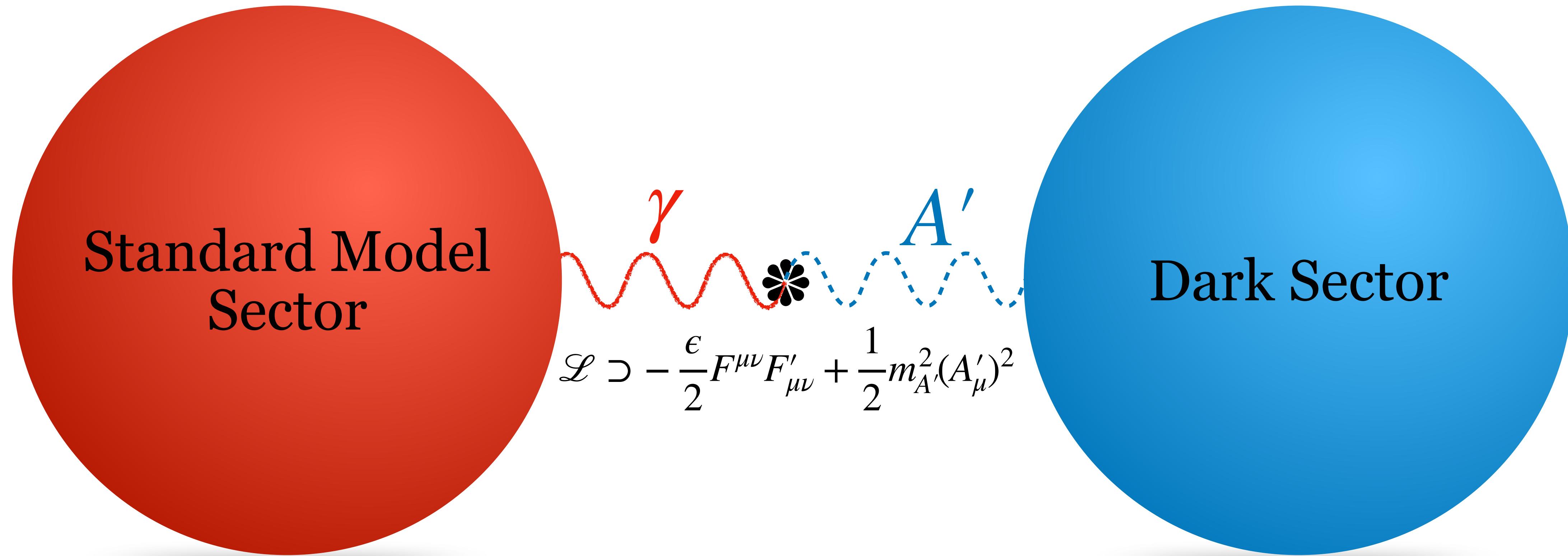


Cosmological Signatures of Dark Photons

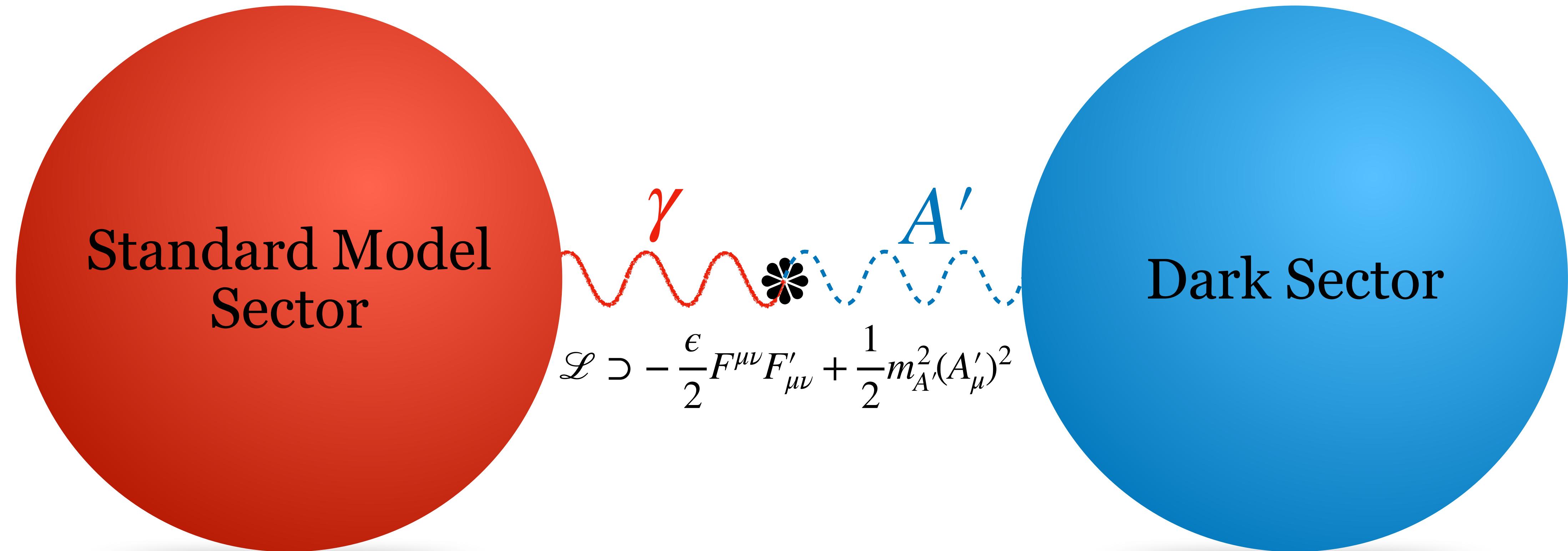
Hongwan Liu
NYU & Princeton

Dark Photons



Vector mediator of the dark sector.
Mixing with SM photon generated by UV physics.

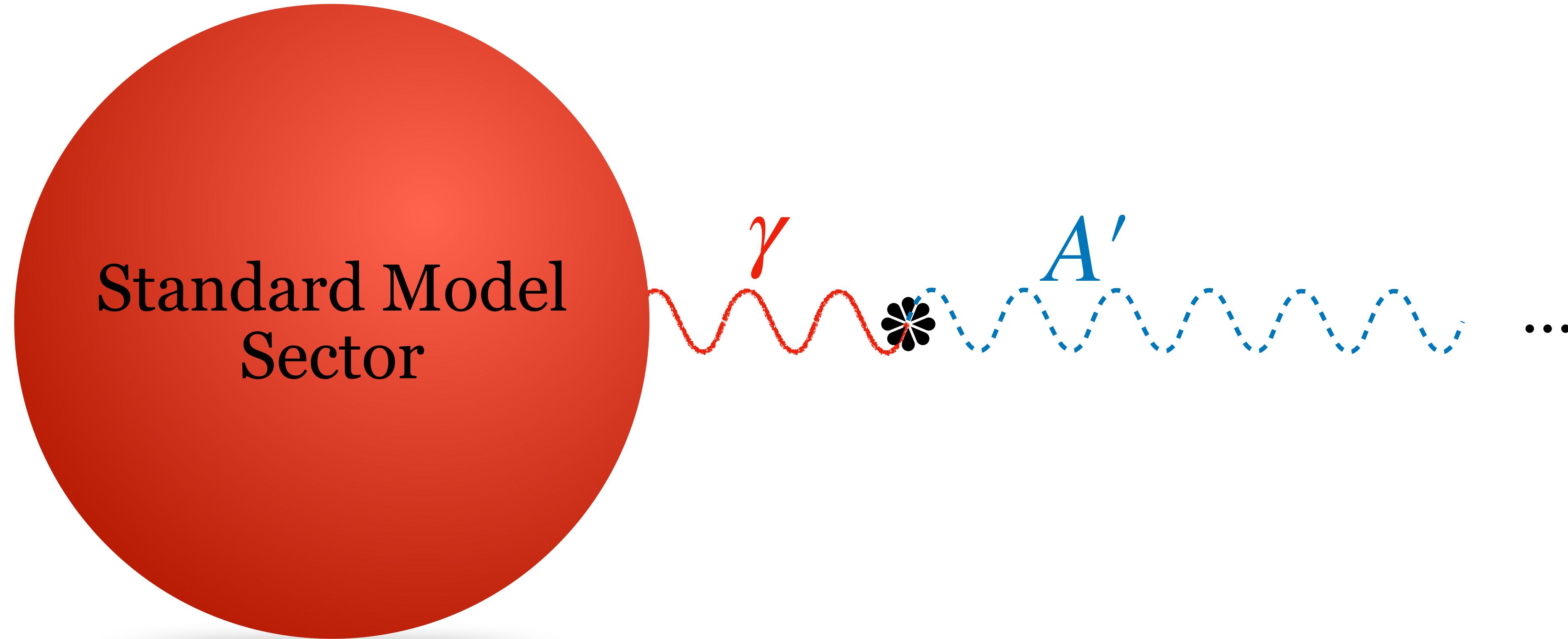
Dark Photons



Simple, renormalizable interaction between two sectors.

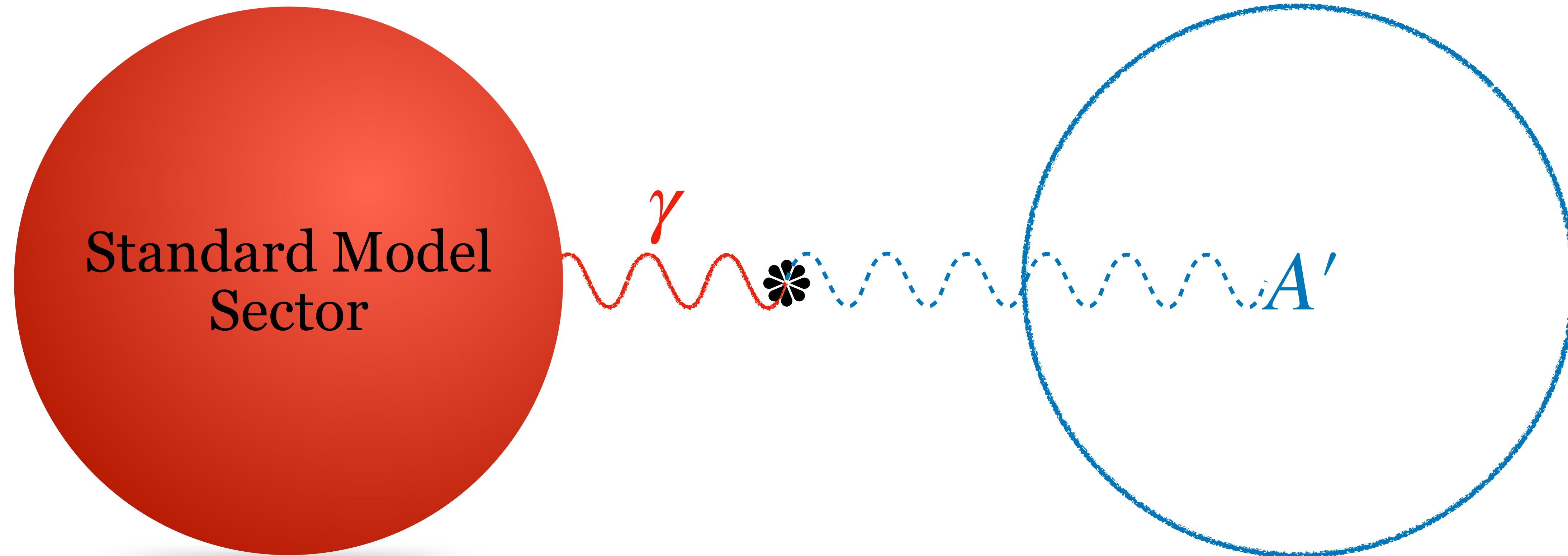
Two parameters: **mixing ϵ** and **mass $m_{A'}$** .

Scenario I: Dark Photon Existence

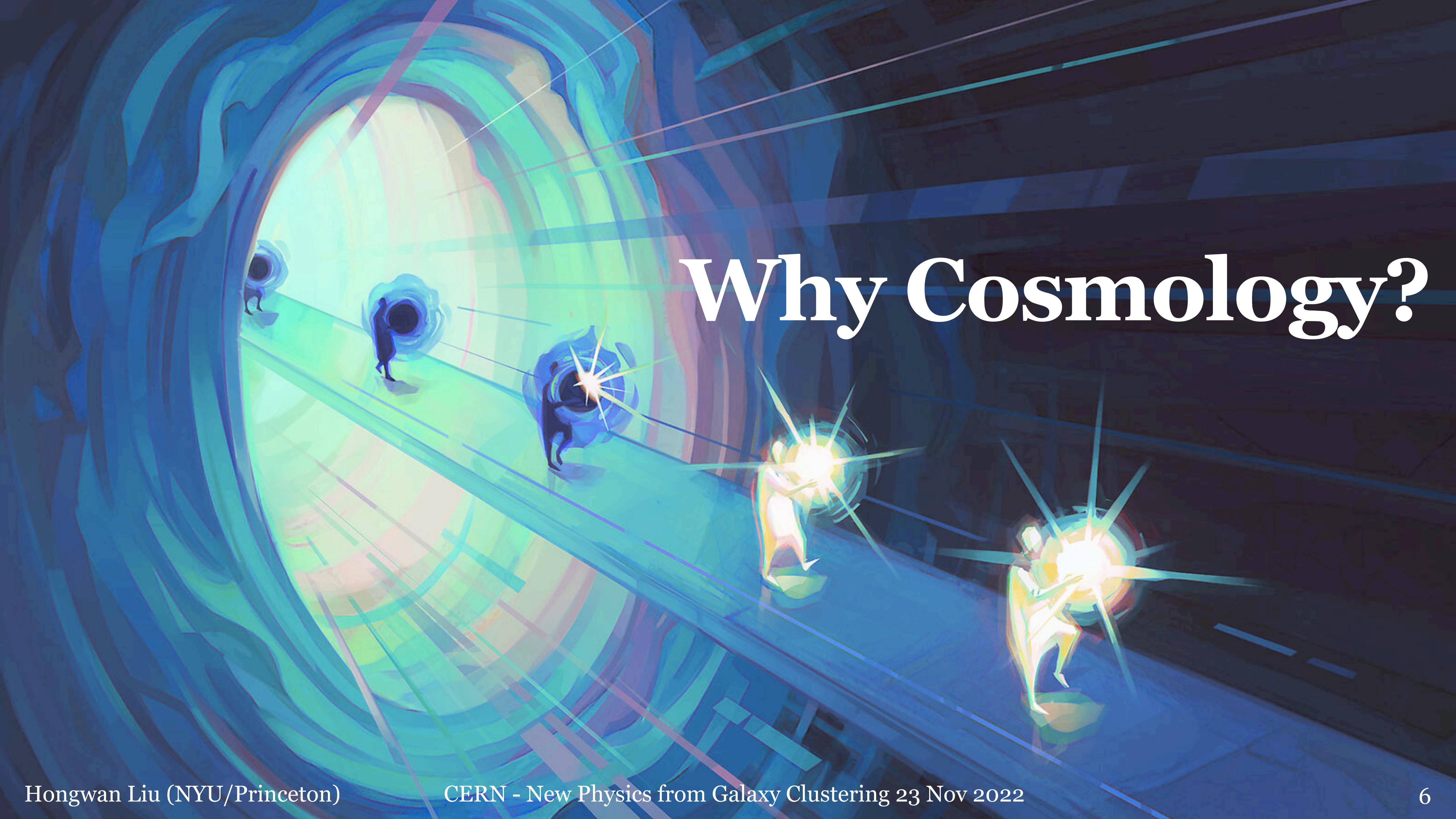


The existence of the dark photon, **with no further assumptions**, already leads to cosmological signatures.

Scenario II: Dark Photon Dark Matter

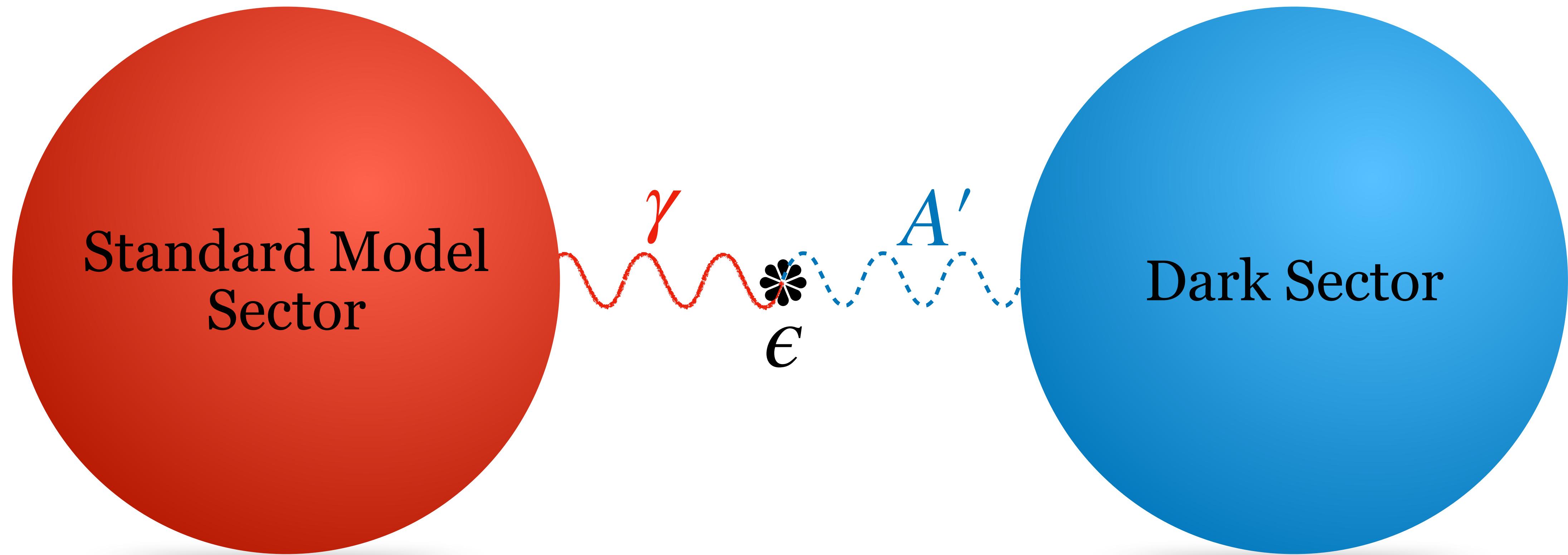


Light dark photons may even be **all of dark matter** itself:
additional and distinct cosmological signatures.

A vibrant, abstract illustration set within a circular frame. The scene depicts a tunnel or wormhole with swirling blue and green patterns. Several glowing, multi-colored particles, resembling stars or galaxies, are scattered throughout. Two small, stylized figures are visible: one near the center-left and another near the bottom-right. The overall aesthetic is futuristic and cosmic.

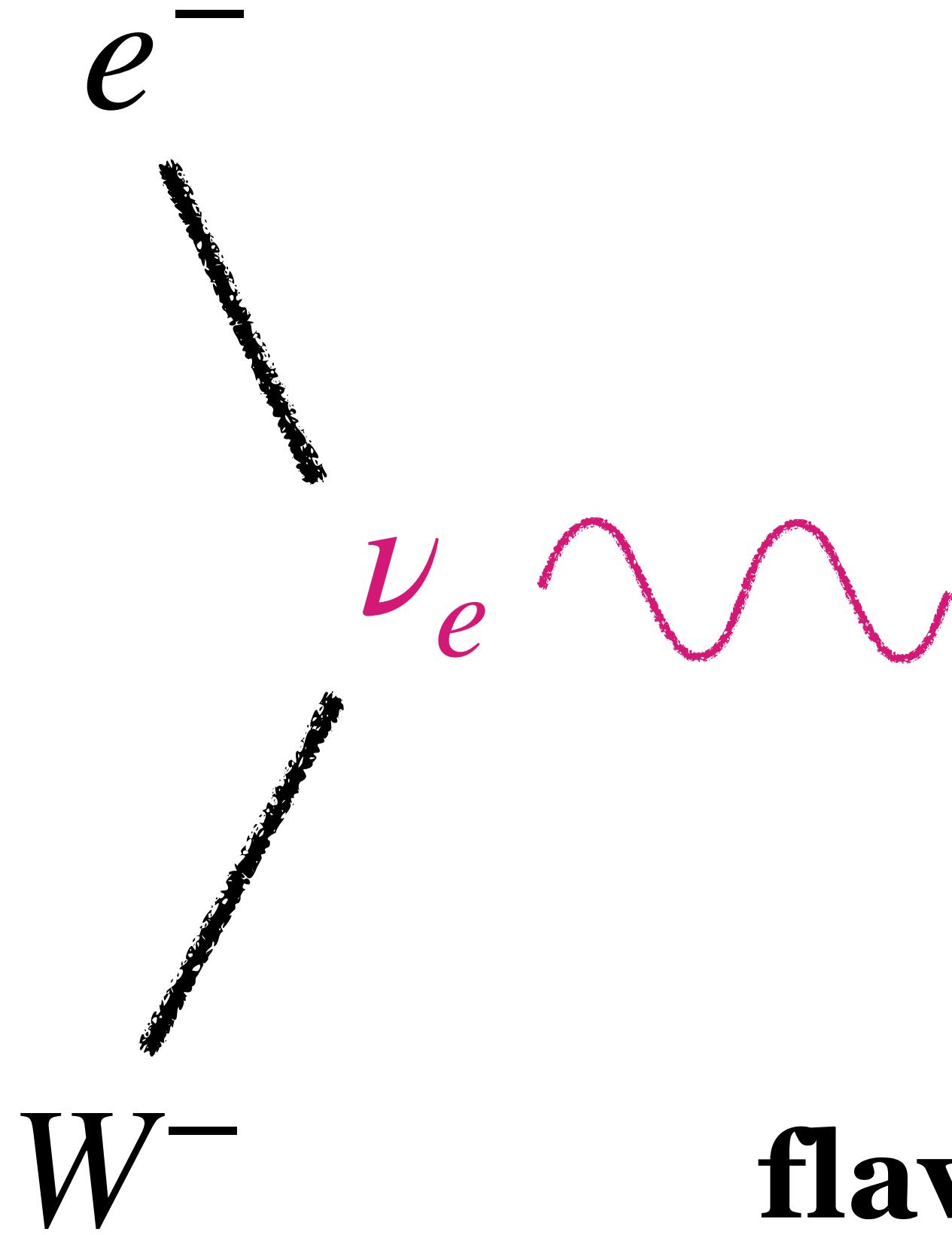
Why Cosmology?

Dark Photon Oscillations



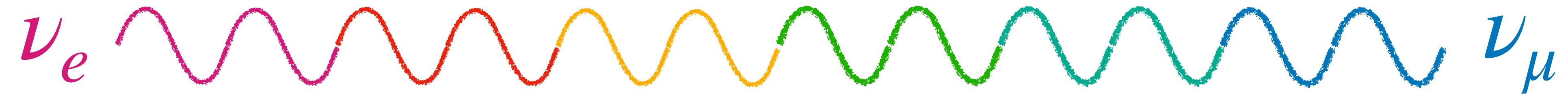
SM charged under **interaction eigenstate** of the photon,
which is **not a propagation eigenstate**.

Mixing in Neutrinos



Neutrinos are produced in
flavor or interaction eigenstates...

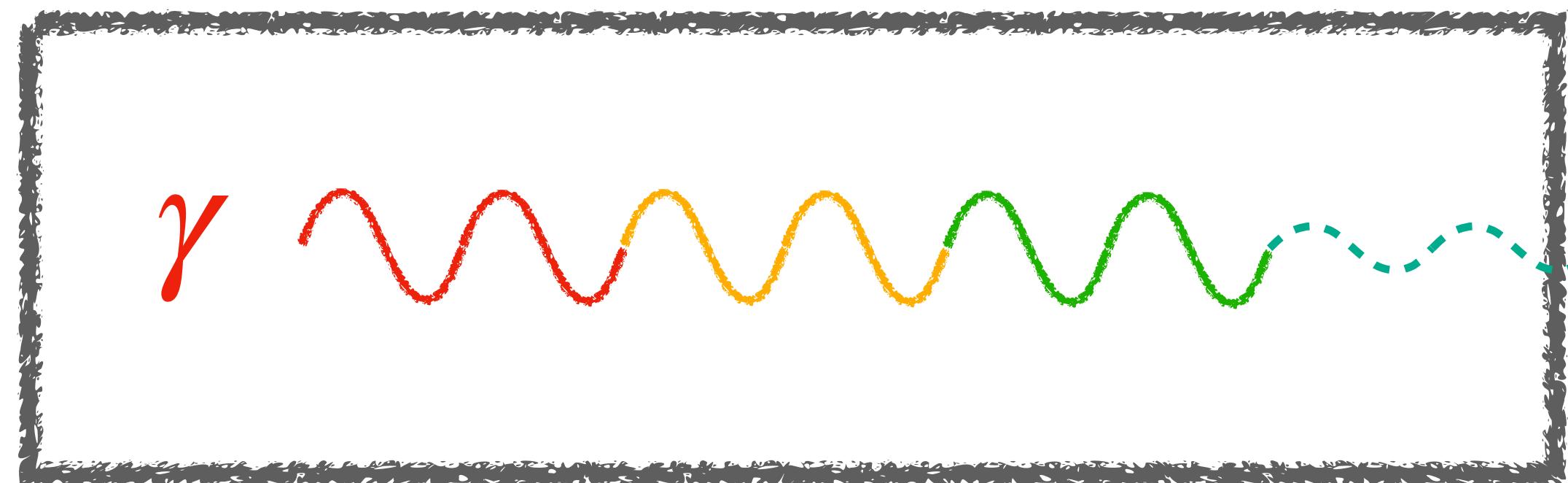
Neutrino Oscillations



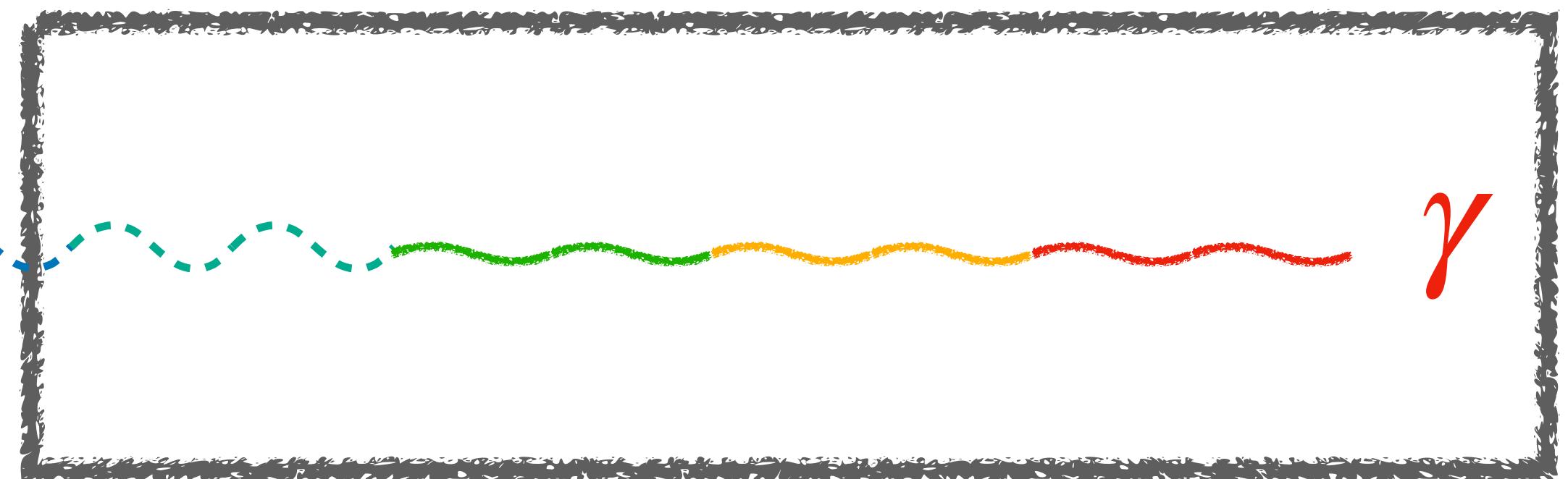
... that are not propagation eigenstates.

Light-Shining-Through-Wall

Emitter RF Cavity



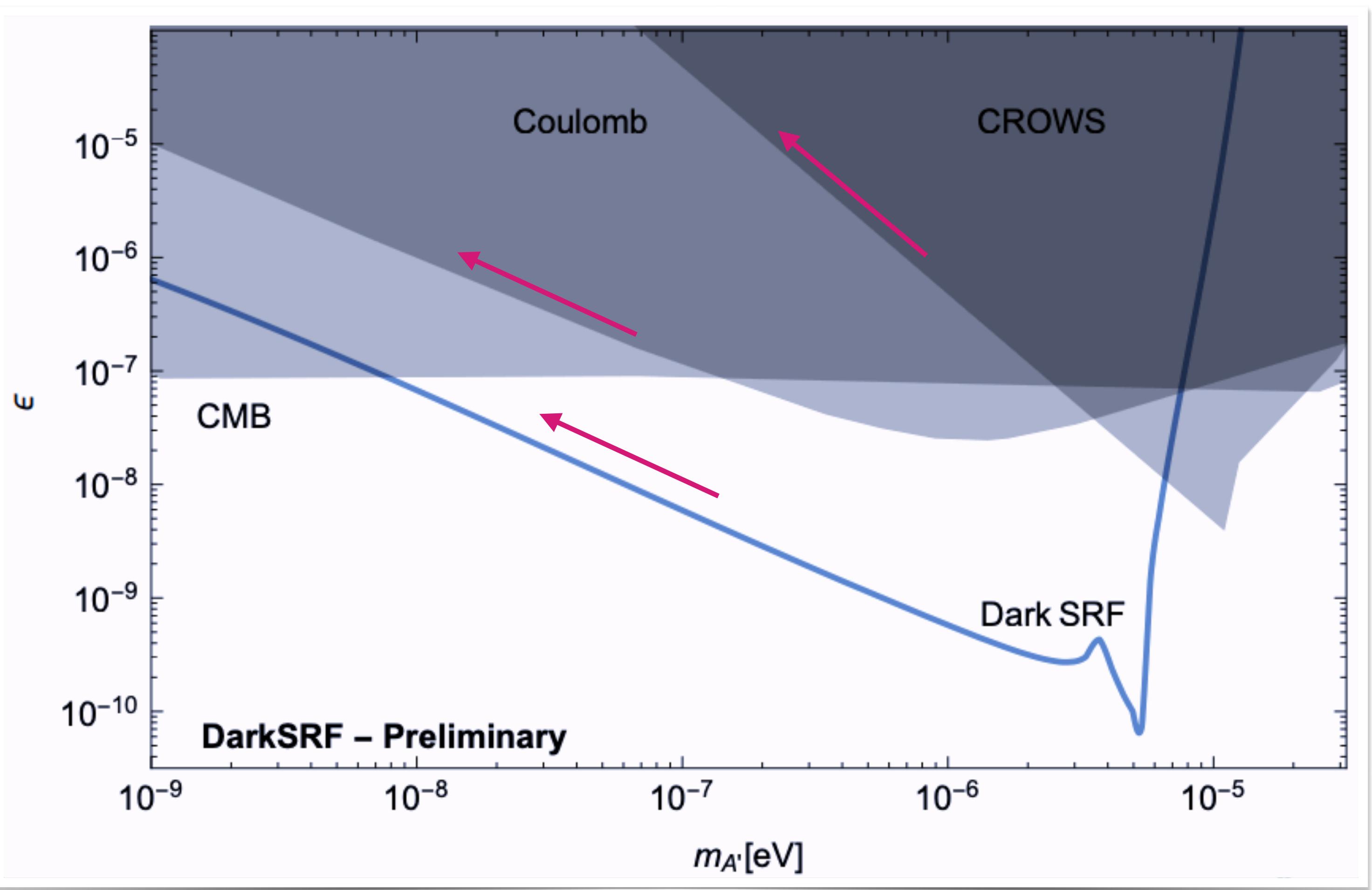
A'



Receiver RF Cavity

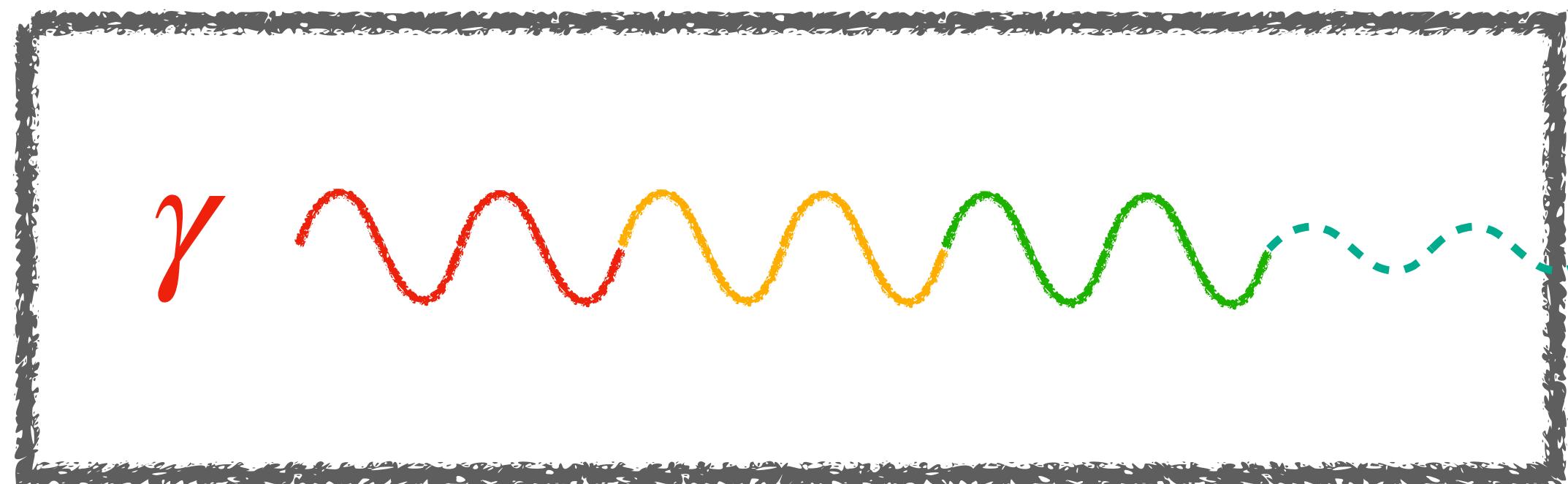
Photons can likewise oscillate into dark photons **in vacuum**.

DarkSRF

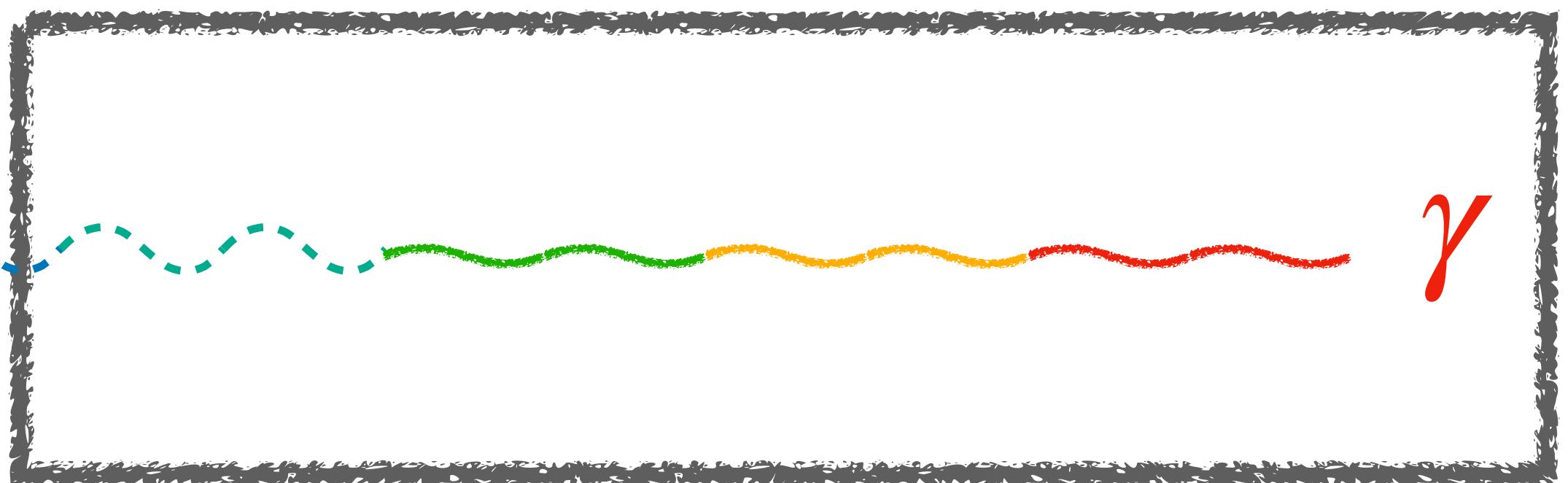


Light-Shining-Through-Wall

Emitter RF Cavity



A'



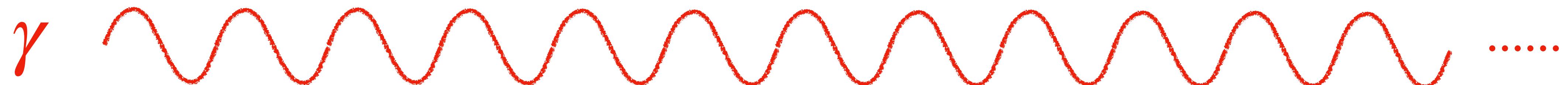
Receiver RF Cavity

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

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

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

Lighter Dark Photons

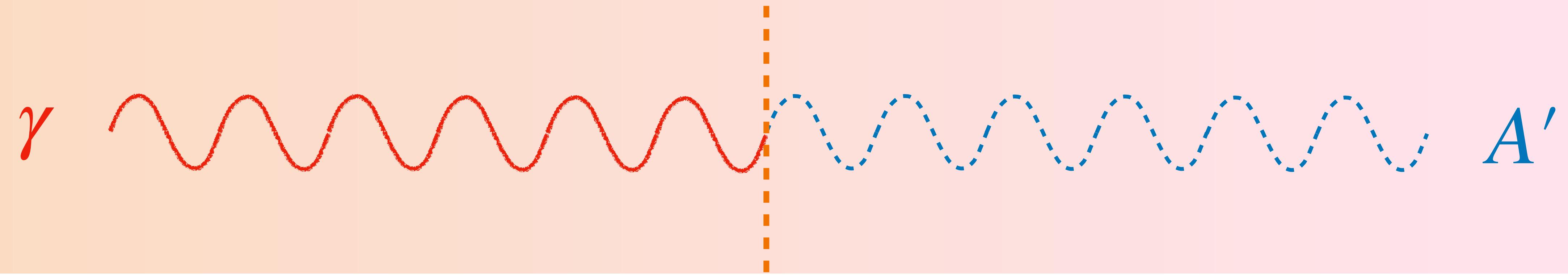


$$L \sim 10^6 \text{ m} \left(\frac{10^{-9} \text{ eV}}{m_{A'}} \right)^2 \left(\frac{\nu}{\text{GHz}} \right)$$

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

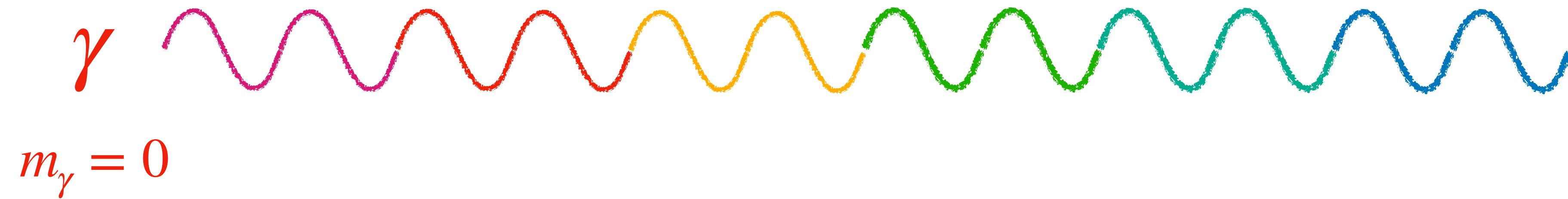
Reason #1 for Cosmology: Difficult with **terrestrial probes**.

Lighter Dark Photons



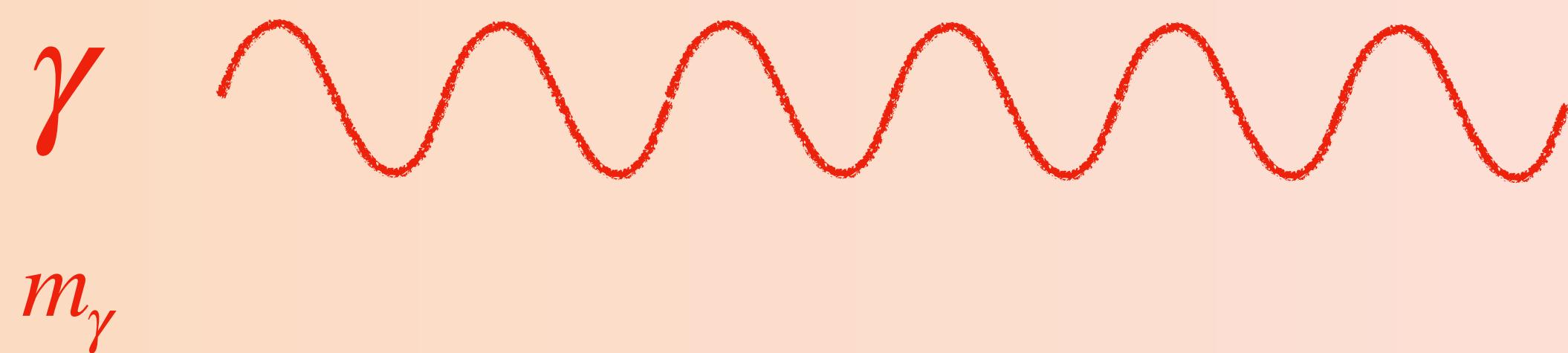
Reason #2 for Cosmology: **Propagation medium effects can help.**

Nonresonant Oscillations



Photons are massless in vacuum. **Energy gap** between γ and A' lead to **nonresonant oscillations** (like neutrinos).

Photon Plasma Mass

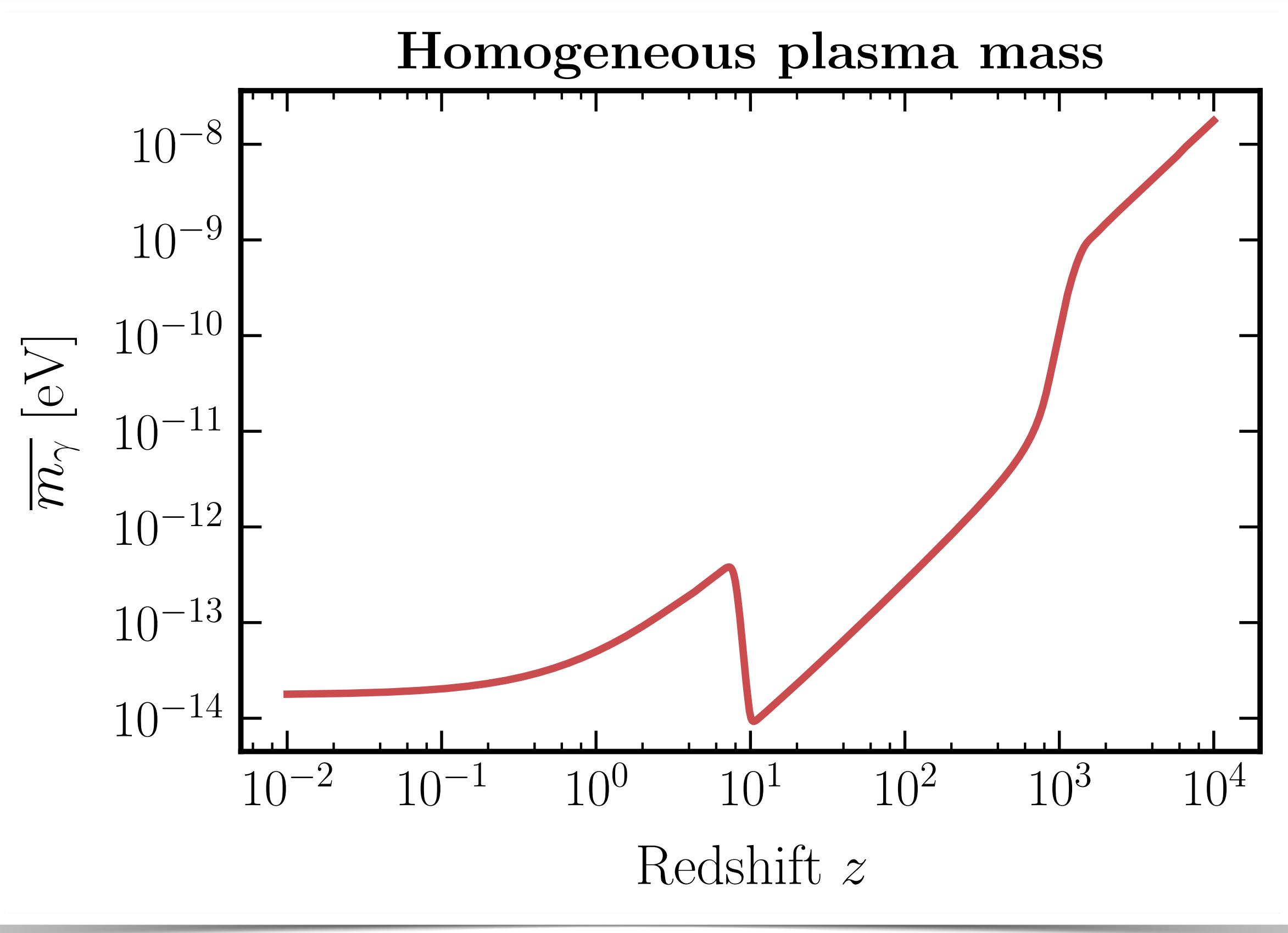


$$m_\gamma \simeq 2 \times 10^{-14} \text{ eV} \left(\frac{n_e}{2.5 \times 10^{-7} \text{ cm}^{-3}} \right)^{1/2}$$

mean electron
number density today

But photons pick up an **effective mass** in a plasma.

Homogeneous Plasma Mass



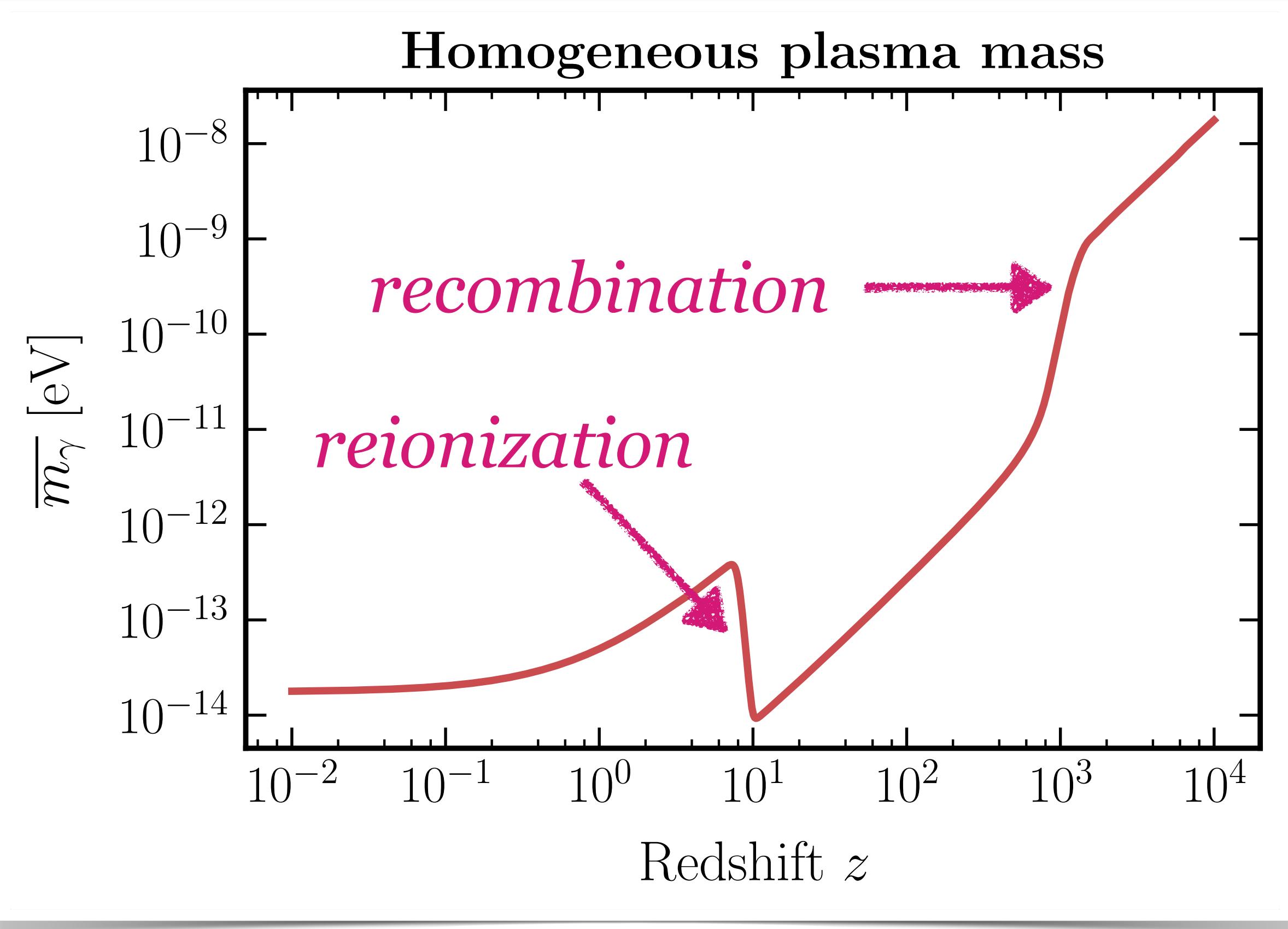
free electron fraction

$$\overline{m}_\gamma \simeq 2 \times 10^{-14} \text{ eV} (\overline{n}_{e,0} x_e)^{1/2} (1 + z)^{3/2}$$

mean electron number density today

Under the assumption of homogeneity,
 $10^{-14} \text{ eV} \lesssim \overline{m}_\gamma \lesssim 10^{-9} \text{ eV}$ after recombination.

Homogeneous Plasma Mass



free electron fraction

$$\bar{m}_\gamma \simeq 2 \times 10^{-14} \text{ eV} (\bar{n}_{e,0} x_e)^{1/2} (1+z)^{3/2}$$

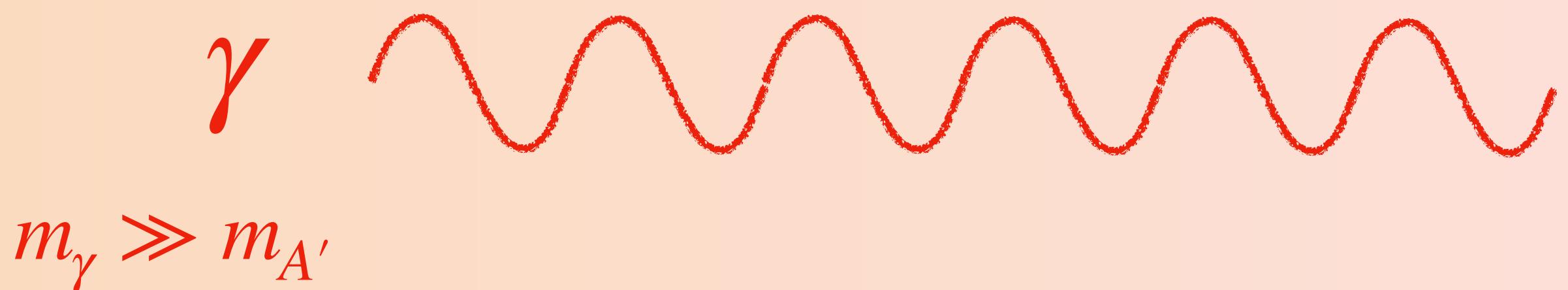
mean electron number density today

Under the assumption of homogeneity,
 $10^{-14} \text{ eV} \lesssim \bar{m}_\gamma \lesssim 10^{-9} \text{ eV}$ after recombination.

Resonant Oscillations

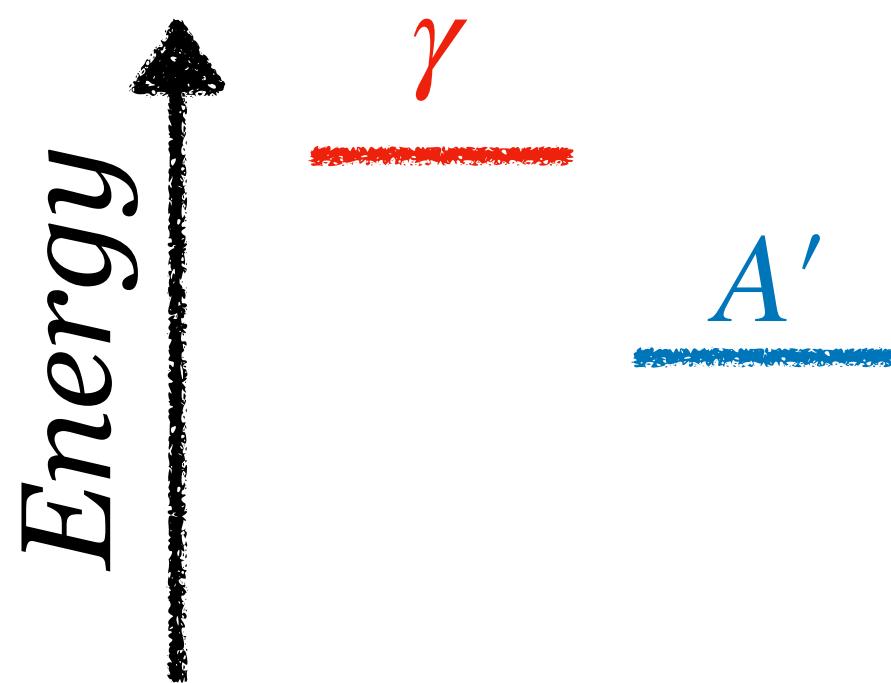
→ later time, decreasing redshift

$$\hat{H} = \frac{1}{4\omega} \begin{pmatrix} m_\gamma^2 - m_{A'}^2 & 2\epsilon m_{A'}^2 \\ 2\epsilon m_{A'}^2 & -m_\gamma^2 + m_{A'}^2 \end{pmatrix}$$



$m_\gamma \gg m_{A'}$

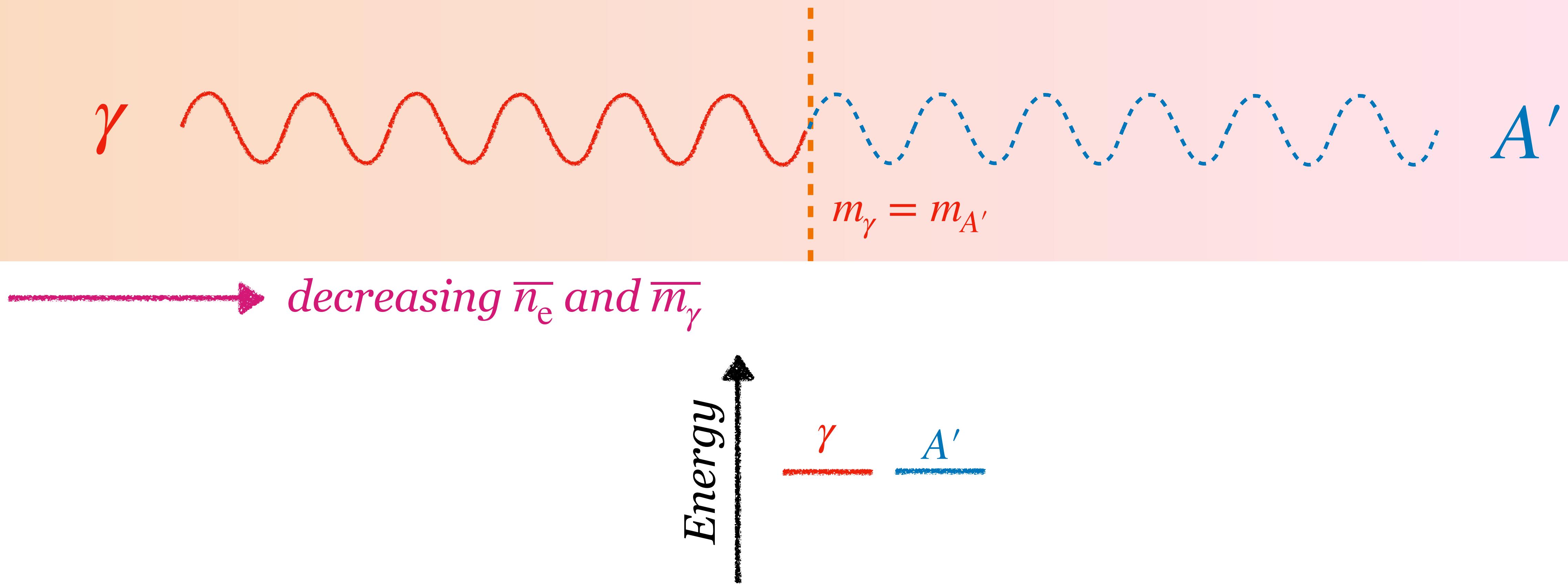
→ decreasing \bar{n}_e and \bar{m}_γ



Resonant Oscillations

→ later time, decreasing redshift

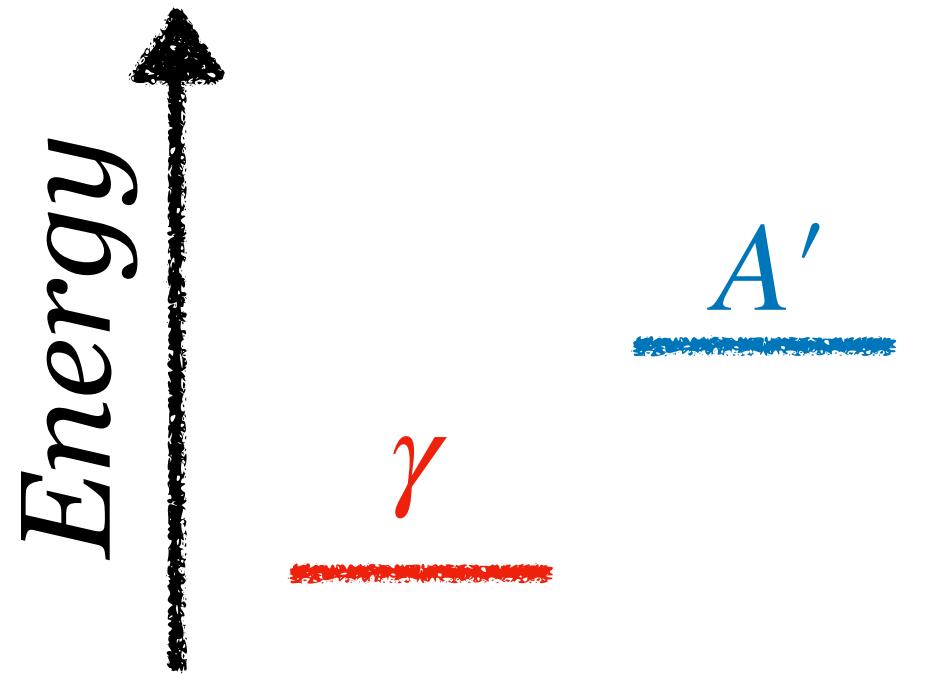
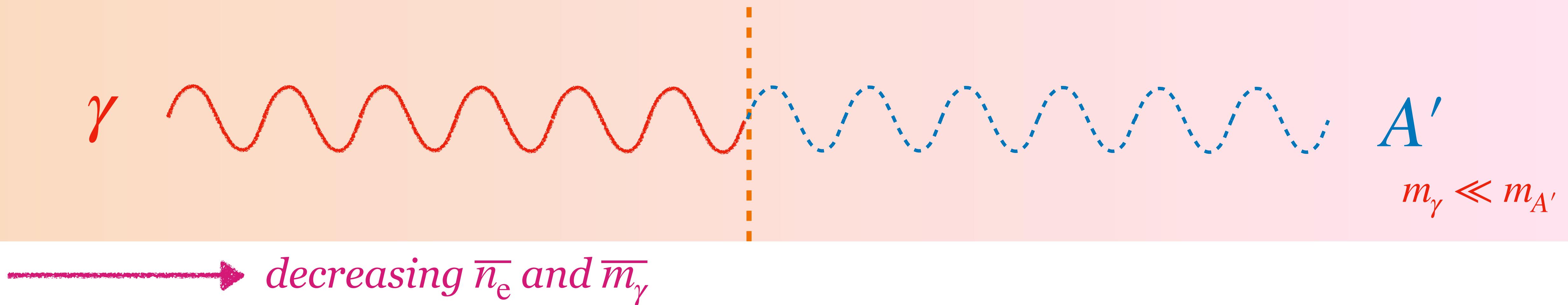
$$\hat{H} = \frac{1}{4\omega} \begin{pmatrix} m_\gamma^2 - m_{A'}^2 & 2\epsilon m_{A'}^2 \\ 2\epsilon m_{A'}^2 & -m_\gamma^2 + m_{A'}^2 \end{pmatrix}$$



Resonant Oscillations

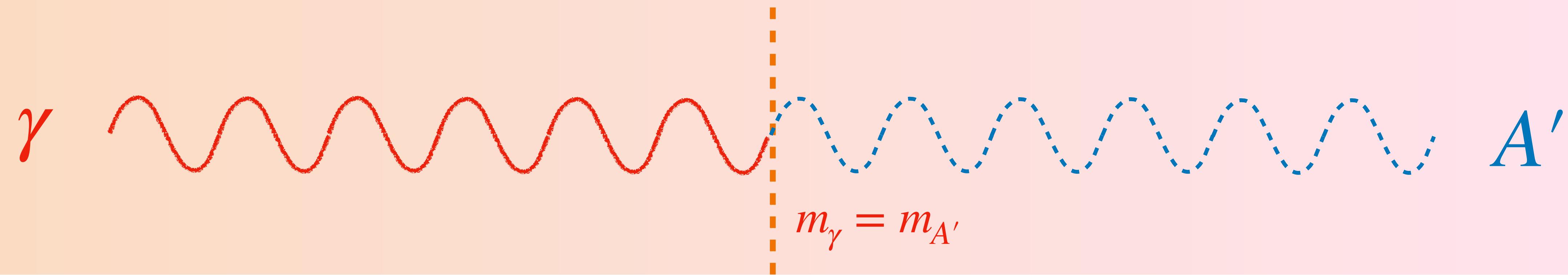
→ later time, decreasing redshift

$$\hat{H} = \frac{1}{4\omega} \begin{pmatrix} m_\gamma^2 - m_{A'}^2 & 2\epsilon m_{A'}^2 \\ 2\epsilon m_{A'}^2 & -m_\gamma^2 + m_{A'}^2 \end{pmatrix}$$



Resonant Oscillations

→ *later time, decreasing redshift*



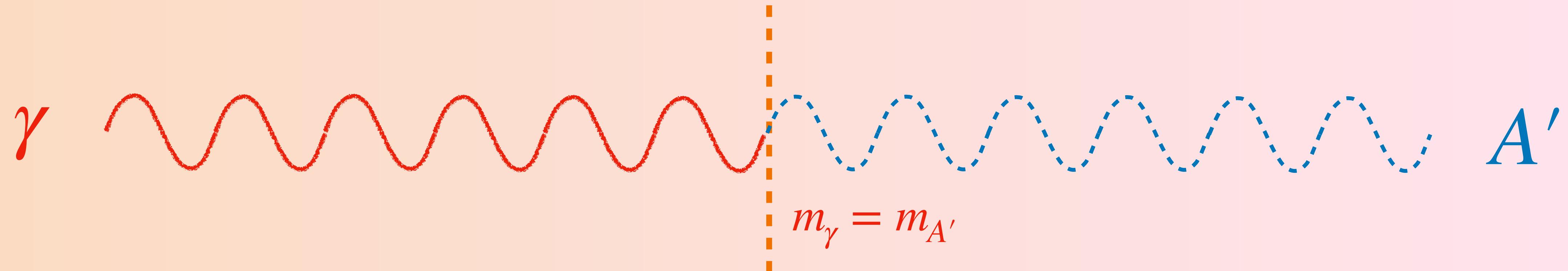
→ *decreasing \bar{n}_e and \bar{m}_γ*

$$P_{\gamma \rightarrow A'} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1}_{m_\gamma=m_{A'}}$$

Resonant Oscillations

→ later time, decreasing redshift

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



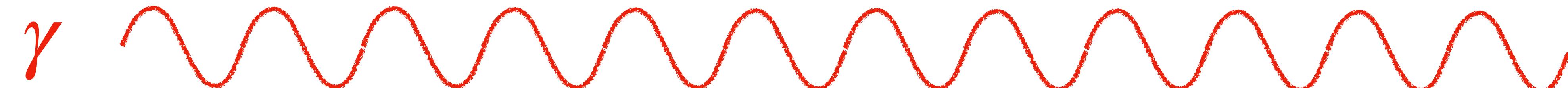
→ decreasing \bar{n}_e and \bar{m}_γ

mixing

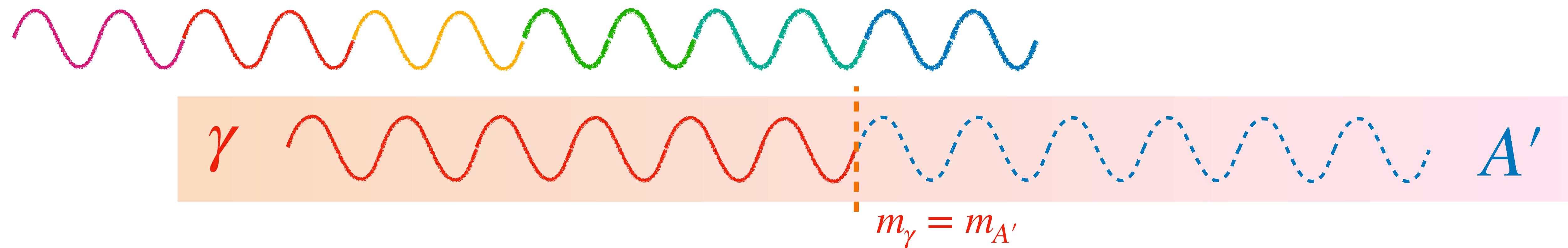
$$P_{\gamma \rightarrow A'} = 2\pi \times \epsilon^2 \times \frac{m_{A'}^2}{2\omega} \times \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1}$$

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

Takeaways



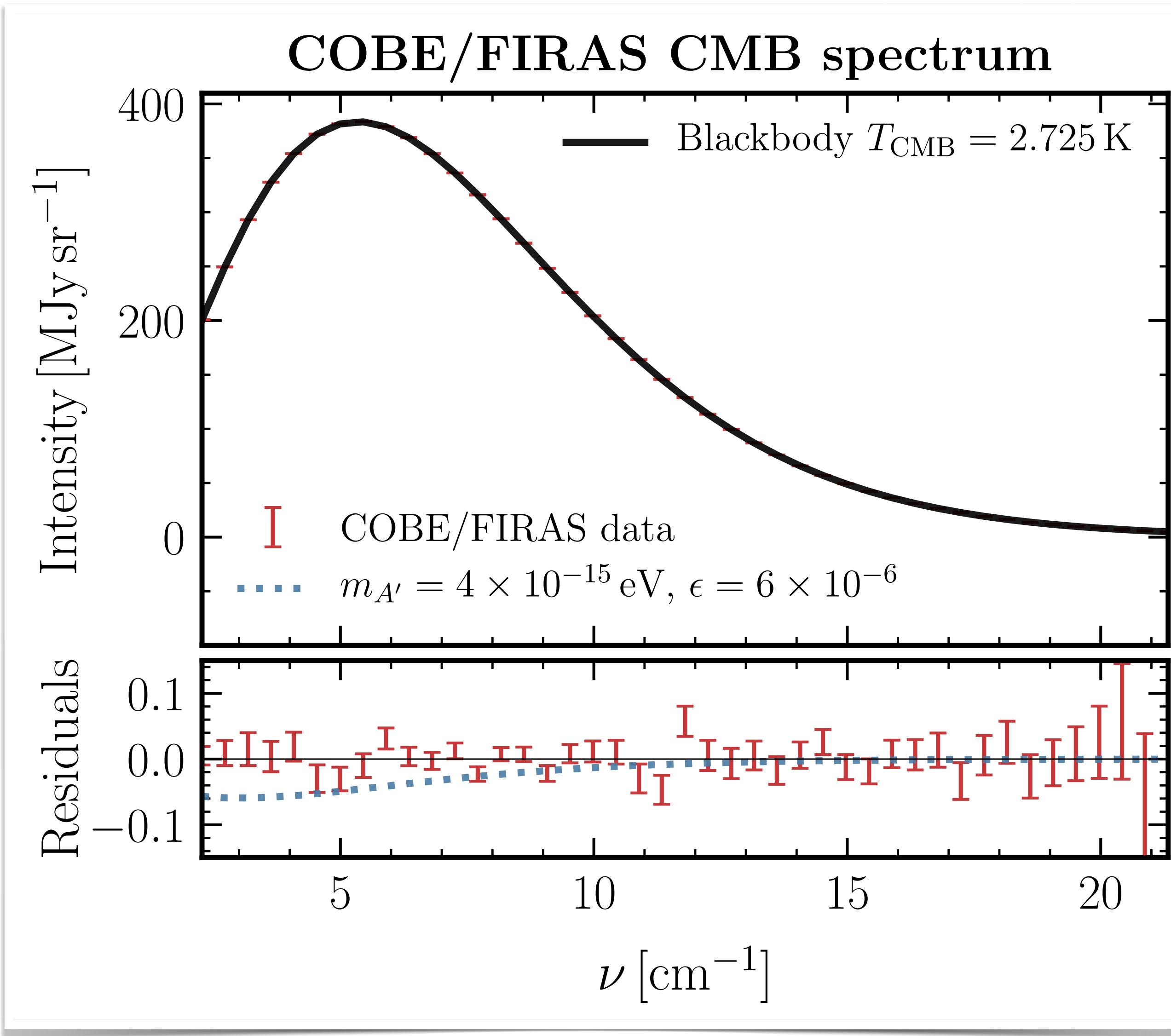
1. Cosmological scales good for long oscillation length.



2. There are nonresonant (vacuum) vs. resonant oscillations.

Resonant Oscillations in the Real Universe

Cosmic Microwave Background

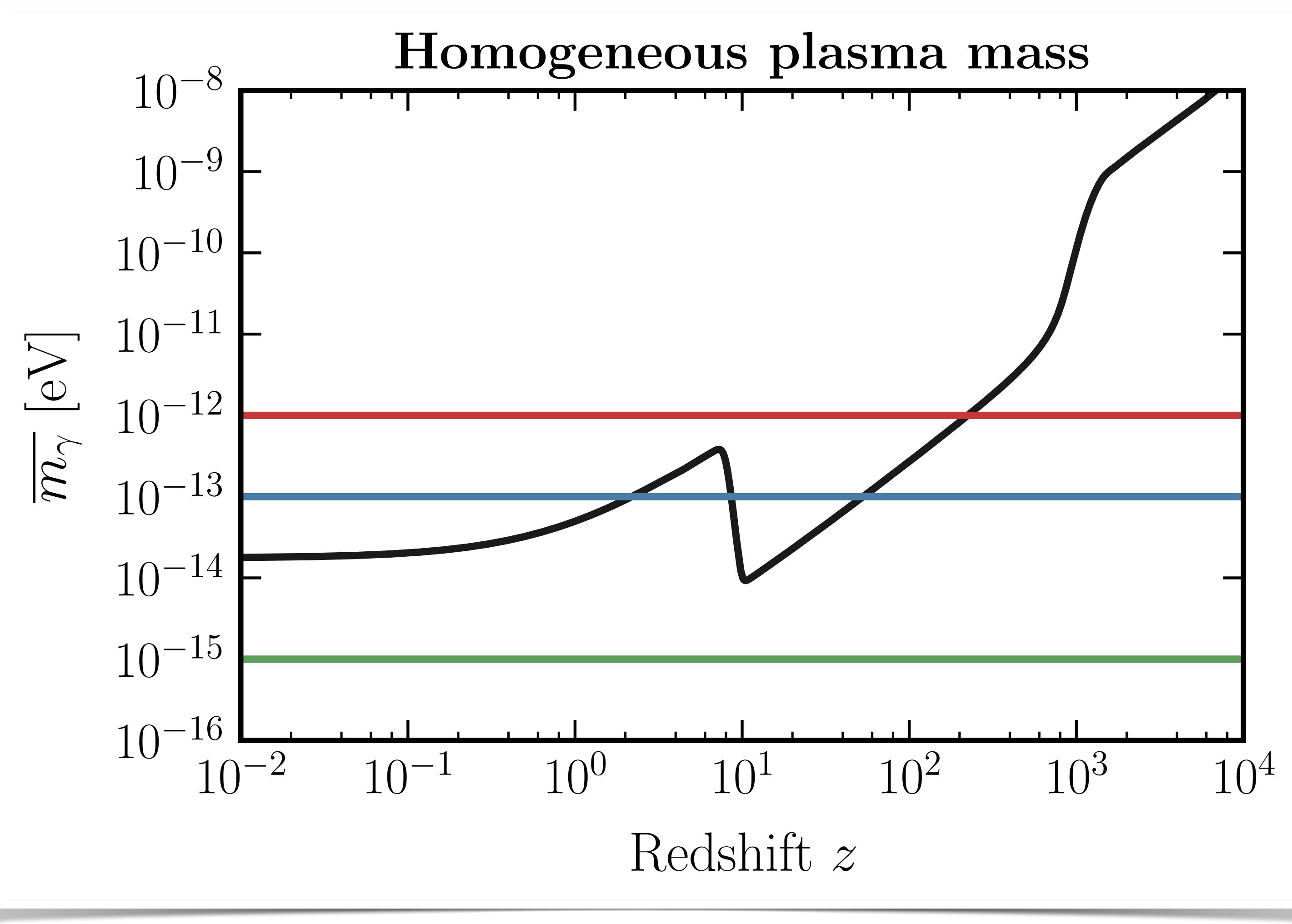


The CMB is very close to a **perfect blackbody**.

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

$$P_{\gamma \rightarrow A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|_{t_i=t_{\text{res}}}^{-1}$$

Resonant Oscillations

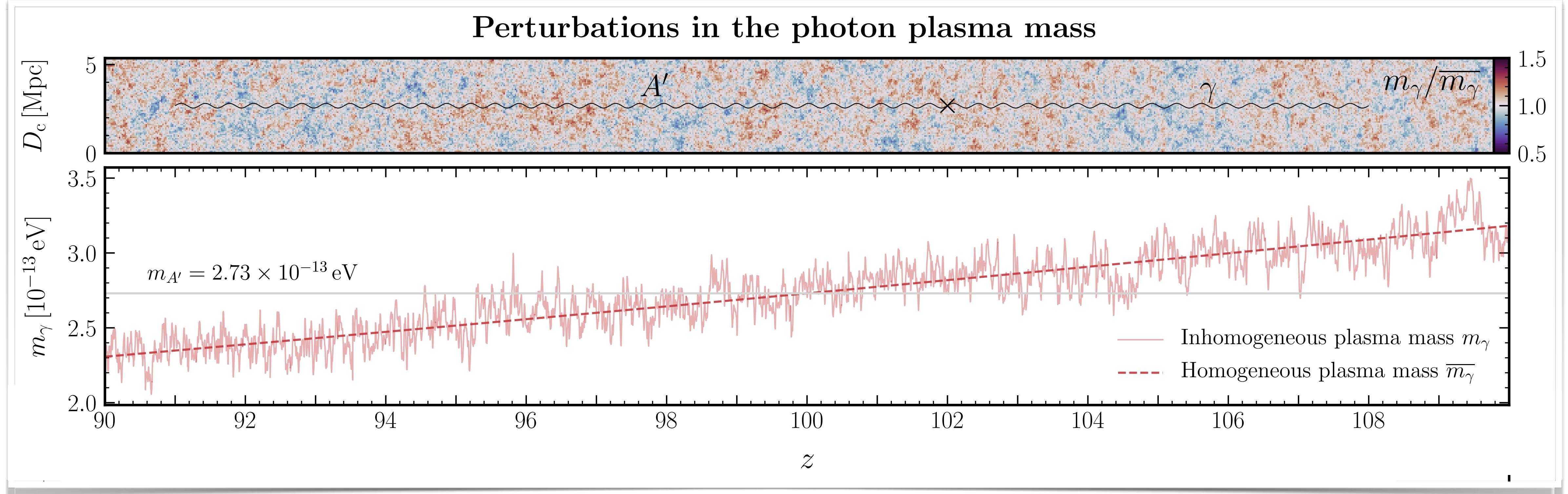


$$P_{\gamma \rightarrow A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|_{t_i=t_{\text{res}}}^{-1}$$

Resonant oscillations when
 $m_\gamma = m_{A'}.$

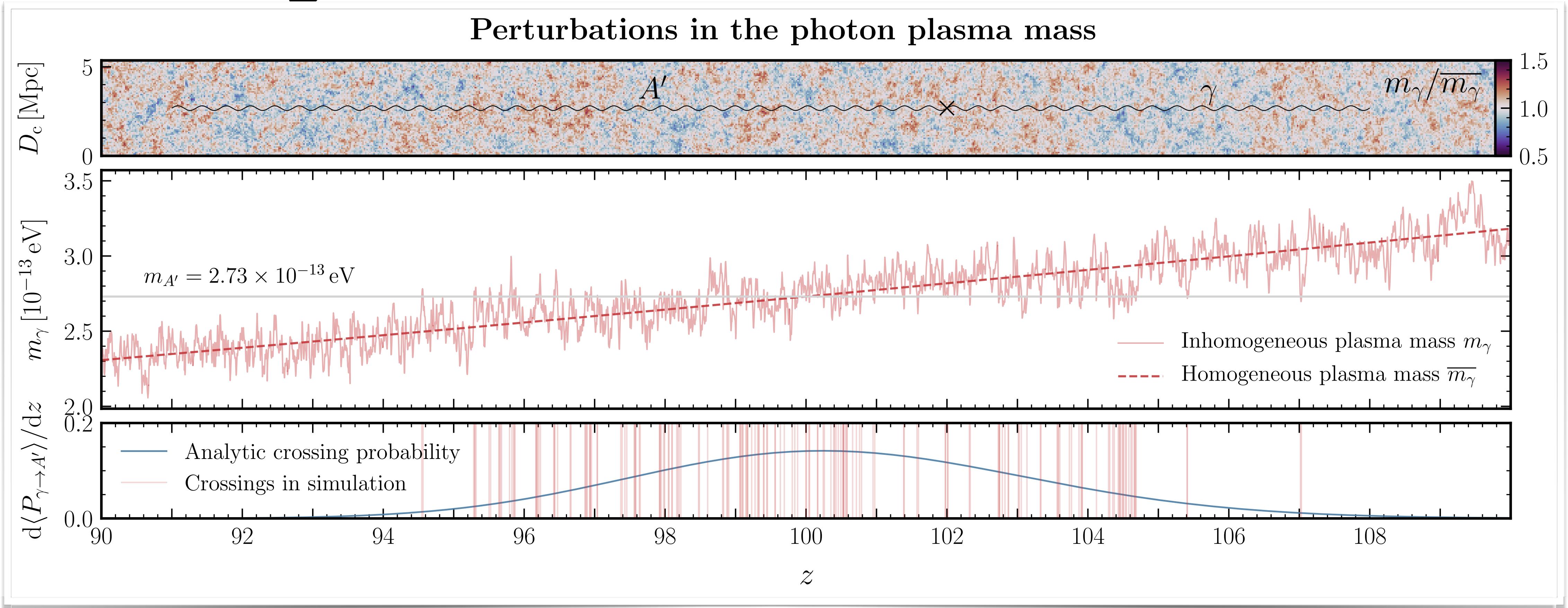
Conversions after
recombination covers
 $10^{-14} \text{ eV} \lesssim m_{A'} \lesssim 10^{-9} \text{ eV}.$

Inhomogeneities



Fluctuations in electron density means $m_\gamma \neq \bar{m}_\gamma$.
Numerous resonance crossings along each photon path...

Analytic Formalism



... but we can average over photon paths analytically!

Analytic Formalism

$$P_{\gamma \rightarrow A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1} = \int dt \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) m_\gamma^2$$

Change of integration measure

Analytic Formalism

$$P_{\gamma \rightarrow A'} = \int dt \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) m_\gamma^2$$

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

Average over
distribution of m_γ^2

$$\langle P_{\gamma \rightarrow A'} \rangle = \int dt \int dm_\gamma^2 f(m_\gamma^2; t) \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) m_\gamma^2$$

Analytic Formalism

$$\langle P_{\gamma \rightarrow A'} \rangle = \int dt \int dm_\gamma^2 f(m_\gamma^2; t) \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \delta_D(m_\gamma^2 - m_{A'}^2) m_\gamma^2$$

Integrate over m_γ^2

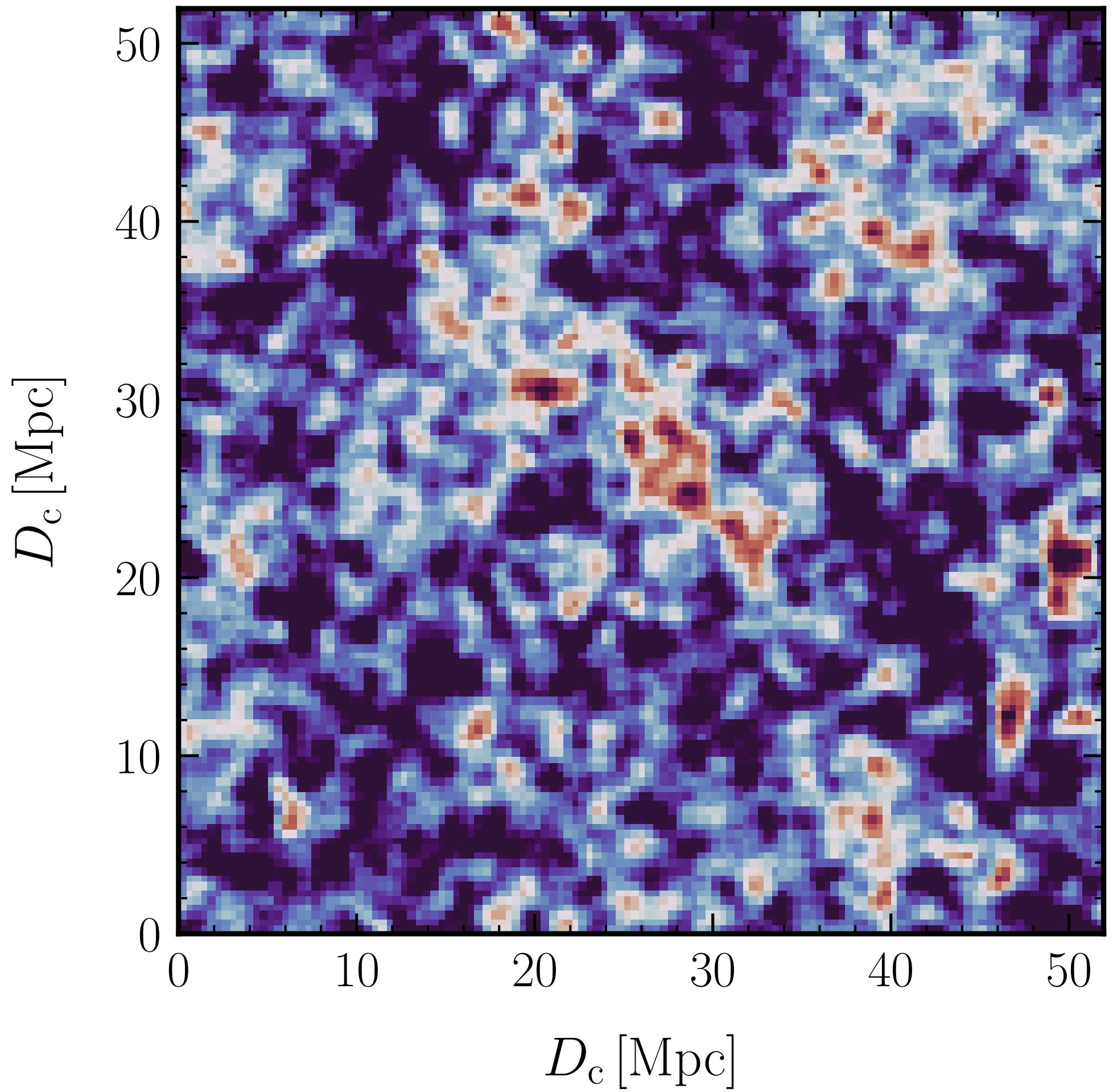
$$\langle P_{\gamma \rightarrow A'} \rangle = \int dt f(m_\gamma^2 = m_{A'}^2; t) \frac{\pi \epsilon^2 m_{A'}^4}{\omega(t)}$$

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

One-Point PDF

$$m_\gamma \simeq 2 \times 10^{-14} \text{ eV} \left(\frac{n_e}{2.5 \times 10^{-7} \text{ cm}^{-3}} \right)^{1/2} \left(\frac{x_e}{1.0} \right)^{1/2}$$

Gaussian simulation



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

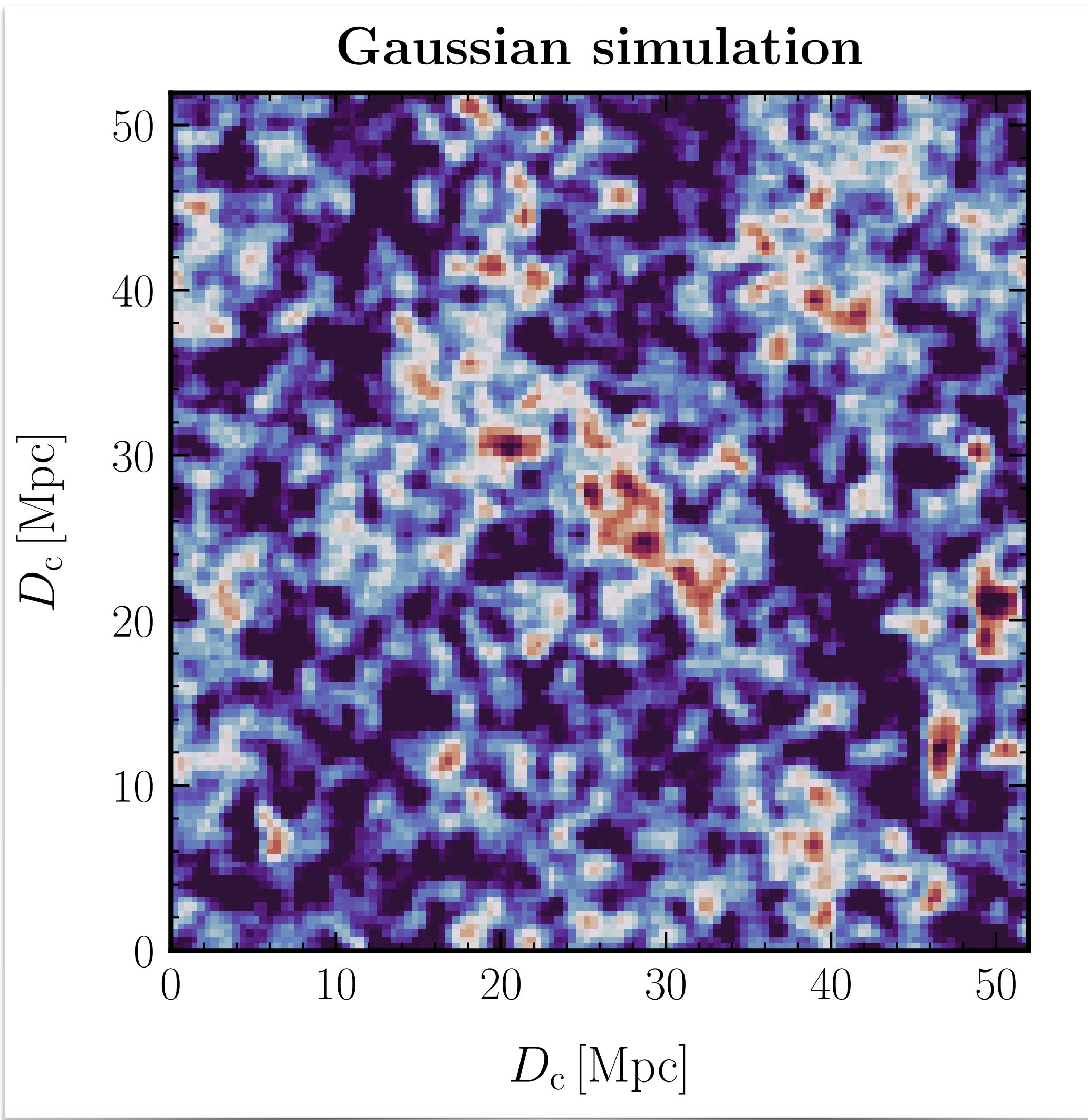
*one-point PDF
of baryon fluctuations*

$$\delta_b \equiv \frac{\rho_b - \bar{\rho}_b}{\bar{\rho}_b}$$

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

Linear Regime

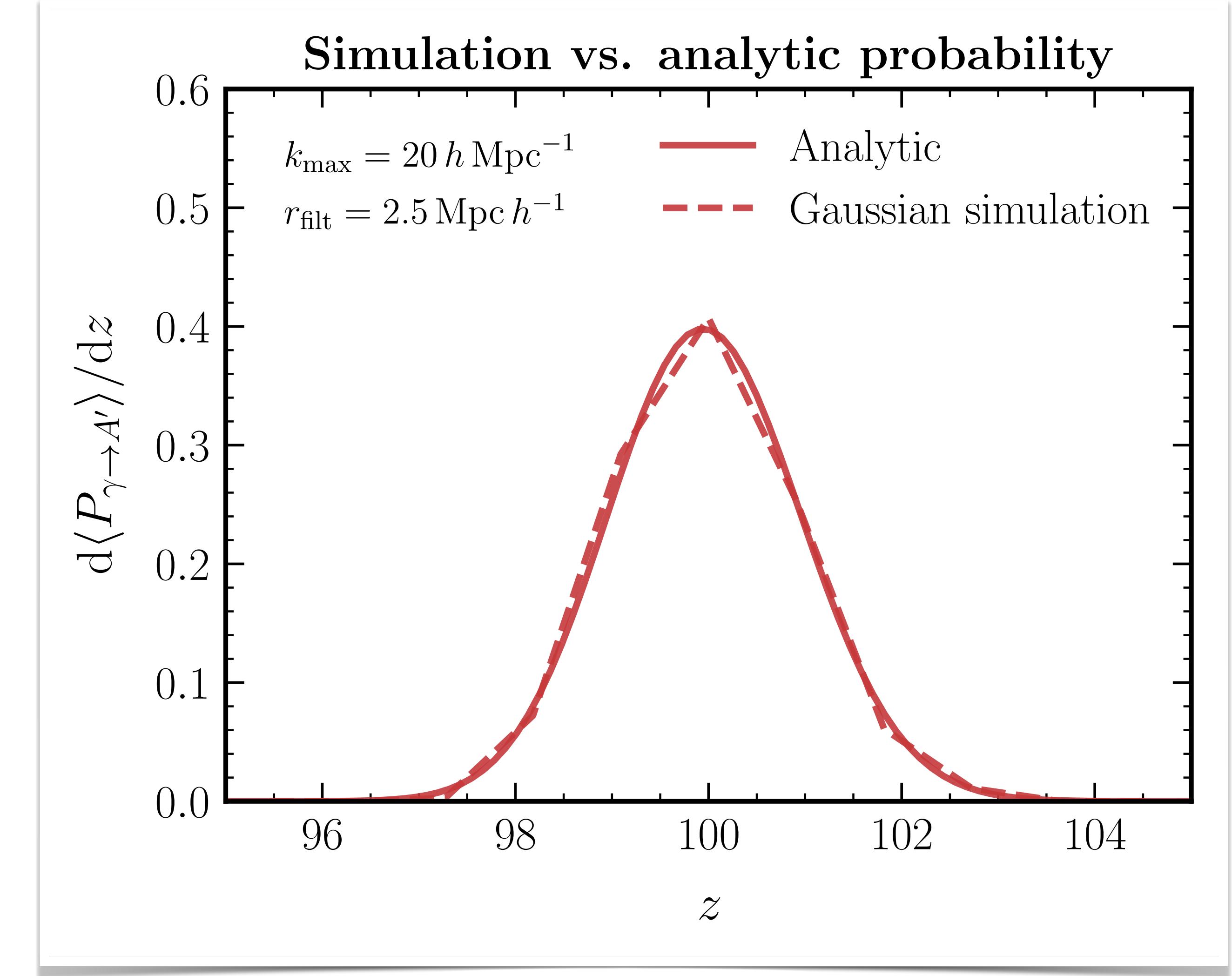
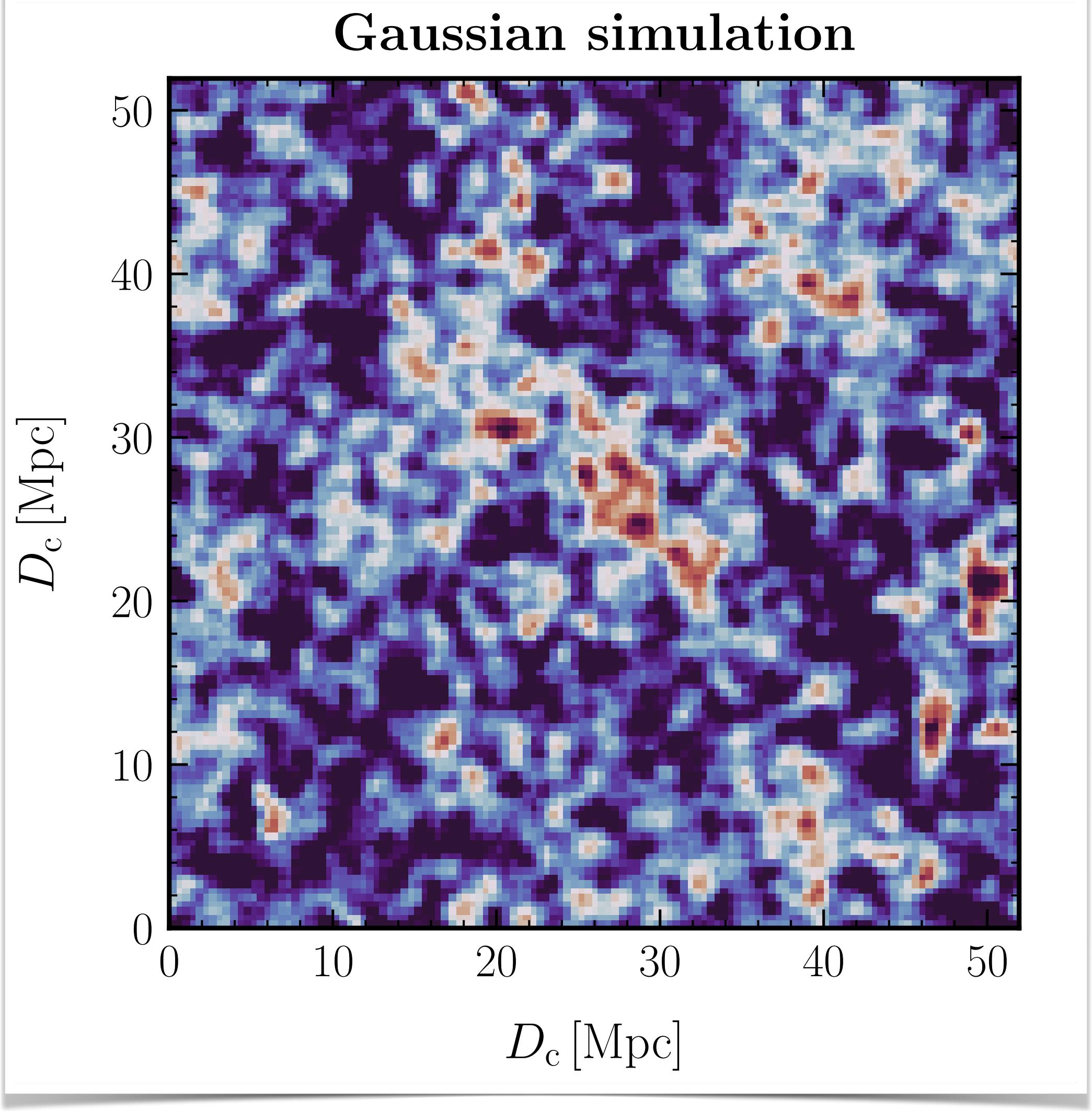
$$\delta_b \equiv \frac{\rho_b - \bar{\rho}_b}{\bar{\rho}_b}$$



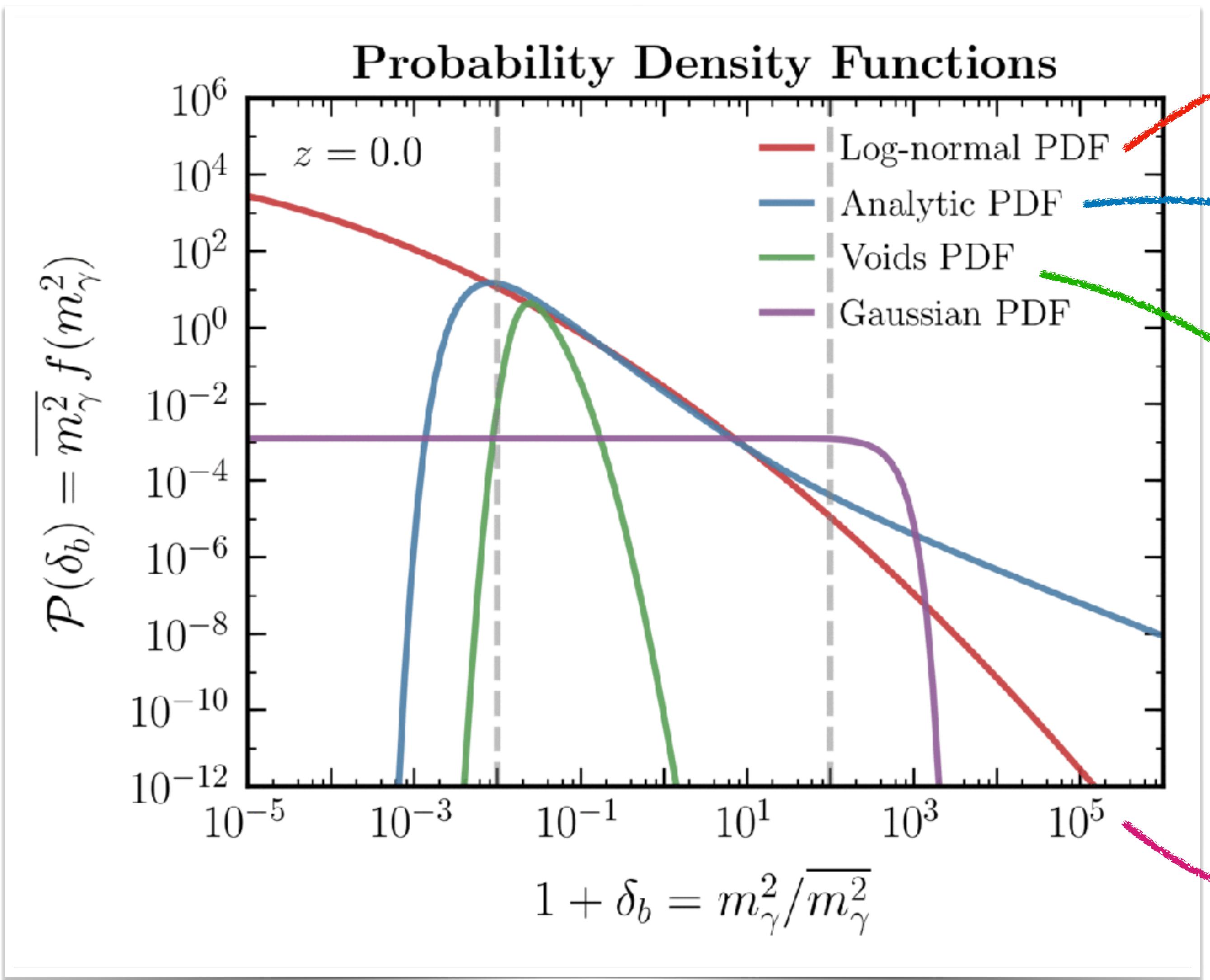
$$\mathcal{P}(\delta_b; z) = \frac{1}{\sqrt{2\pi\sigma_b^2(z)}} \exp\left(-\frac{\delta_b^2}{2\sigma_b^2(z)}\right)$$

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

Analytic vs. Simulation



PDF in the Nonlinear Regime



*phenomenological:
variance from
baryonic simulations.*

*theoretically motivated,
but DM only.*

Ivanov, Kaurov & Sibiryakov 1811.07913

*from simulations of voids:
useful for underdensities*

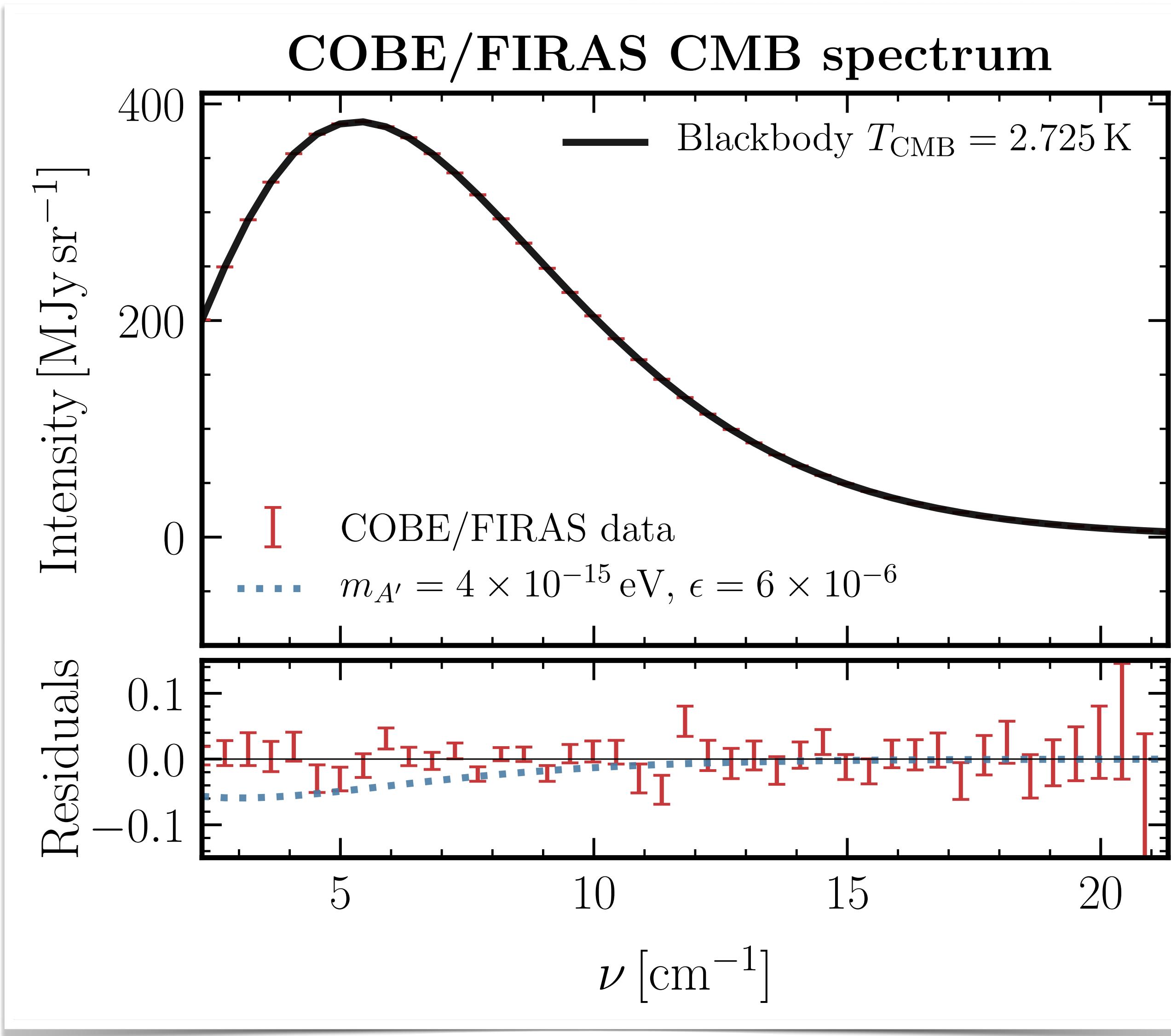
Adermann, Elahi, Lewis & Power
1703.04885, 1807.02938

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

fiducial

Constraints on Dark Photons Existing

Cosmic Microwave Background



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

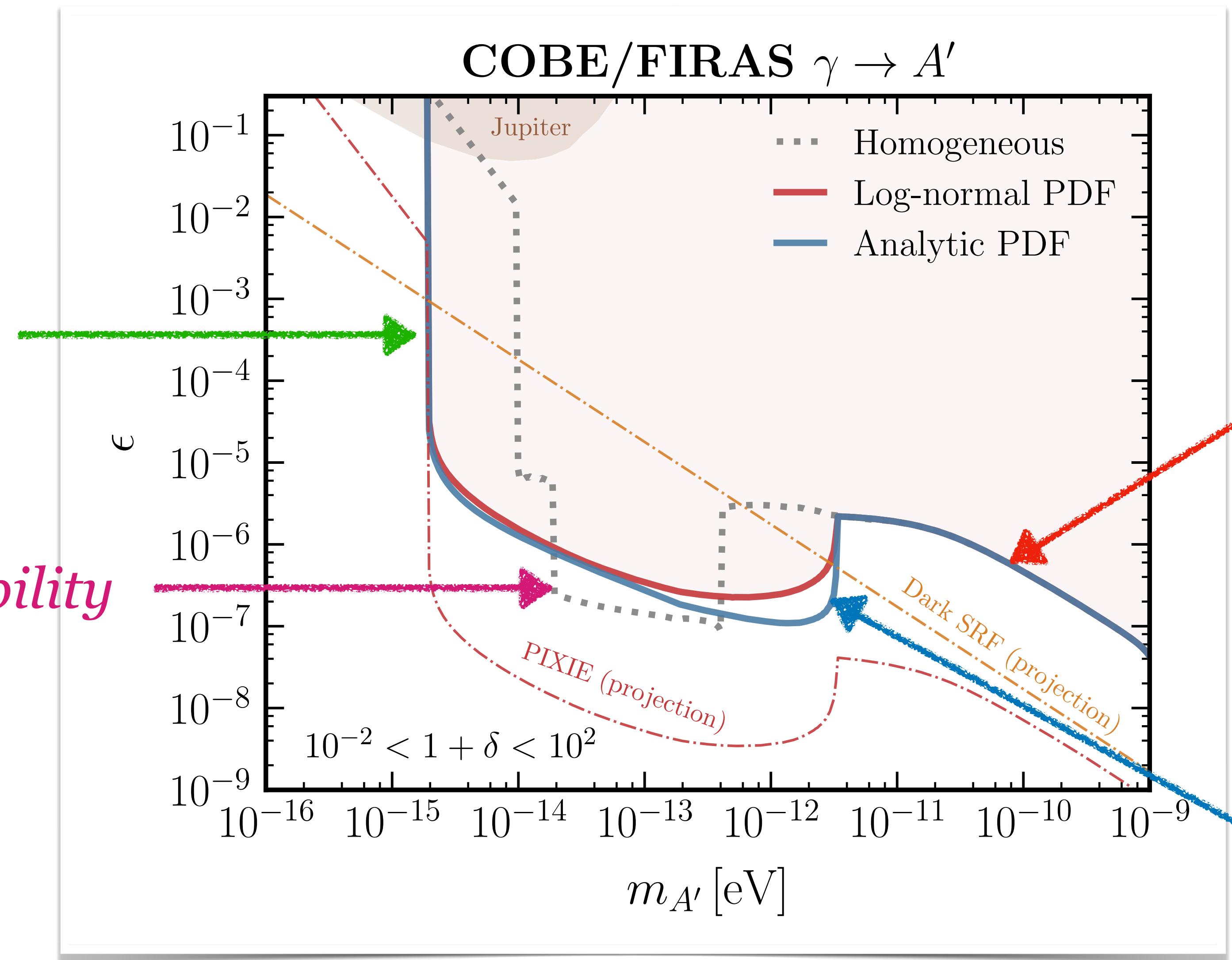
Spectral distortions due to disappearing photons are **highly constrained**.

$$P_{\gamma \rightarrow A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|_{t_i=t_{\text{res}}}^{-1}$$

Constraints with Inhomogeneities

conversions in underdensities at low redshifts

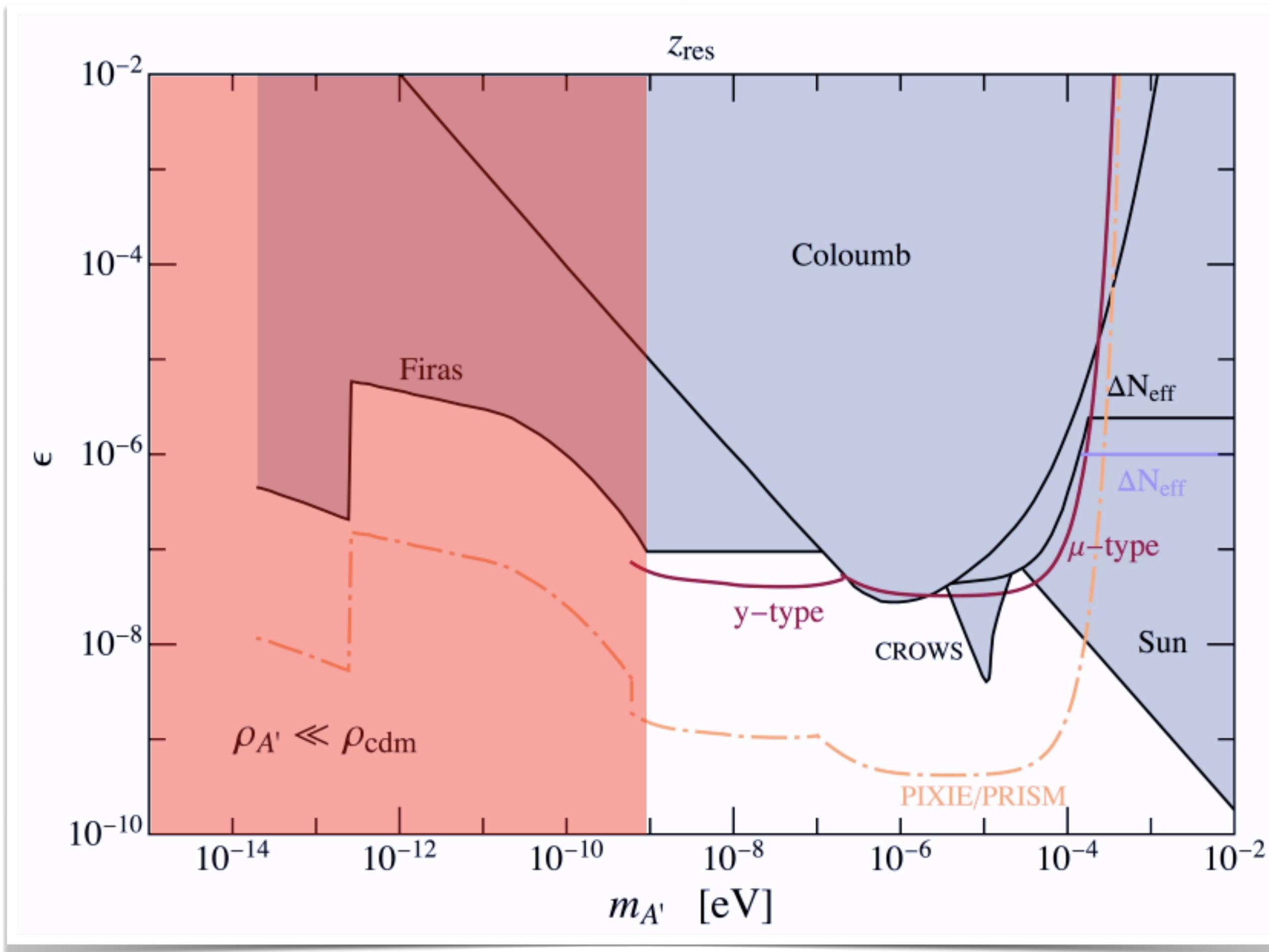
weakening as conversion probability pushed into future



inhomogeneities unimportant

conversions in overdensities at reionization

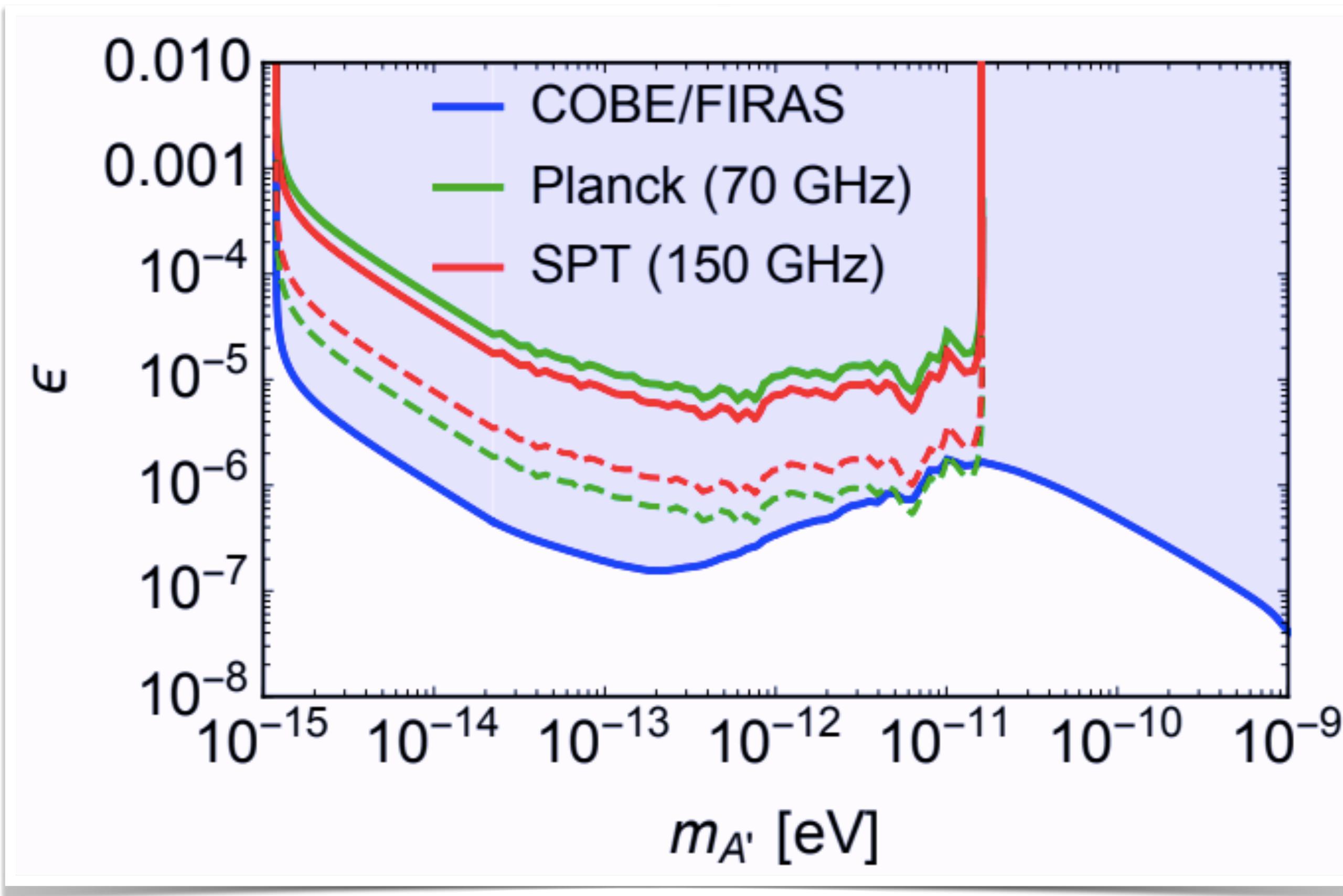
Before Recombination



Density fluctuations not important: universe is smooth.

Existing literature inconsistent and likely incorrect, but small difference.

Two-Point Statistics?

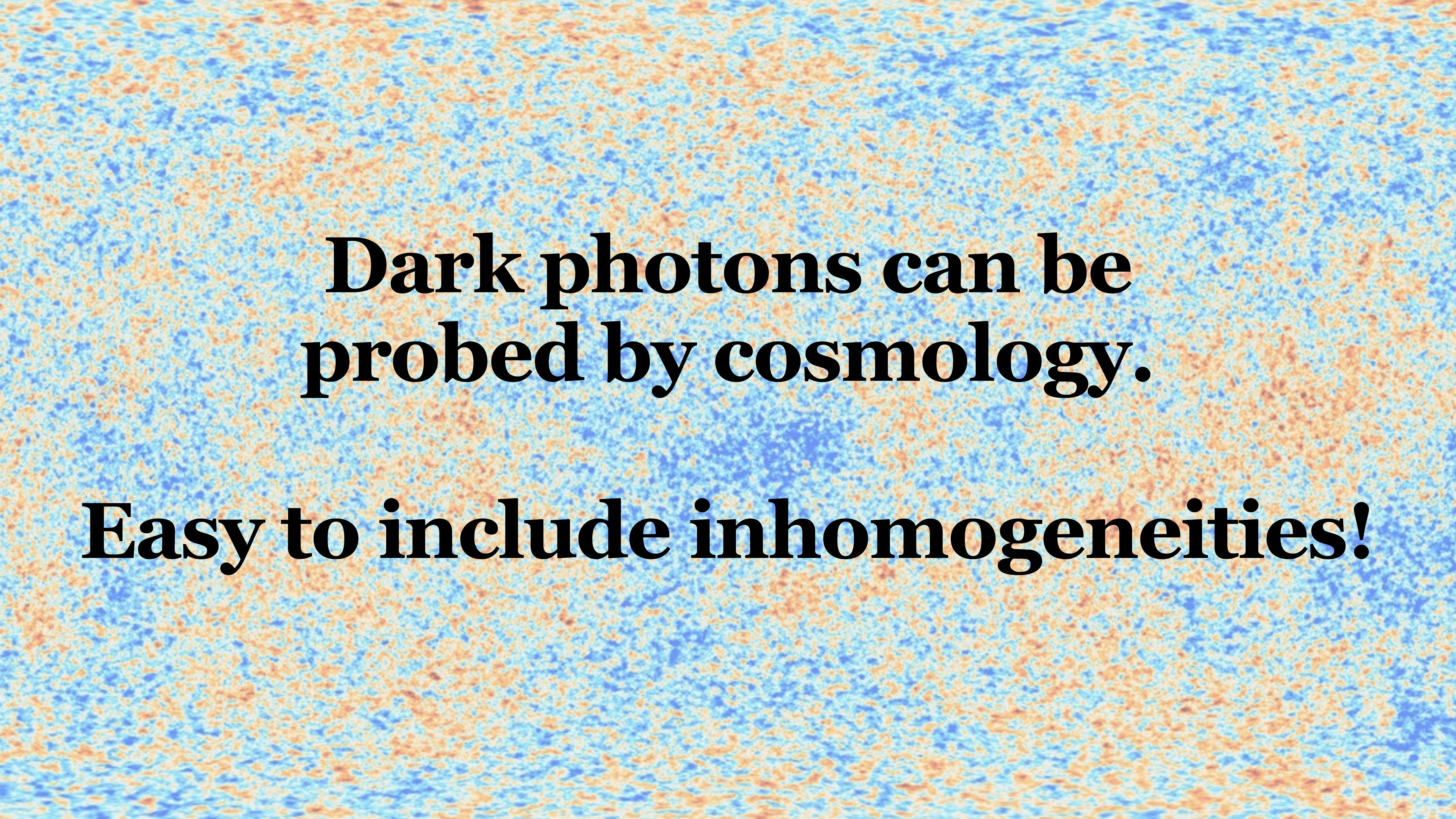


Simple estimate:

$$\langle \delta T_{\gamma \rightarrow A'}^2 \rangle \sim (10^{-5} T_0)^2$$

But what about angular dependence?

Two-point correlations with other observables?

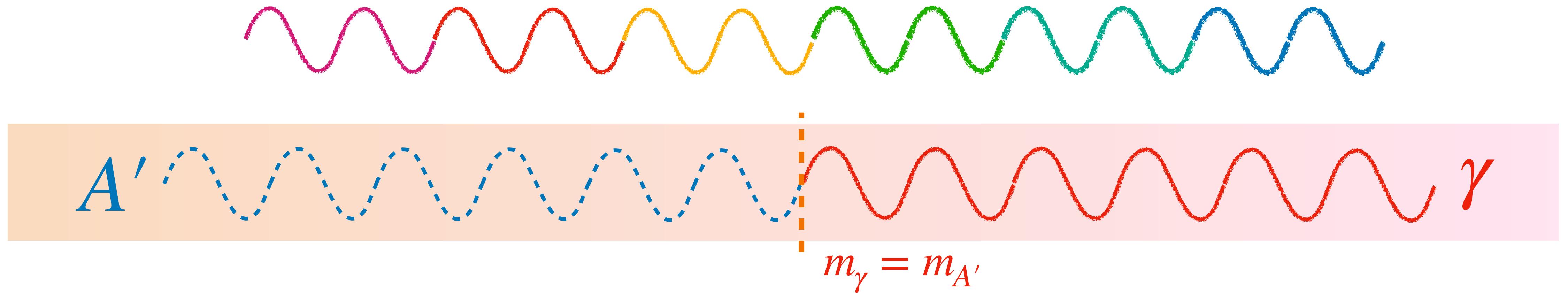


**Dark photons can be
probed by cosmology.**

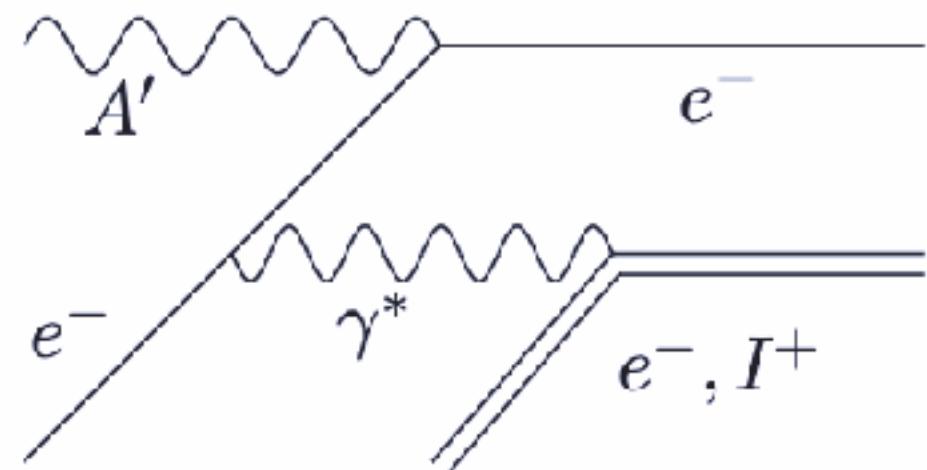
Easy to include inhomogeneities!

Dark Photon Dark Matter

Oscillation into Photons



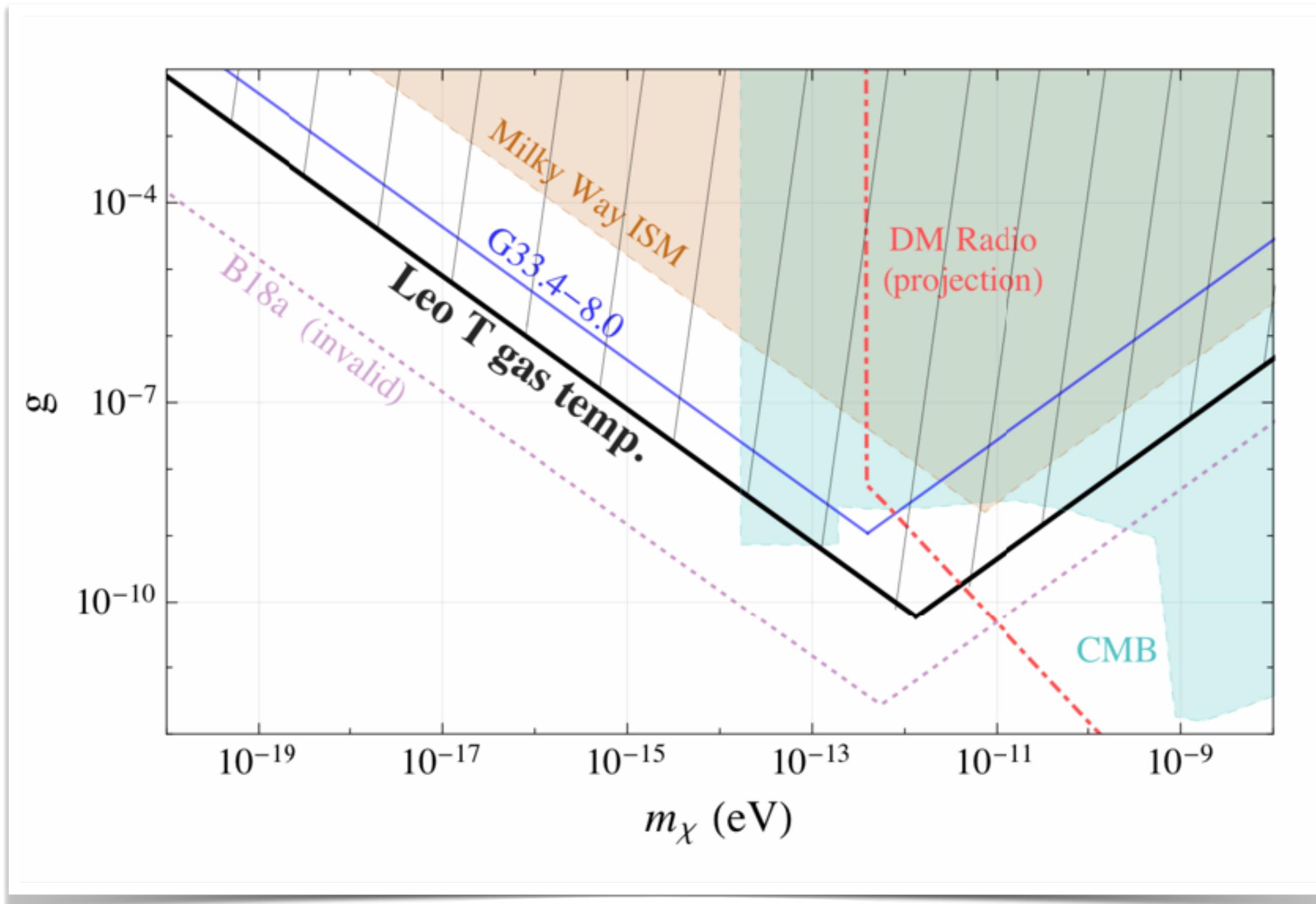
Oscillations convert A' dark matter
to low frequency photons which are rapidly absorbed.



$$\nu = 2.5 \text{ Hz} \left(\frac{m_{A'}}{10^{-14} \text{ eV}} \right)$$

$$\lambda_{\text{mfp}} = \frac{140 \text{ pc}}{(1+z)^6} \Delta_b^{-2} \left(\frac{T}{10^4 \text{ K}} \right)^{3/2} \left(\frac{m_{A'}}{10^{-14} \text{ eV}} \right)^2$$

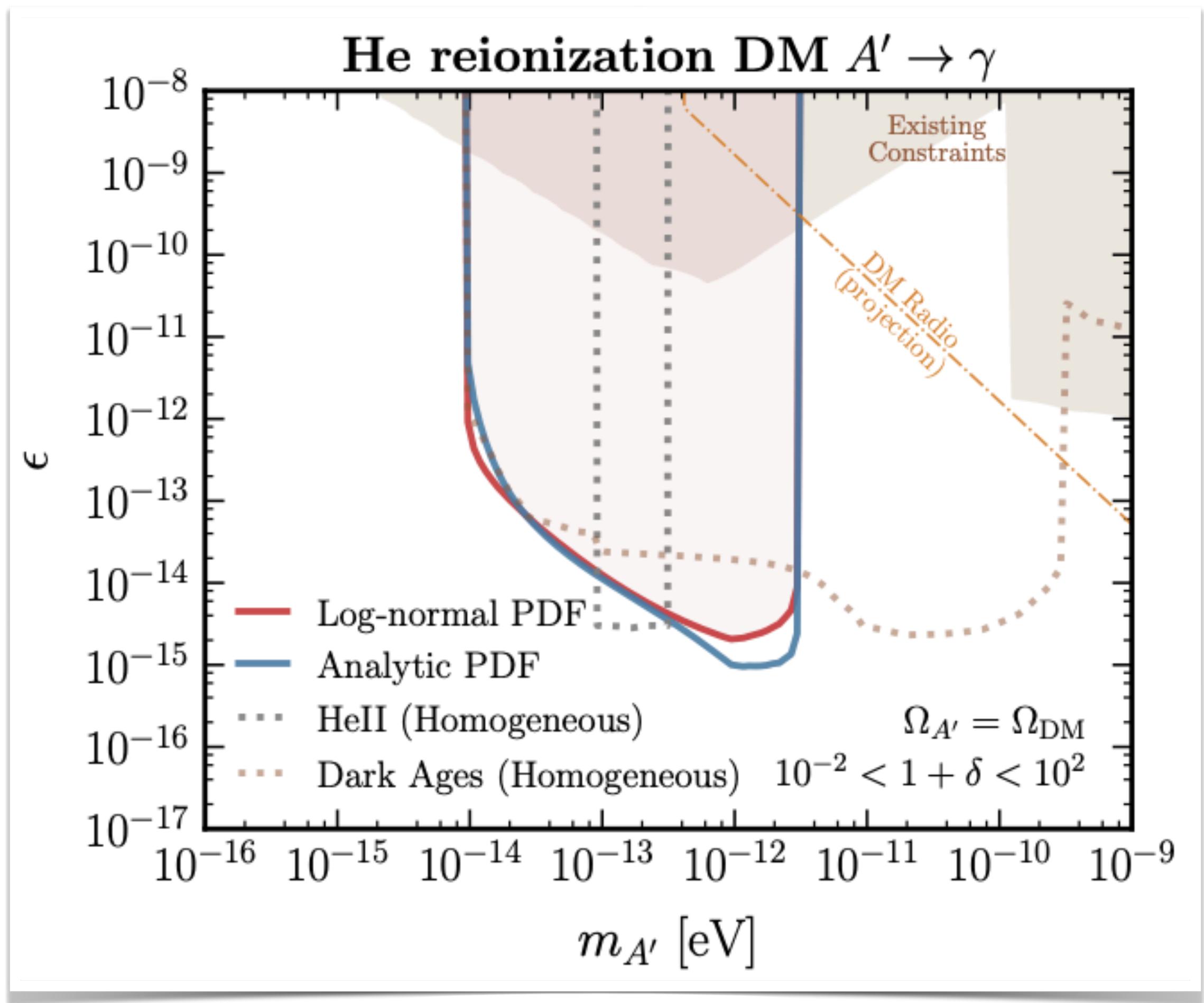
Galactic Heating



Nonresonant oscillations convert A' dark matter to **low frequency photons** which are **rapidly absorbed**.

Compare heating rate with cooling rate in interstellar medium/dwarf galaxy gas.

Intergalactic Medium Heating

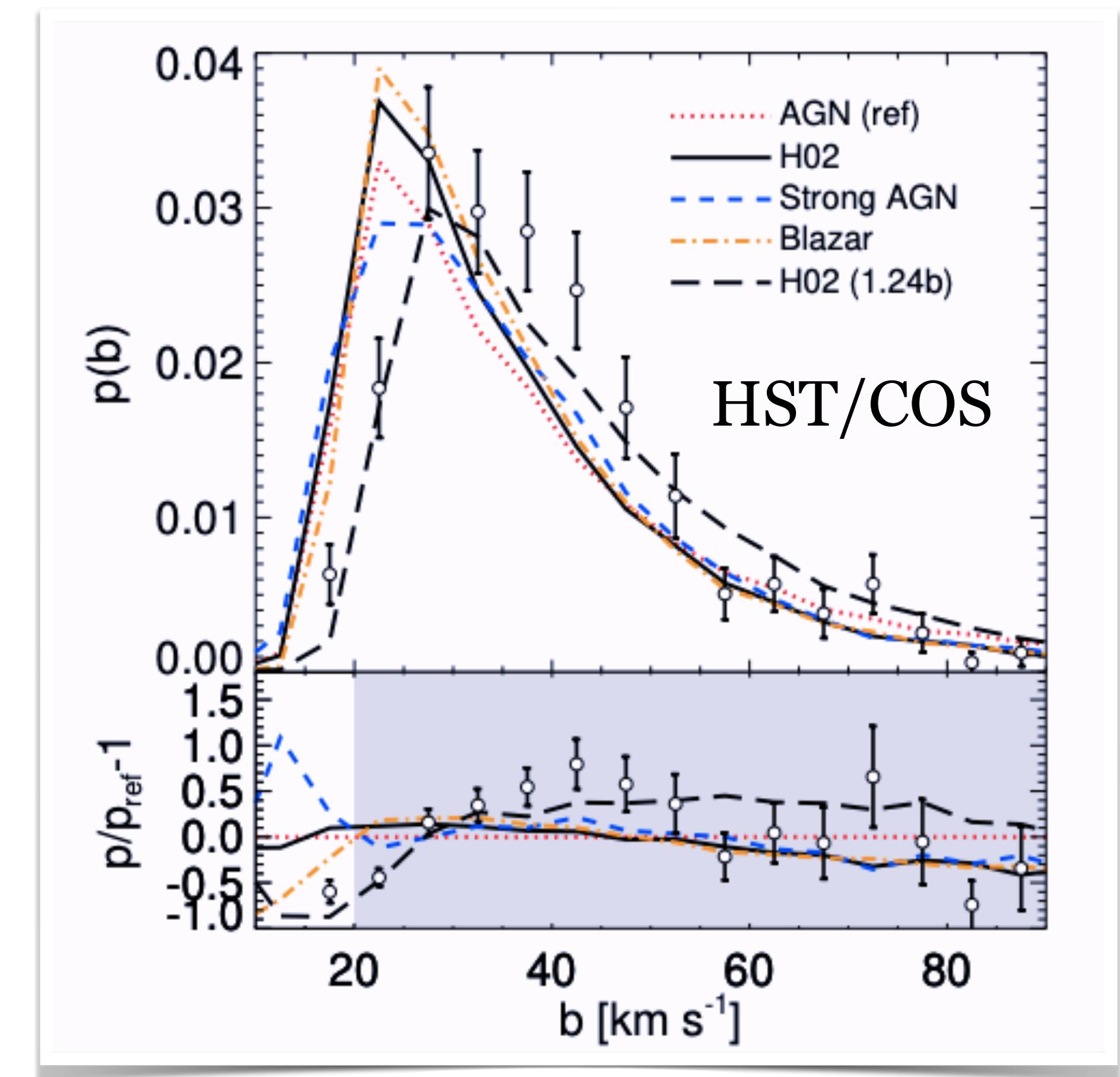
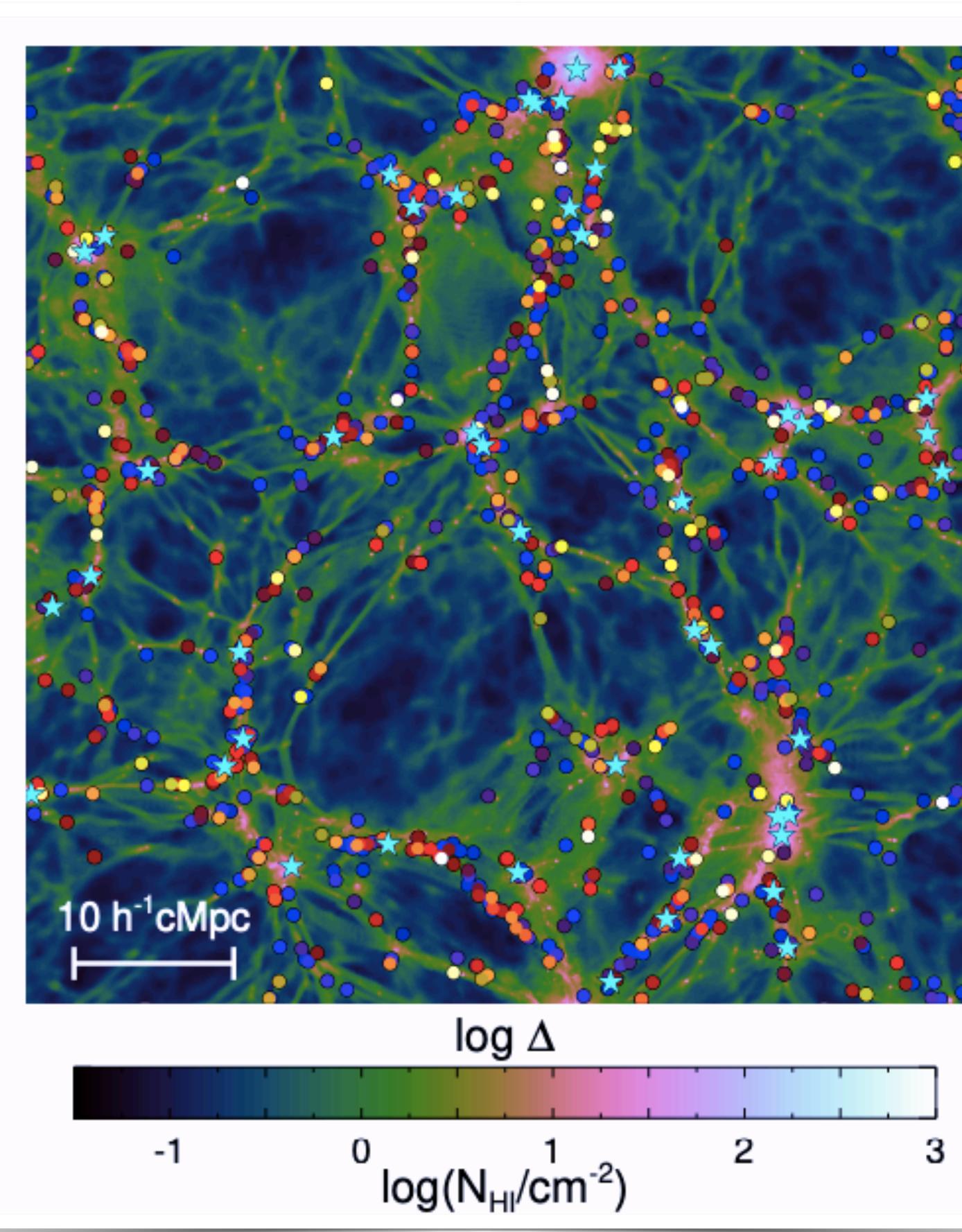


Dark matter $A' \rightarrow \gamma$ resonant conversions produce low-energy photons that heat the IGM.

Must include **inhomogeneities**.

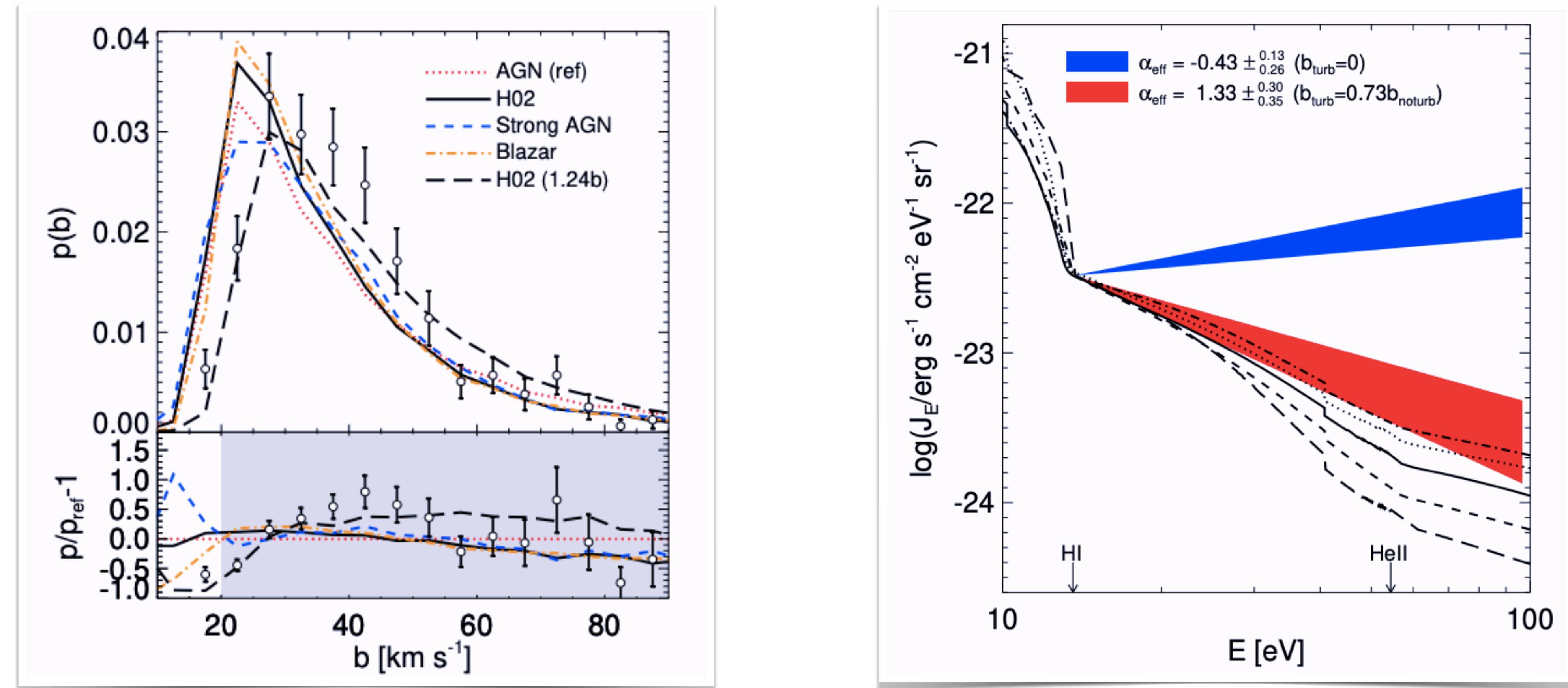
Constraints can be roughly set by requiring $T_{\text{IGM}} \lesssim 10^4 \text{ K}$ for consistency with $2 \lesssim z \lesssim 5$ Ly α forest.

Low-Redshift Ly α Discrepancy



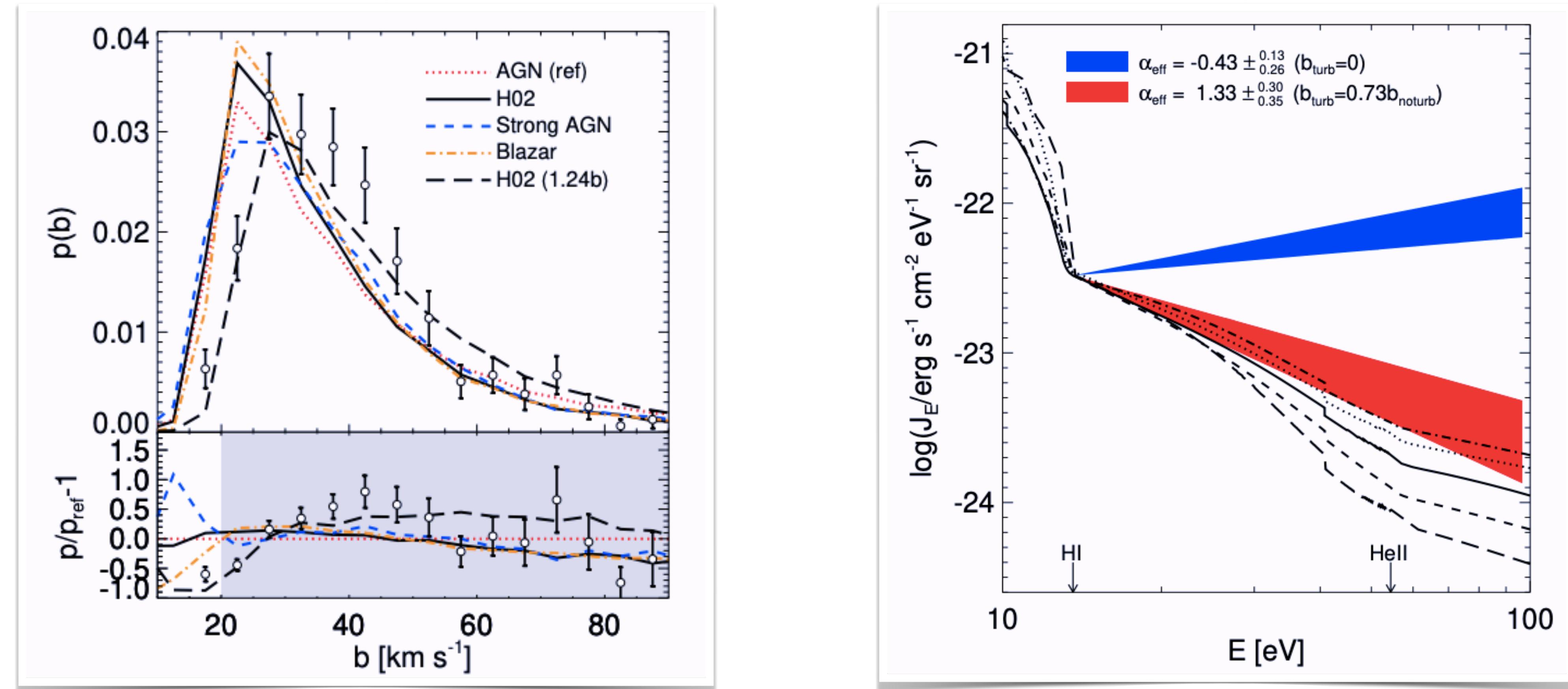
IGM simulations find Ly α Doppler widths that are **too narrow** at low redshifts compared to observations.

Low-Redshift Ly α Discrepancy



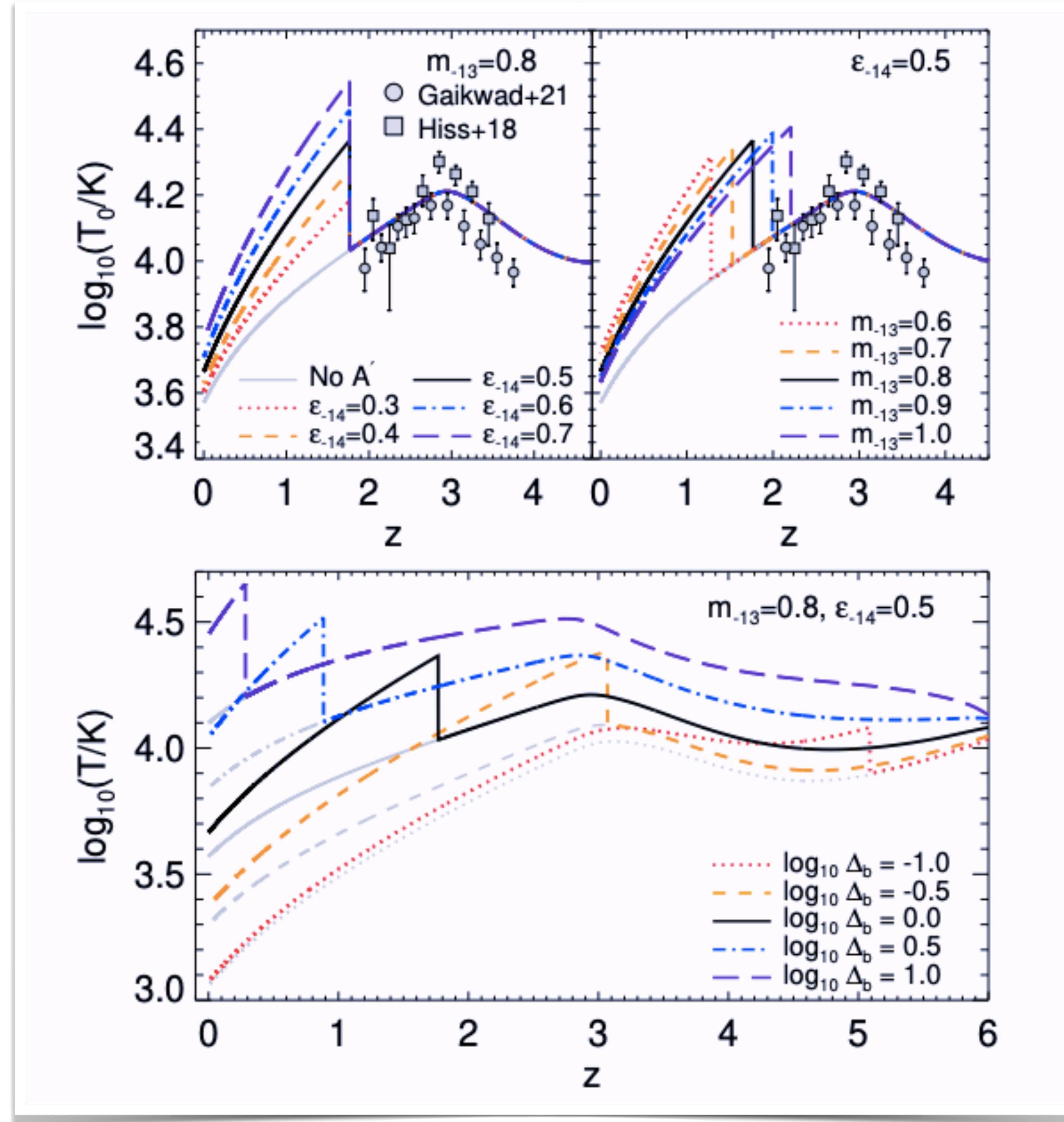
Cannot be explained by increased feedback,
or steeper ionizing radiation spectrum.

Low-Redshift Ly α Discrepancy



Requires $u = 6.9 \text{ eV}$ per baryon of energy for $z \lesssim 2$, with density dependence $u \propto \Delta^{0.6}$. Possibly: turbulence, dust.

Dark Photon Dark Matter Heating



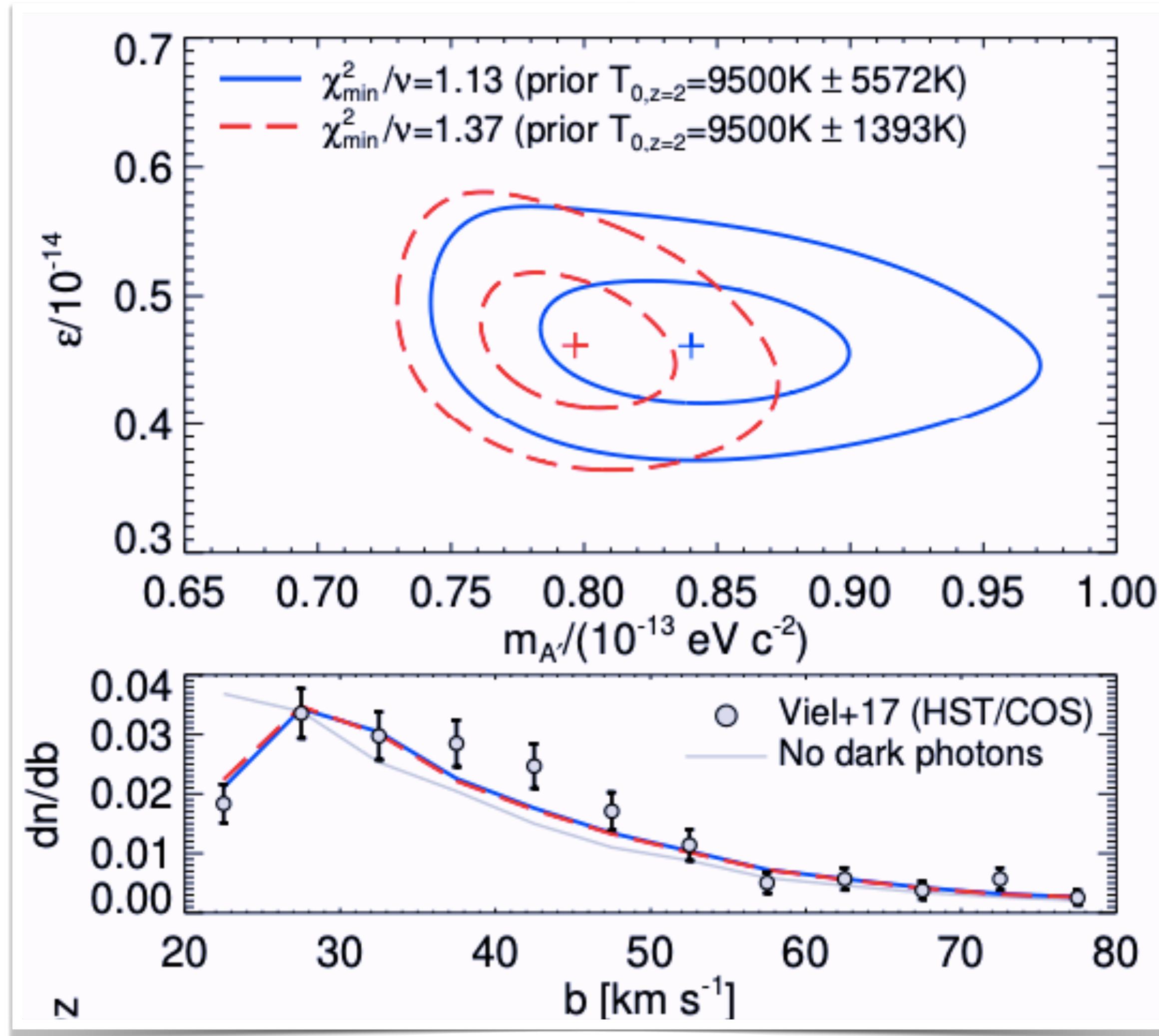
$$P_{A' \rightarrow \gamma} = \pi \epsilon^2 m_{A'} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1} \Big|_{m_{A'} = m_\gamma}$$

Dark matter $A' \rightarrow \gamma$ conversions can give anomalous heating.

$m_{A'} \lesssim 8 \times 10^{-14} \text{ eV}$ to be consistent with Ly α forest at $2 \lesssim z \lesssim 5$.

$u \propto \Delta^{1/2}$ due to photon plasma mass evolution.

Dark Photon Dark Matter Heating



Significantly better agreement with HST/COS Doppler widths.

Future Work

Predicts **inverted temperature-density relation** at $z \sim 3$, for which we have mild evidence for (Rorai+).

Use these simulations to set **robust limits on A' DM**, improving on current estimates.

Stay tuned!

