Microlensing constraints on axion stars including finite lens and source size effects

Seminar at Osaka University (2022/05/31)

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Content

- **Introduction**
- **Axion Stars**
- **Microlensing Constraints on Axion Stars**

The Strong CP Problem

- **CP-violating phase in the SM**

$$\mathcal{L}_{\rm SM} \supset \bar{\theta}\frac{g_s^2}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$G_{\mu\nu}$ **:Gluon field strength**

$$\tilde{G}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{\rho\sigma}$$

Naive expectation:

$$\bar{\theta} \sim \mathcal{O}(1)$$

- **A measurement of the neutron electric dipole moment**

[Baker et al. (2006)]

$$\bar{\theta} < 10^{-10}$$

Why $\bar{\theta}$ is tiny? (strong CP problem)

QCD axion (1)

- **Peccei-Quinn Mechanism** [Peccei, Quinn (1977)]

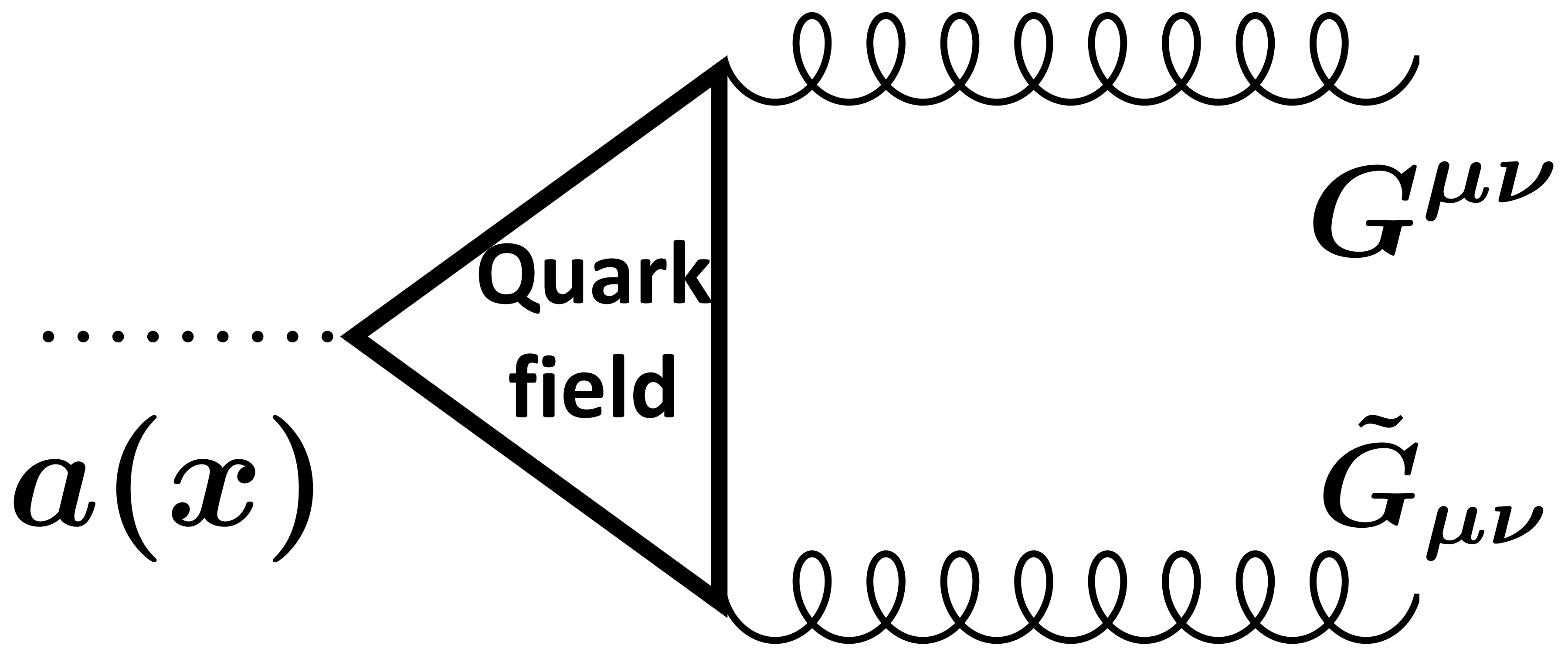
  Introduce an additional (global) $U(1)_{\mathrm{PQ}}$ symmetry

  which is spontaneous broken at some scale F_a.

$$\langle \Phi_{\mathrm{PQ}} \rangle = F_a e^{ia(x)/F_a}$$

Nambu-Goldstone boson $a(x)$ is called "(QCD) axion"

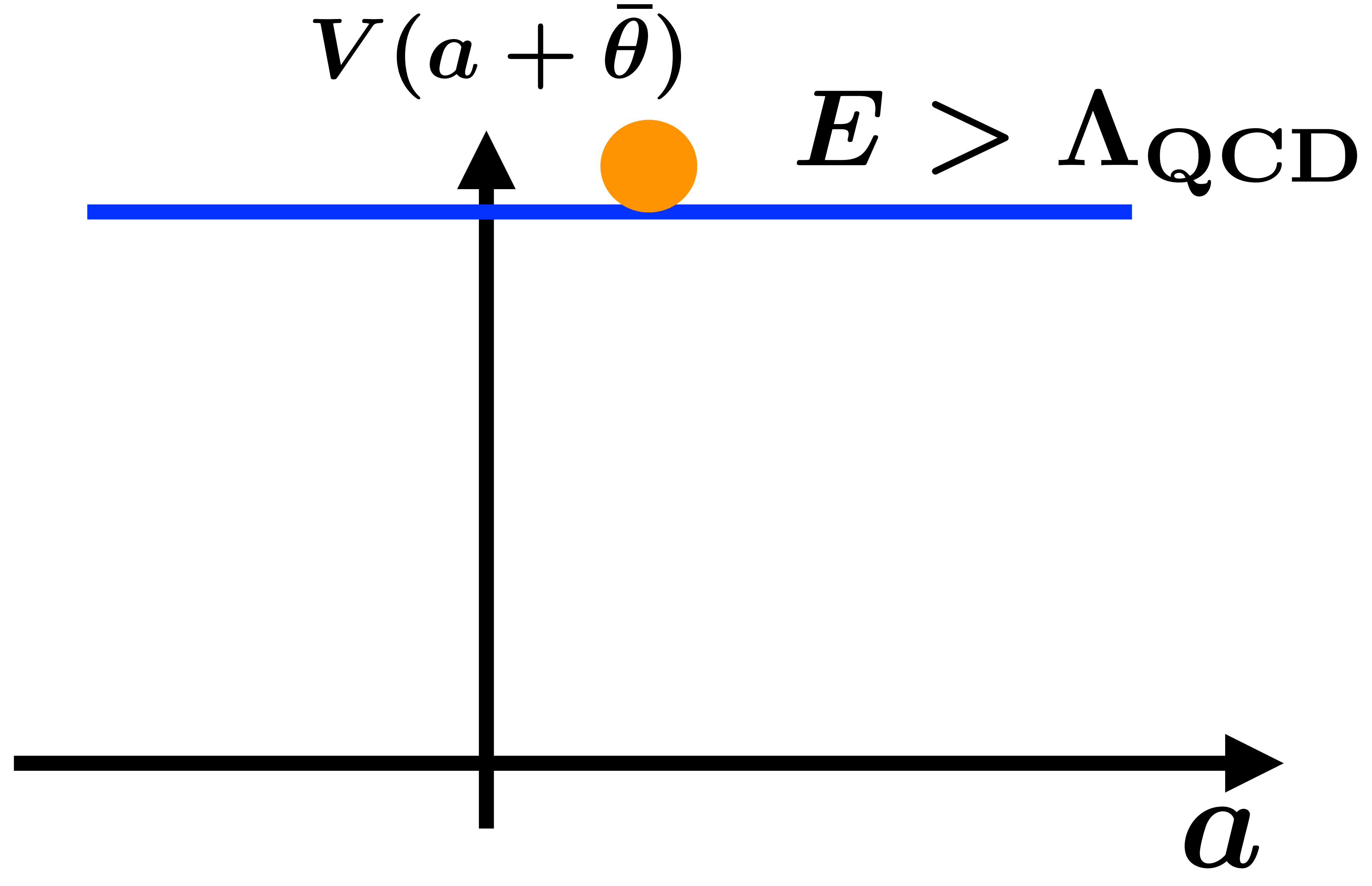
- **Suppose that $U(1)_{\mathrm{PQ}}$ is anomalous under $SU(3)_C$**

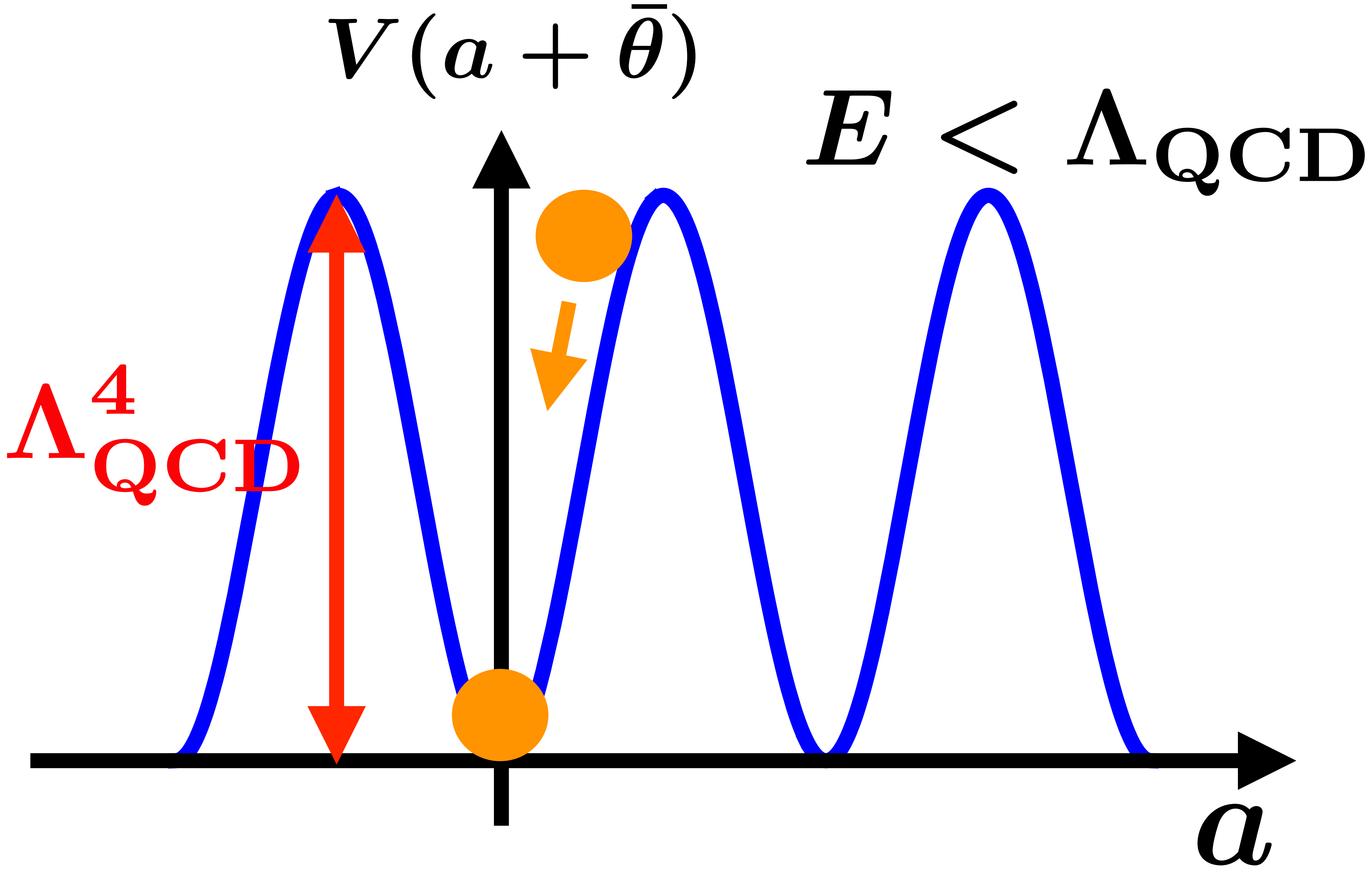


$$\frac{g_s^2}{32\pi^2}\left(a(x)+\bar{\theta}\right)G^{\mu\nu}\tilde{G}_{\mu\nu}$$

QCD axion (2)

Below the QCD scale $\Lambda_{\rm QCD} \sim 100\,\mathrm{MeV}$, the axion acquires potential by non-perturbative effects!





$$V(a) \sim \Lambda_{\rm QCD}^4 \cos\left(a(x)/F_a + \bar{\theta}\right)$$

Observable CP-violating phase

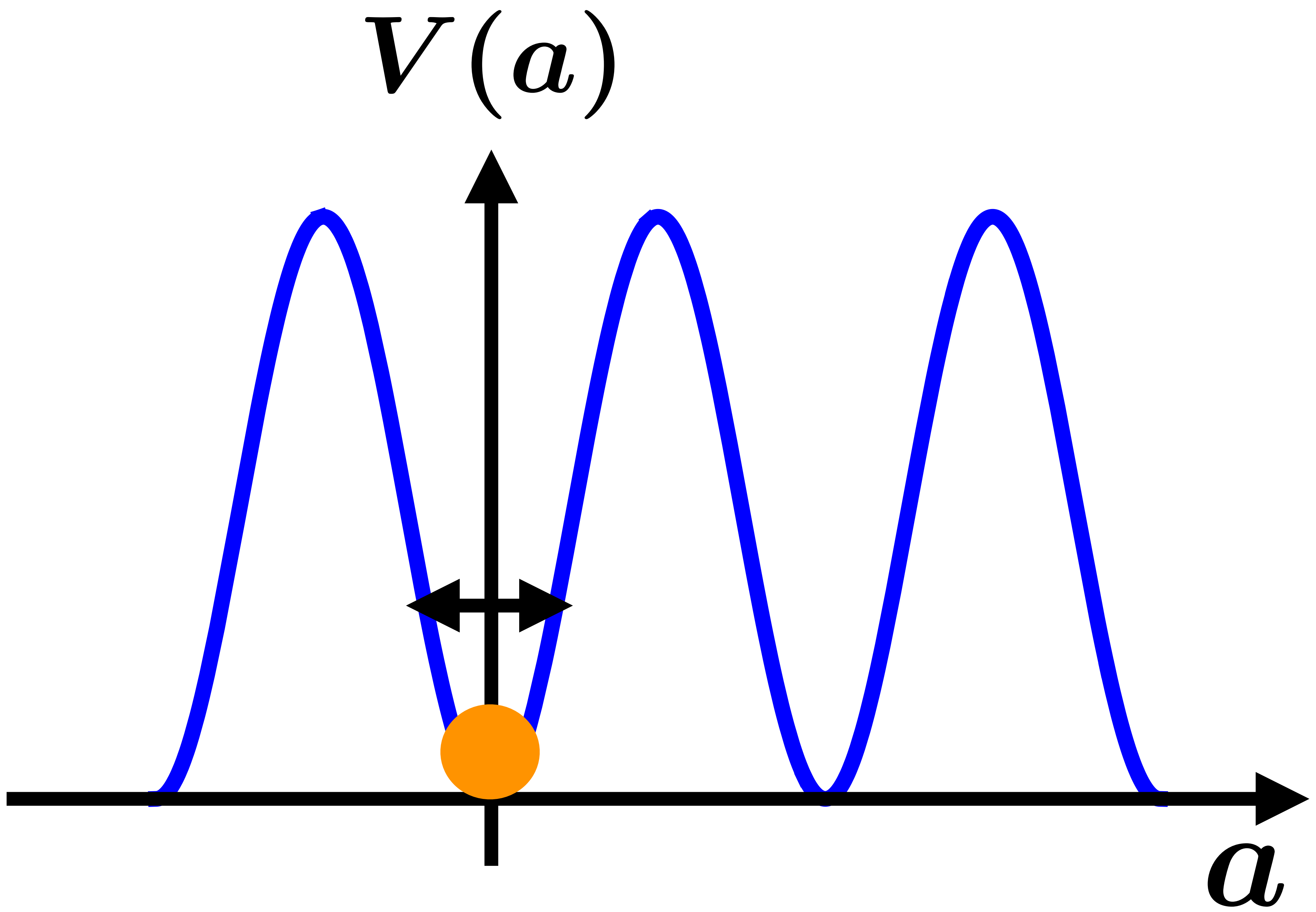
The potential minimum is CP symmetric!

(Strong CP problem can be solved!)

QCD axion (3)

$$V(a) \sim \Lambda_{\mathrm{QCD}}^4 \cos\left(\frac{a(x)}{F_a}\right)$$

$$V(a) = \frac{1}{2} m_a^2 a^2 - \frac{\lambda}{4!} a^4 + \cdots \qquad m_a = \Lambda_{\mathrm{QCD}}^2 / F_a \qquad \lambda \sim \Lambda_{\mathrm{QCD}}^4 / F_a^4$$



The axion mass:

$$m_a \sim 10^{-5}\,\mathrm{eV}$$

Attractive self-coupling:

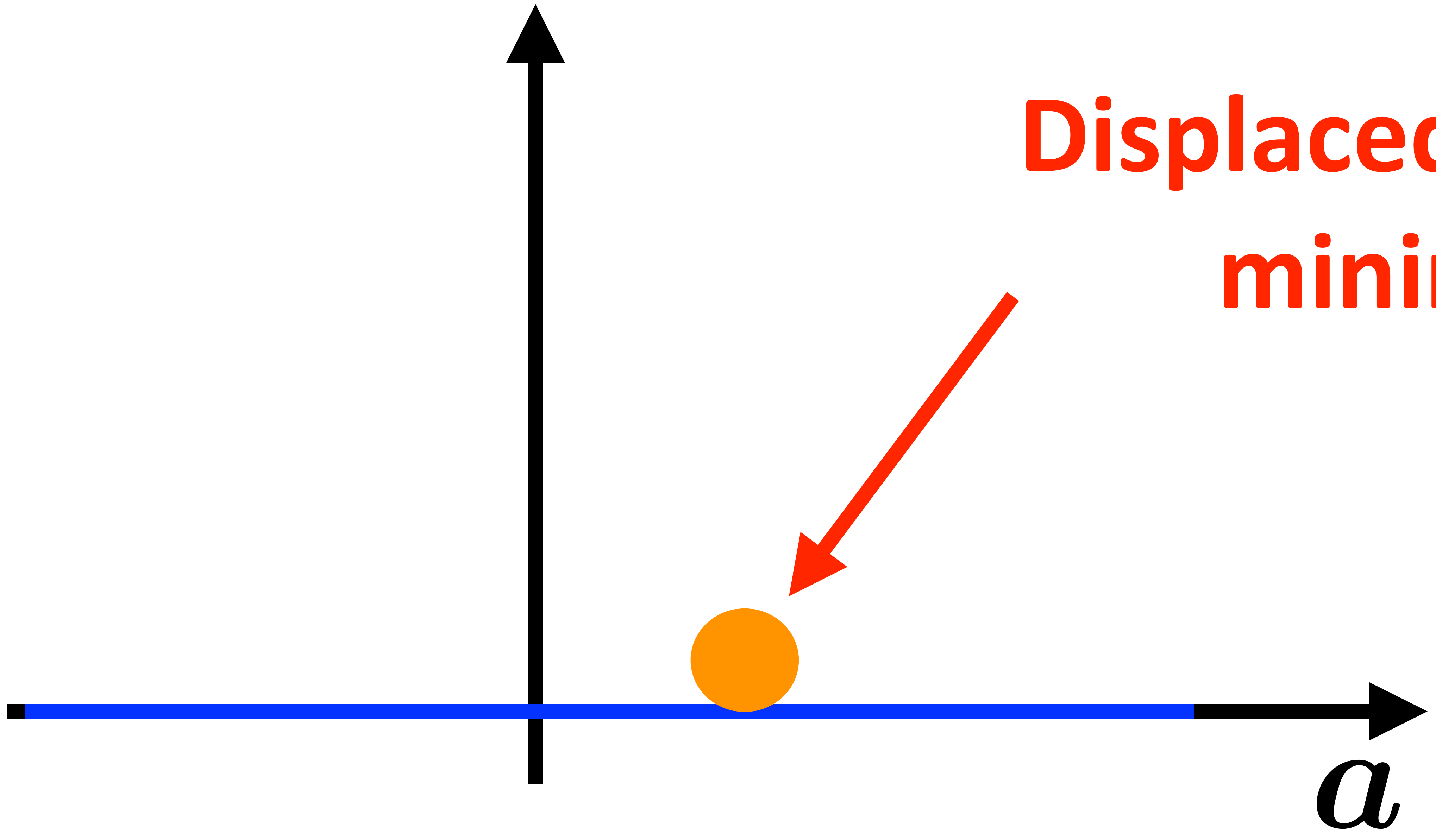
$$\lambda \sim 10^{-52}$$

when $F_a \sim 10^{12}\,\mathrm{GeV}$

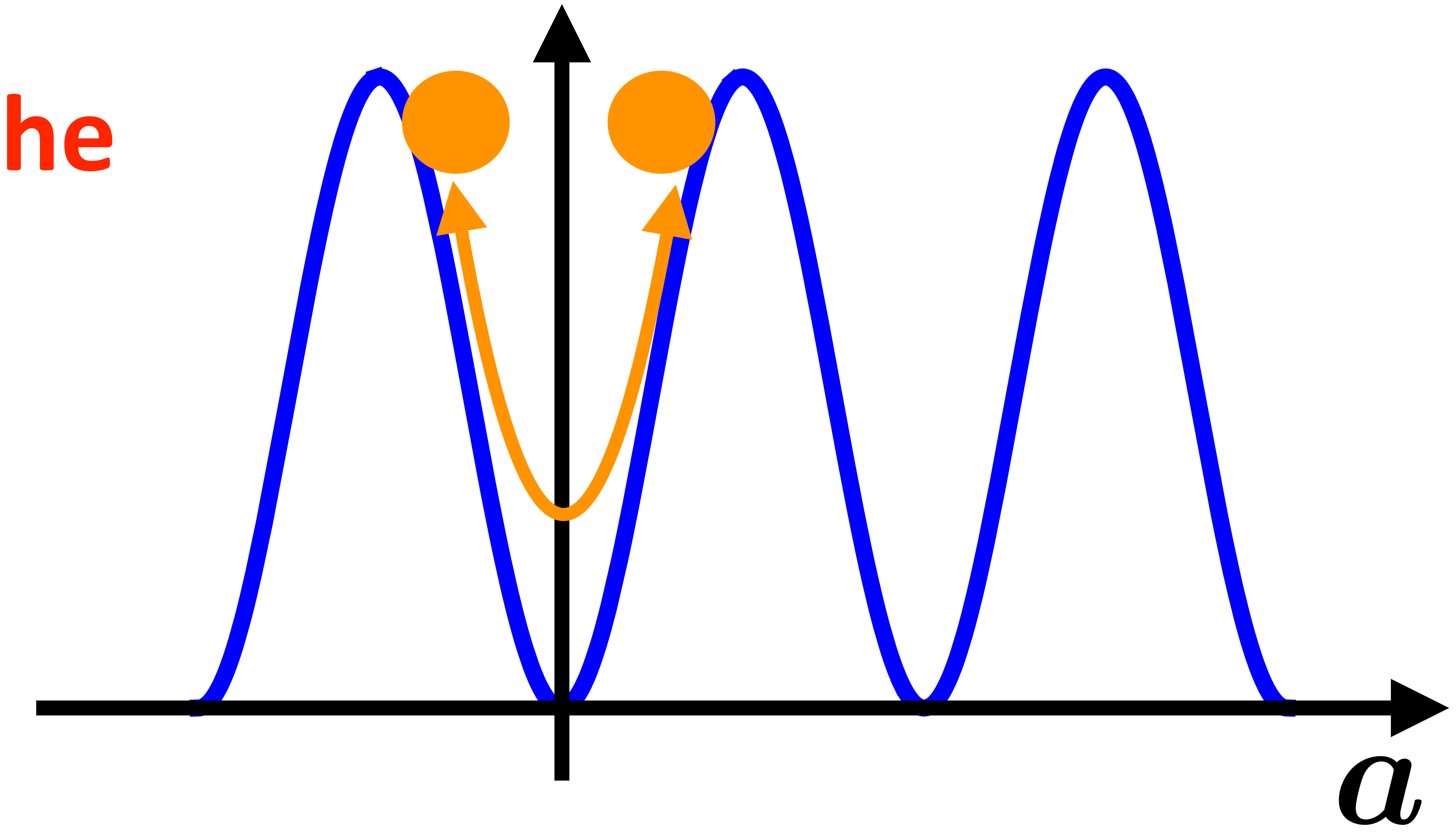
Dark matter axions (1)

The QCD axion can be dark matter candidate!

$T > \Lambda_{\rm QCD}$



$T \sim \Lambda_{\rm QCD}$

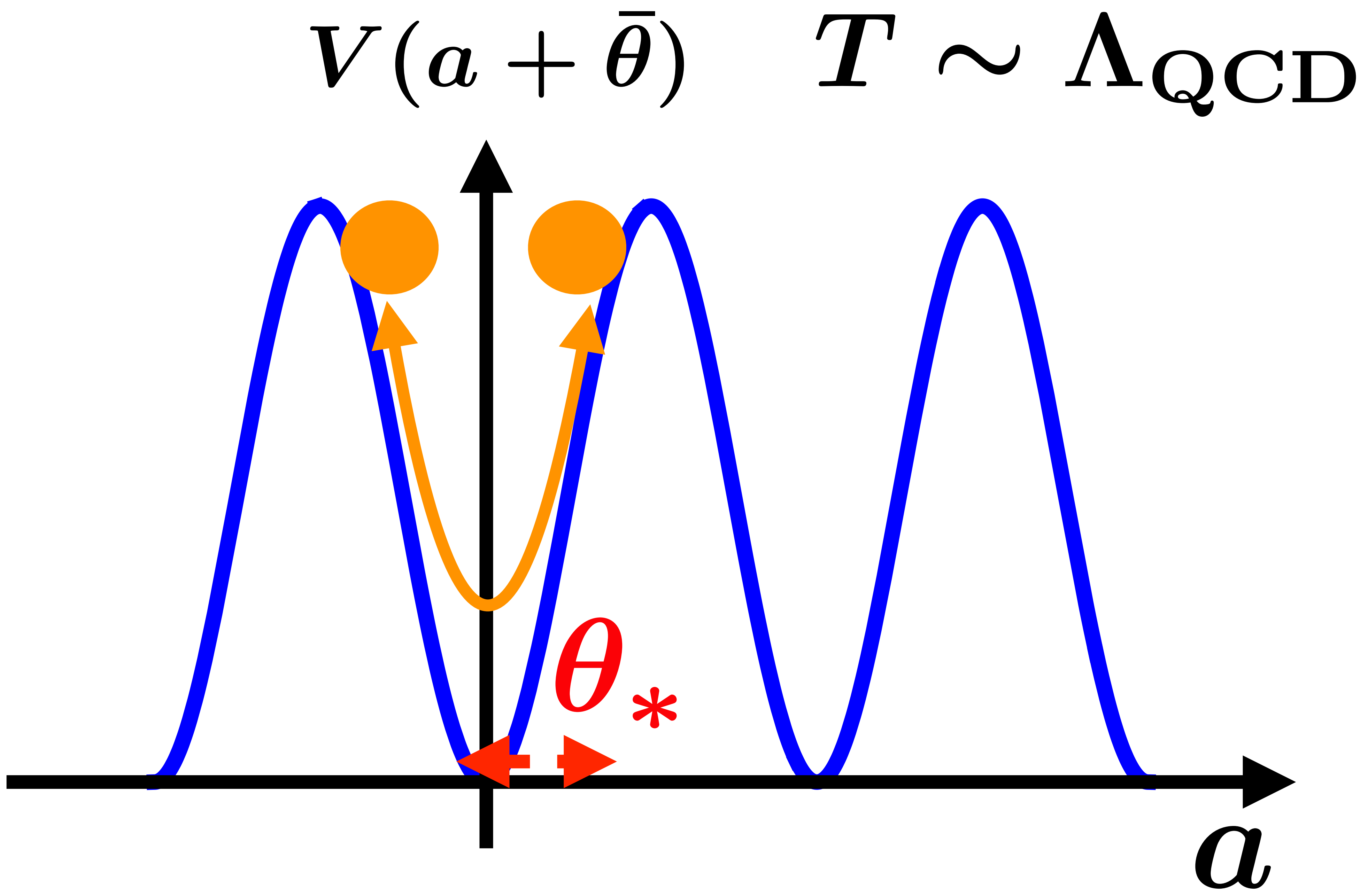


$$\ddot{a} + 3H(T)\dot{a} + m_a^2 a \simeq 0$$

$H(T)$:Hubble parameter

The axion starts to oscillate at $H(T_*) \sim m_a(T_*)$.

Dark matter axions (2)



Coherent oscillation of the axion behave like cold dark matter.

$$\Omega_{\rm osc} h^2 \sim \theta_*^2 \left(\frac{F_a}{10^{12}\,\mathrm{GeV}} \right)^{1.19}$$

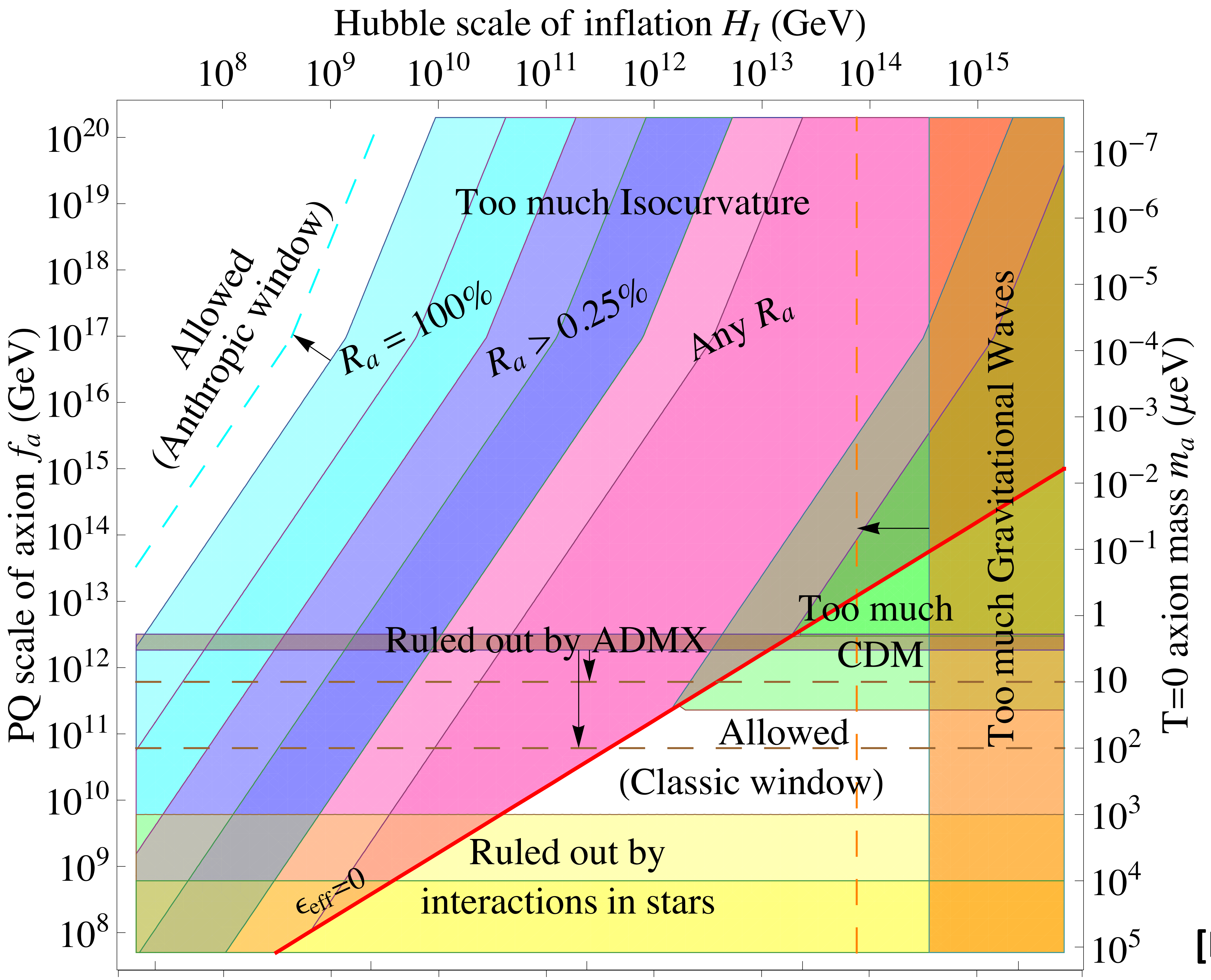
[Kawasaki, Nakayama (2013)]

θ_*: initial misalignment angle

Coherent oscillation of generic light scalar fields (axion-like particles) can be DM!

[Svrcek, Witten (2006)]

The QCD Axion Window



[Hertzberg, Tegmark, Wilczek (2008)]

Energy loss rate of supernova **Dark matter overproduction**

$$10^9 \lesssim F_a/\mathrm{GeV} \lesssim 10^{12}$$

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Axions in the early Universe

✔ **Non-relativistic axions are produced with high occupancy.**

Small velocity dispersion:

$$\delta v \sim \frac{\delta p}{m_a} \sim \frac{H(T_{\rm QCD})}{m_a} \sim 10^{-6} \ll 1$$

Occupancy number:

$$n_{\rm gal} = \frac{\rho_{\rm gal}}{m_a} \sim 10^{14}\,{\rm cm}^{-3}$$

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✔ **Axions are bosons and no number violating process.**

Axion-photon coupling is suppressed by F_a.

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✔ **Axions are bosons and no number violating process.**

✔ **Thermalization of axions (?)**

[Sikivie, Yang (2009)] [Erken, Sikivie, Tam, Yang (2011)] [Saikawa Yamaguchi (2013)] [Noumi, Saikawa, Sato, Yamaguchi (2014)]

[… and so many works…]

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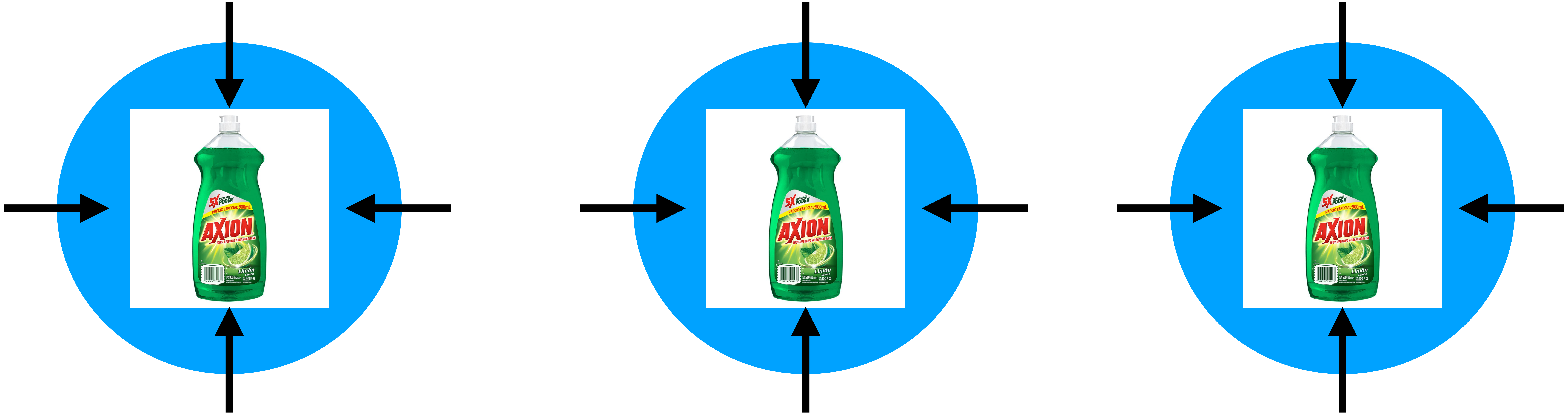
High occupancy and thermalization suggest axion Bose-Einstein condensate.

A consequence of Bose-Einstein condensate

When Bose-Einstein condensate takes place, many axions are in the ground state labeled by wavefunction $\phi_{\mathrm{BEC}}(x,t)$!

Claim: “Localized clumps” made of axions bounded by gravity (axion stars) are formed.

[Guth, Hertzberg, Weinstein (2014)]



The Ground State of Axions

- **Non-relativistic effective field theory of a real scalar field:**

$$\phi_{\mathrm{BEC}}(\mathrm{x},t) = \frac{1}{\sqrt{2m_a}}\left(e^{-im_a t}\psi(\mathrm{x},t) + e^{im_a t}\psi^*(\mathrm{x},t)\right)$$

[Eby et al. (2021)]
[Salehian et al. (2021)]

$\nabla\psi(x,t) \ll m_a\psi(x,t),\ \dot{\psi}(x,t) \ll m_a\psi(x,t)$ $\quad n(x) \equiv \psi^*(x)\psi(x)$ **:Number density**

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- **The equation of motion of non-relativistic field ψ with gravity:**

$$i\dot{\psi} = \underbrace{-\frac{1}{2m_a}\nabla^2\psi}_{\text{Pressure}} \underbrace{- Gm_a^2\psi\int d^3x'\frac{|\psi(x')|^2}{|x-x'|}}_{\text{Gravity}} \underbrace{- \frac{\lambda}{8m_a^2}|\psi|^2\psi}_{\text{Self-coupling}}$$

Pressure **Gravity** **Self-coupling**

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Pressure **Gravity** **Self-coupling**

- **This equation is similar to the Schrödinger equation of a hydrogen atom (when we forget about λ)!**

Axion Stars (1)

Let us find the ground state for **fixed particle number** N **by using variational principle.**

N: **Number of axions in the ground state** $\int d^3x|\psi(x)|^2 = N$

$$H_{\rm tot} = H_{\rm kin} + H_{\rm int} + H_{\rm gravity}$$

$$H_{\rm kin} = \frac{1}{2m_a}\int d^3\mathbf{x}\nabla\psi^*(\mathbf{x})\nabla\psi(\mathbf{x})$$

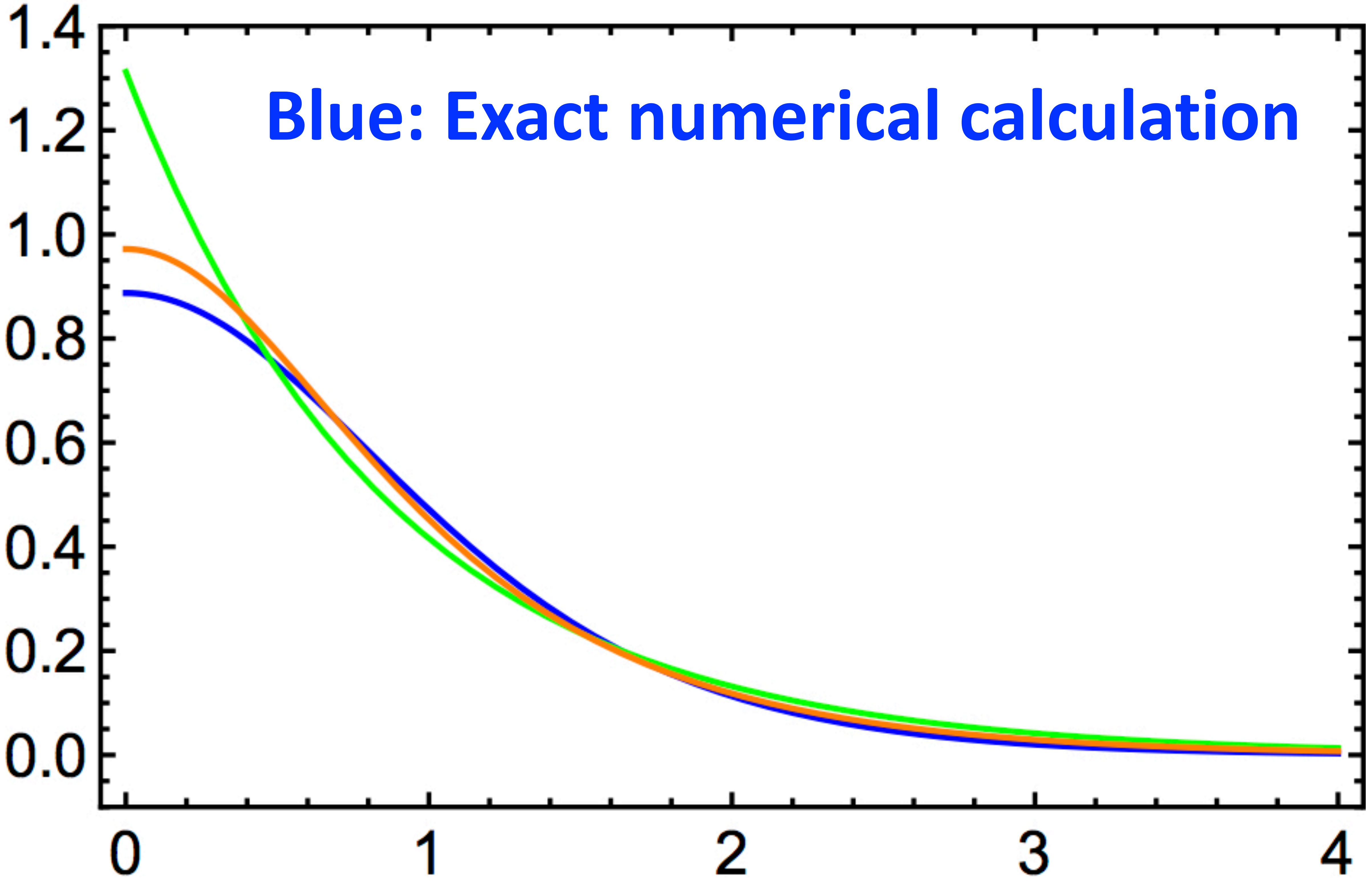
$$H_{\rm int} = -\frac{\lambda}{16m_a^2}\int d^3\mathbf{x}|\psi(\mathbf{x})|^4$$

$$H_{\rm gravity} = -\frac{G_N m_a^2}{2}\int d^3\mathbf{x}\int d^3\mathbf{x}'\frac{|\psi(\mathbf{x})|^2|\psi(\mathbf{x}')|^2}{|\mathbf{x}-\mathbf{x}'|}$$

Ansatz of configuration

$$\psi(r) = \sqrt{\frac{3N}{\pi^3 R^3}}\,\mathrm{sech}\left(\frac{r}{R}\right) \qquad \psi(r) = \sqrt{\frac{N}{\pi R^3}}\,e^{-r/R}$$

$\psi(r)$



r/R

$$\int d^3x |\psi(x)|^2 = N$$

R **:Typical radius of the axion stars**

[Schiappacasse, Hertzberg (2017)]

Axion Stars (2)

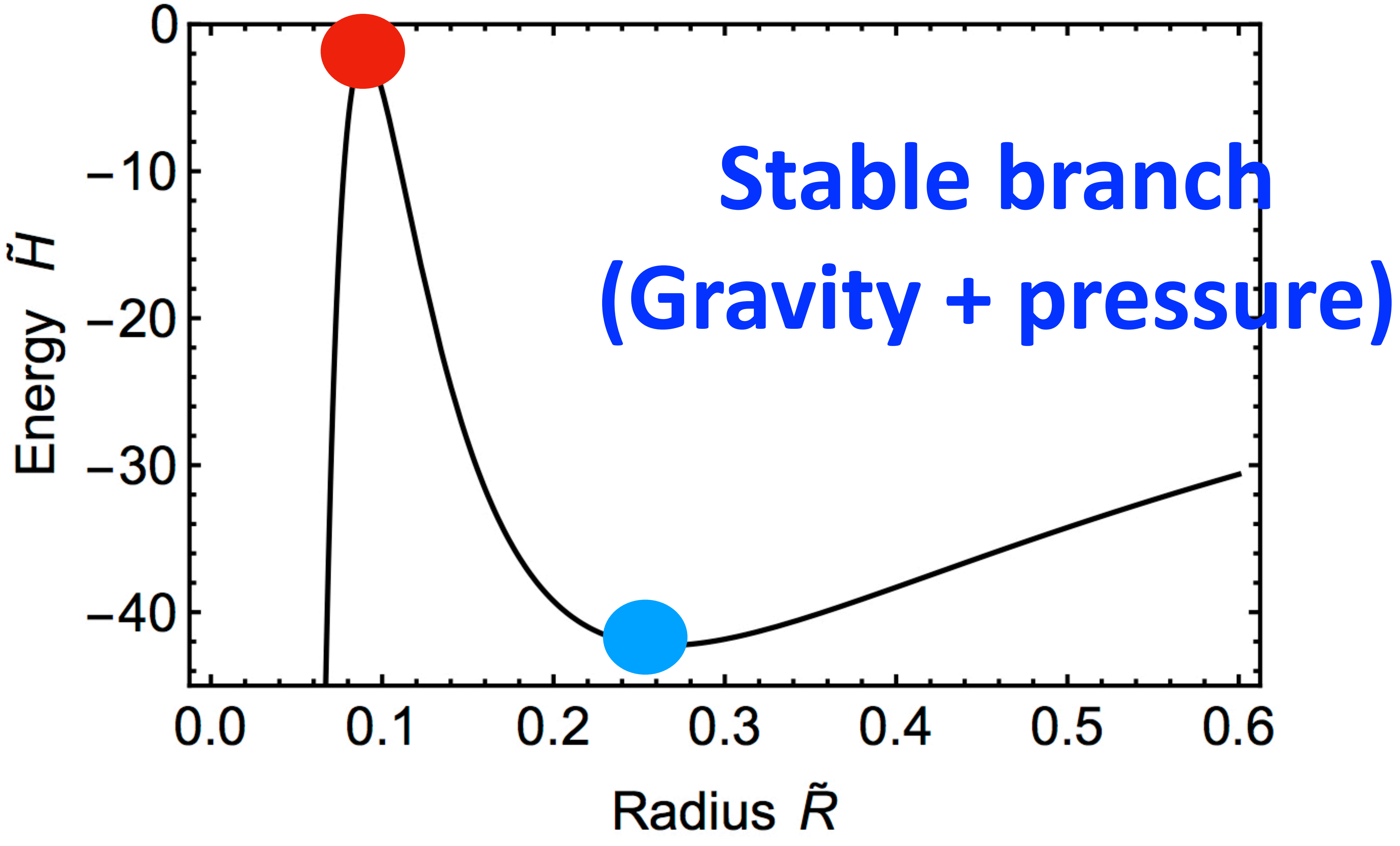
$$\widetilde{H}_{\mathrm{tot}} = a\frac{\widetilde{N}}{\widetilde{R}^2} - b\frac{\widetilde{N}^2}{\widetilde{R}} - c\frac{\widetilde{N}^2}{\widetilde{R}^3}$$

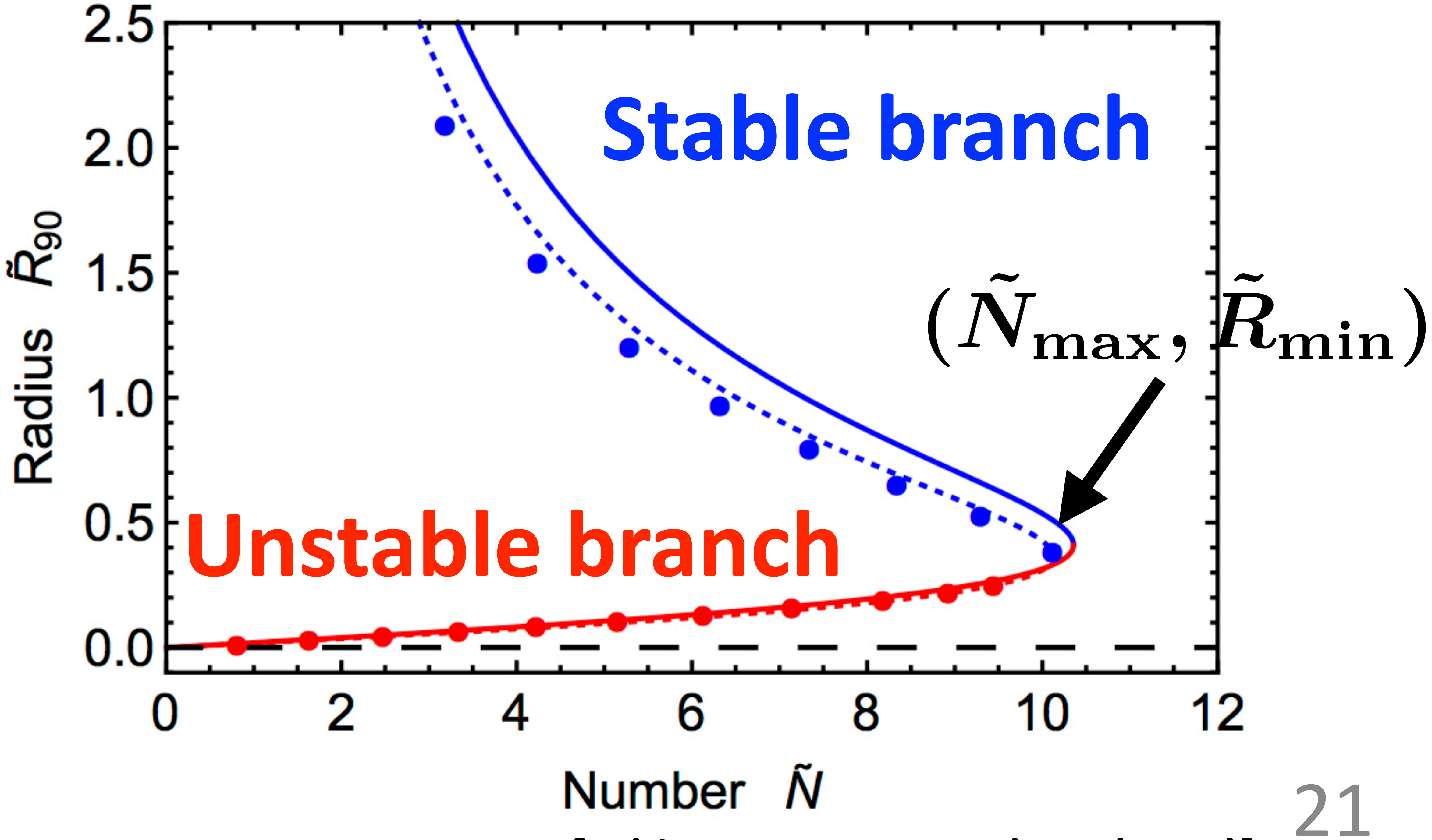
$$\widetilde{N} \equiv \frac{m_a^2\sqrt{G_N}}{F_a}N$$

$$\tilde{R} = m_a\sqrt{G_N}F_aR$$

$$\widetilde{H}_{\mathrm{tot}} \equiv \frac{m_a}{F_a^3\sqrt{G_N}}H_{\mathrm{tot}}$$

Unstable branch
(self-coupling dominate)





[Schiappacasse, Hertzberg (2017)]

Parameters

$$\widetilde{N} = \alpha \widetilde{N}_{\max}, \ \tilde{R} = \frac{1}{\alpha}\tilde{R}_{\min}\left(1+\sqrt{1-\alpha^2}\right) \qquad 0 \le \alpha \le 1$$

F_a : the breaking scale of axion

m_a : the axion mass

α : the clump density

$m_a = \Lambda_{\mathrm{QCD}}^2 / F_a$ for the QCD axion

(For axion-like particles, there is no relation.)

$\Omega_{\mathrm{clump}}/\Omega_{\mathrm{DM}}$: Fraction of dark matter collapsed into clumps

(Generically, $\Omega_{\mathrm{clump}} \le \Omega_a$ (Ω_a :axion energy density)

Axion Stars (3)

Typical radius and mass of (QCD) axion stars

$$N \simeq 1.7 \times 10^{60} \times \alpha \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)^2 \times \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)$$

$$R \simeq 1.8 \times 10^{4}\,\mathrm{m} \times \left(\frac{1+\sqrt{1-\alpha^2}}{\alpha}\right) \times \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right) \times \left(\frac{10^{12}\mathrm{GeV}}{F_a}\right)$$

$$M_{\mathrm{clump}} = N m_a \simeq 1.5 \times 10^{-11} M_{\odot} \times \alpha \left(\frac{10^{-5}\mathrm{eV}}{m_a}\right) \times \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)$$

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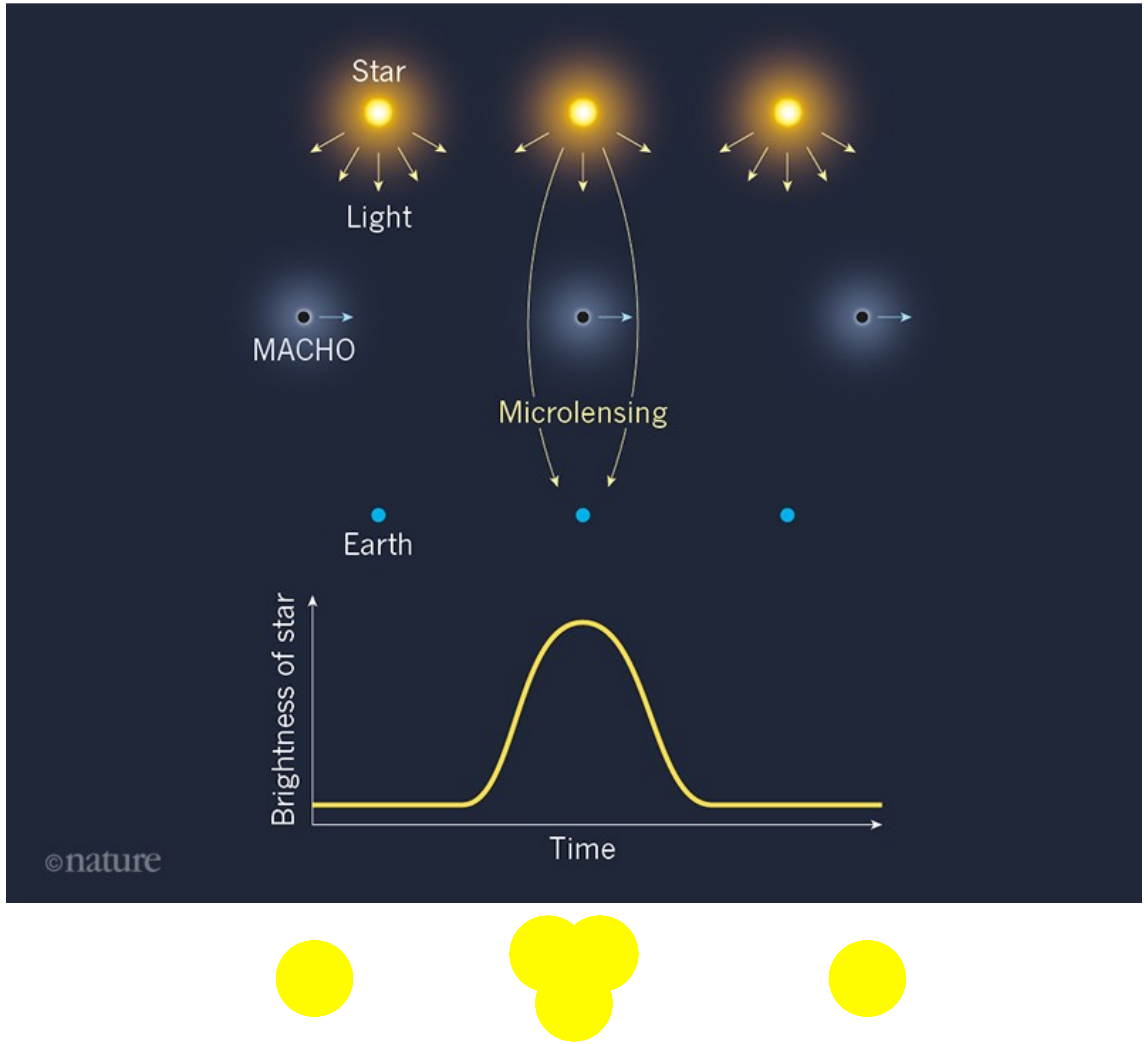
$$M_{\mathrm{clump}} = N m_a \simeq \underline{1.5 \times 10^{-11} M_{\odot}} \times \alpha \left(\frac{10^{-5}\mathrm{eV}}{m_a} \right) \times \left(\frac{F_a}{10^{12}\mathrm{GeV}} \right)$$

Heavy.

Is it possible to constrain the axion star by observation of microlensing events?

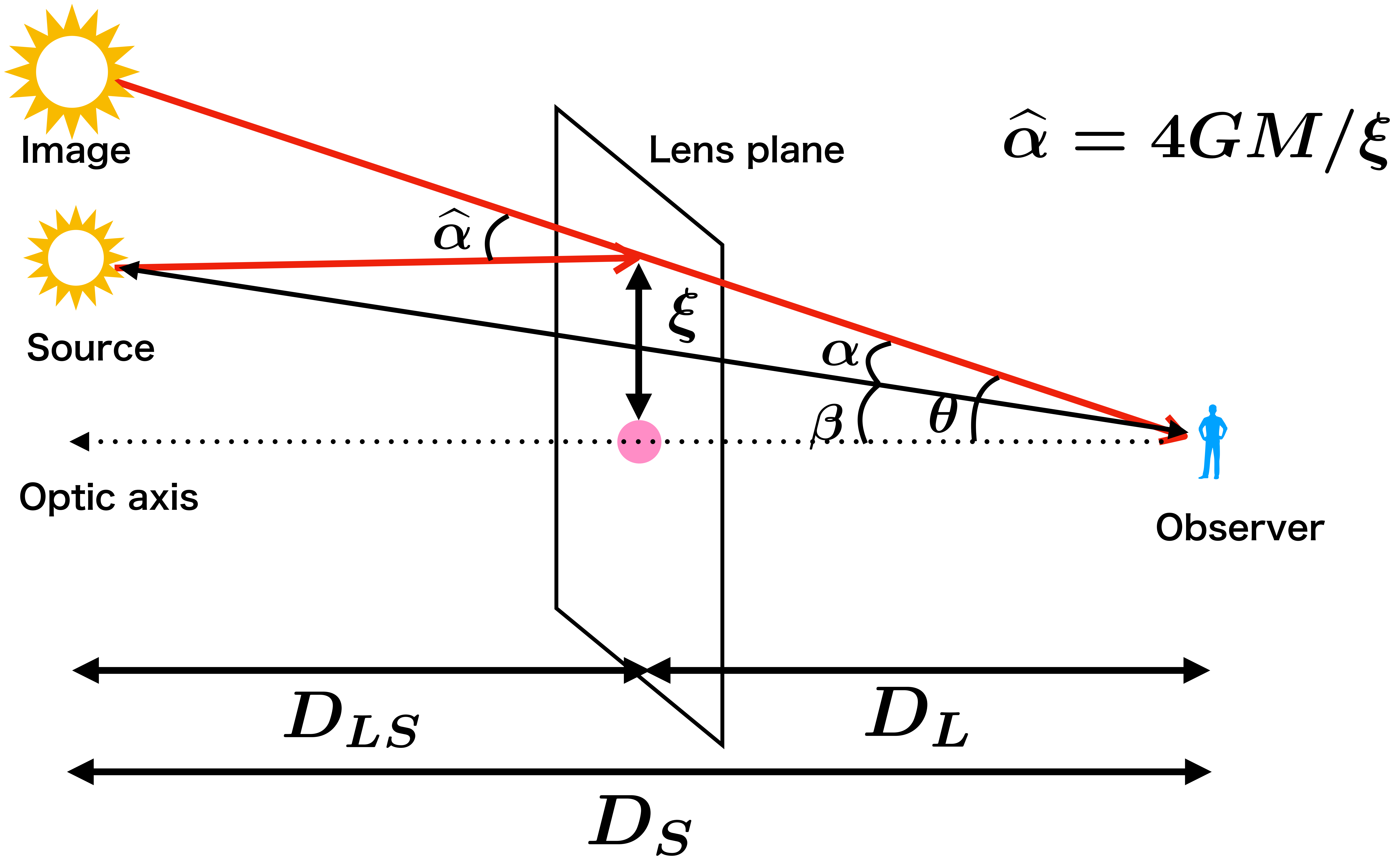
Gravitational lens

- Image of a background source star is distorted when massive object pass close to its line-of-sight.
- One can observe time varying amplification of the source star. (Microlensing events)
- Massive compact objects are constrained by microlensing events!

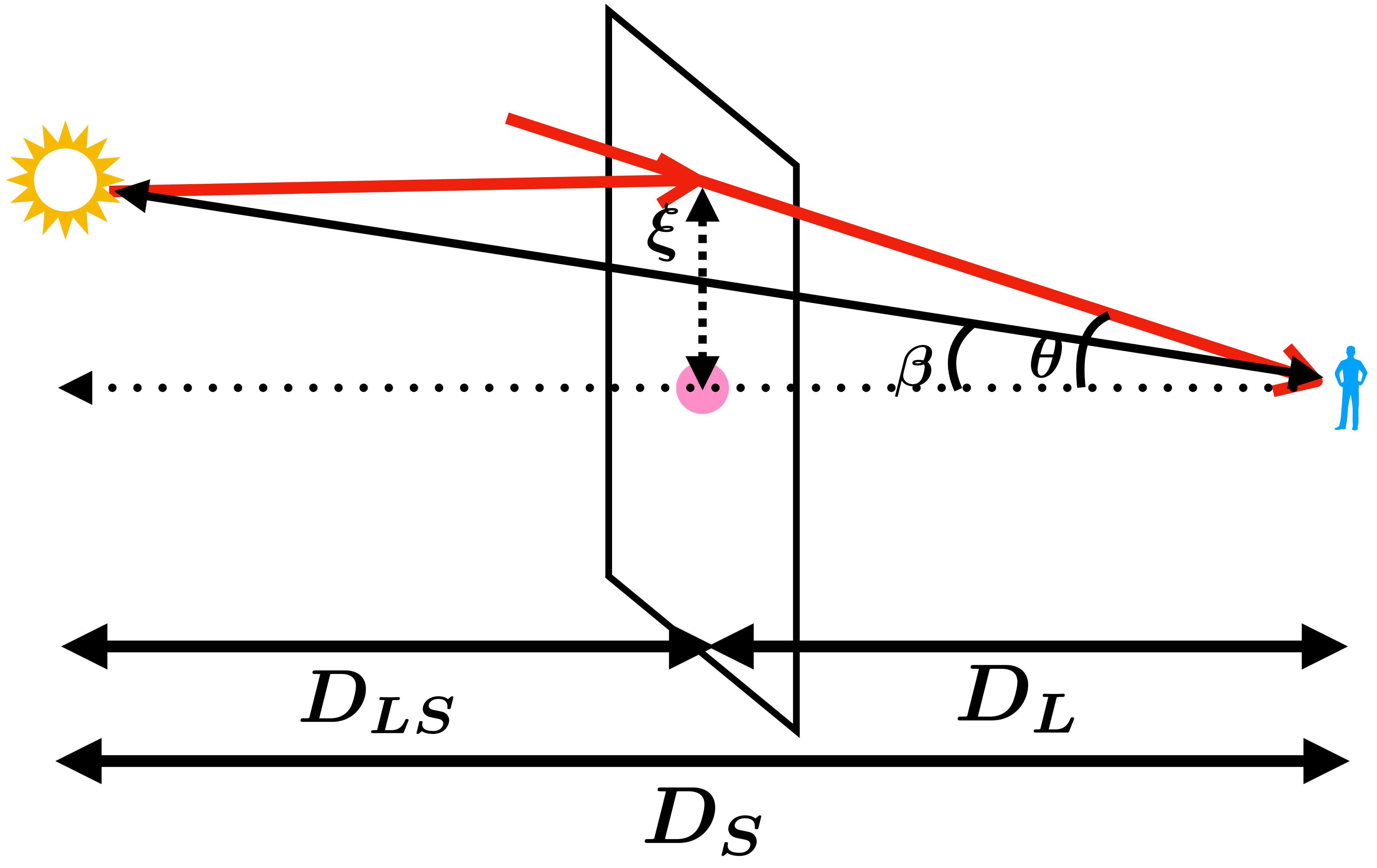


Microlensing by a point mass lens
(e.g. PBHs)

Setup (Compact Massive Object)



Magnification (Point mass lens)



Magnification:

$\mu \equiv$ **Image area / Source area**

$$\mu = \frac{\theta}{\beta}\frac{d\theta}{d\beta} = \frac{u^2+2}{u\sqrt{u^2+4}}$$

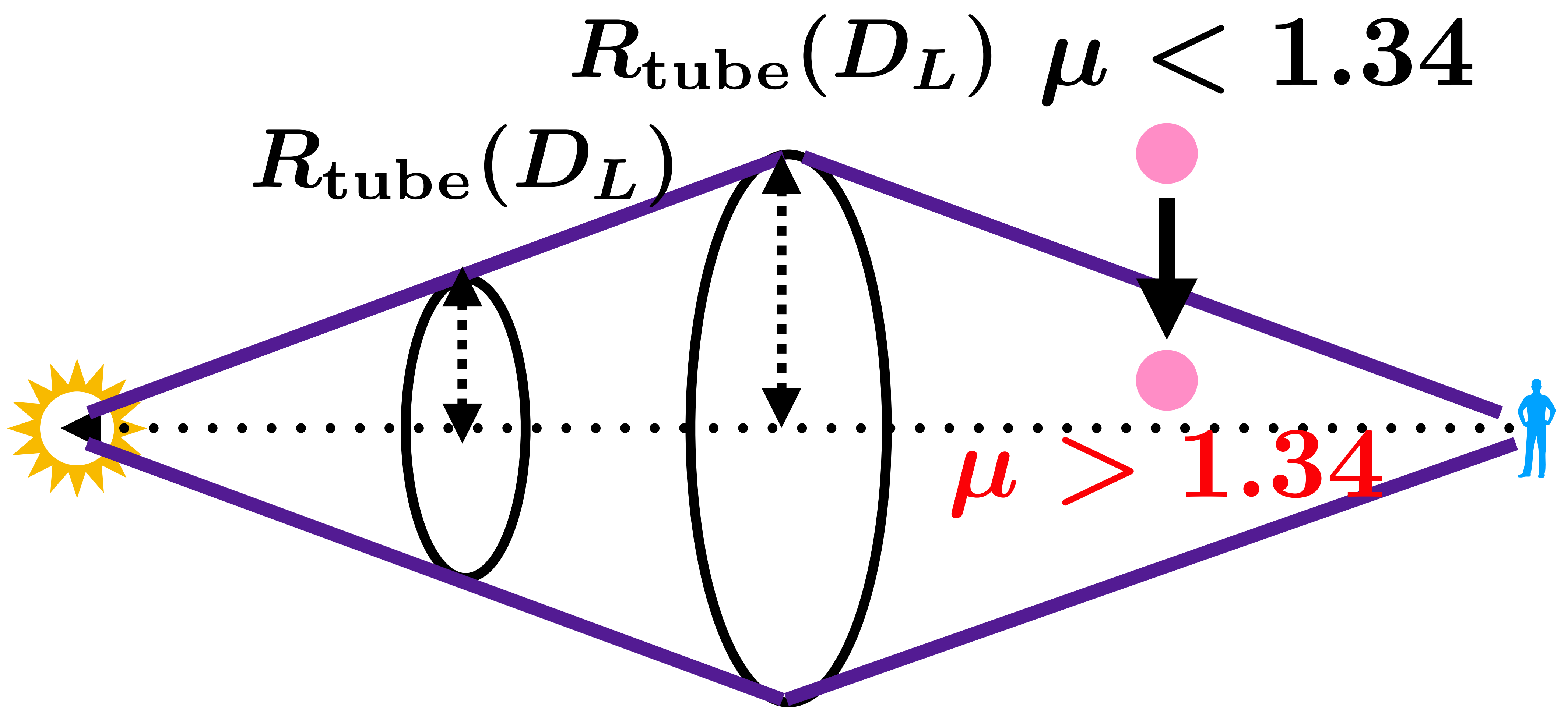
$$u = \beta/\theta_E, \ \theta_E \sim \sqrt{4GM_{\mathrm{clump}}/D_L}$$

Microlensing events are defined by $\mu(u) > 1.34$.

If $u < u_T = 1$, microlensing events occur!

Expected number of events

Microlensing event occurs when the DM crosses microlensing tube!



$$R_{\rm tube} \equiv u_T R_E \sim \sqrt{G M_{\rm clump} \left(\frac{D_L (D_S - D_L)}{D_S} \right)}$$

R_E **: The (point-like) Einstein ring radius**

The (point-like) Einstein ring radius: $R_E \sim \sqrt{GMD_L}$

∼(Schwarzschild radius of compact object × distance from source)$^{1/2}$

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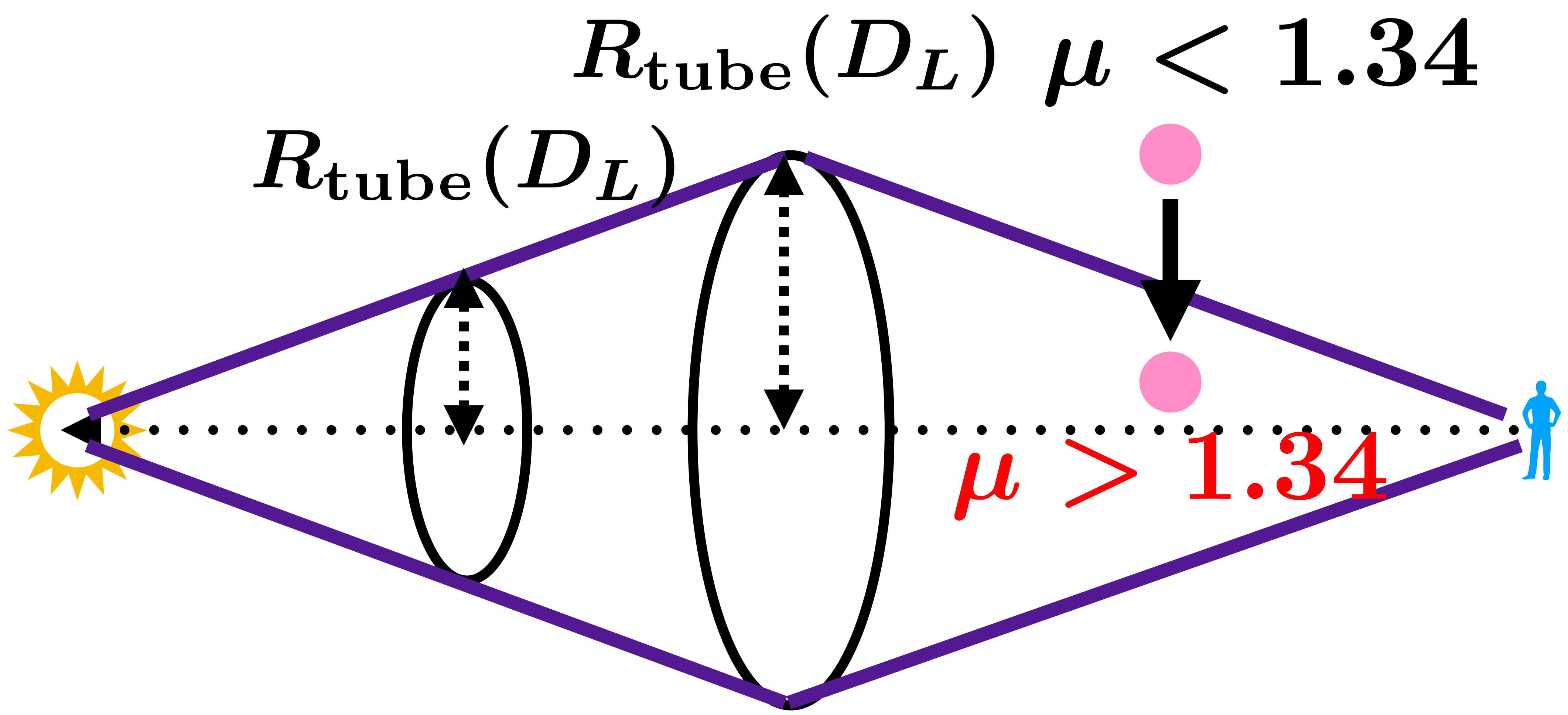
R_E **: The (point-like) Einstein ring radius**



For given u_T, DM halo model, DM velocity, observation time,… etc, one can calculate expected number of events.

$$N_{\rm exp} = N_{\rm exp}(u_T, M_{\rm clump}, \rho_{\rm DM}, f_{\rm DM}(v), T_{\rm obs})$$

Microlensing Constraints

Assumption: Microlensing events follow Poisson distribution.

The probability to observe microlensing event:

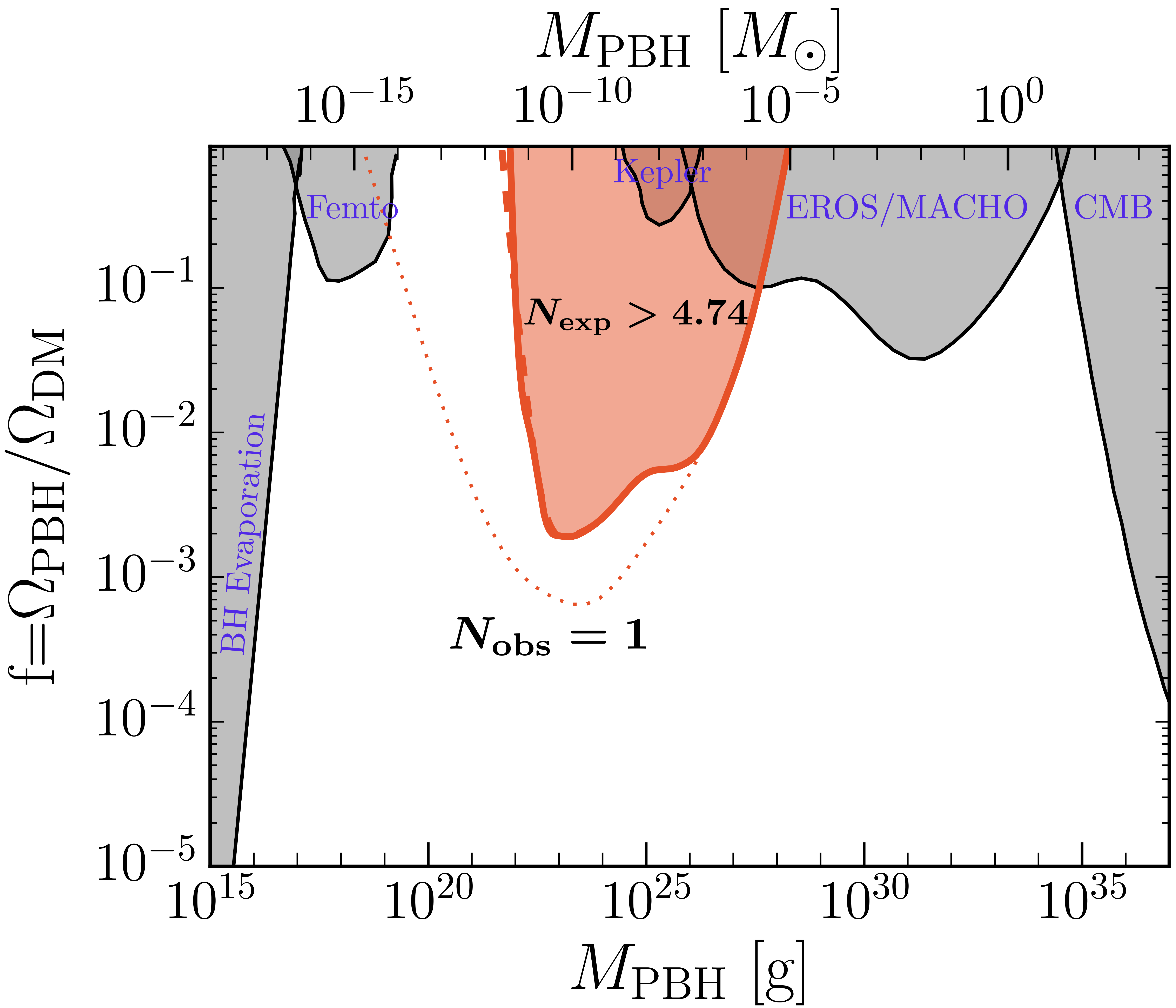
$$P(N_{\rm obs}, N_{\rm exp}) = (N_{\rm exp})^{N_{\rm obs}} e^{-N_{\rm exp}} / N_{\rm obs}!$$

$N_{\rm exp}$ **: Expected number of events**

$N_{\rm obs}$ **: Observed microlensing events**

If $N_{\rm obs} = 0\ (1), N_{\rm exp} > 3\ (4.74)$ is excluded at 95% confidence level.

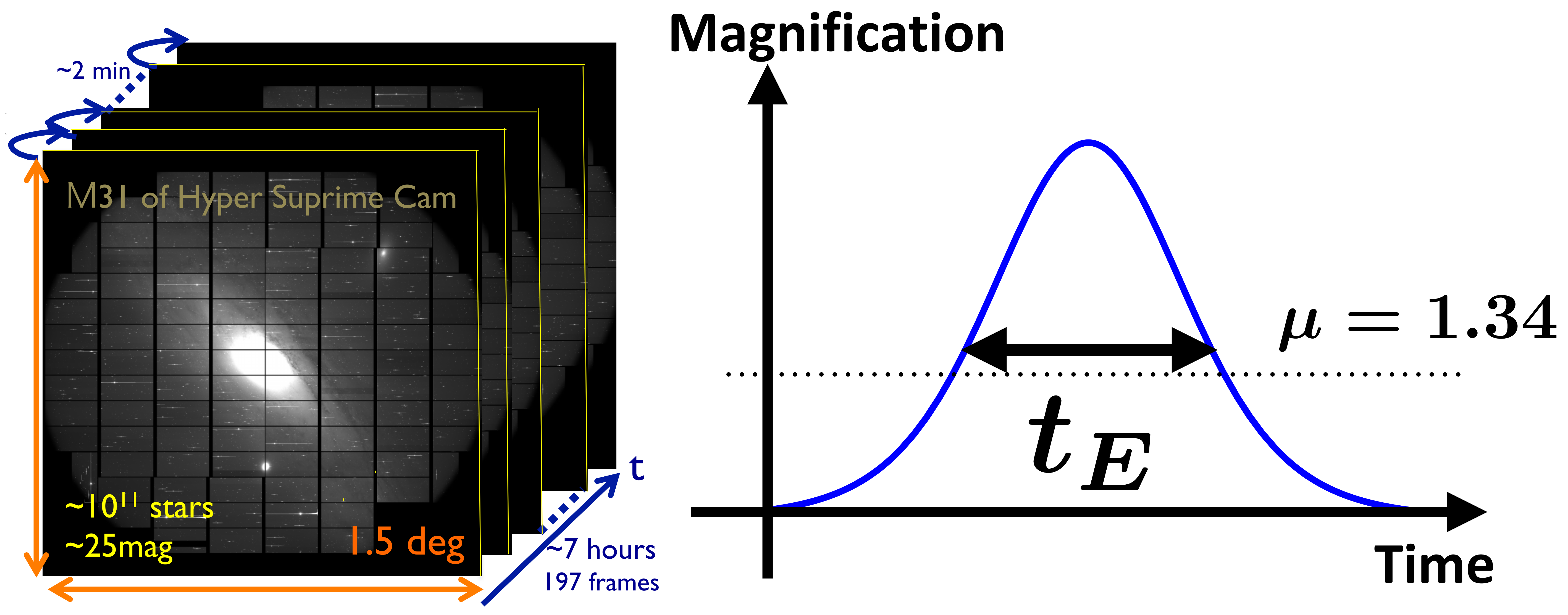
Microlensing constraints on compact object



[Niikura et al. (2017)]

Microlensing constraints on compact object

Detection time scale ~ mass of constrained compact objects



$$t_E \sim R_E/v \sim 10\,\mathrm{min}\left(\frac{M_{\rm PBH}}{10^{-8}M_\odot}\right)^{\frac{1}{2}}\left(\frac{d}{100\,\mathrm{kpc}}\right)^{\frac{1}{2}}\left(\frac{v}{200\,\mathrm{km/s}}\right)^{-1}$$

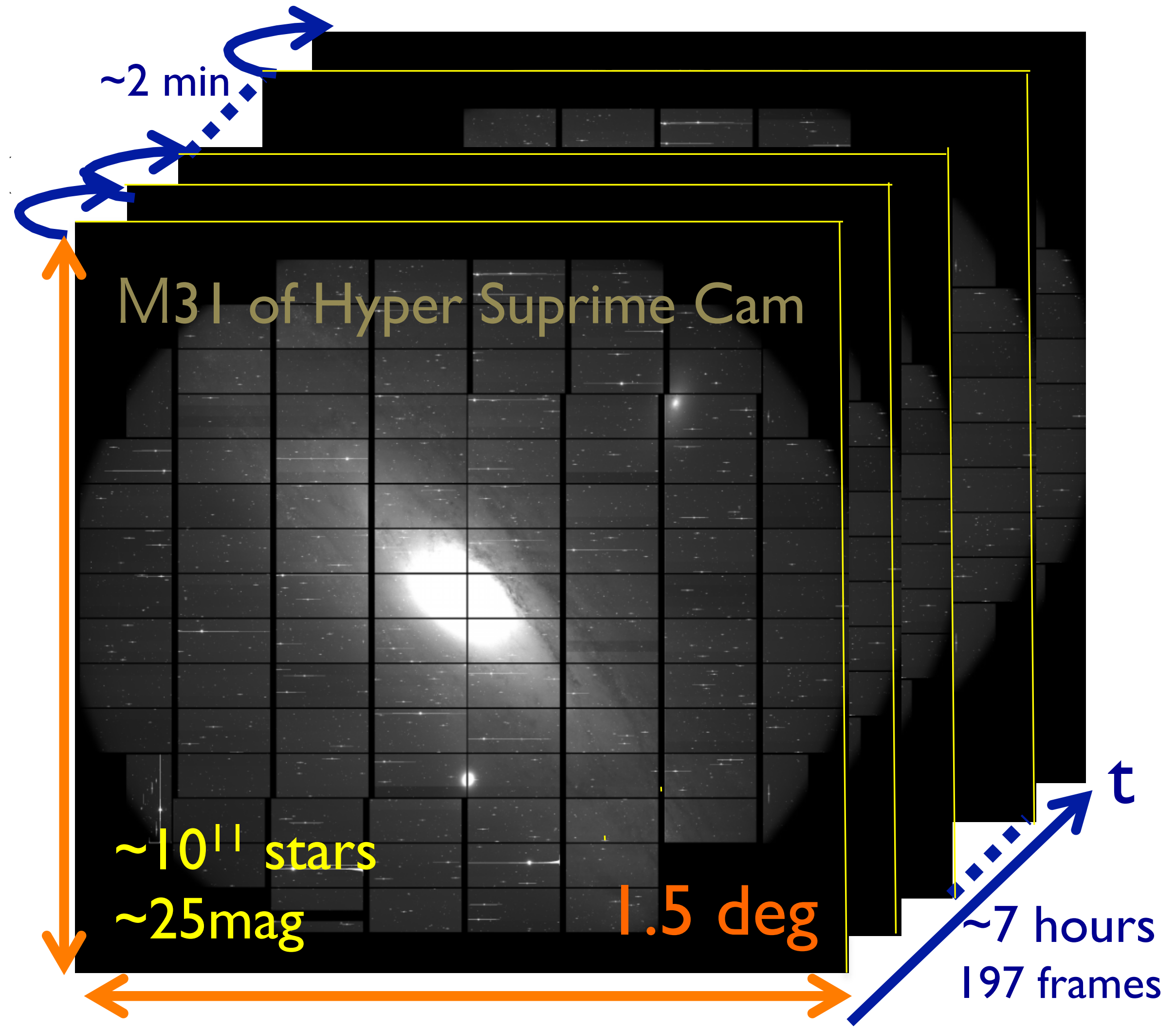
e.g.) Subaru Hyper Suprime-Cam

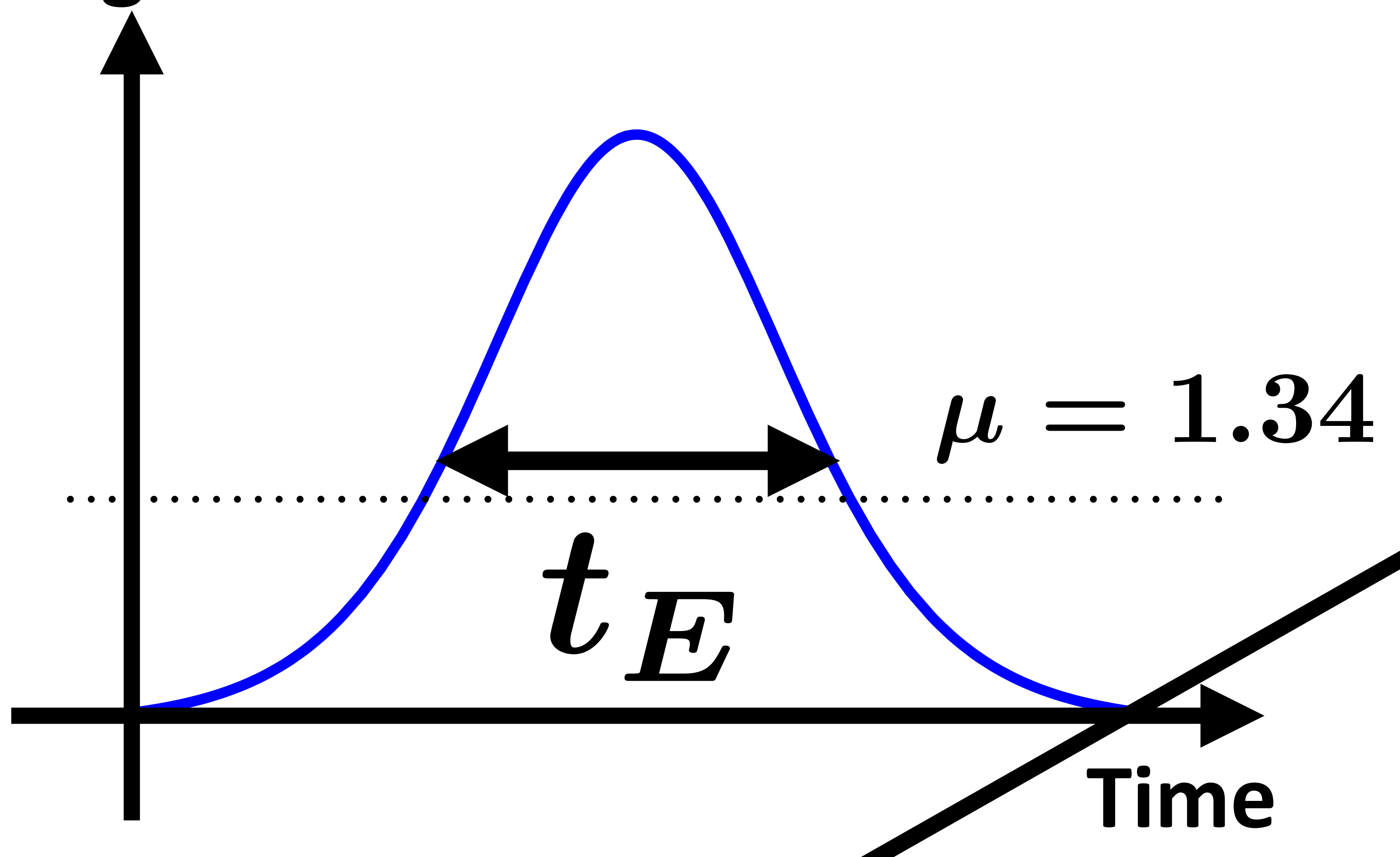
$$2\,\mathrm{min} < t_E < 7\,\mathrm{hr}$$

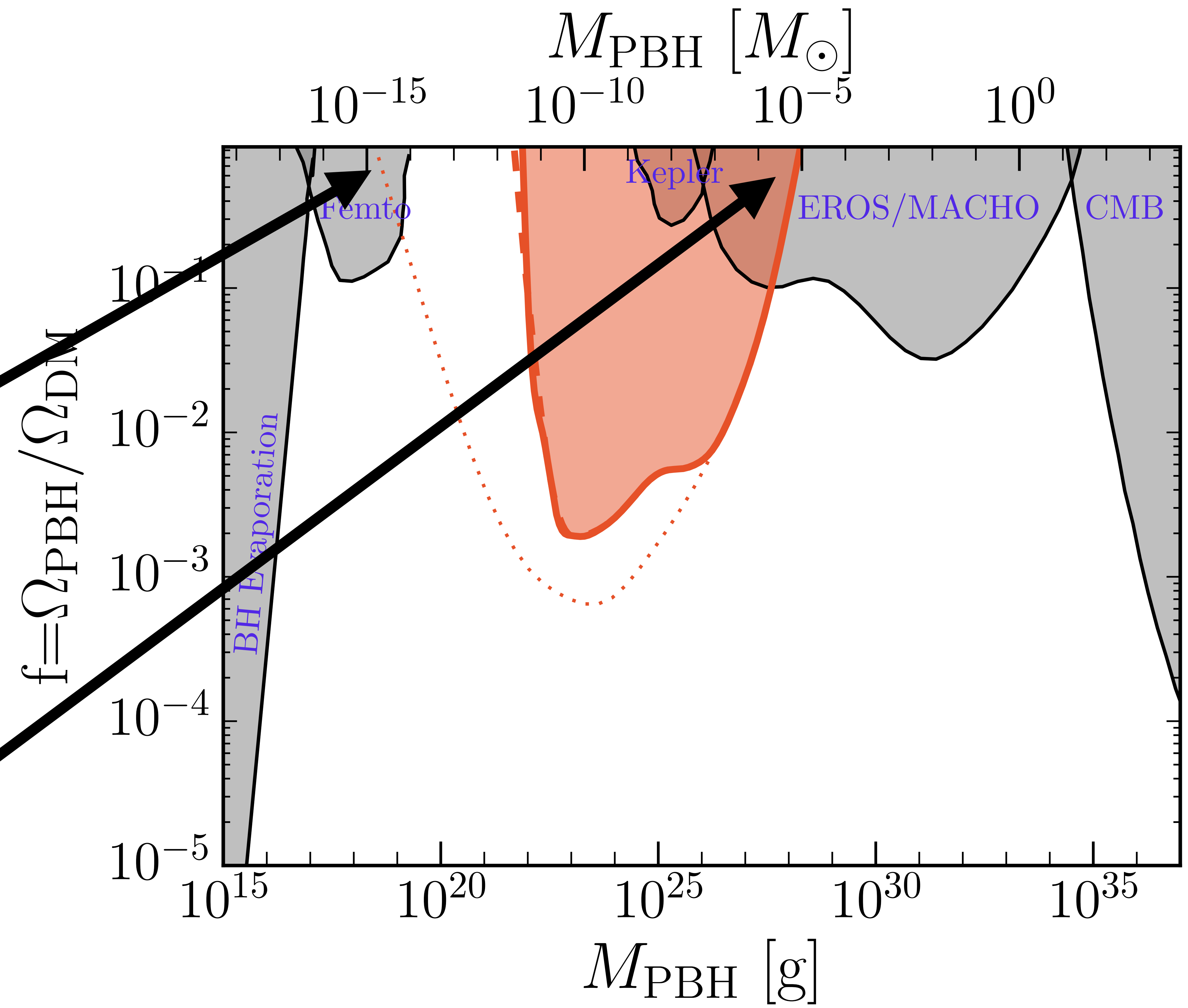
$$7\,\mathrm{hr} \Rightarrow M_{\rm PBH} \sim 10^{-5}M_\odot$$

Microlensing constraints on compact object

Detection time scale ~ mass of constrained compact objects







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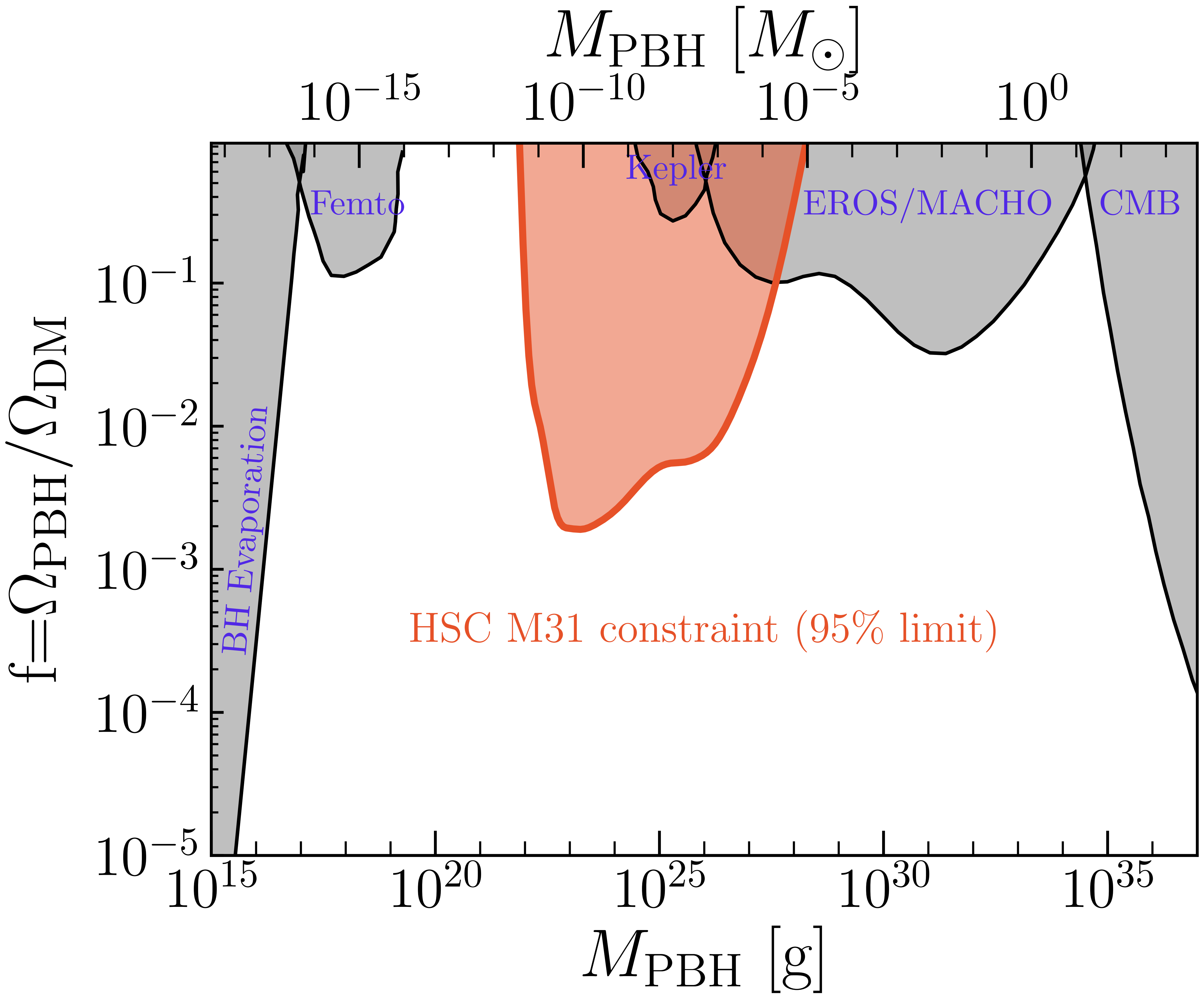
e.g.) Subaru Hyper Suprime-Cam

$$2\,\mathrm{min} < t_E < 7\,\mathrm{hr}$$

$$7\,\mathrm{hr} \Rightarrow M_{\rm PBH} \sim 10^{-5} M_\odot$$

Microlensing by axion stars

How about axion stars?



One can consider microlensing constraints with replacements:

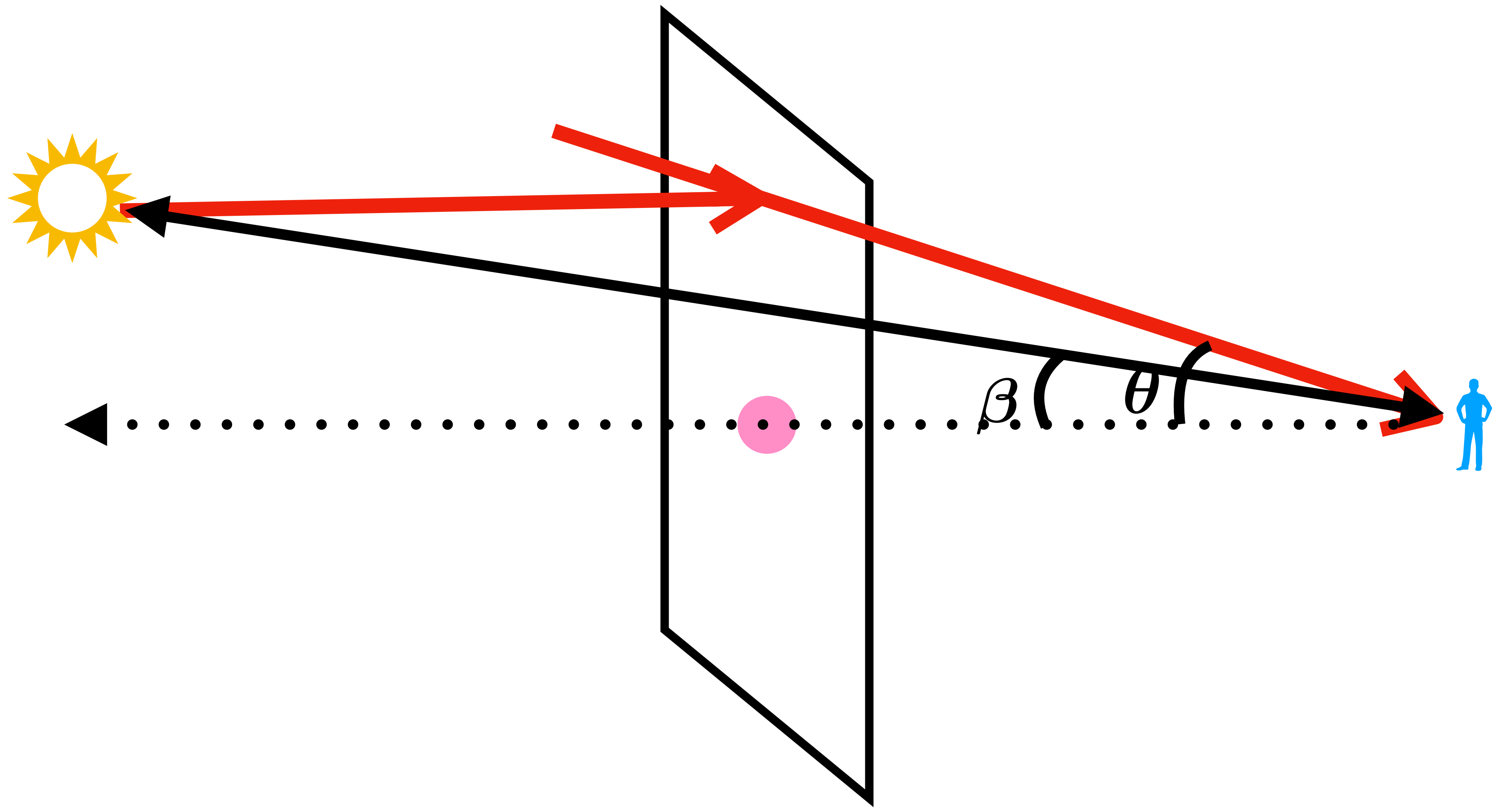
$$M_{\rm PBH} \to M_{\rm clump}(m_a, F_a, \alpha)$$

$$\Omega_{\rm PBH}/\Omega_{\rm DM} \to \Omega_{\rm clump}/\Omega_{\rm DM}$$

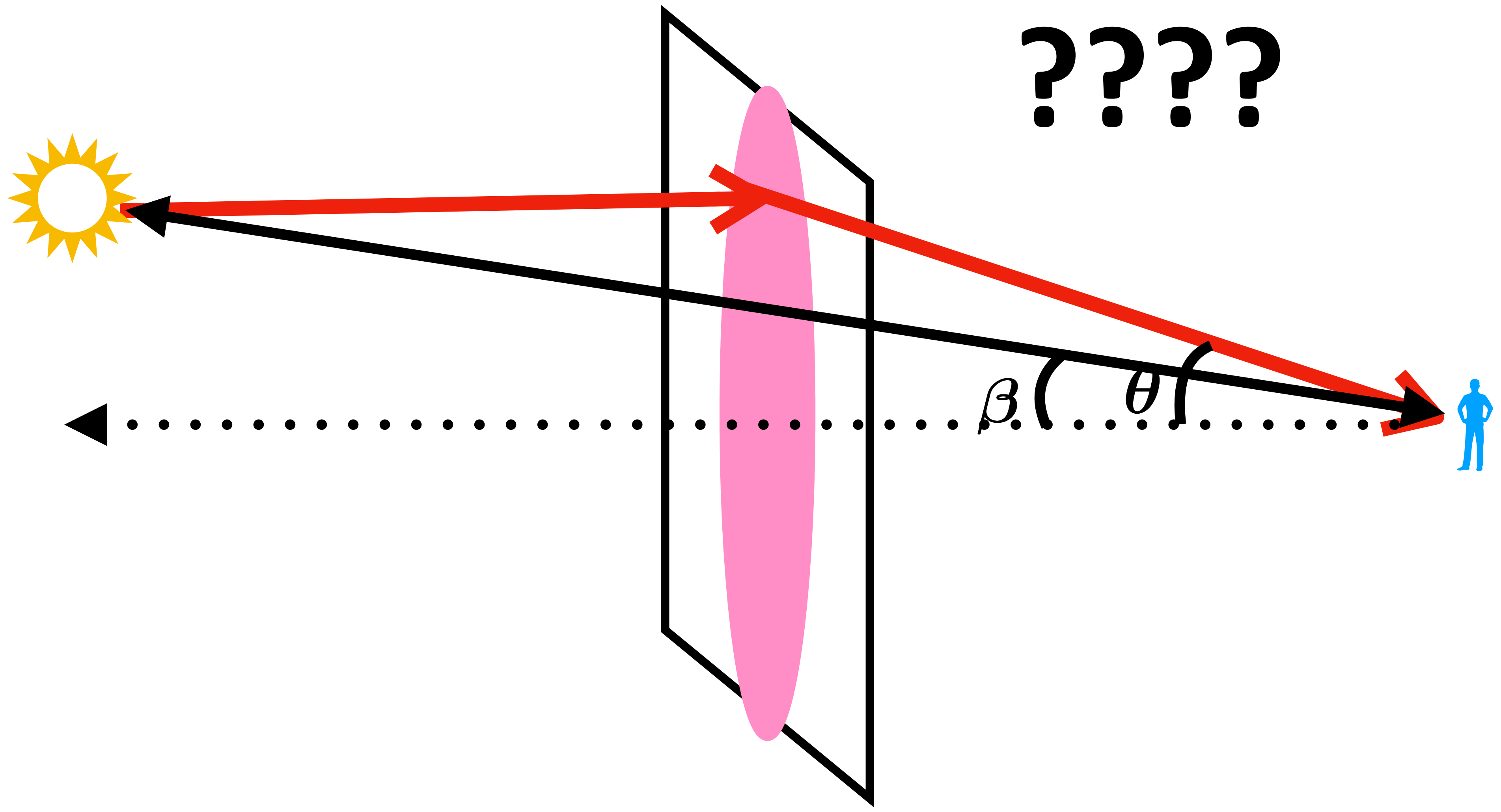
We are not satisfied this argument since…

Axion Stars may not be "compact"

Compact Massive Object (PBH)



Axion Stars

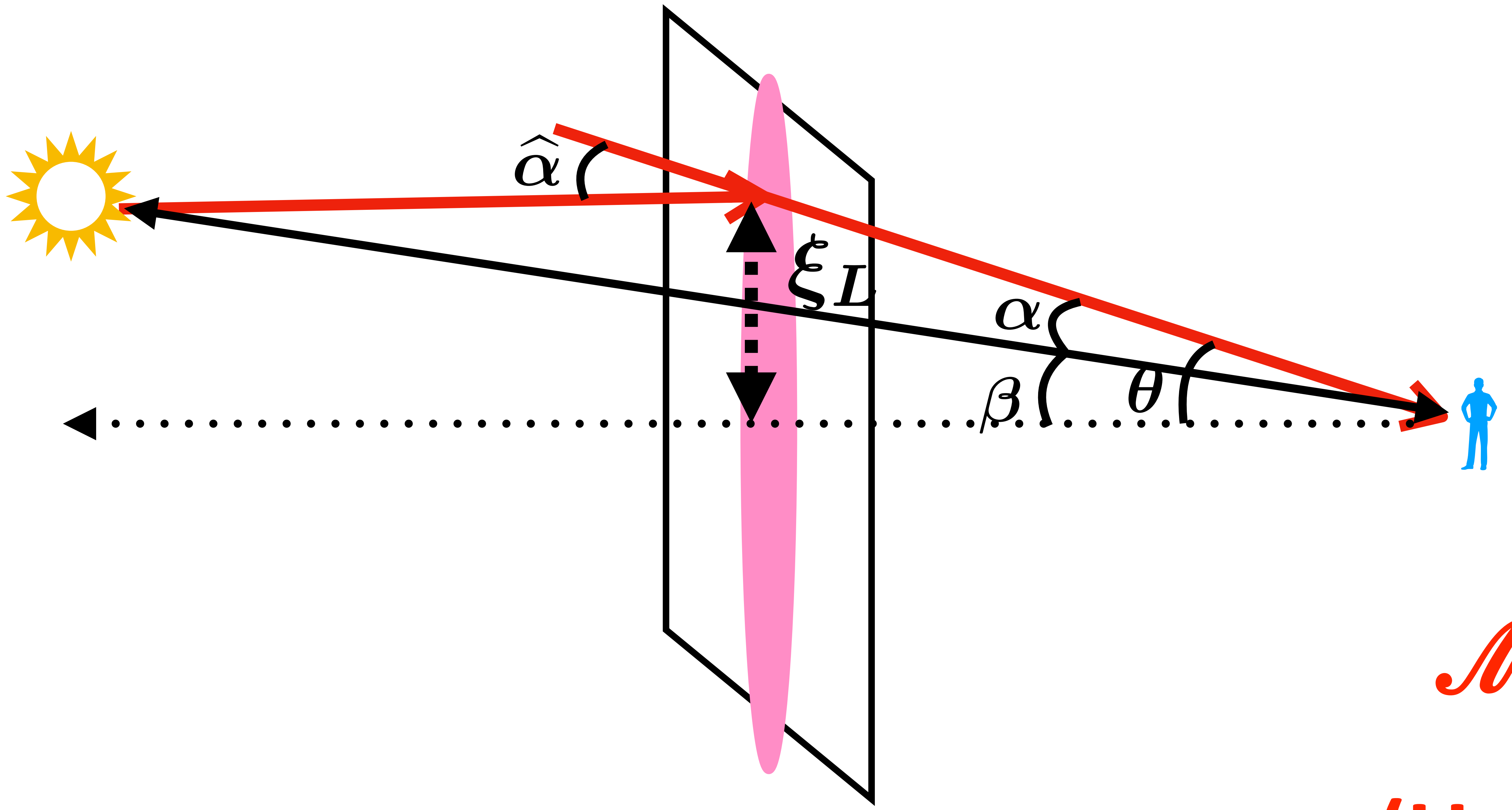


Naive argument:

If radius of the axion star is shorter than the (point-like) Einstein ring radius, microlensing constraints would be same as the PBHs.

We find that this argument works well!

Gravitational lens with finite extent



Mass distribution is projected onto lens plane:

$$\hat{\alpha} = 4G\frac{\mathcal{M}(\xi_L)}{\xi_L}$$

$\mathscr{M}(\xi_L)$: Clump mass within radius ξ_L

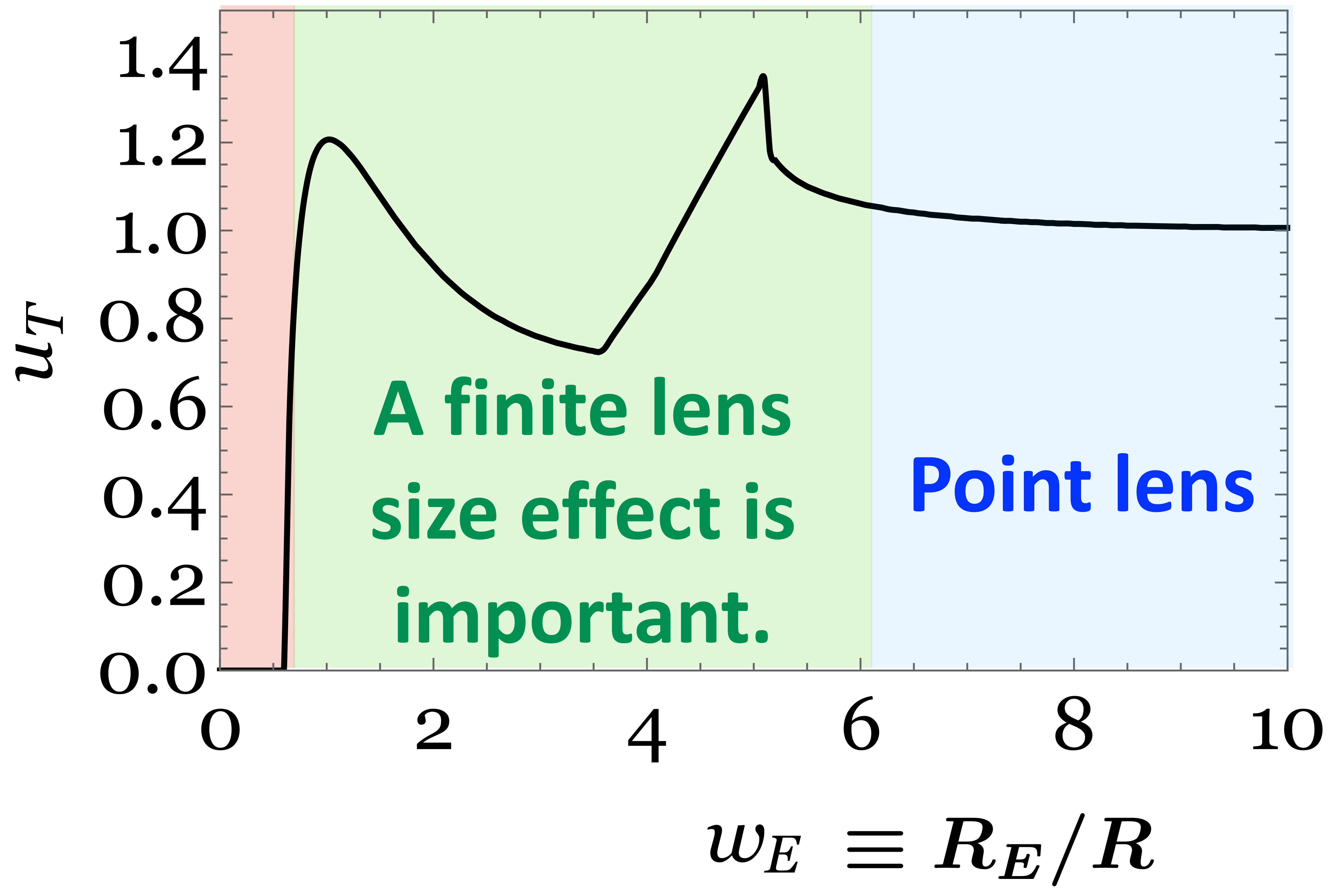
(Using a configuration of the axion star)

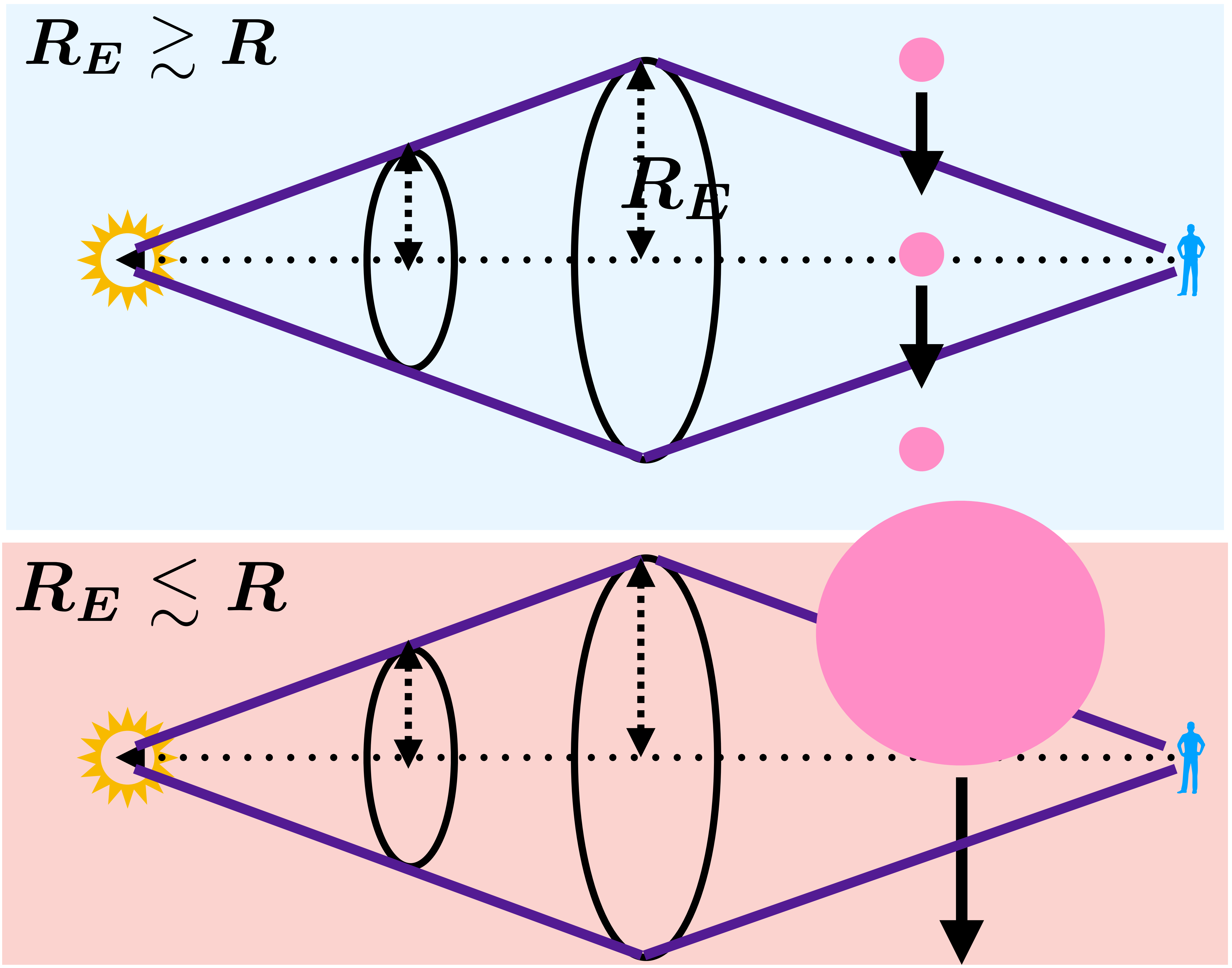
Microlensing events occur when $\mu(u, R_E/R) > 1.34$.

Threshold impact parameter $u_T(R_E/R)$

is a function of axion star radius!

A numerical result

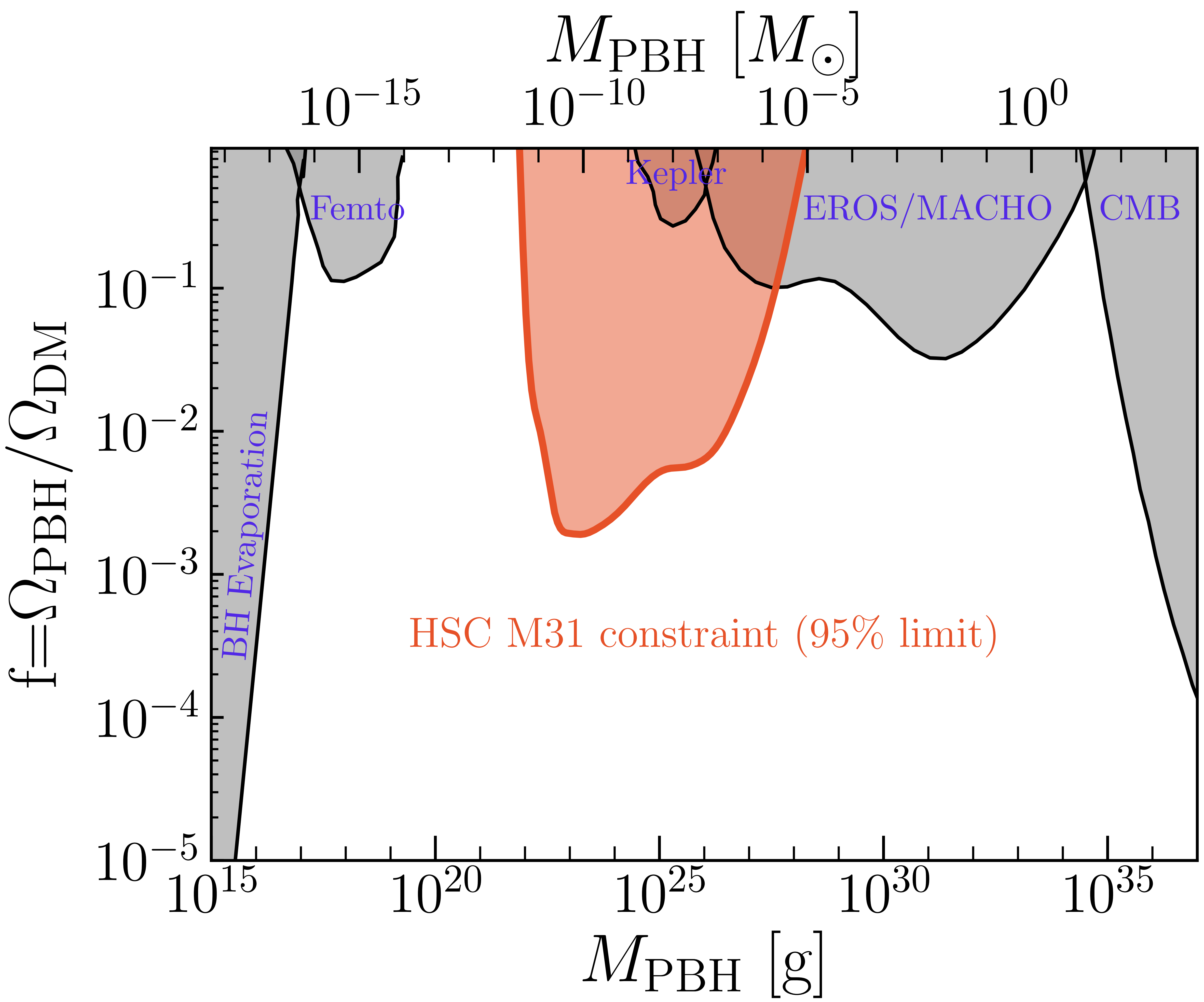




No microlensing events for $R_E \lesssim 0.6 \times R$.

(The Axion star is too spread to cause the microlensing event.)

Answer: How about axion stars?



One can consider microlensing constraints with replacements:

$$M_{\rm PBH} \to M_{\rm clump}(m_a, F_a, \alpha)$$

$$\Omega_{\rm PBH}/\Omega_{\rm DM} \to \Omega_{\rm clump}/\Omega_{\rm DM}$$

$$R_E(M_{\rm clump}) \gtrsim R(m_a, F_a, \alpha)$$

Very roughly speaking, this is conclusion of our paper.

I would like to show you results obtained by detailed numerical calculations.

We focus on EROS-2 (and Subaru HSC) observations.

Free Parameters:

F_a : the breaking scale of axion

m_a : the axion mass

α : the clump density

$\Omega_{\rm clump}/\Omega_{\rm DM}$: Fraction of dark matter collapsed into clumps

Result1 (EROS-2 survey)

- **The detection time scale:**

[1 day, 250 day]

$$10^{-4}M_\odot < M_{\rm clump} < 10M_\odot$$

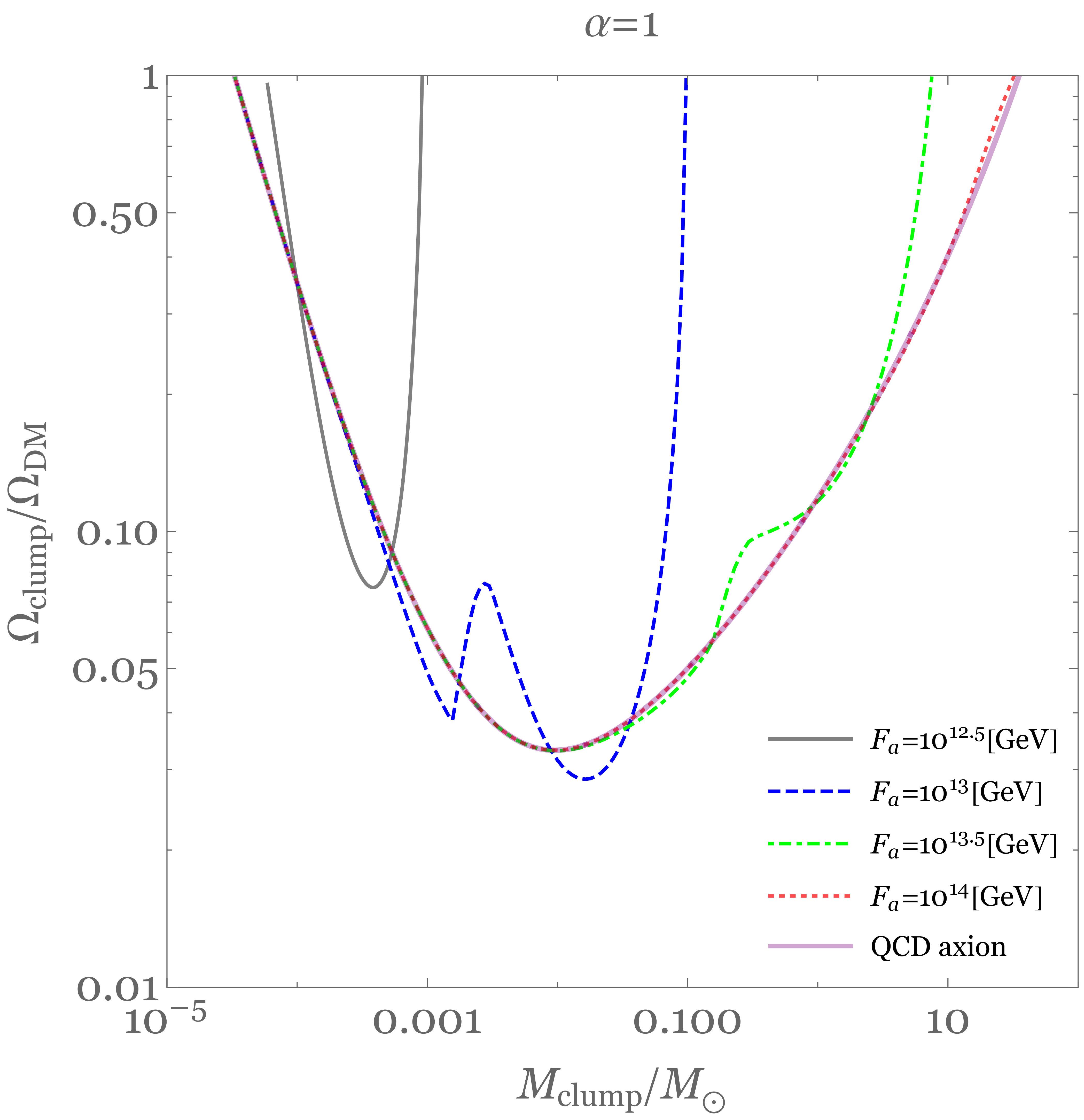
- **Free Parameters:**

$$(m_a,\ F_a,\ \Omega_{\rm clump}/\Omega_{\rm DM},\ \alpha)$$

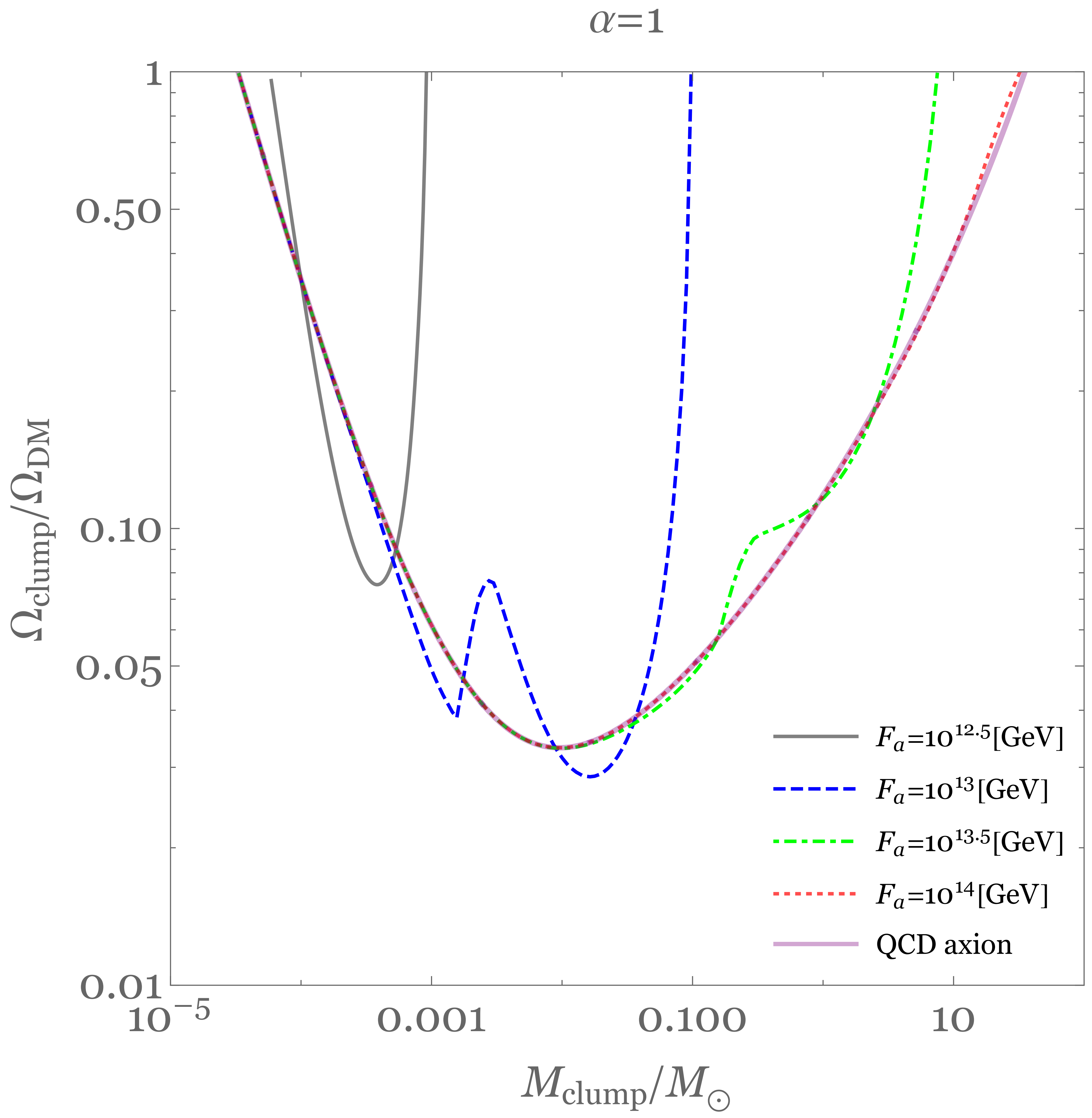
$$\downarrow$$

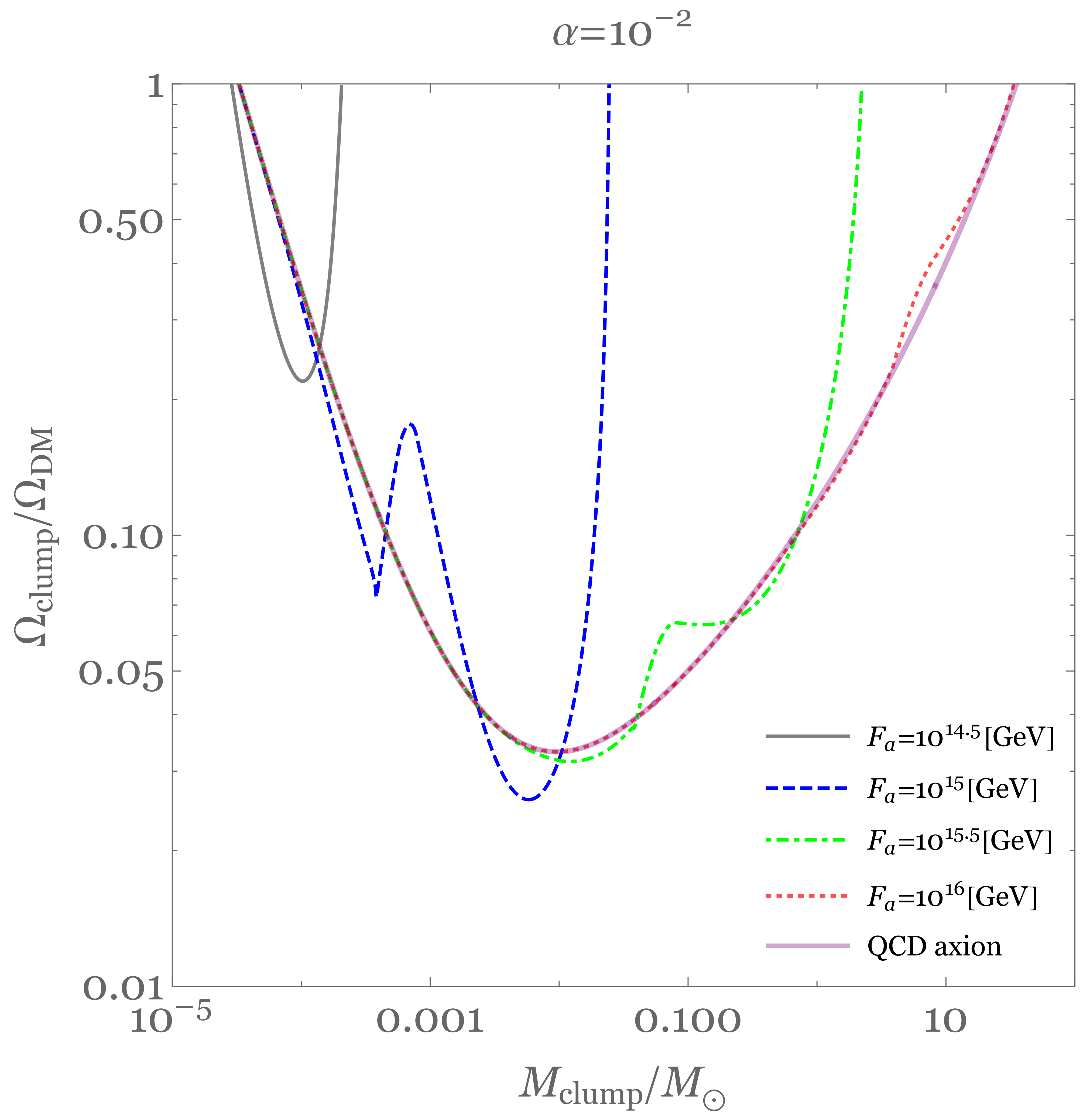
$$(M_{\rm clump},\ F_a,\ \Omega_{\rm clump}/\Omega_{\rm DM},\ \alpha)$$

with fixed F_a, α.



Result2 (EROS-2 survey)





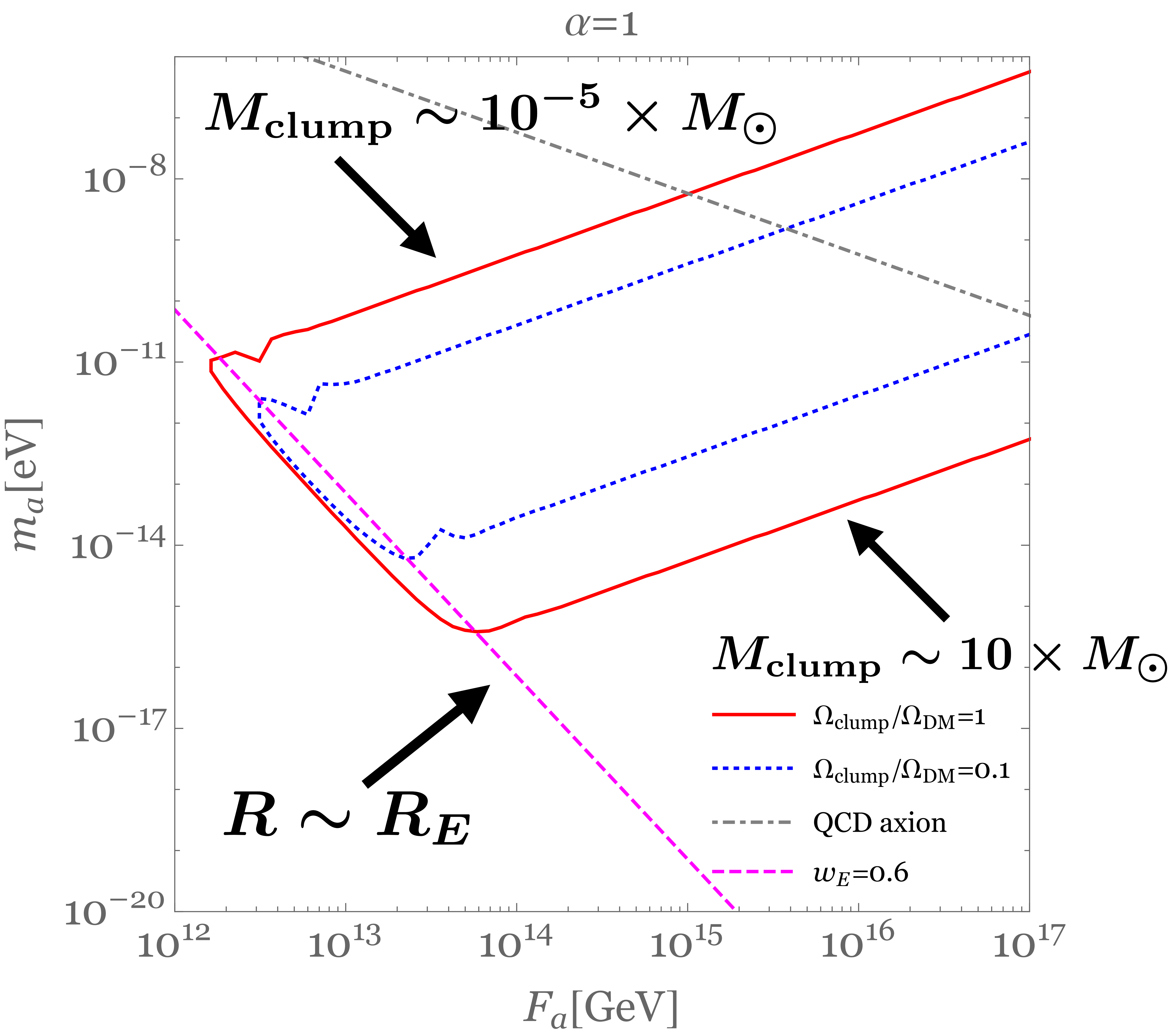
Changing α (Smaller density)

Result3 (EROS-2 survey)

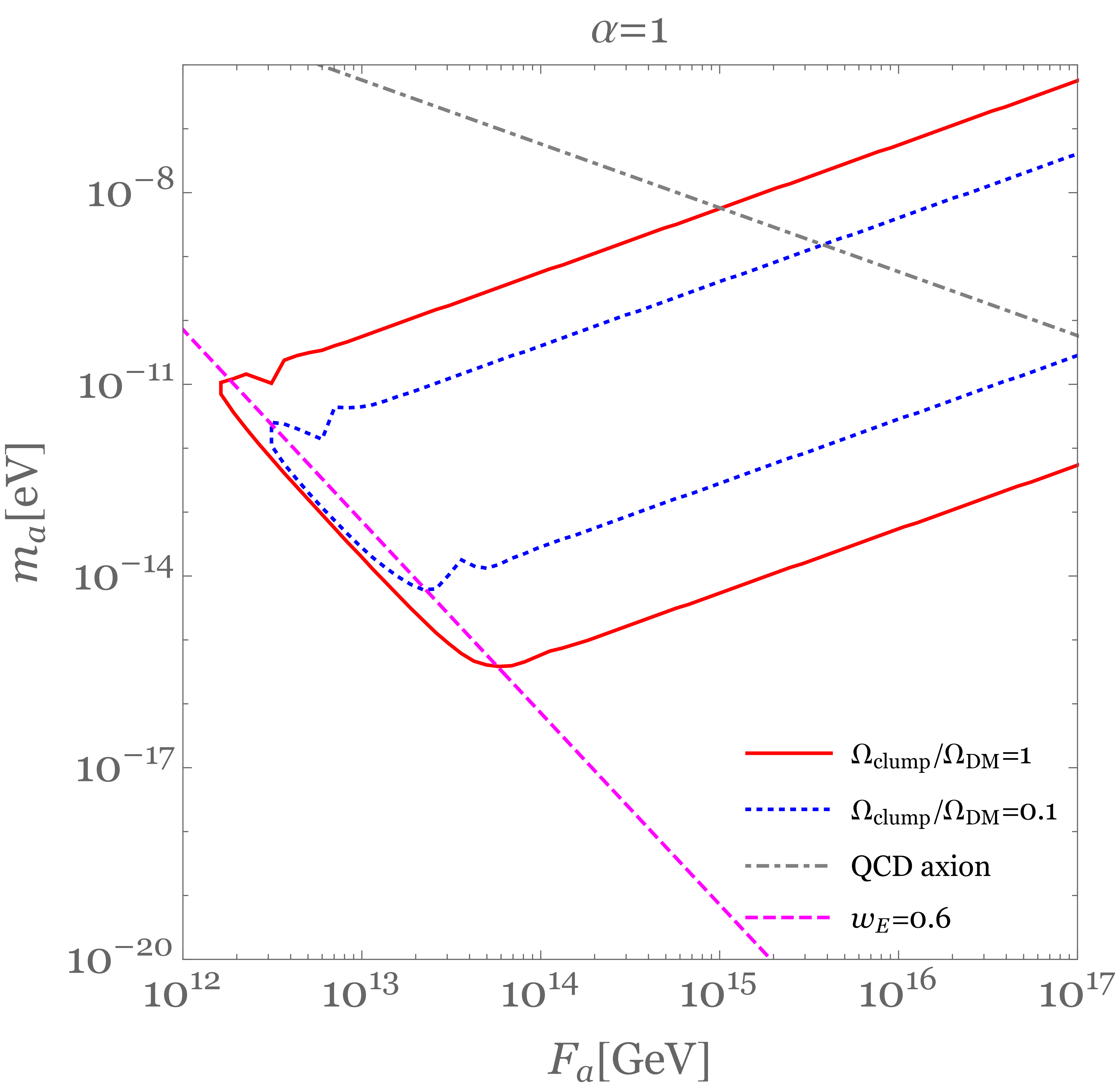
Constraint on $(F_a,\, m_a)$-plane with fixed $\Omega_{\rm clump}/\Omega_{\rm DM}$ and α.

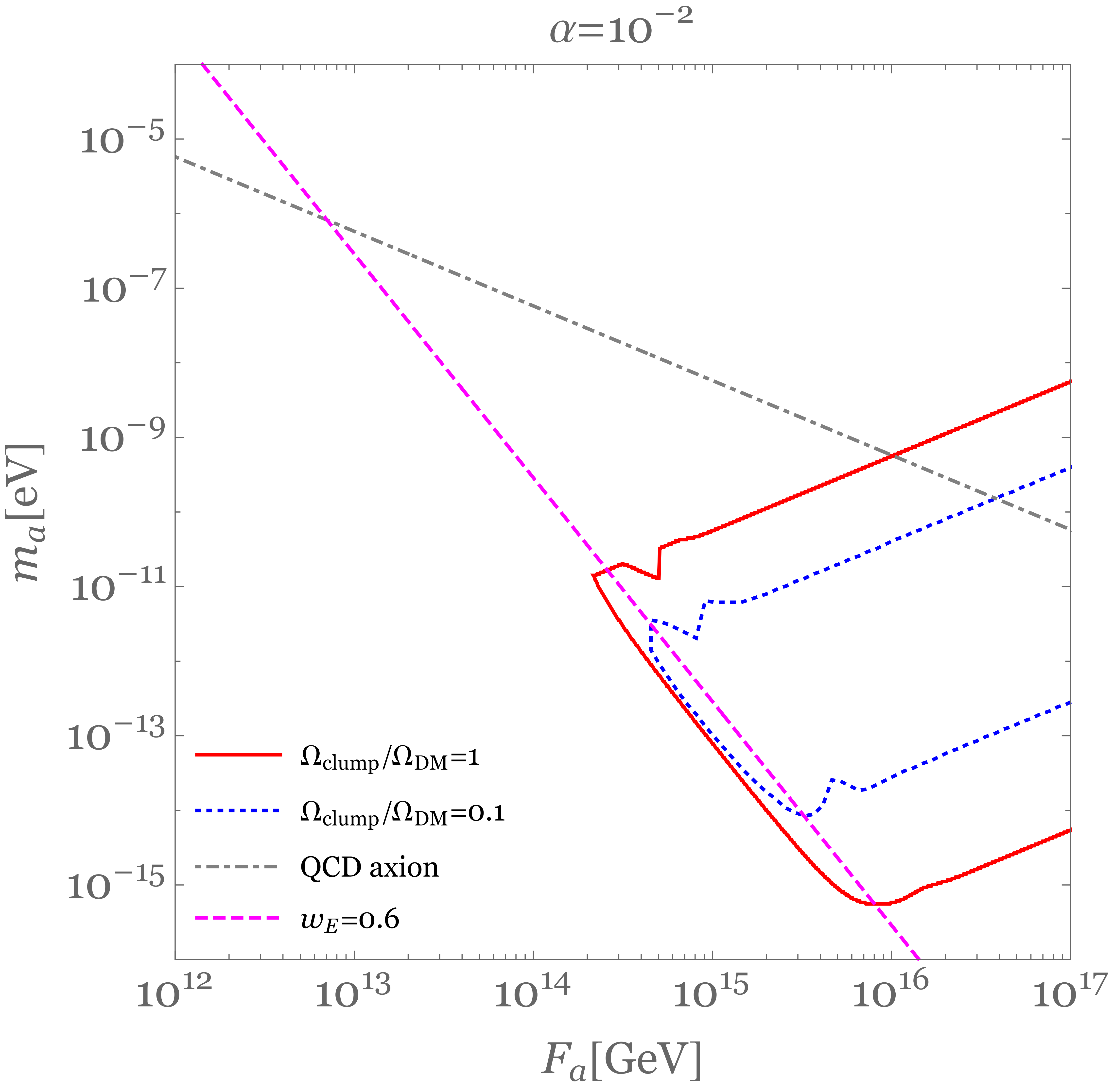
There is no constraint for $R \gtrsim R_E$.

High breaking scale can be constrained for the QCD axion.
$(10^{15} < F_a/\mathrm{GeV} < 10^{17})$



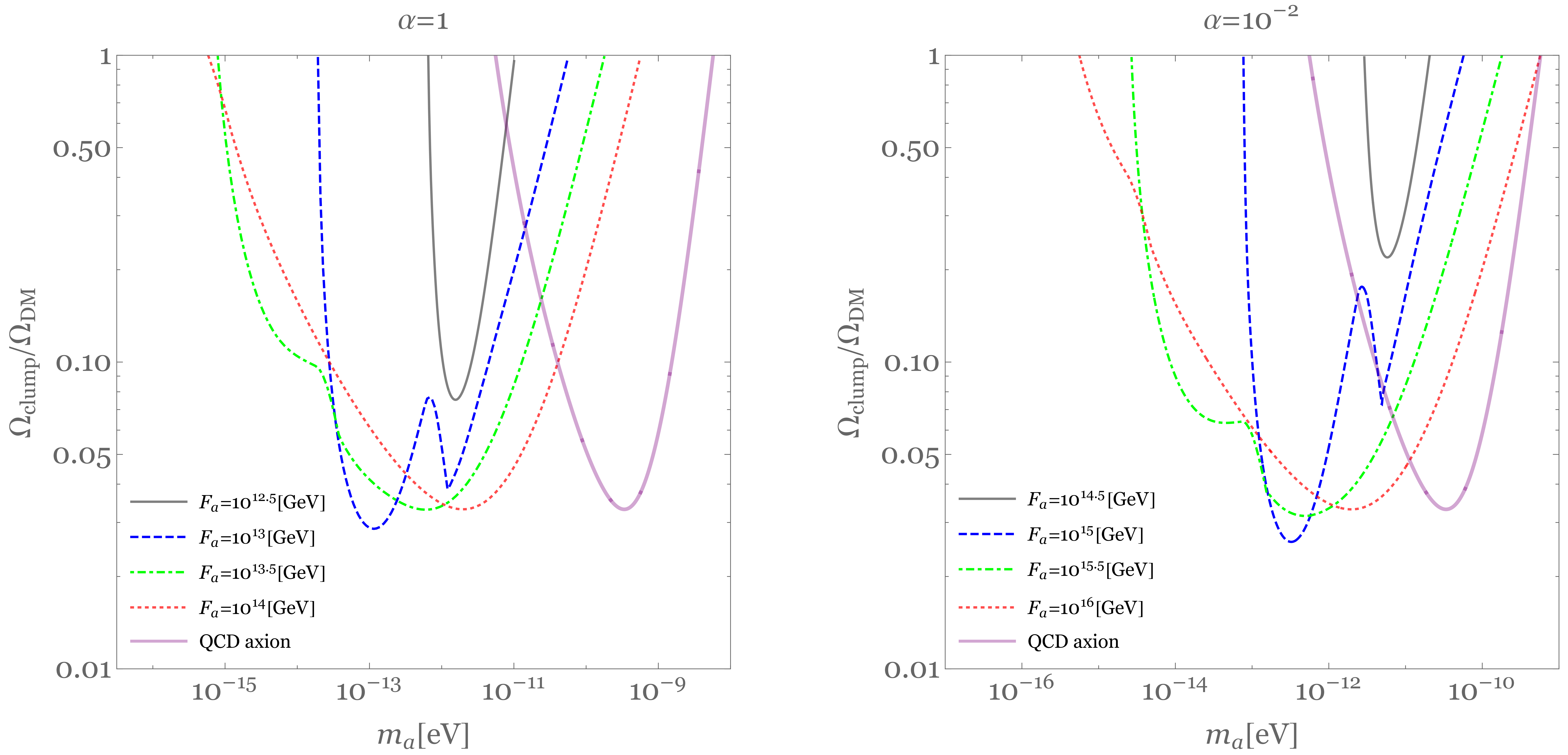
Result4 (EROS-2 survey)





Changing α (Smaller density)

Result5 (EROS-2 survey)



Constraint with fixed α, F_a

Conclusions

- **The QCD axion can solve strong CP problem and be a good dark matter candidate!**
- **In the early Universe, axions may form localized clumps called axion stars.**
- **We give microlensing constraints on axion stars including a finite lens size effect.**
- **Unfortunately, the QCD axion window cannot be constrained even if axion stars are plentiful.**

Thank you!

Subaru HSC observation

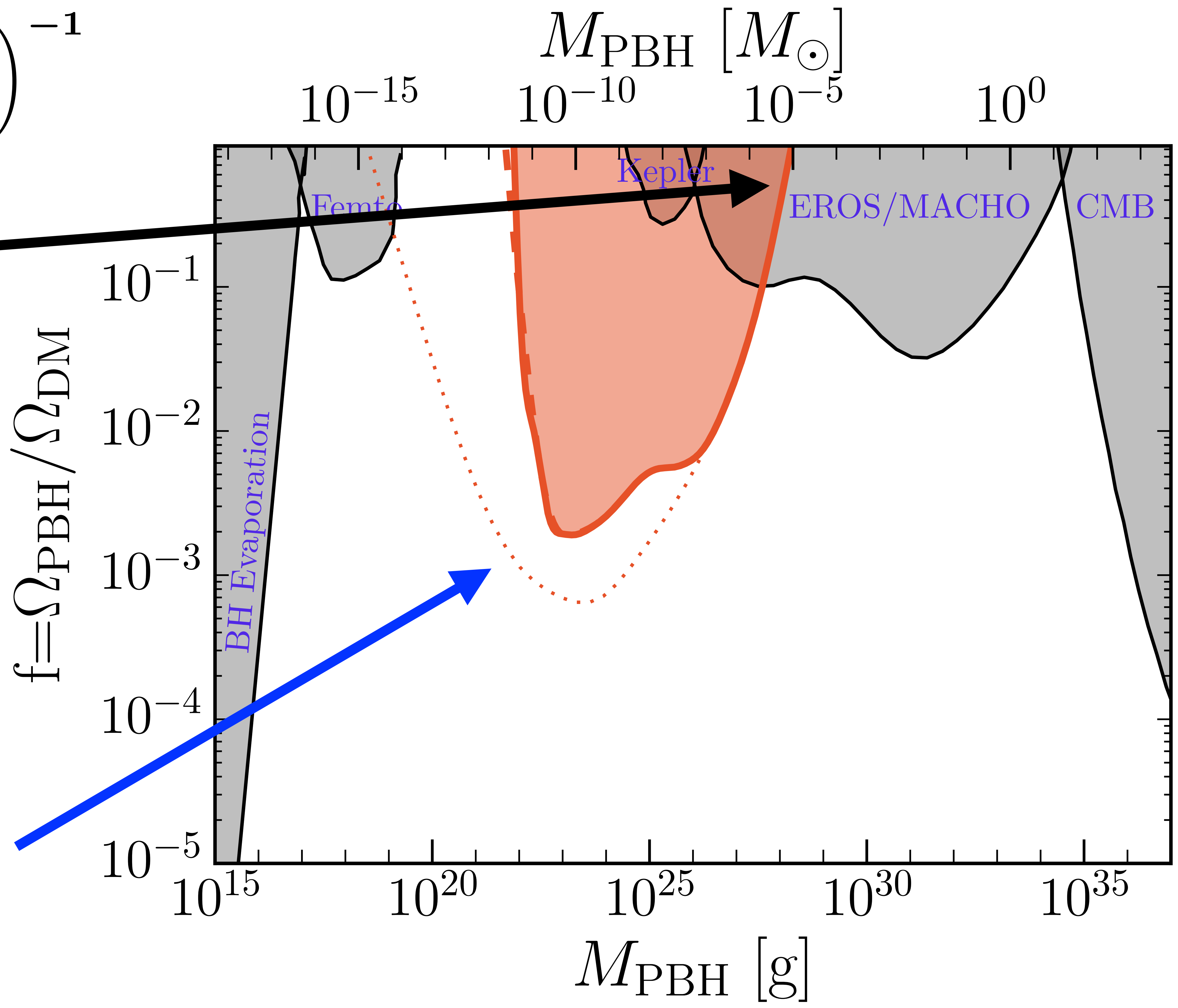
A finite source size effect becomes important for Subaru!

$$t_E \sim R_E/v \sim 10\,\mathrm{min}\left(\frac{M_{\rm PBH}}{10^{-8}M_\odot}\right)^{\frac{1}{2}}\left(\frac{d}{100\,\mathrm{kpc}}\right)^{\frac{1}{2}}\left(\frac{v}{200\,\mathrm{km/s}}\right)^{-1}$$

$$7\,\mathrm{hr} \Rightarrow M_{\rm PBH} \sim 10^{-5} M_\odot$$

$$R_E \simeq 10^4 \times R_\odot \times \left(\frac{M_{\rm clump}}{M_\odot}\right)^{\frac{1}{2}} \times \left(\frac{D_S}{100\,\mathrm{kpc}}\right)^{\frac{1}{2}}$$

For $M_{\rm clump} < 10^{-8} M_\odot$, the Einstein ring radius is order of the solar radius.



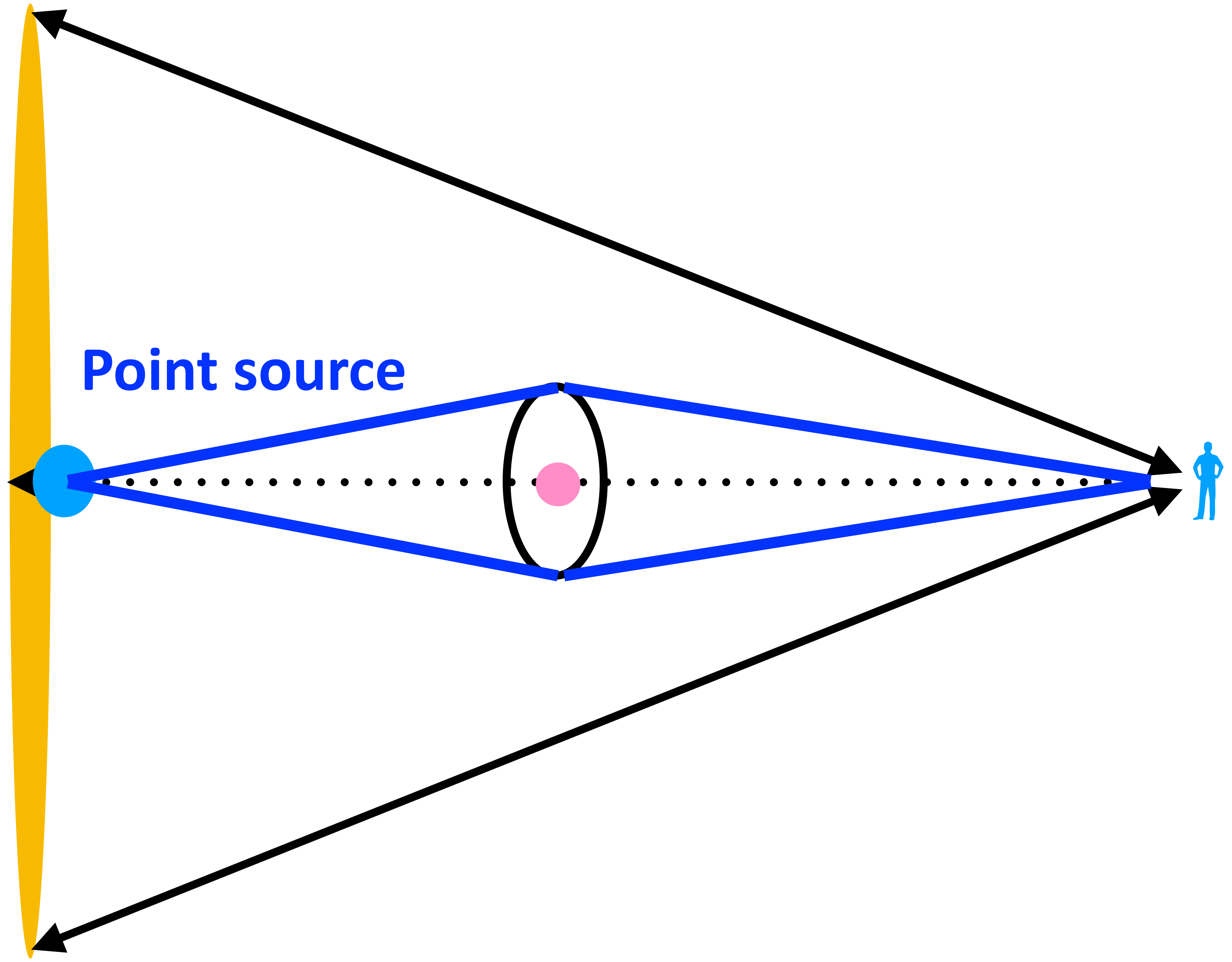
A finite source size

An "effective" impact parameter is determined by a source radius.

Naive expectation:

When a radius of source star is longer than the Einstein ring radius, magnification is strongly suppressed.

Radical Case $R_S \gg R_E$



This naive expectation is also correct.

A finite source and lens size effect

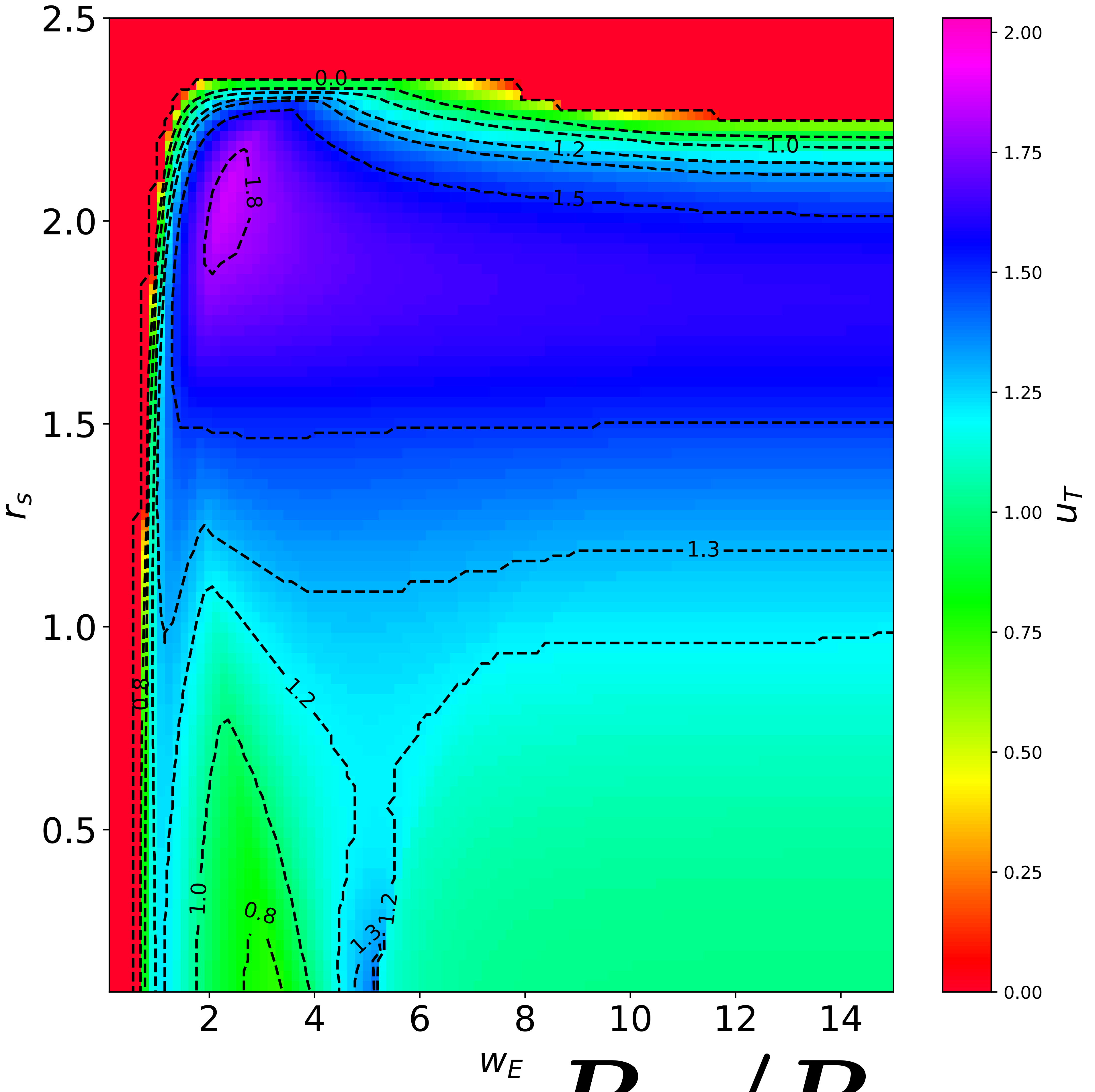
We solve lens equation including both of finite lens and source size effects!

R_S : Source star radius

No microlensing events for $R_S > 2.3 \times R_E$.
(A finite source size effect)

No microlensing events for $R > 0.6 \times R_E$.
(A finite lens size effect)

R_S/R_E

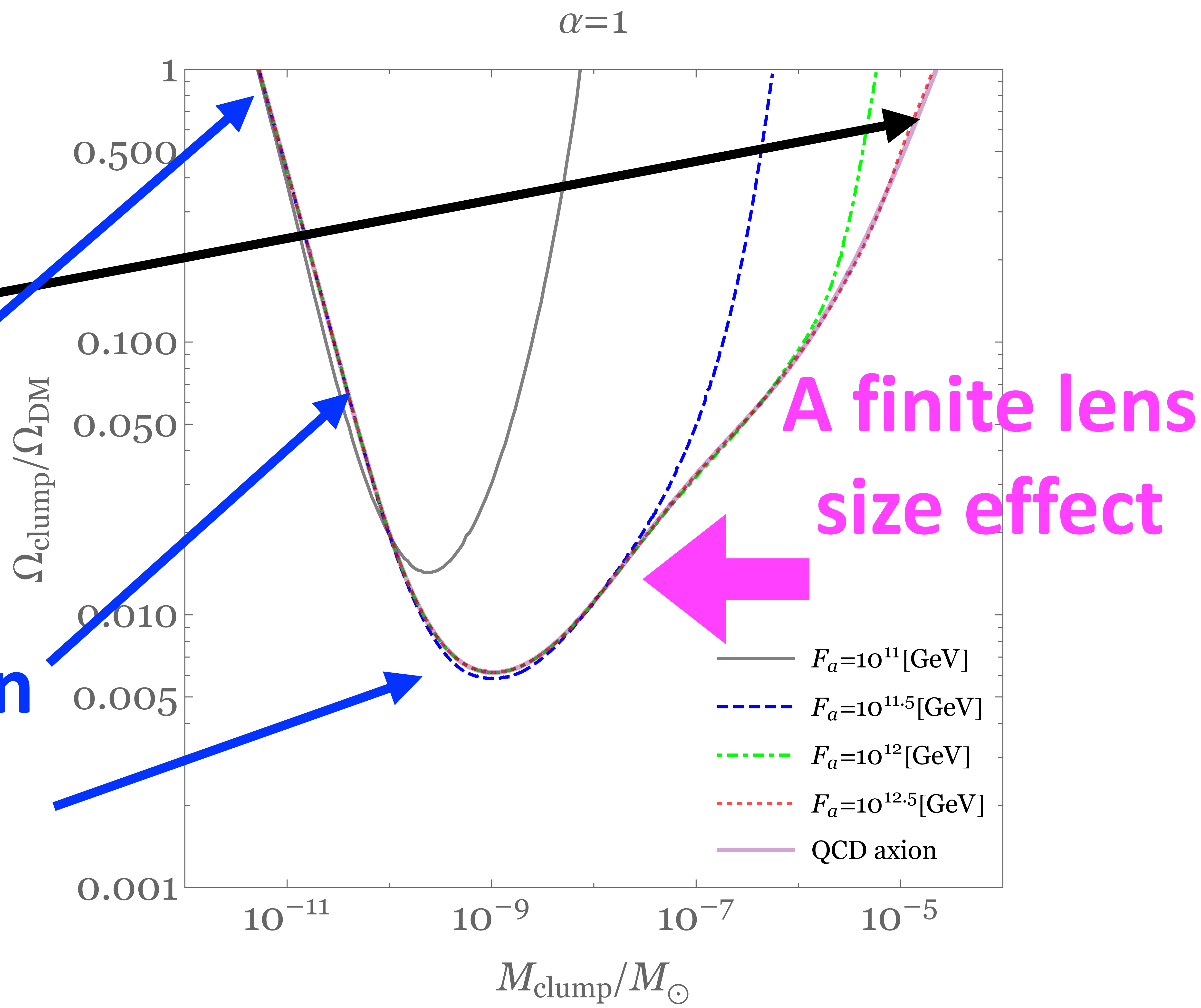


R_E/R

Result1 (Subaru HSC)

The detection time scale:

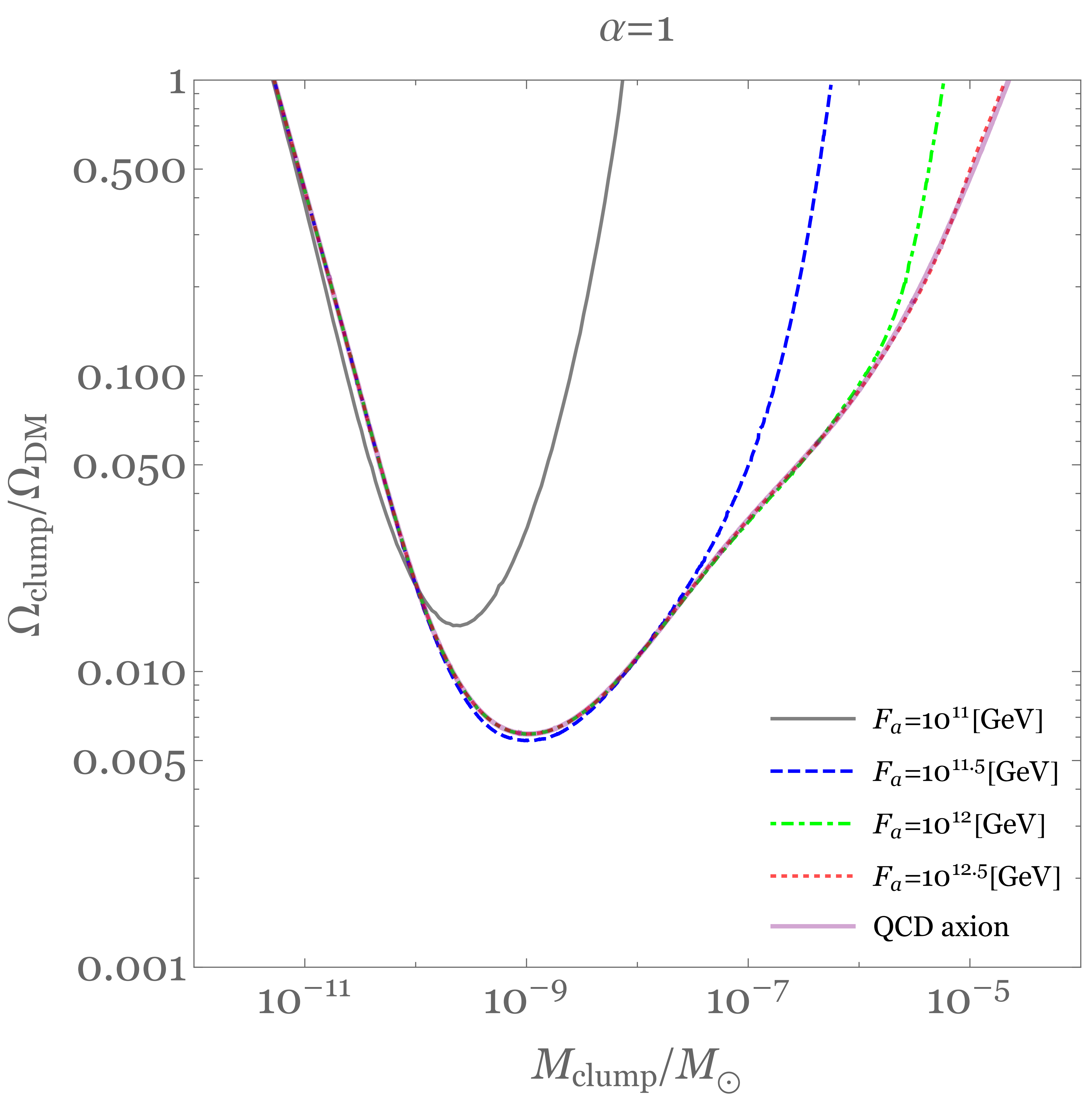
$$7\,\mathrm{hr} \Rightarrow M_{\mathrm{PBH}} \sim 10^{-5} M_{\odot}$$

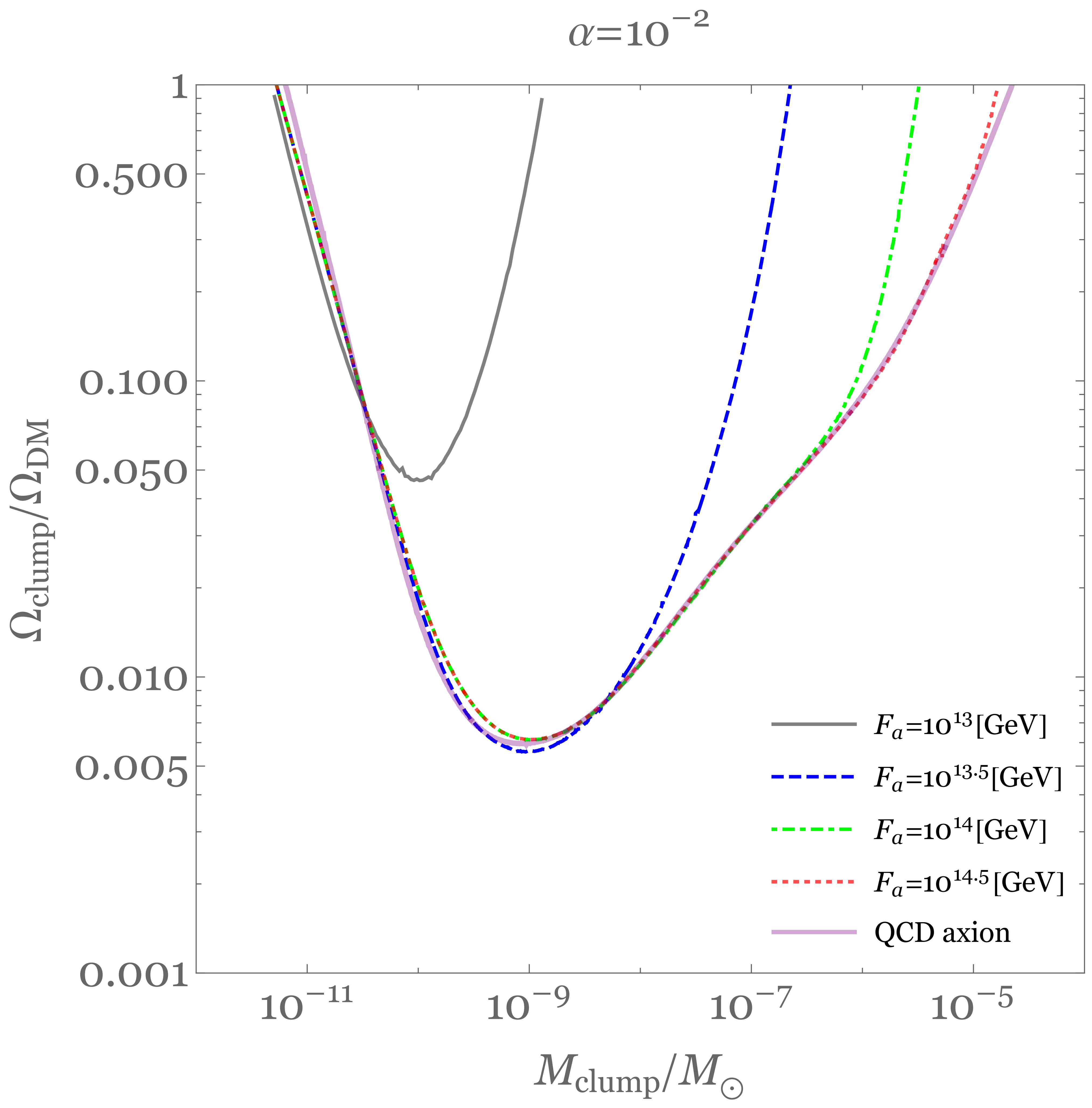


For $M_{\mathrm{clump}} < 10^{-8} M_{\odot}$, the Einstein ring radius is shorter solar radius.

Significant suppression from a finite source size effect for a light mass region!

Result2 (Subaru HSC)





Result3 (Subaru HSC)

Mass of QCD axion star

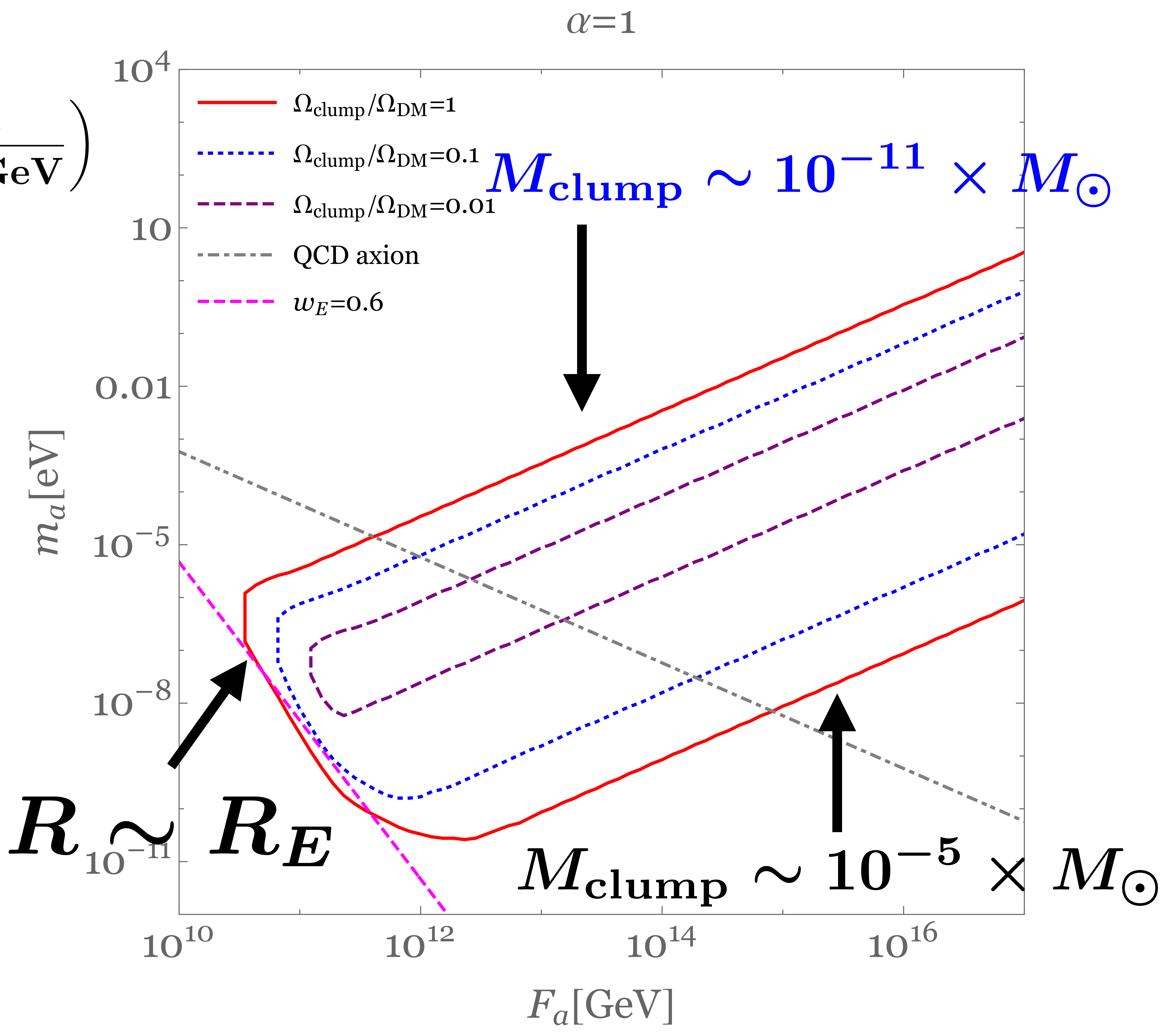
$$M_{\rm clump} = N m_a \simeq 1.5 \times 10^{-11} M_\odot \times \alpha \left(\frac{10^{-5}\text{eV}}{m_a}\right) \times \left(\frac{F_a}{10^{12}\text{GeV}}\right)$$

Classical QCD axion window:

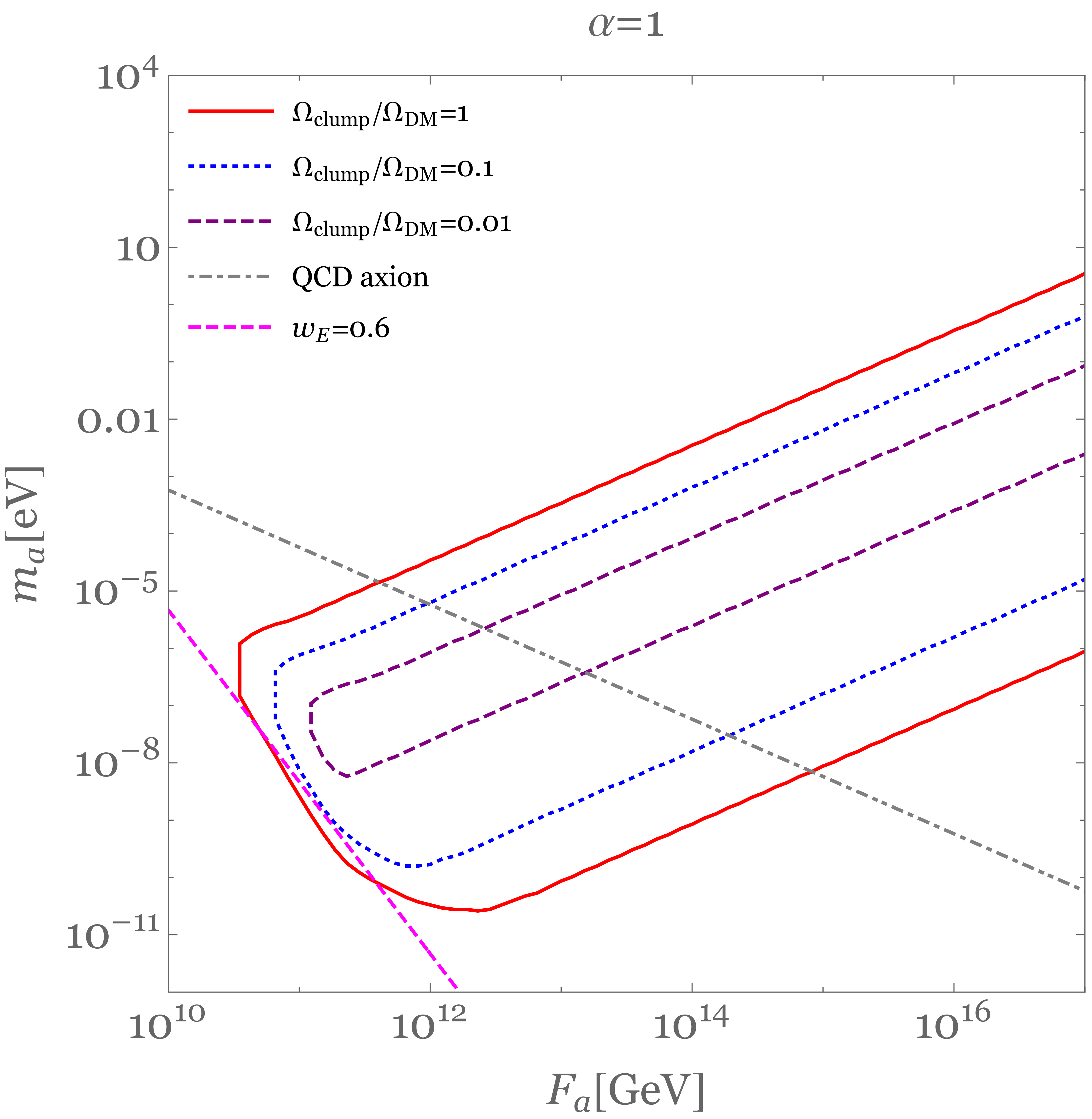
$$10^9 < F_a/\text{GeV} < 10^{12}$$

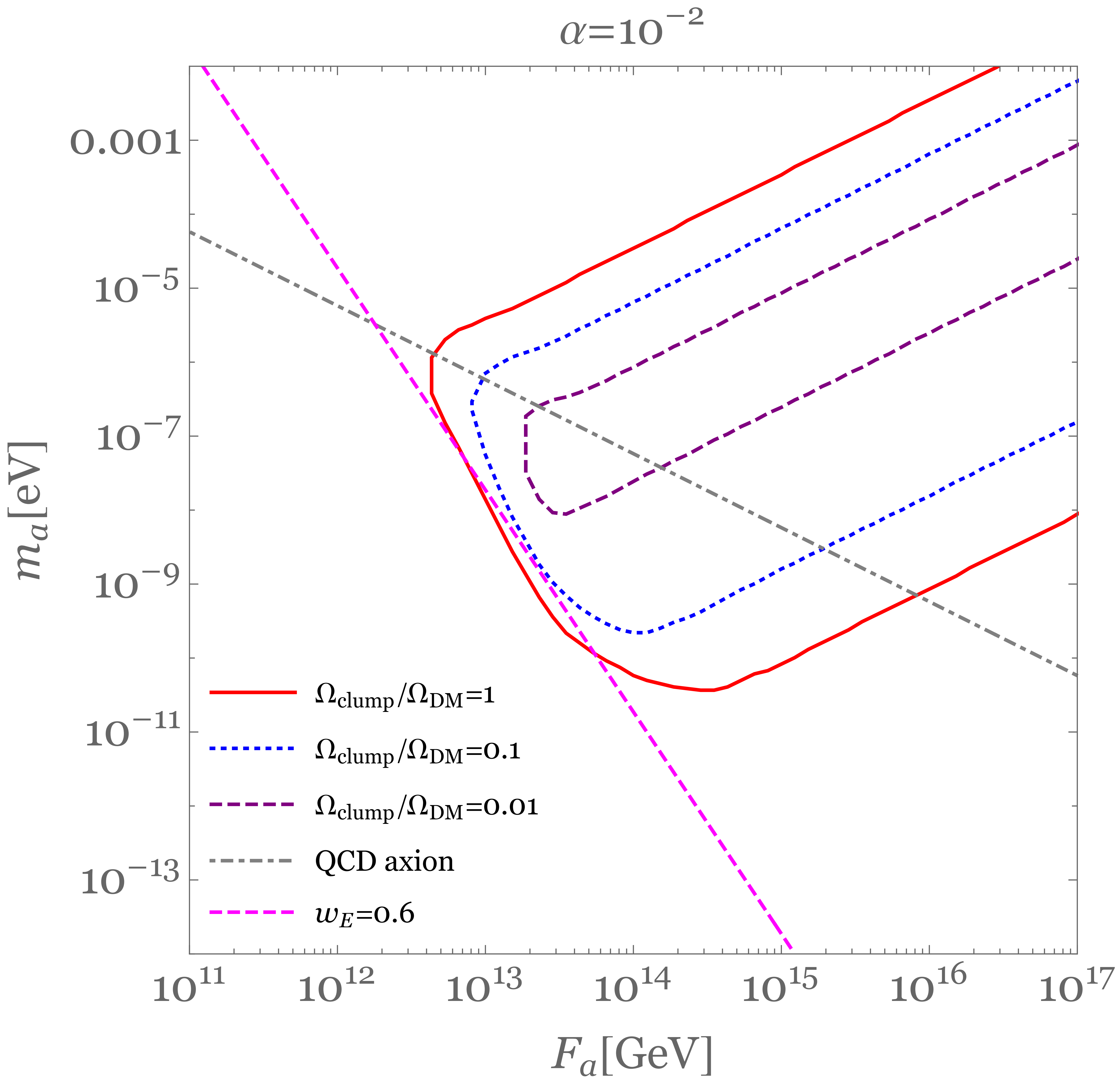
The classical QCD axion window cannot be constrained due to a finite source size effect.

A higher breaking scale can be constrained.

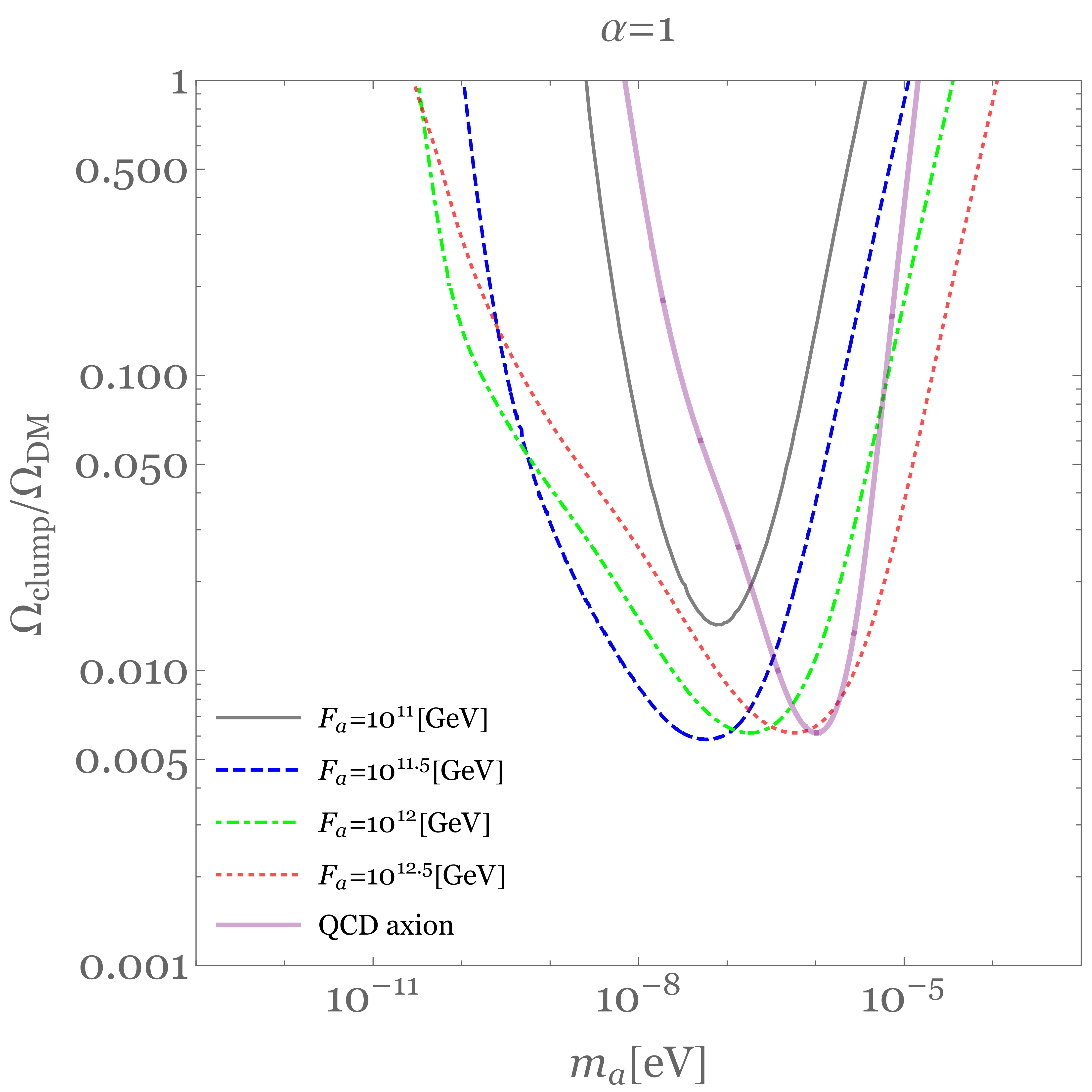


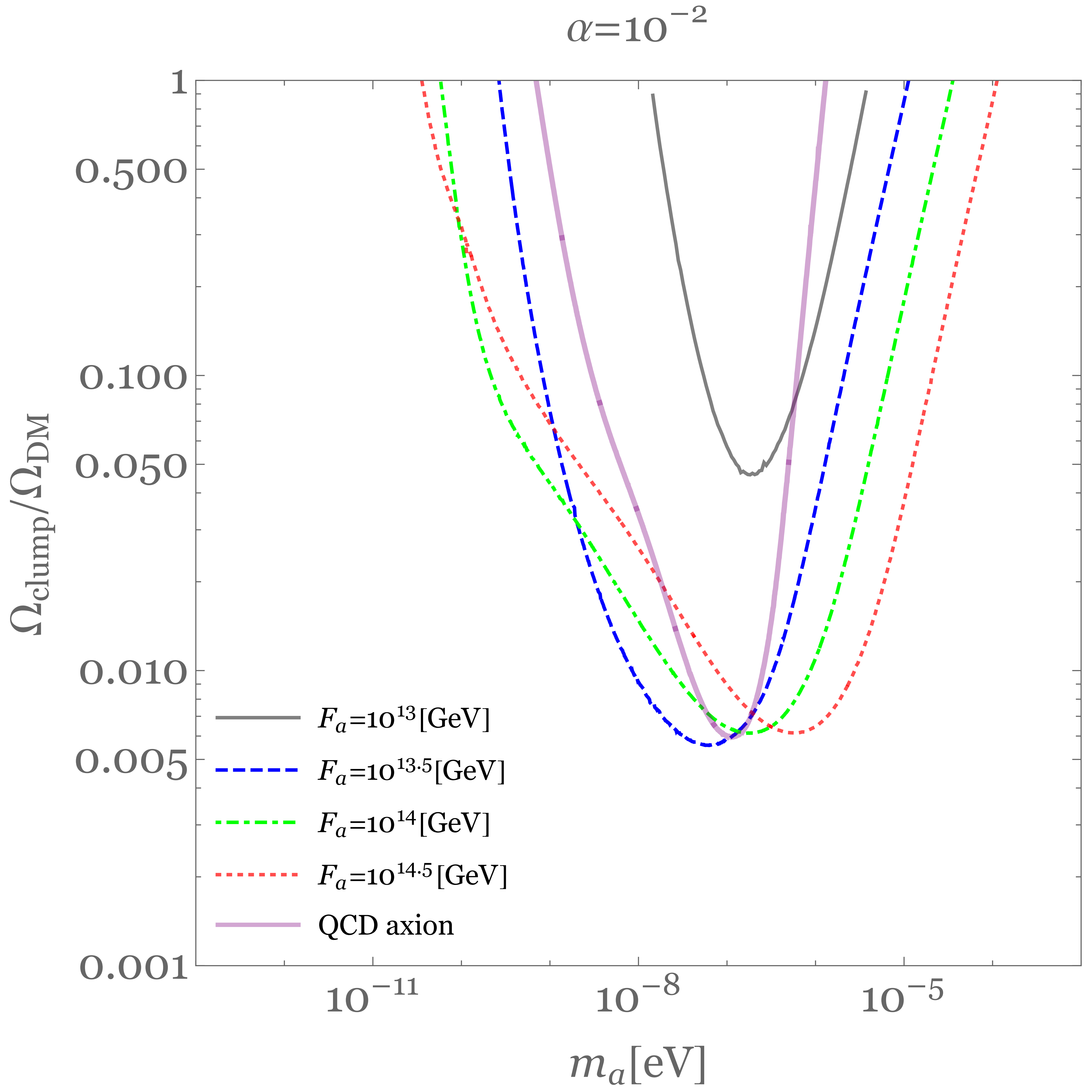
Result4 (Subaru HSC)





Result5 (Subaru HSC)

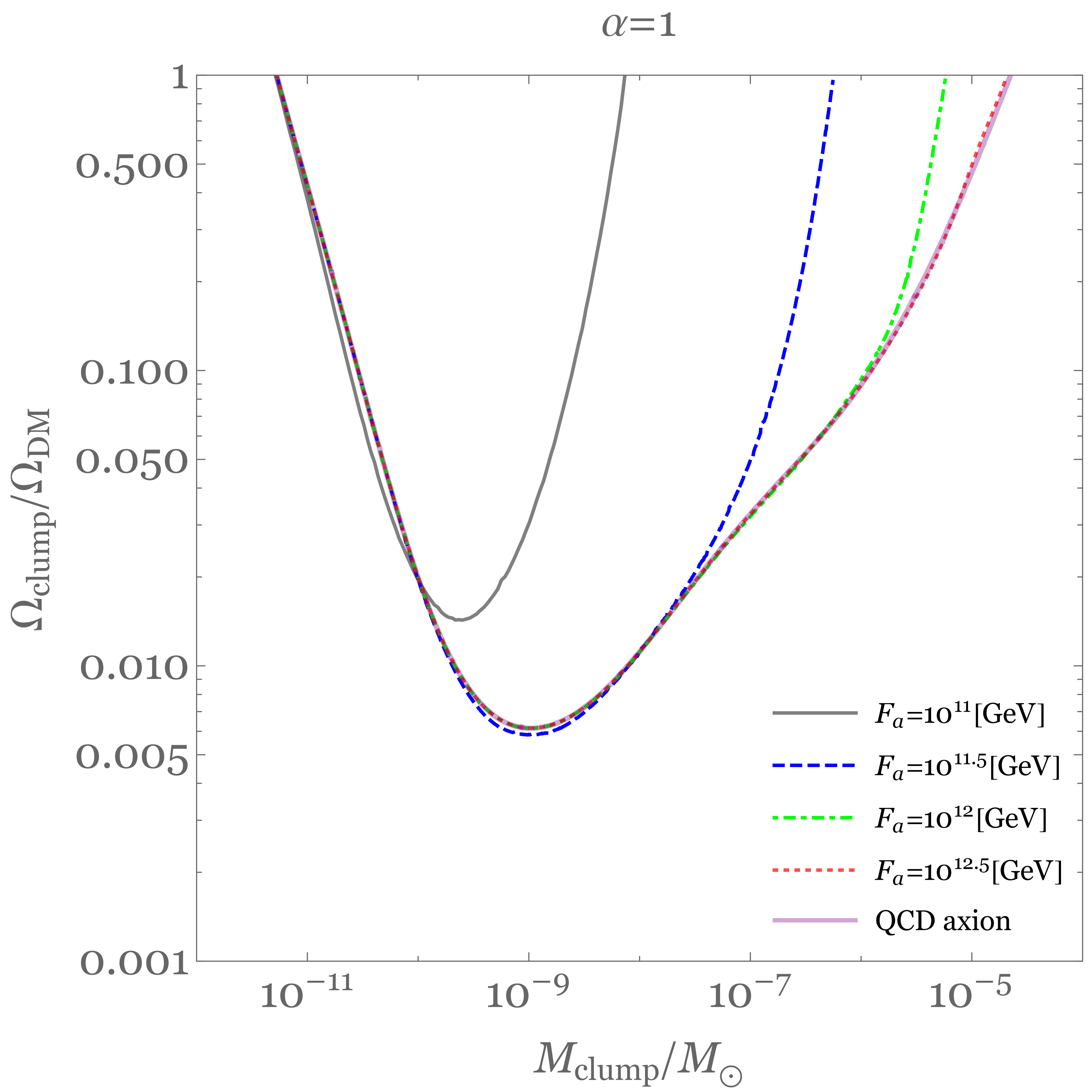




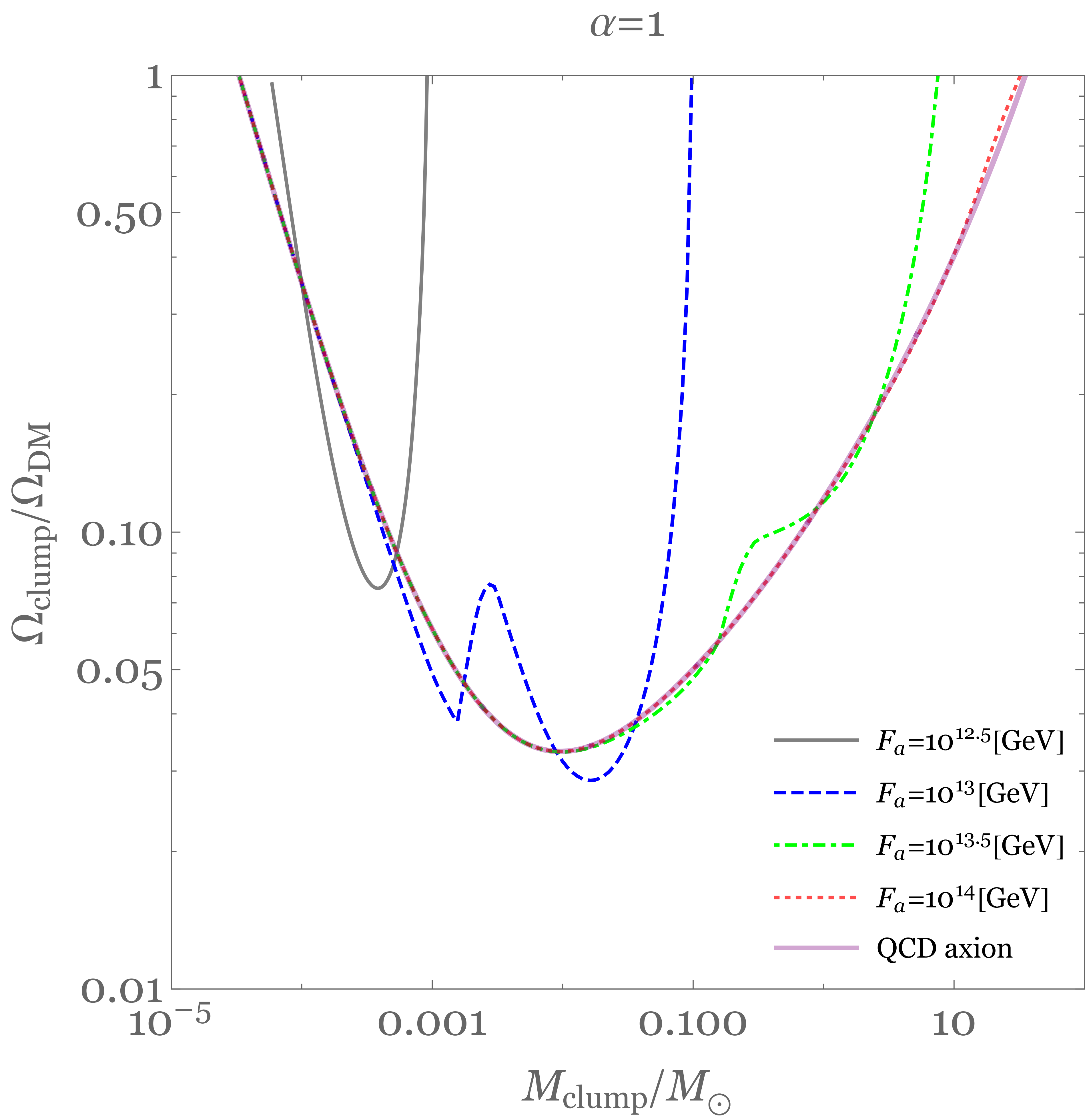
Result1

$(M_{\rm clump}(m_a),\ F_a,\ \Omega_{\rm clump}/\Omega_{\rm DM},\ \alpha)$ with fixed F_a, α.

Subaru HSC



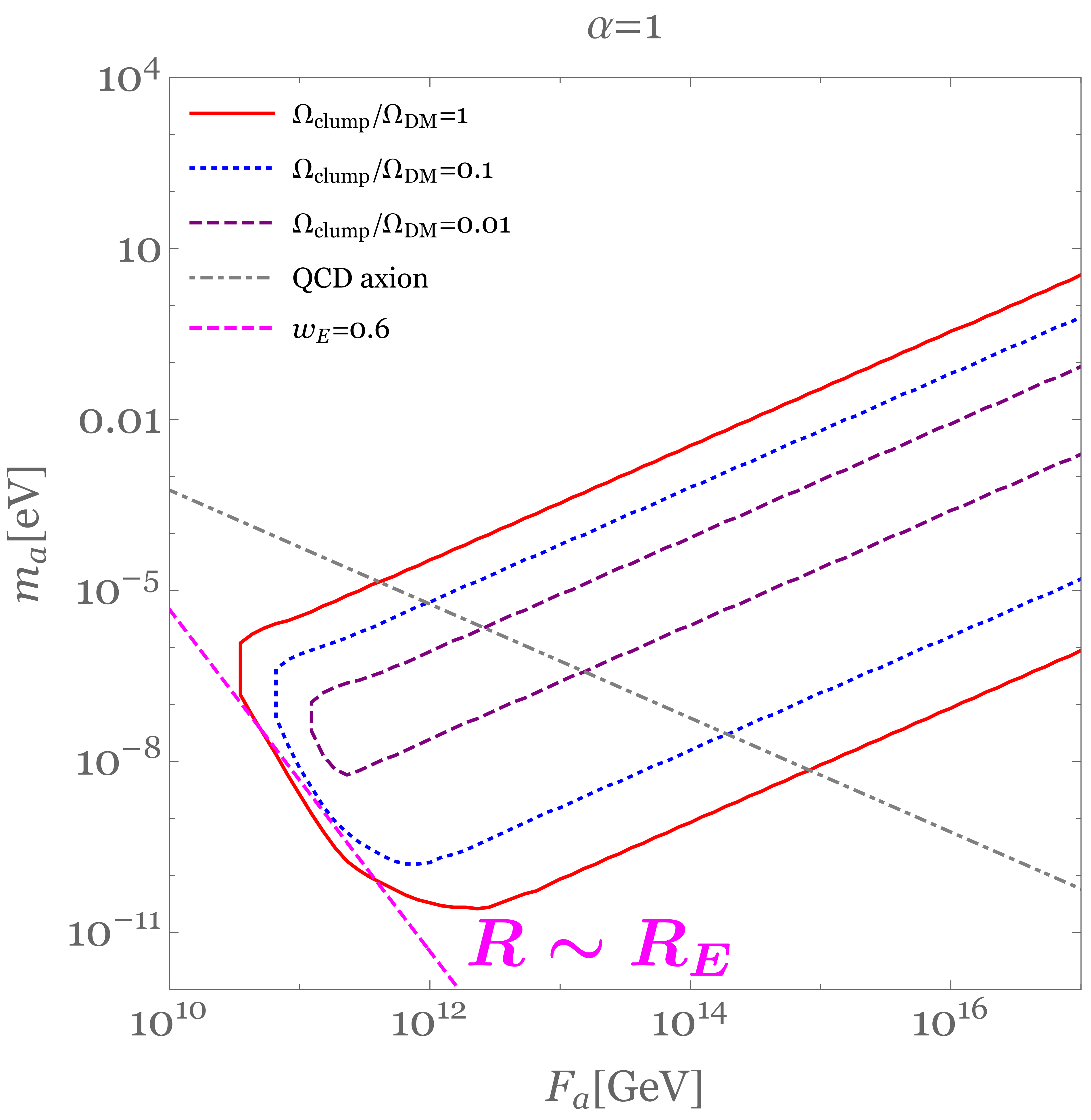
EROS-2



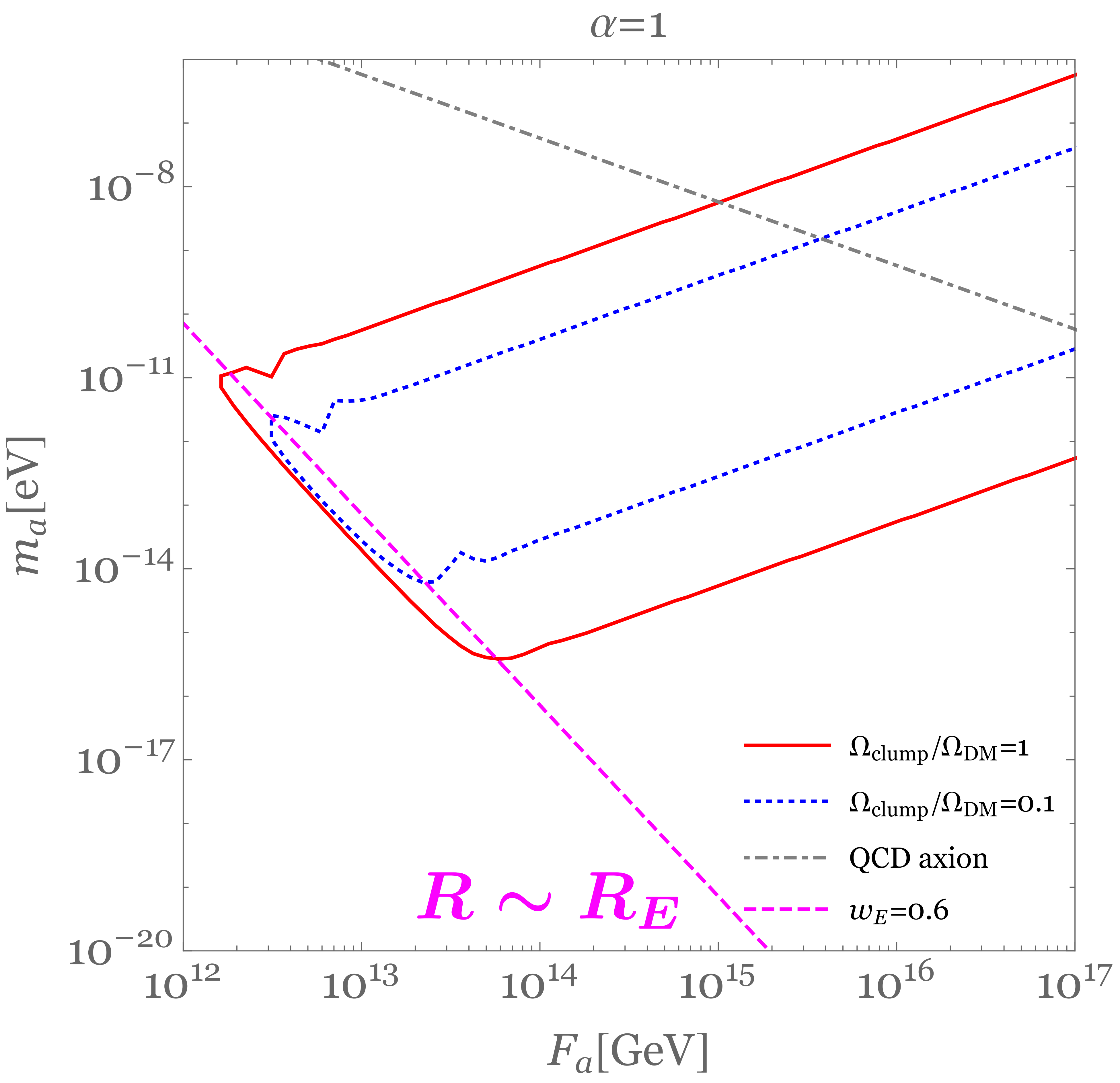
Result2 (1)

$(M_{\rm clump}(m_a),\ F_a,\ \Omega_{\rm clump}/\Omega_{\rm DM},\ \alpha)$ with fixed $\Omega_a/\Omega_{\rm DM}, \alpha$.

Subaru HSC



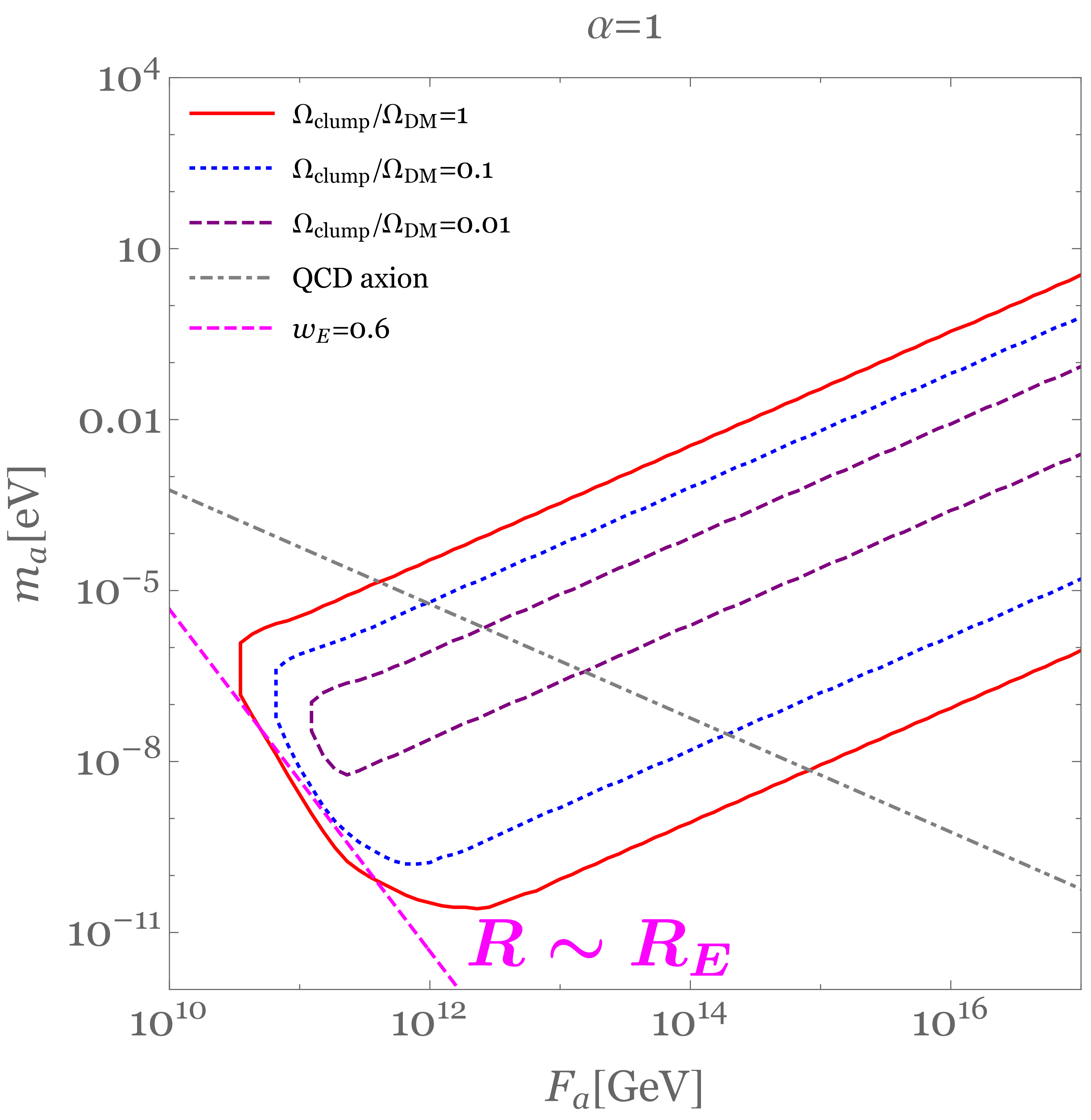
EROS-2



Result2 (2)

Unfortunately, classical QCD axion window cannot be constrained.

Subaru HSC



EROS-2