Implications of Hubble tension for very early universe cosmology

@ Seminar talk, Nagoya University 10th May

Wen Yin (殷　文) from Tohoku University

Based on Takahashi, WY, 2112.06710
and Daido, Takahashi, WY, 1702.03284, 1710.11107,

Contents

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- 2. Stochastic axionic curvaton for $n_s = 1$
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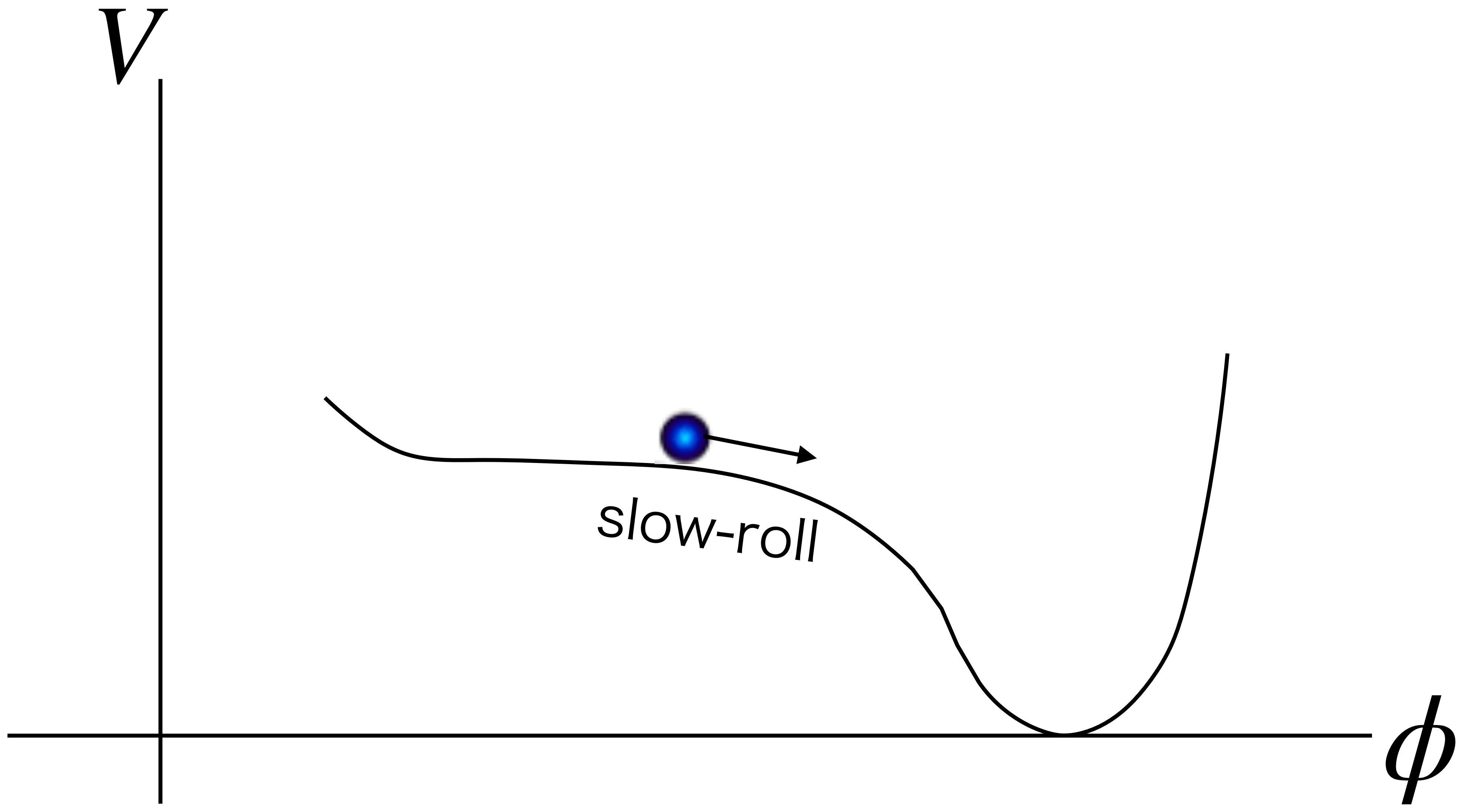
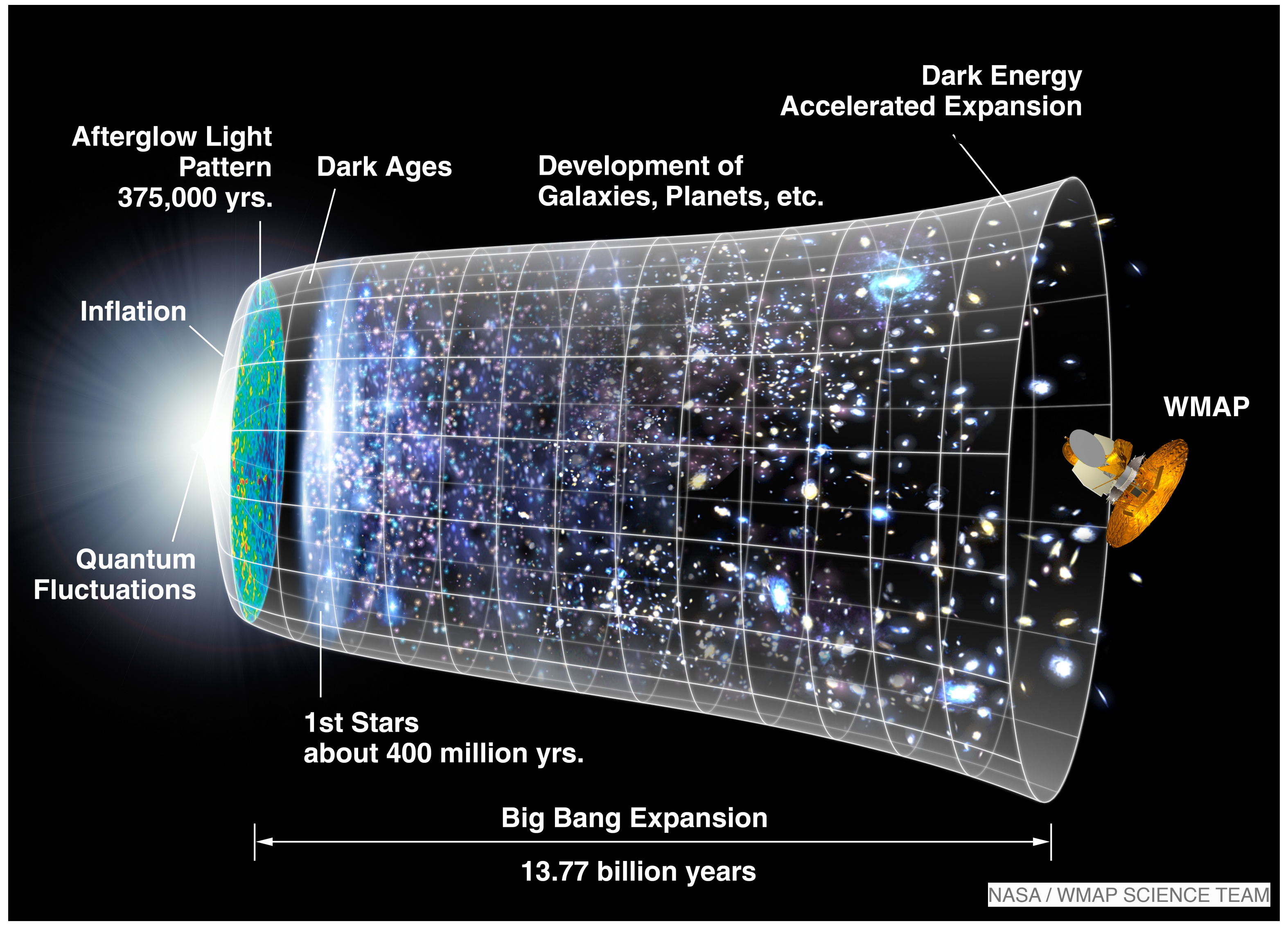
Inflationary Cosmology

A.Guth, 1980; K.Sato, 1980; A.Starobinsky, 1980; Kazanas, 1980; A.Linde, 1981; Albrecht, Steinhardt, 1981;

Much before the thermal history, there was inflation.

Inflation solves horizon and flatness problems.





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- is a BSM scalar field
- has flat potential
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- Explains primordial density perturbation

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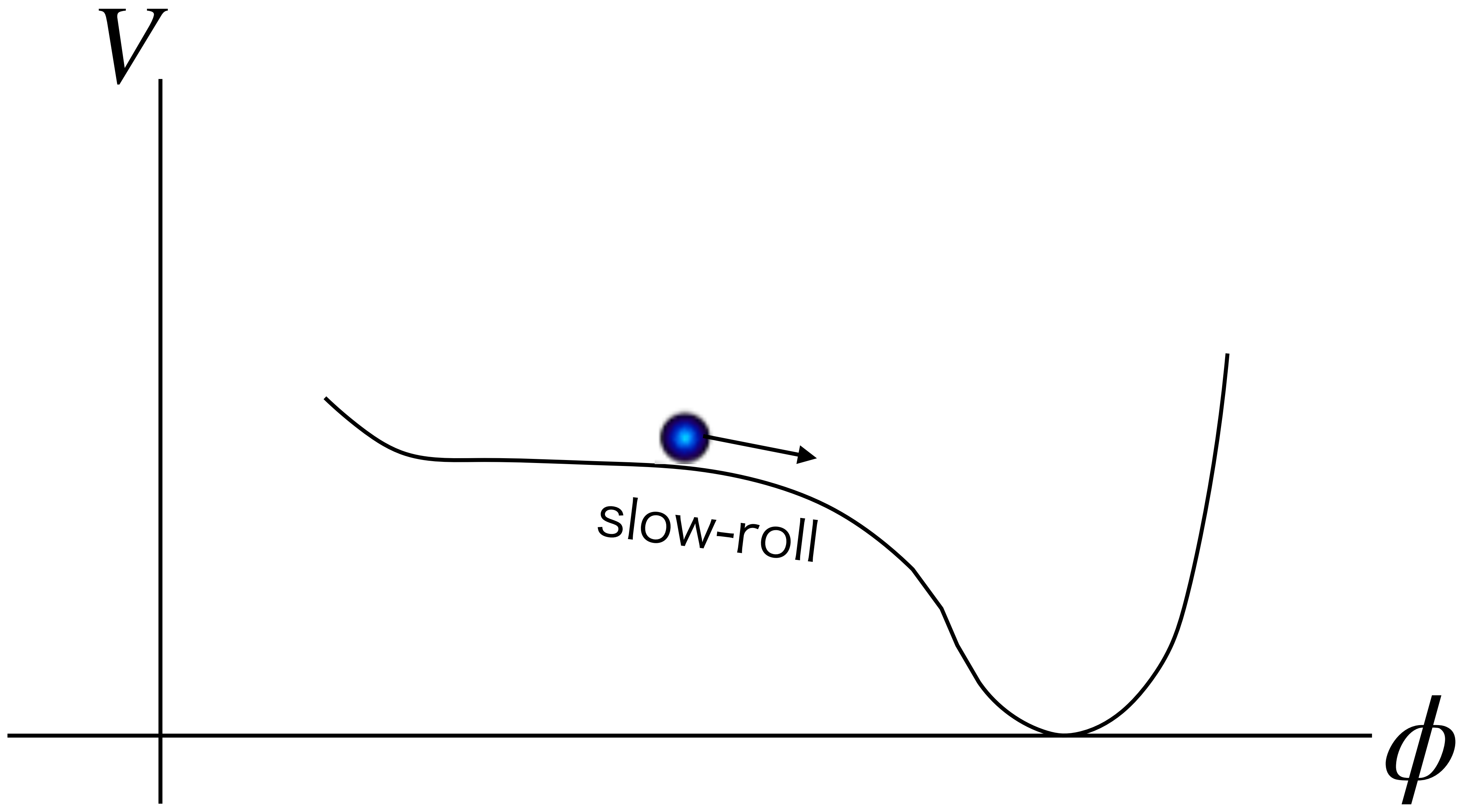

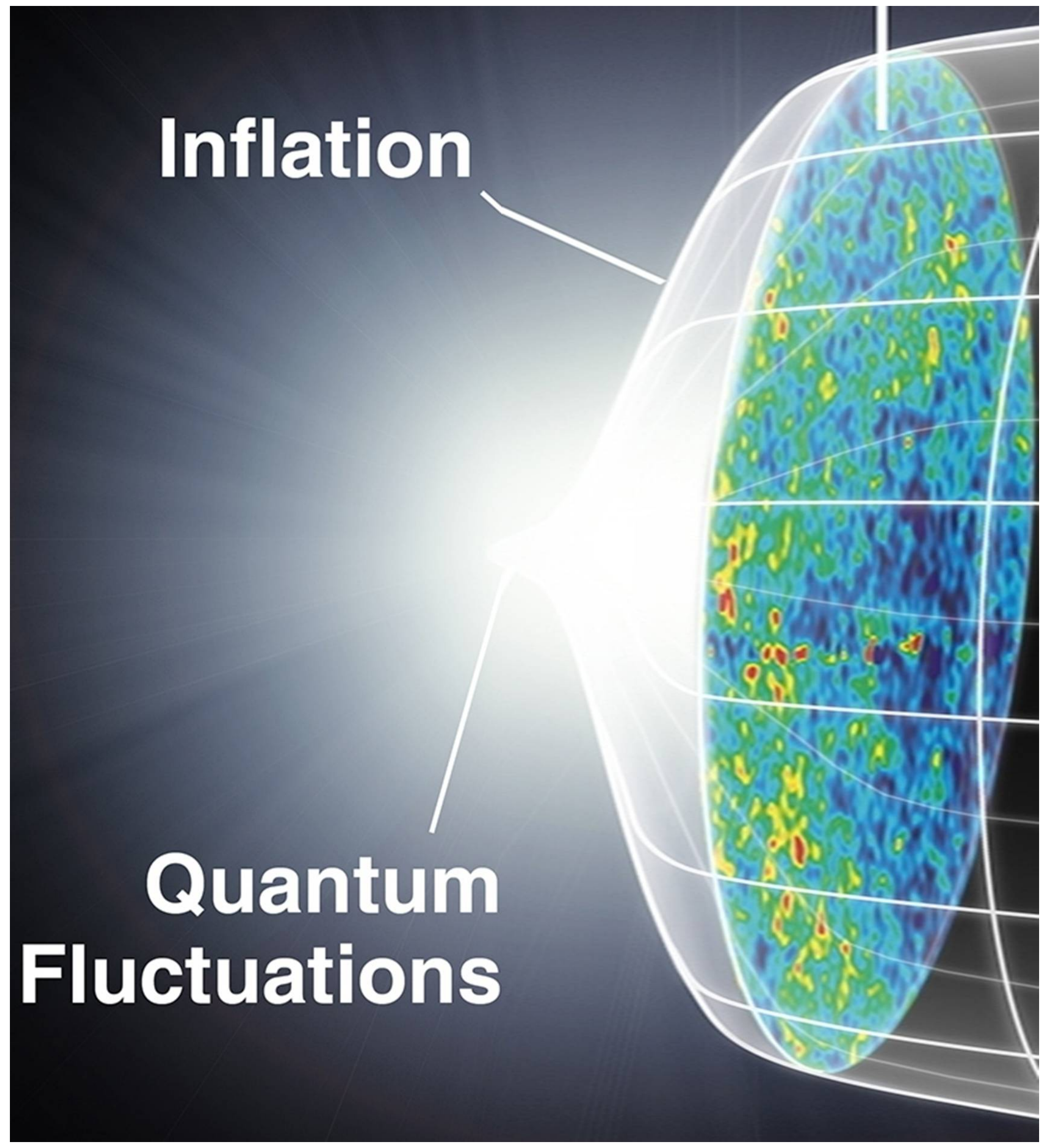

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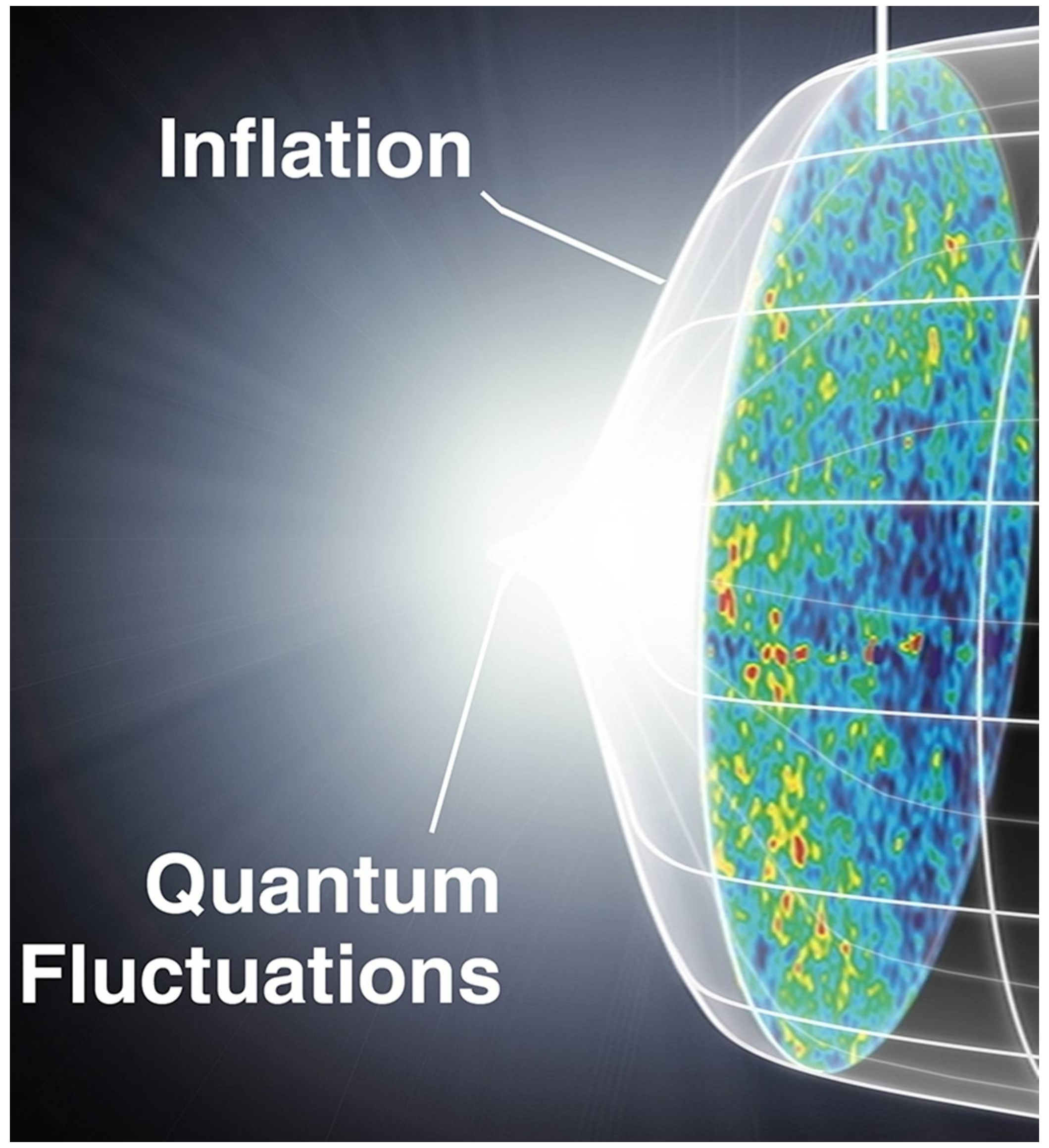

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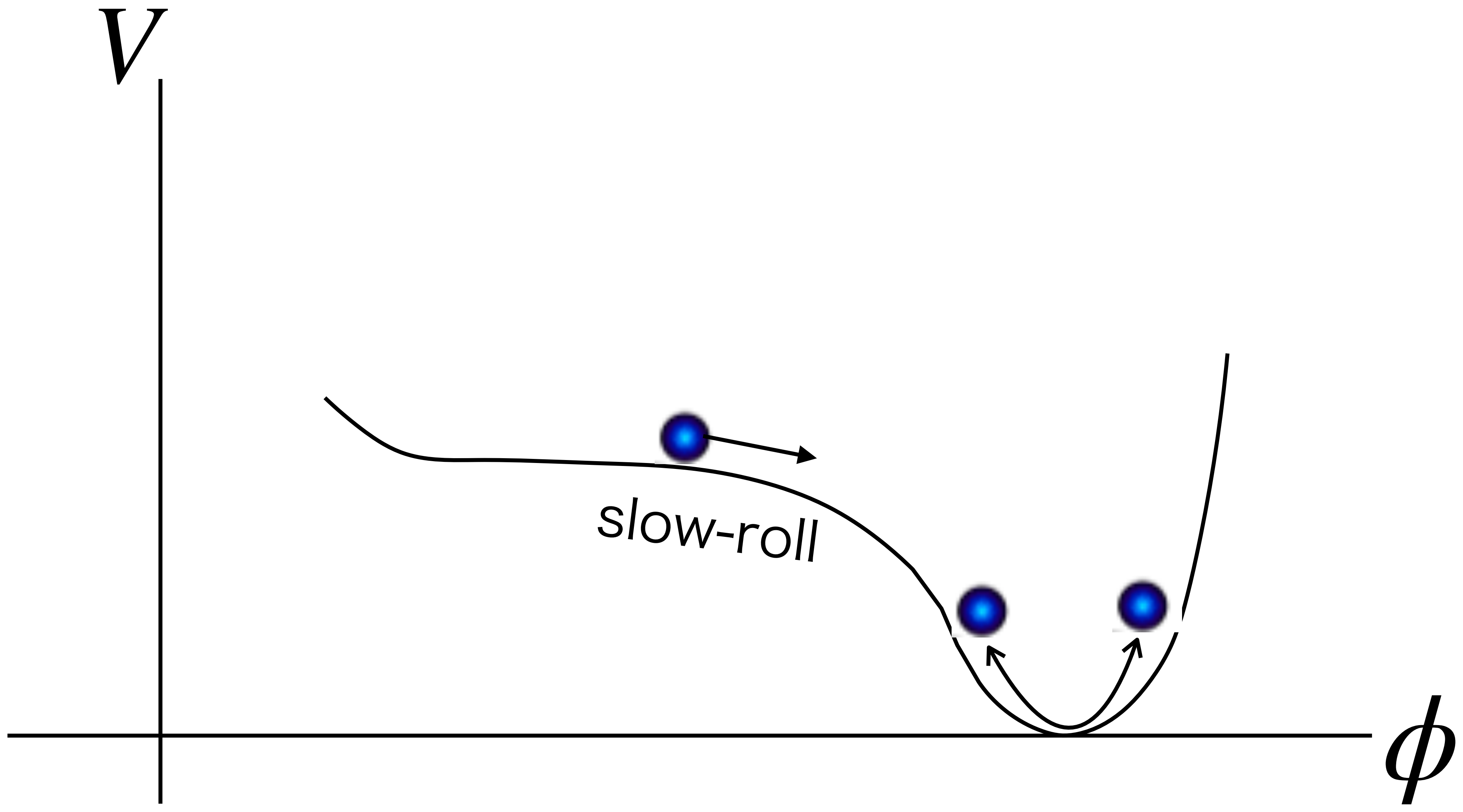

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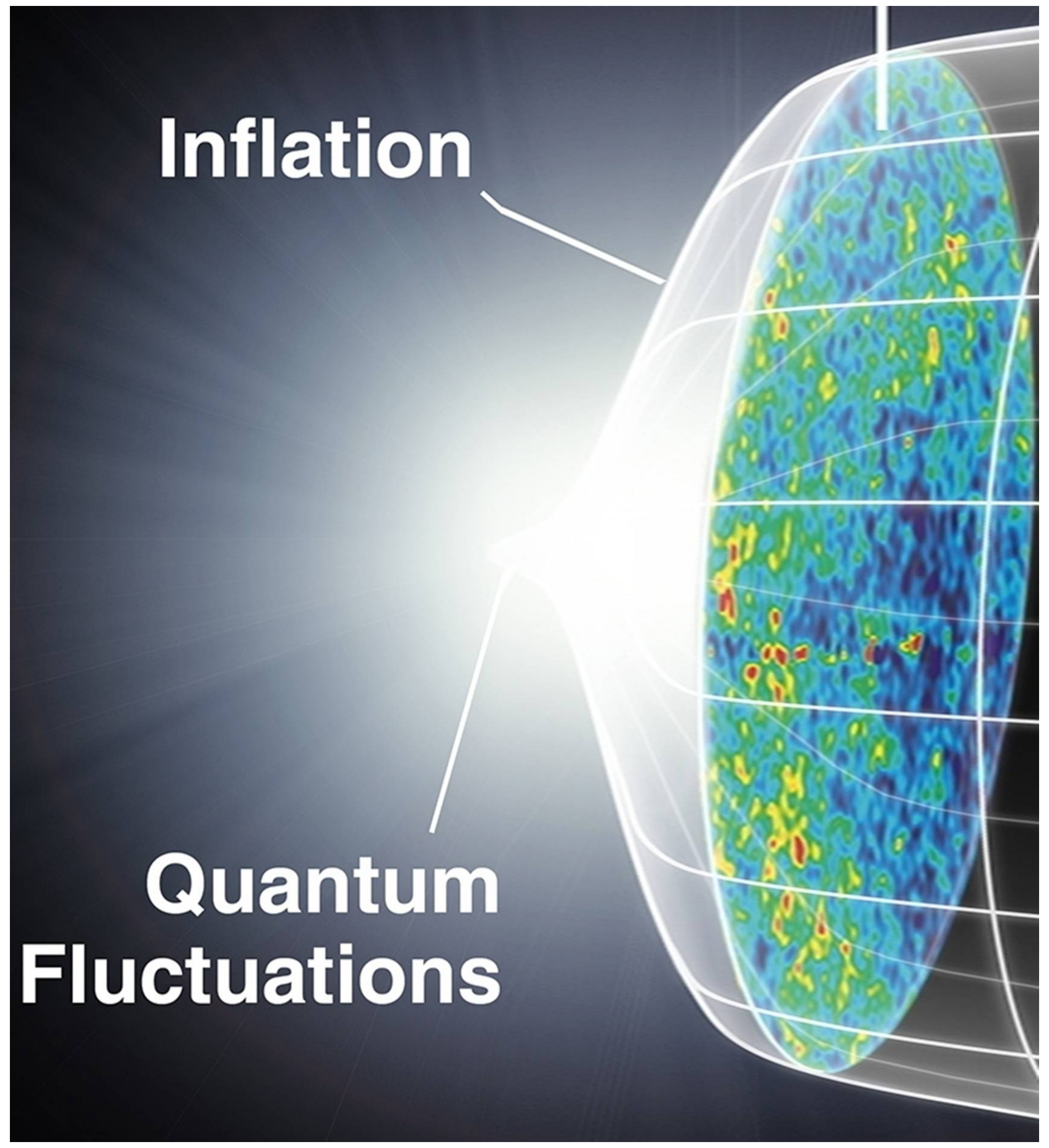

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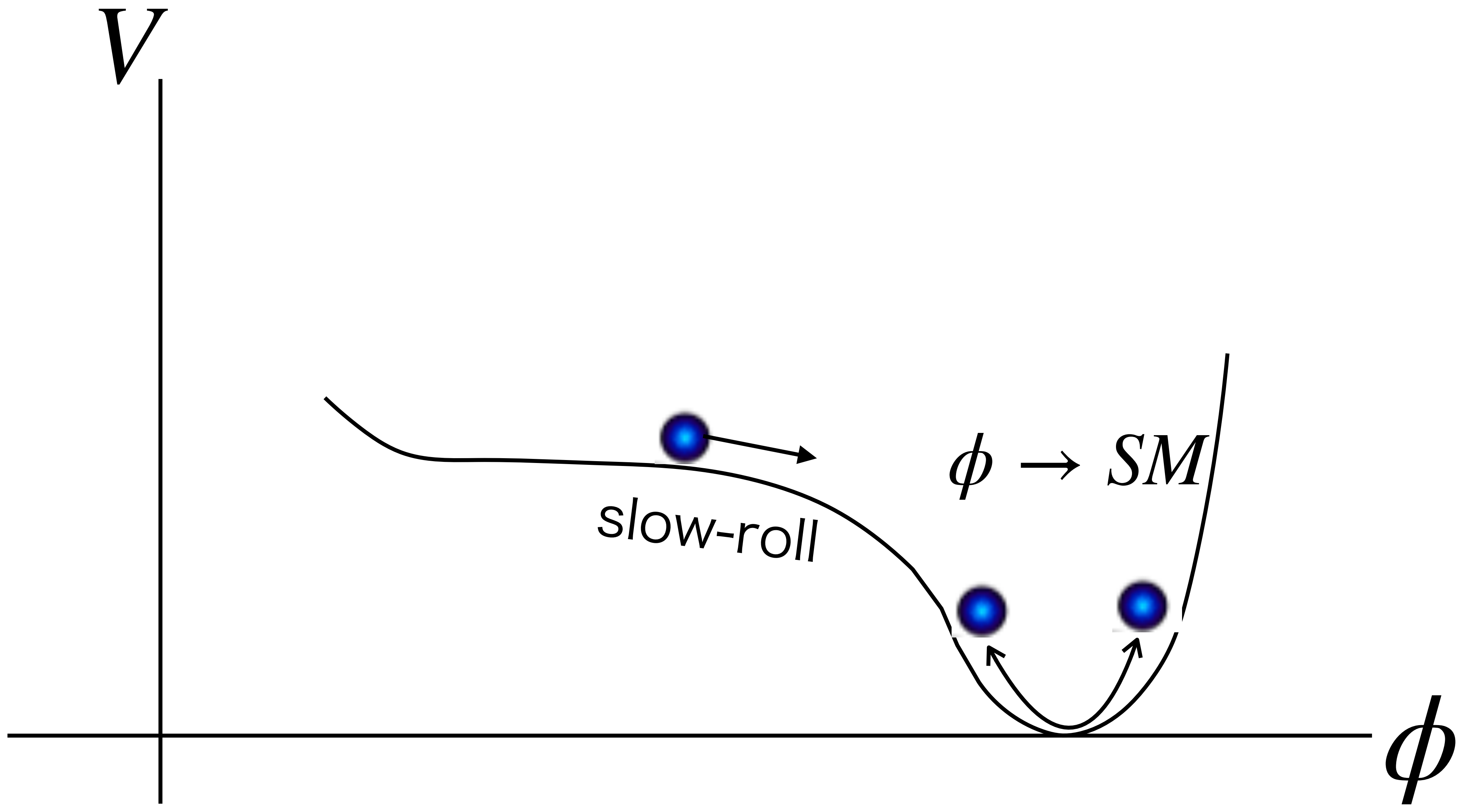

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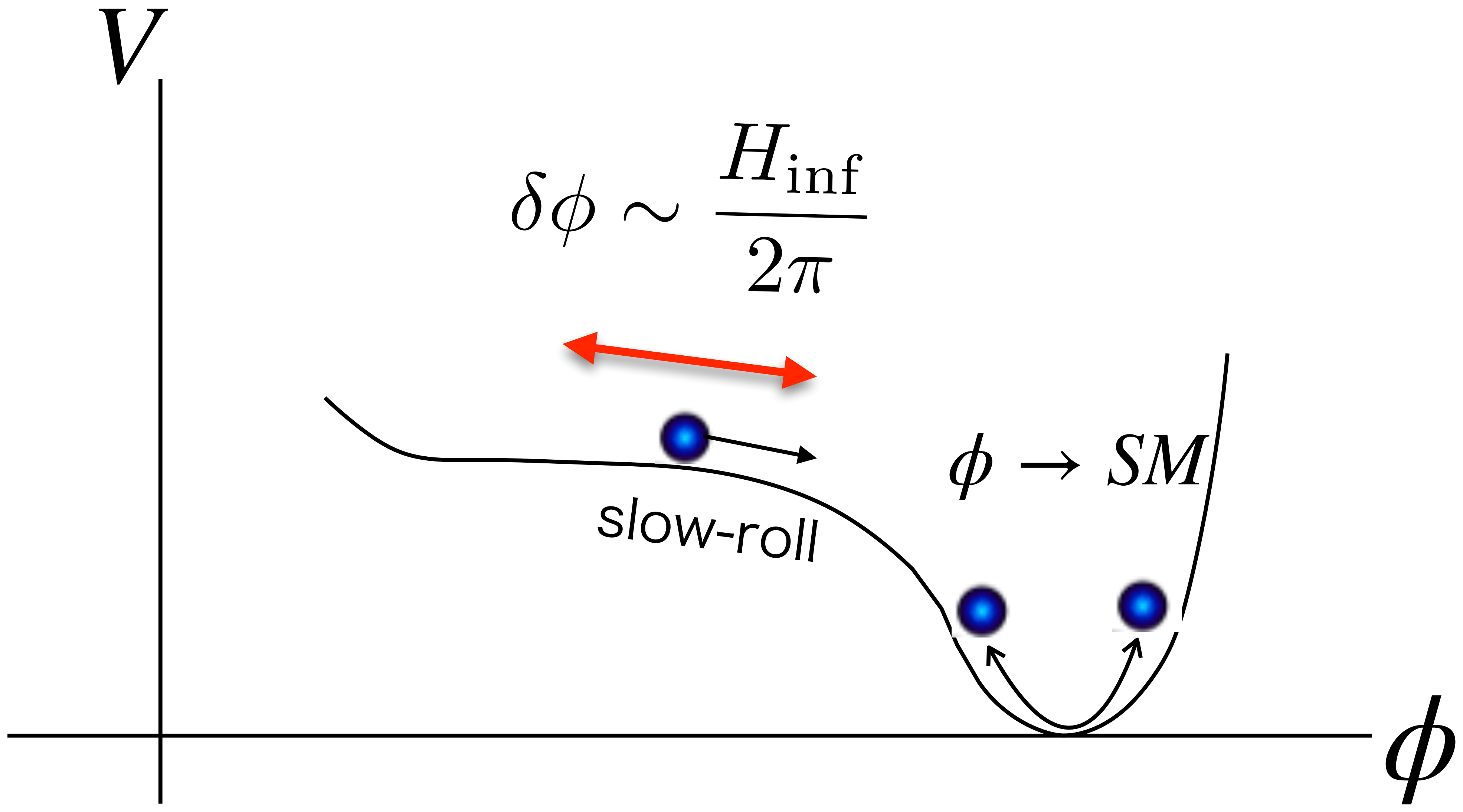

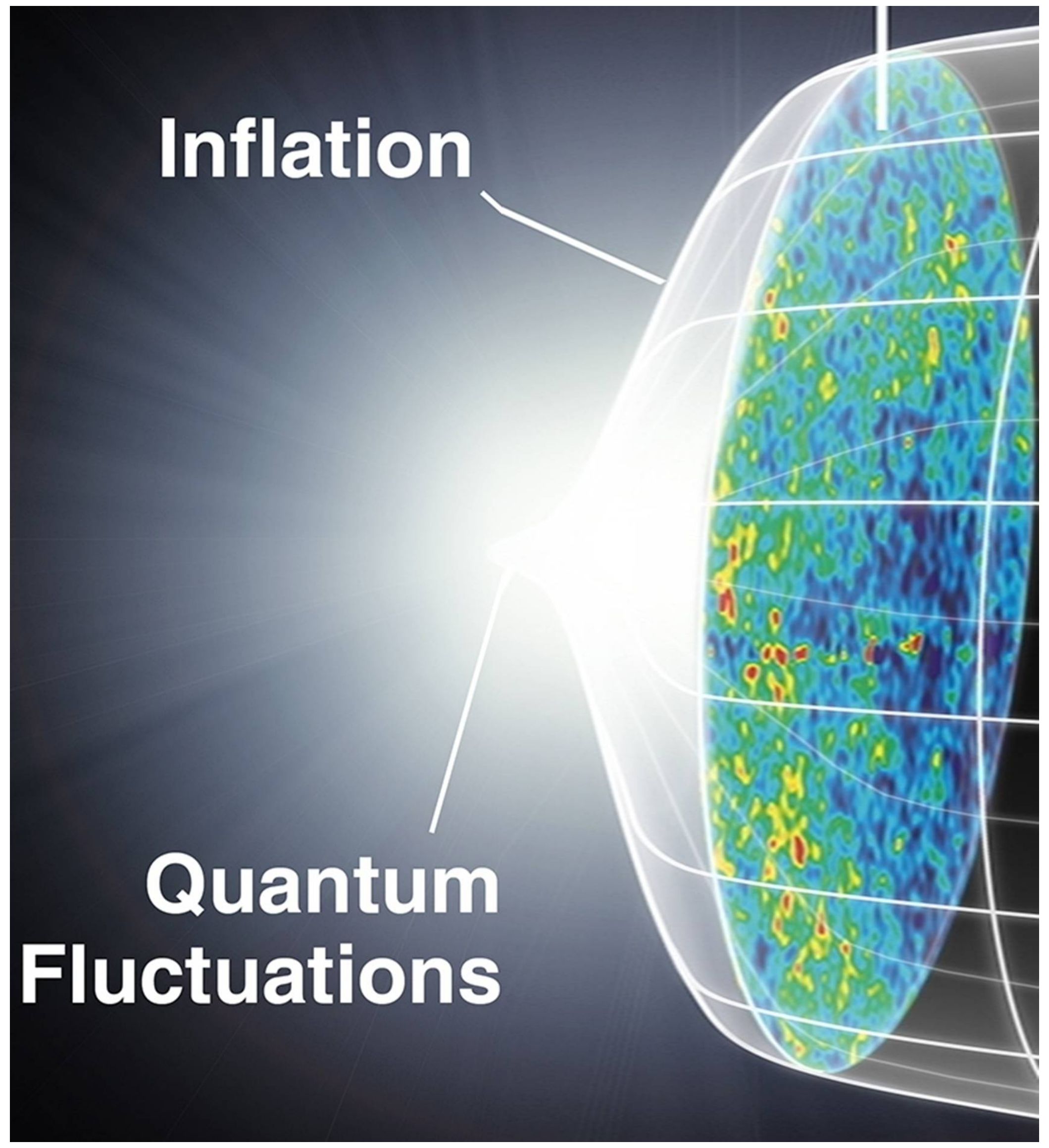

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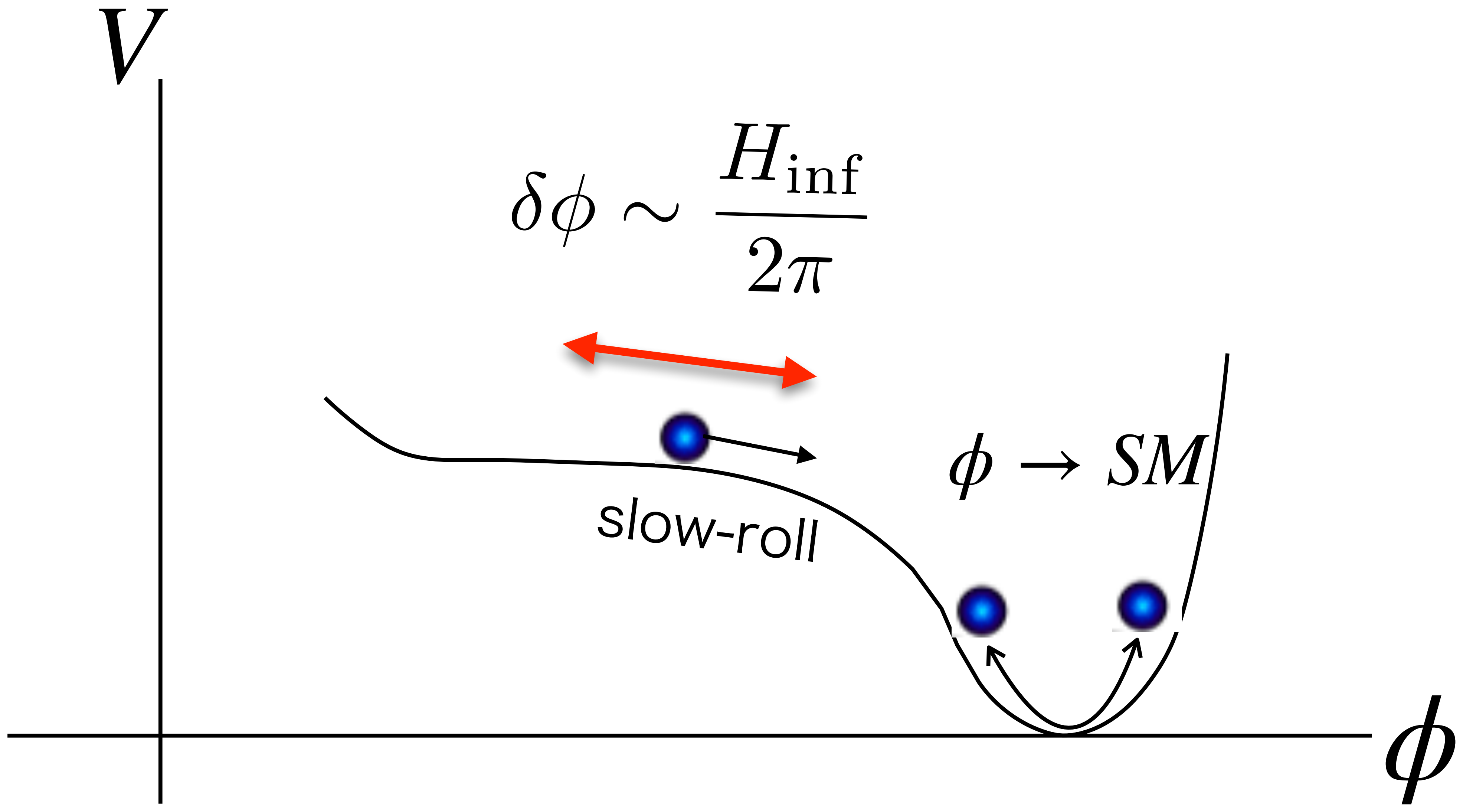
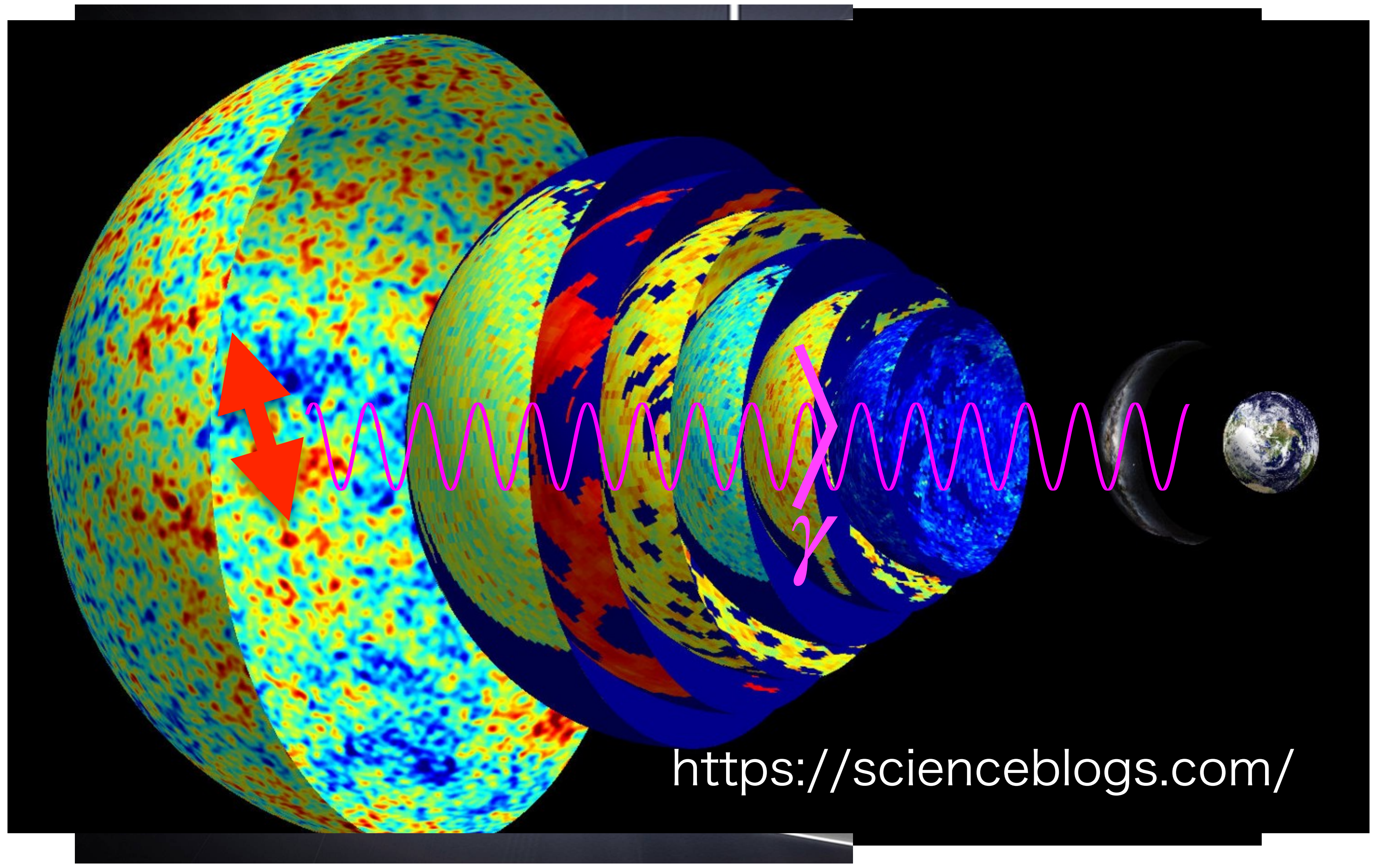


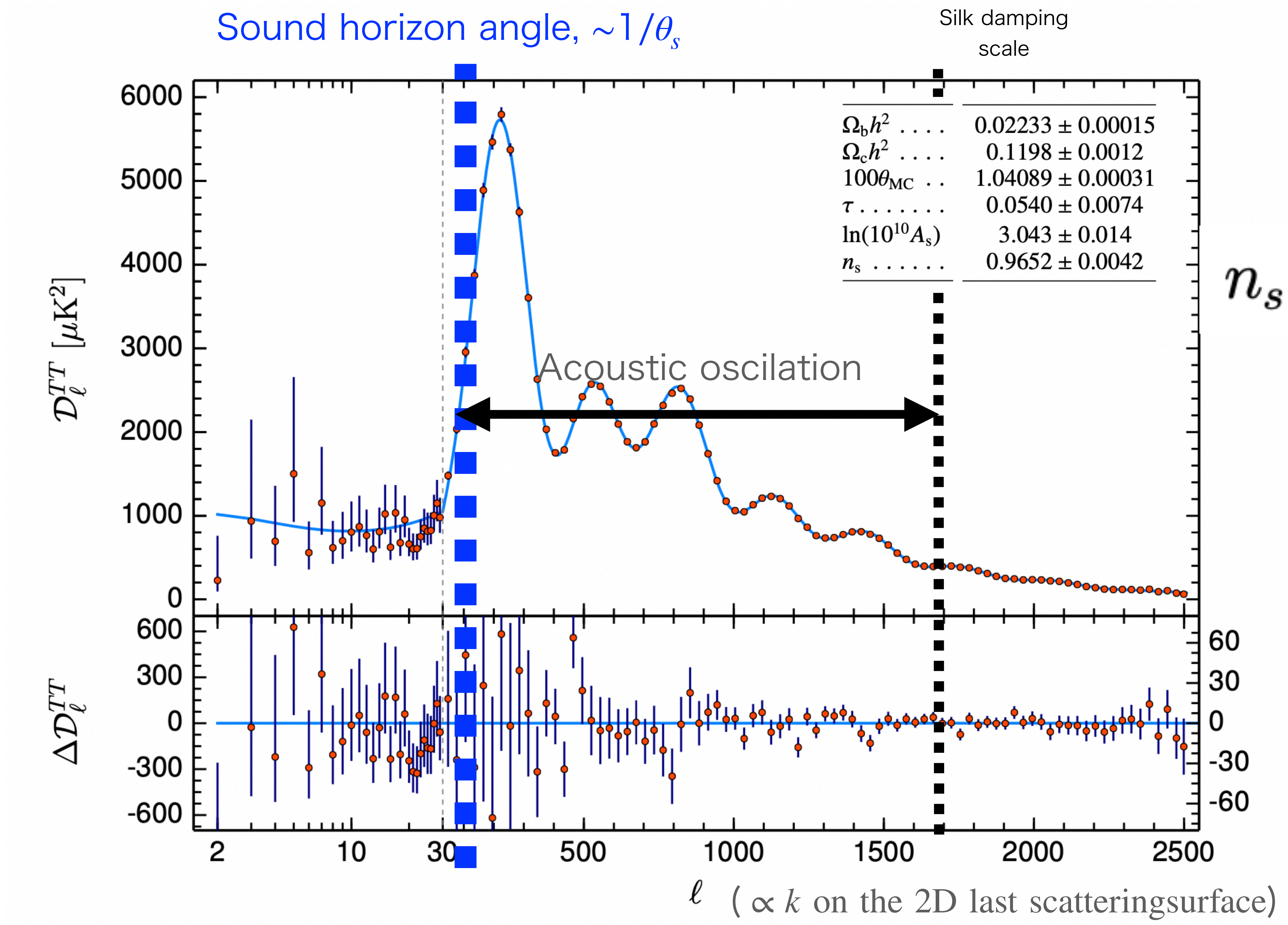
Last scattering of photon at recombination



Inflation predicts temperature fluctuation in CMB.

Primordial curvature perturbation and CMB

The temperature fluctuation can be explained by LambdaCDM with initial condition of inflation. Planck 2018



The power spectrum of the primordial curvature perturbation.

$$\mathscr{P}_\zeta[k] = \mathscr{P}_\zeta[k_{\rm CMB}]\left(\frac{k}{k_{\rm CMB}}\right)^{n_s-1} \qquad \mathscr{P}_\zeta[k_{\rm CMB}] = \frac{H_*^2}{8\pi^2\varepsilon M_{\rm pl}^2},$$

$$n_s - 1 \simeq -6\varepsilon + 2\eta, \qquad \varepsilon \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V'_{\rm inf}}{V_{\rm inf}}\right)^2, \qquad \eta \equiv M_{\rm pl}^2\frac{V''_{\rm inf}}{V_{\rm inf}}.$$

@ horizon exit during inflation

+

Acoustic oscillation+Silk damping

@ around and before last scattering

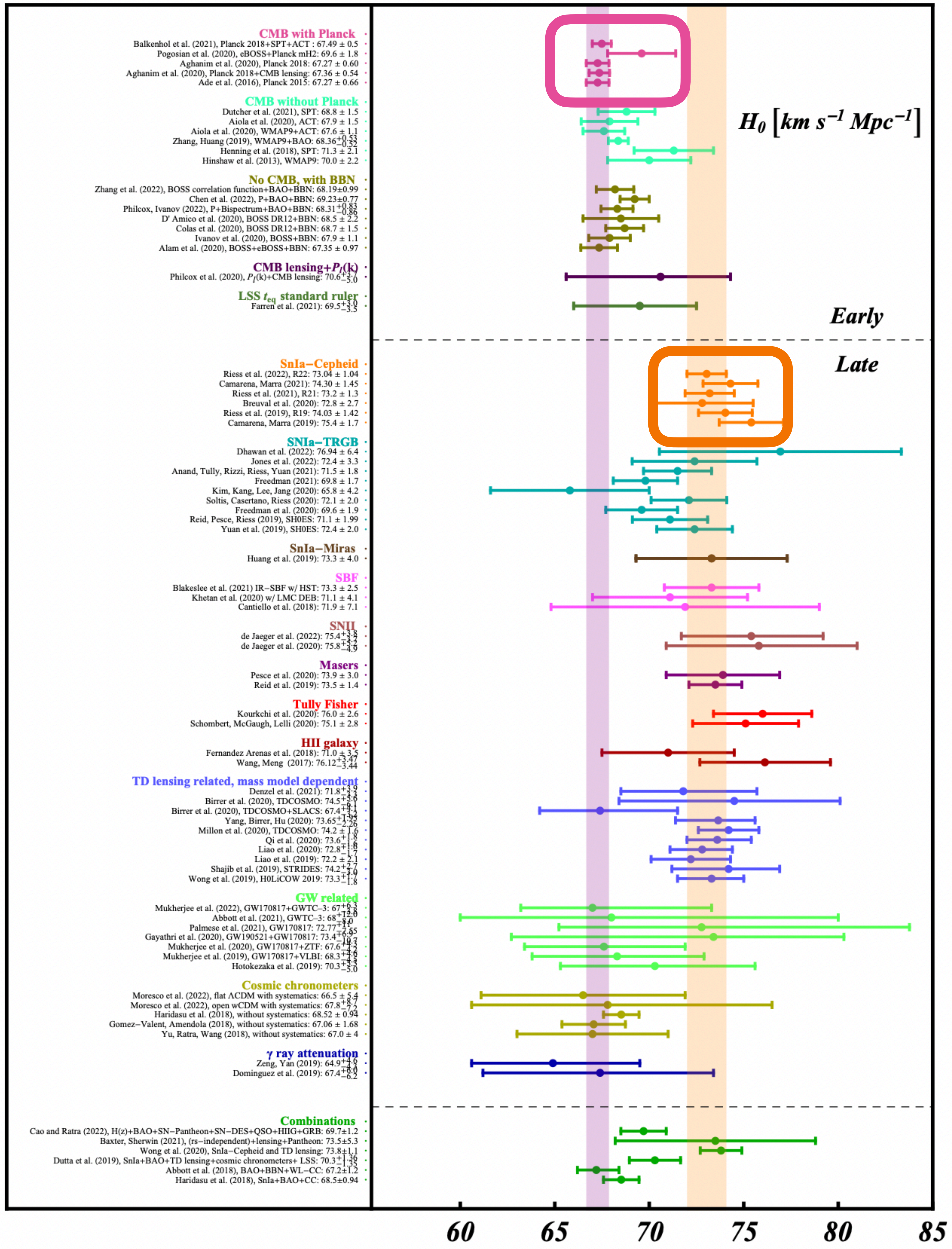
+

Doppler shift+ gravitational effect

(Sachs-Wolfe (SW) effect+ integrated SW effect)

@ photon propagation around and after last scattering

A review by Perivolaropoulos, Skara 2105.05208

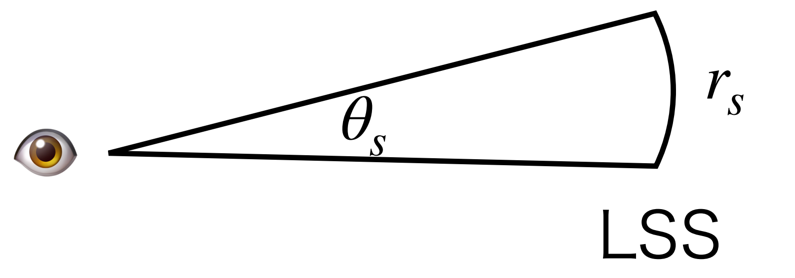


The H_0 tension

CMB+ΛCDM   CMB spectrum tells us, $\Omega_r, \Omega_c, \rho_\gamma/\rho_{baryon}, \theta_s$

Sound horizon angle

$$\theta_s = \frac{r_s}{\int_0^{z_{\rm rec}} dz/H[z, \Omega_x, H_0]}$$



Sound horizon radius

$$r_s = \int_{z_d \sim z_{\rm rec}}^{\infty} dz \frac{c_s[\rho_\gamma/\rho_{baryon}]}{H[z, \Omega_x, H_0]}$$

$$H_0^{\rm CMB} = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1} .$$

H_0 from redshift vs distance

SH0ES collaboration, 2112.04510

$$H_0^{\rm SH0ES} = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1} .$$

5σ tension with CMB+ΛCDM prediction!

Many BSM models modify the history around or after recombination to explain the H_0 tension

"The H0 Olympics: A fair ranking of proposed models" Schöneberg et al, 2107.10291 (c.f. Tokyo Olympic 2021/7/23)

	Model	$\Delta N_{\mathrm{param}}$	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	$\Delta\mathrm{AIC}$		Finalist
Early time solution, changing sound horizon, i.e. the relation between CMB power spectrum and H_0	ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X
	ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X
	SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓ 3
	mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X
	DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X
	SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X
	Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ 2
	primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓ 3
	varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ 1
	varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ 1
	EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ 2
	NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ 2
	EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ 2
Late-time solution	CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X
	PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X
	GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X
	DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X
	DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X

The H0 tension may seriously affect the very early Universe model-building.

Takahashi, WY, 2112.06710; D'Amico, Kaloper, Westphal, 2112.13861; Kallosh, Linde, 2204.02425; etc

Some promissing models predict $n_s \neq 0.97$

New Early Dark Energy 🥈: Niedermann, Sloth, 2006.06686

Parameter	ΛCDM		NEDE	
	w/ H_0	w/o H_0	w/ H_0	w/o H_0
$100\,\omega_b$	$2.251^{+0.014}_{-0.013}$ (2.251)	$2.240^{+0.014}_{-0.014}$ (2.242)	$2.292^{+0.022}_{-0.024}$ (2.297)	$2.271^{+0.020}_{-0.020}$ (2.271)
$\omega_{\rm cdm}$	$0.1184^{+0.0009}_{-0.0009}$ (0.1183)	$0.1194^{+0.0009}_{-0.0009}$ (0.1194)	$0.1304^{+0.0034}_{-0.0035}$ (0.1306)	$0.1261^{+0.0033}_{-0.0042}$ (0.1254)
h	$0.6813^{+0.0041}_{-0.0041}$ (0.6816)	$0.6763^{+0.0042}_{-0.0042}$ (0.6764)	$0.714^{+0.010}_{-0.010}$ (0.715)	$0.696^{+0.010}_{-0.013}$ (0.695)
$\ln 10^{10} A_s$	$3.053^{+0.014}_{-0.016}$ (3.053)	$3.049^{+0.013}_{-0.015}$ (3.050)	$3.067^{+0.014}_{-0.015}$ (3.068)	$3.059^{+0.014}_{-0.016}$ (3.058)
n_s	$0.9686^{+0.0037}_{-0.0037}$ (0.9698)	$0.9661^{+0.0038}_{-0.0037}$ (0.9672)	$0.9889^{+0.006}_{-0.006}$ (0.9912)	$0.9792^{+0.0073}_{-0.0082}$ (0.9794)
τ_{reio}	$0.0599^{+0.0071}_{-0.0078}$ (0.0598)	$0.0570^{+0.0064}_{-0.0075}$ (0.0572)	$0.0571^{+0.0068}_{-0.0077}$ (0.0572)	$0.0562^{+0.0065}_{-0.0075}$ (0.0558)
$f_{\rm NEDE}$	–	–	$0.126^{+0.032}_{-0.029}$ (0.1296)	$0.077^{+0.038}_{-0.040}$ (0.072)
$\log_{10}(m/m_0)$	–	–	$2.56^{+0.12}_{-0.10}$ (2.57)	2.58 (fixed)
H_*/m	–	–	0.2 (fixed)	0.2 (fixed)
$w^*_{\rm eff}$	–	–	2/3 (fixed)	2/3 (fixed)
c_s^2	–	–	2/3 (fixed)	2/3 (fixed)
σ_8	$0.8090^{+0.0060}_{-0.0065}$ (0.8092)	$0.8104^{+0.0057}_{-0.0061}$ (0.8110)	$0.841^{+0.010}_{-0.010}$ (0.841)	$0.828^{+0.0010}_{-0.012}$ (0.826)
S_8	$0.814^{+0.010}_{-0.010}$	$0.824^{+0.010}_{-0.010}$	$0.841^{+0.012}_{-0.012}$	$0.837^{+0.012}_{-0.012}$
r_s^d [Mpc]	$147.40^{+0.23}_{-0.23}$ (147.38)	$147.20^{+0.23}_{-0.23}$ (147.19)	$141.0^{+1.6}_{-1.7}$ (140.9)	$143.5^{+2.1}_{-1.8}$ (143.8)
z_*	–	–	4920^{+620}_{-730} (4960)	5100^{+80}_{-70} (5110)
Tension SH$_0$ES	–	$4.3\,\sigma$	–	$2.5\,\sigma$
Tension S$_8$	$1.9\,\sigma$	$2.3\,\sigma$	$2.8\,\sigma$	$2.7\,\sigma$
$\Delta\chi^2$	0	0	-15.6	-2.9
$f_{\rm NEDE} \neq 0$	–	–	$4.3\,\sigma$	$1.9\,\sigma$

TABLE I. The mean value and $\pm 1\,\sigma$ error (with bestfit value in parentheses) of the cosmological parameters

Majoron 🥈: Escudero, Witte, 1909.04044

Parameter	ΛCDM	ΛCDM+$\Delta N_{\rm eff}$	Majoron + $\Delta N_{\rm eff}$
$\Delta N_{\rm eff}$	–	$0.43\ (0.358) \pm 0.18$	$0.52\ (0.545) \pm 0.19$
$m_\phi/{\rm eV}$	–	–	(0.33)
$\Gamma_{\rm eff}$	–	–	(8.1)
$100\,\Omega_b h^2$	$2.252\ (2.2563) \pm 0.016$	$2.270\ (2.2676) \pm 0.017$	$2.280\ (2.2765) \pm 0.02$
$\Omega_{\rm cdm} h^2$	$0.1176\ (0.11769) \pm 0.0012$	$0.125\ (0.1243) \pm 0.003$	$0.127\ (0.1279) \pm 0.004$
$100\ \theta_s$	$1.0421\ (1.04223) \pm 0.0003$	$1.0411\ (1.04125) \pm 0.0005$	$1.0410\ (1.04102) \pm 0.0005$
$\ln(10^{10} A_s)$	$3.09\ (3.1102) \pm 0.03$	$3.10\ (3.072) \pm 0.03$	$3.11\ (3.116) \pm 0.03$
n_s	$0.971\ (0.9690) \pm 0.004$	$0.981\ (0.9780) \pm 0.006$	$0.990\ (0.99354) \pm 0.010$
$\tau_{\rm reio}$	$0.051\ (0.0500) \pm 0.008$	$0.052\ (0.0537) \pm 0.008$	$0.052\ (0.0576) \pm 0.008$
H_0	$68.98\ (69.04) \pm 0.57$	$71.27\ (70.60) \pm 1.1$	$71.92\ (71.53) \pm 1.2$
$(R-1)_{\rm min}$	0.009	0.009	0.03
$\chi^2_{\rm min}$ high-ℓ	2341.56	2345.39	2338.84
$\chi^2_{\rm min}$ lowl	22.45	21.56	20.81
$\chi^2_{\rm min}$ lowE	395.72	395.89	396.40
$\chi^2_{\rm min}$ lensing	9.91	9.21	10.69
$\chi^2_{\rm min}$ BAO	4.74	4.5	4.69
$\chi^2_{\rm min}$ SH$_0$ES	12.34	5.82	3.10
$\chi^2_{\rm min}$ CMB	2769.6	2772.1	2766.7
$\chi^2_{\rm min}$ TOT	2786.7	2782.4	2774.5
$\chi^2_{\rm min} - \chi^2_{\rm min}\vert^{\Lambda{\rm CDM}}$	0	-4.3	-12.2

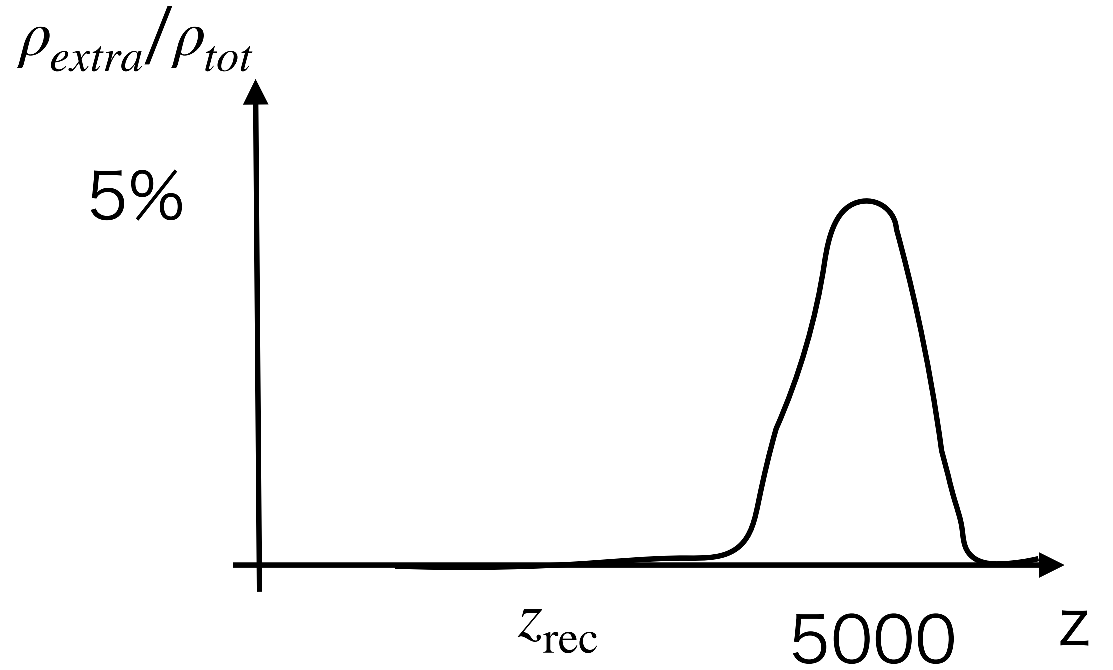
TABLE I. Mean (best-fit) values with $\pm 1\sigma$ errors of the cosmological parameters reconstructed from our combined analysis of Planck2018+BAO+SH$_0$ES data in each scenario. For comparison, the best-fit χ^2 we find for ΛCDM using Planck2018+BAO data only with $(R-1)_{\rm min} = 0.007$ is: $\chi^2_{{\rm high}-\ell} = 2340.25$, $\chi^2_{\rm lowl} = 22.54$, $\chi^2_{\rm lowE} = 395.74$, $\chi^2_{\rm lensing} = 8.92$, $\chi^2_{\rm BAO} = 3.57$, $\chi^2_{\rm CMB} = 2767.45$.

$$\boxed{n_s \approx 1 \ !?}$$

In addition, by including the local measured H0 data, $n_s = 1$ is not excluded even within the ΛCDM by varying $N_{\rm eff}, Y_{\rm He}$ Benetti, Graef, Alcaniz, 1702.06509, 1808.09201, etc

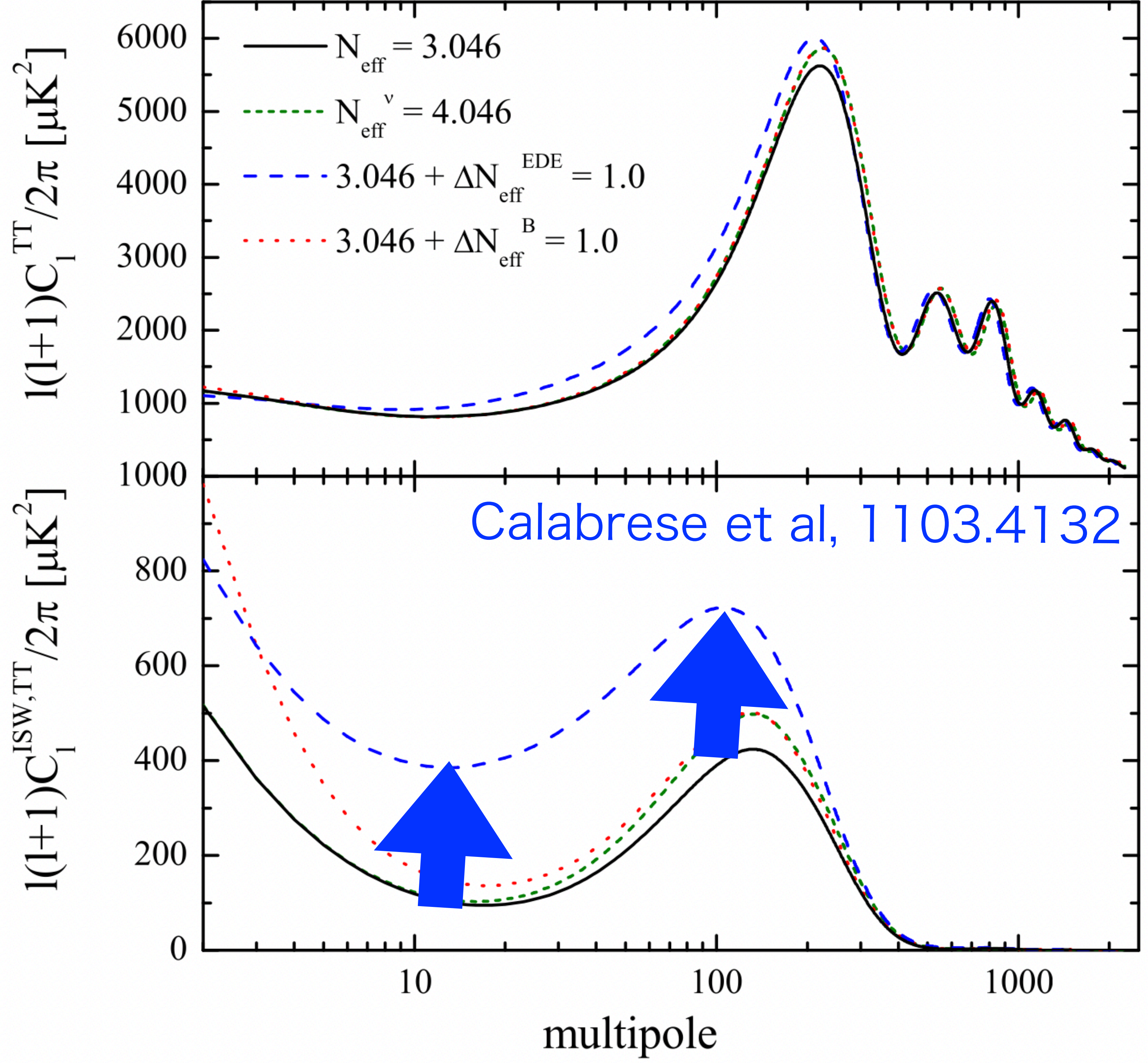
The reason of $n_s > 0.97$ in EDE

EDE: A prompt early energy components increase early H and decrease r_s, thus increase H_0



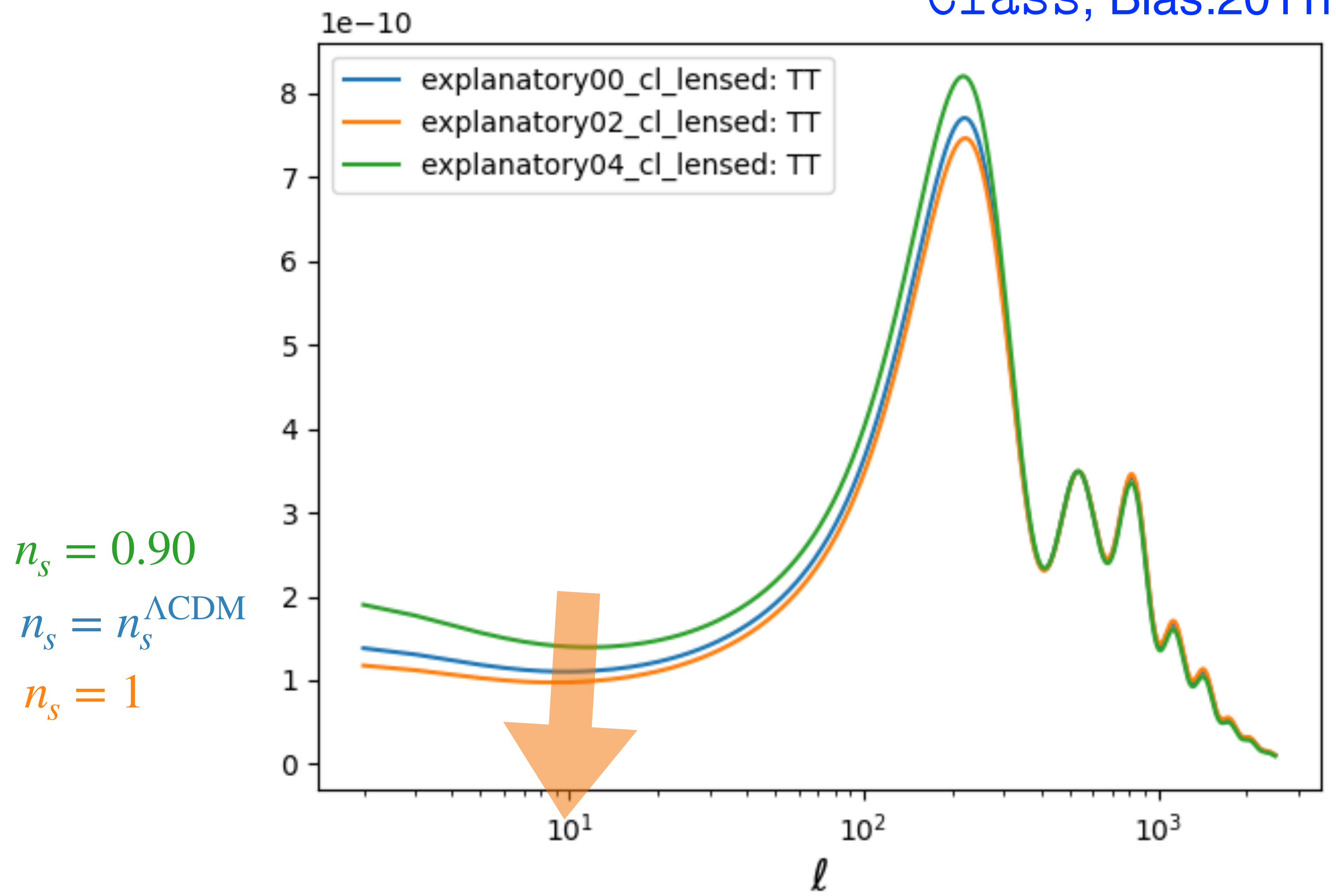
$$r_s = \int_{z_d \sim z_{\rm rec}}^{\infty} dz \frac{c_s[\rho_\gamma/\rho_{baryon}]}{H[z, \Omega_x, H_0]}$$

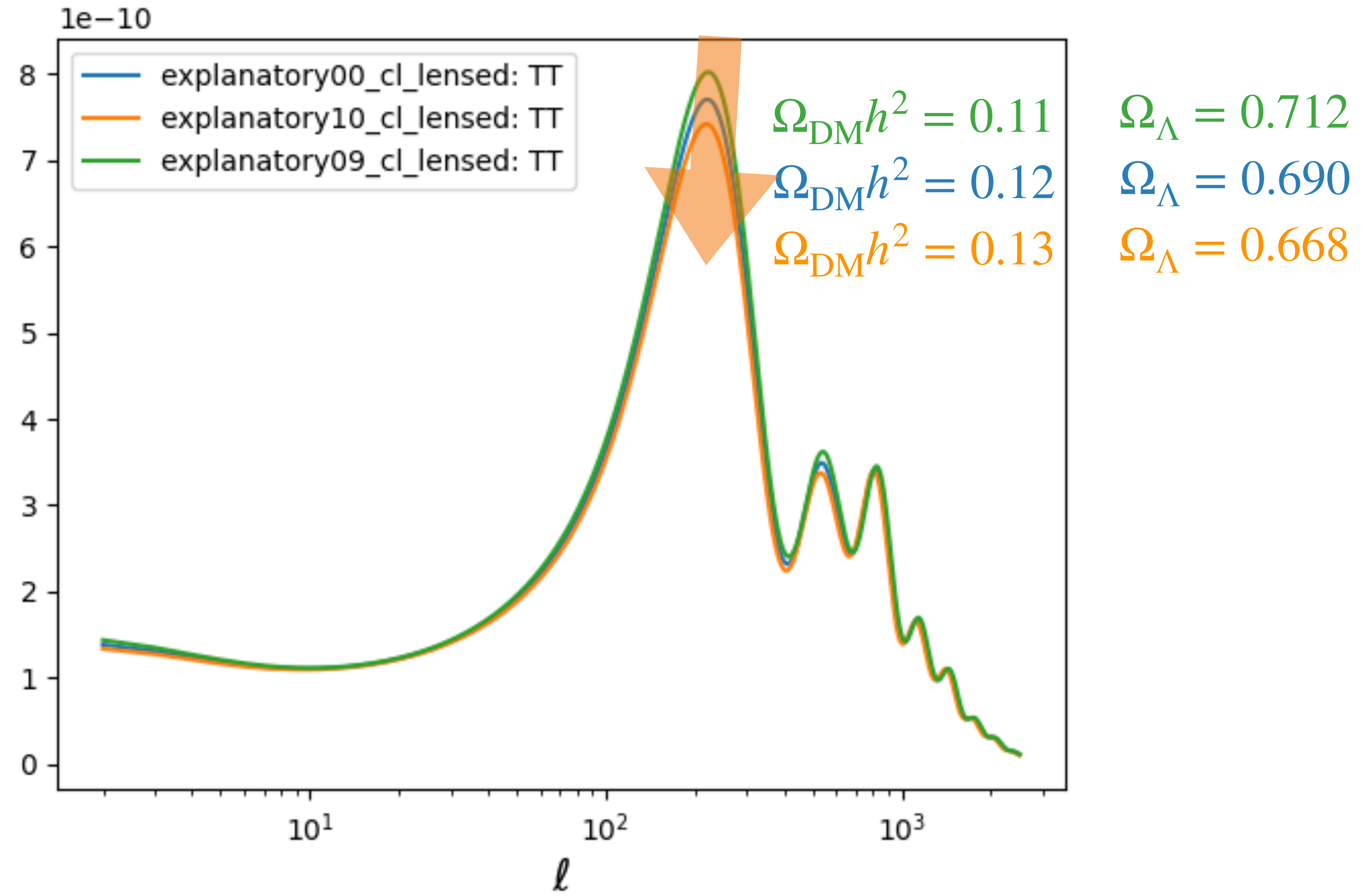
$$H_0 \propto \theta_s^{\rm measured}/r_s \propto 1/r_s$$



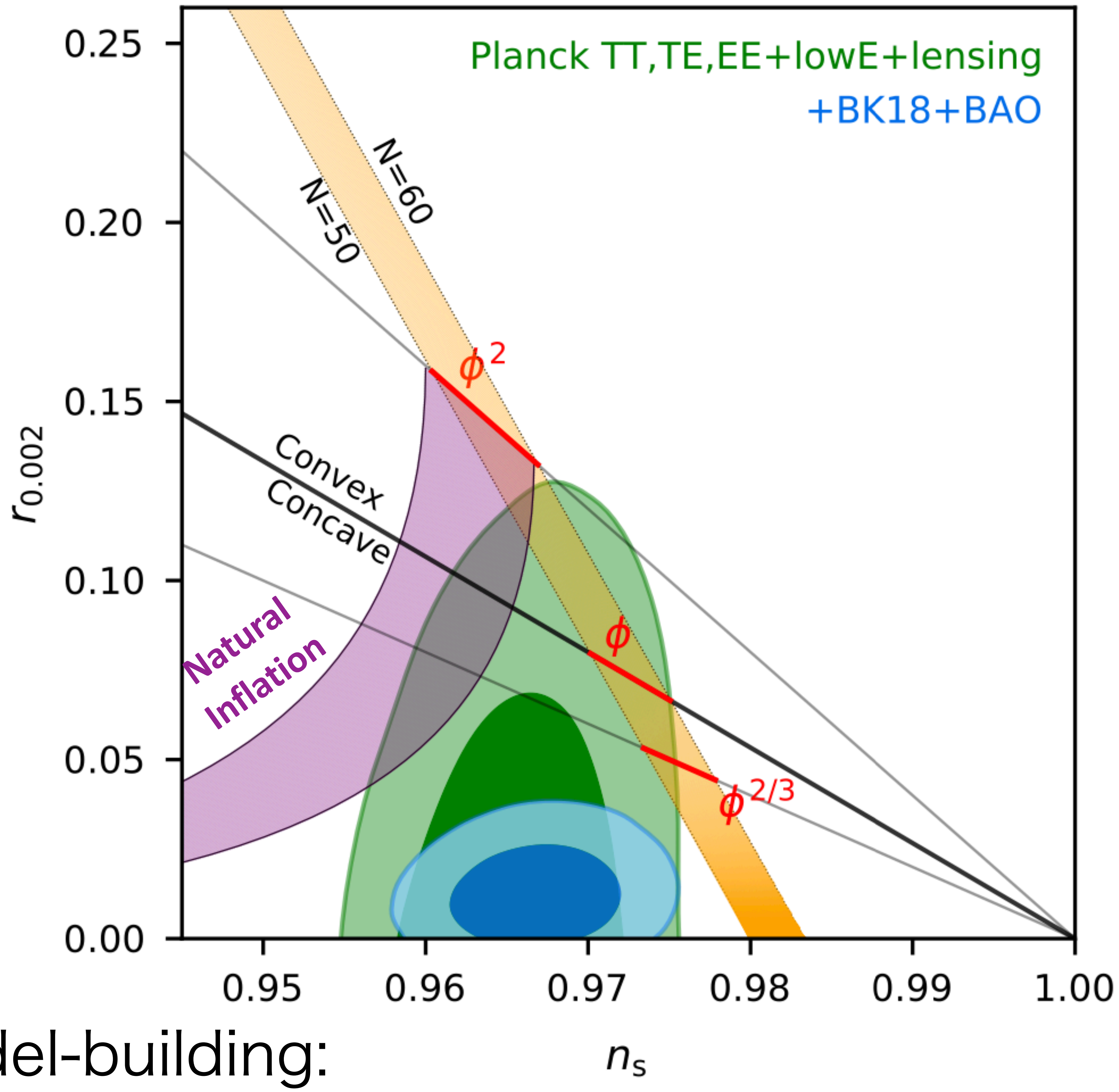
To compensate the extra Integrated Sachs-Wolfe effect, we need to increase DM density and n_s

Class, Blas:2011rf





Very early Universe cosmology is sensitive to n_s.



Comments for inflation model-building:

✦The scalar should have flat potential but a large coupling for reheating.

✦A super-Planckian field excursion is questioned from the theoretical viewpoint.

✦$n_s \neq 1$ is the prediction of the inflation.

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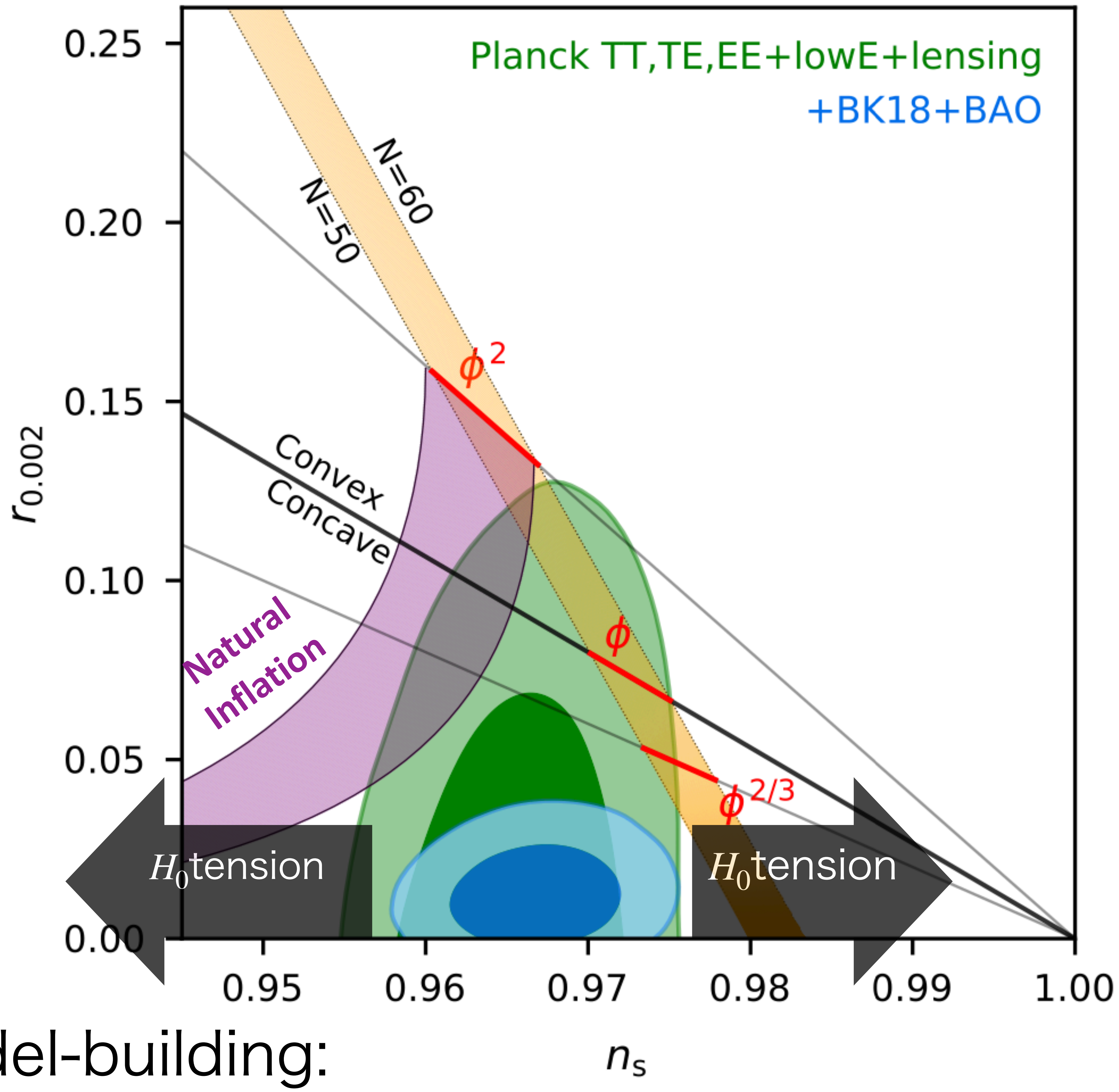

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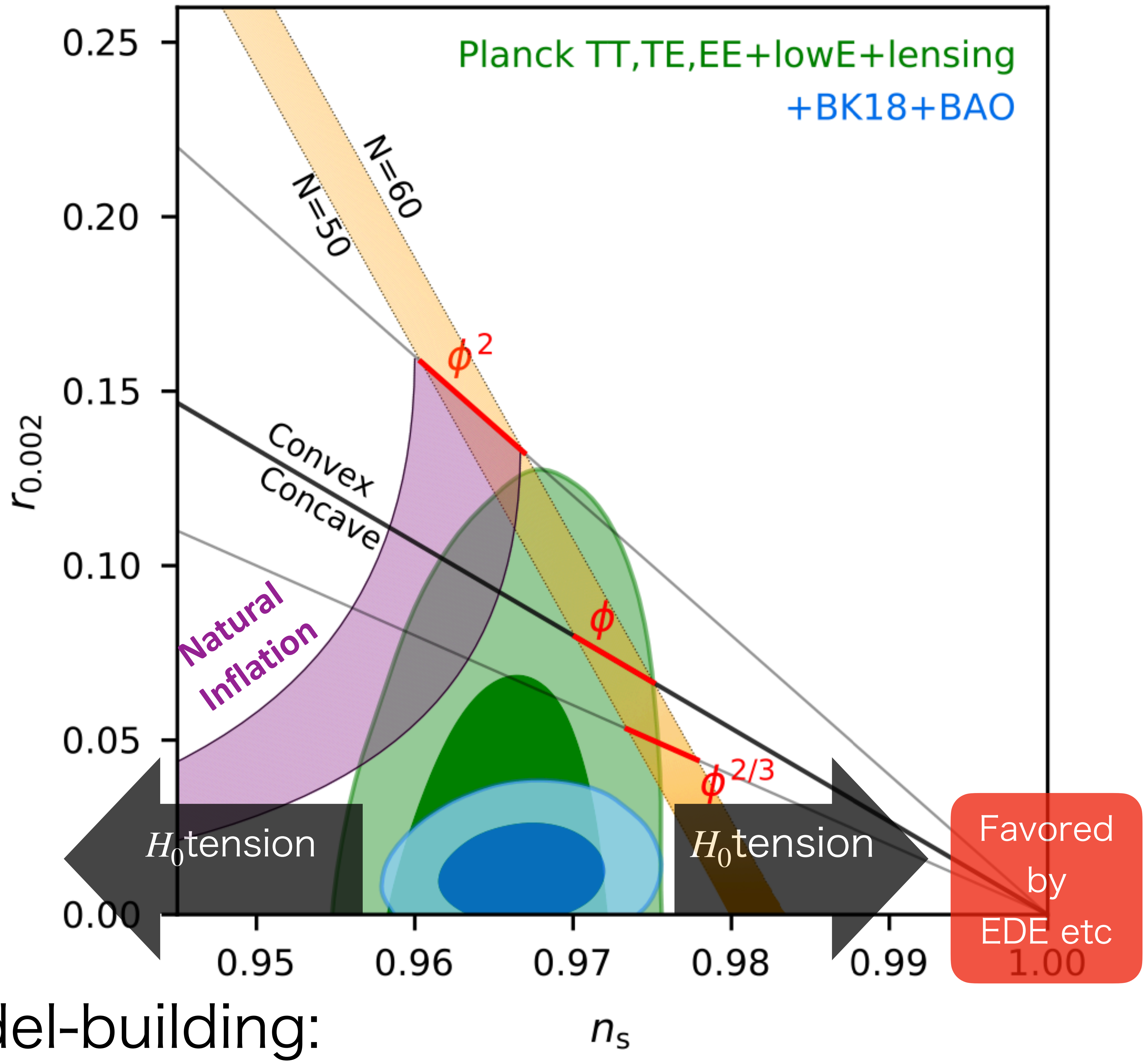

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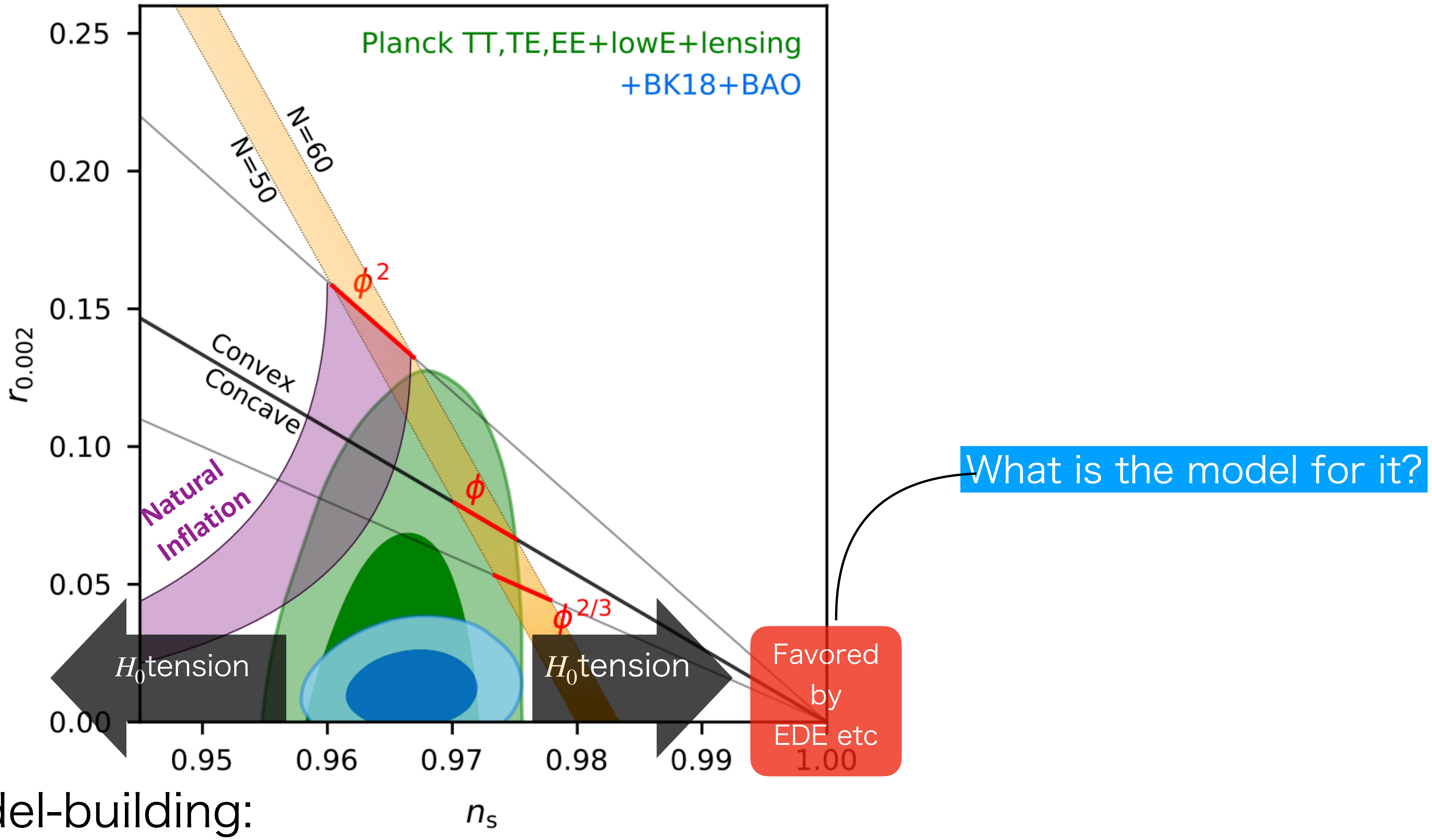

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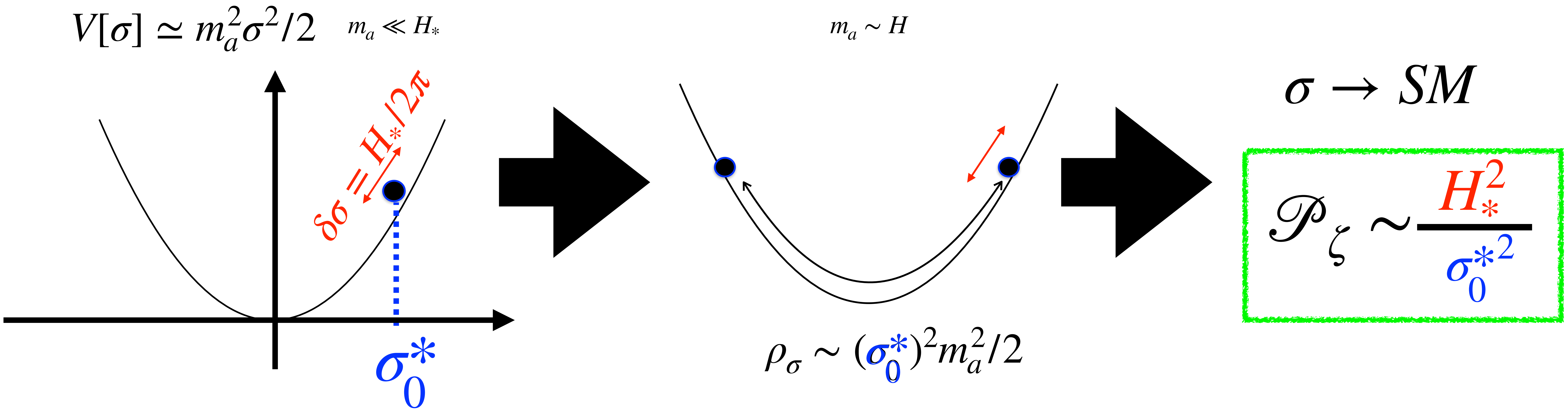
2. Stochastic axionic curvaton for $n_s = 1$

Takahashi, WY, 2112.06710;

Review of curvaton scenario

Inflaton ϕ+curvaton σ+SM

Linde, Mukhanov, 9610219; Enqvist, Sloth, 0109214;
Lyth, Wands, 0110002; Moroi, Takahashi, 0110096;



@ horizon exit of inflation

@ onset of oscillation after inflation

@ Reheating by curvaton

- Inflaton drives inflation.
- Curvaton explains primordial curvature perturbation and reheating.
- Prediction depends on its initial field value.
- String theory goes very well with the curvaton scenario c.f. moduli problem.
- The scenario naturally explains $n_s \simeq 1$.
- Thus it is difficult to explain $n_s \sim 0.97$ 😖

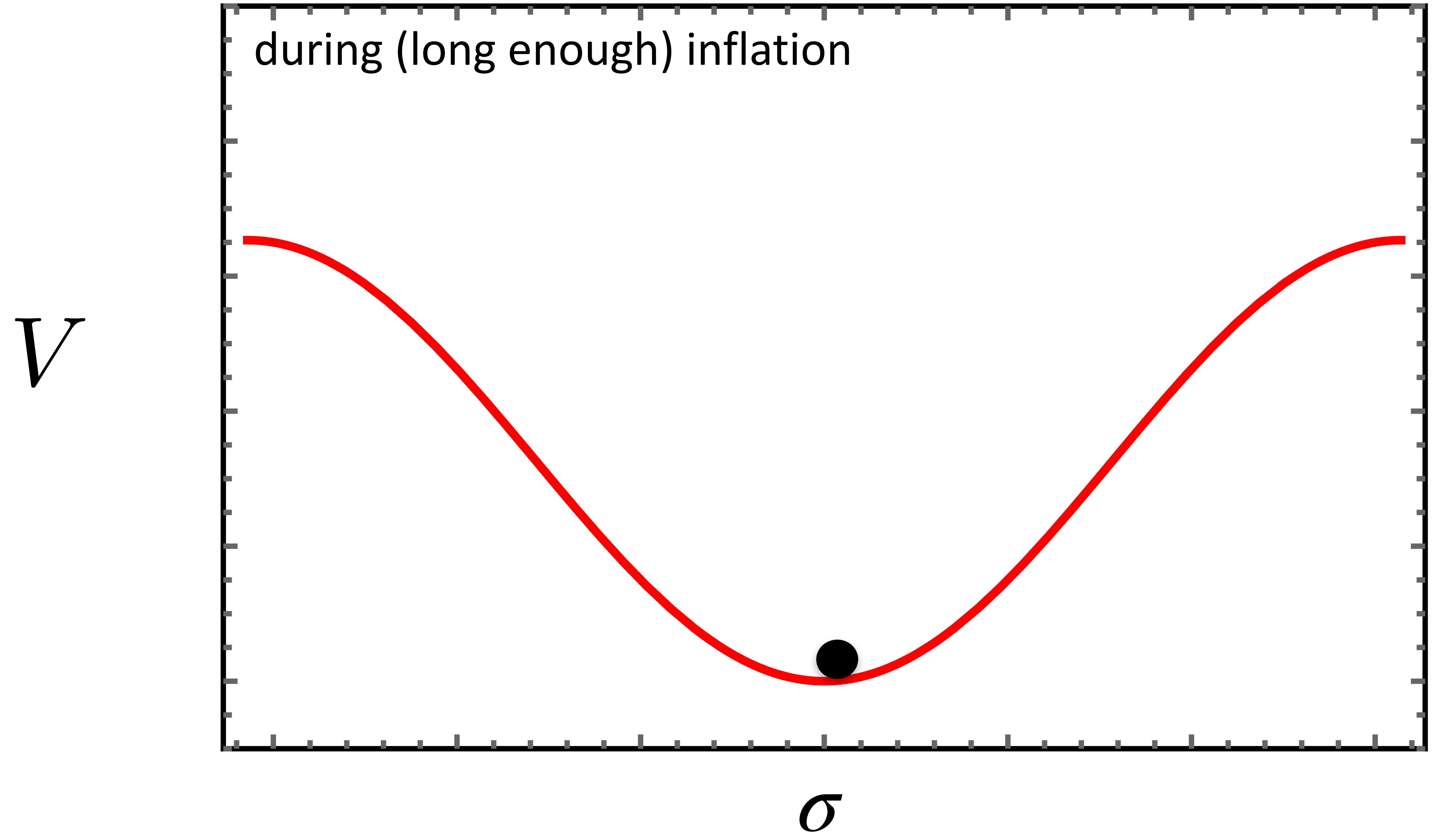
See the case with negative curvature and non-gausianity:
Kawasaki, Nakayama and Takahashi, 0810.1585;
Kawasaki, Kobayashi and Takahashi, 1107.6011;

- Given the Hubble tension preference of $n_s = 1$, the curvaton scenario becomes important. We revisit the curvaton scenario with $n_s \approx 1$.

Takahashi, WY, 2112.06710;

Light scalar distribution during inflation

Light scalar has a prefered field value during the inflation due to the equilibrium between classical motion and quantum diffusion. Starobinsky 1986, Starobinskym Yokoyama 9407016,



For stochastic axion dark matter,
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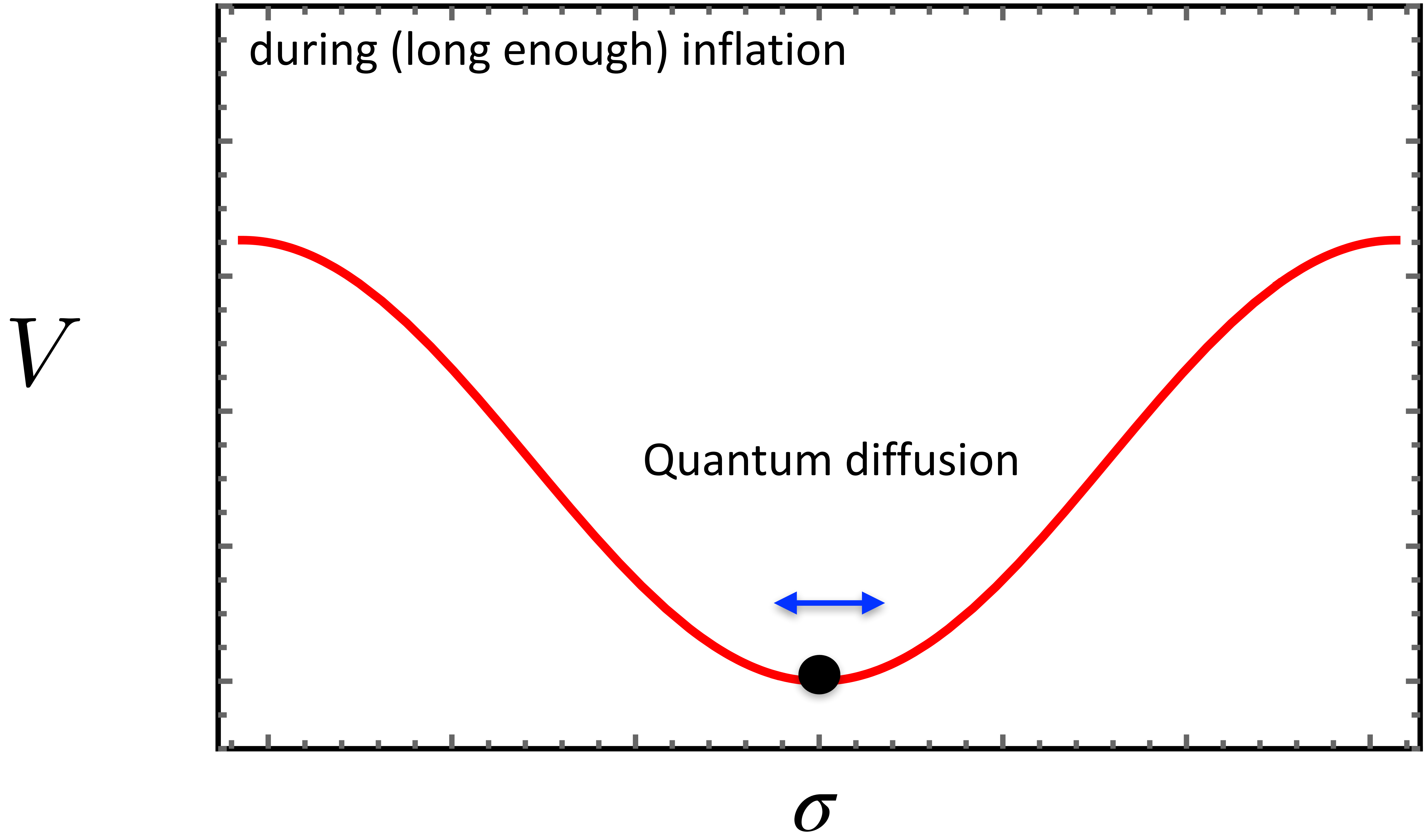

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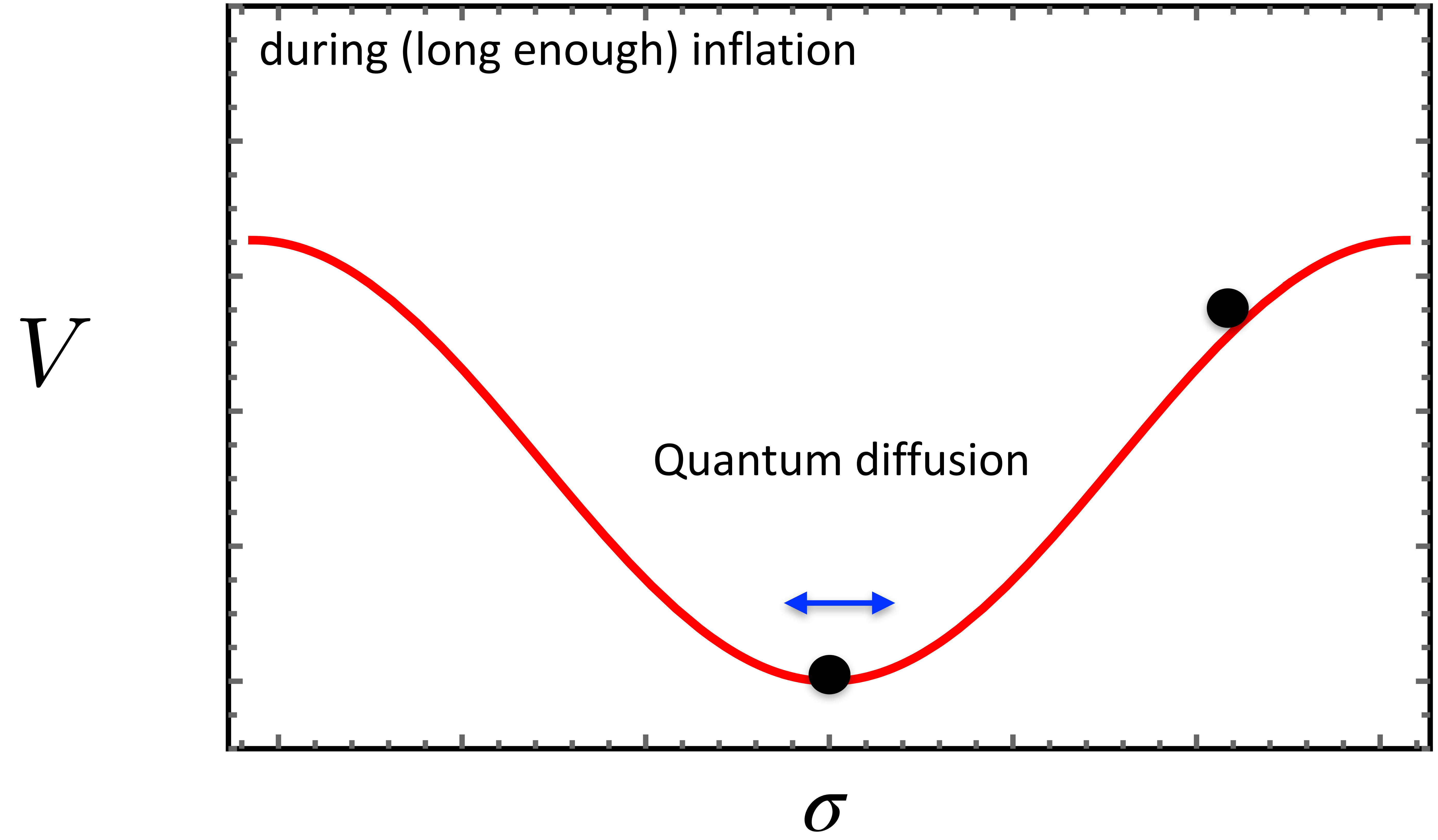

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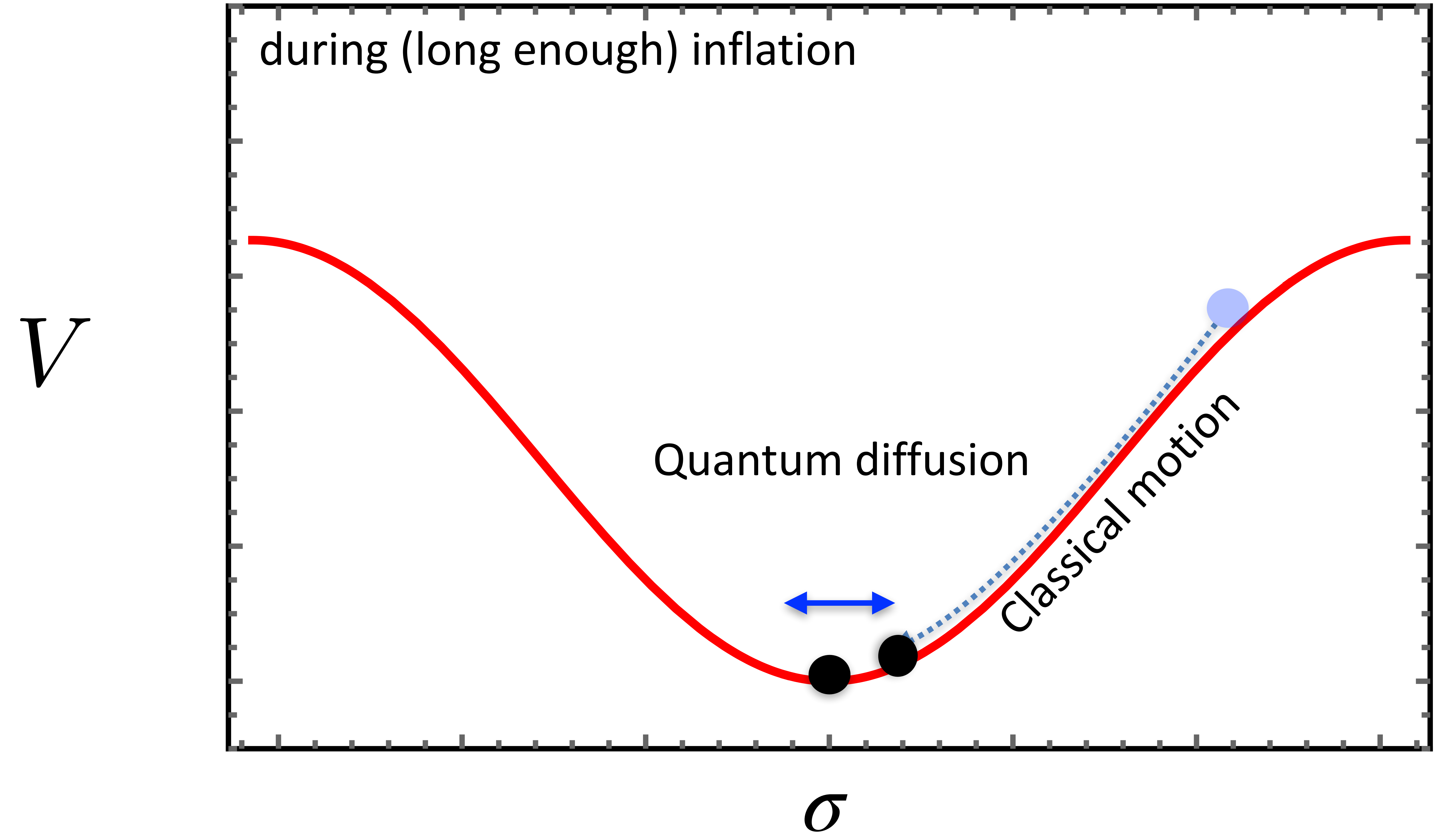

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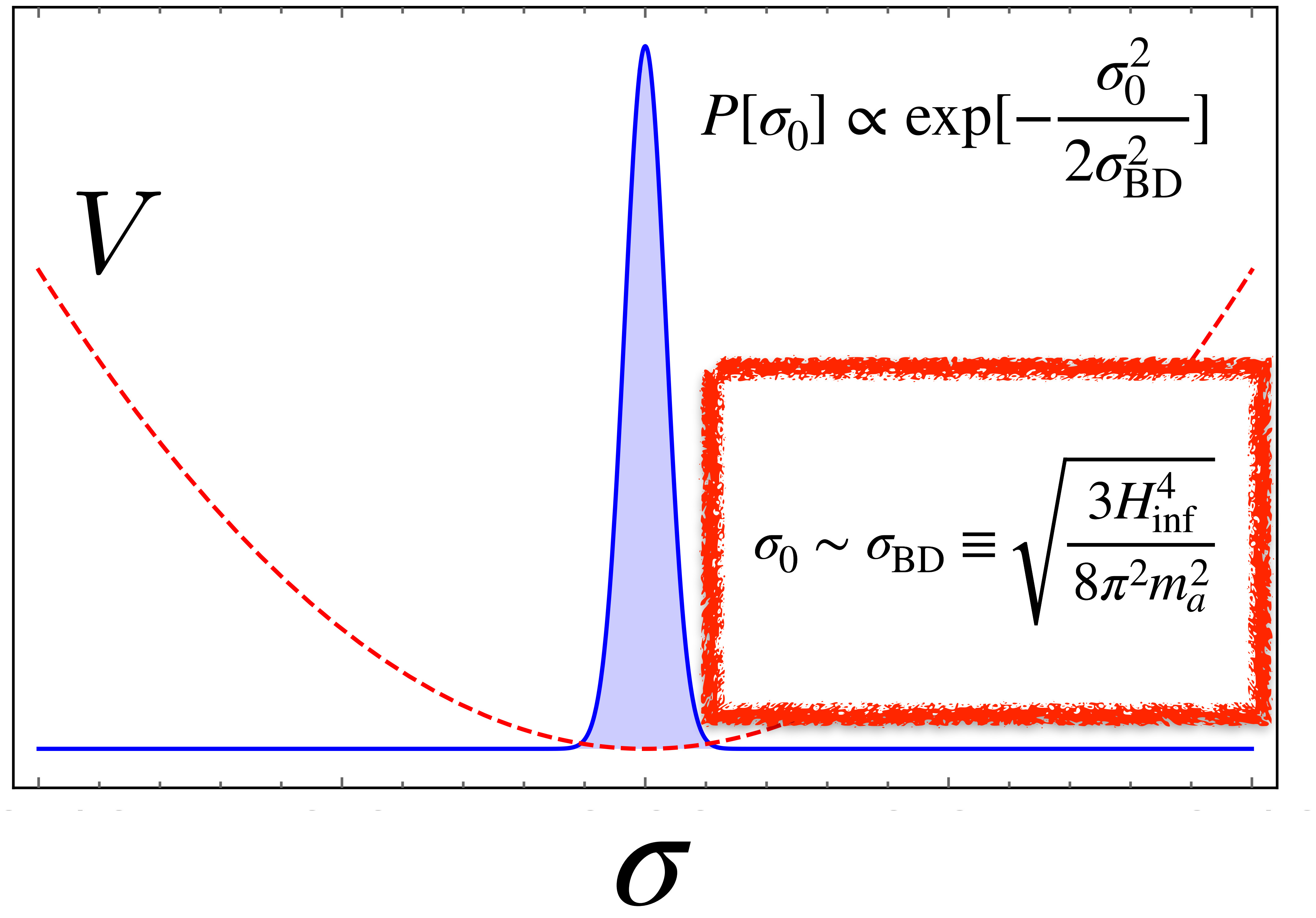
Light scalar distribution during inflation

An equilibrium distribution is formed during the long inflation.

Starobinsky 1986, Starobinskym Yokoyama 9407016,



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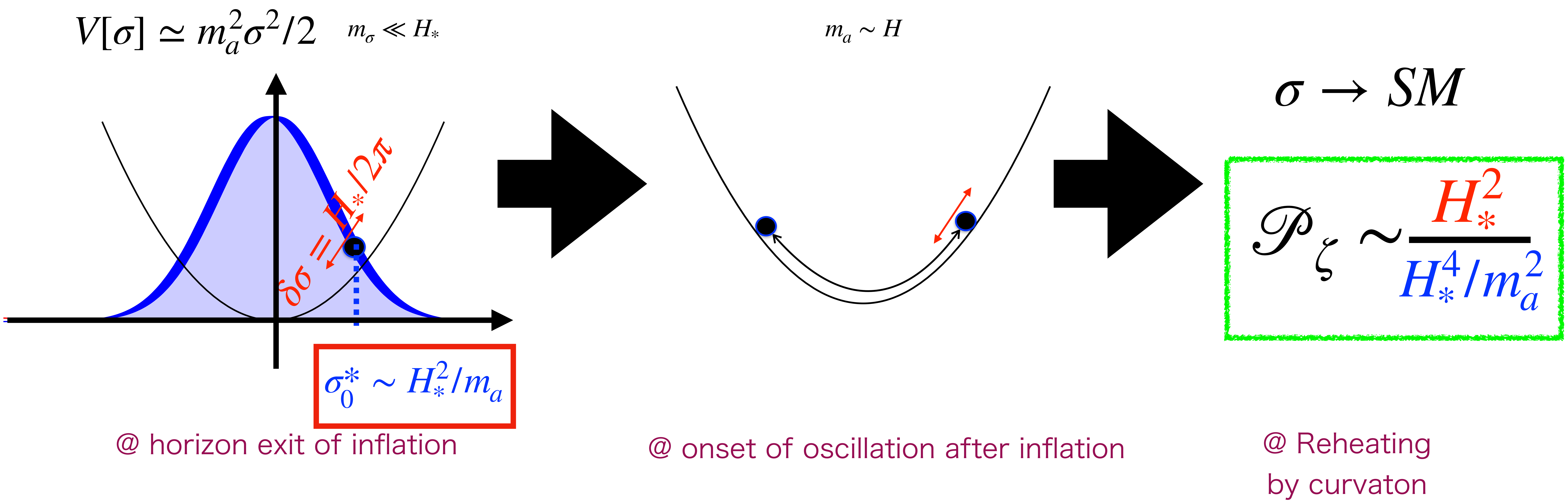
Stochastic curvaton

Takahashi, WY, 2112.06710



We include the stochastic effect to the curvaton scenario that predicts $n_s \approx 1$. The resulting power spectrum is $\mathscr{P}_\zeta \propto H_*^{-2}$

(in contrast to ordinary case $\propto H_*^2$.)

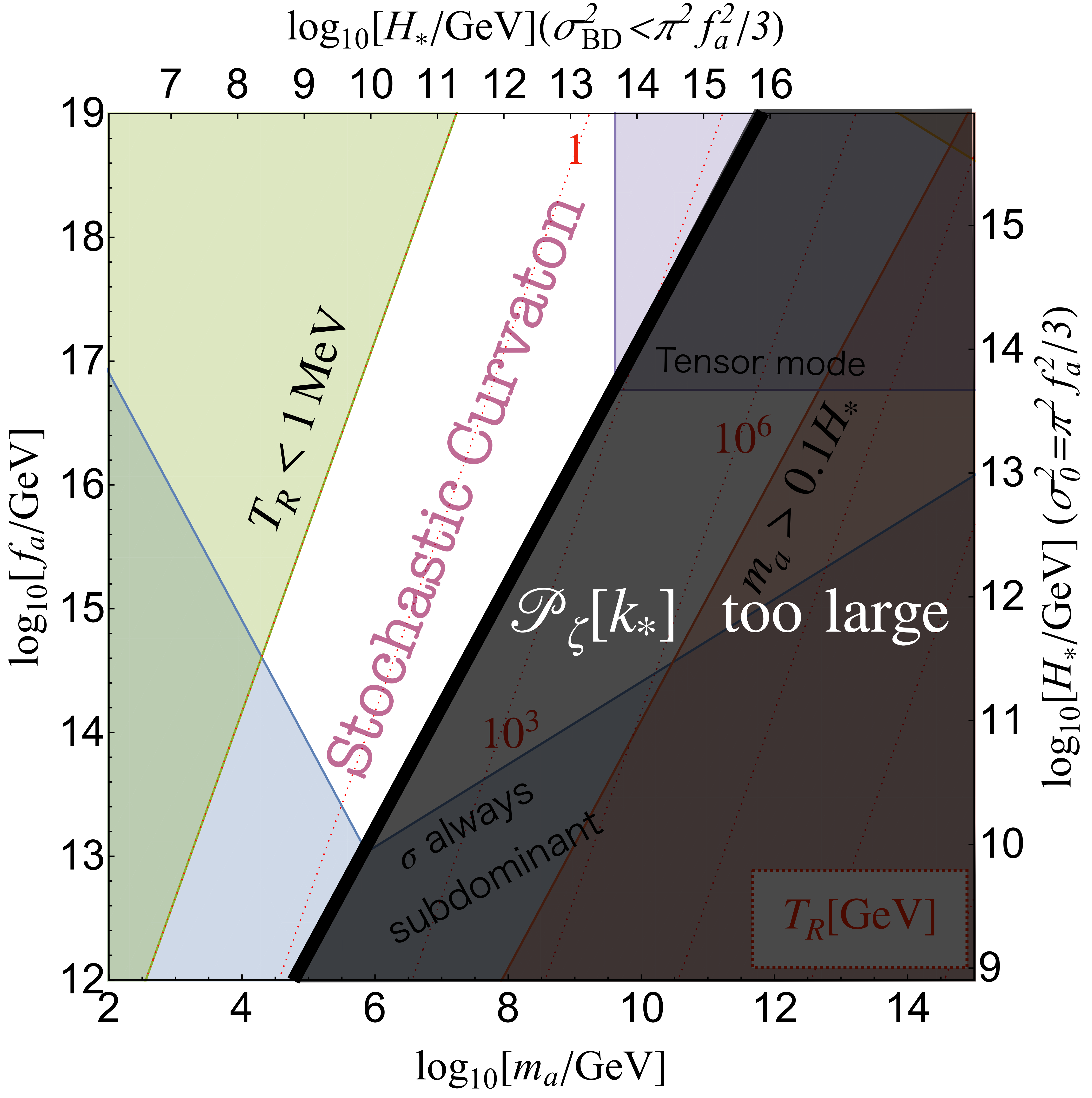
Stochastic axionic curvaton

Takahashi, WY, 2112.06710

$$V[\sigma] = \Lambda^4(1 - \cos[\sigma/f_a])$$

$$\Gamma_{\mathrm{dec},\gamma} = c_\gamma^2 \frac{\alpha^2}{64\pi^3}\frac{m_a^3}{f_a^2}\,.$$

1. The heavy mass region is incompatible.
2. subplanckian f_a, σ_0, inflaton field.
3. f_a consistent with string axion.



Short summary

1. The 5 σ Hubble tension may indicate $n_s \neq 0.97$.
2. This significantly affects the very early Universe model-building.
3. If $n_s = 1$, the axionic curvaton scenario is important.
4. We found a new parameter region "stochastic axionic curvaton", where the initial condition is set by equilibrium distribution.

3. ALP miracle, n_s, and DM mass

Daido, Takahashi WY, 1702.03284, 1710.11107;

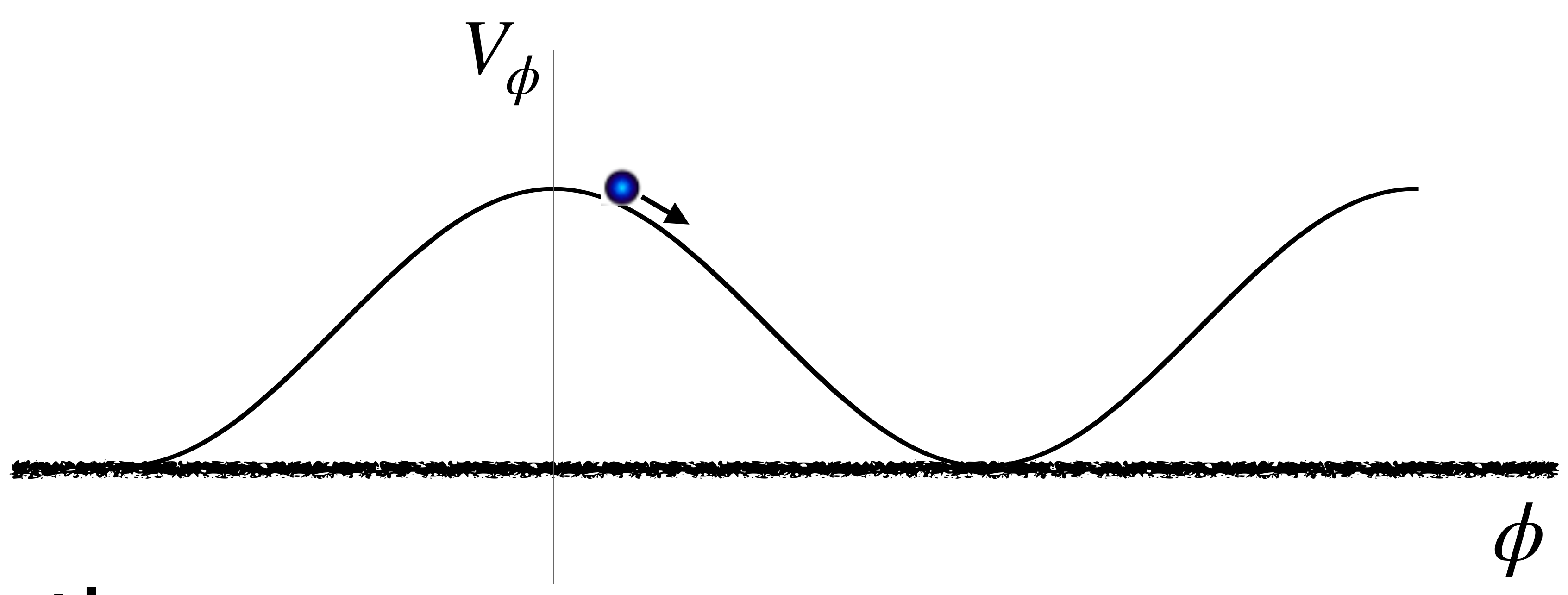
Inflaton vs dark matter (DM)

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

- Inflaton

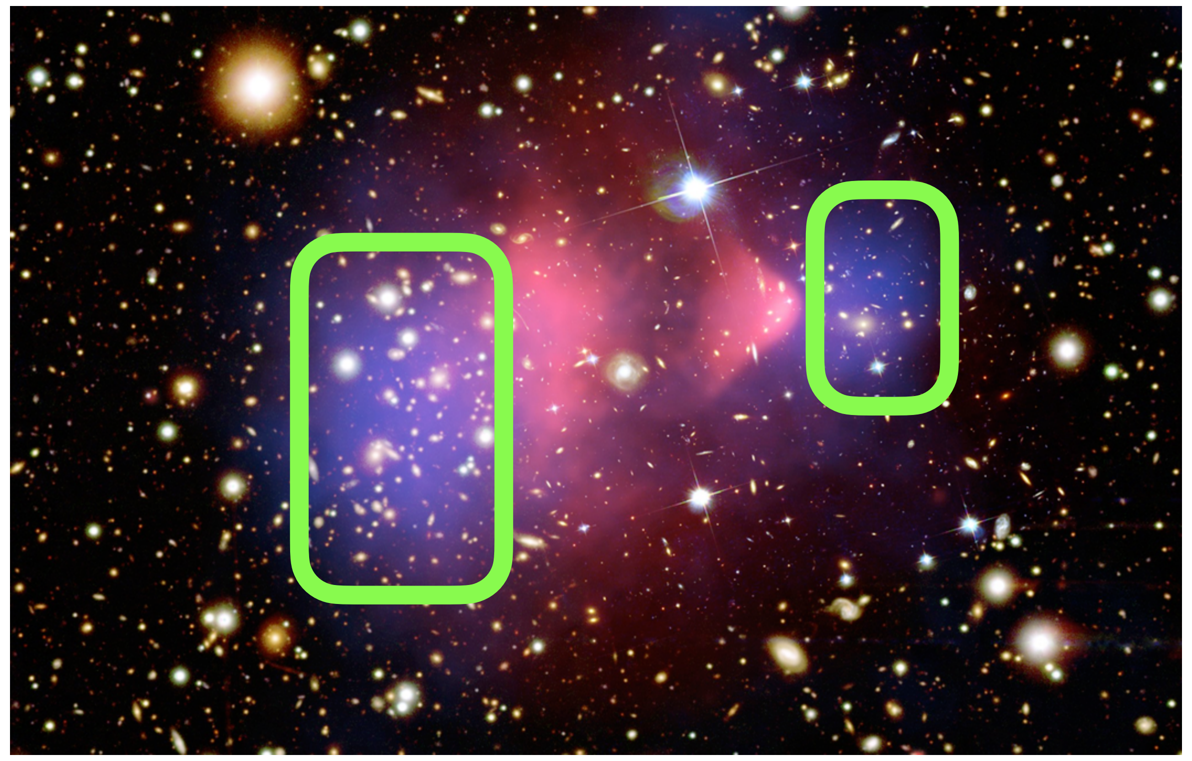
Very flat potential $\longrightarrow$ Neutral field
for slow-roll inflation.
Reheat the Universe.
Induce primordial density perturbation.

slow-roll inflation

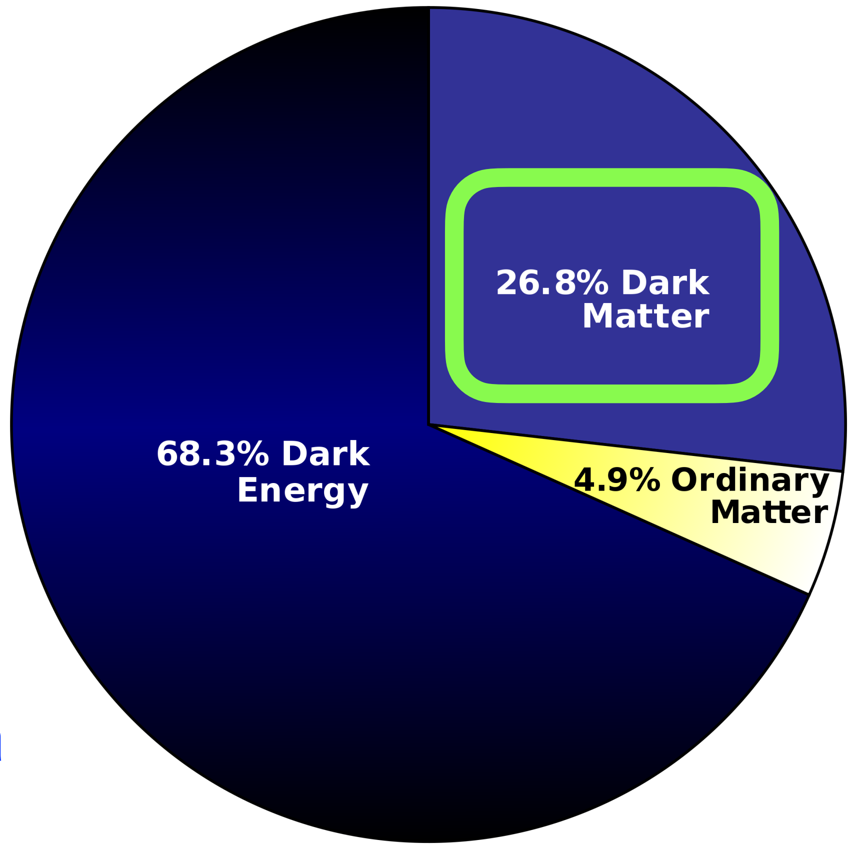


- Dark matter (DM)

Neutral, cold, and long-lived.
Suppressed isocurvature DM modes.



wikipedia



Inflaton and DM are similar: neutral, dominating early Universe, density fluctuations. The very difference is that inflaton decays but DM does not.

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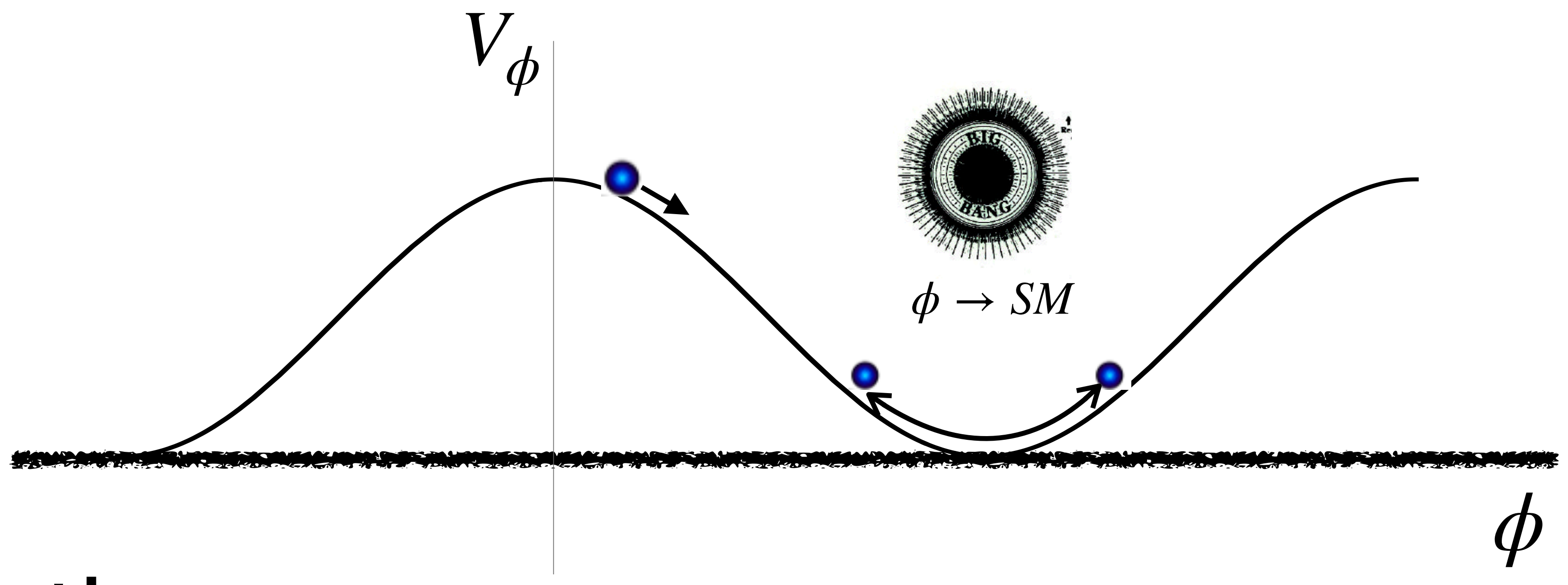

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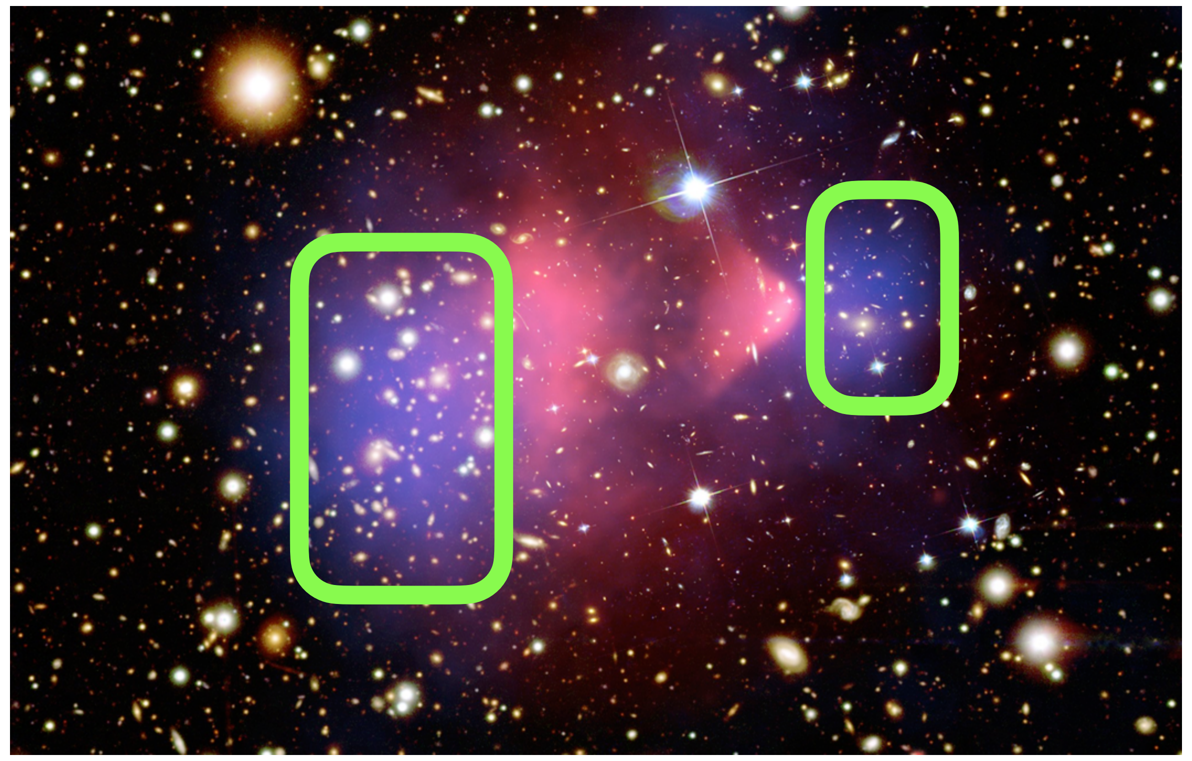

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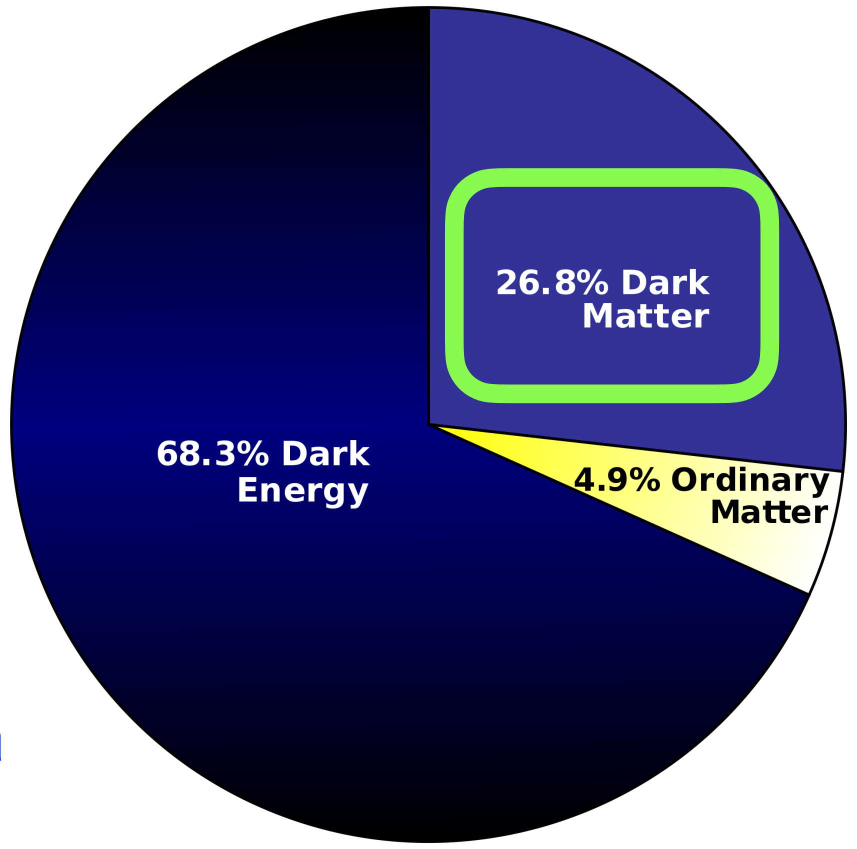

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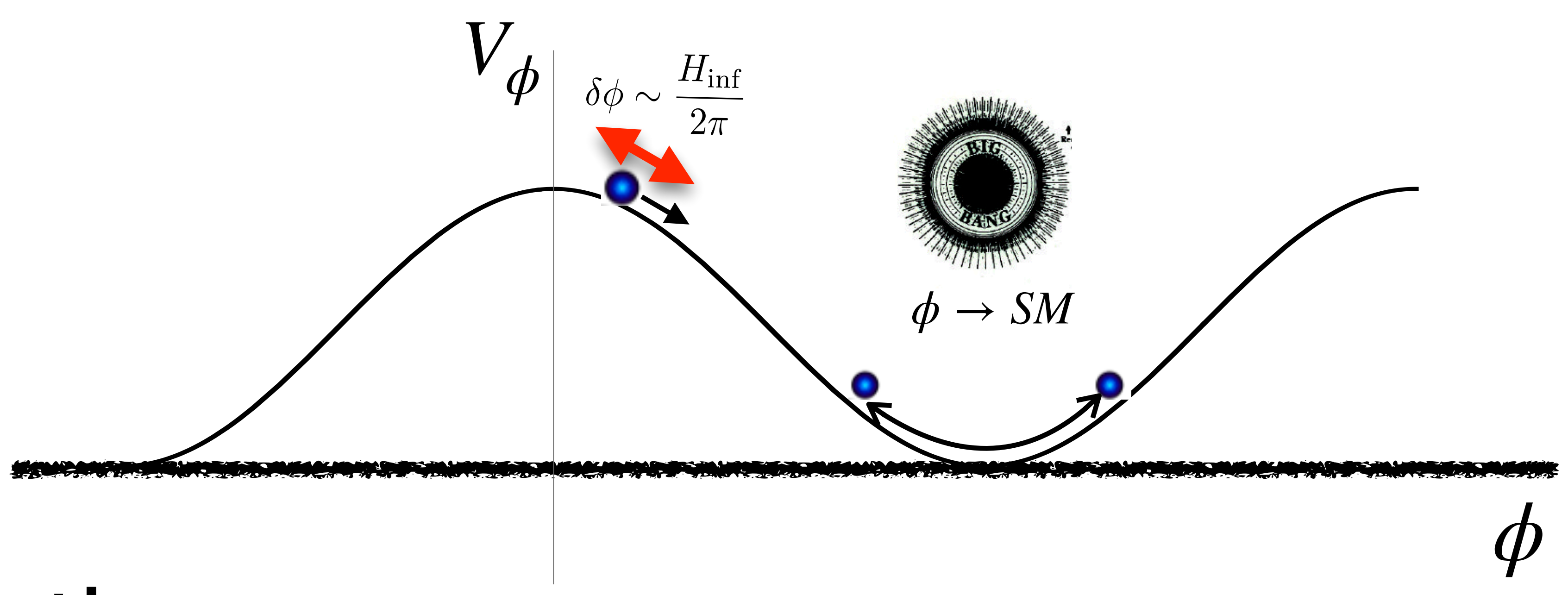

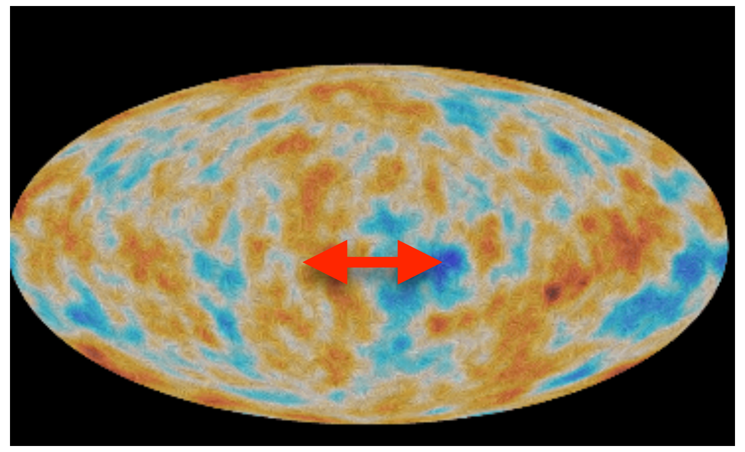

https://www.esa.int/esearch?q=Polarisation

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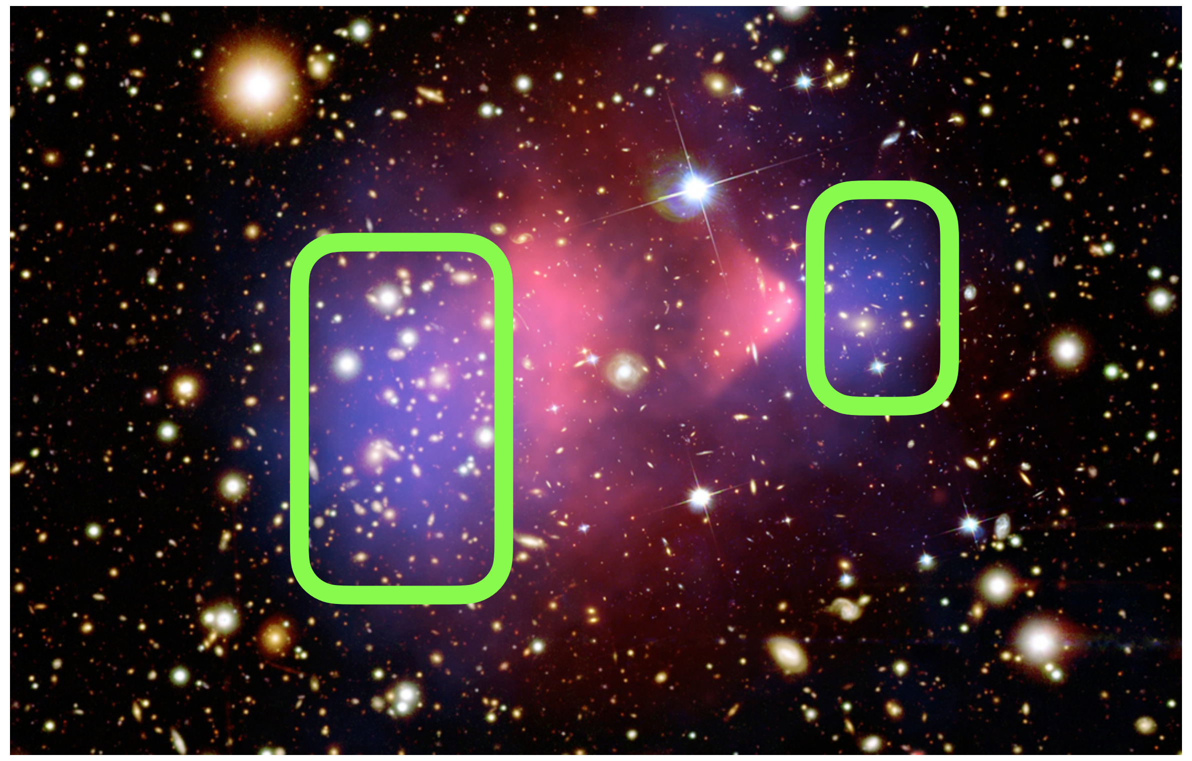

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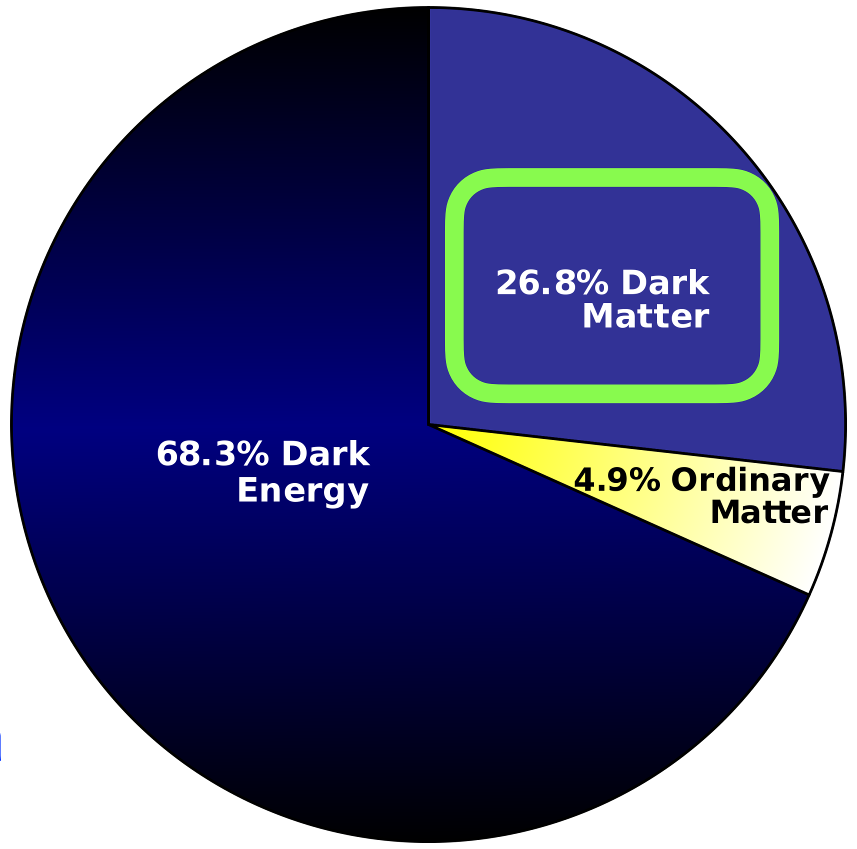

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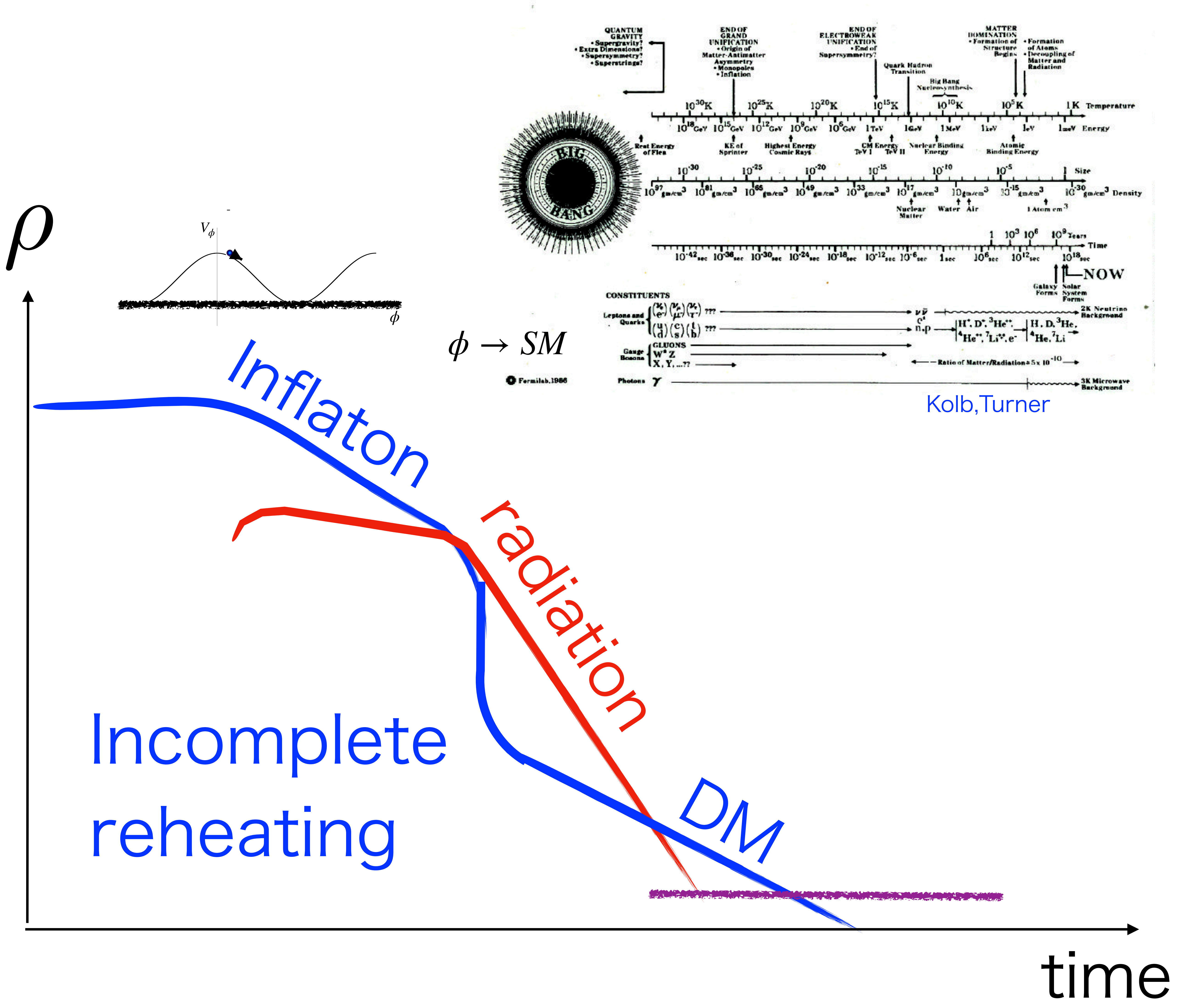
Inflaton = DM?



Longevity of inflaton in the vacuum due to

- Symmetry

  Kofman et al, hep-ph/9704452, hep-th/9405187;
  Bastero-Gil. et al, 1501.05539 ;
  Hooper, et al 1807.03308; etc

- Slow-roll condition in axion inflation

  this talk

  Daido, Takahashi WY, 1702.03284, 1710.11107;

Axion inflation

The slow-roll flat direction is stable under radiative corrections if ϕ is an axion featuring a discrete shift symmetry:

$$\phi \to \phi + 2\pi f_\phi$$

$$\longrightarrow \quad V_{\rm inf}(\phi) = V_{\rm inf}(\phi + 2\pi f_\phi)$$

<u>Realization of axion inflation:</u>

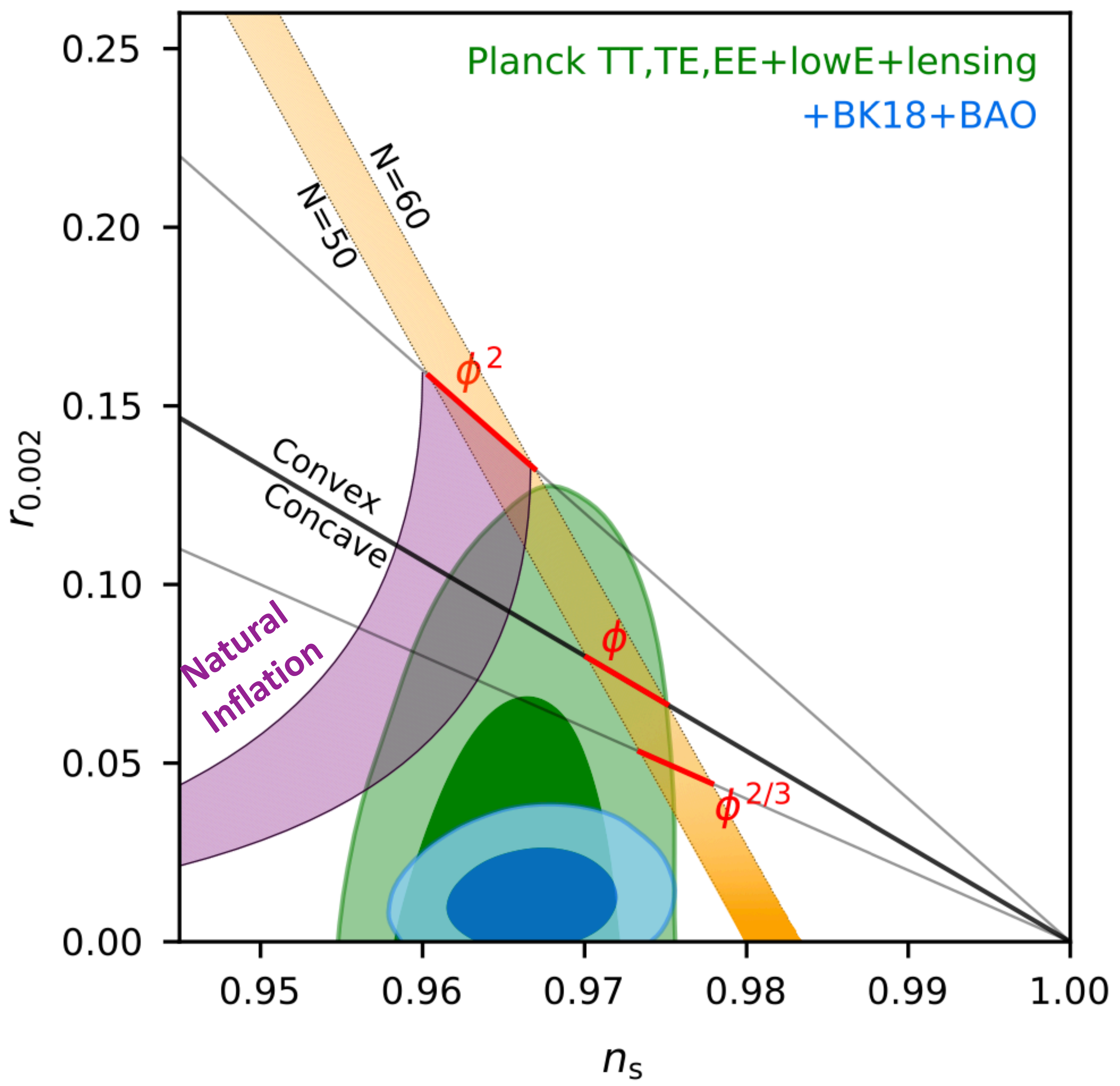
Natural inflation: single cosine

Freese, Frieman, Olinto `90

$$V_{\rm inf} = \Lambda^4(1 - \cos(\phi/f_\phi))$$

$f_\phi > M_{\rm pl}$ and excluded due to too high scale for inflation…

BICEP and Keck Collaborations, 2110.00483



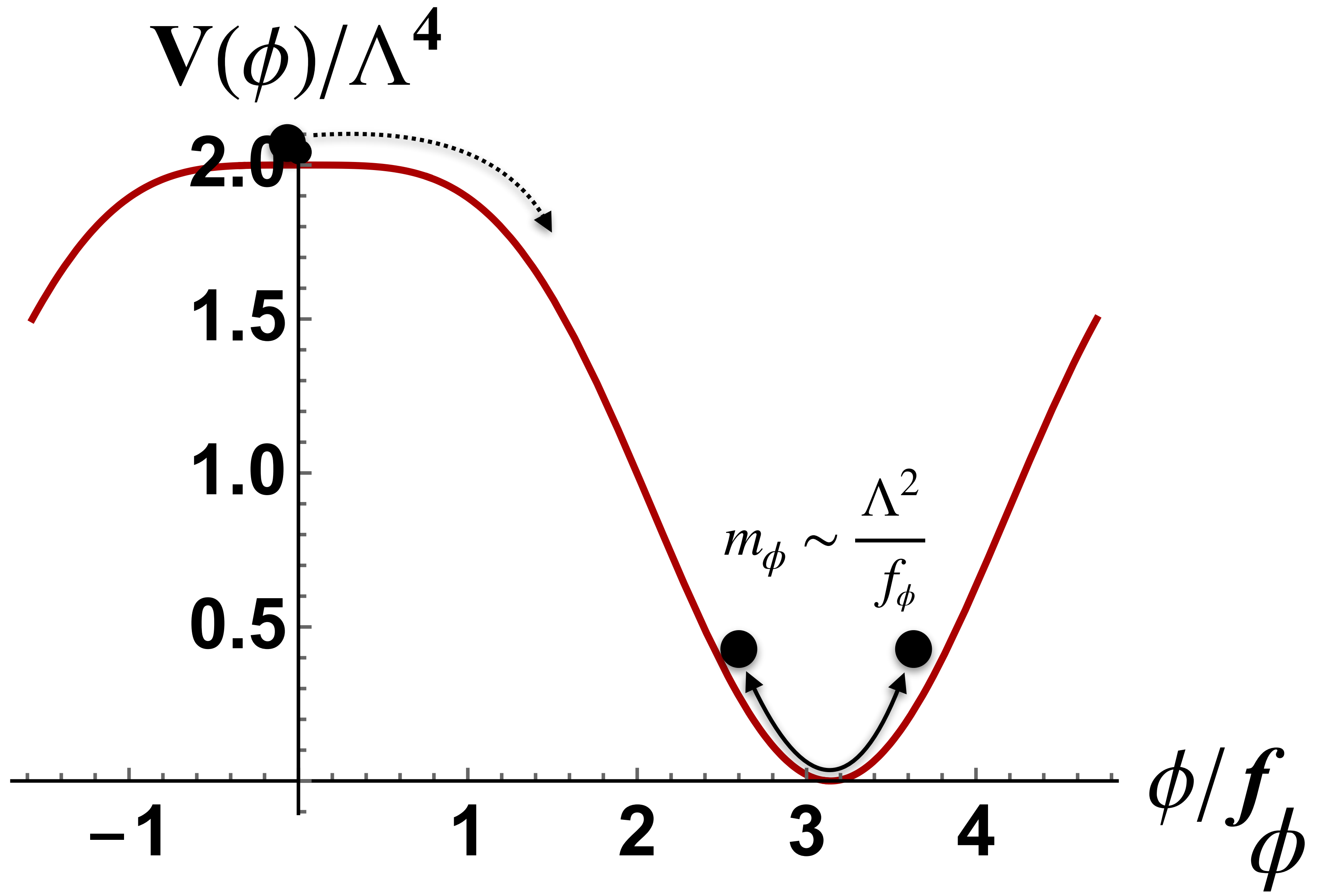
Multi-natural inflation: $V_{\rm inf}$ from 2 or more cos terms

Czerny, Takahashi 1401.5212; Czerny, Higaki, Takahashi 1403.0410, 1403.5883; Daido, Takahashi, and WY 1702.03284; 1710.11107; Takahashi and WY, 1903.00462;

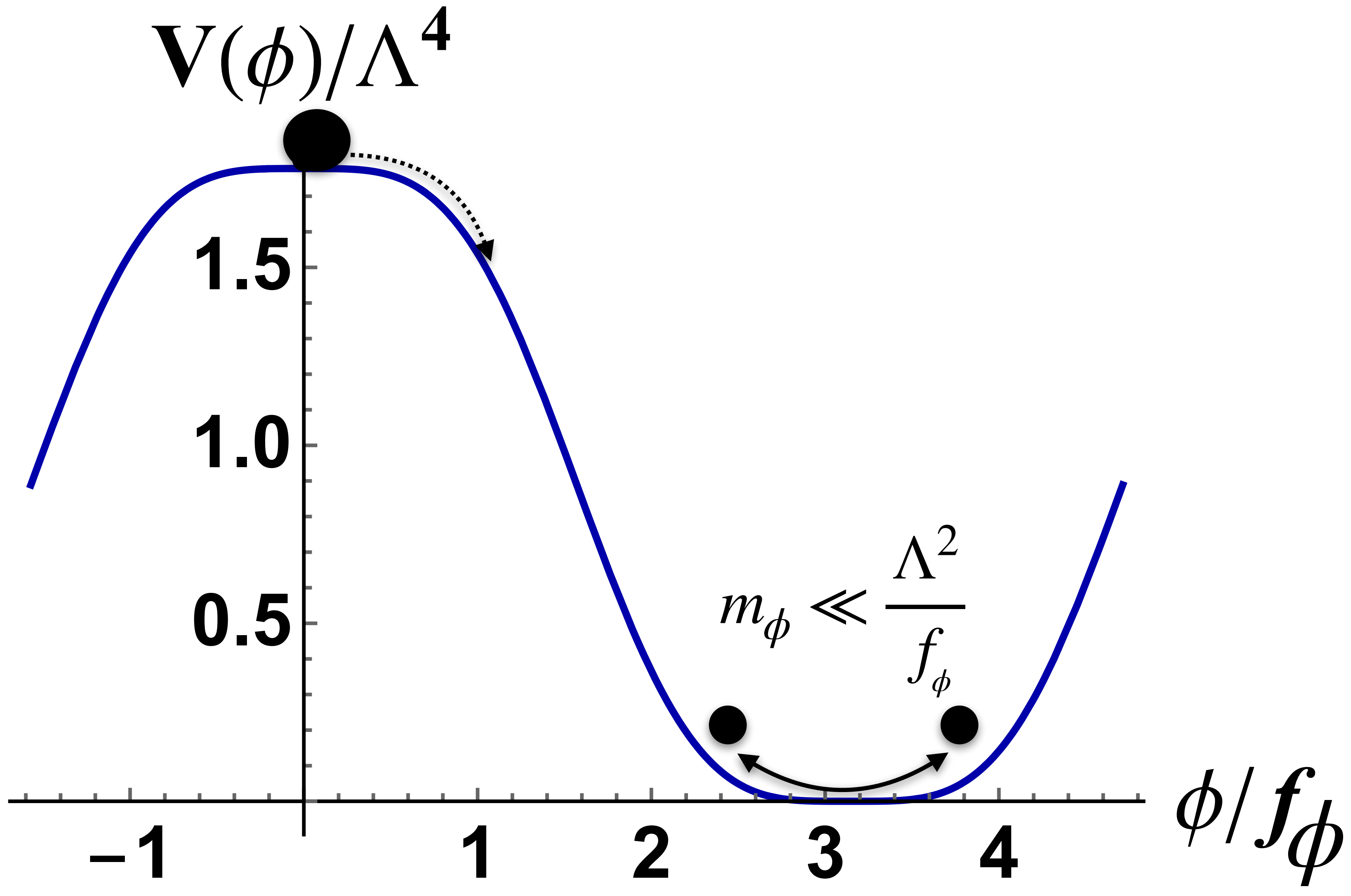
In multi-natural inflation, CMB data can be well explained with $f_\phi \ll M_{\rm pl}$.

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

The inflaton masses depend on the parity of n.



Even n



Odd n

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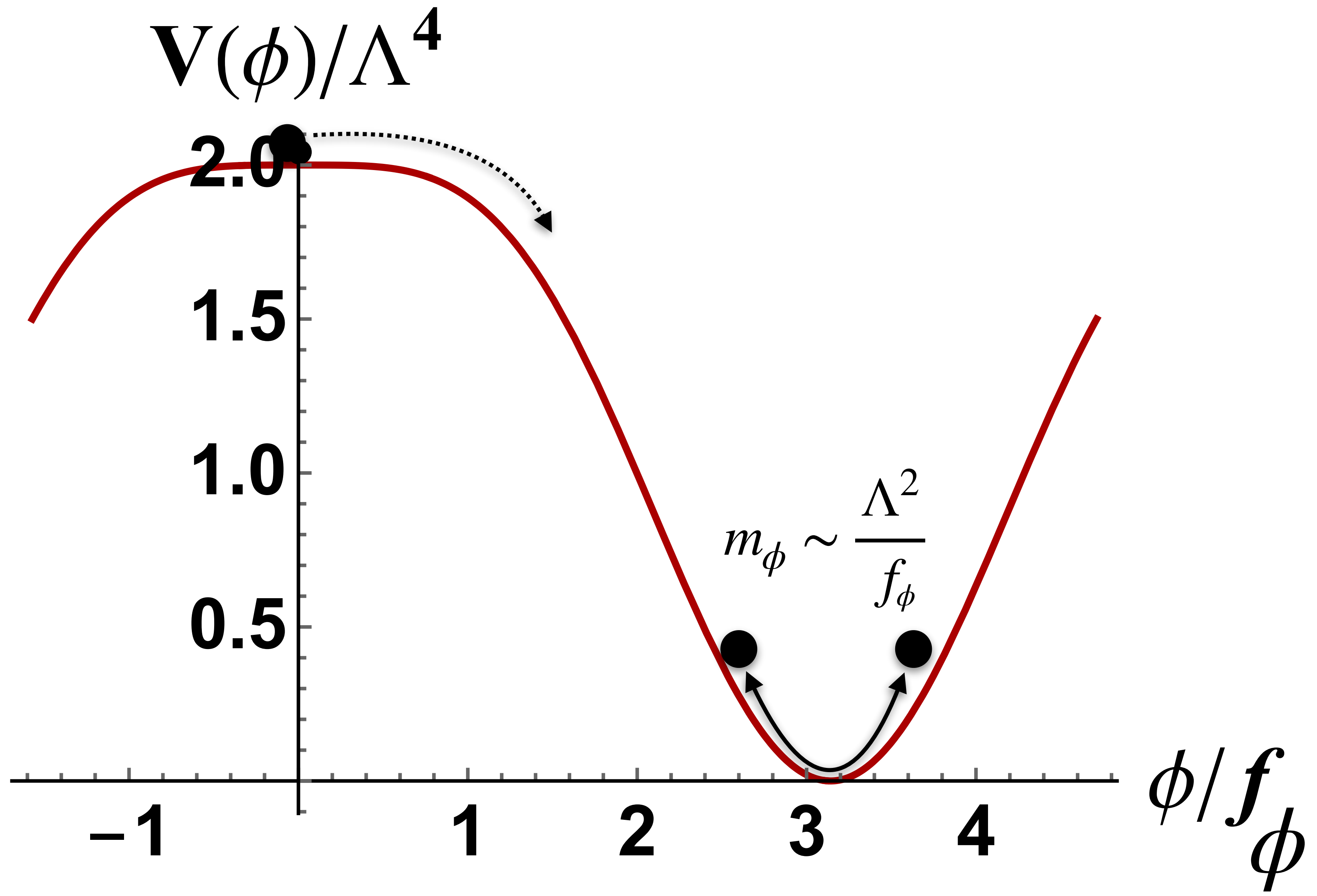

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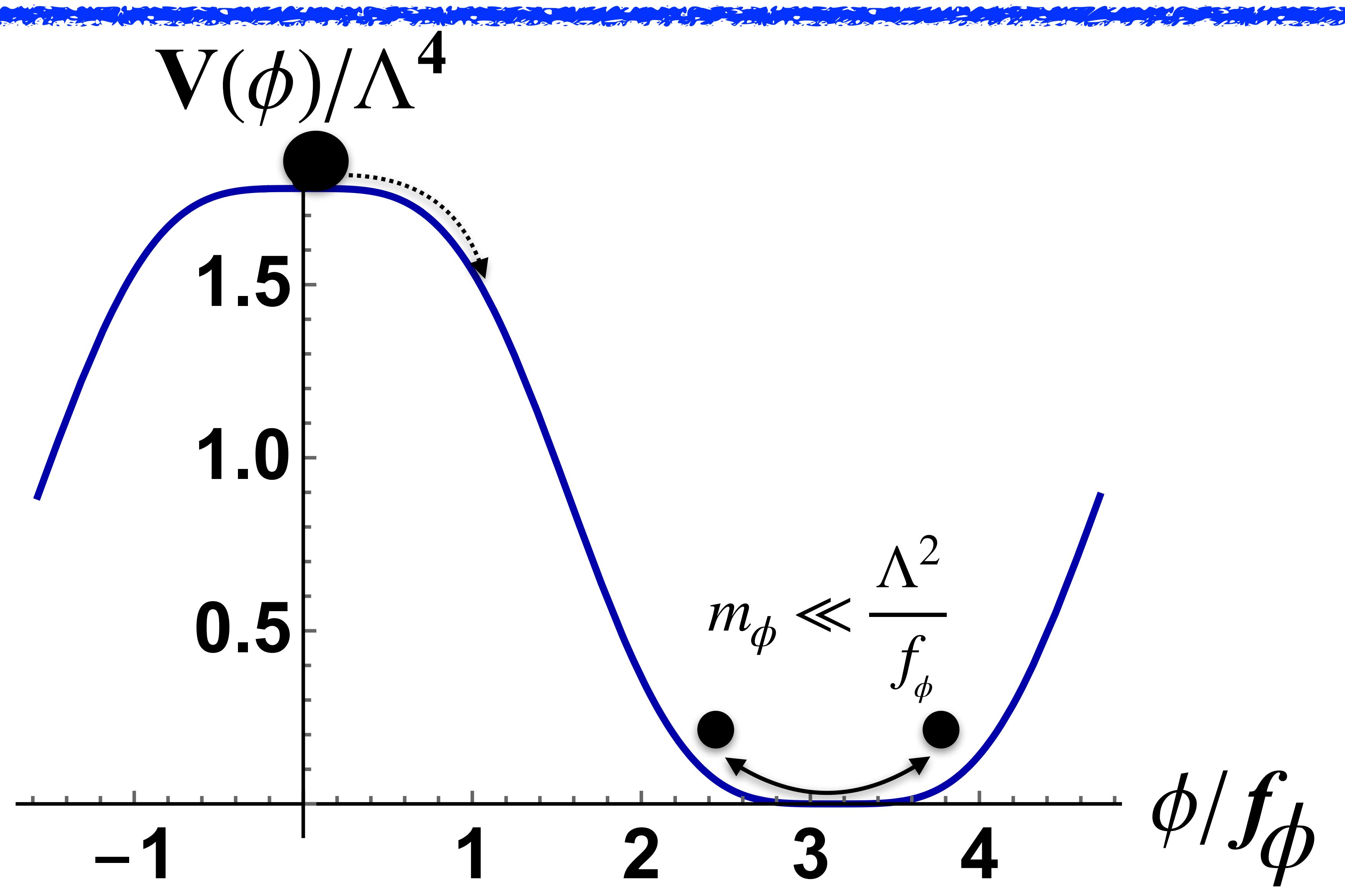

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Axion Hilltop inflation

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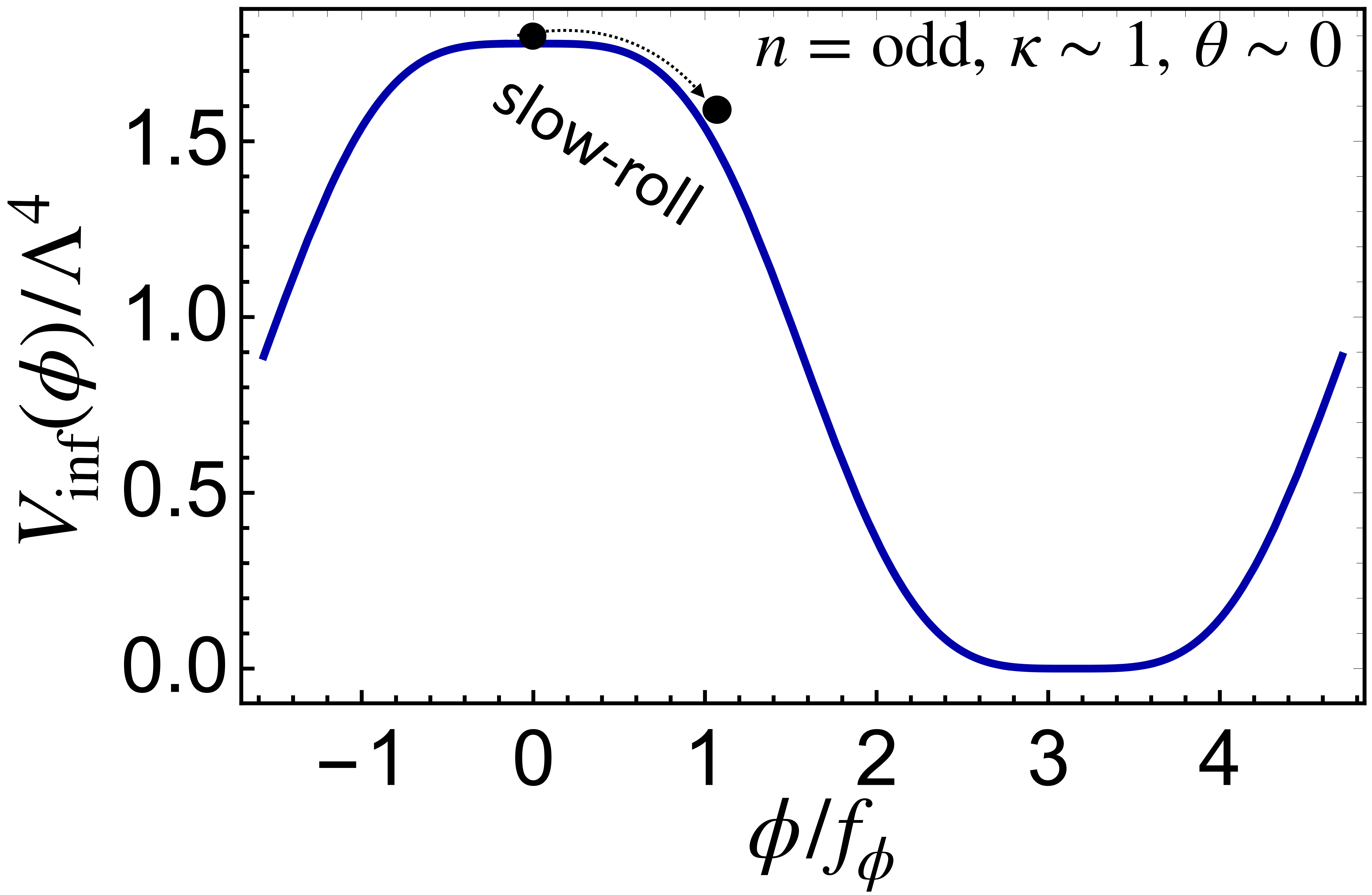
$$\simeq V_0 - \lambda \phi^4 - \Lambda^4 \theta \frac{\phi}{f_\phi} + \cdots .$$



- Almost quartic hilltop inflation.
- n_s corrected from non-vanishing θ
- Upside-down symmetry when $n = \text{odd}$

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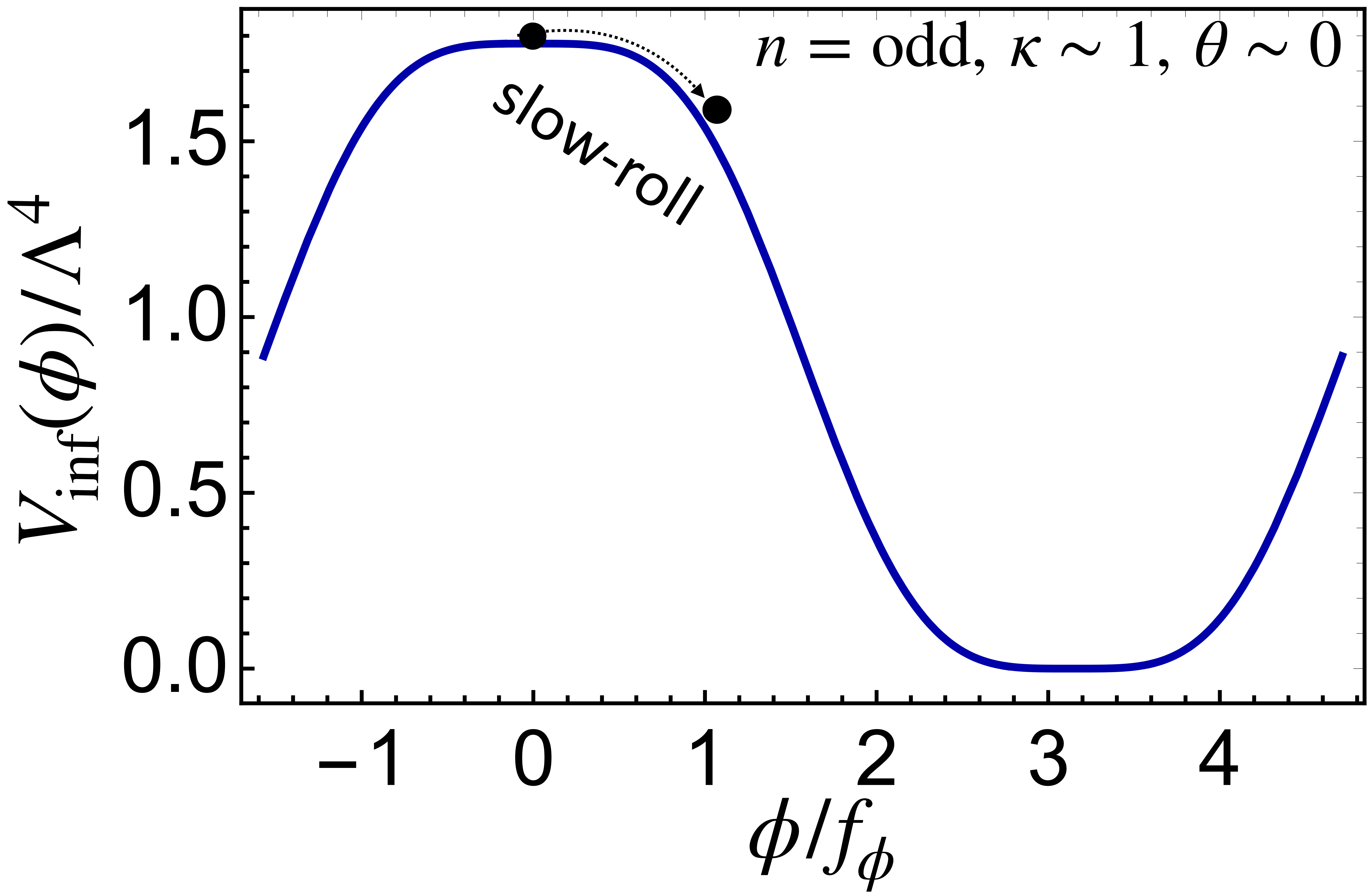
$$\simeq V_0 - \boxed{\lambda\phi^4} - \Lambda^4\theta\frac{\phi}{f_\phi} + \cdots.$$



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  CMB normalization:
  $$\lambda \sim \Lambda^4/f_\phi^4 \sim 10^{-12}$$

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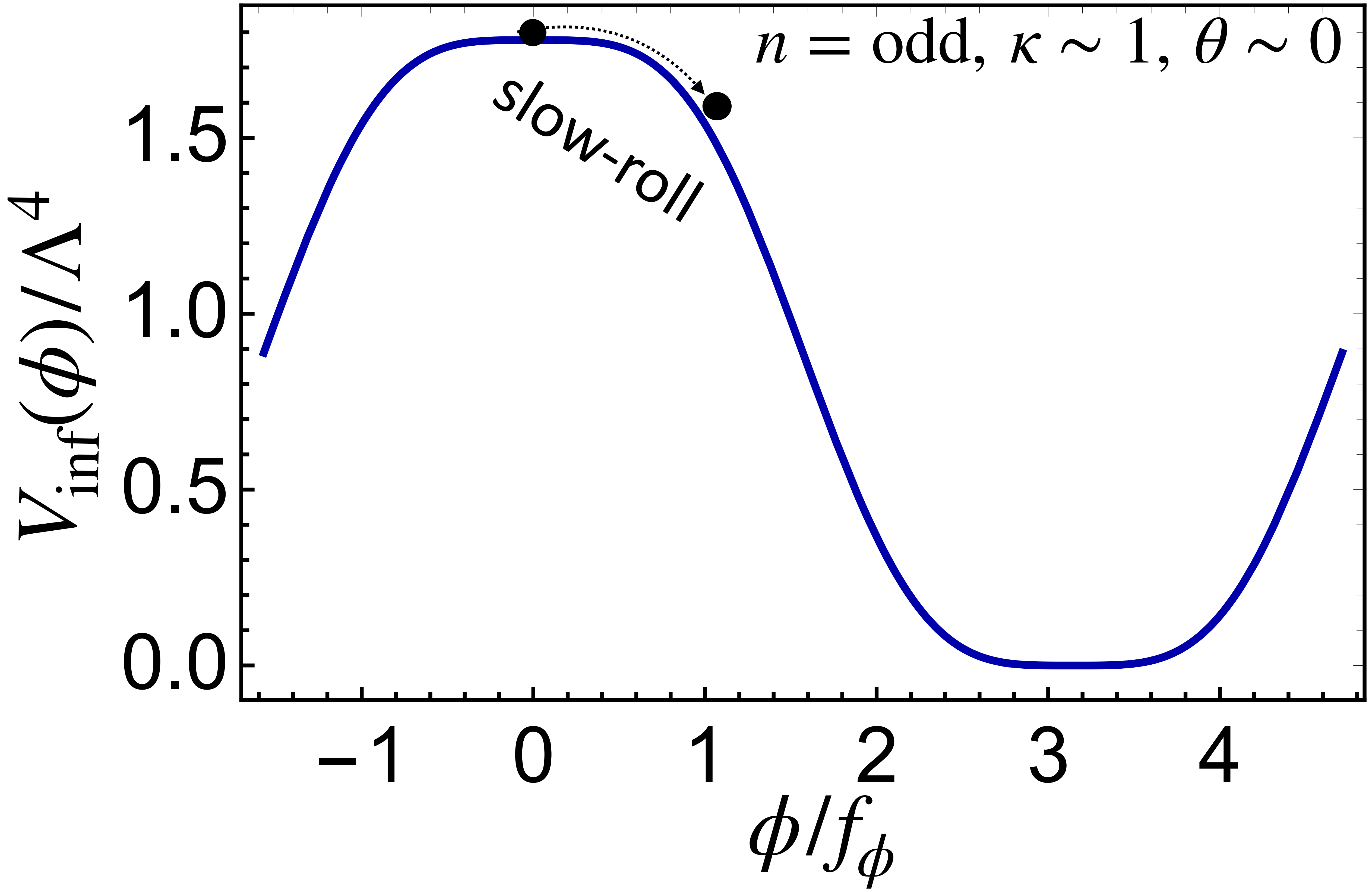
A linear term can give better fit of n_s.

Takahashi,1308.4212



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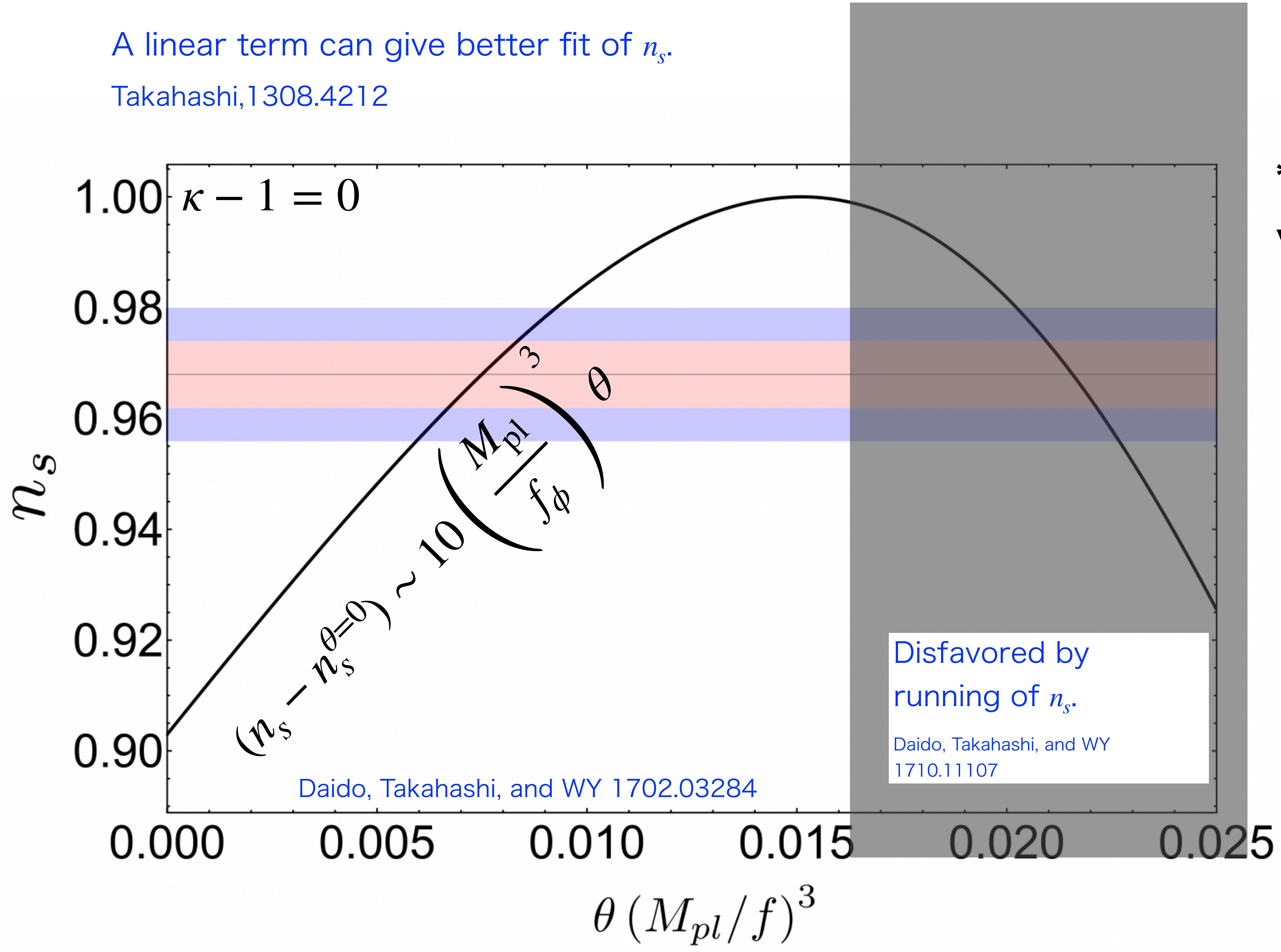
n_s in ALP inflation with varying θ.



*ALP inflation can explain various n_s in its parameter region.

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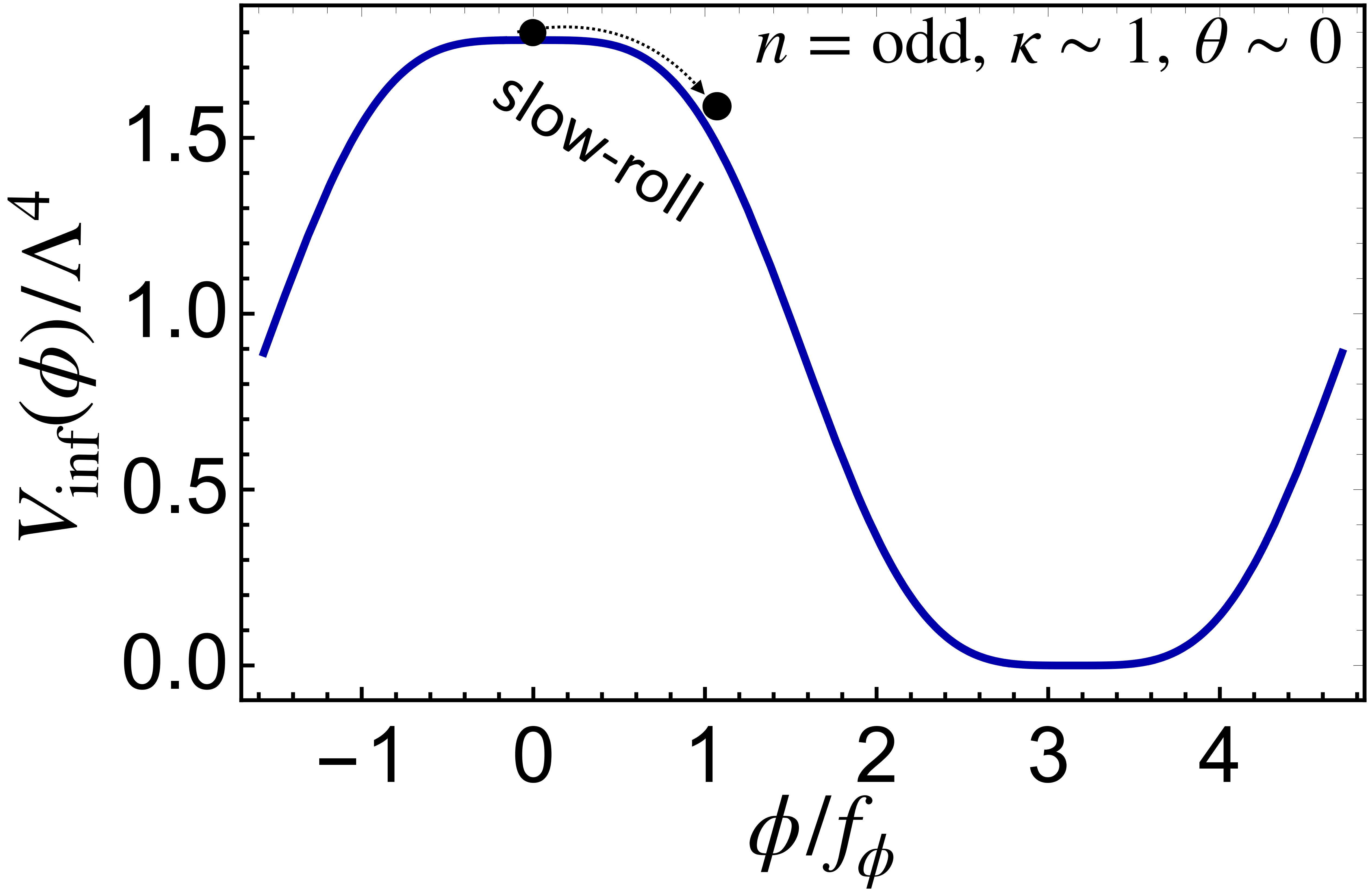

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  $$-2V''_{\rm inf}/3H^2_{\rm inf} \sim (n_s - n_s(\theta = 0))^{2/3}$$

  $$V''_{\rm inf}|_{\rm hilltop} \approx -O(0.1-1)H^2_{\rm inf}$$

- Upside-down symmetry when $n = {\rm odd}$

Upside-down symmetry in axion hilltop inflation

Daido, Takahashi, WY 1702.03284, 1710.11107; Takahashi and WY,1903.00462;
UV model for hilltop condition: e.g. Croon and Sanz 1411.7809; Higaki, Takahashi 1501.02354;

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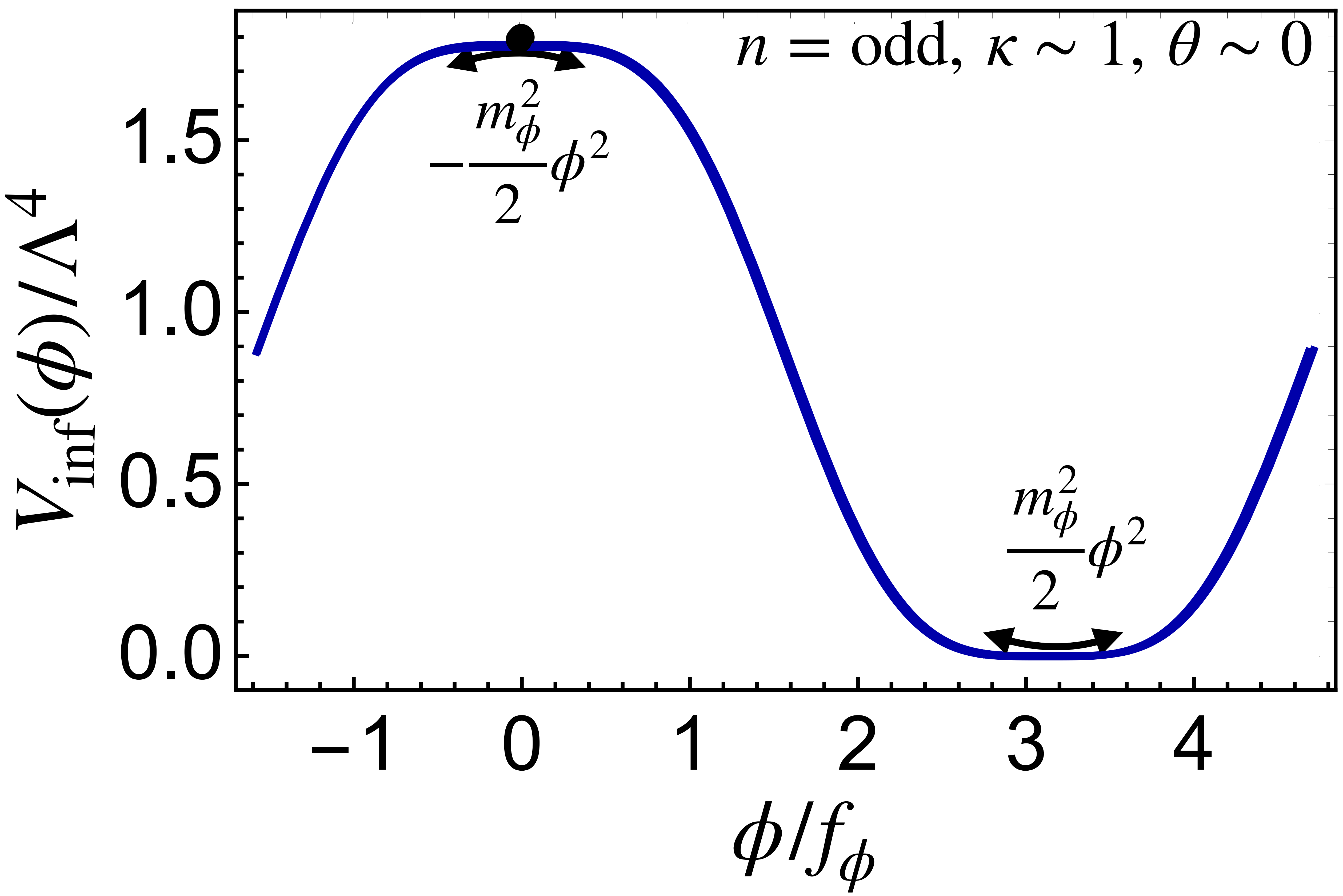

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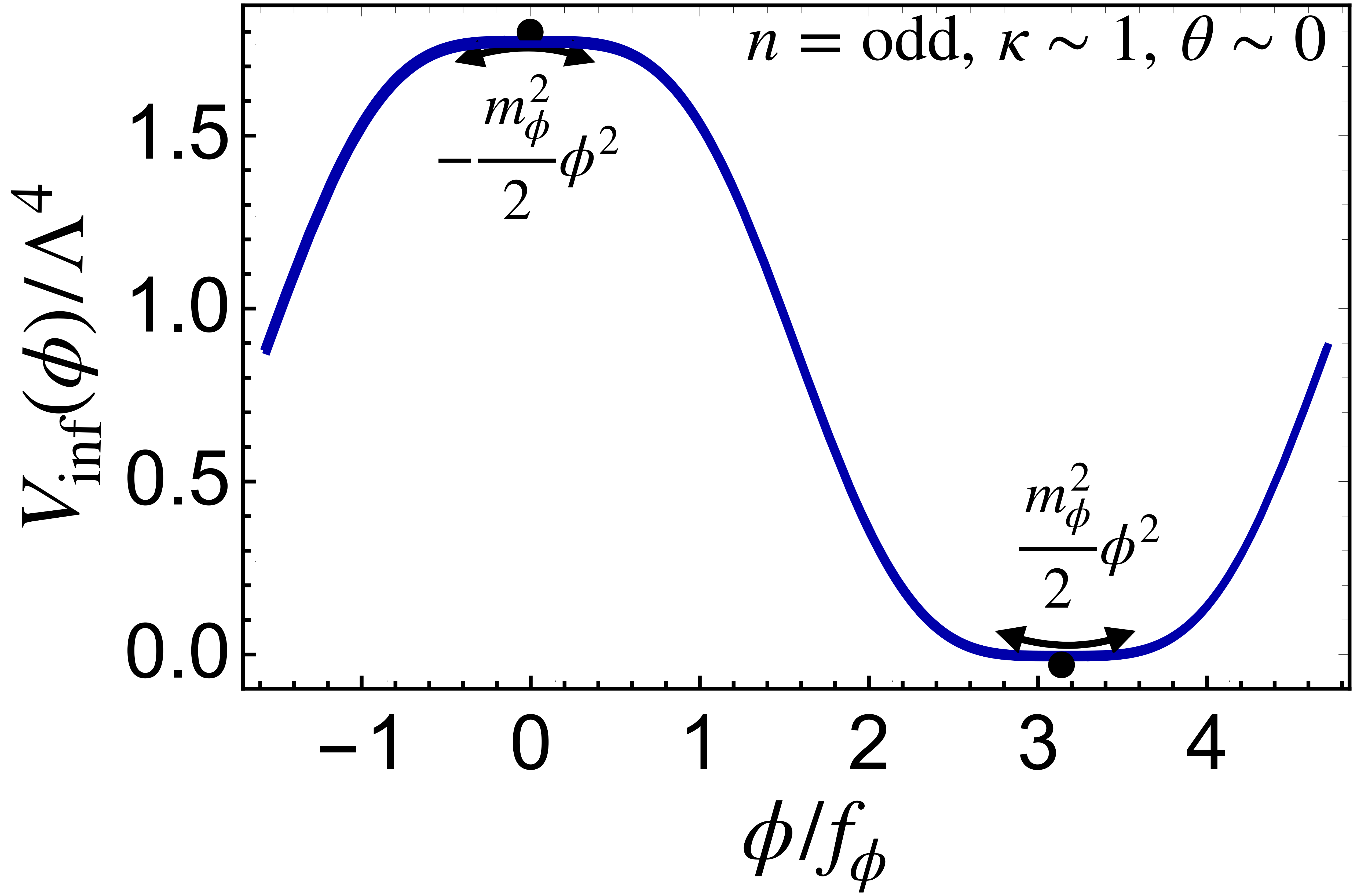

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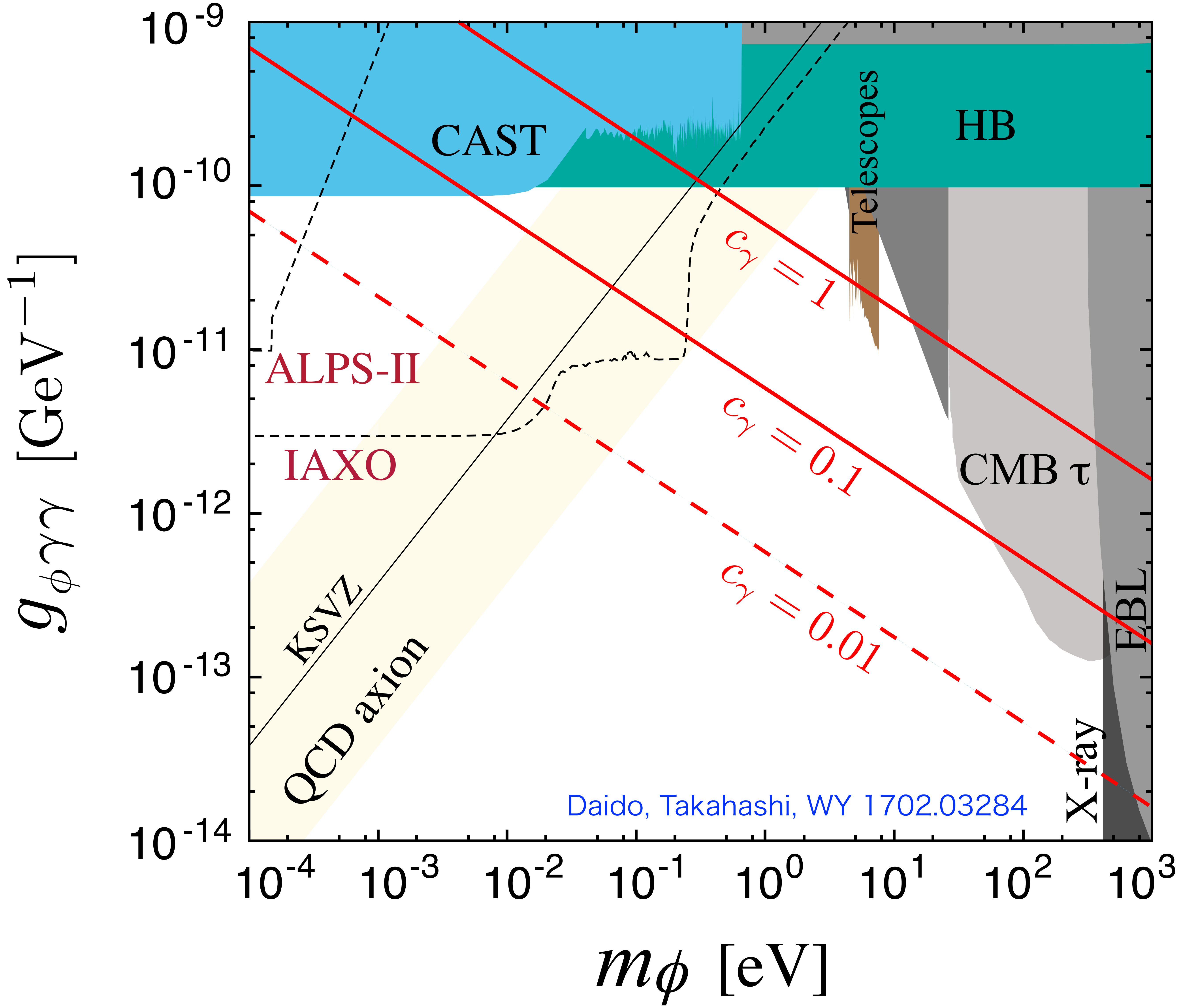
$$\boxed{\begin{array}{c}\lambda(\text{self-coupling}) \sim 10^{-12} \\ m_\phi \sim 10^{-6}(n_s - n_s(\theta=0))^{1/3}\dfrac{f_\phi^2}{M_{\rm pl}}\end{array}}$$

(Note $H_{\rm inf} \sim \Lambda^2/M_{\rm pl}$)

ALP(axion coupled to photon)=inflaton

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



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—> sub-eV or eV-scale ALP DM candidate.

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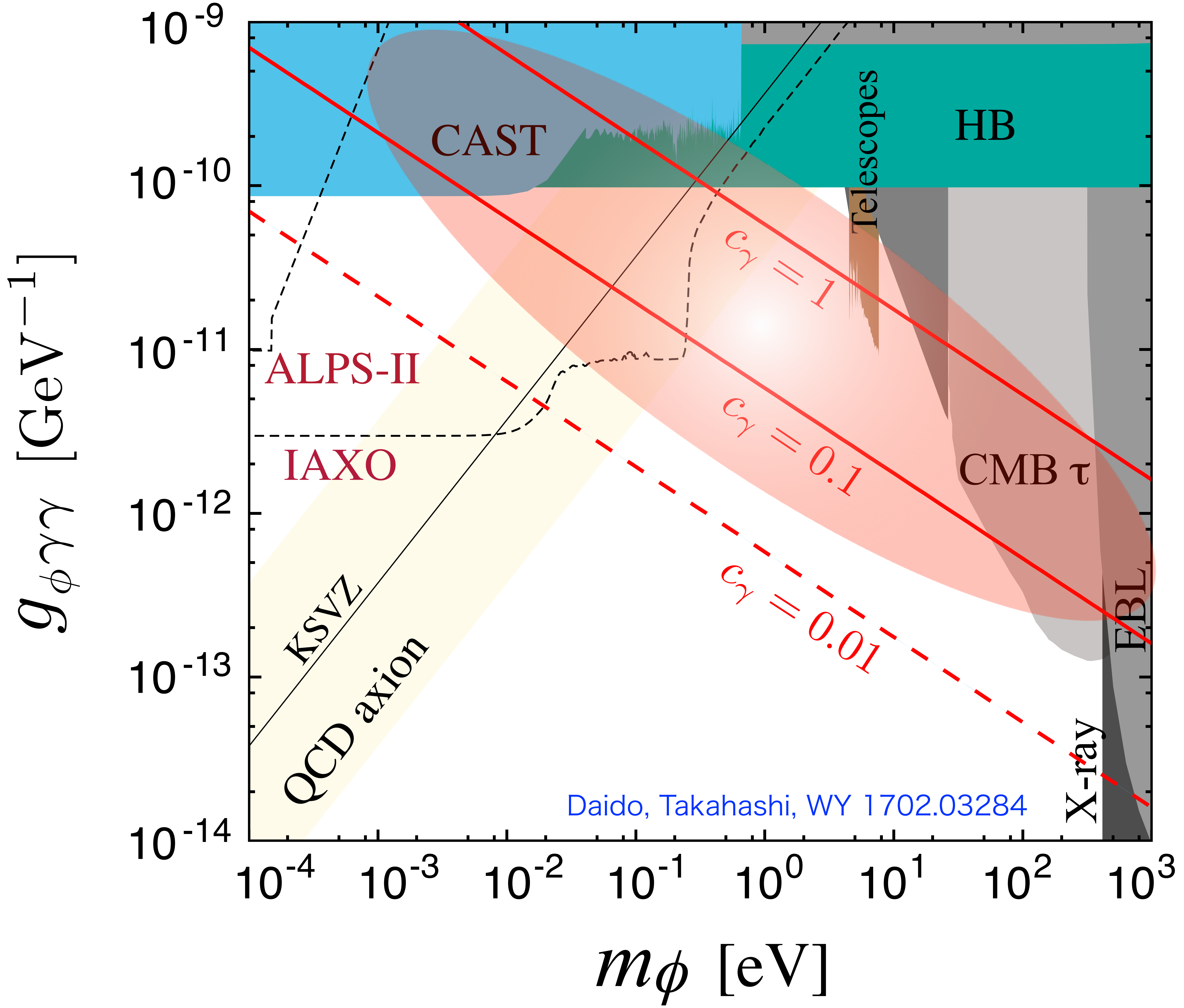

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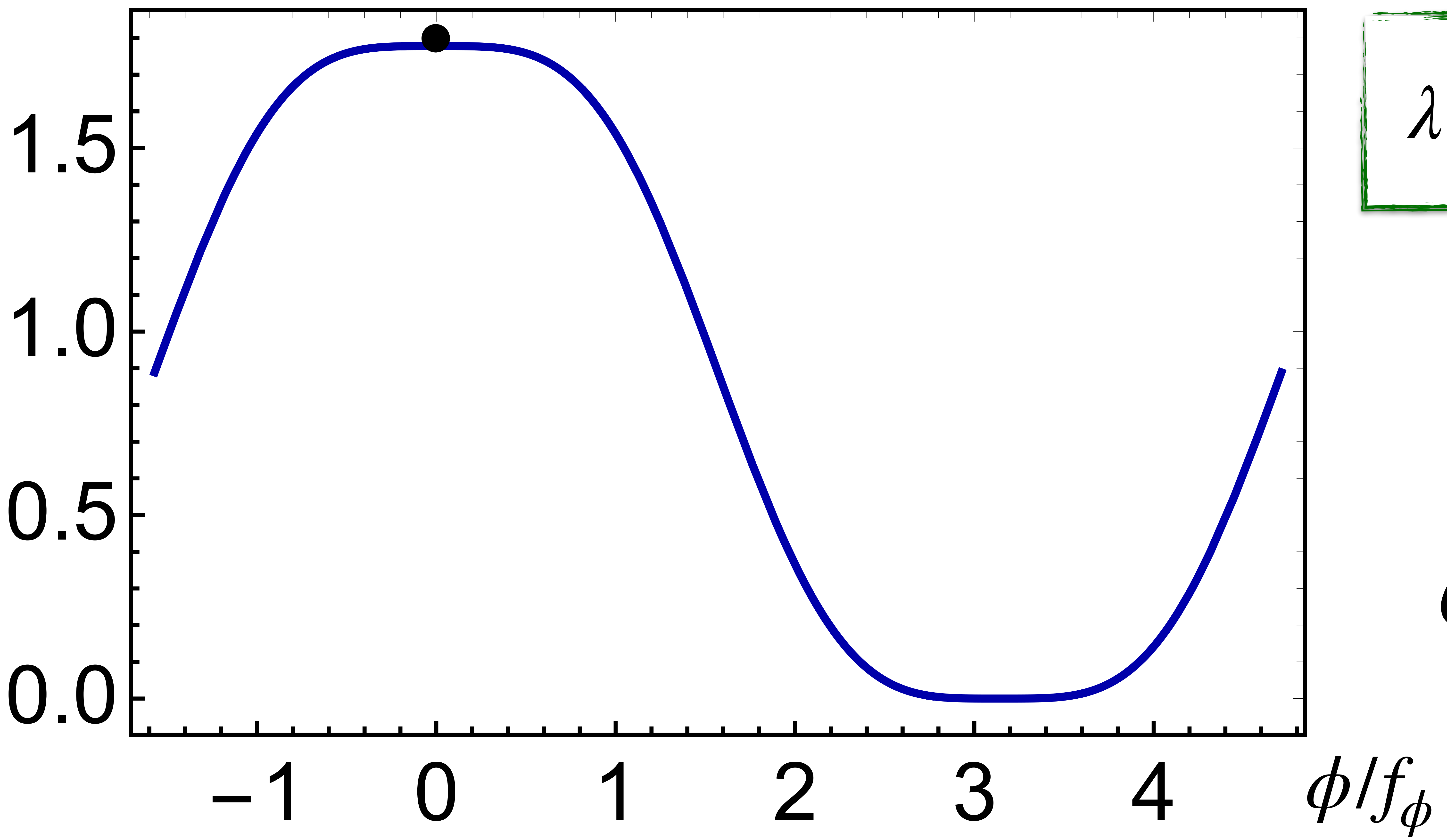
Successful inflation

—> sub-eV or eV-scale ALP DM candidate.

Inflaton decays due to large effective mass

Just after inflation, ϕ acquires an effective mass

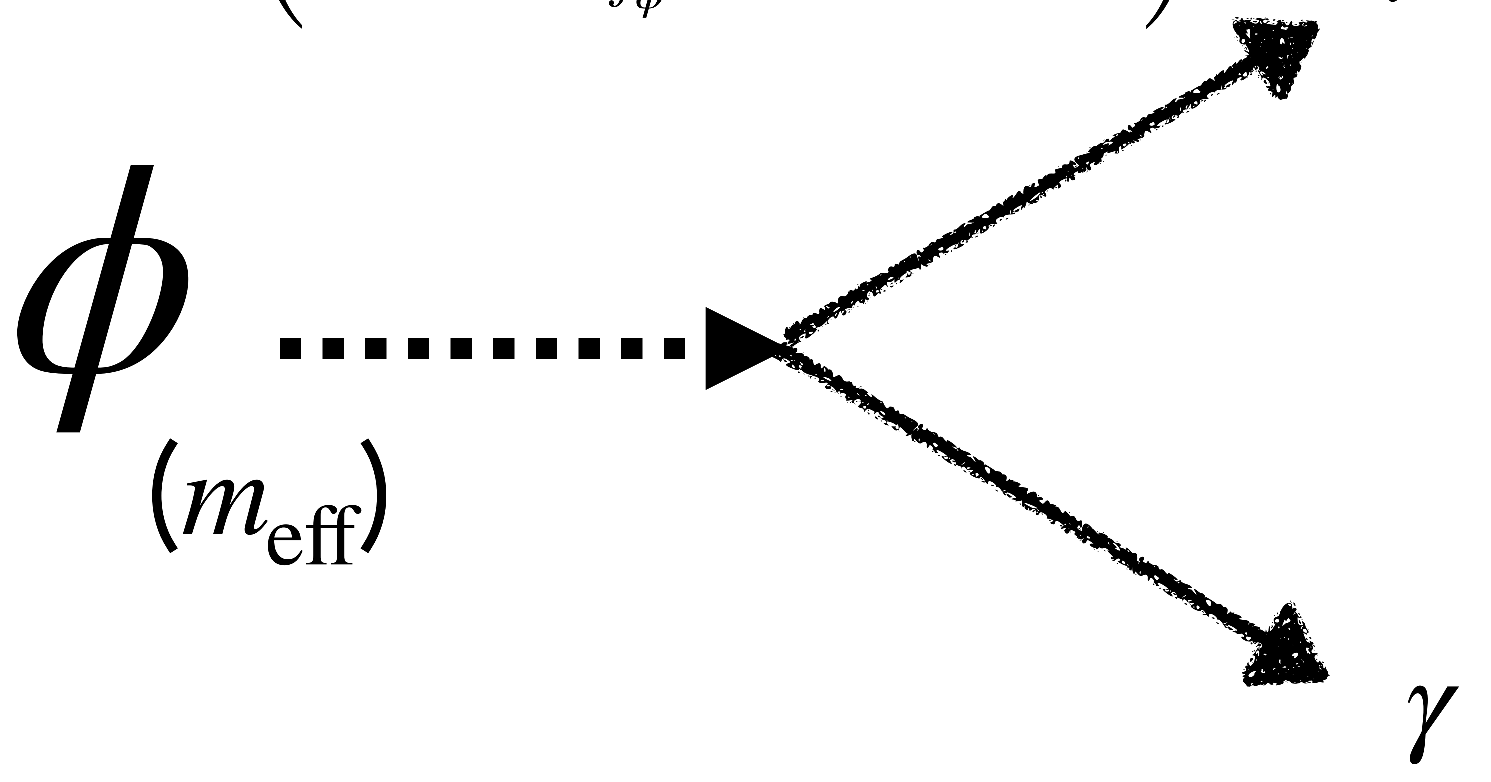
$$m_{\rm eff} \sim \sqrt{\lambda}\phi_{\rm amp} \sim 10{\rm GeV}\left(\frac{\phi_{\rm amp}}{10^7\,{\rm GeV}}\right).$$



$$\boxed{\lambda(\text{self-coupling}) \sim 10^{-12}}$$

$\Gamma_{\phi\to\gamma\gamma}|_{\rm reheating}$

$$\left(\sim 10^{33}\left(\frac{10^7 GeV}{f_\phi}\right)^3\Gamma_{\phi\to\gamma\gamma}|_{\rm vacuum}\right)$$



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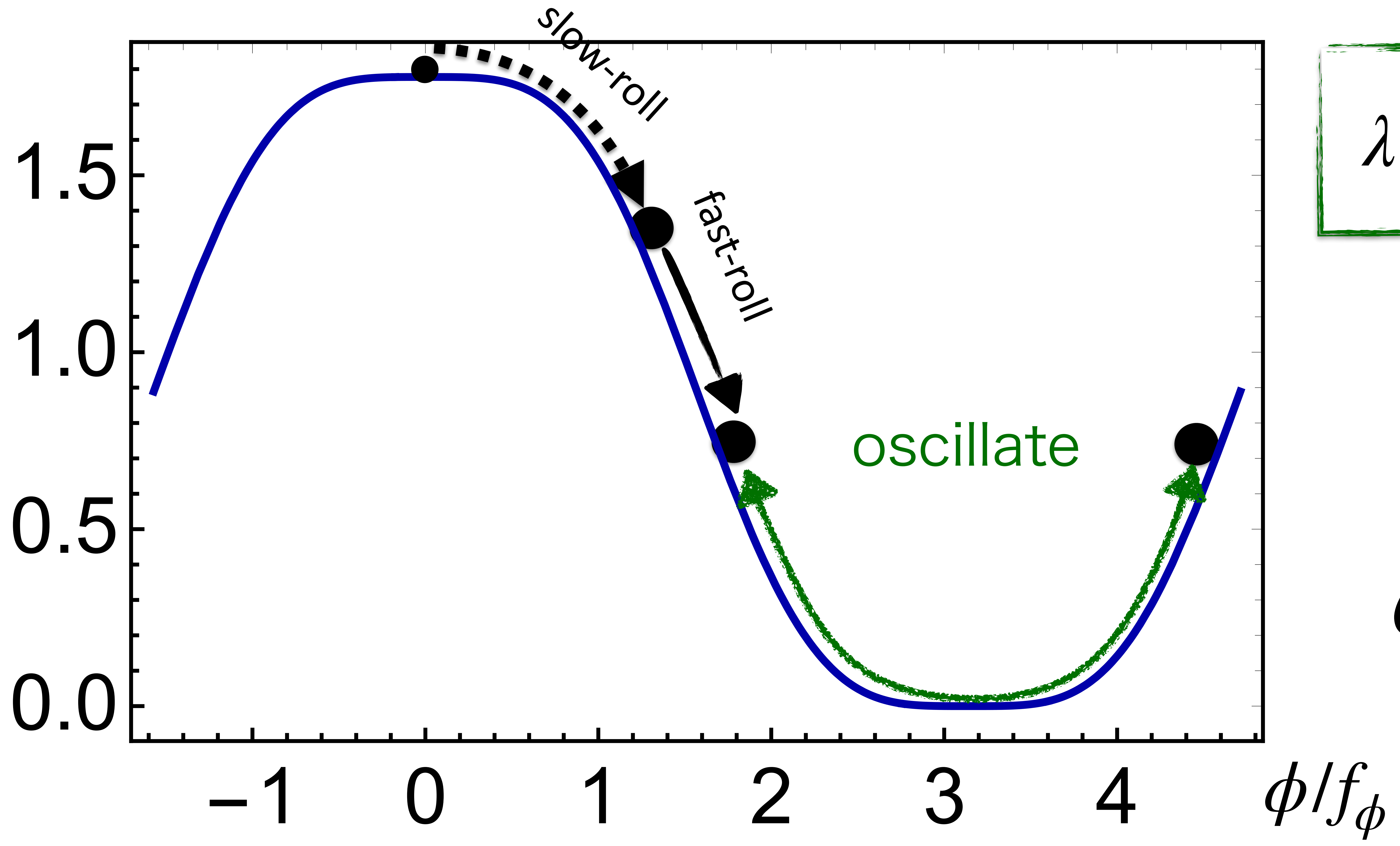

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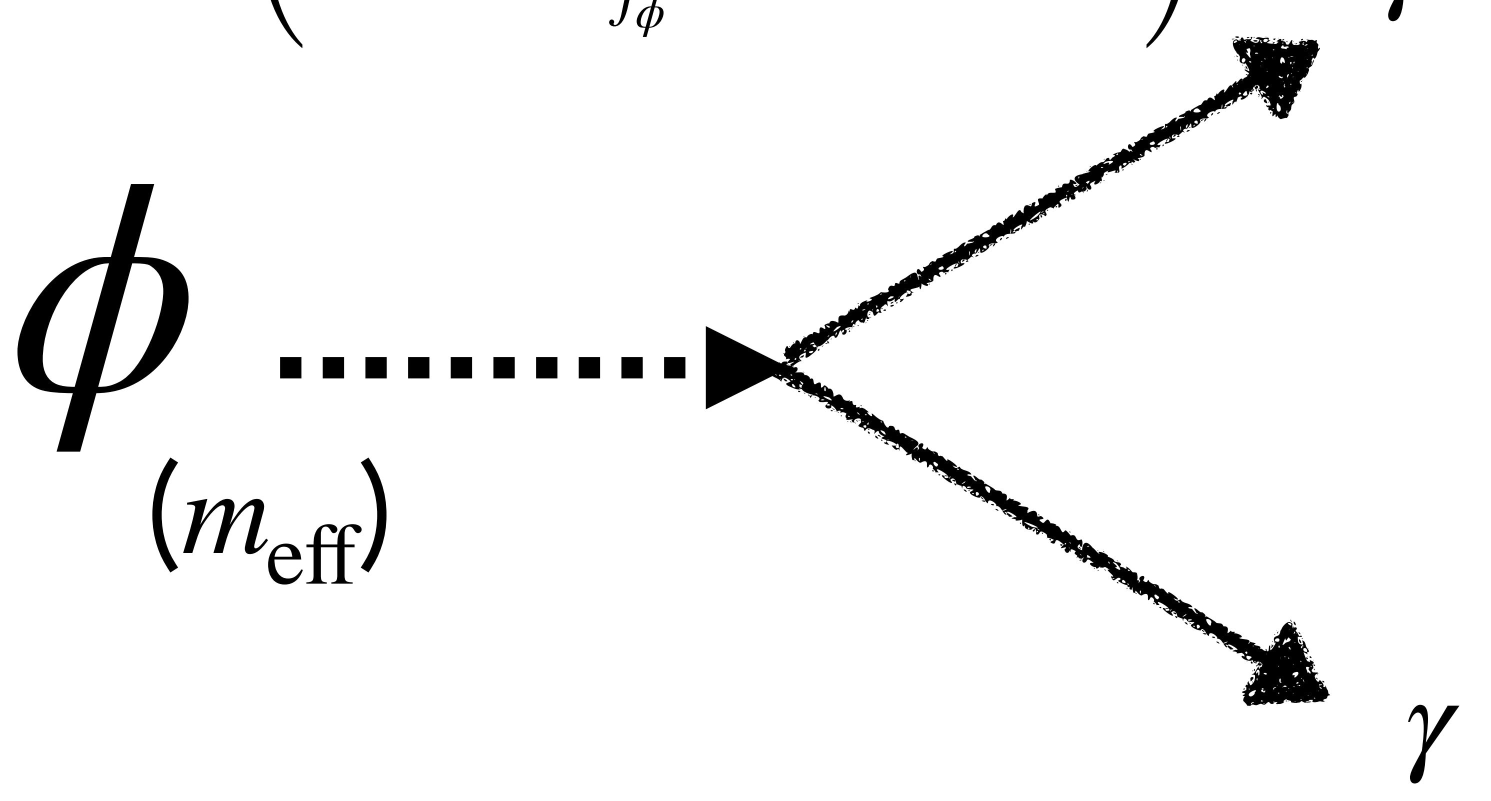
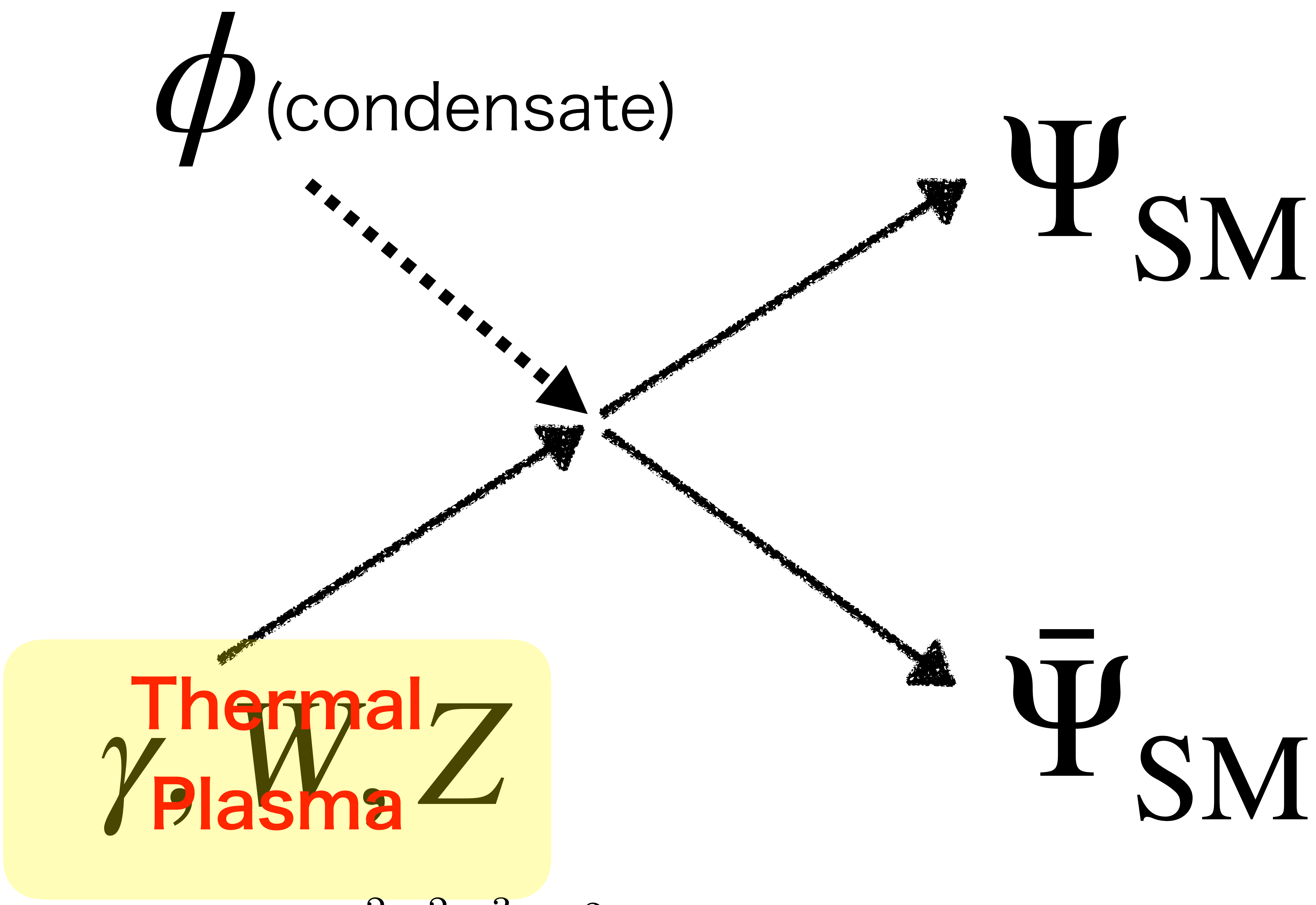


Cold ALP DM from incomplete reheating.

Reheating proceeds due to thermal scattering when $eT \gtrsim m_{\rm eff}$.

Dissipation effect for reheating

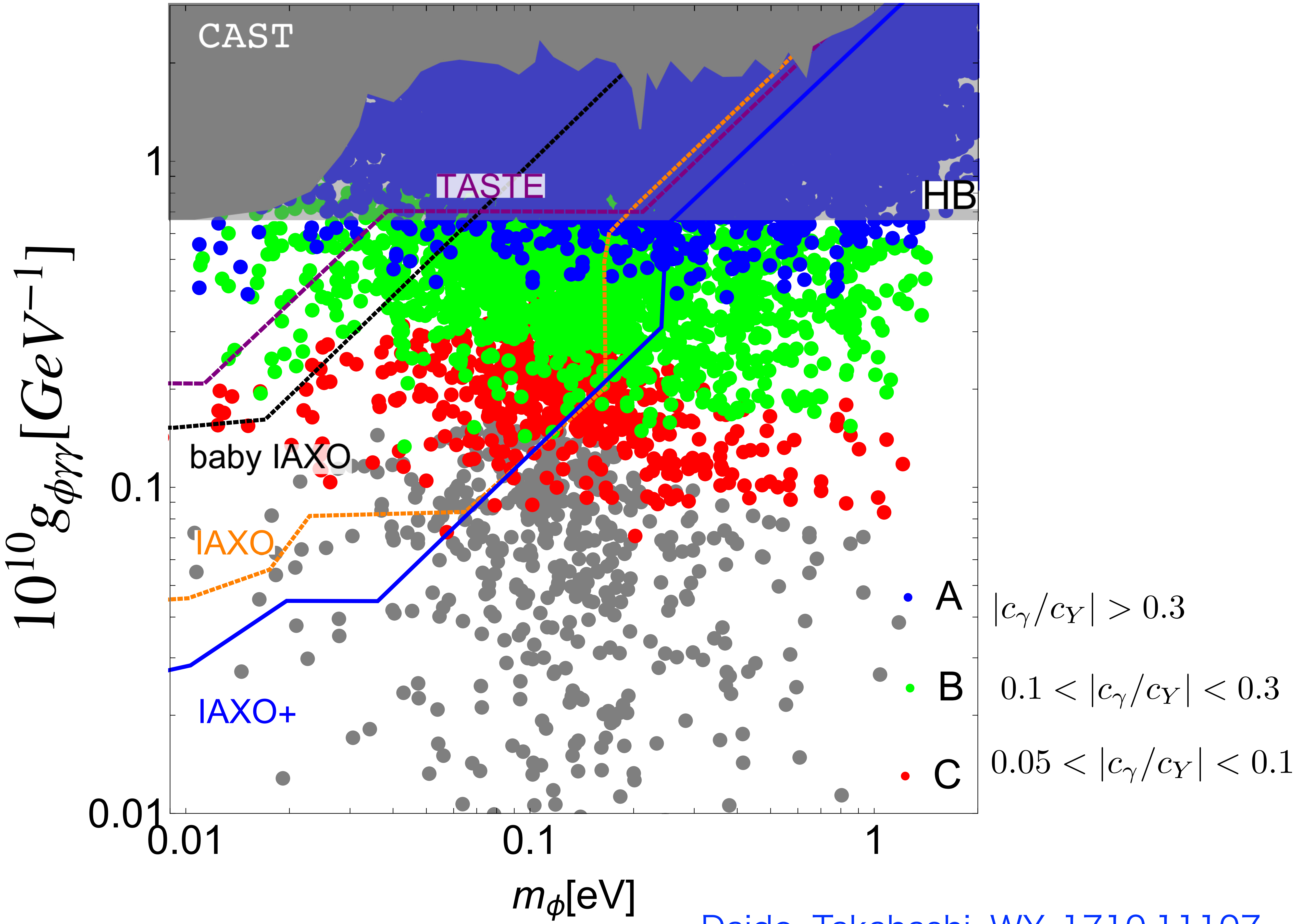


$$\Gamma_{{\rm dis},\gamma} = C \frac{c_\gamma^2 \alpha^2 T^3}{8\pi^2 f^2} \frac{m_{\rm eff}^2}{e^4 T^2}$$

Moroi, Mukaida, Nakayama and Takimoto,1407.7465;

C=O(10) to take account of self-resonance, Lozanov, and Amin, 1710.06851;

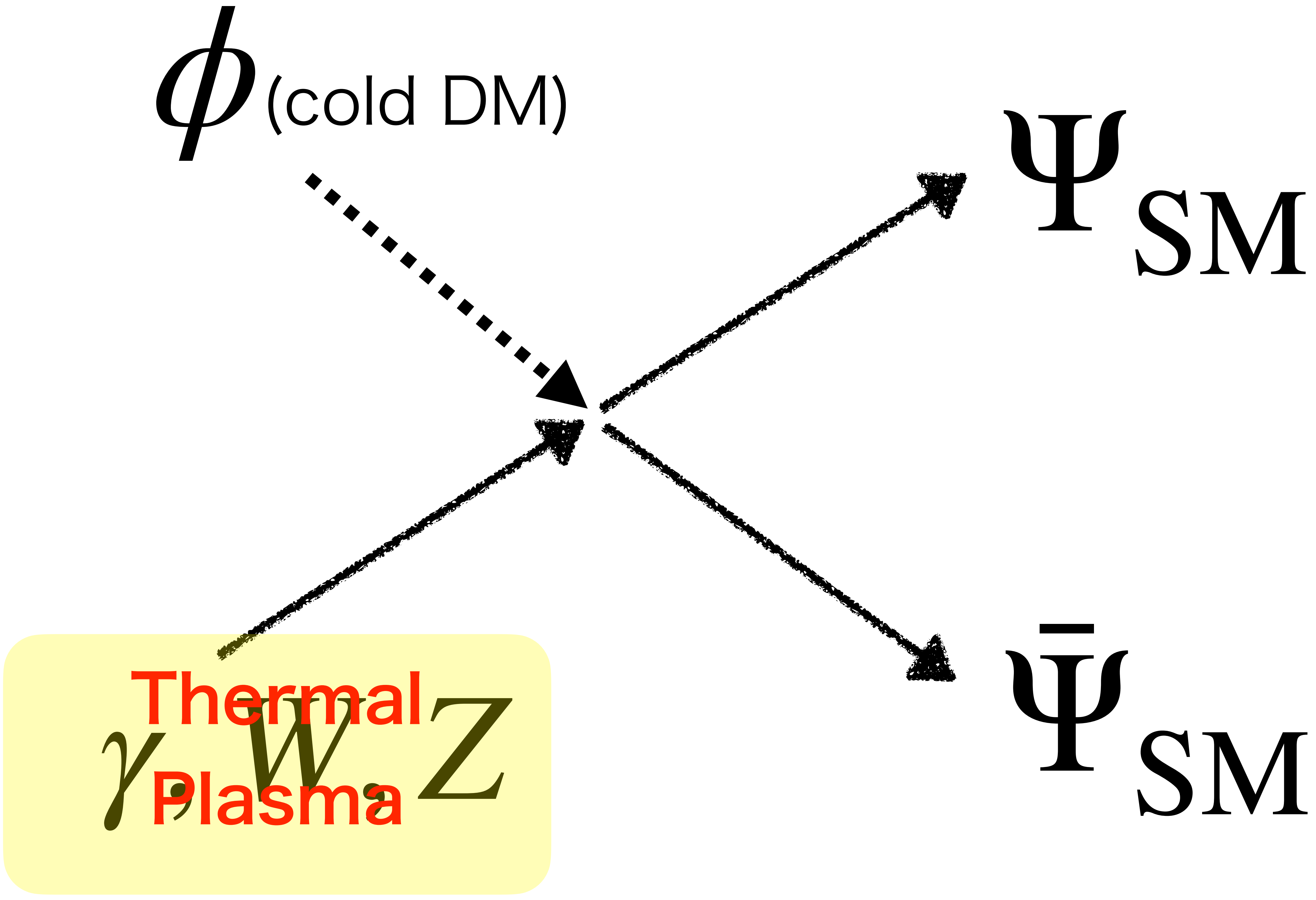
Imposing $\Omega_\phi^{(\rm remnant)} h^2 \sim \Omega_{DM} h^2$ we obtain



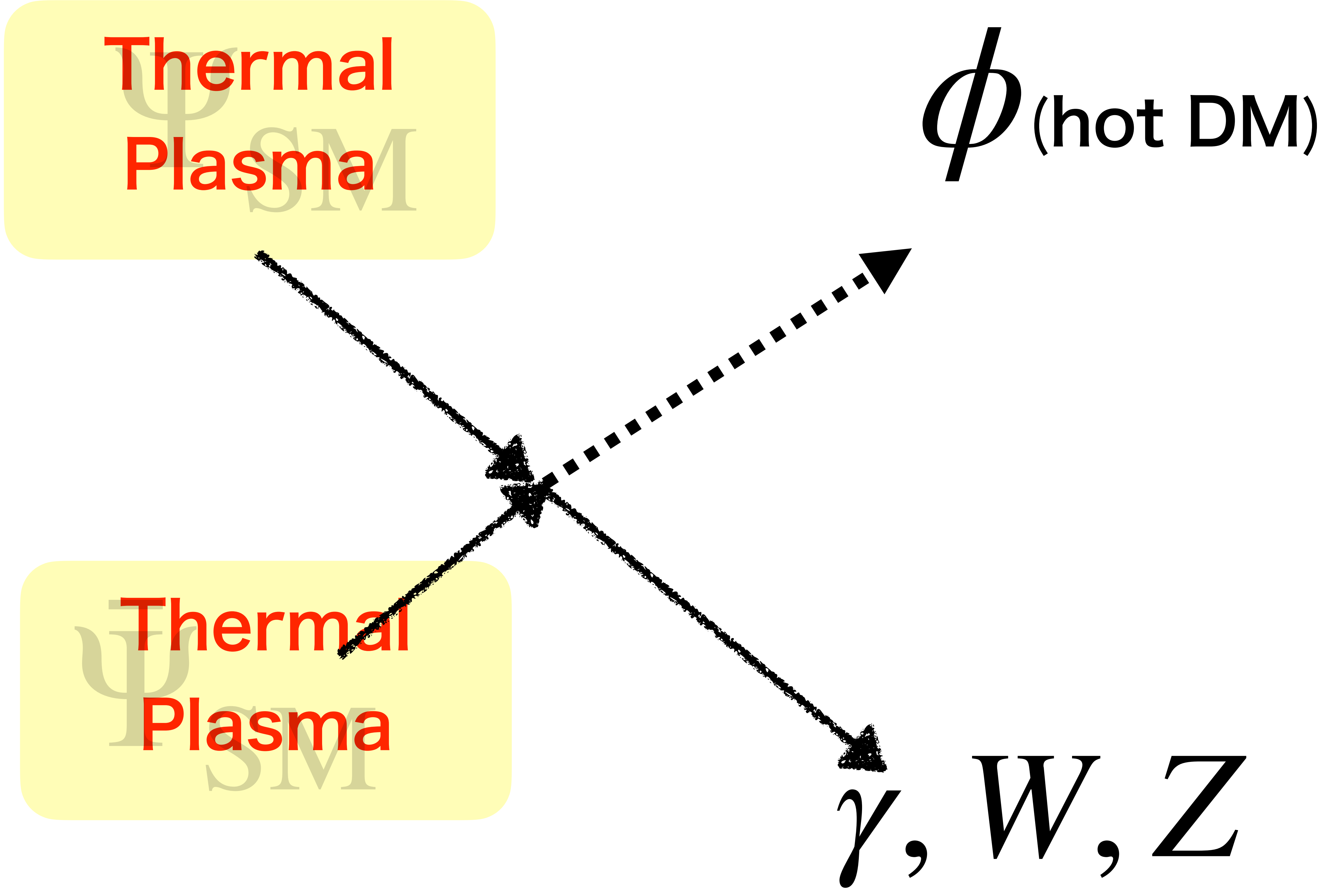
Daido, Takahashi, WY, 1710.11107

Successful reheating means two typical momenta of DM.

Dissipation effect for reheating

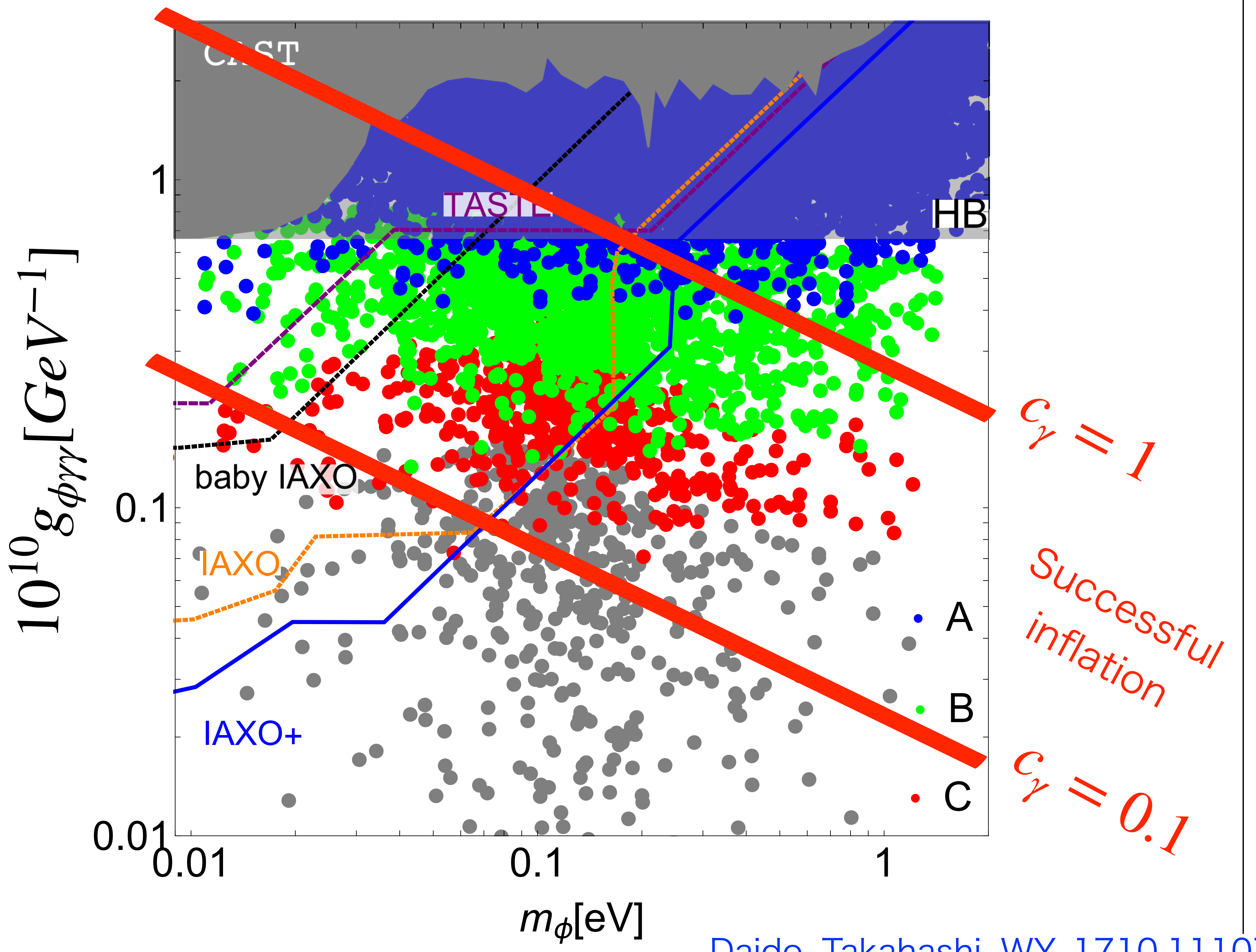


Thermal production of hot DM



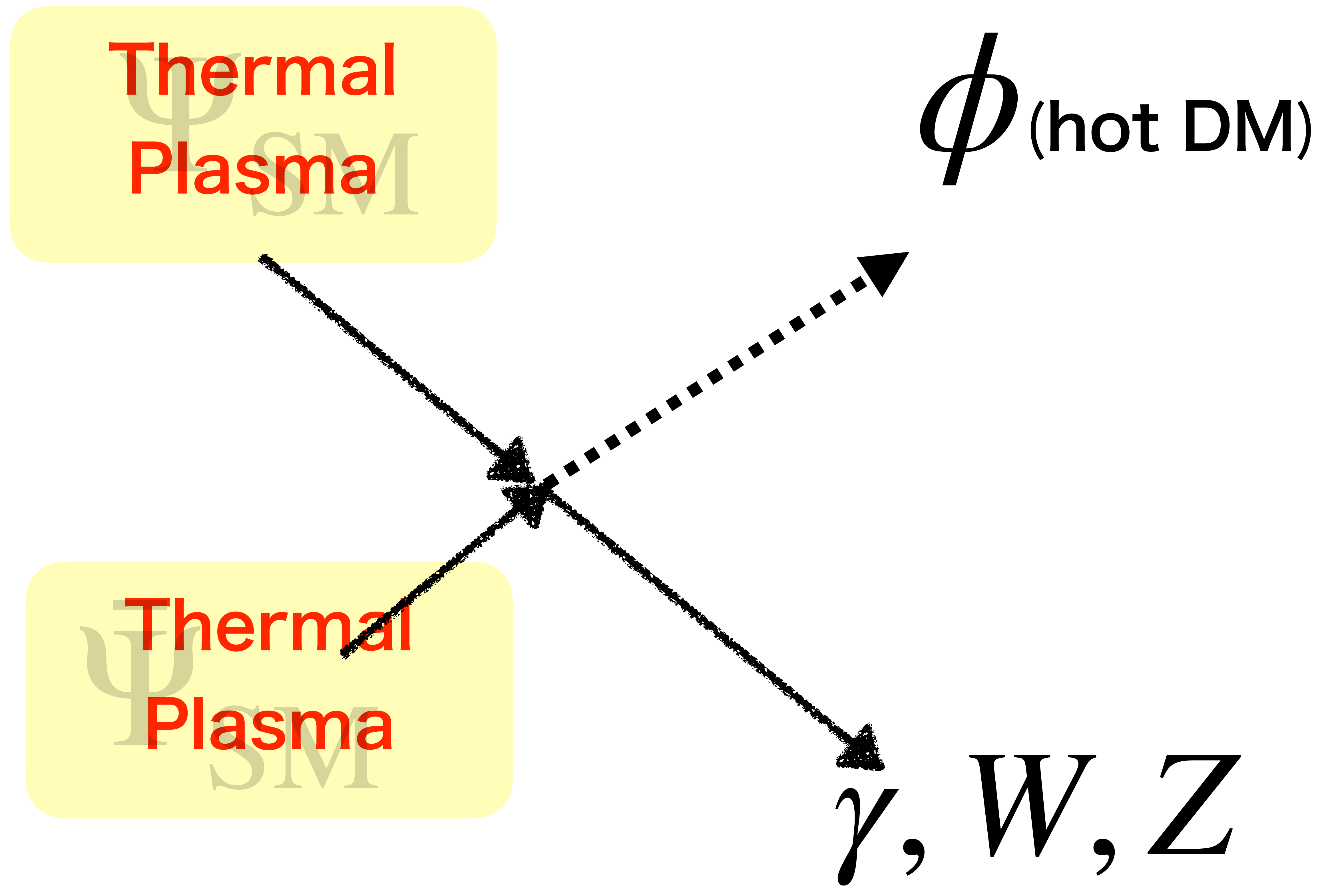
DM components: Cold ALP condensate + hot ALP with $\Delta N_{\rm eff} \sim 0.03$

Hot DM bound: $m_\phi \lesssim 1\,\mathrm{eV}$



Daido, Takahashi, WY, 1710.11107

Thermal production of hot DM



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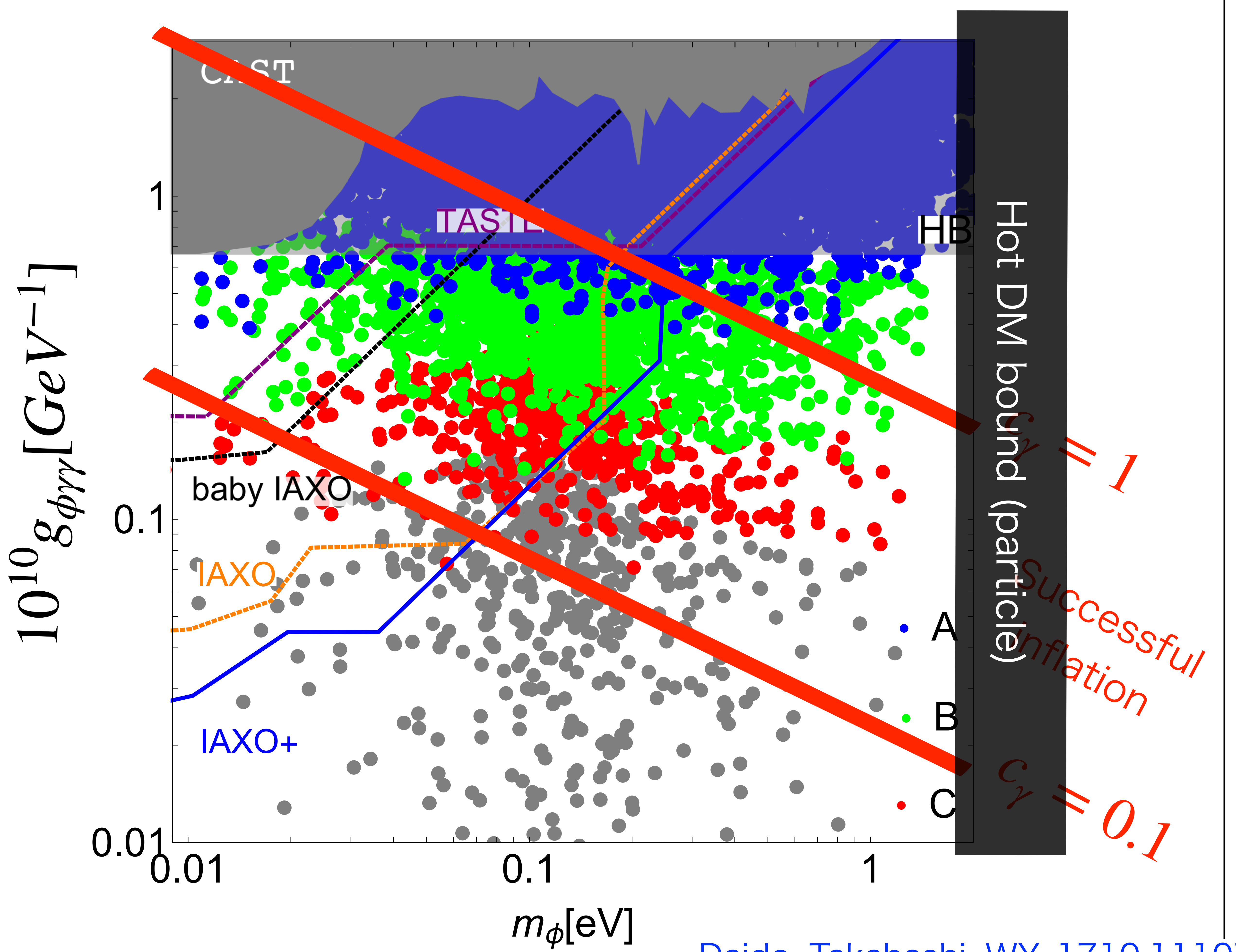

Daido, Takahashi, WY, 1710.11107

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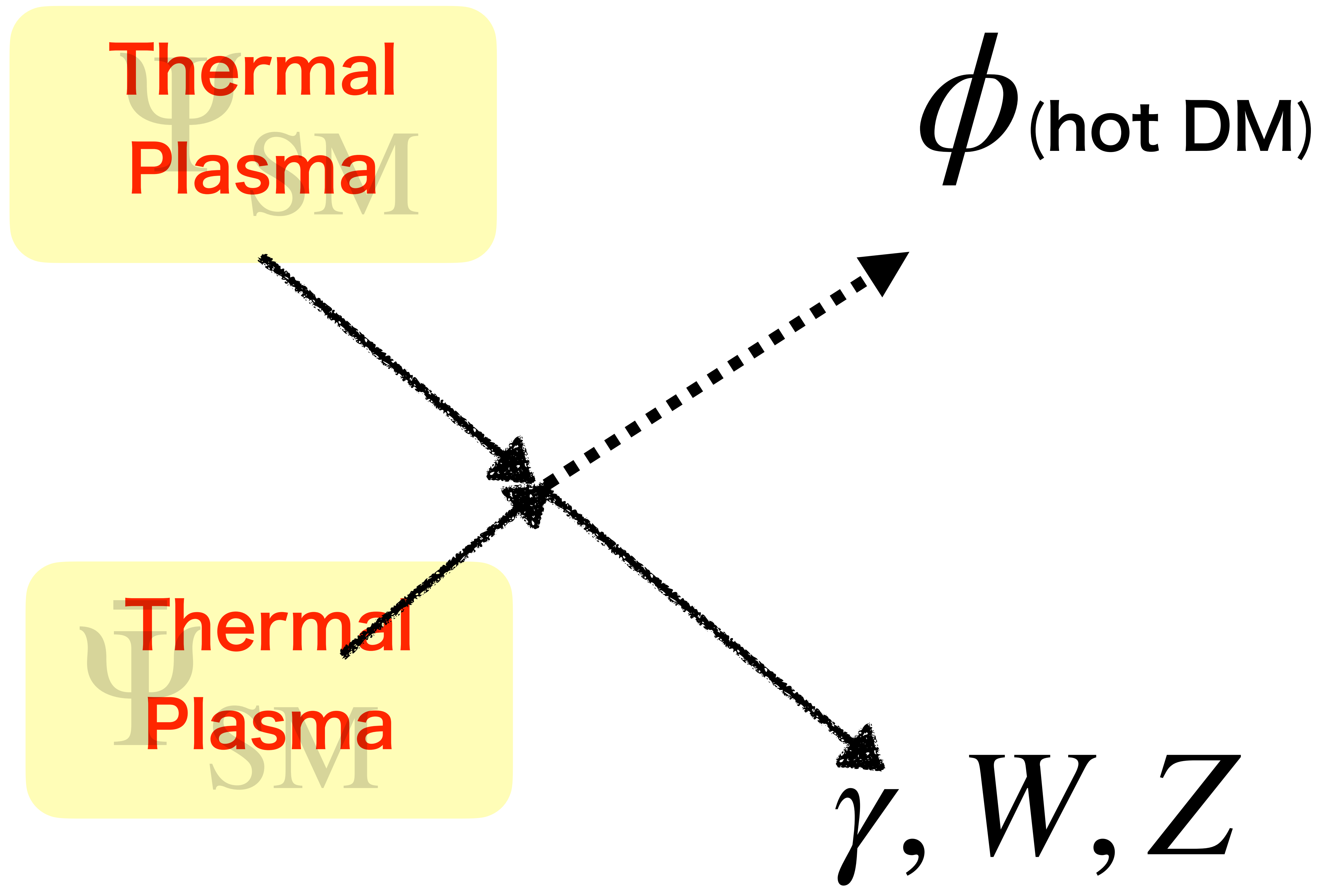

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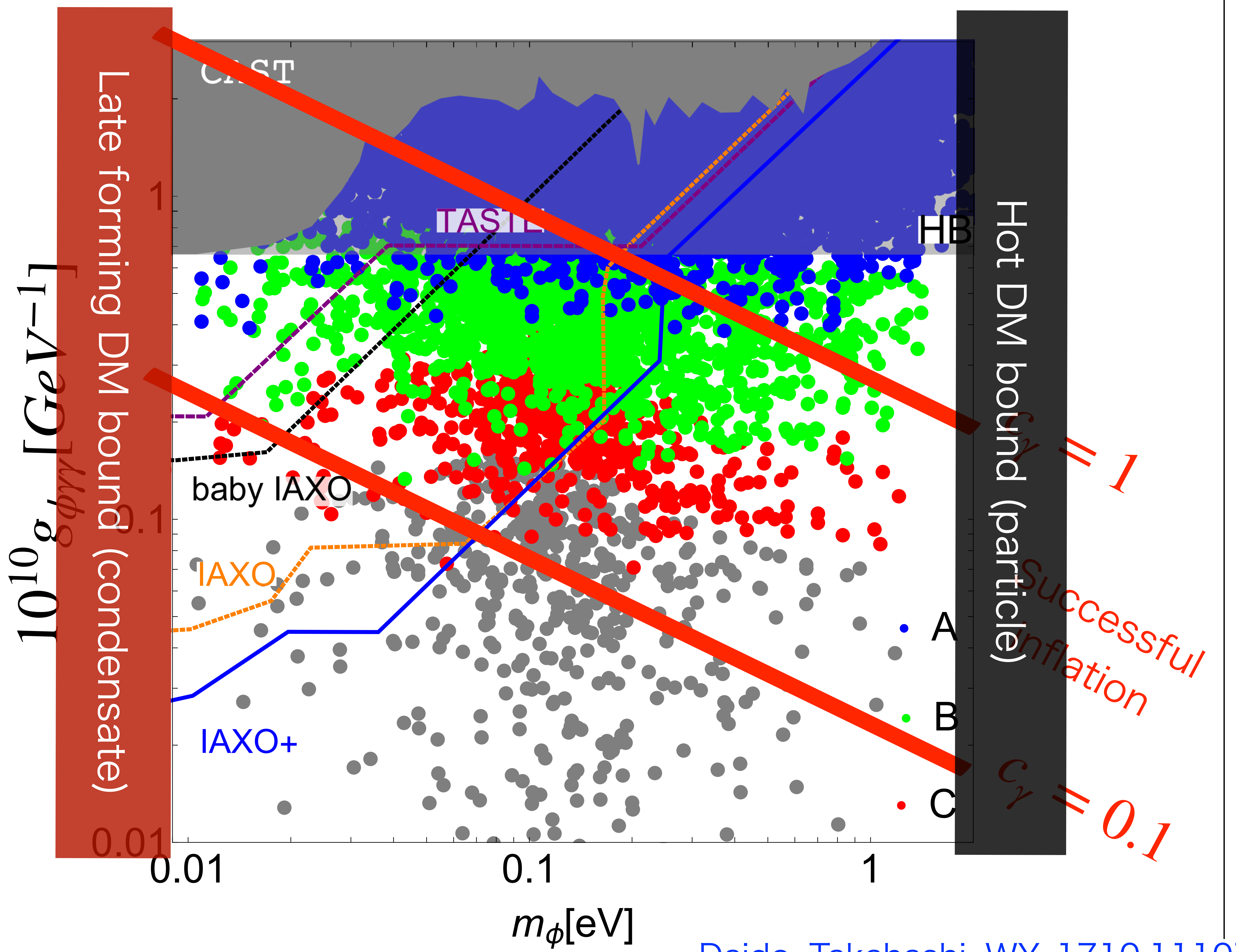
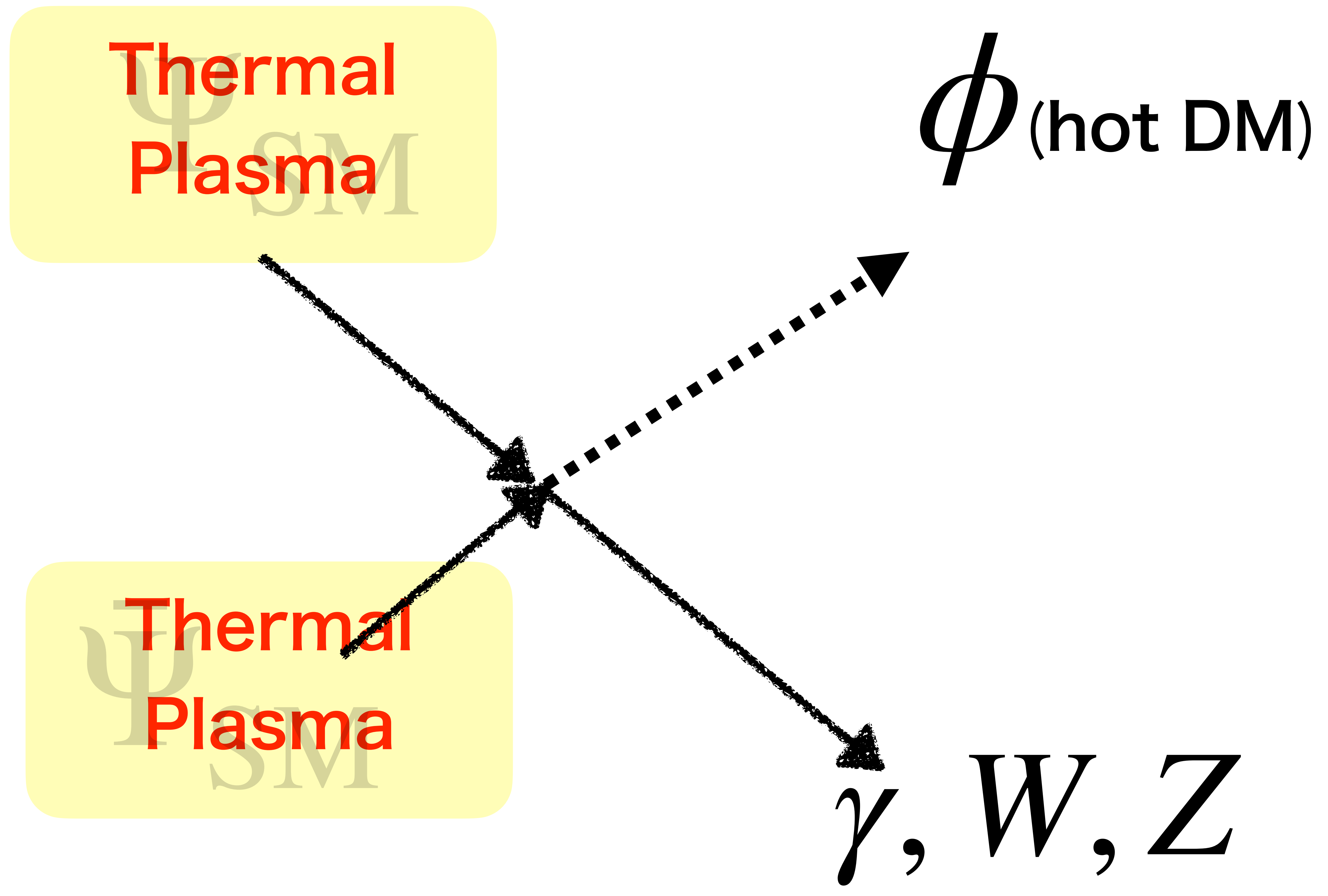
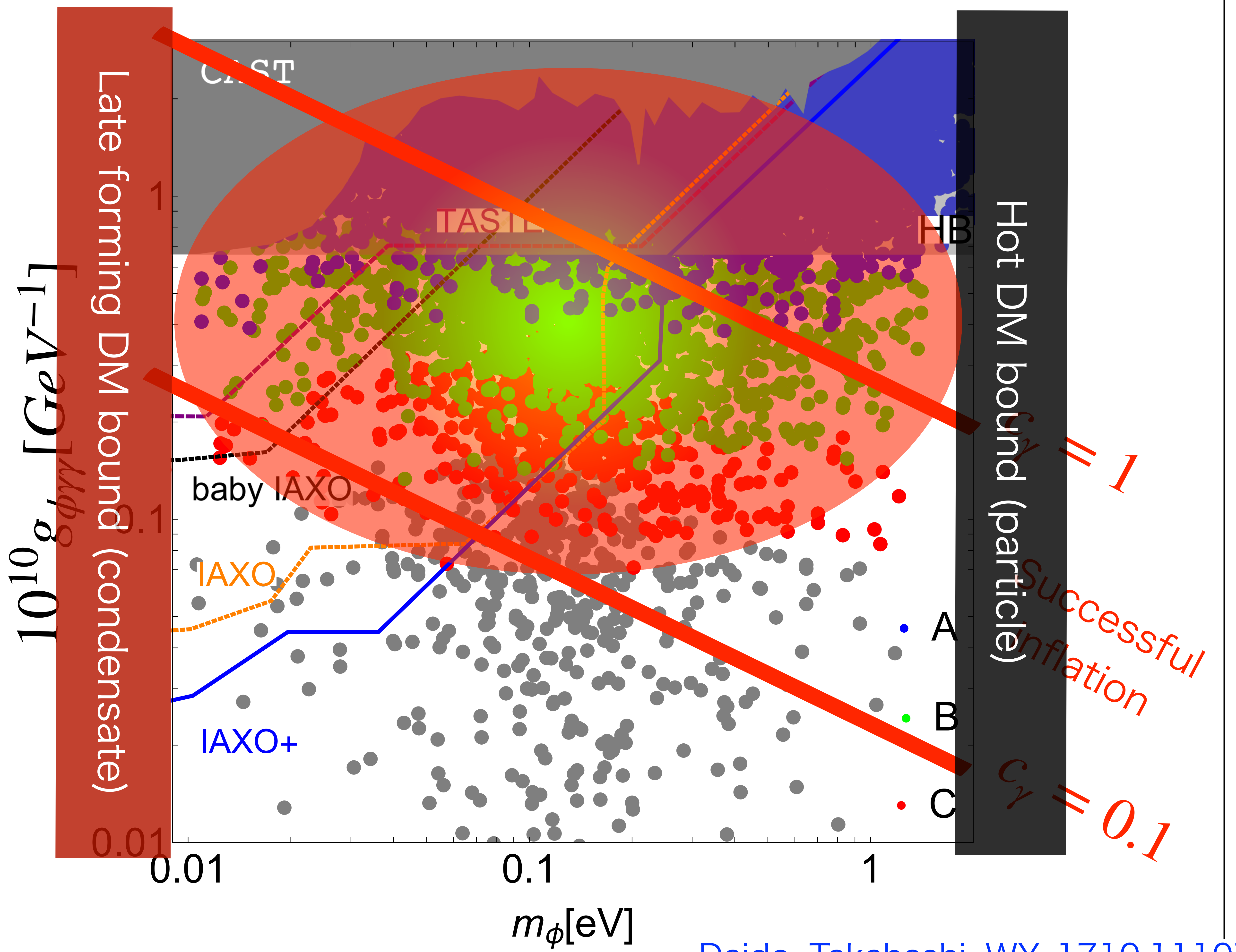


Daido, Takahashi, WY, 1710.11107



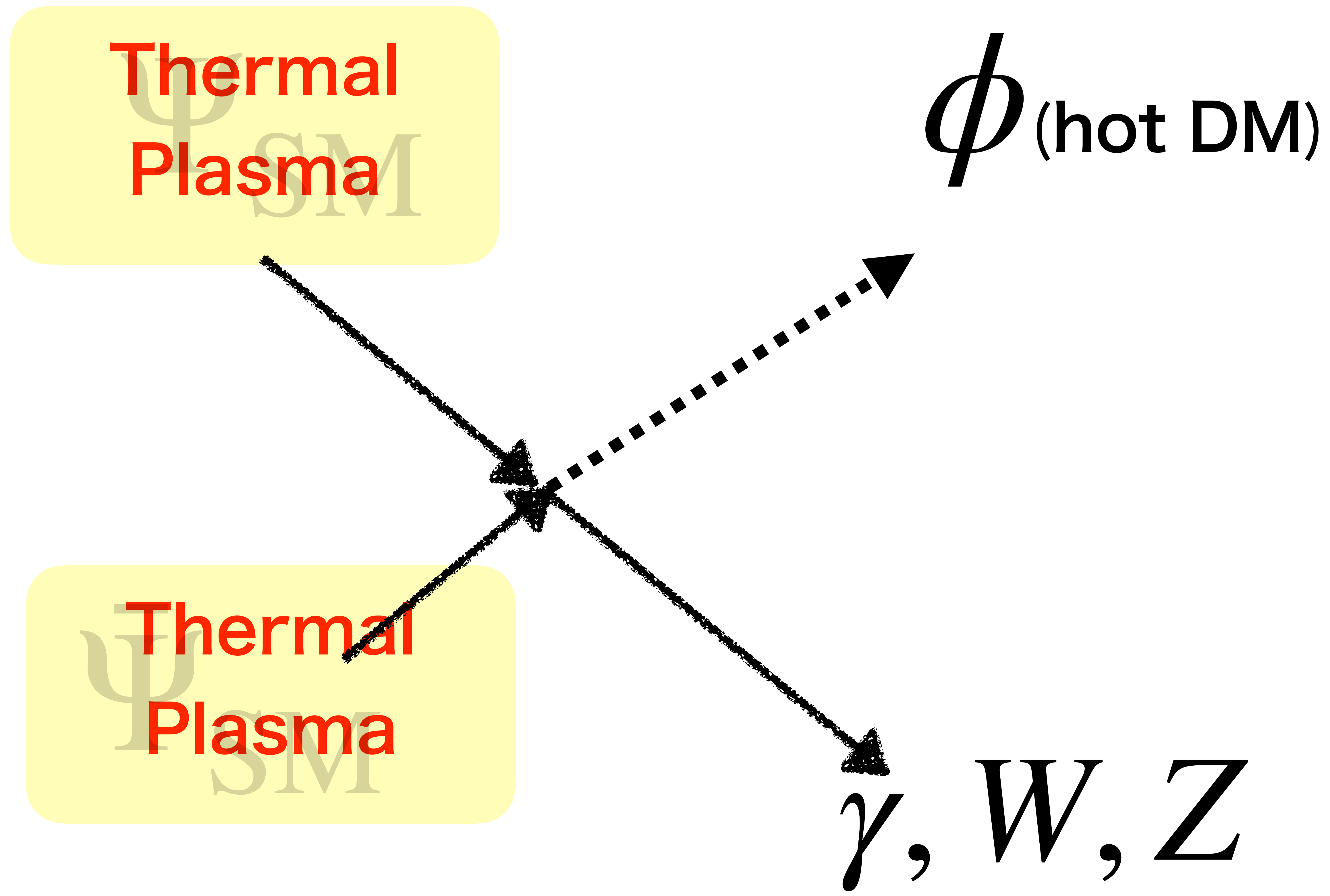
Hot DM bound: $m_\phi \lesssim 1\,\mathrm{eV}$

Several independent conditions point to the region!



Daido, Takahashi, WY, 1710.11107

Thermal production of hot DM



"The ALP miracle".

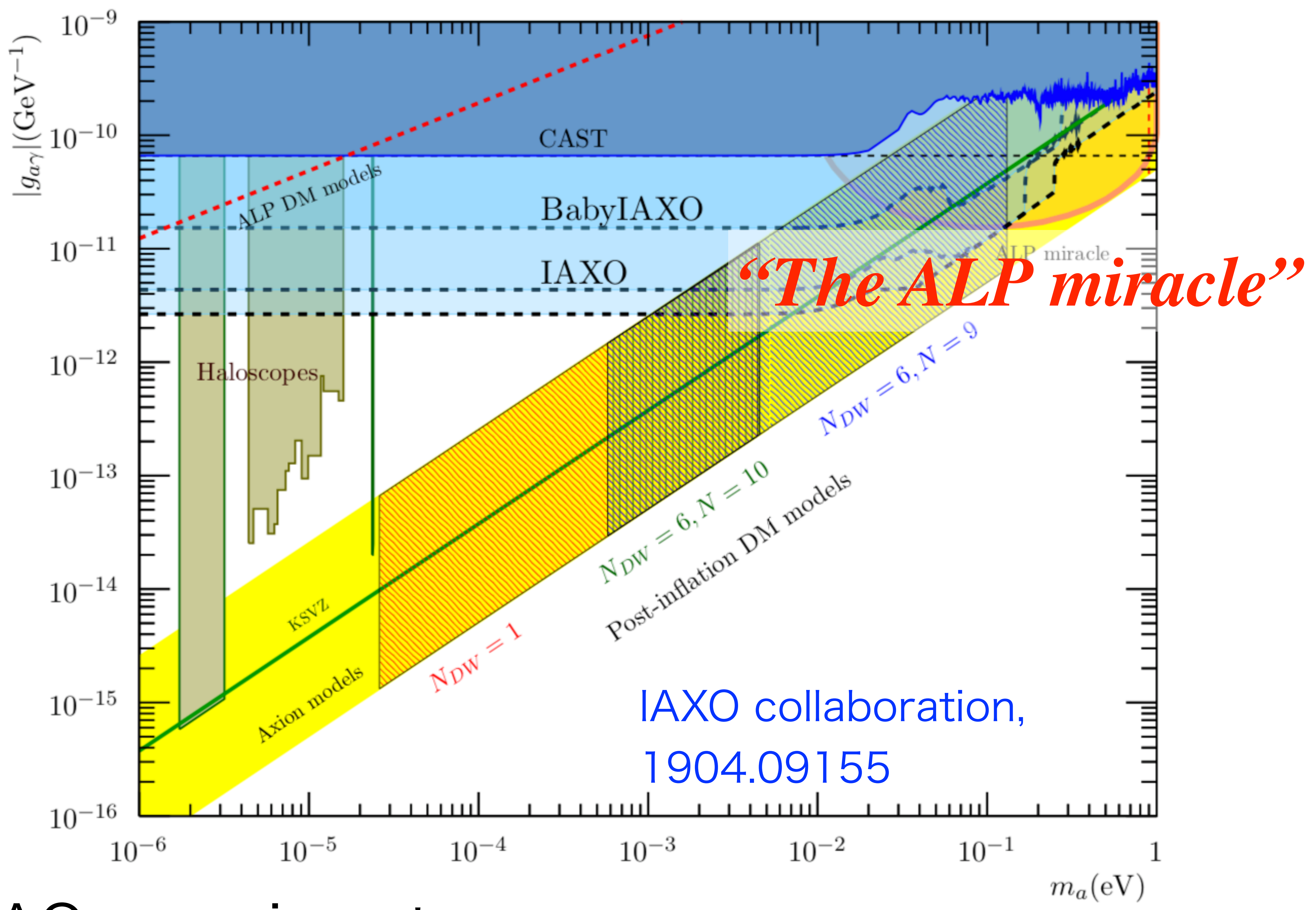
Daido, Takahashi, WY 1702.03284,1710.11107

Inflaton = DM = ALP

$$0.01\,\mathrm{eV} \lesssim m_\phi \lesssim 1\,\mathrm{eV}$$

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

significantly overlapping with future reach of axion helioscopes, IAXO/TASTE.



- $\Delta N_{\rm eff} \approx 0.03$ probed in the future CMB and BAO experiments.
- Overlapping with a cooling hint of HB stars.

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

- O(1) eV ALP with $g_{\phi\gamma\gamma} \sim 10^{-10}\mathrm{GeV}^{-1}$ is hinted by EBL analysis

Korochkin et al,1911.13291

In particular, in eV range, measuring isotropic/anisotropic EBL or optical photon from dSph may find it.

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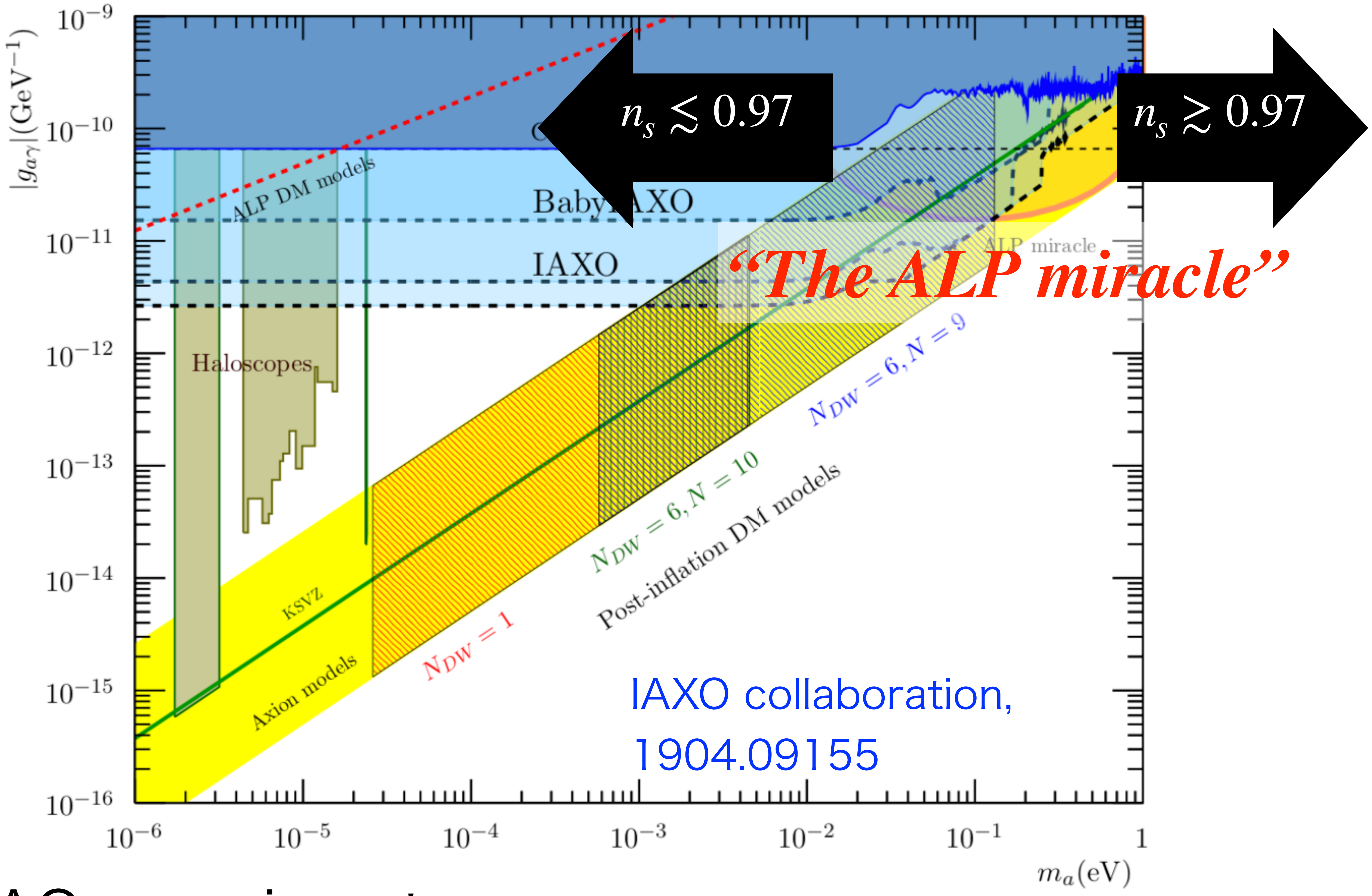

IAXO collaboration, 1904.09155

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In particular, in eV range, measuring isotropic/anisotropic EBL or optical photon from dSph may find it.

Conclusions

Takahashi, WY, 2112.06710;

1. The 5 σ Hubble tension may indicate $n_s \neq 0.97$.

2. This significantly affects the very early Universe model-building. If $n_s = 1$, the curvaton scenario is promising, and we proposed "stochastic curvaton scenarios"

Daido, Takahashi, WY, 1702.03284, 1710.11107;

3. In a class of ALP inflation models, ALP inflaton can be the DM, whose stability is due to the slow-roll conditions. The mass is linked to n_s.

4. The Hubble tension affects the DM mass region.

Backup

Axionic curvaton, $\sigma_0 \sim f_a$.

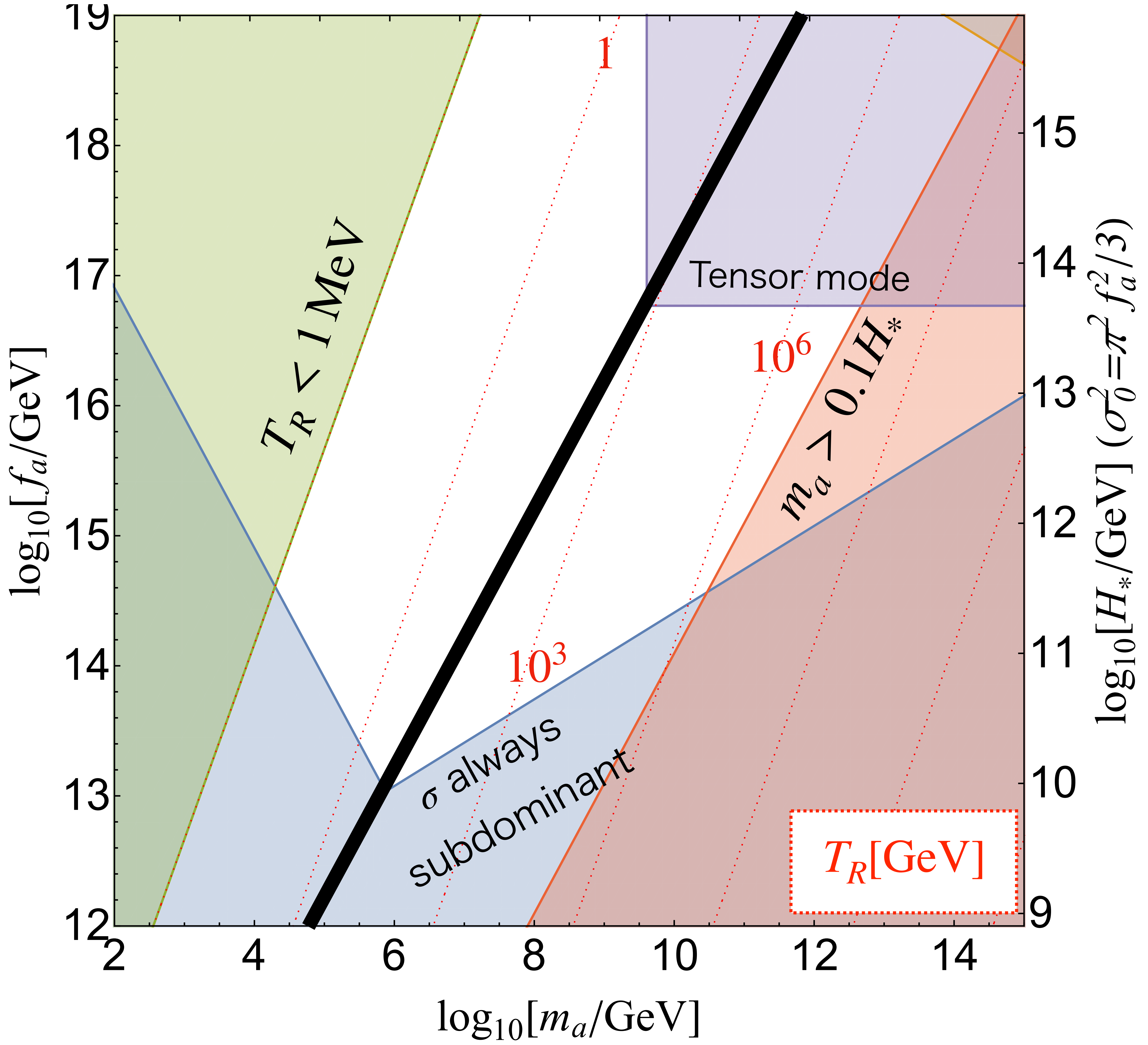
(e.g. inflation is not long enough, axion-inflaton mixing)

$$V[\sigma] = \Lambda^4(1 - \cos[\sigma/f_a])$$

$$\Gamma_{\mathrm{dec},\gamma} = c_\gamma^2 \frac{\alpha^2}{64\pi^3}\frac{m_a^3}{f_a^2}\,.$$

Interestingly,

1. subplanckian f_a, σ_0, inflaton field
2. f_a consistent with string axion



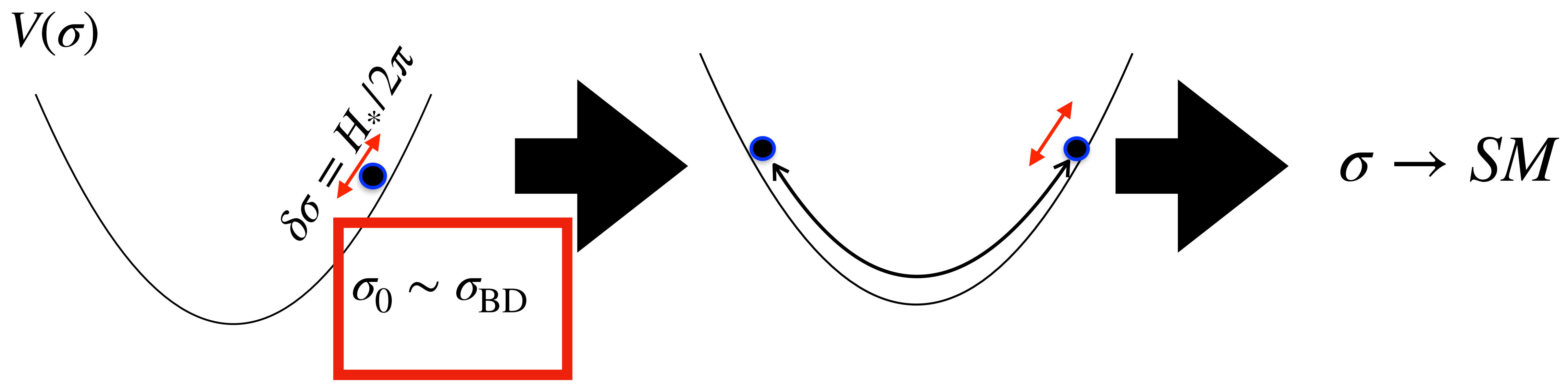
Stochastic curvaton for $n_s \approx 1$

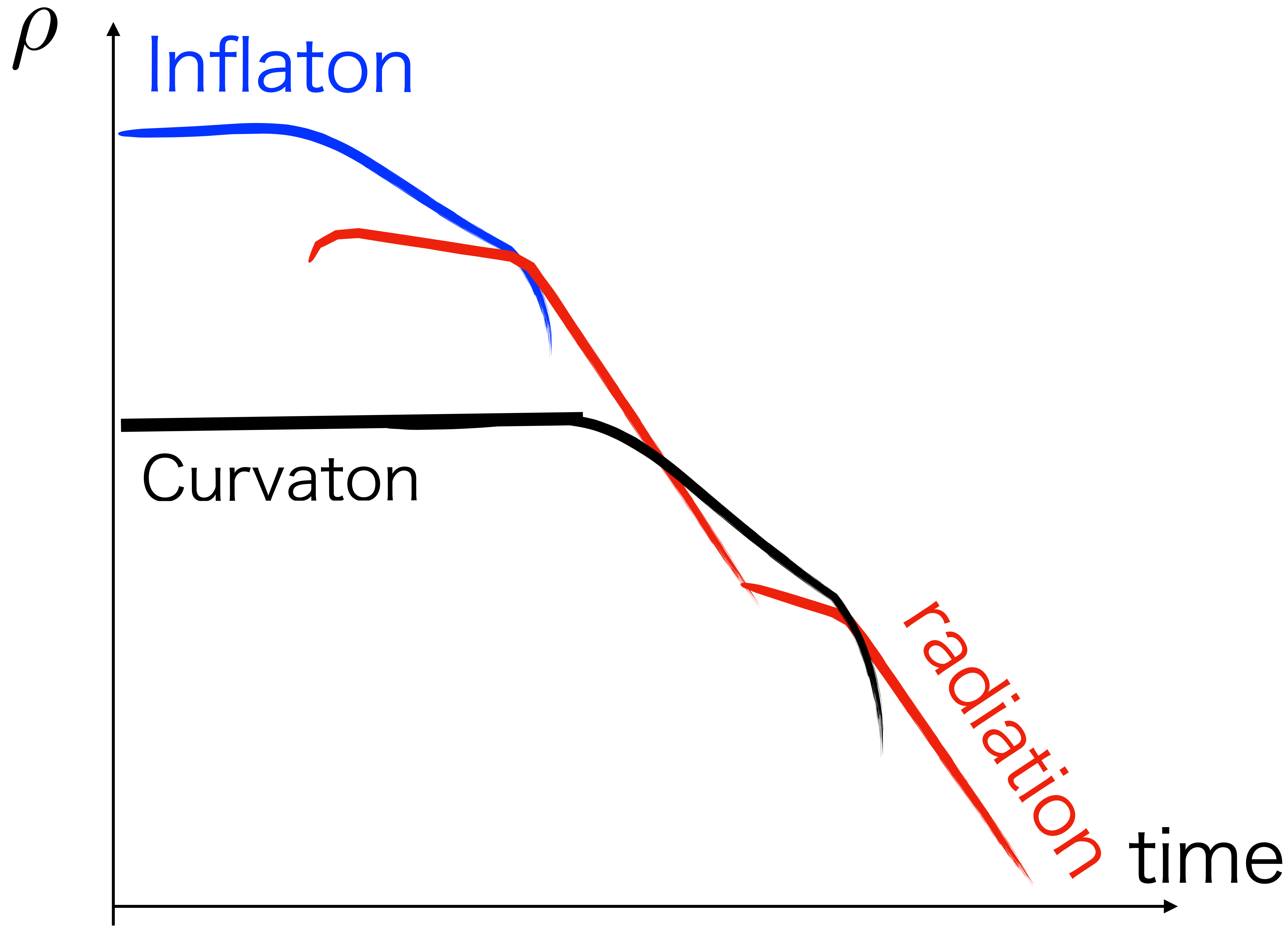
$$
\begin{cases}
H_* \approx 4.4 \times 10^{12} GeV \left(\dfrac{\sigma_{0*}}{10^{16} GeV} \right). \\[2ex]
\sigma_0^* \sim \sigma_{\rm BD} \equiv \sqrt{\dfrac{3H_*^4}{8\pi^2 m_a^2}} \\[2ex]
n_s - 1 \simeq \dfrac{2}{3} \dfrac{m_a^2}{H_*^2}
\end{cases}
$$

We obtain

$$
\begin{cases}
H_* \sim 1.2 \times 10^4 \, m_a \\[1ex]
n_s - 1 = O(10^{-9})
\end{cases}
$$

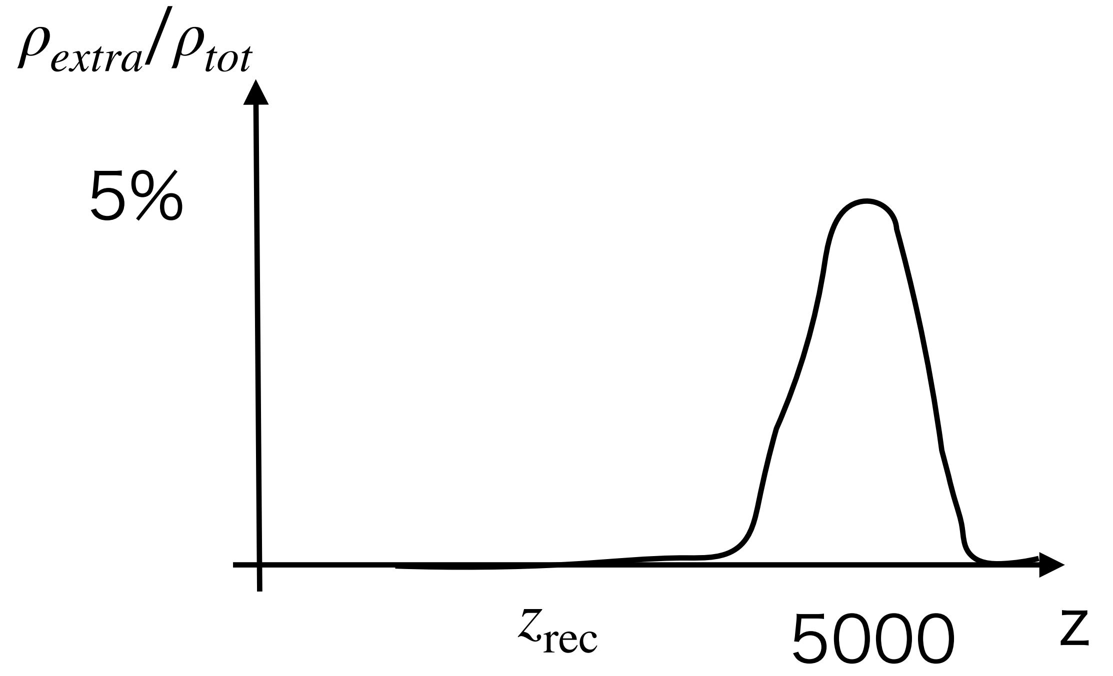
(by neglecting $2\dot{H}/H^2$).





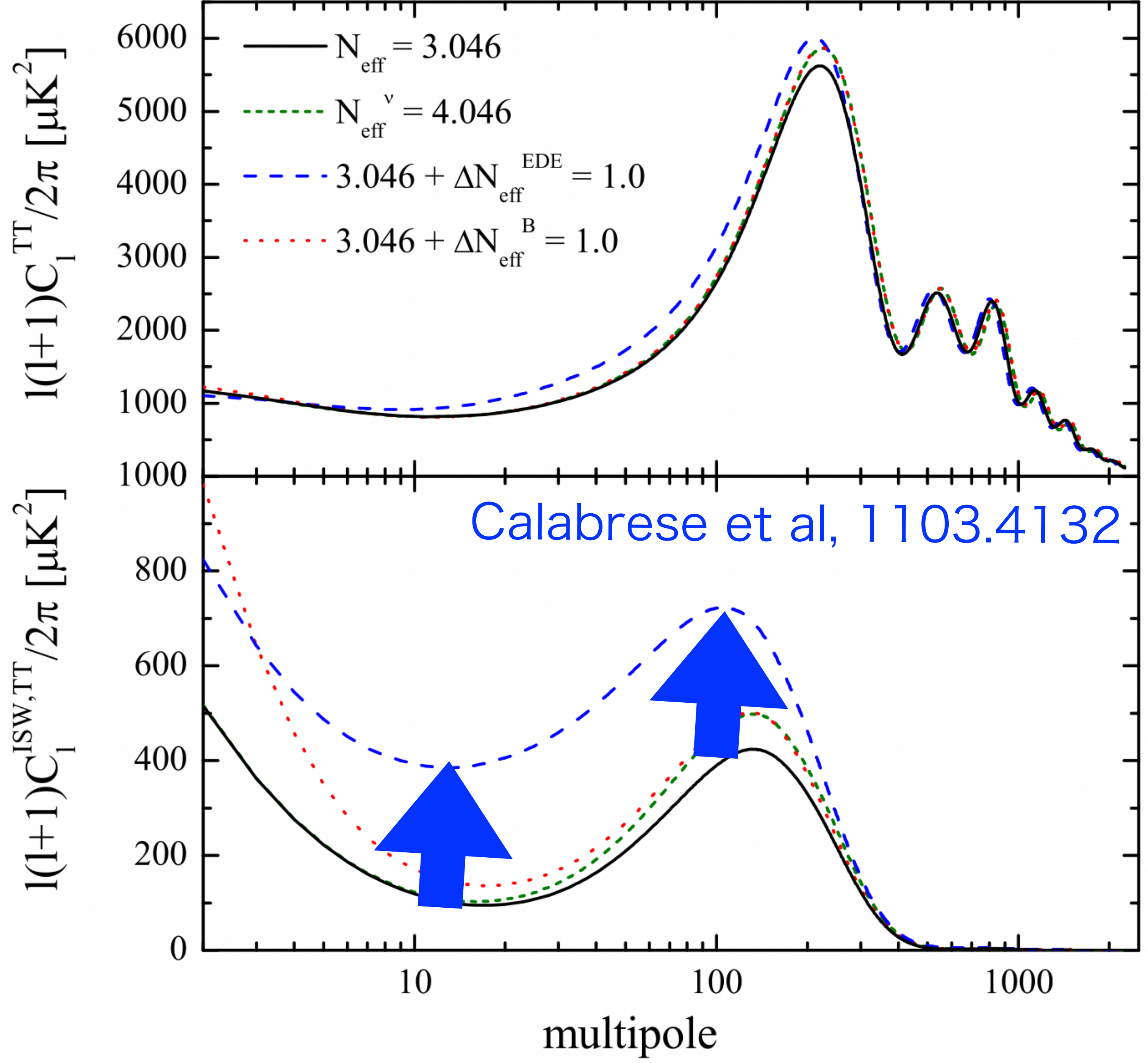
$n_s \neq n_s^{\Lambda\mathrm{CDM}}$: case of EDE

EDE: A prompt early energy components increase early H and decrease r_s, thus increase H_0



$$r_s = \int_{z_d \sim z_{\mathrm{rec}}}^{\infty} dz \frac{c_s[\rho_\gamma/\rho_{baryon}]}{H[z, \Omega_x, H_0]}$$

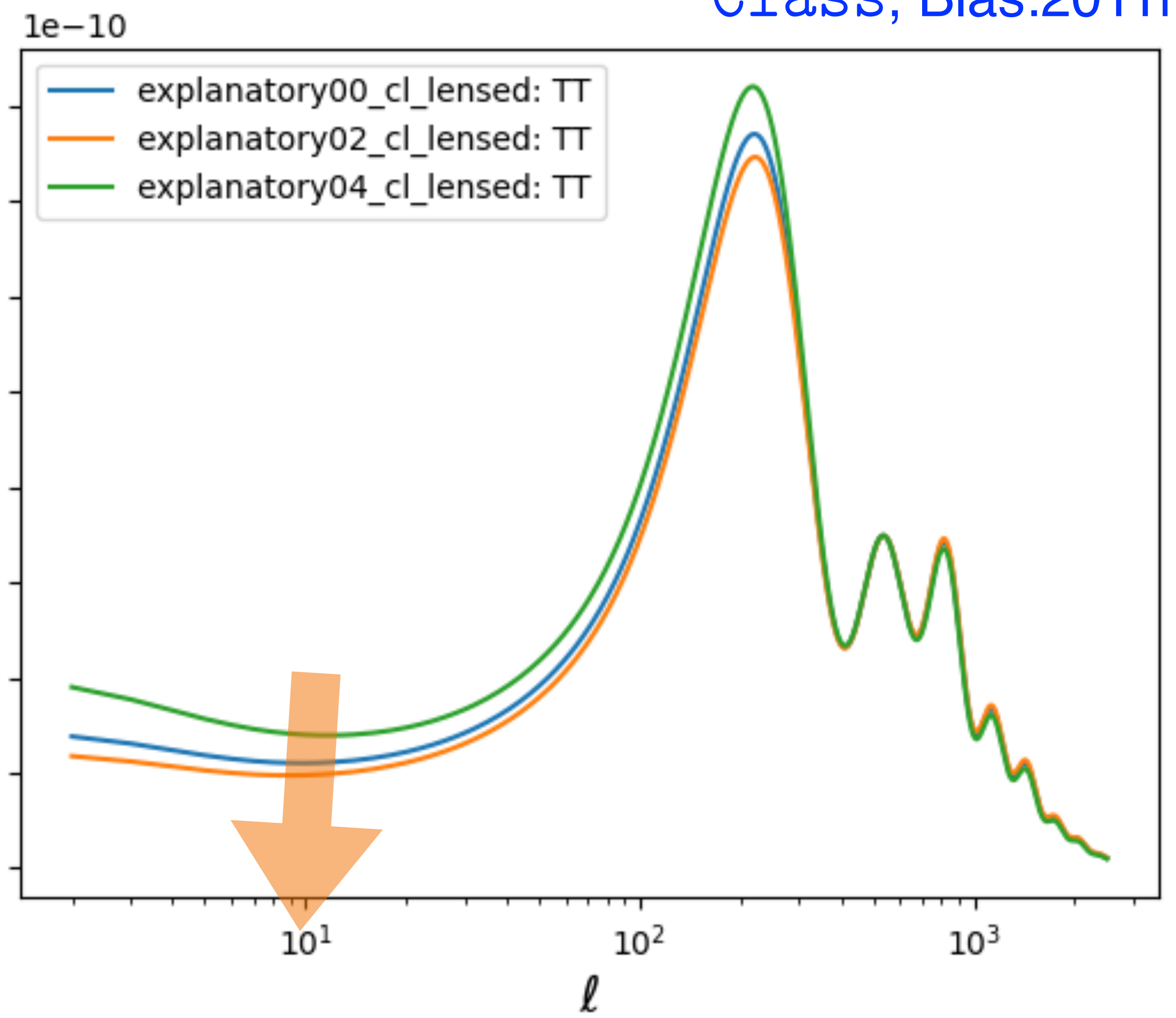
$$H_0 \propto \theta_s^{\mathrm{measured}}/r_s \propto 1/r_s$$



Calabrese et al, 1103.4132

To compensate the extra Integrated Sachs-Wolfe effect, we need to increase DM density and n_s

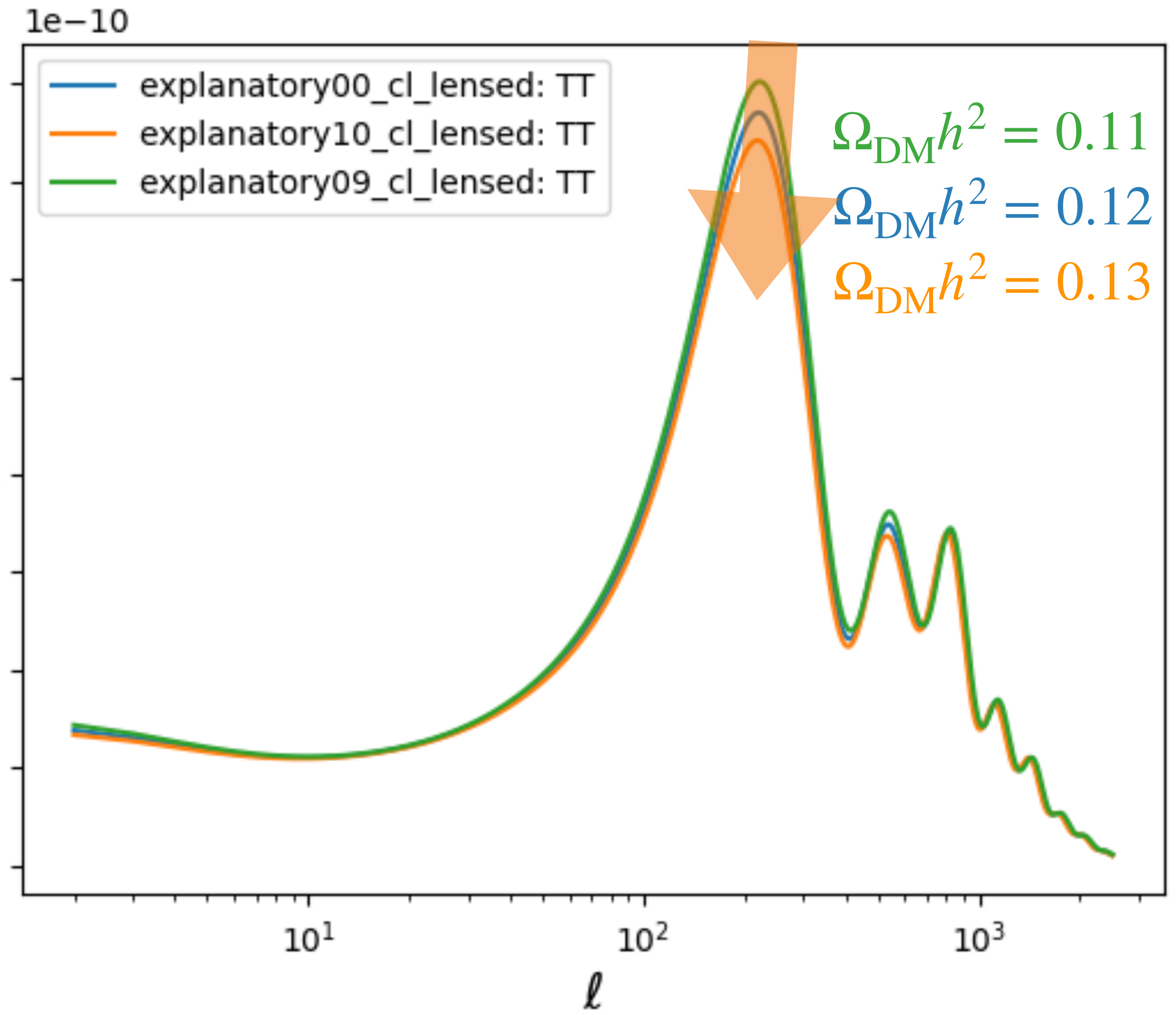
Class, Blas:2011rf



$n_s = 0.90$

$n_s = n_s^{\Lambda\mathrm{CDM}}$

$n_s = 1$



$\Omega_{\mathrm{DM}}h^2 = 0.11$ $\Omega_\Lambda = 0.712$

$\Omega_{\mathrm{DM}}h^2 = 0.12$ $\Omega_\Lambda = 0.690$

$\Omega_{\mathrm{DM}}h^2 = 0.13$ $\Omega_\Lambda = 0.668$

Primordial curvature perturbation and CMB

The power spectrum of
the primordial curvature perturbation is

$$\mathscr{P}_\zeta[k] = \mathscr{P}_\zeta[k_{\rm CMB}]\left(\frac{k}{k_{\rm CMB}}\right)^{n_s-1}$$

$$n_s - 1 \simeq -6\varepsilon + 2\eta, \qquad \varepsilon \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V'_{\rm inf}}{V_{\rm inf}}\right)^2, \quad \eta \equiv M_{\rm pl}^2\frac{V''_{\rm inf}}{V_{\rm inf}}.$$

@ inflation

$+$

Acoustic oscilation+Silk damping

@ around and before last scattering

$+$

Doppler shift+ Gravitational red-shift

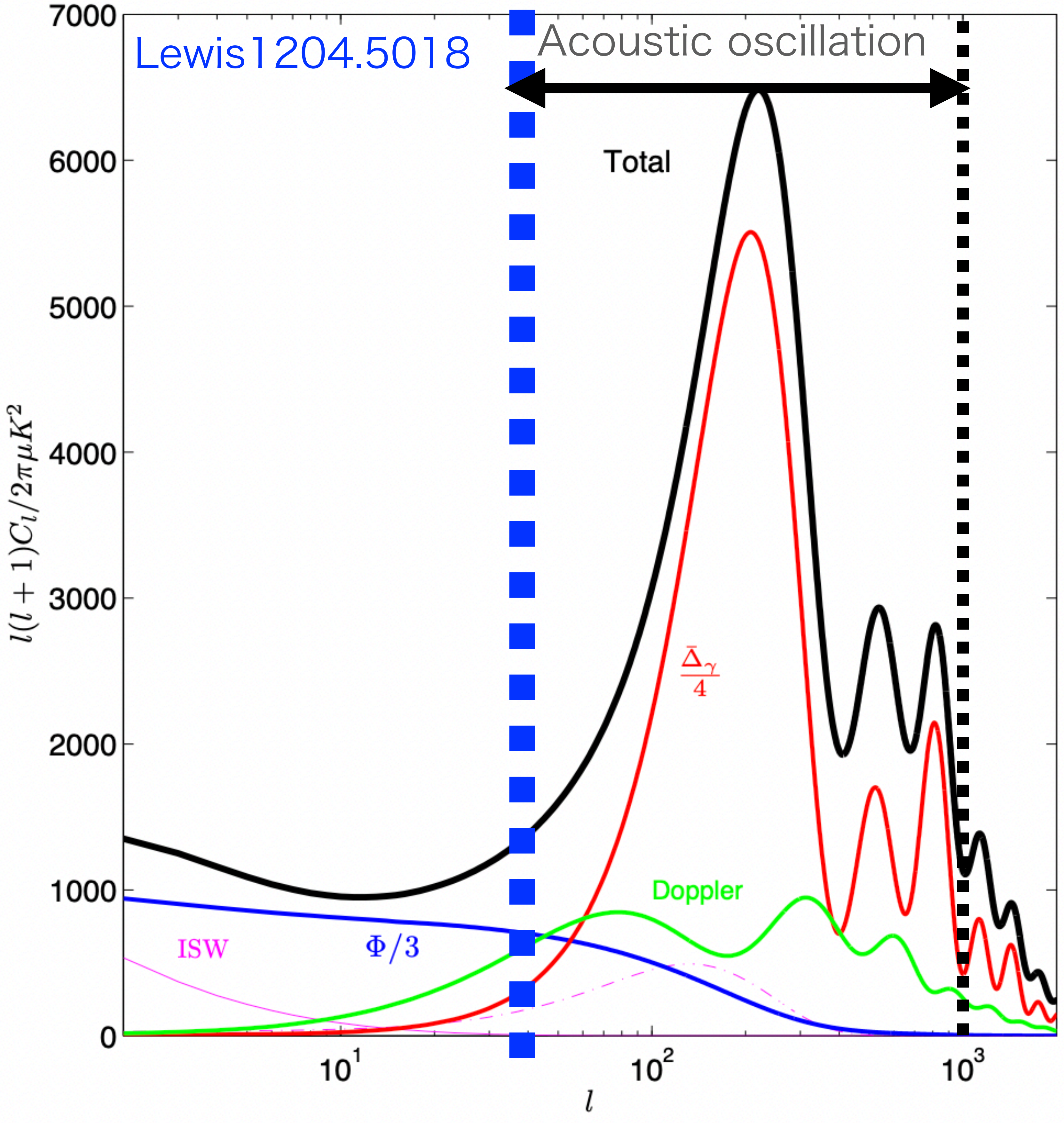
i.e. Sachs-Wolfe (SW) effect+ integrated SW effect

@ photon propagation around and after last scattering

The resulting temperature fluctuation
in Lambda CDM

Sound horizon angle, $\sim 1/\theta_s$

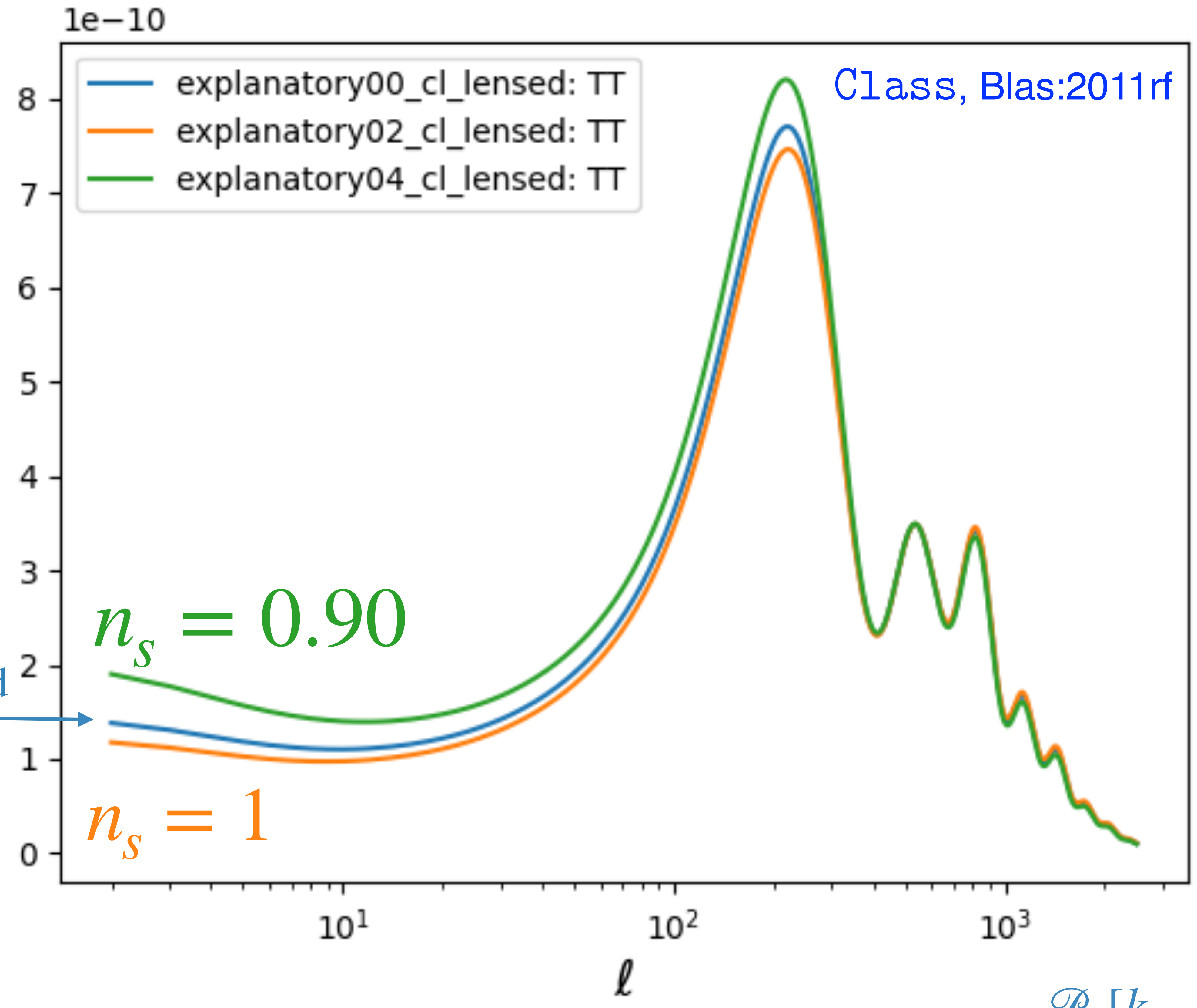
Silk damping
scale

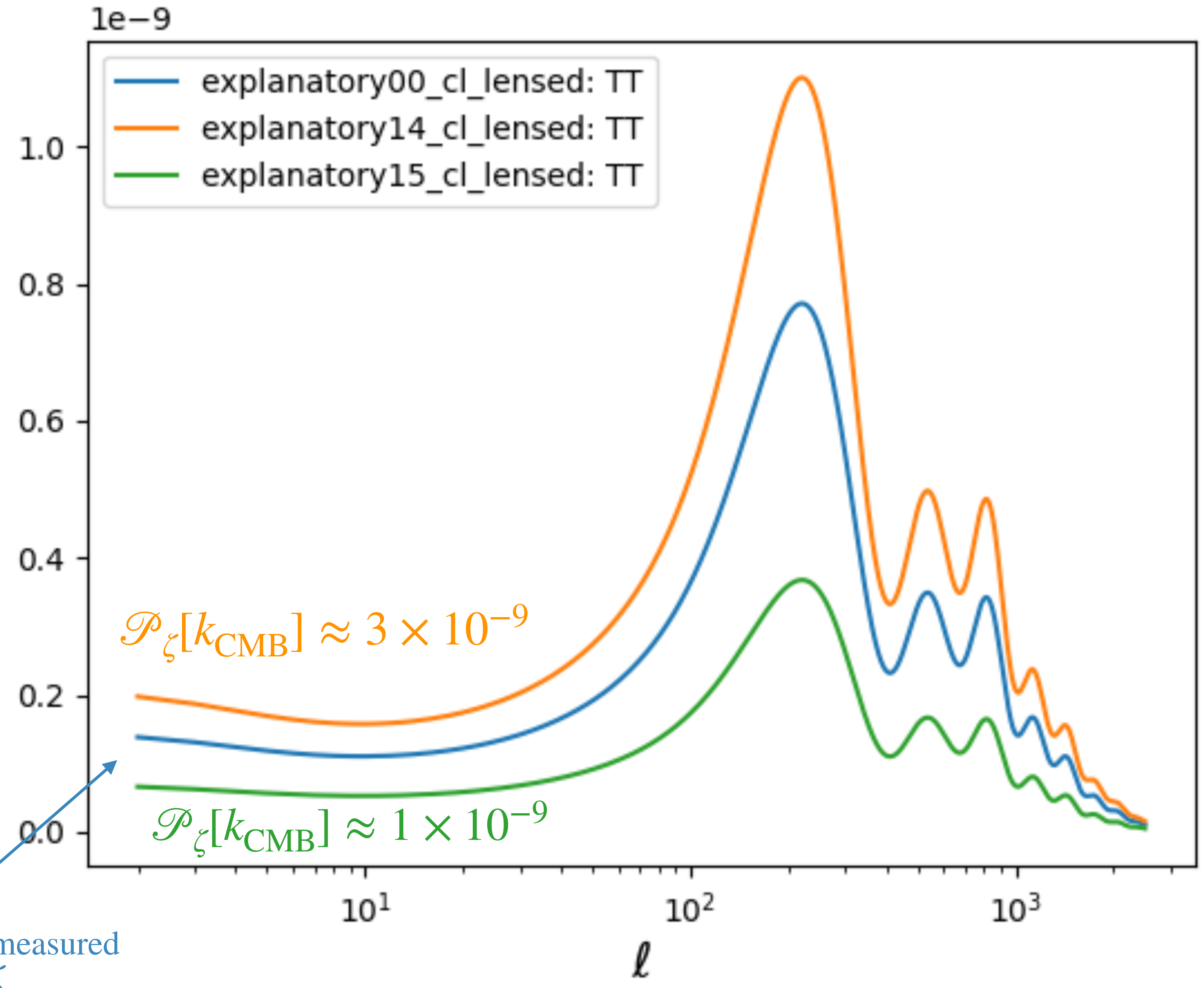


($\propto k$ on the 2D last scatteringsurface)

Superhorizon modes at LSS can constrain inflaton potential.

$n_s = n_s^{\text{measured}}$





$\mathscr{P}_\zeta[k_{\text{CMB}}] \approx \mathscr{P}_\zeta^{\text{measured}}$

Planck 2018,

$$n_s^{\text{measured}} = 0.965 \pm 0.004$$

$$\mathscr{P}_\zeta^{\text{measured}}[k_{\text{CMB}}] \approx 2 \times 10^{-9}$$