PHYSICS AT THE END OF THE WORLD

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String Pheno 2022
Liverpool

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

Oxford Physics

See parallel talks by Apers, Revello

WHERE IS THE CENTRE OF THE WORLD?

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21st **STRING PHENOMENOLOGY**
Conference **LIVERPOOL | 4 - 8 JULY 2022**

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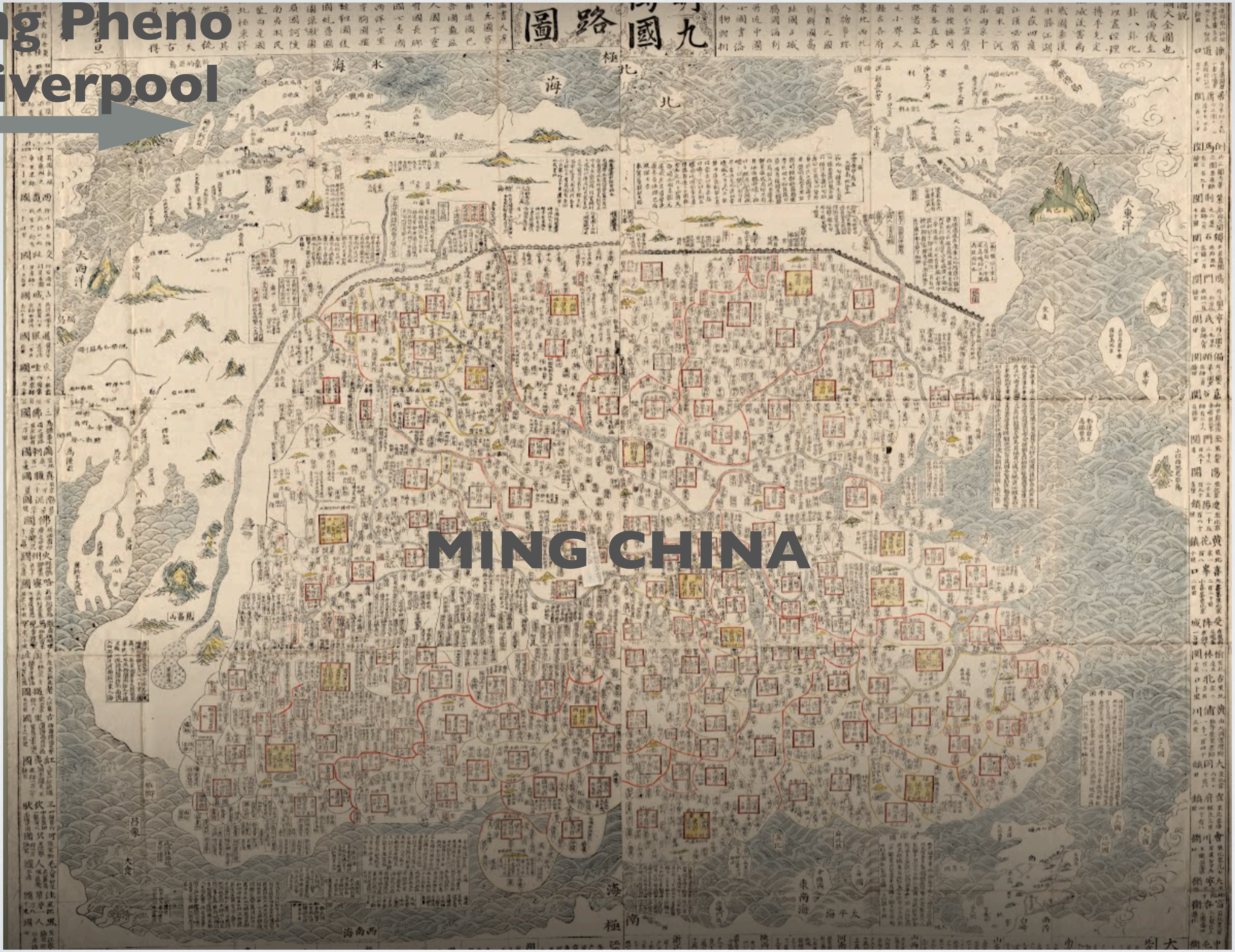


WHERE IS THE CENTRE OF THE WORLD?

- N=0 supersymmetry
  Hierarchies
  Weak couplings

Strong coupling

$$AdS_5 \times S^5$$

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

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? cf Valenzuela talk

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

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

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

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

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

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

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

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

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? What characterises them?
- Two well-studied examples: DGKT and LVS

  (KKLT not in asymptotic region)
- dS is too hard so focus on AdS version

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

LARGE VOLUME SCENARIO

Balasubramanian, Berglund, JC, Quevedo

- 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

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

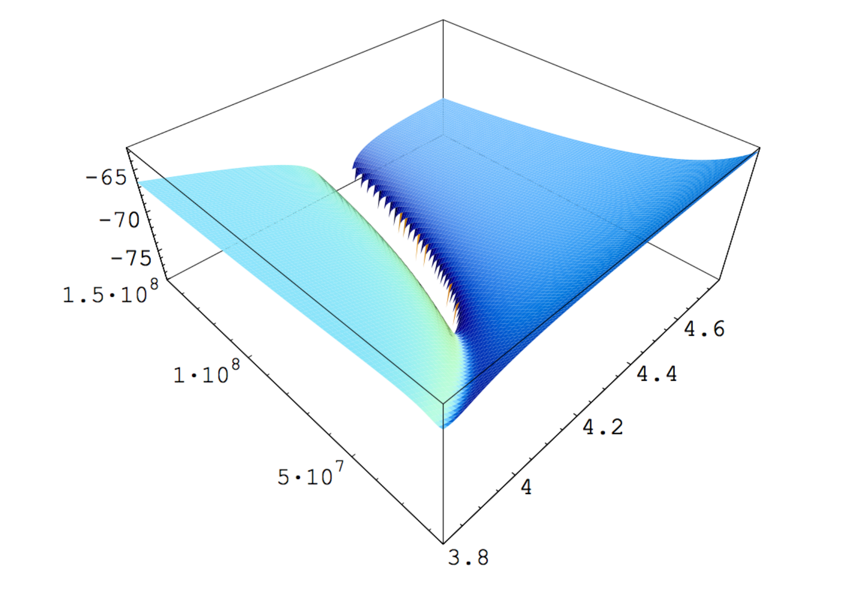


Figure 1: $\ln(V)$ for $P^4_{[1,1,1,6,9]}$ in the large volume limit, as a function of the divisors τ_4 and τ_5. The void channel corresponds to the region where V becomes negative and $\ln(V)$ undefined. As $V \to 0$ at infinite volume, this immediately

cf Hebecker talk

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!

DGKT IIA FLUX VACUA

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

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

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

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

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

Quirant 2022)

van Riet talk
Marchesano talk

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

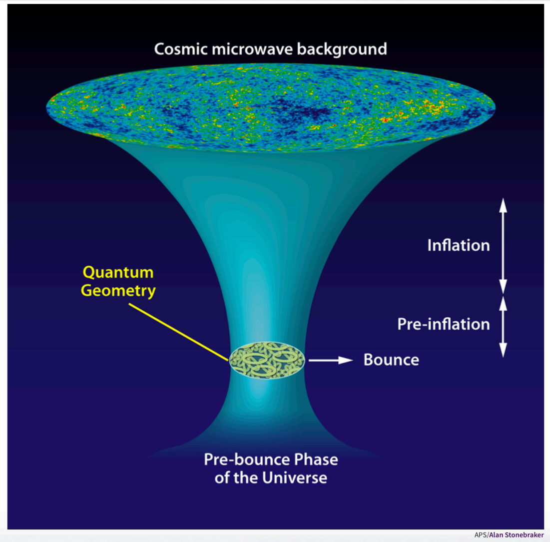
- Not many examples of scale-separated vacua in the asymptotic regions of moduli space - LVS, DGKT - any others?
- Why does DGKT lead to integer conformal dimensions?

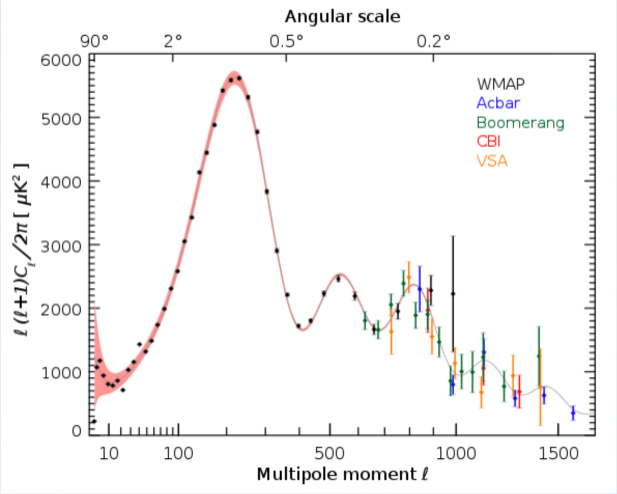
  (Also see M-theory stabilisation, Ning 2206.13332)
- Is this CFT almost-uniqueness a general property of asymptotic vacua? Can this be argued from a CFT side?
- Do these CFT properties rule out uplifts as a way to get to de Sitter?
- Are there any comparable statements for de Sitter vacua?

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,

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

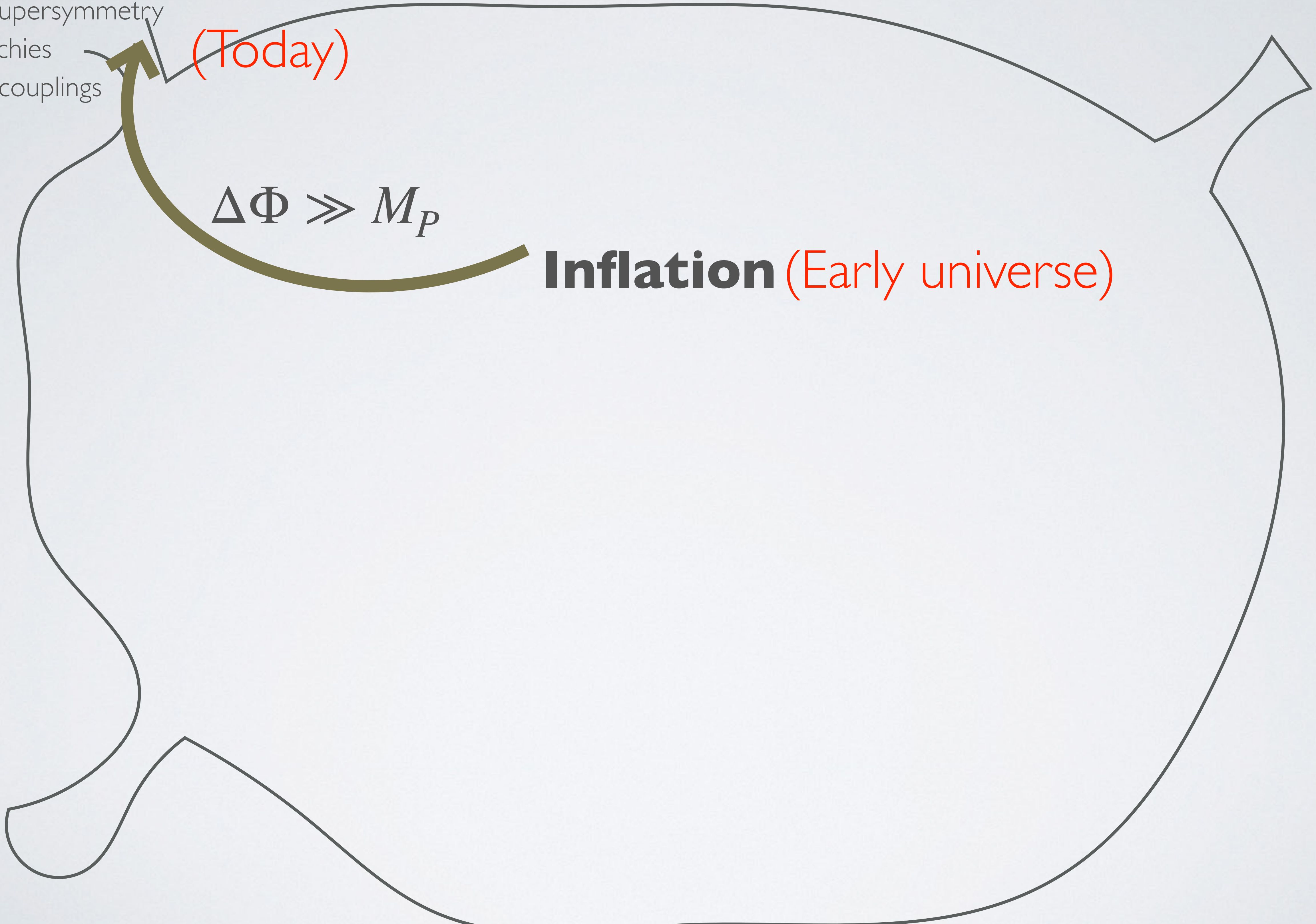
(red) for LVS

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

Brustein/Steinhardt 1992

GETTING TO THE CENTRE OF THE WORLD

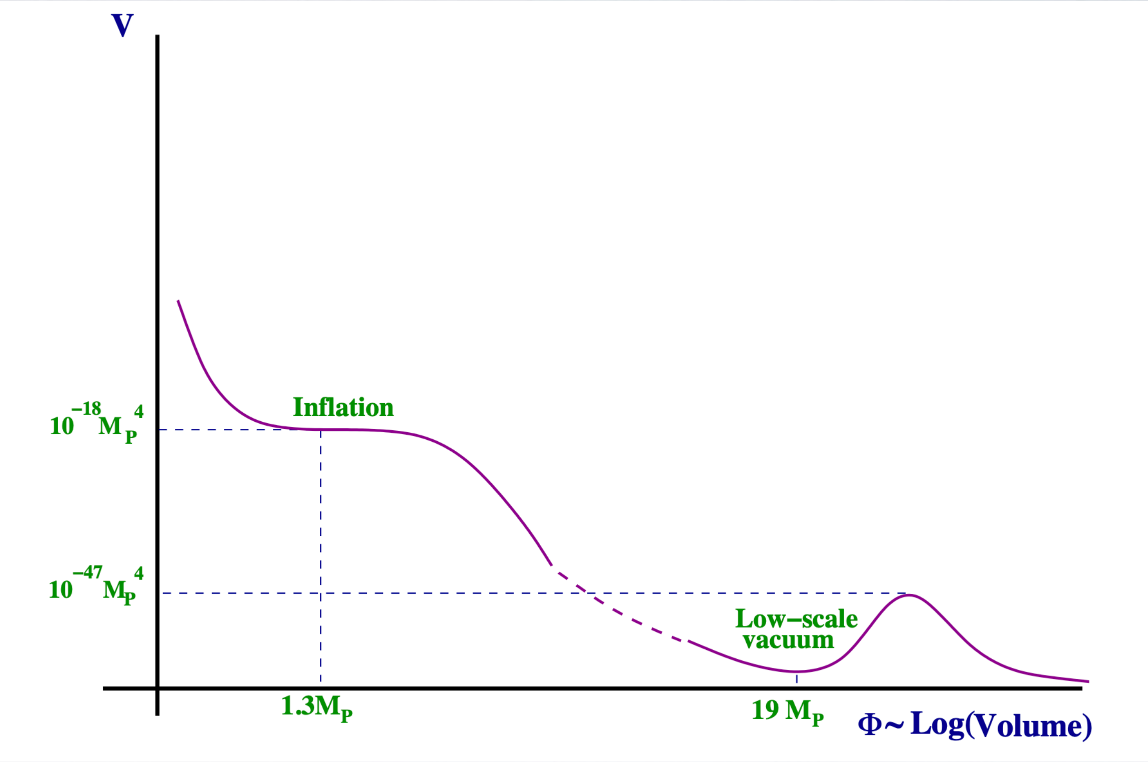
- N=0 supersymmetry
  Hierarchies
  Weak couplings



GETTING TO THE END OF THE WORLD

- Overshoot problem: how to locate the minimum?

cf Quevedo talk



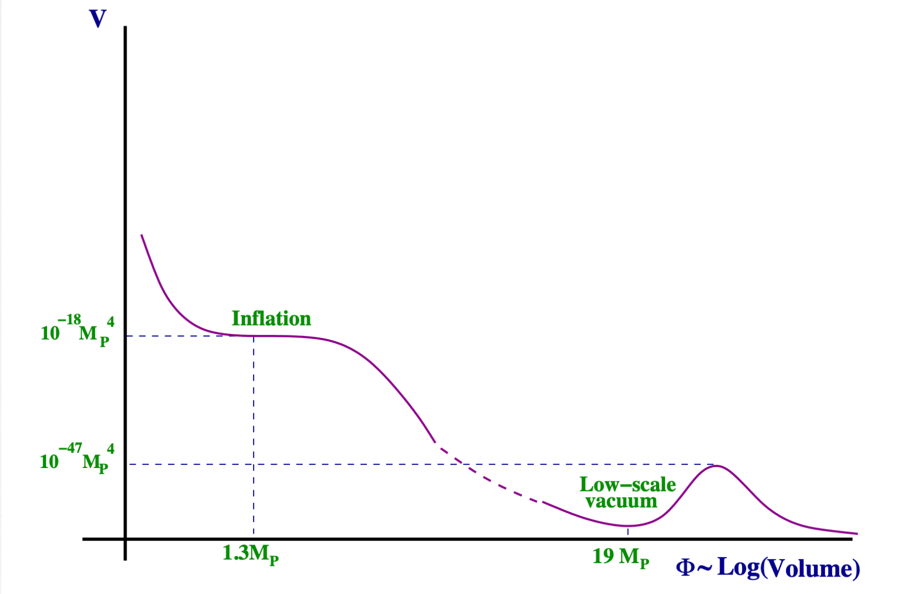
JC, Kallosh, Linde, Quevedo 2008

- 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

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

- 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