PHYSICS AT THE END OF THE WORLD

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Swansea

(based on JC, Revello 2207.00567, Apers, JC, Ning, Revello 2202.09330)

Oxford Physics

WHERE IS THE CENTRE OF THE WORLD?

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- N=0 supersymmetry
  Hierarchies
  Weak couplings

Strong coupling

$$AdS_5 \times S^5$$

M-theory

$$g_s \sim 1, \mathrm{Volume} \sim \mathrm{l}_\mathrm{s}^6$$

Black hole entropy

Dualities

$$\mathcal{N} \geq 2 \text{ Supersymmetry}$$

Landau-Ginzburg models

PLAN

- Where is the end of the world?
- What does the end of the world look like?
- How do we get to the end of the world?

PLAN

- Where is the end of the world?

Near the asymptotic boundaries of moduli space

- What does the end of the world look like?

Special! For AdS vacua, distinctive and limited CFTs with special values for conformal dimensions

- How do we get to the end of the world?

Through a long period of kination with exciting phenomenological opportunities

OUR HOME, THE UNIVERSE

- Our universe is *filled* with hierarchies and small numbers

$$\frac{\Lambda_{EW}}{M_P} \sim 10^{-16}$$

$$\frac{\delta\rho_{CMB}}{\rho} \sim 10^{-5}$$

$$\Lambda_{cc} \sim 10^{-120} M_P^4$$

$$\alpha_{SU(3)} \sim \frac{1}{11}, \alpha_{SU(2)} \sim \frac{1}{30}, \alpha_{U(1)_Y} \sim \frac{1}{60}$$

$$y_e \sim 10^{-5}, y_\mu \sim 10^{-3}, y_\tau \sim 10^{-2}$$

$$m_\nu \sim 10^{-3}\text{eV}$$

$$\theta_{QCD} \lesssim 10^{-10}$$

OUR HOME, THE UNIVERSE

- The true string vacuum is the vacuum of *this* universe
- It must contain a method to generate hierarchies, small couplings and small numbers
- This makes the boundaries of moduli space appealing

LIVING AT THE EDGE OF THE WORLD

- The `edge of the world' are the parts of moduli space separated from the $g_s = 1, R = l_s$ centre by field displacements $\Delta\Phi \gg M_P$
- Can vacua exist here with hierarchies and scale separation **(decoupling of KK scale from AdS scale, $m_{KK} \gg R_{AdS}^{-1}$)**? What characterises them?
- Two well-studied examples: DGKT and LVS
  (KKLT not in asymptotic region)
- dS is too hard so focus on AdS version

TWO EXAMPLES

- This talk focuses mainly on two examples. These are especially interesting because they are scale-separated vacua *in asymptotic regions of moduli space.*

- LVS (Large Volume Scenario): interplay of α' and non-perturbative effects in IIB flux vacua to give non-susy AdS vacuum with stabilised volume at $\mathcal{V} \sim e^{\frac{c}{g_s}}$ for some constant c

- Type IIA DGKT flux vacua: flux stabilisation can give large volumes and scale separation (Susy / Non-Susy)

LARGE VOLUME SCENARIO

Balasubramanian, Berglund, JC, Quevedo 2005

- IIB flux compactifications with perturbative corrections to K and non-perturbative corrections to W

$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-2\pi a_i T_i}$$

$$K = -2\ln\left(\mathcal{V} + \xi'\right) + \ln\left(\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S})$$

- Resulting scalar potential has minimum at *exponentially large* values of the volume

$$V = \frac{A\sqrt{\tau_s}\, e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{B\tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{C}{\mathcal{V}^3}$$

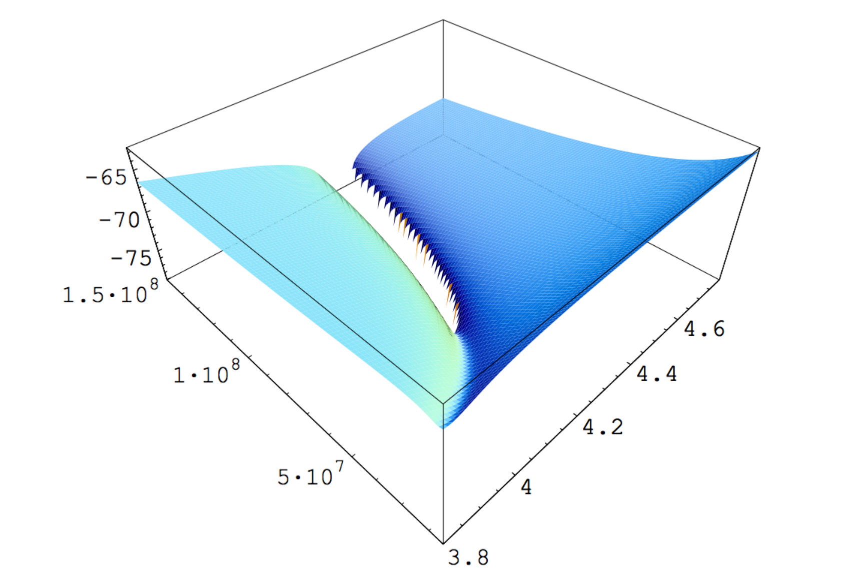


Figure 1: $\ln(V)$ for $P^4_{[1,1,1,6,9]}$ in the large volume limit, as a function of the divisors τ_4 and τ_5. The void channel corresponds to the region where V becomes negative and $\ln(V)$ undefined. As $V \to 0$ at infinite volume, this immediately

DGKT IIA FLUX VACUA

In contrast to type IIB models, in IIA fluxes can generate a potential for all the moduli, and in certain limits give vacua at large volumes with scale separation

De Wolfe, Giryavets, Kachru Trivedi 2005

- $$V = \frac{p^2}{4}\frac{e^{2D}}{k}e^{-\sqrt{2}\sum_i \phi_i} + \left(\sum_i e_i^2 e^{2\sqrt{2}\phi_i}\right)\frac{e^{4D-\sqrt{2}\sum_i \phi_i}}{2k} + \frac{m_0^2}{2}e^{4D}ke^{\sqrt{2}\sum_i \phi_i} - \sqrt{2}\,|m_0 p|\,e^D .$$

$$\mathcal{L}_{axions} = \frac{1}{4}\sum_{i=1}^{3} e^{-2\sqrt{2}\phi_i}\partial_\mu b_i \partial^\mu b_i + \frac{1}{2}e^{2D}\partial_\mu \xi \partial^\mu \xi - \frac{e^{4D}}{\mathscr{V}}\left(b_1 e_1 + b_2 e_2 + b_3 - p\xi\right)^2$$

$$-\frac{e^{4D}}{2}\sum_{i=1}^{3}\left(m_0^2 e^{-2\sqrt{2}\phi_i}\mathscr{V}\, b_i^2 - 2m_0 e^{2\sqrt{2}\phi_i - \sqrt{2}(\phi_1+\phi_2+\phi_3)} b_1 b_2 b_3 \frac{e_i}{b_i}\right).$$

(Cf Marchesano+Quirant 2019, 2020
JC. Ning, Revello 2020
Apers, Montero, van Riet, Wrase 2022

Quirant 2022)

LIVING AT THE EDGE OF THE WORLD

- Take an asymptotic limit (as $\mathbf{Vol} \to \infty$)

  In DGKT, this corresponds to scaling fluxes $N \to \infty$

  In LVS this corresponds to stabilising at $g_s \ll 1$ as stabilised volume satisfies $\mathbf{Vol} \sim \mathrm{e}^{\frac{\xi^{2/3}}{g_s}}$

- Ask about *properties of vacuum from a holographic perspective*

- We **suppose** a dual exists and ask, what is the spectrum of low-lying operators?

HOLOGRAPHY

- CFT dimensions of dual operators:

$$\Delta(\Delta-3)=m_{\Phi}{}^{2}R_{AdS}^{2} \qquad c\to\infty$$

- In infinite volume / asymptotic limit can classify the possible modes in the holographic dual as:

heavy $m_{\Phi}^{2}\gg R_{AdS}^{-2},\Delta\to\infty \quad \text{as} \quad \mathcal{V}\to\infty$

light $m_{\Phi}^{2}\ll R_{AdS}^{-2},\Delta\to 3 \quad \text{as} \quad \mathcal{V}\to\infty$

interesting $m_{\Phi}^{2}\sim R_{AdS}^{-2},\Delta\to\mathcal{O}(1-10) \quad \text{as}\,\mathcal{V}\to\infty$

LVS HOLOGRAPHY

Mode	Spin	Parity	Conformal dimension
$T_{\mu\nu}$	2	+	3
a	0	-	3
Φ	0	+	$8.038 = \frac{3}{2}\left(1+\sqrt{19}\right)$

Table 1. The low-lying single-trace operator dimensions for CFT duals of the Large Volume Scenario in the limit $\mathcal{V} \to \infty$.

In minimal LVS, AdS effective theory has small number of fields which correspond to specific predictions for dual conformal dimensions

No Landscape - properties of low-dimension C FT operators completely fixed!

LVS HOLOGRAPHY

- n-point self interactions of volume modulus

$$\mathcal{L}_{n-pt} = (-1)^{n-1}\lambda^n (n-1)\left(-3\frac{M_P^2}{R_{AdS}^2}\right)\frac{1}{n!}\left(\frac{\delta\Phi}{M_P}\right)^n\left(1+\mathcal{O}\left(\frac{1}{\ln\mathcal{V}}\right)\right)$$

$$\left(\lambda = \sqrt{27/2}\right)$$

- Mixed interactions of volume modulus and axion

$$\mathcal{L}_{\Phi^n aa} = \left(-\sqrt{\frac{8}{3}}\right)^n \frac{1}{2n!}\left(\frac{\delta\Phi}{M_P}\right)^n \partial_\mu a \partial^\mu a$$

- Again, unique form for interactions in large-volume limit: fluxes, W_0, etc all drop out

DGKT IIA FLUX VACUA

- Interestingly, something similar happens with DGKT vacua in large-volume scale-separated limit
- Again, conformal dimensions and 3-point couplings of low-dimension primaries reduce to single values and lose all dependence on fluxes (up to discrete sign choices which determine whether vacuum is Susy or non-Susy)
- The landscape again disappears……

DGKT IIA FLUX VACUA

- Conformal dimensions for saxion sector of stabilised Kahler moduli are

$$\Delta_{\varphi} = (10,6,6,6)$$

- For Kahler axions, dimensions depend on flux signs $sgn(m_0 e_i)$ (which change whether vacuum is Susy or non-Susy)

  Non-susy cases (-1,-1,-1) and (-1,1,1):

$$\Delta_a = (8,8,8,2) \quad \text{or} \quad \Delta_a = (8,8,8,1)$$

  Susy case (1,1,1) and non-susy case (1,-1,-1)

$$\Delta_a = (11,5,5,5)$$

DGKT IIA FLUX VACUA

- Conformal dimensions for saxion sector of stabilised Kahler moduli are $\Delta = (10,6,6,6,\ldots)$ and $\Delta = (11,5,5,5,...)$ for axions.
- Conformal dimensions for complex structure moduli are $\Delta = 2$ for moduli and $\Delta = 3$ for axions.
- Result holds for all Calabi-Yau choices for the extra dimensions

OPEN QUESTIONS

- Not many examples of scale-separated vacua in the asymptotic regions of moduli space - LVS, DGKT - any others?
- Why does DGKT lead to integer conformal dimensions?

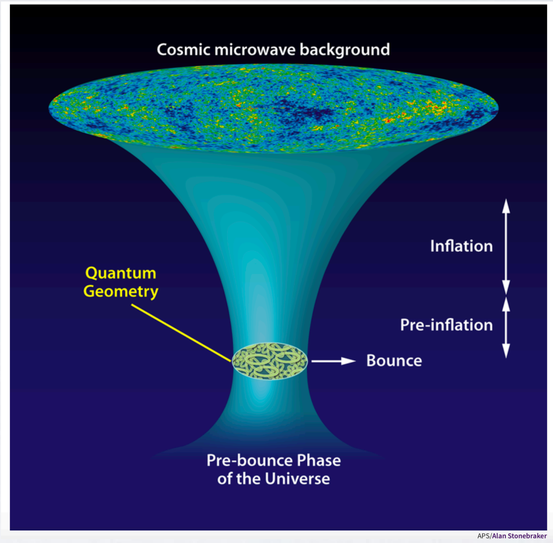
  (Also see M-theory stabilisation, Ning 2206.13332)
- Is this CFT almost-uniqueness a general property of asymptotic vacua? Can this be argued from a CFT side?
- Do these CFT properties rule out uplifts as a way to get to de Sitter?
- Are there any comparable statements for de Sitter vacua?

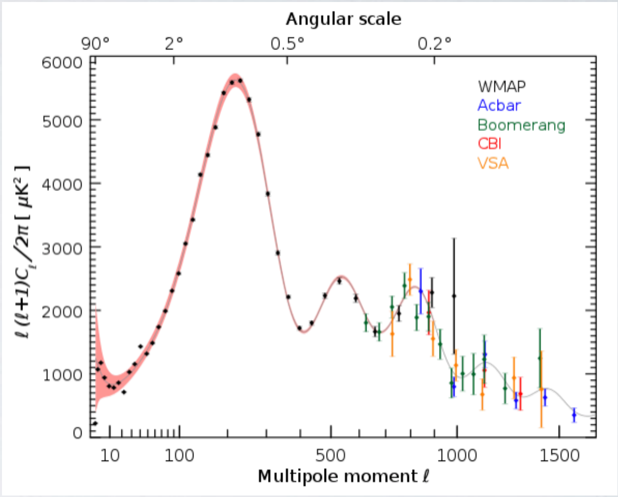
GETTING TO THE END OF THE WORLD

JC, Revello 2207.00567

- Inflation (probably) occurred in the early universe,

$$V_{inf} \lesssim (10^{16}\,\mathrm{GeV})^4$$





- Scales much lower in current universe,

$$m_{3/2} \sim 100\mathrm{TeV}(?),\ V_{barrier} \sim m_{3/2}^{2(3)} M_P^{2(1)} \ll V_{inf}$$

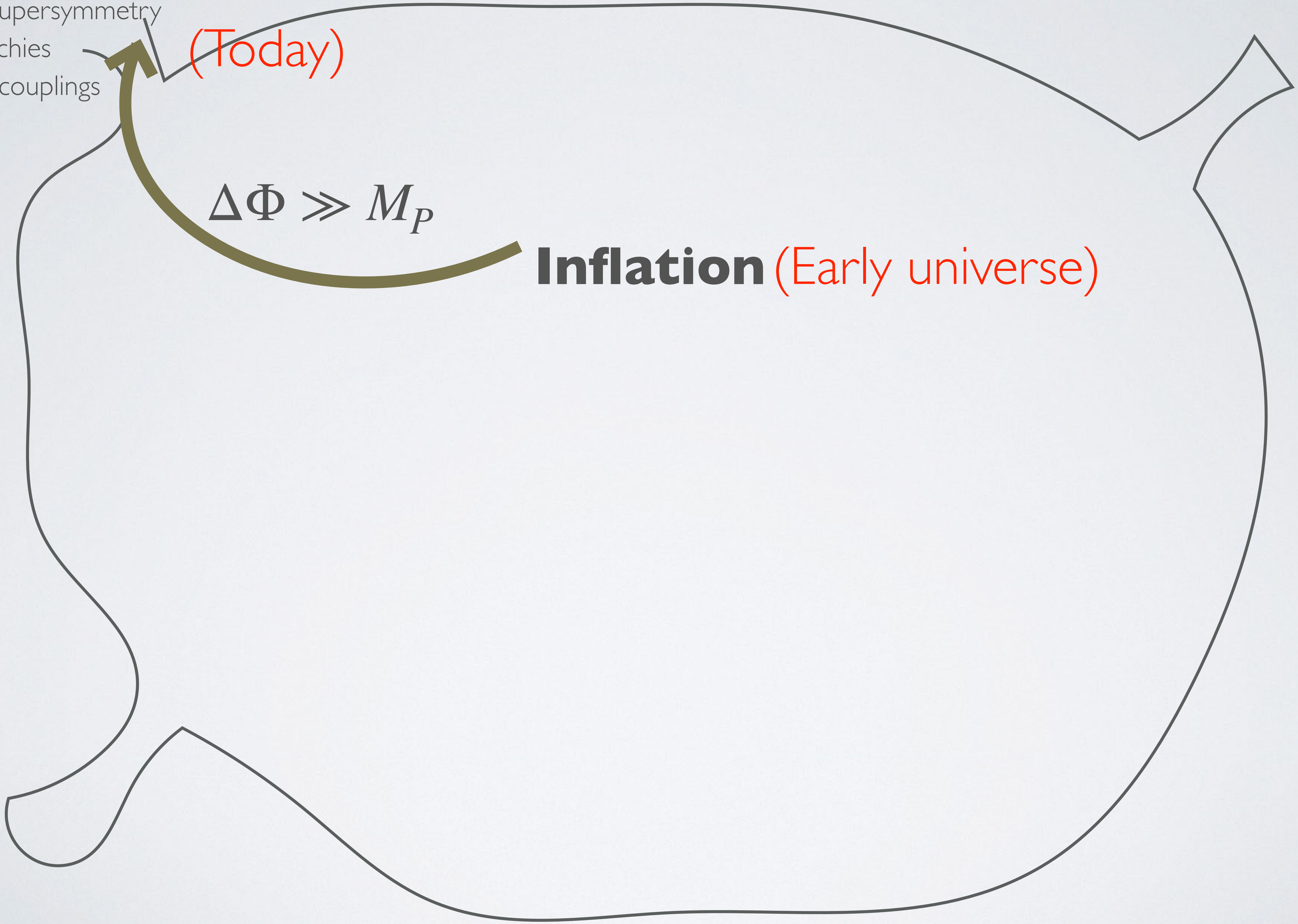
(red) for LVS

- How to go from A to B? (Overshoot Problem!)

Brustein/Steinhardt 1992

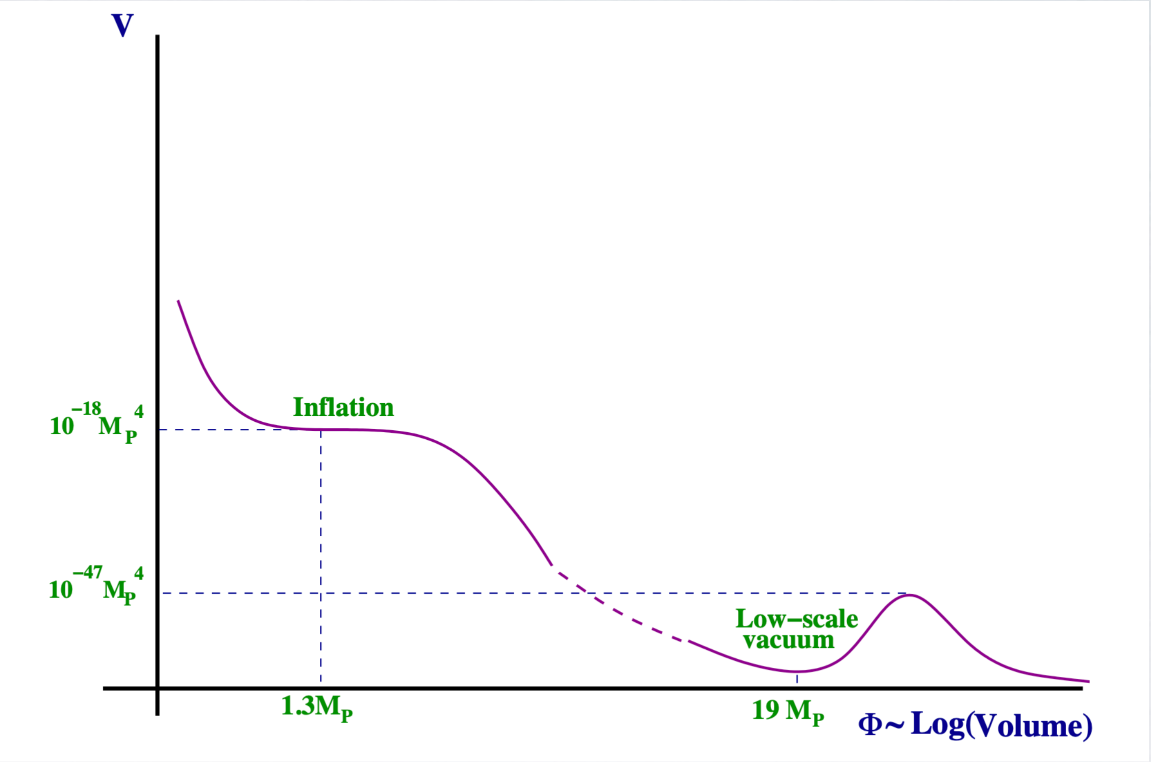
GETTING TO THE CENTRE OF THE WORLD

- N=0 supersymmetry
  Hierarchies
  Weak couplings



GETTING TO THE END OF THE WORLD

- Overshoot problem: how to locate the minimum?



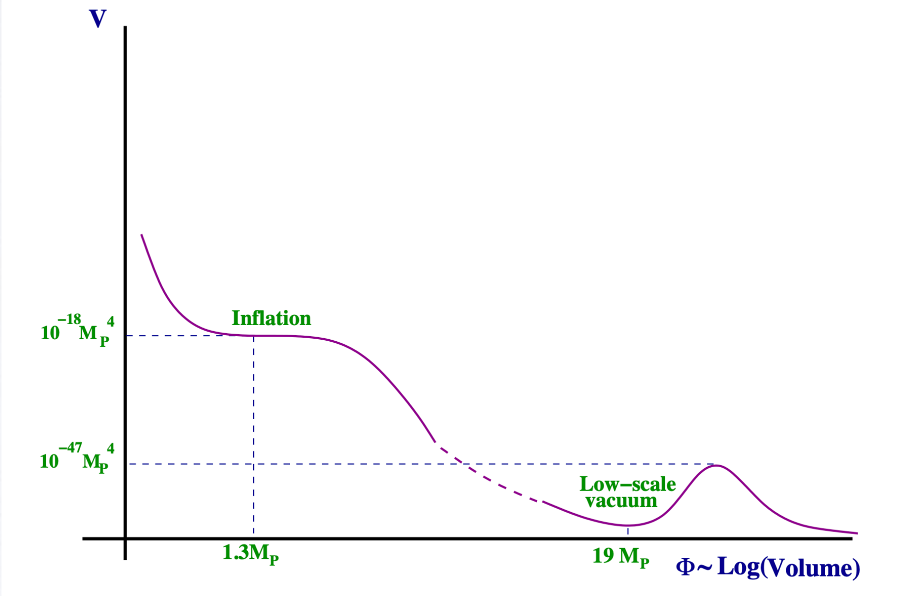
JC, Kallosh, Linde, Quevedo 2008

- Imagine rolling a ball down Mt Everest and trying to trap it in a hole with nanometer sides.

GETTING TO THE END OF THE WORLD

- Overshoot problem: how to locate the minimum?
- We are agnostic about inflation model (discuss later)
- After inflation, field starts rolling down exponential slope

$$V \sim V_0 \exp\left(-\sqrt{\frac{27}{2}}\frac{\Phi}{M_P}\right)$$



- Universe enters a *kination* epoch

$$a(t) \sim t^{1/3}, \qquad \rho_{KE} \sim \frac{1}{a(t)^6}, \qquad \rho_\gamma \sim \frac{\epsilon}{a(t)^4}$$

KINATION

- During roll, with universe in kination epoch, field evolves as

$$\Phi(t) = \Phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

- Field moves through $\sim M_P$ in field space each Hubble time

  Long kination epoch implies large transPlanckian field excursions

- String theorists should **care!** - lots of work on problems and backreactions with trans-Planckian field excursions $\Delta\Phi \gg M_P$ during inflation.

- Much less work on kination epochs and string theory

AVOIDING OVERSHOOT

- During *kination* epoch

$$a(t) \sim t^{1/3}, \qquad \rho_{KE} \sim \frac{1}{a(t)^6}, \qquad \rho_\gamma \sim \frac{\epsilon}{a(t)^4}$$

- Any seed radiation grows relative to kinetic energy and **eventually** catches up, brings universe onto radiation tracker with

$$\Omega_\gamma = \frac{57}{81}, \qquad \Omega_{KE} = \frac{16}{81}, \qquad \Omega_{V(\Phi)} = \frac{8}{81}$$

(Copeland 97, Ferreira+Joyce 97, Wetterich 97)

- Field is evolving as $\Phi(t) = \Phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$

- For small initial ρ_γ , Φ must travel many Planckian distances to reach tracker solution **and avoid overshoot.**

$$\Delta\Phi_{to\ reach\ tracker} = \sqrt{\frac{3}{2}} M_P \ln\left(\frac{\rho_{KE}(t_0)}{\rho_\gamma(t_0)}\right)$$

SOURCES OF SEED RADIATION

- Thermal de Sitter inflationary bath with $T_{dS} = \frac{H_{inf}}{2\pi}$,

$$\rho_{\gamma,init} = \frac{pi^2}{30} g_* \left(\frac{H_{inf}}{2\pi} \right)^4$$

- Perturbative `decays' of volume field to radiation as it starts rolling down exponential slope

$$\Gamma \sim \frac{g_{dec}}{16\pi} \frac{\sqrt{V''(\Phi)}^{3/2}}{M_P^2}$$

- Both result in $\Omega_{\gamma,init} \sim \kappa \frac{H^2}{M_P}$

SOURCES OF SEED RADIATION

- *Gravitational waves emitted by cosmic strings formed at the end of brane inflation*

- Suppose brane inflation ends with production of cosmic superstrings which form a string network with $\rho_{strings,init} \sim \mu H^2$

- String networks enter a scaling regime and lose energy via emission of gravitational radiation

- Here $\mu \sim m_s^2$ is the string tension (could easily be $10^{-4} M_P^2$ at end of inflation)

INTERESTING PHENOMENOLOGY

- Gravitational radiation grows relative to kinetic energy; eventually reach tracker solution for which
$$\Omega_{GW} = \frac{57}{81}$$
- Universe goes through epoch where energy density dominated by gravitational waves (!)
- Fundamental string tension decreases through kination epoch as volume increases (also un-warps warped throats)
- As $\mu \sim m_s^2$ we can today have an LVS fundamental cosmic string network with $10^{-7} \lesssim \mu M_P^2 \lesssim 10^{-11}$ - in reach of upcoming experiments

AN ~~ANTHROPIC~~ ARGUMENT

- Avoiding overshoot requires
  (1) A long distance to roll in, to allow radiation to `catch up' with kinetic energy
  (2) As much initial seed radiation as possible

- In all scenarios, seed radiation scales as $\left(\frac{H}{M_P}\right)^{\alpha}$ - the *higher* the inflationary scale, the more seed radiation

- The lower the 'weak scale' (i.e. minimum and barrier), the *longer* there is roll

- Avoiding overshoot is only possible with a large inflation/weak scale hierarchy

CONCLUSIONS

- If *String Phenomenology* means understanding this universe, the boundaries of moduli space are natural places to live
- CFT analysis suggests such vacua are restrictive in their spectra
- This motivates a distinctive cosmology (a long kination epoch) with interesting phenomenological opportunities

A BAD ARGUMENT

- "You cannot use AdS/CFT arguments when discussing non-susy AdS solutions.

  This is because if AdS is unstable, even to exponentially suppressed processes, then decay is effectively instantaneous and so no CFT can exist:

$$\Gamma_{total} = \int_{AdS} \Gamma_{bubble} \sim \mathrm{Vol(AdS)}\Gamma_{\mathrm{bubble}} \sim \infty \times \Gamma_{\mathrm{bubble}} = \infty$$

  as AdS has infinite volume but a finite travel time from boundary to centre"

A BAD ARGUMENT

- This is a bad physics argument:

1. It relies on the **infinite volume of exact AdS**, and so preserves the perfect AdS structure all the way to the boundary
2. A cosmological evolution to AdS will never produce exact AdS.
3. Holographically, using the infinite volume of AdS is equivalent to exact conformality all the way to the infinite UV.
3. On this argument, CFT techniques have no applicability to a theory that slowly walks its coupling constant over a hundred orders of magnitude in energy but runs in the infinite UV.
4. This is not a good physics argument. Such theories *can* be regarded as approximately conformal in a physics sense
5. One such example is QCD and its friends.