Shaping Dark Photon Spectral Distortions

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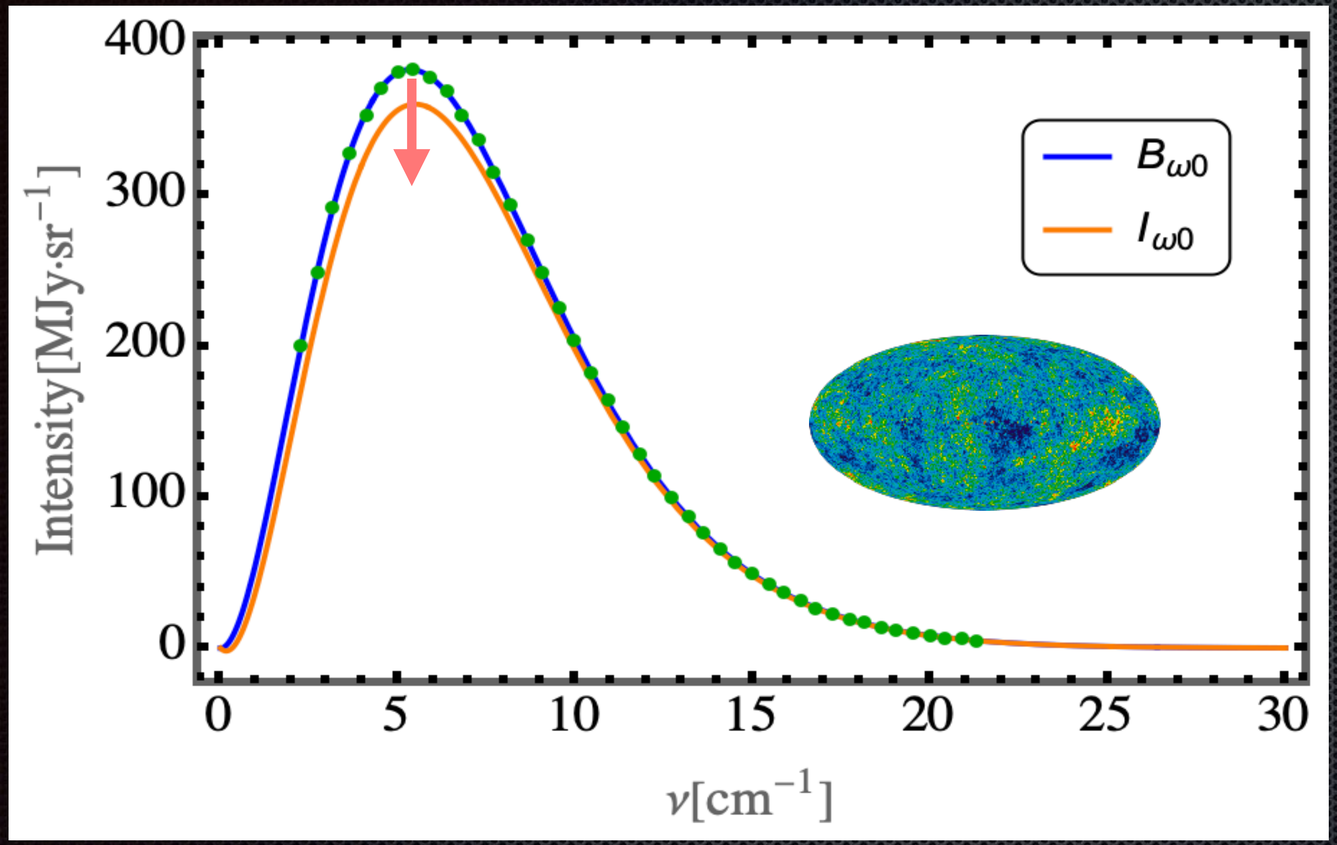
240X.XXXXX

Collaborators:

Giorgi Arsenadze, Andrea Caputo, Hongwan Liu, Joshua Ruderman

CMB Spectral Distortion



CMB is blackbody

Any process remove or inject photons

$\chi + \chi \rightarrow \mathrm{SM} + \mathrm{SM}$

$\gamma \rightarrow A'$

Why the Dark Photon ?

LHC Measurement

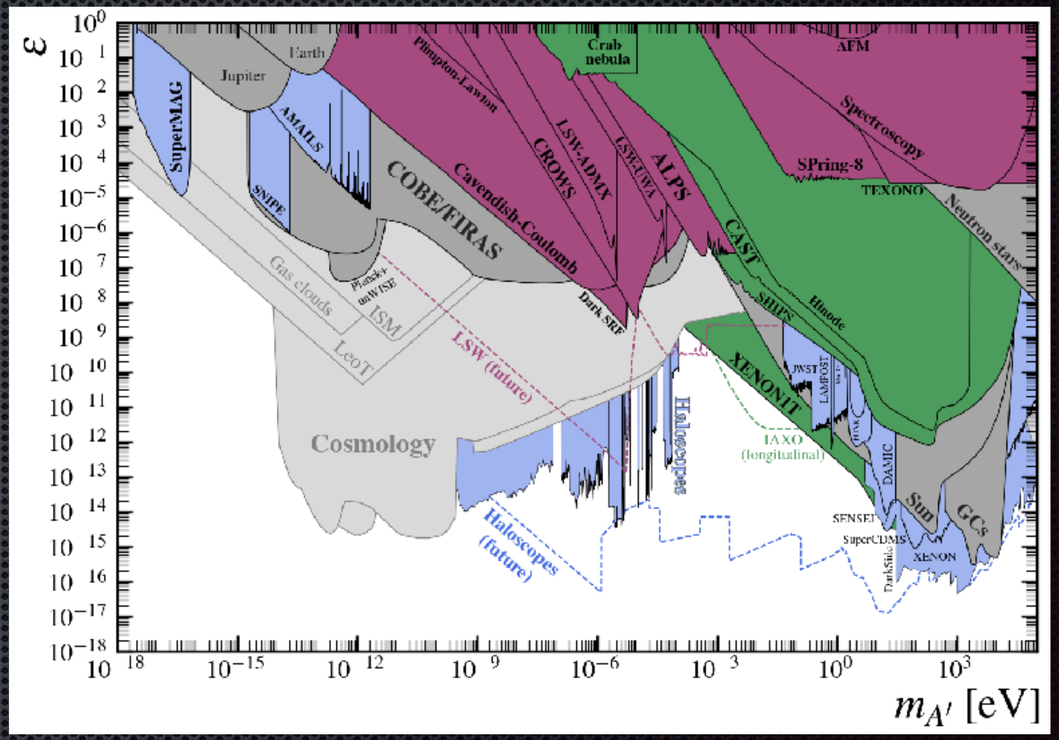
$m_{\Psi,\Psi'} > 100\,GeV$

TeVPA!!!

Bob Holdom 1985

Why the Dark Photon ?

Bob Holdom 1985

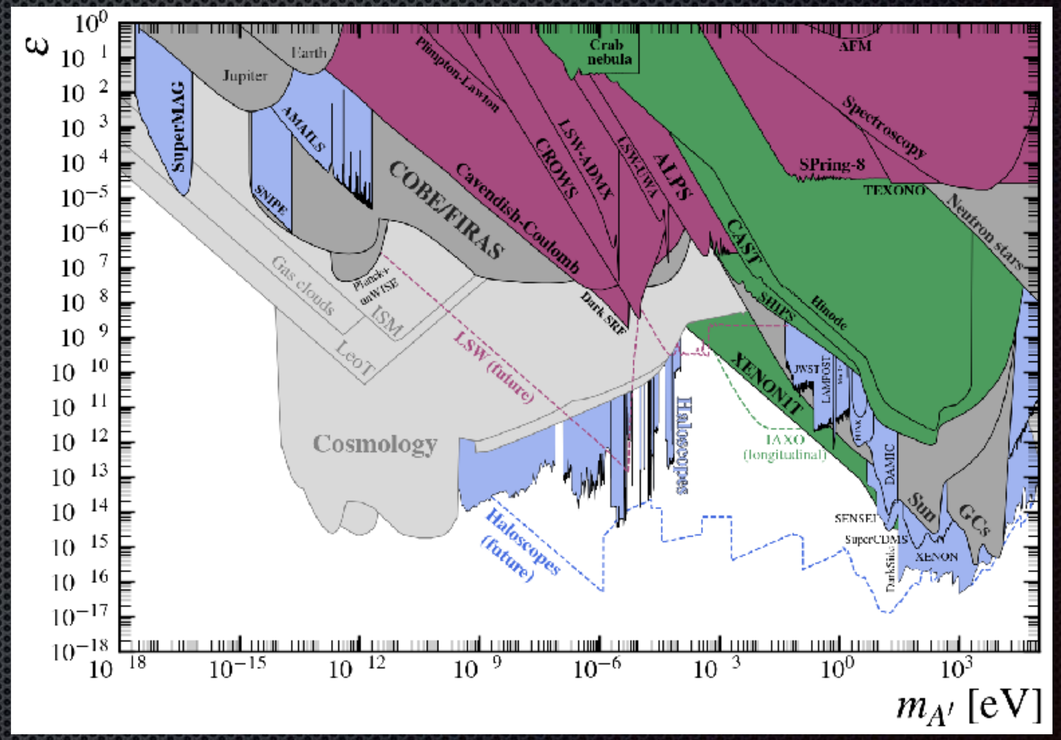


Dark Photon Limit Website

Why the Dark Photon ?

Atomic clock,
EP test,…

$$\mathscr{L} \supset \frac{1}{2}\frac{\phi}{\Lambda} FF'$$

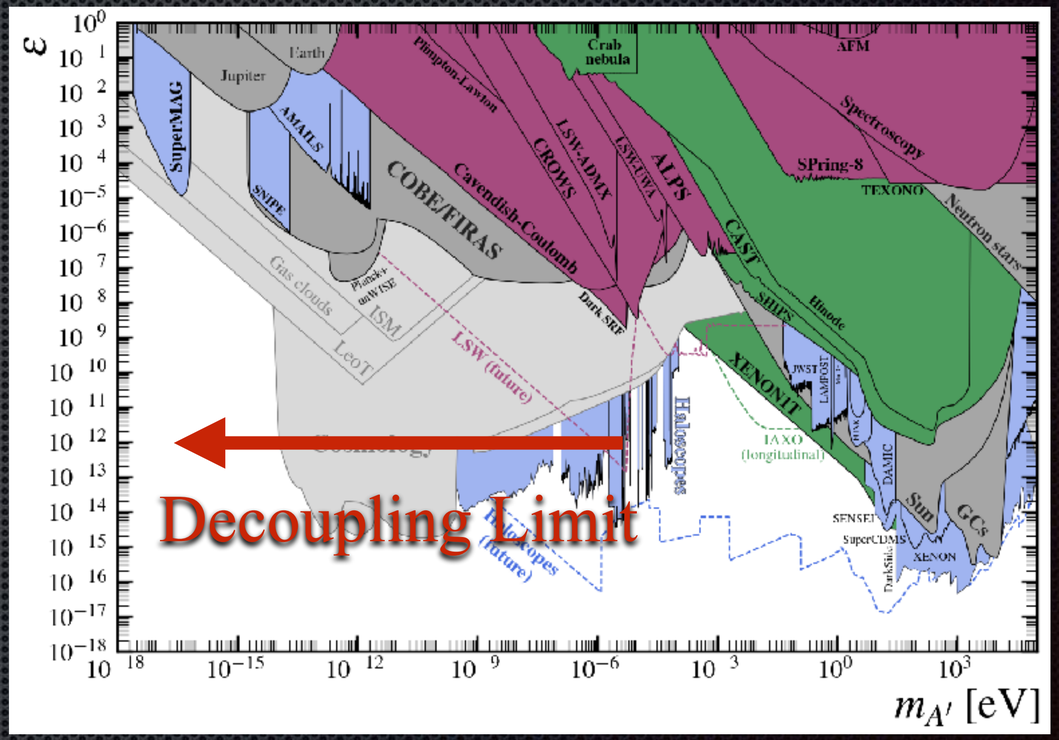


Dark Photon Limit Website

Xucheng Gan, Di Liu 2023
arXiv. 2302.03056

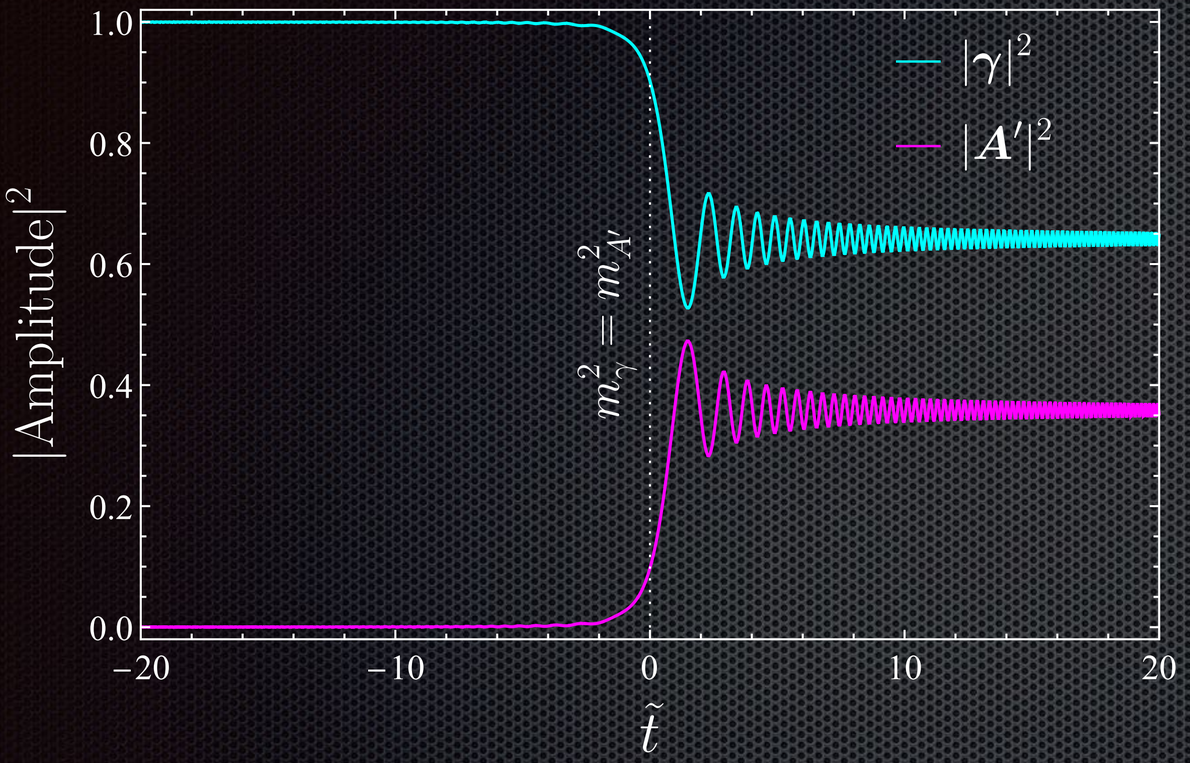
Why CMB Spectral Distortion ?

Bob Holdom 1985

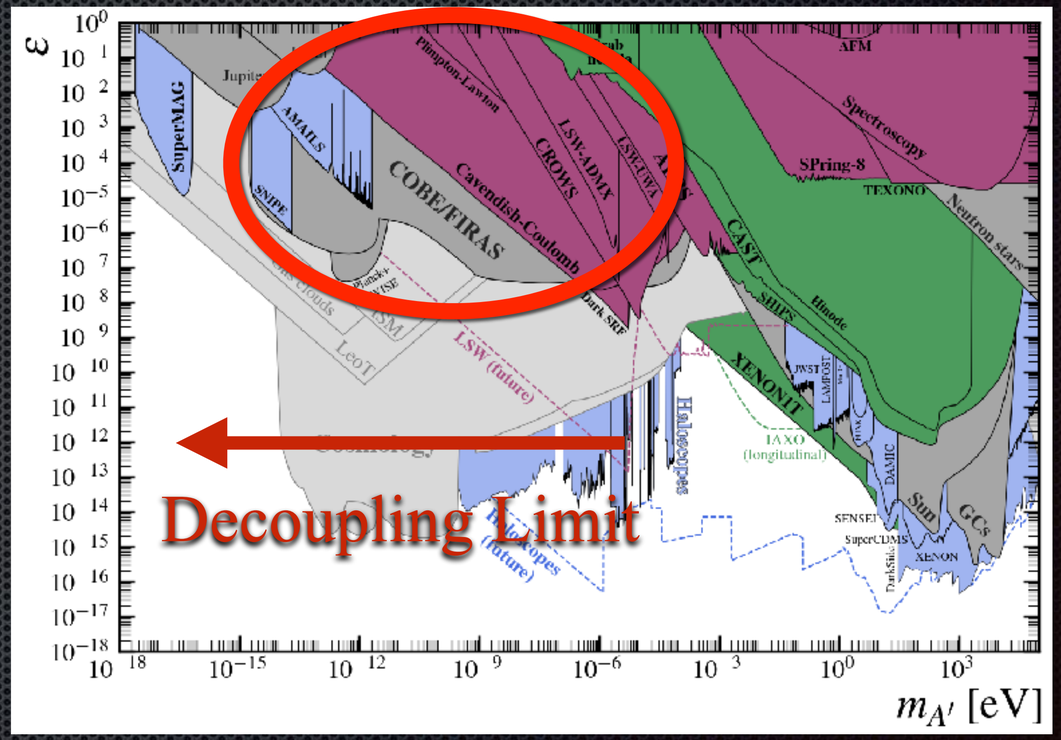


Dark Photon Limit Website

Why CMB Spectral Distortion ?



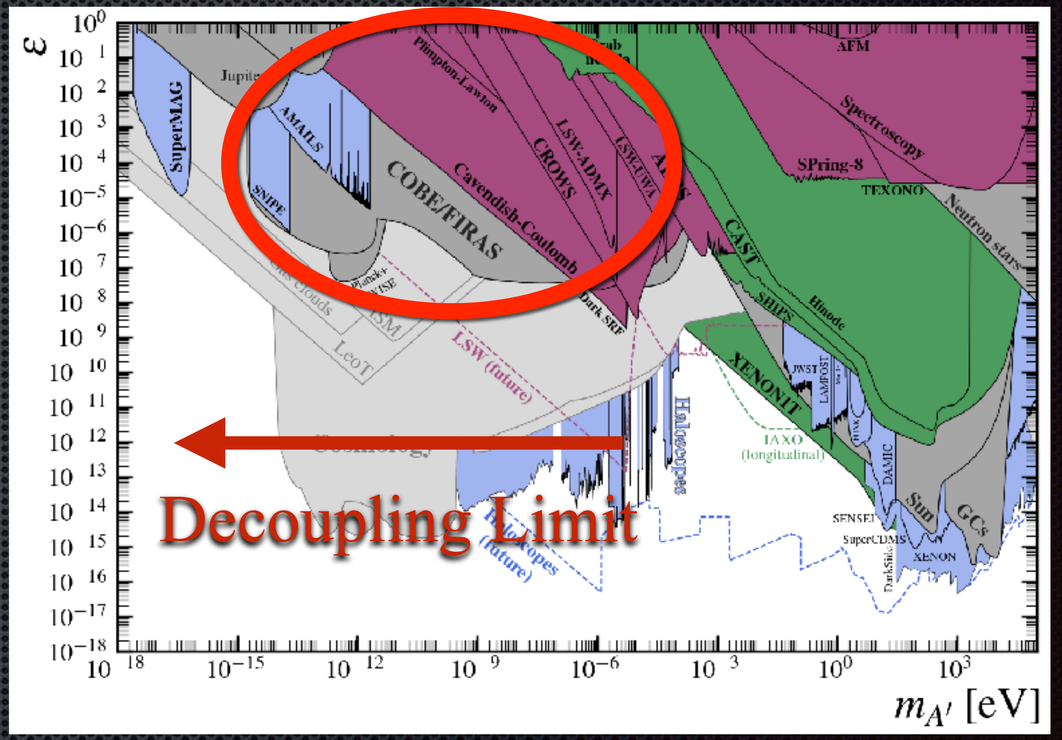
Berlin, Dror, **Xucheng Gan**, Ruderman 2022



Dark Photon Limit Website

Why CMB Spectral Distortion ?

CMB spectral distortion is currently the most sensitive test for the dark photon with $10^{-15}\text{eV} \lesssim m_{A'} \lesssim 10^{-3}\text{eV}$.



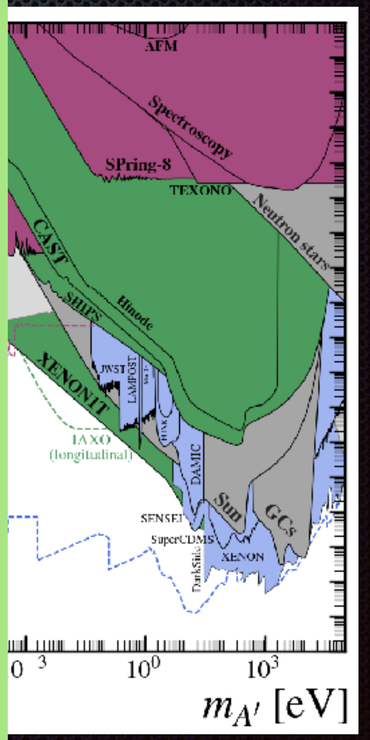
Dark Photon Limit Website

Why CMB Spectral Distortion ?

CMB sp
currentl
test for t
with 10⁻

Questions:

1. What's the correct formalism?
2. What's the correct constraint?
3. What's the correct smoking gun?



Dark Photon Limit Website

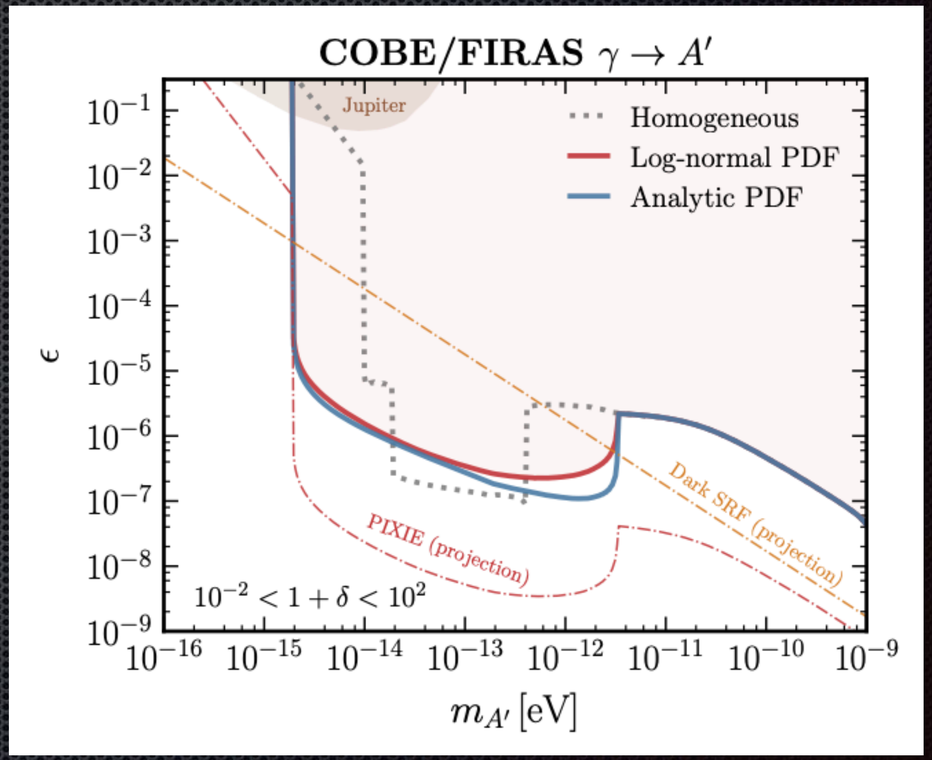
Previous Treatments

$$I(\nu) = \bar{I}_0(\nu) \cdot (1 - P_{\gamma \to A'})$$

Mirrizi, Redondo, Sigl 2008

Caputo, Liu, Mishra-Sharma, Ruderman 2020

Works perfectly in low redshift



Caputo, Liu, Mishra-Sharma, Ruderman 2020

Previous Treatments

$$I(\nu) = \bar{I}_0(\nu) \cdot (1 - P_{\gamma \to A'})$$

Mirrizi, Redondo, Sigl 2008

Caputo, Liu, Mishra-Sharma, Ruderman 2020

High redshift

Compton Scattering

$$e^- + \gamma \leftrightarrow e^- + \gamma$$

Double Compton Scattering

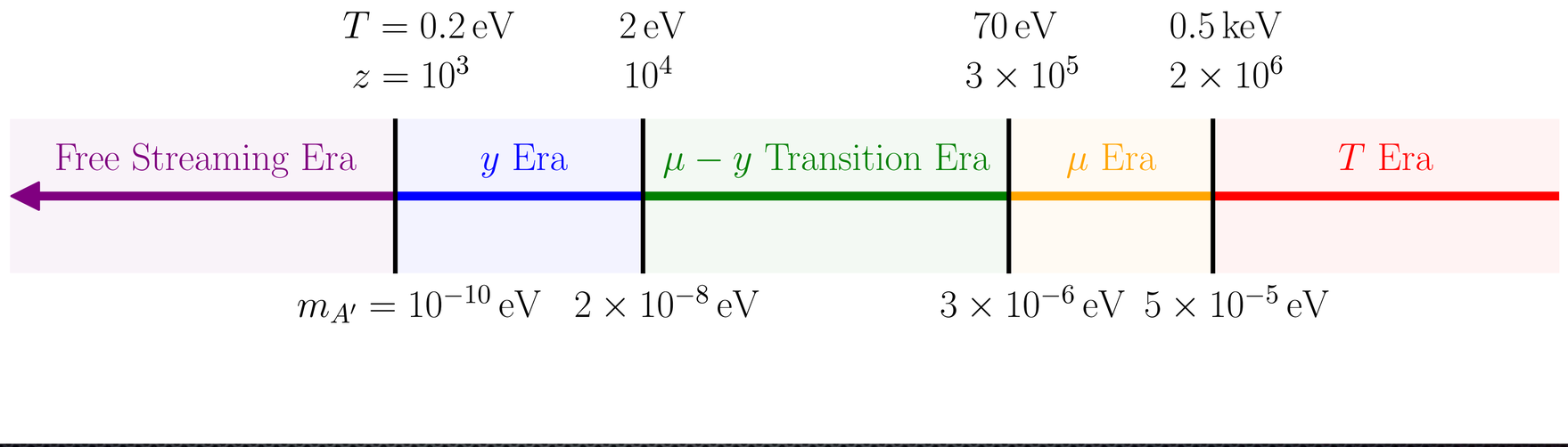
$$e^- + \gamma \leftrightarrow e^- + \gamma + \gamma$$

Bremsstrahlung

$$e^- + X \leftrightarrow e^- + X + \gamma$$

Previous Treatments

Compton Scattering



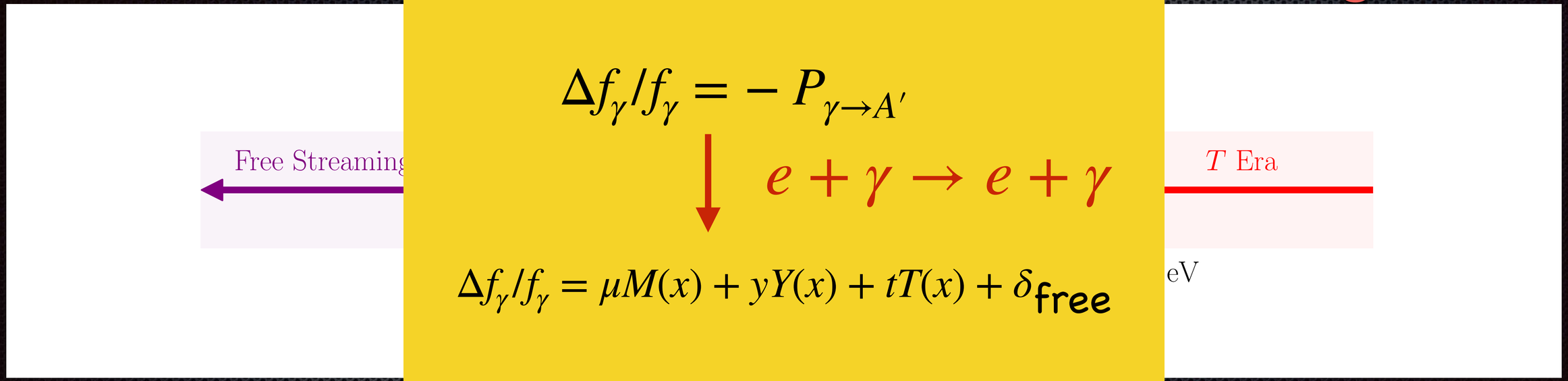
Ca

High redshift

Bremsstrahlung

$e^- + X \leftrightarrow e^- + X + \gamma$

Previous Treatments



$$\Delta f_\gamma / f_\gamma = -P_{\gamma \to A'}$$

$$e + \gamma \to e + \gamma$$

$$\Delta f_\gamma / f_\gamma = \mu M(x) + y Y(x) + t T(x) + \delta_{\text{free}}$$

Previous Treatments

Recast $|\mu|$ and $|y|$ with

$$\Delta I_\gamma(x; T_0) = \int dz'\, G^{th}(x', z'; T_0) \frac{d(Q/\overline{\rho}_\gamma)}{dz'}$$

McDermott, Witte 2019

Dark Photon Limit Website

$\gamma \to A'$ is **NOT** thermalized energy injection ($P_s \to 0$)

We need self-consistent treatment of $\mu - y$ Transition Era

Our Treatments

Thermalized Energy Removal

$P_s = 0$

$$\Delta I_\gamma(x; T_0) = \int dz'\, G^{th}(x', z'; T_0) \frac{d(Q/\bar{\rho}_\gamma)}{dz'}$$

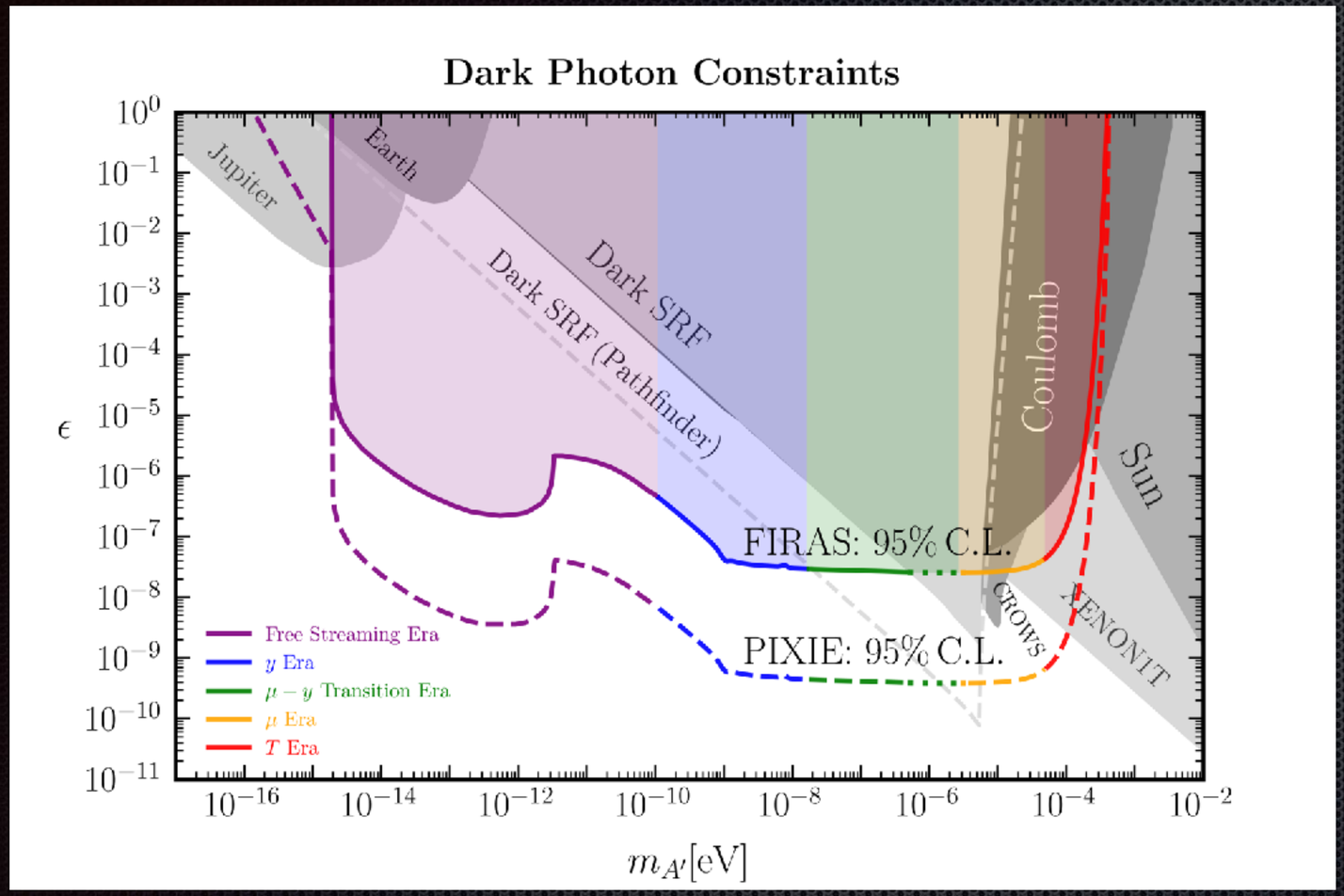
Photon Removal

$P_s = 1$

$$\Delta I_\gamma(x; T_0) = \int dx' \int dz'\, G(x; x', z'; T_0)\, \mathcal{S}(x', z')$$

$$\mathcal{S}(x', z') = \frac{1}{\bar{n}_\gamma} \frac{d\bar{n}_\gamma}{dx'} \frac{\Gamma_{\gamma \to A'}(z')}{(1+z')H(z')}$$

Dark Photon COBE-FIRAS Bound



$z < 10^3$ Free Streaming Era

$10^3 < z < 10^4$ y Era

$10^4 < z < 3 \times 10^5$ $\mu - y$ Era

$3 \times 10^5 < z < 2 \times 10^6$ μ Era

$z > 2 \times 10^6$ T Era

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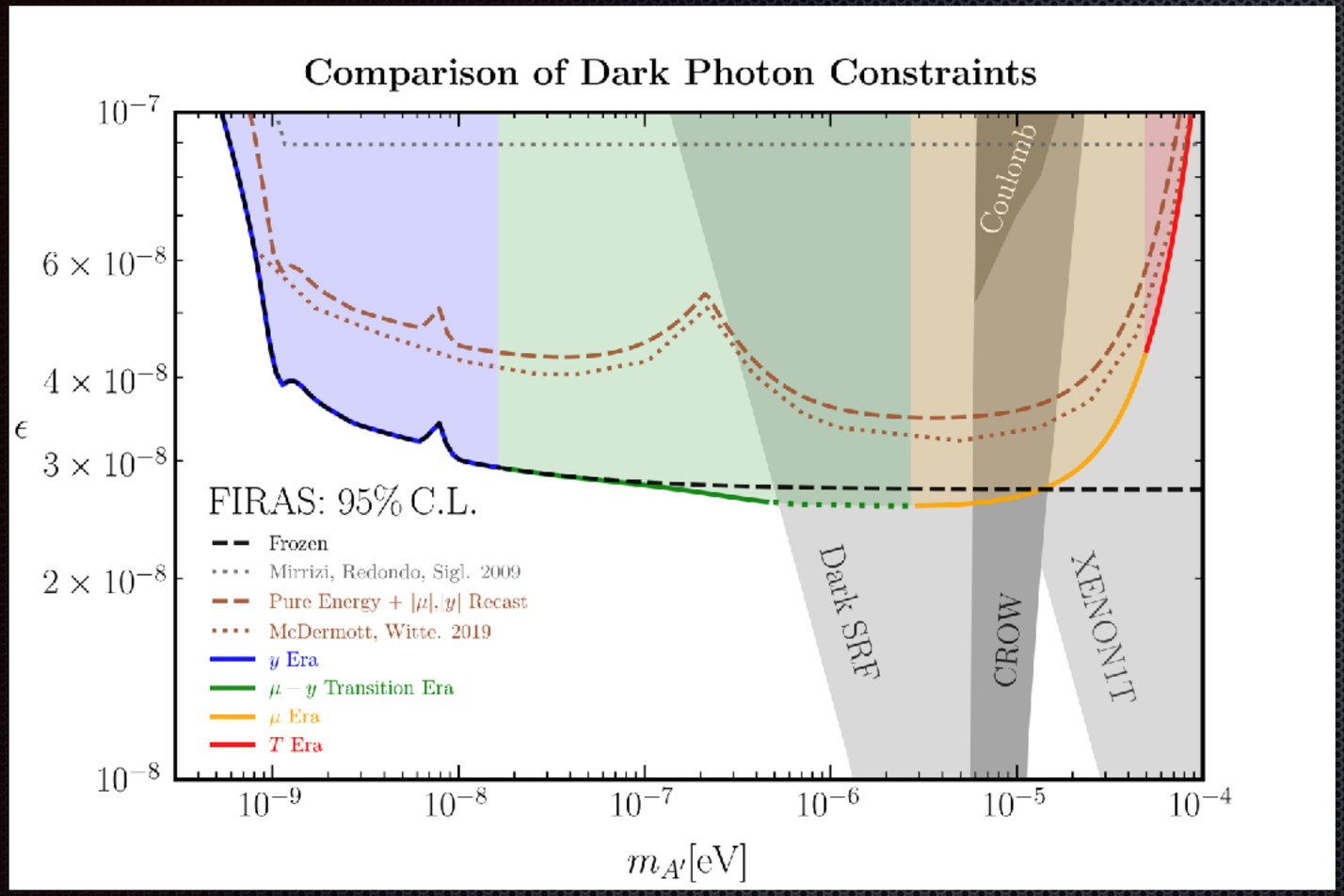
Comparing with Previous Works



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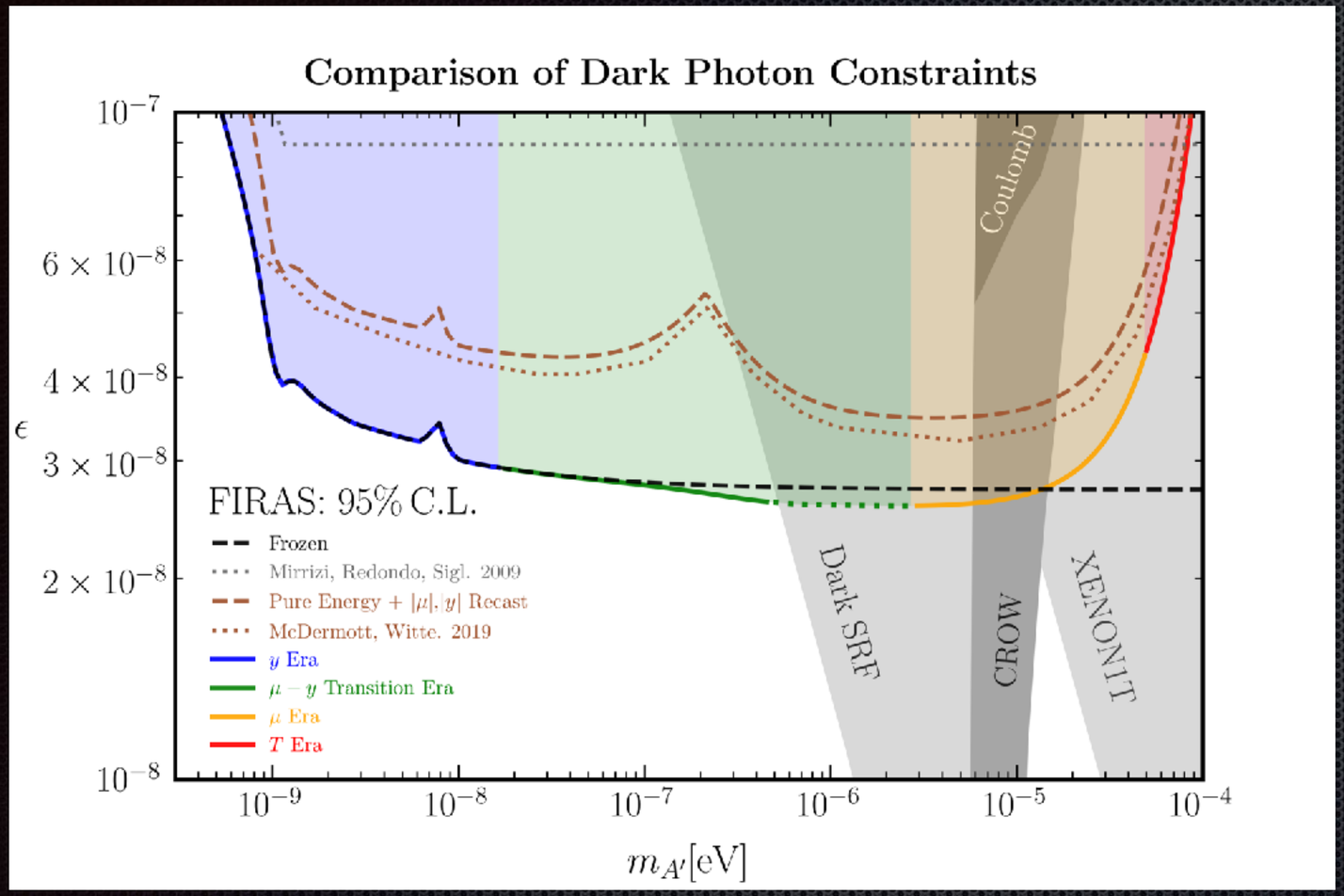
Comments on Redondo et al. 09

1. Does not consider photon redistribution
2. Need hard cutoff at T-era
3. Out-of-date $X_e(z)$
4. Incorrect smoking gun

Dark Photon COBE-FIRAS Bound Revisit



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Comments on Redondo et al. 09

1. Does not consider photon redistribution
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3. Out-of-date $X_e(z)$
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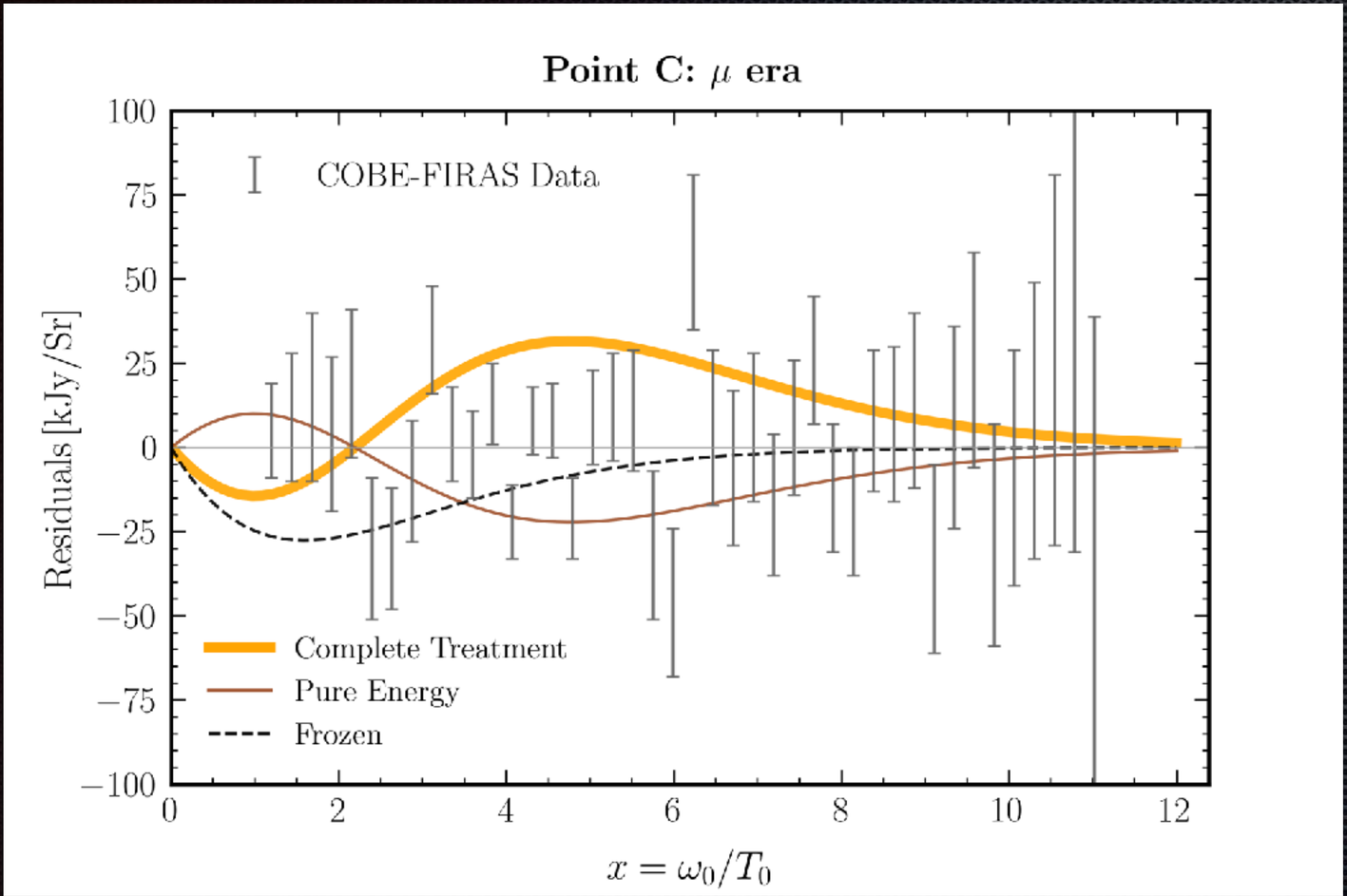
Comments on McDermott et al. 19

1. Inconsistent treatment of $\mu - y$ era
2. Cannot smoothly transit to the free streaming era
3. Incorrect smoking gun

Dark Photon COBE-FIRAS Bound Revisit



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μ Era Distortion

$$\mu_{inj} = \alpha_\rho x_{inj} \frac{3}{\kappa_c} \left[1 - P_s \frac{x_0}{x_{inj}} \right] \frac{\Delta n_{\gamma,inj}}{n_\gamma}$$

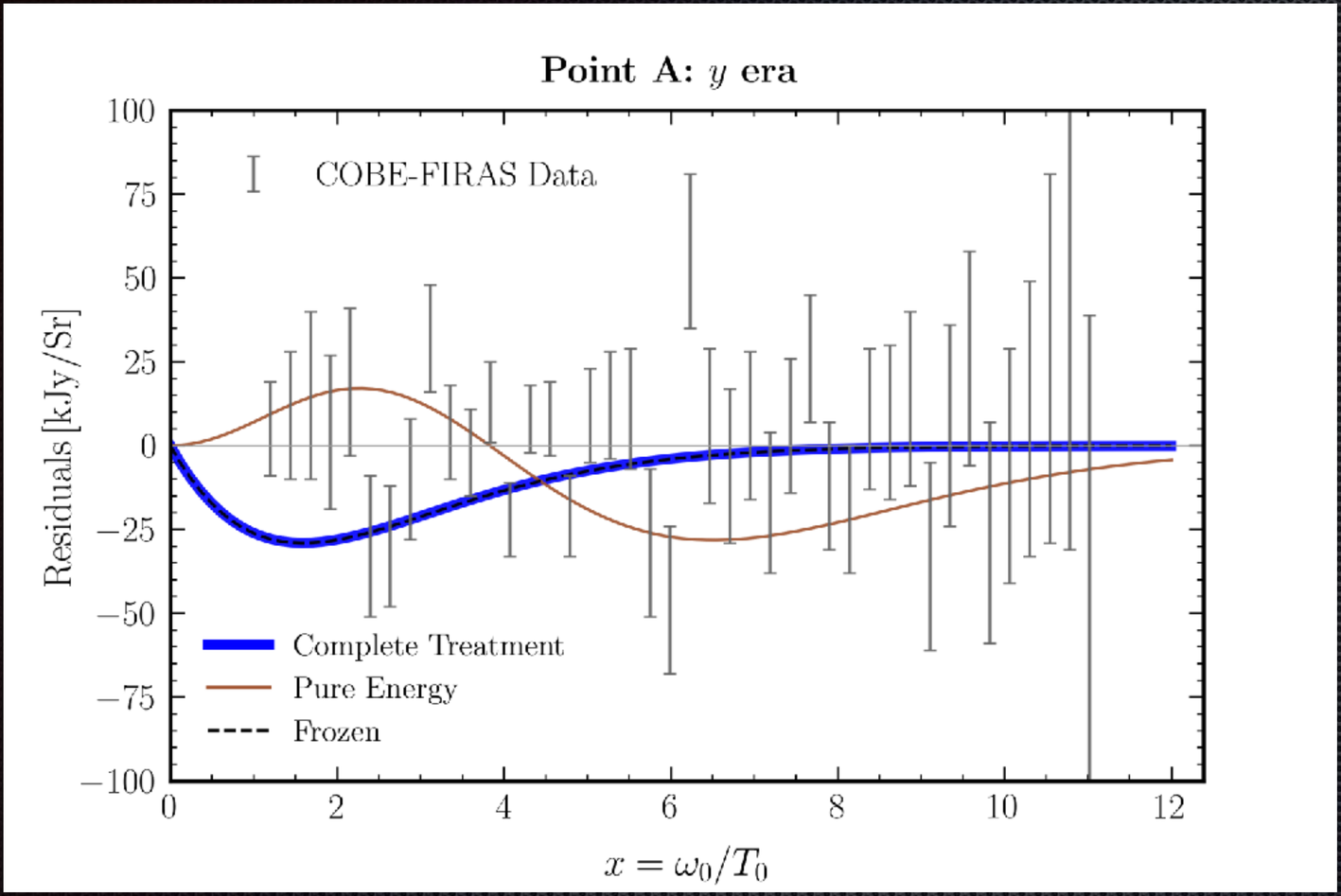
McDermott et al.: $P_s = 0$

Real Case: $P_s = 1$

$$\frac{\mu_{inj}|_{P_s=1}}{\mu_{inj}|_{P_s=0}} = 1 - \frac{x_0}{x_{inj}}$$

$x_{inj} < x_0$: μ flips the sign!

Dark Photon COBE-FIRAS Bound Revisit



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y Era Distortion

$$G_y(x,x',z') = \alpha_\rho x' \cdot \left(1 - P_s(x',z')\right) \frac{Y(x)}{4}$$
$$+\alpha_\rho x' \cdot P_s(x',z') \cdot \frac{\bar{\rho}_\gamma(T_0)}{2T_0} \cdot \delta(x-x')$$

McDermott et al.: $P_s = 0$

$\Delta I(x) \propto Y(x)$

Real Case: $P_s = 1$

$\Delta I(x) \simeq -P_{\gamma\to A'}(x) \cdot I_0(x)$

Summary

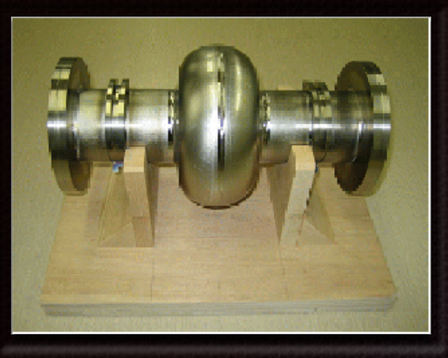
1. CMB spectral distortion is a extrodinary tool to test the photon injection/removal from BSM.

2. CMB spectral distortion is currently the best way to detect the ultralight dark photon in the mass range .

3. Previous treatments either neglected the photon redistribution from the Compton Scattering, or used the incomplete formalism considering the thermalized energy injection.

4. We revisit the dark photon, and do it with the complete formalism. We not only fix the dark photon COBE-FIRAS bound, but also predit the smoking guns for the future PIXIE-like experiments.

Appendix



Dark SRF Experiment

Light Shinning Through The Wall

Emitter Cavity
($\gtrsim 10^{25}$ Photons)

Receiver Cavity
(Empty)