Inflationary Models in String Theory

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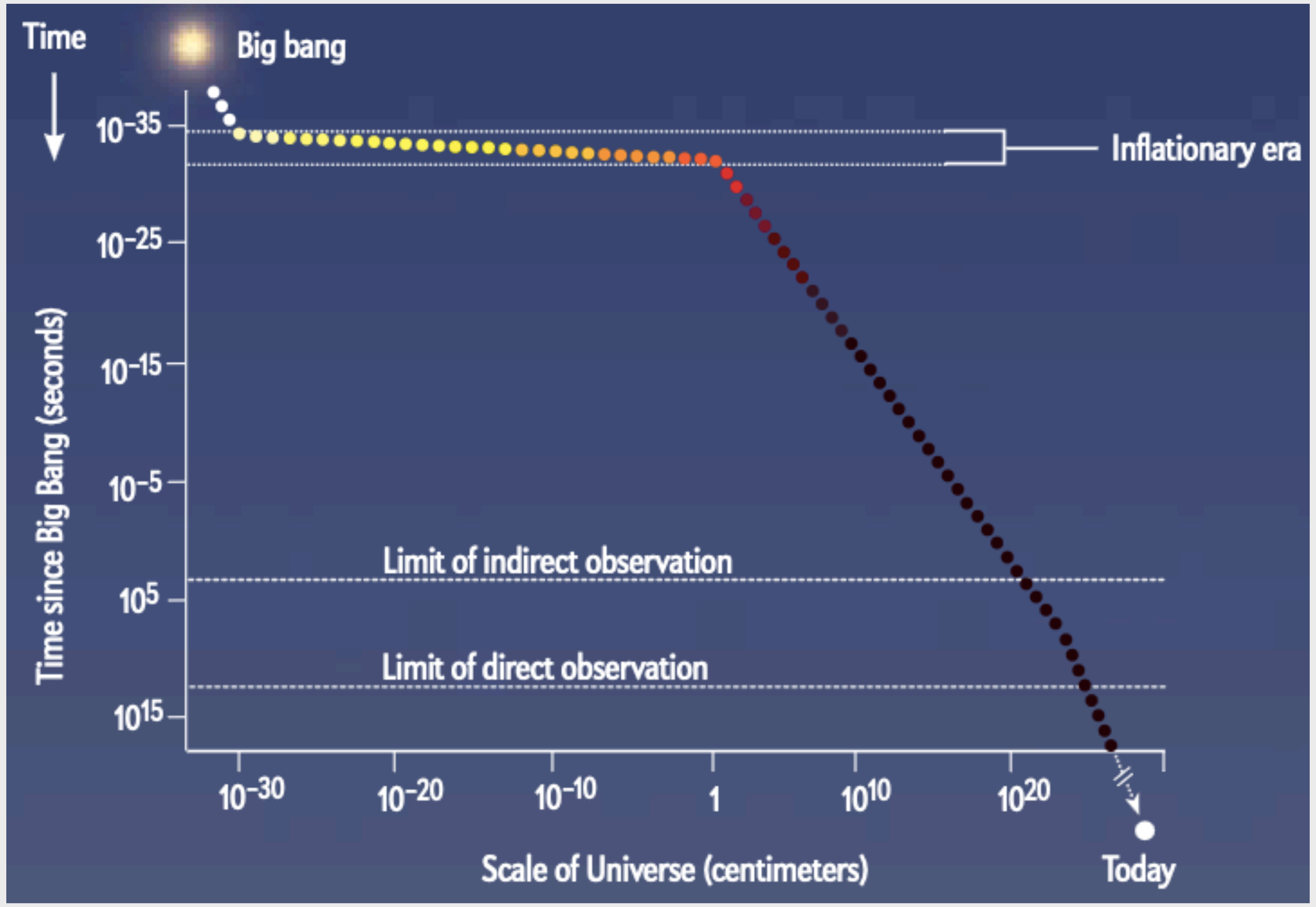
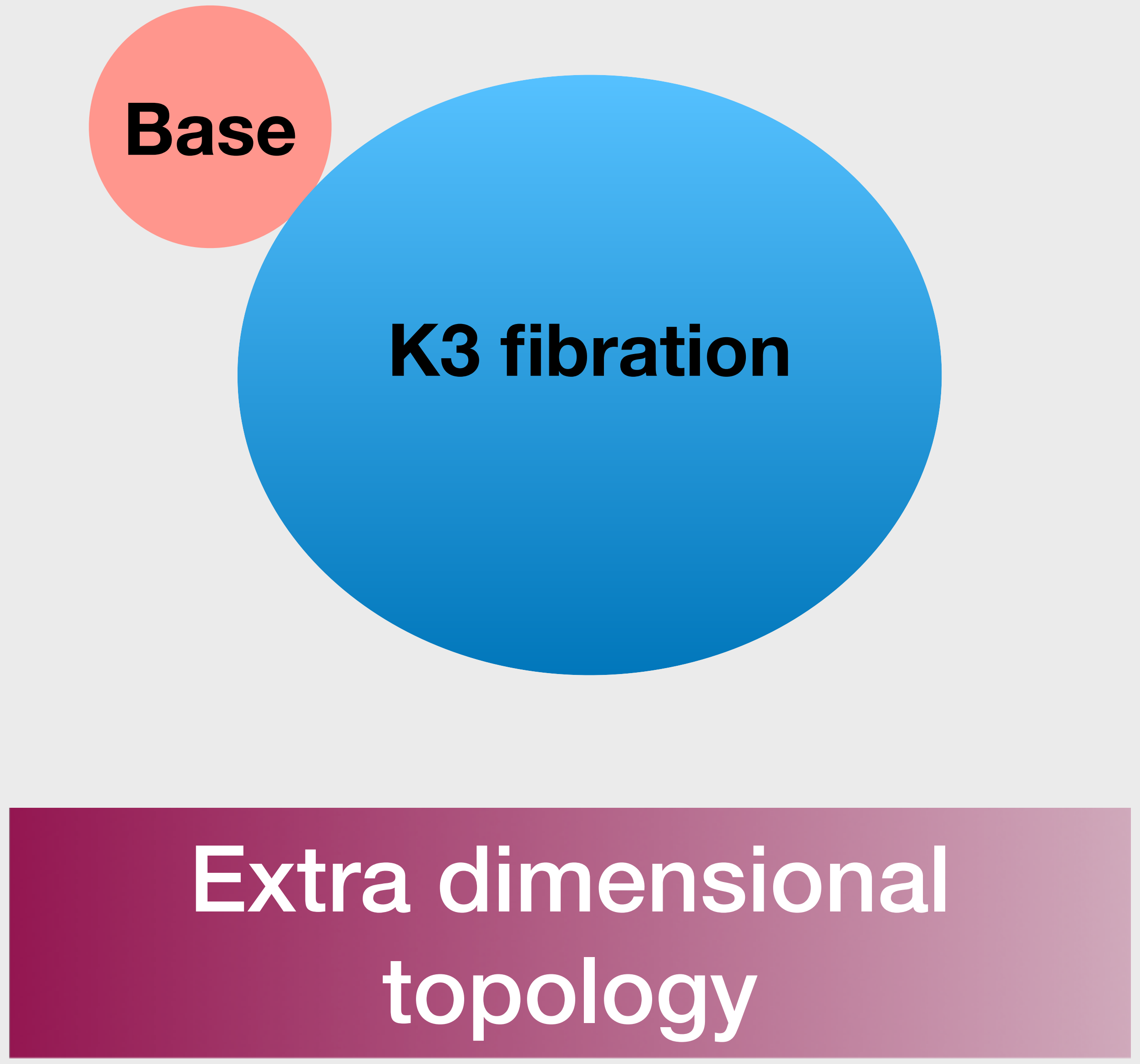
Hearing beyond the standard model with cosmic sources of Gravitational Waves
8th January 2025

Keywords

- Inflation
- String Theory Model building
- Moduli stabilisation





Left Image source: P.J. Steinhardt, Scientific American , Vol. 304, No. 4 (April 2011)

Keywords

- Inflation

[Ref: SriramKumar's, Ivonne's, Gianmassimo's talk]

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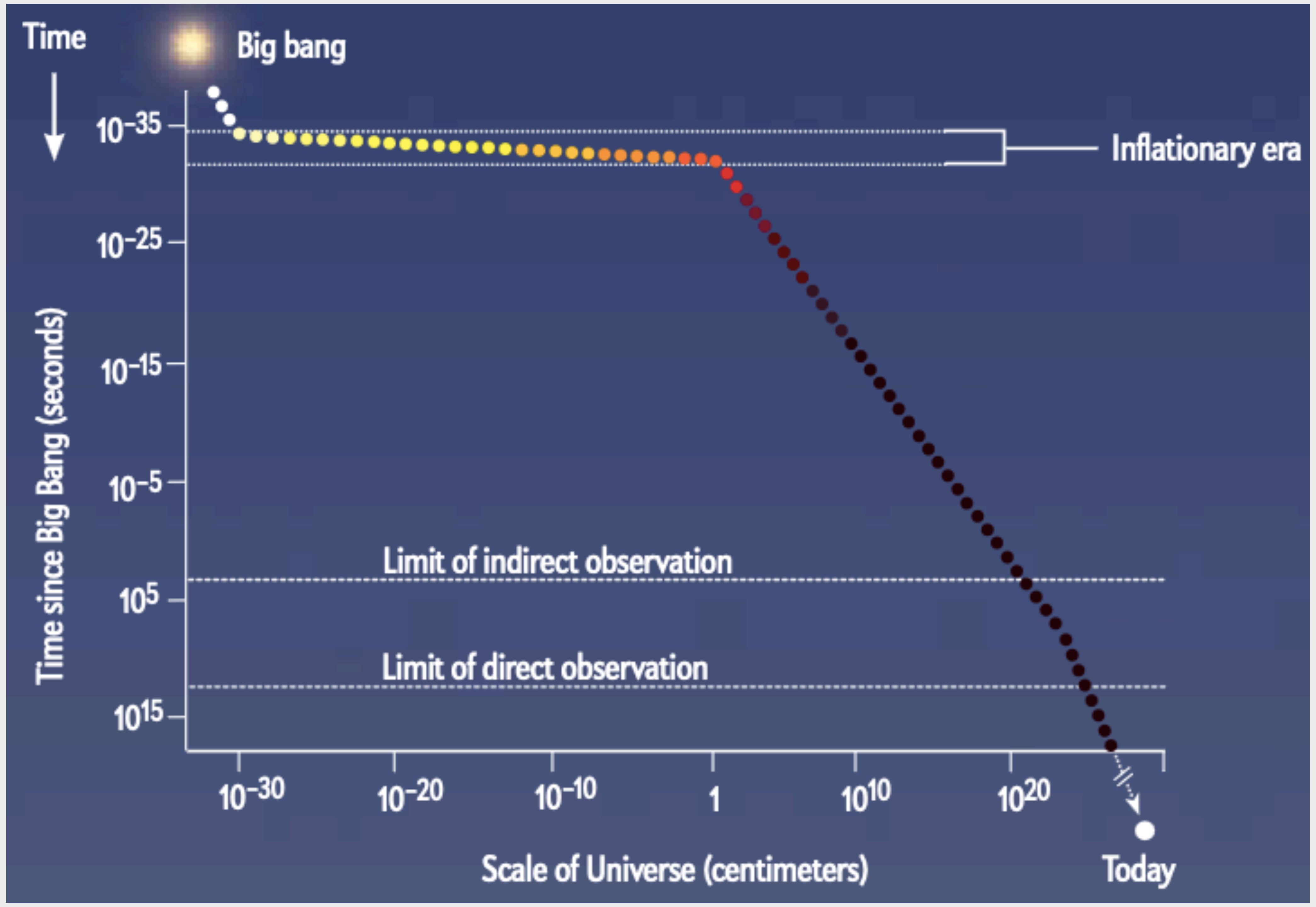
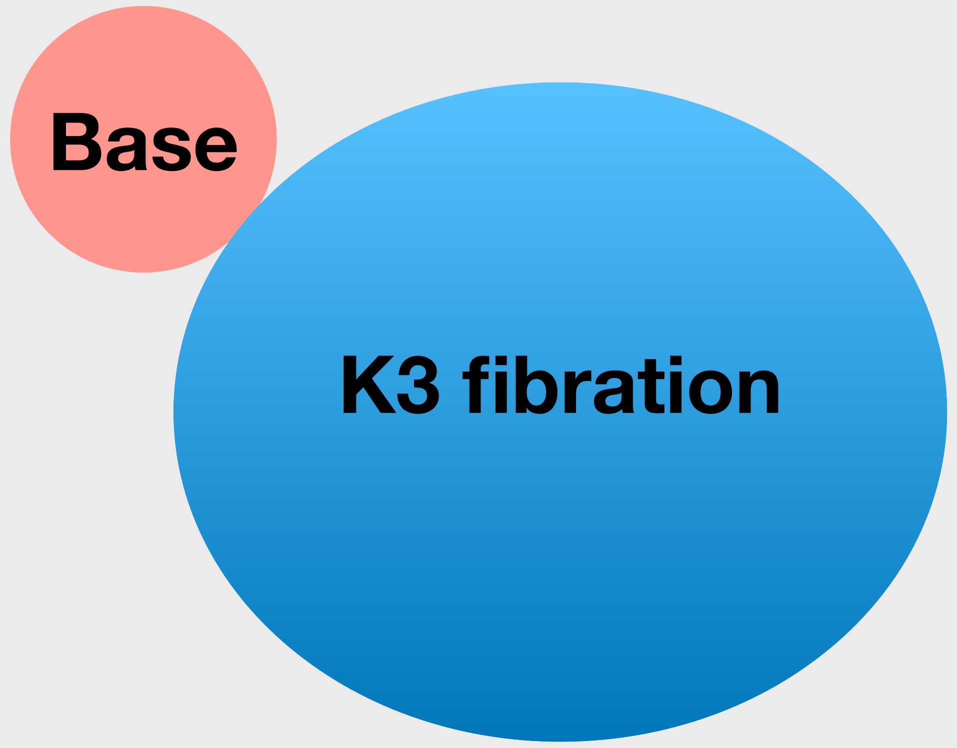
- Moduli stabilisation





Extra dimensional topology

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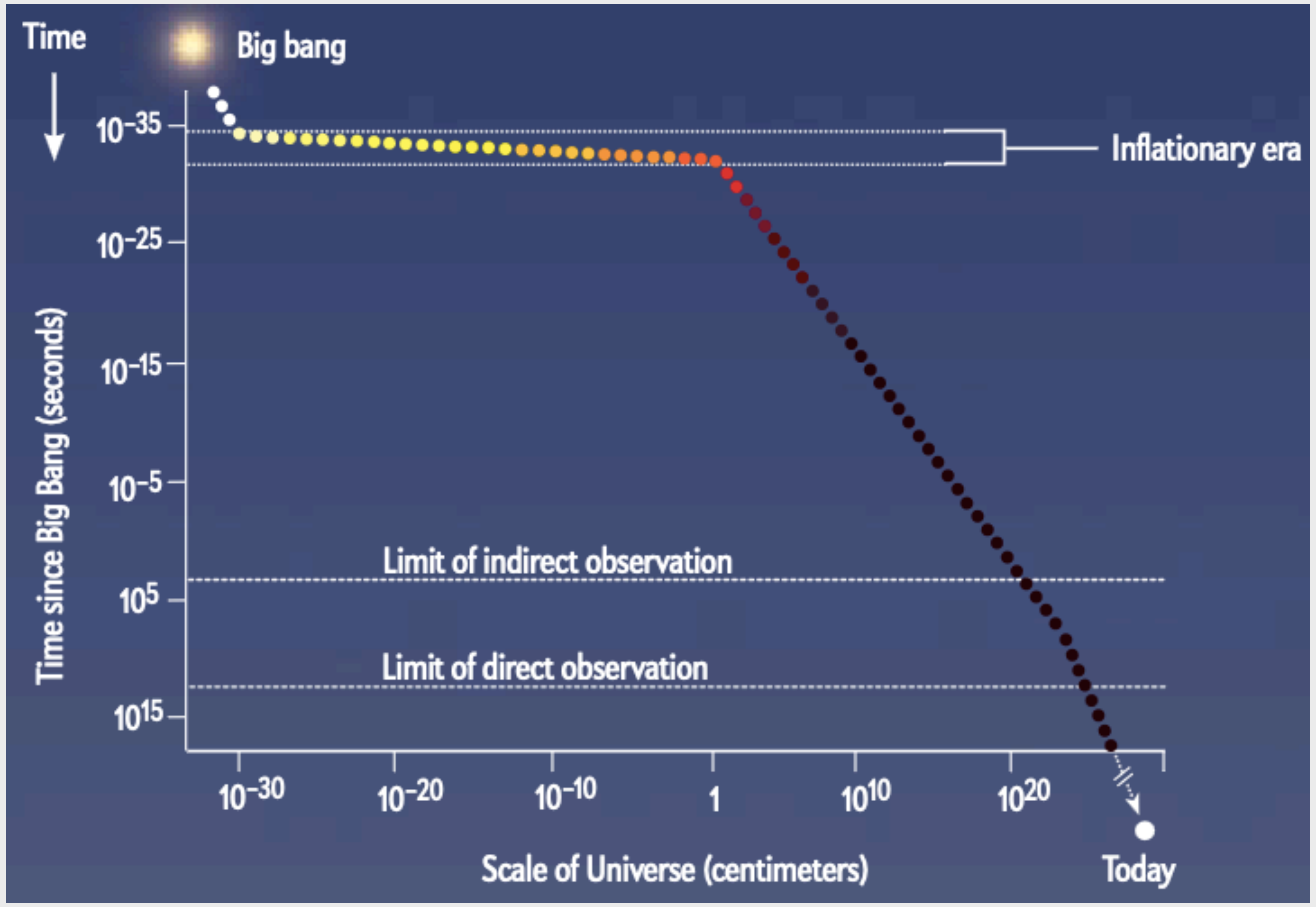

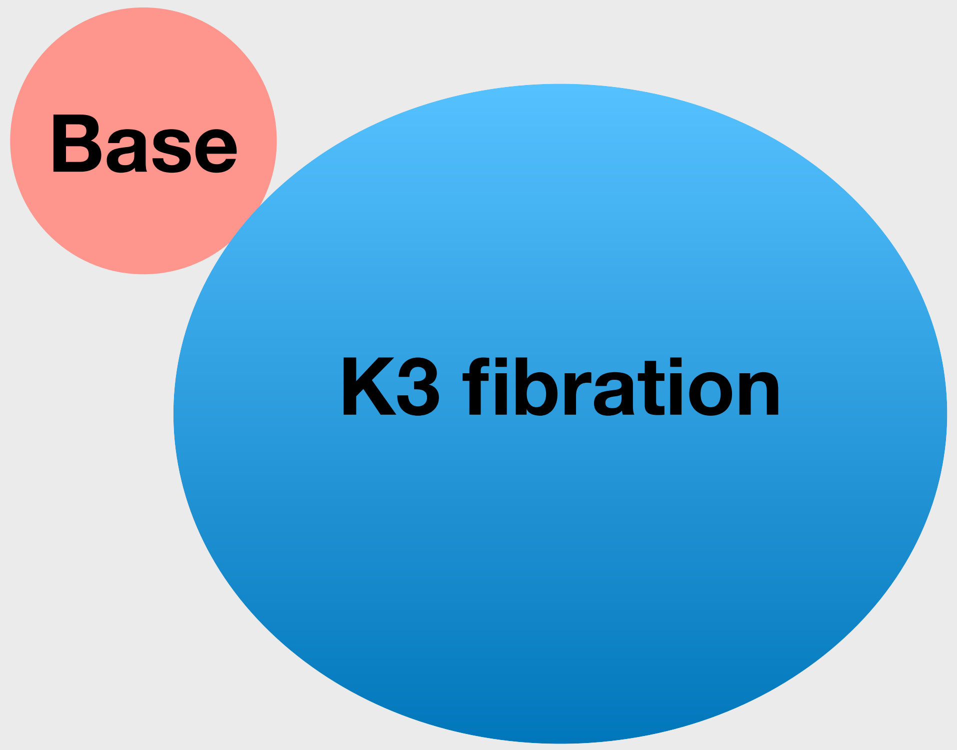

Extra dimensional topology

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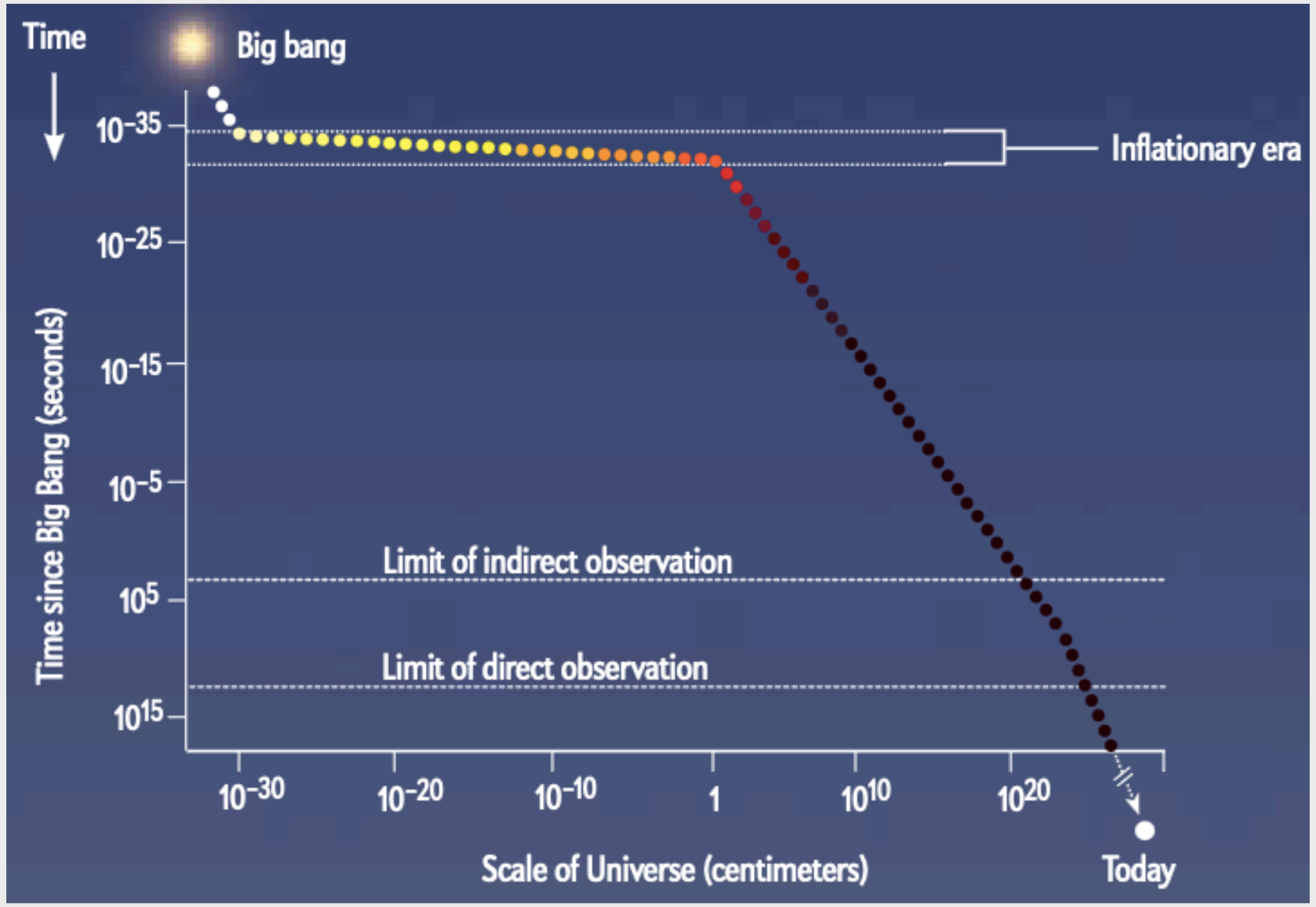
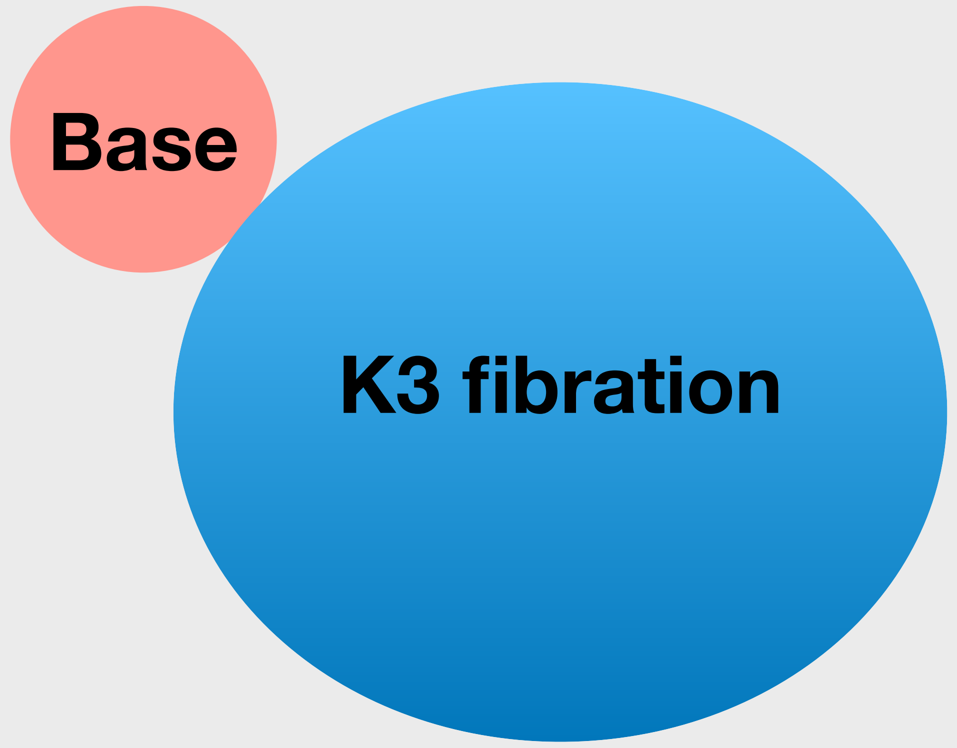
- Inflation →

Volume Inflation | **Fibre Inflation**

- String Theory Model building
- Moduli stabilisation





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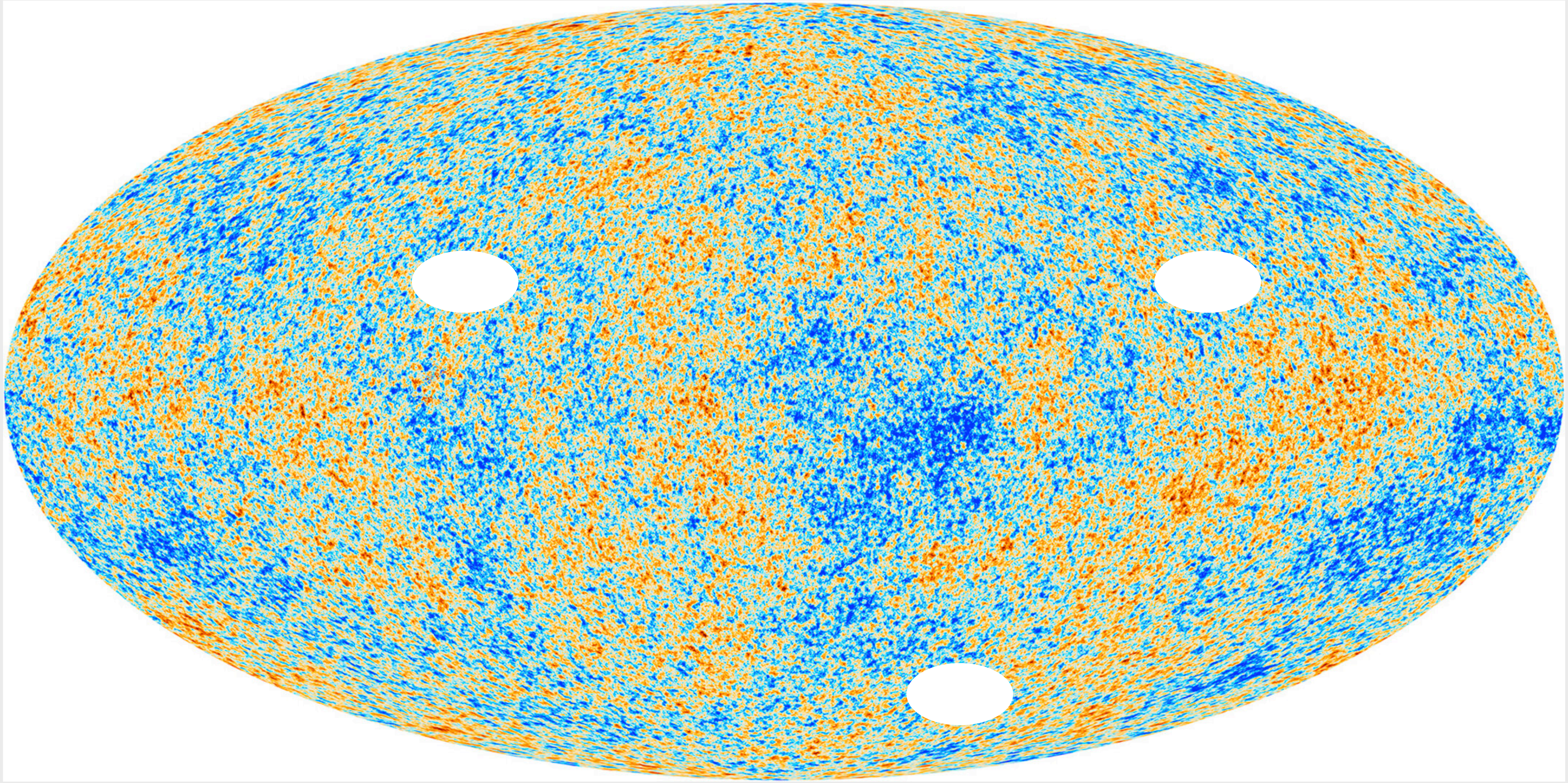
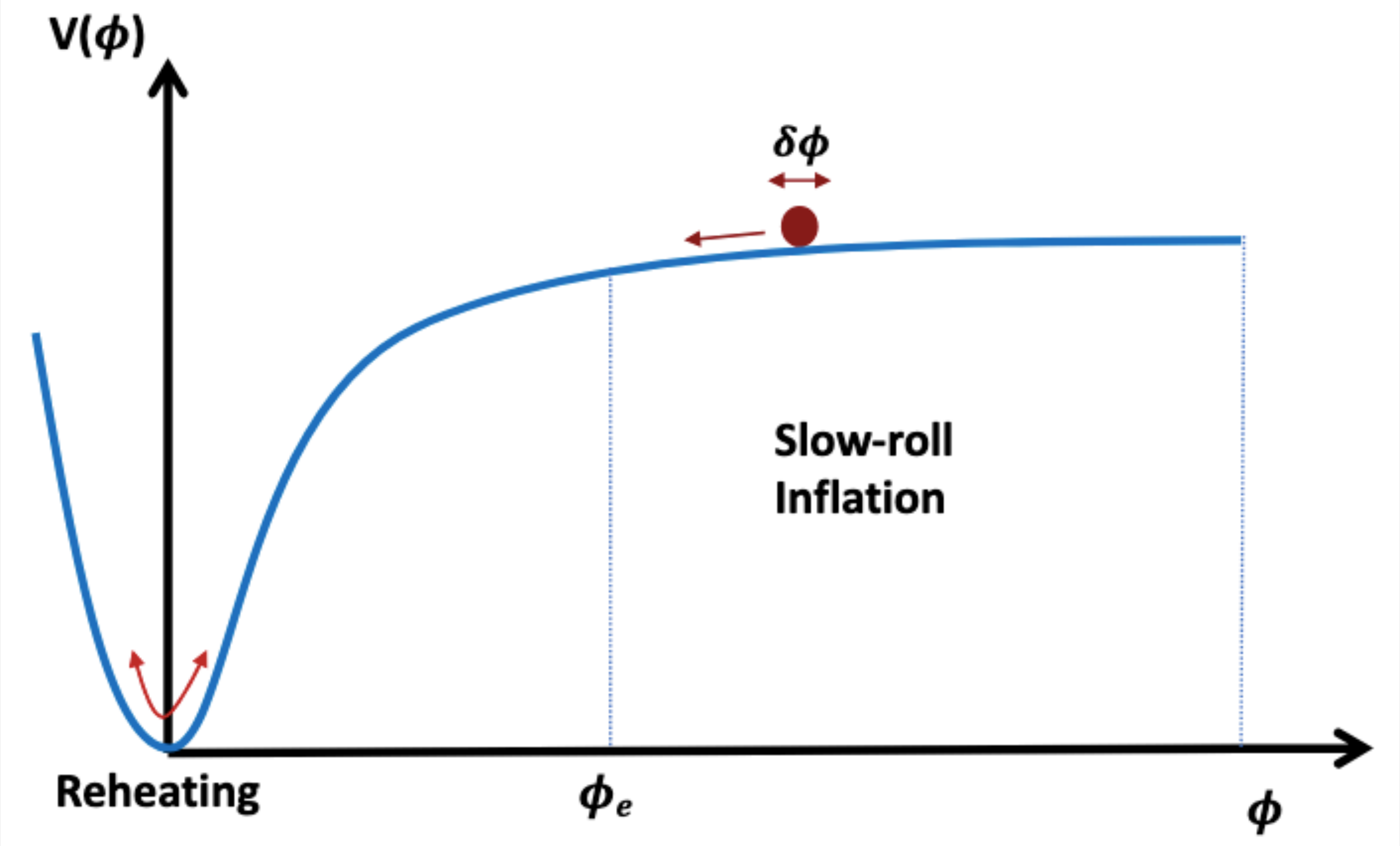
Why inflation



The **horizon problem**: antipodal points in the CMB sky share the same temperature modulo an anisotropy of 1 parts in a million despite not being in causal contact at the time of decoupling. [Ref: Subhodip's talk]

Minimally coupled scalar field driven inflation



Scalar field minimally coupled to gravity driving **slow-roll** inflation

Image source: arXiv:2303.04819

Slow-roll inflation

EOM

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

Slow-roll parameters

$$\epsilon_H = -\frac{\dot{H}}{H^2}, \quad \eta_H = \frac{\dot{\epsilon}_H}{\epsilon_H H}, \quad \epsilon_V = \frac{1}{2}\left(\frac{V_{,\phi}}{V(\phi)}\right)^2, \quad \eta_V = \frac{V_{,\phi\phi}}{V(\phi)}$$

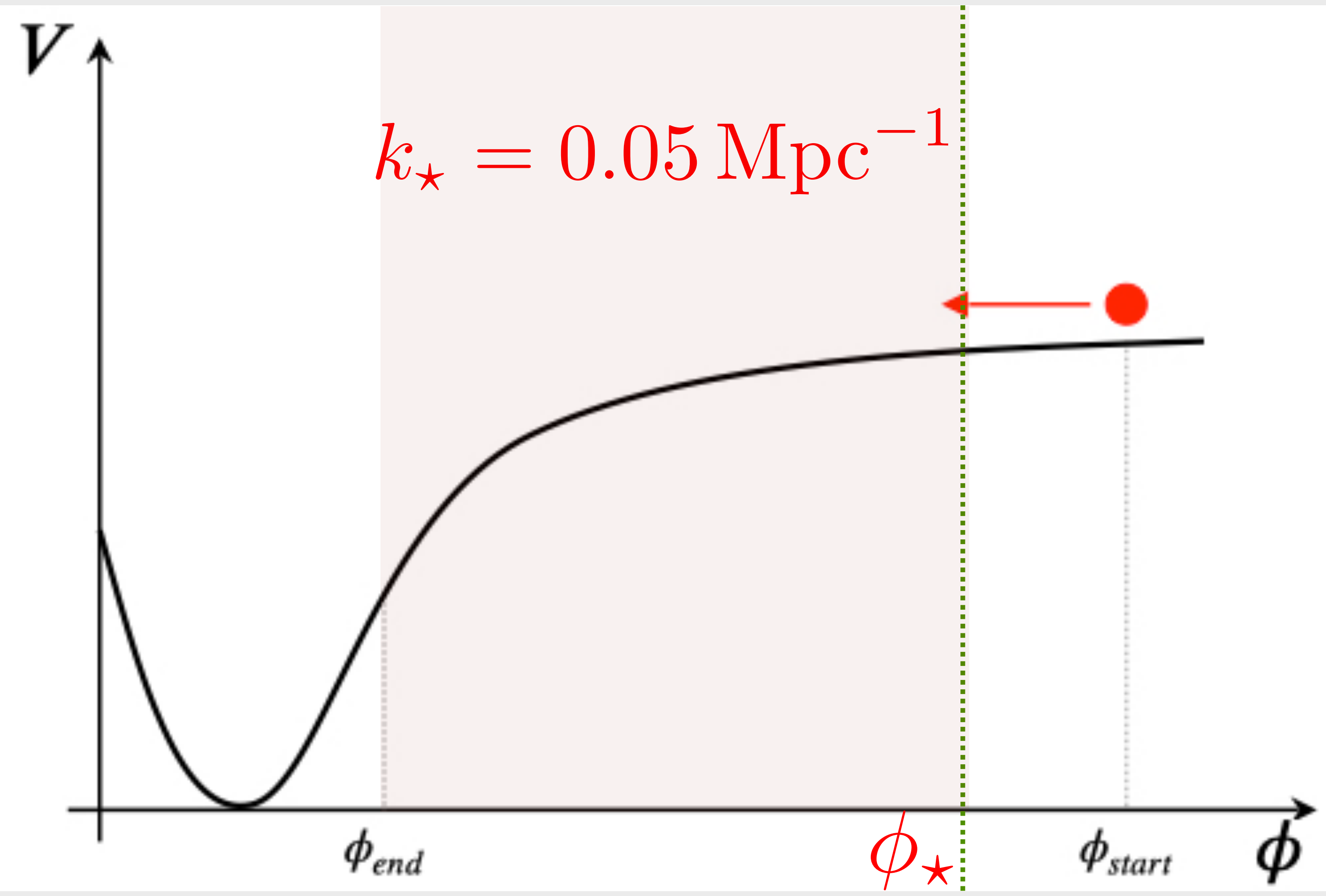
Cosmological parameters

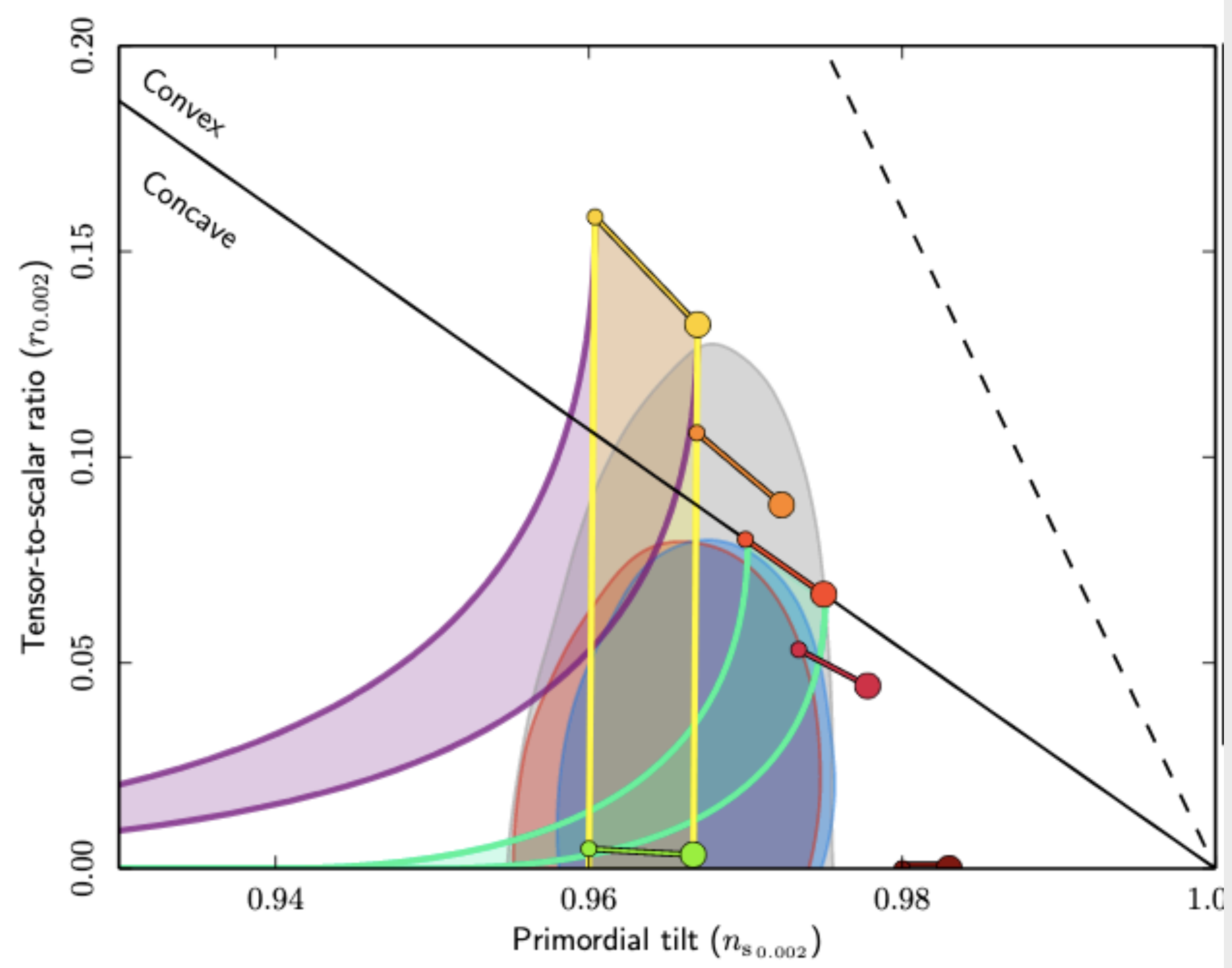
$$P_s = \frac{V(\phi)^\star}{24\pi^2\epsilon_H^\star} = 2.105 \pm 0.03 \times 10^{-9}$$

$$n_s = 1 - 2\epsilon_H^\star - \eta_H^\star \simeq 2\eta_V^\star - 6\epsilon_V^\star = 0.9649 \pm 0.0042$$

$$r = 16\epsilon_H^\star \simeq 16\epsilon_V^\star < 0.036$$

$$N(\phi) = \int H dt = \int_{\phi_{end}}^{\phi_\star} \frac{1}{\sqrt{2\epsilon_H}} d\phi \simeq \int_{\phi_{end}}^{\phi_\star} \frac{V(\phi)}{V'(\phi)} d\phi \simeq 60$$





Planck 2018: Cosmological Parameters in Inflation

String Cosmology

Exploring String Inflation - rich structures dubbed in moduli

- A unification of all the interactions? Leading candidate - String Theory

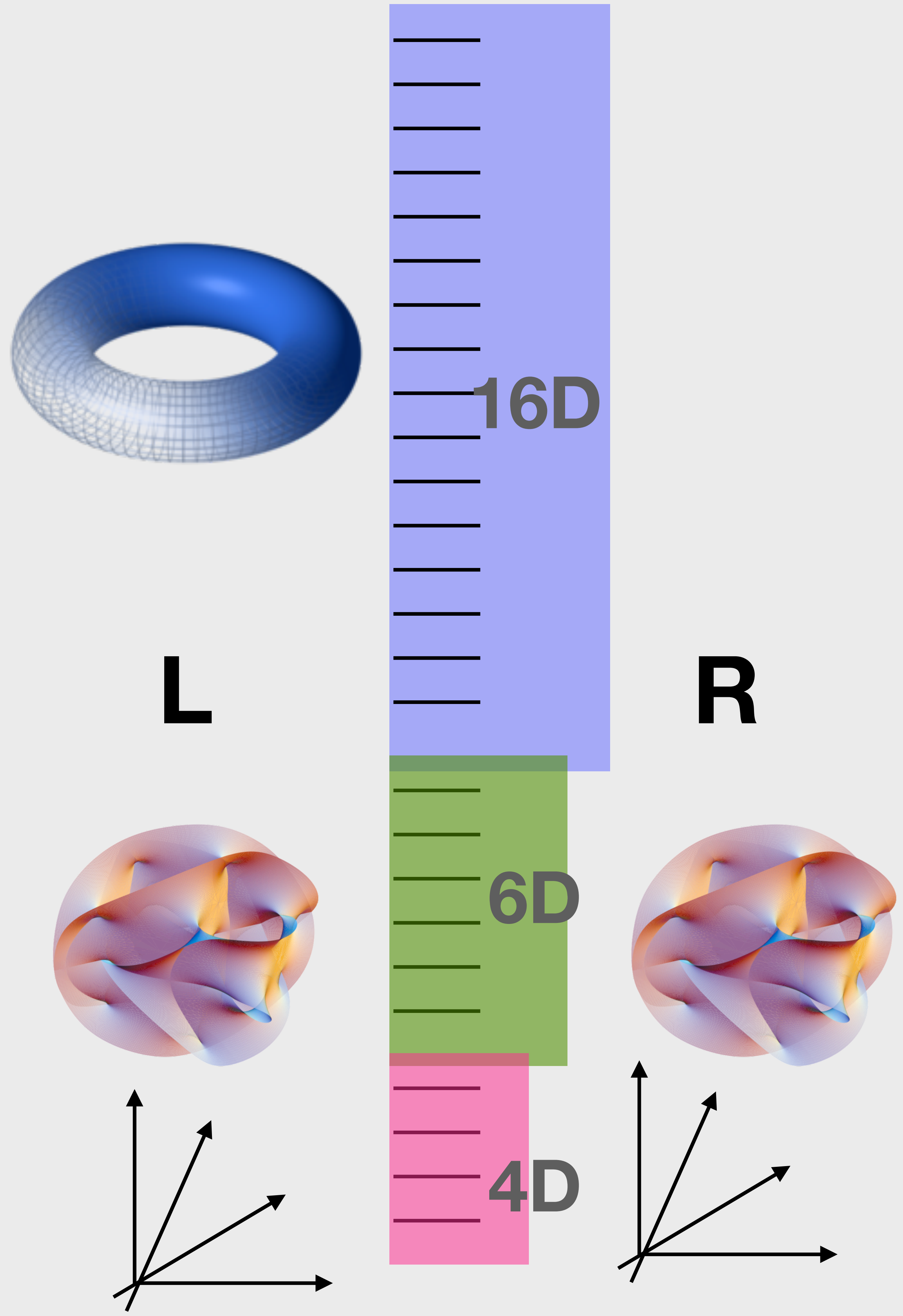
- No experimental proof— connection between ST and Cosmology is essential in fundamental physics.

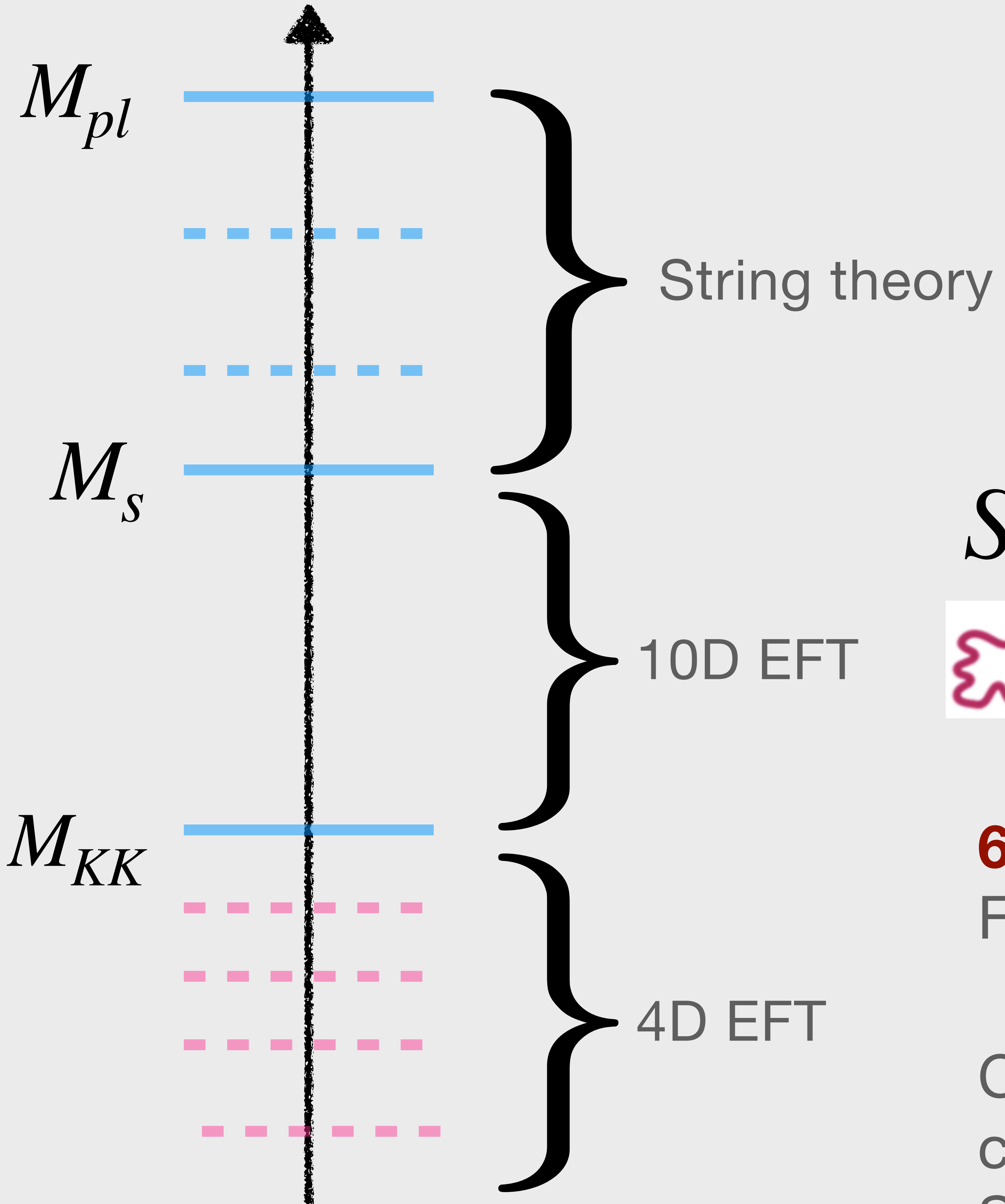
- Plethora of scalar fields — “moduli”— can act as inflaton — light and has gravitational strength interactions [Ref: Sonia’s talk]

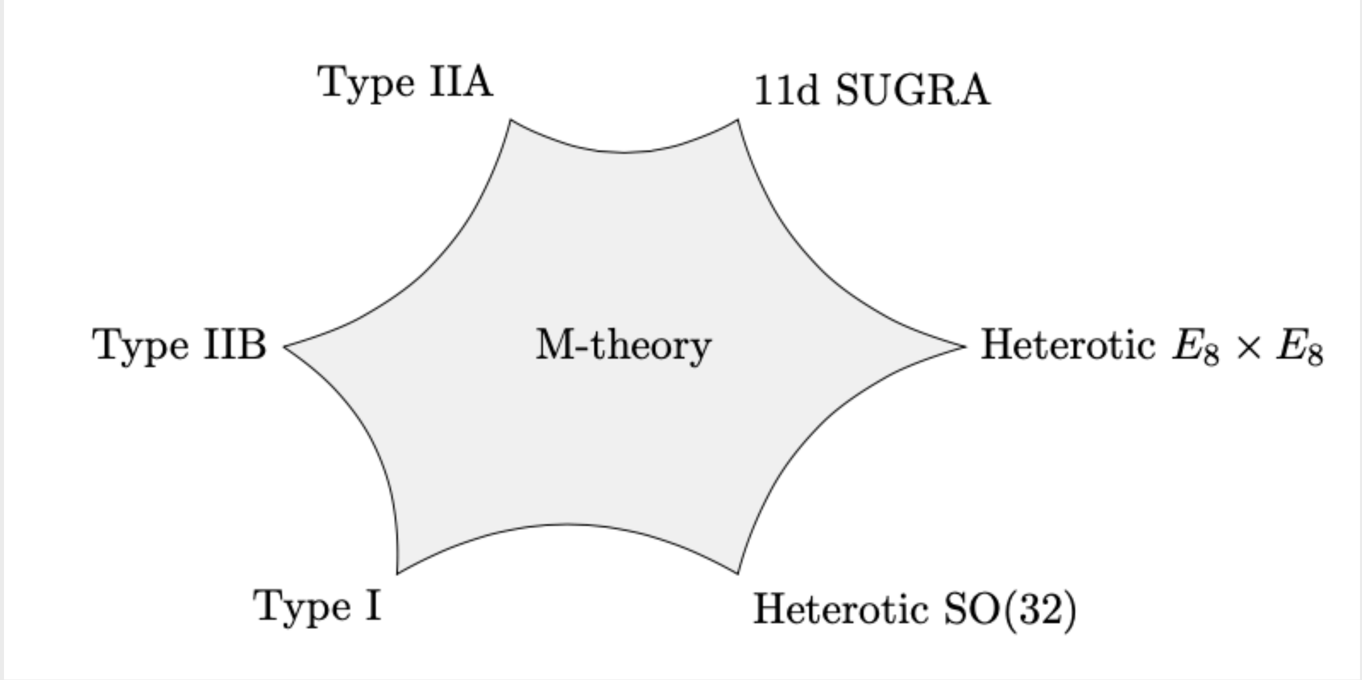
- Understanding the potential energy functional is crucial — they have to be stabilised to avoid fifth force. [Ref: Wan’s talk]

String Compactification in a nutshell

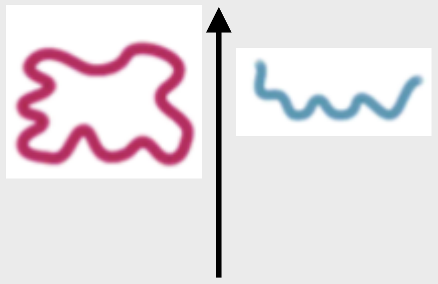
To make contact with the observed world, 10d or higher dimensional string theory needs to be compactified down to 4d







$$S_{10}[C] \xrightarrow[\mathcal{M}_{10} \to \mathcal{M}_4 \times X_6]{\textbf{Compactification}} S_4[\varphi]$$



6d internal space: Topology, geometry, Fluxes, Local sources (D-branes, O-planes)

Compactify on a **Calabi-Yau 3-fold:** complex Ricci-flat K¨ahler manifolds with SU(3) holonomy/structure group

Current Focus: Type IIB String Theory

Moduli of Calabi-Yau 3-folds

The geometric moduli of a CY3 (X) are determined by the number of embedded 2- 3- spheres. Massless deformation of the internal manifold, massless particles on 4D

			1					b_0
		0		0				b_1
	0		$h^{1,1}$		0			b_2
1		$h^{1,2}$		$h^{1,2}$		1		b_3
	0		$h^{1,1}$		0			b_4
		0		0				b_5
			1					b_6

$b_i's$ denote Betti numbers which are cohomology dimensions,

$$b_i = \dim_{\mathbb{R}} H^i_{dR}(X)$$

Kahler moduli (τ) **—** $h^{1,1}(X) = b_2$ — 2 cycles— related to the overall volume of the internal space.

Complex structure moduli (z^a) **—** $h^{1,2}(X) = \frac{b_3}{2} - 1$ — 3 cycles — related to the shape of the internal space.

Axio-dilaton (S) **—** related to the string coupling

☑ **Current Focus:** U, S stabilised at their minima and perturbation around that minima to stabilise τ. Study inflation with a certain τ.

Moduli must be stabilised! If left unstabilised then they can mediate fifth force or missing energy in the collider — not observed in nature.

General idea: use fluxes to generate a potential and non-zero vev for moduli.

Outline of the talk

- Addressing moduli stabilisation problem
- Finding a dS vacuum in String Theory — based only on the perturbative corrections
- If found! — YES
- Examine their interesting cosmological implications— such as Inflation.

Type IIB effective Supergravity

Basic ingredients: Superpotential W and Kahler potential K.

The fluxes in type-IIB are: $F_3 = dC_2$ and $H_3 = dB_2$ and $G_3 = F_3 - SH_3$, giving us the flux induced superpotential of GVW type[a]:

$$W_0 = \int \Omega_3(z_a) \wedge G_3$$

W-flatness conditions: $\mathcal{D}_{z^a} W = 0, \;\; \mathcal{D}_S W = 0$ → (z^a, S) stabilised but Kahler moduli not stabilised!

Type -IIB theory's effective Kahler potential,

$$\mathcal{K}_0 = -\log(S+\bar{S}) - \log\left(-i\int \Omega_3 \wedge \Omega_3\right) - 2\log \mathcal{V}$$

Block diagonal form

The associated F-term scalar potential takes the following form,

$$V_F = e^{\mathcal{K}}\left(\sum_{I,J} \mathcal{K}^{I\bar{J}} \mathcal{D}_I W_0 \mathcal{D}_{\bar{J}} \bar{W}_0 - 3|W_0|^2\right)$$

$$I, J = S, z^a, T_i$$

Dependence on the Kahler moduli drops out due to block diagonal form of Kahler metric

(a) Gukov, Vafa, Witten' 00

Road-map

Kahler moduli completely undetermined

$$\mathcal{K}_0 = -\log(S+\bar{S}) - \log\left(-i\int \Omega_3 \wedge \Omega_3\right) - 3\log(T+\bar{T})$$

$$\mathcal{K}^{T\bar{T}} = \frac{(T+\bar{T})^2}{3} \qquad \mathcal{D}_T W_0 = K_T W_0$$

$$\boxed{V_{F_T} = e^{\mathcal{K}}\left(\mathcal{K}^{T\bar{T}}\mathcal{D}_T W_0 \mathcal{D}_{\bar{T}}\bar{W}_0 - 3|W_0|^2\right) = 0}$$

No scale structure

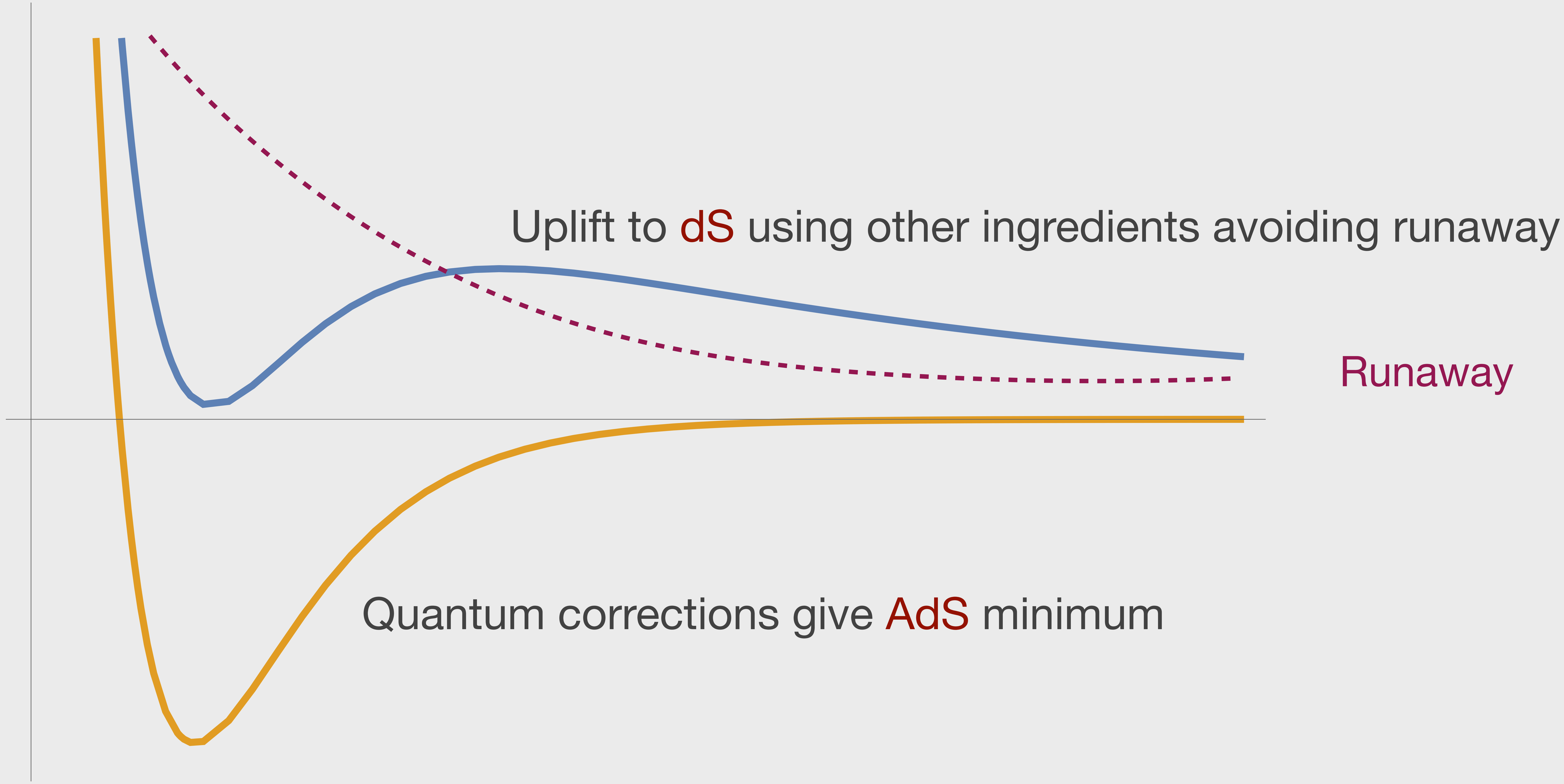
Two-step moduli stabilisation

- Stabilise the complex structure and axio-dilaton by the GVW superpotential.
- Engineering the appropriate geometric setup and calculate Kahler moduli-dependent quantum corrections.

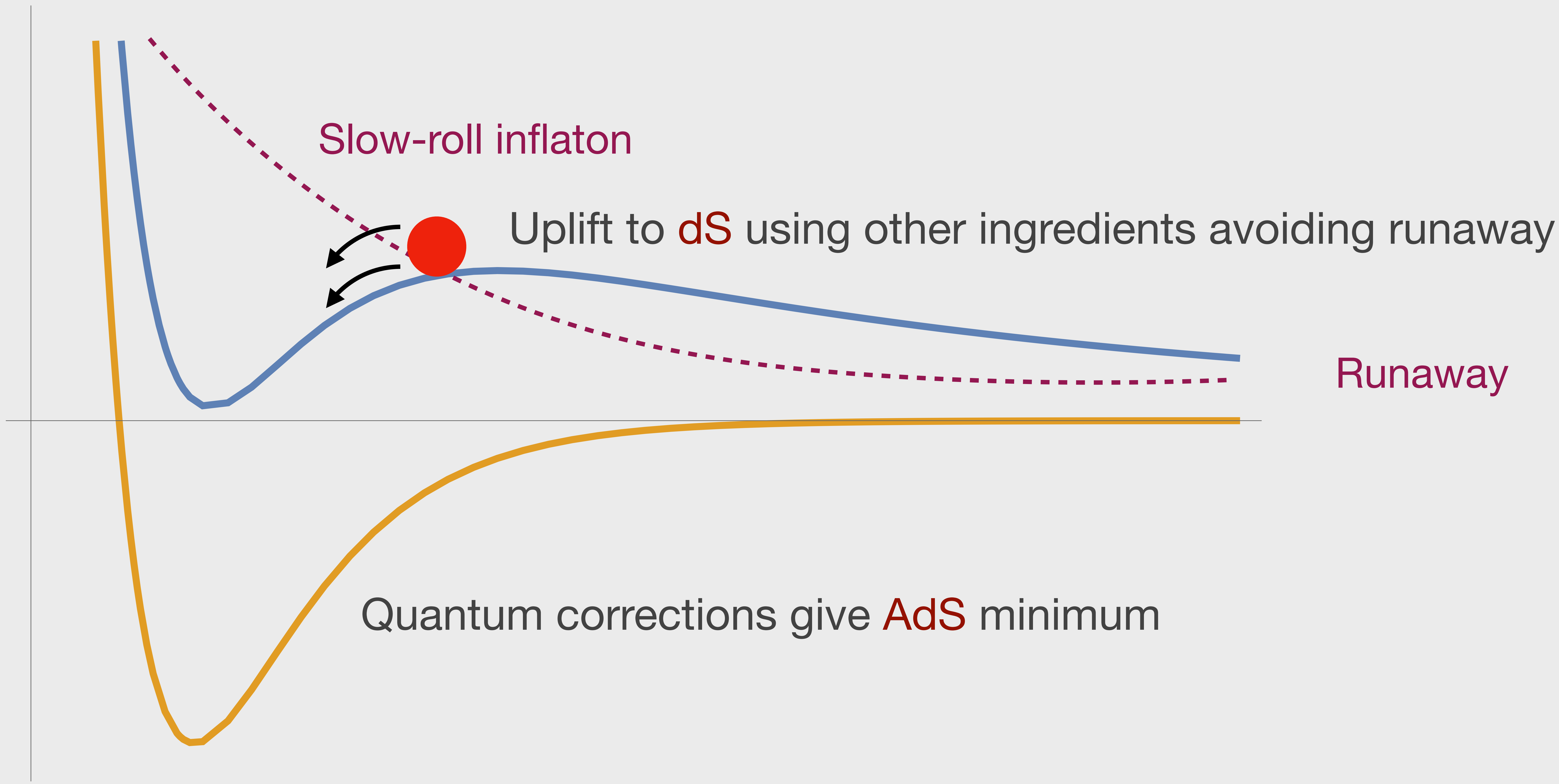
Generate a non-zero vev for Kahler moduli

$$V_{F_T} \neq 0$$

Goal - add quantum corrections



Goal - add quantum corrections and inflate with the lifted direction



The Classification of Quantum Corrections

Perturbative corrections

- In inverse string tension $\propto \alpha'/R^2$
  - $\alpha'^3 -$ corr
  - $\log -$corr
  - higher derivative corr
- In string coupling constant $\propto g_s$
  - KK 1-loop open string
  - winding 1-loop open string

Non-perturbative corrections

- D3-branes instantons
- Gaugino condensation

Present focus

Addressing the stabilisation of KM in absence of NP effects

List of Corrections

α'^3–corrections[a]

$$K \propto -2\log\left(\mathcal{V} + \frac{\xi(S+\bar{S})^{3/2}}{2}\right) = -2\log\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right)$$

Log-loop corrections[b,c,d]

$$K = -2\log(\mathcal{V} + \eta\log\mathcal{V})$$

Higher derivative corrections[e,f,g]

$$V_{F_4} = -\frac{-\lambda k^2|W_0|^4}{g_s^{3/2}\mathcal{V}^4}\Pi_\alpha t^\alpha, \quad \text{where } \Pi_\alpha = \int_X c_2 \wedge D_\alpha$$

String loops[h,i,k]

$$V_{g_s}^W = -2k\frac{|W_0|^2}{\mathcal{V}^3}\sum_\alpha \frac{C_\alpha^W}{t_\cap^\alpha}$$

(a) Becker, Becker, Haack, Louis’ 02

(b) Green, Vanhove’97 (c) Antoniadis, Ferrara, Minasian, Narain’ 97 (d) Kiritsis, Pioline’97

(e) Ciupke, Louis, Westphal, (f) Green, Mayer, Weissenbacher, (g) Cicoli, Ciupke, de Alois, Muia

(h) Ciupke, Louis, Westphal, (i) Green, Mayer, Weissenbacher, (k) Cicoli, Ciupke, de Alois, Muia

Large Volume Scenario

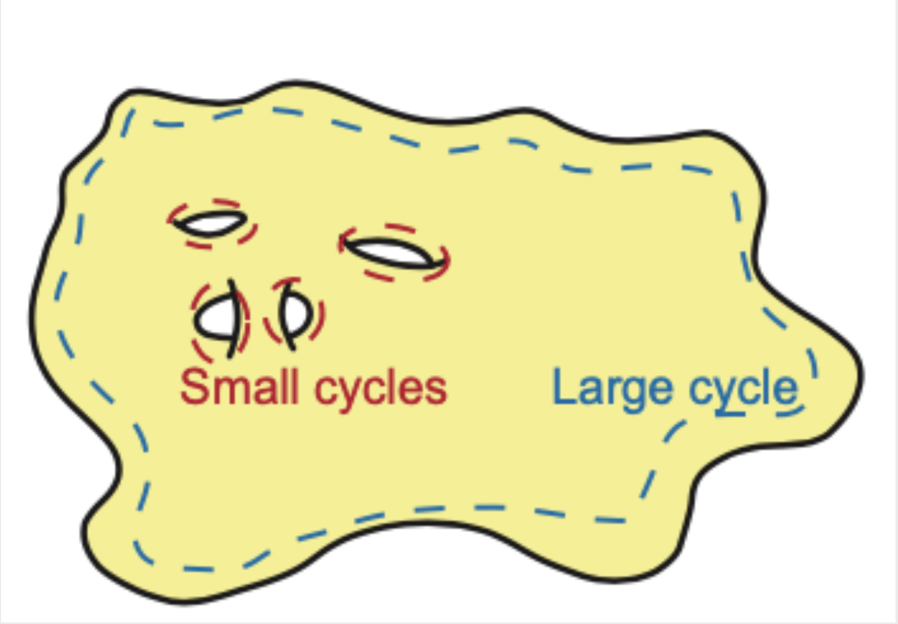
Key ingredients: inclusion of α'^3 corrections in the Kahler potential
Non-perturbative instanton corrections in the superpotential

$$K = -2\log\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right) - \log\left(i\int \Omega_3 \wedge \Omega_3\right) - \log(S + \bar{S})$$

$$W = \int G_3 \wedge \Omega_3 + \sum_i A_i e^{-aT_i}$$

Non-perturbative effect

$$\mathcal{V} = \tau_L^{3/2} - \sum_{i=1}^{N_{\mathrm{small}}=h^{1,1}-1} \tau_s^{3/2}$$



$$V_{\mathrm{LVS}} \simeq \frac{\alpha_1}{\mathcal{V}^3} - \frac{\alpha_2 \tau_s}{\mathcal{V}^2} e^{-a_s \tau_s} + \frac{\alpha_3 \sqrt{\tau_s}}{\mathcal{V}} e^{-2a_s\tau_s} \quad \langle \mathcal{V} \rangle \simeq \frac{\alpha_2 \sqrt{\langle \tau_s \rangle}}{2\,\alpha_3} e^{a_s \langle \tau_s \rangle}, \ \langle \tau_s \rangle \simeq \hat{\xi}^{2/3} \left(\frac{9\, k_{sss}}{8}\right)^{1/3}.$$

Large Volume Scenario

Global embedding

Perturbative Large Volume Scenario [(a,b,c)]

Key ingredients: inclusion of α'^3 corrections + higher orders in the Kahler potential
NO Non-perturbative instanton corrections in the superpotential

$$K = -2\log\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right) - \log\left(i\int \Omega_3 \wedge \Omega_3\right) - \log(S + \bar{S})$$

$$W = \int G_3 \wedge \Omega_3 + \cancel{\sum_i A_i e^{-aT_i}}$$

$$\mathcal{V} = \tau_L^{3/2} \cancel{- \sum_{i=1}^{N_{\mathrm{small}}=h^{1,1}-1}} \tau_s^{3/2}$$

$$\mathcal{V} = n_0\, t^1 t^2 t^3 = \frac{1}{\sqrt{n_0}}\sqrt{\tau_1\tau_2\tau_3}, \quad \tau_\alpha = \partial_{t^\alpha}\mathcal{V}, \quad n_0 = 2$$

(a) Antoniadis, Chen, Leontaris' 18, 19, (b) Antoniadis, Lacombe, Leontaris' 20, 21, (c) Shukla, Leontaris' 22

Perturbative Large Volume Scenario

In the large volume limit with BBHL corrections plus log-loop effects

$$K = -2\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}} + g_s^{1/2}\frac{\zeta(2)}{\zeta(3)}\xi(\ln\mathcal{V} - 1)\right) \qquad V_f \approx \mathcal{C}_1 \frac{\xi - 4\eta + 2\eta\log(\mathcal{V})}{\mathcal{V}^3}$$

Features:

- Minimum exists for $\eta < 0, C_1 \propto W_0^2$
- Stabilisation at large volume:

$$\mathcal{V}_{min} = e^{\frac{7}{3}+\frac{\xi}{2|\eta|}} \sim e^{\frac{1}{g_s^2}}$$

$$\boxed{\begin{aligned} g_s &= 0.2 \Rightarrow \langle\mathcal{V}\rangle = 95593.3 \\ g_s &= 0.1 \Rightarrow \langle\mathcal{V}\rangle = 7\cdot 10^{16} \end{aligned}}$$

- For F-term potential, AdS-minimum

$$(V_F)_{min} \propto \frac{\eta}{\mathcal{V}^3} < 0$$

(a) Antoniadis, Chen, Leontaris' 18, 19, (b) Antoniadis, Lacombe, Leontaris' 20, 21, (c) Shukla, Leontaris' 22

Perturbative Large Volume Scenario

In the large volume limit with BBHL corrections plus log-loop effects+D-terms

$$K = -2\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}} + g_s^{1/2}\frac{\zeta(2)}{\zeta(3)}\xi(\ln\mathcal{V} - 1)\right) \qquad V_f \approx \mathcal{C}_1 \frac{\xi - 4\eta + 2\eta\log(\mathcal{V})}{\mathcal{V}^3} \quad + \sum_{\alpha=1}^{3}\frac{d_\alpha}{\tau_\alpha^3}$$

In terms of canonical normalised fields,

$$\varphi^\alpha = \frac{1}{\sqrt{2}}\ln\tau_\alpha, \quad \phi^1 = \frac{1}{\sqrt{3}}(\varphi^1 + \varphi^2 + \varphi^3) = \sqrt{\frac{2}{3}}\ln(\sqrt{n_0}\mathcal{V}),$$

$$\phi^2 = \frac{1}{\sqrt{2}}(\varphi^1 - \varphi^2) \qquad \phi^3 = \frac{1}{\sqrt{6}}(\varphi^1 + \varphi^2 - 2\varphi^3)$$

(a) Antoniadis, Chen, Leontaris' 18, 19, (b) Antoniadis, Lacombe, Leontaris' 20, 21, (c) Shukla, Leontaris' 22

Perturbative Large Volume Scenario - a dS with D-terms and no NP effects

Extremisation conditions yield the following relations

$$a_1 = e^{-\sqrt{\frac{3}{2}}\langle\phi\rangle}\left(\sqrt{\frac{3}{2}}\langle\phi^1\rangle - a_2\right), \quad \langle\phi^2\rangle = \frac{1}{6}\left(\frac{d_1}{d_2}\right), \quad \langle\phi^3\rangle = \frac{1}{6\sqrt{3}}\left(\frac{d_1 d_2}{d_3^2}\right)$$

$$a_1 \equiv -\frac{(d_1 d_2 d_3)^{1/3}}{n_0^{3/2}\eta\mathcal{C}_1} \geq 0, \quad a_2 = -\frac{\xi}{2\eta} + \frac{7}{3} + \frac{1}{2}\ln n_0 > 0$$

To ensure single-field inflation and a dS minimum imposes the following constraint

$$\mathcal{R}_{\text{hierarchy}} \equiv \frac{m_{\phi^1}^2}{m_{\phi^\alpha}^2} = \frac{\left(1 + a_2 - \sqrt{\frac{3}{2}}\langle\phi^1\rangle\right)}{2\left(\sqrt{\frac{3}{2}}\langle\phi^1\rangle - a_2\right)} \ll 1, \; \alpha = \{2,3\}$$

$$\boxed{\frac{2}{3} + a_2 \leq \sqrt{\frac{3}{2}}\langle\phi^1\rangle < 1 + a_2}$$

$$\langle V_0\rangle = -\eta\, n_0^{3/2}\mathcal{C}_1 e^{-3\sqrt{\frac{3}{2}}\langle\phi^1\rangle}\left(\sqrt{\frac{3}{2}}\langle\phi^1\rangle - a_2 - \frac{2}{3}\right)$$

$$\boxed{M_1 = \frac{1}{2}M_2 = \frac{1}{2}M_3}$$

(a) Bera, **Chakraborty**, Shukla, Leontaris' 24

Perturbative Large Volume Scenario - a dS with D-terms and no NP effects

Re-defining some parameters — x takes care of the uplifting now on

$$a_1 \equiv e^{-a_2-1-x}, \quad \sqrt{\frac{3}{2}}\phi^1 - a_2 - 1 = \sqrt{\frac{3}{2}}\phi$$

$$V_{\rm inf} = -\tilde{\mathcal{B}} e^{-3\sqrt{\frac{3}{2}}\phi}\left(\sqrt{\frac{3}{2}}\phi - \frac{3}{2}e^{-x+\sqrt{\frac{3}{2}}\phi} + \frac{4}{3}\right), \quad \tilde{\mathcal{B}} = \tilde{\mathcal{B}}(|W_0|, g_s) > 0$$

The potential features several extremas:

$$\phi_{\rm min} = -\sqrt{\frac{2}{3}}\left(1 + \mathcal{W}_0[-e^{-1-x}]\right), \qquad \phi_{\rm max} = -\sqrt{\frac{2}{3}}\left(1 + \mathcal{W}_{-1}[-e^{-1-x}]\right),$$

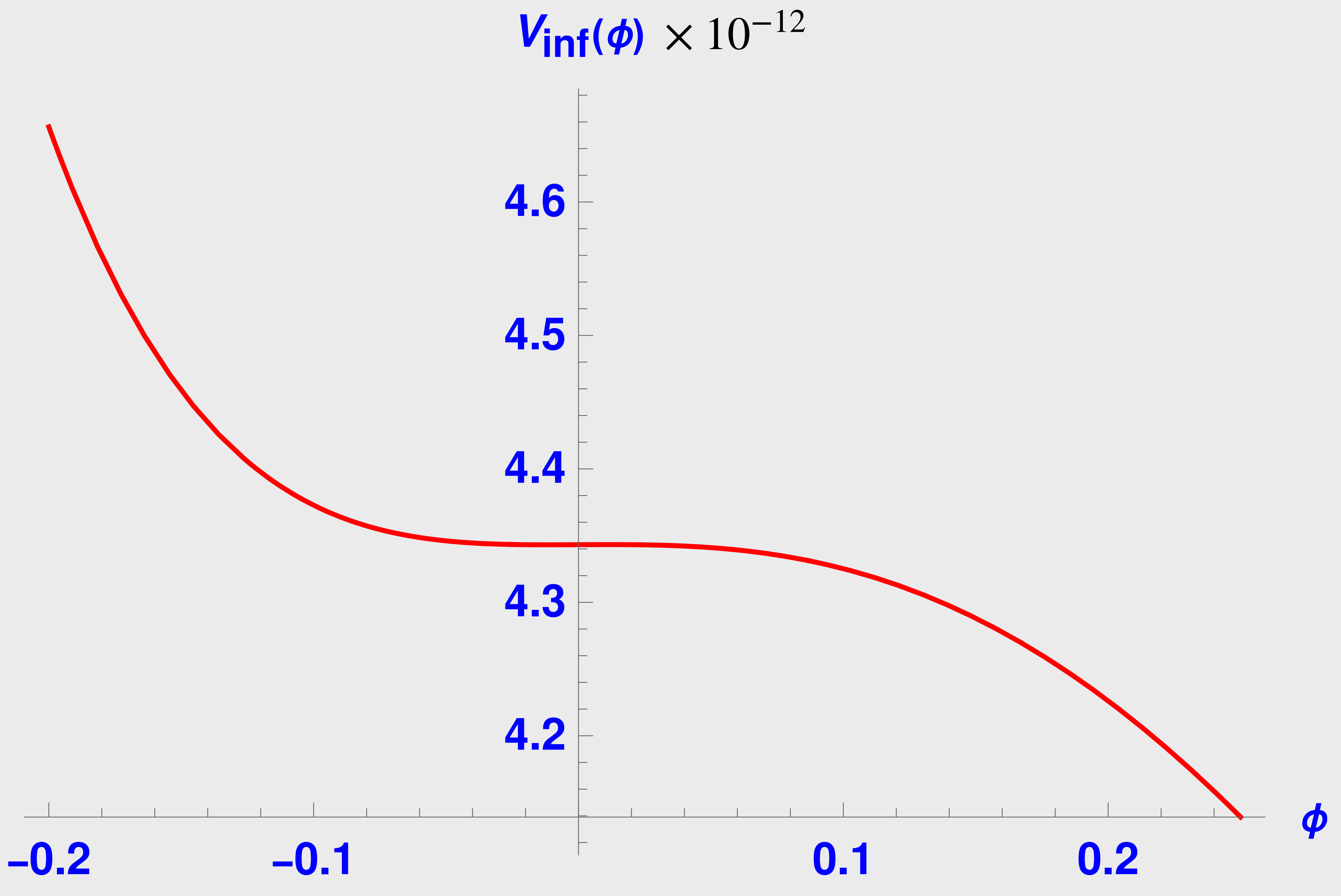
$$\phi_{\rm inflec1} = -\sqrt{\frac{2}{3}}\left(\frac{2}{3} + \mathcal{W}_0\left[-\frac{2}{3}\,e^{-\frac{2}{3}-x}\right]\right), \quad \phi_{\rm inflec2} = -\sqrt{\frac{2}{3}}\left(\frac{2}{3} + \mathcal{W}_{-1}\left[-\frac{2}{3}\,e^{-\frac{2}{3}-x}\right]\right).$$

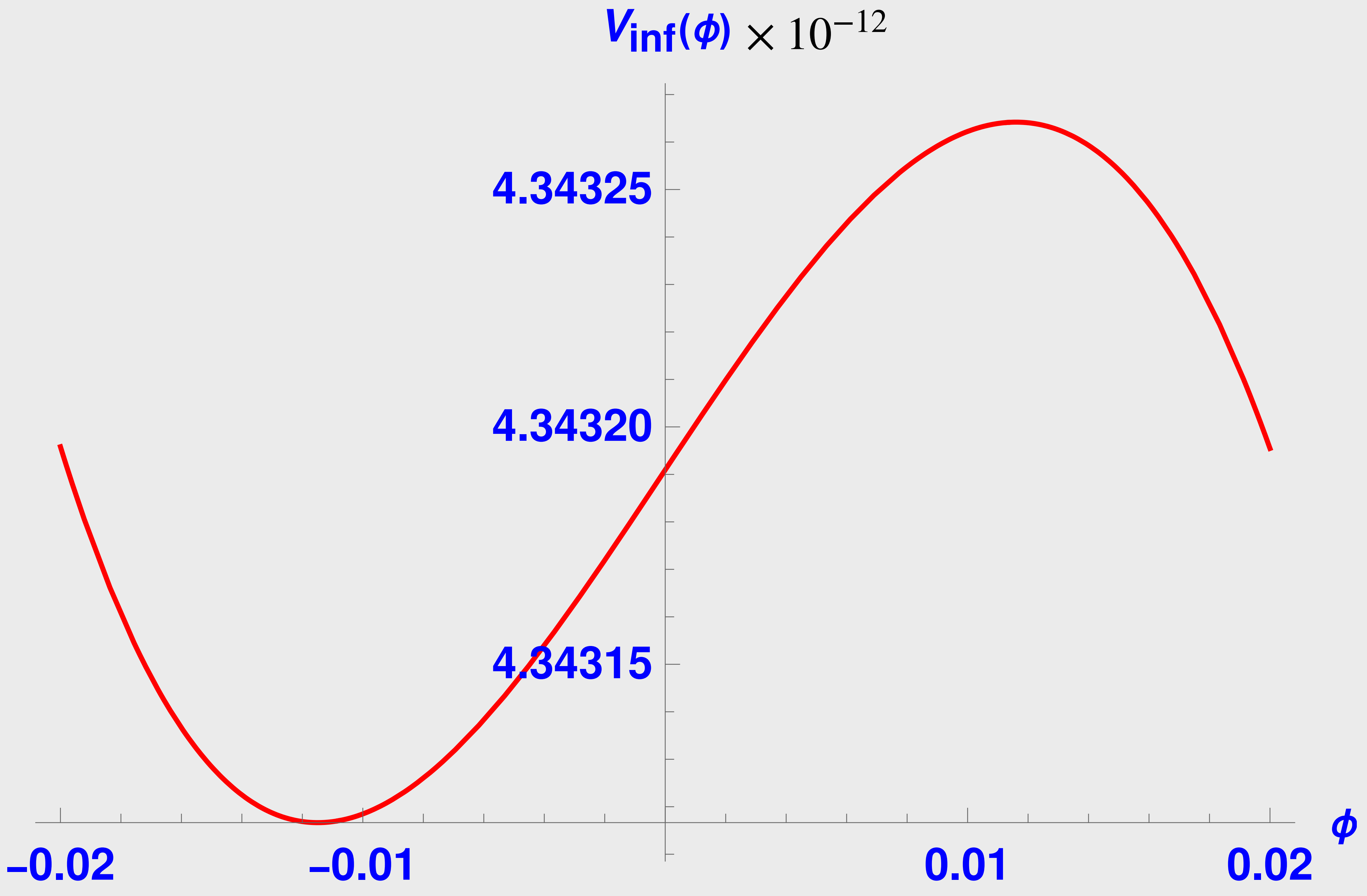
(a) Bera, **Chakraborty**, Shukla, Leontaris' 24

A benchmark model

The inflationary observables are the following:

$$V_{\rm inf} = -\tilde{\mathcal{B}} e^{-3\sqrt{\frac{3}{2}}\phi}\left(\sqrt{\frac{3}{2}}\phi - \frac{3}{2}e^{-x+\sqrt{\frac{3}{2}}\phi} + \frac{4}{3}\right), \quad \tilde{\mathcal{B}} = \tilde{\mathcal{B}}(|W_0|, g_s) > 0$$





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A benchmark model

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$$V_{\rm inf} = -\tilde{\mathcal{B}} e^{-3\sqrt{\frac{3}{2}}\phi}\left(\sqrt{\frac{3}{2}}\phi - \frac{3}{2}e^{-x+\sqrt{\frac{3}{2}}\phi} + \frac{4}{3}\right), \quad \tilde{\mathcal{B}} = \tilde{\mathcal{B}}(|W_0|, g_s) > 0$$

$$x = 0.0001, \qquad a_2 = 6, \qquad \tilde{\mathcal{B}} = 7.56 \times 10^{-12},$$
$$-\chi(\mathrm{CY})|W_0|^2 \simeq 1.23, \qquad d = (d_1 d_2 d_3)^{1/3} = 2.2735 \times 10^{-6}\, n_0,$$
$$\langle \phi^1 \rangle = 5.70398, \qquad g_s = 0.316, \qquad \langle \tau_\alpha \rangle = 105.349,$$
$$\langle \mathcal{V} \rangle \simeq 1081.31, \qquad \frac{m_{\phi^1}}{m_{\phi^2}} = 0.0844882 = \frac{m_{\phi^1}}{m_{\phi^3}}.$$

$$\epsilon_V^\star \simeq 2.42 \times 10^{-6}, \qquad r = \epsilon_V^\star = 3.88 \times 10^{-5},$$
$$\eta_V^\star = -0.02, \qquad n_s^\star - 1 = -0.04$$

(a) Bera, **Chakraborty**, Shukla, Leontaris' 24

Robustness of Perturbative Large Volume Scenario

In the presence of BBHL corrections plus log-loop effects plus string loop and higher derivative corrections — after integrating out the two moduli, the potential becomes

$$V_{\rm inf}(\phi) = -\tilde{\mathcal{B}} e^{-3\sqrt{\frac{3}{2}}\phi}\left(\sqrt{\frac{3}{2}}\phi - \frac{3}{2}e^{-x+\sqrt{\frac{3}{2}}\phi} + \frac{4}{3}\right) + \tilde{\mathcal{C}}_2 e^{-5\sqrt{\frac{2}{3}}\phi} + \tilde{\mathcal{C}}_3 e^{-\frac{11}{\sqrt{6}}\phi}$$

$$\tilde{\mathcal{B}} \equiv \tilde{\mathcal{B}}(|W_0|, g_s) = -\kappa \frac{\chi(\mathrm{CY})\sqrt{g_s}\,|W_0|^2\, e^{-10-\frac{9\zeta[3]}{g_s^2\,\pi^2}}}{64\pi} > 0,$$

$$\tilde{\mathcal{C}}_2 = \frac{15}{4}\kappa\,\mathcal{C}_w\,|W_0|^2 n_0^{1/3}\, e^{-\frac{100}{9}-\frac{10\zeta[3]}{g_s^2\,\pi^2}}, \qquad \tilde{\mathcal{C}}_3 = -\frac{72\,\kappa^2\,\lambda\,|W_0|^4}{g_s^{3/2}\,n_0^{1/3}}\, e^{-\frac{110}{9}-\frac{11\zeta[3]}{g_s^2\,\pi^2}},$$

(a) Bera, **Chakraborty**, Shukla, Leontaris' 24

Robustness of Perturbative Large Volume Scenario

In the presence of BBHL corrections plus log-loop effects plus string loop and higher derivative corrections — after integrating out the two moduli, the potential becomes

$$V_{\rm inf}(\phi) = -\tilde{\mathcal{B}} e^{-3\sqrt{\frac{3}{2}}\phi}\left(\sqrt{\frac{3}{2}}\phi - \frac{3}{2}e^{-x+\sqrt{\frac{3}{2}}\phi} + \frac{4}{3}\right) + \tilde{\mathcal{C}}_2 e^{-5\sqrt{\frac{2}{3}}\phi} + \tilde{\mathcal{C}}_3 e^{-\frac{11}{\sqrt{6}}\phi}$$

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$$\chi({\rm CY}) = -224, \quad n_0 = 2, \quad g_s = \frac{1}{3}, \quad x = 10^{-4},$$

$$\tilde{\mathcal{B}} = 1.51694\times 10^{-9}\,|W_0|^2, \qquad \tilde{\mathcal{C}}_2 = 1.22570\times 10^{-9}\,\mathcal{C}_w\,|W_0|^2,$$

$$\tilde{\mathcal{C}}_3 = -8.47389\times 10^{-9}\,\lambda\,|W_0|^4.$$

Robustness of Perturbative Large Volume Scenario

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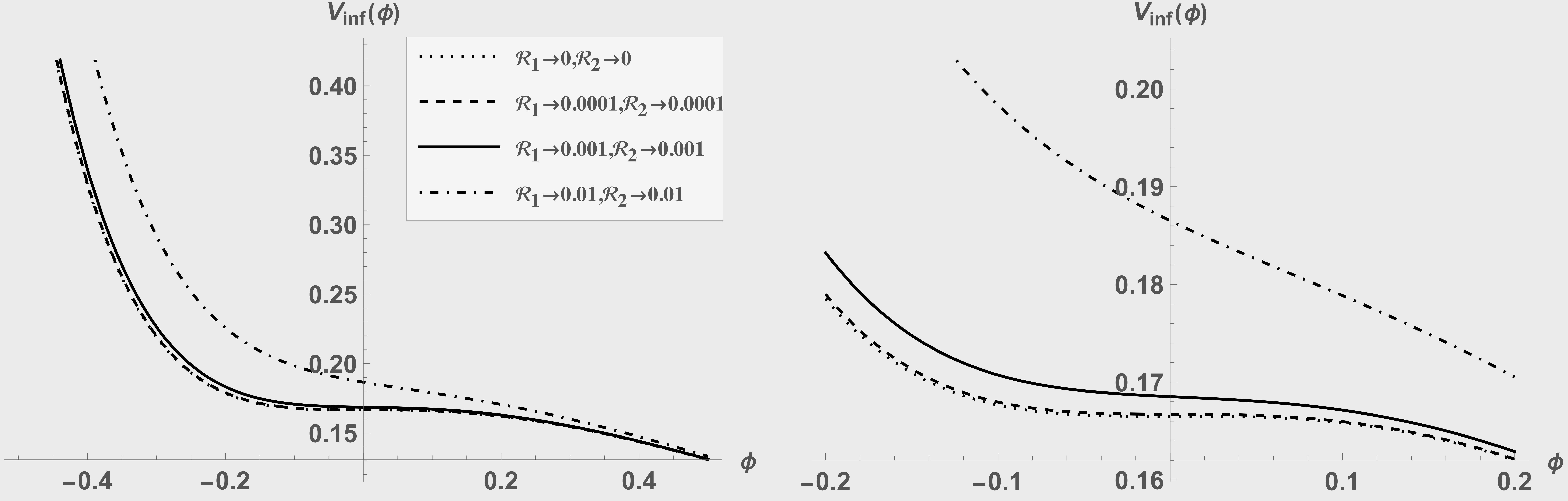
$$\mathcal{R}_1 = \frac{\tilde{\mathcal{C}}_2}{\tilde{\mathcal{B}}} = 0.80801\,\mathcal{C}_w, \qquad \mathcal{R}_2 = \frac{\tilde{\mathcal{C}}_3}{\tilde{\mathcal{B}}} = -5.58619\,|W_0|^2\lambda.$$



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$$W_0 = 0.038, \qquad \mathcal{C}_w = 5\cdot 10^{-5}, \qquad \lambda = -10^{-4},$$

$$\tilde{\mathcal{B}} = 2.19046\times 10^{-12}, \qquad \tilde{\mathcal{C}}_2 = 8.84958\times 10^{-17}, \qquad \tilde{\mathcal{C}}_3 = 1.76692\times 10^{-18},$$

$$\langle\phi\rangle = -0.00841545, \quad \langle\tau_\alpha\rangle = 103.409, \quad \langle\mathcal{V}\rangle = 743.568, \quad \langle V\rangle = 3.64835\times 10^{-13},$$

$$m_\phi^2 = 0.015697\, m_{\phi^\alpha}^2, \qquad m_{\phi^\alpha}^2 = 6.70767\times 10^{-12} \quad \text{for} \quad \alpha\in\{2,3\},$$

$$\phi^* = 0.000567702, \quad \epsilon_V^* = 7.05464\times 10^{-7}, \qquad \eta_V^* = -0.0199979, \qquad N_e \simeq 97,$$

$$P_s = 2.1\times 10^{-9}, \;\; n_s = 0.96, \;\; r = 1.13\times 10^{-5}$$

Global Embedding of Fibre Inflation

The Model: $h^{1,1} = 3$ and a toroidal like volume form $\mathcal{V} = \sqrt{\dfrac{\tau_1\tau_2\tau_3}{k_{123}}}$

The ansatz: $\tau_1 = q\tau_2, \quad q = 1$

$$\tau_3 = \tau_f = e^{2\varphi/\sqrt{3}}, \quad \varphi = \langle\varphi\rangle + \phi$$

The Potential: $$V = \mathcal{C}_0\left(\mathcal{C}_{\rm up} + \mathcal{R}_0 e^{-\gamma\phi} - e^{-\frac{\gamma}{2}\phi} + \mathcal{R}_1 e^{\frac{\gamma}{2}\phi} + \mathcal{R}_2 e^{\gamma\phi}\right),$$

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$$\gamma = 2/\sqrt{3},\ \frac{\mathcal{R}_2}{\mathcal{R}_0} = \frac{\mathcal{C}_2\mathcal{C}_{w3}e^{2\gamma\langle\varphi\rangle}}{\mathcal{C}_3\langle\mathcal{V}\rangle}\left[1 + \hat{\mathcal{C}}_w\left(1 + \frac{e^{\sqrt{3}(\phi+\langle\varphi\rangle)}}{\langle\mathcal{V}\rangle\sqrt{2}}\right)^{-1}\right],$$

(a) Bera, **Chakraborty**, Leontaris, Shukla' 24

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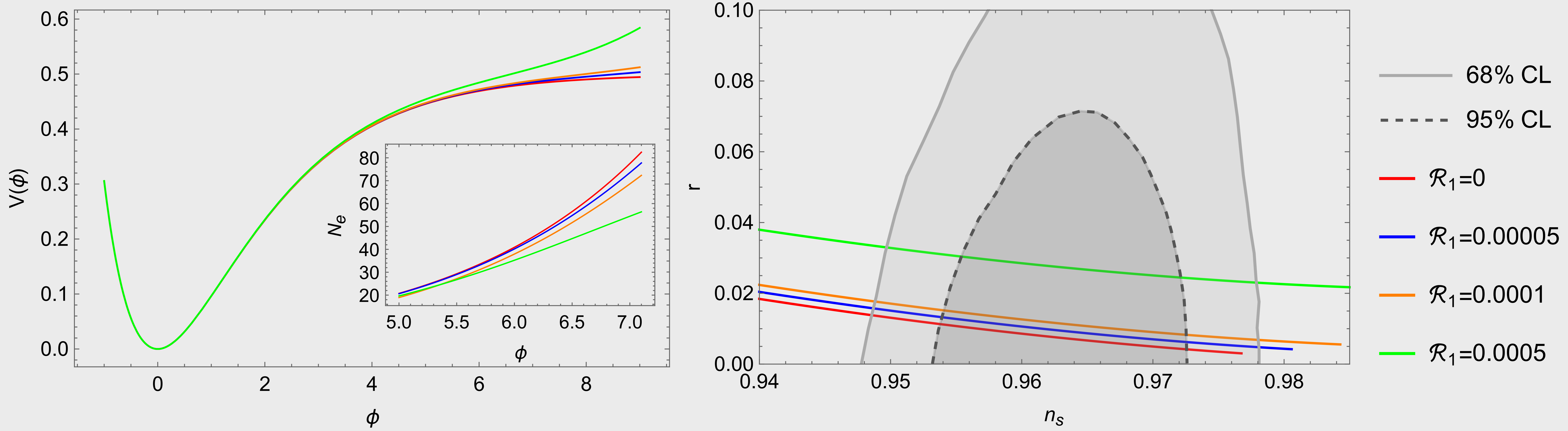

(a) Bera, **Chakraborty**, Leontaris, Shukla' 24

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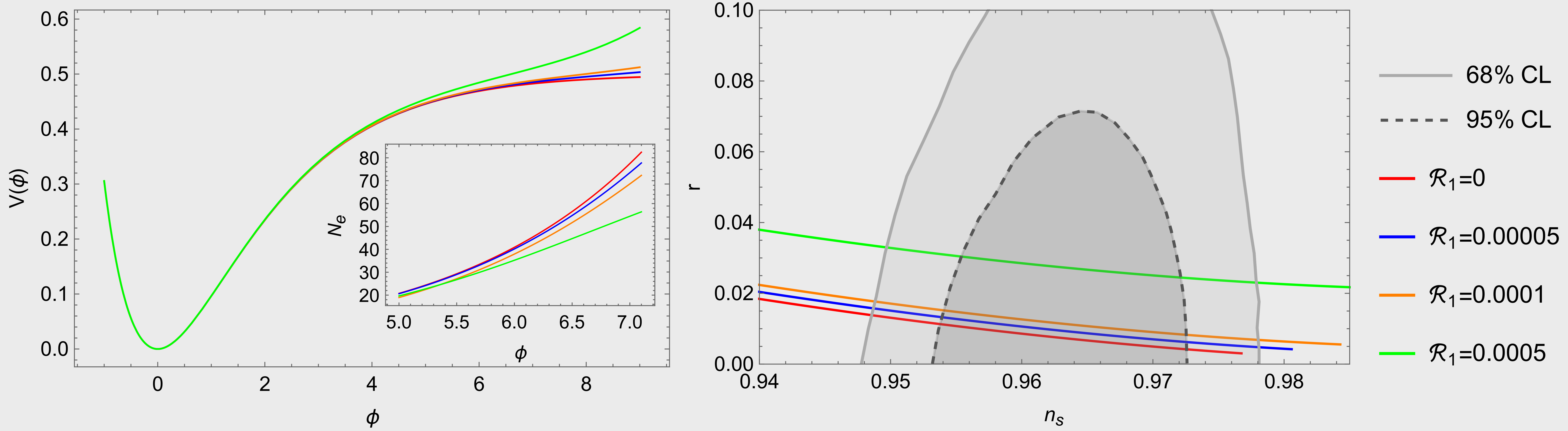

$e^{\frac{1}{2}K_{\rm cs}}|W_0| = 145, \quad \tilde{\mathcal{C}}_w = 5.3, \quad \mathcal{C}_{w3} = 10^{-2}, \quad \hat{\mathcal{C}}_w = 0, \quad |\lambda| = 10^{-4}, \quad \langle\varphi\rangle = 0.1$

$g_s = 0.3, \quad \langle\mathcal{V}\rangle \simeq 15000, \quad \mathcal{C}_0 \simeq 5.26\cdot 10^{-10}, \quad \mathcal{R}_0 \simeq 0.462, \quad \mathcal{R}_1 \simeq 5.18\cdot 10^{-5}, \quad \mathcal{R}_2 \simeq 1.06\cdot 10^{-7},$

$N_e^* \simeq 50, \quad P_s^* \simeq 2.1\cdot 10^{-9}, \quad n_s^* \simeq 0.966, \quad r^* \simeq 8\cdot 10^{-3}, \quad \phi^* \simeq 6.22, \quad \phi_{\rm end} \simeq 0.92.$

(a) Bera, **Chakraborty**, Leontaris, Shukla' 24

Conclusion

☑ Presented the global embedding of the inflationary model in the context of perturbative LVS in a K3 fibred CY — global toroidal like structure.

Moduli stabilisation is addressed in presence of only perturbative - BBHL+ log-loop type corrections

Robustness of inflationary model is checked — volume inflation is studied — small field inflation — satisfying distance conjecture.

Improvement over previous constructions — is it again robust against anther type of log-loop effects? — what are the implications of water fall fields?

☑ Global embedding of fibre inflation — in absence of exceptional del-pezzo divisor — devoid of non-perturbative effects.

☑ Viable inflation without a geometric Kahler cone bound on the field excursion.

Thank you!

Fibre Inflation revisited

Features:

- ✦ The CYs are "weak" Swiss-cheese which have $h^{1,1} = 3$

$$\mathcal{V} = \lambda_f \tau_b \sqrt{\tau_f} - \lambda_s \tau_s^{3/2}$$

- ✦ Overall volume and τ_s are fixed by standard LVS, leaving τ_f as a flat direction — serves as inflaton.
- ✦ Inclusion string-loop corrections lifts the τ_f direction— giving the leading order scalar potential as

$$V(\tau_f) = V_{\rm up} + \frac{|W_0|^2}{\mathcal{V}^2}\left(\frac{B_1}{\tau_f^2} - \frac{B_2}{\mathcal{V}\sqrt{\tau_f}} + \frac{B_3\,\tau_f}{\mathcal{V}^2}\right),$$

V_{up} depends on the uplifting and B_is depend on CS moduli.

(a) Cicoli, Burgess, Quevedo' 08

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(a) Bera, **Chakraborty**, Leontaris, Shukla' 24

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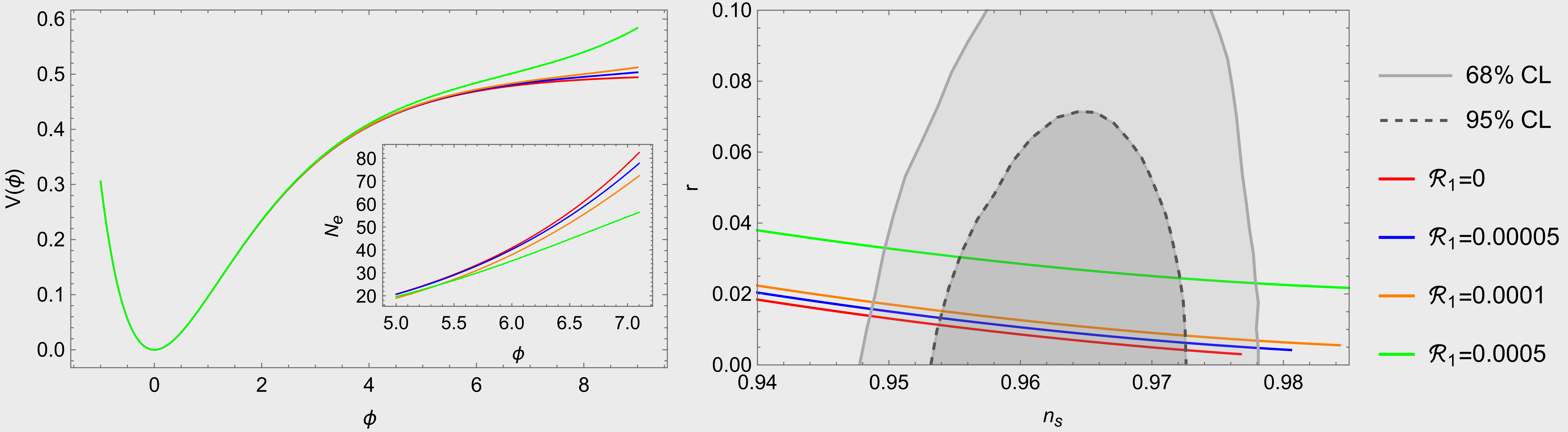

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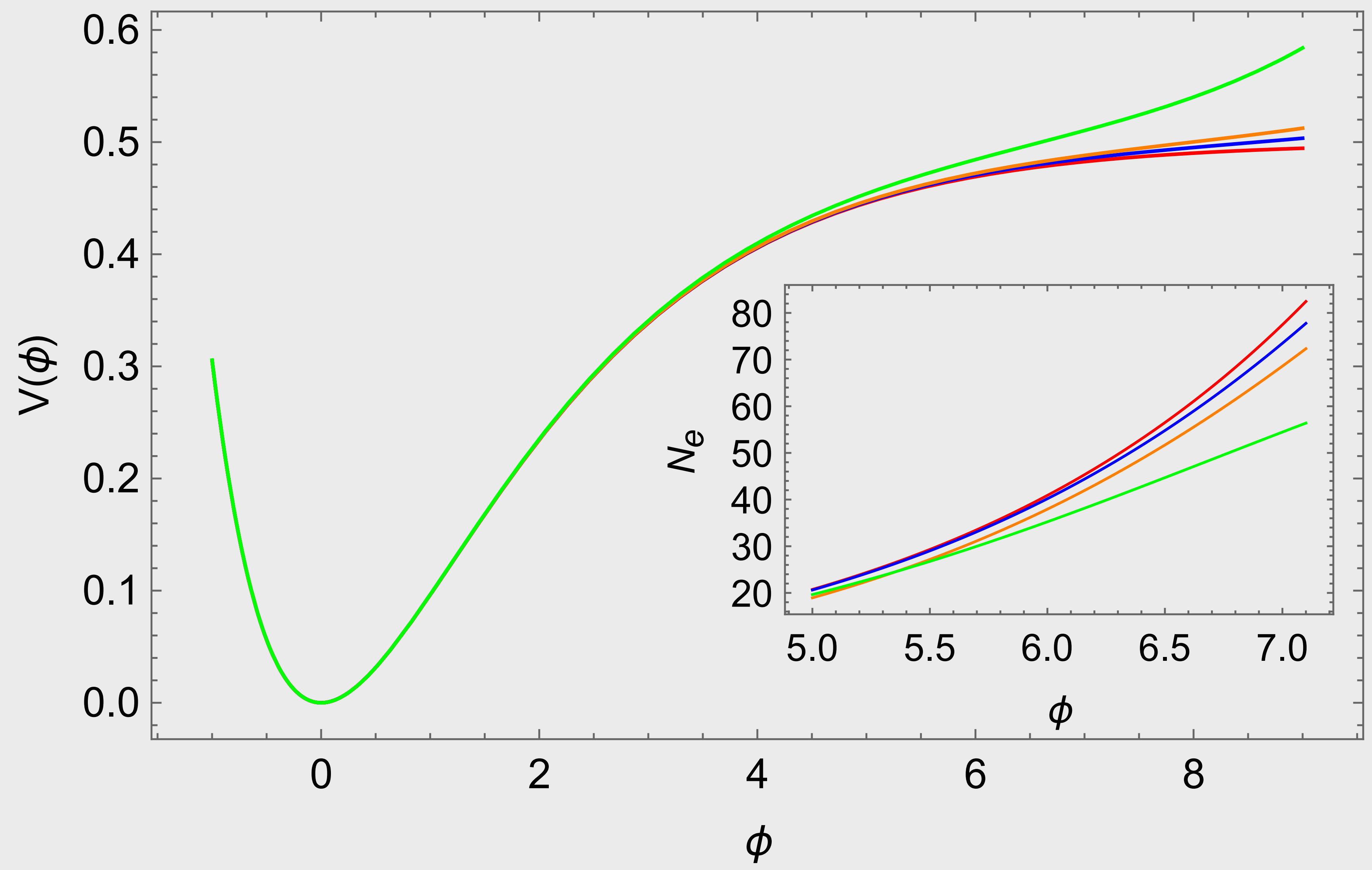

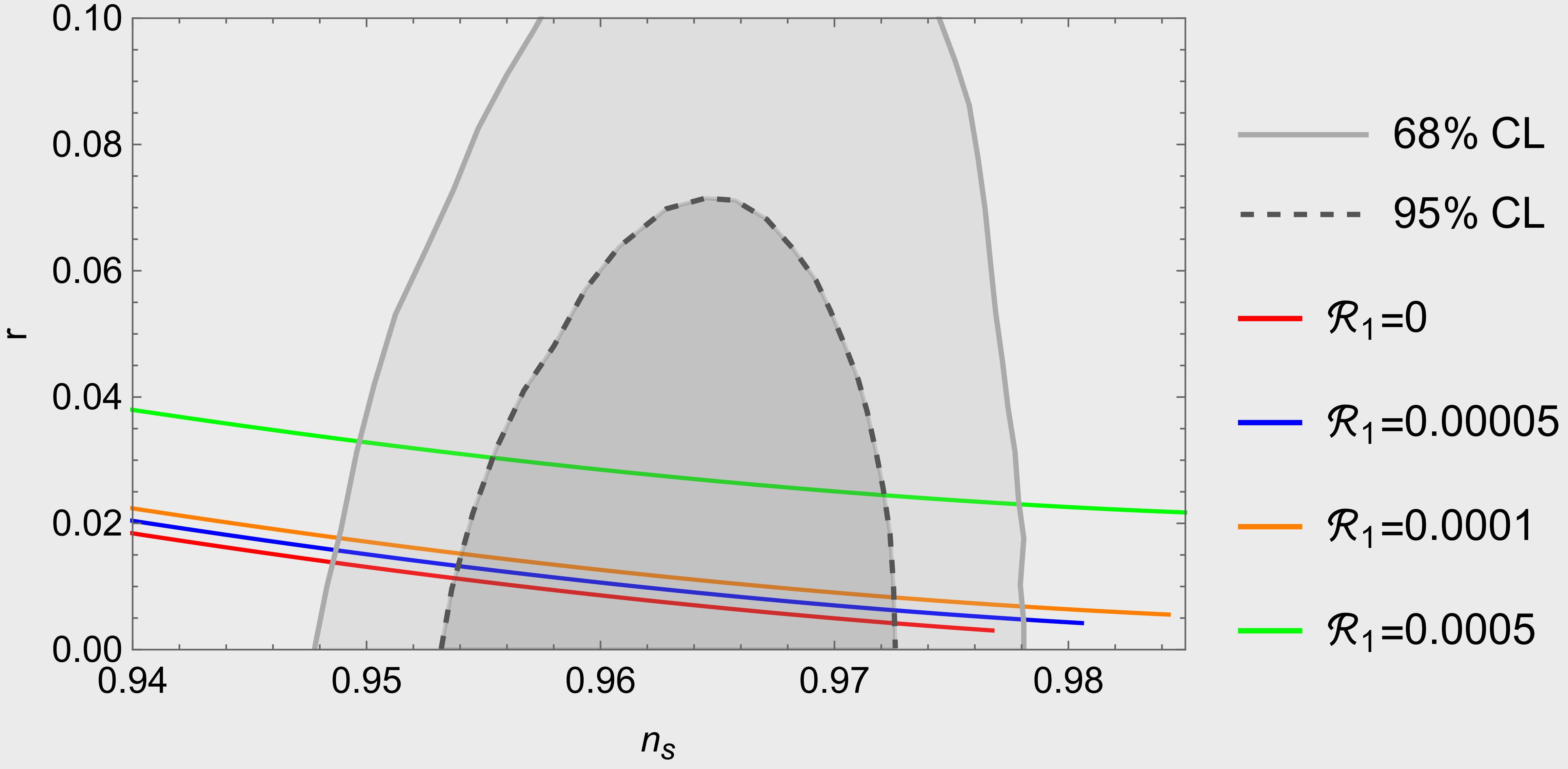

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The Source of Quantum Corrections (perturbative)

The tree-level 10D action of type IIB supergravity action is given by

$$S_{IIB} = \frac{1}{k_{10}^2}\int d^{10}x\sqrt{-g}\,[\mathcal{L}_{NSNS} + \mathcal{L}_{RR} + \mathcal{L}_{CS}] + S_{\text{loc}}$$

The corrections from higher derivatives operators,

$$S_{IIB} = S_{0,\text{tree}} + (\alpha')^3 S_{0,(3)} + \ldots + (\alpha')^n S_{0,(n)} + S_{CS,\text{tree}} +$$

$$+ S_{\text{loc,tree}} + (\alpha')^2 S_{\text{loc},(2)} + \ldots + ((\alpha')^n) S_{\text{loc},(n)}$$

$$S_{\text{CS,tree}} = \frac{1}{2k_{10}^2}\int d^{10}x\sqrt{-g}\mathcal{L}_{\text{CS}}$$

$$(\alpha')^3 S_{0,(3)} \sim \frac{1}{k_{10}^2}\int d^{10}x\sqrt{-g}\big[\mathcal{R}^4 + \mathcal{R}^3(G_3G_3 + G_3\bar{G}_3 + \bar{G}_3\bar{G}_3 + F_5^2 + (\nabla\tau)^2 +$$

$$+\mathcal{R}^2\left(G_3^4 + G_3^2 + \bar{G}_3^2 + \ldots + (\nabla G_3)^2 + (\nabla F_5)^2 + \ldots\right) +$$

$$+\mathcal{R}\left(G_3^6 + \ldots + G_3^2(\nabla G_3)^2 + \ldots\right) + G_3^8 + \ldots\big]$$

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$$+ \mathcal{R} \left(G_3^6 + \ldots + G_3^2 (\nabla G_3)^2 + \ldots\right) + G_3^8 + \ldots\Big]$$

How does the potential arise?

A 5-d scalar field compactified on $\mathscr{M} = \mathbb{R}^4 \times S^1$ with $x^5 \in [0, 2\pi R)$ splits into an infinite number of scalar fields.

The action: $$S_5 = \int d^5X \, \frac{1}{2}(\partial_M \Phi)(\partial^M \Phi) \qquad X \equiv (x^\mu, y)$$

The EOM: $$\partial_M \partial^M \Phi = \partial_\mu \partial^\mu \phi(x) + \partial_5 \partial^5 \phi(y) = 0$$

Since the 5d scalar is compactified, we can expand the scalar field into Fourier series:

$$\Phi(X) = \sum_{n=0}^{\infty} \phi_n(x) \, e^{\frac{iny}{R}}$$

The action:

$$S = 2\pi R \int d^4x \left[\frac{1}{2}(\partial \phi(x))^2 + V(\phi(x)) + \frac{1}{2} \sum_{n=1}^{\infty} \left((\partial \phi_n(y))^2 + m_n^2 \phi_n(y)^2 \right) \right], \quad m_n = n/R$$

α'^3-corrections[a]

$$S \propto \int d^{10}x\sqrt{-g}e^{-2\phi}\left(R + 4(\partial\phi)^2 + \alpha'^3 c_1 J_0\right)$$

$\propto f(\mathcal{R}^4)$

Dilation

Chern class

This gives rise to a correction in the Kahler potential

$$K \propto -2\log\left(\mathcal{V} + \frac{\xi(S+\bar{S})^{3/2}}{2}\right) = -2\log\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right)$$

6D volume: $\mathcal{V} = \frac{1}{3!}\int_X J\wedge J\wedge J = \frac{1}{6}k_{ijk}t^i t^j t^k, \text{ where } t^i : \text{ volume of 2-cycles}$

$$\xi = -\frac{\zeta(3)\chi(X)}{4(2\pi)^3} \text{ where } \chi(X) : \text{ Euler characteristics} \Rightarrow \chi(X) = 2(h^{1,1} - h^{2,1})$$

(a) Becker, Becker, Haack, Louis' 02

Log-loop corrections

Correction sourced via fourth power of curvature and KK-exchange induce correction to the Einstein-Hilbert term [a,b,c]

$$\propto \zeta(2)\chi(X)\int_{M_4}\left(1+\sum_{i=1,2,3} e^{2\phi}\underbrace{\tau_i}_{\text{D7 brane tension}}\log(\underbrace{R^i_\perp}_{\text{D7 transverse 2-dimension}})\right)R_{(4)}$$

This again corrects the Kahler potential

$$K = -2\log(\mathcal{V} + \eta\log\mathcal{V})$$

η depends on the Euler characteristics

(a) Green, Vanhove'97 (b) Antoniadis, Ferrara, Minasian, Narain' 97 (c) Kiritsis, Pioline'97

Higher derivative corrections

$\alpha'^3 F^4$ terms from 10D $R^2 G_3^4$ term sources the following potential [a]

$$V_{F_4} = -\frac{-\lambda k^2 |W_0|^4}{g_s^{3/2}\mathcal{V}^4}\Pi_\alpha t^\alpha, \quad \text{where } \Pi_\alpha = \int_X c_2 \wedge D_\alpha$$

$|\lambda| \sim \mathcal{O}(10^{-4})$: From dimensional reduction [b]

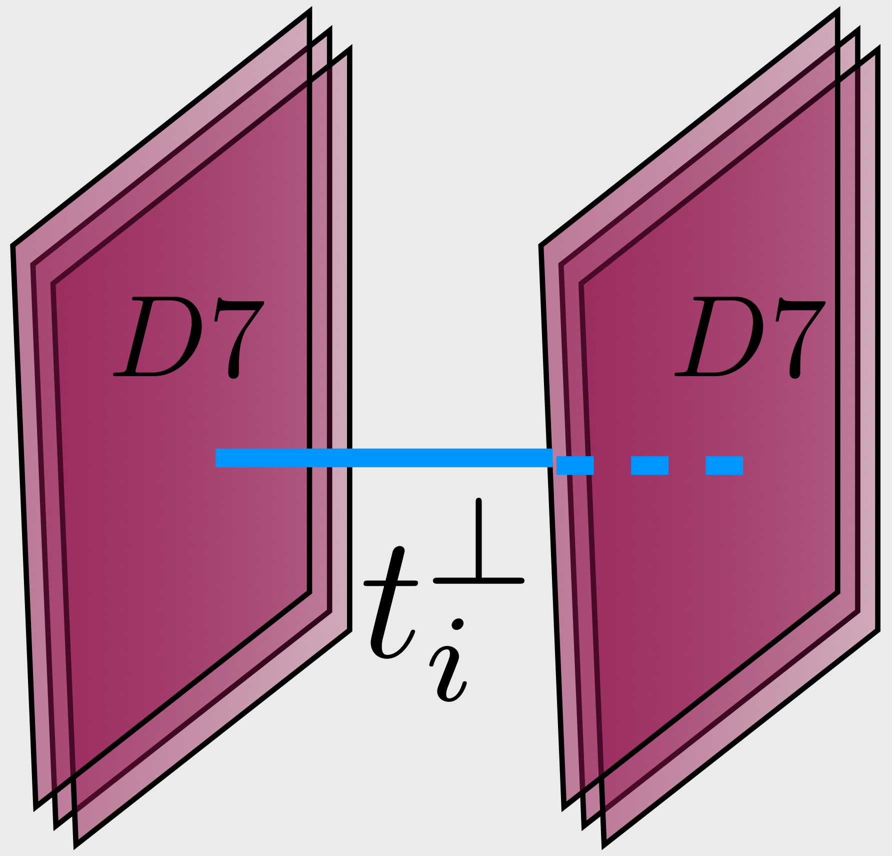
$\lambda < 0$: Fix all LVS flat directions for arbitrary CY [c]

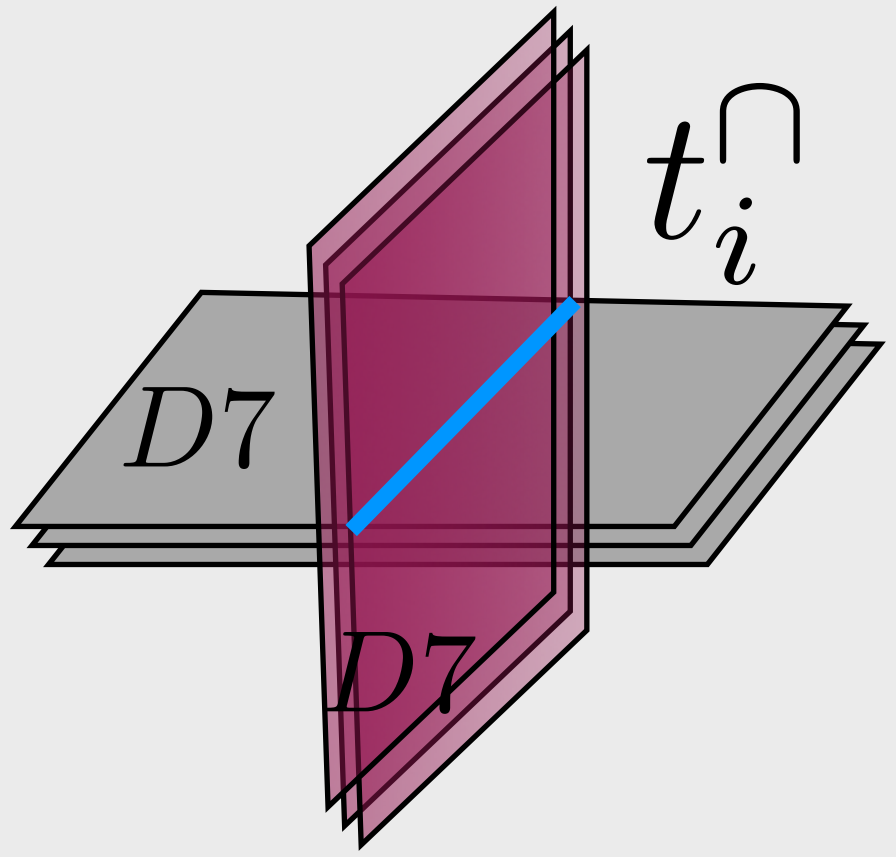
(a) Ciupke, Louis, Westphal, (b) Green, Mayer, Weissenbacher, (c) Cicoli, Ciupke, de Alois, Muia

String loops

KK+ winding 1-loop open string corrections[a,b,c] in terms of 2-cycle volume

$$K_{g_s}^{KK} = g_s \sum_i \frac{C_i^{KK} t_i^{\perp}}{\mathcal{V}} \qquad\qquad K_{g_s}^{W} = \sum_i \frac{C_i^{W}}{\mathcal{V} t_i^{\cap}}$$





$$V_{g_s}^{KK} = k g_s \frac{|W_0|^2}{16\mathcal{V}^4} \sum_{\alpha,\beta} C_\alpha C_\beta \left(2 t_\alpha^{\cap} t_\beta^{\cap} - 4\mathcal{V} k^{\alpha\beta}\right) \qquad\qquad V_{g_s}^{W} = -2k \frac{|W_0|^2}{\mathcal{V}^3} \sum_\alpha \frac{C_\alpha^W}{t_\cap^\alpha}$$

(a) Ciupke, Louis, Westphal, (b) Green, Mayer, Weissenbacher, (c) Cicoli, Ciupke, de Alois, Muia

The Inflationary Potentials - a quick trailer

Global model — master formula — in terms of Kahler moduli

$$V_{\rm tot} = \left[\frac{d_1}{\tau_1}\left(\frac{q_{12}}{\tau_2}+\frac{q_{13}}{\tau_3}\right)^2+\frac{d_2}{\tau_2}\left(\frac{q_{21}}{\tau_1}+\frac{q_{23}}{\tau_3}\right)^2+\frac{d_3}{\tau_3}\left(\frac{q_{31}}{\tau_1}+\frac{q_{32}}{\tau_2}\right)^2\right]+\mathcal{C}_1\left(\frac{\hat{\xi}-4\,\hat{\eta}+2\,\hat{\eta}\,\ln\mathcal{V}}{\mathcal{V}^3}\right)$$
$$+\frac{\mathcal{C}_2}{\mathcal{V}^4}\left(\tau_1+\tau_2+\tau_3+\frac{\tau_1\tau_2}{2(\tau_1+\tau_2)}+\frac{\tau_2\tau_3}{2(\tau_2+\tau_3)}+\frac{\tau_3\tau_1}{2(\tau_3+\tau_1)}\right)+\frac{\mathcal{C}_3}{\mathcal{V}^3}\left(\frac{1}{\tau_1}+\frac{1}{\tau_2}+\frac{1}{\tau_3}\right)$$
$$+6\,\mathcal{C}_1\left(\frac{3\hat{\eta}\hat{\xi}+4\hat{\eta}^2+\hat{\xi}^2-2\hat{\eta}\hat{\xi}\ln\mathcal{V}-2\hat{\eta}^2\,\ln\mathcal{V}}{\mathcal{V}^4}\right)+\mathcal{O}(\mathcal{V}^{-n})+\dots\,,\qquad n>4$$

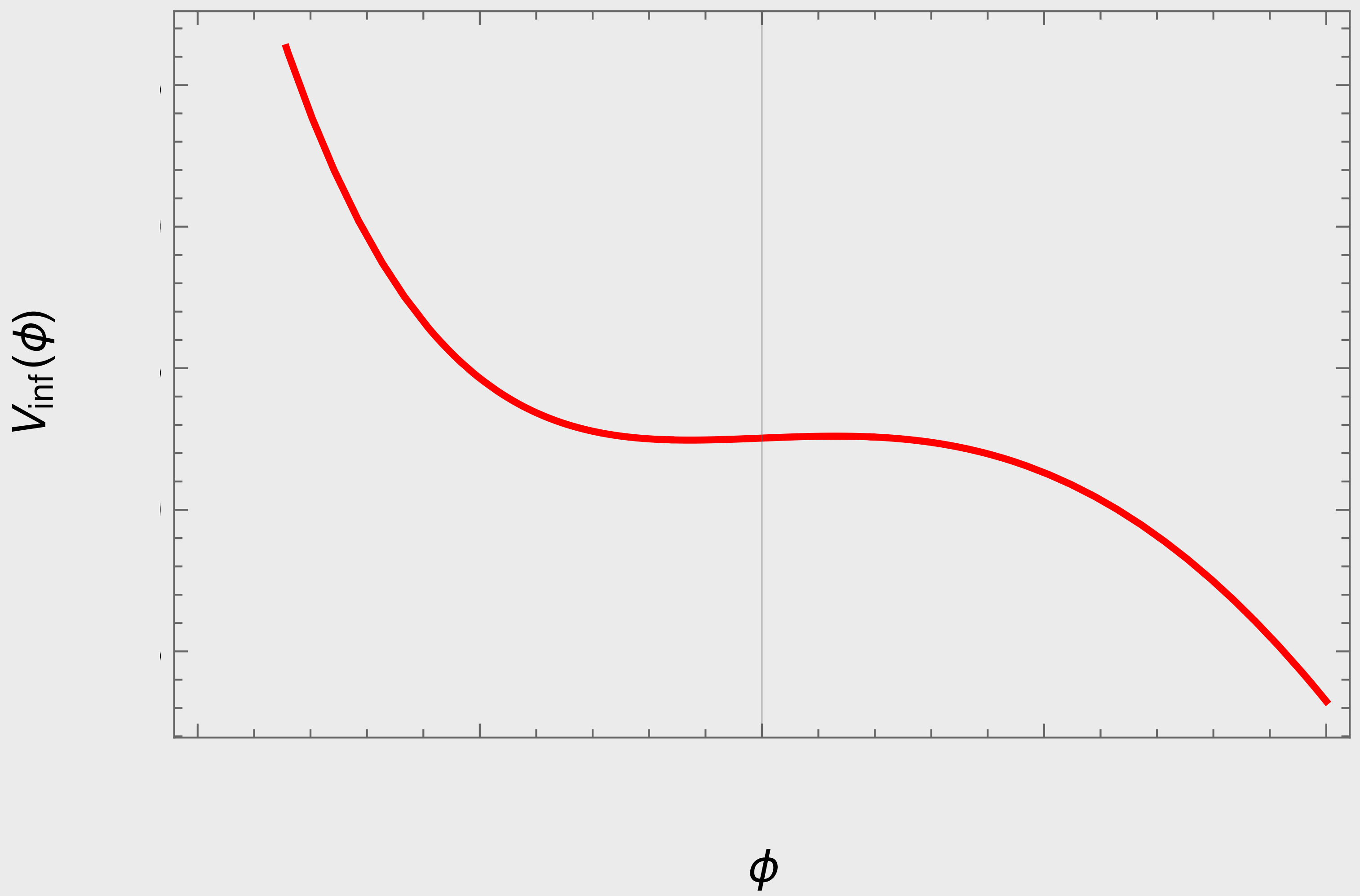
$\tau_i' s$: scalar fields
Parameters: Stringy details

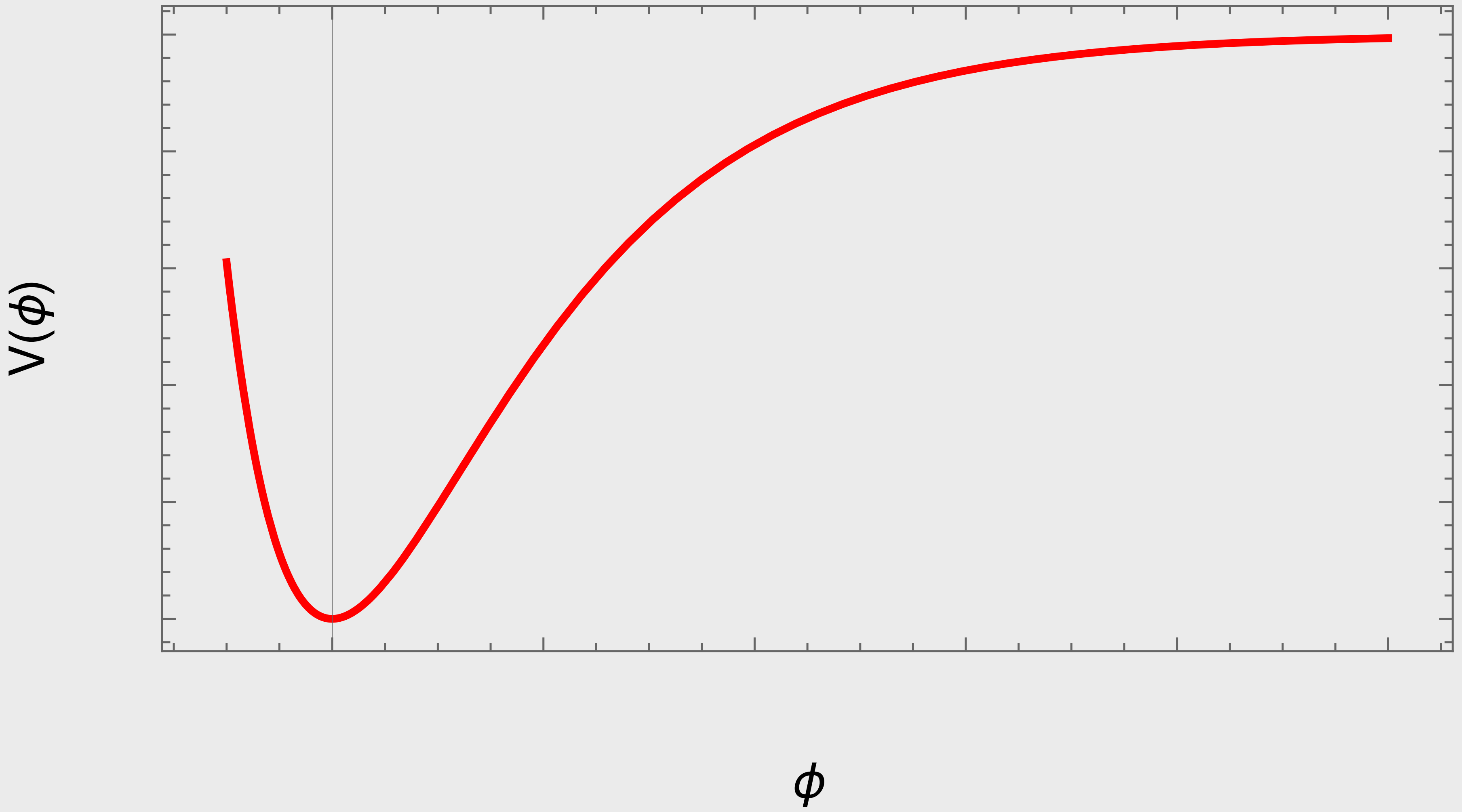
The Inflationary Potentials - a quick trailer

After transforming to canonical coordinates

$$V_{\rm inf}(\phi) = -\tilde{\mathcal{B}}\, e^{-3\sqrt{\frac{3}{2}}\phi}\left(\sqrt{\frac{3}{2}}\phi - \frac{3}{2}\, e^{-x+\sqrt{\frac{3}{2}}\phi} + \frac{4}{3}\right) + \tilde{\mathcal{C}}_2\, e^{-5\sqrt{\frac{2}{3}}\phi} + \tilde{\mathcal{C}}_3\, e^{-\frac{11}{\sqrt{6}}\phi}$$

$$V(\phi) = \mathcal{C}_0\Bigg(1 - e^{-\frac{2\phi}{\sqrt{3}}} - \mathcal{R}_0\left(1 - e^{-\frac{2\phi}{\sqrt{3}}}\right) - \mathcal{R}_1\left(1 - e^{\frac{\phi}{\sqrt{3}}}\right) - \mathcal{R}_2\left(1 - e^{\frac{2\phi}{\sqrt{3}}}\right)\Bigg)$$





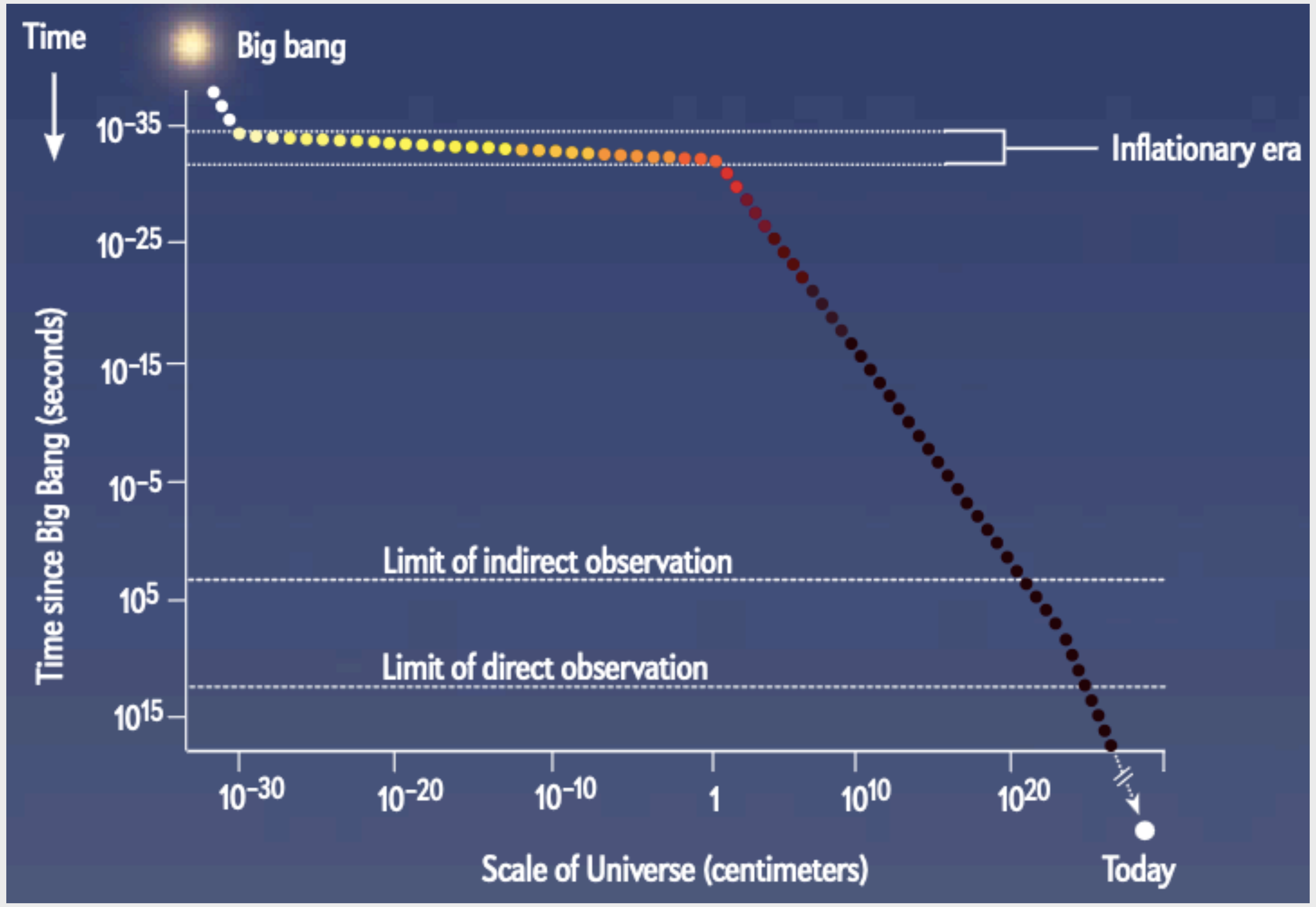
Volume Inflation

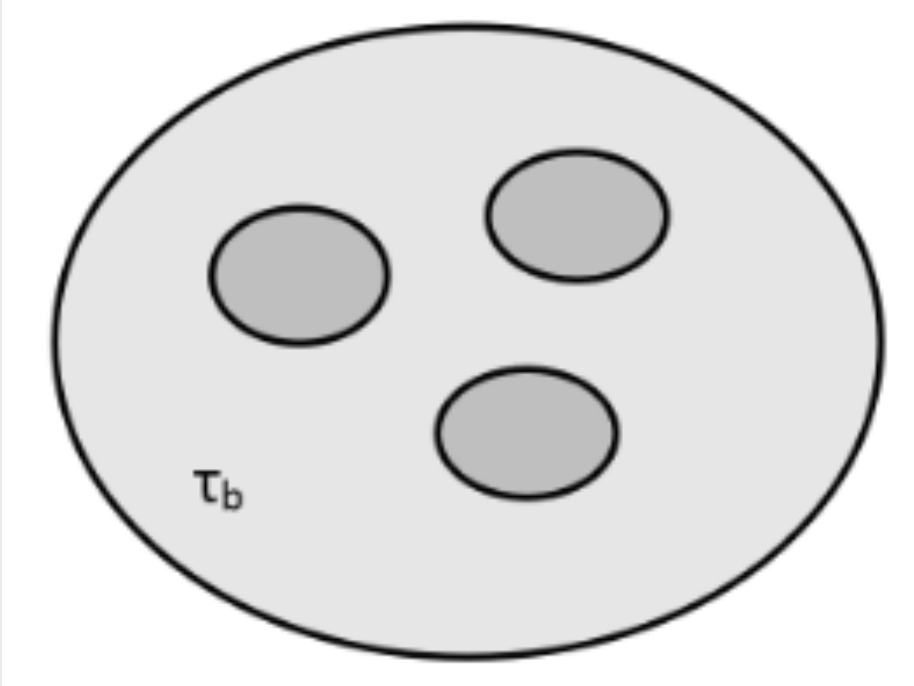
ϕ : scalar fields
Parameters: Stringy details

Fibre Inflation

Keywords

- String Theory Model building
- Moduli stabilisation
- Inflation → **Volume Inflation** | **Fibre Inflation**

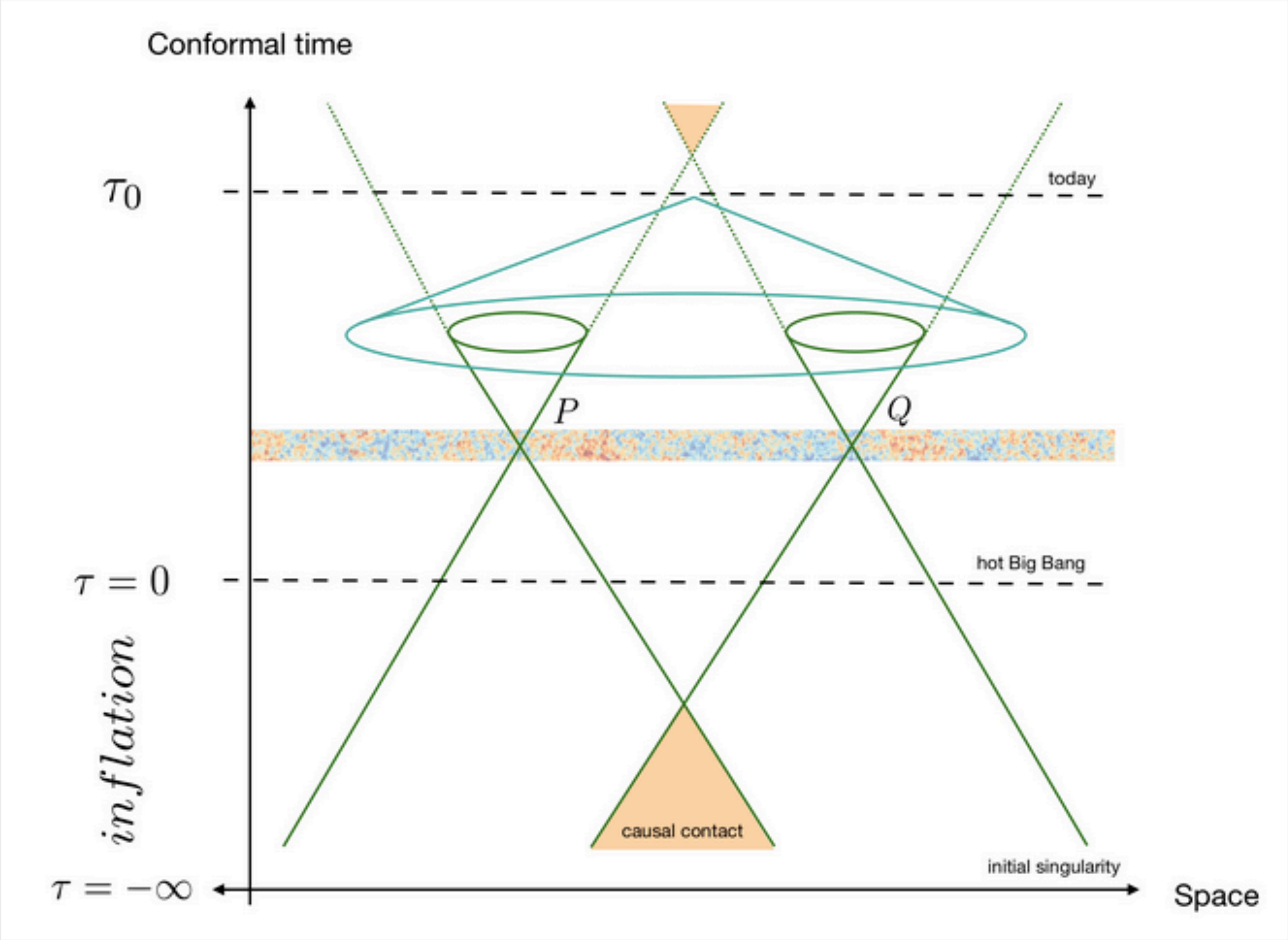




Extra dimensional topology

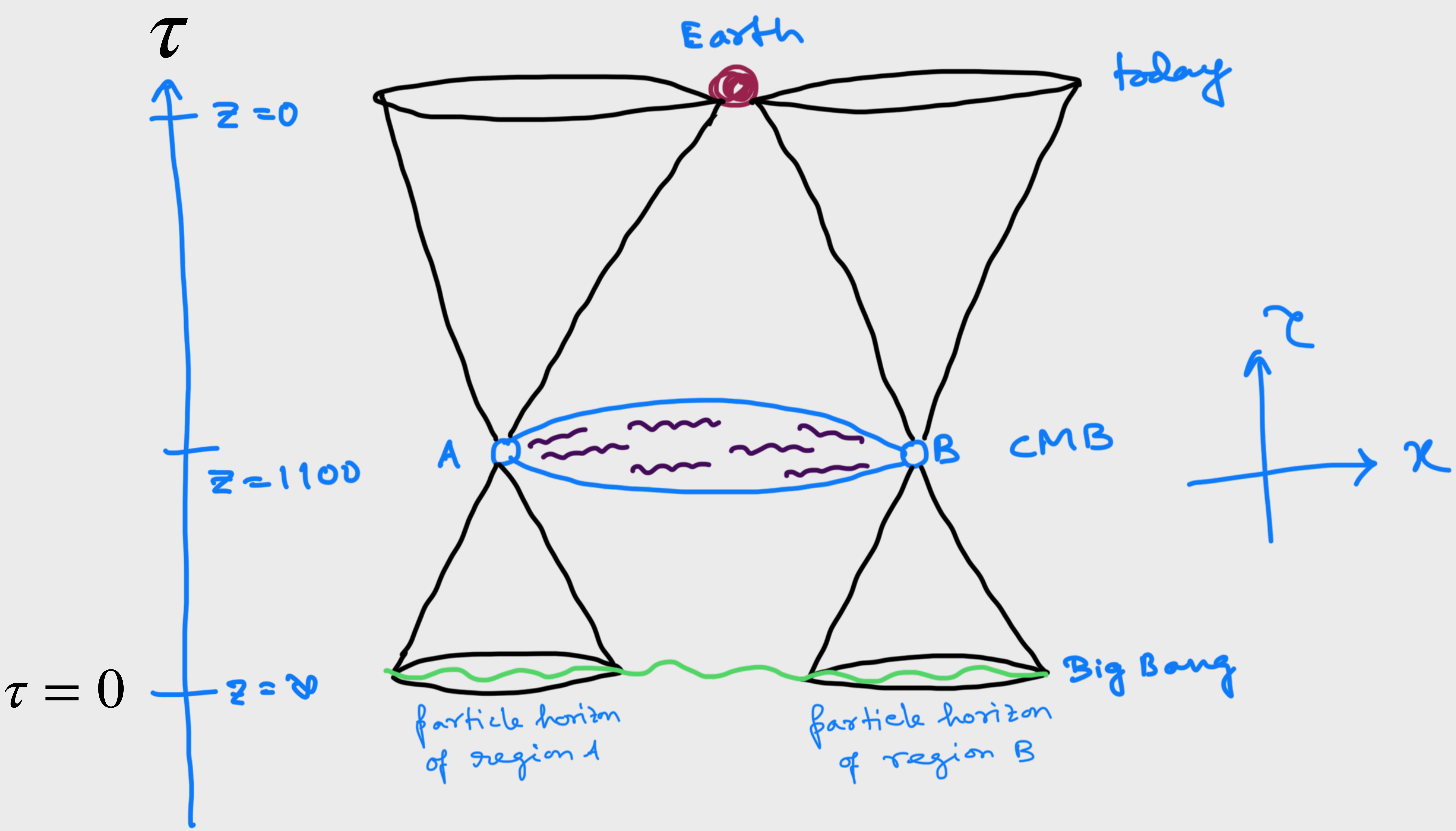
Left Image source: P.J. Steinhardt, Scientific American , Vol. 304, No. 4 (April 2011)

Why inflation



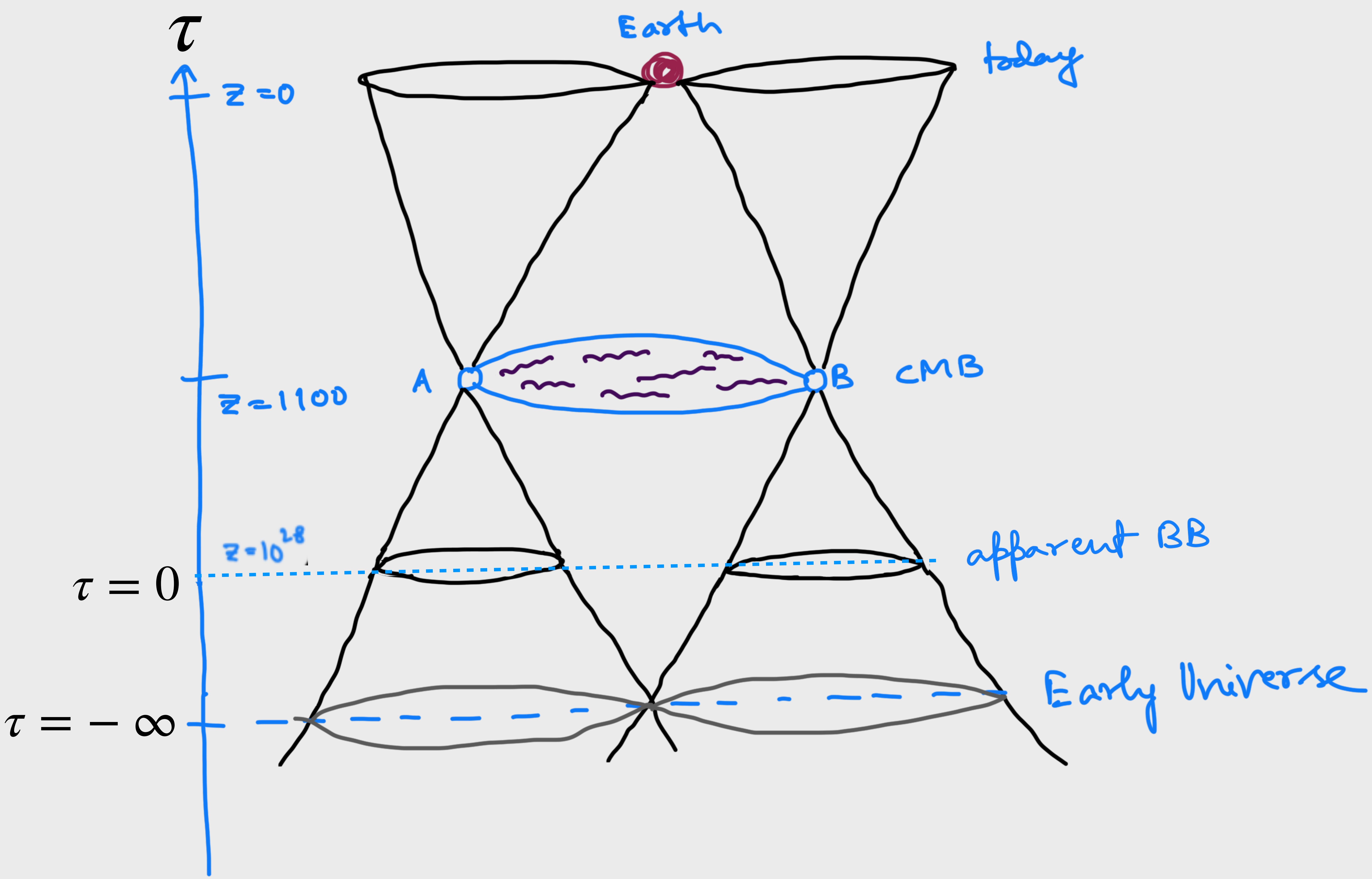
The resolution

The horizon Problem



Lights from A and B met on Earth today were not in contact at the time of Big Bang.

Why inflation



Inflation taking place between $\tau = -\infty \rightarrow \tau = 0$ can make the forward light cone and backward light cone of same size, **solving the horizon problem**.