Gamma-ray spectral modulations induced by photon-ALP-dark photon oscillations

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MultiDark Consolider Workshop, Zaragoza, Apr 03, 2019

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

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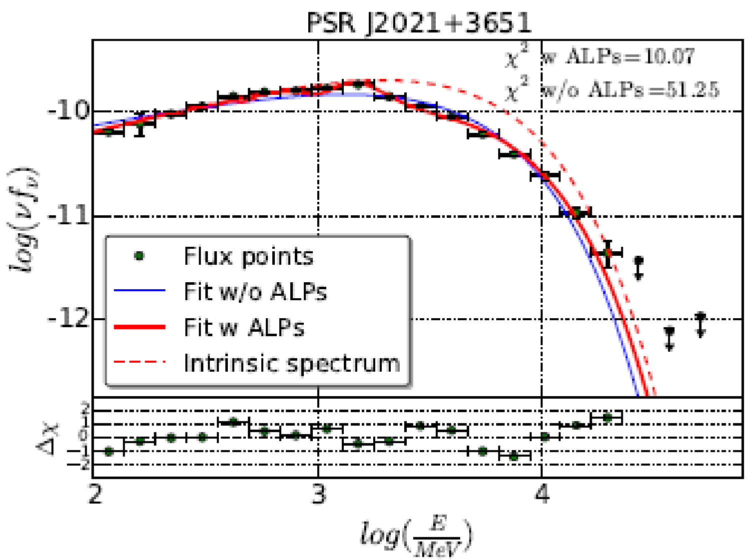
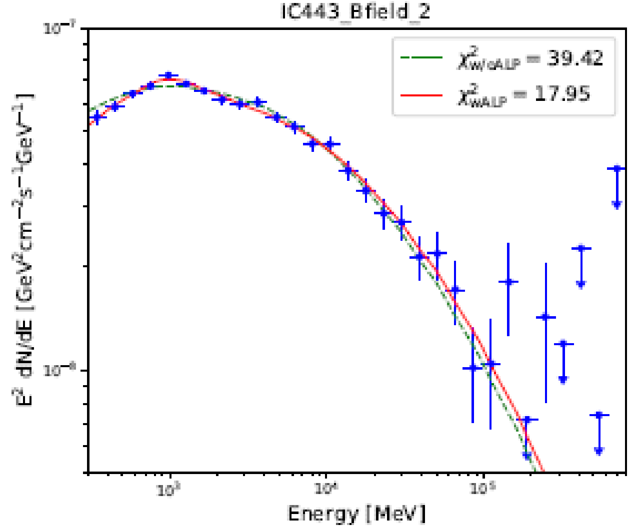
Motivation

Spectral irregularity (or modulation) of gamma-rays from certain galactic pulsars and supernova remnants:

[Majumdar et al, 1801.08813; Xia et al, 1801.01646]





According to 1801.08813 & 1801.01646, Fermi-LAT data of certain galactic pulsars and supernova remnants indicate a depletion of gamma rays at E > GeV, which might be due to the conversions of gamma rays to some invisible particles.

An explanation proposed in *1801.08813* and *1801.01646*

Assume an axion-like-particle (ALP) "a" with

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

$$\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \qquad \left(g_{a\gamma\gamma} \sim \text{few} \times 10^{-10} \text{GeV}^{-1} \right)$$

In the presence of background galactic B-fields, there can be photon-ALP oscillations caused by the ALP-photon coupling: *[Raffelt & Stodolsky '88]*

$$\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad \Rightarrow \quad g_{a\gamma\gamma} a \frac{\partial \vec{A}}{\partial t} \cdot \langle \vec{B} \rangle = g_{a\gamma\gamma} B_T \omega \times a A_{\parallel}$$

$$\left(\vec{B}_T = \langle \vec{B} \rangle - \hat{k}(\hat{k} \cdot \langle \vec{B} \rangle), \quad A_{\parallel} = \frac{\vec{B}_T \cdot \vec{A}}{B_T} \right)$$

➔ $$\left[w + i\partial_z - \frac{1}{2\omega} \mathcal{M}^2 \right] \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} = 0 \qquad \mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & g_{a\gamma\gamma'} B_T \omega \\ g_{a\gamma\gamma'} B_T \omega & m_a^2 \end{pmatrix} \left(m_\gamma^2 = \frac{e^2 n_e}{m_e} + \ldots \right)$$

For background B-field which is approximately constant over a distance "d":

$$(P_{\gamma\to a})_{g_{a\gamma\gamma}} = \left(\frac{\omega^2}{\omega^2+\tilde{\omega}_c^2}\right)\sin^2\frac{\tilde{\Delta}_{\rm osc}d}{2} \qquad \left(\tilde{\omega}_c = \frac{m_a^2}{2g_{a\gamma\gamma}B_T}, \quad \tilde{\Delta}_{\rm osc} = g_{a\gamma\gamma}B_T\sqrt{1+\left(\frac{\tilde{\omega}_c}{\omega}\right)^2}\right)$$

$$\left(m_\gamma \ll m_a, \quad \omega/\tilde{\omega}_c = \tan 2\theta\right)$$

i) the conversion of low energy photons $(\omega \ll \tilde{\omega}_c)$ to ALP is negligible.

ii) for a sizable conversion of high energy photons with $\omega \gtrsim \tilde{\omega}_c$,

we need $g_{a\gamma\gamma}B_T d \gtrsim \mathcal{O}(1)$.

Depletion of gamma-rays with E > 1 GeV at galactic distance scales:

$$\tilde{\omega}_c \sim 1\ \text{GeV}, \quad d \sim 1\,\text{kpc}, \quad B_T \sim 1\,\mu\text{G}$$

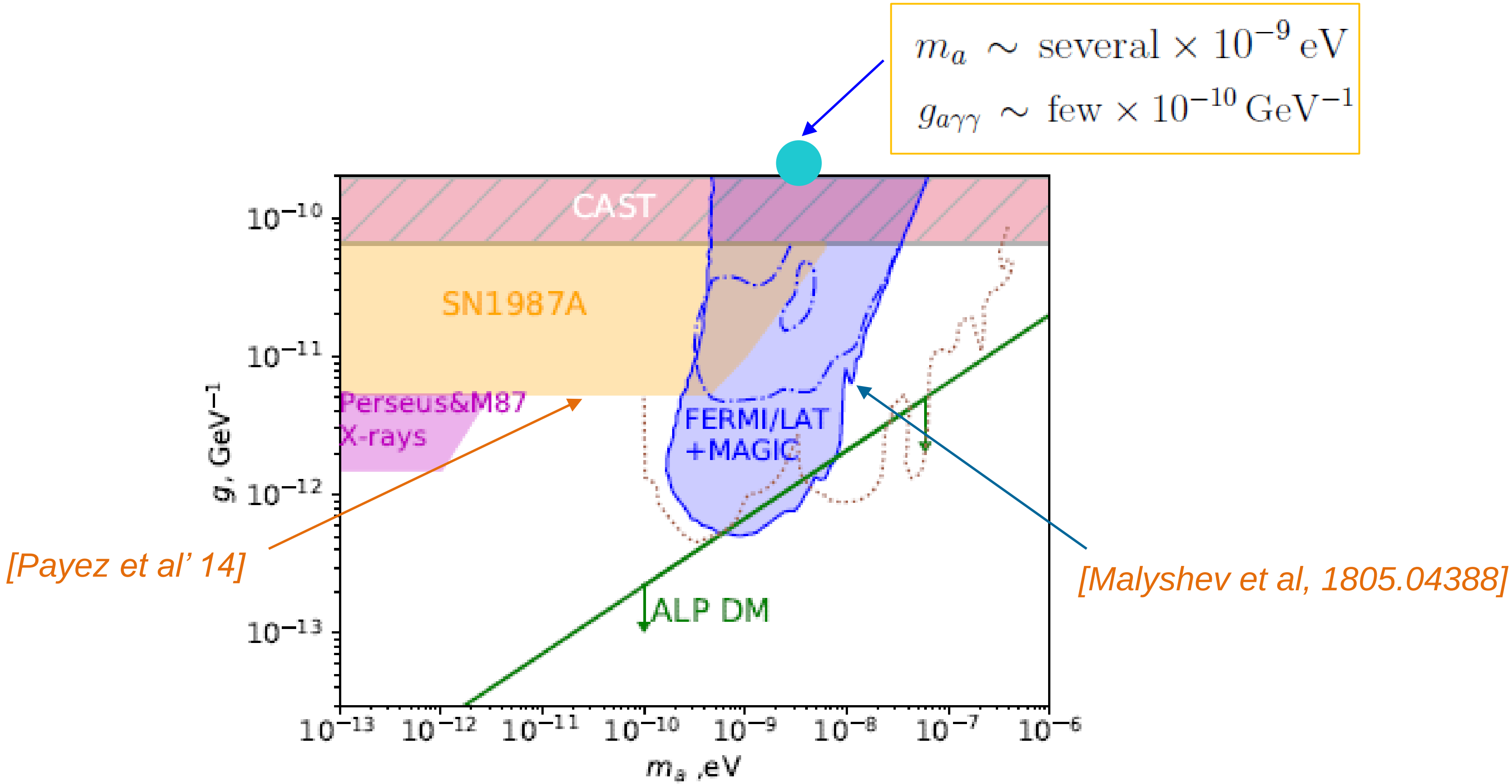
$$\Rightarrow \qquad m_a \sim \text{several} \times 10^{-9}\,\text{eV}, \quad g_{a\gamma\gamma} \sim \text{few} \times 10^{-10}\,\text{GeV}^{-1}$$

However, as noticed already in *1801.08813* and *1801.01646*, this scenario is in conflict with a variety of observational constraints, including

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

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

(c) Fermi-LAT+ MAGIC data on gamma-rays from Perseus cluster.



Alternative explanation *[KC, S. Lee, H. Seong, S. Yun, 1806.09508]*

(which can be compatible with the observational constraints)

Introduce a massless dark photon X_μ together with an ALP which couples to the ordinary photon & dark photon as

$$\frac{1}{2} g_{a\gamma\gamma'} a X_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma'} a \left(\vec{E} \cdot \vec{B}_X + \vec{B} \cdot \vec{E}_X \right)$$

Photon-ALP-dark photon oscillations induced by $g_{a\gamma\gamma'}$ in background ordinary B-fields and dark photon fields (B_X,E_X):

$$\left[w + i\partial_z - \frac{1}{2\omega} \mathcal{M}^2 \right] \begin{pmatrix} A_\parallel \\ X_\parallel \\ a \end{pmatrix} = 0 \quad \mathcal{M}^2 = \begin{pmatrix} m_\gamma^2 & 0 & g_{a\gamma\gamma'} B_{XT}\omega \\ 0 & 0 & g_{a\gamma\gamma'} B_T \omega \\ g_{a\gamma\gamma'} B_{XT}\omega & g_{a\gamma\gamma'} B_T \omega & m_a^2 \end{pmatrix} \left(m_\gamma^2 = \frac{e^2 n_e}{m_e} + ... \right)$$

$$A_\parallel = \frac{\vec{B}_{XT} \cdot \vec{A}}{B_{XT}}, \quad X_\parallel = \frac{\vec{B}_T \cdot \vec{X}}{B_T}$$

$$\begin{aligned} \vec{B}_T &= \langle \vec{B} \rangle - \hat{k}(\hat{k} \cdot \langle \vec{B} \rangle) \\ \vec{B}_{XT} &= \left(\langle \vec{B}_X \rangle - \hat{k}(\hat{k} \cdot \langle \vec{B}_X \rangle) \right) - \hat{k} \times \langle \vec{E}_X \rangle \end{aligned}$$

Conversion of photon to ALP or dark photon in **background B and (B_X,E_X)** which are approximately constant over a distance "d":

$$P_{\gamma\to a} = P_{a\to\gamma} = \left(\frac{B_{XT}^2}{B_{XT}^2 + B_T^2}\right)\left(\frac{\omega^2}{\omega^2+\omega_c^2}\right)\sin^2\frac{\Delta_{\rm osc} d}{2},$$

$$P_{\gamma\to\gamma'} = P_{\gamma'\to\gamma} = \frac{2B_{XT}^2 B_T^2}{(B_{XT}^2+B_T^2)^2}\left(1-\cos\frac{\Delta_a d}{2}\cos\frac{\Delta_{\rm osc} d}{2}\right.$$
$$\left. -\frac{\omega_c}{\sqrt{\omega^2+\omega_c^2}}\sin\frac{\Delta_a d}{2}\sin\frac{\Delta_{\rm osc} d}{2} - \frac{\omega^2}{2(\omega^2+\omega_c^2)}\sin^2\frac{\Delta_{\rm osc} d}{2}\right)$$

$$\omega_c = \frac{m_a^2}{2g_{a\gamma\gamma'}B_{\rm eff}}, \quad \Delta_a = \frac{m_a^2}{2\omega}, \quad \Delta_{\rm osc} = \frac{g_{a\gamma\gamma'}B_{\rm eff}\sqrt{\omega^2+\omega_c^2}}{\omega}$$

$$B_{\rm eff} \equiv \sqrt{B_{XT}^2 + B_T^2} \qquad \begin{aligned}\vec{B}_T &= \langle\vec{B}\rangle - \hat{k}(\hat{k}\cdot\langle\vec{B}\rangle)\\ \vec{B}_{XT} &= \left(\langle\vec{B}_X\rangle - \hat{k}(\hat{k}\cdot\langle\vec{B}_X\rangle\right) - \hat{k}\times\langle\vec{E}_X\rangle\end{aligned}$$

Sizable depletion of gamma-rays with E > 1 GeV at galactic distance scales:

$$B_{XT} \gtrsim \frac{1}{2}B_X \sim 0.5\,\mu{\rm G}, \quad \omega_c \sim \frac{m_a^2}{g_{a\gamma\gamma'}B_{XT}} \sim 1\,{\rm GeV}, \quad g_{a\gamma\gamma'}B_{XT} \gtrsim 1\,{\rm kpc}^{-1}$$

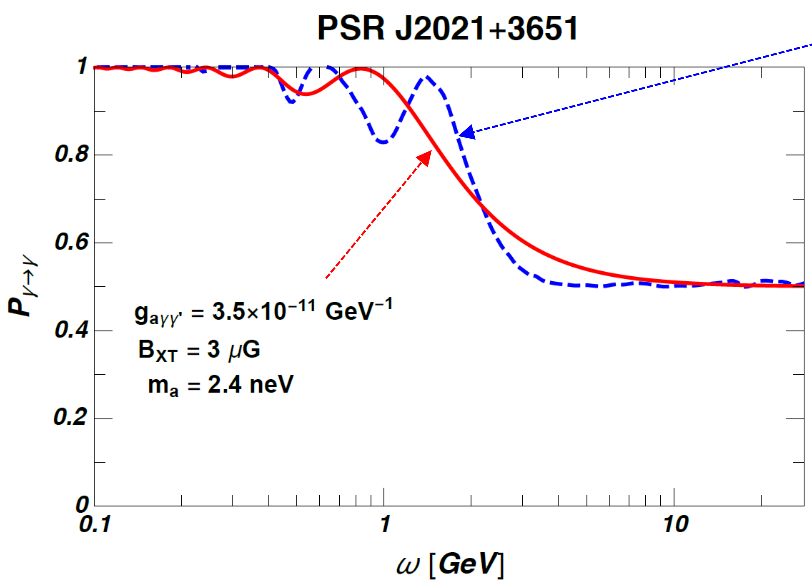
For instance,

$$B_{XT} \sim 0.5 - 5\ \mu\mathrm{G}, \quad m_a \sim \mathrm{several}\times 10^{-9}\,\mathrm{eV}, \quad g_{a\gamma\gamma'} \sim \mathrm{few}\times(10^{-11}-10^{-10})\,\mathrm{GeV}^{-1}$$

can result in the desired form of spectral modulations of galactic pulsars and supernova remnants, while being compatible with the observational constraints:

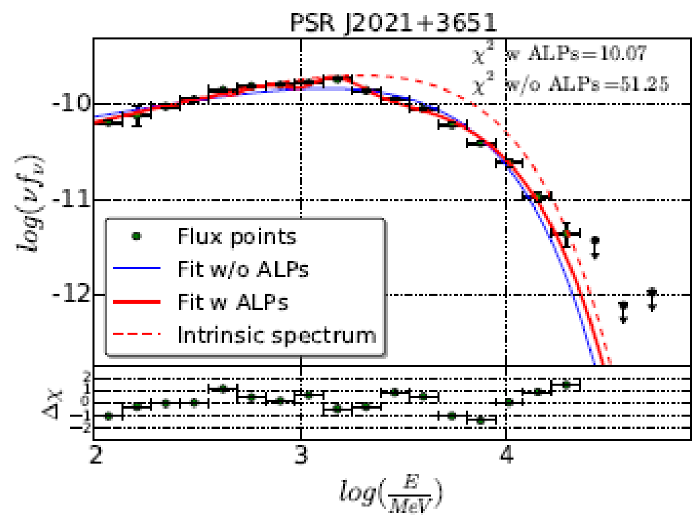
[KC, S. Lee, H. Seong, S. Yun, 1806.09508]

Photon survival probability for PSR J2021+3651



ALP coupling suggested in 1801.08813 to explain the pulsar data:

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



Two key questions

i) Is this scenario compatible with the known observational constraints?

ii) How to generate the necessary background dark photon gauge fields **(B_X, E_X)** in the early Universe?

Observational constraints on $\frac{1}{2} g_{a\gamma\gamma'} a X_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma'} a \left(\vec{E} \cdot \vec{B}_X + \vec{B} \cdot \vec{E}_X \right)$

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

i) Bound from CAST or similar axion search experiments?

No constraint as there is no $a \to \gamma$ induced by background $\langle B \rangle$

ii) Stellar emission of ALP or dark photon:

Plasmon decays: $\gamma(\text{plasmon}) \to a + \gamma'(\text{dark photon})$

$$\Rightarrow \quad g_{a\gamma\gamma'} \lesssim 5 \times 10^{-10}\ \text{GeV}^{-1} \quad \text{for} \quad m_a, m_X \lesssim 10\,\text{keV}$$

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

$$a \text{ or } \gamma' \text{ emitted from SN1987A} \quad \to \quad \gamma \quad (\text{in background } \langle B_X \rangle \text{ and/or } \langle E_X \rangle)$$

iv) CMB distortion due to $\text{CMB } \gamma \quad \to \quad a \text{ or } \gamma'$

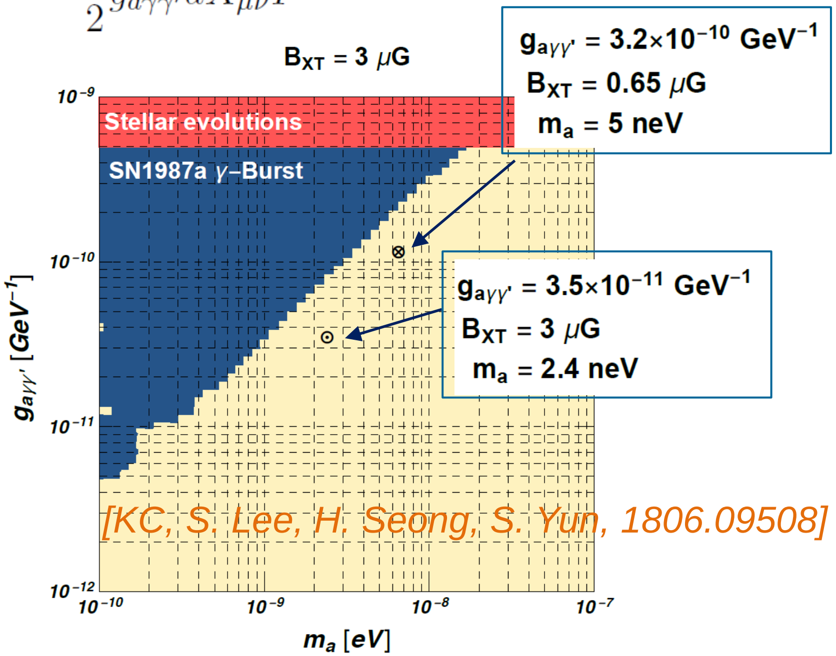
$(\text{in background } \langle B_X \rangle \text{ and/or } \langle E_X \rangle)$

v) Spectral irregularity of other gamma-ray sources, e.g. NGC 1275 in the Perseus cluster

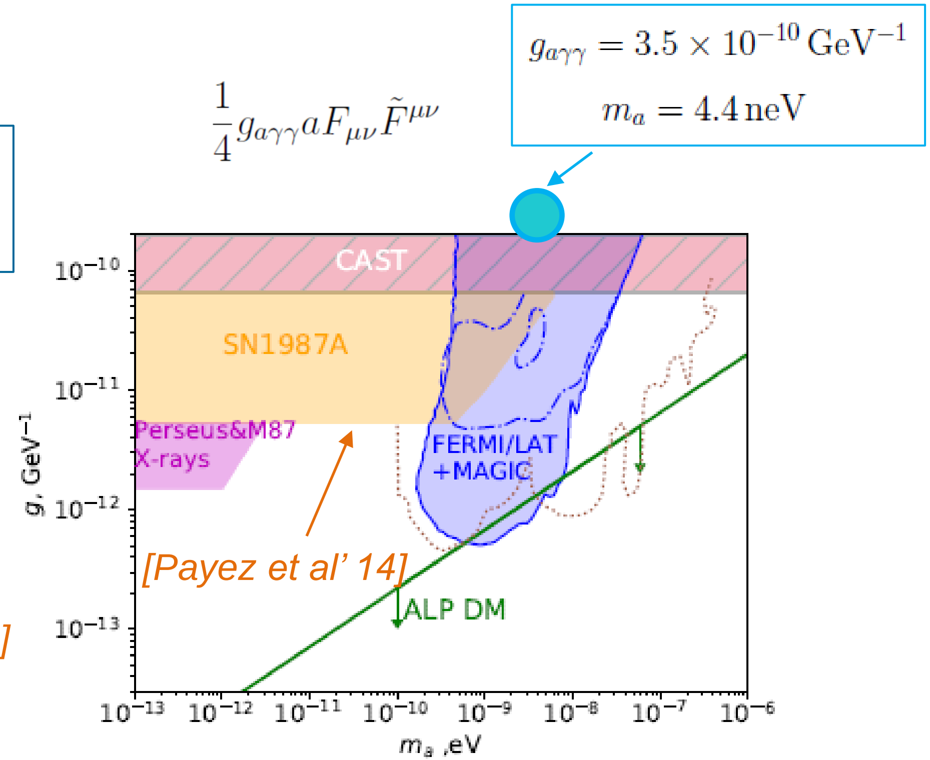
Absence of gamma-ray bursts associated with SN1987A

ALPs or dark photons emitted from SN1987A by plasmon decays and subsequent conversion to gamma-rays by background B_X/E_X

$$\frac{1}{2} g_{a\gamma\gamma'} a X_{\mu\nu} \tilde{F}^{\mu\nu}$$



$$\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

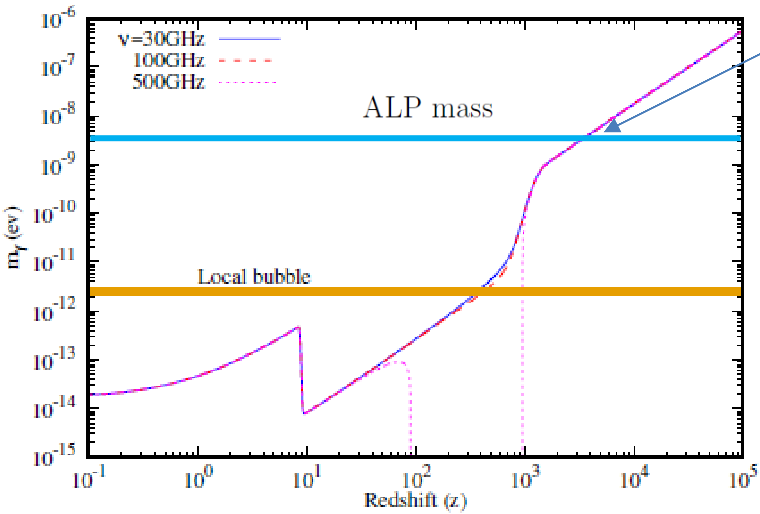


Compared to $g_{a\gamma\gamma}$, the bound on $g_{a\gamma\gamma'}$ is weaker as it is less efficient (plasmon decay vs Primakov process) in producing ALP from SN1987A.

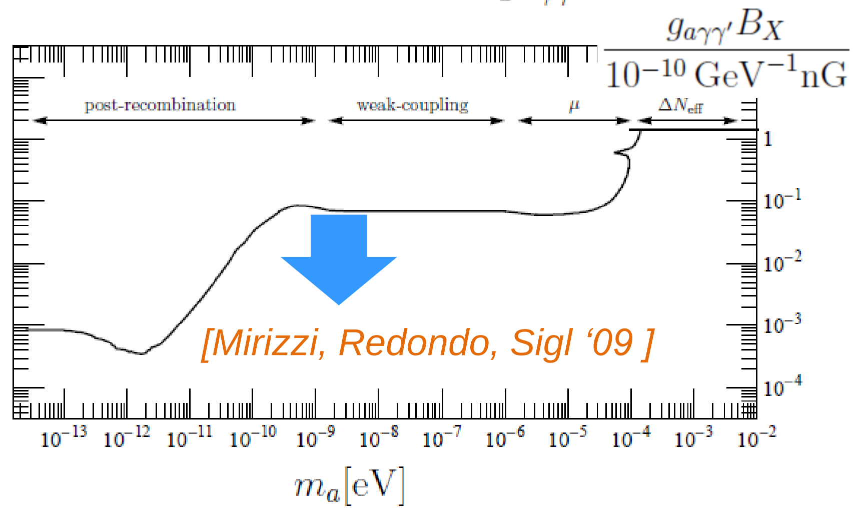
Absence of CMB distortion

Reasonant conversion of CMB photon to ALP at level crossing ($z \sim 3 \times 10^3$) by $g_{a\gamma\gamma'}\langle B_X \rangle$ if B_X were produced at earlier time

Effective photon mass in the early Universe



Resulting upper bound on $g_{a\gamma\gamma'} B_X$



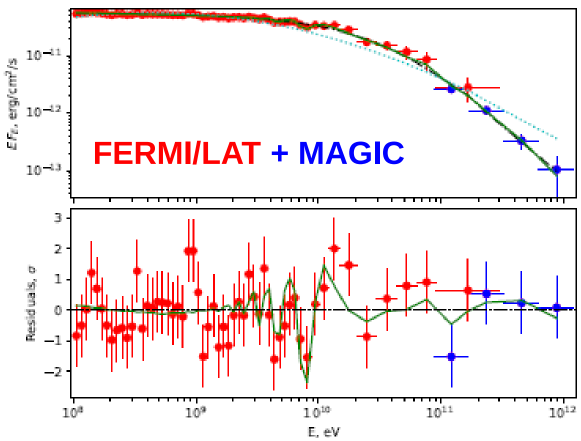
➔ $g_{a\gamma\gamma'}\langle B_X \rangle < 10^{-11}\,\mathrm{GeV}^{-1} \cdot \mathrm{nG}$ if B_X were generated at $z > 3000$

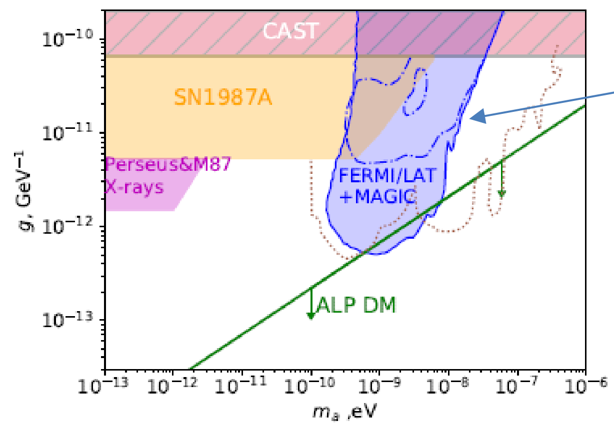
On the other hand, we need $g_{a\gamma\gamma'}\langle B_X \rangle \sim 10^{-7}\mathrm{GeV}^{-1} \cdot \mathrm{nG}$ to explain the gamma-ray modulations, so should avoid this bound.

➔ Generate B_X at z < 3000.

Spectral irregularity of gamma-rays from NGC 1275 in Perseus cluster?

Using the known features of B fields inside the Perseus cluster, one can study the spectral irregularities caused by $\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$ and found the FERMI/LAT data disfavors certain region of ALP parameters:





Disfavored by FERMI/LAT & MAGIC data

[Malyshev et al, 1805.04388]

One may try to constrain $\frac{1}{2} g_{a\gamma\gamma'} a X_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma'} a \left(\vec{E} \cdot \vec{B}_X + \vec{B} \cdot \vec{E}_X \right)$ also, but the corresponding spectral irregularity severely depends on the detailed profile of **(B_X, E_X) and B** along the line of sight between the Perseus cluster and the earth (d ~ 68 Mpc), about which we don't have any information.

How to generate the background dark photon fields?

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

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

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

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

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

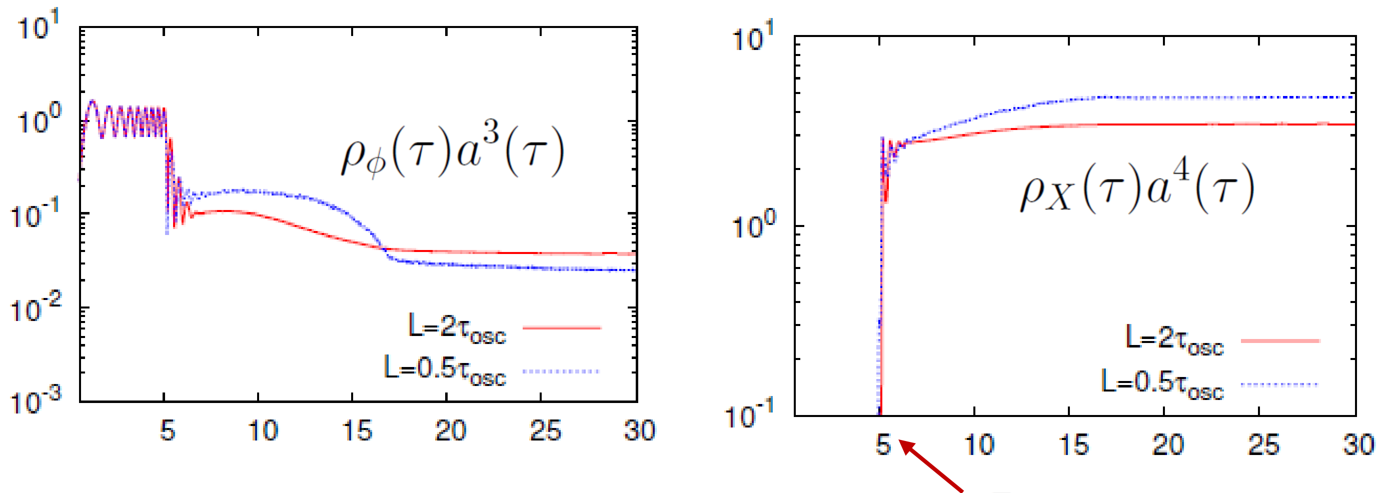
Tachyonic instability of X caused by oscillating ϕ, resulting in exponential amplification of the vacuum fluctuations of X until τ_{prod} when X is amplified enough:

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

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

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

[KC, H. Kim, T. Sekiguchi, 1802.07269]



$\tau_{\rm prod}$

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

$$B_X \sim E_X \sim 0.3\,\mu{\rm G}\left(\frac{f}{10^{17}\,{\rm GeV}}\right) \ \text{ produced at } \ z_{\rm prod} \equiv \frac{a(\tau_0)}{a(\tau_{\rm prod})} \sim 300\left(\frac{m_\phi}{10^{-28}\,{\rm eV}}\right)^{1/2}$$

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

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

[Hlozek, Marsh, Grin, 1708.05681]

Conclusion

- Recently noticed gamma-ray spectral modulations of certain galactic pulsars and supernova remnants might be explained by the photon-ALP-dark photon oscillations induced by the ALP coupling $\frac{1}{2} g_{a\gamma\gamma'} a X_{\mu\nu} \tilde{F}^{\mu\nu}$ in background dark photon gauge fields, while being compatible with the known observational constraints:

$$B_{XT} \sim 0.5 - 5\ \mu\text{G}, \quad m_a \sim \text{several} \times 10^{-9}\,\text{eV}, \quad g_{a\gamma\gamma'} \sim \text{few} \times (10^{-11} - 10^{-10})\,\text{GeV}^{-1}$$

- The required background dark photon gauge fields can be produced by another ultra-light ALP ϕ with $m_\phi \lesssim 10^{-26}\,\text{eV}$, whose late oscillations cause a tachyonic instability of X, exponentially amplifying the vacuum fluctuations of X-fields at a time late enough to avoid the CMB distortion by $g_{a\gamma\gamma'}$.