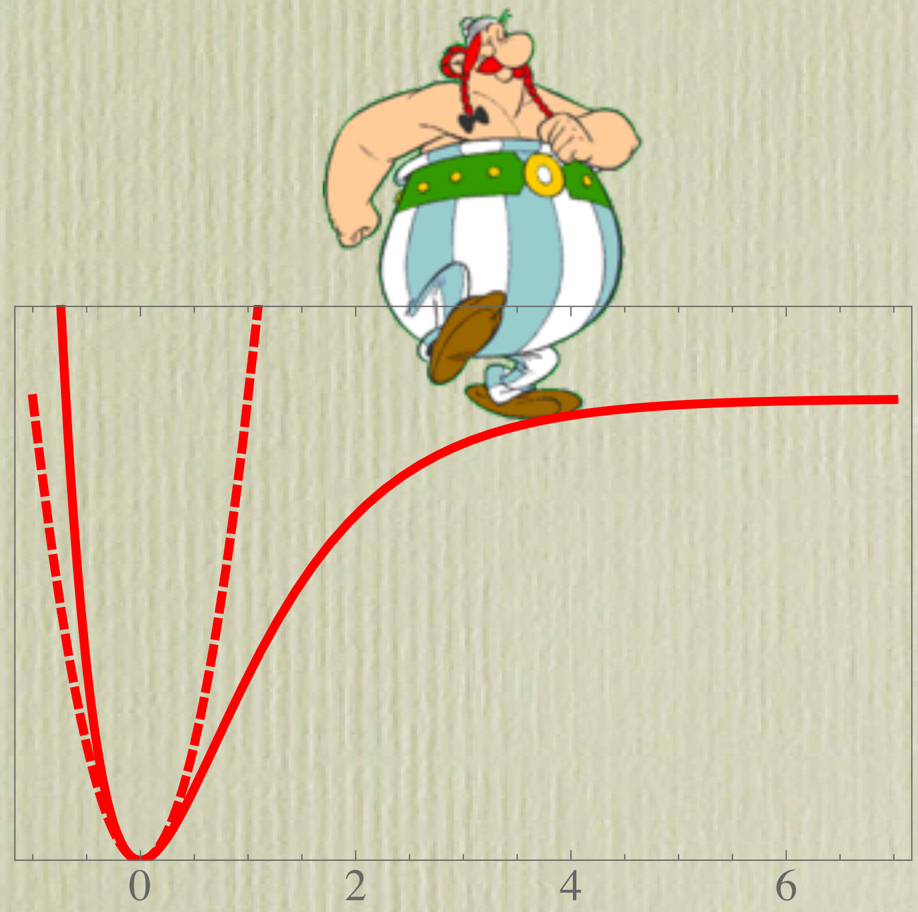
The Flattened Road to Acceleration in String Theory

with J. Moritz, A. Retolaza [1707.05830]

with R. Kallosh, A. Linde, D. Roest, Y. Yamada [1707.08678]



And work with: I. Ben-Dayan, W. Buchmüller, E. Dudas, K. Dutta, R. Flauger, L. Heurtier, E. Pajer, F. Pedro, F. Rühle, E. Silverstein, A. Uranga, C. Wieck, M. Winkler, T. Wrase, G. Xu

Alexander Westphal
(DESY)

slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]

$$\cancel{\ddot{\phi}} + 3H\dot{\phi} = -\partial_\phi V \equiv -V' \quad , \quad H^2 = \frac{1}{3}\left(\frac{1}{2}\cancel{\dot{\phi}^2} + V\right)$$

$$a \sim e^{Ht}$$

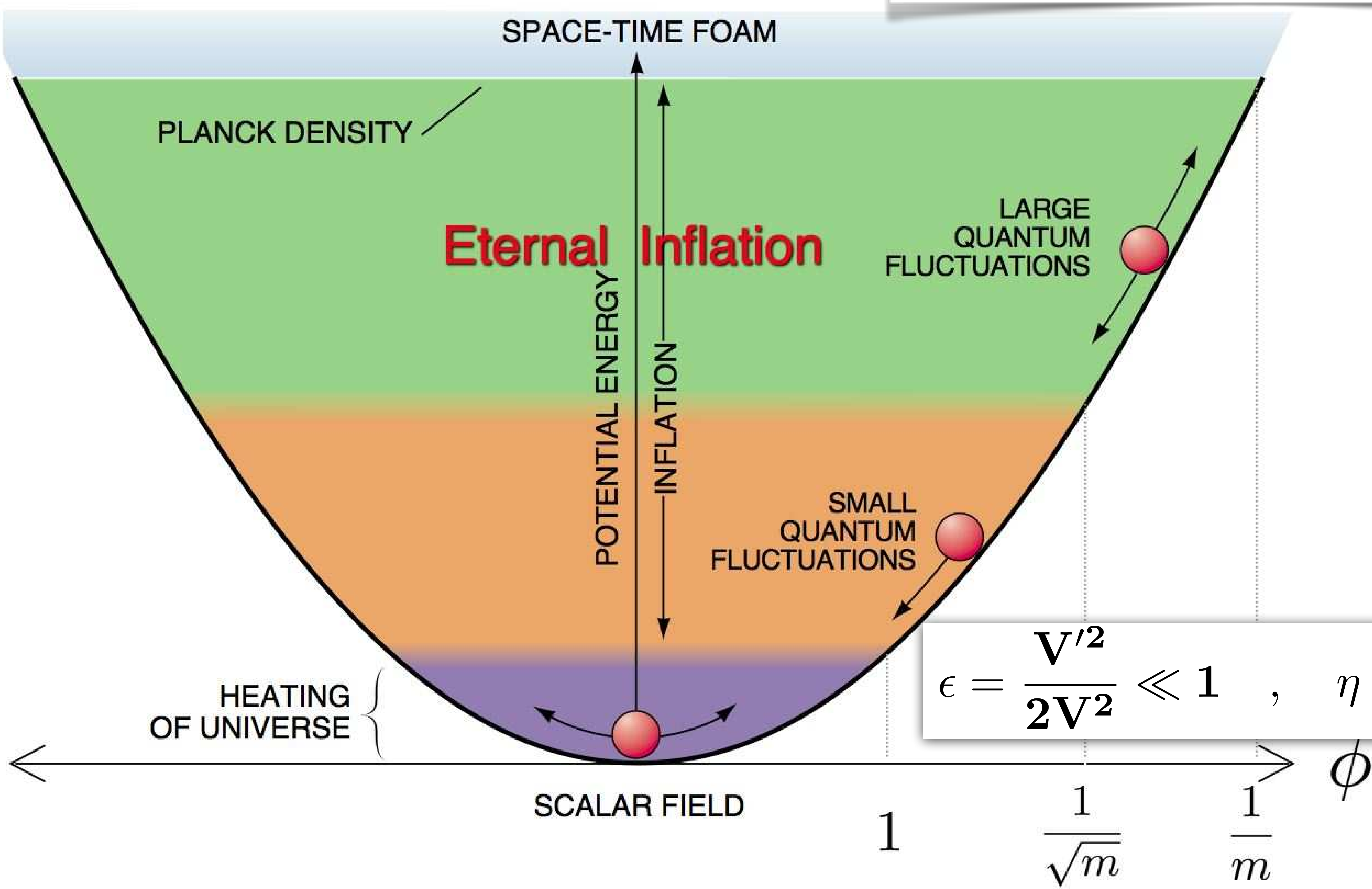
$$\epsilon = \frac{\mathbf{V'^2}}{\mathbf{2V^2}} \ll \mathbf{1} \quad , \quad \eta = \frac{\mathbf{V''}}{\mathbf{V}} \ll \mathbf{1}$$

slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]

$$V(\phi) = \frac{m^2}{2}\phi^2$$

$$3H\dot{\phi} \simeq -V' \ , \ H^2 \simeq \frac{1}{3}V$$



$$\epsilon = \frac{\mathbf{V'^2}}{\mathbf{2V^2}} \ll \mathbf{1} \quad , \quad \eta = \frac{\mathbf{V''}}{\mathbf{V}} \ll \mathbf{1}$$

[picture from lecture notes: Linde '07]

slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]

$$V(\phi) = \frac{m^2}{2}\phi^2$$

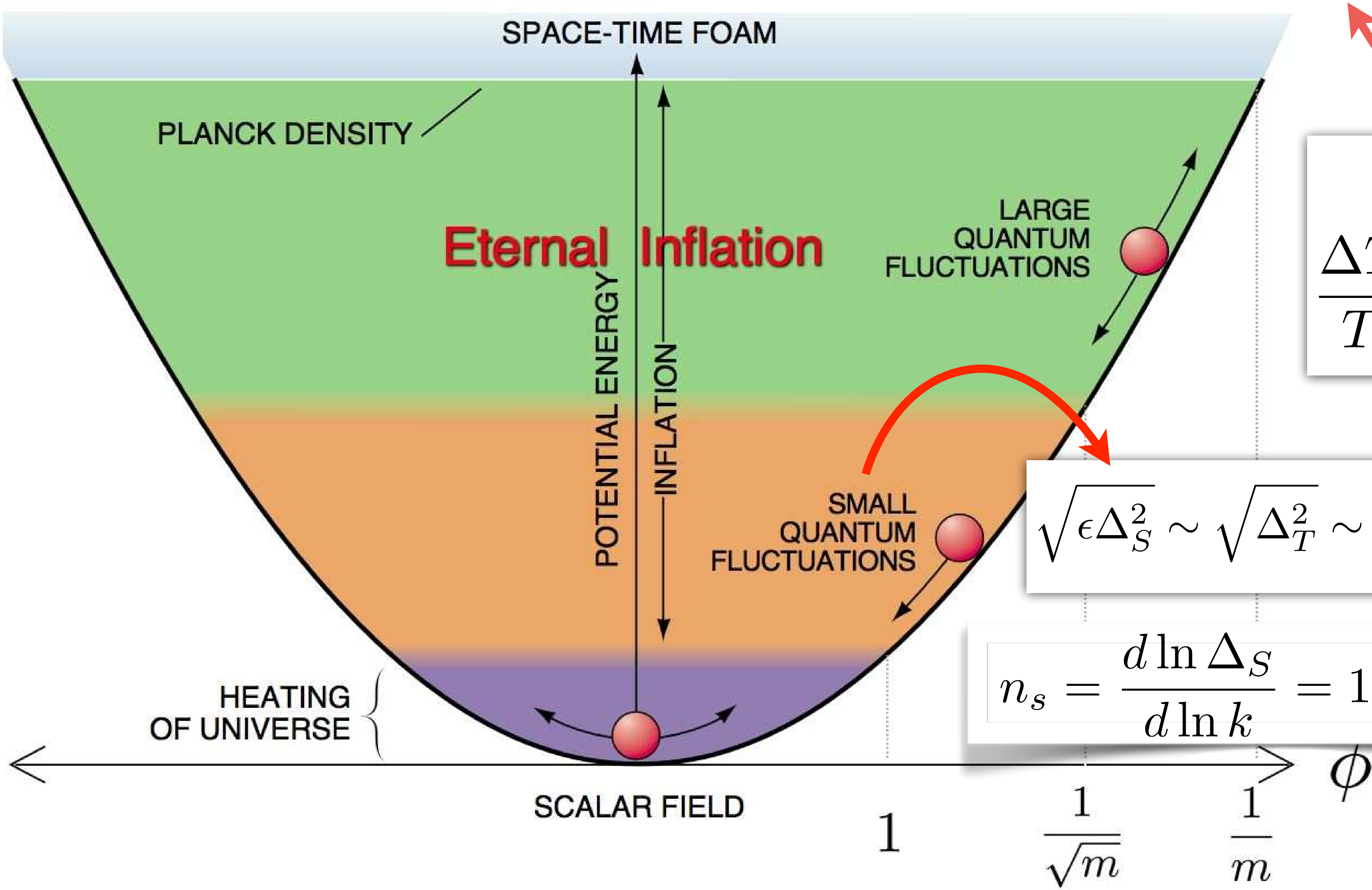
$$m \sim 10^{13}\,\mathrm{GeV}$$

CMB:

$$\frac{\Delta T}{T} \sim 10^{-5}$$

$$\sqrt{\epsilon \Delta_S^2} \sim \sqrt{\Delta_T^2} \sim \frac{H}{M_P} \sim 10^{-5}$$

$$n_s = \frac{d \ln \Delta_S}{d \ln k} = 1 - 6\epsilon + 2\eta$$



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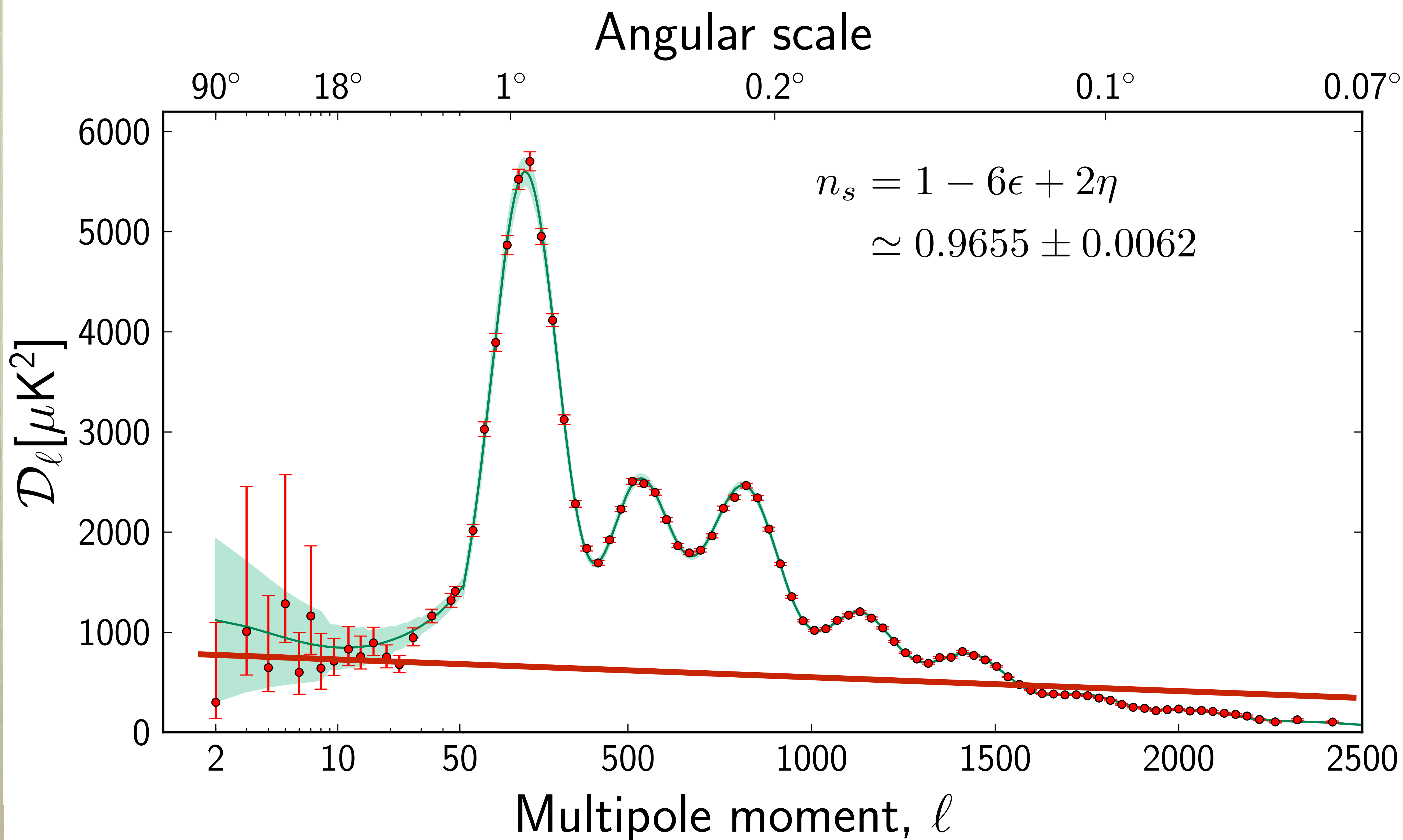
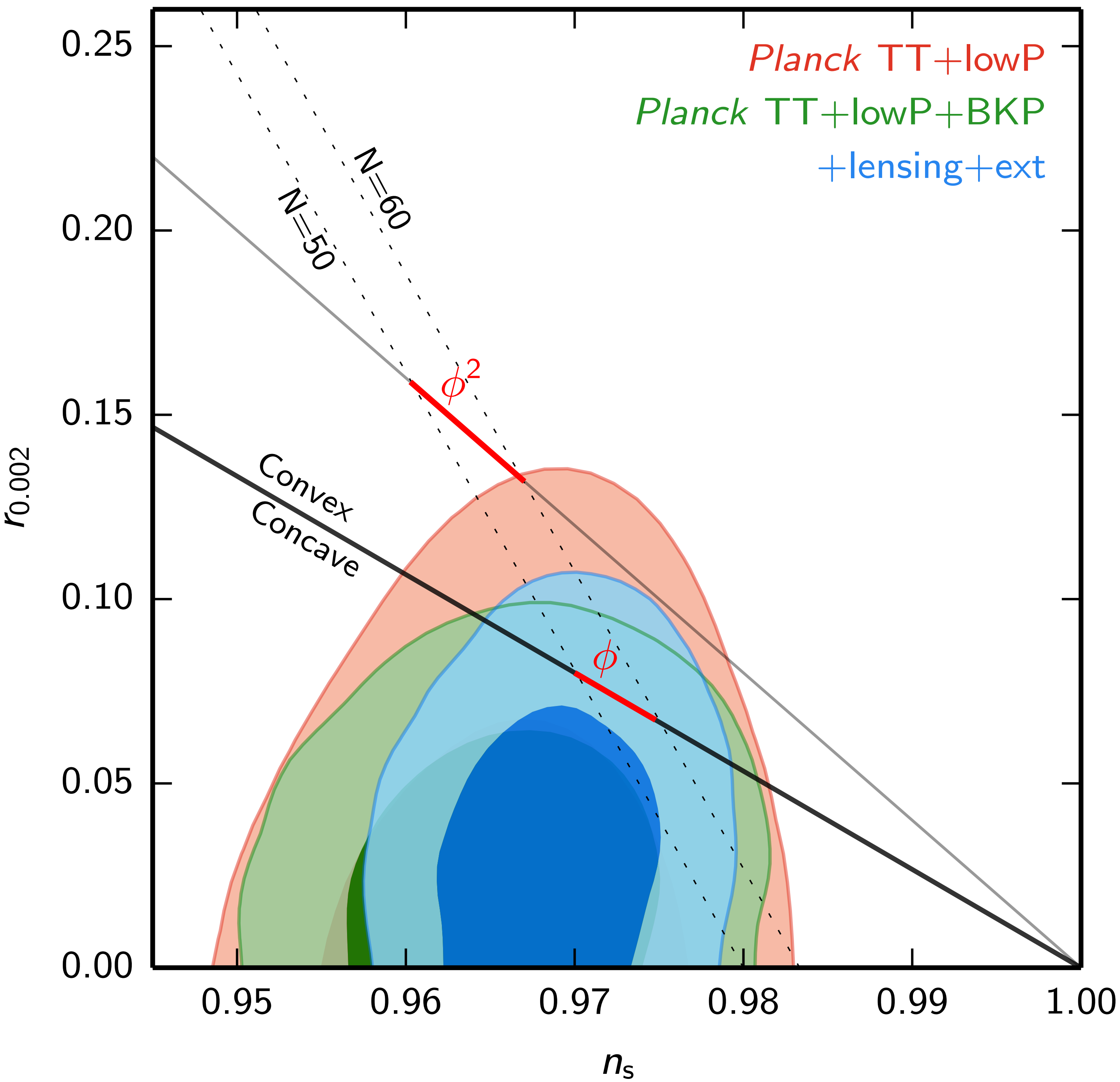


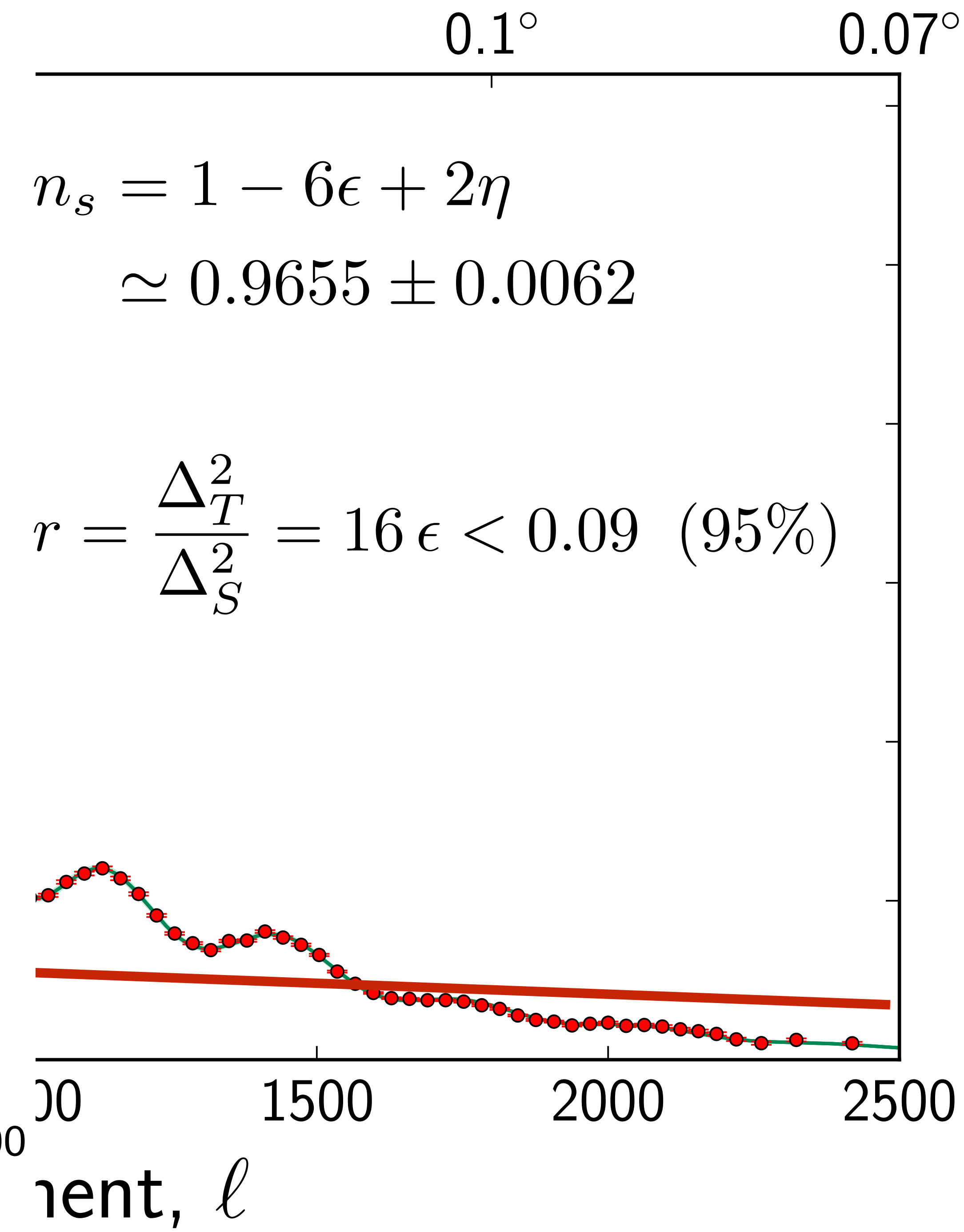
slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]

$$V(\phi) = \frac{m^2}{2}\phi^2$$

Angular scale





$$n_s = 1 - 6\epsilon + 2\eta$$
$$\simeq 0.9655 \pm 0.0062$$

$$r = \frac{\Delta_T^2}{\Delta_S^2} = 16\,\epsilon < 0.09 \quad (95\%)$$

erc

slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]

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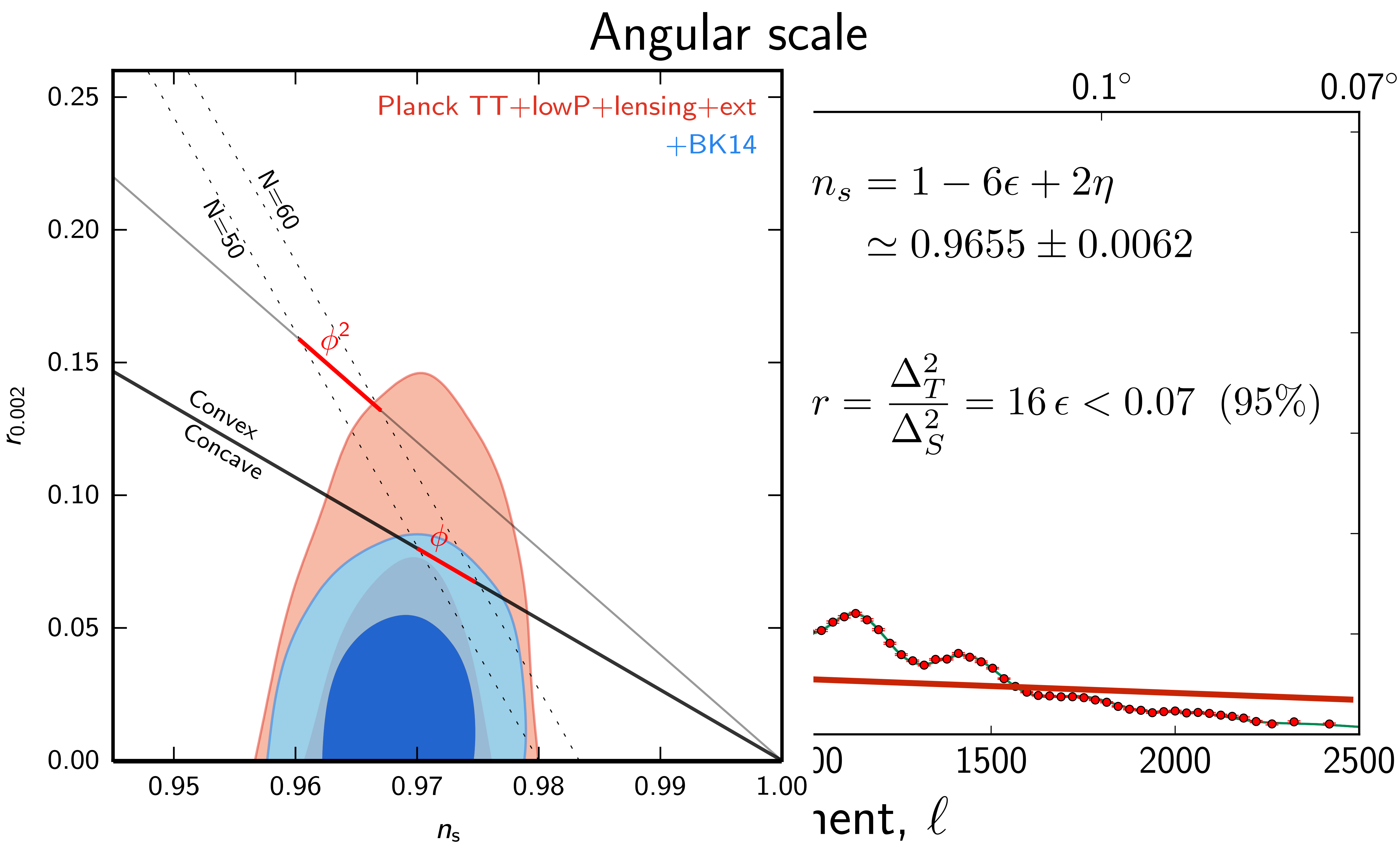
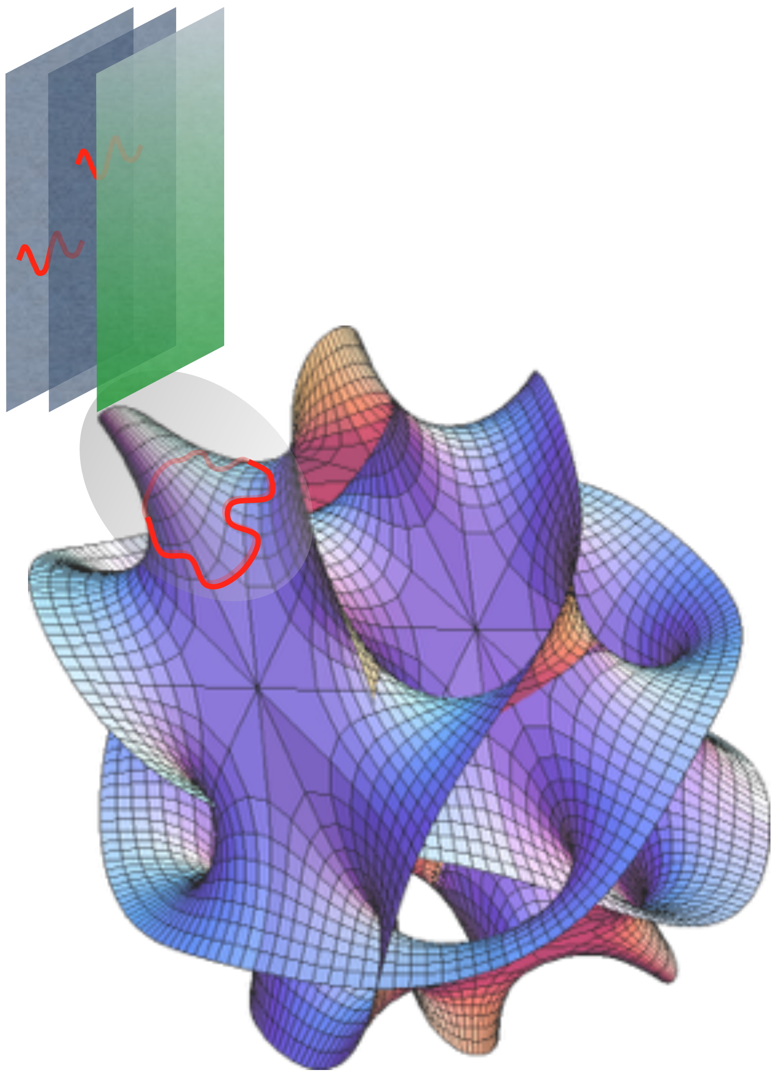


$$n_s = 1 - 6\epsilon + 2\eta$$
$$\simeq 0.9655 \pm 0.0062$$

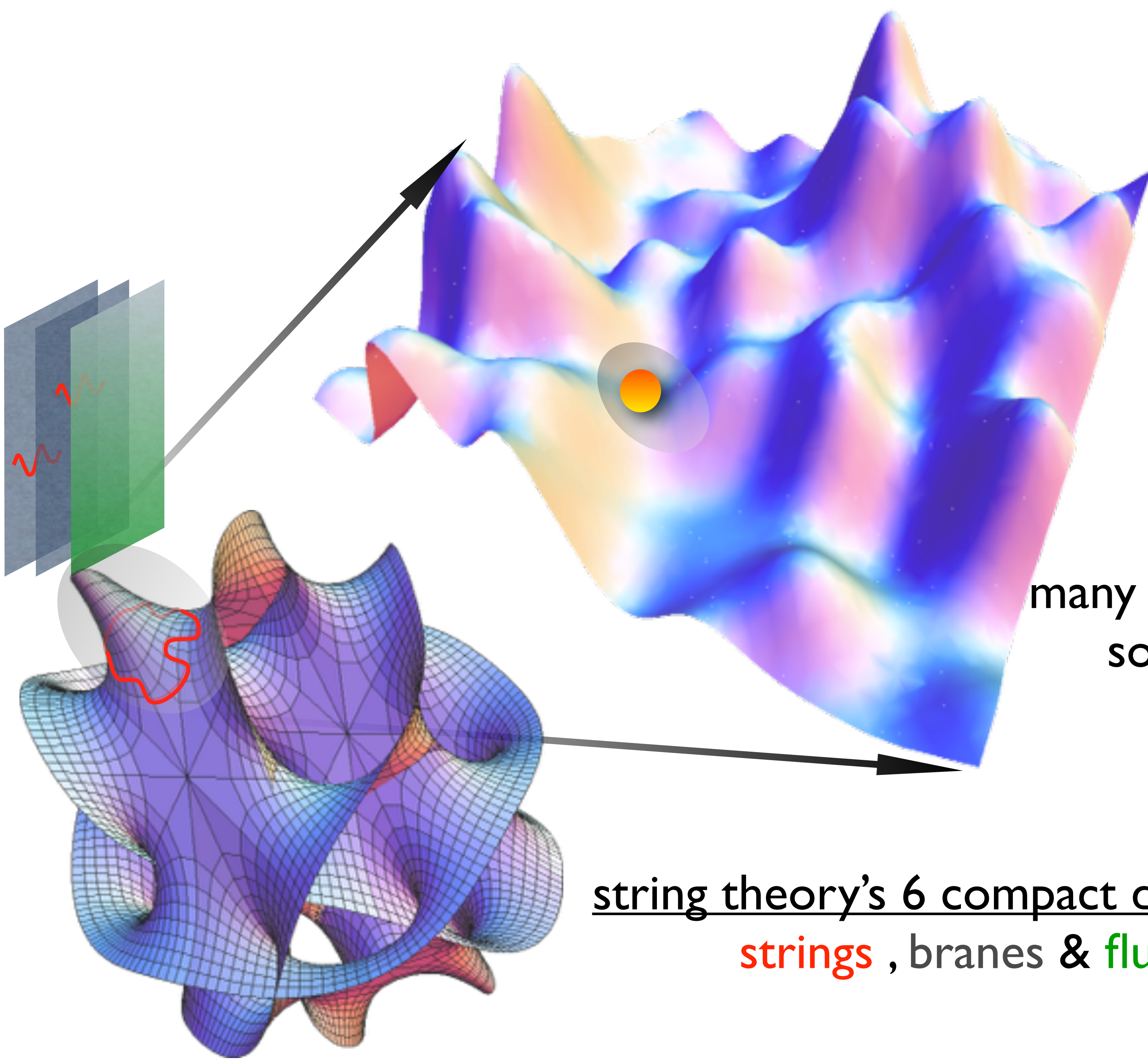
$$r = \frac{\Delta_T^2}{\Delta_S^2} = 16\,\epsilon < 0.07 \quad (95\%)$$

test string theory
with inflation & CMB



string theory's 6 compact dimensions:

strings , branes & fluxes



the string theory *landscape*:
many isolated *vacua*, connected by tunneling
some mountain slopes drive *inflation*

string theory's 6 compact dimensions:
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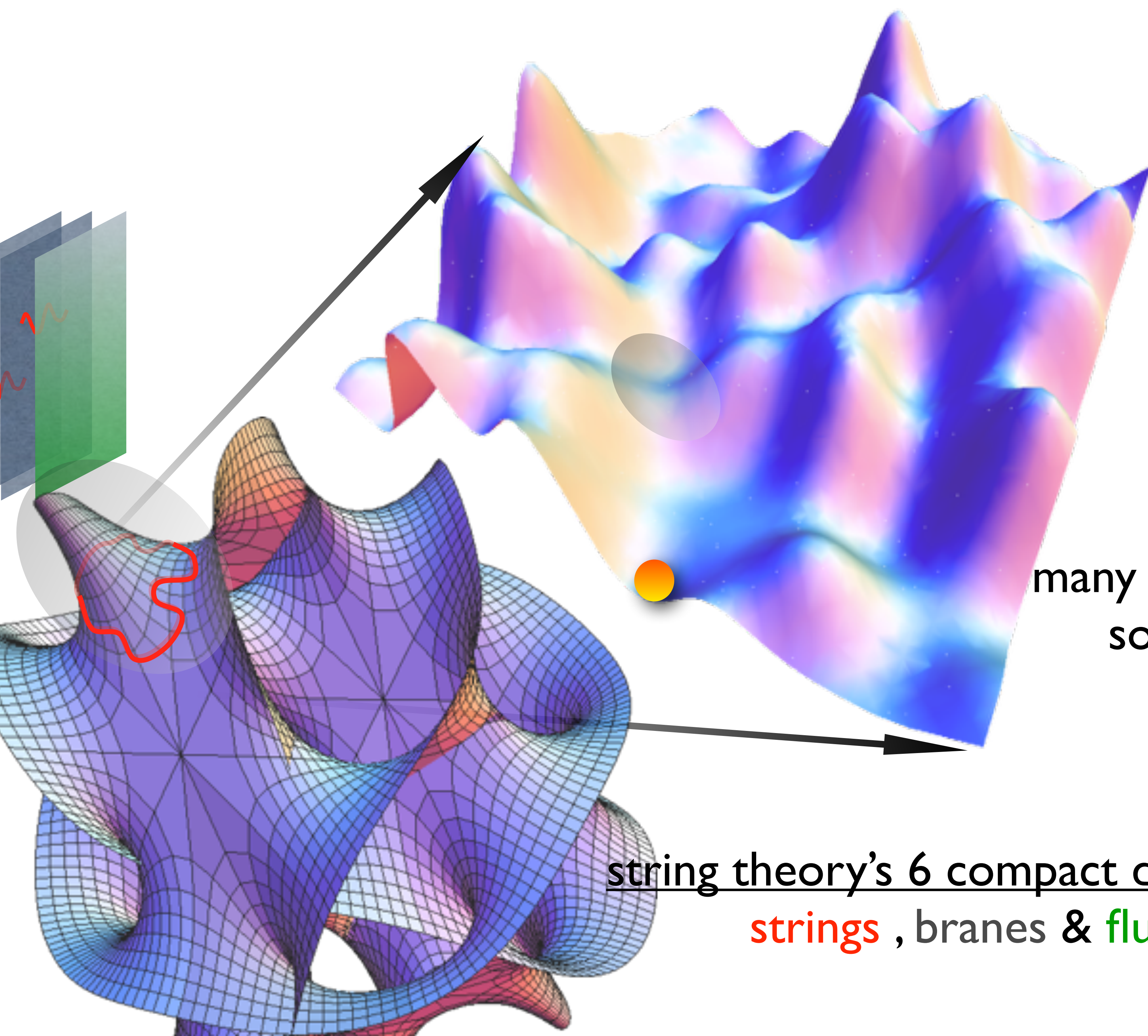

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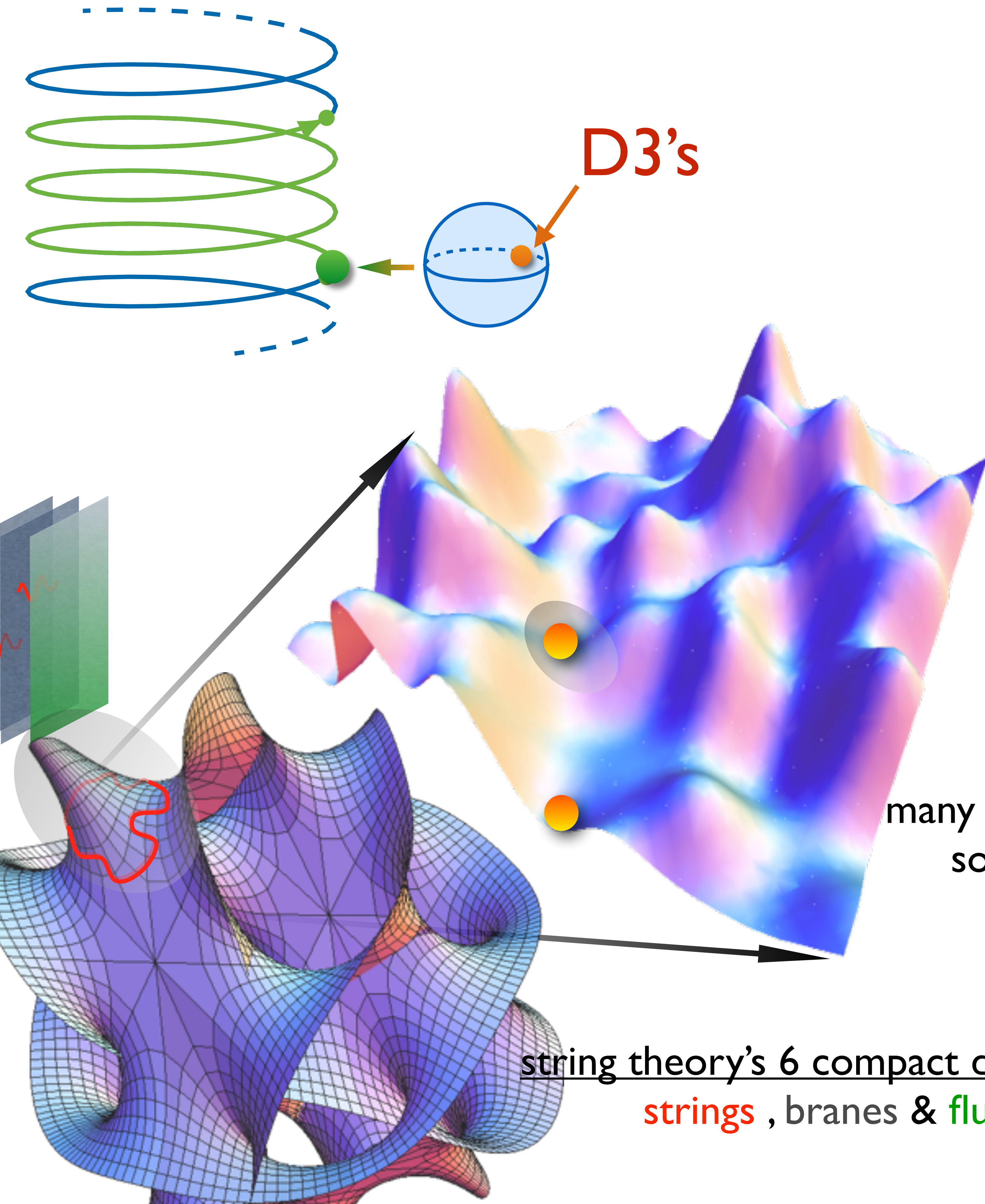

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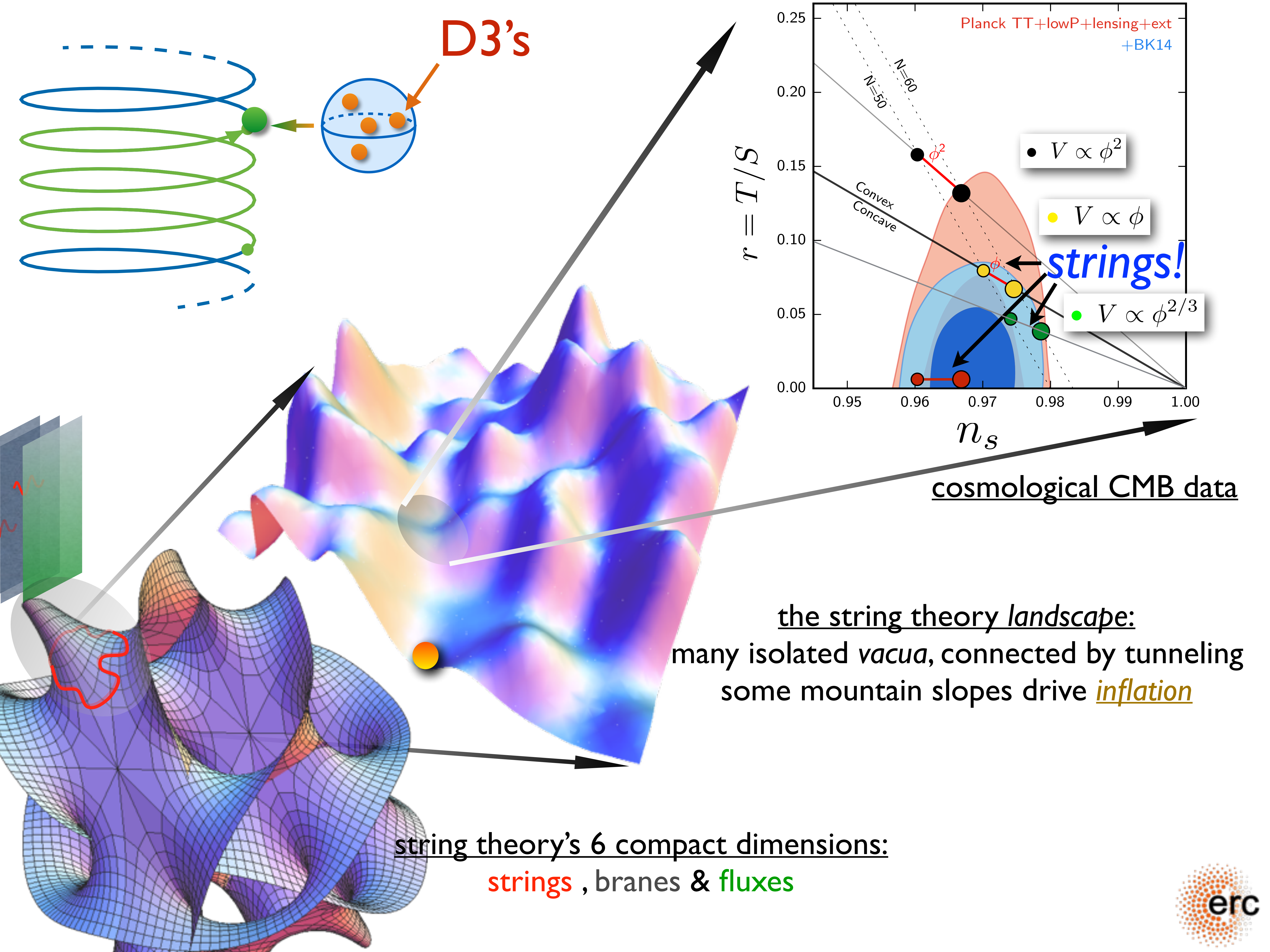

D3's
Planck TT+lowP+lensing+ext
+BK14
N=60
N=50
Convex
Concave
ϕ^2
ϕ
$V \propto \phi^2$
$V \propto \phi$
$V \propto \phi^{2/3}$
strings!
$r = T/S$
n_s
0.25
0.20
0.15
0.10
0.05
0.00
0.95
0.96
0.97
0.98
0.99
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cosmological CMB data
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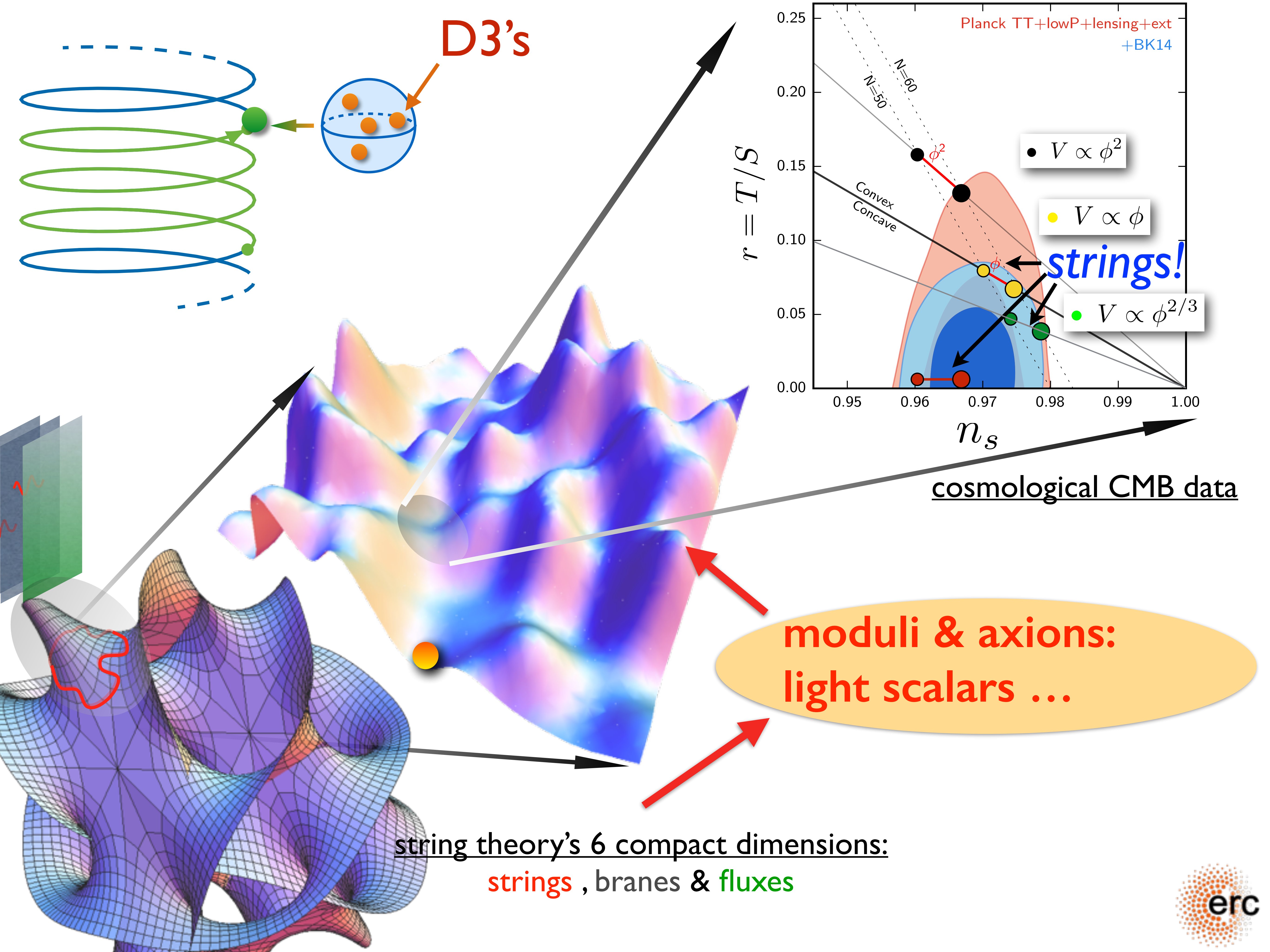
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moduli & axions:
light scalars …
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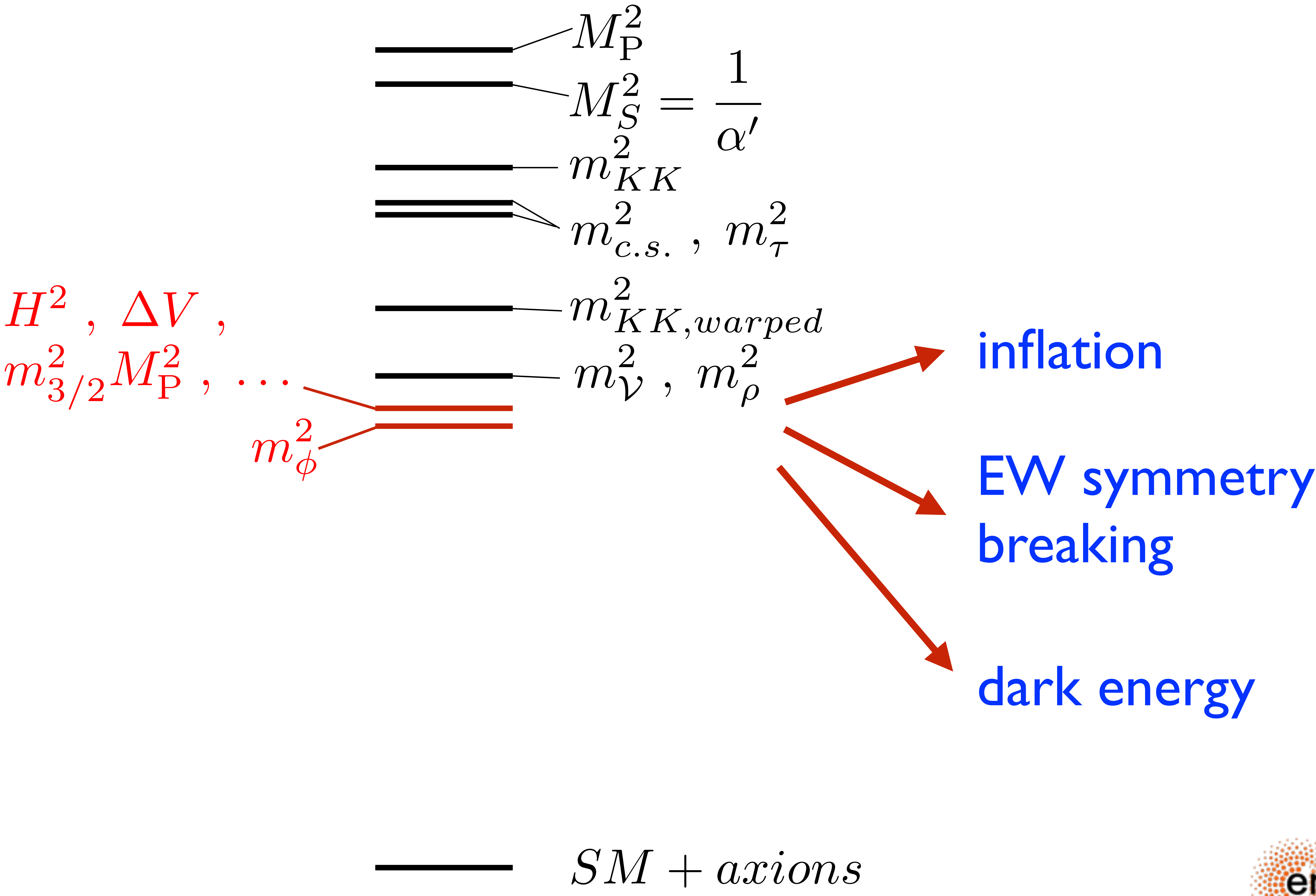


$M_{\rm P}^2$
$M_S^2 = \frac{1}{\alpha'}$
m_{KK}^2
$m_{c.s.}^2\ ,\ m_\tau^2$
$m_{KK,warped}^2$
$m_{\mathcal{V}}^2\ ,\ m_\rho^2$
$H^2\ ,\ \Delta V\ ,$
$m_{3/2}^2 M_{\rm P}^2\ ,\ \ldots$
m_ϕ^2
inflation
EW symmetry breaking
dark energy
$SM + axions$

flattened acceleration from slow-roll: inflation

[Dong, Horn, Silverstein & AW '10]

2-field system: $$V(\phi,\chi) = g\,\phi^2\chi^2 + M^2(\chi-\chi_0)^2$$

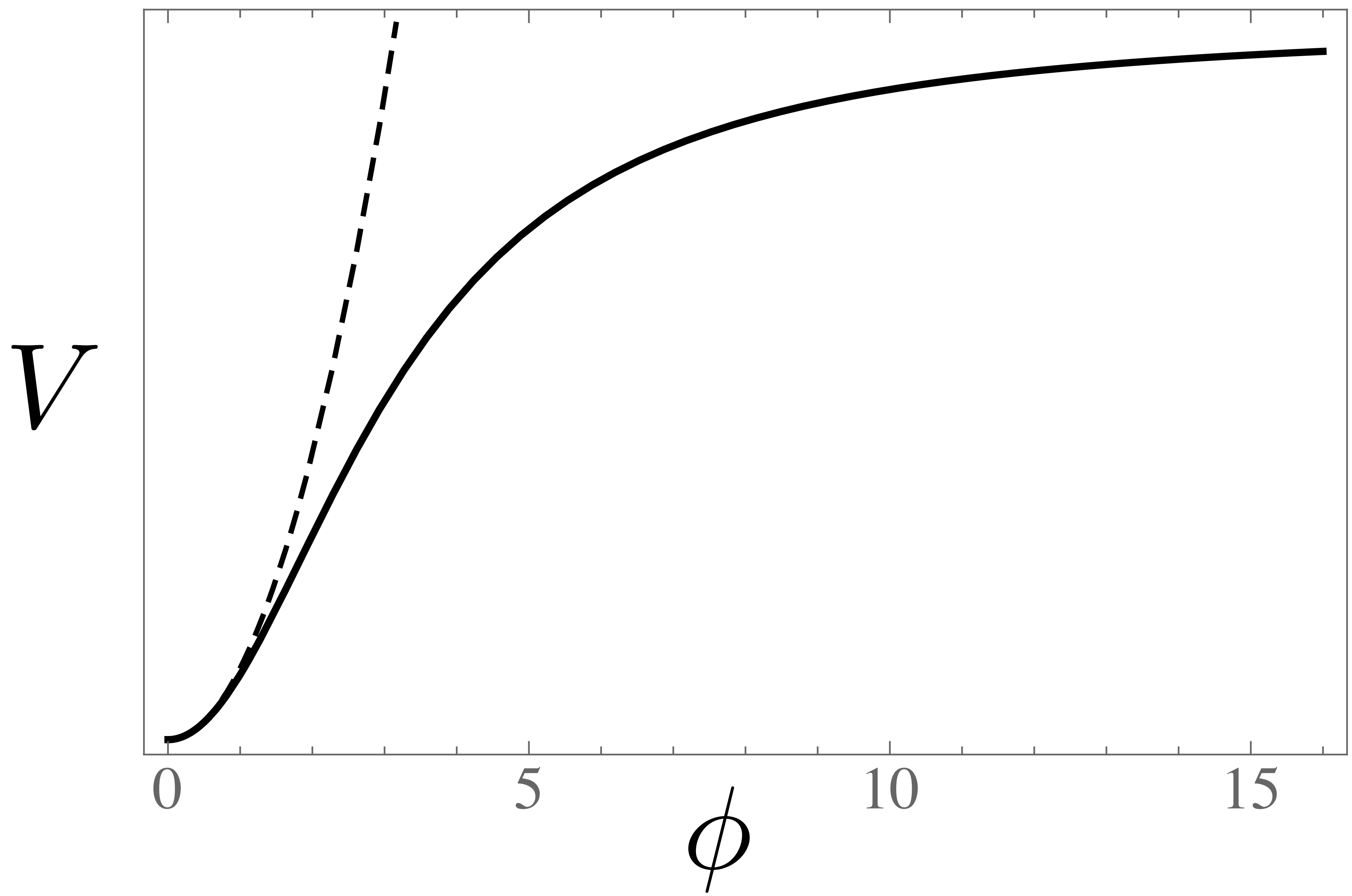
$$m_\phi^2 = g\,\chi_0^2 \sim \chi_0^2 \ll M^2 \qquad (g \lesssim 1)$$

effective potential: $$V_{eff.}(\phi) = M^2\chi_0^2\,\frac{g\,\phi^2}{M^2+g\,\phi^2}$$

$$= \frac{m_\phi^2\phi^2}{1+\frac{m_\phi^2}{M^2}\cdot\frac{\phi^2}{\chi_0^2}} \simeq \frac{m_\phi^2\phi^2}{1+\frac{\phi^2}{M^2}}$$

flattened acceleration from slow-roll: inflation

effective potential — flattened inflation !



[Dong, Horn, Silverstein & AW '10]

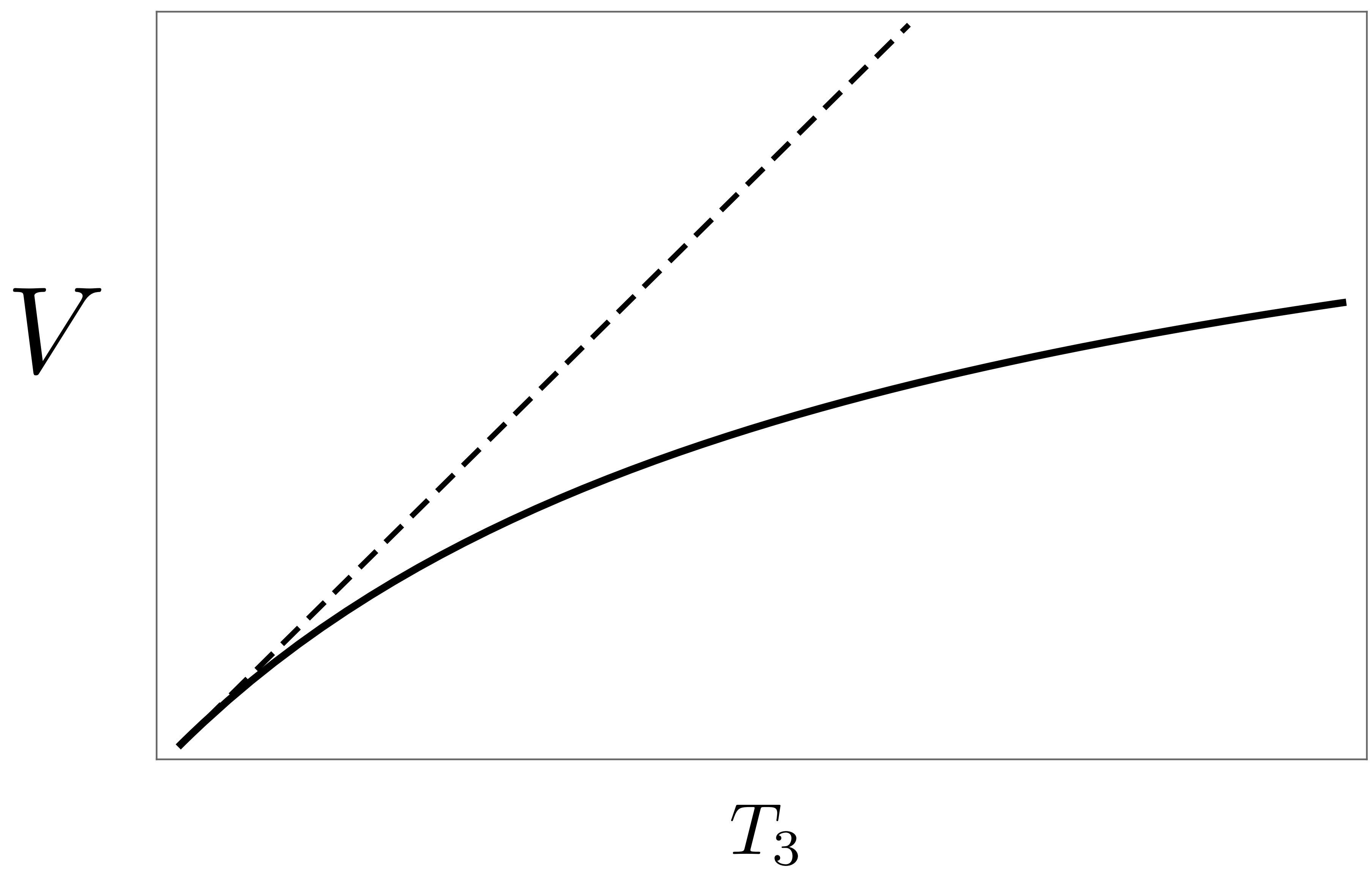
slow-roll field → parameter (e.g. anti-brane tension)

2-field system: $$\phi^2 \to T_3$$

effective potential: $$V \sim \frac{T_3}{1 + \frac{T_3}{M^2}}$$

flattened acceleration from slow-roll: inflation

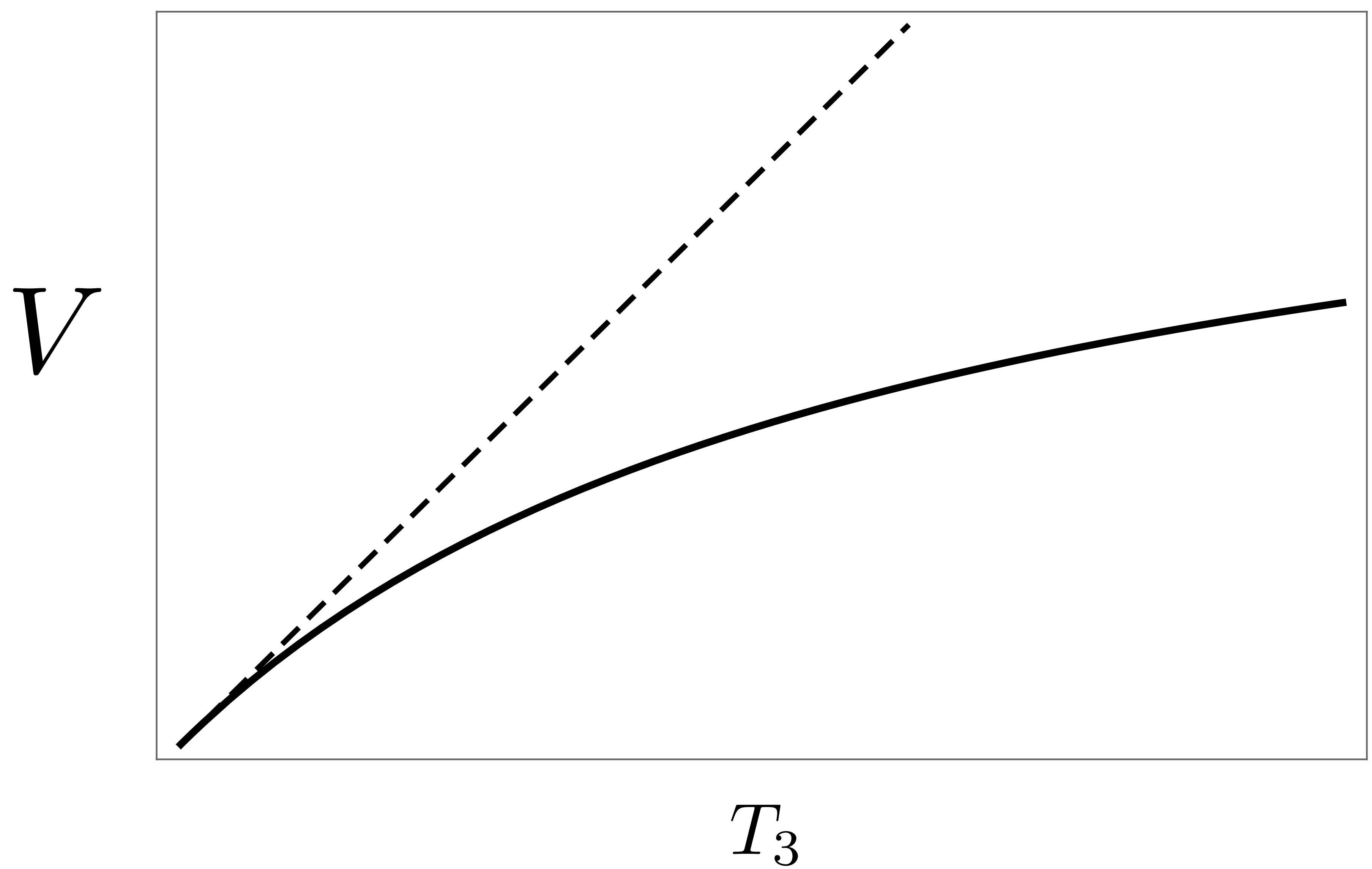
effective potential — flattened uplift ???



... ?

flattened acceleration from slow-roll: inflation

effective potential — flattened uplift ???



. . . ?

yes !

axion monodromy — a summary

[Silverstein & AW; McAllister, Silverstein & AW; Kaloper & Sorbo '08]
[Kaloper, Lawrence & Sorbo '11]

- 5D U(1) gauge symmetry — 4D Stueckelberg mech.

$$S = \int_{\mathcal{M}_4\times S^1} d^5x \left(\frac{1}{4}F^{MN}F_{MN} - |(\partial_M + iqA_M)\phi|^2 + \lambda(|\phi|^2-\rho^2)^2\right)$$

$$\phi = \langle\phi\rangle = \rho e^{iC_0}$$

$$= \int_{\mathcal{M}_4} d^4x \int_{S^1} dy \left(\frac{1}{4}B^{MN}B_{MN} - q^2\rho^2|B_M|^2\right) \quad , \quad B_M = A_M + \frac{1}{q}\partial_M C_0$$

$$A_M \to A_M + \partial_M\Lambda\ ,\ C_0 \to C_0 - q\Lambda \quad \to \quad B_M \to B_M$$

$$S = \int_{\mathcal{M}_4} d^4x \left(\frac{1}{2}(\partial_\mu b)^2 - q^2\rho^2 b^2 + \ldots\right) \quad , \quad b = \oint_{S^1} B_5$$

axion mass term

Flattening 1: moduli backreact in axion monodromy

- bare bones monodromy: $\int \mathrm{d}^{10}x \left(\frac{|dB|^2}{g_s^2} + |F_1|^2 + |F_3|^2 + \left|\tilde{F}_5\right|^2 \right)$

$$V = \frac{C_1}{\phi} + C_2\phi^2(\mu^2 + b^2) \quad \longrightarrow \quad \langle\phi\rangle = \langle\phi\rangle_0(1 + b^2/\mu^2)^{-1/3}$$

- 2 types of flattening — **additive & multiplicative:**

$$V_{eff.}(b) = V|_{\langle\phi\rangle} \sim \langle\phi\rangle_0^2 \frac{b^2}{(1 + b^2/\mu^2)^{2/3}} \sim \begin{cases} b^2 - \frac{2}{3}\frac{b^4}{\mu^2} \quad , & \mu \gg 1 \\ b^{2/3} \quad , & \mu \ll 1 \end{cases}$$

- other powers as well: ϕ, $\phi^{4/3}$, ϕ^2

[McAllister, Silverstein, AW & Wrase '14]
[Hebecker et al. '14]
[Buchmüller, Dudas, Heurtier, AW, Wieck & Winkler '15]

Flattening 2:
pole inflation/α-attractors in string theory

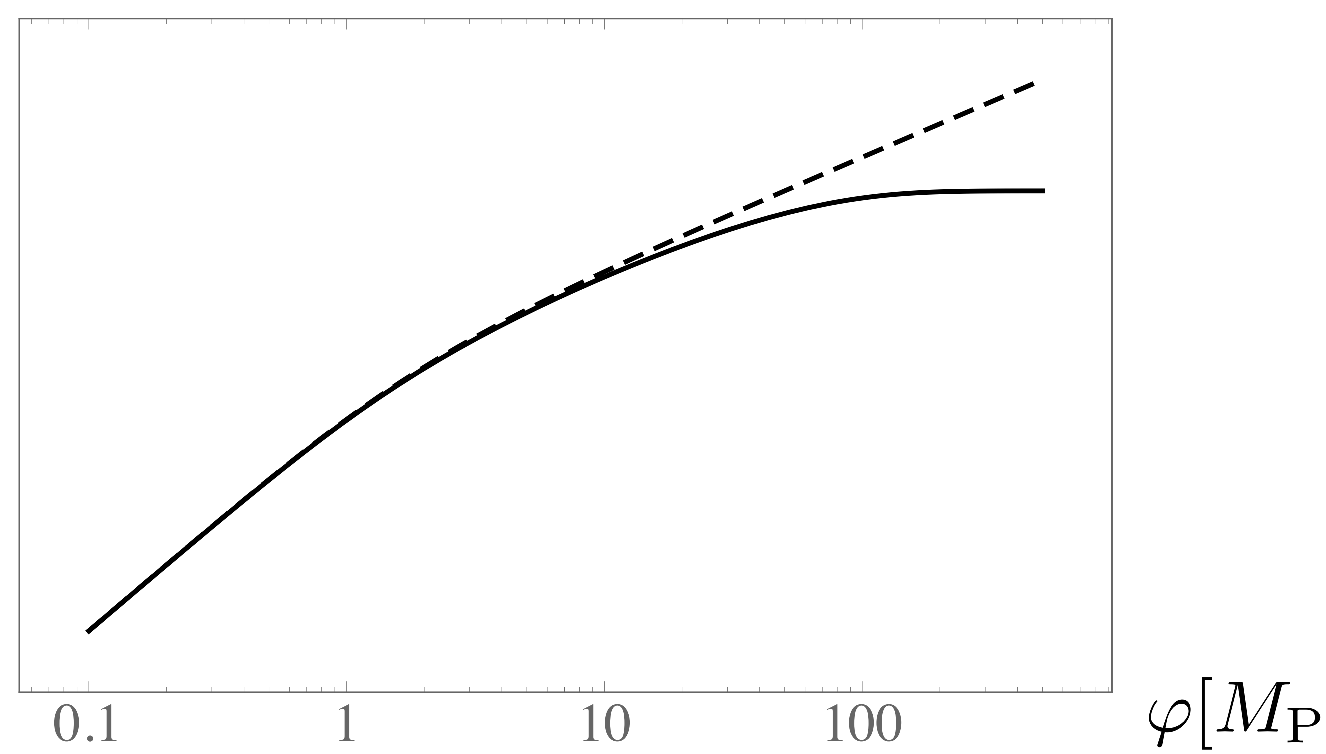
- backreaction for moduli & axions — singular kinetic terms:

$$\mathcal{L}_{kin} = \frac{1}{\phi^2}\left((\partial\phi)^2 + (\partial a)^2\right) \qquad V = V_0(\phi) - c(\phi)\,a + \ldots$$

$$\phi = \phi_0 \to \phi_0 + \epsilon\, a \quad , \quad \epsilon \ll 1$$

$$\mathcal{L}_{kin} \to \frac{1}{\epsilon^2}\frac{(\partial a)^2}{a^2}$$

$$V \to V_0 - ce^{-\epsilon\,\varphi} + \ldots$$



[Galante, Kallosh, Linde & Roest ‘14; Broy, Galante, Roest & AW ‘15]
[Palti, van Riet, Valenzuela; Marchesano, Wieck, Broy, Pedro; ’15-‘17] …

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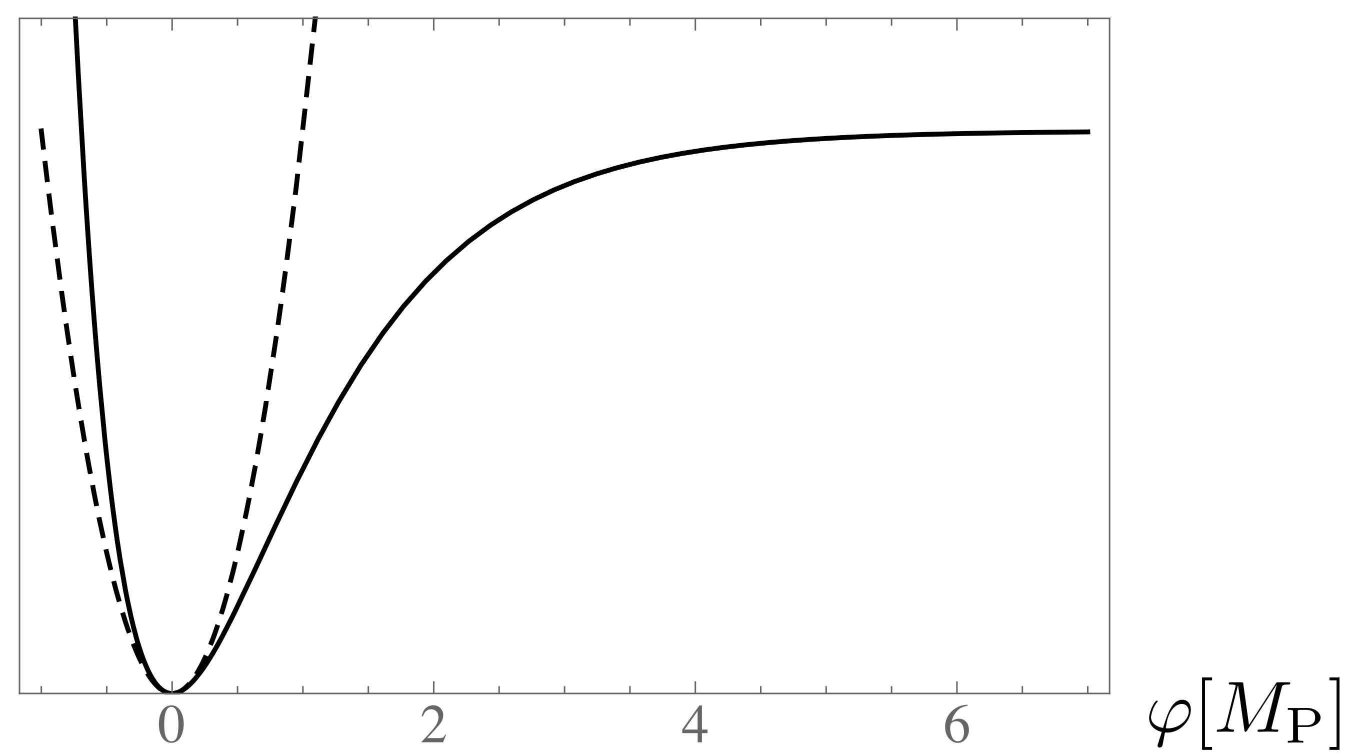

[Galante, Kallosh, Linde & Roest '14; Broy, Galante, Roest & AW '15]
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Flattening 2:
pole inflation/α-attractors in string theory

[Burgess, Cicoli & Quevedo '08; and/or de Alwis, Broy, Ciupke, Diaz, Guidetti, Muia, Pedro, Shukla, AW, Williams '14-'17]

- string realization - 'fibre inflation':

[Kallosh, Linde, Roest, AW & Yamada '17]

supergravity + extra dimensions

$$\mathcal{L}_{kin} = \frac{(\partial\phi)^2}{4\phi^2} + \frac{(\partial\chi)^2}{2\chi^2}$$

loop corrections

$$V = \left(\frac{1}{\langle\sqrt{\phi}\chi\rangle}\right)^2 \cdot \left(V_0(\phi,\chi) - \frac{c}{\chi} + \frac{\delta}{\phi^{p/2}} + \ldots\right)$$

$$\mathcal{V} = R^6 = const. \;\; \Rightarrow \phi \sim 1/\chi^2 \; , \; \chi \to e^{-\varphi/\sqrt{3}}$$

erc

Flattening 2: pole inflation/α-attractors in string theory

[Burgess, Cicoli & Quevedo ’08; and/or de Alwis, Broy, Ciupke, Diaz, Guidetti, Muia, Pedro, Shukla, AW, Williams ‘14-‘17]

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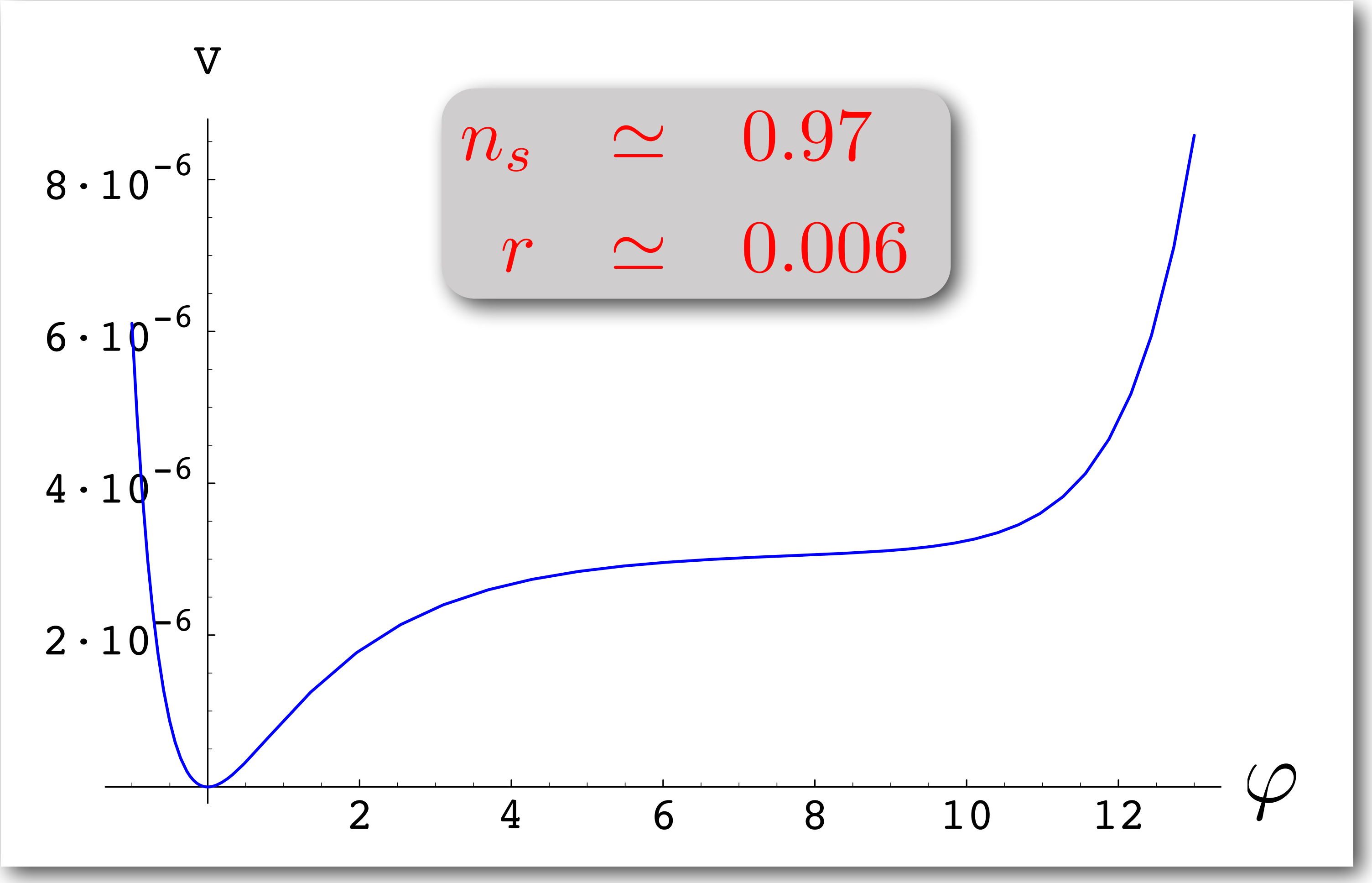
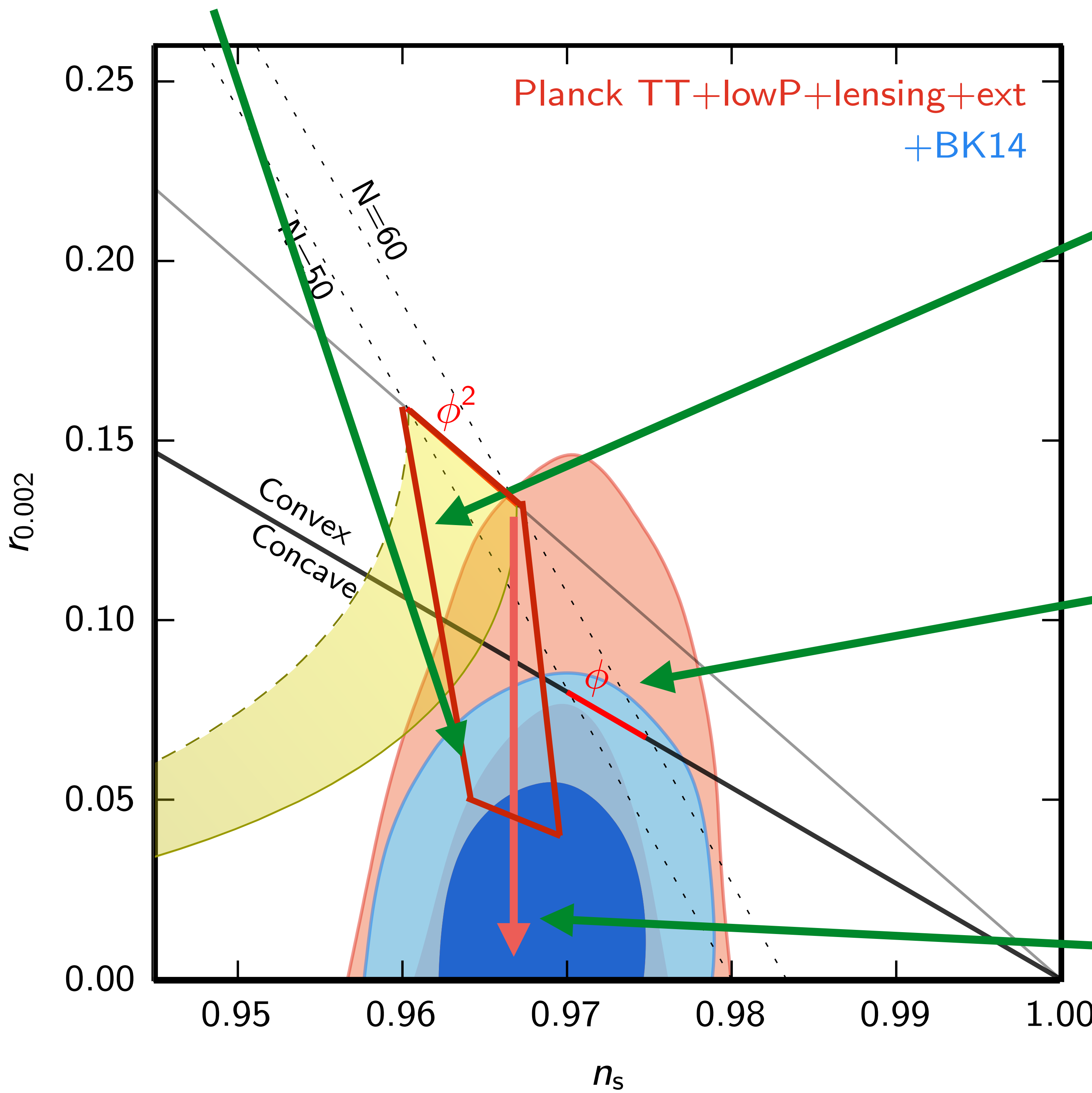


$$\rightarrow V = \frac{1}{\mathcal{V}^2}\cdot\left(V_0 - c\,e^{-\varphi/\sqrt{3}} + \delta e^{+p\varphi/\sqrt{3}} + \ldots\right)$$

phenomenology ... flattening !

n_s-r limits Planck, TT + lowP + BICEP2/Keck/Planck joint analysis 2015

'flux flattening': [Landete, Marchesano, Shiu, Zoccarato '17]



additive flattening:

$\phi^2 - \lambda\phi^4$

multiplicative flattening:

$\phi^{p - \Delta p}$

exponential flattening:

$1 - c\,\phi \longrightarrow 1 - c\,e^{-\phi}$

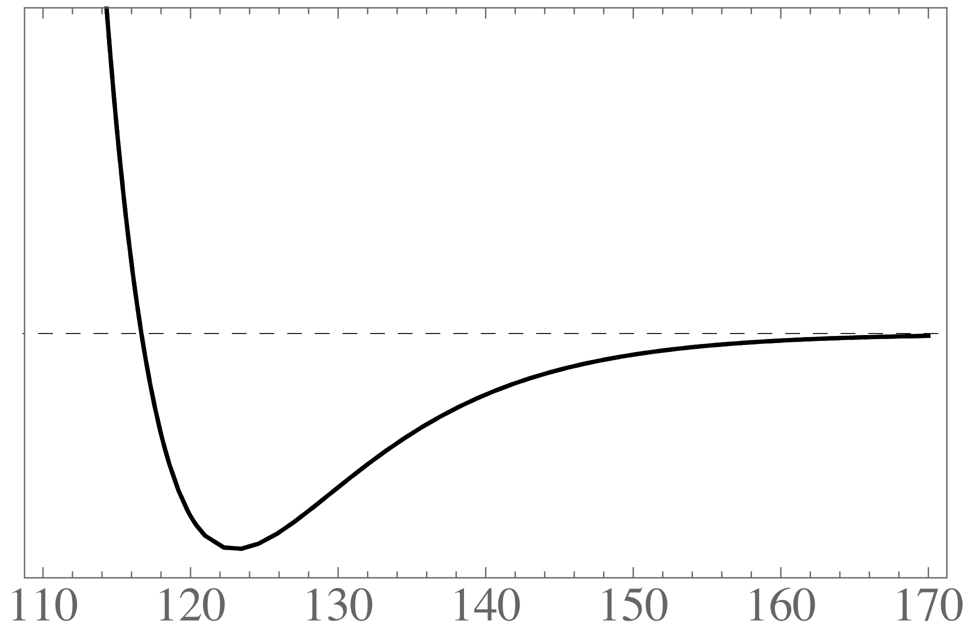
Flattening 3 - the CC : KKLT de Sitter vacua ? [KKLT '03]

KKLT - I:

$$K = -3\ln(T+\bar{T})\ ,\ W = W_0 + Pe^{-aT}$$

$$V = e^K\left(K^{T\bar{T}}|D_TW|^2 - 3|W|^2\right)$$

$$= -\frac{W_0}{\rho^2}e^{-a\rho} + \frac{1}{\rho}e^{-2a\rho}$$



Flattening 3 - the CC : KKLT de Sitter vacua ? [KKLT '03]

KKLT - 1:

$$K = -3\ln(T+\bar{T})\;,\;W = W_0 + Pe^{-aT}$$

$$V = e^K(K^{T\bar{T}}|D_T W|^2 - 3|W|^2)$$

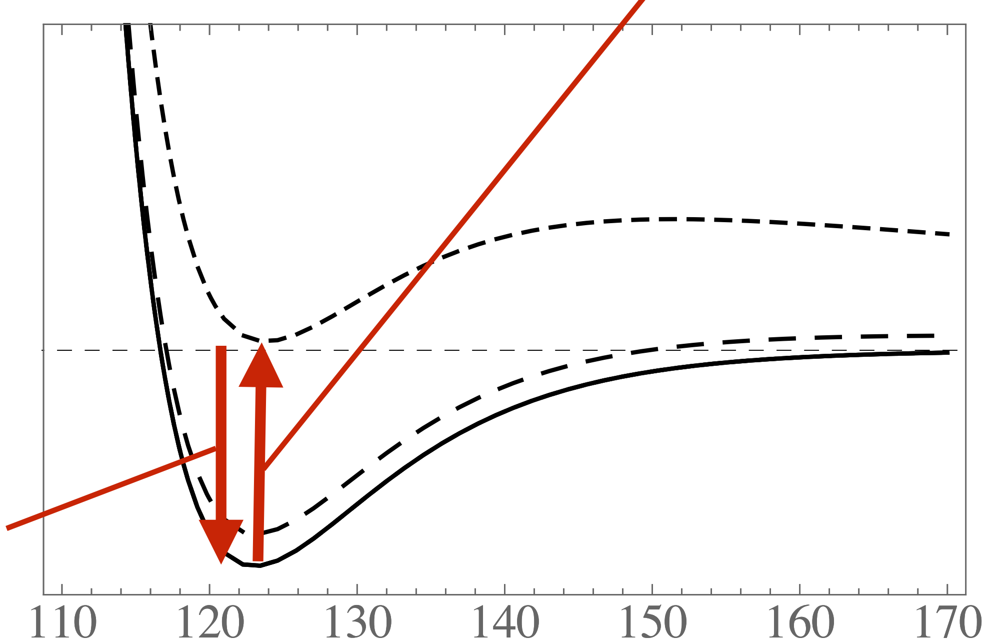
$$= -\frac{W_0}{\rho^2}e^{-a\rho} + \frac{1}{\rho}e^{-2a\rho}$$

KKLT - 2:

$$V \to V + \delta V \quad , \quad \delta V = \frac{\epsilon\, T_3}{\rho^2}$$

$\overline{D3} - brane$
[KPV '01]

$V_{AdS} \sim -m_\rho^2 M_\mathrm{P}^2$



Flattening 3 - the CC : KKLT de Sitter vacua ?

[Moritz, Retolaza & AW '17]

uplift: $\epsilon \ll 1$

usually: warping …

$\epsilon \sim e^{4A} = const. \ll 1$

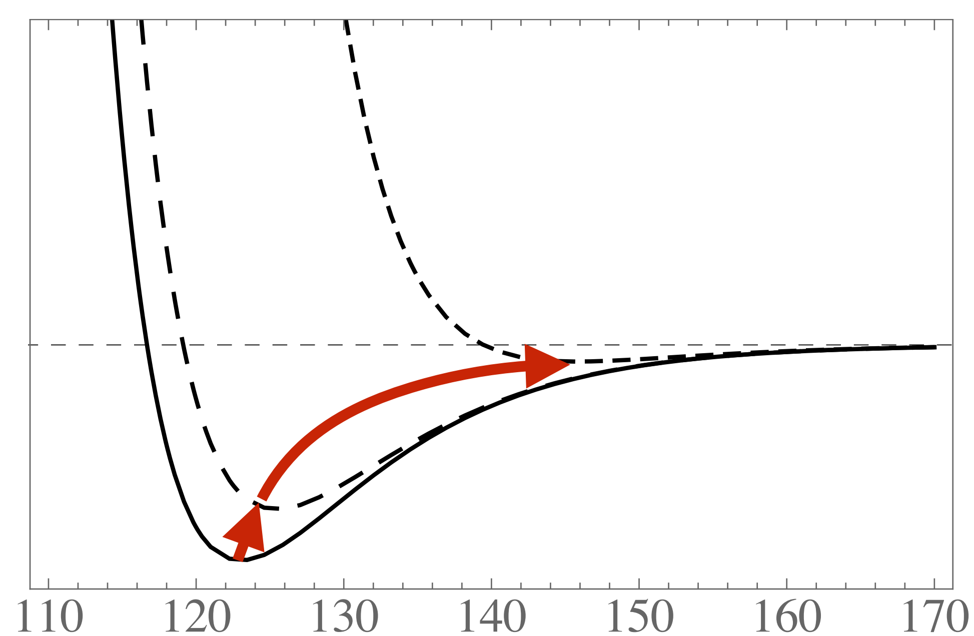
but: why not … ?

$\epsilon \sim e^{-2a\rho}$

flattened uplift !!

once:

$\delta V \gtrsim |V_{AdS}| \sim m_\rho^2 M_{\rm P}^2$



$V < 0$!!

Flattening 3 - the CC : KKLT de Sitter vacua ?

[Volkov & Akulov ’73; subsets of: Aalsma, Antoniadis, Bandos, Bergshoff, Dudas, Ferrara, Dasgupta, Garcia del Moral, Heller, Kallosh, Kuzenko, Linde, Martucci, McDonough, Parameswaran, van Proeyen, Quevedo, Quiroz, Roest, Scalisi, van der Schaar, Sorokin, Uranga, Vercnocke, Wrase, Yamada, Zavala ‘14-‘17; …]

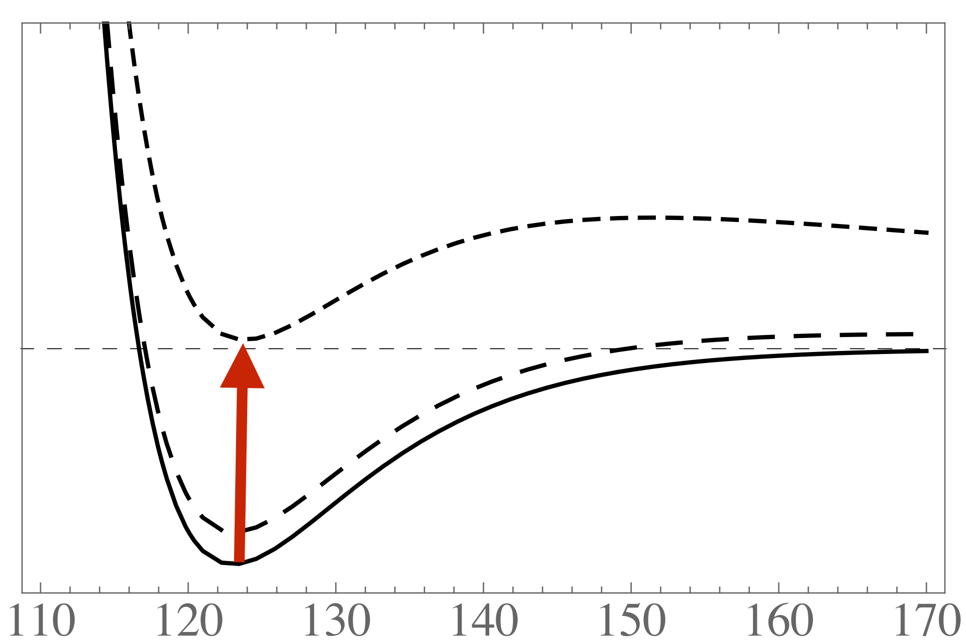
- nilpotent superfield S parametrizes the nonlinear anti-D3-SUSY:

$$K = -3\ln(T + \bar{T} - S\bar{S})$$

$$W = W_0 + Pe^{-aT} + B\,S$$

$$B = e^{2A}\sqrt{T_3}\ ,\quad e^{2A} \sim \sqrt{\epsilon} \sim e^{-a\rho}$$

$$\delta V_F \sim e^{4A}\frac{T_3}{\rho^2}$$



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$$K = -3\ln(T + \bar{T} - S\bar{S})$$

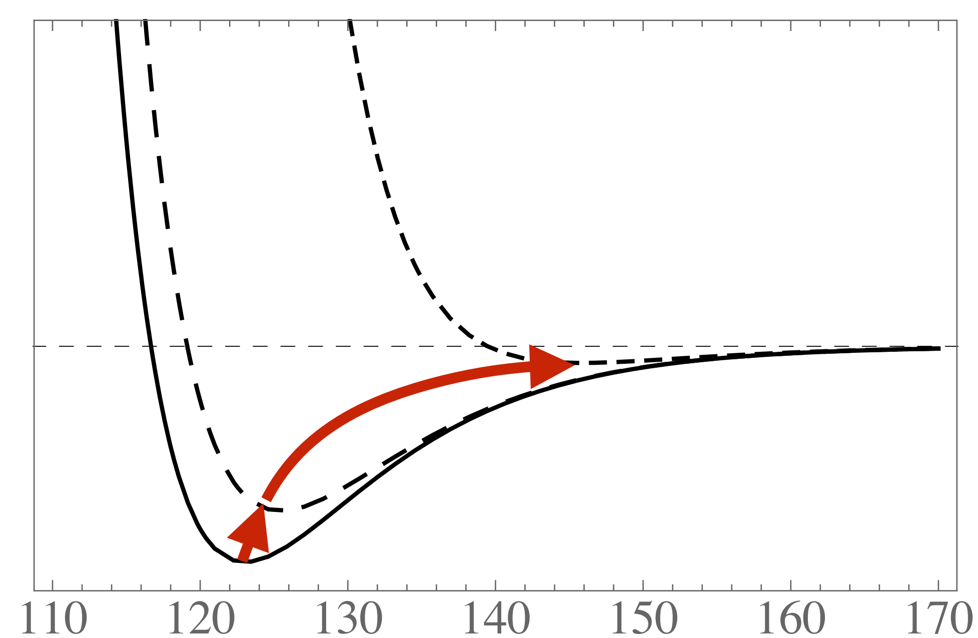
[Moritz, Retolaza & AW '17]

$$W = W_0 + (P + C\,S)e^{-aT} + B\,S$$

$$B = 0 \;\;,\;\; C = \mathcal{O}(1)\sqrt{T_3}$$

$$\Downarrow$$

$$\delta V_F \sim e^{-2a\rho}\frac{T_3}{\rho^2}$$



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[Moritz, Retolaza & AW '17]

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?? ??

Determine by matching to 10D description …

Flattening 3 - the CC : KKLT de Sitter vacua ?

[Heidenreich, McAllister & Torroba; Dymarsky & Martucci '10]
[Moritz, Retolaza & AW '17]

- need 10D analysis to fix sign of 4D CC:

  - dim. reduction of 7-brane flux-condensate coupling

  - use flux e.o.m to find flux profiles encoding presence of condensate

  - Use 10D Einstein & Bianchi eq.s to determine sign of 4D curvature — **assuming** backreacted solution with anti-D3 brane **exists** !!

$$\tilde{\nabla}^2\Phi^- = \tilde{R}_{4D} + e^{-6A}|\partial\Phi^-|^2 + e^{2A}\frac{\Delta^{flux+loc}}{2\pi}$$

erc

Flattening 3 - the CC : KKLT de Sitter vacua ?

[Moritz, Retolaza & AW '17]

- extracting gaugino bilinear from D7-action
  & insert in flux e.o.m.:

$$\frac{e^{2A}}{2\pi}\Delta^{D7} = \int \frac{d^6y\sqrt{g}}{8\pi^3\mathcal{V}_w\tilde{\mathcal{V}}_w}\left(4\left|\sum_{a=1}^{n}\frac{\langle\lambda\lambda\rangle_a}{16\pi^2}\nabla_i\nabla_j\Psi_a\right|^2 - 3\sum_{a=1}^{n}\left|\frac{\langle\lambda\lambda\rangle_a}{16\pi^2}\nabla_i\nabla_j\Psi_a\right|^2\right)$$

$$> 0 \quad \text{for} \quad n = 1 \quad !$$

Flattening 3 - the CC : KKLT de Sitter vacua ?

[Moritz, Retolaza & AW '17]

- this fixes sign of 4D CC:

$$\overline{D3}\text{-brane:}\;\; \Delta^{loc} > 0 \qquad\qquad \Rightarrow \quad \langle V \rangle \sim \int_{CY} \tilde{R}_4 < 0 \;\; !!$$

$$D7\text{-brane:}\;\; \Delta^{D7} > 0$$

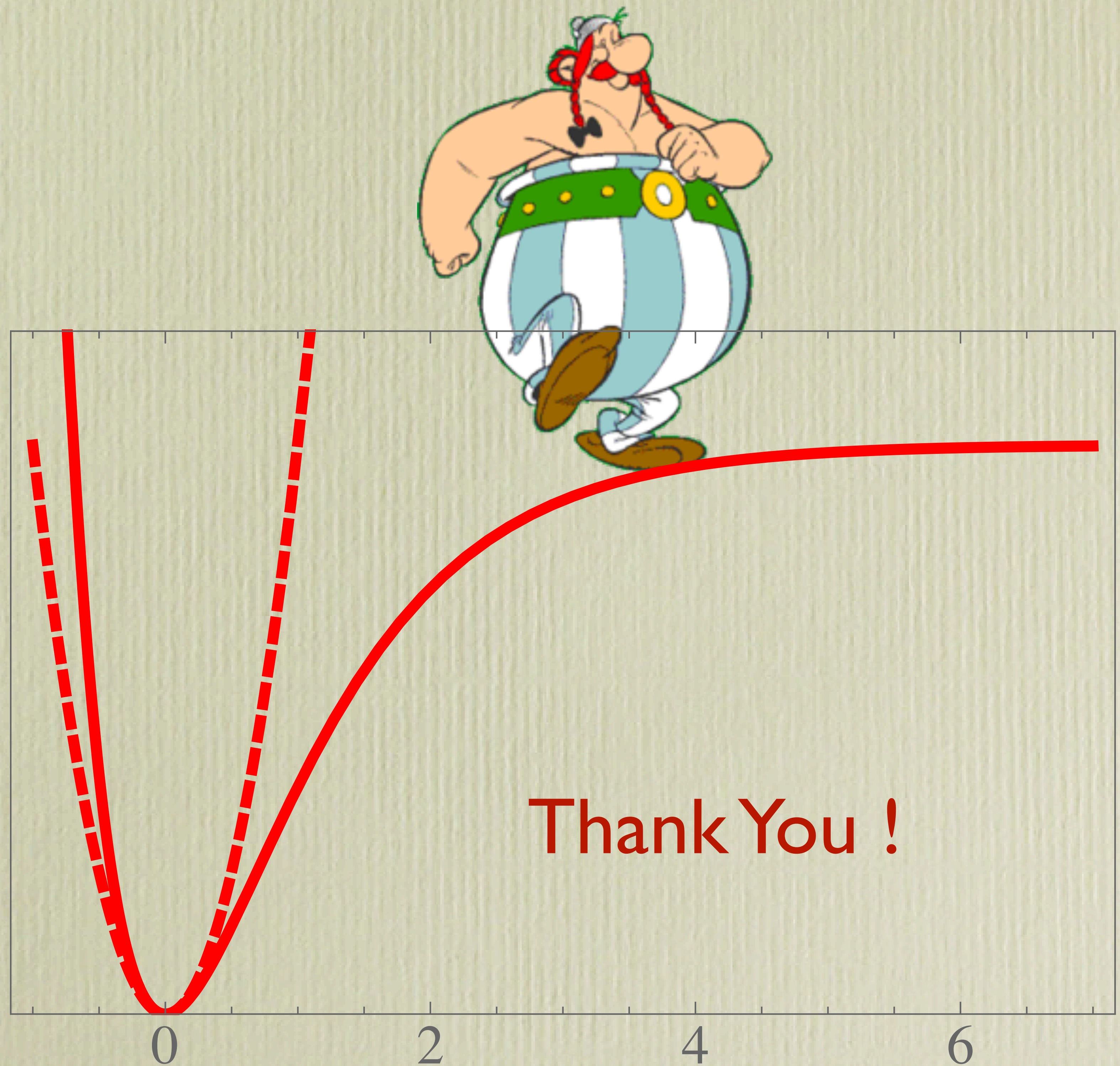
- 10D input necessary to fix 4D EFT of KKLT — otherwise neglect of coupling:

$$\mathcal{O}(1)\,\sqrt{T3}\,e^{-a\rho}$$

- simplest KKLT — ρ & 1 gaugino condensate — does not give dS !

- need racetrack: <u>**two**</u> $e^{-a\rho}$ - terms — can give dS !

all forms of positive vacuum energy in string theory
flatten below linearly adding up sources !



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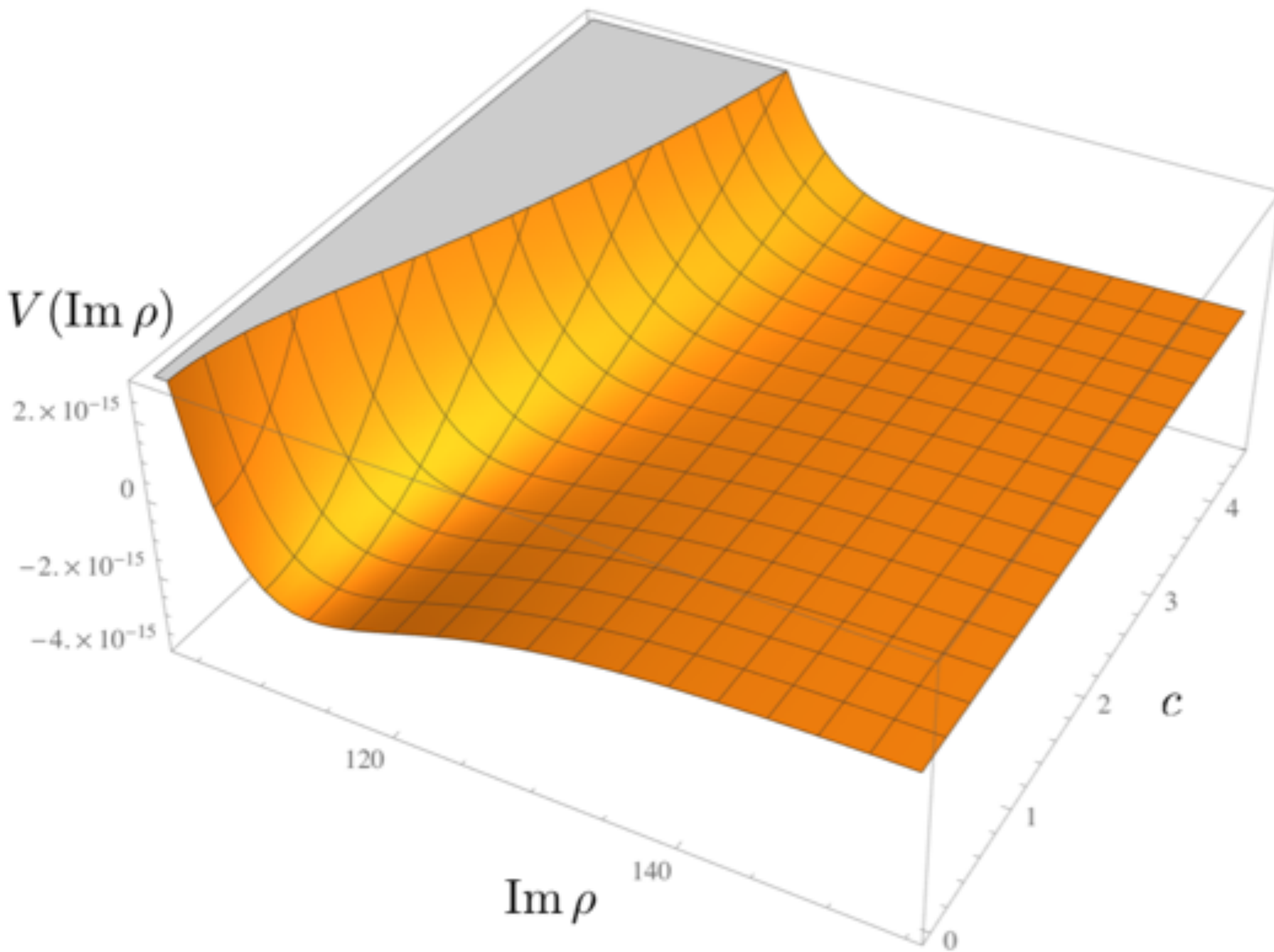

- single condensate

- racetrack