The ALP miracle

unified inflaton and dark matter

Wen Yin (殷 文)

IHEP, Chinese Academy of Sciences

Based on
arXiv:1702.03284, JCAP 1705, 05, 044
arXiv:1710.XXXX

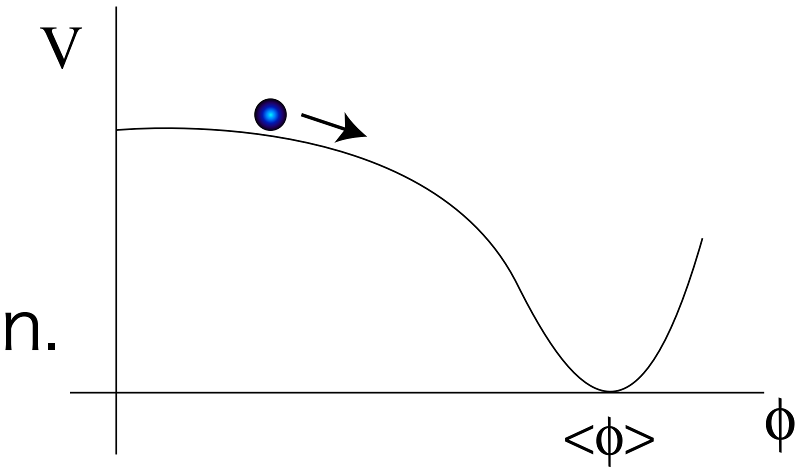
In collaborating with Ryuji Daido and Fuminobu Takahashi (Tohoku)

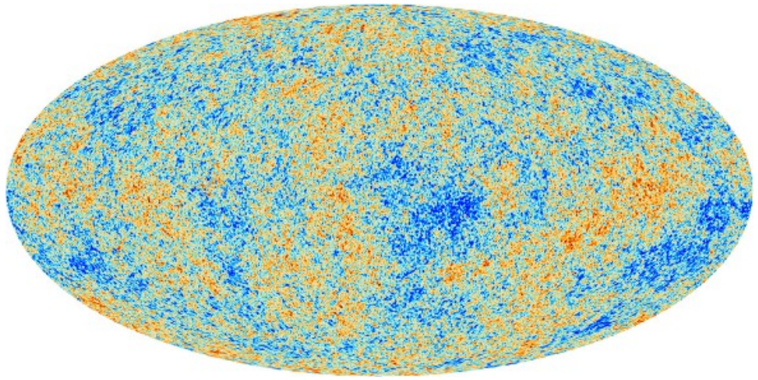
1. Introduction

Success of the ΛCDM model relies on the two unknown degrees of freedom (except for the origin of Λ)

- Inflaton

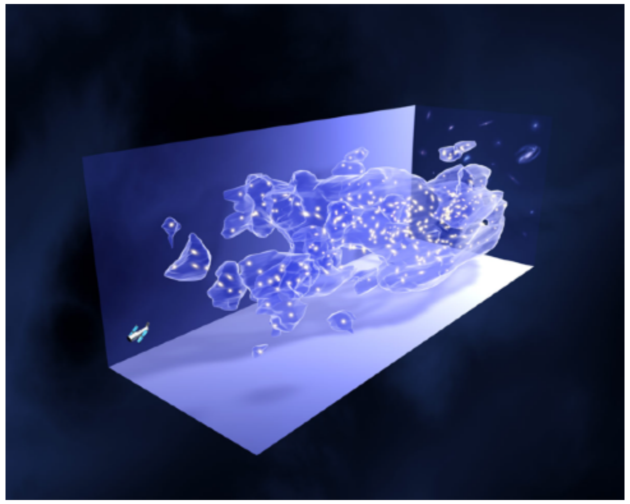
Very flat potential for slow-roll inflation.





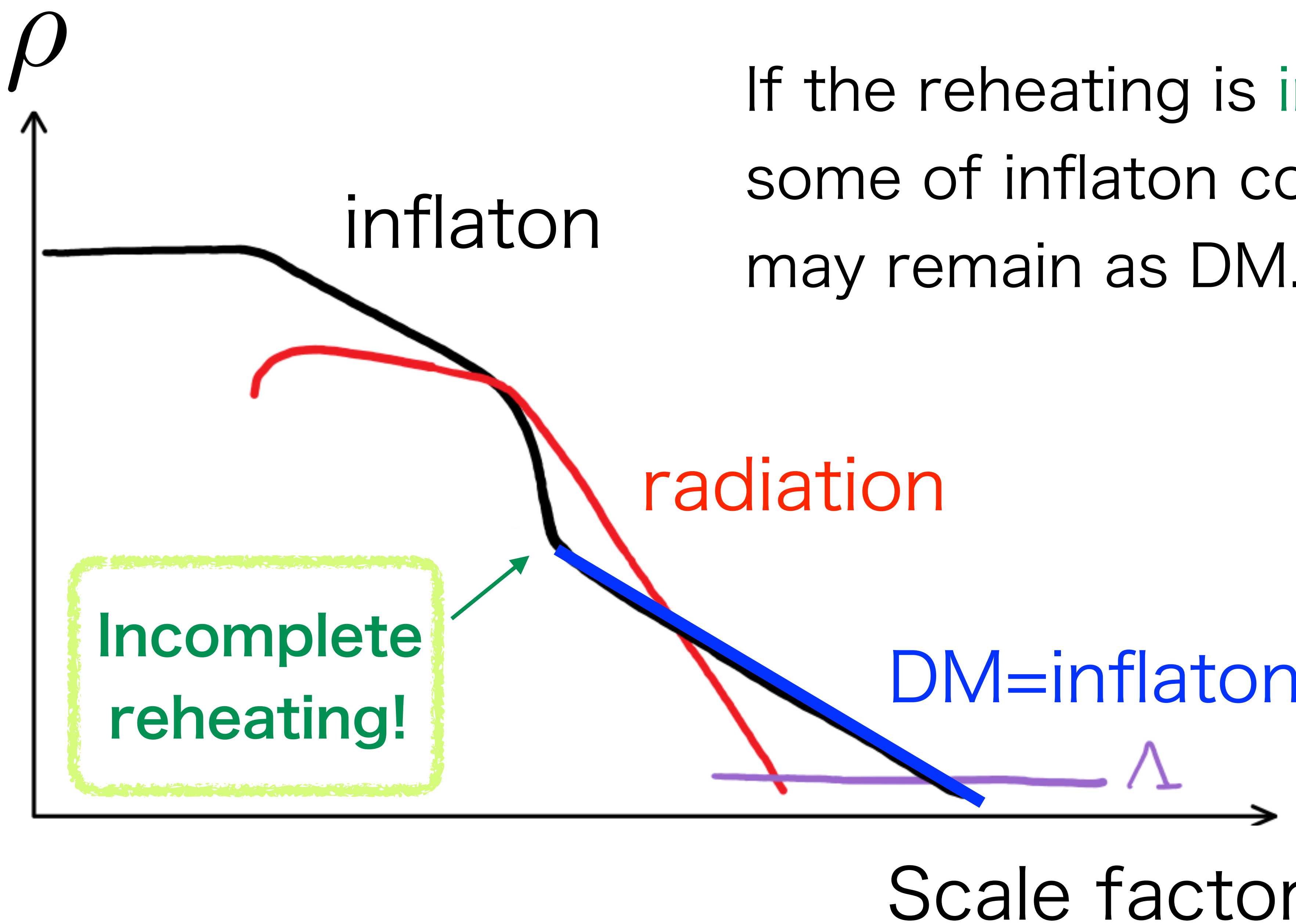
- Dark matter

Cold, neutral, and long-lived.



Both are neutral and occupied a significant fraction of the energy density of the Universe.

Inflaton = DM ?



If the reheating is incomplete, some of inflaton condensate may remain as DM.

The remnant inflaton condensate due to incomplete reheating can be dark matter.

cf. Kofman, Linde, Starobinsky `94, Mukaida, Nakayama 1404.1880, Bastero-Gil, Cerezo, Rosa,1501.05539
see also Lerner, McDonald 0909.0520, Okada, Shafi 1007.1672, Khoze 1308.6338 for inflaton WIMP.

What we did

Daido, Takahashi, and WY
1702.03284, 1710.XXXX

- **Inflaton = DM = Axion-like particle (ALP)**

- The observed density perturbations fix the relation between the ALP mass m_ϕ and decay constant f .

- Successful reheating and the DM abundance point to

$$m_\phi = \mathcal{O}(0.01 - 0.1)\,\mathrm{eV}\,,\;\; g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

within the reach of IAXO, TASTE! *"The ALP miracle"*

- Relax the missing satellite problem.

- Thermalized ALPs contribute to $\Delta N_{\rm eff} \simeq 0.03$.

2. ALP Inflation

Let us suppose that the inflaton is an axion which enjoys a (discrete) shift symmetry,

$$\phi \to \phi + 2\pi f \qquad V(\phi) = V(\phi + 2\pi f)$$

Natural Inflation

Freese, Frieman, Olinto `90

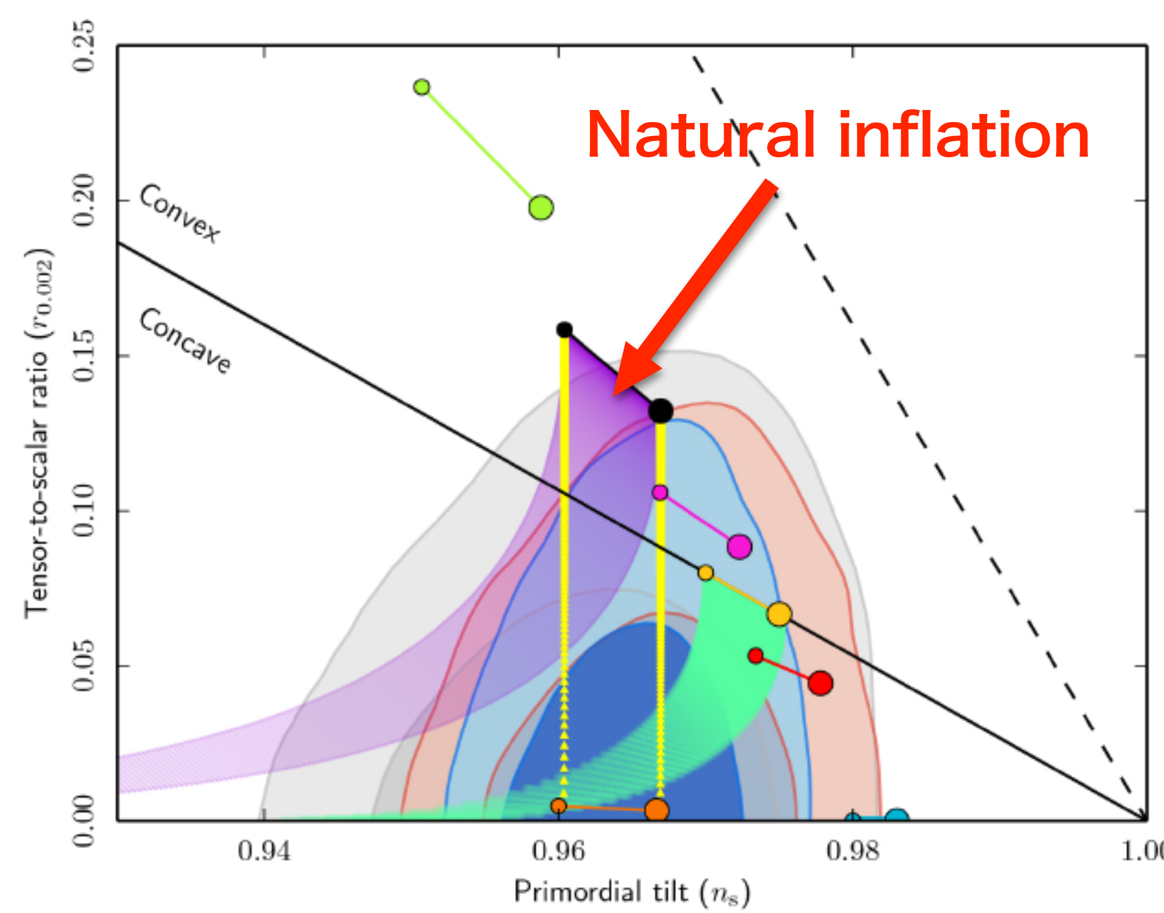
$$V = \Lambda^4 \cos(\phi/f) + \Lambda^4$$

Only large-field inflation is possible with a single cosine term.

- Super-Planckian decay constant required:

$$f \gtrsim 5 M_P$$

- Predicted (ns,r) are not favored by CMB obs.



Planck 2015

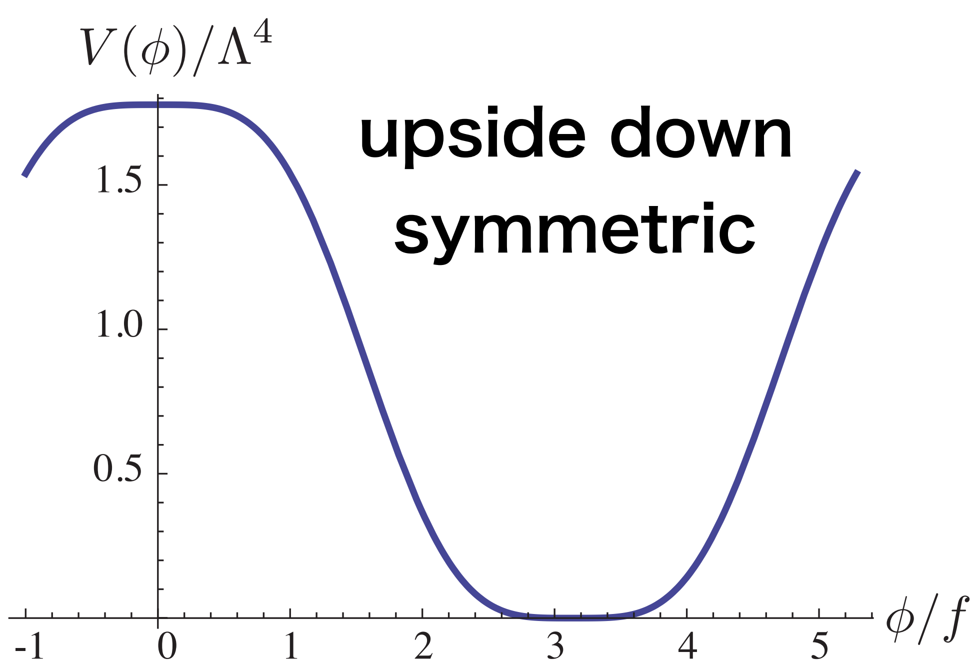
Axion hilltop inflation

Czerny, Takahashi 1401.5212,
Czerny, Higaki, Takahashi 1403.0410, 1403.5883
Croon and Sanz, 1411.7809

Axion hilltop inflation can be realized with (at least) two cosine terms: “*Multi-natural inflation*”

$$V_{\rm inf}(\phi) = \Lambda^4\left(\cos\left(\frac{\phi}{f}+\theta\right) - \frac{\kappa}{n^2}\cos\left(\frac{n\phi}{f}\right)\right) + {\rm const.} \qquad f \ll M_{pl}$$

$$= V_0 - \lambda\phi^4 - \theta\frac{\Lambda^4}{f}\phi + (\kappa-1)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots \qquad \lambda \sim \frac{\Lambda^4}{f^4}$$



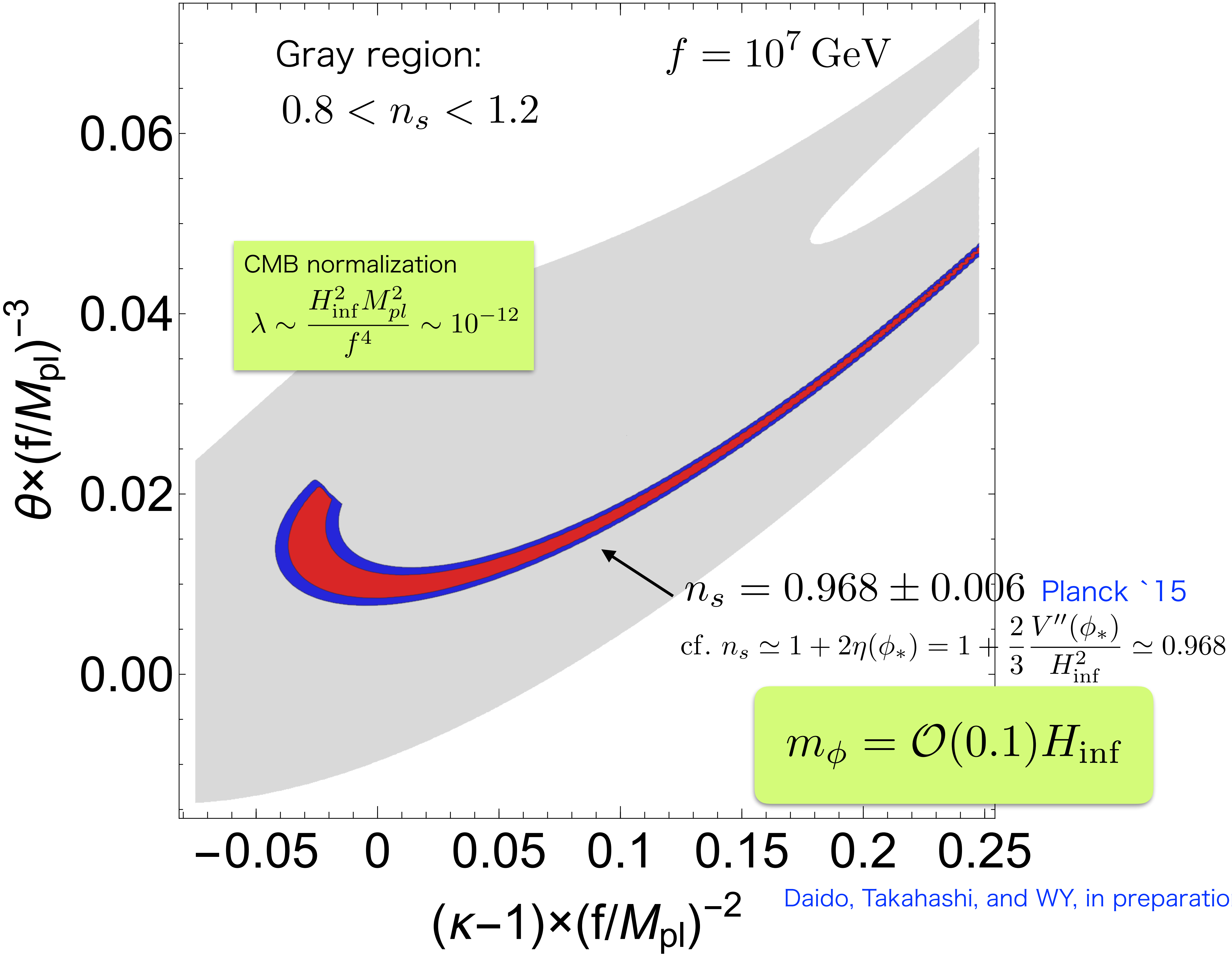
Odd n

- Inflaton potential is upside-down sym.
- In particular, inflaton is light both during inflation and in the true min.

$$m_\phi^2 = V''(\phi_{\rm min}) = -V''(\phi_{\rm max})$$

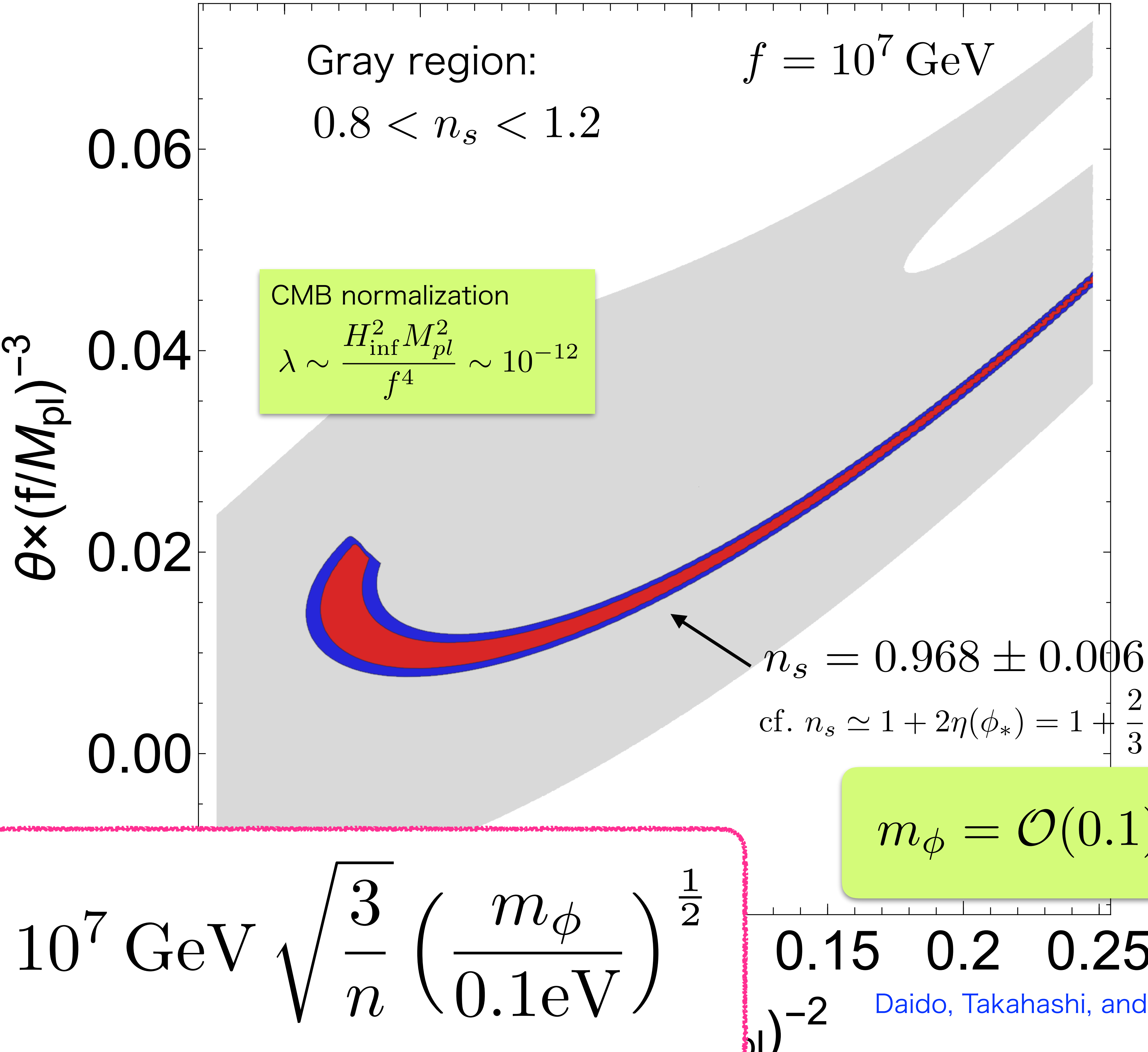
Flatness implies longevity.

• Inflaton (ALP) mass and Decay constant



Daido, Takahashi, and WY, in preparation

・Inflaton (ALP) mass and Decay constant

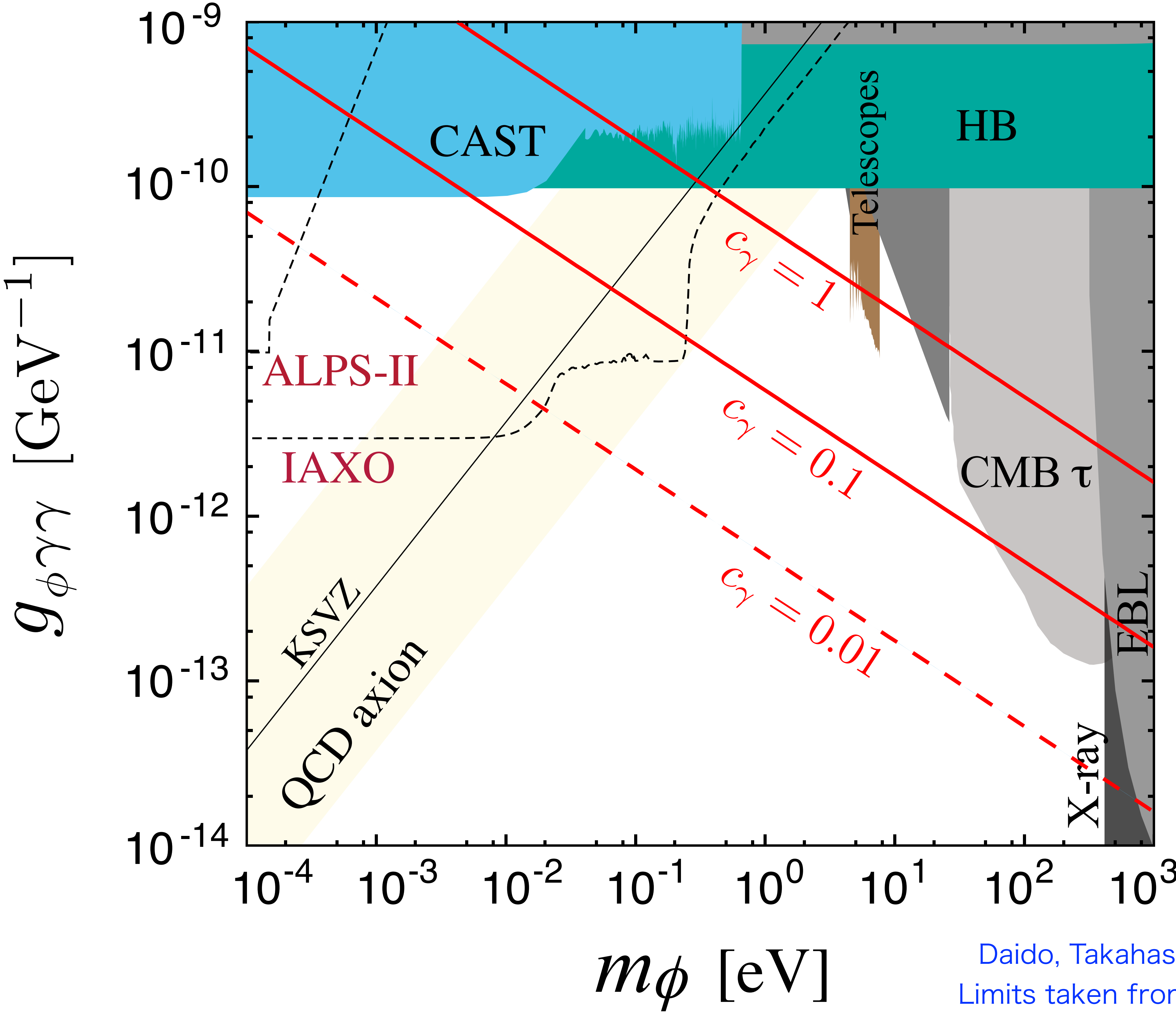


$$f \sim 10^7\,\mathrm{GeV}\sqrt{\frac{3}{n}}\left(\frac{m_\phi}{0.1\mathrm{eV}}\right)^{\frac{1}{2}}$$

Daido, Takahashi, and WY, in preparation

- **Inflaton (ALP) mass and coupling to photons**

$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad g_{\phi\gamma\gamma} = \frac{c_\gamma \alpha}{\pi f}$$

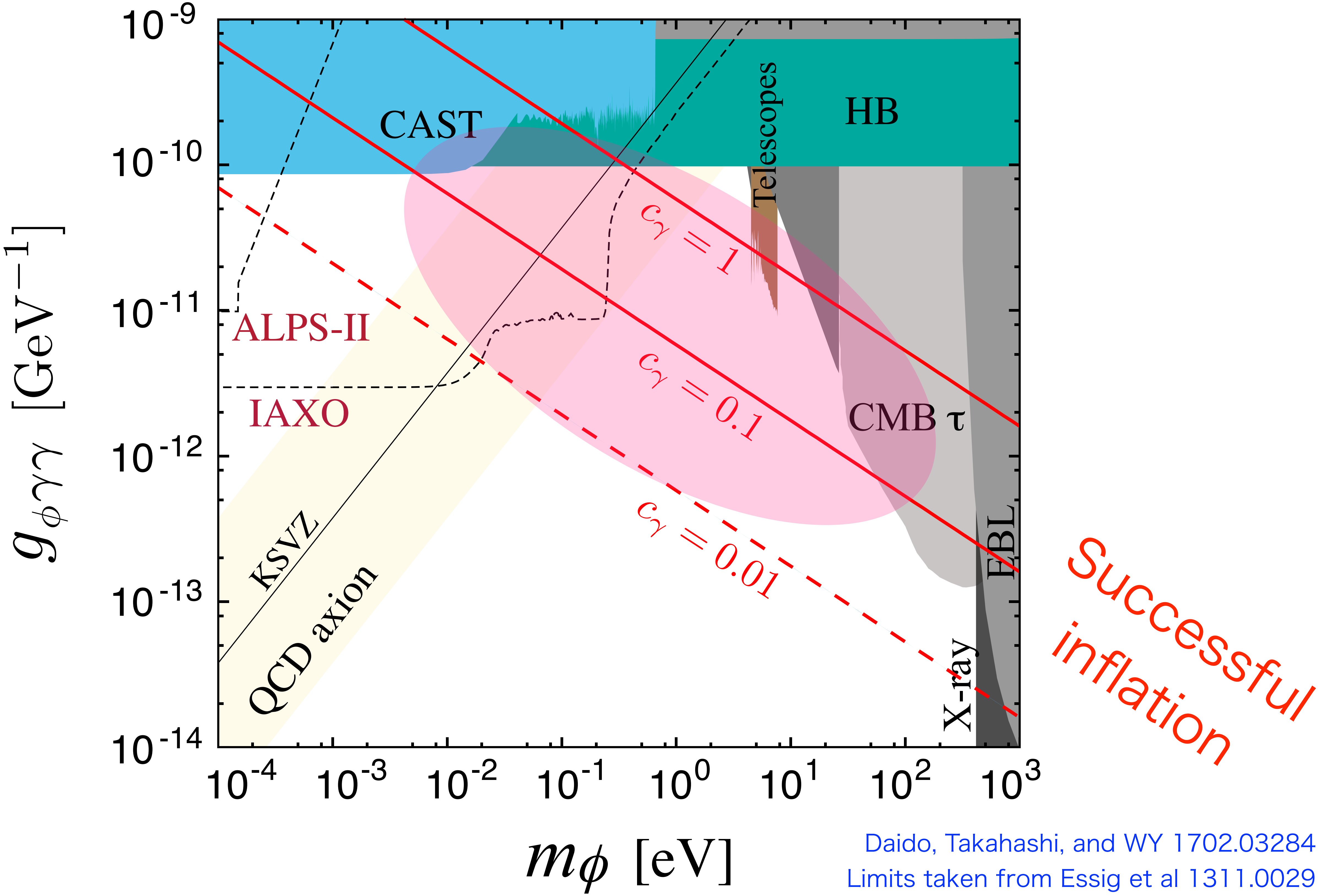


Daido, Takahashi, and WY 1702.03284

Limits taken from Essig et al 1311.0029

•Inflaton (ALP) mass and coupling to photons

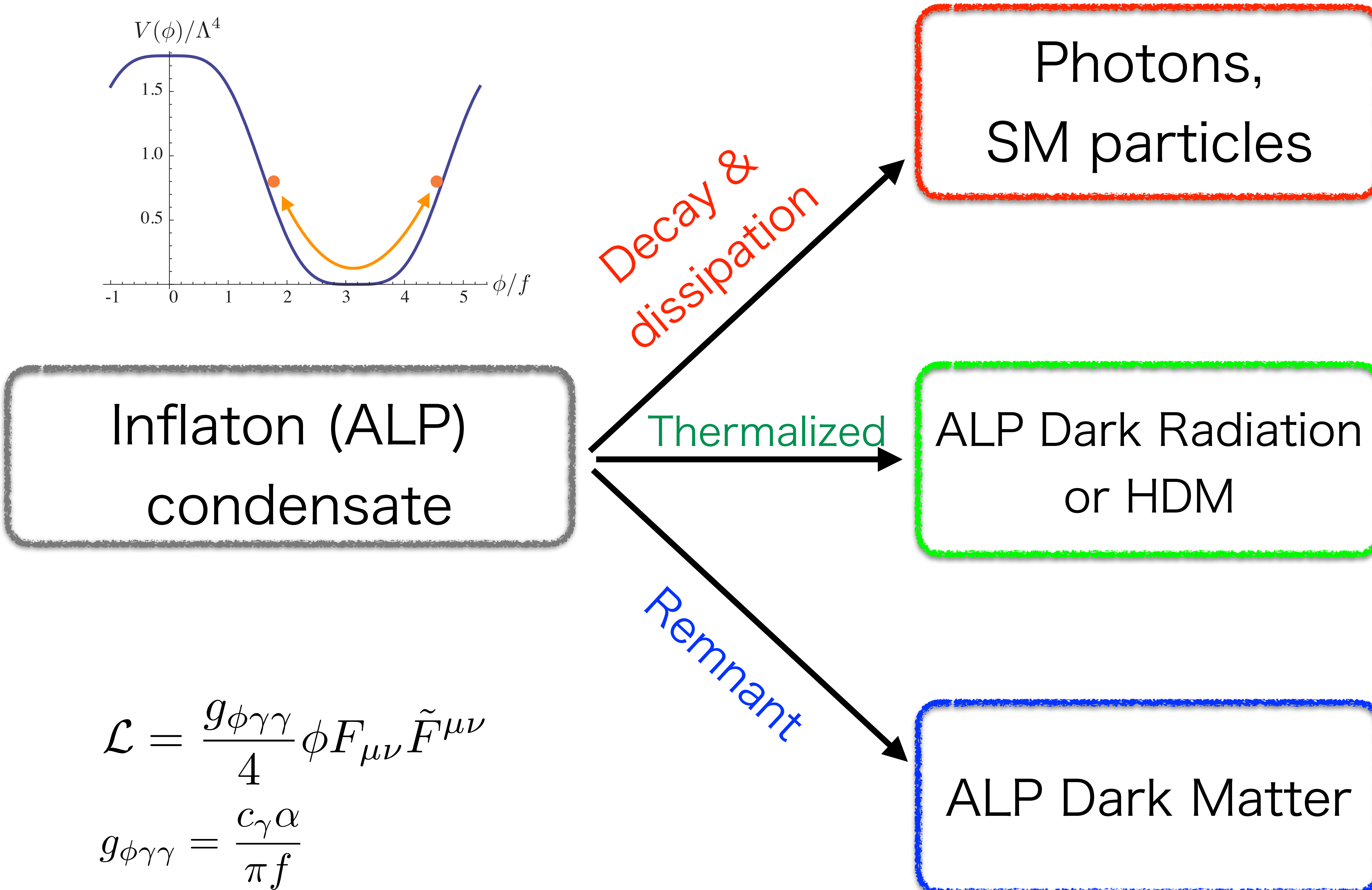
$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad g_{\phi\gamma\gamma} = \frac{c_\gamma \alpha}{\pi f}$$



Daido, Takahashi, and WY 1702.03284

Limits taken from Essig et al 1311.0029

3. Reheating and ALP DM



$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

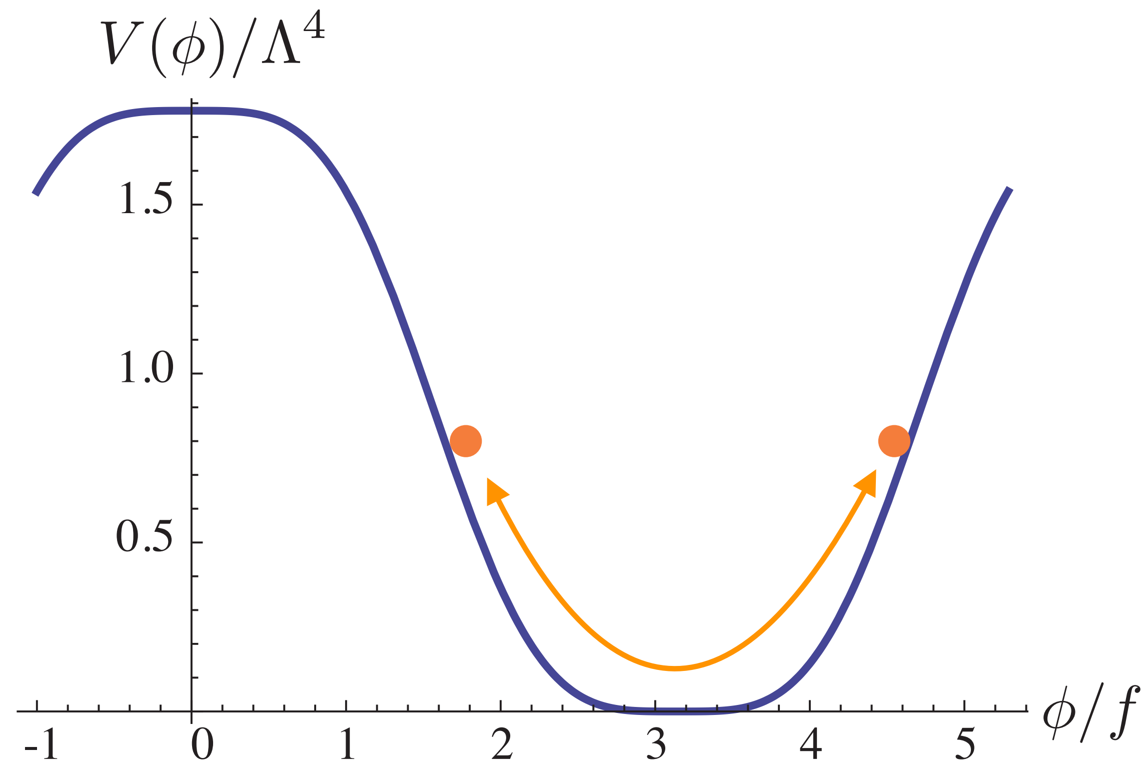
$$g_{\phi\gamma\gamma} = \frac{c_\gamma \alpha}{\pi f}$$

• Decay and dissipation

✓ The decay rate into two photons :

$$\Gamma_{\rm dec}(\phi \to \gamma\gamma) = \frac{c_\gamma^2 \alpha^2}{64\pi^3} \frac{m_{\rm eff}^3}{f^2} \sqrt{1 - \left(\frac{2m_\gamma^{(th)}}{m_{\rm eff}}\right)^2}$$

where $m_{\rm eff}^2(t) = V''(\phi_{\rm amp}) = 12\lambda\phi_{\rm amp}^2$



✓ The dissipation rate is roughly given by

$$\Gamma_{{\rm dis},\gamma} = \frac{c_\gamma^2 \alpha^2 T^3}{8\pi^2 f^2} \frac{C m_{\rm eff}^2}{e^4 T^2},$$

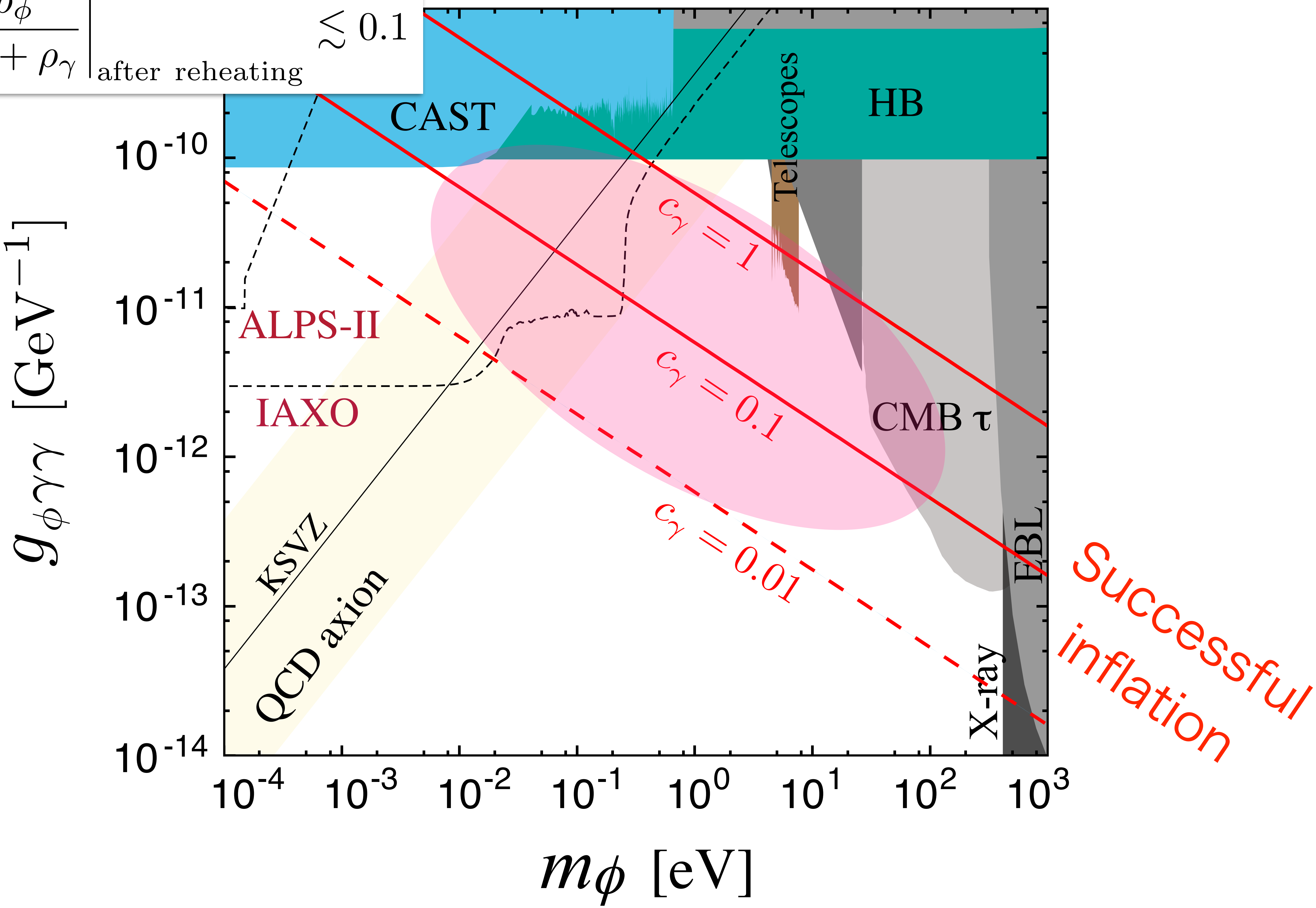
Moroi, Mukaida, Nakayama and Takimoto,1407.7465
cf. Salvio, Strumia, Xue, 1310.6982

Here C=O(10) represents an uncertainty of the order-of-magnitude estimate as well as spatial inhomogeneities due to tachyonic preheating and scalar resonance.

Brax, Dufaux and Mariadassou,1012.4656
Micha, Tkachev 0403101

cf. BBN bound $\Delta N_{\rm eff} < 1$

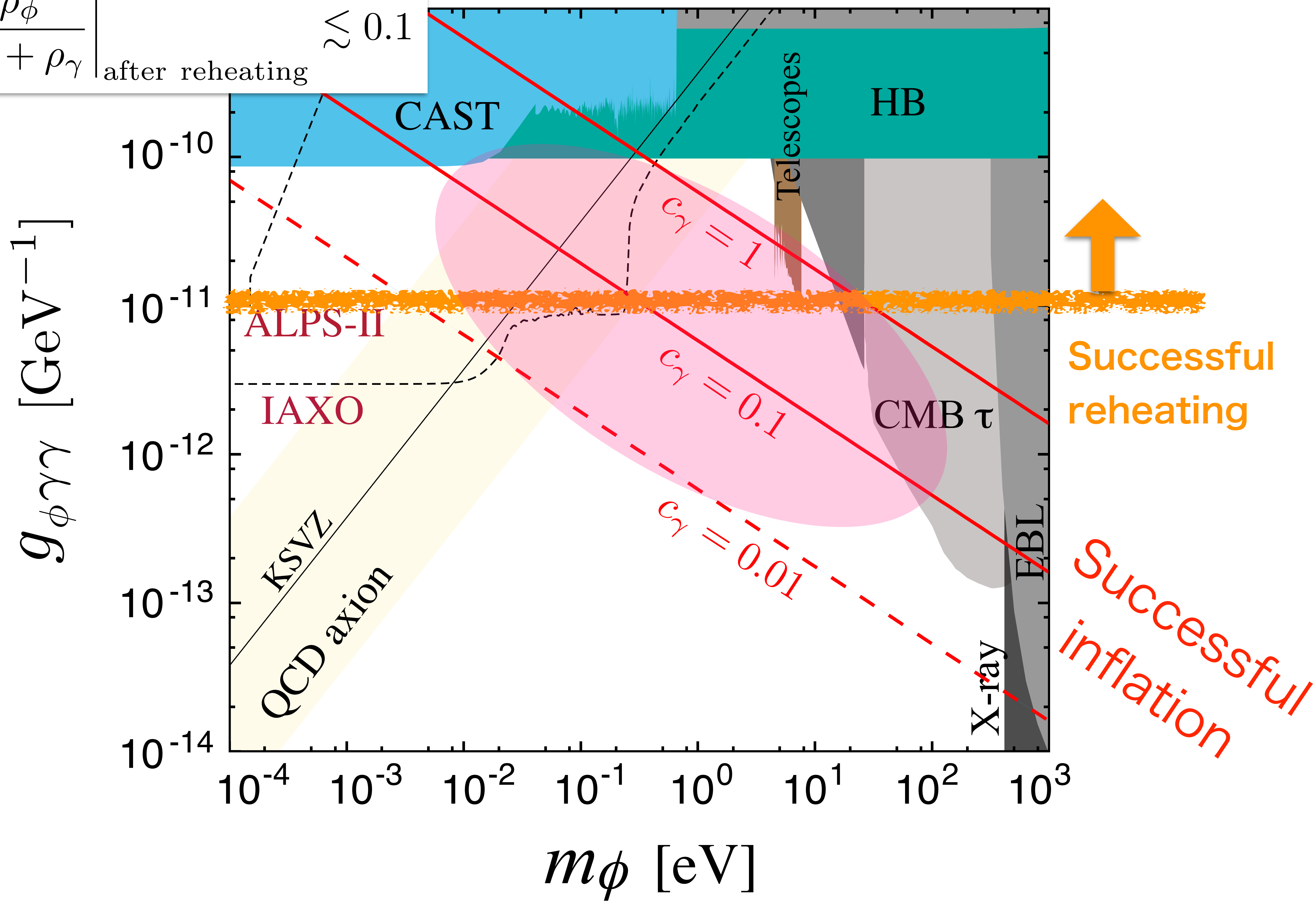
$$\left.\frac{\rho_\phi}{\rho_\phi + \rho_\gamma}\right|_{\rm after\ reheating} \lesssim 0.1$$



Thermalized ALPs contribute to HDM with $\Delta N_{\rm eff} \simeq 0.03$

cf. BBN bound $\Delta N_{\mathrm{eff}} < 1$

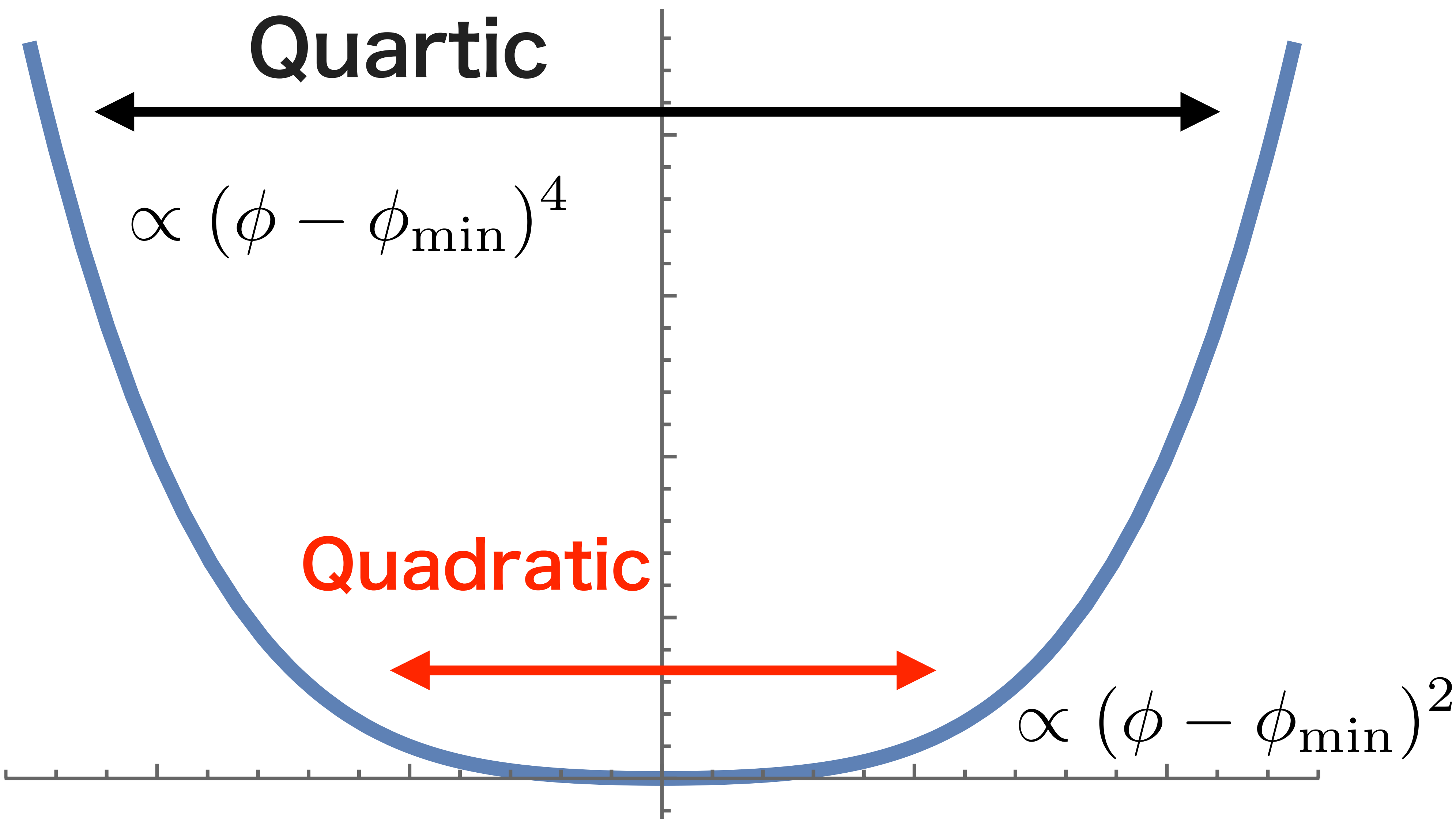
$$\left.\frac{\rho_\phi}{\rho_\phi + \rho_\gamma}\right|_{\text{after reheating}} \lesssim 0.1$$



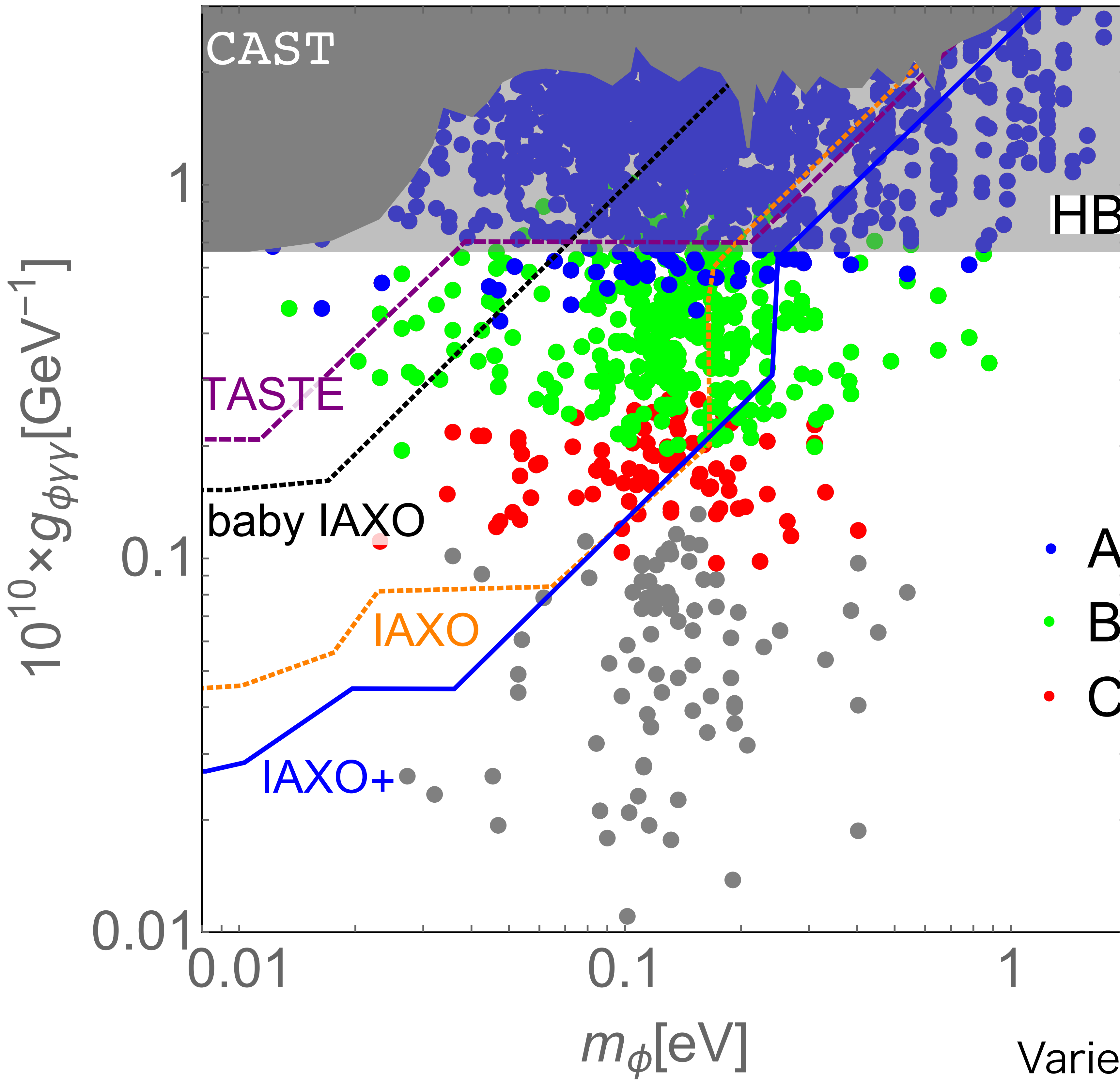
Thermalized ALPs contribute to HDM with $\Delta N_{\mathrm{eff}} \simeq 0.03$

・ALP condensate as CDM

ρ_ϕ decreases like radiation when oscillating in a quartic potential and becomes matter-like in a quadratic potential.



ALP abundance



$$5\times 10^6\ \mathrm{GeV} < f < 2.5\times 10^7\ \mathrm{GeV}$$

$$0.08 < \Omega_\phi h^2 < 0.16$$

$$\mathcal{L} = c_2 \frac{\alpha_2}{8\pi}\frac{\phi}{f} W_{\mu\nu}\tilde{W}^{\mu\nu} + c_Y \frac{\alpha_Y}{4\pi}\frac{\phi}{f} B_{\mu\nu}\tilde{B}^{\mu\nu},$$

with $c_2 = \sum_i q_i,\quad c_Y = \sum_j q_j Y_j^2 \quad c_\gamma = \frac{c_2}{2} + c_Y$

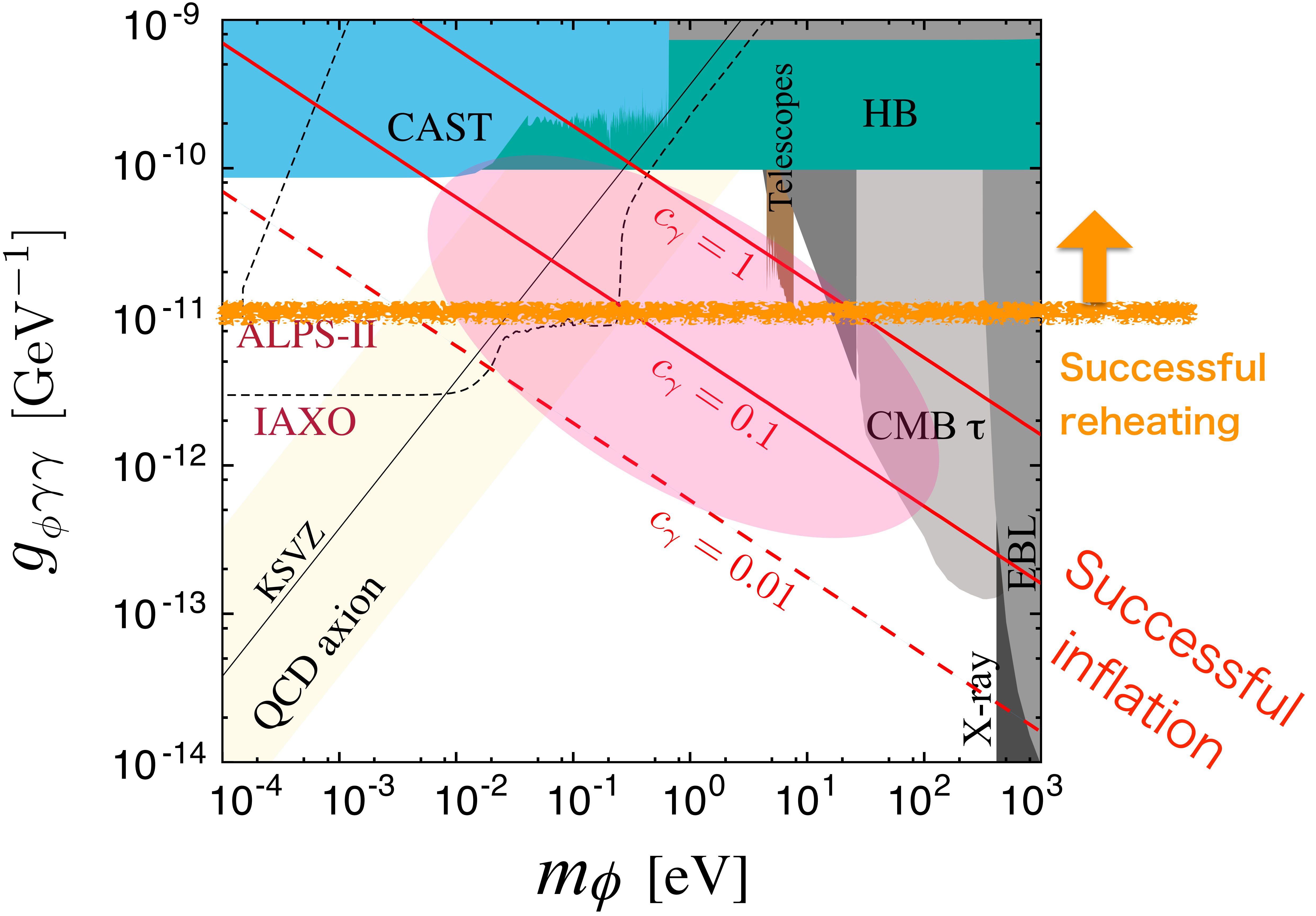
A $|c_\gamma/c_Y| > 0.3$

B $0.1 < |c_\gamma/c_Y| < 0.3$

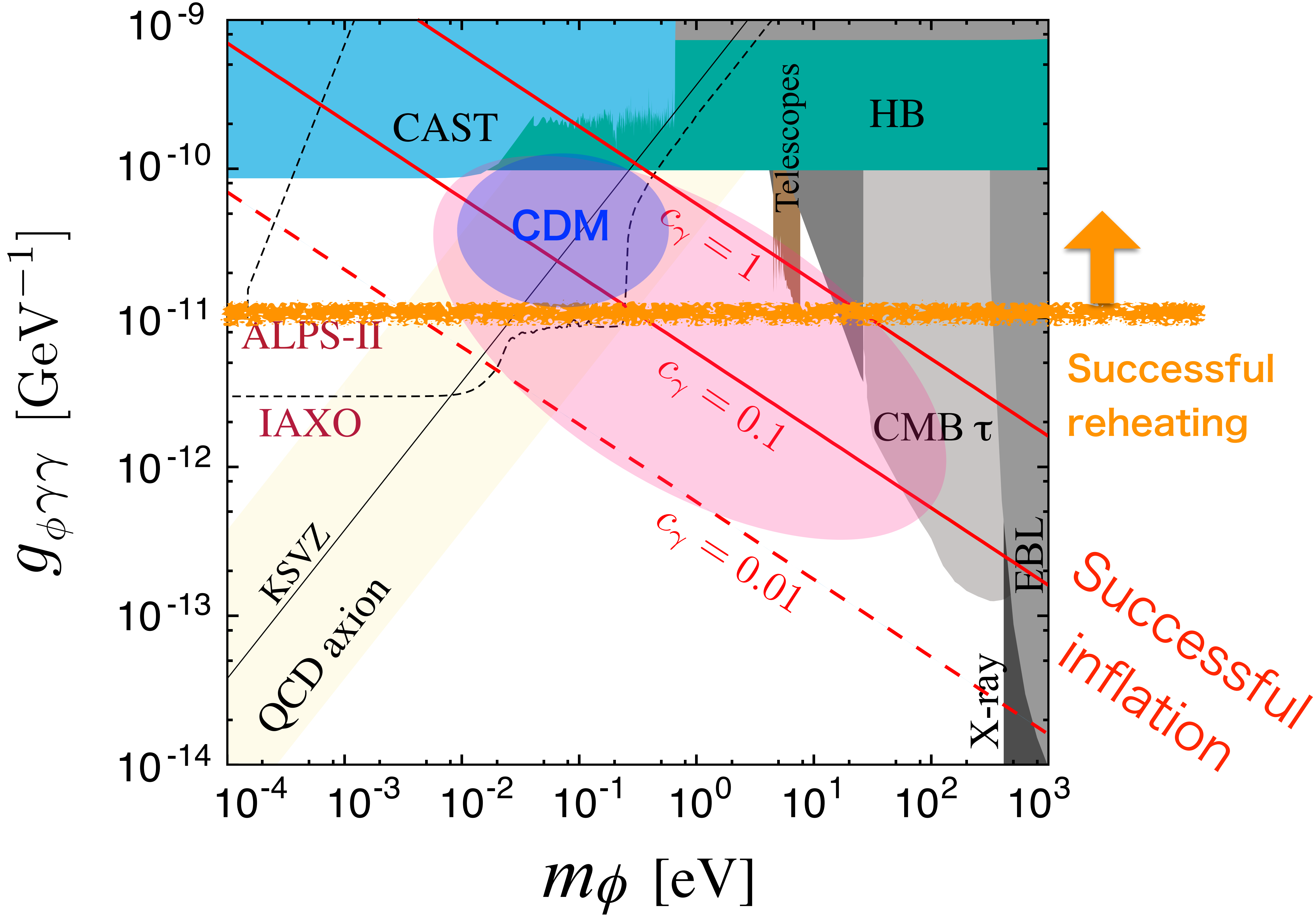
C $0.05 < |c_\gamma/c_Y| < 0.1$

Varied the other params by O(1).

C=50 Daido, Takahashi, and WY, in preparation

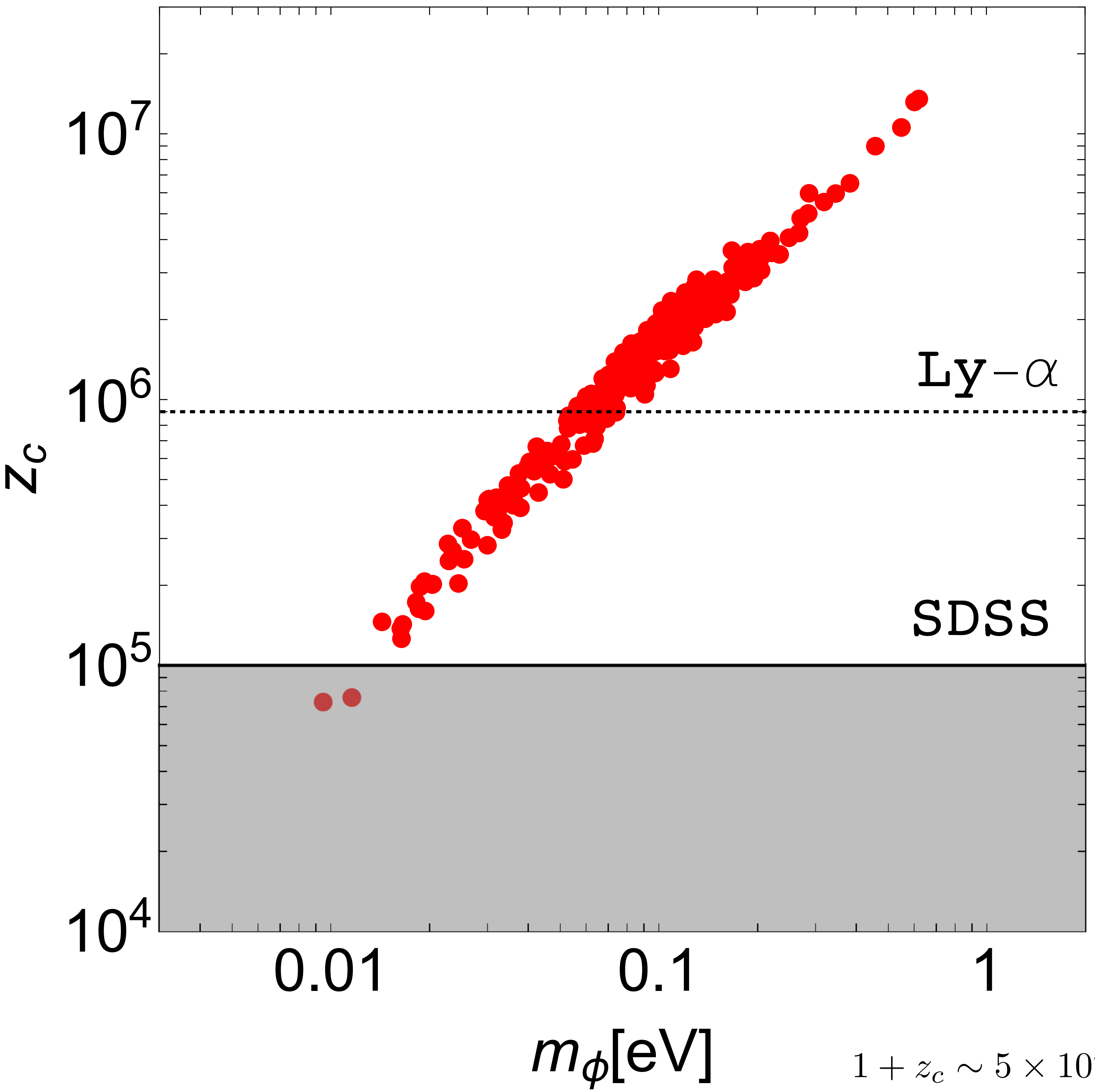


$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
CAST
HB
Telescopes
ALPS-II
IAXO
KSVZ
QCD axion
CMB τ
EBL
X-ray
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
Successful reheating
Successful inflation



CAST
HB
Telescopes
CDM
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
Successful reheating
Successful inflation
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

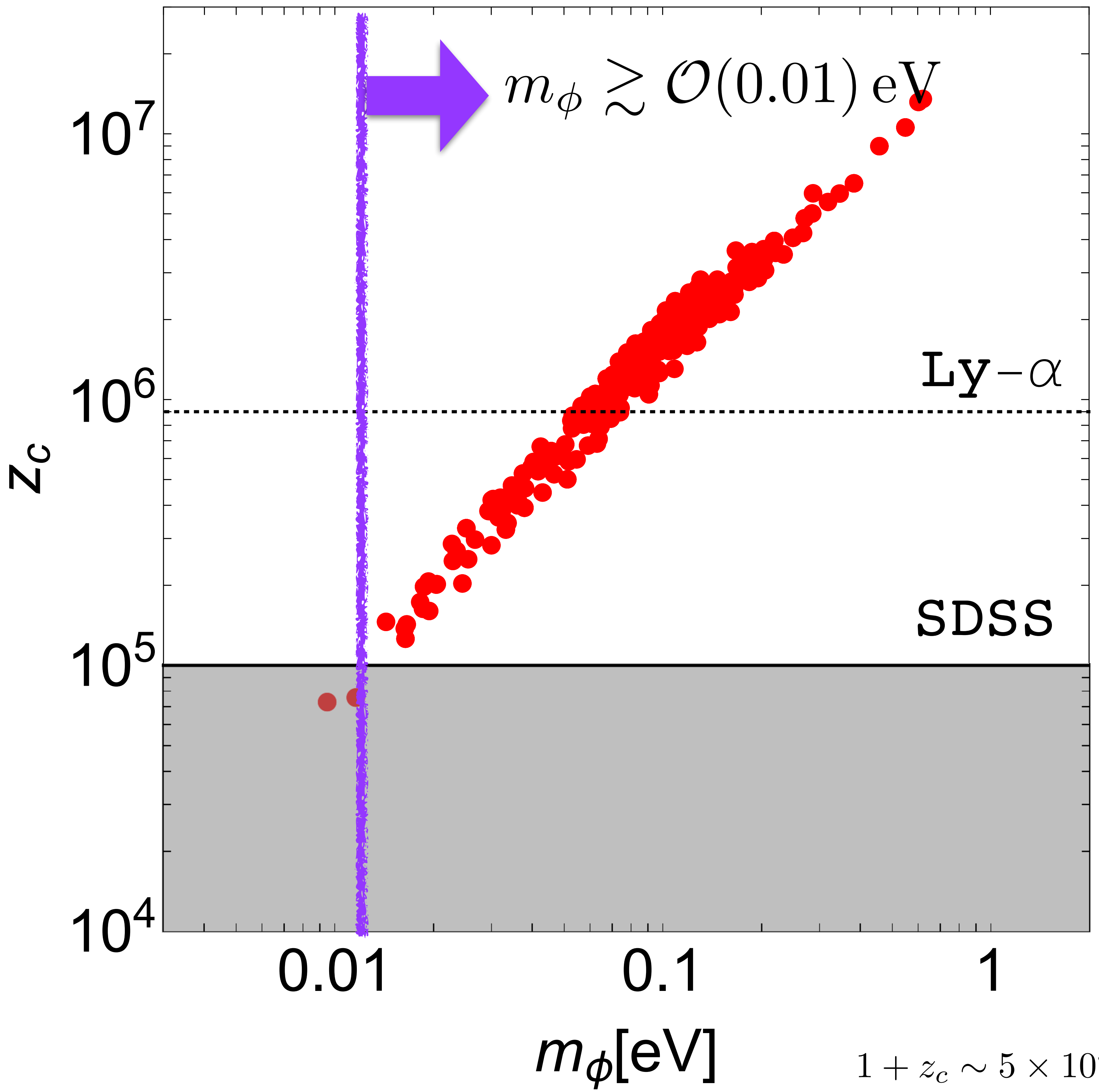
The red-shift at the transition vs. the ALP mass



Limits taken from
Sarkar, Das, Sethi, 1410.7129

$$1 + z_c \sim 5 \times 10^5 \left(\frac{0.12}{\Omega_\phi h^2}\right)^{\frac{1}{3}} \left(\frac{10^{-12}}{\lambda}\right)^{\frac{1}{3}} \left(\frac{m_\phi}{0.05\,\mathrm{eV}}\right)^{\frac{4}{3}}$$

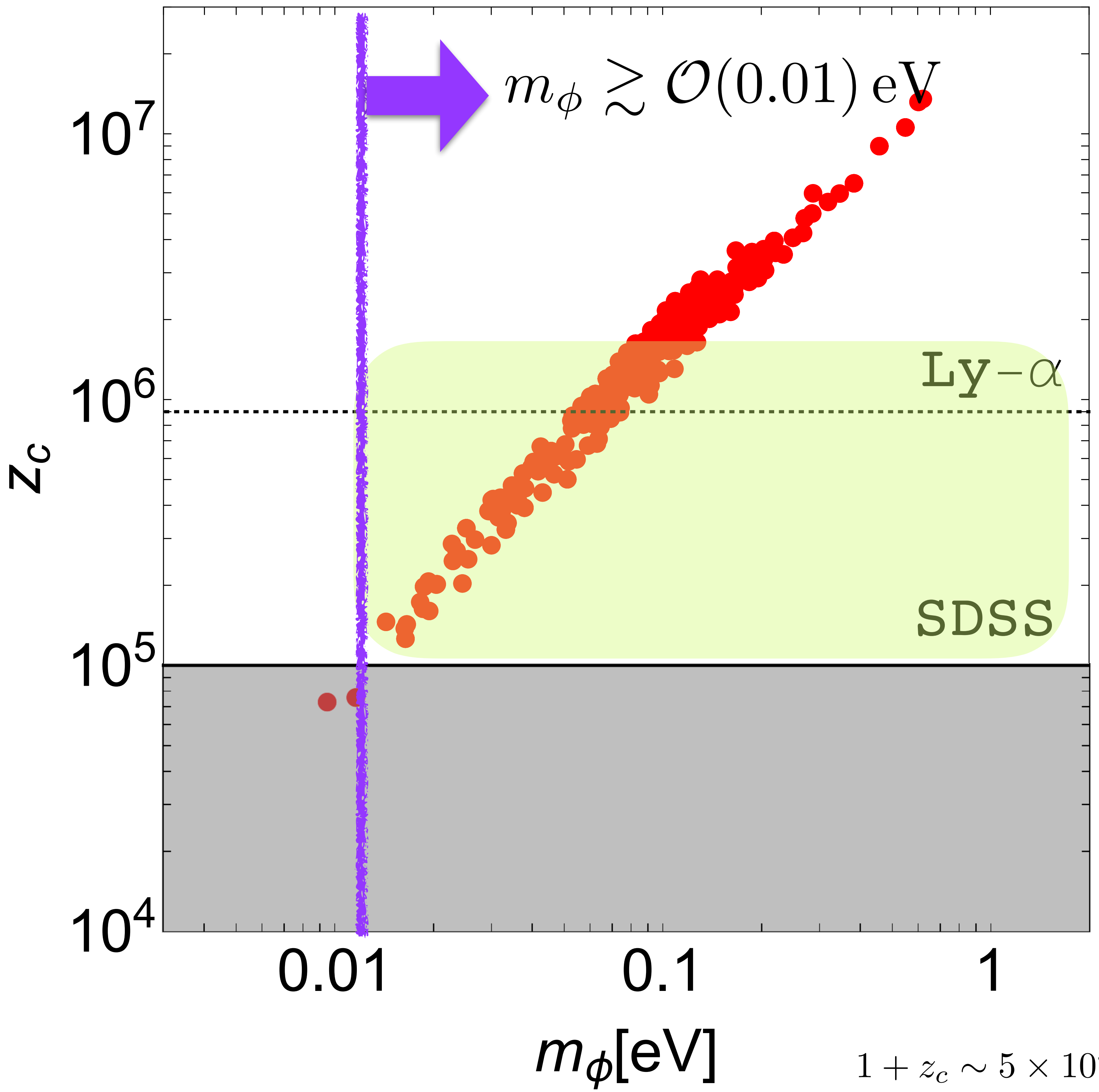
The red-shift at the transition vs. the ALP mass



Limits taken from
Sarkar, Das, Sethi, 1410.7129

$$1 + z_c \sim 5 \times 10^5 \left(\frac{0.12}{\Omega_\phi h^2}\right)^{\frac{1}{3}} \left(\frac{10^{-12}}{\lambda}\right)^{\frac{1}{3}} \left(\frac{m_\phi}{0.05\,\mathrm{eV}}\right)^{\frac{4}{3}}$$

The red-shift at the transition vs. the ALP mass

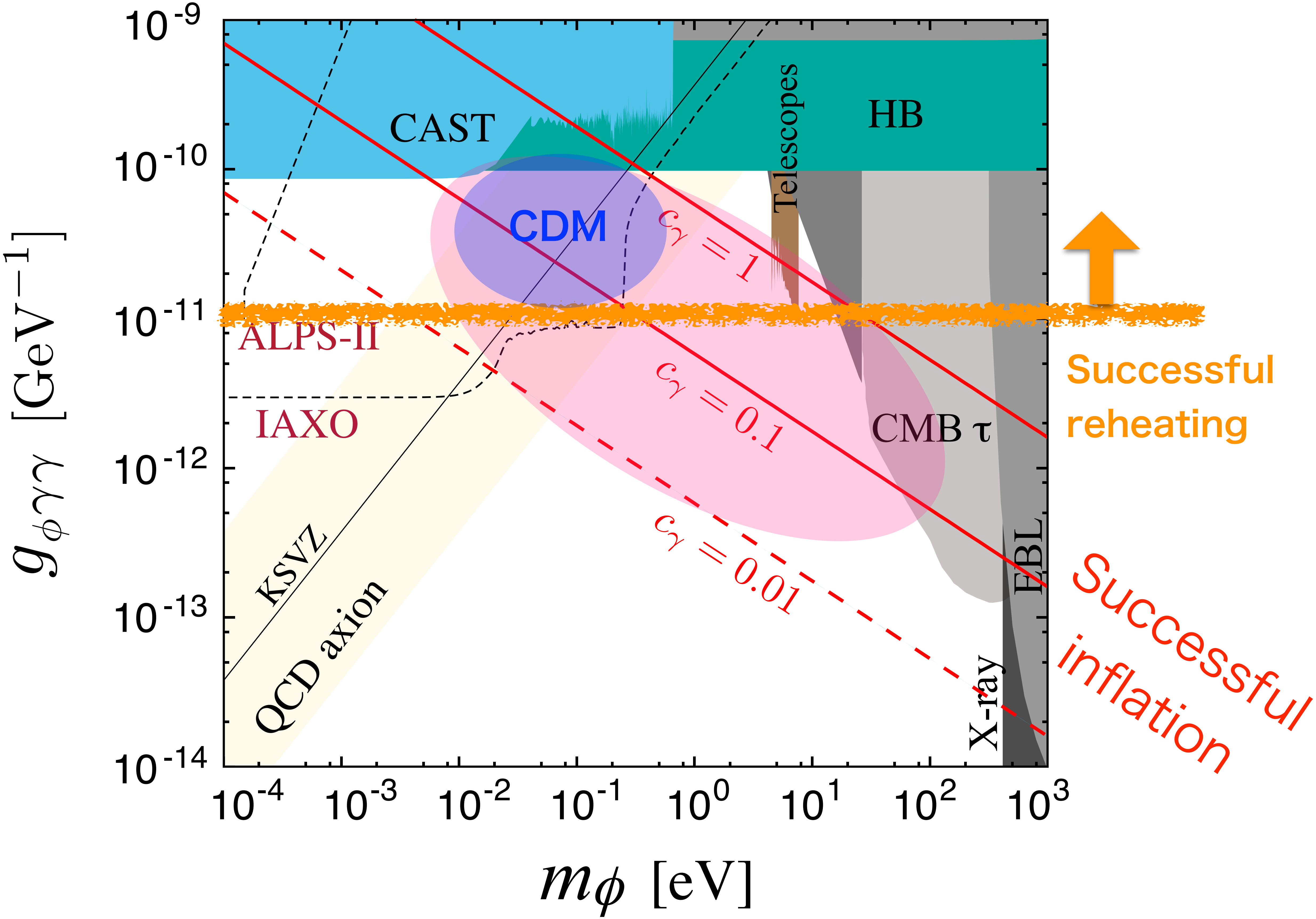


Missing satellite problem may be solved.

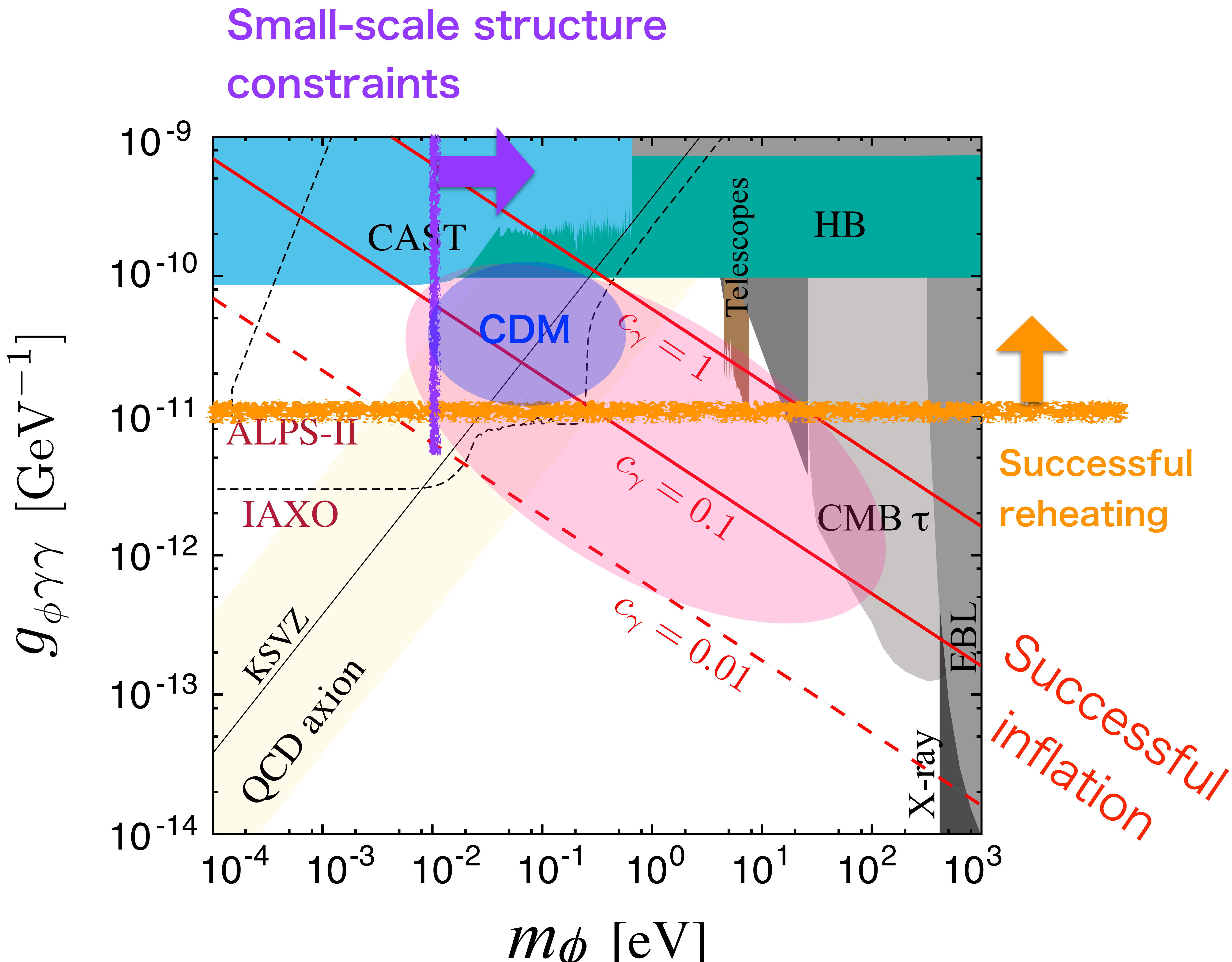
Agarwal et al, 1412.1103

Limits taken from
Sarkar, Das, Sethi, 1410.7129

$$1 + z_c \sim 5 \times 10^5 \left(\frac{0.12}{\Omega_\phi h^2}\right)^{\frac{1}{3}} \left(\frac{10^{-12}}{\lambda}\right)^{\frac{1}{3}} \left(\frac{m_\phi}{0.05\,\mathrm{eV}}\right)^{\frac{4}{3}}$$



10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
CAST
HB
Telescopes
CDM
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
Successful reheating
Successful inflation

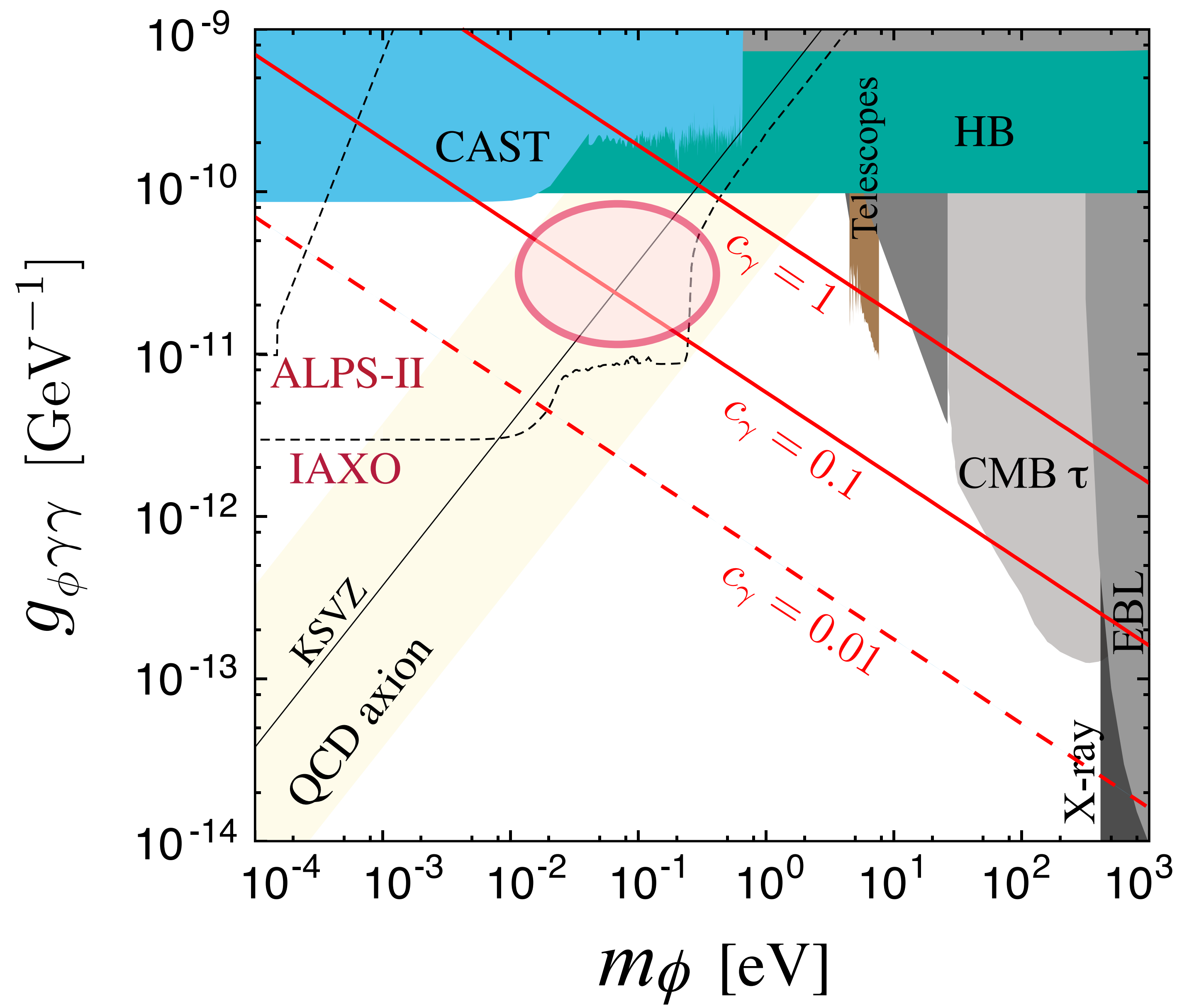


Small-scale structure constraints
CAST
HB
Telescopes
CDM
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
Successful reheating
Successful inflation
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Inflaton = DM = ALP

$$m_\phi = \mathcal{O}(0.01 - 0.1)\,\mathrm{eV}$$
$$g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

within the reach of future axion helioscopes and laser experiments.



*Plus, there is a preference for extra cooling of HB stars

$$g_{\phi\gamma\gamma} = (0.29 \pm 0.18) \times 10^{-11}\,\mathrm{GeV}$$

Ayala, Dominguez, Giannotti, Mirizzi and Straniero, 1406.6053, DESY- PROC-2015-02

We call the coincidence as *"The ALP miracle"*.

Summary

- **Inflaton = DM = Axion-like particle (ALP)**
  - The observed CMB and LSS data fix the relation between the ALP mass and decay constant.
  - Successful reheating and DM abundance point to specific values

$$m_\phi = \mathcal{O}(0.01 - 0.1)\,\mathrm{eV}\,, \quad g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

  within the reach of IAXO, TASTE, and laser exp.

  - Thermalized ALPs contribute to HDM with $\Delta N_{\rm eff} \simeq 0.03$.
  - Late transition to matter leads to suppression at small scales, relaxing the missing satellite problem.

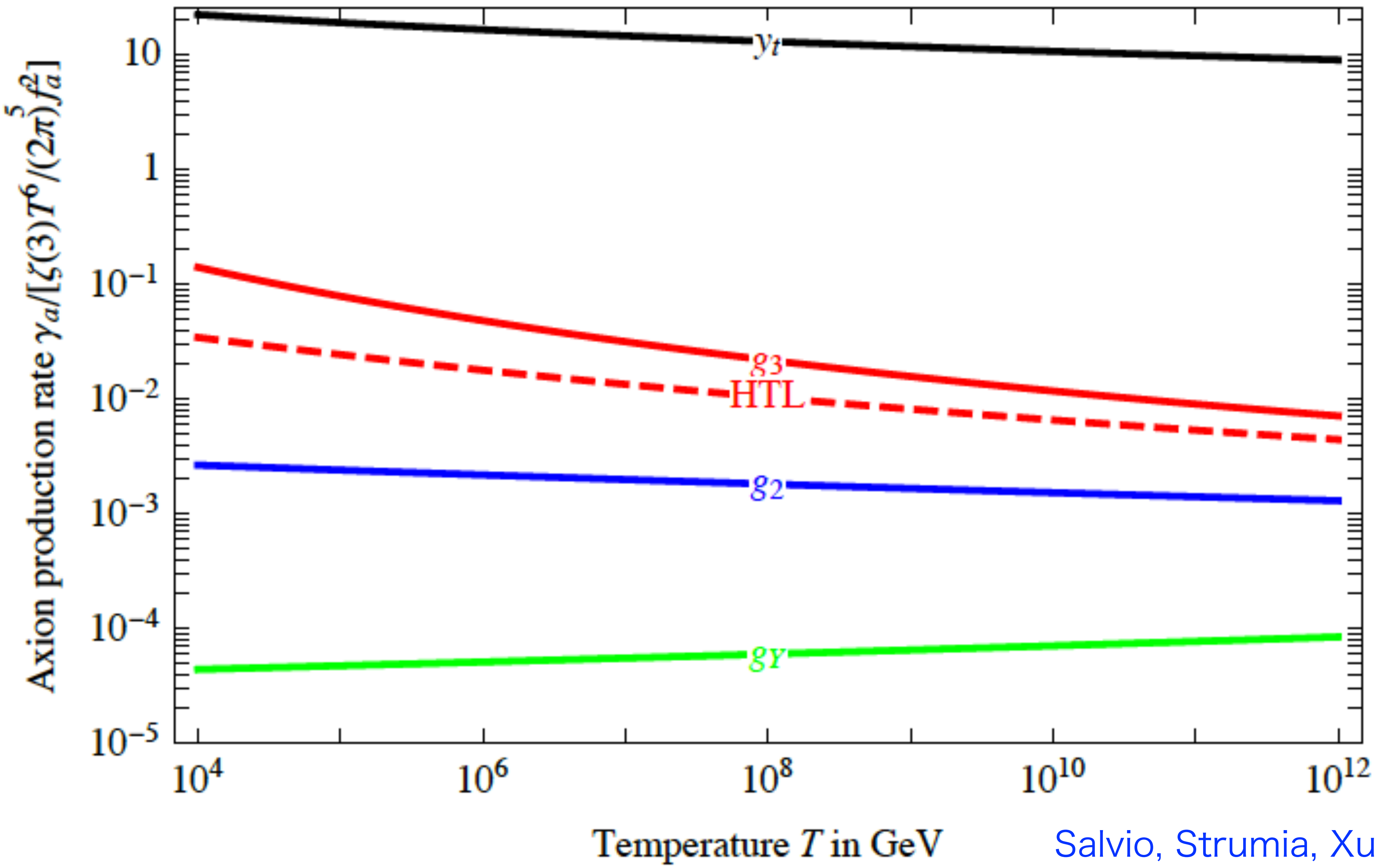
Thank You for Attending.

Back-ups

• Thermalized ALPs as HDM

The ALP is thermalized if r > 1:

$$r = \frac{2.4}{Y_a^{\rm eq}} \frac{\gamma_a}{Hs}\bigg|_{T=T_{\rm RH}} = 1.7 \frac{T_{\rm RH}}{10^7\,{\rm GeV}} \left(\frac{10^{11}\,{\rm GeV}}{f_a}\right)^2 \frac{\gamma_a}{T^6\zeta(3)/(2\pi)^5 f_a^2}\bigg|_{T=T_{\rm RH}}$$



Salvio, Strumia, Xue, 1310.6982v3

• Thermalized ALPs as HDM

In our case, the ALP is thermalized until the temperature drops down to the weak scale,

$$r \sim \left(\frac{T}{80\,\mathrm{GeV}}\right)\left(\frac{8\times10^{6}\,\mathrm{GeV}}{f/c_2}\right)^2$$

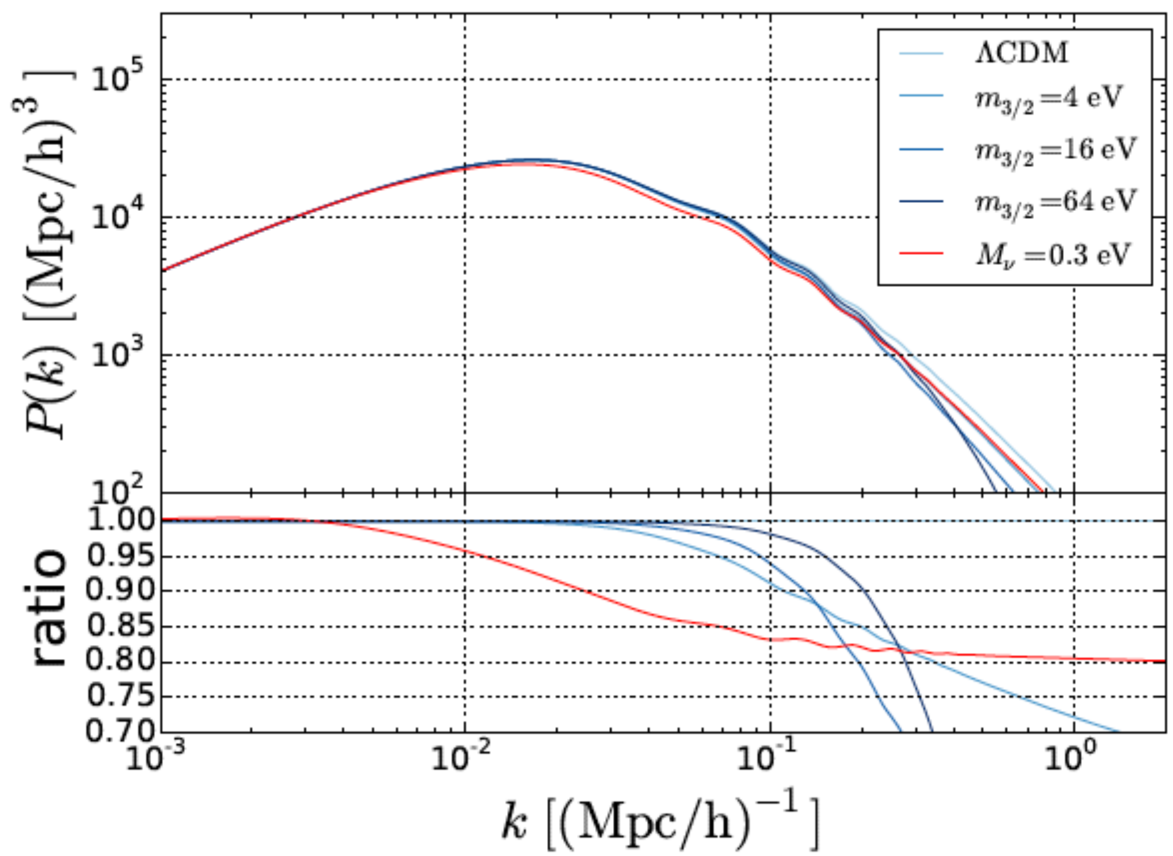
The thermalized ALPs contribute to HDM with $\Delta N_{\rm eff} \simeq 0.03$

<u>HDM abundance:</u>

$$\Omega_\phi^{(th)}h^2 \simeq 0.007\left(\frac{m_\phi}{10\,\mathrm{eV}}\right)\left(\frac{g_{*s}}{106.75}\right)^{-1}$$

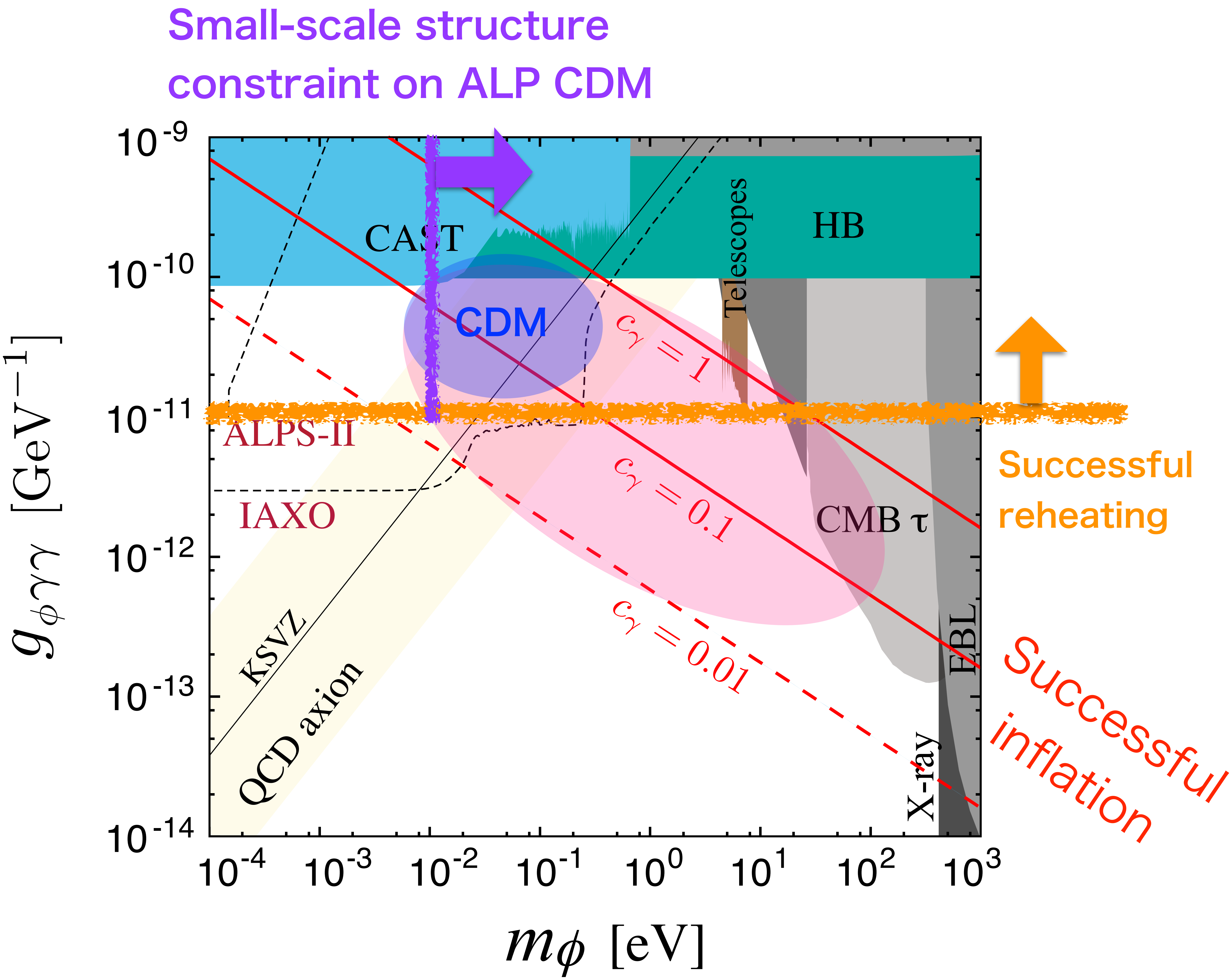
<u>Upper bound on the mass:</u>

$$m_\phi \lesssim 7\,\mathrm{eV}$$

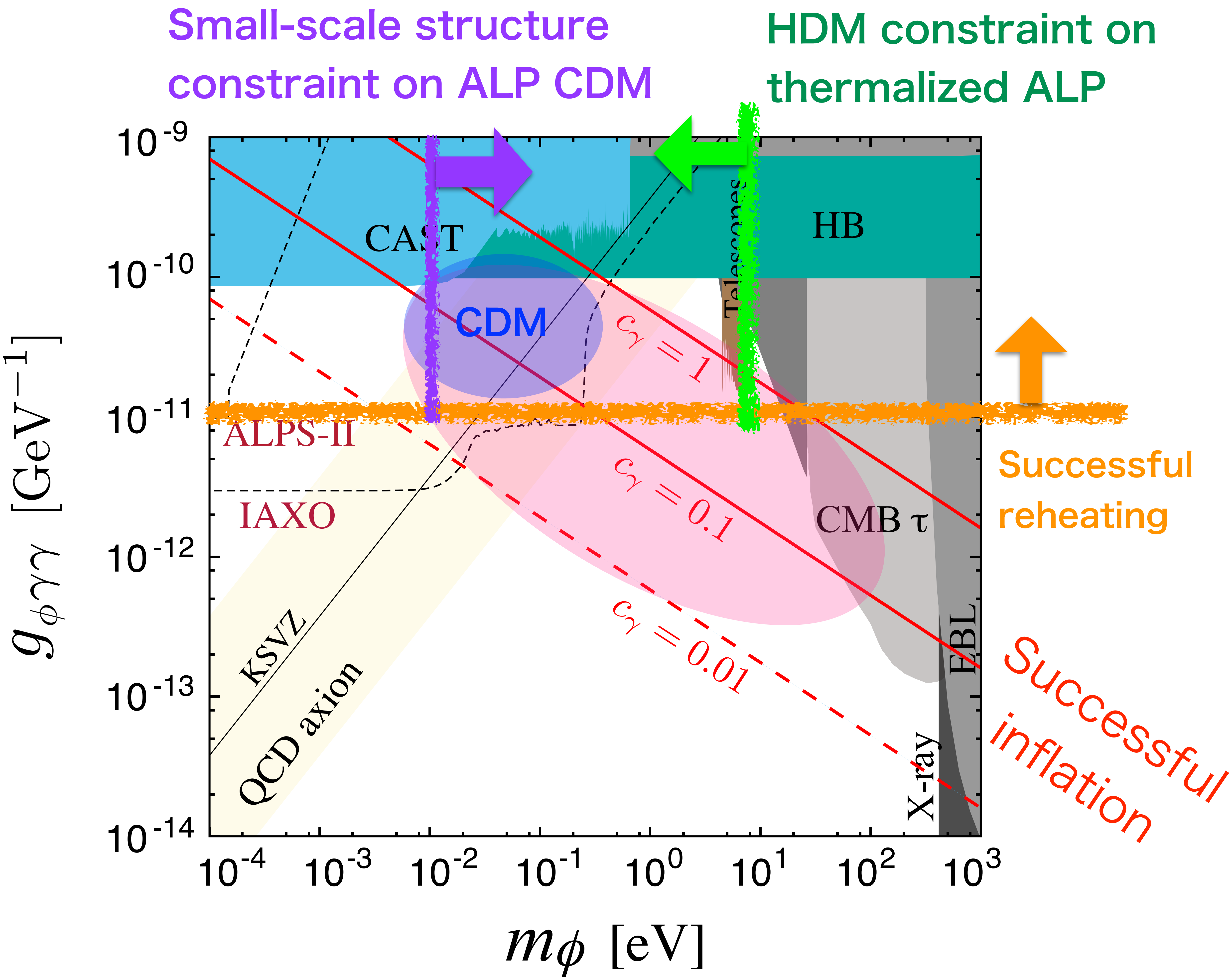


K. Osato, T. Sekiguchi, M. Shirasaki, A. Kamada and N. Yoshida, 1601.07386

*The thermalized ALP is close to DR for the parameters of our interest.



Small-scale structure
constraint on ALP CDM
CAST
HB
Telescopes
CDM
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
Successful
reheating
Successful
inflation
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}



Small-scale structure
constraint on ALP CDM
HDM constraint on
thermalized ALP
CAST
HB
Telescopes
CDM
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
Successful
reheating
Successful
inflation
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]