DARK MATTER-DARK RADIATION INTERACTIONS AND COSMIC REIONIZATION

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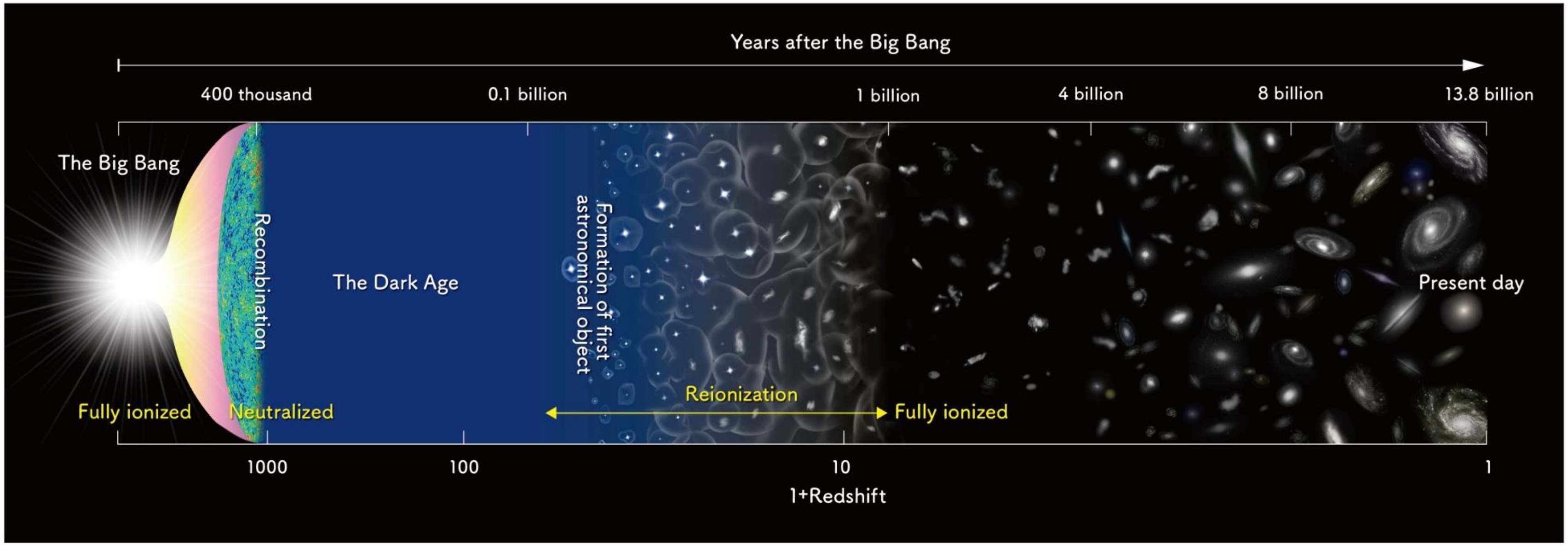

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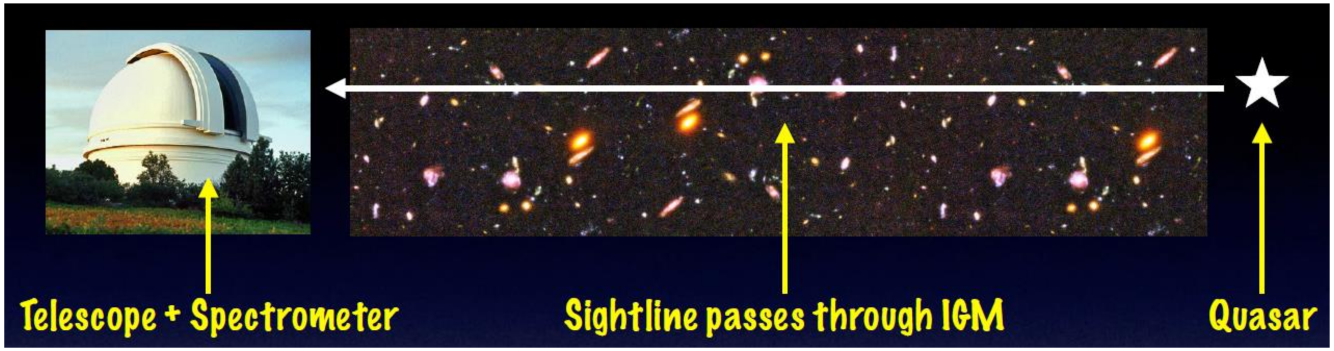
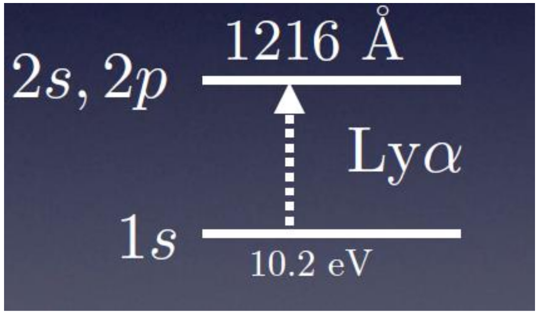
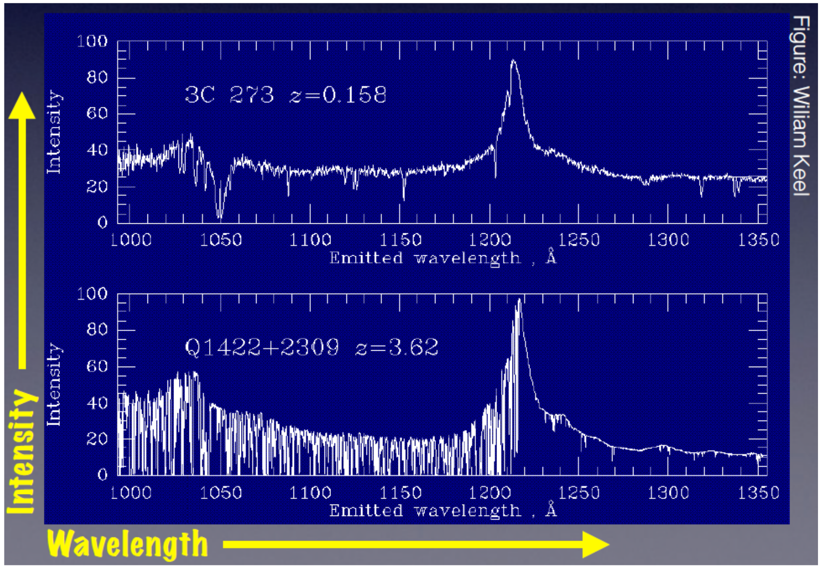
(w Subinoy Das, Rajesh Mondal and Srikanth Suresh)

Observational constraints on reionization

- Quasar absorption spectra traces neutral hydrogen

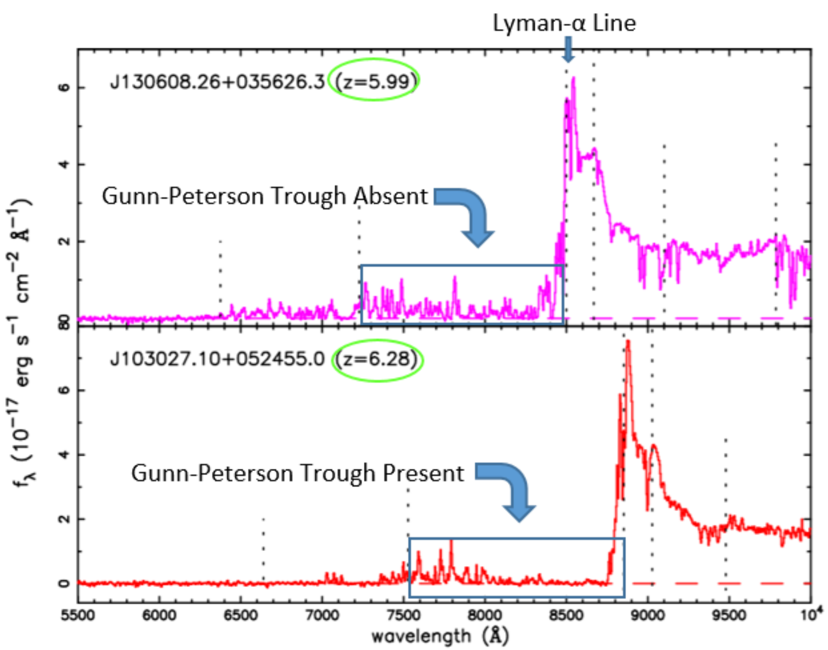






Observational constraints on reionization

- Gunn-Peterson trough



Above $z \simeq 6$,

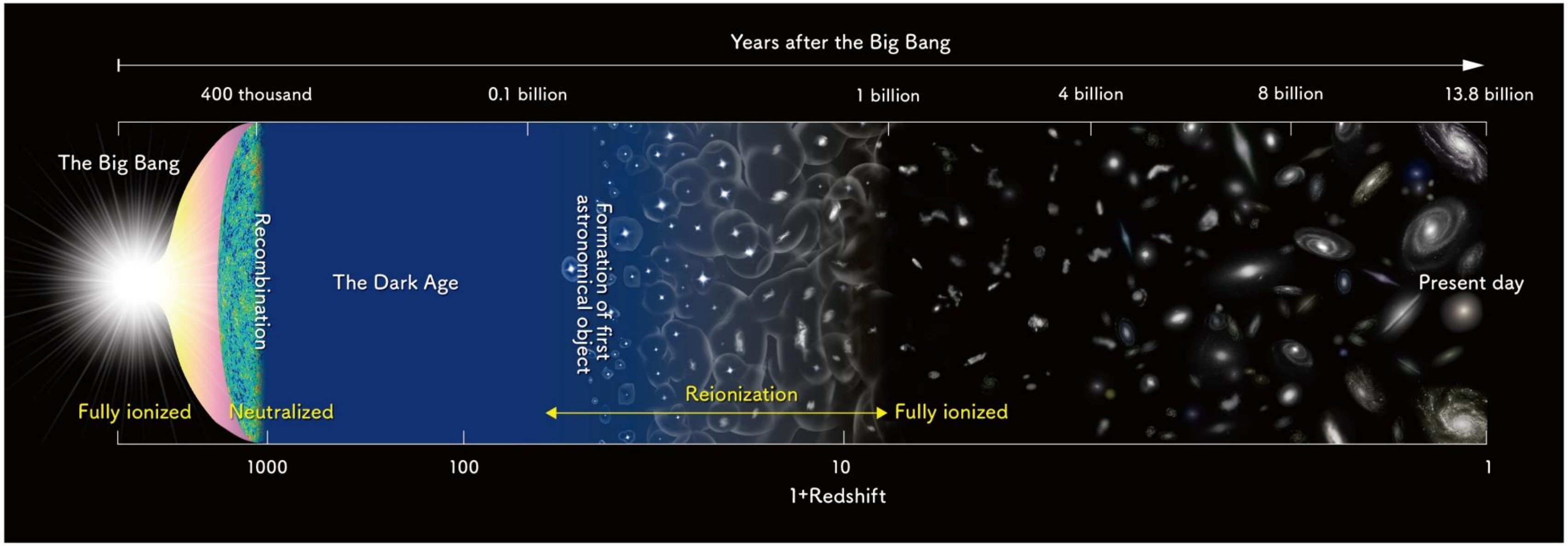
$$\bar{x}_{\rm H\,I} \equiv \frac{n_{\rm HI}}{n_B} \gtrsim 10^{-3}$$

$$z_{\rm reio} \gtrsim 6$$

Observational constraints on reionization

- Optical depth to CMB

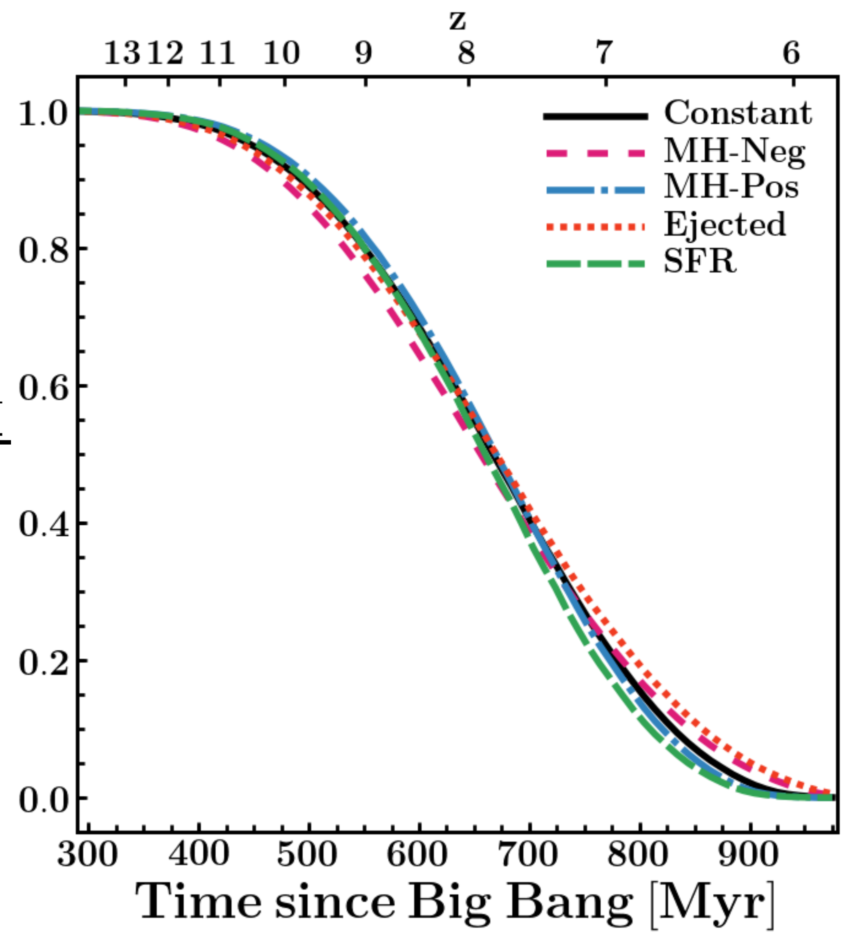
$$\tau = 0.058 \pm 0.012$$



$$\tau \sim \int n_e \sigma_T dl \qquad z_{\rm reio} \lesssim 10$$

When does reionization happen?

$$\bar{x}_{\mathrm{H\,I}} \equiv \frac{n_{\mathrm{HI}}}{n_B}$$



Seiler, Jacob *et al.*
*astro-ph/*1902.01611

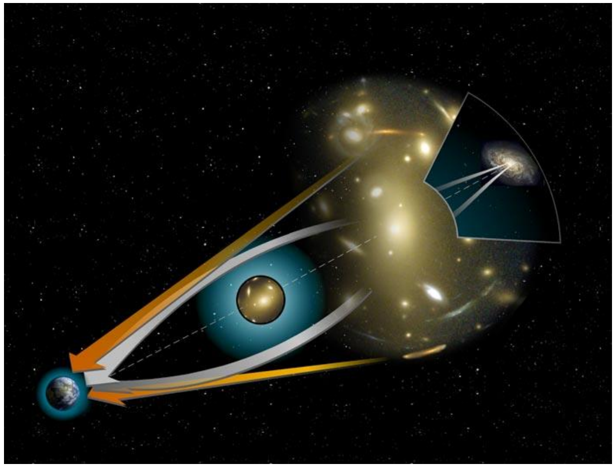
$$6 \lesssim z_{\mathrm{reio}} \lesssim 10$$

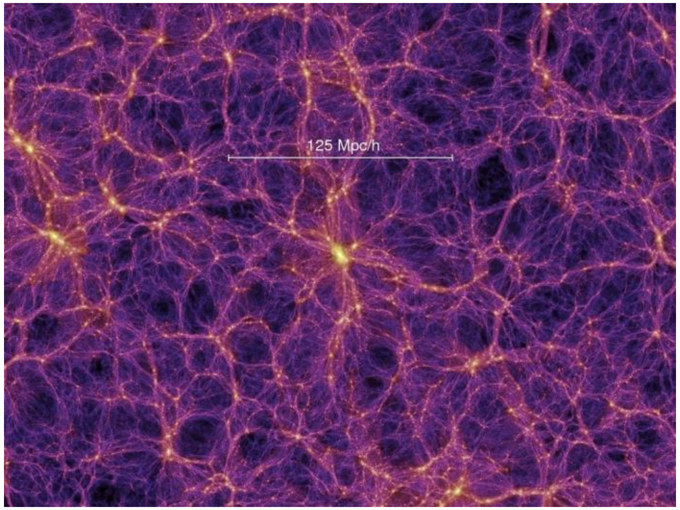
Can we constrain dark matter particle physics models with these observations?

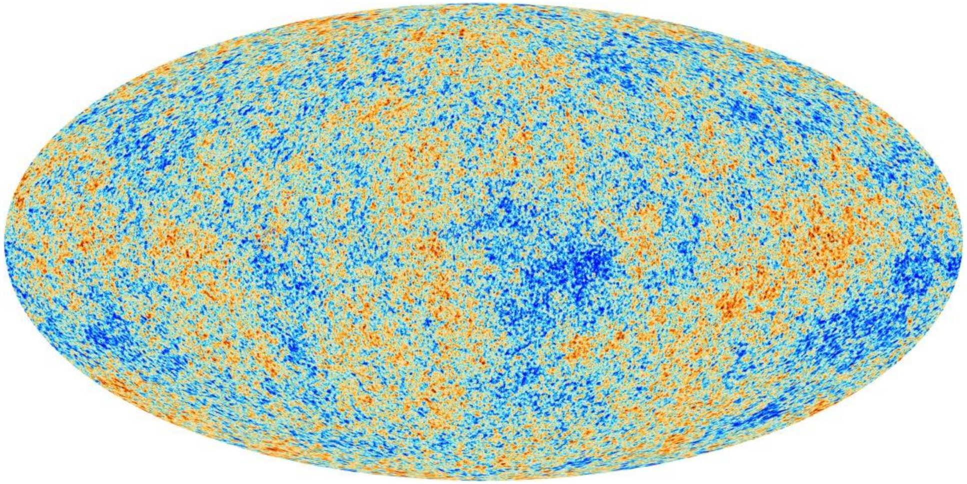
Outline

- Self-interacting dark matter
- ETHOS framework
- Structure formation
- Constraints from Cosmic Reionization
- Future observables
- 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)

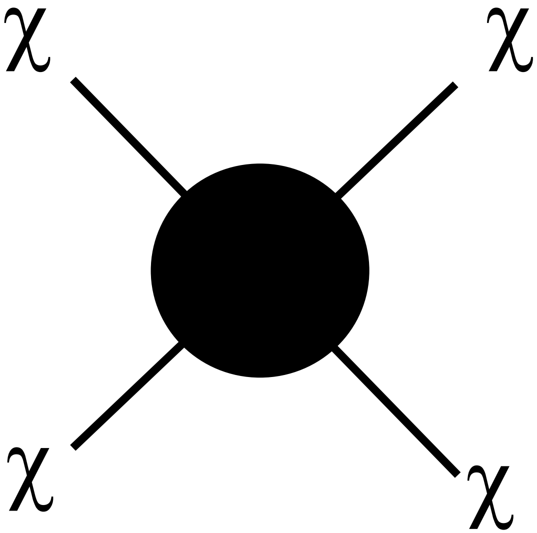
Baryonic feedback or dark matter self interactions?

(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

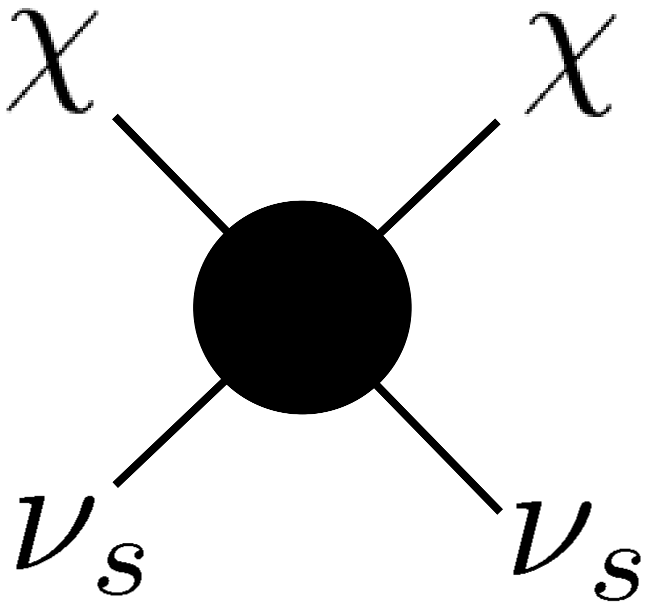


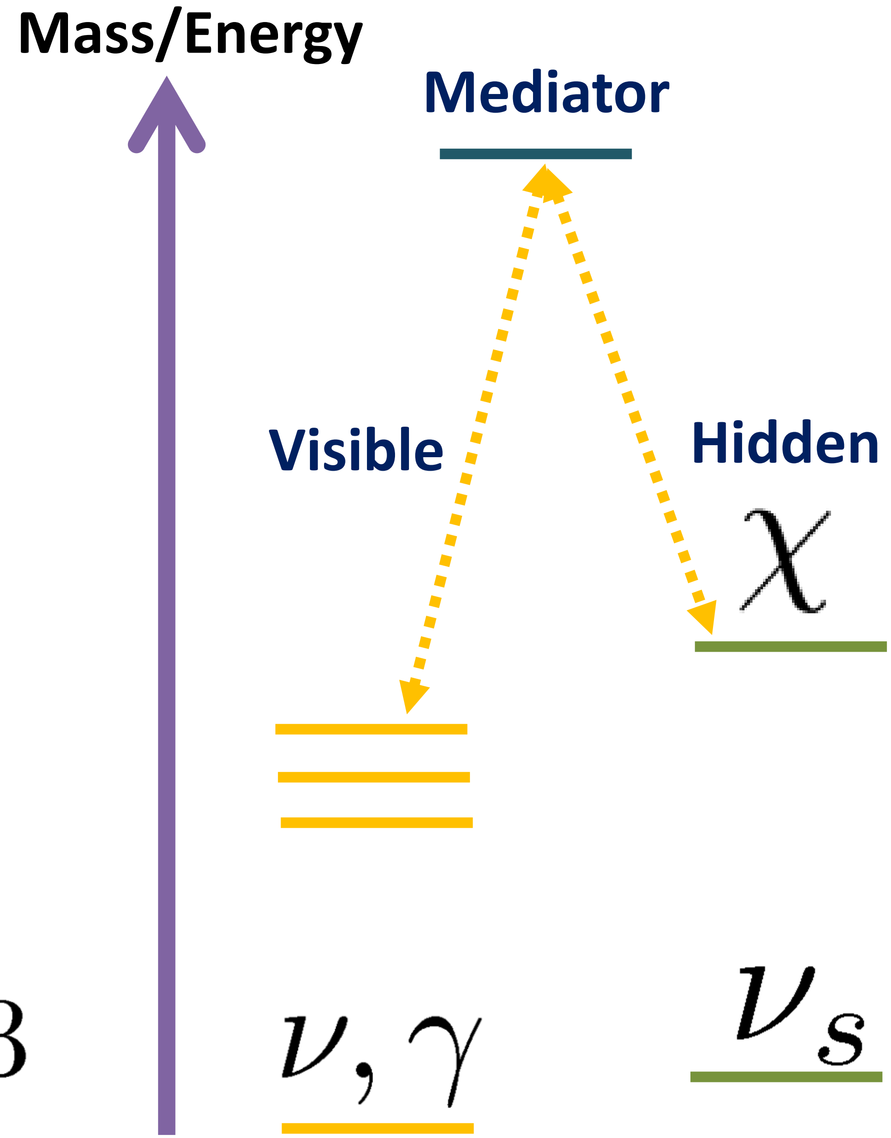
Spergel, Steinhardt PRL, 1999

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

Harvey et al, Science, 2015

Dark matter and dark radiation



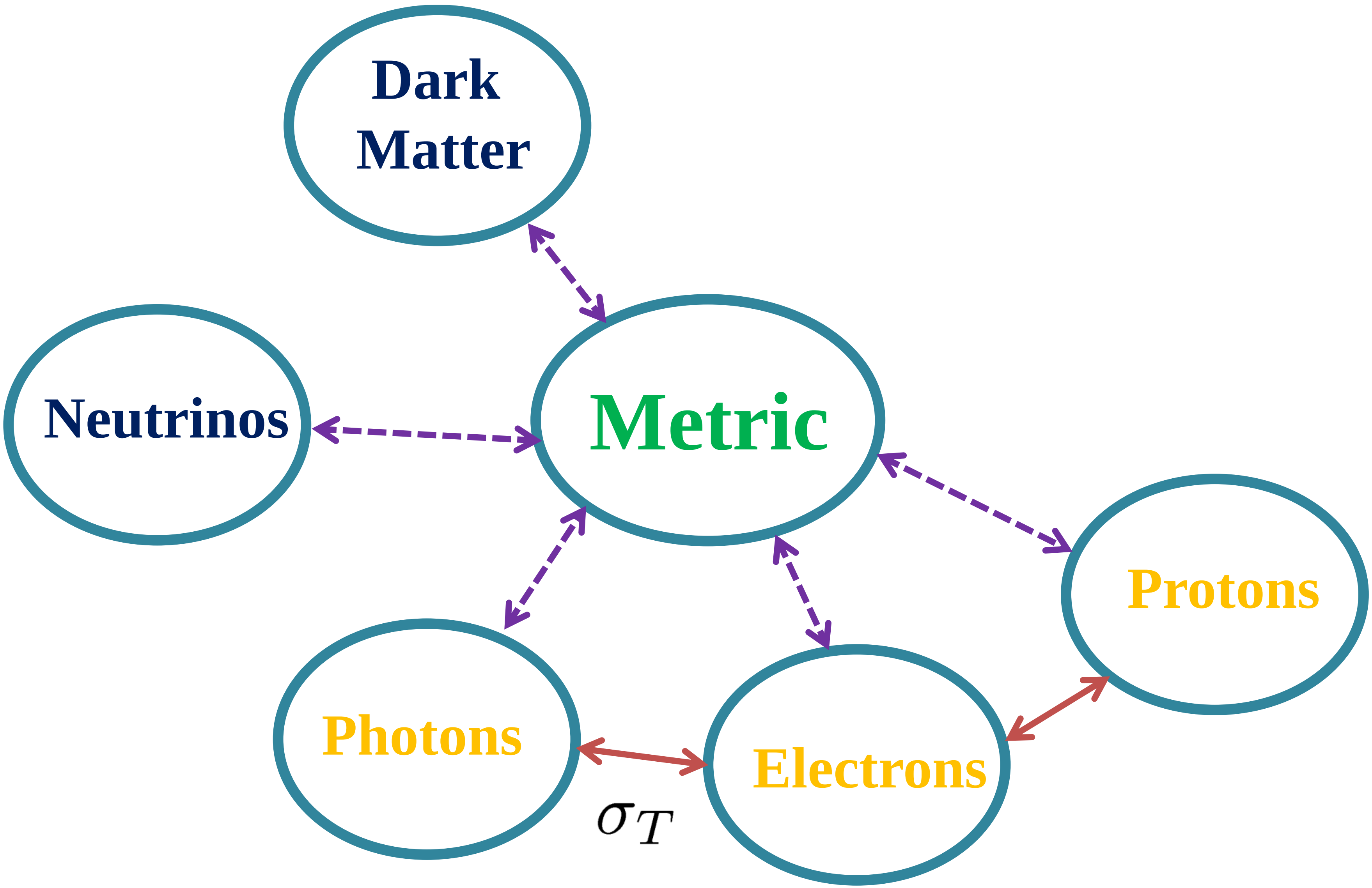


Light particles are generic:

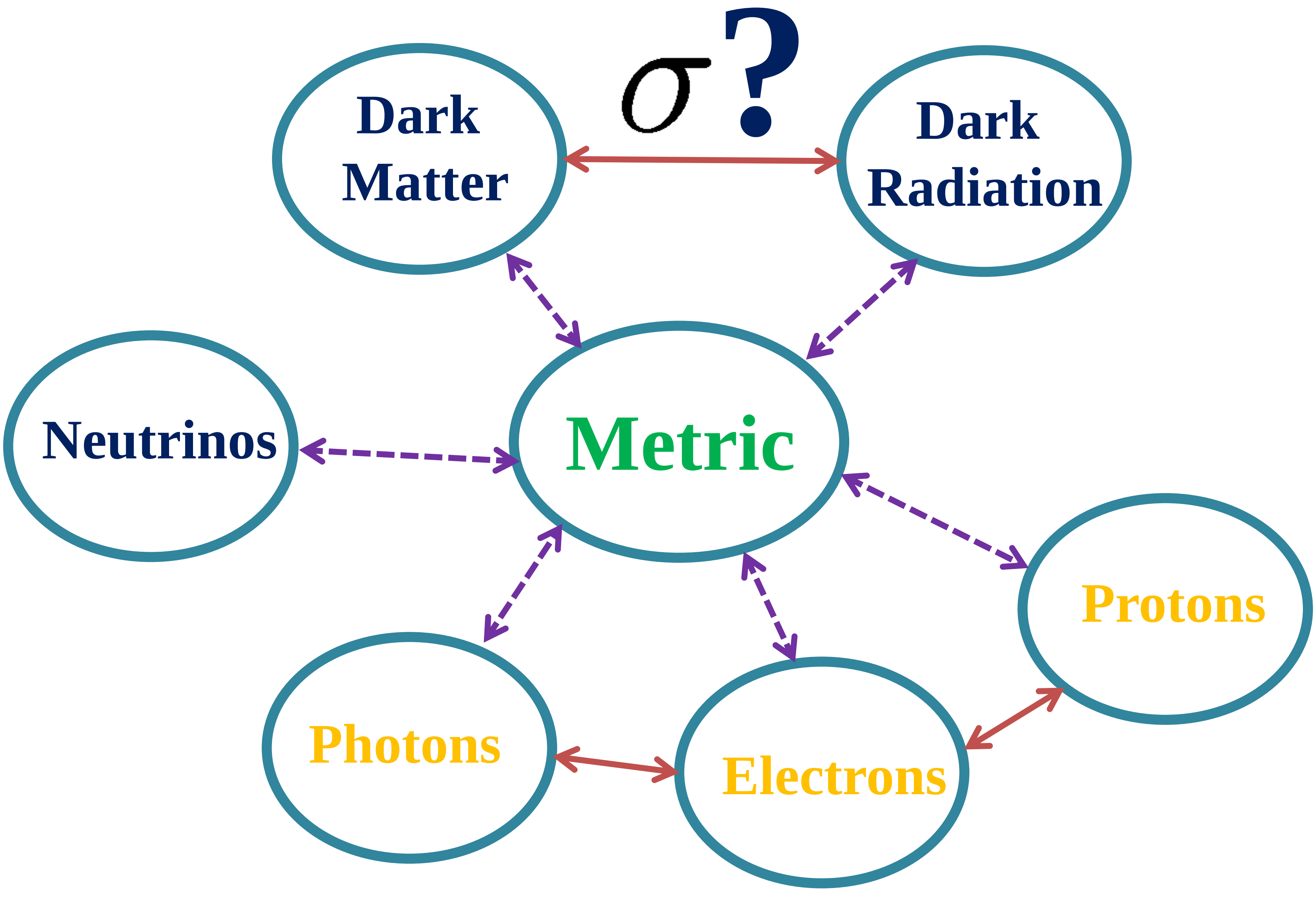
Goldstone bosons, chiral fermions, gauge bosons

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

Evolution of cosmological perturbations

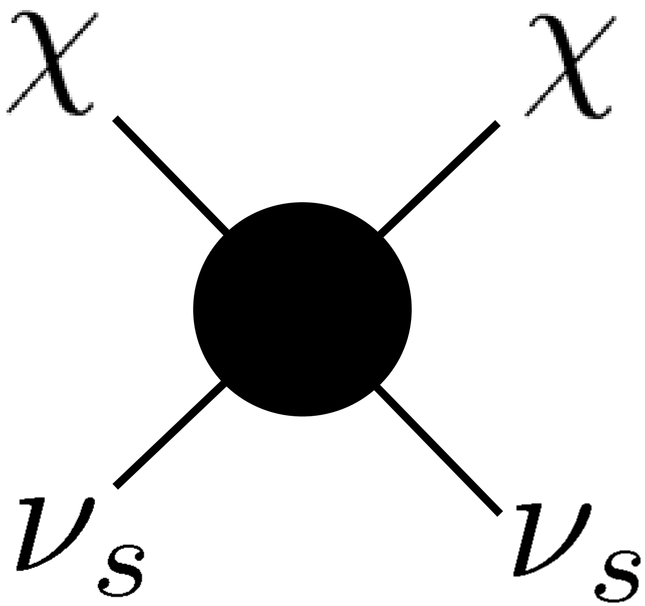


Evolution of cosmological perturbations



What is the impact of Dark Matter-Dark Radiation interactions on reionization?

- Impact on structure formation
- Impact on reionization



$$\sigma$$

Impact on structure formation

ETHOS framework

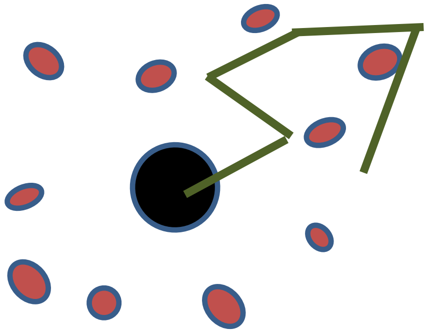
(Cyr-Racine et al 2016)

Particle physics -> Cosmology

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

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

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



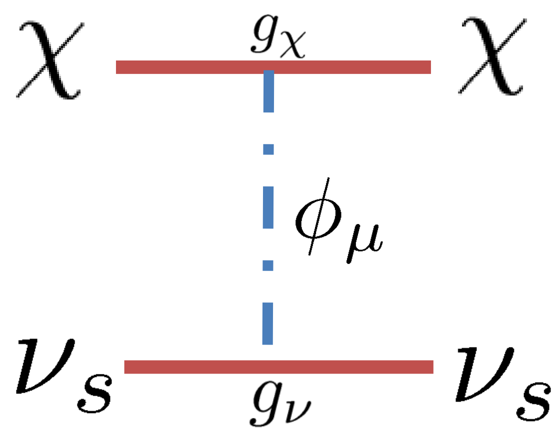
ETHOS model 1

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

χ Dark matter particle

ϕ_μ Mediator

ν_s Dark radiation



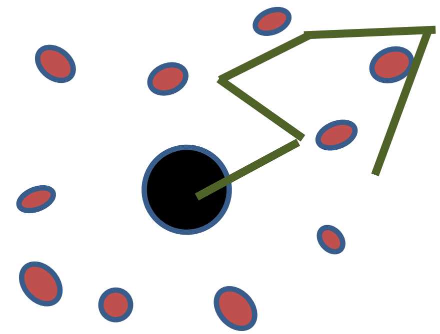
$$n \sim T^3 \qquad \sigma \sim g_\chi^2 g_\nu^2 \frac{T^2}{m_\phi^4}$$

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

$$a_4 = 0.6 \times 10^5 \left(\frac{g_\chi}{1}\right)^2 \left(\frac{g_\nu}{1}\right)^2 \left(\frac{0.468 \text{ MeV}}{m_\phi}\right)^4 \left(\frac{2 \text{ TeV}}{m_\chi}\right) \left(\frac{\xi}{0.5}\right)^2 \text{ Mpc}^{-1}$$

Decoupling of DM and DR

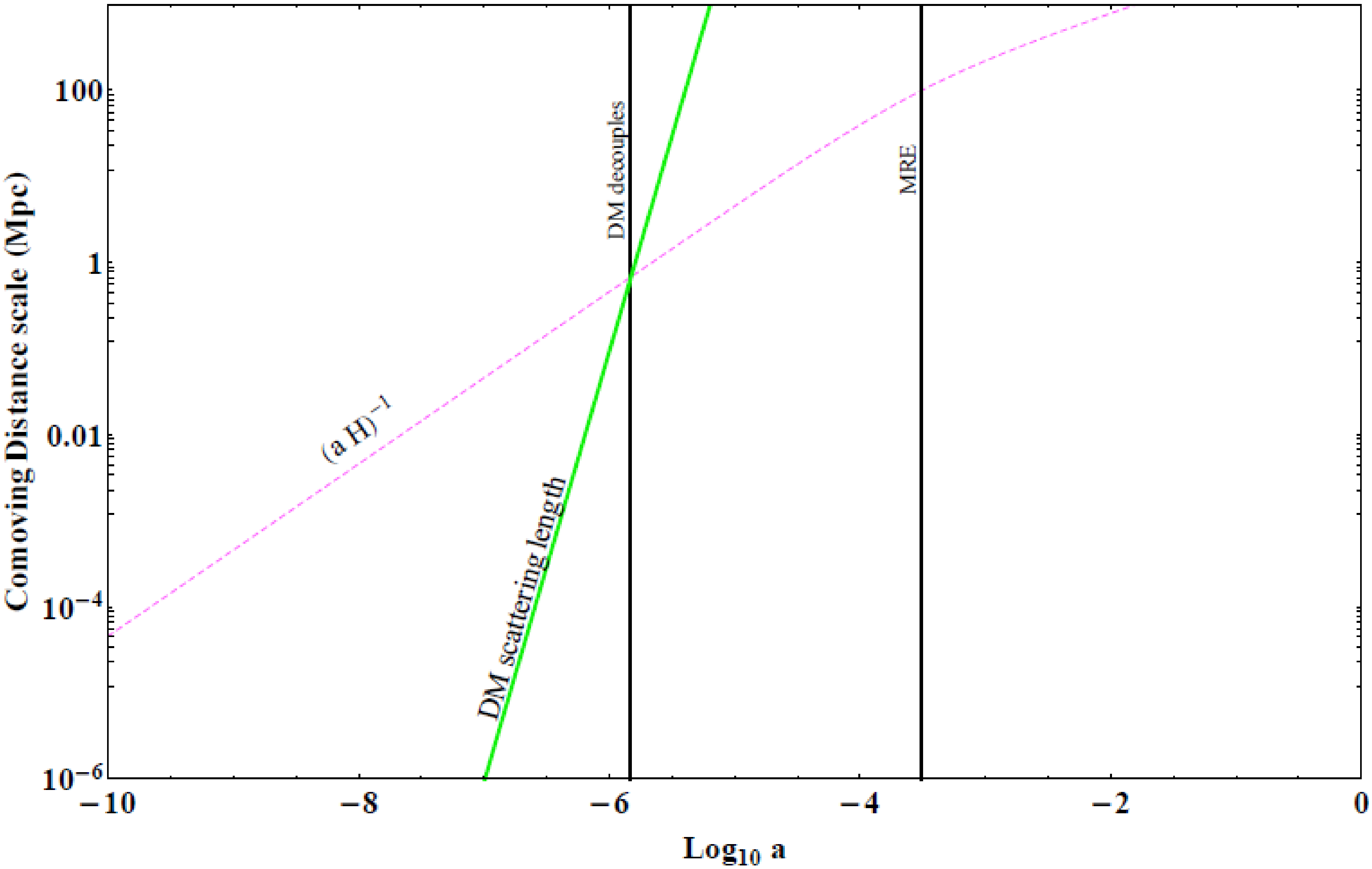
- Comoving Hubble scale $(aH)^{-1}$
- Scattering length λ



Early times	$\lambda \ll (aH)^{-1}$	DM and DR are tightly coupled (dark acoustic oscillations)
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

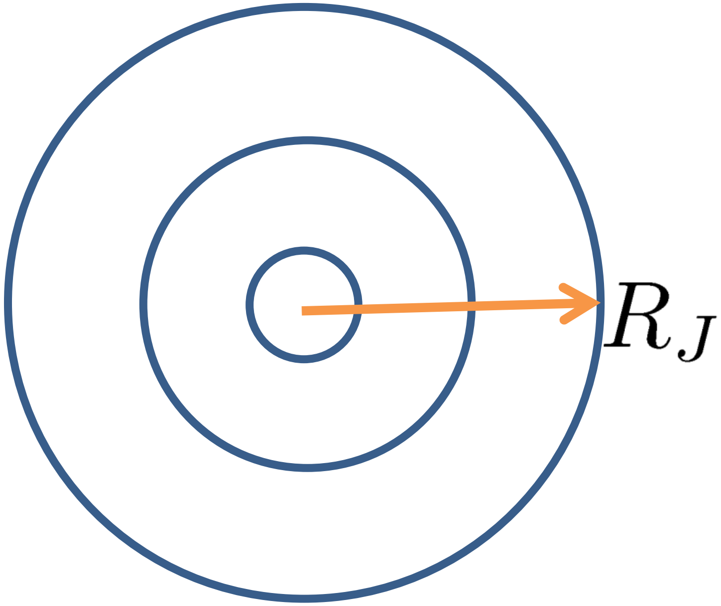


Jeans scale (pre-decoupling)

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

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

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

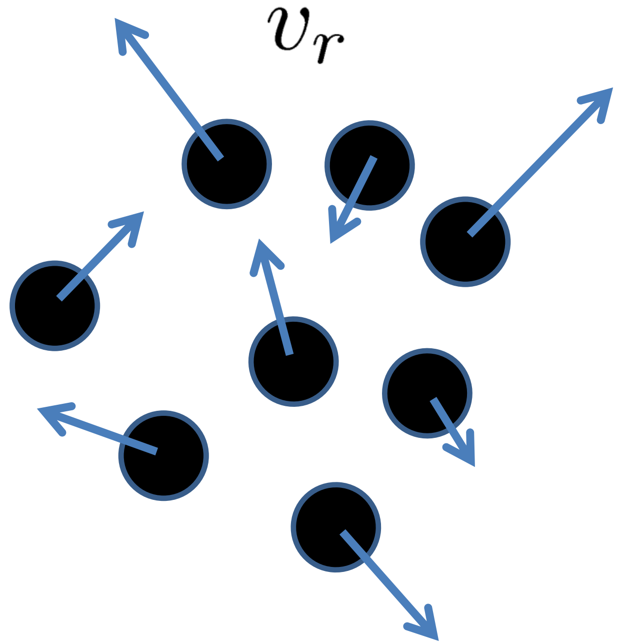


Jeans scale (post-decoupling)

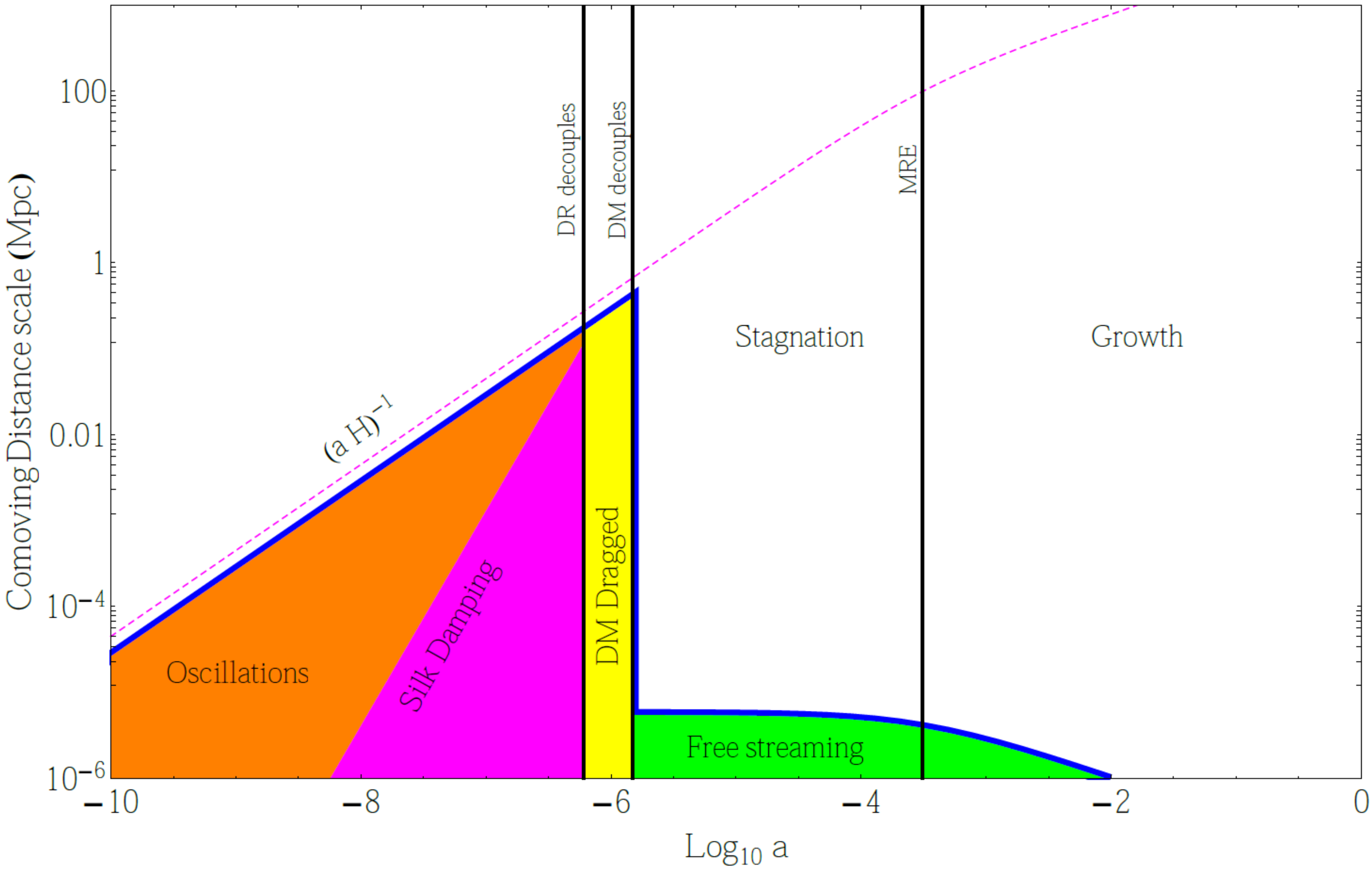
$$R_J \sim v_r t_{\text{turn-around}}$$

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

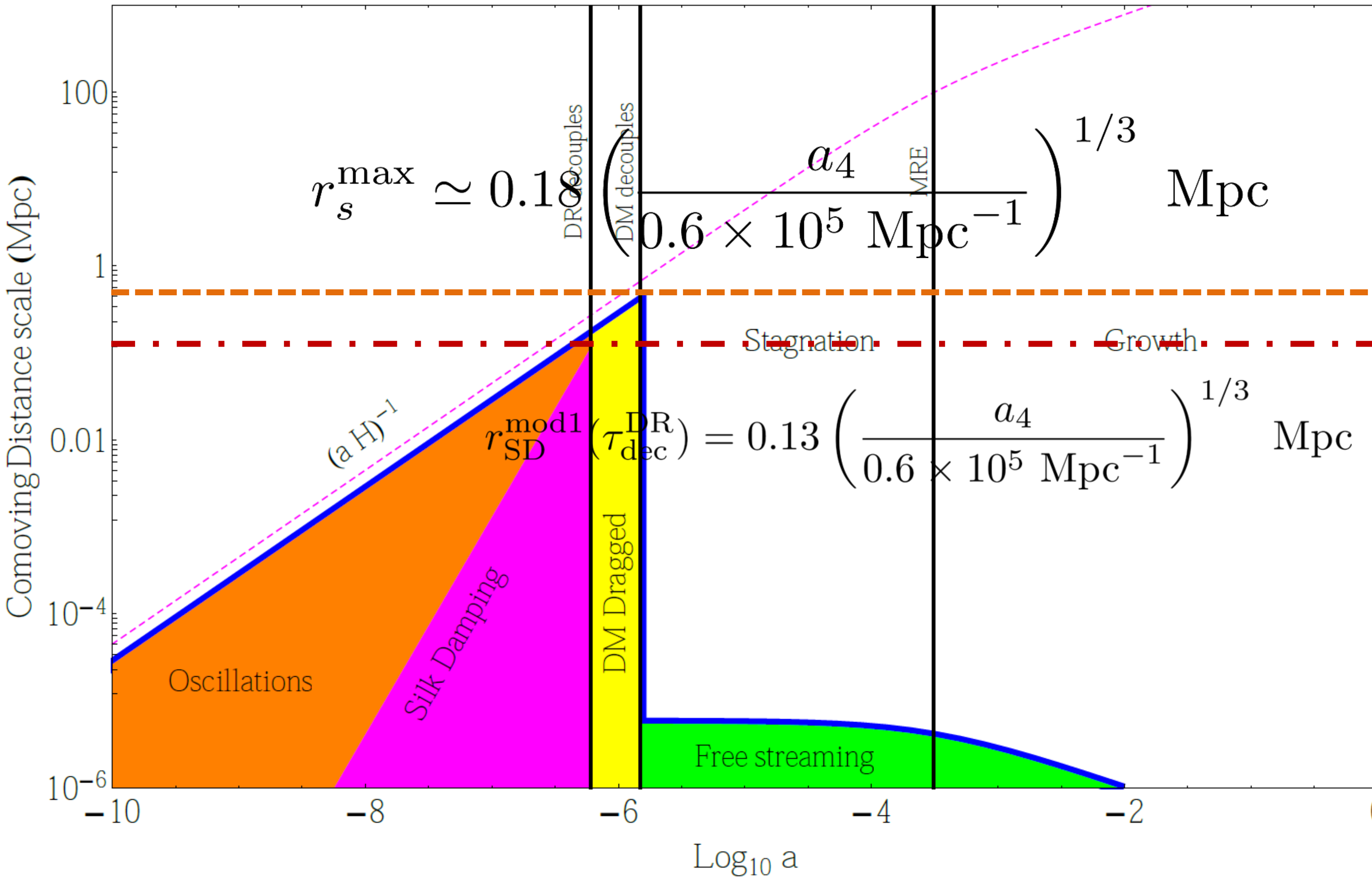
$$p_\chi = m_\chi v_r \sim (1+z)$$



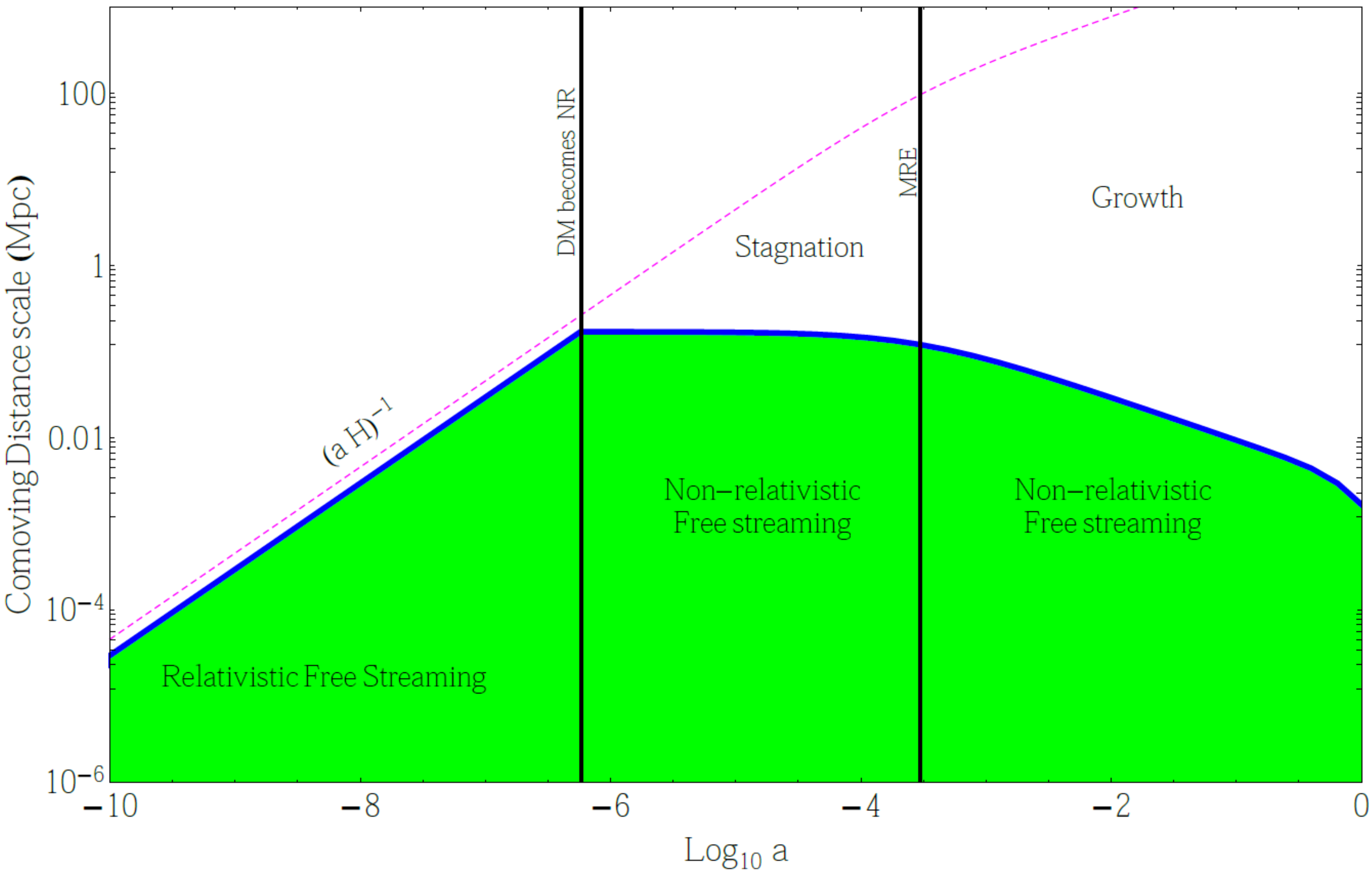
Evolution of Jeans scale in ETHOS 1



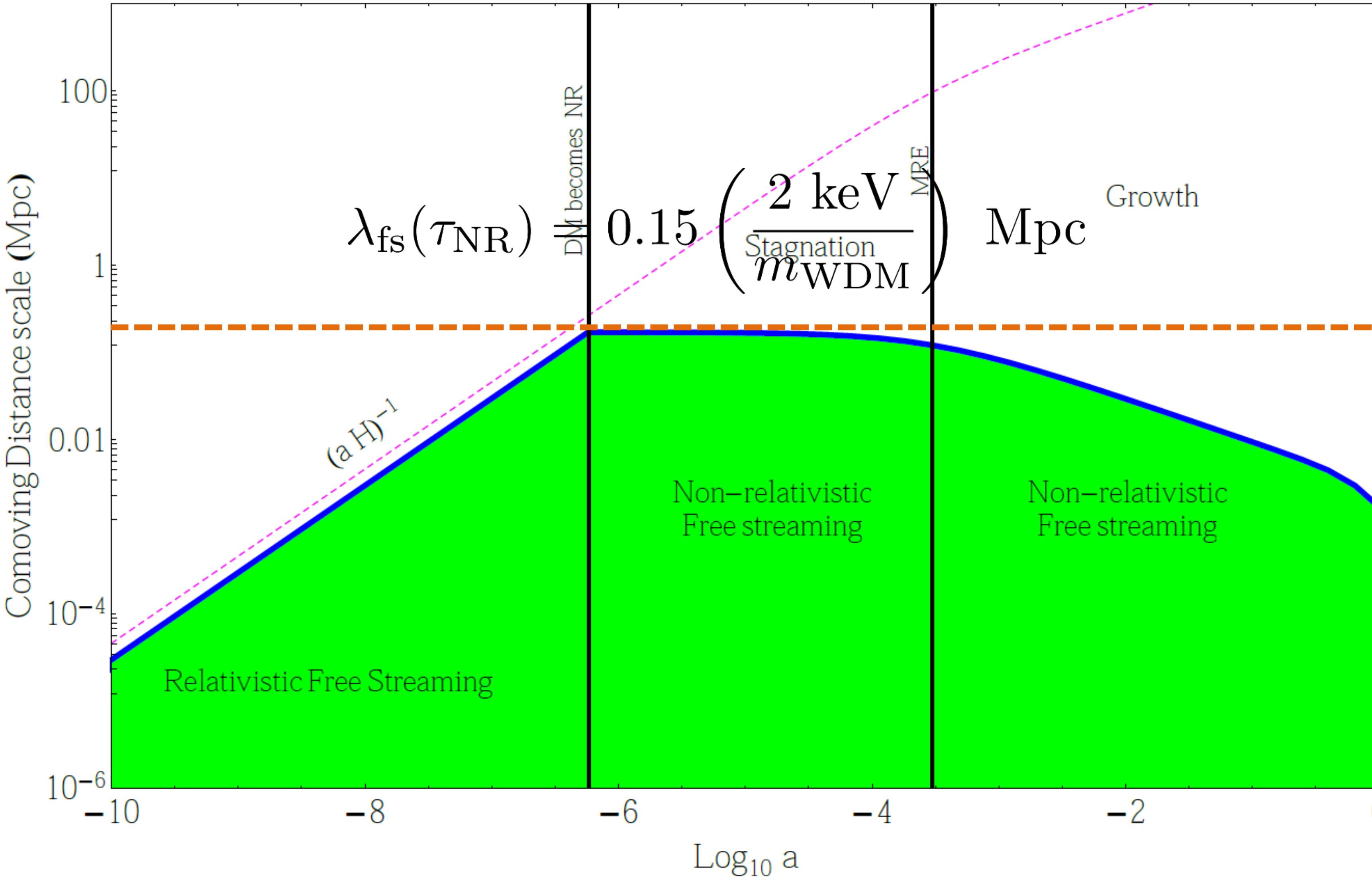
Evolution of Jeans scale in ETHOS 1



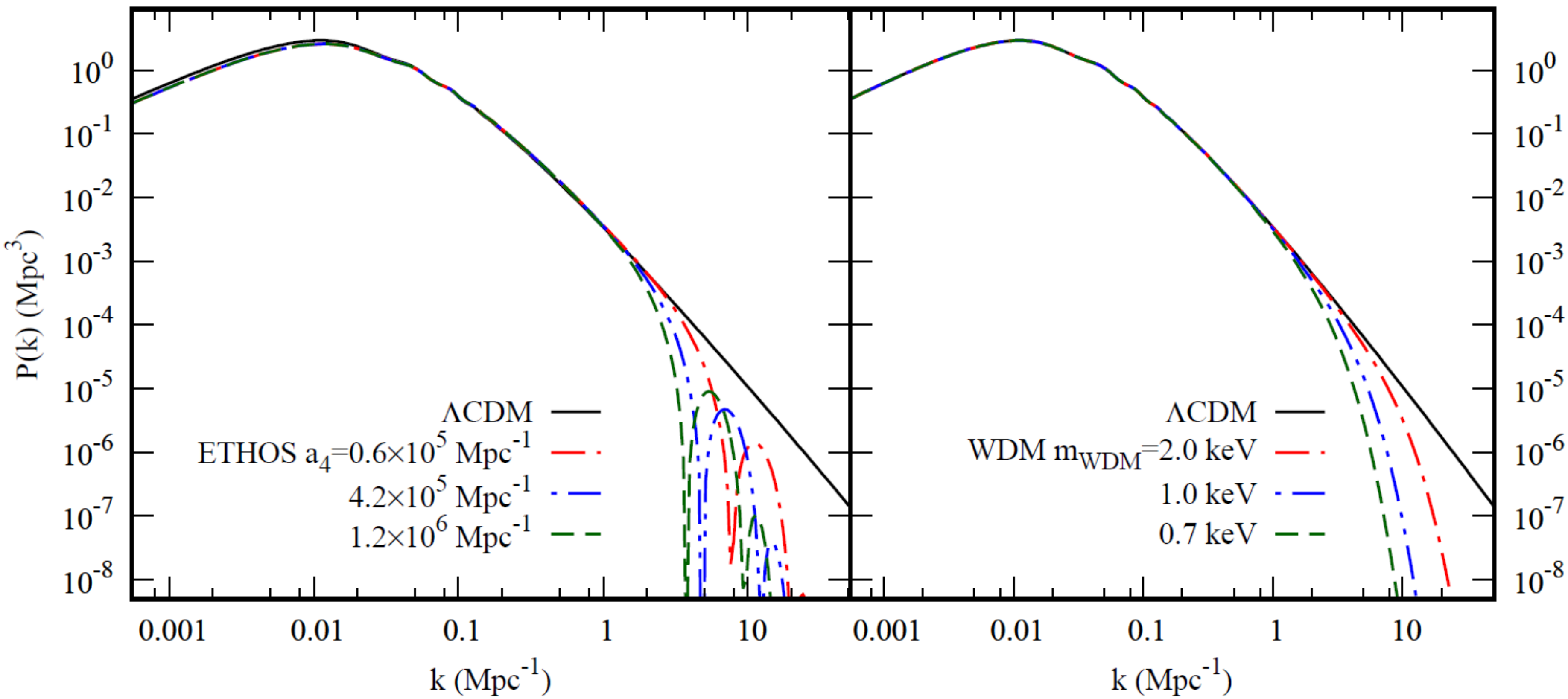
Evolution of Jeans scale in WDM models



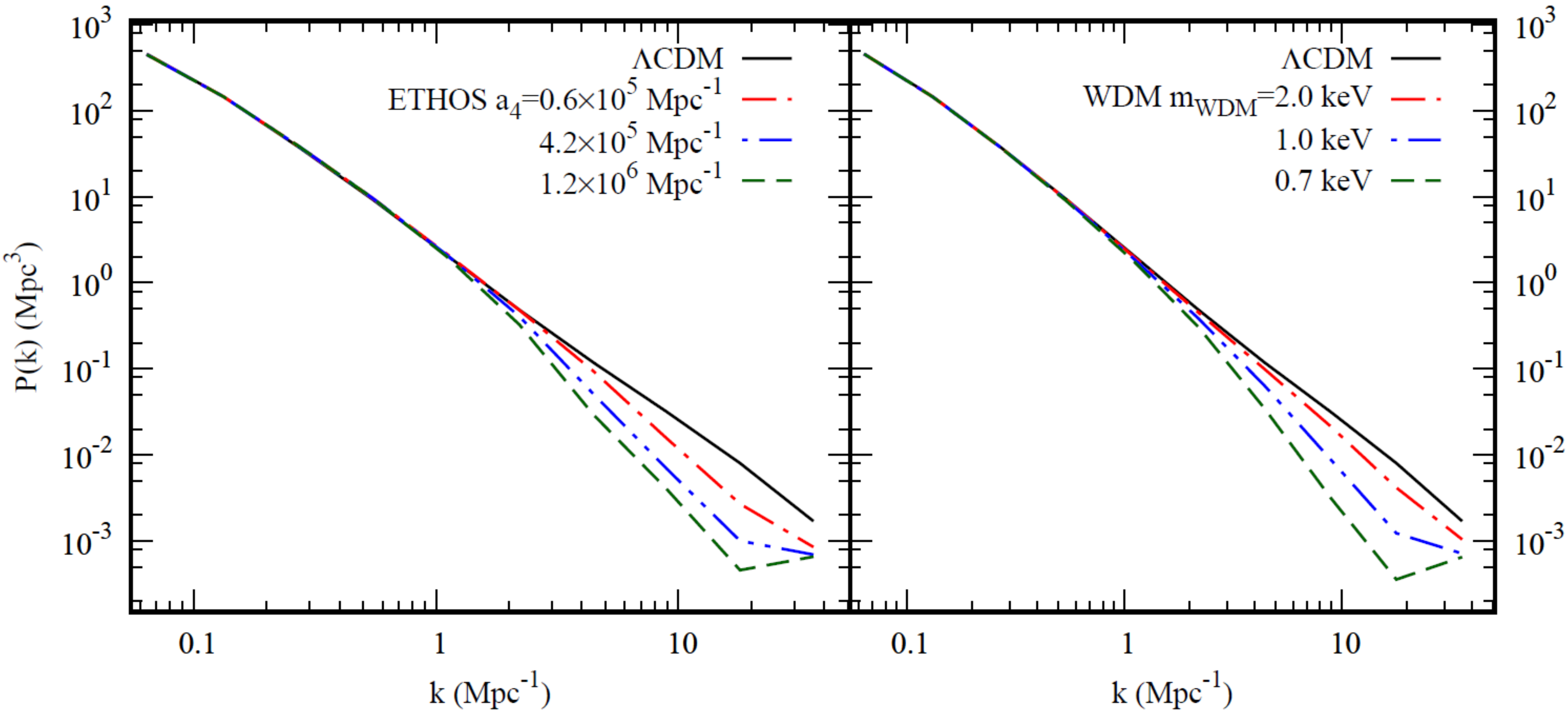
Evolution of Jeans scale in WDM models



Linear Power Spectrum (z=124)



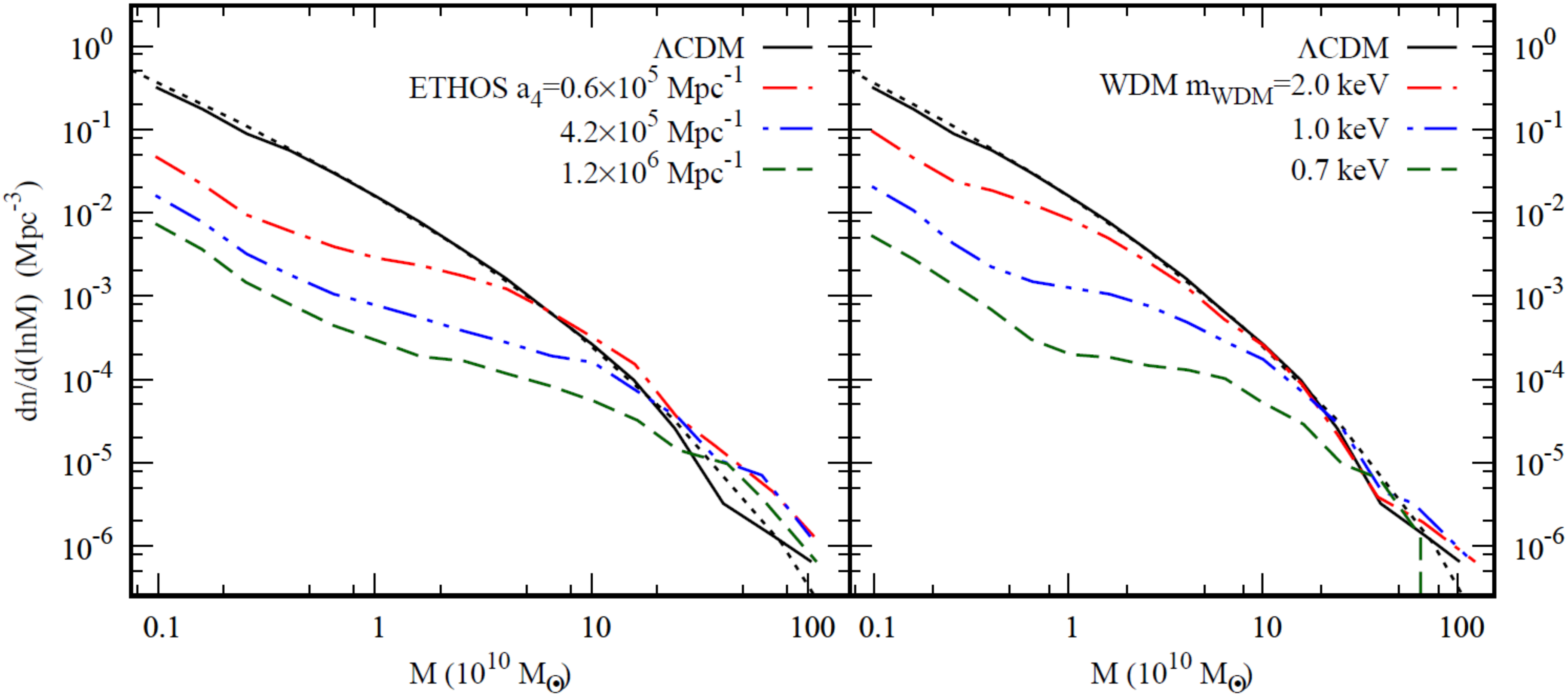
Non-Linear power spectrum (z=8)



from N-body simulation

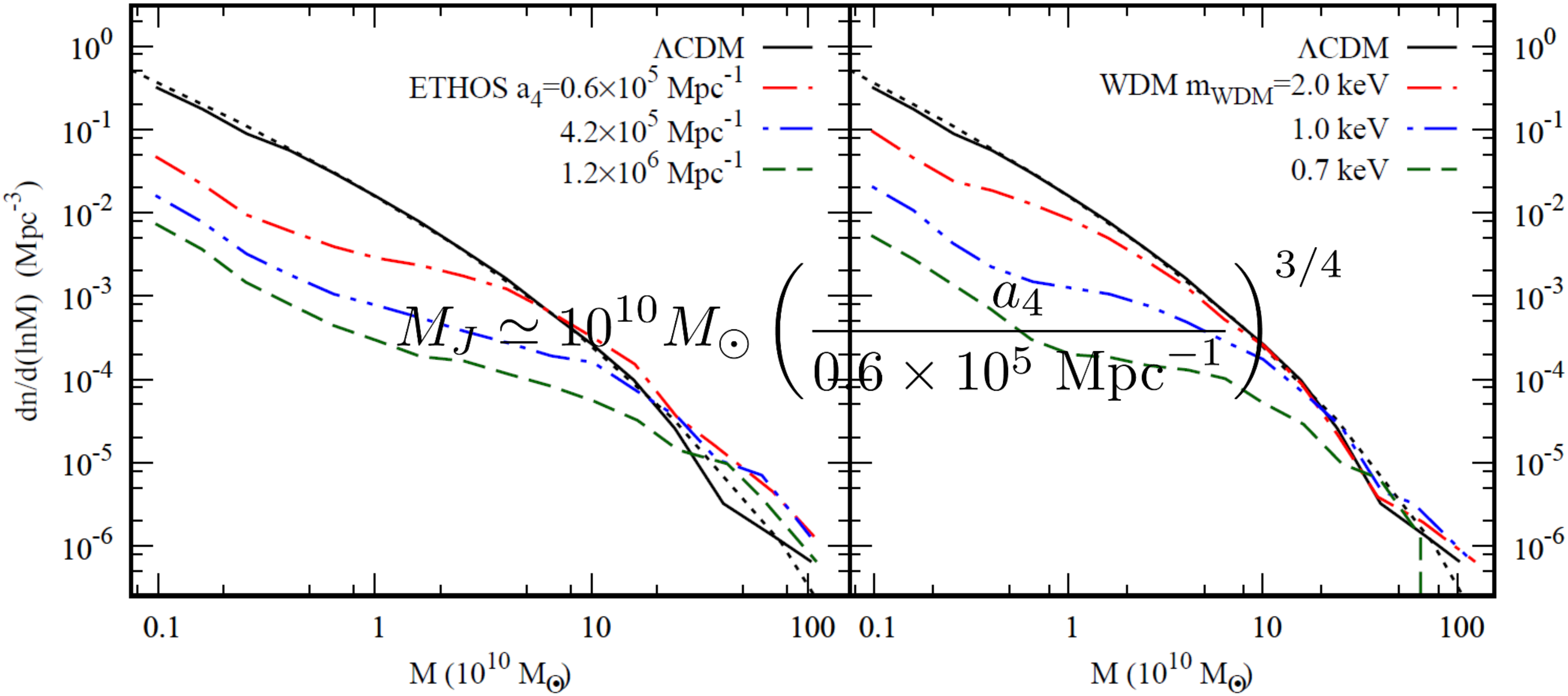
Lyman-alpha constraints rule out m_x < 3.5 keV

Halo mass distribution (z=8)



from Halo finding algorithm

Halo mass distribution (z=8)

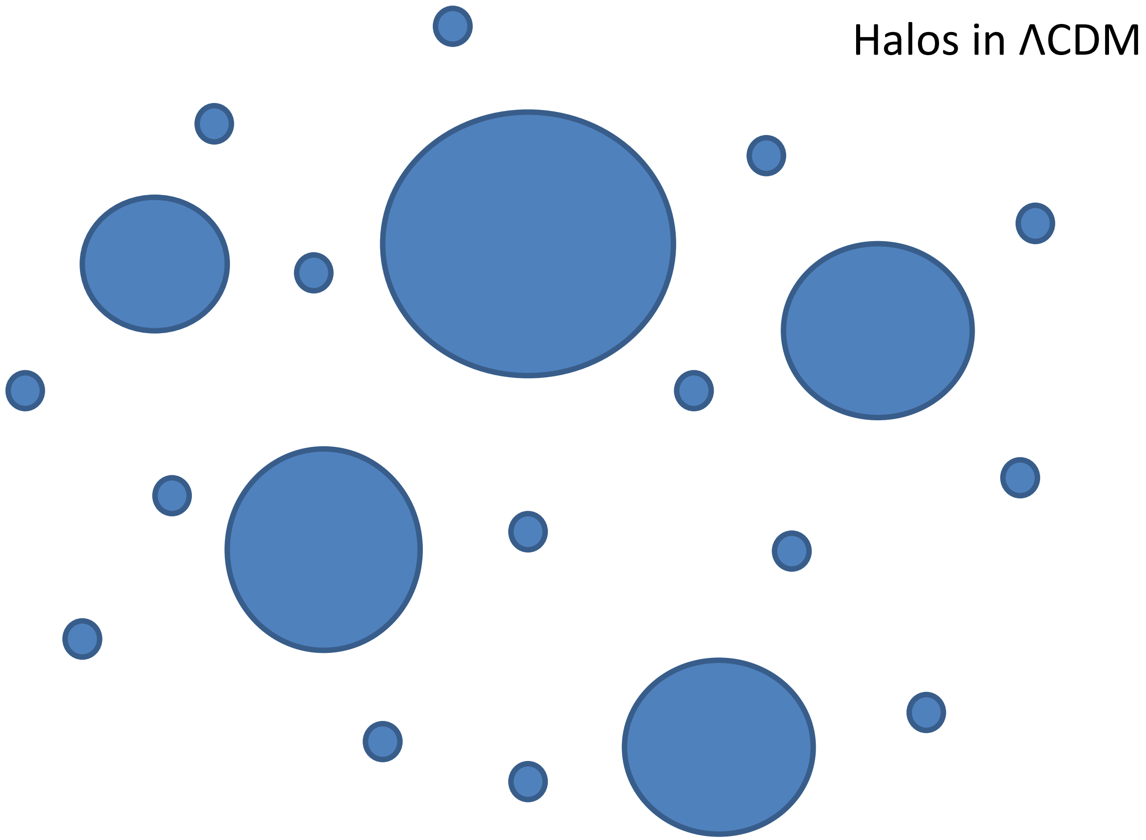


$$M_J \simeq 10^{10} M_\odot \left(\frac{a_4}{0.6\times10^5\ \mathrm{Mpc}^{-1}}\right)^{3/4}$$

from Halo finding algorithm

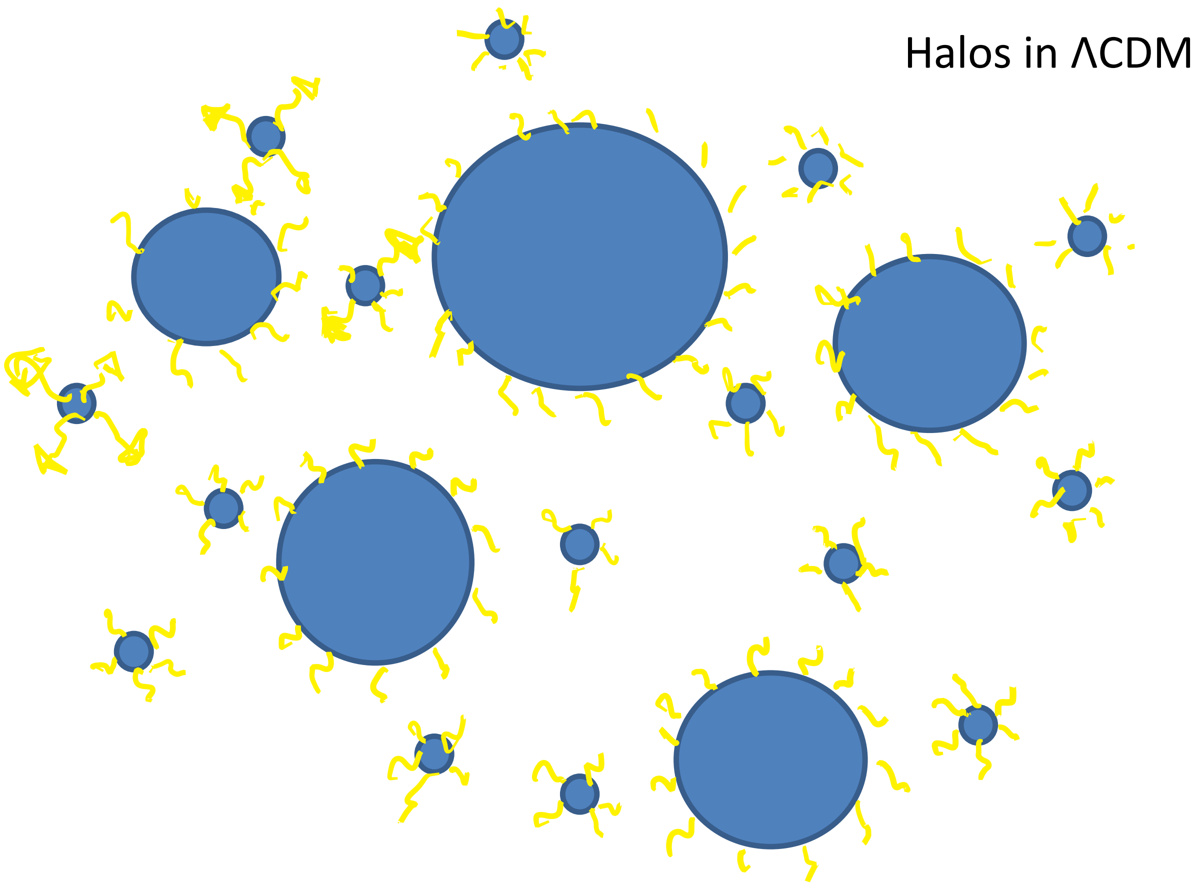
Impact on reionization

From structure to reionization



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

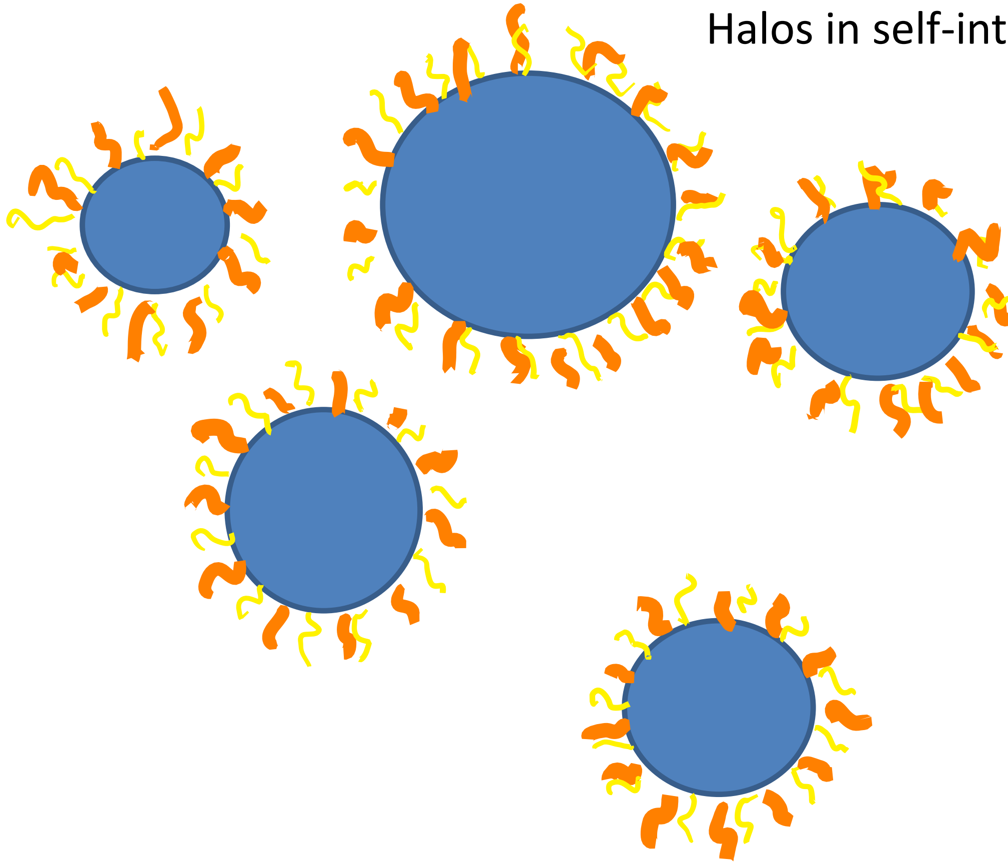
From structure to reionization



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

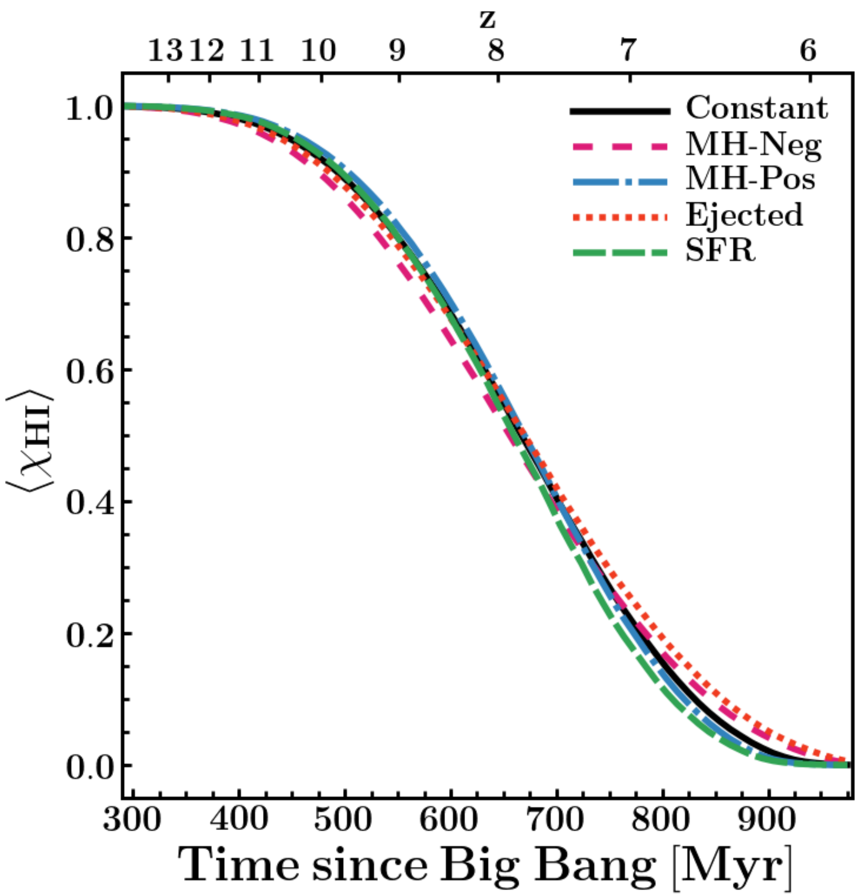
From structure to reionization

Halos in self-interacting DM model



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

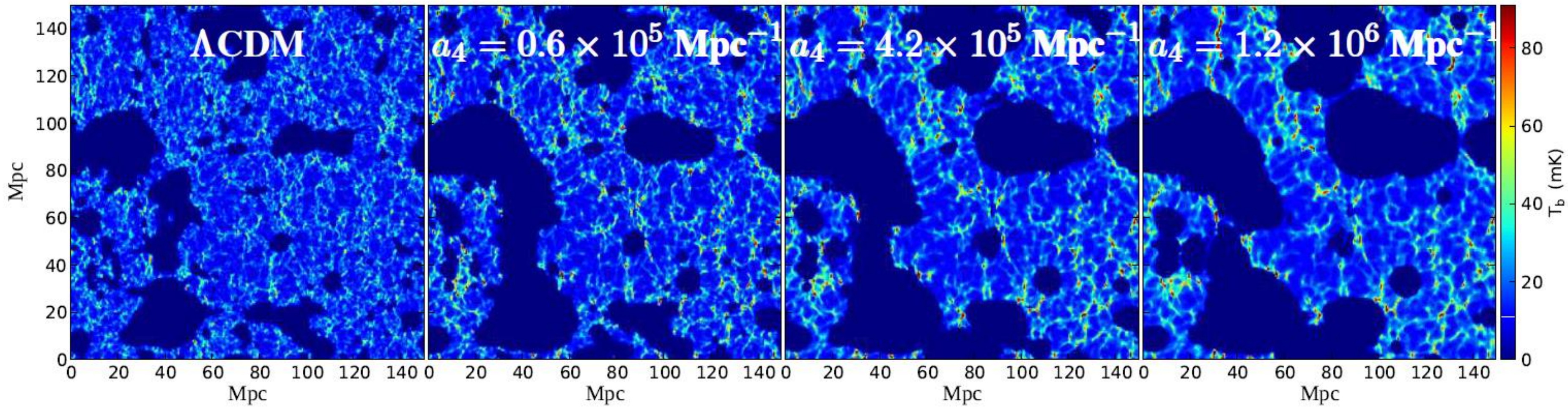
What value of N_{ion} do we need for successful reionization?



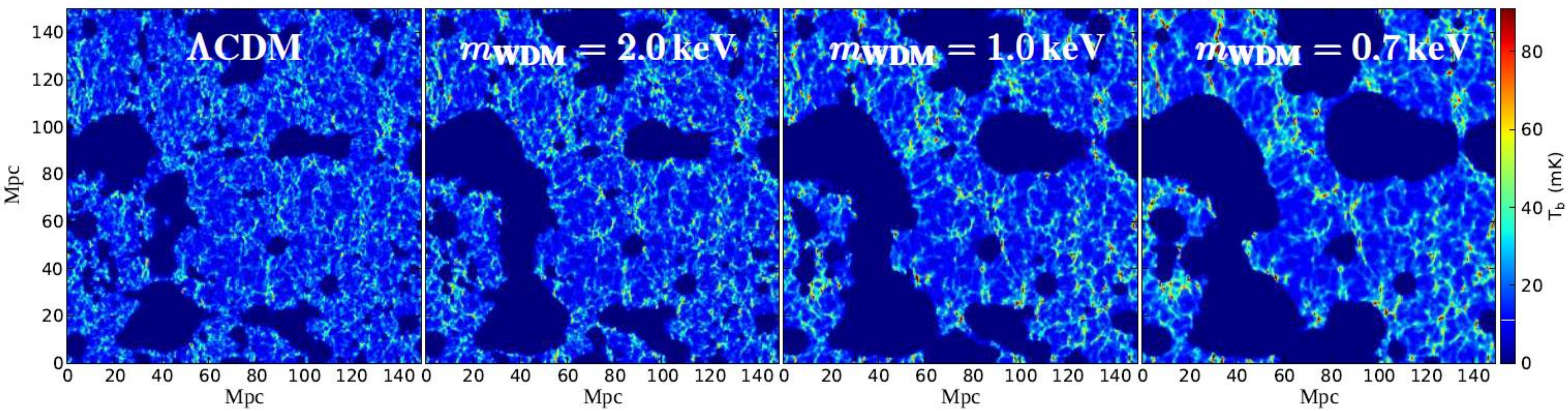
$$6 \lesssim z_{\rm reio} \lesssim 10$$

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

HI brightness temperature (z = 8)



N_{ion} 23 100 321 721



N_{ion} 23 57 225 861

Can we estimate N_{ion}?

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

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

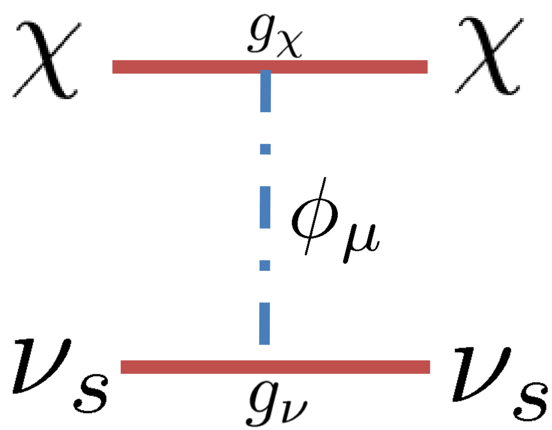
Depends on metallicity, IMF, SF efficiency, escape fraction

Large systematic uncertainties!

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

Our Results

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

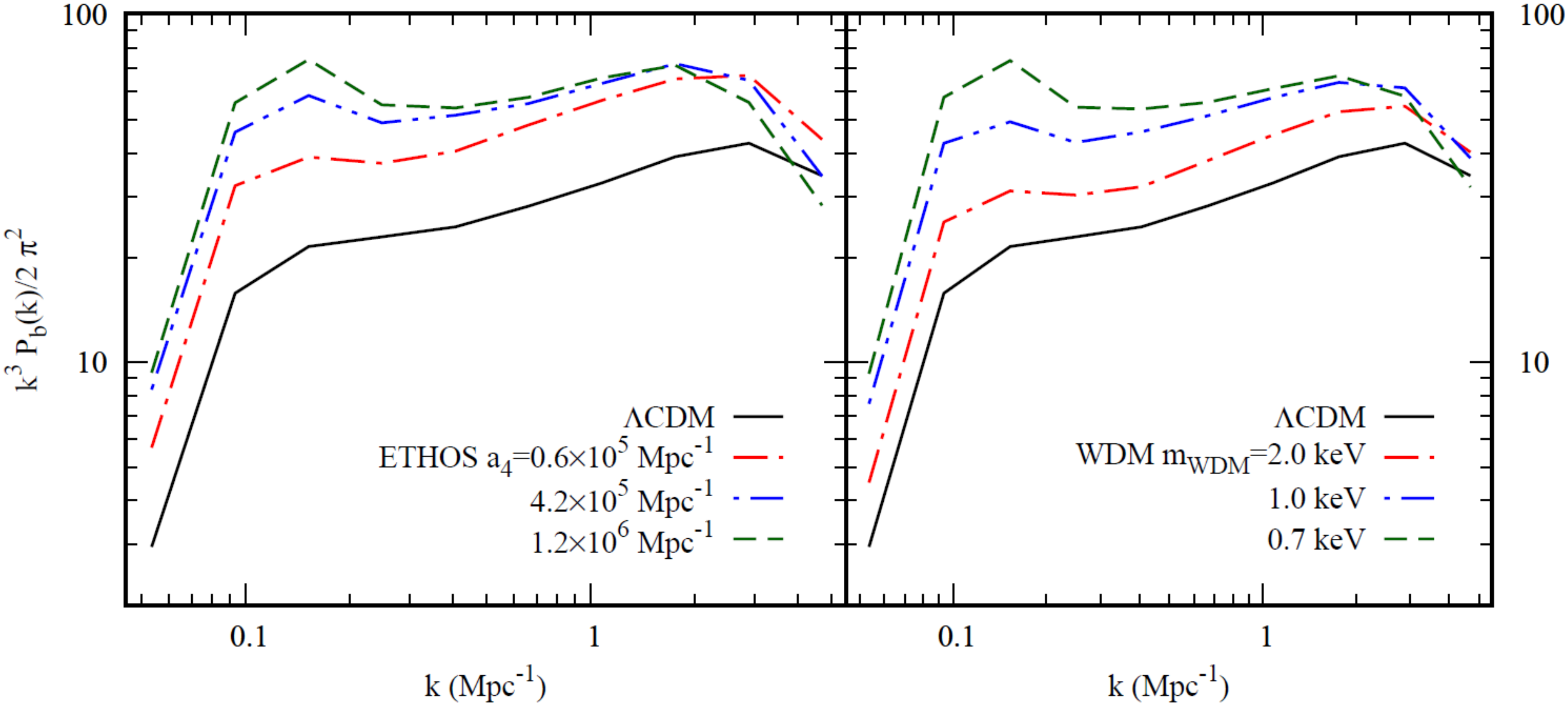


$$a_4 = 0.6 \times 10^5 \left(\frac{g_\chi}{1}\right)^2 \left(\frac{g_\nu}{1}\right)^2 \left(\frac{0.5\ \mathrm{MeV}}{m_\phi}\right)^4 \left(\frac{2\ \mathrm{TeV}}{m_\chi}\right)\ \mathrm{Mpc}^{-1}$$

$$a_4 \lesssim 1.2 \times 10^6\ \mathrm{Mpc}^{-1}$$

$$m_{\mathrm{WDM}} \gtrsim 0.7\ \mathrm{keV}$$

Future: HI brightness power spectrum



Future 21 cm surveys could measure this difference

GMRT, LOFAR, MWA, PAPER, SKA, HERA …

Other future observations

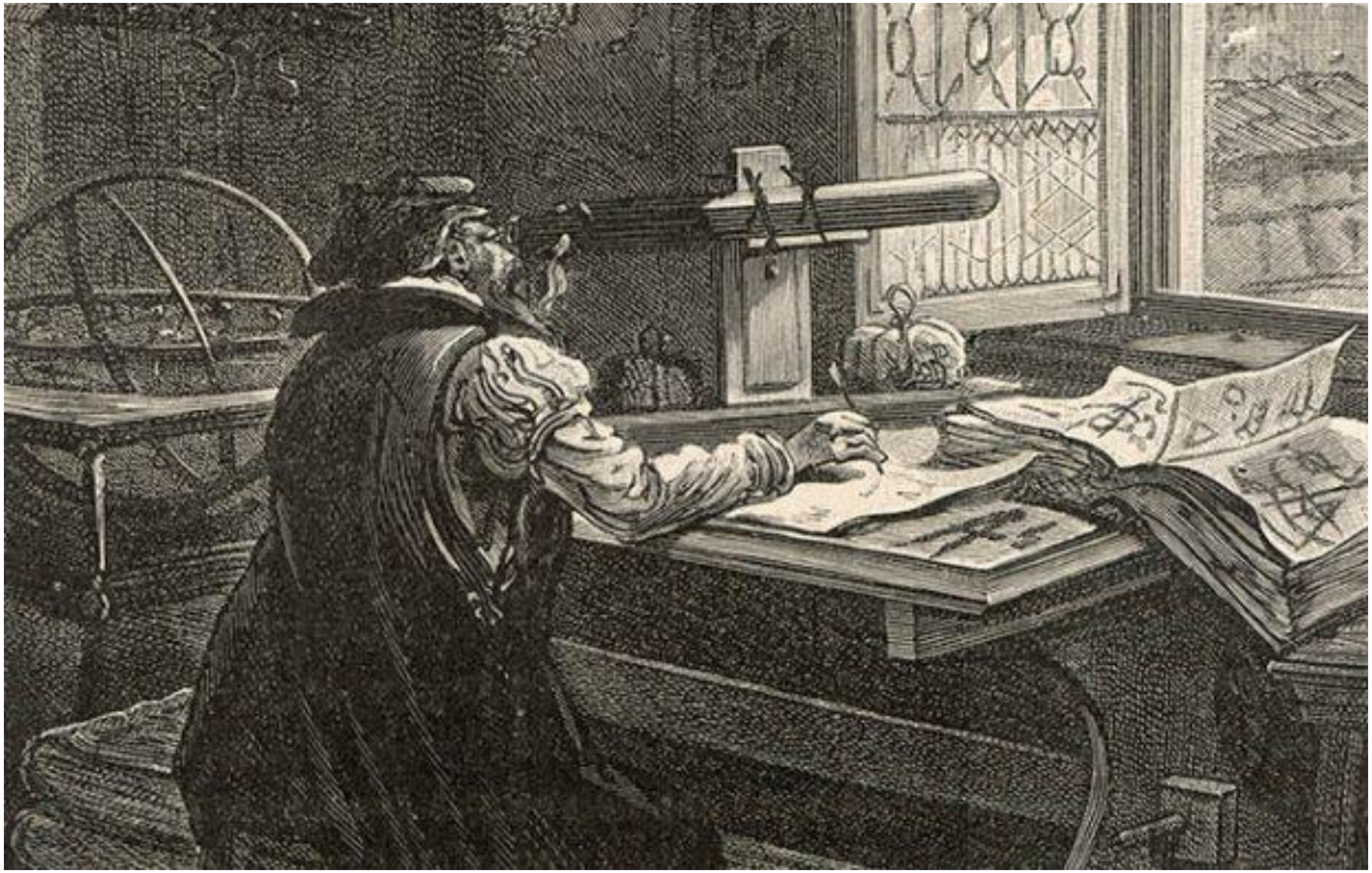
How can we reduce systematic uncertainties on $\mathbf{N}_{\mathbf{ion}}$?

- Direct observations of early galaxies that reionized the universe (using near IR observations)
- Pop III stars (JWST)
- Improved galaxy formation simulations matched to data

Conclusions

- 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
- 21 cm surveys could potentially detect the impact of DM-DR interactions on cosmological perturbations

QUESTIONS, COMMENTS, SUGGESTIONS?

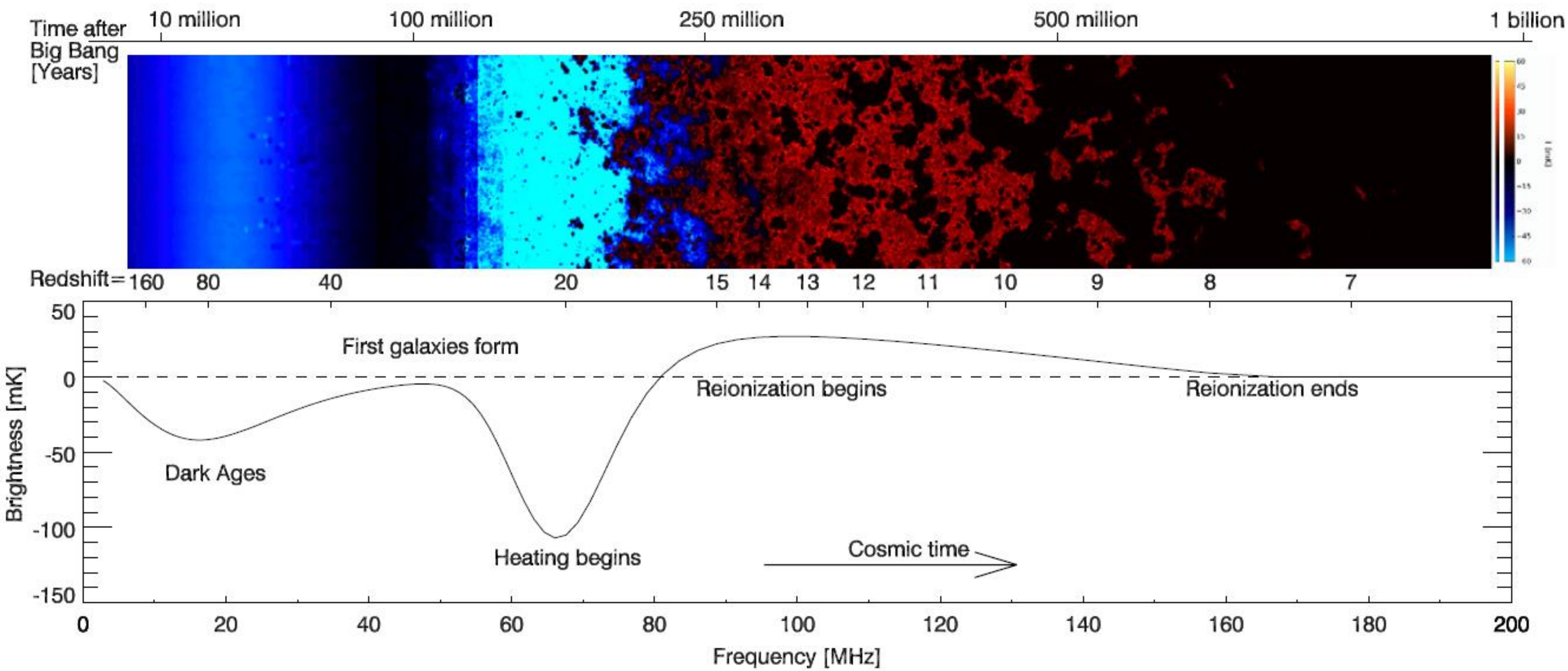


Backup Slides

Robustness check

Model/$\bar{x}_{\mathrm{H\,I}}(z = 8)$	40%	50%	60%
ΛCDM	28	24	19
ETHOS $a_4 = 0.6 \times 10^5$ Mpc^{-1}	121	100	80
ETHOS $a_4 = 4.2 \times 10^5$ Mpc^{-1}	380	300	234
ETHOS $a_4 = 1.2 \times 10^6$ Mpc^{-1}	955	721	541
WDM $m_{\mathrm{WDM}} = 2.0$ keV	69	58	47
WDM $m_{\mathrm{WDM}} = 1.0$ keV	282	226	178
WDM $m_{\mathrm{WDM}} = 0.7$ keV	1155	861	645

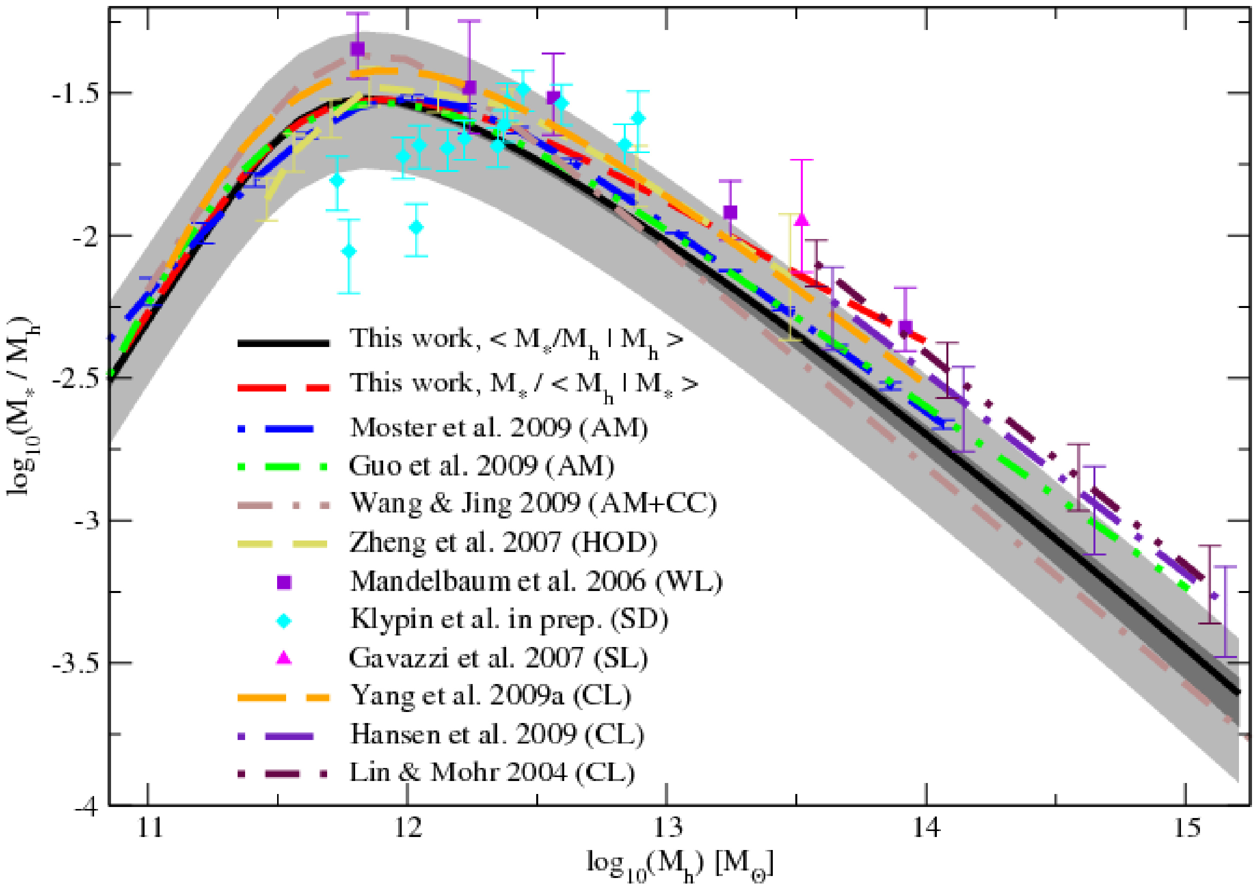
Global history of reionization



Pritchard (2011)

EDGES, SARAS, DARE …

Abundance Matching



The Current Status of Galaxy Formation - Silk, Joe *et al.* arXiv:1207.3080