The ALP miracle

@PPP2017

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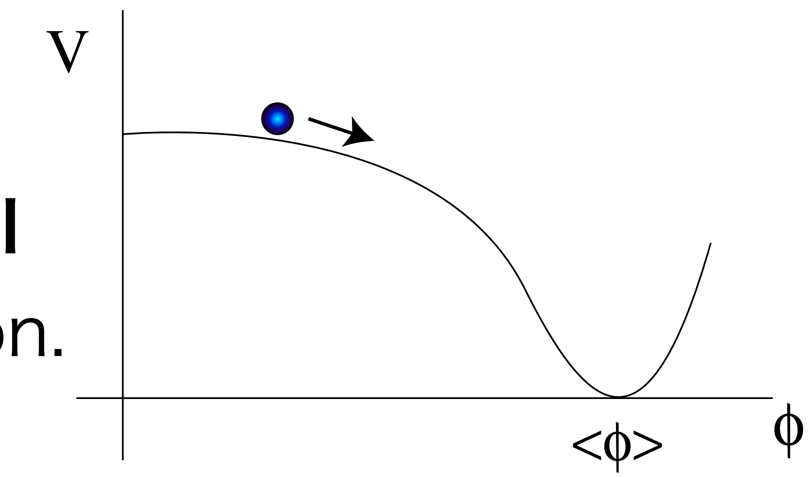
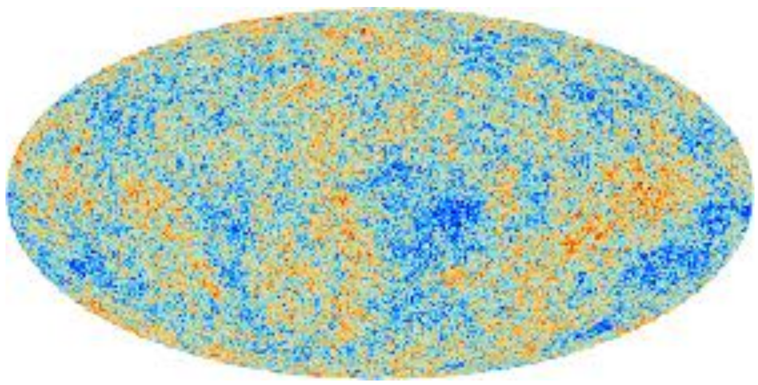
1. Introduction

There are two unknown degree of freedom in the ΛCDM.
(except for the origin of Λ.)

- Inflaton

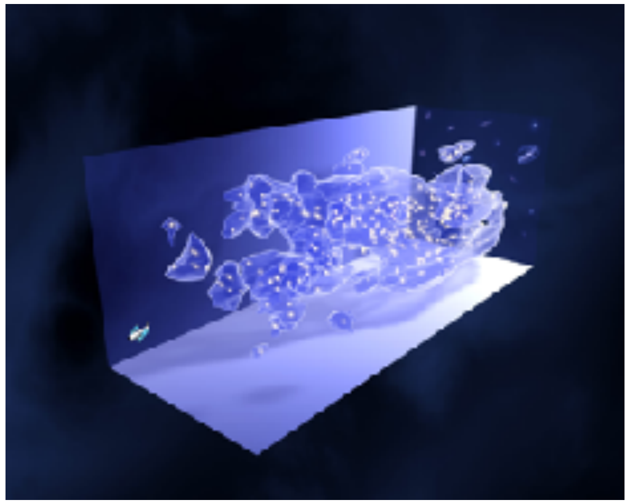
Very flat potential
for slow-roll inflation.





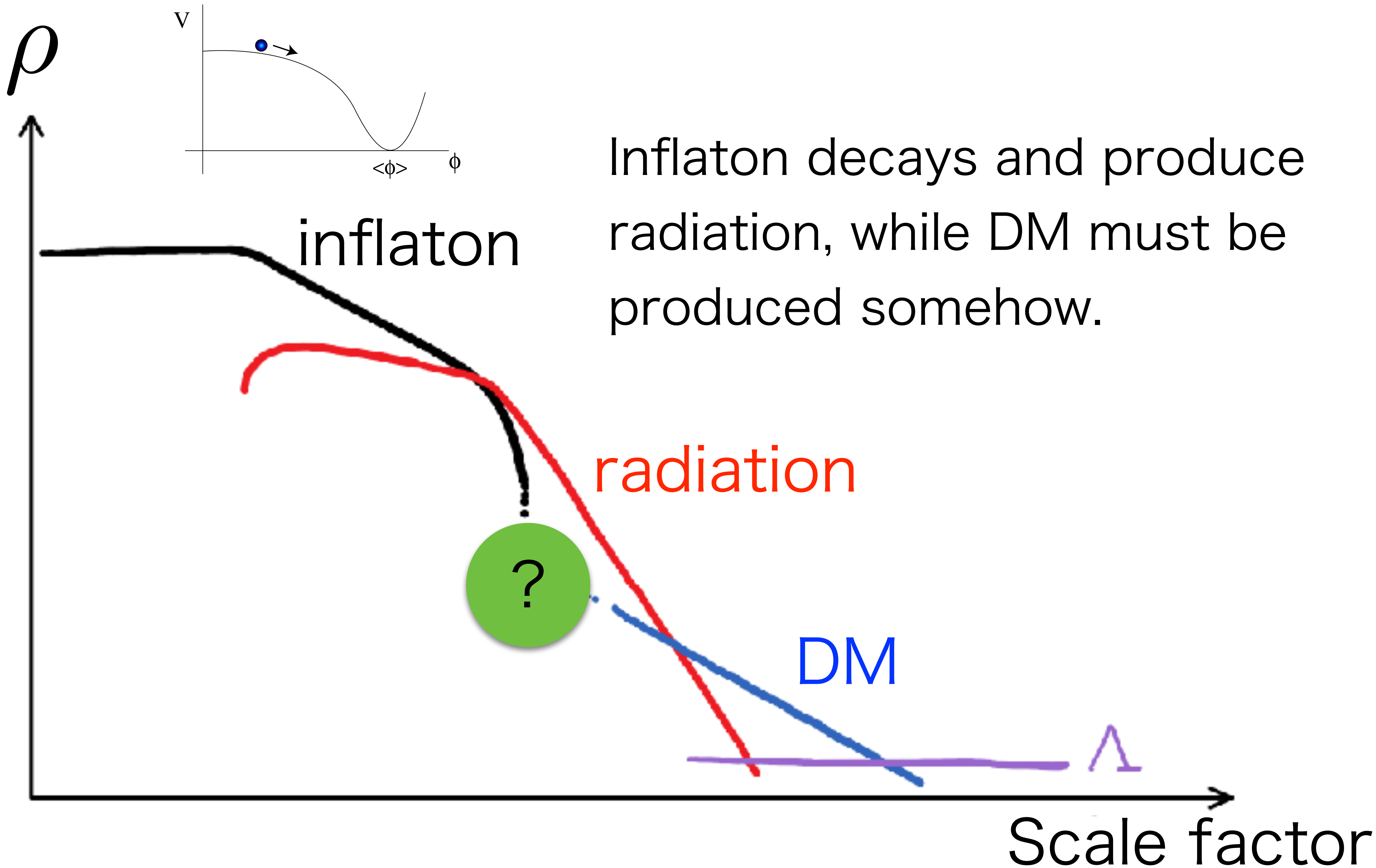
- Dark matter

Cold, neutral,
and **long-lived**.



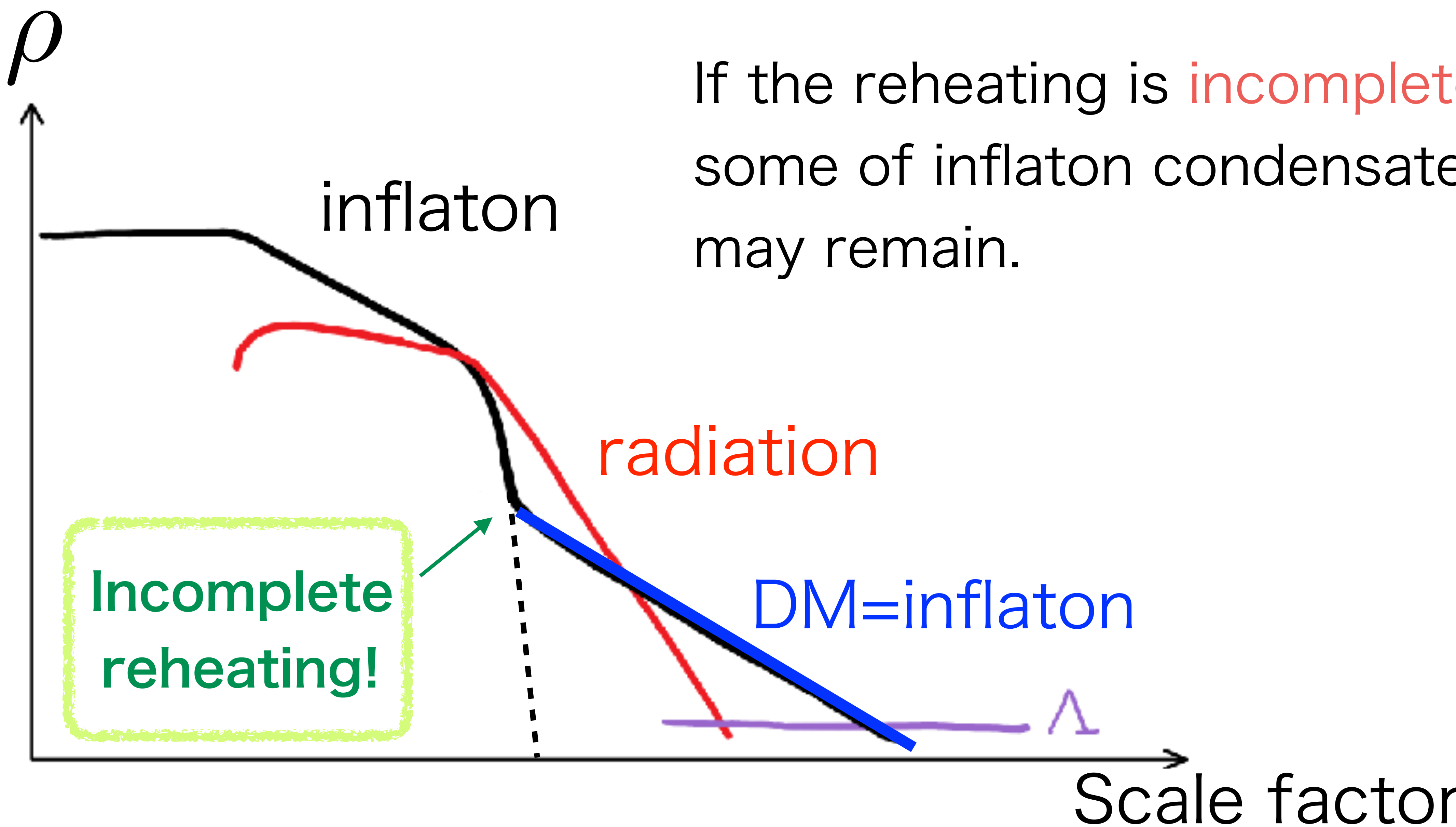
Both are neutral and occupied a significant fraction of the energy density of the Universe.

Thermal history



Inflaton decays and produce radiation, while DM must be produced somehow.

Inflaton = DM ?



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

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

- **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

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

within the reach of IAXO.

2. Axion and Inflation

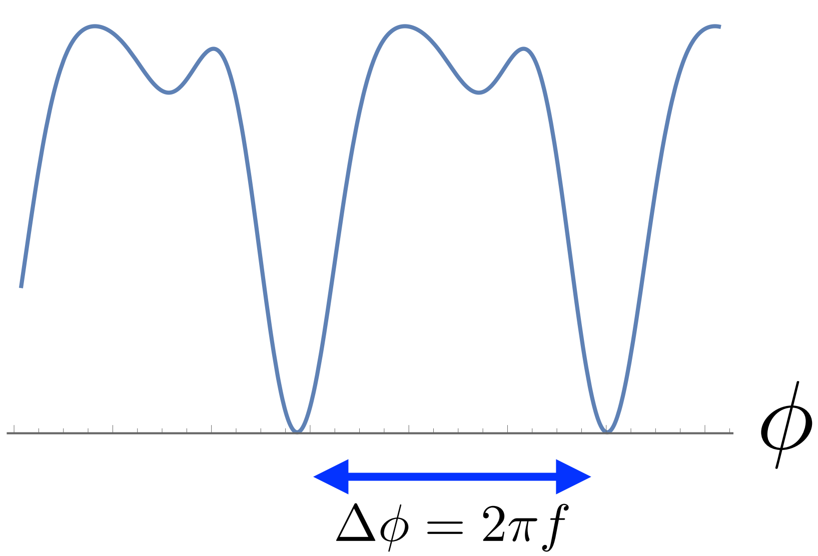
Axion is a pseudo NG boson, and enjoys a discrete shift symmetry.

$$\phi \to \phi + 2\pi n f \qquad n \in \mathbf{Z}$$

Since dangerous radiative corrections are naturally suppressed, axion is compatible with inflation.

The axion potential is periodic, i.e.

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



and can be expressed as Fourier series,

$$V(\phi) = \sum_{n \in \mathbf{Z}} c_n e^{in\frac{\phi}{f}}$$

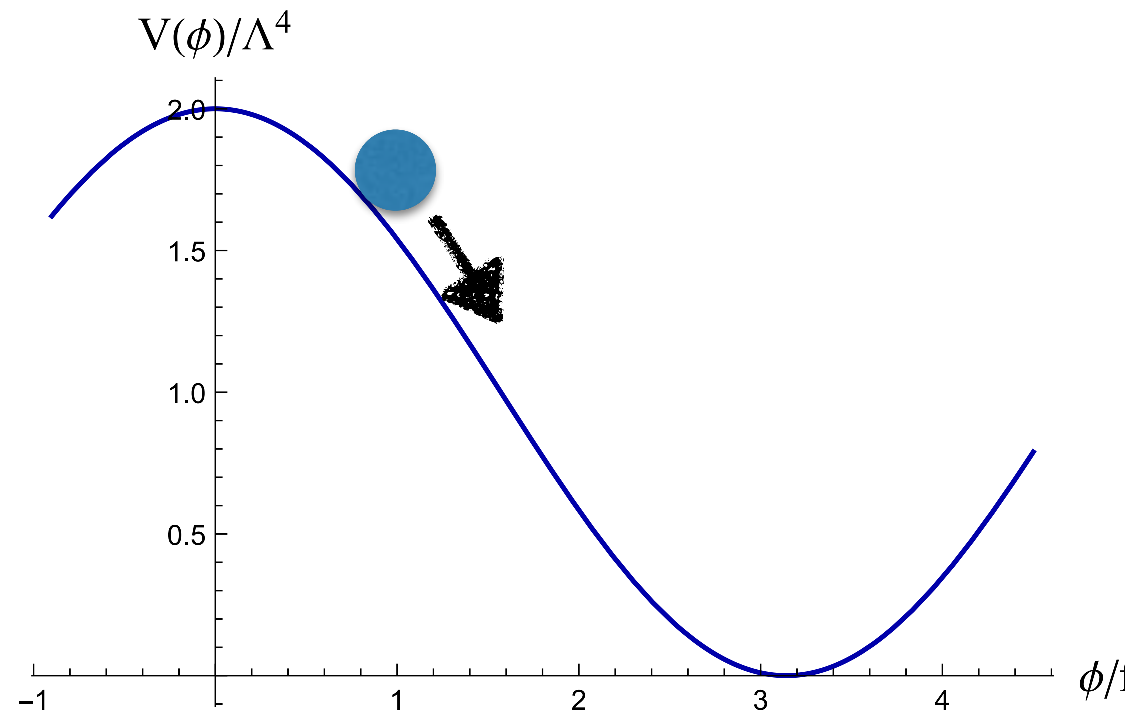
Axion and Inflation

- **Natural inflation**

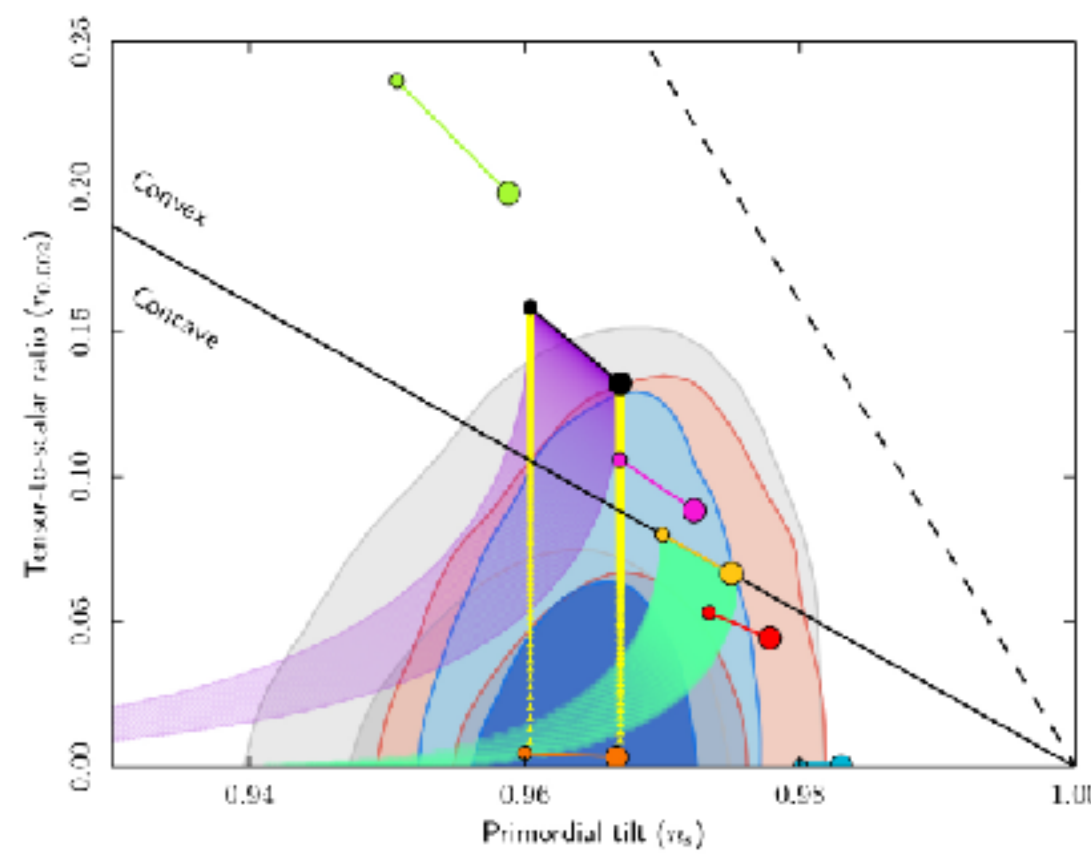
Freese, Frieman, Olinto `90

The simplest model is the natural inflation.

$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$



- Large field inflation
- Super-Planckian decay constant is required. $f \gtrsim 5 M_P$
- Predicted (n_s, r) are not favored by recent observations.



Axion and Inflation

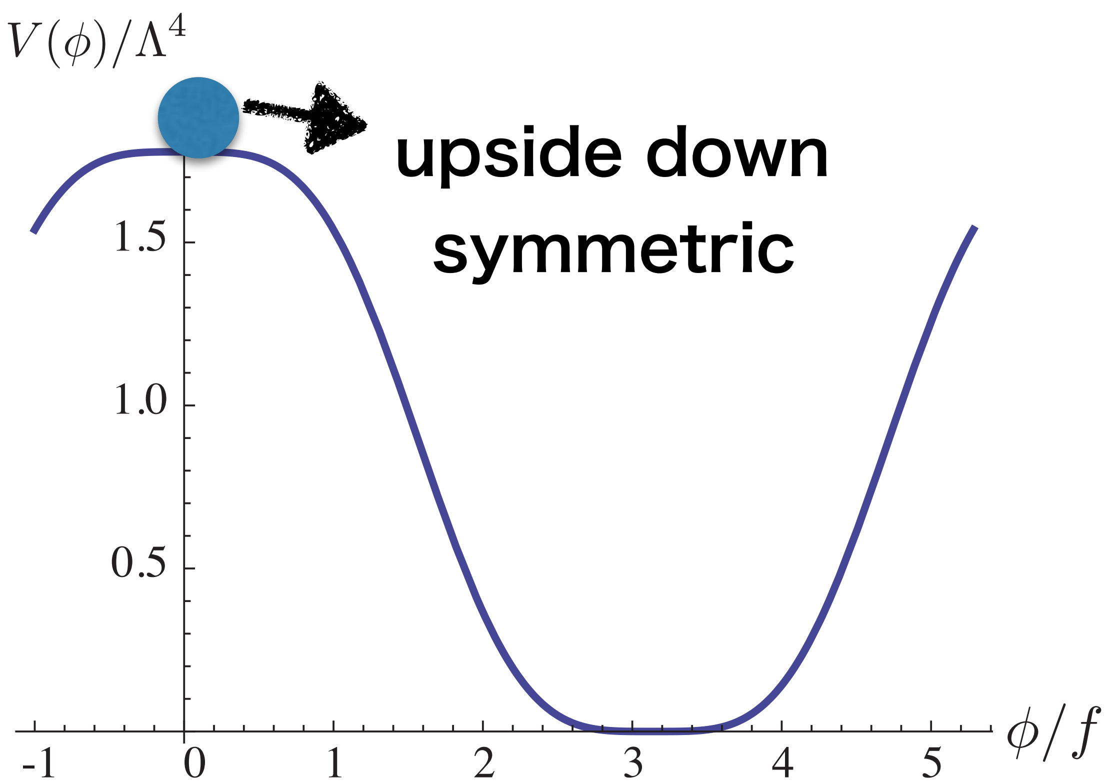
- **Axion hilltop inflation**

Czerny, Takahashi 1401.5212,
Czerny, Higaki, Takahashi 1403.0410, 1403.5883

Hilltop inflation can be realized with two cosine terms.

(Minimal extension)

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f} + \theta\right) - \frac{\kappa}{n^2} \cos\left(n\frac{\phi}{f}\right)\right) + C$$
$$= V_0 - \lambda\phi^4 - \Lambda^4\theta\frac{\phi}{f} + (\kappa - 1)\frac{\Lambda^4}{2f^2}\phi^2 + \ldots$$



Odd n

- The decay constant can be sub-Planckian. $f \ll M_P$
- Inflaton is light both during inflation and in the true min.

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

Flatness=longevity

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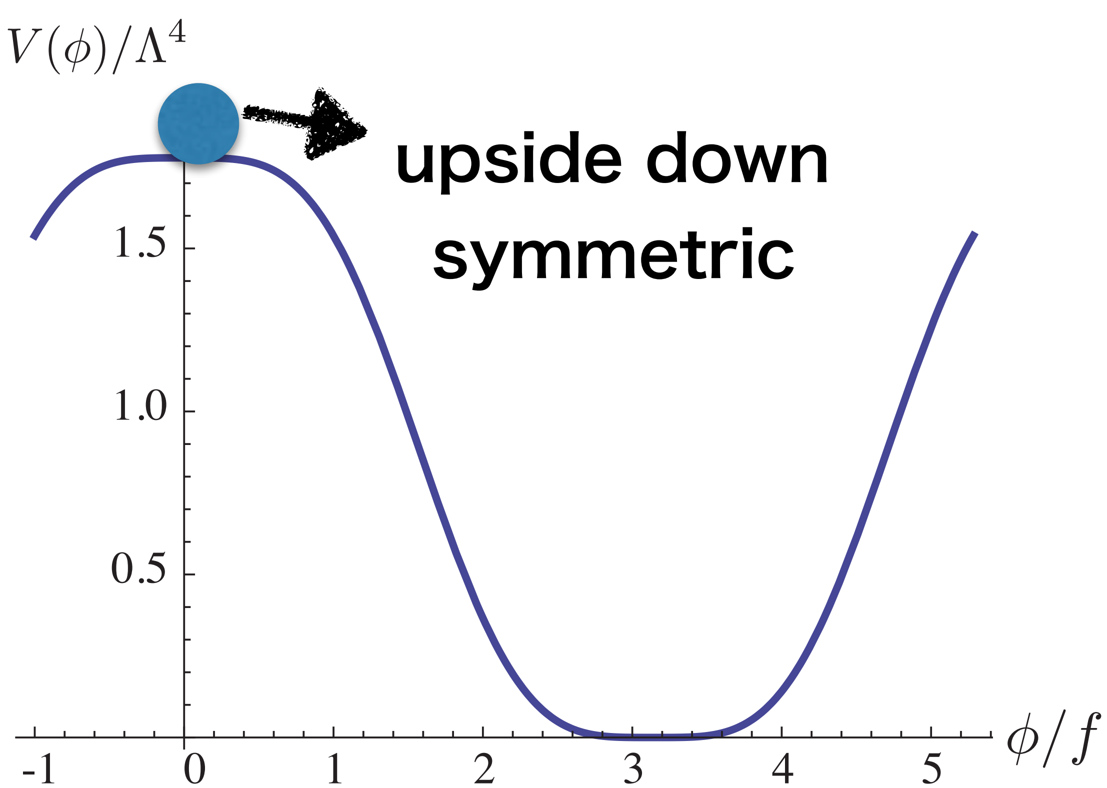


Odd n

Planck normalization

$$\lambda \simeq 7.5 \times 10^{-14} \left(\frac{N_*}{50}\right)^{-3}.$$

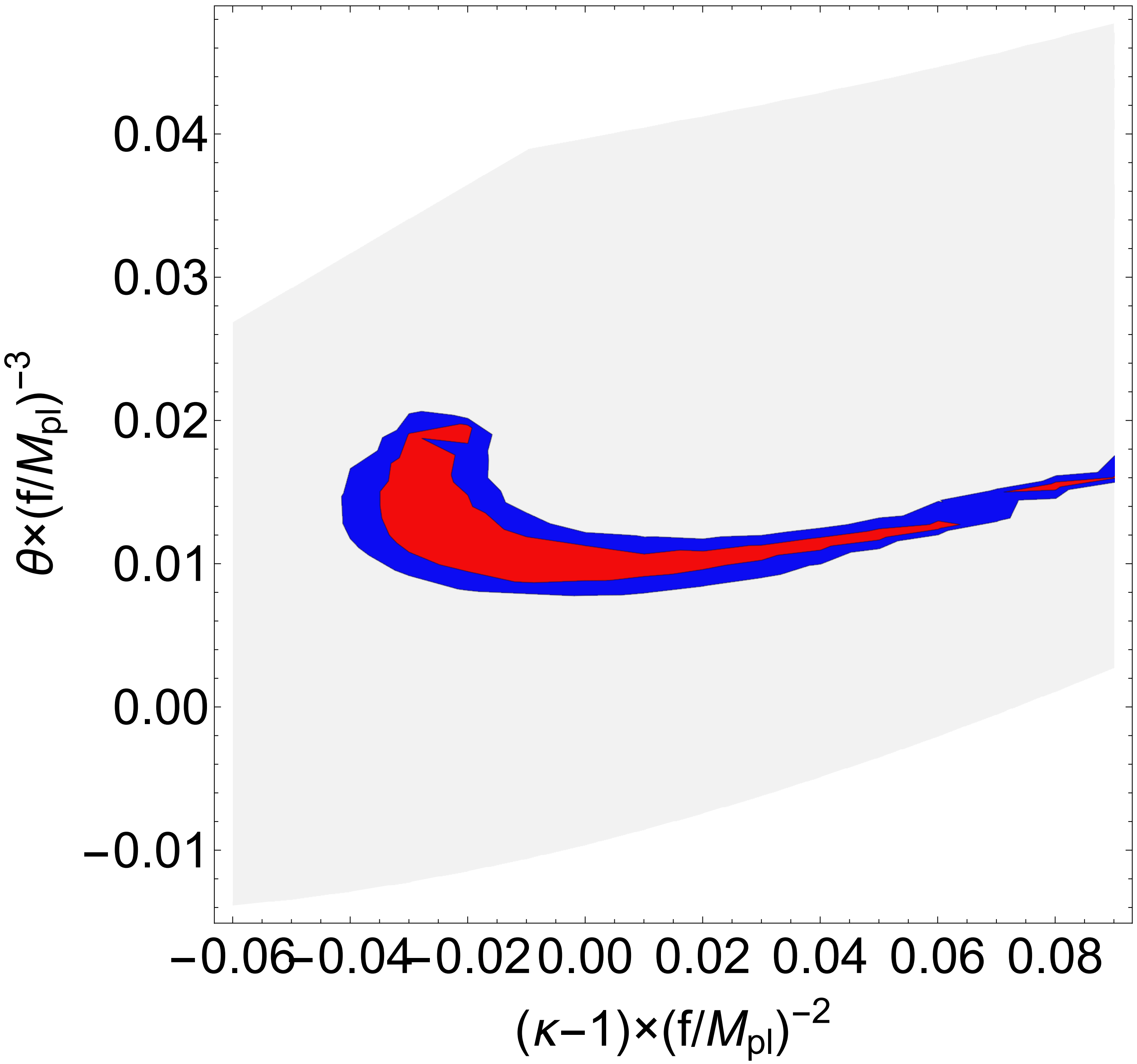
$$N_* \simeq 61 + \ln\left(\frac{H_*}{H_{\rm inf}}\right)^{\frac{1}{2}} + \ln\left(\frac{H_{\rm inf}}{10^{14}{\rm GeV}}\right)^{\frac{1}{2}}$$

Spectral index

$$n_s \simeq 1 + 2\eta(\phi_*) \simeq 1 - \frac{3}{N_*}$$

Spectral index

$$n_s = 0.968 \pm 0.006$$



cf. $n_s \simeq 1 + 2\eta(\phi_*)$

The typical inflaton mass: $\boxed{m_\phi \sim \theta^{\frac{1}{3}} \frac{\Lambda^2}{f} = \mathcal{O}(0.1) H_{\rm inf}}$

Relation between m_ϕ and f

The Planck normalization of density perturbation and the spectral index fix the relation between m_ϕ and f,

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-13}$$: Planck normalization

$$\Lambda^4 \sim H_{\rm inf}^2 M_{pl}^2$$: Friedman eq.

$$m_\phi \sim 0.1 H_{\rm inf}$$: Scalar spectral index

cf. $n_s \simeq 1 + 2\eta(\phi_*)$

$$\boxed{f \sim 5 \times 10^7\,\mathrm{GeV} \left(\frac{n}{3}\right)^{1/2} \left(\frac{m_\phi}{1\,\mathrm{eV}}\right)^{0.51}}$$

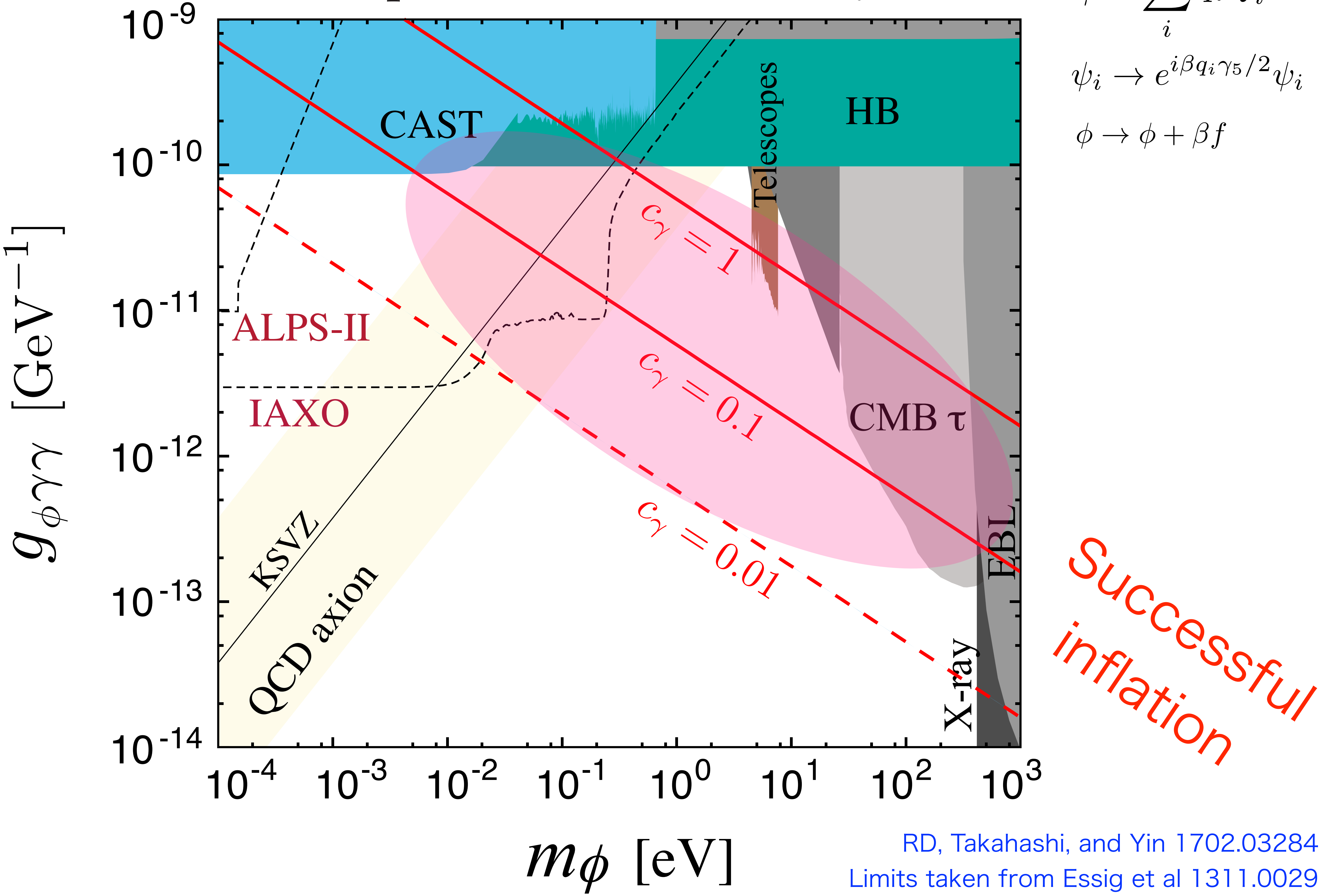
Mass and coupling to photons

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

$$c_\gamma = \sum_i q_i Q_i^2$$

$$\psi_i \to e^{i\beta q_i \gamma_5/2}\psi_i$$

$$\phi \to \phi + \beta f$$



RD, Takahashi, and Yin 1702.03284

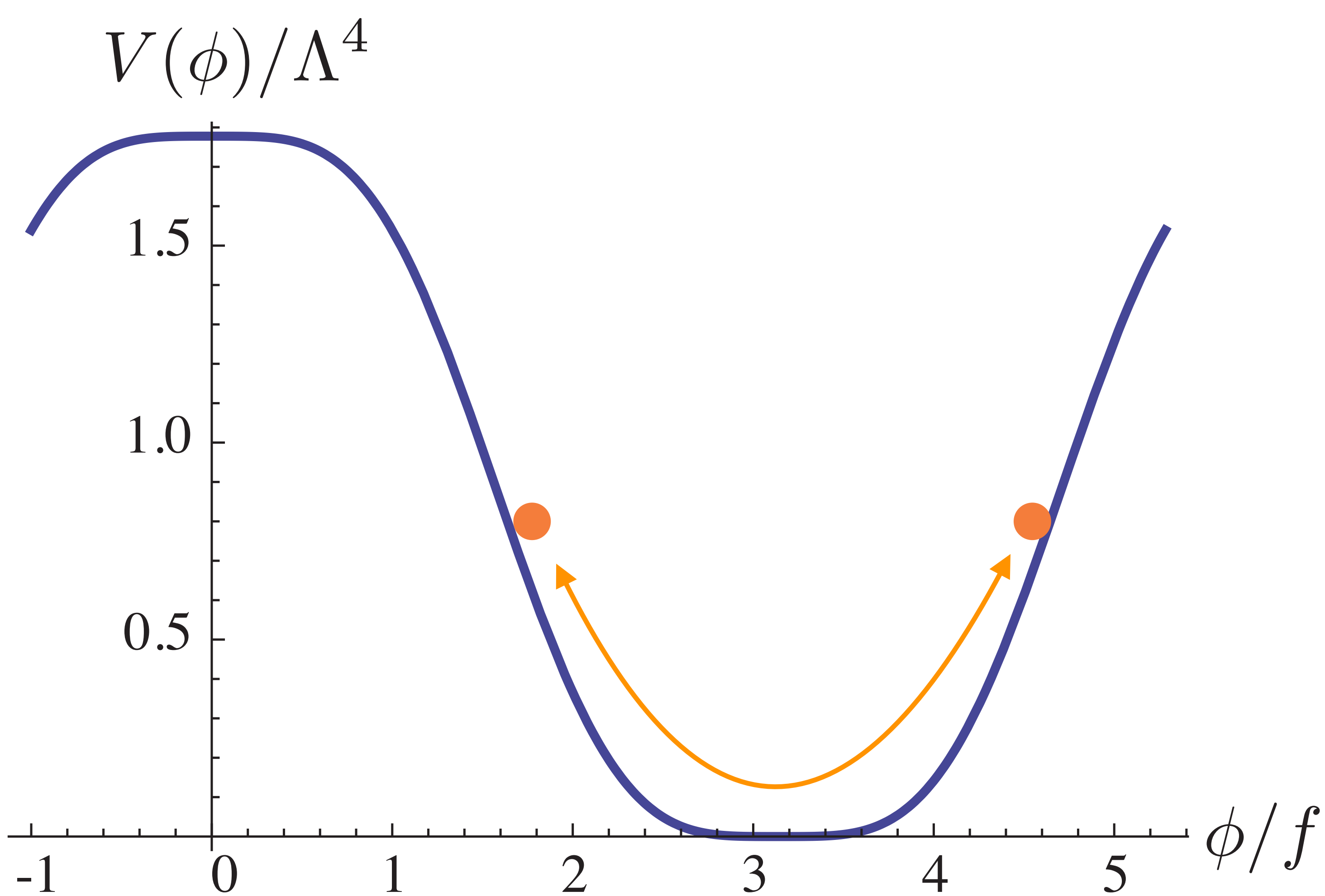
Limits taken from Essig et al 1311.0029

3. Reheating and ALP DM

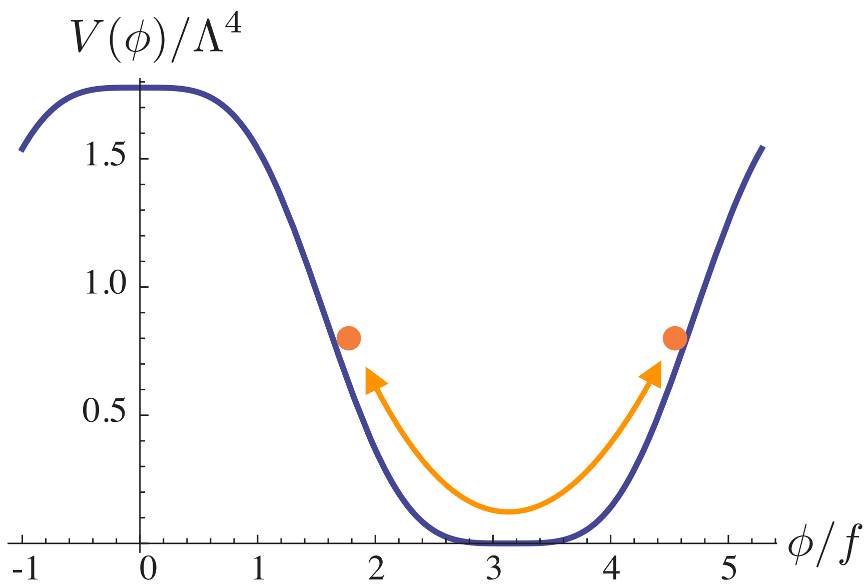
The inflaton oscillates about $\phi_{\rm min} = \pi f$ in a quartic potential.

The effective mass, $m_{\rm eff}^2(t) = V''(\phi_{\rm amp}) = 12\lambda\phi_{\rm amp}^2$ decreases with time, and so, decay and dissipation become inefficient at later times.

➡ **Incomplete reheating**



3. Reheating and ALP DM



Inflaton (ALP) condensate

Decay & dissipation

Photons, SM particles

Remnant

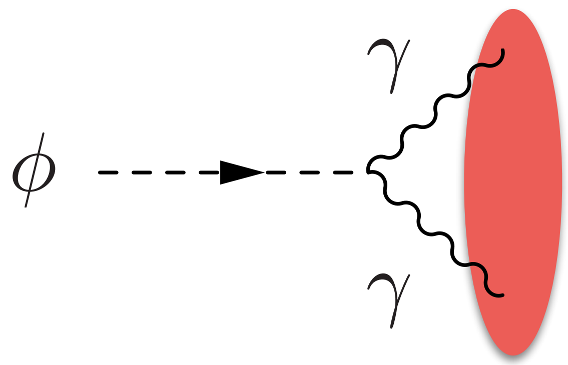
ALP Dark Matter

$$\xi \equiv \left. \frac{\rho_\phi}{\rho_\phi + \rho_R} \right|_{\rm after\ \ reheating}$$

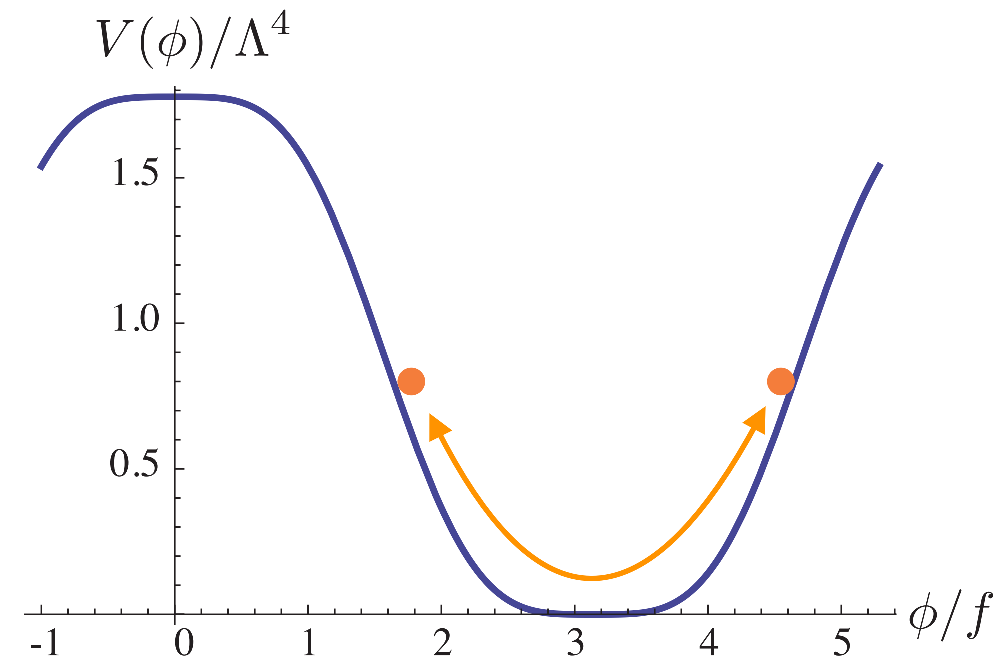
• Reheating

✓The decay rate into two photons:

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



$$m_\gamma^{(th)} \sim eT$$

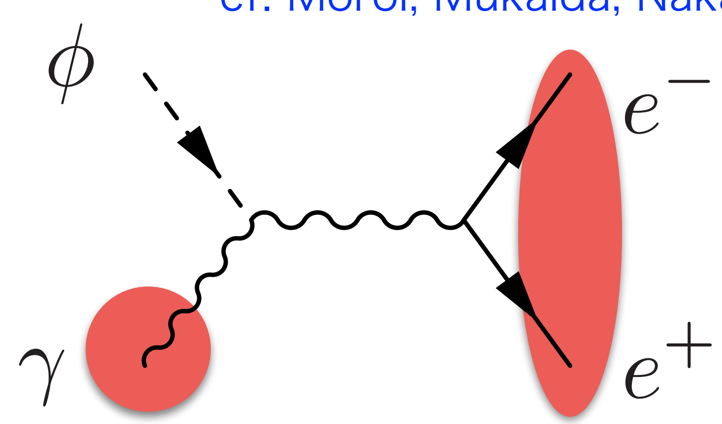


$$m_{\rm eff}^2(t) = V''(\phi_{\rm amp}) = 12\lambda\phi_{\rm amp}^2$$

✓The dissipation rate is roughly estimated as

cf. Moroi, Mukaida, Nakayama and Takimoto,1407.7465

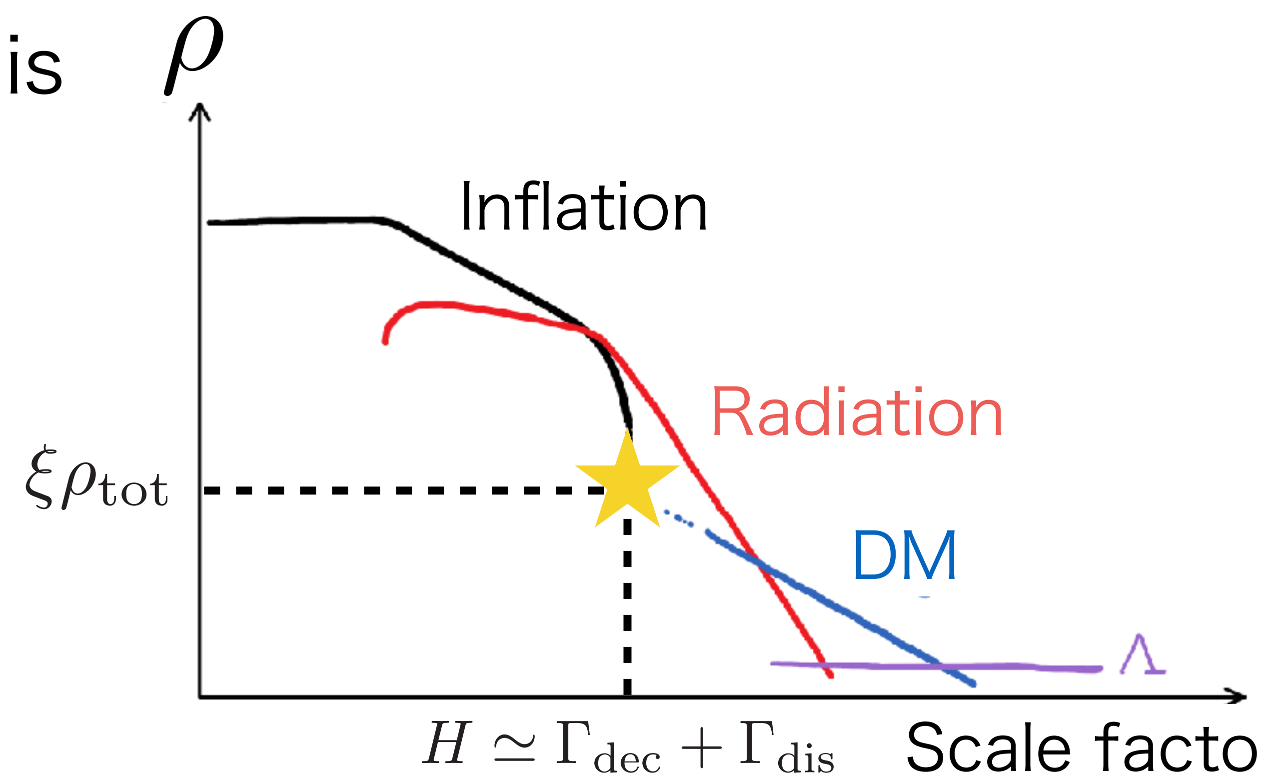
$$\Gamma_{{\rm dis},\gamma} = C\frac{c_\gamma^2\alpha^2 T^3}{8\pi^2 f^2}\frac{m_{\rm eff}^2}{e^4 T^2}$$



• Reheating

The remnant inflaton condensate is expressed by

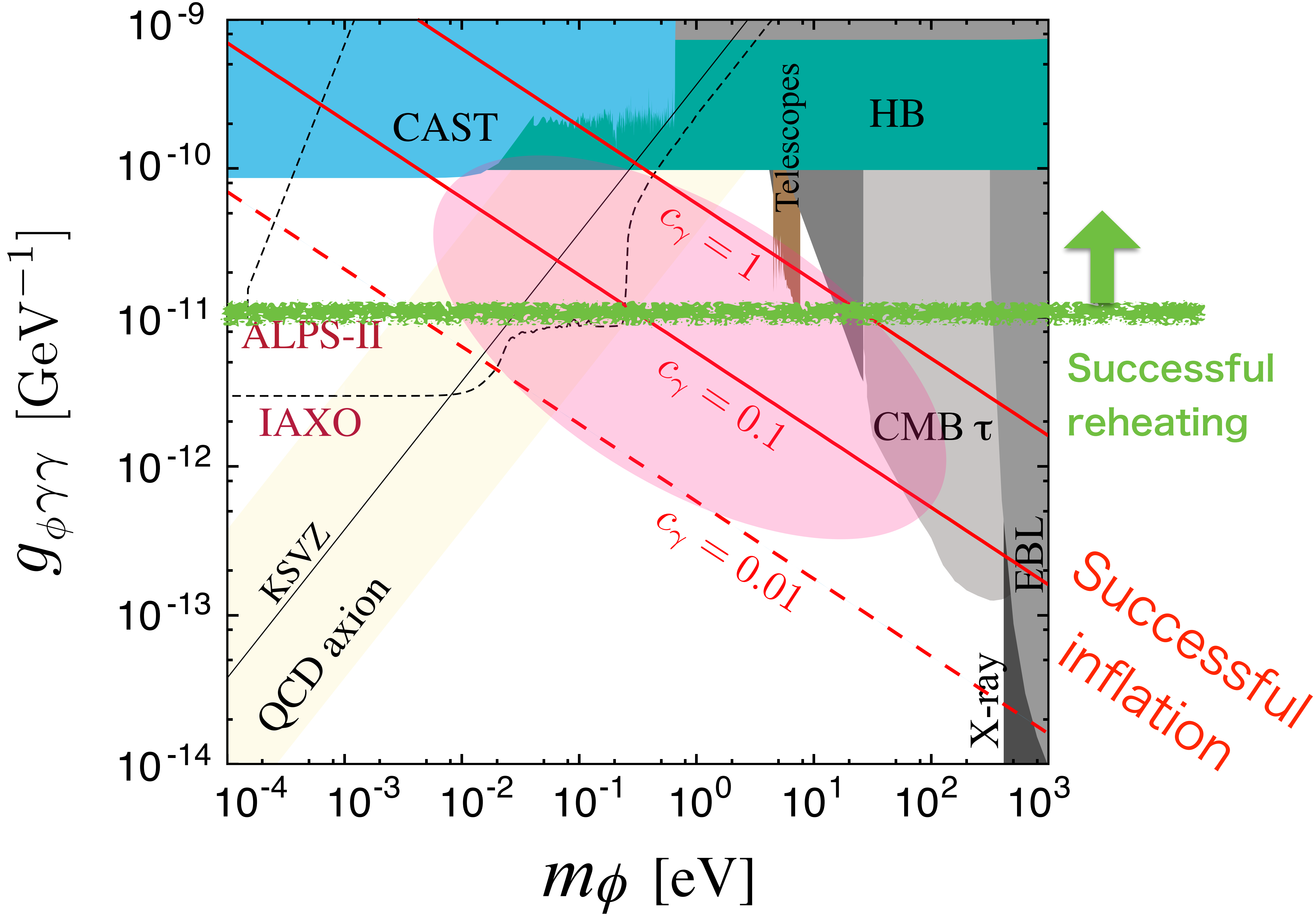
$$\boxed{\xi \equiv \left.\frac{\rho_\phi}{\rho_\phi + \rho_R}\right|_{\text{after reheating}}}$$



Solving following equations, we found

$$\begin{cases} \dot{\rho}_\phi + 4H\rho_\phi = -\Gamma_{\rm tot}\rho_\phi \\ \dot{\rho}_r + 4H\rho_r = \Gamma_{\rm tot}\rho_\phi \end{cases} \Rightarrow \boxed{g_{\phi\gamma\gamma} \gtrsim 10^{-11}\,\mathrm{GeV}^{-1}}$$

for successful reheating $\xi \lesssim \mathcal{O}(0.01)$.



10^{-9}
10^{-10}
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10^{0}
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10^{2}
10^{3}
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
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CAST
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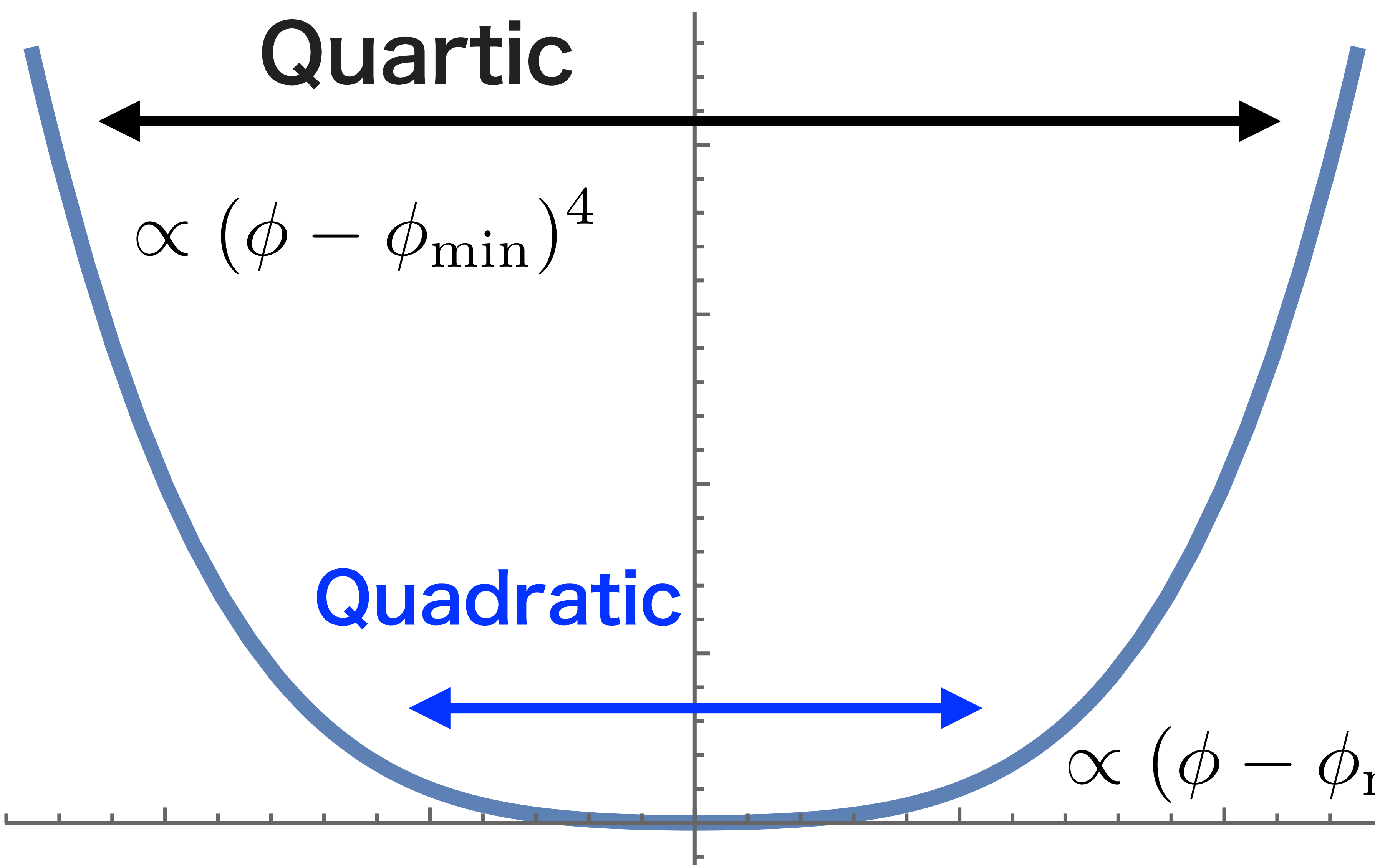
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
Successful reheating
Successful inflation

• ALP condensate as CDM

After the reheating, ρ_ϕ decreases like radiation until the potential becomes quadratic.

cf. $w \equiv \frac{P}{\rho} = \frac{n-2}{n+2}$ for ϕ^n



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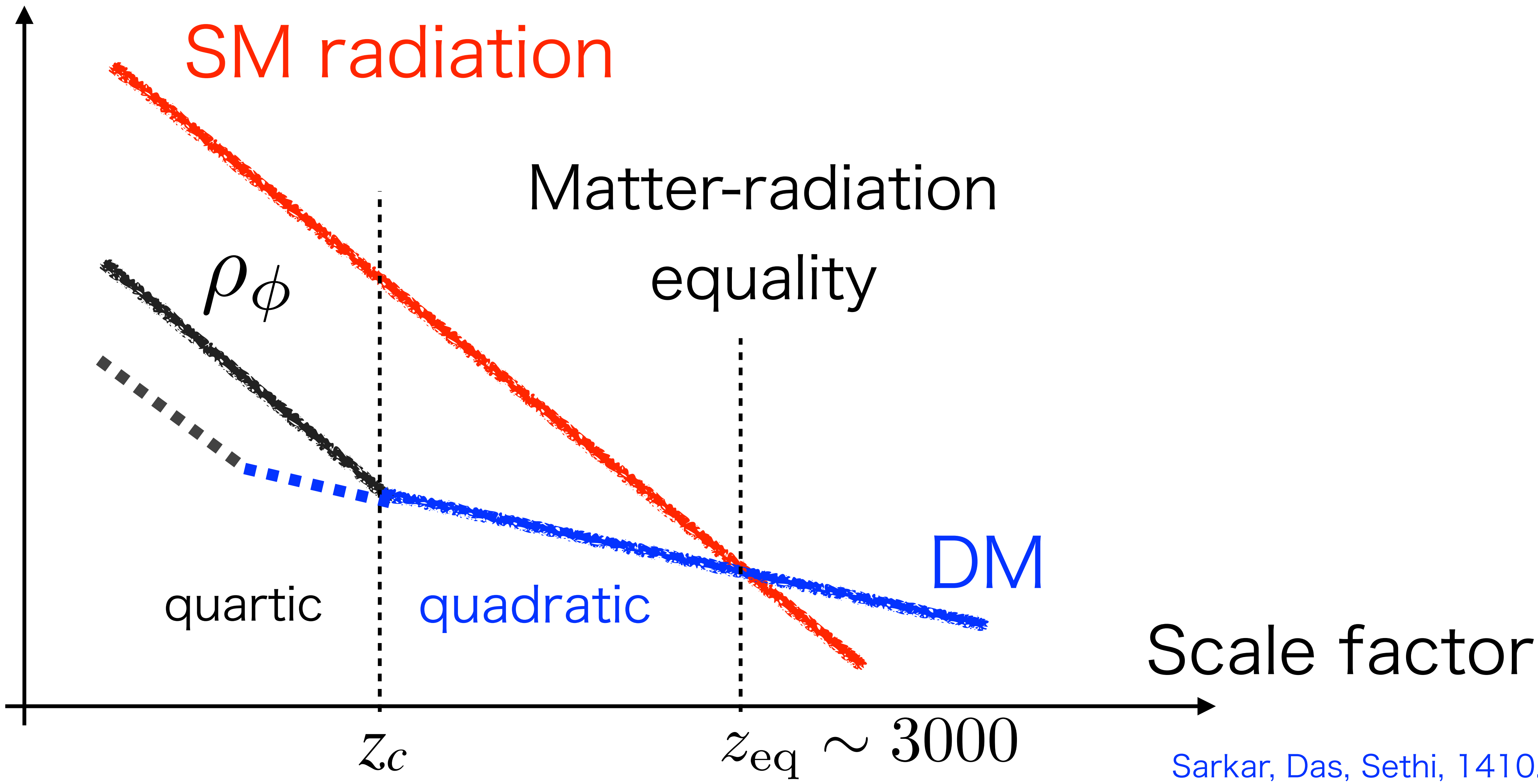
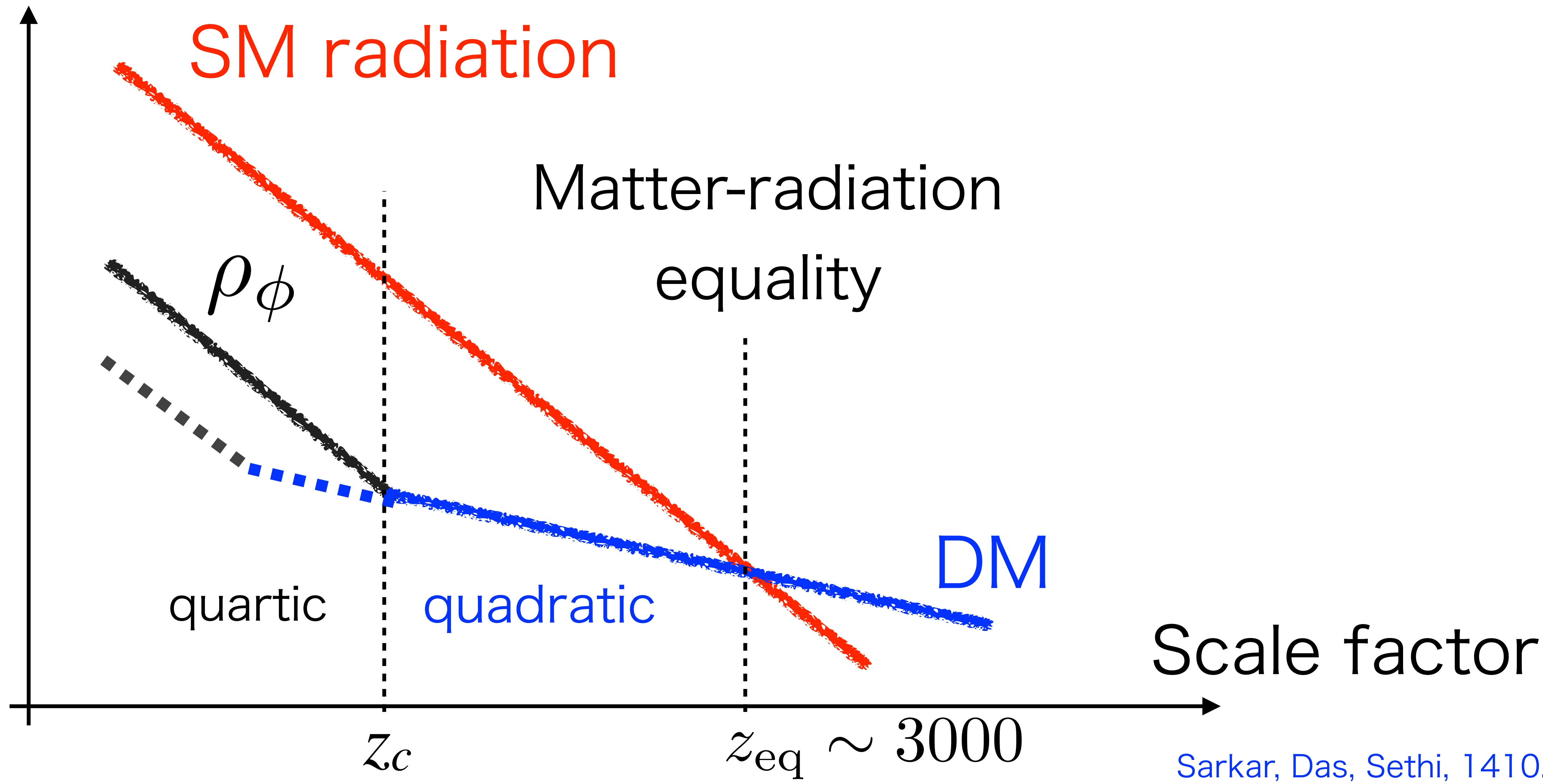


Sarkar, Das, Sethi, 1410.7129

DM should be formed before $z_c \gtrsim \mathcal{O}(10^5)$ by SDSS and Ly-alpha

$$\xi \lesssim 0.02 \left(\frac{g_{*s}(T_R)}{106.75}\right)^{\frac{1}{3}} \left(\frac{3.909}{g_{*s}(T_c)}\right)^{\frac{1}{3}} \left(\frac{\Omega_\phi h^2}{0.12}\right) \left(\frac{5\times 10^5}{1+z_c}\right).$$

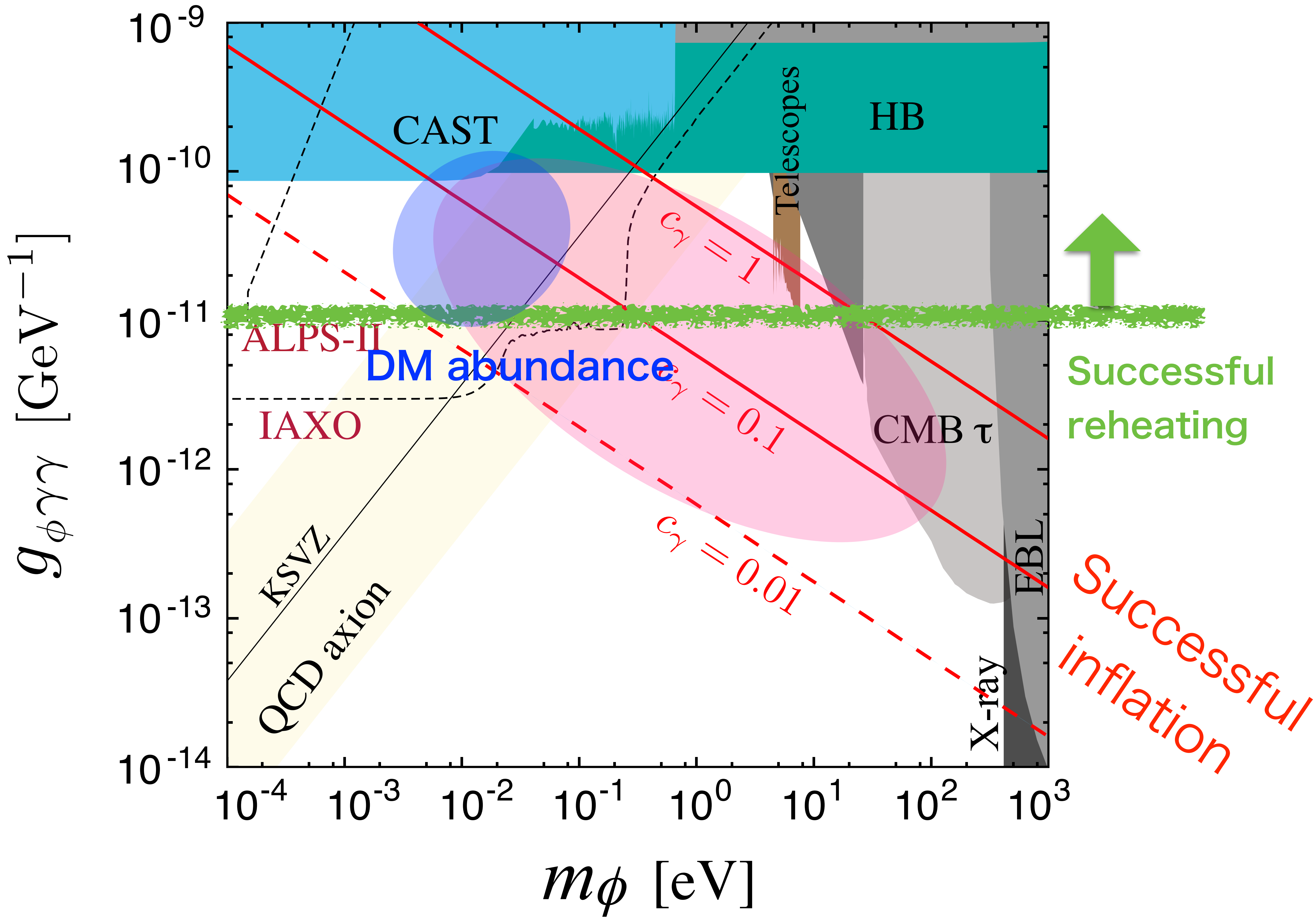
• ALP condensate as CDM



Sarkar, Das, Sethi, 1410.7129

$$\frac{\rho_\phi}{s} \simeq \frac{3}{4}\xi^{\frac{3}{4}} \frac{m_\phi T_R}{\sqrt{2\lambda} f x}$$

$$\boxed{\begin{aligned} m_\phi &\simeq 0.07\, x^{-1} \left(\frac{\xi}{0.01}\right)^{-\frac{3}{4}} \left(\frac{\Omega_\phi h^2}{0.12}\right) \mathrm{eV}, \\ &\gtrsim 0.04\, x^{-1} \left(\frac{106.75}{g_{*s}(T_R)}\right)^{\frac{1}{4}} \left(\frac{g_{*s}(T_c)}{3.909}\right)^{\frac{1}{4}} \left(\frac{\Omega_\phi h^2}{0.12}\right)^{\frac{1}{4}} \left(\frac{1+z_c}{5\times 10^5}\right)^{\frac{3}{4}} \mathrm{eV} \end{aligned}}$$



CAST
HB
Telescopes
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
ALPS-II
DM abundance
IAXO
CMB τ
KSVZ
QCD axion
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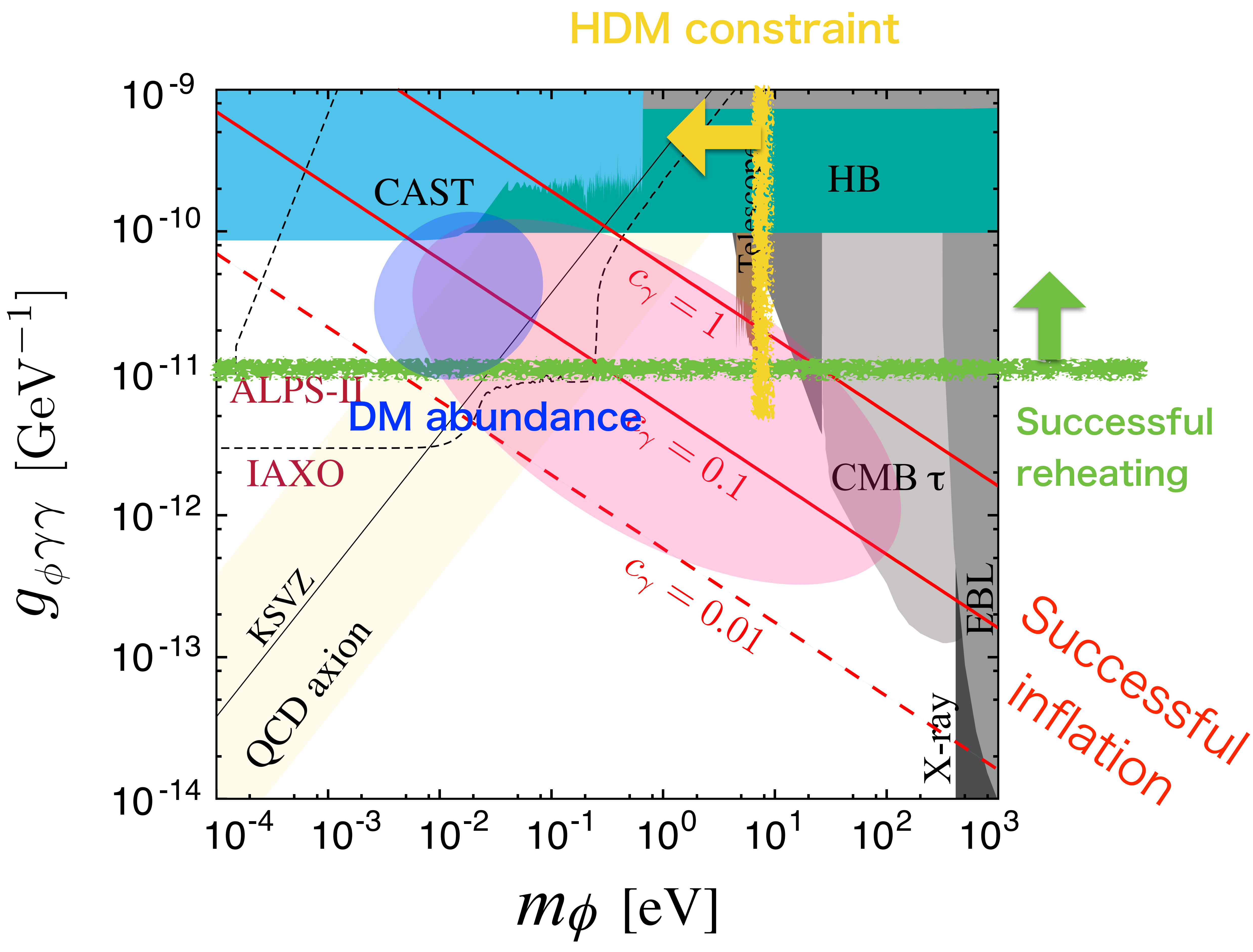
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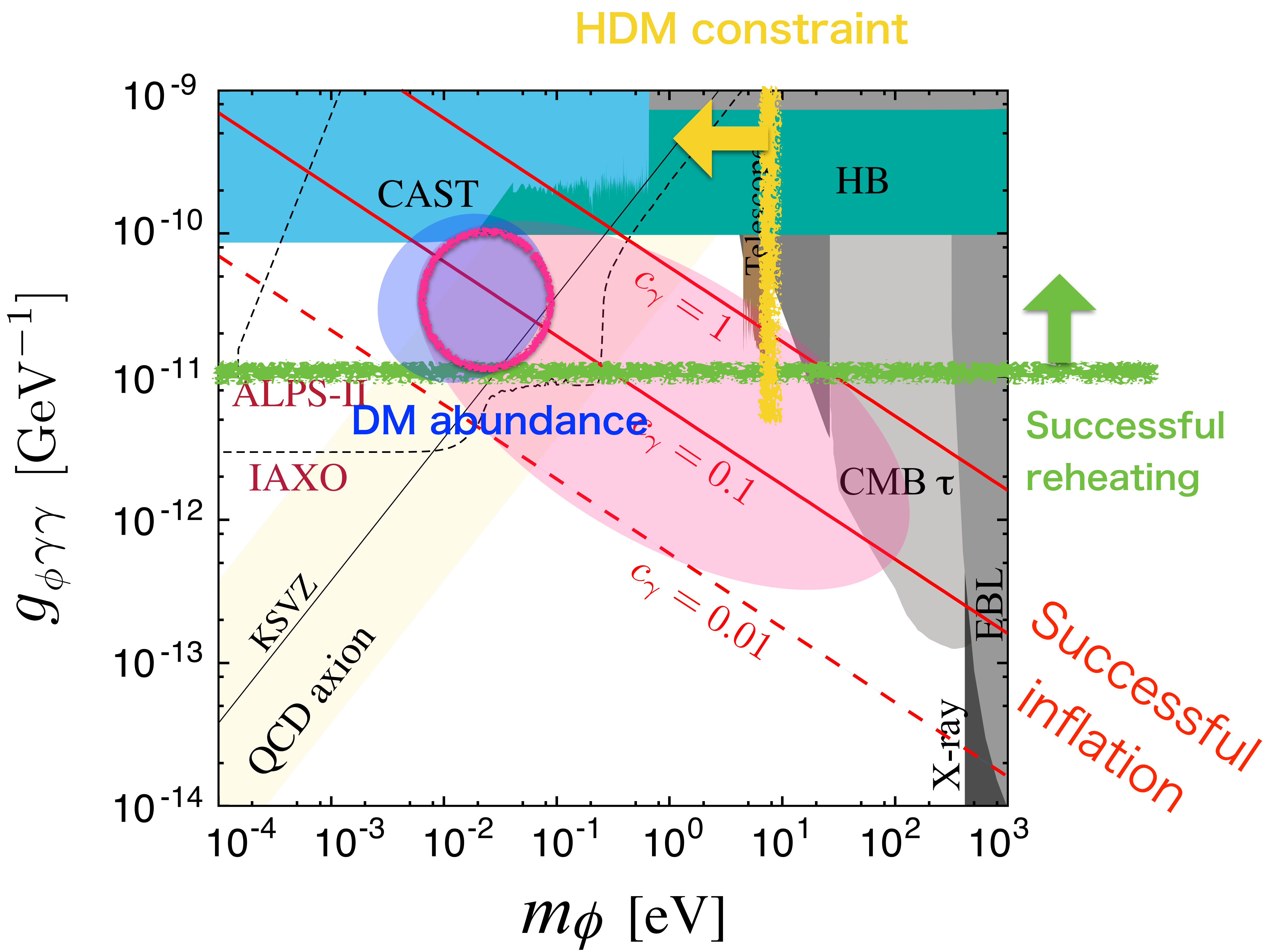

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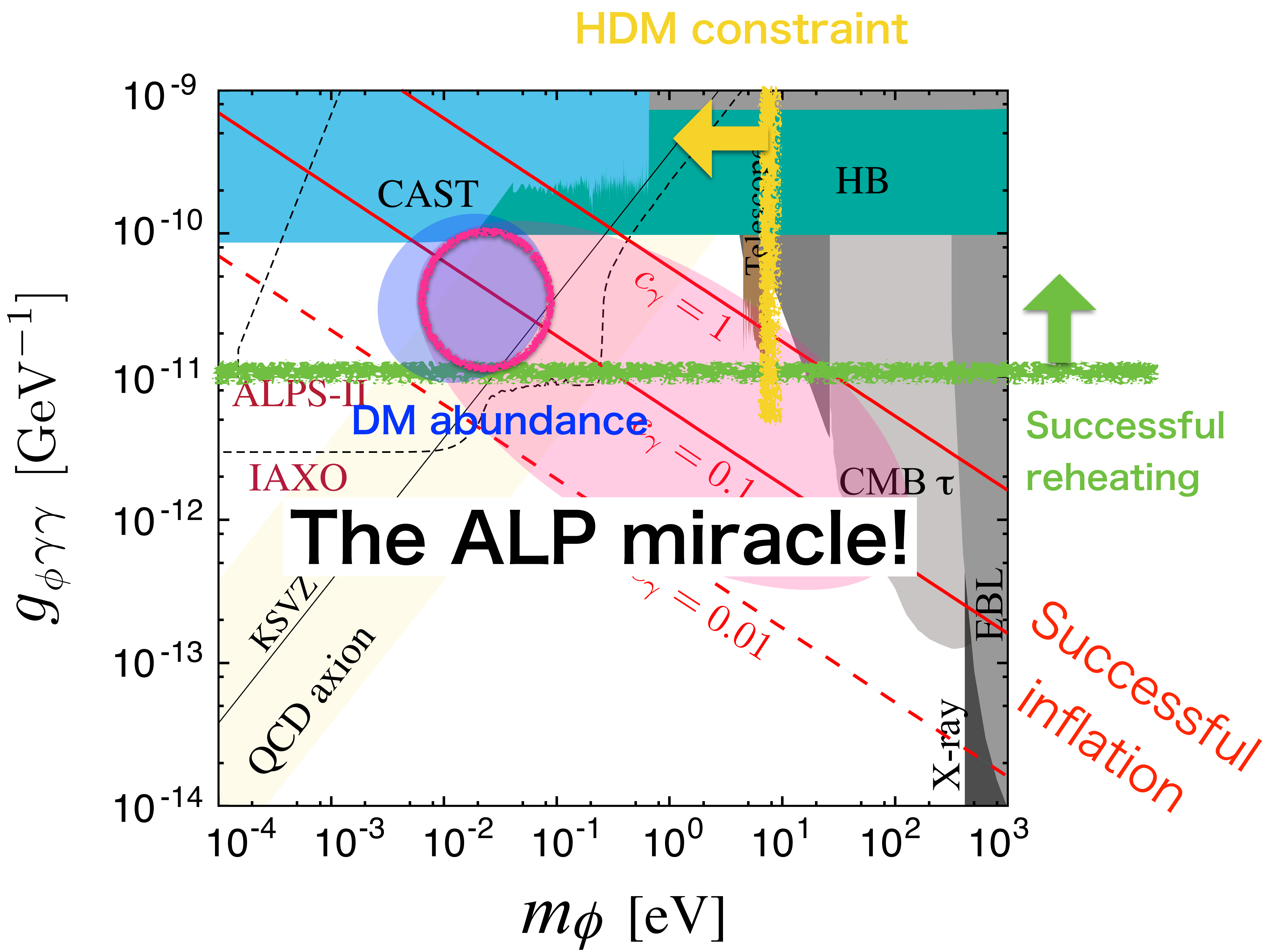
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Summary

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

・The observed CMB and LSS data fix the relation between the ALP mass and decay const.

・Successful inflation, reheating and DM abundance point to

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