An optimistic view on inflaton hunt

Mar. 7 2019@Tohoku University

“Revealing the history of the universe with underground particle and nuclear research 2019” (March 7-9).

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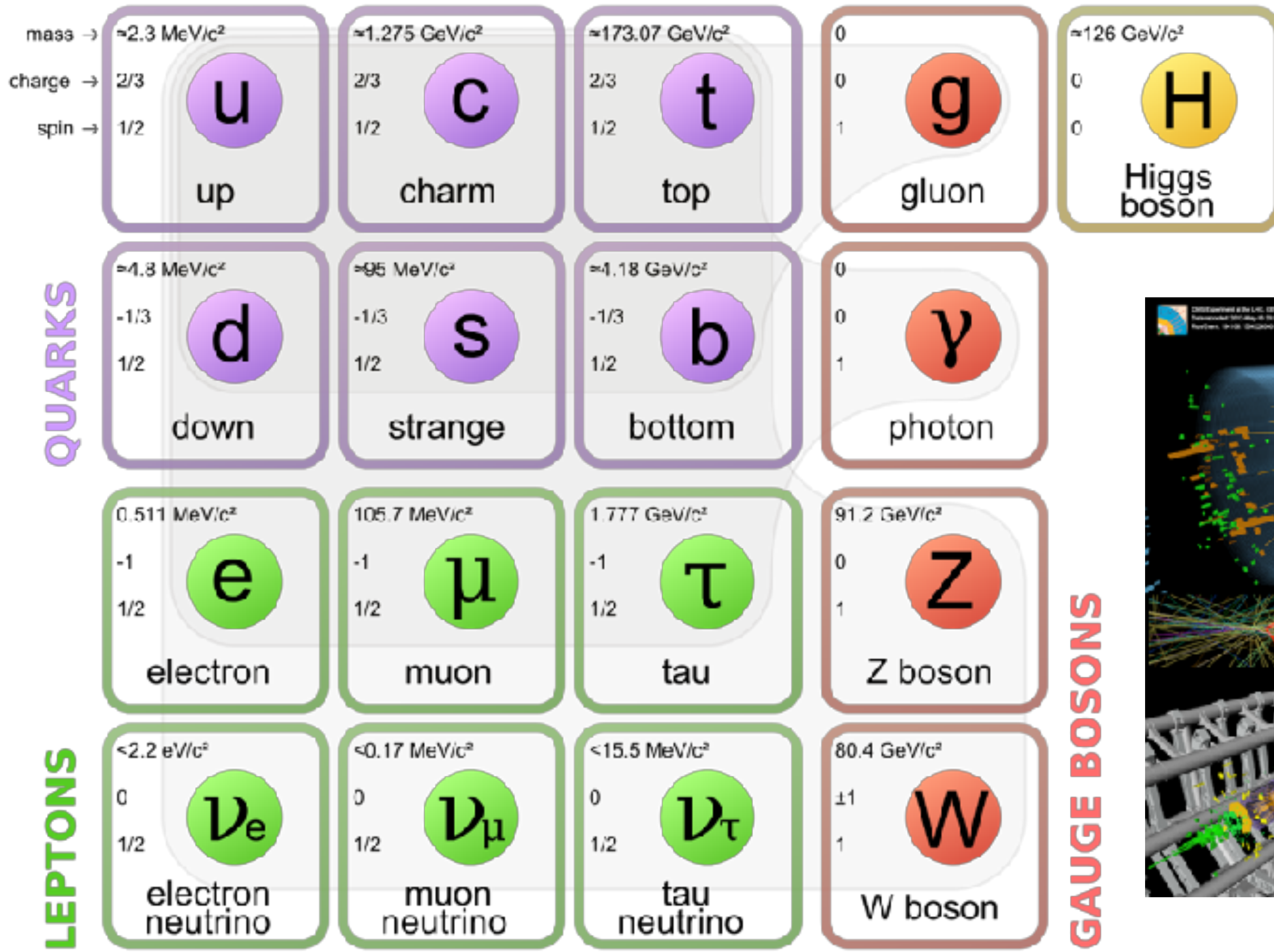
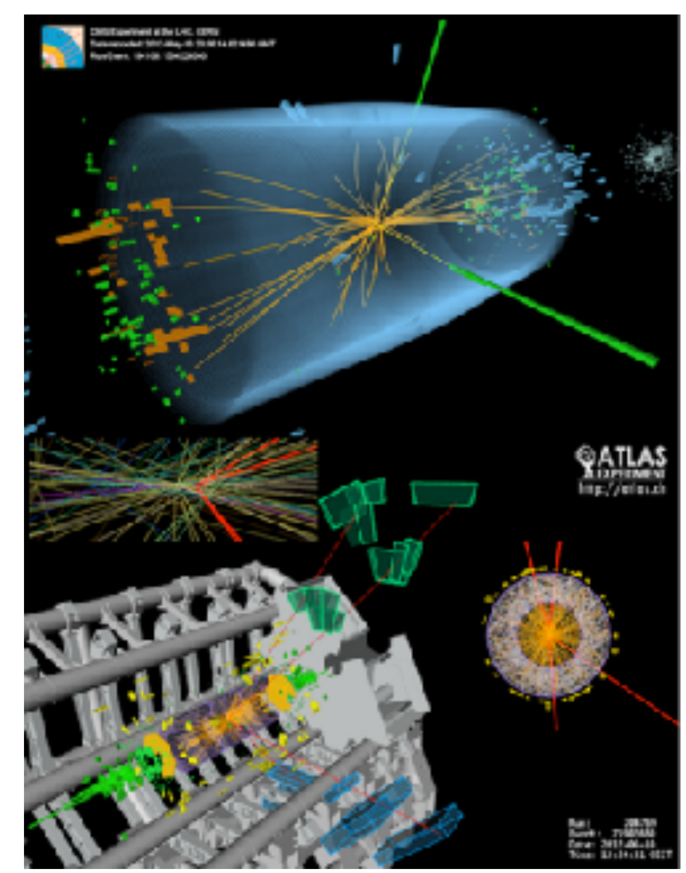
(Tohoku)

Based on Daido, FT, Yin, 1702.03284, 1710.11107, FT and Yin, 1903.00462

1. Introduction

The standard model (SM) of particle physics has been tested by numerous experiments with great accuracy.





from wikibooks

https://home.cern/science/physics/higgs-boson

Is this the end of the story?

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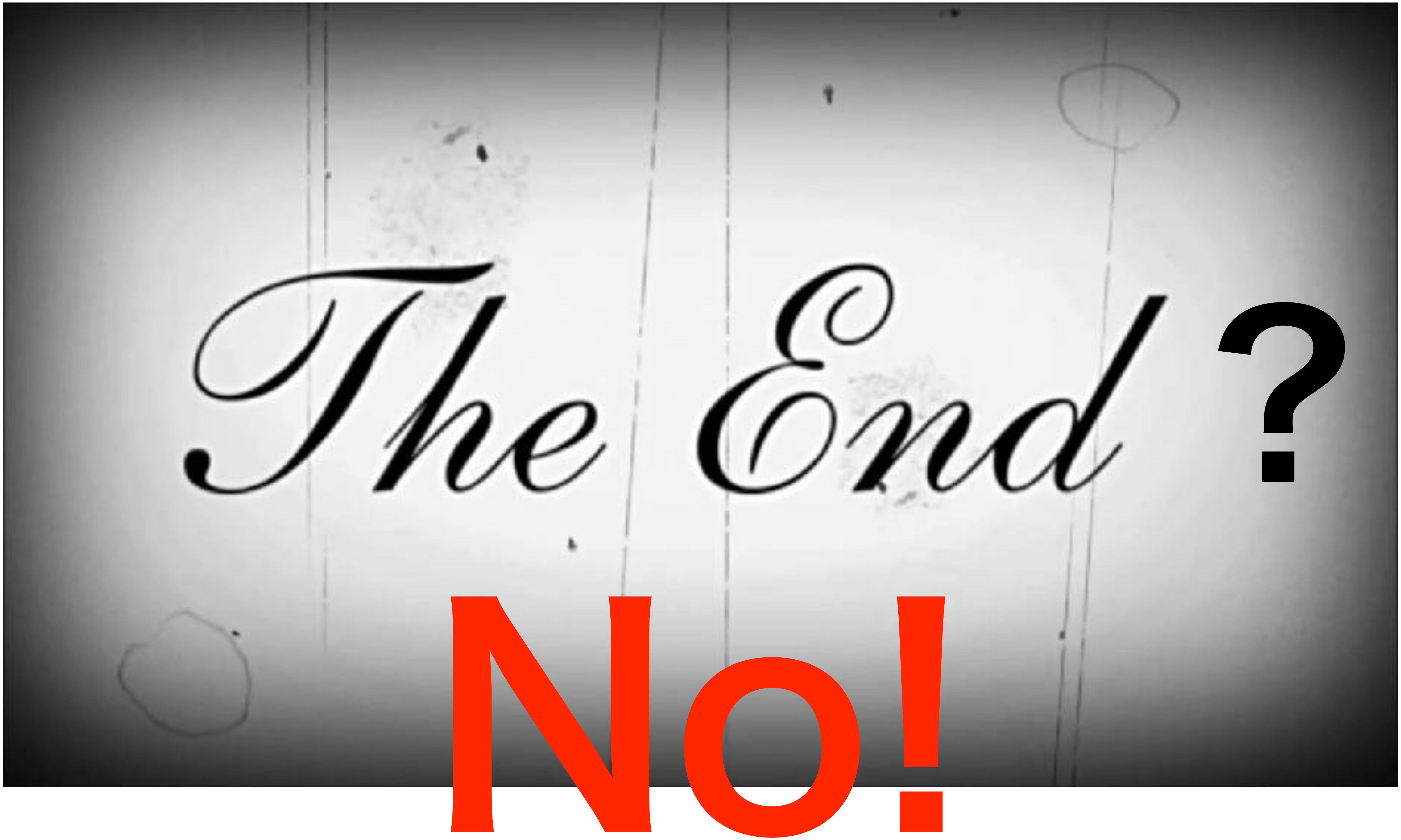
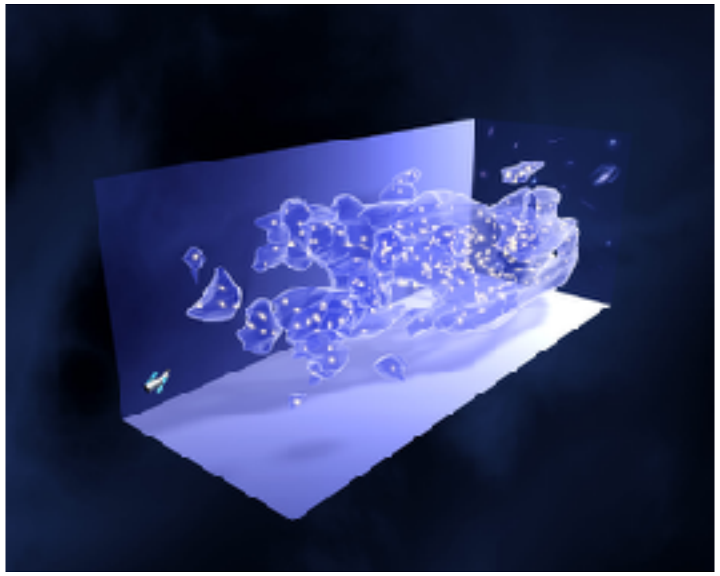


Known unknowns in Cosmology

Success of the ΛCDM model relies on the two unknown degrees of freedom:

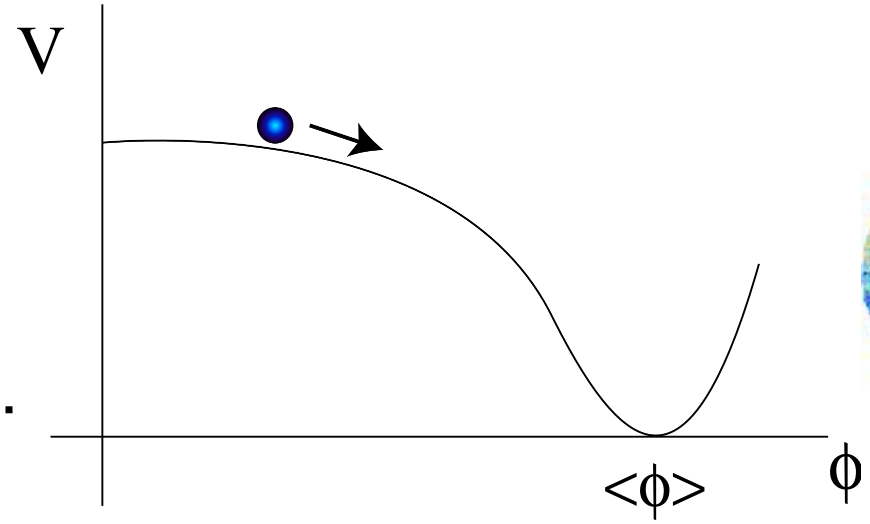
- **Dark matter**

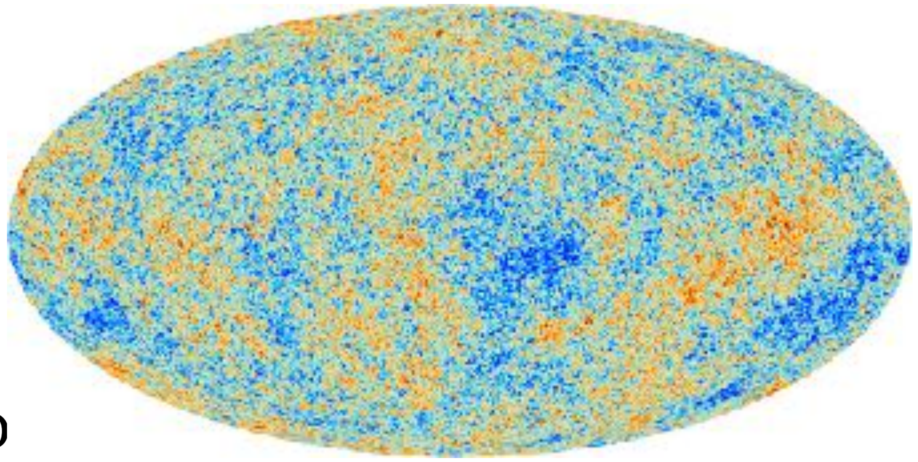
  Cold, neutral,
  and long-lived.



- **Inflaton**

  Very flat potential
  for slow-roll inflation.





Direct evidence for the physics beyond the SM!

Then, where should we look for ?

Niels Bohr

“We are all agreed that your theory is crazy. The question that divides us is whether it is crazy enough to have a chance of being correct.”

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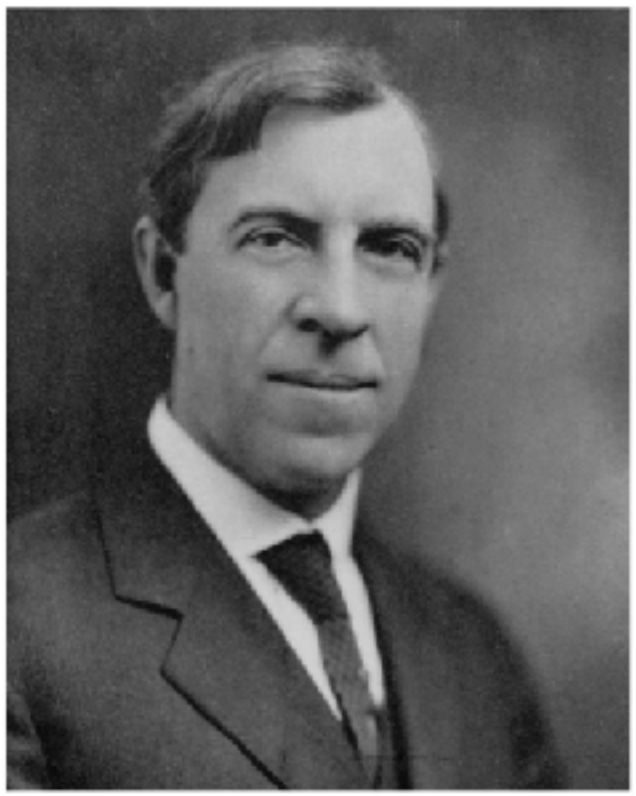
Steven Weinberg

"…My advice is to try crazy ideas and innovative experiments. Something will come up."

(In answer to "Do you have any advice to offer the next generation?")

https://physics.aps.org/articles/v11/134



F. K. Richtmyer

"The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place."

So, let us try a crazy idea, which might be lurking at the next decimal place.

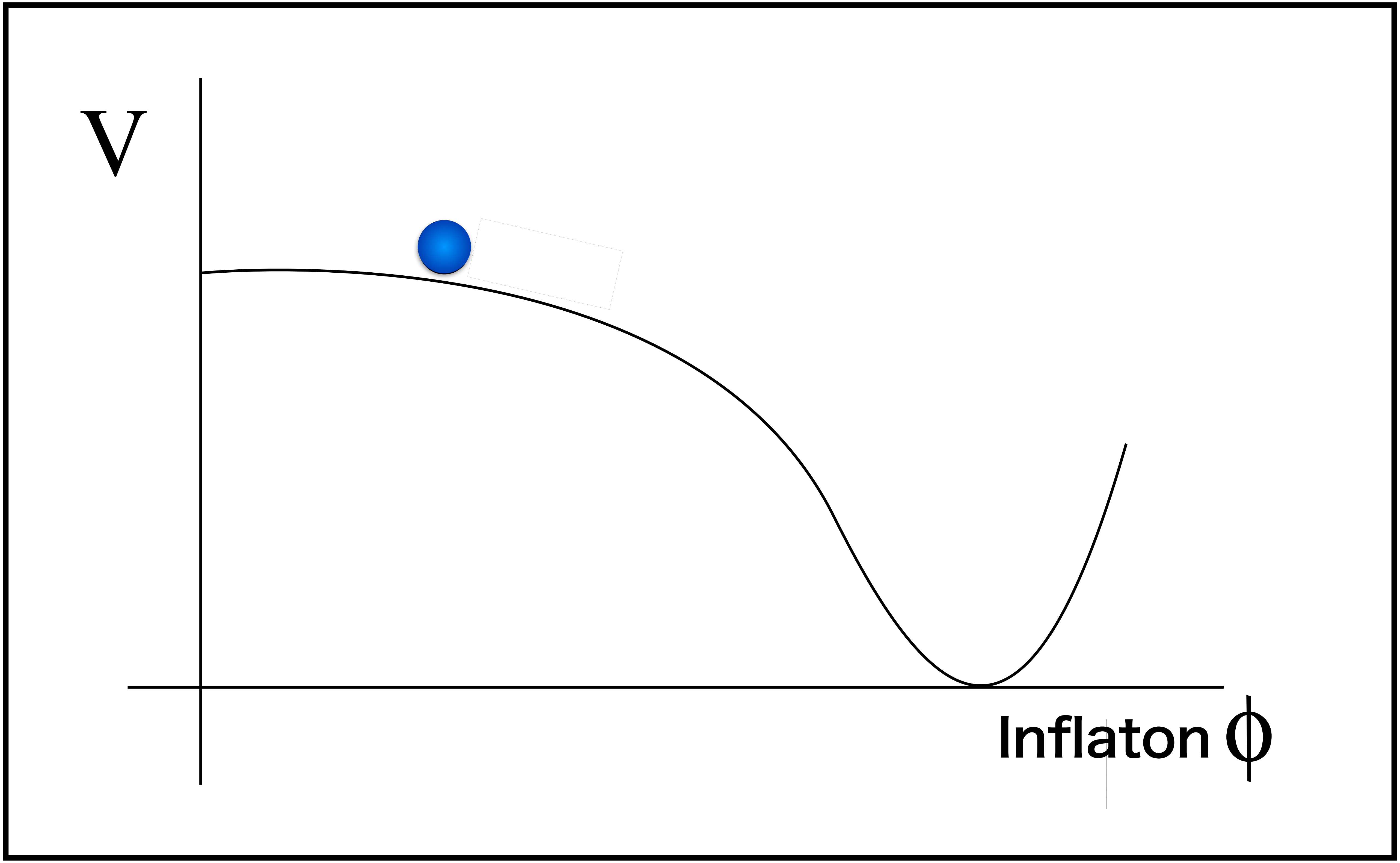
So, let us try a crazy idea, which might be lurking at the next decimal place.

I want the inflaton (+DM) that can be probed by ground-based experiments.

2.What is the inflaton?

Inflation

Guth `81, Sato `80, Starobinsky `80, Kazanas `80, Brout, Englert, Gunzig, `79
Linde `82, Albrecht and Steinhardt `82



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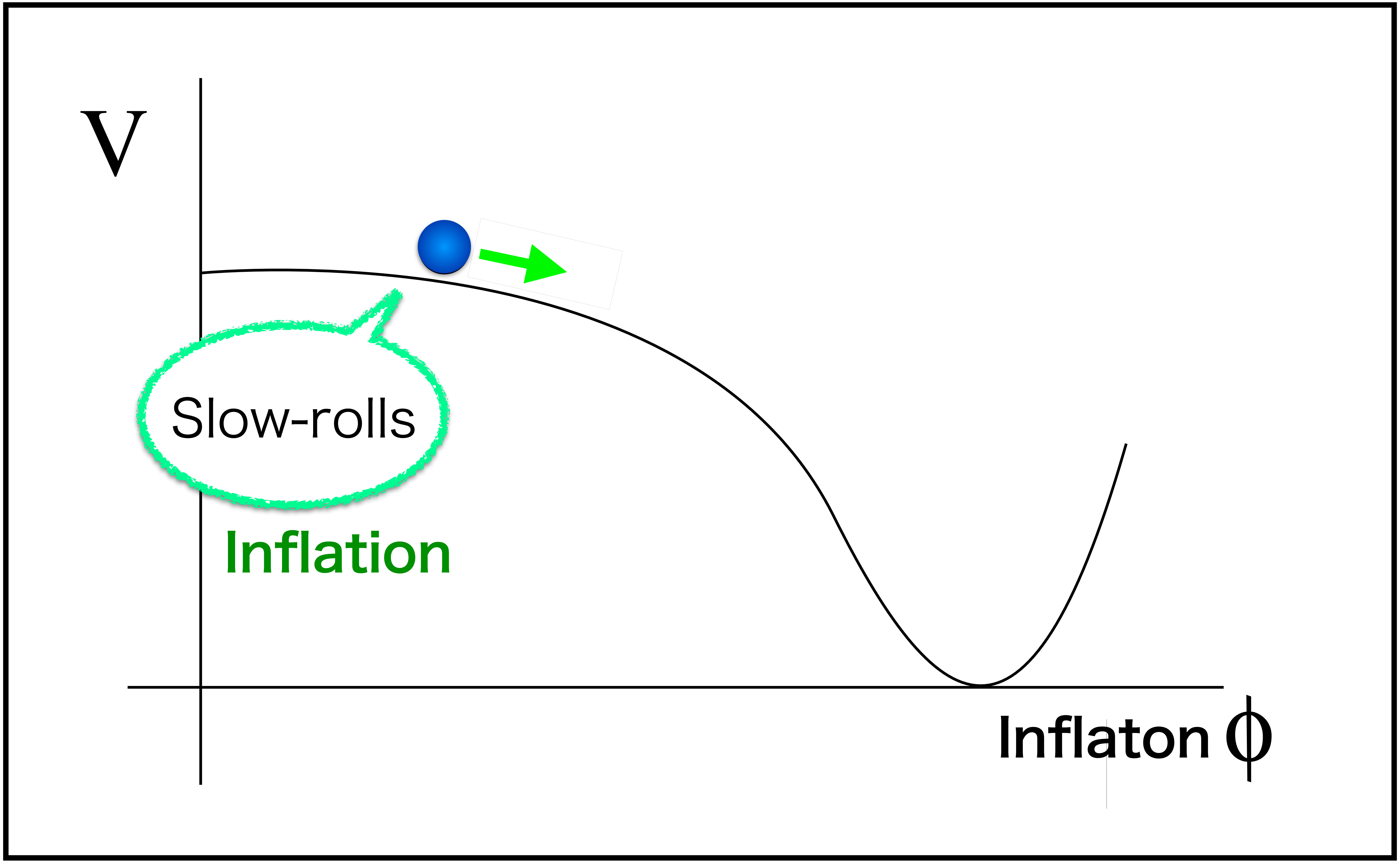

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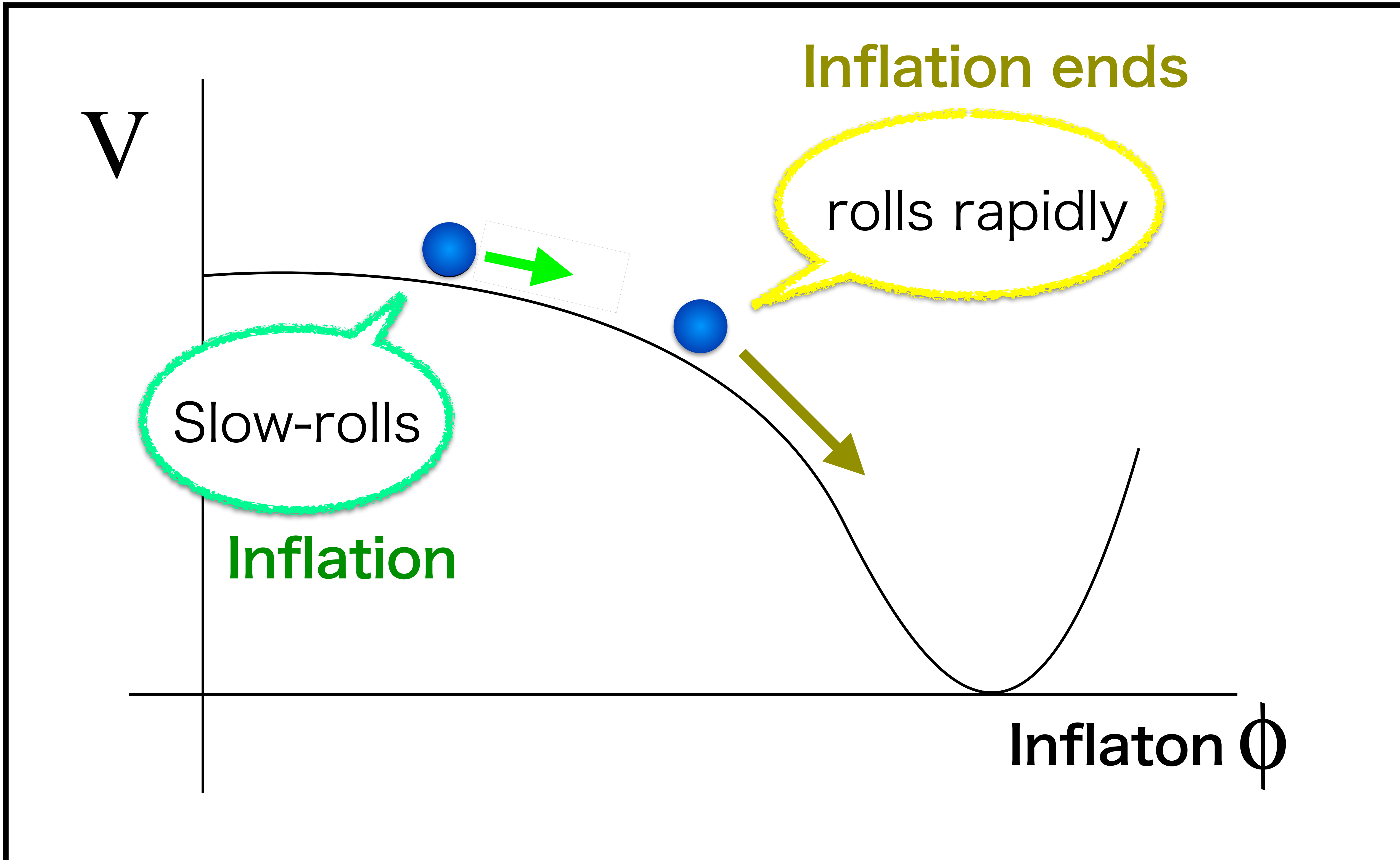

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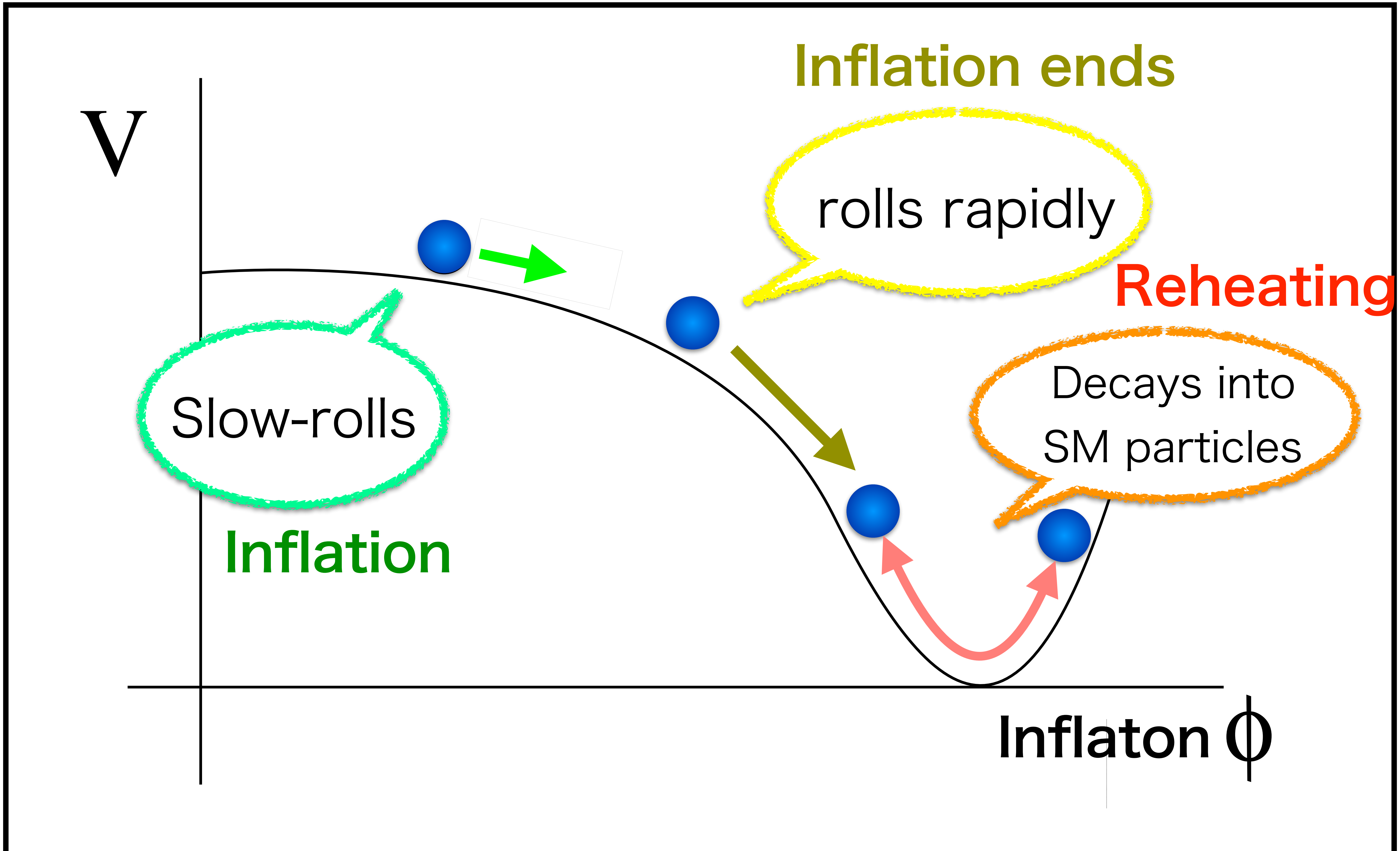

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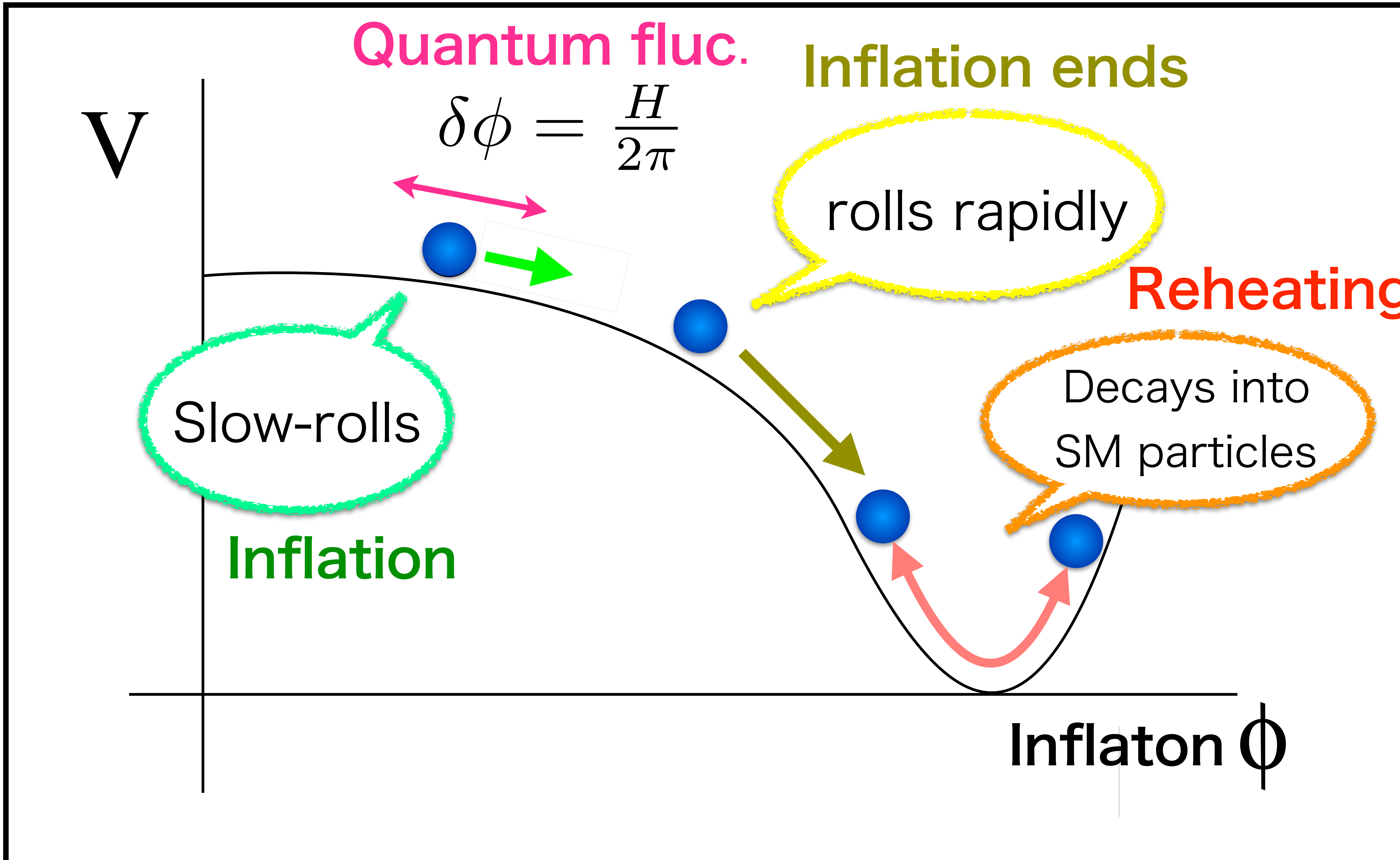
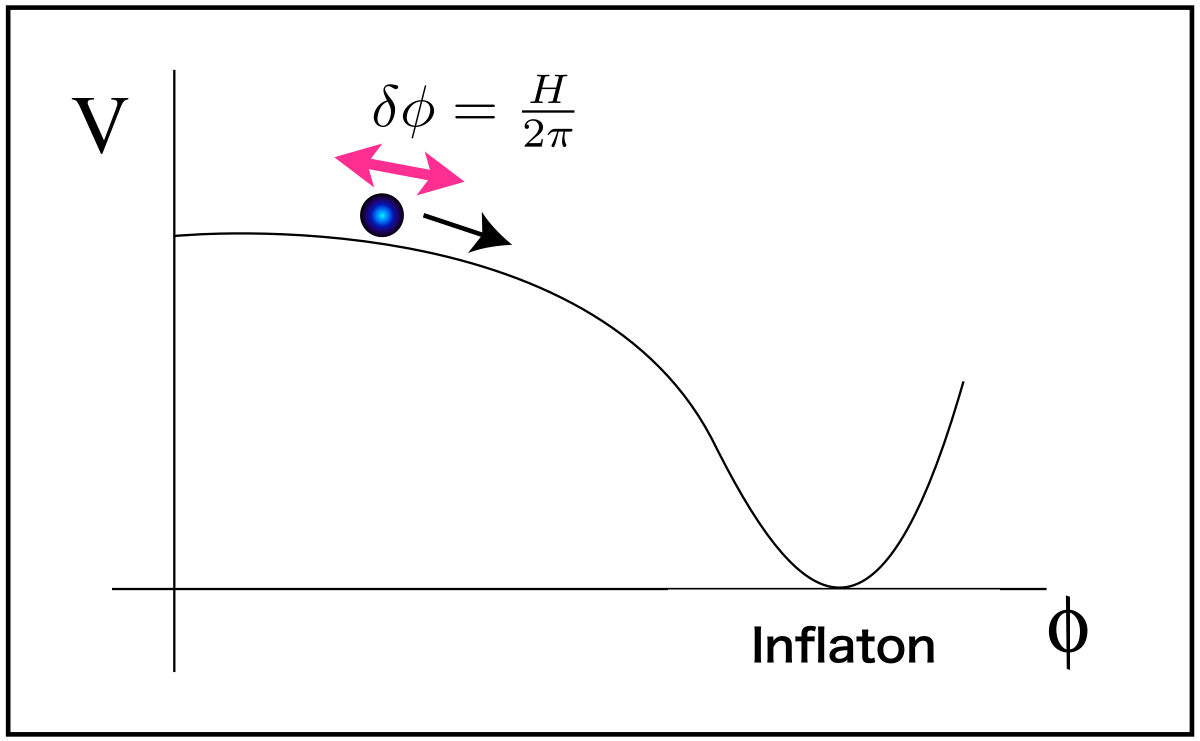
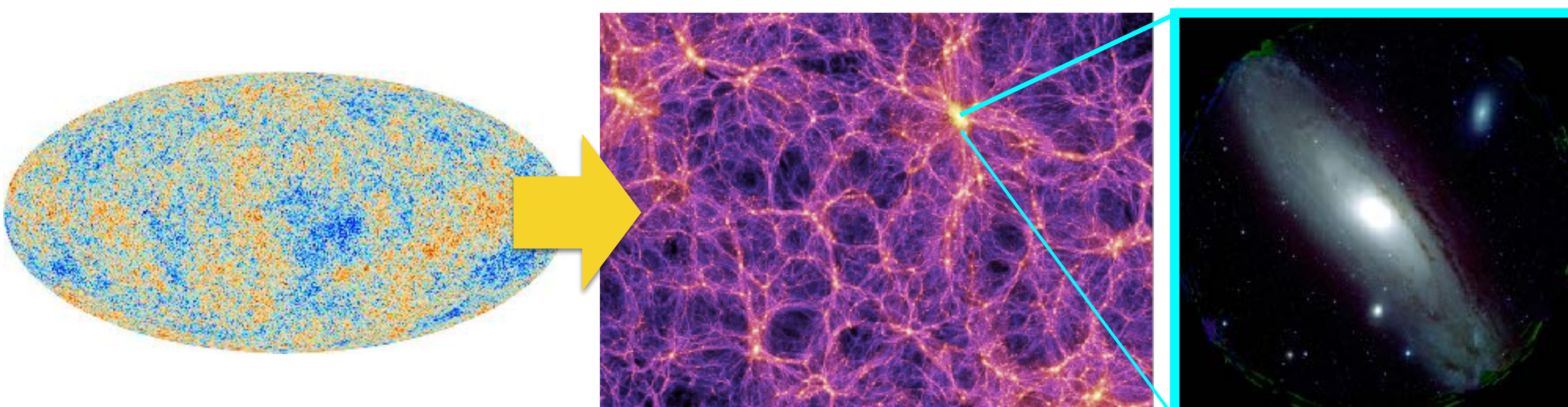


Inflation and density perturbations



The quantum fluctuations lead to slightly different evolution at different points.

Fluctuation in time
= Fluctuation in volume
= Density perturbations



Scalar mode perturbations

Amplitude:

$$\frac{\delta\rho}{\rho} \sim \left|\frac{V^{3/2}}{V' M_P^3}\right| \sim 10^{-5}$$

: CMB normalization

The potential must be flatter for lower inflation scale.

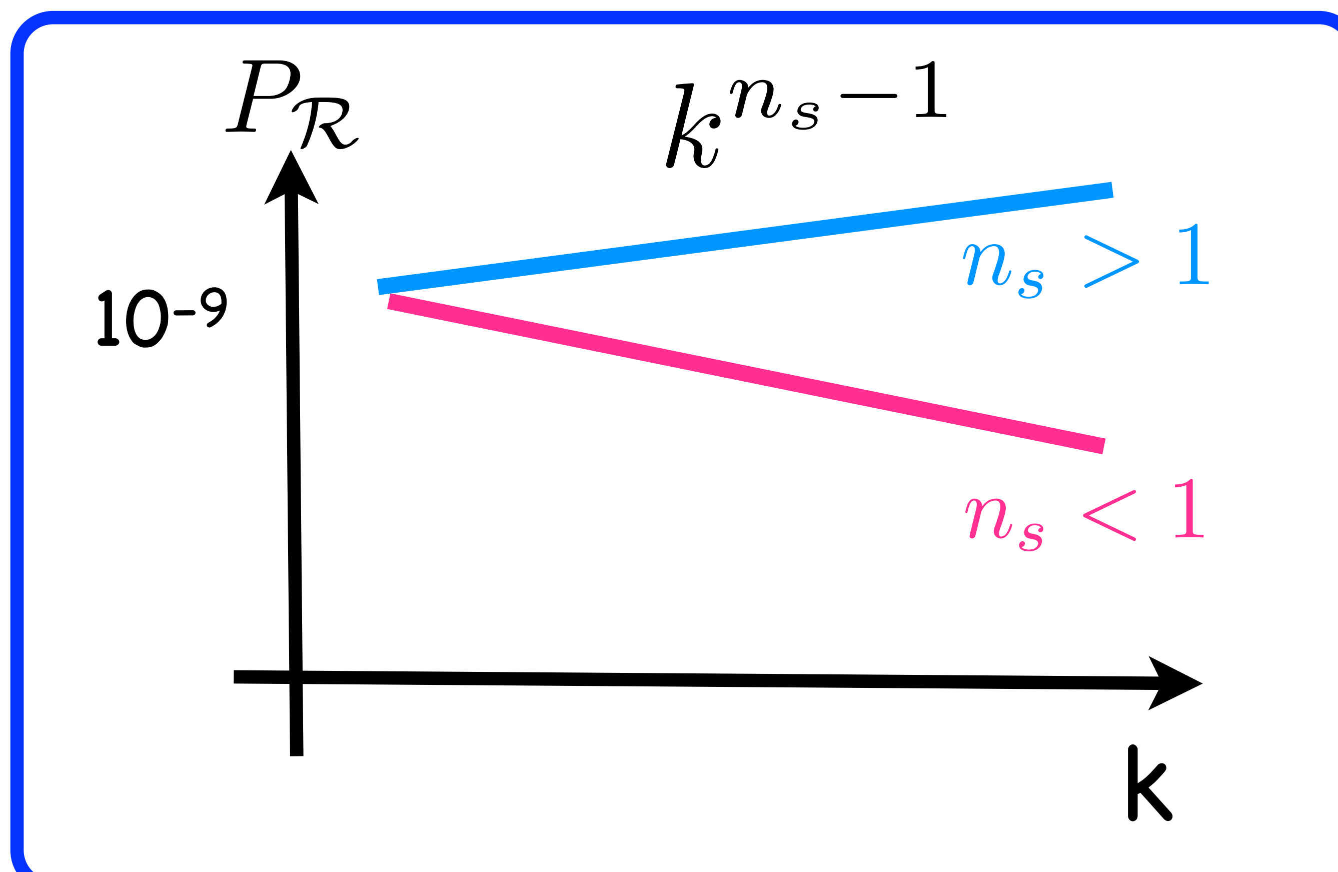
Spectral index: $n_s = 0.965 \pm 0.004$ Planck 2018

$$n_s - 1 = \frac{d \ln(\delta\rho_k/\rho)^2}{d \ln k}$$

$$\simeq -\frac{V'}{V}\frac{d}{d\phi}\ln\left(\frac{V^3}{V'^2}\right)$$

$$= -3\frac{V'^2}{V^2} + 2\frac{V''}{V}$$

ns is determined mainly by V''
for low-scale inflation.



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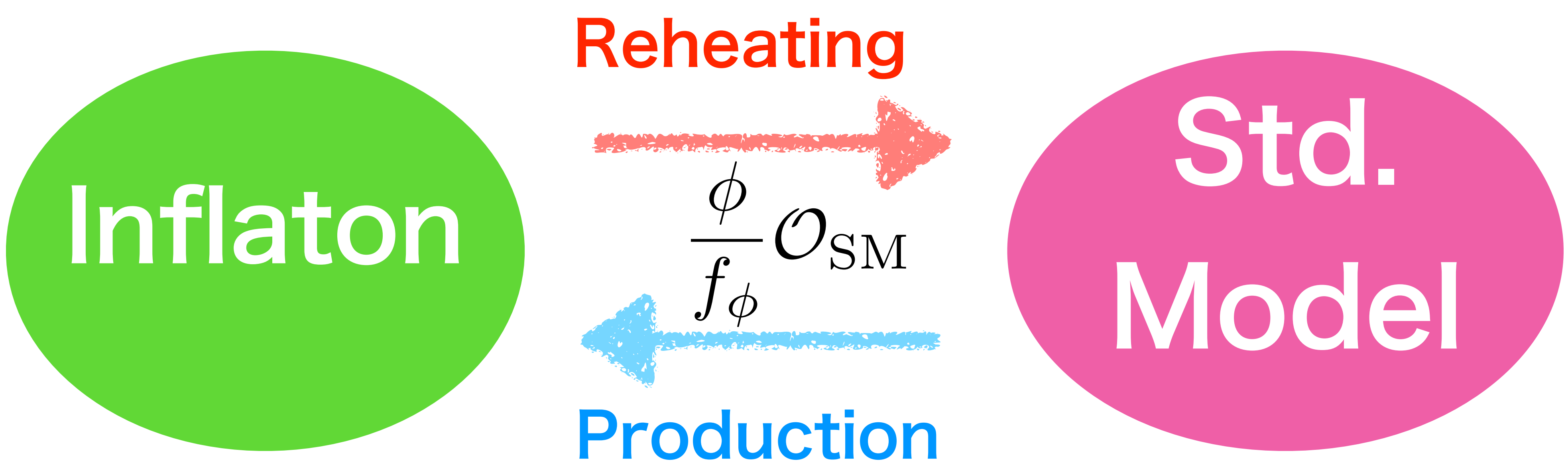
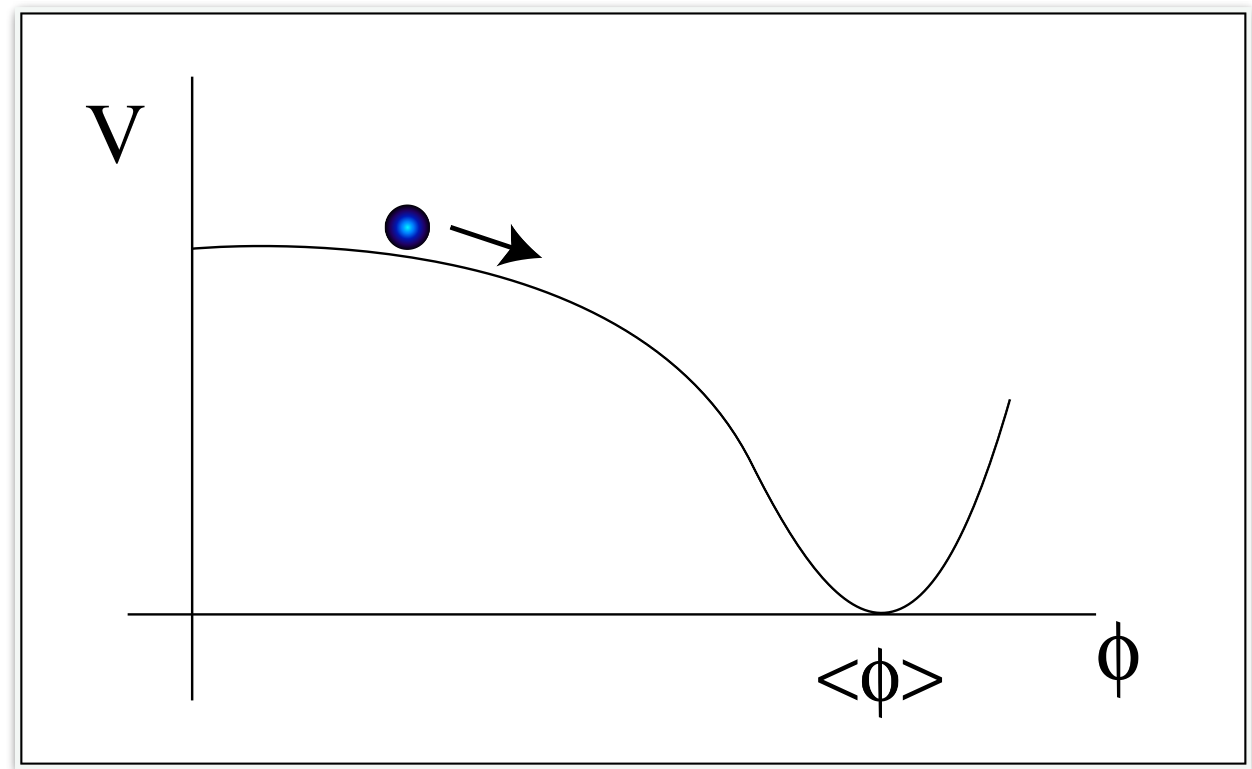


The inflaton may be produced at experiments or astrophysical environment (e.g. inside stars)

Suppose that the inflaton is so light that it is kinematically accessible for experiments.

2) The inflaton potential is extremely flat, in spite of large couplings to the SM.

$$\frac{\delta\rho}{\rho} \sim \left| \frac{V^{3/2}}{V' M_P^3} \right| \sim 10^{-5}$$



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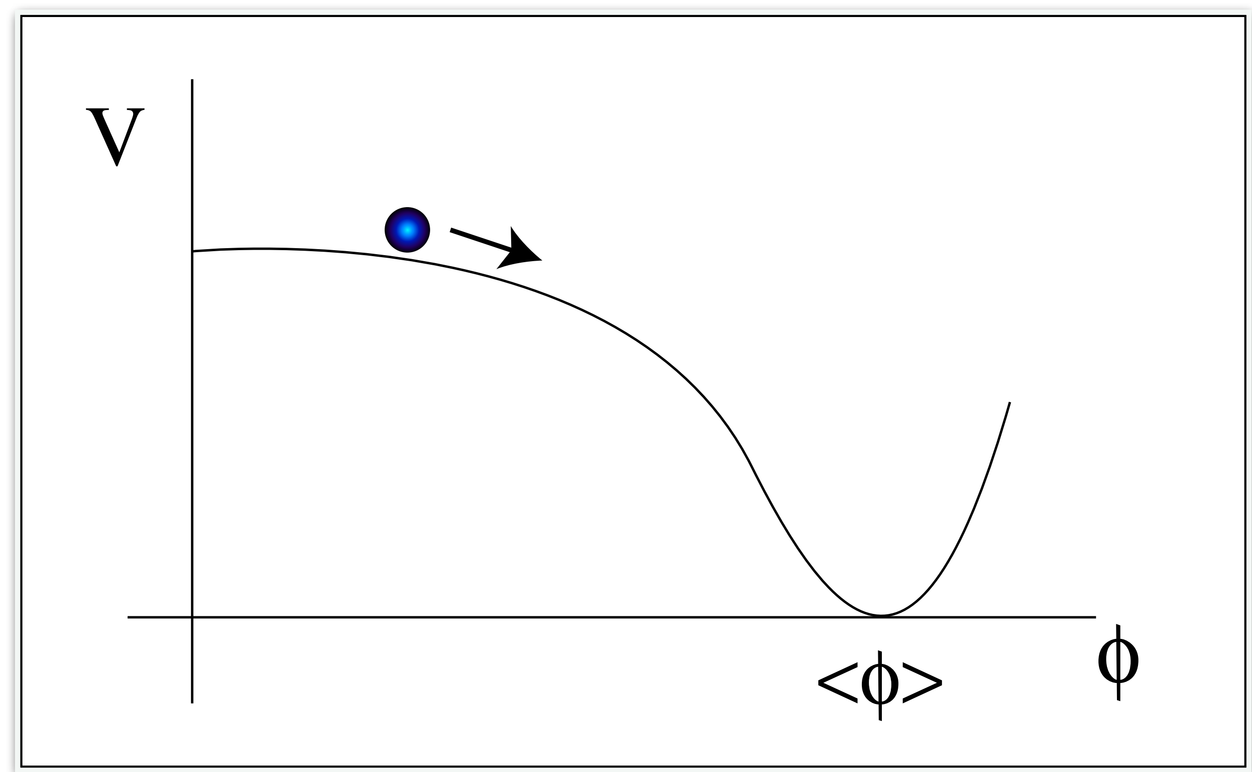


The flatness of the inflaton potential can be ensured by shift symmetry, if it is an NG boson.

Suppose that the inflaton is so light that it is kinematically accessible for experiments.

The inflaton is likely **an axion/ALP with sizable couplings to the SM**.

Do we have any testable predictions?

See talks by Kawasaki, Ringwald, and Tokiyasu for axions.

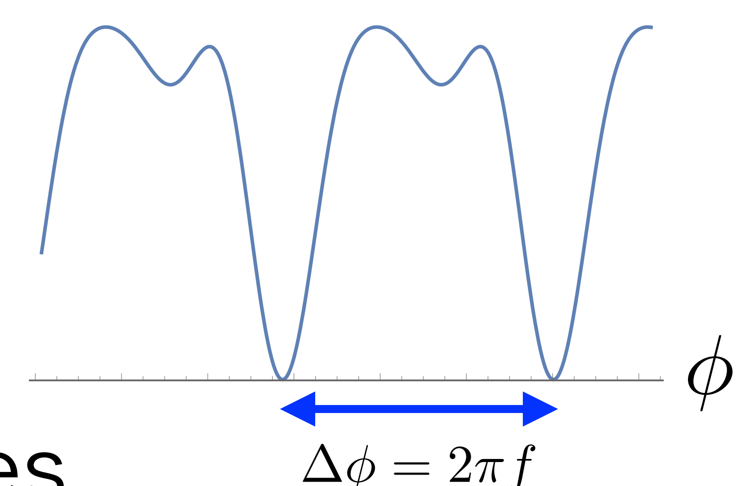
Inflaton = ALP

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

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

suppressing dangerous radiative correction. Then, the inflaton potential is periodic, i.e.,

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



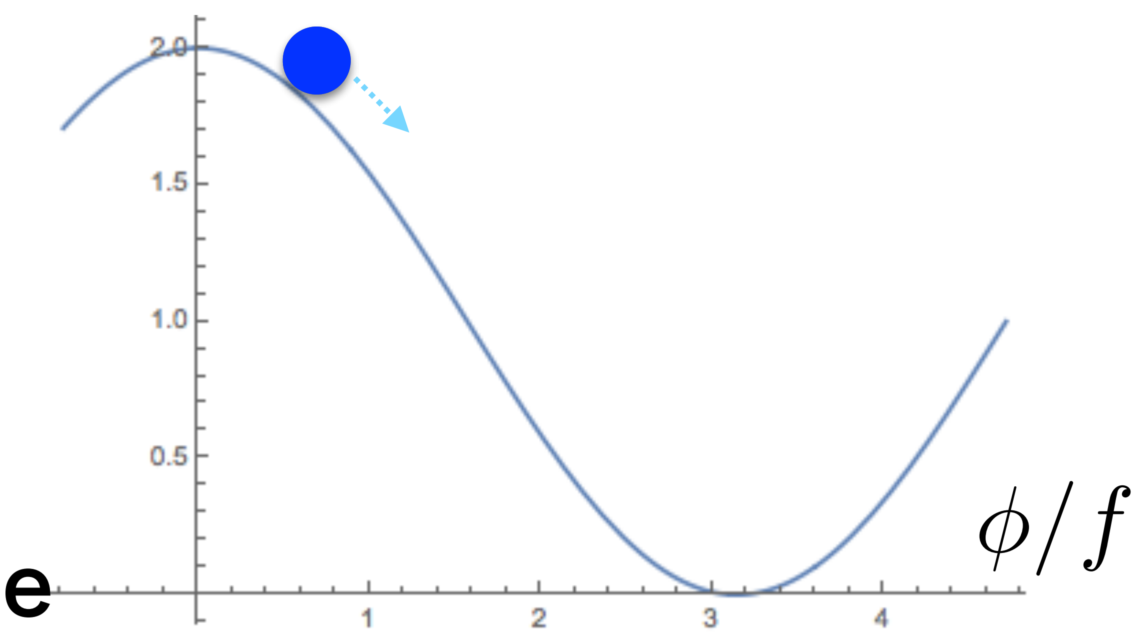
and can be expressed as Fourier series,

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

• Natural inflation

Freese, Frieman, Olinto `90

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

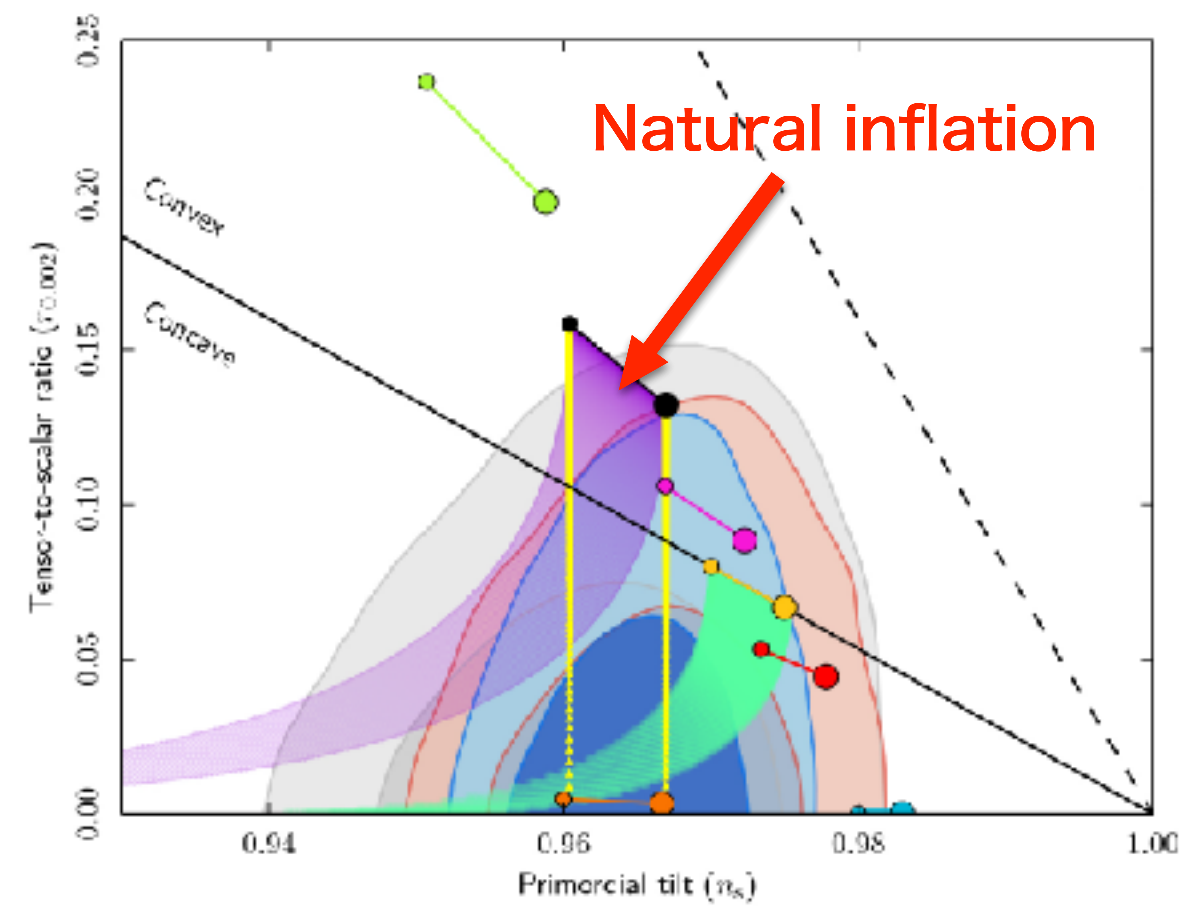


Only large-field inflation is possible with a single cosine term.

- 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, FT 1401.5212,
Czerny, Higaki, FT 1403.0410, 1403.5883
Croon and Sanz, 1411.7809
FT, Yin, 1903.00462

Low-scale axion inflation can be realized with **at least two cosine terms**: *"Multi-natural inflation"*

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

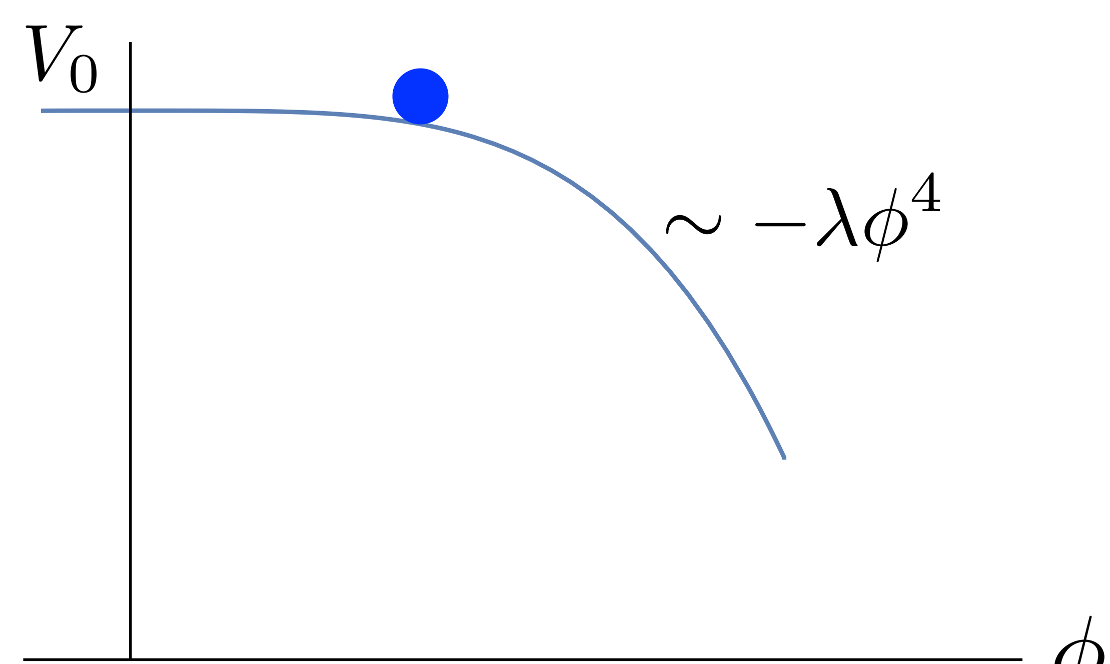
$$= \boxed{V_0 - \lambda\phi^4} - \theta\frac{\Lambda^4}{f}\phi + (\kappa-1)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots \quad \text{where} \quad \lambda \sim \frac{\Lambda^4}{f^4}$$

for $|\theta| \ll 1$ and $|\kappa - 1| \ll 1$

CMB normalization:

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

independent of V_0



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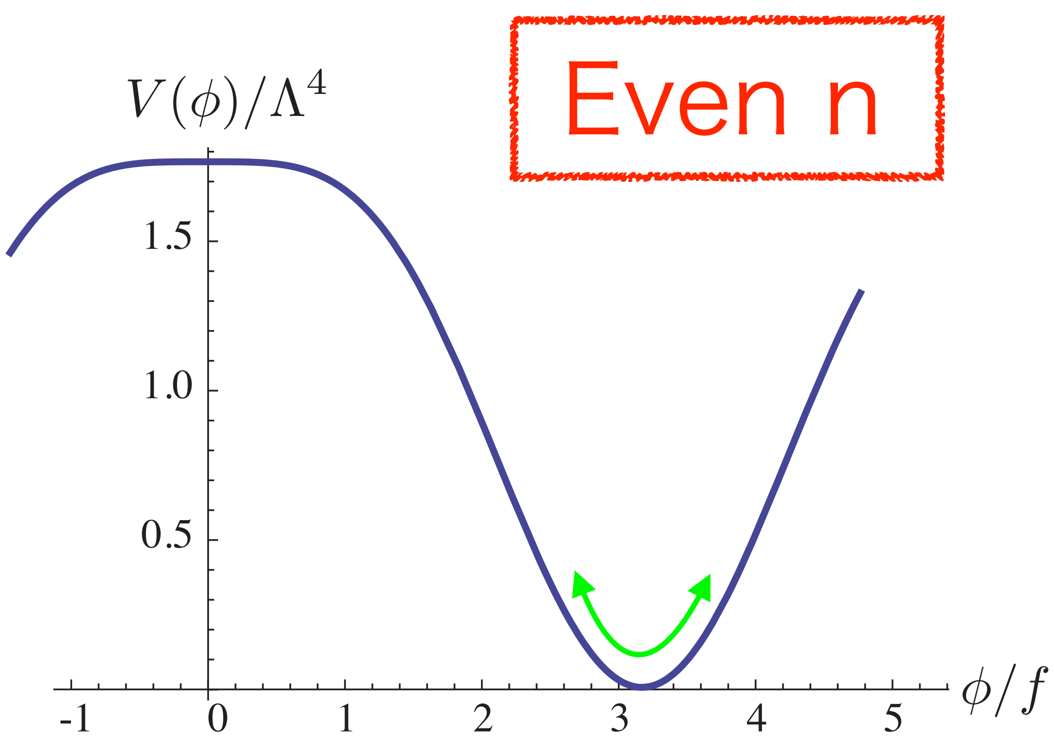
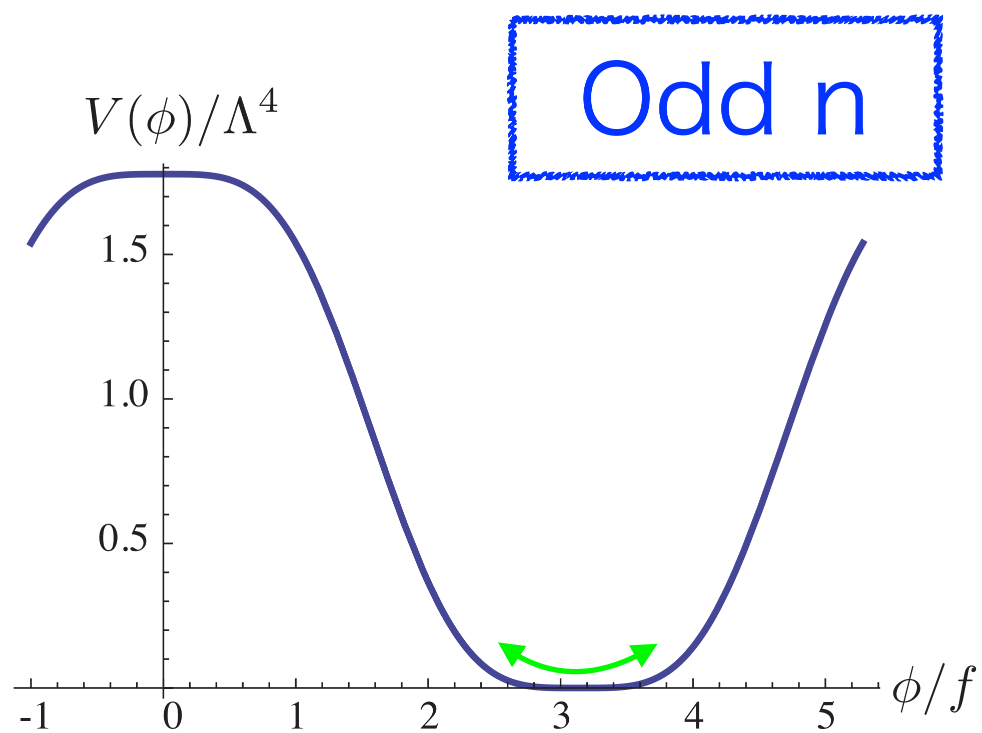
The inflaton mass at the minimum, m_ϕ , depends on *n*.



$$m_\phi \sim \Lambda^2/f$$



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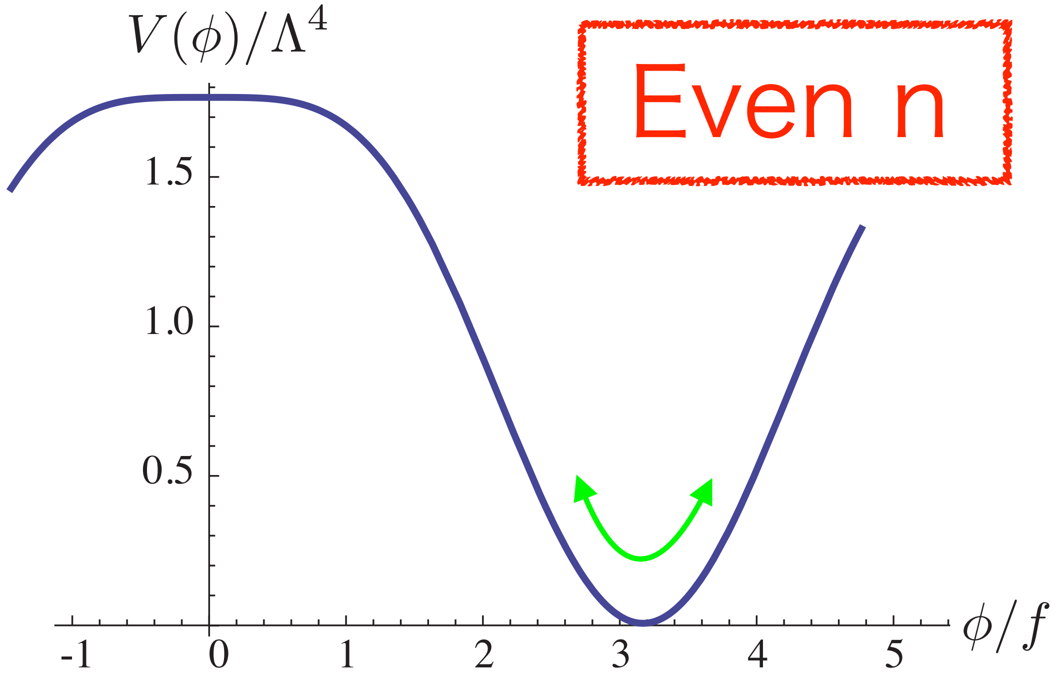


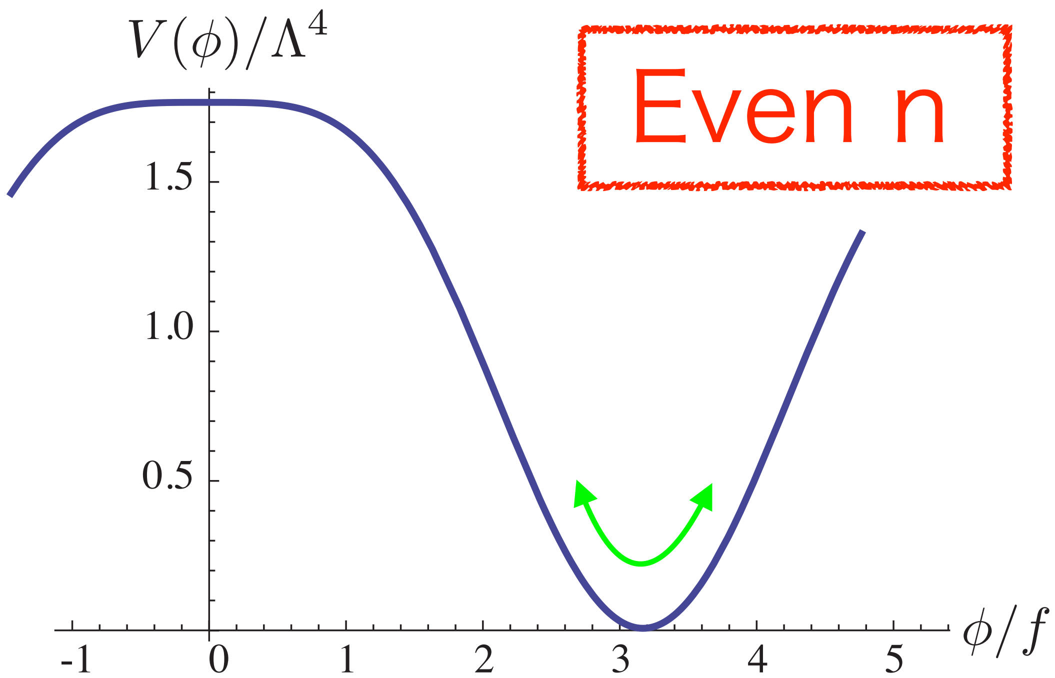
The potential is flat only around the potential maximum.

$$m_\phi \sim \frac{\Lambda^2}{f}$$

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-13}$$ **: CMB norm**

$$\Rightarrow \quad f \sim 10^6 m_\phi$$

Czerny, Higaki, FT 1403.0410, FT and Yin, 1903.00462



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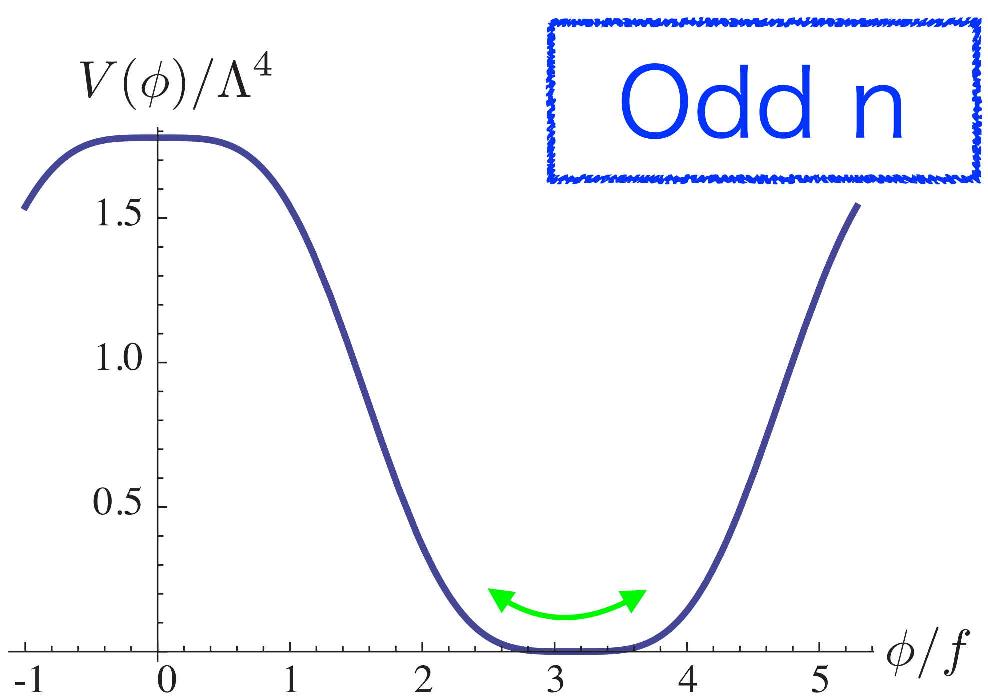


The potential is flat both around the maximum and minimum.

$$1 - n_s = -2M_p^2 \frac{V''}{V} \simeq \frac{2}{3}\frac{m_\phi^2}{H_{\rm inf}^2} \simeq 0.04$$

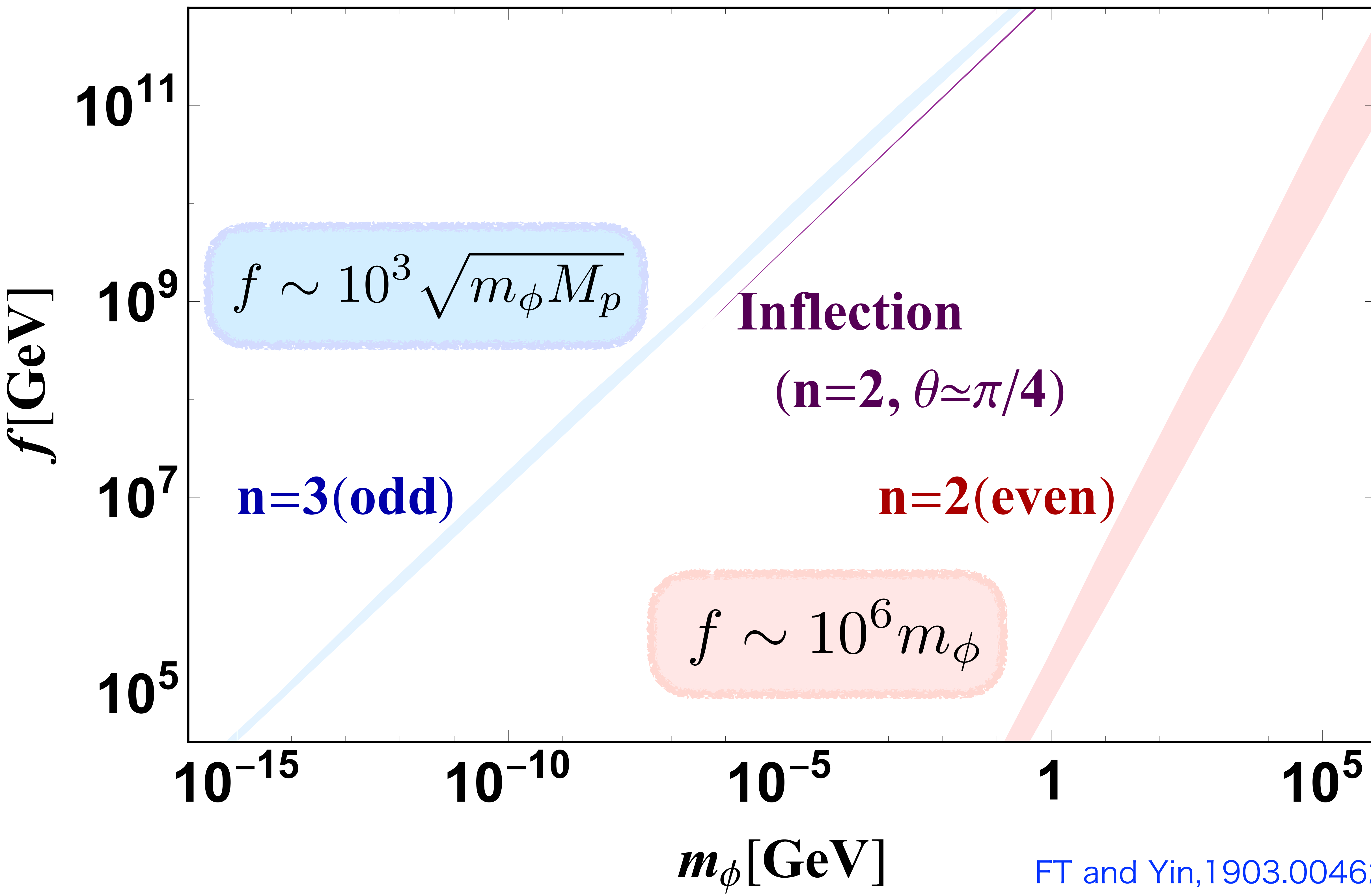
So $m_\phi \sim 0.1 H_{\rm inf} \sim 0.1 \dfrac{\Lambda^2}{M_p}$ **+ CMB norm.**

$$\boxed{f \sim 10^3 \sqrt{m_\phi M_p}}$$

Daido, FT, Yin, 1702.03284, 1710.11107

ALP mass and decay constant

cf. $f \sim 10^{12}\,\mathrm{GeV}(m_a/6\,\mu\mathrm{eV})^{-1}$ for QCD axion



FT and Yin,1903.00462

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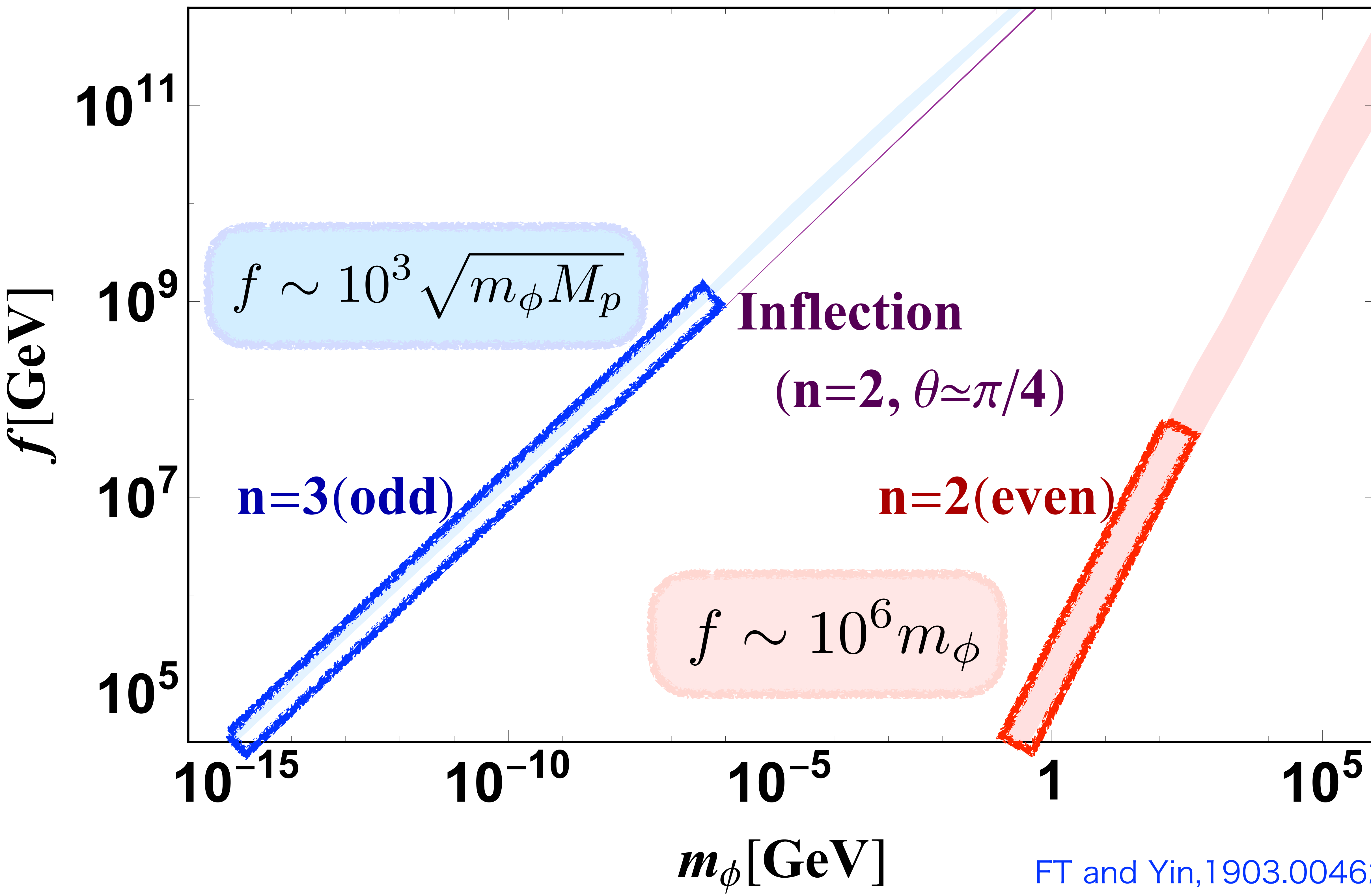

FT and Yin,1903.00462

ALP mass and decay constant

In the case of the ALP coupled to photons

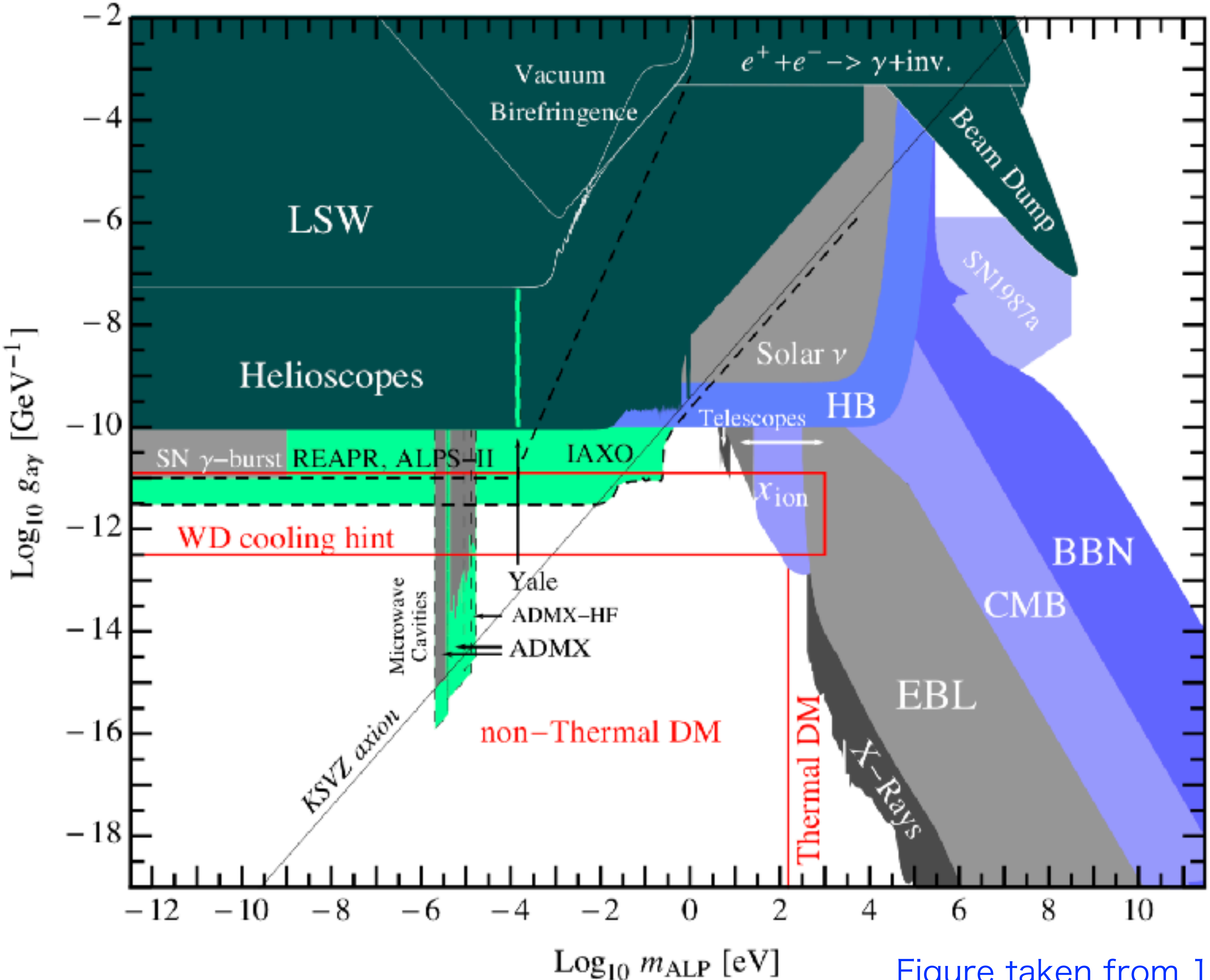

Figure taken from 1205.2671

ALP mass and decay constant

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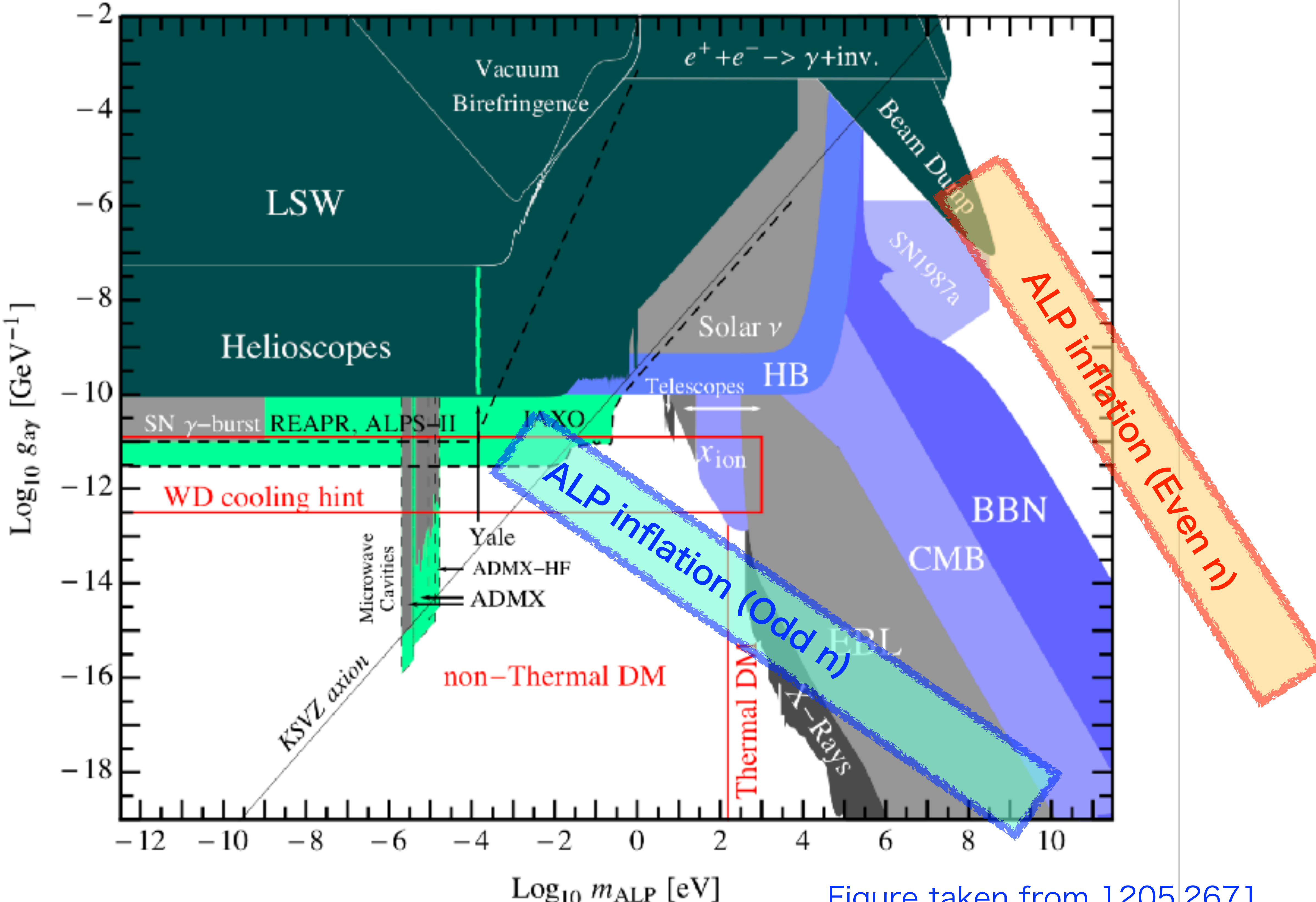

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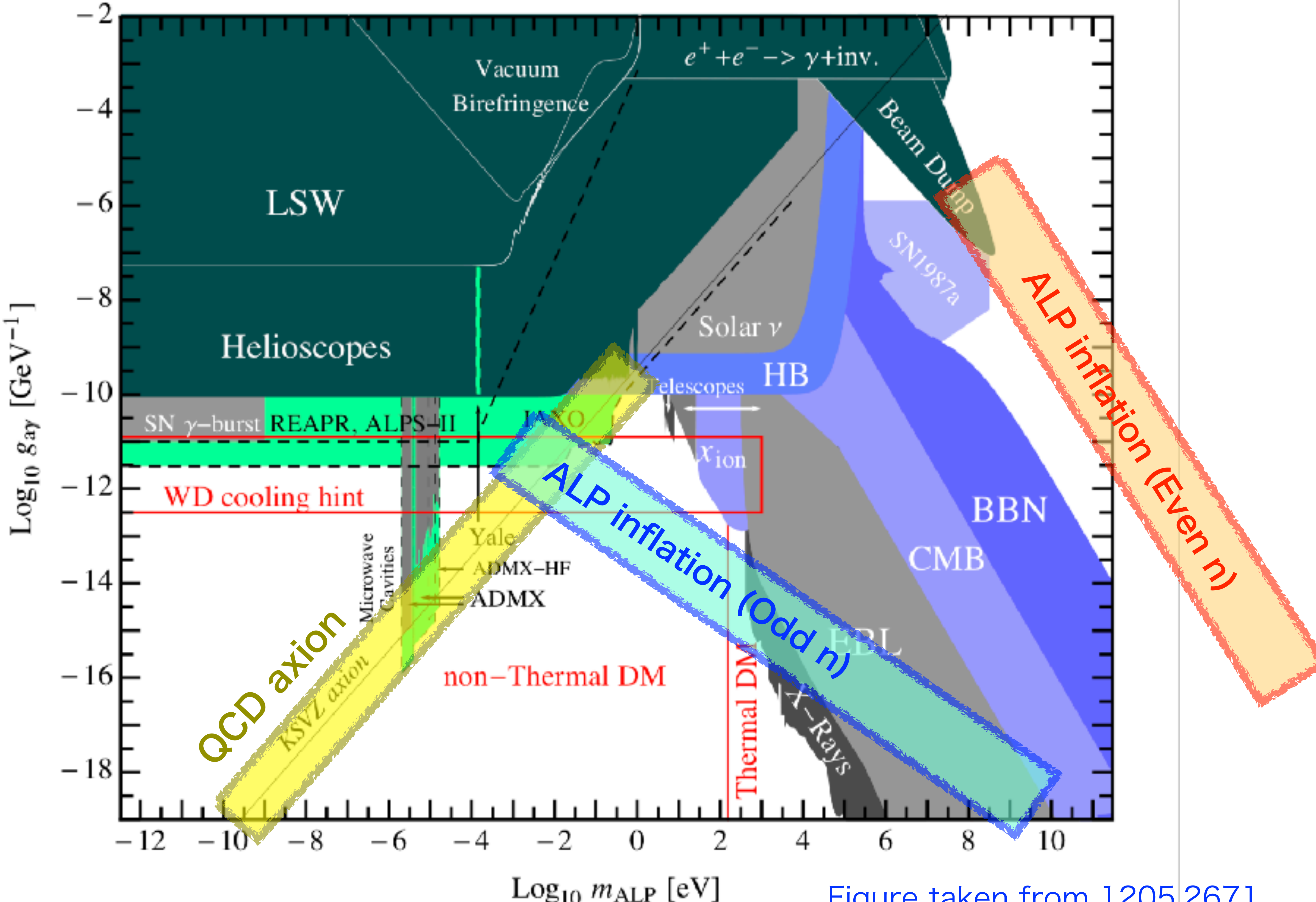
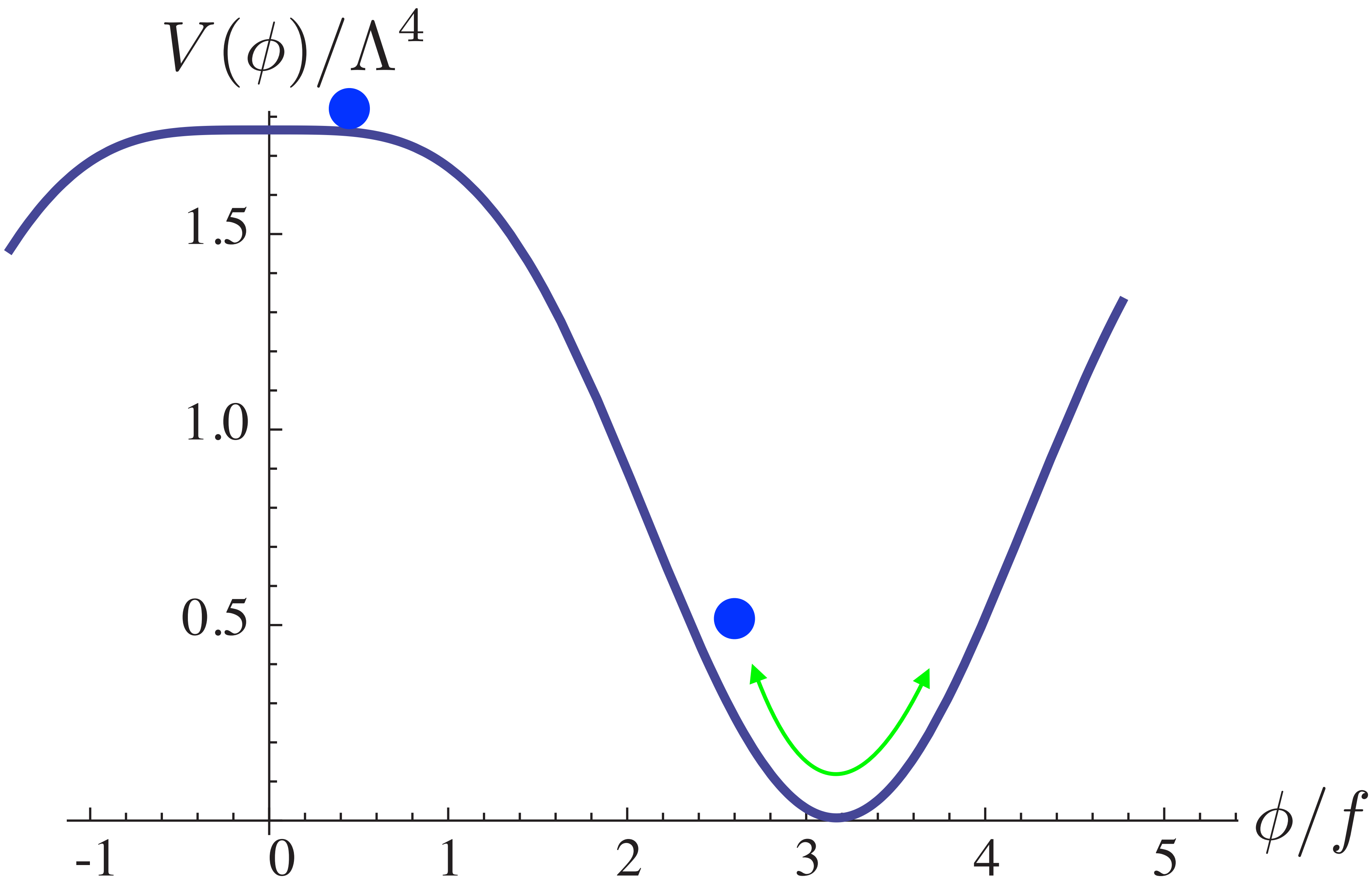


Figure taken from 1205.2671

3. Inflaton hunt by ground-based experiments

The case of even n



We consider the following ALP inflaton couplings to the SM:

(1) Coupling to photons (or weak gauge bosons at high T)

$$\mathcal{L} = c_\gamma \frac{\alpha}{4\pi} \frac{\phi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu},$$

(2) Couplings to the SM fermions

$$\mathcal{L} = \sum_k i \frac{c_k m_k}{f} \phi \bar{\psi}_k \gamma_5 \psi_k,$$

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

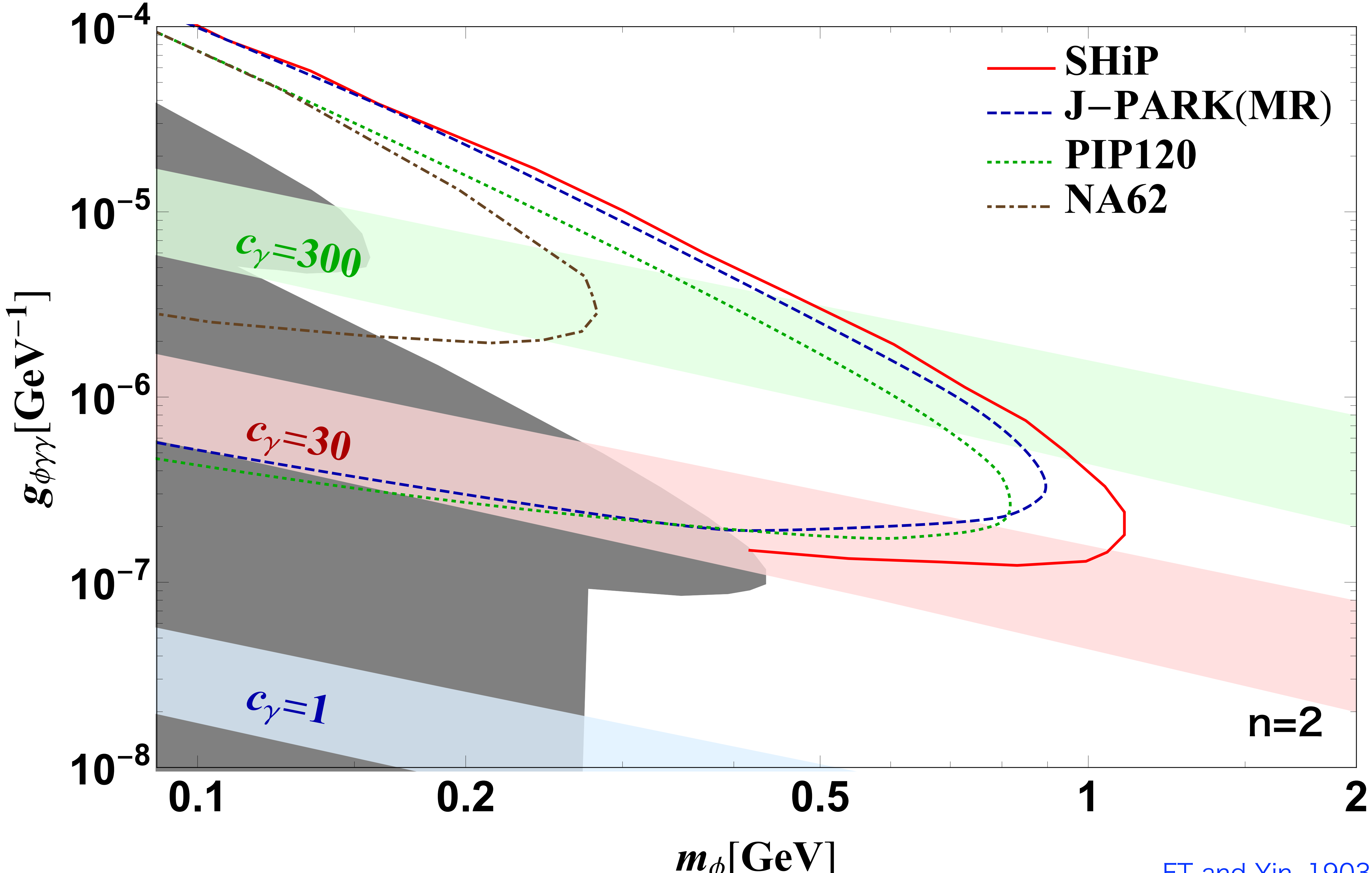
where the anomaly coefficient is related to charges of the extra fermions Ψ_i as

$$c_\gamma = \sum_i \underbrace{q_i}_{\text{PQ charge}} \underbrace{Q_i^2}_{\text{EM charge}}$$

$$\Psi_i \to e^{i\beta q_i \gamma_5/2} \Psi_i$$
$$\phi \to \phi + \beta f$$

The precise value of c_γ is model-dependent, and it can be of order 10^{-2} - 10^{2} without invoking a contrived set-up.

Parameter regions predicted by ALP inflation (with even n)

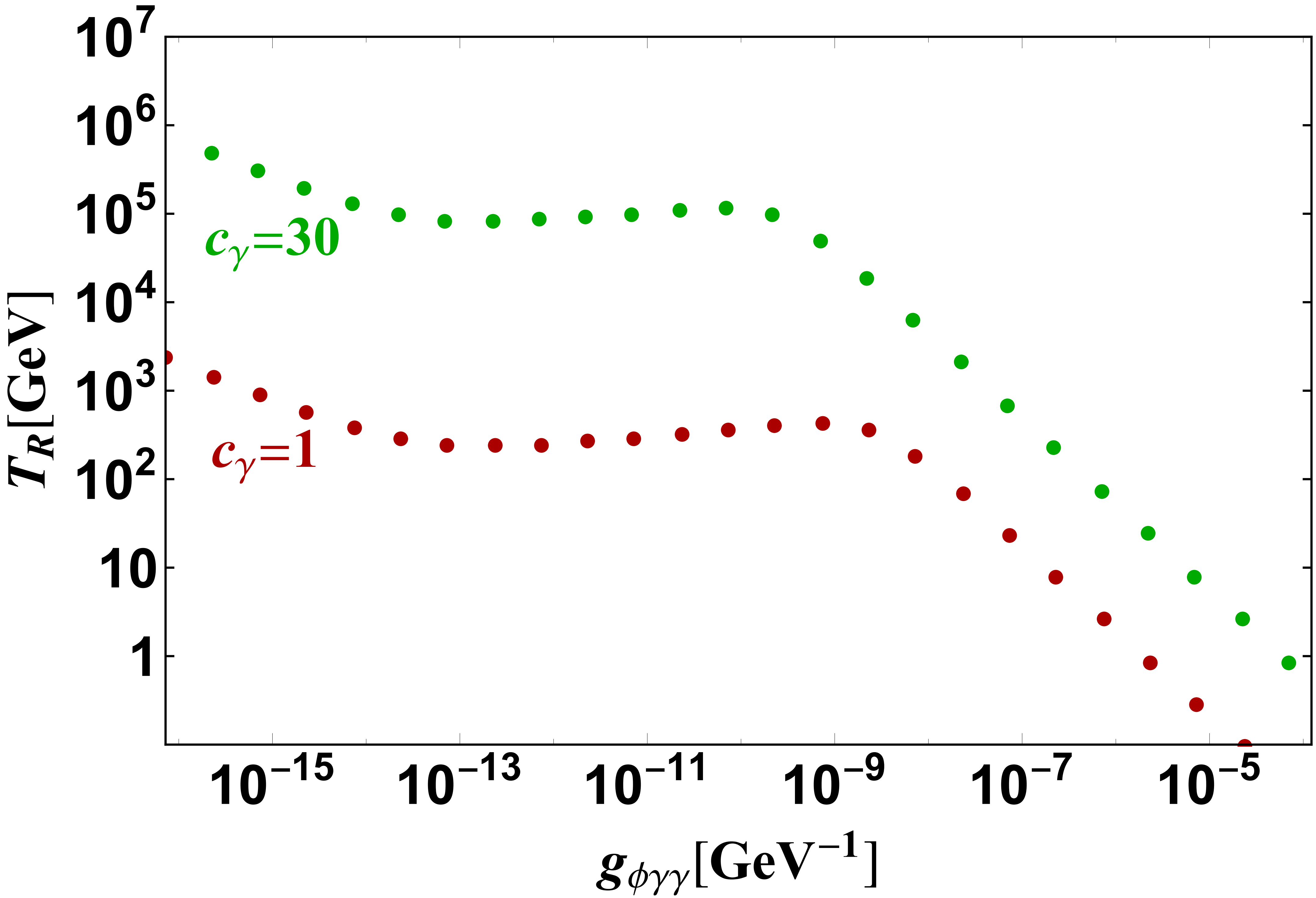


FT and Yin, 1903.00462,
Limits adopted from Harland-Land et al 1902.04878.

For $c_\gamma \gtrsim 10$, the predicted region overlaps with the SHiP sensitivity.

Reheating thru ALP-photon coupling

The ALP inflaton decays into photons, $\phi \to \gamma\gamma$, and also dissipate through scattering, e.g., $\phi + \gamma \to e^+ + e^-$.



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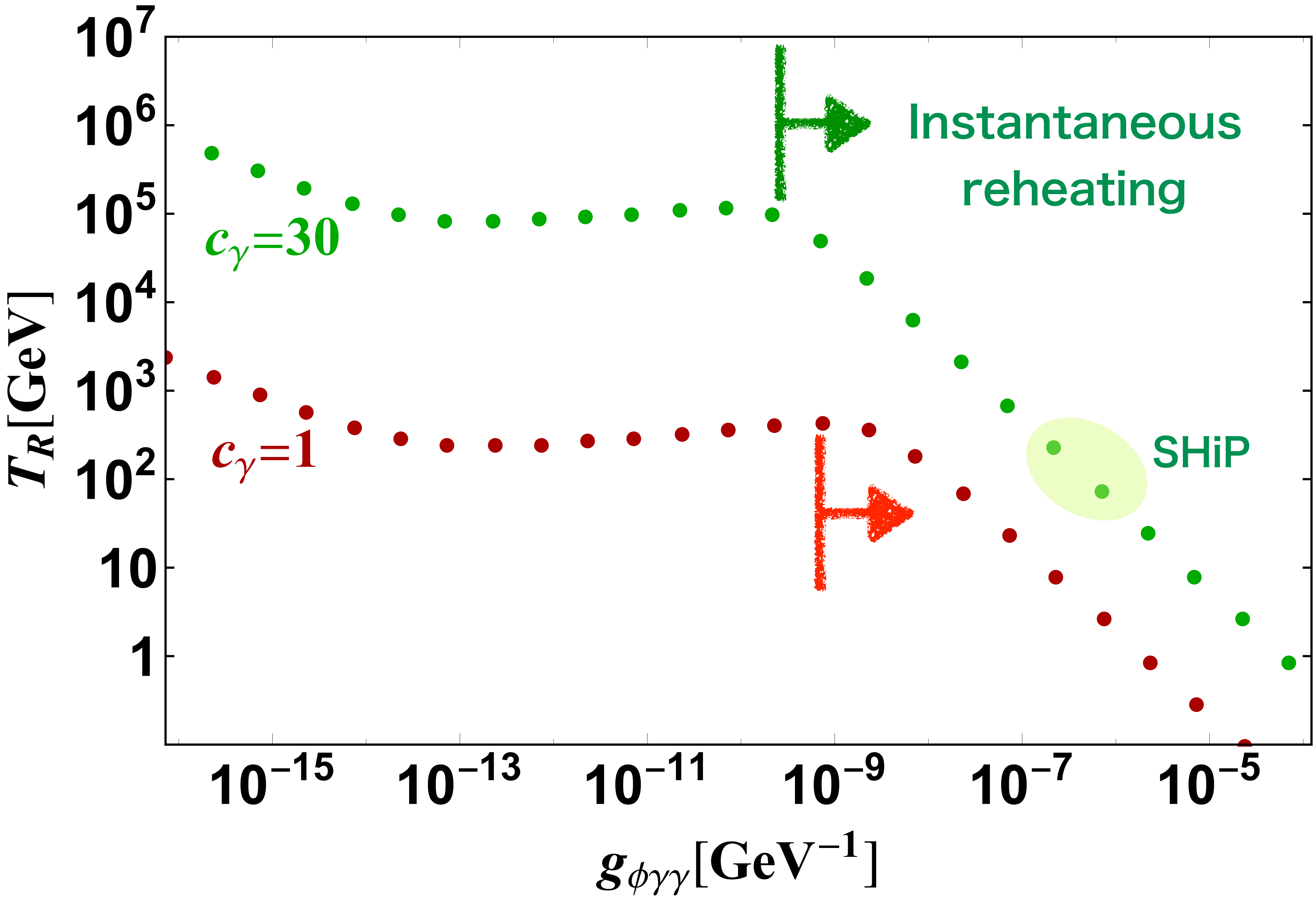


(2) Couplings to the SM fermions

$$\mathcal{L} = \sum_k i \frac{c_k m_k}{f} \phi \bar{\psi}_k \gamma_5 \psi_k \,,$$

Such couplings arise if we introduce two Higgs doublets as in the DFSZ axion model. After integrating out the heavy degrees of freedom, we obtain

$$H_1 = \underbrace{H}_{\text{SM Higgs}} \cos\beta \exp\left[i \overbrace{Q_{H_1}}^{\text{PQ charge}} \frac{\phi}{f} \right],$$

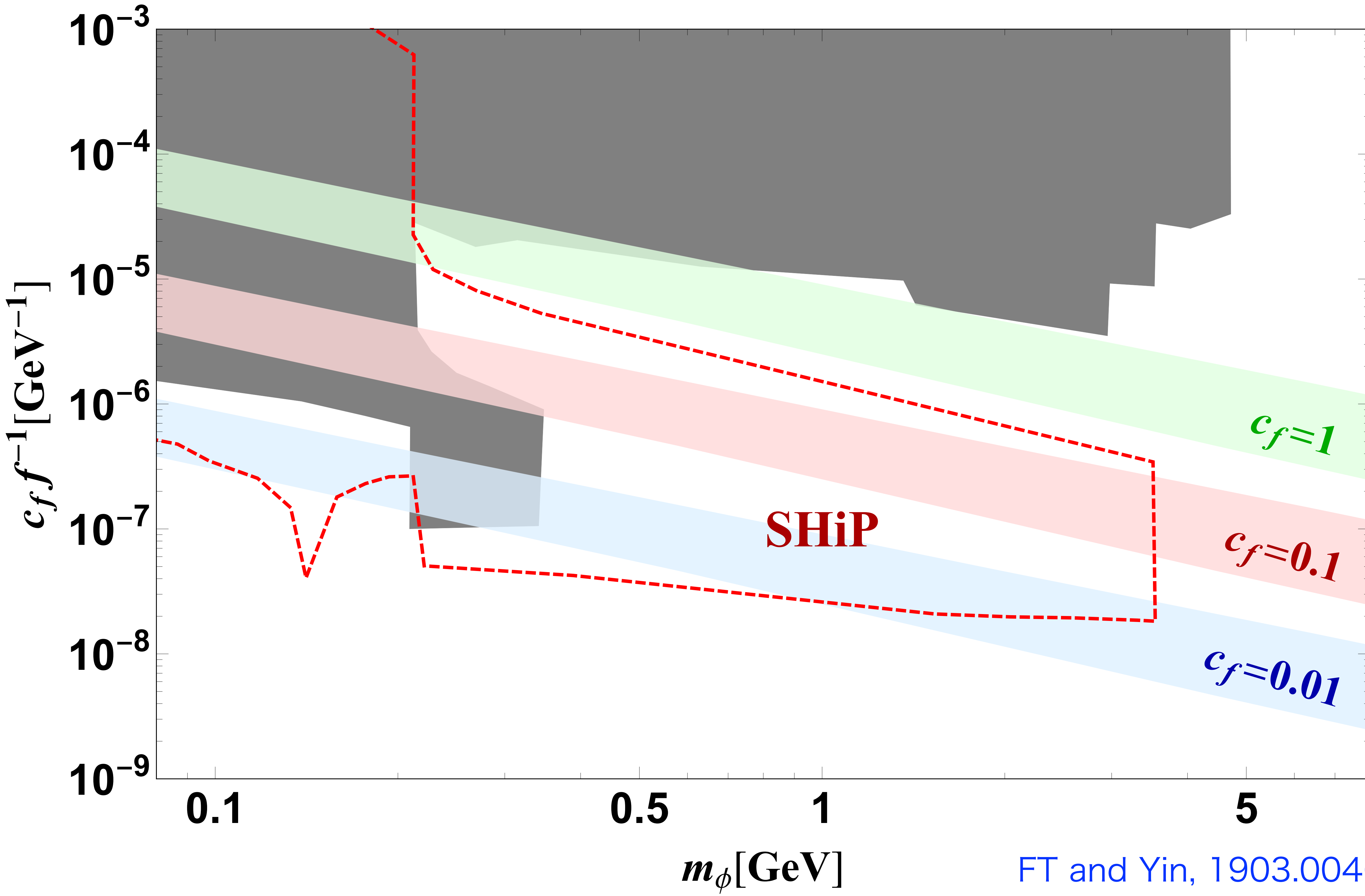
$$H_2 = \tilde{H} \sin\beta \exp\left[i Q_{H_2} \frac{\phi}{f} \right],$$

$$\tan\beta \equiv \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle}$$

$$\Rightarrow \quad c_i = Q_{H_1} \text{ or } \; Q_{H_2}$$

(i.e. PQ charge of the Higgs that it is coupled to.)

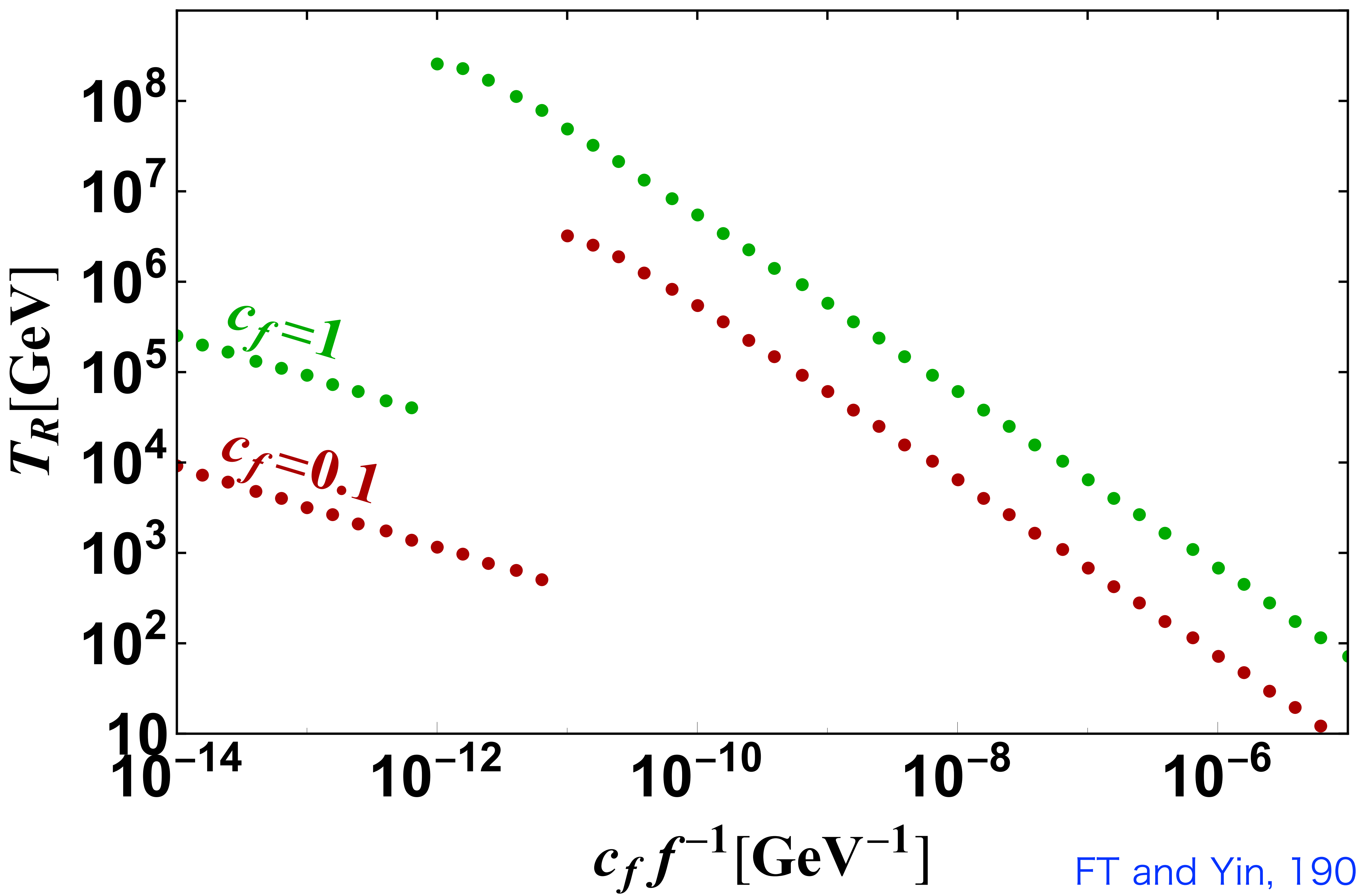
In the case that the inflaton has (universal) Yukawa-like interactions, i.e., $c_i = c_f$



FT and Yin, 1903.00462

Reheating thru Yukawa-like couplings

The ALP inflaton decays into the SM fermions (+Higgs if kinematically allowed), and dissipate through thermalscattering.



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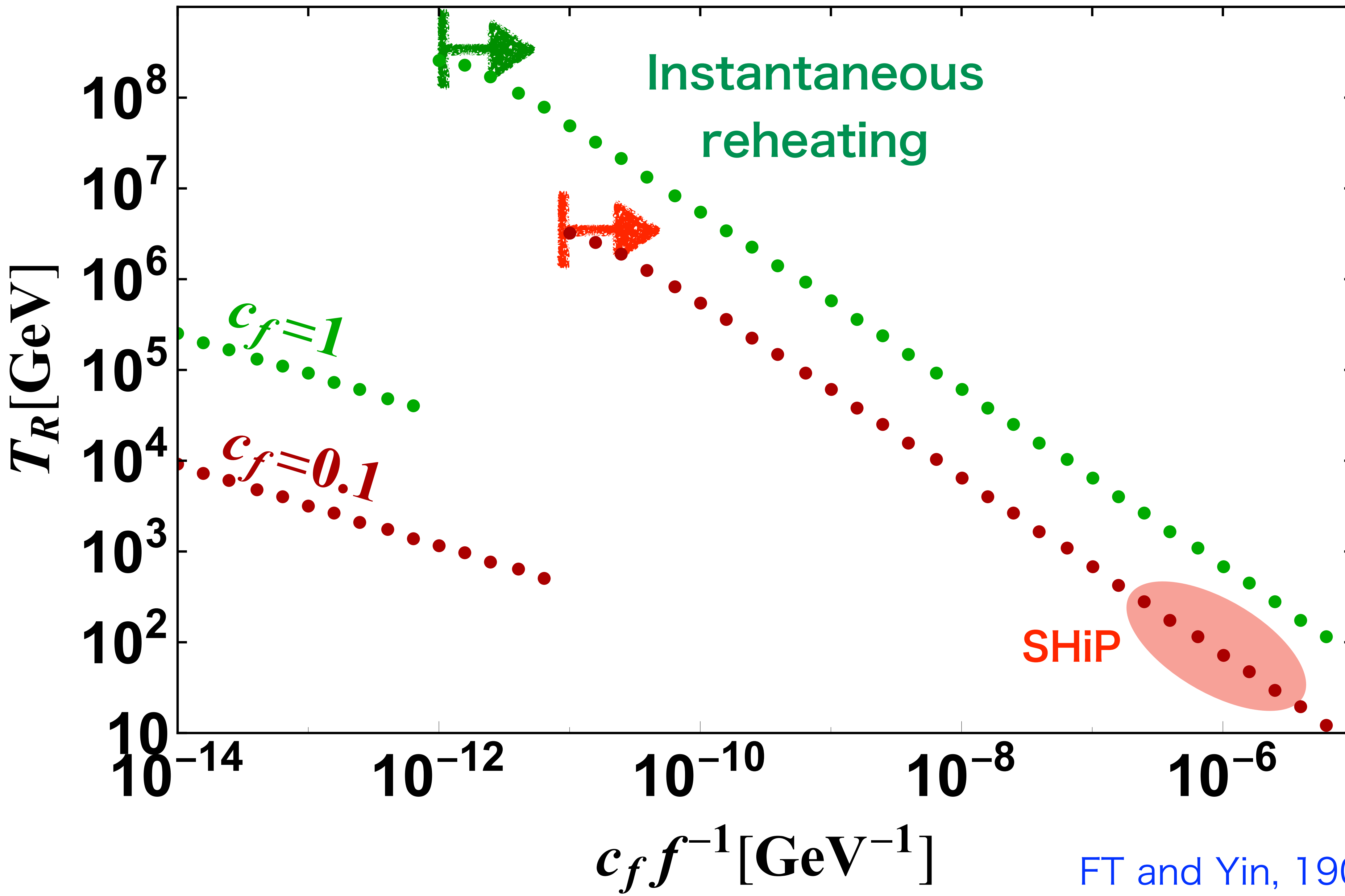
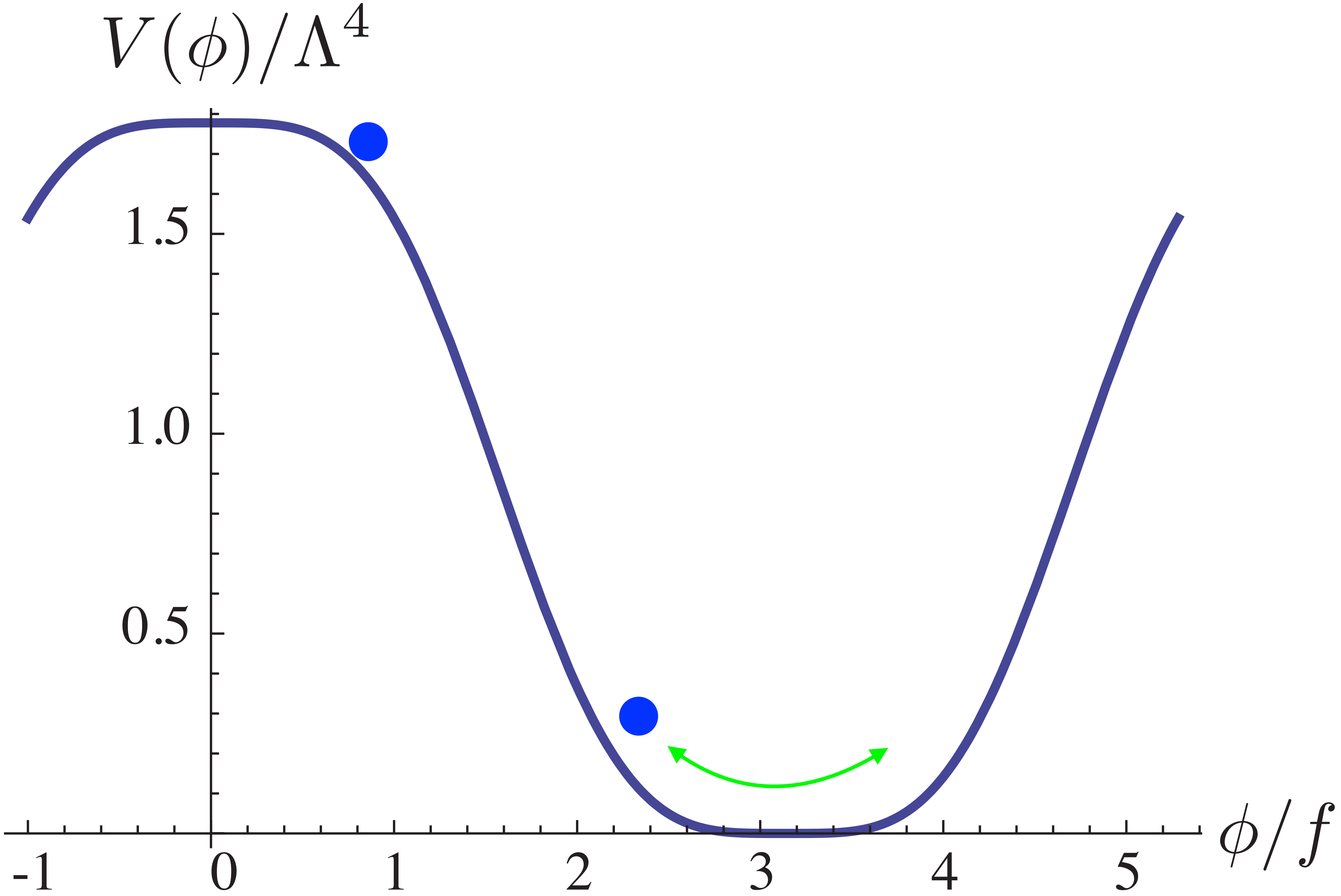


FT and Yin, 1903.00462

The case of odd n



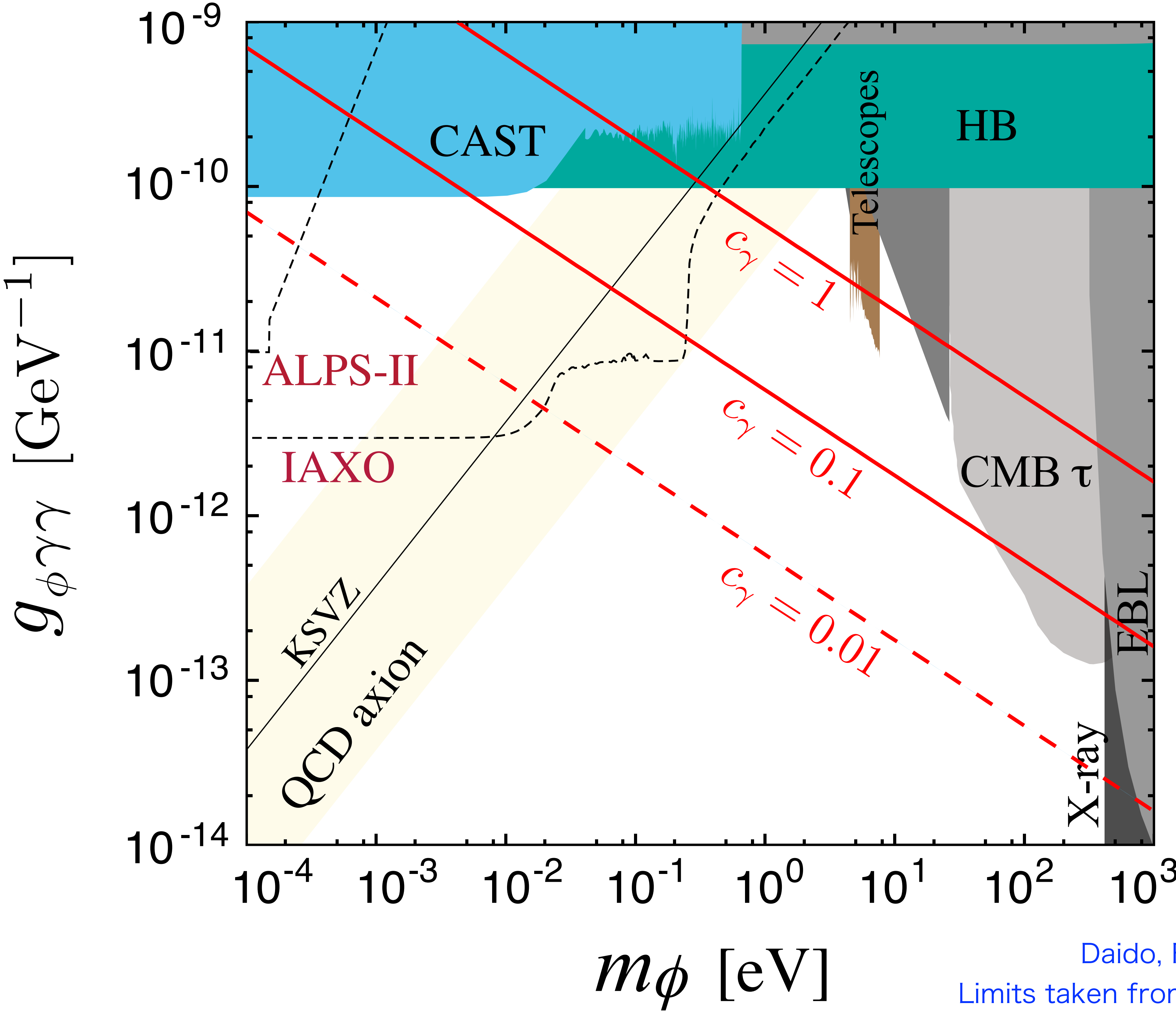
- Inflaton (ALP) mass and coupling to photons

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

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

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

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



Daido, FT, and Yin 1702.03284

Limits taken from Essig et al 1311.0029

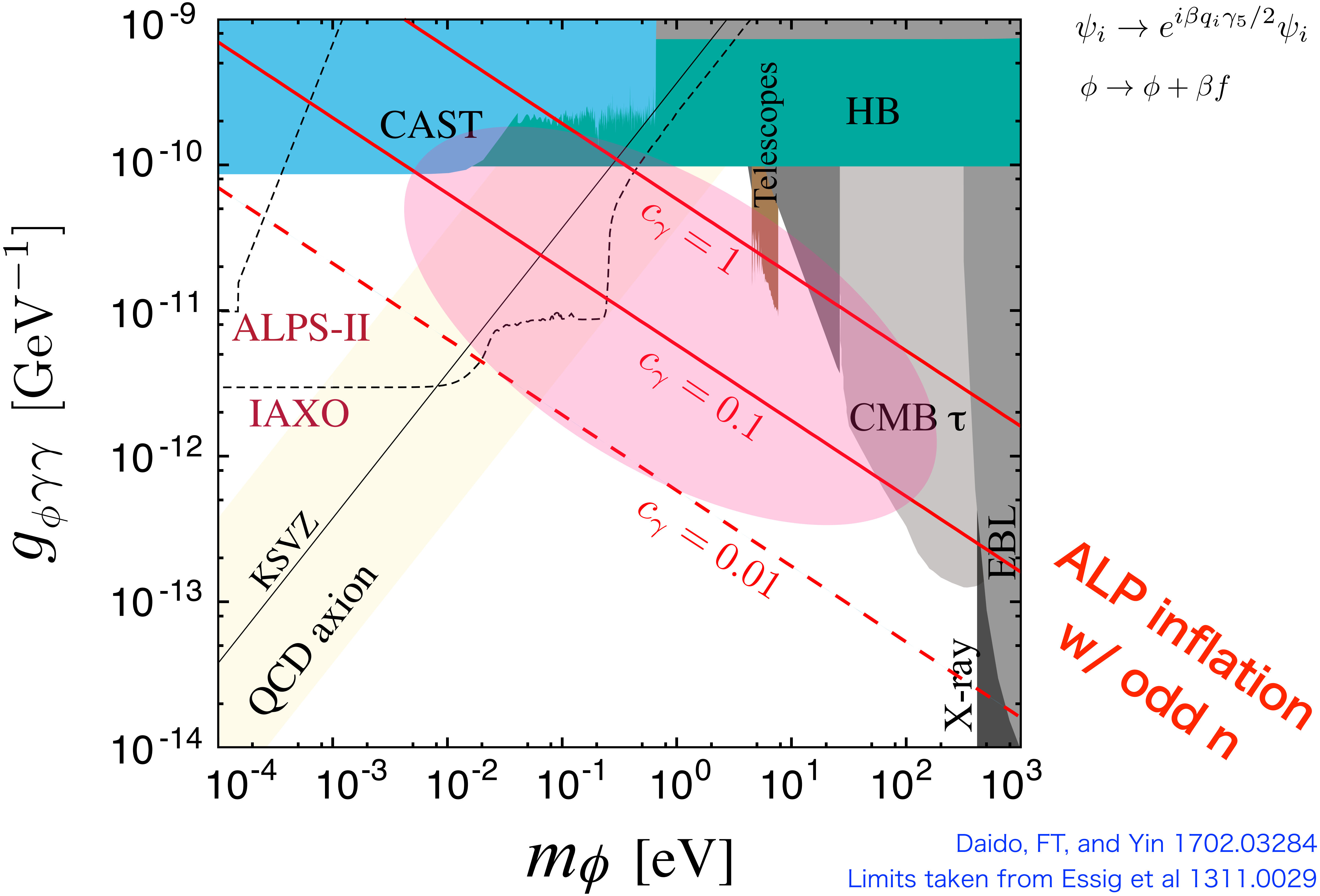
•Inflaton (ALP) mass and coupling to photons

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

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

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

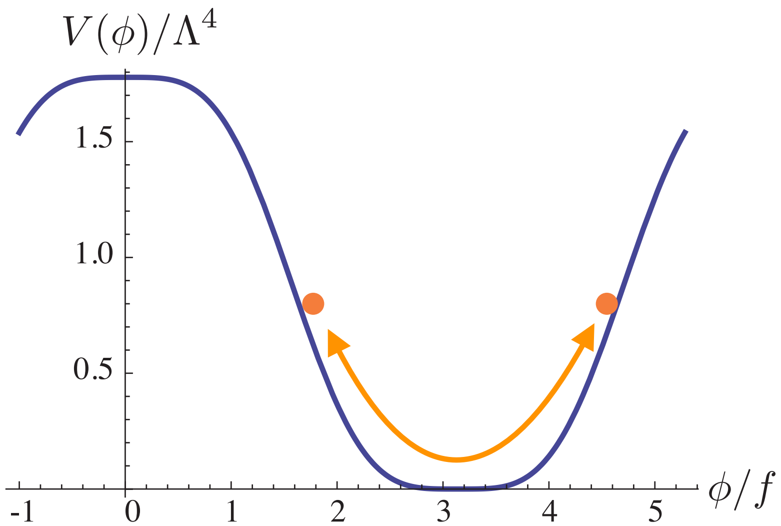
$$\phi \to \phi + \beta f$$



Daido, FT, and Yin 1702.03284

Limits taken from Essig et al 1311.0029

Reheating and ALP DM



Inflaton (ALP) condensate

Decay & dissipation → Photons, SM particles

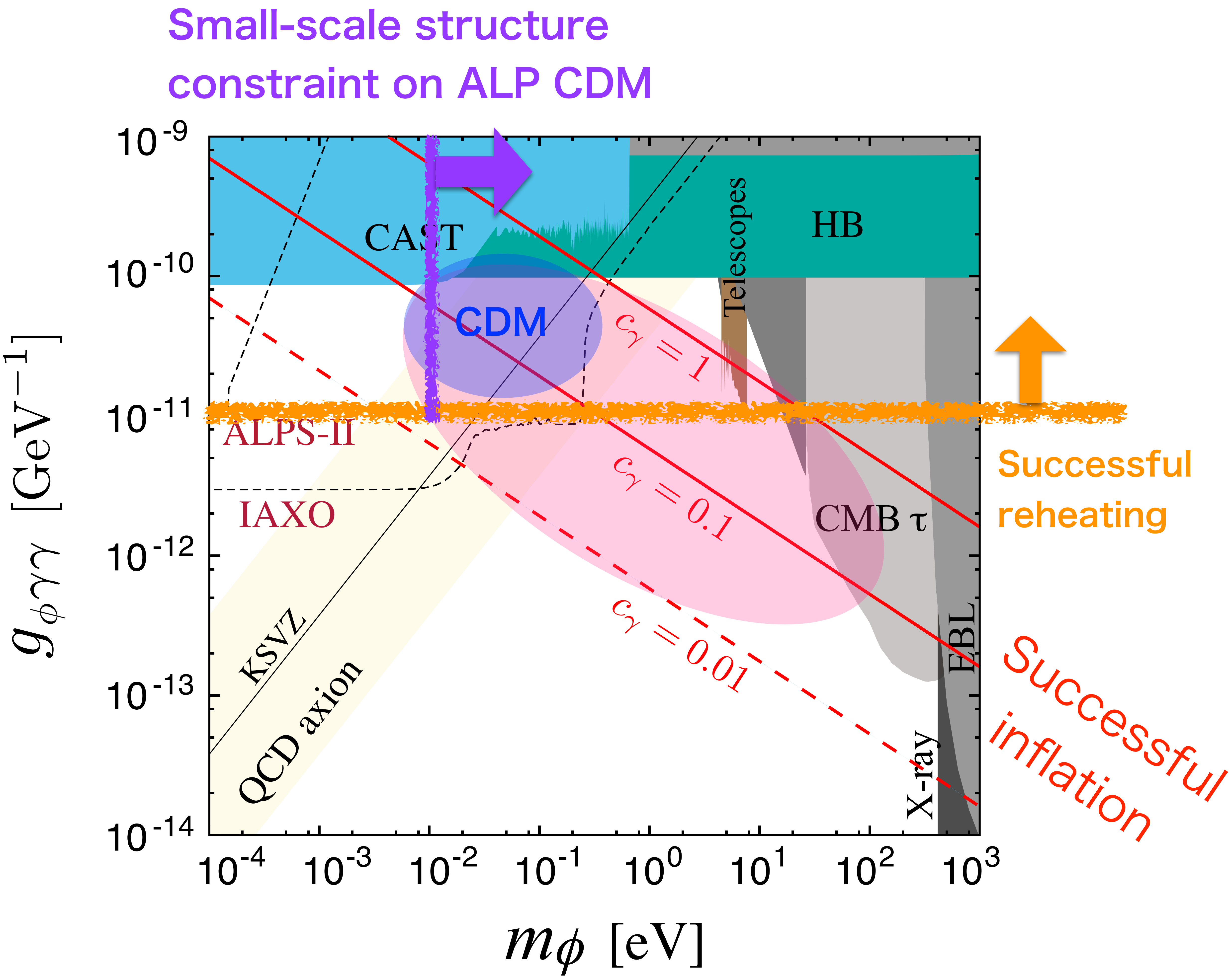
Thermalized → ALP Dark Radiation or HDM

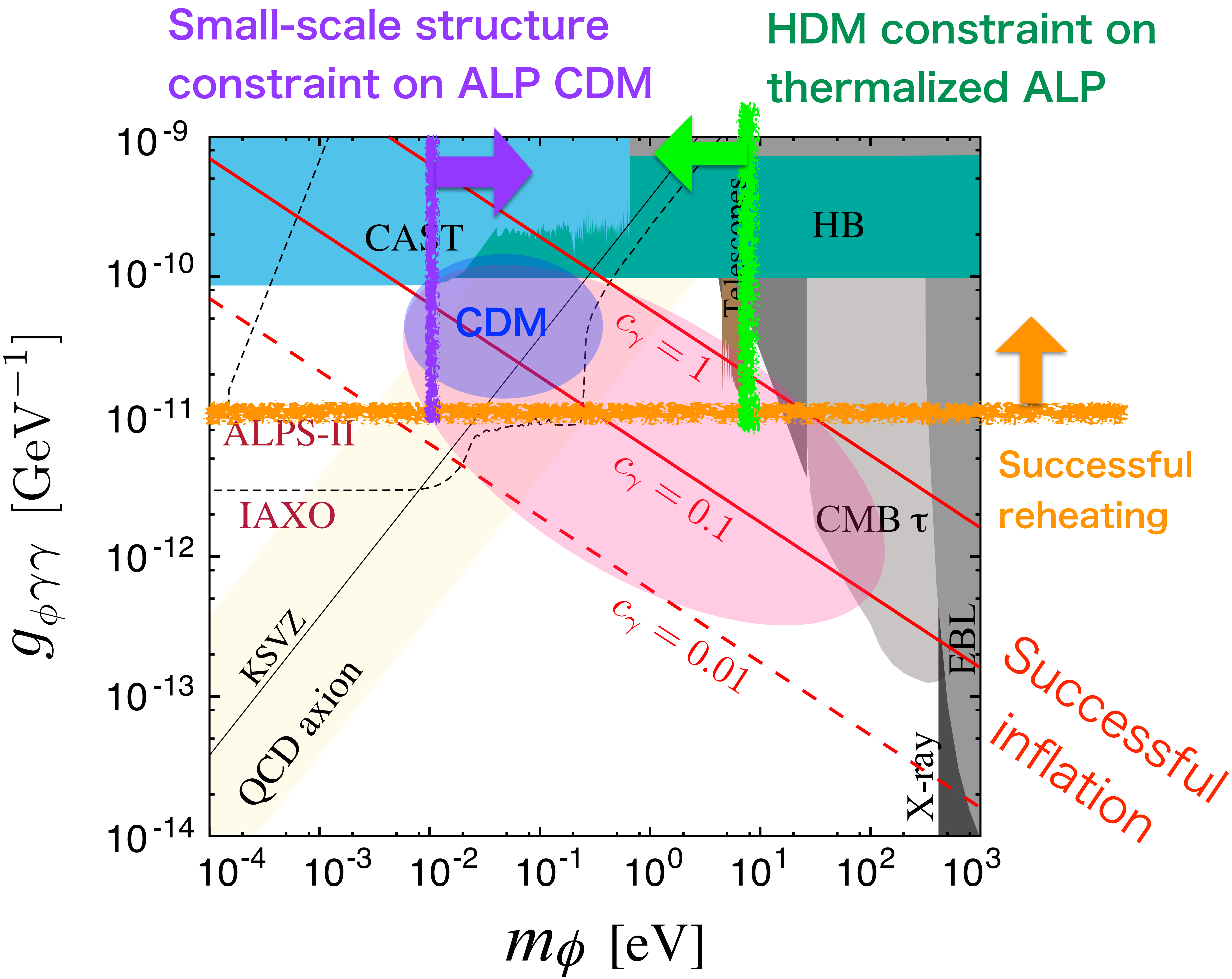
Remnant → ALP Dark Matter

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

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

As we shall see, $\xi = \mathcal{O}(0.01)$ is required to explain DM.


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
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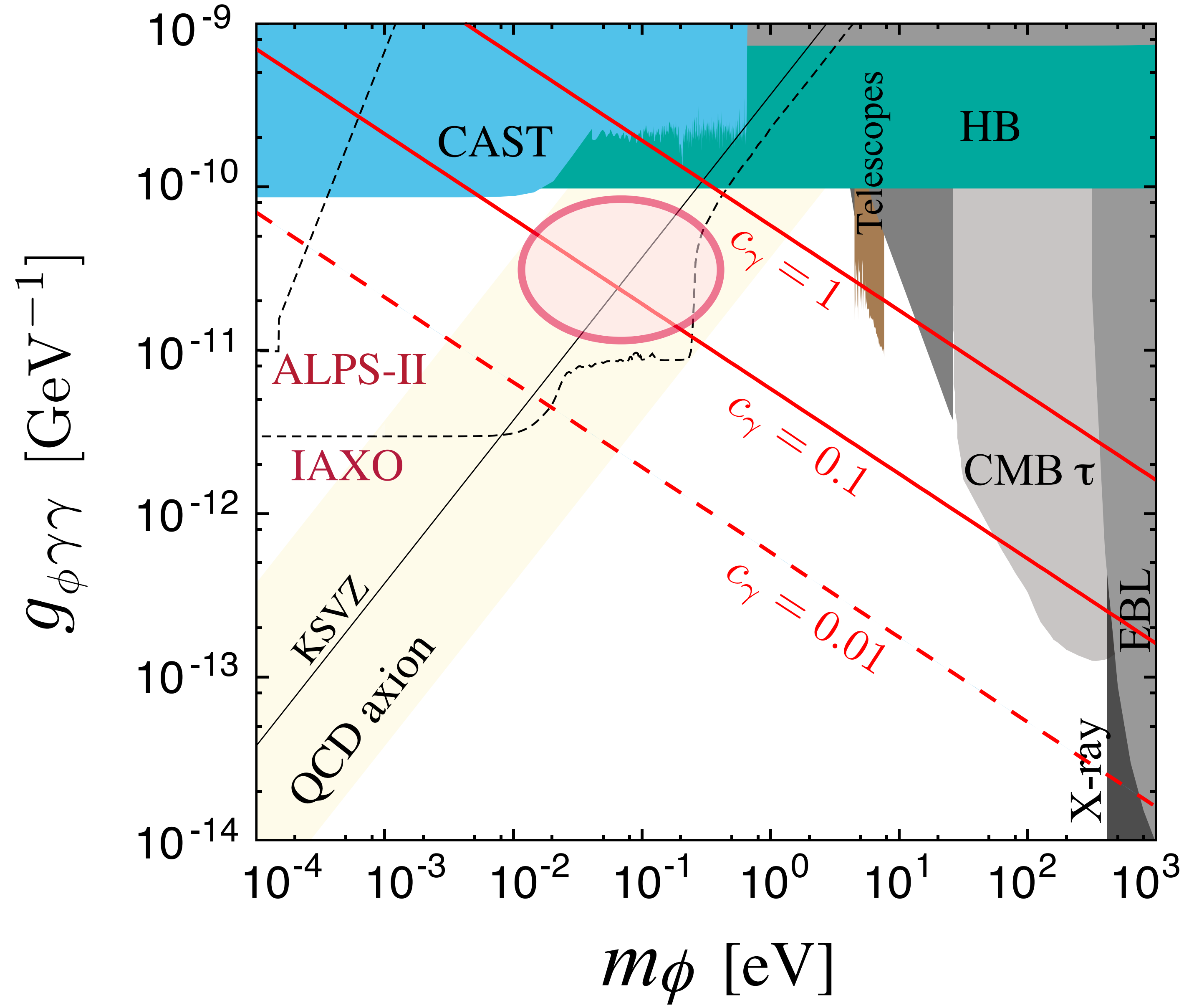
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Inflaton = DM = ALP

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

within the reach of future axion helioscopes and laser experiments.



"An ALP miracle"

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

$$g_{\phi\gamma\gamma} = (0.29 \pm 0.18) \times 10^{-10}\,\mathrm{GeV}^{-1}$$

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

Summary

- Inflaton may be searched for at experiments, if the inflaton is an NG boson with sizable couplings to SM.

- The predicted relations between the mass and decay constant are

Even n

$$f \sim 10^6 m_\phi$$

- **SHiP (beam dump exp. at CERN)**

$$m_\phi = O(0.1 - 1)\,\mathrm{GeV}$$

- **The decay of the axion is same as the reheating!**

"Big Bang on Earth"

Odd n

$$f \sim 10^3 \sqrt{m_\phi M_p}$$

- **IAXO/TASTE (Solar axion search)**

$$m_\phi = O(0.01 - 1)\,\mathrm{eV}$$

- **The remnant inflaton can be DM. "ALP miracle"**
- **Dark radiation with** $\Delta N_{\rm eff} \simeq 0.03$