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

Kuan-Yen Chou (National Tsing Hua University)

With Jan Tristram Acuña and Po-Yan Tseng

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

The Future is Whispering
06/26/2025

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

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

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

Gravitational Lensing

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

- $\vec{\beta} = \vec{\theta} - \vec{\alpha}$

- $\alpha_{\mathrm{grav}}(\theta) = \dfrac{D_{\mathrm{LS}}}{D_{\mathrm{S}}} \dfrac{4GM_{\mathrm{L}}(\theta)}{D_{\mathrm{L}}\theta}$

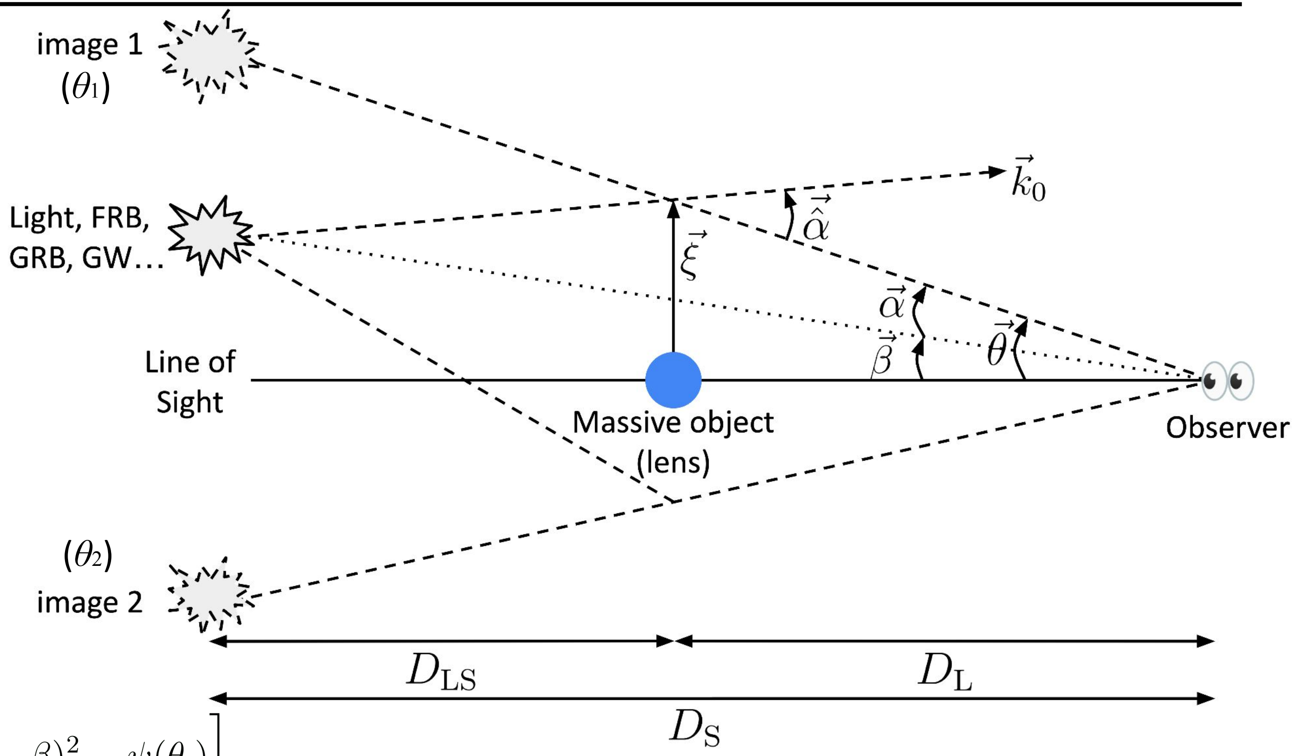
- Signatures:

  - Magnification:

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

  - Time delay:

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



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

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

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

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

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

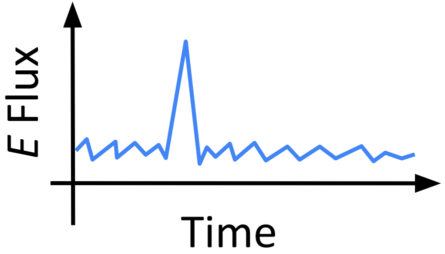
$w_{\mathrm{E}} \sim \mathcal{O}(1)$: finite size effect is notable

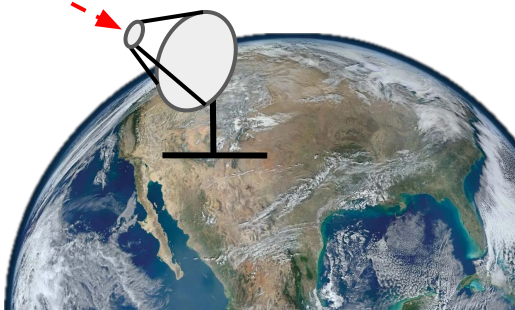
aγγ strength parameter: $A \equiv \frac{1}{\pi G_N} \left(\frac{g_{a\gamma\gamma}}{4 k_0 R_{\mathrm{AS}}}\right)^2 \propto \frac{g_{a\gamma\gamma}^2}{f_0^2}$

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

Fast Radio Burst (FRB)

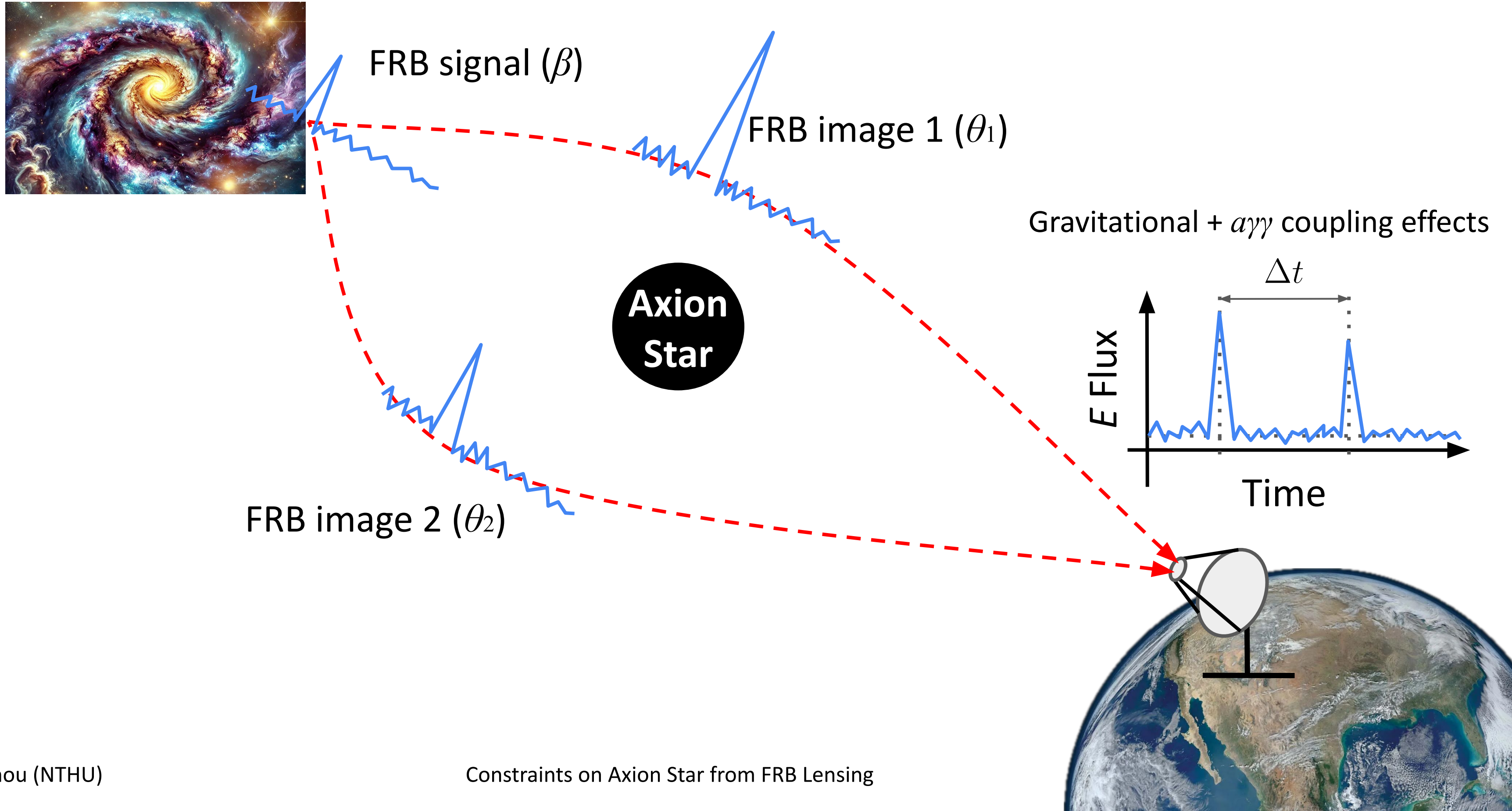
1. From extragalactic space
2. Unknown origins
3. High energy flux density (~Jy)
4. Duration (~ms)
5. Rate: 10^3-10^4/sky/day (expected)





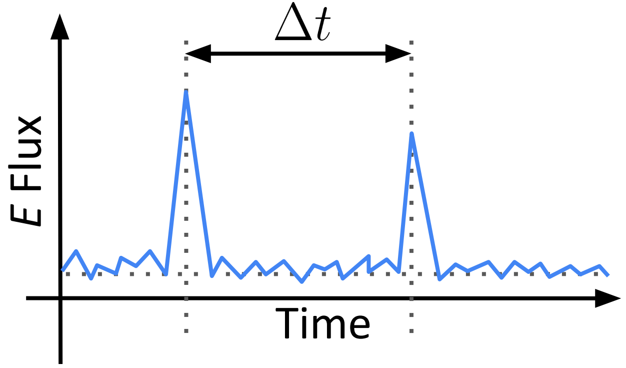
Lensing of FRBs

[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]

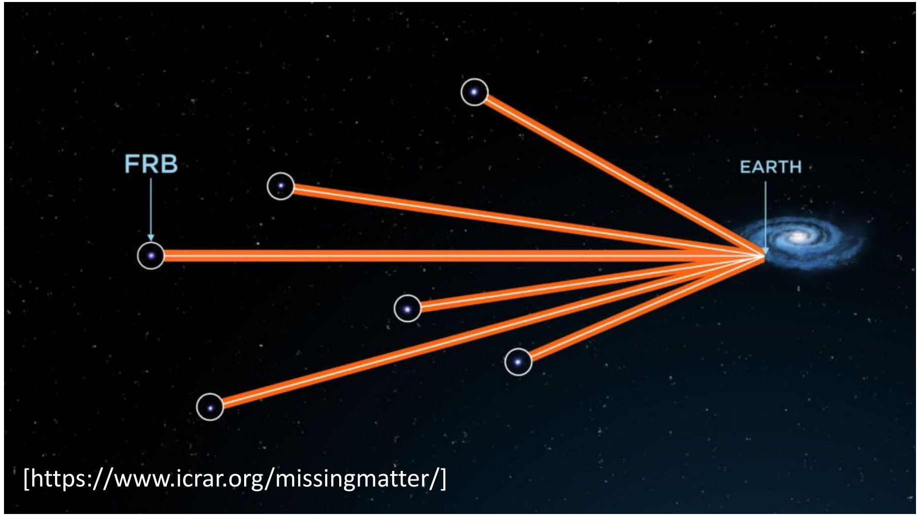
- Optical depth: $\bar{\tau}(M_{\rm AS}) = \int {\rm d}z_{\rm S} N_{\rm FRB}(z_{\rm S}) \int {\rm d}\chi(z_{\rm L})(1+z_{\rm L})^2 n(M_{\rm AS})\sigma(M_{\rm AS}, z_{\rm L})$

- 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:

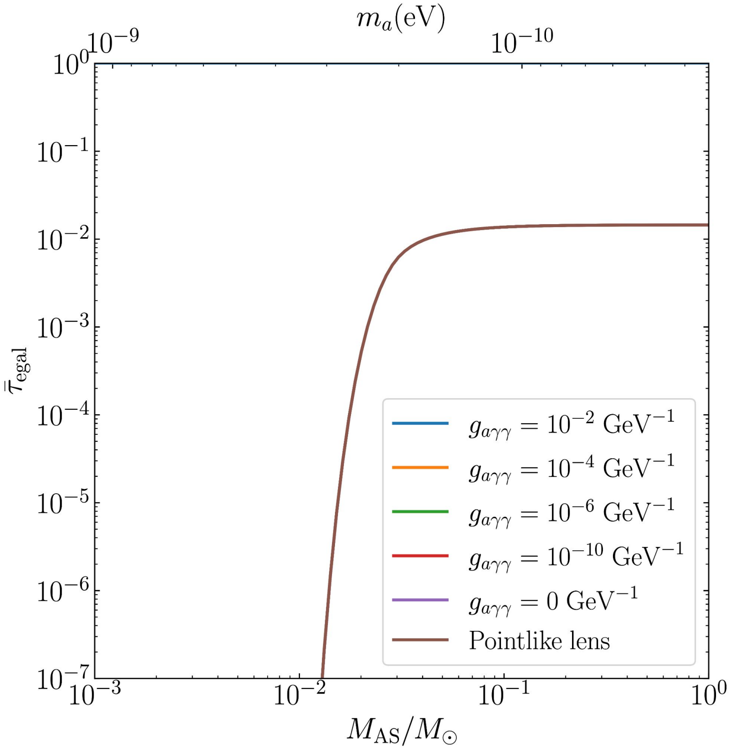
$$P = 1 - e^{-\bar{\tau}}$$



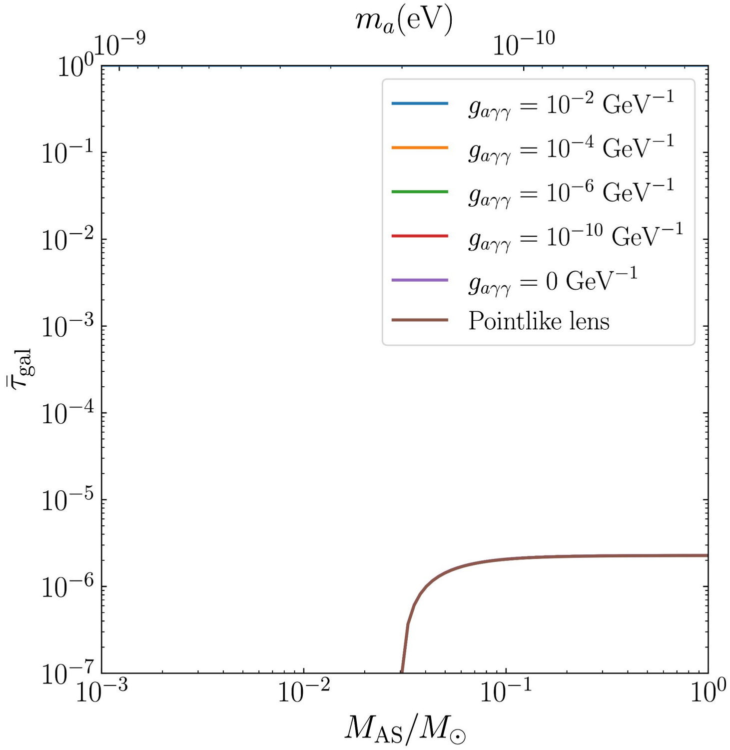
Lensing Probability (QCD Axion)

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

Extragalactic contribution



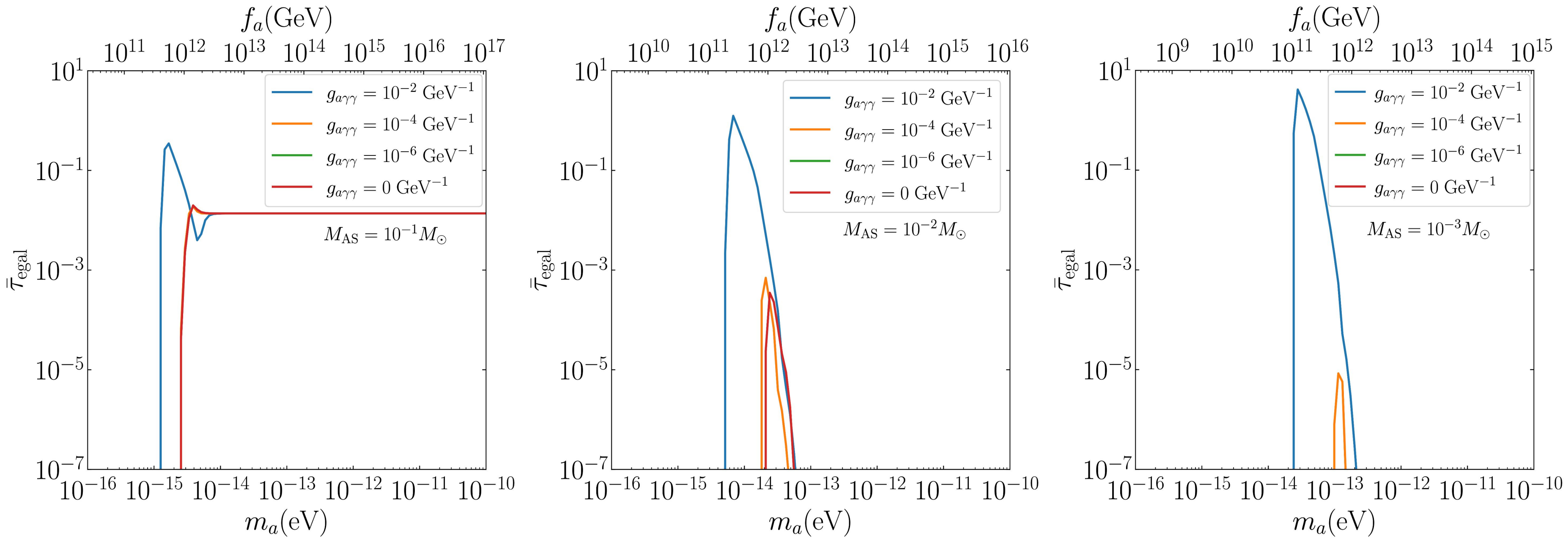
Galactic contribution



Lensing Probability (ALP)

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

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]

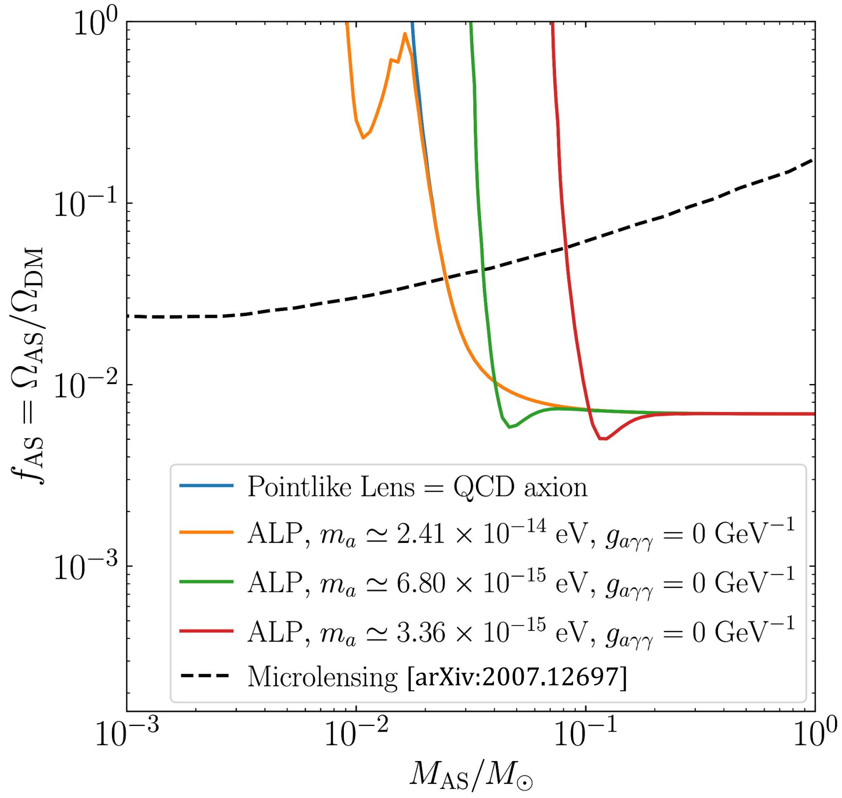
- Assuming 10^4 observed FRB signals for 0 lensed FRB signal

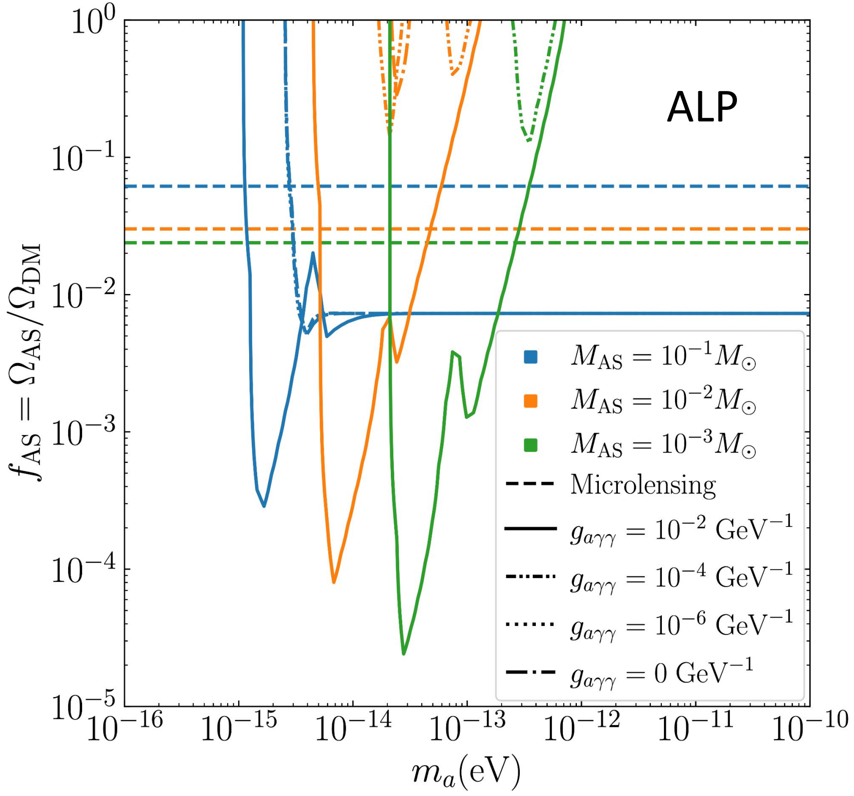
  $\rightarrow$ Exclude the axion parameter spaces that give $N_{\text{lensed}} > 1$

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

Constraints

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





Summary and Conclusion

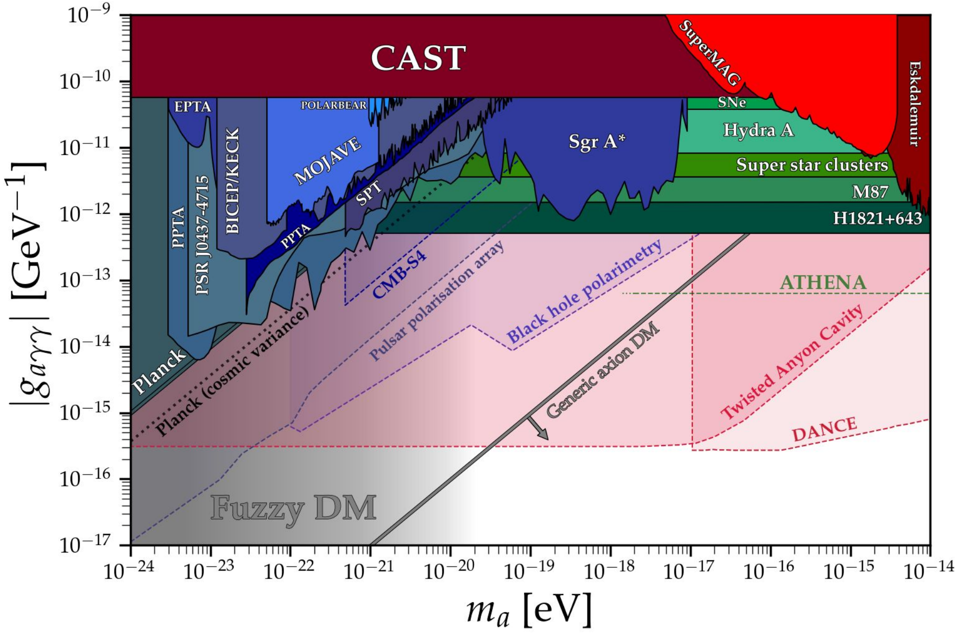
1. QCD axions and ALPs can form the localized astrophysical object: axion stars.

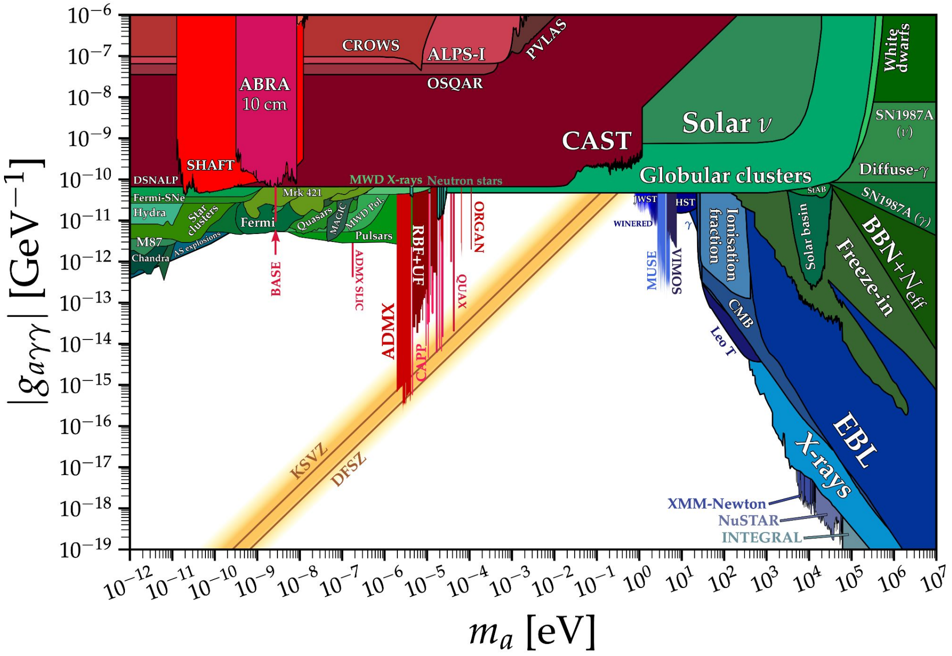
2. We combine the gravitational effect with additional finite-size and axion-photon coupling effects on FRB lensing.

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

Thank You

Backup


CAST
SuperMAG
Eskdalemuir
EPTA
POLARBEAR
SNe
Hydra A
Sgr A*
MOJAVE
BICEP/KECK
PSR J0437-4715
PPTA
Super star clusters
M87
H1821+643
SPT
CMB-S4
ATHENA
Planck
Planck (cosmic variance)
Pulsar polarisation array
Black hole polarimetry
Generic axion DM
Twisted Anyon Cavity
DANCE
Fuzzy DM
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]


CROWS
ALPS-I
PVLAS
OSQAR
ABRA 10 cm
SHAFT
CAST
Solar ν
White dwarfs
SN1987A (ν)
Diffuse-γ
SN1987A (γ)
Globular clusters
DSNALP
Fermi-SNe
Hydra
M87
Chandra
Star clusters
Fermi
Mrk 421
Quasars
MAGIC
MWD Pol.
Pulsars
MWD X-rays
Neutron stars
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
QUAX
ORGAN
JWST
WINERED
MUSE
VIMOS
HST
Ionisation fraction
Solar basin
BBN+Neff
Freeze-in
CMB
Leo T
EBL
X-rays
XMM-Newton
NuSTAR
INTEGRAL
KSVZ
DFSZ
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]

Axion Star Profile

[Enrico D. Schiappacasse and Mark P. Hertzberg. JCAP 01(2018)037]
[Eric Braaten and Hong Zhang. Rev. Mod. Phys. 91, 041002 2019]

Axion star is described by non-relativistic EFT and Newtonian gravity.

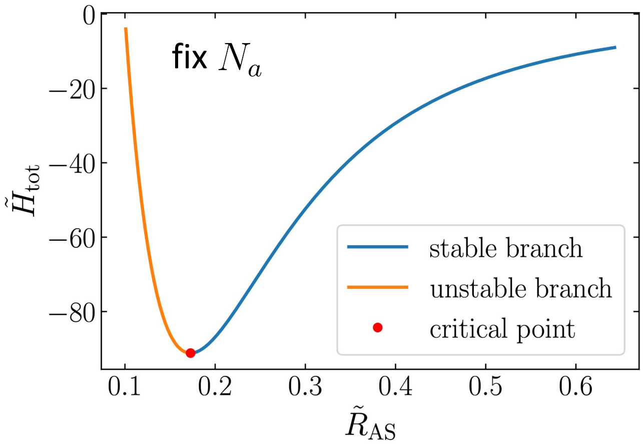
$$\mathcal{L} \xrightarrow[\text{transform}]{\text{Legendre}} \mathcal{H} \qquad H_{\text{tot}} = H_{\text{kin}} + H_{\text{grav}} + H_{\text{int}}$$

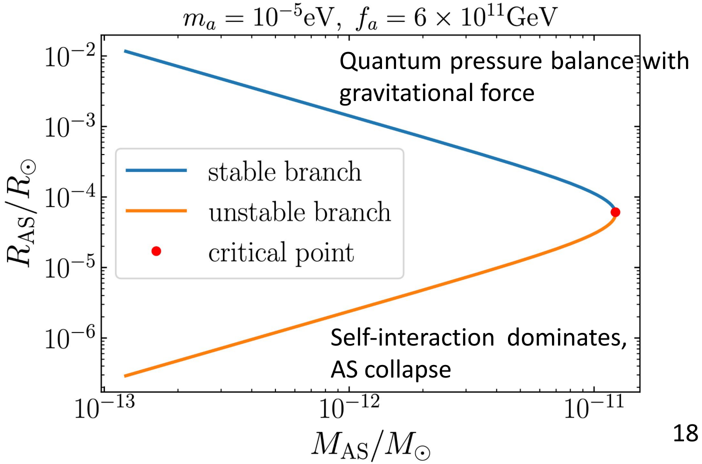
For axion field with Gaussian radial profile:

$$N_a \simeq 2.2786 \times 10^{60} \times \alpha \left(\frac{10^{-5}\text{eV}}{m_a}\right)^2 \left(\frac{f_a}{10^{12}\text{GeV}}\right)$$

$$R_{\text{AS}} \simeq 2.4304 \times 10^4\text{m} \left(\frac{1+\sqrt{1-\alpha^2}}{\alpha}\right) \left(\frac{10^{-5}\text{eV}}{m_a}\right) \left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

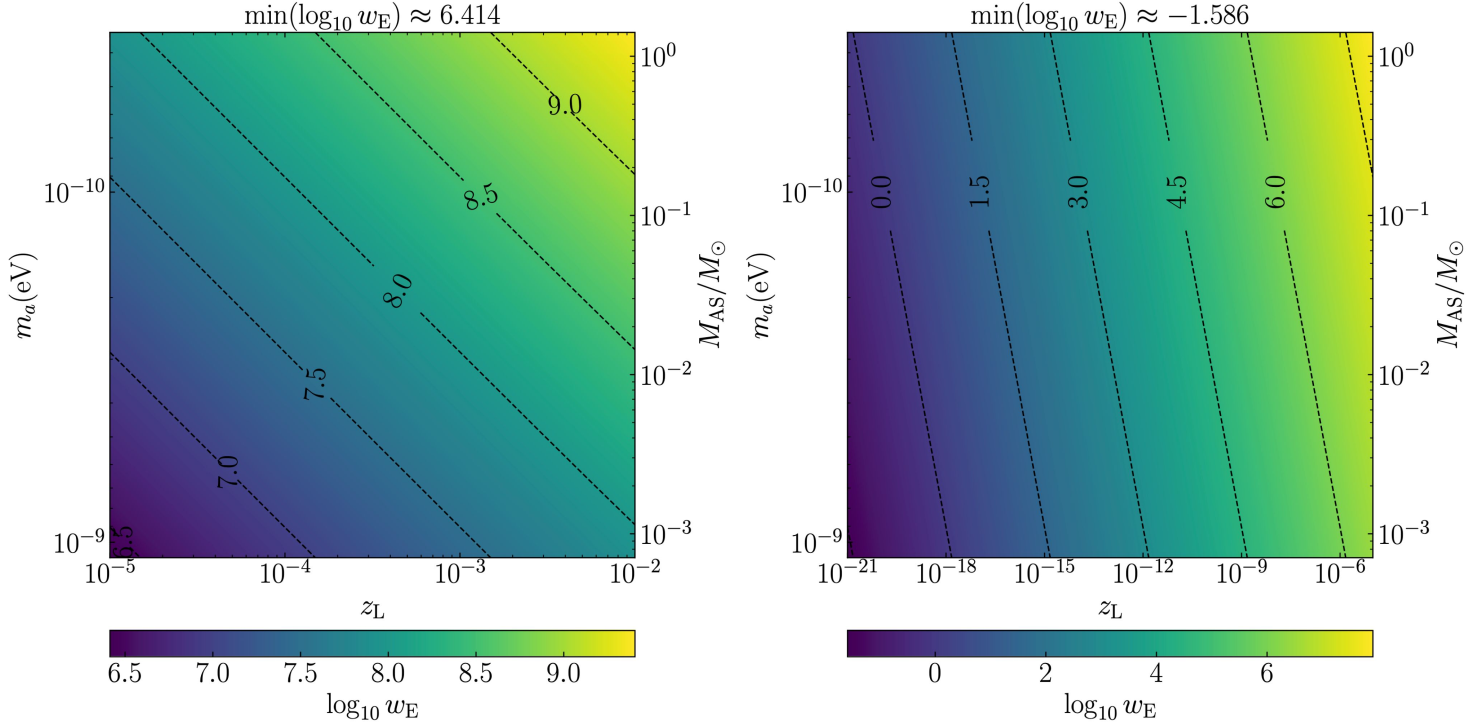
$$M_{\text{AS}} \simeq 2.0399 \times 10^{-11} M_\odot \times \alpha \left(\frac{10^{-5}\text{eV}}{m_a}\right) \left(\frac{f_a}{10^{12}\text{GeV}}\right)$$





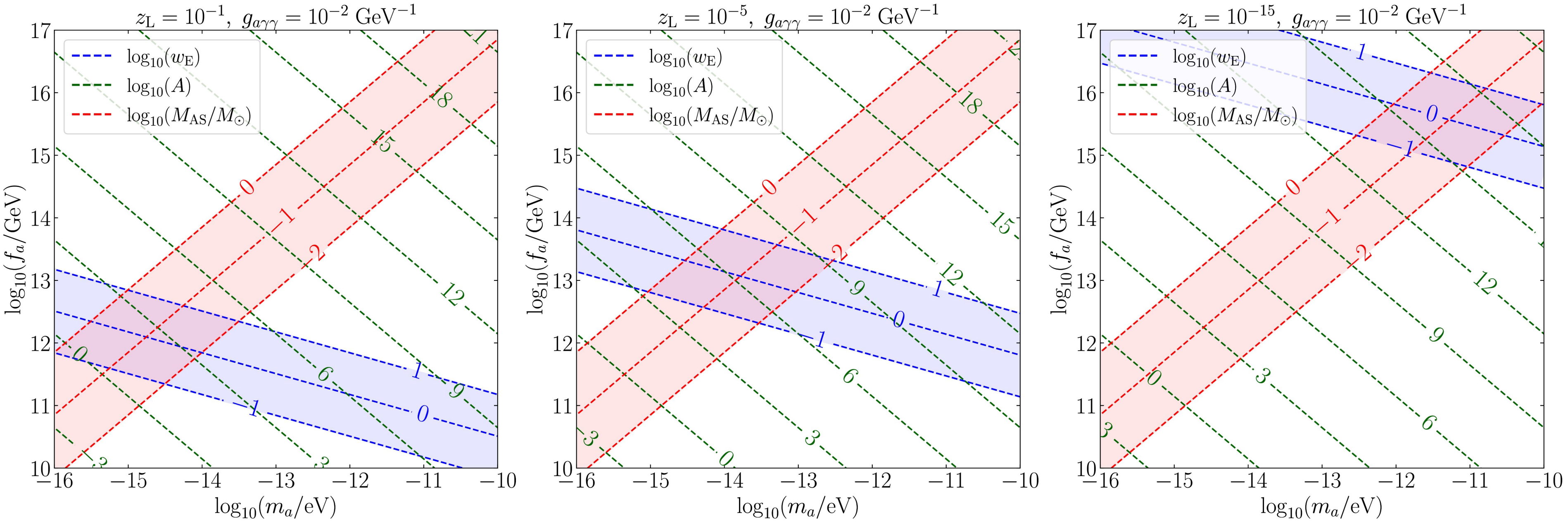
QCD Axion - w_E Distribution

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



ALP - w_E, A, M_{AS} Distribution

Desire parameter region satisfies: $10^{-1} \le w_E \le 10^1$ $10^{-2} \le M_{AS}/M_\odot \le 10^0$ $A \gg 1$



Scanned parameter region: $10^{-16} \le m_a/\mathrm{eV} \le 10^{-10}$ $10^{10} \le f_a/\mathrm{GeV} \le 10^{17}$

FRB Lensing Probability

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

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

- $n(M_{\rm AS})$: NFW profile (galactic contribution)
  : 0.3 GeV/cm3 (extragalactic contribution)

- Constant comoving number density:

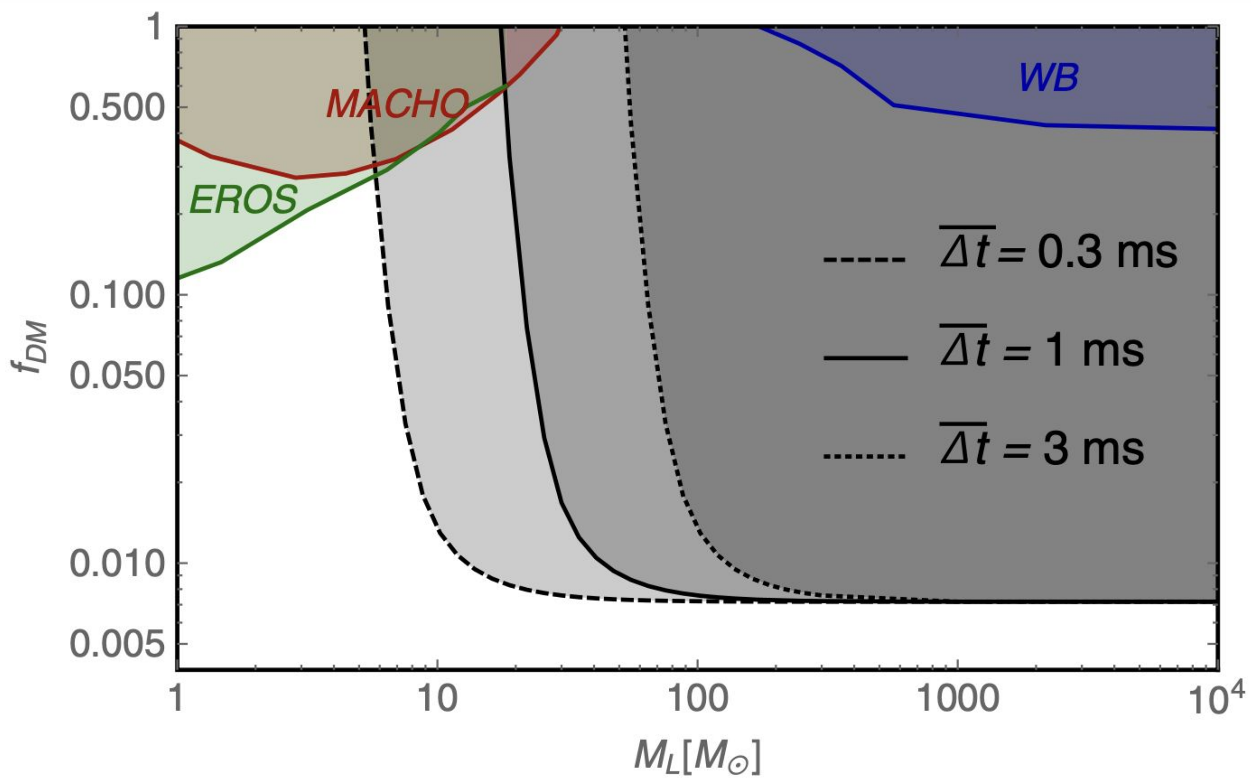
$$N_{\rm FRB}(z) = \mathcal{N} \frac{\chi^2(z)}{H(z)(1+z)} \exp\left(-\frac{d_{\rm L}^2(z)}{2d_{\rm L}^2(0.5)}\right)$$

- Lensing probability:

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

Constraint: PBH

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



Constraint: PBH

[Simon C.-C. Ho et al. ApJ 950 53 (2023)]