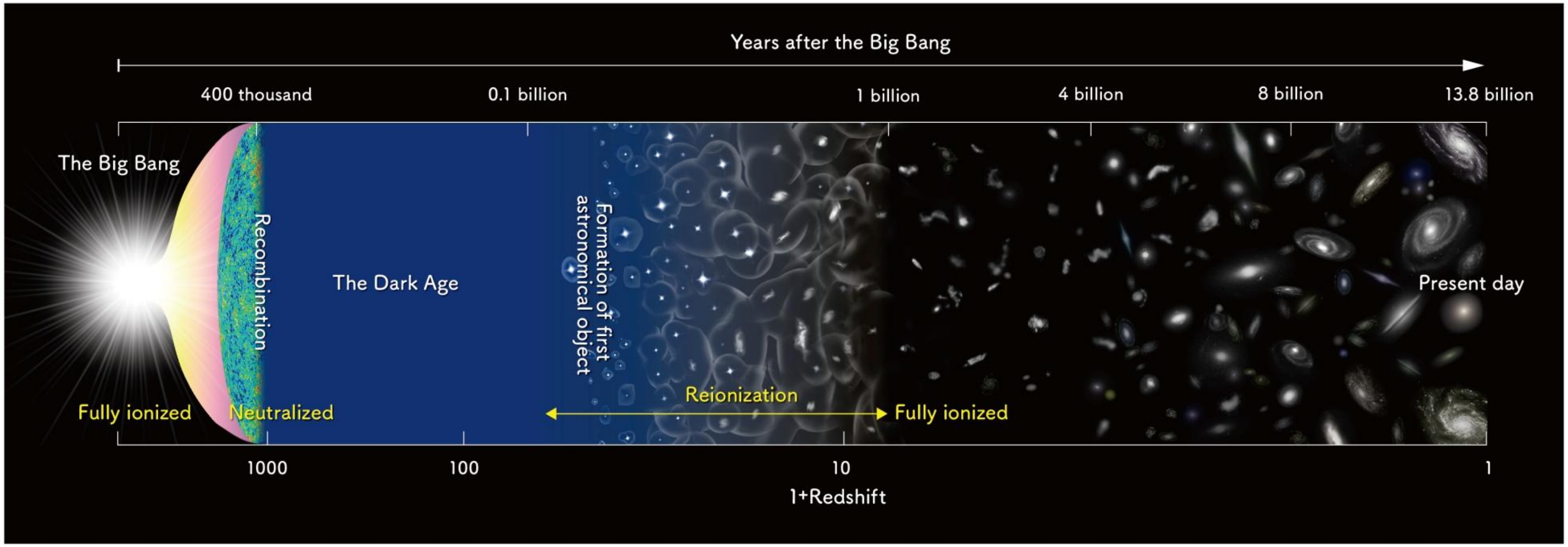
# DARK MATTER SELF-INTERACTIONS AND COSMIC REIONIZATION





Vikram Rentala

Indian Institute of Technology Bombay

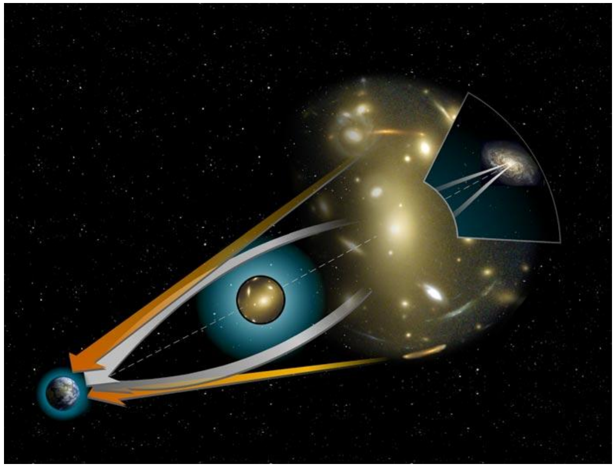

astro-ph/1712.03976

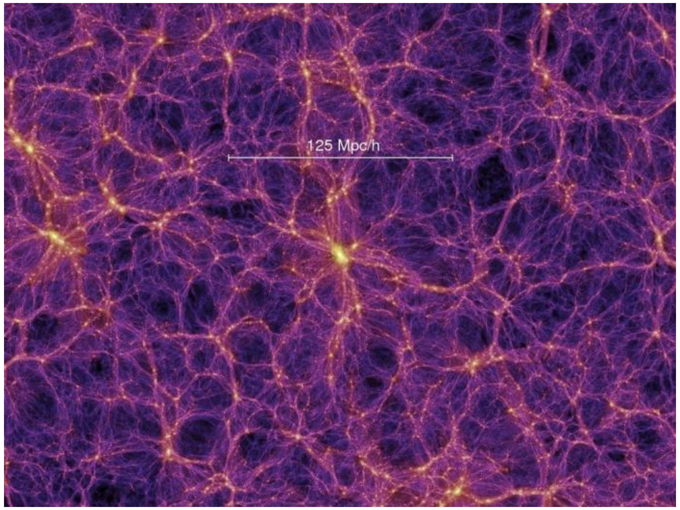
(w Subinoy Das, Rajesh Mondal and Srikanth Suresh)

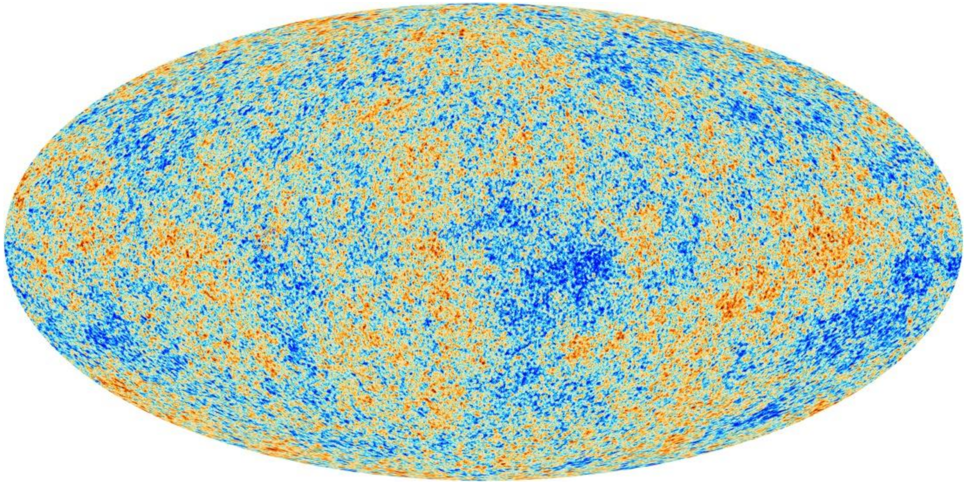
# Outline

- Self-interacting dark matter
- ETHOS framework
- Structure formation
- Cosmic Reionization
- Conclusions

# Astrophysical and cosmological evidence for dark matter





# Problems with the standard LCDM

## Small scales

- Missing satellite problem (Klypin et al, Moore et al, 1999)
- Too big to fail problem (Boylan-Kolchin et al, 2011)
- Core cusp problem (Oh et al, 2010)

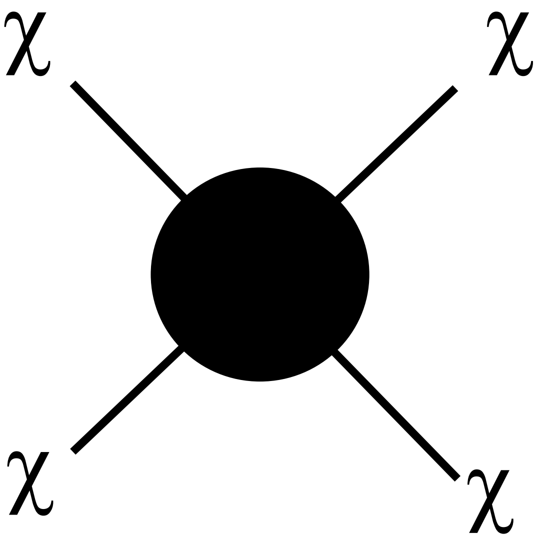
Baryonic feedback or dark matter self interactions?

(Bullock et al 2000, Benson et al 2002, Governato et al 2010)

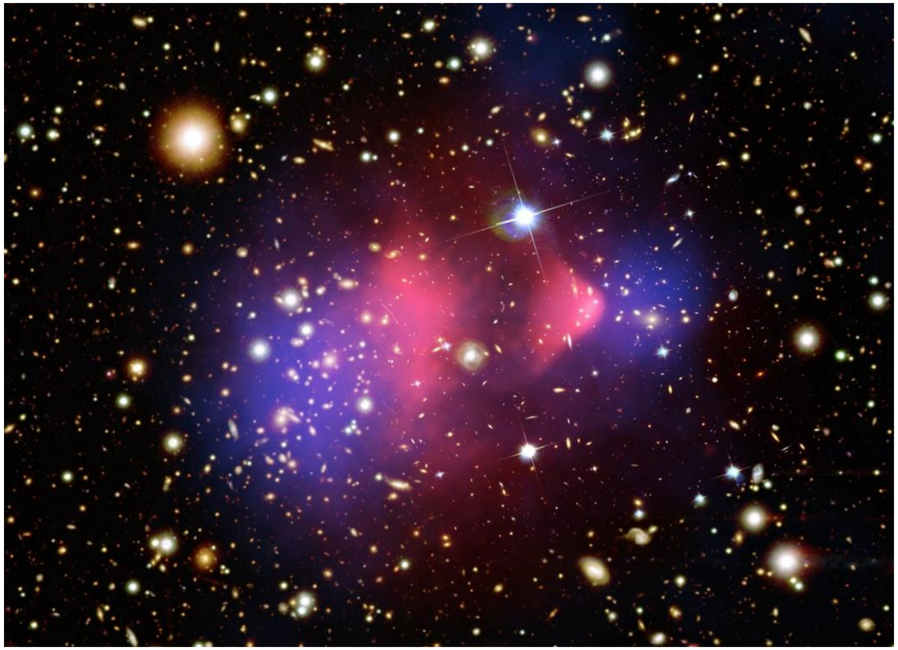
## Large scales

- Hubble tension (Zhang et al, 2017)
- $\boldsymbol{\sigma}_8$ tension (Battye et al 2014)
- Effective number of neutrinos (Mangano et al 2005, Lesgourges et al 2016)

# Self-interacting dark matter



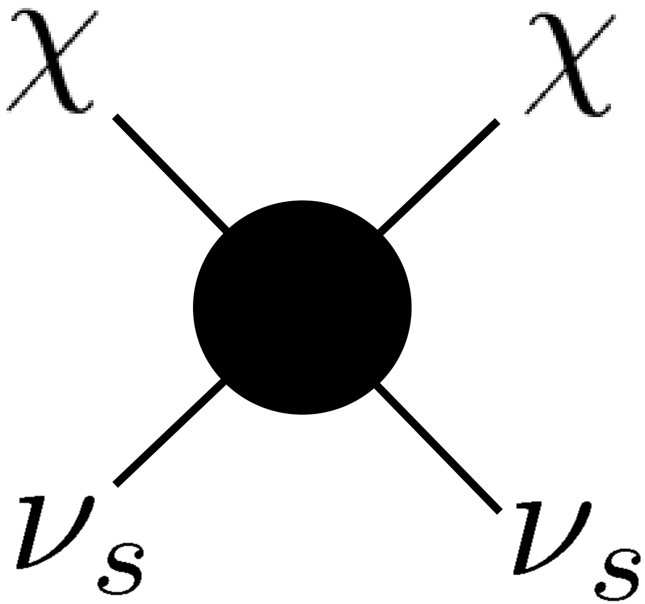

Spergel, Steinhardt PRL, 1999

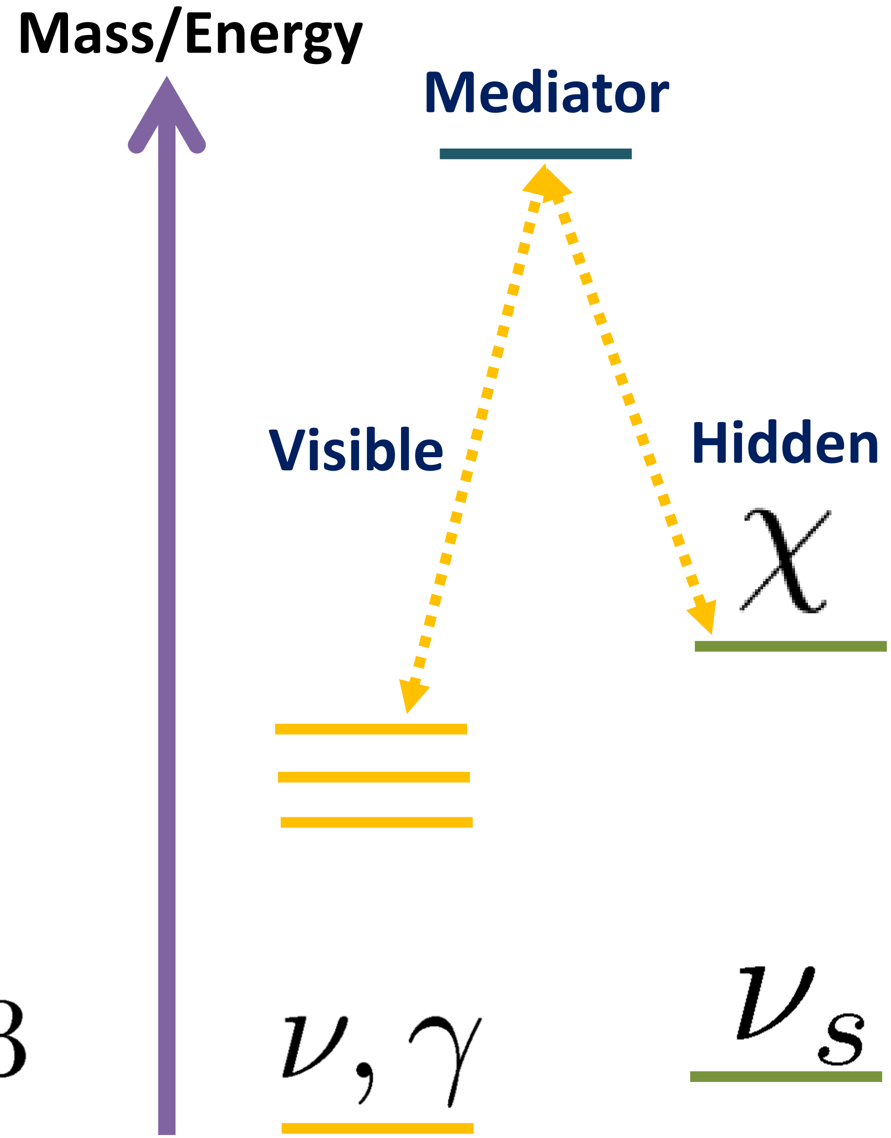


$$\frac{\sigma(\chi\chi\to\chi\chi)}{m_\chi} \lesssim 1\ \mathrm{cm^2\ g^{-1}}$$
$$\lesssim 1\ \mathrm{barn/GeV}$$

Harvey et al, Science, 2015

# Dark matter and dark radiation



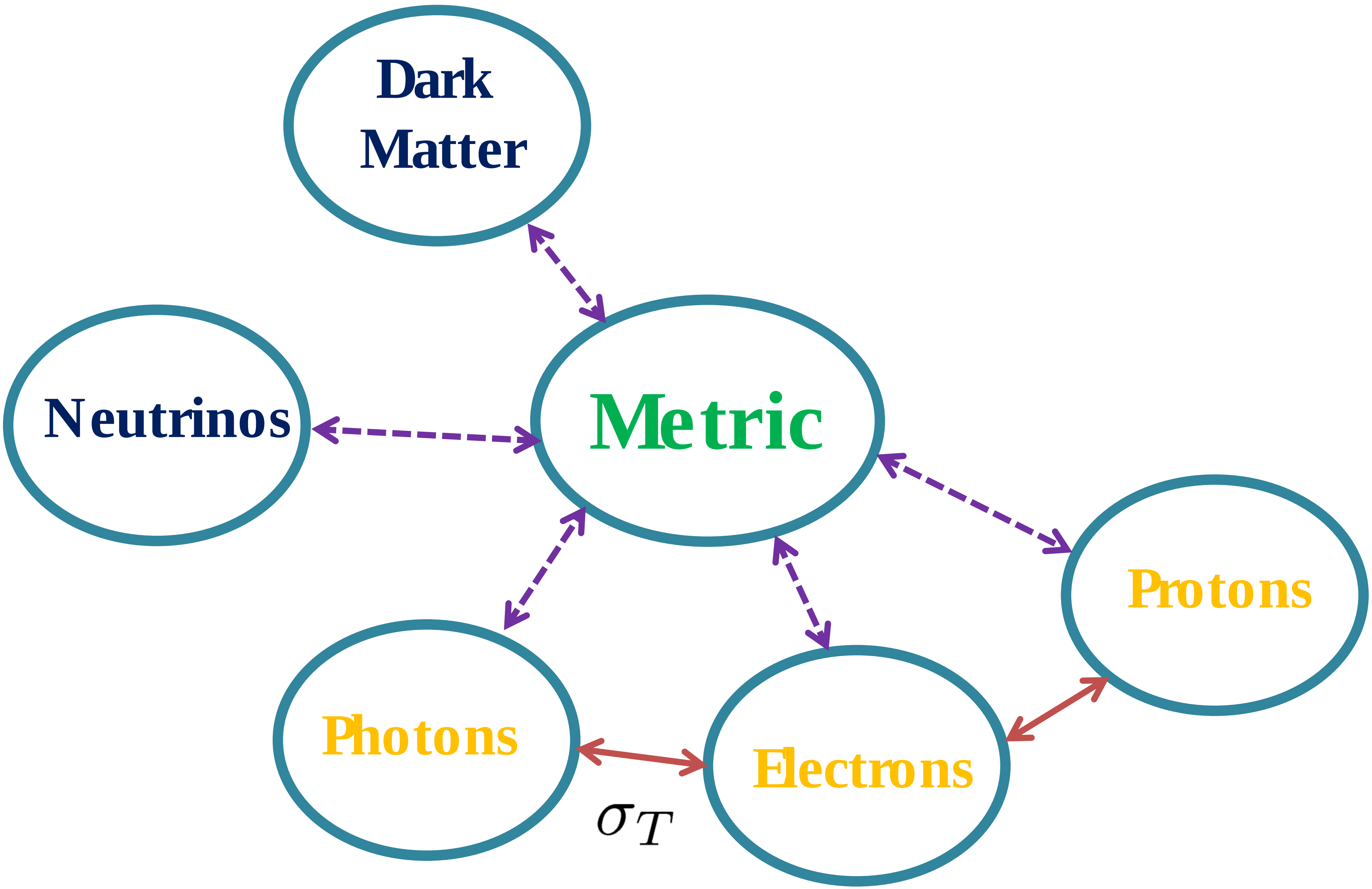




***Light particles are generic:***

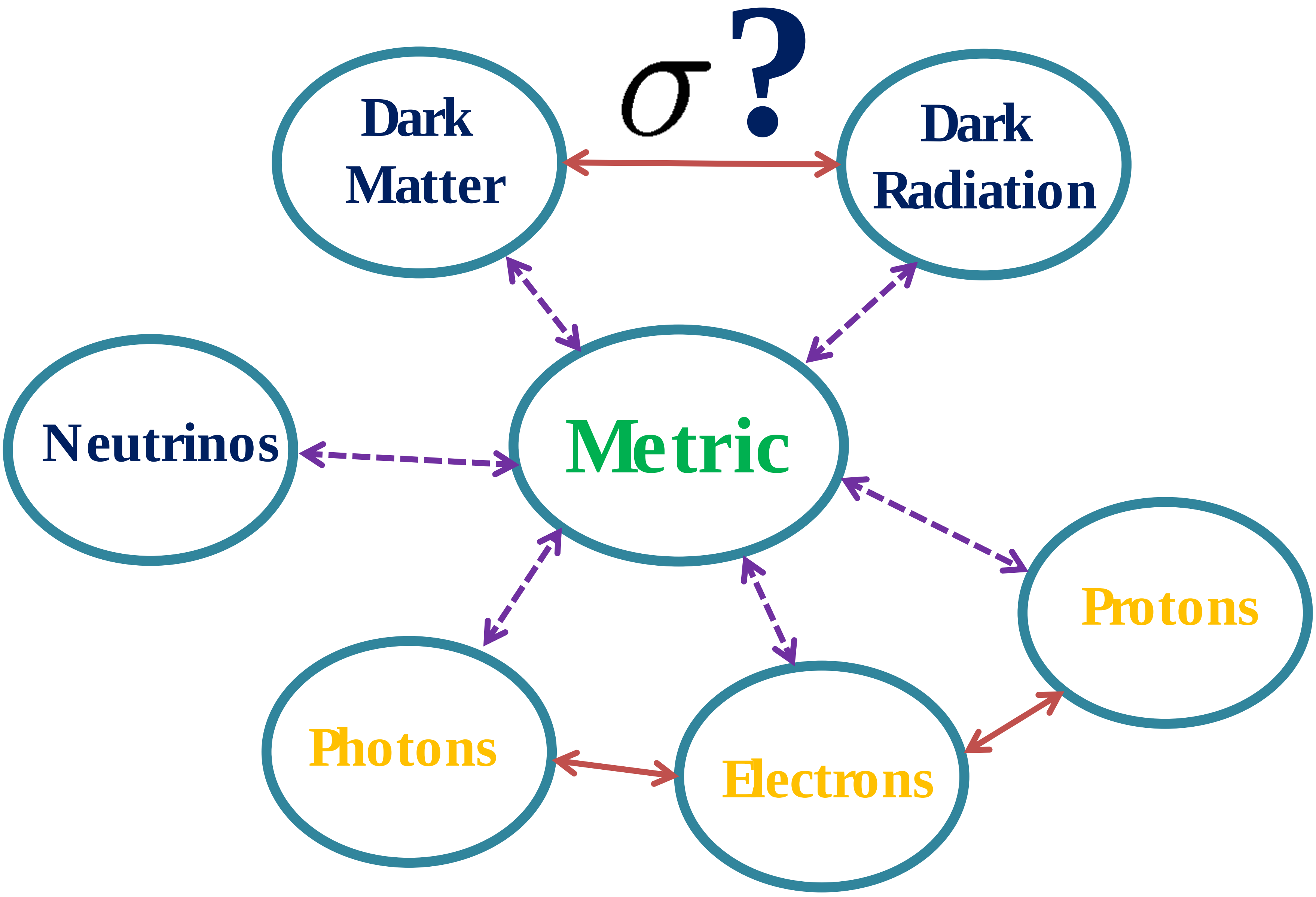
**Goldstone bosons, chiral fermions, gauge bosons**

**CMB:** $\Delta N_{\text{eff}} < 0.3$

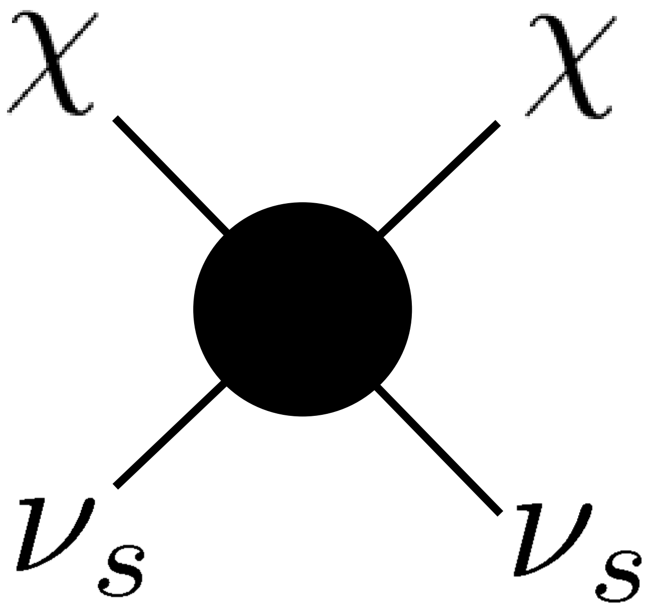
# Evolution of cosmological perturbations



# Evolution of cosmological perturbations



# Can we discover or constrain Dark Matter-Dark Radiation interactions?




$\sigma$

# ETHOS framework

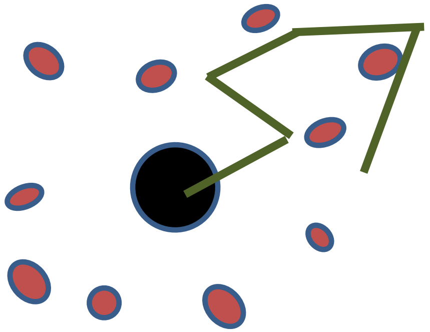
(Cyr-Racine et al 2016)

Particle physics -> Cosmology

Basic idea: Map all the particle physics parameters to coefficients of a red-shift series expansion of the collision term

$$-\dot{\kappa} \simeq 1/\lambda \simeq (n\sigma)$$

$$\dot{\kappa}_\chi \sim \sum_n a_n (1+z)^{n+1}$$



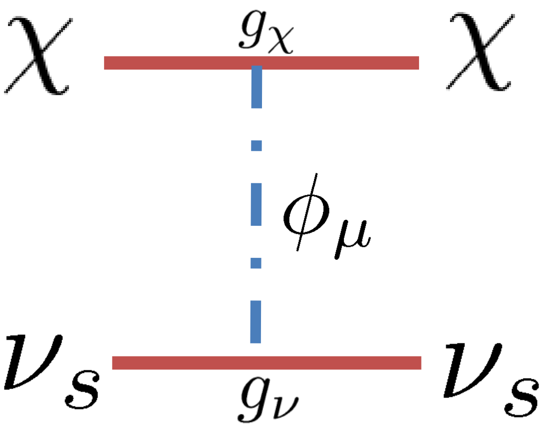
# ETHOS model 1

(Cyr-Racine et al, Binder et al 2016)

$\chi$ Dark matter particle

$\phi_\mu$ Mediator

$\nu_s$ Dark radiation

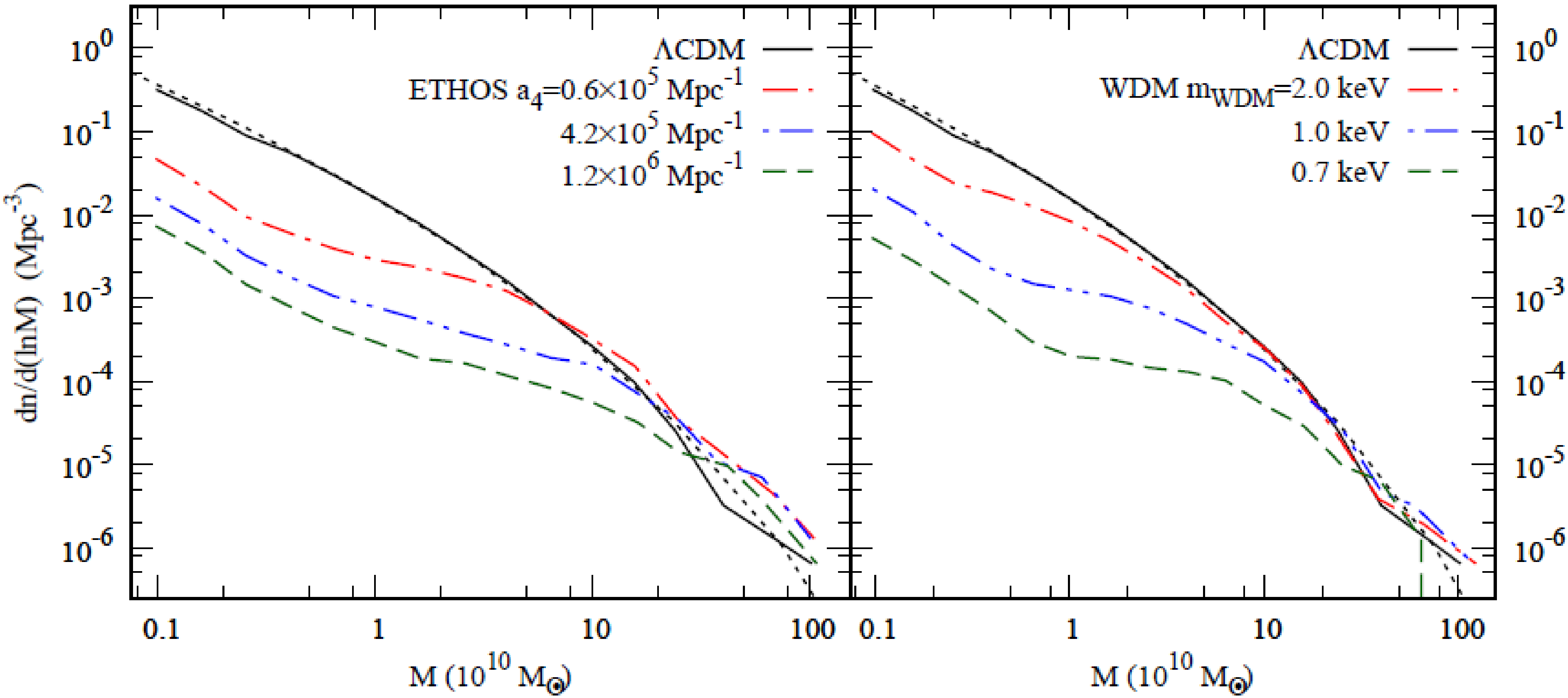



$$n \sim T^3 \qquad \sigma \sim g_\chi^2 g_\nu^2 \frac{T^2}{m_\phi^4}$$

$$\dot{\kappa}_\chi \sim 1/\lambda \sim n\sigma \sim a_4 T^{4+1} \qquad T \sim (1+z)$$

$$a_4 = 0.6 \times 10^5 \left(\frac{g_\chi}{1}\right)^2 \left(\frac{g_\nu}{1}\right)^2 \left(\frac{0.5\ \mathrm{MeV}}{m_\phi}\right)^4 \left(\frac{2\ \mathrm{TeV}}{m_\chi}\right)\ \mathrm{Mpc}^{-1}$$

# Halo mass distribution (z=8)



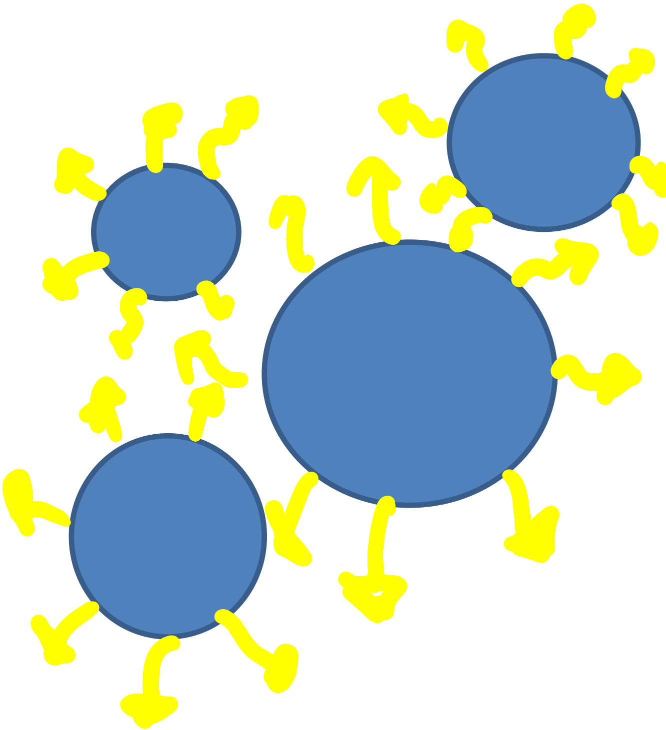

$$M_J \simeq 10^{10} M_\odot \left( \frac{a_4}{0.6 \times 10^5 \ \mathrm{Mpc}^{-1}} \right)^{3/4}$$

# From structure to reionization

**Key Parameter:** $N_{\rm ion}$

$$N_\gamma^{\rm halo} = N_{\rm ion}\frac{M_{\rm halo}}{m_H}$$

$$N_{\rm ion} = 8\left(\frac{N_{\rm ion}^{\rm b}}{4000}\right)\left(\frac{M_{\rm b}/M_{\rm halo}}{1/5}\right)\left(\frac{\epsilon_{\rm esc}}{10\%}\right)\left(\frac{\epsilon_{\rm SF}}{10\%}\right)$$



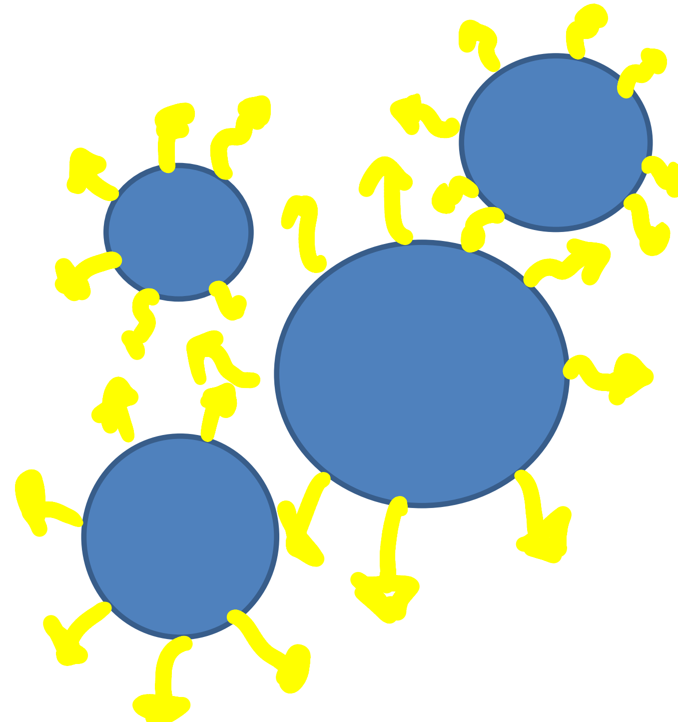
$N_{\rm ion} \leq 500$ **can be safely assumed**

# From structure to reionization

**Constraints:**

1. $\tau = 0.058 \pm 0.012$

2. Gunn-Peterson bound

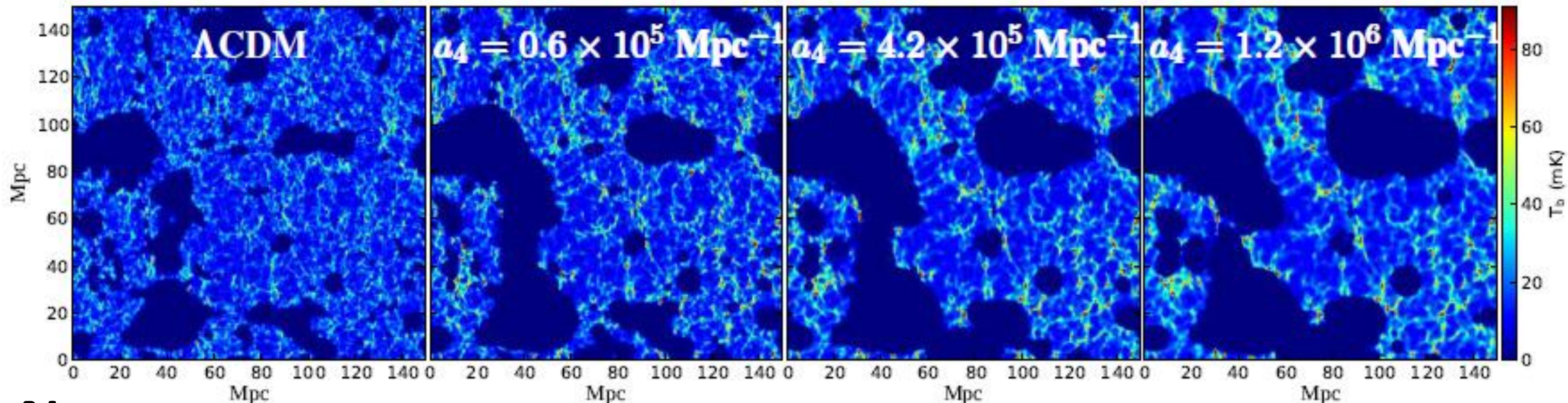


**Simplified constraint**

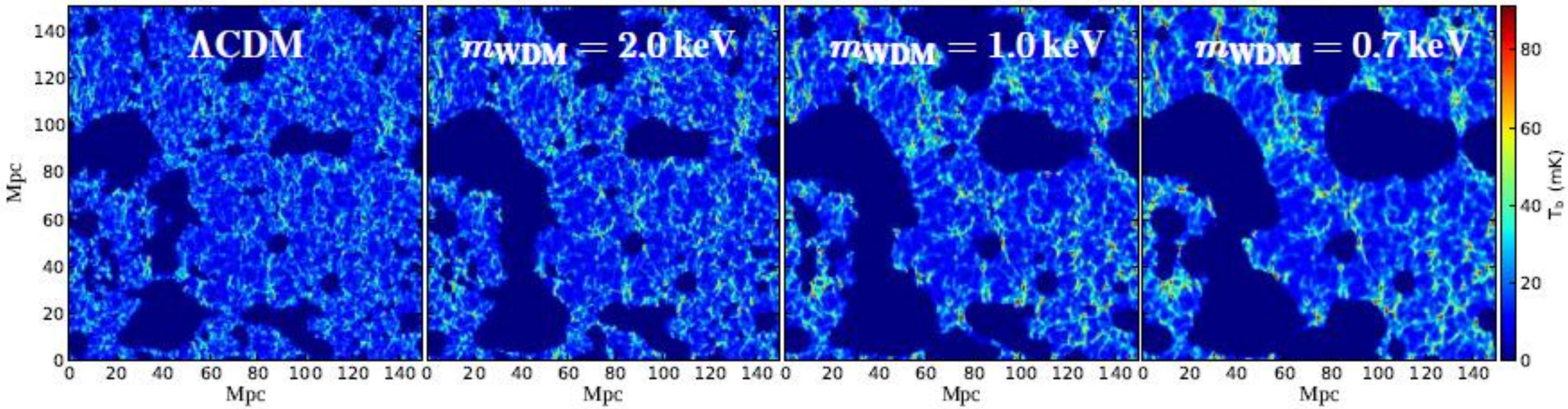
$$\bar{x}_{\mathrm{H\,I}}(z=8) \equiv \left.\frac{n_{\mathrm{HI}}}{n_B}\right|_{z=8} = 0.5$$

**With suppressed small scale structure we need higher values of $N_{ion}$ in order to achieve reionization!**

# HI brightness temperature (z = 8)



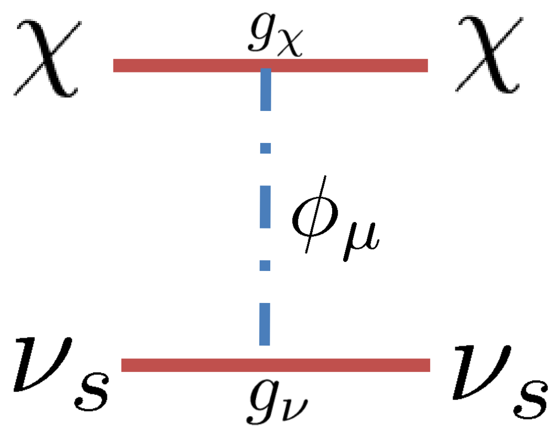

$N_{ion}$ 23 100 321 721




$N_{ion}$ 23 57 225 861

# Our Result

- Constraint on $a_4$ from demanding consistency with global history of reionization

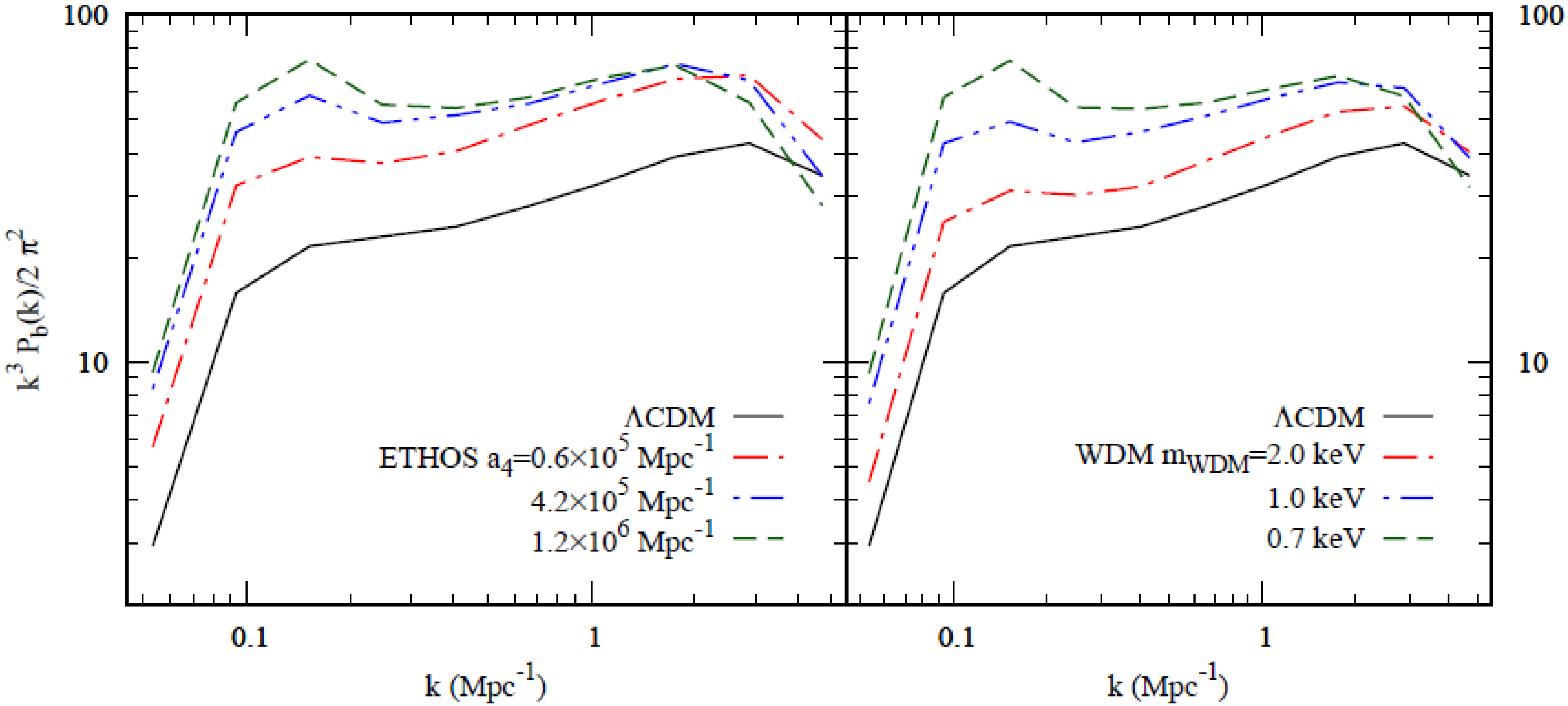



$$a_4 = 0.6 \times 10^5 \text{ Mpc}^{-1} \left(\frac{g_\chi}{1}\right)^2 \left(\frac{g_\nu}{1}\right)^2 \left(\frac{0.5 \text{ MeV}}{m_\phi}\right)^4 \left(\frac{2 \text{ TeV}}{m_\chi}\right)$$

$$\lesssim 1.2 \times 10^6 \text{ Mpc}^{-1}$$

$$(\text{also } m_{\text{WDM}} \gtrsim 0.7 \text{ keV})$$

# HI brightness power spectrum




**Future 21 cm surveys could measure this difference**

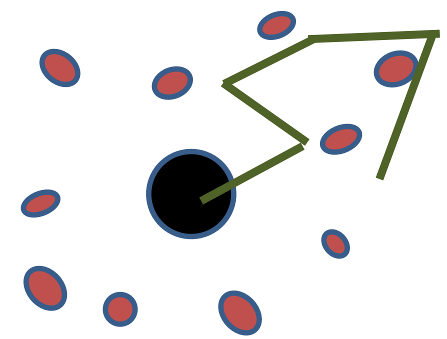
# Summary

- Dark Matter - Dark radiation interactions can lead to suppression of the small scale matter power spectrum
- Global history of reionization can set strong constraints on DM-DR interactions
- Need to have a realistic understanding of the astrophysical uncertainties of the EoR
- 21 cm surveys could potentially detect the impact of DM-DR interactions on cosmological perturbations


QUESTIONS, COMMENTS, SUGGESTIONS?

# Decoupling of DM and DR

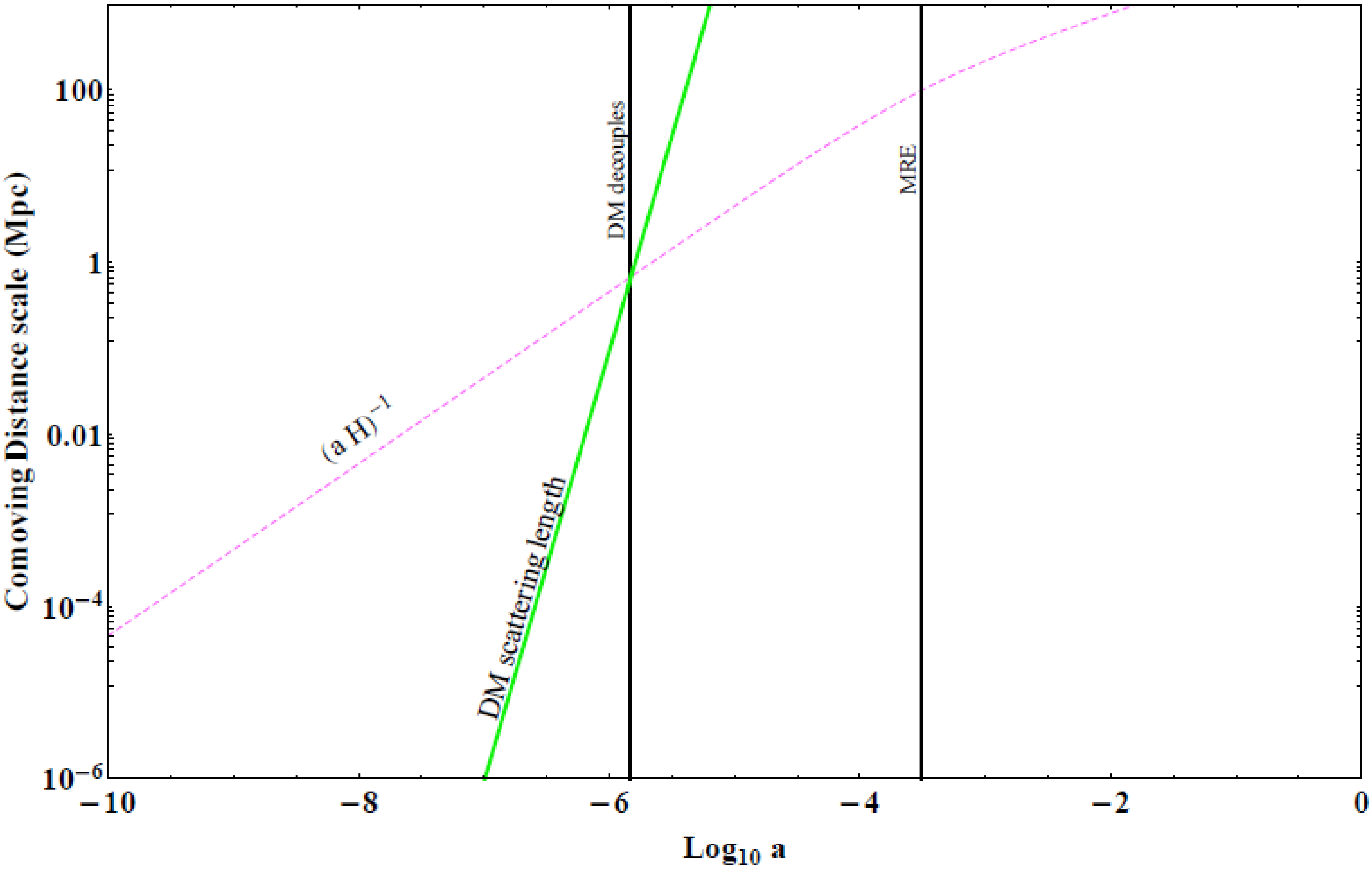
- Comoving Hubble scale $(aH)^{-1}$
- Scattering length $\lambda$



| | | |
|---|---|---|
| Early times | $\lambda \ll (aH)^{-1}$ | DM and DR are tightly coupled (dark acoustic oscillations and damping) |
| Late times | $\lambda \gg (aH)^{-1}$ | DM and DR are decoupled (DM free streams) |

* We will assume that this transition takes place in the radiation dominated universe

# Decoupling of dark matter and dark radiation

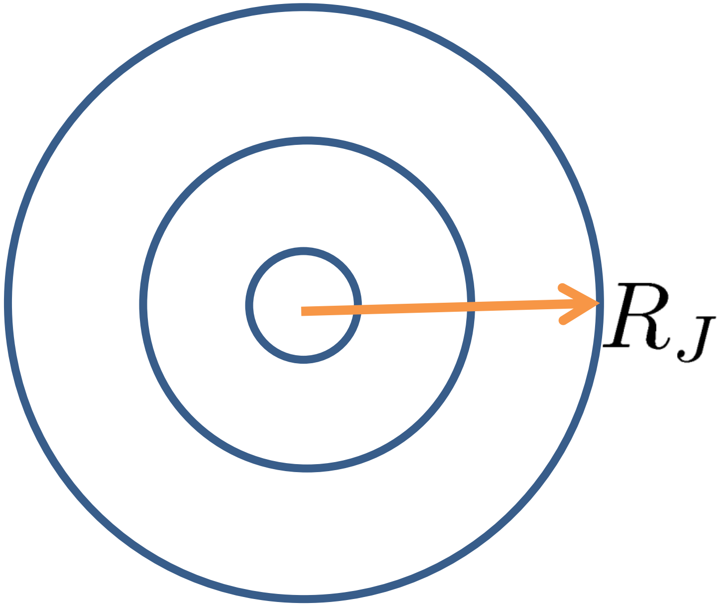


# Jeans scale (pre-decoupling)

$$R_J \sim c_s t_{\text{turn-around}}$$

$$c_s \simeq c/\sqrt{3}$$

$$t_{\text{turn-around}} \sim \frac{1}{\sqrt{G\rho}} \sim \frac{1}{aH}$$

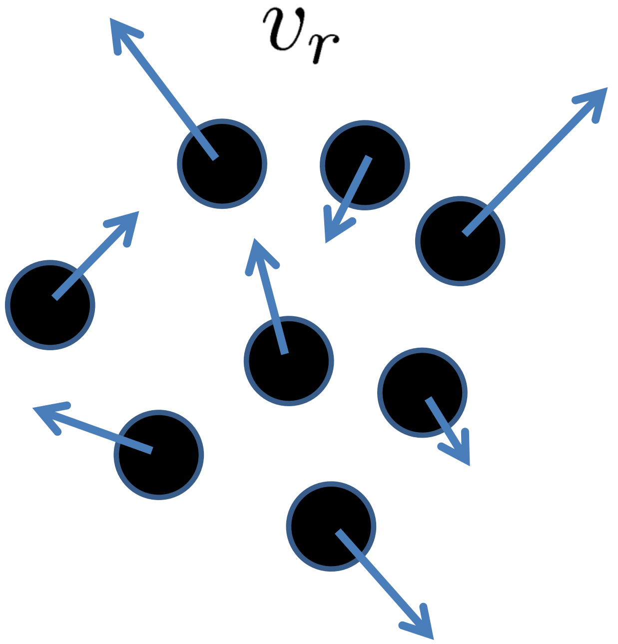


# Jeans scale (post-decoupling)

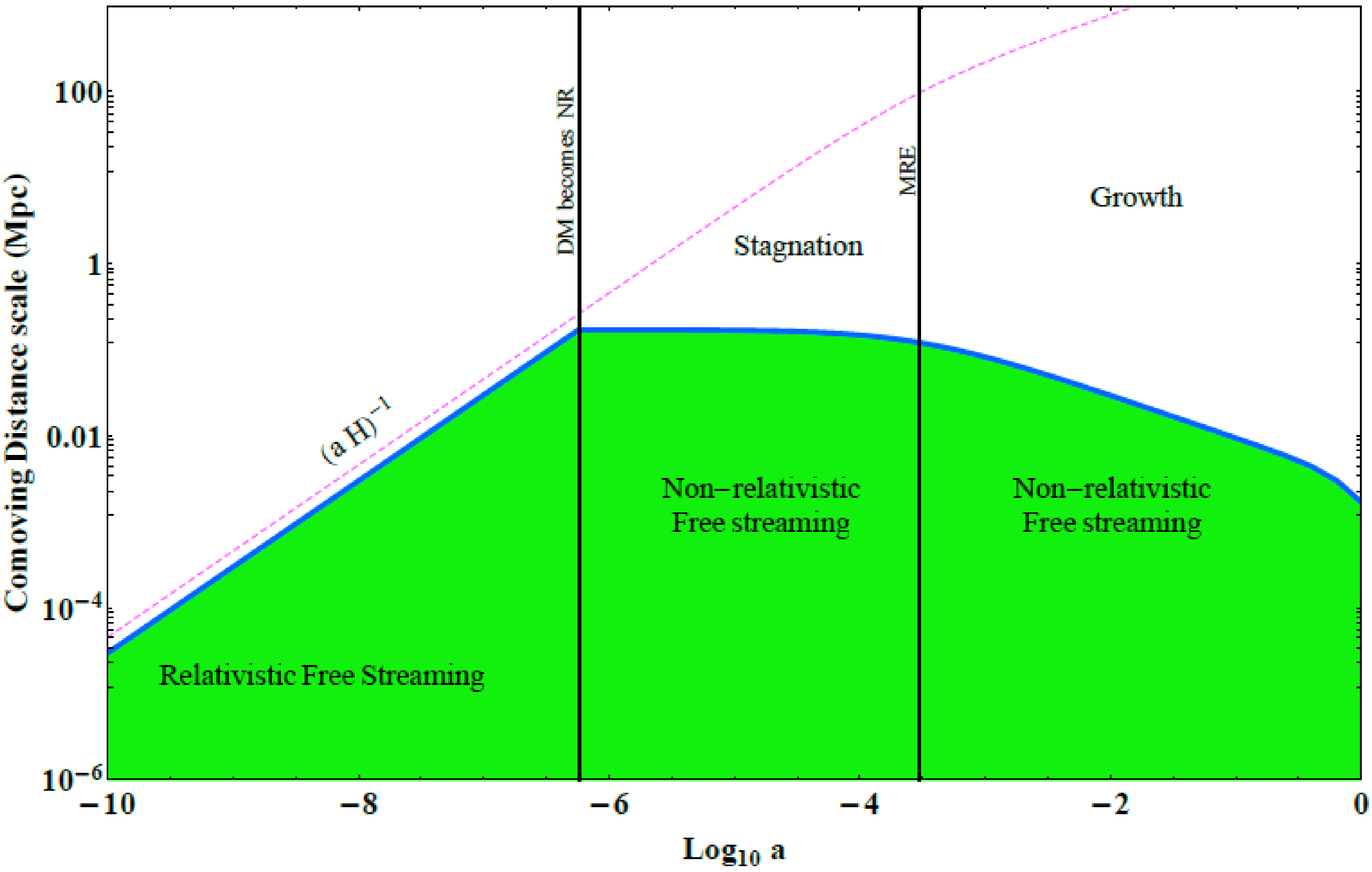
$$R_J \sim v_r t_{\text{turn-around}}$$

$$t_{\text{turn-around}} \sim \frac{1}{\sqrt{G\rho}} \sim \frac{1}{aH}$$

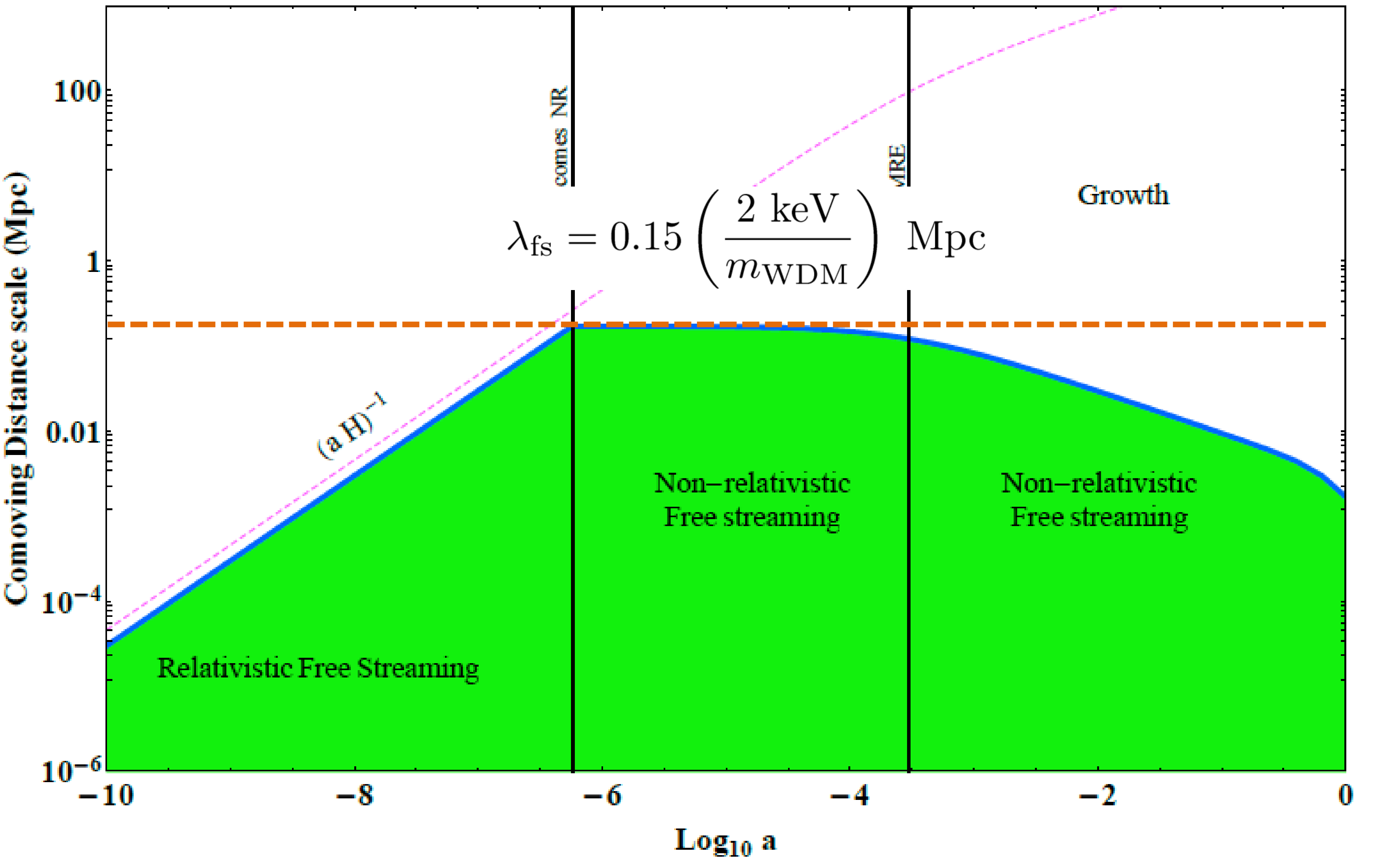
$$p_\chi = m_\chi v_r \sim (1+z)$$



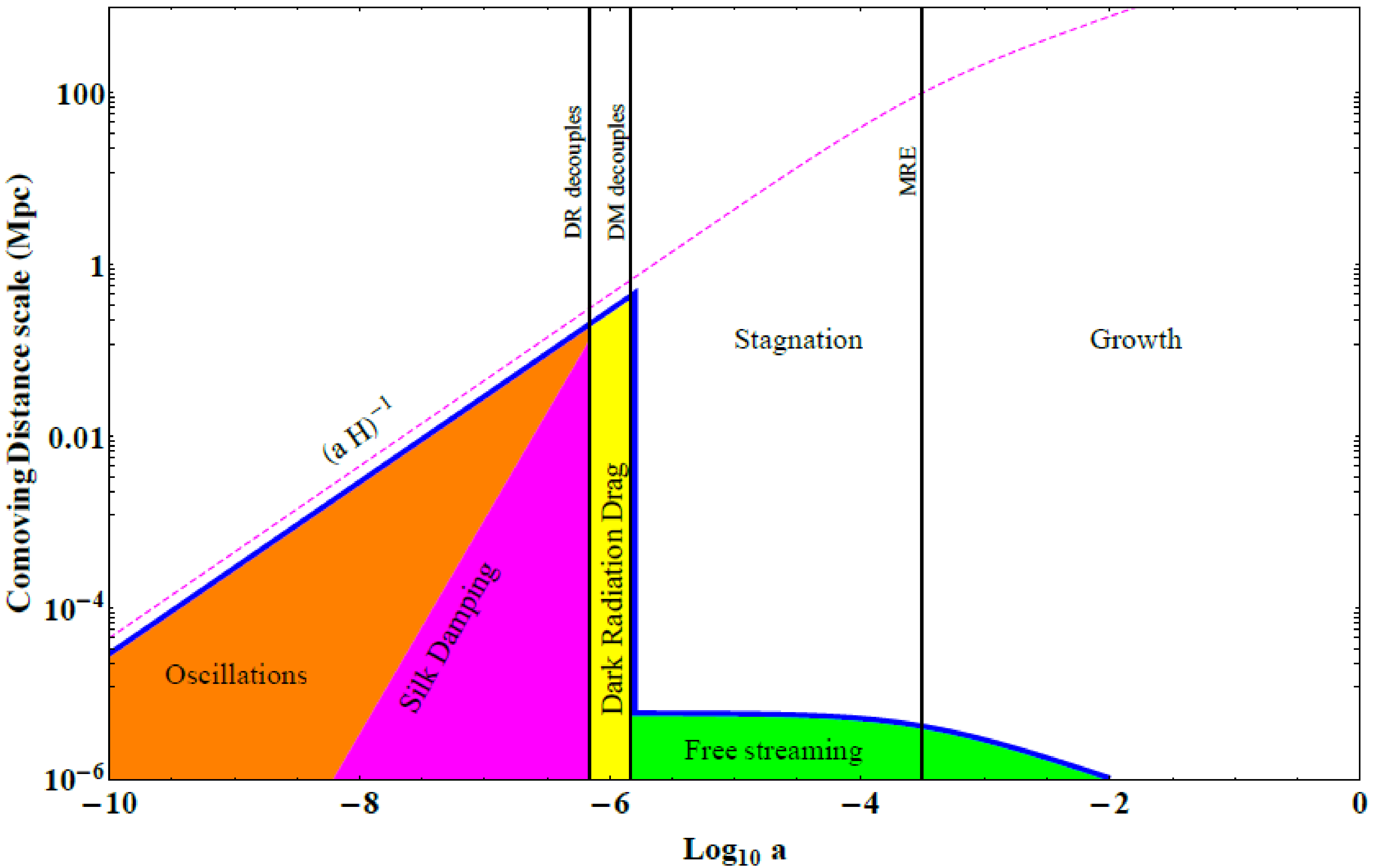
# Evolution of Jeans scale in WDM models



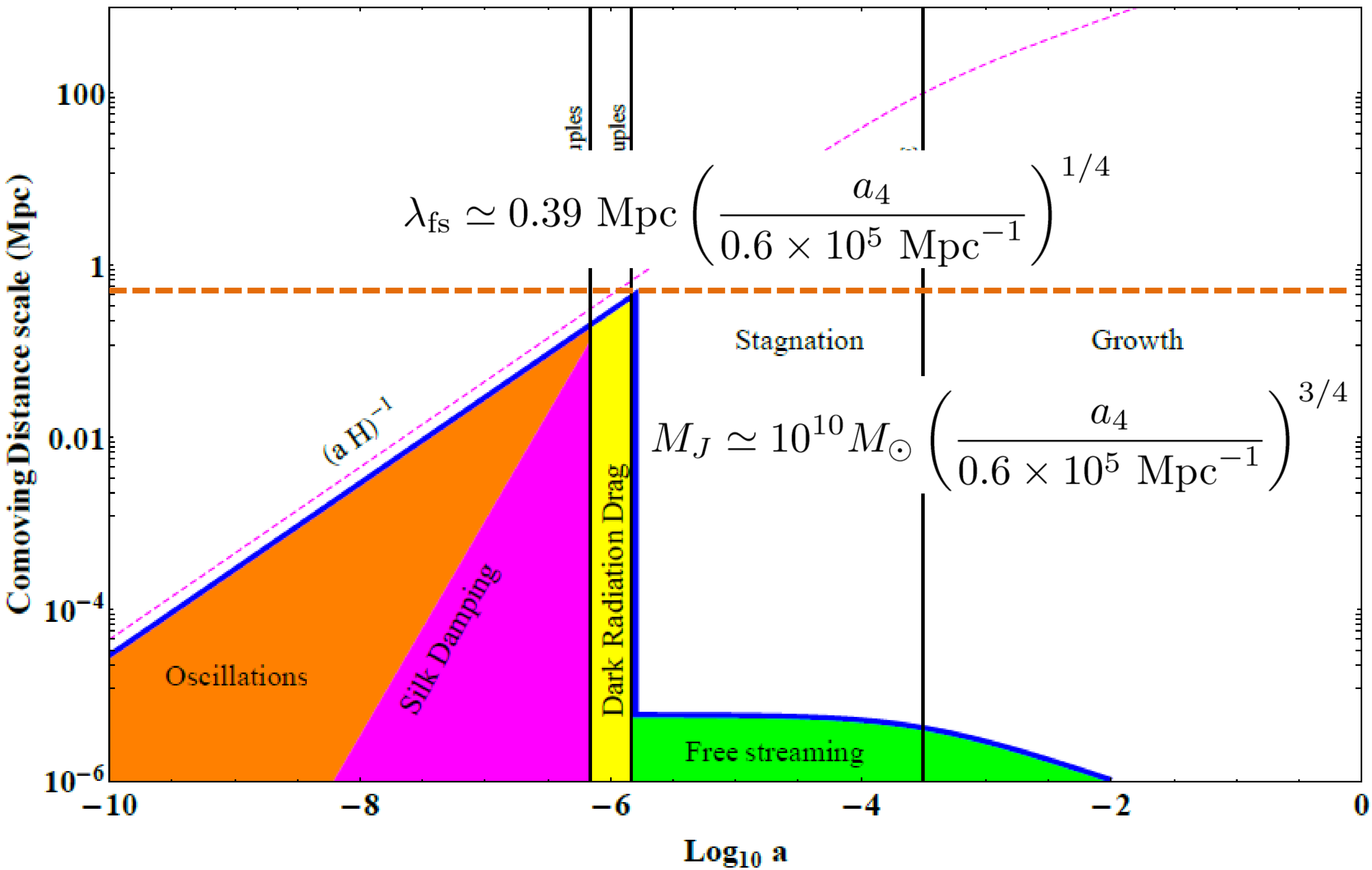
# Evolution of Jeans scale in WDM models



# Evolution of Jeans scale in ETHOS 1



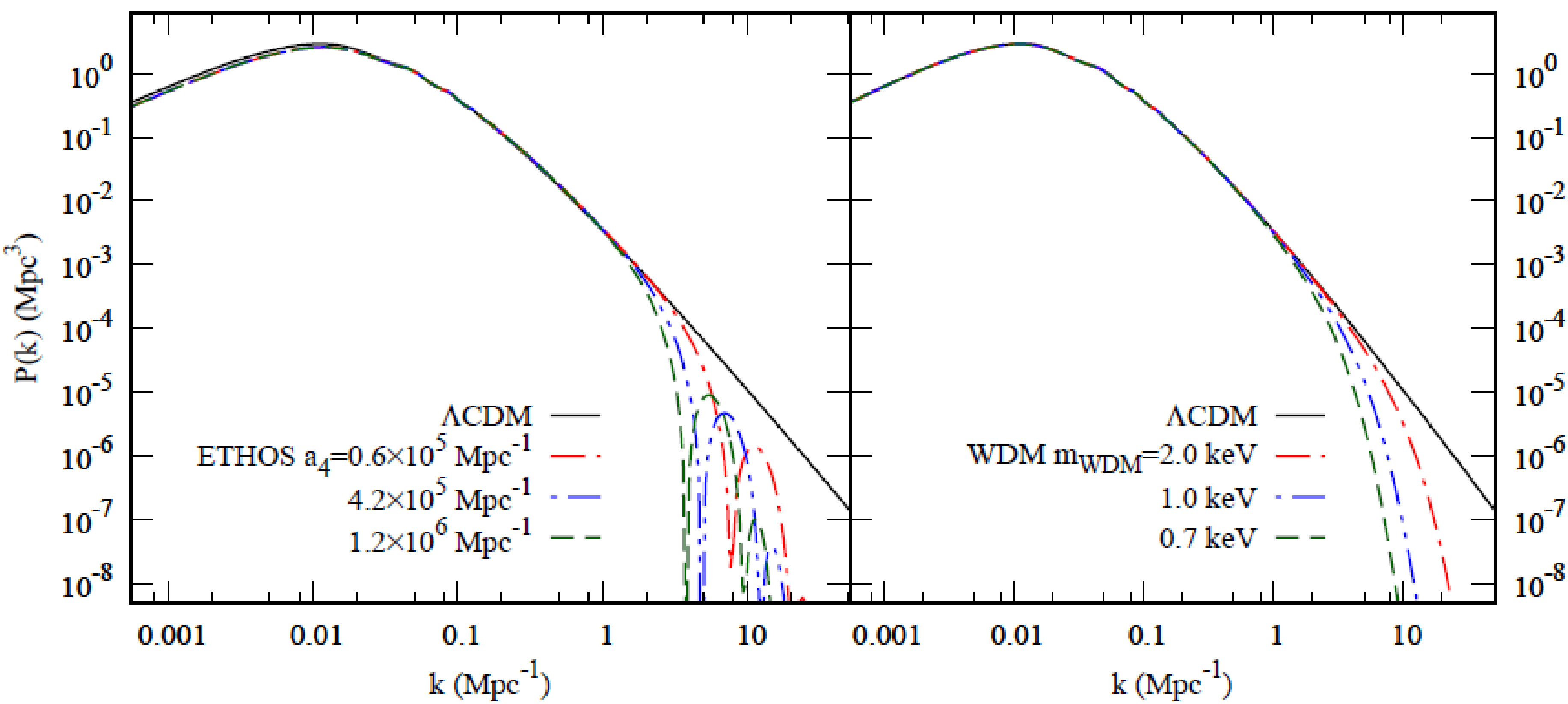
# Evolution of Jeans scale in ETHOS 1



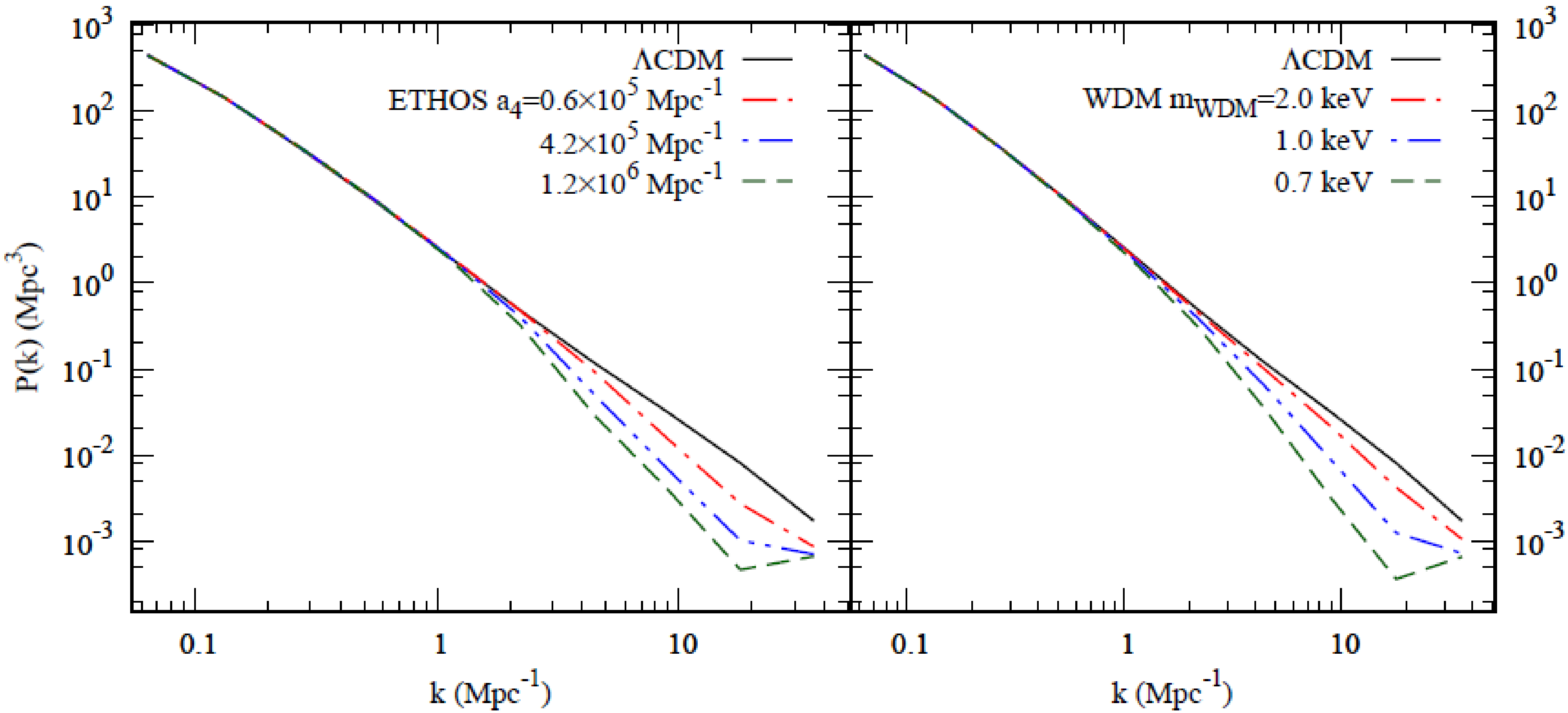

$$\lambda_{\rm fs} \simeq 0.39\ \mathrm{Mpc} \left( \frac{a_4}{0.6 \times 10^5\ \mathrm{Mpc}^{-1}} \right)^{1/4}$$

$$M_J \simeq 10^{10} M_\odot \left( \frac{a_4}{0.6 \times 10^5\ \mathrm{Mpc}^{-1}} \right)^{3/4}$$

# Linear Power Spectrum (z=124)



# Non-Linear power spectrum (z=8)




from N-body simulation

**Lyman-alpha constraints rule out $m_x$ < 3.5 keV**