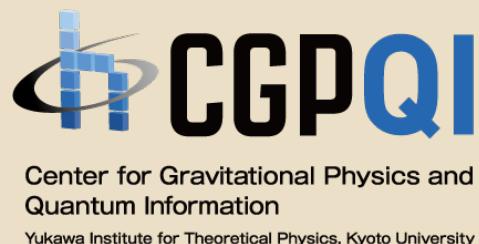


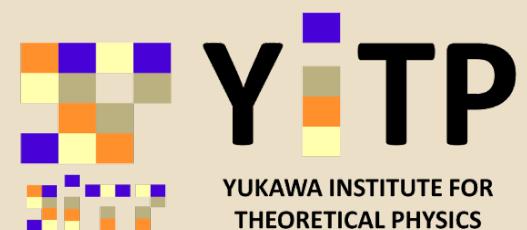


June 28,  
2022

# Hybrid inflation and waterfall field in string theory from D7-branes



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(YITP, Kyoto University)



Based on 2007.10362, 2109.03243

In collaboration with: Ignatios Antoniadis (LPTHE, Paris)  
George K. Leontaris (University of Ioannina)

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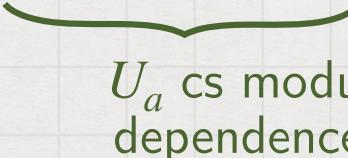
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*Becker, Becker, Haack, Louis '02*

*Conlon, Pedro '10 Grimm, Savelli, Weissenbacher '13*

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*Antoniadis, Chen, Leontaris '18, '19*

*Burgess, Quevedo '22 Gao, Hebecker, Schreyer, Venken '22*

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$$q \equiv \frac{\xi}{2\gamma}, \quad C \equiv -3\mathcal{W}_0^2 \gamma > 0 \quad \sigma \equiv \frac{2(d_1 d_2 d_3)^{1/3}}{9\mathcal{W}_0^2 \gamma} \equiv -\exp\left(q - \frac{16}{3} - x\right)$$

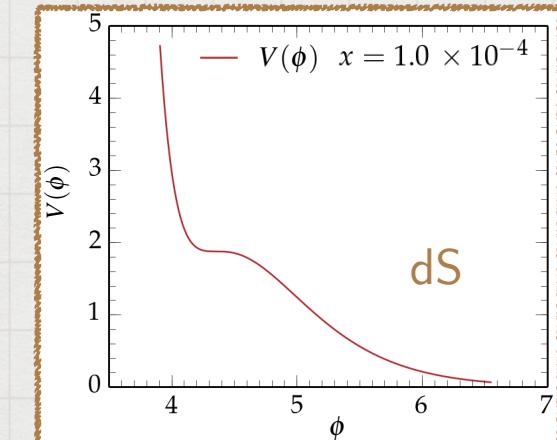
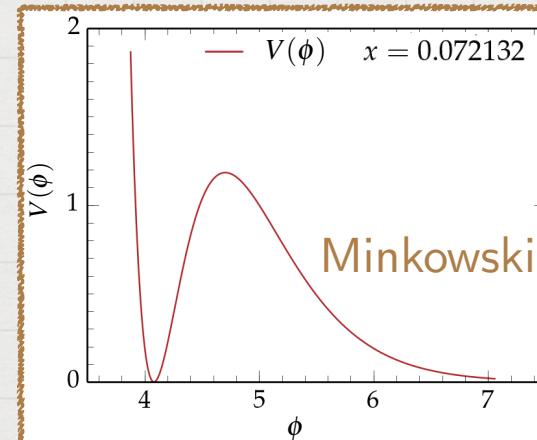
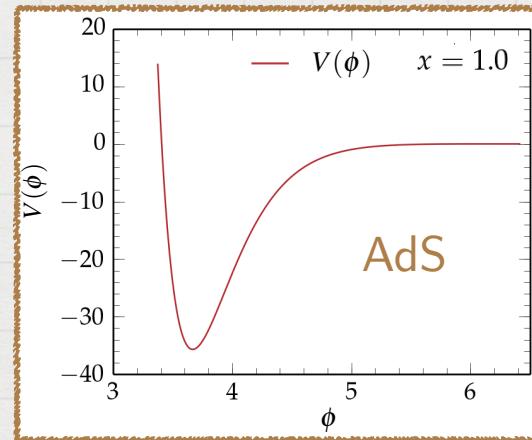
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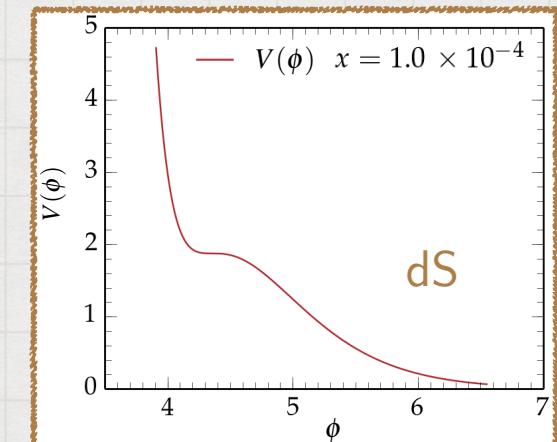
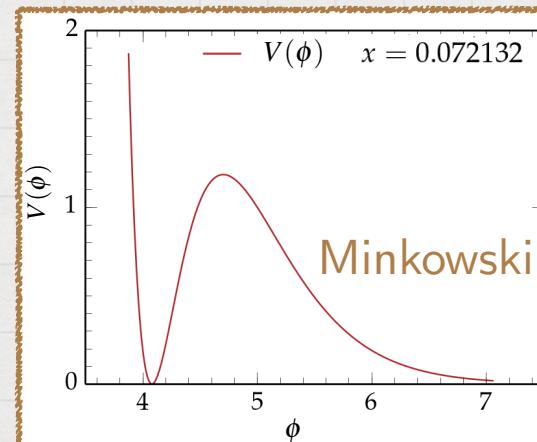
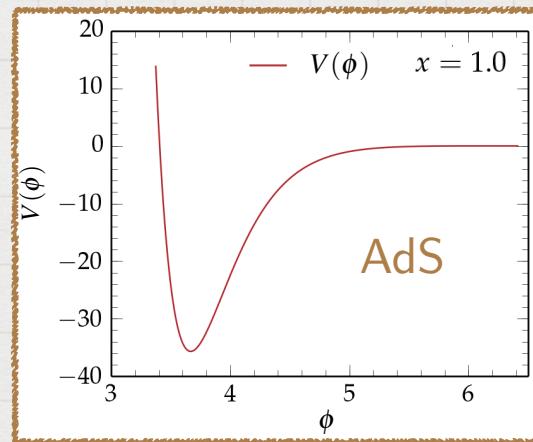
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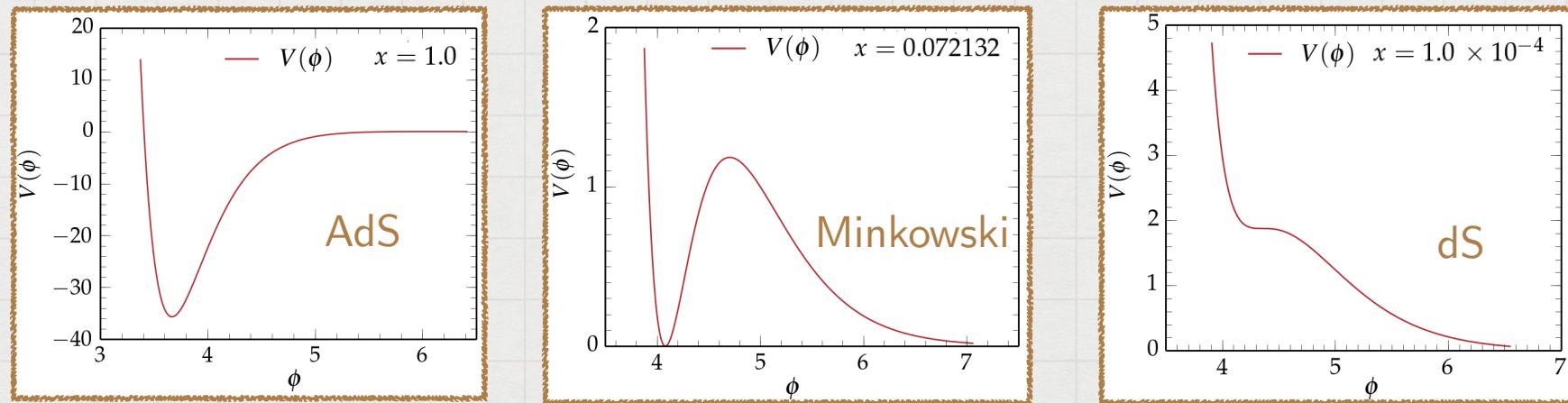
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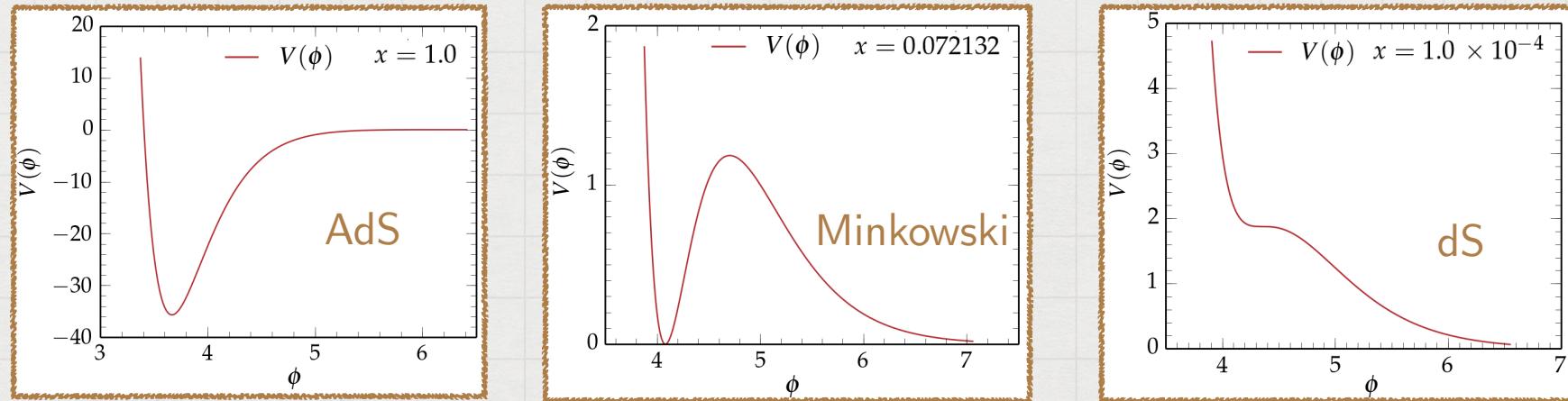
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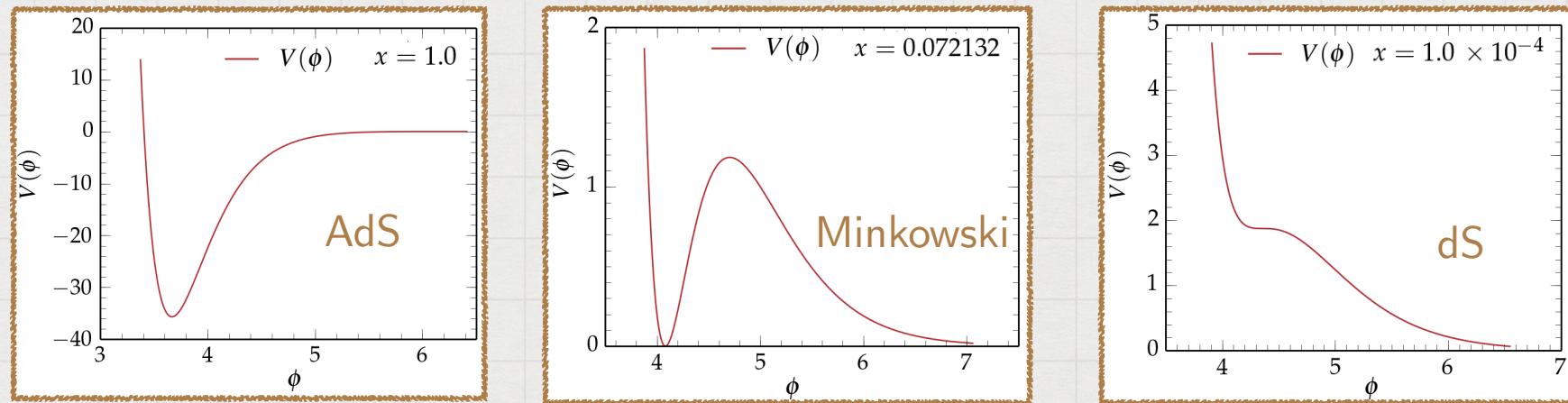
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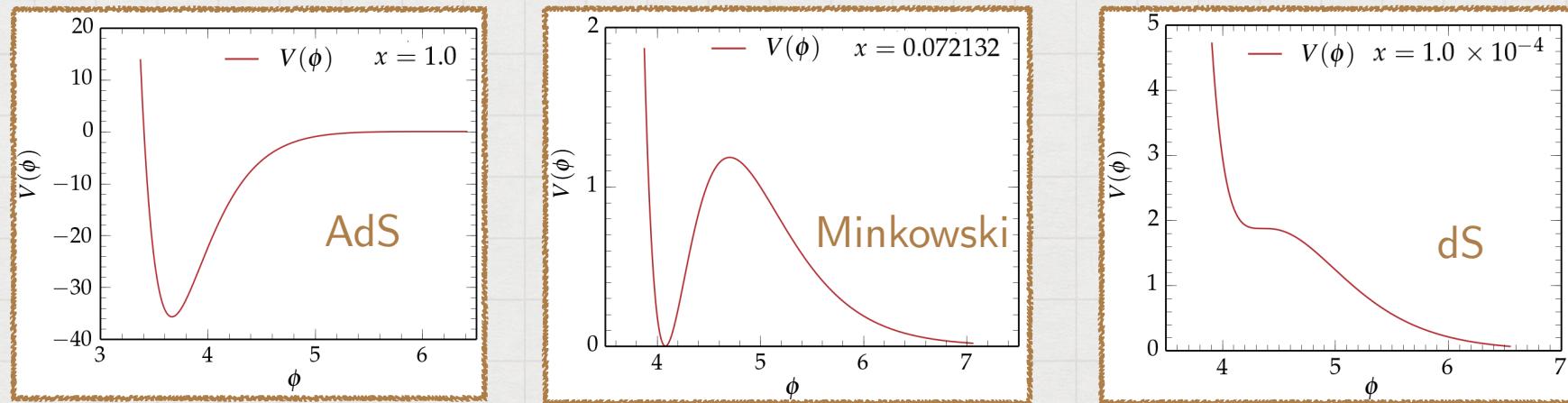
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- Shape of the minimum (very shallow). How does inflation end ?

# Outline of the talk

1. Introduction
2. Inflationary scenario from moduli stabilization
3. Hybrid inflation and waterfall fields
4. A concrete (toy) model
5. Summary & Outlook

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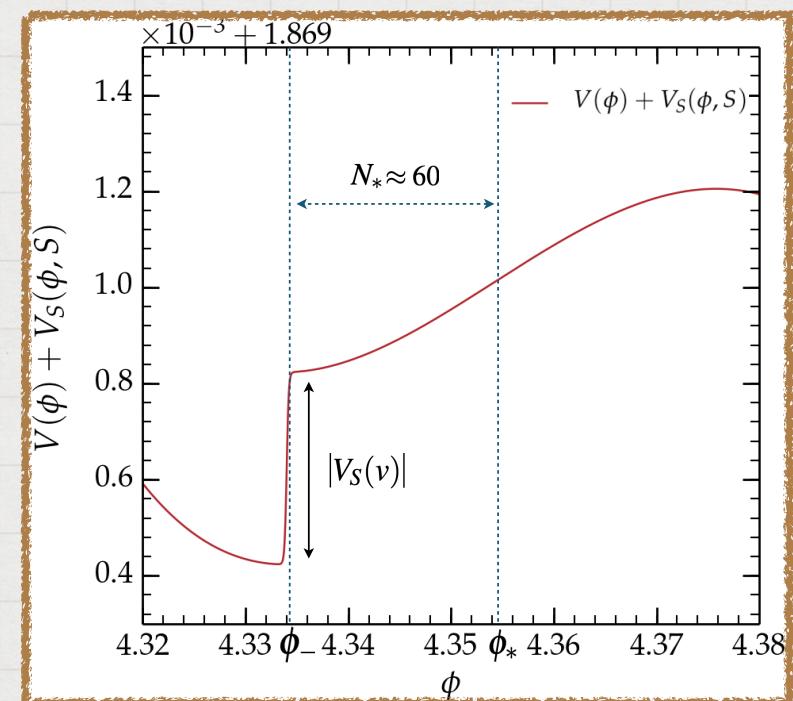
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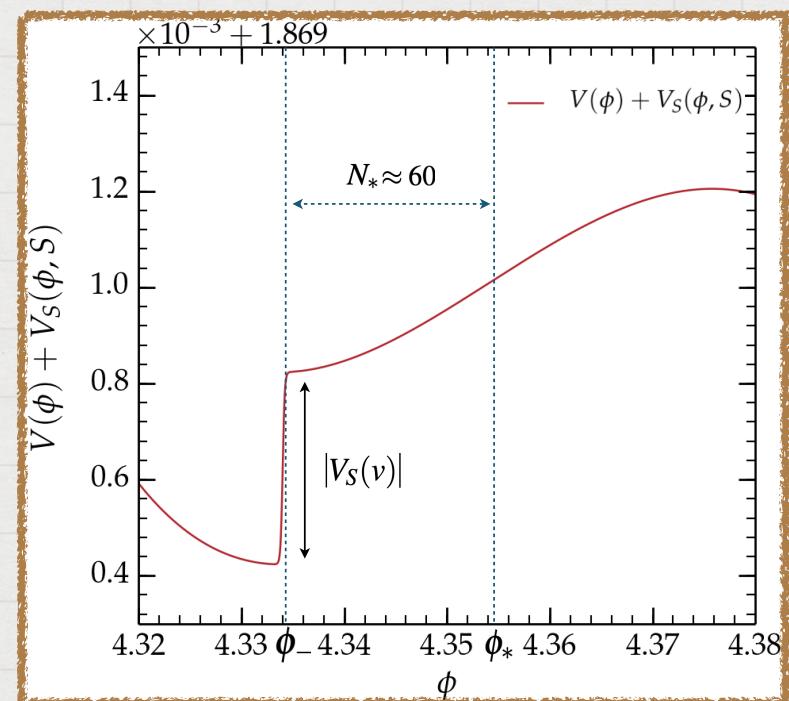
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*steep*: ends inflation,

*large*: lowers the global minimum



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magnetic field (2-torus):  $A_n^a = \frac{1}{2} H_{nm}^a X^m$  w.s. term induces modified b.c.

$$(\partial_\sigma X^m + 2\pi\alpha' H_{mn} X^n) \Big|_{\sigma=0}^{\sigma=\pi} = 0 \quad \rightarrow T\text{-dual to brane at angles } \theta^b, \text{ same b.c.}$$

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mass of charged state  $2\alpha' M^2 = (2n_{45} + 1) \left| \zeta_L^{(i)} + \zeta_R^{(i)} \right| + 2\Sigma_{45} \left( \zeta_L^{(i)} + \zeta_R^{(i)} \right)$

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mass of charged state  $2\alpha' M^2 = \underbrace{(2n_{45} + 1)}_{\text{Landau levels}} \left| \zeta_L^{(i)} + \zeta_R^{(i)} \right| + \underbrace{2\Sigma_{45}}_{\text{internal helicity}} \left( \zeta_L^{(i)} + \zeta_R^{(i)} \right)$

# SUSY breaking with magnetic fluxes

- Modified b.c.  $\implies$  modified oscillator solutions, oscillator shift:

e.g.  $T^2$  on (45)  $\zeta_a = \frac{1}{\pi} \text{Arctan}(2\pi\alpha' q_a H_{(45)}^a) = \frac{1}{\pi} \text{Arctan} \left( \frac{q_a \alpha' k^{(45)}}{\mathcal{A}_{45}} \right) \approx \frac{q_a \alpha' k^{(45)}}{\pi \mathcal{A}_{45}}$

internal area dependence!

- Flux quantized:  $m \int_{T^2} H = 2\pi n \rightarrow 2\pi H_{(45)}^a \mathcal{A}_{45} = k_a^{(45)} \quad k_a^{(45)} = \frac{n_a^{(45)}}{m_a^{(45)}} \in \mathbb{Q}$ ,

- Extract spectrum: partition function or field theory

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$\rightarrow$  masses depends on spin: SUSY is broken

# Waterfall field in string theory (2)

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- Open strings between two D-branes

*separated in (67)  $\Delta x_{ab}$ , magnetized on (45)  $k_{ab}^{(45)}$*

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- Mass depending on internal volume  $\mathcal{V}$ , i.e. inflaton  $\phi$ , as required for waterfall field
- Explicit construction with ingredients required for moduli stab. + waterfall field ?

# Outline of the talk

1. Introduction
2. Inflationary scenario from moduli stabilization
3. Hybrid inflation and waterfall fields
4. A concrete (toy) model
5. Summary & Outlook

# Toy model in toroidal orbifold

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*3 magnetized D7-brane with orthogonal co-volumes*
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- Brane configuration:

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D7 <sub>1</sub>	•	⊗	×
D7 <sub>2</sub>	×	•	⊗
D7 <sub>3</sub>	⊗	×	•

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- × worldvolume spanning this plane
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→ magnetic field on each D7 necessary to have 3  $d_i \neq 0$  coefficients

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$D7_1$	$\alpha' m^2 = -2 \zeta_1^{(2)} $	$\alpha' m^2 =  \zeta_2^{(3)}  -  \zeta_1^{(2)} $	$\alpha' m^2 =  \zeta_1^{(2)}  -  \zeta_3^{(1)} $
$D7_2$		$\alpha' m^2 = -2 \zeta_2^{(3)} $	$\alpha' m^2 =  \zeta_3^{(1)}  -  \zeta_2^{(3)} $
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recall  $\zeta_a = \frac{1}{\pi} \text{Arctan}(2\pi\alpha' q_a H_{(45)}^a) = \frac{1}{\pi} \text{Arctan} \left( \frac{q_a \alpha' k^{(45)}}{\mathcal{A}_{45}} \right) \approx \frac{q_a \alpha' k^{(45)}}{\pi \mathcal{A}_{45}}$

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$D7_2$		$\alpha'm^2 = -2 \zeta_2^{(3)} $	$\alpha'm^2 =  \zeta_3^{(1)}  -  \zeta_2^{(3)} $
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- To eliminate mixed state tachyons  $D7_i - D7_j$  :  $|\zeta_1^{(2)}| = |\zeta_2^{(3)}| = |\zeta_3^{(1)}|$
- Left with doubly charged states tachyons  $D7_i - D7_i$  (brane and image)

# Spectrum (2)

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The diagram illustrates the transformation of a 3x3 grid of symbols, representing the spectrum of D-branes, under the addition of Wilson lines or brane separations.

**Initial State (Left):**

	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	×
D7 <sub>2</sub>	×	•	⊗
D7 <sub>3</sub>	⊗	×	•

**Final State (Right):**

	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	$\times_{A_1}$
D7 <sub>2</sub>	×	$\bullet \pm x_2$	⊗
D7 <sub>3</sub>	⊗	$\times_{A_3}$	•

# Spectrum (2)

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	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	×
D7 <sub>2</sub>	×	•	⊗
D7 <sub>3</sub>	⊗	×	•



	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	$\times_{A_1}$
D7 <sub>2</sub>	×	$\bullet \pm x_2$	⊗
D7 <sub>3</sub>	⊗	$\times_{A_3}$	•

→ *lowest-lying states*

$$y = f(x_2, U_2)$$

$$a_i = g(A_3, U_i)$$

$$\alpha' m_{11}^2 \approx -\frac{2\alpha' |k_1^{(2)}|}{\pi \mathcal{A}_2} + \frac{\alpha' a_1^2}{\mathcal{A}_3}$$

$$\alpha' m_{22}^2 \approx -\frac{2\alpha' |k_2^{(3)}|}{\pi \mathcal{A}_3} + \frac{y \mathcal{A}_2}{\alpha'}$$

$$\alpha' m_{33}^2 \approx -\frac{2\alpha' |k_3^{(1)}|}{\pi \mathcal{A}_1} + \frac{\alpha' a_3^2}{\mathcal{A}_2}$$

# Spectrum (2)

- To eliminate doubly charged tachyons: Wilson lines/brane separations

	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	×
D7 <sub>2</sub>	×	•	⊗
D7 <sub>3</sub>	⊗	×	•



	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	× <sub>A<sub>1</sub></sub>
D7 <sub>2</sub>	×	• <sub>±x<sub>2</sub></sub>	⊗
D7 <sub>3</sub>	⊗	×	× <sub>A<sub>3</sub></sub>

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$$\begin{aligned} \alpha' m_{11}^2 &\approx -\frac{2\alpha' |k_1^{(2)}|}{\pi \mathcal{A}_2} + \frac{\alpha' a_1^2}{\mathcal{A}_3} \approx -\frac{2 |k_1^{(2)}|}{\pi r_2 \mathcal{V}^{1/3}} + \frac{a_1^2}{r_3 \mathcal{V}^{1/3}} \\ \alpha' m_{22}^2 &\approx -\frac{2\alpha' |k_2^{(3)}|}{\pi \mathcal{A}_3} + \frac{y \mathcal{A}_2}{\alpha'} \approx -\frac{2 |k_2^{(3)}|}{\pi r_3 \mathcal{V}^{1/3}} + y r_2 \mathcal{V}^{1/3} \\ \alpha' m_{33}^2 &\approx -\frac{2\alpha' |k_3^{(1)}|}{\pi \mathcal{A}_1} + \frac{\alpha' a_3^2}{\mathcal{A}_2} \approx -\frac{2 |k_3^{(1)}|}{\pi r_1 \mathcal{V}^{1/3}} + \frac{a_3^2}{r_2 \mathcal{V}^{1/3}} \end{aligned}$$

Moduli ratio stabilization as described before  $\tau_i \leftrightarrow \mathcal{A}_i \rightarrow \mathcal{A}_i = r_i \mathcal{V}^{1/3}$

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D7 <sub>3</sub>	⊗	×	•



	(45)	(67)	(89)
D7 <sub>1</sub>	•	⊗	× <sub>A<sub>1</sub></sub>
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	(45)	(67)	(89)
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$$\begin{aligned} V_D &= \sum_a \frac{g_{U(1)_a}^2}{2} \left( \xi_a + \sum_n q_a^n |\varphi_a^n|^2 \right)^2 + \dots \\ &= \sum_{a=1,3} \frac{g_{U(1)_a}^2}{2} \xi_a^2 + \frac{g_{U(1)_2}^2}{2} \left( \xi_2 - 2 |\varphi_-|^2 + \dots \right)^2 + \dots \end{aligned}$$

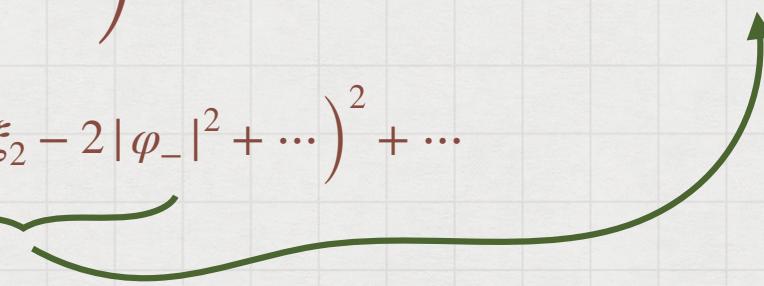
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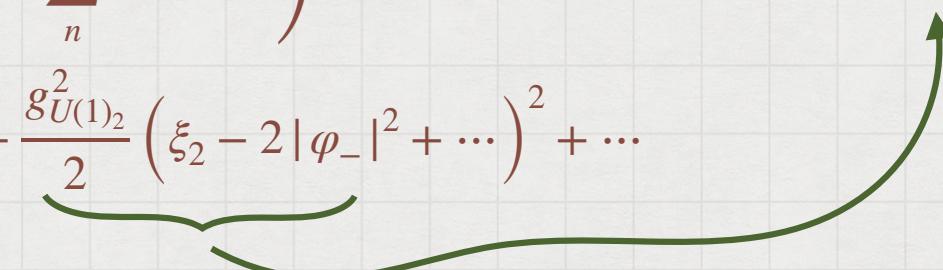
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 &= \sum_{a=1,3} \underbrace{\frac{g_{U(1)_a}^2}{2} \xi_a^2}_{d_a} + \underbrace{\frac{g_{U(1)_2}^2}{2} \left( \xi_2 - 2|\varphi_-|^2 + \dots \right)^2}_{\text{red term}} + \dots
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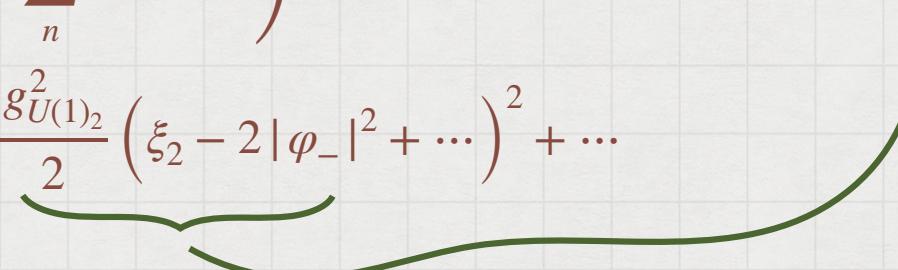
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 + \quad \frac{1}{g_{U(1)_a}^2} \propto \frac{\mathcal{V}}{g_s} \frac{\alpha'}{\mathcal{A}_a} &\rightarrow \quad \xi_a = \dots, \quad d_a \propto \frac{1}{2} g_s^3 \left( \frac{k_a^{(j)}}{\pi} \right)^2
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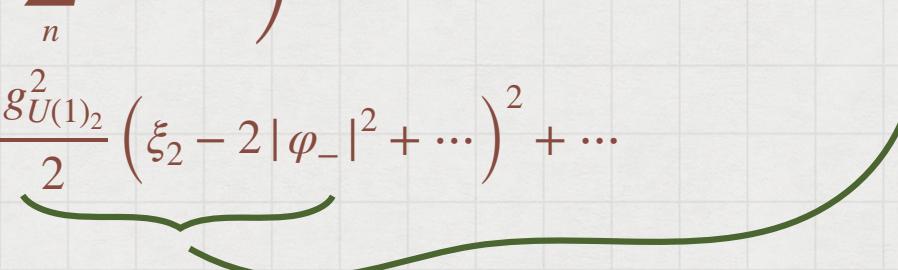
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 &+ \frac{1}{g_{U(1)_a}^2} \propto \frac{\mathcal{V}}{g_s} \frac{\alpha'}{\mathcal{A}_a} \quad \rightarrow \quad \xi_a = \dots, \quad d_a \propto \frac{1}{2} g_s^3 \left( \frac{k_a^{(j)}}{\pi} \right)^2
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- Wilson line or brane separation: F-term from superpotential (*SUSY*)

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- Magnetic field contribution: D-term (*SUSY breaking*)

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*inflationary phase: as described before*

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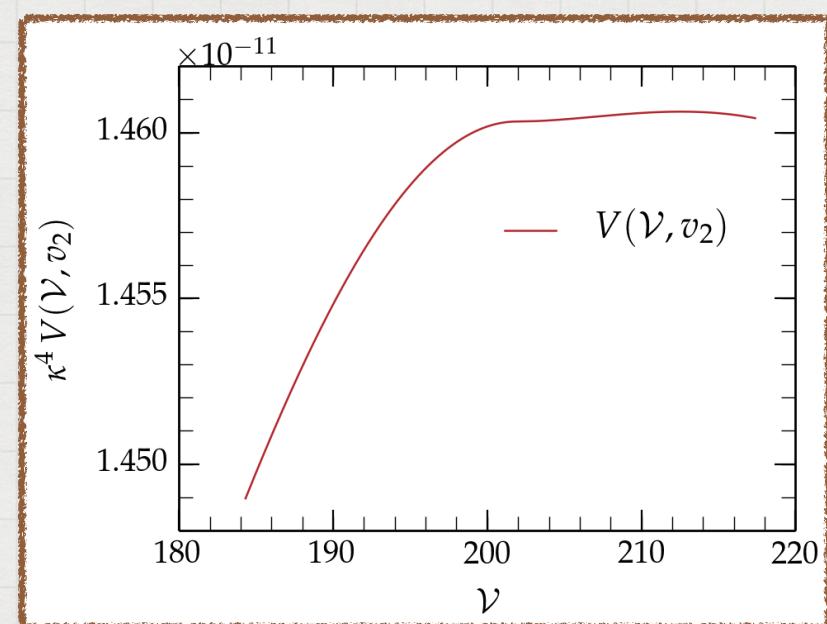
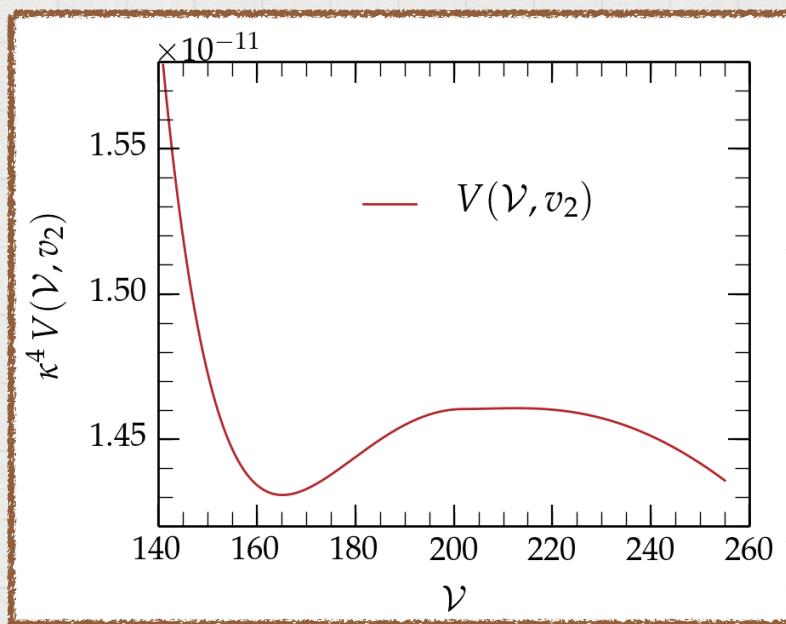
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 depends on: fluxes, brane position  
 $\rightarrow$  choose it near  $\mathcal{V}_-$



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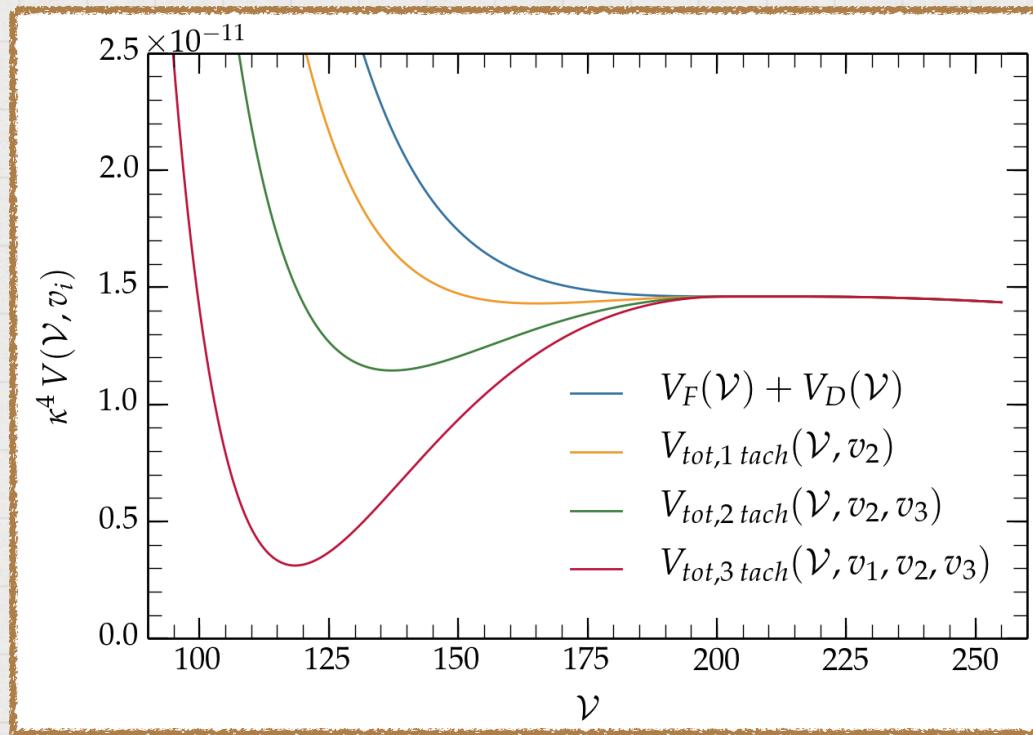
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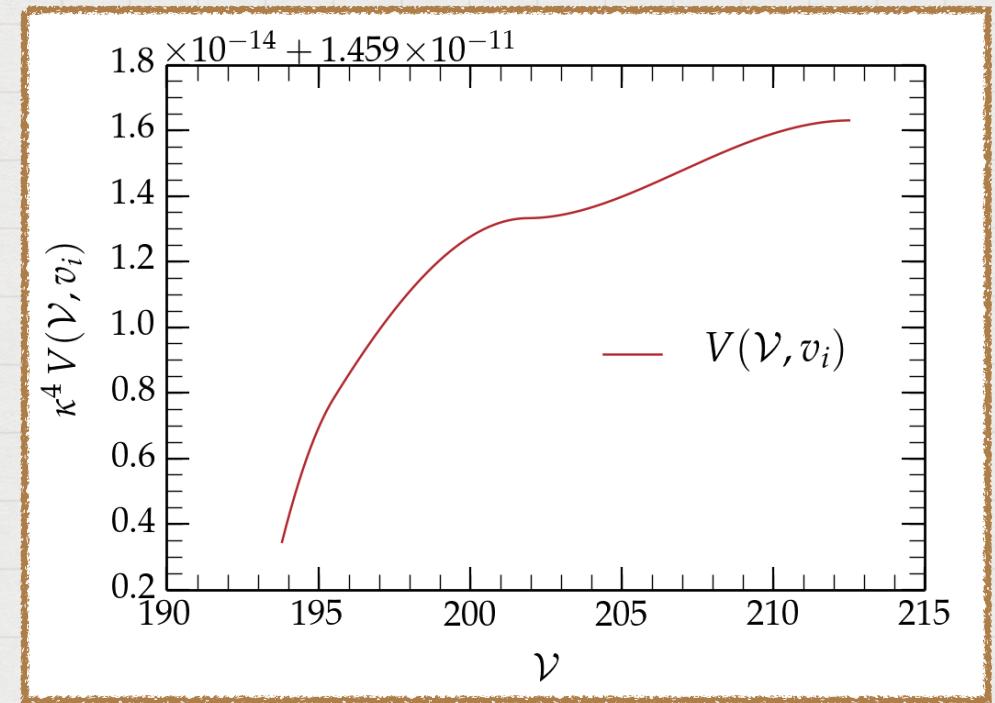
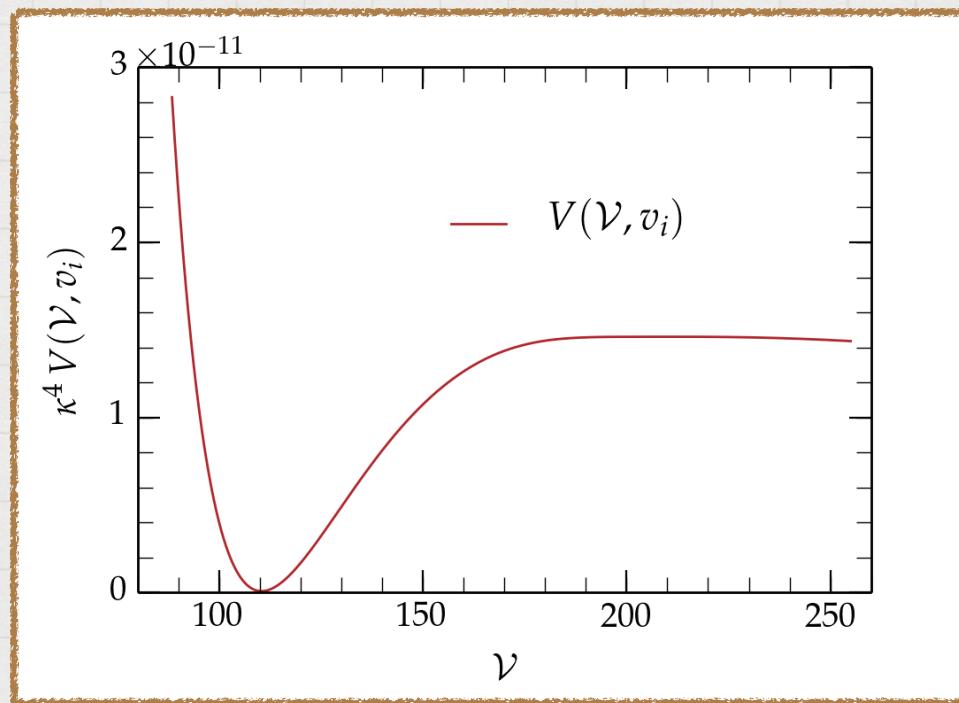
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- Add a 4th brane parallel to one of the initial stack !



# Outline of the talk

1. Introduction
2. Inflationary scenario from moduli stabilization
3. Hybrid inflation and waterfall fields
4. A concrete (toy) model
5. Summary & Outlook

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  - Yoga Dark energy realization ?    *Burgess, Dineen, Quevedo '21*

Thank you

for  
all

# Back-up slides



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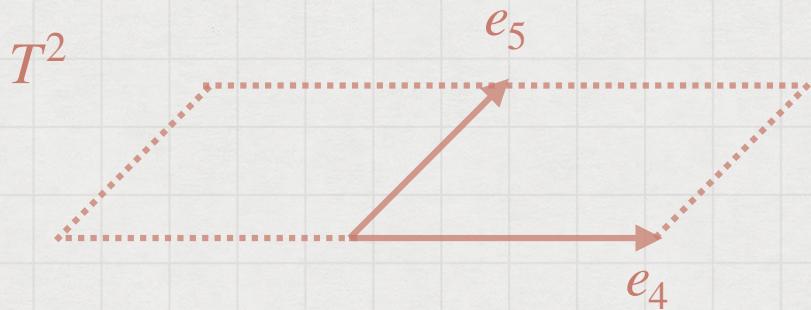
$R_\perp^k$  size of  $\perp$ -space  
 $w$  localization width  
 $T_k$  brane tension

Antoniadis, Chen, Leontaris '18, '19

- $\mathcal{R}_{(4)} \leftrightarrow$  Planck mass (hence  $\mathcal{K}$ ) corrections, break no-scale structure

# Toroidal orbifolds

- Toroidal orbifold : torus+discrete symmetry group  
*identification of space-time points:*  $\mathbf{X} \sim g\mathbf{X} + 2\pi\mathbf{L}, \quad g \in G$
- Allows for **twisted** b.c.:
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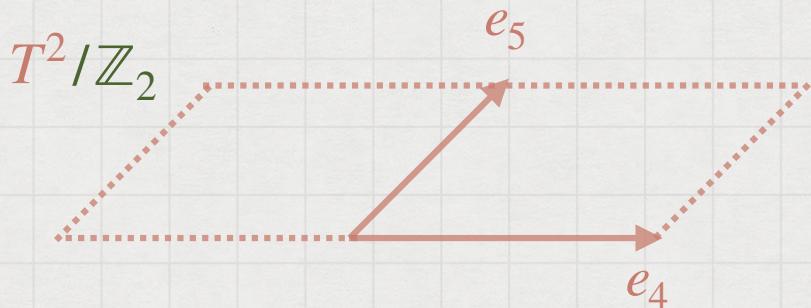
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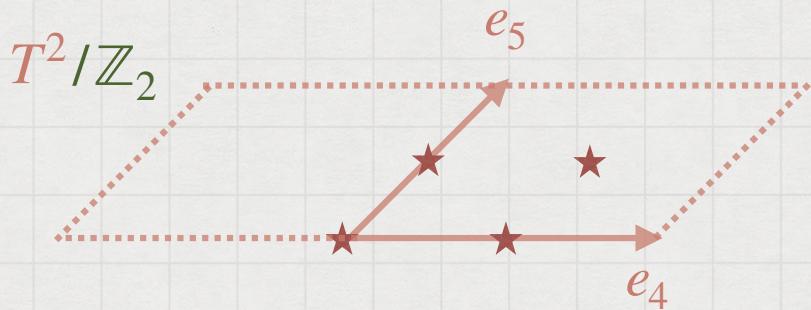
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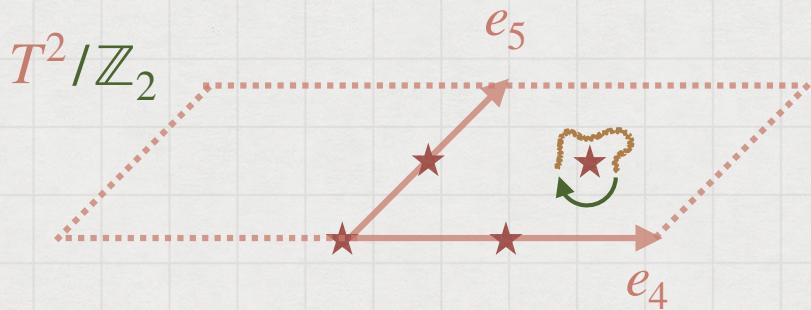
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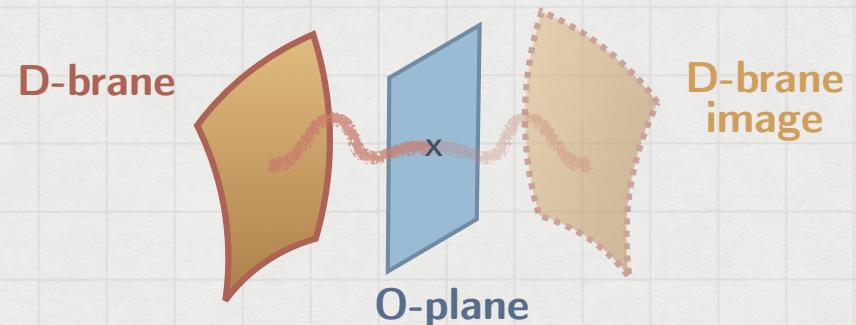
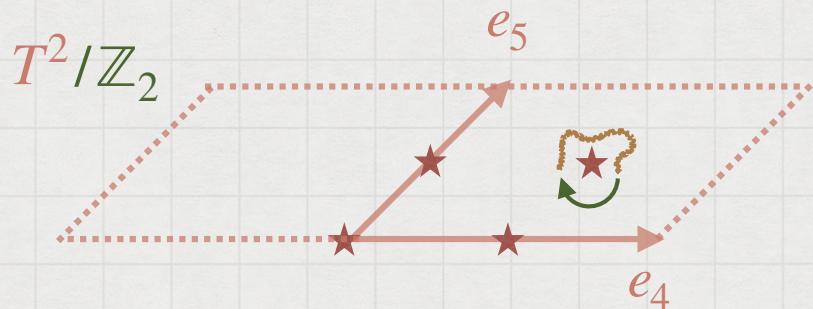
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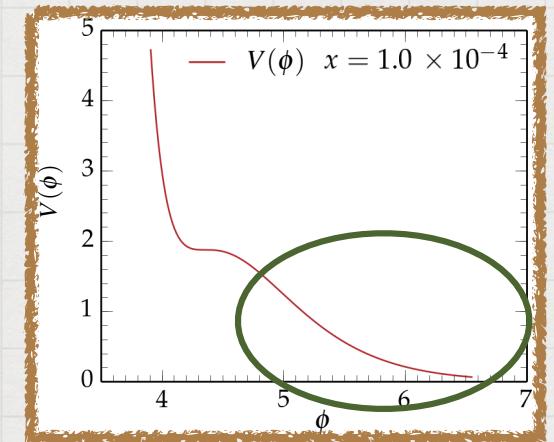


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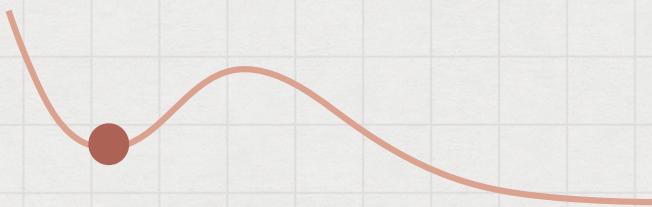
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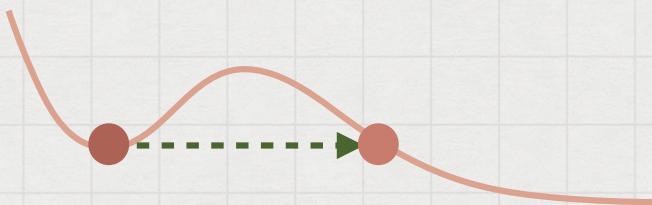
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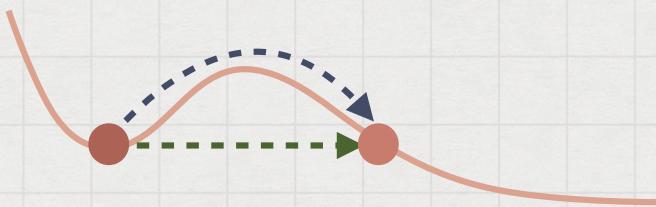
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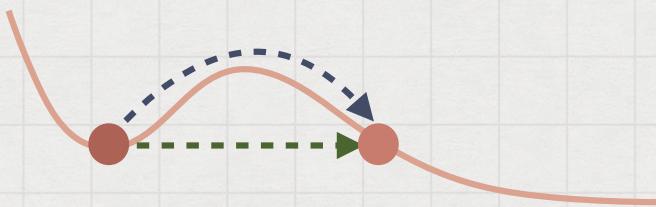


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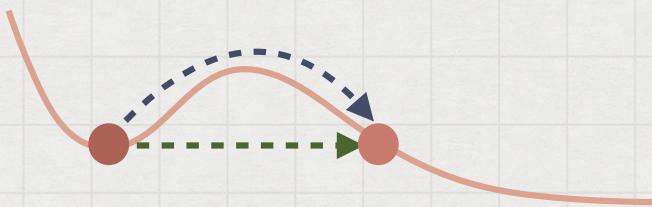
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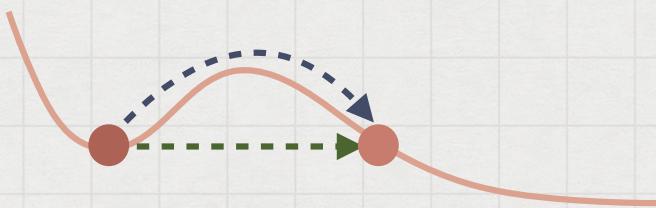


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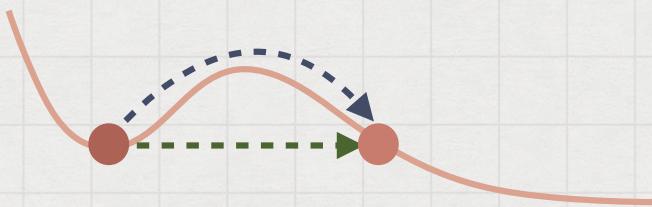
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$$H_- = H(\varphi_-) < H_c$$

Jensen, Steinhardt '84  
Balek, Demetrian '04

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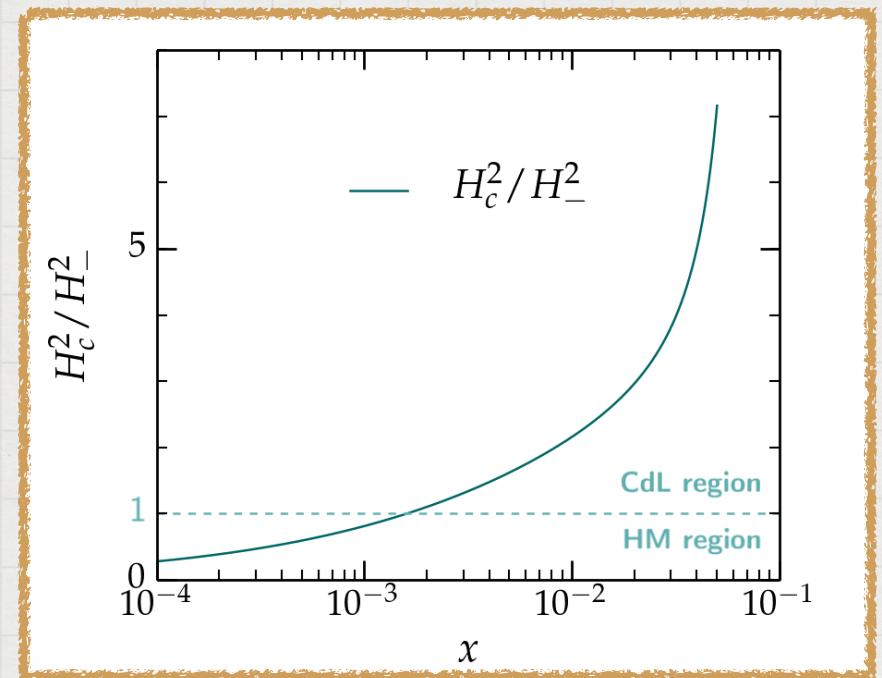
- Compute rate:  $\Gamma = Ae^{-B}$  with  $B = S_E(\varphi) - S_E(\varphi_-)$ ,

$B$  : energy cost of  $\varphi$  **bounce** solutions  
(Euclidean action analysis)

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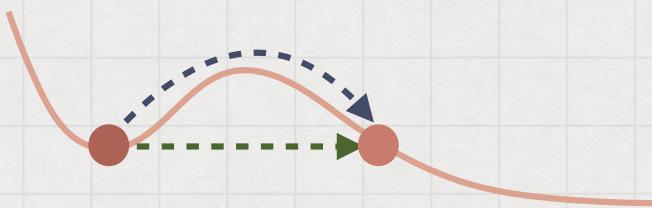
$$H_- = H(\varphi_-) < H_c$$

Jensen, Steinhardt '84  
Balek, Demetrian '04



# Stability of the vacuum

- Probability of escaping to the runaway direction ?



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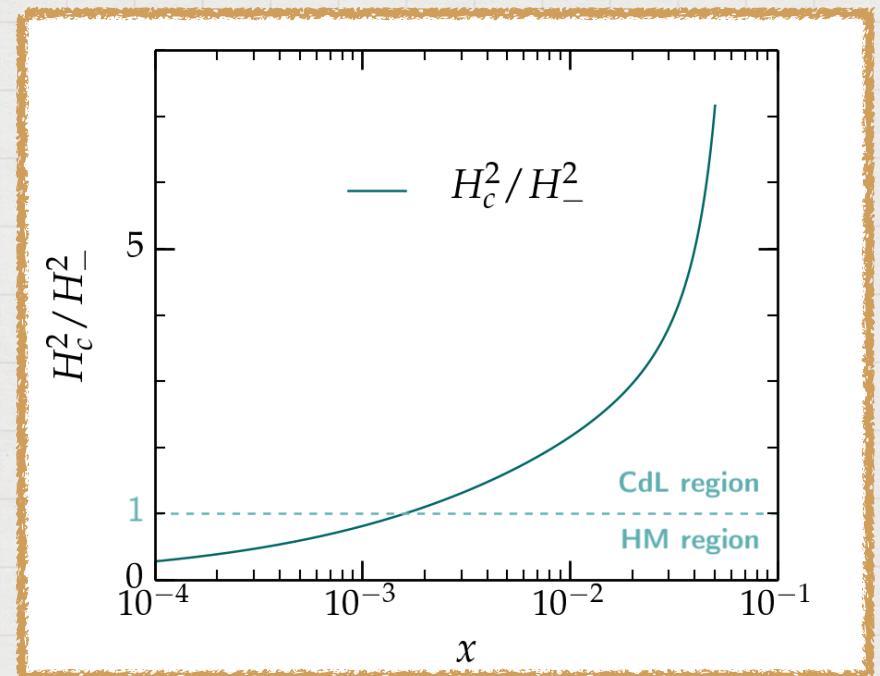
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$$H_- = H(\phi_-) < H_c \quad \begin{matrix} \text{Jensen, Steinhardt '84} \\ \text{Balek, Demetrian '04} \end{matrix}$$

- HM estimate  $B \approx \frac{8\pi^2 \Delta V}{3H_*^4} \approx 3.3 \times 10^9$



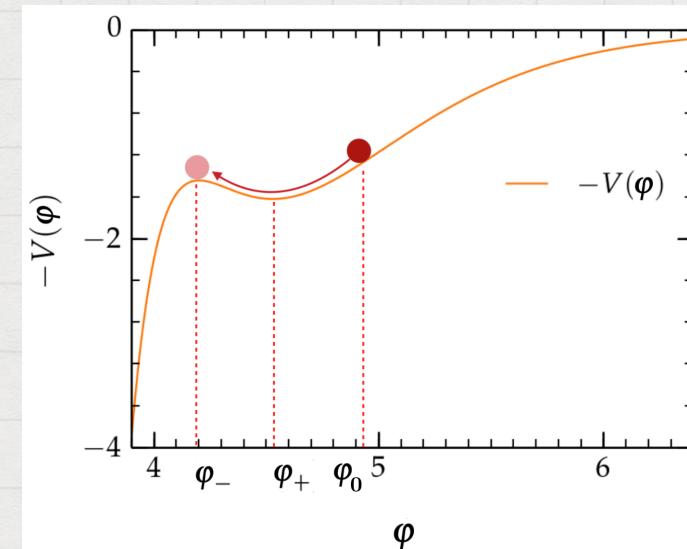
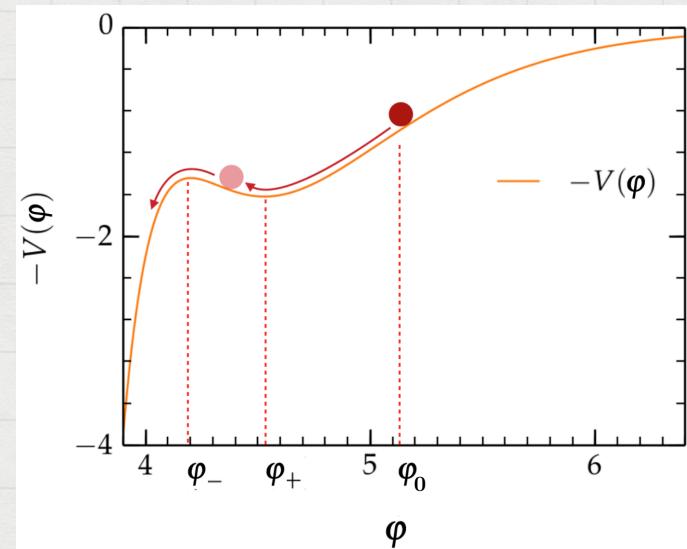
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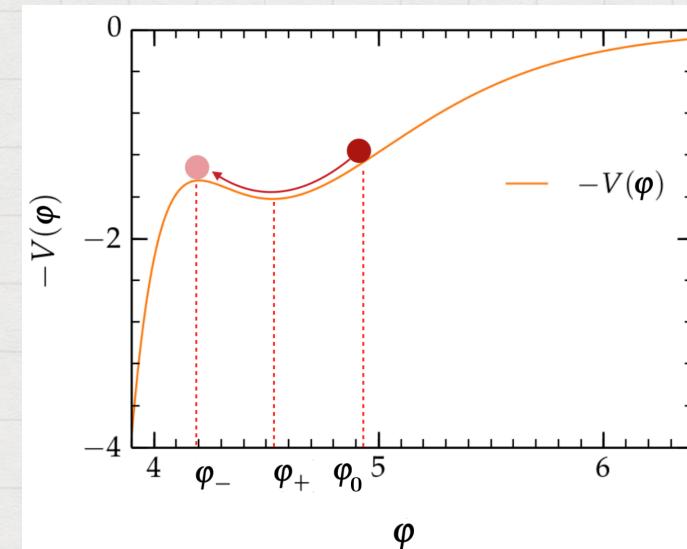
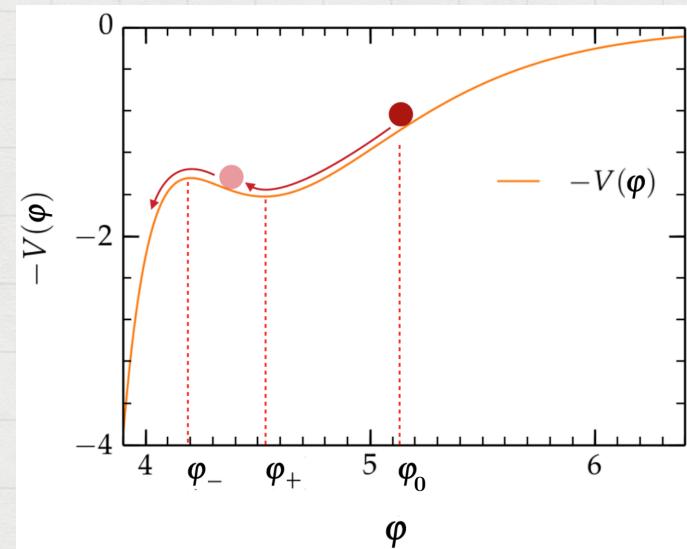
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- HM bounce  $\varphi_+$ :  $B = S_E(\varphi_+) - S_E(\varphi_-) = -\frac{24\pi^2}{\kappa^4 V(\varphi_+)} + \frac{24\pi^2}{\kappa^4 V(\varphi_-)} \simeq \frac{8\pi^2 \Delta V}{3H_*^4} \approx 3.3 \times 10^9$

# Vacuum amplitudes

- Vacuum amplitudes: propagation open string glued back to it self, with(out) orientation reversal, *corresponding to annulus (Möbius strip) topologies*. For 1 unique state  $\phi$ :

$$Z(\phi, \tau_2) = \langle \phi | e^{-(2\pi\alpha' p^+ \tau_2)H} | \phi \rangle = \langle \phi | e^{-\tau_2 \pi \alpha' \sum_i p^i p^i} q^{\frac{1}{2}(N+E_0)} | \phi \rangle \quad q \equiv e^{2\pi i \tau_2}$$

- Sum over states,  $\tau_2$  :  $A = \frac{N^2}{2} \int_{\tau_2 > 0} \frac{d\tau_2}{\tau_2^2} \frac{1}{\tau_2^{(D-2)/2}} \text{tr}_{\mathcal{H}_{\text{osc}}} q^{\frac{1}{2}(N+E_0)},$

- Toroidal orbifold model

$$8A_0 = (N_1 \bar{N}_1 W_1 \tilde{P}_2 P_3 + N_2 \bar{N}_2 P_1 W_2 \tilde{P}_3 + N_3 \bar{N}_3 \tilde{P}_1 P_2 W_3) T_{oo}(0,0,0)$$

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$\exists$  bosonic coord. contribution:  
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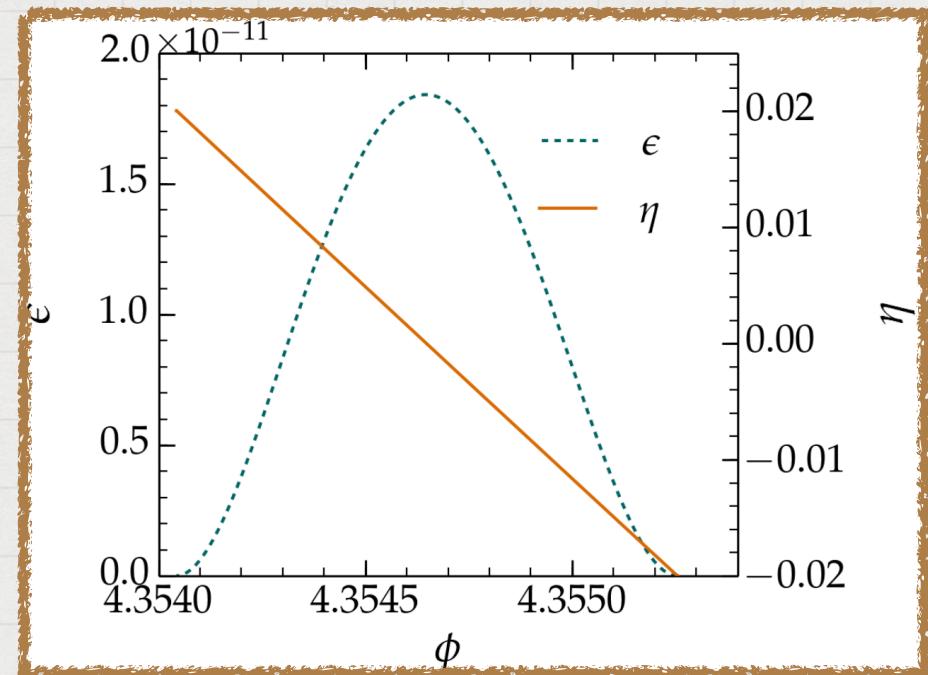
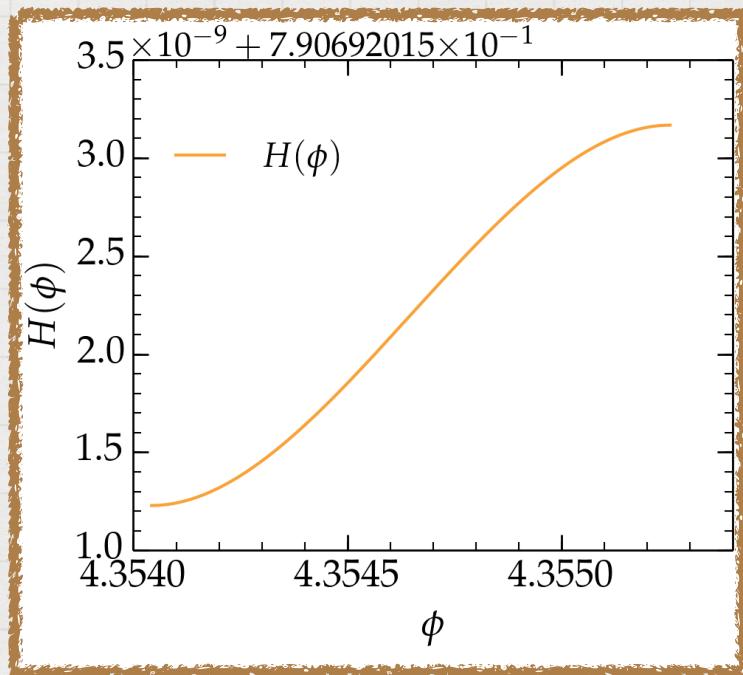
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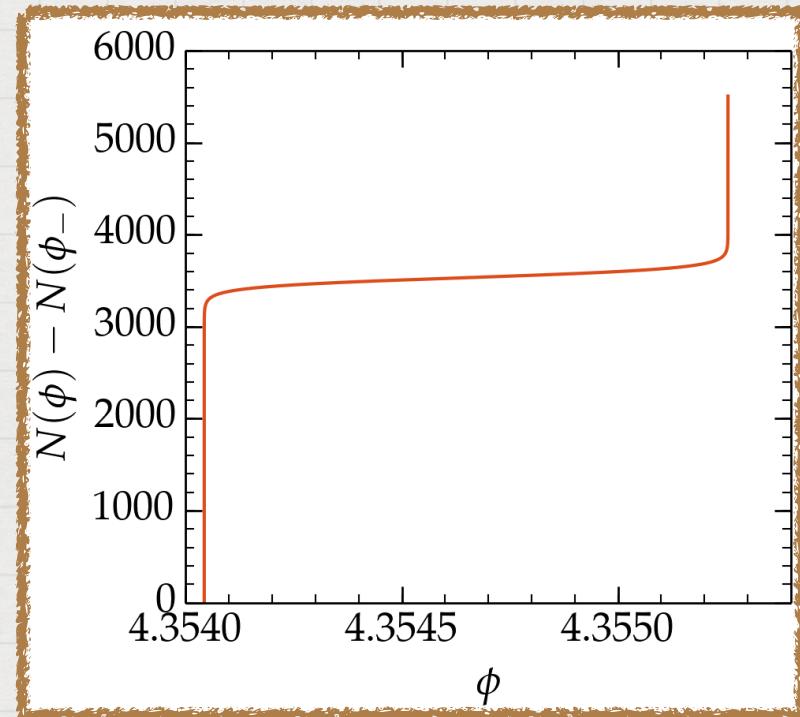
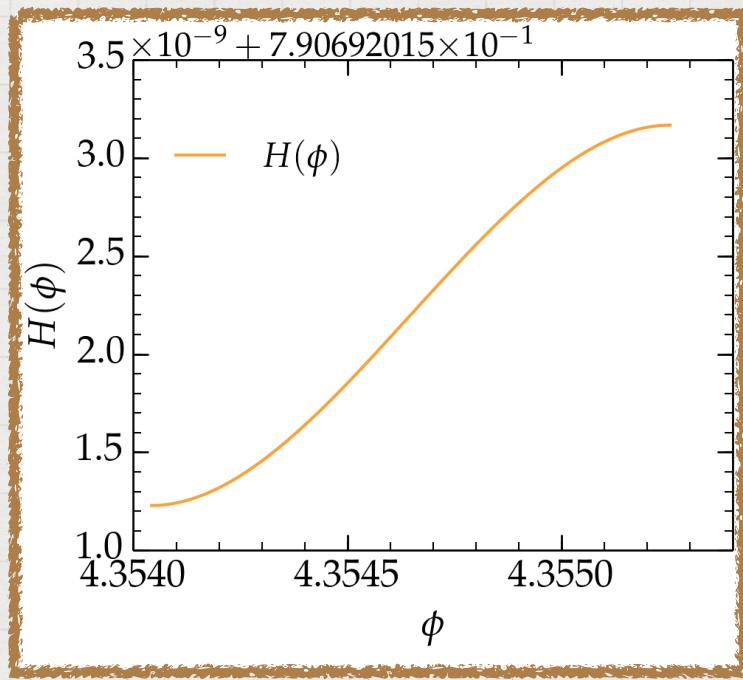
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