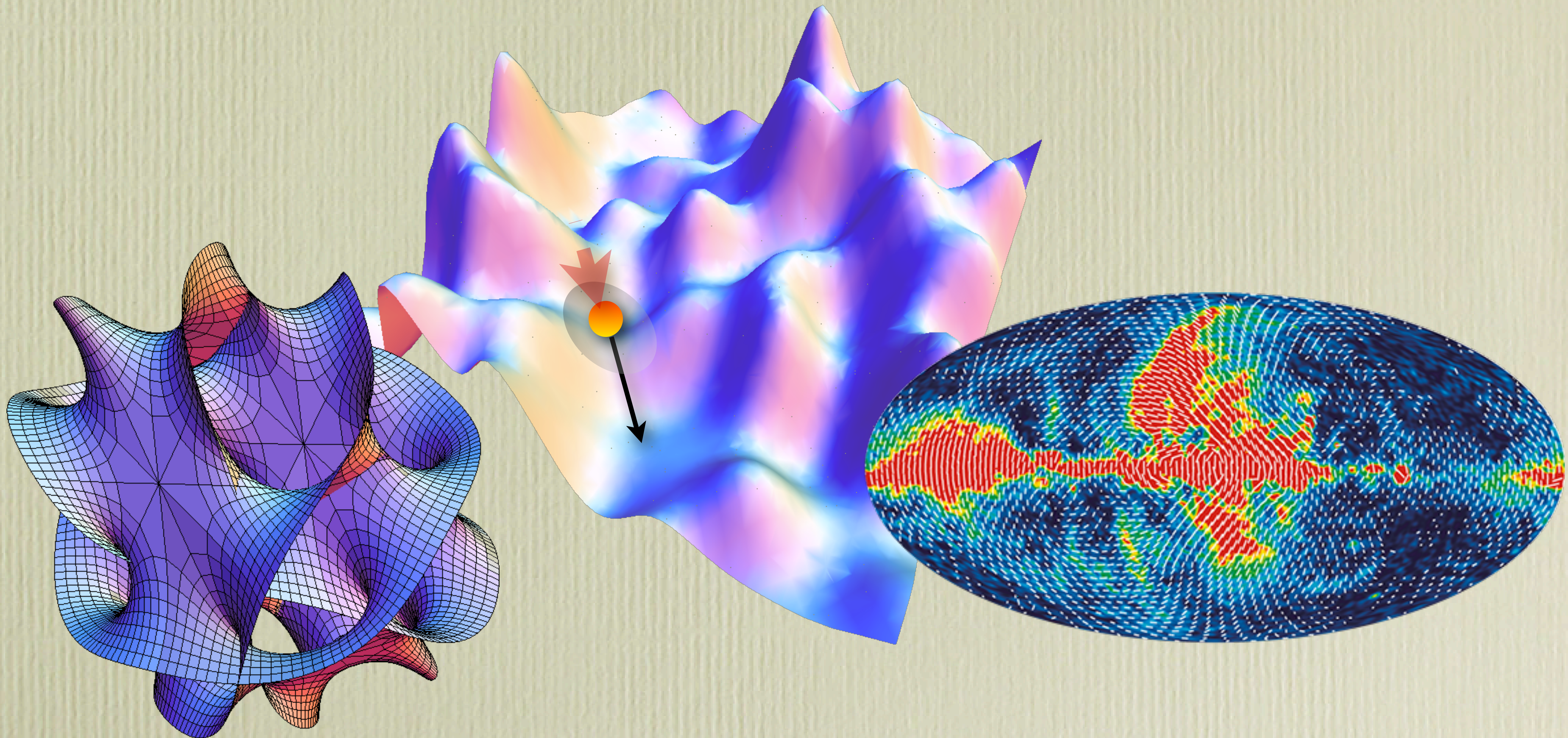
Tensors in the Landscape ...



arXiv: 1206.4034, 1303.3224

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premises / assumptions ...

- large-field inflation needs shift symmetry to control UV corrections:

$$\mathcal{O}_6 \sim V(\phi)\frac{\phi^2}{M_{\rm P}^2} \quad \Rightarrow \quad m_\phi^2 \sim H^2 \ , \ \eta \sim 1$$

➡️(i) shift symmetries only from p-form gauge fields of string theory

- scalar fields with shift symmetry in string compactifications:

➡️(ii) axions - field range is limited to < M_P

premises / assumptions ...

- population of the many vacua:

  ➡(iii) only known mechanism:
  CdL or HM tunneling, combined with eternal inflation

- basic structure of the landscape of vacua

  ➡(iv-1) exponentially many vacua in multi-dimensional moduli space

  ➡(iv-2) neighbouring vacua typically have large differences in vacuum energy:
  - any vacuum with relatively small c.c. has neighbours with large c.c.

premises / assumptions ...

- eternal inflation

progenitor: *highest* dS vacuum seeds all other vacua

➡️volume-weighted global measures only if discard eternal volume growth

[Linde '07]
[Linde, Vanchurin & Winitzki '08]

➡️there is global-local duality for:

- causal patch measure

[Bousso, Freivogel & Yang '06]
[Freivogel, Sekino, Susskind & Yeh '06]

- scale factor time measure

[de Simone, Guth, Linde, Noorbala, Salem & Vilenkin '08]

- light-cone time cutoff measure

[Bousso '09]
[Bousso & Yang '09]
[Bousso, Freivogel, Leichenauer & Rosenhaus '10]

progenitor: *longest-lived* dS vacuum seeds all other vacua
$V_{inf} \ll V_{progen.} \ll 1$, still very high !

consequences of (i) & (ii)

- N-flation ... or need a potential $V(\phi)$ which is monotonic:

$$V(\phi) \to V(\phi + \Delta\phi) > V(\phi) \quad \text{even if:} \quad \phi \to \phi + \Delta\phi = \phi$$

periodic

- called " $V(\phi)$ has a monodromy in ϕ " - e.g. axion monodromy:

$$S_{5-\text{brane}} \sim \frac{1}{g_s} \int_{\mathcal{M}_4 \times \text{2-sphere}} d^6\xi \sqrt{\det(G+B)}$$

$$= \frac{1}{g_s} \int_{\mathcal{M}_4} d^4x \sqrt{-g} \sqrt{v^2 + b^2}$$

monodromy; breaks perturbative shift symmetry in B_2

consequences of (i) & (ii)

➥ the upshot:

- the specific monodromy mechanism & field is irrelevant

- without a field in string theory *with* a good shift symmetry *and* an unbounded/non-periodic fundamental domain ...

  ... some monodromy in the potential energy is necessary for single-field parametrically-large-field inflation - by the very definition of the word 'monodromy'

further consequences of (i) & (ii)

axion monodromy gives effective potential:

$$V(\phi,\chi) = V_0(\phi) + \Lambda^4(\chi)\,\cos\left(\frac{\phi}{2\pi f}\right) + U_{mod.}(\chi)$$

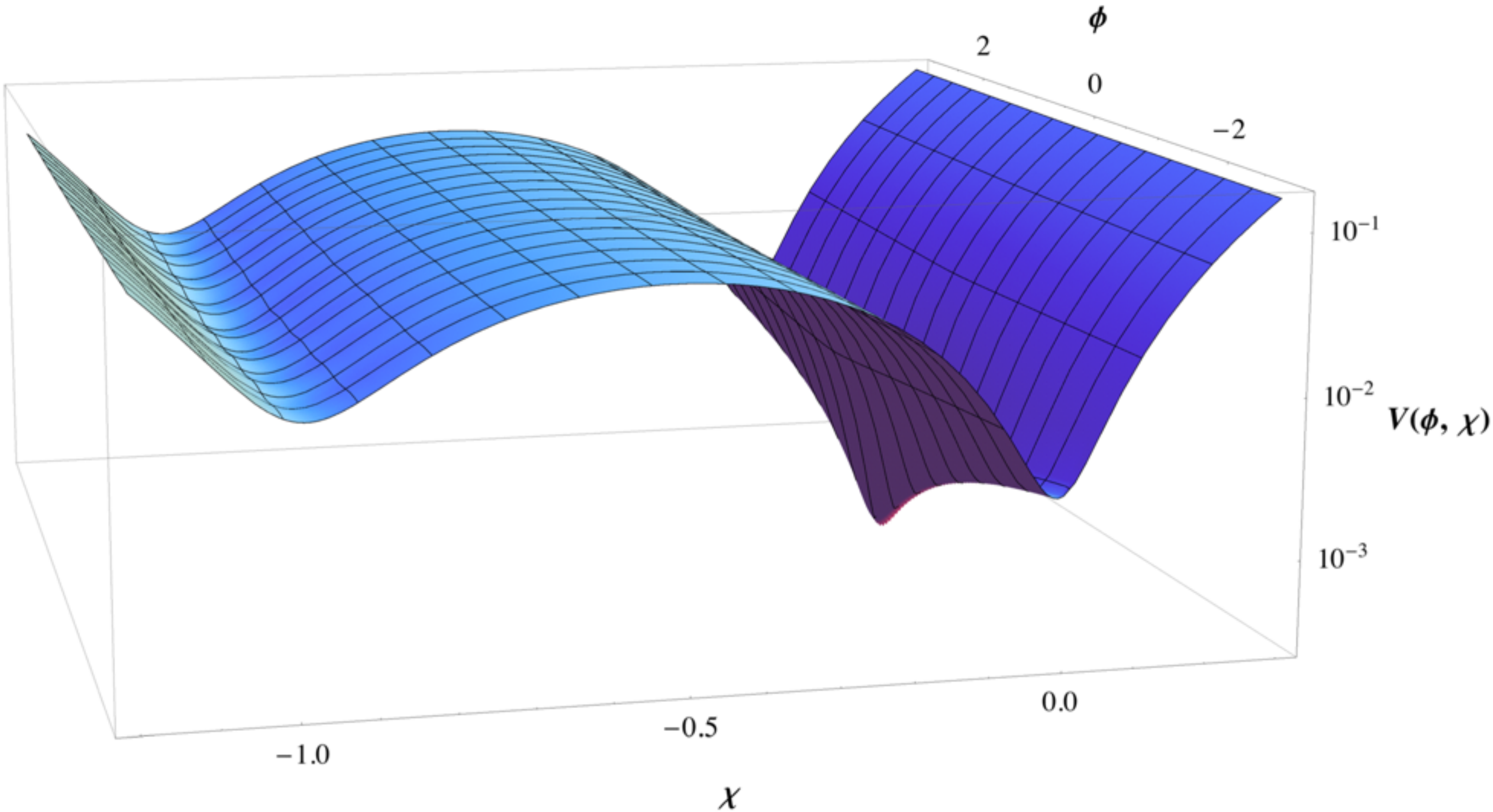
instanton corrections

moduli potential

$$V_0(\phi) \sim \phi^p \quad , \quad 0 < p < 2 \qquad \text{for} : \phi \gtrsim M_{\rm P}$$

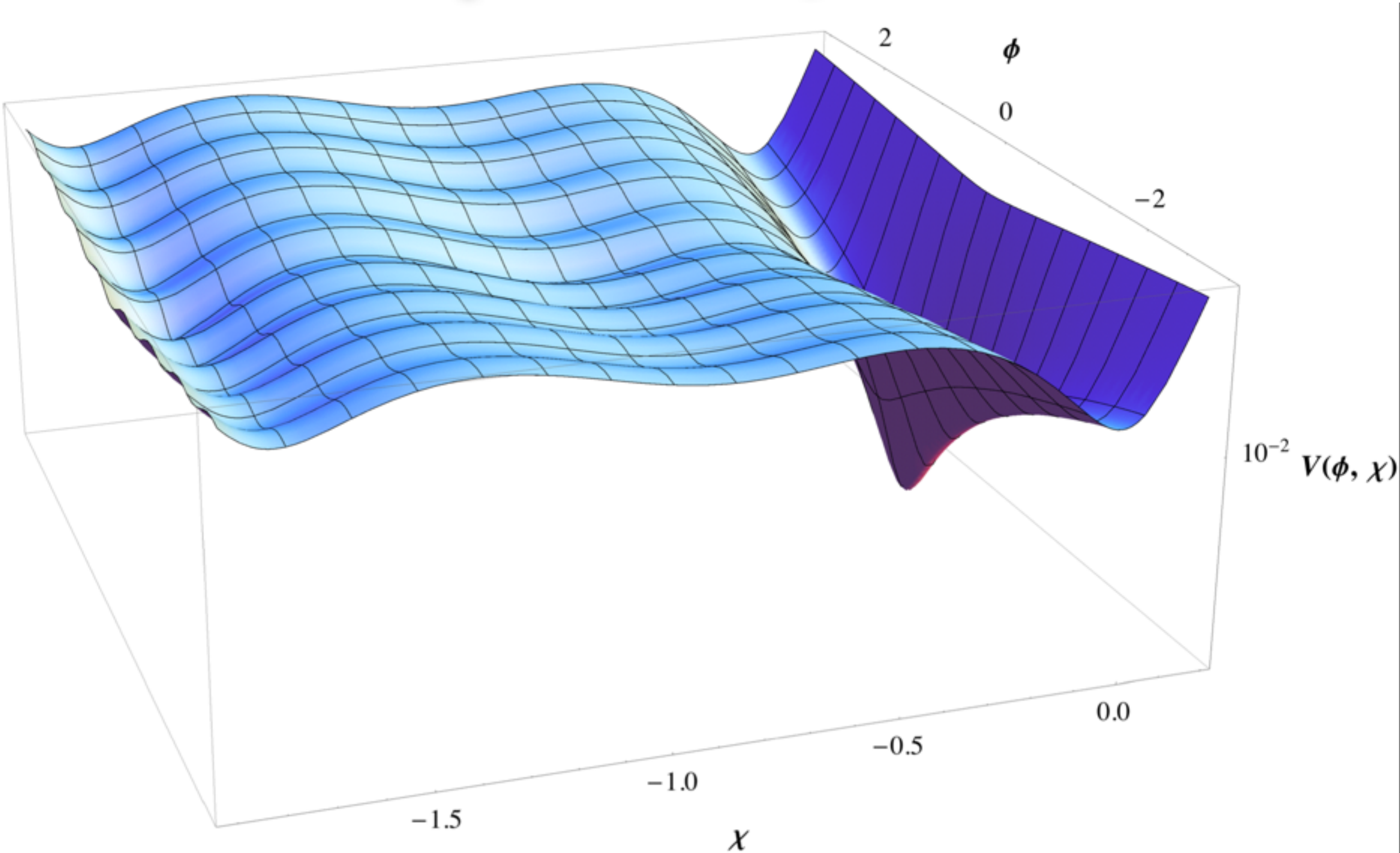
good shift symmetry for Φ demands near-perfect decoupling from the moduli χ - in particular, the minimum/minima in Φ do not shift as a function of the moduli

consequences of (i) , (ii) & (vi-2)



global measures: ***highest*** metastable dS is progenitor to all small-c.c. dS vacua

consequences of (i) , (ii) & (vi-2)



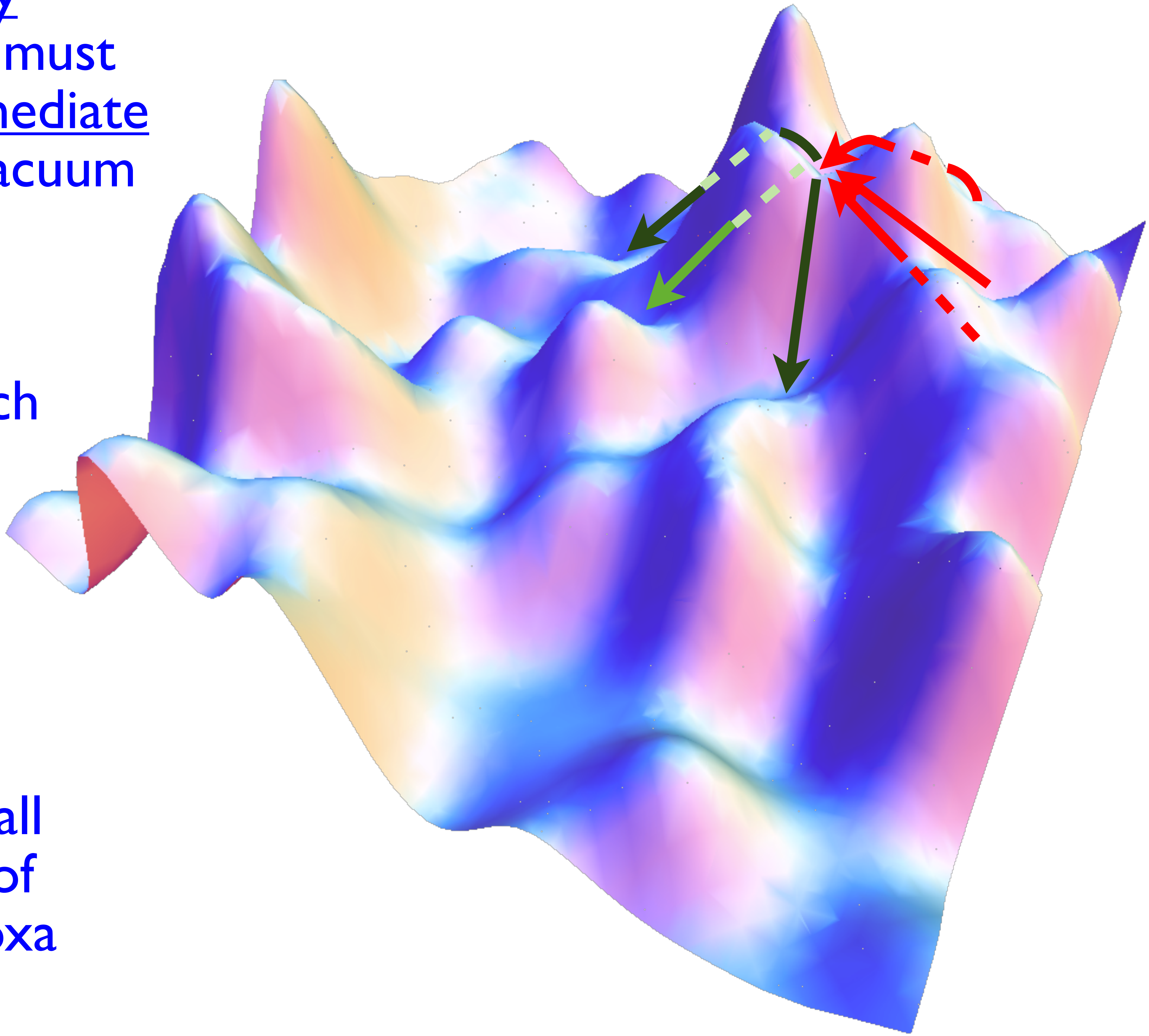
local measures: longest-lived dS - still generically of ***very high-scale*** c.c. - is progenitor to all small-c.c. dS vacua

consequences of (iii) & (vi)

- population of sufficiently many small-c.c. vacua must go via an intermediate very large c.c vacuum

↕

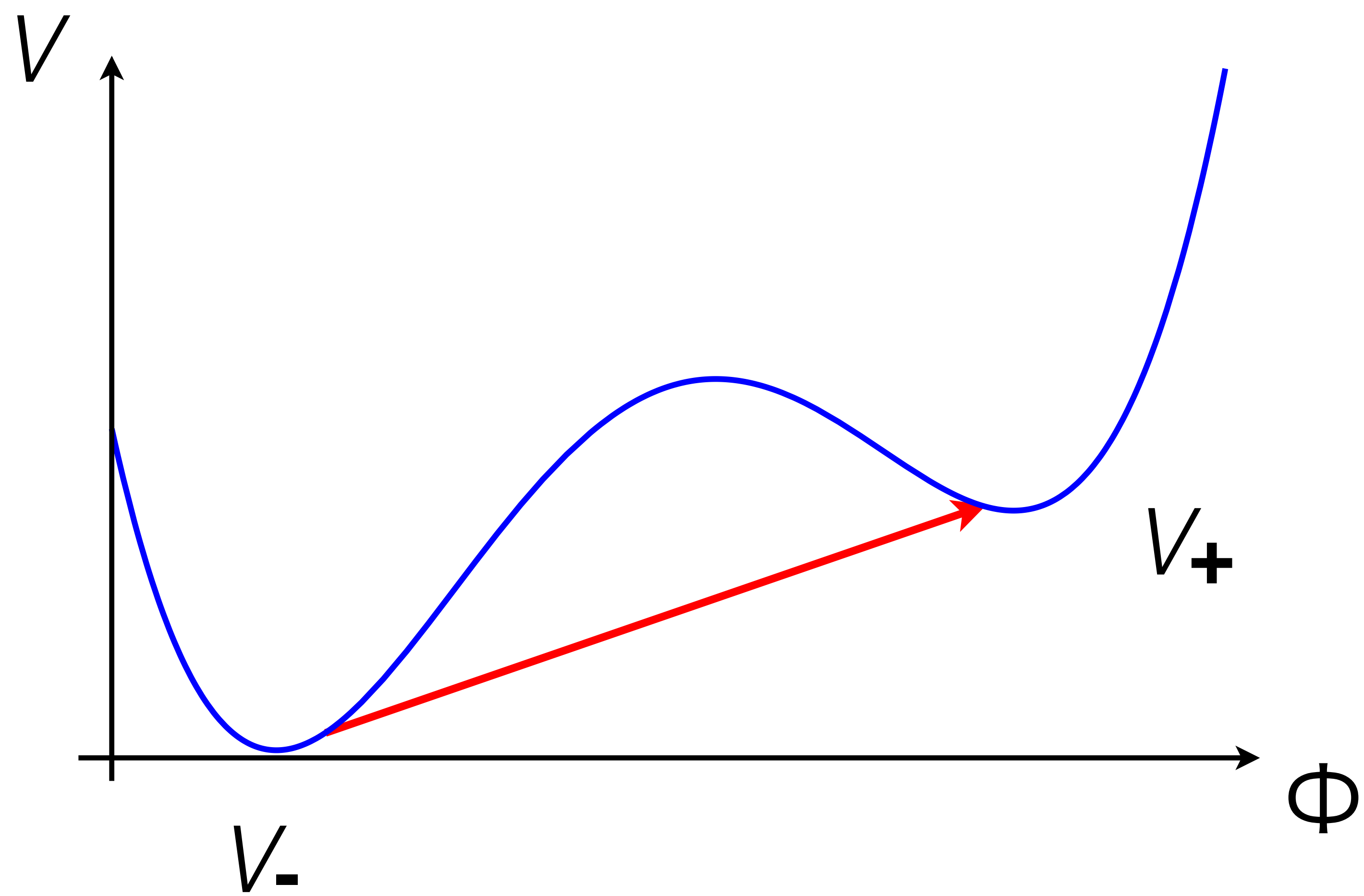
because down tunneling is much more efficient



- maintained by all measures free of obvious paradoxa

consequences of (iii) tunneling ...

➡ up tunneling very expensive & undemocratic



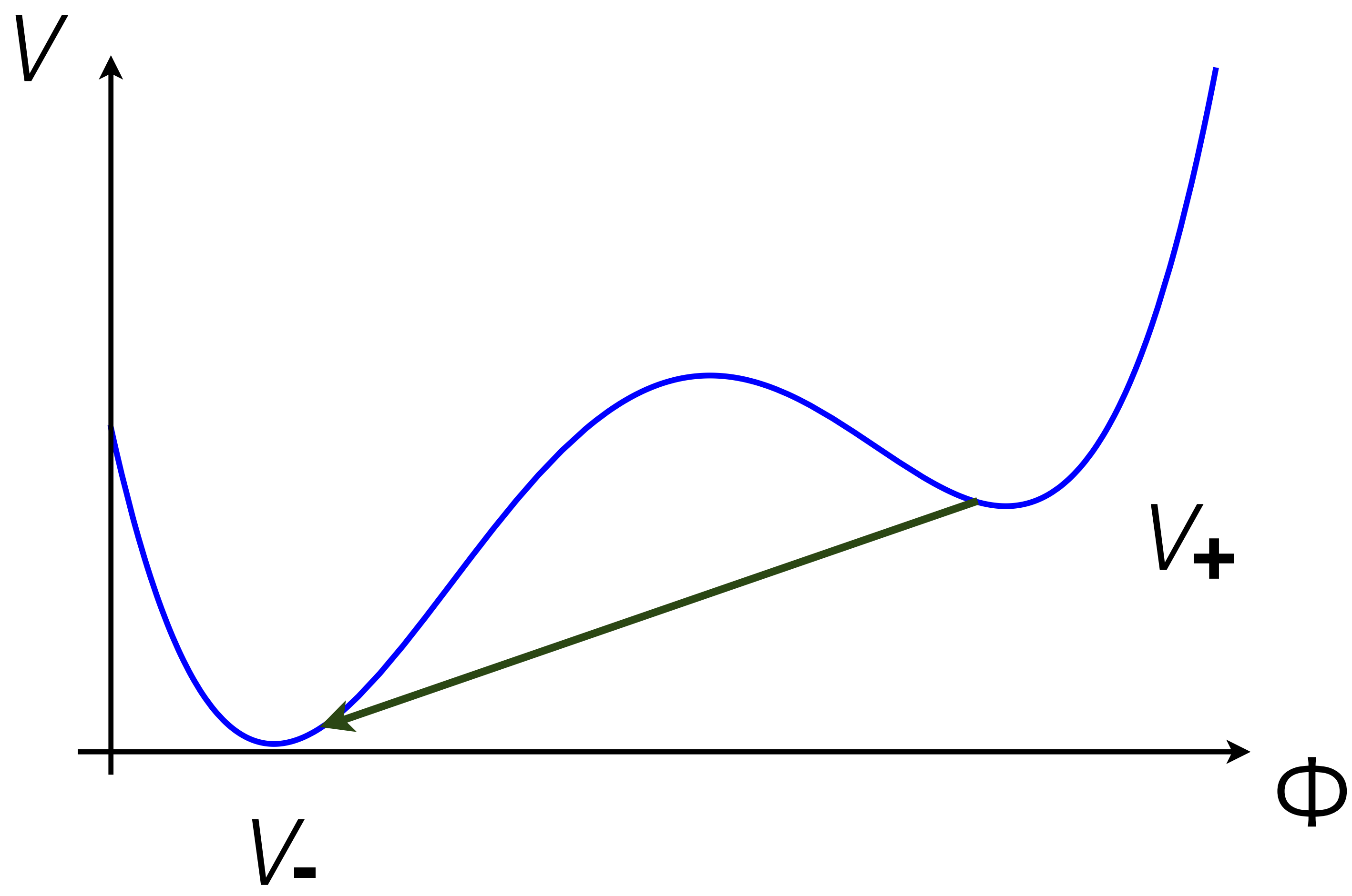
$$\Gamma_{V_+} \sim e^{-\left(\frac{1}{V_-} - \frac{1}{V_+}\right)}$$

➡ ratio of up tunneling rates into 2 different higher dS vacua

$$\frac{\Gamma_{V'_+}}{\Gamma_{V_+}} \sim e^{-\frac{1}{V_+}} \quad , \quad V'_+ > V_+$$

consequences of (iii) tunneling ...

➡ down tunneling less expensive & democratic



$$\Gamma_{V_-} \sim e^{-\frac{1}{V_+}+S_E(\phi)}$$

consequences of (iii) tunneling ...

➥ down tunneling less expensive & democratic

$$S_E(\phi) \sim \int d\xi a^3(\xi) V(\phi)$$
$$\sim S_E^{(0)}(\phi) \left[1 + \mathcal{O}\left(\frac{V_-}{V_+}\right)\right]$$

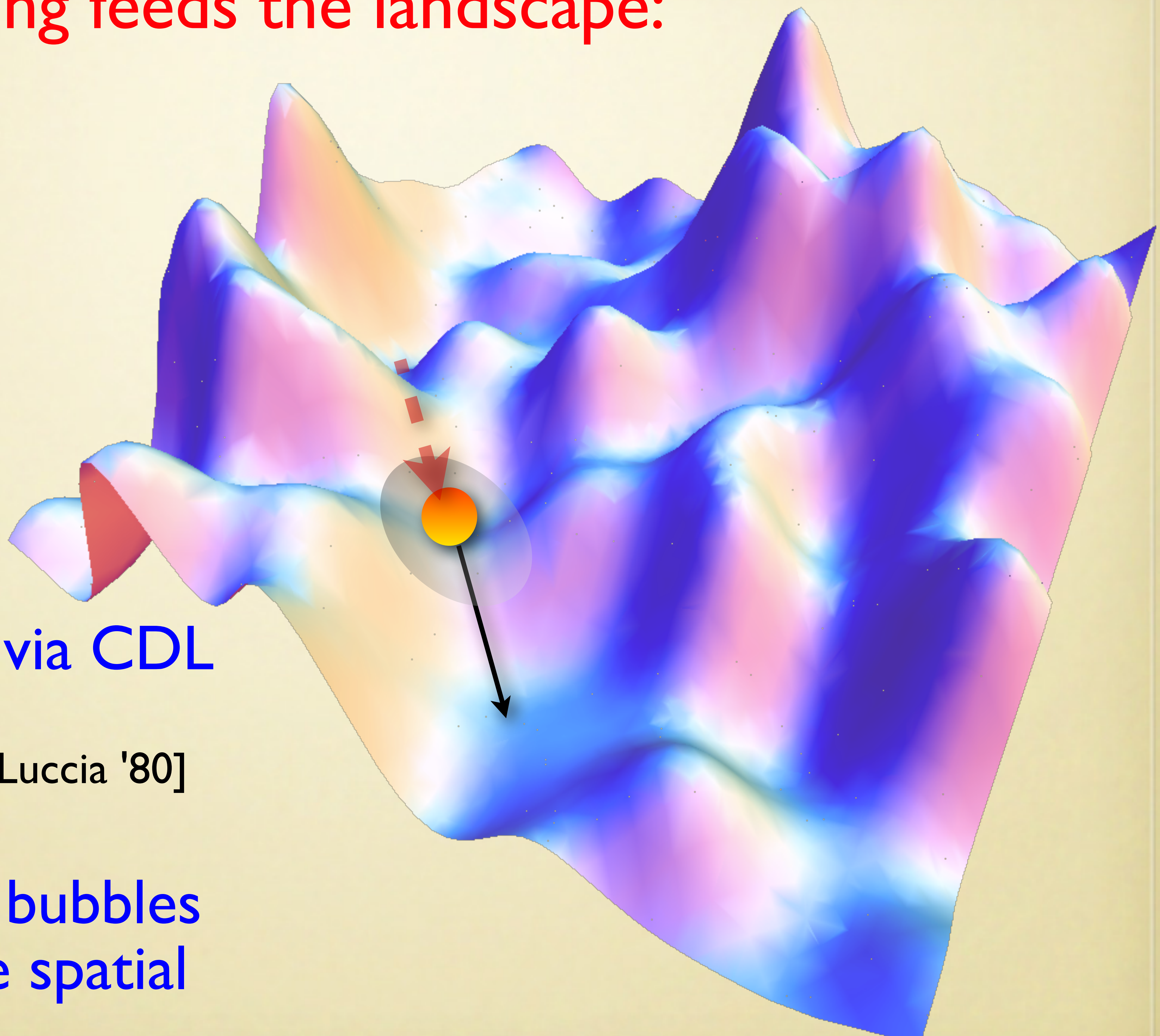
- independent from small V_-

- can ***average*** over barrier height

➥ averaged ratio of down tunneling rates into 2 lower dS vacua

$$\frac{\Gamma^{av.}_{V'_-}}{\Gamma^{av.}_{V_-}} \sim 1 \quad , \quad V_+ \gg V_- \ , \ V'_-$$

- (iii) Tunneling feeds the landscape:



➡️ proceeds via CDL instanton [Coleman, De Luccia '80]

➡️ nucleates bubbles of negative spatial curvature

consequences of (iii) tunneling ...

- CDL tunneling dictates very special initial conditions & e.o.m. after transition:

$$a(t) = t + \mathcal{O}(t^3)$$

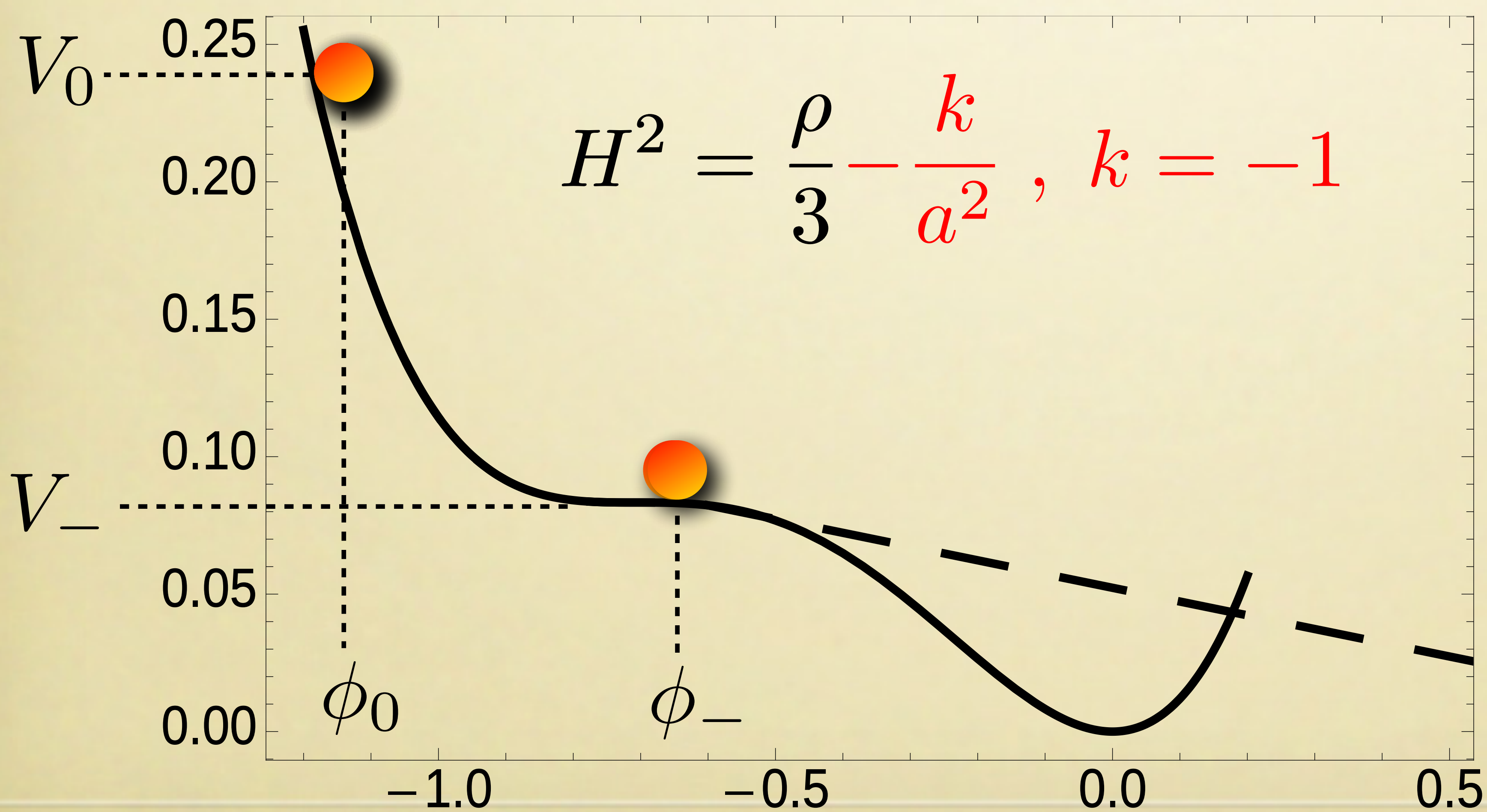
$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

$$\dot{\phi}_0 \equiv \dot{\phi}(t=0) = 0$$

$$H^2 = \frac{1}{3M_P^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right) + \frac{1}{a^2}$$

➡️ overshoot problem [Brustein, Steinhardt '93]

➡️ the inside of a CDL bubble is an open, negatively curved FRW universe ...



➡️ resulting friction term severely slows the field on steep potentials --- ***No*** *overshoot!*

[Dvali, Kachru '03]
[Freivogel et al. '05]
[Dutta, Vaudrevange, AW '11]

consequences of (i) , (ii) , (iii) & (iv)

➡ consequence:

if the measure choice decouples & tunneling treats small-field and large-field regimes approximately neutral ...

distribution of field-range is fully determined by number frequency of inflationary solutions

➡ 'valley' statistics determines *r* , as vacuum statistics (anthropically) determines late-time c.c. ! This is in principle a string theory question ...

valley statistics

➥ essential question:
how many small-field saddle points per meta-stable dS vacuum - versus how many large-field realizations

➥ just from accidentally fine-tuned saddle points in the moduli potential there can be many small-field regions - use random matrix theory to study critical points of random supergravity:

[Susskind ’04; Douglas ’04; Denef & Douglas ’04; Aazami & Easther ’05; Marsh, McAllister & Wrase ’11; Chen, Shiu, Sumitomo & Tye '11; Bachlechner, Marsh, McAllister & Wrase ’12; ...]

valley statistics ...

➥ parametrize unknown counting factors - example: CY landscape ...

- The landscape '*Drake equations*' of tensor modes

$$N_{\Delta\phi < M_P} \sim N_{CY} \cdot N_{cr.} \cdot \beta_{dS-vac.} \cdot \beta_{flat\ saddle} \cdot \left(1 - \beta_{V^{\frac{1}{4}} > 10^{16}\,\mathrm{GeV}}\right)$$

$\sim e^{c_H N_H}$

$\sim e^{-c_L N_L^p}$

??

$$N_{\Delta\phi > M_P} \lesssim \underbrace{\beta_{h_-^{1,1} > 0} N_{CY}} \cdot N_{cr.} \cdot \beta_{dS-vac.} \cdot \langle h_-^{1,1} \rangle \cdot \beta_{V^{\frac{1}{4}} > 10^{16}\,\mathrm{GeV}}$$

# of CYs supporting topological requirements of axion monodromy ??

➡ **we know:**

$\beta_{h_{-}^{1,1}>0} < 1$ not all CYs support the topology for axion monodromy

$\beta_{\tilde{r}} \ll 1$ arranging couplings and scales for for large extra tensor signal is non-generic

➡ **we need:**

$$\beta_{flat\ saddle}$$