Dark Photon and CMB data in our inhomogeneous universe

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In collaboration with H. Liu, S. Mishra-Sharma, J. Ruderman
arXiv 2004.06733 (PRD 2020)
arXiv 2002.05165 (PRL 2020)

(see also arXiv:2009.03899, PRL 2021)

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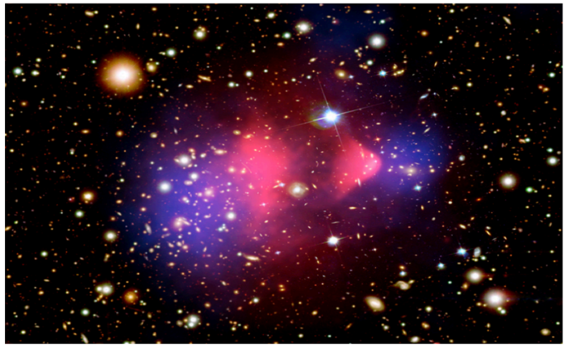
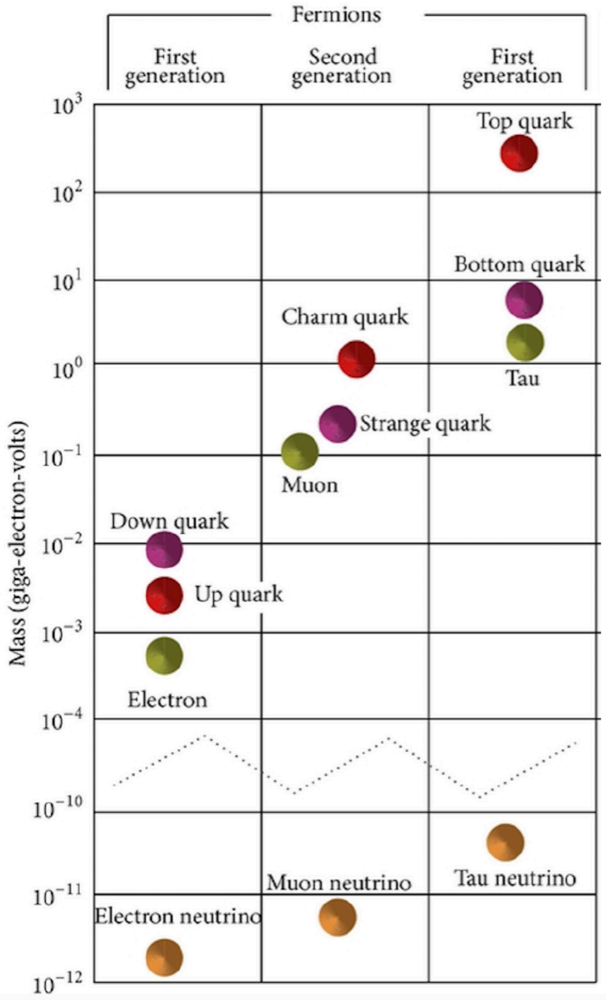
https://github.com/andrea0292/ -------- https://github.com/smsharma ------------ https://github.com/hongwanliu

We have a lot of evidences for physics beyond the Standard Model

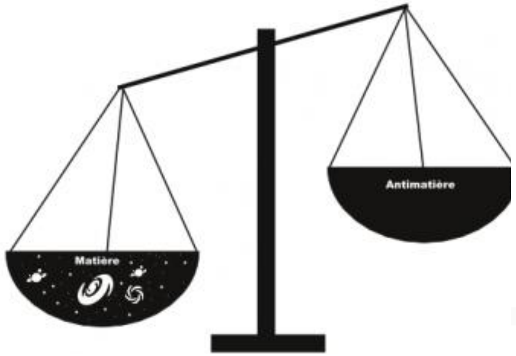
Dark Matter



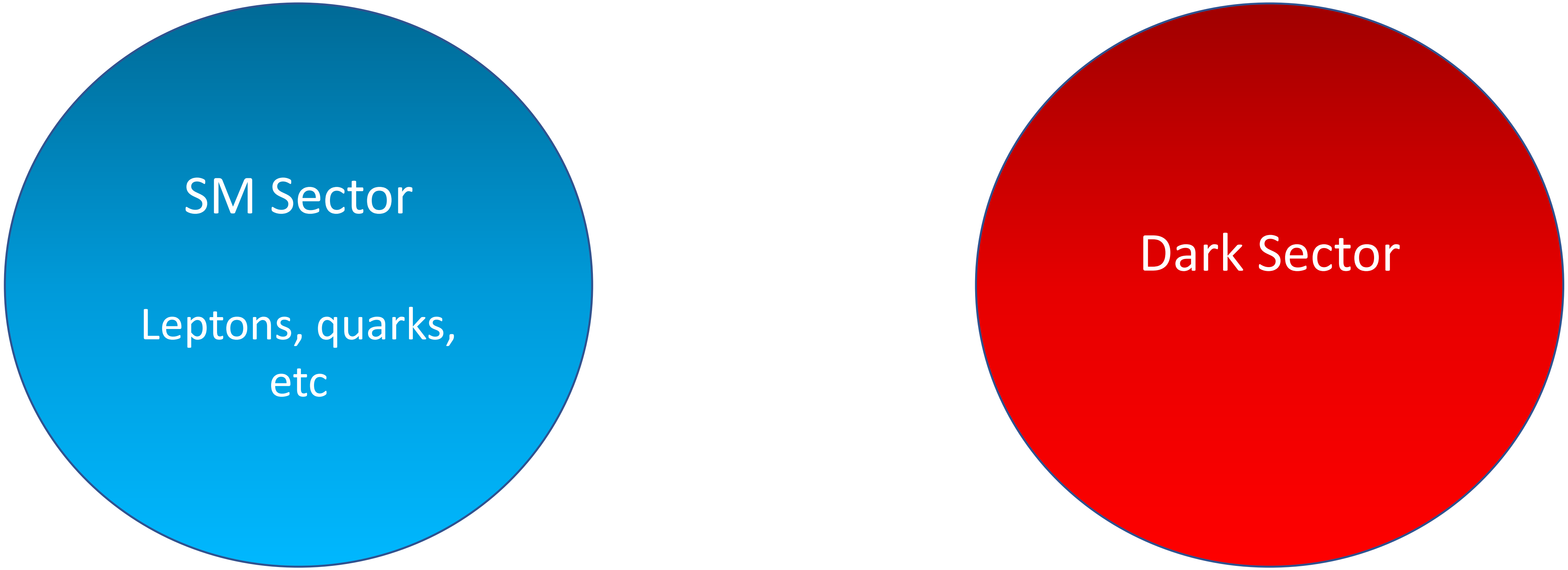
Neutrino Masses



Matter Antimatter asymmetry



Usually what we do is to introduce a Dark Sector, that may or may not be connected with the SM



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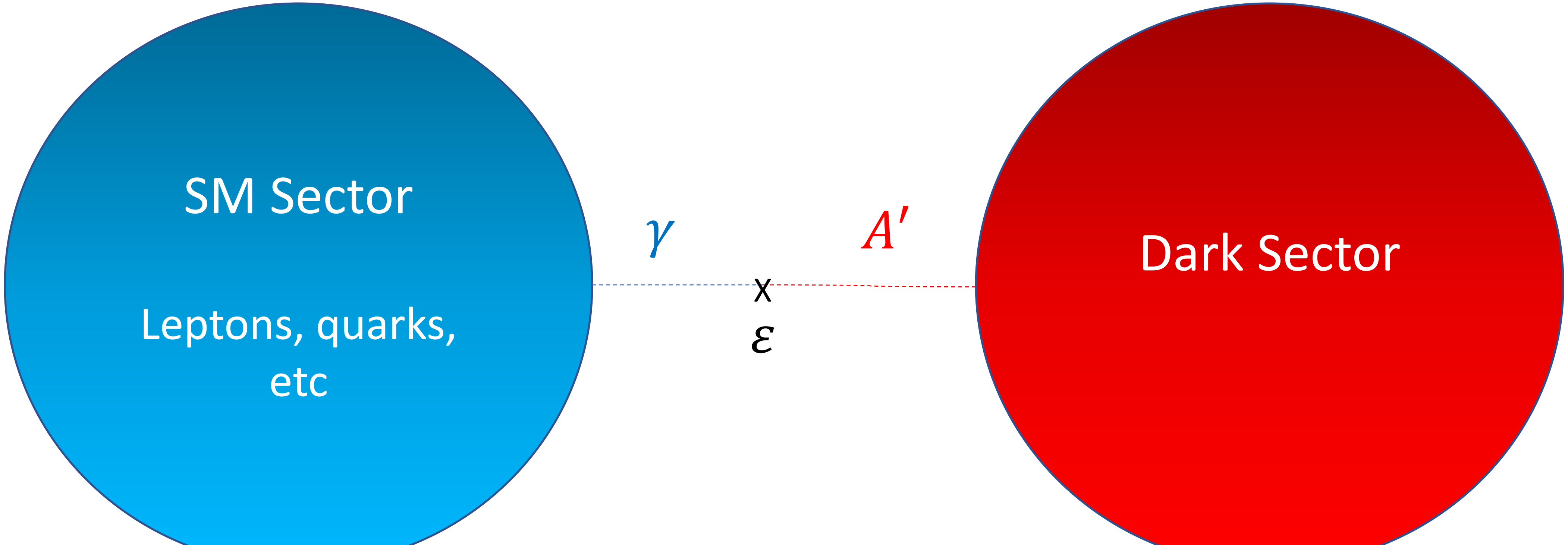
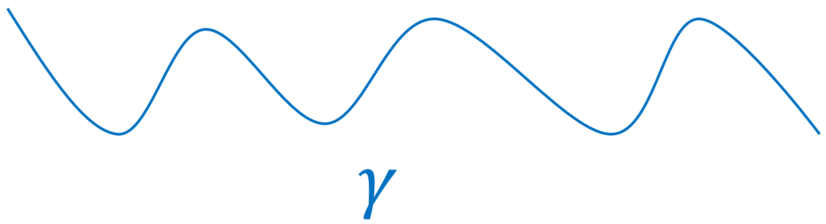


Holdom Phys. Lett. 166B, 196 (1986)

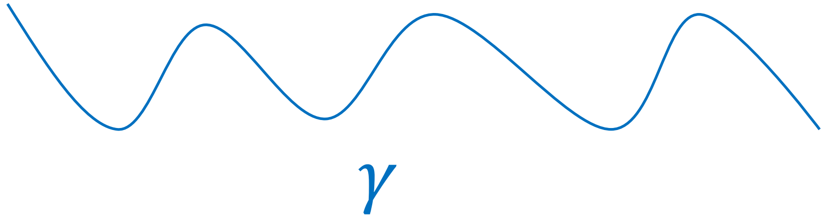
We explored the so called vector portal, introducing a kinetic mixing among the SM photon and a **Dark photon** (other portal are possible, such as Higgs portal or neutrinos portal)

Now some plasma physics

Photons in Vacuum are massless



However medium effects give photon a mass, the usually called plasma mass



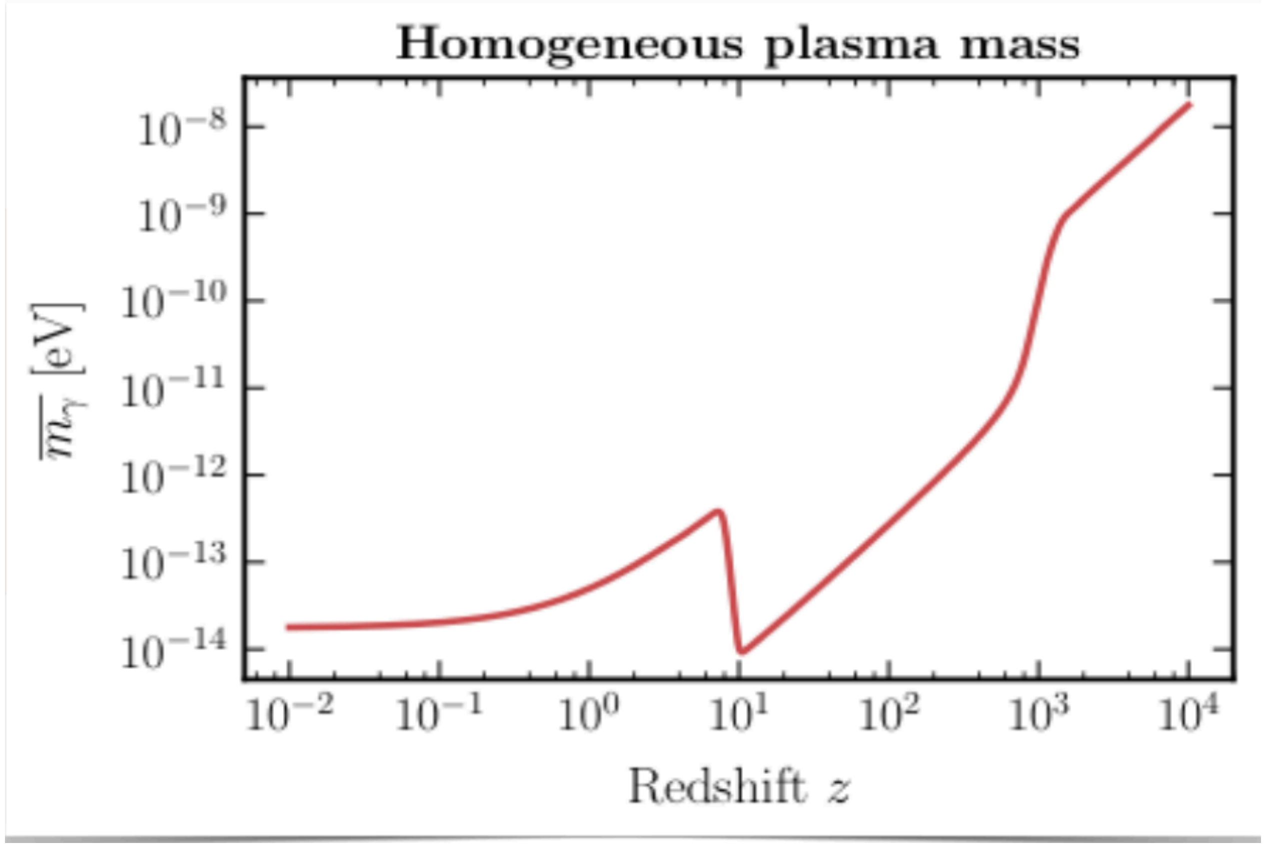
$$m_\gamma^2(z,\vec{x}) \simeq 1.4 \times 10^{-21}\,\mathrm{eV}^2 \left(\frac{n_\mathrm{e}(z,\vec{x})}{\mathrm{cm}^{-3}}\right)$$

Generally in media the dispersion relations are generally modified by the interactions with the background.

$$\omega^2 = k^2 + \omega_\mathrm{P}^2 \left(1 + \frac{k^2}{\omega^2}\frac{T}{m_e}\right) \qquad \text{Transverse,}$$

$$\omega^2 = \omega_\mathrm{P}^2 \left(1 + 3\,\frac{k^2}{\omega^2}\frac{T}{m_e}\right) \qquad \text{Longitudinal.}$$

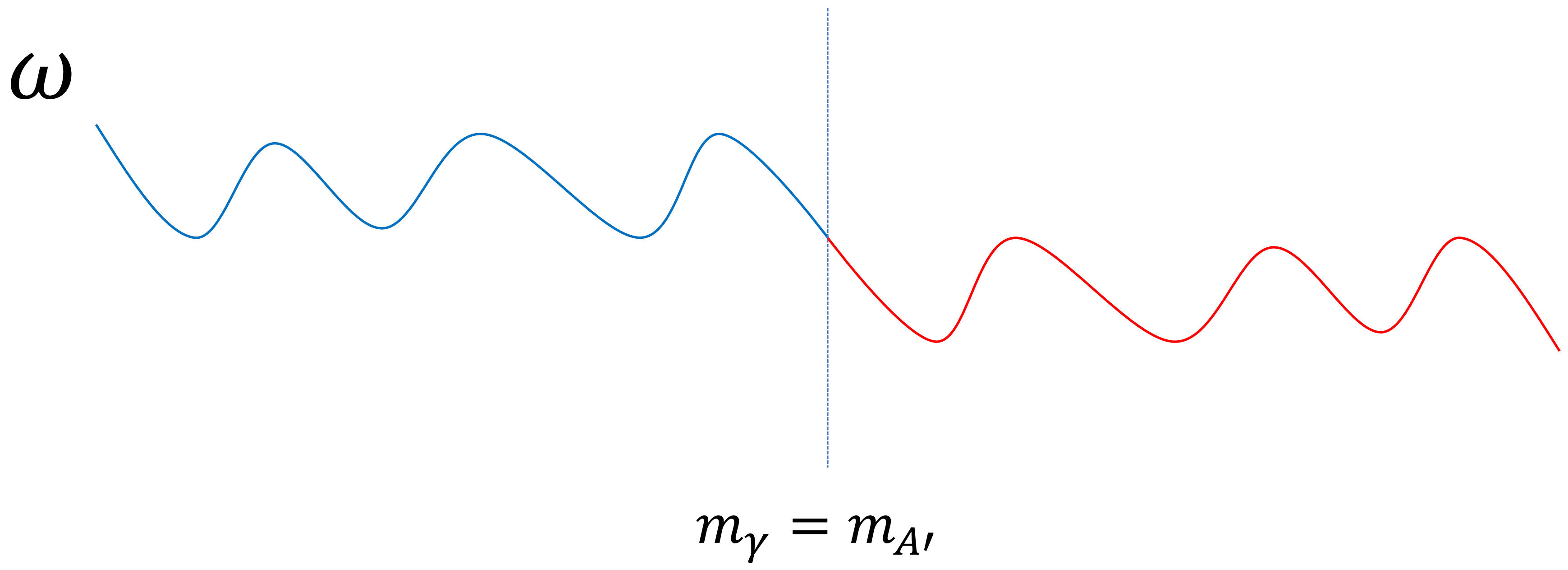
Homogeneous Plasma Mass



In the assumption of homogeneous medium, the photon mass after recombination varies between $10^{-9} and\ 10^{-14} eV$

Resonant Oscillations

T.-K. Kuo & Pantaleone Rev. Mod. Phys. 61 (1989) 937 Mirizzi, Redondo & Sigl 0901.0014 Caputo, HL, Mishra-Sharma & Ruderman 2004.06733



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

Landau-Zener approximation

Resonant Oscillations

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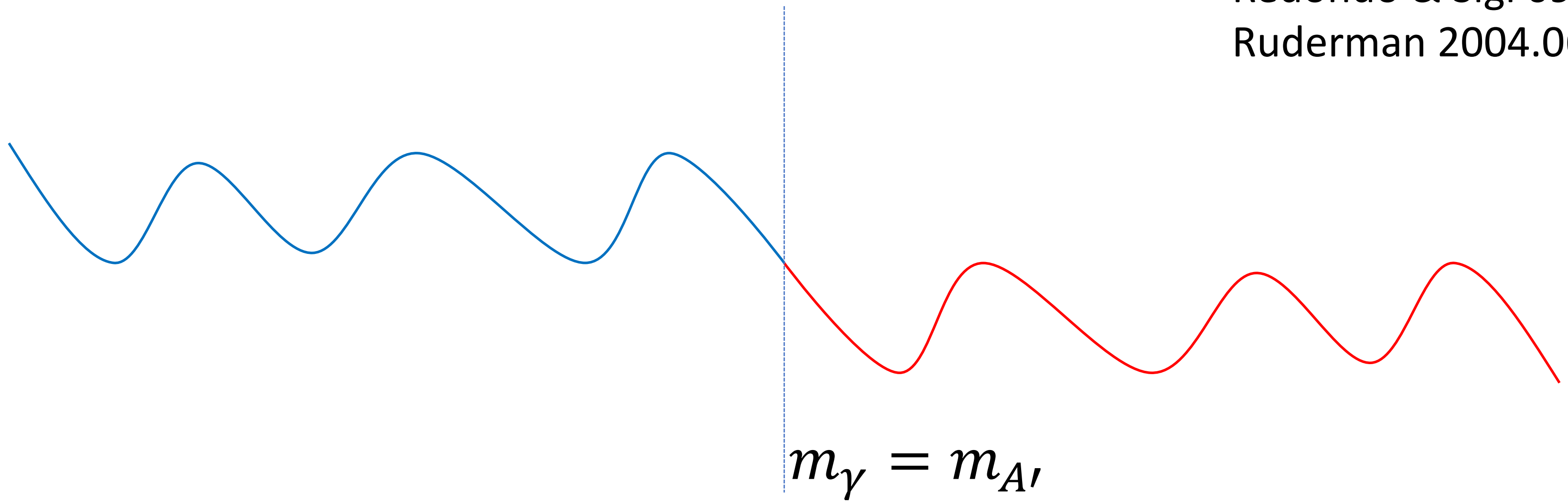


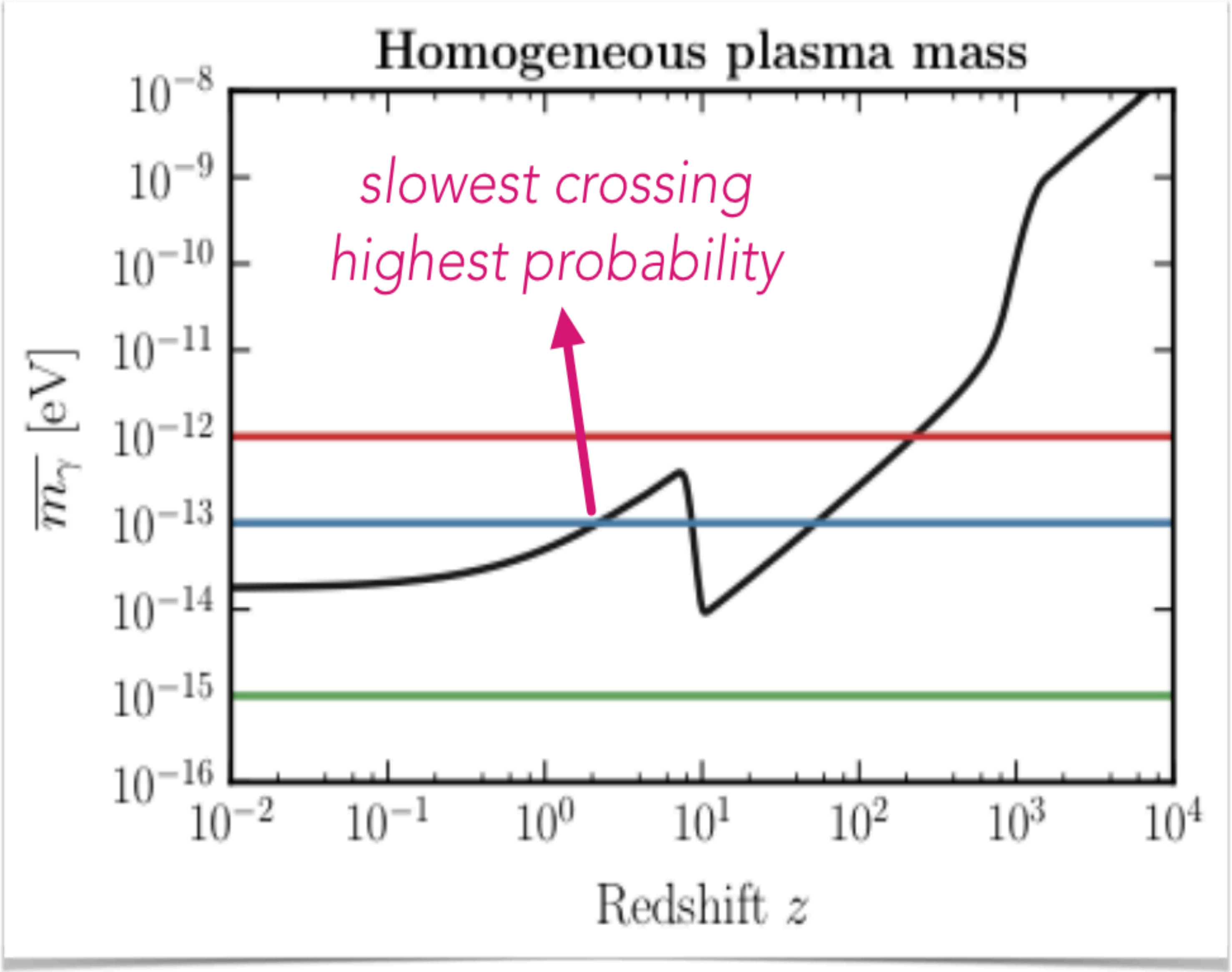
$(\gamma \to A'$ *vacuum oscillation length*$)^{-1}$

mixing

resonance timescale
$\sim H^{-1}$

$$P_{\gamma \to A'} = 2\pi \times \epsilon^2 \times \frac{m_{A'}^2}{2\omega} \times \left| \frac{\mathrm{d} \ln m_\gamma^2}{\mathrm{d}t} \right|^{-1}_{m_\gamma = m_{A'}}$$

You can also have multiple resonances!



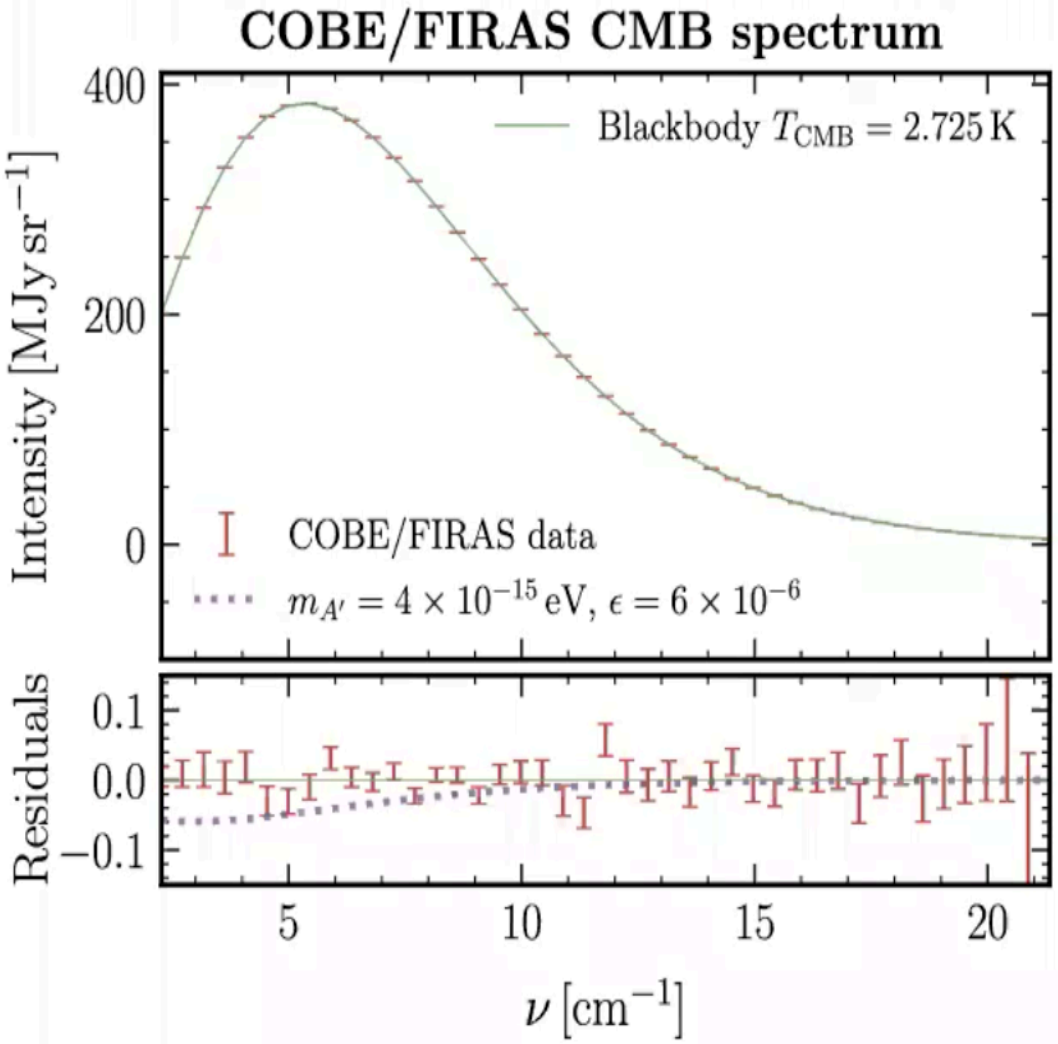
$$P_{\gamma\to A'} = \sum_i \frac{\pi\epsilon^2 m_{A'}^2}{\omega}\left|\frac{\mathrm{d}\ln m_\gamma^2}{\mathrm{d}t}\right|^{-1}_{t_i=t_{\rm res}}$$

1 crossing

3 crossings

0 crossings

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



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

Blackbody spectrum

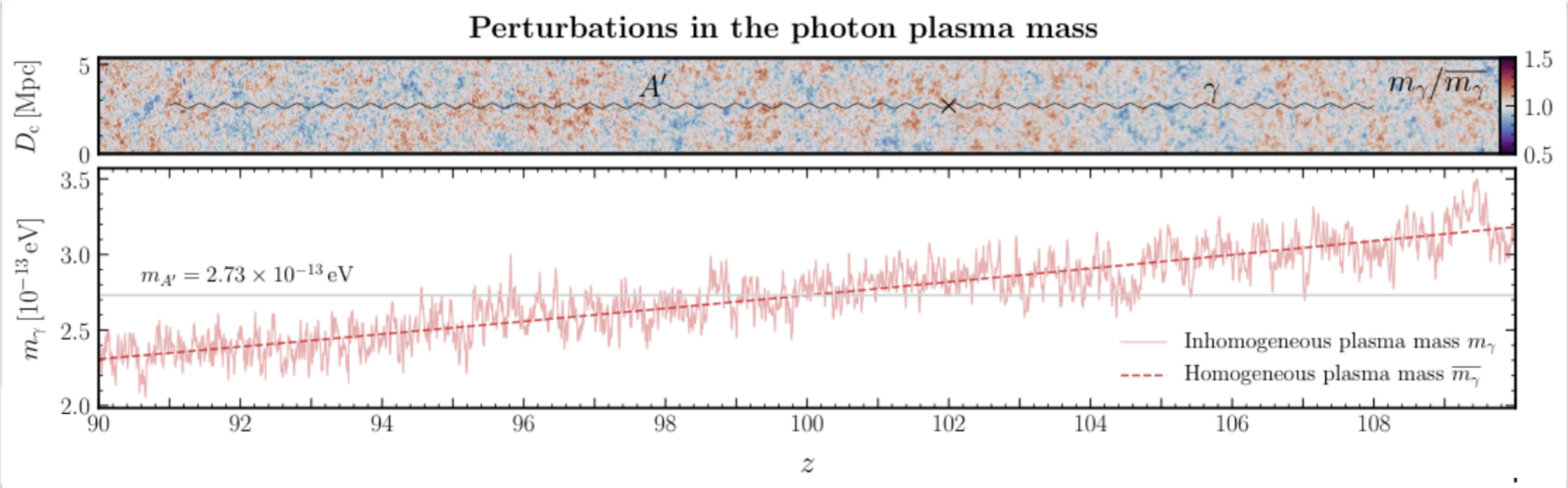
$$B_\omega = \frac{\omega^3}{2\pi^2}\left[\exp\left(\frac{\omega}{T_{\rm CMB}}\right) - 1\right]^{-1}$$

γ disappearance probability

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

Mirizzi, Redondo & Sigl 0901.0014

However there is an important piece missing. The Universe is not homogeneous!



A. Caputo, H. Liu, S. Mishra-Sharma & J. T. Ruderman 2002.05165 and 2004.06733

See also the related works: Bondarenko, Pradler & Sokolenko 2002.08942 A. A. Garcia+ 2003.10465 Witte+ 2003.13698

The analytical formula

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

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

Average over distribution of m_γ^2

(time-dependent) probability density function

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

The analytical formula

$$P_{\gamma\to A'} = \int \mathrm{d}t \, \frac{\pi\epsilon^2 m_{A'}^2}{\omega(t)} \, \delta_D(m_\gamma^2 - m_{A'}^2) \, m_\gamma^2$$

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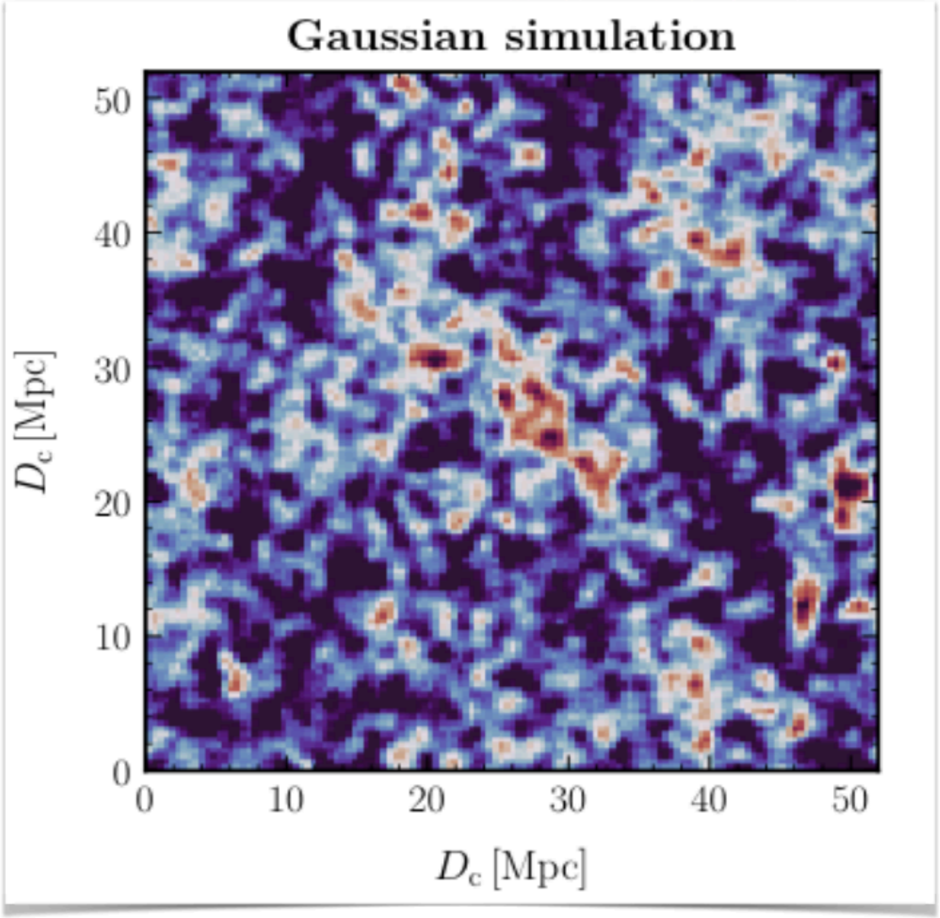
Then integrating over the mass using the delta function

$$\langle P_{\gamma\to A'} \rangle = \int \mathrm{d}t \, f(m_\gamma^2 = m_{A'}^2; t) \, \frac{\pi\epsilon^2 m_{A'}^4}{\omega(t)}$$

The average conversion probability is related the PDF of the plasma mass squared

One point PDF



$$m_\gamma^2 \propto n_e \implies f(m_\gamma^2; t) \propto \mathscr{P}(\delta_b; t)$$

one-point PDF of baryon fluctuations

$$\delta_b \equiv \frac{\rho_b - \overline{\rho_b}}{\overline{\rho_b}}$$

m_γ^2 fluctuations directly related to **baryon density** fluctuations, a well-defined **cosmological parameter**.

For example in the Gaussian case (z > 20) we would have

$$\mathscr{P}(\delta_b; z) = \frac{1}{\sqrt{2\pi\sigma_b^2(z)}} \exp\left(-\frac{\delta_b^2}{2\sigma_b^2(z)}\right)$$

Alternative PDF prescriptions

Log-normal PDF

Log-normal PDF with nonlinear baryon power spectrum

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

"Analytic" PDF

Non-linear spherical collapse of linear matter field

Ivanov, Kaurov, Sibiryakov [1811.07913]

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

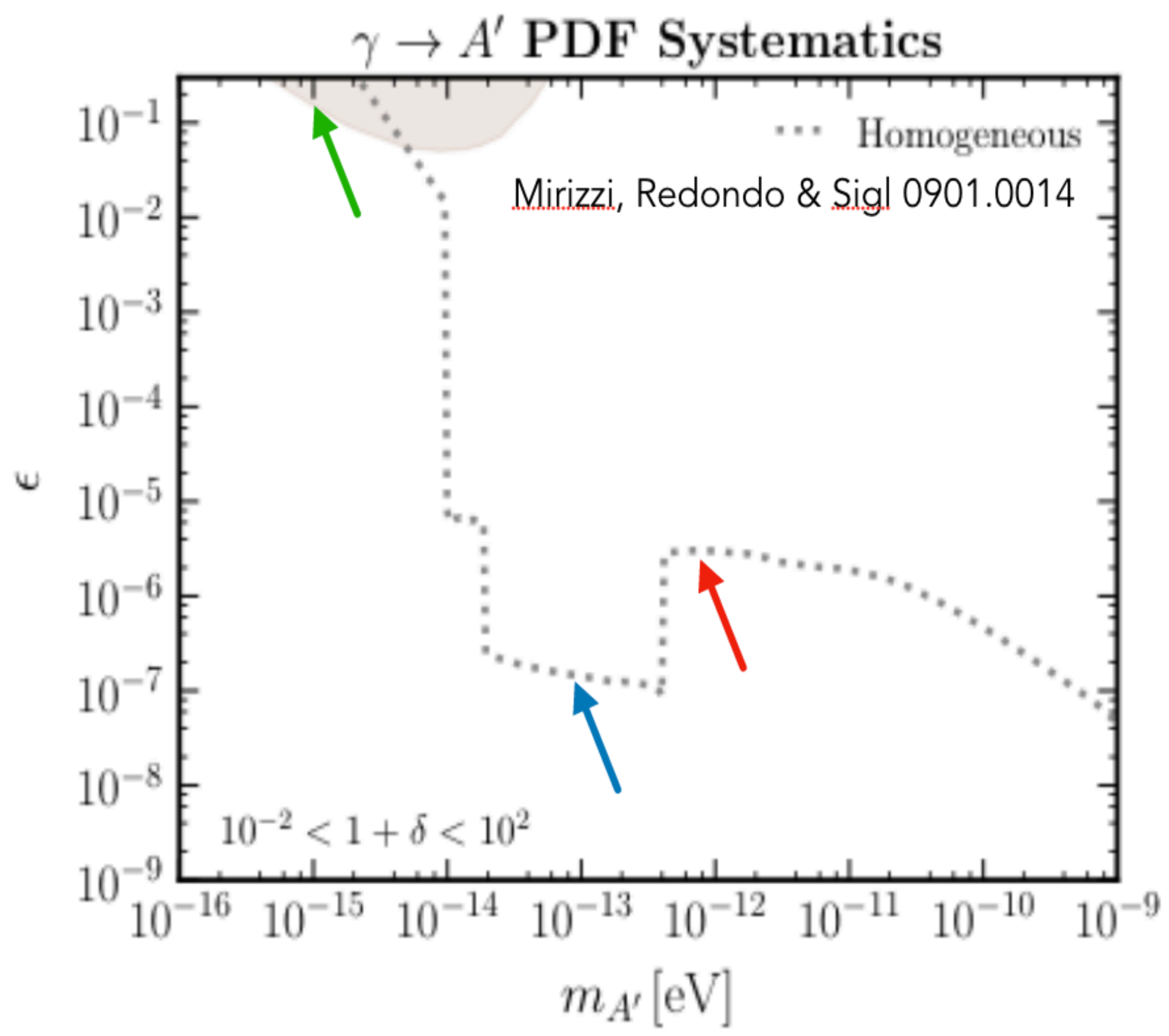
Cosmic voids PDF

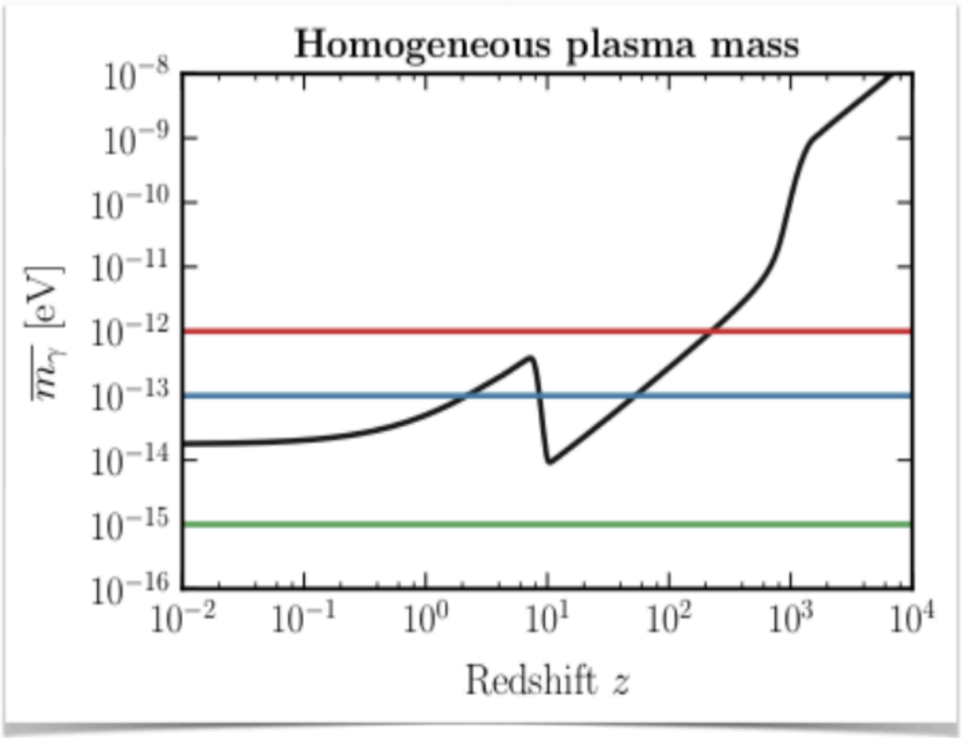
PDF of matter underdensities

Adermann et al [1703.04885, 1807.02938]

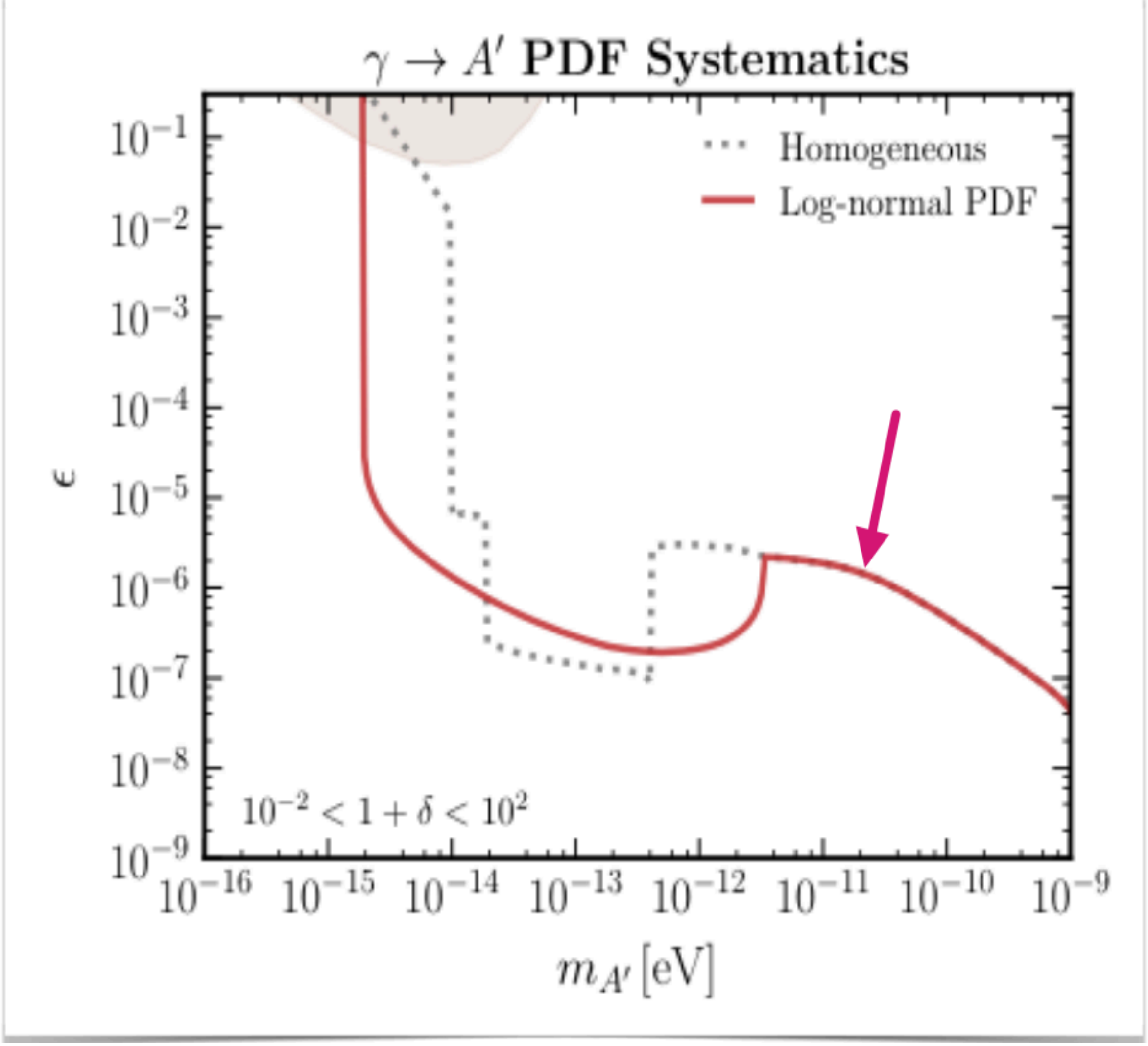
$$\mathscr{P}_{\rm voids}\left(\delta_{\rm b};z\right)\sim\text{from simulations}$$

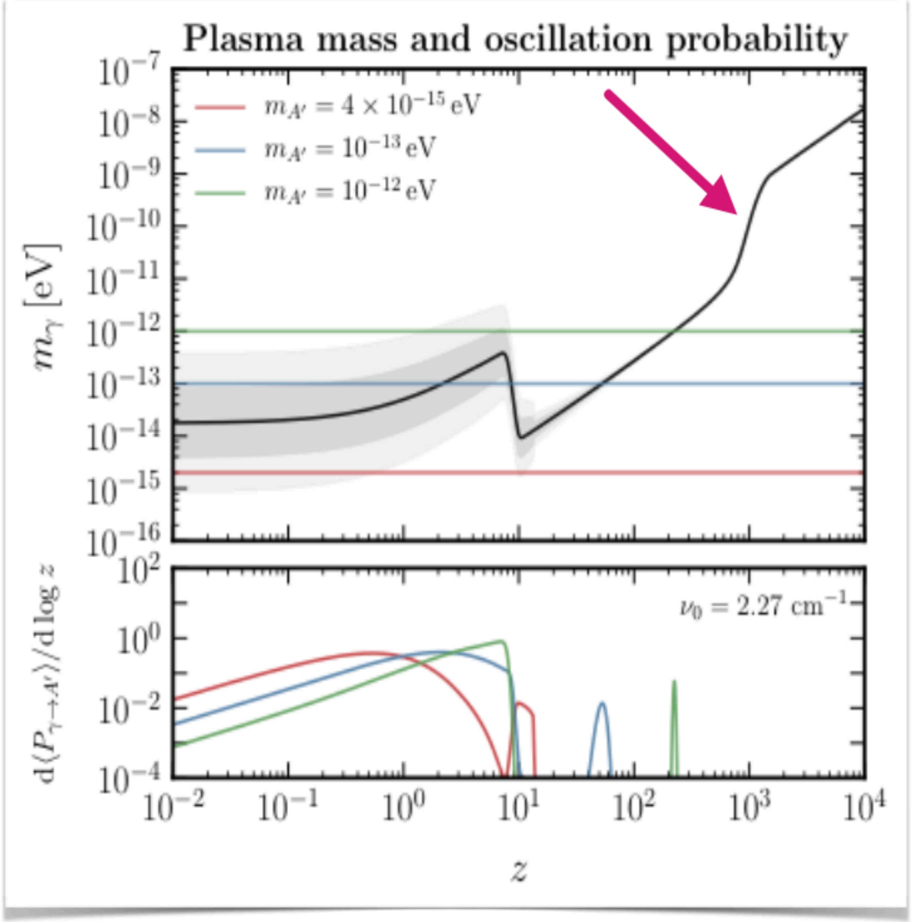
CMB Constraints





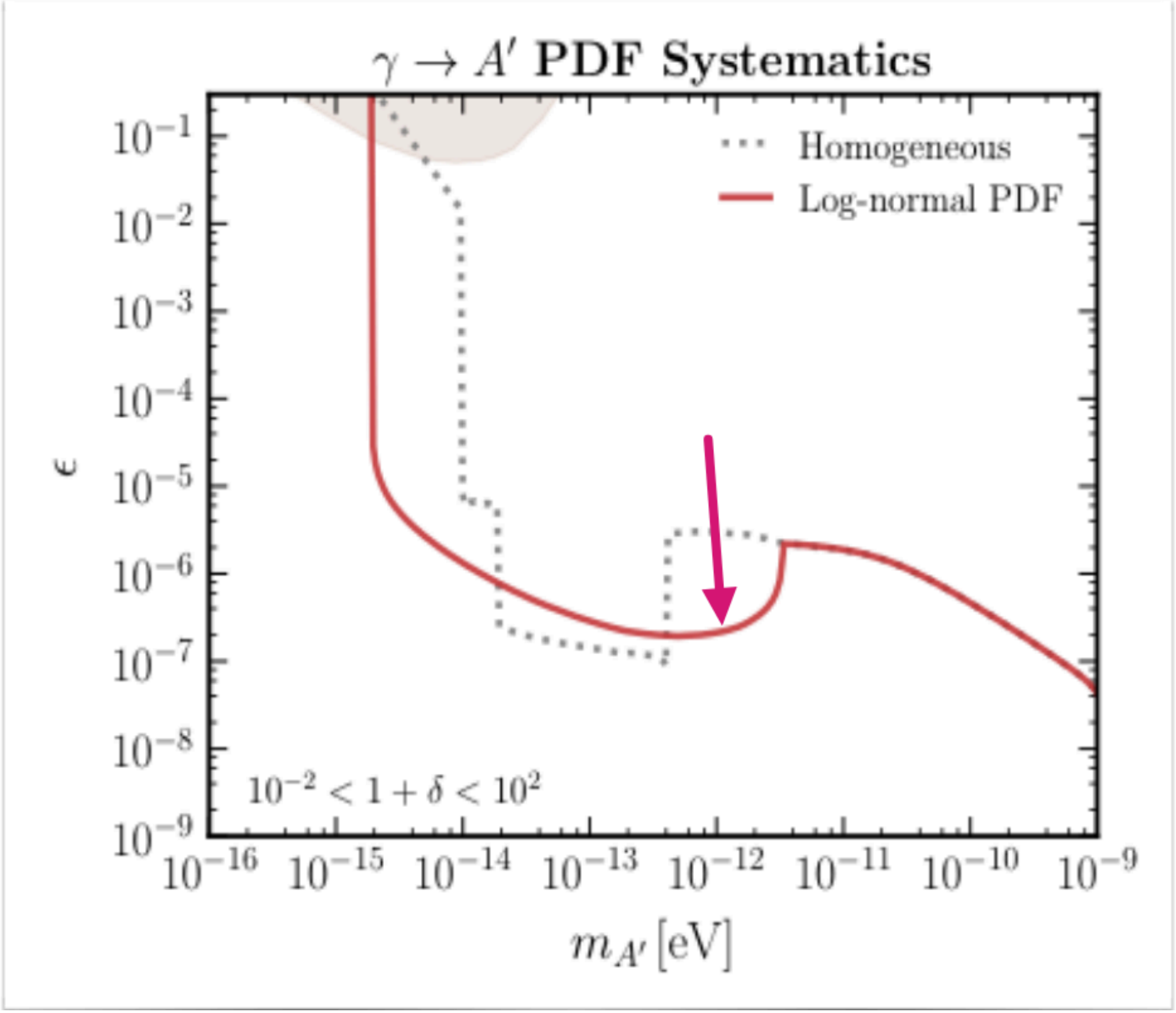
CMB Constraints

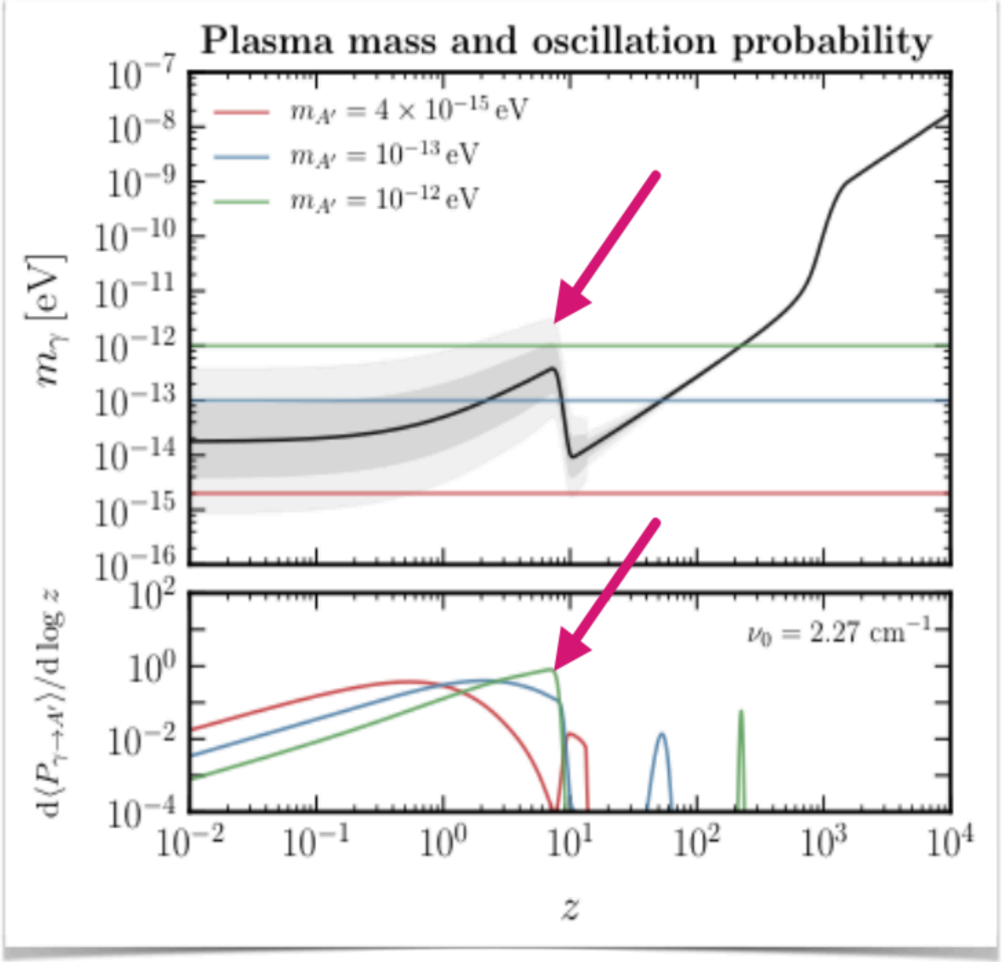




Small fluctuations at high redshift: similar to the homogeneous case

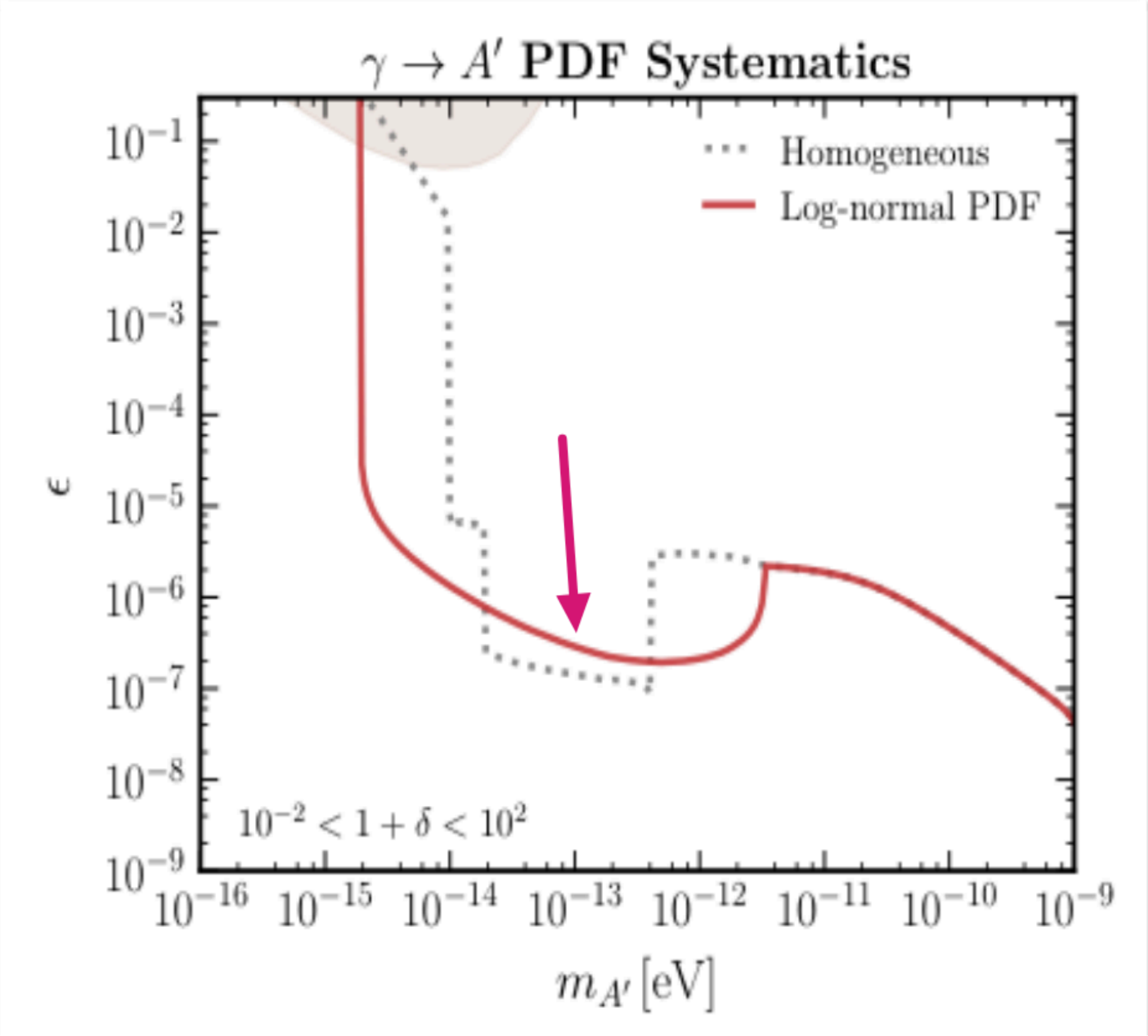
CMB Constraints

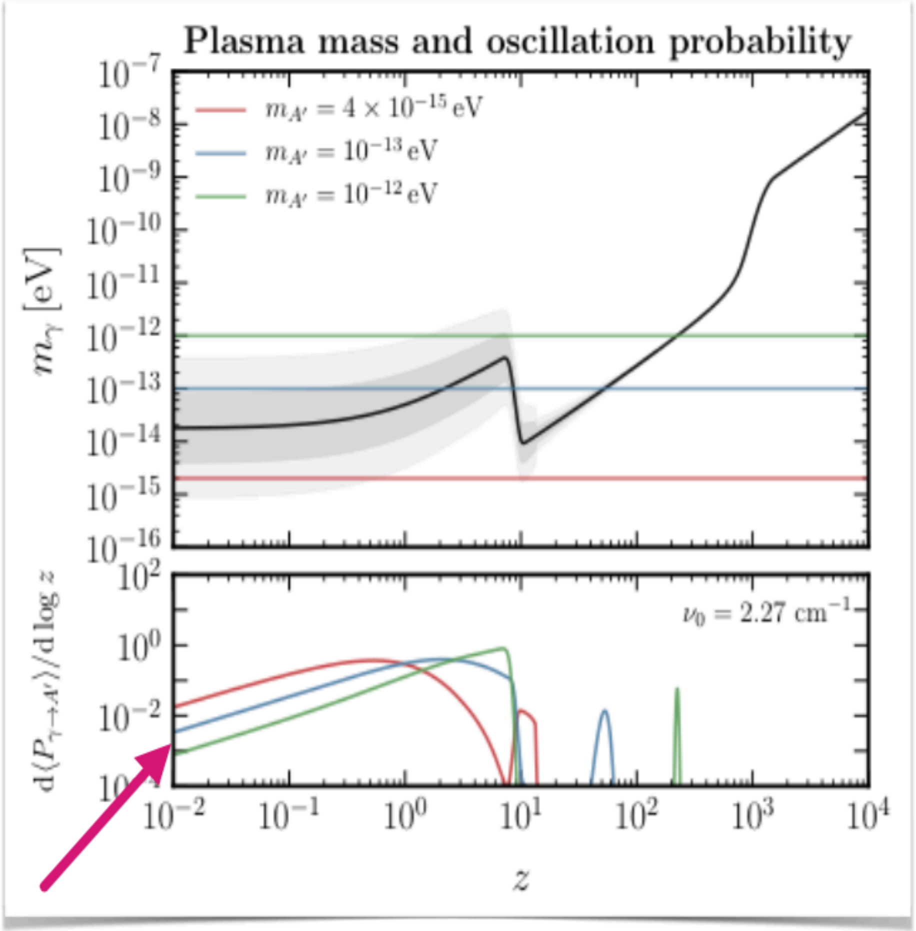




Later conversions available

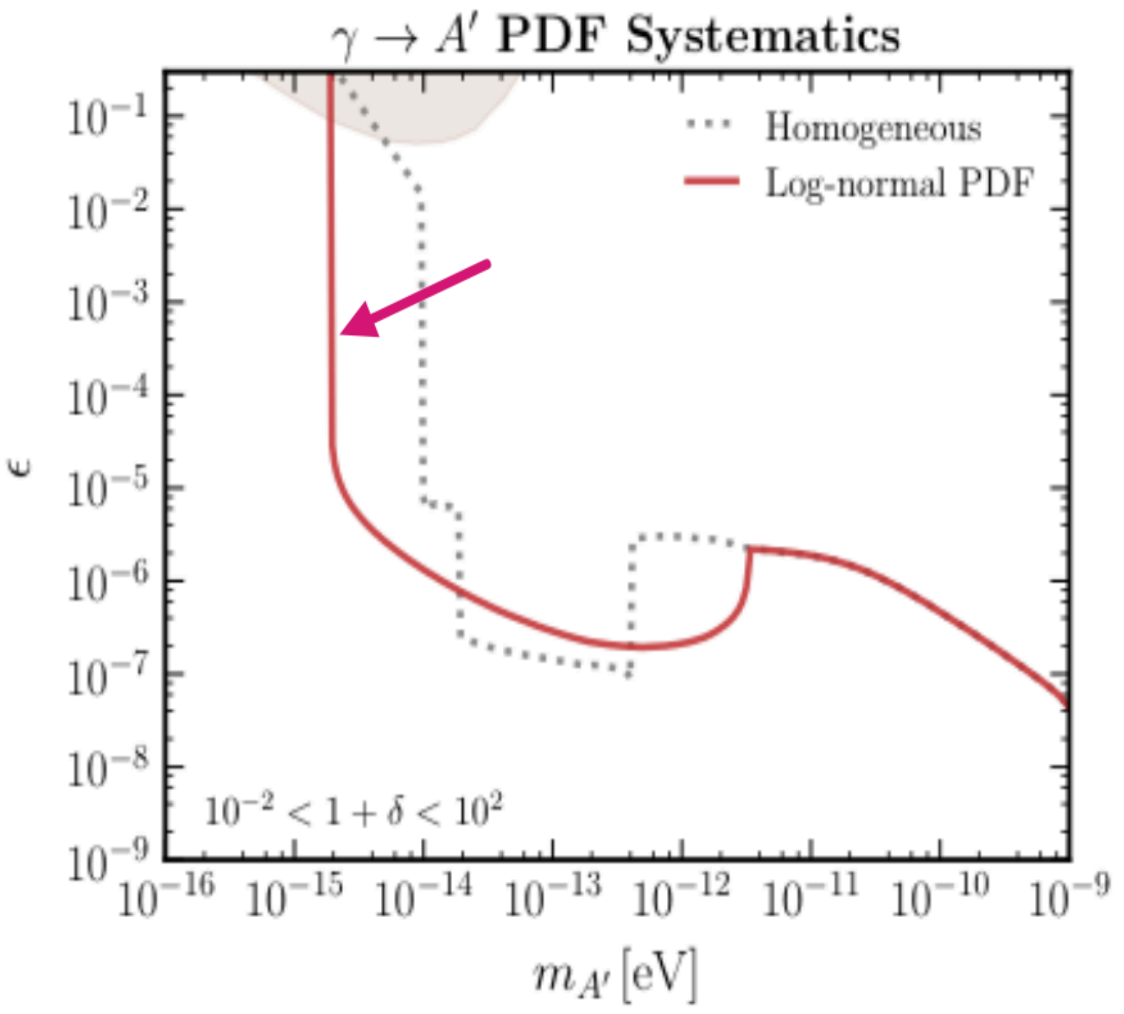
CMB Constraints

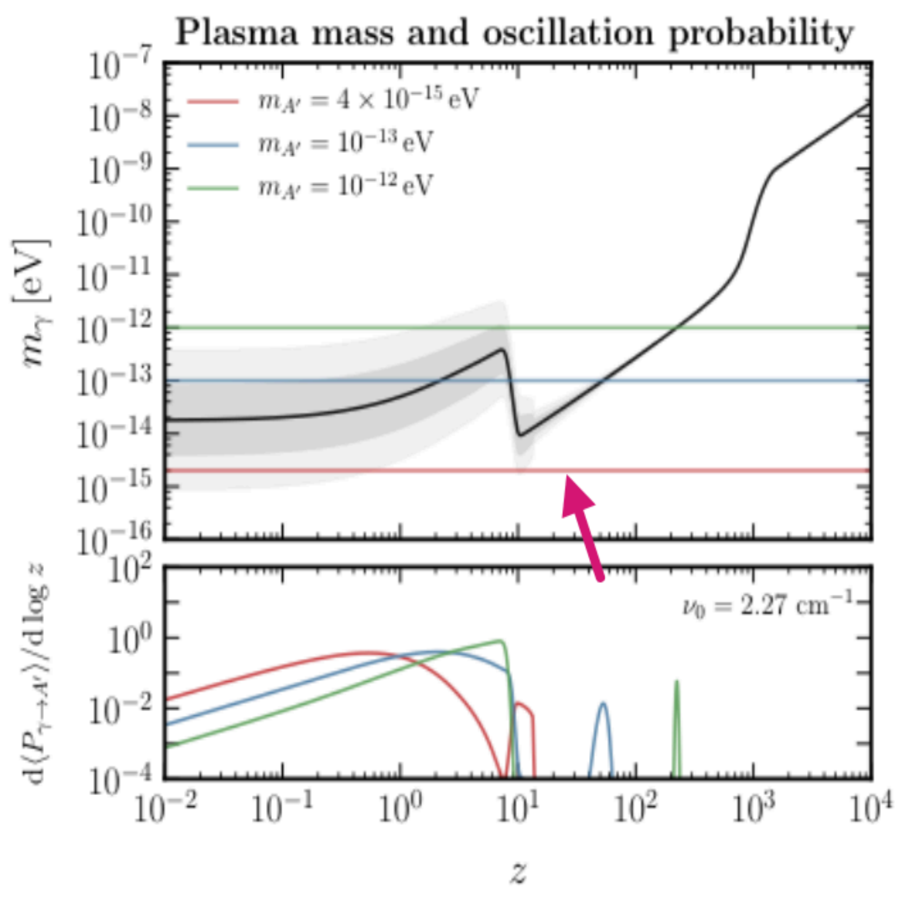




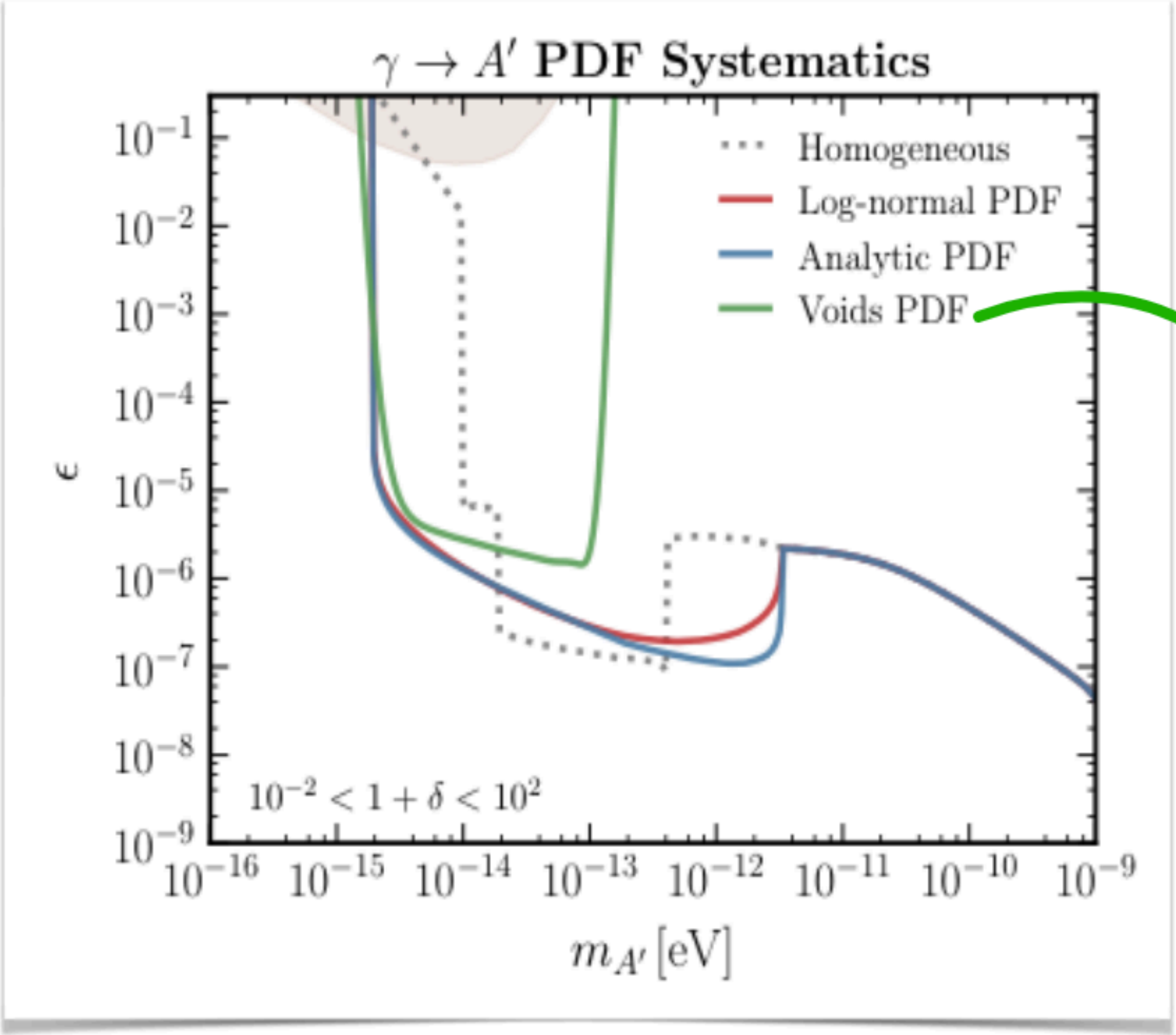
Constraints weakened here, as some conversion probability is in the future

CMB Constraints





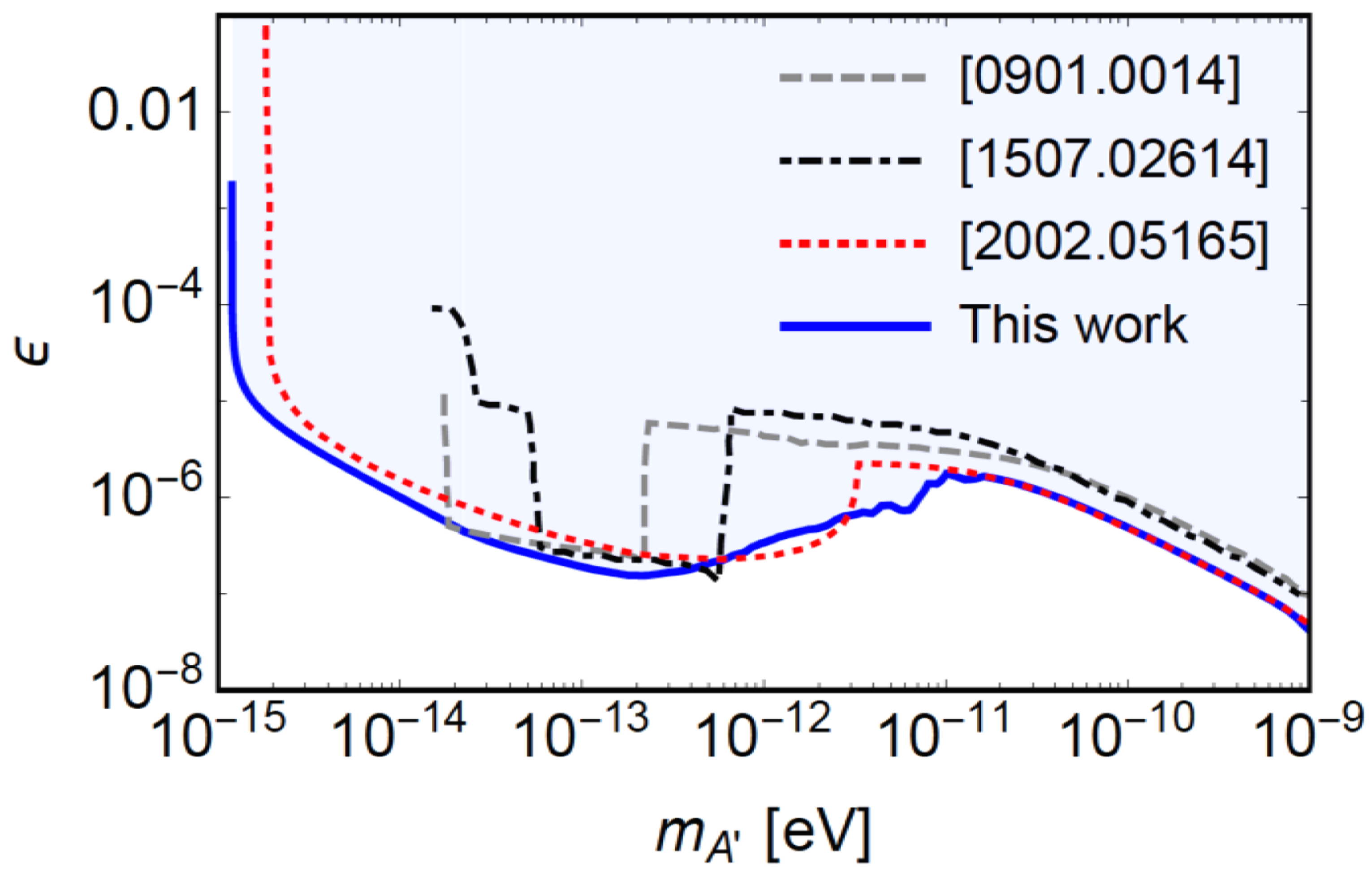
Limits extend to lower masses because of under-fluctuations



check for underdensities

E. Adermann et al, (2018)

Comparison with numerical approach



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

Conclusions

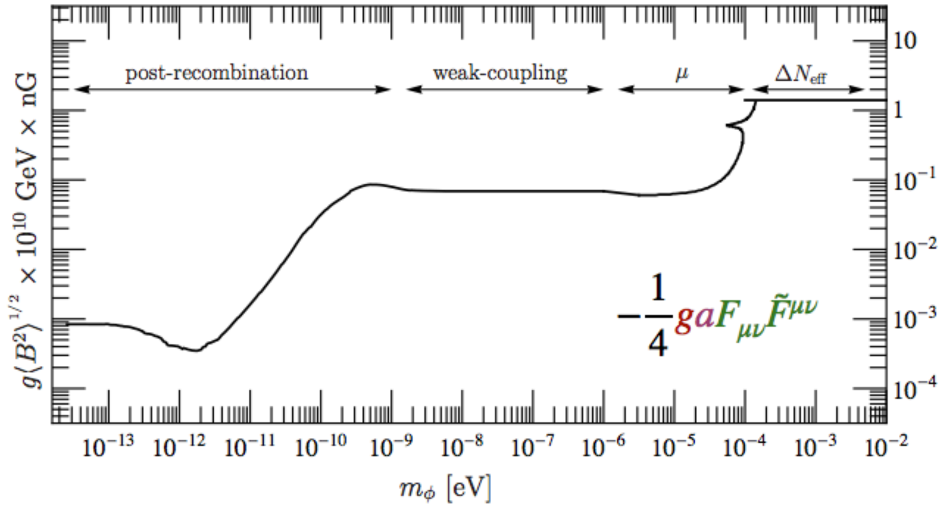
- The interplay between particle physics, astrophysics and cosmology is crucial;
- CMB for example can put strong constraints on dark photon models; for these is of particular importance to treat universe inhomogeneities!
  We provide a simple analytical recipe to do so

Thanks for the attention!

Backup slides

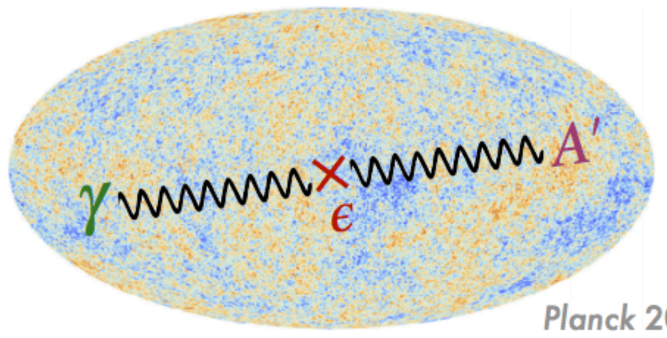
Work in Progress

Implications for axion-like particles

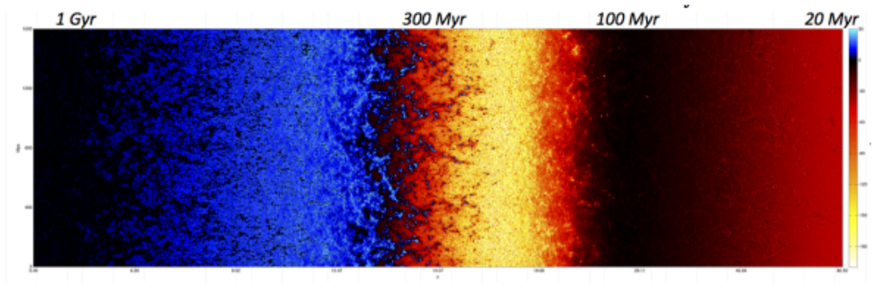


Mirizzi, Redondo, Sigl [0905.4865]

Effect on CMB and 21-cm anisotropy



Planck 2018



Messinger, Greig, Sobacchi [1602.07711]

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

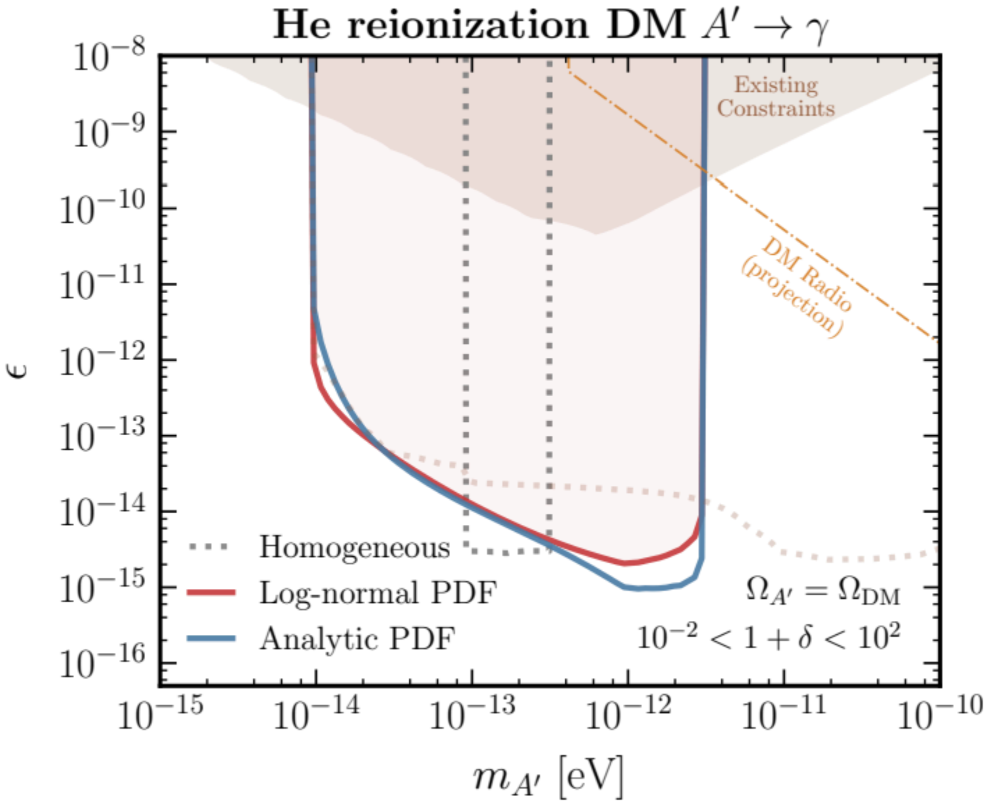
$A' \to \gamma$

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

Statistical Analysis

We construct a Gaussian log-likelihood as

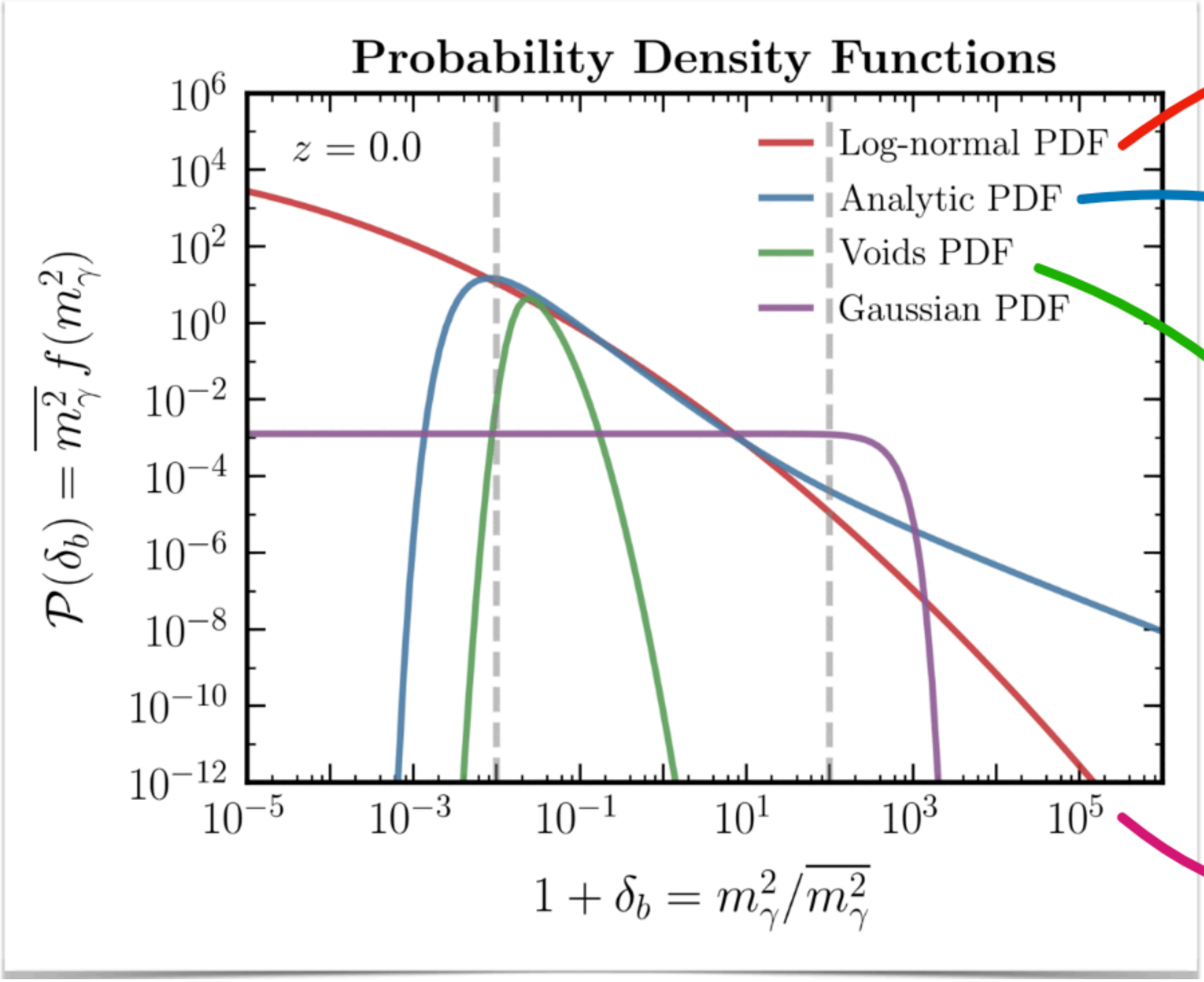
$$\ln \mathcal{L}(d|m_{A'}, \epsilon) = \max_{T_{\mathrm{CMB}}} \left[-\frac{1}{2} \Delta \vec{I}^T \, \mathsf{C}_{I_d}^{-1} \, \Delta \vec{I} \right], \qquad \text{(A2)}$$

where $\Delta \vec{I} = \left(\vec{I}(m_{A'}, \epsilon; T_{\mathrm{CMB}}) - \vec{I}_d \right)$ is the residual between the distorted CMB spectrum $\vec{I}(m_{A'}, \epsilon; T_{\mathrm{CMB}}) = \{I_{\omega_1}, I_{\omega_2}, \ldots\}$ and the FIRAS data vector $\vec{I}_d$, and C_{I_d} is the data covariance matrix. We treat the CMB temperature as a nuisance parameter and profile over it by maximizing the log-likelihood for T_{CMB} at each $\{m_{A'}, \epsilon\}$ point. We define our test-statistic as

$$\mathrm{TS}(m_{A'}, \epsilon) = 2 \left[\ln \mathcal{L}(d|m_{A'}, \epsilon) - \ln \mathcal{L}(d|m_{A'}, \hat{\epsilon}) \right], \qquad \text{(A3)}$$

where $\hat{\epsilon}$ is the value of ϵ that maximizes the log-likelihood for a given $m_{A'}$, and obtain our limit by finding the value of ϵ at which $\mathrm{TS} = -2.71$ corresponding to 95% containment for the one-sided χ^2 distribution.

PDF Functional Form



phenomenological

theoretically motivated PDF from first principles

Ivanov, Kaurov & Sibiryakov 1811.07913

fiducial

from simulations of voids: useful for underdensities

good agreement between fiducial for $10^{-2} \leq 1 + \delta_b \leq 10^2$.