

# Photon-ALP-dark photon oscillations and its implications for 21 cm observation

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Collaborated with Kiwoon Choi, and Hyeonseok Seong

Based on arXiv:1911.XXXX (tomorrow)



# Outline

**01** Photon-ALP oscillation

**02** Photon-ALP-dark photon oscillation

- *Non-resonant*
- *Resonant*

**03** Implications

- Gamma-ray spectral irregularities (arXiv:1806.09508)
- 21cm absorption line (arXiv:1911.xxxxx)

**04** Conclusion

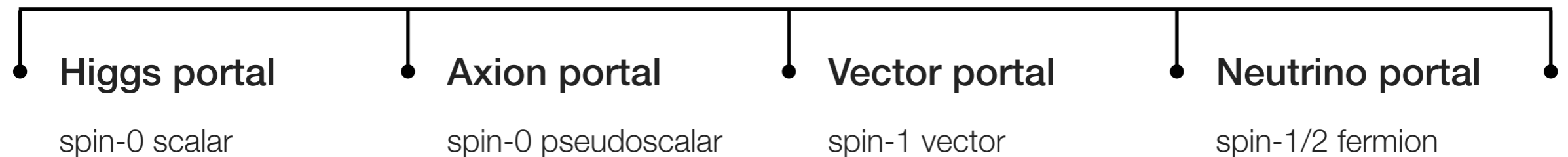
# Portal physics

01

02

03

04



$$|S|^2 H^\dagger H$$

$$a/f_a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$F_{\mu\nu} Z'^{\mu\nu}$$

$$LHN$$

$$(\partial_\mu a/f_a) \bar{\psi} \gamma^\mu \psi$$

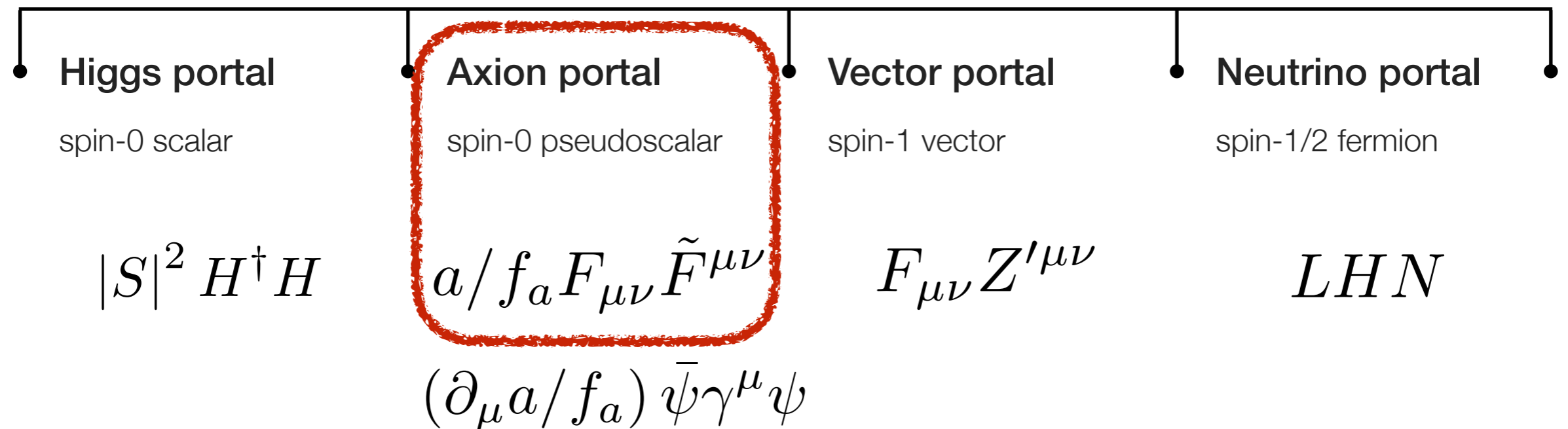
# Portal physics

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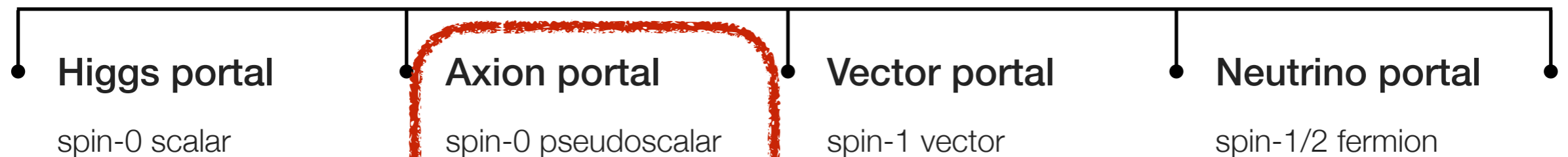
# Portal physics

01

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H. Lee's talk

**Dark axion portal**

$$a/f_a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

# Photon-ALP oscillation

- In the presence of background magnetic field, Photon and ALP are oscillated through the Axion-portal

relativistic  $v \approx c$

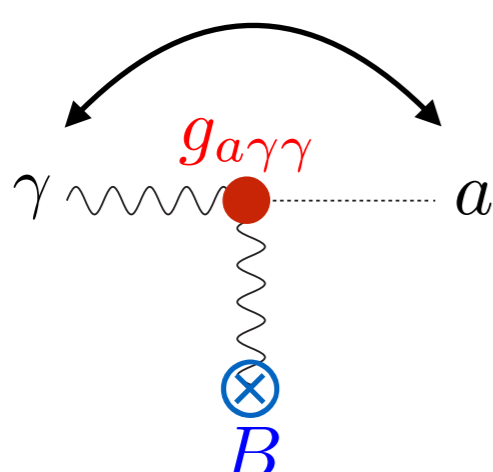
$$\left[ \omega + i\partial_z - \begin{pmatrix} \omega_{\text{pl}}^2/2\omega & g_{a\gamma\gamma}B/2 \\ g_{a\gamma\gamma}B/2 & m_a^2/2\omega \end{pmatrix} \right] \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} = 0$$

$\vec{A}_{\parallel} \parallel \vec{B}$

$$-g_{a\gamma\gamma}aF\tilde{F}/4 = a\vec{E} \cdot \vec{B}$$

# Photon-ALP oscillation

- When propagating coherent background magnetic field and plasma contribution to the refractive index on the photon is stationary (i.e. adiabatically), the conversion probability is



$$\Delta_{\text{osc}}^2 = (g_{a\gamma\gamma} B)^2 + (m_a^2 - \omega_{\text{pl}}^2)^2 / 4\omega^2$$

phase retardation

$$P_{a\leftrightarrow\gamma} = \underbrace{\sin^2 2\theta}_{\text{mixing angle}} \sin^2 \frac{\Delta_{\text{osc}} l}{2}$$

$$\frac{1}{2} \tan 2\theta = \frac{\omega g_{a\gamma\gamma} B}{m_a^2 - \omega_{\text{pl}}^2}$$

at large mixing,  $\simeq \sin^2 \frac{\Delta_{\text{osc}} l}{2} \propto (g_{a\gamma\gamma} B_{\text{ext}} l)^2$

$$\theta \approx \pi/4$$

$$\omega > \omega_c = |m_a^2 - \omega_{\text{pl}}^2| / 2g_{a\gamma\gamma} B \rightarrow \text{Falling down spectral modulation}$$

# Gamma-ray spectral modulations

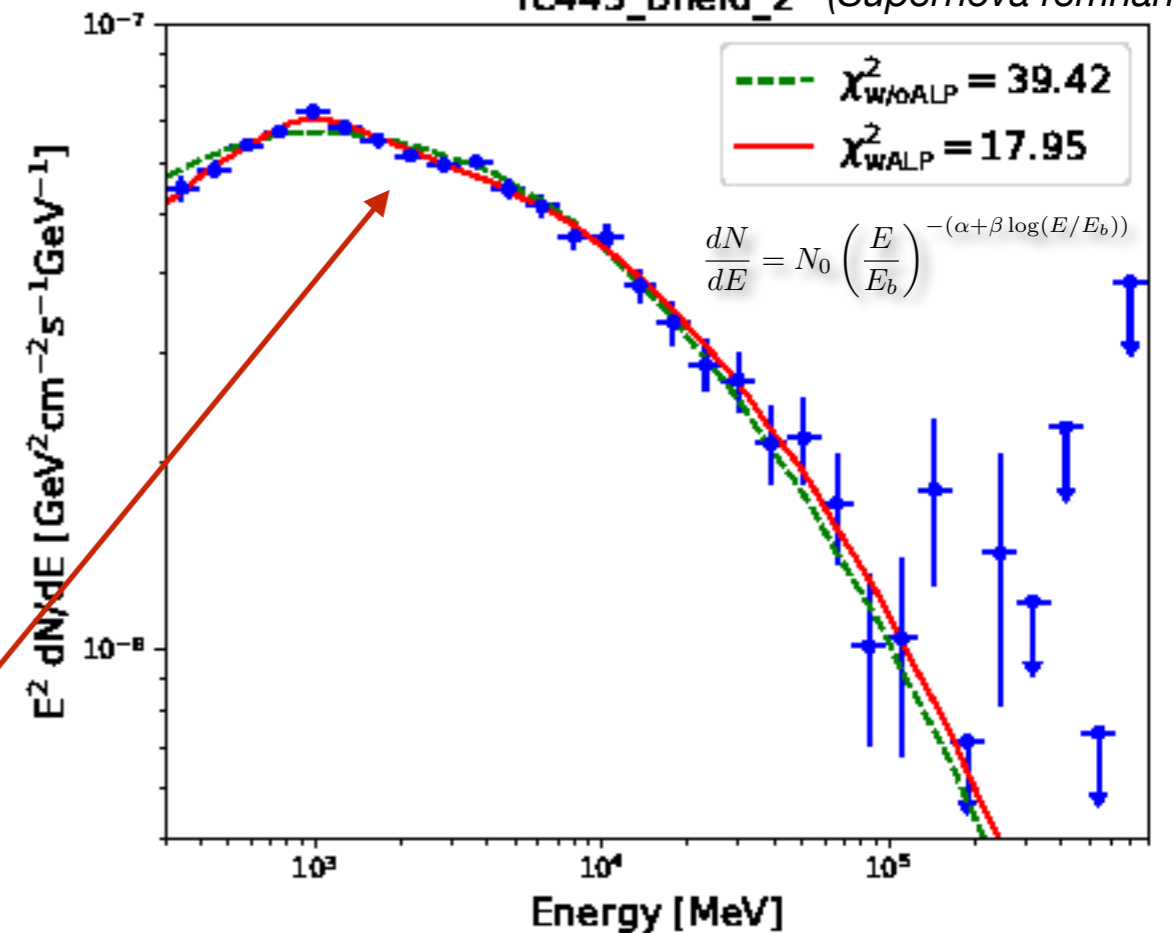
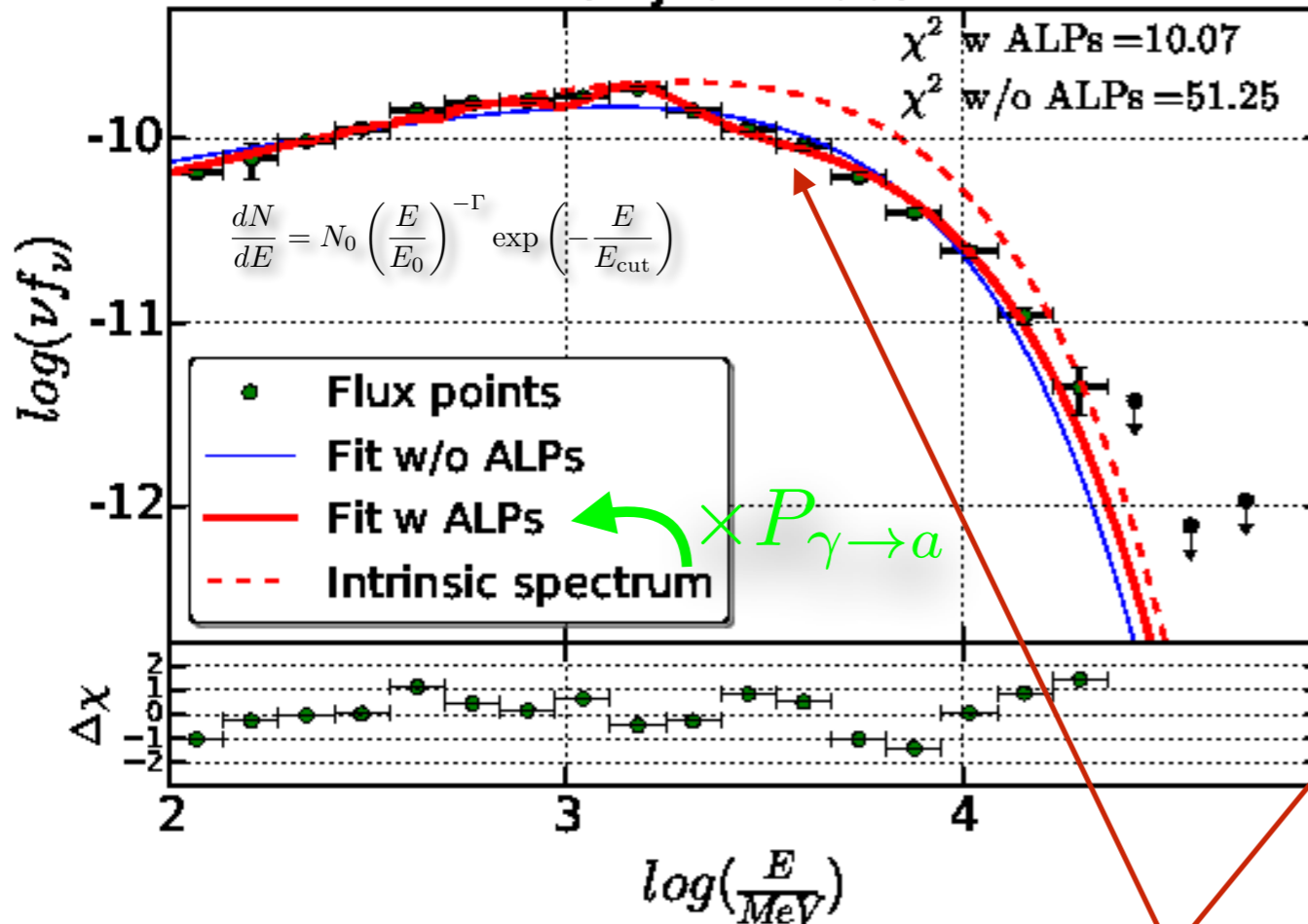
## Photon-ALP conversion

[J. Majumdar et al., 18]

[Z. Xia et al., 18]

PSR J2021+3651 (Pulsar)

IC443\_Bfield\_2 (Supernova remnant)

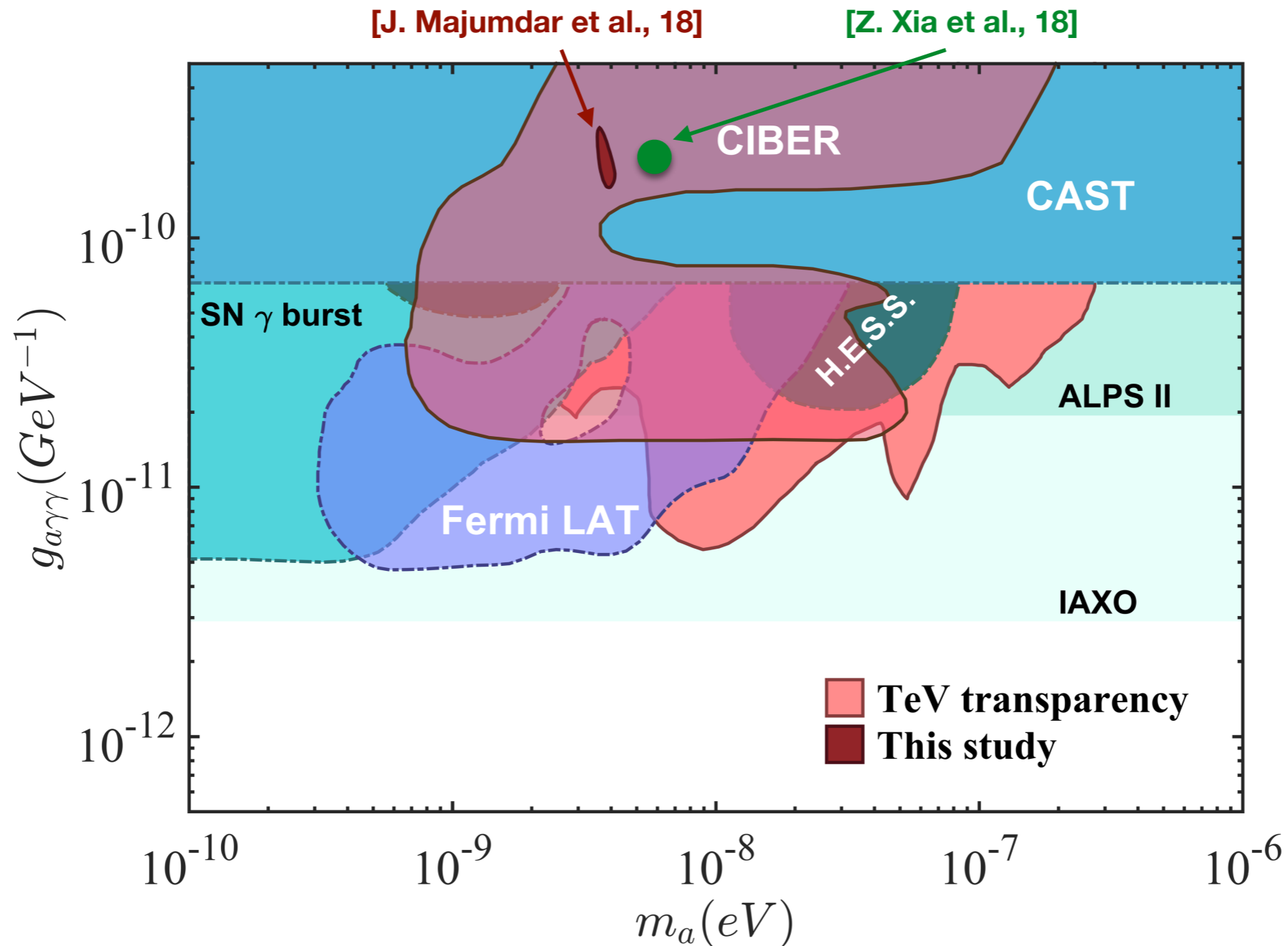


$$\omega \simeq \omega_c = 250 \text{ MeV} \left(\frac{m_a}{\text{neV}}\right)^2 \left(\frac{10^{-10} \text{ GeV}^{-1}}{g_{a\gamma\gamma}}\right) \left(\frac{1 \mu\text{G}}{B}\right)$$



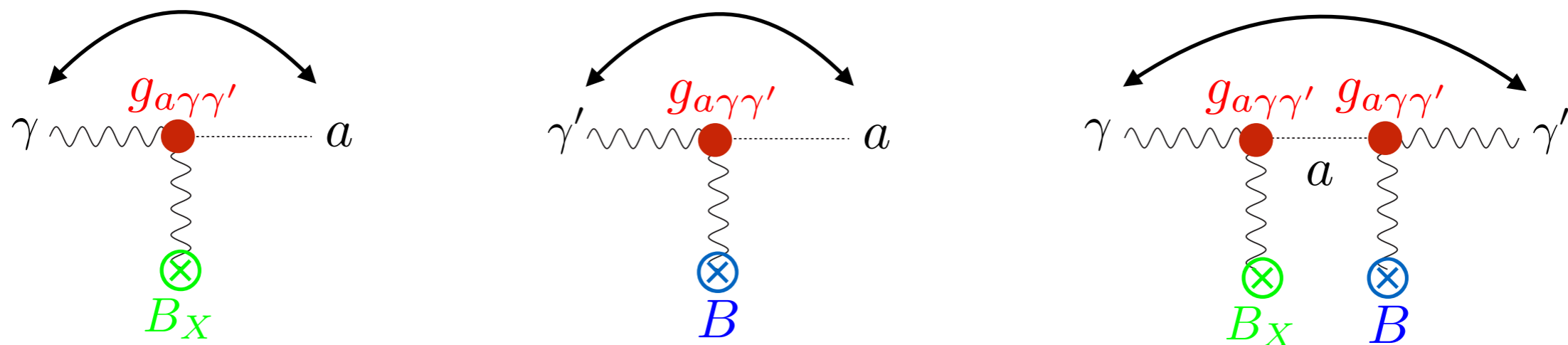
# Gamma-ray spectral modulations

## Photon-ALP conversion



# Photon-ALP-Dark photon oscillation

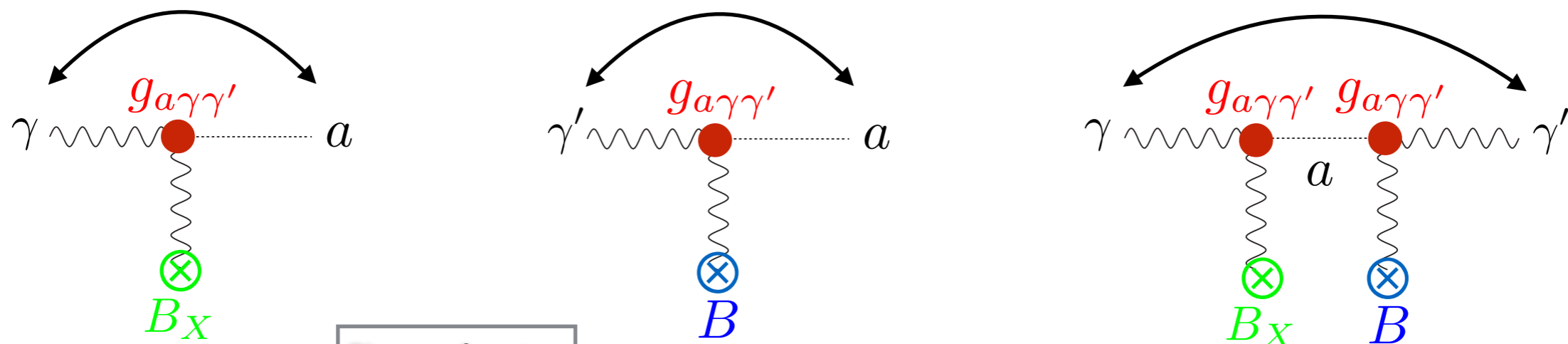
- In the presence of **background dark photon field** as well as magnetic field, **Photon, ALP, and Dark photon** are oscillated through the **Dark axion-portal**



$$\Rightarrow \left[ \omega + i\partial_z - \begin{pmatrix} \omega_{\text{pl}}^2/2\omega & 0 & g_{a\gamma\gamma'} B_X/2 \\ 0 & 0 & g_{a\gamma\gamma'} B/2 \\ g_{a\gamma\gamma'} B_X/2 & g_{a\gamma\gamma'} B/2 & m_a^2/2\omega \end{pmatrix} \right] \begin{pmatrix} A_{\parallel} \\ X_{\parallel} \\ a \end{pmatrix} = 0$$

# Photon-ALP-Dark photon oscillation

- In the presence of **background dark photon field** as well as magnetic field, **Photon, ALP, and Dark photon** are oscillated through the **Dark axion-portal**



Photon fraction

$$P_{\gamma \leftrightarrow a} \simeq \left( \frac{B_X^2}{B_{\text{eff}}^2} \right) \sin^2 \frac{\Delta_{\text{oscl}} l}{2}$$

$$P_{\gamma \leftrightarrow \gamma'} \simeq 4 \left( \frac{B_X^2}{B_{\text{eff}}^2} \right) \left( \frac{B^2}{B_{\text{eff}}^2} \right) \sin^4 \frac{\Delta_{\text{oscl}} l}{4}$$

at large mixing,

$$\omega > \omega_c$$

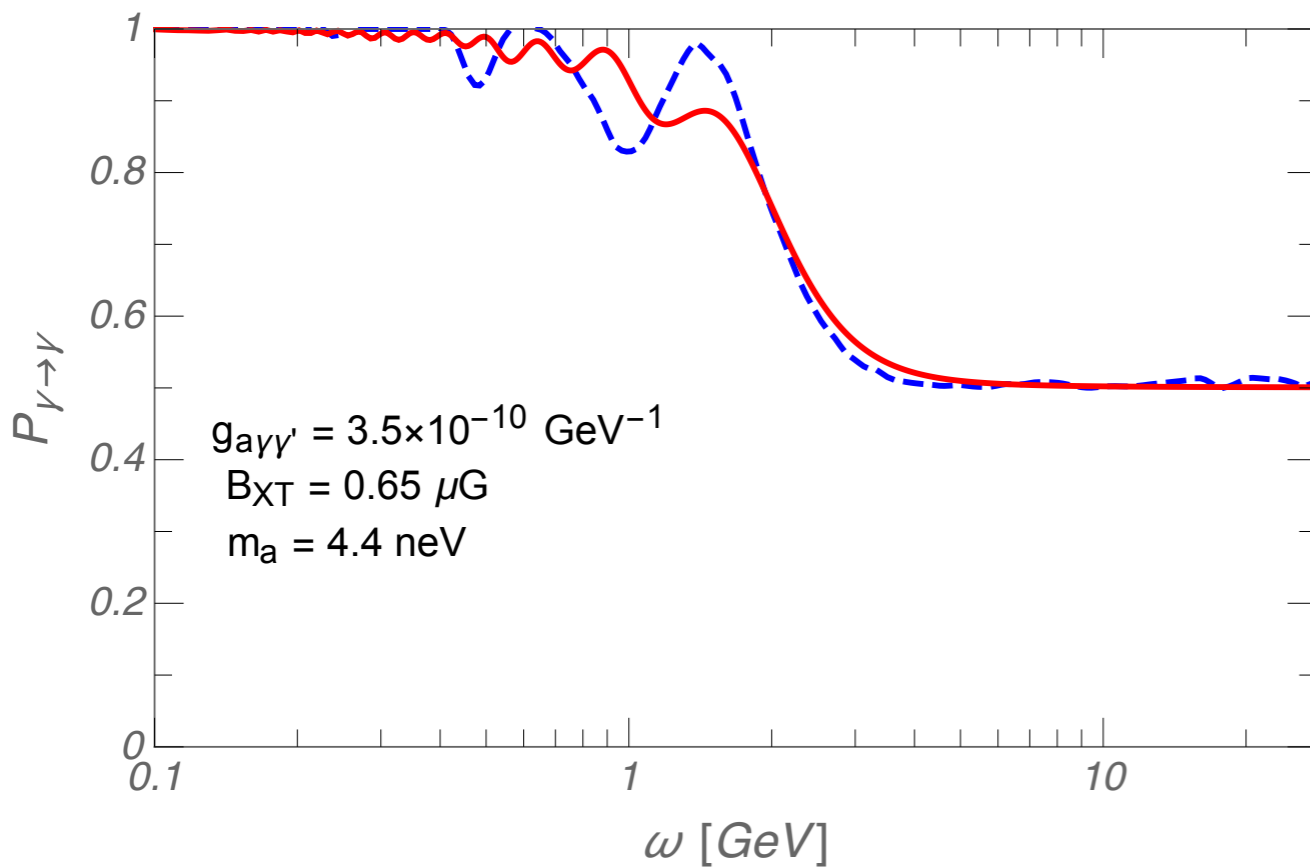
# Gamma-ray spectral modulations

Photon-ALP-Dark photon conversion

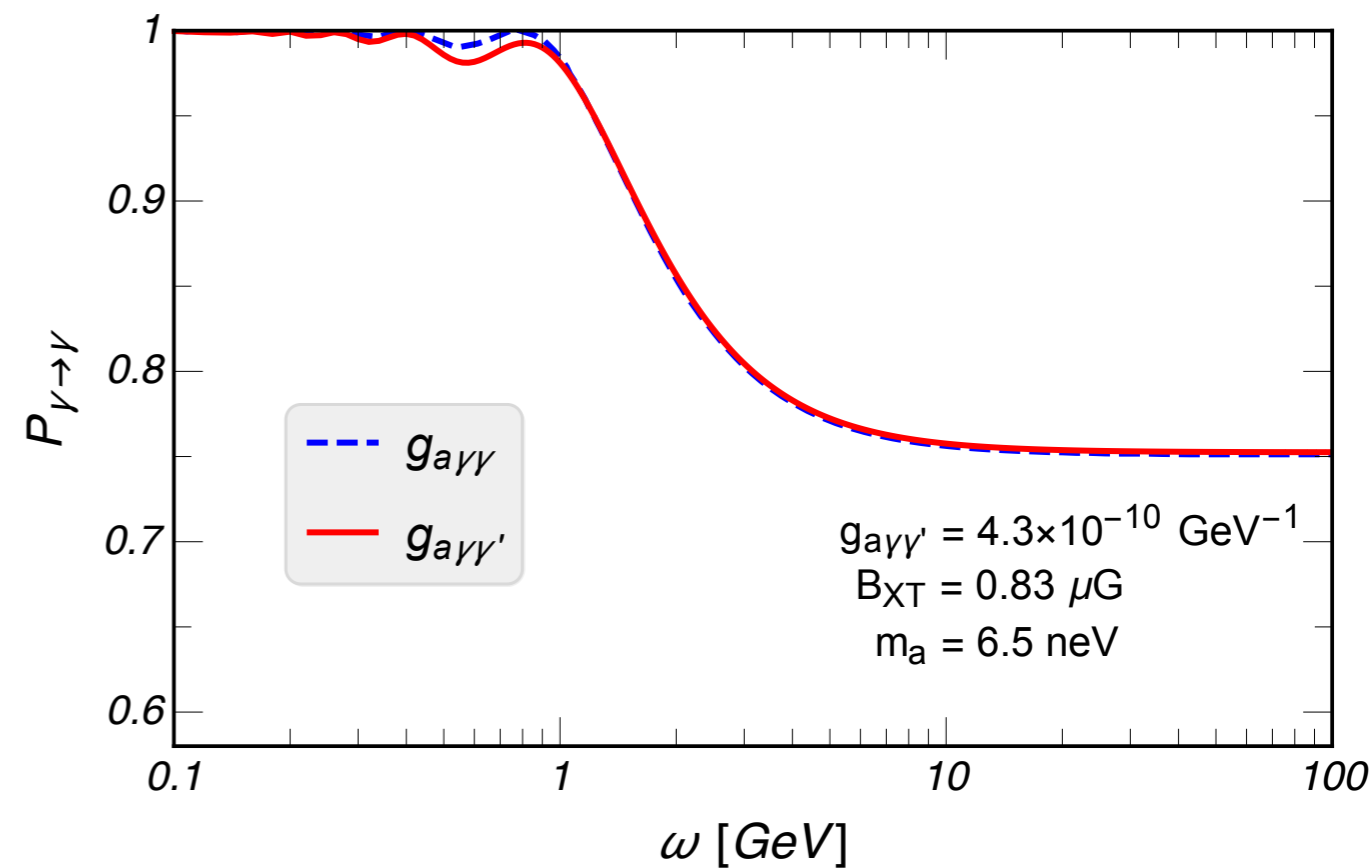
see [K. Choi, H. Kim, T. Sekiguchi, 18]  $B_X \sim \mathcal{O}(100)\text{nG}$ ,  $l \sim \mathcal{O}(10)\text{kpc}$

Tachyonic instability

PSR J2021+3651



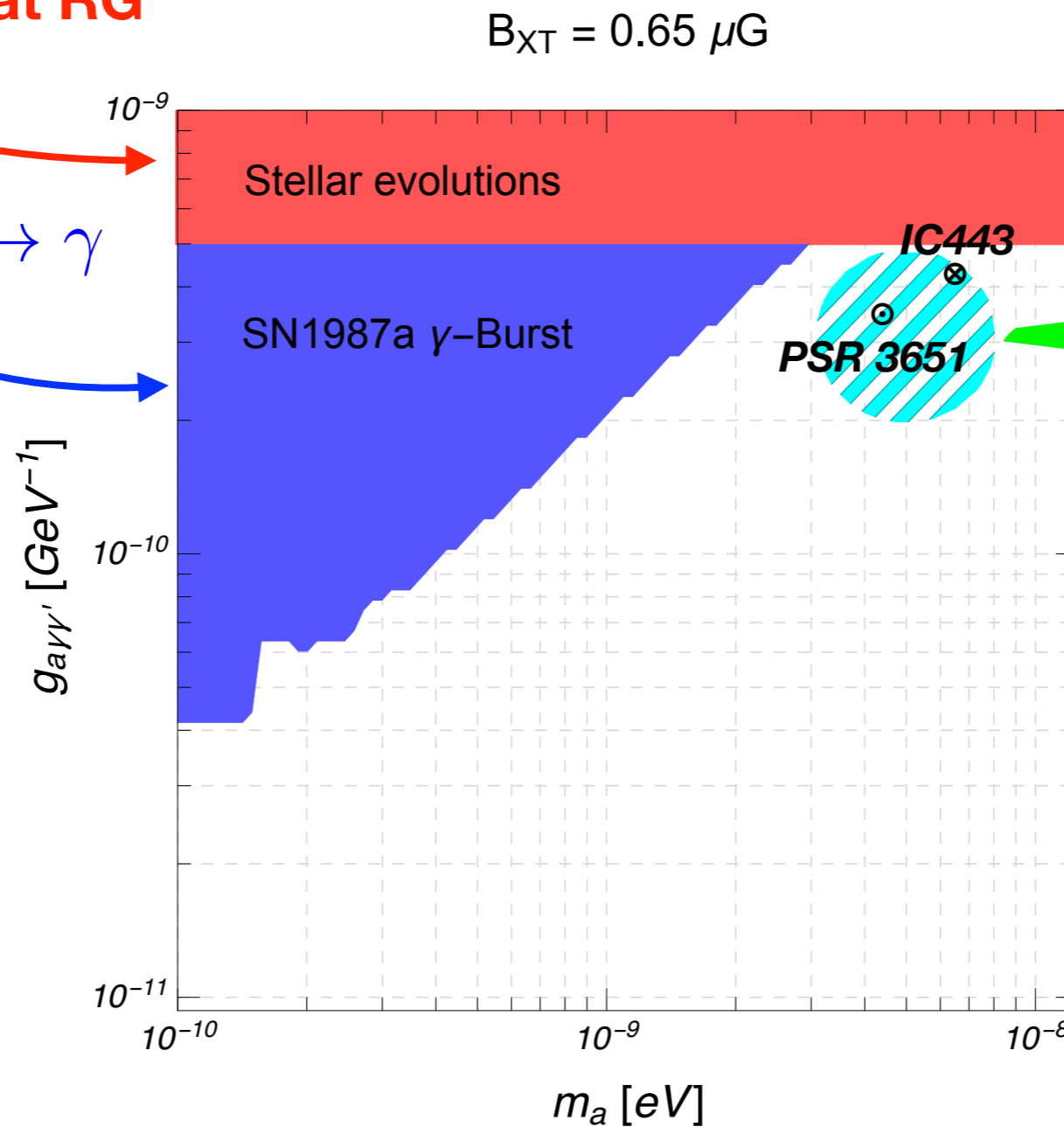
IC443



# Observational constraints

Core mass increase at RG

$\gamma$ -burst from  $a, \gamma' \rightarrow \gamma$



$\omega_c \sim \mathcal{O}(1) \text{ GeV}^{-1}$   
 $P_{\gamma \rightarrow \gamma} \sim 50 - 70\%$

# Resonant conversion

- Photon oscillations can be modified by the refractive properties of the medium

$$\omega_{\text{pl}}^2 = 4\pi\alpha n_e / m_e$$

- Effective mass-squared matrix

$$\mathcal{M}^2 = \begin{bmatrix} \omega_{\text{pl}}^2 & m_{\text{mix}}^2 \\ m_{\text{mix}}^2 & m_{\phi}^2 \end{bmatrix}$$

$$m_{\text{mix}}^2 = \begin{cases} g_{a\gamma\gamma} B\omega & \dots & a \\ \epsilon m_{\gamma'}^2 & \dots & \gamma' \end{cases}$$

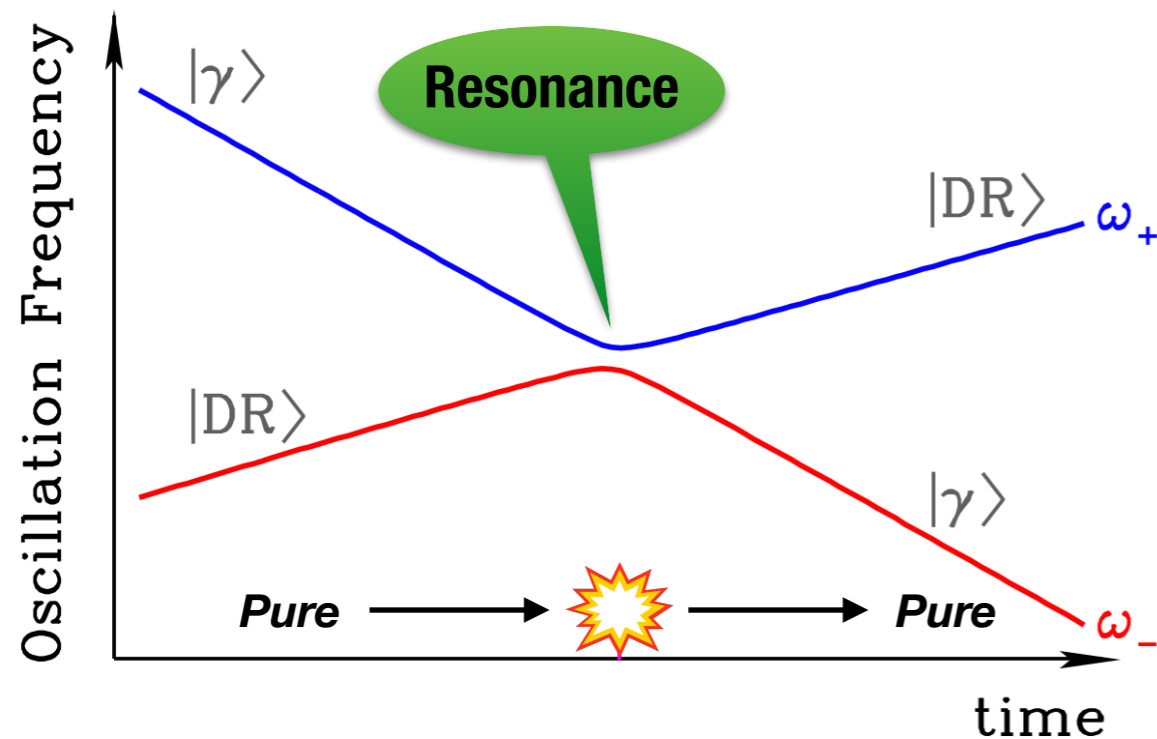
$$\tan 2\theta = \frac{2m_{\text{mix}}^2}{m_{\phi}^2 - \omega_{\text{pl}}^2}$$



**Resonant conversion when**  $\omega_{\text{pl}}^2 = m_{\phi}^2$

# Resonant conversion

In the basis of mass eigenstates,



1. Adiabatic condition for eigenstates except the resonance point
2. Resonance period short enough



***Can be derived analytically!***

# Resonant conversion probability

Level-crossing transition at resonance

- The resonant conversion probability is

$$P_{\text{res}}^{\gamma \leftrightarrow \phi} \simeq \frac{1}{2} + \left( p - \frac{1}{2} \right) \cos 2\theta_0 \cos 2\theta_i$$

$$\simeq 1 - p$$

$\cos 2\theta_0 = -\cos 2\theta_i = 1$

- The level-crossing transition rate is determined by adiabaticity at the resonance

[S. J. Parke, 86], [C.Zener, 32]

$$p \simeq \exp \left( -2\pi r k \sin^2 \theta_0 \right)_{t=t_{\text{res}}} \quad r = \left| \frac{d \ln \omega_{\text{pl}}^2}{dt} \right|^{-1}$$

- The resonant conversion probability in non-adiabatic level-crossing case  $p \approx 1$

$$P_{\text{res}}^{\gamma \leftrightarrow \phi} \simeq r \frac{\pi m_{\text{mix}}^4}{\omega m_{\phi}^2}$$



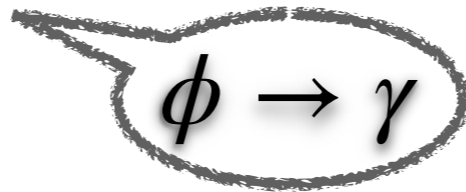
# EDGES anomaly

$$\omega_{21\text{cm}}/T_{\text{CMB}} \sim 10^{-3}$$

- 21cm brightness temperature relative to CMB at  $z \sim 20$

$$T_{21} \propto 1 - \frac{T_{\gamma}}{T_s}$$

- Anomalously large amount of absorption than expected (factor of 2)
- Dark radiation (e.g. ALP or dark photon) conversion into photon heats up the Rayleigh-Jeans tail of the CMB

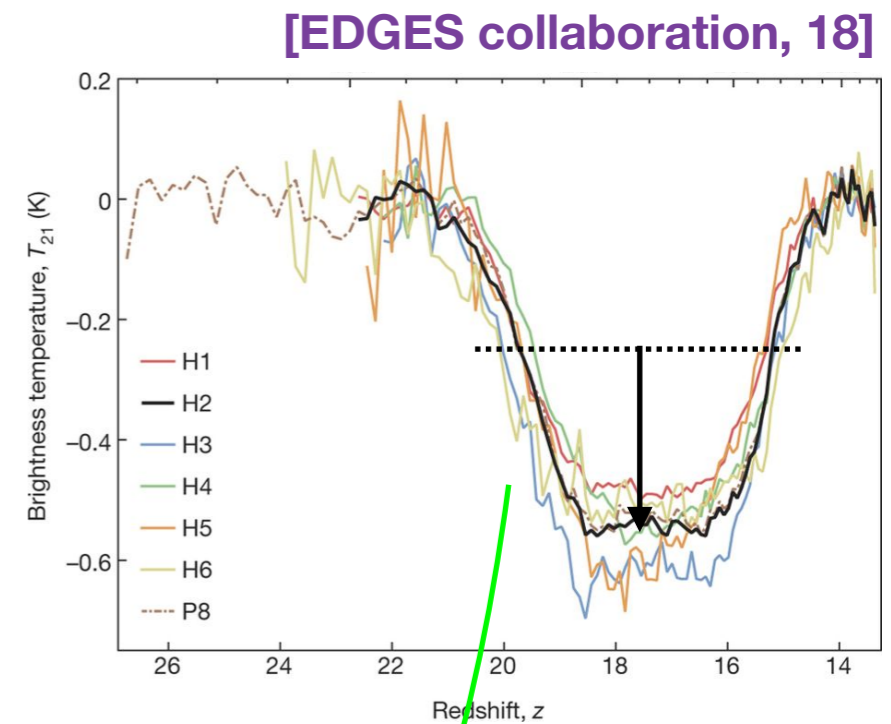


**ALP conversion**

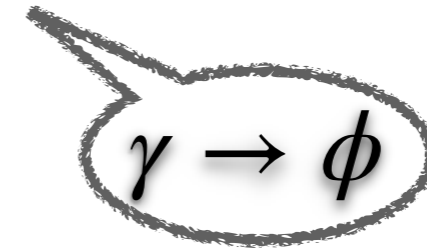
[T. Moroi et al., 18]

**Dark photon conversion**

[M. Pospelov et al., 18]

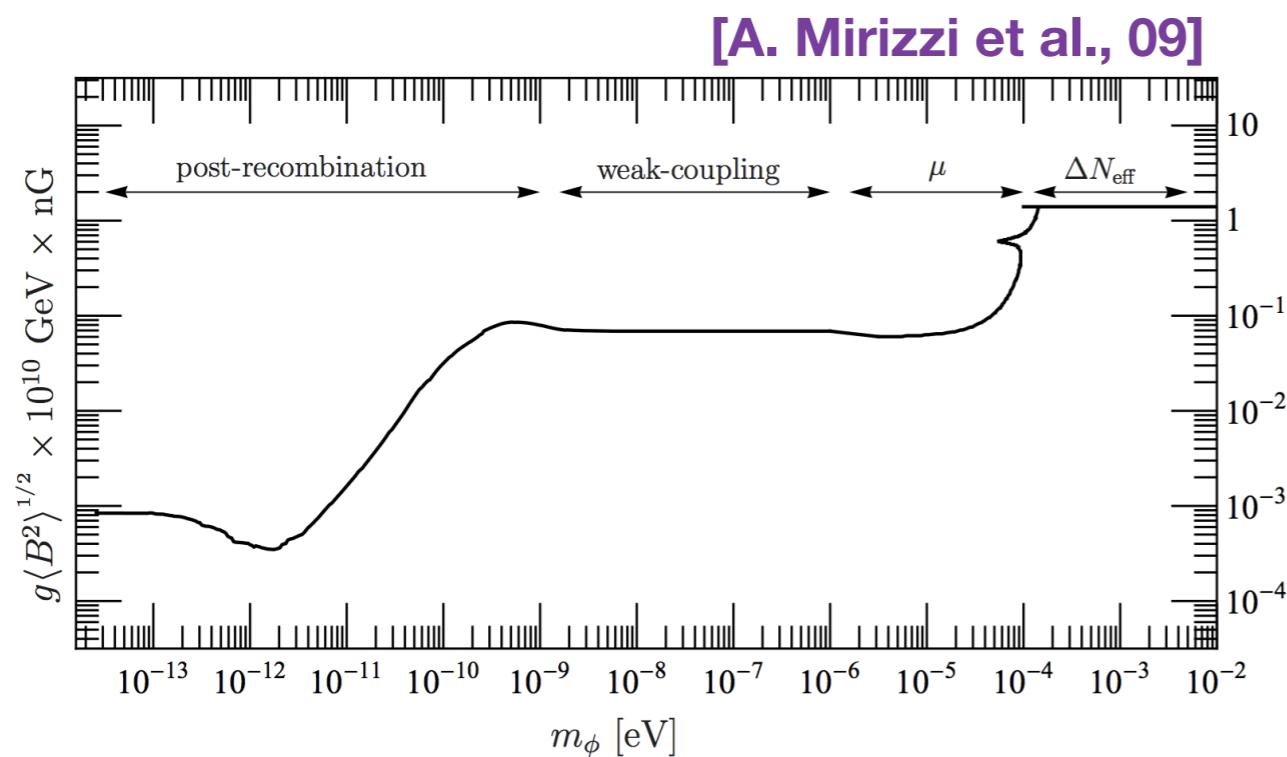


# CMB distortion constraints

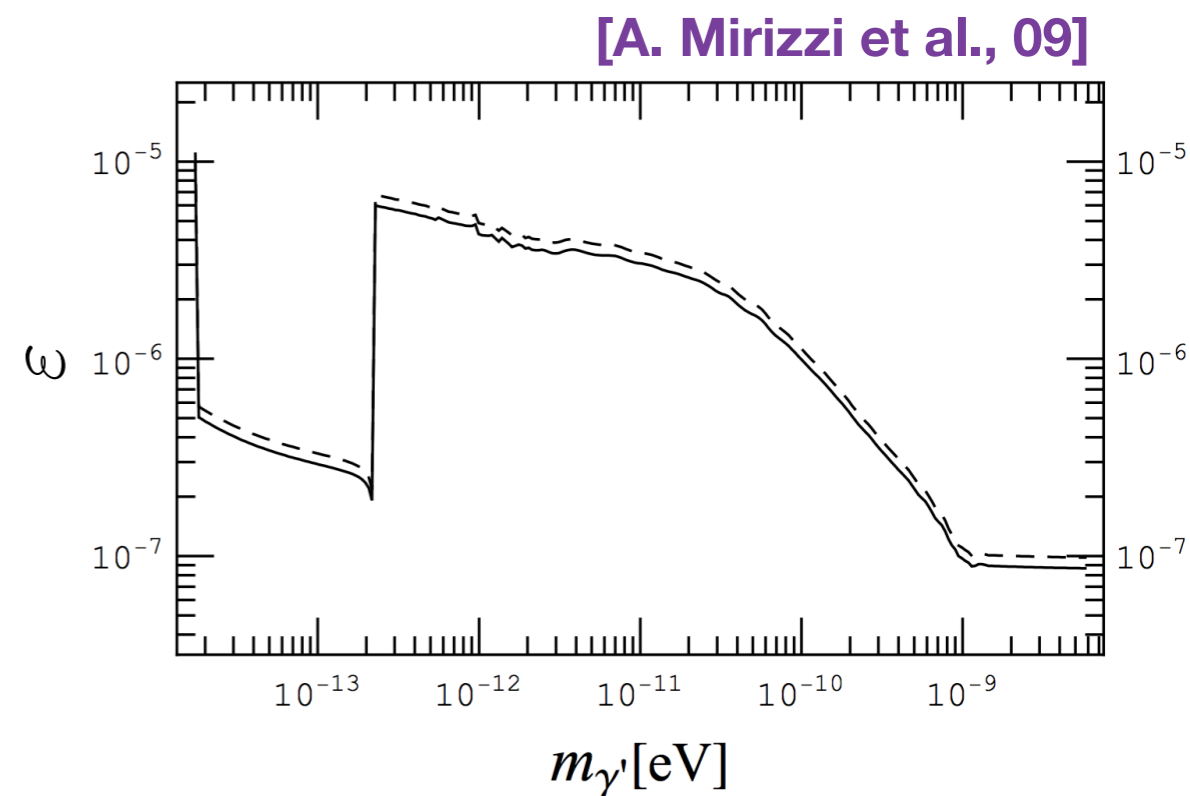


$$1.2 \leq \omega/T \leq 11.3$$

- COBE-FIRAS data which fits well to the black-body spectrum can give stringent bound

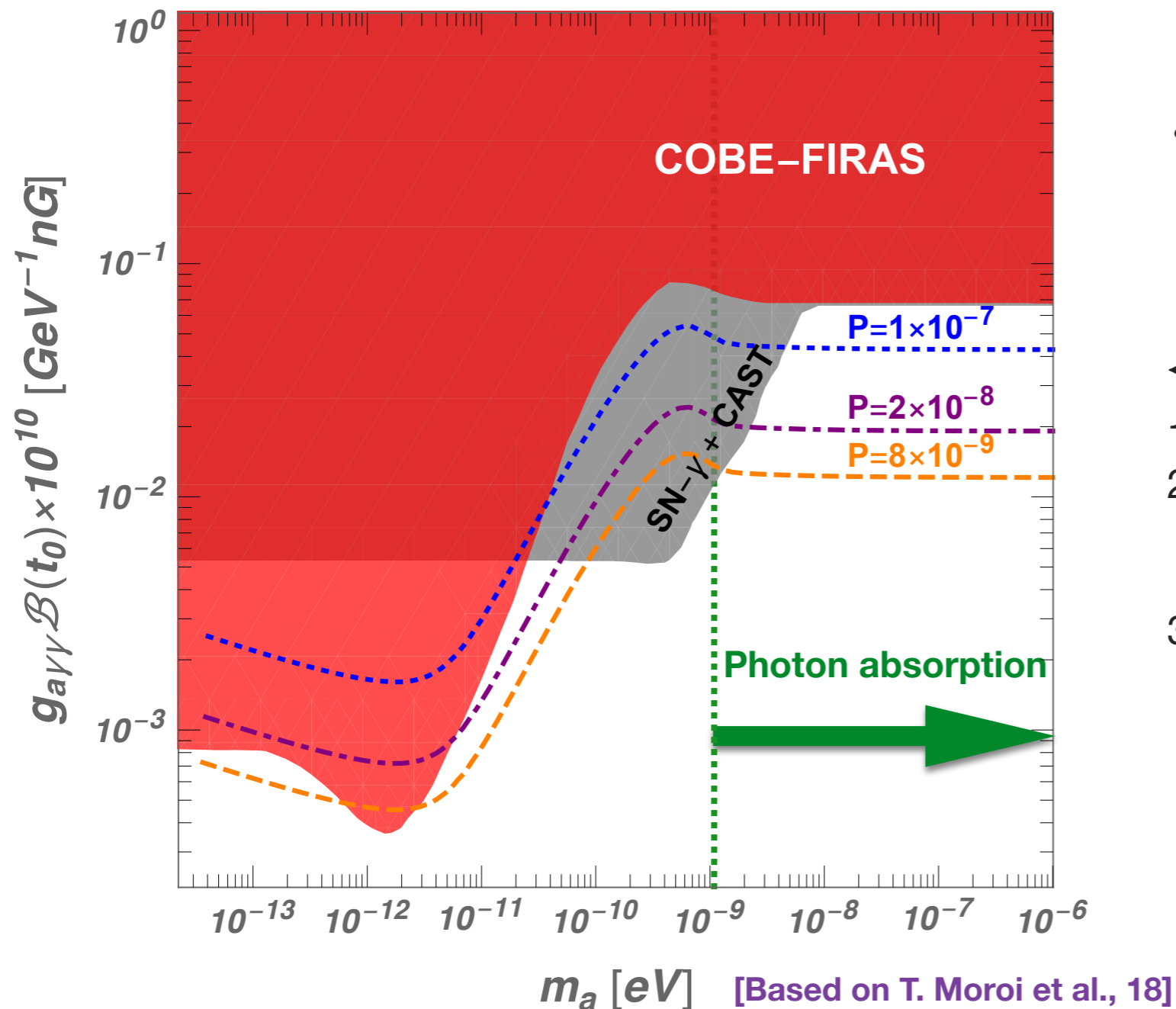


[ALP]



[Dark photon]

# ALP-Photon conversion and its effect on 21cm



- Required conversion probability

$$P_{a \rightarrow \gamma}^{\omega_{21\text{cm}}} \sim 10^{-9} (f_a^{\omega_{21\text{cm}}} \Delta N_{\text{eff}})^{-1} \propto \omega$$

## ◆ Issues

1. To generate dark radiation properly
2. Dangerous primordial background magnetic field is required (may heat up the gas)  $B < 0.1 \text{ nG}$  [T. Minoda et al., 18]
3. Improved constraint from future CMB experiments (PIXIE or PRISM)

# Resonant photon-ALP-dark photon conversion

- General effective mass-squared matrix in basis of  $(\gamma, \gamma', a)$  when  $B_X \gg B$

$$\mathcal{M}^2 = \begin{pmatrix} \omega_{\text{pl}}^2 & 0 & g_{a\gamma\gamma'} B_X \omega \\ 0 & 0 & g_{a\gamma'\gamma'} B_X \omega \\ g_{a\gamma\gamma'} B_X \omega & g_{a\gamma'\gamma'} B_X \omega & m_a^2 \end{pmatrix}$$

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- Expectation? resonance occurs when  $\omega_{\text{pl}}^2 = m_a^2$

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- Expectation? resonance occurs when  $\omega_{\text{pl}}^2 = m_a^2$

$$g_{a\gamma'\gamma'} B_X \omega < m_a^2$$

- In small dark mixing regime, resonant conversion is equivalent to **ALP-photon case** but just replace  $g_{a\gamma\gamma} B$  with  $g_{a\gamma\gamma'} B_X$   $P_{\text{res}} \propto \omega$

$$\omega < \frac{m_a^2}{g_{a\gamma'\gamma'} B_X} \Big|_{t=t_{\text{res}}}$$

# Large dark mixing $g_{a\gamma'\gamma'} B_X \omega > m_a$

- Mixing between dark sector particles could change the resonant conversion patterns

$$\mathcal{M}^2 = \begin{pmatrix} \omega_{\text{pl}}^2 & 0 & g_{a\gamma\gamma'} B_X \omega \\ 0 & 0 & g_{a\gamma'\gamma'} B_X \omega \\ g_{a\gamma\gamma'} B_X \omega & g_{a\gamma'\gamma'} B_X \omega & m_a^2 \end{pmatrix} \text{dark sector}$$

Eigenvalue in large dark mixing regime

- In large dark mixing, resonance occurs when  $\omega_{\text{pl}}^2 = g_{a\gamma'\gamma'} B_X \omega$

# Large dark mixing $g_{a\gamma'\gamma'}\mathbf{B}_X\omega > m_a$

- Mixing between dark sector particles could change the resonant conversion patterns

$$\mathcal{M}^2 = \begin{pmatrix} \omega_{\text{pl}}^2 \propto n_e \propto a^{-3} & 0 & g_{a\gamma\gamma'} B_X \omega \\ 0 & 0 & g_{a\gamma'\gamma'} B_X \omega \\ g_{a\gamma\gamma'} B_X \omega & g_{a\gamma'\gamma'} B_X \omega & m_a^2 \end{pmatrix} \text{dark sector}$$

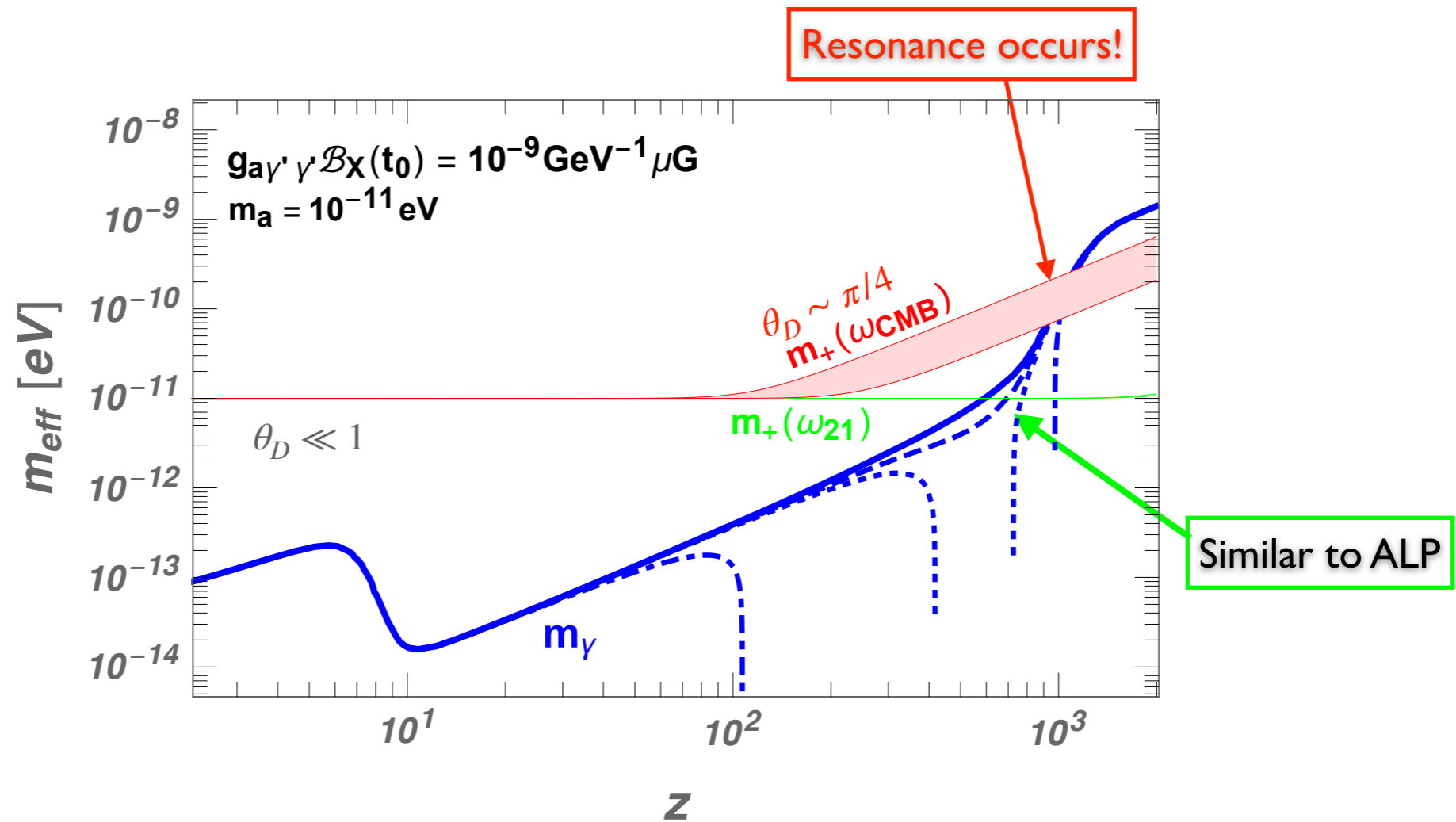
Eigenvale in large dark mixing regime  $\propto a^{-3}$

- In large dark mixing, resonance occurs when  $\omega_{\text{pl}}^2 = g_{a\gamma'\gamma'}\mathbf{B}_X\omega \propto a^{-3}$
- Due to the same redshift of  $\omega_{\text{pl}}^2$  and  $g_{a\gamma'\gamma'}\mathbf{B}_X\omega$ , CMB distortion constraint can be evaded when

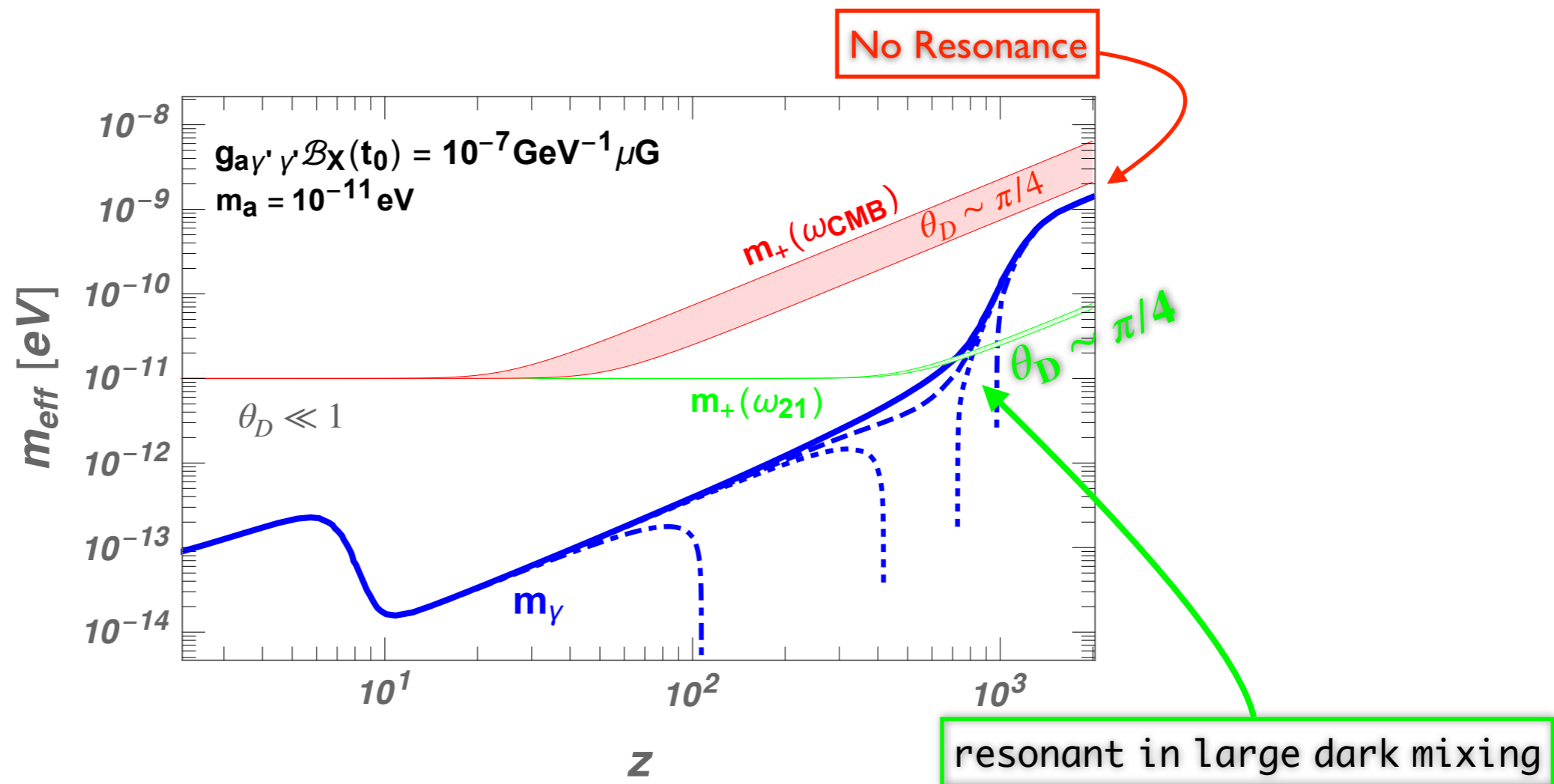
$$\mathbf{g}_{a\gamma'\gamma'}\mathbf{B}_X(\mathbf{t}_0) > 4.6 \times 10^{-8} \text{GeV}^{-1} \mu\text{G}$$



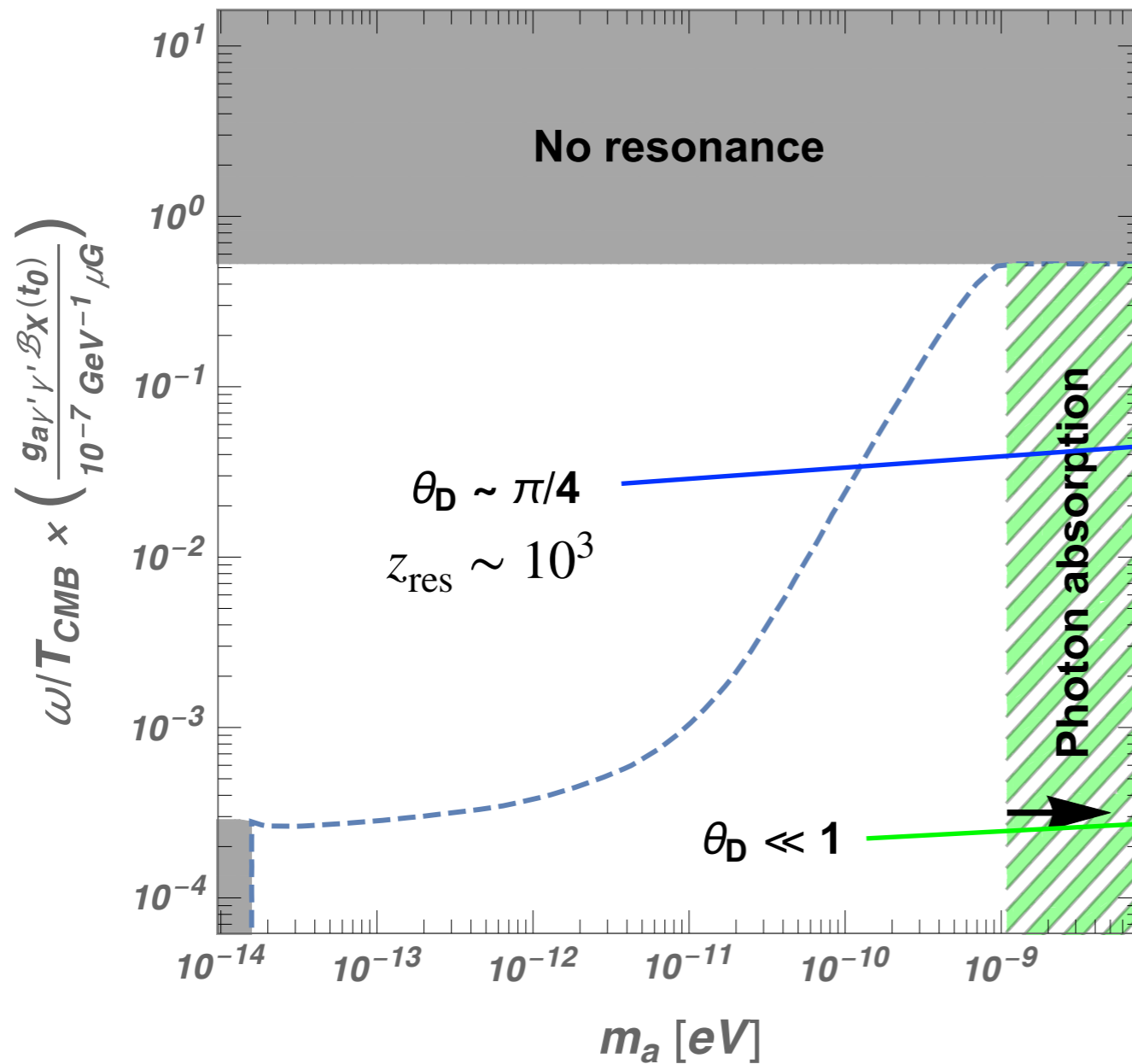
# Large dark mixing resonance



# Large dark mixing resonance



# Large dark mixing resonance



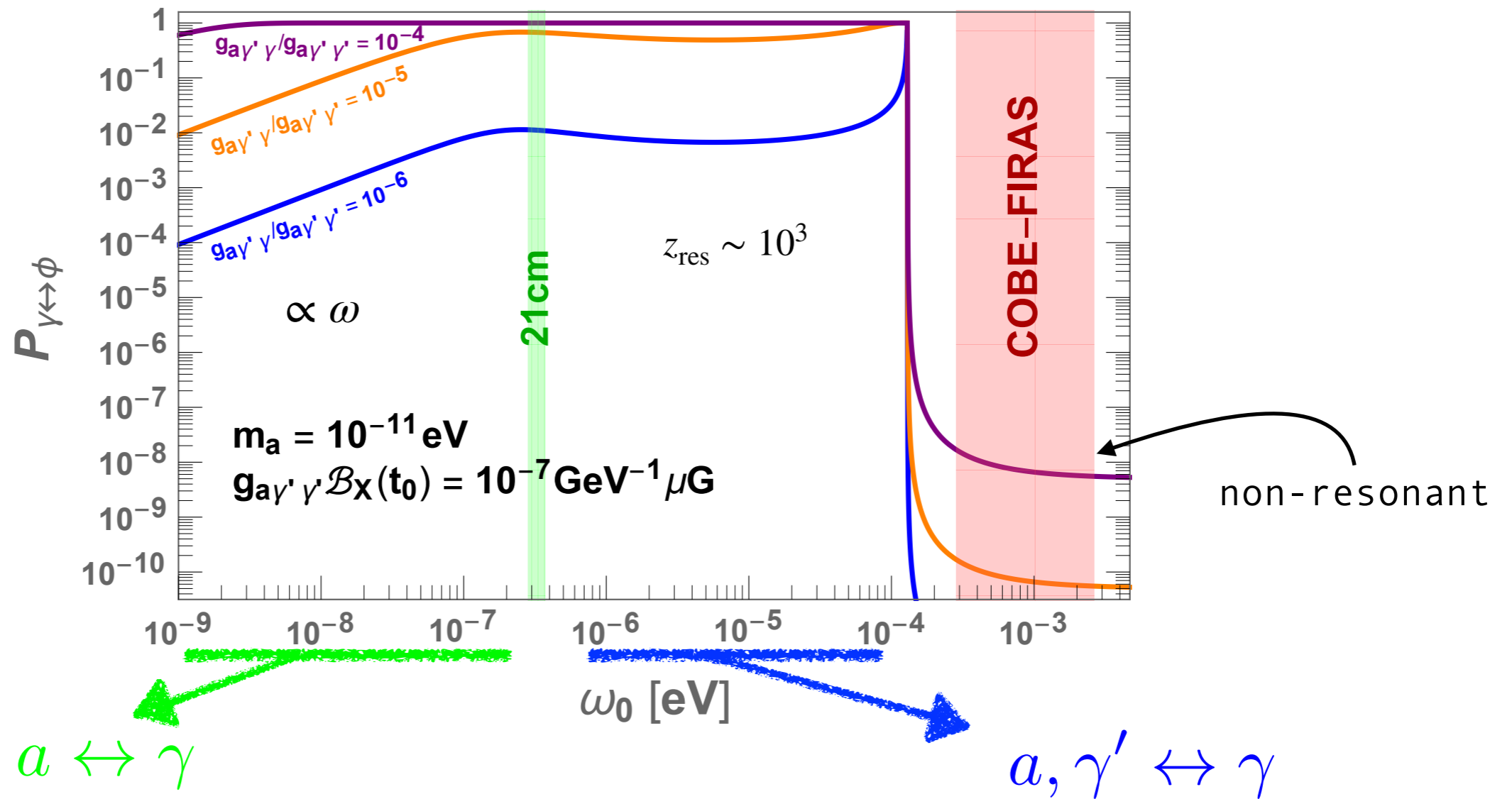
$$a, \gamma' \leftrightarrow \gamma$$

- Large dark mixing
- Right after recombination, hydrogen ionization fraction decreases rapidly so the specific energy range can be resonantly oscillated
- Unique feature that the energy-dependence of conversion become weakened
- Resonance even in a very small ALP mass

$$a \leftrightarrow \gamma$$

- Small dark mixing
- Same to ALP case

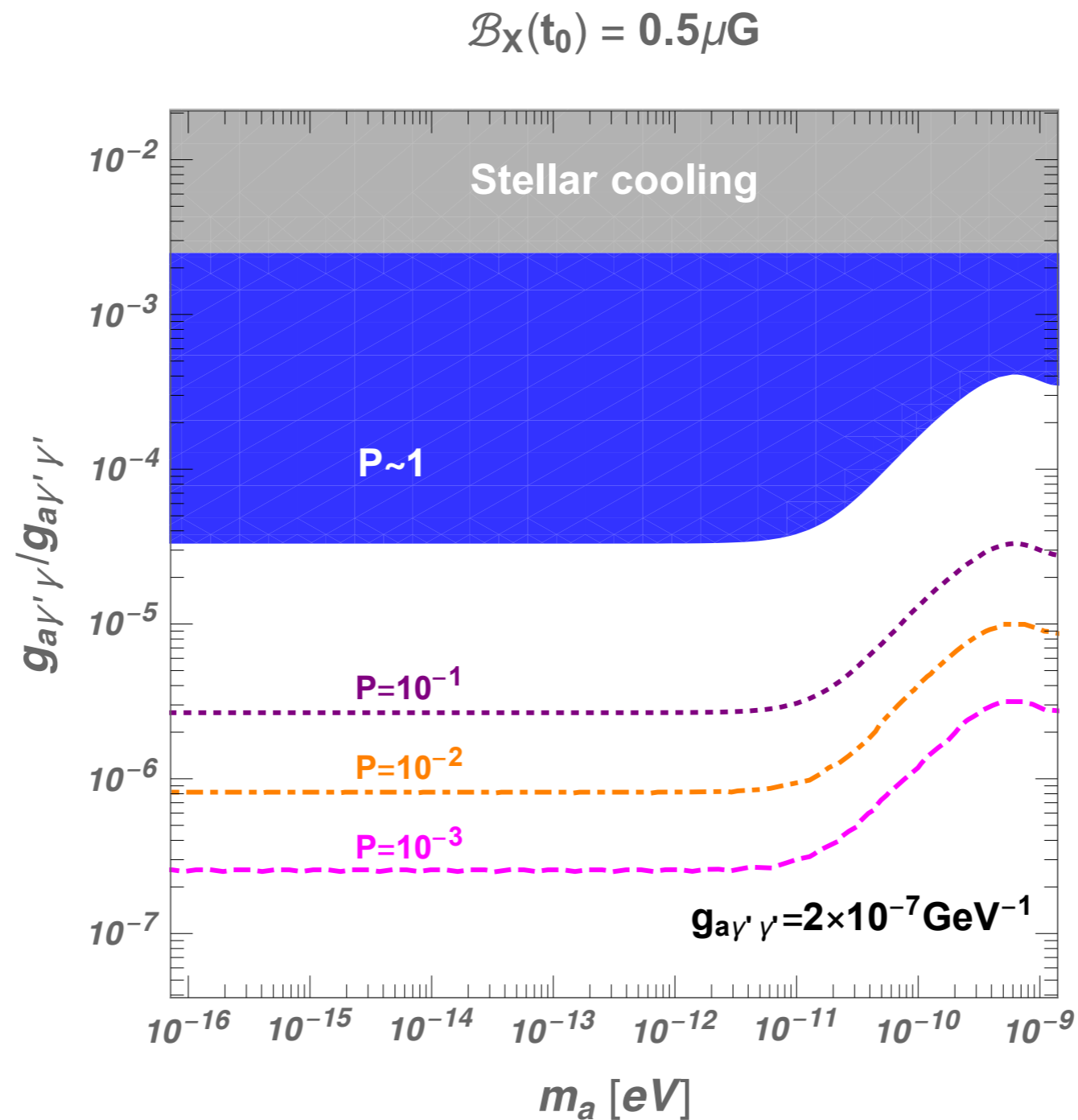
# Large dark mixing resonance



- Small dark mixing
- Same to ALP case

- Large dark mixing
- Weaken energy-dependence

# Large dark mixing resonance



# Conclusion

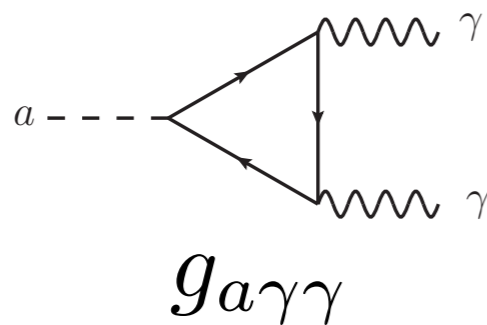
- We discussed the phenomenological implications on the photon-ALP conversion physics: (i) gamma-ray spectral irregularities of point-like sources, (ii) 21cm observation
- The required parameter value in the photon-ALP scenario is in conflict with the present phenomenological constraints, but it is not in the photon-ALP-dark photon scenario
- The photon-ALP-dark photon resonant conversion gives the unique and very interesting features
- The new coupling might open up new avenues to search for the beyond Standard Model

# Back up

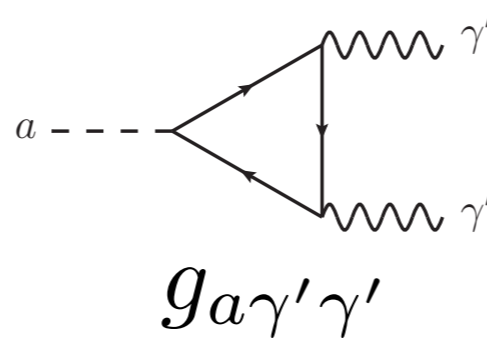
# Dark axion portal

- Portal connecting Dark photons (Vector-portal) and Axions or ALPs (Axion-portal) at the same time
- Not just a product of two individual portals, but rather new

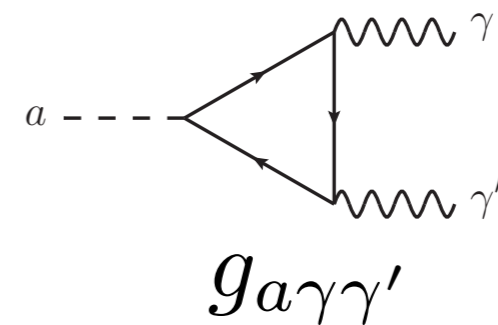
$$U(1)_{PQ} \otimes U(1)_{em} \otimes U(1)_{em}$$



$$U(1)_{PQ} \otimes U(1)_D \otimes U(1)_D$$



$$U(1)_{PQ} \otimes U(1)_{em} \otimes U(1)_D$$

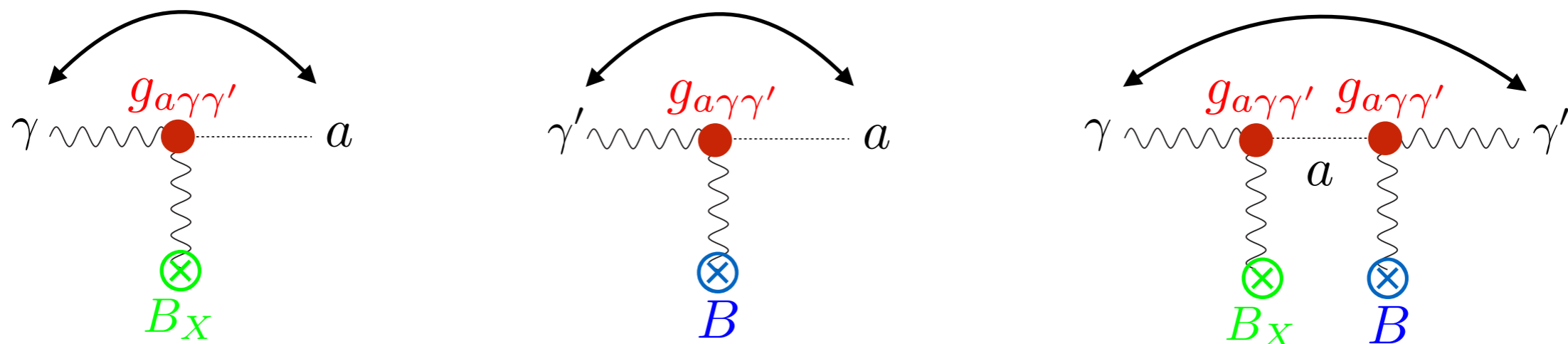


- Can be sizable?



# Photon-ALP-Dark photon oscillation

- In the presence of **background dark photon field** as well as magnetic field, **Photon, ALP, and Dark photon** are oscillated through the **Dark axion-portal**



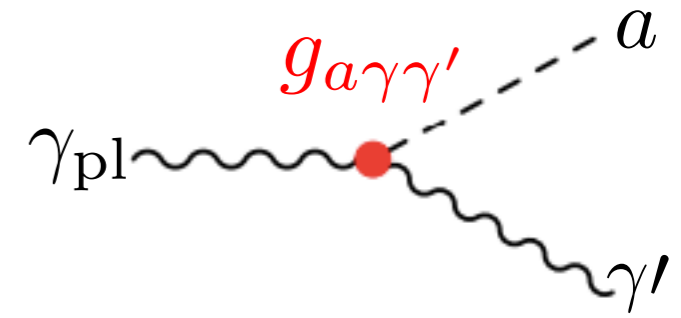
$$P_{\gamma \leftrightarrow a} = \frac{B_X^2}{B_{\text{eff}}^2} \left( \frac{1}{1 + \omega_c^2/\omega^2} \right) \sin^2 \frac{\Delta_{\text{osc}} d}{2}$$

$$\omega_c = m_a^2 / 2g_{a\gamma\gamma'} B_{\text{eff}}$$

$$B_{\text{eff}} = \sqrt{B^2 + B_X^2}$$

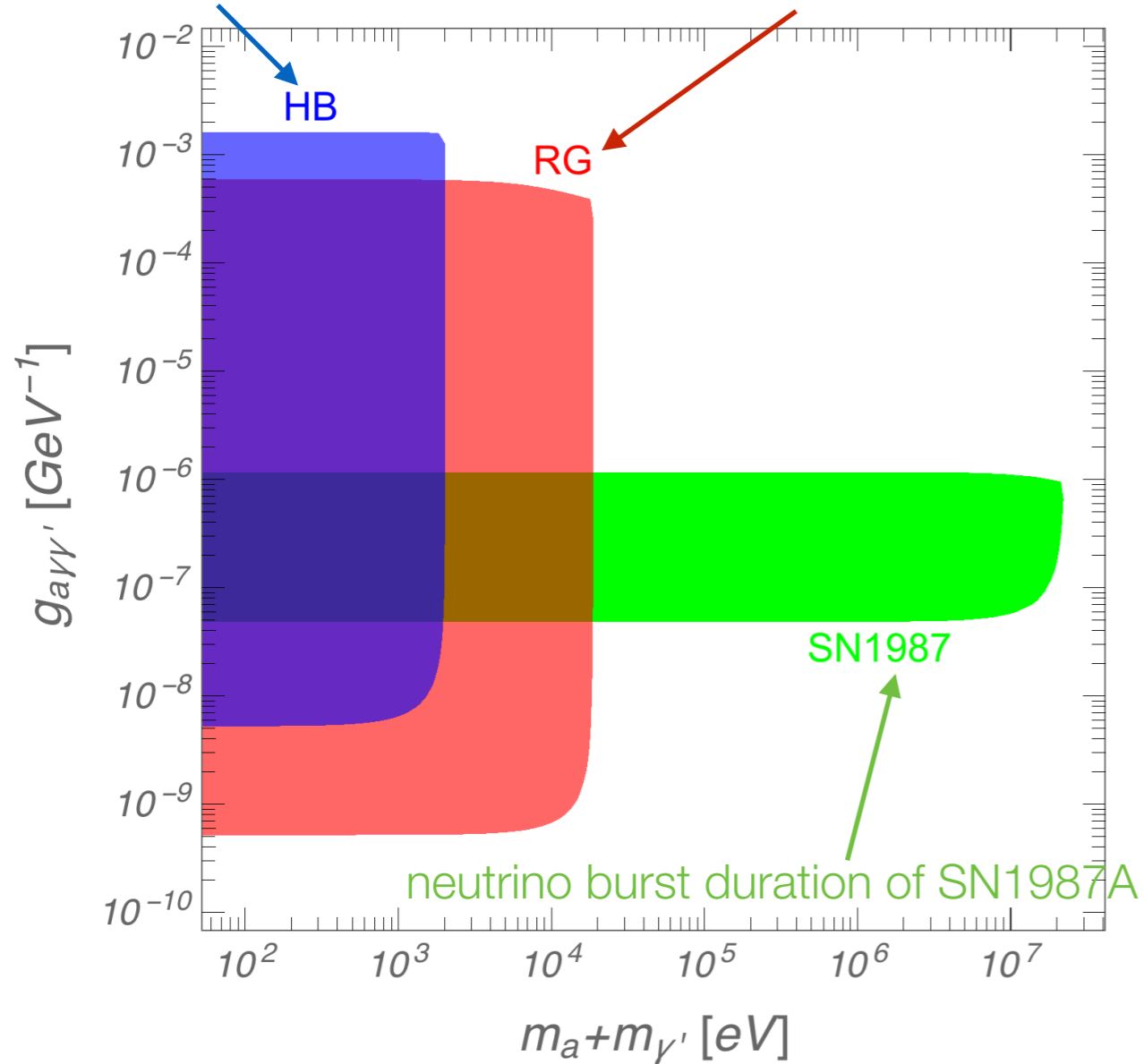
$$P_{\gamma \leftrightarrow \gamma'} = \frac{2B^2 B_X^2}{B_{\text{eff}}^4} \left( 1 - \cos \frac{m_a^2 d}{4\omega} \cos \frac{\Delta_{\text{osc}} d}{2} - \frac{\omega_c/\omega}{\sqrt{1 + \omega_c^2/\omega^2}} \sin \frac{m_a^2 d}{4\omega} \sin \frac{\Delta_{\text{osc}} d}{2} - \frac{1}{2(1 + \omega_c^2/\omega^2)} \sin^2 \frac{\Delta_{\text{osc}} d}{2} \right)$$

# Stellar cooling constraints



lifetime of Horizontal brach

core mass increase at the tip of red giant



- Stellar cooling via novel particles emission
- Plasmon decay

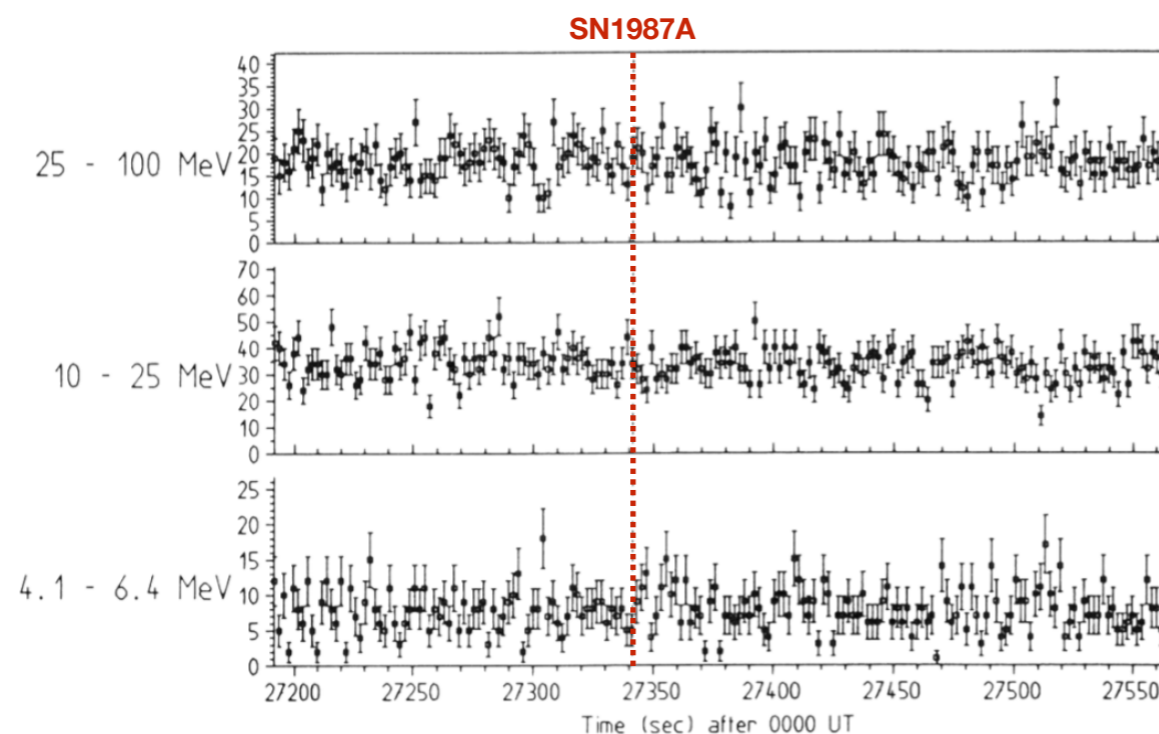
plasmon mass  $\propto n_e$

$$\Gamma_{\text{pl}} = \frac{g_{a\gamma\gamma'}^2}{96\pi} \frac{\omega_{\text{pl}}^4}{\omega} \left[ \beta \left( 1, \frac{m_a}{\omega_{\text{pl}}}, \frac{m_a}{\omega_{\text{pl}}} \right) \right]^{3/2}$$

$$Q_{\text{pl}} = \frac{2}{2\pi^2} \int_0^\infty dk k^2 \frac{\omega \Gamma_{\text{pl}}}{e^{\omega/T} - 1}$$

# SN1987A gamma-ray burst bound

- At the time when the neutrino bursts from SN1987A were observed, the Gamma-Ray Spectrometer of the Solar Maximum Mission were operative and could have potentially detected the ALP signal converted into the gamma-ray.
- The lack of a gamma-ray signal coincidence with the neutrino emission from SN1987A provides a strong bound on ALP parameters.



$\gamma$  fluence limit for 10s

$$< 0.6 \text{ cm}^{-2}$$

$$< 0.4 \text{ cm}^{-2}$$

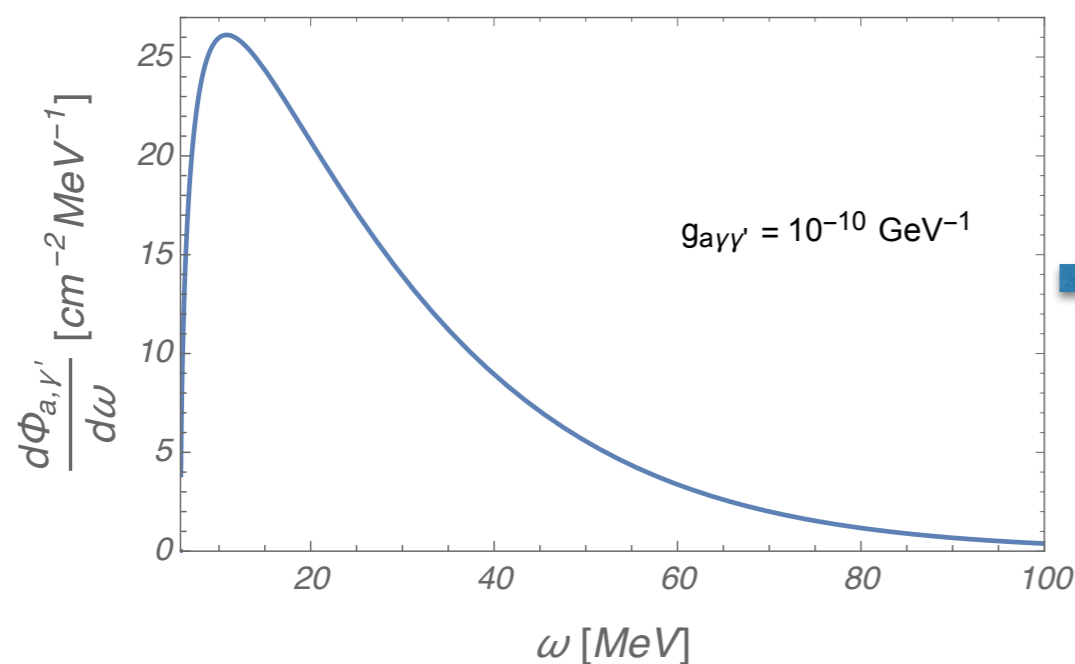
$$< 0.9 \text{ cm}^{-2}$$

# SN1987A gamma-ray burst bound

- Differential ALP and dark photon flux per unit energy at the Earth

$$\frac{d\Phi_{a\gamma'}}{d\omega} = \frac{1}{4\pi d^2} \left( \frac{2}{2\pi^2} \frac{2\omega \sqrt{4\omega^2 - \omega_{\text{pl}}^2}}{e^{2\omega/T_c} - 1} \Gamma_{\text{pl}} \right) \frac{4\pi}{3} r_c^3 \cdot t_{\text{dur}}$$

distance ~ 50 kpc
plasmon number density
plasmon decay rate
core radius ~ 10 km
duration ~ 10 sec



$$\Phi_{a\gamma'}^{4.1-6.4 \text{ MeV}} = 6.2 \text{ cm}^{-2} \left( \frac{g_{a\gamma\gamma'}}{10^{-10} \text{ GeV}^{-1}} \right)^2$$

$$\Phi_{a\gamma'}^{10-25 \text{ MeV}} = 335 \text{ cm}^{-2} \left( \frac{g_{a\gamma\gamma'}}{10^{-10} \text{ GeV}^{-1}} \right)^2$$

$$\Phi_{a\gamma'}^{25-100 \text{ MeV}} = 361 \text{ cm}^{-2} \left( \frac{g_{a\gamma\gamma'}}{10^{-10} \text{ GeV}^{-1}} \right)^2$$

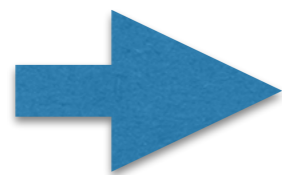
# Resonant ALP-photon conversion

- Due to spin mismatching, ALP-photon conversion occurs not in vacuum, but in the presence of spin-1 background field.
- ALP-photon oscillation have to be treated as 3-body system in  $(\gamma_{\perp}, \gamma_{\parallel}, a)$

$$\begin{pmatrix} m_{\gamma}^2 & \frac{d\varphi}{dt} 2\omega & 0 \\ \frac{d\varphi}{dt} 2\omega & m_{\gamma}^2 & g_{\gamma\gamma} B\omega \\ 0 & g_{\gamma\gamma} B\omega & m_a^2 \end{pmatrix}$$

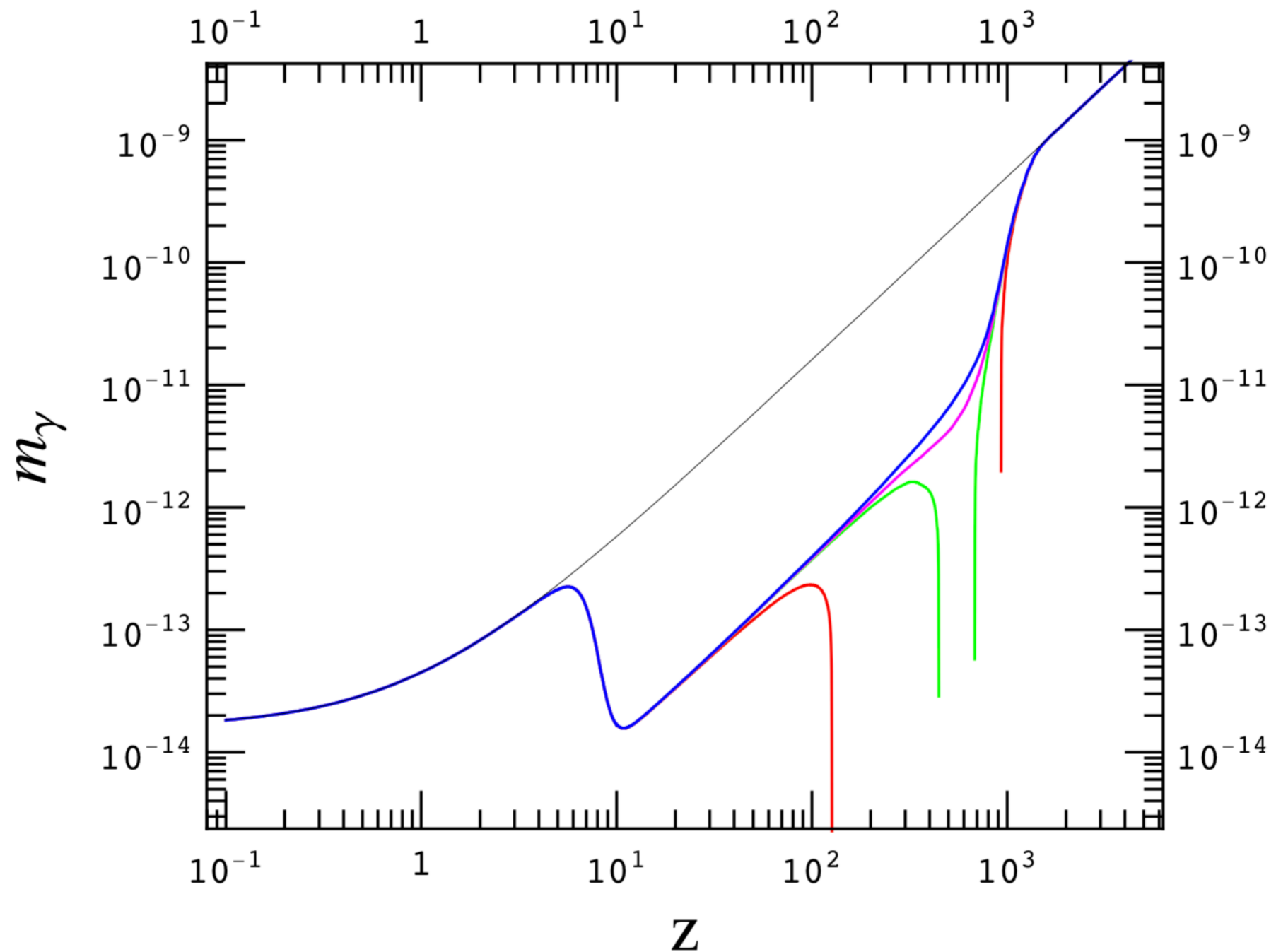
Time variation of photon polarization

- Typically, the photon mixing effect could be negligible even though they are maximally mixed

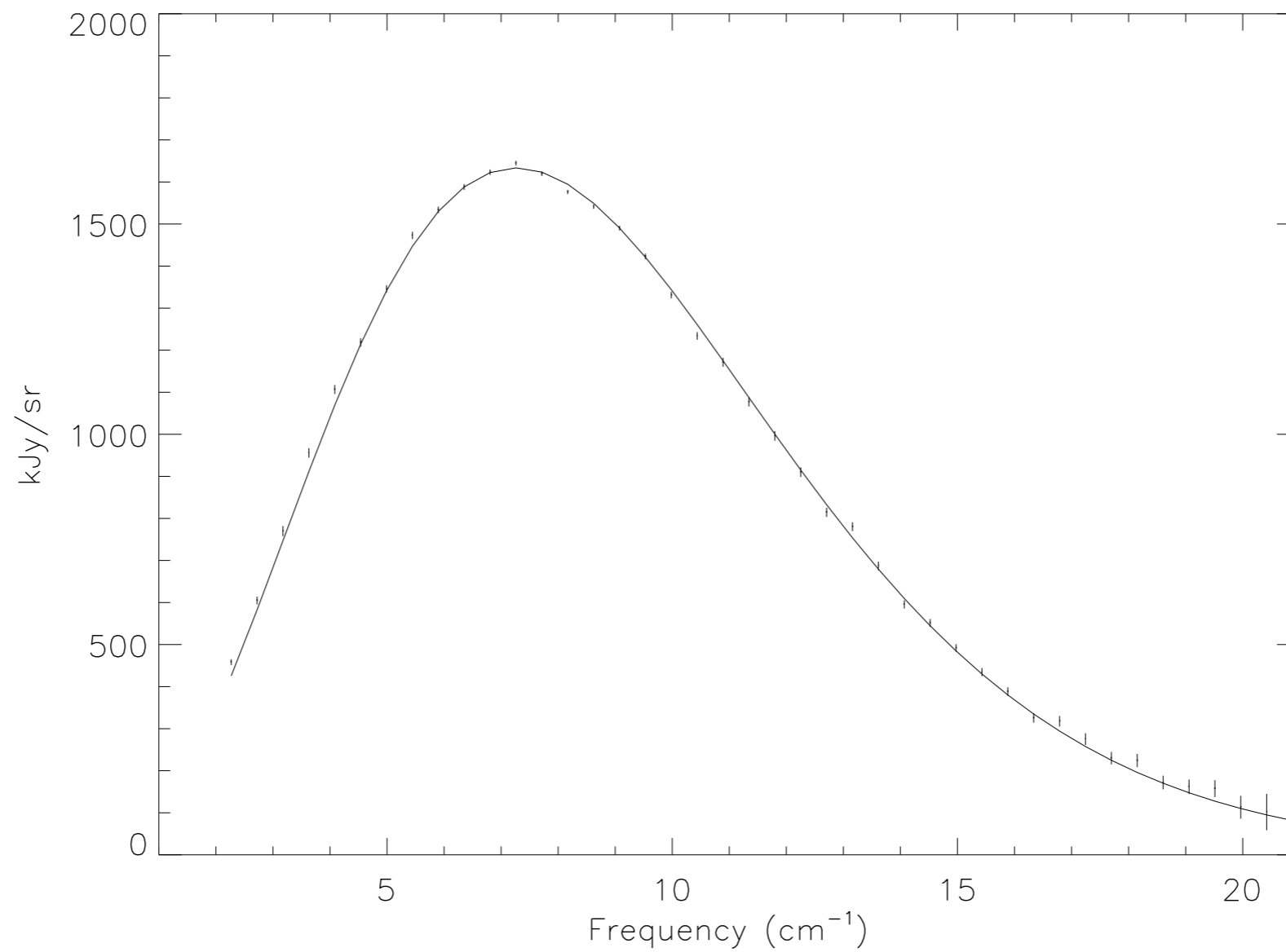


**Effective 2-body system is still valid**

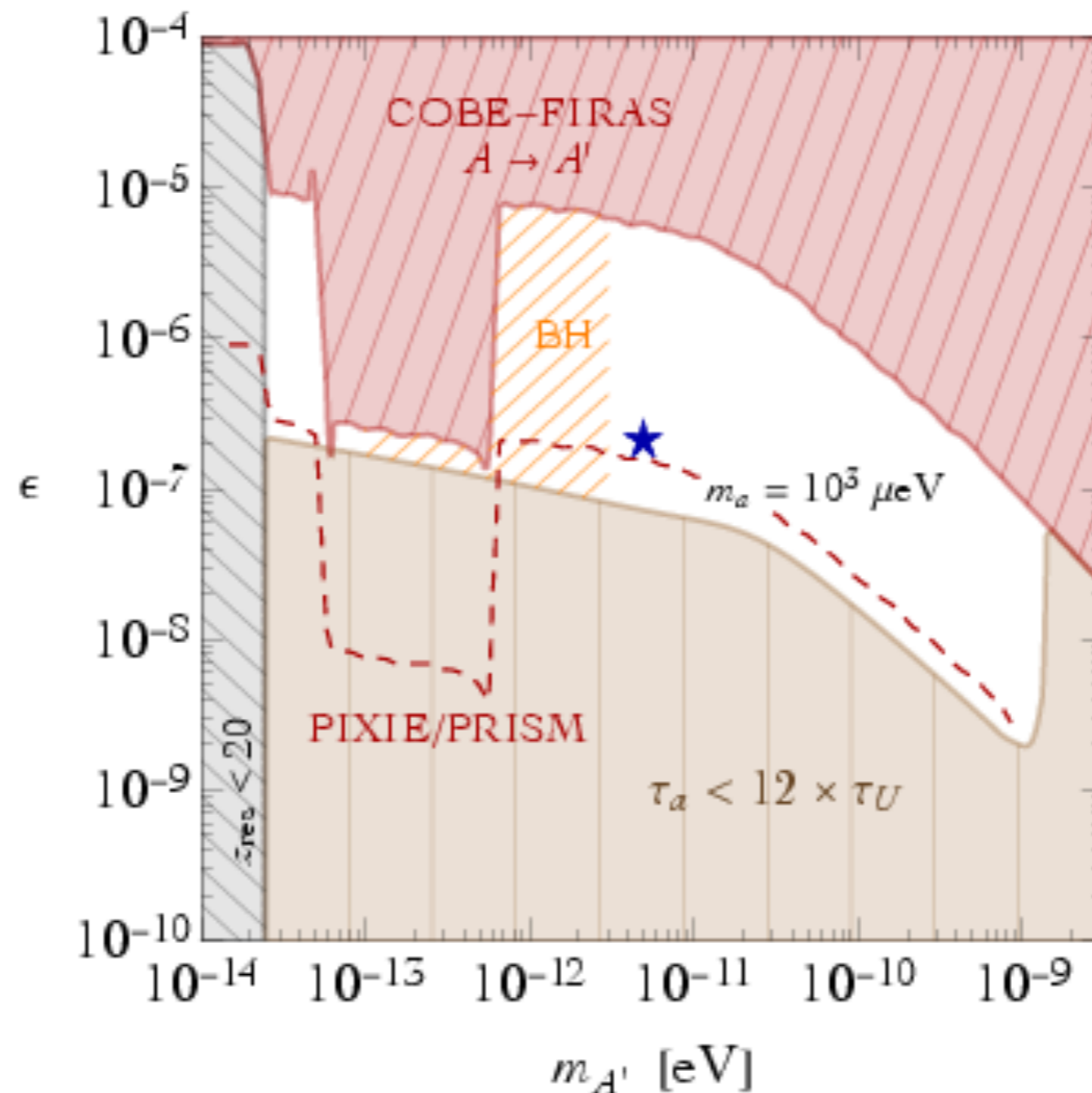
# Effective photon mass profile



# COBE-FIRAS data



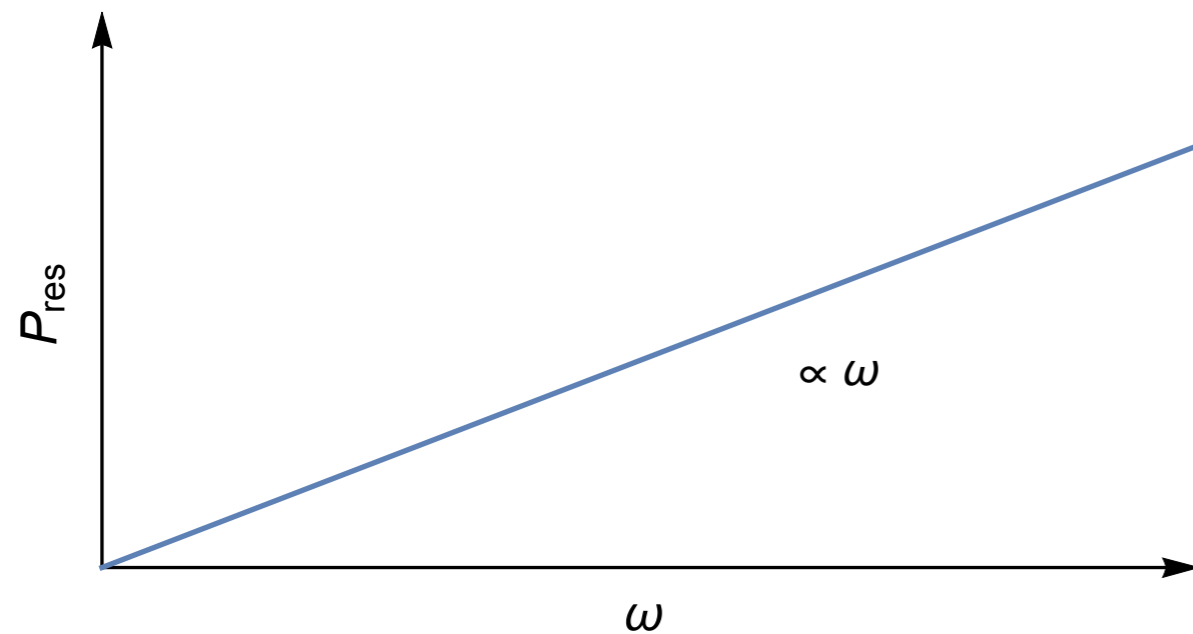
# Dark photon-Photon conversion and its effect on 21cm



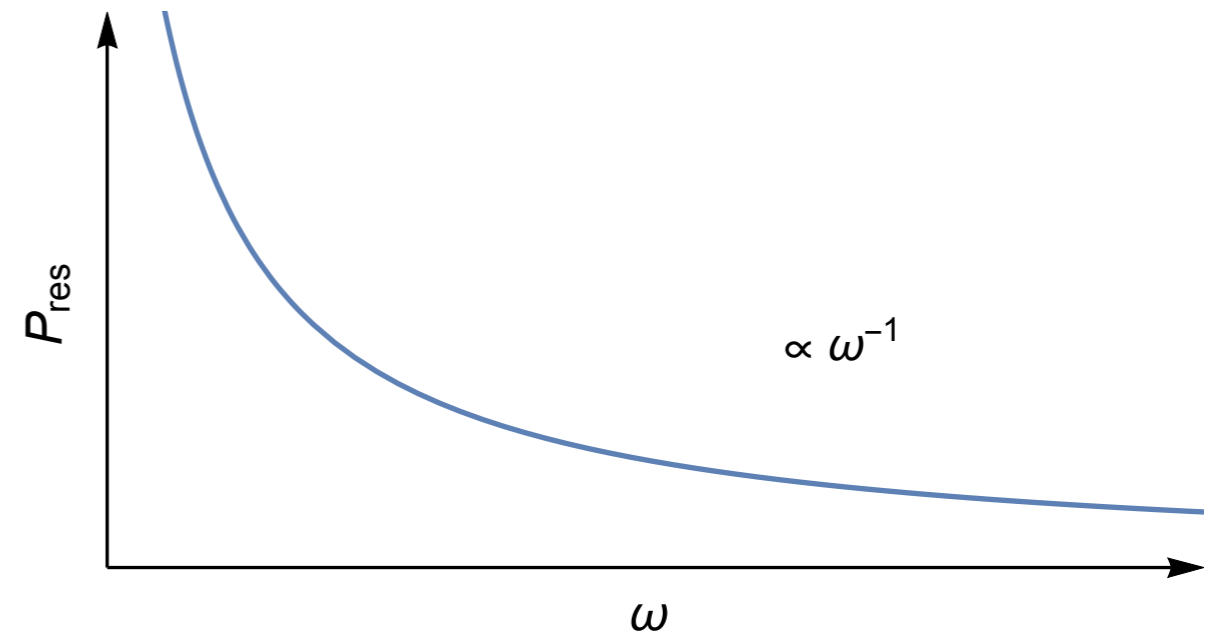


# Resonant conversion probability

**ALP case**



**Dark photon case**



# Large dark mixing resonance

