Missing Neutrinos: How Late Kinetic Decoupling can Change $N_{\rm eff}$

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Goals

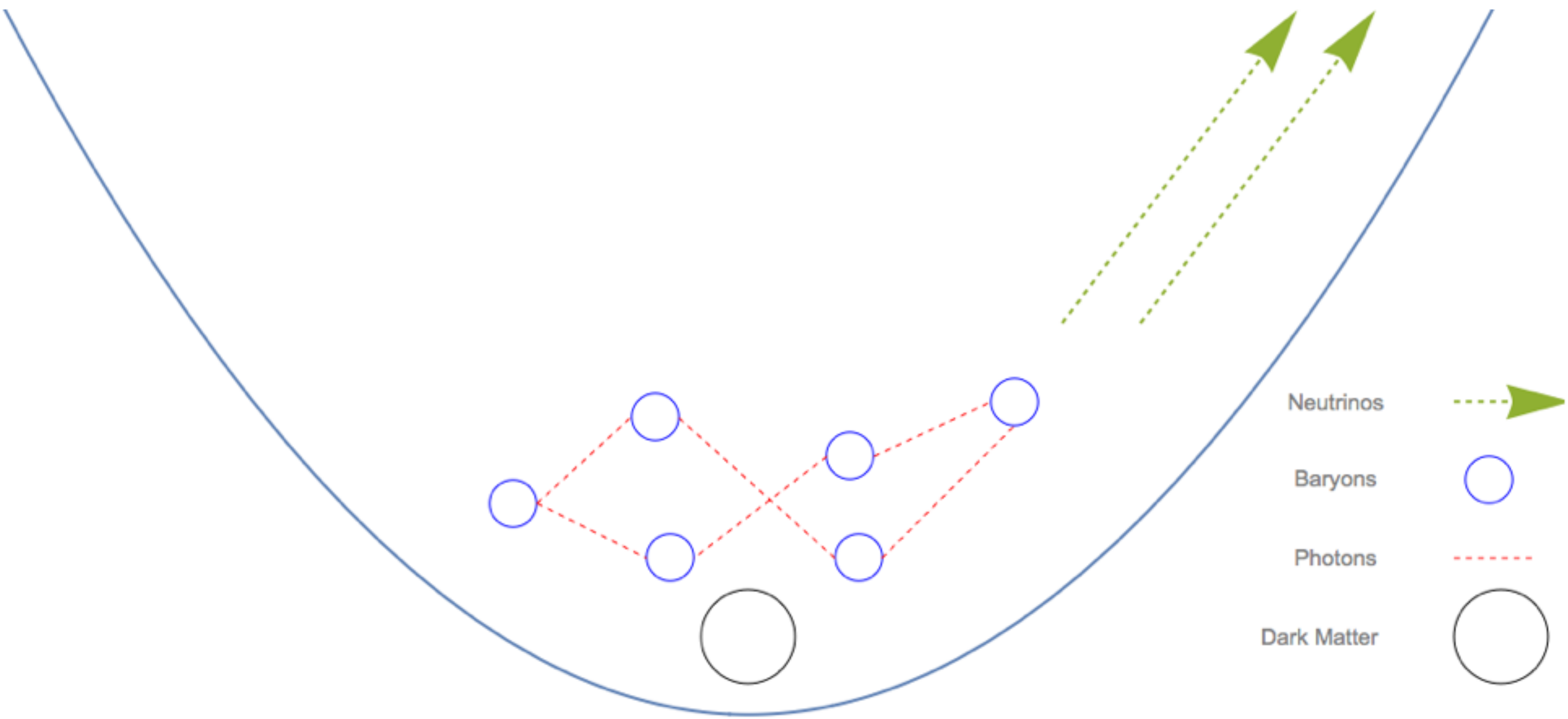
- To give a brief introduction to Late Kinetic Decoupling

- To discuss 2 Dark Matter models

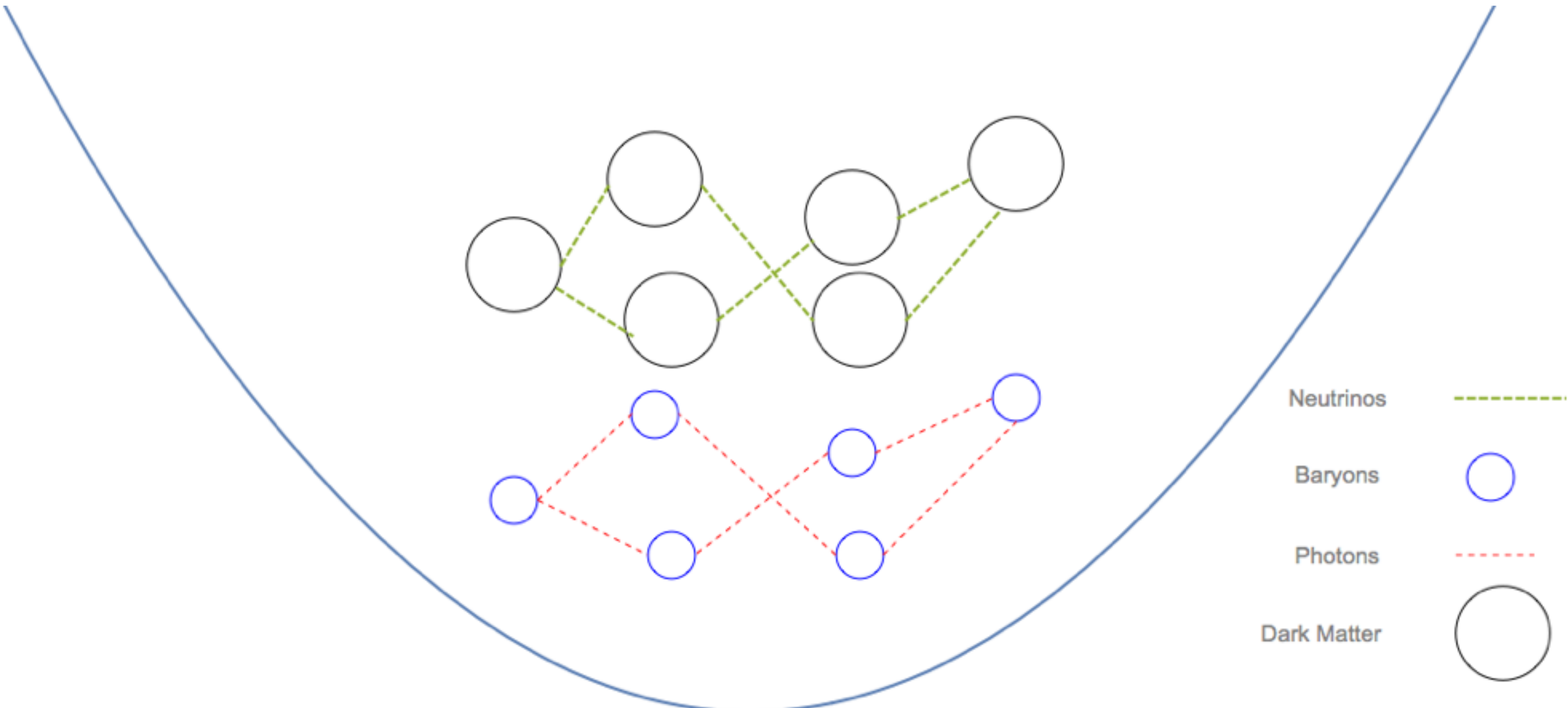
$$\left.\begin{array}{ll}\text{- Late Kinetic Decoupling from photons} & (\mathrm{LKD}\gamma) \\ \text{- Late Kinetic Decoupling from neutrinos} & (\mathrm{LKD}\nu)\end{array}\right\}(\mathrm{LKD})$$

- To show that both models can change N_{eff} without the need for introducing new particles

Early Universe with Cold Dark Matter (CDM)

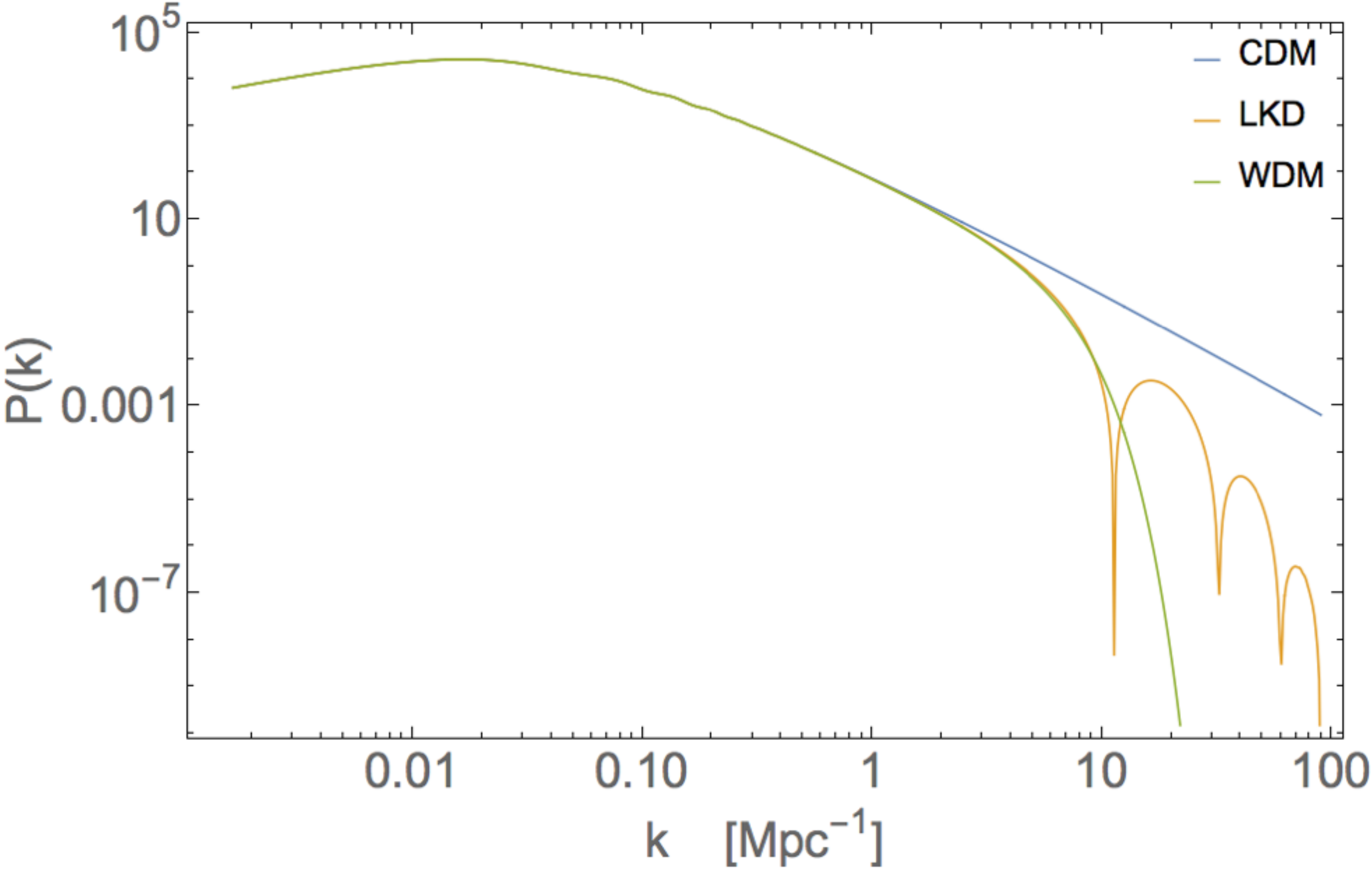


Late Kinetic Decoupling LKDν

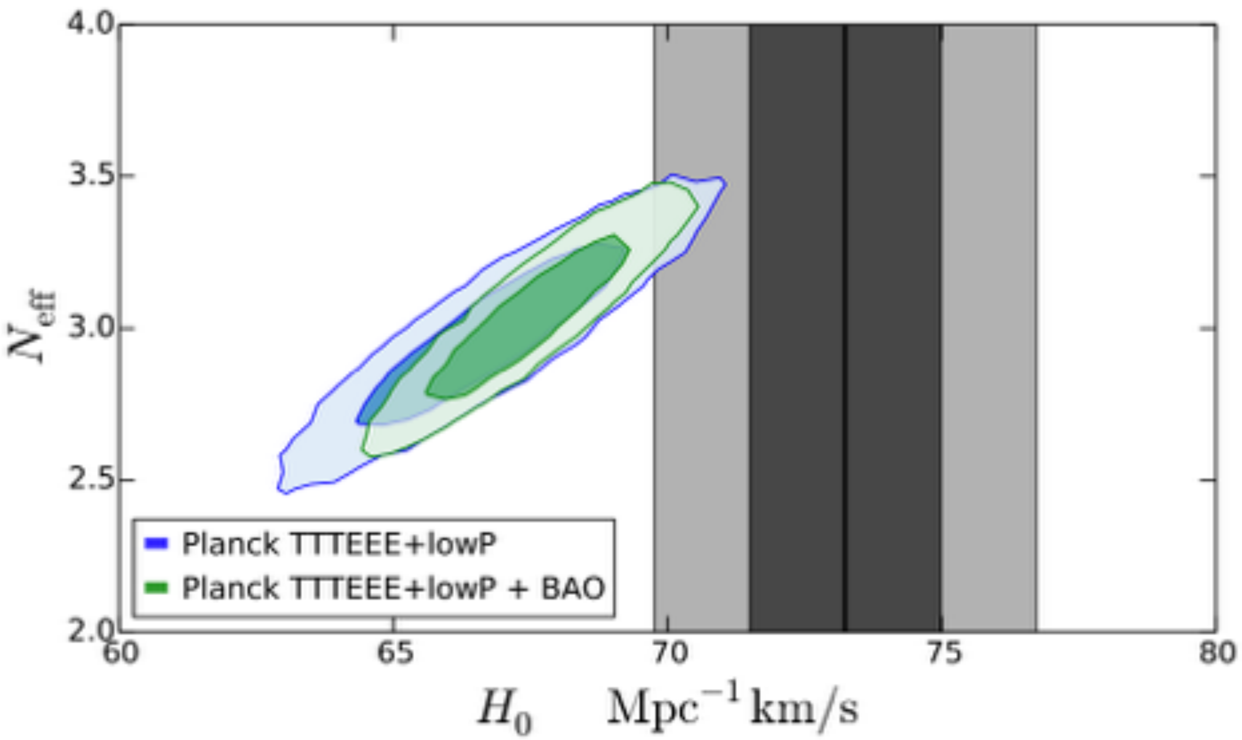


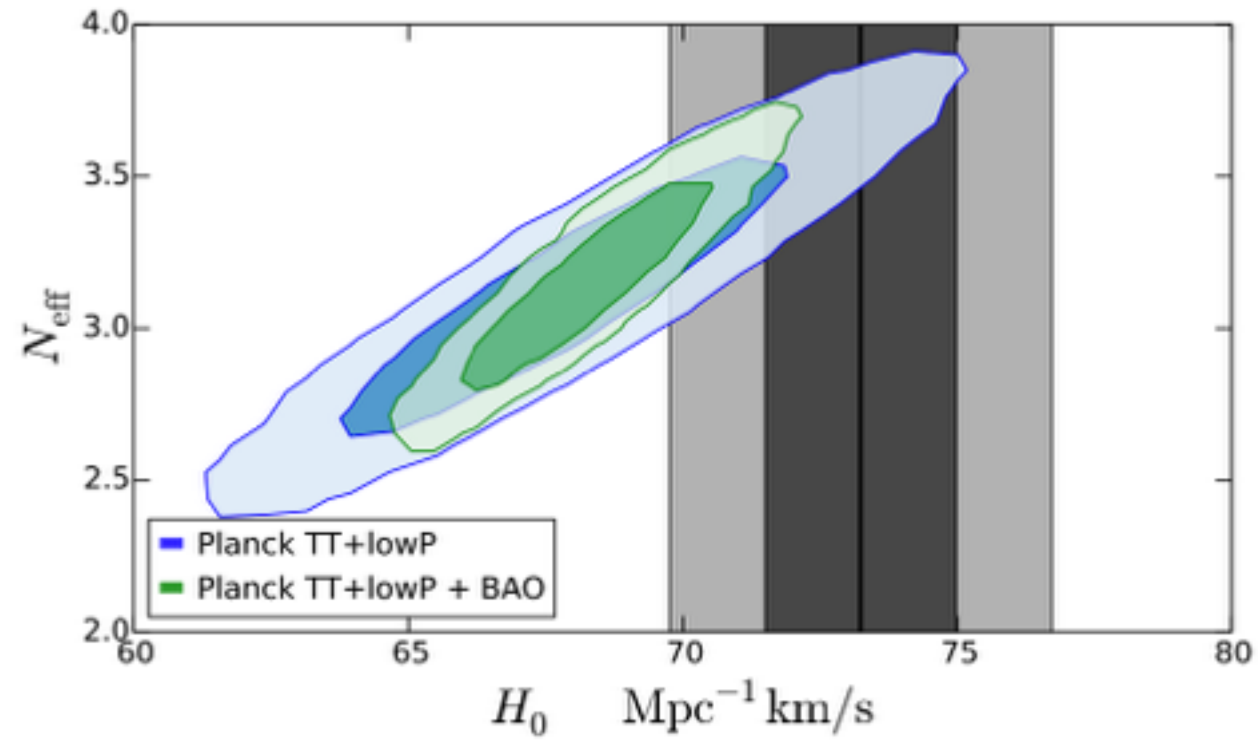
- Neutrinos interact with DM $\Rightarrow$ collisional damping below some small-scale.

Motivation



The Trouble with H_0





J. Bernal, L. Verde and A. Riess (2016)
1607.05617

Setting Up the Problem

$$\frac{\rho_\nu}{\rho_\gamma} \equiv \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}$$

- If ρ_ν is ever increased/decreased wrt ρ_γ it will appear as though $N_{\rm eff}$ increases

$$\Delta N_{\rm eff} \equiv N_{\rm eff} - 3.046$$

- Energy is transferred from the SM to the dark sector via collisions when the sectors are coupled

- Instead of cooling adiabatically with $T_\chi \propto 1/a^2$ the DM is now in thermal equilibrium with the radiation

$$T_\chi \approx T_\gamma \propto 1/a$$

Late Kinetic Decoupling from Photons (LKDγ)

- Equations of motion for a coupled photon-baryon and photon-DM fluid.

Velocity Divergence

Gravitational Source

Expansion

Density perturbation

Baryon-photon coupling

$$\dot{\theta}_b = k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}\left(\theta_b - \theta_\gamma\right),$$

$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}\left(\theta_\gamma - \theta_b\right)$$

$$- \dot{\mu}\left(\theta_\gamma - \theta_{\mathrm{DM}}\right),$$

Photon-DM coupling

$$\dot{\theta}_{\mathrm{DM}} = k^2\psi - \mathcal{H}\theta_{\mathrm{DM}} - S^{-1}\dot{\mu}\left(\theta_{\mathrm{DM}} - \theta_\gamma\right).$$

- Interaction rate for photon-DM scattering

$$\dot{\mu} = a\sigma_{\mathrm{DM}-\gamma} c n_{\mathrm{DM}}$$

Interaction rate for photon-baryon scattering

$$\dot{\kappa} = a\sigma_{\mathrm{Th}} c n_e$$

- $\dot{\kappa}/\dot{\mu}$ is proportional to

$$u_\gamma \equiv \frac{\sigma_{\mathrm{DM}-\gamma}}{\sigma_{\mathrm{Th}}} \frac{100\mathrm{GeV}}{m_{\mathrm{DM}}}$$

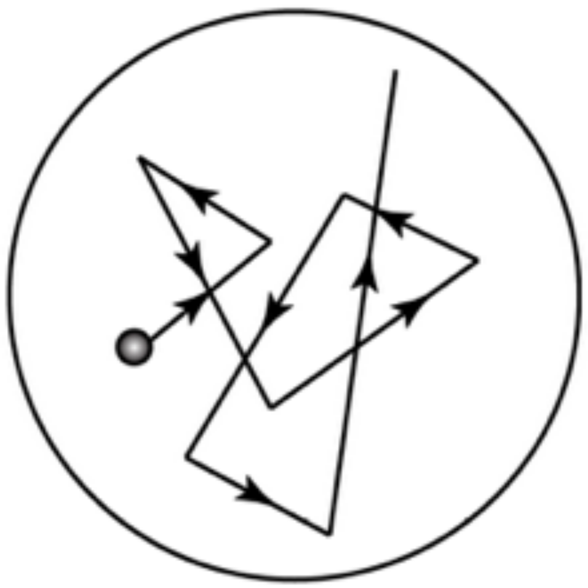
R. Wilkinson, J. Lesgourgues and C. Boehm (2013)
1309.7588

Massive DM particles in local thermodynamic equilibrium with a heat bath $m_\chi >> T$

In a typical collision:

$$\Delta p_\chi \sim p_\nu \sim T$$

$$\Rightarrow \frac{\Delta p_\chi}{p_\chi} \sim \sqrt{\frac{T}{m_\chi}}$$



S. Profumo, pre-SUSY 2016 lecture

Number of total collisions in a random (Brownian) walk

$$N_{\text{coll}} = \left(\frac{p_\chi}{\Delta p_\chi}\right)^2 \sim \frac{m_\chi}{T}$$

A very large number of collisions is required to keep the DM in kinetic equilibrium

Relaxation time can therefore be estimated as:

$$\tau_{\text{relax}} \sim \frac{m_\chi}{T}\tau_{\text{coll}}$$

$$\Gamma_{\text{relax}} \sim \frac{T}{m_\chi} n_\gamma \sigma_{\chi-\gamma}$$

S. Hofmann, D. Schwarz, H. Stocker (2001) 0104173

How do we calculate the change in energy density?

$$\rho_\gamma \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\Delta\rho_\gamma}{\rho_\gamma}\right) = -3\,\Gamma_{\mathrm{relax}} n_\gamma \left(T_\gamma - T_\chi\right)$$

Change in energy density / time $=$ Γ_{relax} $\times$ No. density of photons $\times$ Kinetic energy exchanged per collision

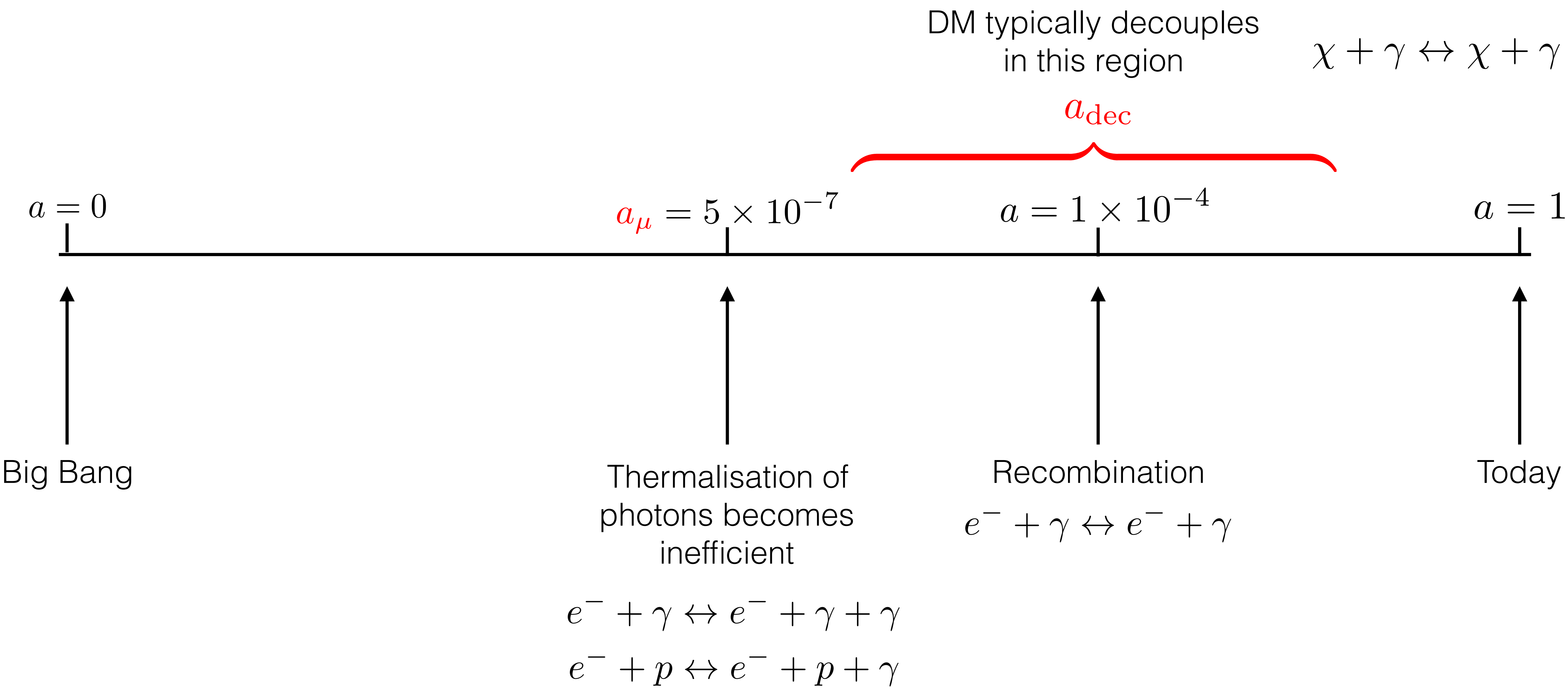
$$\Gamma_{\mathrm{relax}} \sim \frac{T}{m_\chi} n_\gamma \sigma_{\chi-\gamma}$$

Momentum relaxation rate $\sim$ $\dfrac{\text{Total no. of collisions}}{\text{No. of collisions required to appreciably change the DM momentum}}$ / time

- We can simply integrate both sides wrt time to find $\Delta\rho_\gamma$

Y, Ali-Haimoud, J. Chluba, M. Kamionkowski (2015)
1506.04745

Timeline of Universe's evolution



Final expression $\mathrm{LKD}\gamma$

$$\frac{\Delta N_{\rm eff}}{N_{\rm eff}} = \frac{1.72\mathrm{eV}}{m_{\rm DM}} \log\left(\frac{a_{\rm dec}}{a_\mu}\right)$$

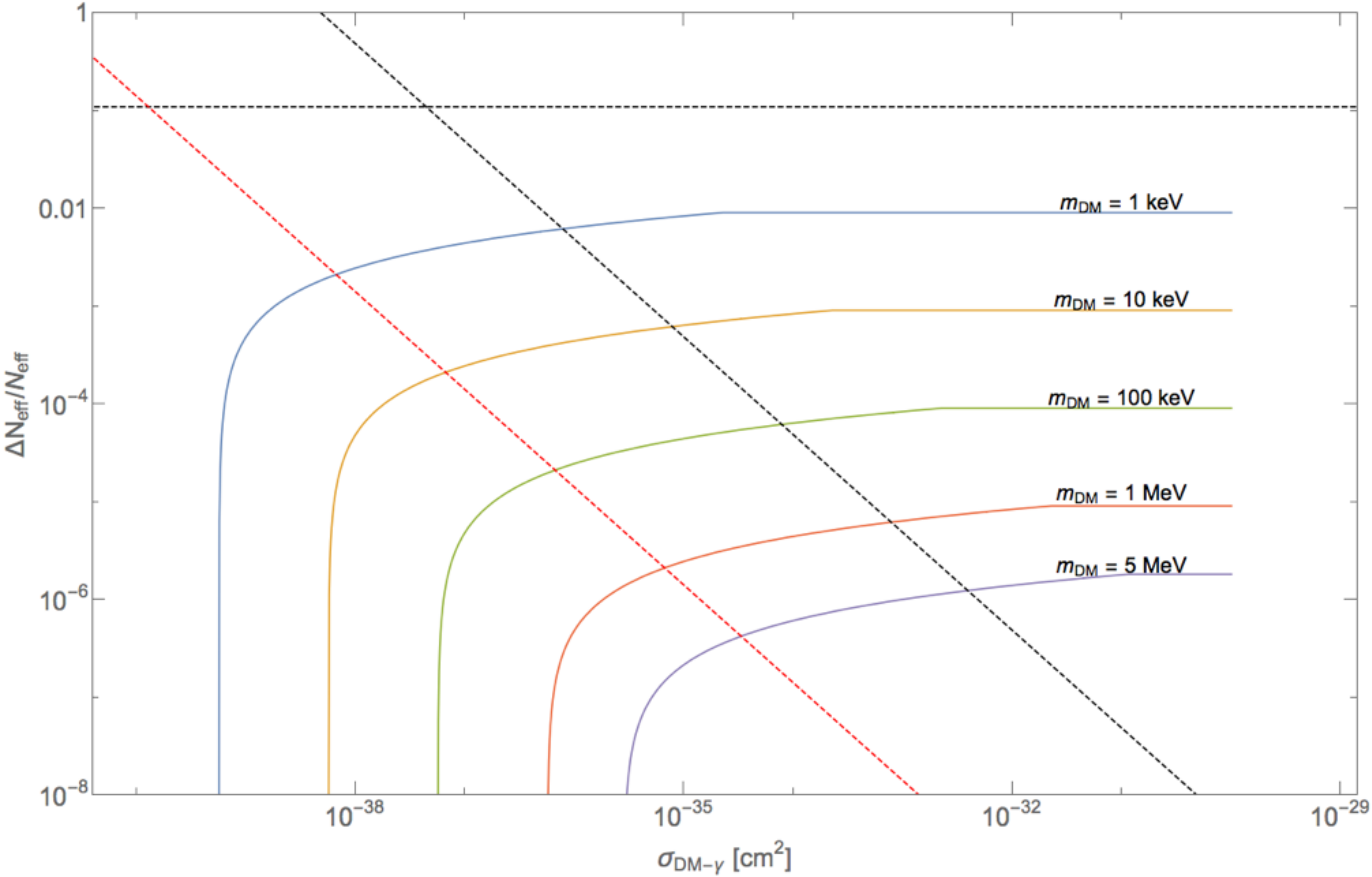
$$\Rightarrow \frac{\Delta N_{\rm eff}}{N_{\rm eff}} = \frac{1.72\,\mathrm{eV}}{m_{\rm DM}} \log\left(\frac{\frac{2}{3}\sqrt{6.6\times 10^{-6}\,u_\gamma}}{2\times 10^{-7}}\right)$$

- Inversely proportional to DM mass.
- Depends explicitly on how long the DM is coupled to photons while thermalisation is inefficient.
- Positive sign $\Rightarrow$ increase in $N_{\rm eff}$

Results

1σ CMB constraints

Solves small-scale probs



Late Kinetic Decoupling from Neutrinos (LKDν)

- Equations of motion for a coupled neutrino-DM fluid.

Velocity Divergence
Gravitational Source
Density perturbation
Anisotropic Stress
Neutrino-DM interactions

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right),$$

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\theta_{\rm DM} - S^{-1}\dot{\mu}\left(\theta_{\rm DM} - \theta_\nu\right).$$

- Interaction rate for neutrino-DM scattering

$$\dot{\mu} = a\sigma_{\rm DM-\nu}c n_{\rm DM}$$

Interaction rate for photon-baryon scattering

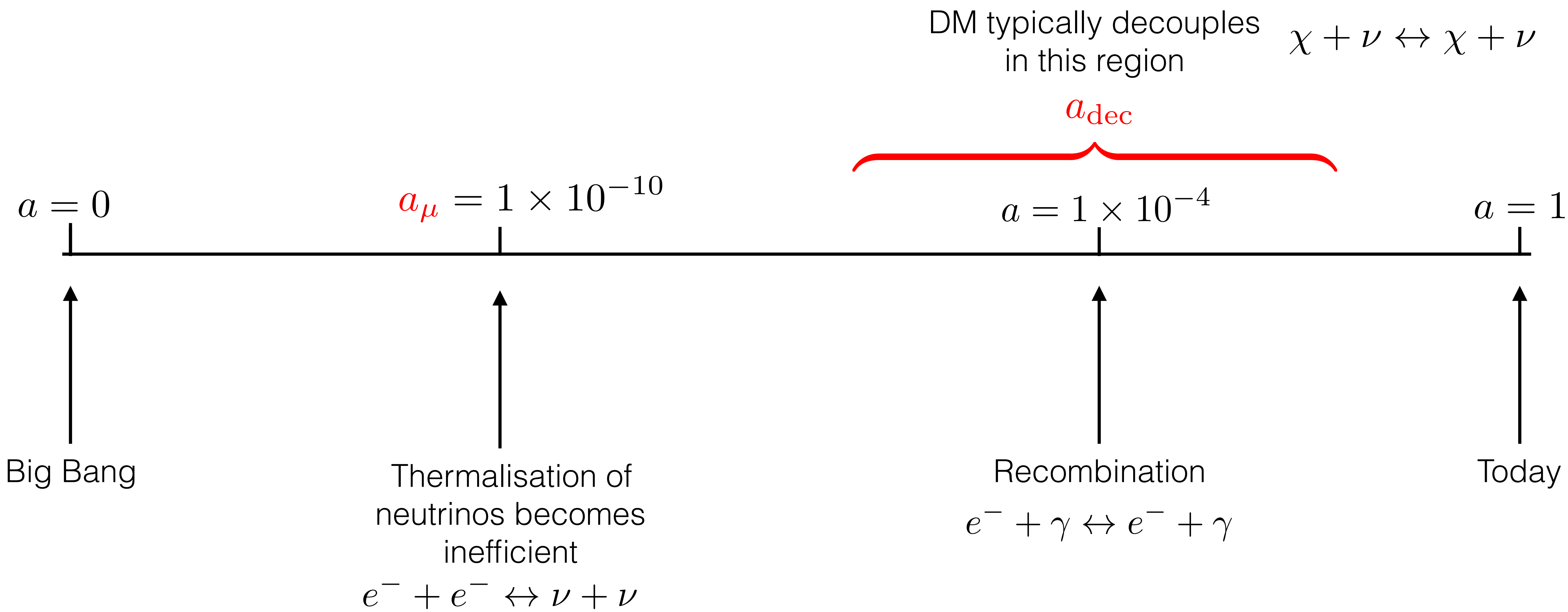
$$\dot{\kappa} = a\sigma_{\rm Th}c n_e$$

- $\dot{\kappa}/\dot{\mu}$ is proportional to

$$u_\nu \equiv \frac{\sigma_{\rm DM-\nu}}{\sigma_{\rm Th}}\frac{100\rm GeV}{m_{\rm DM}}$$

R. Wilkinson, J. Lesgourgues and C. Boehm (2014) 1401.7597

Timeline of Universe's evolution



Final expression $\mathrm{LKD}\nu$

$$\frac{\Delta N_{\rm eff}}{N_{\rm eff}} = -\frac{1.77\,\mathrm{eV}}{m_{\rm DM}} \log\left(\frac{a_{\rm dec}}{a_\mu}\right)$$

$$\frac{\Delta N_{\rm eff}}{N_{\rm eff}} = -\frac{1.77\,\mathrm{eV}}{m_{\rm DM}} \log\left(\frac{\frac{2}{3}\sqrt{6.6\times 10^{-6}\,u_\nu}}{1\times 10^{-10}}\right)$$

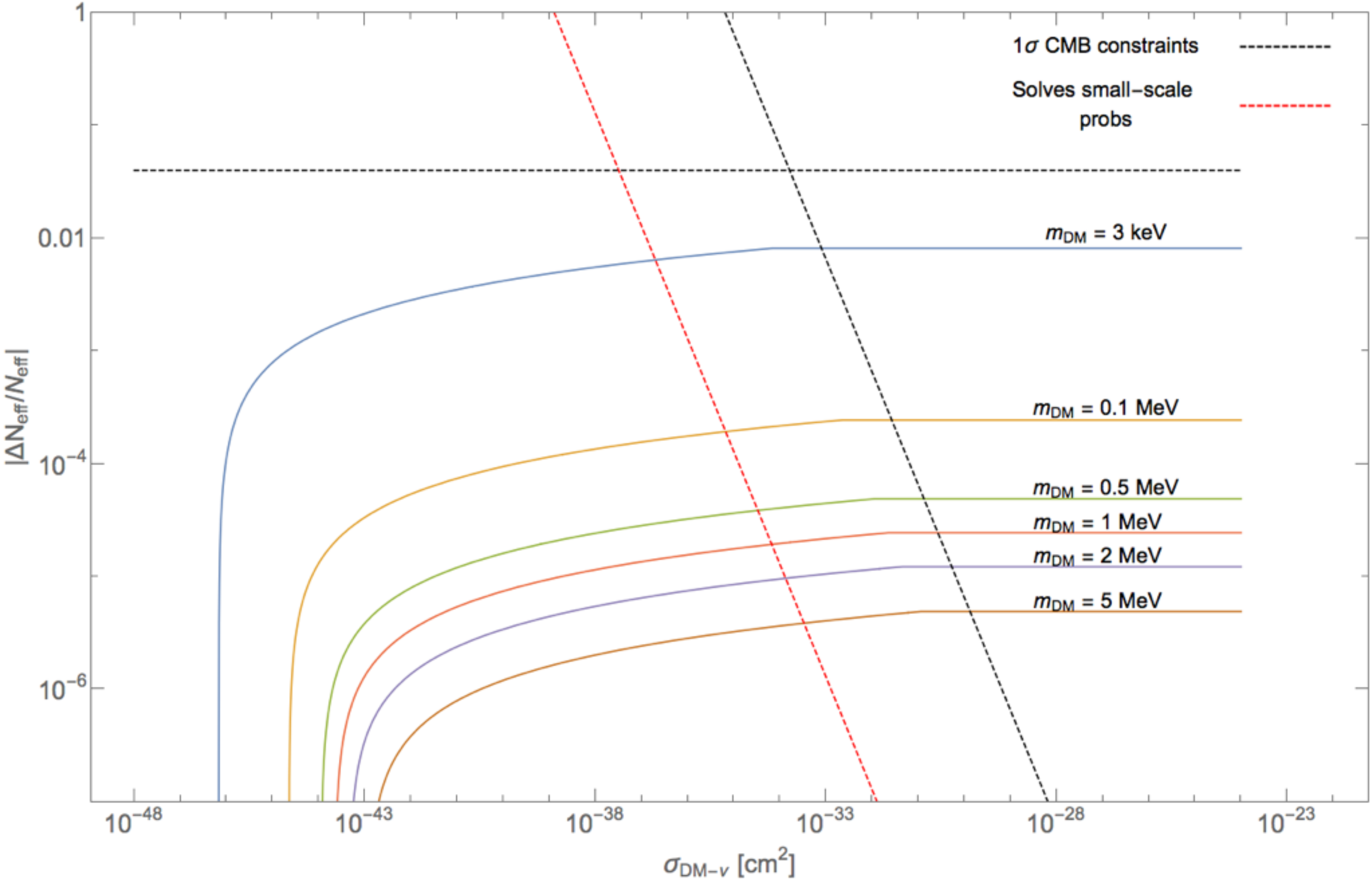
- Inversely proportional to DM mass.

- a_μ is much smaller than the $\mathrm{LKD}\gamma$ case because number changing processes freeze out earlier for neutrinos.

  $\Rightarrow$ same $\Delta N_{\rm eff}$ for smaller cross-sections.

- Negative sign $\Rightarrow$ decrease in $N_{\rm eff}$

Results



1
0.01
10^{-4}
10^{-6}
$|\Delta N_{eff}/N_{eff}|$
10^{-48}
10^{-43}
10^{-38}
10^{-33}
10^{-28}
10^{-23}
$\sigma_{DM-\nu}$ [cm^2]
1σ CMB constraints
Solves small-scale probs
m_{DM} = 3 keV
m_{DM} = 0.1 MeV
m_{DM} = 0.5 MeV
m_{DM} = 1 MeV
m_{DM} = 2 MeV
m_{DM} = 5 MeV

Conclusions

- Relativistic species can transfer energy to the dark sector through collisions

- Photon-DM interactions $\mathrm{LKD}\gamma$ lead to an increase in N_{eff}

- Neutrino-DM interactions $\mathrm{LKD}\nu$ lead to a decrease in N_{eff}

- CMB S4 has conservative projected error bars of $\sigma(N_{\mathrm{eff}}) \sim 0.03$ which will start to set tight constraints on $\sigma_{\mathrm{DM}-\nu}$ for light DM masses

- These constraints will be even more aggressive if a large N_{eff} is required to solve the H_0 dilemma

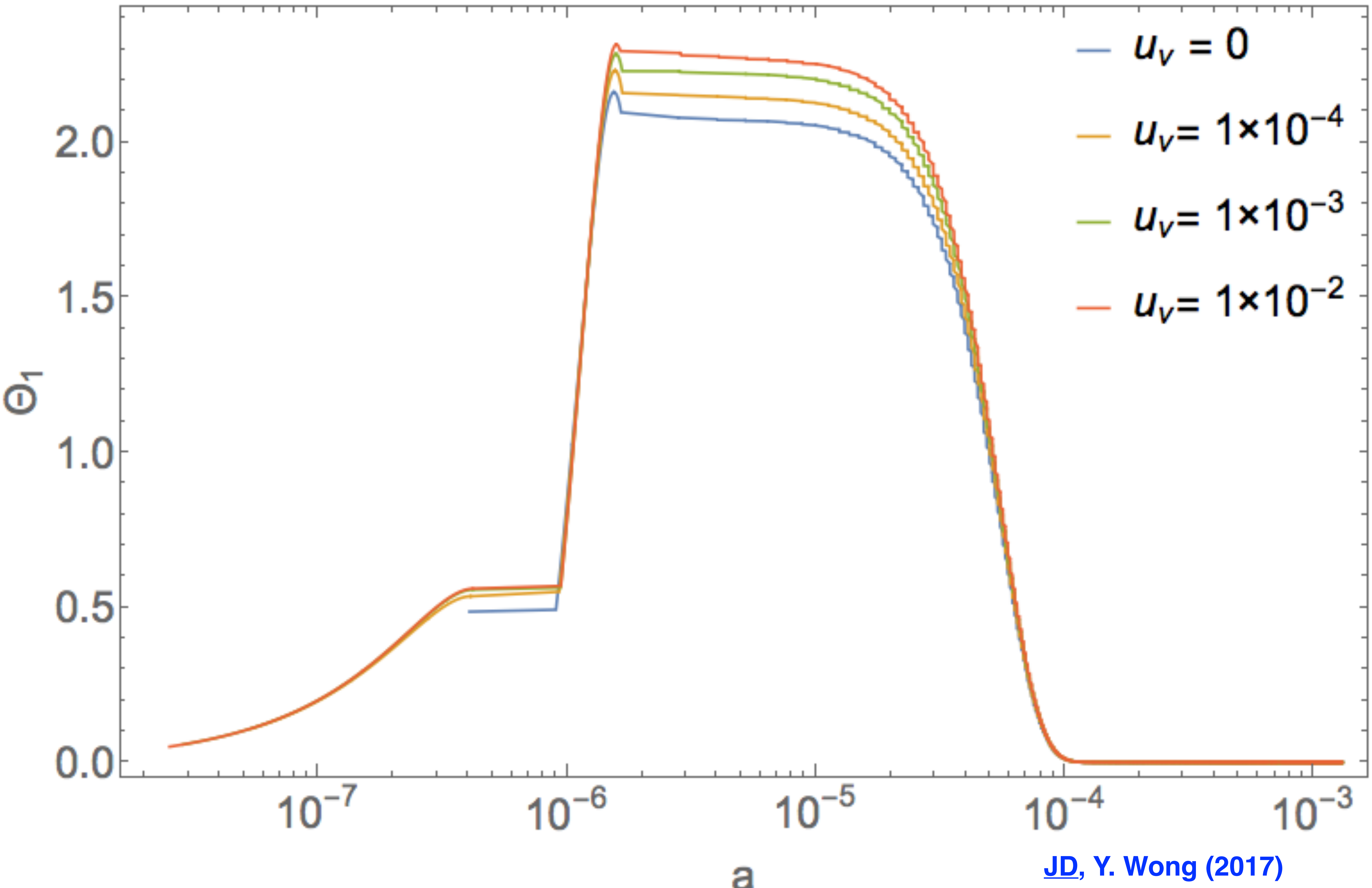
- Realistic $\mathrm{LKD}\gamma$ parameters unfortunately don't help solve the H_0 dilemma

CMB S4 Collaboration (2016)
1610.02743

Future Work

$k = 10\,\mathrm{Mpc}^{-1}$

- Envelope of photon transfer function $\propto \delta\rho_\gamma$



JD, Y. Wong (2017)
17xx.xxxx