Title: Dark photons and the cosmic radiation background

Speakers: Hongwan Liu

Series: Particle Physics

Date: April 13, 2021 - 1:00 PM

URL: http://pirsa.org/21040016

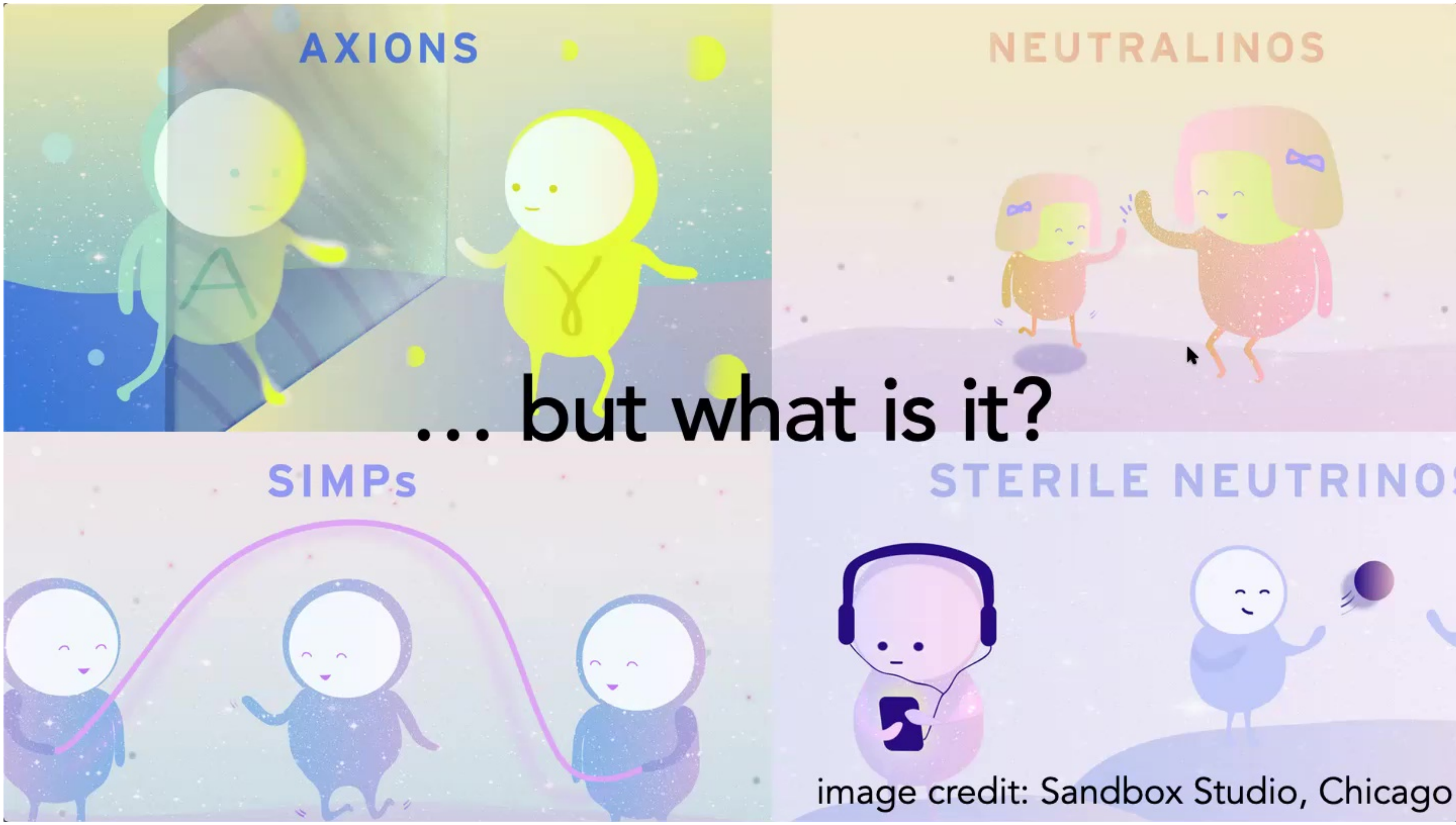
Abstract: The dark photon is a well-motivated extension of the Standard Model which can mix with the regular photon. This mixing is enhanced whenever the dark photon mass matches the primordial plasma frequency, leading to resonant conversions between photons and dark photons. These conversions can produce observable cosmological signatures, including distortions to the cosmic radiation background. In this talk, I will discuss a new analytic formalism for these conversions that can account for the inhomogeneous distribution of matter in our universe, leading to new and revised limits on the mixing parameter of light dark photons derived from the COBE/FIRAS measurement of the cosmic microwave background spectrum. I will then describe some ongoing work on a dark sector model that can explain the longstanding ARCADE radio background excess through resonant conversions of dark photons.

Dark Photons and the Cosmic Radiation Background

Andrea Caputo, **Hongwan Liu**, Siddharth Mishra-Sharma & Joshua T. Ruderman

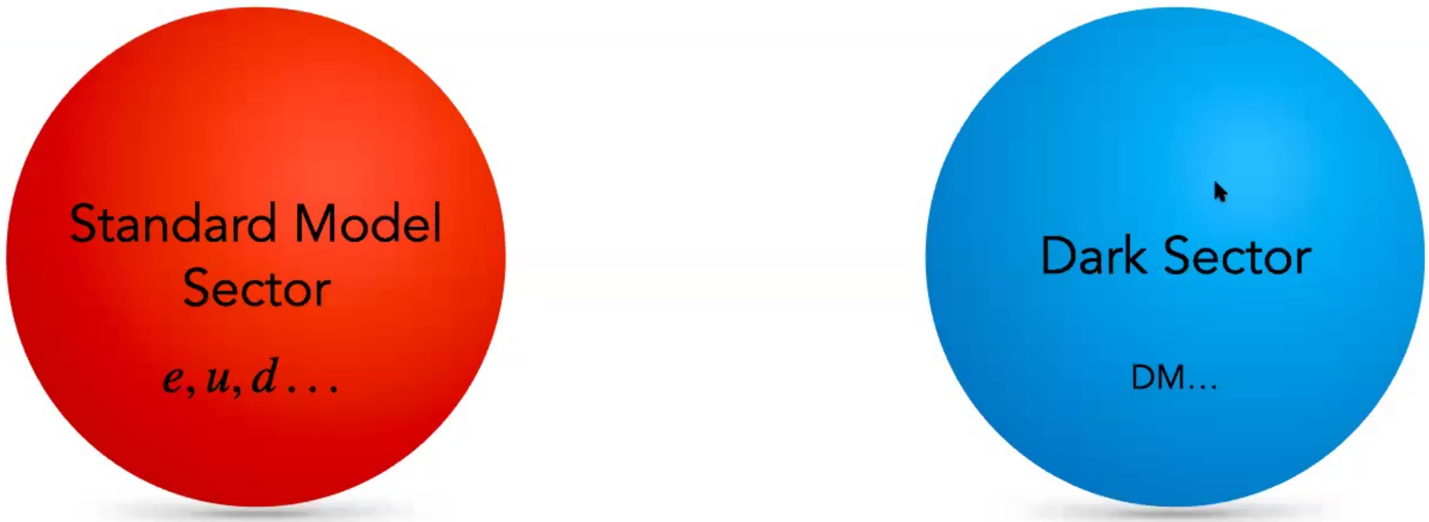
arXiv:2002.05165 (PRL), arXiv:2004.06733 (PRD)

and upcoming work (+Maxim Pospelov)


AXIONS
NEUTRALINOS
... but what is it?
SIMPs
STERILE NEUTRINOS
image credit: Sandbox Studio, Chicago


Hongwan Liu

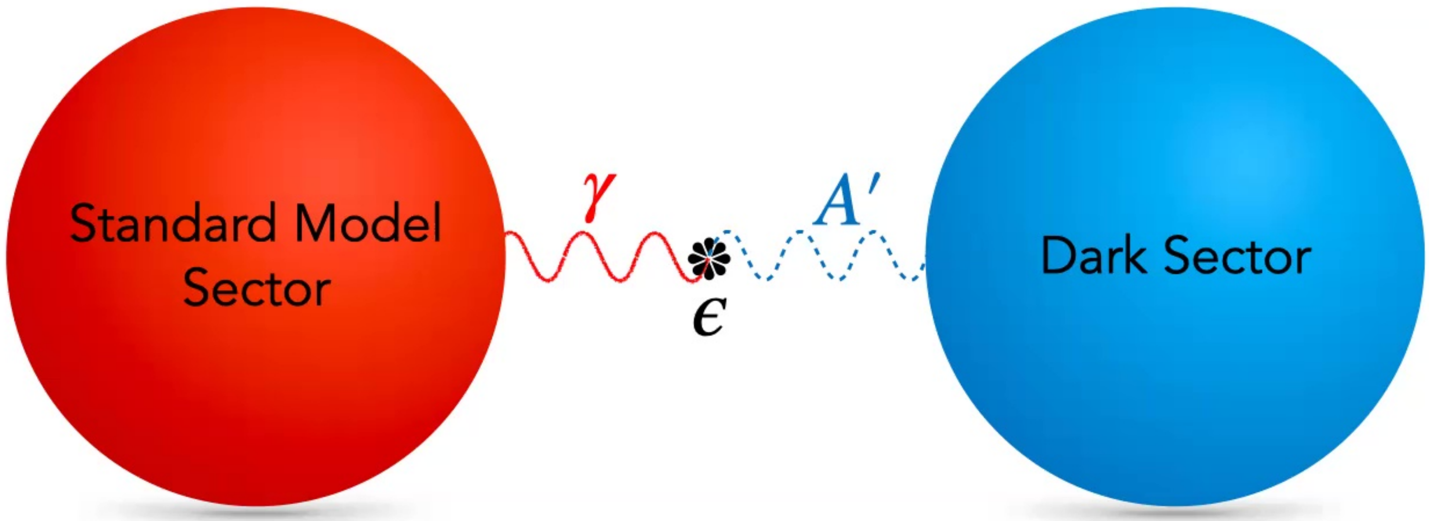
Dark Sectors



Sectors are mostly separate with their own interactions…

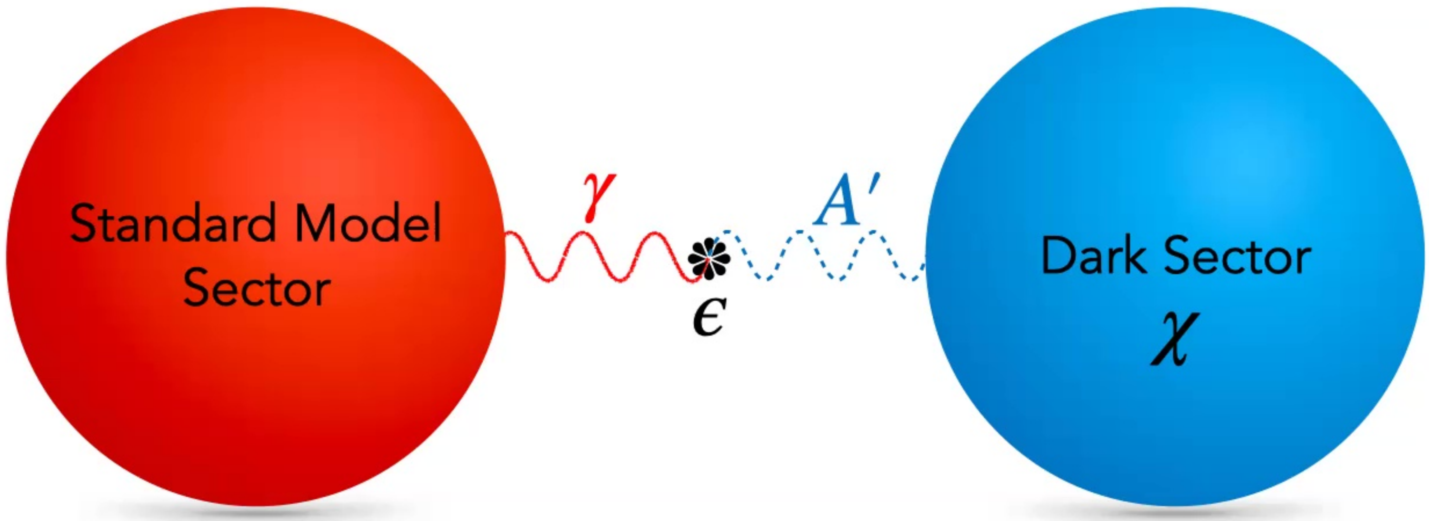
Dark Photons

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



… with **mediator** possessing a **small mixing** with the SM.

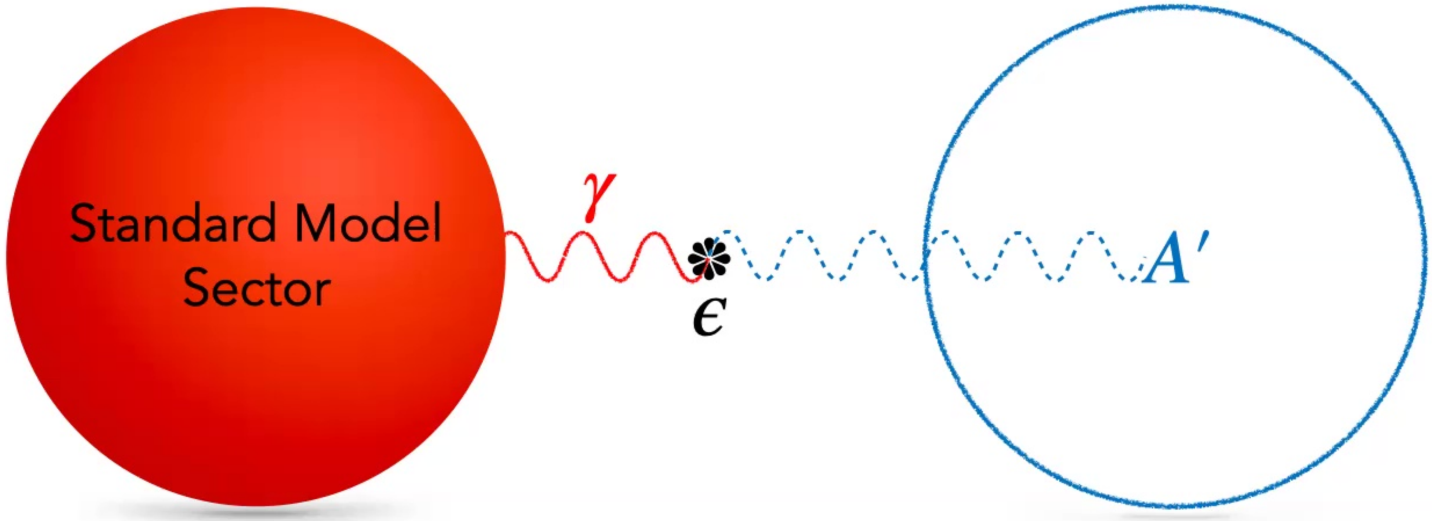
Dark Photons



Dark photons over **a wide range of masses** have been considered.
Dark matter may be **charged** under the dark photon…

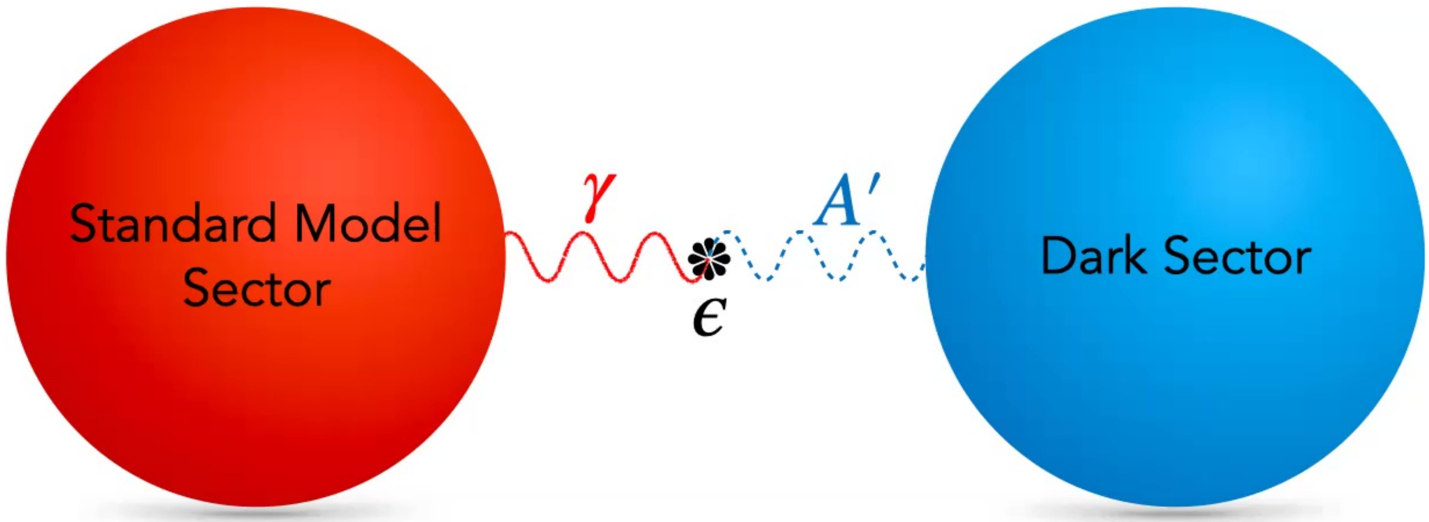
DP Dark Matter

Redondo & Postma 0811.0326
Nelson & Scholtz 1105.2812
Arias+ 1201.5902
Fradette+ 1407.0993
H. An+ 1412.8378
Graham+ 1504.02102
Agrawal+ 1810.07188
Dror+ 1810.07195
Co+ 1810.07196
Bastero-Gil+ 1810.07208
Long & L.-T. Wang 1901.03312
…



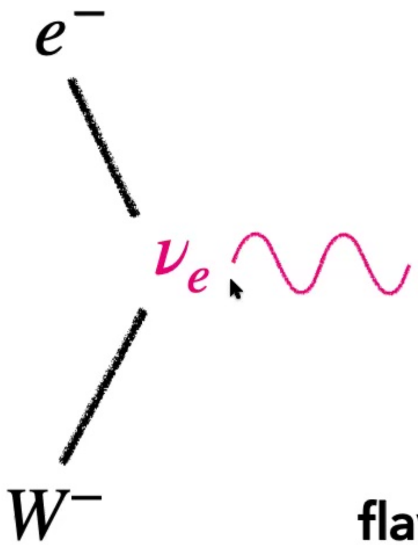
… or light dark photons may even be **all of dark matter** itself.

Dark Photon Oscillations



SM charged under **interaction eigenstate** of the photon, which is **not a propagation eigenstate**.

Mixing in Neutrinos

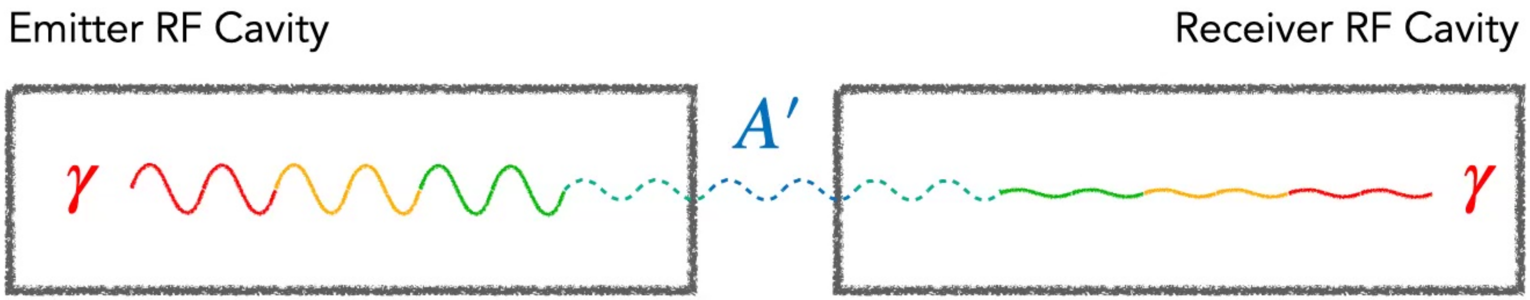


Neutrinos are produced in
flavor or **interaction eigenstates**…

Neutrino Oscillations

… that are not **propagation eigenstates**.

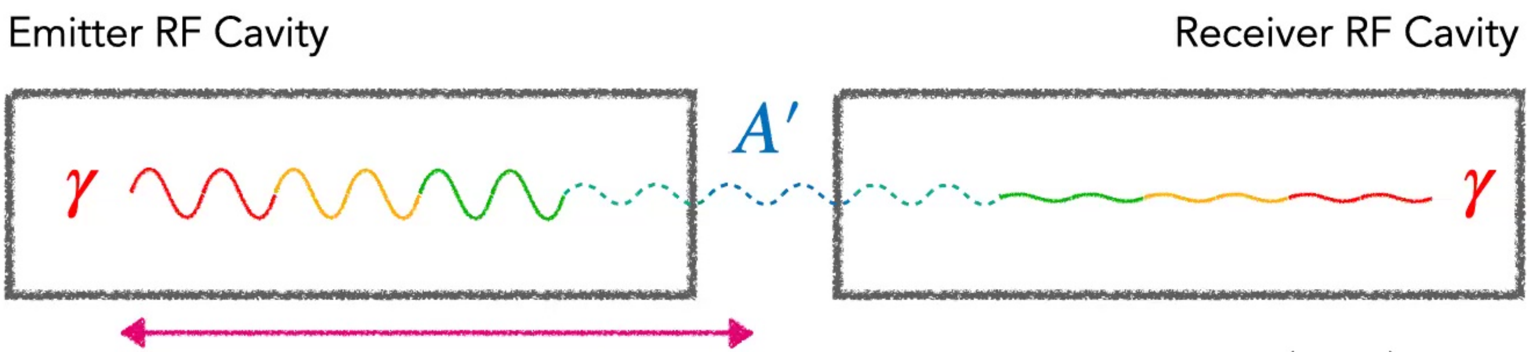
Light-Shining-Through-Wall



Photons can likewise oscillate into dark photons **in vacuum**.

Betz+ 1310.8098
Graham+ 1407.4806 - parametrically better to search for produced longitudinal A'
R. Harnik https://indico.fnal.gov/event/19433/contributions/52134/
A. Grasselino https://indico.fnal.gov/event/19433/contributions/52137/

Light-Shining-Through-Wall



$$L \sim \frac{\omega}{m_{A'}^2} \sim 0.8\,\mathrm{m}\left(\frac{10^{-6}\,\mathrm{eV}}{m_{A'}}\right)^2\left(\frac{\nu}{\mathrm{GHz}}\right)$$

$$P_{\gamma\to A'} = 4\epsilon^2 \sin^2\left(\frac{m_{A'}^2 L}{4\omega}\right)$$

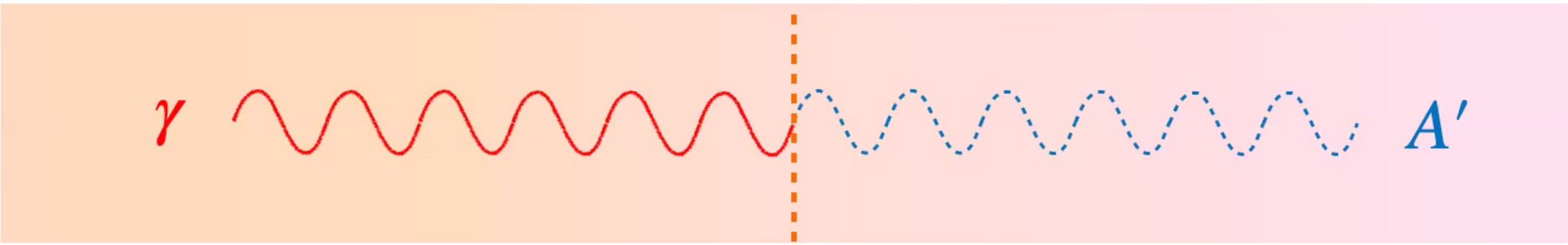
There is a characteristic **oscillation length** of **maximum** conversion.

Lighter Dark Photons

$$L \sim 10^6\,\mathrm{m}\left(\frac{10^{-9}\,\mathrm{eV}}{m_{A'}}\right)^2\left(\frac{\nu}{\mathrm{GHz}}\right) \qquad P_{\gamma\to A'} = 4\epsilon^2 \sin^2\left(\frac{m_{A'}^2 L}{4\omega}\right)$$

Difficult with **terrestrial probes**.

Lighter Dark Photons

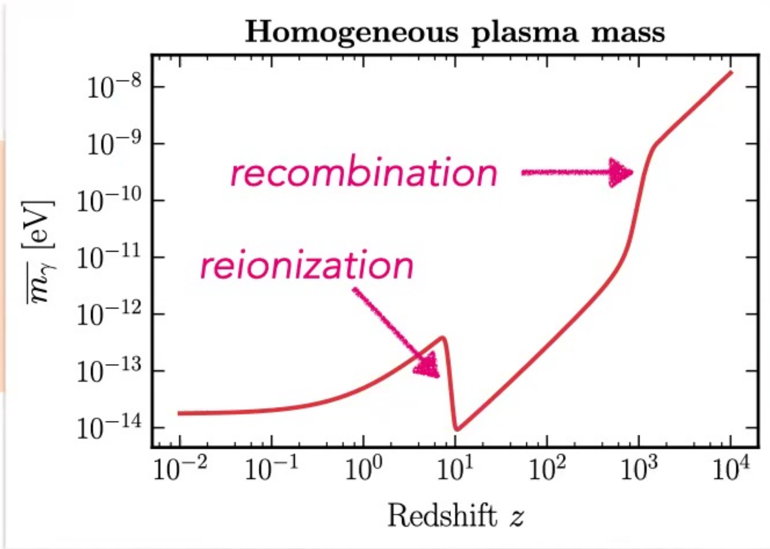


Propagation medium effects can help.

Dark Photons and the Cosmic Microwave Background

Mirizzi, Redondo & Sigl 0901.0014
Arias+ 1201.5902
McDermott & Witte 1911.05086

Homogeneous Plasma Mass



free electron fraction

$$\overline{m_\gamma} \simeq 2 \times 10^{-14}\,\mathrm{eV}\,(\overline{n_{\mathrm{e},0}}x_{\mathrm{e}})^{1/2}(1+z)^{3/2}$$

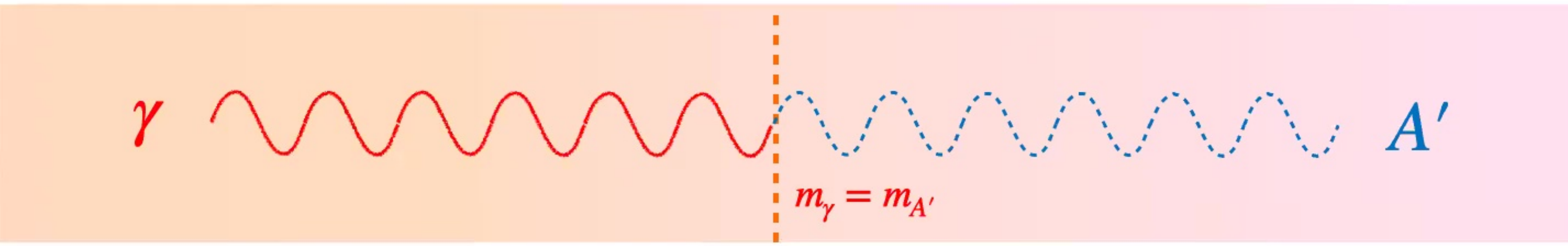
mean electron number density today

Under the assumption of **homogeneity**,
$10^{-14}\,\mathrm{eV} \lesssim \overline{m_\gamma} \lesssim 10^{-9}\,\mathrm{eV}$ after recombination.

Resonant Oscillations

$$P^{\text{vac}}_{\gamma\to A'} \sim 4\epsilon^2 \sin\left(\frac{m_{A'}^2 L}{4\omega}\right) \sim 2\times\epsilon^2\times\frac{m_{A'}^2}{2\omega}\times L$$

later time, decreasing redshift



decreasing $\overline{n_e}$ and $\overline{m_\gamma}$

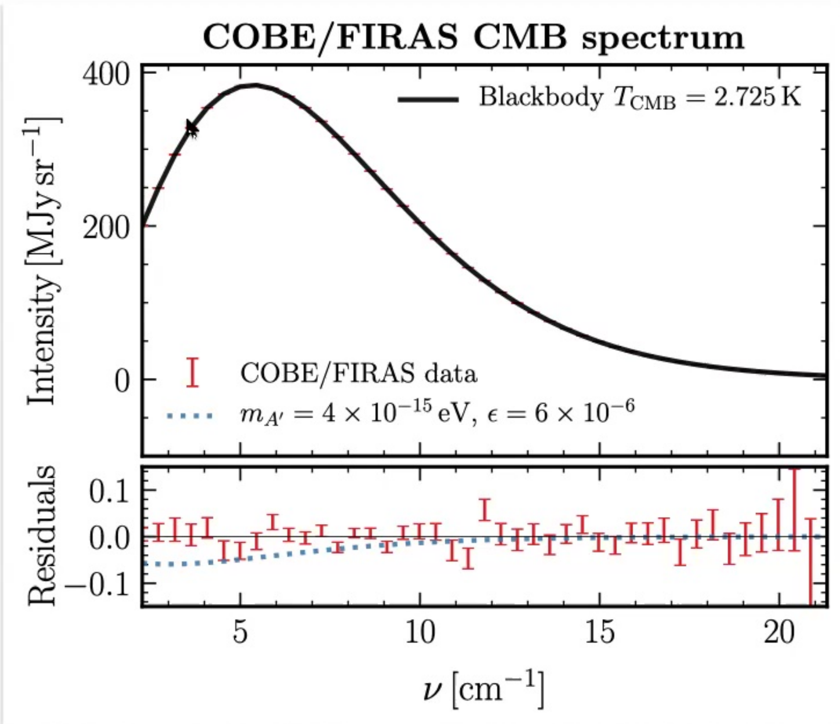
mixing

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

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

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

Cosmic Microwave Background

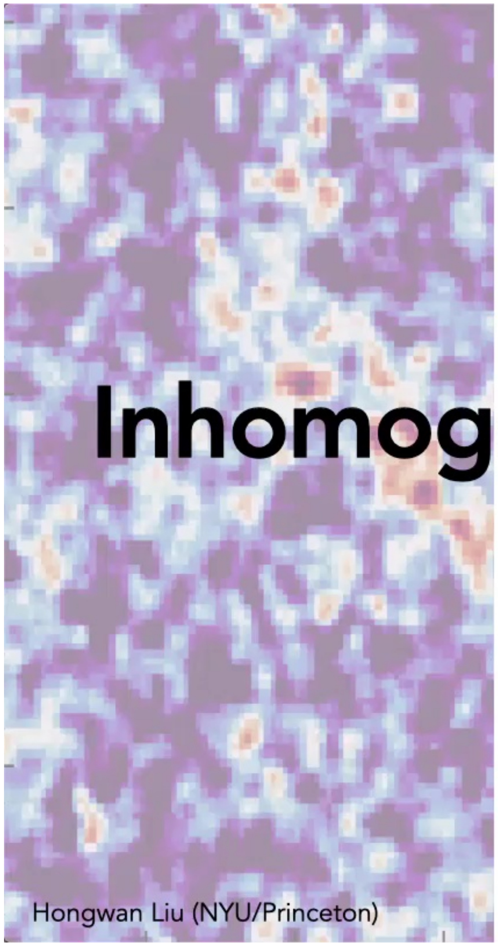


Fixsen+ astro-ph/9605054

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

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

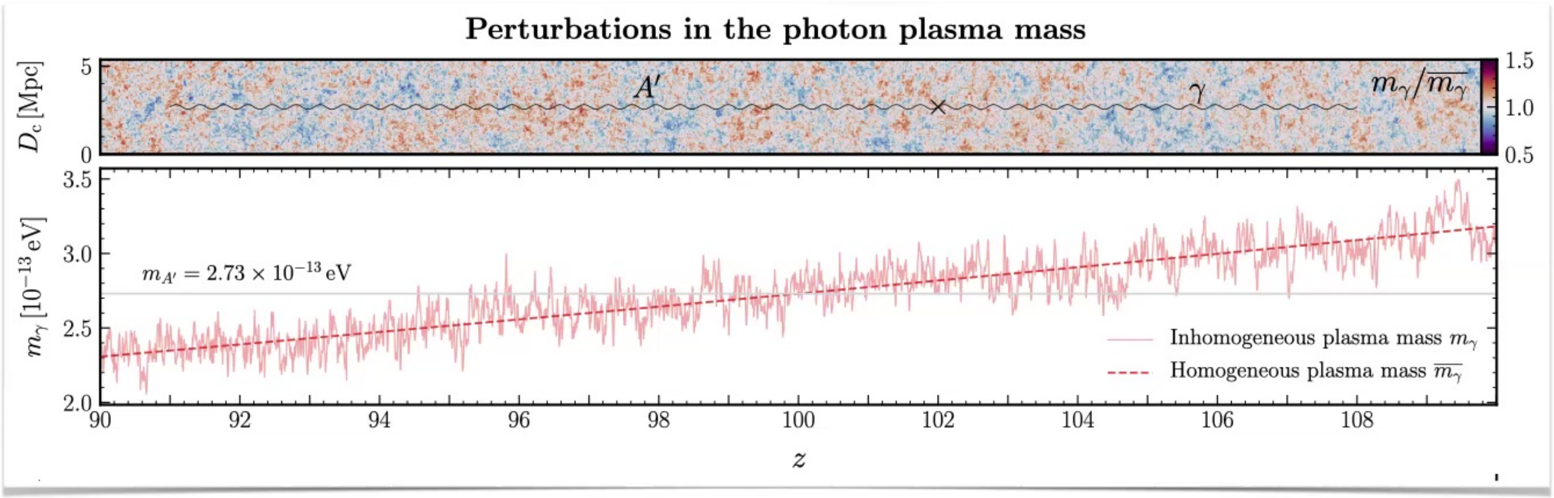
$$P_{\gamma \to A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{\mathrm{d} \ln m_\gamma^2}{\mathrm{d}t} \right|^{-1}_{t_i = t_{\rm res}}$$



Inhomogeneities

related work:
Bondarenko, Pradler & Sokolenko 2002.08942
A. A. Garcia+ 2003.10465
Witte+ 2003.13698

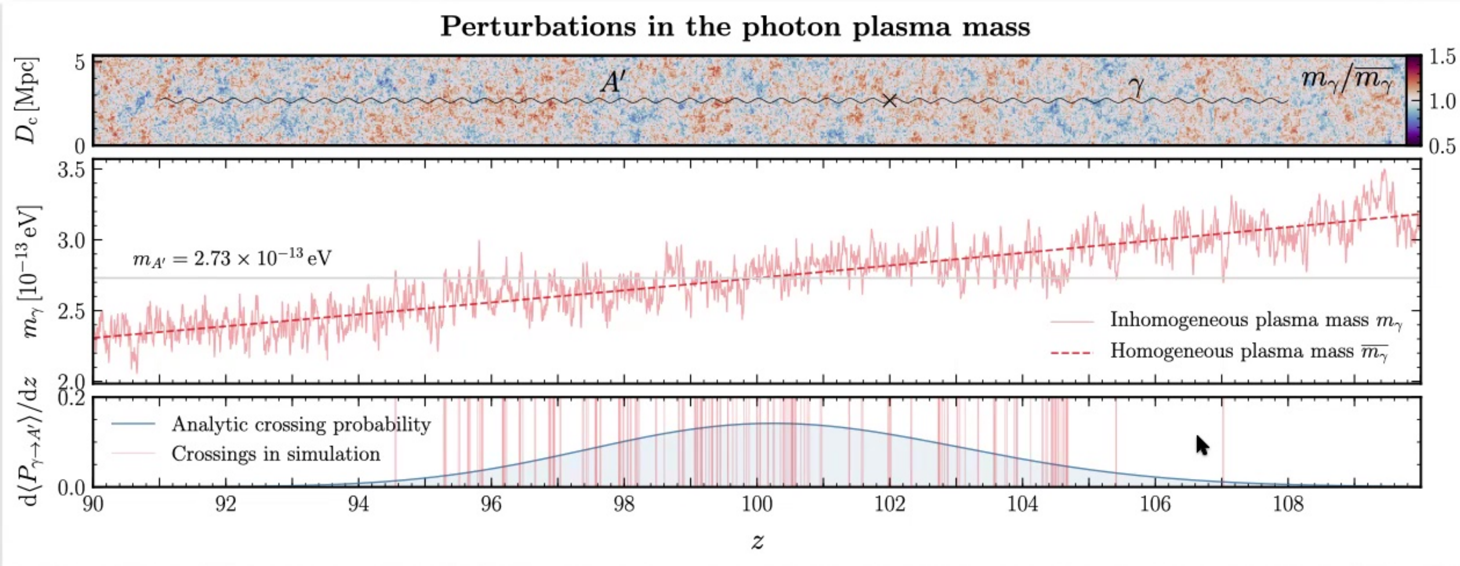
The Reality



Fluctuations in electron density means $m_\gamma \neq \overline{m_\gamma}$.

Numerous resonance crossings along each photon path…

Analytic Formalism



… but we can **average over photon paths** analytically!

Analytic Formalism

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

Change of integration measure

Analytic Formalism

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

Average over distribution of m_γ^2

(time-dependent) probability density function of m_γ^2

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

Analytic Formalism

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

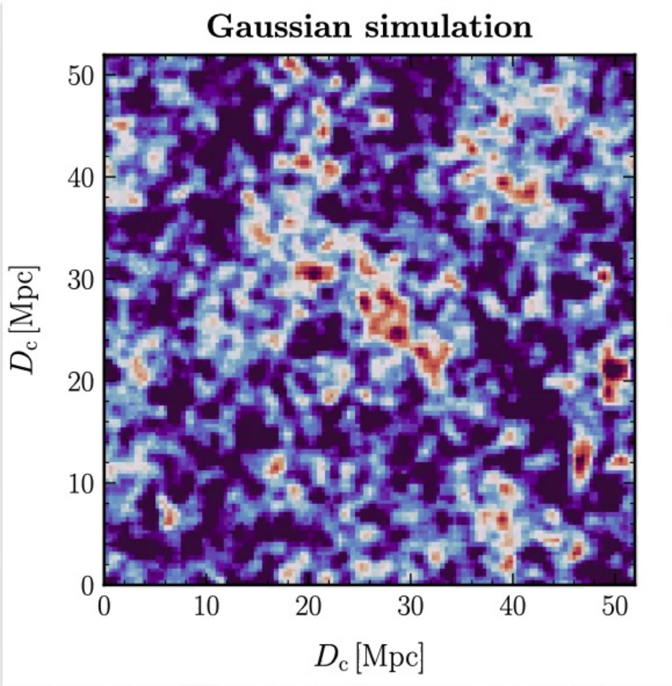
Integrate over m_γ^2

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

Finding the average conversion probability reduces to knowing the **PDF of the plasma mass squared**.

One-Point PDF

$$m_\gamma \simeq 2 \times 10^{-14}\,\mathrm{eV} \left(\frac{n_\mathrm{e}}{2.5 \times 10^{-7}\,\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{x_\mathrm{e}}{1.0} \right)^{1/2}$$



$$m_\gamma^2 \propto n_\mathrm{e} \implies f(m_\gamma^2; t) \propto \mathscr{P}(\delta_\mathrm{b}; t)$$

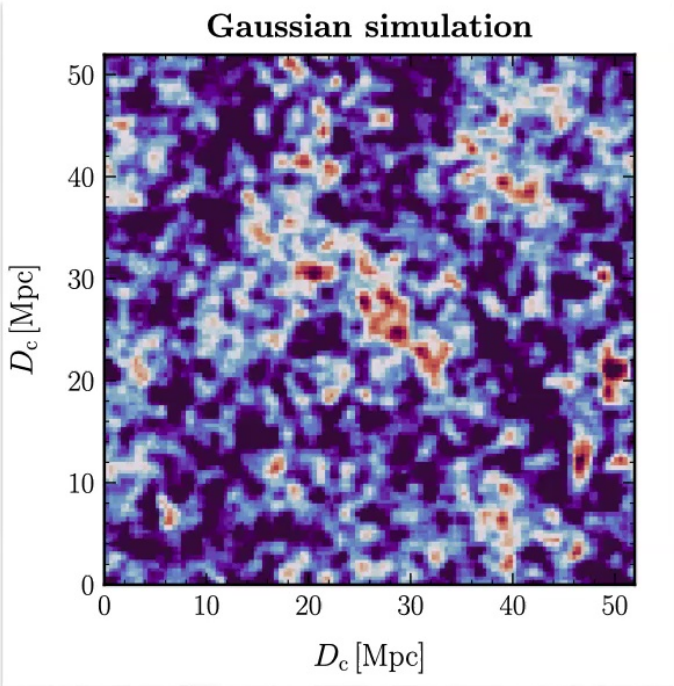
one-point PDF of baryon fluctuations

$$\delta_\mathrm{b} \equiv \frac{\rho_\mathrm{b} - \overline{\rho_\mathrm{b}}}{\overline{\rho_\mathrm{b}}}$$

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

Linear Regime

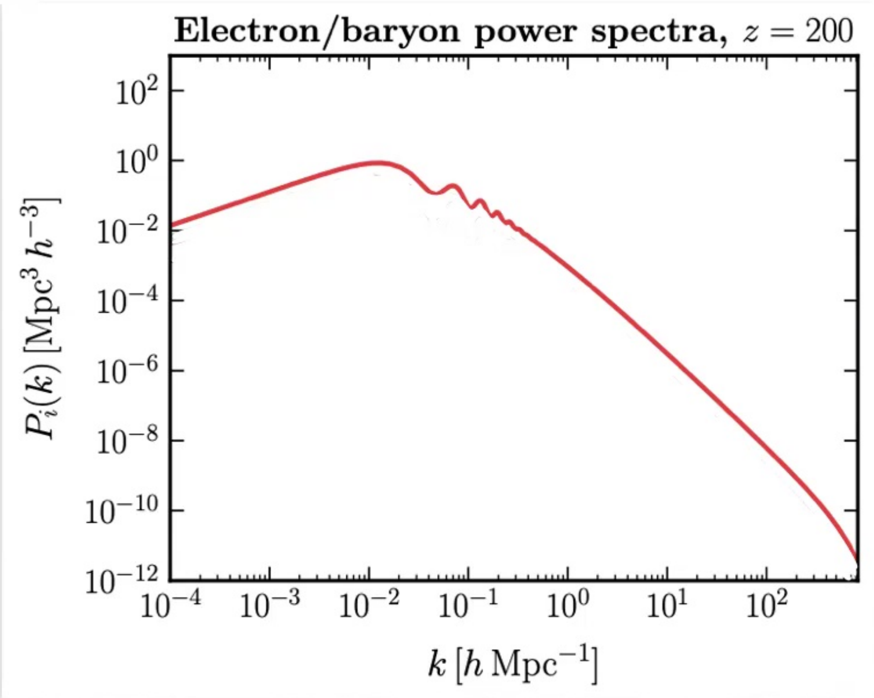
$$\delta_b \equiv \frac{\rho_b - \overline{\rho_b}}{\overline{\rho_b}}$$



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

When $z \gg 20$, fluctuations are **small** and **Gaussian**, characterized fully by the **variance**, σ_b^2.

Variance and Power Spectrum

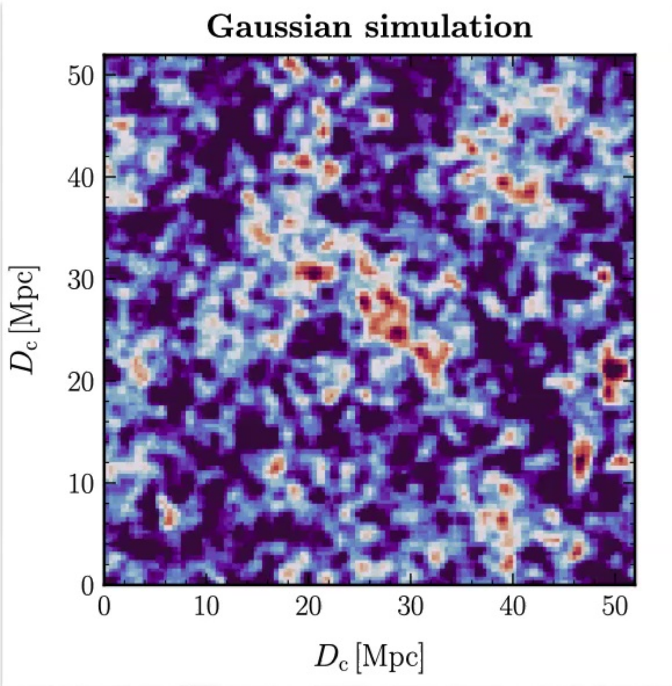


$$\mathscr{P}(\delta_\mathrm{b}; z) = \frac{1}{\sqrt{2\pi\sigma_\mathrm{b}^2(z)}} \exp\left(-\frac{\delta_\mathrm{b}^2}{2\sigma_\mathrm{b}^2(z)}\right)$$

$$\sigma_\mathrm{b}^2 = \int \frac{d^3\vec{k}}{(2\pi)^3} P_\mathrm{b}(k)$$

Variance given by **integral over the power spectrum**.

Analytic vs. Simulation



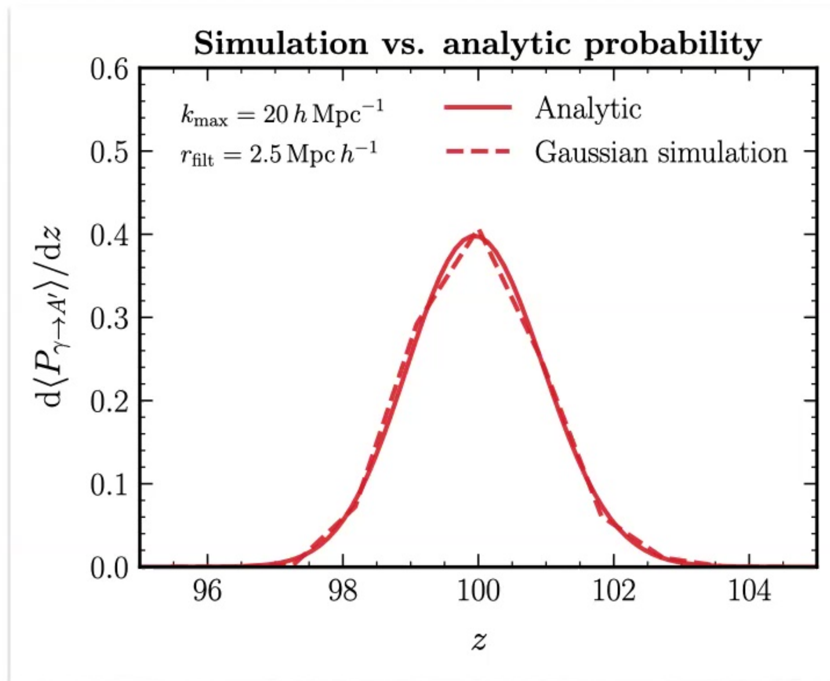


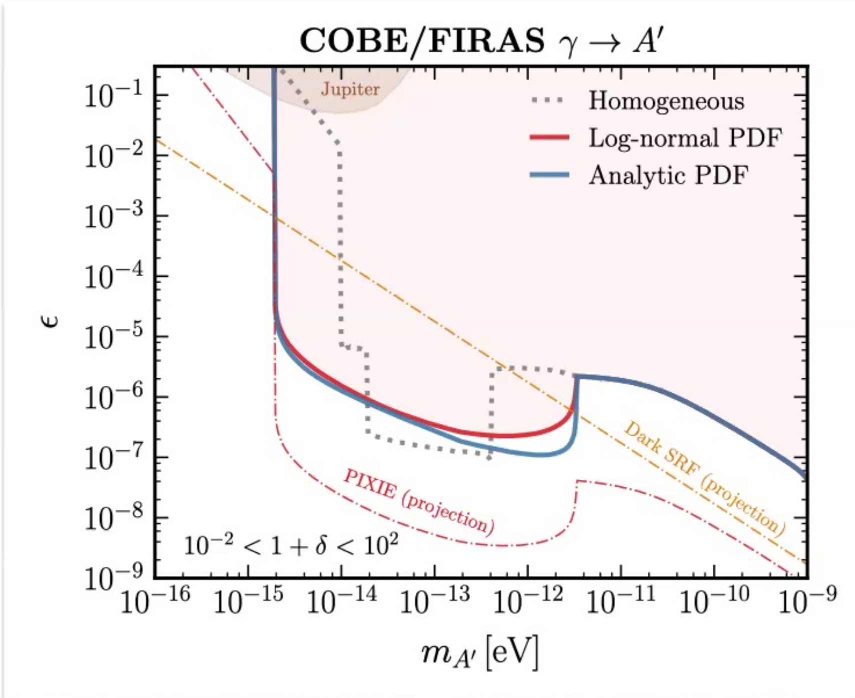
image credit: EAGLE simulation

Nonlinear Regime?

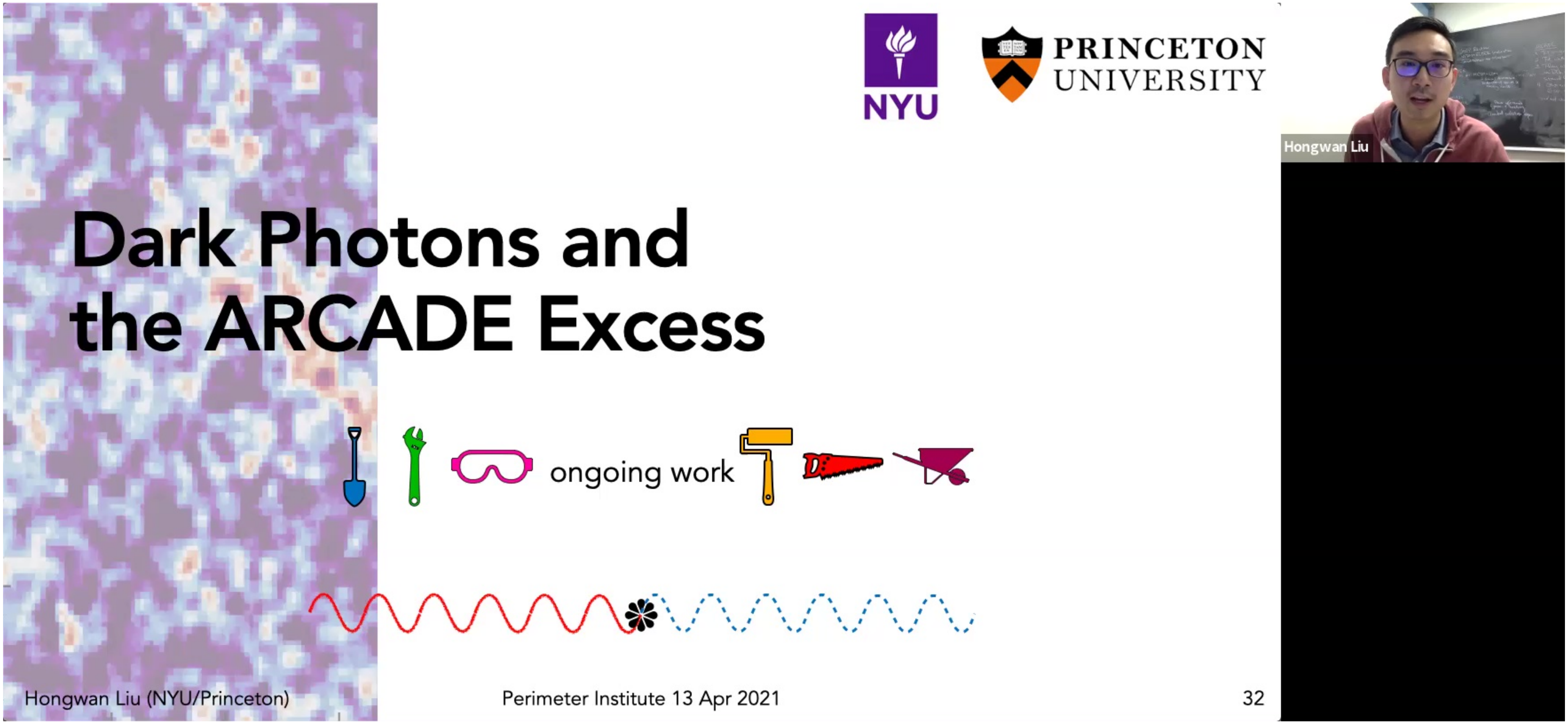
$$\mathscr{P}(\delta_{\rm b}; z) = \frac{1}{\sqrt{2\pi\sigma_{\rm b}^2(z)}} \exp\left(-\frac{\delta_{\rm b}^2}{2\sigma_{\rm b}^2(z)}\right)$$

1. Need a new **PDF** that works in nonlinear regime.
2. The **variance** of the PDF determined by power spectrum, which should incorporate **nonlinear effects**.

Constraints with Inhomogeneities



Dark photons can be probed by cosmology, and it's easy to include inhomogeneities!


NYU
PRINCETON UNIVERSITY
Hongwan Liu
Dark Photons and the ARCADE Excess
ongoing work
Hongwan Liu (NYU/Princeton)
Perimeter Institute 13 Apr 2021
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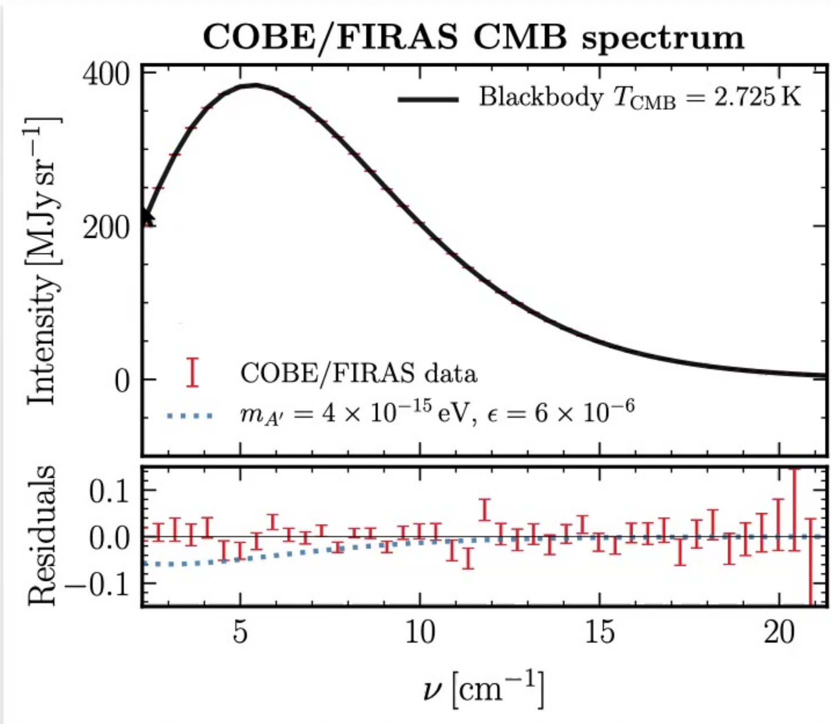
Cosmic Microwave Background



Fixsen+ astro-ph/9605054
Fixsen 0911.1955

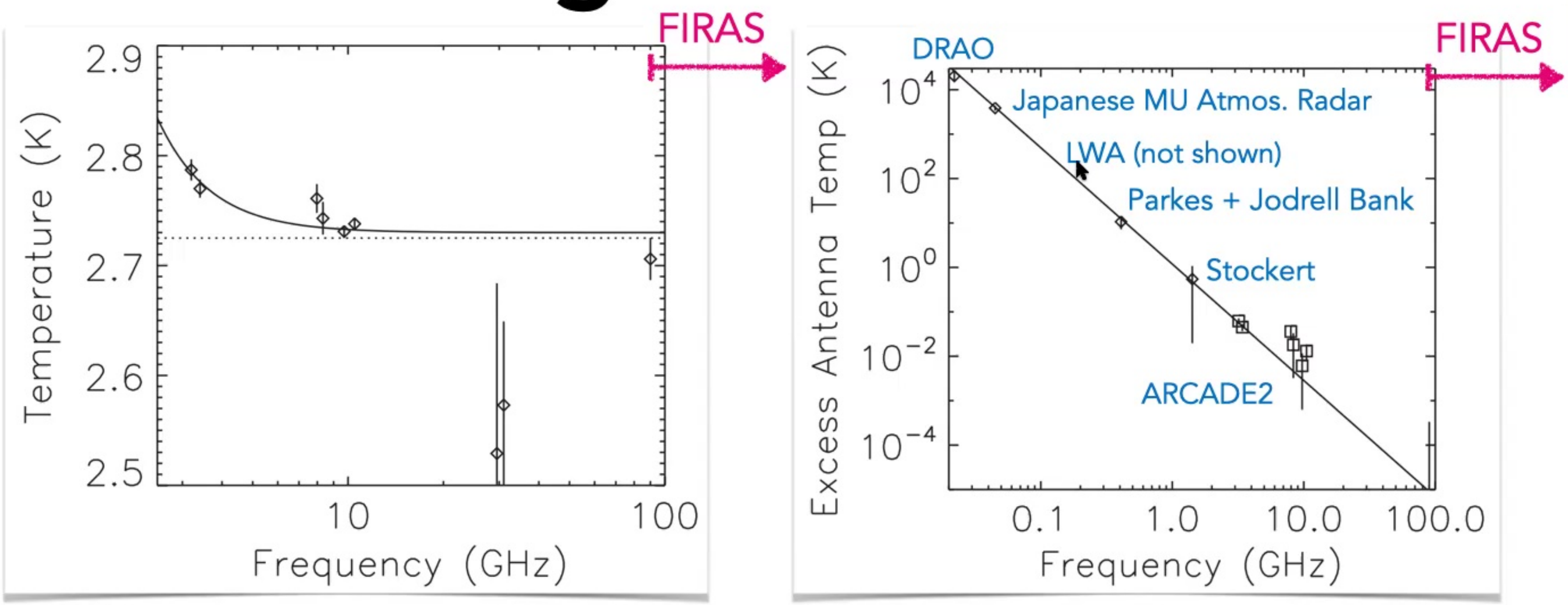
The CMB is very close to a **perfect blackbody**…

$$2.72548 \pm 0.00057\ {\rm K}$$

but what about the **radio background**?

Radio Background

Fixsen+ 0901.0555



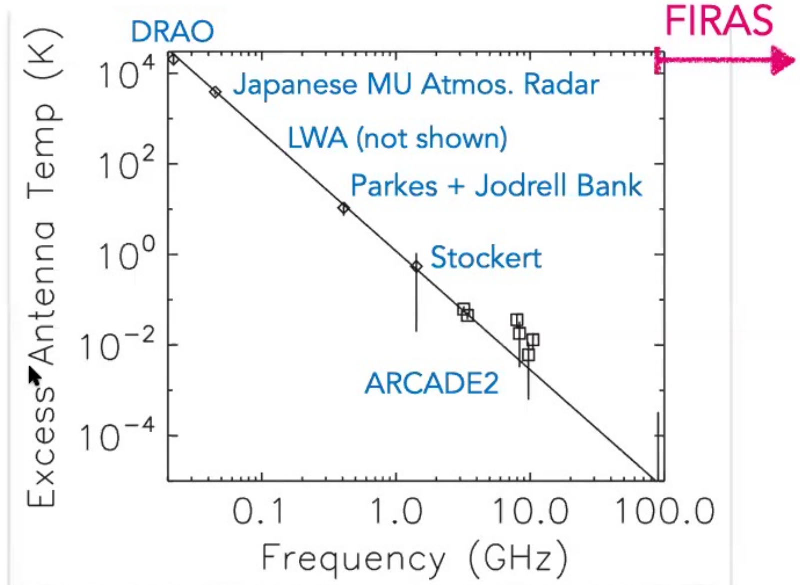
Broad series of **radio experiments** see a **power law excess** in the sky temperature (after subtracting the modelled galactic contribution).

ARCADE Excess

Fixsen+ 0901.0555

$$T = 2.729\,\mathrm{K} + 1.19\,\mathrm{K}\left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-2.62}$$

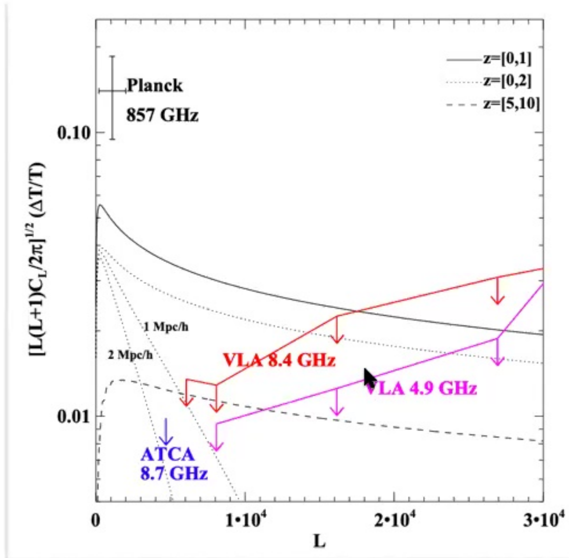
$$T = \frac{\pi^2}{\omega}\frac{dn_\gamma}{d\omega} \implies \frac{dn_\gamma}{d\omega} \propto \omega^{-1.62}$$



Broad series of **radio experiments** see a **power law excess** in the sky temperature (after subtracting the modelled galactic contribution).

Smooth Emission

Holder 1207.0856



The emission is extremely **smooth**: assuming perfect correlation with structure, it **cannot be emitted when** $z \lesssim 5$, or **dominated by large structures** ($\gtrsim$ few Mpc).

Not Fully Primordial

Mondal+ 2004.00678

$$T(z) = \left[2.729\,\mathrm{K} + \underbrace{1.19\,\mathrm{K}}_{}^{\color{magenta}{T_{\mathrm{GHz}}}} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-2.62}\right](1+z)$$

LOFAR @ z = 9.1: $T_{\mathrm{GHz}} < 0.65\,\mathrm{K}$ at 95% confidence.

LOFAR 21-cm power spectrum upper limits show that the full distortion cannot be produced at $z > 9.1$.

Existing Explanations?

$$T = T_0 + T_{\mathrm{GHz}} \left(\frac{\nu}{1\,\mathrm{GHz}} \right)^{\beta}$$

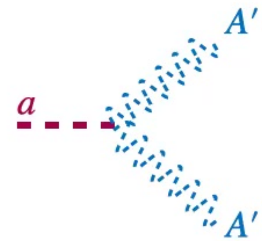
Astrophysics Mechanism	T_{GHz}	β	$\Delta T/T$	z	
Milky Way Synchrotron Emission	No	Yes	~No	Yes	Singal+ 1501.00499
Discrete Extragalactic Synchrotron	~10%	Yes	?	Yes	Condon+ 1207.2439
Diffuse Extragalactic Synchrotron	<5%	Yes	?	Yes	Brown+ 1703.07829
Galaxy Cluster Mergers + Optimism	Yes	~	Yes	Yes	Ke Fang & Linden 1506.05807
Supermassive Black Holes at z ~ 20	Yes	Yes	Yes	~No	Biermann+ 1403.3804
DM Ann. + Synchrotron + Optimism	~Yes	~No	~Yes	Yes	Ke Fang & Linden 1412.7545

see Singal+ 1711.09979 for summary

The Model

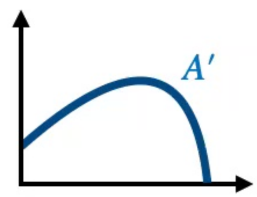
based on Pospelov+ 1803.07048
proposed to explain EDGES

1. Dark matter is an axion-like particle a, cosmologically stable, mass m_a.



2. Decays into dark photons A' with mass $m_{A'}$, $a \to A'A'$ (effective coupling g).

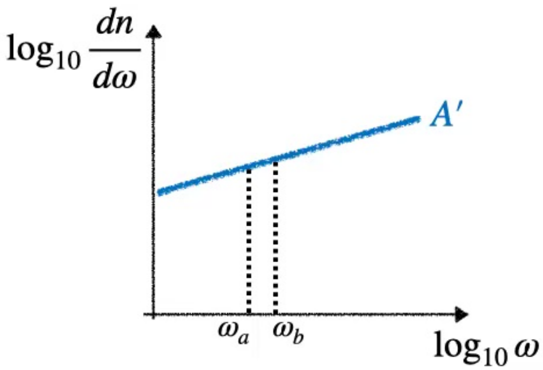
3. Dark photons kinetically mix with SM photons, $A' \leftrightarrow \gamma$ (mixing ϵ).

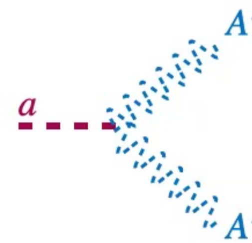


4. Relic background of A', temperature $T_{A'}$ ($< T_{\rm CMB}$).

Dark Photon Spectrum

Goal: $dn/d\omega \propto \omega^{-3/2}$

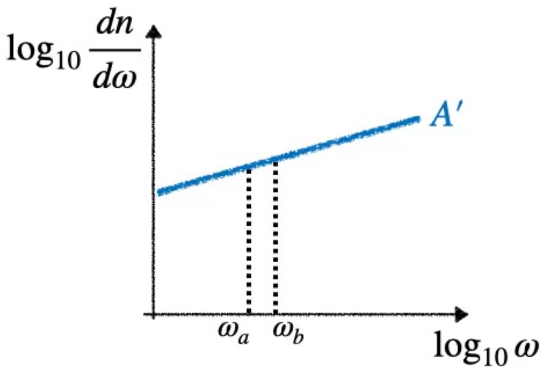




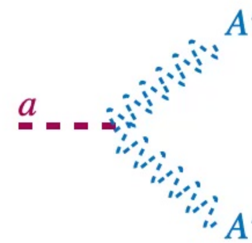
A' with energy ω was produced at $(1 + z_\star) = m_a/2\omega$.

Dark Photon Spectrum

Goal: $dn/d\omega \propto \omega^{-3/2}$



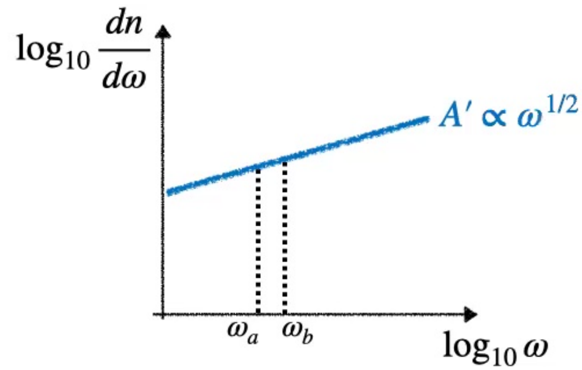
$$\omega \frac{dn_{A'}}{d\omega} = (1 + z_\star) \frac{dn_{A'}}{d(1+z)}(z_\star)$$

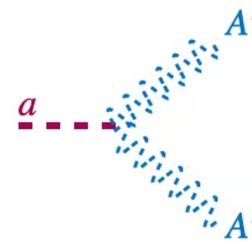


A' with energy ω was produced at $(1 + z_\star) = m_a/2\omega$.

Dark Photon Spectrum

Goal: $dn/d\omega \propto \omega^{-3/2}$





$$\omega \frac{dn_{A'}}{d\omega} = (1 + z_\star) \frac{dn_{A'}}{d(1+z)}(z_\star)$$

$$= (1 + z_\star) \times \frac{dn_{A'}}{dt}(z_\star) \times \frac{dt}{dz}(z_\star)$$

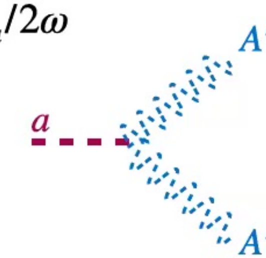
$$\frac{dn_{A'}}{d\omega} = \frac{1 + z_\star}{\omega} \times \frac{2\Gamma \rho_a(z_\star)}{m_a} \times \frac{1}{H(z_\star)(1 + z_\star)}$$

$$\frac{dn_{A'}}{d\omega} \propto \frac{1}{\omega^2} \times \omega^3 \times \frac{1}{\omega^{1/2}} = \omega^{1/2}$$

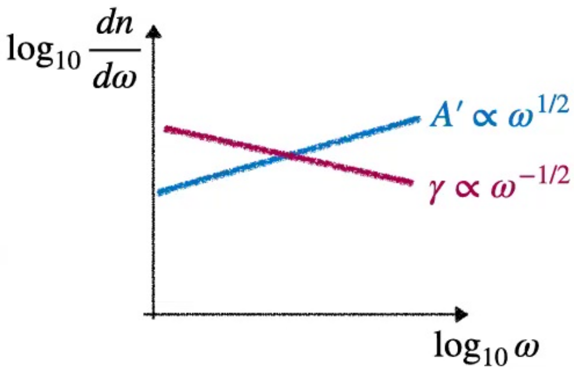
A' with energy ω was produced at $(1 + z_\star) = m_a / 2\omega$.

Photon Spectrum

$1 + z_\star = m_a / 2\omega$



Goal: $dn/d\omega \propto \omega^{-3/2}$



$$\omega \frac{dn_{A'}}{d\omega} = (1+z_\star) \frac{dn_{A'}}{d(1+z)}(z_\star)$$

$$= (1+z_\star) \times \frac{dn_{A'}}{dt}(z_\star) \times \frac{dt}{dz}(z_\star)$$

$$\frac{dn_{A'}}{d\omega} = \frac{1+z_\star}{\omega} \times \frac{2\Gamma \rho_a(z_\star)}{m_a} \times \frac{1}{H(z_\star)(1+z_\star)}$$

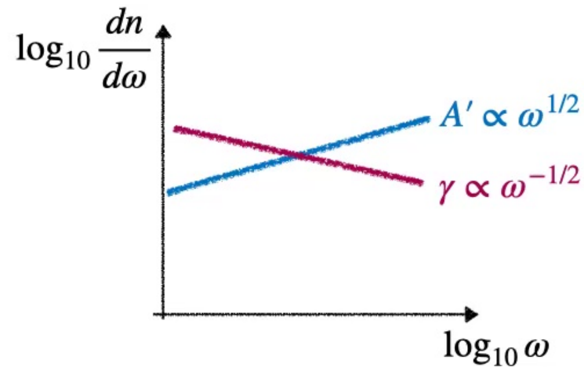
$$\frac{dn_{A'}}{d\omega} \propto \frac{1}{\omega^2} \times \omega^3 \times \frac{1}{\omega^{1/2}} = \omega^{1/2}$$

Probability of $\gamma \to A'$ conversion (homogeneous):

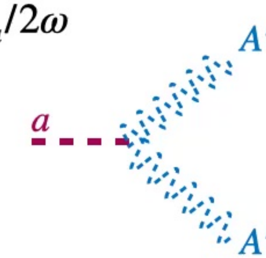
$$P_{\gamma \to A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{\mathrm{d} \ln m_\gamma^2}{\mathrm{d}t} \right|^{-1}_{t_i = t_{\mathrm{res}}}$$

Photon Spectrum

Goal: $dn/d\omega \propto \omega^{-3/2}$



$$1 + z_\star = m_a/2\omega$$



$$\omega \frac{dn_{A'}}{d\omega} = (1 + z_\star) \frac{dn_{A'}}{d(1+z)}(z_\star)$$

$$= (1 + z_\star) \times \frac{dn_{A'}}{dt}(z_\star) \times \frac{dt}{dz}(z_\star)$$

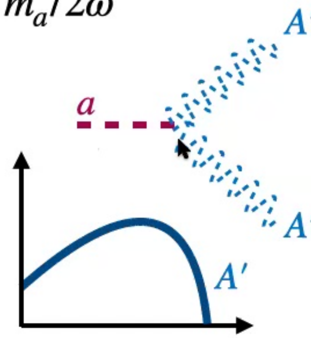
$$\frac{dn_{A'}}{d\omega} = \frac{1 + z_\star}{\omega} \times \frac{2\Gamma \rho_a(z_\star)}{m_a} \times \frac{1}{H(z_\star)(1 + z_\star)}$$

$$\frac{dn_{A'}}{d\omega} \propto \frac{1}{\omega^2} \times \omega^3 \times \frac{1}{\omega^{1/2}} = \omega^{1/2}$$

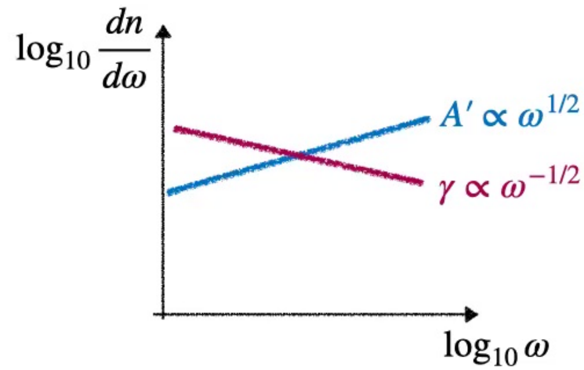
$$\frac{dn_\gamma}{d\omega} \sim \frac{dn_{A'}}{d\omega} P_{\gamma \to A'} = \propto \omega^{-1/2}$$

Stimulated Decay

$1 + z_\star = m_a/2\omega$



Goal: $dn/d\omega \propto \omega^{-3/2}$



$$\omega\frac{dn_{A'}}{d\omega} = (1+z_\star)\frac{dn_{A'}}{d(1+z)}(z_\star)$$

$$= (1+z_\star) \times \frac{dn_{A'}}{dt}(z_\star) \times \frac{dt}{dz}(z_\star)$$

$$\frac{dn_{A'}}{d\omega} = \frac{1+z_\star}{\omega} \times \frac{2\Gamma\rho_a(z_\star)}{m_a} \times \frac{2T_0'}{\omega} \times \frac{1}{H(z_\star)(1+z_\star)}$$

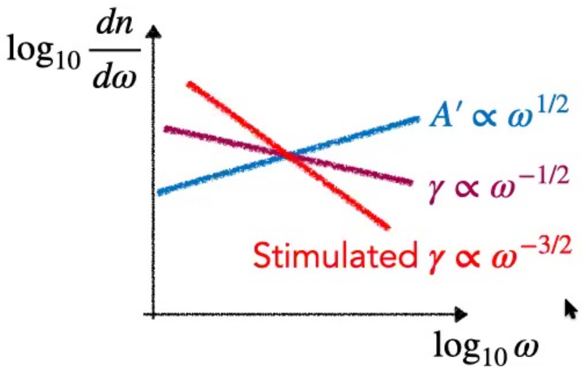
$$\frac{dn_{A'}}{d\omega} \propto \frac{1}{\omega^2} \times \omega^3 \times \frac{1}{\omega} \times \frac{1}{\omega^{1/2}} = \omega^{-1/2}$$

In the presence of a **thermal bath of** A', Bose-enhanced stimulated decay:

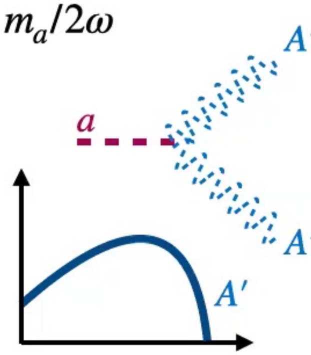
$$\Gamma \to \left(1 + \frac{2}{e^{m_a/2T'} - 1}\right)\Gamma \approx \frac{4T'(z_*)}{m_a}\Gamma$$

Stimulated Decay

Goal: $dn/d\omega \propto \omega^{-3/2}$



$$1 + z_\star = m_a/2\omega$$



$$\omega \frac{dn_{A'}}{d\omega} = (1 + z_\star) \frac{dn_{A'}}{d(1+z)}(z_\star)$$

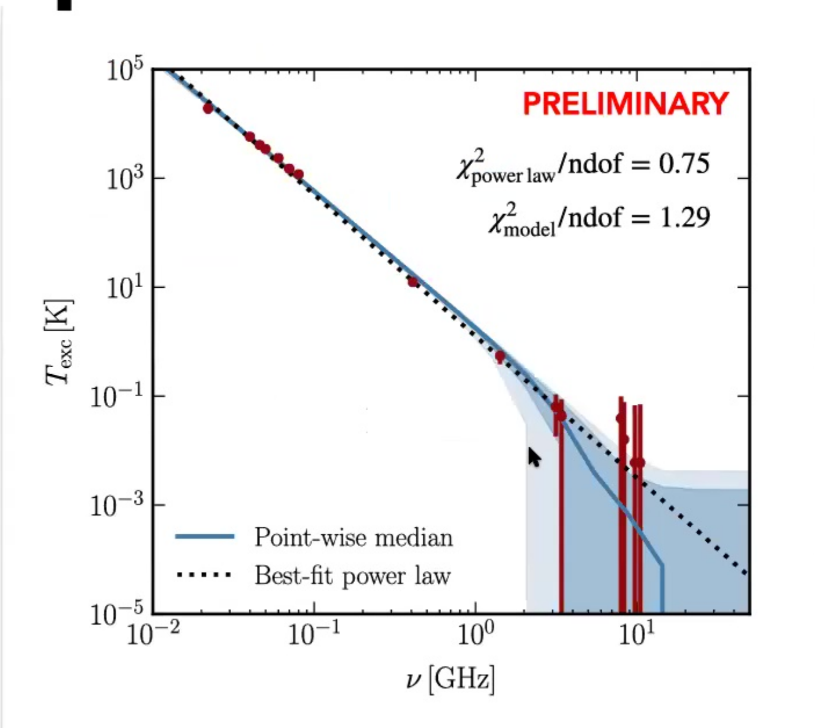
$$= (1 + z_\star) \times \frac{dn_{A'}}{dt}(z_\star) \times \frac{dt}{dz}(z_\star)$$

$$\frac{dn_{A'}}{d\omega} = \frac{1 + z_\star}{\omega} \times \frac{2\Gamma \rho_a(z_\star)}{m_a} \times \frac{2T_0'}{\omega} \times \frac{1}{H(z_\star)(1 + z_\star)}$$

$$\frac{dn_{A'}}{d\omega} \propto \frac{1}{\omega^2} \times \omega^3 \times \frac{1}{\omega} \times \frac{1}{\omega^{1/2}} = \omega^{-1/2}$$

$$\frac{dn_\gamma}{d\omega} \sim \frac{dn_{A'}}{d\omega} P_{\gamma \to A'} = \propto \omega^{-3/2}$$

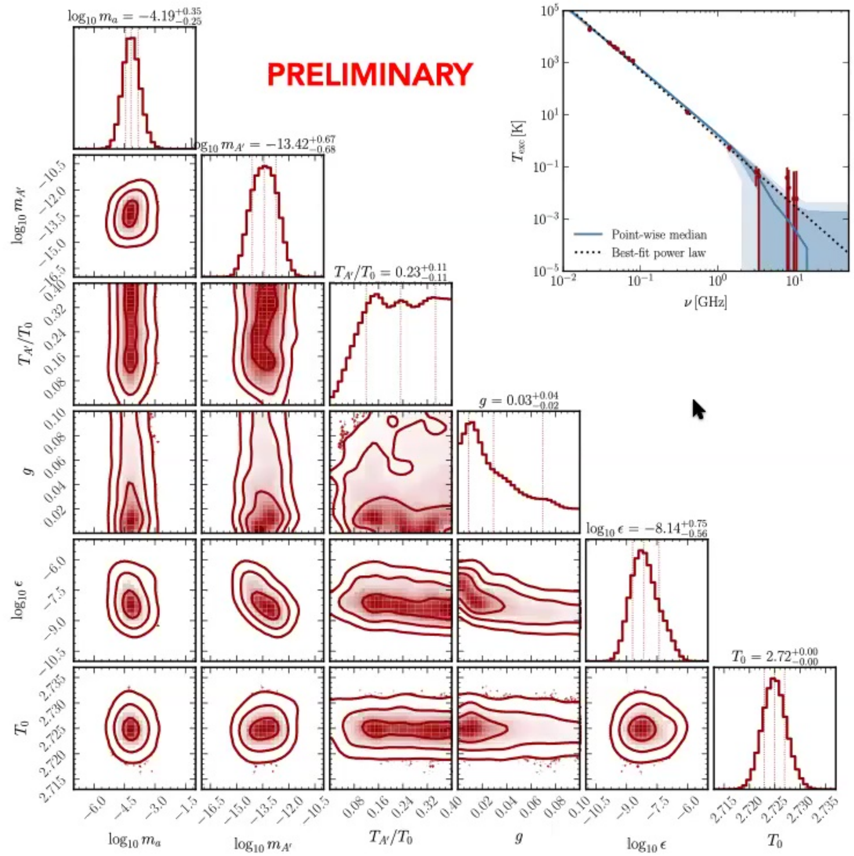
Spectral Fit



$$m_a = 6 \times 10^{-5}\,\text{eV}$$
$$m_{A'} = 4 \times 10^{-14}\,\text{eV}$$
$$g = 0.04\,\text{GeV}^{-1}$$
$$\epsilon = 5 \times 10^{-9}$$
$$T_{A'} = 0.2 T_{\text{CMB}}$$

Includes **inhomogeneities**, thermal $A' \to \gamma$ oscillations, and 20% extragalactic background.

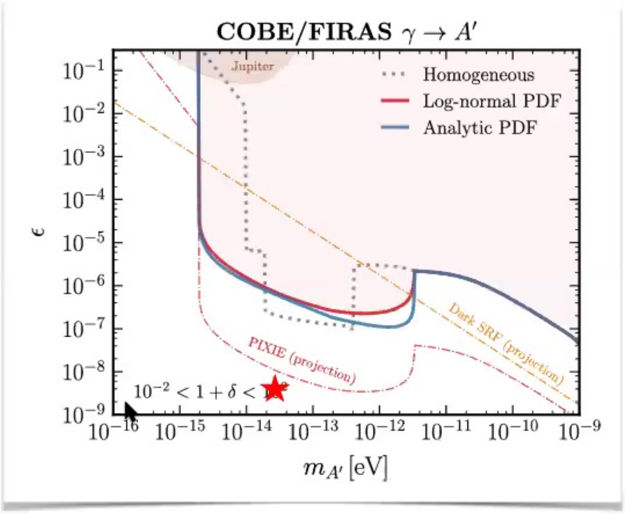
Parameters


PRELIMINARY
$\log_{10} m_a = -4.19^{+0.35}_{-0.25}$
$\log_{10} m_{A'} = -13.42^{+0.67}_{-0.68}$
$T_{A'}/T_0 = 0.23^{+0.11}_{-0.11}$
$g = 0.03^{+0.04}_{-0.02}$
$\log_{10} \epsilon = -8.14^{+0.75}_{-0.56}$
$T_0 = 2.72^{+0.00}_{-0.00}$
$\log_{10} m_a$
$\log_{10} m_{A'}$
$T_{A'}/T_0$
g
$\log_{10} \epsilon$
T_0
T_{exc} [K]
ν [GHz]
Point-wise median
Best-fit power law

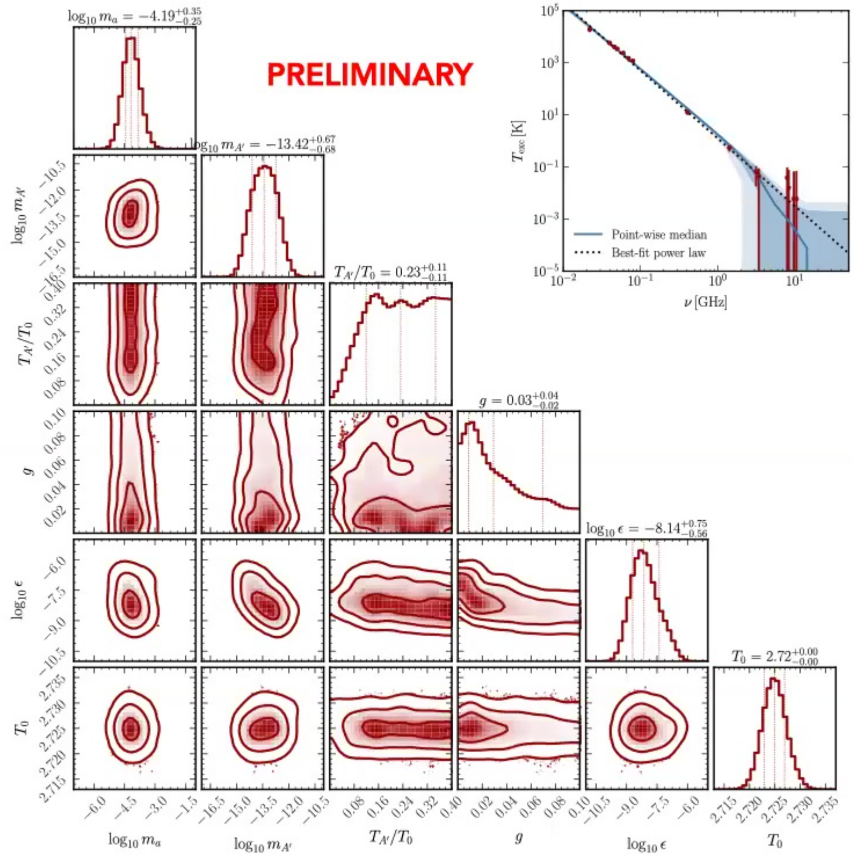

Hongwan Liu

Constraints

Caputo, **HL**, Mishra-Sharma & Ruderman 2002.05165



$m_{A'}$, ϵ consistent with $\gamma \to A'$ constraints shown earlier.



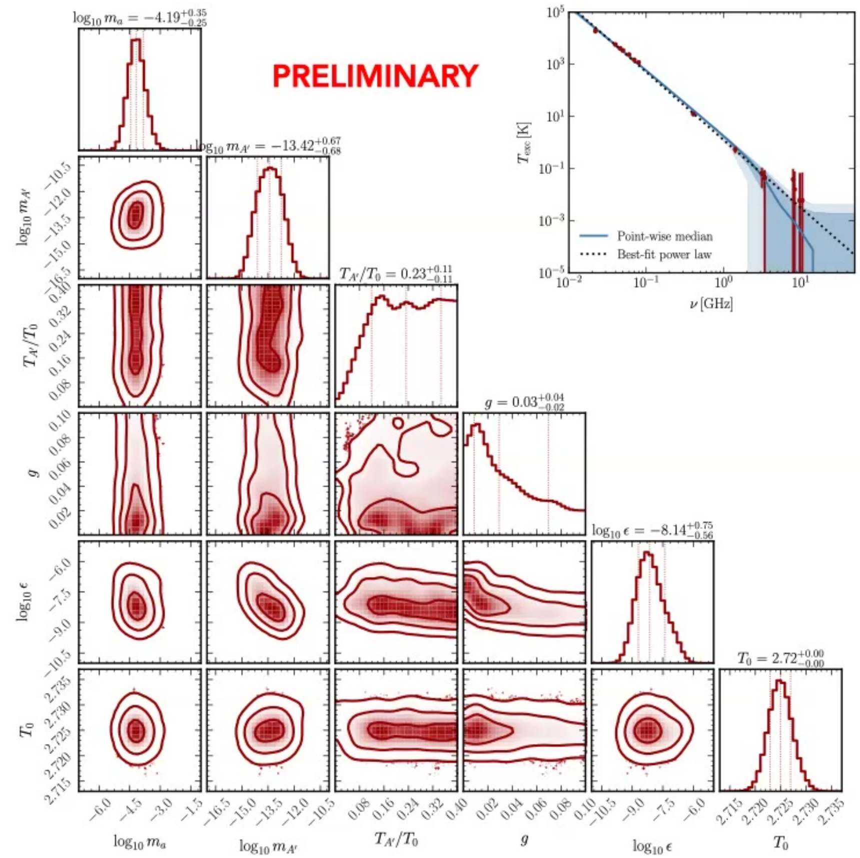
Constraints

Poulin+ 1606.02073

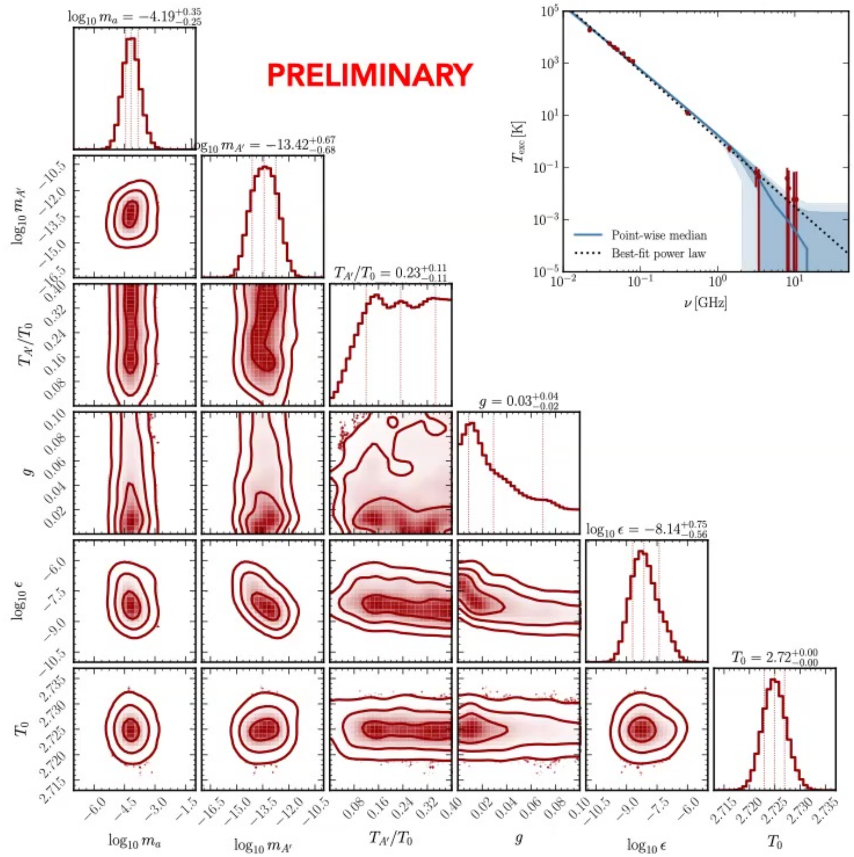
CMB constraint on DM lifetime is **159 Gyr**, with no stimulated emission.

With stimulated emission, we estimate from this constraint:

$$\tau > 840\,\text{Gyr} \times \frac{T_{A',0}}{m_a}$$



Constraints



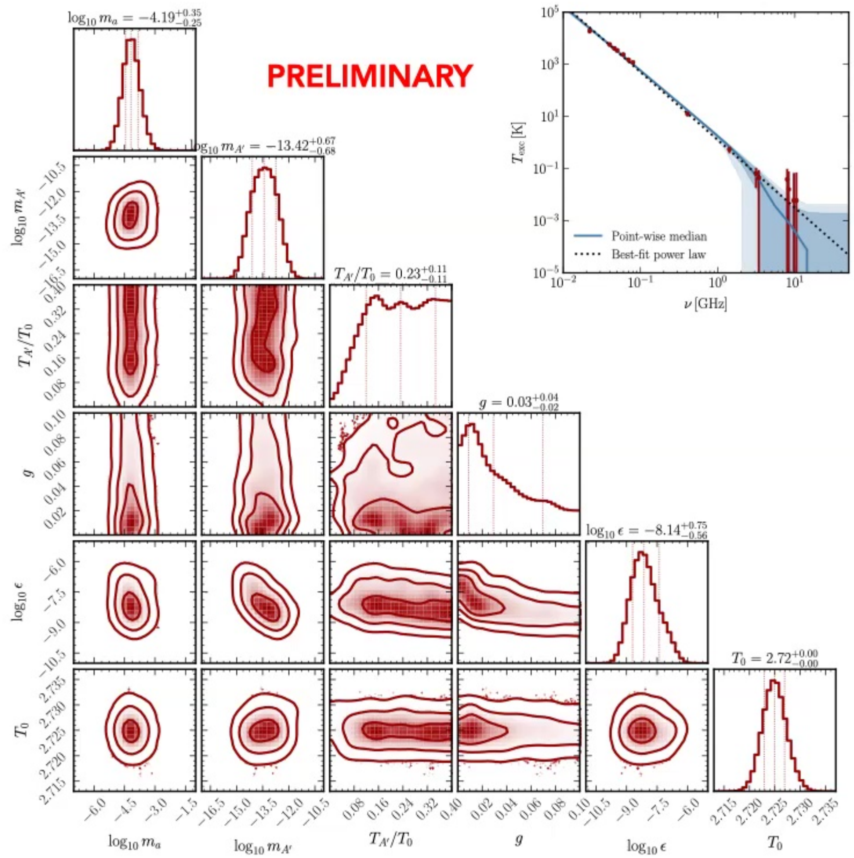
Pospelov+ 1803.07048

Stellar cooling constraints from $\gamma_T^* \to A'a$, $\epsilon g \lesssim 2 \times 10^{-9}\,\mathrm{GeV}^{-1}$.

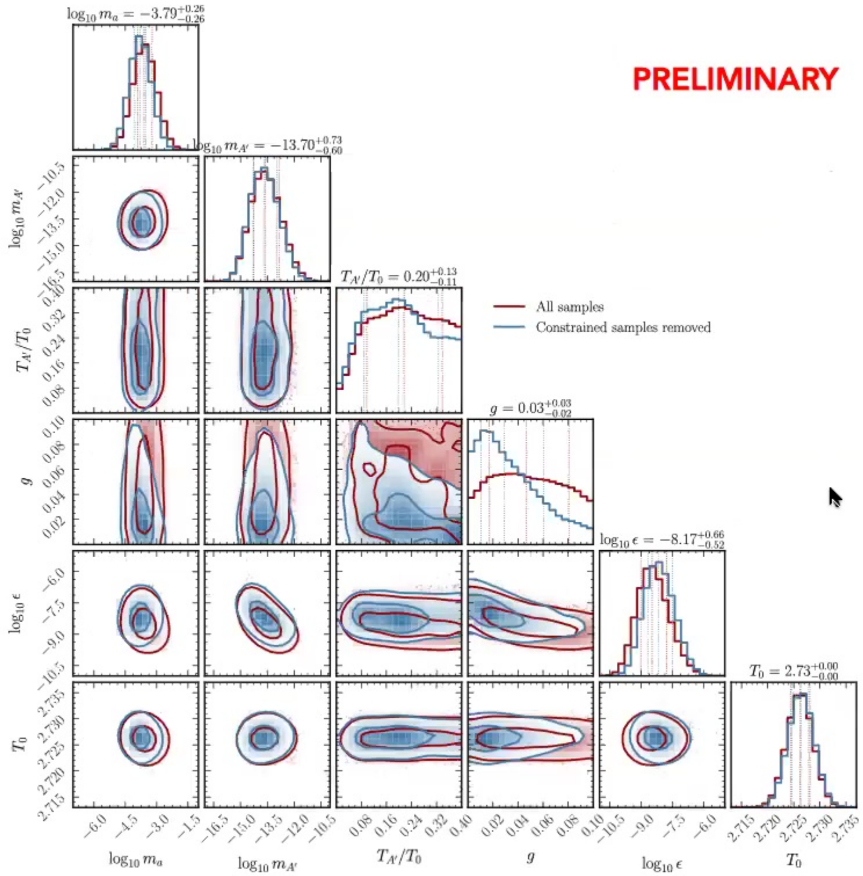
Constraints

Planck Collab. 1807.06209

Relic A' is relativistic, constrained by $\Delta N_{\rm eff} < 3.32$ or $T_{A'}/T_{\rm CMB} \lesssim 0.4$.



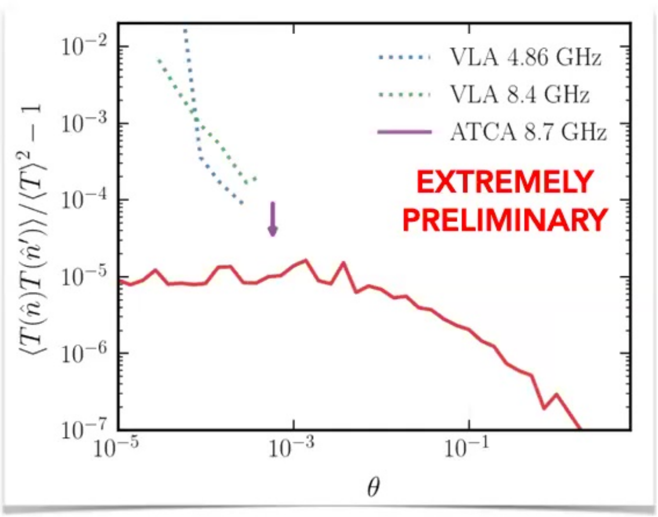
Constraints



PRELIMINARY

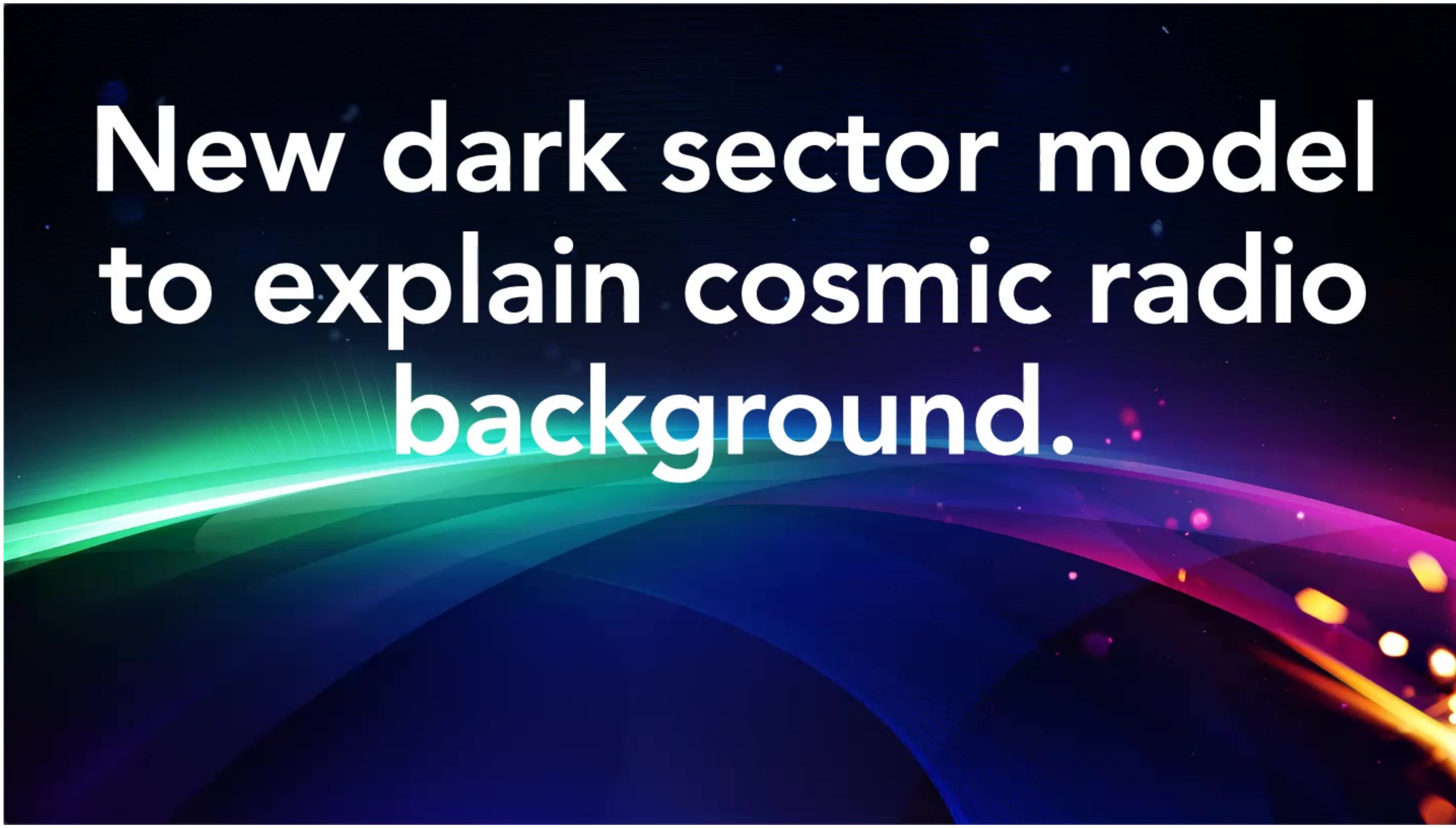
Existing experimental constraints **does not significantly affect central value of fit**.

Smoothness



$$\frac{\langle T_{\rm exc}(\hat{n})T_{\rm exc}(\hat{n}')\rangle}{\langle T_{\rm exc}\rangle^2} = \frac{\left\langle \int_{\hat{n}} dz \frac{dP_{A'\to\gamma}}{dz} \int_{\hat{n}'} dz' \frac{dP_{A'\to\gamma}}{dz'} \right\rangle}{\left\langle \int dz \frac{dP_{A'\to\gamma}}{dz} \right\rangle^2}$$

Still investigating, looks promising: conversions occur at **mean density regions**.


New dark sector model
to explain cosmic radio
background.


Hongwan Liu