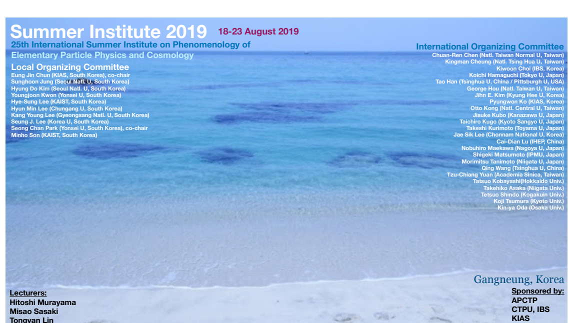
Photon-ALP-dark photon oscillations and its phenomenological implications

Seokhoon Yun

Collaborated with Kiwoon Choi, Sangjun Lee, and Hyeonseok Seong

Based on arXiv:1806.09508 and work in progress (arXiv:1908.xxxxx)



imagine the impossible
KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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 (in progress, arXiv:1908.xxxxx)

04 **Conclusion**

Portal physics

01	02	03	04
Higgs portal	**Axion portal**	**Vector portal**	**Neutrino portal**
spin-0 scalar	spin-0 pseudoscalar	spin-1 vector	spin-1/2 fermion
$\|S\|^2 H^\dagger H$	$a/f_a F_{\mu\nu} \tilde{F}^{\mu\nu}$	$F_{\mu\nu} Z'^{\mu\nu}$	LHN
	$(\partial_\mu a/f_a)\, \bar{\psi}\gamma^\mu\psi$		

Portal physics

01

Higgs portal

spin-0 scalar

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

02

Axion portal

spin-0 pseudoscalar

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

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

03

Vector portal

spin-1 vector

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

04

Neutrino portal

spin-1/2 fermion

$$LHN$$

Portal physics

01

Higgs portal

spin-0 scalar

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

02

Axion portal

spin-0 pseudoscalar

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

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

03

Vector portal

spin-1 vector

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

04

Neutrino portal

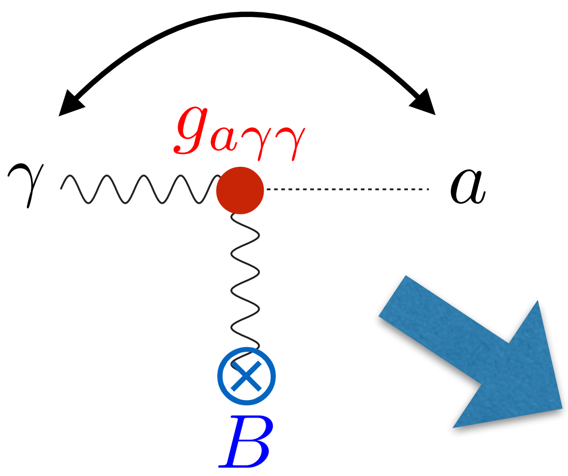
spin-1/2 fermion

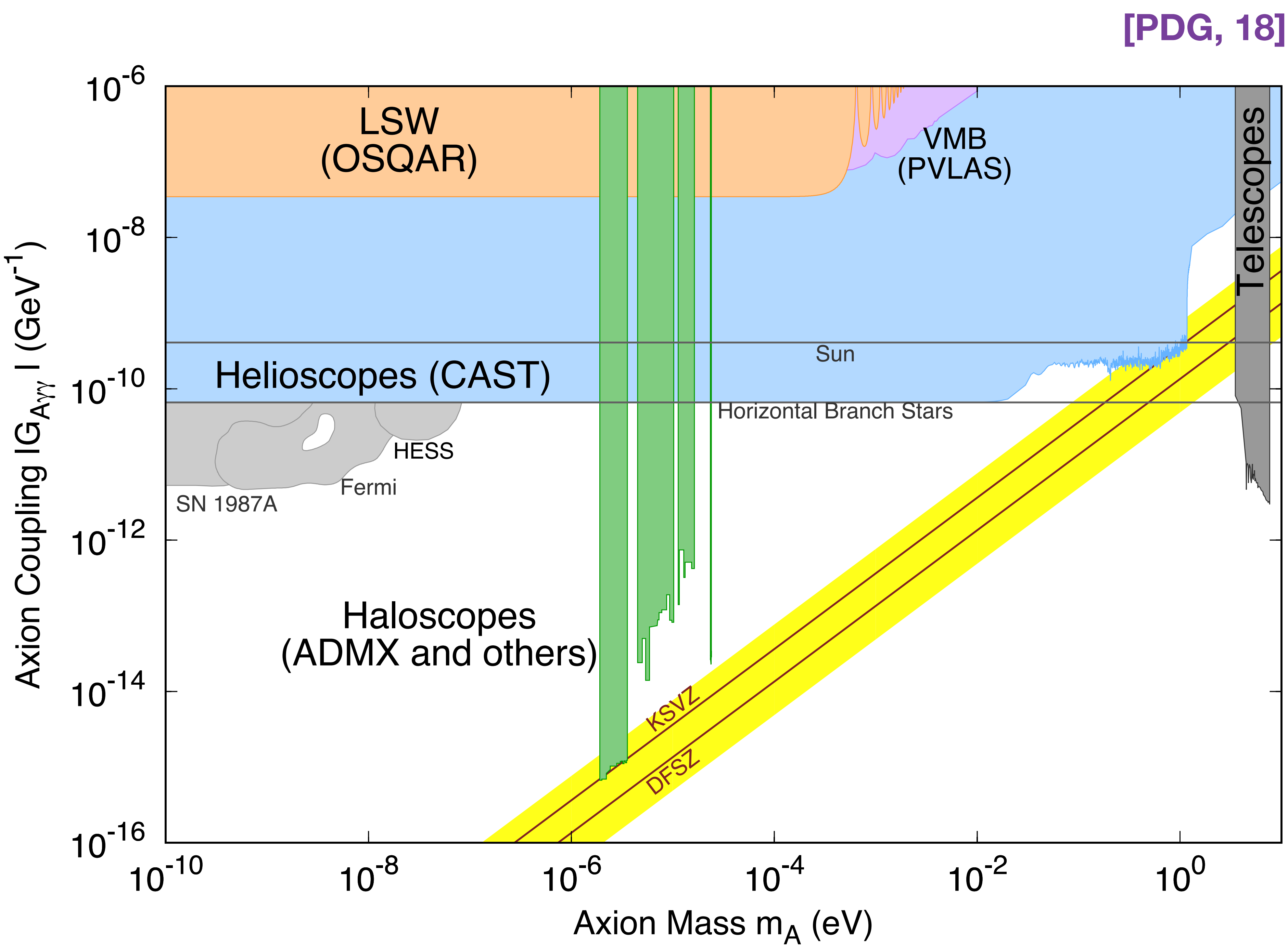
$$LHN$$

Dark axion portal

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

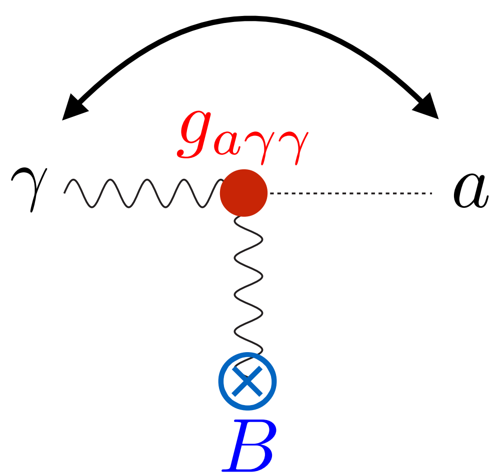
Current constraints on Axion and ALP





Photon-ALP oscillation

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



relativistic $v \approx c$

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

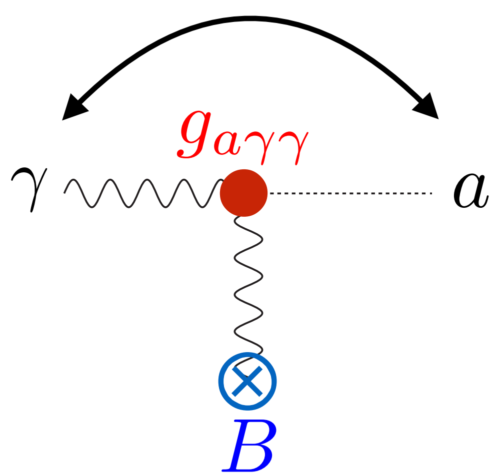
$\vec{A}_{\|} \| \vec{B}$

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

[G. Raffelt et al., 88]

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



$$\triangle^2_{\rm osc} = (g_{a\gamma\gamma}B)^2 + \left(m_a^2 - \omega_{\rm pl}^2\right)^2/4\omega^2$$

phase retardation

$$P_{a\leftrightarrow\gamma} = \sin^2 2\theta \sin^2 \frac{\triangle_{\rm osc} l}{2}$$

mixing angle $\frac{1}{2}\tan 2\theta = \frac{\omega g_{a\gamma\gamma}B}{m_a^2 - w_{\rm pl}^2}$

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

No energy dependence

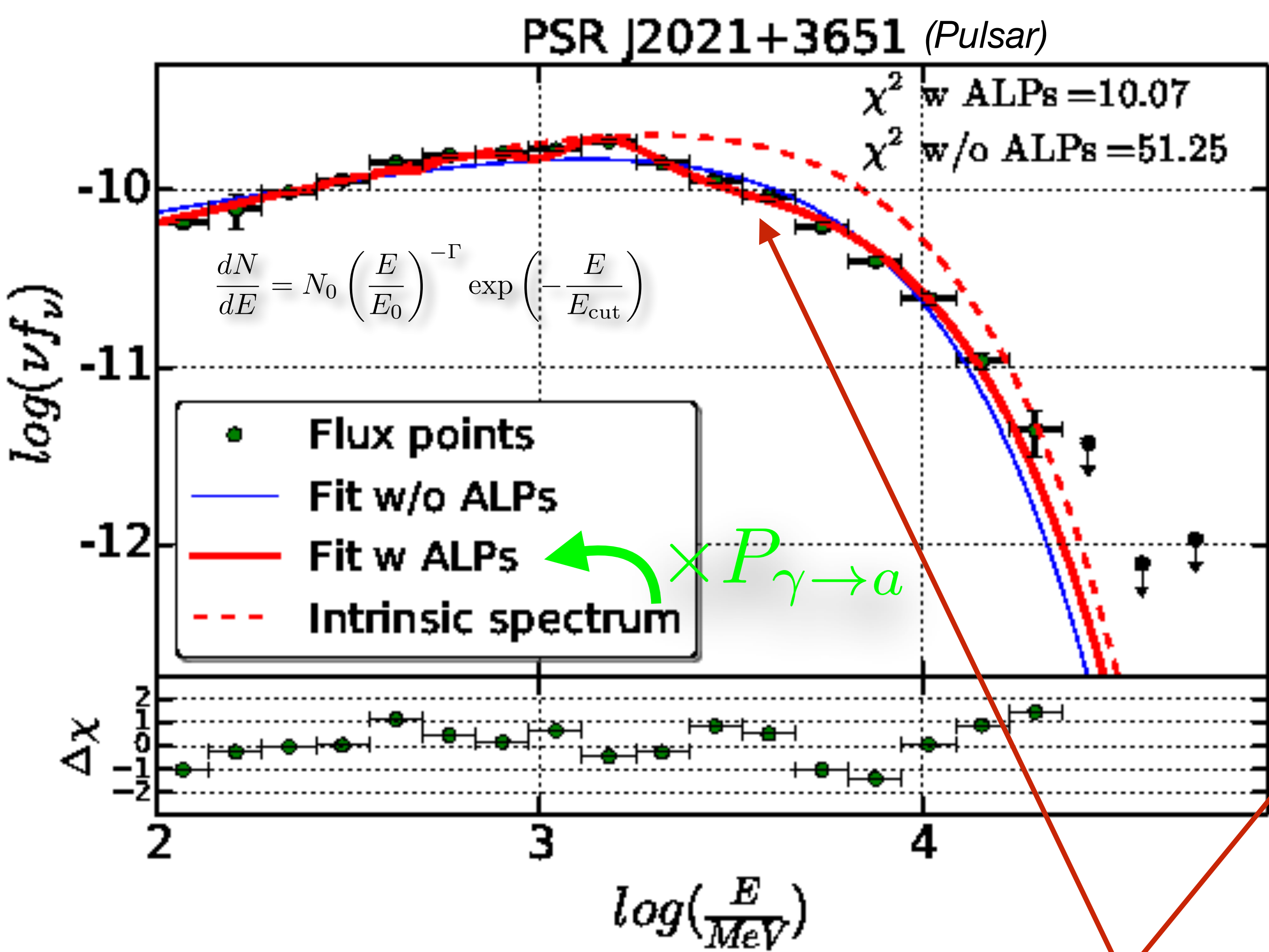
$\theta \approx \pi/4$

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

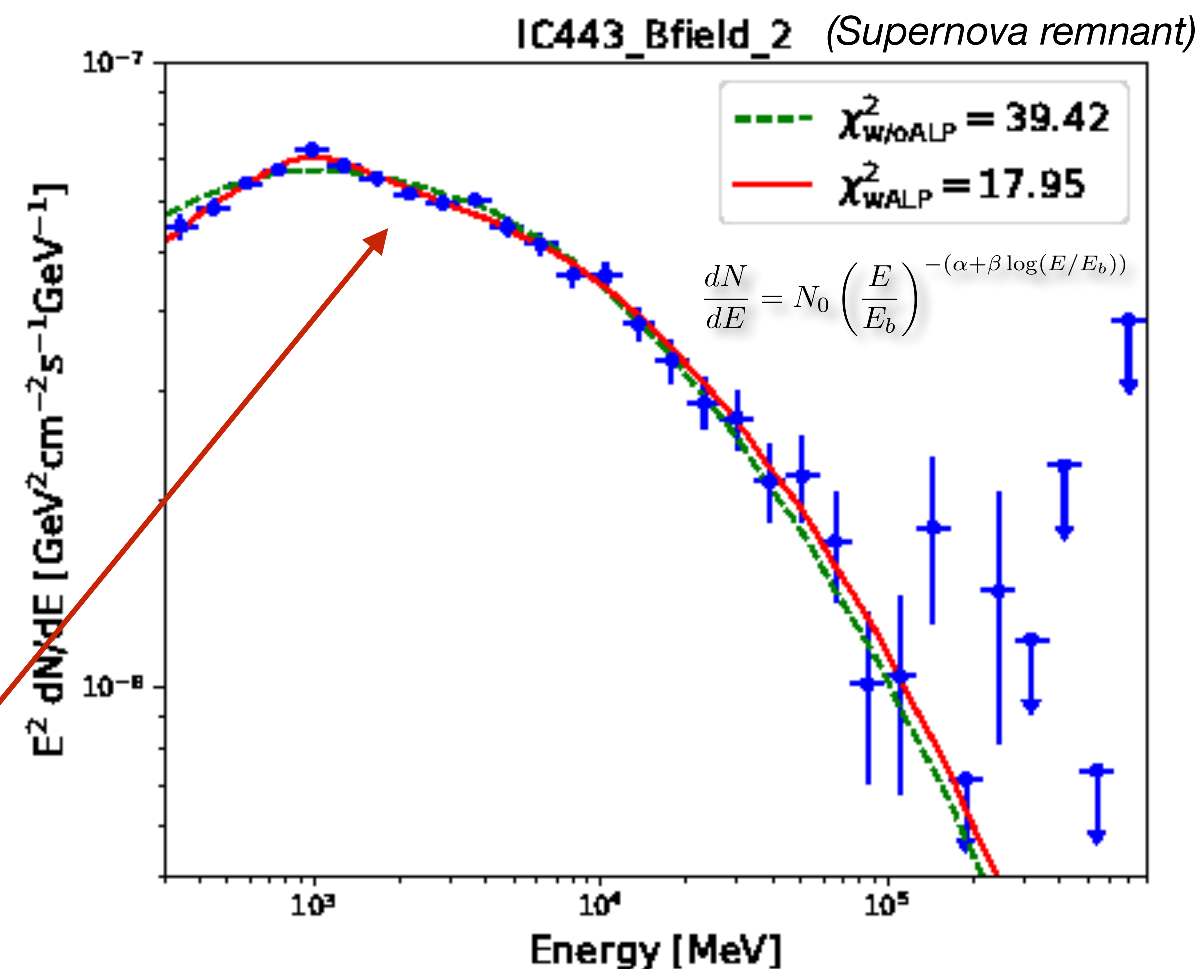
Gamma-ray spectral modulations

Photon-ALP conversion

[J. Majumdar et al., 18]



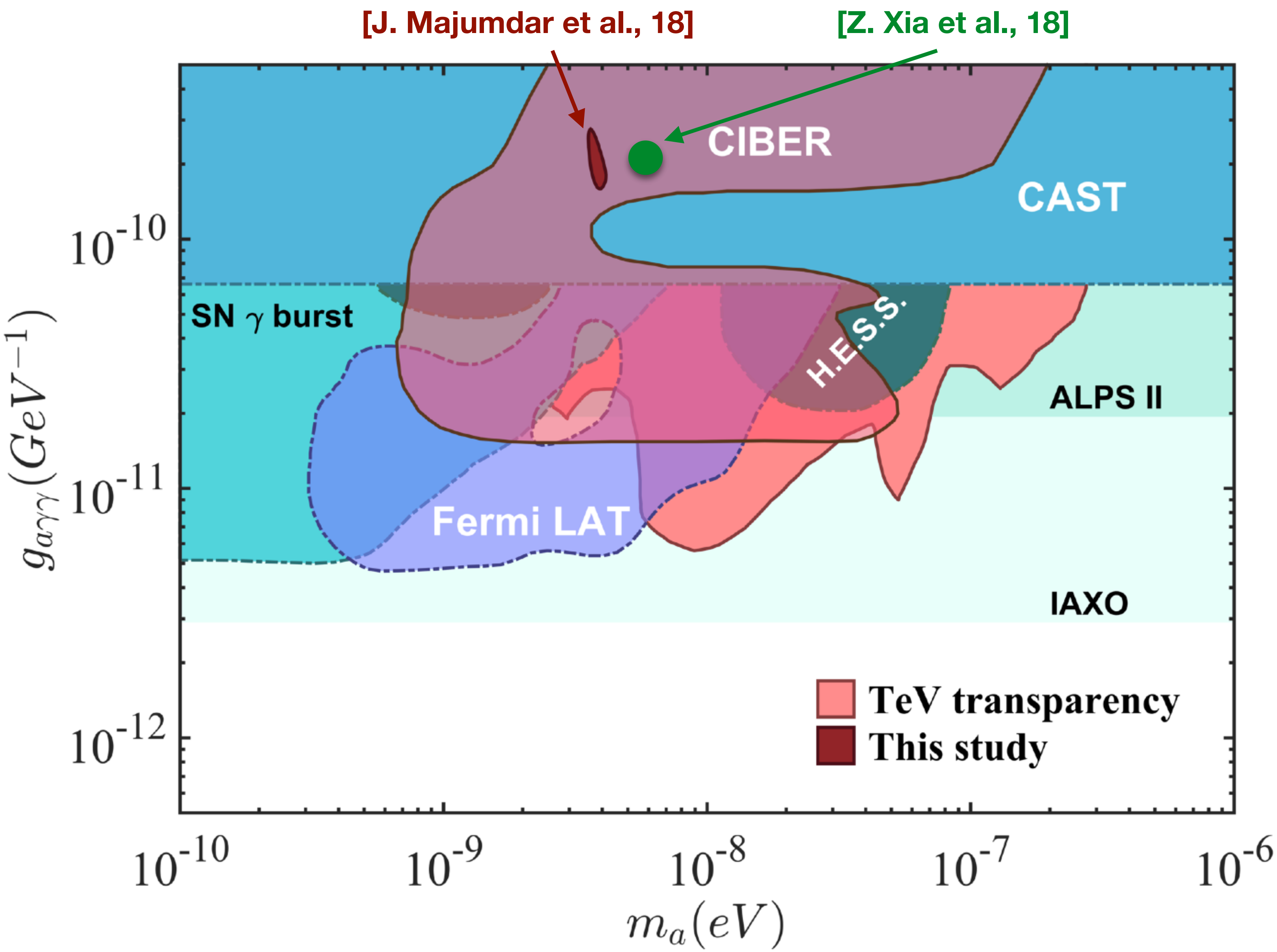
[Z. Xia et al., 18]



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

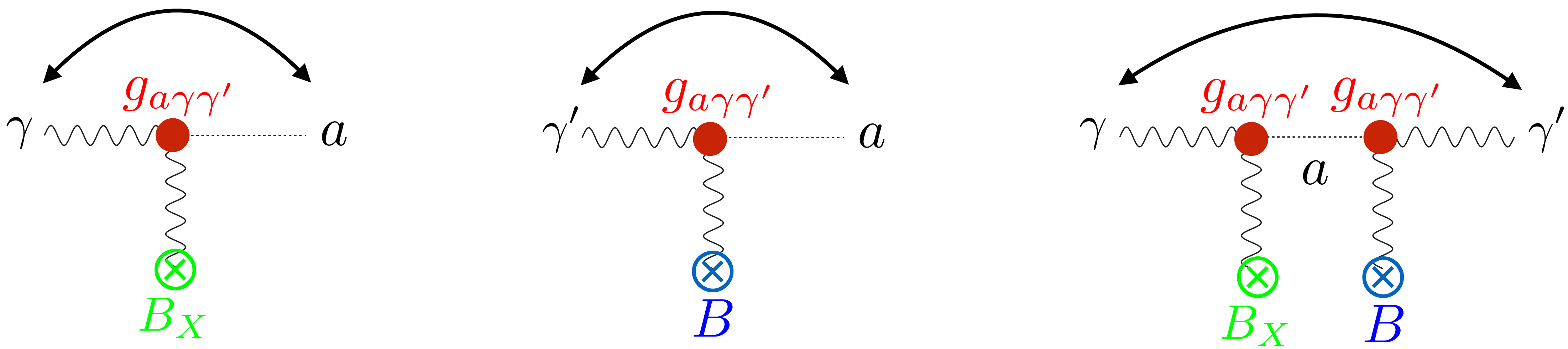
Gamma-ray spectral modulations

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**

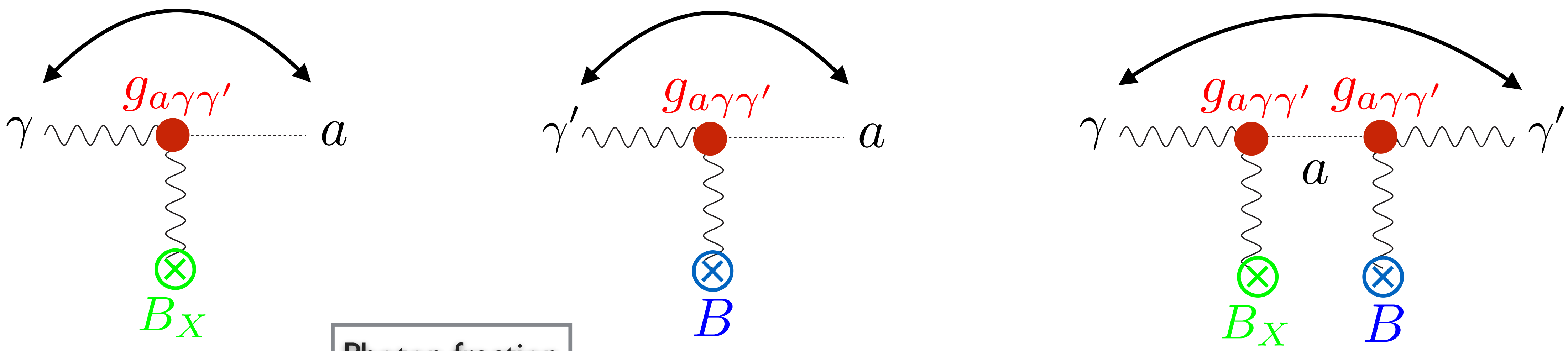


$$\left[\omega + i\partial_z - \begin{pmatrix} \omega_{\rm pl}^2/2\omega & 0 & g_{a\gamma\gamma'}B_X/2 \\ 0 & 0 & g_{a\gamma\gamma'}B/2 \\ g_{a\gamma\gamma'}B_X/2 & g_{a\gamma\gamma'}B/2 & m_a^2/2\omega \end{pmatrix}\right]\begin{pmatrix} A_\parallel \\ X_\parallel \\ a \end{pmatrix} = 0$$

[K. Choi, S. Lee, H. Seong, SY, 18]

Photon-ALP-Dark photon oscillation

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



Photon fraction

$$P_{\gamma\leftrightarrow a} \simeq \left(\frac{B_X^2}{B_{\rm eff}^2}\right)\sin^2\frac{\triangle_{\rm osc} l}{2}$$

at large mixing,

$\omega > \omega_c$

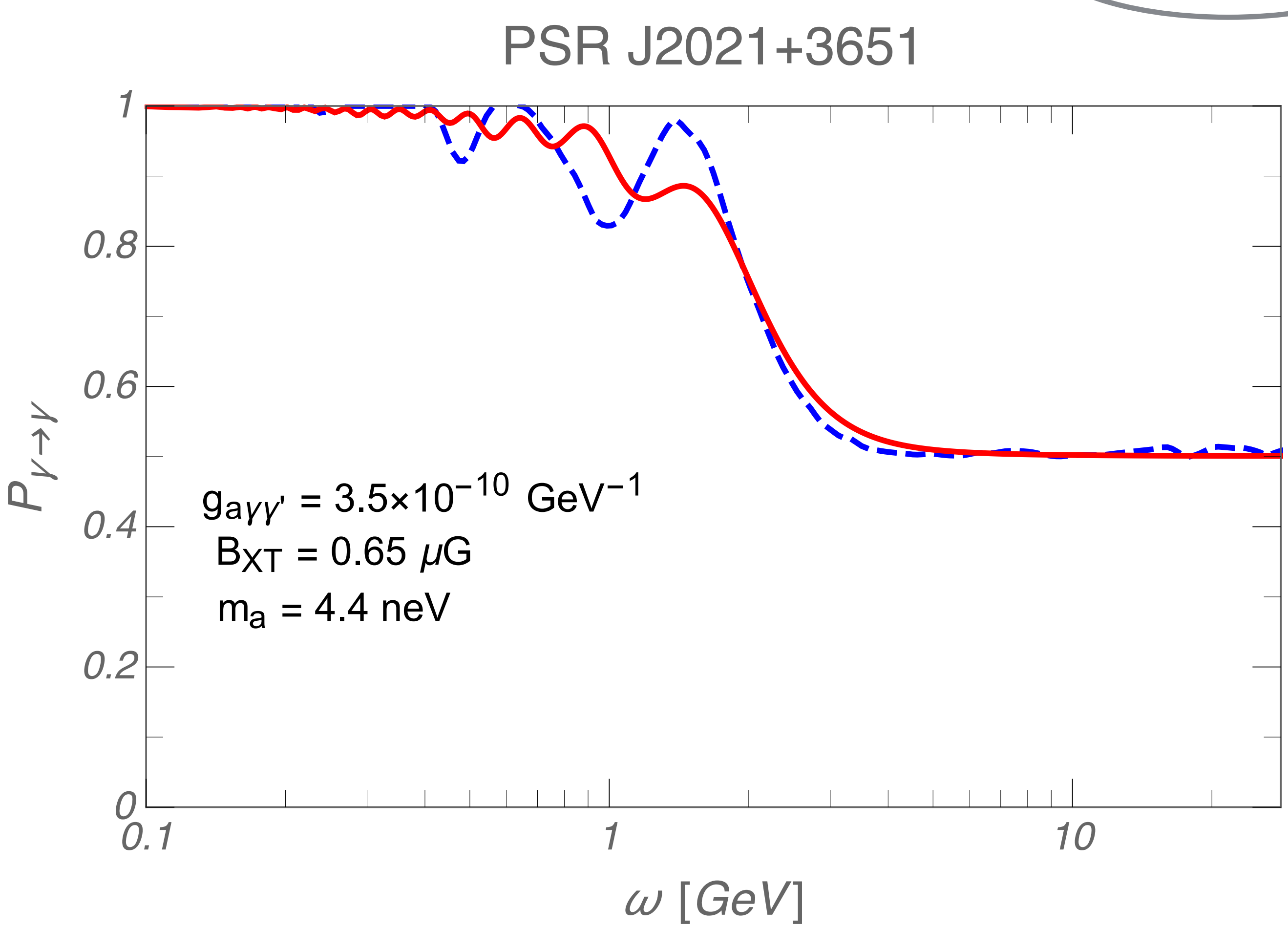
$$P_{\gamma\leftrightarrow\gamma'} \simeq 4\left(\frac{B_X^2}{B_{\rm eff}^2}\right)\left(\frac{B^2}{B_{\rm eff}^2}\right)\sin^4\frac{\triangle_{\rm osc} l}{4}$$

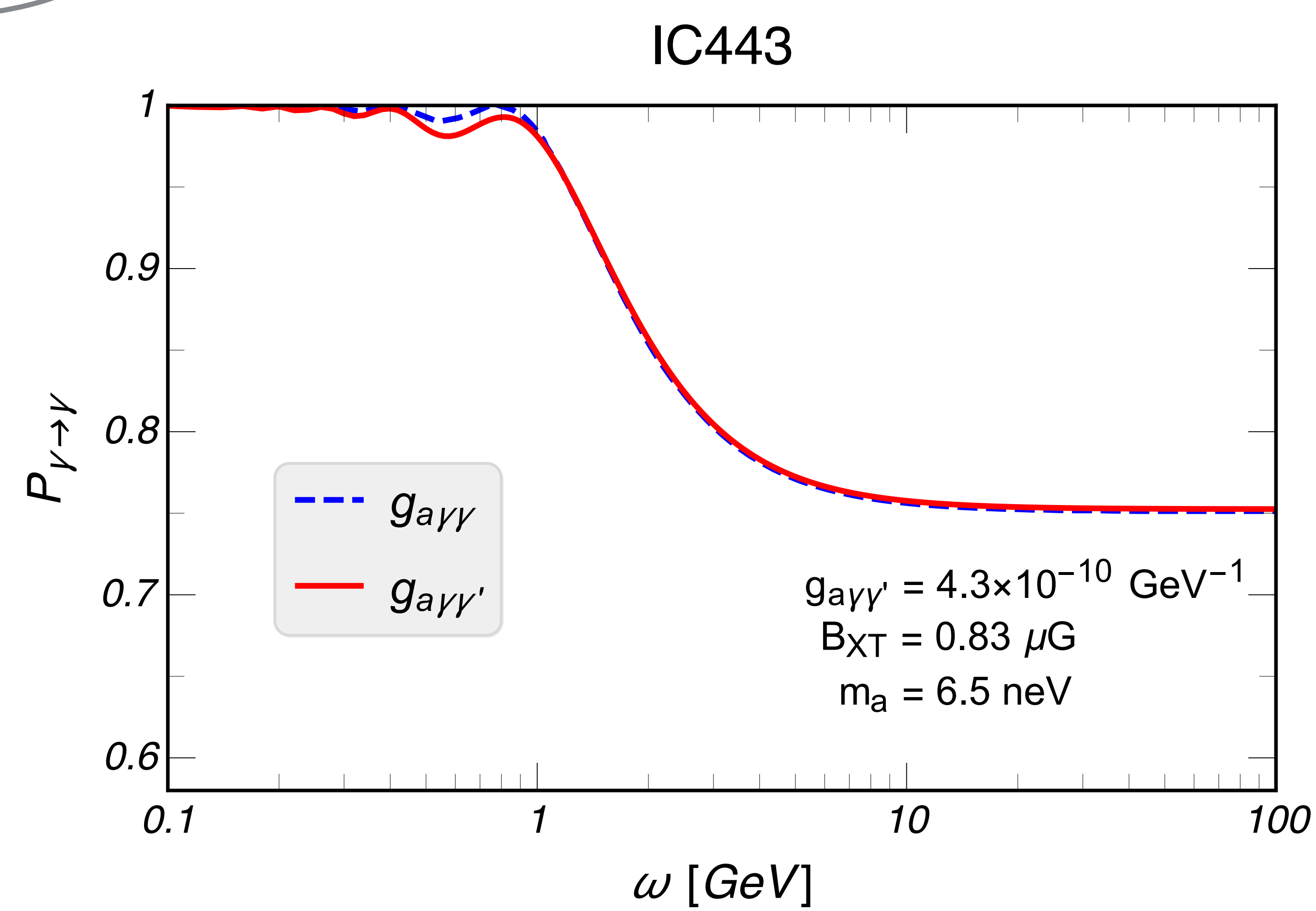
Gamma-ray spectral modulations

Photon-ALP-Dark photon conversion

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

Tachyonic instability



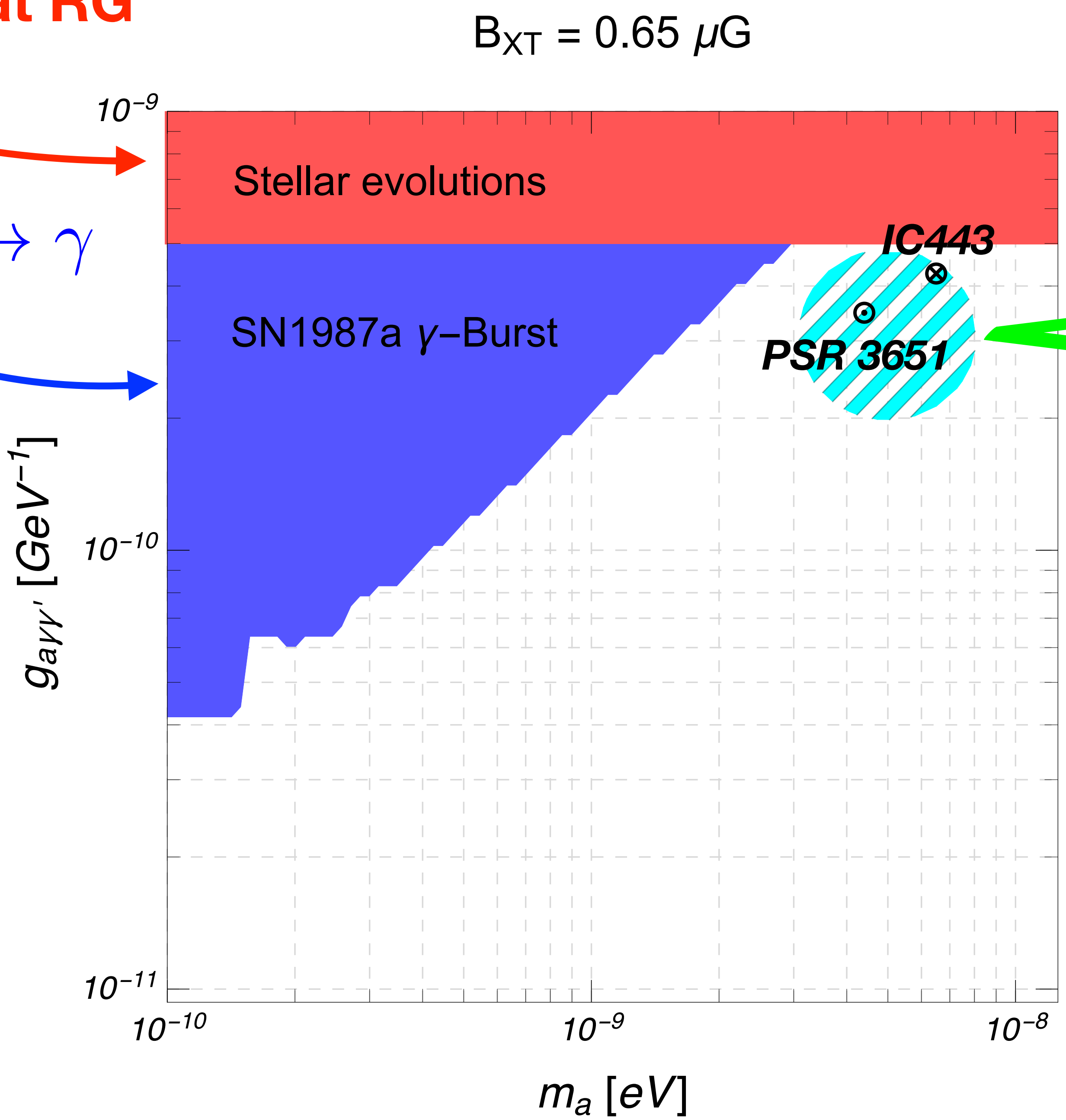


[K. Choi, S. Lee, H. Seong, SY, 18]

Observational constraints

Core mass increase at RG

γ-burst from $a, \gamma' \to \gamma$



$\omega_c \sim \mathcal{O}(1)\,\mathrm{GeV}^{-1}$

$P_{\gamma\to\gamma} \sim 50 - 70\%$

Resonant conversion

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

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

- Effective mass-squared matrix

$$m_{\rm mix}^2 = \begin{cases} g_{a\gamma\gamma}B\omega & \cdots\ a \\ \varepsilon m_{\gamma'}^2 & \cdots\ \gamma' \end{cases}$$

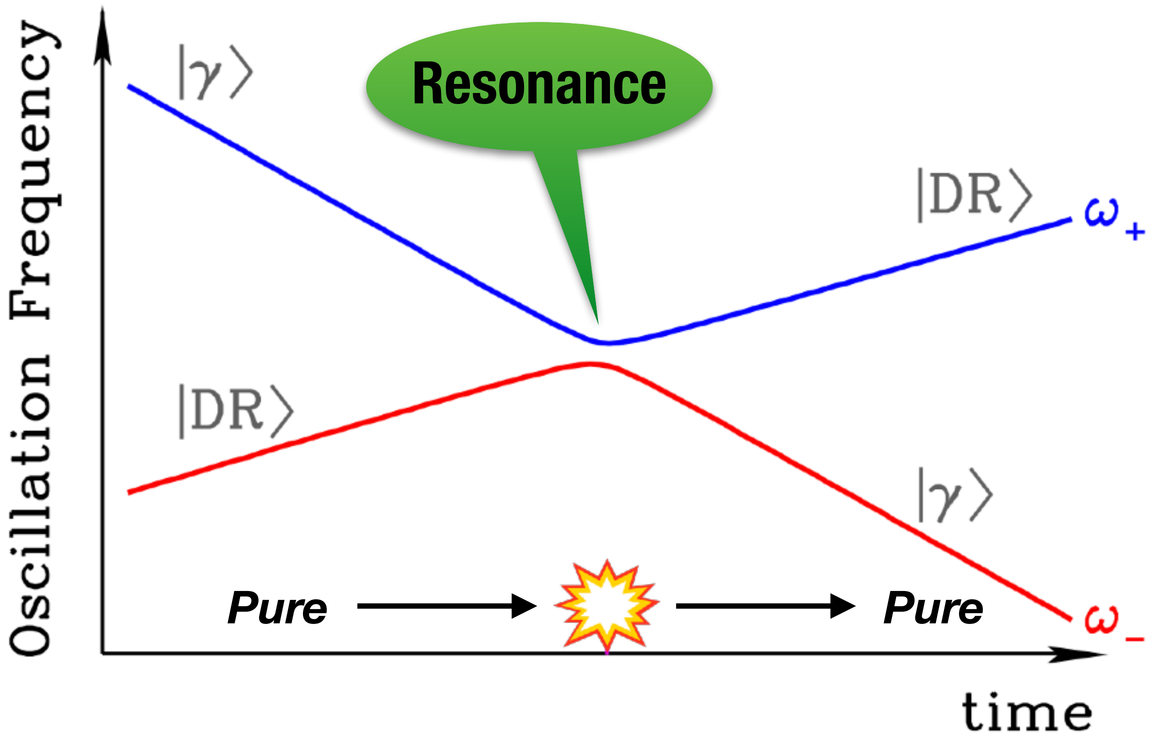
$$\mathcal{M}^2 = \begin{bmatrix} \omega_{\rm pl}^2 & m_{\rm mix}^2 \\ m_{\rm mix}^2 & m_\phi^2 \end{bmatrix}$$

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

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

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

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

$$\simeq 1 - p$$

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

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

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

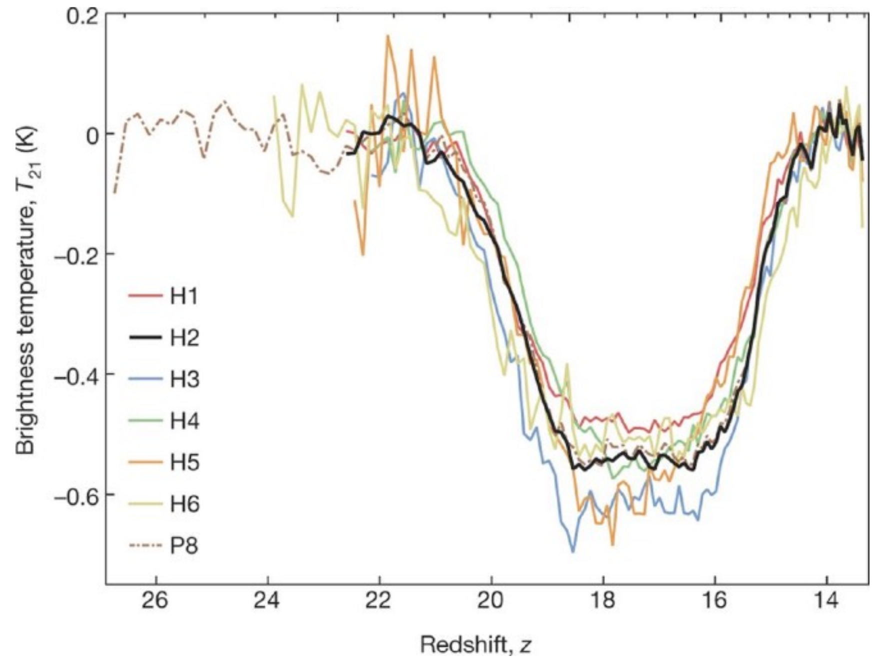
$$p \simeq \exp\left(-2\pi r k \sin^2\theta_0\right)_{t=t_{\rm res}}$$

$$r = \left|\frac{d\ln\omega_{\rm pl}^2}{dt}\right|^{-1}$$

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

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

EDGES anomaly



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

- 21cm brightness temperature relative to CMB at z ~ 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

$\phi \rightarrow \gamma$

ALP conversion [T. Moroi et al., 18]

Dark photon conversion [M. Pospelov et al., 18]

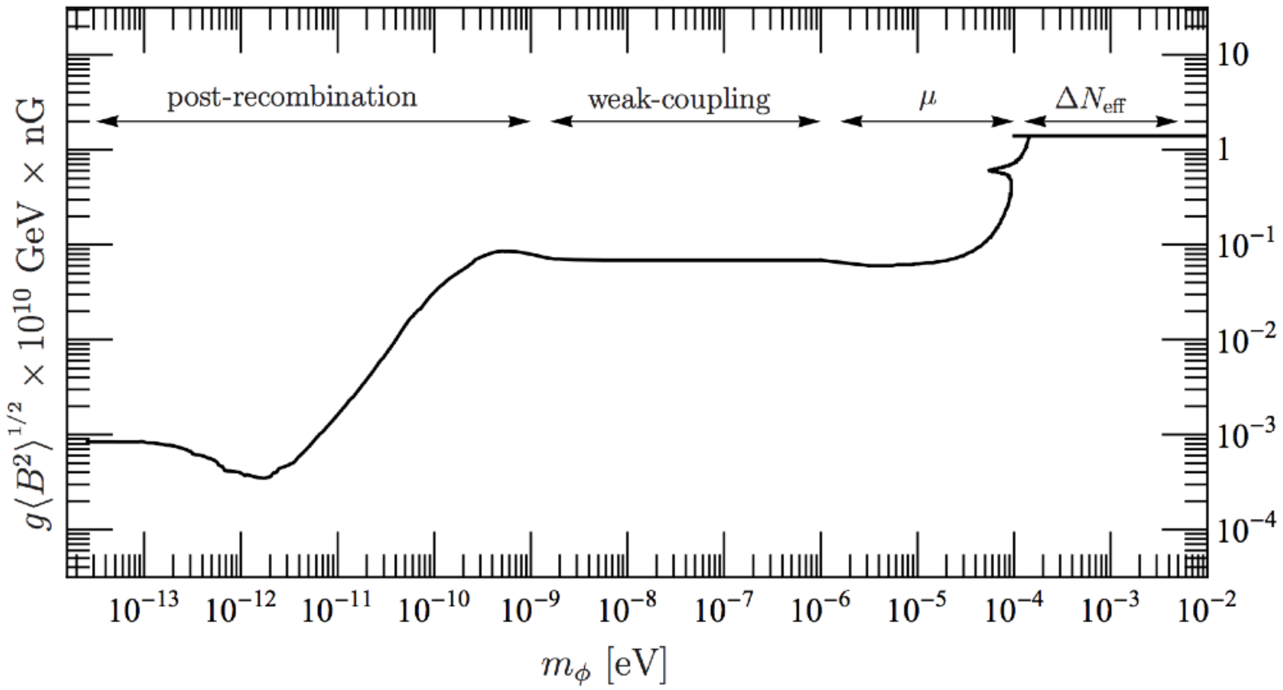
CMB distortion constraints

$\gamma \to \phi$

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

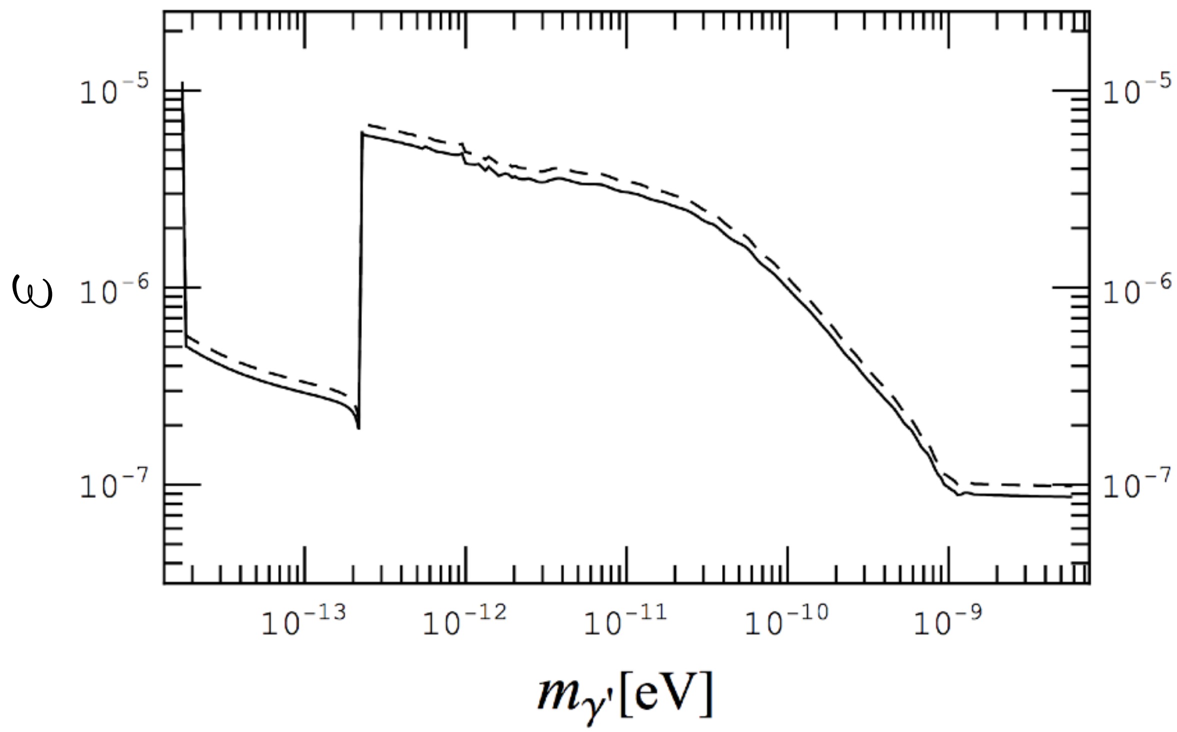
- COBE-FIRAS data which fits well to the black-body spectrum can give stringent bound

[A. Mirizzi et al., 09]



[ALP]

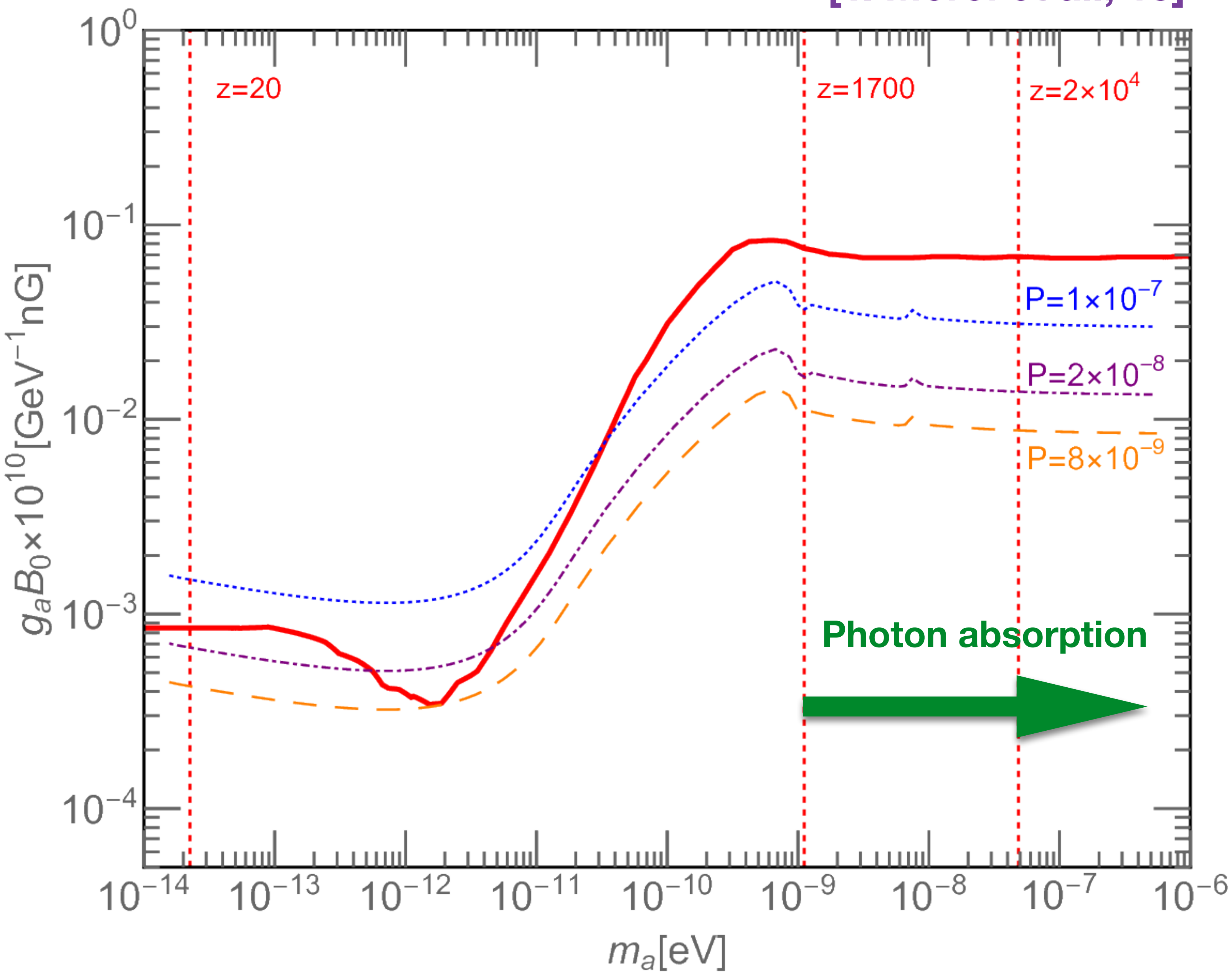
[A. Mirizzi et al., 09]



[Dark photon]

ALP-Photon conversion and its effect on 21cm

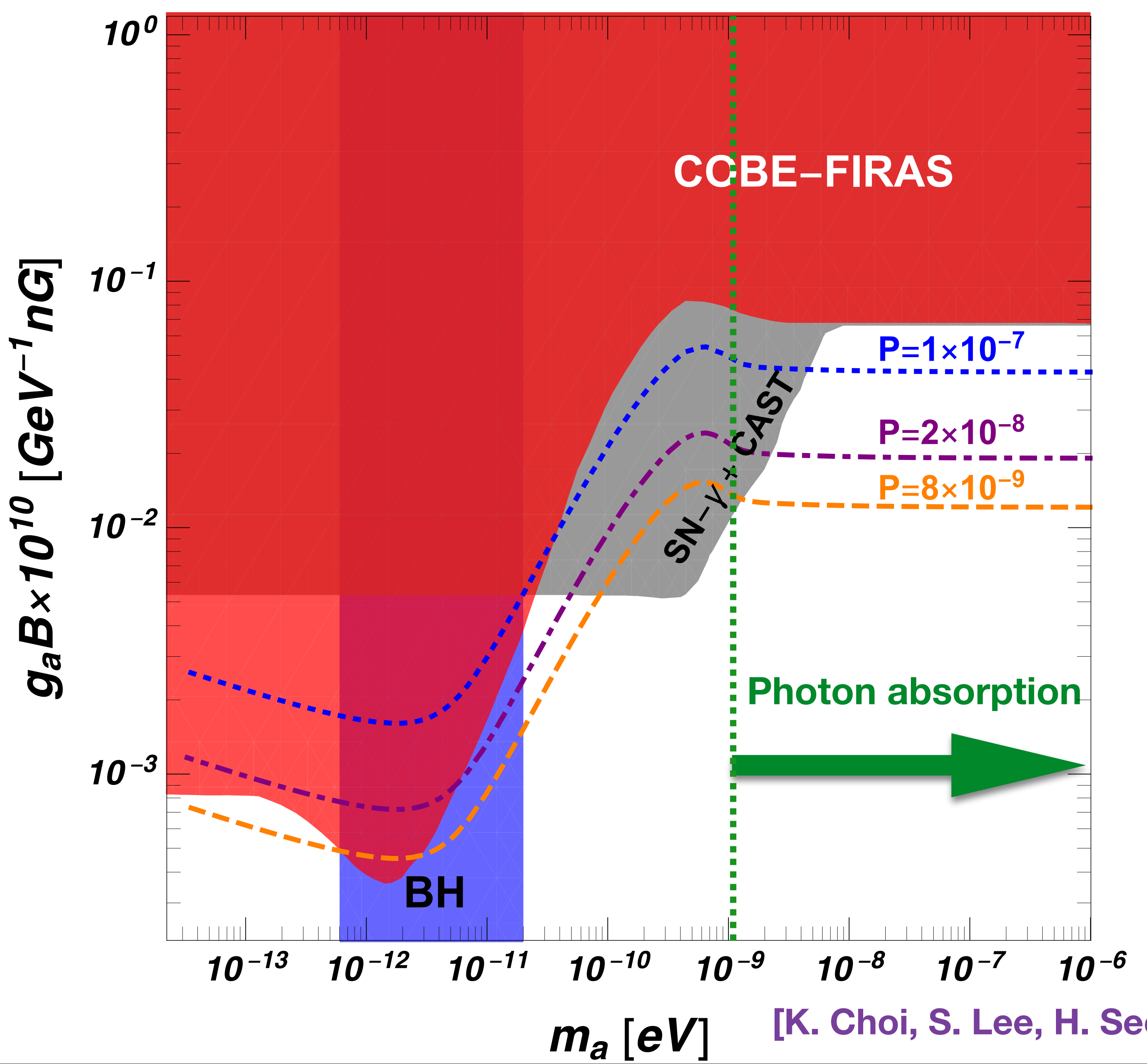
[T. Moroi et al., 18]



- Required conversion probability

$$P_{a\to\gamma}^{\omega_{21\mathrm{cm}}} \sim 10^{-9}\left(f_a^{\omega_{21\mathrm{cm}}}\Delta N_{\mathrm{eff}}\right)^{-1}$$

ALP-Photon conversion and its effect on 21cm



[K. Choi, S. Lee, H. Seong, SY, in preparation]

- Required conversion probability

$$P_{a\to\gamma}^{\omega_{21\text{cm}}} \sim 10^{-9}\left(f_a^{\omega_{21\text{cm}}}\Delta N_{\text{eff}}\right)^{-1}$$

✦ ***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)

[K. Choi, S. Lee, H. Seong, SY, in preparation]

Resonant photon-ALP-dark photon conversion

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

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

[K. Choi, S. Lee, H. Seong, SY, in preparation]

Resonant photon-ALP-dark photon conversion

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

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

Eigenvalue in small dark mixing regime

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

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

$$\omega < \left. \frac{m_a^2}{g_{a\gamma'\gamma'} B_X} \right|_{t=t_{\rm res}}$$

[K. Choi, S. Lee, H. Seong, SY, in preparation]

Large dark mixing

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

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

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

$\omega_{\rm pl}^2 \propto n_e \propto a^{-3}$

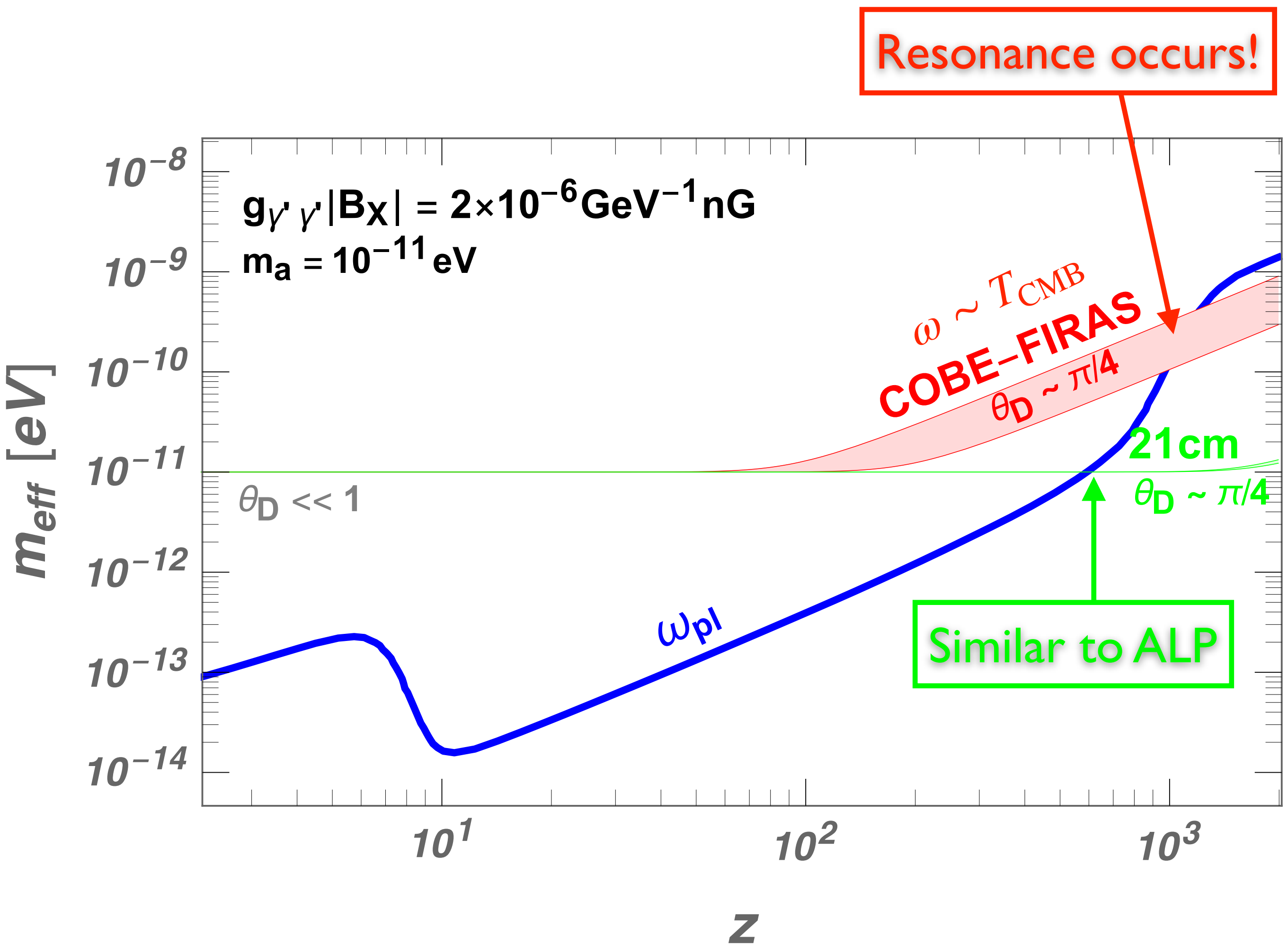
Eigenvalue in large dark mixing regime $\propto a^{-3}$

- In large dark mixing, resonance occurs when $\omega_{\rm pl}^2 = g_{a\gamma'\gamma'} B_X \omega$
- CMB distortion constraint can be evaded when

$$g_{a\gamma'\gamma'} B_{X,0} > 4.6 \times 10^{-5}\ \mathrm{GeV}^{-1}\mathrm{nG}$$

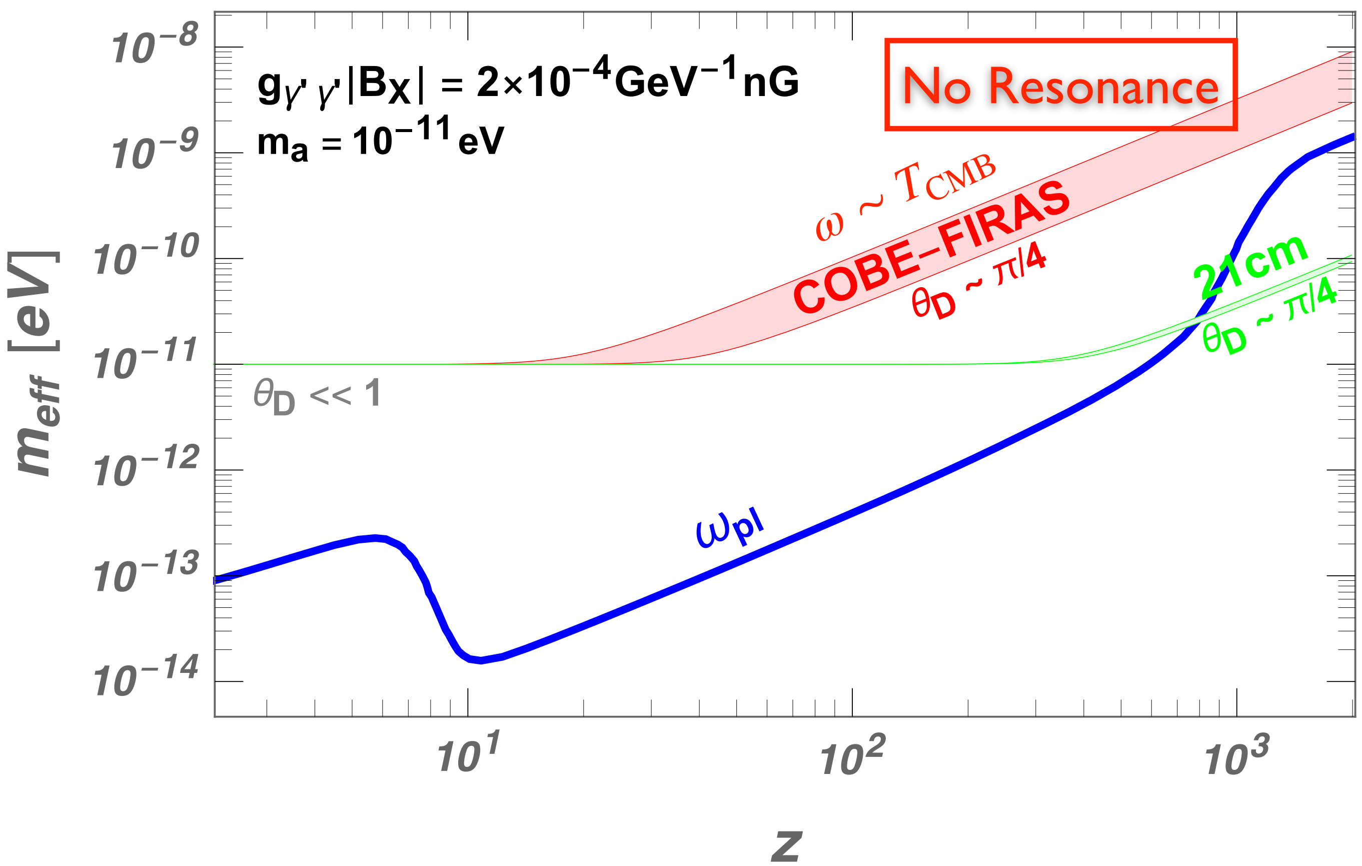
[K. Choi, S. Lee, H. Seong, SY, in preparation]

Large dark mixing resonance

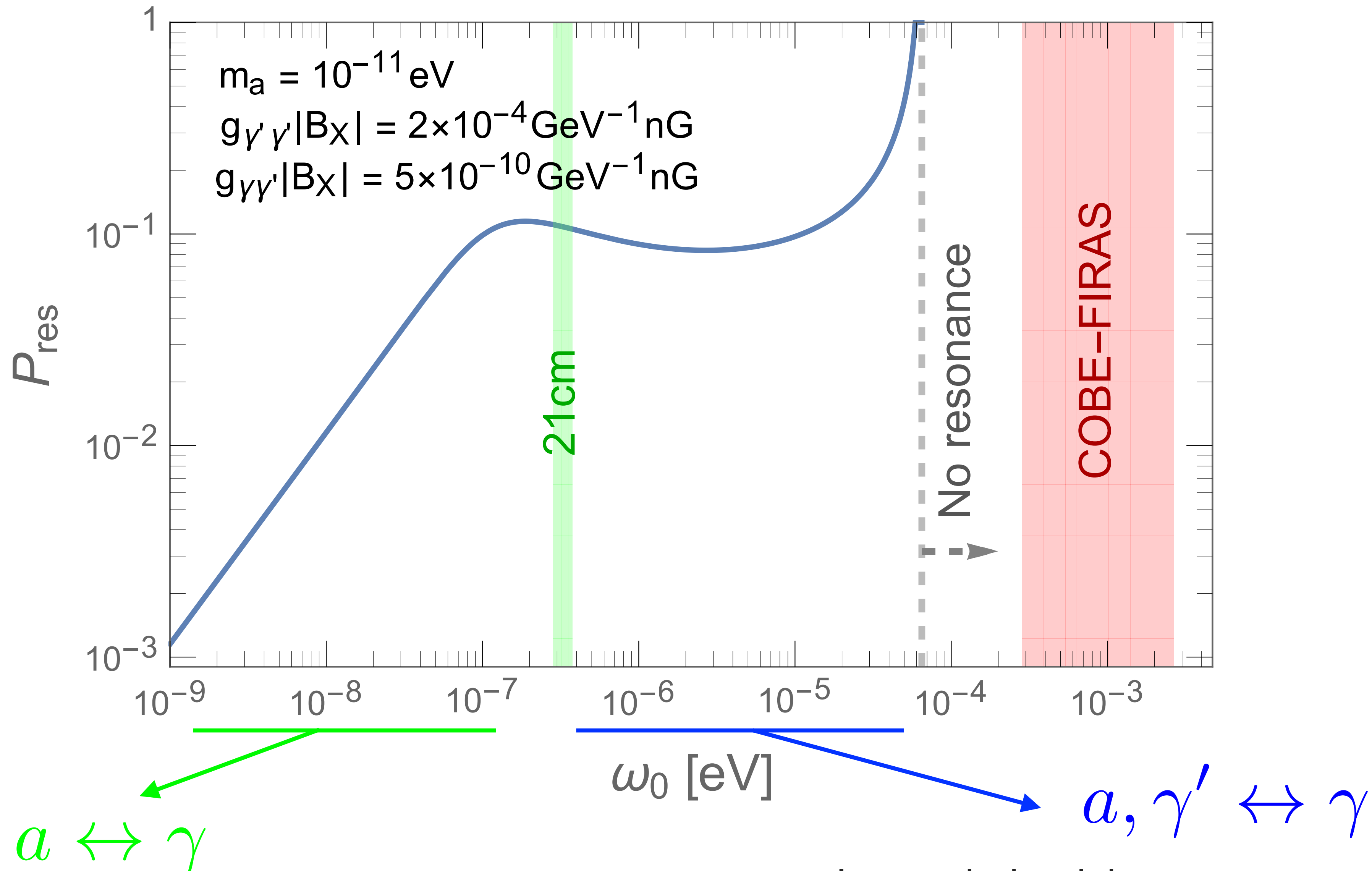


[K. Choi, S. Lee, H. Seong, SY, in preparation]

Large dark mixing resonance



Large dark mixing resonance



- Small dark mixing
- Same to ALP case

- Large dark mixing
- After recombination, hydrogen ionization fraction decreases so the specific energy range can be resonantly oscillated
- Unique feature

Conclusion

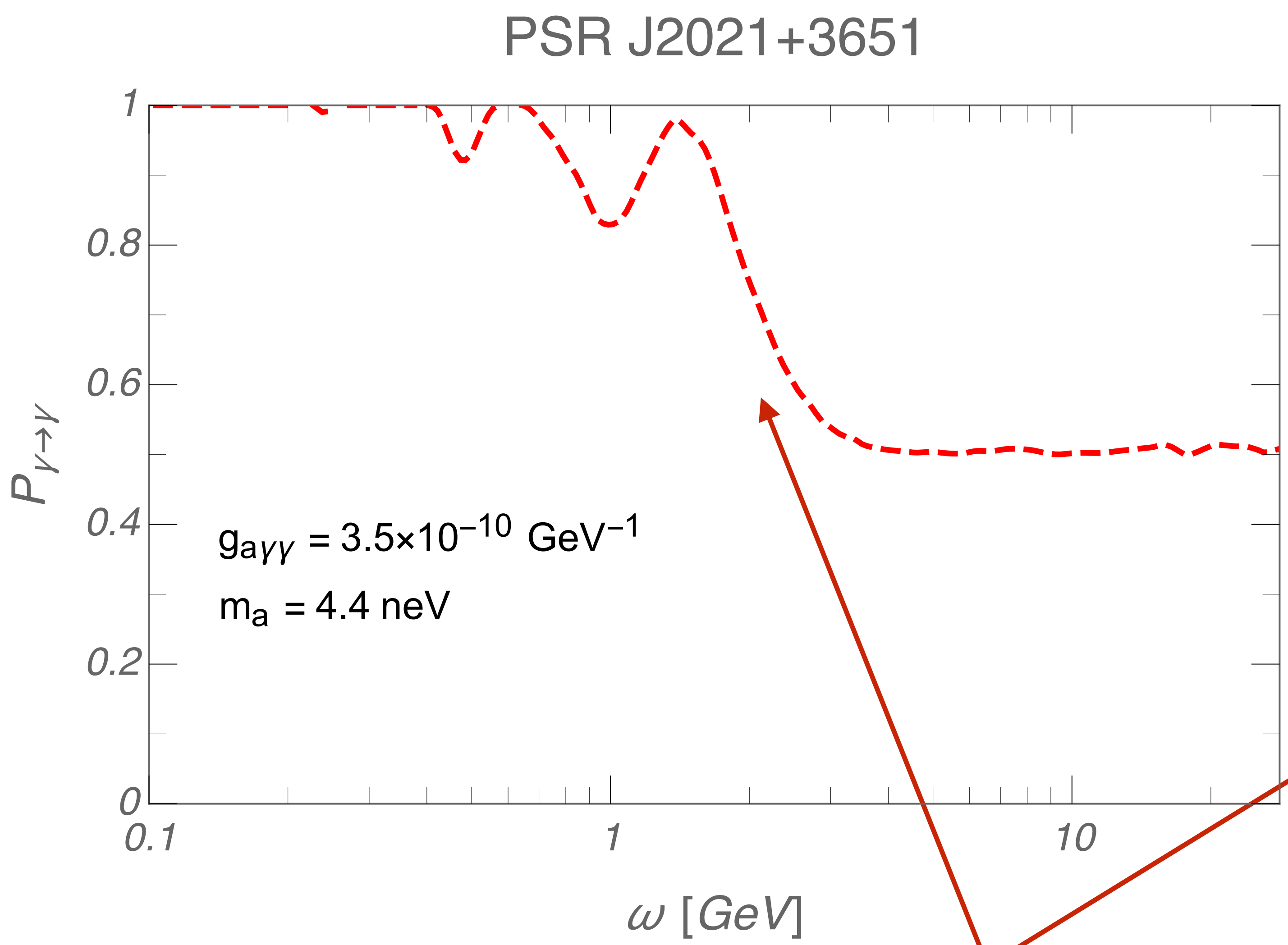
- We discussed the phenomenological implications on the photon-ALP conversion physics: (i) gamma-ray spectral irregularities of point-like sources, (ii) 21cm observation
- The required parameter value in the photon-ALP scenario is in conflict with the present phenomenological constraints, but it is not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

Back up

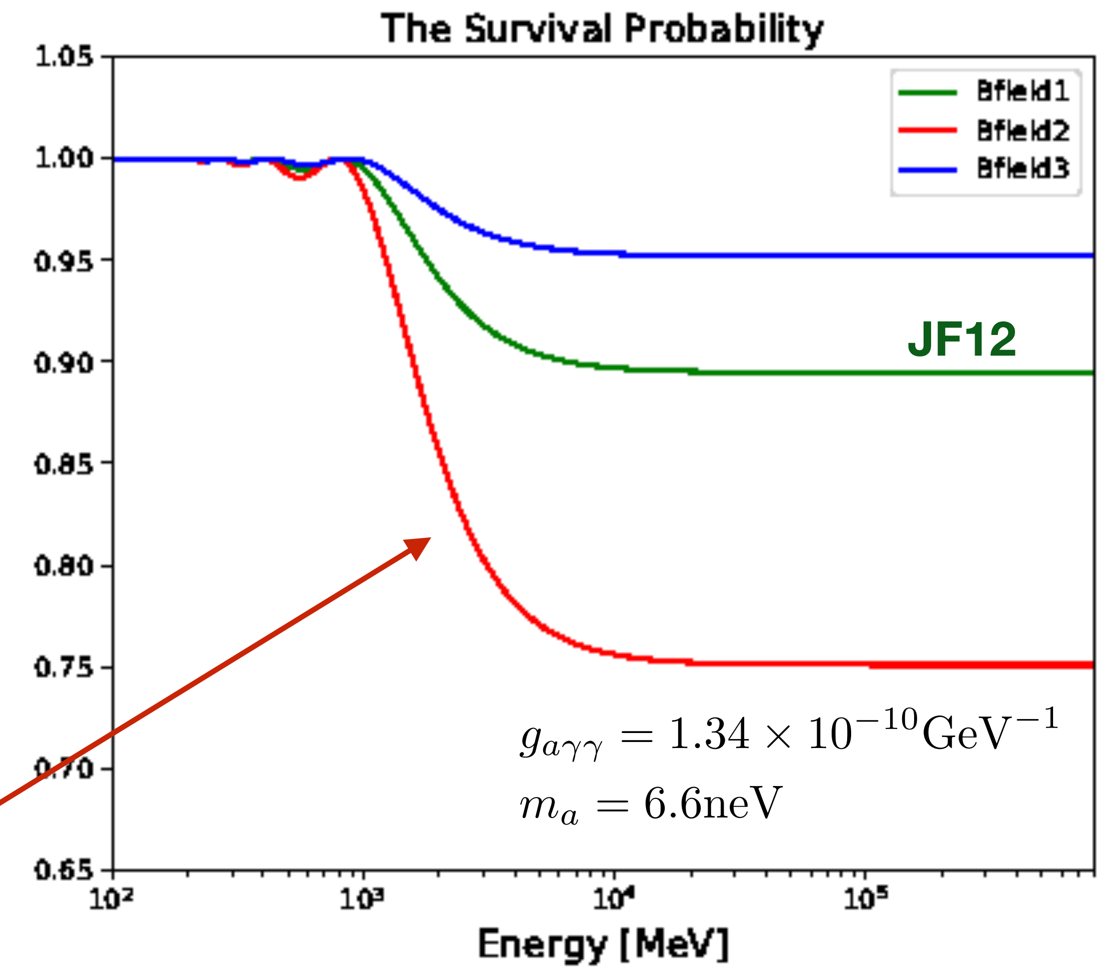
Gamma-ray spectral modulations

Photon-ALP conversion

[J. Majumdar et al., 18]



[Z. Xia et al., 18]

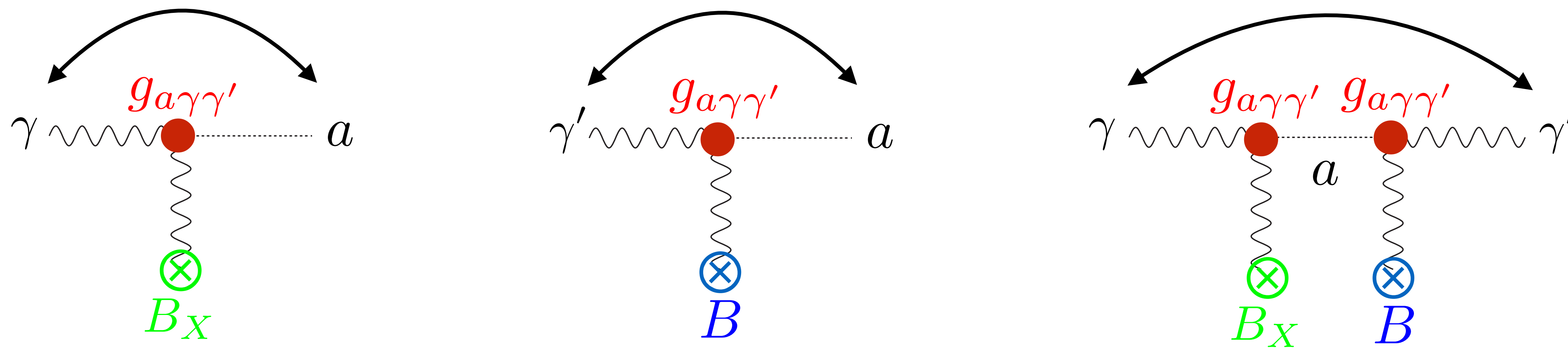


$$\omega \simeq \omega_c = 250\,\mathrm{MeV}\left(\frac{m_a}{\mathrm{neV}}\right)^2\left(\frac{10^{-10}\,\mathrm{GeV}^{-1}}{g_{a\gamma\gamma}}\right)\left(\frac{1\,\mu\mathrm{G}}{B}\right)$$

[K. Choi, S. Lee, H. Seong, SY, 18]

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**

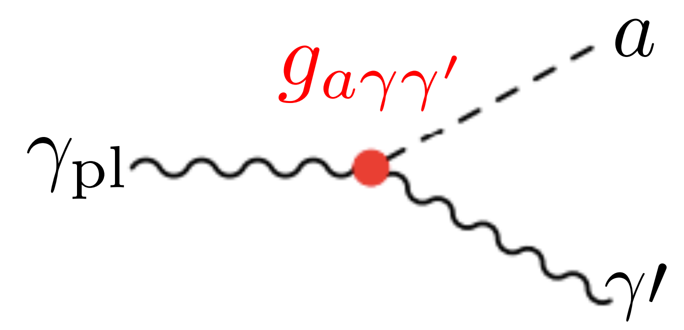


$$P_{\gamma\leftrightarrow a} = \frac{B_X^2}{B_{\rm eff}^2}\left(\frac{1}{1+\omega_c^2/\omega^2}\right)\sin^2\frac{\triangle_{\rm osc}d}{2}$$

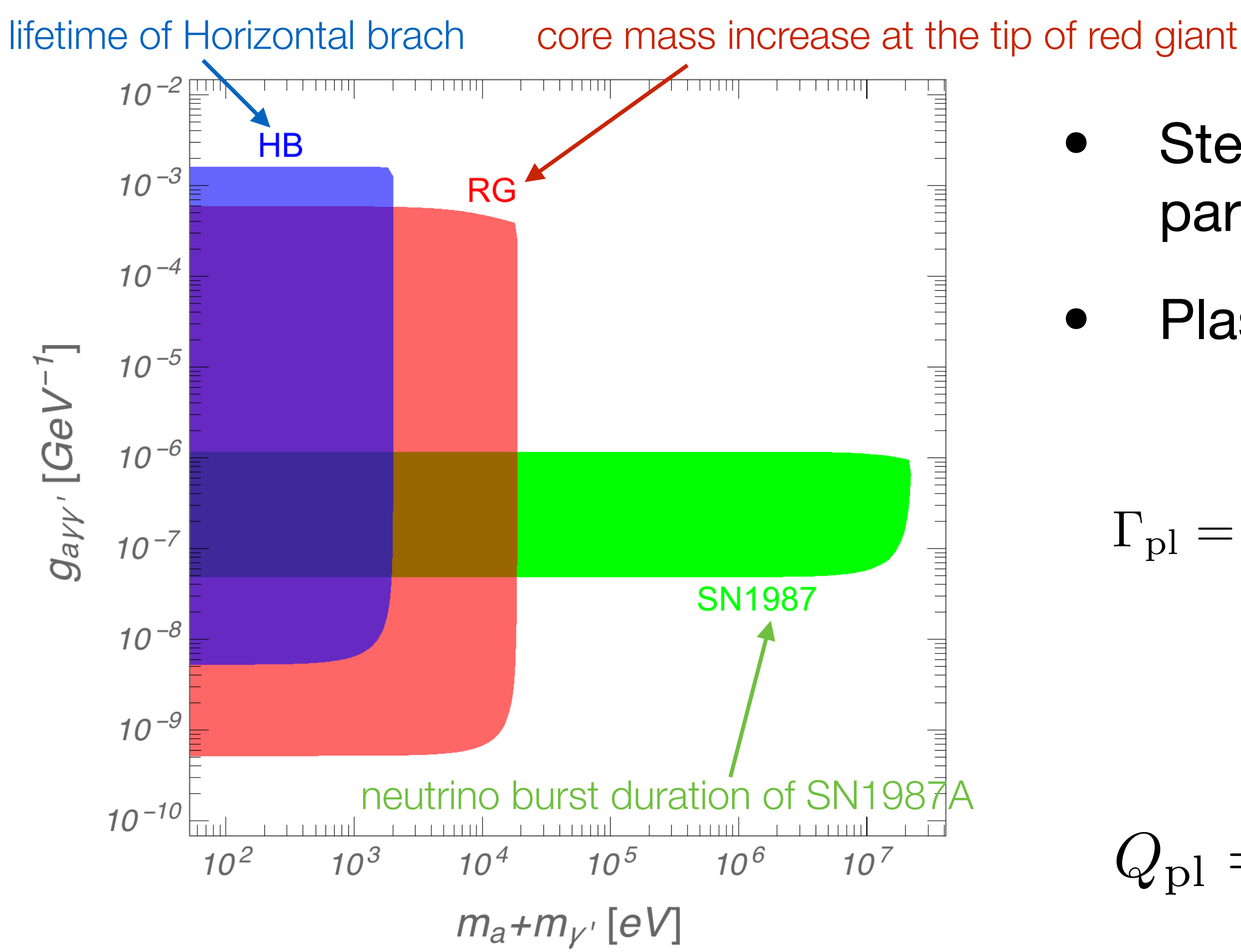
$$\omega_c = m_a^2/2g_{a\gamma\gamma'}B_{\rm eff}$$
$$B_{\rm eff} = \sqrt{B^2+B_X^2}$$

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

[H. Lee, SY, in preparation]



Stellar cooling constraints



- Stellar cooling via novel particles emission
- Plasmon decay

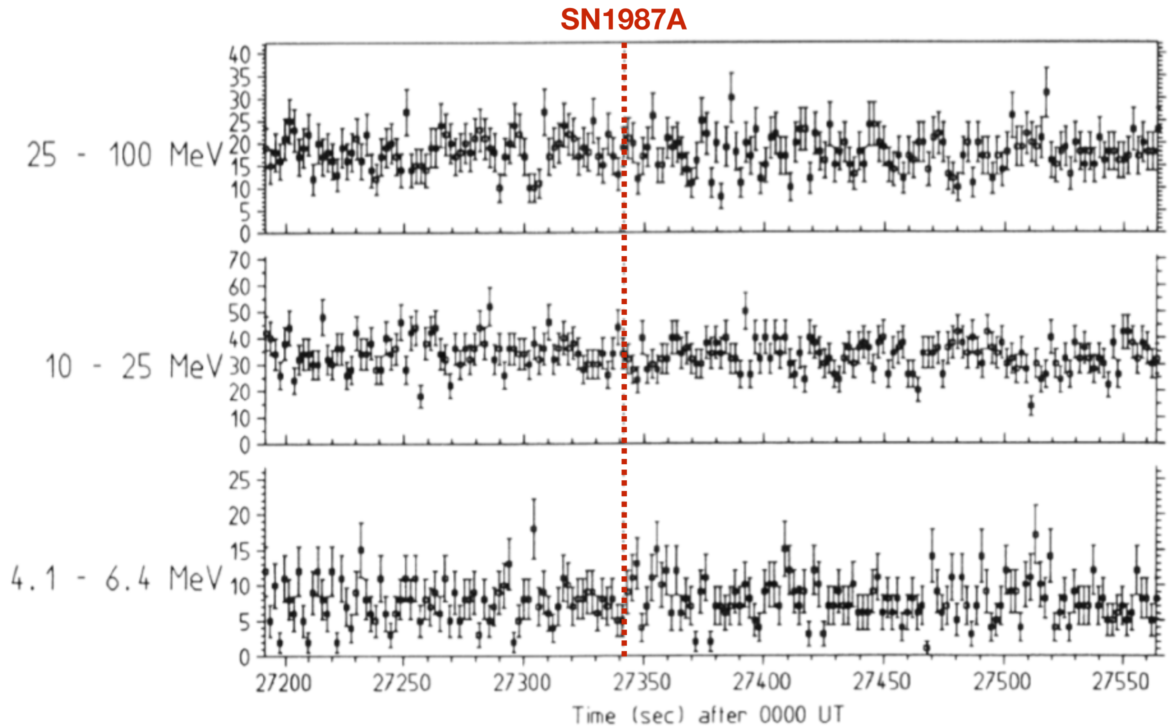
plasmon mass $\propto n_e$

$$\Gamma_{\rm pl} = \frac{g^2_{a\gamma\gamma}}{96\pi}\frac{w_{\rm pl}^4}{\omega}\left[\beta\left(1, \frac{m_a}{w_{\rm pl}}, \frac{m_a}{w_{\rm pl}}\right)\right]^{3/2}$$

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

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.



γ fluence limit for 10s

$< 0.6\,\mathrm{cm}^{-2}$

$< 0.4\,\mathrm{cm}^{-2}$

$< 0.9\,\mathrm{cm}^{-2}$

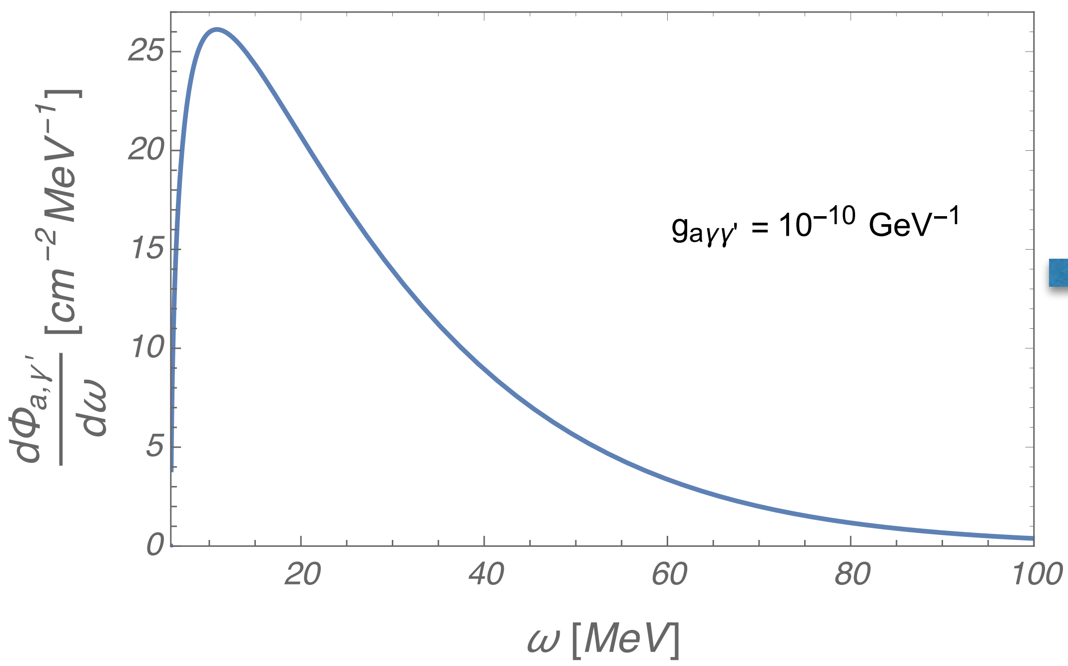
[K. Choi, S. Lee, H. Seong, SY, 18]

SN1987A gamma-ray burst bound

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

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

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



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

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

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

[K. Choi, S. Lee, H. Seong, SY, 18]

Observational constraints

SN1987A gamma-ray burst

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

$$\frac{d\Phi_\gamma}{d\omega} = P_{a\to\gamma}\frac{d\Phi_a}{d\omega} + P_{\gamma'\to\gamma}\frac{d\Phi_{\gamma'}}{d\omega}$$

- For $m_a \sim \mathcal{O}(\mathrm{neV})$ and $g_{a\gamma\gamma'} \sim \mathcal{O}(10^{-10}\mathrm{GeV}^{-1})$, small mixing regime

$$P_{a,\gamma'\to\gamma} \propto (\omega/\omega_c)^2$$

→ **Similar constraints on two different energy bin**

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 $(\gamma_{\perp}, \gamma_{\|}, a)$

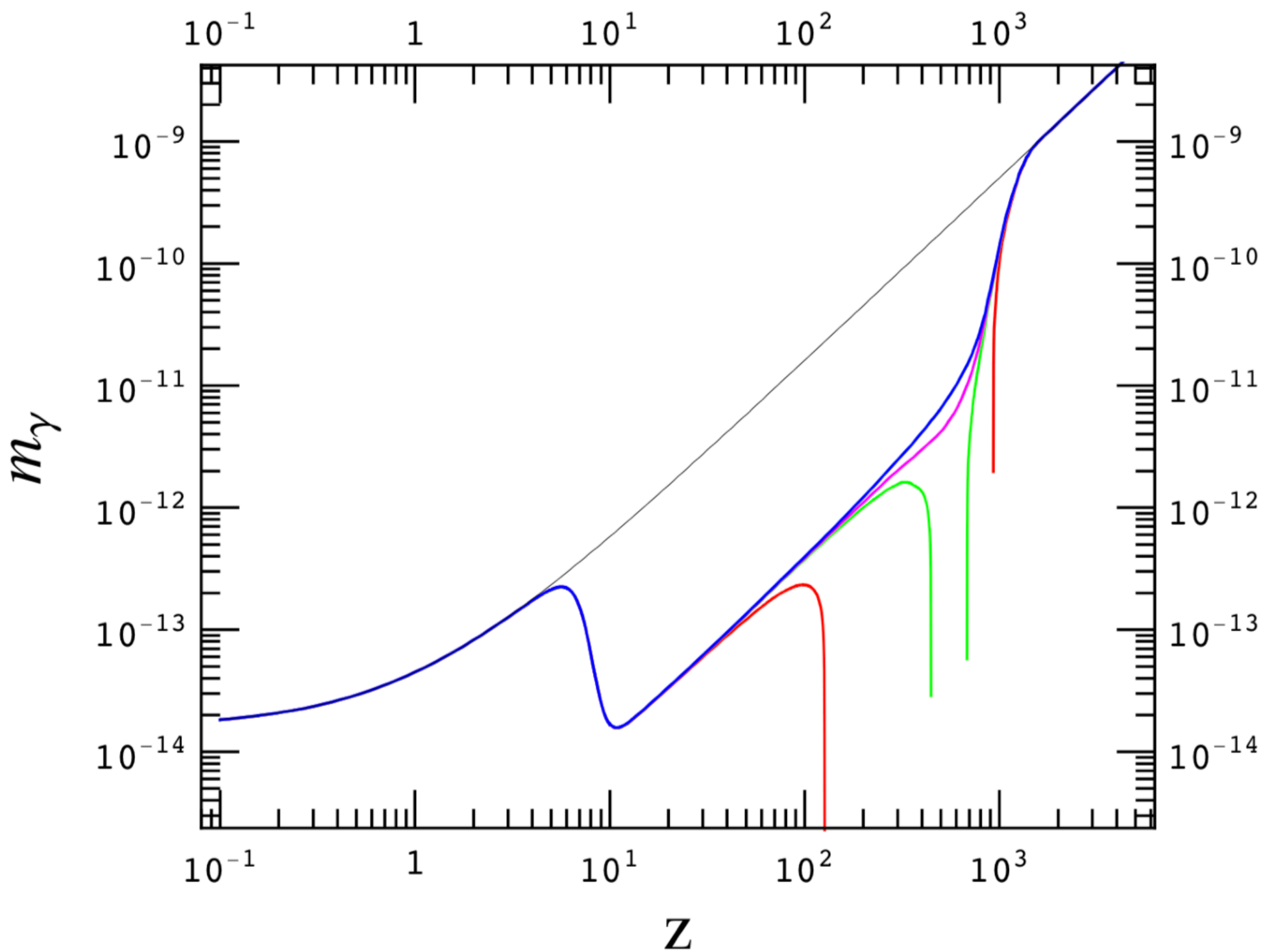
$$\begin{pmatrix} m_\gamma^2 & \frac{d\varphi}{dt}2\omega & 0 \\ \frac{d\varphi}{dt}2\omega & m_\gamma^2 & g_{\gamma\gamma}B\omega \\ 0 & g_{\gamma\gamma}B\omega & m_a^2 \end{pmatrix}$$

Time variation of photon polarization

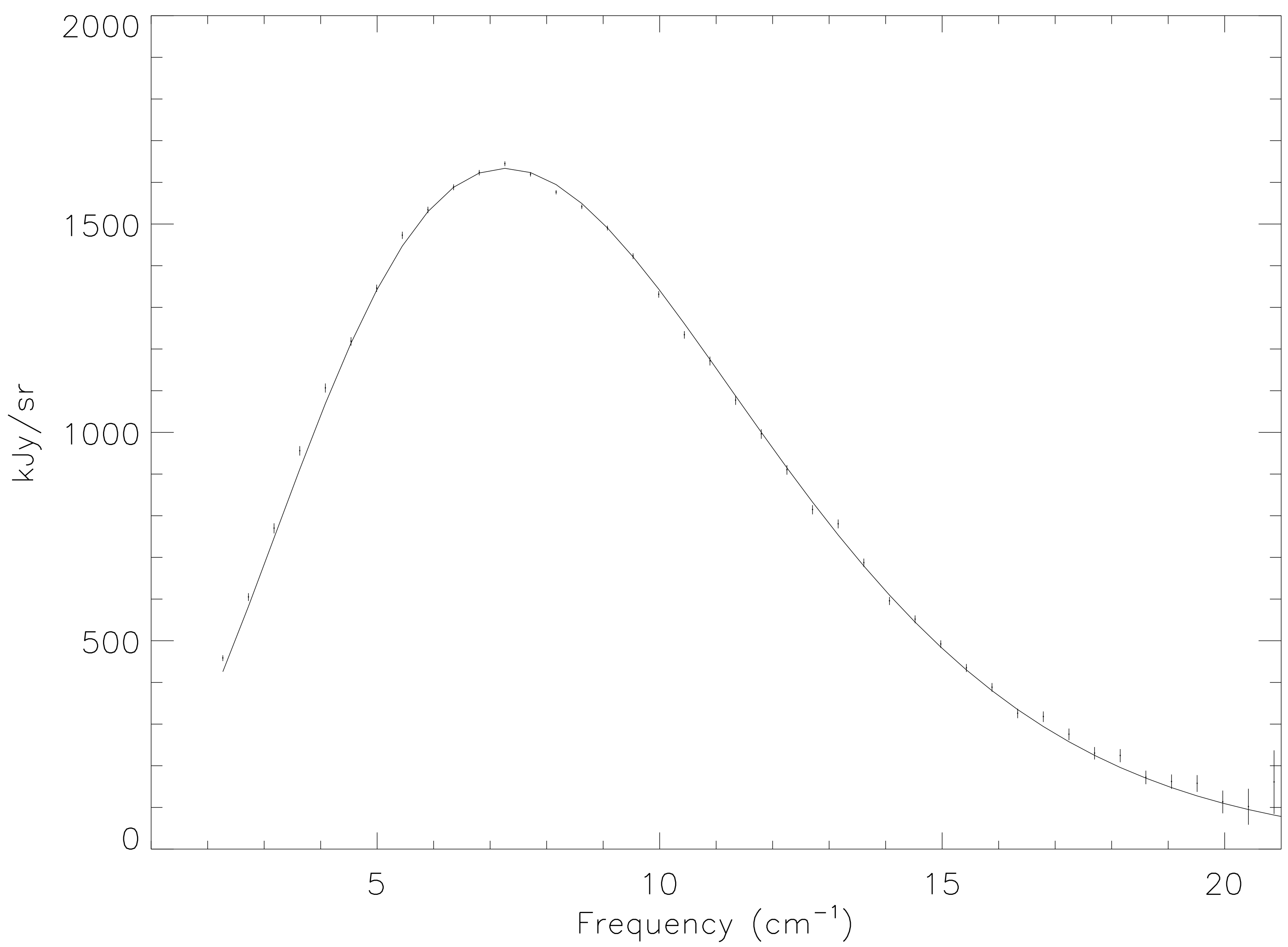
- Typically, the photon mixing effect could be negligible even though they are maximally mixed

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

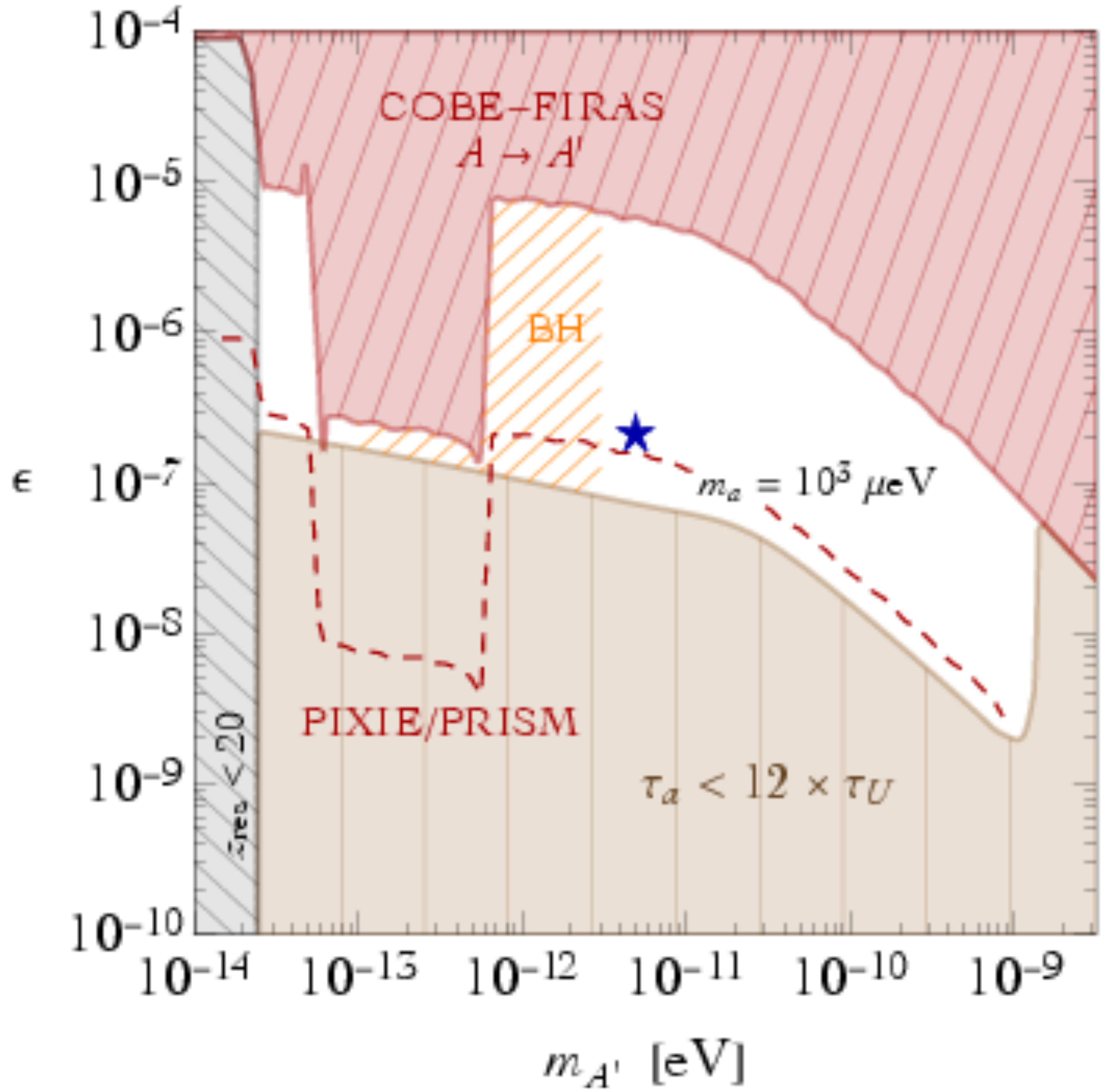
Effective photon mass profile



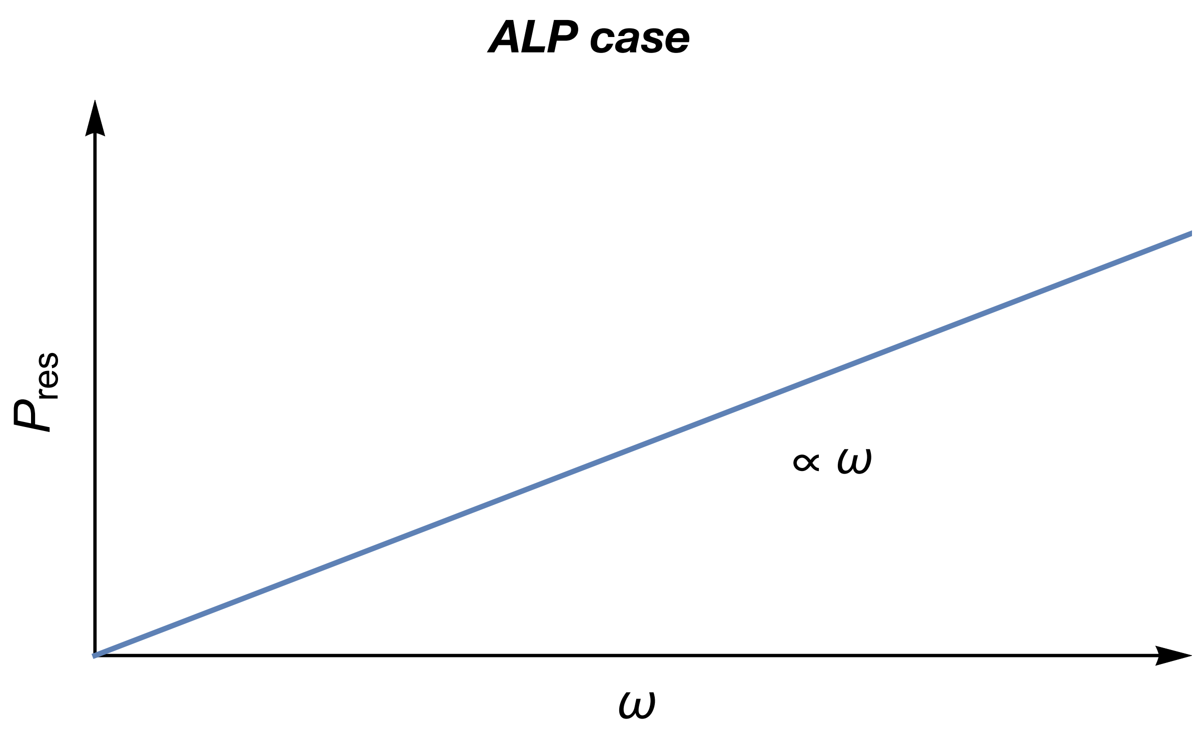
COBE-FIRAS data

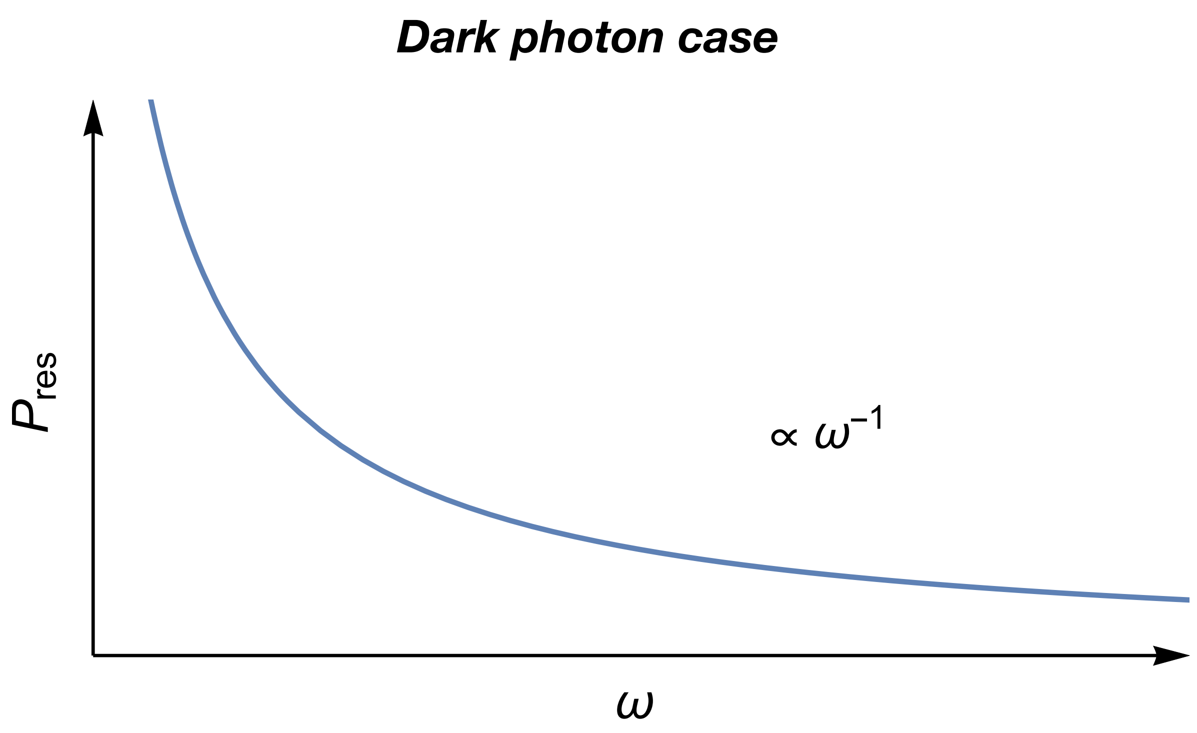


Dark photon-Photon conversion and its effect on 21cm

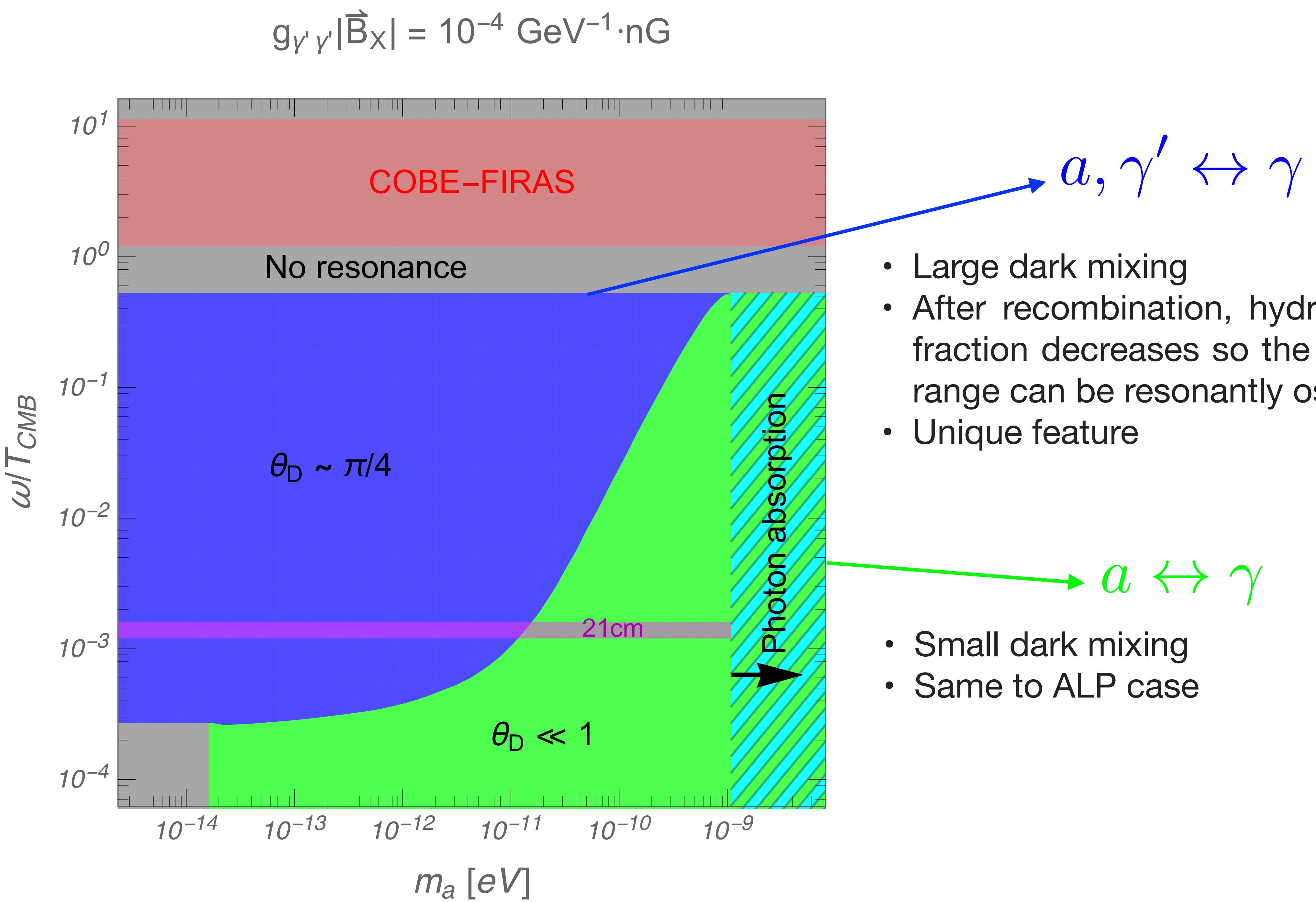


Resonant conversion probability





Large dark mixing resonance



- Large dark mixing
- After recombination, hydrogen ionization fraction decreases so the specific energy range can be resonantly oscillated
- Unique feature

- Small dark mixing
- Same to ALP case