The ALP miracle: unified inflaton and DM

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1702.03284
1710.11107

Outline

Part1: アクシオンのレビュー

アクシオンとは？

アクシオン探索の現状

Part2: The ALP miracle

イントロダクション

インフレーション

再加熱と暗黒物質

まとめ

Strong CP problem

標準模型の強い相互作用のラグランジアンにはθ 項が存在する。

$$\mathcal{L} \supset \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

~~CP~~ ~~P~~

θ :パラメータ　$G^a_{\mu\nu}$:グルーオン場　$\tilde{G}^a_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} G^{a\rho\sigma}$

中性子の電気双極子モーメントの測定によって θパラメータの大きさに強い制限がついている。

$$|\theta| \lesssim 10^{-10}$$

Baker et al. 2006

なぜこんなにθ は小さい？

Axion

$U(1)_{\rm PQ}$ 対称性を課す（$U(1)_{\rm PQ}\, SU(3)^2$ anomaly）　Peccei, Quinn　1977

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

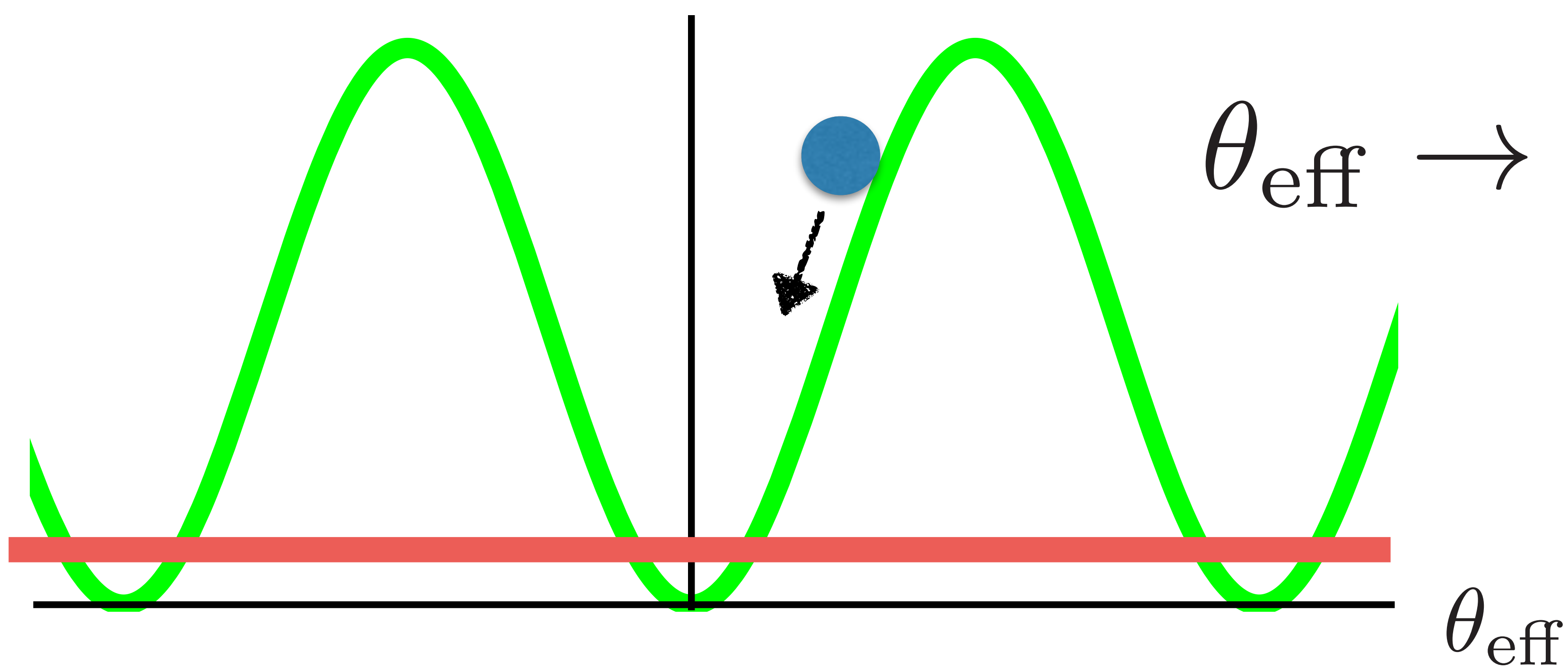
$= \theta_{\rm eff}$

a : 擬NGボソン＝アクシオン

F_a: 崩壊定数

（〜対称性の破れのスケール）

$$V = const \quad \Rightarrow \quad V \simeq \Lambda^4 \left[1 - \cos\left(\frac{a}{F_a}\right)\right]$$



ダイナミカルにstrong CP問題を解決できる

Axion

特徴

・非摂動的な効果により周期的なポテンシャルを持つ。

$$V \simeq \Lambda^4 \left[1 - \cos\left(\frac{a}{F_a}\right)\right]$$

・２つのパラメータで特徴付けられる。

崩壊定数: F_a　　質量: $m_a \equiv \frac{\Lambda^2}{F_a}$

e.g.

- QCDアクシオン（1パラメータ）

O. Wantz, E. P. S. Shellard 2009

$$m_a(T) = \begin{cases} 4.05 \times 10^{-4} \frac{\Lambda_{\rm QCD}^2}{F_a} \left(\frac{T}{\Lambda_{\rm QCD}}\right)^{-3.34} & T > 0.26\Lambda_{\rm QCD} \\ 3.82 \times 10^{-2} \frac{\Lambda_{\rm QCD}^2}{F_a} & T < 0.26\Lambda_{\rm QCD} \end{cases}$$

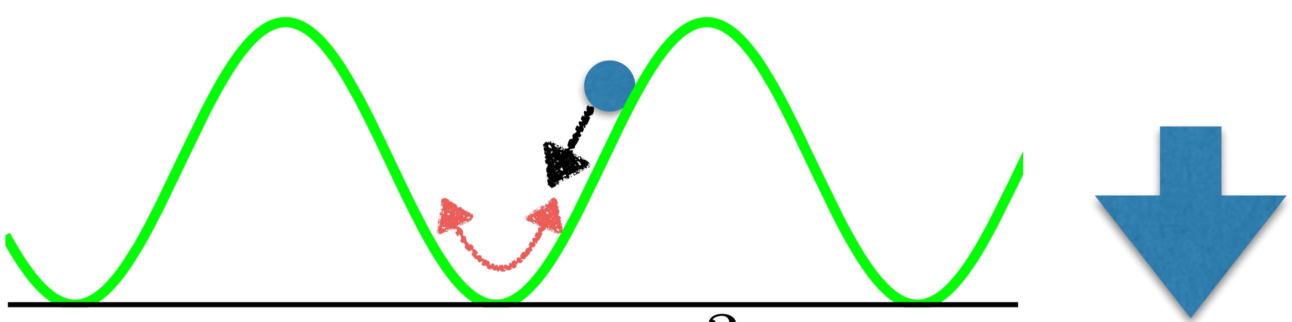
$\Lambda_{\rm QCD} = \mathcal{O}(100)\,\mathrm{MeV}$

- ストリングアクシオン

Axion Dark Matter

・アクシオンは他の粒子とほとんど相互作用せず、かつ非常に軽いので宇宙年齢より長い寿命を持つ。

・ポテンシャルを振動するスカラー場は、非相対論的粒子として振る舞う



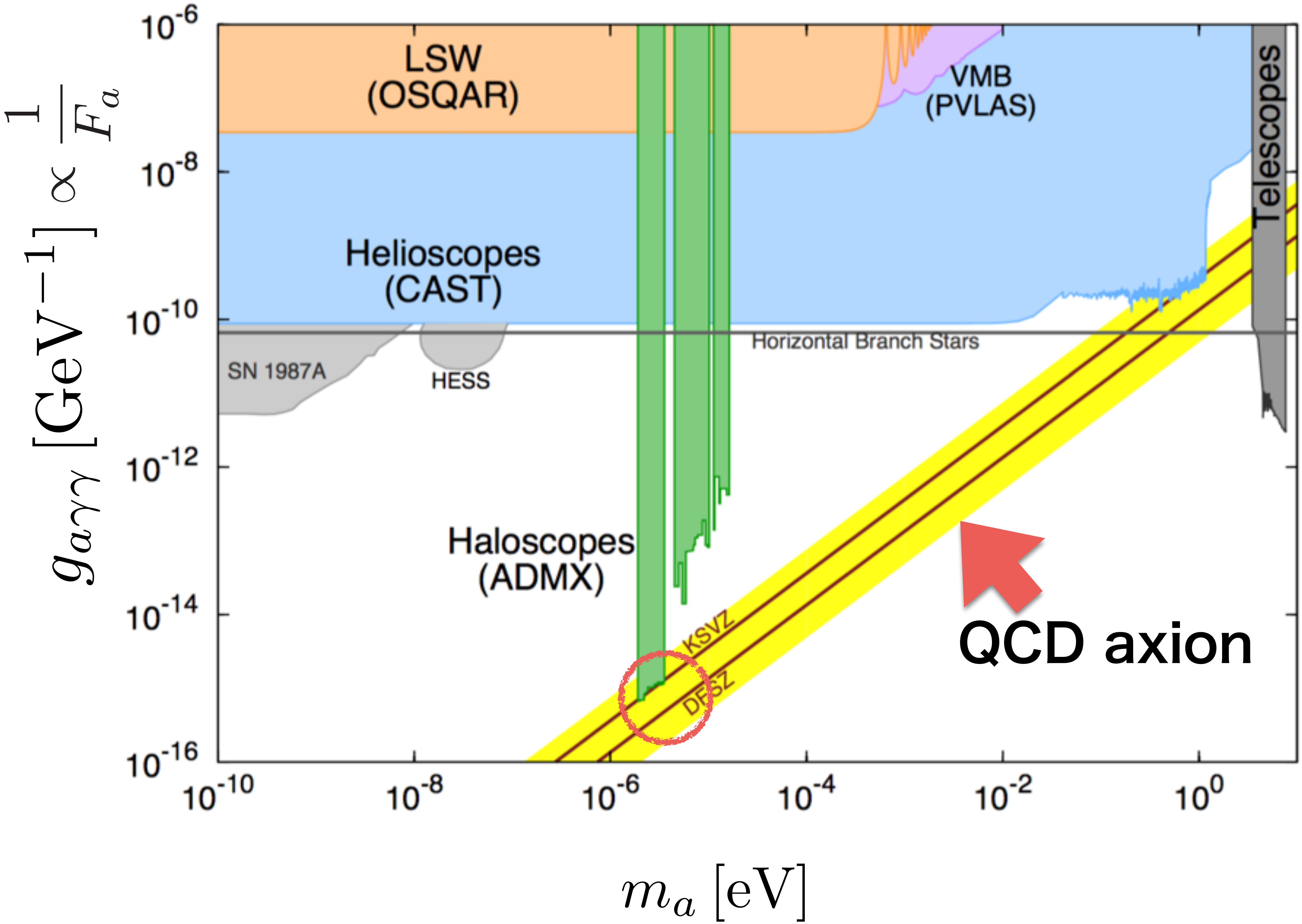
$$\rho_a \propto R^{-3}$$

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

アクシオンは暗黒物質に寄与する。

QCD axion $$\Omega_a h^2 \simeq 0.18\,\theta_i^2 \left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{\mathrm{QCD}}}{400\,\mathrm{MeV}}\right)$$

ALP $$\Omega_{\mathrm{ALP}} h^2 \simeq 0.50\,\theta_i^2 \left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{2} \left(\frac{m_a}{0.01\,\mathrm{eV}}\right)^{1/2}$$



LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes
(CAST)
Horizontal Branch Stars
SN 1987A
HESS
Haloscopes
(ADMX)
KSVZ
DFSZ
QCD axion
$g_{a\gamma\gamma}\,[\mathrm{GeV}^{-1}] \propto \frac{1}{F_a}$
$m_a\,[\mathrm{eV}]$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

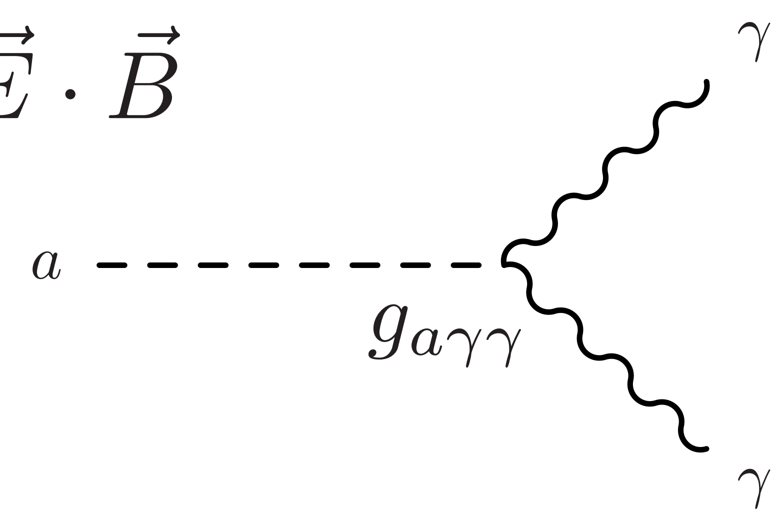
Axion Coupling

アクシオンは一般に光子や電子、核子に結合する。

光子

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\vec{E}\cdot\vec{B}$$

$$g_{a\gamma\gamma} \equiv \frac{c_\gamma \alpha}{\pi F_a} \sim 10^{-3}\frac{c_\gamma}{F_a}$$



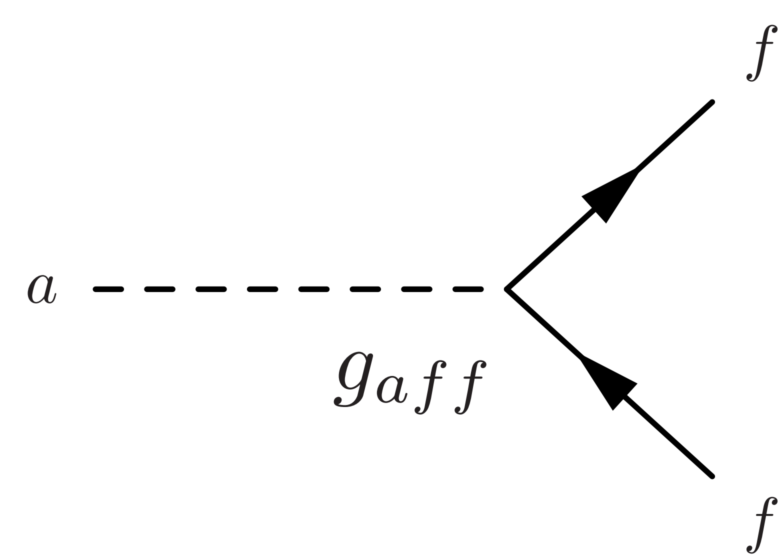
電子、核子

$$\mathcal{L}_{aff} = -i g_{aff} a \bar{\Psi}_f \gamma_5 \Psi_f$$

$$g_{aee} \equiv \frac{c_e m_e}{F_a} \sim 10^{-3}\frac{c_e}{F_a/\mathrm{GeV}}$$

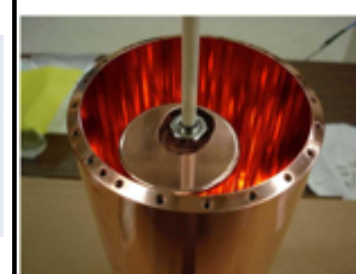
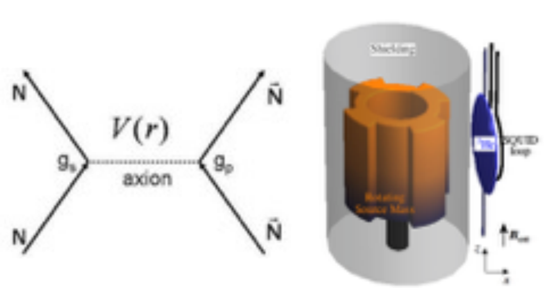
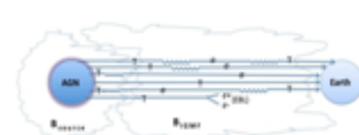
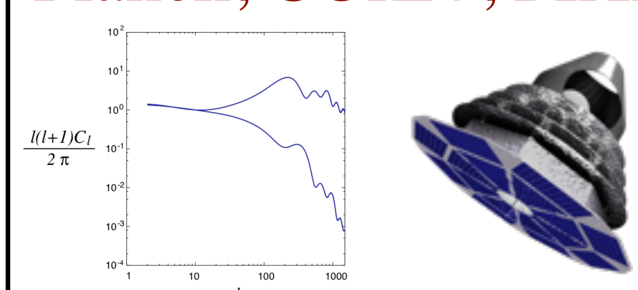
$$g_{aNN} \equiv \frac{c_N m_N}{F_a} \sim \frac{c_N}{F_a/\mathrm{GeV}}$$

$$N = p, n$$



アクシオン探索

from F. Takahashi's slide

		生成過程		
		地上	天体起源	初期宇宙
検出方法	直接	LSTW, Photon pol. ALPS,OSQAR, PVLAS, 	Solar axion CAST, IAXO,TASTE  	Axion DM ADMX, CAPP,ORPHEUS LC-circuits, CASPEr, XMASS, EDELWISE,XENON100.  
	間接	Fifth force ARIADNE 	Excessive cooling of WD, RGB, HB, NS Spectral irreg. Transparency Fermi, IACT. 	Isocurvature, DR, spectral distortion, caustics, GW, etc. Planck, COrE+, PIXIE 

Axion and Astrophysics

星の中のプラズマ（光子、電子など）から生成されたアクシオンは、
外へとエネルギーを持ち出し、冷却剤としてはたらく。

➡ 相互作用の大きさに上限がつく

$m_a \lesssim \mathrm{few} \times 10\,\mathrm{keV}$のアクシオンに対して

・**Horizontal Branch stars**

$$g_{a\gamma\gamma} < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

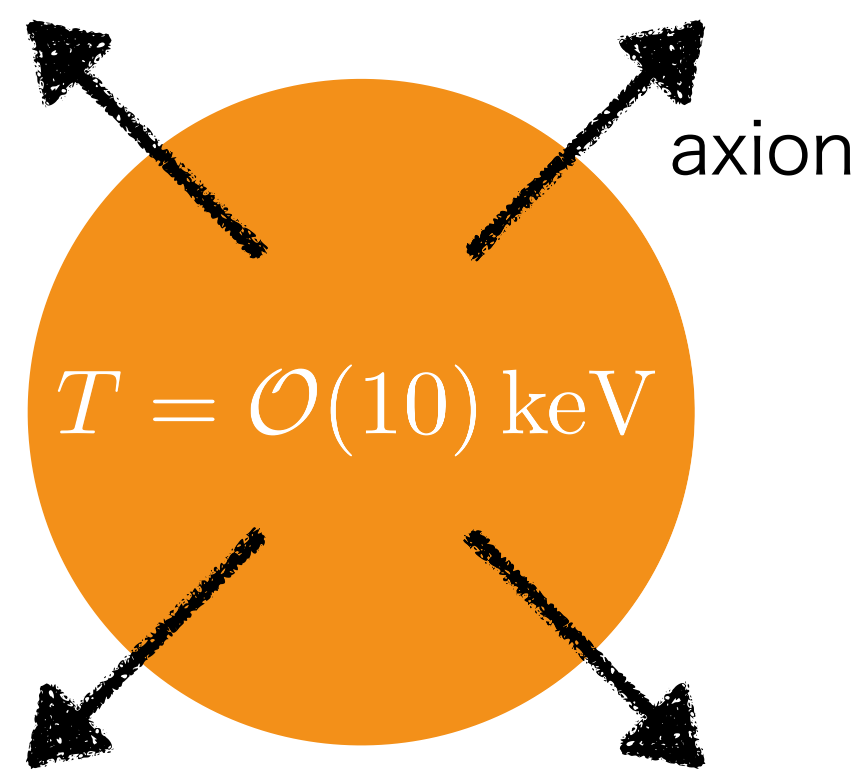
$$F_a \gtrsim 3c_\gamma \times 10^7\mathrm{GeV}$$

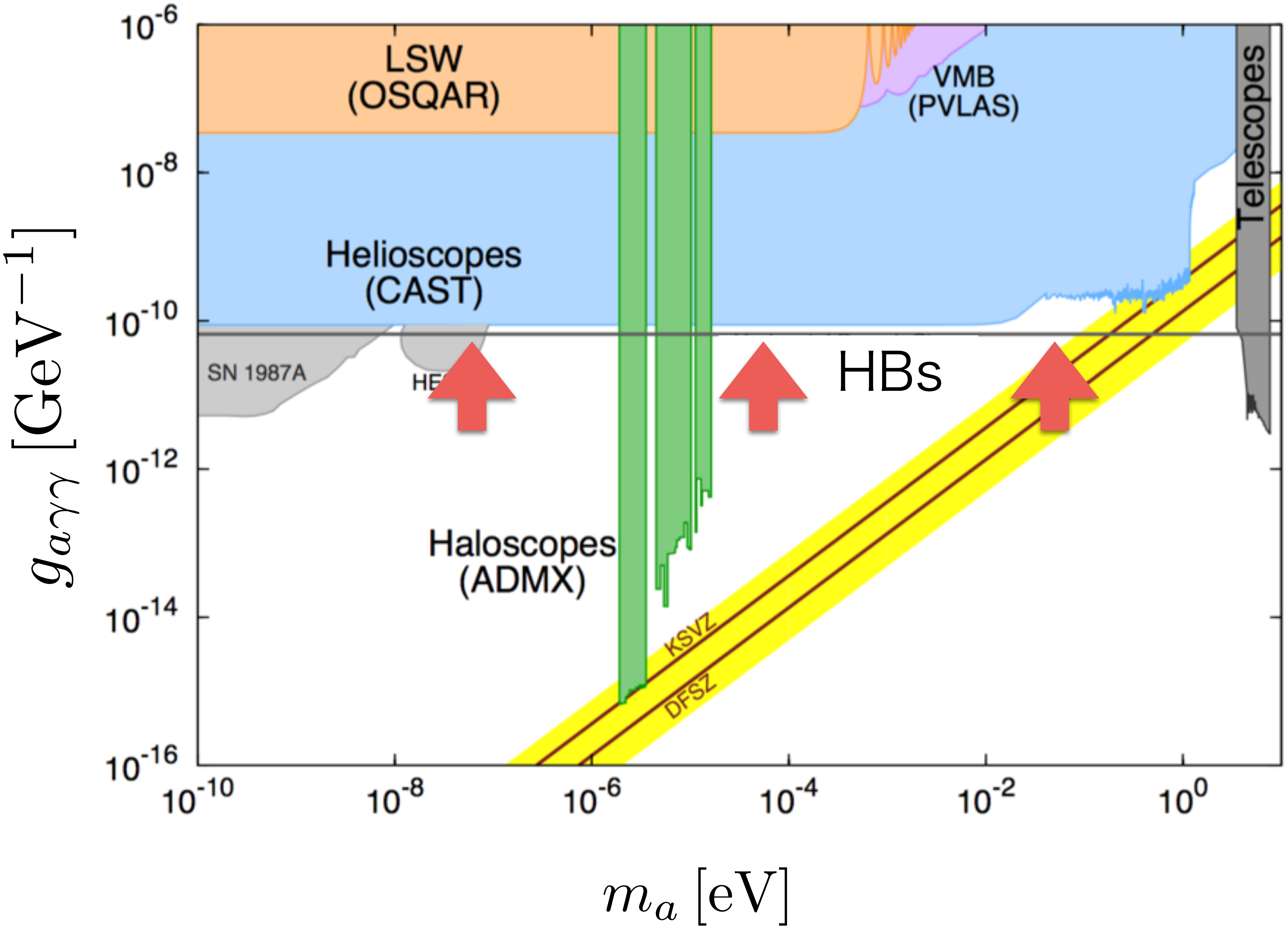
・**Red Giants**

$$g_{aee} < 4.3 \times 10^{-13}$$

$$F_a \gtrsim c_e \times 10^9\,\mathrm{GeV}$$

PDG 2016





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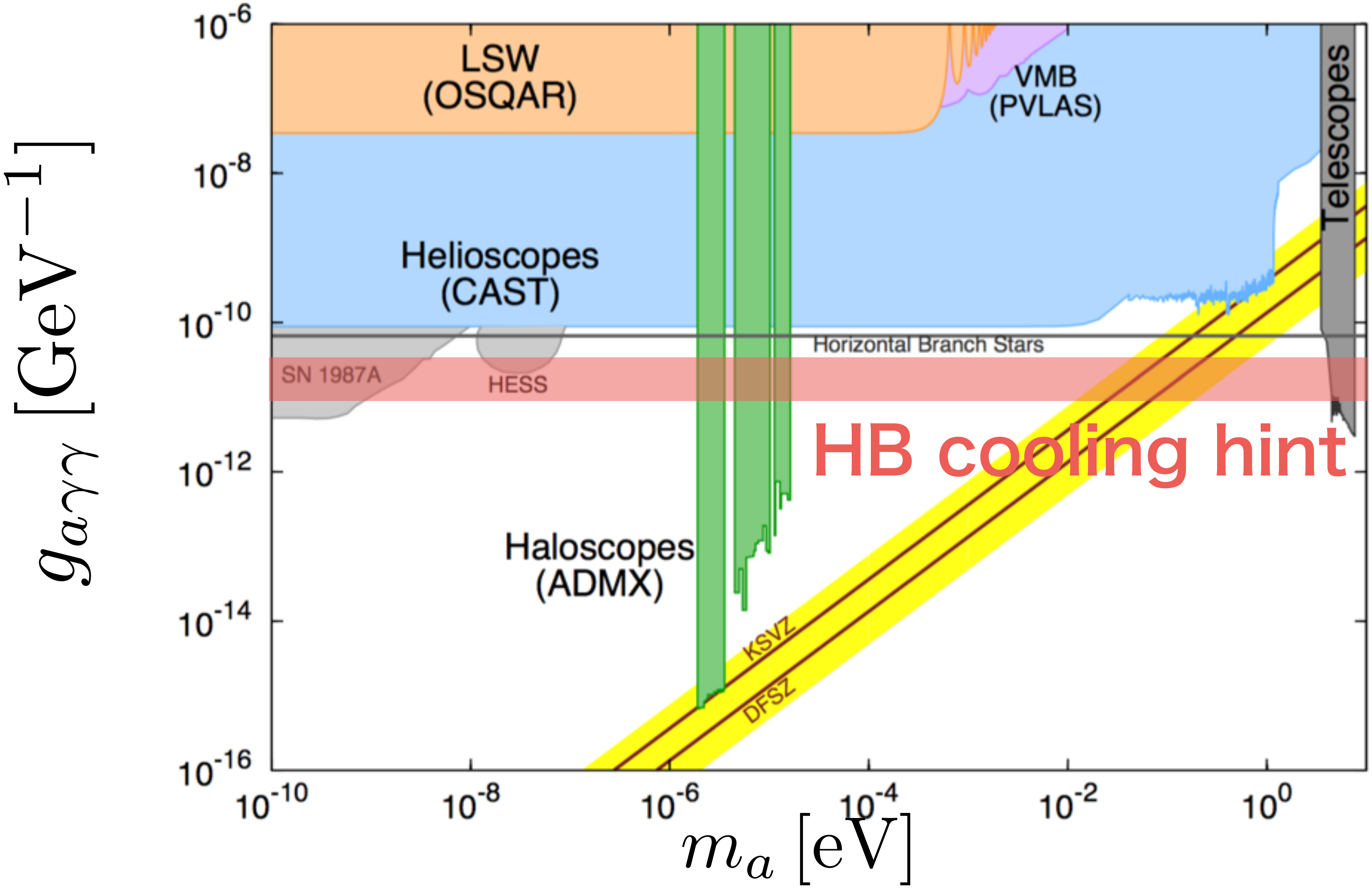
KSVZ
DFSZ
$g_{a\gamma\gamma}\,[\mathrm{GeV}^{-1}]$
$m_a\,[\mathrm{eV}]$

Cooling Hints?

いくつかの星の進化の過程において、冷却が足りていないというアノマリーが指摘されている。

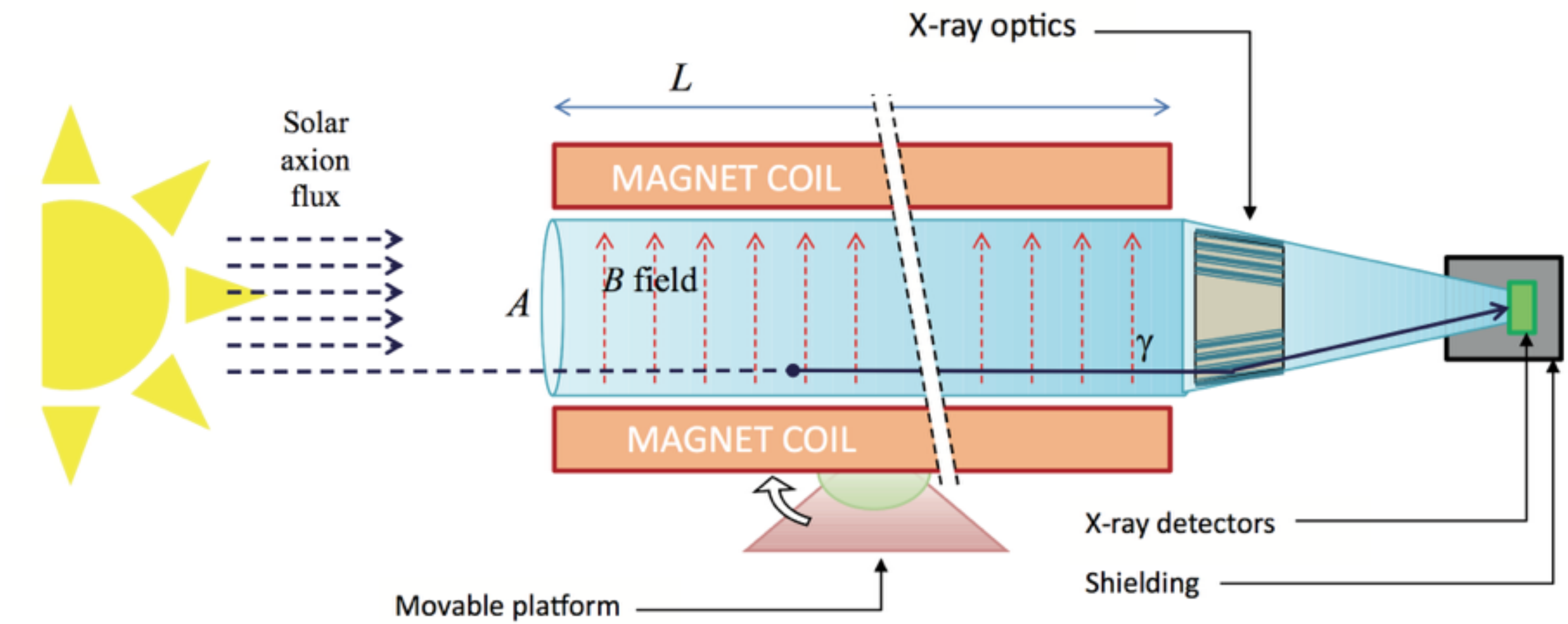
e.g. HB: $g_{a\gamma\gamma} = (0.29 \pm 0.18) \times 10^{-10}\,\mathrm{GeV}^{-1}$

Gianotti et al. 2015



Solar axion search

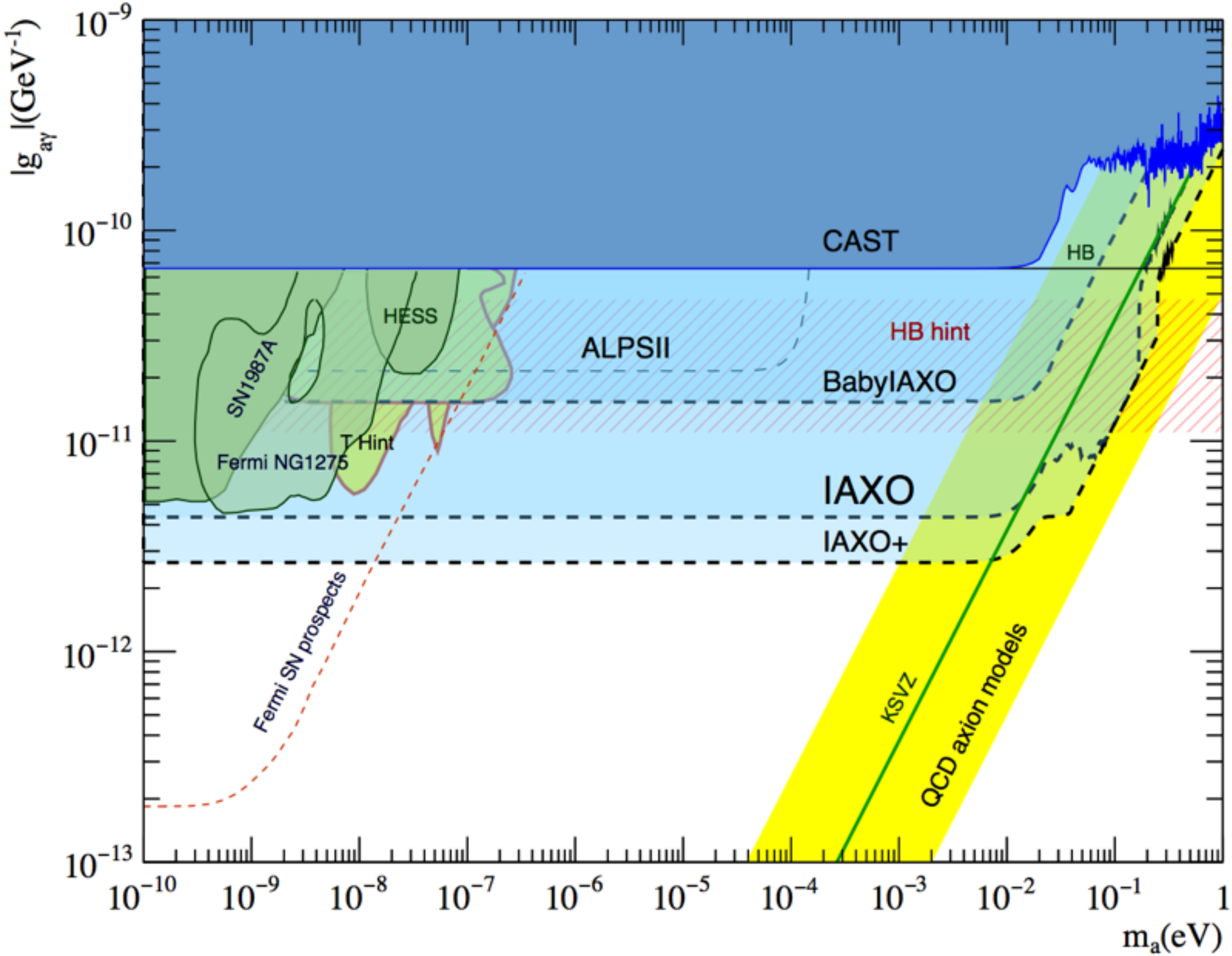
天体起源のアクシオンの直接探索としては、太陽アクシオン探索がある。（CAST, IAXO）



CAST bound

$$g_{a\gamma\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$$

CAST collaboration 2017



次の世代の太陽アクシオン探索実験（IAXO）は、現在より1桁ほど感度が良くなる！

Part1 Summary

・アクシオンは、strong CP問題や暗黒物質の物理と関連している。

・アクシオンは、光子や電子と結合し、星の進化に大きく影響を及ぼす。

$$g_{a\gamma\gamma} < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$$
$$F_a \gtrsim 3c_\gamma \times 10^7\mathrm{GeV}$$

$$g_{aee} < 4.3 \times 10^{-13}$$
$$F_a \gtrsim c_e \times 10^9\,\mathrm{GeV}$$

・星の進化においてアノマリーが指摘されていて、アクシオンによって解決できる可能性がある。

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

・太陽アクシオン探索からは、間接探索と同じくらいの制限が得られていて、次の世代の実験では１桁ほど感度が良くなる。

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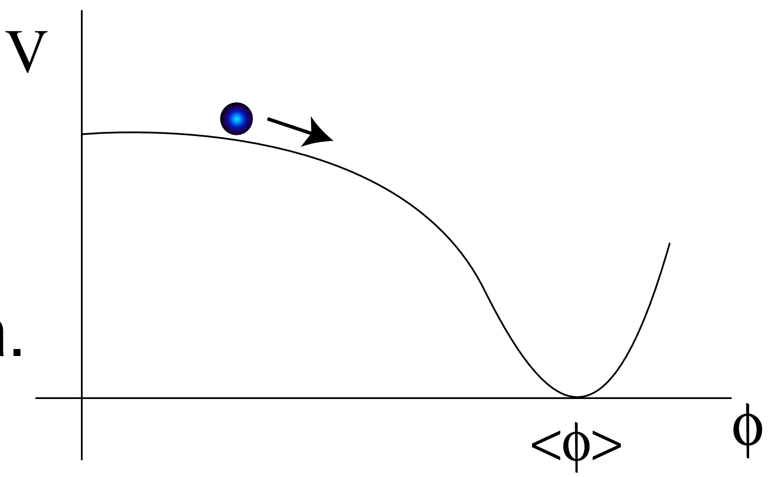
- アクシオンインフレーション
- 再加熱と暗黒物質
- まとめ

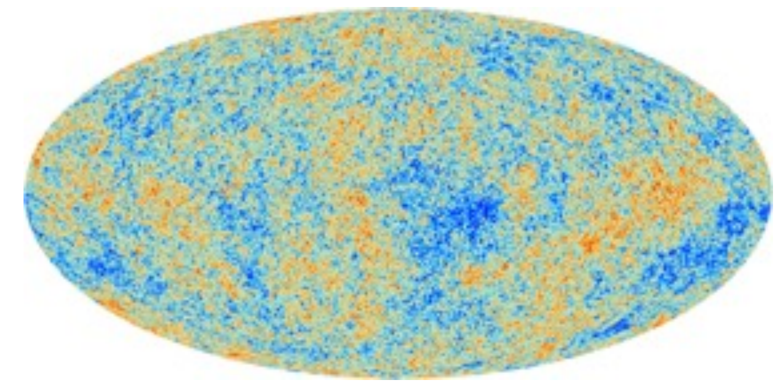
1. Introduction

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

- Inflaton

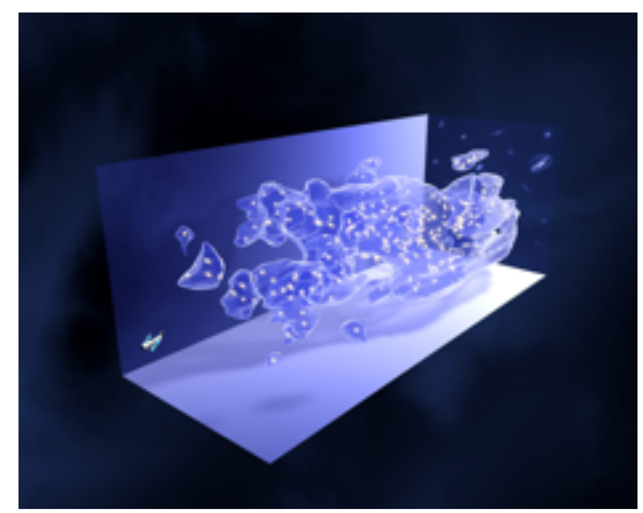
Very flat potential
for slow-roll inflation.





- Dark matter

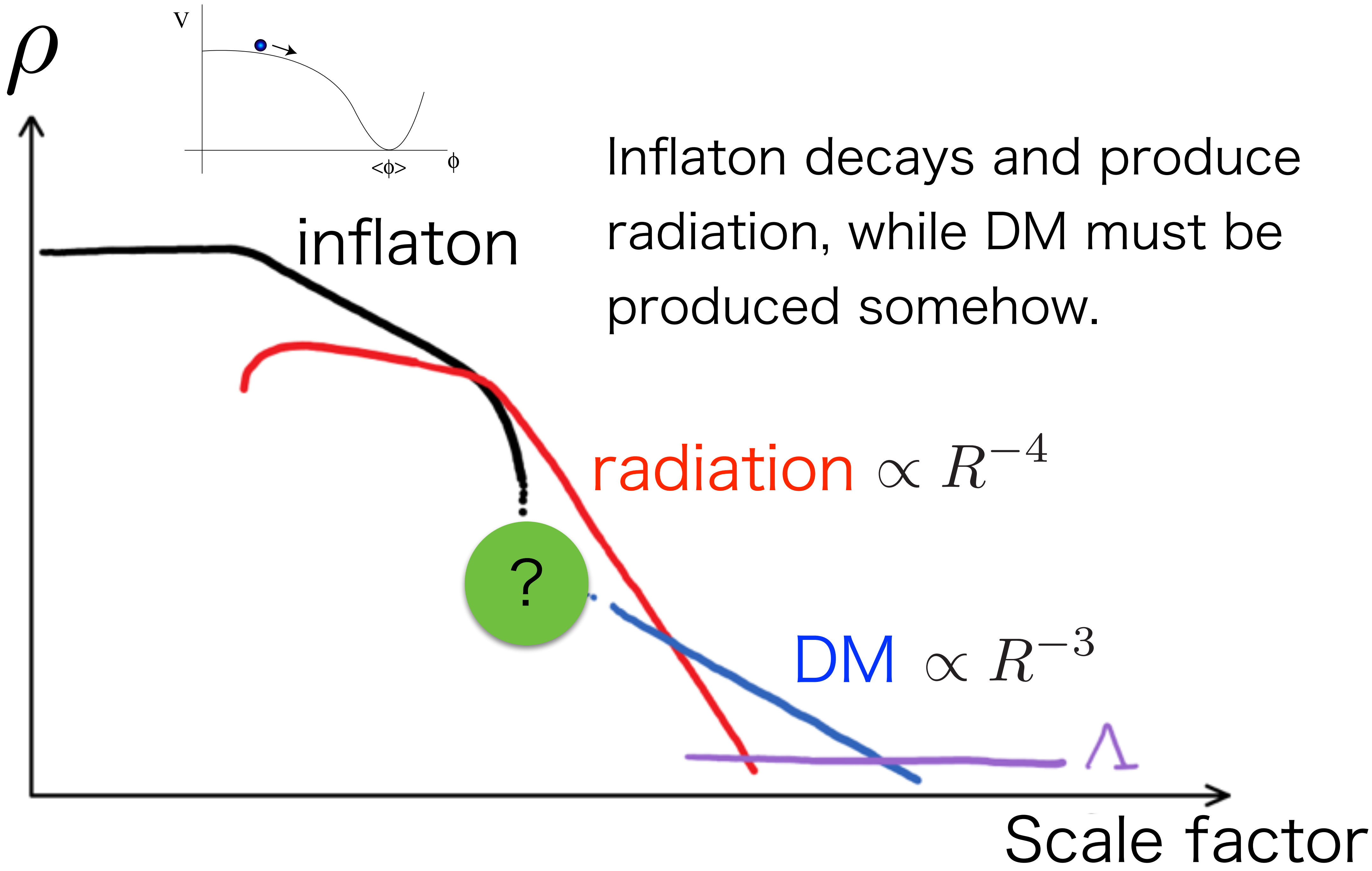
Cold, neutral,
long-lived, and
$\Omega_{\rm DM} h^2 \simeq 0.12$



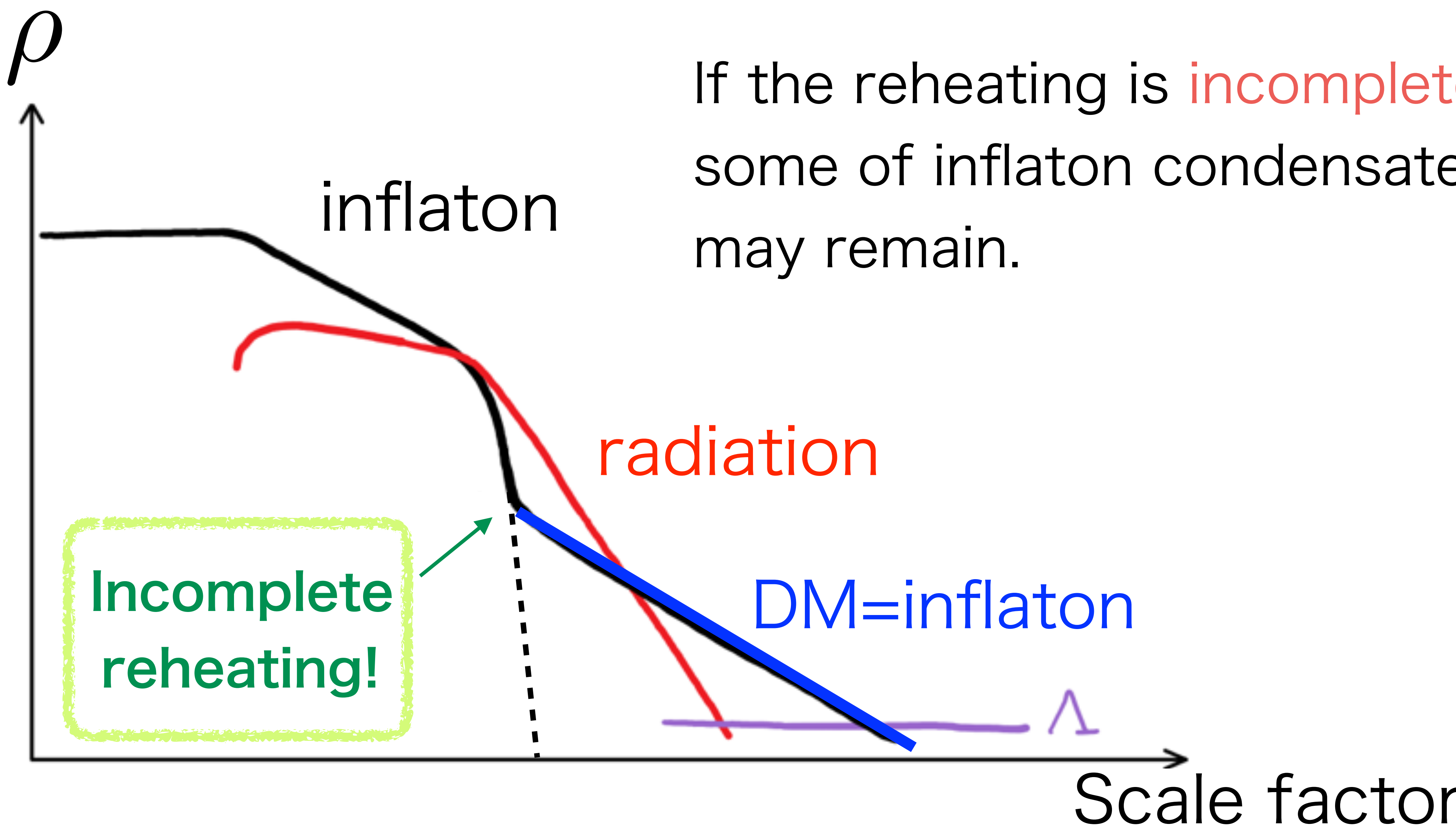
Both are neutral and occupied a significant fraction of the energy density of the Universe.

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

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

within the reach of IAXO.

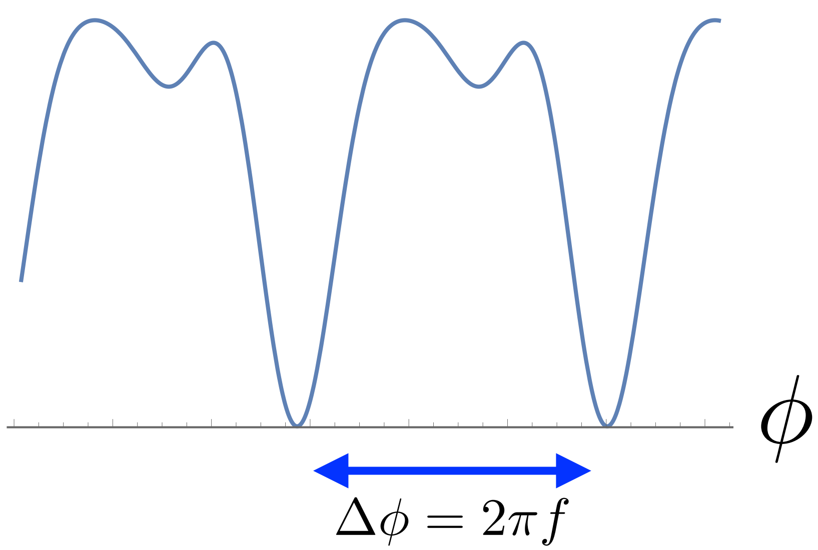
2. Axion and Inflation

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,

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

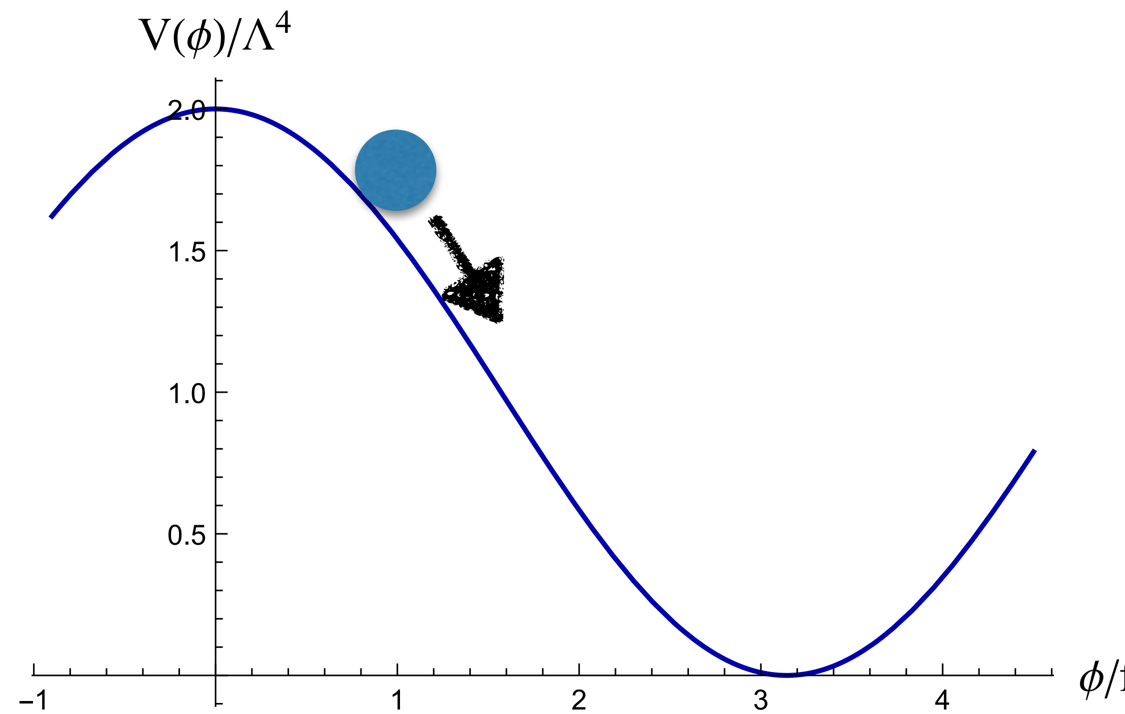
Axion and Inflation

- **Natural inflation**

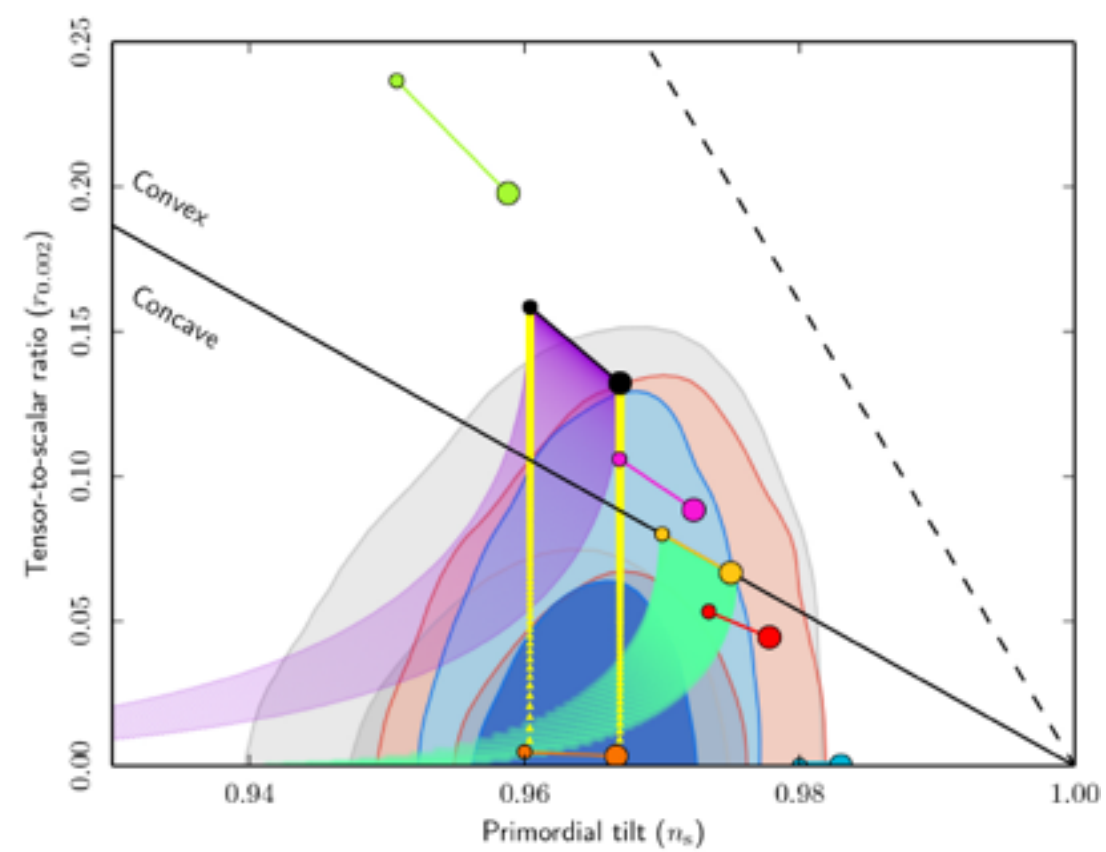
Freese, Frieman, Olinto `90

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

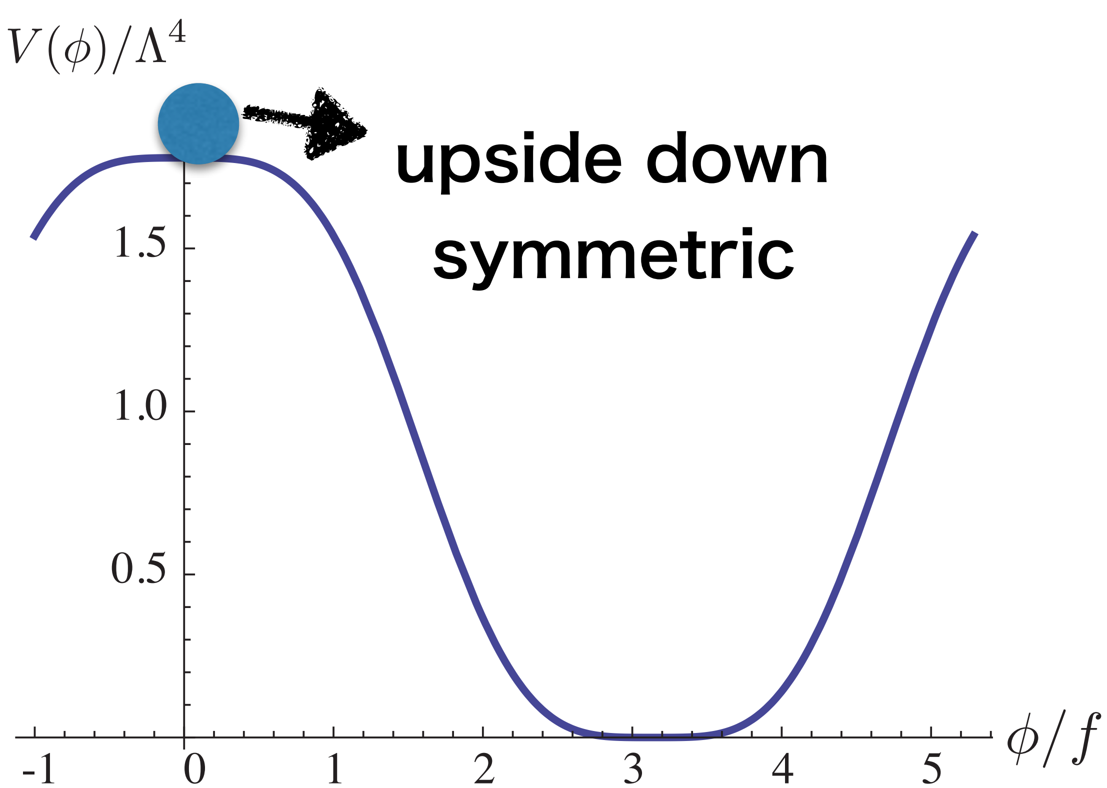
- **Axion hilltop inflation**

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

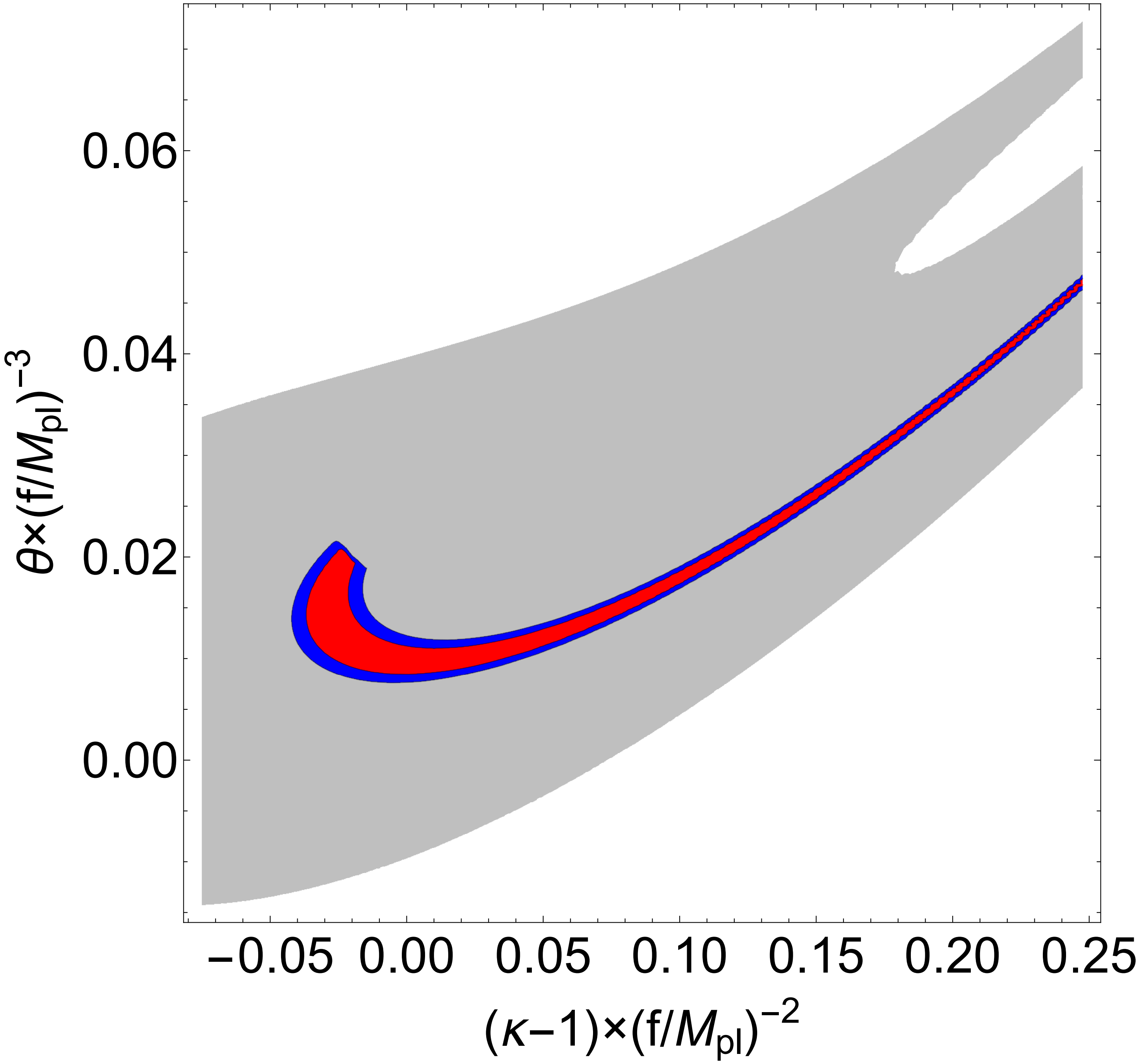
- The decay constant can be sub-Planckian. $f \ll M_P$
- Inflaton is light both during inflation and in the true min.

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

Flatness=longevity

Spectral index

$$n_s = 0.968 \pm 0.006$$



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

$$\eta \equiv M_p^2 \left(\frac{V''}{V}\right) \sim \frac{m^2}{H_{\rm inf}^2}$$

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

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

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

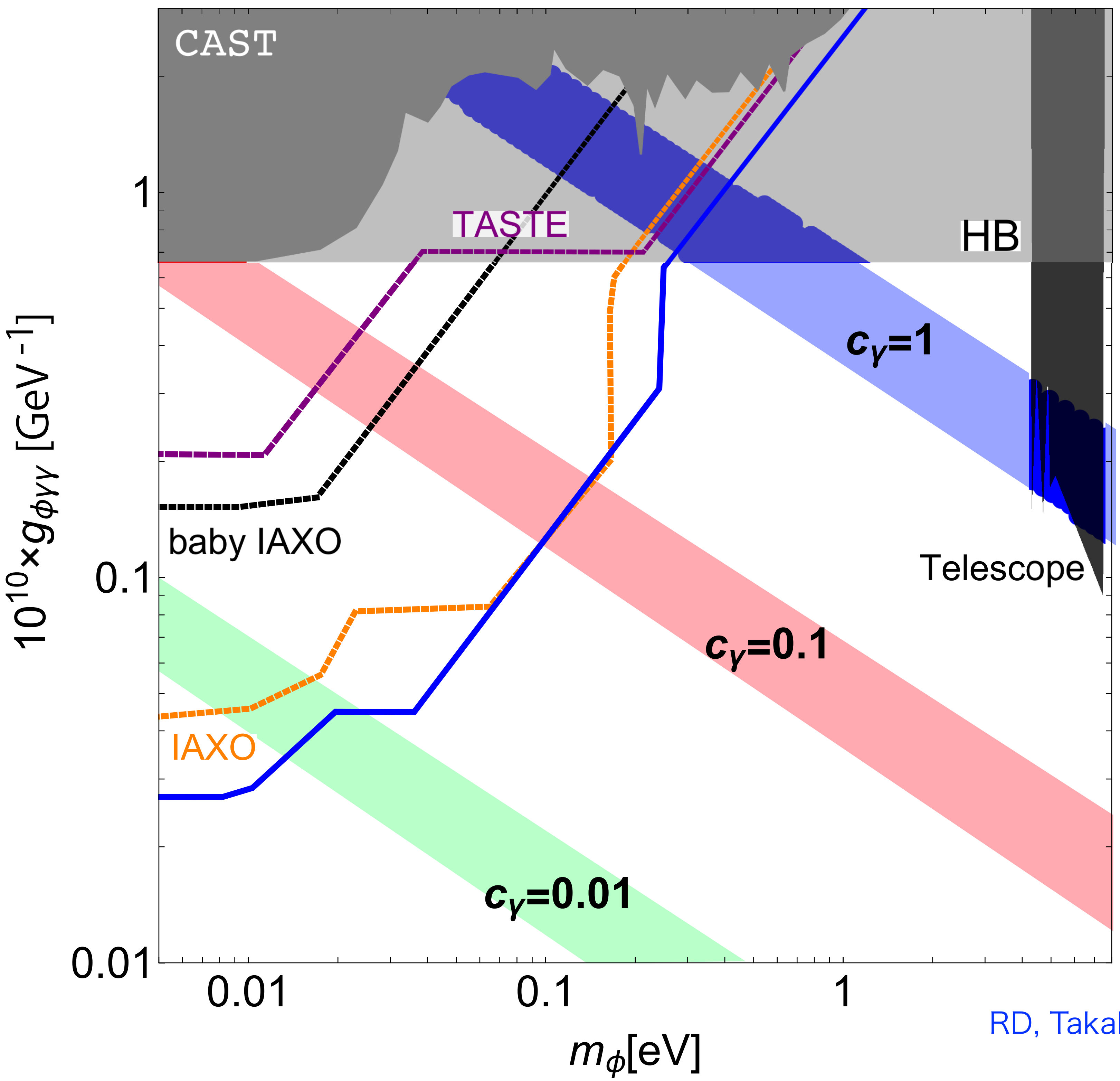
Mass and coupling to photons

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

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

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

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



Successful inflation

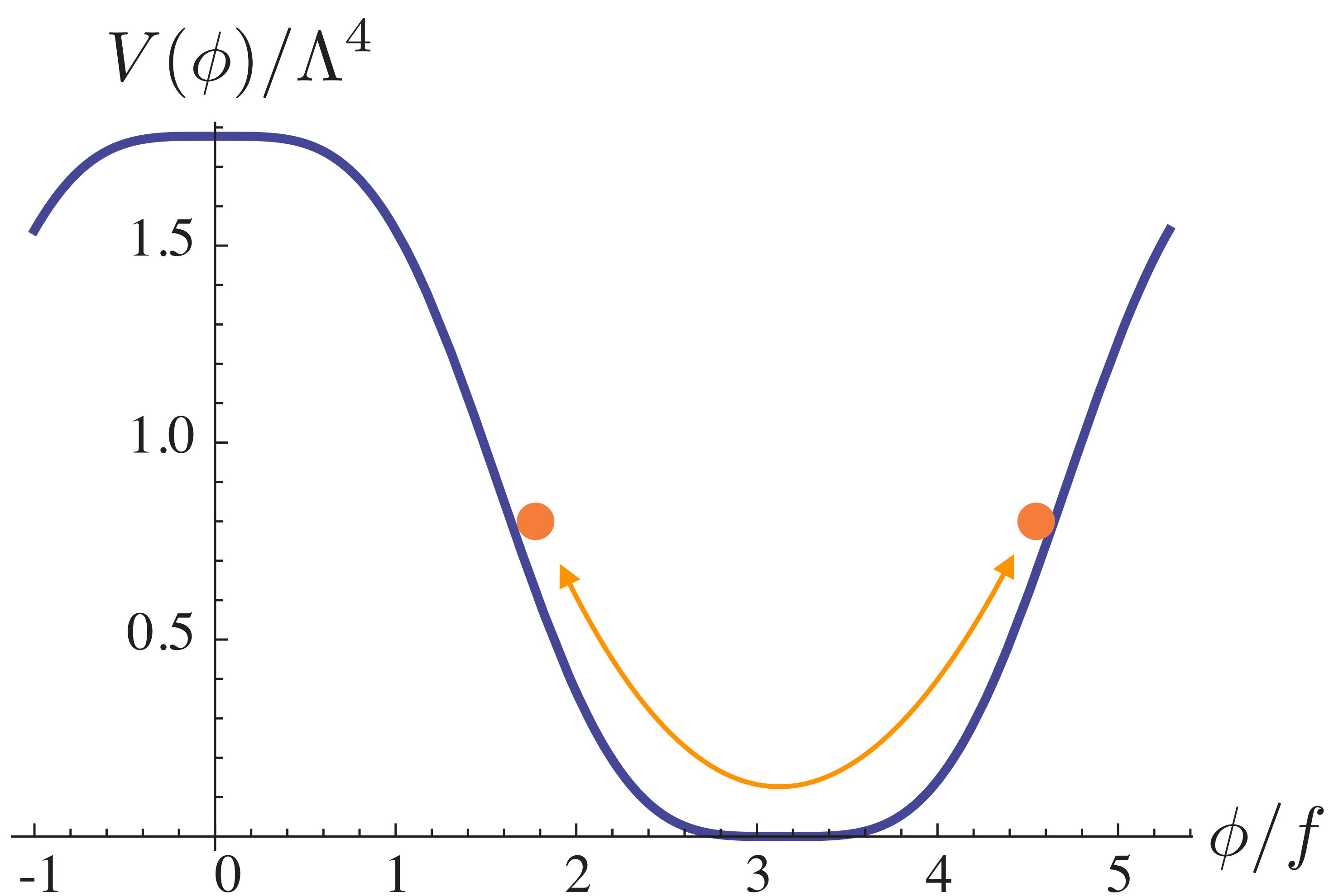
RD, Takahashi, and Yin 1702.03284
1710.11107

3. Reheating and ALP DM

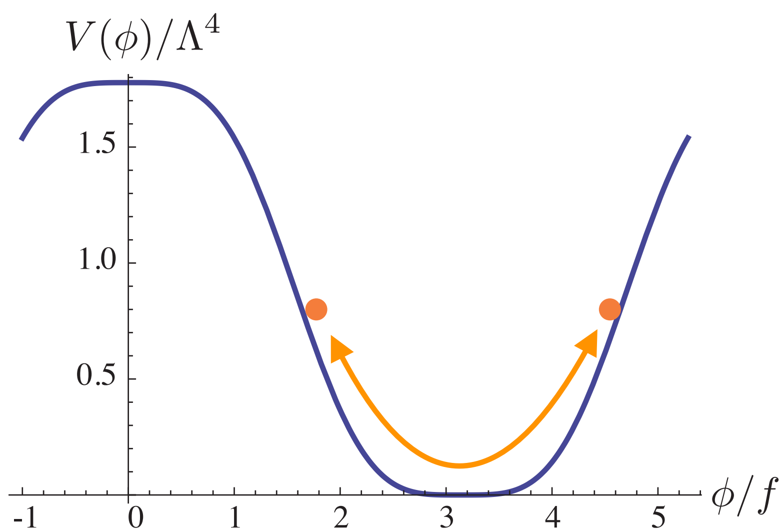
The inflaton oscillates about $\phi_{\rm min} = \pi f$ in a quartic potential.

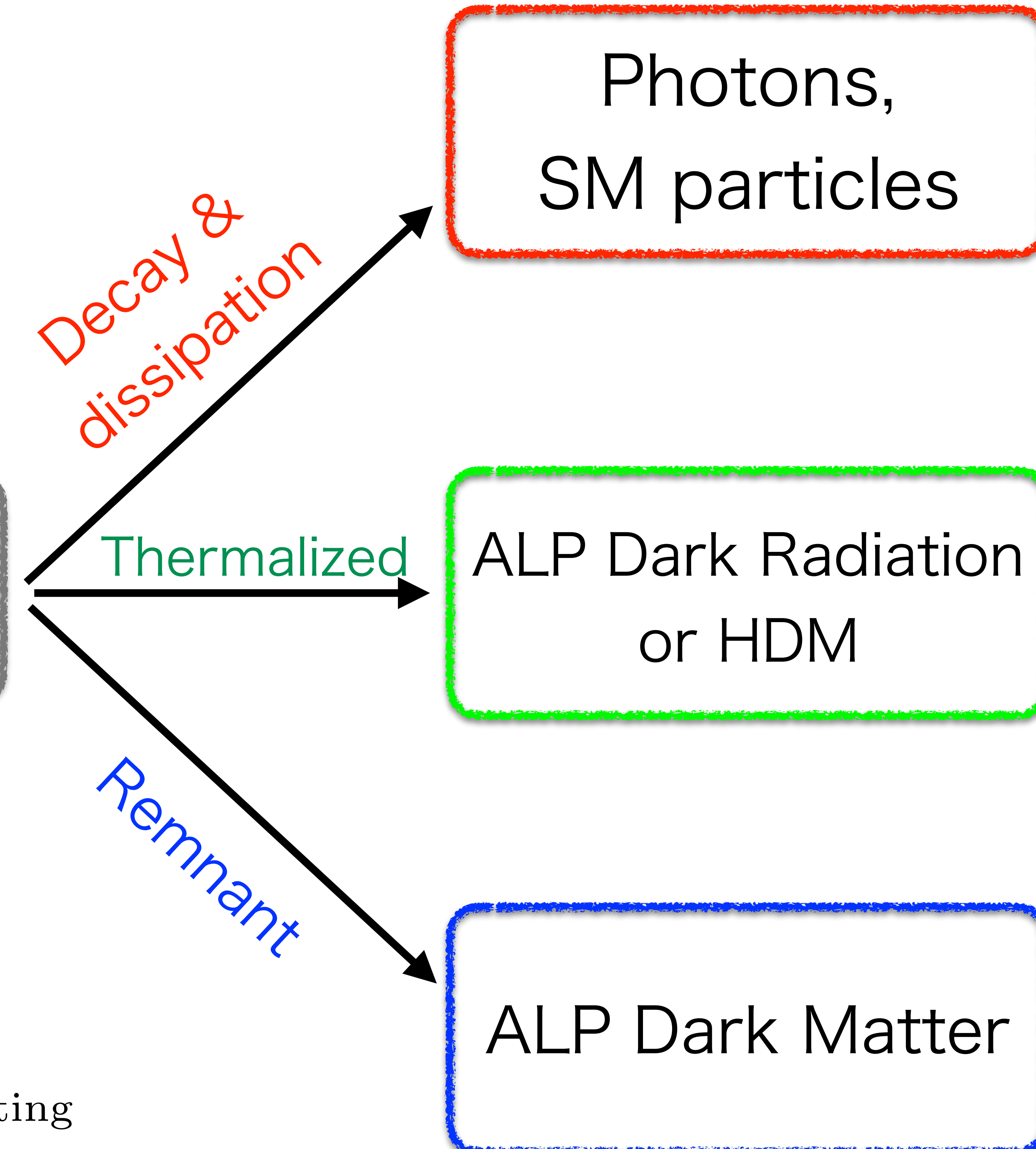
The effective mass, $m_{\rm eff}^2(t) = V''(\phi_{\rm amp}) = 12\lambda\phi_{\rm amp}^2$ decreases with time, and so, decay and dissipation become inefficient at later times.

Incomplete reheating



Reheating and ALP DM





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

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

As we shall see, $\xi \lesssim \mathcal{O}(0.1)$ is required to explain DM.

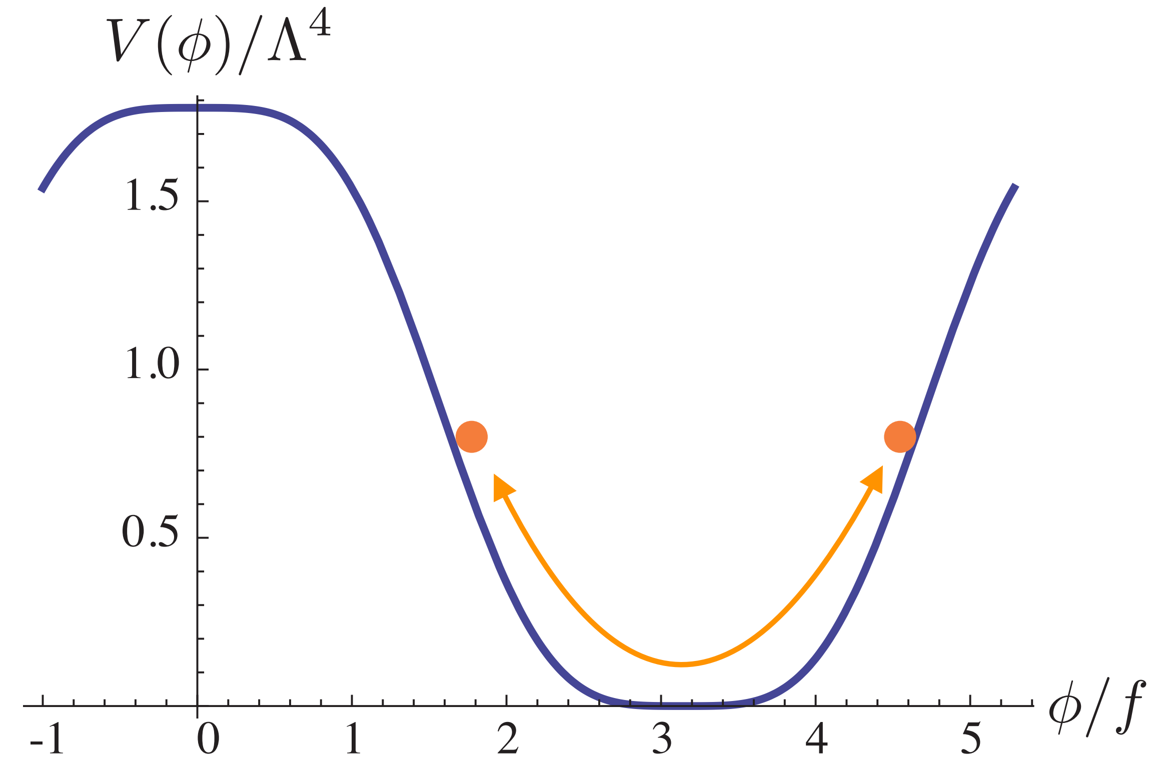
• Decay and dissipation

✓ The decay rate into two photons :

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

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

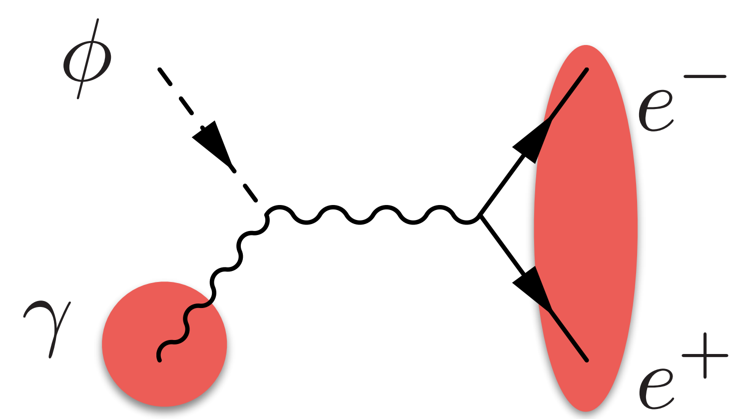
where



✓ The dissipation rate is roughly given by

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

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



Here C is a numerical constant of $\mathcal{O}(10)$ which represents an uncertainty of the order-of-magnitude estimate as well as the effect of tachyonic preheating and scalar resonance.

Amin et al 1710.06851

• Decay and dissipation

At T > 100 GeV, one should consider couplings to weak gauge bosons instead of photons:

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

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

We adopt the following dissipation rate at T > 100 GeV

$$\Gamma_{\rm dis,EW} = C' \frac{c_2^2 \alpha_2^2 T^3}{32\pi^2 f^2} \frac{m_{\rm eff}^2}{g_2^4 T^2} + C'' \frac{c_Y^2 \alpha_Y^2 T^3}{8\pi^2 f^2} \frac{m_{\rm eff}^2}{g_Y^4 T^2},$$

Decay and dissipation

Due to the decay and dissipation,

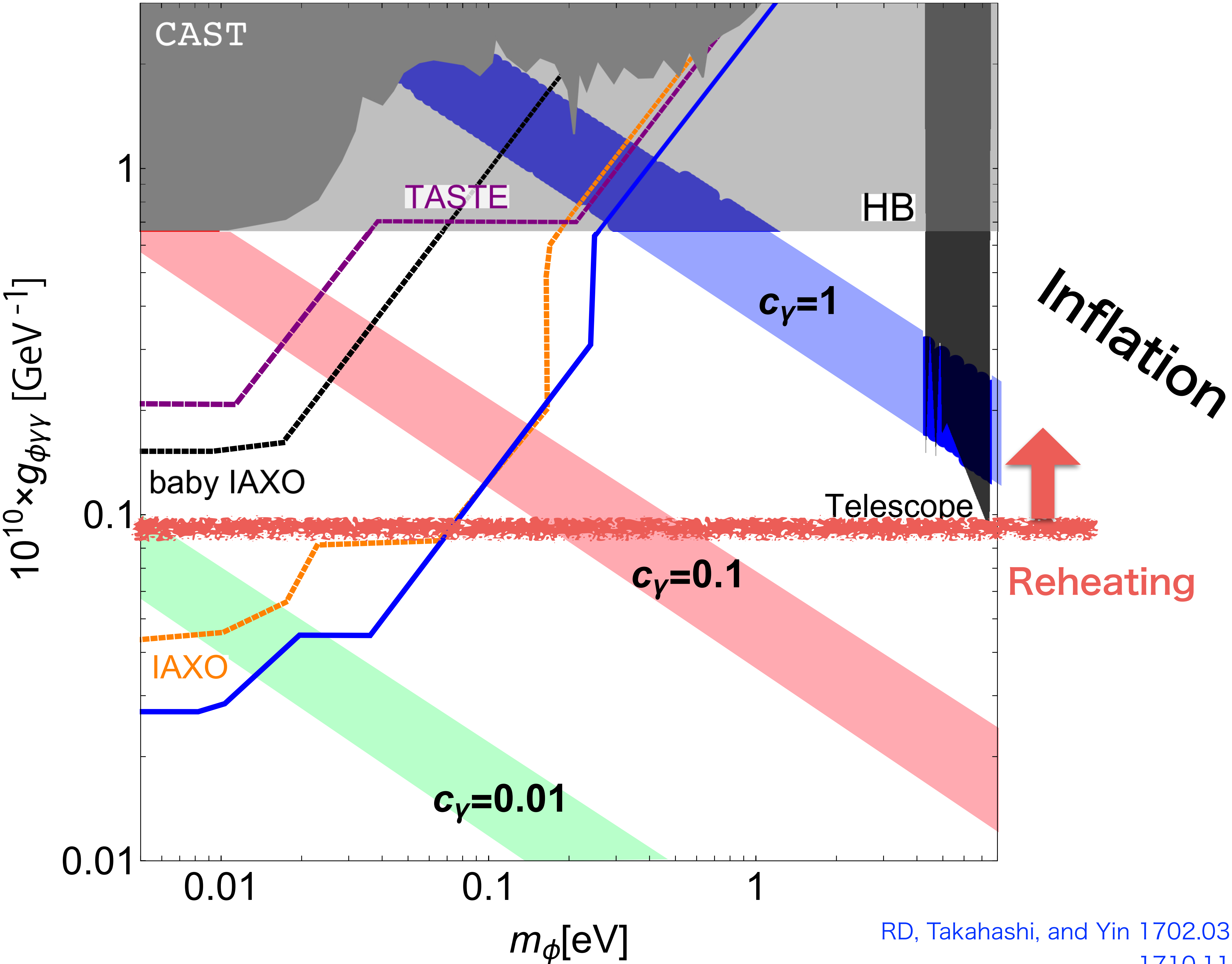
$$\xi \equiv \left. \frac{\rho_\phi}{\rho_\phi + \rho_R} \right|_{\text{after reheating}} = \mathcal{O}(0.01 - 0.1)$$

for $g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$ and $c_2, c_Y = \mathcal{O}(1)$

For successful reheating with $\xi \lesssim \mathcal{O}(0.1)$, one needs

$$g_{\phi\gamma\gamma} \gtrsim 10^{-11}\,\mathrm{GeV}^{-1}$$

The typical reheating temperature $T_R \sim \mathcal{O}(10)\,\mathrm{TeV} \left(\frac{m_\phi}{1\,\mathrm{eV}}\right)^{\frac{1}{2}}$

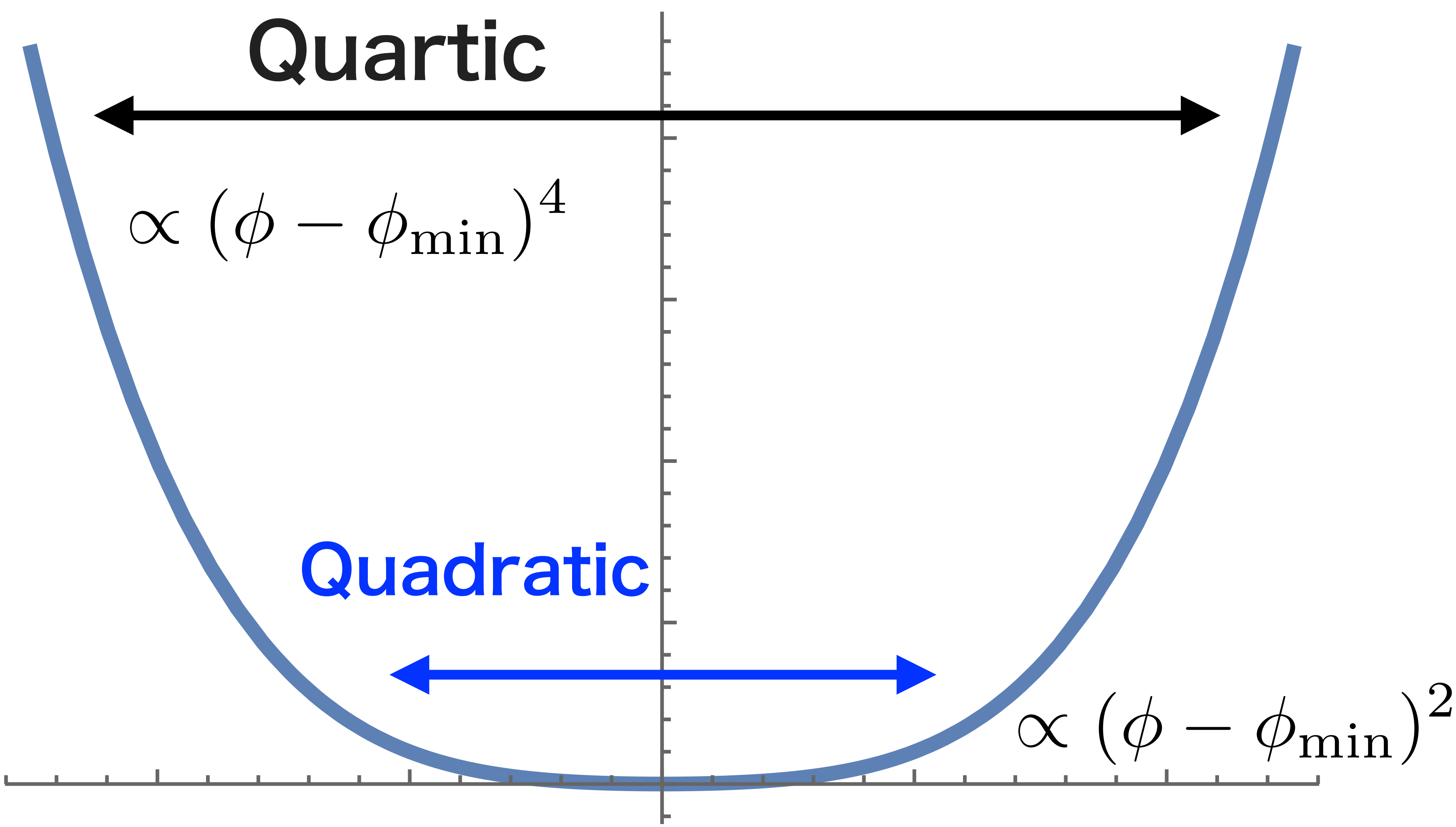


RD, Takahashi, and Yin 1702.03284
1710.11107

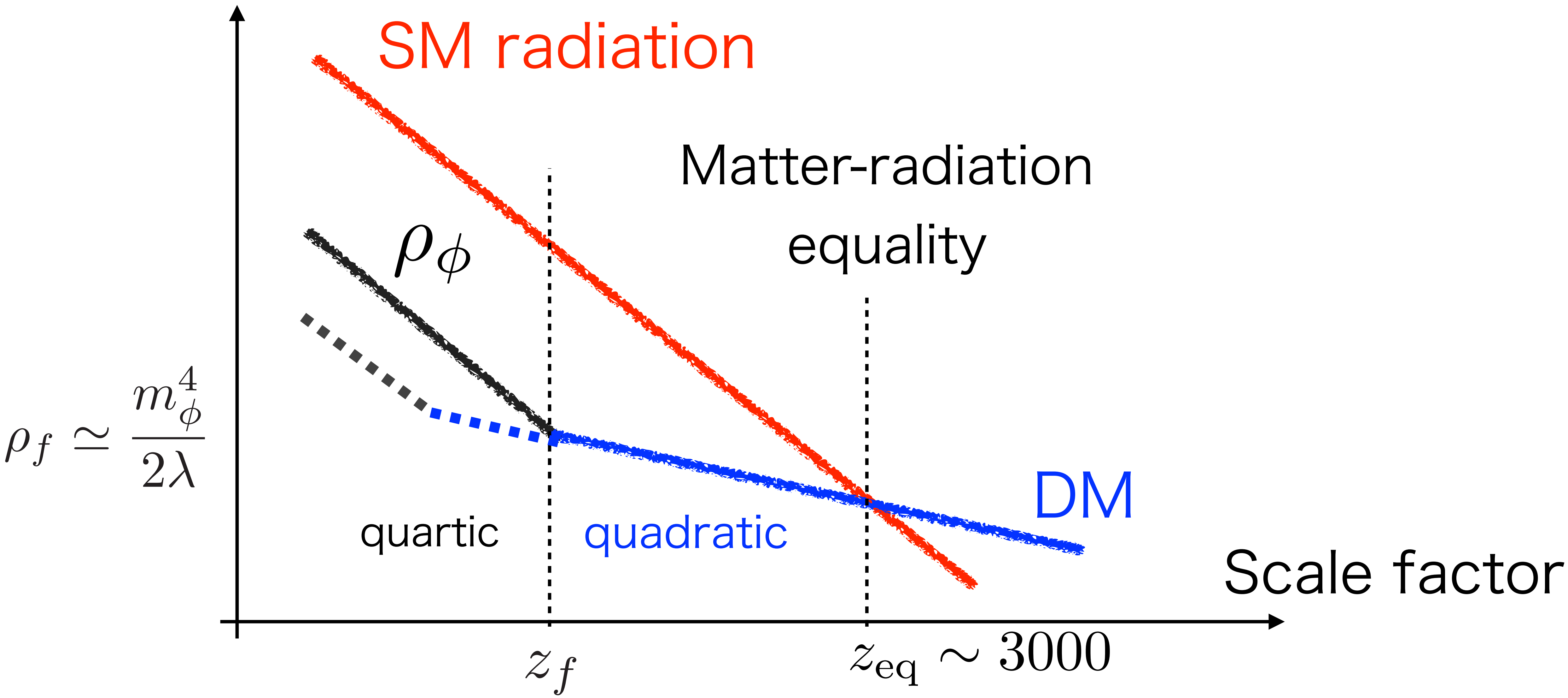
• ALP condensate as CDM

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



• ALP condensate as CDM

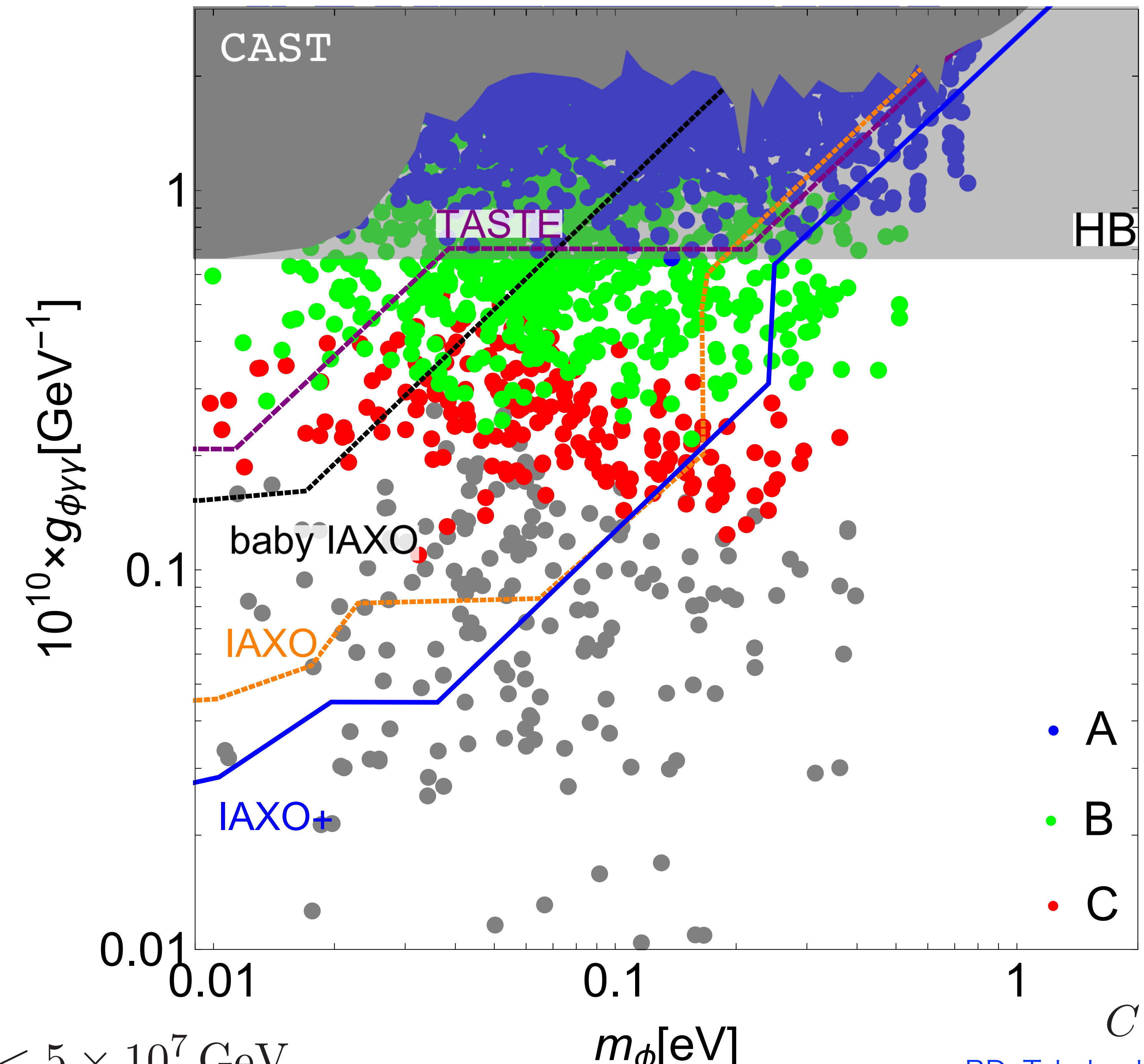


DM should be formed before $z_f \gtrsim \mathcal{O}(10^5)$ by SDSS and Ly-alpha

Sarkar, Das, Sethi, 1410.7129

$$m_\phi \gtrsim 0.01\,\mathrm{eV}$$

• ALP condensate as CDM



$|c_\gamma/c_Y| > 0.3$

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

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

$C = C' = C'' = 10$

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

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

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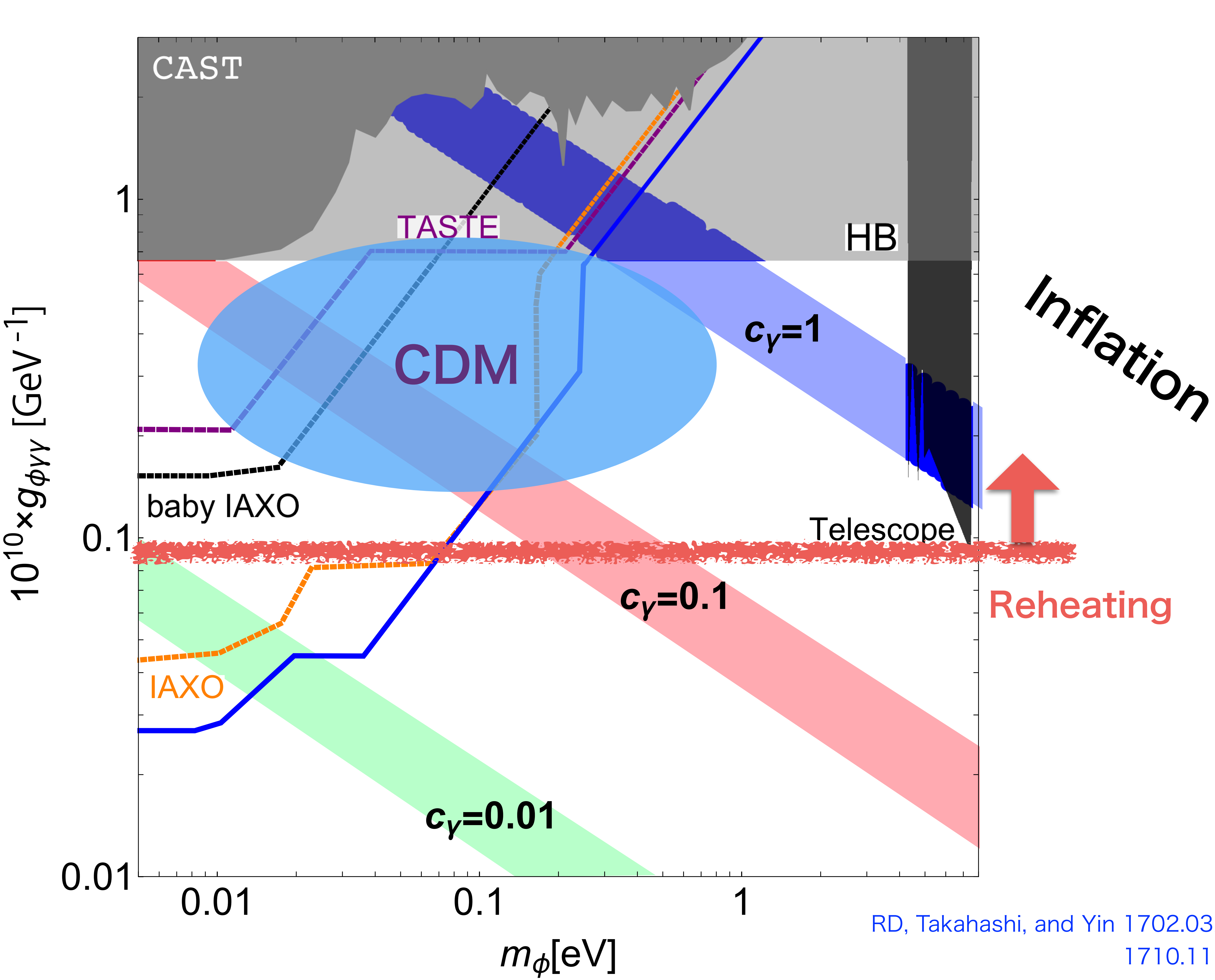

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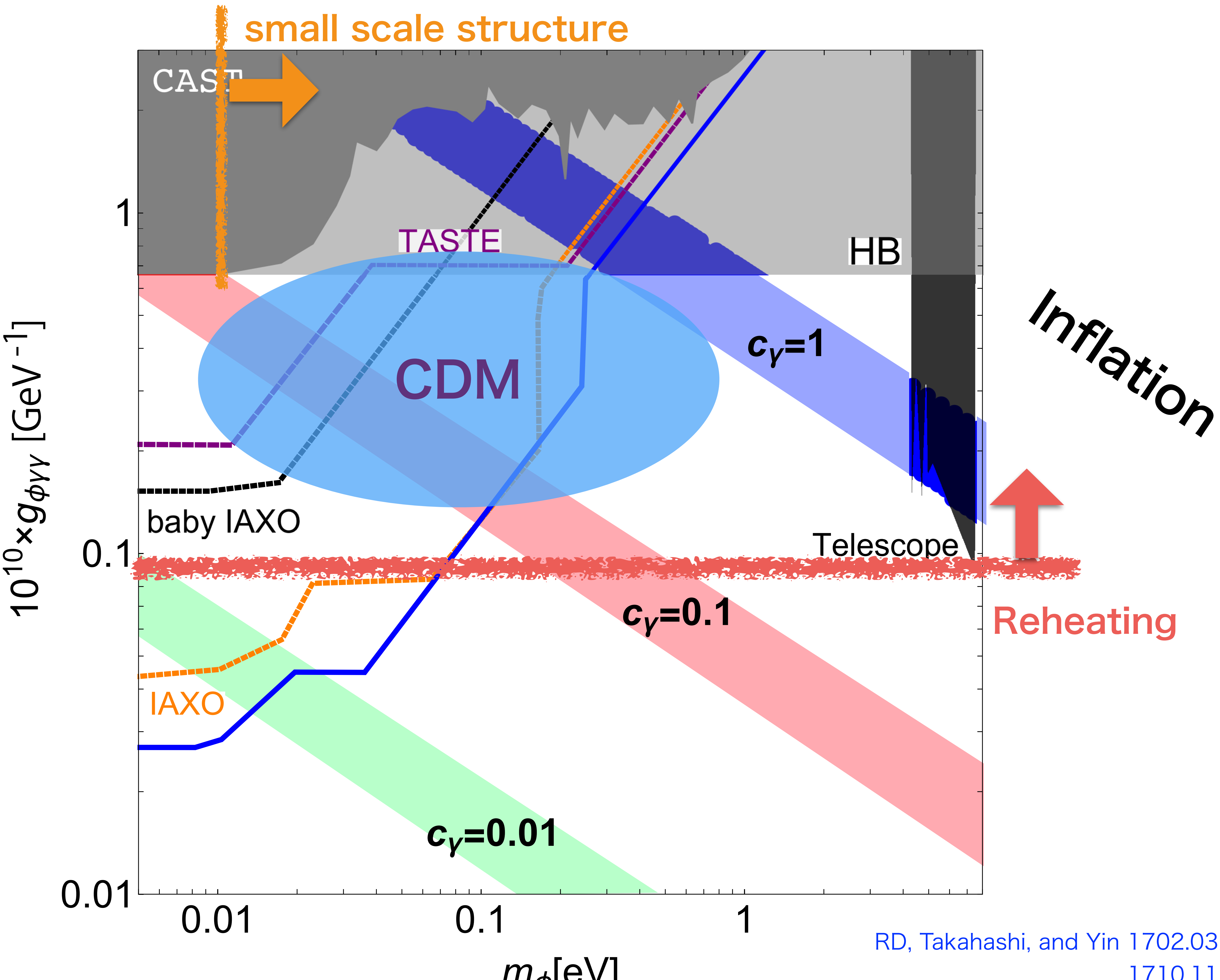

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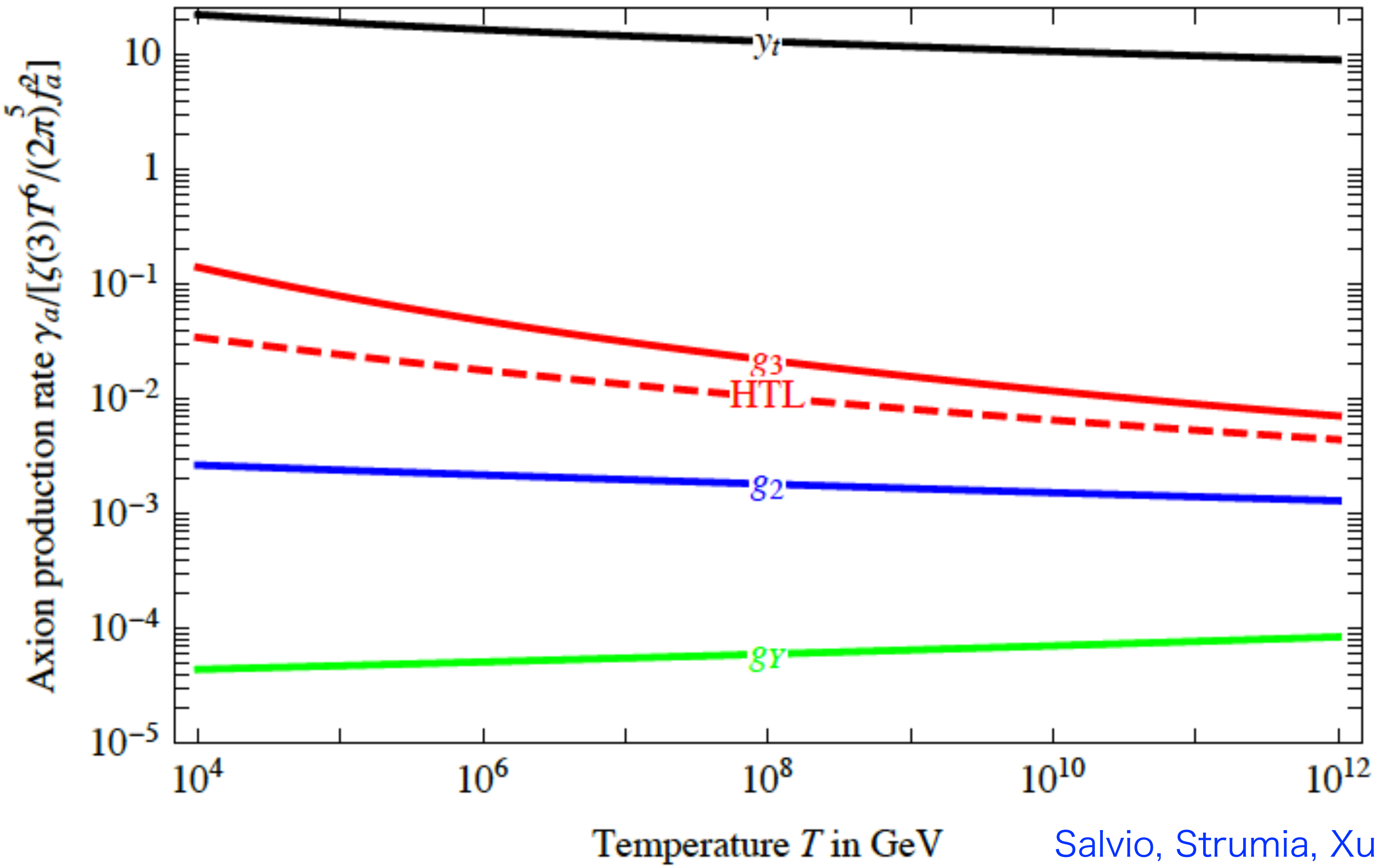
• Thermalized ALPs as HDM

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,

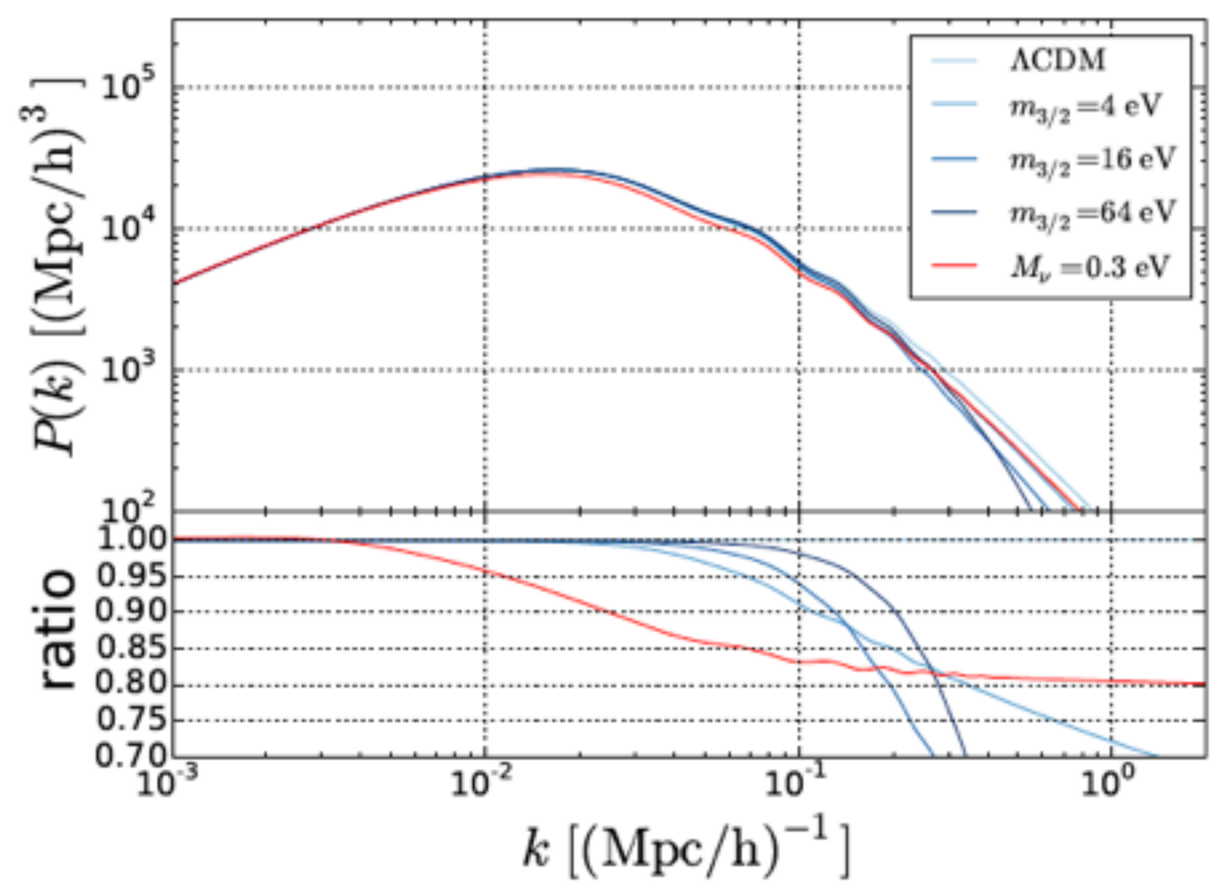
$$r \sim \left(\frac{T}{80\,\mathrm{GeV}}\right)\left(\frac{8\times 10^6\,\mathrm{GeV}}{f/c_2}\right)^2$$

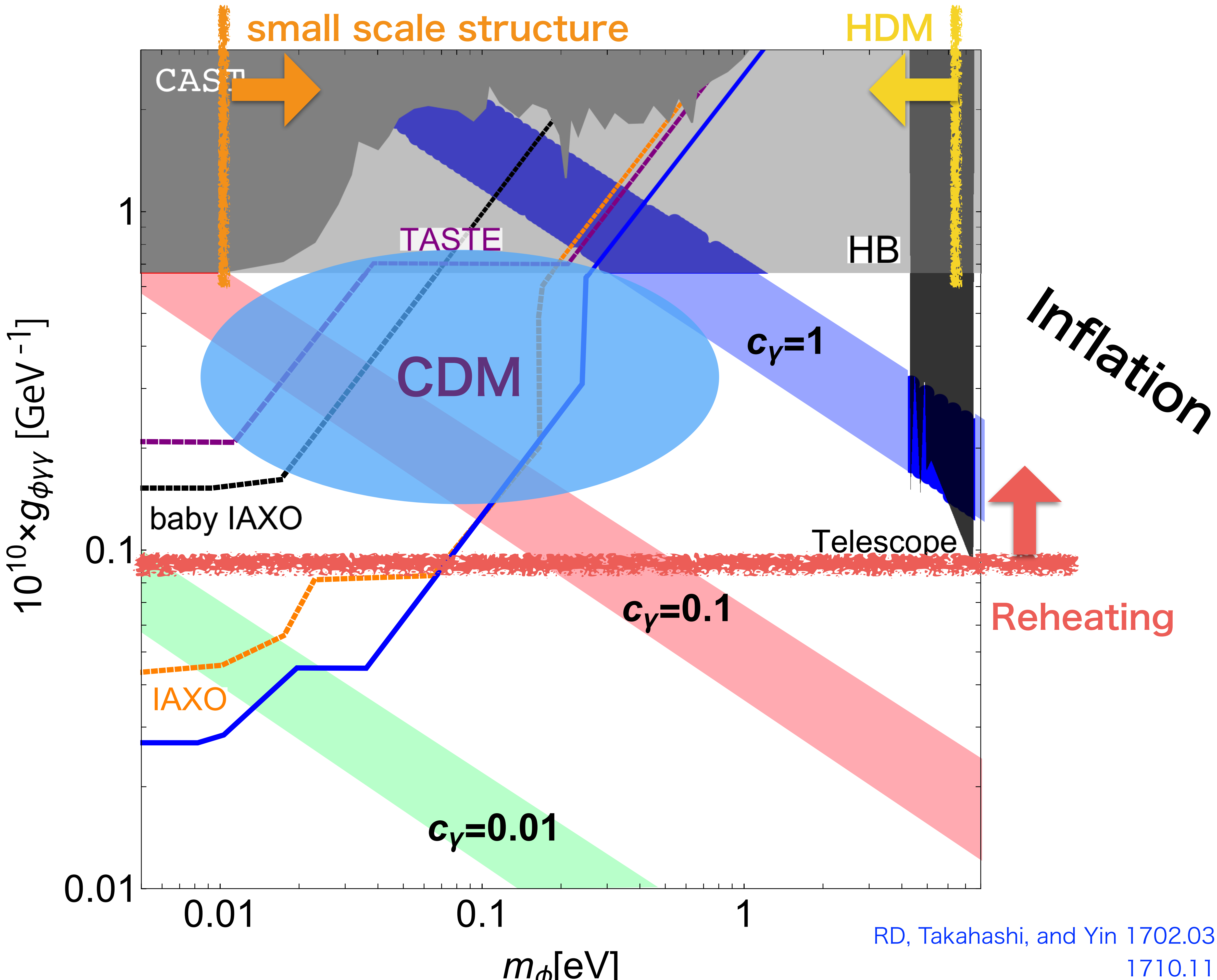
The thermalized ALPs contribute to HDM with $\Delta N_{\rm eff} \simeq 0.03$

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

$$m_\phi < m_{\phi,\mathrm{HDM}}^{\mathrm{bound}} \simeq 7.7\,\mathrm{eV}\left(\frac{0.03}{\Delta N_{\rm eff}}\right)^{3/4}$$

K. Osato, T. Sekiguchi, M. Shirasaki, et al, 1601.07386





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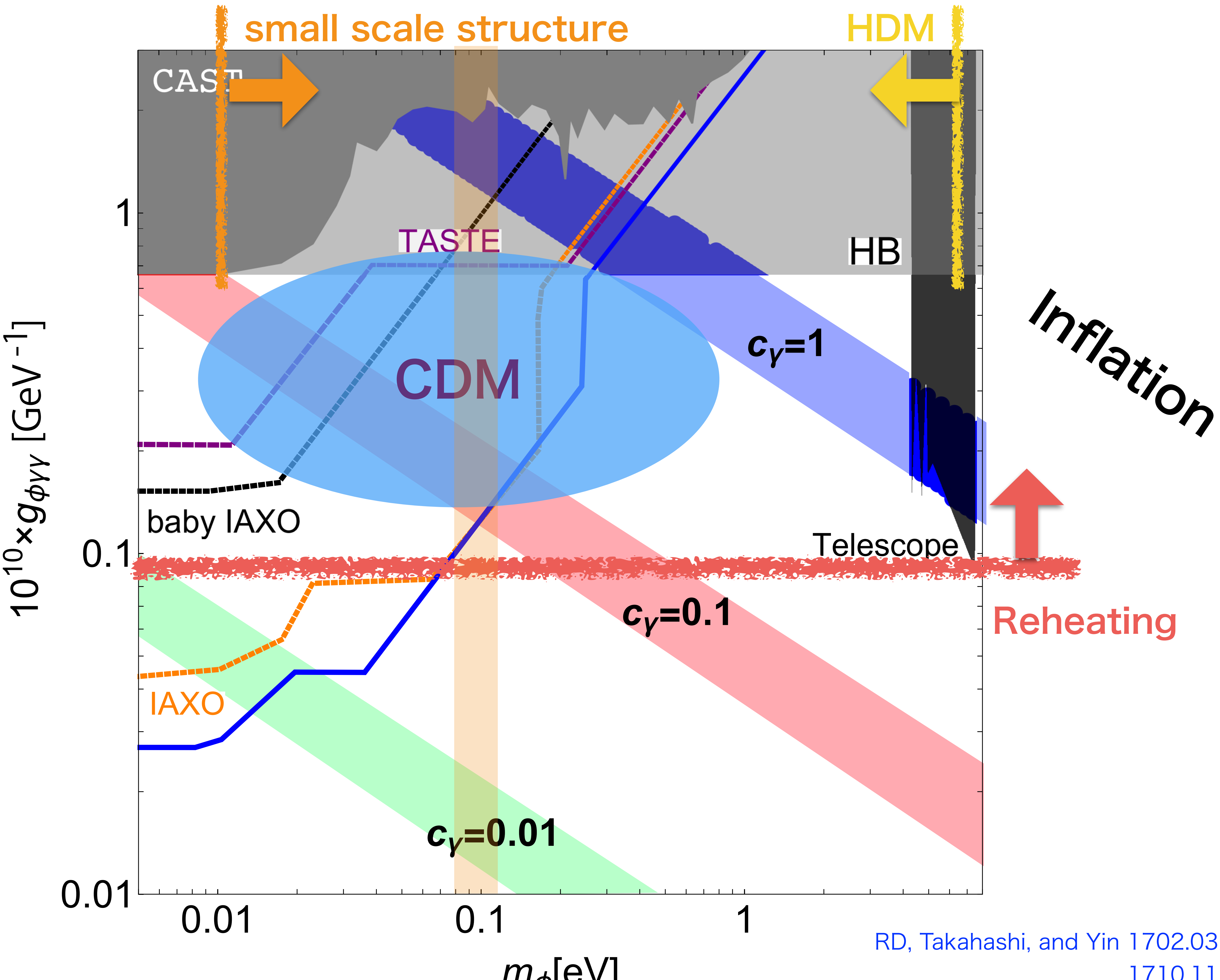

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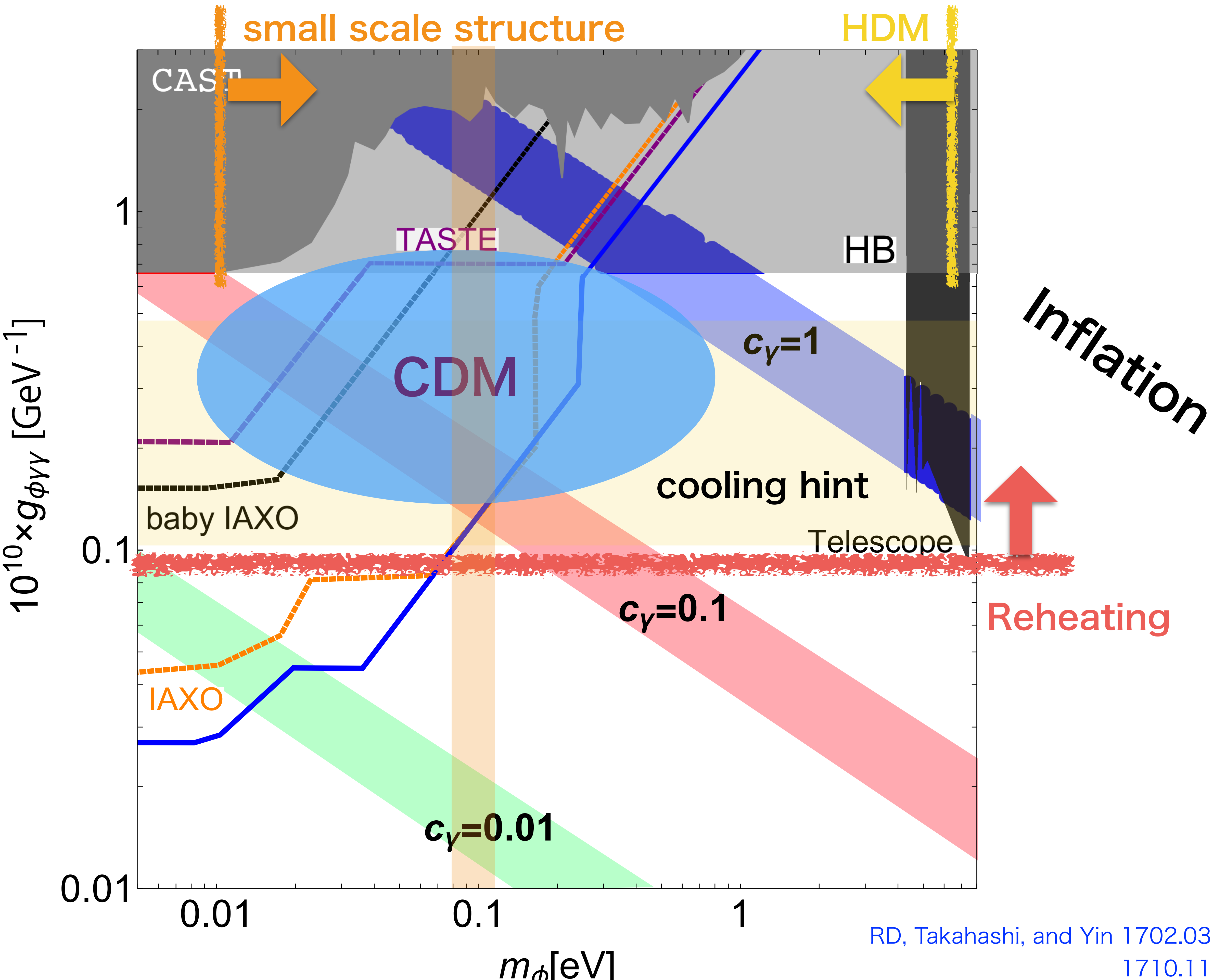

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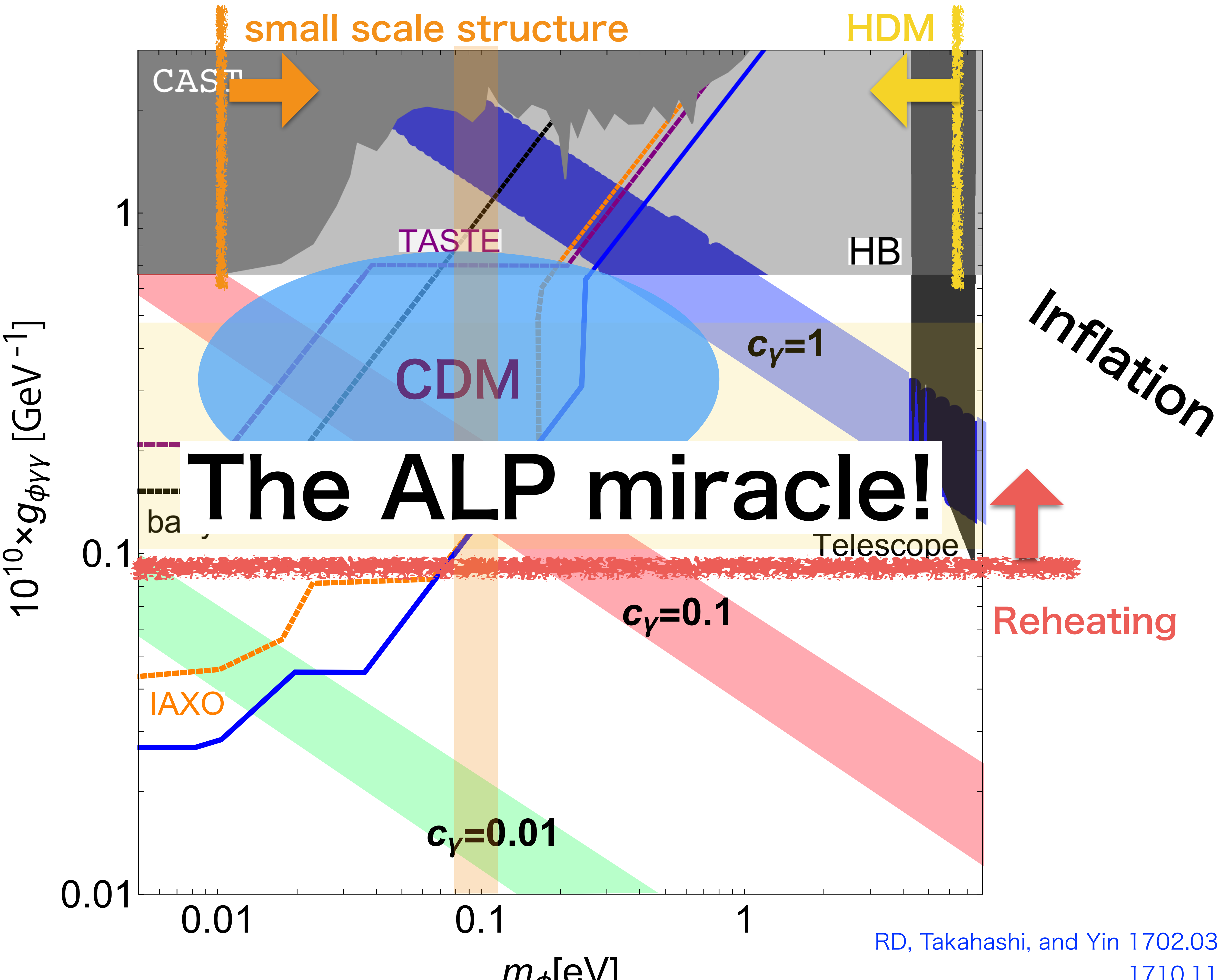

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Summary

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

- The observed CMB and LSS data fix the relation between the mass and decay consttant.

- Successful inflation,reheating and DM abundance point to

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

within the reach of IAXO.

- Interestingly, there are some anomalies which can be interpreted as a hint for the ALP in the ALP miracle region.