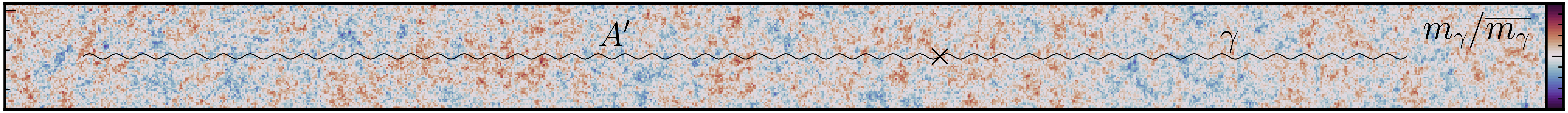
Dark photon oscillations in our inhomogeneous Universe



Siddharth Mishra-Sharma

NYU | Center for Cosmology and Particle Physics

BSM PANDEMIC

October 13, 2020

Collab

Andrea Caputo
(Weizmann/Tel-Aviv)

Hongwan Liu
(NYU/Princeton)

Josh Ruderman
(NYU)

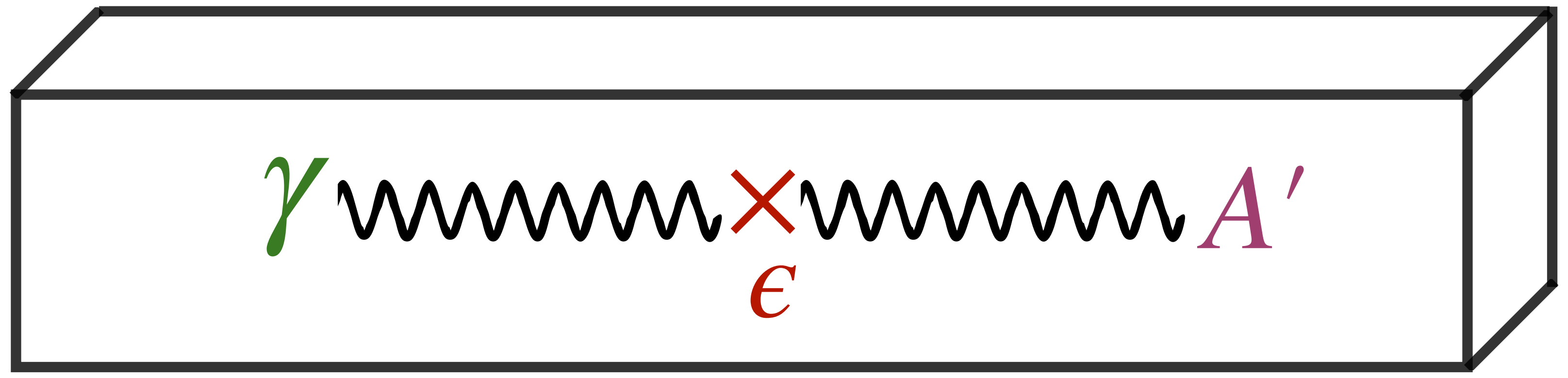
Alfredo Urbano
(INFN Trieste)

Maxim Pospelov
(Minnesota)

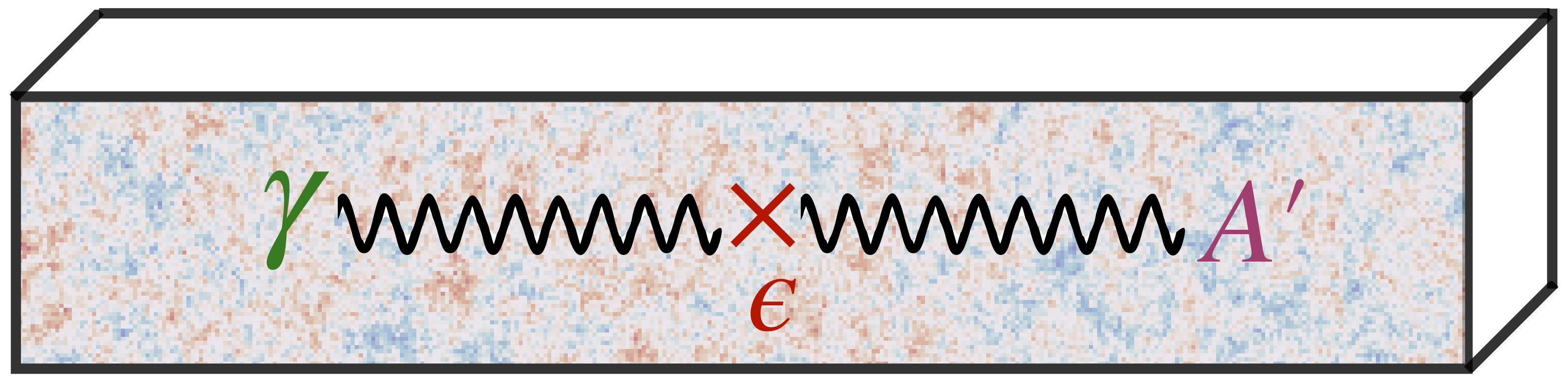
Papers

1. Caputo, Liu, SM, Ruderman, *"Dark Photon Oscillations in Our Inhomogeneous Universe,"* PRL [arXiv:2002.05165]
2. Caputo, Liu, SM, Ruderman , *"Modeling Dark Photon Oscillations in Our Inhomogeneous Universe,"* PRD [arXiv:2004.06733]
3. + Pospelov, Urbano, *"Edges and Endpoints in 21-cm Observations from Resonant Photon Production,"* [arXiv:2009.03899]

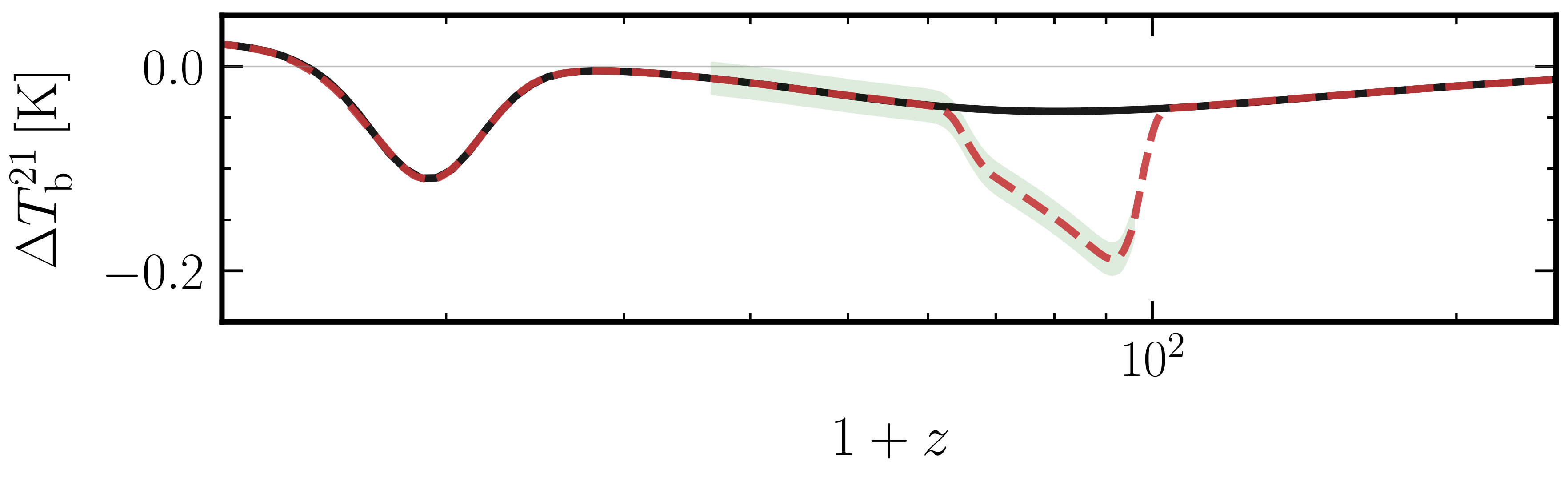
Outline



Dark photons
and resonant conversions

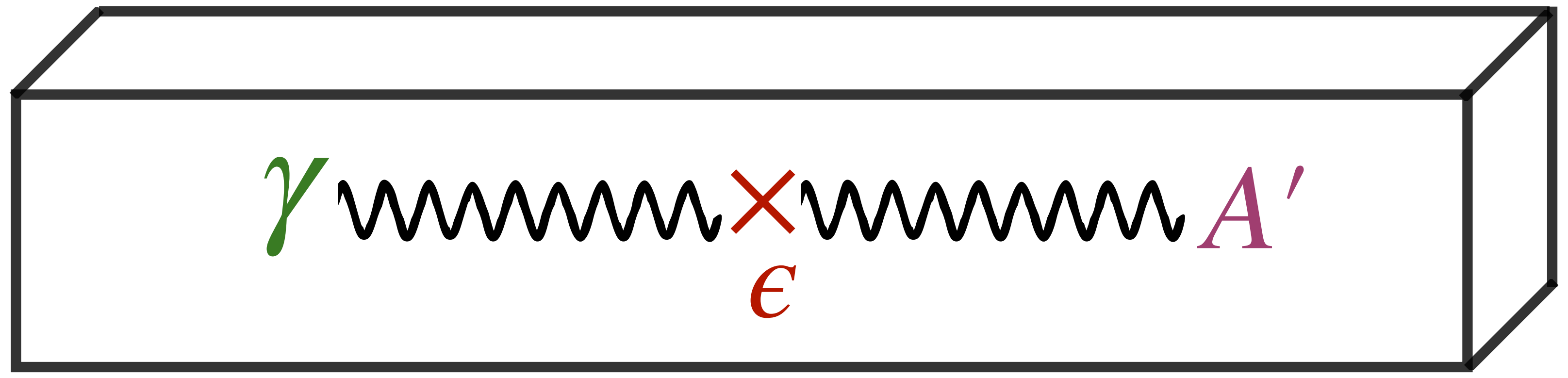


Dark photon oscillations
with inhomogeneities



Dark photon signatures
in 21-cm

Outline



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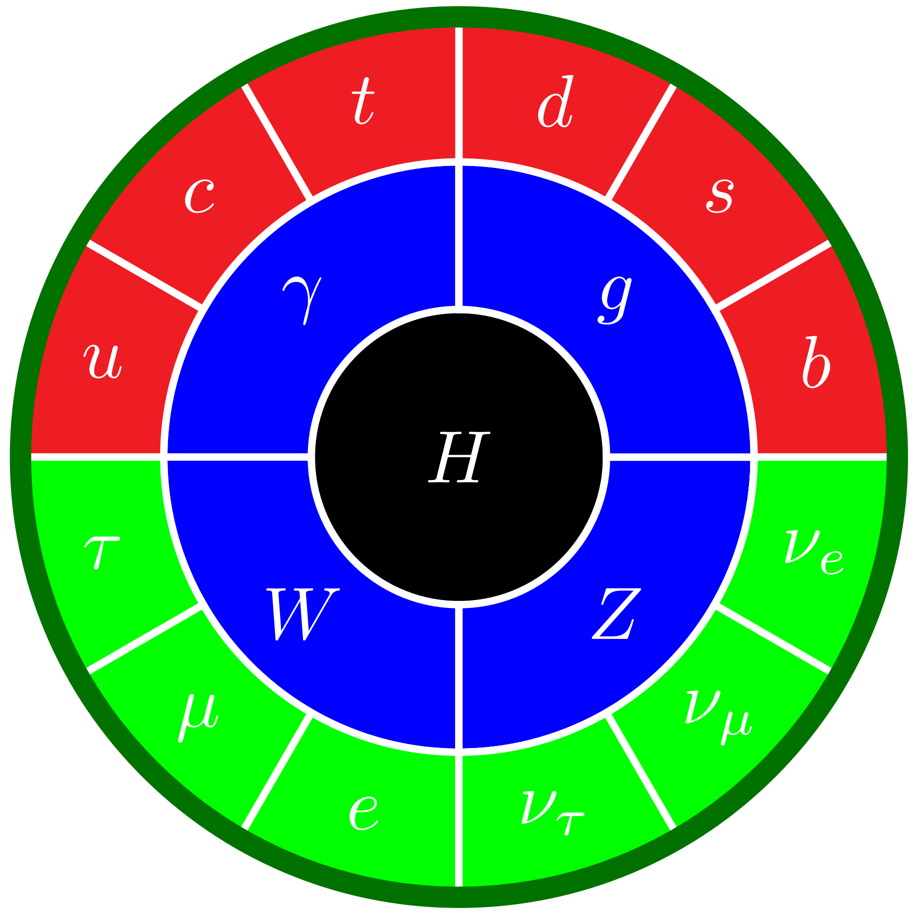
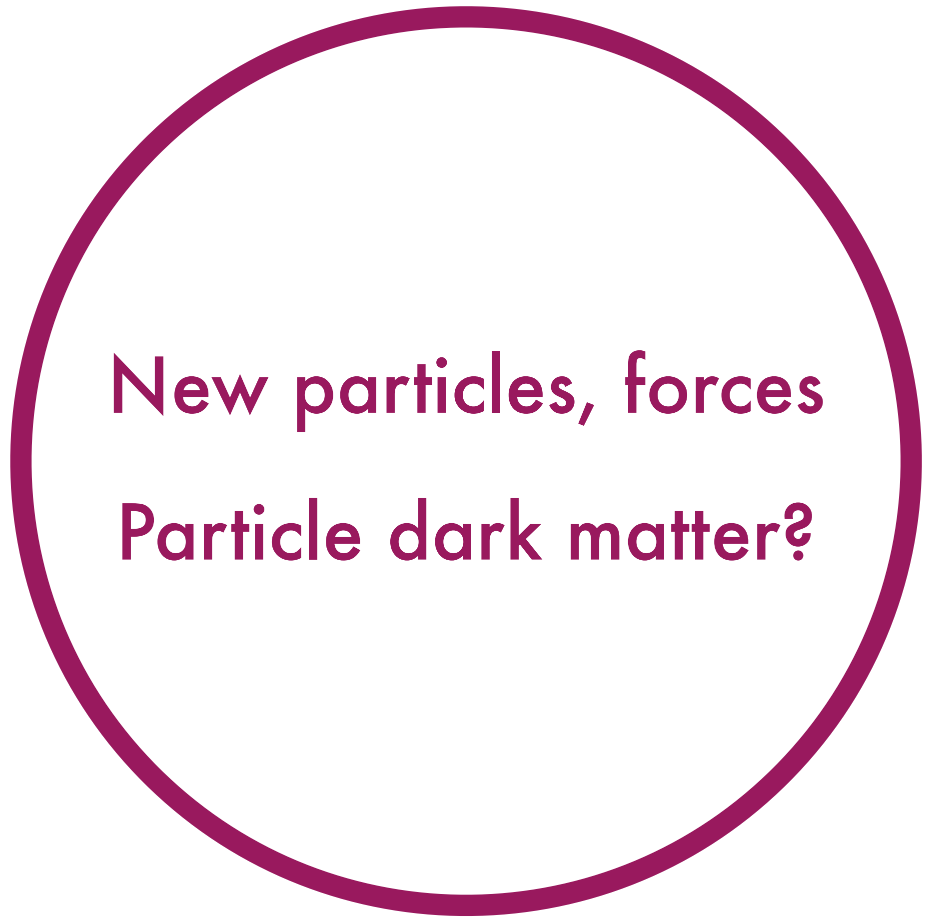
Portals to the dark sector

Standard Model



Dark Sector



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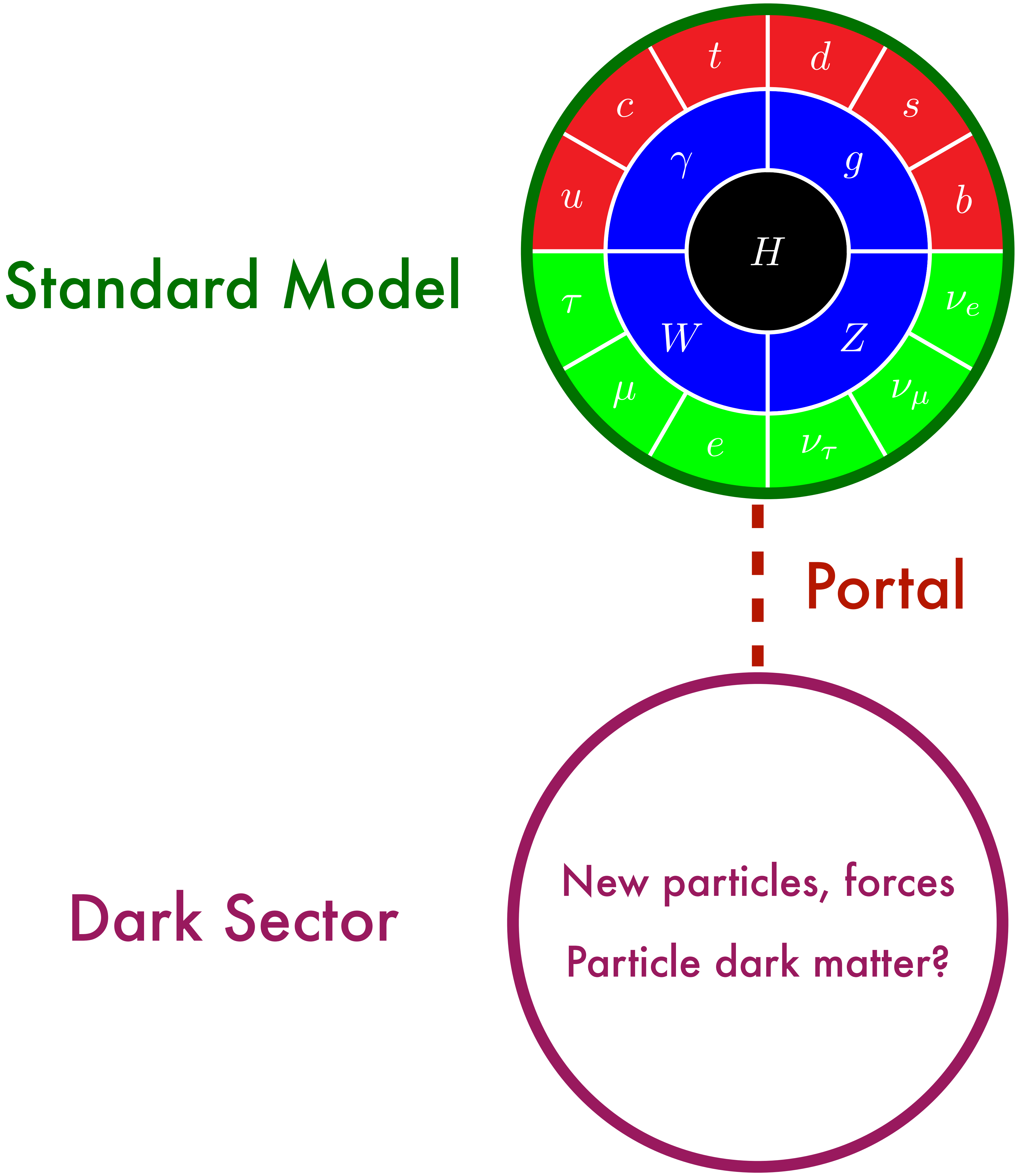

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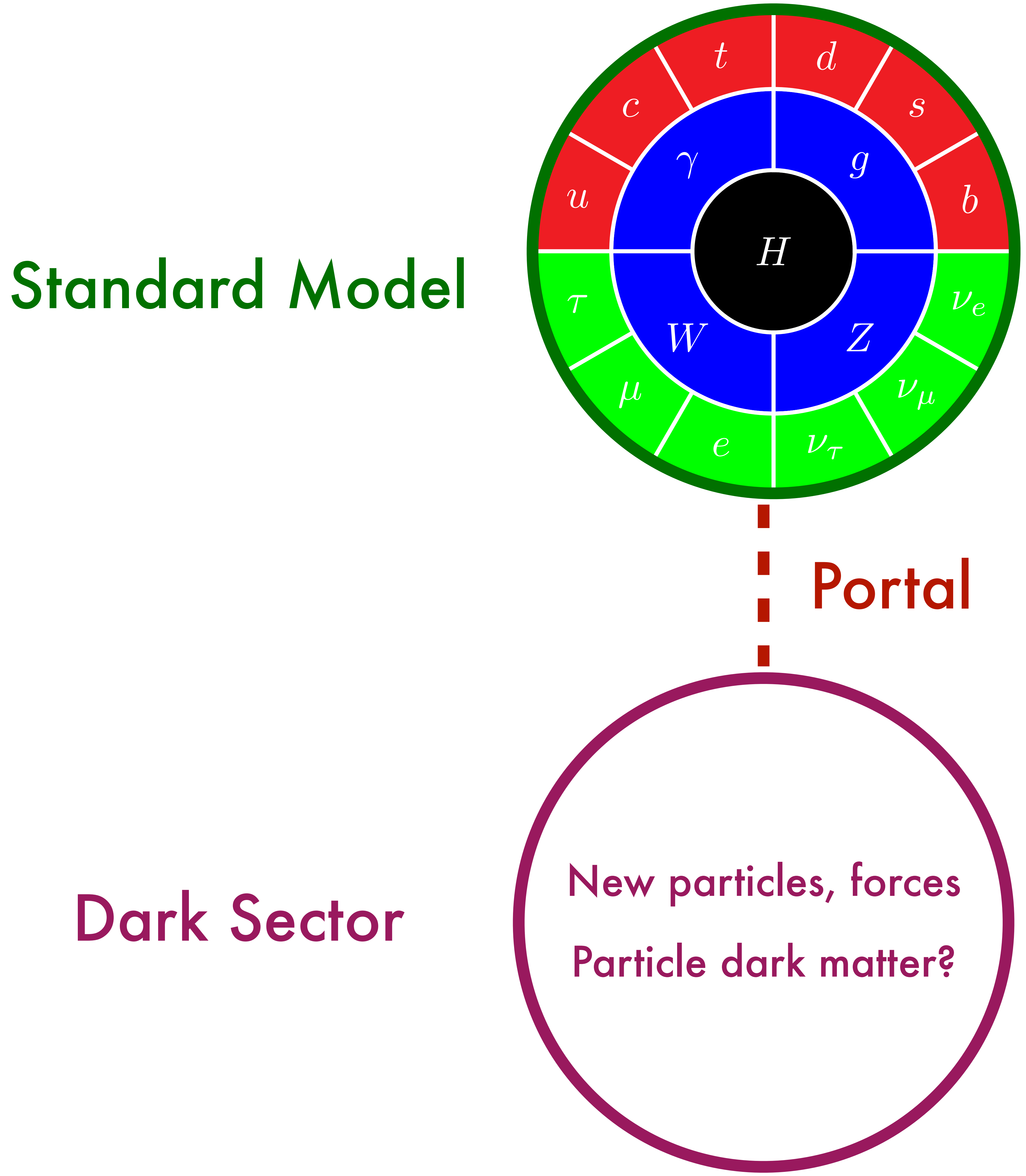
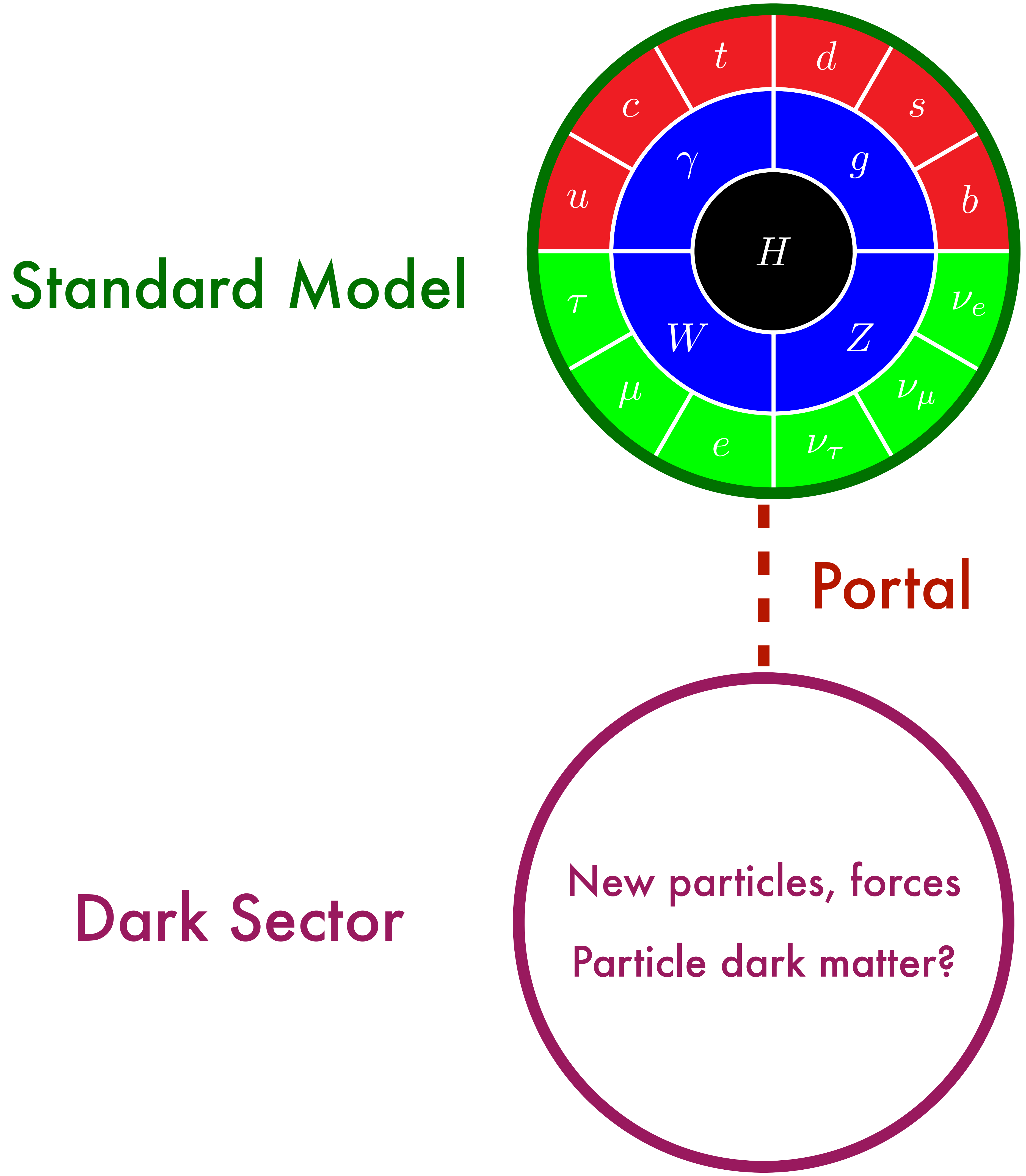


(Some) Canonical portals:

- **Scalar** — $\lambda H^2 S^2 + \mu H^2 S$
  Higgs portal
- **Fermion** — $y(HL)N$
  Neutrino portal
- **Vector** — $\epsilon F^{\mu\nu} F'_{\mu\nu}$
  Kinetic mixing portal

Portals to the dark sector



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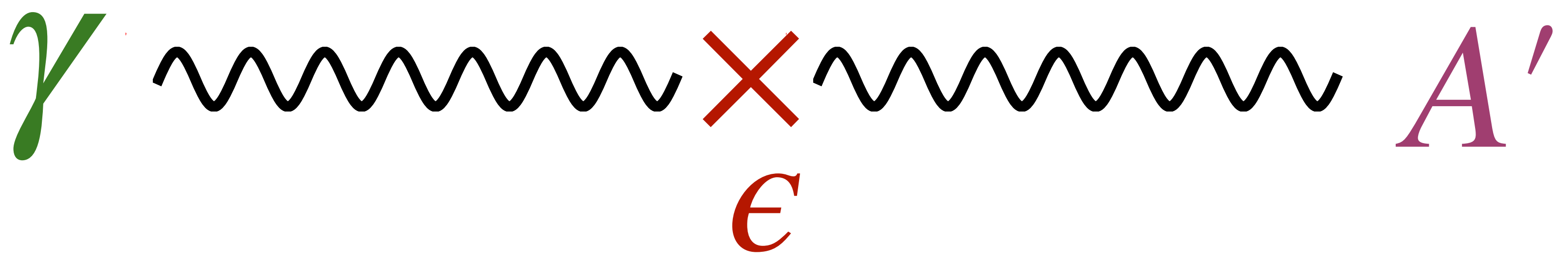
Kinetic mixing portal $U(1)'$

$$\Delta\mathscr{L} = -\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'^2$$



Holdom, PLB (1986)

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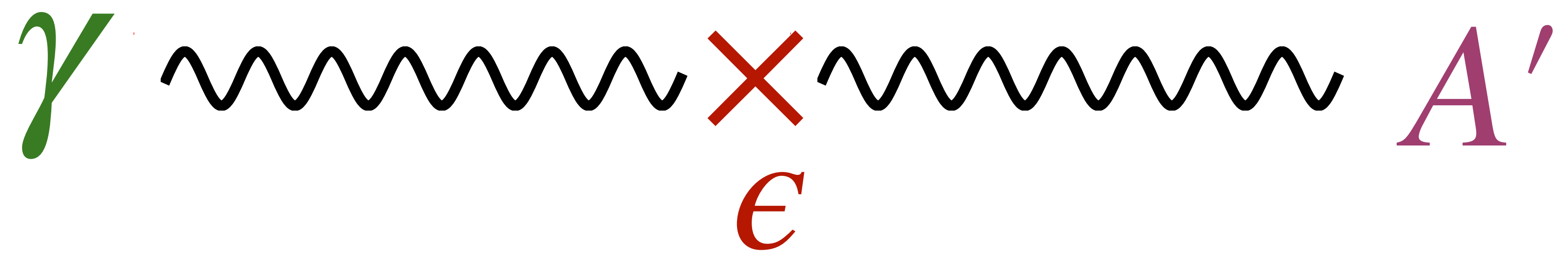

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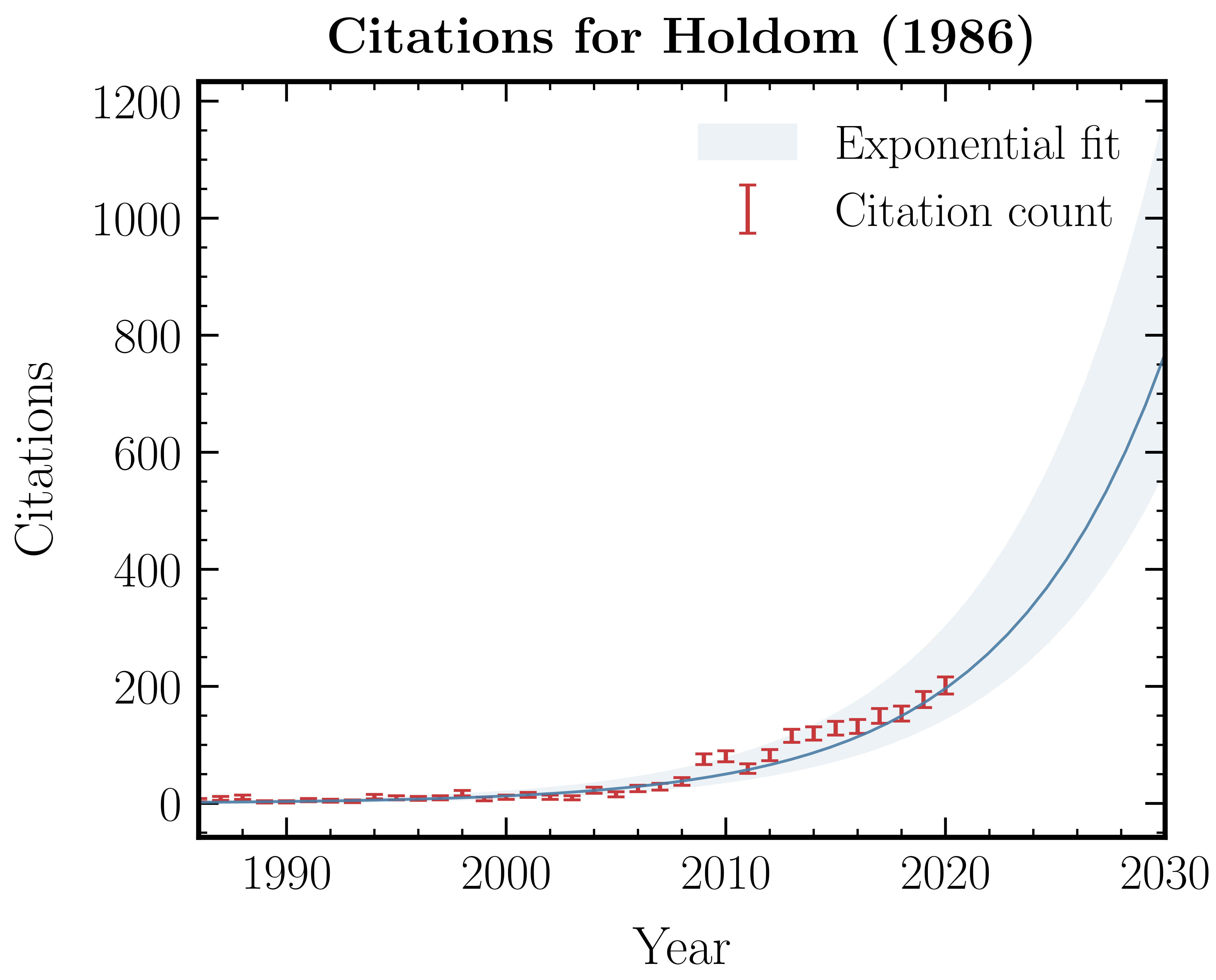

$\epsilon - m_{A'}$ plane

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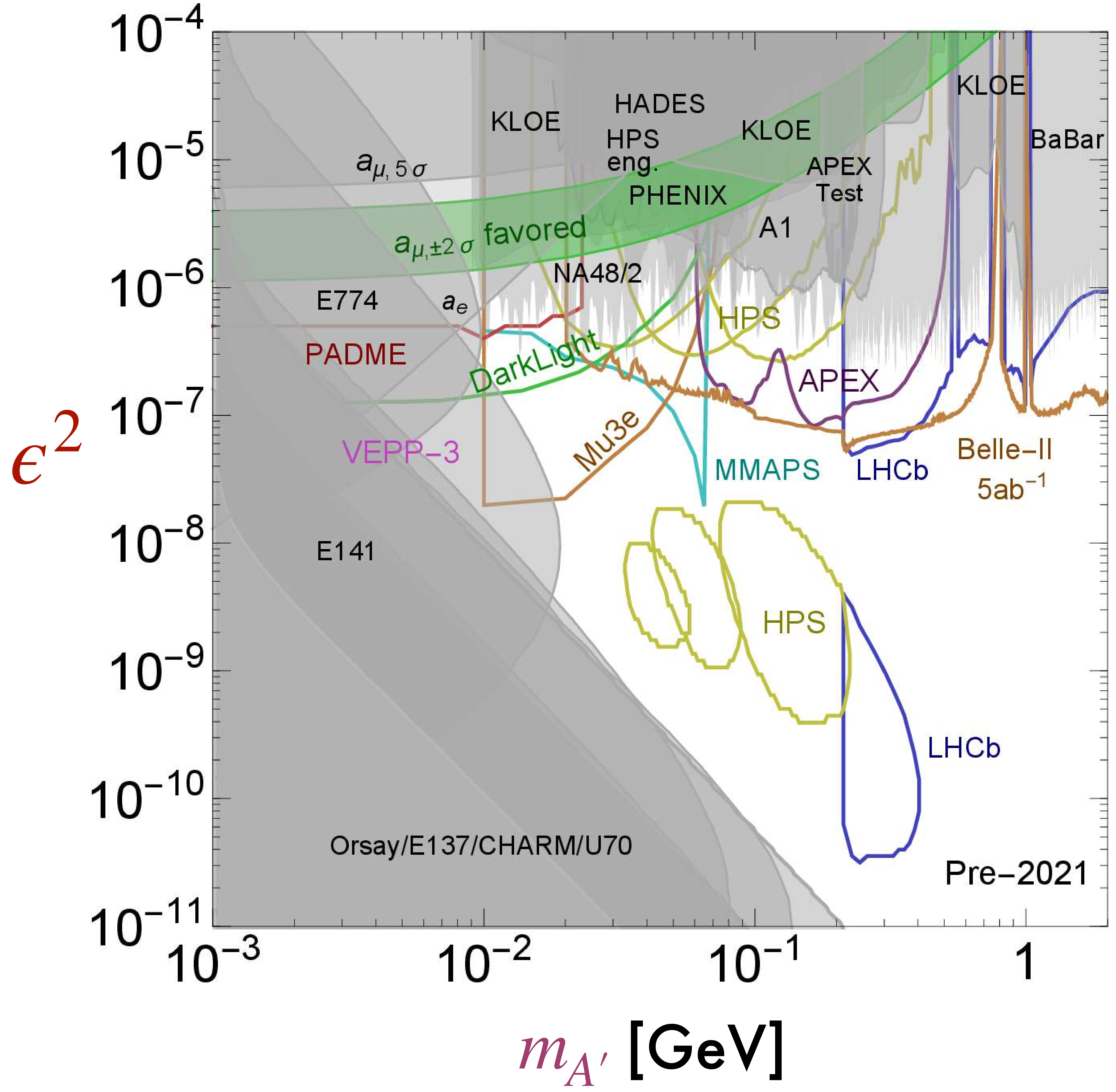

US Cosmic Visions [1707.04591]

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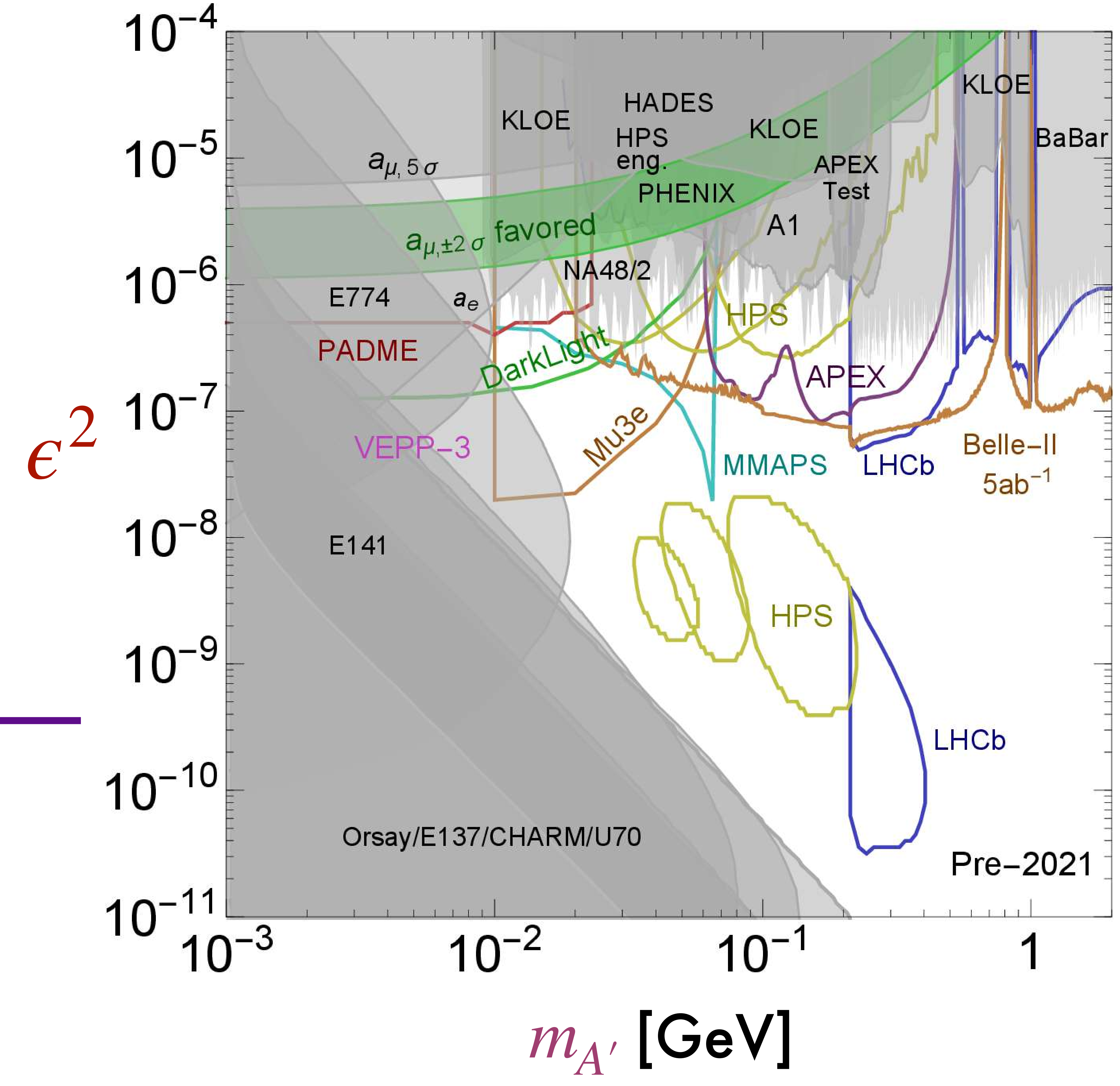

This talk ←

US Cosmic Visions [1707.04591]

$\epsilon - m_{A'}$ plane: "ultralight" dark photons

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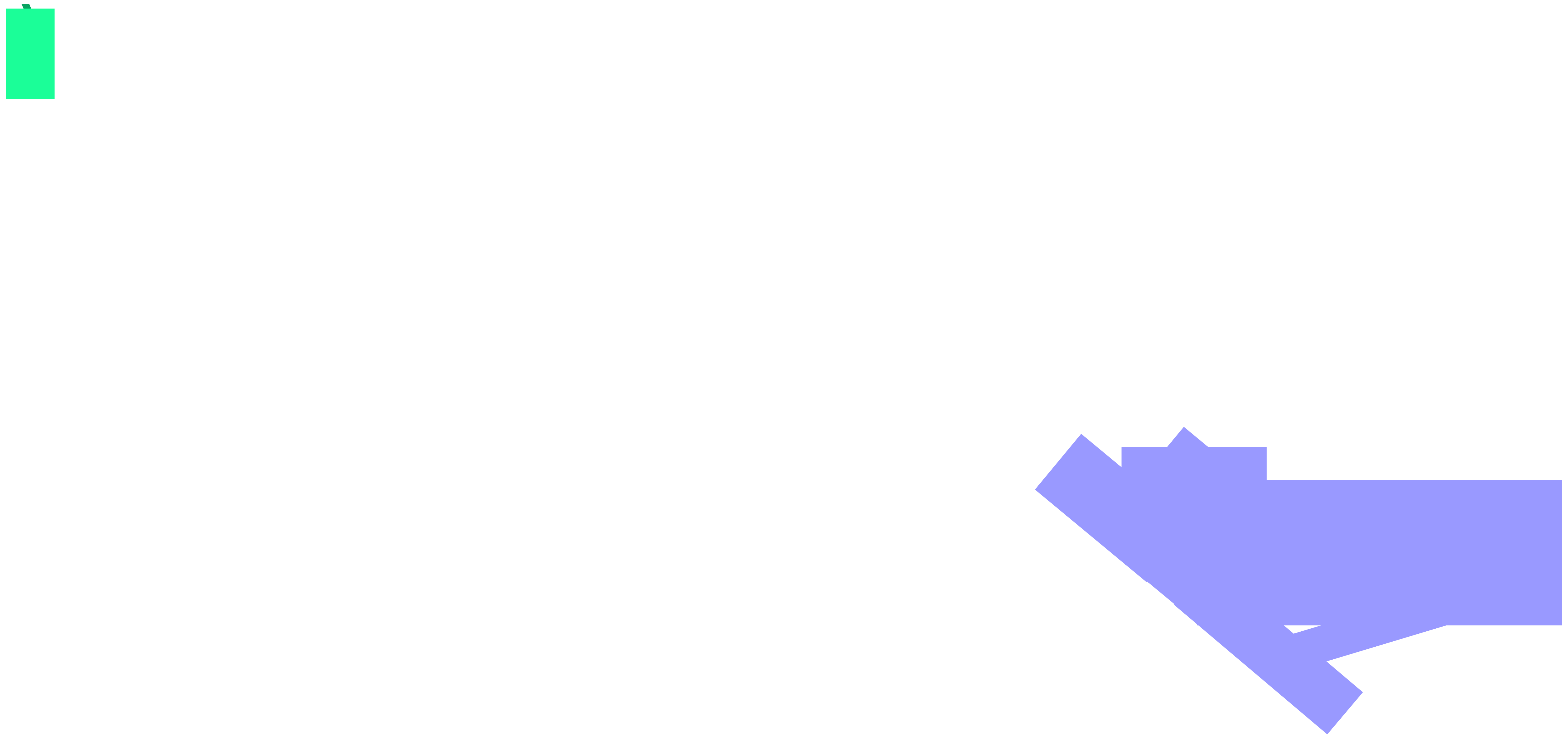

Dark Sectors [1311.0029]

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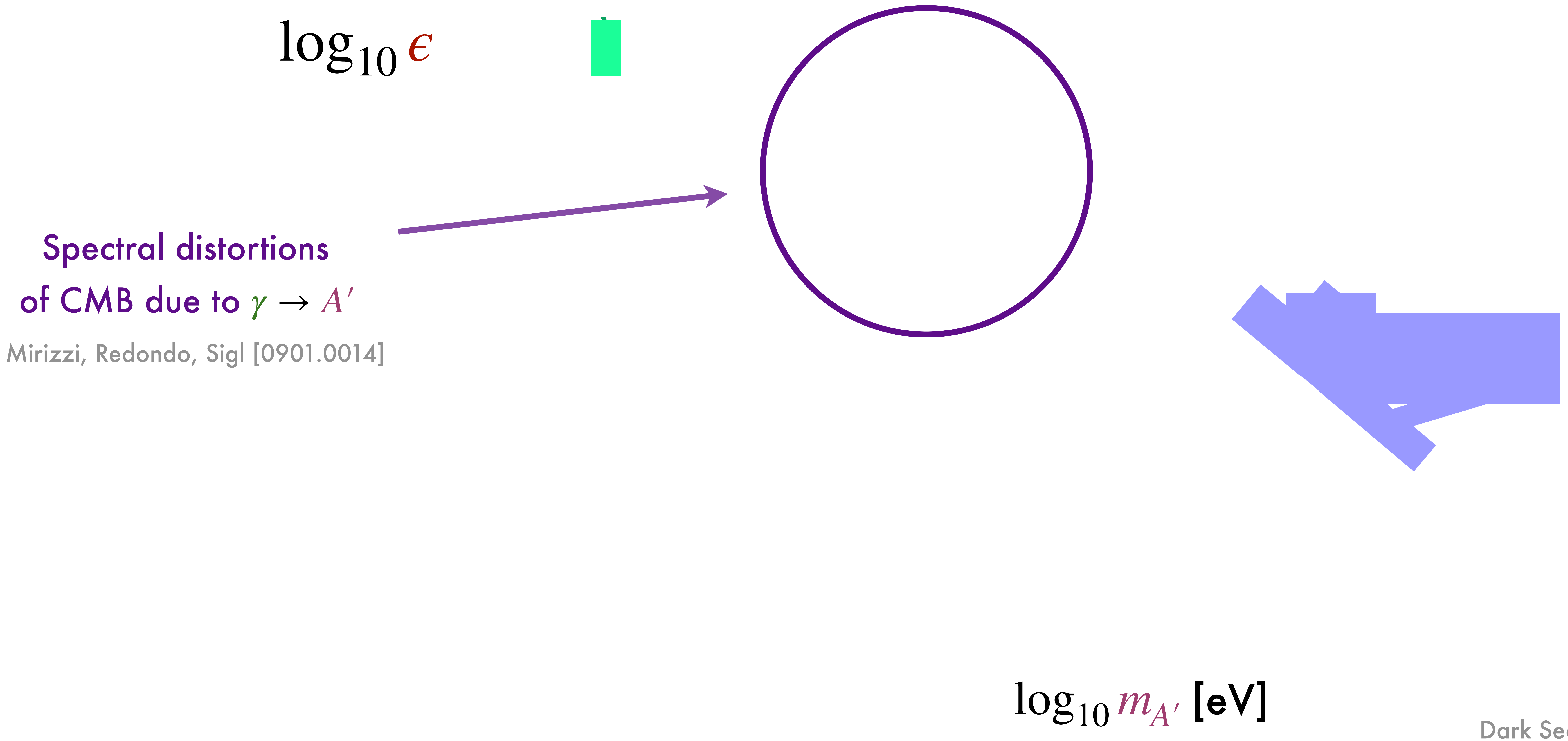
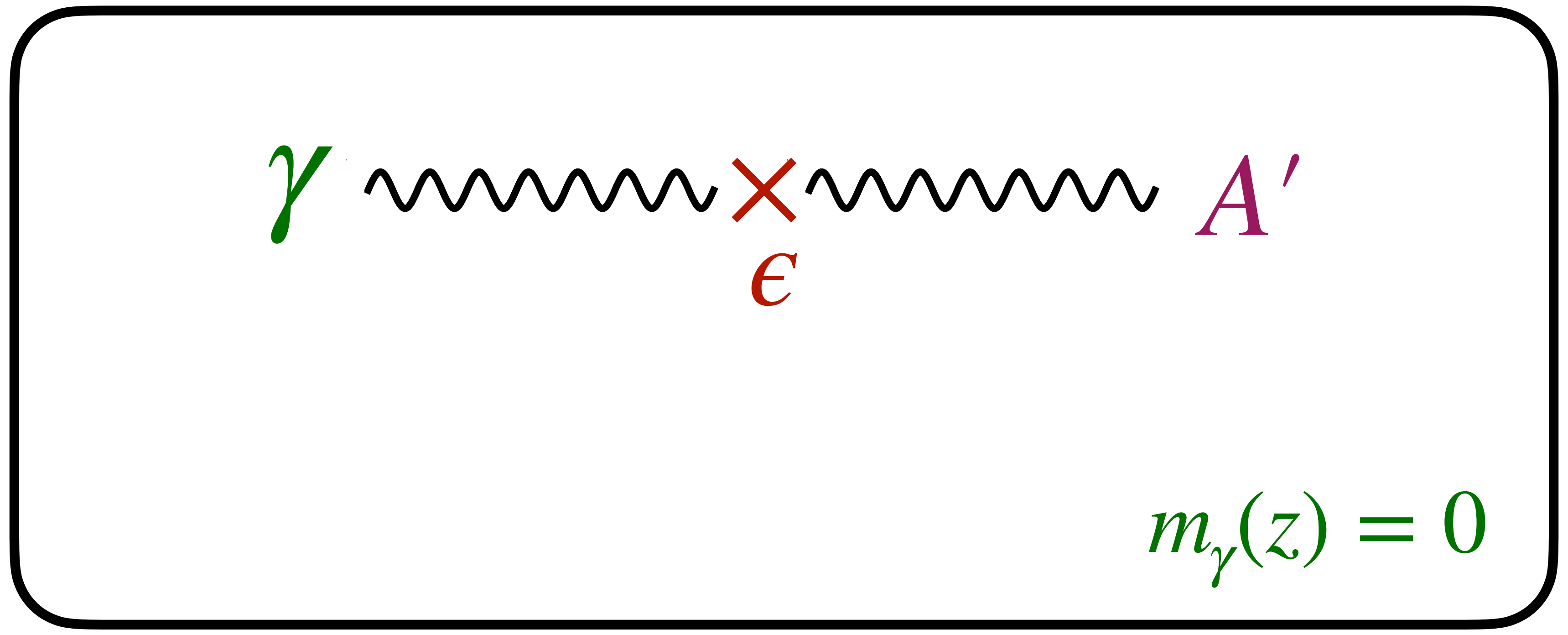


Dark Sectors [1311.0029]

Vacuum and resonant (in-medium) oscillations

Oscillations in vacuum

$$\omega^2 = k^2$$



$$P_{\gamma \to A'} \sim \epsilon^2$$

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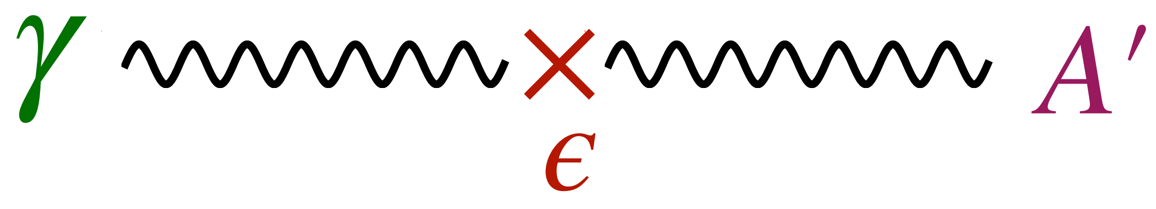
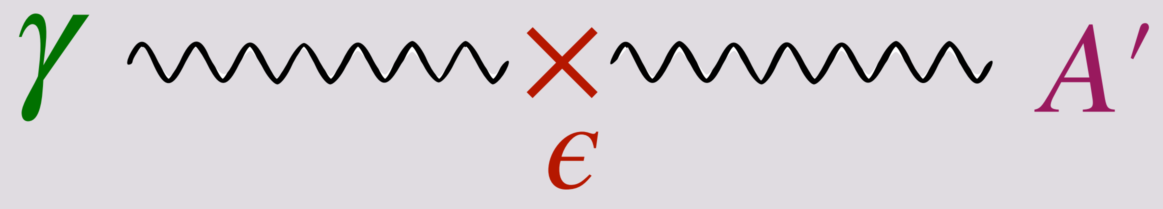


$m_\gamma(z) = 0$

$$P_{\gamma \to A'} \sim \epsilon^2$$

Oscillations in medium (plasma)

$\omega^2 \approx k^2 + m_\gamma^2$



$m_\gamma \approx m_{A'}$

$m_\gamma^2(z) \approx \frac{4\pi\alpha\, n_e(z)}{m_e}$

$$P_{\gamma \to A'} \gg \epsilon^2$$

Cosmological plasma mass

$$m_\gamma^2(z) \approx \frac{4\pi\alpha\, n_\mathrm{e}(z)}{m_\mathrm{e}} \approx \frac{4\pi\alpha}{m_\mathrm{e}}\, x_\mathrm{e}(z)\, n_\mathrm{H}(z)$$

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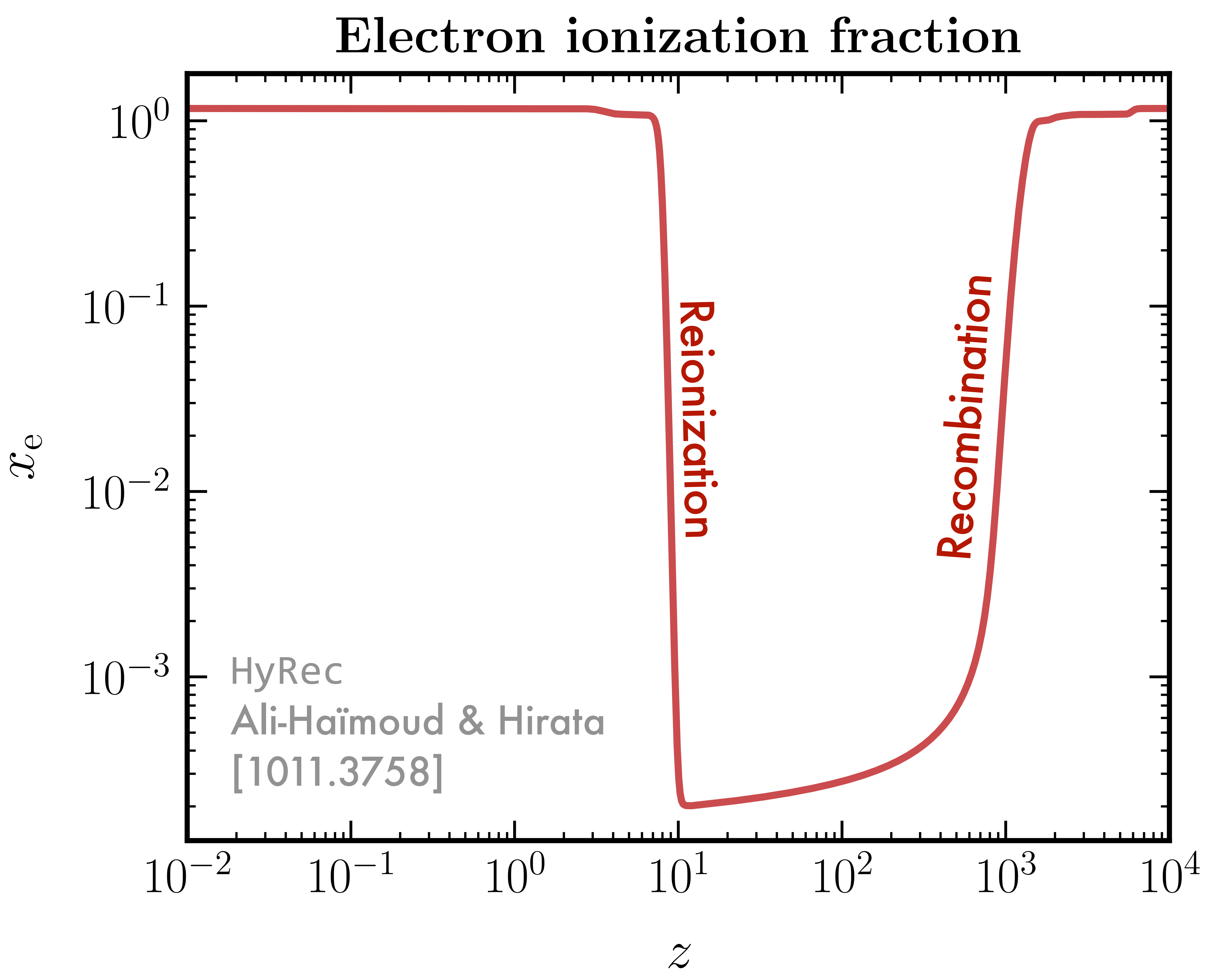

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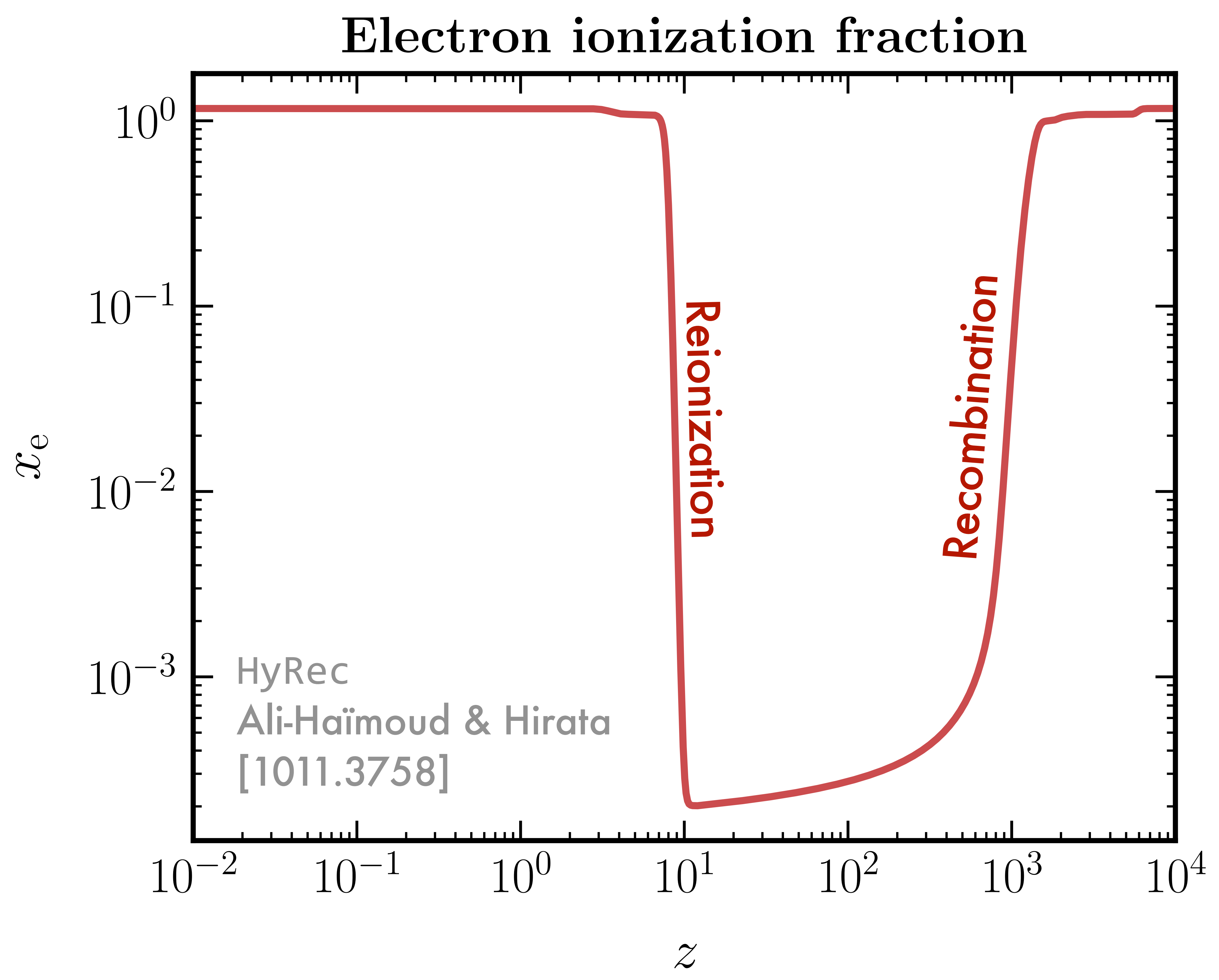

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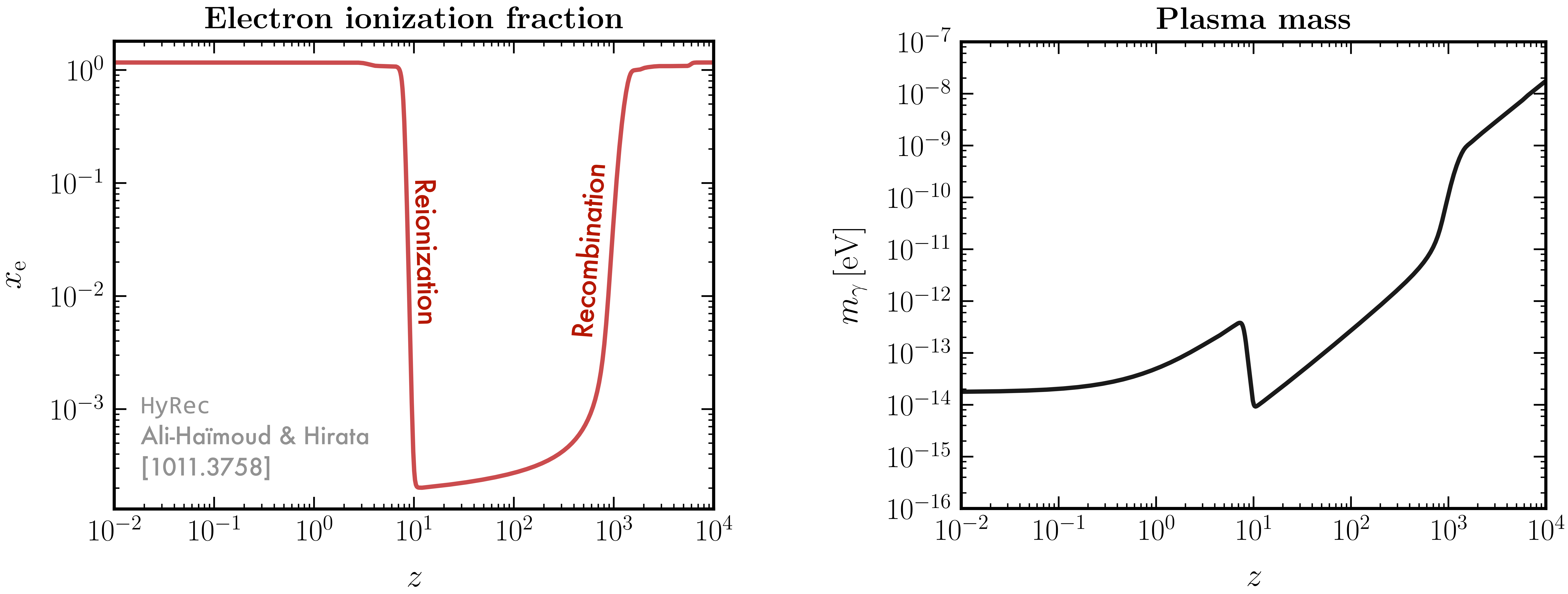
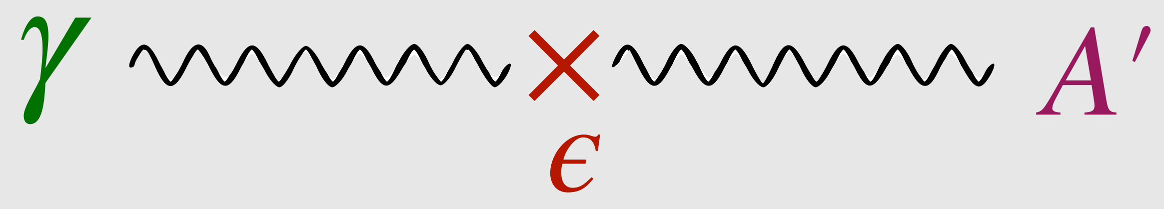


Resonant oscillations in plasma: Landau-Zener formalism



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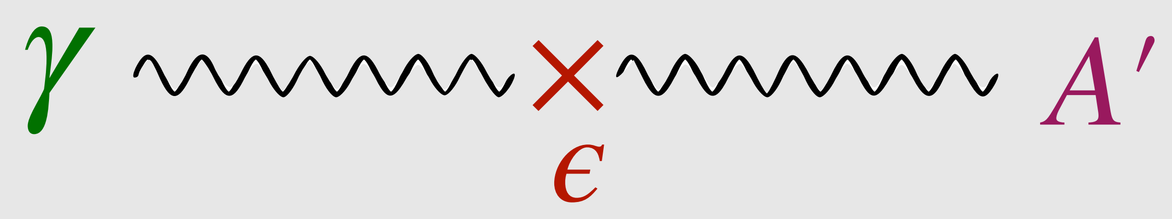

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Conversion probability

$$P_{\gamma\to A'} \simeq \frac{\pi \epsilon^2 m_{A'}^2}{\omega\left(z_{\rm res}\right)} \left| \frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t} \right|^{-1}_{z=z_{\rm res}}$$

$\omega(z_{\rm res}) = \omega_{\rm obs}(1 + z_{\rm res})$

$\Longrightarrow$ Later resonances typically dominate

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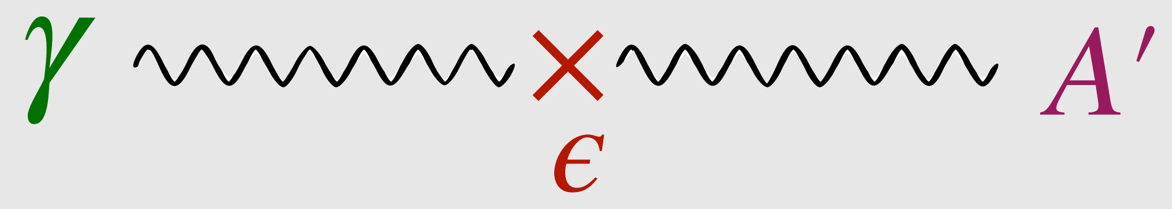

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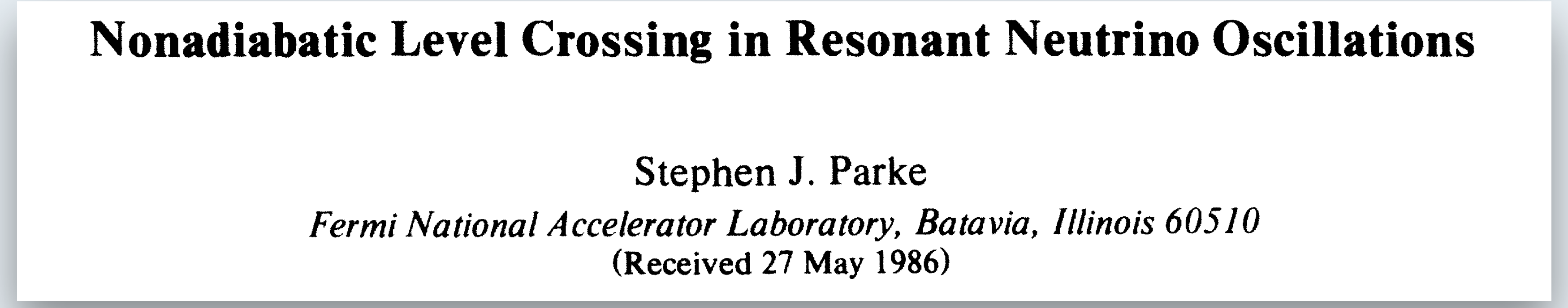
Similar formalism for neutrino oscillations (MSW effect)


Nonadiabatic Level Crossing in Resonant Neutrino Oscillations

Stephen J. Parke

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 27 May 1986)

Resonant oscillations in photon plasma

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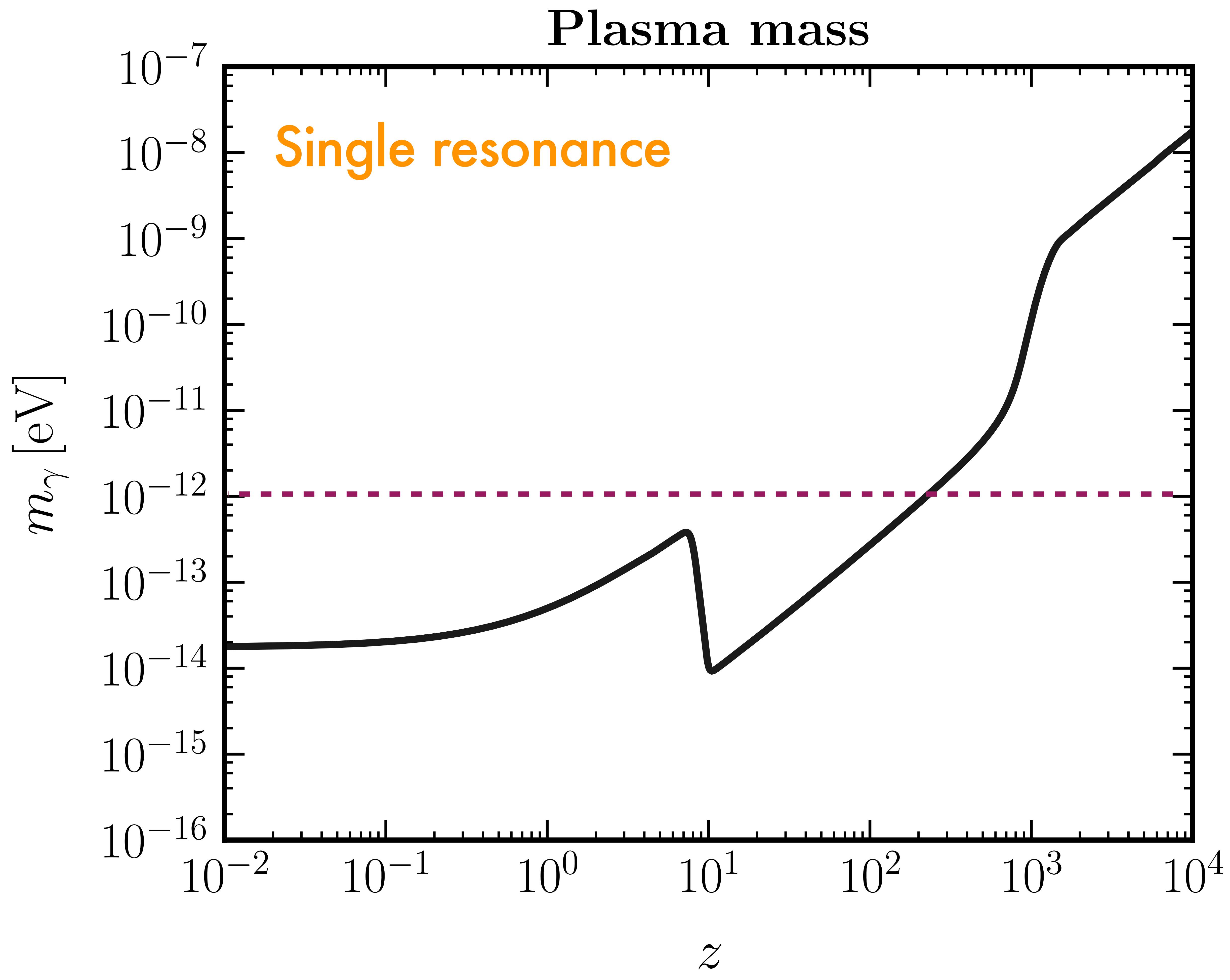

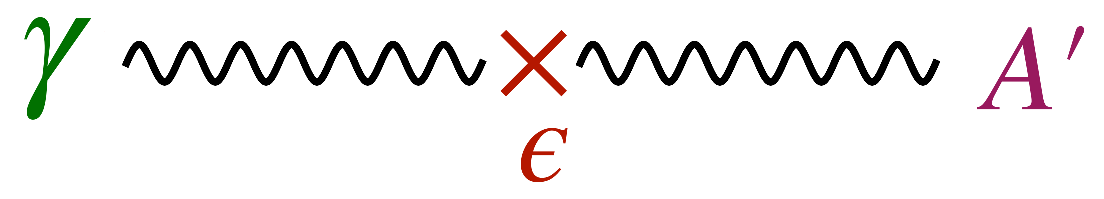

$m_{A'} = 10^{-12}\,\mathrm{eV}$

Resonant oscillations in photon plasma

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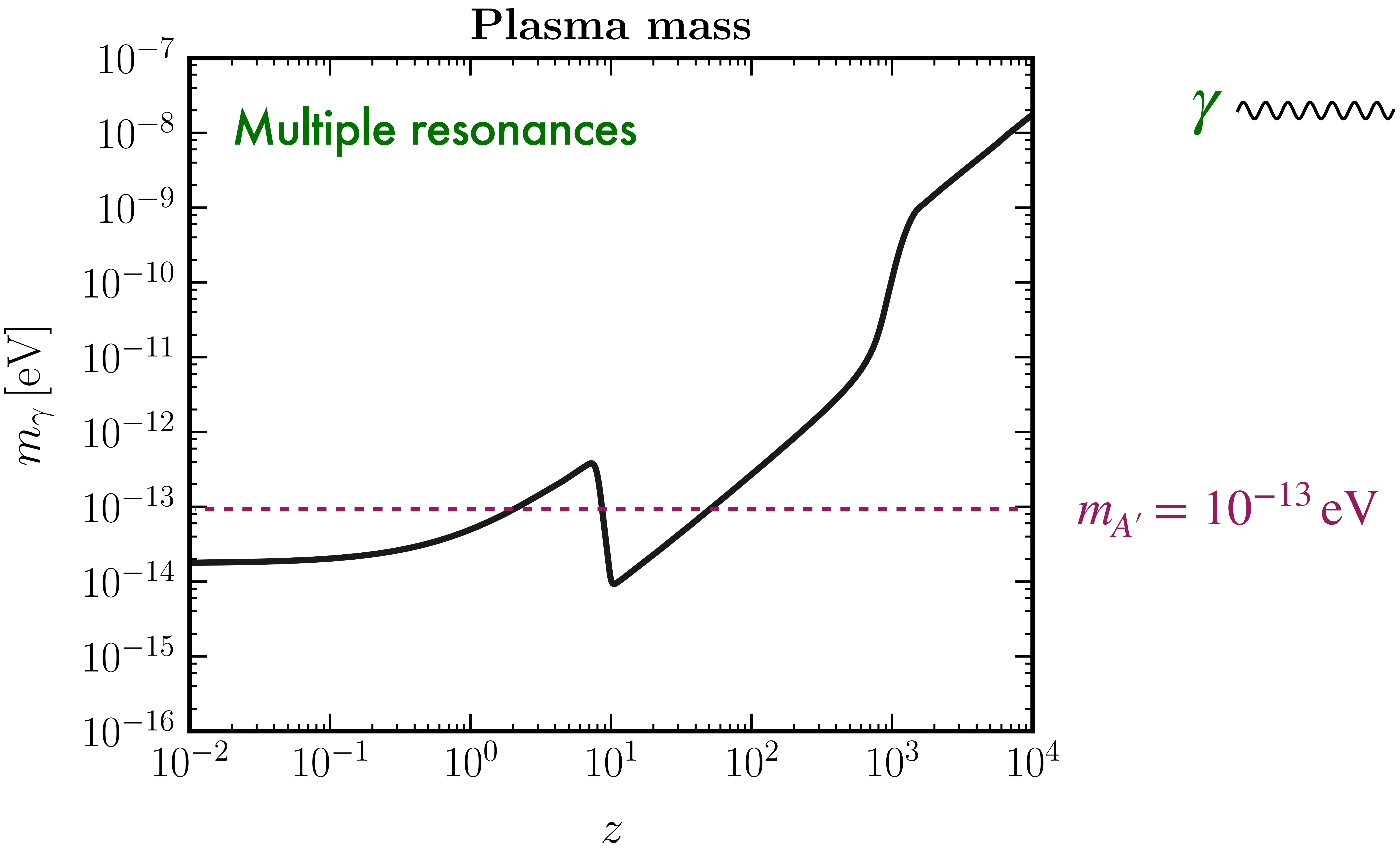

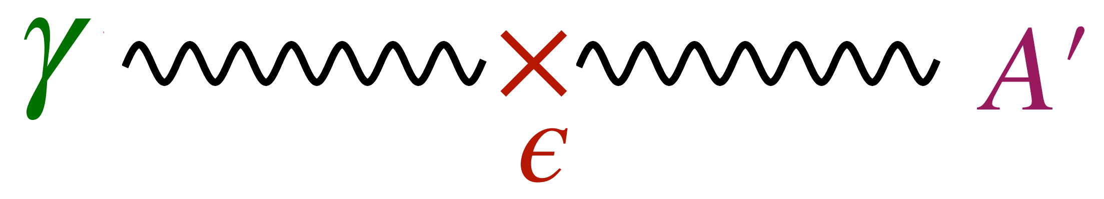

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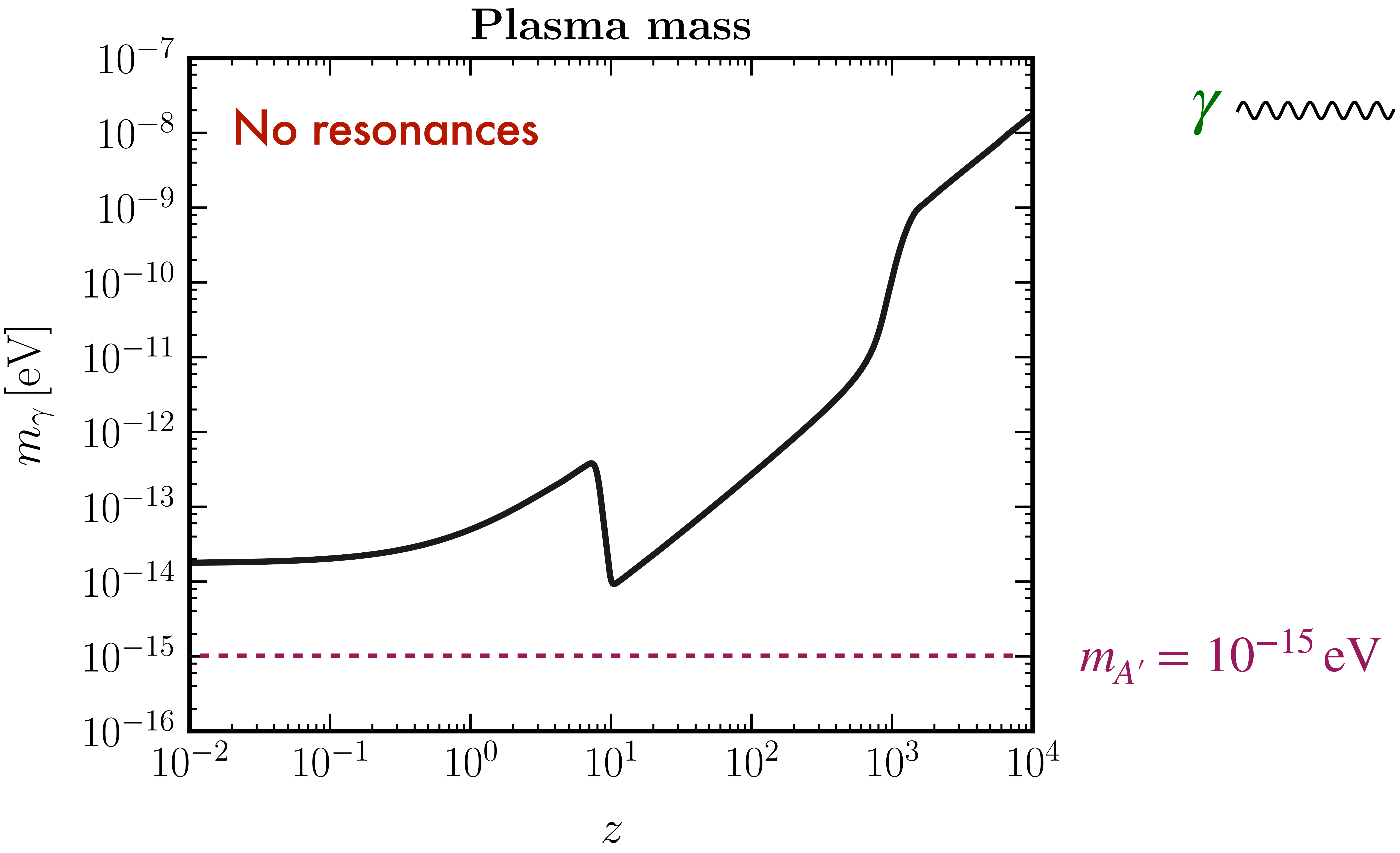
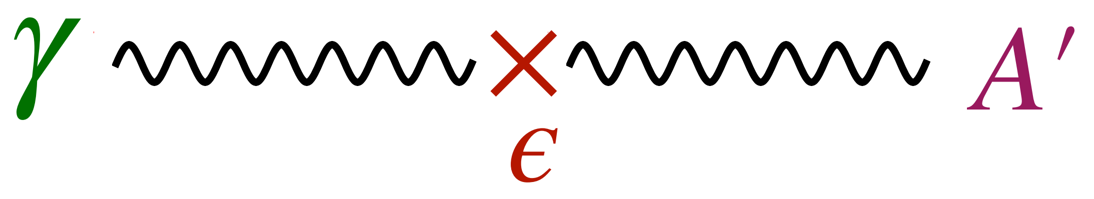
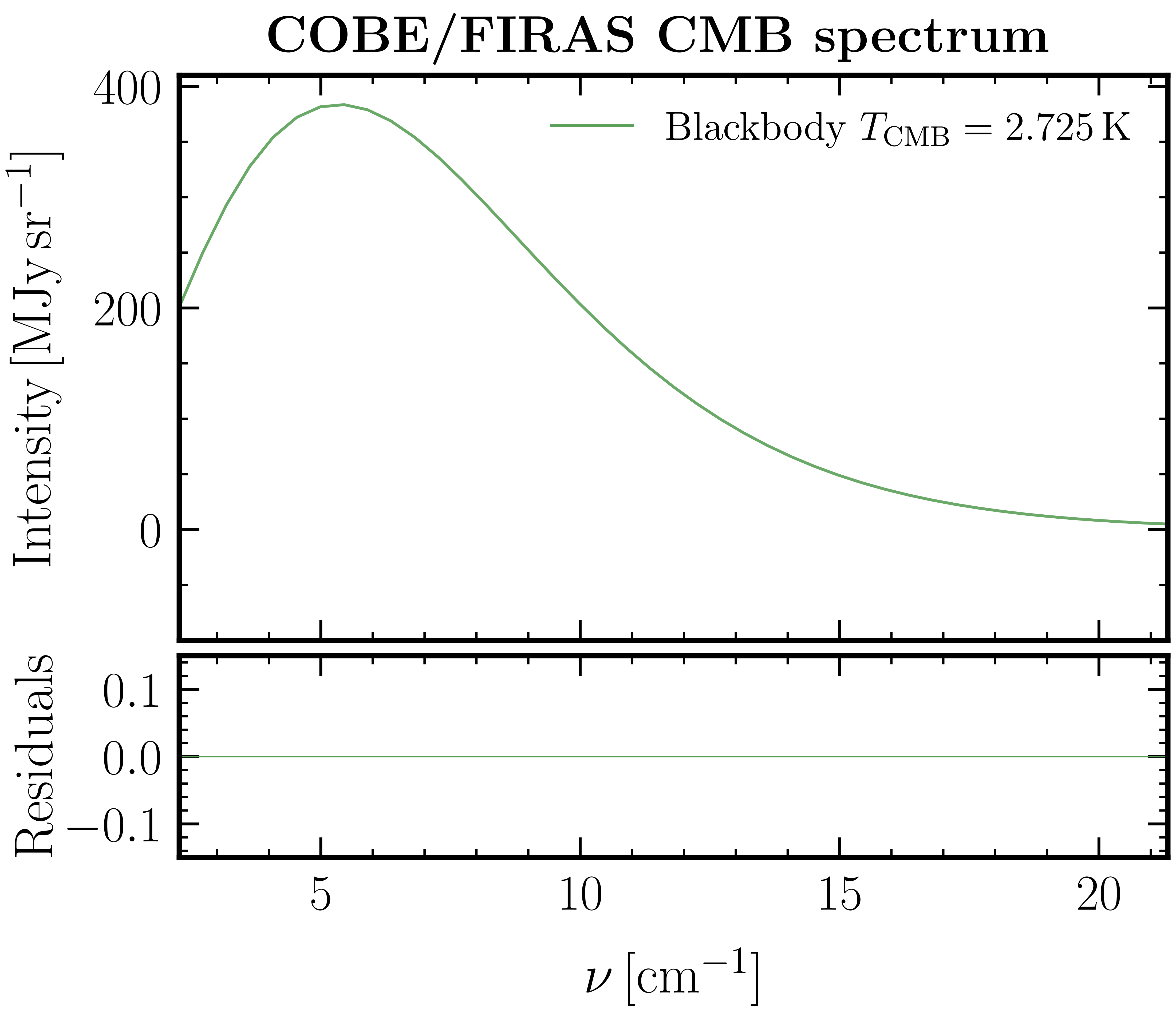




CMB spectral distortions due to $\gamma \to A'$



$$I_\omega\left(m_{A'}, \epsilon; T_{\rm CMB}\right) = B_\omega$$

Blackbody spectrum

$$B_\omega = \frac{\omega^3}{2\pi^2}\left[\exp\left(\frac{\omega}{T_{\rm CMB}}\right) - 1\right]^{-1}$$

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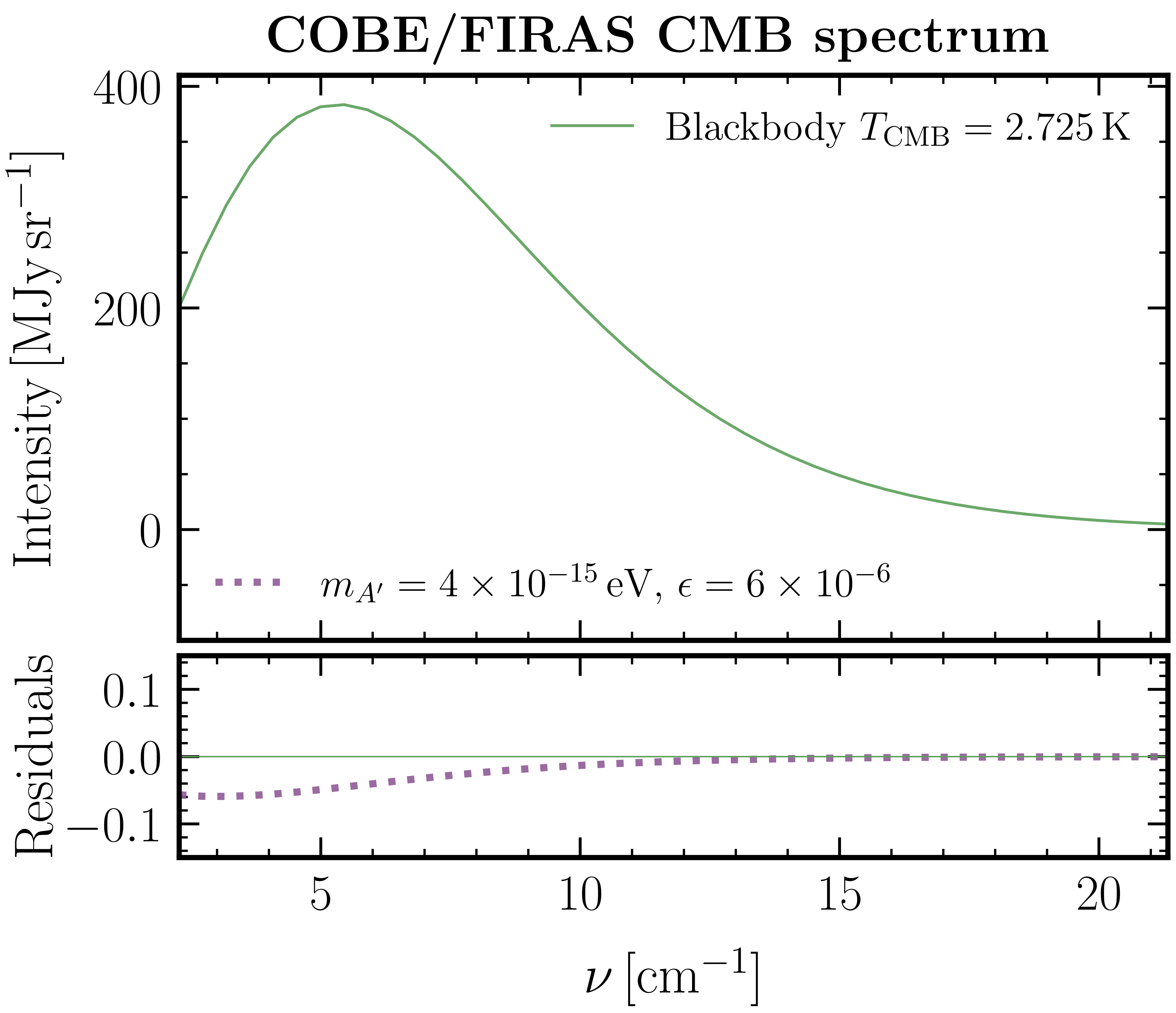

$$I_\omega\left(m_{A'}, \epsilon; T_{\rm CMB}\right) = B_\omega\left(1 - P_{\gamma\to A'}\right)$$

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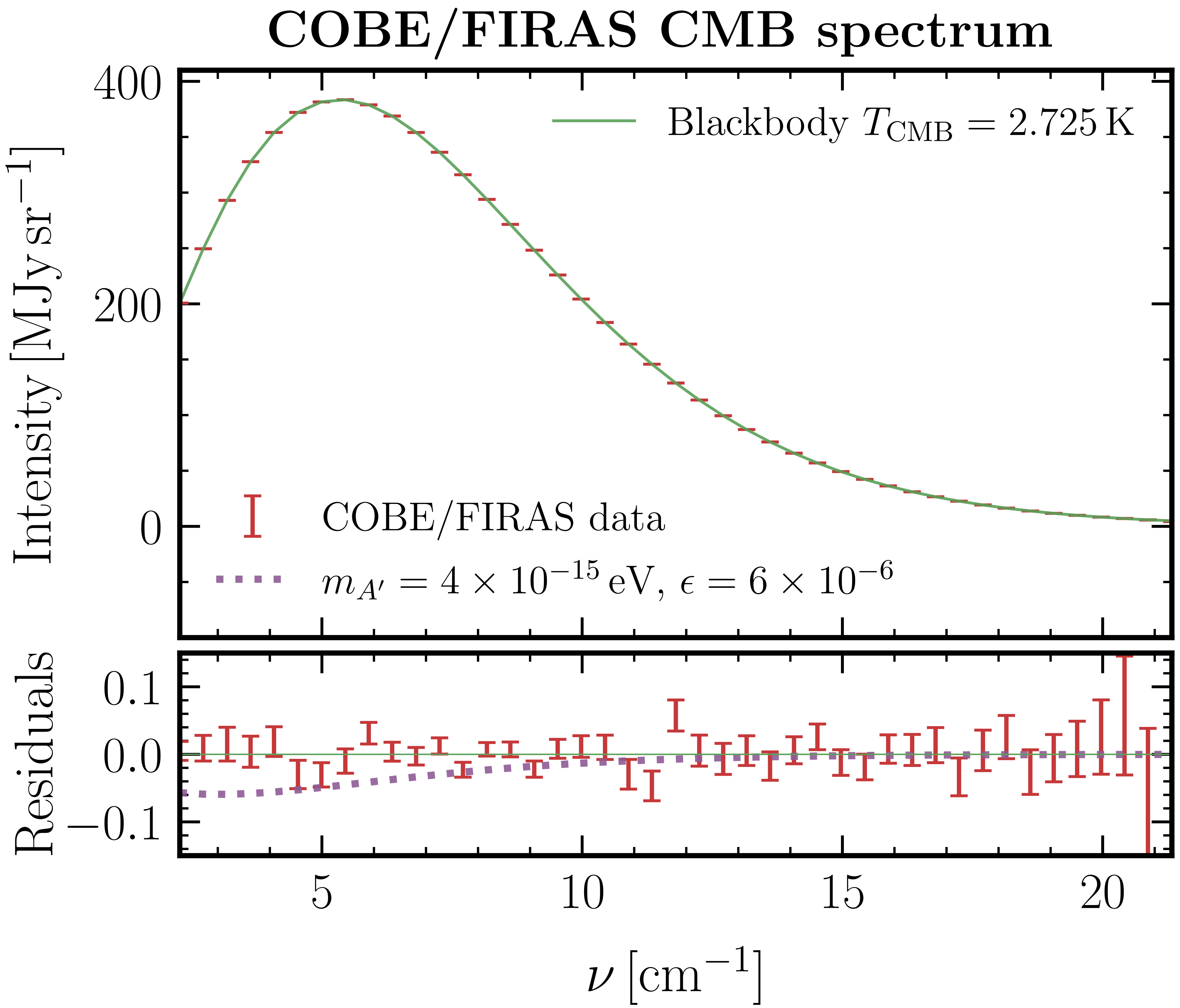

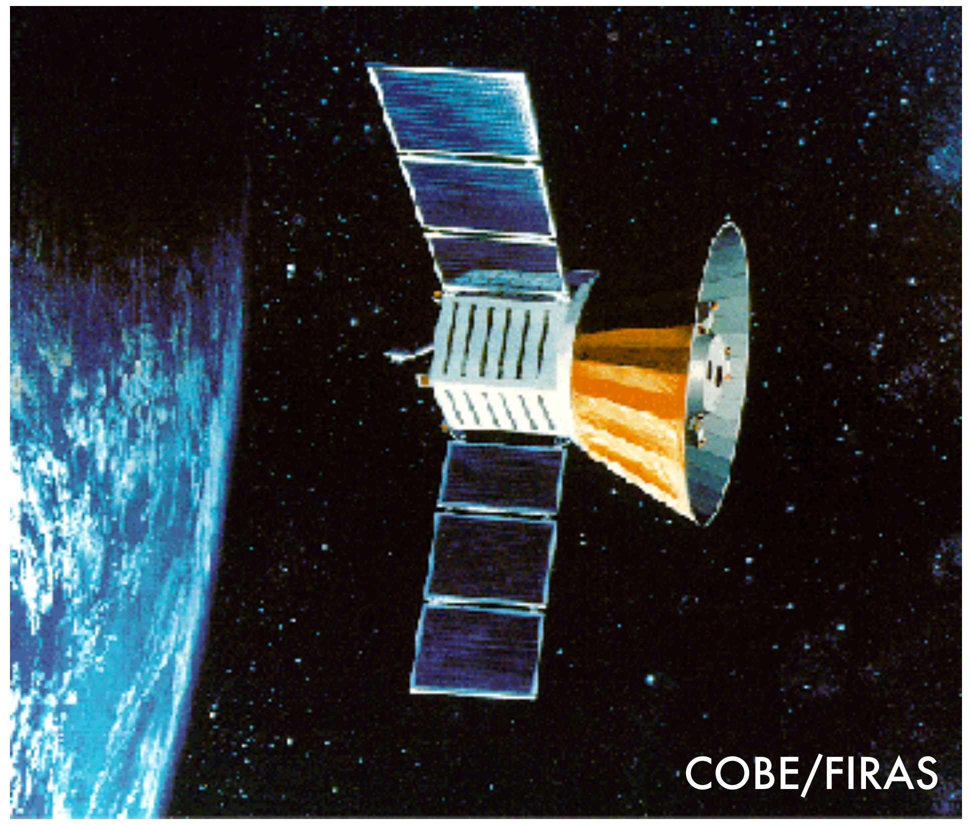

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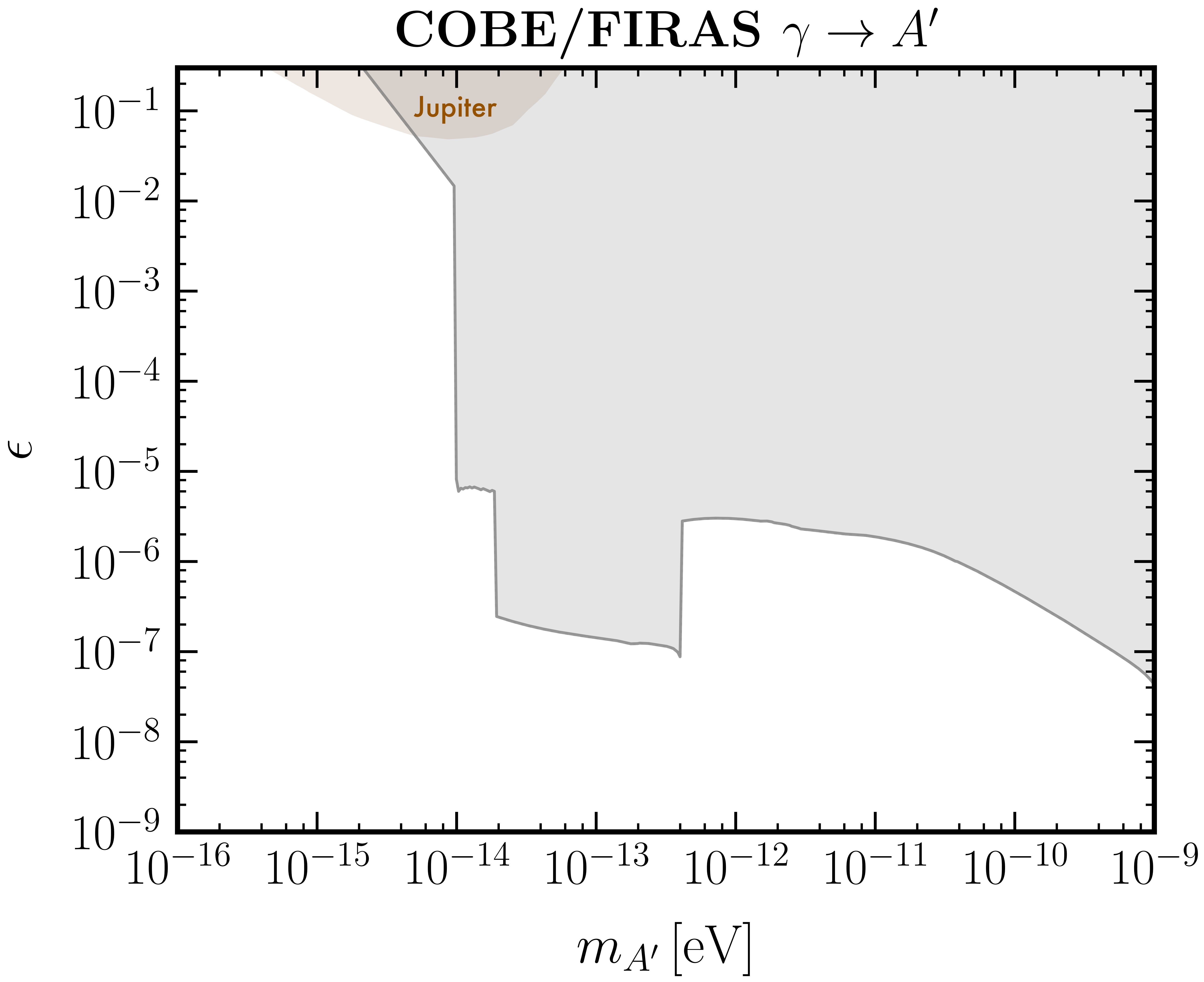
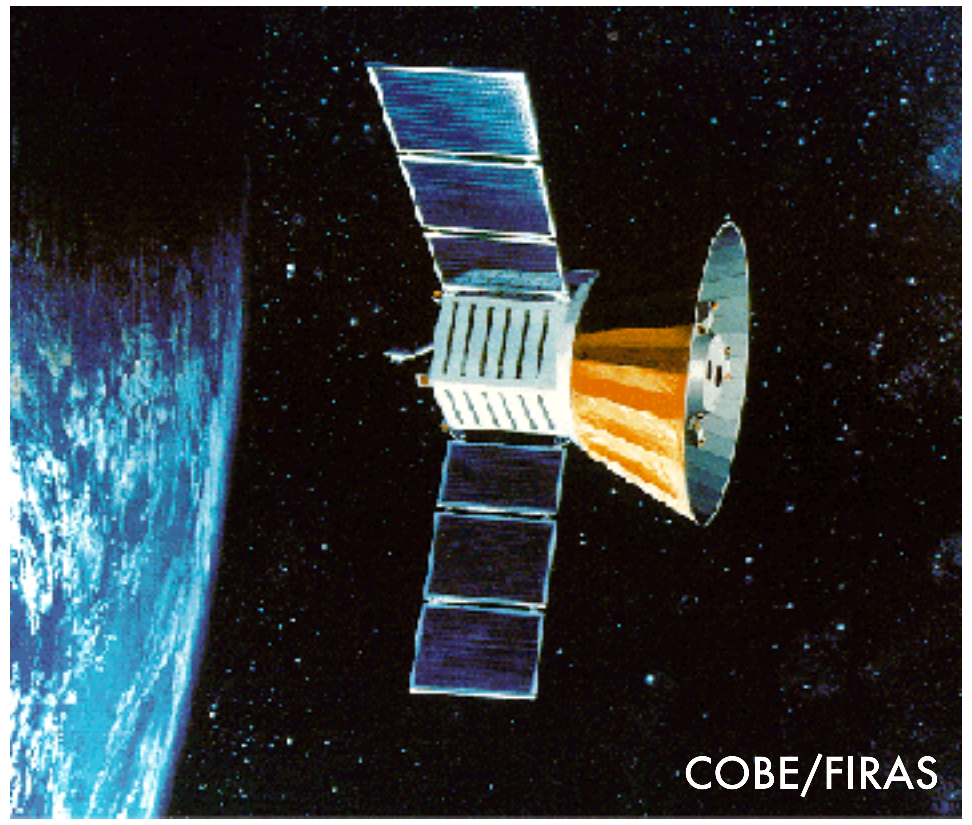
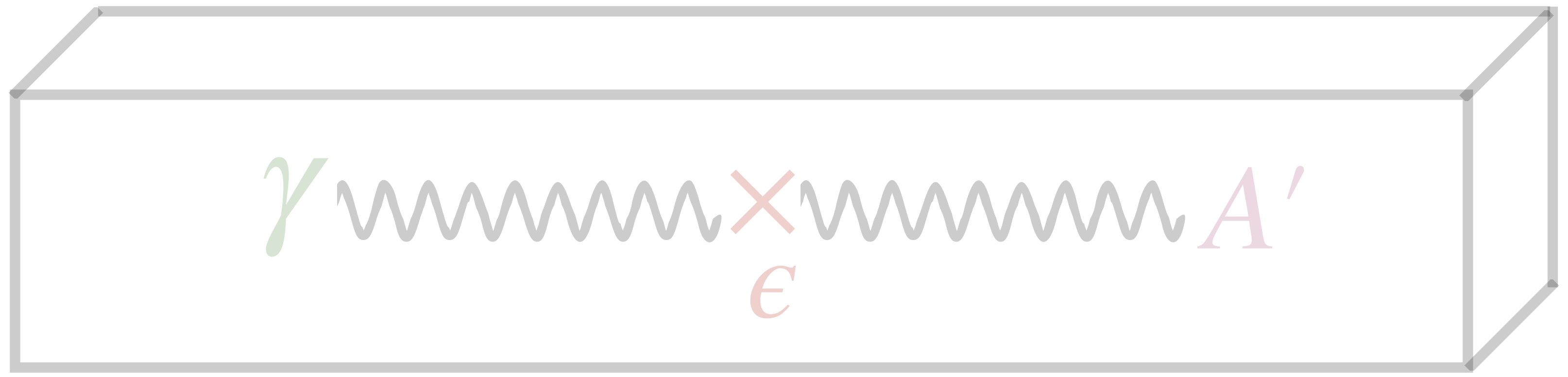
$\epsilon - m_{A'}$ constraints from COBE/FIRAS





Mirizzi, Redondo, Sigl [0901.0014]

Outline



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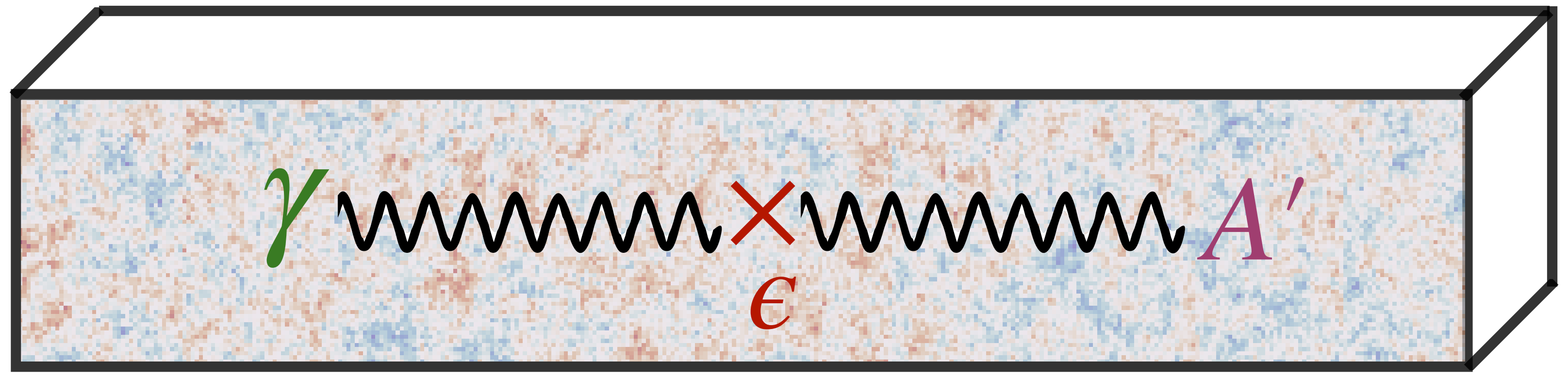

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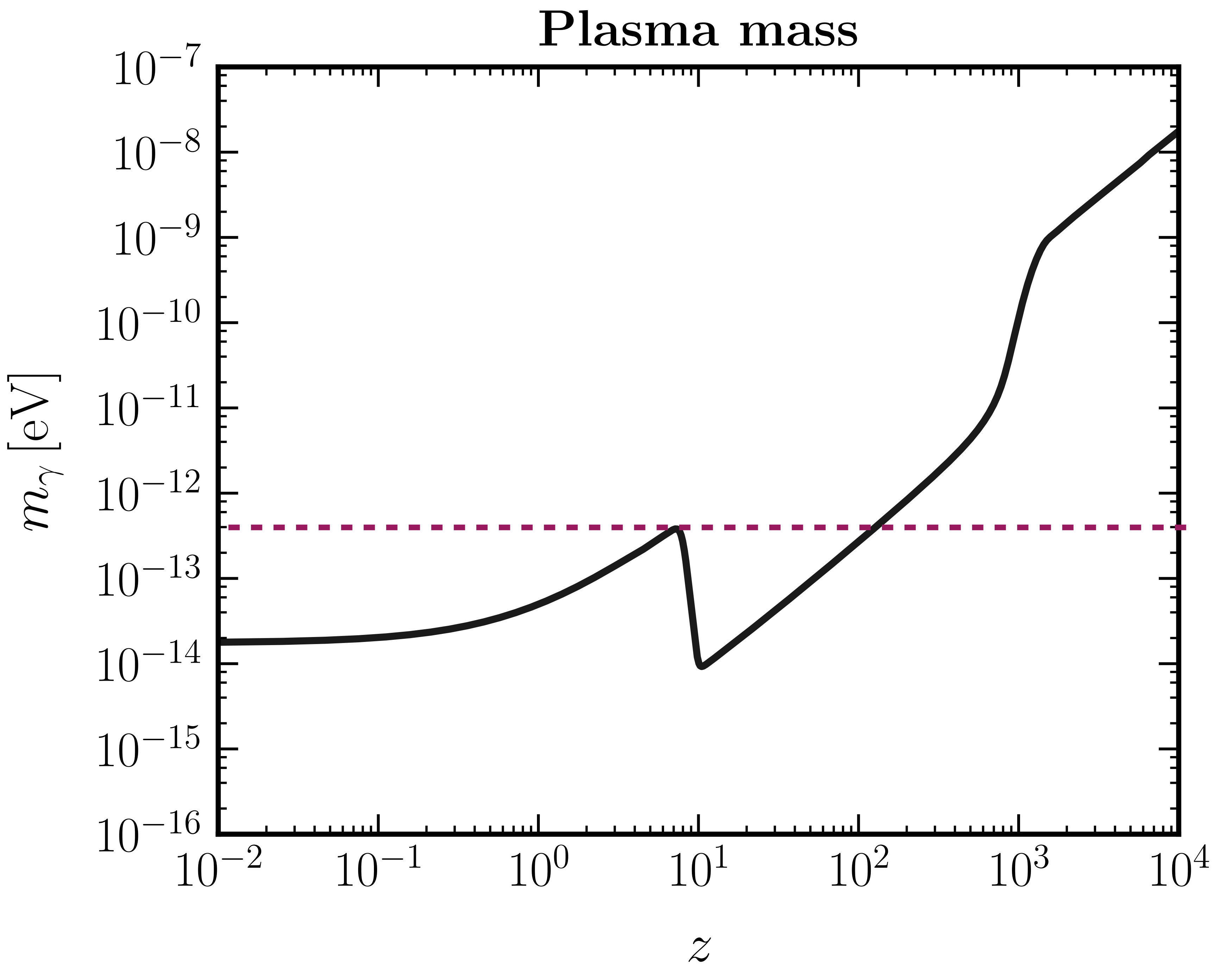
The inhomogeneous photon plasma

$$m_\gamma^2(z) \approx \frac{4\pi\alpha\, \overline{n_e(z)}}{m_e}$$



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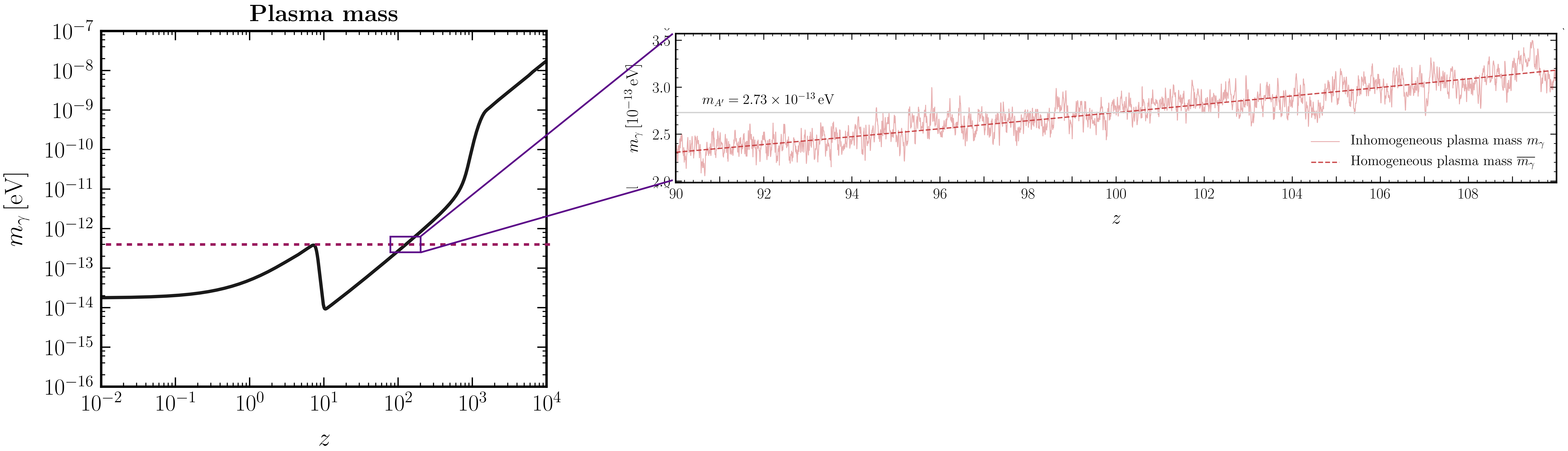

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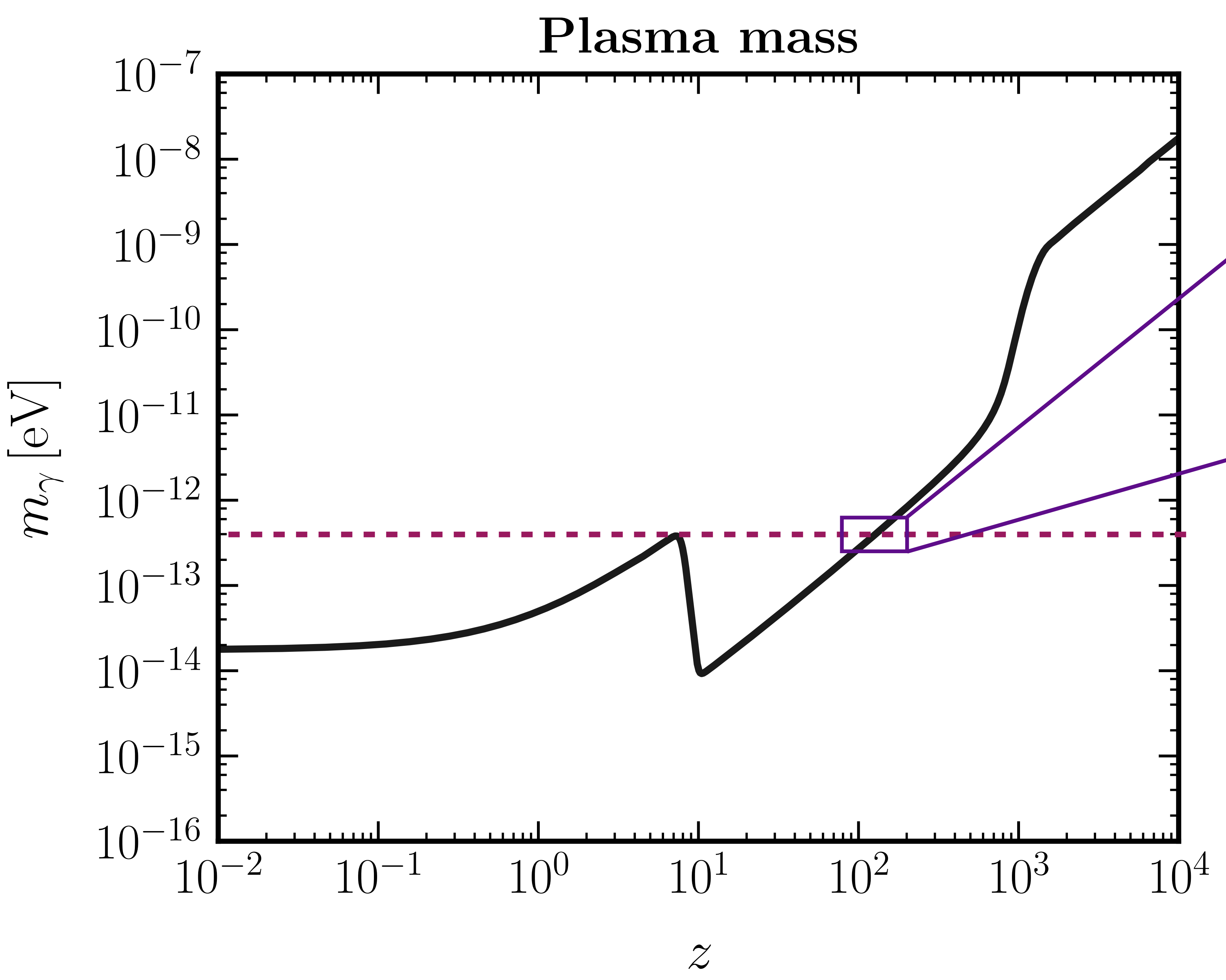

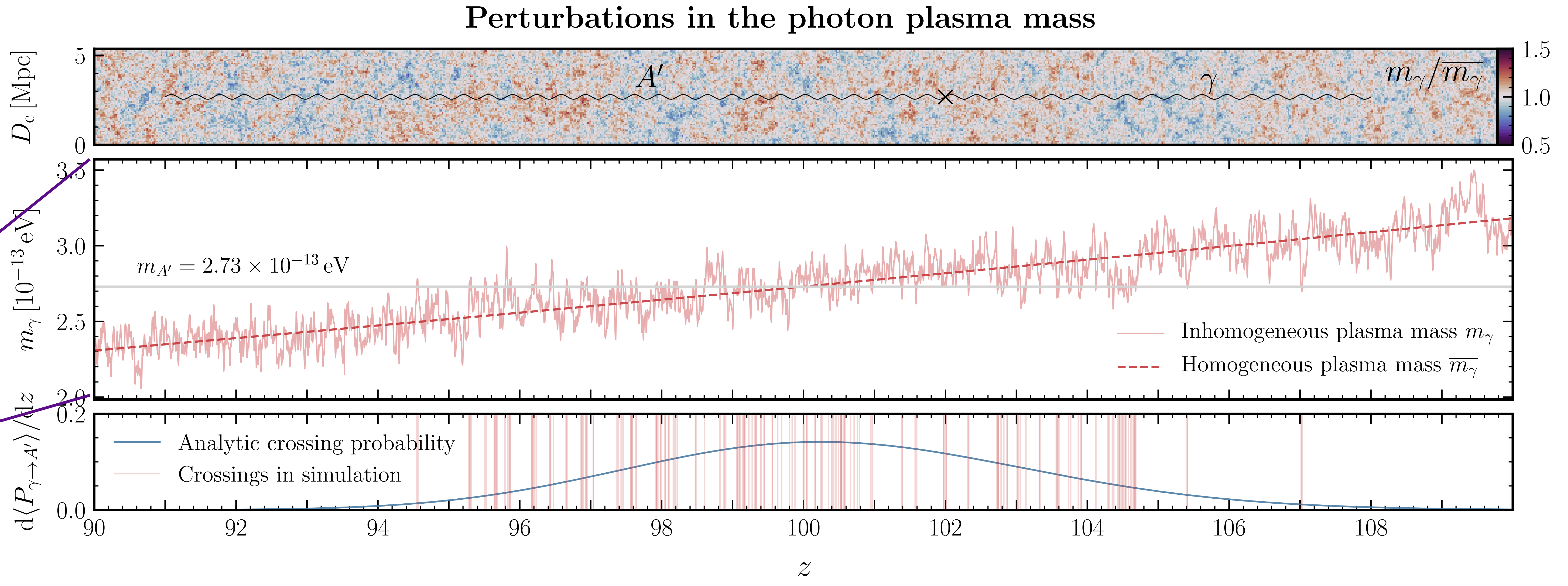

Resonant oscillations efficient over a range of z

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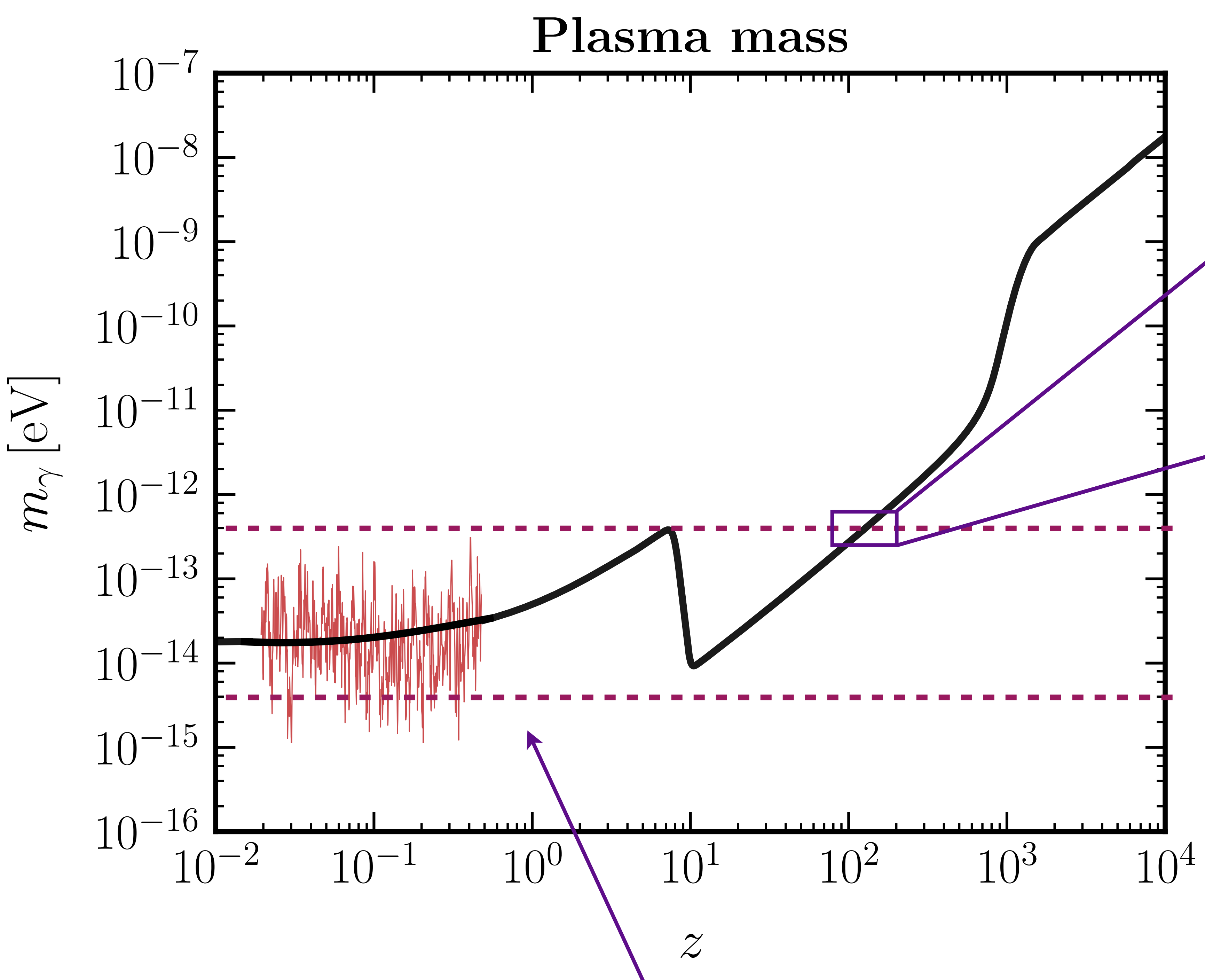

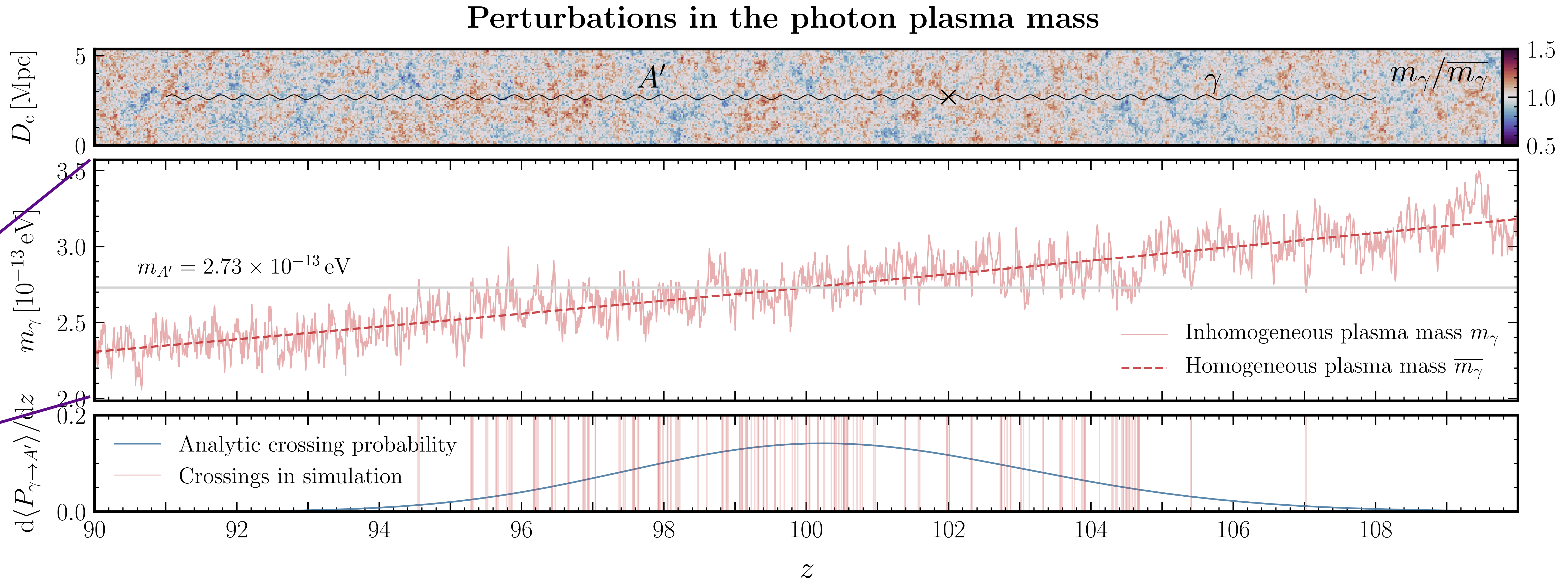

Resonant oscillations efficient over a range of z

Resonant conversions for otherwise inaccessible $m_{A'}$

Computing conversion probability

Analytic approach

$$P_{\gamma \to A'} \simeq \pi \epsilon^2 m_{A'}^2 \left\langle \sum_i \frac{1}{\omega_i\left(z_{\mathrm{res},i}\right)} \left| \frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t} \right|_{z=z_{\mathrm{res},i}}^{-1} \right\rangle$$

Compute average of stochastic process

Computing conversion probability

Analytic approach

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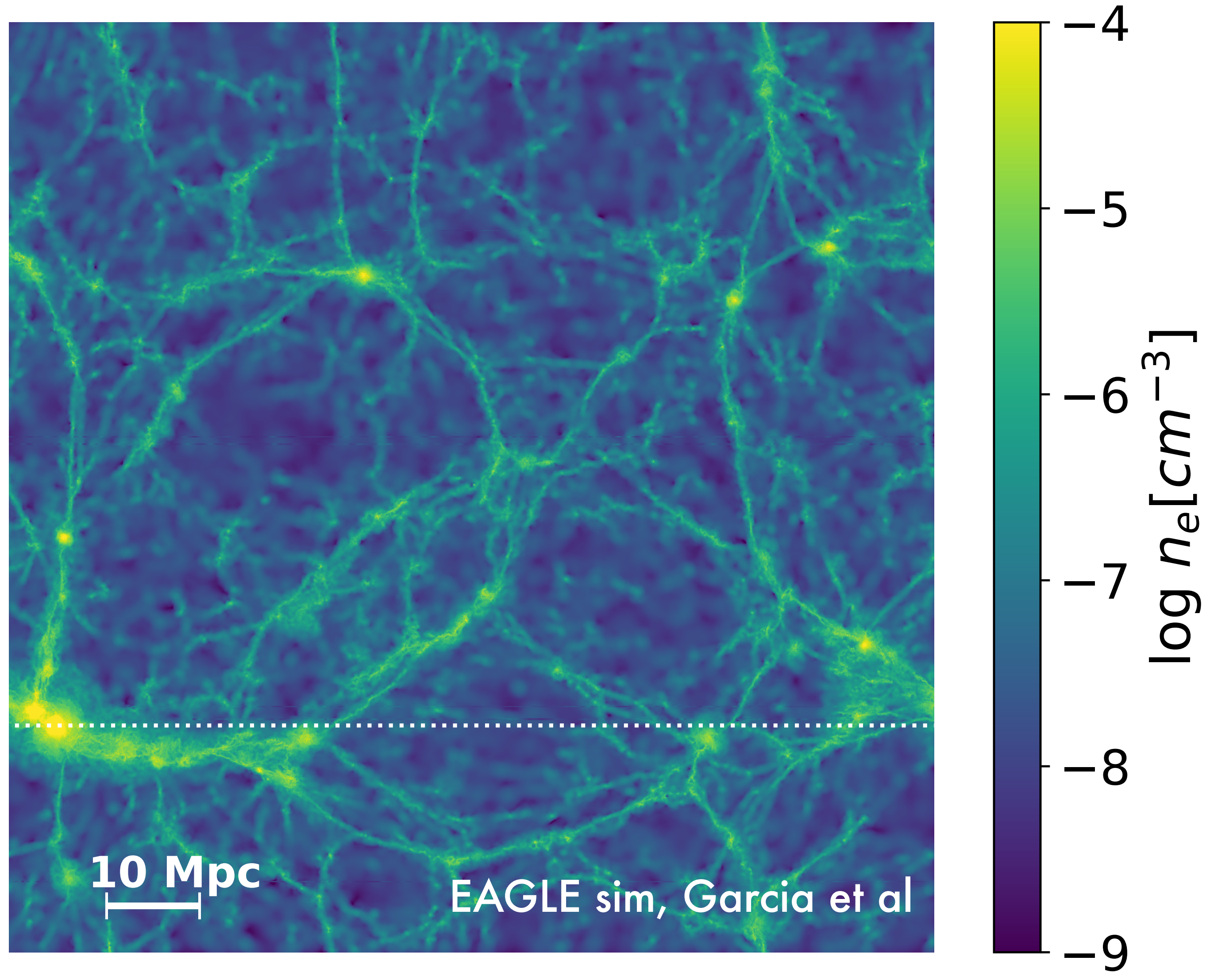
Numerical approach



Bondarenko, Pradler, Sokolenko [2002.08942]
Garcia et al [2003.10465]

Analytic formalism for inhomogeneous conversions

1. Conversion probability along line of sight

$$\frac{\mathrm{d}P_{\gamma\to A'}}{\mathrm{d}t} = \frac{\pi m_{A'}^2 \epsilon^2}{\omega(t)} \delta_{\mathrm{D}}\left(m_\gamma^2(t) - m_{A'}^2\right) m_\gamma^2(t)$$

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3. Enforce resonance condition $m_\gamma^2 = m_{A'}^2$

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Rice's Formula (1944)

Mathematical Analysis of Random Noise

By S. O. RICE

INTRODUCTION

THIS paper deals with the mathematical analysis of noise obtained by passing random noise through physical devices. The random noise

PDF of plasma mass fluctuations

$$m_\gamma^2(\vec{x}, z) = \overline{m_\gamma^2}(z)\ \left(1+\delta_e(\vec{x}, z)\right)$$

$$f(m_\gamma^2) = \frac{\mathrm{d}\delta_e}{\mathrm{d}m_\gamma^2}\mathscr{P}(\delta_e) = \frac{\mathscr{P}(\delta_e)}{\overline{m_\gamma^2}}$$

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Electron and baryon fluctuations

$$\bar{n}_e(1+\delta_e) = \bar{x}_e(1+\delta_{x_e})\,\bar{n}_H(1+\delta_b)$$

$$\implies \delta_e = \delta_b + \delta_{x_e} + \delta_{x_e}\delta_b$$

If $\delta_{x_e} \ll \delta_b \implies \delta_e \approx \delta_b$

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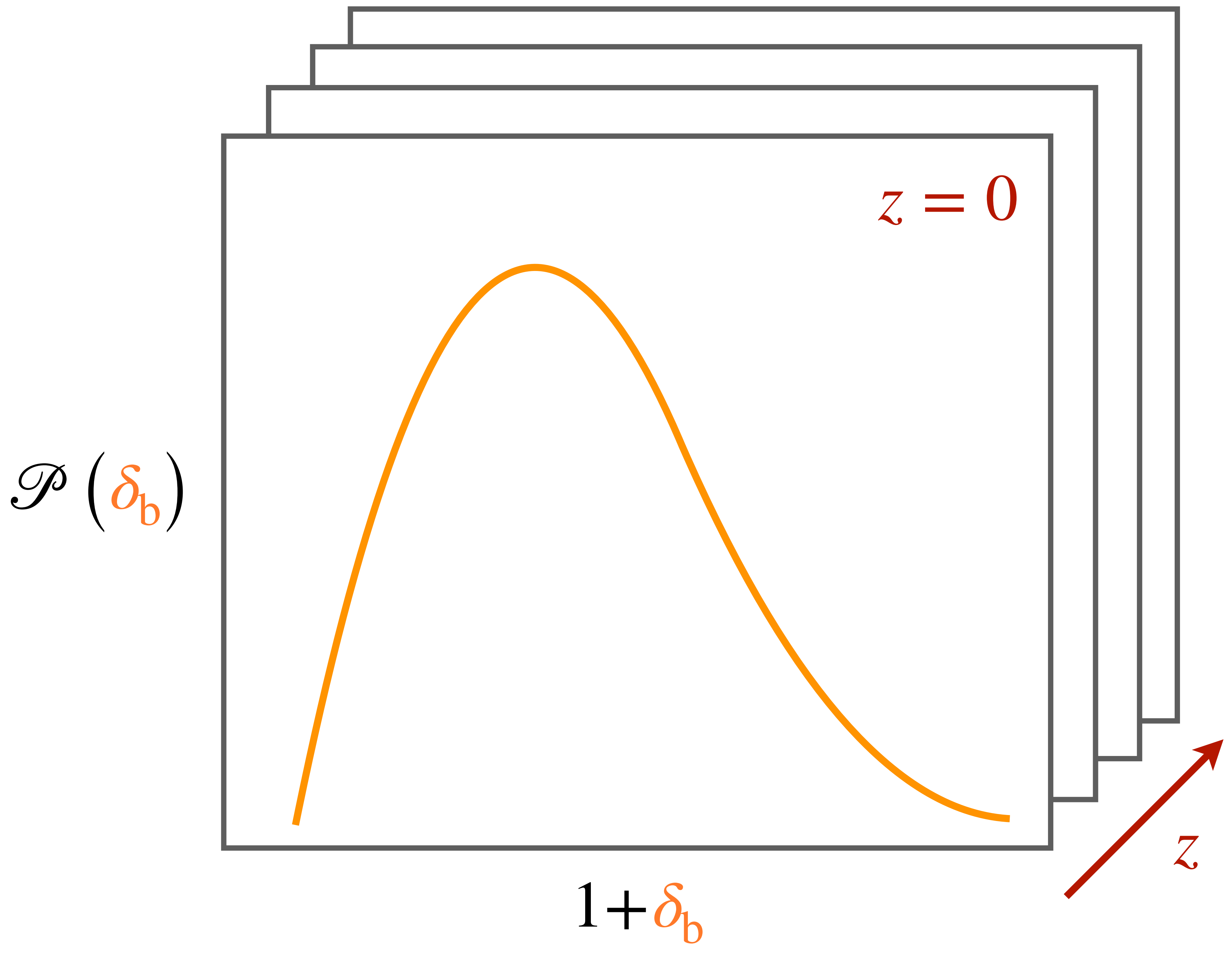

Ingredients:

1. Functional form of PDF
2. Variance of PDF(z)

PDF of plasma mass fluctuations: Gaussian toy example

1. PDF functional form

$$\mathscr{P}_{\mathrm{G}}\left(\delta_{\mathrm{b}}; z\right)=\frac{1}{\sqrt{2 \pi \sigma_{\mathrm{b}}^{2}(z)}} \exp \left(-\frac{\delta_{\mathrm{b}}^{2}}{2 \sigma_{\mathrm{b}}^{2}(z)}\right)$$

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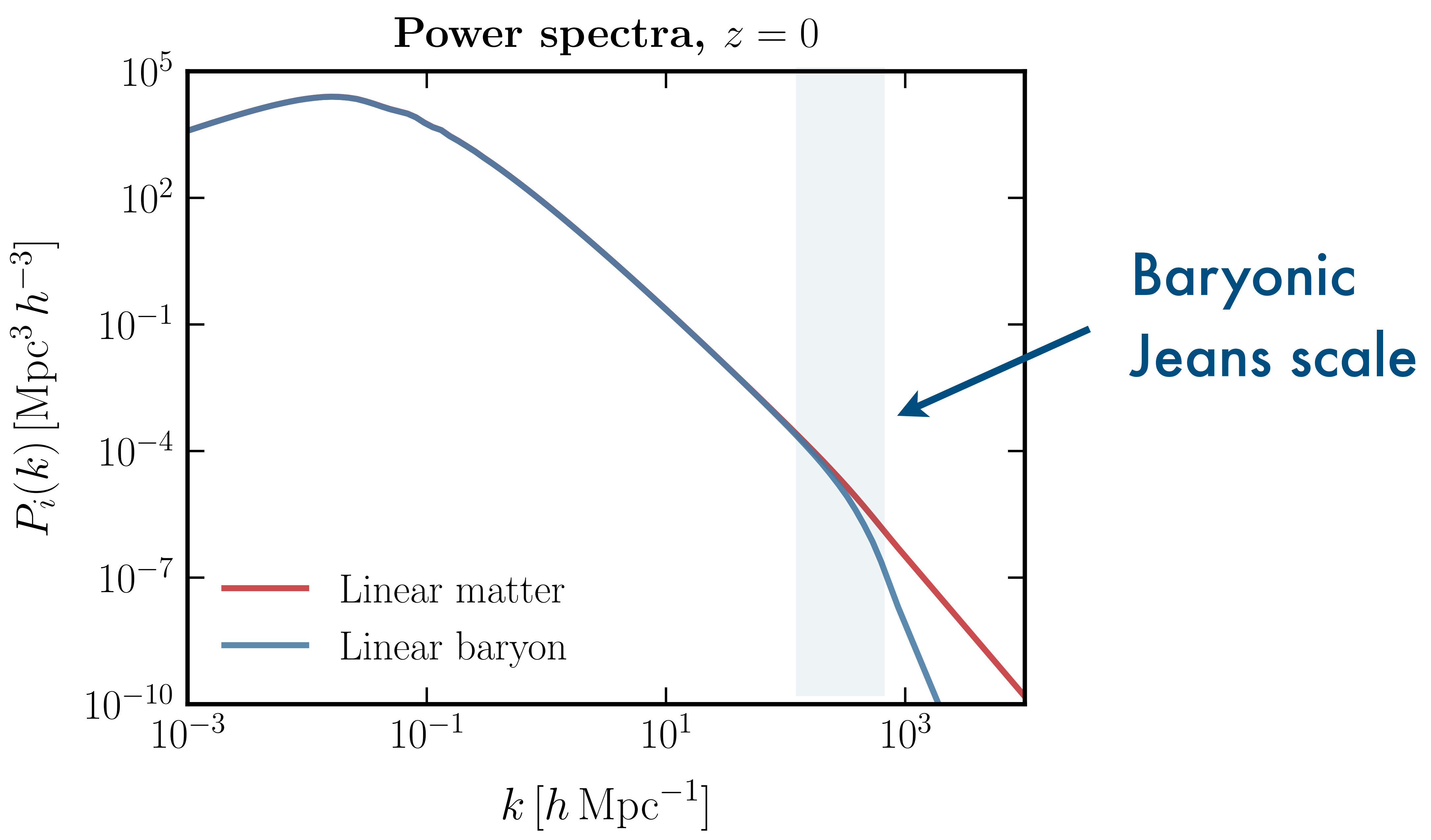
2. PDF variance

$$\sigma_{\rm b}^2(z) = \int \frac{{\rm d}^3\vec{k}}{(2\pi)^3} P_{\rm bb}(k, z)$$



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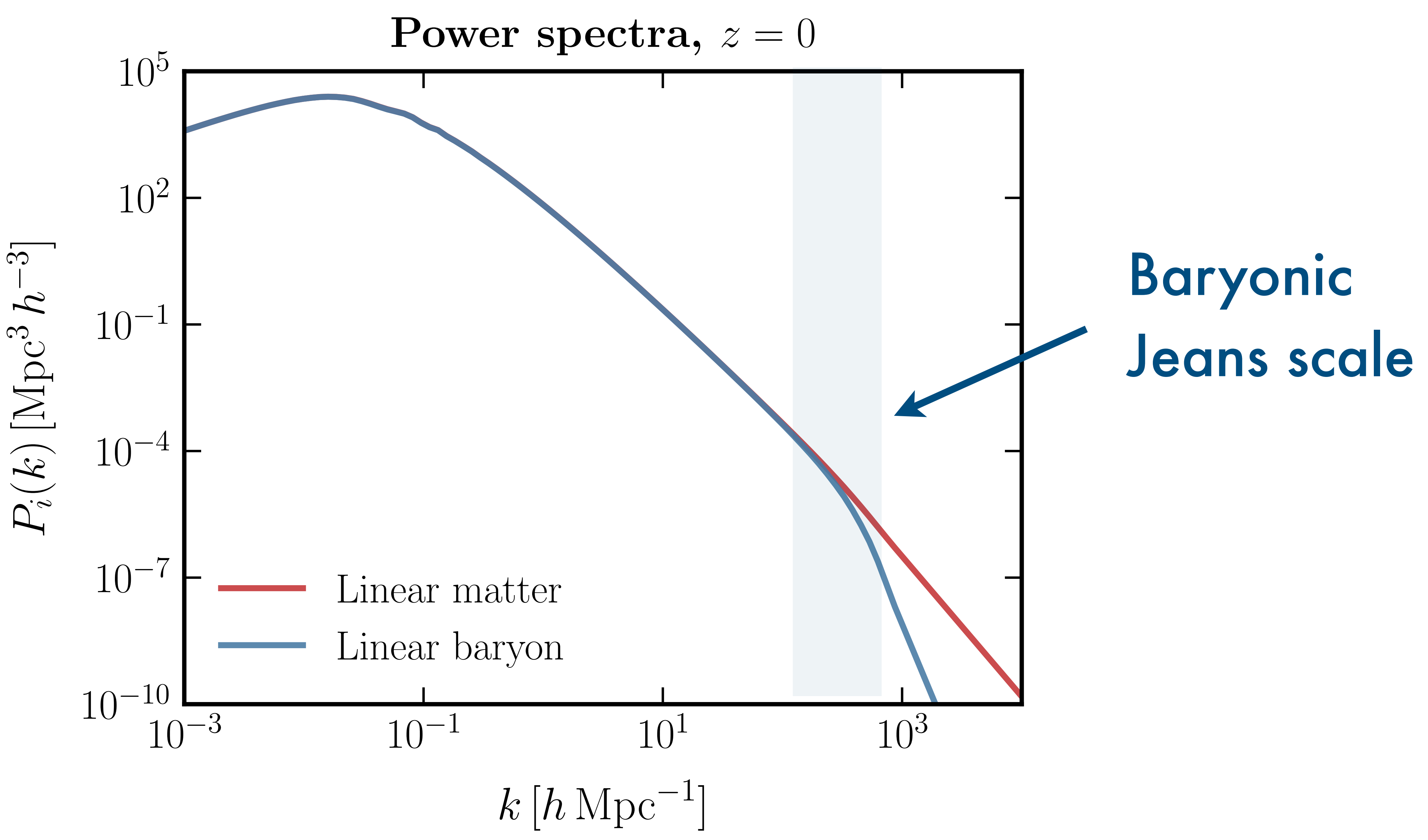

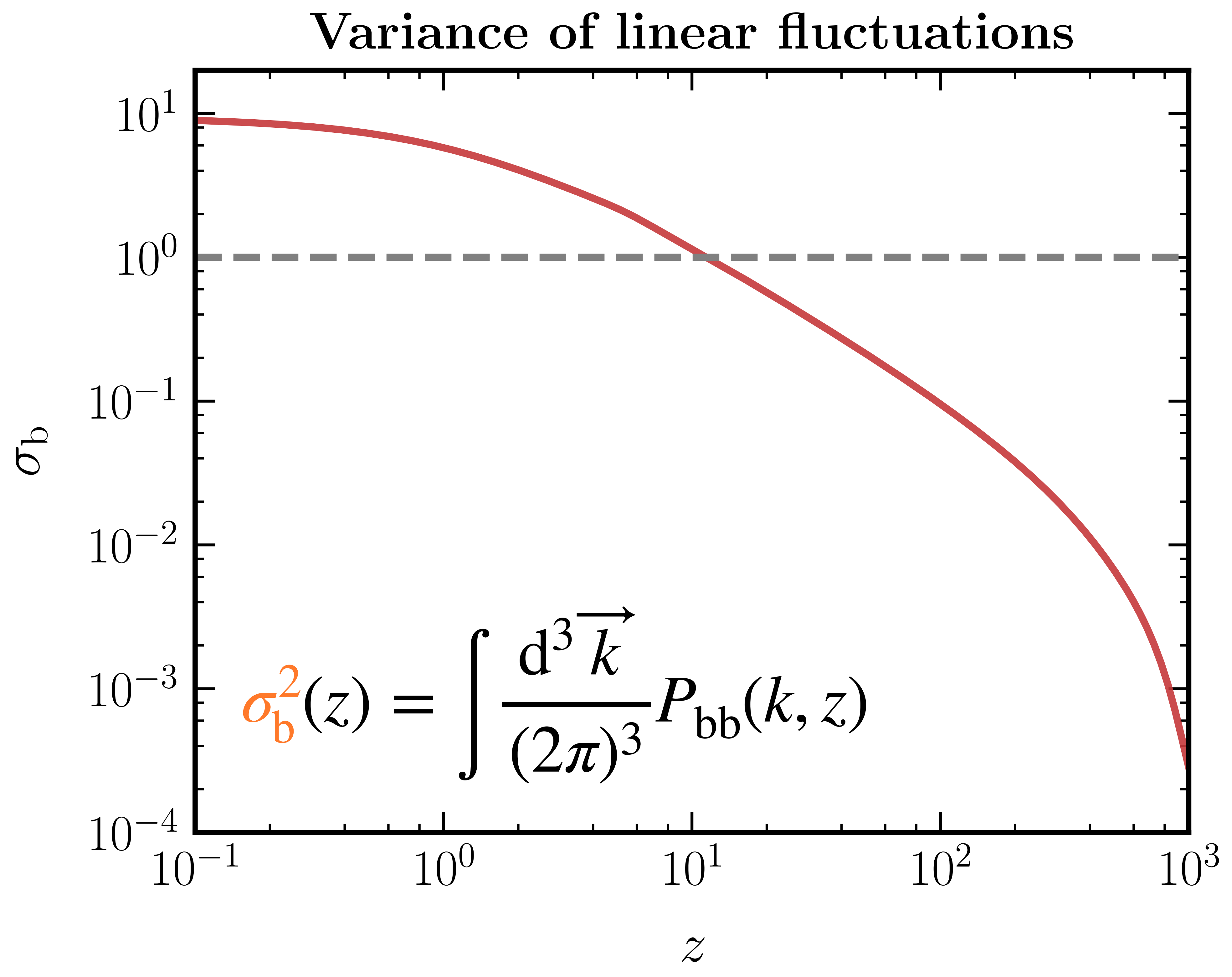

Fluctuations at late times highly non-Gaussian, non-linear

Log-normal PDF

$$\mathscr{P}_{\mathrm{LN}}\left(\delta_{\mathrm{b}}; z\right) = \frac{\left(1+\delta_{\mathrm{b}}\right)^{-1}}{\sqrt{2\pi\,\Sigma^2(z)}} \exp\left(-\frac{\left[\ln\left(1+\delta_{\mathrm{b}}\right)+\Sigma^2(z)/2\right]^2}{2\Sigma^2(z)}\right)$$

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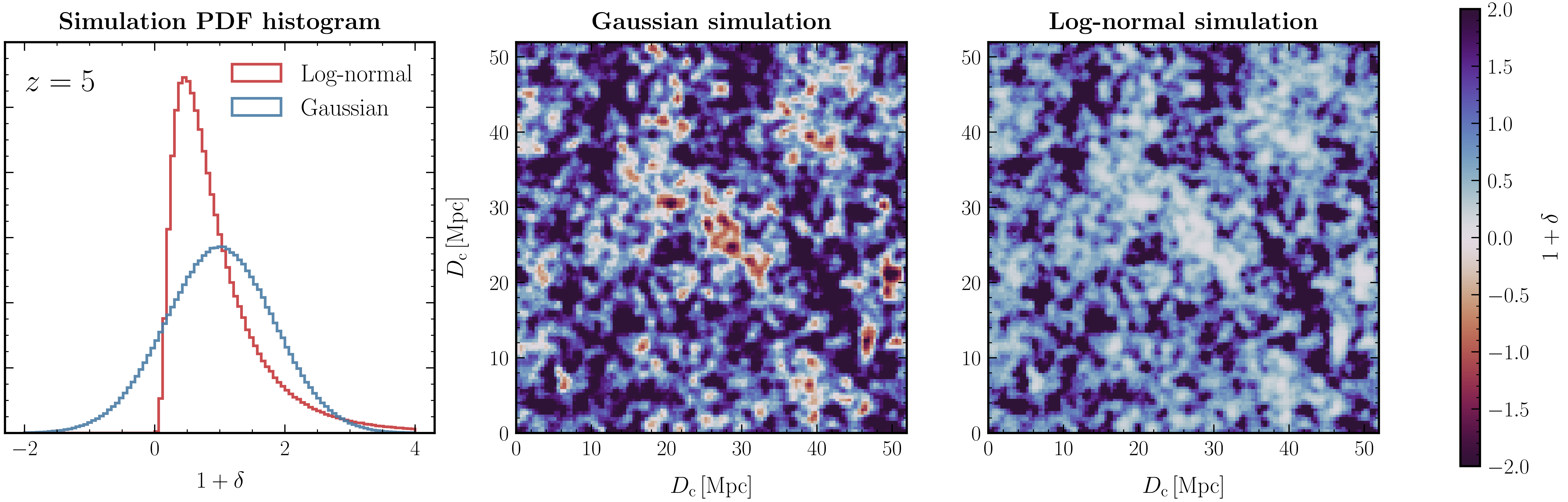
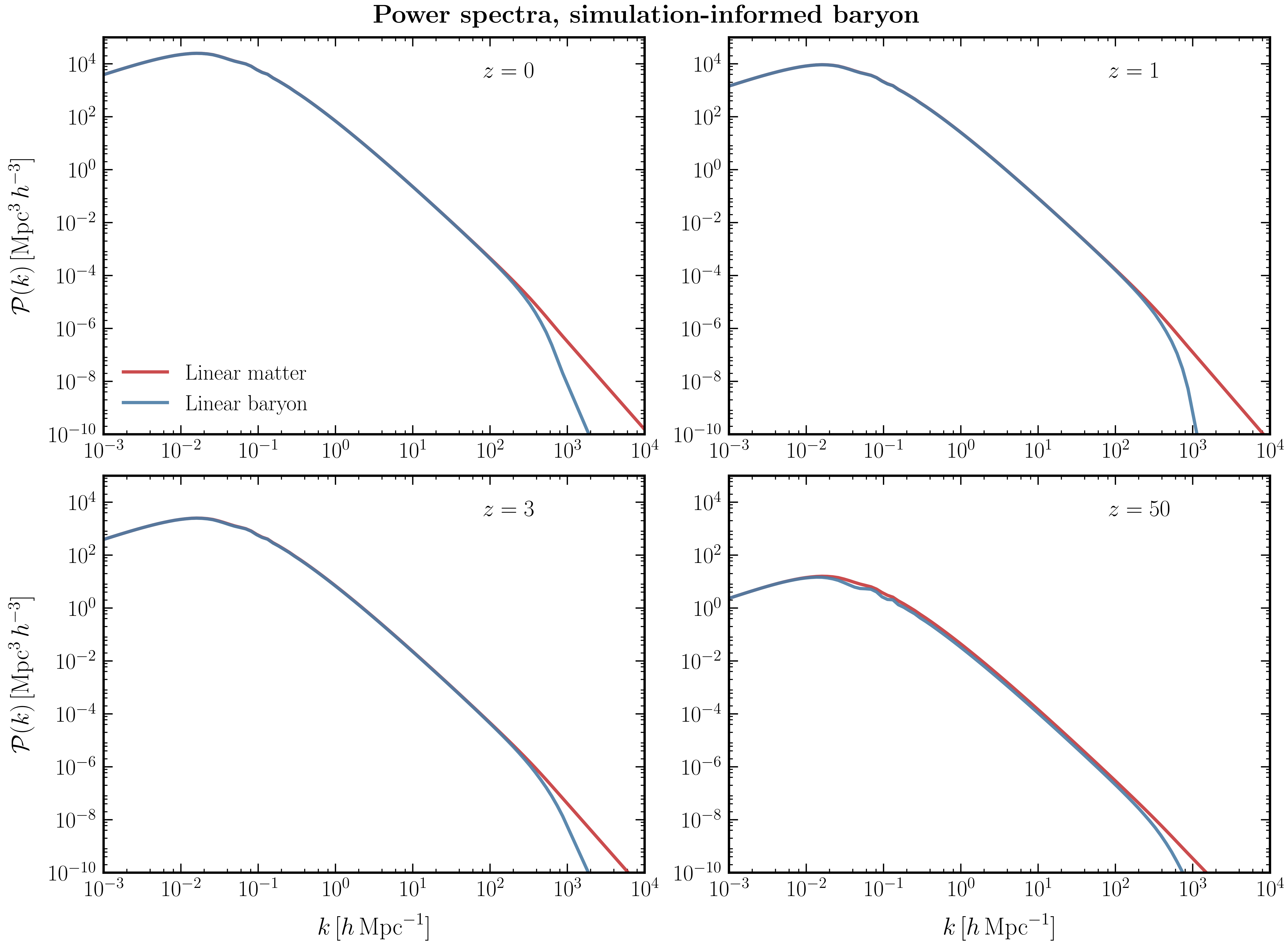


The non-linear baryonic power spectrum



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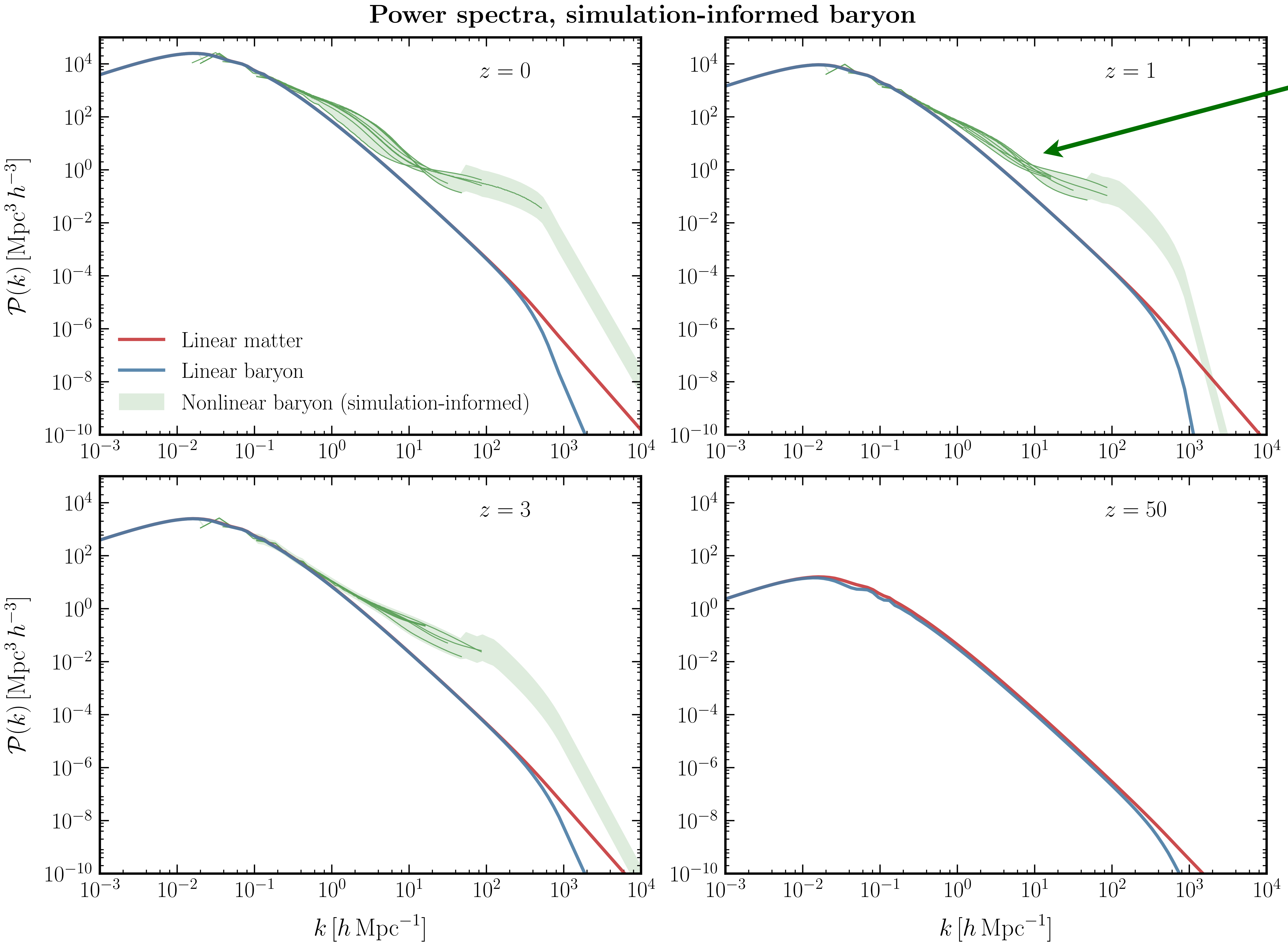

Non-linear baryonic power spectra from hydrodynamical simulations:

- Illustris
- IllustrisTNG
- BAHAMAS
- EAGLE

Foreman et al [1910.03597]
van Daalen et al [1906.00968]

Alternative PDF prescriptions

Log-normal PDF

Log-normal PDF with nonlinear baryon power spectrum

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"Analytic" PDF

Non-linear spherical collapse of linear matter field

Ivanov, Kaurov, Sibiryakov [1811.07913]

$$\mathscr{P}_{\mathrm{an}}\left(\delta_{\mathrm{b}};z\right)=\frac{\hat{C}\left(\delta_{\mathrm{b}}\right)}{\sqrt{2\pi\sigma^2_{R_{\mathrm{J}}}(z)}}\exp\left[-\frac{F^2\left(\delta_{\mathrm{b}}\right)}{2\sigma^2_{R_{\mathrm{J}}}(z)}\right]$$

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Log-normal PDF

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Cosmic voids PDF

PDF of matter underdensities

Adermann et al [1703.04885, 1807.02938]

$$\mathscr{P}_{\rm voids}\left(\delta_{\rm b}; z\right) \sim \text{from simulations}$$

Alternative PDF prescriptions

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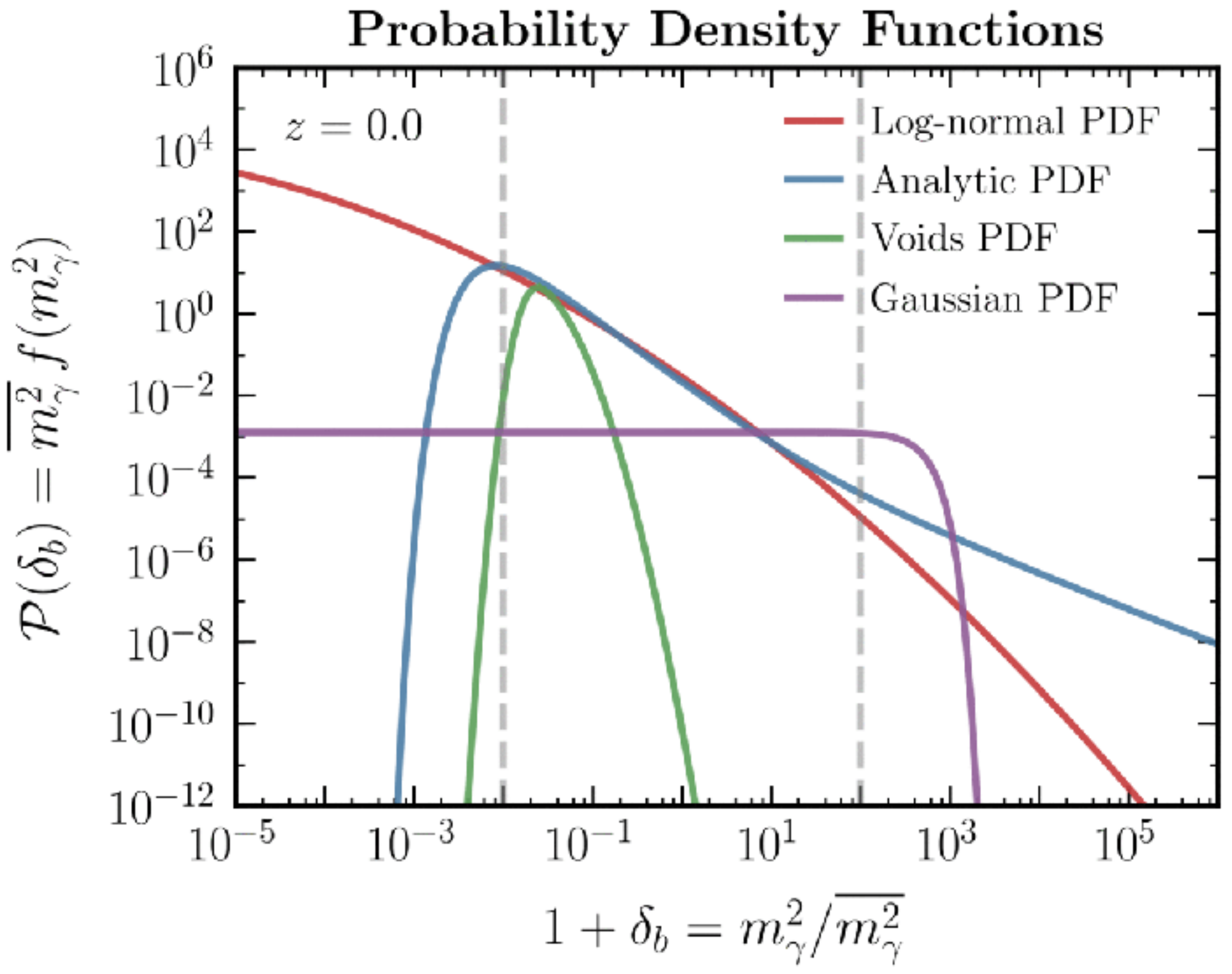
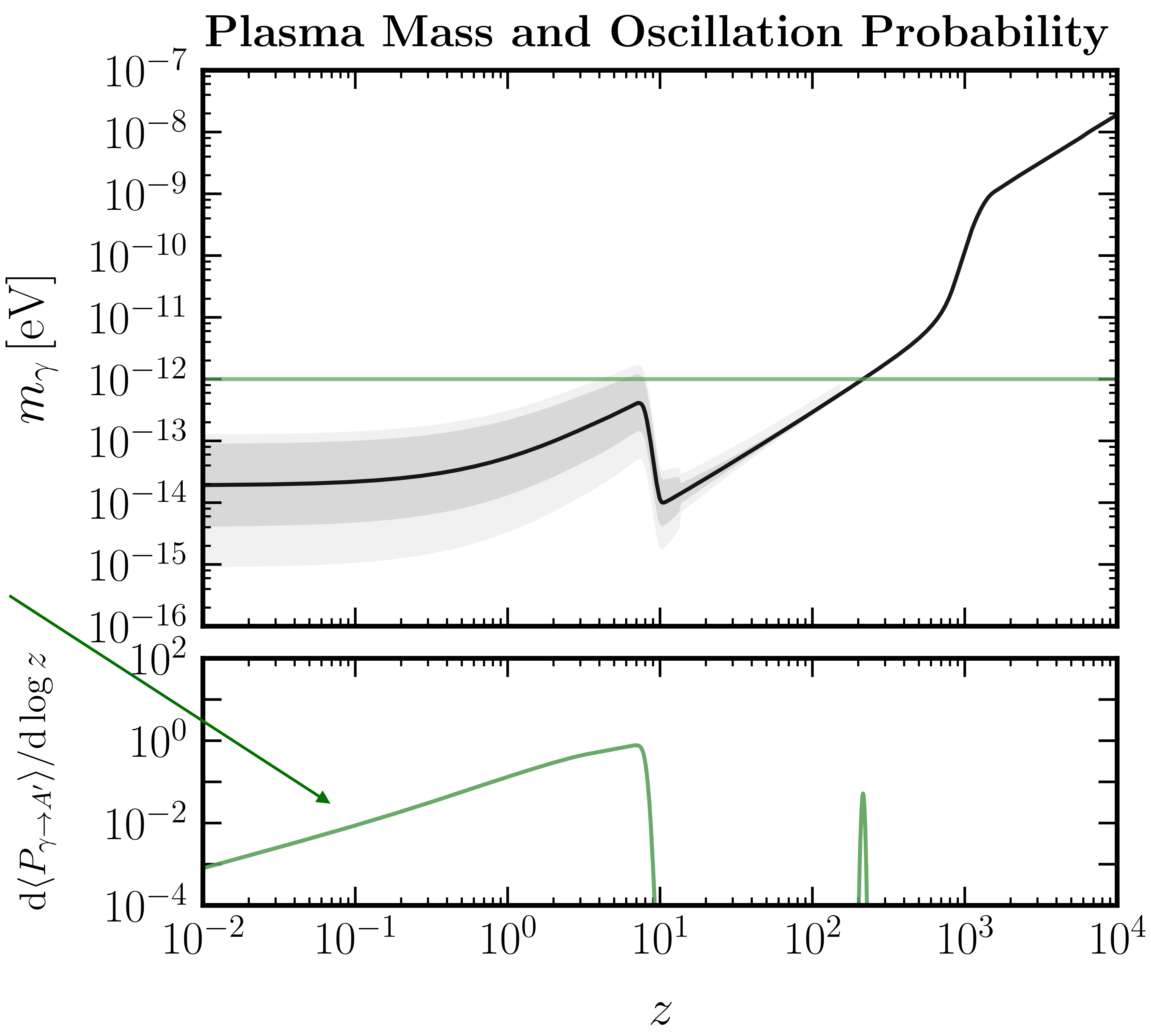


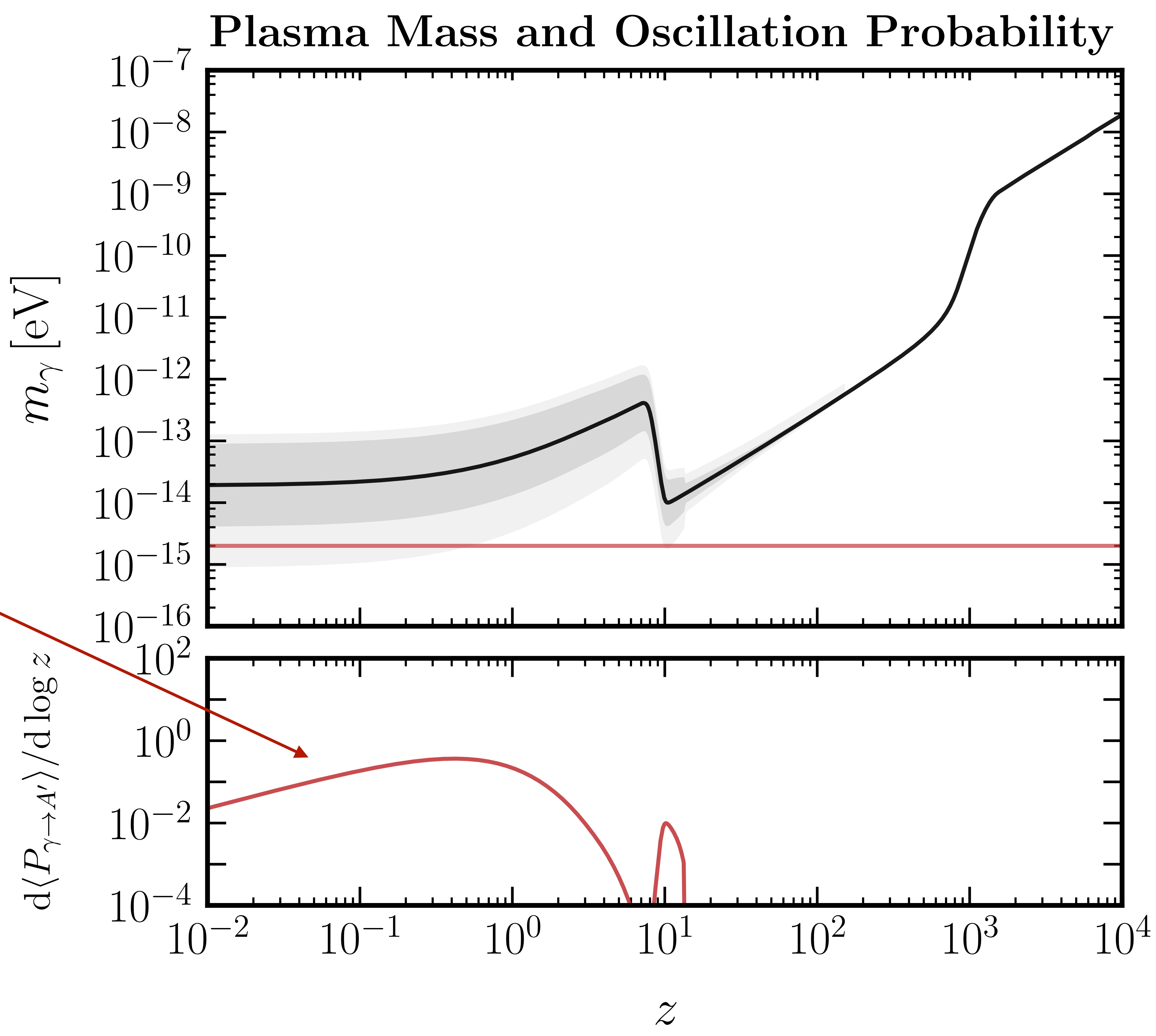
Conversion probability with inhomogeneities

Conversions in overdensities



Conversion probability with inhomogeneities

Conversions in underdensities



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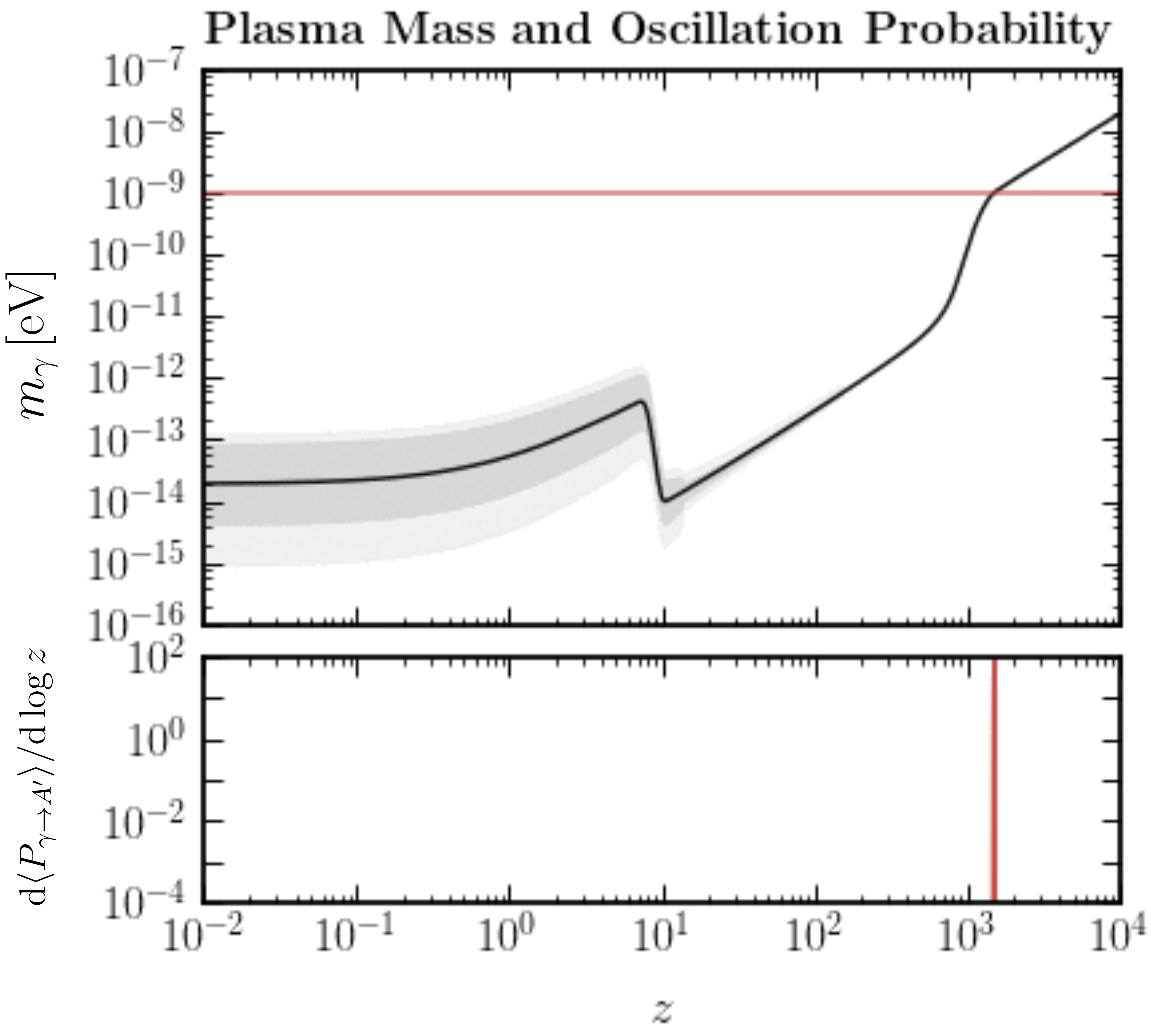

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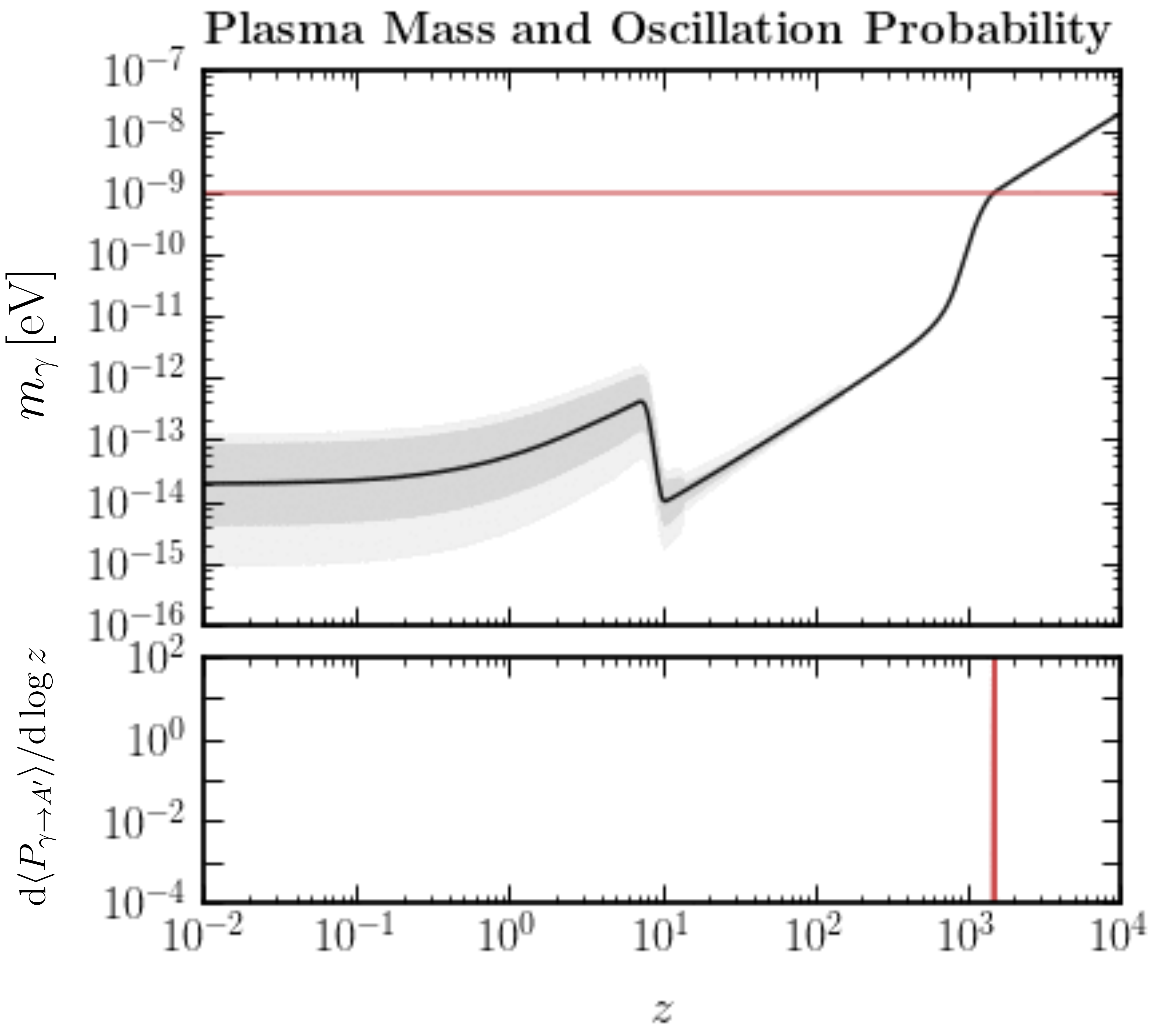
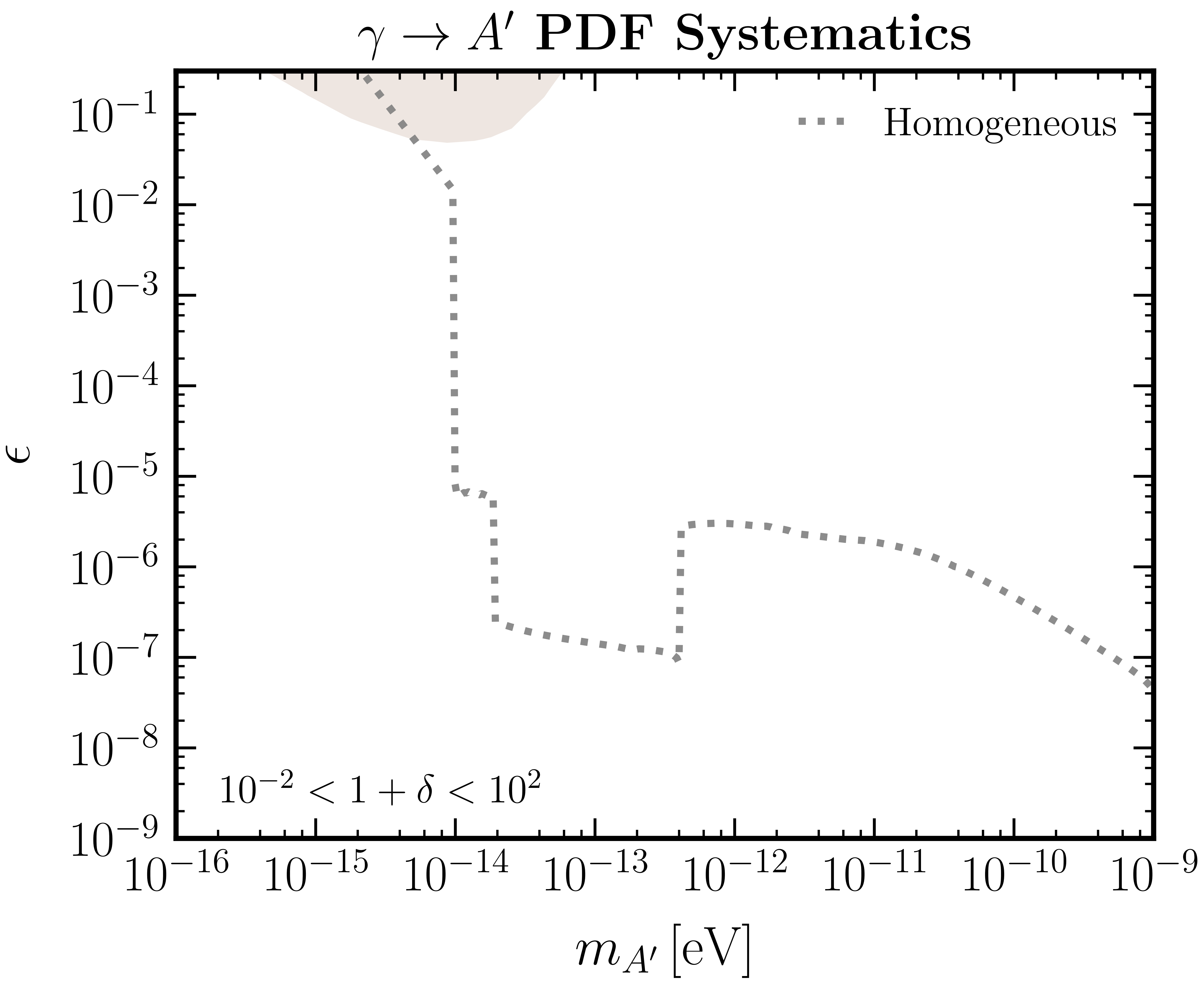


$\epsilon - m_{A'}$ constraints with inhomogeneities



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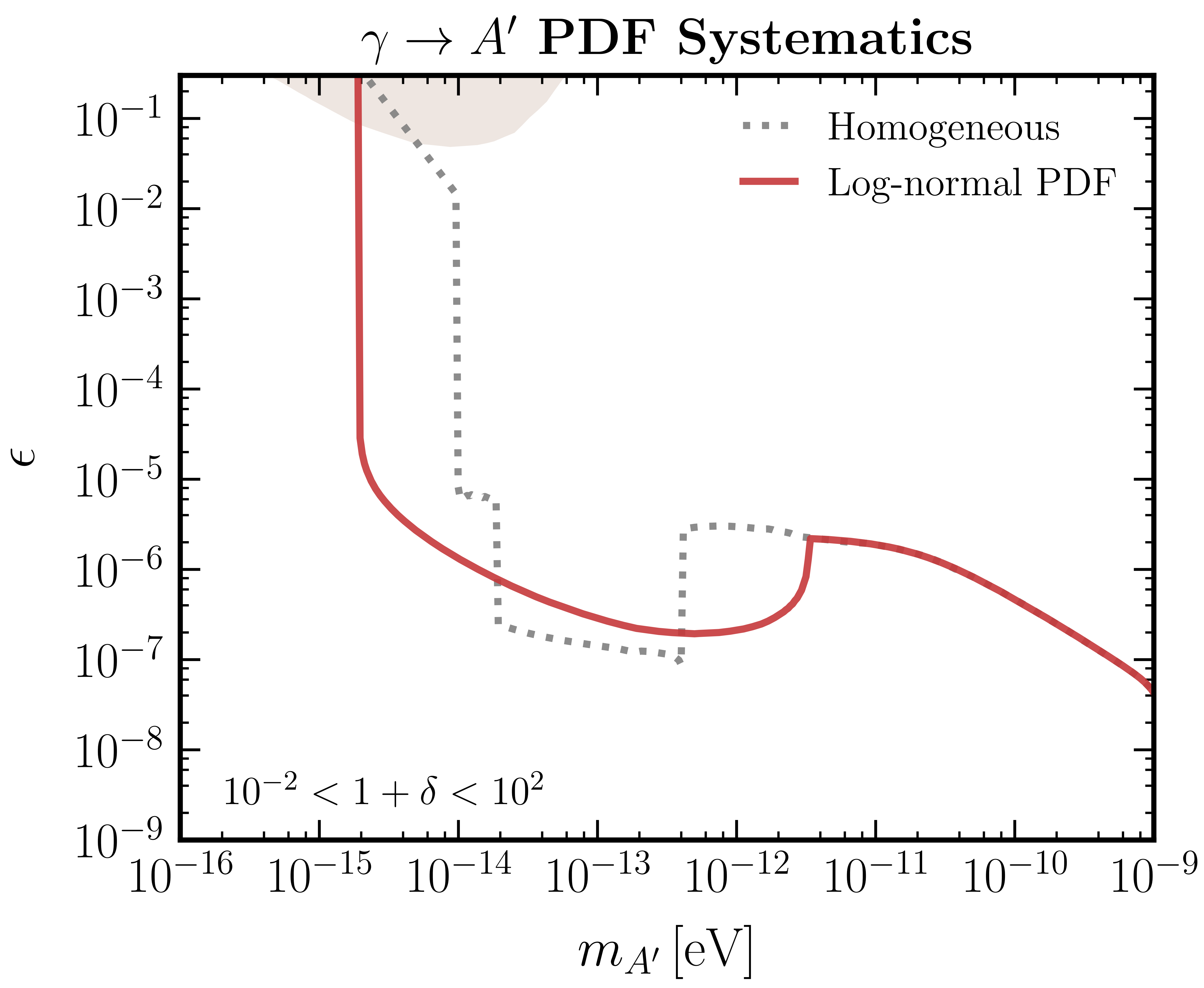

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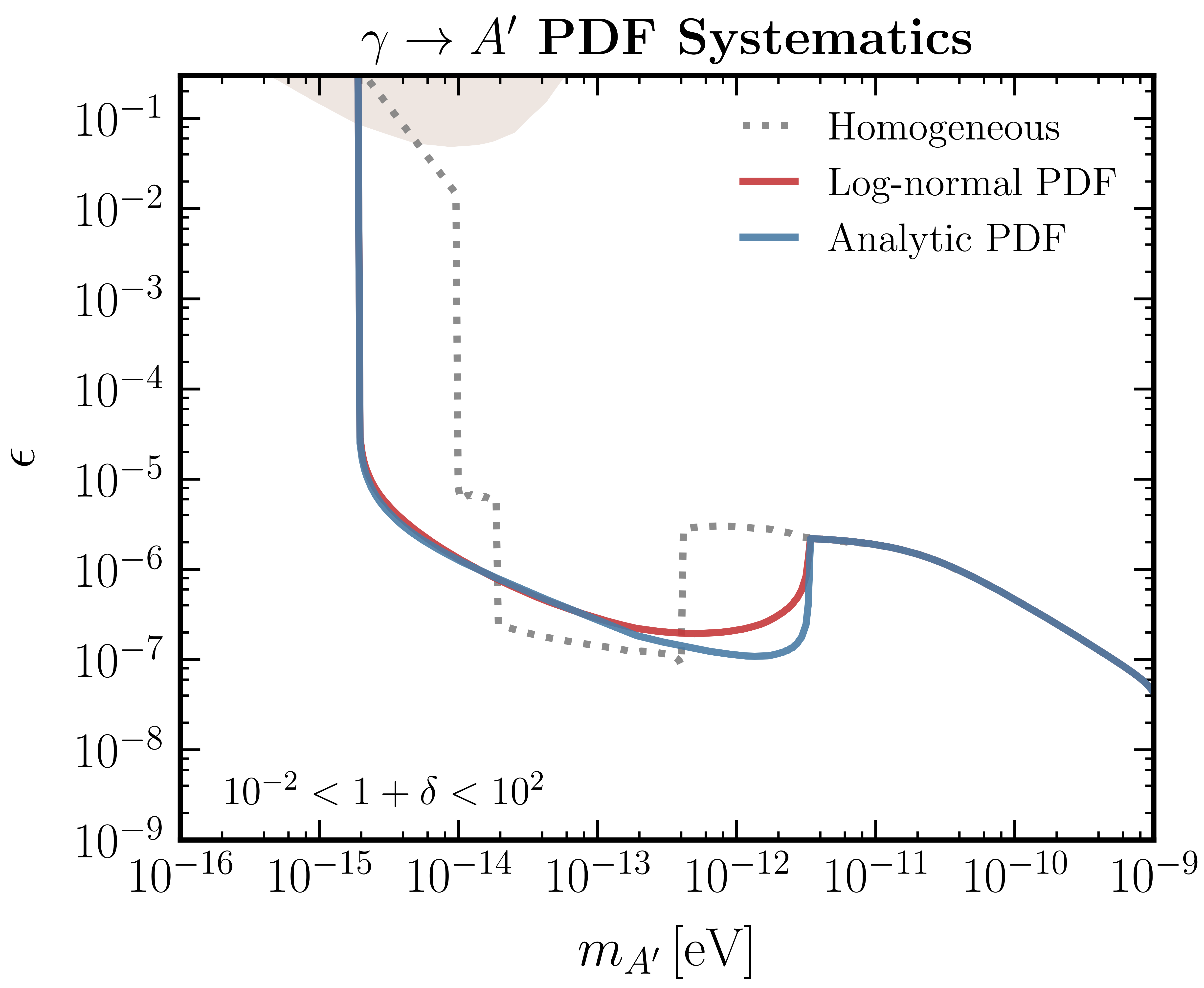

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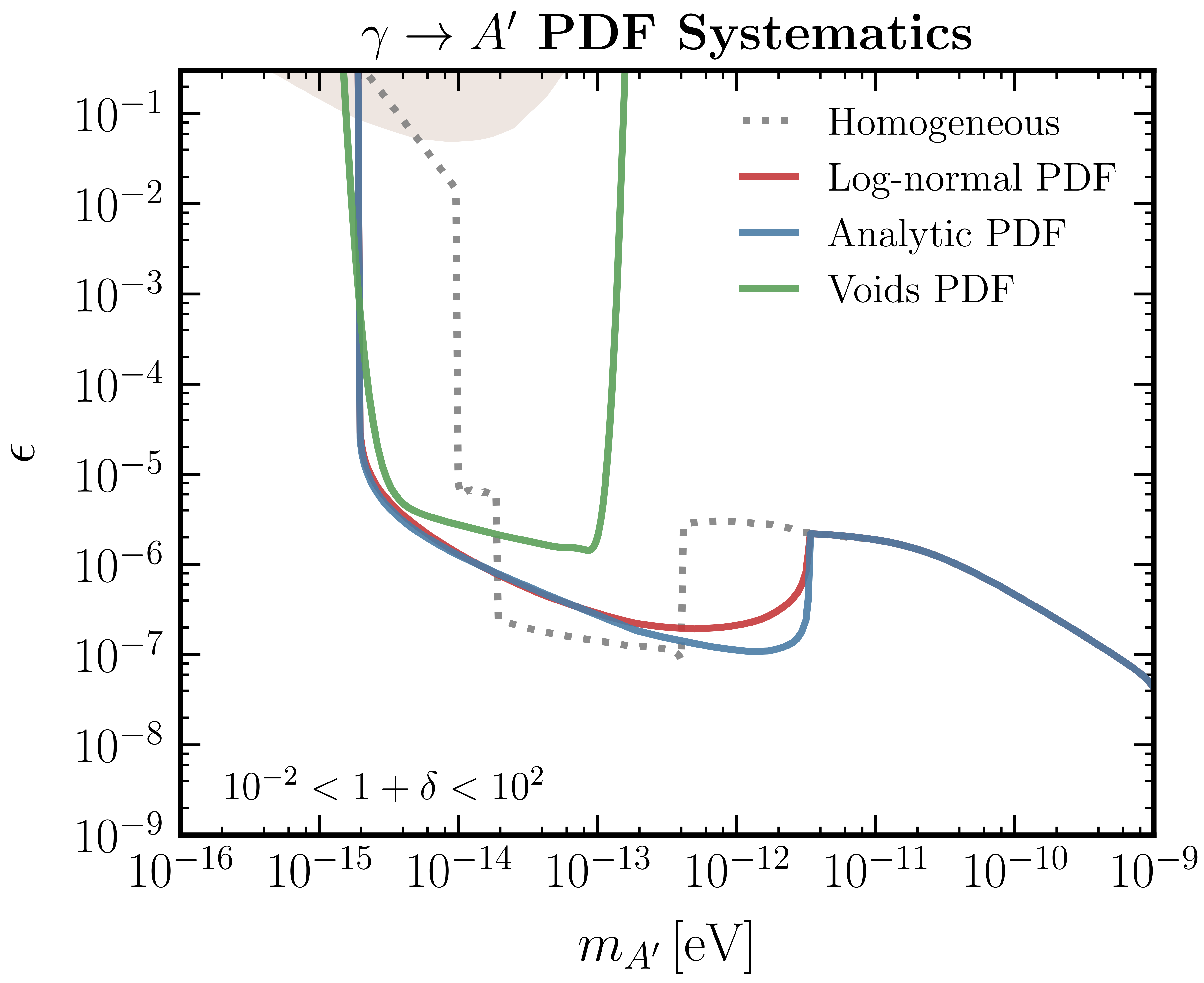

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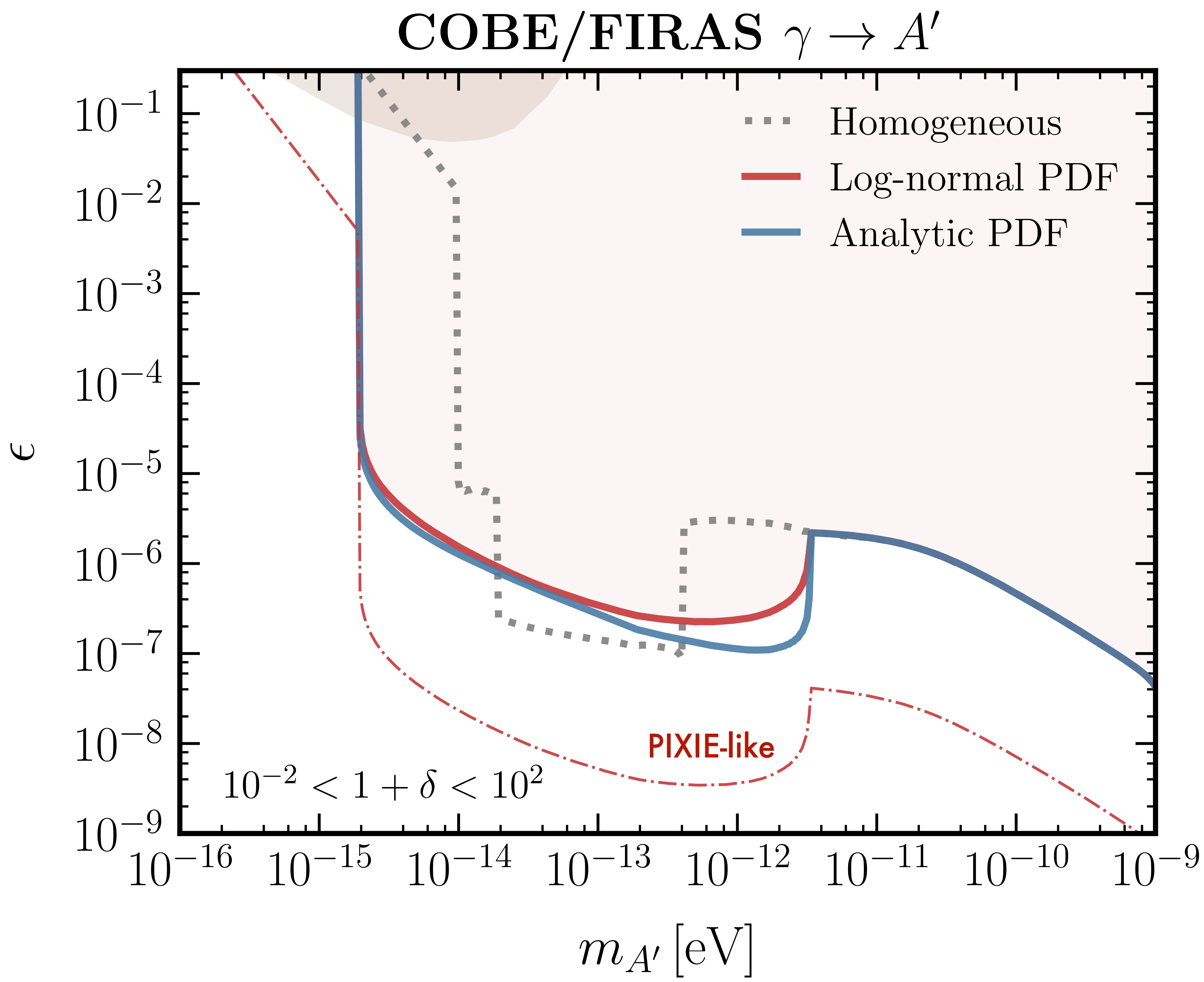
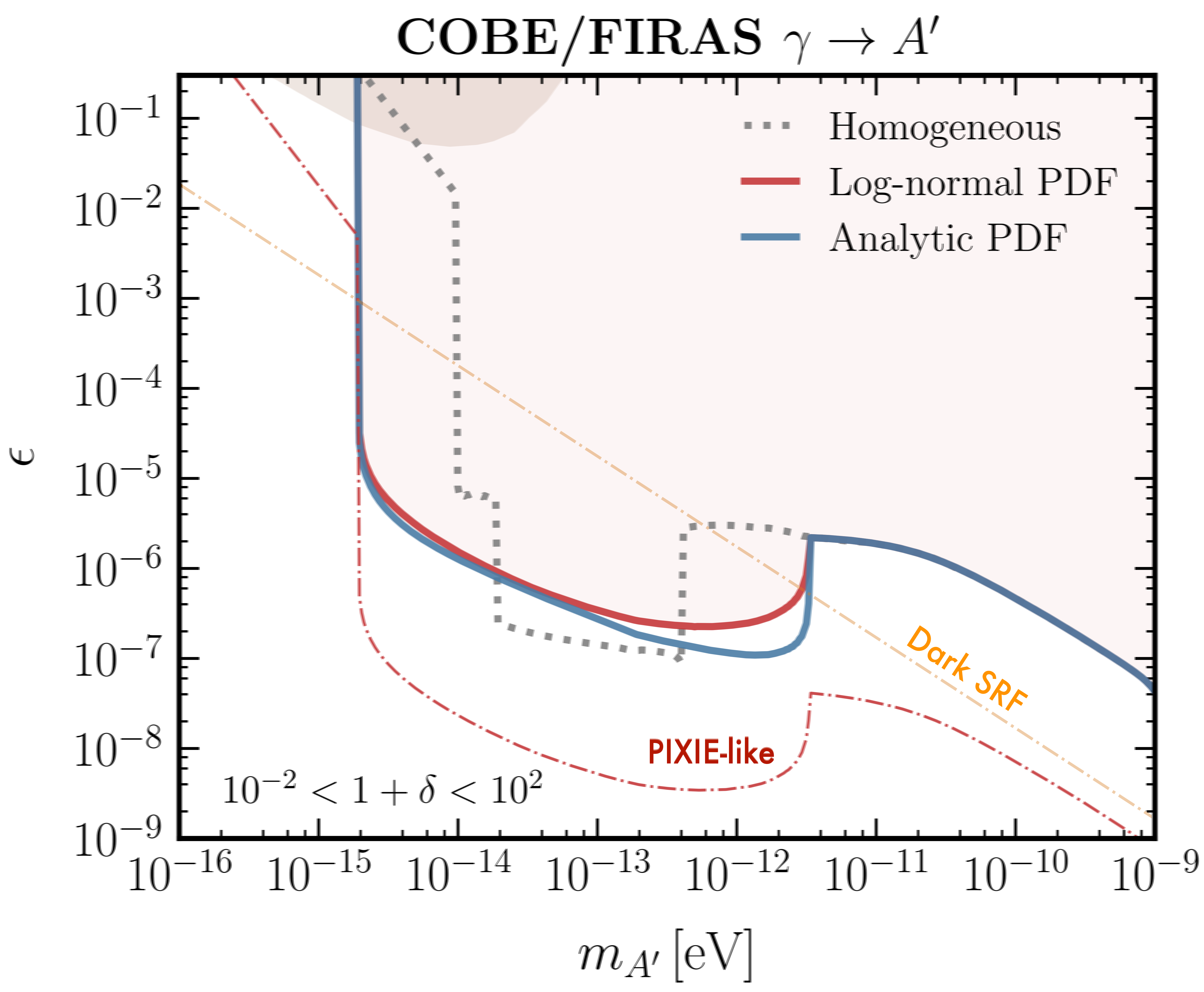


$\epsilon - m_{A'}$ constraints with inhomogeneities

$\gamma \to A'$



$\epsilon - m_{A'}$ constraints with inhomogeneities

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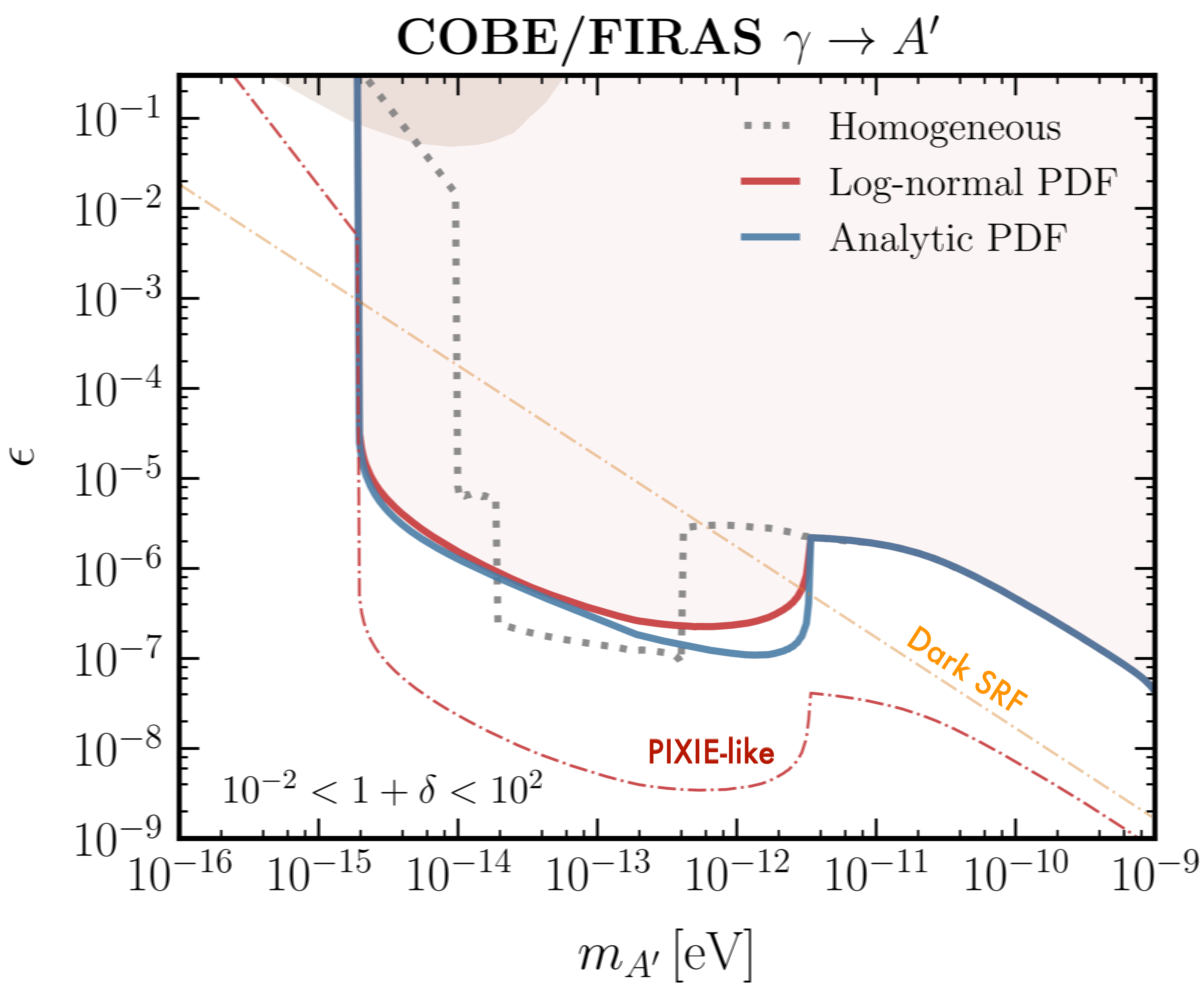
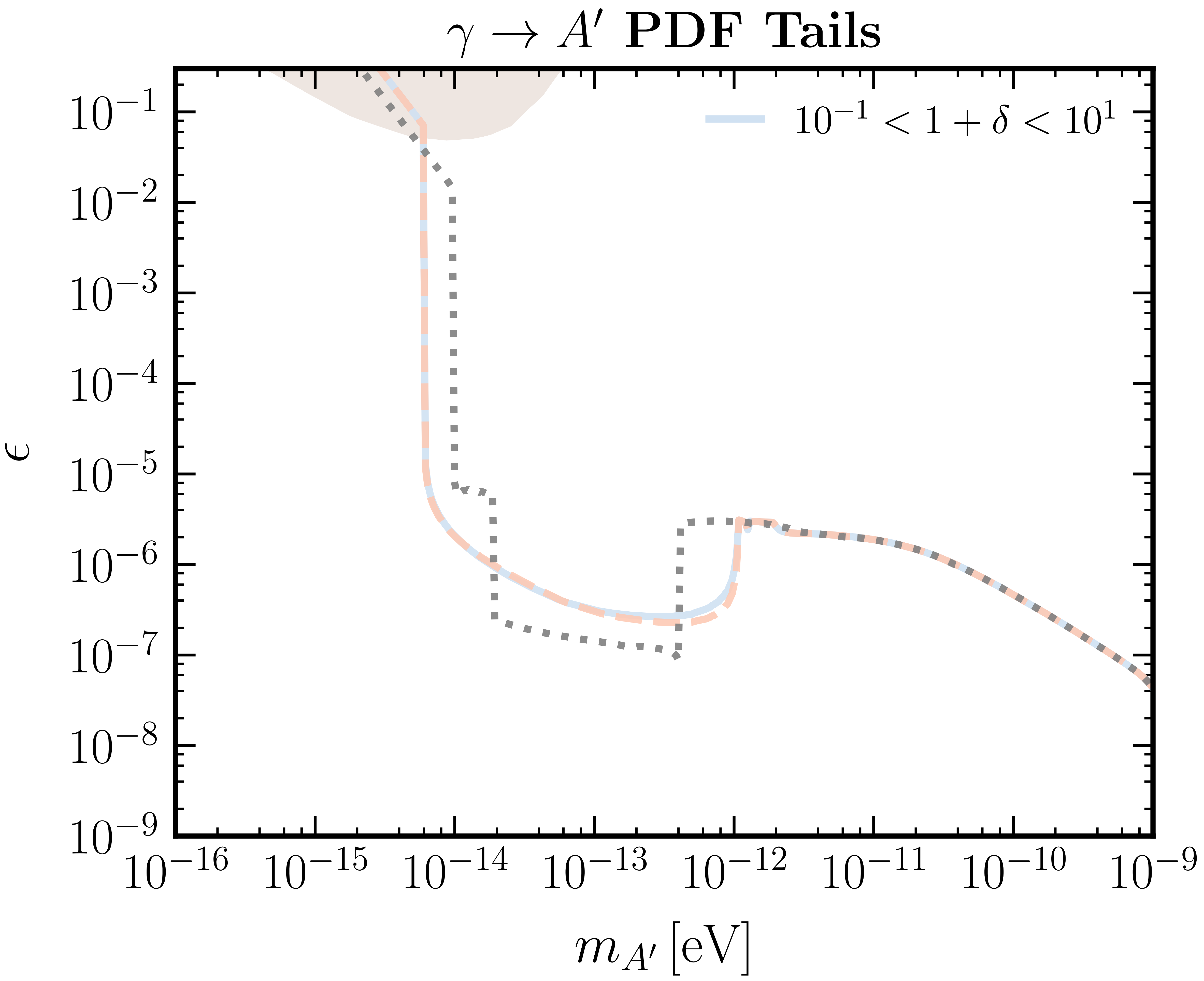


Note: Additional constraints apply when A' is the DM; see papers, also Witte et al [2003.13698]

Effect of larger over/under-densities



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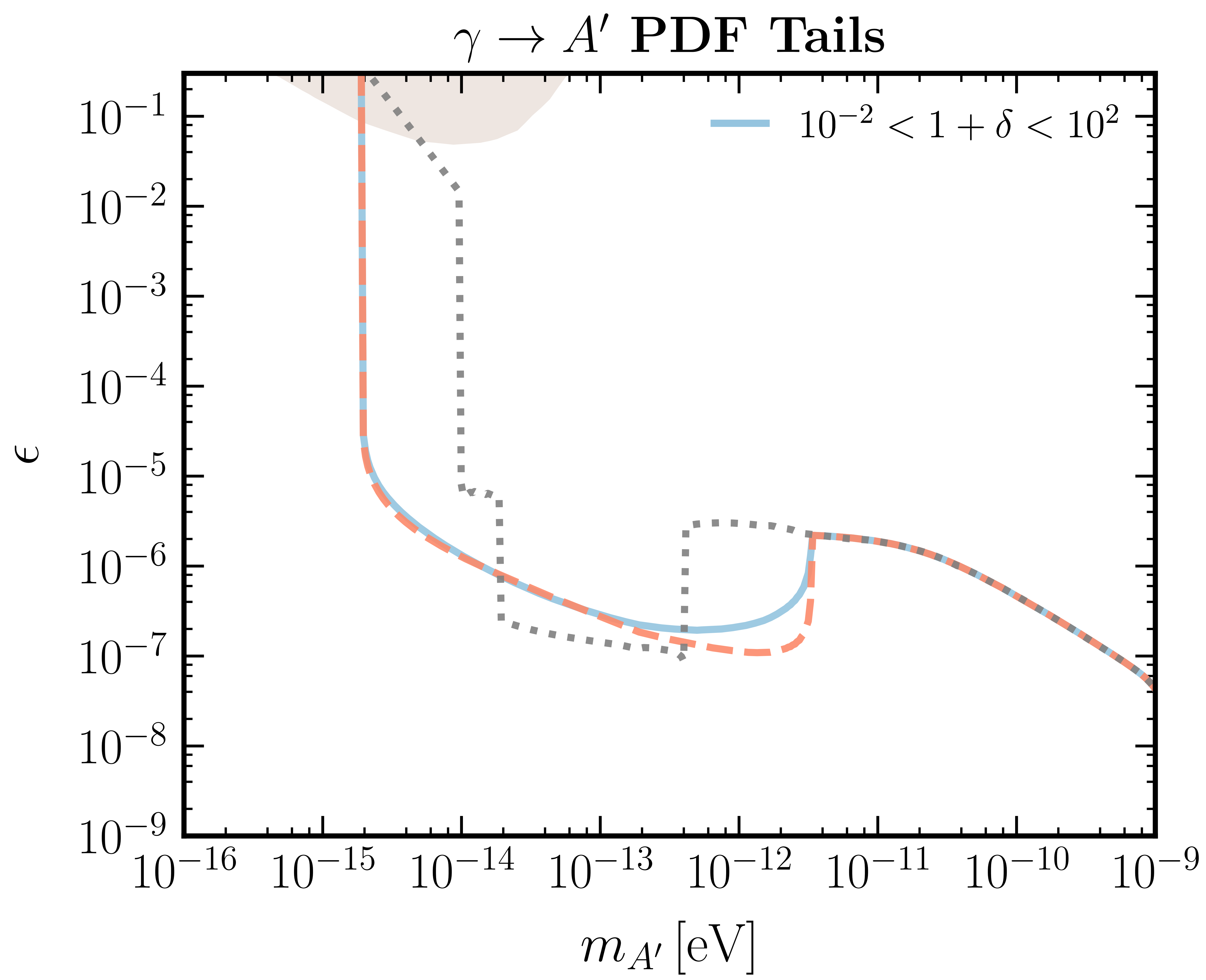

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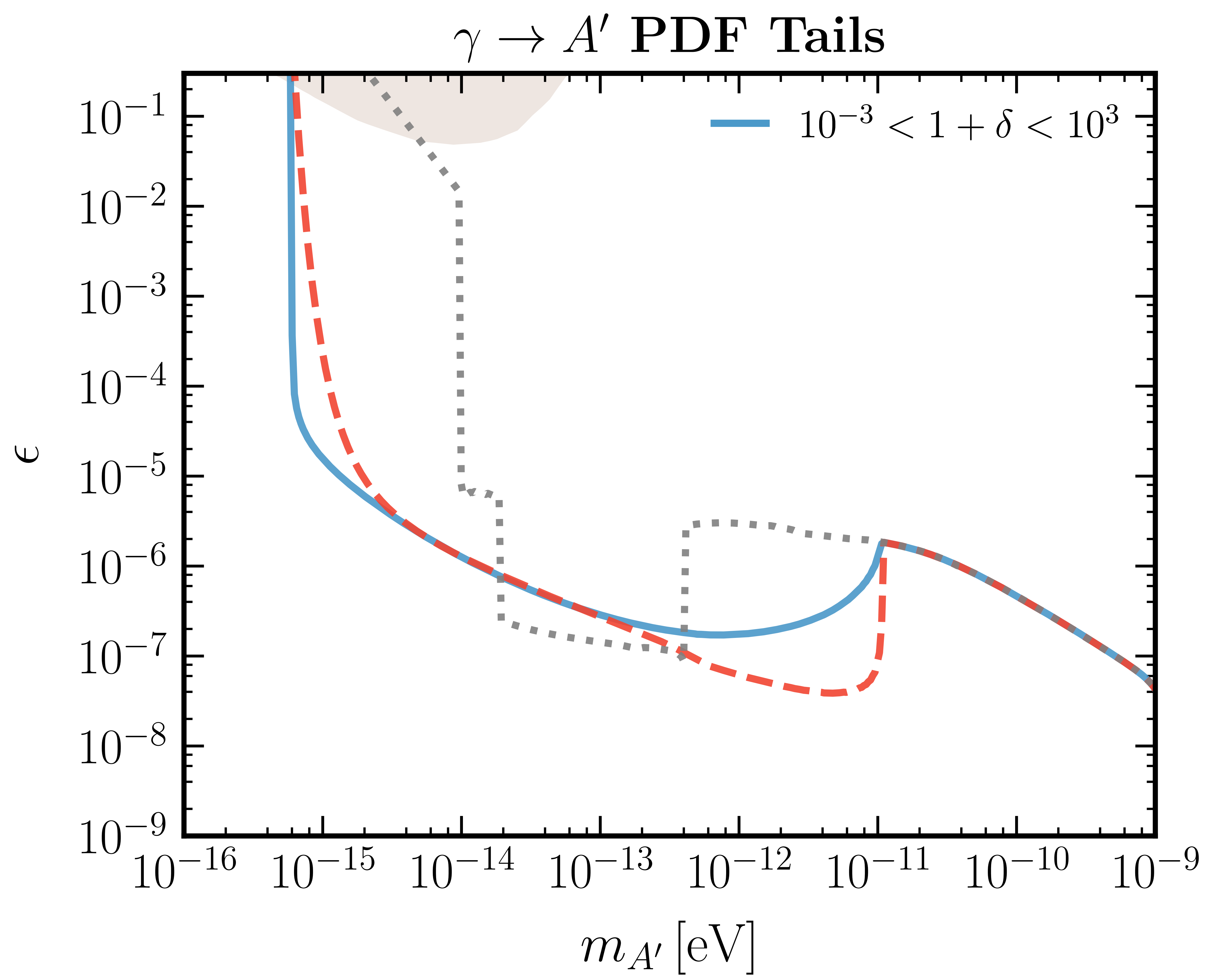

Effect of larger over/under-densities

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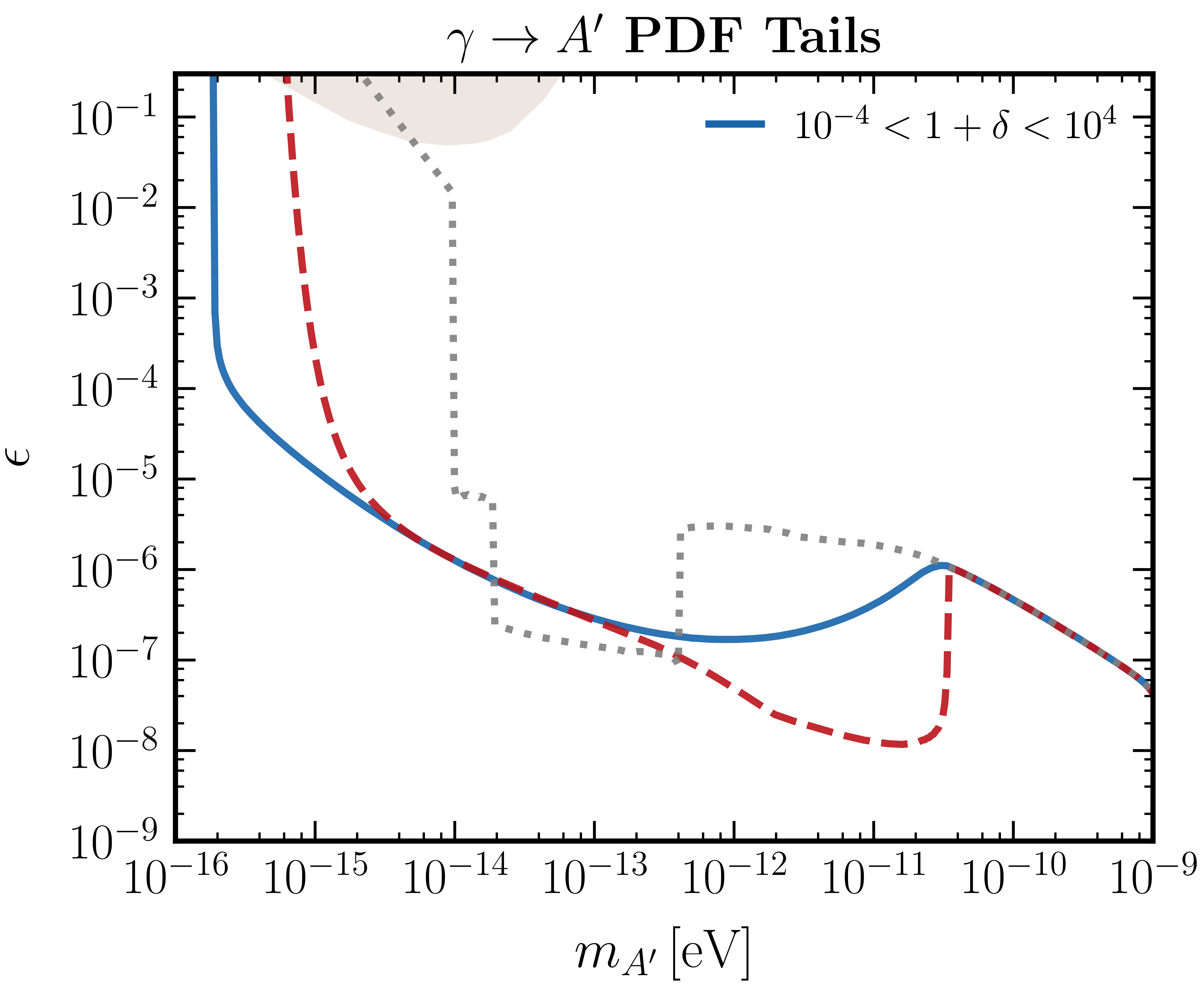

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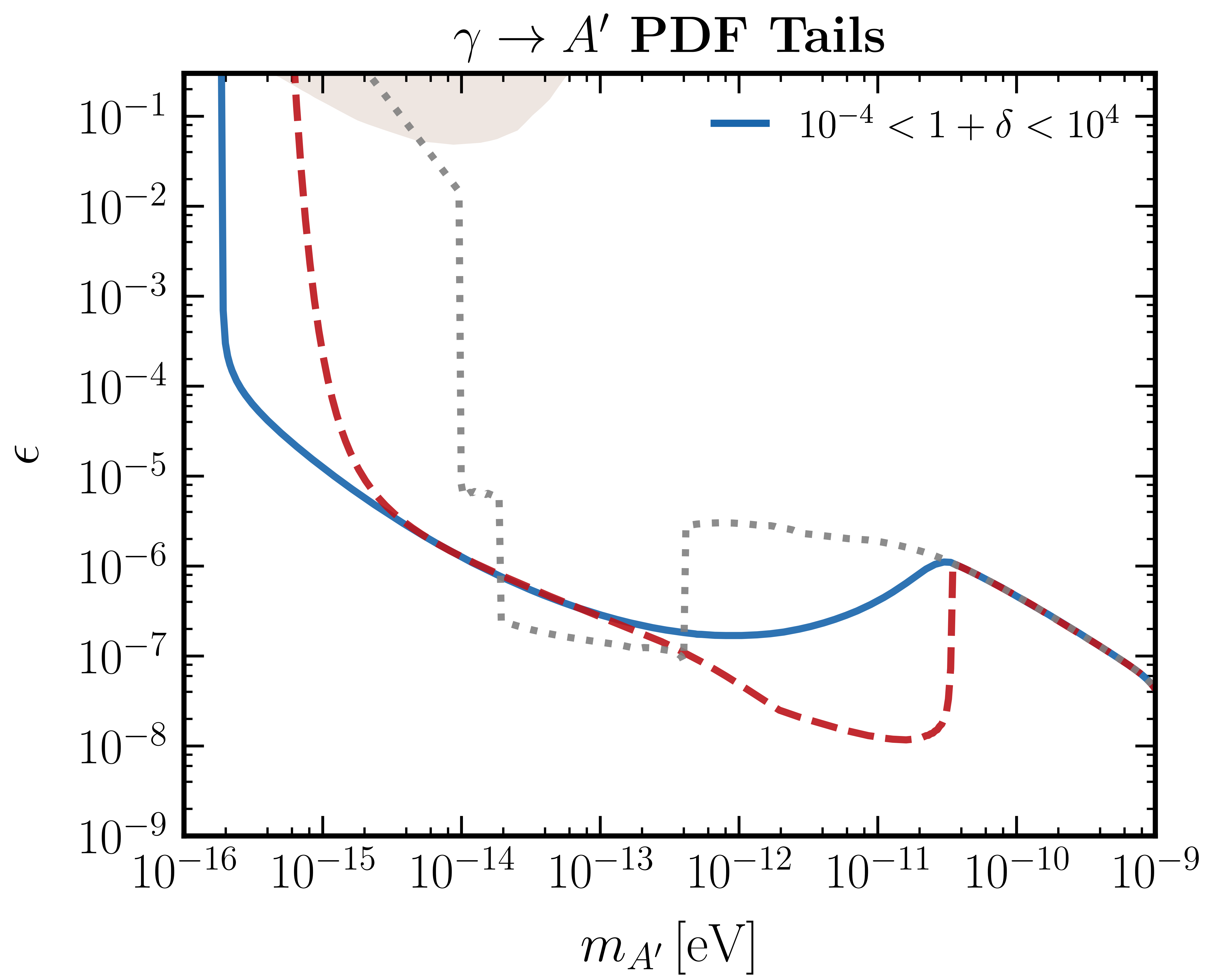
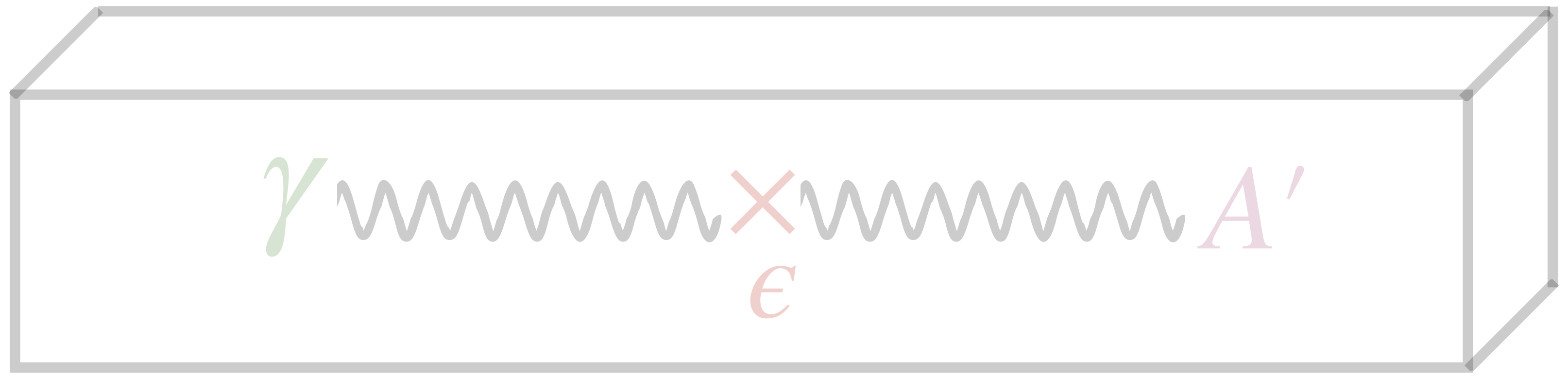
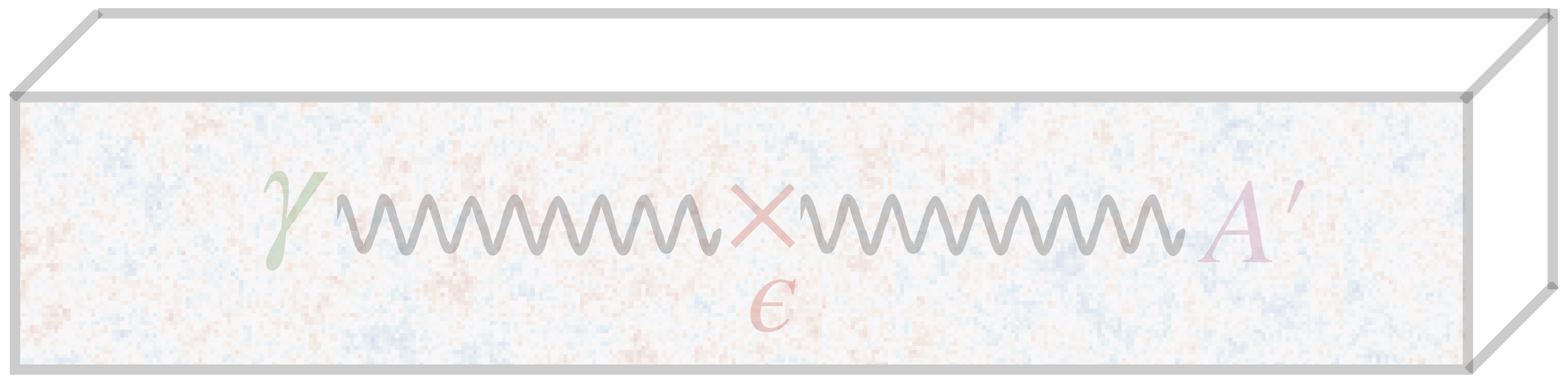


Stronger constraints are possible with a better understanding of larger over/under-densities

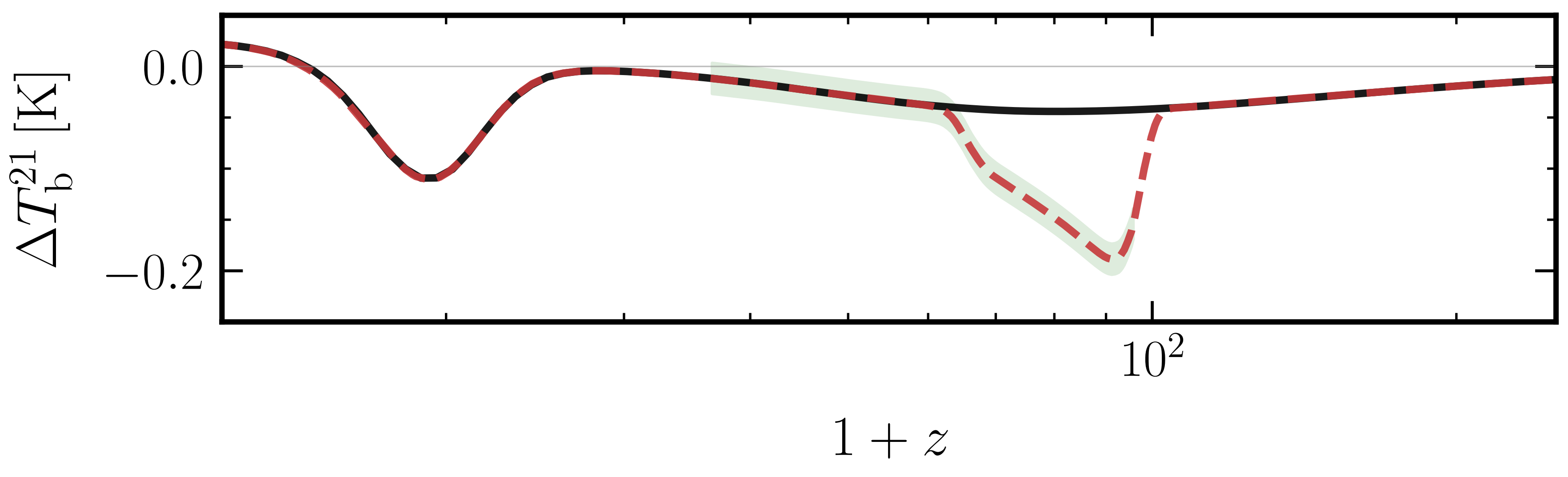
Outline



Dark photons
and resonant conversions



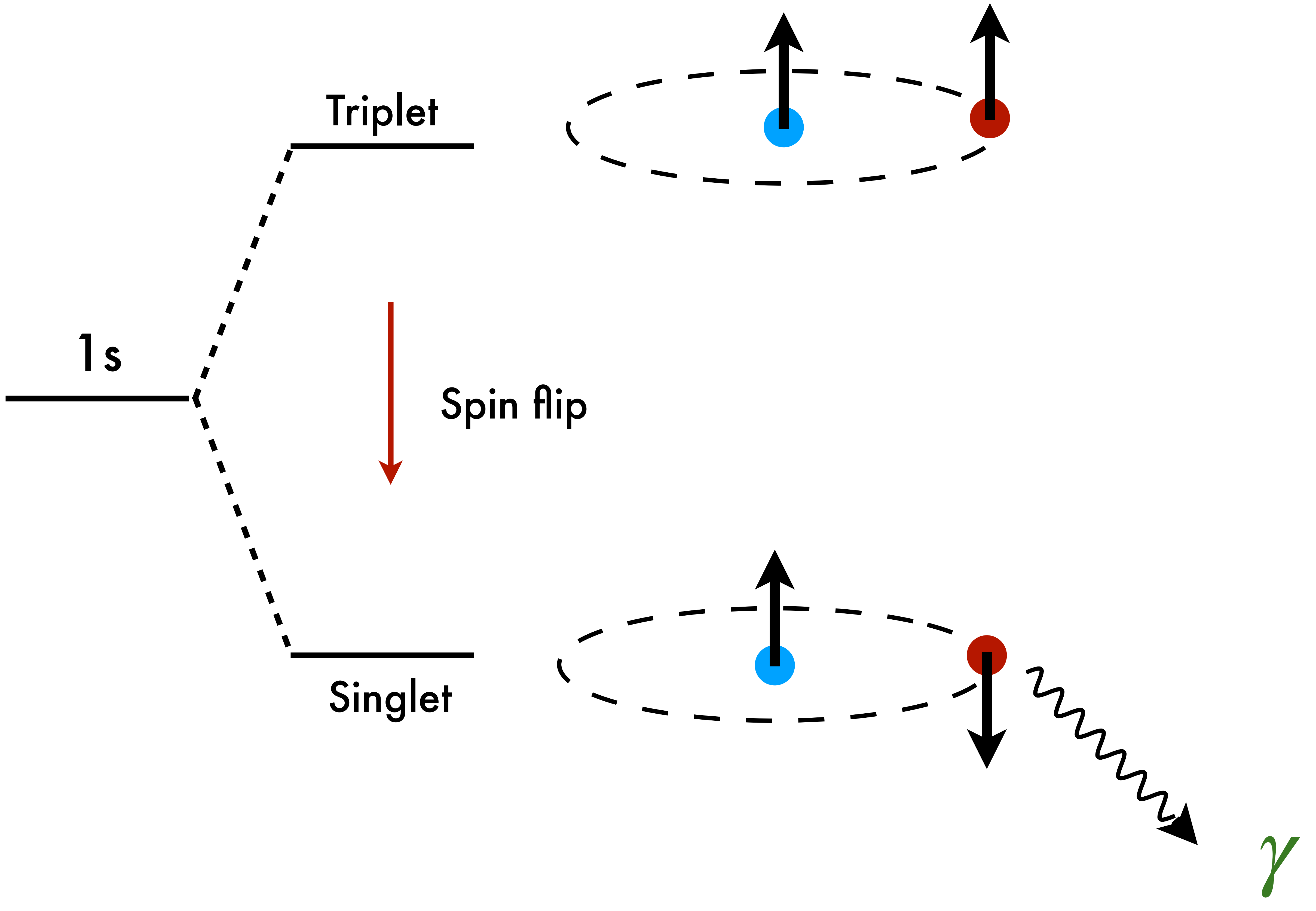
Dark photon oscillations
with inhomogeneities



Dark photon signatures
in 21-cm

21-cm primer

Hyperfine splitting of hydrogen 1s:



$\omega \approx 5.9\,\mu\mathrm{ev}$

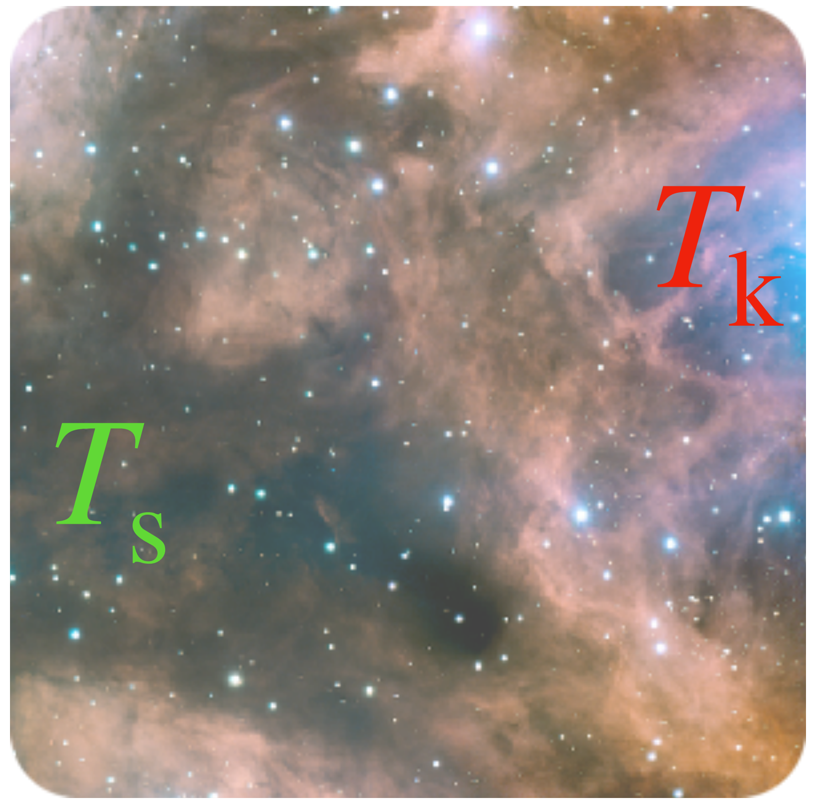
$\lambda \approx 21\,\mathrm{cm}$

Spin temperature T_s

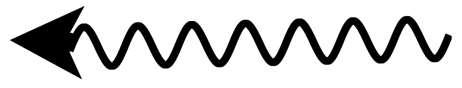
$$\frac{n_t}{n_s} \equiv 3\exp\left(-\frac{\omega_{21}}{T_s}\right)$$

21-cm primer

Neutral hydrogen (HI)
In the intergalactic medium (IGM)

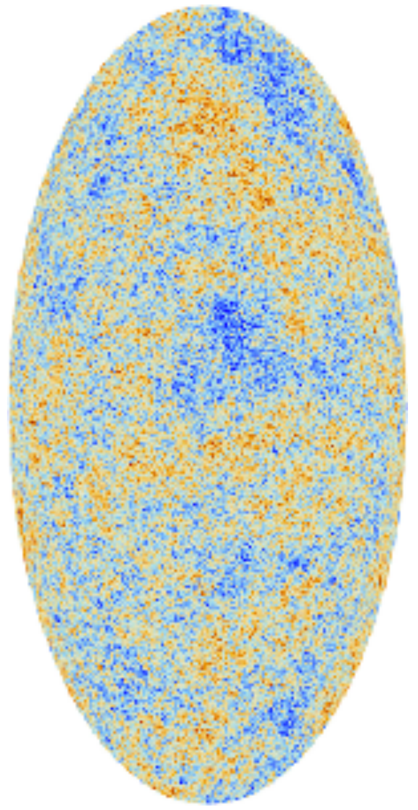


$\omega = \omega_{21}$



T_γ

CMB
Source of 21-cm photons



Spin temperature T_s

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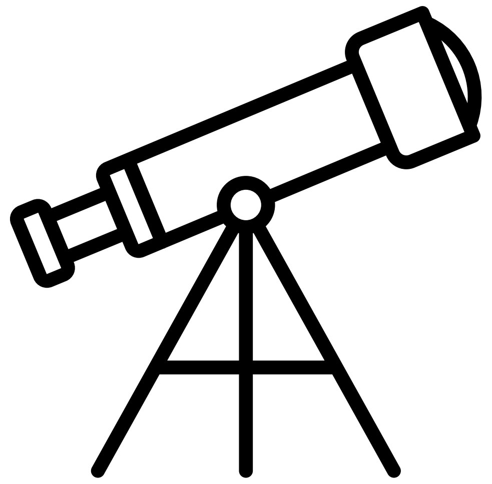
21-cm primer

Observation

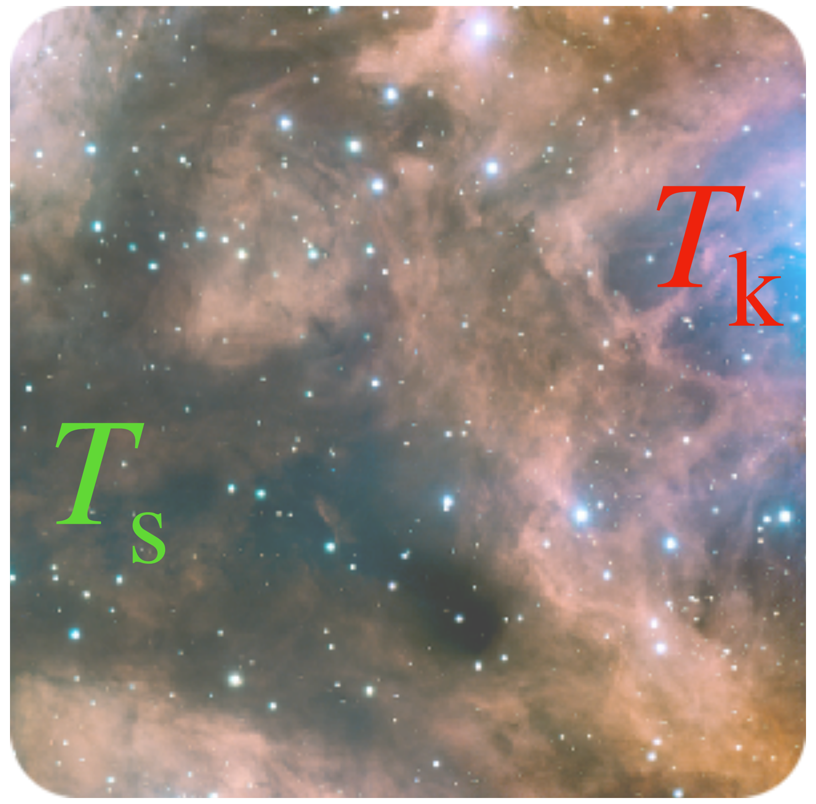


$$\omega_{\rm obs} = \frac{\omega_{21}}{1+z}$$

$T_{\rm b}^{21}$

Neutral hydrogen (HI)

In the intergalactic medium (IGM)



$T_{\rm k}$

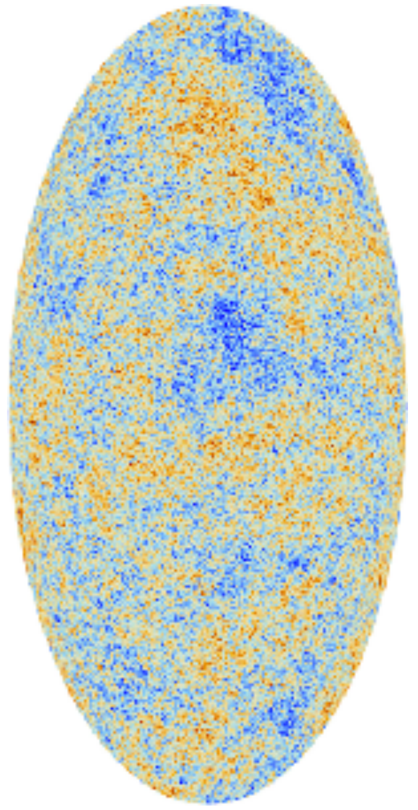
$T_{\rm s}$

$\omega = \omega_{21}$

T_γ

CMB

Source of 21-cm photons

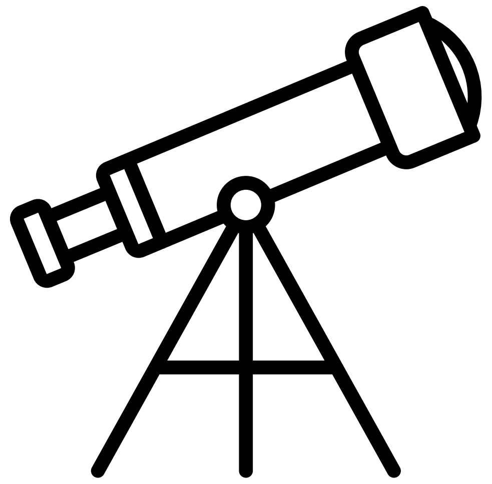


Spin temperature $T_{\rm s}$

$$\frac{n_{\rm t}}{n_{\rm s}} \equiv 3 \exp\left(-\frac{\omega_{21}}{T_{\rm s}}\right)$$

21-cm primer

Observation

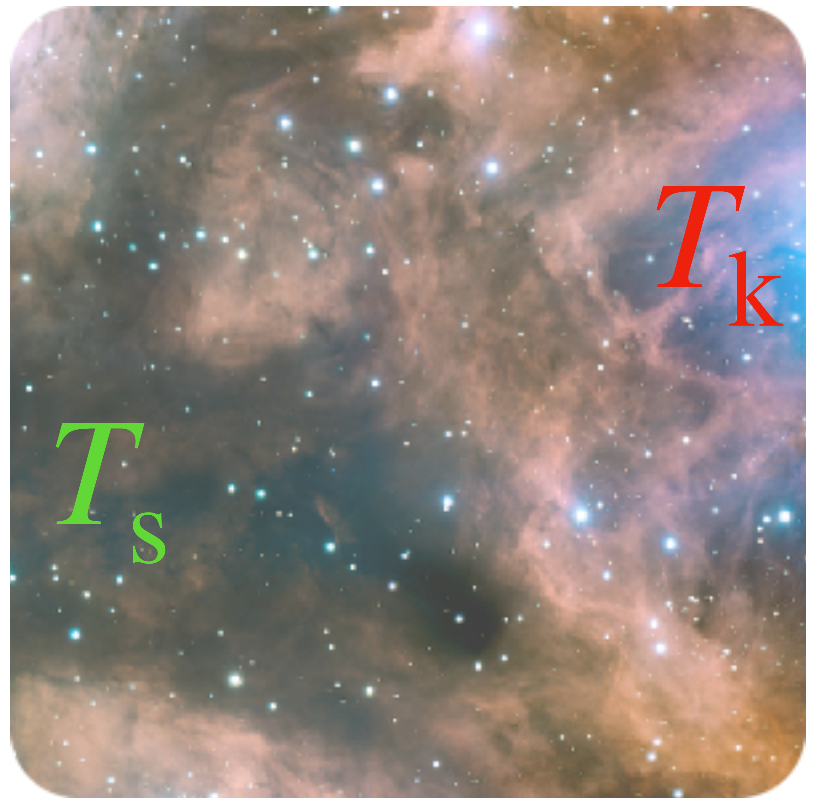


$$\omega_{\text{obs}} = \frac{\omega_{21}}{1+z}$$

T_{b}^{21}

Neutral hydrogen (HI)

In the intergalactic medium (IGM)



T_{k}

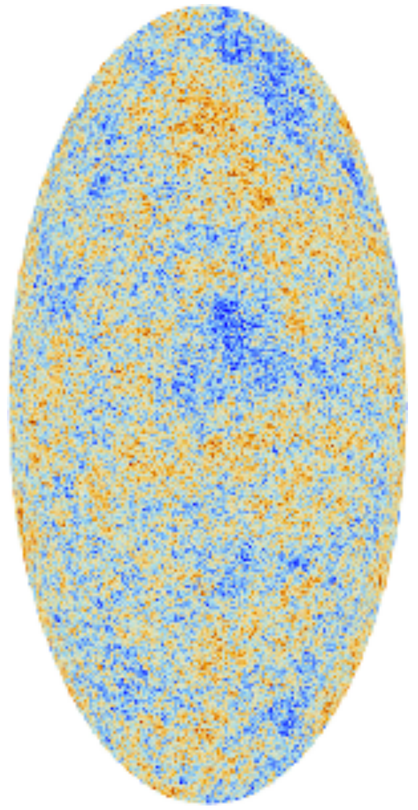
T_{s}

$\omega = \omega_{21}$

T_γ

CMB

Source of 21-cm photons



Brightness temperature ΔT_{b}^{21}

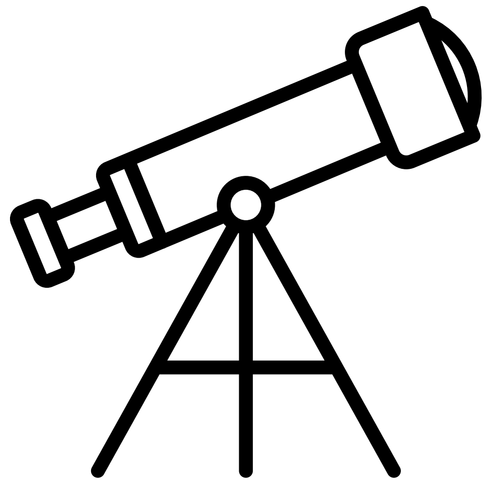
$$\Delta T_{\text{b}}^{21} \propto x_{\text{HI}} \left(1 - \frac{T_\gamma}{T_{\text{s}}}\right)$$

Spin temperature T_{s}

$$\frac{n_{\text{t}}}{n_{\text{s}}} \equiv 3 \exp\left(-\frac{\omega_{21}}{T_{\text{s}}}\right)$$

21-cm primer

Observation

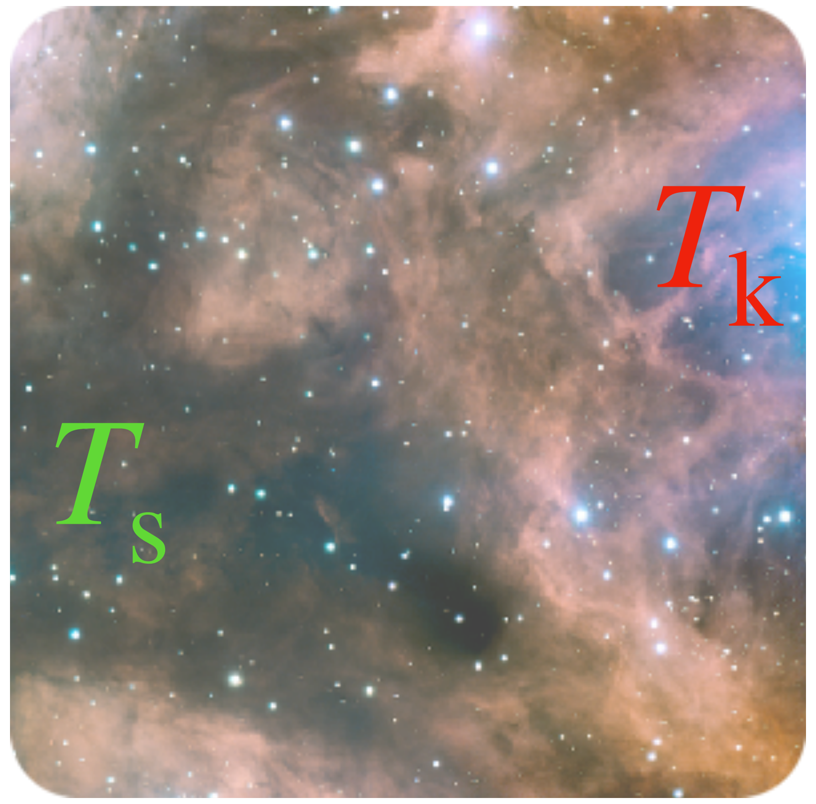


$$\omega_{\rm obs} = \frac{\omega_{21}}{1+z}$$

$T_{\rm b}^{21}$

Neutral hydrogen (HI)

In the intergalactic medium (IGM)



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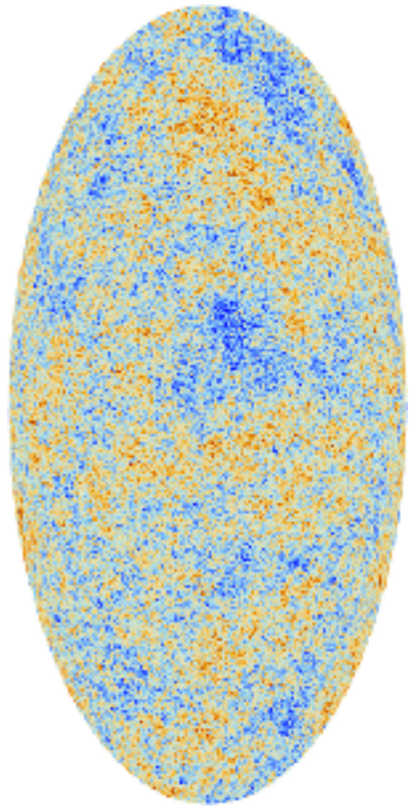


Brightness temperature $\Delta T_{\rm b}^{21}$

$$\Delta T_{\rm b}^{21} \propto x_{\rm HI}\left(1 - \frac{T_\gamma}{T_{\rm s}}\right)$$

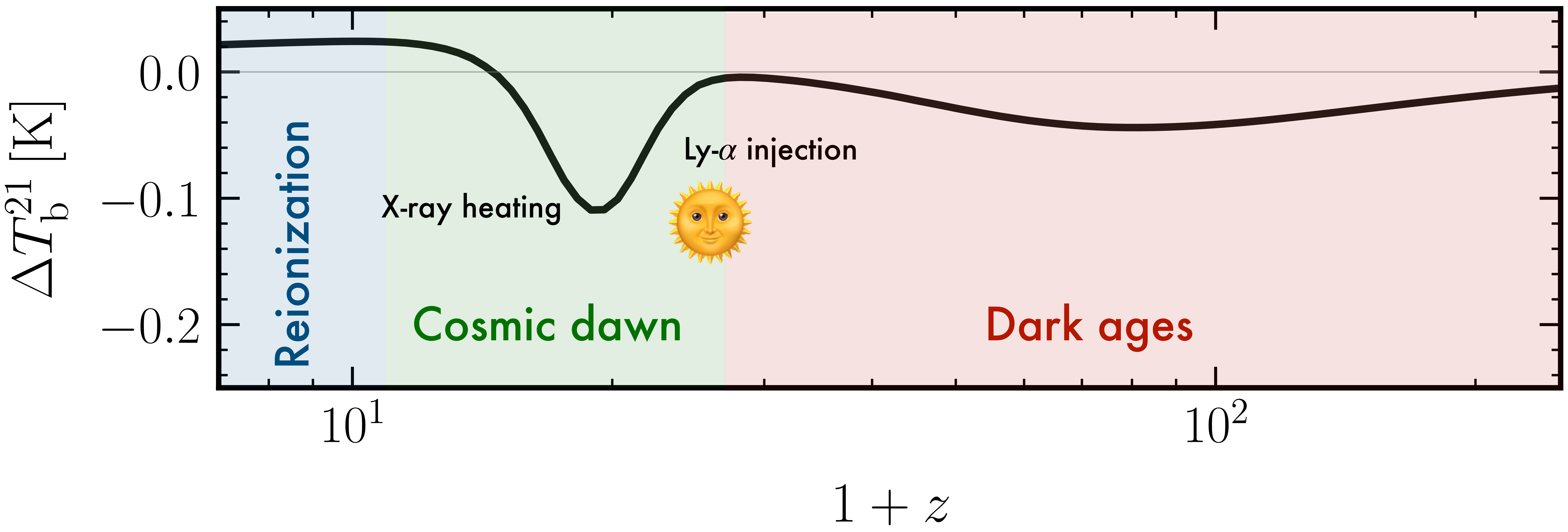
$T_{\rm s} > T_\gamma \implies \Delta T_{\rm b}^{21} > 0$ (emission)

$T_{\rm s} < T_\gamma \implies \Delta T_{\rm b}^{21} < 0$ (absorption)

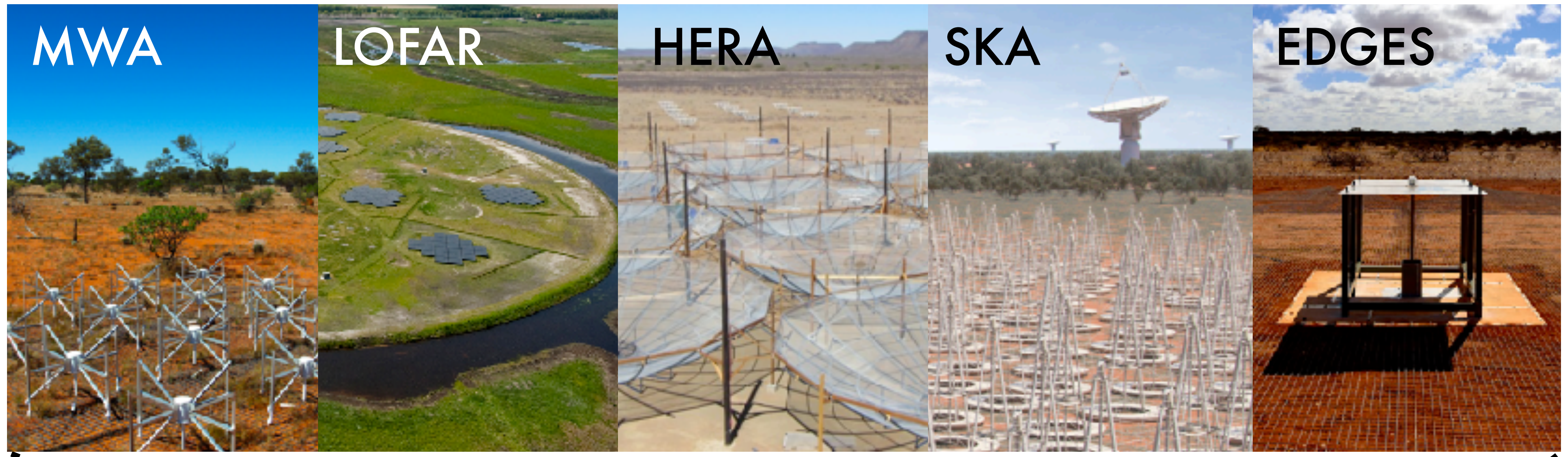
Spin temperature $T_{\rm s}$

$$\frac{n_{\rm t}}{n_{\rm s}} \equiv 3\exp\left(-\frac{\omega_{21}}{T_{\rm s}}\right)$$

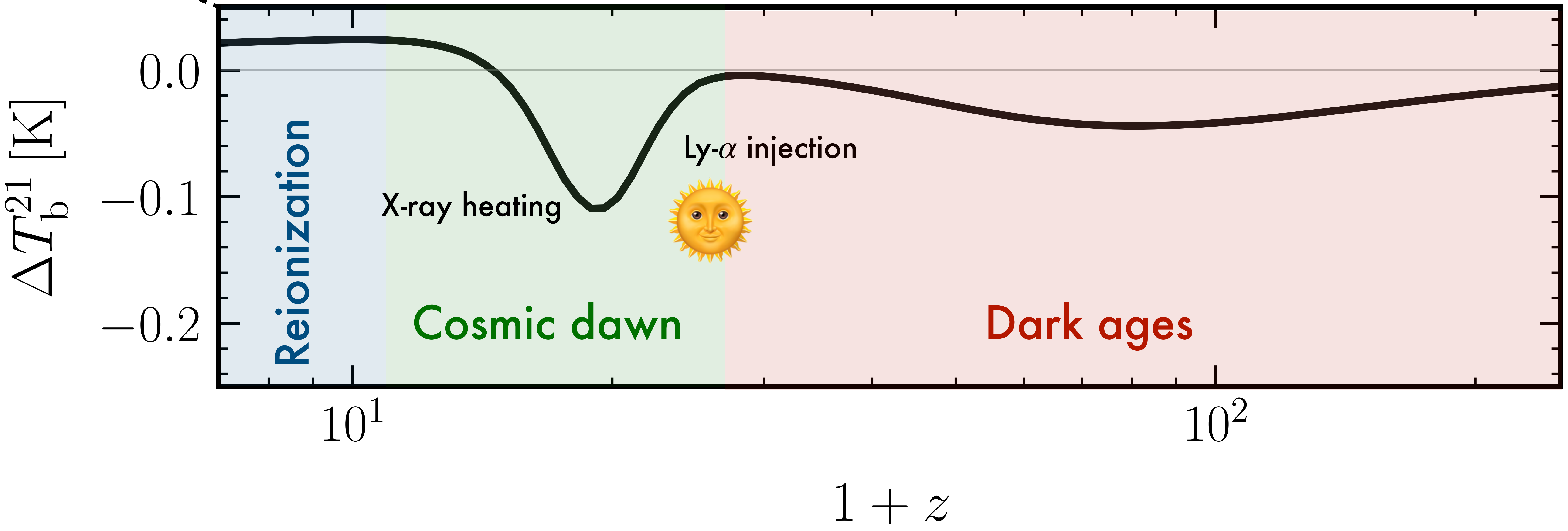
Observations of the (global) 21-cm signal



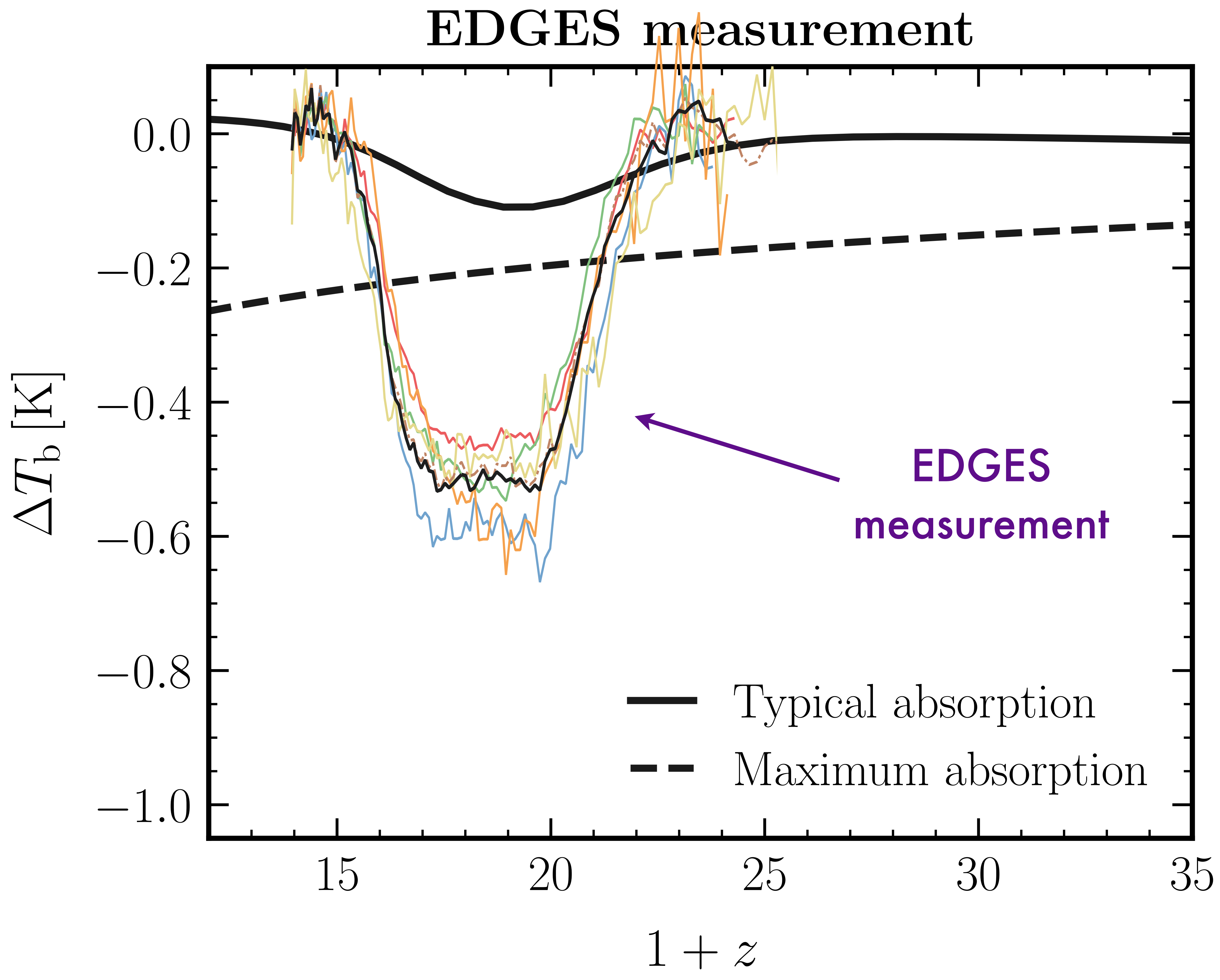
Observations of the (global) 21-cm signal



Many current/upcoming observations targeting cosmic dawn and reionization



EDGES 21-cm signal
(Experiment to Detect the Global EoR Signature)



Bowman et al, Nature (2018)

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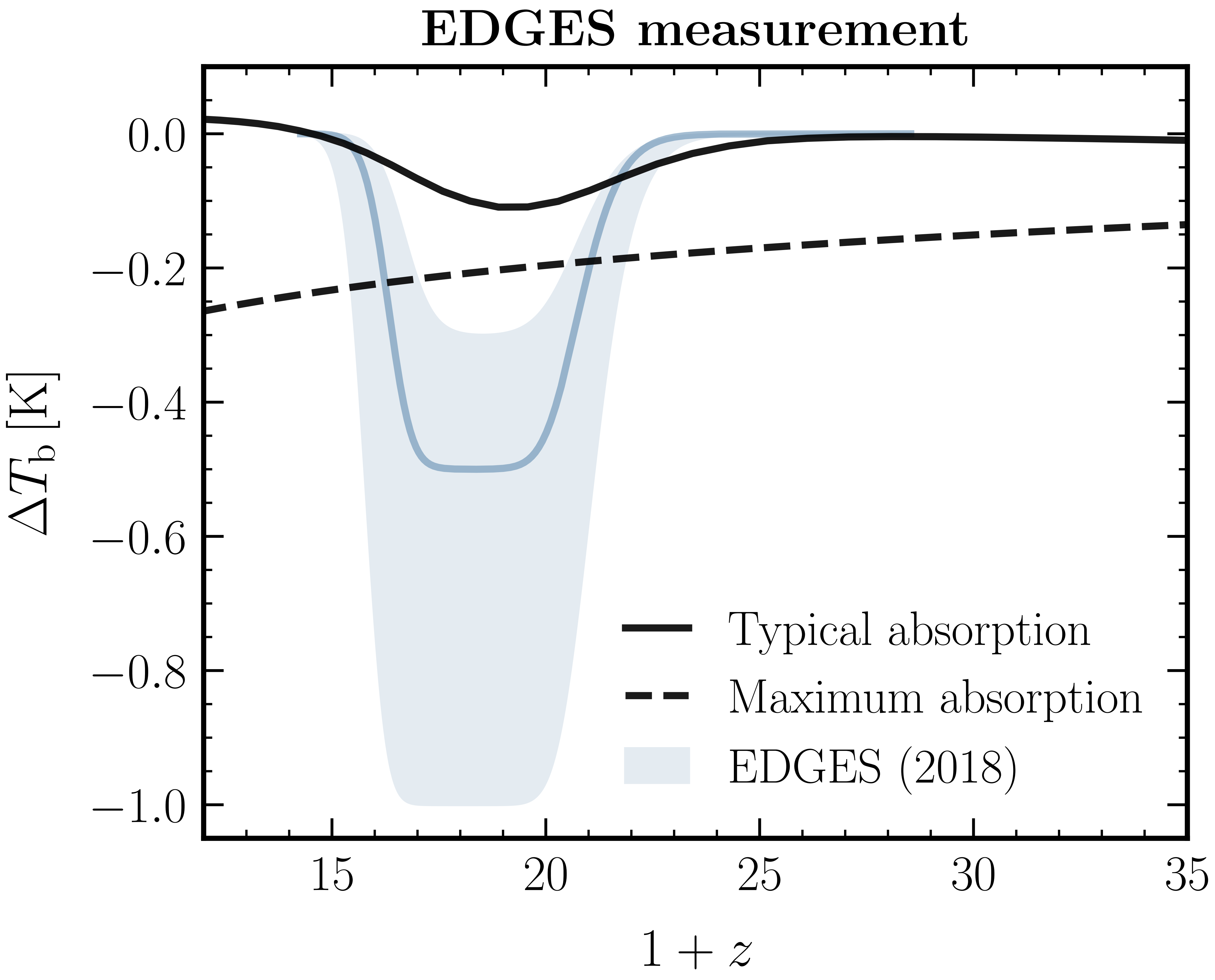

Bowman et al, Nature (2018)

Extra 21-cm absorption with new physics

$$\Delta T_{\mathrm{b}}^{21} \propto 1 - \frac{T_\gamma}{T_{\mathrm{s}}}$$

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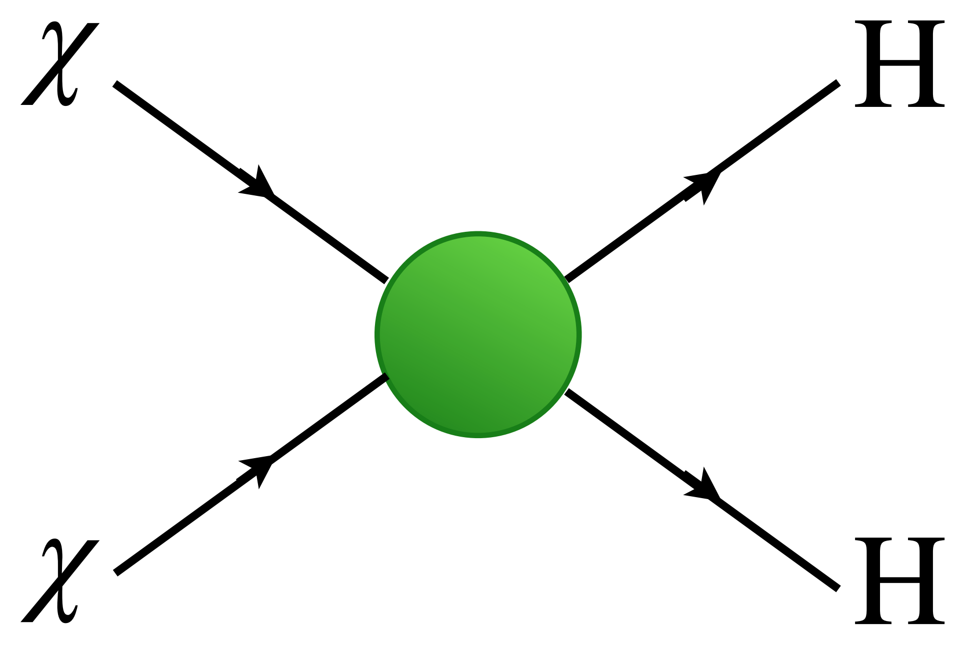
Cool baryons

Muñoz & Loeb [1802.10094]
Falkowski & Petraki [1803.10096]
Barkana [1803.06698]
Barkana et al [1803.03091]
Berlin et al [1803.02804]
Liu et al [1908.06986]



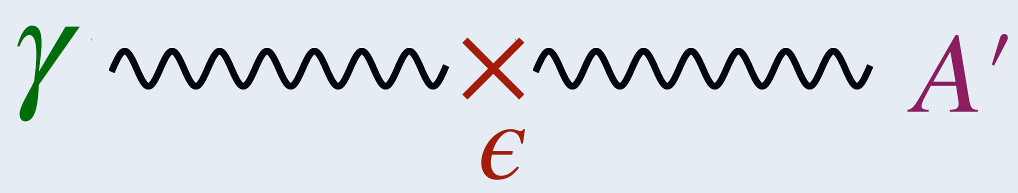
Extra 21-cm absorption with new physics

$$\Delta T_b^{21} \propto 1 - \frac{T_\gamma}{T_s}$$

Heat photons

Pospelov et al [1803.07048]
Moroi, Nakayama, Tang [1804.10378]
Choi, Seong, Yun [1911.00532]

$$T_\gamma > T_{\rm CMB}$$



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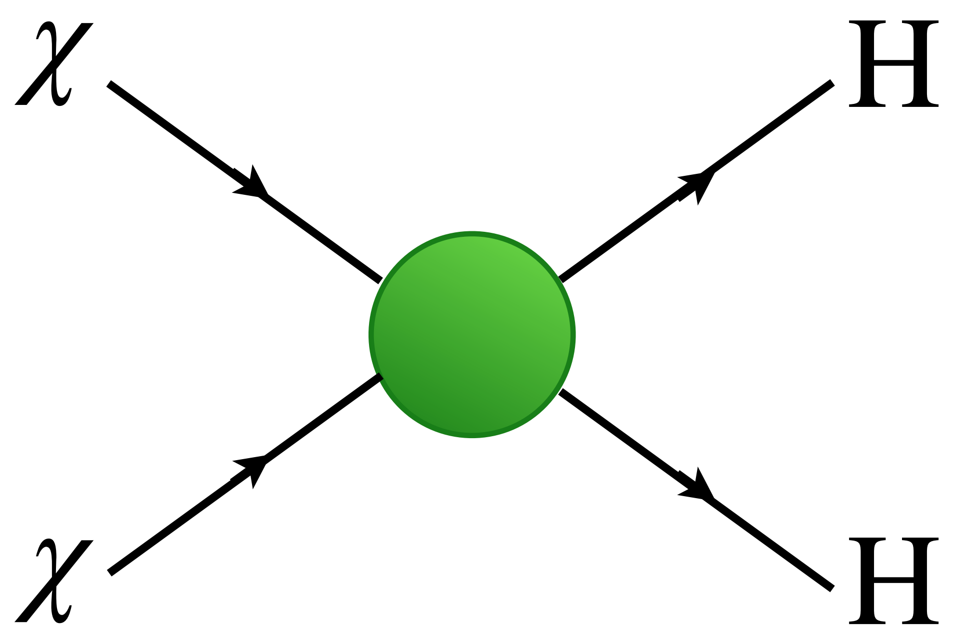
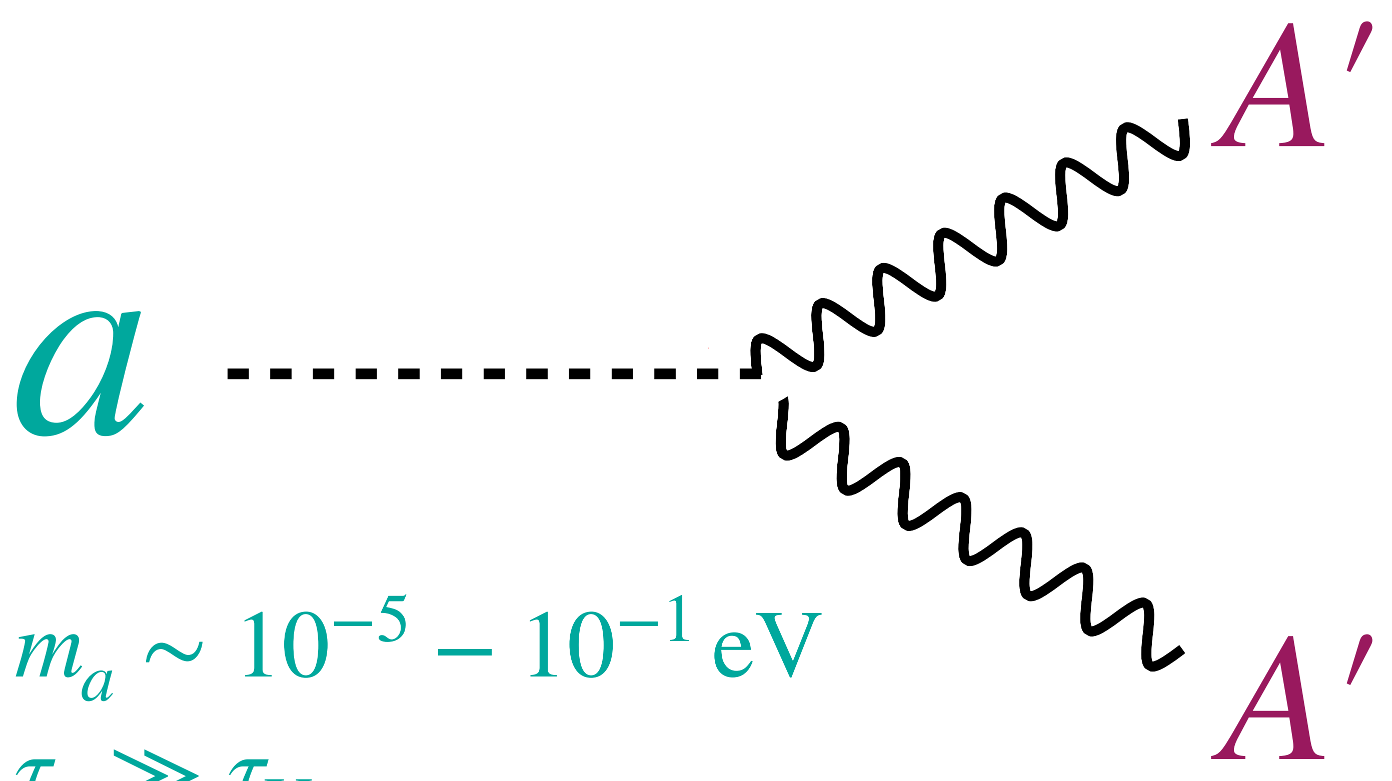


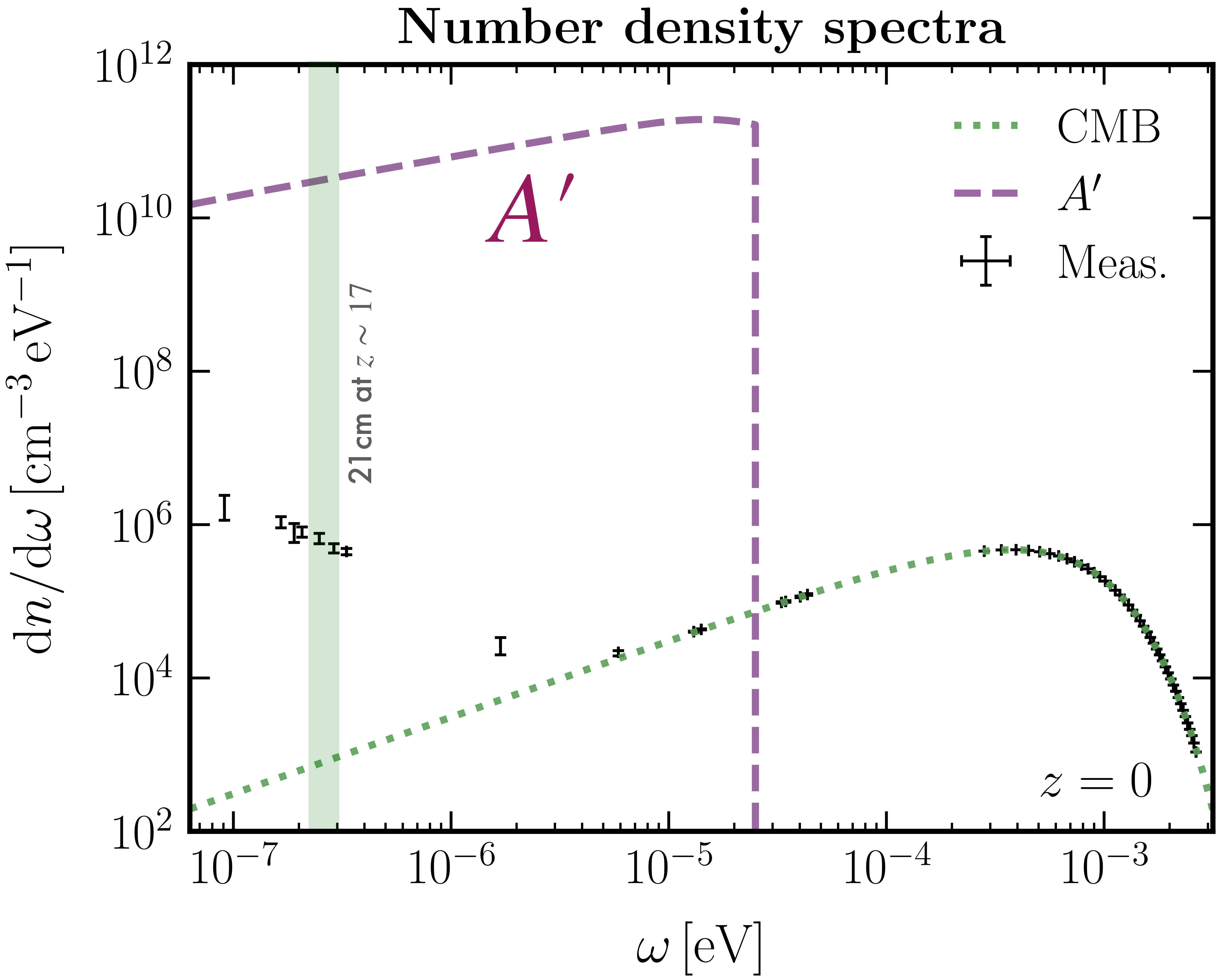
Heating the CMB with dark photon oscillations

Pospelov, Pradler, Ruderman, Urbano [1803.07048]

1. Decay of long-lived particle a (DM) to A'



$m_a \sim 10^{-5} - 10^{-1}\,\mathrm{eV}$
$\tau_a \gg \tau_U$
$\Omega_a = \Omega_{DM}$



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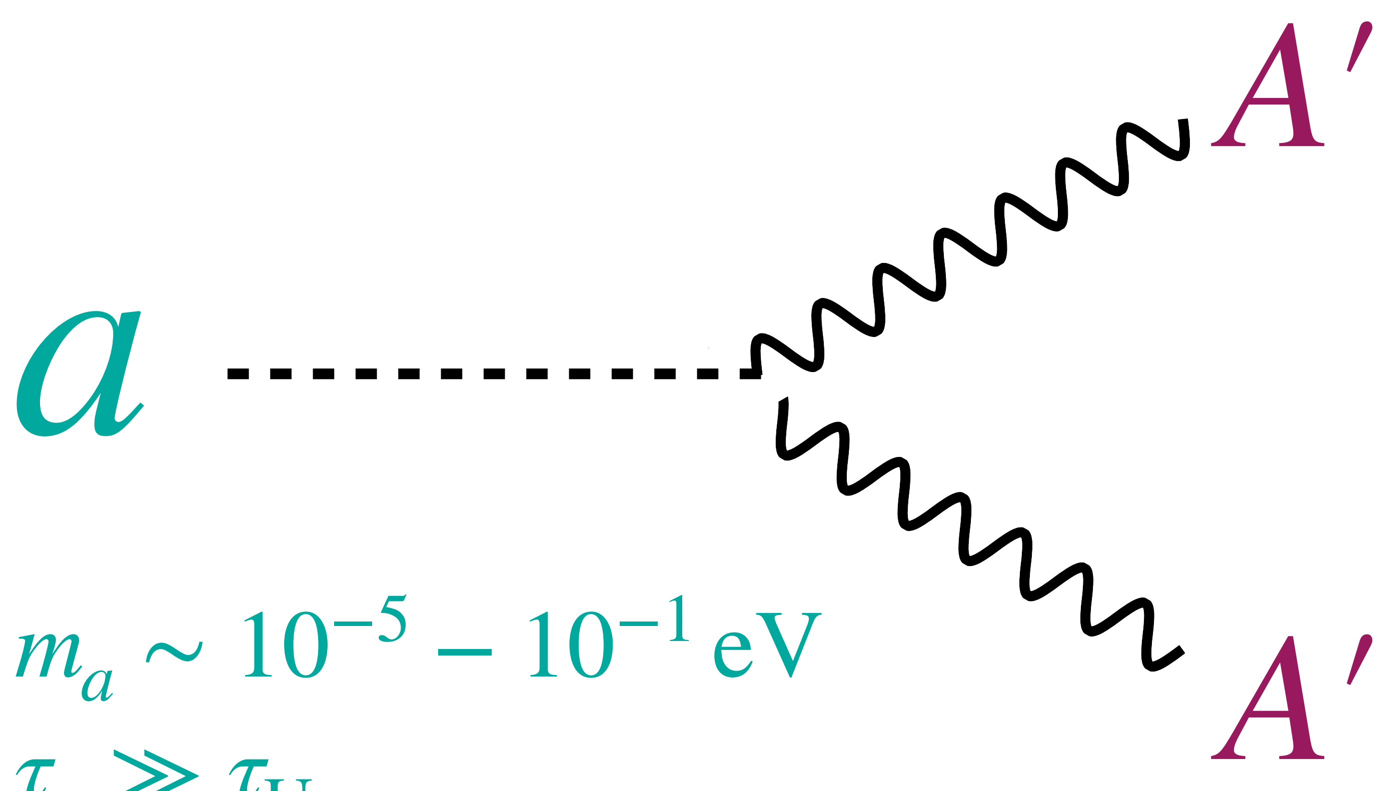
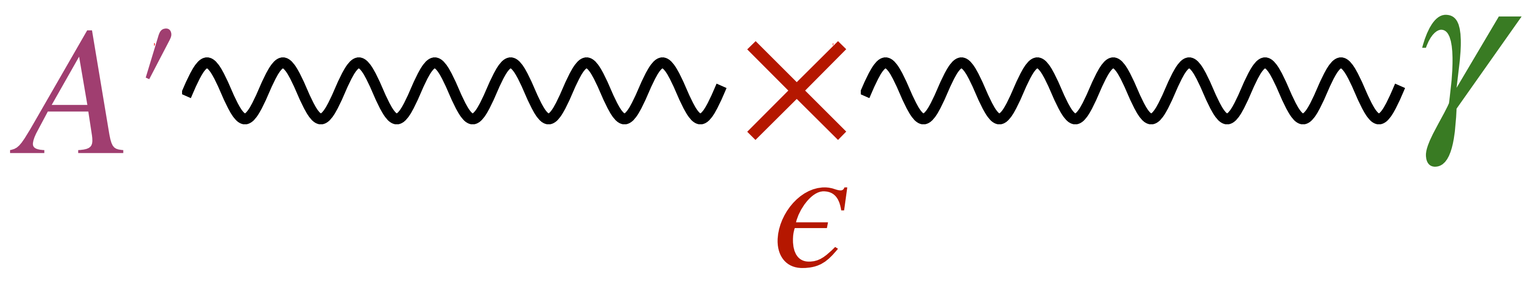


$m_a \sim 10^{-5} - 10^{-1}\,\mathrm{eV}$

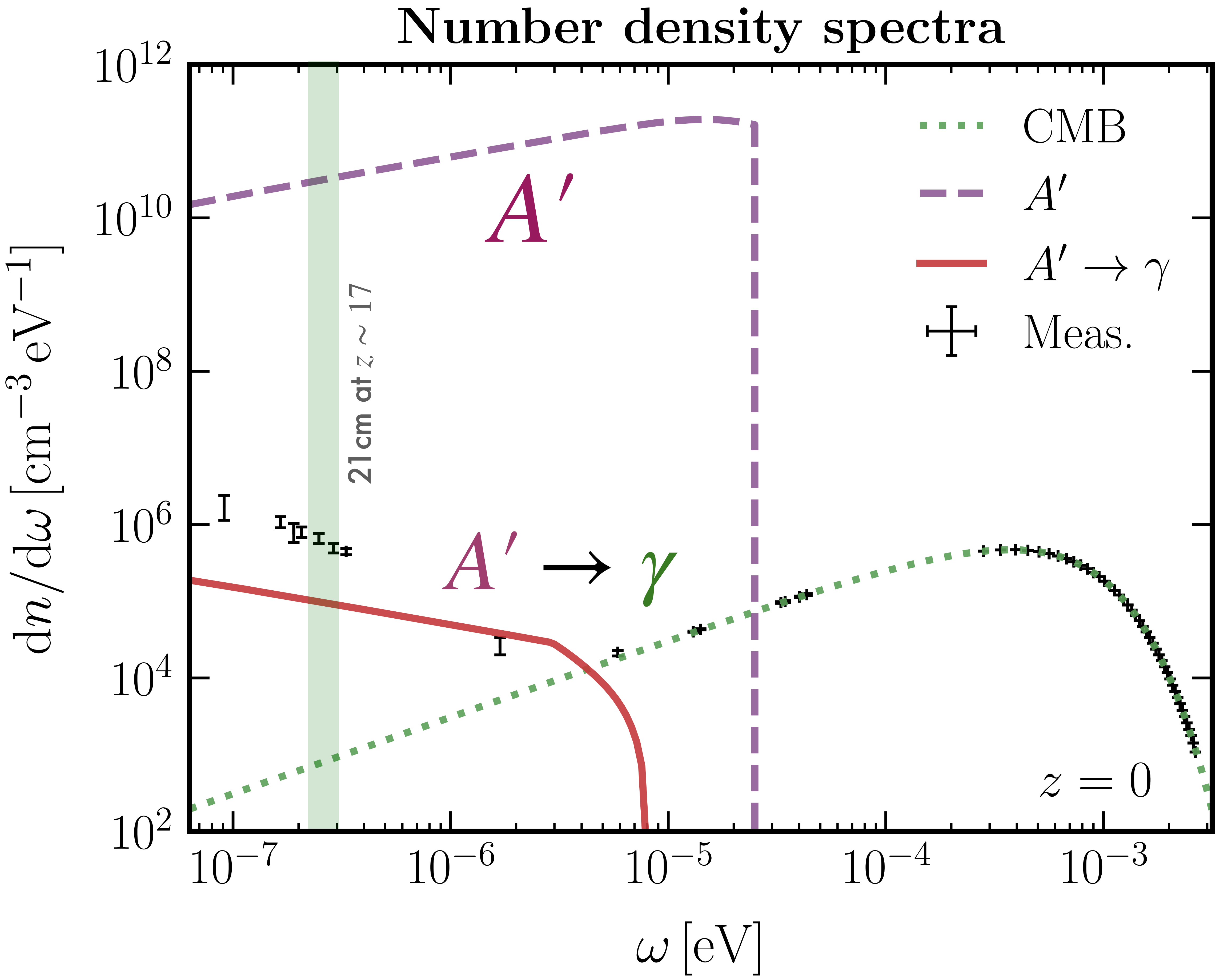
$\tau_a \gg \tau_U$

$\Omega_a = \Omega_{DM}$

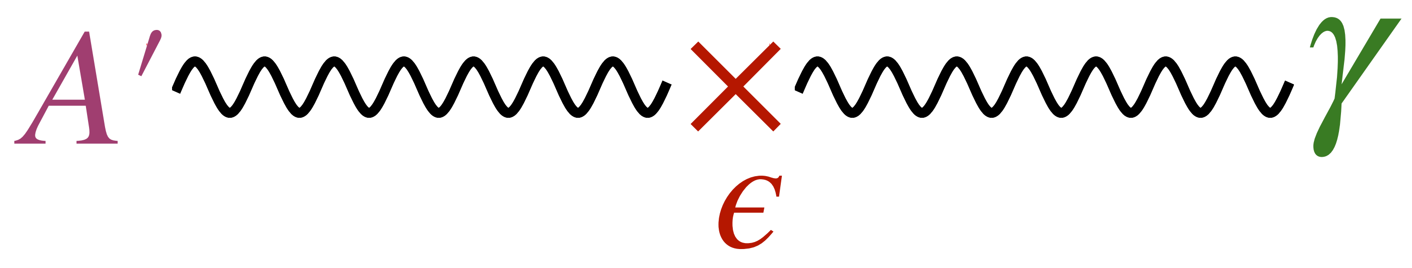
2. Resonant conversion of A' to γ

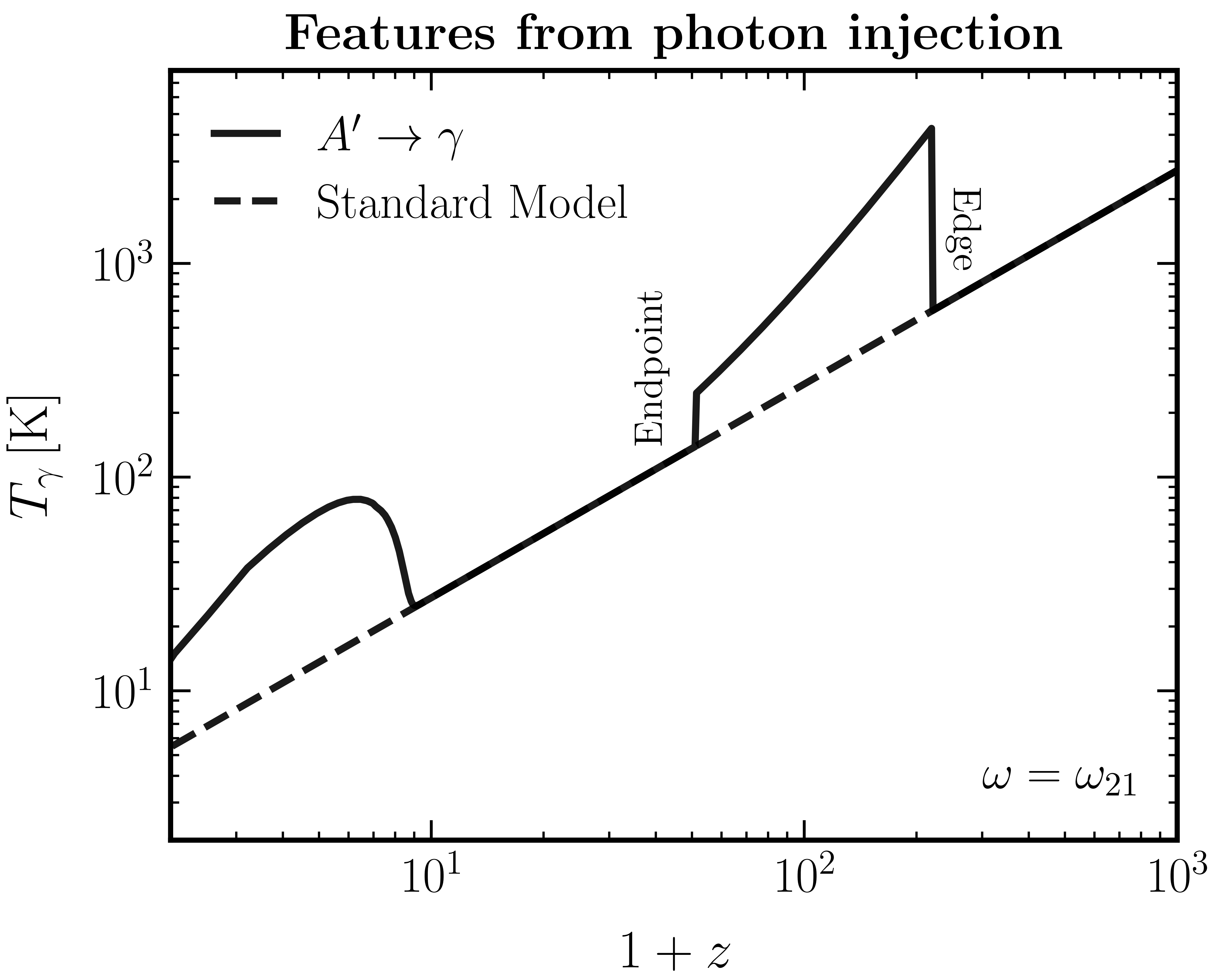


$m_{A'} \sim 10^{-13} - 10^{-9}\,\mathrm{eV}$



Features in 21-cm from dark photons





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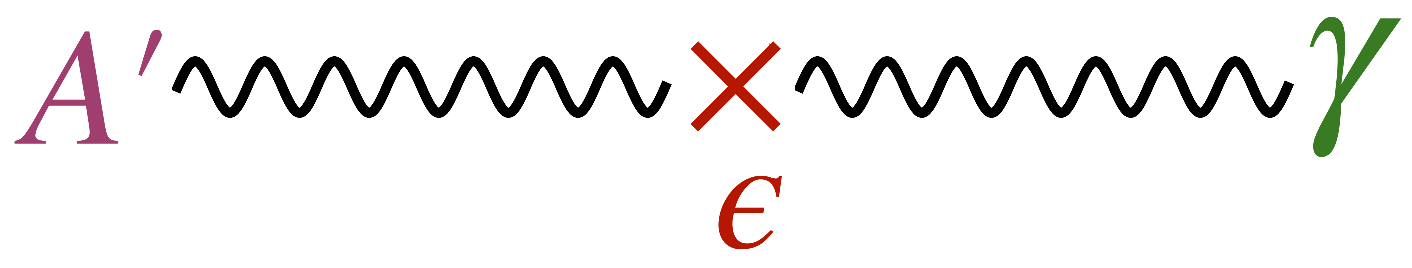
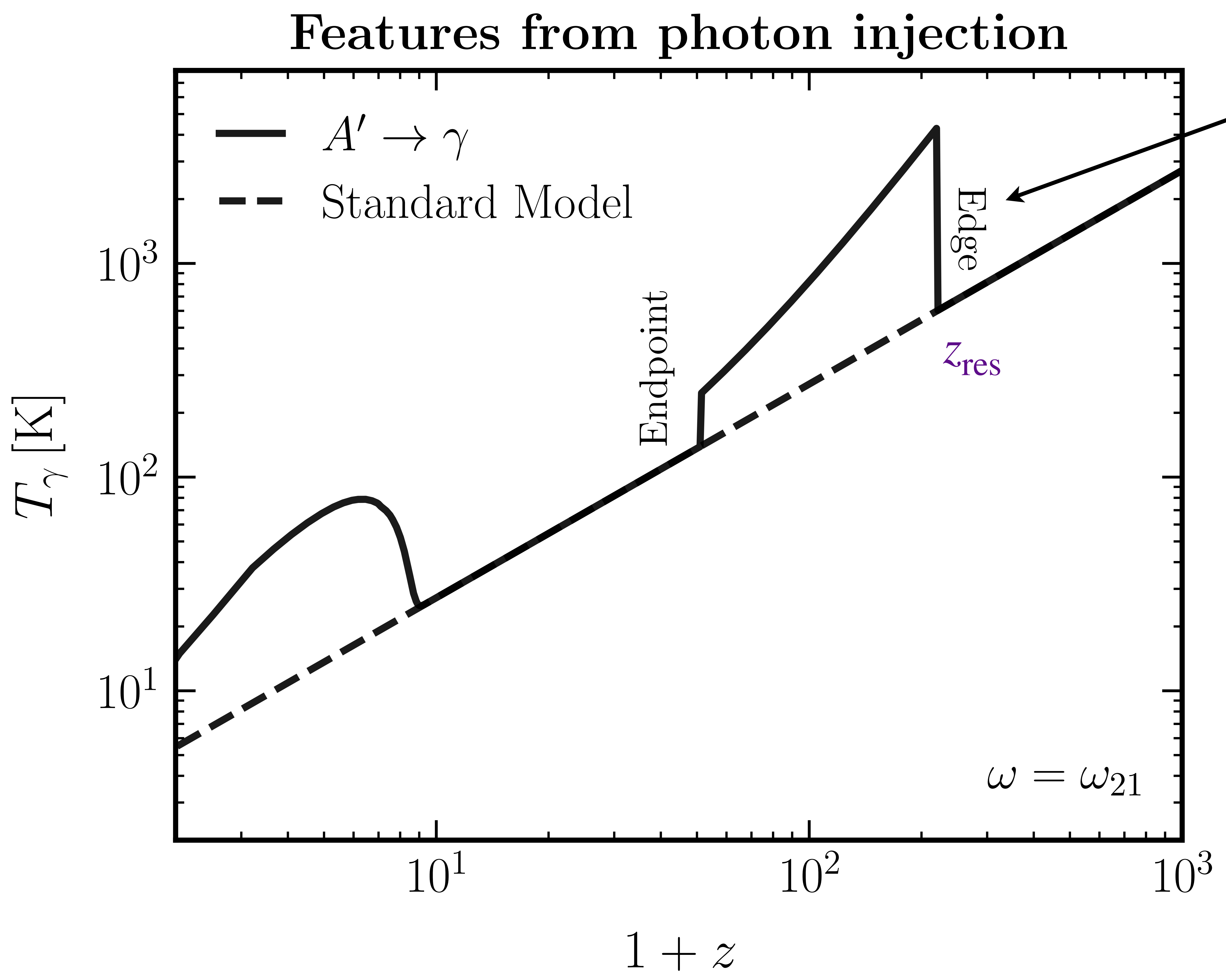




Edge due to photon injection z_{res}

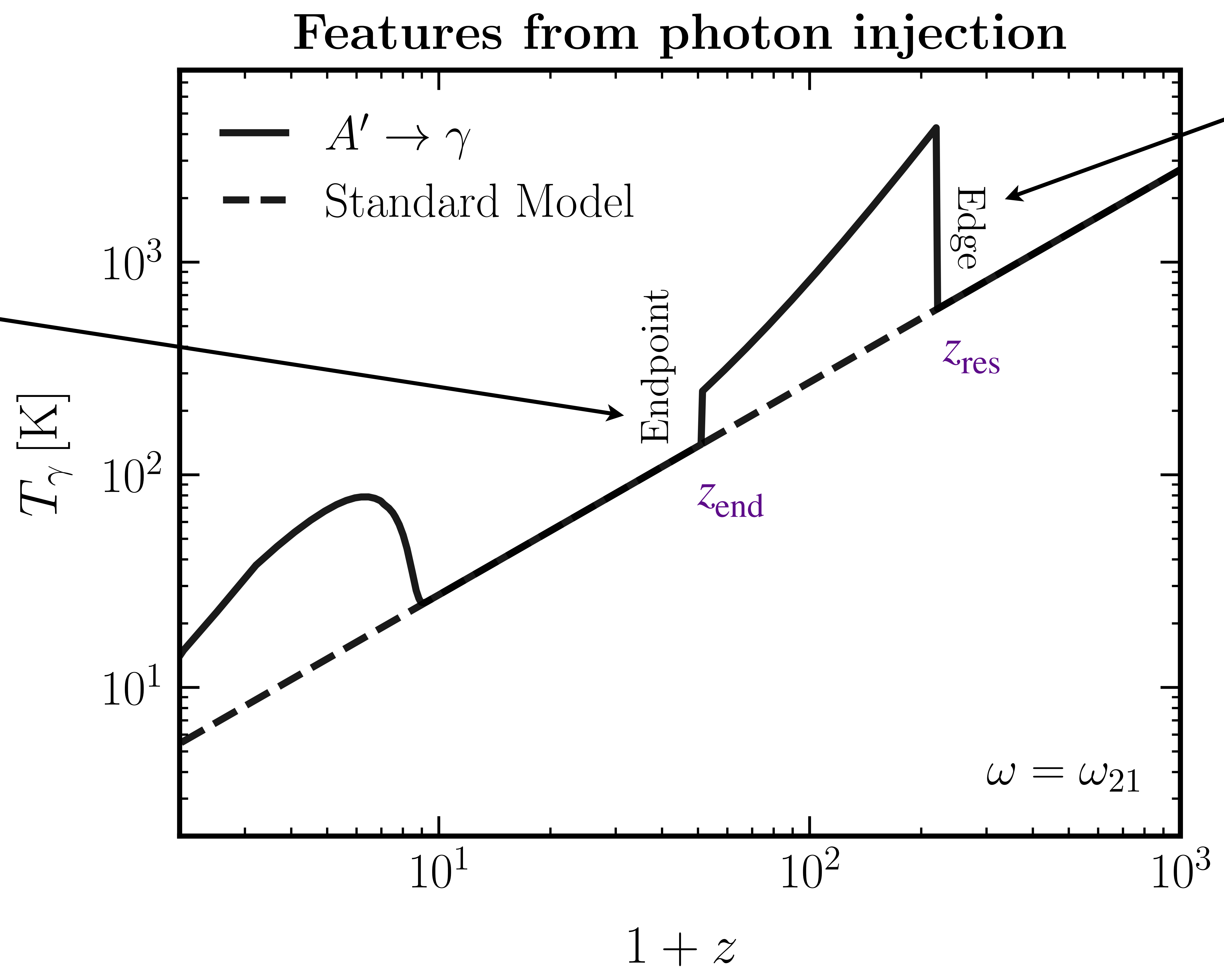
$\overline{m_\gamma}\left(z_{res}\right) \approx m_{A'}$

Features in 21-cm from dark photons

$A' \sim\sim\sim \times_{\epsilon} \sim\sim\sim \gamma$

Kinematic endpoint z_{end}

$$\frac{m_a}{2}\left(\frac{1+z_{\mathrm{end}}}{1+z_{\mathrm{res}}}\right) \approx \omega_{21}$$



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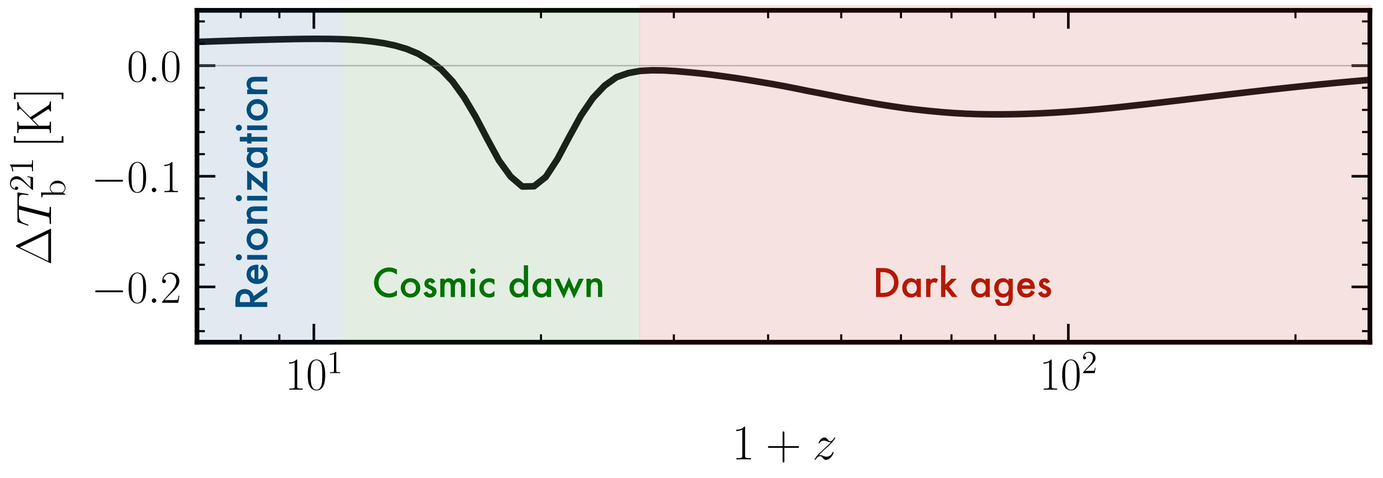
Benchmark 1: signal during cosmic dawn



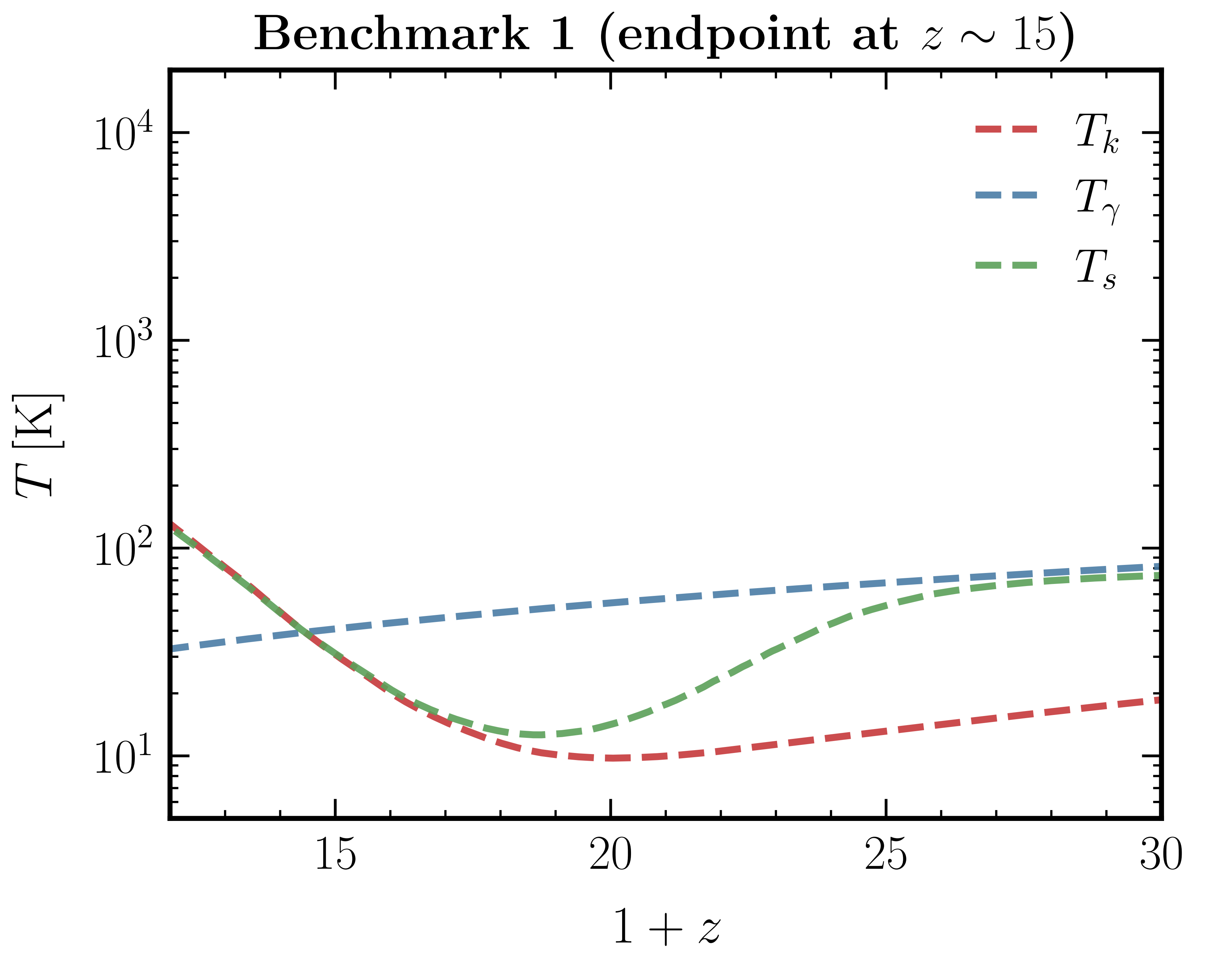
$m_{A'} = 10^{-11}\,\text{eV}$

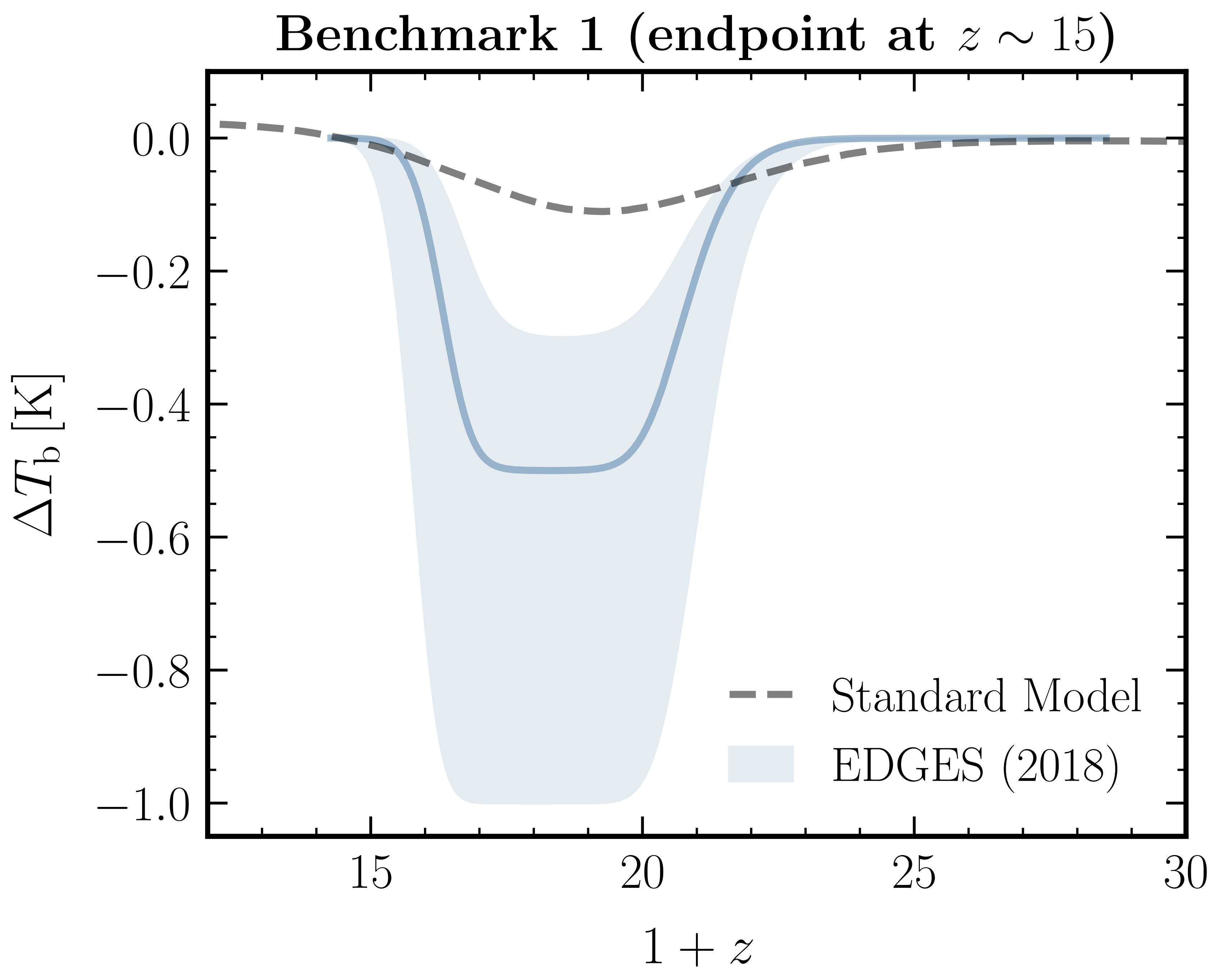
$m_a = 5 \times 10^{-4}\,\text{eV}$

$\epsilon = 5 \times 10^{-8}$

$z_{\text{edge}} \simeq 660$

$z_{\text{end}} \simeq 15$





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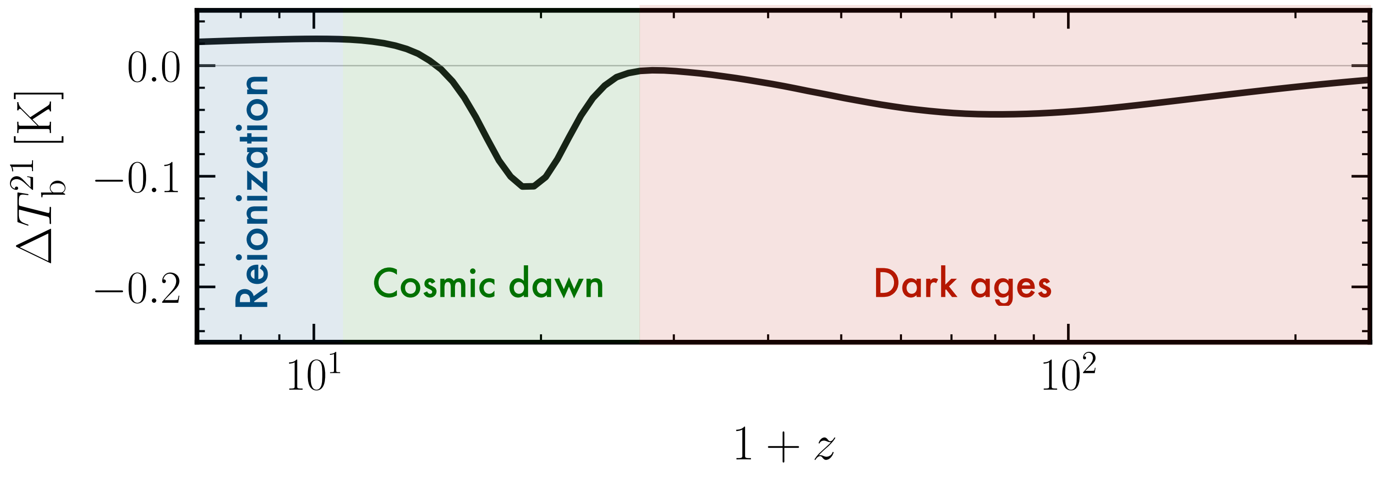

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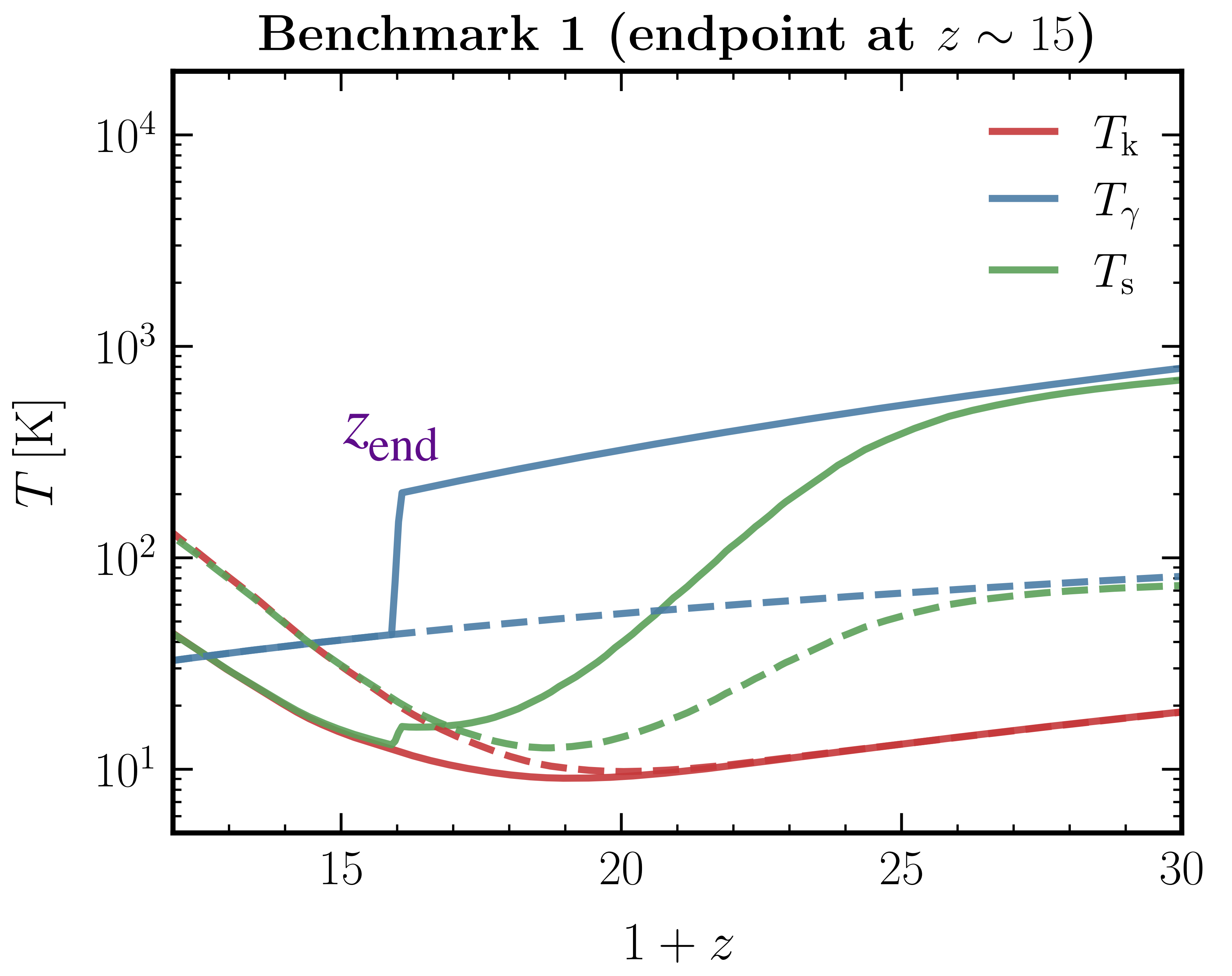
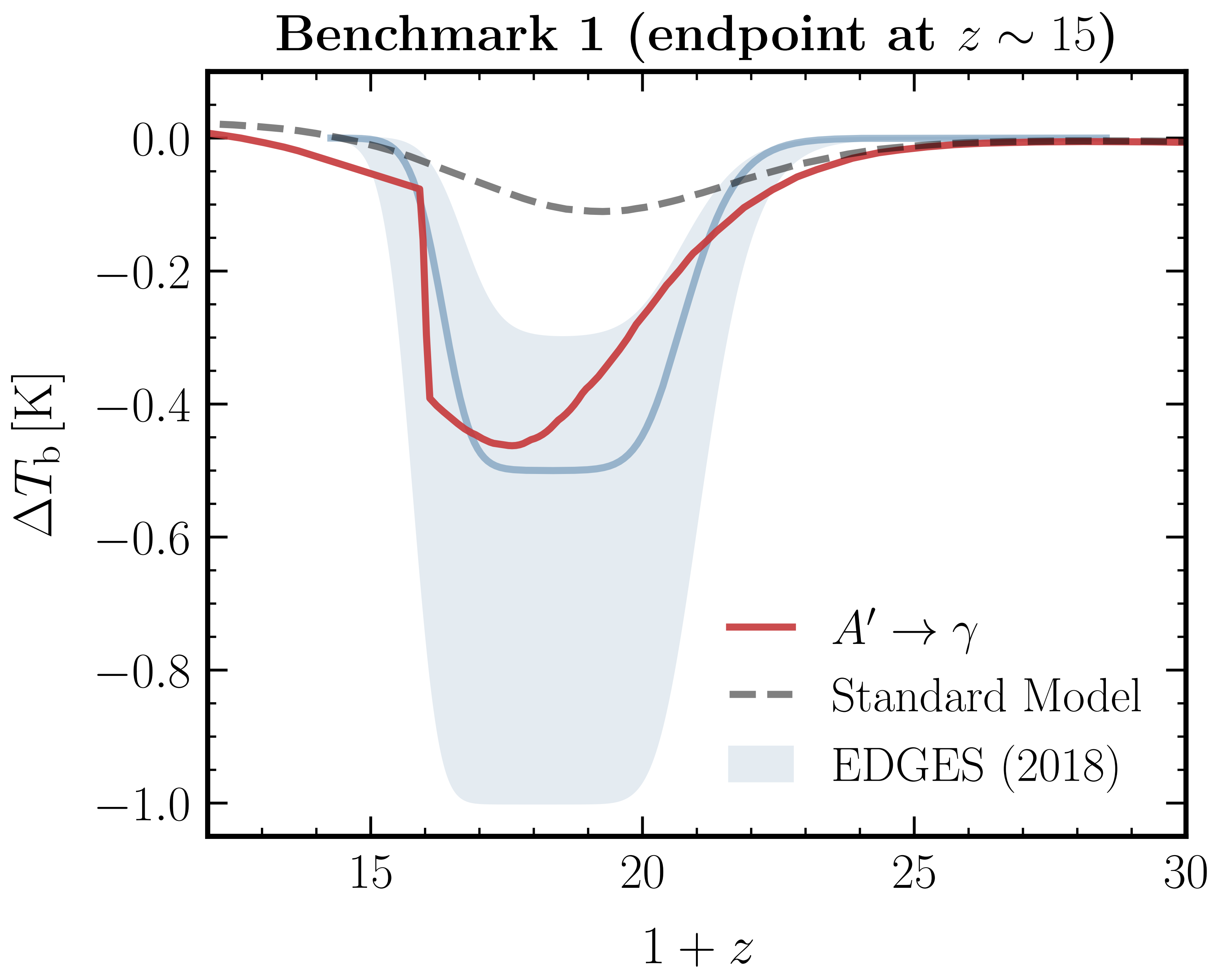
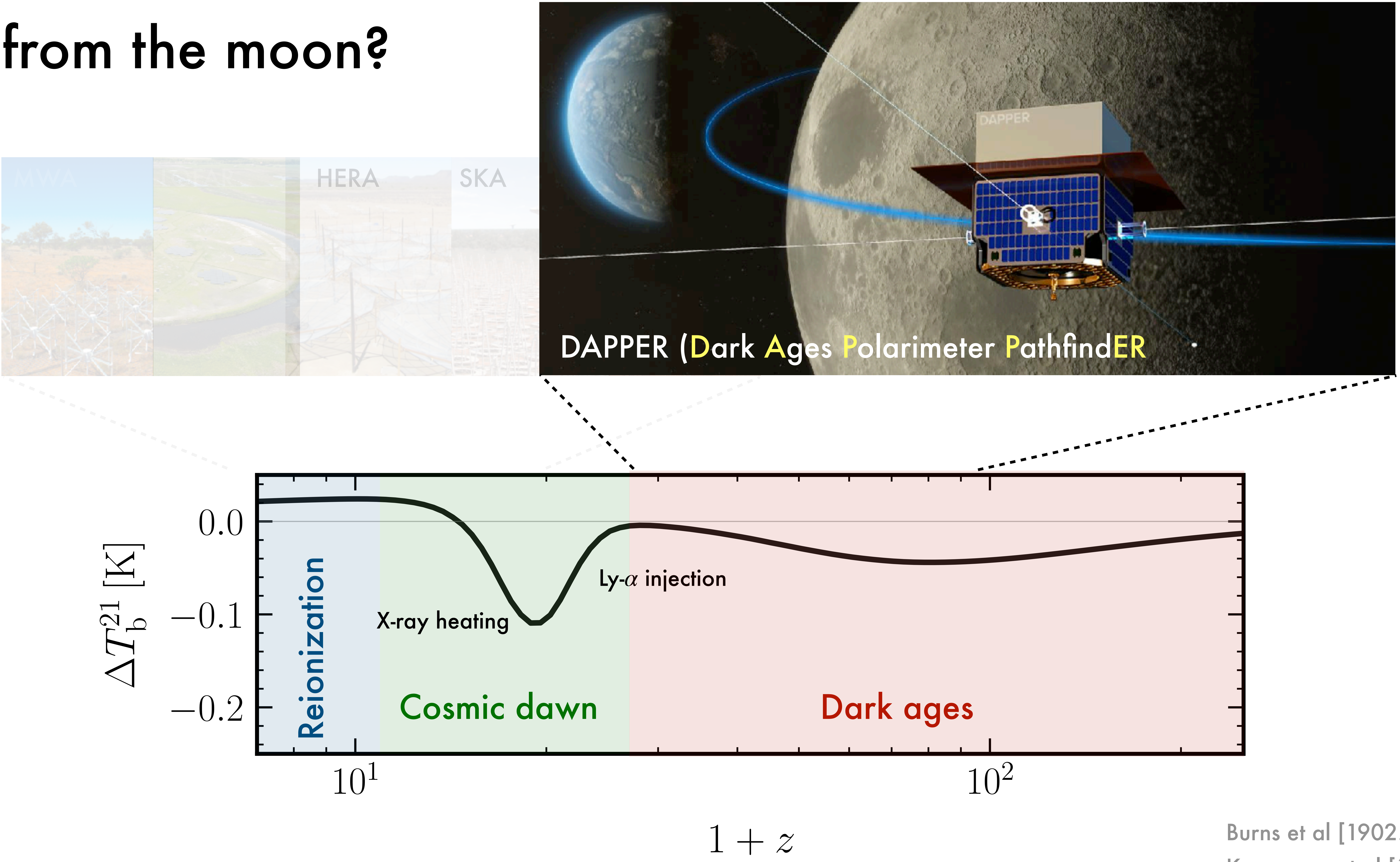




21-cm from the moon?



Burns et al [1902.06147]
Koopmans et al [1908.04296]

Benchmark 2: signatures during dark ages

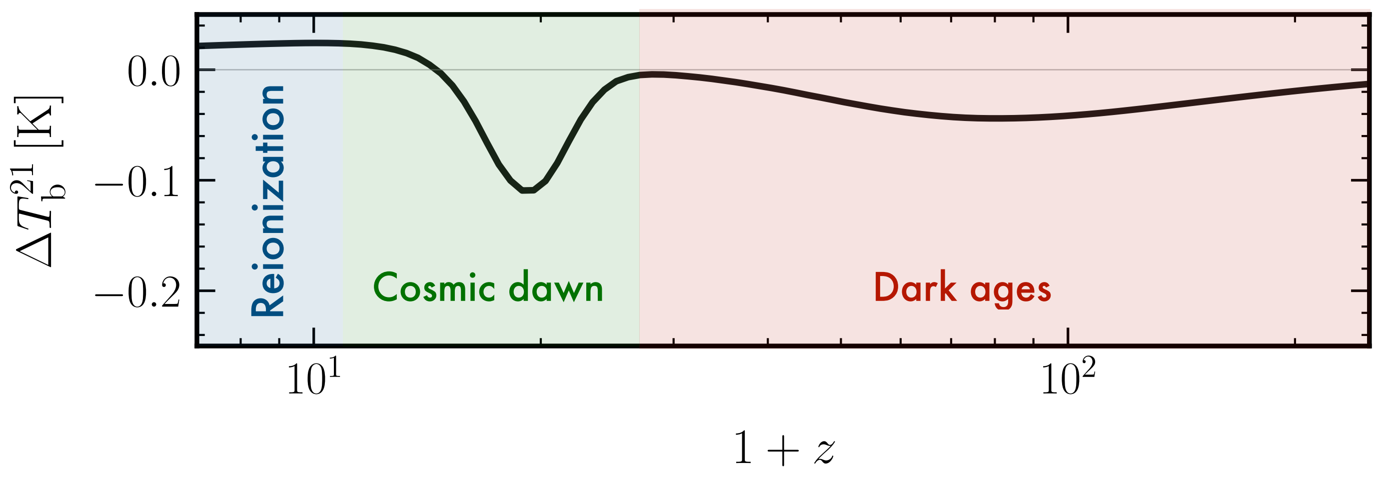
$m_{A'} = 3 \times 10^{-13}\,\mathrm{eV}$

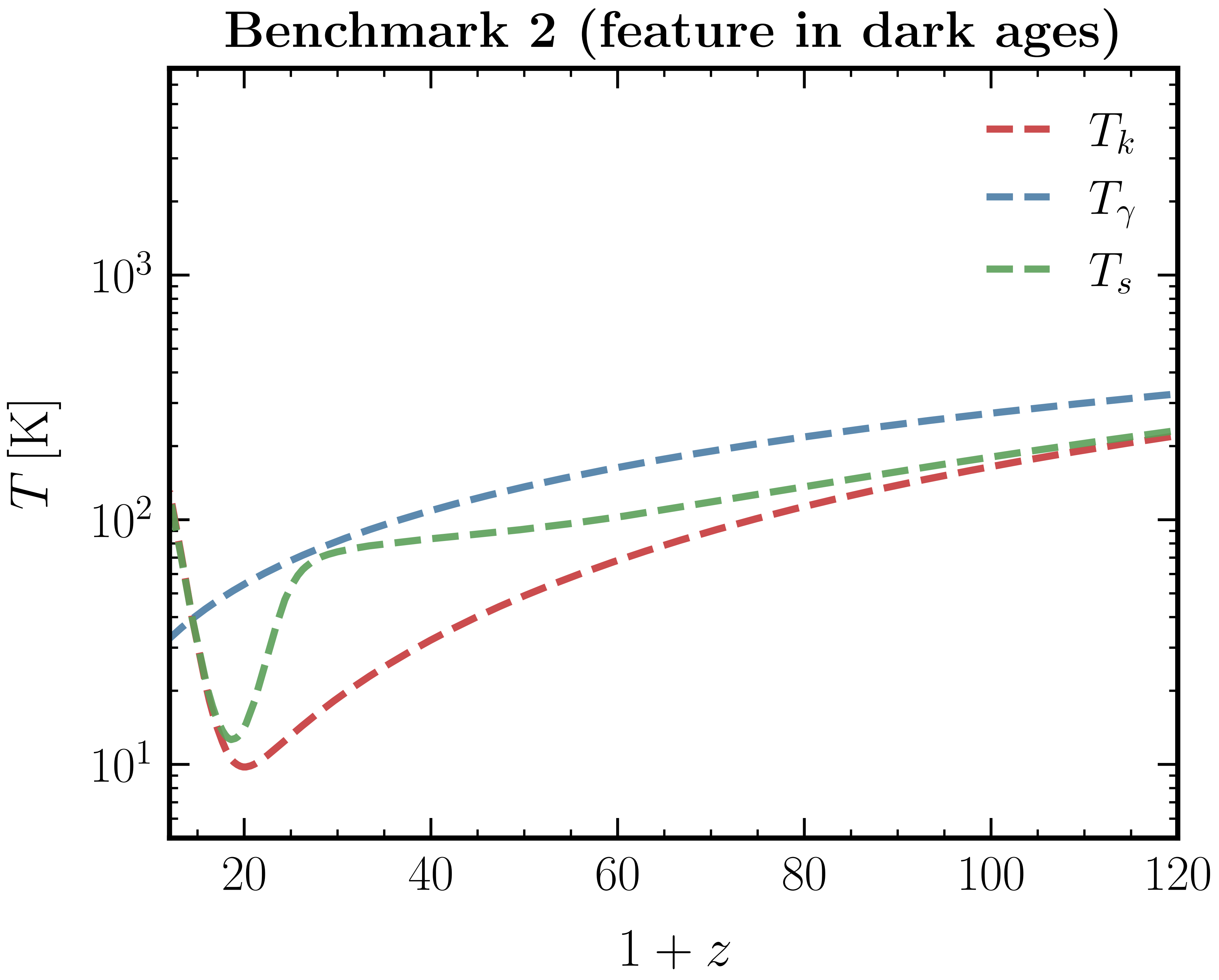
$m_a = 2 \times 10^{-5}\,\mathrm{eV}$

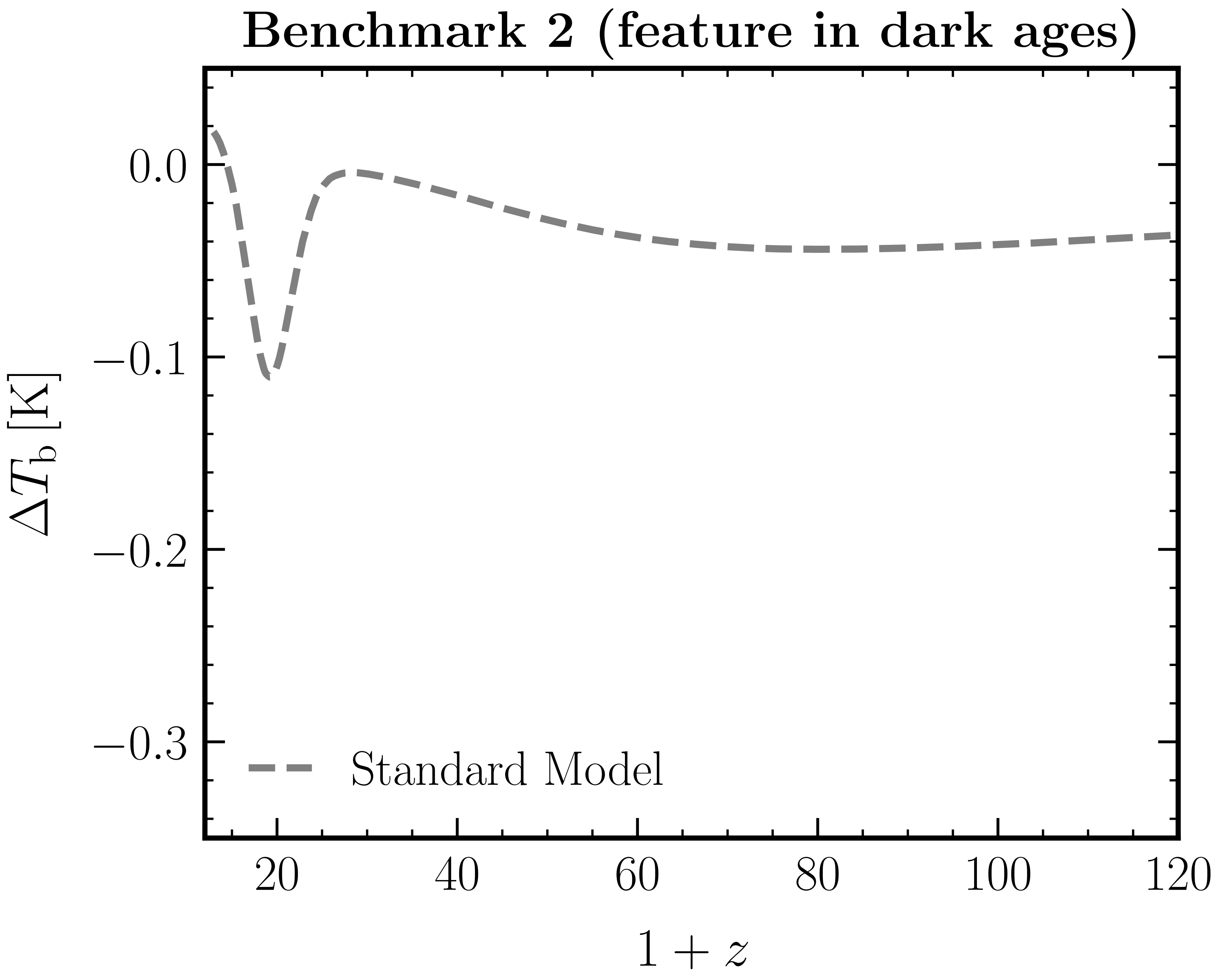
$\epsilon = 5 \times 10^{-10}$

$z_{\mathrm{edge}} \simeq 95$

$z_{\mathrm{end}} \simeq 65$







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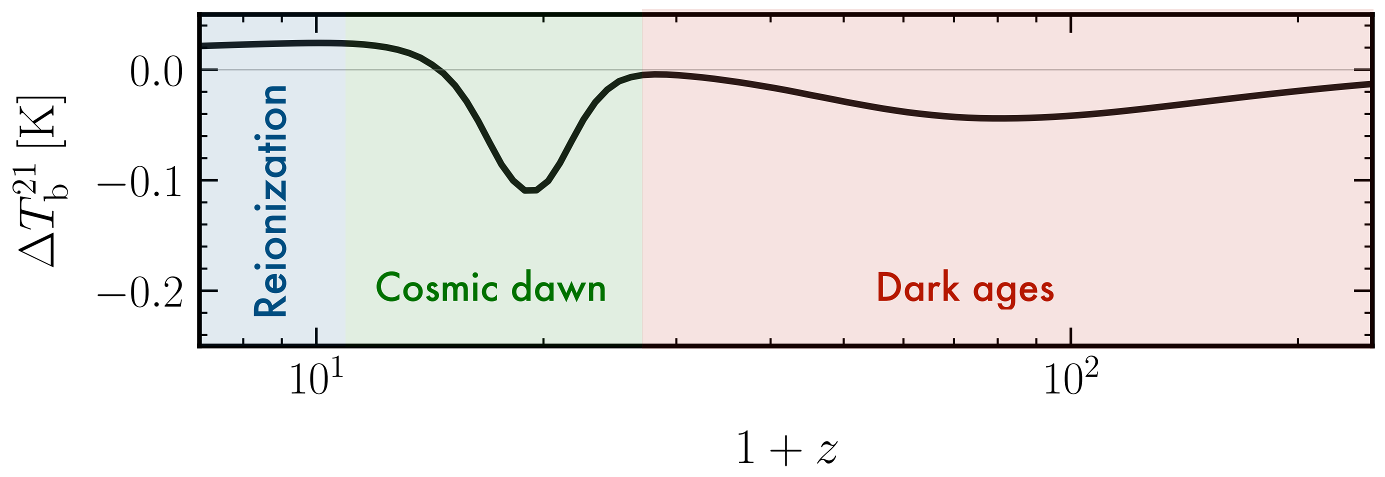

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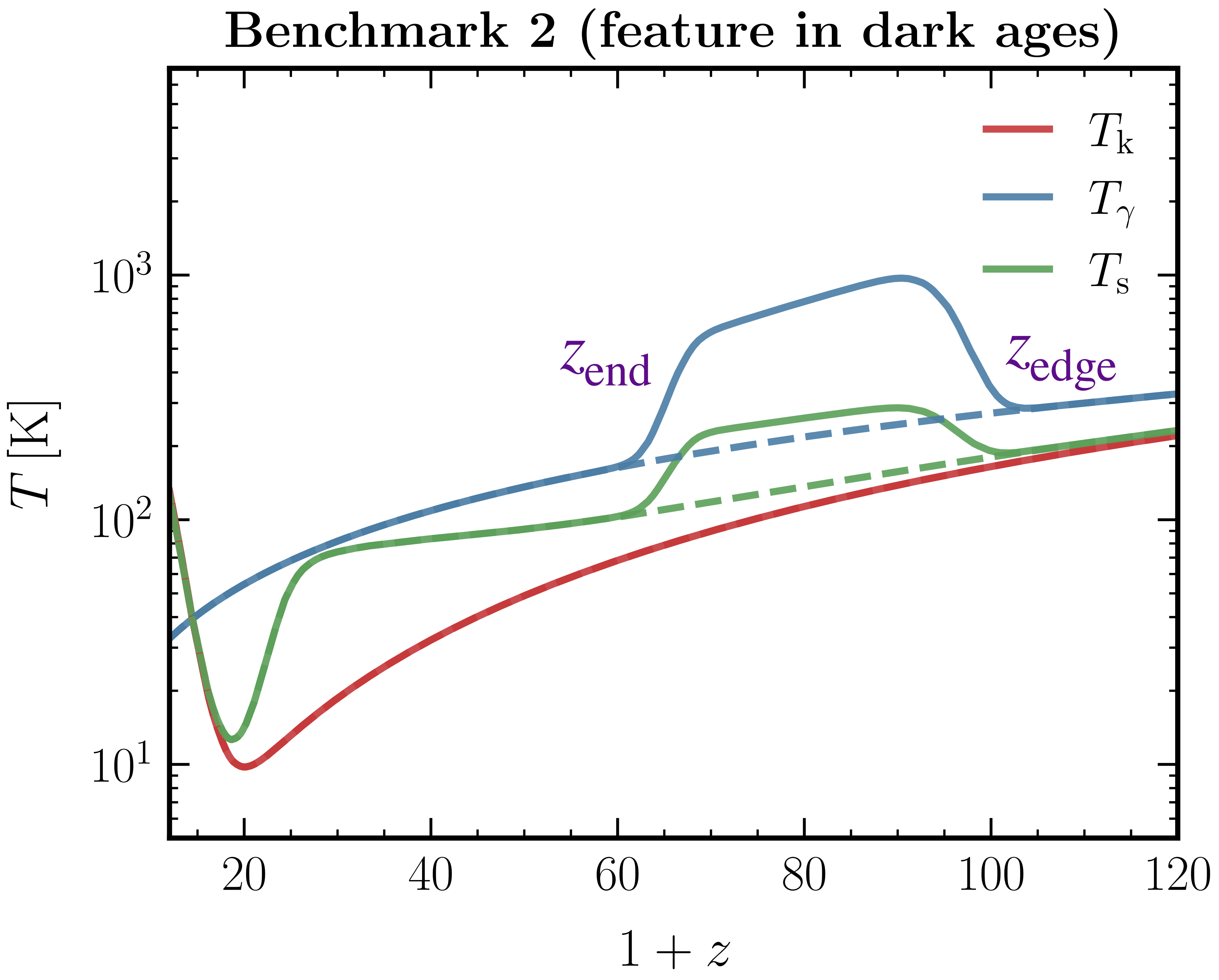
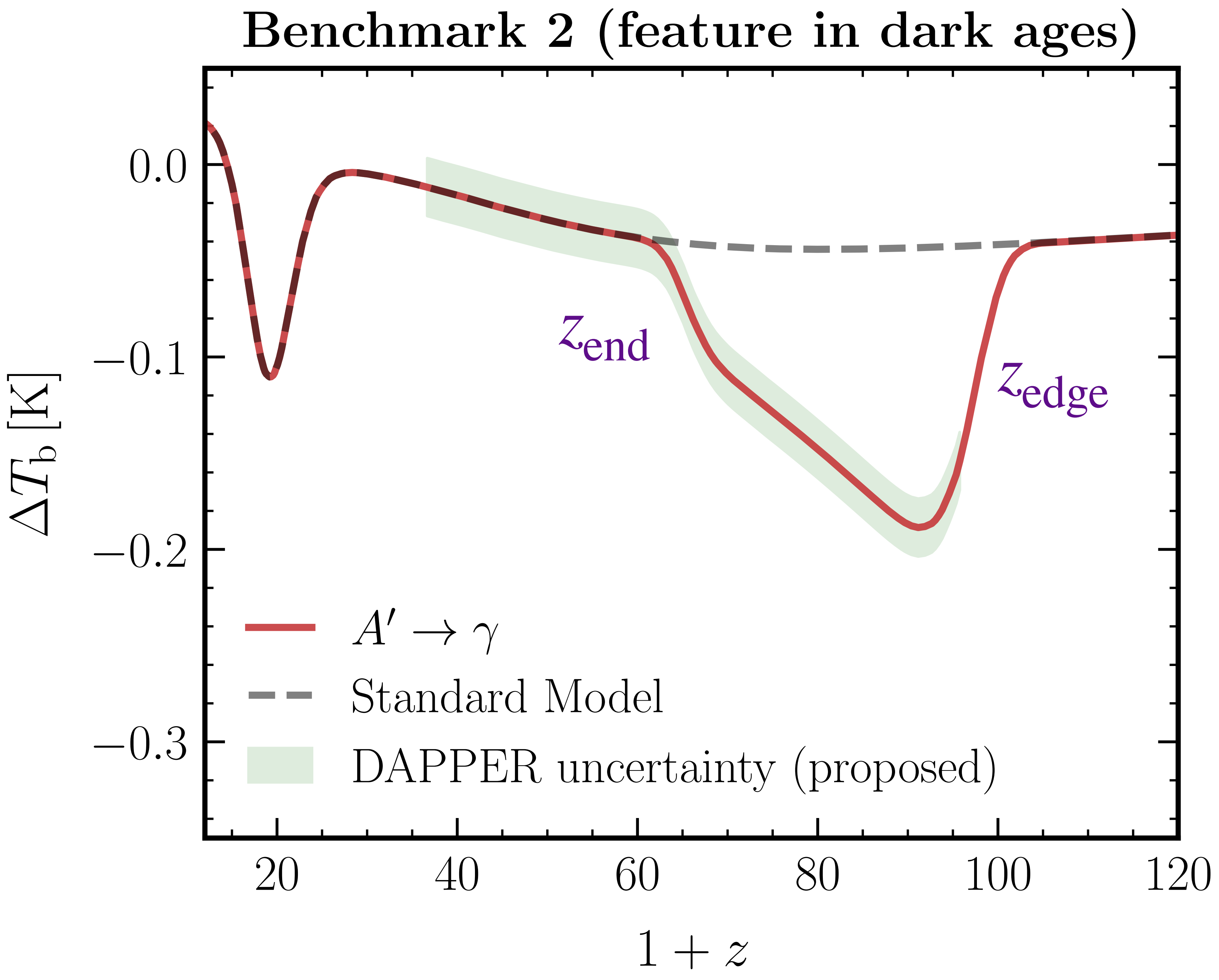
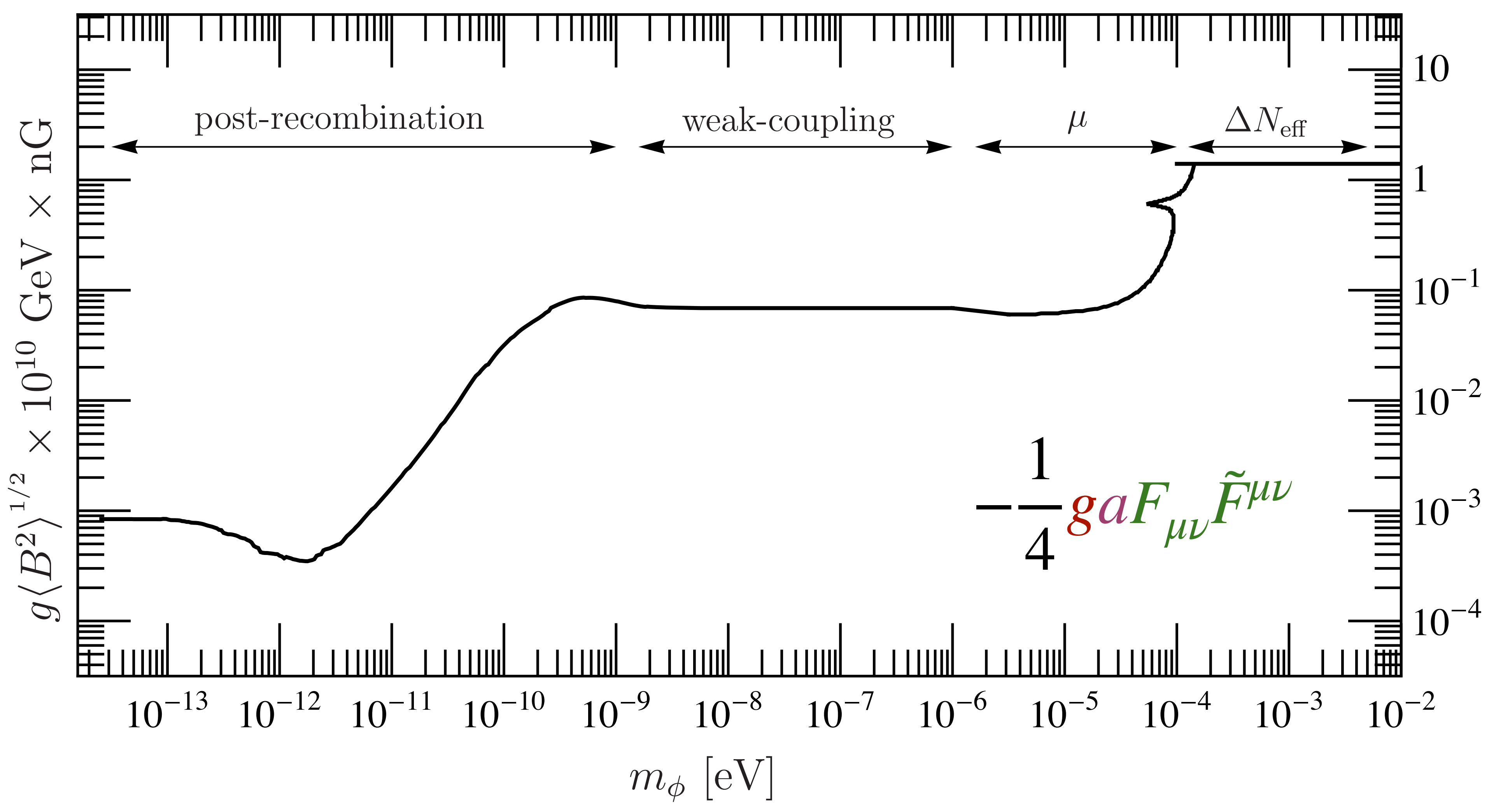




Work in progress

Implications for axion-like particles



Mirizzi, Redondo, Sigl [0905.4865]

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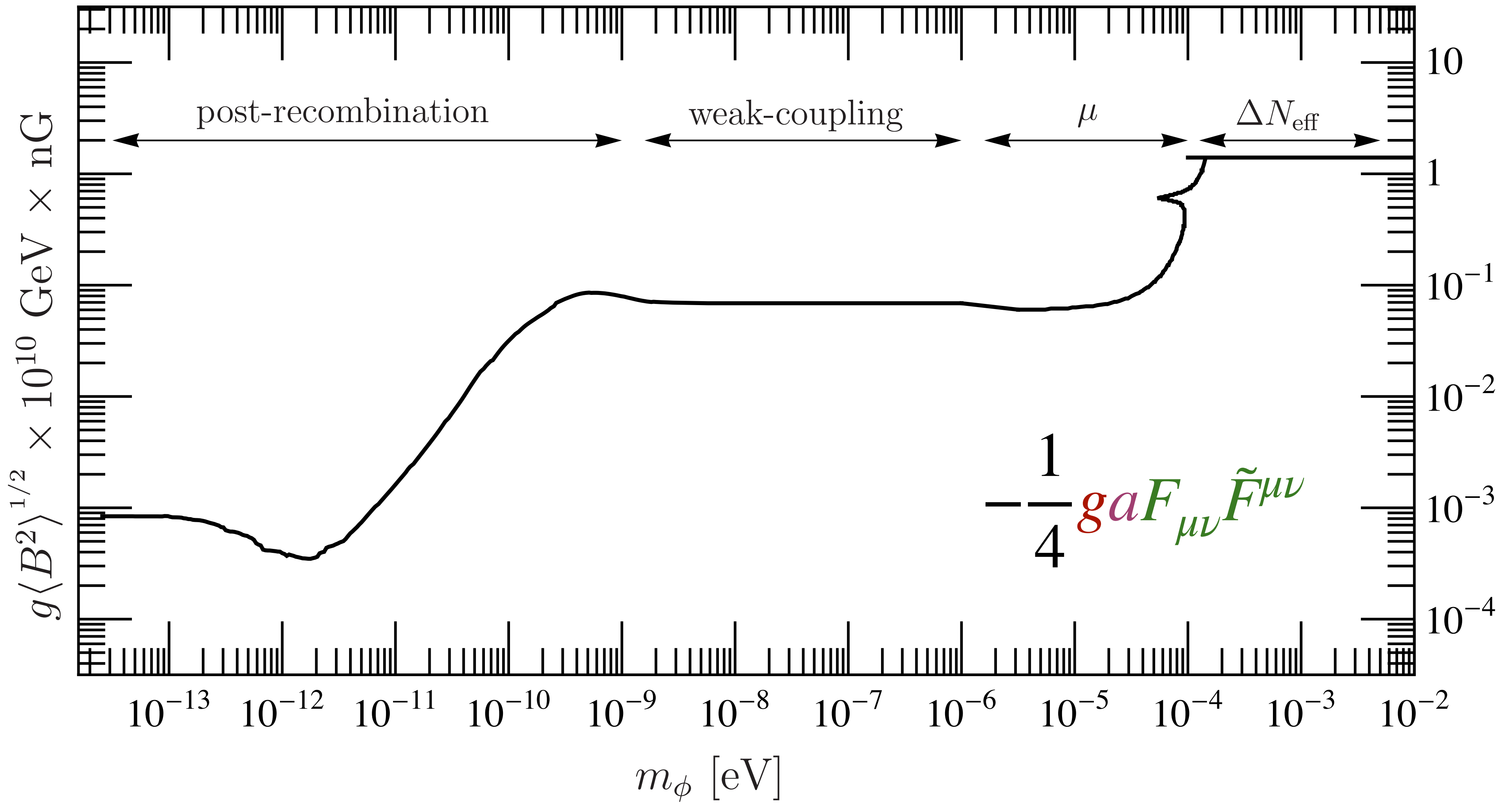
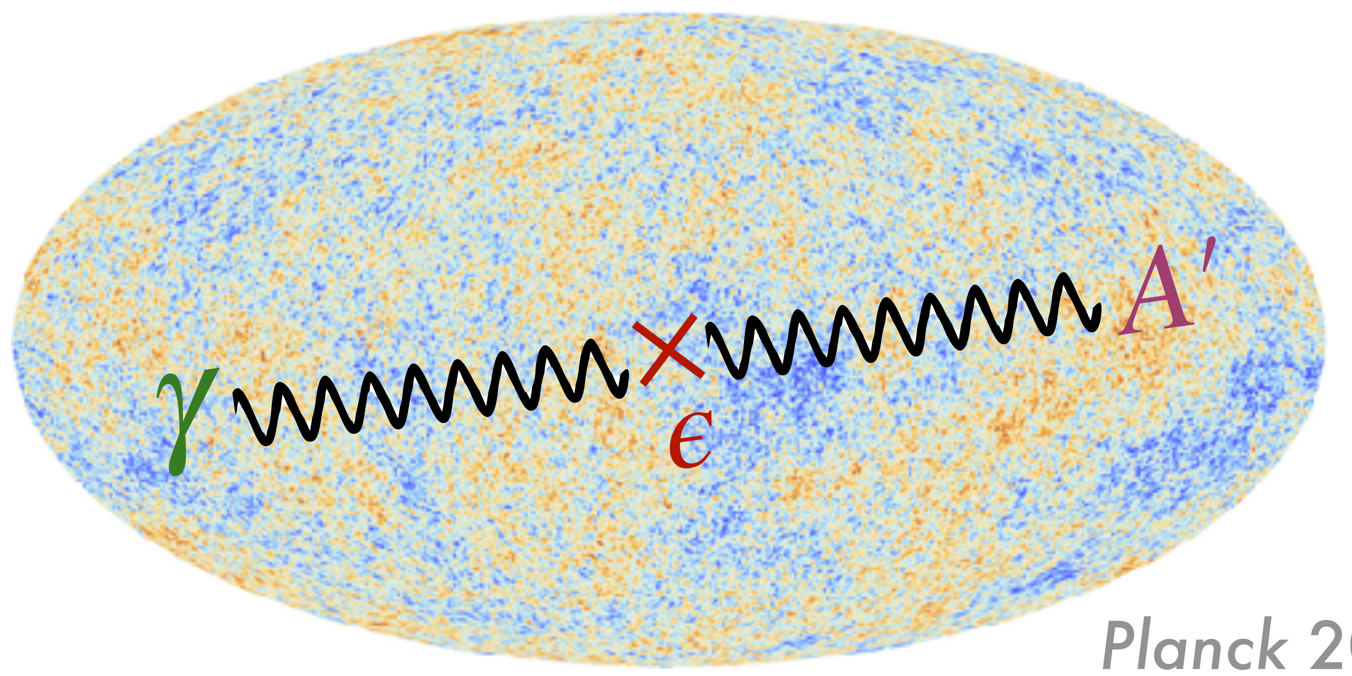
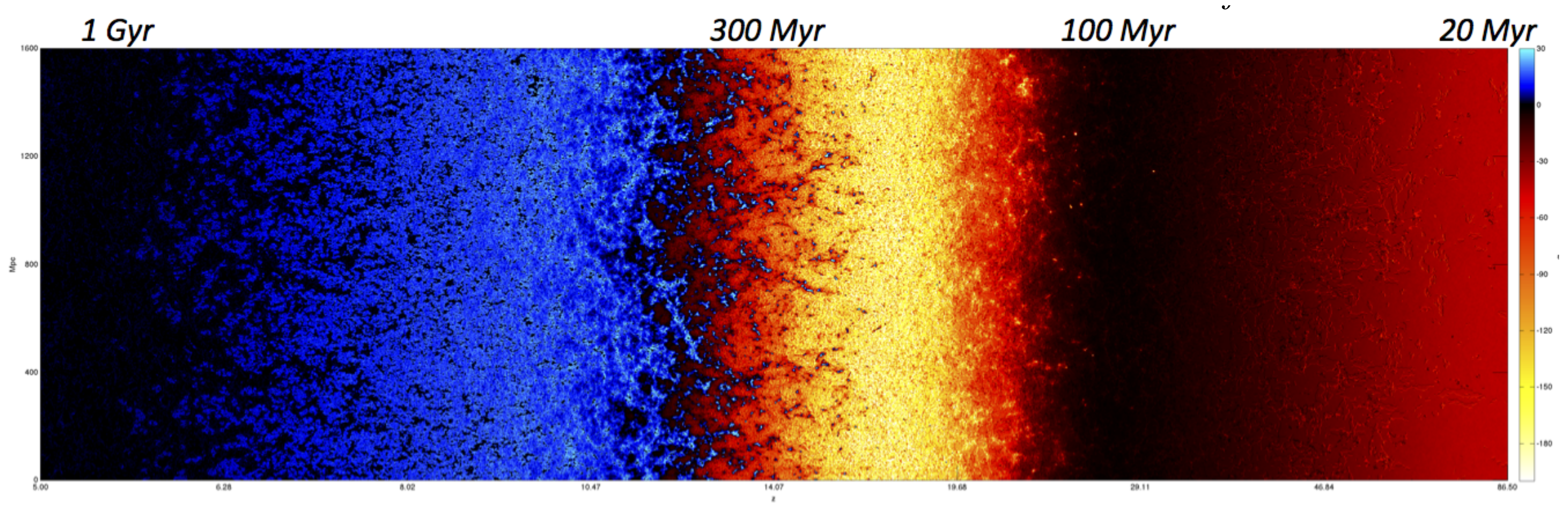


Mirizzi, Redondo, Sigl [0905.4865]

Effect on CMB and 21-cm anisotropy

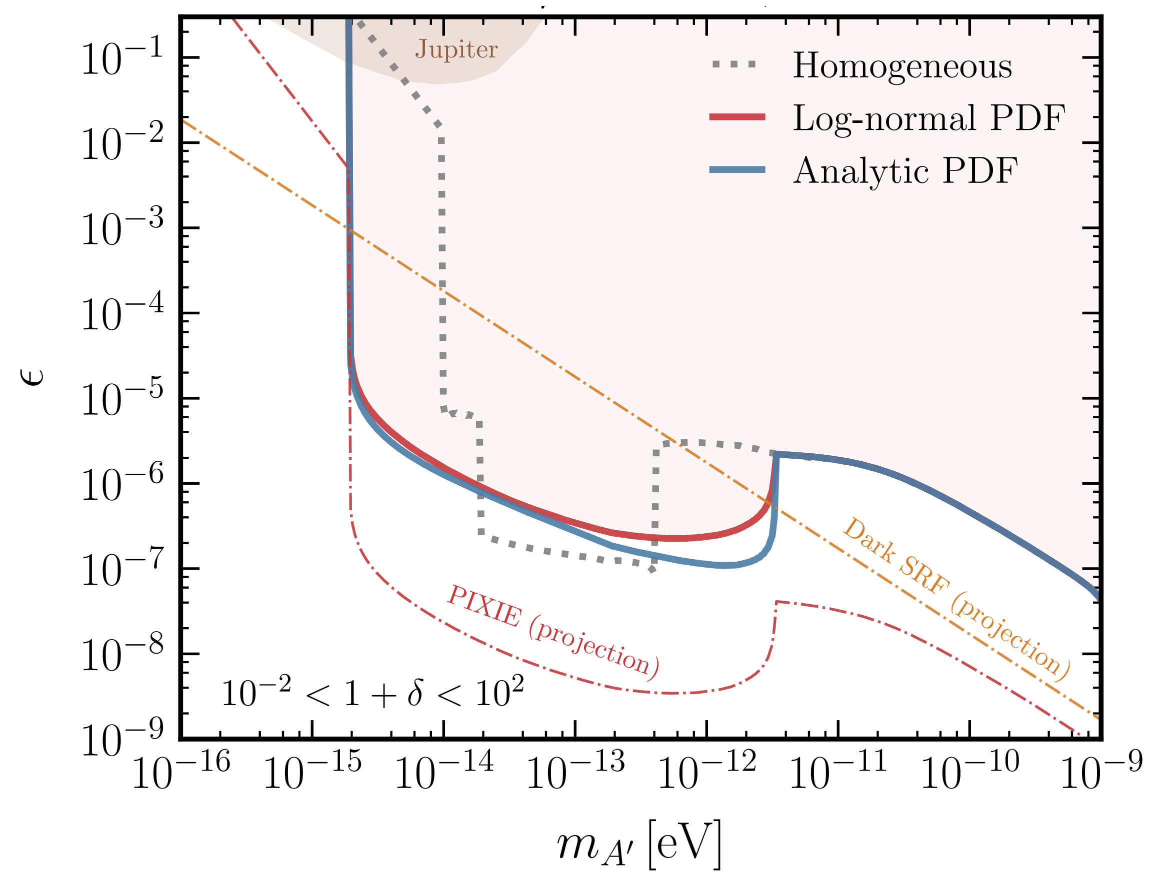


Planck 2018



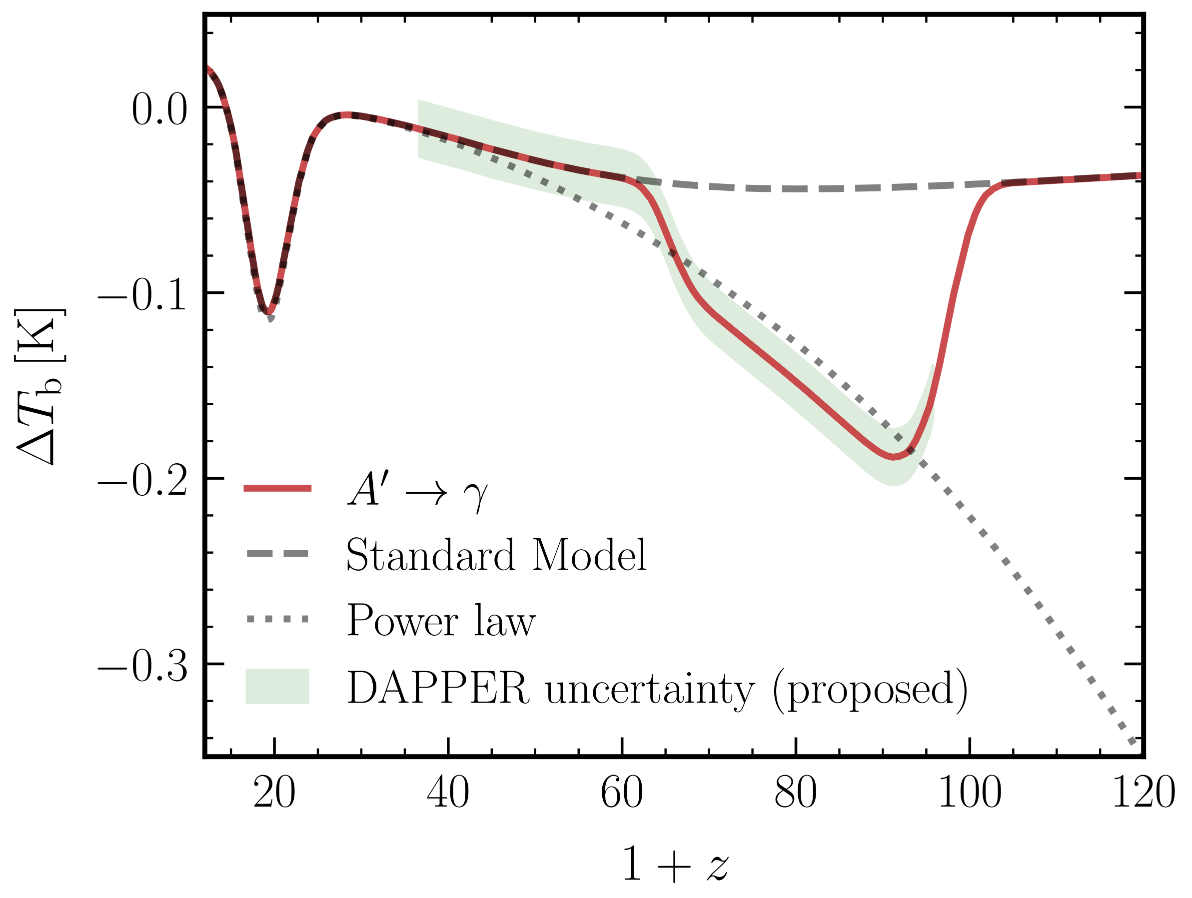
Messinger, Greig, Sobacchi [1602.07711]

Conclusions



$\gamma \rightarrow A'$

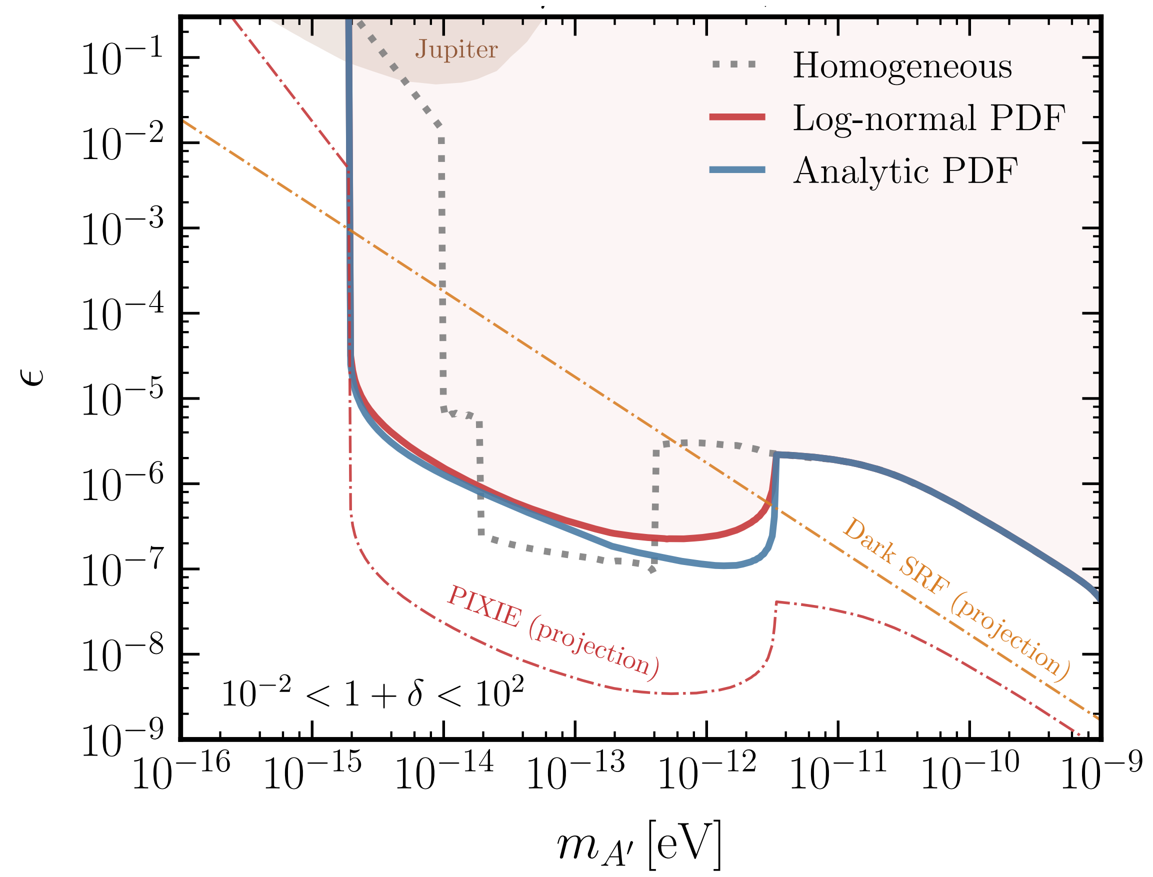
Inhomogeneities can have significant observable effects for resonant photon-to-dark photon conversions



$A' \rightarrow \gamma$

Resonant dark photon-to-photon conversion can leave striking signatures in 21-cm observations

Conclusions



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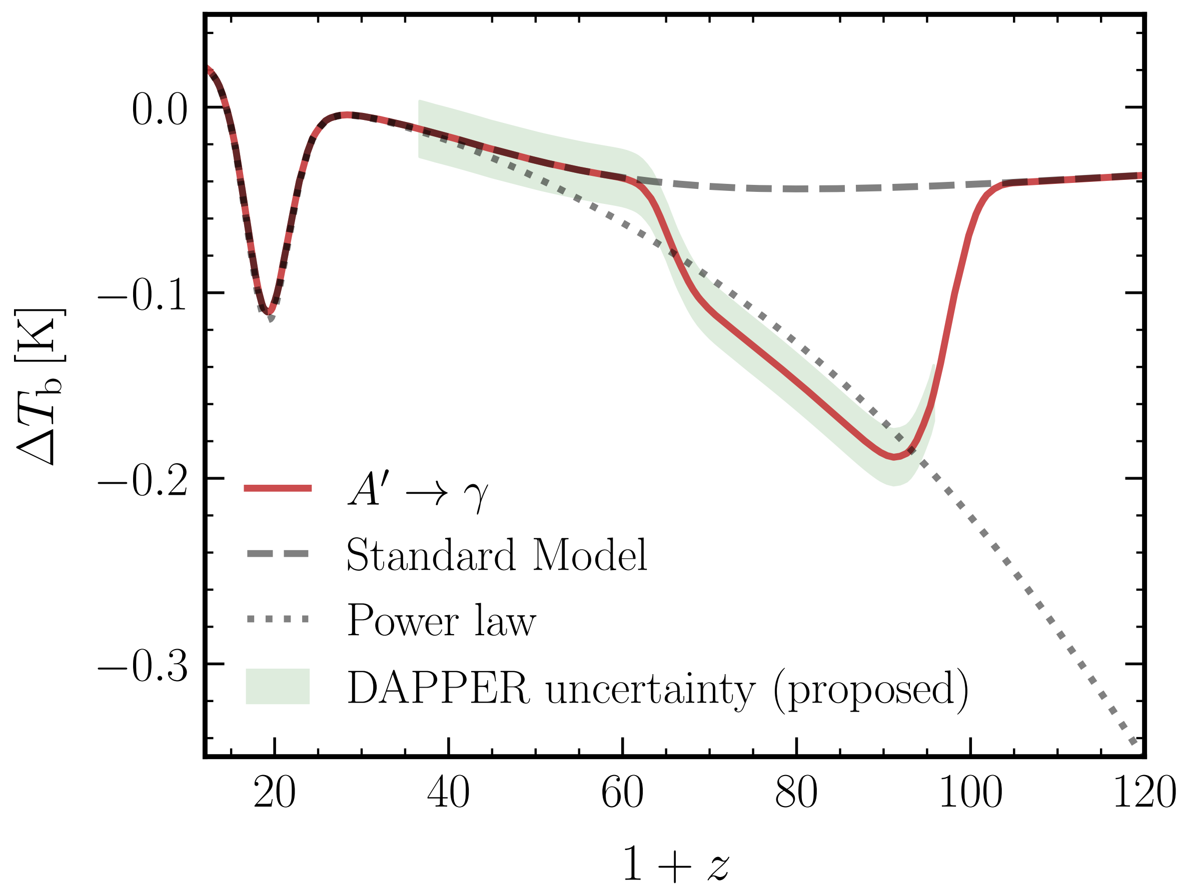

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More information ℹ️

Papers:

- *"Dark Photon Oscillations in Our Inhomogeneous Universe,"* Caputo, Liu, SM, Ruderman [2002.05165]
- *"Modeling Dark Photon Oscillations in Our Inhomogeneous Universe,"* Caputo, Liu, SM, Ruderman [2004.06733]
- *"Edges and Endpoints in 21-cm Observations from Resonant Photon Production,"* + Pospelov, Urbano [2009.03899]

Codes:

- https://github.com/smsharma/dark-photons-perturbations
- https://github.com/smsharma/edges-endpoints-21cm
- https://github.com/smsharma/twentyone-global

Additional slides

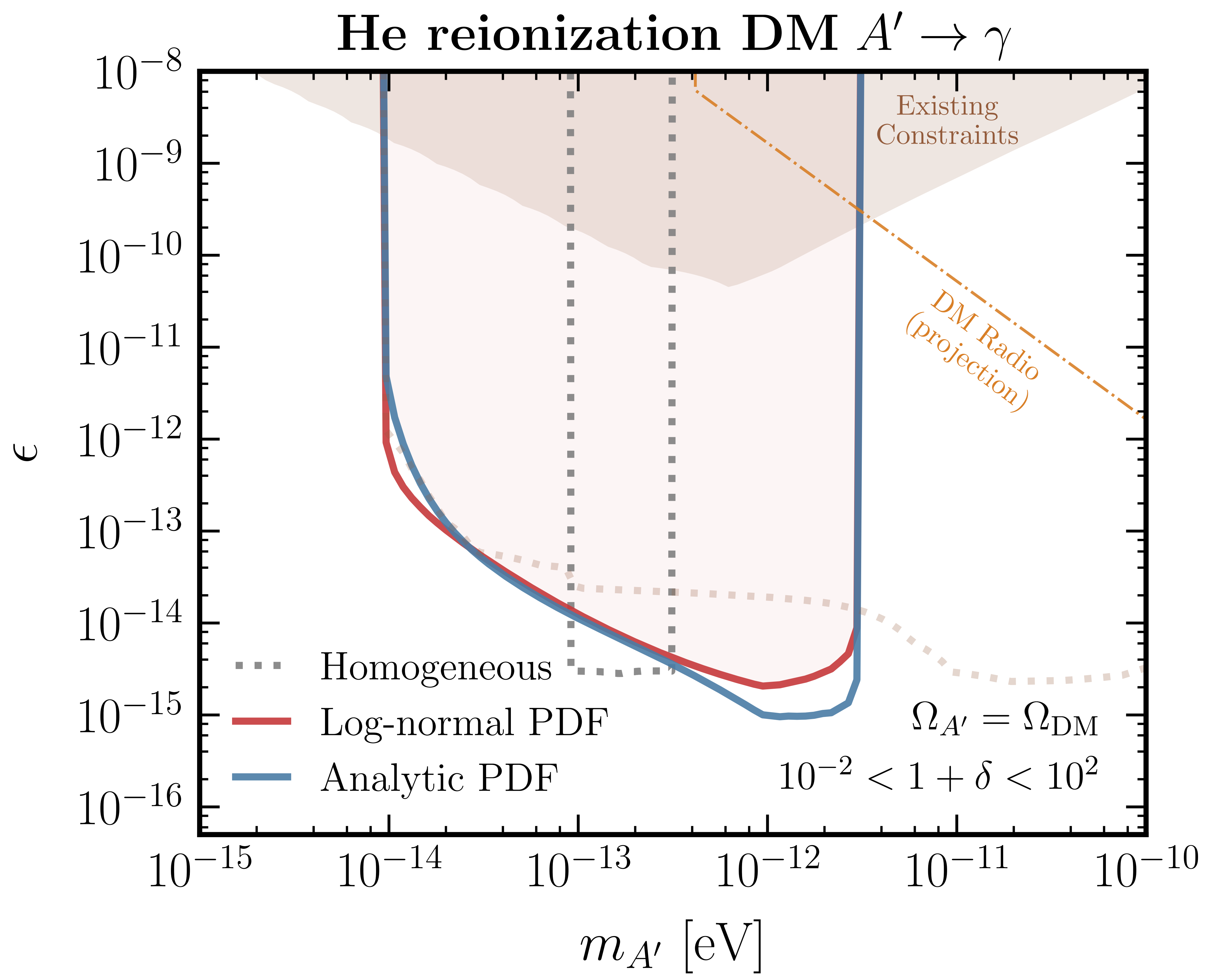
$\epsilon - m_{A'}$ constraints on dark photon dark matter*

Additional constraints apply when the A' is the dark matter

McDermott & Witte [1911.05086]

- Anomalous heating of the IGM during He II reionization is constrained to be < 1 eV
- This constrains the energy injected due to $A' \to \gamma$ during $2 \lesssim z \lesssim 6$

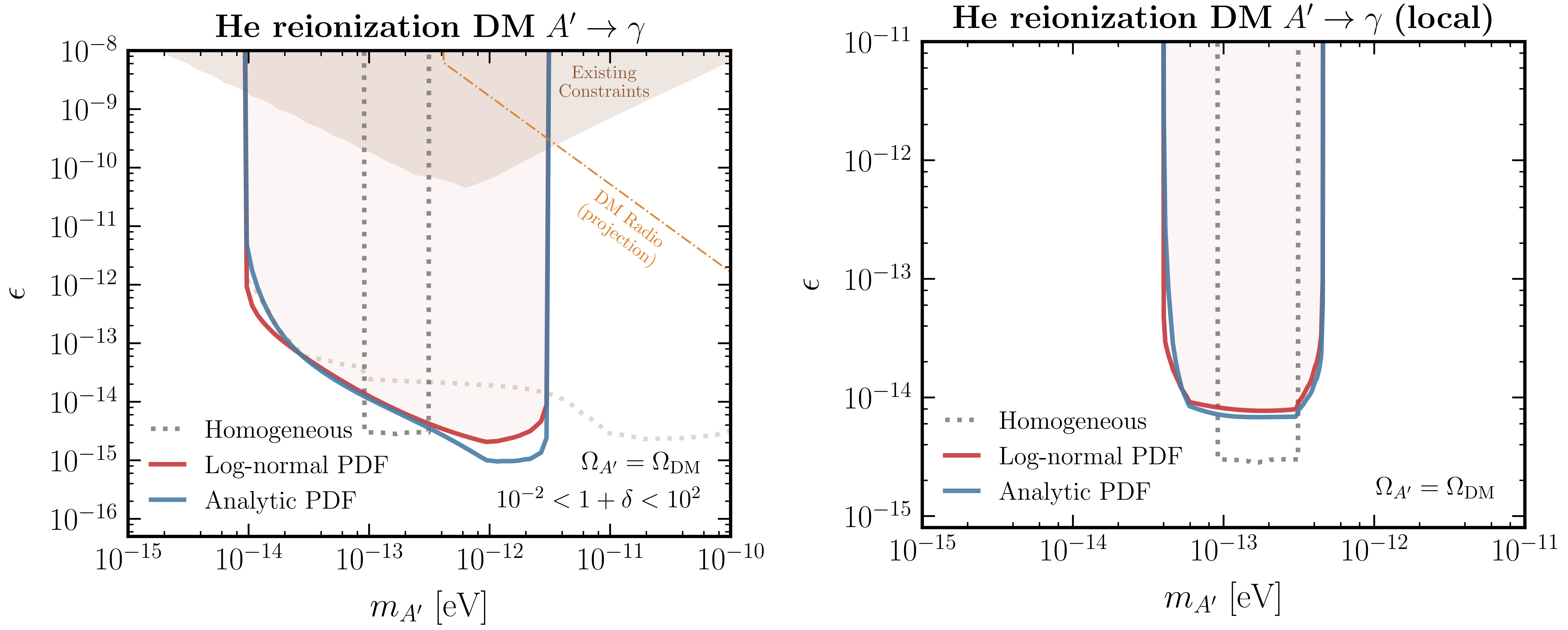
See also Witte et al [2003.13698]



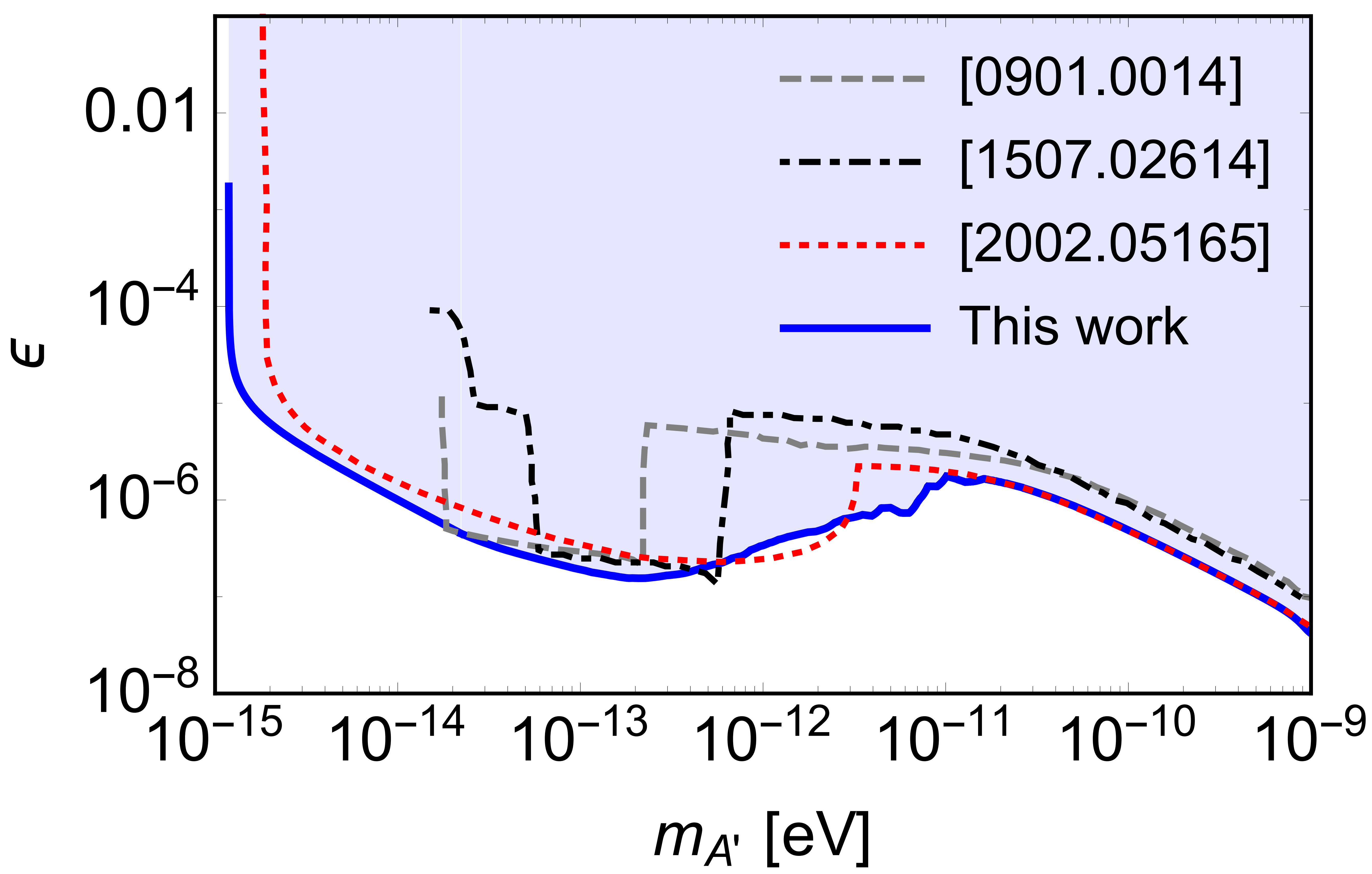
$$\frac{\mathrm{d}\left\langle E_{A'\to\gamma}\right\rangle_{\rm local}}{\mathrm{d}z} = \pi m_{A'}^3 \epsilon^2 \frac{\bar{\rho}_{A'}}{b \bar{n}_{\rm b}} \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| f\left(m_\gamma^2 = m_{A'}^2; t\right) \; *$$

*Assumes energy is uniformly distributed among baryons

Local heating prescription for A' DM $\to \gamma$



Comparison with numerical approach



Bondarenko, Pradler, Sokolenko [2002.08942]
Garcia et al [2003.10465]

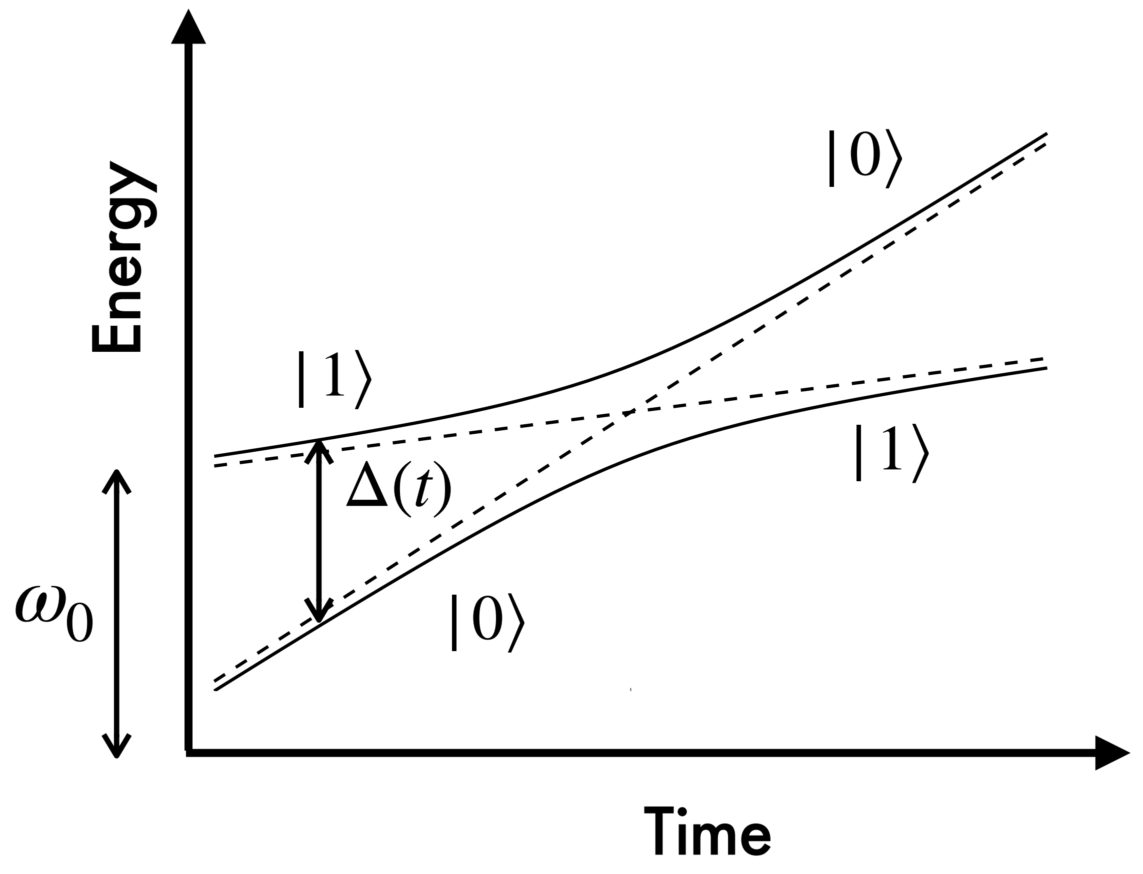
Resonant oscillations in plasma: Landau-Zener formalism

Non-adiabatic level crossings for two-level quantum system

$$H = \begin{pmatrix} 0 & \Omega^\dagger e^{+i\omega t} \\ \Omega e^{-i\omega t} & \omega_0 \end{pmatrix}$$

$$\Delta = \omega - \omega_0$$

$$P_0 \approx e^{-2\pi\Omega^2/\dot{\Delta}}$$



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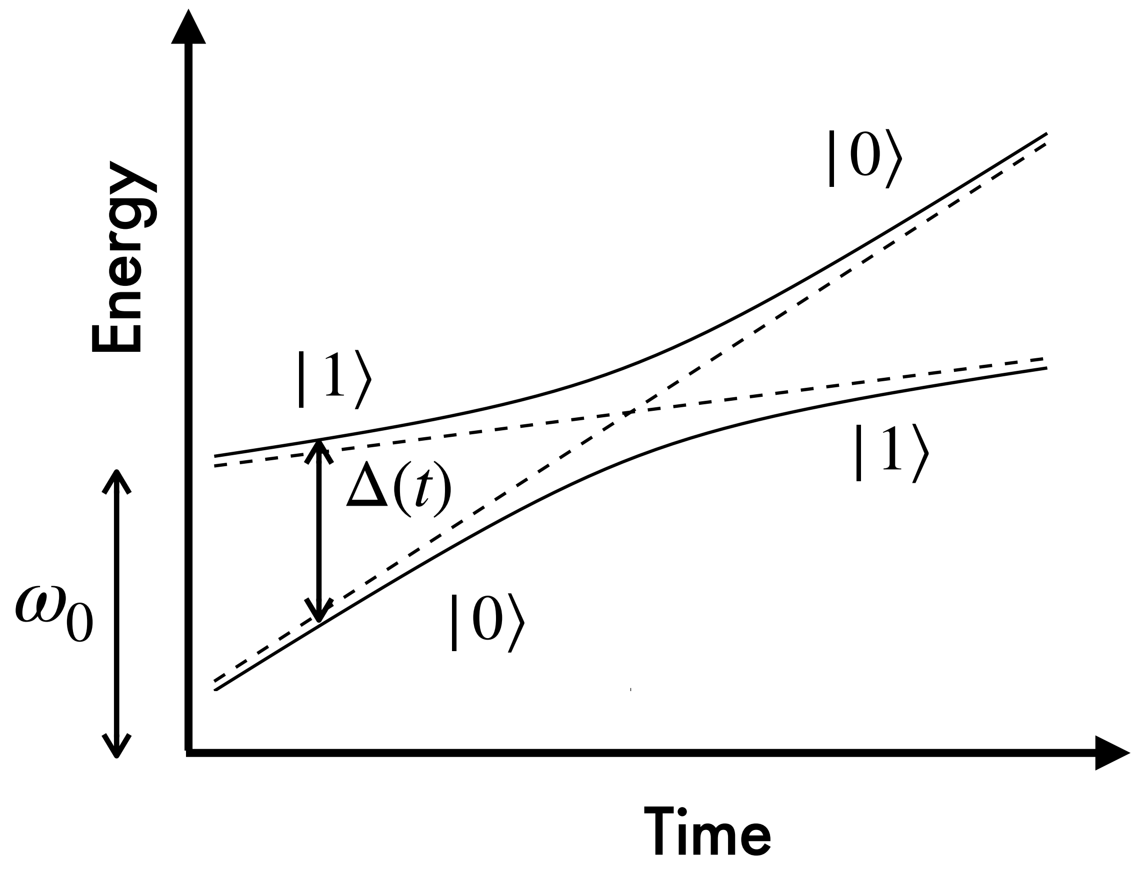

Similar formalism for neutrino oscillations (MSW effect)

Nonadiabatic Level Crossing in Resonant Neutrino Oscillations

Stephen J. Parke

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 27 May 1986)

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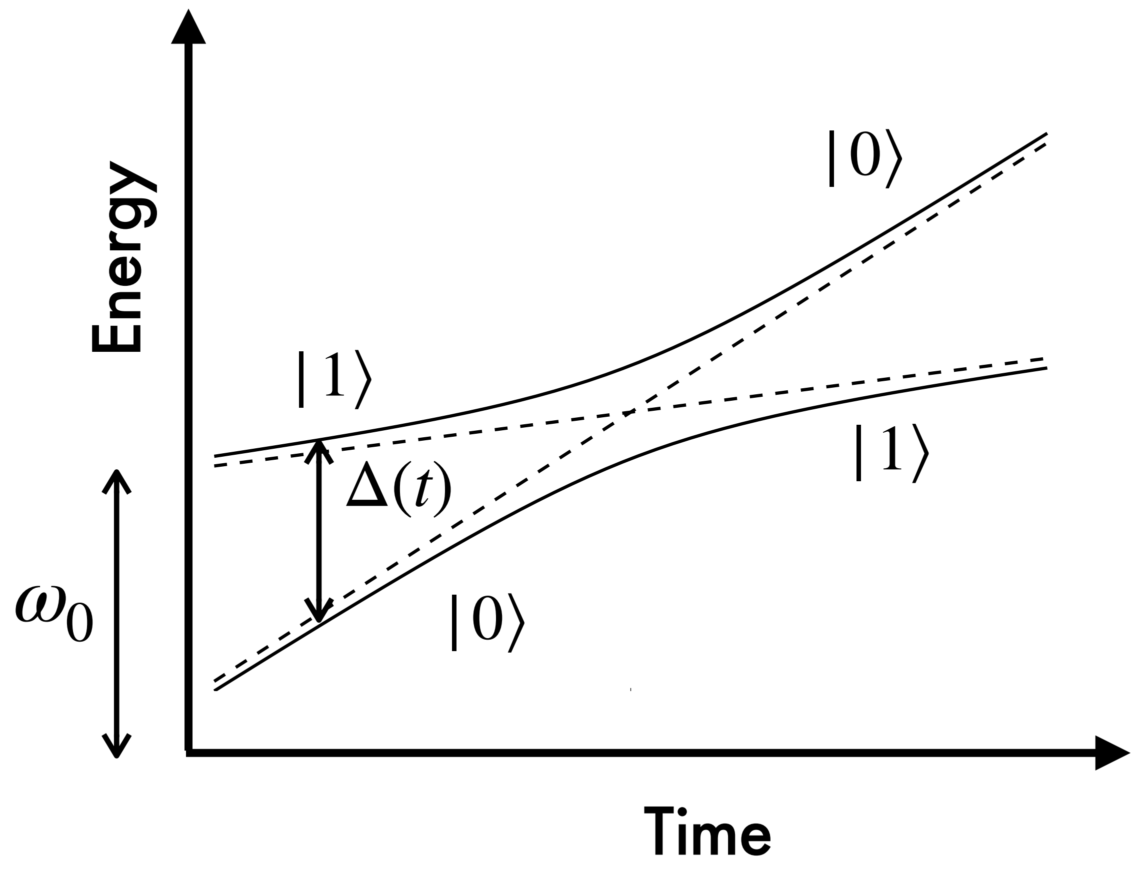

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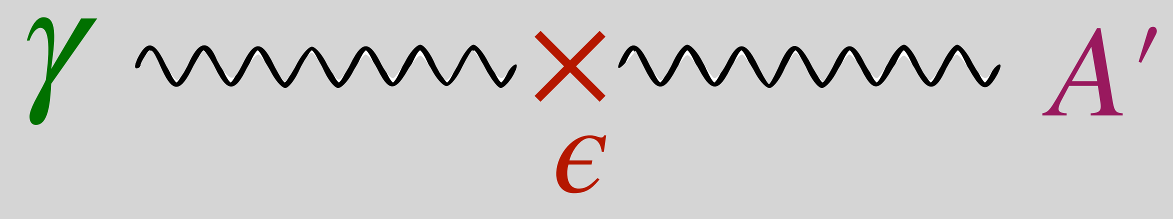


$m_\gamma \approx m_{A'}$

$m_\gamma^2(z) \approx \frac{4\pi\alpha\, n_e(z)}{m_e}$

$$P_{\gamma\to A'} \simeq \frac{\pi\epsilon^2 m_{A'}^2}{\omega\left(z_{\rm res}\right)} \left|\frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t}\right|^{-1}_{z=z_{\rm res}}$$

$$\omega(z_{\rm res}) = \omega_{\rm obs}(1+z_{\rm res})$$

$\Longrightarrow$ Later resonances typically dominate

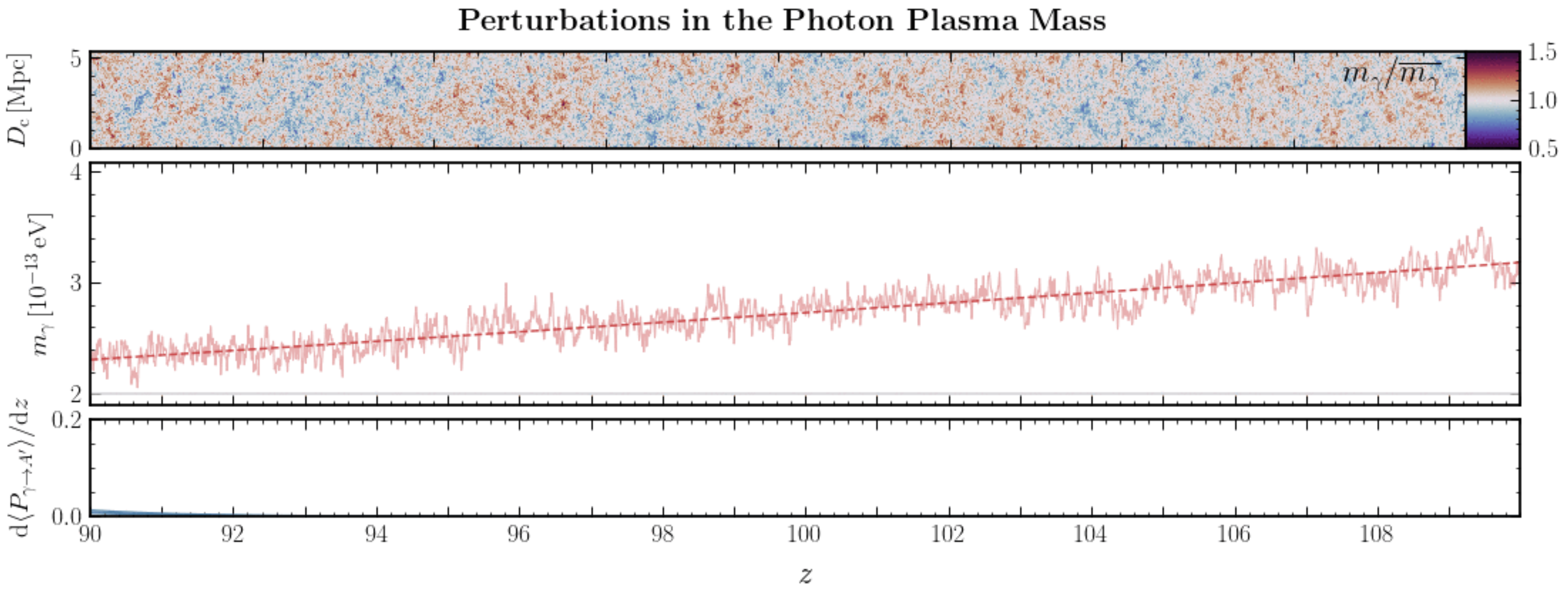
$P_{\gamma\to A'}$ in an inhomogeneous plasma

Conversion along a line of sight

$$P_{\gamma\to A'} \simeq \pi\epsilon^2 m_{A'}^2 \sum_i \frac{1}{\omega_i\left(z_{\mathrm{res},i}\right)} \left|\frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t}\right|^{-1}_{z=z_{\mathrm{res},i}}$$

Averaged conversion probability

$$P_{\gamma\to A'} \simeq \pi\epsilon^2 m_{A'}^2 \left\langle \sum_i \frac{1}{\omega_i\left(z_{\mathrm{res},i}\right)} \left|\frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t}\right|^{-1}_{z=z_{\mathrm{res},i}} \right\rangle$$



$P_{\gamma\to A'}$ in an inhomogeneous plasma

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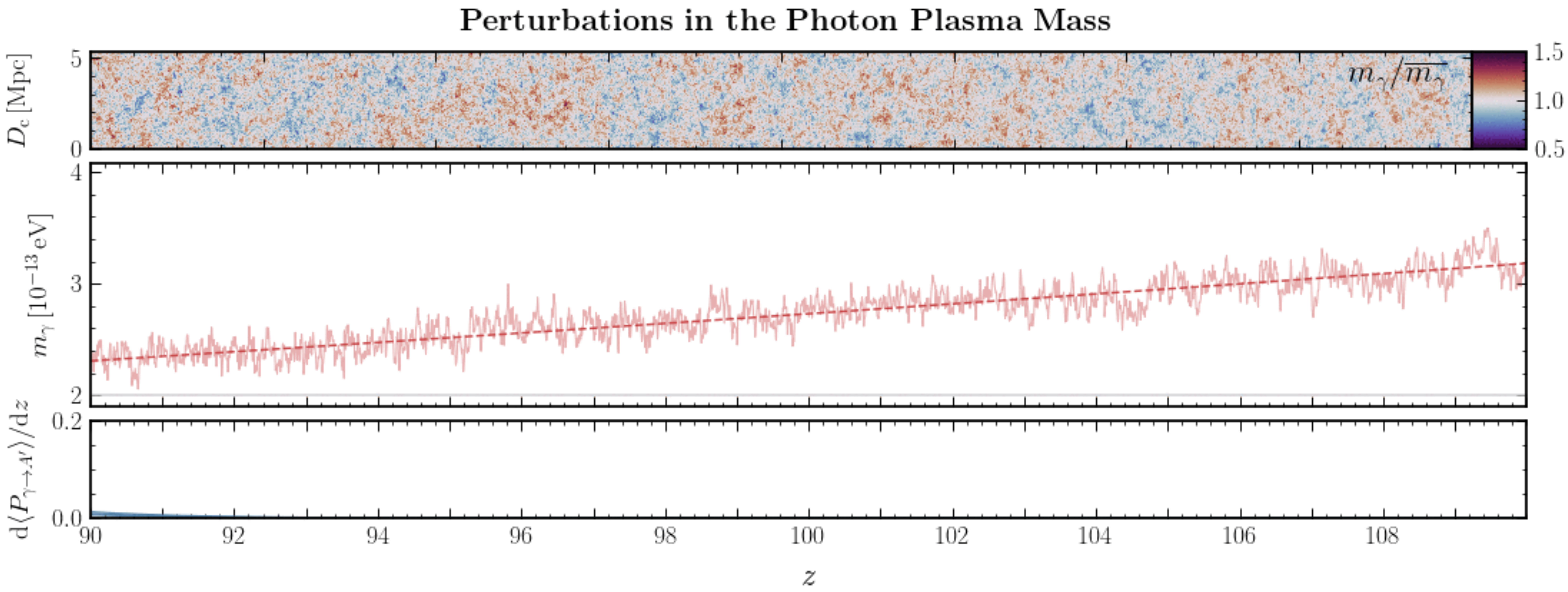
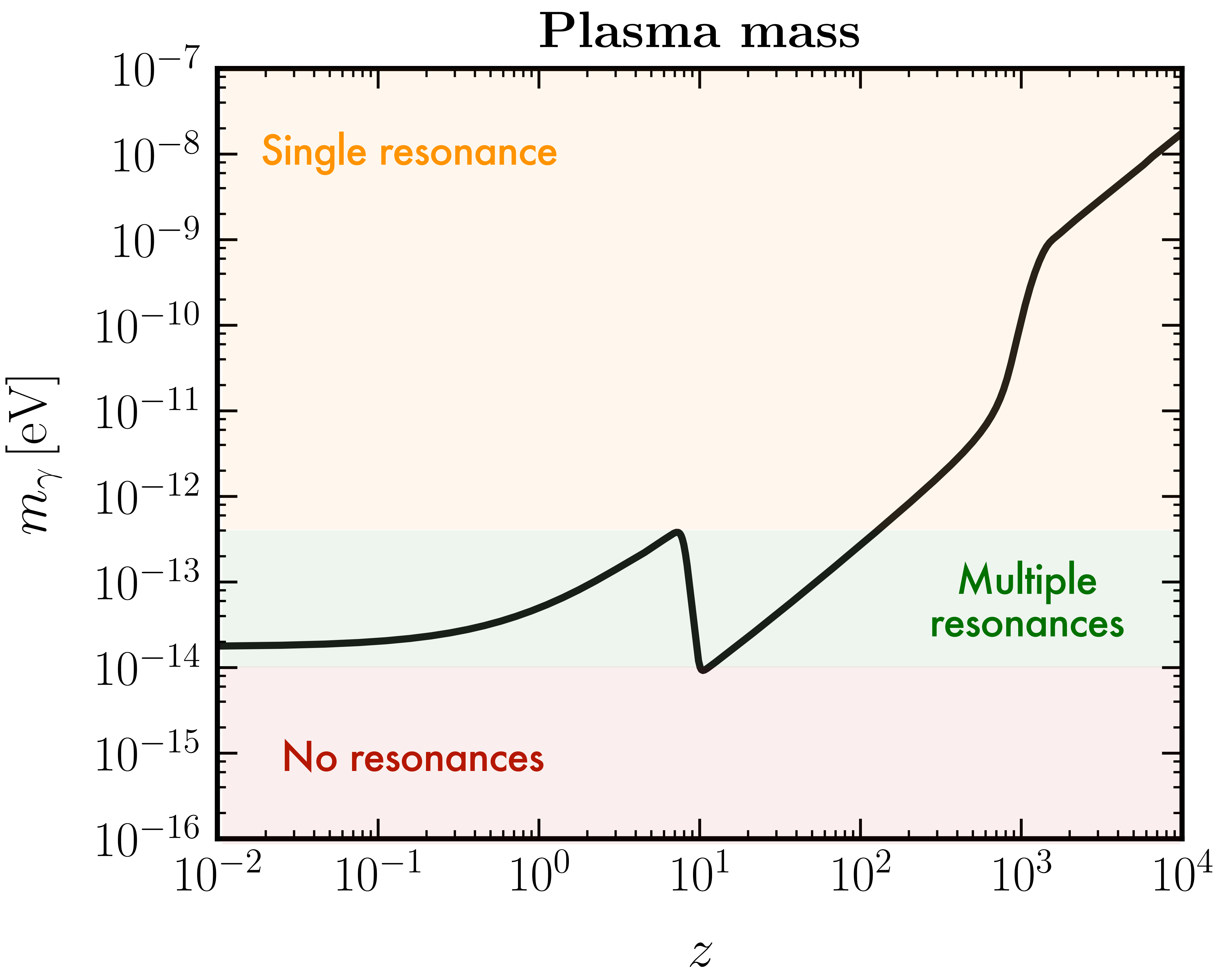
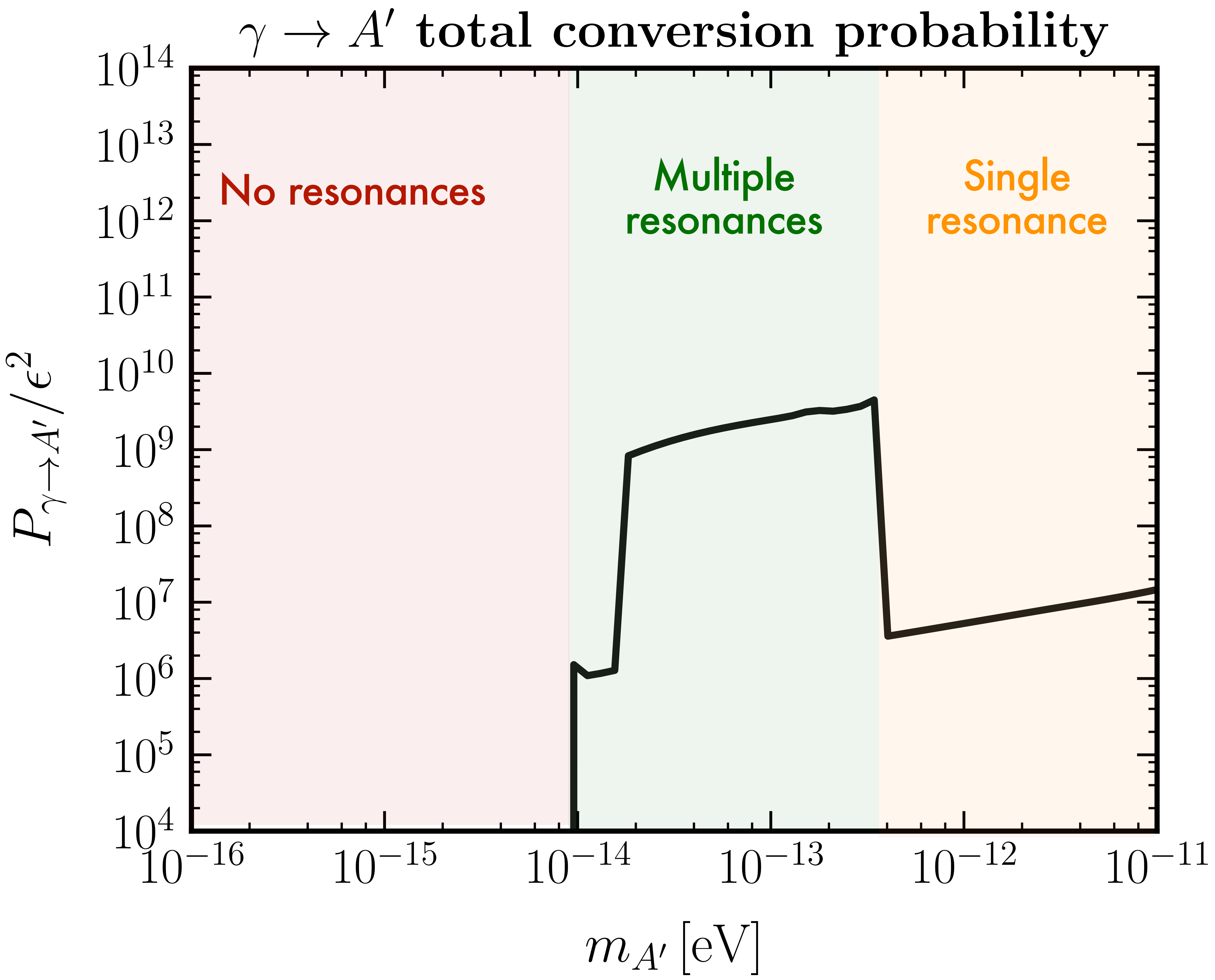


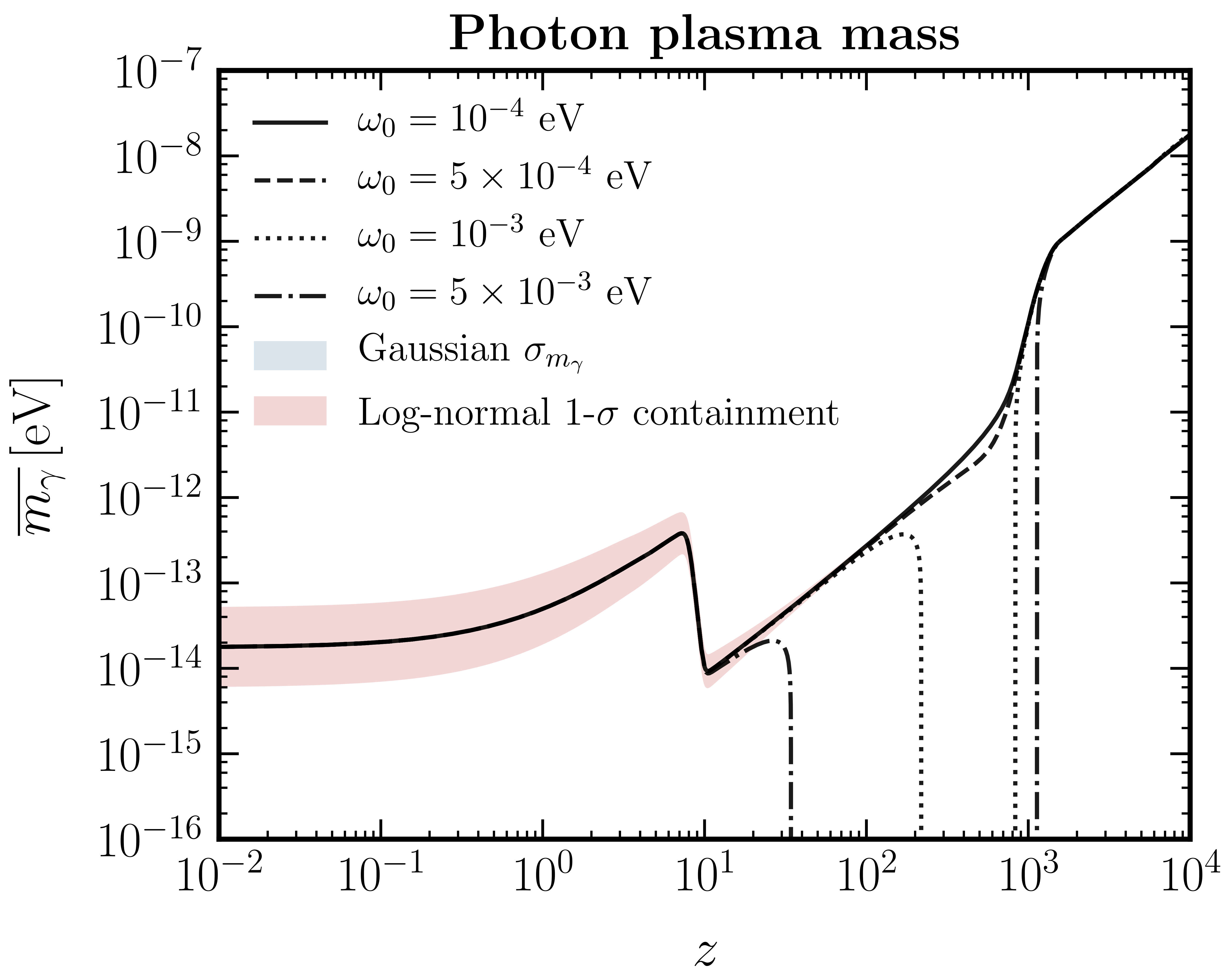
Resonant oscillations in photon plasma

$$P_{\gamma\to A'} \simeq \frac{\pi\epsilon^2 m_{A'}^2}{\omega\left(z_{\rm res}\right)}\left|\frac{\mathrm{d}\ln m_\gamma^2(t)}{\mathrm{d}t}\right|^{-1}_{z=z_{\rm res}}$$

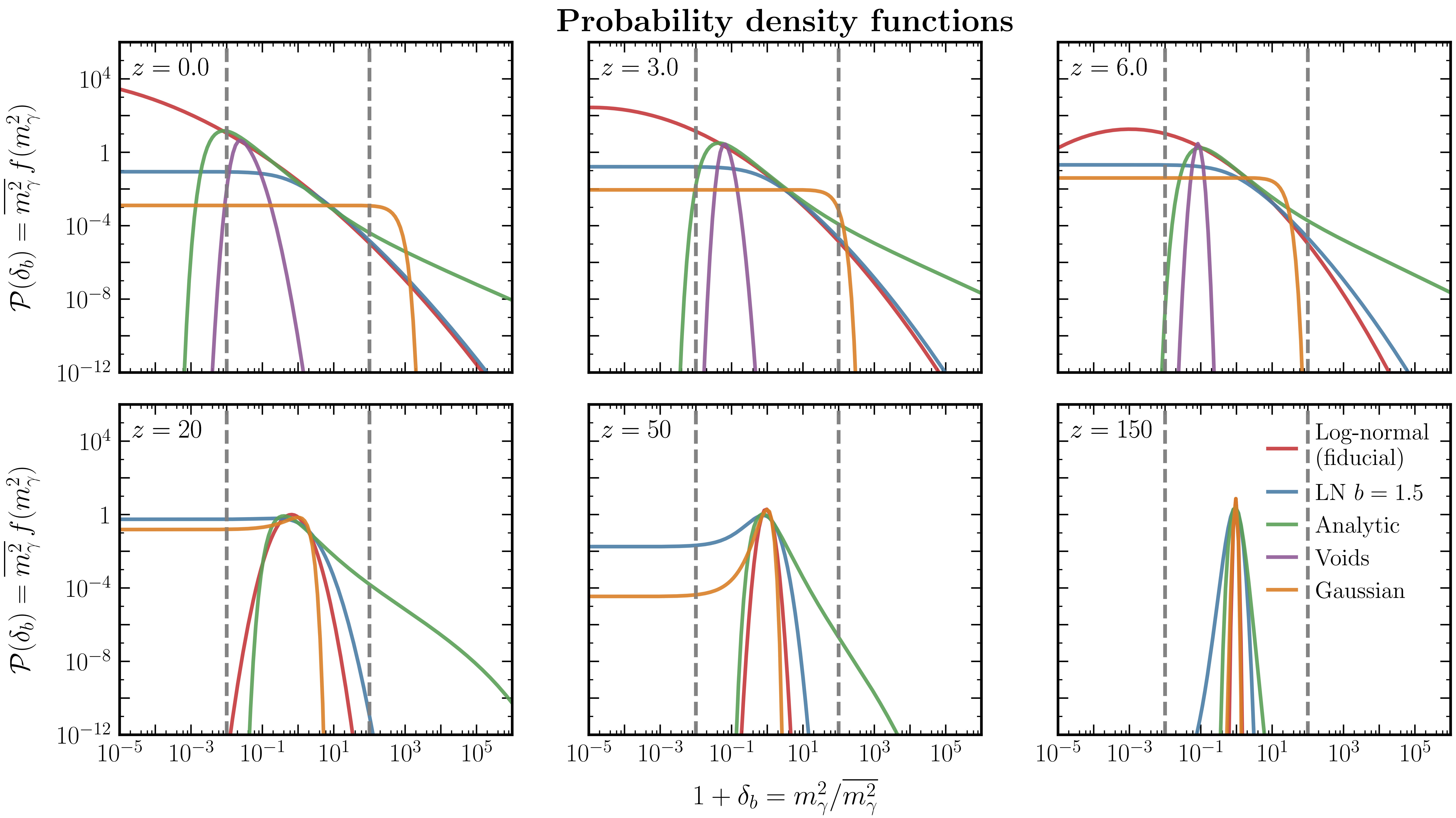




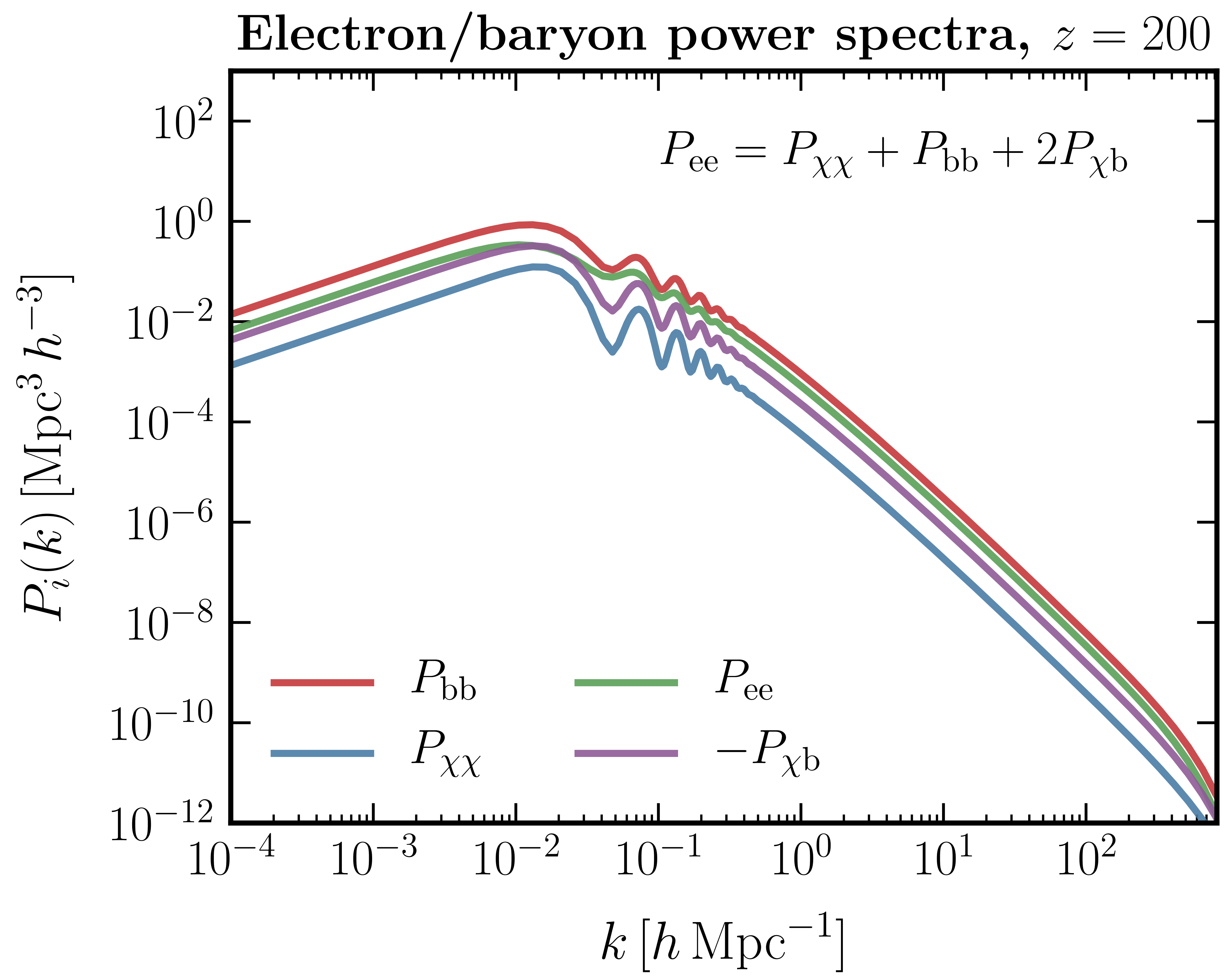
Photon plasma mass variance

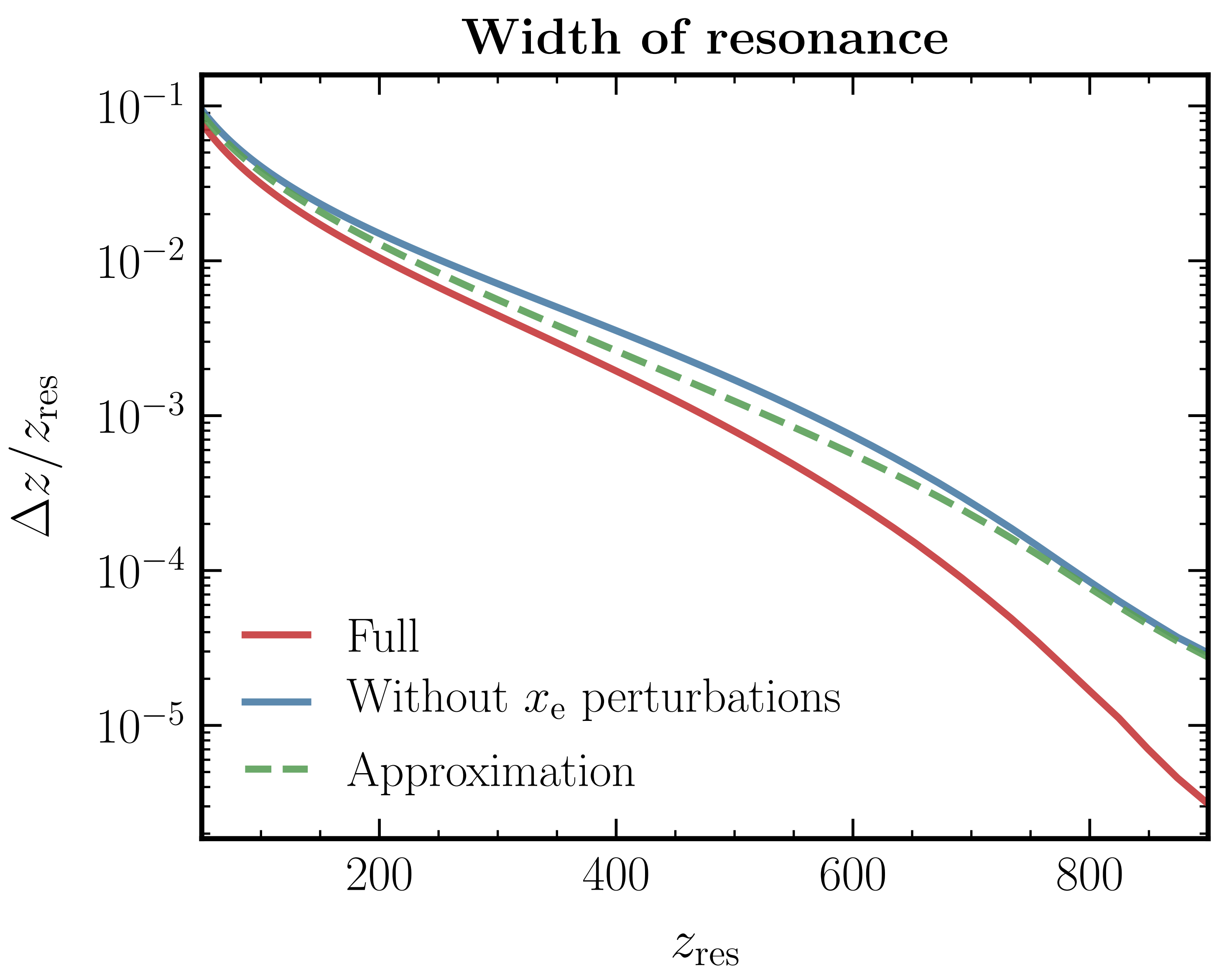


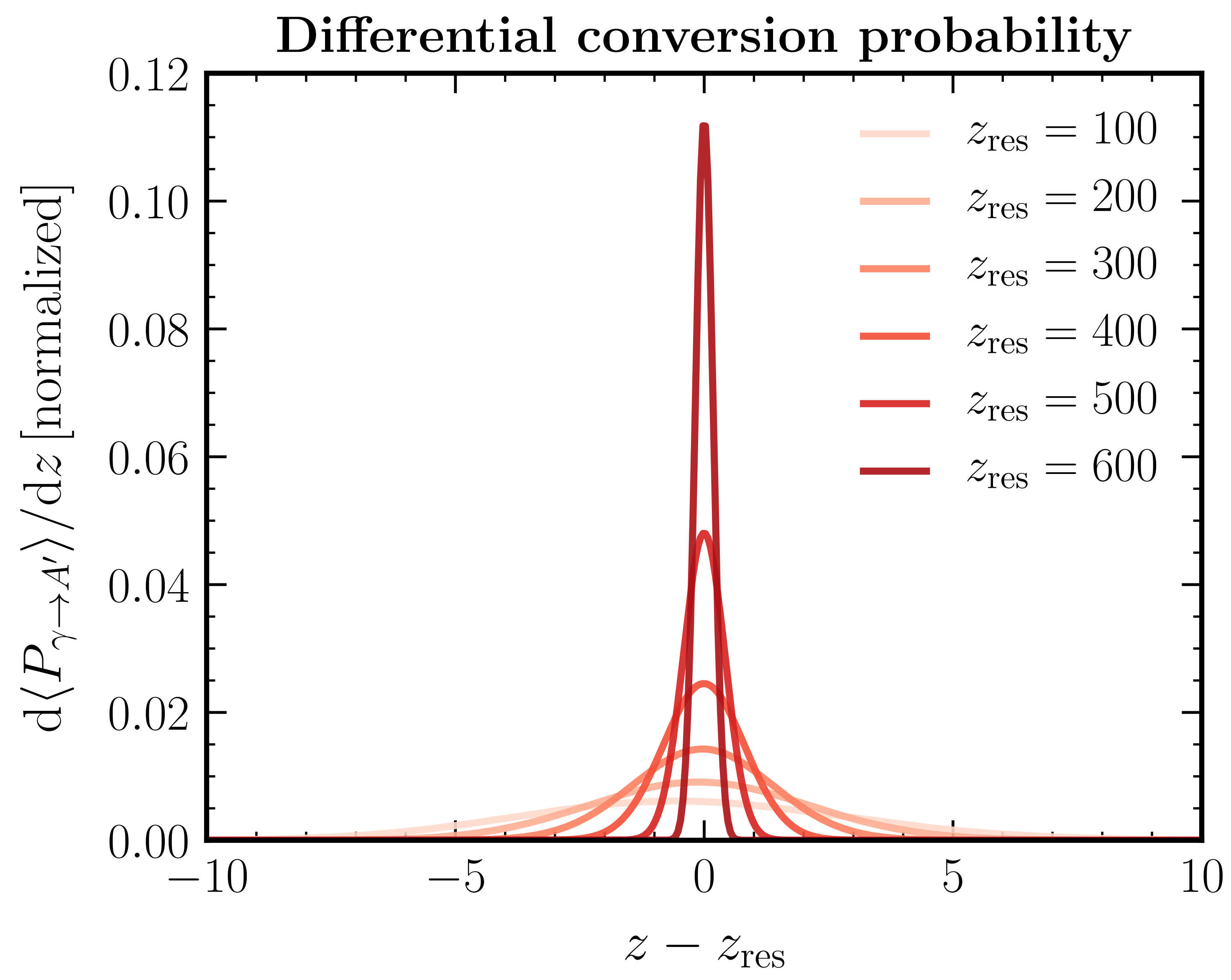
PDF snapshots



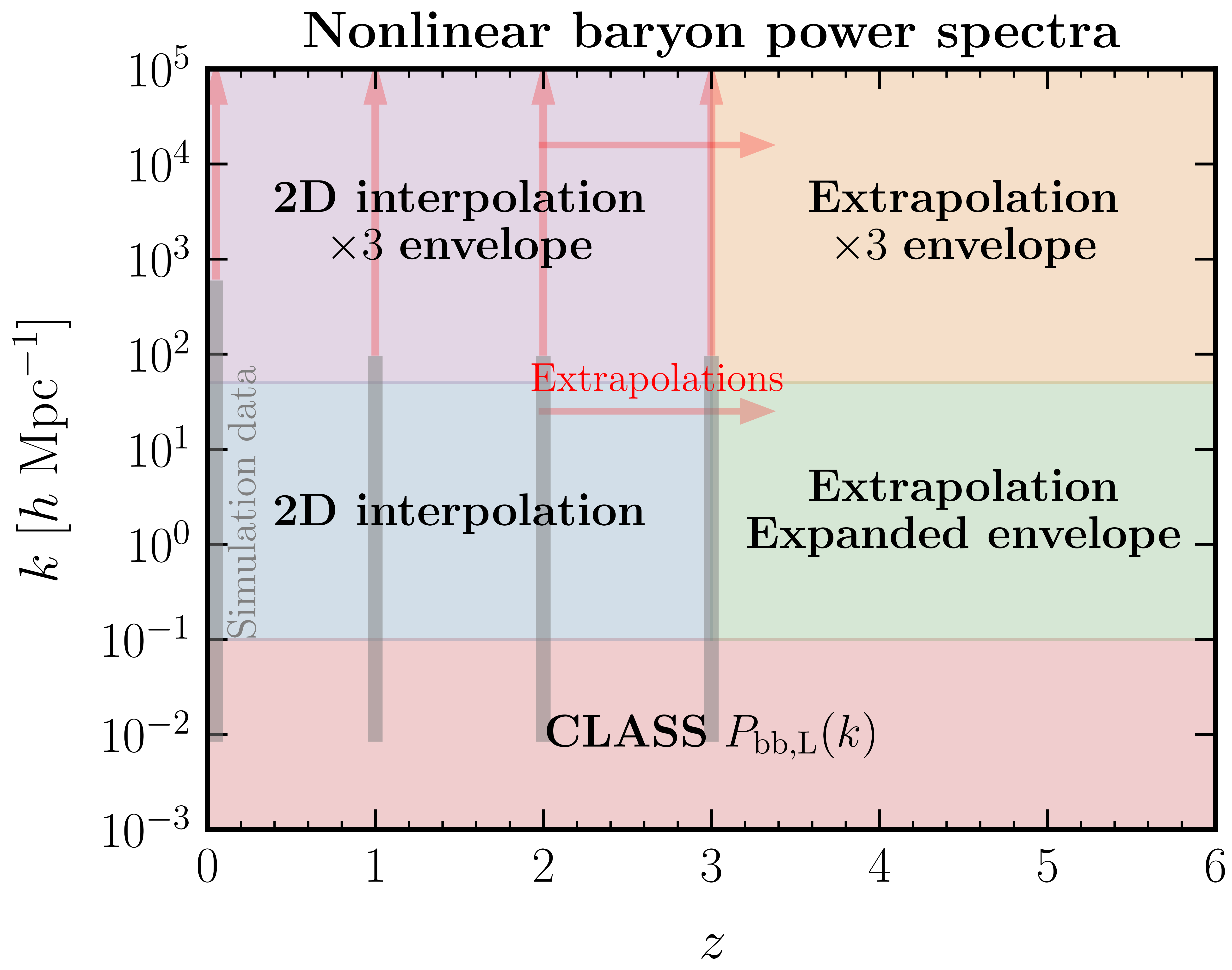
Baryon/electron fluctuations

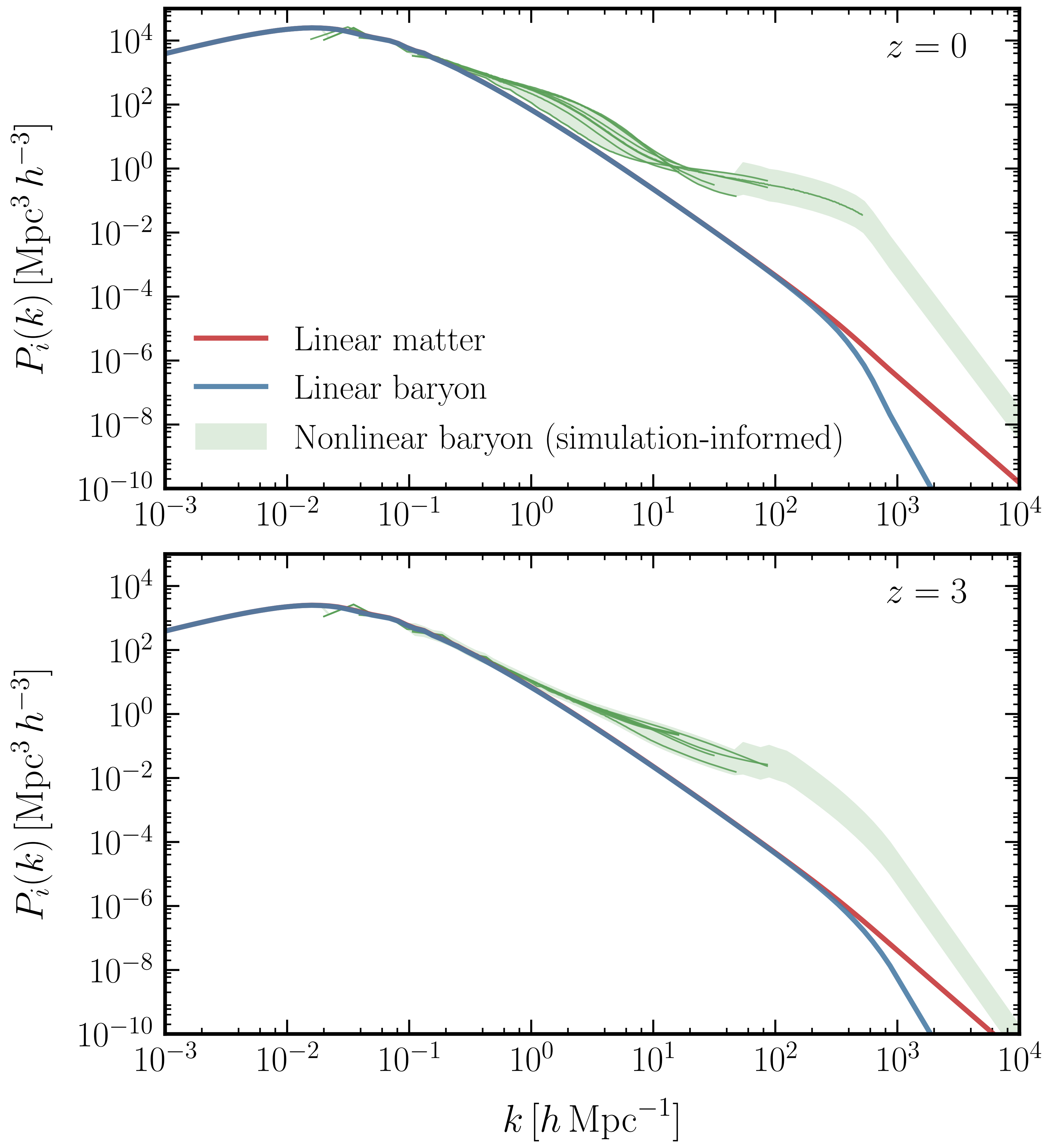




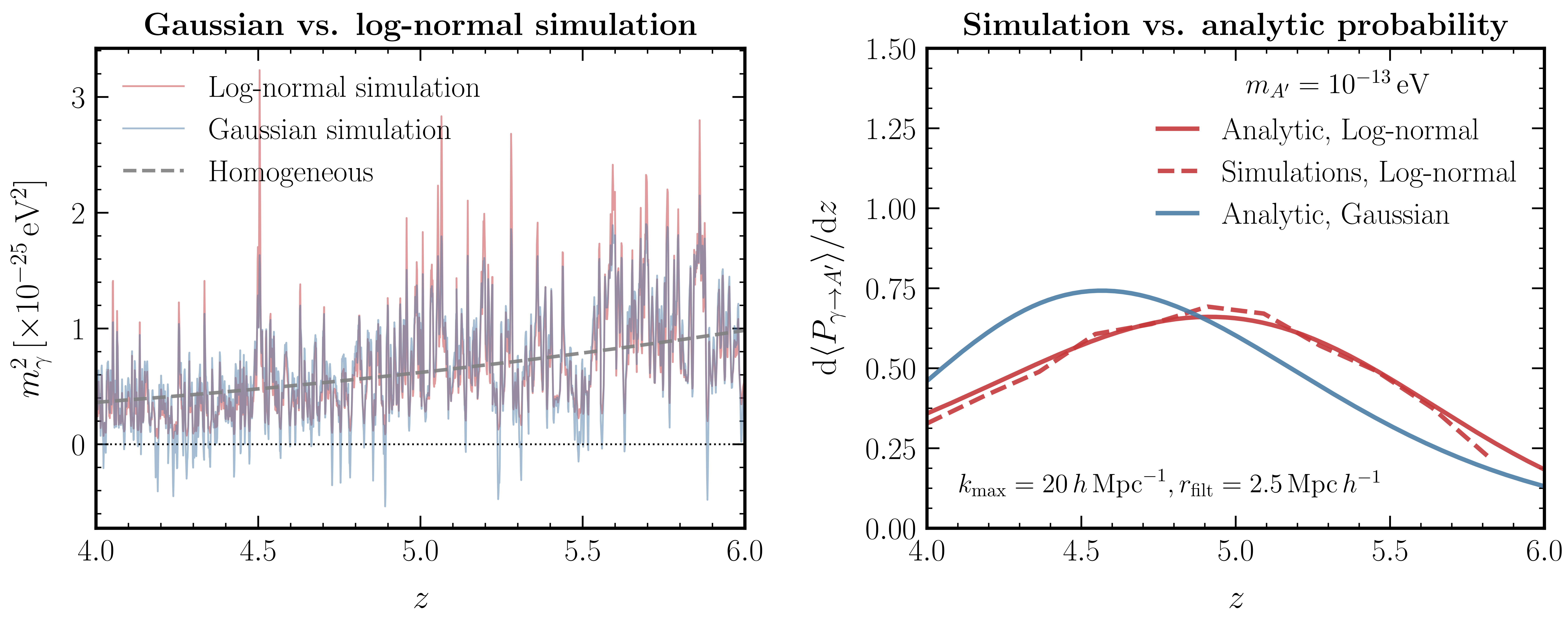


Simulation-inferred baryon power spectra

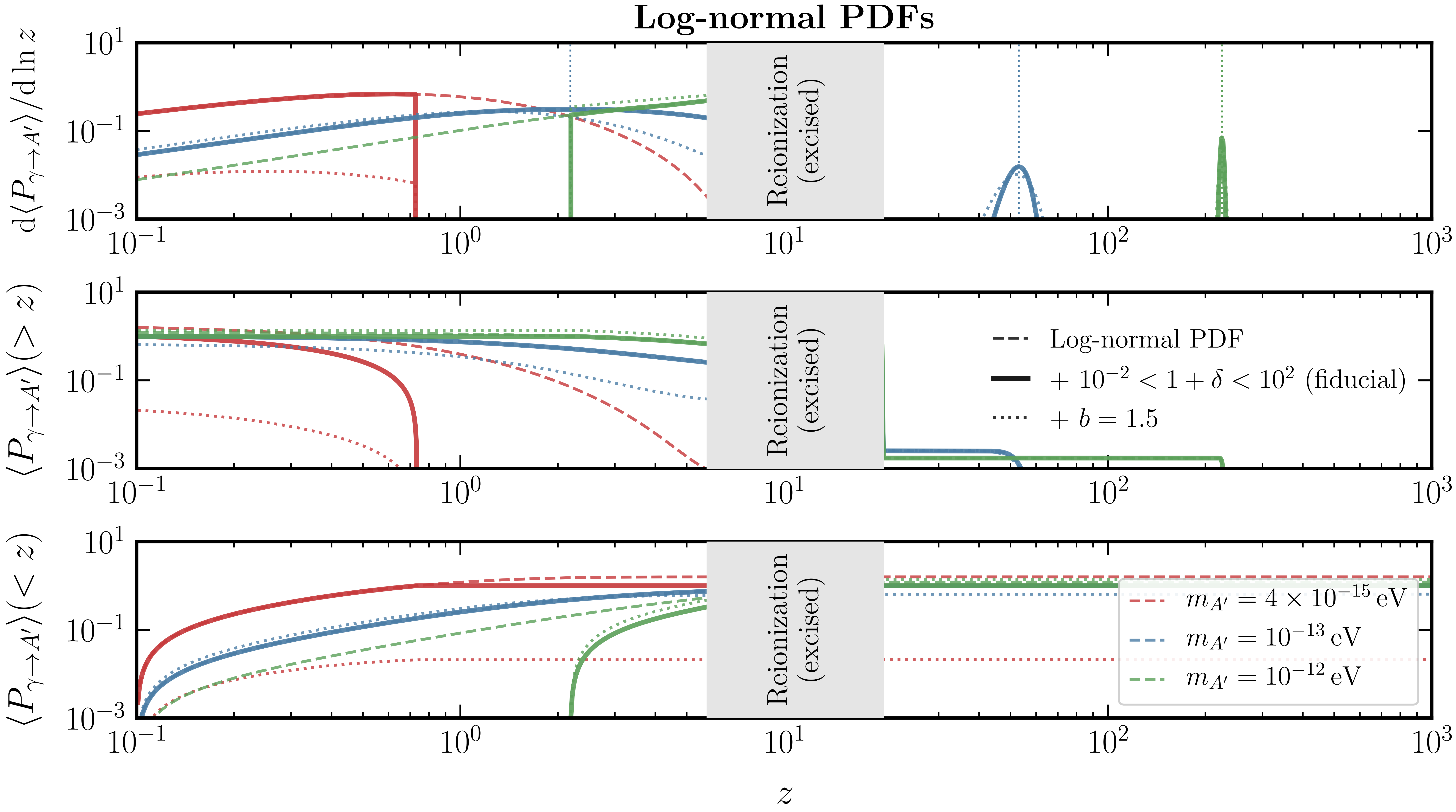




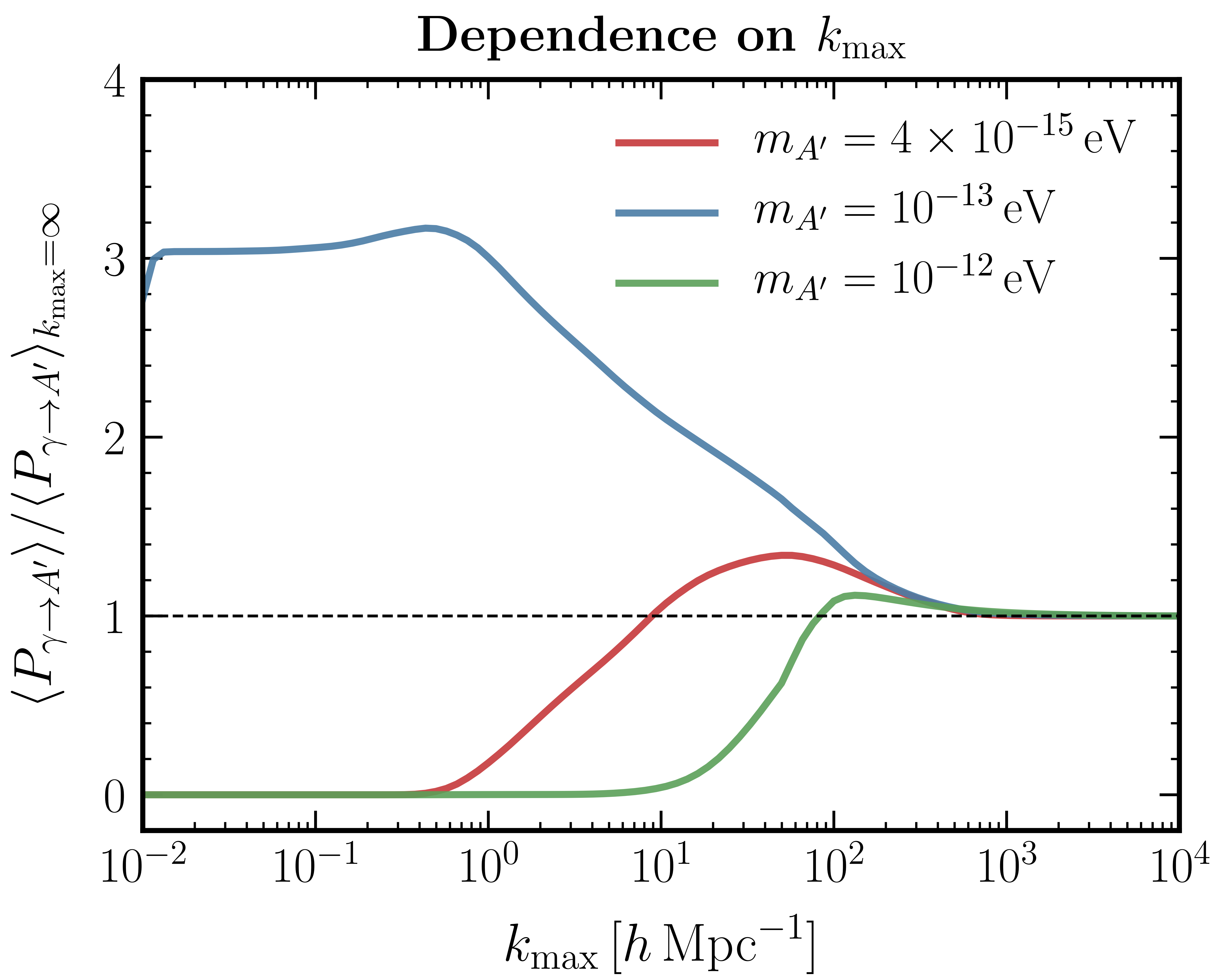
Simulation vs analytics comparison



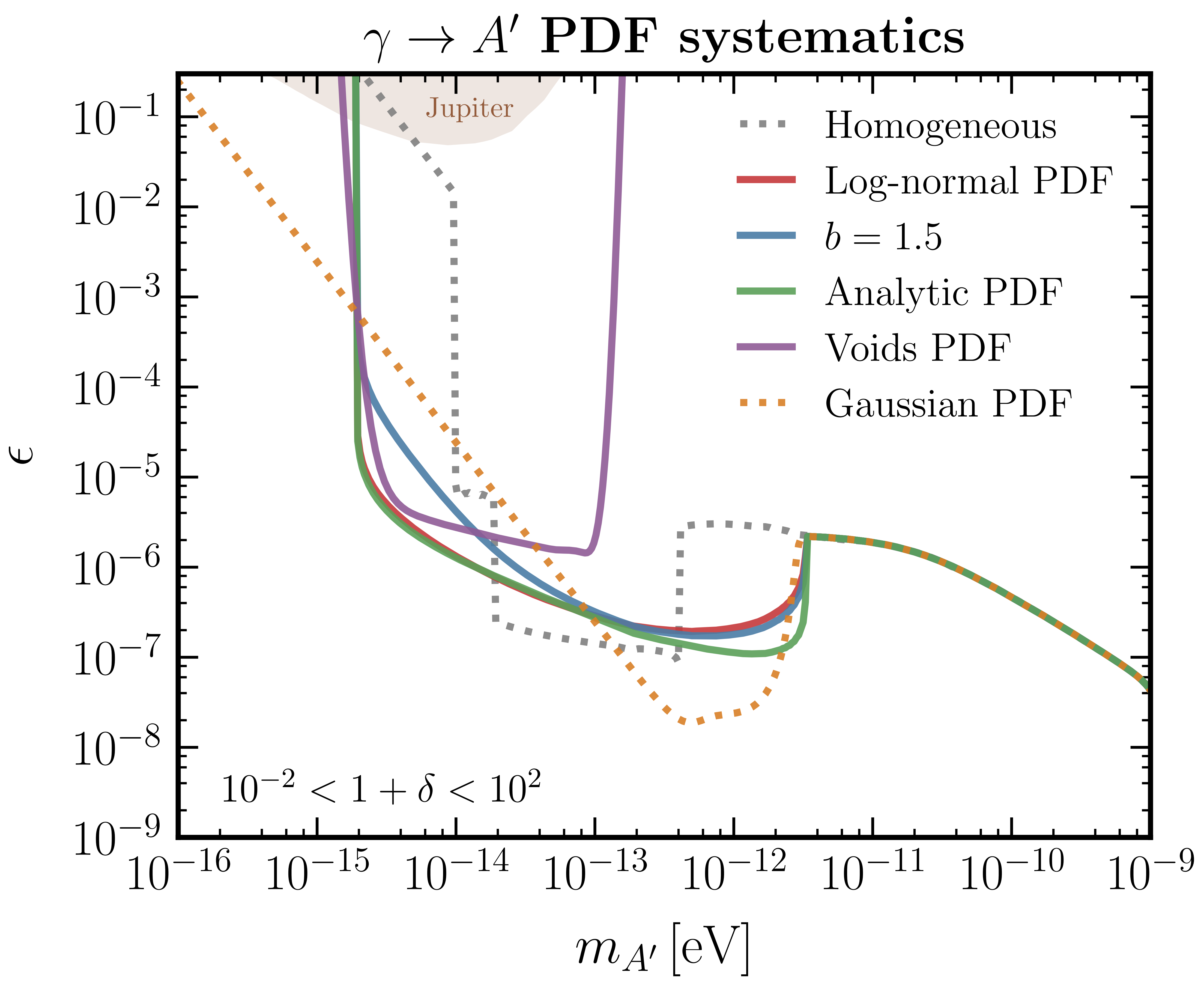
Conversion probabilities

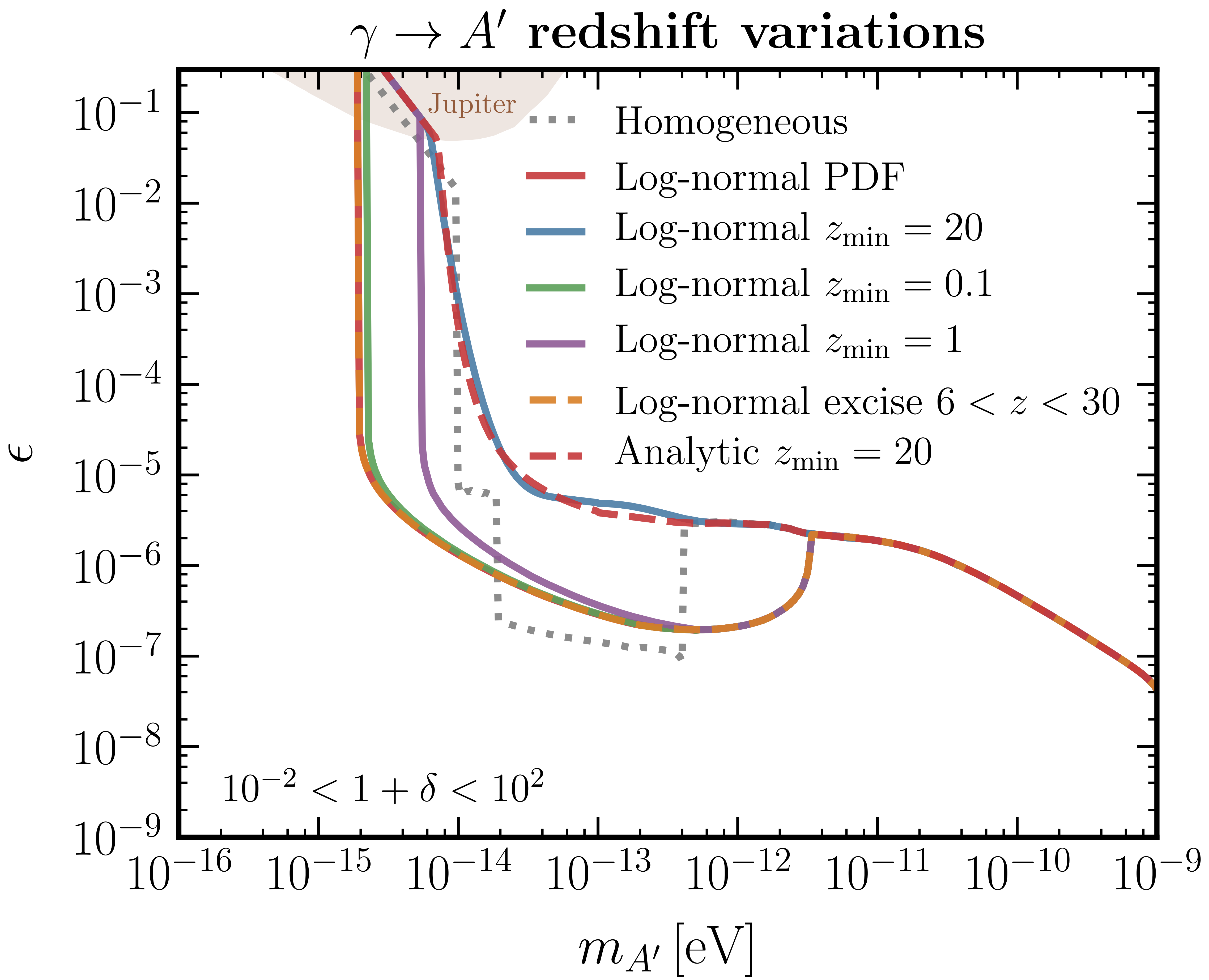


Dependence of total probability on $k_{\max}$



Redshift and PDF systematics

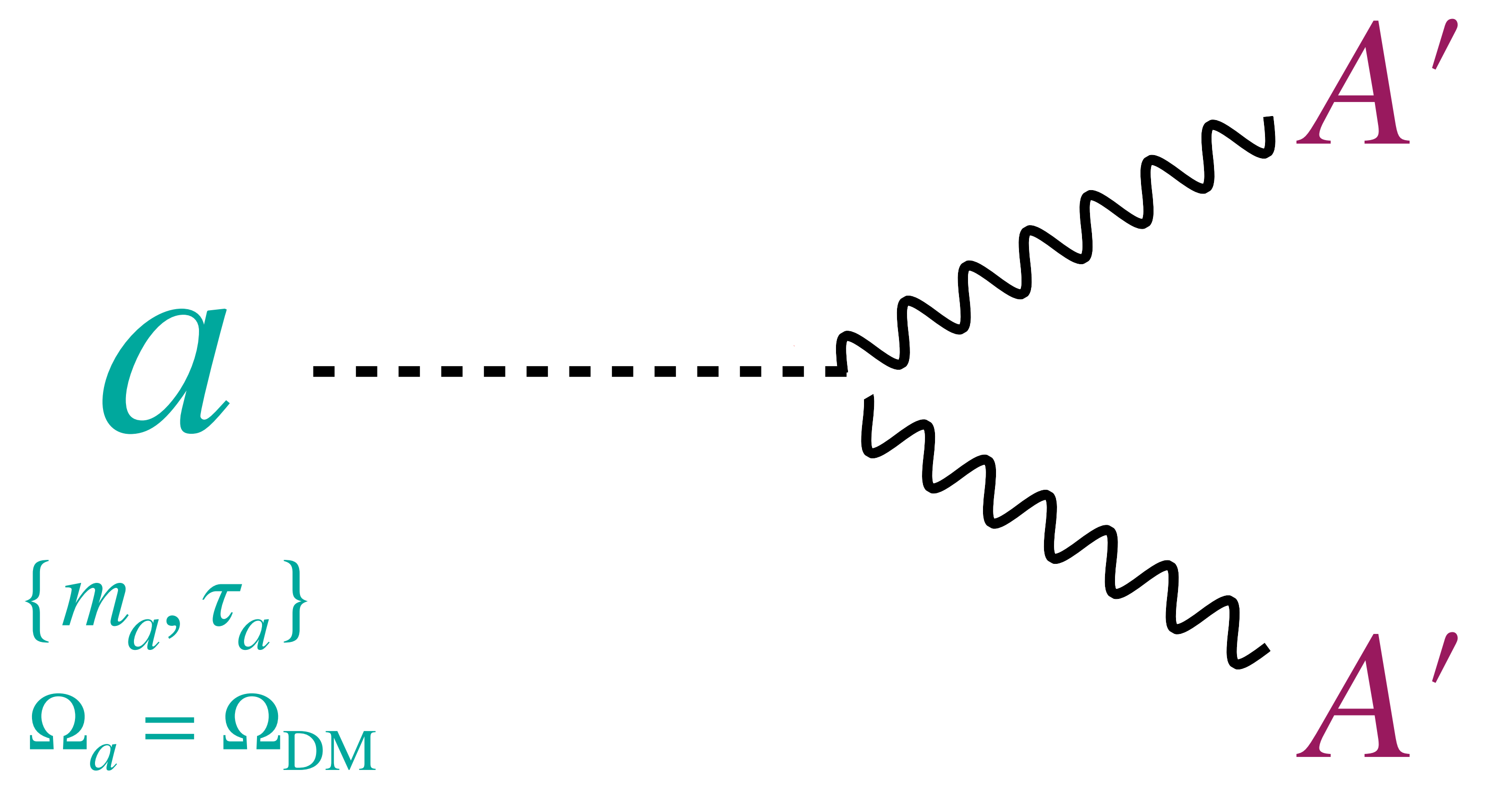


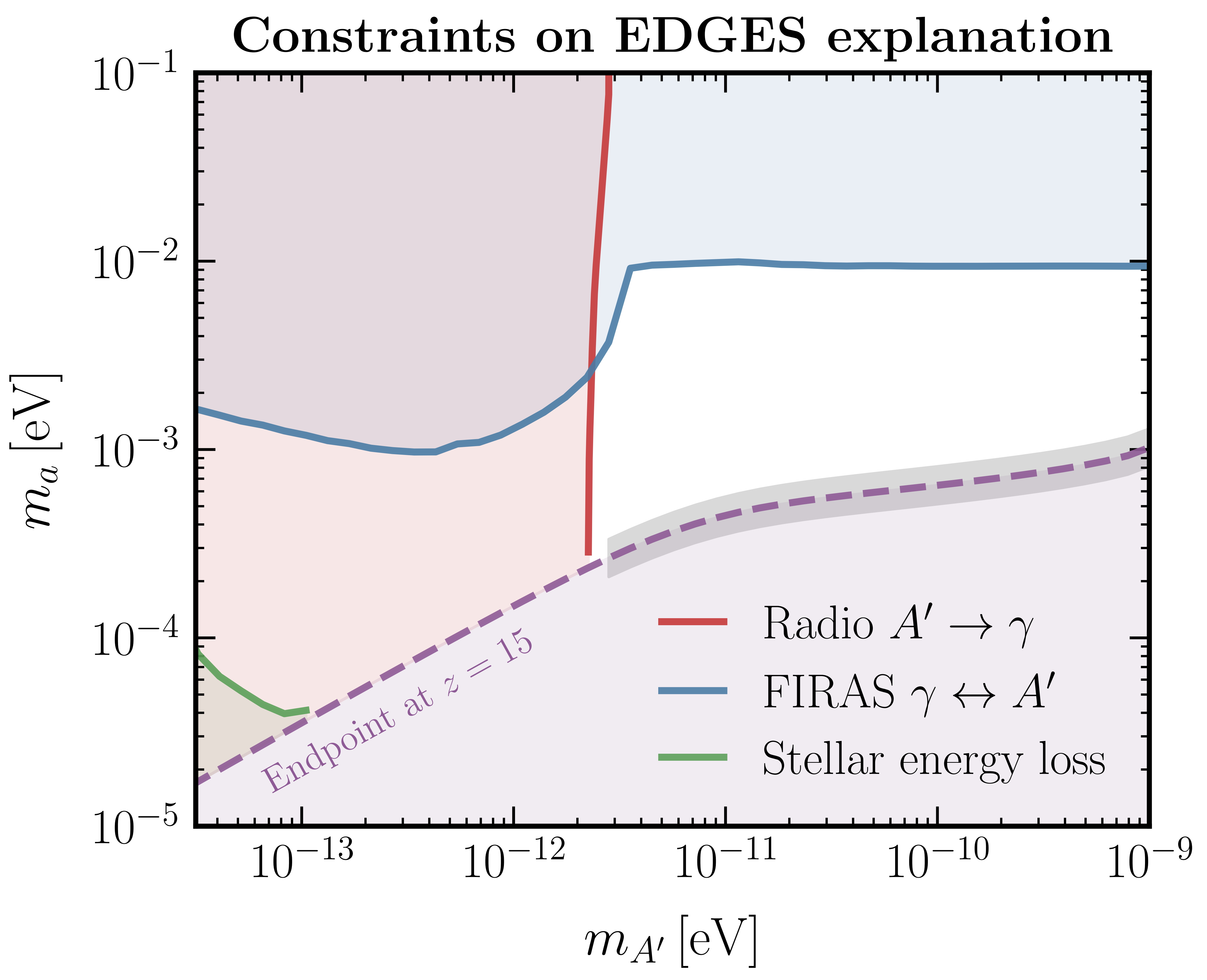


Constraints on EDGES explanation of model

Pospelov, Pradler, Ruderman, Urbano [1803.07048]

1. Decay of long-lived particle a (DM) to A'





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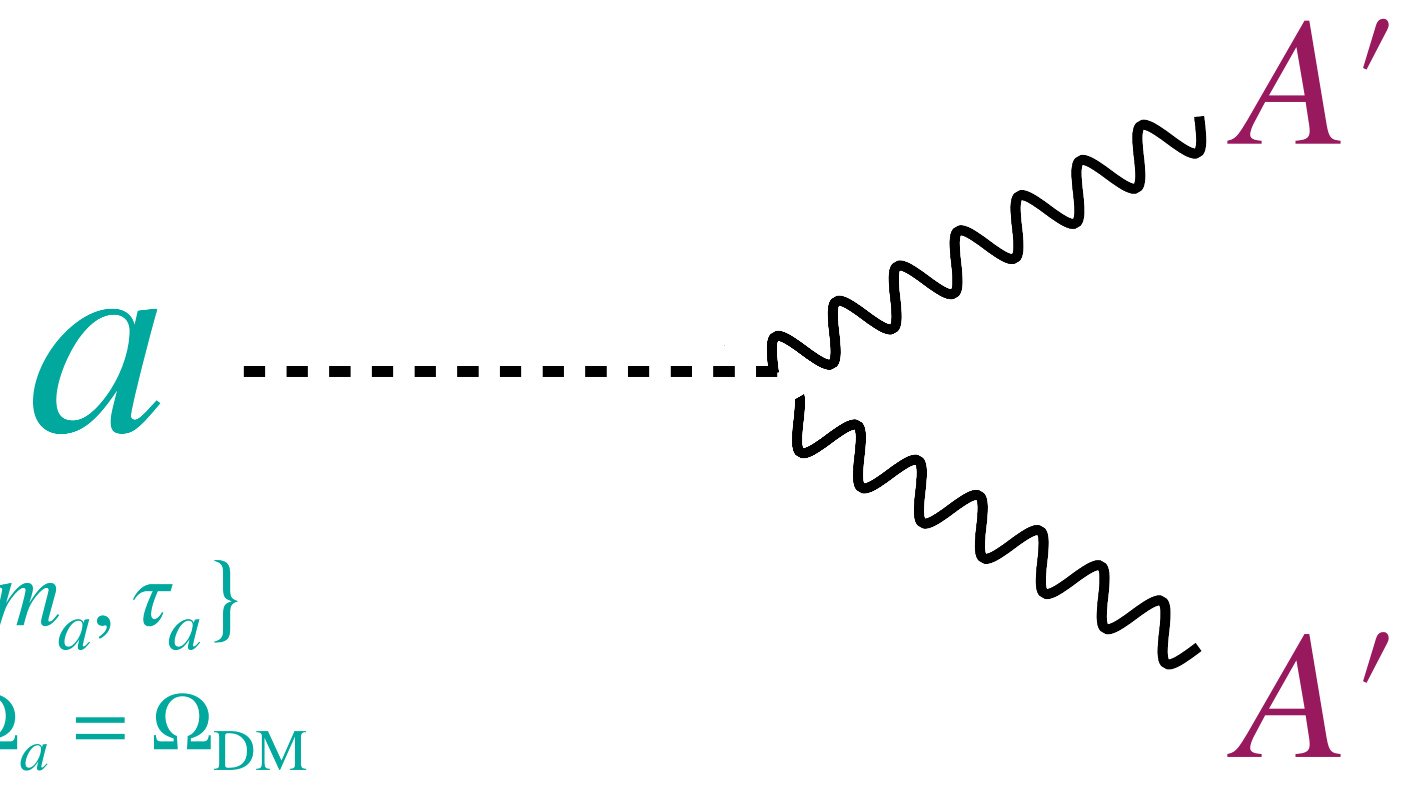
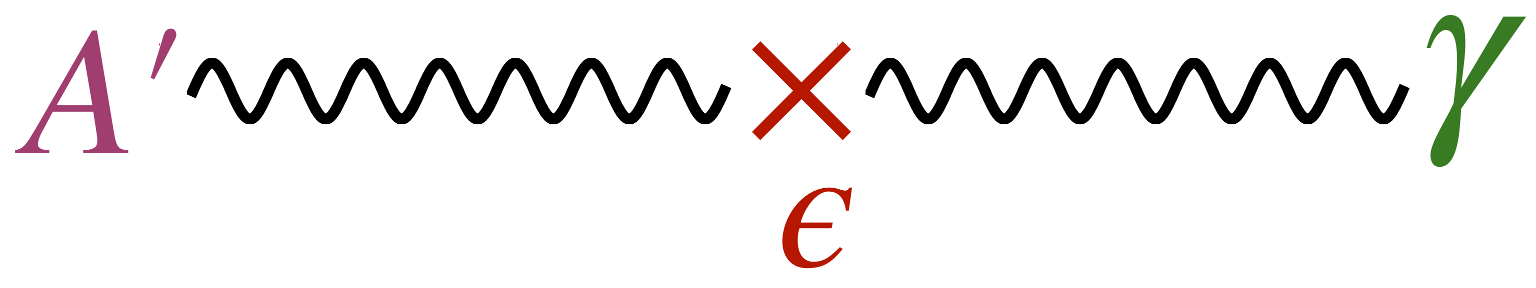
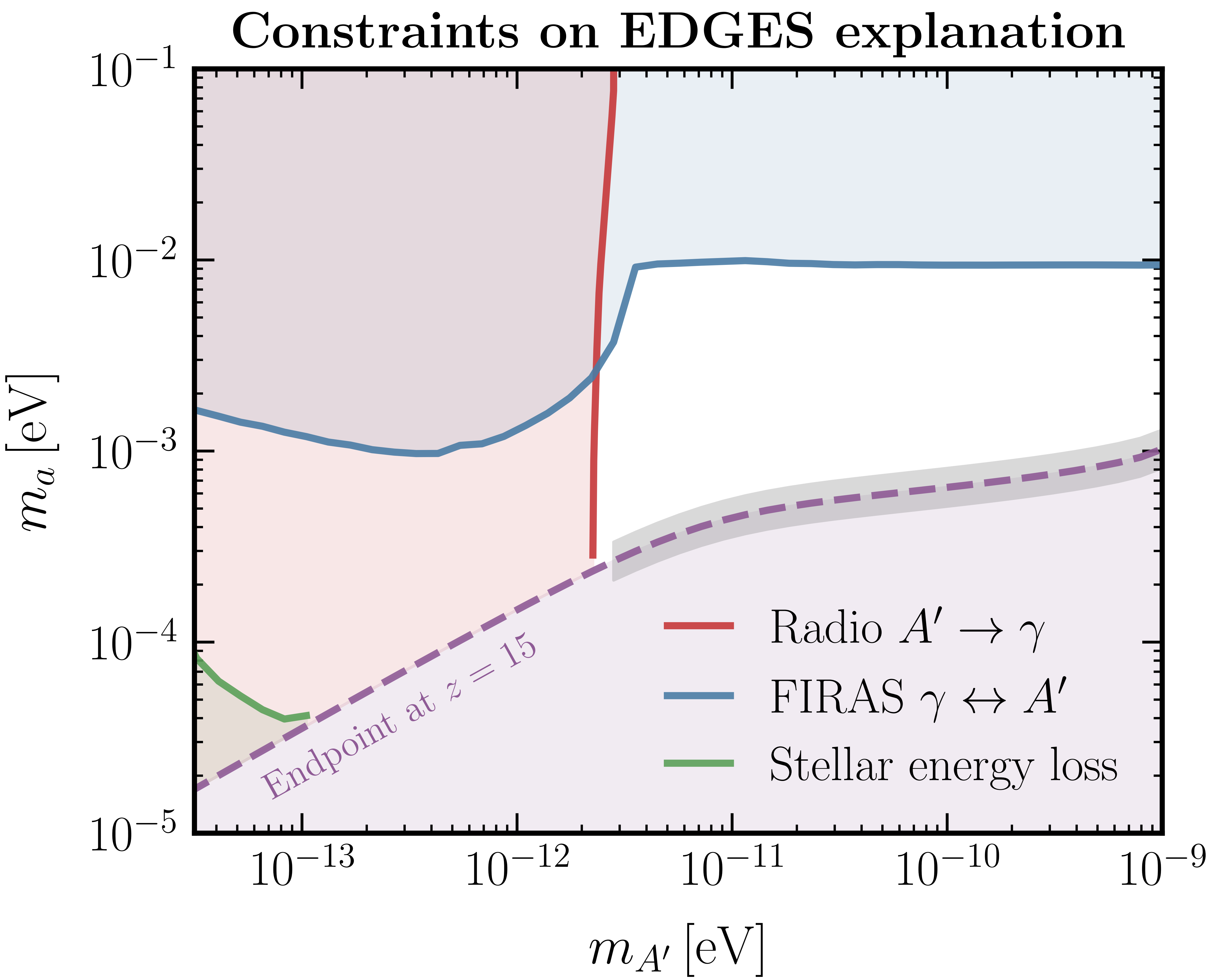


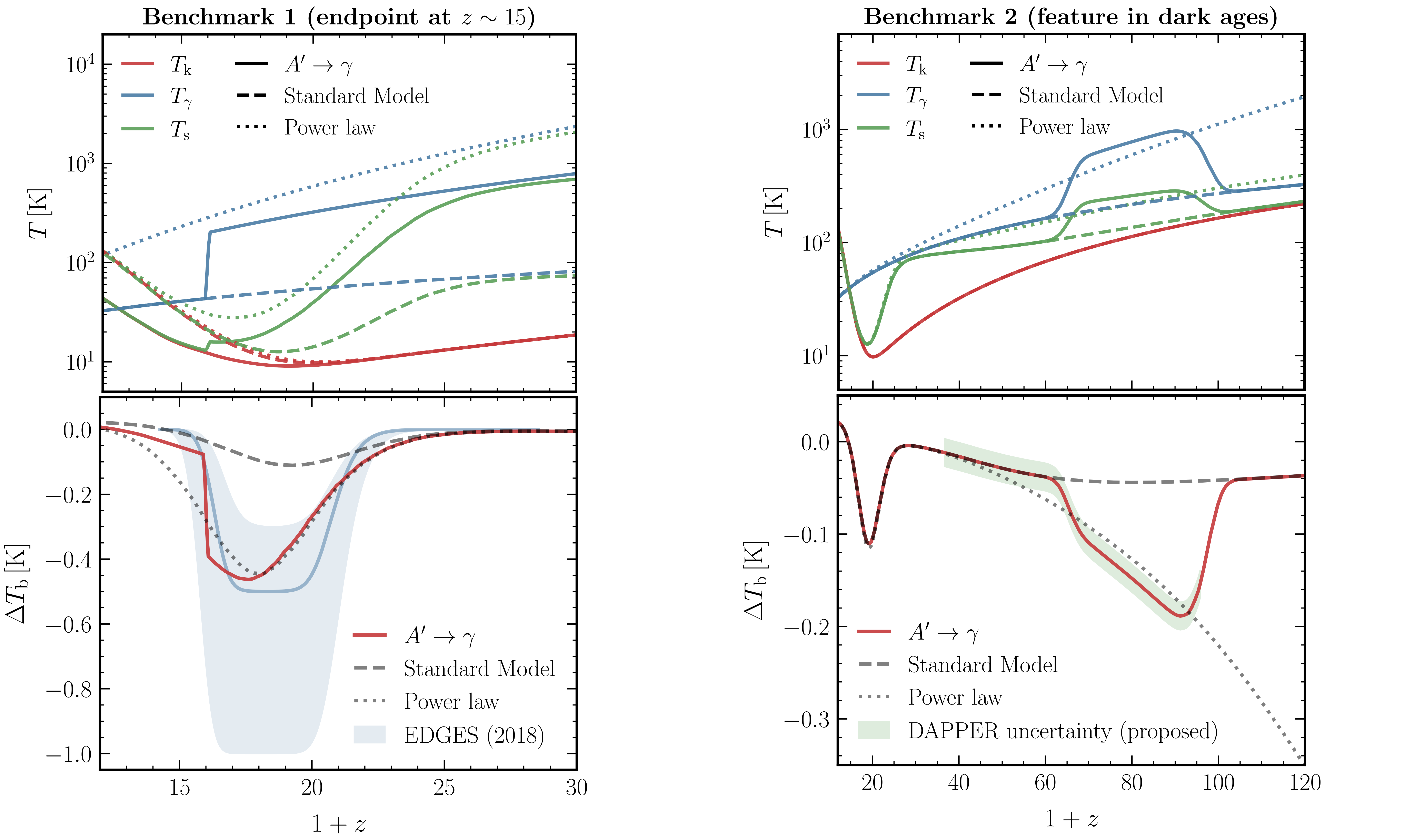
2. Resonant conversion of A' to γ





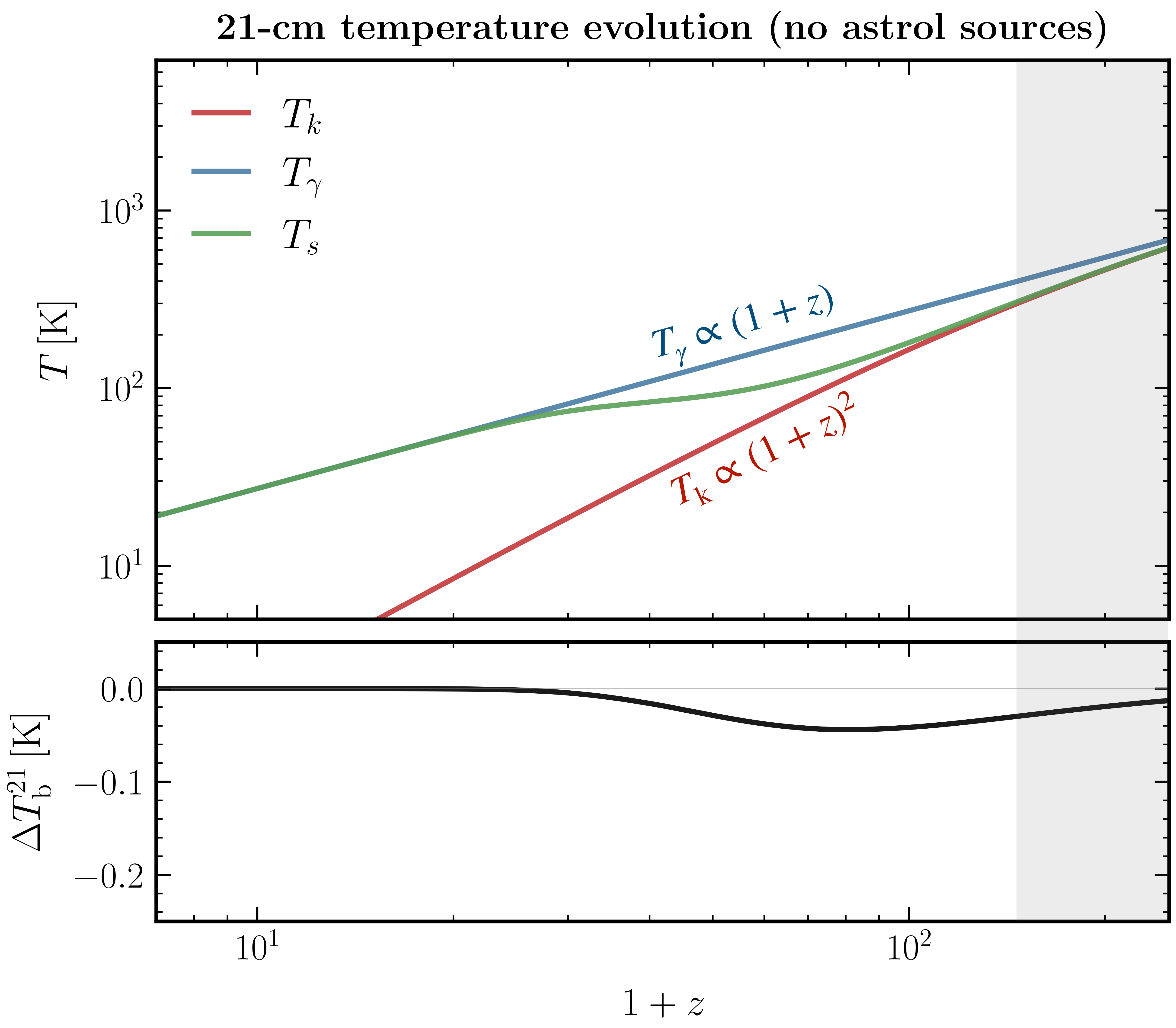
Power-law injection of CMB photons

$$T_\gamma^{21} = T_{\rm CMB}(1+z)\left[1+f_{\rm r}A_{\rm r}\left(\frac{\nu_{21}/(1+z)}{78{\rm MHz}}\right)^{\beta}\right]$$



21-cm temperature evolution

$$\Delta T_b^{21} \propto x_{HI}\left(1 - \frac{T_\gamma}{T_s}\right)$$



- Collisional coupling $T_k \approx T_s$
- Compton scattering effective, $T_k \approx T_\gamma$
- $\Delta T_b^{21} \approx 0$

- Gas adiabatically cools as $(1+z)^{-2}$
- $T_s < T_\gamma \implies \Delta T_b^{21} < 0$ (absorption)

- Collisional coupling becomes ineffective
- $\Delta T_b^{21} \approx 0$

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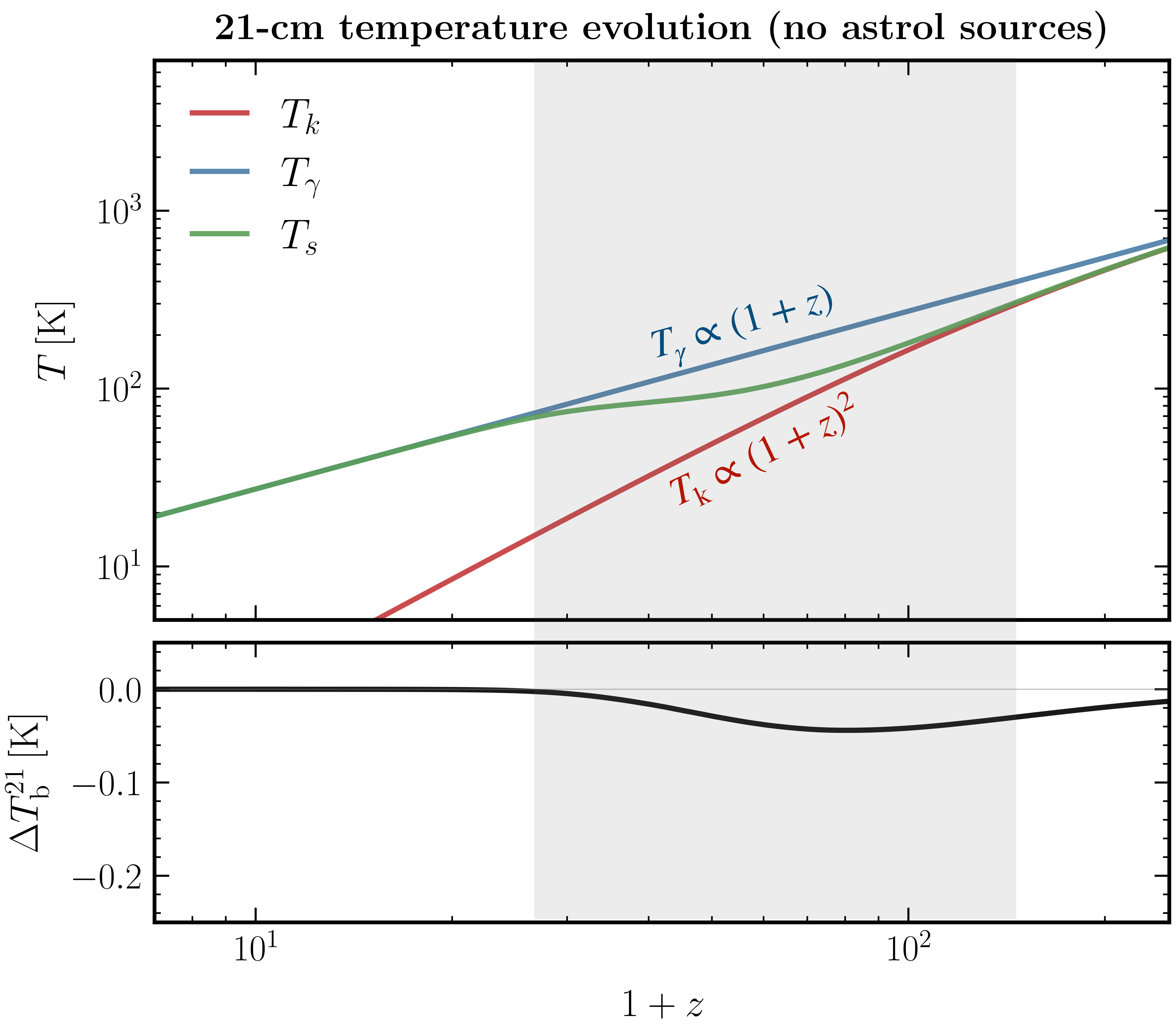

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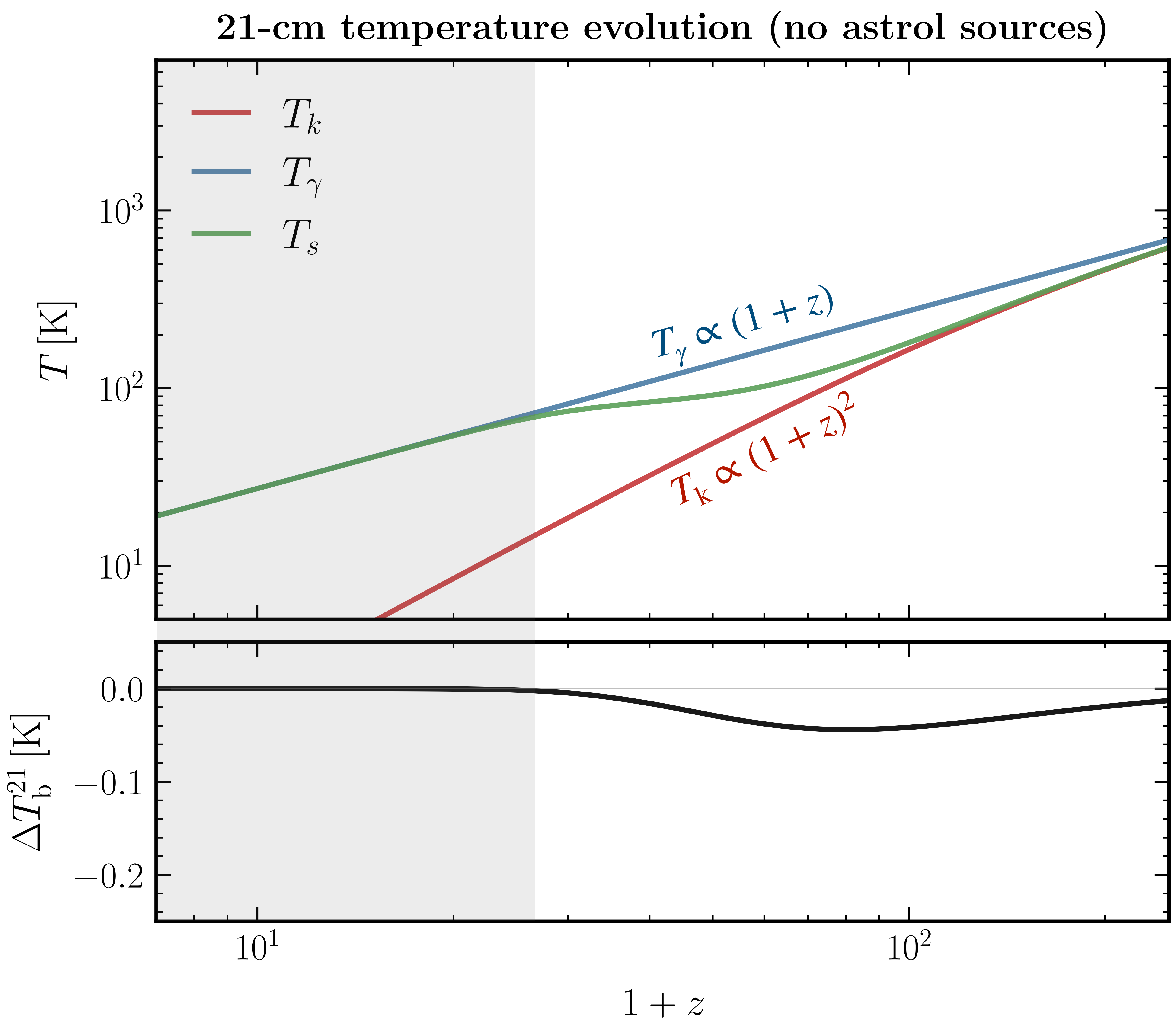

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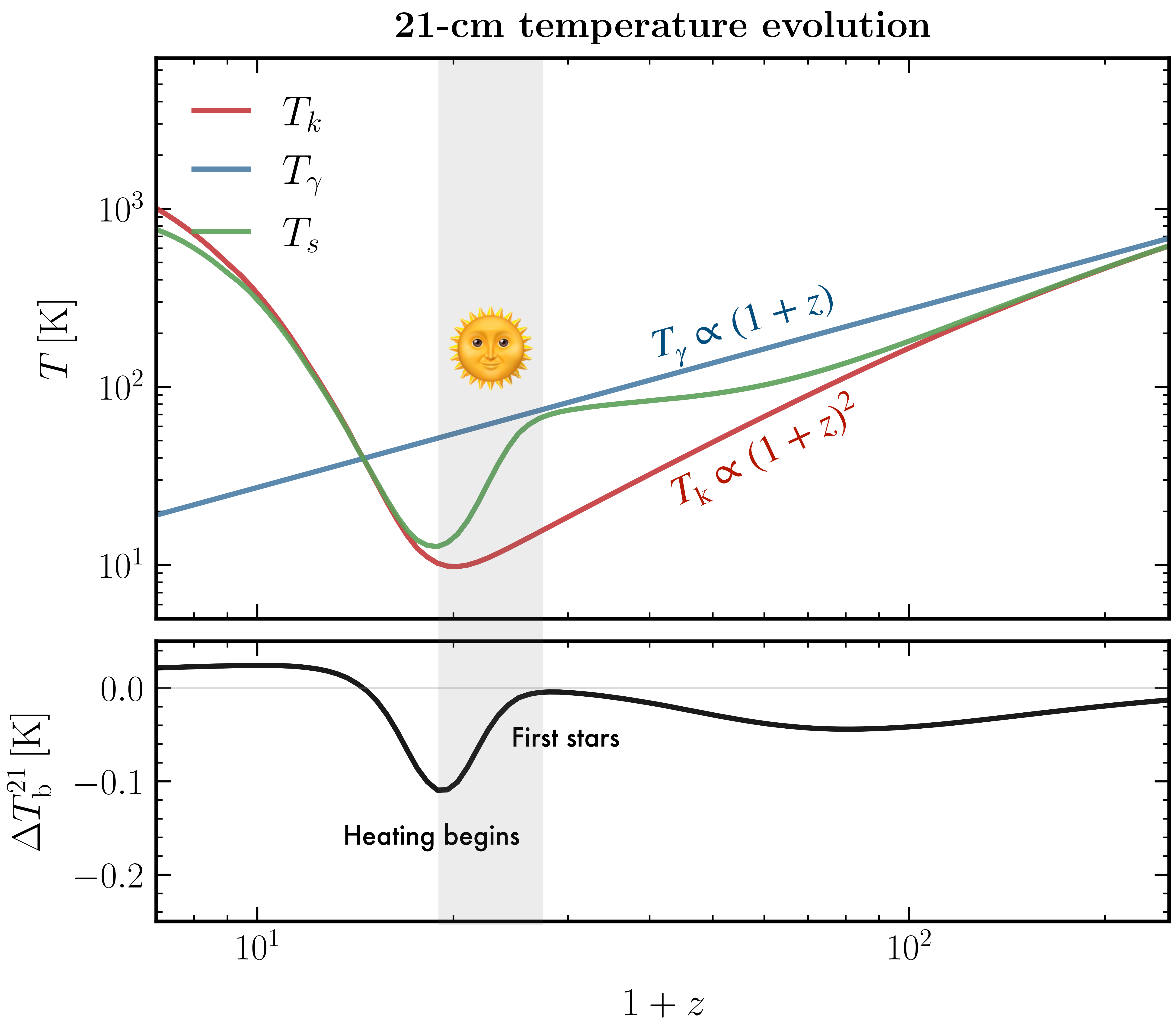

- First stars produce Ly-α photons, couples T_s to T_k
- $\Delta T_\mathrm{b}^{21} < 0$ (absorption feature)

- X-ray sources (e.g. quasars) heat the gas
- $T_\mathrm{s} > T_\gamma$
- $\Delta T_\mathrm{b}^{21} > 0$ (emission feature)

21-cm temperature evolution

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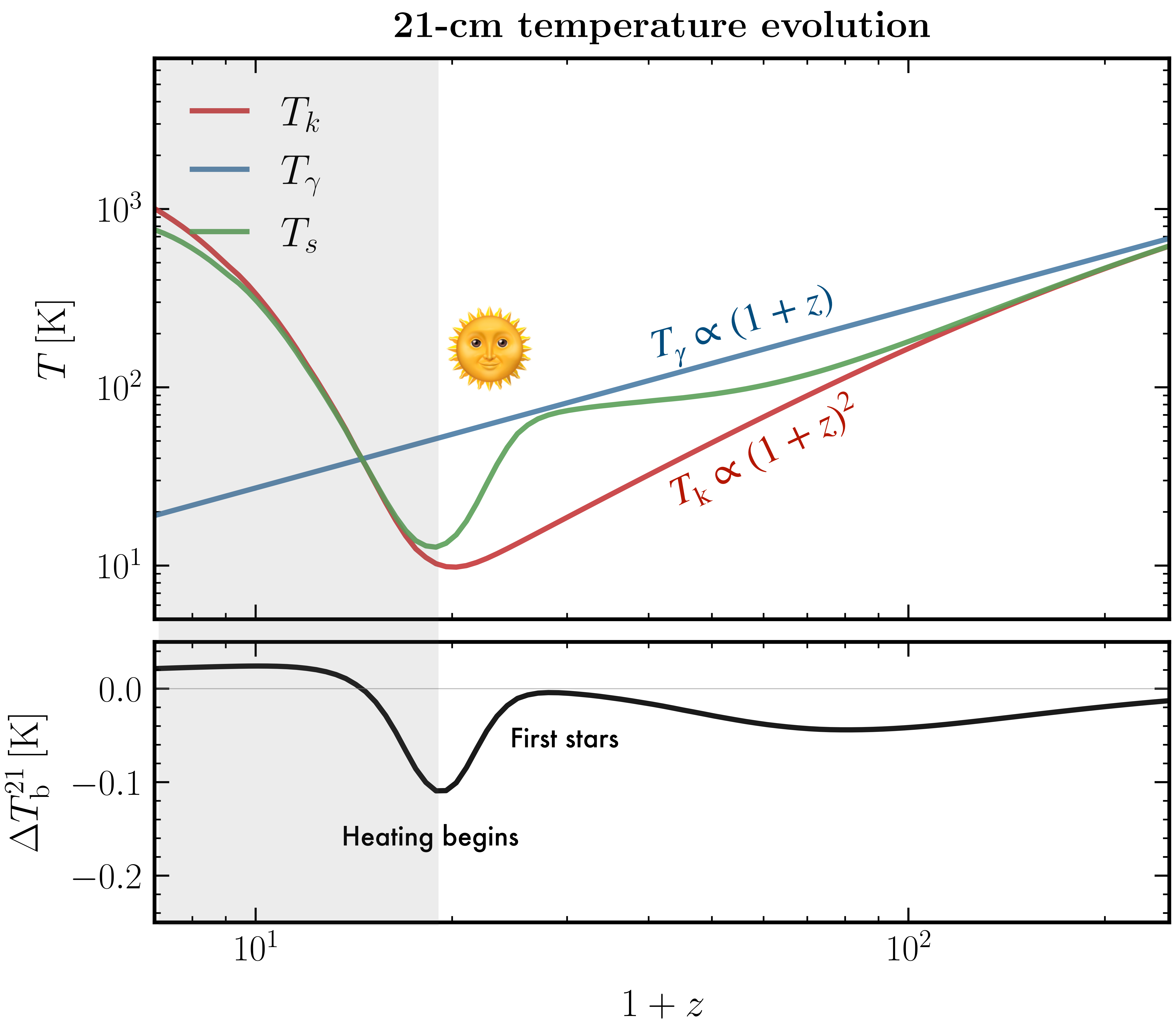

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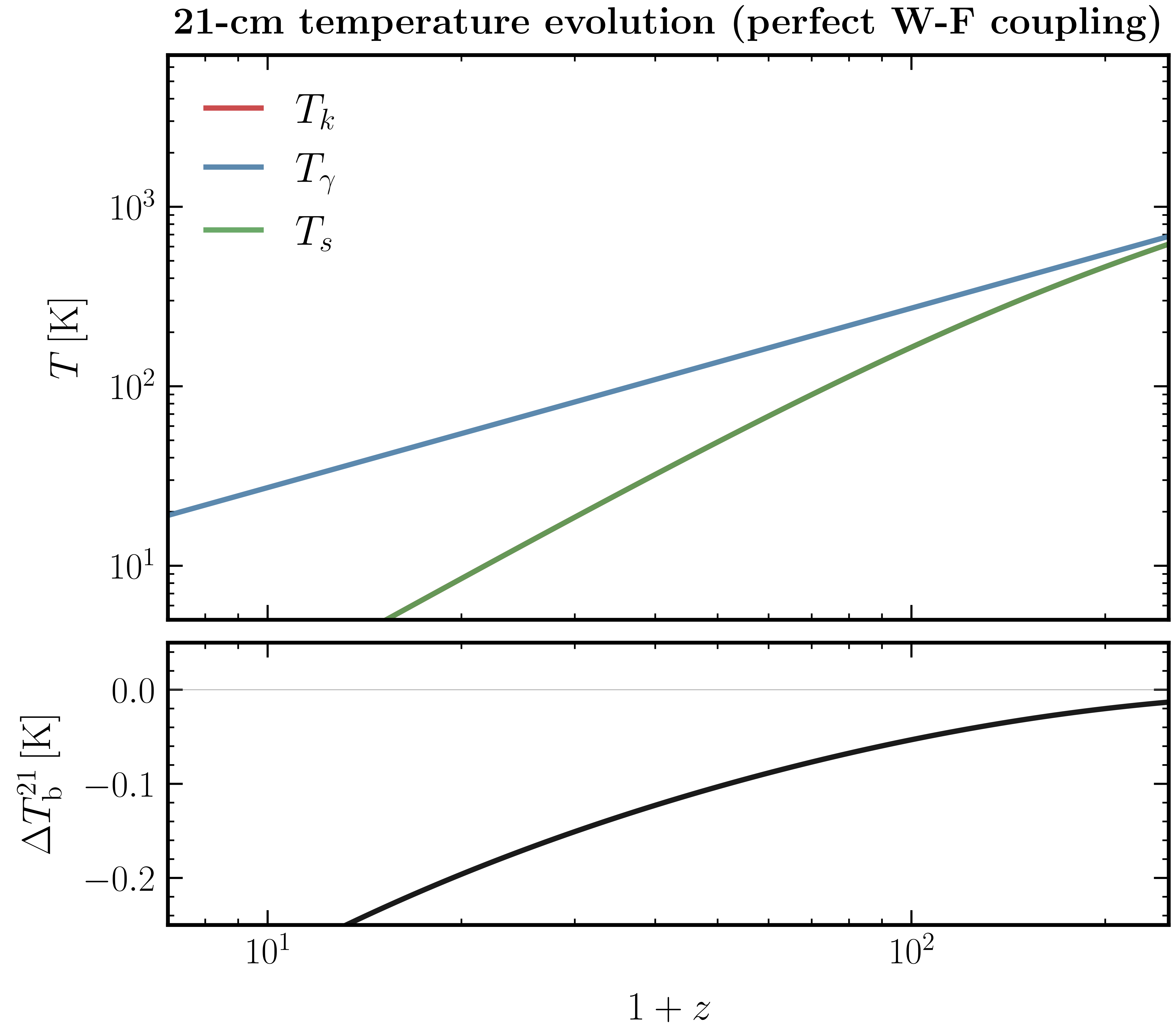
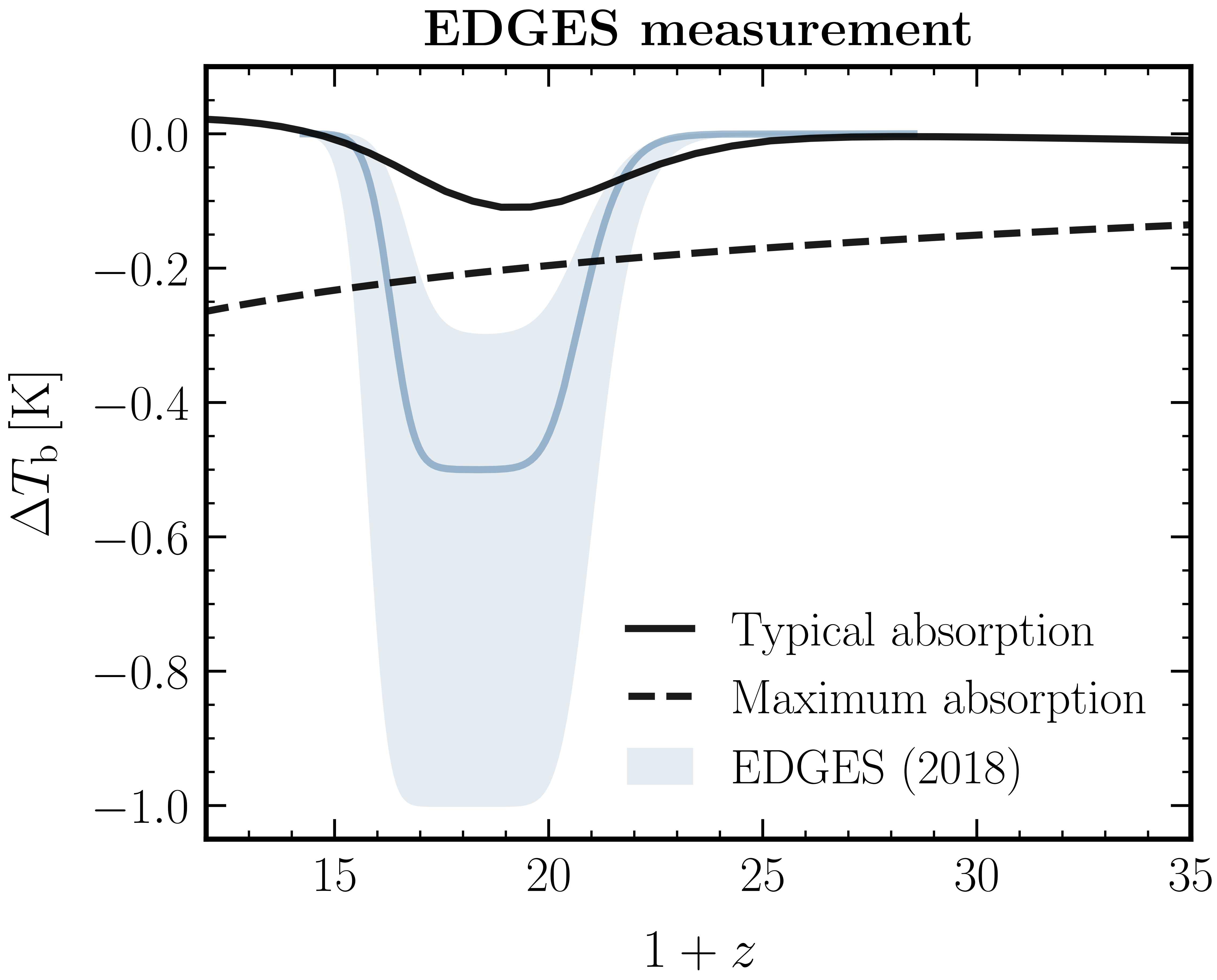
21-cm temperature evolution under perfect W-F coupling





21-cm public code

https://github.com/smsharma/twentyone-global

- Lightweight code to model global 21-cm signal
- Simple models of astrophysical (UV/X-ray) emission
- Easy to add extra sources of photons