# Implication of axion like particle by GRB observation and its search with eDANCE

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Ando Group Seminar 2024/6/7

# Abstract

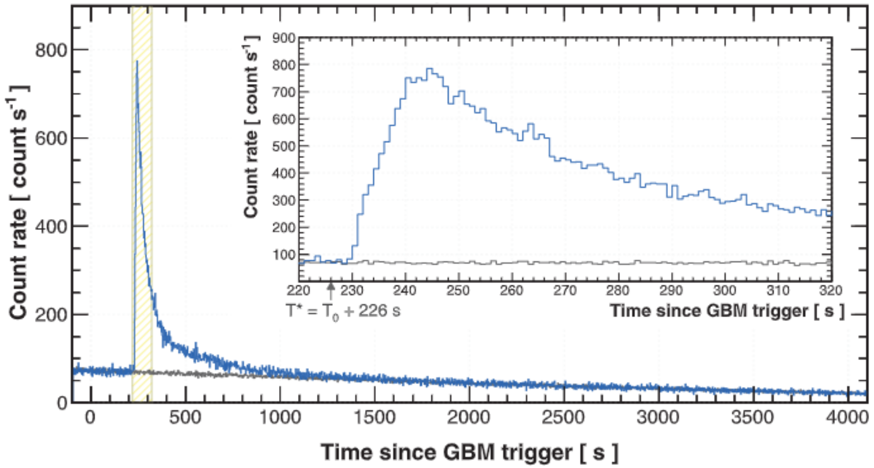
- Introducing a paper "Observability of the Very-High-Energy Emission from GRB 221009A" published by PRL 131, 251001 (2023)
  - Huge gamma-ray burst (GRB) with its energy extending up to 18 TeV
  - Very unlikely due to the extragalactic background light

  - This high energy photon can be explained by the existence of axion-like particle (ALP)
  - Proposed mass $m_a = 10^{-11}$-$10^{-7}$ eV and coupling $g_{a\gamma\gamma} = (3\text{-}5) \times 10^{-12}$ GeV$^{-1}$

- Proposing extended DANCE to search for this parameter space

# High energy gamma-ray

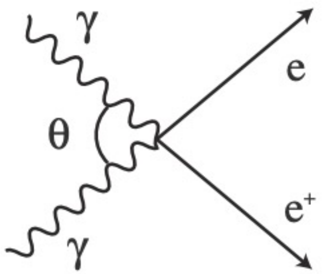
- GRB 221009A at z = 0.151: 18 TeV
  - Brightest GRB ever
    v.s. CRB190829A at z = 0.079 with 3 TeV
  - Detection of highest photon energy reaching 18 TeV by LHASSO collaboration
  - Potential detection of even 251 TeV photon by Carpet-2 collaboration




LHASSO collaboration,
Science 380, 1390 (2023)

- Almost impossible observation
  - Large optical depth due to the extragalactic background light (EBL)
  - $\gamma\gamma \rightarrow e^+e^-$ (electron positron pair production) in the EBL
  - Expecting the possibility of ALPs

Gamma-ray




Background photon

# Cosmic photon extinction

- Cosmic photon extinction

Astropart. Phys. 43, 112 (2023)

  - A gamma-ray photon above certain threshold interacts with a background photon and produces an electron pair
  - The cross-section depends on the energy of the photons

$$\epsilon_{th}(E_\gamma, \mu, z) = \frac{2\,(m_e c^2)^2}{E_\gamma\,(1-\mu)}$$

$$\sigma_{\gamma\gamma}(E_\gamma, \epsilon, \mu, z) = \frac{3\sigma_T}{16}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta)}{(1-\beta)}\right)\right]$$

$$\beta \equiv \sqrt{\left(1-\frac{\epsilon_{th}}{\epsilon}\right)}$$

  - Cross section peak at β = 0.70

$$E_\gamma(TeV) = \frac{1.07}{\epsilon(eV)\,(1-\mu)} = \frac{0.86\,\lambda(\mu m)}{(1-\mu)}$$

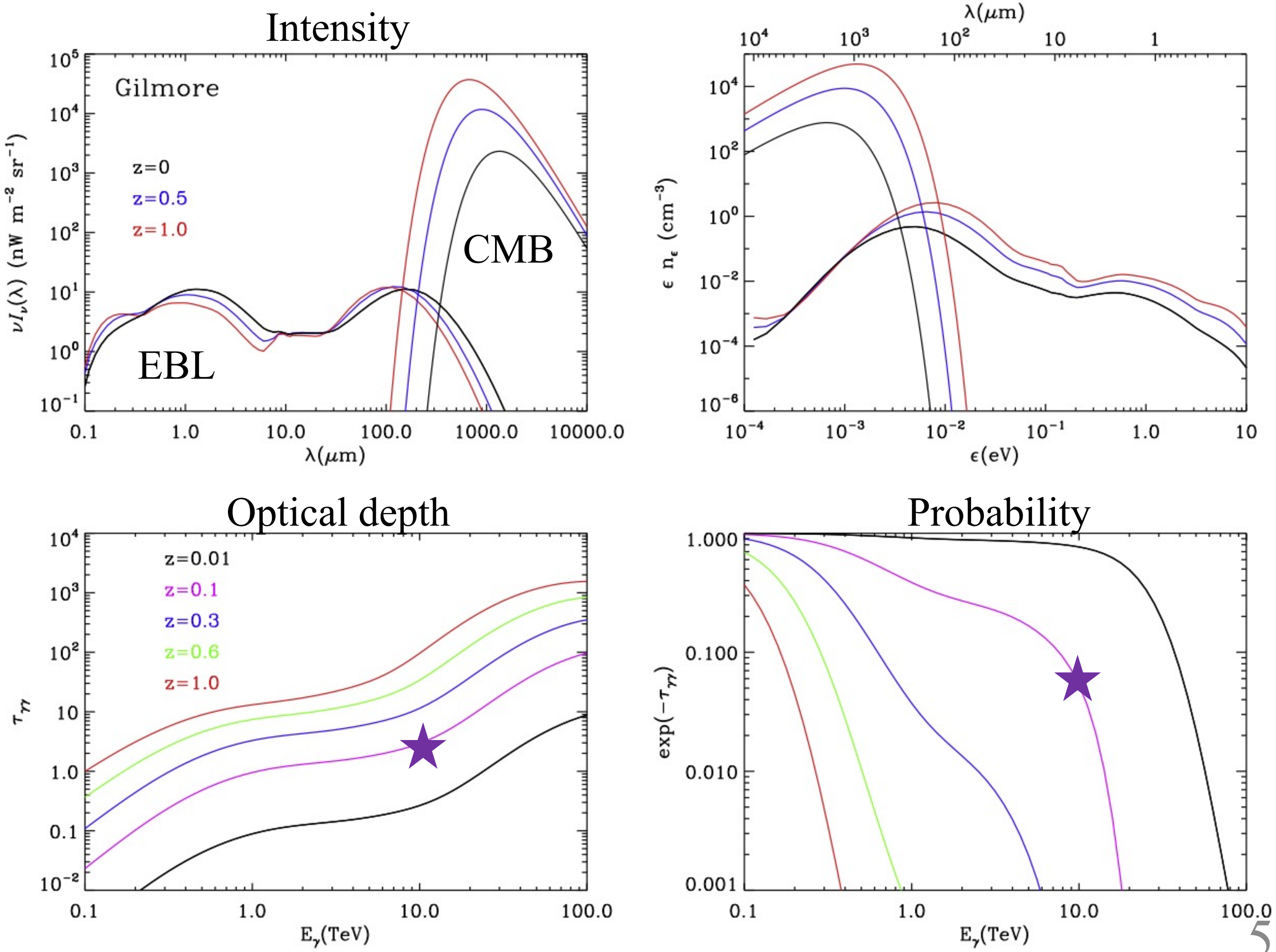
- The photon survival probability at the energy of Ɛ

$$P_{CP}(\mathcal{E}; \gamma \to \gamma) = e^{-\tau(\mathcal{E})}$$

$$\tau_{\gamma\gamma}(E_\gamma, z) = \int_0^z dz' \frac{d\ell}{dz'} \int_{-1}^{1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{th}}^{\infty} d\epsilon\, n_\epsilon(\epsilon, z')(1+z')^3 \sigma_{\gamma\gamma}(\beta', z')$$

# Survival probability

- ➢Intensity spectrum from the EBL
- ➢Energy dependence of the optical depth
  - $\tau > 1$ at 10 TeV from $z = 0.1$
- ➢Survival probability
  - $P < 0.1$ at 10 TeV from $z = 0.1$



# Survival probability

➢10 TeV < $\mathcal{E}$ < 20 TeV and 0.1 < z < 0.2 are very critical region

| $\mathcal{E}$ | 10 TeV | 15 TeV | 18 TeV | 100 TeV | 251 TeV |
|---|---|---|---|---|---|
| z | 0.1 | 0.151 | | | |
| $P_{CP}(z, \mathcal{E})$ | ~ 0.1 | $3\times10^{-6}$ | $1\times10^{-8}$ | $3\times10^{-96}$ | ~ 0 |

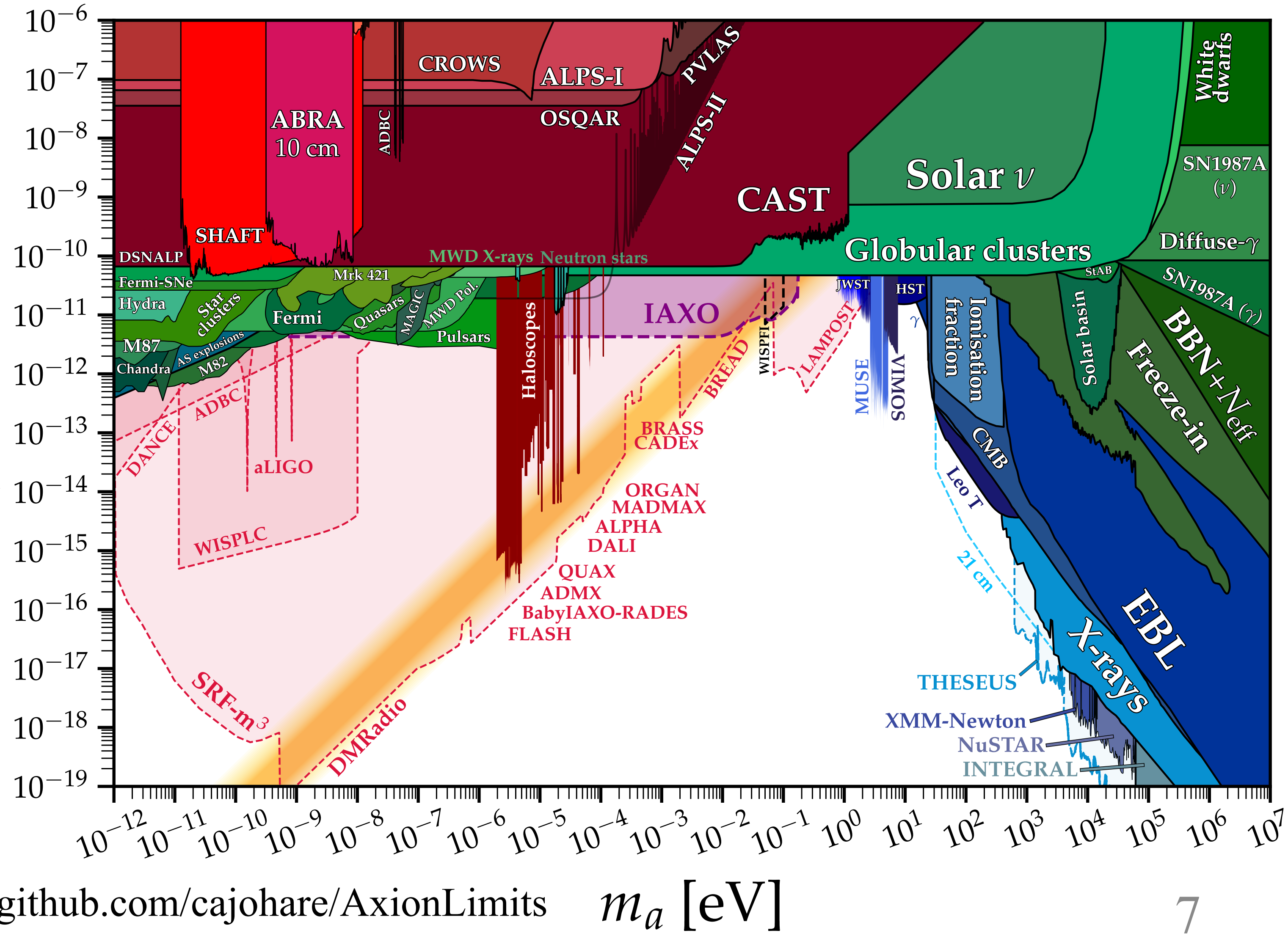
➢Observed 18 TeV gamma-ray cannot be explained by the conventional model of the EBL

➢Conversion to the axion can avoid the interaction with the EBL

# Axion-like particle (ALP)

- Predicted by many extensions of the standard model

- The mass-coupling parameters constrained by various experiments (from table-top scale to astrophysical one)




https://github.com/cajohare/AxionLimits

# ALP-photon conversion

- Described by the Lagrangian:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a, \qquad (1)$$

Two-photon coupling    Electromagnetic tensor    ALP field

- An external magnetic field causes $\gamma \leftrightarrow a$ conversions or oscillations

- Other effects
  - QED vacuum polarization
  - Photon dispersion on the CMB

# ALP-photon conversion

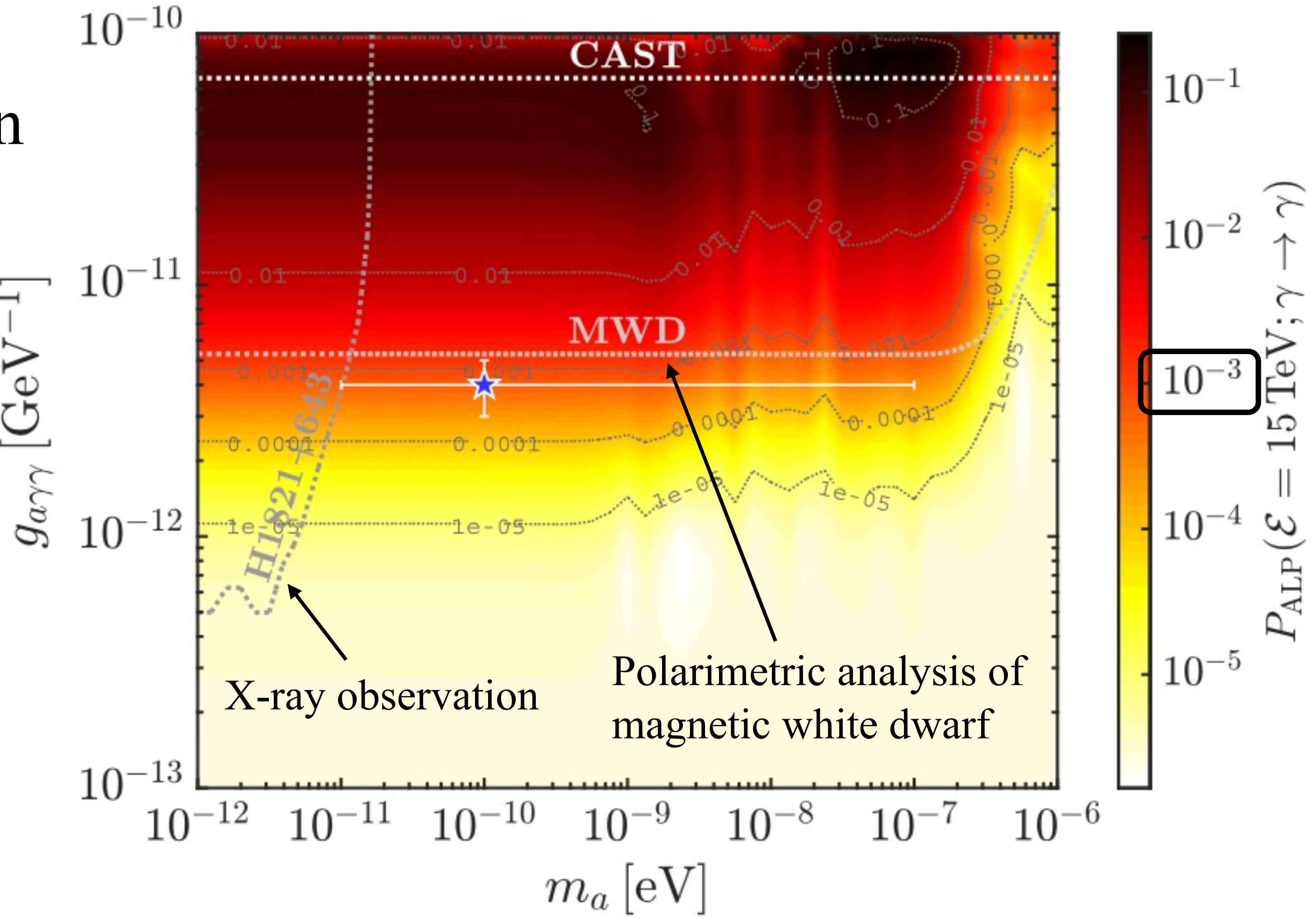
- Discussion on where the conversion takes place
  - Inside the source
    Large electron density and large magnetic field strength, but negligible
  - Inside the host galaxy
    Typical magnetic strength of O(10) uG in the spiral or starburst galaxy
  - In extragalactic space
    Very uncertain but assuming $10^{-7}$ nG < $B_{ext}$ < 1.7 nG, in either case not so critical
  - In the Milky Way
    Well known magnetic field

# Proposed ALP parameters

- Contour plot of the survival probability of 15 TeV photon

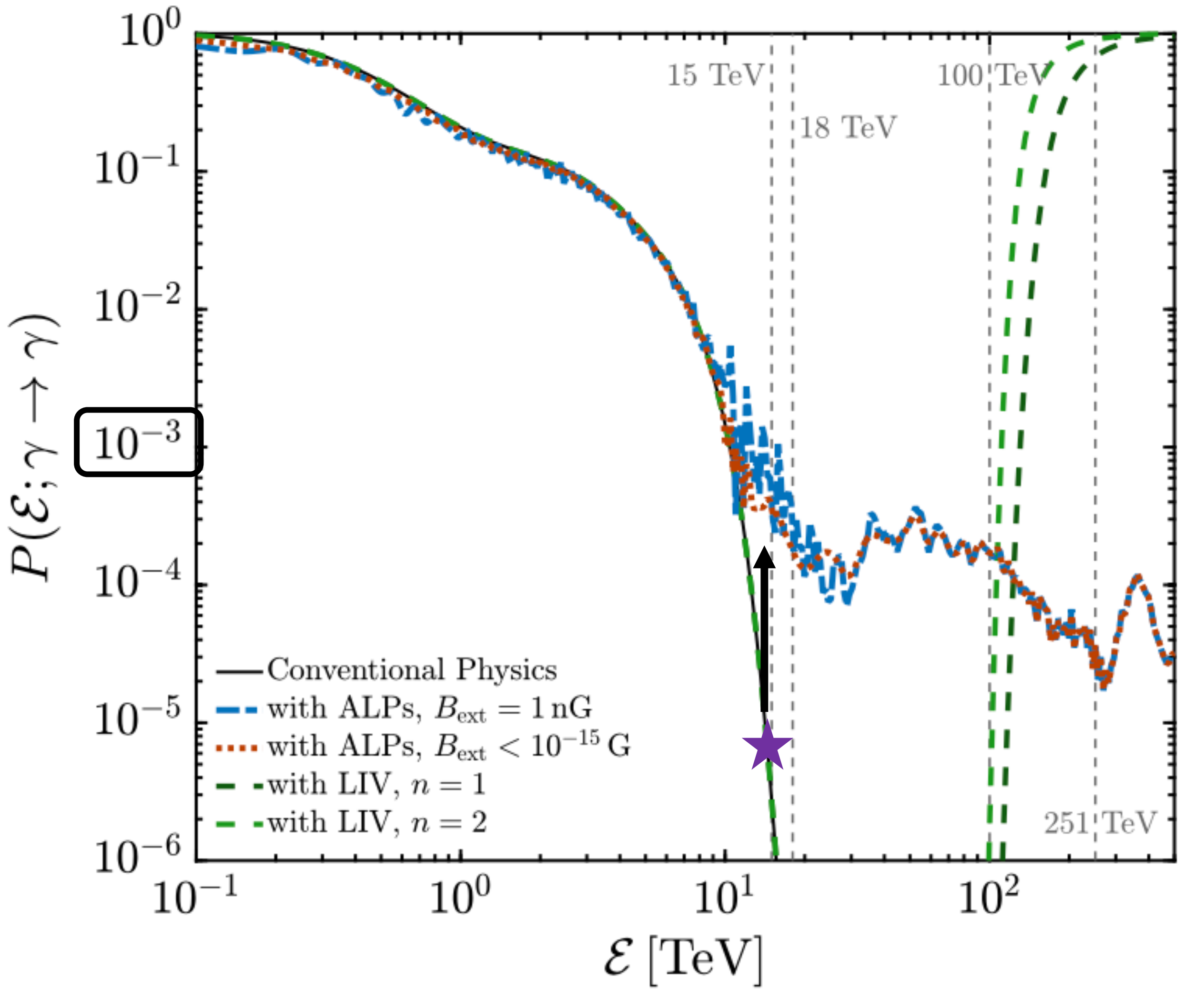
- Proposed ALP parameters
  - $m_a \sim (10^{-11} - 10^{-7})$ eV
  - $g_{a\gamma\gamma} \sim (3 - 5) \times 10^{-12}$ GeV$^{-1}$

- The same parameters also suggested by MWD and another gamma-ray observation



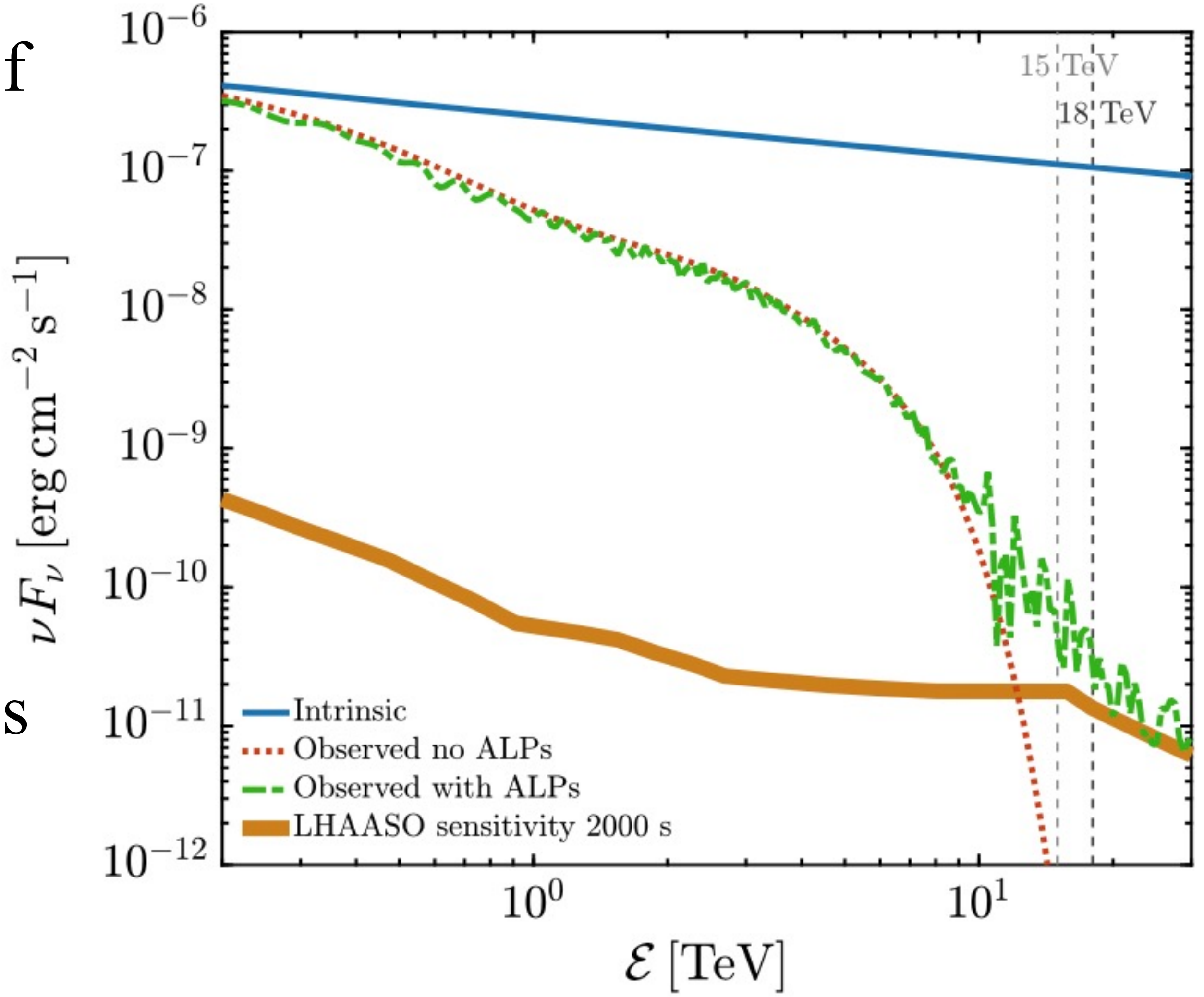
# Survival probability

- ➢Survival probability of 15 TeV photon ~ 1e-3 with the proposed ALP
- ➢Independent from the uncertain extragalactic magnetic field $B_{ext} < 10^{-6}$ nG or $B_{ext} = 1$ nG
- ➢Lorentz invariance violation cannot explain the 18 TeV photon



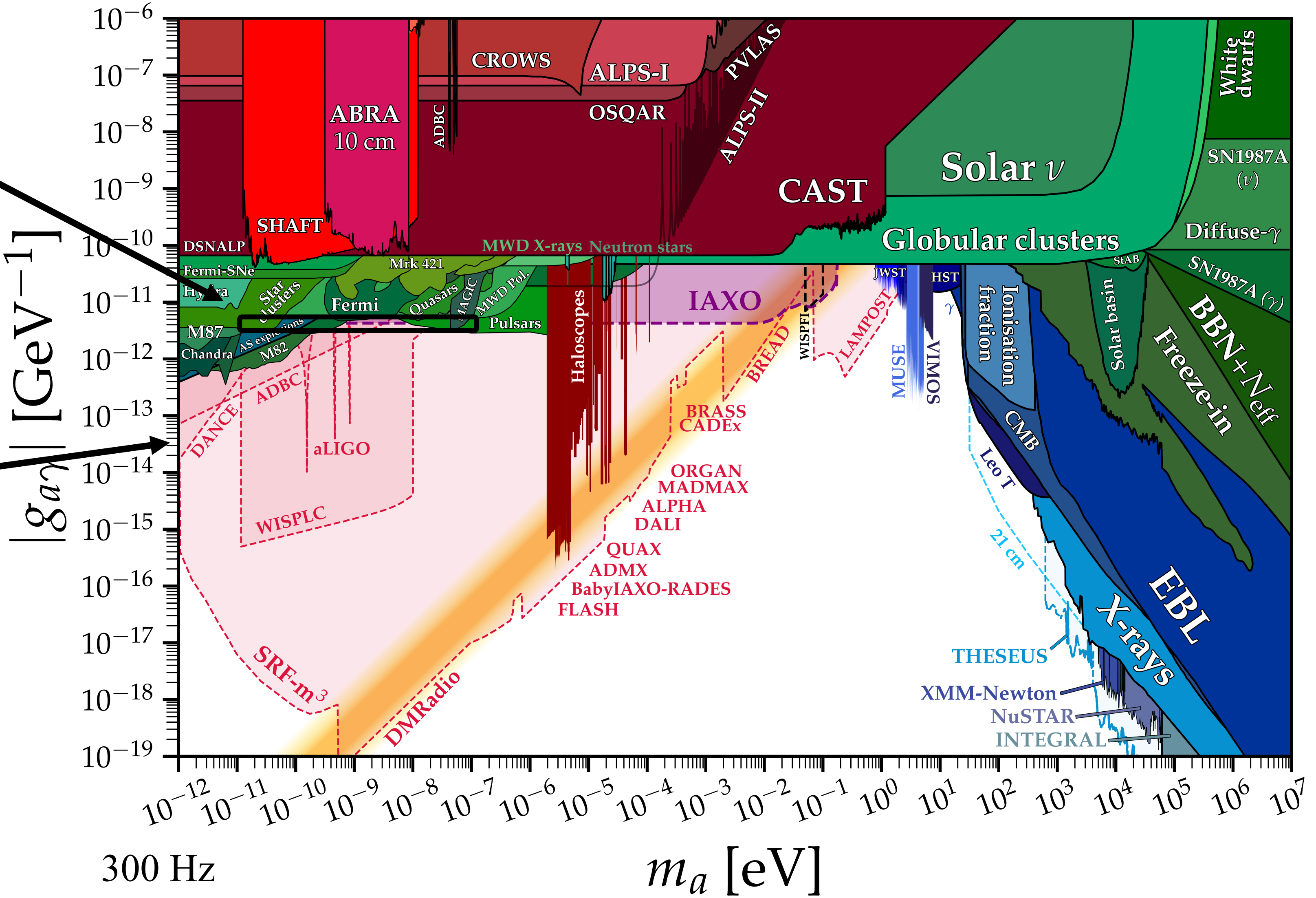
# GRB spectrum

- Assuming the intrinsic spectrum of optimistic gamma-ray emission
- Without ALPs, the observed spectrum is below the LHAASO sensitivity
- With ALPs, the spectrum surpasses the sensitivity



# ALP parameter

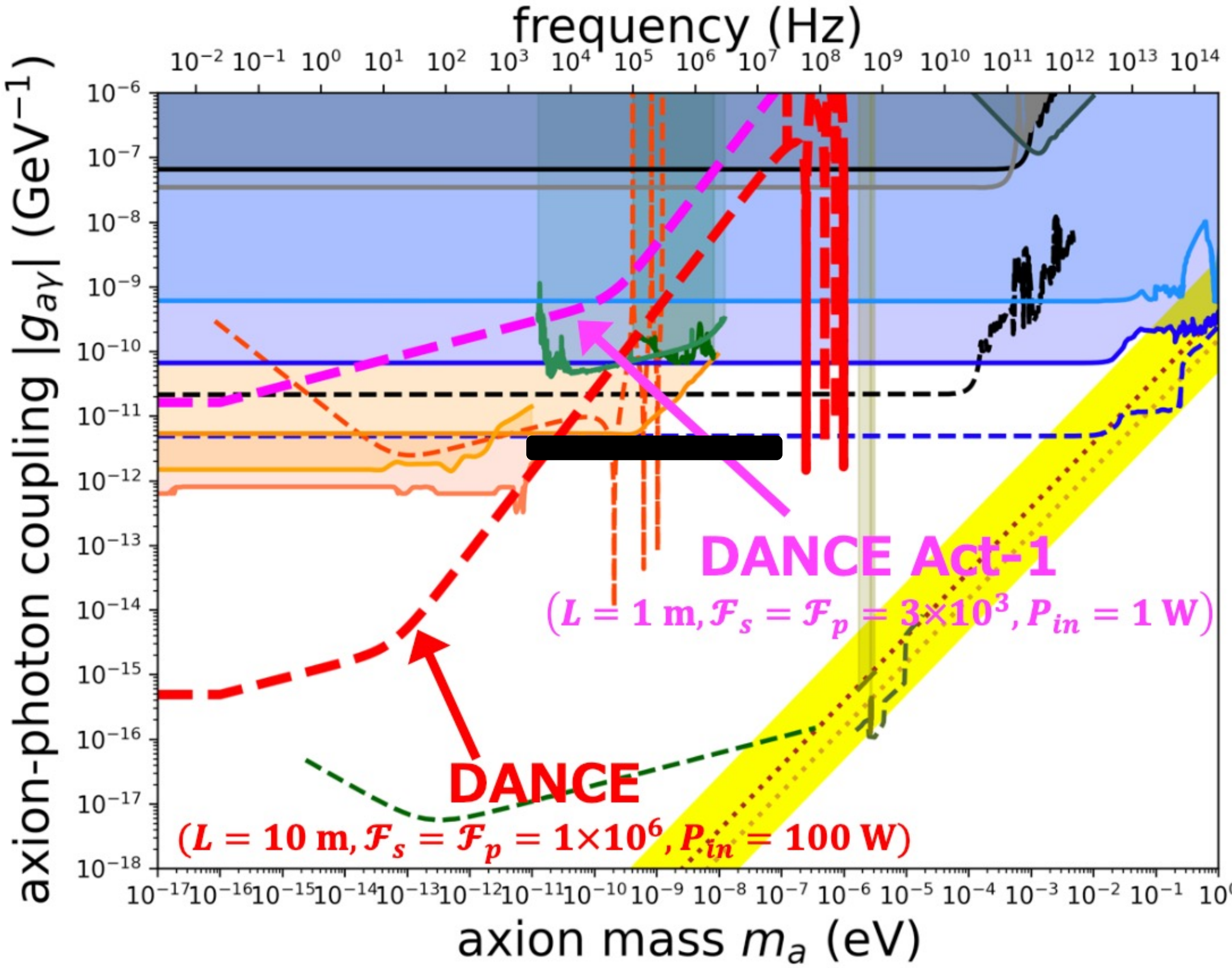
- ➢Proposed parameters have not been constrained fully
- ➢The parameter space constrained by the future DANCE is not overlapped but close



# DANCE

- Measurement of the polarization rotation of laser light from ALPs

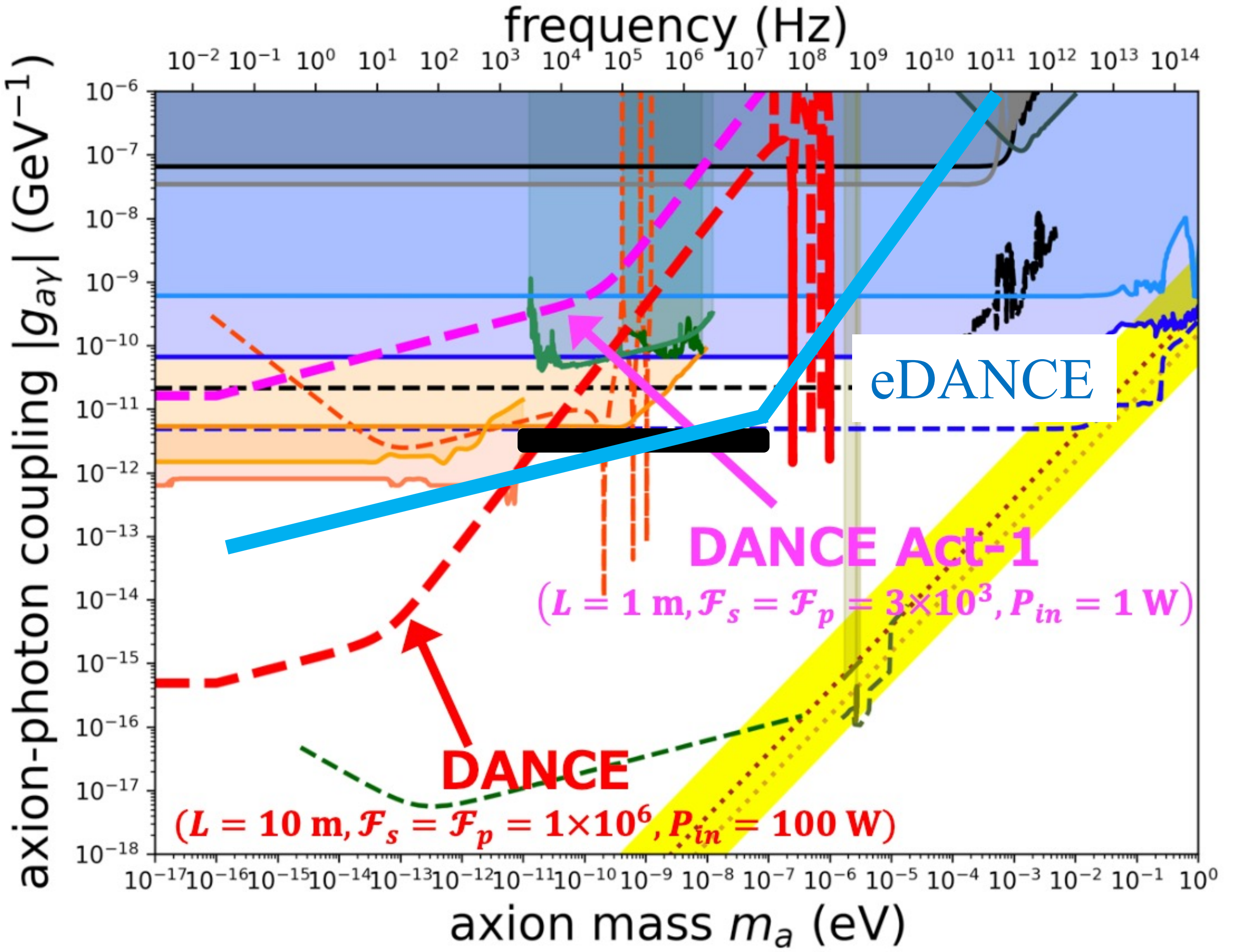
- Due to the very small cavity line width, the upper limit DANCE can set at high frequencies does not reach the proposed parameter



Fujimoto-kun's master thesis

# DANCE

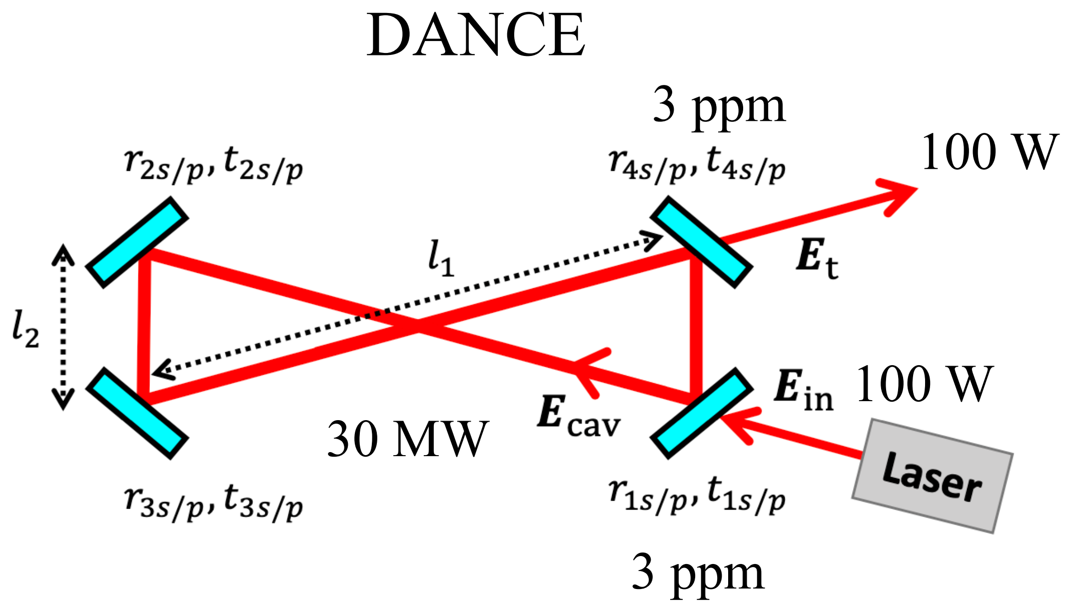
- ➢Measurement of the polarization rotation of laser light from ALPs
- ➢Due to the very small cavity line width, the upper limit DANCE can set at high frequencies does not reach the proposed parameter
- ➢I would like to propose extended DANCE

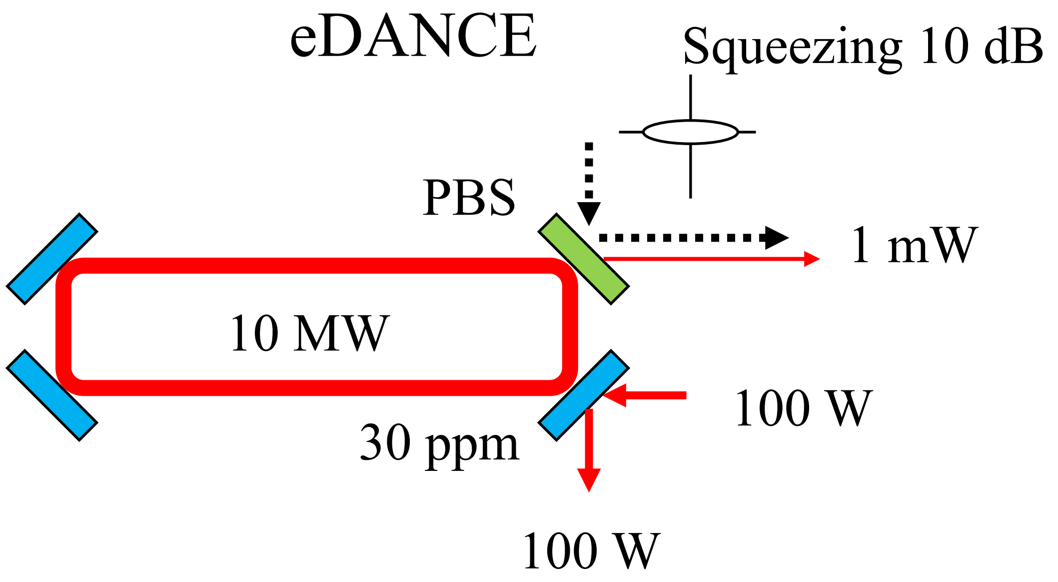



Fujimoto-kun's master thesis

# eDANCE

- ➢Extended DANCE for broadband search up to MHz




- ➢The PBS extracts the axion signal (p-pol) from only that port up to the FSR frequency
- ➢Moderate power and optical loss

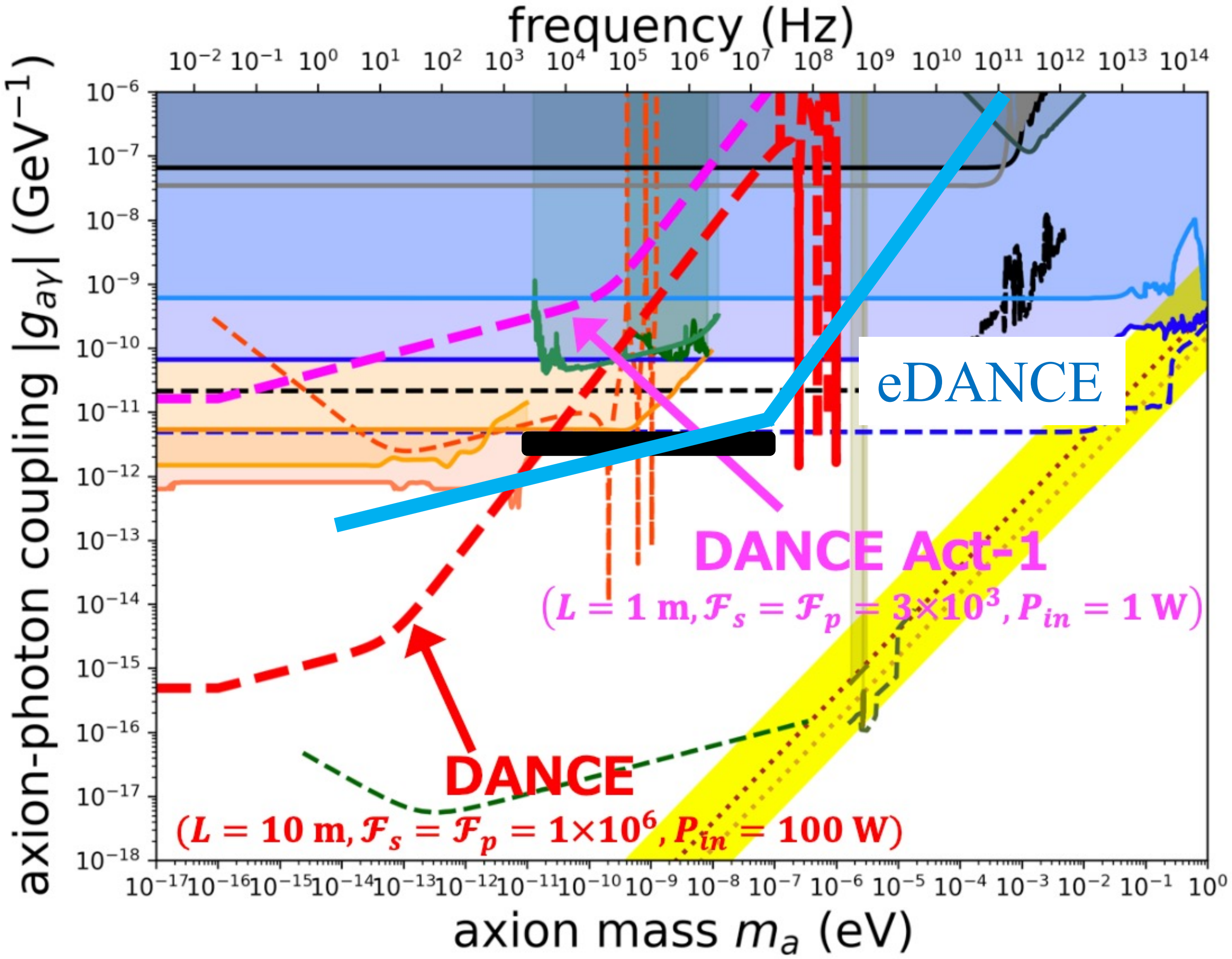
# Comparison

- The floor sensitivity is degraded by $100\sqrt{5}$, but the bandwidth is increased from 15 Hz to 15 MHz

| | DANCE | eDANCE | Imp. factor |
|---|---|---|---|
| Cavity | Critical | Over | $\sqrt{2}$ |
| Carrier finesse | $10^6$ | $2 \times 10^5$ | $1/\sqrt{5}$ |
| Sideband finesse | $10^6$ | $\pi$ | $\sqrt{\pi}/1000$ |
| Wave length | 1064 nm | 1550 nm | $\sqrt{1.5}$ |
| Squeezing | 0 dB | 10 dB | $\sqrt{10}$ |
| Intra-cavity power | 30 MW | 10 MW | - |
| Requirement to optical loss | $< \sim 1$ ppm | $< \sim 10$ ppm | - |

# Advantages of eDANCE

- ➢No requirement on p/s-light simultaneous resonance
- ➢1550 nm
- ➢10-fold mitigation on the optical loss requirement
- ➢Very pure local oscillator
- ➢Squeezing
- ➢Less noise at high frequencies
- ➢No need to keep long cavity locking to search at high frequencies



# Summary

- Report on observation of the high energy gamma-ray >10 TeV (GRB221009A) suggesting the possibility of ALP at certain parameter space: $m_a = 10^{-11}$-$10^{-7}$ eV and $g_{a\gamma\gamma} = (3\text{-}5) \times 10^{-12}$ GeV$^{-1}$

- This parameter space is close to that constrained by the future DANCE

- Proposing extended DANCE tuning to this parameter space with the over-coupled cavity and PBS