ALP-photon-dark photon oscillations & their cosmological or astrophysical implications

Kiwoon Choi

Light scalars: origin, cosmology, astrophysics and experimental probes

Benasque, Apr 10, 2019

KC, S. Lee, H. Seong, S. Yun, 1806.09508

and work in preparation

The IBS Center for Theoretical Physics of the Universe

Outline

➢ Motivations

➢ $a - \gamma - \gamma'$ oscillation and some applications

➢ Generation of the cosmological background dark photon gauge fields

Motivations

ALP-photon oscillations (conversion) induced by the ALP-photon coupling $\frac{g_a}{4}aF^{\mu\nu}\tilde{F}_{\mu\nu} = g_a a\vec{E} \cdot \vec{B}$ in background B-field can have many interesting implications:

* Experimental detection of axion or ALP (talk by Igor Irastorza)
* Spectral anomaly of X or γ rays from astrophysical sources
* Transparency of high energy γ rays
* Distortion of CMB, …..

γ-ray depletions for certain galactic pulsars or SN remnant?

Majumdar et al, 1801.08813; Xia et al, 1801.01646

Spectral irregularity of γ-rays (Fermi-LAT data) from certain galactic pulsars and supernova remnants, indicating a depletion of photons at E > GeV, which might be due to the conversion of gamma rays to some invisible particles.
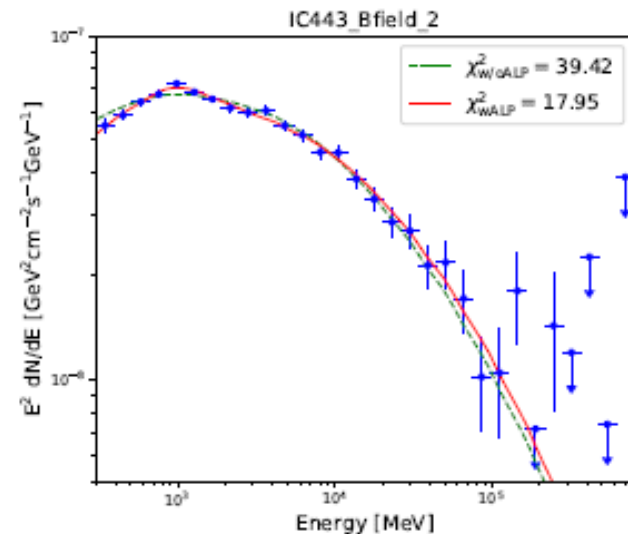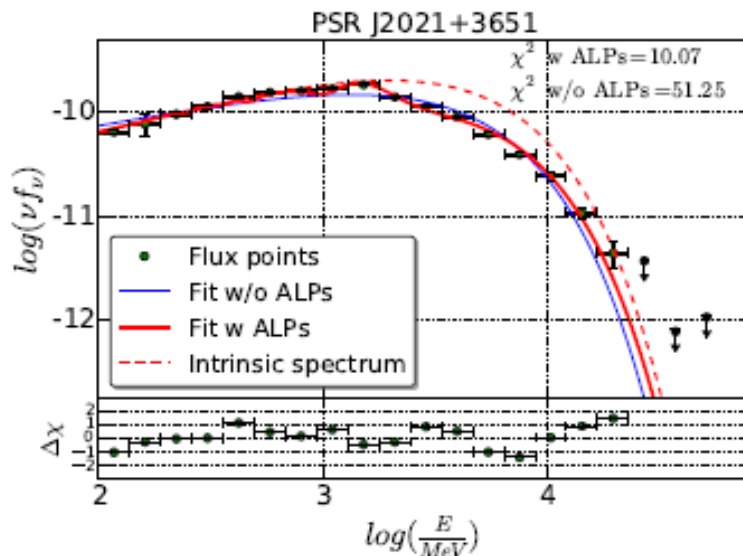
As suggested in *1801.08813* and *1801.01646* , such γ-ray depletion at E > 1 GeV might be explained by the ALP-photon oscillations:

$$\frac{g_a}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_a a \vec{E} \cdot \vec{B} \quad \Rightarrow \quad g_a a \frac{\partial \vec{A}}{\partial t} \cdot \langle \vec{B} \rangle \quad \textit{Raffelt \& Stodolsky '88}$$

$$\Rightarrow \quad \left[w + i\partial_z - \frac{1}{2\omega}\mathcal{M}^2 \right] \begin{pmatrix} \gamma \\ a \end{pmatrix} = 0 \qquad \mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & g_a B_T \omega \\ g_a B_T \omega & m_a^2 \end{pmatrix} \left(\vec{B}_T = \vec{B} - \hat{k}(\hat{k} \cdot \vec{B}) \right)$$

In static and homogeneous backgrounds,

$$P_{\gamma \to a} = \frac{\omega^2}{\omega^2 + \omega_c^2} \sin^2 \frac{\Delta_{\rm osc} d}{2} \qquad \left(\omega_c = \frac{|m_a^2 - m_\gamma^2|}{2 g_a B_T}, \quad \Delta_{\rm osc} = g_a B_T \sqrt{1 + \left(\frac{\omega_c}{\omega} \right)^2} \right)$$

For typical galactic B-field and distance, $B_T \sim 1\ \mu{\rm G},\ d \sim 1\ {\rm kpc}$, significant depletion of gamma-rays with $\omega > \omega_c \sim$ 1 GeV can be achieved when

$$m_a \sim {\rm several} \times 10^{-9}\,{\rm eV}, \quad g_a \sim {\rm few} \times 10^{-10}\,{\rm GeV}^{-1}$$

However, as noticed already in *1801.08813* and *1801.01646* , this scenario is in conflict with

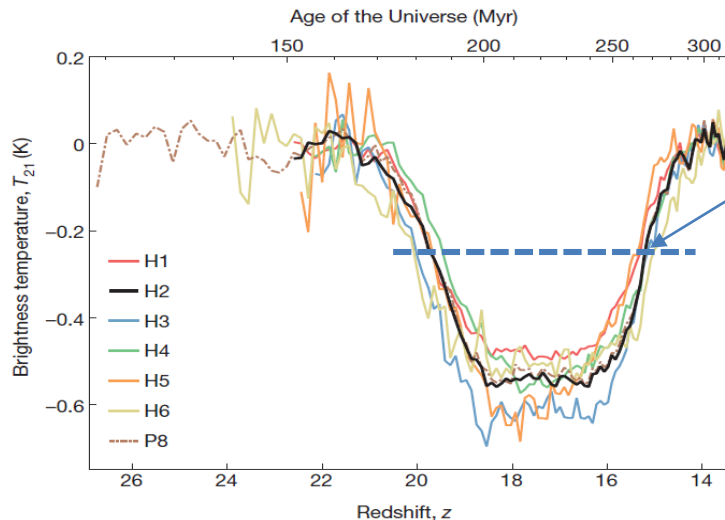(a) the CAST bound: $g_a < 6 \times 10^{-11}\,\mathrm{GeV}^{-1}$ for $m_a < 1\,\mathrm{keV}$

(b) non-observation of gamma-ray bursts associated with SN1987A,

$m_a \sim \text{several} \times 10^{-9}\,\mathrm{eV}$

$g_a \sim \text{few} \times 10^{-10}\,\mathrm{GeV}^{-1}$

[Payez et al' 14]

[1801.08813]
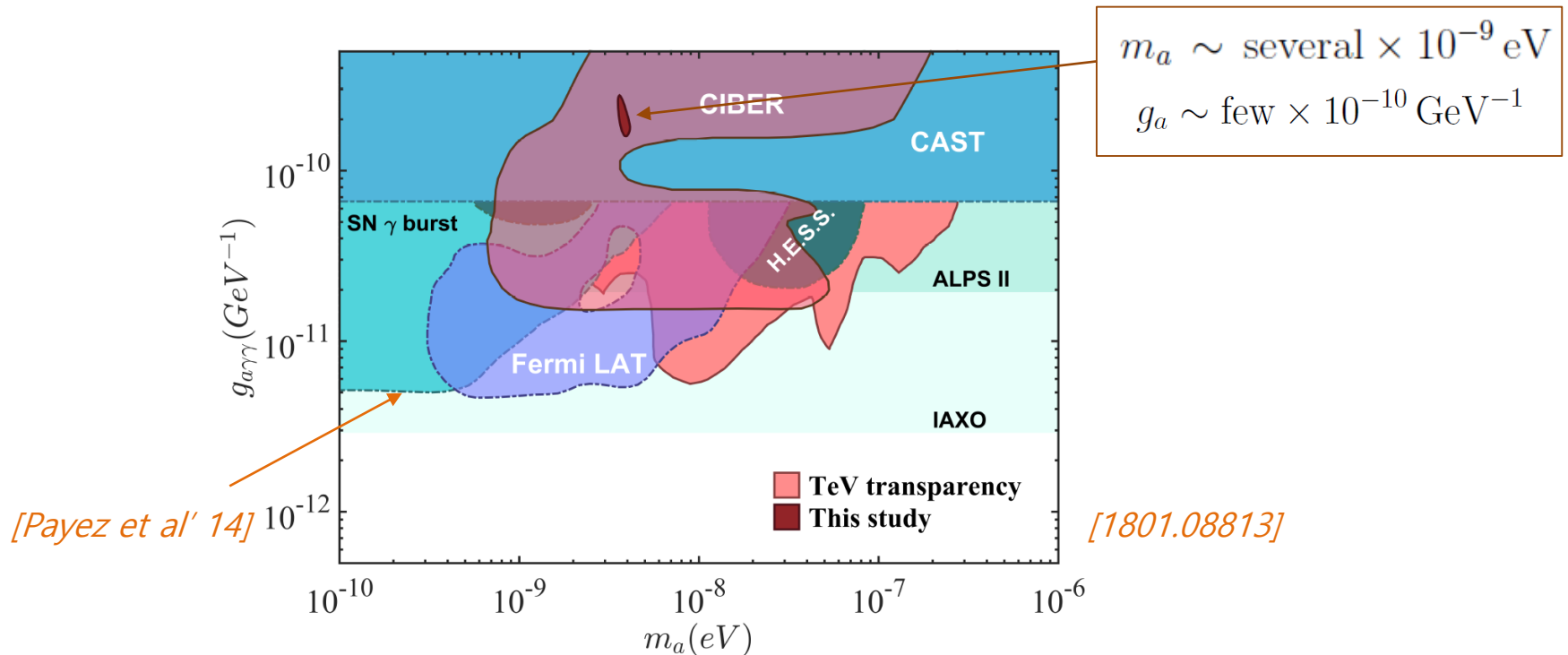
Recent study shows that this is disfavored also by the Fermi-LAT+ MAGIC data on gamma-rays from Perseus cluster. *[Malyshev et al, 1805.04388]*

Detection of 21cm absorption (EDGES)?

Absorption depth predicted by ΛCDM

Bowman et al (2018)

21cm brightness temperature $T_{21} \propto (T_s - T_\gamma)$

➔ either cool down the H-gas or heat up the photons (Pradler's talk)

An efficient way to heat up the photons is a resonant conversion of DR (dark radiations such as dark photons or axion-like particles) to photons at 20 < z < 1700.

Pospelov, Pradler, Ruderman, Urbano, 1803.07048;
Moroi, Nakayama, Tang, 1804.10378

While this idea can be successfully implemented for the $\gamma - \gamma'$ conversion, the $\gamma - a$ conversion scenario is difficult to be realized due to the severe constraint from the CMB distortion (COBE-FIRAS).

Resonant DR-photon conversion in the early Universe: *Mirizzi, Redondo, Sigl, 09*

$$\mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & m_{\mathrm{mix}}^2 \\ m_{\mathrm{mix}}^2 & m_{\mathrm{DR}}^2 \end{pmatrix} \quad \Rightarrow \quad P_{\gamma \leftrightarrow \mathrm{DR}} \simeq \frac{\pi m_{\mathrm{mix}}^4}{m_{\mathrm{DR}}^2 \omega} \left(\left| \frac{d \ln(m_{\mathrm{DR}}^2 / m_\gamma^2)}{dt} \right| \right)^{-1}_{m_\gamma = m_{\mathrm{DR}}}$$

$$\left((m_\gamma^2)_i \gg (m_{\mathrm{DR}}^2)_i, \quad (m_\gamma^2)_f \ll (m_{\mathrm{DR}}^2)_f, \quad \cos 2\theta_f \simeq -\cos 2\theta_i \simeq 1 \right)$$

$$\mathrm{DR} = \gamma' \ \mathrm{with} \ \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \quad \Rightarrow \quad m_{\mathrm{mix}}^2 = \epsilon m_{\gamma'}^2 \quad \Rightarrow \quad P_{\gamma \leftrightarrow \gamma'} \propto \frac{1}{\omega}$$

$$\mathrm{DR} = \mathrm{ALP} \ \mathrm{with} \ \frac{g_a}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} \quad \Rightarrow \quad m_{\mathrm{mix}}^2 = g_a B_T \omega \quad \Rightarrow \quad P_{\gamma \leftrightarrow a} \propto \omega$$

On the other hand, $\omega_{\mathrm{CMB}} \sim 10^3 \omega_{21}$, and therefore for the case of $\gamma - a$ conversion, the conversion rate in the CMB regime is much stronger than the rate in the 21cm regime.

Indeed, the $\gamma - a$ conversion scenario is practically excluded by CMB distortion (COBE-FIRAS) when combined with the constraints from SN γ-ray burst and BH superradiance.

$$P_{\mathrm{DR}\to\gamma}(\omega_{21}) \sim 10^{-9}/f_{\mathrm{DR}}(\omega_{21})\Delta N_{\mathrm{eff}} \gtrsim 4 \times 10^{-8}$$ for EDGES data
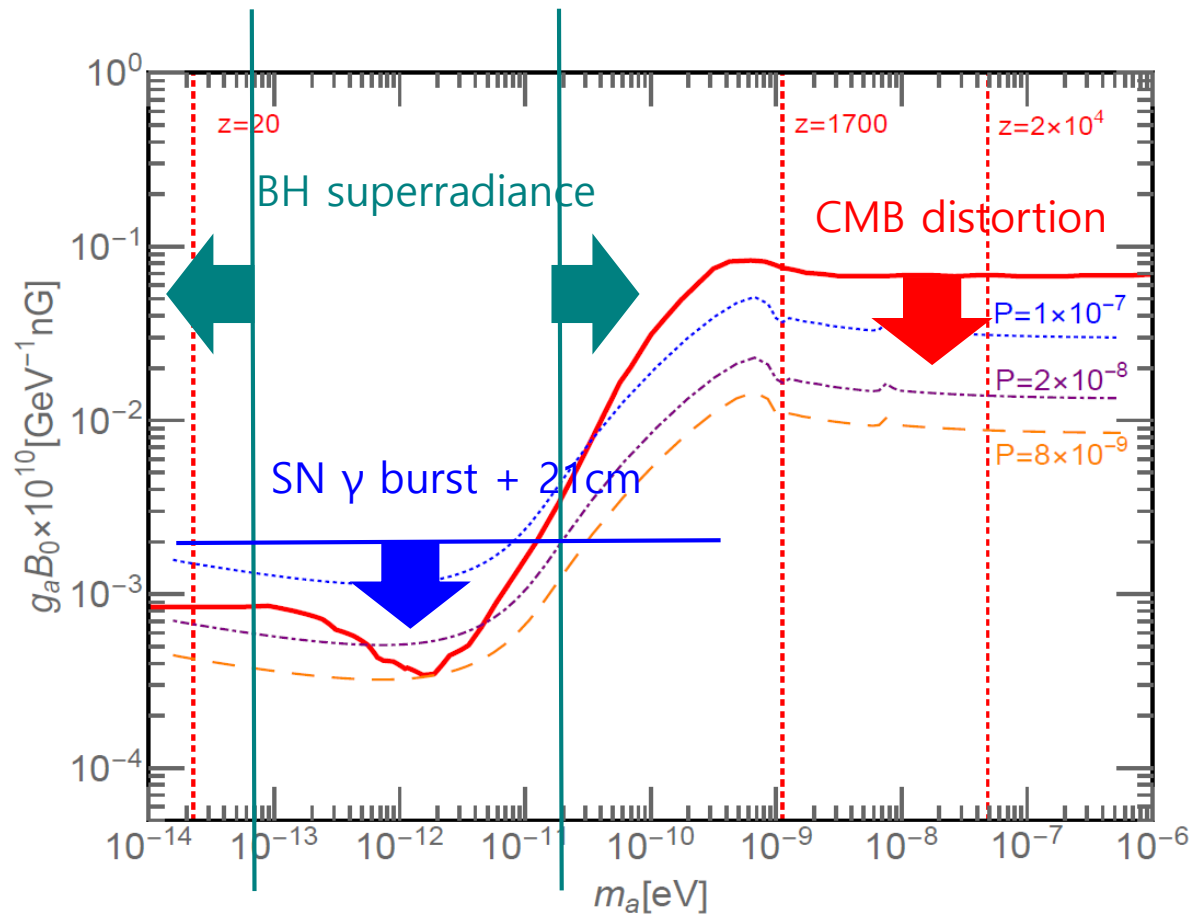
Moroi et al,1804.10378

Mirrizi, Redondo, Sigl, 09;
Stott, Marsh,18;
Payez et al,14;
Monoda et al, 18

$a - \gamma - \gamma'$ oscillations

Like the axions or ALP, light dark photon is also a compelling candidate for BSM physics in light dark world.

The simplest possibility would be an exactly massless dark photon associated with unbroken U(1)′ gauge symmetry as in such case we don't need to introduce a mechanism to generate a tiny mass of γ' at very low energy scale.

Most general $a - \gamma - \gamma'$ couplings (in the basis without kinetic mixing)

$$\frac{1}{4} a \left(g_a F^{\mu\nu} \tilde{F}_{\mu\nu} + g_a' F^{\mu\nu} \tilde{F}'_{\mu\nu} + g_a'' F'^{\mu\nu} \tilde{F}'_{\mu\nu} \right)$$

$$\frac{1}{4}a\left(g_a F^{\mu\nu}\tilde{F}_{\mu\nu} + g_a' F^{\mu\nu}\tilde{F}'_{\mu\nu} + g_a'' F'^{\mu\nu}\tilde{F}'_{\mu\nu}\right)$$

Severe constraints on g_a, but weaker constraints on g_a' and much weaker constraints on g_a''.
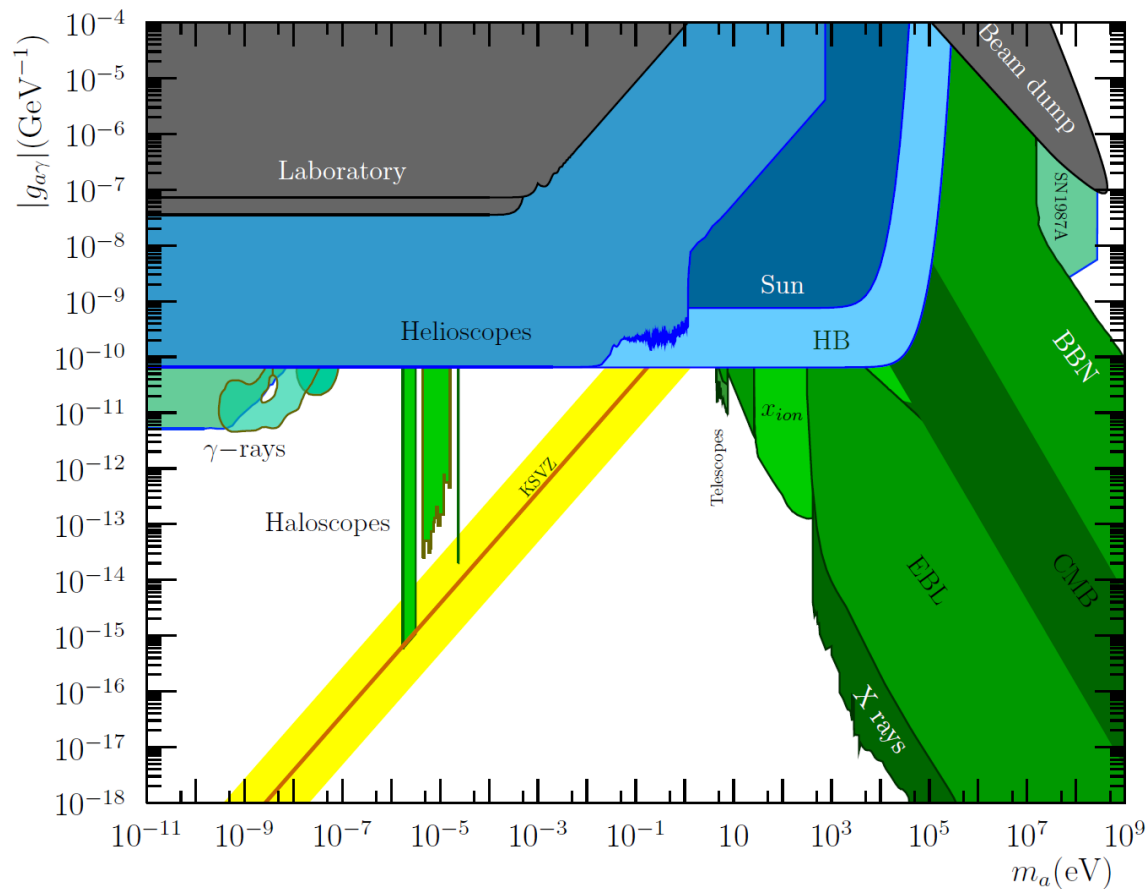
Redondo, Irastroza, 18

Some remarks on the ALP couplings:

$$\frac{1}{4}a\left(g_a F^{\mu\nu}\tilde{F}_{\mu\nu} + g'_a F^{\mu\nu}\tilde{F}'_{\mu\nu} + g''_a F'^{\mu\nu}\tilde{F}'_{\mu\nu}\right)$$

i) As the ALP couplings to gauge fields are often quantized, some of the ALP couplings can be simply vanishing, while others are nonzero.

ii) More generically, ALP couplings can have hierarchical structure, which might be generated by either alignment or the clockwork mechanism.

A key ingredient of our scenario is the background dark photon gauge fields **(E', B')** in addition to the ordinary background **B**-field.

➜ $$\left[w + i\partial_z - \frac{1}{2\omega}\mathcal{M}^2\right]\begin{pmatrix}\gamma \\ \gamma' \\ a\end{pmatrix} = 0 \qquad \mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & 0 & \tilde{g}\tilde{B}\omega \\ 0 & 0 & \tilde{g}'\tilde{B}'\omega \\ \tilde{g}\tilde{B}\omega & \tilde{g}'\tilde{B}'\omega & m_a^2 \end{pmatrix}$$

$$\tilde{g}\tilde{B} = |g_a\vec{B}_T + g'_a(\vec{B}'_T - \hat{k}\times\vec{E}')|, \quad \tilde{g}'\tilde{B}' = |g'_a\vec{B}_T + g''_a(\vec{B}'_T - \hat{k}\times\vec{E}')|$$

One of our major concerns is if this $a - \gamma - \gamma'$ oscillation can explain the depletion of gamma-rays from galactic pulsars and SN remnants at E > 1 GeV, while satisfying the known observational constraints.

Conversion probabilities in background B and (B′,E′) which are approximately constant over a distance d:

$$P_{a \leftrightarrow \gamma} = \left(\frac{\tilde{g}^2 \tilde{B}^2}{\tilde{g}^2 \tilde{B}^2 + \tilde{g}'^2 \tilde{B}'^2} \right) \left(\frac{\omega^2}{\omega^2 + \omega_c^2} \right) \sin^2 \frac{\Delta_{\mathrm{osc}} d}{2} \qquad \left(m_\gamma^2 \ll \min \left(\tilde{g} \tilde{B} \omega, \, \tilde{g}' \tilde{B}' \omega, \, m_a^2 \right) \right)$$

$$P_{\gamma \leftrightarrow \gamma'} = \left(\frac{2 \tilde{g}^2 \tilde{B}^2 \tilde{g}'^2 \tilde{B}'^2}{(\tilde{g}^2 \tilde{B}^2 + \tilde{g}'^2 \tilde{B}'^2)^2} \right) \left(1 - \cos \frac{\Delta_a d}{2} \cos \frac{\Delta_{\mathrm{osc}} d}{2} \right.$$

$$\left. - \frac{\omega_c}{\sqrt{\omega^2 + \omega_c^2}} \sin \frac{\Delta_a d}{2} \sin \frac{\Delta_{\mathrm{osc}} d}{2} - \frac{\omega^2}{2(\omega^2 + \omega_c^2)} \sin^2 \frac{\Delta_{\mathrm{osc}} d}{2} \right)$$

$$\left(\omega_c = \frac{m_a^2}{2 \sqrt{\tilde{g}^2 \tilde{B}^2 + \tilde{g}'^2 \tilde{B}'^2}}, \quad \Delta_{\mathrm{osc}} = \sqrt{\tilde{g}^2 \tilde{B}^2 + \tilde{g}'^2 \tilde{B}'^2} \left(1 + (\omega_c/\omega)^2 \right)^{1/2}, \quad \Delta_a = \frac{m_a^2}{2\omega} \right)$$

Parameter region to induce a sizable depletion of γ rays at E > 1 GeV, while being compatible with the observational constraints:
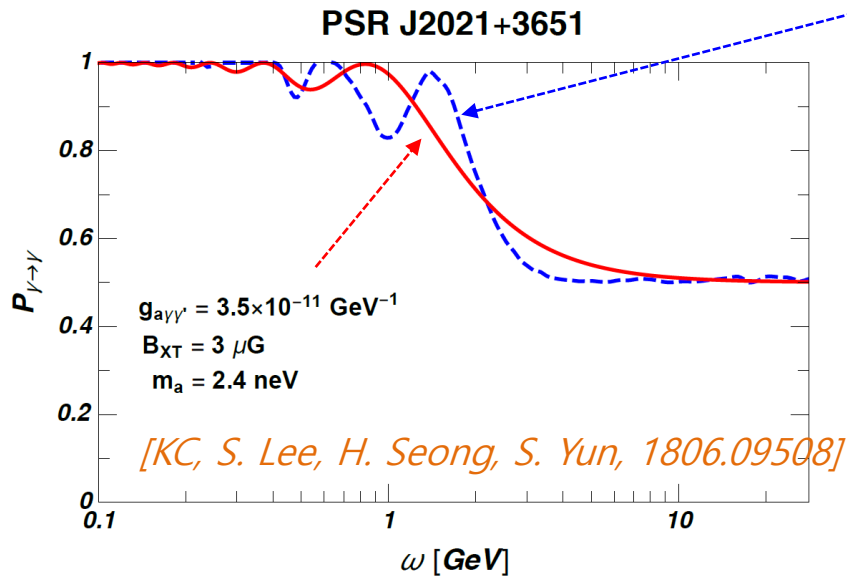
$$g_a \ll g_a', \quad g_a'' \lesssim \mathcal{O}(g_a'), \quad B' \sim E' \gtrsim B \sim 1\,\mu\text{G},$$

$$\tilde{g}\tilde{B} \sim \tilde{g}'\tilde{B}' \sim g_a'B' \gtrsim 1\,\text{kpc}^{-1}, \quad \omega_c \sim \frac{m_a^2}{g_a'B'} \sim 1\,\text{GeV}$$

➡ $$g_a' = \mathcal{O}(10^{-10} - 10^{-11})\,\text{GeV}^{-1}, \quad m_a = \mathcal{O}(10^{-9})\,\text{eV}, \quad B' = \mathcal{O}(1)\,\mu\text{G}$$
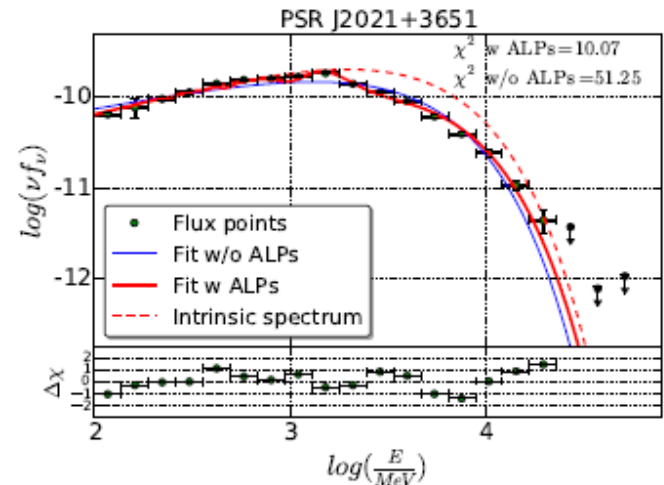
$$g_a < 5 \times 10^{-12}\,\text{GeV}^{-1}, \quad g_a'' \lesssim \mathcal{O}(g_a')$$

ALP coupling suggested in 1801.08813 to explain the pulsar data:

$$g_{a\gamma\gamma} = 3.5 \times 10^{-10}\,\text{GeV}^{-1} \quad m_a = 4.4\,\text{neV}$$

Photon survival probability for PSR J2021+3651

PSR J2021+3651

$g_{a\gamma\gamma'} = 3.5 \times 10^{-11}$ GeV^{-1}
$B_{XT} = 3\,\mu$G
$m_a = 2.4$ neV

[KC, S. Lee, H. Seong, S. Yun, 1806.09508]

Constraints on $\frac{1}{4}g'_a F^{\mu\nu}\tilde{F}'_{\mu\nu}$ *KC, S. Lee, H. Seong, S. Yun, 1806.09508*

1) No constraint from CAST as there is no $a \rightarrow \gamma$ induced by background $\langle B \rangle$

2) Stellar emission of ALP or dark photon:

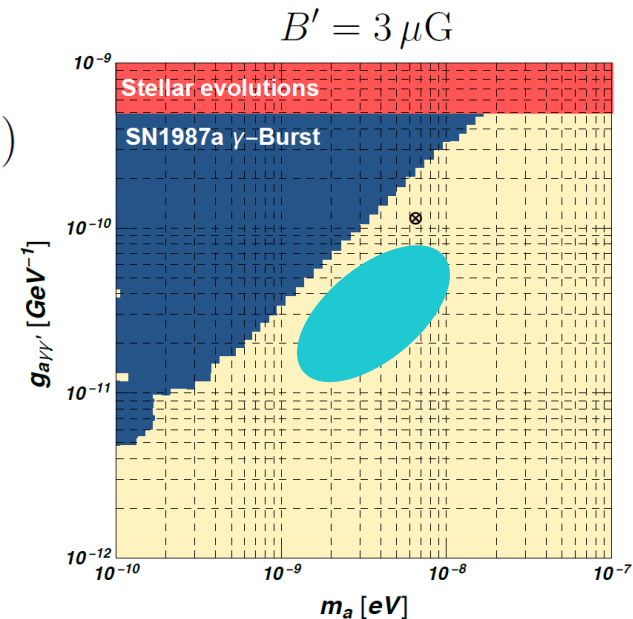Plasmon decays: $\gamma(\text{plasmon}) \rightarrow a + \gamma' \quad \Rightarrow \quad g'_a < 5 \times 10^{-5}\,\text{GeV}^{-1}$

3) Gamma-ray bursts associated with SN1987A, resulting from

a or γ' emitted from SN1987A $\rightarrow \gamma$
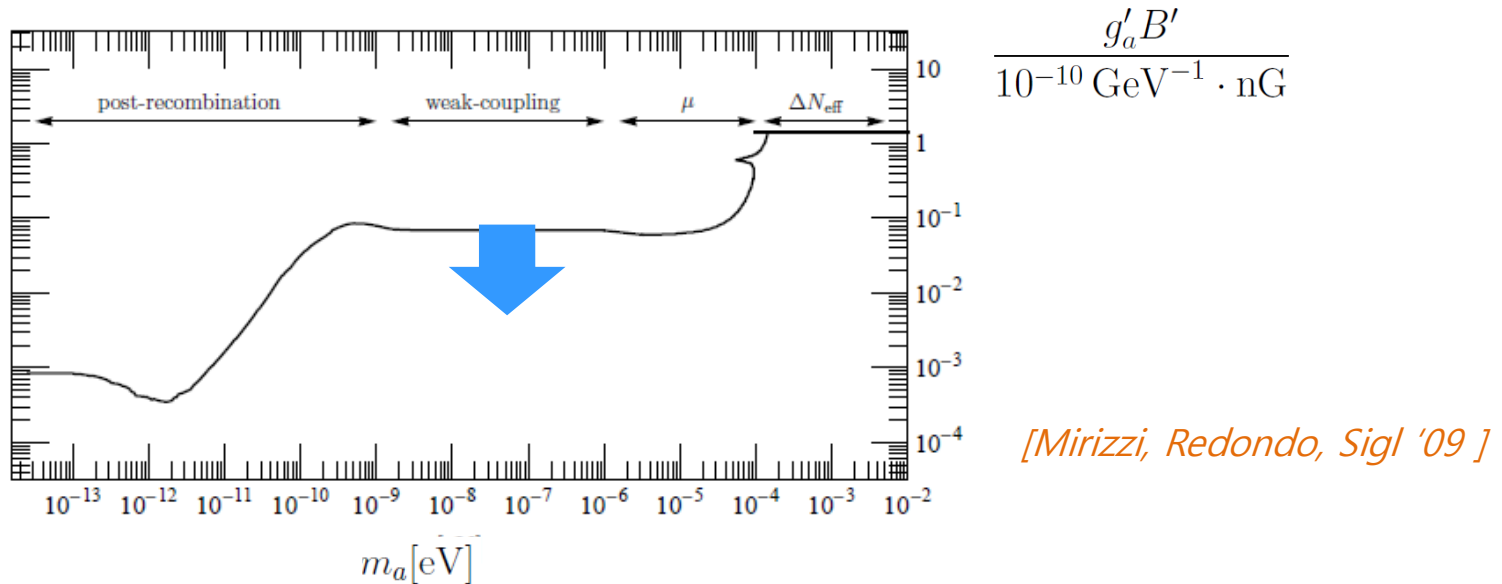
(in background B' or E')

Compared to g_a, the bound is weaker as g'_a is less efficient in producing ALP from SN1987A.

(plasmon decay vs Primakov process)

4) CMB distortion

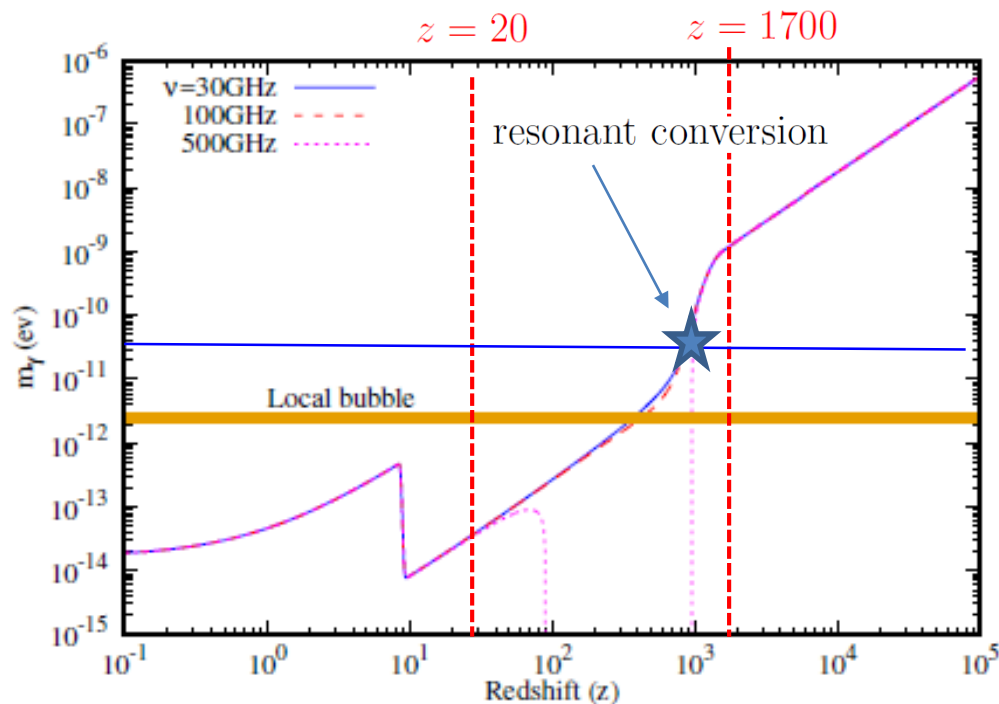Upper bound on $g_a B$ or $g'_a B'$ from CMB distortion

$$\frac{g'_a B'}{10^{-10}\,\mathrm{GeV}^{-1}\cdot\mathrm{nG}}$$

[Mirizzi, Redondo, Sigl '09]

➔ $\quad g'_a B' < 10^{-11}\,\mathrm{GeV}^{-1}\cdot\mathrm{nG}$ if B' were generated at $z > 3000$

On the other hand, we need $g'_a B' \sim 10^{-7}\,\mathrm{GeV}^{-1}\cdot\mathrm{nG}$ to explain the γ ray depletions, so should avoid this bound.

➔ Generate B′ at z < 3000.

Our next concern is if the EDGES anomaly can be explained by a resonant DR conversion to 21cm photons through the $a - \gamma - \gamma'$ oscillations without causing a significant distortion of CMB.

$$\mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & m_{\text{mix}}^2 \\ m_{\text{mix}}^2 & m_{\text{DR}}^2 \end{pmatrix} \qquad P_{\gamma \leftrightarrow \text{DR}} \simeq \frac{\pi m_{\text{mix}}^4}{m_{\text{DR}}^2 \omega} \left(\left| \frac{d \ln(m_{\text{DR}}^2 / m_\gamma^2)}{dt} \right| \right)^{-1}_{m_\gamma = m_{\text{DR}}}$$

$$\left((m_\gamma^2)_i \gg (m_{\text{DR}}^2)_i, \quad (m_\gamma^2)_f \ll (m_{\text{DR}}^2)_f, \quad \cos 2\theta_f \simeq -\cos 2\theta_i \simeq 1 \right)$$

$\gamma - a$ oscillations

$$m_{\text{DR}}^2 = m_a^2, \qquad m_{\text{mix}} = g_a B_T \omega$$

$$\Rightarrow \qquad P_{a \to \gamma} \propto \omega$$

Resonant DR-photon conversion through the $a - \gamma - \gamma'$ oscillations

$$\left[w + i\partial_z - \frac{1}{2\omega}\mathcal{M}^2\right]\begin{pmatrix} \gamma \\ \gamma' \\ a \end{pmatrix} = 0 \qquad \mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & 0 & \tilde{g}\tilde{B}\omega \\ 0 & 0 & \tilde{g}'\tilde{B}'\omega \\ \tilde{g}\tilde{B}\omega & \tilde{g}'\tilde{B}'\omega & m_a^2 \end{pmatrix}$$

$$\tilde{g}\tilde{B} = |g_a\vec{B}_T + g'_a(\vec{B}'_T - \hat{k} \times \vec{E}')|, \quad \tilde{g}'\tilde{B}' = |g'_a\vec{B}_T + g''_a(\vec{B}'_T - \hat{k} \times \vec{E}')|$$

Although the mixing structure is similar to the case of simple $\gamma - a$ oscillation, in some parameter region, the $a - \gamma - \gamma'$ oscillation can result in a resonant conversion probability which has an unusual spectral dependence, allowing an enough conversion of DR to 21cm photons without affecting the CMB.

KC, S. Lee, H. Seong, S. Yun, in preparation

ALP coupling pattern for EDGES anomaly:

$$g_a'' \gg g_a' \gg g_a \quad \left(g_a \sim \epsilon g_a' \sim \epsilon^2 g_a''\right) \quad \Rightarrow \quad \tilde{g}'\tilde{B}' \sim g_a''B' \gg \tilde{g}\tilde{B} \sim g_a'B'$$

(Note that this is different from the coupling pattern $g_a \ll g_a', \quad g_a'' \lesssim \mathcal{O}(g_a')$ that we need to explain the γ ray depletion.)

Spectral dependence of the resonant conversion probability can be read off by considering the effective 2-state oscillation derived from the full 3-state oscillation:

$$\mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & m_{\text{mix}}^2 \\ m_{\text{mix}}^2 & m_{\text{DR}}^2 \end{pmatrix} \qquad P_{\gamma \leftrightarrow \text{DR}} \simeq \frac{\pi m_{\text{mix}}^4}{m_{\text{DR}}^2 \omega} \left(\left| \frac{d \ln(m_{\text{DR}}^2/m_\gamma^2)}{dt} \right| \right)^{-1}_{m_\gamma = m_{\text{DR}}}$$
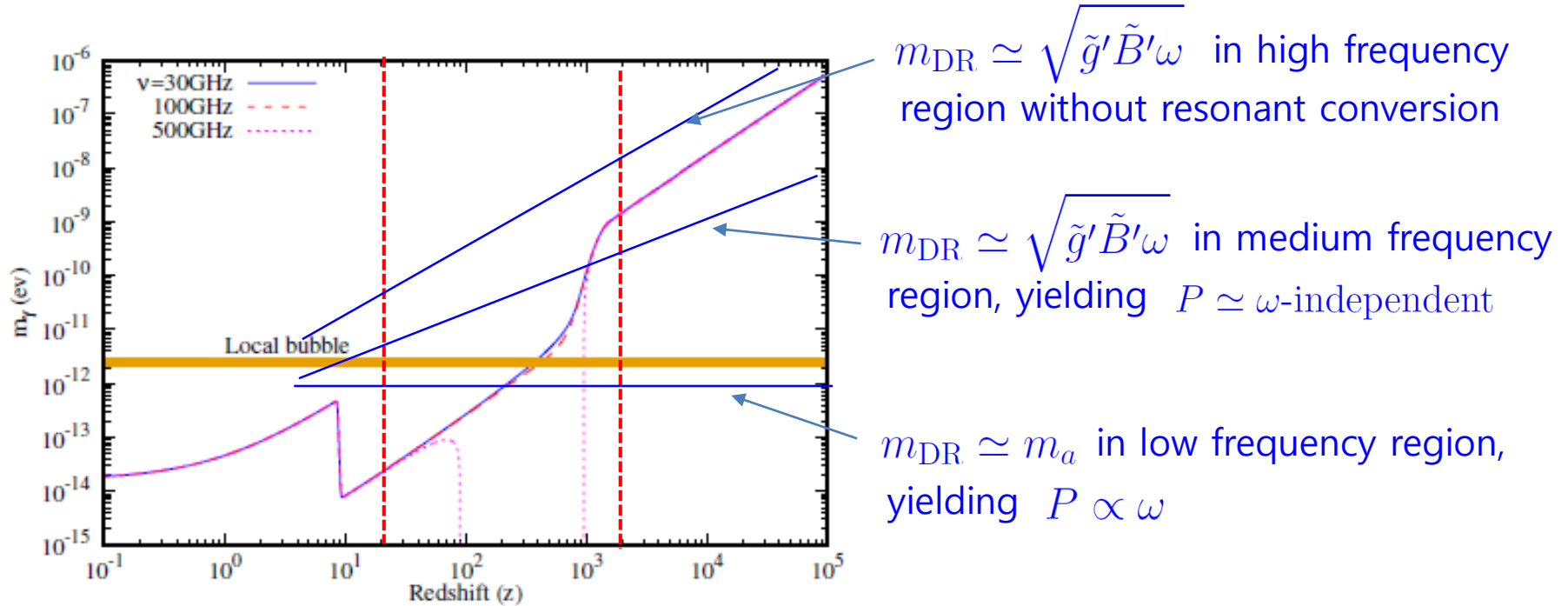
Low frequency regime:

$$\tilde{g}'\tilde{B}'\omega \ll m_a^2 \quad \Rightarrow \quad m_{\text{DR}}^2 \simeq m_a^2, \quad m_{\text{mix}}^2 \simeq \tilde{g}\tilde{B}\omega \quad \Rightarrow \quad P_{a \to \gamma} \propto \omega$$

Medium or high frequency regime:

$$\tilde{g}'\tilde{B}'\omega > m_a^2 \quad \Rightarrow \quad m_{\text{DR}}^2 \sim \pm\tilde{g}'\tilde{B}'\omega, \quad m_{\text{mix}}^2 \simeq \tilde{g}\tilde{B}\omega$$

$$\Rightarrow \quad P_{a \to \gamma} \simeq \omega\text{-independent or no-resonance if } \omega \text{ is large enough}$$

Spectral dependence of the resonant conversion probability:

$m_{DR} \simeq \sqrt{\tilde{g}'\tilde{B}'\omega}$ in high frequency region without resonant conversion

$m_{DR} \simeq \sqrt{\tilde{g}'\tilde{B}'\omega}$ in medium frequency region, yielding $P \simeq \omega$-independent

$m_{DR} \simeq m_a$ in low frequency region, yielding $P \propto \omega$

Wide range of parameter region is available to put the 21cm in the medium frequency region and the CMB in the high frequency region without resonant conversion:

$$\tilde{g}'\tilde{B}' \sim g_a'' B' \gtrsim 4.6 \times 10^{-8}\,\text{GeV}^{-1}\mu\text{G}$$

[KC, S. Lee, H. Seong, S. Yun, in preparation]
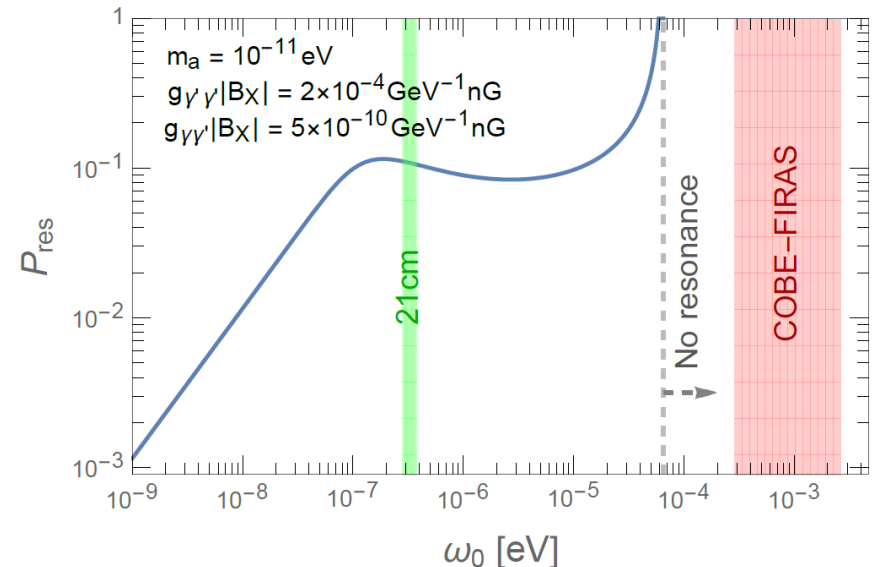
Generation of background dark photon fields

Introduce additional ultra-light ALP ϕ with *KC, H. Kim, T. Sekiguchi, 1802.07269*

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{4}g_{\phi\gamma'\gamma'}\phi F'^{\mu\nu}F'_{\mu\nu} \quad \left(g_{\phi\gamma'\gamma'} \equiv \frac{g_{XX}}{f}, \quad f \equiv \phi_{\text{initial}}\right)$$

Coherent oscillation of ϕ beginning when $3H(\tau_{\text{osc}}) \simeq m_\phi$:

$$\theta(\tau) \equiv \frac{\phi(\tau)}{f} \approx \left(\frac{a(\tau)}{a(\tau_{\text{osc}})}\right)^{-3/2} \cos\left(m_\phi(t - t_{\text{osc}})\right)$$

$$\left(ds^2 = dt^2 - a^2(t)dx^2 = a^2(\tau)\left(d\tau^2 - dx^2\right)\right)$$

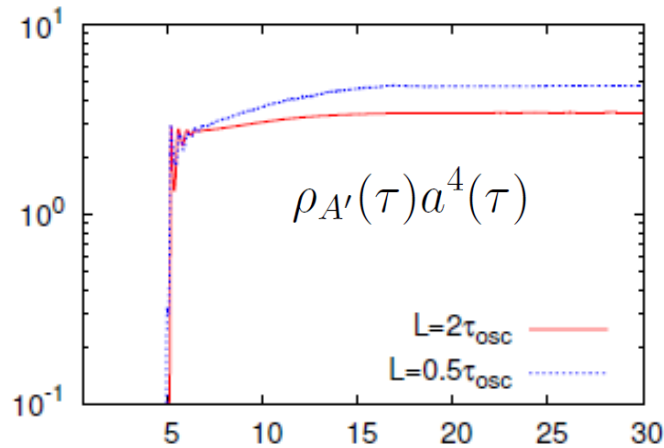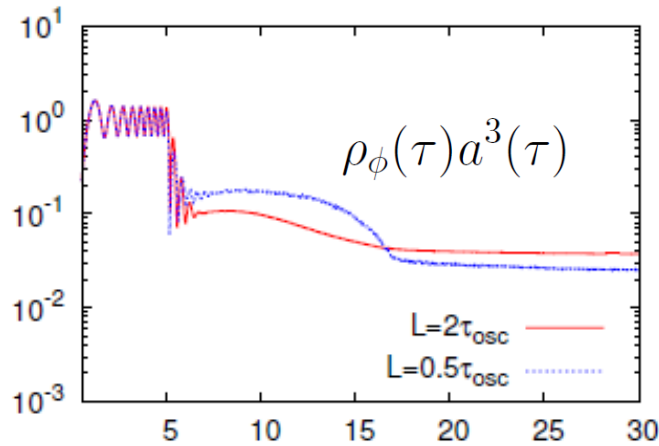Tachyonic instability of A′ caused by oscillating ϕ , resulting in exponential amplification of the vacuum fluctuations of A′:

$$\ddot{X}_{k\pm} + k(k \mp g_{XX}\dot{\theta})X_{k\pm} \simeq 0$$

$$\left(\text{tachyonic instability for } k \sim g_{XX}\dot{\theta} \sim g_{XX}m_\phi\right)$$

Evolution of $\rho_\phi(\tau)a^3(\tau)$ and $\rho_{A'}(\tau)a^4(\tau)$ for $g_{XX} = 100$

KC, H. Kim, T. Sekiguchi, 1802.07269

$$\frac{\tau}{\tau_{\rm osc}} = \frac{a(\tau)}{a(\tau_{\rm osc})}$$

$$B' \sim E' \sim 0.6\,\mu{\rm G} \left(\frac{10^{-28}\,{\rm eV}}{m_\phi}\right)^{1/3} \left(\frac{f}{10^{17}\,{\rm GeV}}\right)$$

$$\text{produced at } z_{\rm prod} \equiv \frac{a(\tau_0)}{a(\tau_{\rm prod})} \sim 300 \left(\frac{m_\phi}{10^{-28}\,{\rm eV}}\right)^{1/2}$$

$$\Omega_\phi h^2 \equiv \frac{\rho_\phi h^2}{\rho_c} \sim 3.6 \times 10^{-6} \left(\frac{m_\phi}{10^{-28}\,{\rm eV}}\right)^{1/2} \left(\frac{f}{10^{17}\,{\rm GeV}}\right)^2$$

$$\left(\text{Safe from the CMB constraints on the ultralight ALP if } \Omega_\phi h^2 \lesssim 10^{-4}.\right)$$

Hlozek, Marsh, Grin, 1708.05681

Conclusion

- Recently noticed gamma-ray spectral modulations of certain galactic pulsars and supernova remnants might be explained by the $a - \gamma - \gamma'$ oscillations in background dark photon gauge fields, while being compatible with the known observational constraints:

- With different ALP parameters, the $a - \gamma - \gamma'$ oscillations can explain the EDGES anomaly without affecting the CMB region, which is possible because of a quite unusual spectral dependence of the resonance conversion probability.

- The required background dark photon gauge fields can be produced by another ultra-light ALP, whose late oscillations cause a tachyonic instability of the massless A', and therefore exponentially amplifying the vacuum fluctuations of A' at a time without causing any conflict with the observational constraints.