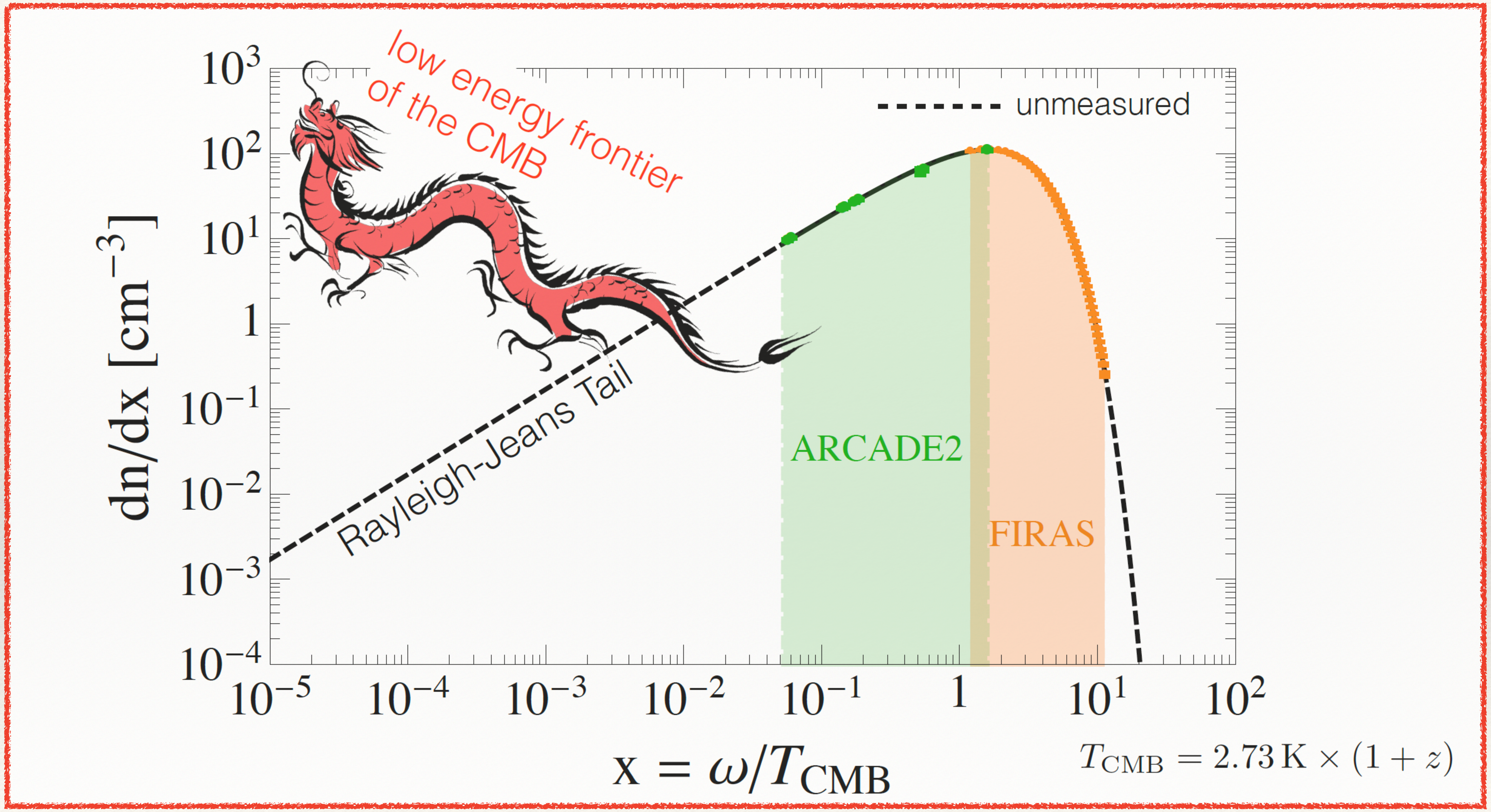
21cm and the RJ tail of the CMB

Andrea Caputo

Trieste, 14 September 2023

Cosmic Microwave Background Spectrum



Credit to J. Ruderman, Moriond 2019

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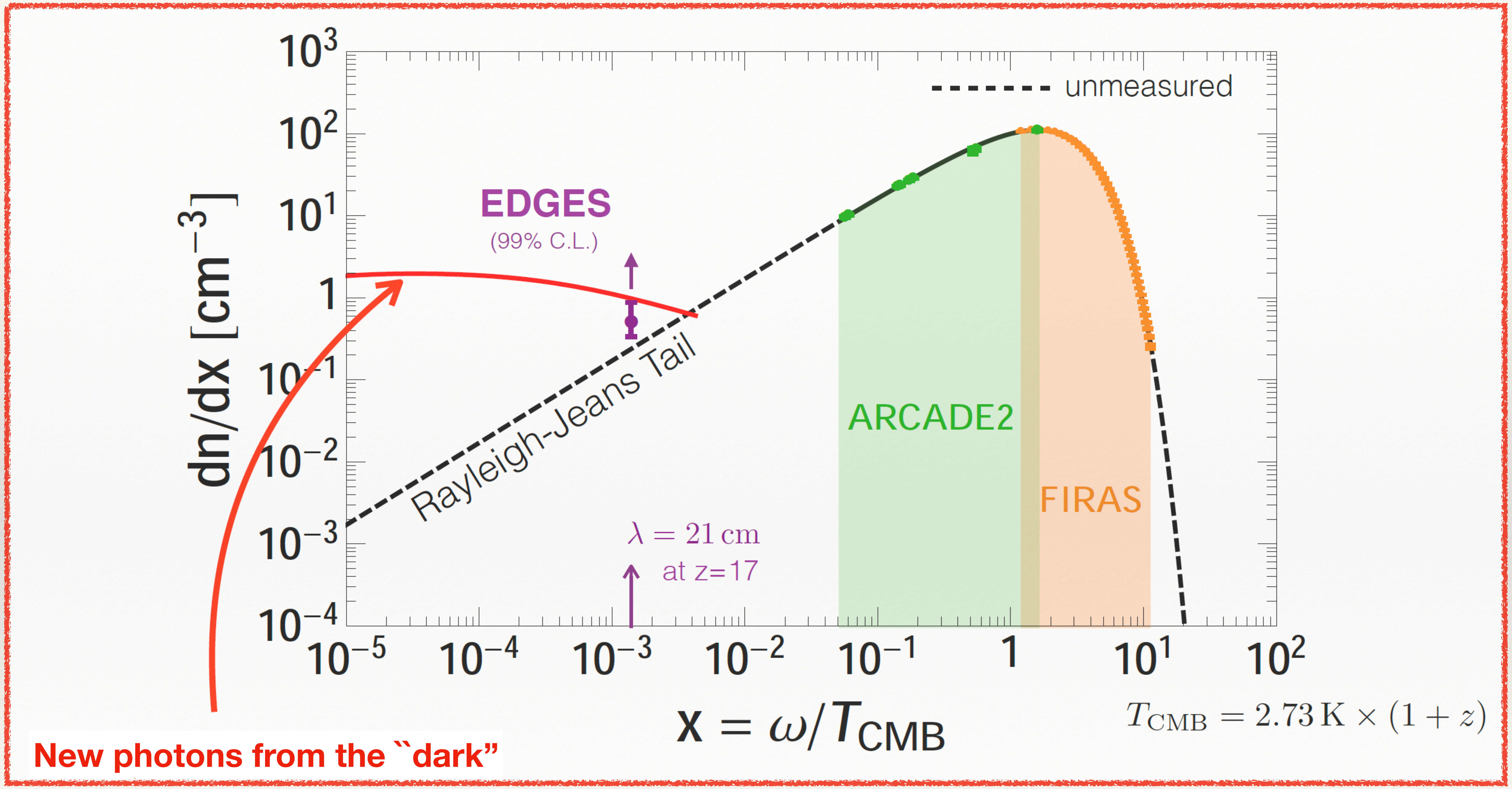

New photons from the ``dark”

Credit to J. Ruderman, Moriond 2019

21 cm, briefly

Brightness temperature

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

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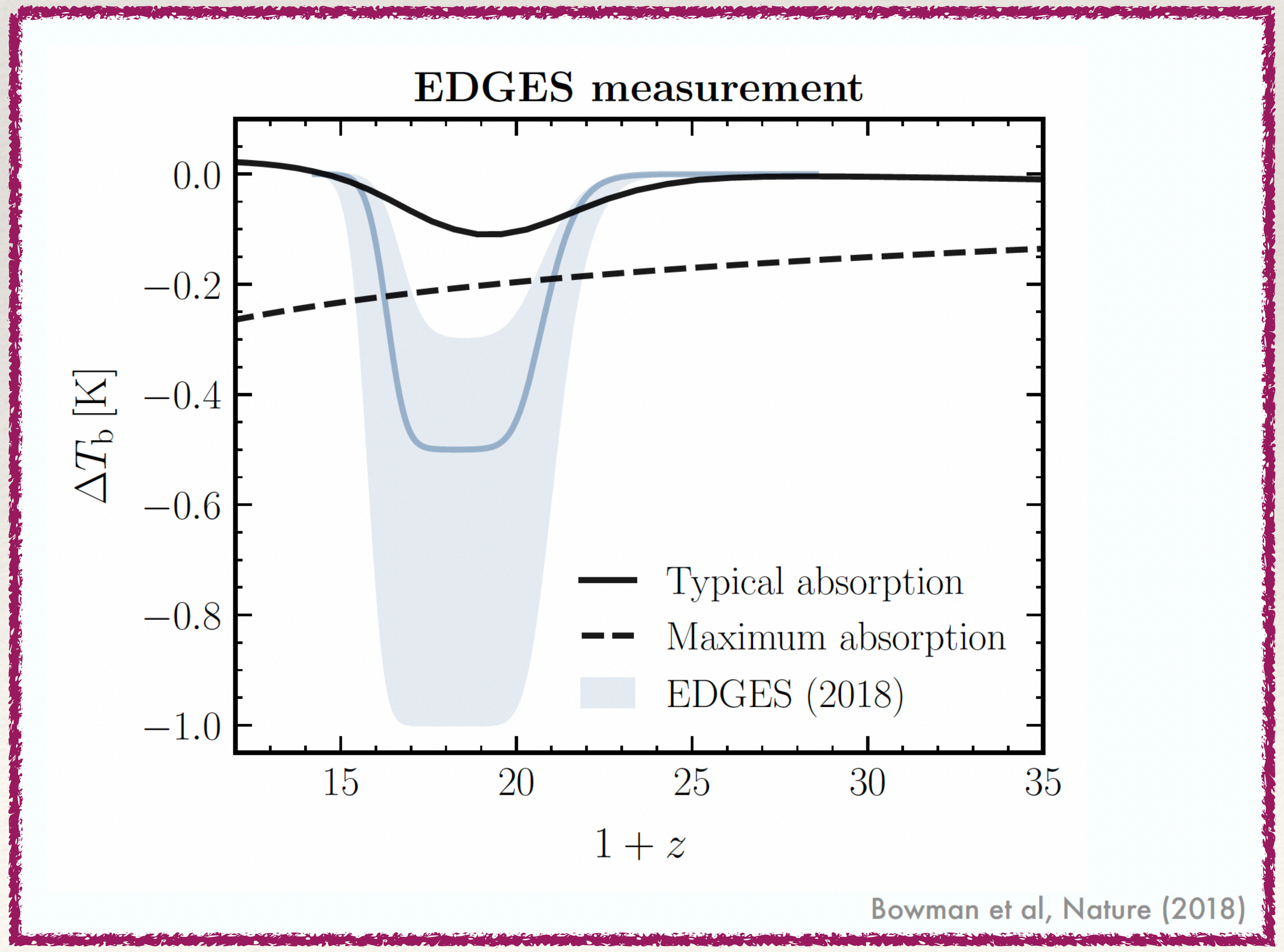

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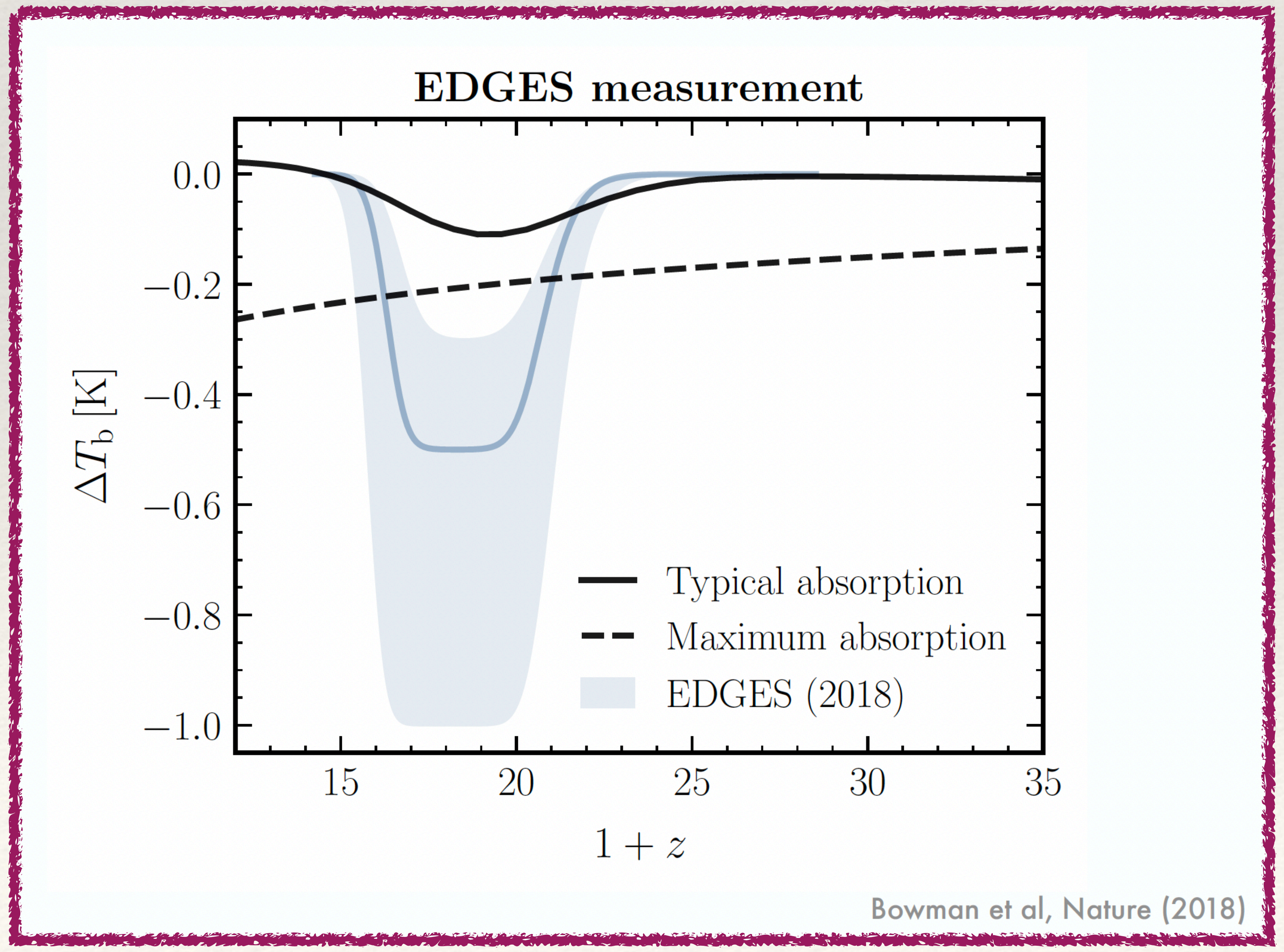

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One can cool baryons

Muñoz & Loeb [1802.10094]
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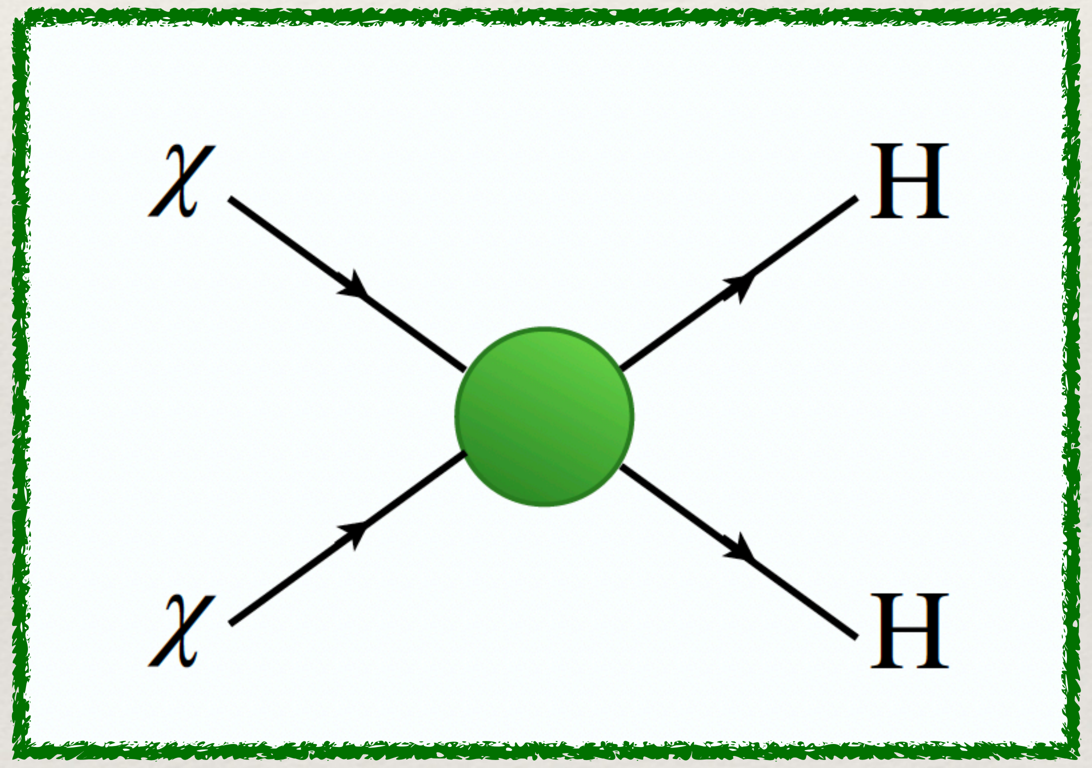

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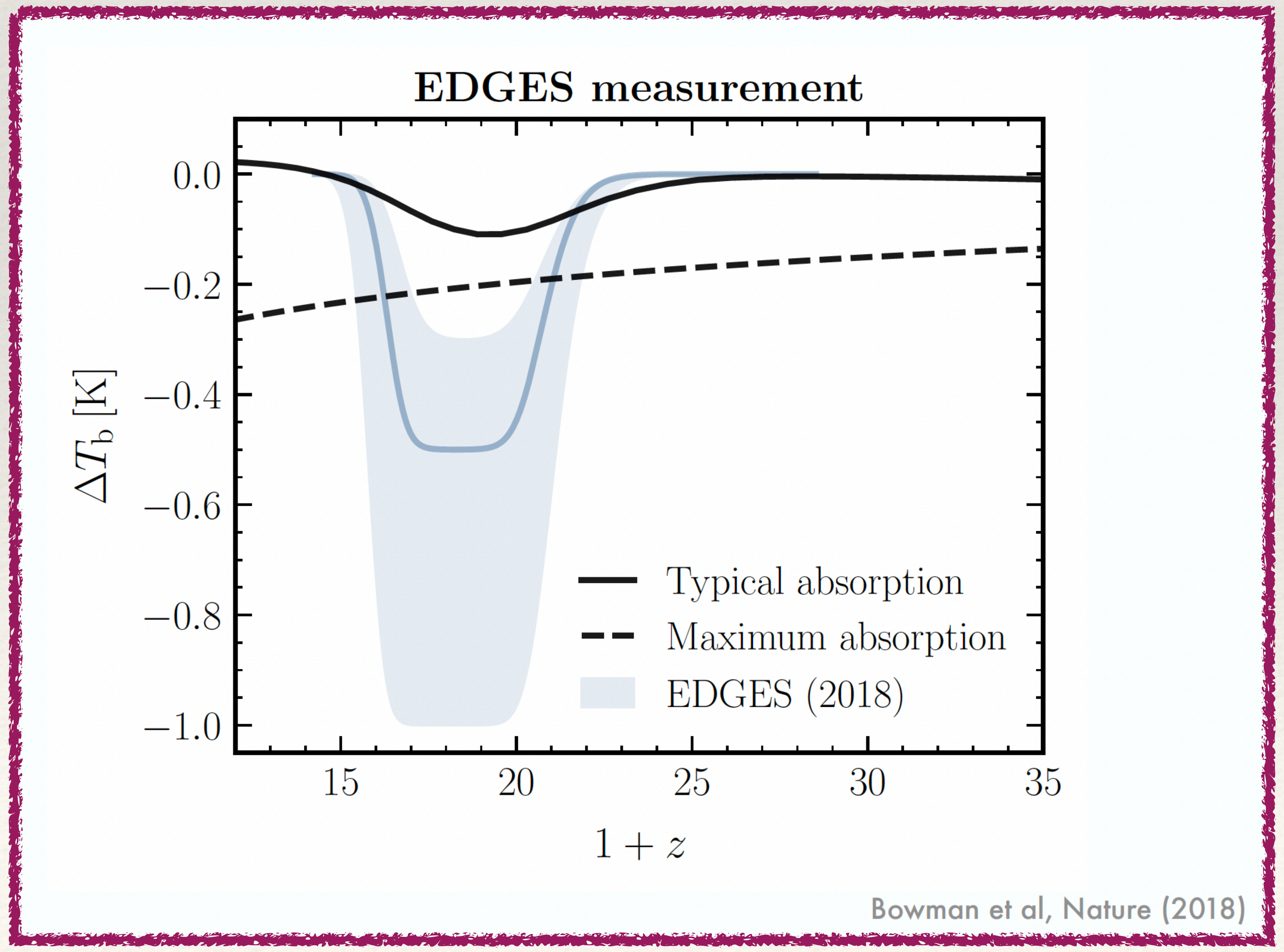

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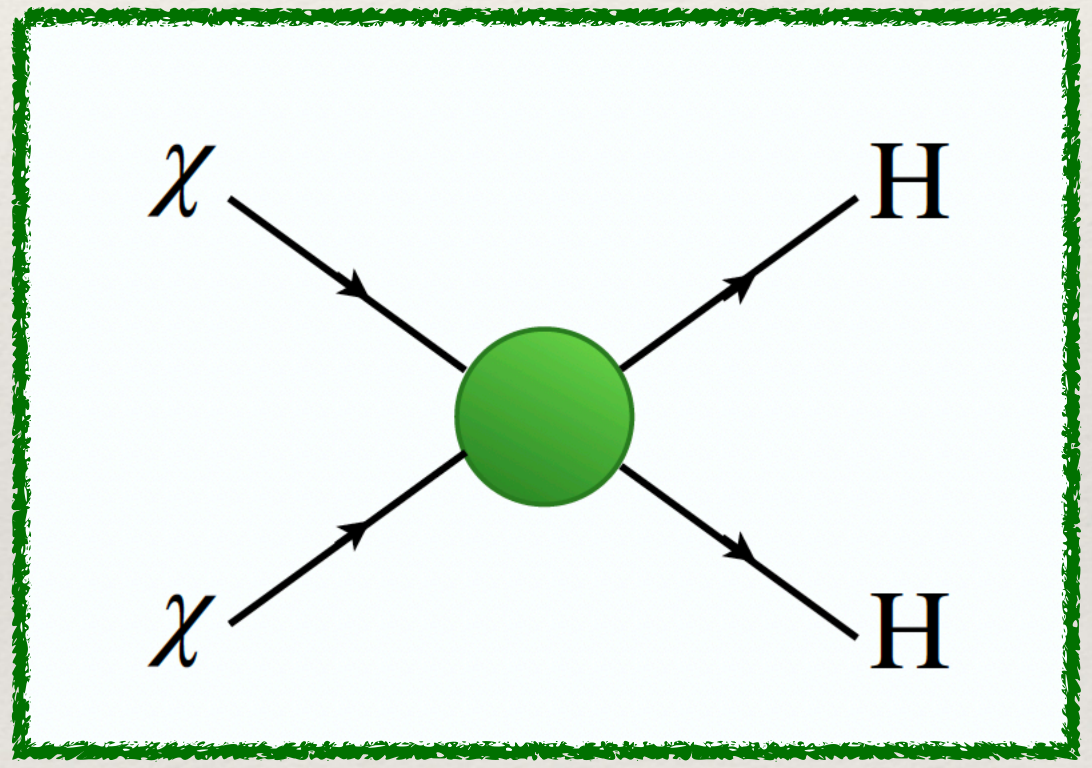

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One can add photons!

$$n_\gamma^{\text{inj}} > n_{\text{CMB}}\ (\lambda = 21cm)$$

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

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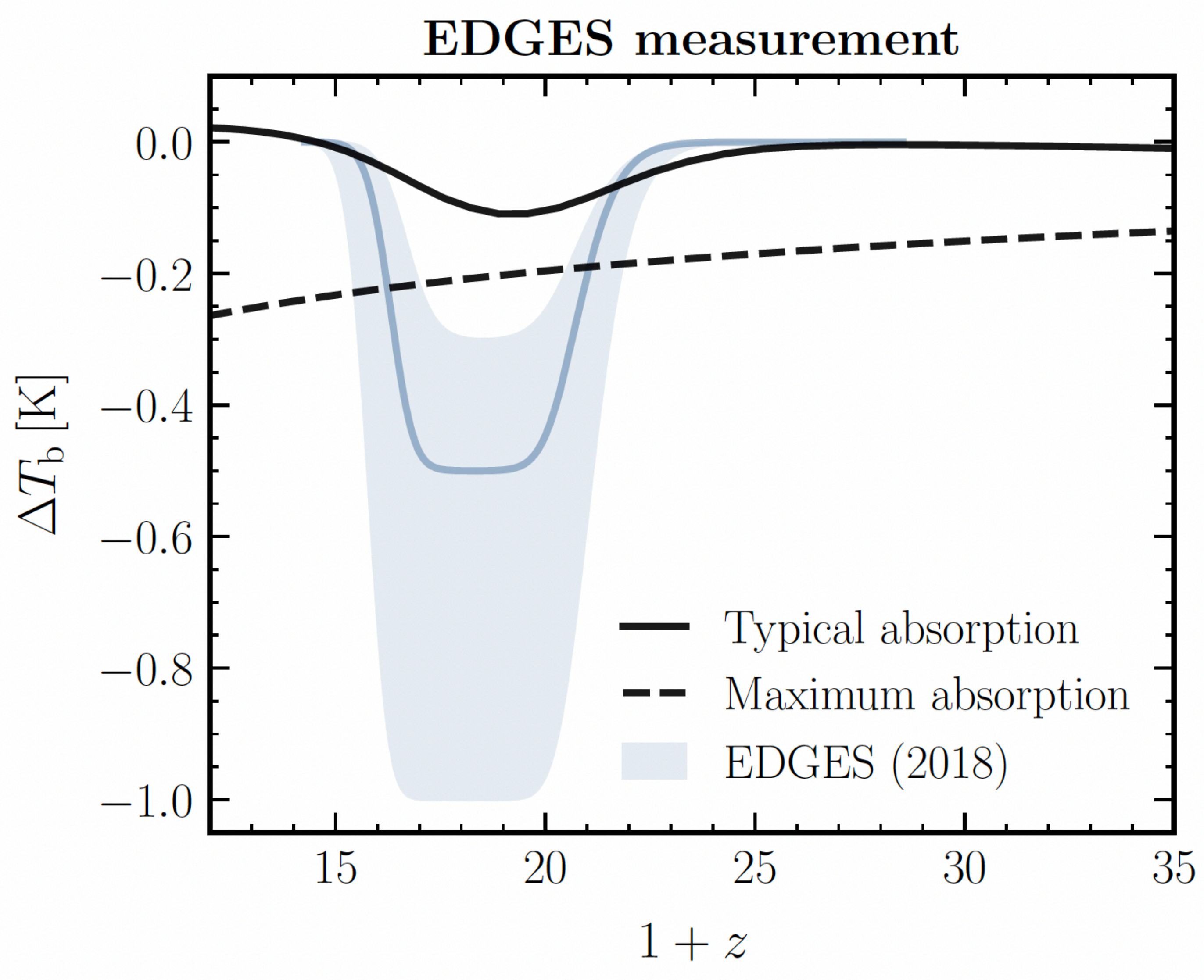

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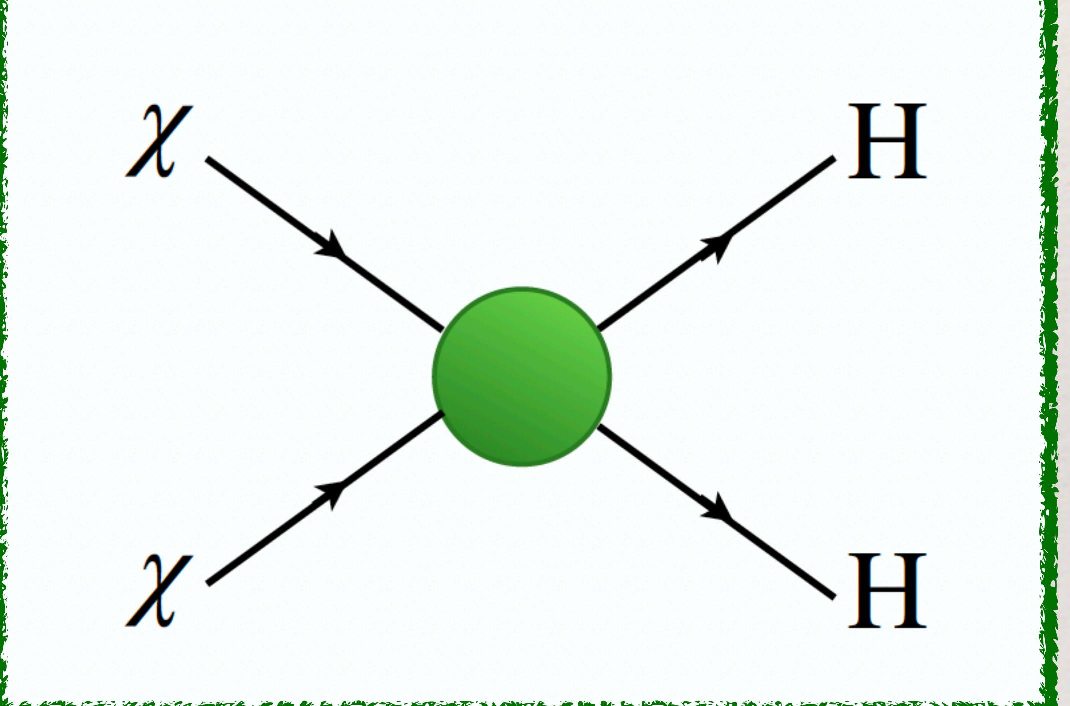

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$$n_\gamma^{\rm inj} > n_{\rm CMB}\ (\lambda = 21cm)$$

$$n_{\rm RJ} = \frac{1}{\pi^2}\int_0^{\omega_{\rm max}} \frac{\omega^2 d\omega}{\exp[\omega/T]-1} \simeq \frac{T\omega_{\rm max}^2}{2\pi^2}$$

$$\simeq 0.21\, x_{\rm max}^2\, n_{\rm CMB}\ , \quad \hbar = c = k = 1 \text{ units}$$

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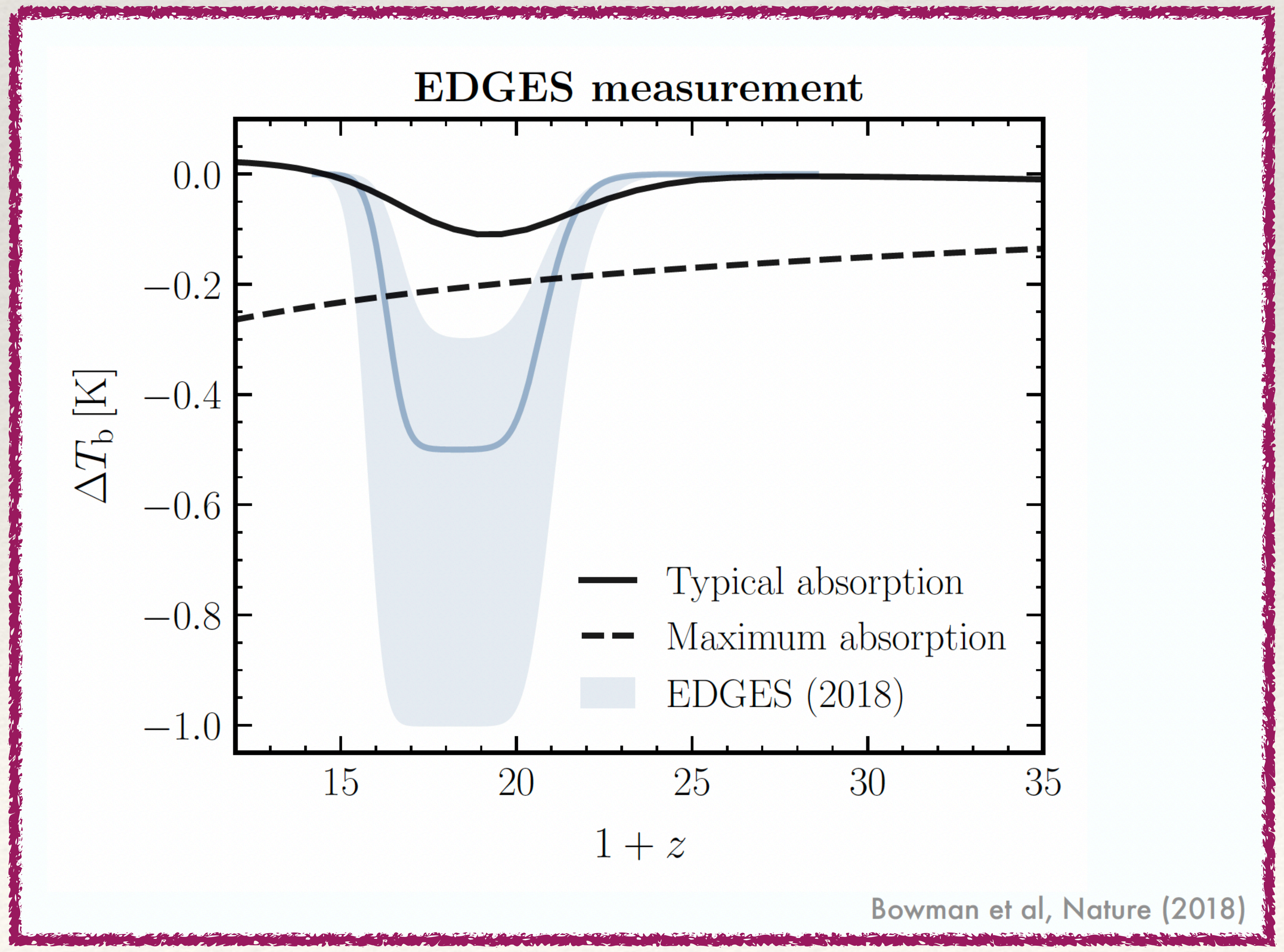

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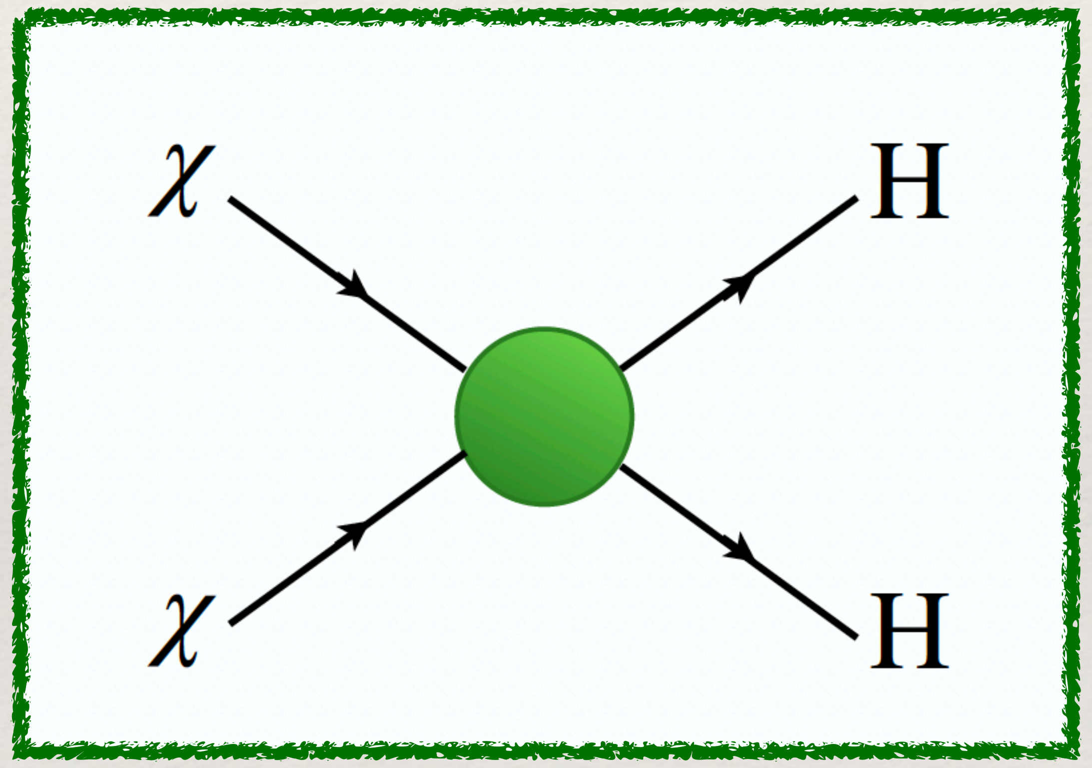

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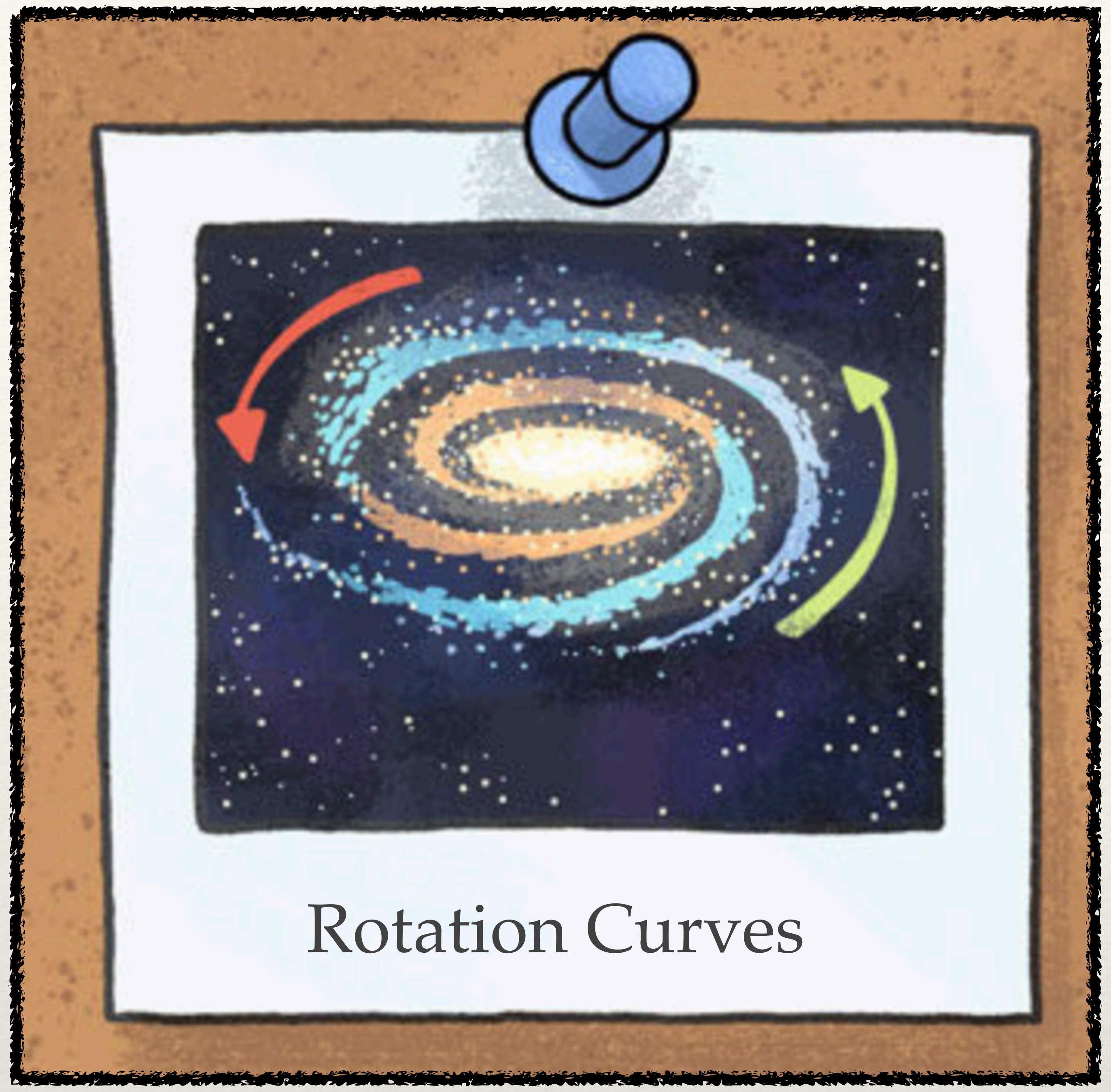
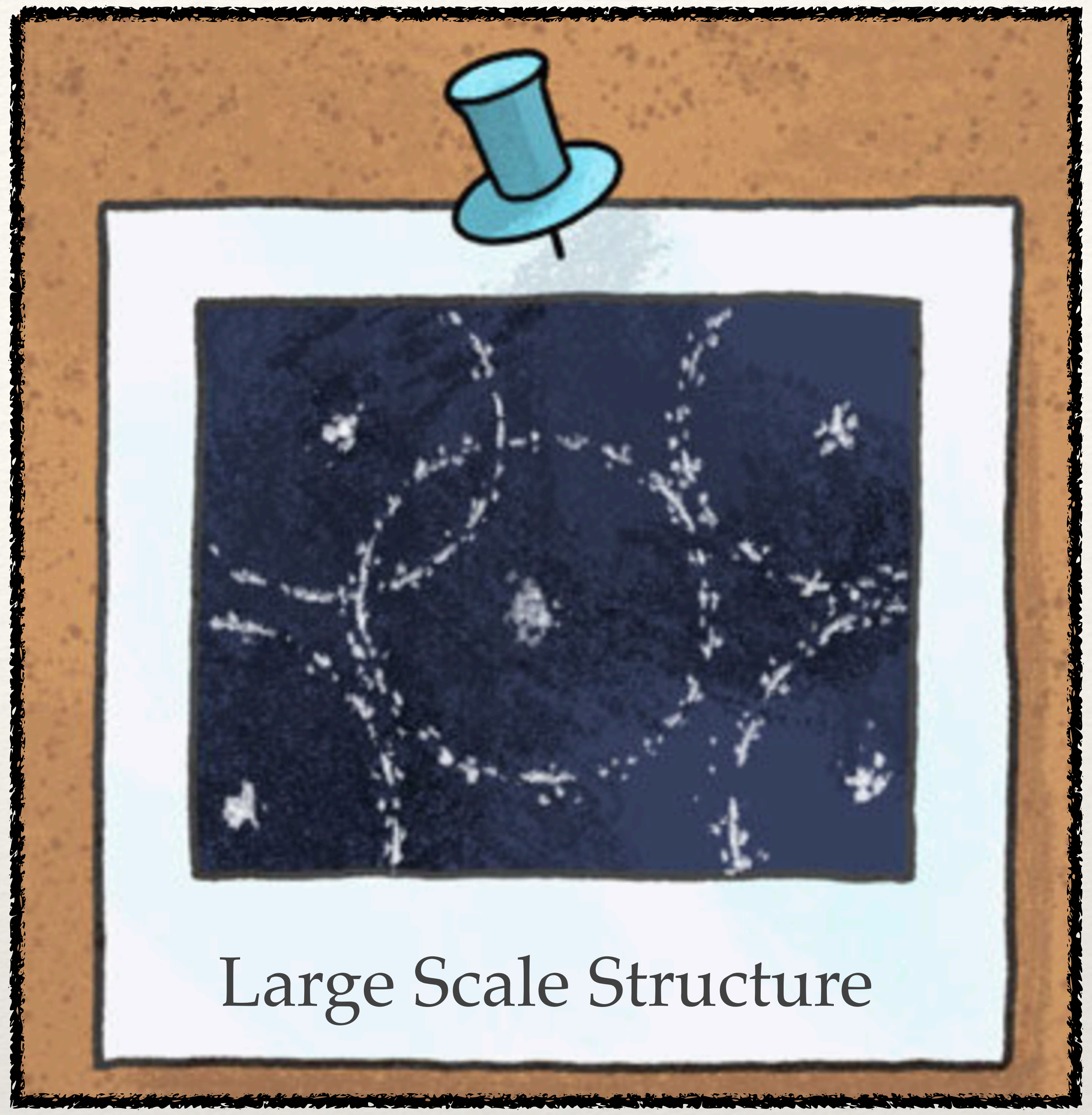
Add numerous, soft quanta

Particle physics motivation

Dark Matter Mystery


Rotation Curves

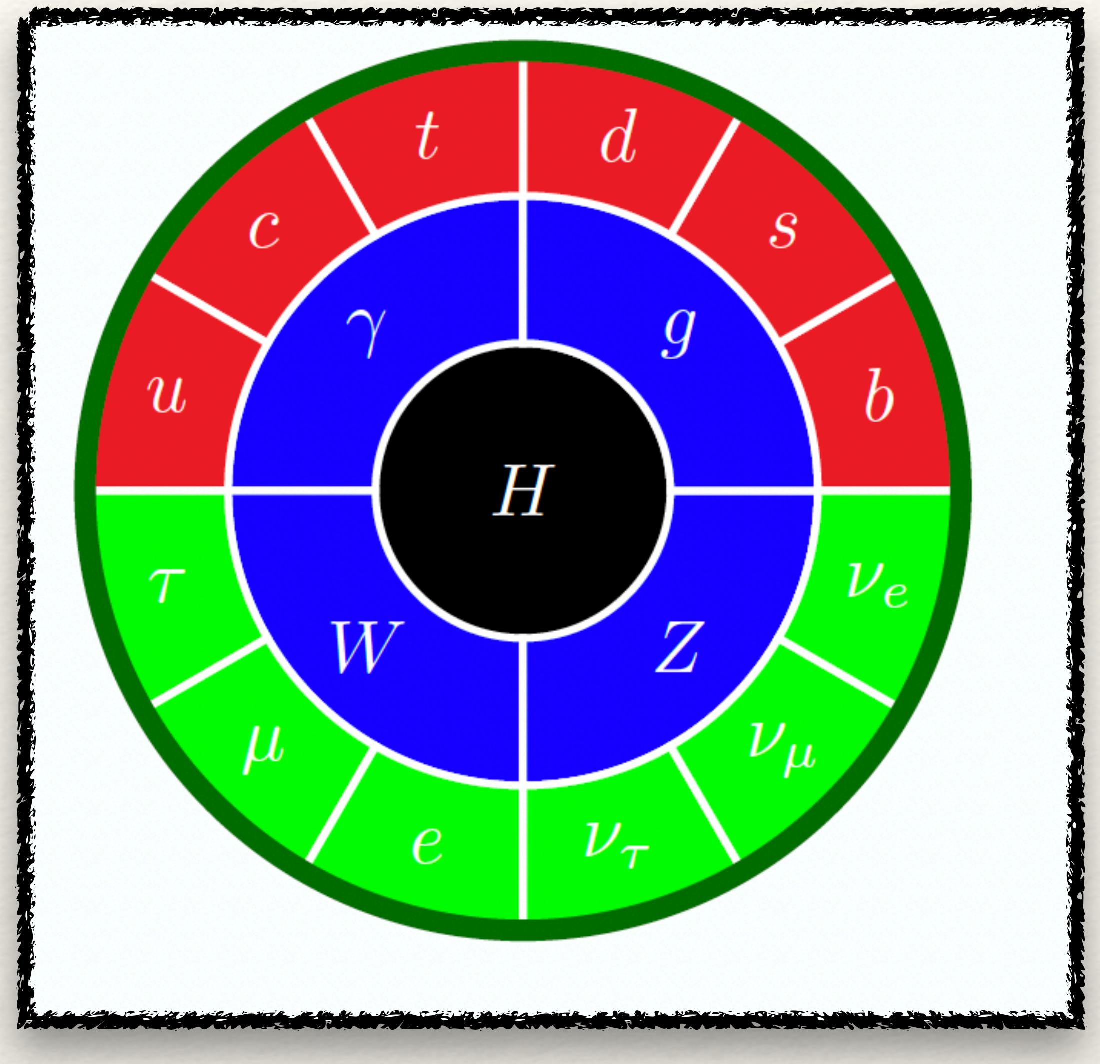

Bullet Cluster


Large Scale Structure

Evidence at all scales!!

Illustrations by Sandbox Studio, Chicago

Standard Model



Dark Sector

Particle dark matter?
New forces?

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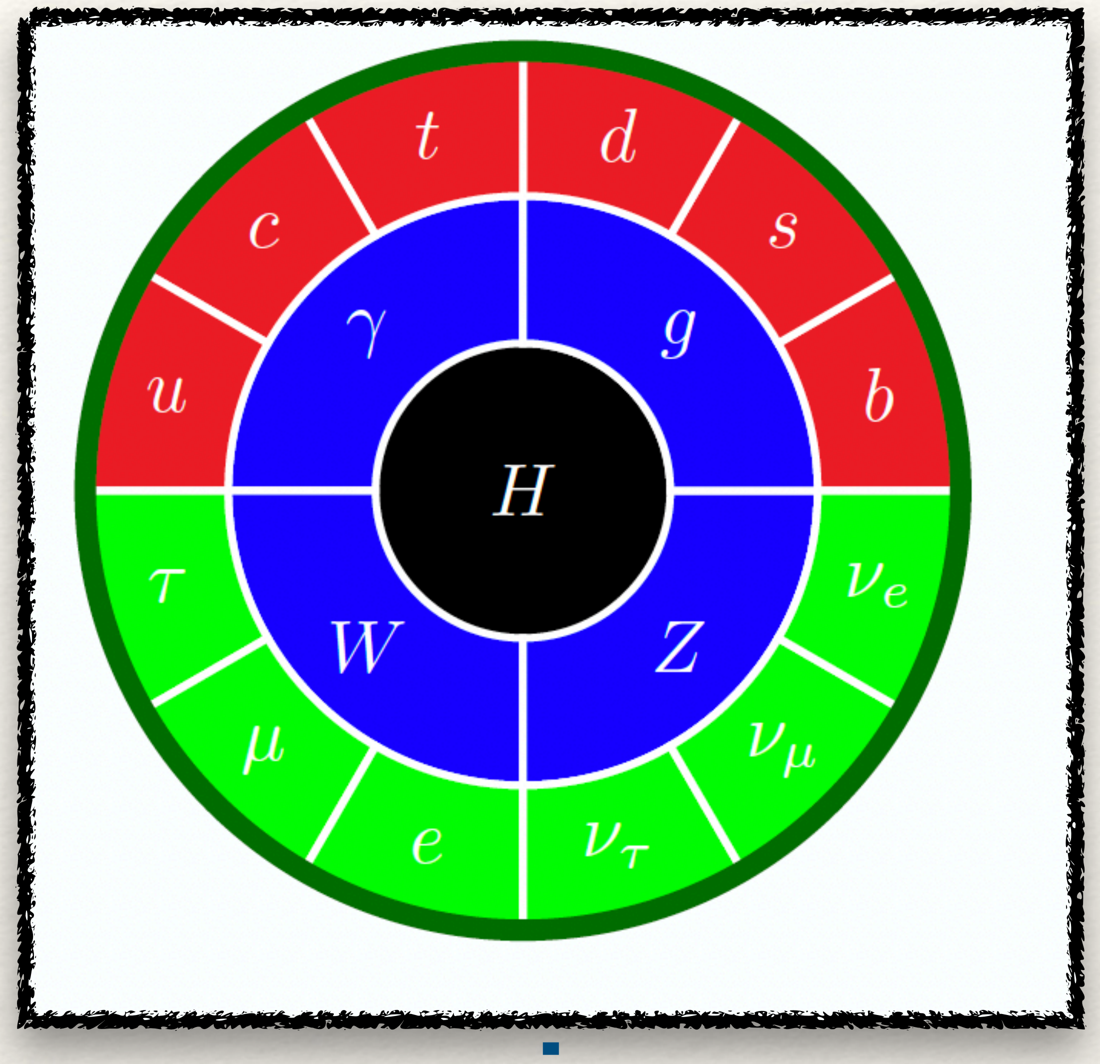

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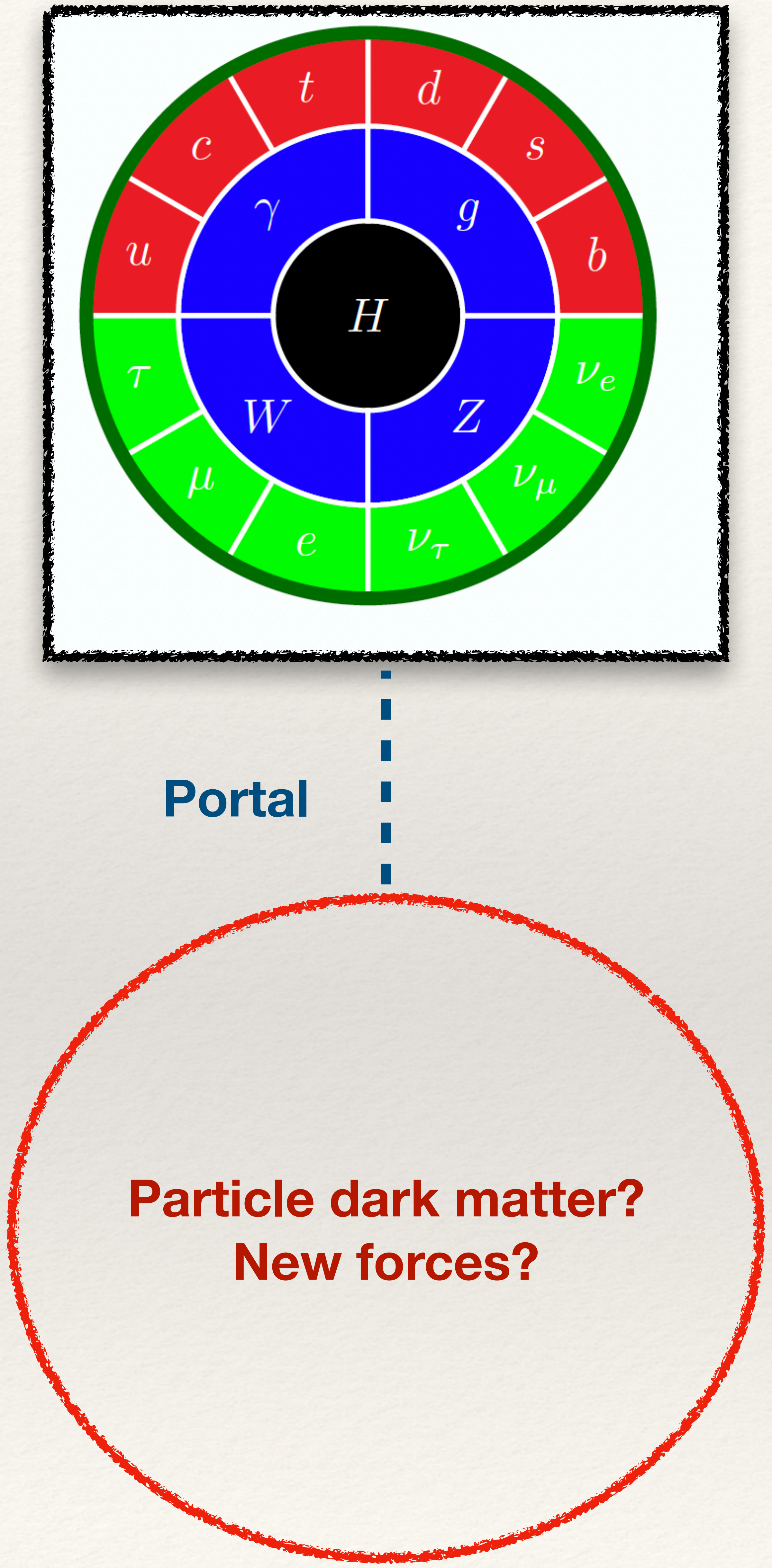

Standard Model

Portal

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(Some) Canonical portals:

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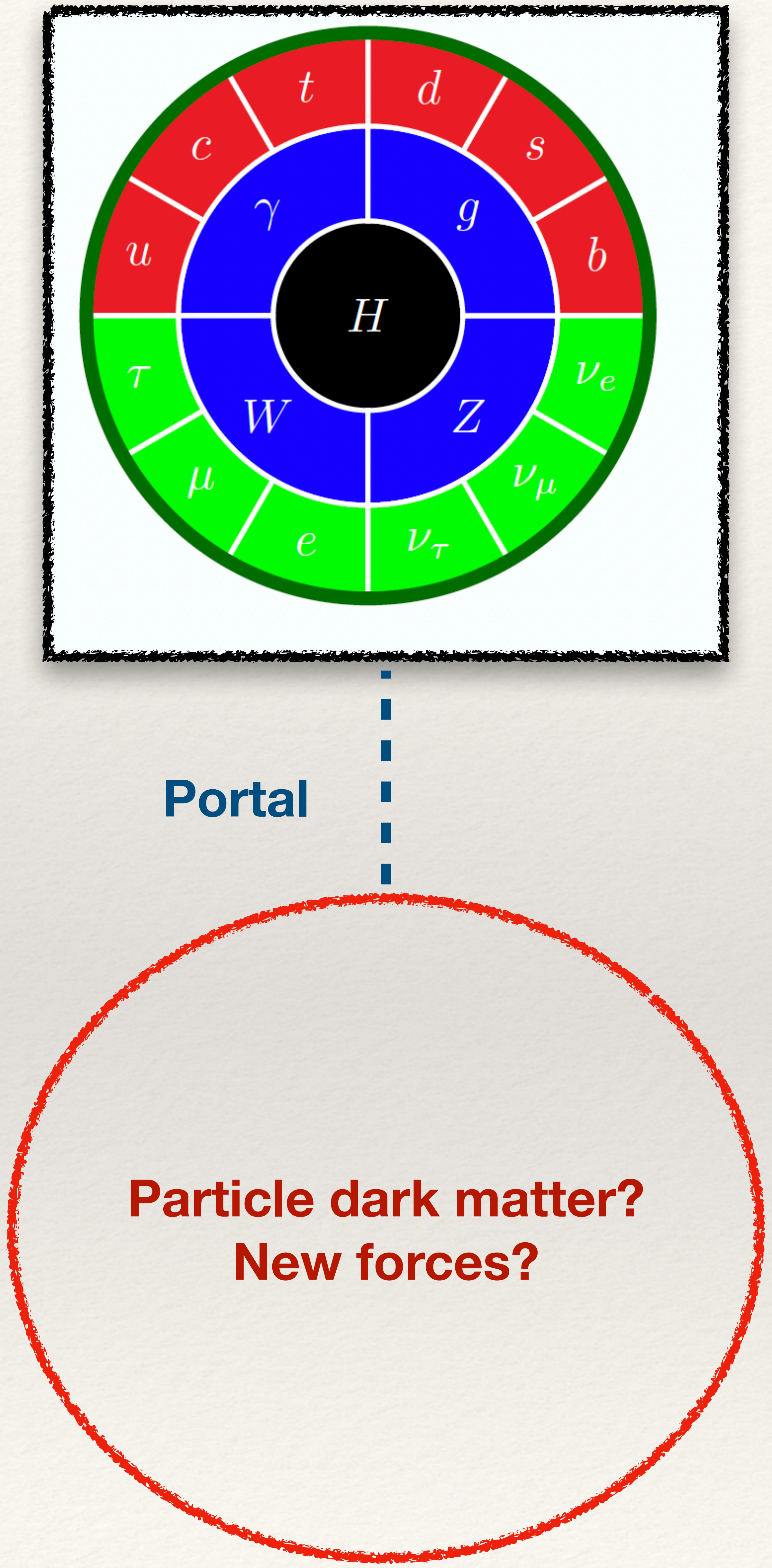
- Fermion $y(HL)N$
  Neutrino portal
- Vector $\epsilon F^{\mu\nu} F'_{\mu\nu}$
  Kinetic mixing portal

Standard Model



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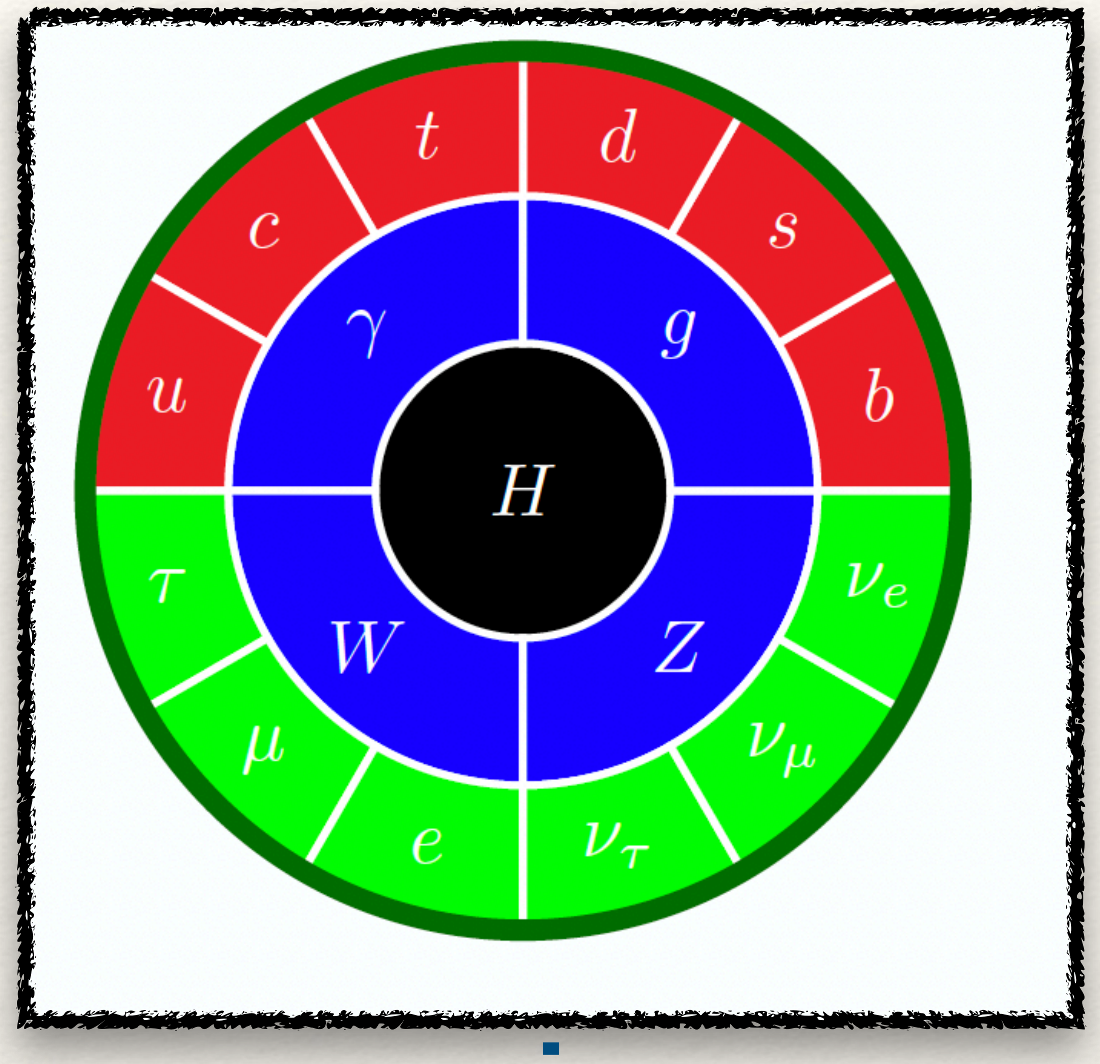

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Plus axion (like) dark matter $aF'\tilde{F}'$

Light DM a, decaying to two dark photons via and ALP coupling:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{a}{4f_a}F'_{\mu\nu}\tilde{F}'^{\mu\nu} + \mathcal{L}_{AA'}$$

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Vector portal

Dark photon mixes with EM via "familiar' kinetic mixing

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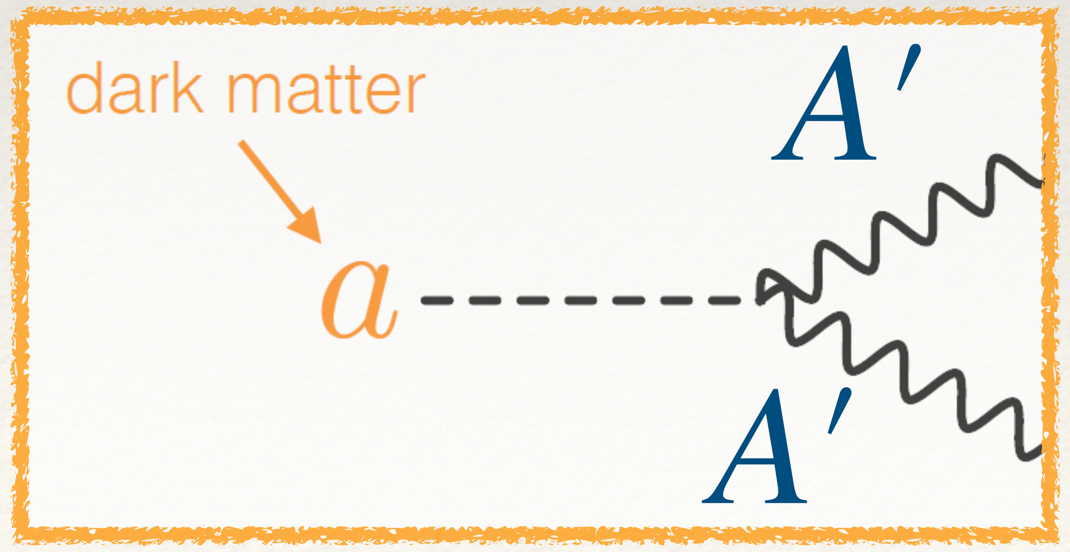

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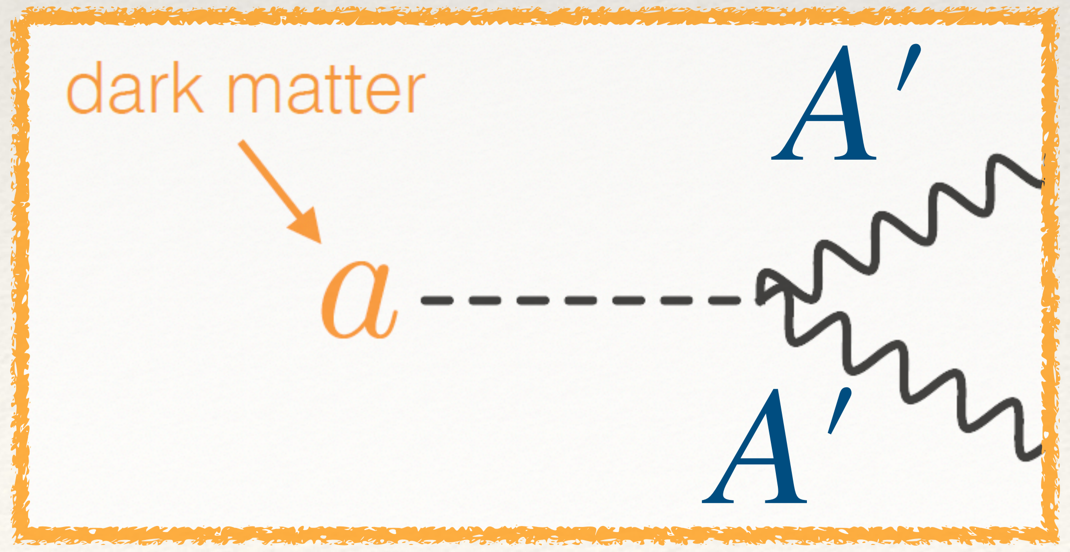

Dark photons resonantly convert into photons

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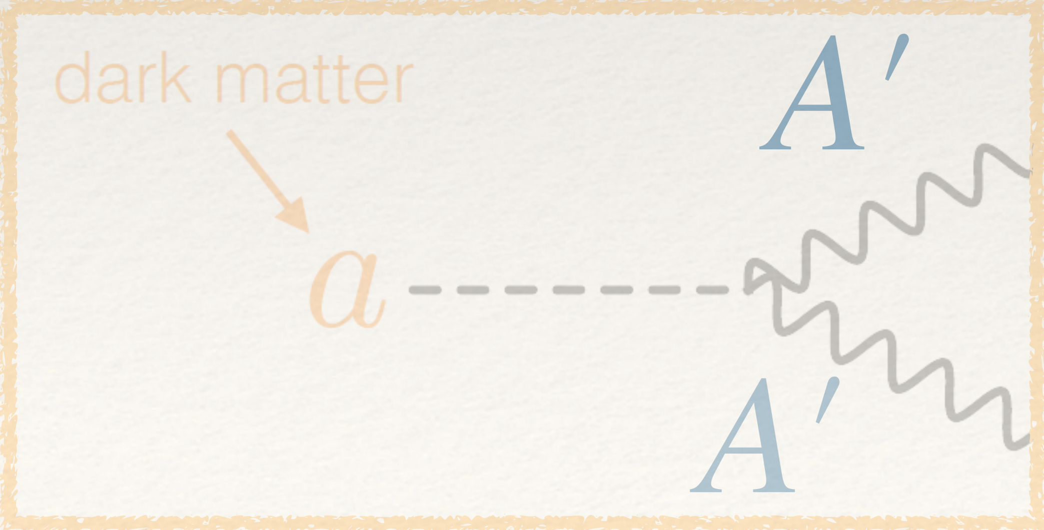

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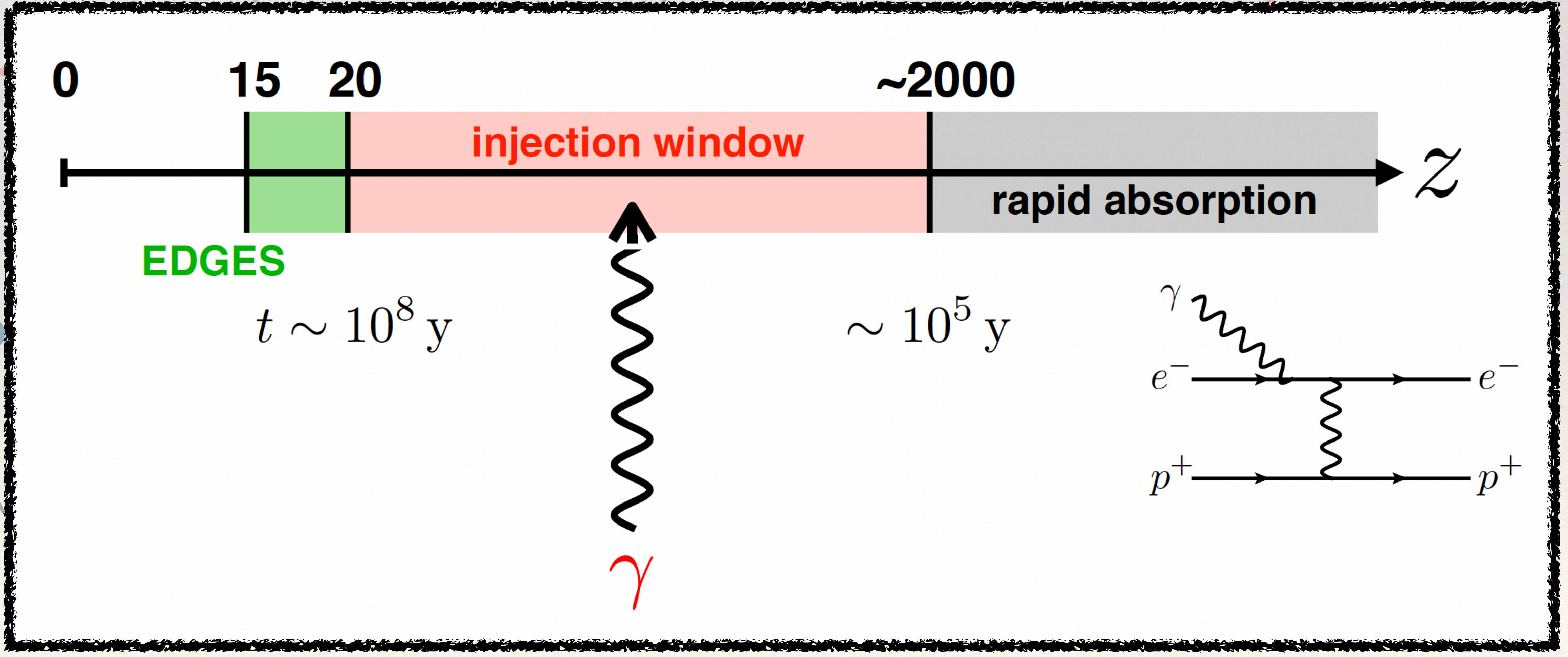
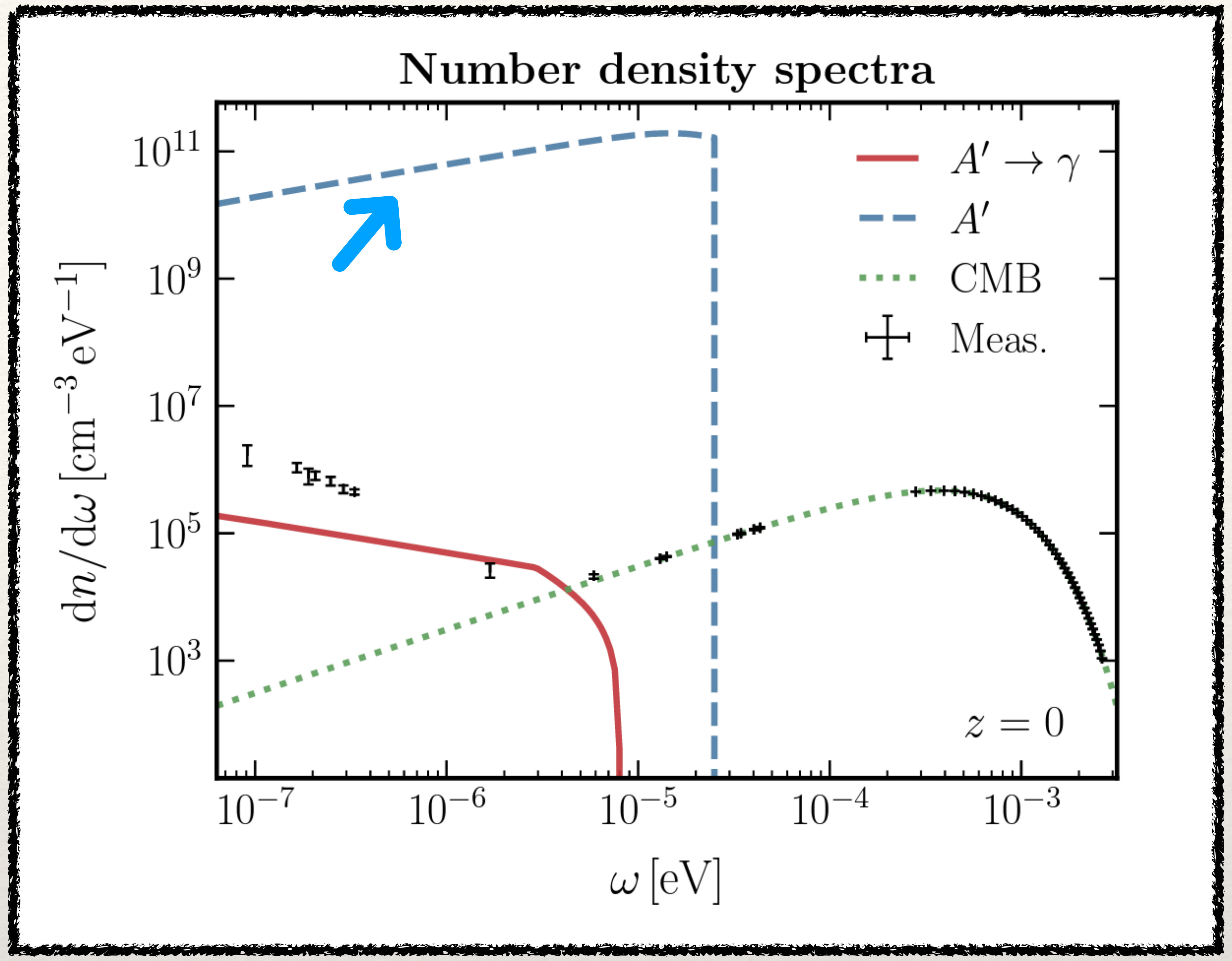


First, axion decays (that’s easy)

$$\frac{\mathrm{d}n_{A'}}{\mathrm{d}\omega} = \frac{2\rho_{\mathrm{DM}}\left(z_{\mathrm{dec}}\right)\left(1+z\right)^3}{\tau_a H\left(z_{\mathrm{dec}}\right) m_a \omega \left(1+z_{\mathrm{dec}}\right)^3}\Theta\left(\frac{m_a}{2}-\omega\right)$$



AC, H. Liu, S. Mishra-Sharma, M. Pospelov, J. T. Ruderman, A. Urbano,
***Phys.Rev.Lett.* 127 (2021) 1, 011102**

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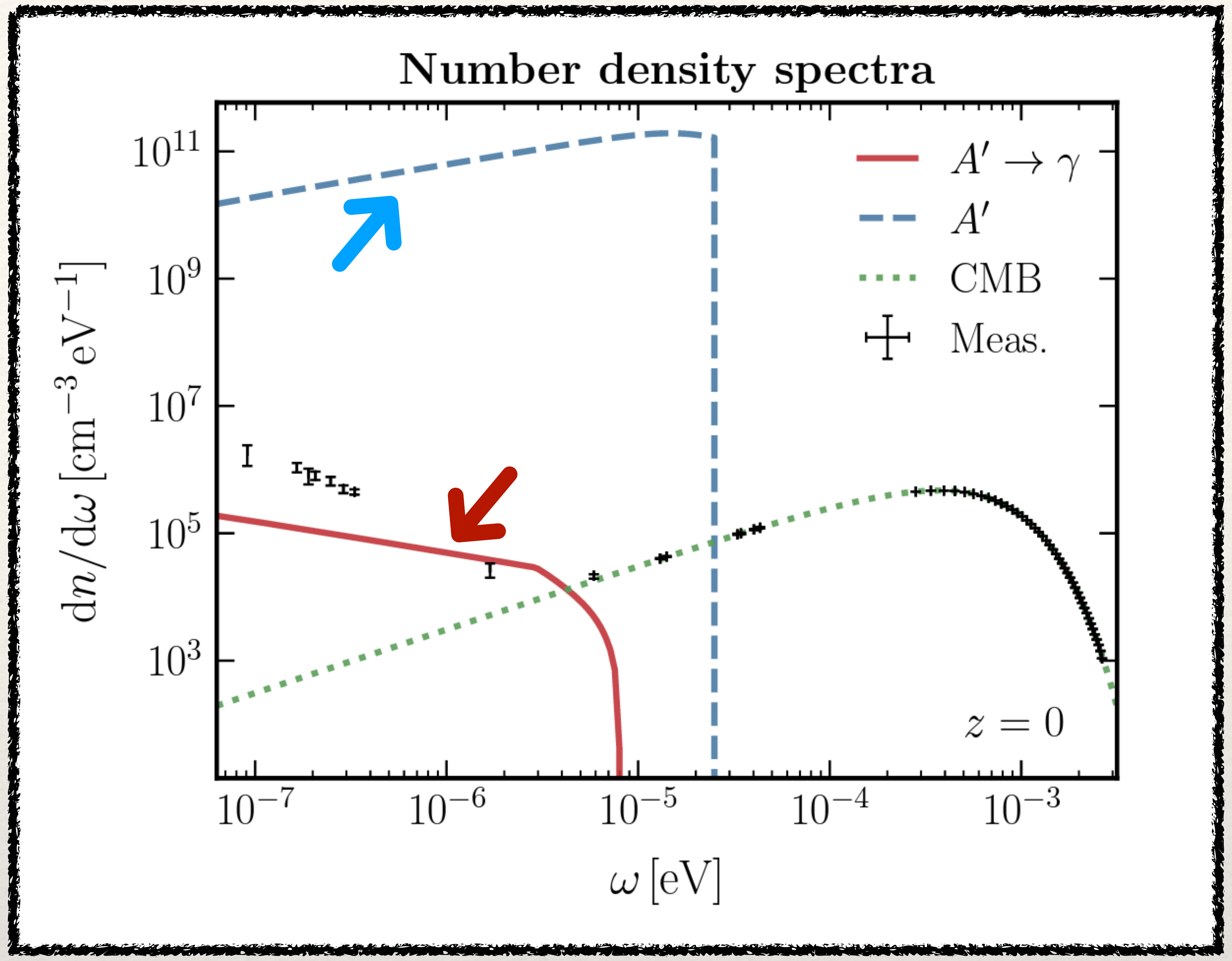

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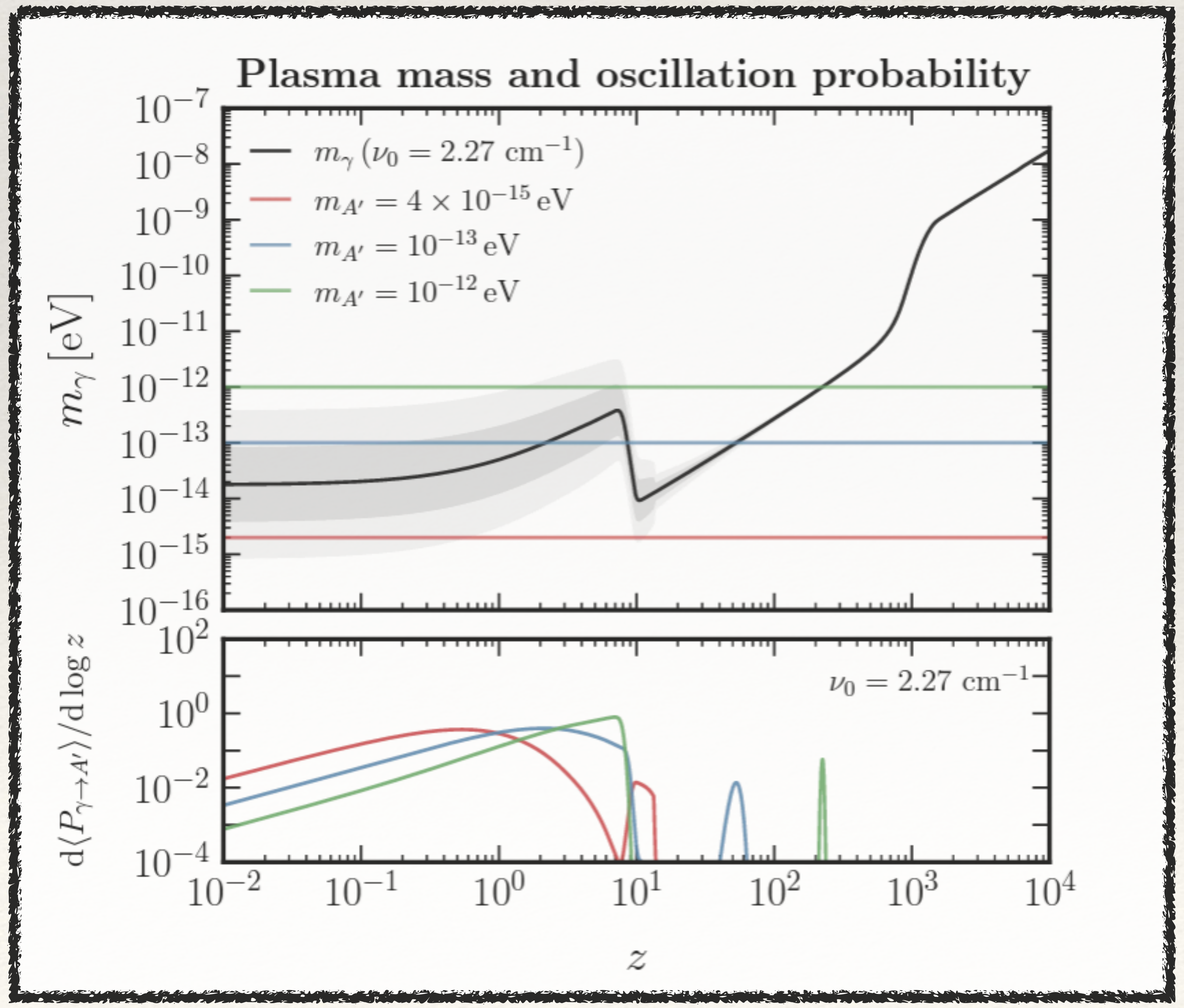
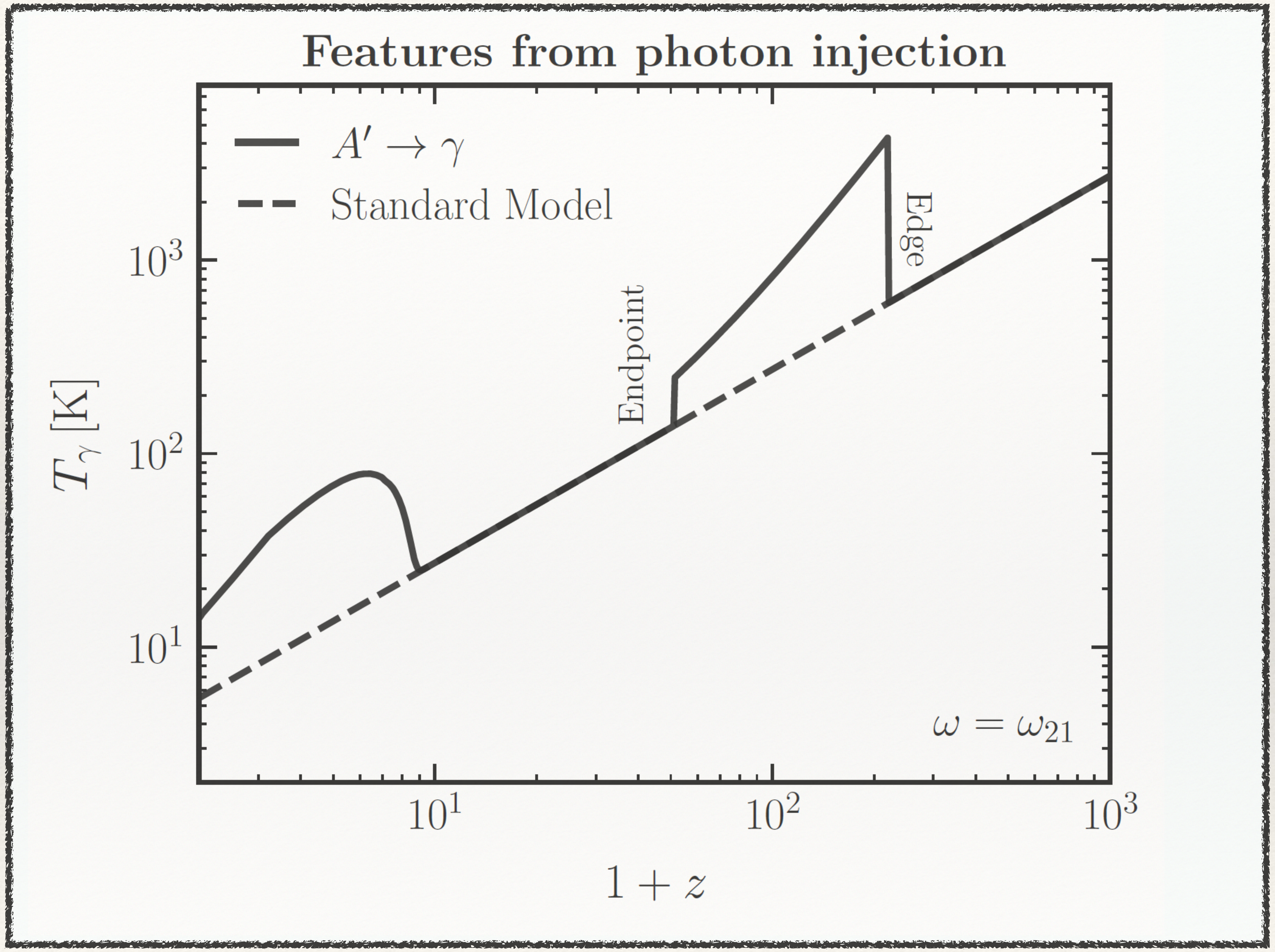
Second, resonant conversion of photons to dark photons



$$\frac{\mathrm{d}\langle P_{\gamma\to A'}\rangle}{\mathrm{d}z} = \frac{\pi m_{A'}^2 \epsilon^2}{\omega(t)}\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \times \int \mathrm{d}m_\gamma^2\, f(m_\gamma^2; t)\,\delta_{\mathrm{D}}(m_\gamma^2 - m_{A'}^2)\, m_\gamma^2$$

AC, H. Liu, S. Mishra-Sharma, J. T. Ruderman, *Phys.Rev.Lett.* 125 (2020) 22, 221303
AC, H. Liu, S. Mishra-Sharma, J. T. Ruderman, *Phys.Rev.D* 102 (2020) 10, 103533

Some nice spectral features from this type of models



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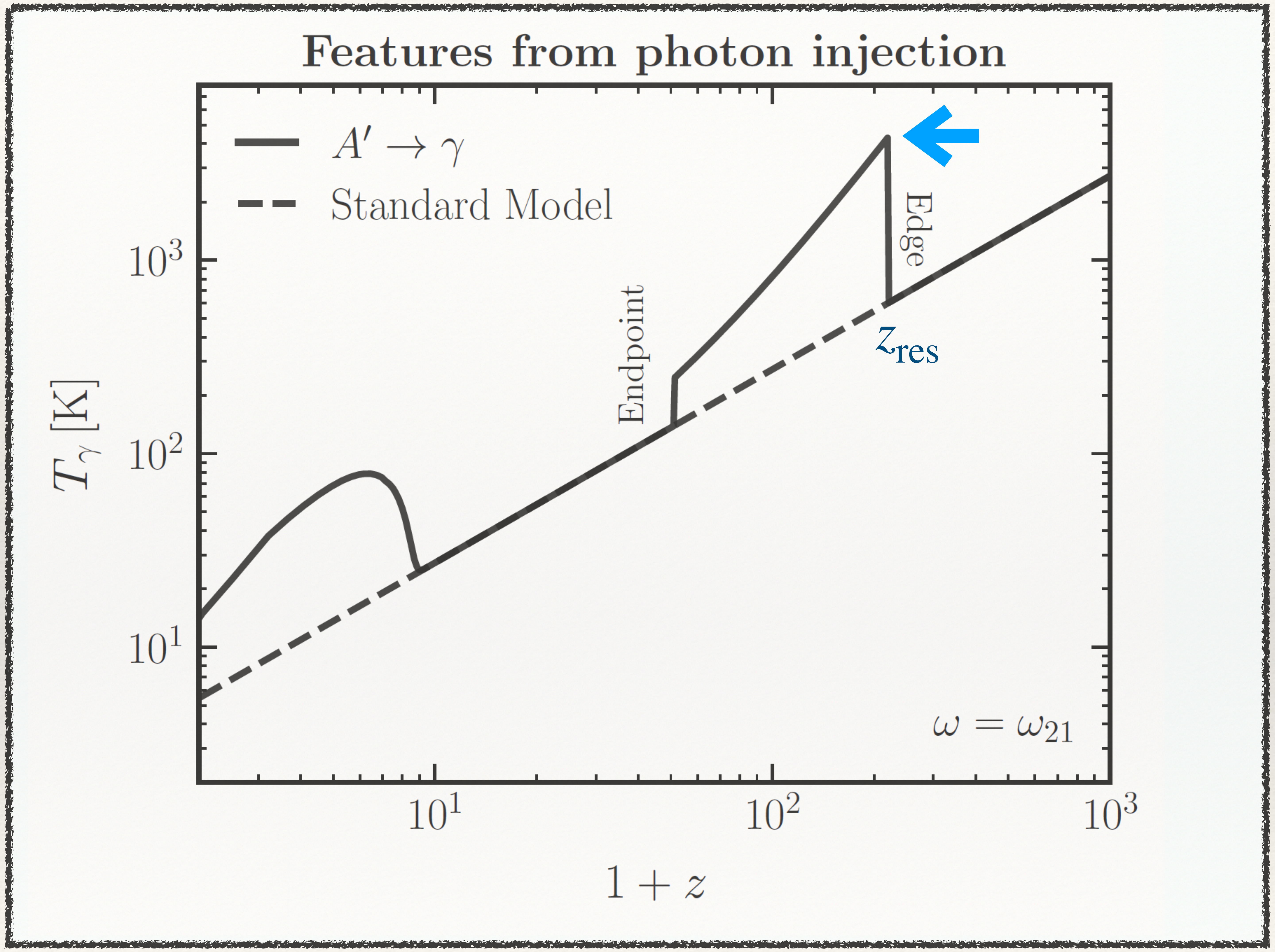

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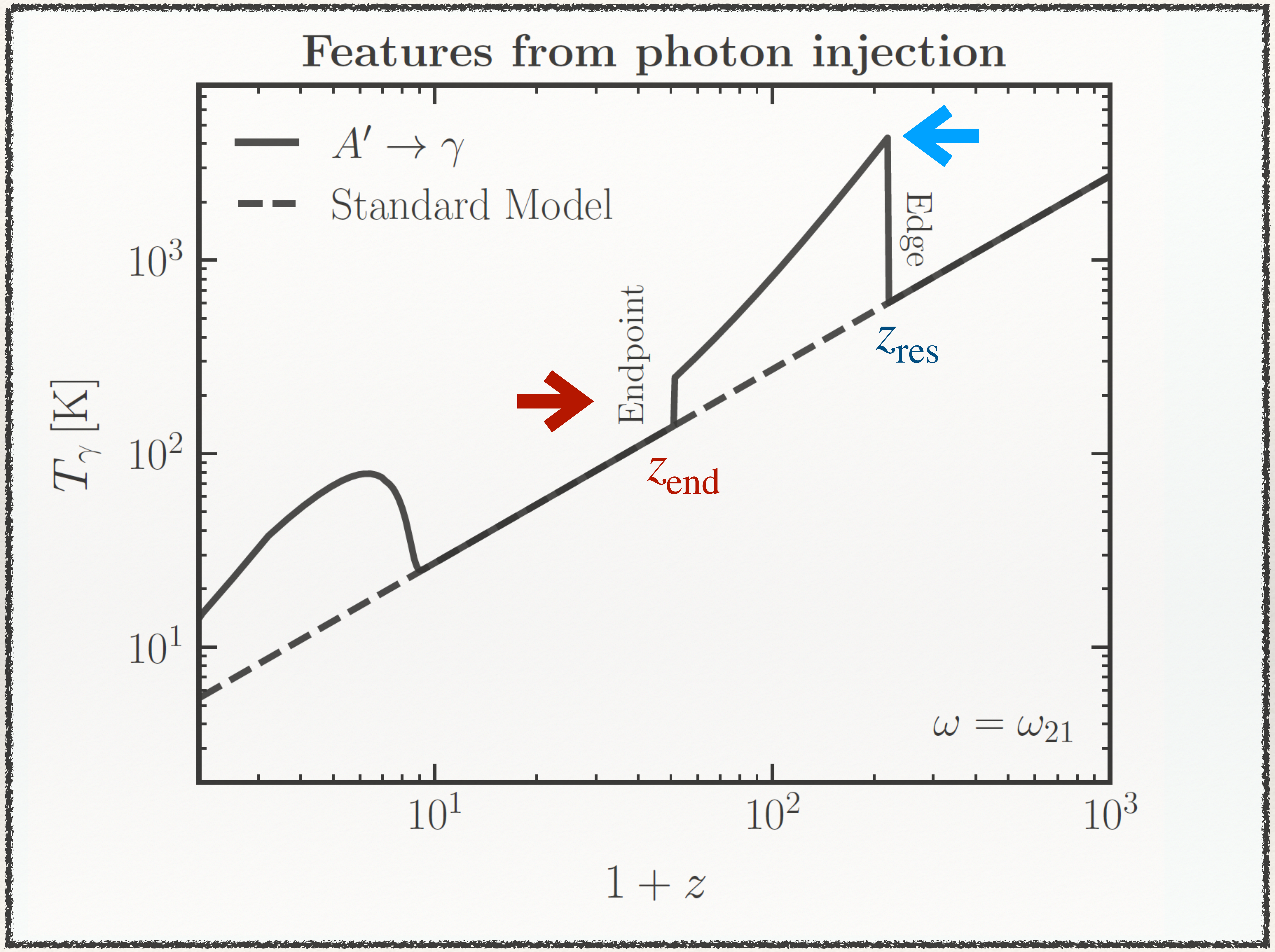
Some nice spectral features from this type of models

Kinematic endpoint

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



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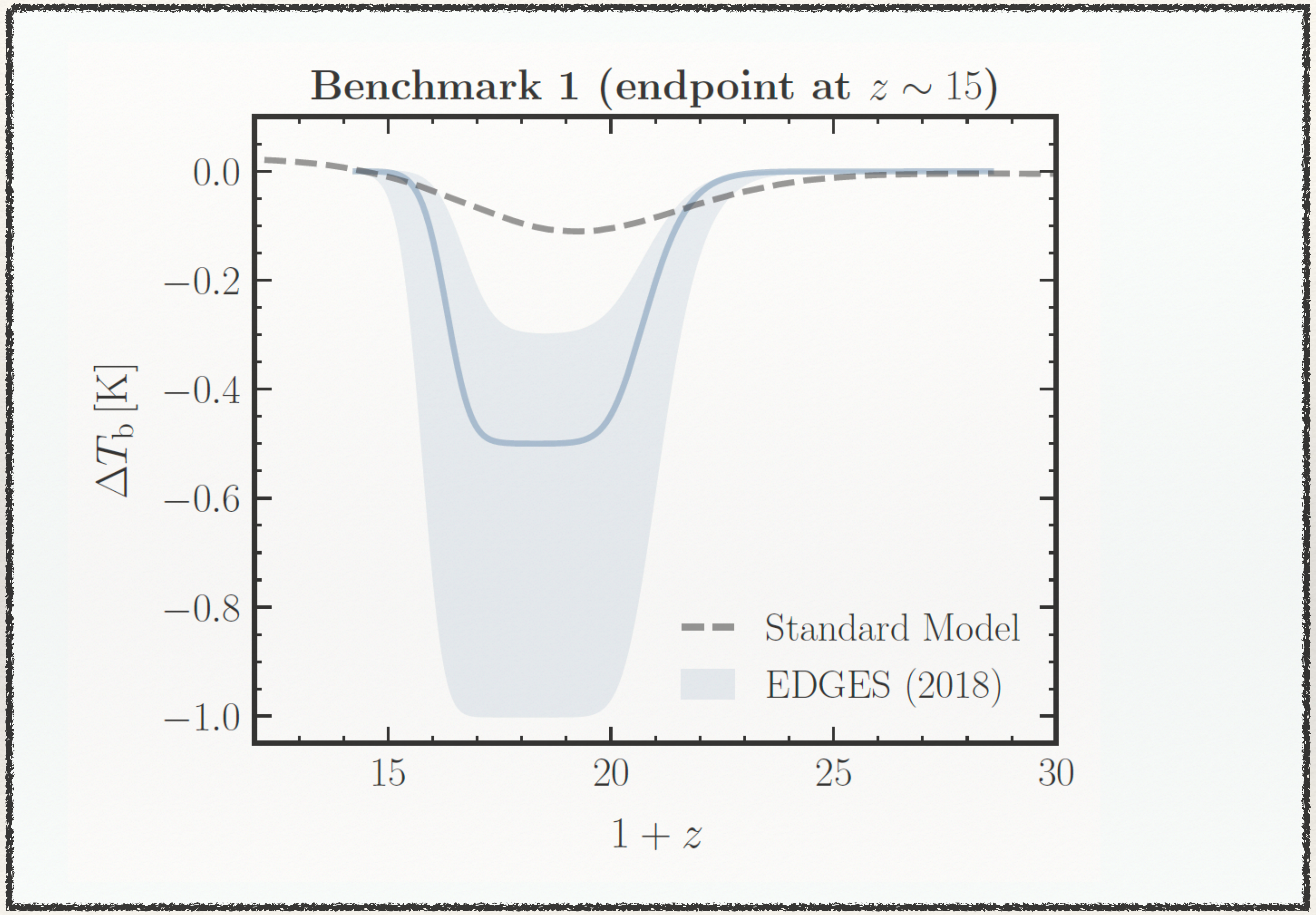
Effect on the brightness temperature



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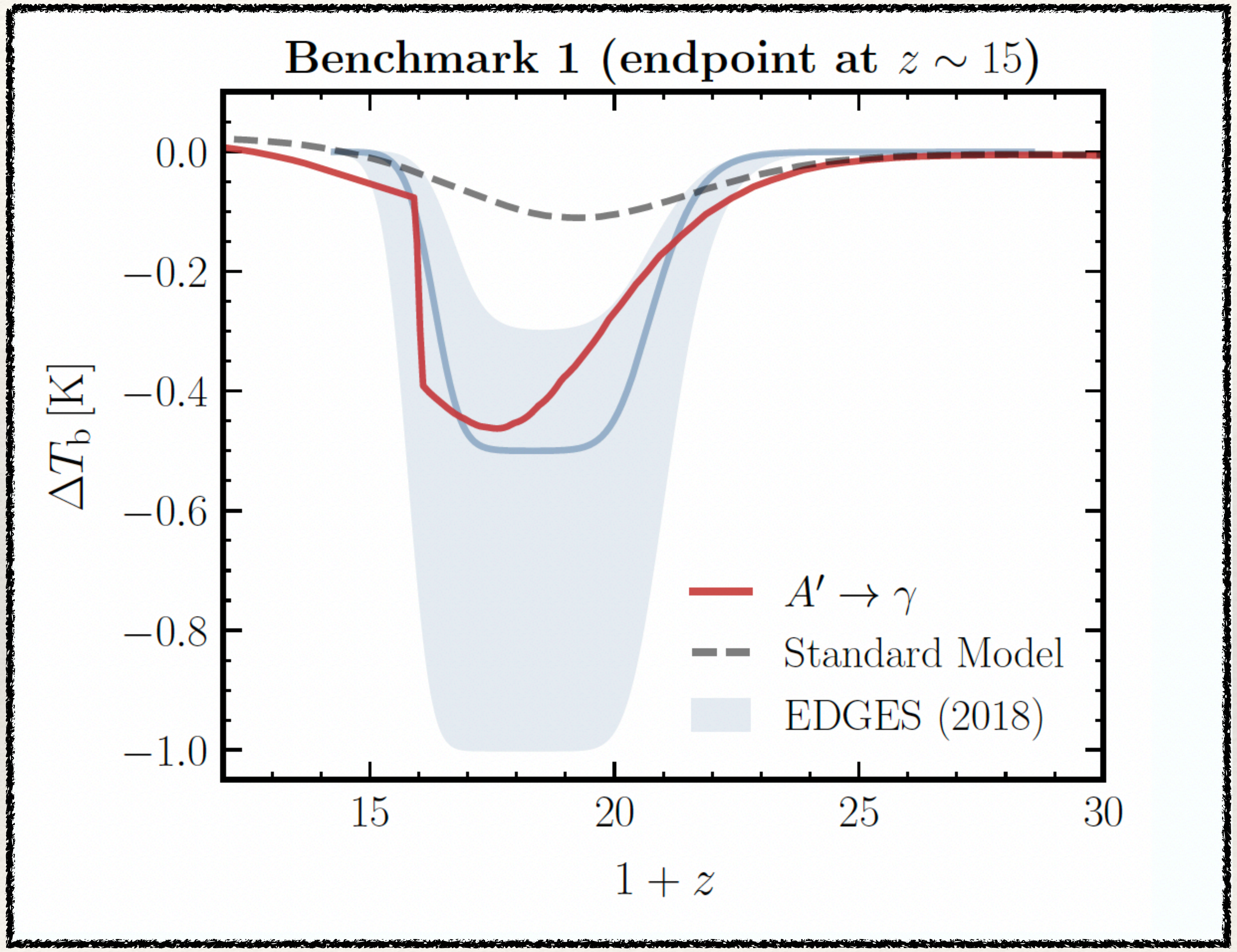

$$m_{A'} = 10^{-11}\,\text{eV}$$

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

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

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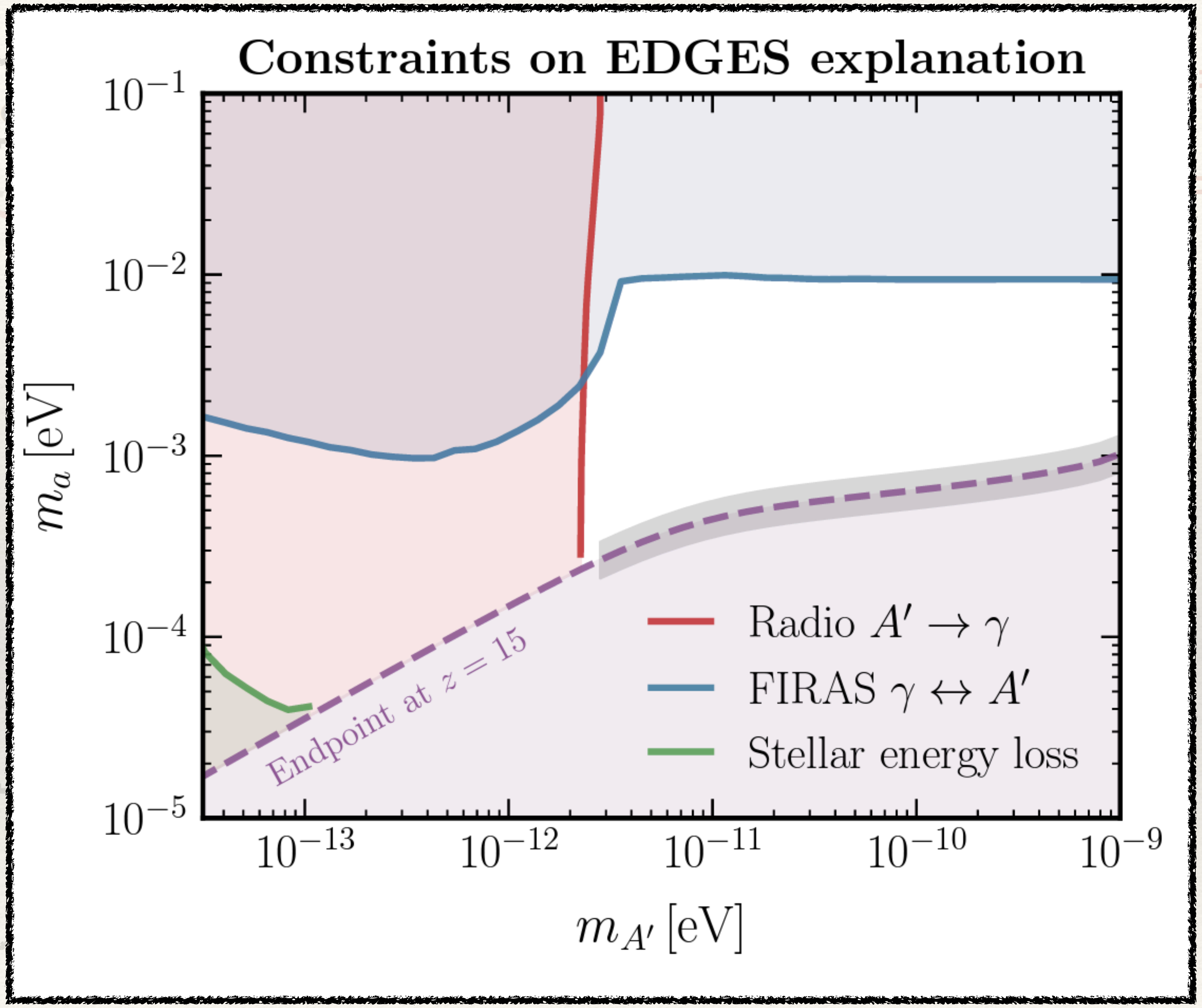
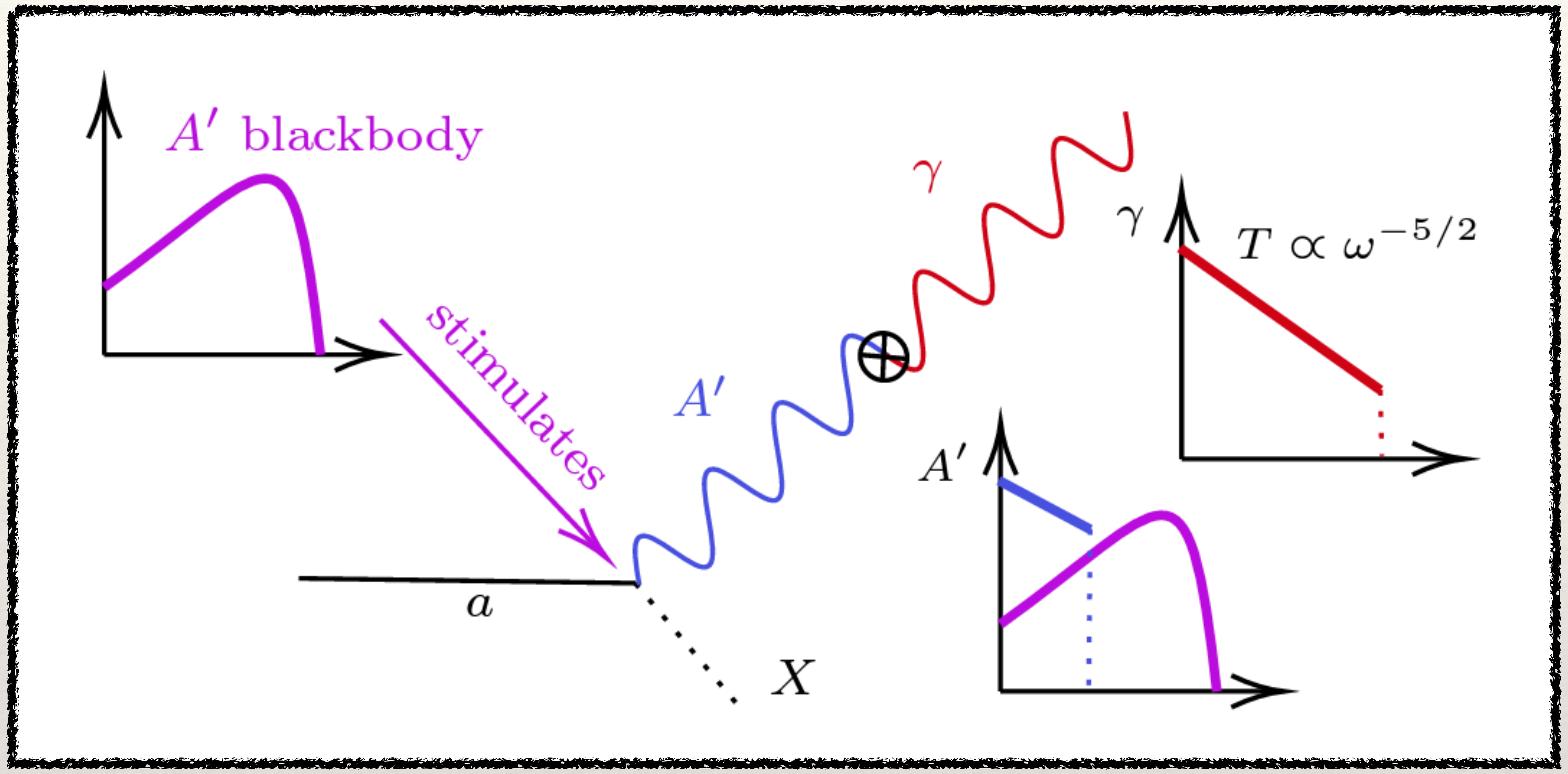


A lot of constraints

AC, H. Liu, S. Mishra-Sharma, M. Pospelov, J. T. Ruderman, A. Urbano, *Phys.Rev.Lett.* 127 (2021) 1, 011102

But the model — despite of EDGES — is interesting, for example it can be enlarged to explain ARCADE excess



Assume there is a background of dark photons

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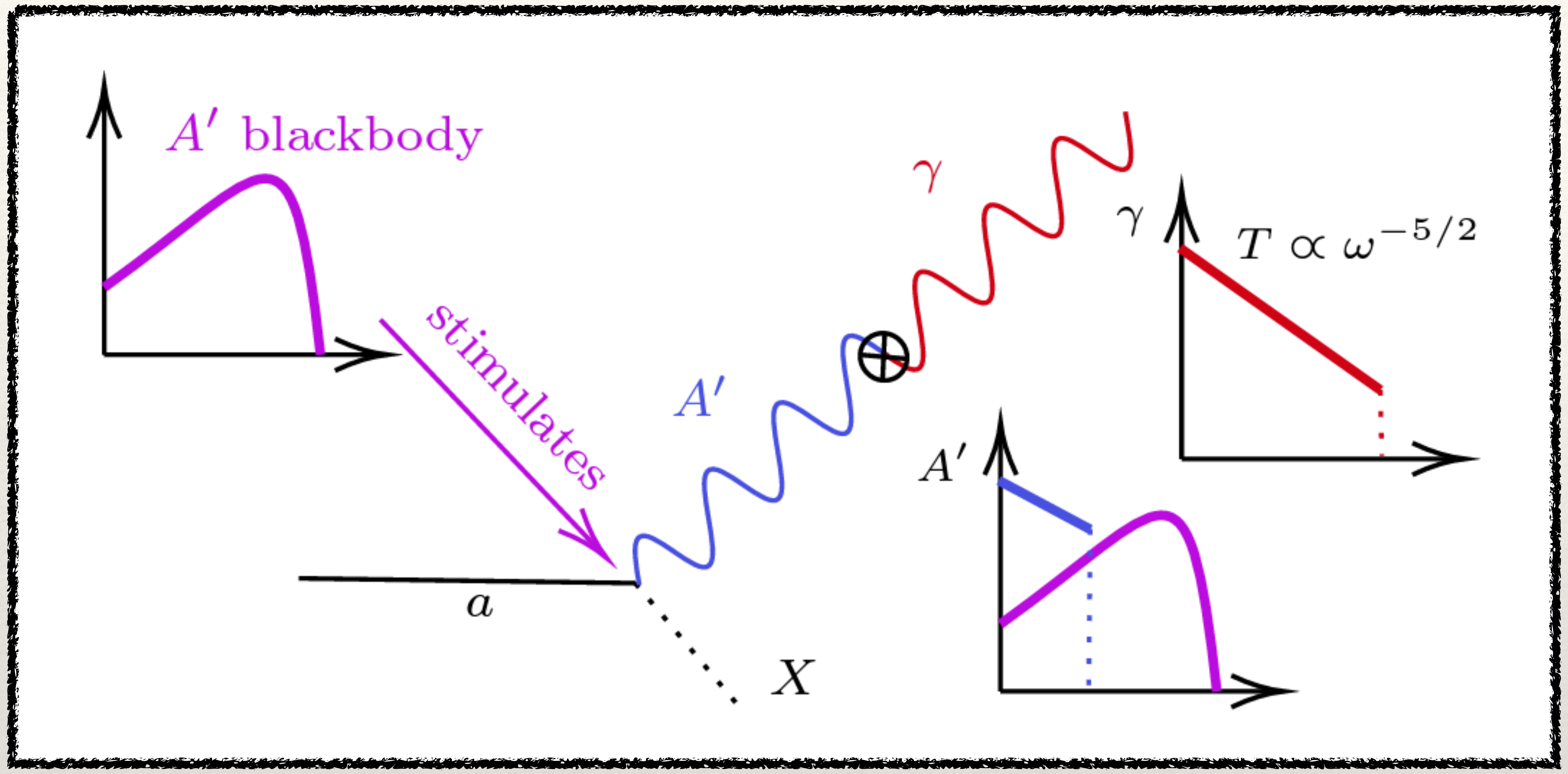

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$$\frac{dn_\gamma}{dx}(x,z) = \frac{\rho_a(z)}{m_a}\frac{\alpha}{x}\underbrace{\frac{1}{\tau(z_\star)}}_{\propto x^{-1}}\underbrace{\frac{1}{H(z_\star)}}_{\propto x^{3/2}}\underbrace{\int_z^{z_\star} dz'\frac{d\langle P_{A'\to\gamma}\rangle}{dz'}}_{\propto x^{-1}}$$

$$\boxed{\tau(z) = \tau_{\rm vac}\left[1 + n f_{A'}^{\rm BB}(z)\right]^{-1}}$$

Stimulated decay

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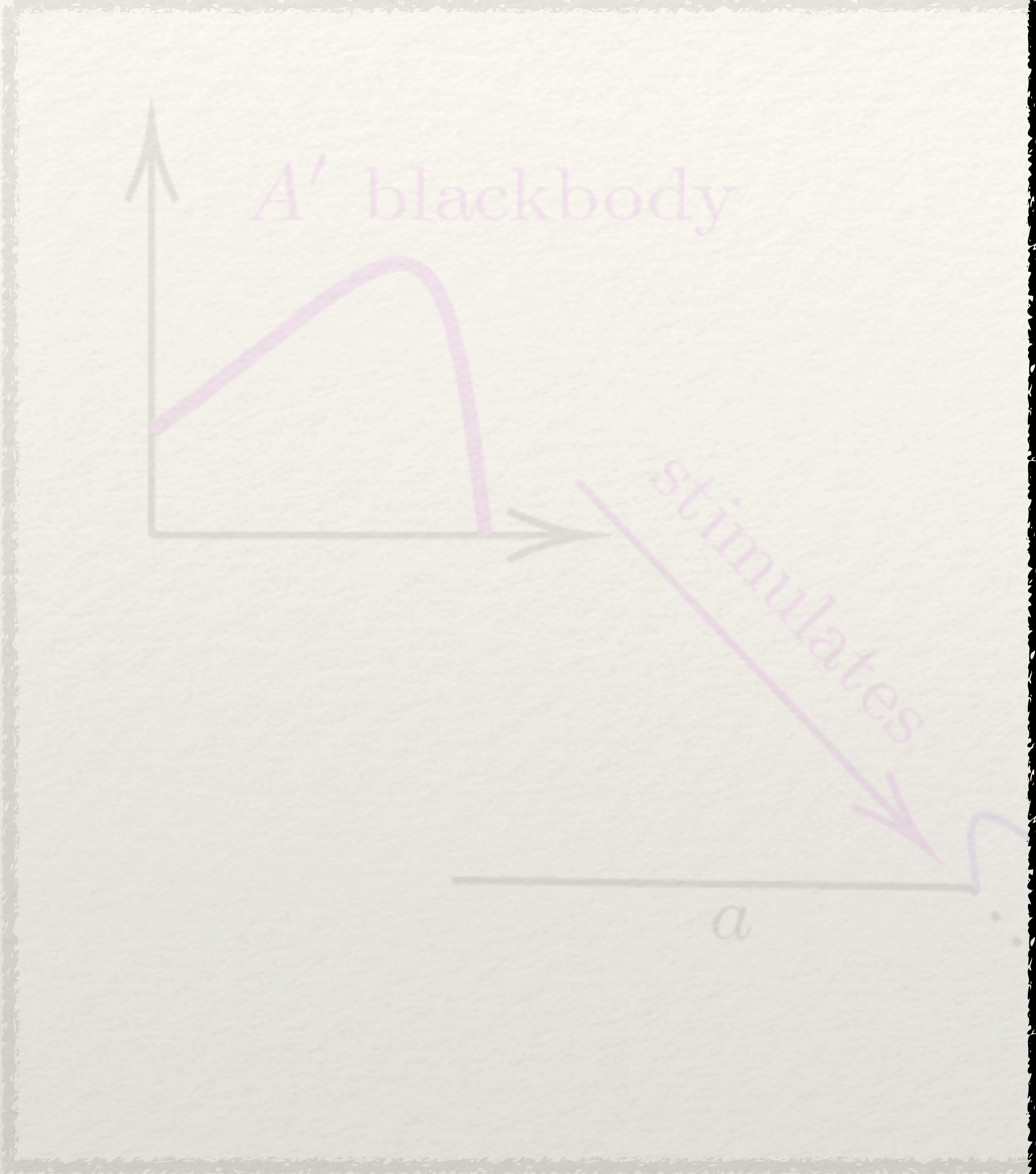

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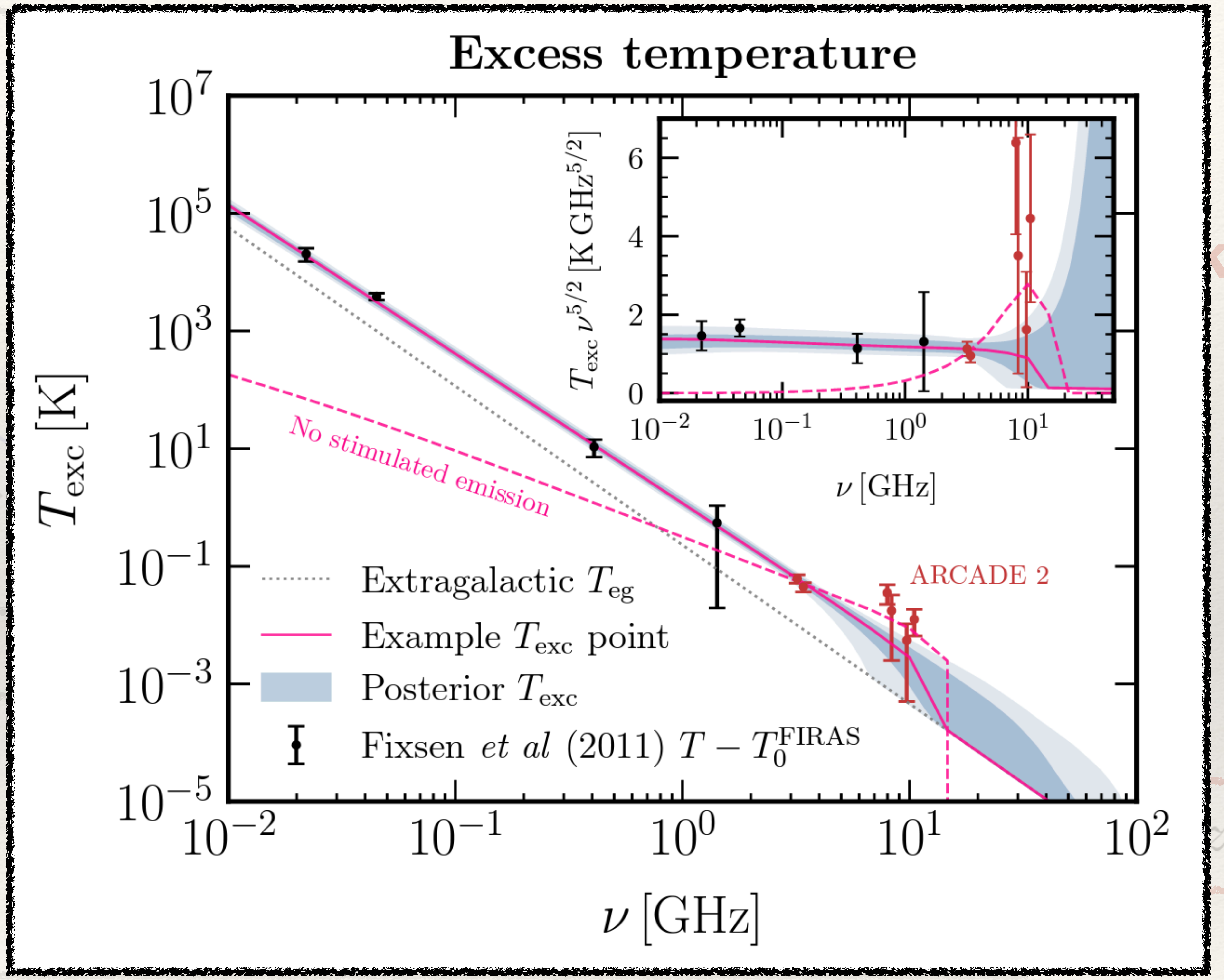

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Stimulated decay

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1) Other models, e.g axion-photon oscillations in magnetic fields

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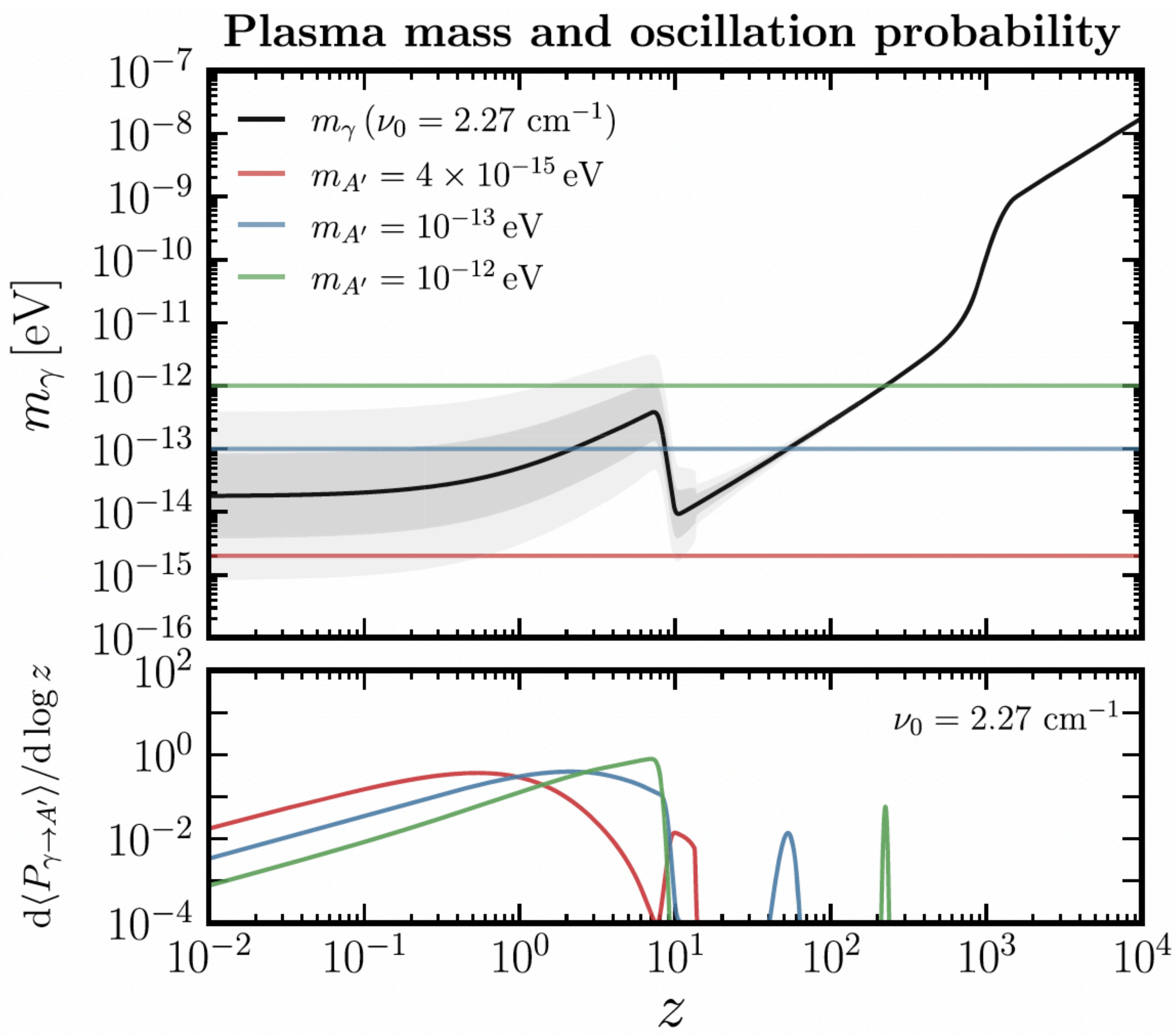
2) Better treatment of astrophysical uncertainties

3) Study CMB and 21 cm anisotropy

Thanks for the attention!

Back-up

Back-up



Dark Photon Mass

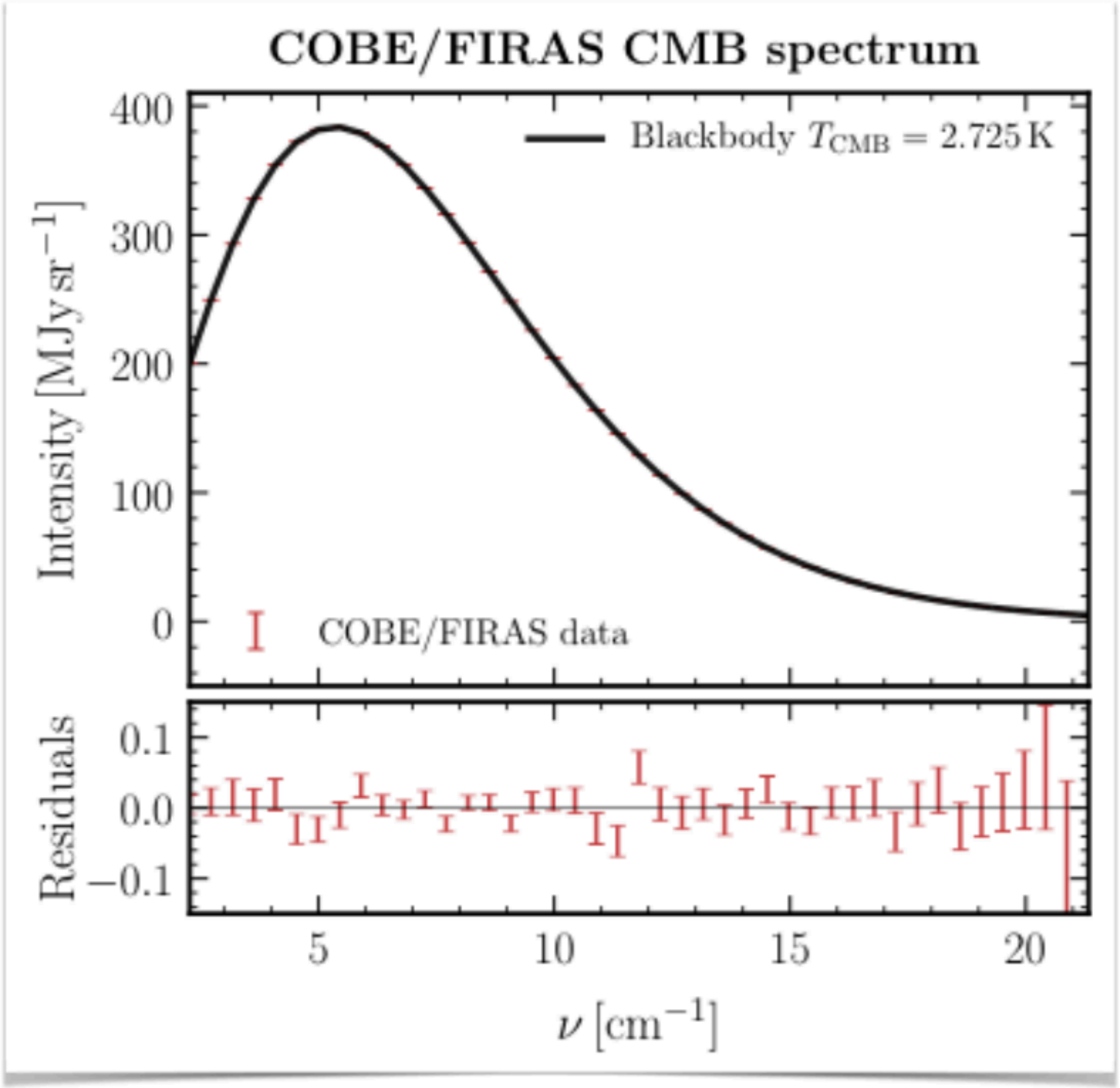
Kinetic mixing

$$\frac{d\langle P_{\gamma\to A'}\rangle}{dz} = \frac{\pi m_{A'}^2\epsilon^2}{\omega(t)}\left|\frac{dt}{dz}\right| \times \int dm_\gamma^2\, f(m_\gamma^2;t)\,\delta_D(m_\gamma^2 - m_{A'}^2)\, m_\gamma^2,$$

Photon Mass PDF

Photon Mass

This will then affect CMB

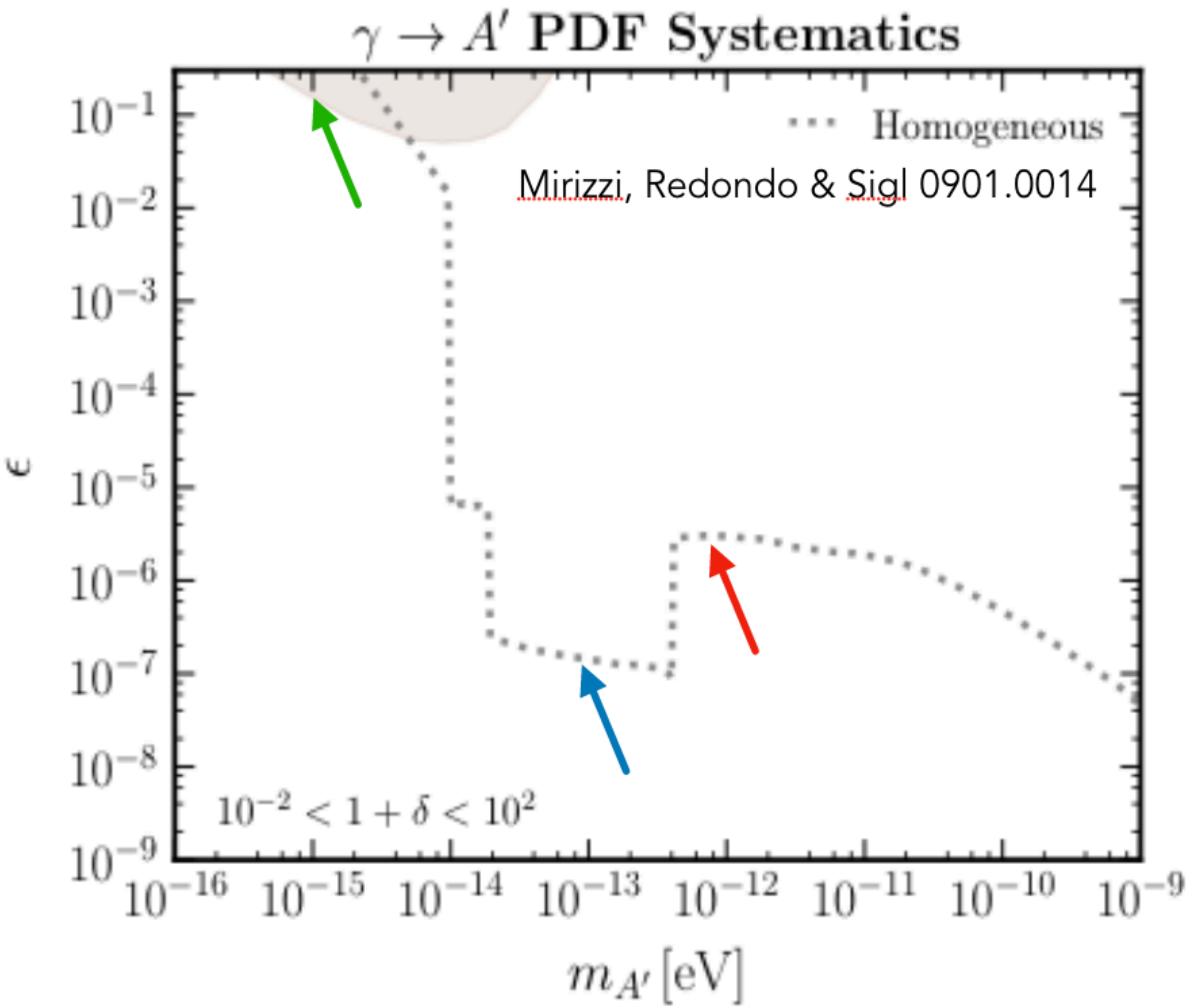


Fixsen+ astro-ph/9605054

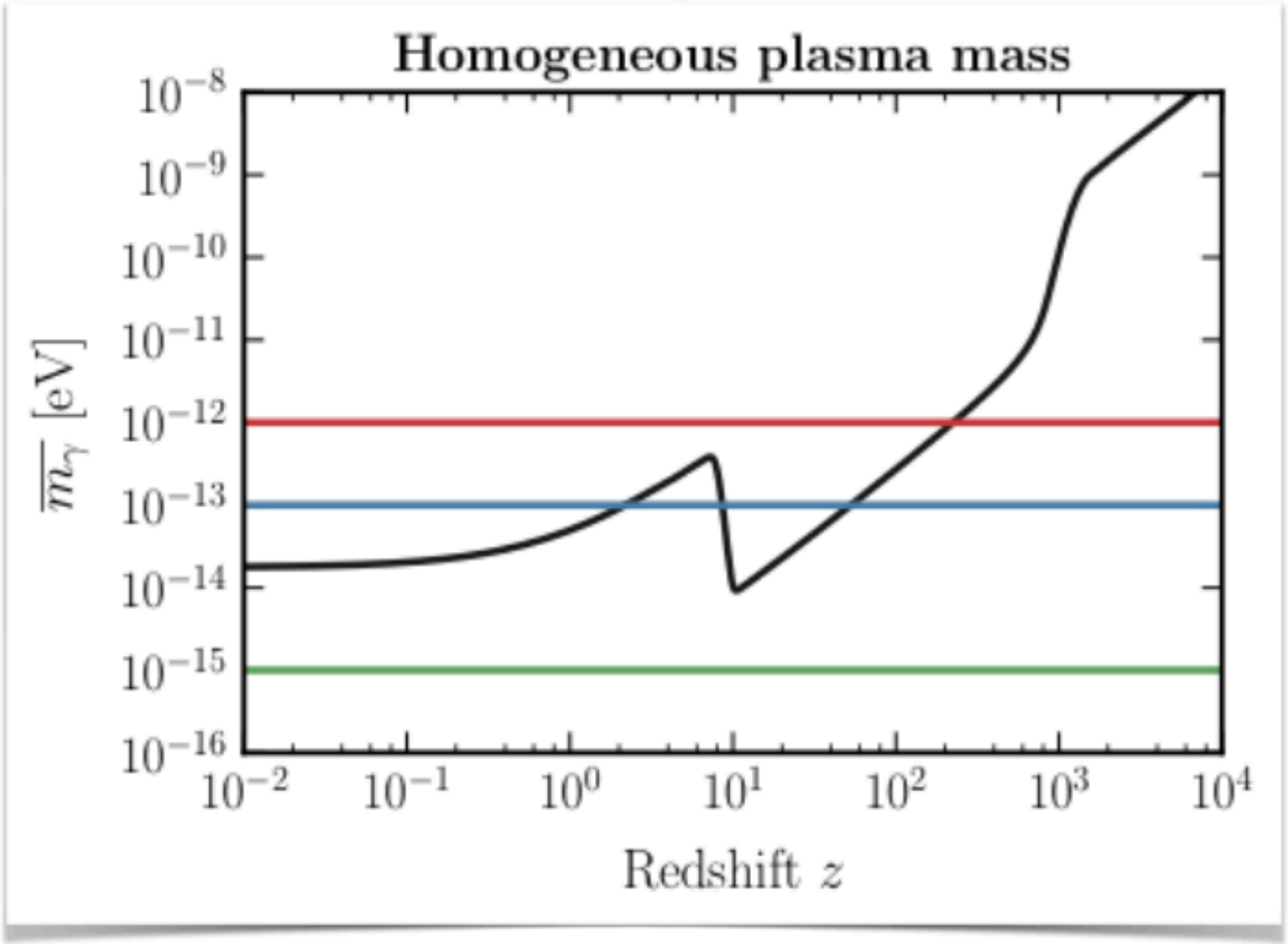
The CMB is very close to a **perfect blackbody**.

Spectral distortions due to disappearing photons are **highly constrained**.

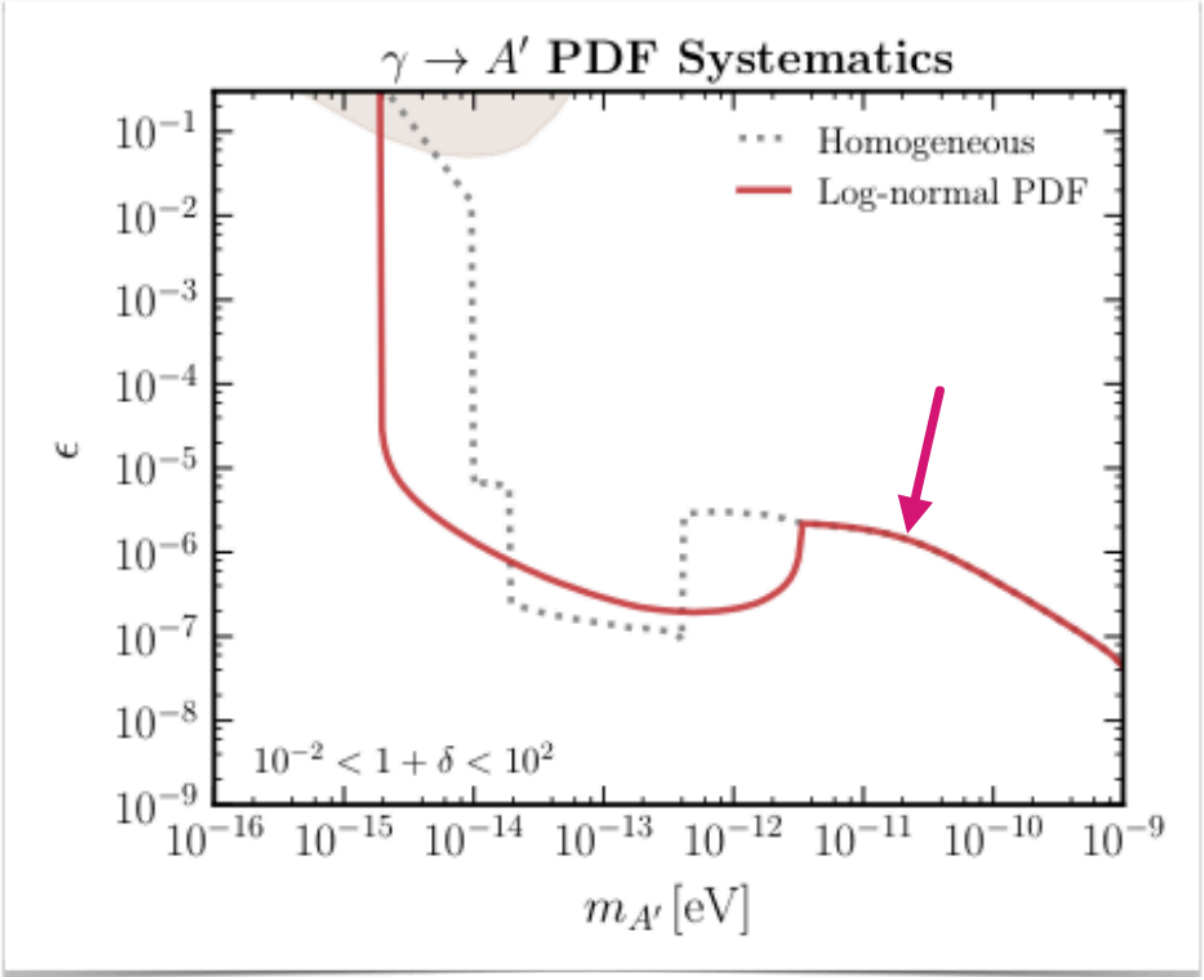
CMB Constraints

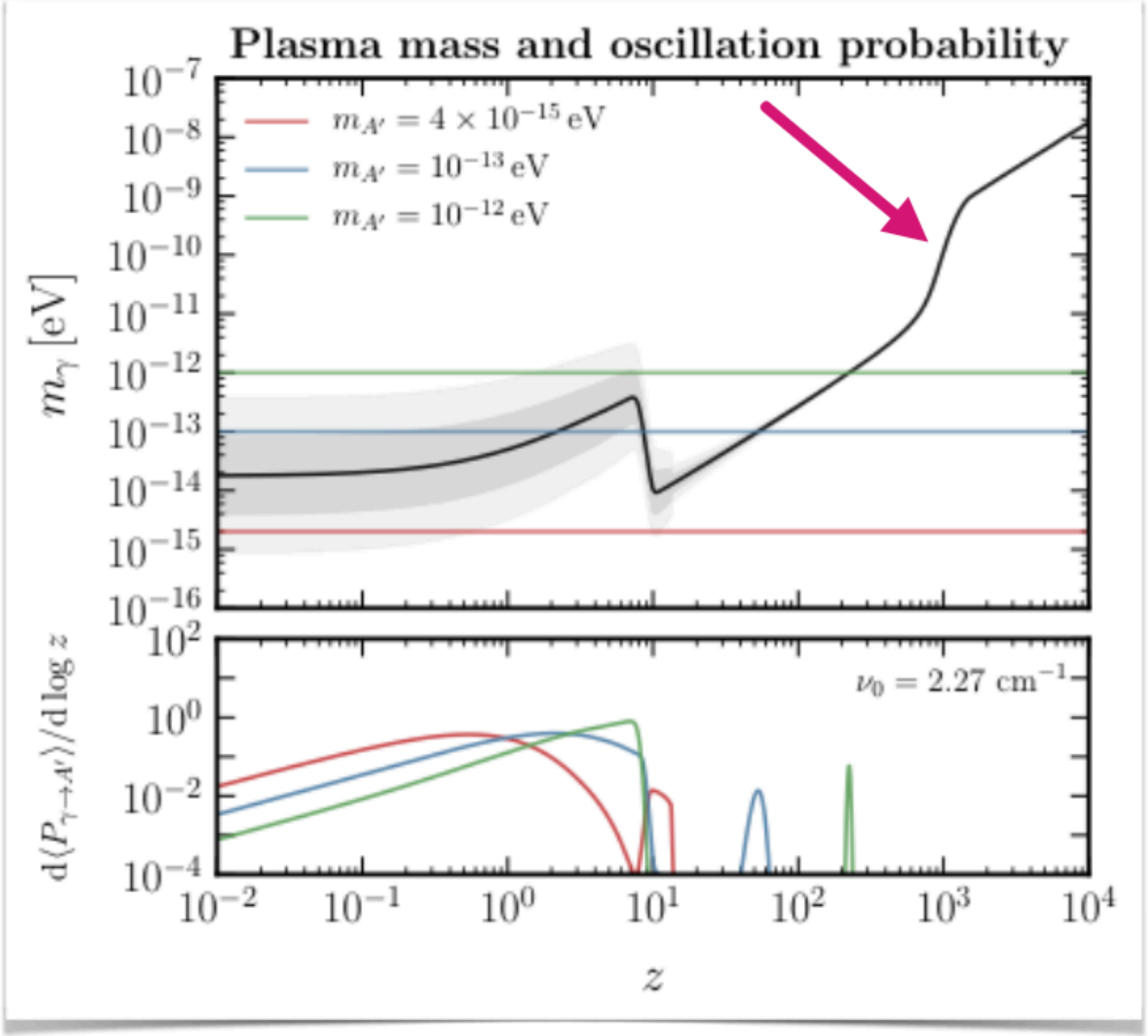


Mirizzi, Redondo & Sigl 0901.0014



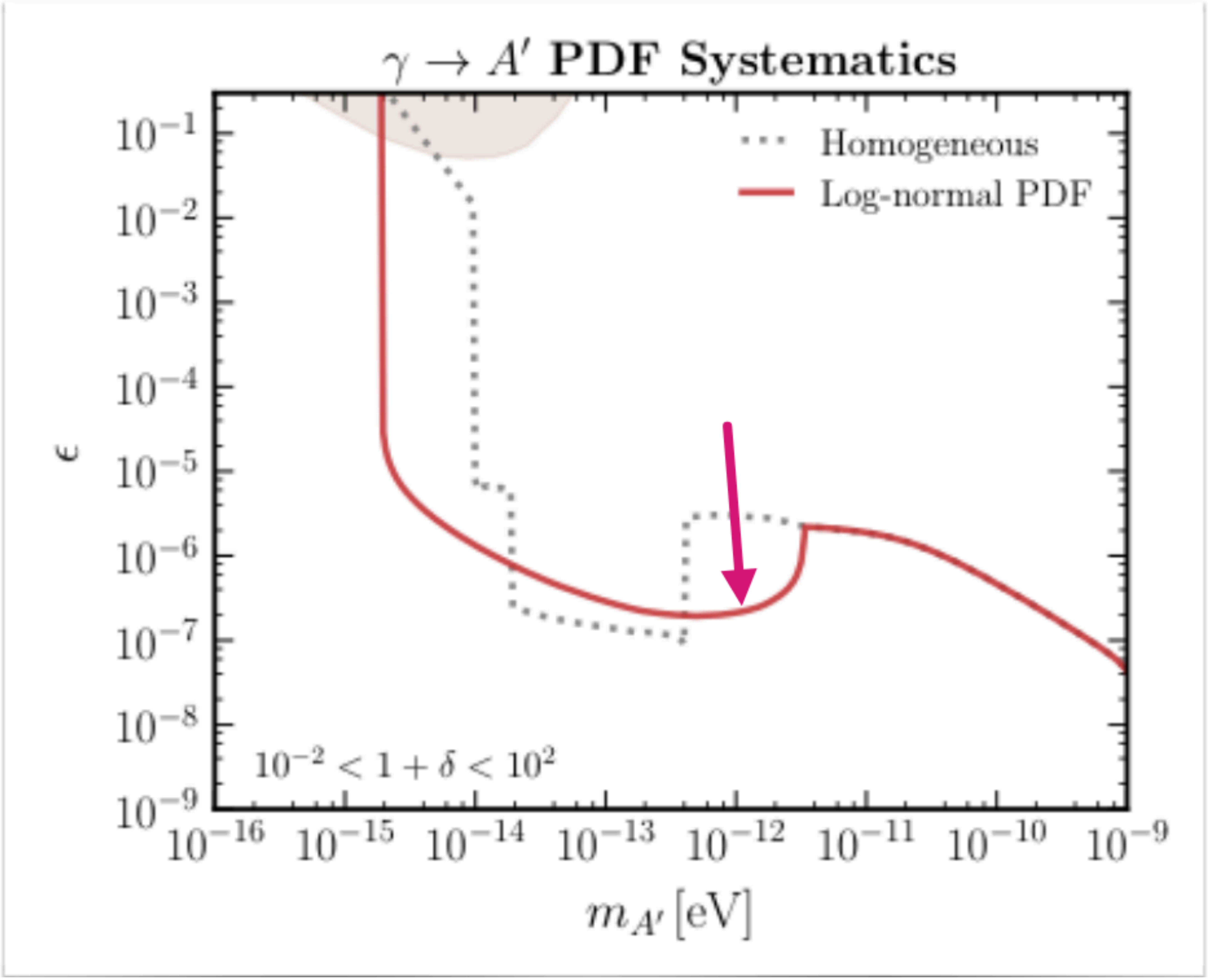
CMB Constraints

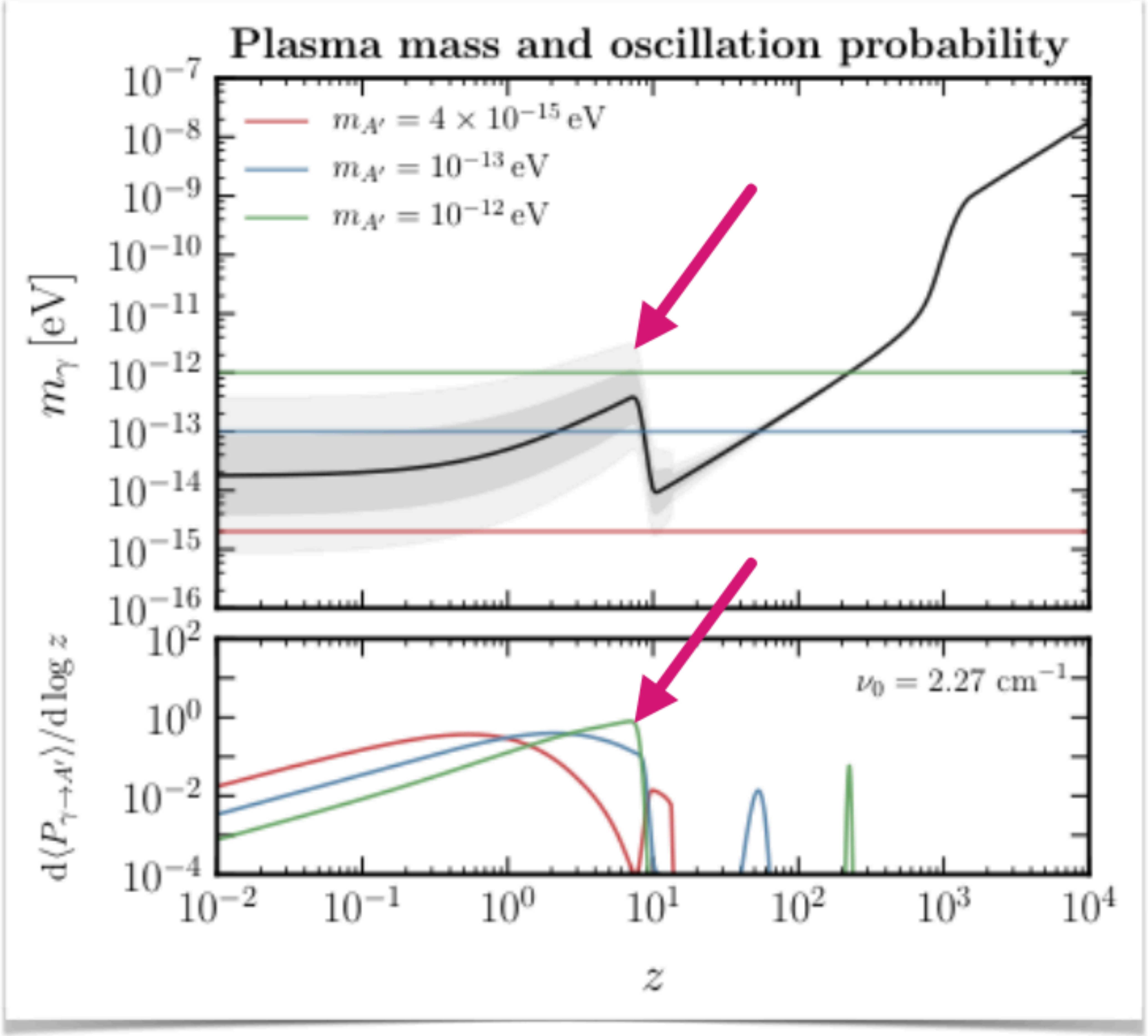




Small fluctuations at high redshift: similar to the homogeneous case

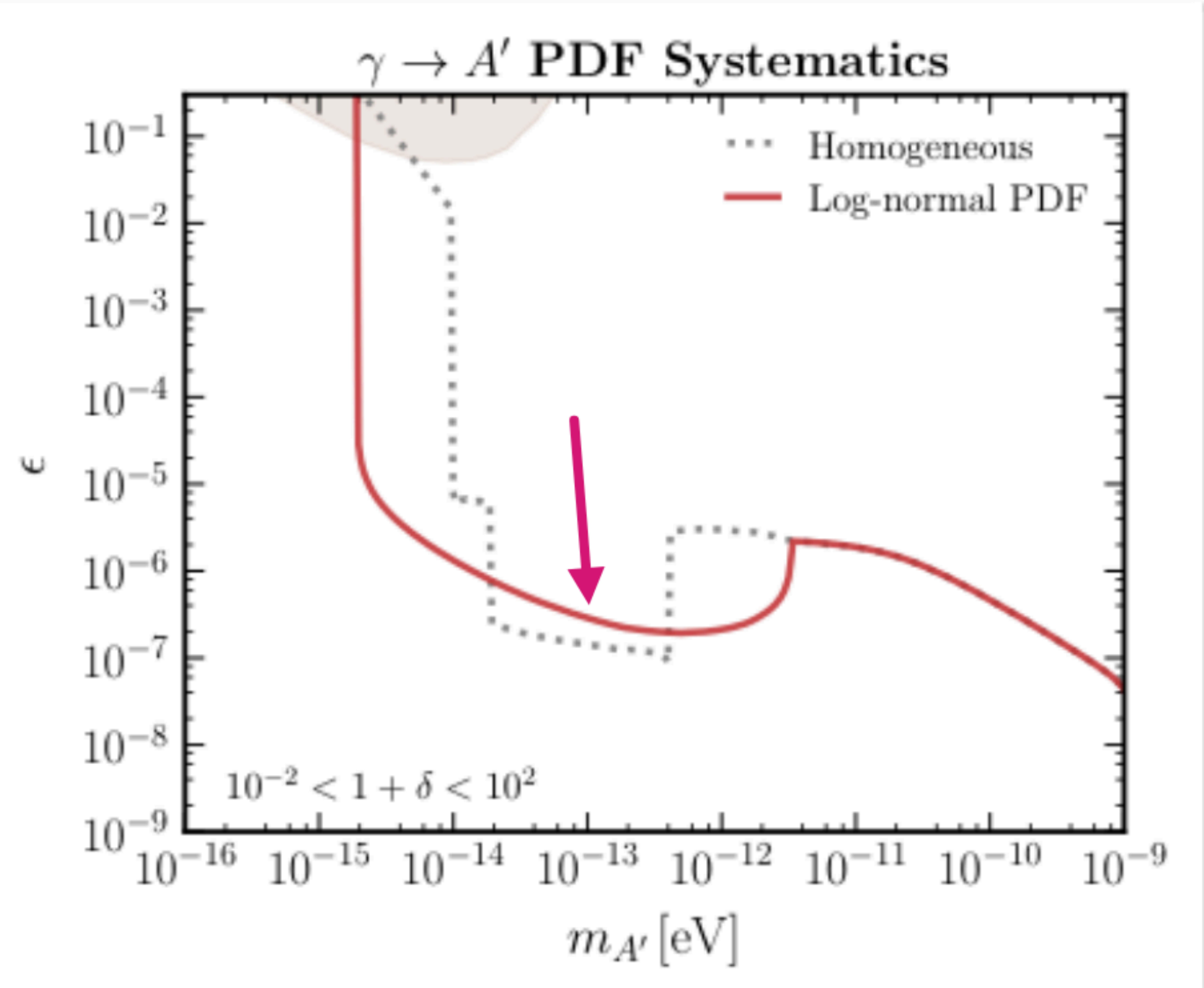
CMB Constraints

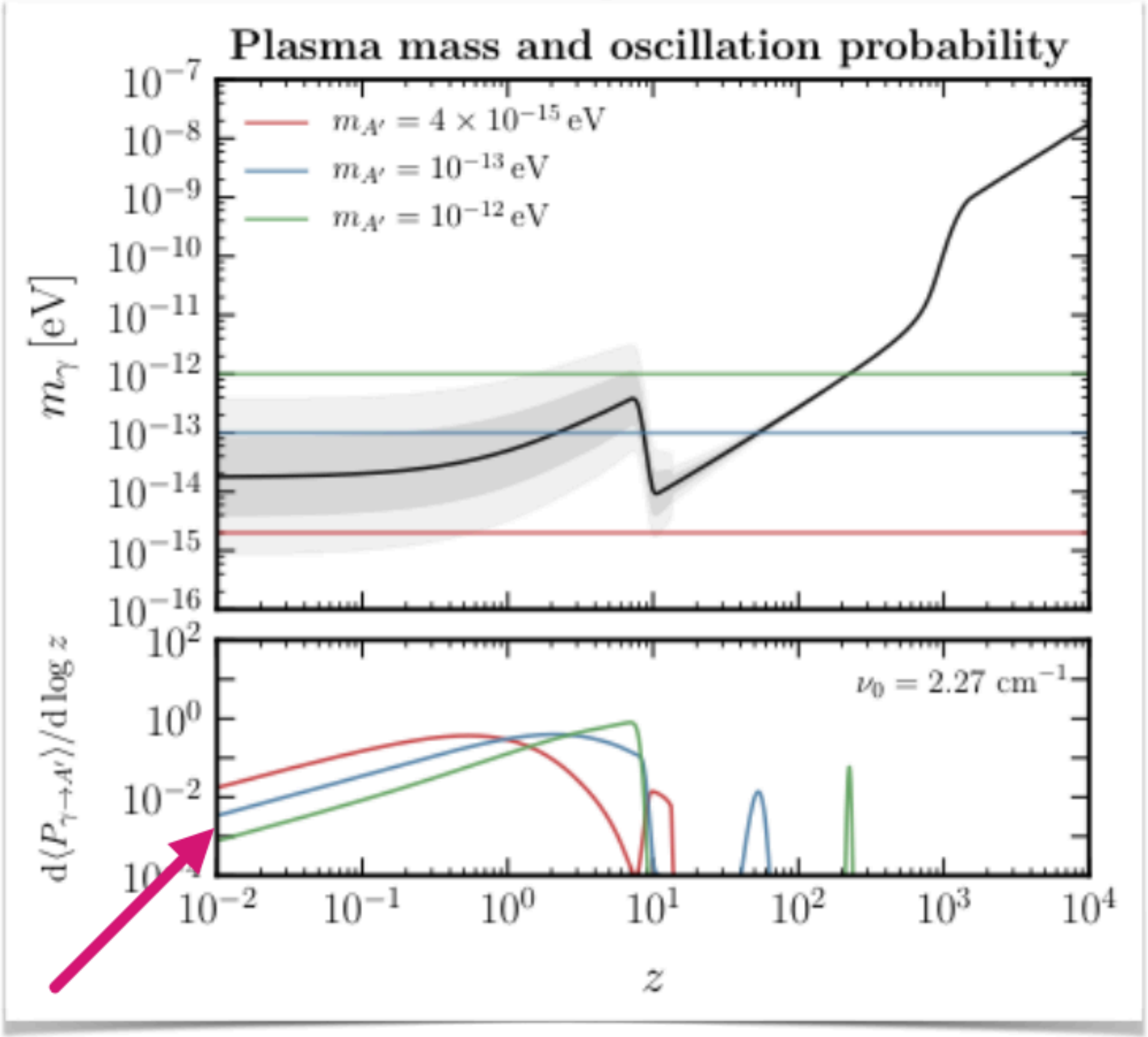




Later conversions available

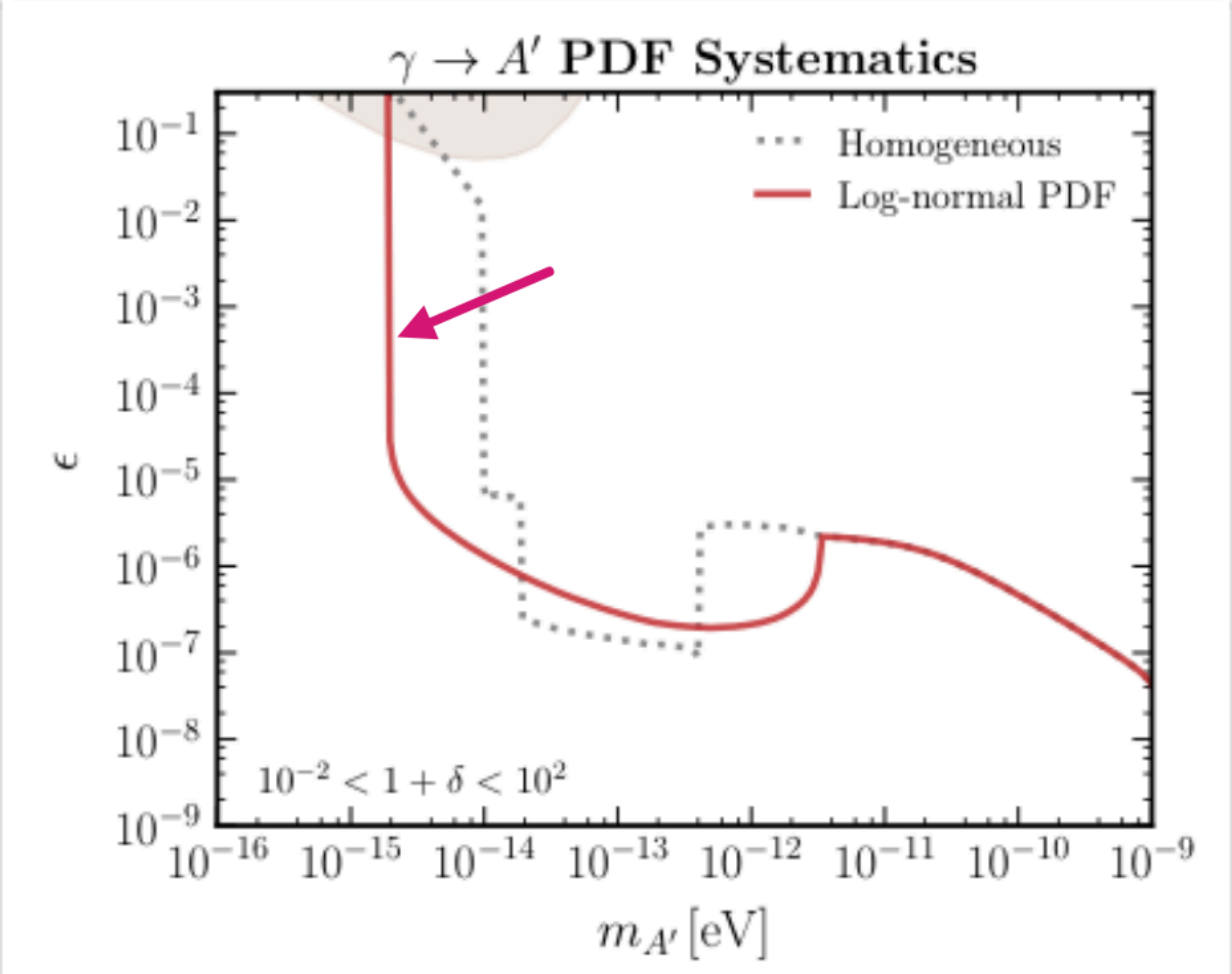
CMB Constraints

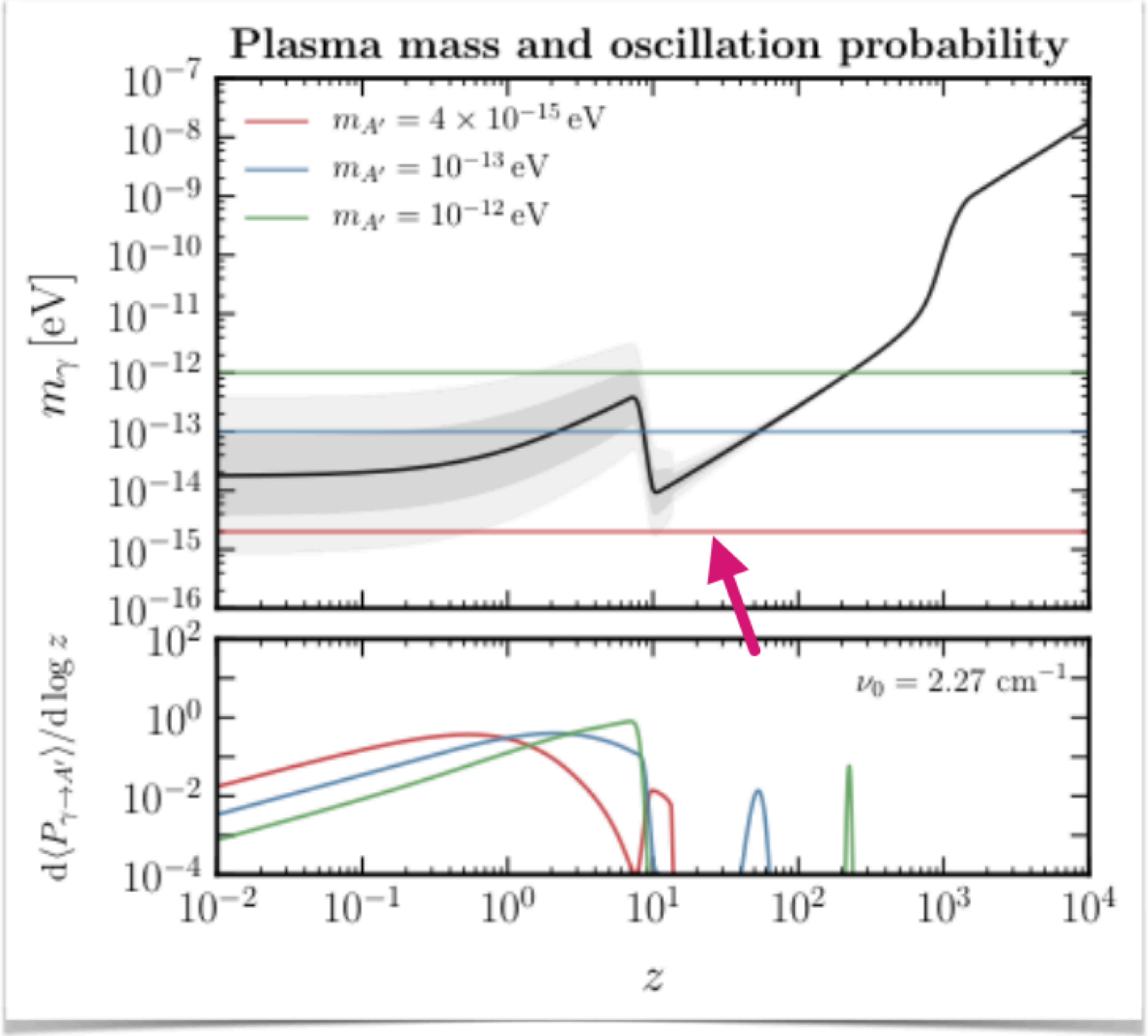




Constraints weakened here, as some conversion probability is in the future

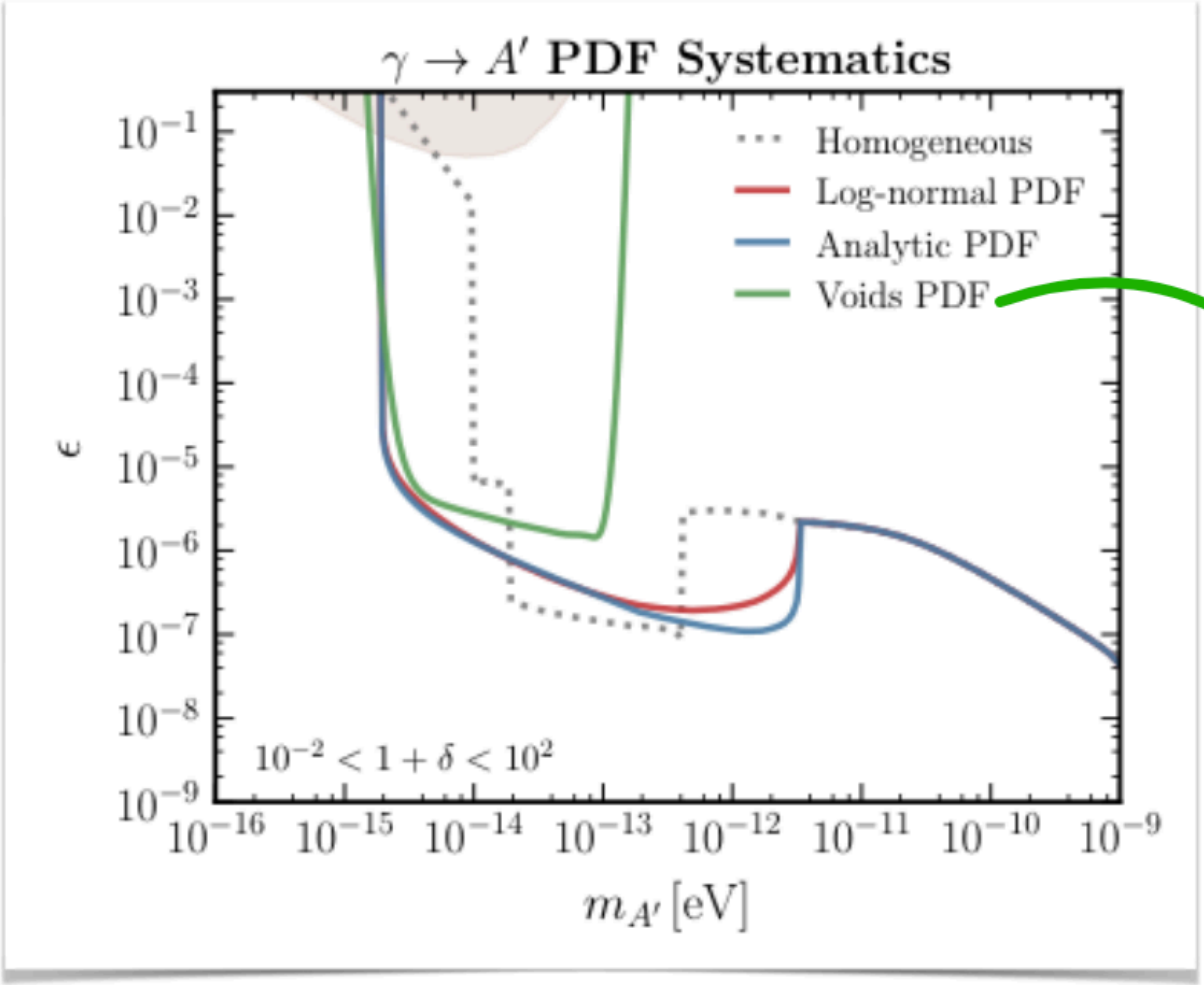
CMB Constraints





Limits extend to lower masses because of under-fluctuations

Check some systematics



check for underdensities

E. Adermann et al, (2018)