Title: The Cosmological Evolution of Light Dark Photon Dark Matter

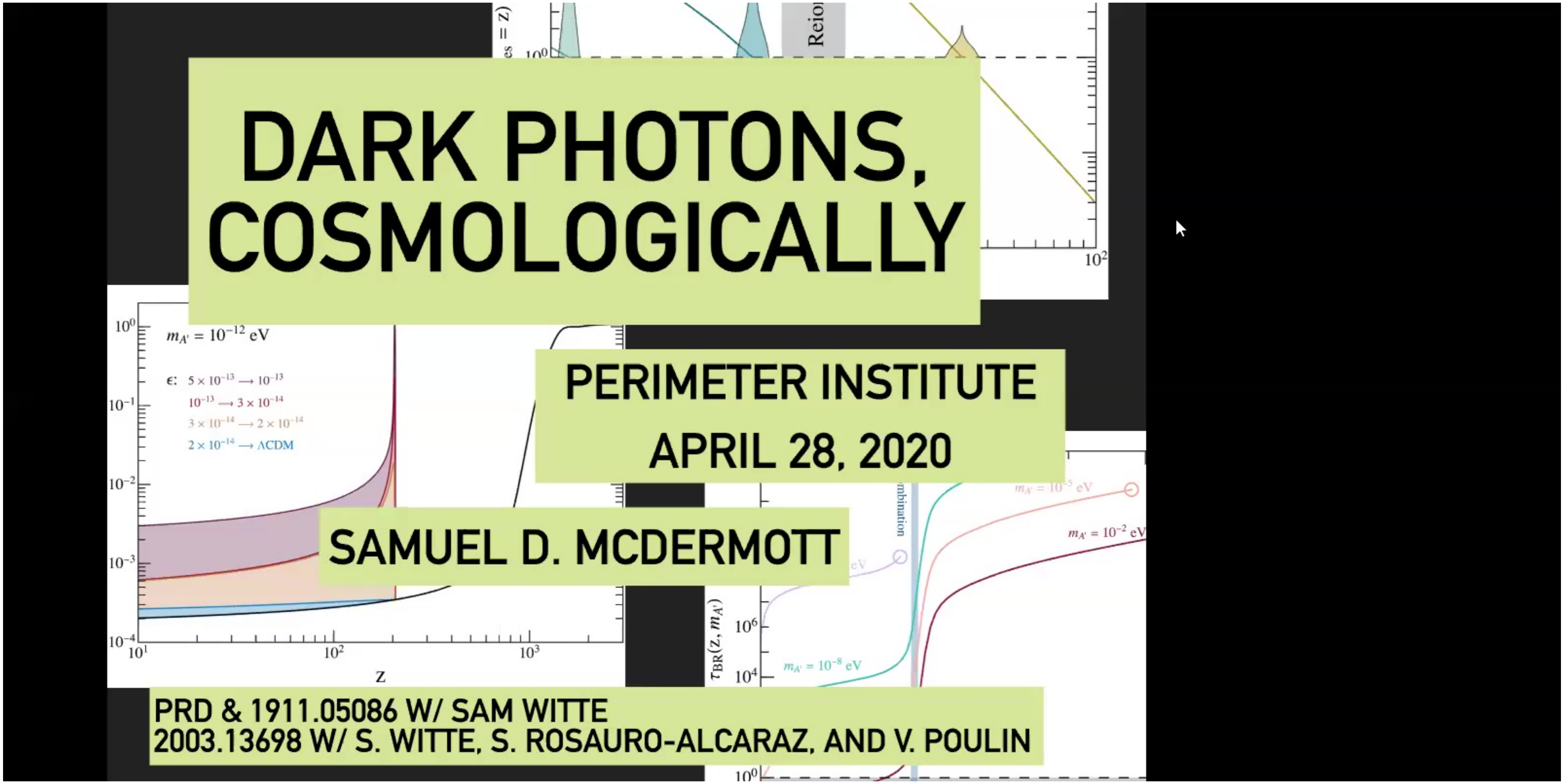
Speakers: Samuel McDermott

Series: Particle Physics

Date: April 28, 2020 - 2:00 PM

URL: http://pirsa.org/20040089

Abstract: Light dark photons are subject to various plasma effects, such as Debye screening and resonant oscillations, which can lead to a more complex cosmological evolution than is experienced by conventional cold dark matter candidates. Maintaining a consistent history of dark photon dark matter requires ensuring that the super-thermal abundance present in the early Universe (i) does not deviate significantly after the formation of the CMB, and (ii) does not excessively leak into the Standard Model plasma after BBN. In this talk, I will clarify the roles of resonant and non-resonant absorption and address some implications of plasma inhomogeneities on resonant transitions.


DARK PHOTONS, COSMOLOGICALLY
PERIMETER INSTITUTE
APRIL 28, 2020
SAMUEL D. MCDERMOTT
PRD & 1911.05086 W/ SAM WITTE
2003.13698 W/ S. WITTE, S. ROSAURO-ALCARAZ, AND V. POULIN

OUTLINE

I. **What?** $\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

II. **Why now?** better genesis mechanisms: starting ca 2015 continuing throughout 2019

III. **What's new?** ~5 orders of magnitude improvement in constraints over ~5 decades in dark matter mass + signals for future observatories

DARK MATTER CANDIDATES

THERMAL

- was once in thermal equilibrium with Standard Model
- need to get energy & entropy *out of* the dark matter sector
- “freeze out” paradigm

NONTHERMAL

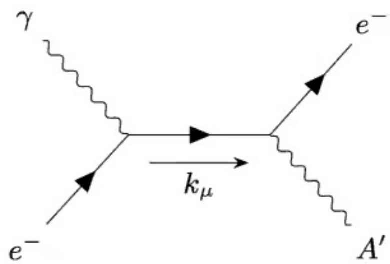
- never thermally equilibrated
- need to get (just the right amount of) energy *into* the dark matter sector
- misalignment, gravitational, …

"FREEZING IN" DARK PHOTONS AS DARK MATTER?

- needs to be stable, but if $m_{A'} \gg m_e$ then

$$\Gamma_{A' \to e^+ e^-} \simeq \epsilon^2 \alpha_{\rm EM} m_{A'}/3 \simeq 10^{40} \epsilon^2 \left(\frac{m_{A'}}{\rm GeV} \right) \tau_U^{-1}$$

- whereas rate for "semi-Compton" goes like



$$\frac{\Gamma_{e\gamma \to eA'}}{H} \sim \frac{\epsilon^2 n_e \sigma_T}{T^2/M_{\rm Pl}} \sim \frac{\epsilon^2 \alpha_{\rm EM}^2 M_{\rm Pl}}{T} \sim 10^{19} \epsilon^2 \left(\frac{\rm GeV}{T} \right)$$

MISALIGNING DARK PHOTON DARK MATTER?

- what about misalignment? axion field density goes like

$$\rho_a \simeq \rho_{\rm CDM} \times \left(\frac{f_a}{10^{12}{\rm GeV}}\right)^{7/6} \Theta_i^2 (1+z)^3$$

"just give it the right kick in the early universe"

MISALIGNING DARK PHOTON DARK MATTER?

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- however, vector modes redshift differently $\Longrightarrow$ misalignment doesn't work for A'

cf. Arias et al. JCAP 1201.5902
Graham, Mardon, Rajendran PRD 1504.02102

NEW PRODUCTION CHANNELS

- inflationary production: $m_{A'} \gtrsim 10\mu\text{eV}$

Vector Dark Matter from Inflationary Fluctuations

1504.02102

Peter W. Graham,[1] Jeremy Mardon,[1,*] and Surjeet Rajendran[2]

Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305

[2]*Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720*

NEW PRODUCTION CHANNELS

- misalignment followed by decay or preheating / parametric resonance

Parametric Resonance Production of Ultralight Vector Dark Matter

1810.07195 Jeff A. Dror,[1,2] Keisuke Harigaya,[3,1,2] and Vijay Narayan[1]

[1] *Berkeley Center for Theoreti*
University of Californi
[2] *Theoretical Physics Group, Lawrence Berke*
[3] *School of Natural Sciences, Institute*

1810.07188 **Relic Abundance of Dark Photon Dark Matter**

Prateek Agrawal,[1] Naoya Kitajima,[2] Matthew Reece,[1] Toyokazu Sekiguchi,[3] and Fuminobu Takahash

[1] *Jefferson Physical Laboratory, Harvard University, 17 Oxford Street, Cambridge, MA 02138, USA*
cs, Nagoya University, Chikusa, Nagoya 464-8602, Japan
for the Early Universe (RESCEU),

Dark Photon Dark Matter from a Network of Cosmic Strings

Andrew J. Long

Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbo

1901.03312

Lian-Tao Wang

itute for Cosmological Physics and Enrico Fermi Institute, University of Chic

(Dated: March 19, 2019)

e study the production of ultralight dark photons from a netwo
gs. We find that dark photons produced in this way are nonrelativ
er for dark photon masses as small as $m_A \sim 10^{-22}$ eV.

Vector dark matter production at the end of inflation

1810.07208

Mar Bastero-Gil,[1,*] Jose Santiago,[1,†] Lorenzo Ubaldi,[2,3,‡] and Roberto Vega-Morales

[1] *Departamento de Física Teórica y del Cosmos and CAFPE,*
Universidad de Granada, Campus de Fuentenueva, E-18071 Granada, Spain
[2] *SISSA International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy*
Spain

Dark Photon Dark Matter Produced by Axion Oscillations

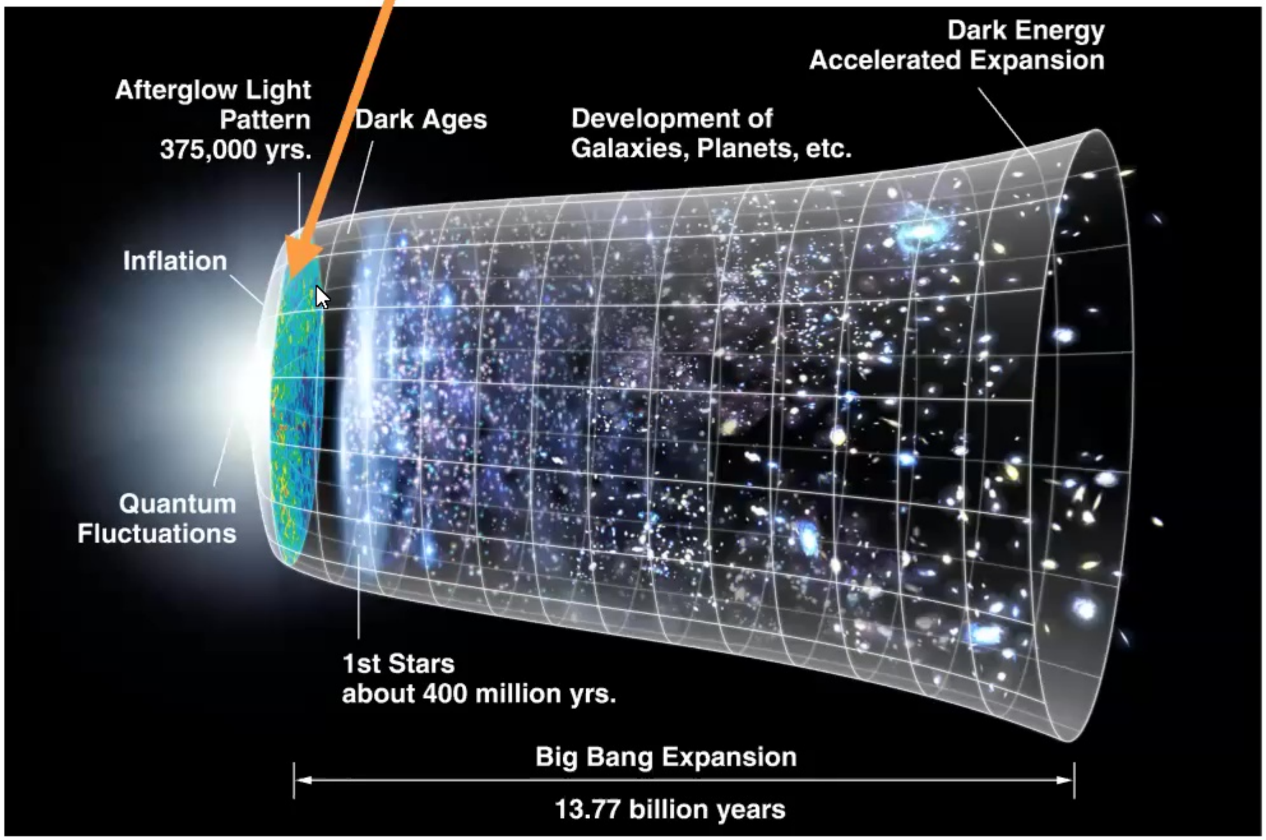
1810.07196

Raymond T. Co,[1] Aaron Pierce,[1] Zhengkang Zhang,[1,2,3] and Yue Zhao[1,4]

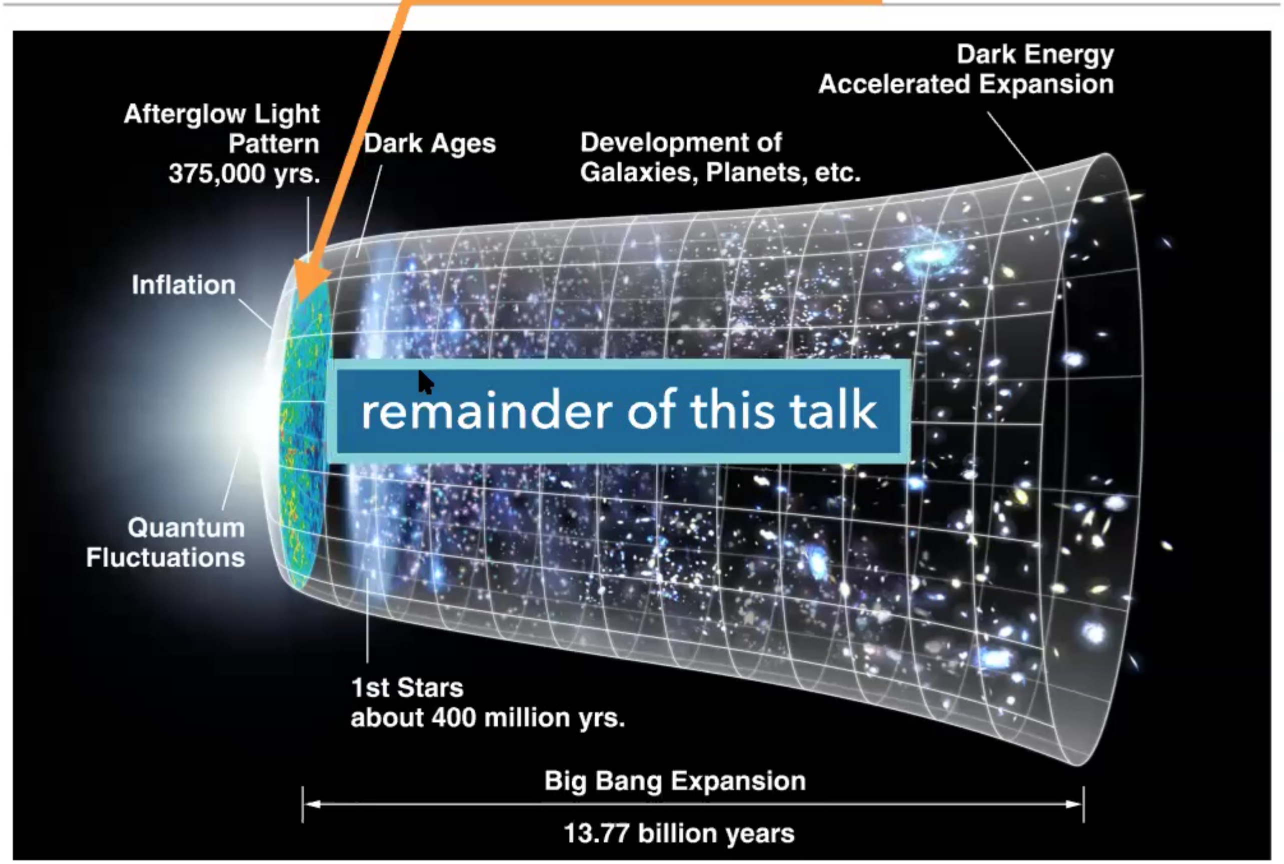
[1] *Leinweber Center for Theoretical Physics, Department of Physics,*
University of Michigan, Ann Arbor, MI 48109, USA
[2] *Department of Physics, University of California, Berkeley, CA 94720, USA*


WHAT DO WE HAVE?
DARK PHOTON DARK MATTER
WHAT ARE WE GOING TO DO WITH IT?
THINK ABOUT HOW TO CONSTRAIN AND/OR OBSERVE IT
imgflip.com

"initial conditions"



“initial conditions”



DARK PHOTONS AND REGULAR PHOTONS

unique interaction with Standard Model

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} F^{\mu\nu}/2 \Longleftrightarrow$$

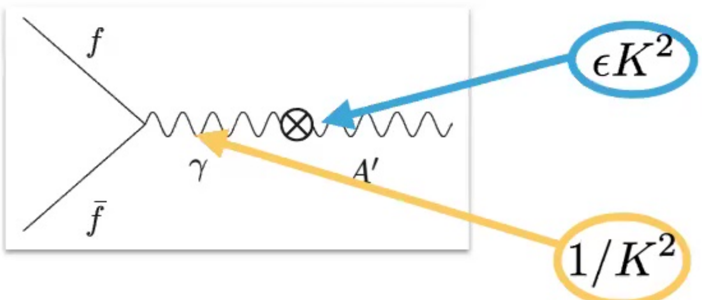
$$\partial_\mu \partial^\mu \to K^2$$

first Okun 1982 Holdom 1986
then Jaeckel, Redondo, Ringwald 0804.4157 Pospelov, Ritz, Voloshin 0807.3279
Redondo and Postma 0811.0326 Mirizzi, Redondo, Sigl 0901.0014

COUPLING TO DARK PHOTON

in vacuum:

$$\mathcal{L} \supset \epsilon J_\mu^{\rm SM} A'^\mu$$



“PLASMAS GIVE PHOTON A MASS”

nonzero density of free electrons modifies the SM photon dispersion relation:

$$\boxed{\omega^2 \simeq k^2 + \omega_p^2}^{*}$$

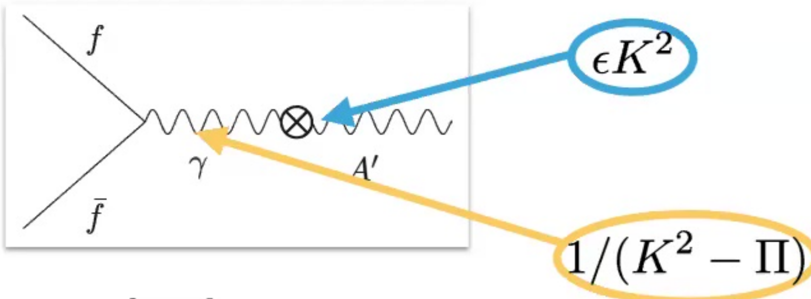
plasma mass: $\omega_p(m_e) \simeq \sqrt{4\pi\alpha_{\mathrm{EM}} n_e / m_e}$

*this is not a real mass (in reality $\omega_p \to \Pi$, the SM photon self-energy, which is momentum-dependent)

PHOTON MIXING IN PLASMA

in vacuum:

$$\mathcal{L} \supset \epsilon J_\mu^{\mathrm{SM}} A'^\mu$$



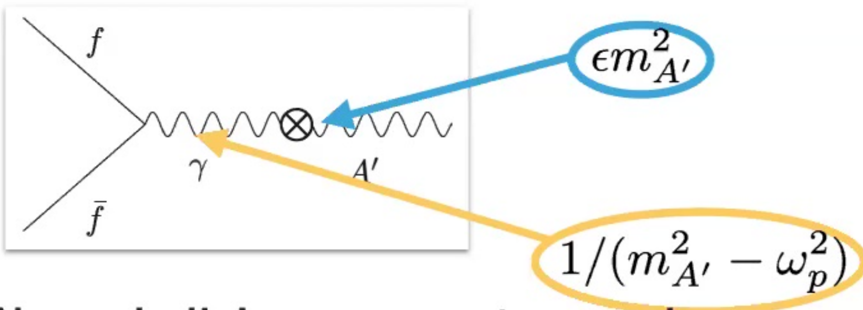
in plasma:

$$\mathcal{L} \supset \frac{\epsilon K^2}{K^2 - \Pi} J_\mu^{\mathrm{SM}} A'^\mu$$

PHOTON MIXING IN PLASMA

in vacuum:

$$\mathcal{L} \supset \epsilon J_\mu^{\rm SM} A'^\mu$$



in plasma, γ & A' on-shell, low-momentum exchange:

$$\mathcal{L} \supset \frac{\epsilon}{1 - \omega_p^2/m_{A'}^2} J_\mu^{\rm SM} A'^\mu$$

DARK PHOTON COSMOLOGY

- SM photon: $\omega_p = \sqrt{\frac{4\pi\alpha\eta_b x_e T_{\rm CMB}^3}{m_e}} \simeq {\rm neV}\left(\frac{1+z}{1+z_{\rm CMB}}\right)^{3/2}$

$$\simeq {\rm MHz}\left(\frac{1+z}{1+z_{\rm CMB}}\right)^{3/2}$$

- Plasma effects are of qualitative importance for cosmological evolution of dark photons below this mass
- Can experience a level crossing – populations determined by Landau-Zener-type formula

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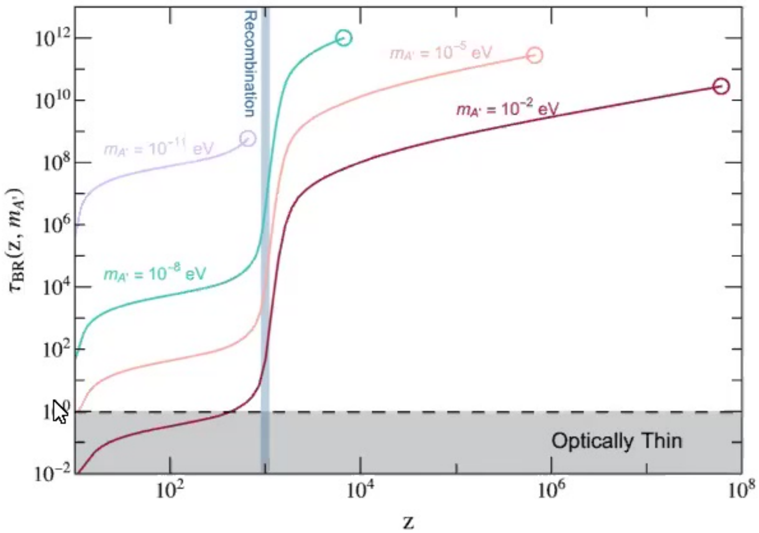
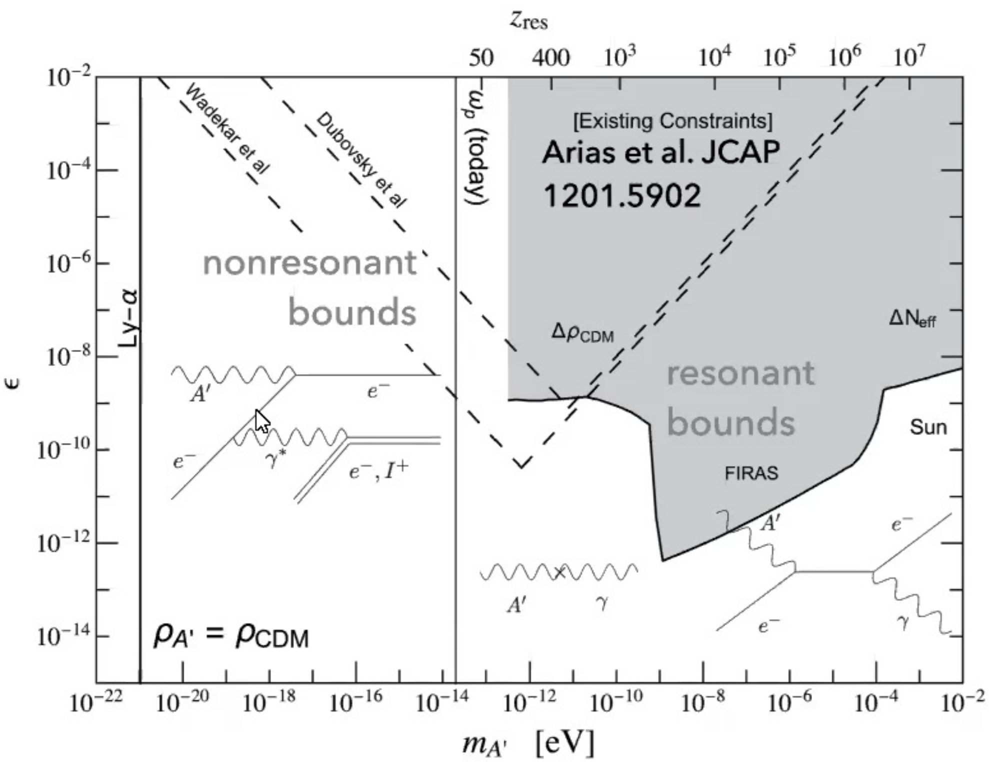
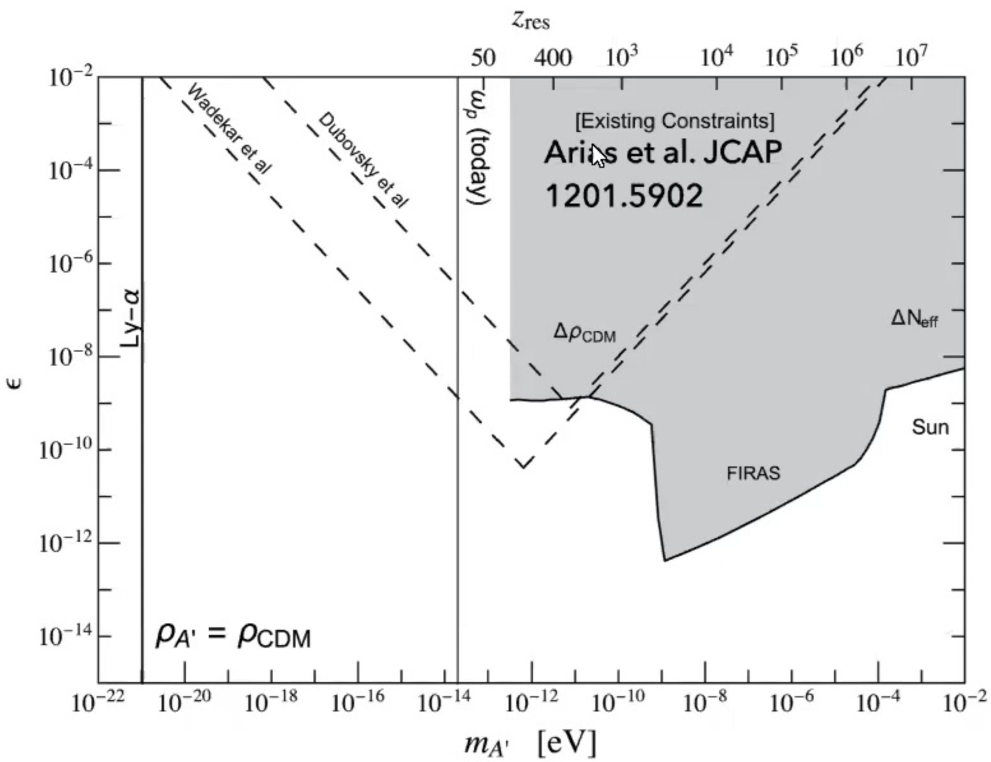
DARK PHOTON COSMOLOGY



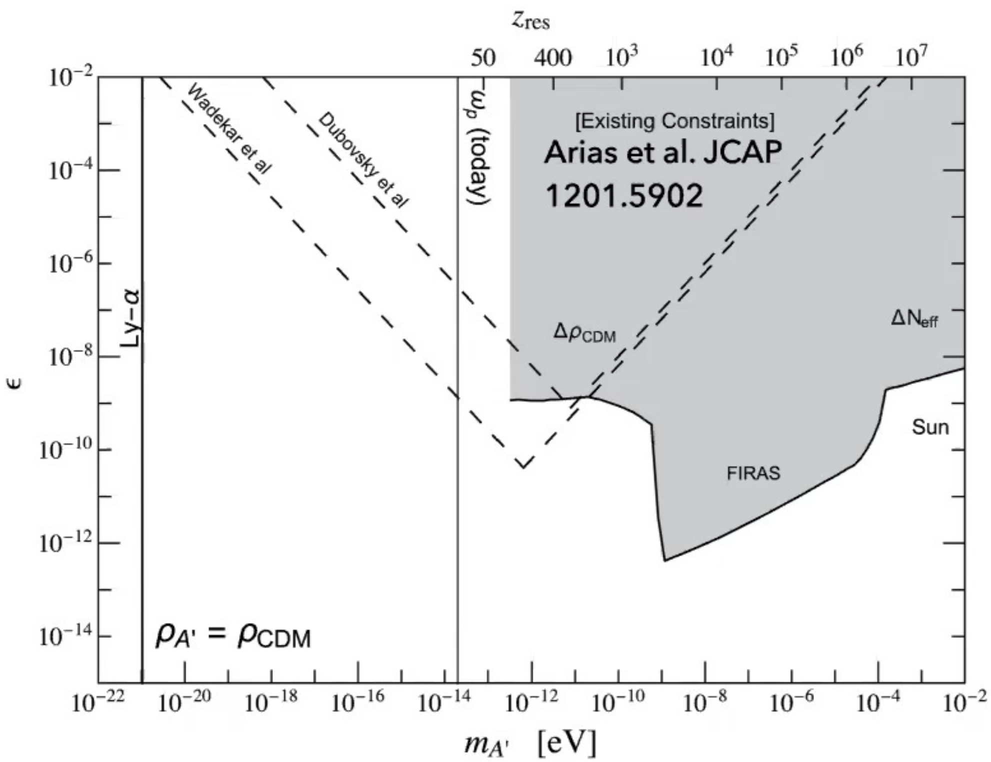
any dark photon in the ~neV mass range that converts to a photon "instantly" heats the medium



z_{res}
50
400
10^3
10^4
10^5
10^6
10^7
Wadekar et al
Dubovsky et al
ω_p (today)
[Existing Constraints]
Arias et al. JCAP
1201.5902
nonresonant
bounds
Ly−α
$\Delta\rho_{CDM}$
ΔN_{eff}
resonant
bounds
Sun
FIRAS
A'
e^-
γ^*
e^-, I^+
γ
$\rho_{A'} = \rho_{CDM}$
ϵ
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-22} 10^{-20} 10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2}
$m_{A'}$ [eV]

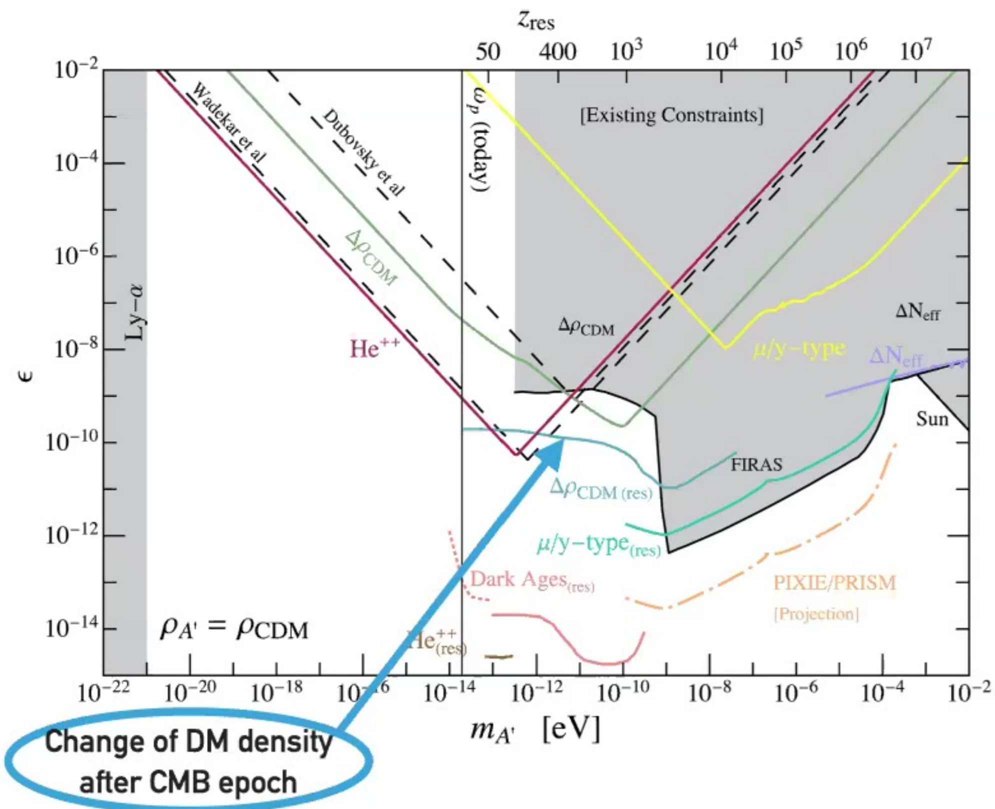


$$\Delta\rho_{\text{CDM}} \iff \text{Prob}_{A'\to\gamma} = \exp(-1)$$



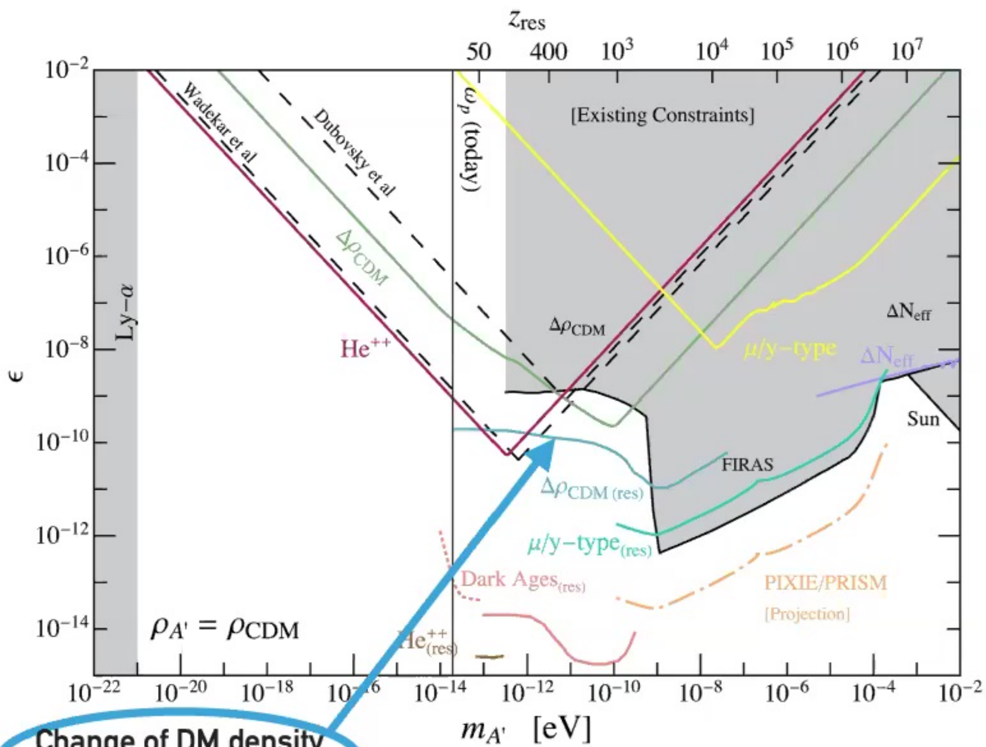
$\Delta\rho_{\rm CDM} \iff {\rm Prob}_{A'\to\gamma} = \exp(-1)$ $\Longleftarrow$ **depleting Ω_{CDM} by 30%!**

SDM and Witte 1911.05086



$$\Delta\rho_{A'}|_{\text{on resonance}} \lesssim 1\% \rho_{A'}$$

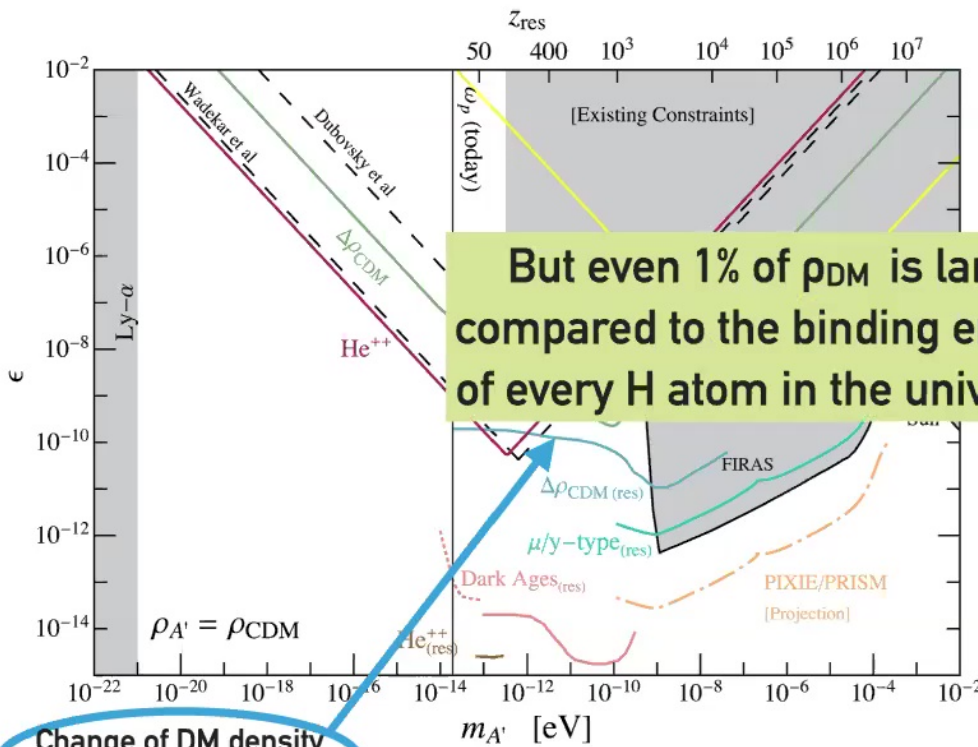
SDM and Witte 1911.05086



Change of DM density after CMB epoch

$$\Delta\rho_{A'}|_{\text{on resonance}} \lesssim 1\%\rho_{A'}$$

SDM **and Witte 1911.05086**

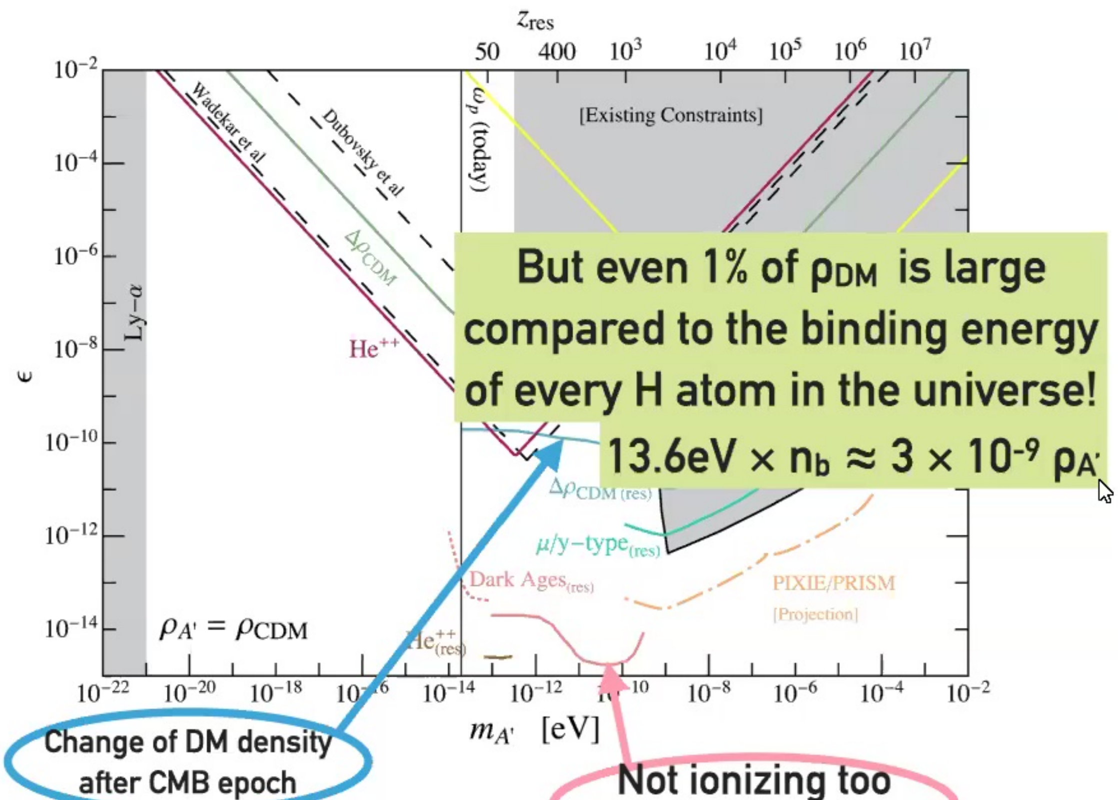


But even 1% of ρ_{DM} is large compared to the binding energy of every H atom in the universe!

Change of DM density after CMB epoch

$$\Delta\rho_{A'}|_{\text{on resonance}} \lesssim 1\%\rho_{A'}$$

SDM and Witte 1911.05086



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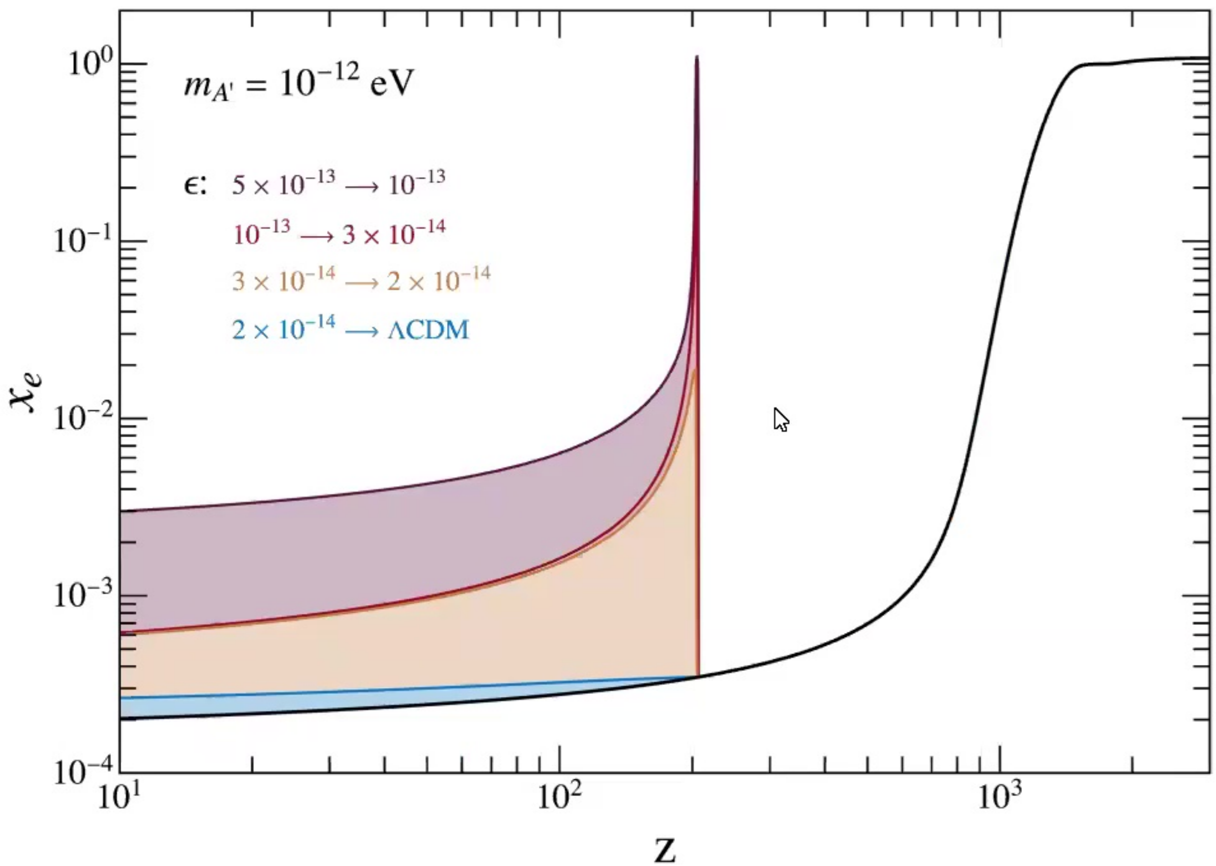
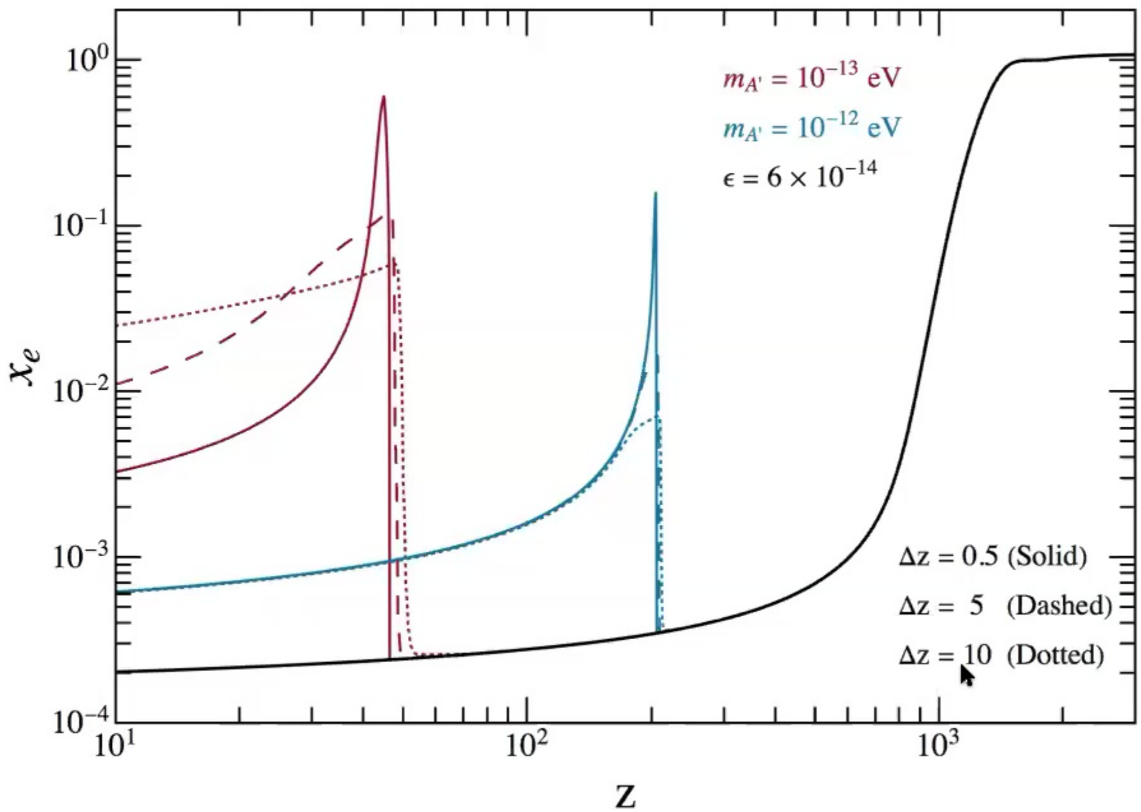
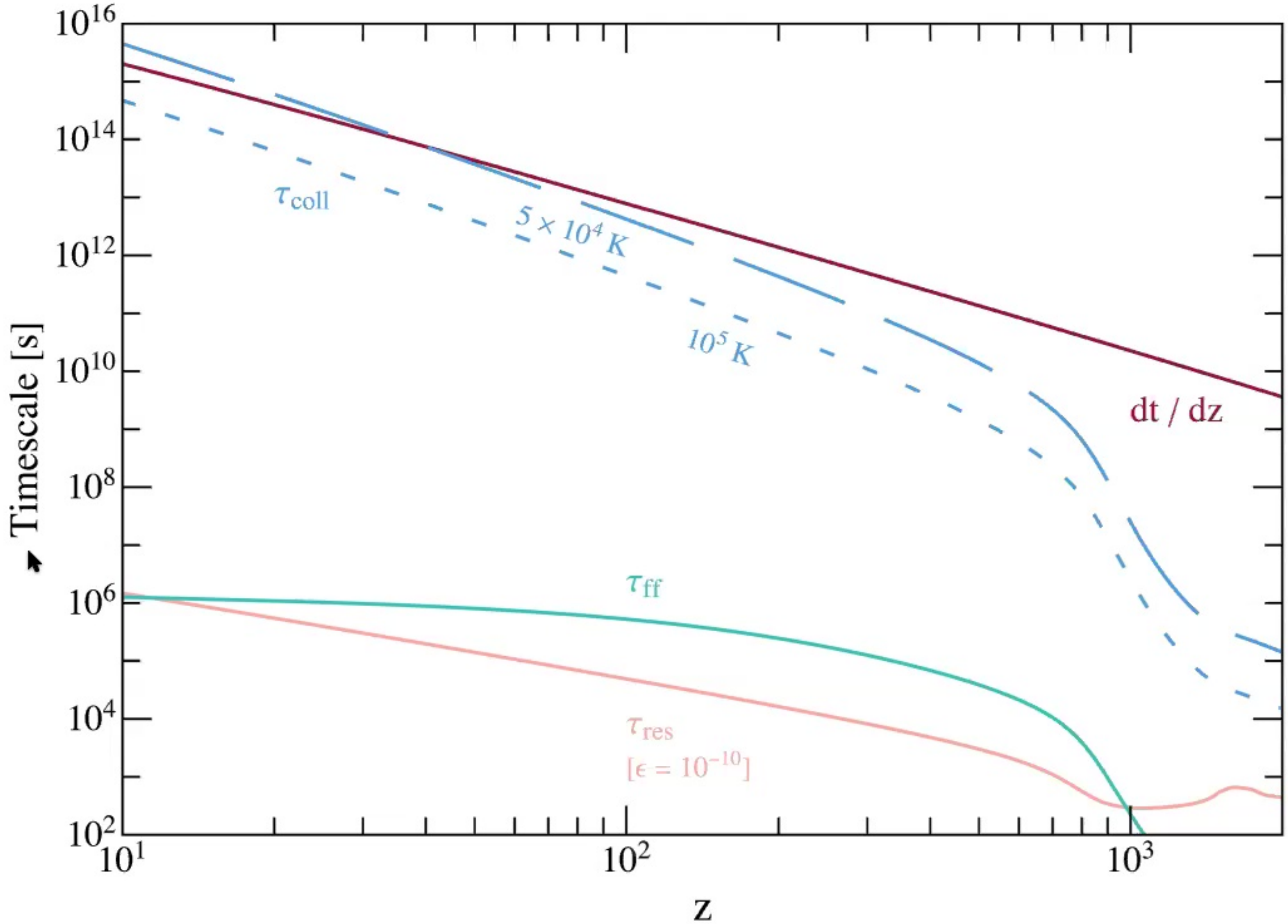


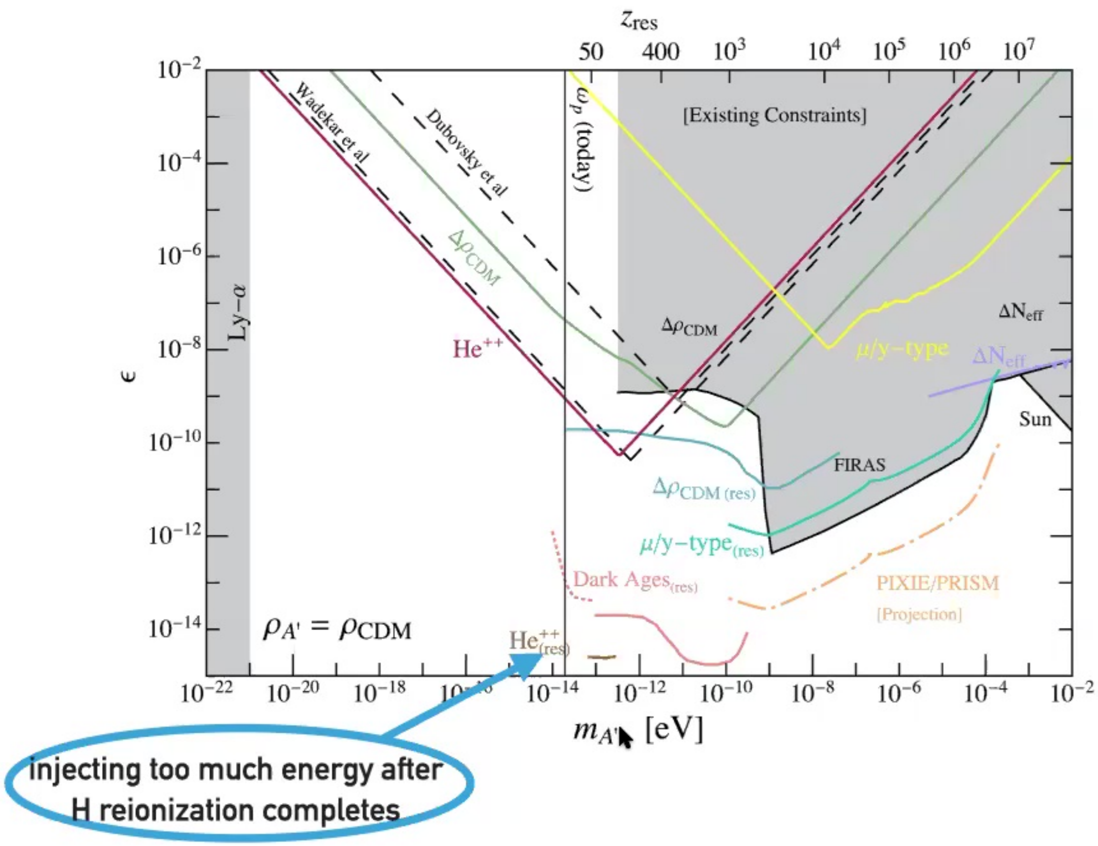
Witte, Rosauro-Alcaraz, *SDM*, Poulin 1911.05086

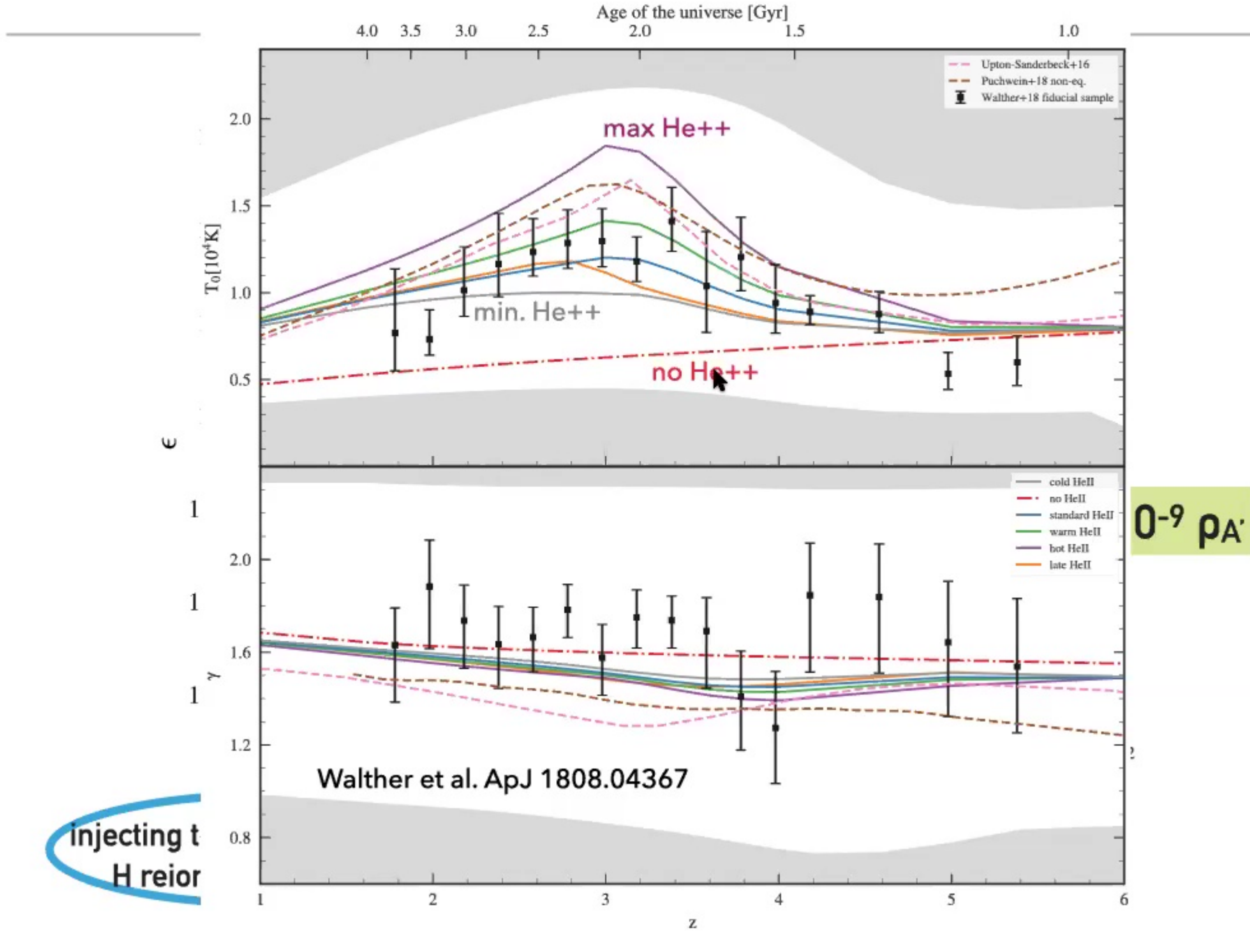




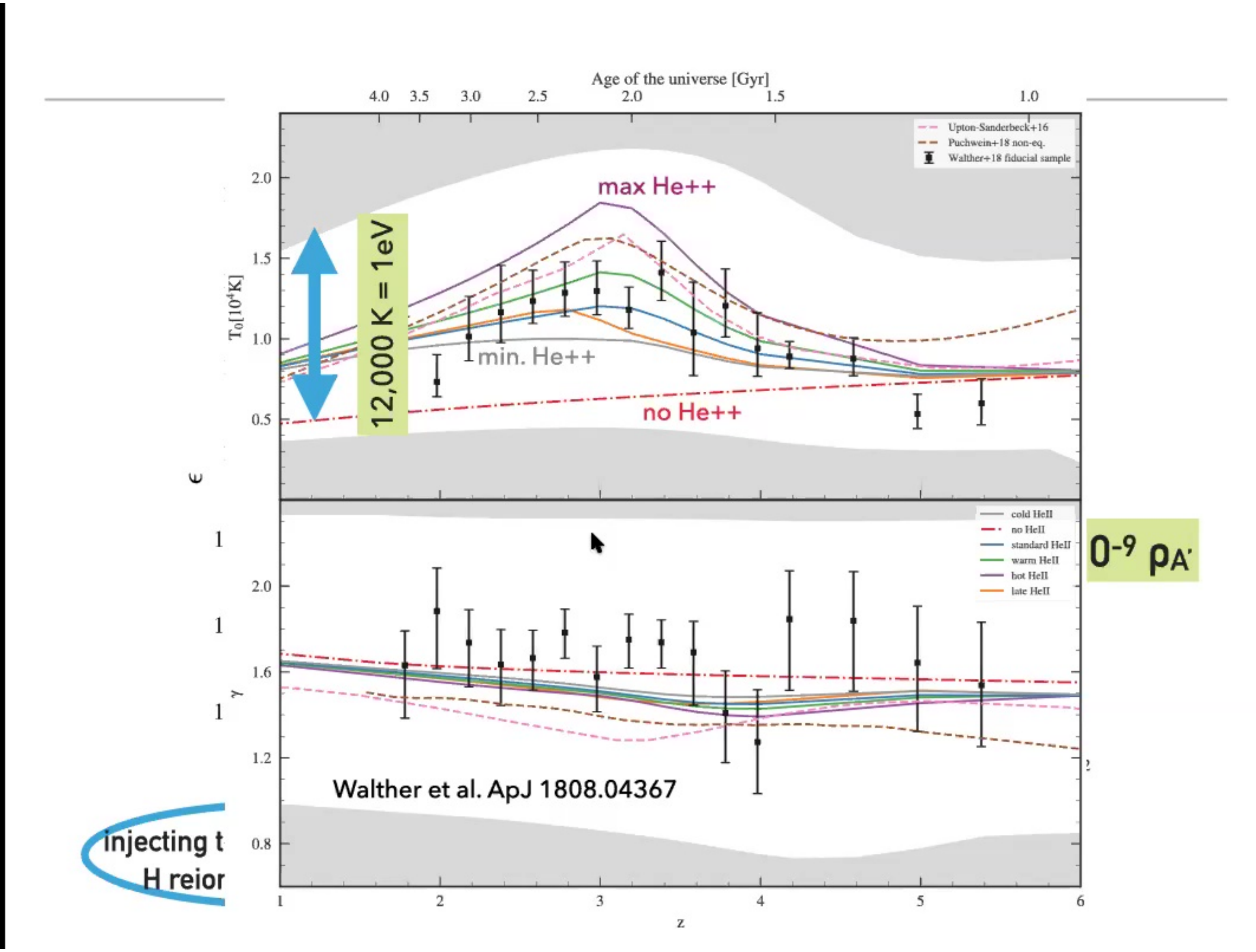
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
Timescale [s]
$\tau_{\rm coll}$
5×10^4 K
10^5 K
dt / dz
$\tau_{\rm ff}$
$\tau_{\rm res}$
$[\epsilon = 10^{-10}]$
10^{1}
10^{2}
10^{3}
z

SDM and Witte 1911.05086





Age of the universe [Gyr]
max He++
min. He++
no He++
Upton-Sanderbeck+16
Puchwein+18 non-eq.
Walther+18 fiducial sample
cold HeII
no HeII
standard HeII
warm HeII
hot HeII
late HeII
Walther et al. ApJ 1808.04367
injecting t
H reior
0-9 ρA'



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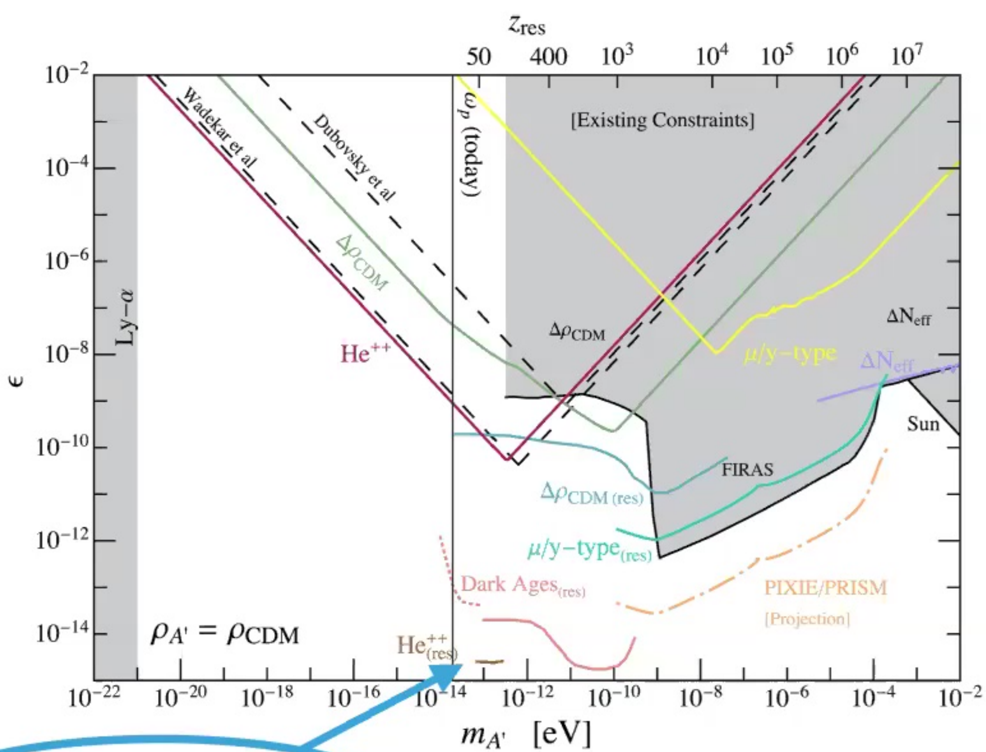


$$\Delta\rho_{\rm CDM} \leq 1\text{eV}\ n_b$$

Witte, Rosauro-Alcaraz, *SDM*, Poulin 2003.13698

INHOMOGENEITIES

- so far all bounds are in the homogeneous limit: there is one special redshift at which $m_{A'} = \omega_p$

$$\frac{d}{dz} P^{\rm homo}_{A'\to\gamma}(z) \simeq \frac{\pi \epsilon^2 m_{A'}}{3H(z)} \delta(z - z^{\rm homo}_{\rm res})$$

- including effects of inhomogeneous structure

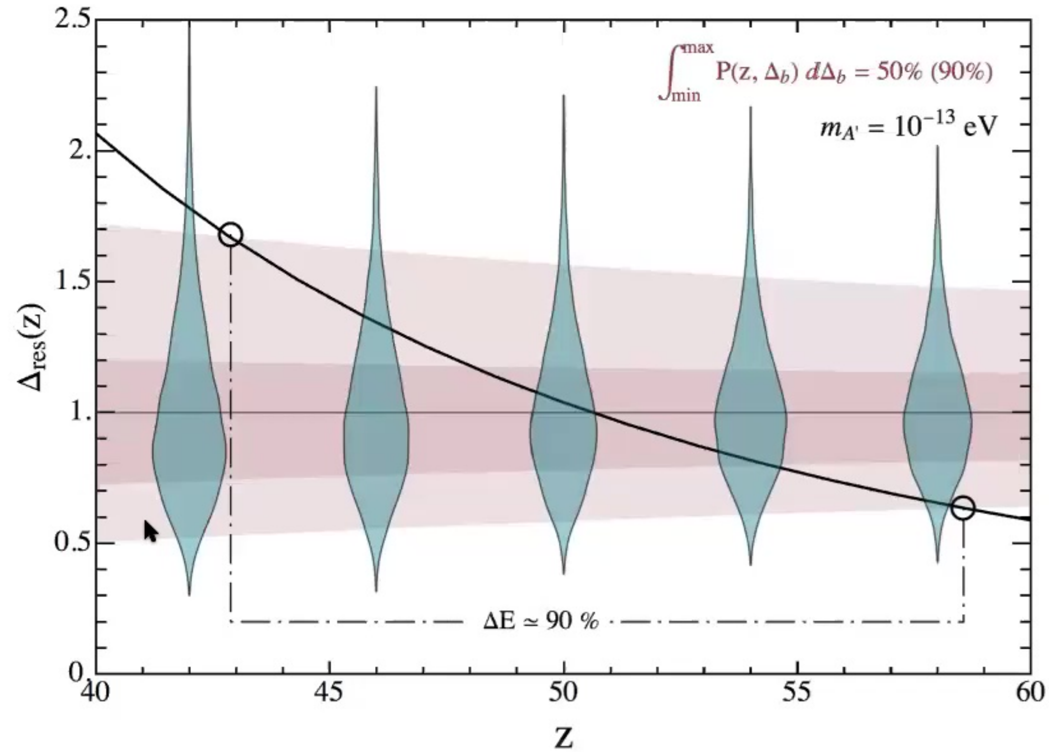
$$\frac{d}{dz} P_{A'\to\gamma}(z, \Delta_b) \simeq \frac{\pi \epsilon^2 m_{A'}}{3H(z)} \delta\left(z - z_{\rm res}(\Delta_b, m_{A'})\right)$$

now depends on overdensity Δ_b

see also Caputo, Liu, Mishra-Sharma, Ruderman 2002.05165 and 2004.06733

Witte, Rosauro-Alcaraz, *SDM*, Poulin 2003.13698

INHOMOGENEITIES



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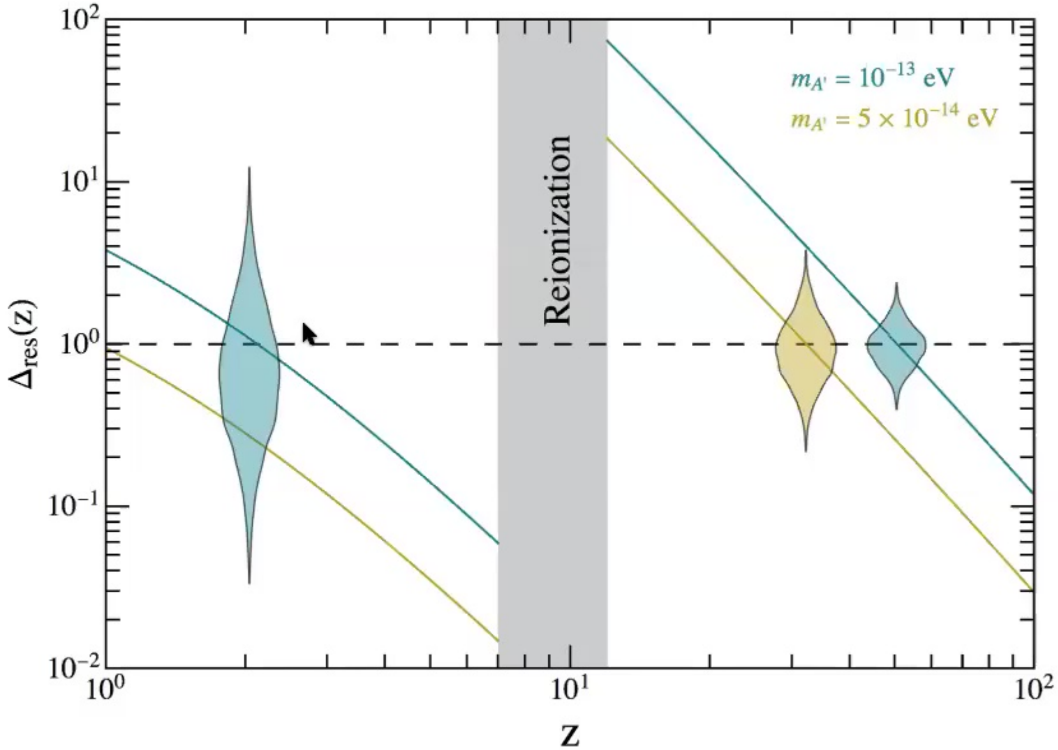
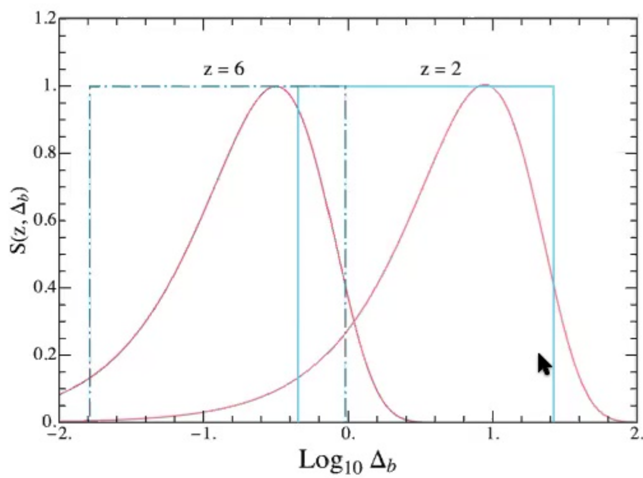
INHOMOGENEITIES



Witte, Rosauro-Alcaraz, *SDM*, Poulin 2003.13698

INHOMOGENEITIES

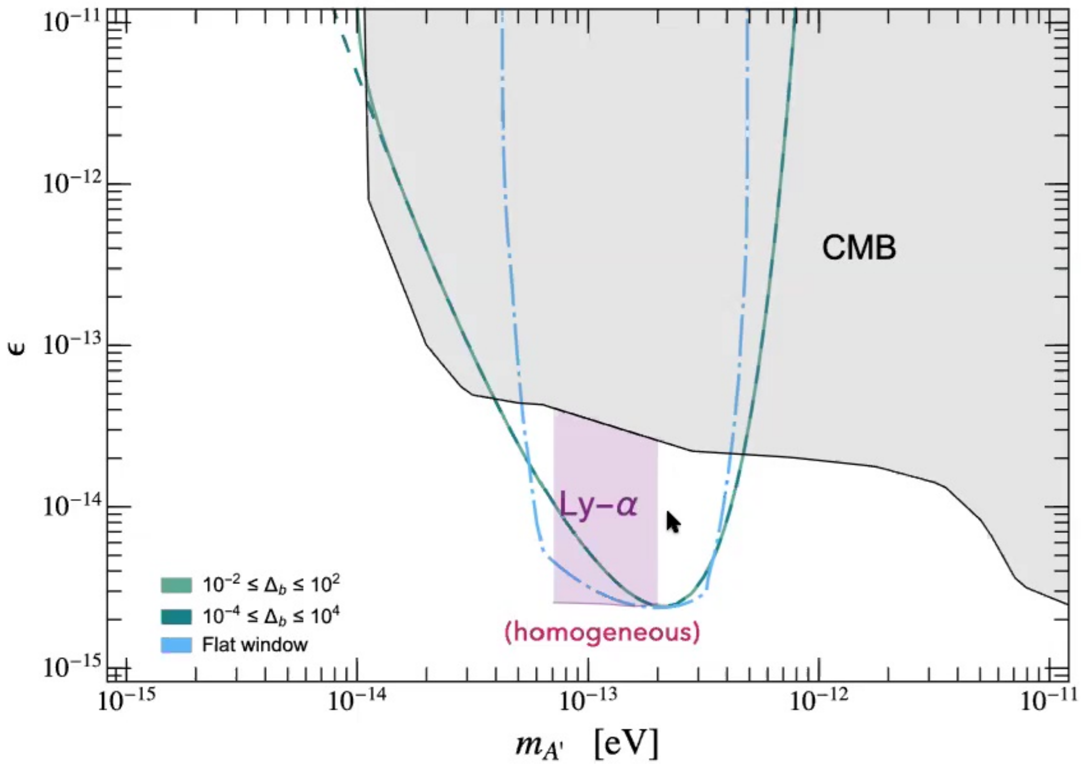
- constraints now depend on models of inhomogeneous structure formation and the observables of choice

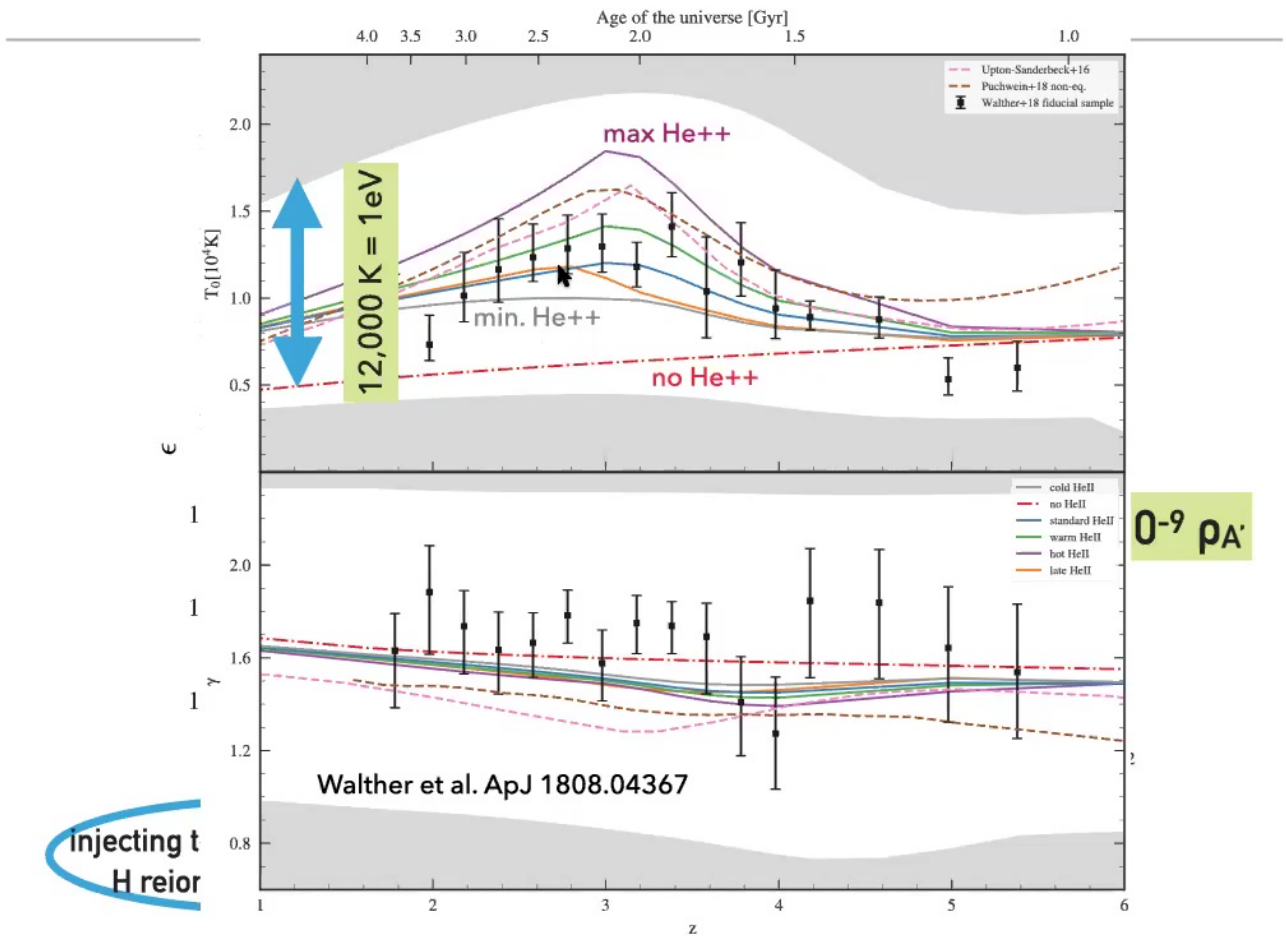


- e.g., observations during He++ epoch probed by Ly-α

Witte, Rosauro-Alcaraz, *SDM*, Poulin 2003.13698

INHOMOGENEITIES





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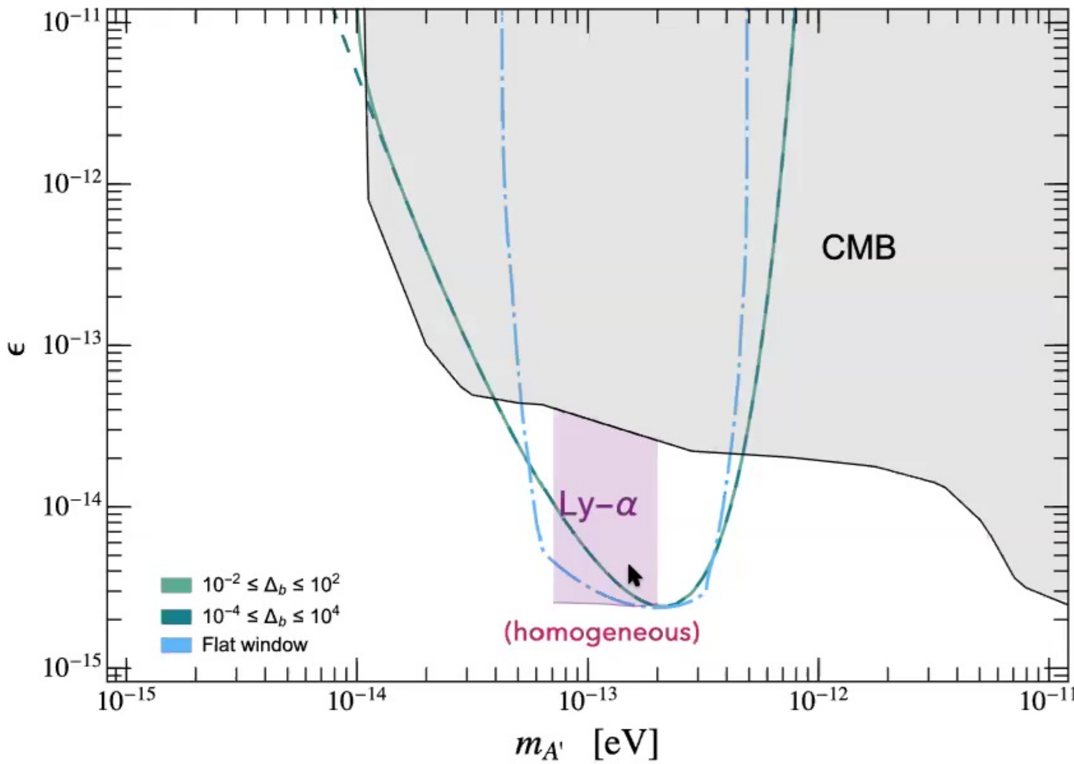
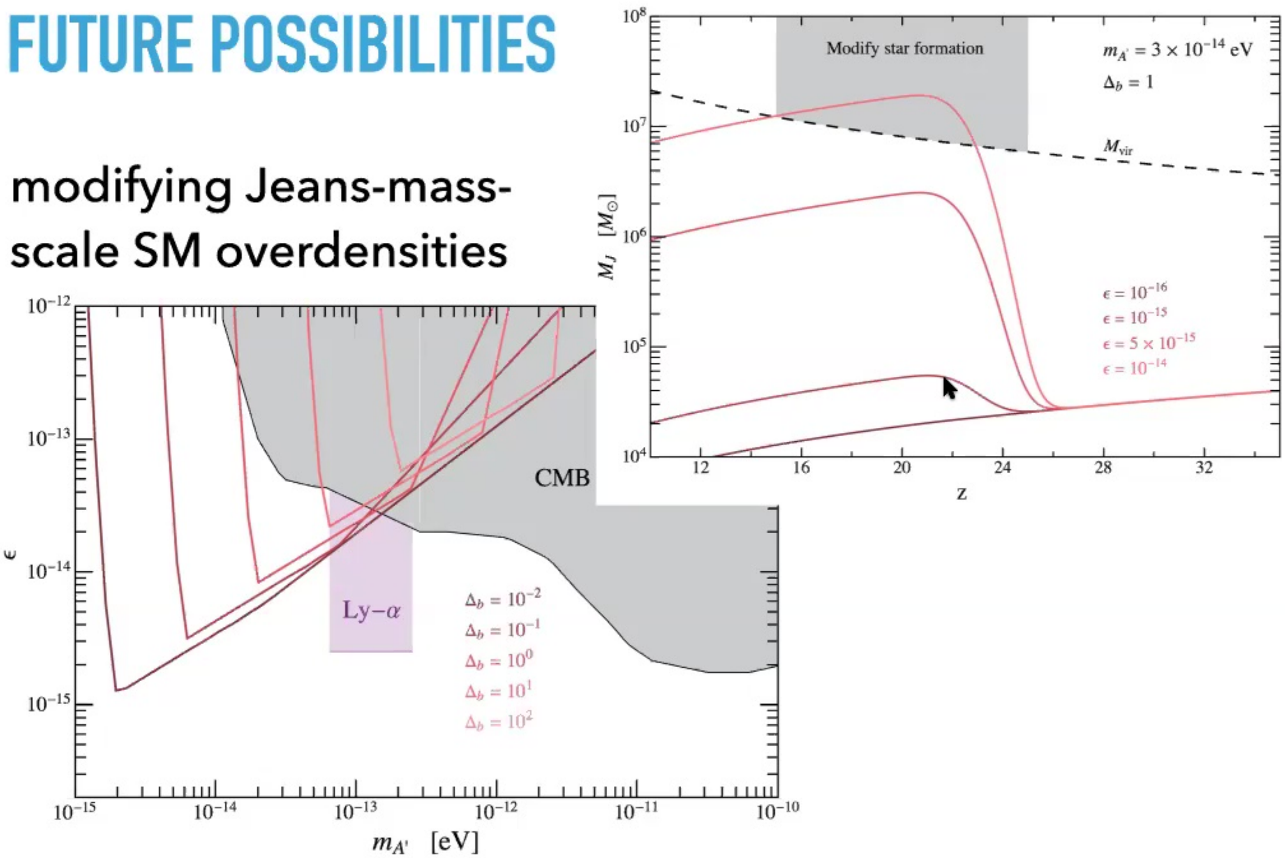
INHOMOGENEITIES



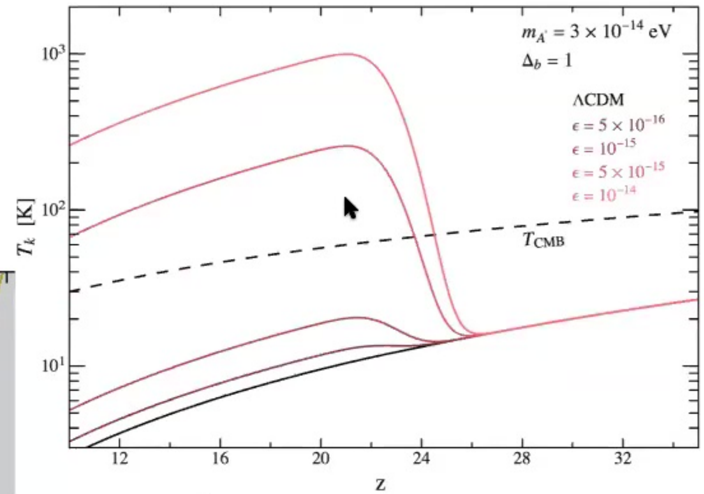
FUTURE POSSIBILITIES

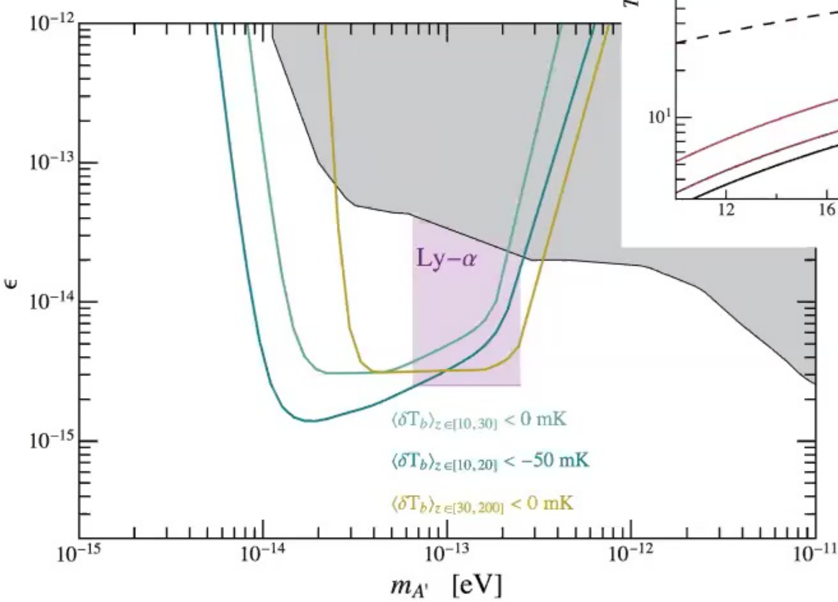
modifying Jeans-mass-scale SM overdensities



FUTURE POSSIBILITIES

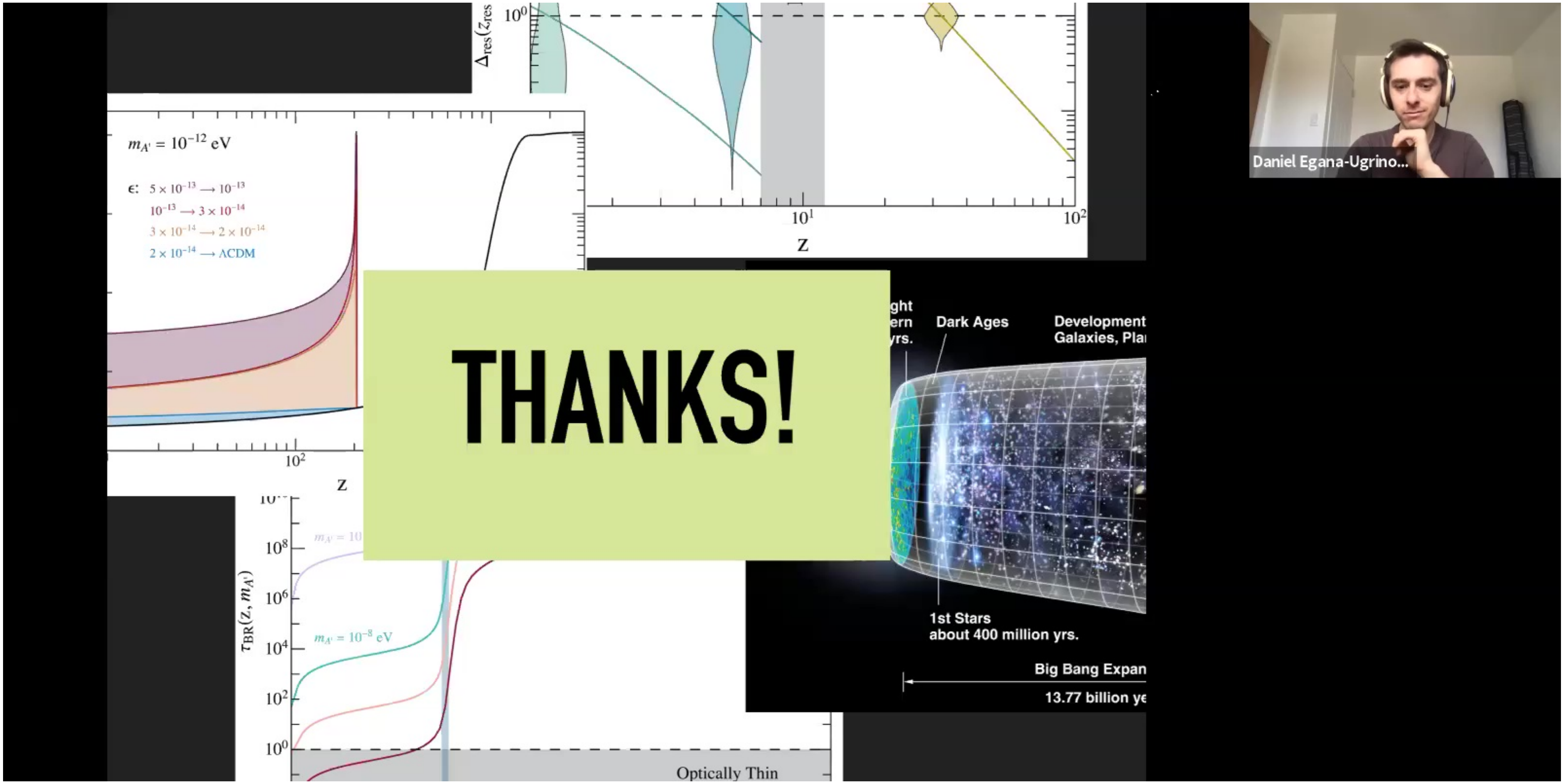
modifying 21cm signal





CONCLUSIONS

- Our understanding of dark photon dark matter has been changing qualitatively over the last few years
- Plasma mass leads to novel signatures unlike canonical dark matter scenarios
- Late-time conversion leads to exciting possibilities for future observations


THANKS!
Daniel Egana-Ugrino...
$m_{A'} = 10^{-12}$ eV
Dark Ages
1st Stars
about 400 million yrs.
Optically Thin