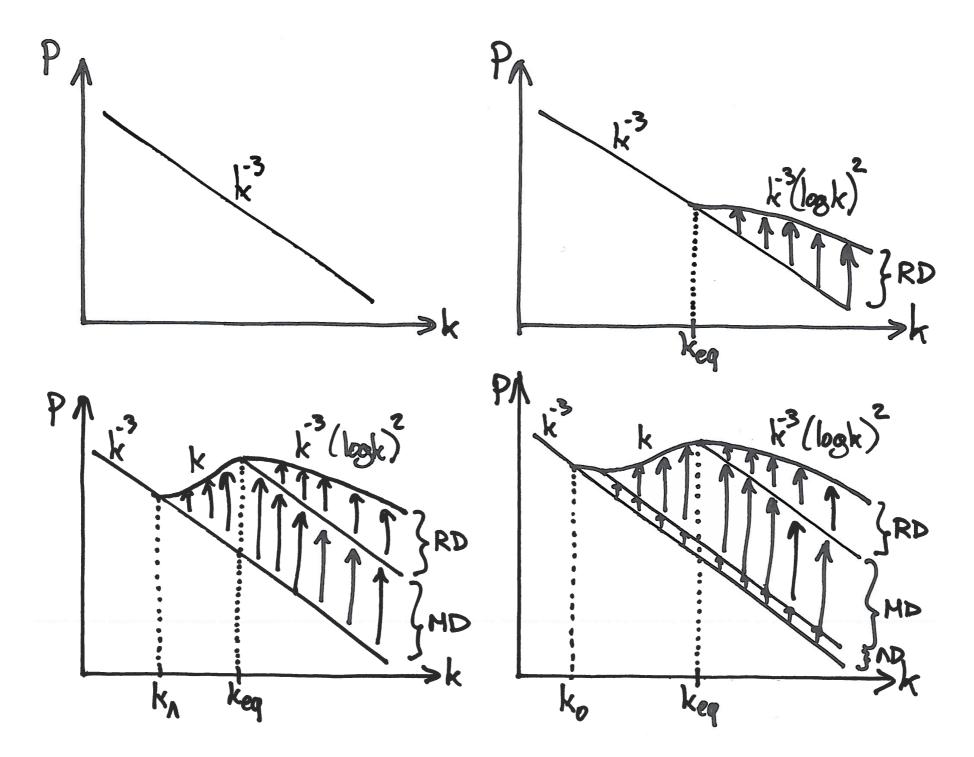
J. Feng, M. Kaplinghat, H. Tu, and H-B. Yu; JCAP 0907 (2009) 004 (arXiv:0905.3039)

## CMB and free-streaming v's



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

## **ACDM growth of perturbations**



Julien Lesgourgues, TASI 2012