# Constraints on Extended Axion Structures from the Lensing of Fast Radio Bursts

**Kuan-Yen Chou**
(National Tsing Hua University, Taiwan)

With Po-Yan Tseng (NTHU) and Jan Tristram Acuña (UP Diliman)

Based on JCAP 04 (2025) 067 [arXiv:2501.07176]

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# Axion Star Formation

[Review see: E. Braaten and H. Zhang. Rev. Mod. Phys. 91, 041002, 2019]

**Axions** → **Axion BECs**

- gravitational thermalization

Axions:
- produced in early universe
- non-relativistic
- high occupation numbers

**Axion BECs** → **Axion Stars**

- gravitational force
- quantum pressure
- self-interaction

**Axion Stars** →

- non-relativistic EFT

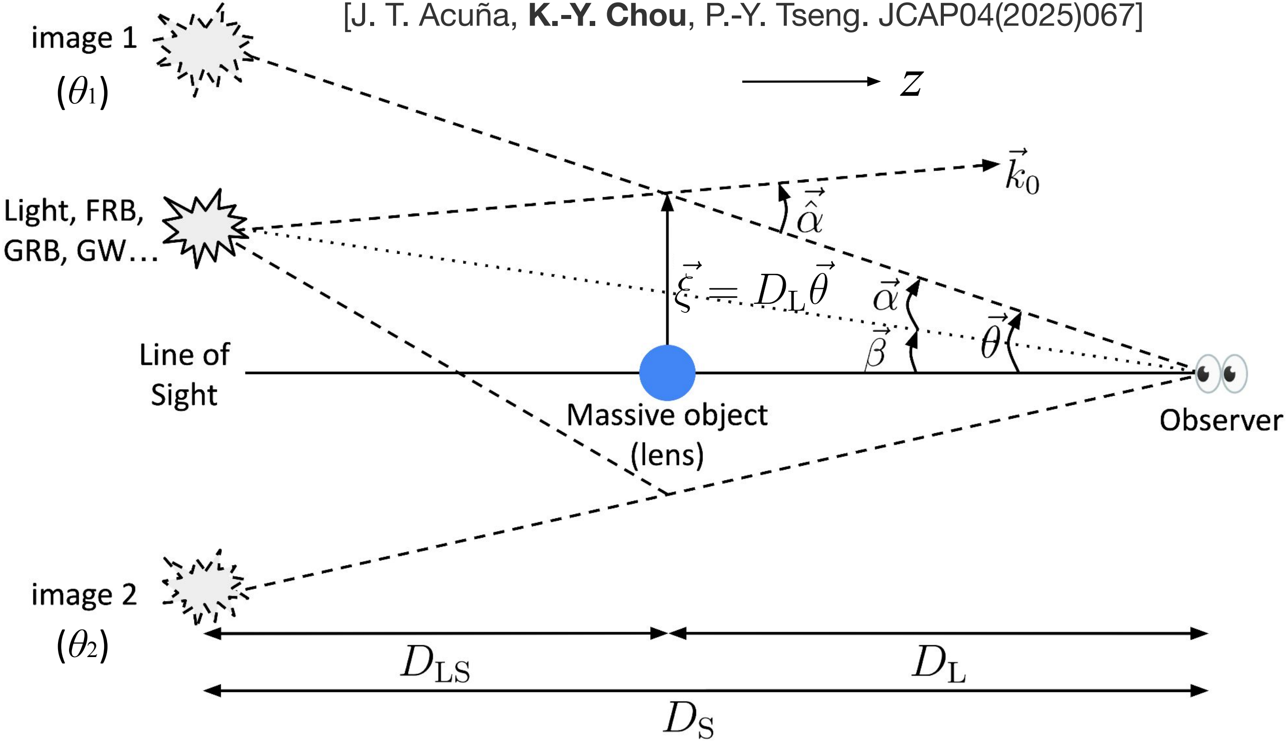
$$R_{\mathrm{AS}} \simeq 2.4350 \times 10^4 \mathrm{m} \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right) \left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

$$M_{\mathrm{AS}} \simeq 2.0391 \times 10^{-11} M_{\odot} \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right) \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)$$

spherically symmetric, Gaussian axion field

# Cosmological Lensing

[J. T. Acuña, **K.-Y. Chou**, P.-Y. Tseng. JCAP04(2025)067]




- $\vec{\beta} = \vec{\theta} - \vec{\alpha}$
- $\alpha_{\rm grav}(\theta) = \dfrac{D_{\rm LS}}{D_{\rm S}} \dfrac{4GM_{\rm L}(\theta)}{D_{\rm L}\theta}$
- Signatures:
  - Magnification
  - Time delay

[R. Narayan, M. Bartelmann. astro-ph/9606001]

# $a\gamma\gamma$ Coupling Induced Bending Angle

- $\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$

Modification on Maxwell's equations and photon dispersion relation

$$\omega^{\pm}(\vec{k}) = |\vec{k}| \pm \frac{g_{a\gamma\gamma}}{2} \left[ \hat{k} \cdot \vec{\nabla} a + \dot{a} \right] \mp g_{a\gamma\gamma} \dot{a} \frac{\omega_{\mathrm{p}}^2}{4|\vec{k}|^2} - \frac{g_{a\gamma\gamma}^2}{8|\vec{k}|} \left[ \dot{a}^2 + (\hat{k} \cdot \vec{\nabla} a)^2 - 2|\vec{\nabla} a|^2 \right] + \mathcal{O}(g_{a\gamma\gamma}^3)$$

[J. I. McDonald and L. B. Ventura, Phys. Rev. D 101, 123503 (2020)]

- $a\gamma\gamma$ coupling induced bending angle

$$\vec{\alpha}_{a\gamma\gamma} \simeq -\frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}} \frac{g_{a\gamma\gamma}^2}{8|\vec{k}_0|^2} \int_{-\infty}^{\infty} \vec{\nabla}_{\perp} (\partial a(\xi, z))^2 \mathrm{d}z$$

# Full Lens Equation

$$\tilde{x} \equiv \frac{x}{\theta_{\rm E}} \quad \theta_{\rm E} = \sqrt{4G_N M_{\rm AS}\frac{D_{\rm LS}}{D_{\rm S}D_{\rm L}}}$$

- Lens equation:

$$\tilde{\beta} \approx \tilde{\theta} - \frac{1}{\tilde{\theta}}\left[1 - \exp\left(-w_{\rm E}^2\tilde{\theta}^2\right)\right] - A\, w_{\rm E}^2\, \tilde{\theta}\, \exp\left(-w_{\rm E}^2\tilde{\theta}^2\right)$$

-> gravity + finite-size + $a\gamma\gamma$ effects

cf. pointlike lens: $\tilde{\beta} = \tilde{\theta} - \frac{1}{\tilde{\theta}}$

- Finite-size parameter: $w_{\rm E} \equiv \frac{D_{\rm L}\theta_{\rm E}}{R_{\rm AS}} = \frac{R_{\rm E}}{R_{\rm AS}}$

$w_{\rm E} \gg 1$ : AS is effectively pointlike

$w_{\rm E} \lesssim 1$ : finite-size effect is notable

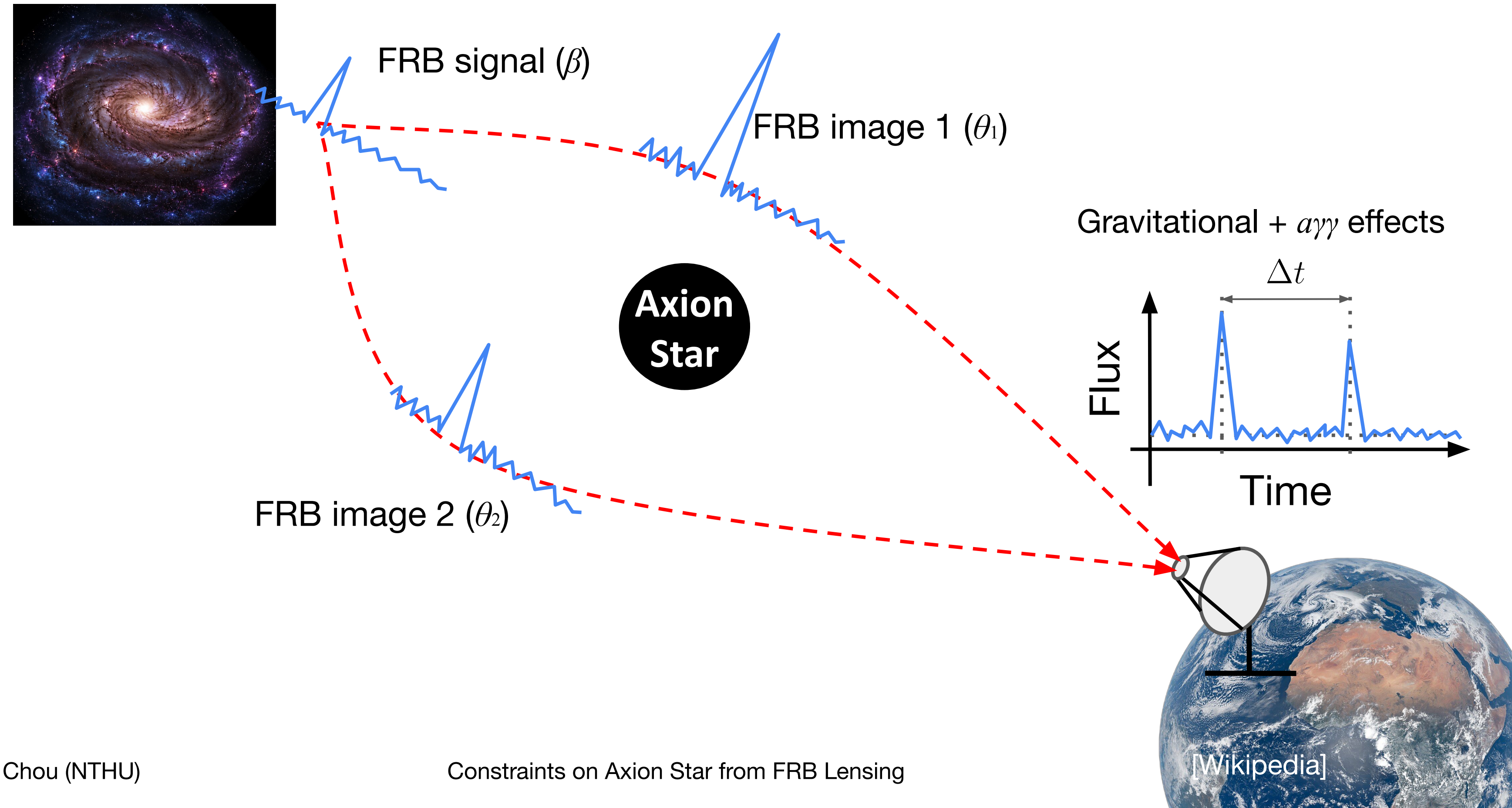
- $a\gamma\gamma$ effect strength parameter: $A \equiv \frac{1}{\pi G_N}\left(\frac{g_{a\gamma\gamma}}{4k_0 R_{\rm AS}}\right)^2 \propto \frac{g_{a\gamma\gamma}^2}{f_0^2}$

$f_0$ → frequency of signal

- Signatures: $\mu(\theta_i) = \mu_{\text{grav.}+a\gamma\gamma}(\theta_i) \qquad t(\theta_i) = t_{\text{grav.}+a\gamma\gamma}(\theta_i)$

# Lensing of FRBs

[FRB grav. lensing: J. B. Muñoz et al. Phys.Rev.Lett. 117 (2016) 9, 091301]



# FRB Lensing Probability

[J. B. Muñoz et al. Phys.Rev.Lett. 117 (2016) 9, 091301]

- Optical depth: $\bar{\tau}(M_{\rm AS}) = \int {\rm d}z_{\rm S} N_{\rm FRB}(z_{\rm S}) \int {\rm d}\chi(z_{\rm L})(1+z_{\rm L})^2 n(M_{\rm AS})\sigma(M_{\rm AS}, z_{\rm L})$

- Magnification ratio:

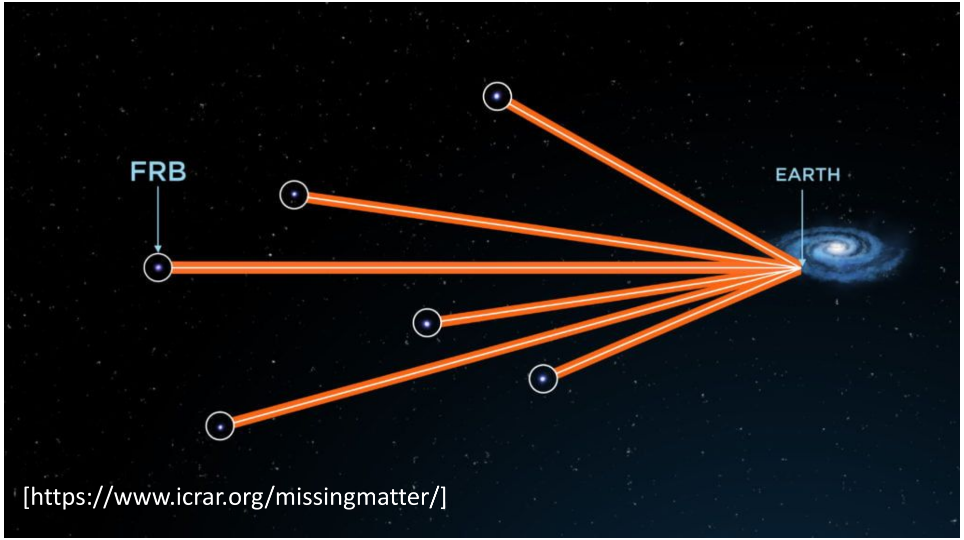
$$R_f \equiv \left| \frac{\max(\mu(\theta_1), \mu(\theta_2))}{\min(\mu(\theta_1), \mu(\theta_2))} \right| \leq R_{f,\max}$$

- Time difference of arrival:

$$\Delta t \equiv |t(\theta_1) - t(\theta_2)| \geq \Delta t_{\min}$$

- Lensing probability:

$$P = 1 - e^{-\bar{\tau}}$$



# Lensed FRB Signals observed by CHIME

- Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope
  1. Observed frequency range: 400-800 MHz
  2. Detected 536 FRB signals in CHIME/FRB first catalog (2018/8/28-2019/7/1)
  3. Observe zero lensed FRB signal [Z. Kader et. al. (CHIME/FRB Collaboration), Phys. Rev. D, 106(4):043016, 2022] [C. Leung et. al. (CHIME/FRB Collaboration), Phys. Rev. D, 106(4):043017, 2022]

- Assuming $10^4$ observed FRB signals for 0 lensed FRB signal

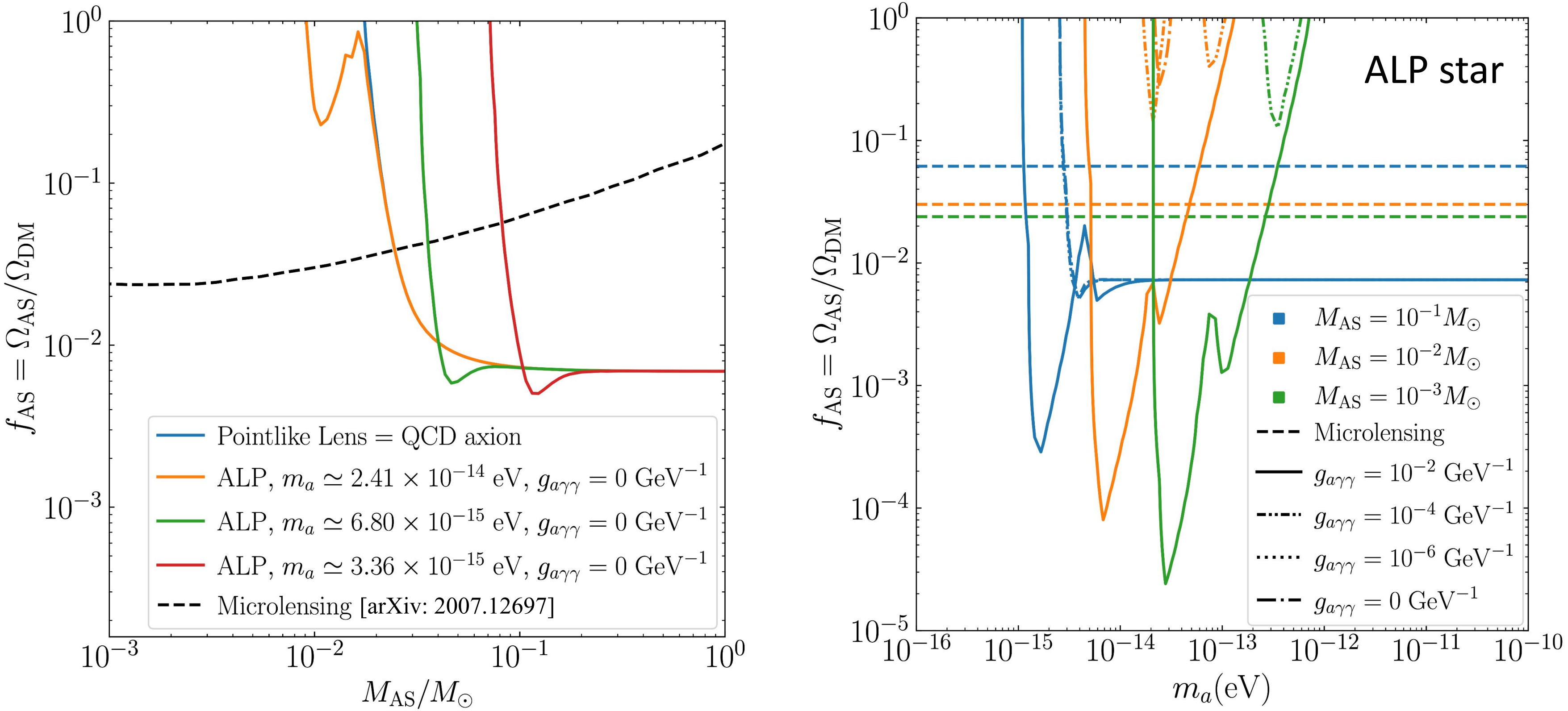
  -> Estimated number of lensed FRB: $N_{\rm lensed} = (1 - e^{-\bar{\tau}})N_{\rm obs}$

  -> Exclude the axion parameter space that gives $N_{\rm lensed} \geq 1$.

# Sensitivities

$N_{\rm obs} = 10^4 \quad R_{f,\max} = 5 \quad \Delta t_{\min} = 1\mu s \quad f_{\rm FRB} = 600 \text{MHz}$

[J. T. Acuña, **K.-Y. Chou**, P.-Y. Tseng. JCAP04(2025)067]



# Summary

- We study FRB lensing by axion stars, including gravitational effect with additional finite-size and axion-photon coupling effects.

- QCD axion stars behave effectively as pointlike lenses in the FRB lensing regime.

- ALP stars can produce novel lensing features, and FRB lensing gives sensitivities competitive with optical microlensing constraints.

Thank you

# Backup

# Axion

- **QCD axion**:
  1. Solution to the Strong CP Problem
  2. $m_a$ and $f_a$ are dependent

$$m_a = 10^{-5}\text{eV}\left(\frac{5.691 \times 10^{11}\text{GeV}}{f_a}\right)$$

- **Axion-like particle (ALP)**:
  1. Shares similar properties with QCD axion, not the solution to strong CP problem
  2. $m_a$ and $f_a$ are independent

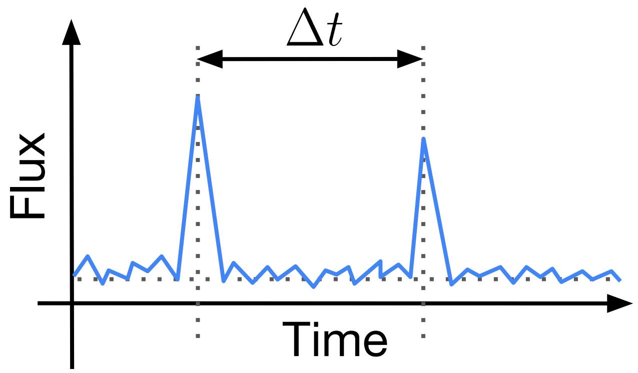
- Key properties: 1. pseudo-scalar boson

  2. couple to Standard Model particles, e.g. $\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$

- Promising dark matter candidate

# FRB Lensing Cross Section

[Julian B. Muñoz et al. Phys.Rev.Lett. 117 (2016) 9, 091301]




- Magnification ratio:

$$R_f \equiv \left| \frac{\max(\mu(\theta_1), \mu(\theta_2))}{\min(\mu(\theta_1), \mu(\theta_2))} \right|$$

- Time difference of arrival:

$$\Delta t \equiv |t(\theta_1) - t(\theta_2)|$$

- Lensing criteria: $R_{f,\max} = 5 \quad \Delta t_{\min} = 1 \mu s$

- $R_f(\beta) \le R_{f,\max} \quad \Delta t(\beta) \ge \Delta t_{\min}$

- Lensing cross section:

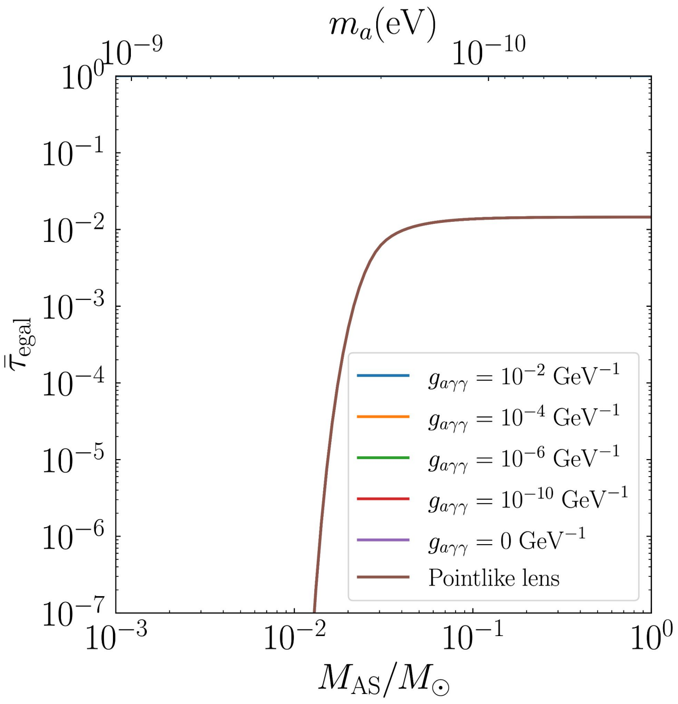
$$\sigma = \pi D_{\mathrm{L}}^2 2 \int_0^{\beta_c} \Theta(R_{f,\max} - R_f(\beta)) \Theta(\Delta t(\beta) - \Delta t_{\min}) \beta d\beta$$

# Lensing Probability (QCD Axion Star)

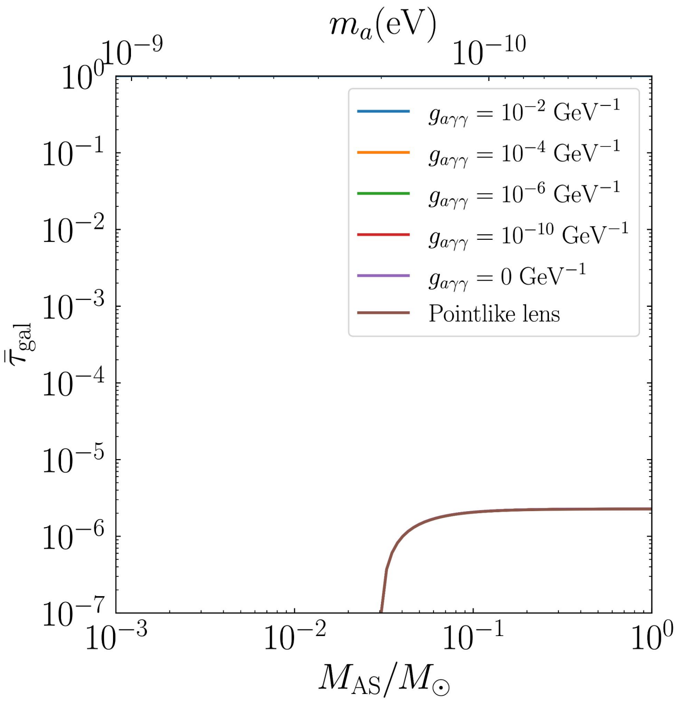
$R_{f,\max} = 5 \quad \Delta t_{\min} = 1\mu\mathrm{s}$

$f_{\mathrm{AS}} = 1 \quad f_{\mathrm{FRB}} = 600\mathrm{MHz}$

extragalactic contribution




galactic contribution




Note:

$$f_a \propto \frac{1}{m_a}$$

$$M_{\mathrm{AS}} \propto \frac{f_a}{m_a}$$

[J. T. Acuña, **K.-Y. Chou**, P.-Y. Tseng. JCAP04(2025)067]

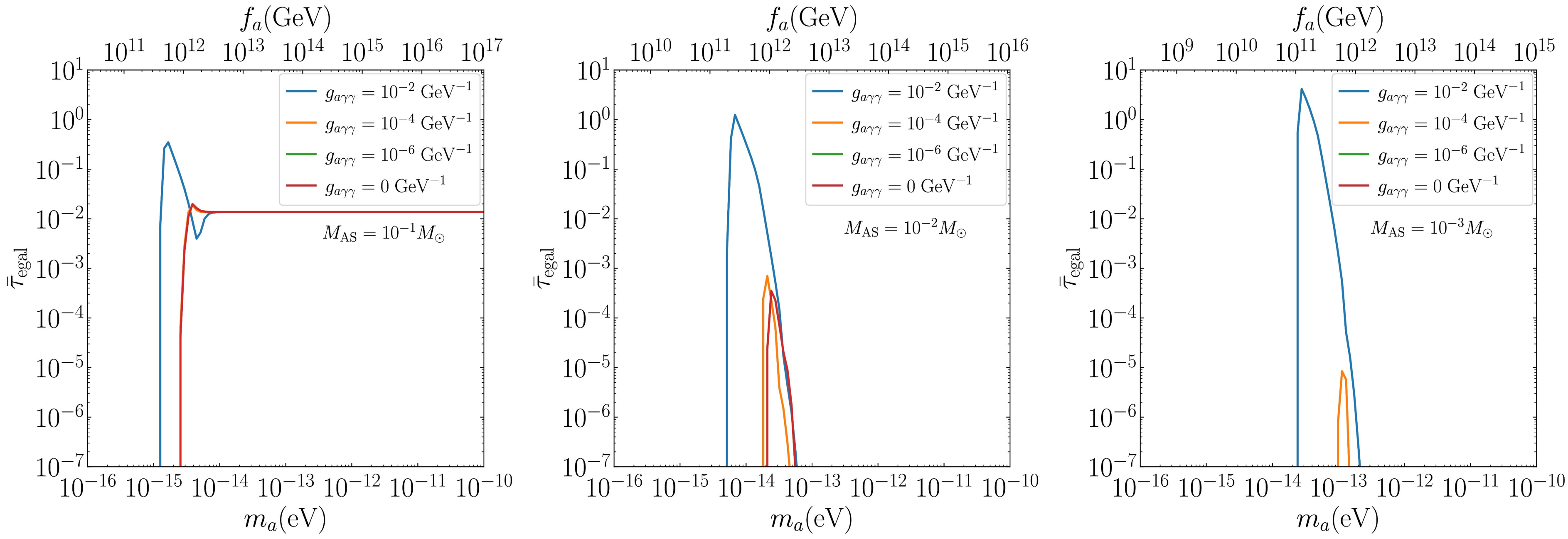
# Lensing Probability (ALP Star)

$R_{f,\max} = 5 \quad \Delta t_{\min} = 1\mu\text{s}$

$f_{\text{AS}} = 1 \quad f_{\text{FRB}} = 600\text{MHz}$

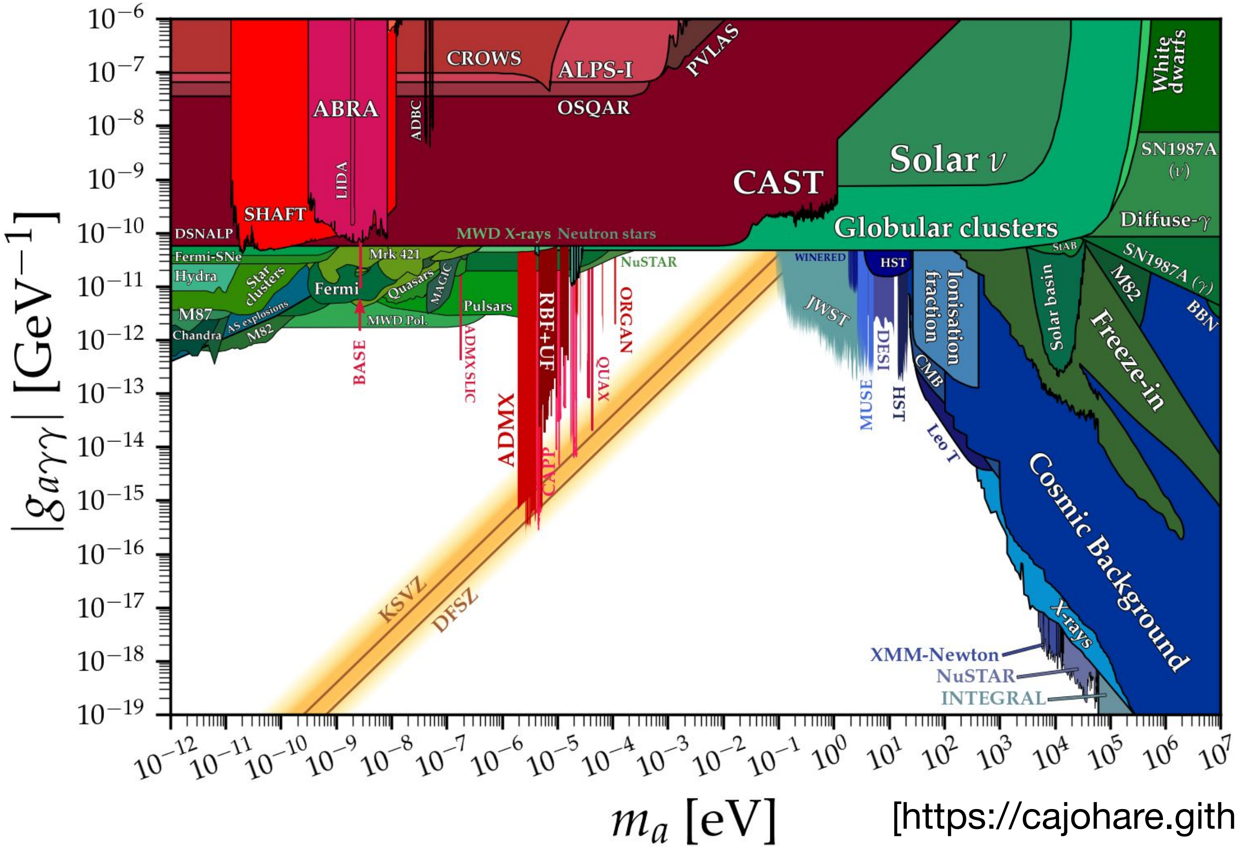
extragalactic contribution (dominant)

Note: $M_{\text{AS}} \propto \frac{f_a}{m_a}$




[J. T. Acuña, **K.-Y. Chou**, P.-Y. Tseng. JCAP04(2025)067]

# Axion Limits




[https://cajohare.github.io/AxionLimits/]