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

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

The Future is Whispering
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Axion

- QCD axion:
  1. Proposed by Peccei and Quinn in 1977 to solve the Strong CP Problem
  2. m_a and f_a are dependent

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

- Axion-Like Particle (ALP):
  1. Shares similar properties with the QCD axion but doesn't solve the Strong CP Problem
  2. m_a and f_a are independent

- Key Properties: pseudo-scalar boson

  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

Axion Star Formation

[Eric Braaten and Hong Zhang. Rev. Mod. Phys. 91, 041002, 2019]
[Kohei Fujikura et al.. Phys. Rev. D 104, 123012 (2021)]

Axions

- produced in early universe
- in coherence
- non-relativistic
- high occupation numbers

→ gravitational thermalization →

Axion BECs

- gravitational force
- axion self-interaction

↓

Axion Stars

non-relativistic EFT

spherically symmetric Gaussian axion field

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

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

Gravitational Lensing

[Ramesh Narayan, Matthias Bartelmann. astro-ph/9606001]

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

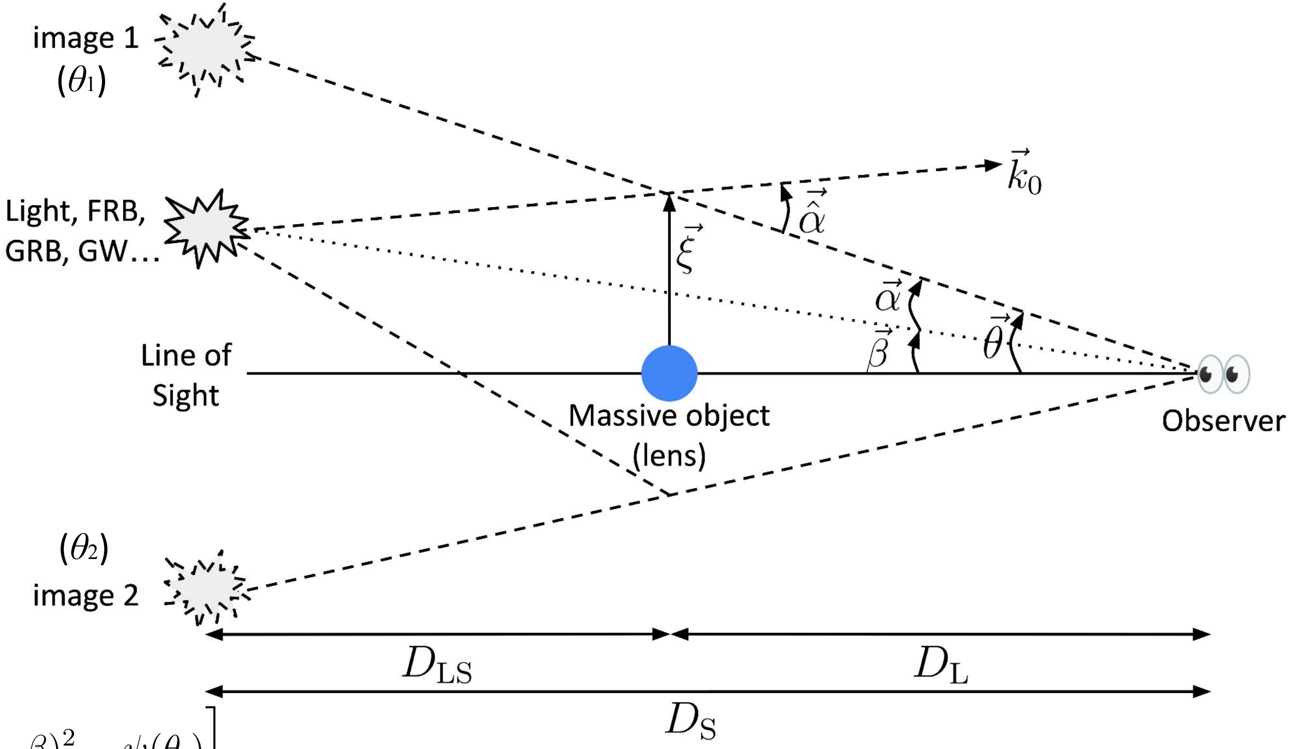
  - Magnification:

$$\mu(\theta_i) = \left| \frac{\beta}{\theta} \frac{d\beta}{d\theta} \Big|_{\theta_i} \right|^{-1}$$

  - Time delay:

$$t(\theta_i) = (1 + z_{\rm L}) \frac{D_{\rm L} D_{\rm S}}{D_{\rm LS}} \left[\frac{1}{2}(\theta_i - \beta)^2 - \psi(\theta_i) \right]$$

$$\vec{\nabla}\psi = \vec{\alpha}$$



$a\gamma\gamma$ 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

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

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

- $a\gamma\gamma$ 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

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

  -> finite-size + gravity + *aγγ* effects $\theta_{\rm E} = \sqrt{4 G_N M_{\rm AS} \frac{D_{\rm LS}}{D_{\rm S} D_{\rm L}}}$

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

  $w_{\rm E} \gg \mathcal{O}(1)$: lens is effectively pointlike

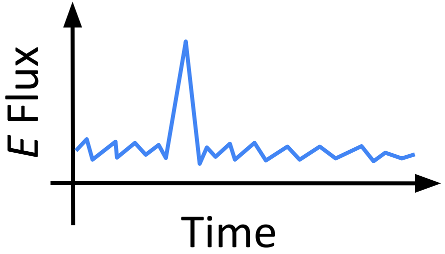
  $w_{\rm E} \sim \mathcal{O}(1)$: finite size effect is notable

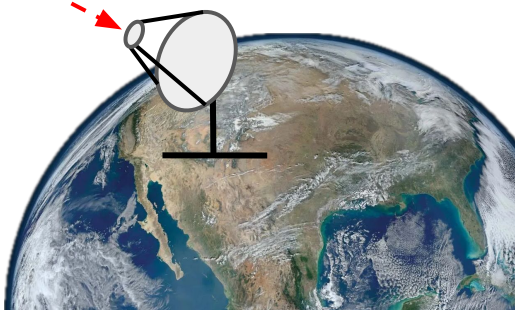
  aγγ strength parameter: $A \equiv \frac{1}{\pi G_N} \left(\frac{g_{a\gamma\gamma}}{4 k_0 R_{\rm AS}}\right)^2 \propto \frac{g_{a\gamma\gamma}^2}{f_0^2}$

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

Fast Radio Burst (FRB)

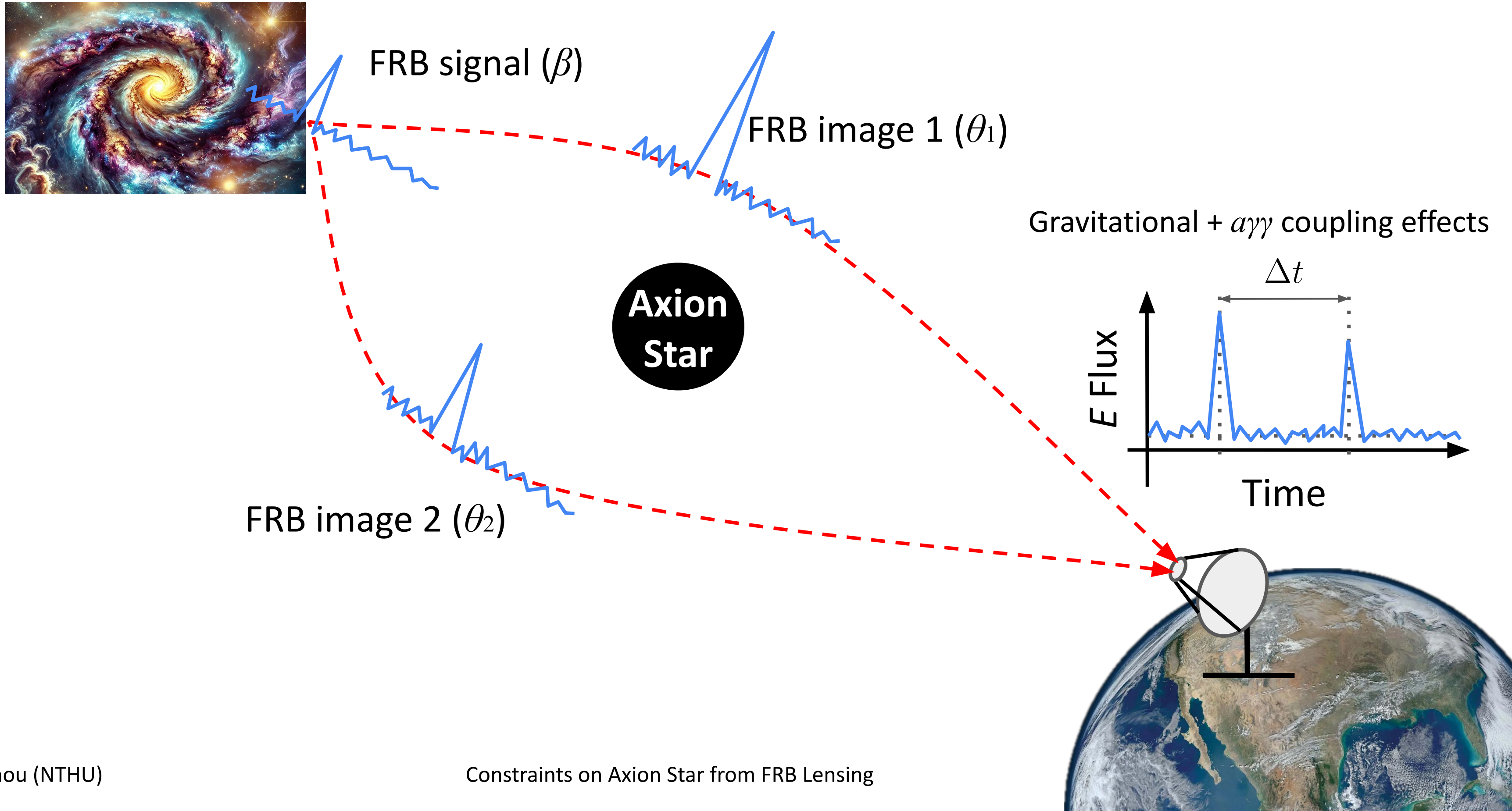
1. From extragalactic space
2. Unknown origins
3. High energy flux density (~Jy)
4. Duration (~ms)
5. Rate: 10^3-10^4/sky/day (expected)





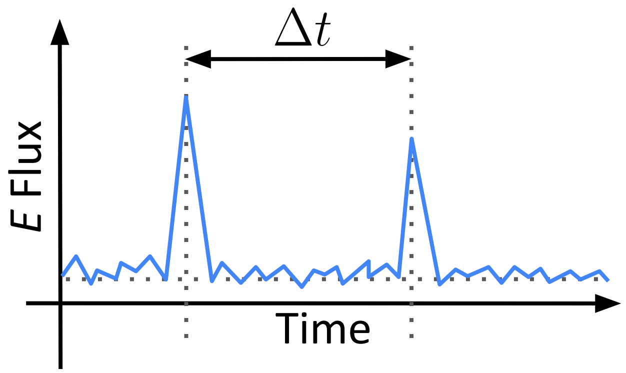
Lensing of FRBs

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



FRB Lensing Cross Section

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



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

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

- Lensing cross section:

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

FRB Lensing Probability

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

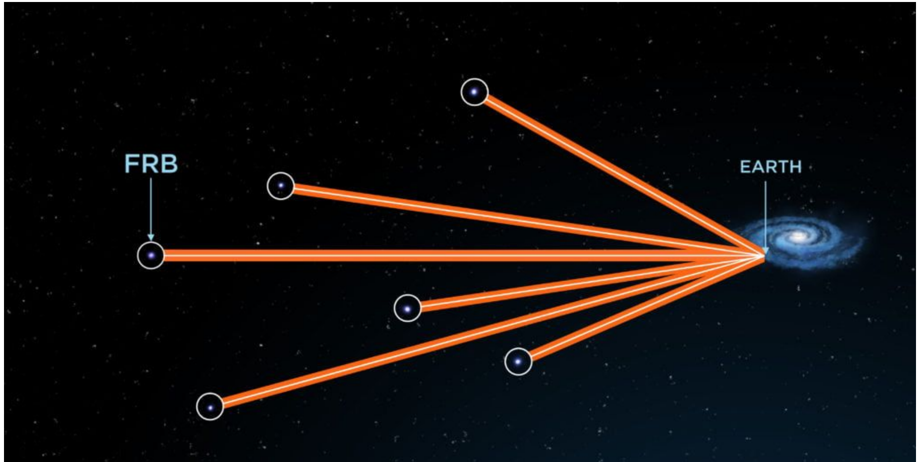
- Optical depth: $\bar{\tau}(M_{\rm AS}) = \int {\rm d}z_{\rm S} N_{\rm FRB}(z_{\rm S}) \int {\rm d}\chi(z_{\rm L})(1+z_{\rm L})^2 n(M_{\rm AS})\sigma(M_{\rm AS}, z_{\rm L})$

- Constant comoving number density:

$$N_{\rm FRB}(z) = \mathcal{N}\frac{\chi^2(z)}{H(z)(1+z)}\exp\left(-\frac{d_{\rm L}^2(z)}{2d_{\rm L}^2(0.5)}\right)$$

- Lensing probability:

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

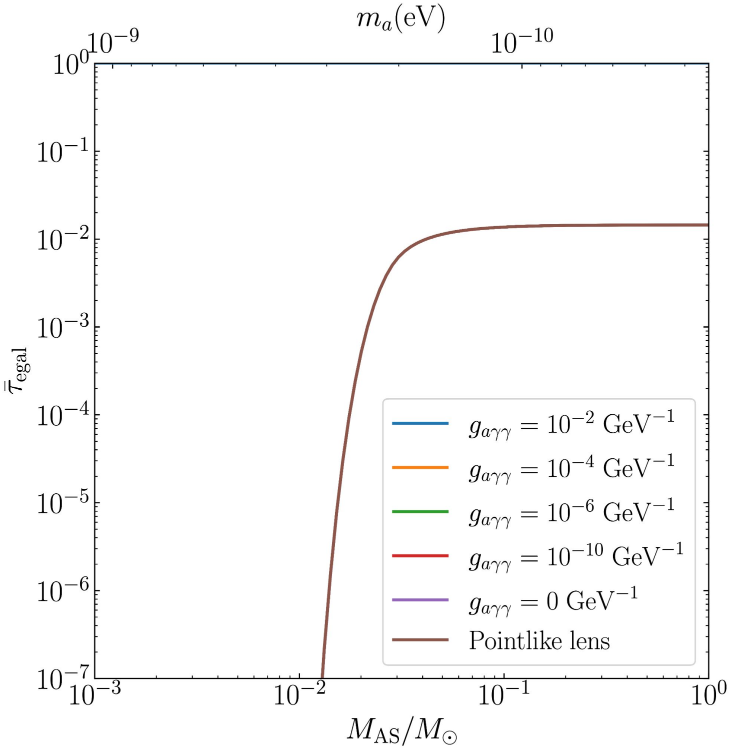


[https://www.icrar.org/missingmatter/]

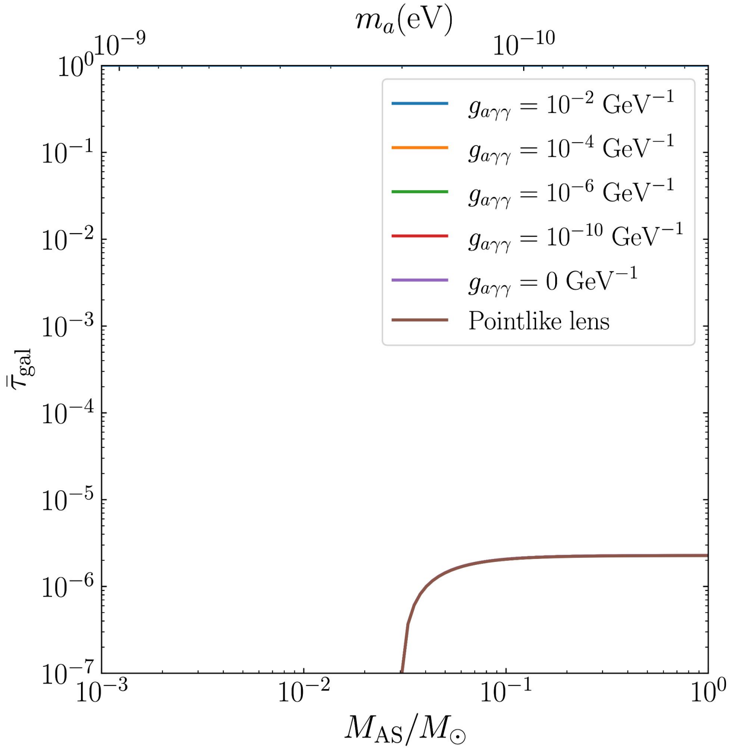
Lensing Probability (QCD Axion)

$R_{f,\max} = 5 \quad \Delta t_{\min} = 1\mu\text{s} \quad f_{\text{FRB}} = 600\text{MHz}$

Extragalactic contribution



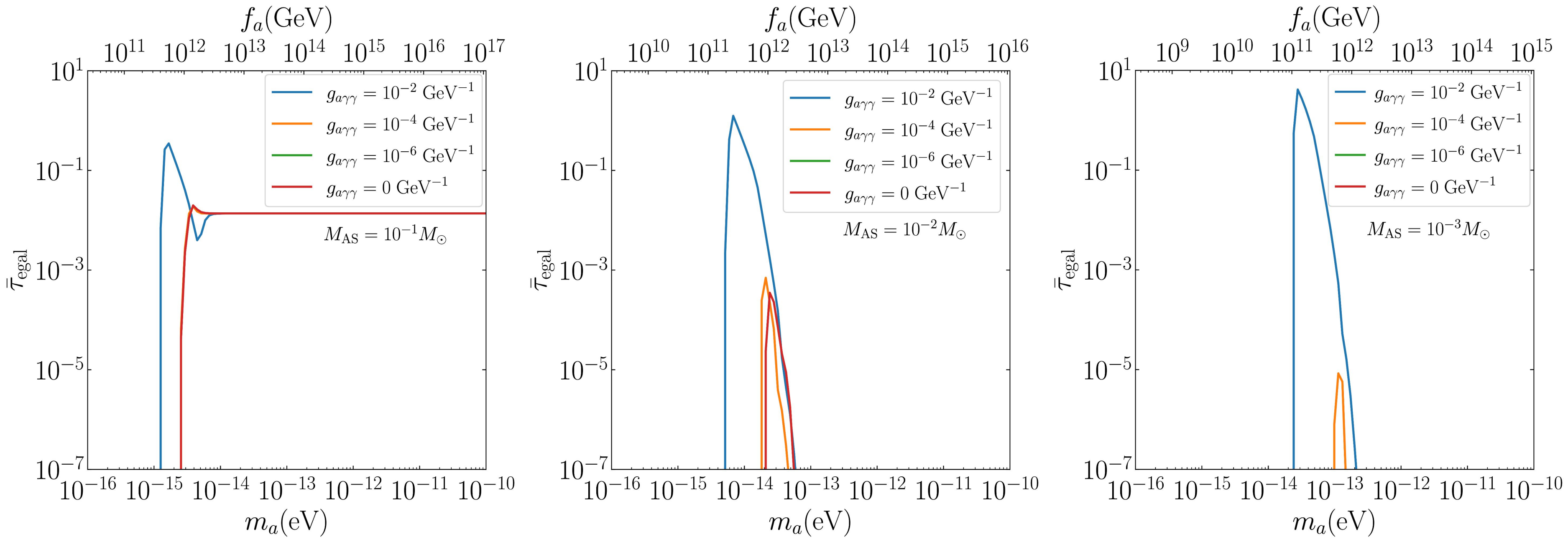
Galactic contribution



Lensing Probability (ALP)

$R_{f,\max} = 5 \quad \Delta t_{\min} = 1\mu s \quad f_{\rm FRB} = 600{\rm MHz}$

Extragalactic contribution (dominant)



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

[Zarif Kader et. al. (CHIME/FRB Collaboration), Phys. Rev. D, 106(4):043016, 2022]
[Calvin Leung et. al. (CHIME/FRB Collaboration), Phys. Rev. D, 106(4):043017, 2022]

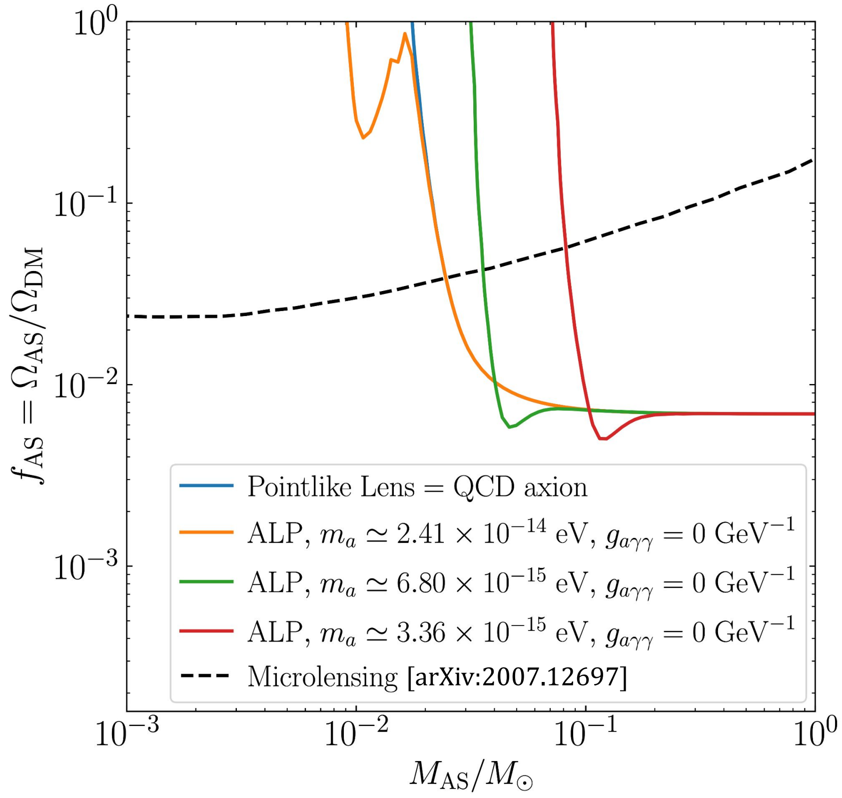
- Assuming 10^4 observed FRB signals for 0 lensed FRB signal

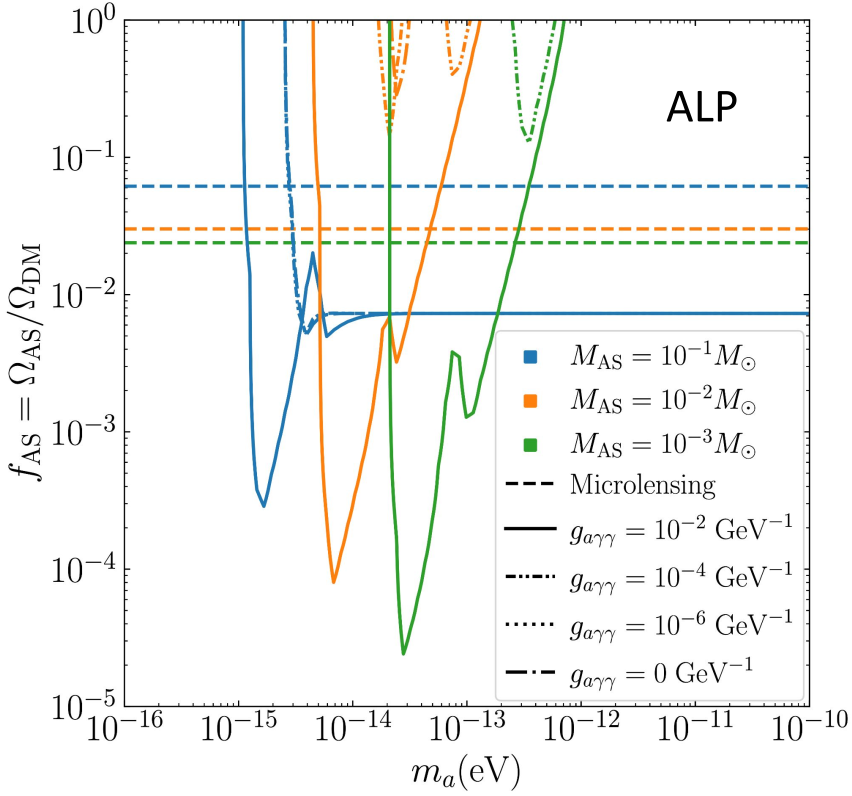
  $\rightarrow$ Exclude the axion parameter spaces that give $N_{\text{lensed}} > 1$

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

Constraints

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





Summary and Conclusion

1. QCD axions and ALPs can form the localized astrophysical object: axion stars.

2. We combine the gravitational effect with additional finite-size and axion-photon coupling effects on FRB lensing.

3. Our results which use FRB lensing to probe axion stars are competitive with the microlensing results which operate in optical band.

Thank You