Using CMB spectral distortions to distinguish between dark matter solutions to the small-scale crisis

James Diacoumis, University of New South Wales

CERN Theory Workshop 2018, Geneva,
12-16th March

Based on **1707.07050** in collaboration with Yvonne Wong

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Intro

- We'd like an elevator pitch for SD's, can they say something definitive about popular DM models?
- Vanilla WIMP DM annihilation does not produce a very strong spectral distortion signal (Pasquale Serpico's talk.)
- Most natural place to look is at DM on small length scales as SD's are sensitive to $1\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 10^4\,\mathrm{Mpc}^{-1}$.
- If we could solve the small-scale structure crisis with SD's we have our "elevator pitch" (Joe Silk's talk.)

To clarify the question:

- We have access to incredibly small scales with spectral distortions. $1\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 10^4\,\mathrm{Mpc}^{-1}.$

- We have a large class of DM models which look to explain "small-scale structure" problems.

- i.e. they change things on the scales accessible by spectral distortions.

- What can we actually say with spectral distortions about these models and is it realistic to go after them with PIXIE???

Small scale crisis

- **Missing Satellites Problem:**

- CDM simulations predict far more satellite galaxies than we actually observe.

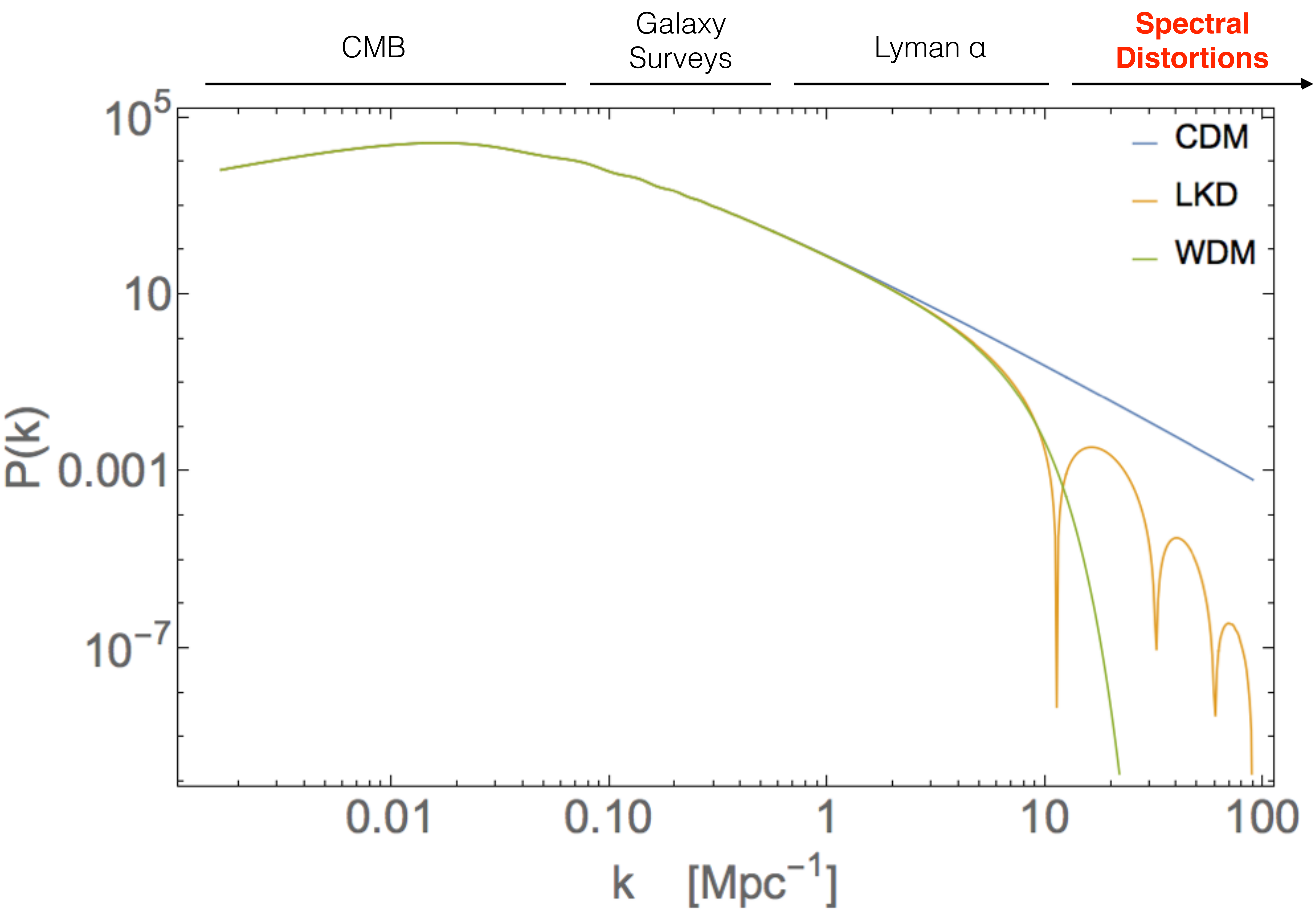
- **Too Big to Fail Problem:**

- CDM simulations predict many more massive and dense satellites than we observe. They are “too big to fail” at forming stars.

- **Core VS Cusp Problem:**

- CDM simulations predict DM density grows at the centre of a galaxy. Observations indicate galactic ‘cores’ with constant density.

Motivation


CMB
Galaxy Surveys
Lyman α
Spectral Distortions
CDM
LKD
WDM
10^5
10
0.001
10^-7
P(k)
0.01
0.10
1
10
100
k [Mpc^-1]

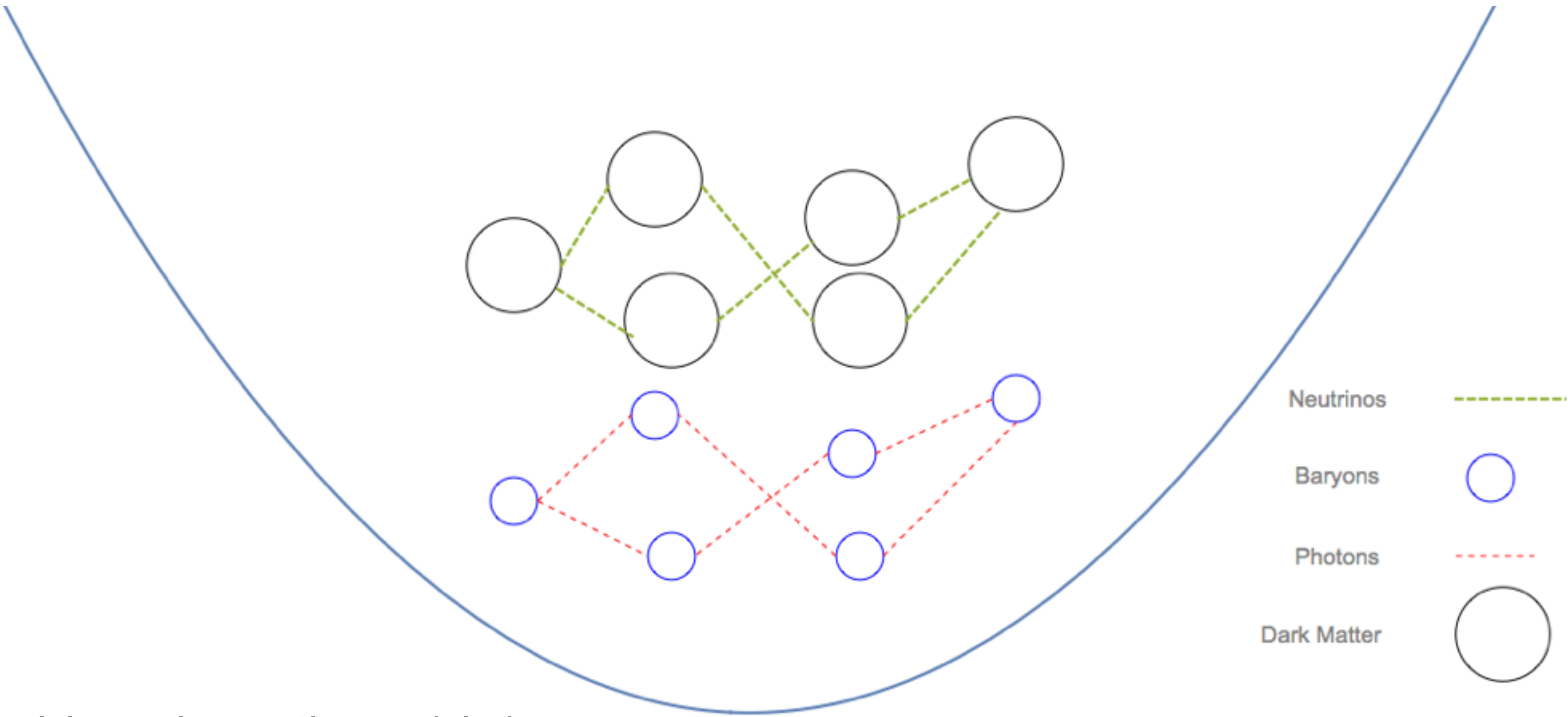
Warm Dark Matter

- μ distortion only occurs in radiation domination.

- Suppression in power either has to be primordial or affect the radiation component to alter spectral distortions.

- Same reasoning for any DM model only influencing the matter component i.e. SIDM

Late Kinetic Decoupling

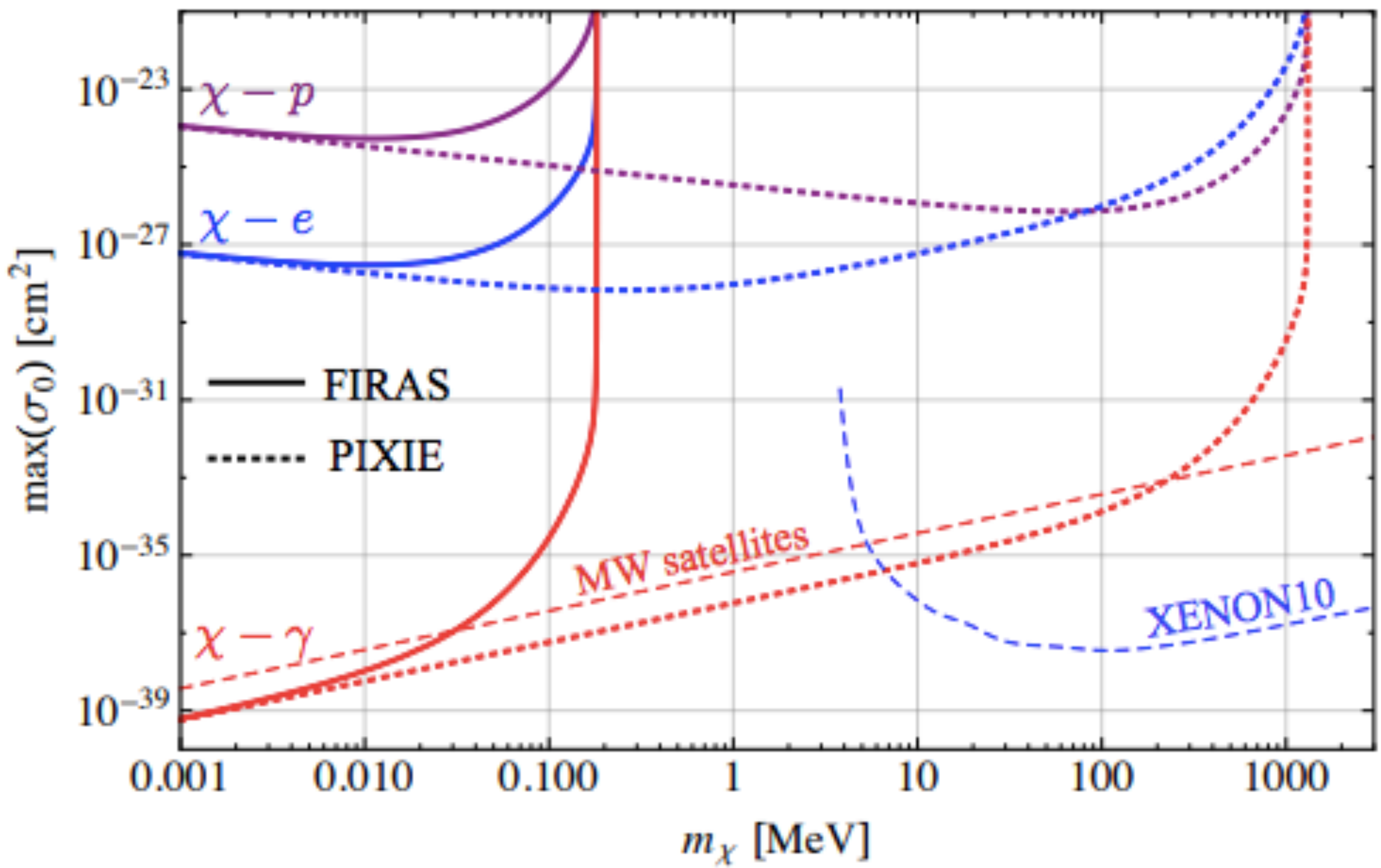


- Neutrinos ‘knock’ the DM out of the wells which washes out structure.

Benchmark

$T_\gamma \propto 1/a$

$T_\chi \propto 1/a^2$

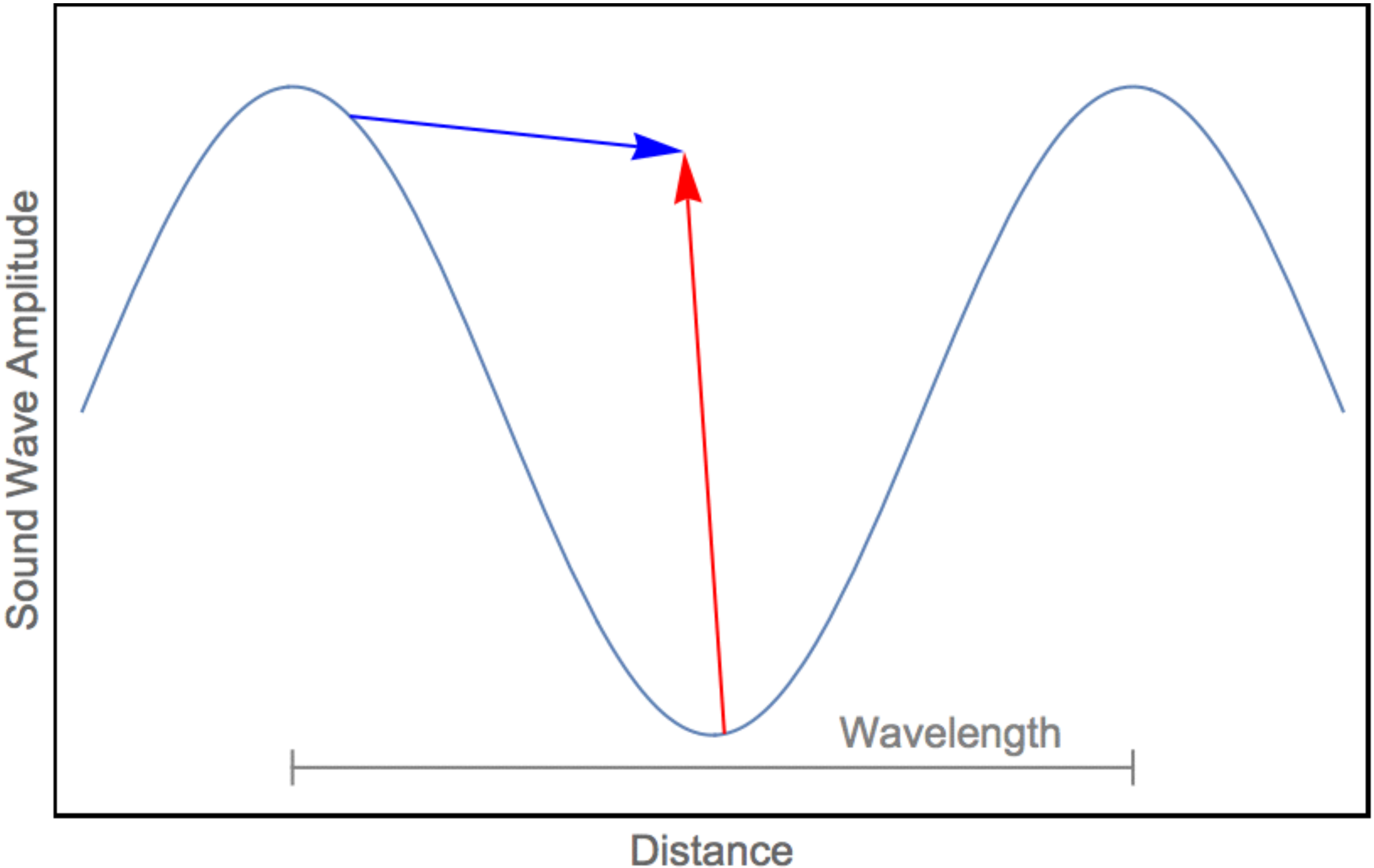


Y. Ali-Ha¨ımoud, J. Chluba and M. Kamionkowski (2015)
1506.04745

Can we improve on this?

- Extend parameter space to higher mass DM.
- Can we include DM-neutrino interactions?
- Don’t consider direct energy transfer but instead consider the effects on the perturbations themselves and how they’re dissipated.

How do Spectral Distortions occur?



R. Khatri, R. Sunyaev and J. Chluba (2012)
1205.2871

Heating Rate

- The heating rate of CMB photons due to dissipation of small-scale acoustic modes is:

$$\frac{\mathrm{d}\left(Q/\rho_\gamma\right)}{\mathrm{d}z} \approx \frac{64c^2}{15\mathcal{H}\dot{\kappa}} \int \frac{\mathrm{d}k}{2\pi^2} k^4\, P_{\mathcal{R}}(k)\ \left(\Theta_1^2 + \ldots\right).$$

Heating Rate $\approx$ Const factors $\int$ Primordial Power Spectrum (**Photon Temp Transfer Functions**).

- The photon temperature transfer function has the form:

$$\Theta_1 \approx A\left(\frac{c_s}{c}\right)\sin(kr_s)\exp\left(-\frac{k^2}{k_D^2}\right).$$

Photon Temp Transfer Function $\approx$ Const factors | Acoustic oscillations | Diffusion damping

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

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

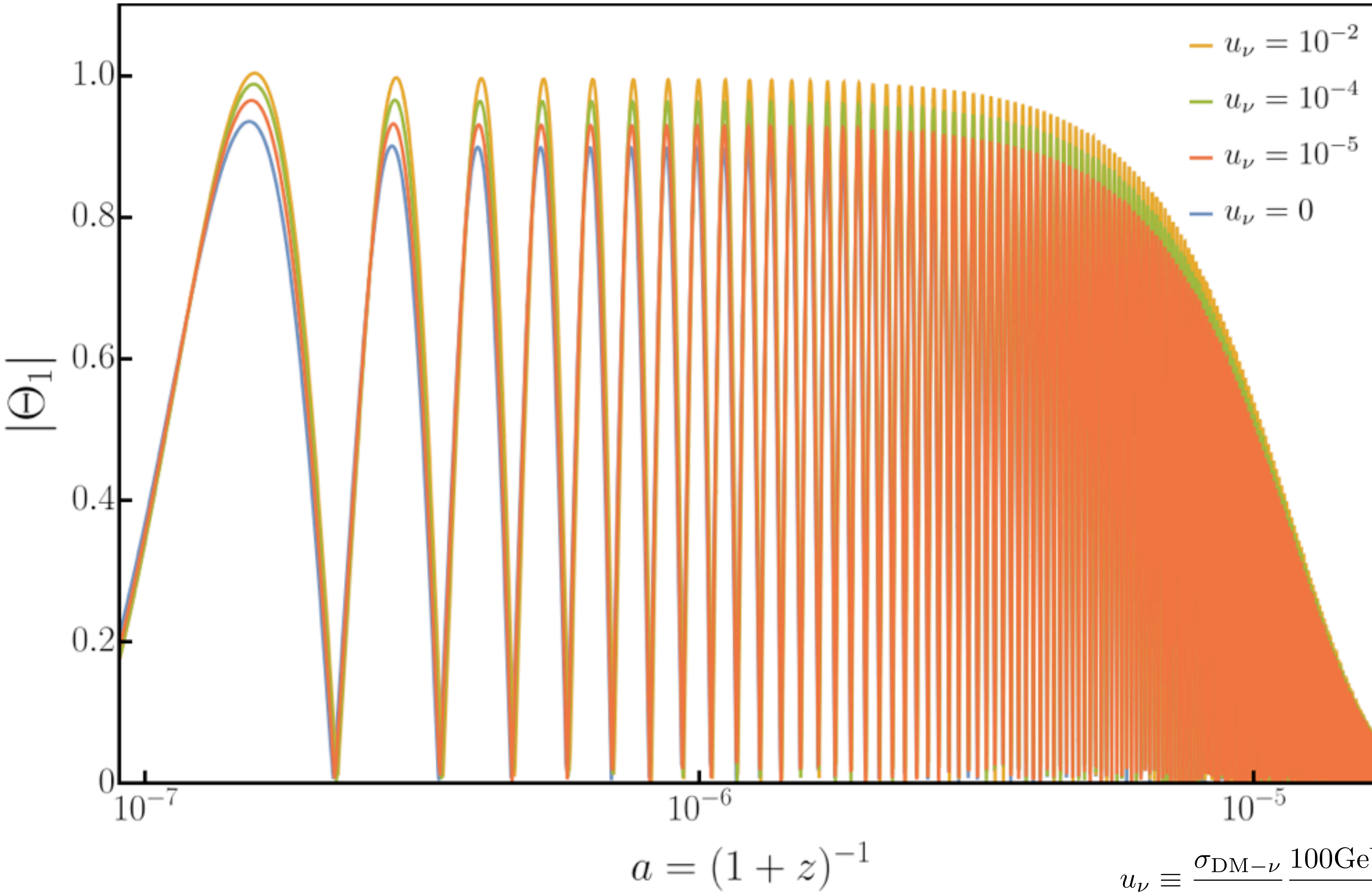
- $\dot{\kappa}/\dot{\mu}$ is proportional to

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

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

Transfer Functions (LKDν)

$k = 100\,\mathrm{Mpc}^{-1}$



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

How can we understand the physics?

- The photon temperature transfer function has the form:

$$\Theta_1 \approx A \left(\frac{c_s}{c} \right) \sin(kr_s) \exp \left(-\frac{k^2}{k_D^2} \right) .$$

Where $A = \dfrac{1}{1 + \frac{4}{15} f_\nu}$ and $f_\nu = \dfrac{\rho_\nu}{\rho_\gamma + \rho_\nu} \simeq 0.41$

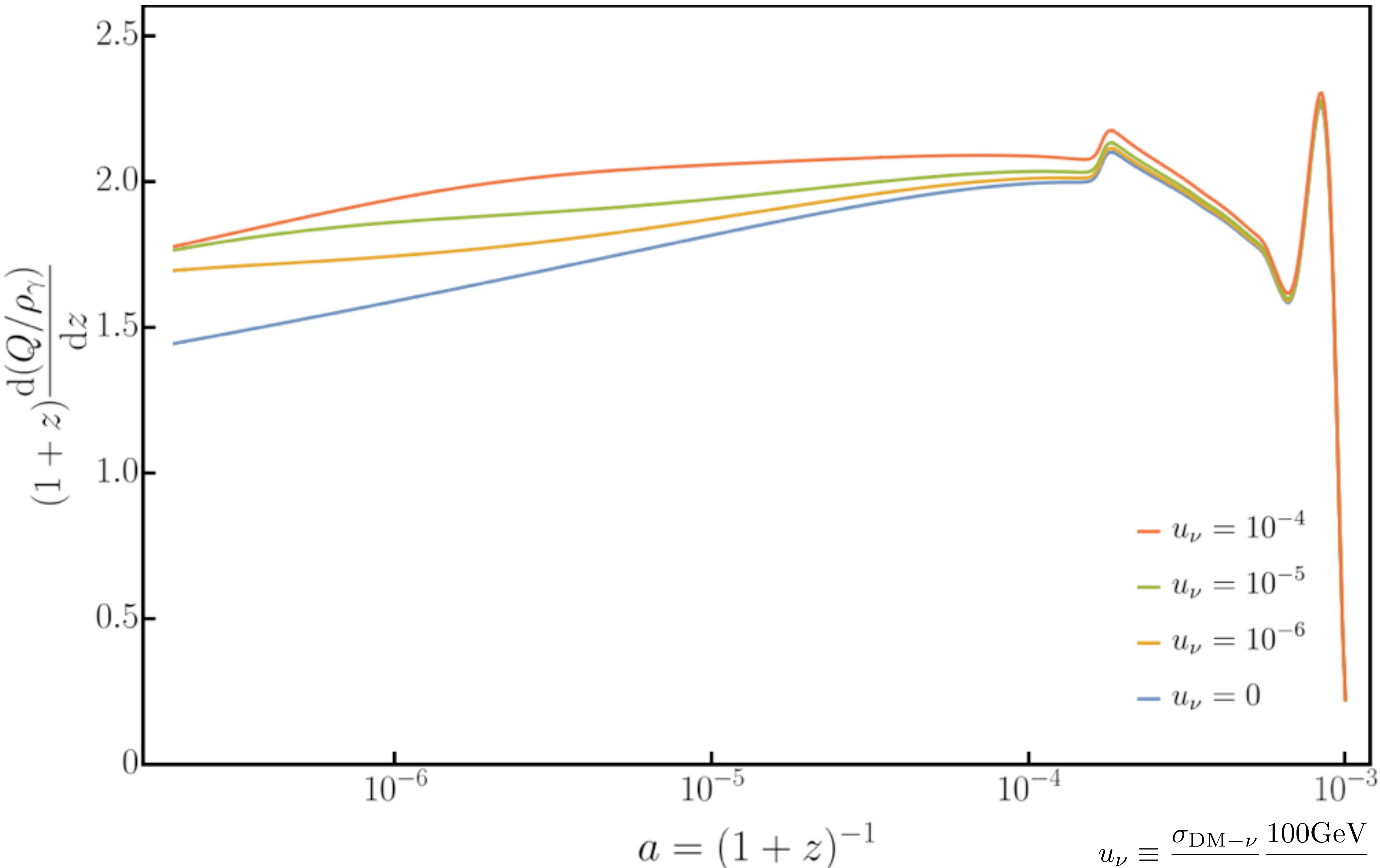
- Neutrinos normally don't participate in acoustic oscillations as they stream freely.

- When coupled to DM they 'cluster' more efficiently and participate in acoustic oscillations as photons.

$\Rightarrow$ Overall increase in oscillation amplitude.

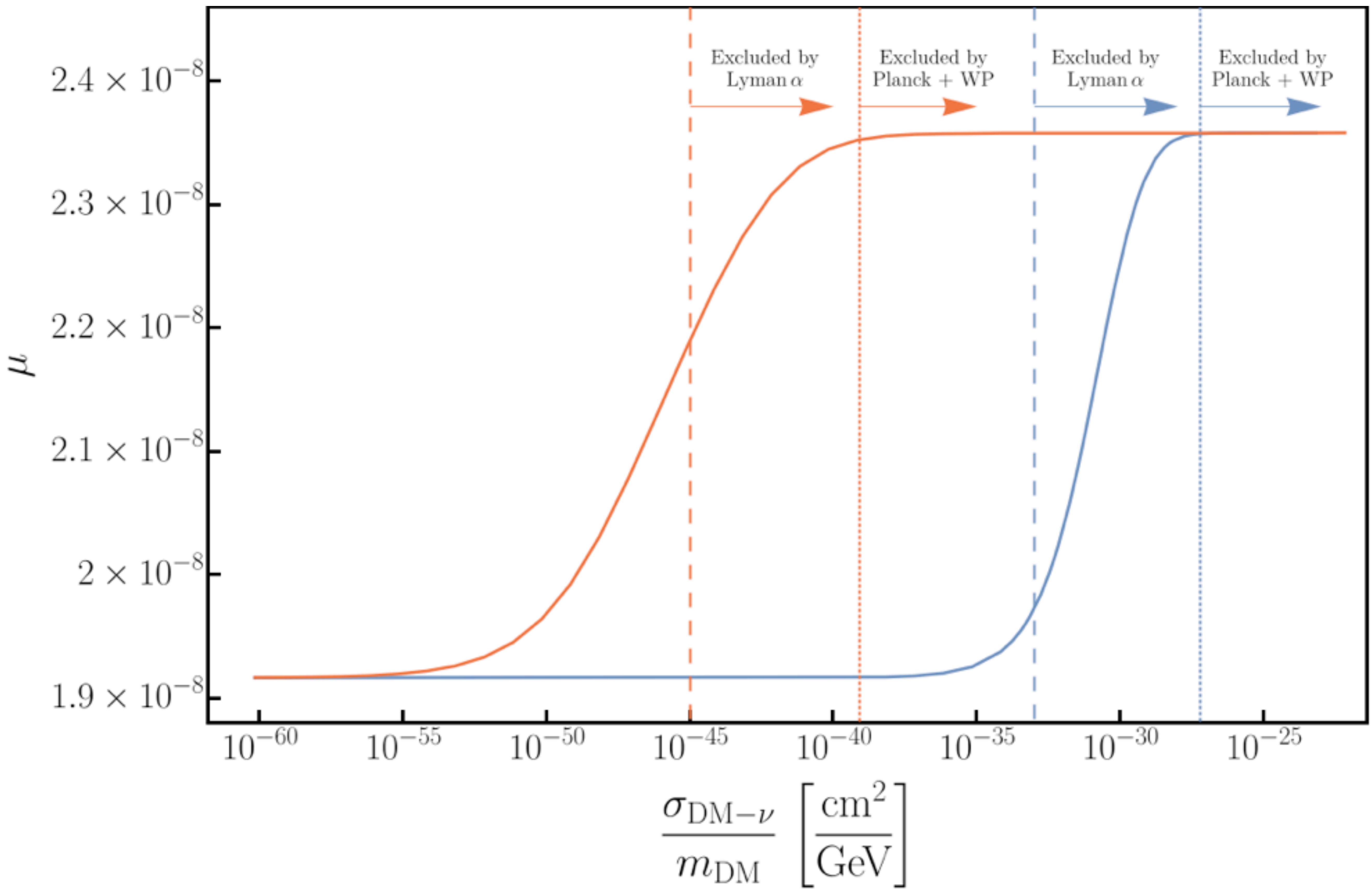
Heating Rate (LKDν)

$\mathcal{A}_i = 1$



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

Expected $\mu-$distortion (LKDν)



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

Heating Rate needs to be modified

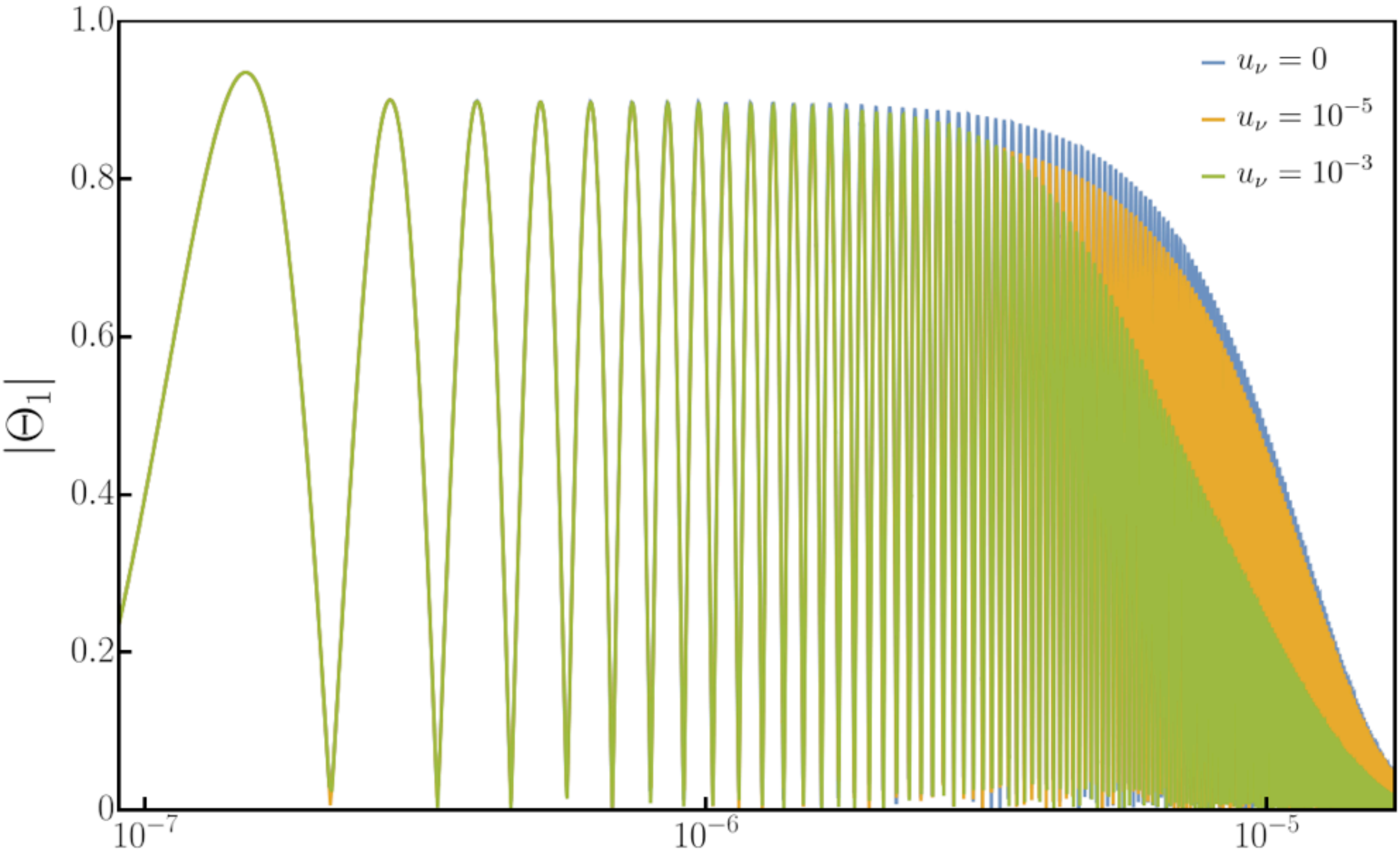
$$\frac{\mathrm{d}\left(Q/\rho_\gamma\right)}{\mathrm{d}z} = \frac{4a\dot{\kappa}}{\mathcal{H}} \int \frac{k^2 \mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k) \left[\frac{\left(3\Theta_1 - v_b\right)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2\left(\Theta_0^{\mathrm{P}} + \Theta_2^{\mathrm{P}}\right) + \sum_{\ell \geq 3}(2\ell+1)\Theta_\ell^2 \right]$$
$$+ \frac{4a\dot{\mu}_\gamma}{\mathcal{H}} \int \frac{k^2 \mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k) \left[\frac{\left(3\Theta_1 - v_{\mathrm{DM}}\right)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2\left(\Theta_0^{\mathrm{P}} + \Theta_2^{\mathrm{P}}\right) + \sum_{\ell \geq 3}(2\ell+1)\Theta_\ell^2 \right],$$

- DM-photon scattering provides a new channel through which small-scale perturbations can be dissipated directly.

- Can be written explicitly in terms of the transfer functions as before

$$\frac{\mathrm{d}\left(Q/\rho_\gamma\right)}{\mathrm{d}z} \simeq \frac{4a}{\mathcal{H}} \int \frac{k^2 \mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k)\, k^2\, \Theta_1^2 \left[\frac{1}{\dot{\kappa} + \dot{\mu}_\gamma} \frac{16}{15} + \frac{3\dot{\mu}_\gamma}{k^2} \left(\frac{k^2}{k^2 + 3S_\gamma^{-2}\dot{\mu}_\gamma^2} \right) \right].$$

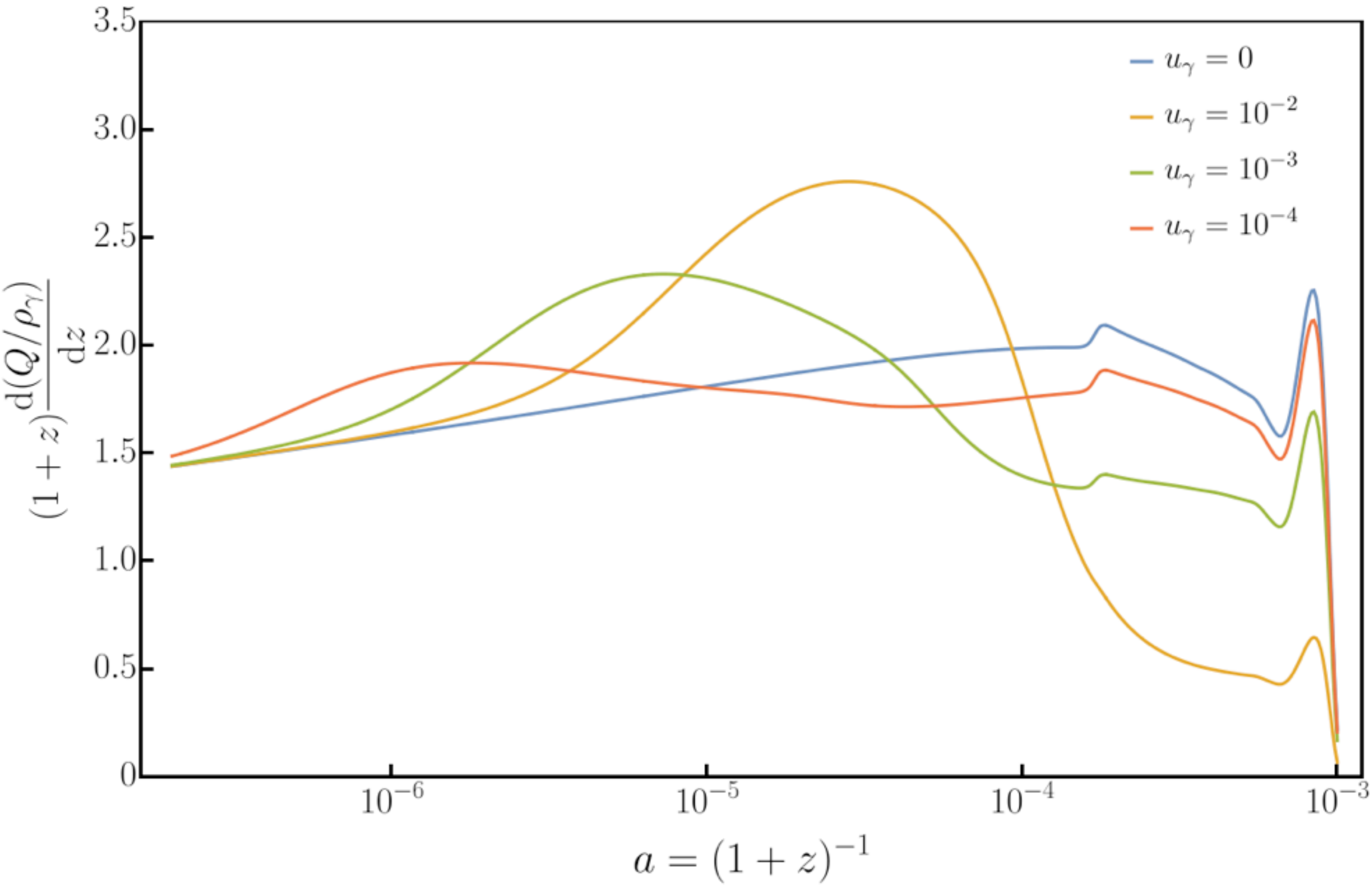
Transfer Functions (LKDγ) $k = 100\,\mathrm{Mpc}^{-1}$



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

Heating Rate (LKDγ)

$\mathcal{A}_i = 1$



How can we understand the physics?

- The photon temperature transfer function has the form:

$$\Theta_1 \approx A\left(\frac{c_s}{c}\right)\sin\left(kr_s\right)\exp\left(-\frac{k^2}{k_D^2}\right).$$

$$R = \frac{3\rho_b}{4\rho_\gamma} \ll 1$$

Baryon - Photon ratio

Where

$$\partial_z {k_D}^{-2} = -\frac{c_s^2 a}{2\mathcal{H}\dot{\kappa}}\left(\frac{16}{15} + \frac{R^2}{1+R}\right).$$

Diffusion Damping = Viscosity + Heat Conduction

- But it **changes** in the presence of photon-DM coupling

$$\partial_z k_D^{-2}(k) \simeq -\frac{c_s^2 a}{2\mathcal{H}}\left(\frac{1}{\dot{\kappa}+\dot{\mu}}\frac{16}{15} + \frac{3\dot{\mu}}{k^2}\left(\frac{k^2}{k^2+3\left(S^{-1}\dot{\mu}\right)^2}\right)\right)$$

- Heat conduction becomes non-negligible when DM is weakly coupled to photons. $S^{-1}\dot{\mu} \lesssim k$

How can we understand the physics?

- The photon temperature transfer function has the form:

$$\Theta_1 \approx A\left(\frac{c_s}{c}\right)\sin\left(kr_s\right)\exp\left(-\frac{k^2}{k_D^2}\right).$$

$S = 3\rho_{\mathrm{DM}}/4\rho_\gamma \ll 1$

DM - Photon ratio

Where

$$\partial_z k_D^{-2}(k) \simeq -\frac{c_s^2 a}{2\mathcal{H}}\left(\frac{1}{\dot{\kappa}+\dot{\mu}}\frac{16}{15}+\frac{3\dot{\mu}}{k^2}\left(\frac{k^2}{k^2+3\left(S^{-1}\dot{\mu}\right)^2}\right)\right)$$

Diffusion Damping $\simeq$ Viscosity $+$ Heat Conduction

- The extra term due to heat conduction is also present for a photon-baryon fluid but suppressed during tight-coupling.

- Heating Rate is damped due to additional viscosity of the fluid and enhanced due to additional heat conduction.

$\Rightarrow$ Competing effects dominate at different times

Something nice

- The heating rate reduces to the exact same standard form

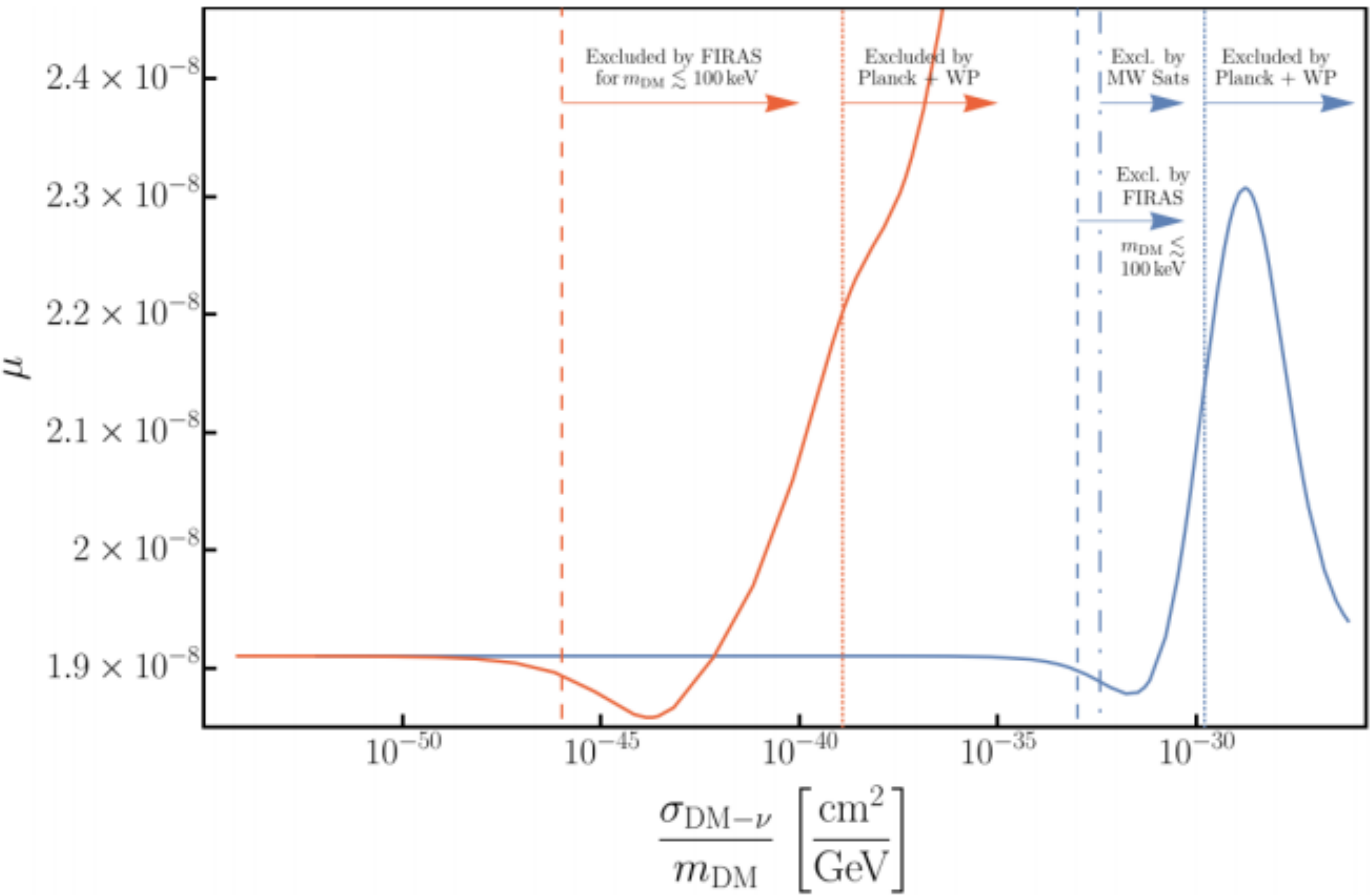
$$\frac{\mathrm{d}Q}{\mathrm{d}z} \approx -4A^2 \int \frac{k^4 \mathrm{d}k}{2\pi^2} P_R(k) \left[\partial_z k_D^{-2}(k)\right] \mathrm{e}^{-2k^2/k_D^2(k)}$$

- Under the proviso that k_D is modified in the presence of DM-photon interactions to become k-dependant.

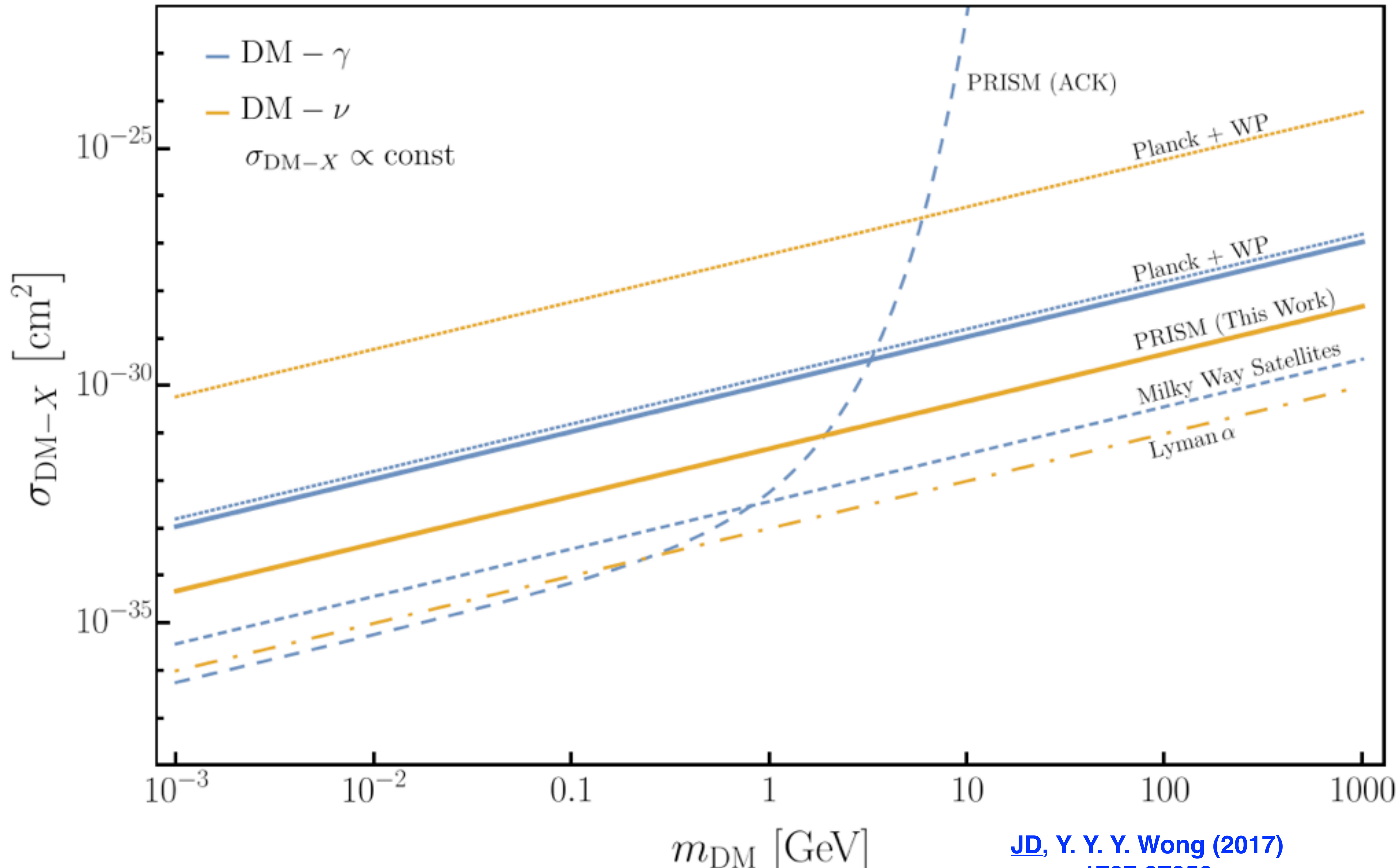
- Can interpret this effect as a modification of the diffusion damping process by DM-photon interactions

$$\partial_z k_D^{-2}(k) \simeq -\frac{c_s^2 a}{2\mathcal{H}} \left(\frac{1}{\dot{\kappa} + \dot{\mu}} \frac{16}{15} + \frac{3\dot{\mu}}{k^2} \left(\frac{k^2}{k^2 + 3\left(S^{-1}\dot{\mu}\right)^2} \right) \right)$$

Expected μ − distortion (LKDγ)

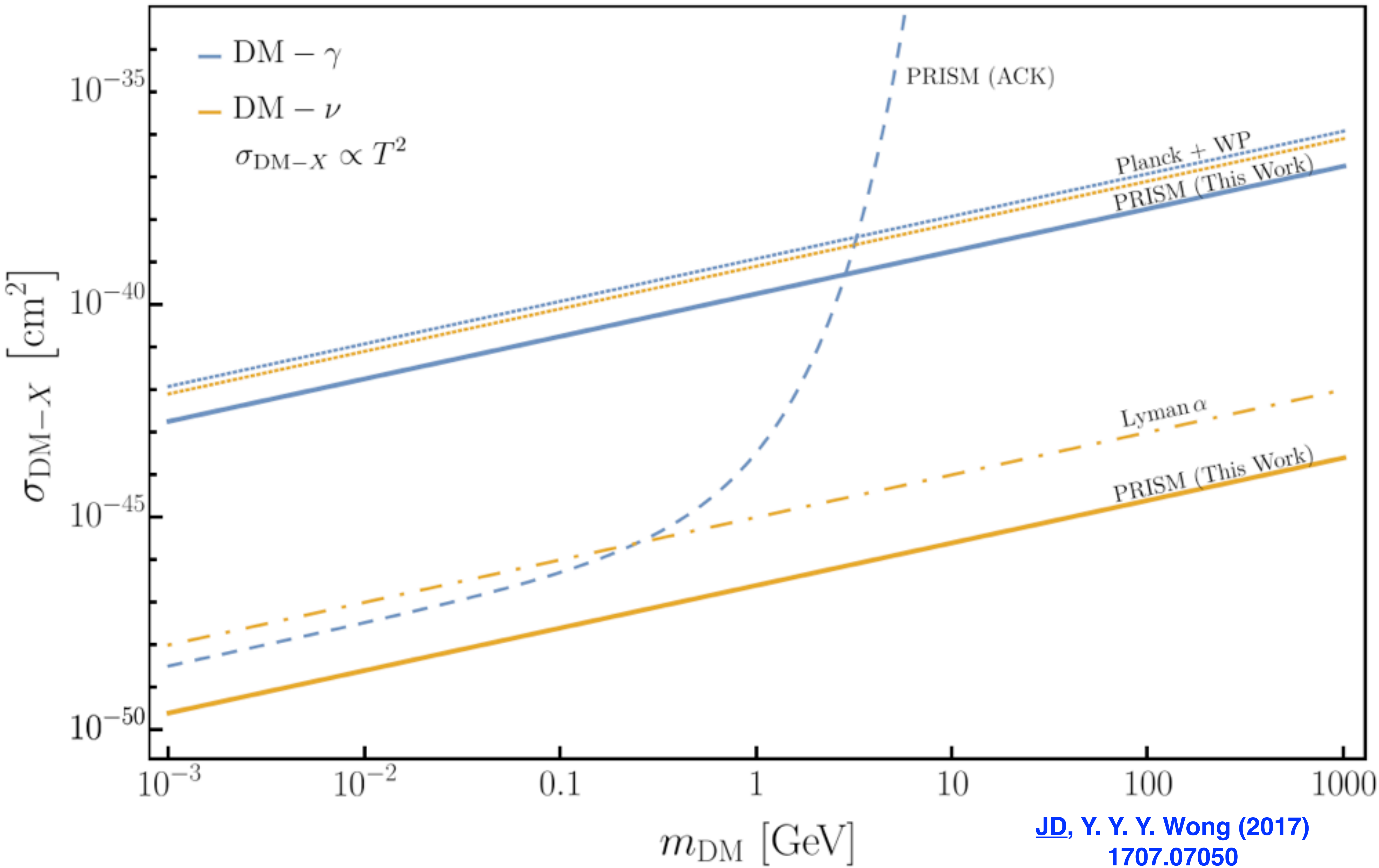


Projected Constraints (PRISM)



JD, Y. Y. Y. Wong (2017)
1707.07050

Projected Constraints (PRISM)



JD, Y. Y. Y. Wong (2017)
1707.07050

Is this the end of the story?

- More to come on $\mathrm{DM} - \nu$ and $\mathrm{DM} - \gamma$ interactions
- Do we need to start pushing precision cosmology to pin down tiny effects?
- Look out for this in the coming weeks on arXiv

<u>JD</u>, Y. Y. Y. Wong (2018)
1803.xxxxx

Conclusions

- Spectral Distortions offer access to phenomenally small-scale physics and by extension DM physics on small-scales.
- We're only sensitive to DM models which have an affect on the radiation component of the universe.
- If probed we can provide the strongest bounds on DM-neutrino scattering (orders of magnitude better than Lyman Alpha).
- But we need an additional order of magnitude on top of PIXIE, as the effect is $\Delta\rho/\rho \sim 10^{-9}$.
- New physics effects such as the change of the diffusion damping scale in the presence of a weakly coupled DM-photon system warrant further study.

Question for the crowd

- How optimistic are we to disentangle small y-distortion effects from the huge late-time background?
- Maybe by knowing measuring mu and r you could infer y?
- If “matter only” DM models would produce tiny y-distortions that deviate from LCDM do we ever have a hope of getting to them?