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

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Based on work done in collaboration with
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Goals

- To give an introduction to CMB Spectral Distortions

- To discuss 2 Dark Matter scenarios

- Late Kinetic Decoupling from photons $(\mathrm{LKD}\gamma)$

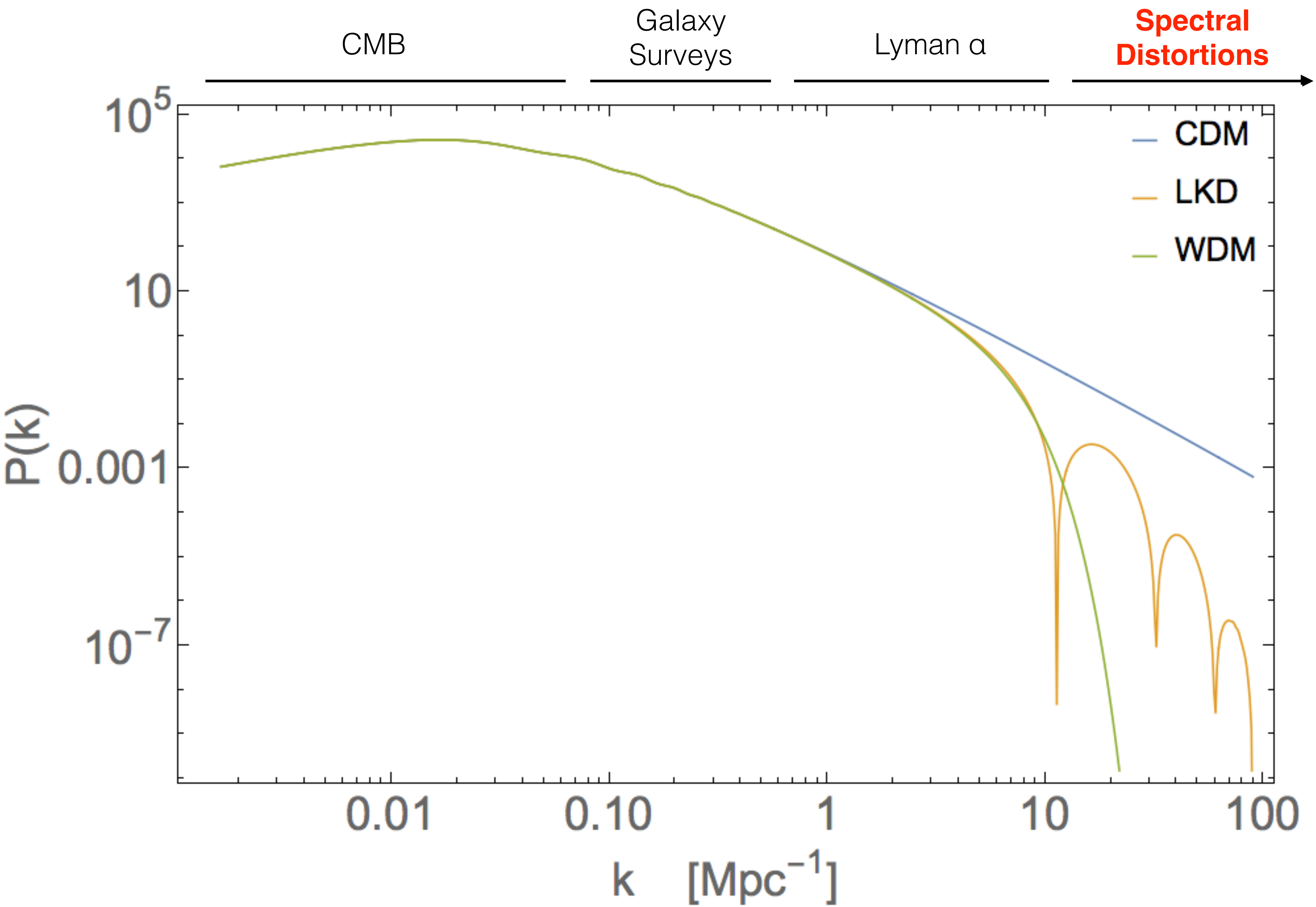
- Late Kinetic Decoupling from neutrinos $(\mathrm{LKD}\nu)$

$\left.\begin{matrix}(\mathrm{LKD}\gamma)\\(\mathrm{LKD}\nu)\end{matrix}\right\}(\mathrm{LKD})$

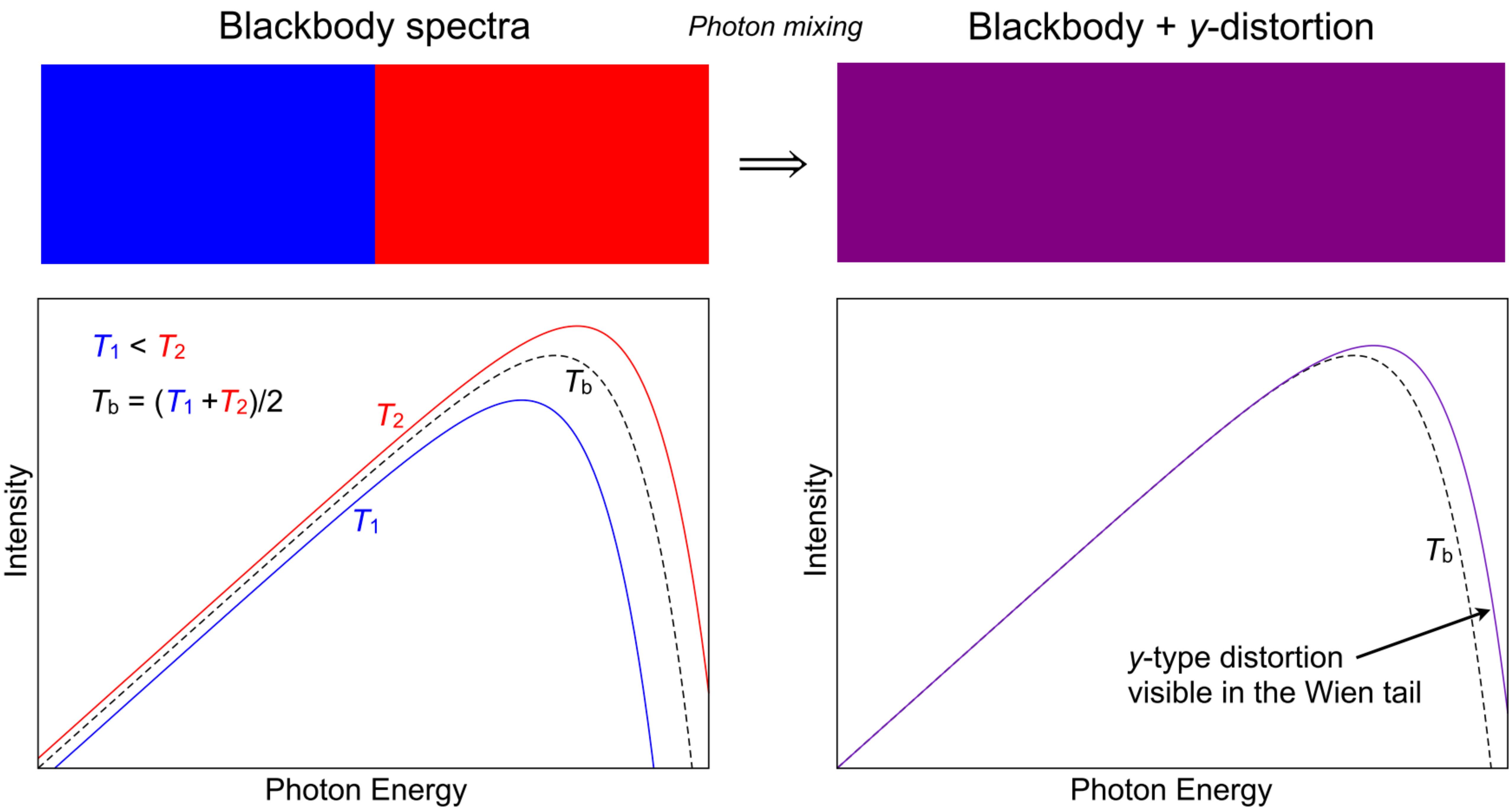
- To point out interesting physical effects occurring in these models

- To show that spectral distortions can be used to these models and distinguish them from other solutions to the small-scale structure problems.

Motivation

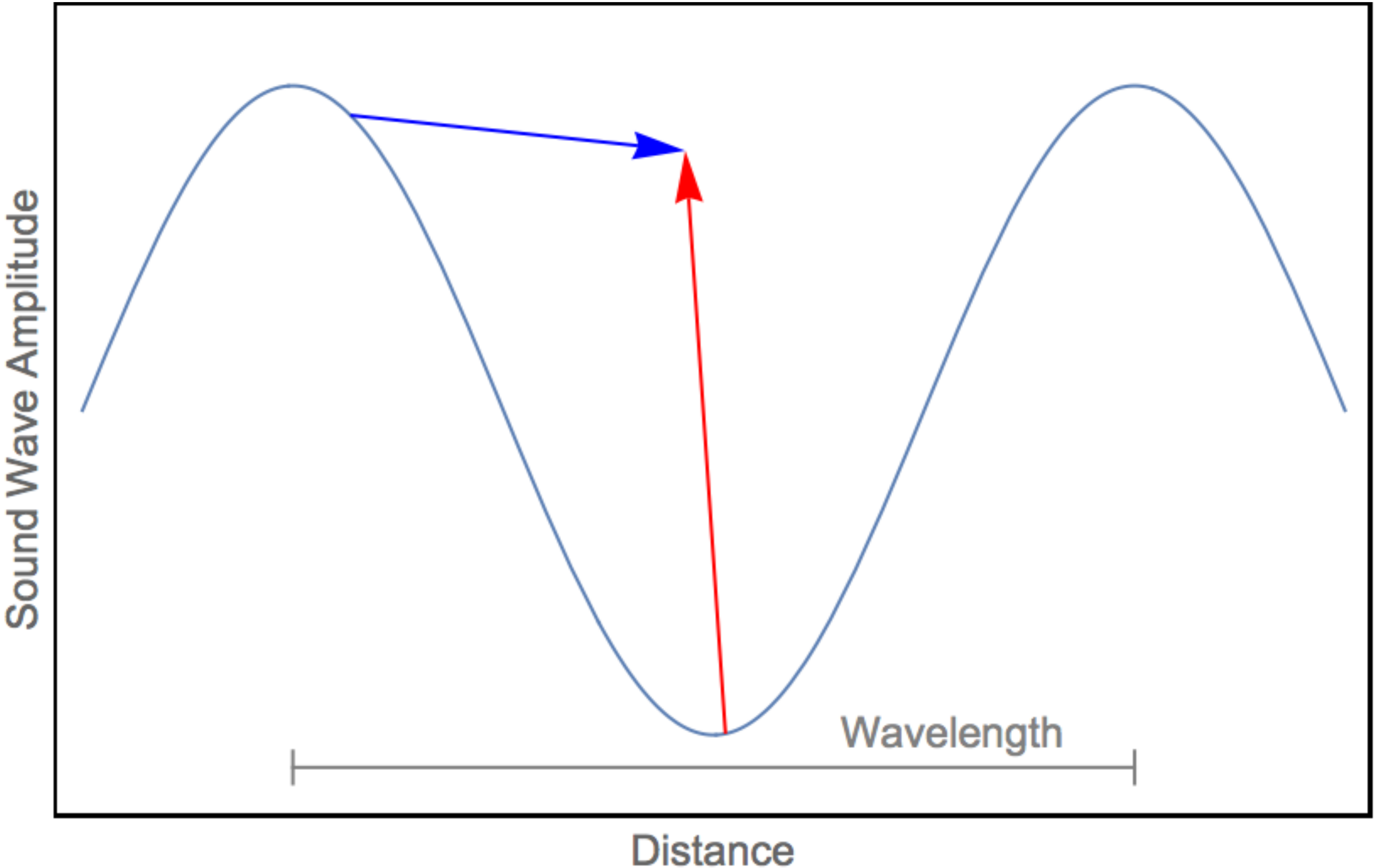

CMB
Galaxy Surveys
Lyman α
Spectral Distortions
10^5
10
0.001
10^−7
P(k)
0.01
0.10
1
10
100
k [Mpc^−1]
CDM
LKD
WDM

What is a Spectral Distortion?



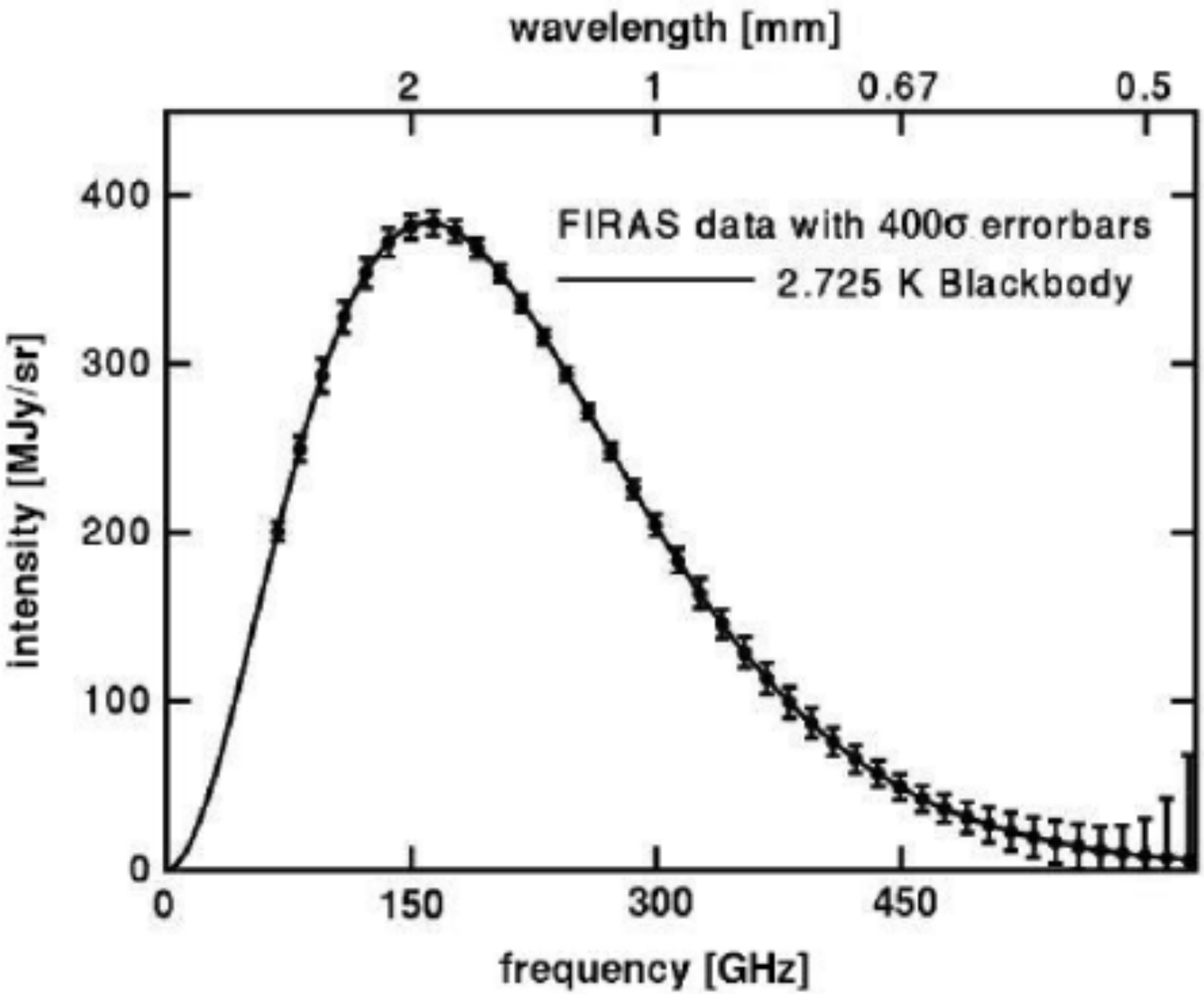
J. Chluba, J. Hamann and S. Patil (2015).

How do Spectral Distortions occur?



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

Detection of Spectral Distortions



COBE/FIRAS Collaboration (1994) Astrophys. J.

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

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

Interaction rate for photon-baryon scattering

$$\dot{\kappa} = a\sigma_{\rm Th}cn_e$$

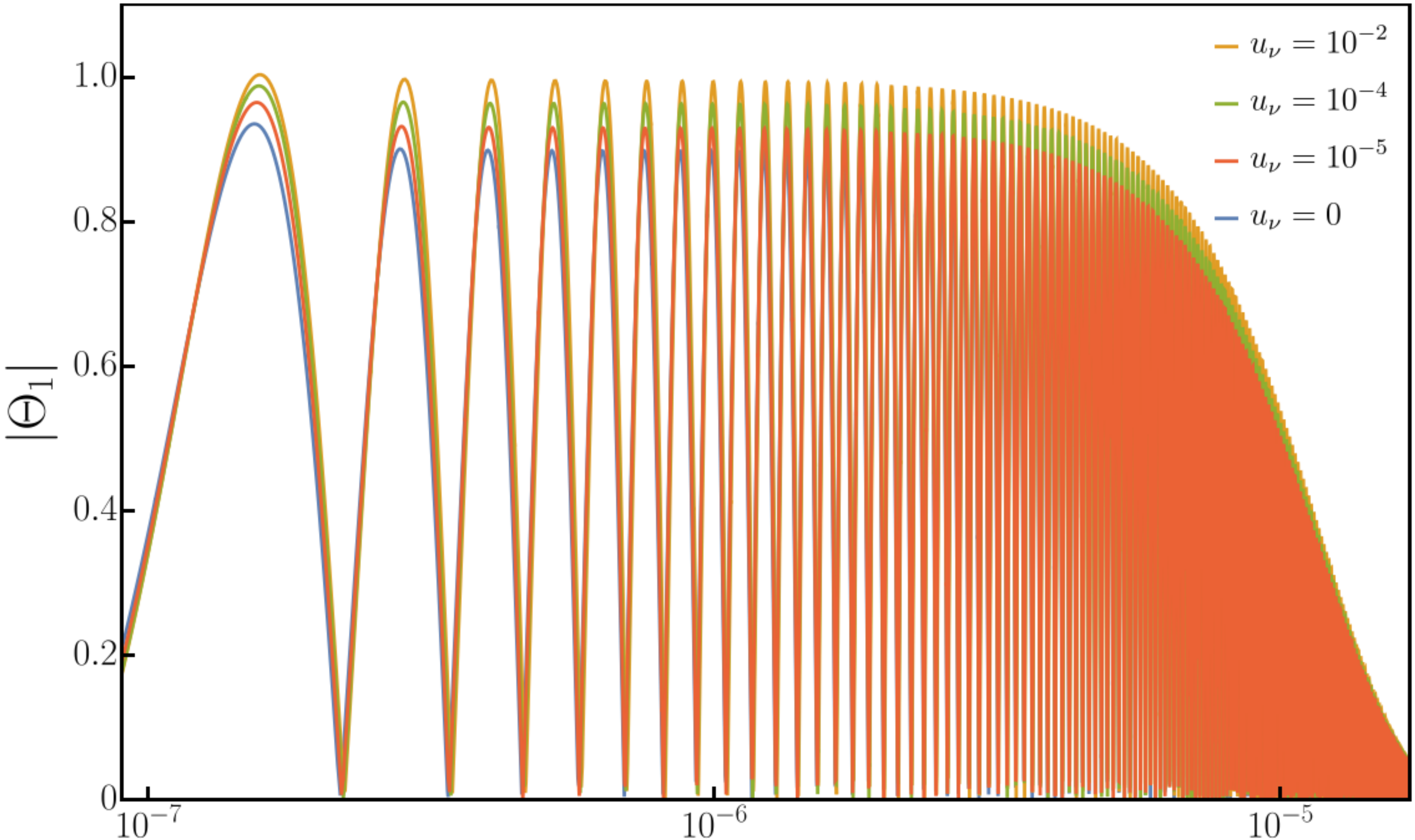
- $\dot{\kappa}/\dot{\mu}$ is proportional to

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

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

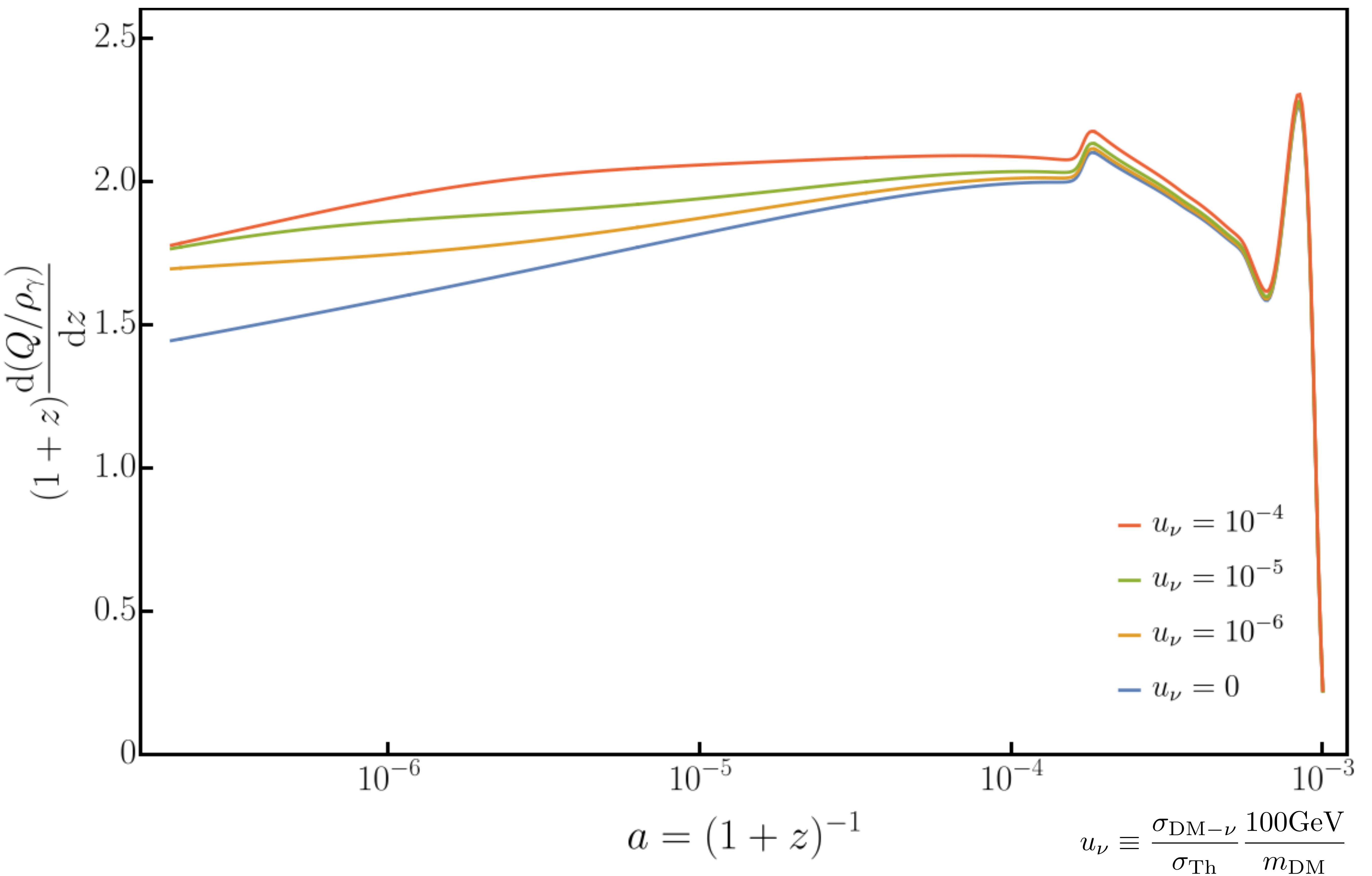
- Neutrinos normally don't participate in acoustic oscillations as they stream freely.

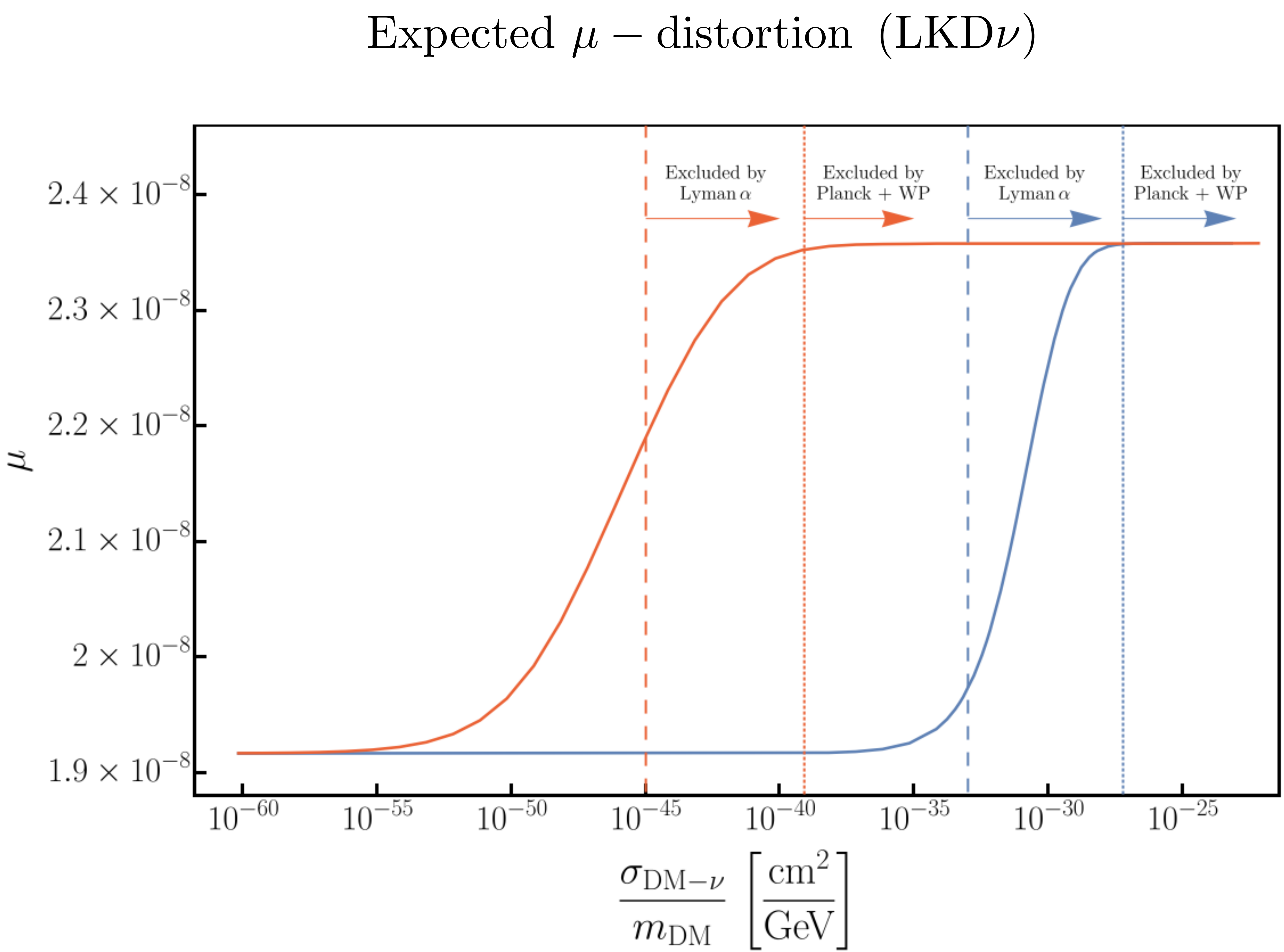
- When coupled to DM they 'cluster' more efficiently and participate in acoustic oscillations as photons.

$\Rightarrow$ Overall increase in oscillation amplitude.

Heating Rate (LKDν)

$\mathcal{A}_i = 1$




Expected μ − distortion (LKDν)
Excluded by Lyman α
Excluded by Planck + WP
Excluded by Lyman α
Excluded by Planck + WP
μ
2.4×10^{-8}
2.3×10^{-8}
2.2×10^{-8}
2.1×10^{-8}
2×10^{-8}
1.9×10^{-8}
10^{-60}
10^{-55}
10^{-50}
10^{-45}
10^{-40}
10^{-35}
10^{-30}
10^{-25}
$\frac{\sigma_{\mathrm{DM}-\nu}}{m_{\mathrm{DM}}}\left[\frac{\mathrm{cm}^2}{\mathrm{GeV}}\right]$

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

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

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

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

Photon-DM coupling

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

- Interaction rate for photon-DM scattering

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

Interaction rate for photon-baryon scattering

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

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

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

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

Heating Rate needs to be modified

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

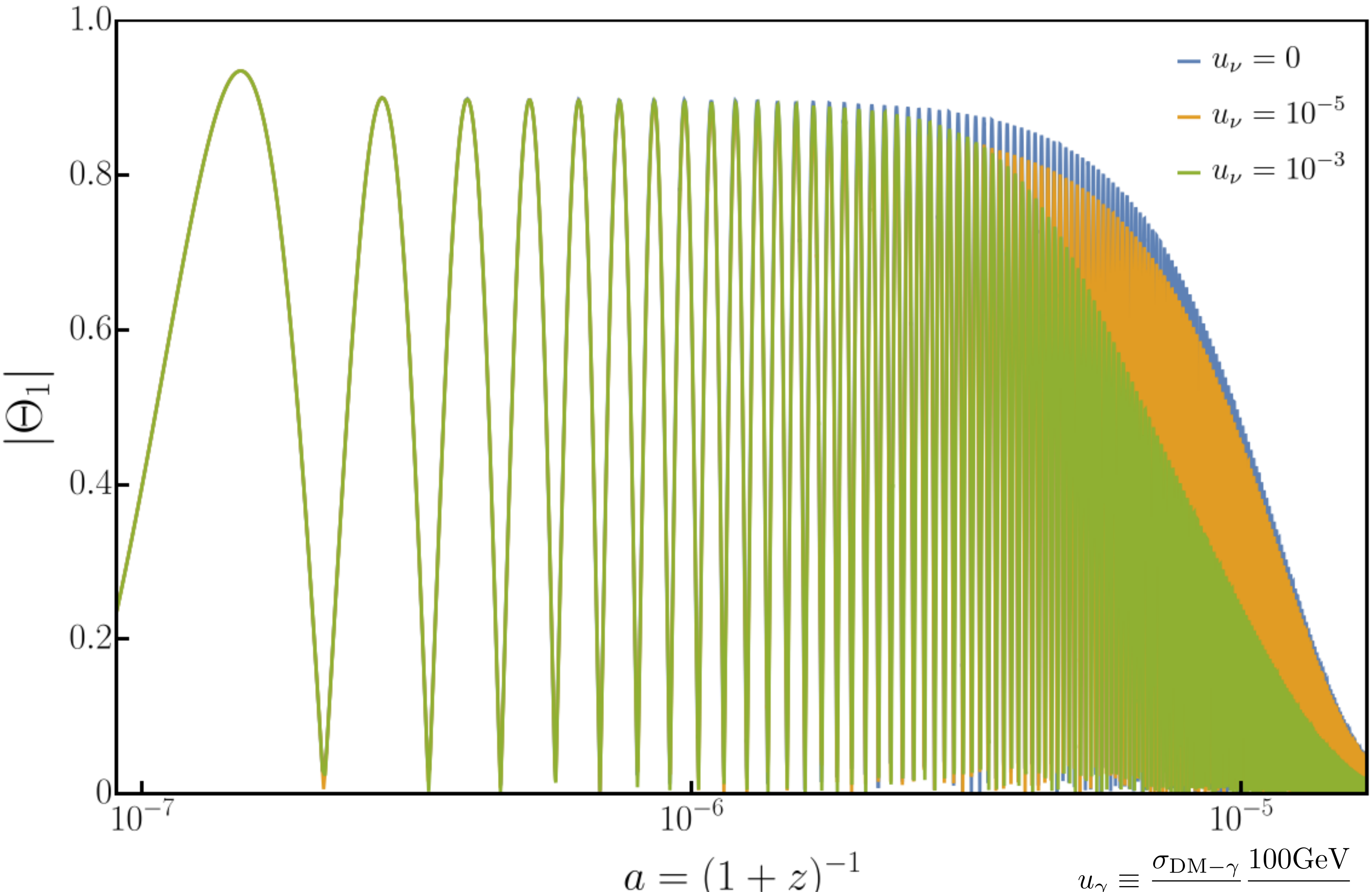
$$+\frac{4a\dot{\mu}_\gamma}{\mathcal{H}}\int \frac{k^2\mathrm{d}k}{2\pi^2}P_{\mathcal{R}}(k)\left[\frac{\left(3\Theta_1 - v_{\mathrm{DM}}\right)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2\left(\Theta_0^{\mathrm{P}} + \Theta_2^{\mathrm{P}}\right) + \sum_{\ell\geq 3}(2\ell+1)\Theta_\ell^2\right],$$

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

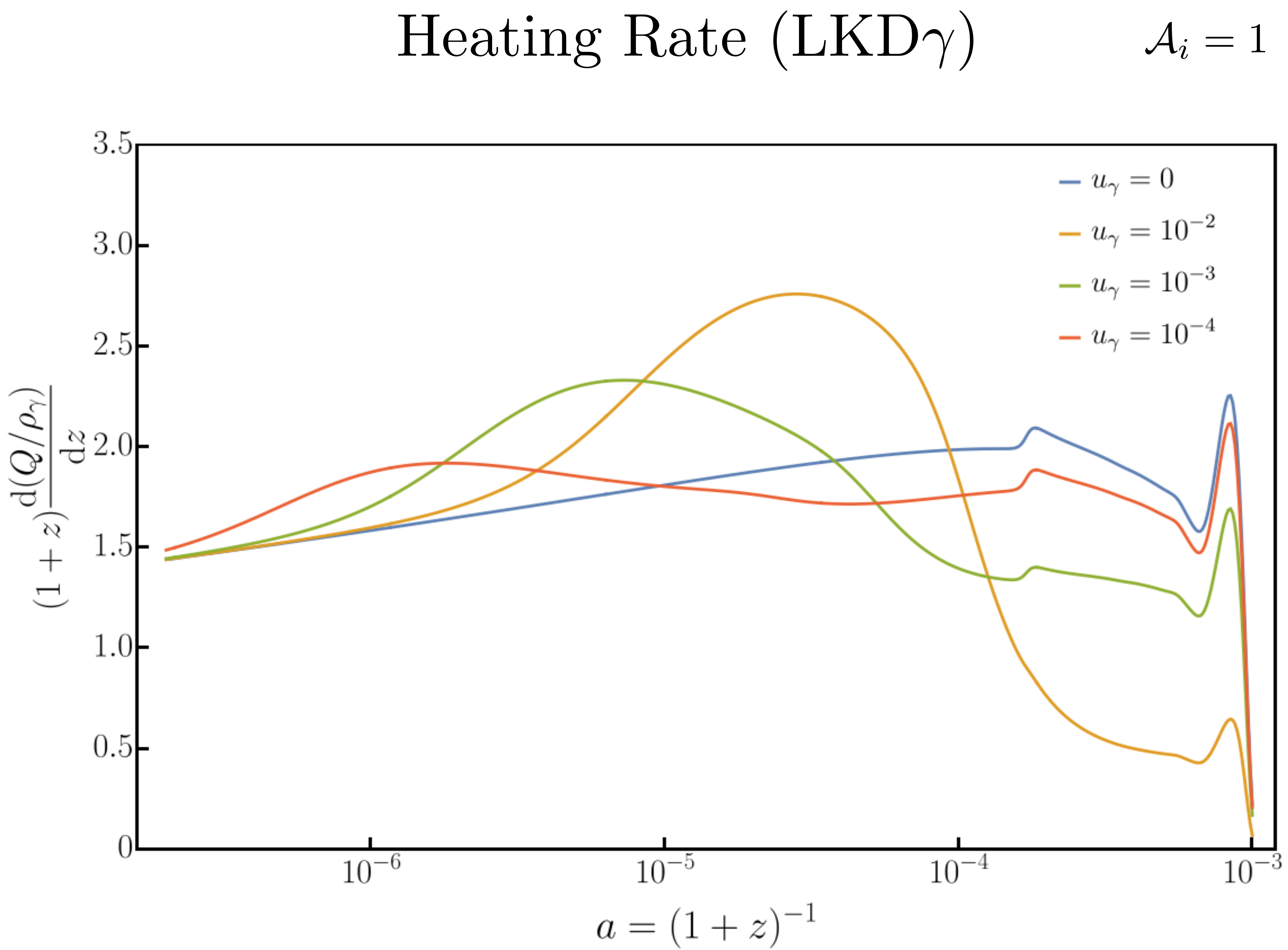
- Can be written explicitly in terms of the transfer functions as before

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

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)
$\mathcal{A}_i = 1$
$u_\gamma = 0$
$u_\gamma = 10^{-2}$
$u_\gamma = 10^{-3}$
$u_\gamma = 10^{-4}$
$(1+z)\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z}$
$a = (1+z)^{-1}$
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
10^{-6}
10^{-5}
10^{-4}
10^{-3}

How can we understand the physics?

- The photon temperature transfer function has the form:

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

Where

$$\partial_z k_D^{-2} \simeq -\frac{a}{6\mathcal{H}}\left(\frac{1}{\dot{\kappa}+\dot{\mu}}\frac{16}{15}+\frac{3\dot{\mu}}{k^2}\left(\frac{k^2}{k^2+3\left(S^{-1}\dot{\mu}\right)^2}\right)\right)$$

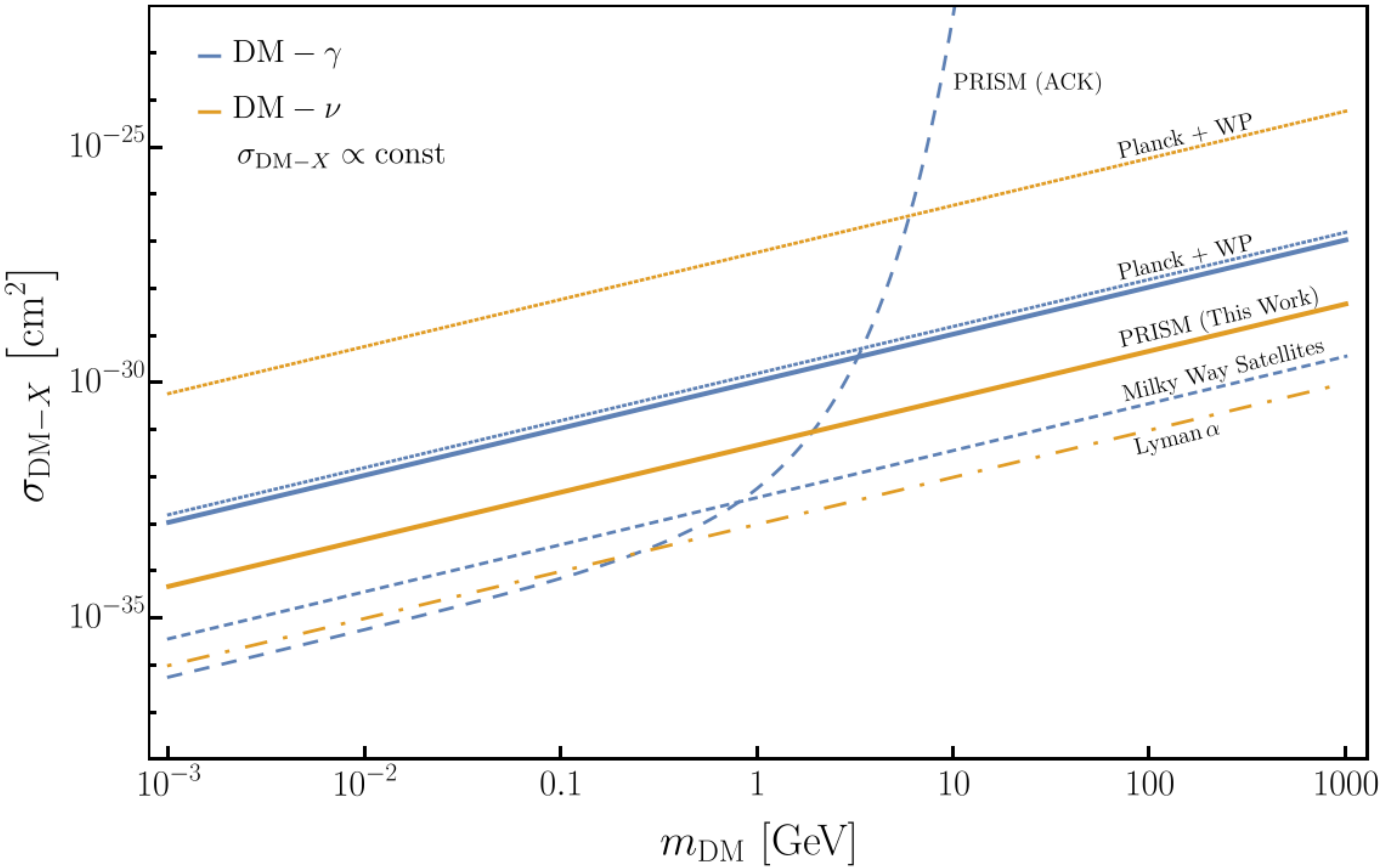
Diffusion Damping $\simeq$ Viscosity $+$ Heat Conduction

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

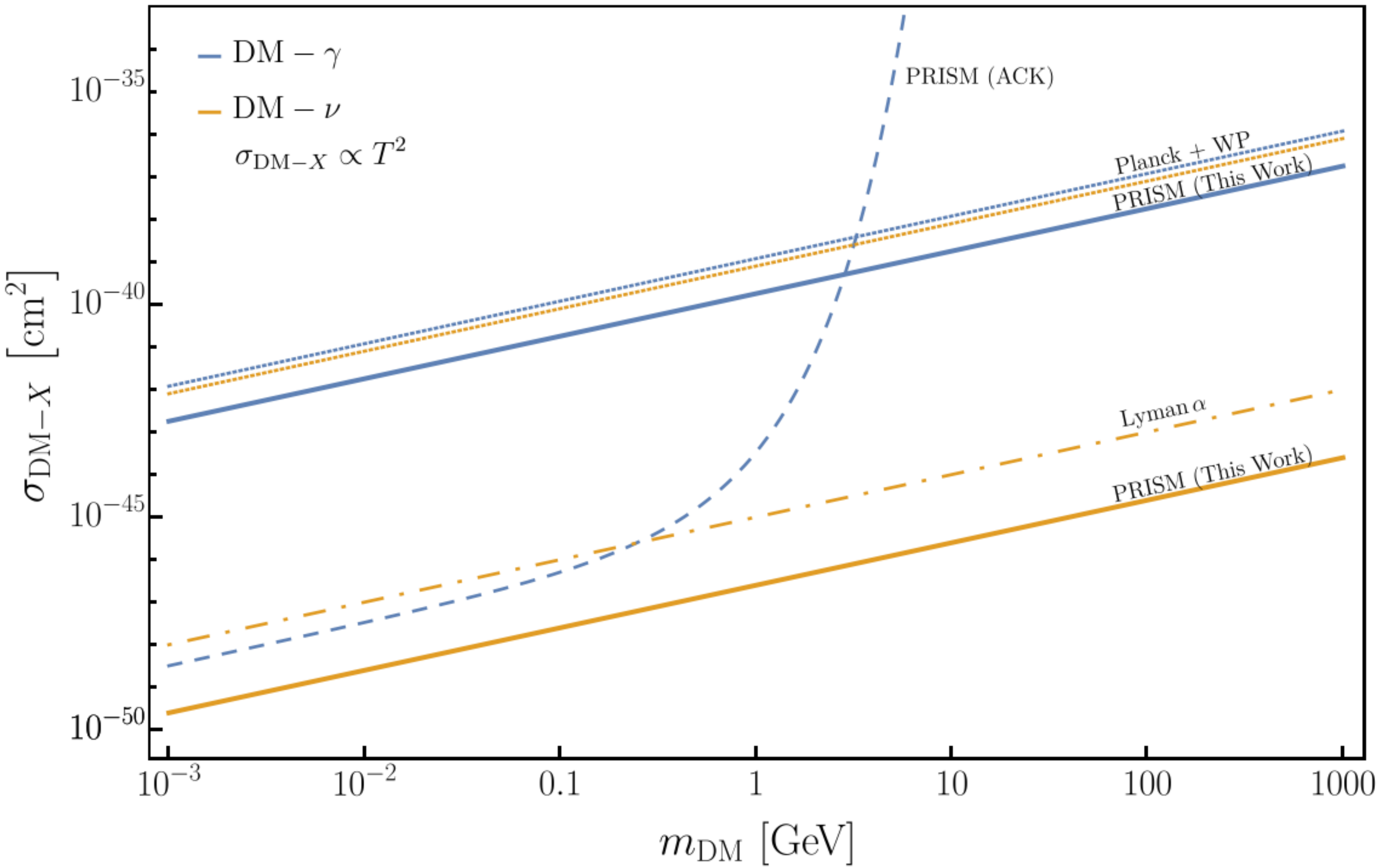
- Heating Rate is damped due to additional viscosity of the fluid and enhanced due to additional heat conduction.

$\Rightarrow$ Competing effects dominate at different times

Projected Constraints (PRISM)



Projected Constraints (PRISM)



Conclusions

- Spectral Distortions offer a unique probe of physics on extremely small-length scales in the early universe.
- They can be used to probe models of late kinetic decoupling and distinguish them from other solutions to the small-scale structure problems.
- Future Experiments such as PRISM can set competitive bounds on the elastic scattering cross sections between DM and SM particles.
- 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.