Linear Modeling of Baryon-Dark Matter Interactions with CLASS

Introducing a Novel Resonance Interaction Type

Markus Rasmussen Mosbech

February 21, 2020

Overview

Structure Formation

- Primordial perturbations

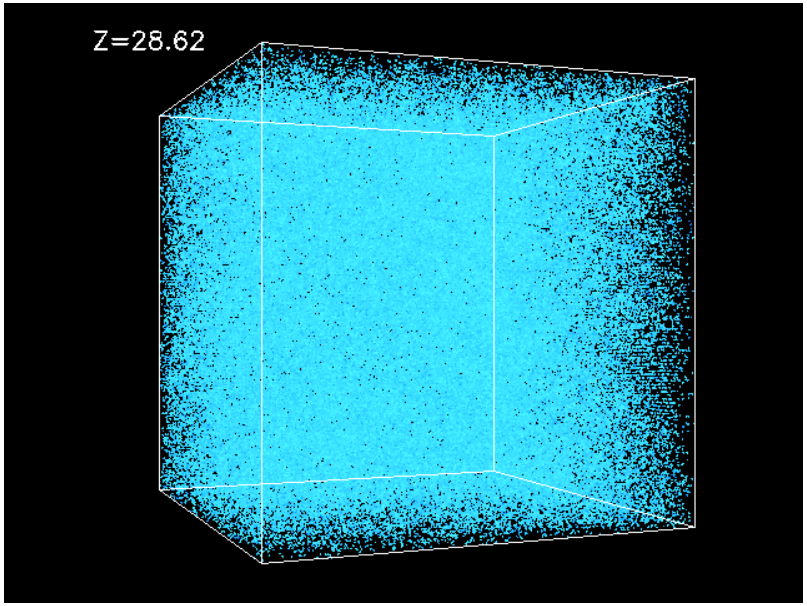
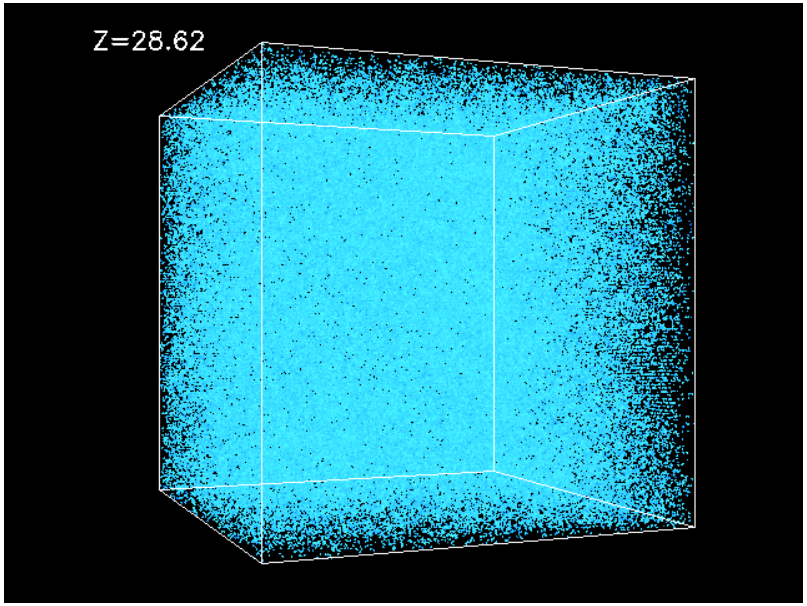


Figure: *simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.*

Structure Formation

- Primordial perturbations
- Gravity



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Structure Formation

- Primordial perturbations
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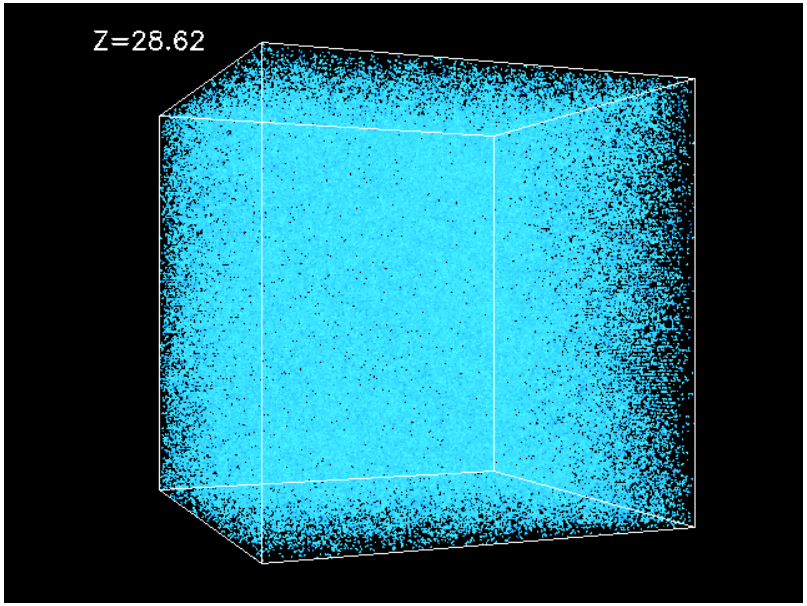
- Pressure



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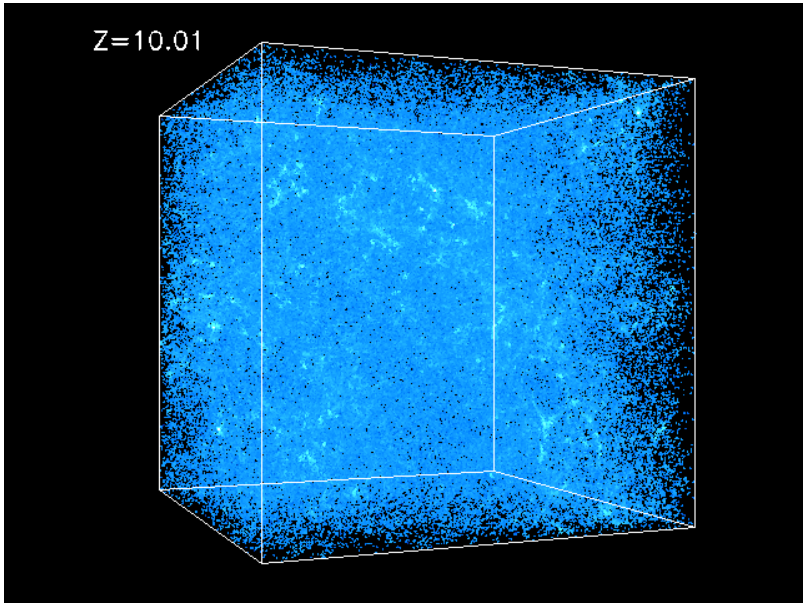

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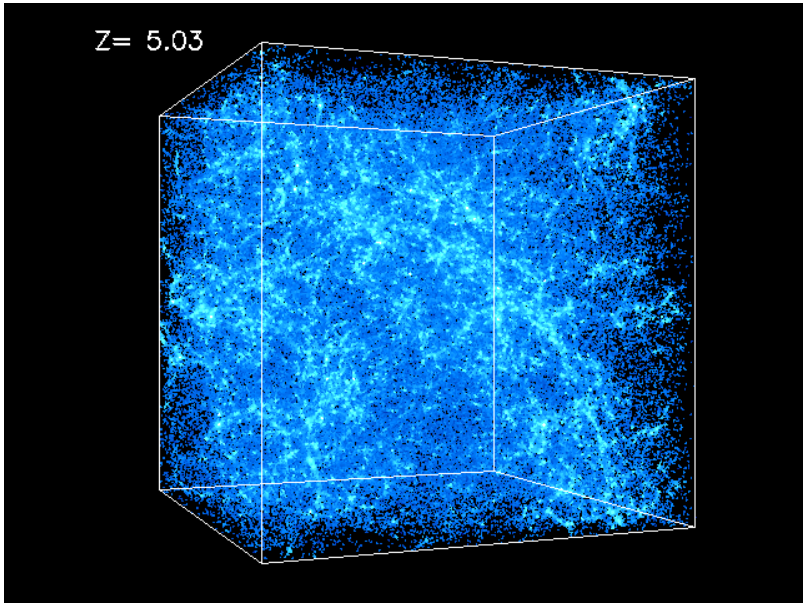

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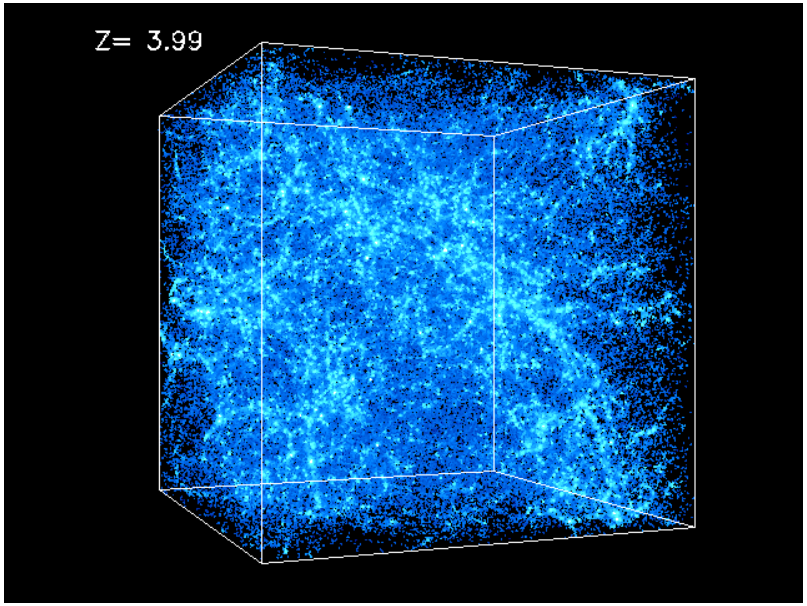

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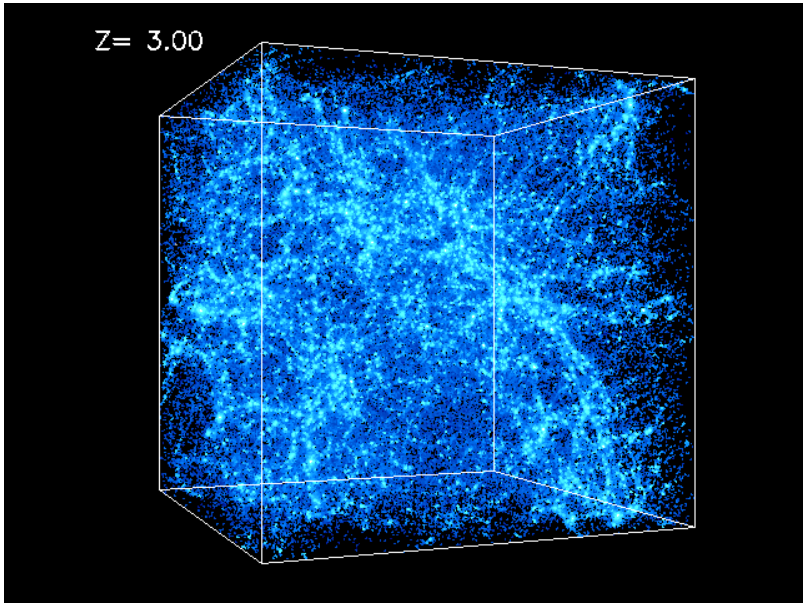

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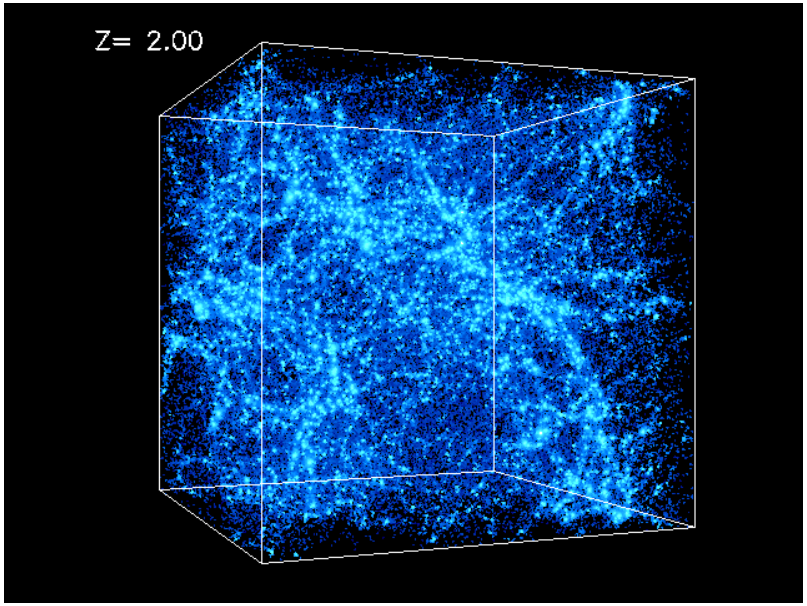

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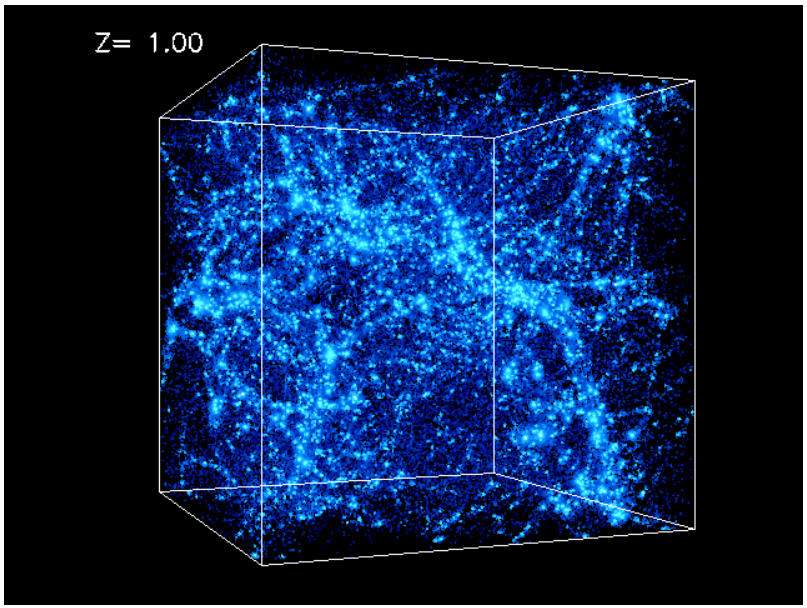

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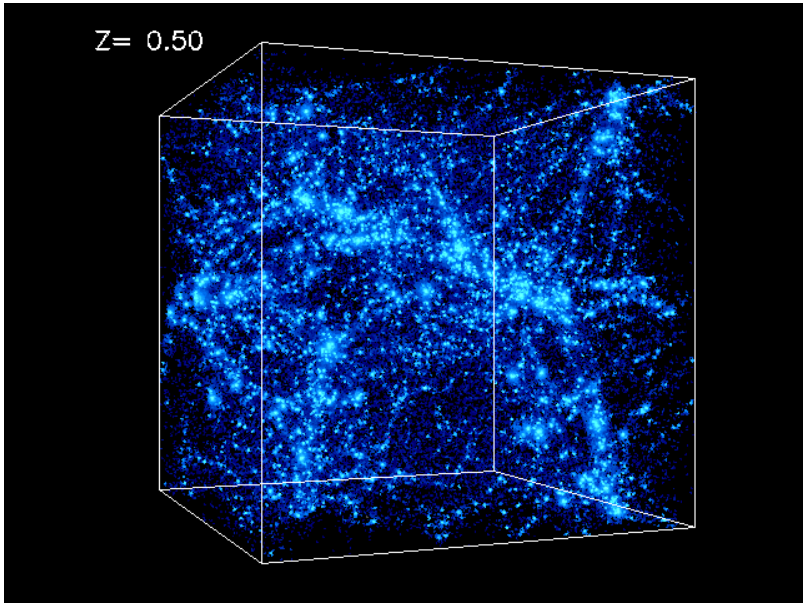

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The CMB spectrum

- Observable

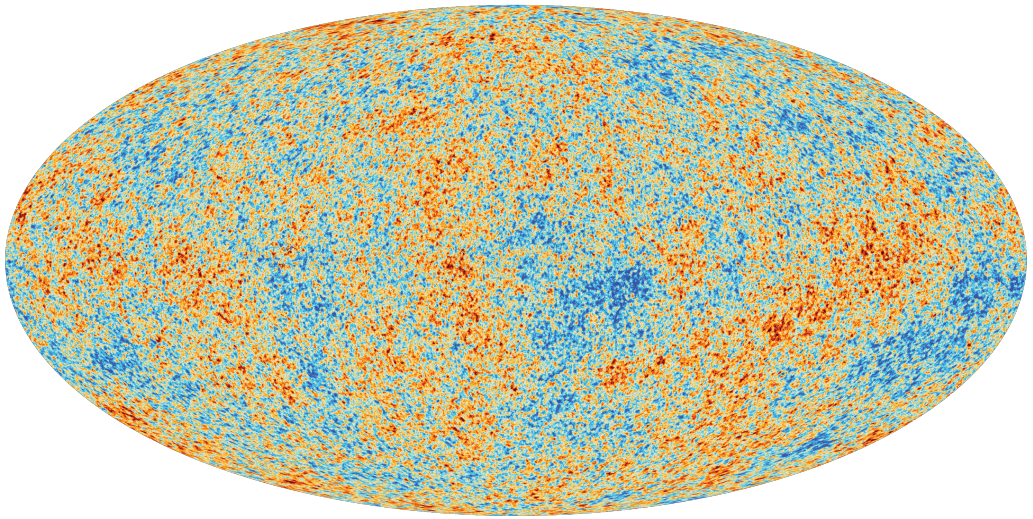


Figure: *by ESA/Planck collaboration*

The CMB spectrum

- Observable
- Recombination

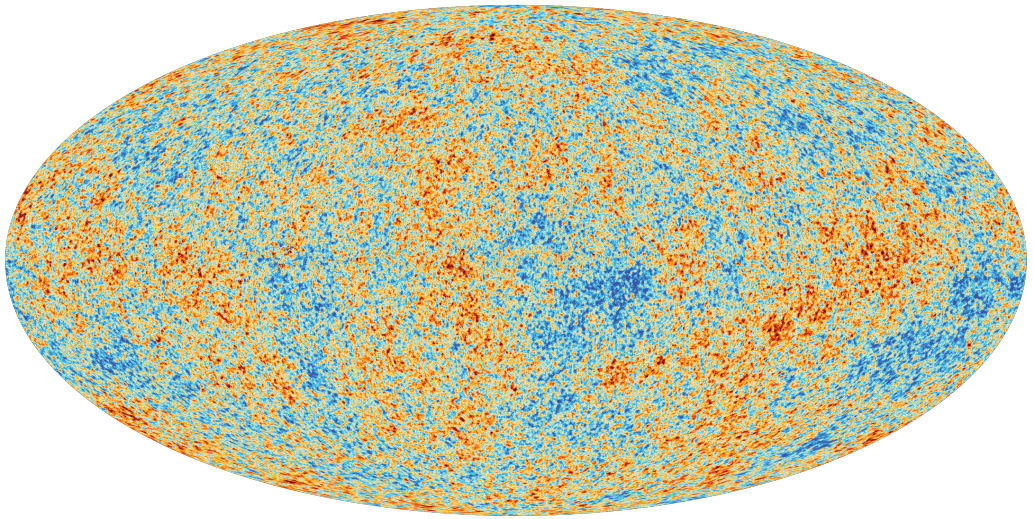
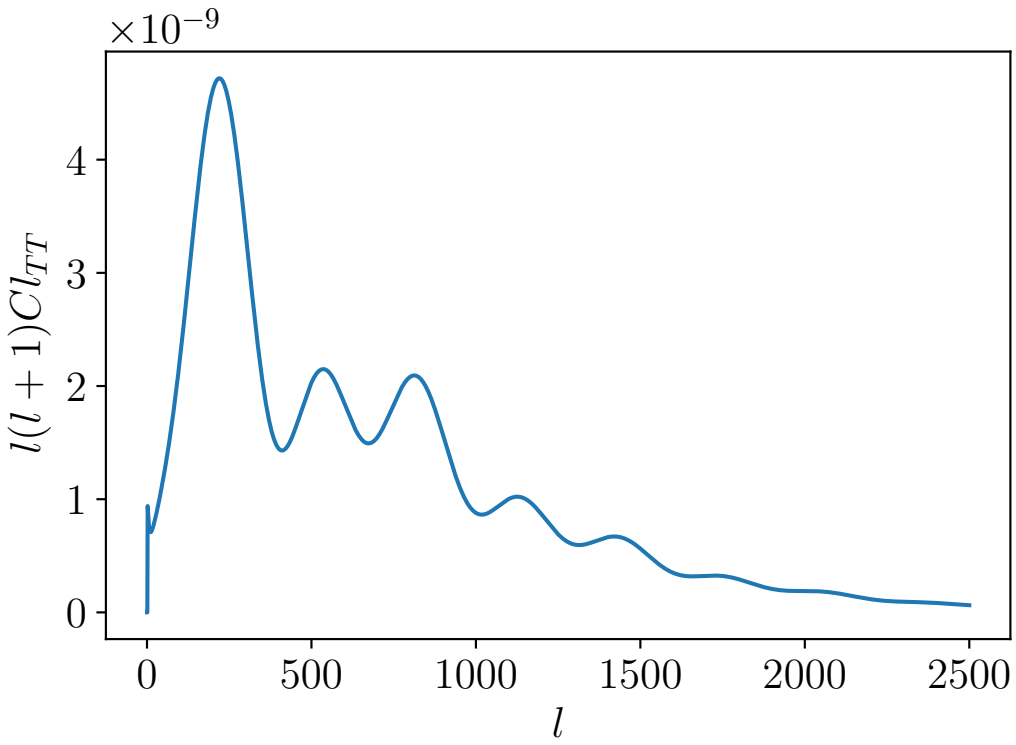


Figure: *by ESA/Planck collaboration*

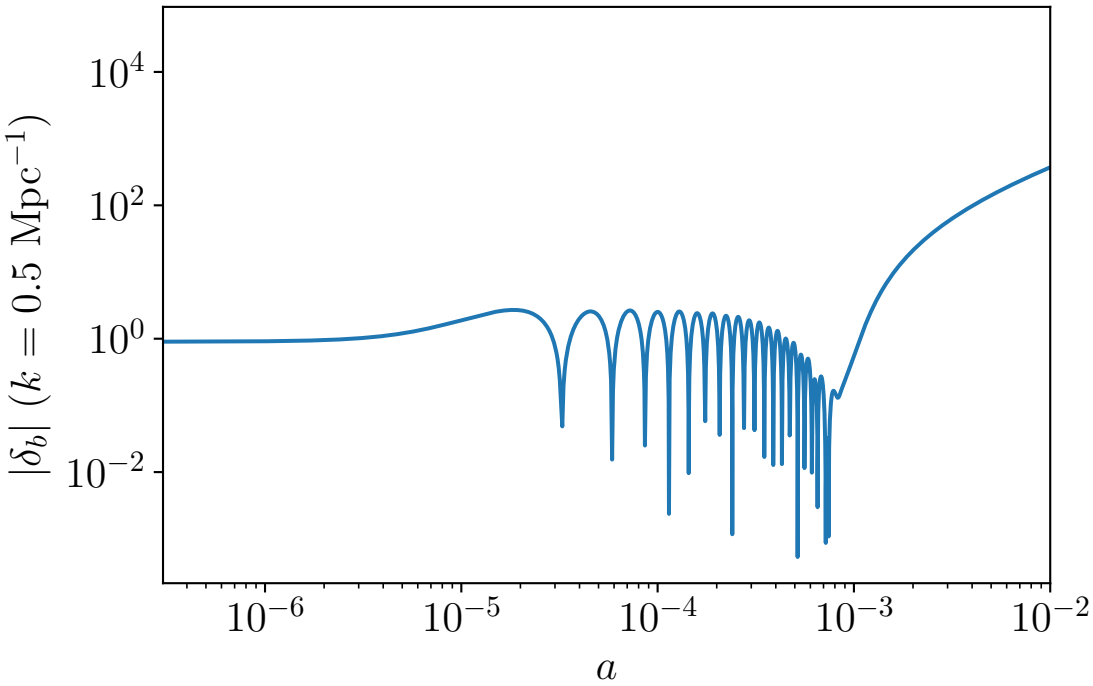
The CMB spectrum

- Observable
- Recombination
- Linear



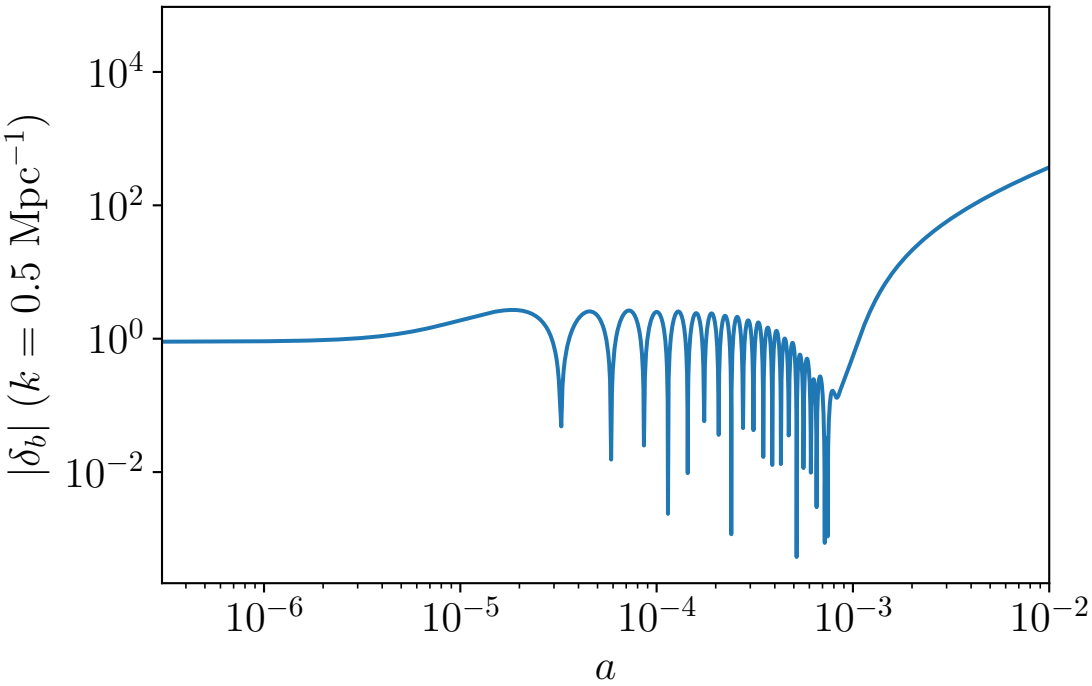
Perturbation Theory

- Small deviation from average



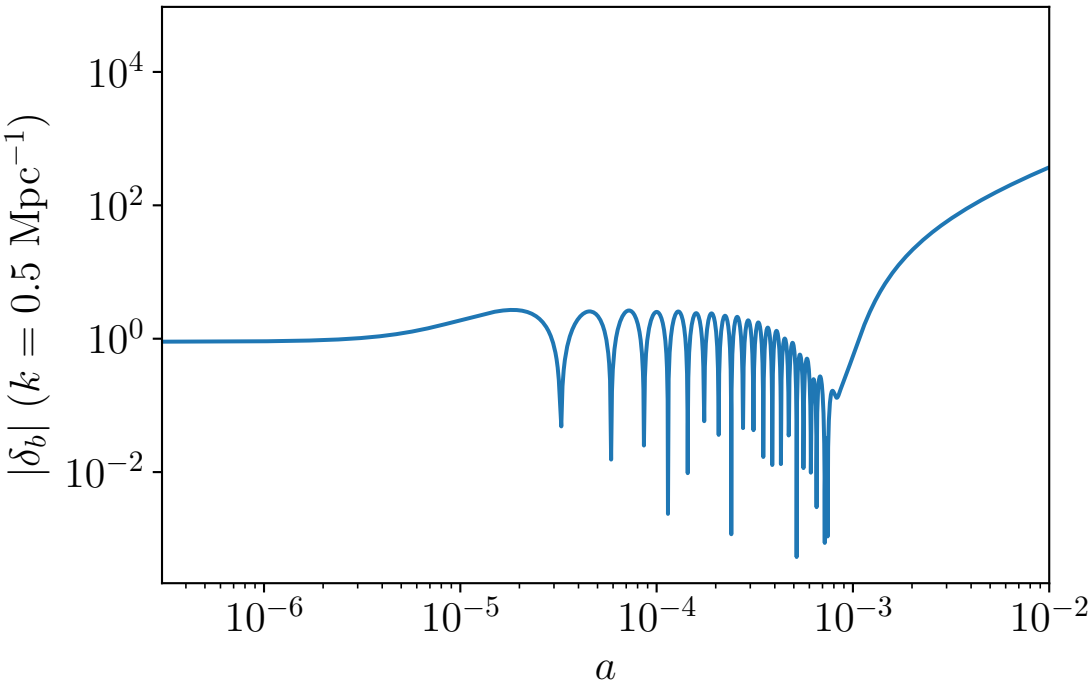
Perturbation Theory

- Small deviation from average
- Early universe



Perturbation Theory

- Small deviation from average
- Early universe
- Advantages in Fourier space



The Boltzmann Equations

- Dark Matter

$$\dot{\delta}_{\mathrm{cdm}} = -\theta_{\mathrm{cdm}} + 3\dot{\Phi},$$
$$\dot{\theta}_{\mathrm{cdm}} = -\frac{\dot{a}}{a}\theta_{\mathrm{cdm}} + k^2\Psi.$$

The Boltzmann Equations

- Dark Matter
- Baryons

$$\dot{\delta}_{\mathrm{b}} = -\theta_{\mathrm{b}} - 3\dot{\Phi},$$

$$\dot{\theta}_{\mathrm{b}} = -\frac{\dot{a}}{a}\theta_{\mathrm{b}} + c_s^2 k^2 \delta_{\mathrm{b}} + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_{\mathrm{b}}} a n_e \sigma_{\mathrm{T}} \left(\theta_\gamma - \theta_{\mathrm{b}}\right) + k^2 \Psi.$$

The Boltzmann Equations

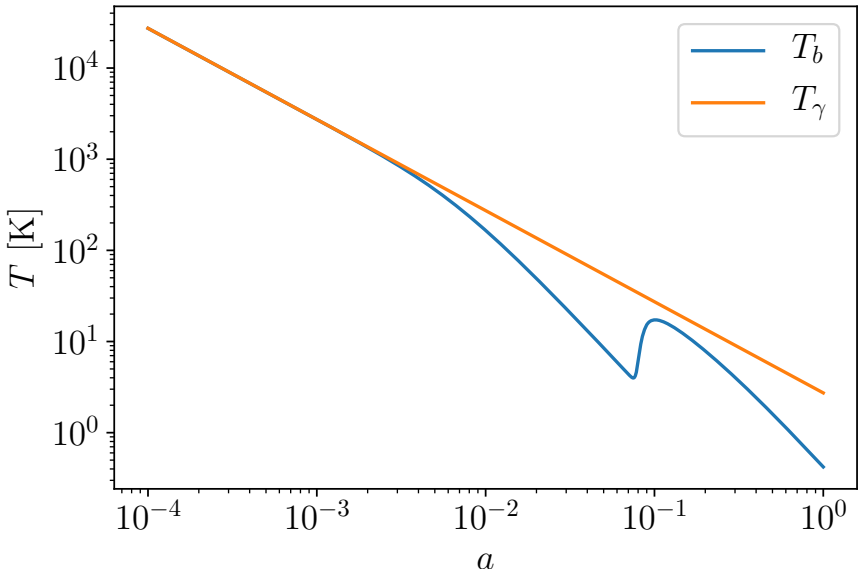
- Dark Matter
- Baryons
- Photons

$$\dot{\delta}_\gamma = -\frac{4}{3}\theta_\gamma + 4\dot{\Phi}$$

$$\dot{\theta}_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + an_e\sigma_\mathrm{T}\left(\theta_\mathrm{b} - \theta_\gamma\right) + k^2\Psi$$

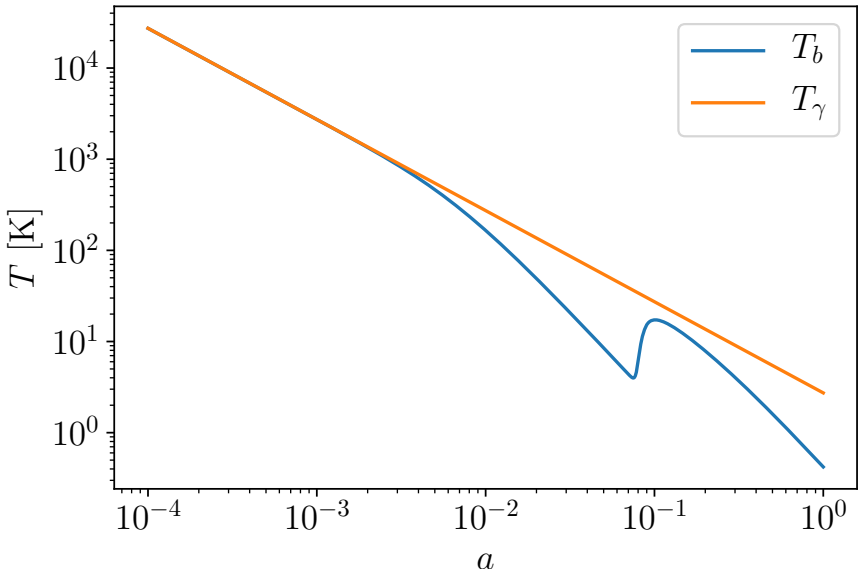
Temperature

- Photons



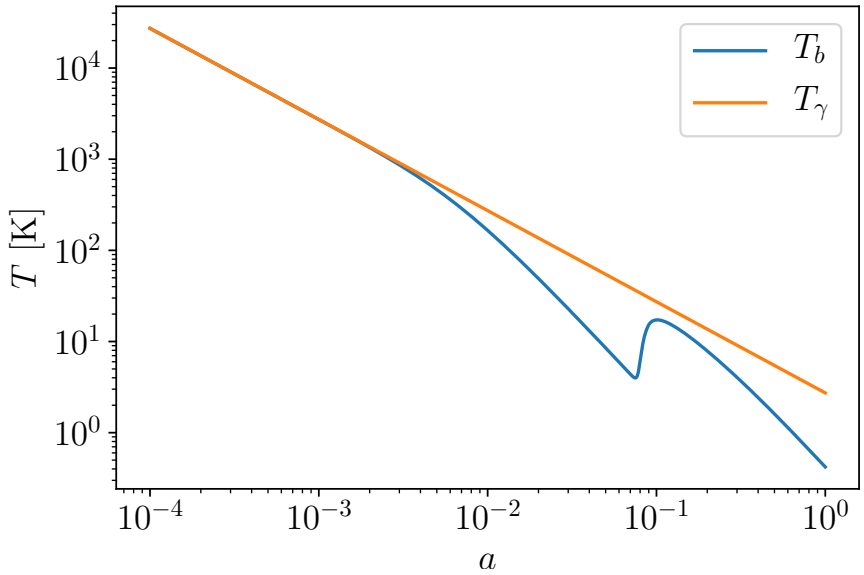
Temperature

- Photons
- Baryons



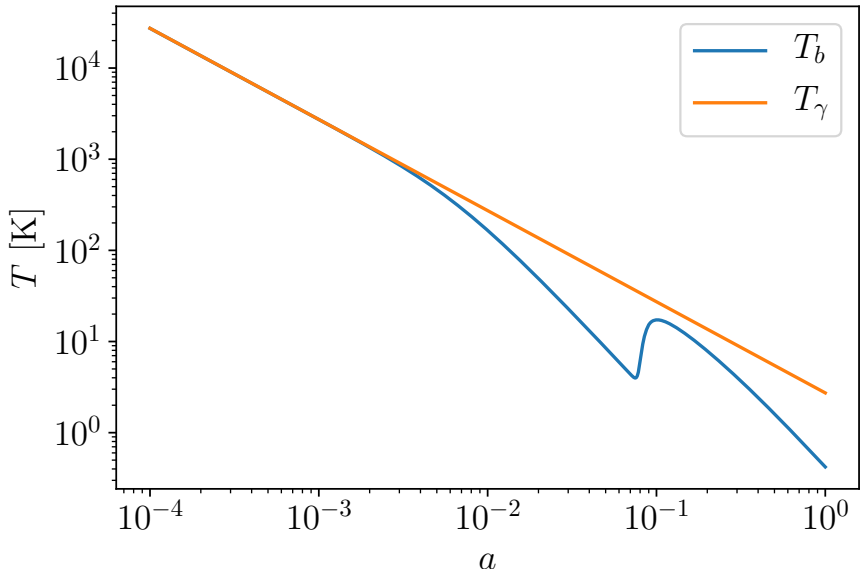
Temperature

- Photons
- Baryons
- Cold dark matter



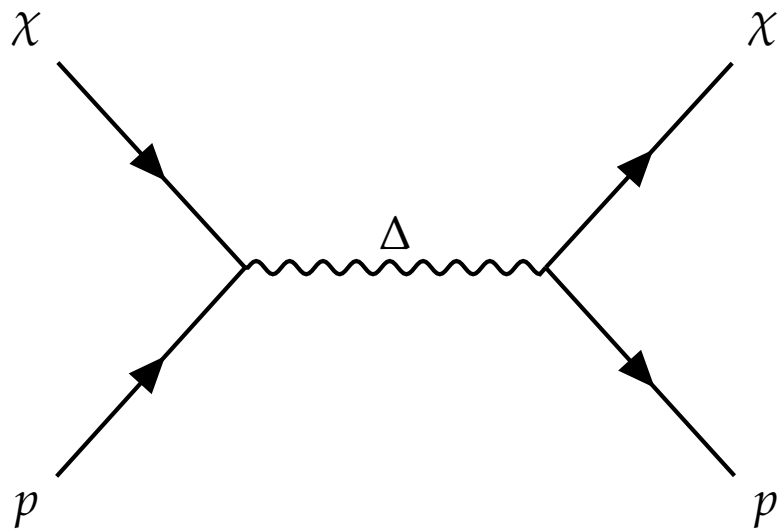
Temperature

- Photons
- Baryons
- Cold dark matter
- EDGES



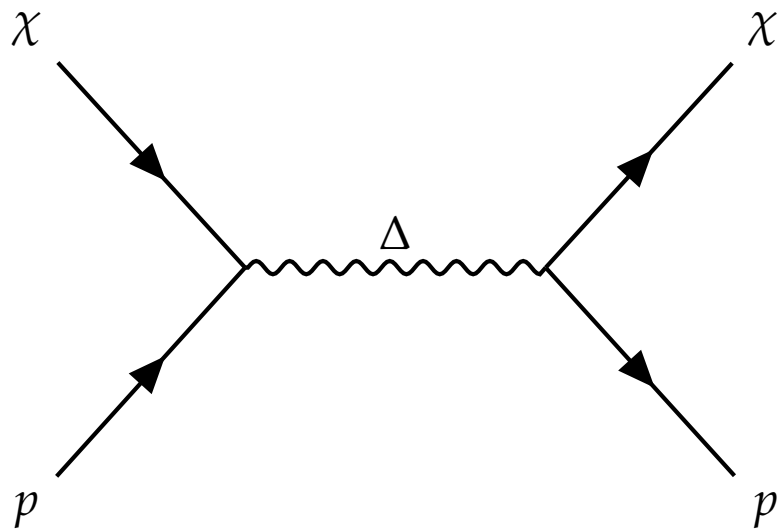
Basic Premise

- Nonzero interaction



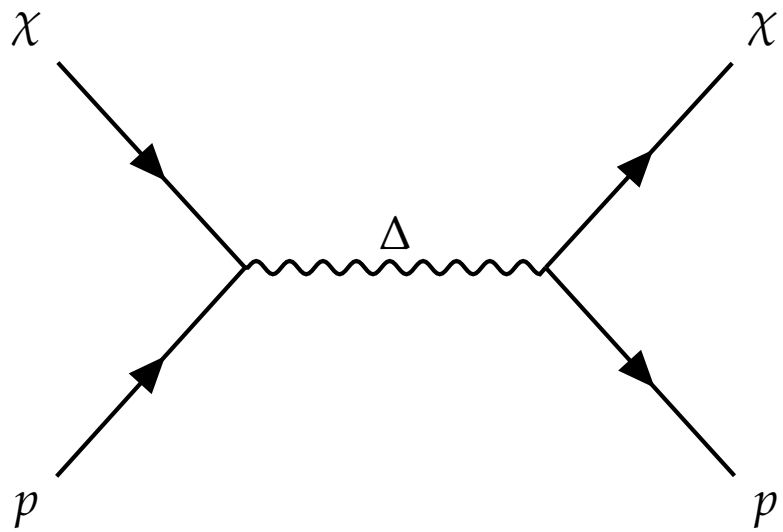
Basic Premise

- Nonzero interaction
- Velocity dependence



Basic Premise

- Nonzero interaction
- Velocity dependence
- Nonzero temperature



Modified Boltzmann equations

- Baryons

$$\dot{\delta}_{\rm b} = -\theta_{\rm b} - 3\dot{\Phi},$$

$$\dot{\theta}_{\rm b} = -\frac{\dot{a}}{a}\theta_{\rm b} + c_s^2 k^2 \delta_{\rm b} + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_{\rm b}} a n_e \sigma_{\rm T} \left(\theta_\gamma - \theta_{\rm b}\right) + k^2 \Psi. + \frac{\rho_\chi}{\rho_b} R_\chi \left(\theta_\chi - \theta_b\right)$$

$$R_\chi = \frac{a\rho_b}{m_\chi + m_H} \langle \sigma v \rangle \mathcal{F}_{\rm He}$$

Modified Boltzmann equations

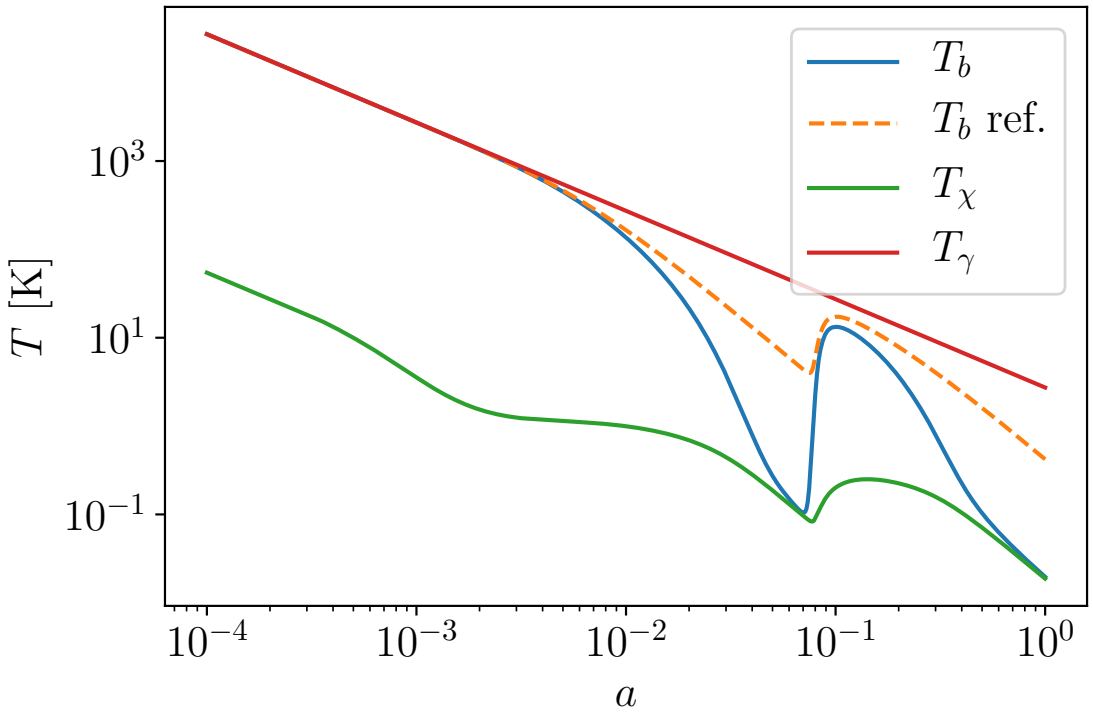
- Baryons
- Dark Matter

$$\dot{\delta}_{\mathrm{cdm}} = -\theta_{\mathrm{cdm}} + 3\dot{\Phi},$$
$$\dot{\theta}_{\mathrm{cdm}} = -\frac{\dot{a}}{a}\theta_{\mathrm{cdm}} + k^2\Psi + R_\chi\left(\theta_b - \theta_\chi\right)$$

$$R_\chi = \frac{a\rho_b}{m_\chi + m_H}\left\langle\sigma v\right\rangle \mathcal{F}_{\mathrm{He}}$$

Power Law Interaction

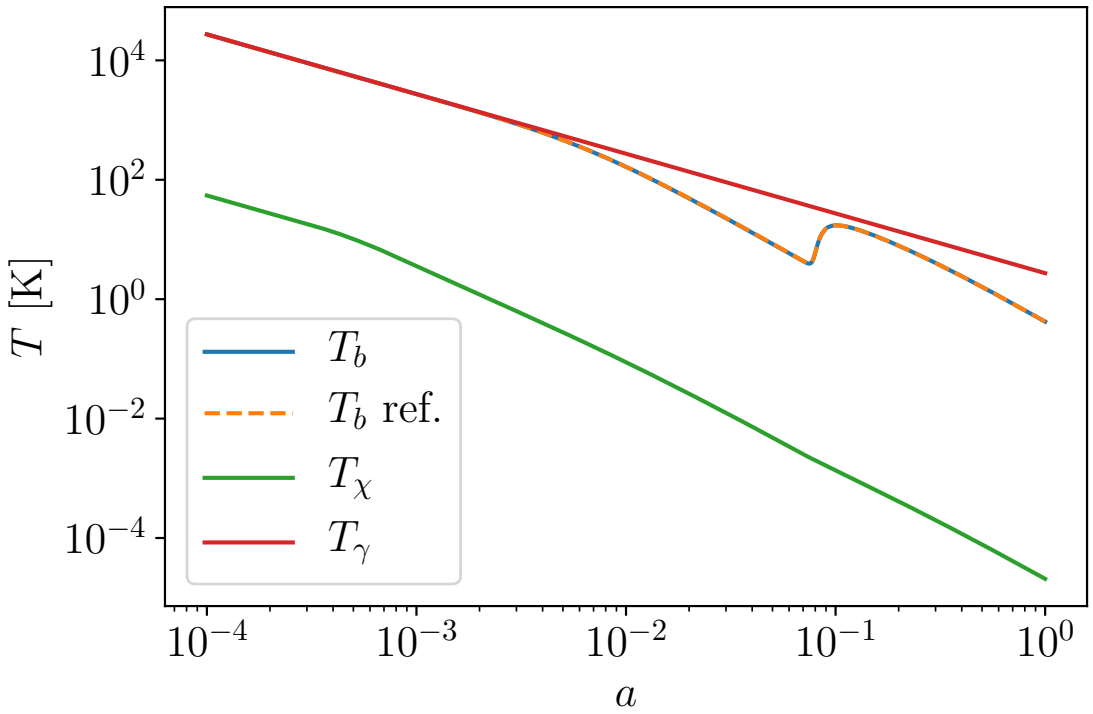
- Coulomb



$$R_\chi = \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\mathrm{rms}}^2}{3} \right)^{\frac{n+1}{2}} \mathcal{F}_{\mathrm{He}}$$

Power Law Interaction

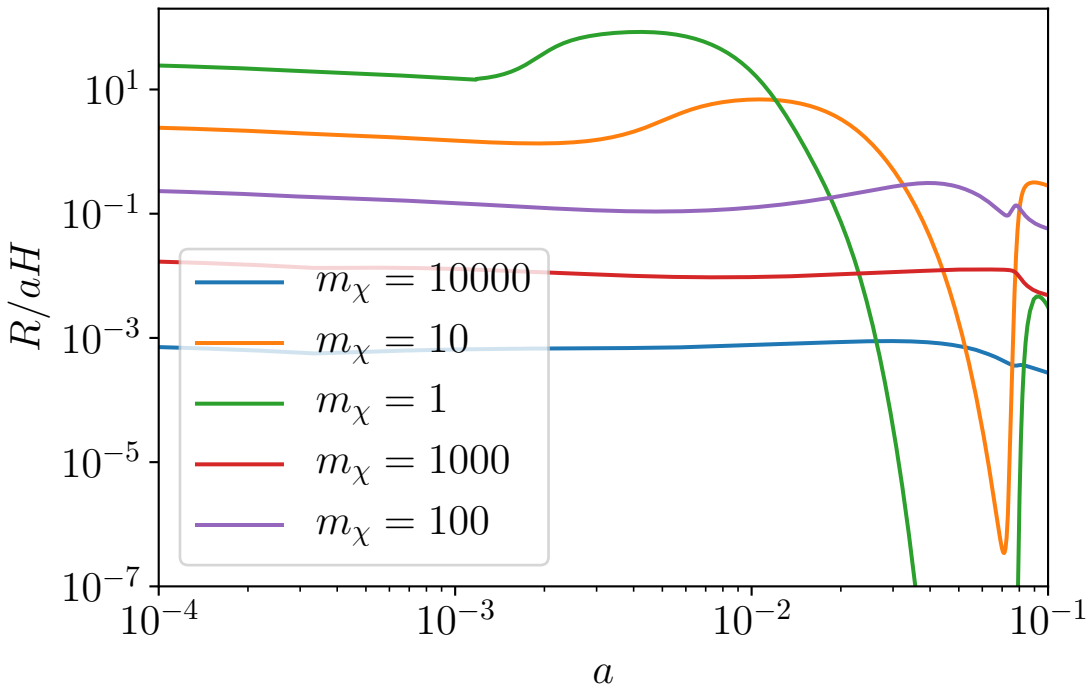
- Coulomb
- Dipole



$$R_\chi = \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\mathrm{rms}}^2}{3} \right)^{\frac{n+1}{2}} \mathcal{F}_{\mathrm{He}}$$

Resonance interaction

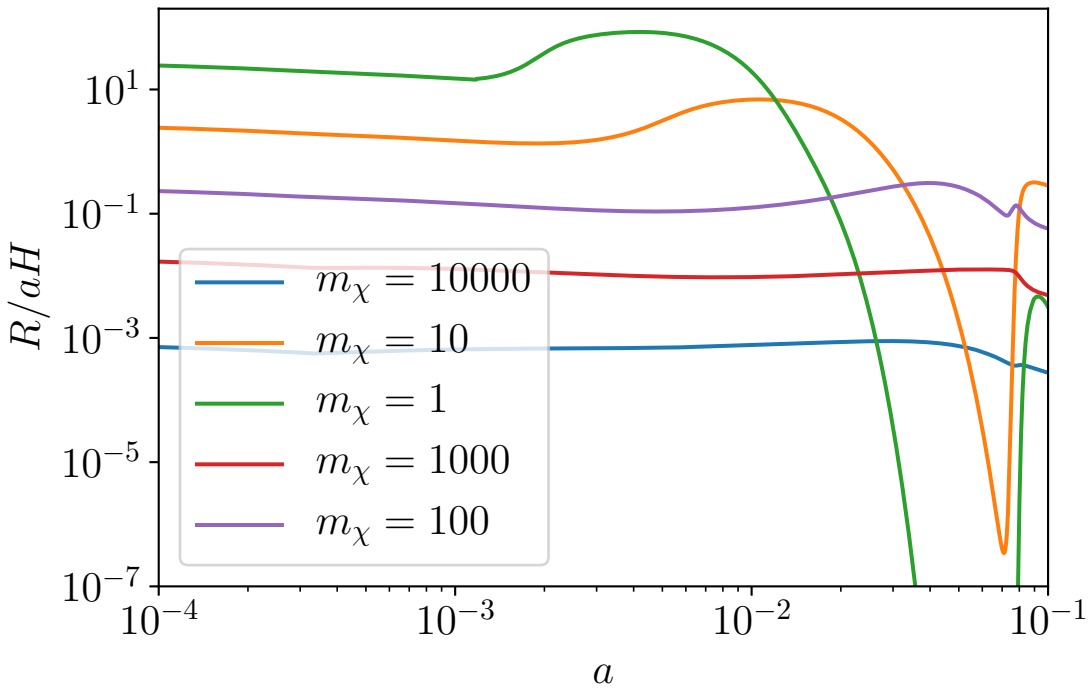
- Assumptions



$$R_\chi = \frac{a\rho_b\sigma_0}{m_\chi + m_H}\frac{x_b x_\chi Q^{3/2}}{m_H m_\chi} K_1\left(\frac{Q}{2}\sqrt{x_b x_\chi}\right)\mathcal{F}_{\mathrm{He}}$$

Resonance interaction

- Assumptions
- Velocity dependence



$$R_\chi = \frac{a\rho_b\sigma_0}{m_\chi + m_H}\frac{x_b x_\chi Q^{3/2}}{m_H m_\chi} K_1\left(\frac{Q}{2}\sqrt{x_b x_\chi}\right)\mathcal{F}_{\mathrm{He}}$$

CLASS

- Boltzmann solver

Figure: *from* `class-code.net`

CLASS

- Boltzmann solver
- Linear

Figure: *from* `class-code.net`

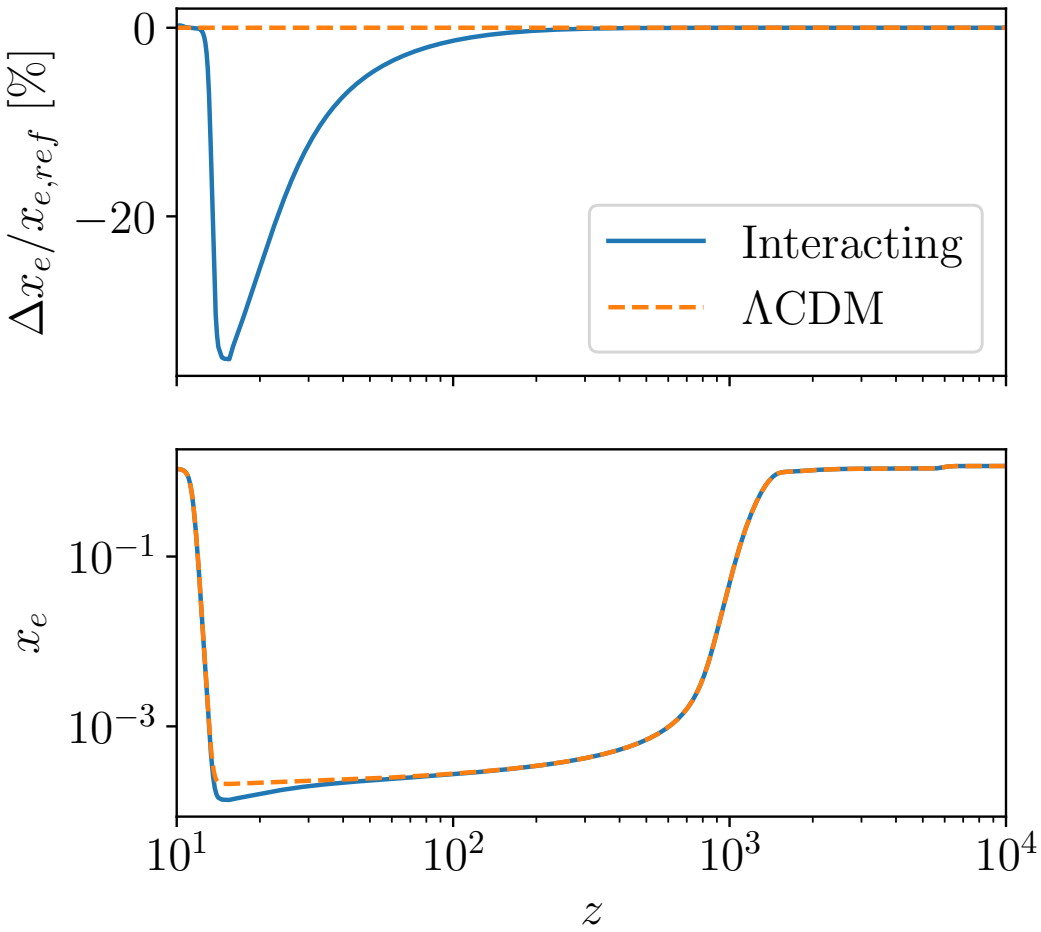
CLASS

- Boltzmann solver
- Linear
- Modular

Figure: *from* `class-code.net`

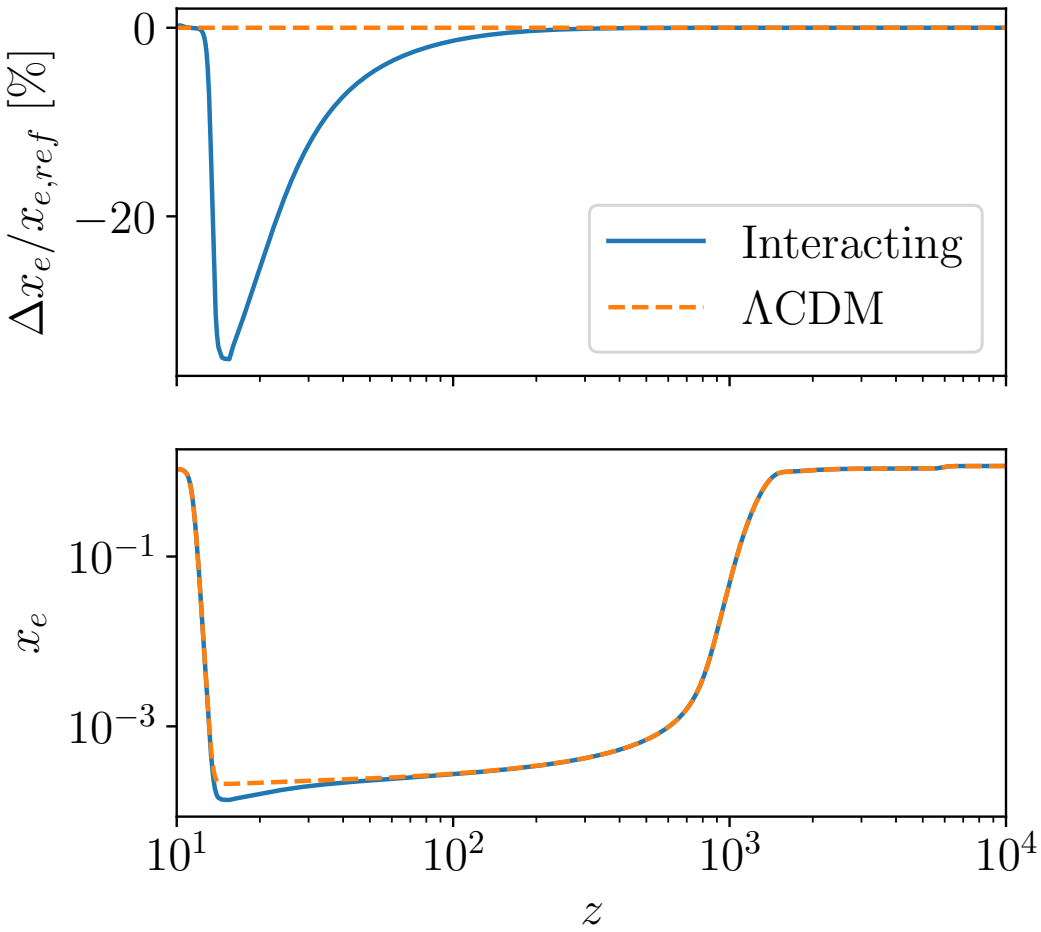
Thermodynamics

- Interactions



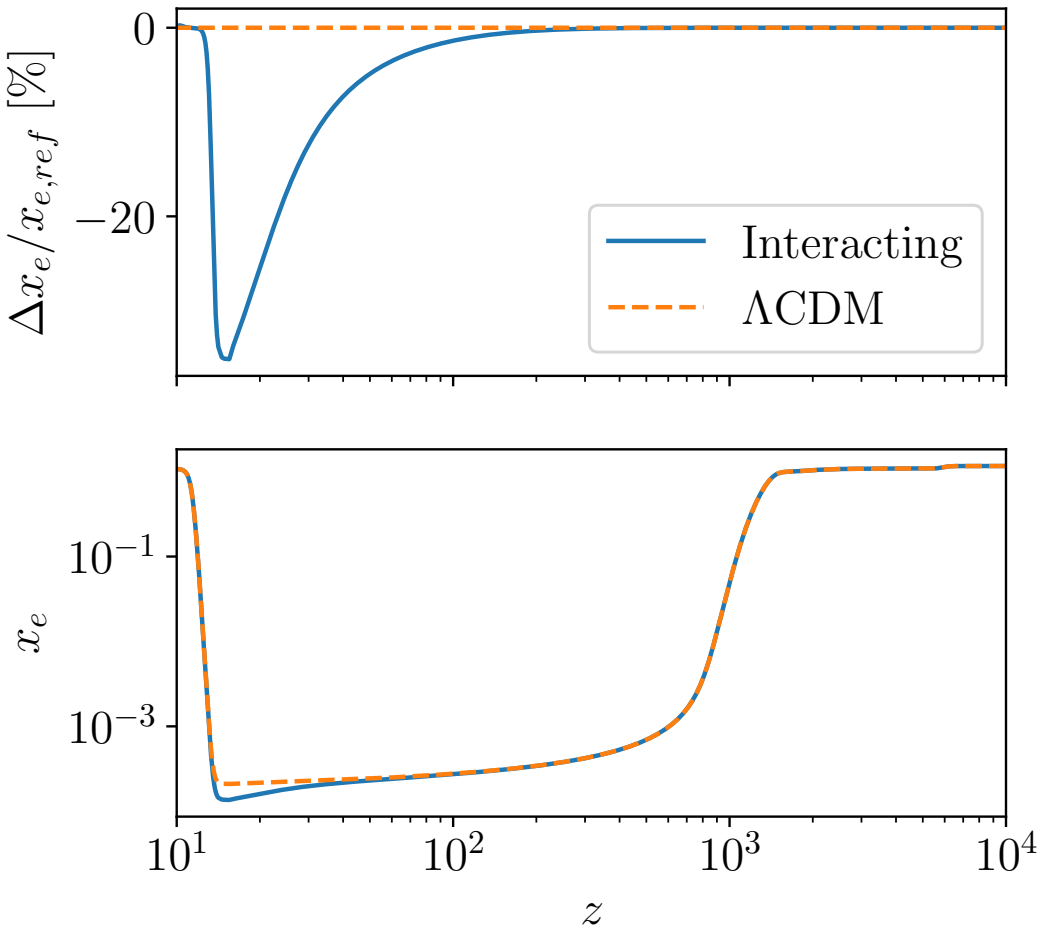
Thermodynamics

- Interactions
- Temperature



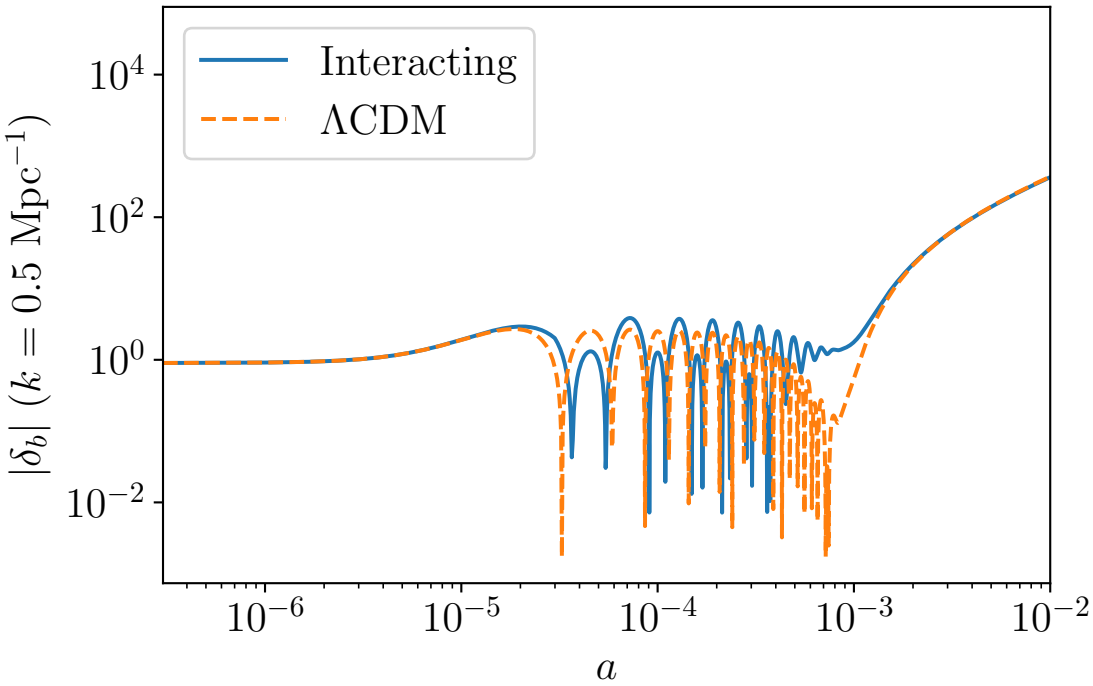
Thermodynamics

- Interactions
- Temperature
- Recombination + reionisation



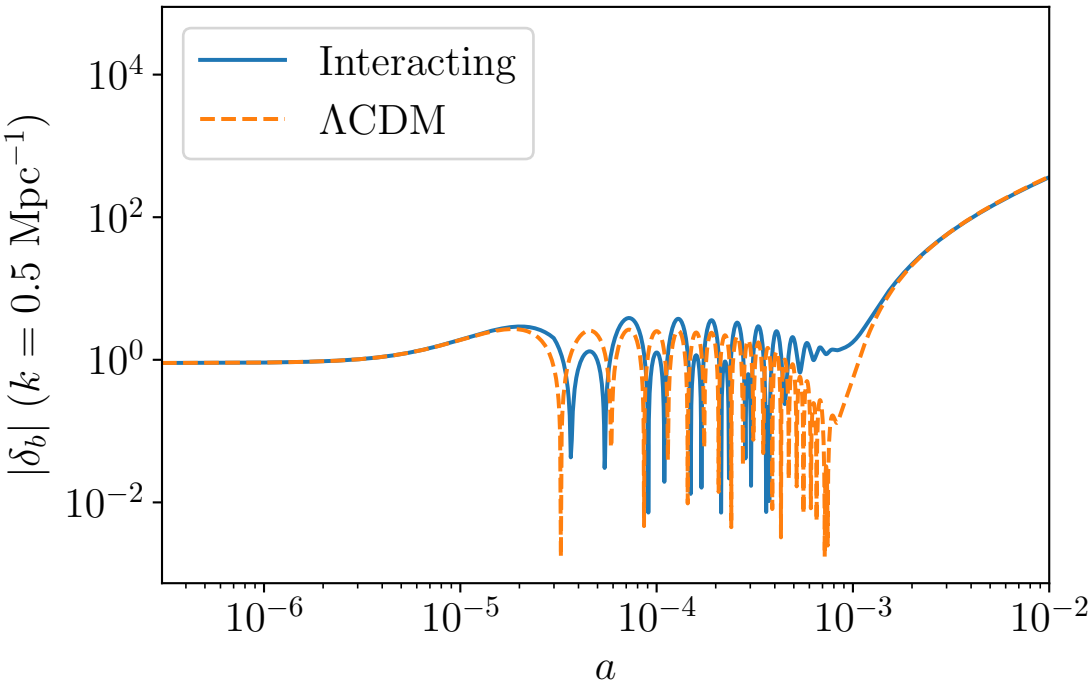
Perturbations

- Modified Boltzmann equations

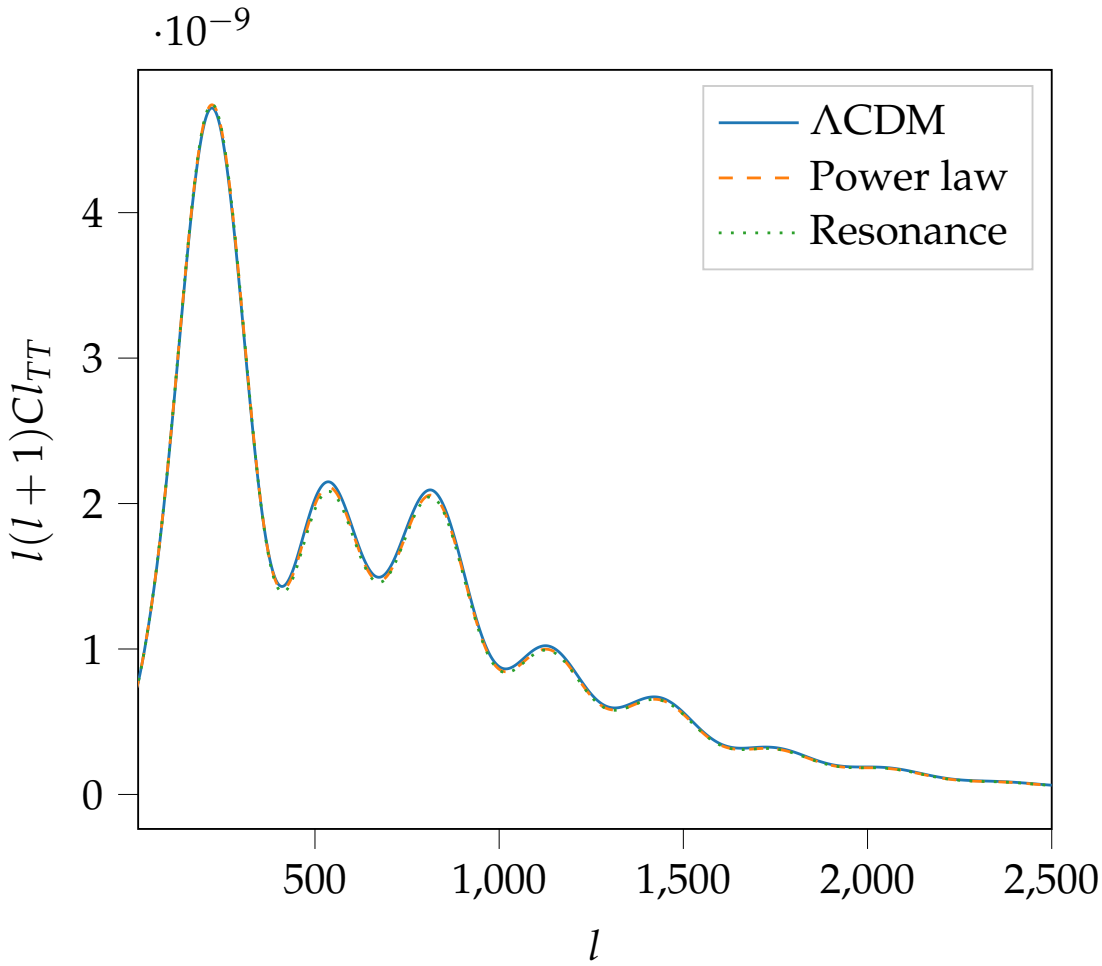


Perturbations

- Modified Boltzmann equations
- Tight coupling approximation



Upper limit ΔCls



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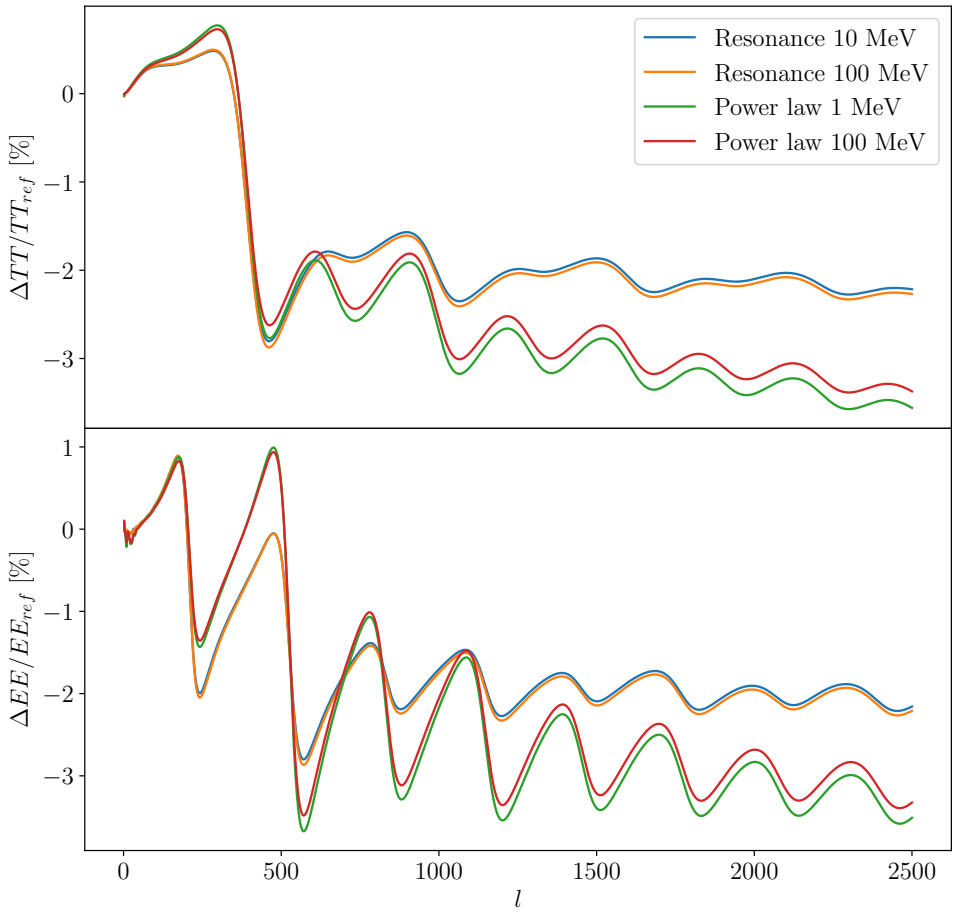
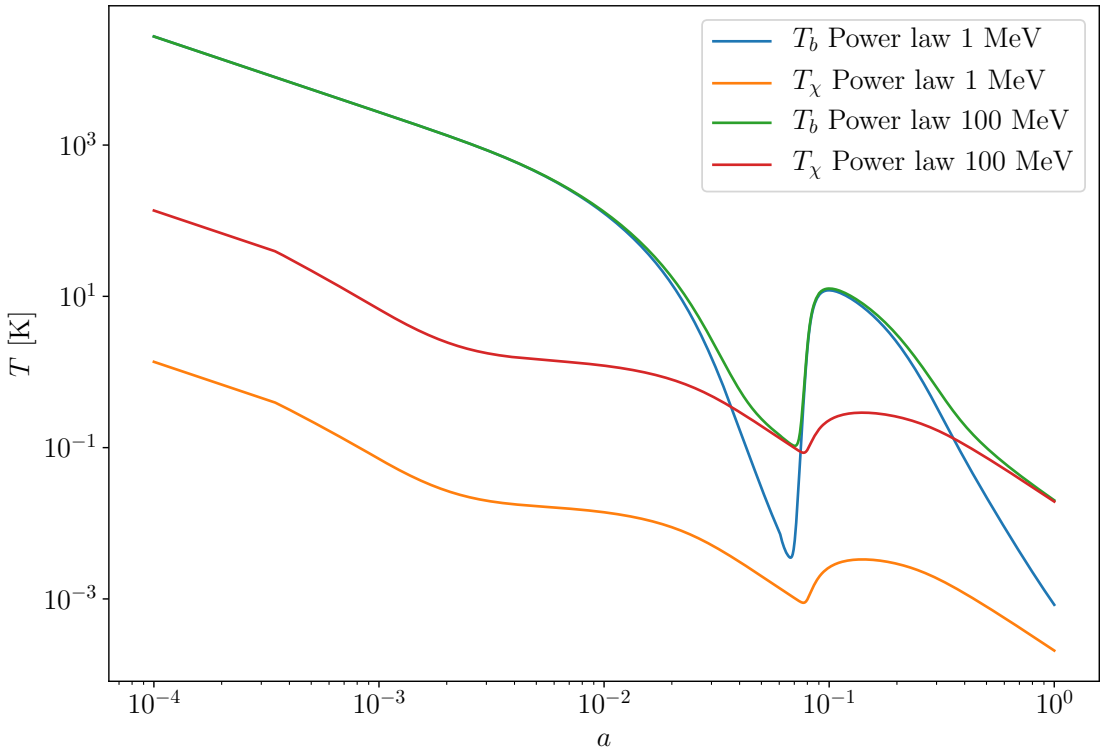


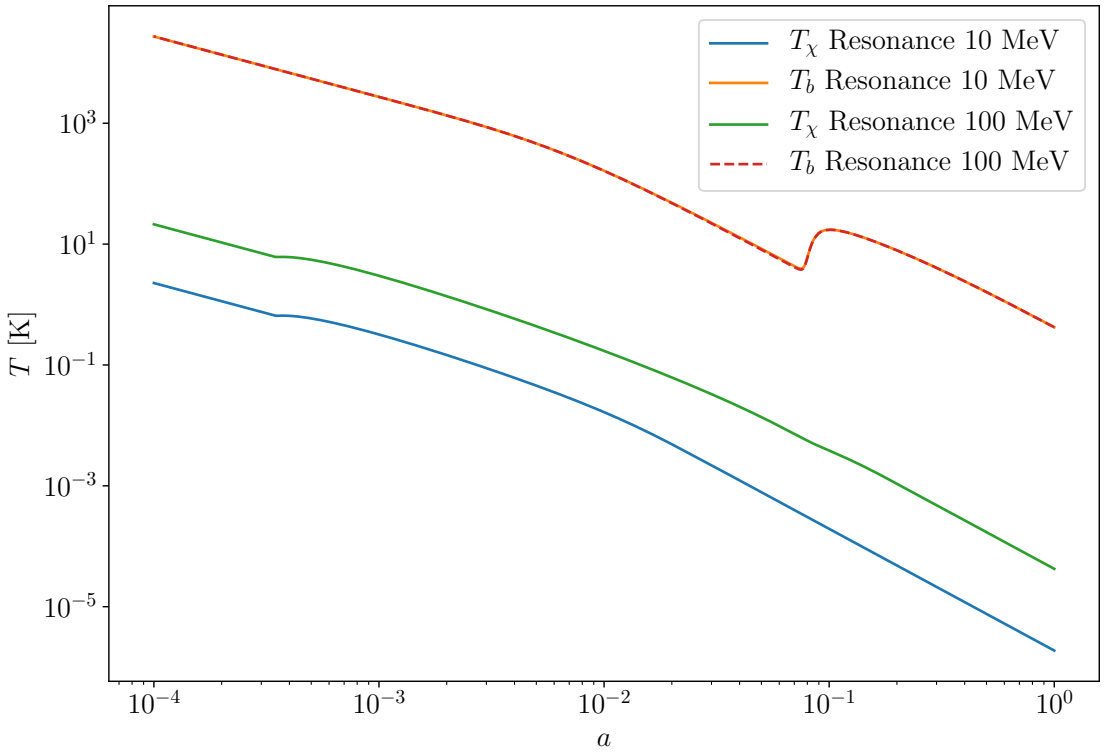
Coulomb-like



Coulomb-like

m_χ	$1\,\mathrm{MeV}$	$100\,\mathrm{MeV}$
σ_0 (95% CL.)	$2.2 \times 10^{-41}\,\mathrm{cm}^2$	$2.3 \times 10^{-41}\,\mathrm{cm}^2$
$T_b(z = 17.2)$	$0.01\,\mathrm{K}$	$0.14\,\mathrm{K}$

Resonance



Resonance

m_χ	$10\,\mathrm{MeV}$	$100\,\mathrm{MeV}$
σ_0 (95% CL.)	5.2×10^{-9}	1.9×10^{-7}
$\tilde{\sigma}_0$ (95% CL.)	$1.2 \times 10^{-51}\,\mathrm{cm}^2$	$1.4 \times 10^{-52}\,\mathrm{cm}^2$
$T_b(z = 17.2)$	$6.97\,\mathrm{K}$	$6.71\,\mathrm{K}$

Further Results

ϵ [MeV]	$m_\chi = 10\,\mathrm{MeV}$	$m_\chi = 100\,\mathrm{MeV}$
1×10^{-11}	$\sigma_0 = 1.05 \times 10^{-8}$	$\sigma_0 = 3.46 \times 10^{-7}$
1×10^{-10}	$\sigma_0 = 2.52 \times 10^{-9}$	$\sigma_0 = 8.36 \times 10^{-8}$
1×10^{-9}	$\sigma_0 = 1.39 \times 10^{-9}$	$\sigma_0 = 2.09 \times 10^{-8}$
1×10^{-8}	$\sigma_0 = 2.84 \times 10^{-9}$	$\sigma_0 = 1.61 \times 10^{-8}$
1×10^{-7}	$\sigma_0 = 9.88 \times 10^{-8}$	$\sigma_0 = 5.29 \times 10^{-8}$
ϵ [MeV]	$m_\chi = 1000\,\mathrm{MeV}$	$m_\chi = 5000\,\mathrm{MeV}$
1×10^{-11}	$\sigma_0 = 1.05 \times 10^{-5}$	$\sigma_0 = 1.25 \times 10^{-4}$
1×10^{-10}	$\sigma_0 = 2.59 \times 10^{-6}$	$\sigma_0 = 2.95 \times 10^{-5}$
1×10^{-9}	$\sigma_0 = 6.79 \times 10^{-7}$	$\sigma_0 = 7.09 \times 10^{-6}$
1×10^{-8}	$\sigma_0 = 1.93 \times 10^{-7}$	$\sigma_0 = 2.25 \times 10^{-6}$
1×10^{-7}	$\sigma_0 = 2.07 \times 10^{-7}$	$\sigma_0 = 2.52 \times 10^{-6}$

Table: *Inferred 95% confidence upper limits of σ_0. Obtained with MontePython using Planck 2015 TT+TE+EE data.*

Further Results

ϵ [MeV]	$m_\chi = 10\,\mathrm{MeV}$	$m_\chi = 100\,\mathrm{MeV}$
1×10^{-11}	$\tilde{\sigma}_0 = 4.43 \times 10^{-52}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 5.29 \times 10^{-53}\,\mathrm{cm}^2$
1×10^{-10}	$\tilde{\sigma}_0 = 3.36 \times 10^{-52}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 4.04 \times 10^{-52}\,\mathrm{cm}^2$
1×10^{-9}	$\tilde{\sigma}_0 = 5.86 \times 10^{-50}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 3.19 \times 10^{-51}\,\mathrm{cm}^2$
1×10^{-8}	$\tilde{\sigma}_0 = 3.79 \times 10^{-48}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 7.78 \times 10^{-50}\,\mathrm{cm}^2$
1×10^{-7}	$\tilde{\sigma}_0 = 4.17 \times 10^{-45}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 8.08 \times 10^{-48}\,\mathrm{cm}^2$
ϵ [MeV]	$m_\chi = 1000\,\mathrm{MeV}$	$m_\chi = 5000\,\mathrm{MeV}$
1×10^{-11}	$\tilde{\sigma}_0 = 1.29 \times 10^{-53}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 1.48 \times 10^{-53}\,\mathrm{cm}^2$
1×10^{-10}	$\tilde{\sigma}_0 = 1.00 \times 10^{-52}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 1.10 \times 10^{-52}\,\mathrm{cm}^2$
1×10^{-9}	$\tilde{\sigma}_0 = 8.36 \times 10^{-52}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 8.38 \times 10^{-51}\,\mathrm{cm}^2$
1×10^{-8}	$\tilde{\sigma}_0 = 7.52 \times 10^{-51}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 8.41 \times 10^{-51}\,\mathrm{cm}^2$
1×10^{-7}	$\tilde{\sigma}_0 = 2.55 \times 10^{-49}\,\mathrm{cm}^2$	$\tilde{\sigma}_0 = 2.98 \times 10^{-49}\,\mathrm{cm}^2$

Table: *Inferred 95% confidence upper limits of $\tilde{\sigma}_0$. Obtained with MontePython using Planck 2015 TT+TE+EE data.*

Further Results

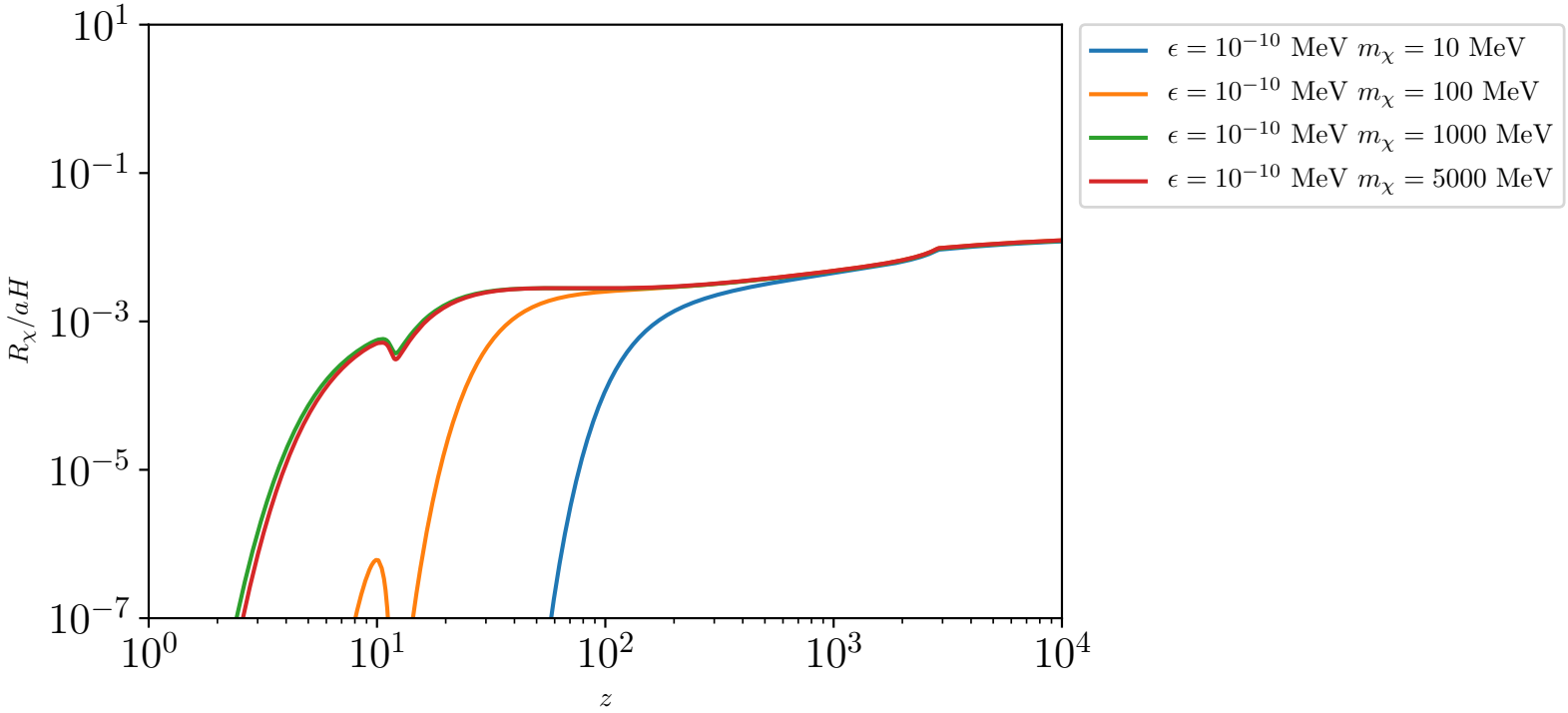


Figure: *The evolution of the momentum exchange rate* R_χ *for* $\epsilon = 1 \times 10^{-10}\,\mathrm{MeV}$, *using the inferred CMB upper limits for* σ_0.

Further Results

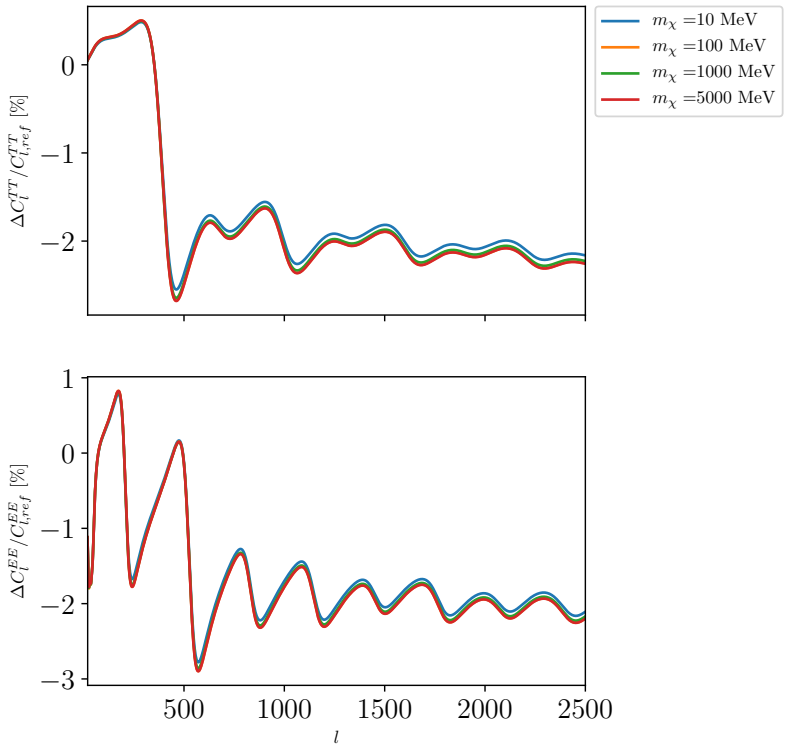


Figure: *Percent residuals of the TT (upper) and EE (lower) spectra with respect to ΛCDM for $\epsilon = 1 \times 10^{-10}$ MeV, using the inferred CMB upper limits for σ_0.*

Further Results

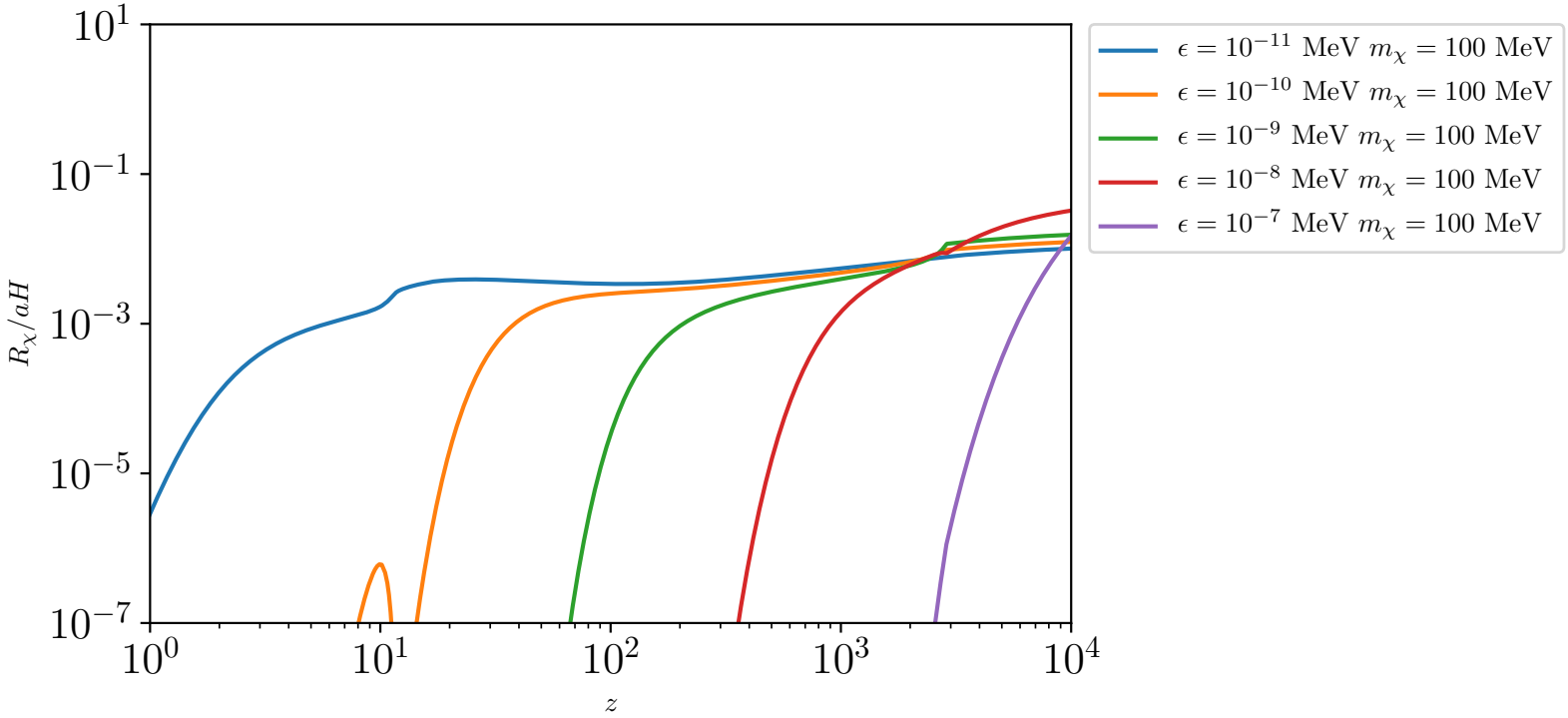


Figure: *The evolution of the momentum exchange rate* R_χ *for* $m_\chi = 100\,\mathrm{MeV}$, *using the inferred CMB upper limits for* σ_0.

Further Results

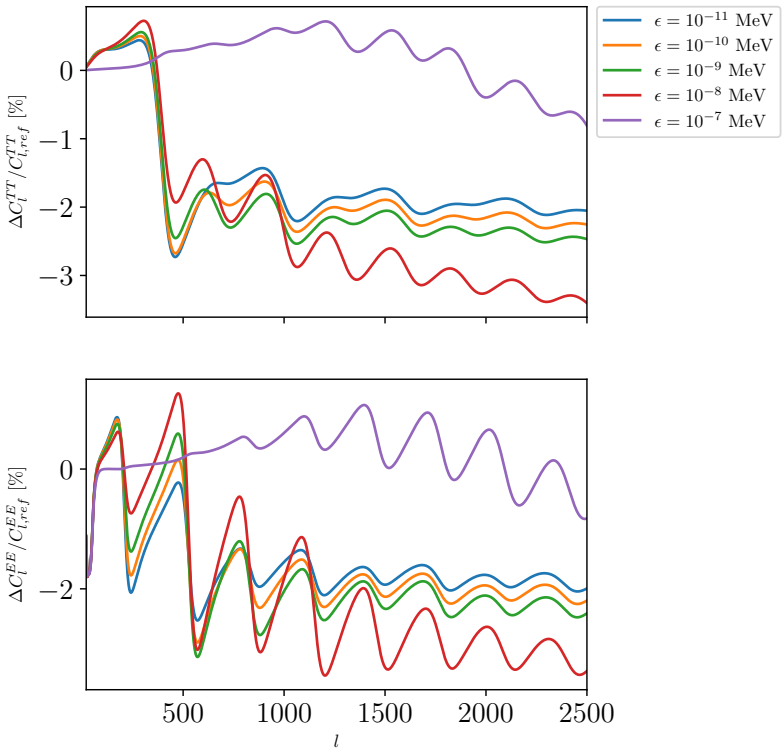


Figure: *Percent residuals of the TT (upper) and EE (lower) spectra with respect to ΛCDM for $m_\chi = 100\,\mathrm{MeV}$, using the inferred CMB upper limits for σ_0.*

Further Results

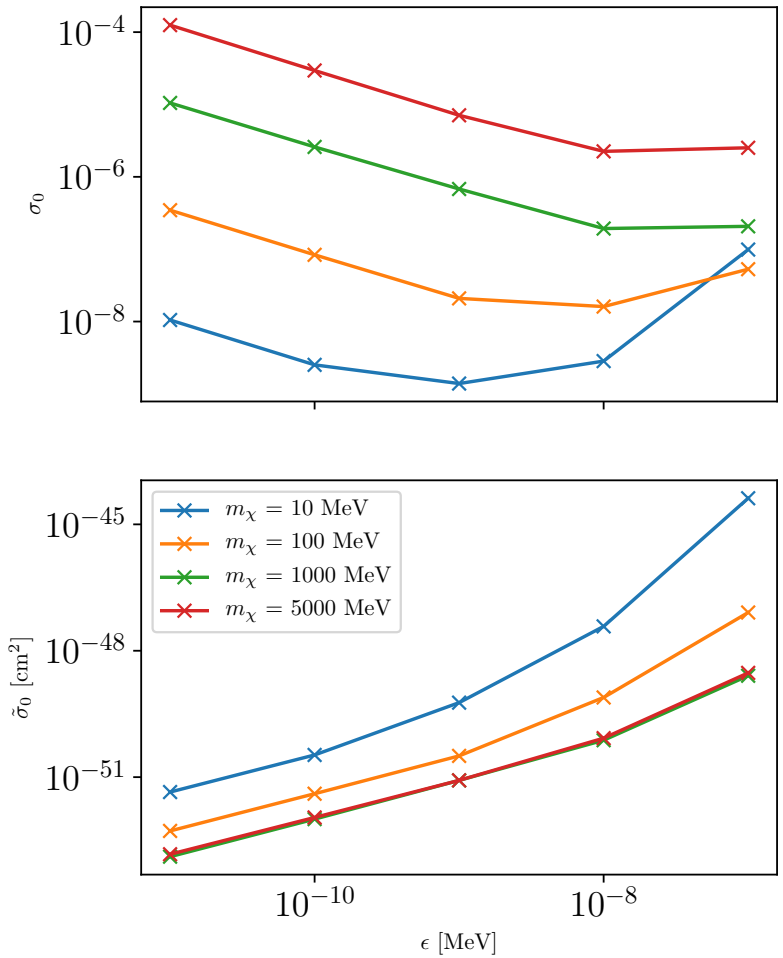


Figure: *Inferred 95% upper limits for σ_0 (upper figure) and $\tilde{\sigma}_0$ (lower figure) as a function of ϵ for each tested m_χ.*

Further Results

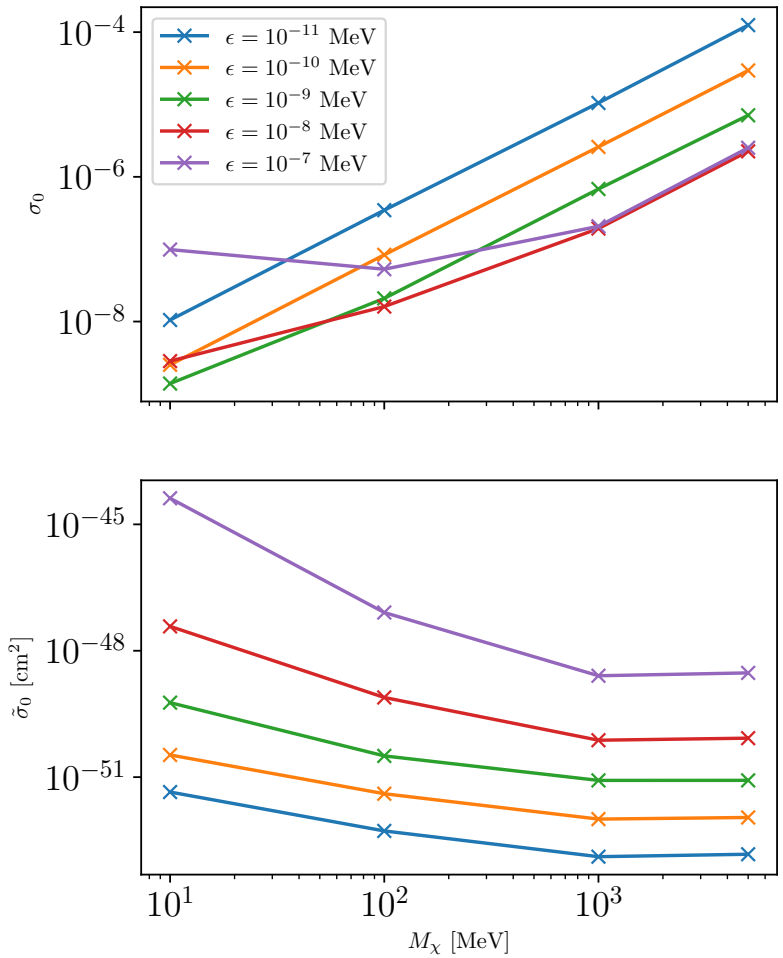


Figure: *Inferred 95% upper limits for σ_0 (upper figure) and $\tilde{\sigma}_0$ (lower figure) as a function of m_χ for each tested ϵ.*

Conclusion

- Upper Limits

Conclusion

- Upper Limits
- EDGES

Conclusion

- Upper Limits
- EDGES
- Other constraints