

Title: String Theory and the Cosmological Constant

Speakers: Fernando Quevedo

Series: Quantum Gravity

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Abstract: An overview is given on moduli stabilization in string theory with emphasis in obtaining de Sitter space solutions. Recent work on vacuum transitions will be emphasised.

Moduli Stabilisation and String Cosmology

Fernando Quevedo
University of Cambridge

Puzzles in Quantum Gravity Landscape
Perimeter Institute
October 2023

Recent detailed reviews:

M.Cicoli, J. Conlon, A. Maharana, S. Parameswaran, FQ, I. Zavala [2303.04819](#) (Physics Reports to appear)
L. McAllister, FQ (Handbook on Quantum Gravity, next week!)

Recent work on vacuum transitions: with S. Cespedes, S. de Alwis, F. Muia, V. Pasarella

Low energy states in string/M theories

Theory	Dimension	Supercharges	Massless Bosons
Heterotic $E_8 \times E_8$	10	16	g_{MN}, B_{MN}, ϕ A_M^{ij}
Heterotic $SO(32)$	10	16	g_{MN}, B_{MN}, ϕ A_M^{ij}
Type I $SO(32)$	10	16	g_{MN}, ϕ, A_M^{ij} C_{MN}
Type IIA	10	32	g_{MN}, B_{MN}, ϕ C_M, C_{MNP}
Type IIB	10	32	g_{MN}, B_{MN}, ϕ C, C_{MN}, C_{MNPQ}
M-Theory	11	32	g_{MN}, B_{MN}, C_{MNP}

Unique theory, no free parameters.

Q: how to get our 4D world from it?

The String Landscape

10D IIB String EFT

$$S_{10}^{(0)} = \frac{1}{2\kappa_{10}^2} \int \sqrt{-g} \left(\mathcal{R} - \frac{|\nabla\tau|^2}{2(\text{Im}\tau)^2} - \frac{|G_3|^2}{12\text{Im}\tau} - \frac{|F_5|^2}{4\cdot 5!} \right) + \frac{1}{8i\kappa_{10}^2} \int \frac{C_4 \wedge G_3 \wedge \bar{G}_3}{\text{Im}\tau},$$

$$G_3 := F_3 - \tau H_3 \quad F_3 := dC_2, \quad H_3 := dB_2,$$

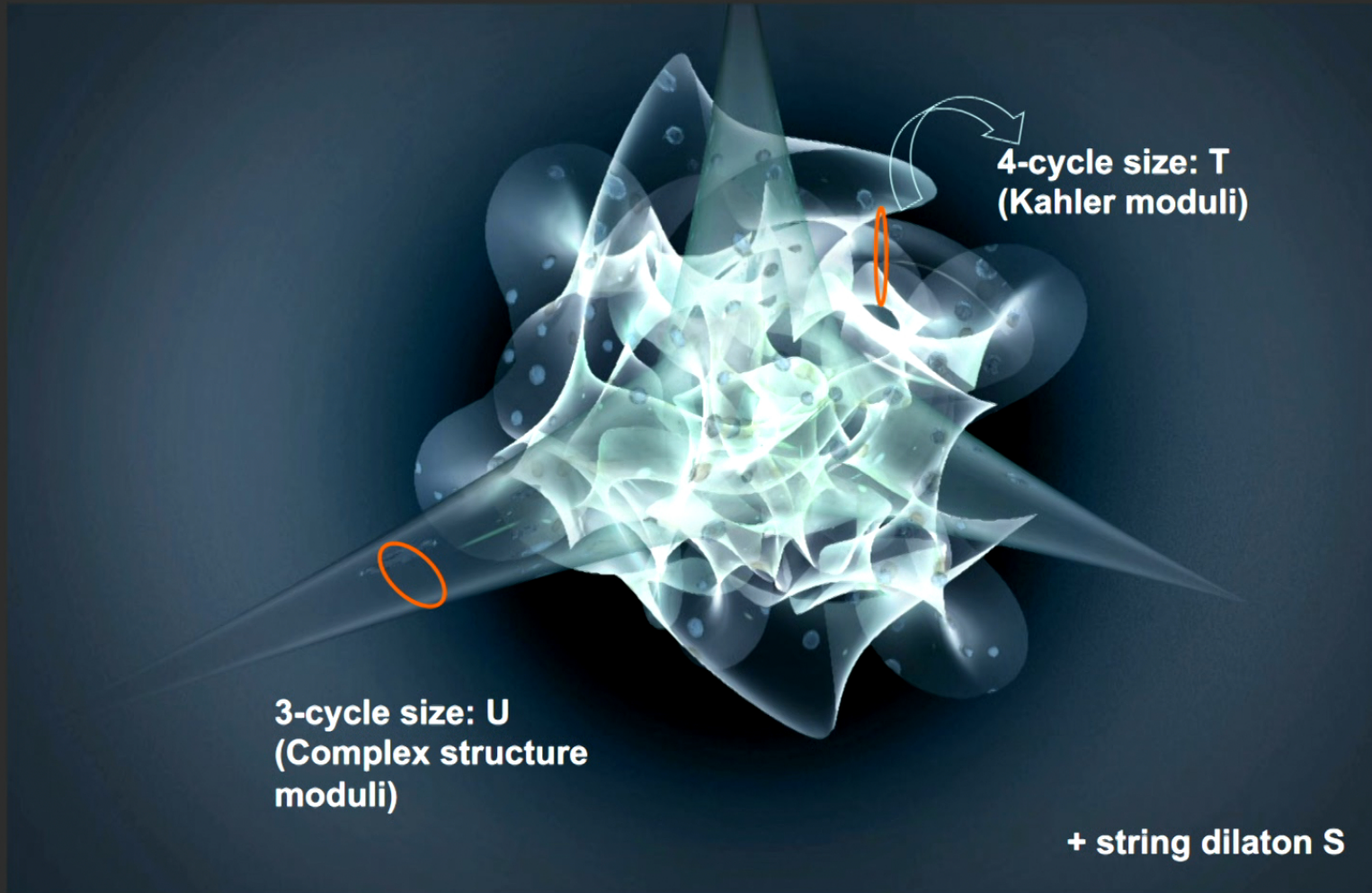
$$\tilde{F}_5 := dC_4 + \frac{1}{2}B_2 \wedge F_3 - \frac{1}{2}C_2 \wedge H_3, \quad \tau := C_0 + ie^{-\phi}.$$

4D Compactifications

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu + g_{mn}(y)dy^m dy^n,$$

Vacuum solutions $R_{\mu\nu} = R_{mn} = 0$ **Flat 4D Minkowski and flat directions: moduli**

Status of moduli stabilisation



IIB: 4D Moduli

10D massless spectrum:

- **NSNS sector:** $g_{MN}, B_2 (dB_2 = H_3), \varphi (e^{\langle\varphi\rangle} = g_s)$
- **RR sector:** $C_0, C_2 (dC_2 = F_3), C_4$

$C_p \leftrightarrow (p-1) \text{ and } (7-p) \text{ D-Branes}$

Compactification to 4D: moduli

- **Axio-dilaton:** $\textcircled{S} = e^{-\varphi} + i C_0$
- **Complex structure moduli:** $\textcircled{U}_\alpha \quad \alpha = 1, \dots, h_{1,2}$
- **Kahler moduli:**

$$\textcircled{T}_i = \tau_i + i b_i, \quad \tau_i = \text{Vol}(D_i), \quad b_i = \int_{D_i} C_4, \quad i = 1, \dots, h_{1,1},$$

Sources of moduli potentials

Fluxes $V(R) \propto R^{-6-2p},$

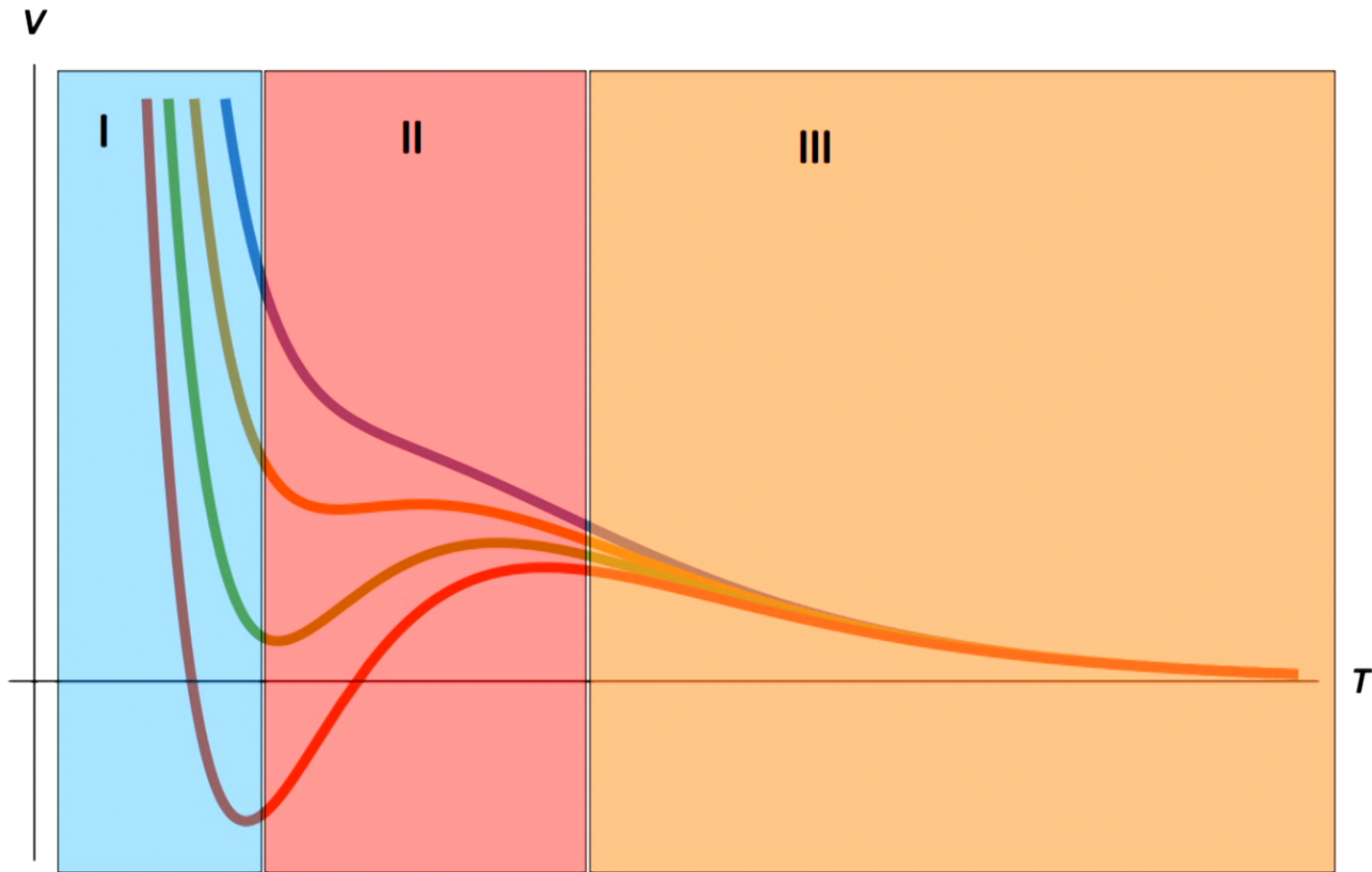
p-branes, Op-planes $V(R) \propto T_p R^{p-15},$

Curvature $V(R) \propto \frac{1}{R^8},$

Perturbative corrections $V(R) \propto \frac{1}{R^{18}}.$

R: typical scale of extra dimensions

Dine-Seiberg Problem



Quick Overview of Flux compactifications

- **Tree-level Kahler potential:**

$$K_{tree} = -2 \ln V(T_i + \bar{T}_i) - \ln(S + \bar{S}) - \ln \left(i \int_{CY} \Omega(U) \wedge \bar{\Omega} \right)$$

- **Tree-level superpotential:**

$$W_{tree} = \int_{CY} G_3 \wedge \Omega(U) \quad G_3 = F_3 + iSH_3$$

- **Flux quantisation:**

$$\frac{1}{2\pi\alpha'} \int_{\Sigma_3^k} H_3 = n_k \quad \frac{1}{2\pi\alpha'} \int_{\Sigma_3^k} F_3 = m_k \quad k = 1, \dots, n = 2h^{1,2} + 2$$

➔ **free parameters** (n_k, m_k)

$$D_S W = 0 \quad D_{U_\alpha} W = 0 \quad \Rightarrow \quad W_0 \equiv \langle W_{tree} \rangle$$

Can fix all U and S
(S ~ m/n >> 1)

$$DW \equiv \partial W + W \partial K$$

$$N_{sol} \approx 10^{2n} = 10^{4(h^{1,2}+1)} \approx 10^{400} \quad \text{for } h^{1,2} \approx O(100)$$

String Landscape

Moduli Stabilisation in IIB String Theory

- **S,U,T Moduli**

$$V_F = e^K \left(K_{M\bar{N}}^{-1} D_M W \bar{D}_{\bar{M}} \bar{W} - 3|W|^2 \right)$$

$$W_{\text{tree}} = W_{\text{flux}}(U, S) \quad K_{i\bar{j}}^{-1} K_i K_{\bar{j}} = 3 \quad \text{No-scale}$$

$$V_F = e^K \left(K_{a\bar{b}}^{-1} D_a W D_{\bar{b}} \bar{W} \right) \geq 0$$

Fix S,U but T flat!

- **Quantum corrections**

$$\delta V \propto W_0^2 \delta K + W_0 \delta W$$

- **Three options:** (i) $W_0 \gg \delta W \quad \delta K \gg \delta W$ **Perturbative Runaway: Dine-Seiberg problem...?**

(ii) $W_0 \sim \delta W = W_{np} = \sum A_i e^{-a_i T_i}$

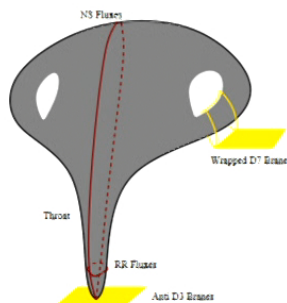
Fix T-modulus: KKL

$W_0 \ll 1$

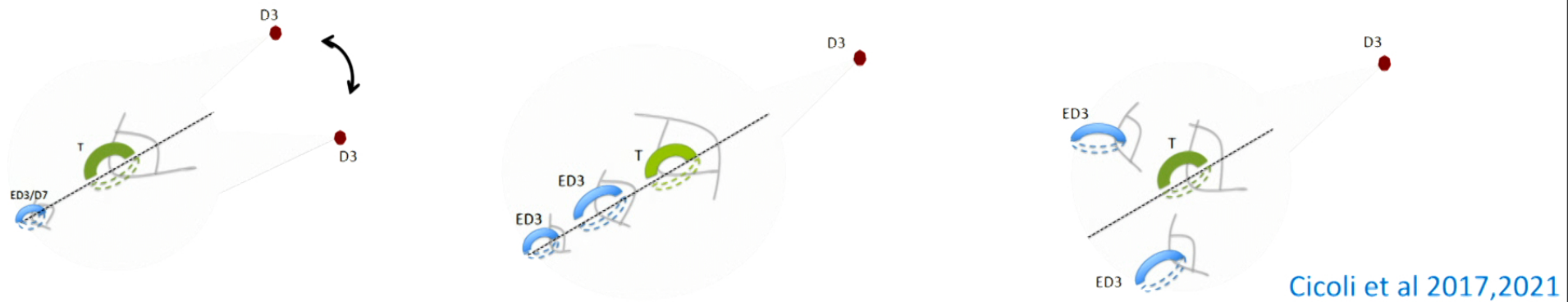
(iii) $\delta K \sim W_0 \delta W$

Fix T-moduli: LVS

$\delta K \sim 1/\mathcal{V}$ and $\delta W \sim e^{-a\tau}$



Embedding in CY compactification with Standard Model brane



De Sitter + ... from String Theory !!

Active debate for many years: 'full control'?

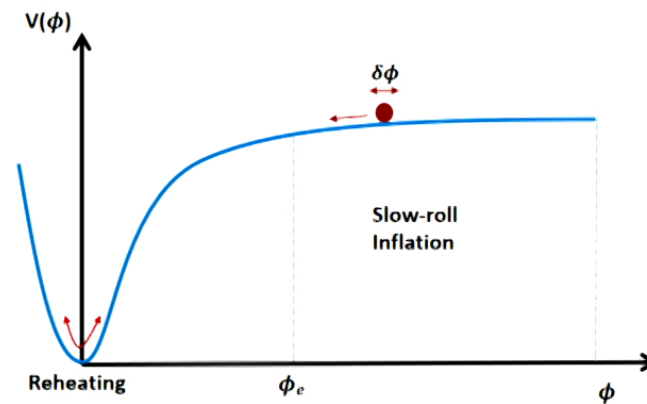
The String Landscape and Dark Energy

- Anthropic prediction $\Lambda \sim 10^{-120}$ (Weinberg 1987)
- Evidence for Dark Energy (1998)
- Concrete proposal (Bousso-Polchinski 2000)
- Explicit String realizations (KKLT, LVS,... 2003+)*

The worst solution to the dark energy problem with the exception of all the others!!!

(see however, C.P. Burgess and FQ [2111.07286](#))

String Inflation



String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N -Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3- $\overline{D3}$ Inflation	0.968	10^{-7}
Inflection Point Inflation	0.923	10^{-6}
D3-D7 Inflation	0.981	10^{-6}
Racetrack Inflation	0.942	10^{-8}
Volume Inflation	0.965	10^{-9}
DBI Inflation	0.923	10^{-7}

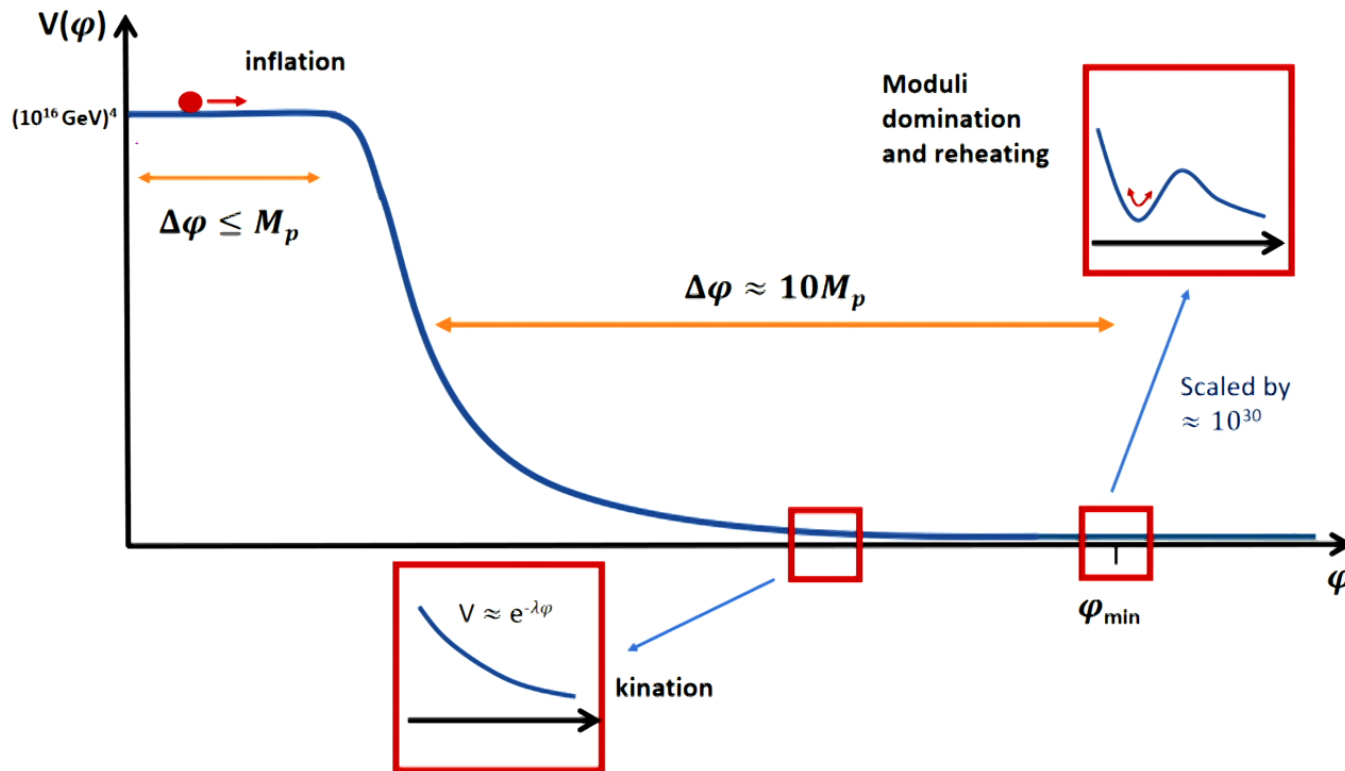
$r_{0.05} < 0.036$ at 95% confidence

$n_s = 0.965 \pm 0.004$.

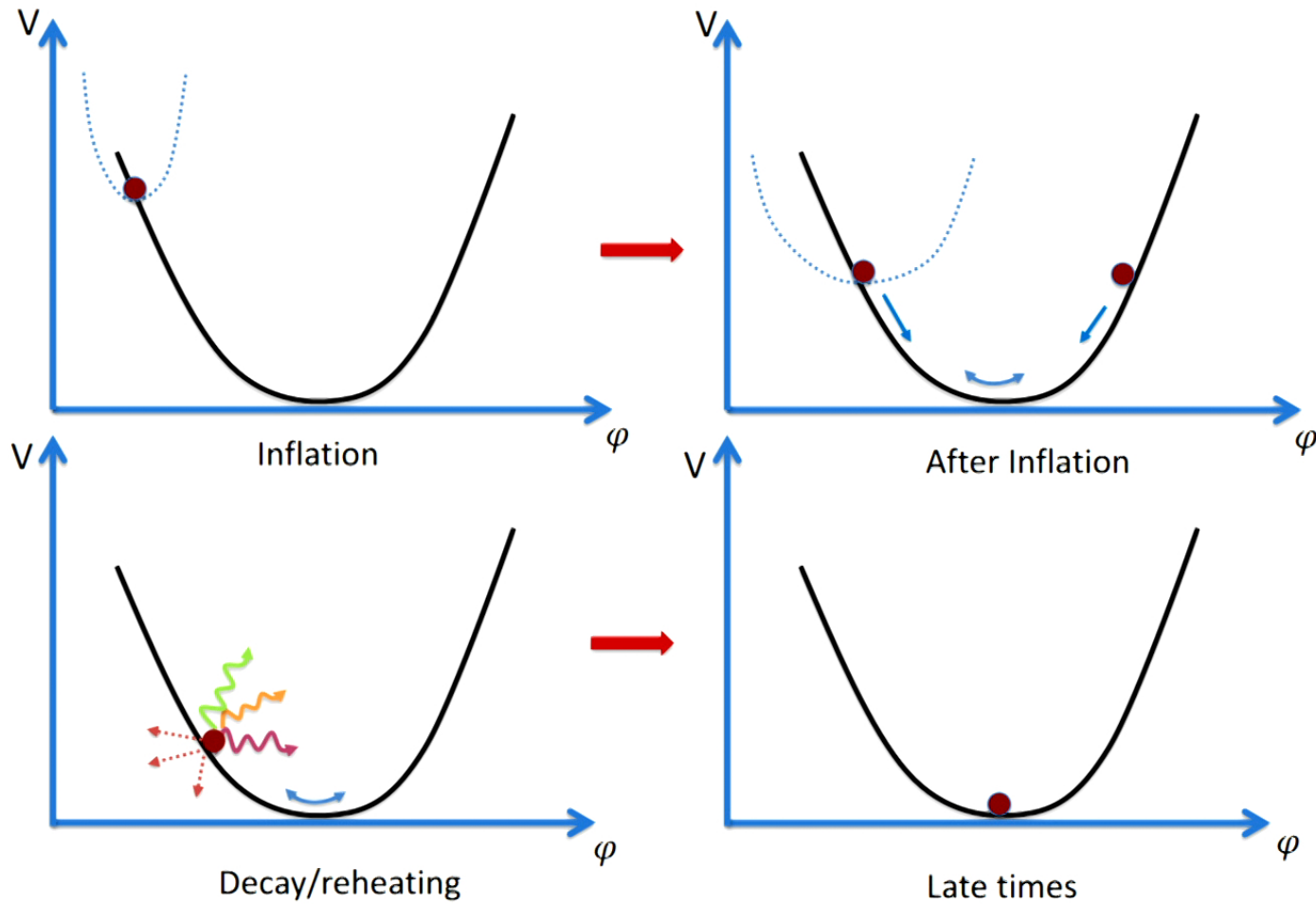
Planck/BICEP 2021

Challenges: eta problem, scales (KL problem), moduli stabilisation, observations?

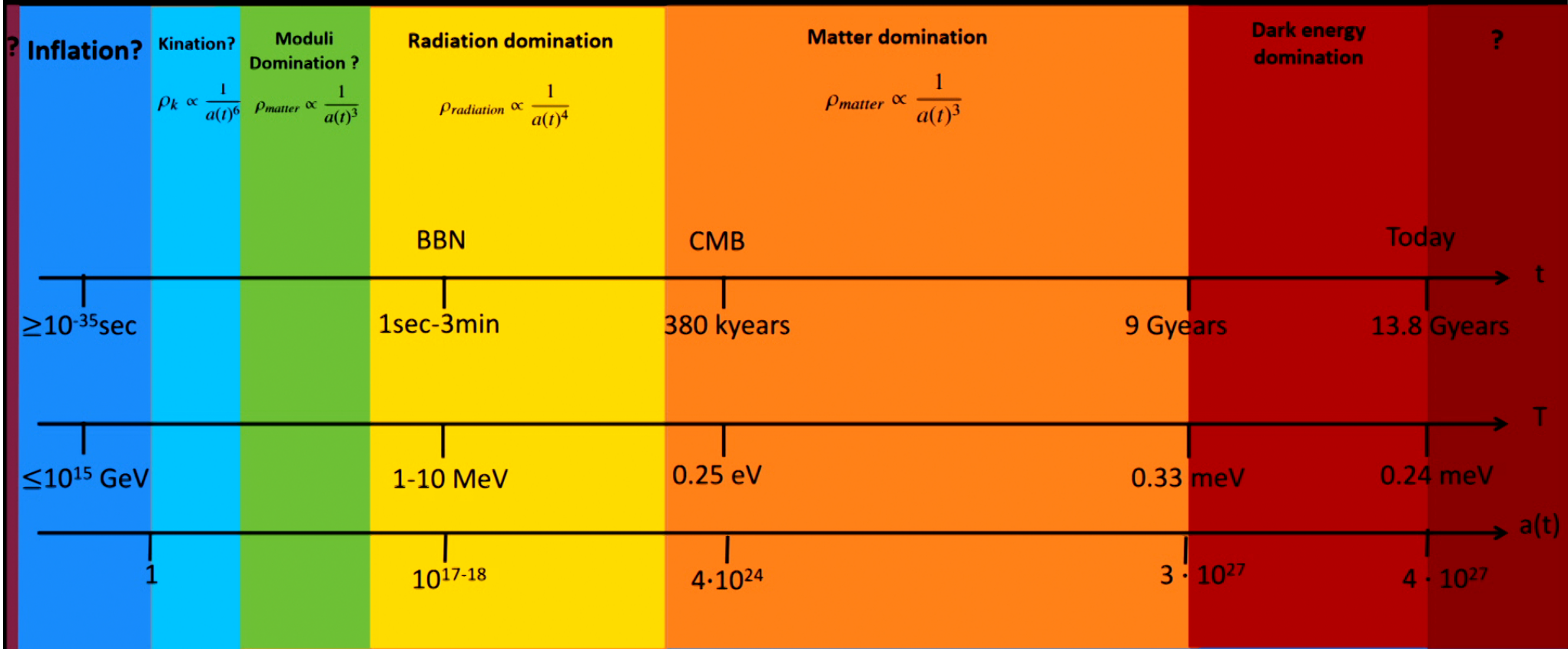
Kination: Kinetic Domination?



Moduli Domination



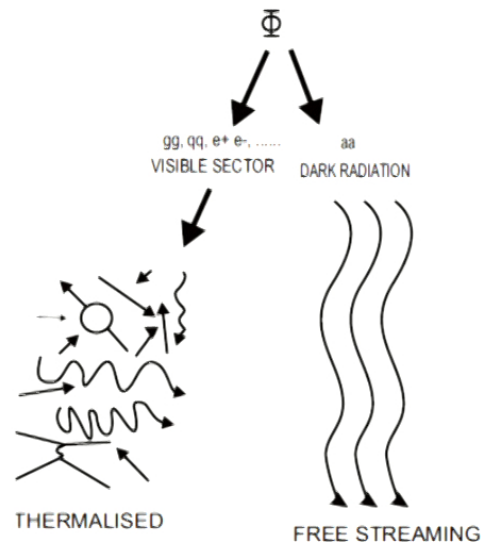
Alternative Histories of the Universe?



Dark Matter ?

- Moduli
- Axions (QCD, fuzzy,...)
- WIMPS
- Primordial black holes
- Hidden sectors (e.g. other branes)

Dark Radiation ?

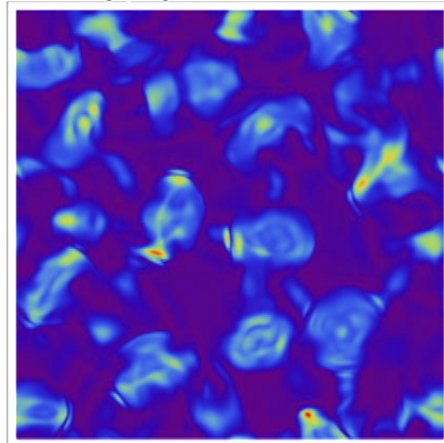


- Axions (ultra light)
- Hidden sector much constrained !!!

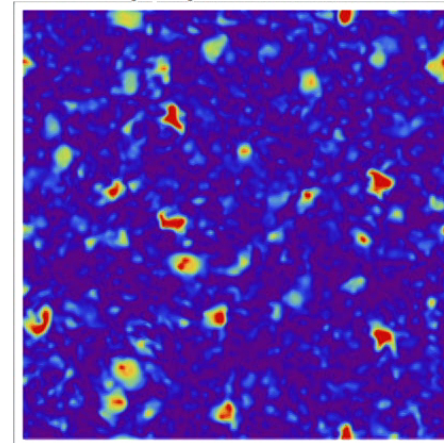
$$\Delta N_{\text{eff}} < 0.2 !$$

Oscillons/Oscillatons

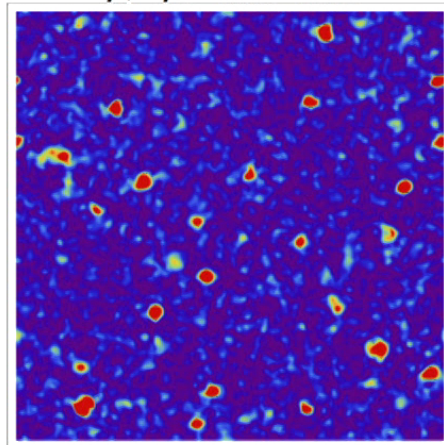
$\rho/\langle\rho\rangle$ at $a=1.26$



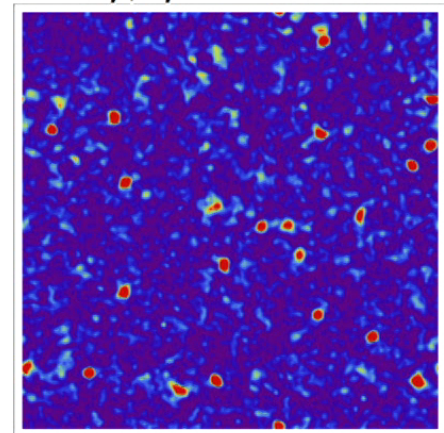
$\rho/\langle\rho\rangle$ at $a=2.$



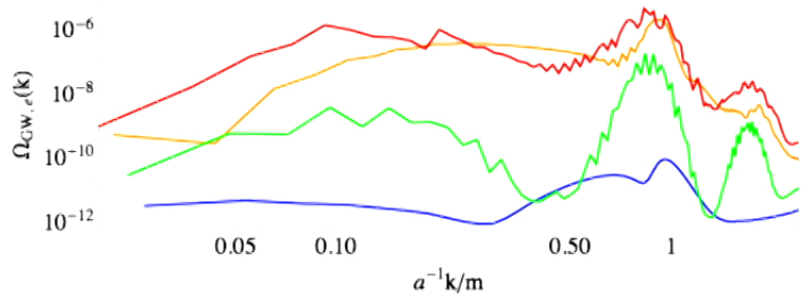
$\rho/\langle\rho\rangle$ at $a=3.02$



$\rho/\langle\rho\rangle$ at $a=4.02$



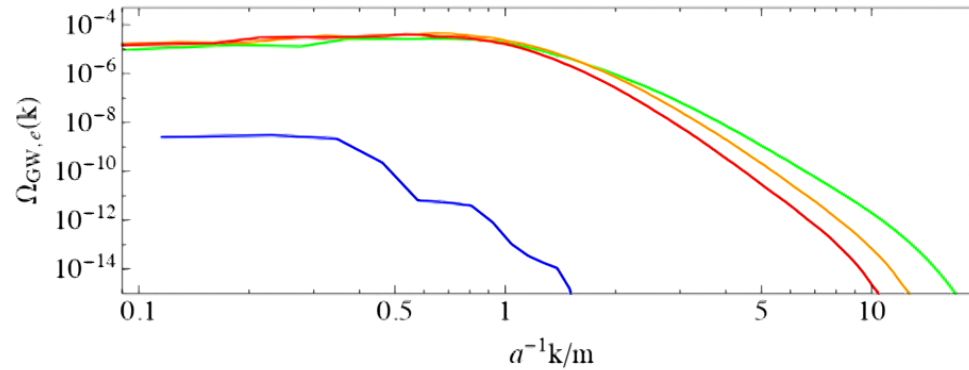
GW spectrum: KKL T



$$f_{0,\text{peak}} \sim 10^9 \text{ Hz}$$

$$\Omega_{\text{GW},0}(f_{0,\text{peak}}) \sim 3 \times 10^{-11}$$

GW spectrum: Blow-up LVS



$$f_0 \sim 10^8 \text{ Hz} - 10^9 \text{ Hz},$$

$$\Omega_{\text{GW},0} \sim 10^{-10} - 5 \times 10^{-10}.$$

Ultra High Frequency Gravitational Waves

CERN-TH-2020-185
THP-2020-28/TH
DESY 20-195

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

N. Aggarwal^{a,*}, O.D. Aguiar^b, A. Bauswein^c, G. Cella^d, S. Clesse^e, A.M. Cruise^f, V. Domcke^{g,h,i,*},
D.G. Figueroa^j, A. Geraci^k, M. Goryachev^l, H. Grote^m, M. Hindmarsh^{n,o}, F. Muia^{p,q,*}, N. Mukund^r,
D. Ottaway^{s,t}, M. Peloso^{u,v}, F. Quevedo^{w,x}, A. Ricciardone^{y,z}, J. Steinlechner^{aa,ab,ac,*}, S. Steinlechner^{ad,ae,*},
S. Sun^{af}, M.E. Tobar^{ag}, F. Torrenti^{ah}, C. Unal^{ai}, G. White^{aj}

Abstract

The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. This white paper outlines the challenges and gains expected in gravitational wave searches at frequencies above the LIGO/Virgo band, with a particular focus on the MHz and GHz range. The absence of known astrophysical sources in this frequency range provides a unique opportunity to discover physics beyond the Standard Model operating both in the early and late Universe, and we highlight some of the most promising gravitational sources. We review several detector concepts which have been proposed to take up this challenge, and compare their expected sensitivity with the signal strength predicted in various models. This report is the summary of the workshop *Challenges and opportunities of high frequency gravitational wave detection* held at ICTP Trieste, Italy in October 2019.

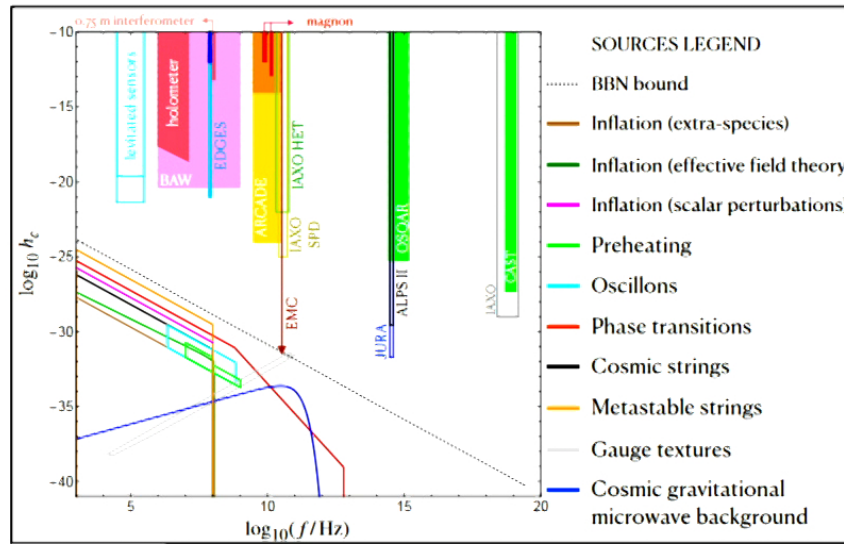
arXiv:2011.12414v1 [gr-qc] 24 Nov 2020

See also:

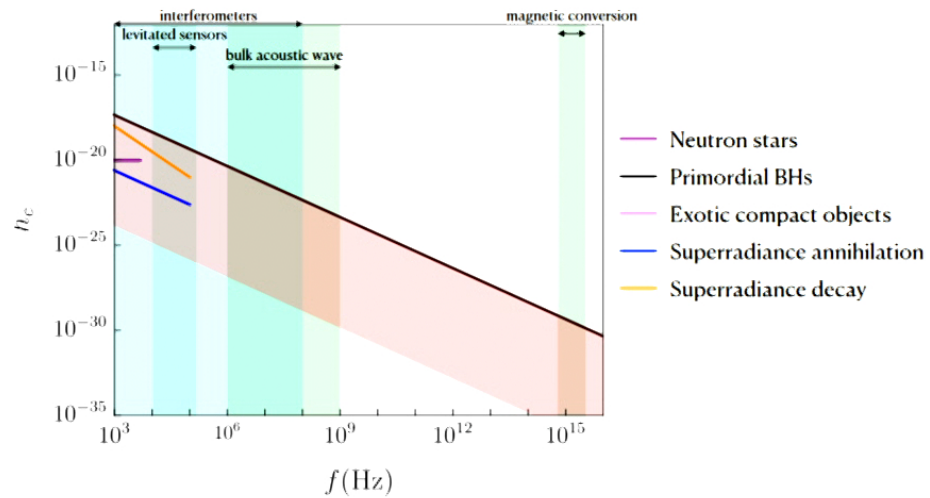
<https://indico.cern.ch/event/1257532/>

*Corresponding authors: Nancy Aggarwal nancy.aggarwal@northwestern.edu, Valerie Domcke valerie.domcke@cern.ch, Francesco Muia fm5389@damtp.cam.ac.uk, Fernando Quevedo fq201@damtp.cam.ac.uk, Jessica Steinlechner jessica.steinlechner@ligo.org, Sebastian Steinlechner s.steinlechner@maastrichtuniversity.nl

Cosmological sources of stochastic High Frequency Gravitational Waves

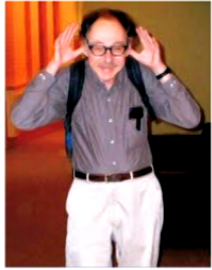


Sources of Coherent Gravitational Waves

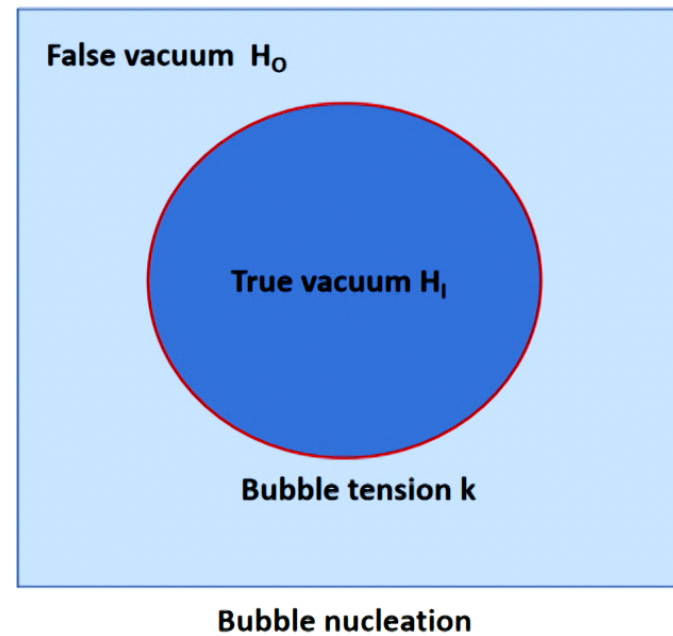
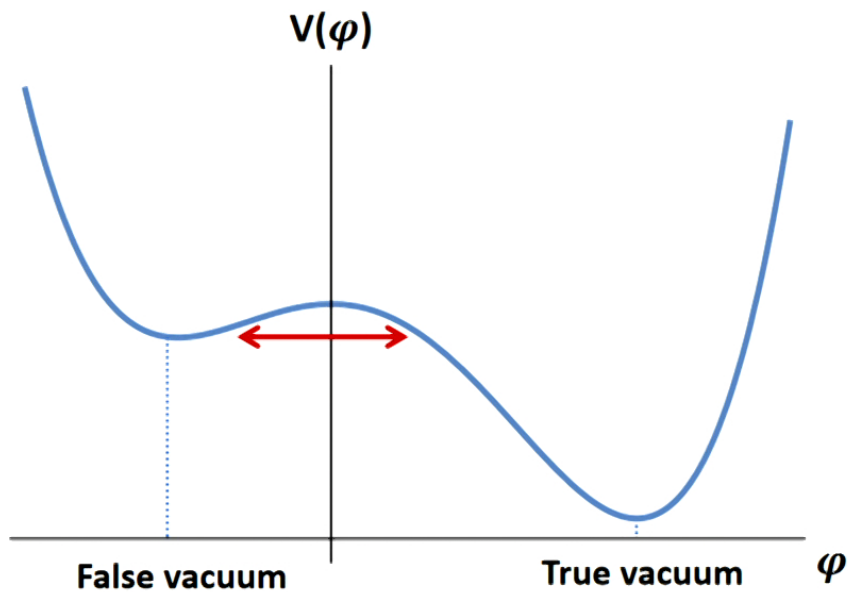


Vacuum Transitions in the Landscape?

Vacuum Transitions



Coleman
1970's-1980s

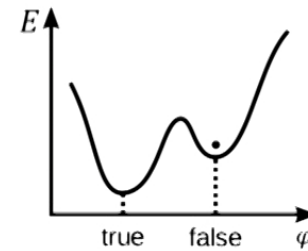


The beginning and end of **our** universe?

Vacuum transitions in the Landscape

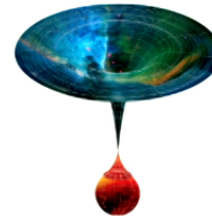
1. Transition between two minima of scalar potential

Coleman-De Luccia 1980

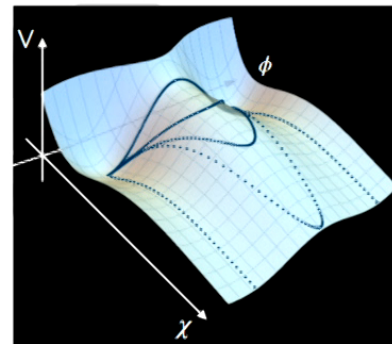
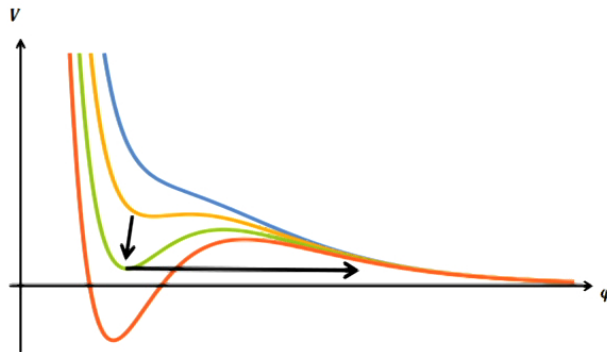


2. No scalar field: M_1 to M_1 +Wall+ M_2

Brown-Teitelboim 87



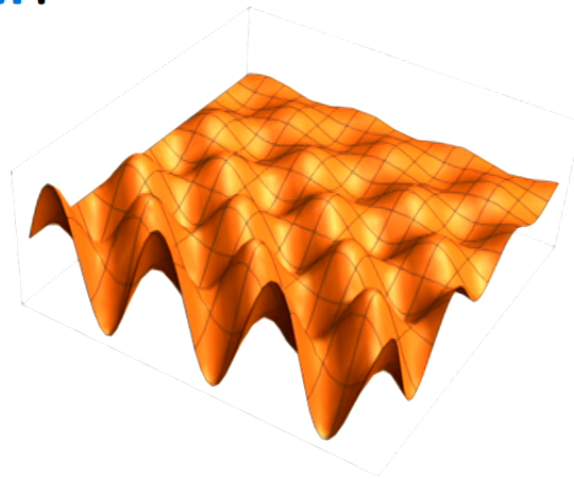
Both realised in string landscape



Approximate picture

Predictions from the landscape?

- Bubble nucleations imply **open universe!**
- Not possible to **tunnel up** from Minkowski nor anti de Sitter.



Hamiltonian Approach

Fischler, Morgan, Polchinski 1990

Metric $ds^2 = -N_t^2(t, r)dt^2 + L^2(t, r)(dr + N_r dt)^2 + R^2(t, r)d\Omega_2^2$, **Spherically symmetric**

Action $S_{\text{tot}} = \frac{1}{16\pi G} \int_{\mathcal{M}} d^4x \sqrt{g} \mathcal{R} + \frac{1}{8\pi G} \int_{\partial\mathcal{M}} d^3y \sqrt{h} K + S_{\text{mat}} + S_{\text{W}}$

$$S_{\text{W}} = -4\pi\sigma \int dt dr \delta(r - \hat{r}) [N_t^2 - L^2(N_r + \dot{\hat{r}})^2]^{1/2} \quad S_{\text{mat}} = -4\pi \int dt dr LN_t R^2 \rho(r), \quad \rho = \Lambda_0 \theta(r - \hat{r}) + \Lambda_1 \theta(\hat{r} - r)$$

Conjugate variables

$$\pi_L = \frac{N_r R' - \dot{R}}{GN_t} R, \quad \pi_R = \frac{(N_r LR)' - \partial_t(LR)}{GN_t},$$

$$\mathcal{H}_g = \frac{GL\pi_L^2}{2R^2} - \frac{G}{R}\pi_L\pi_R + \frac{1}{2G} \left[\left(\frac{2RR'}{L} \right)' - \frac{R'^2}{L} - L \right]$$

$$P_g = R'\pi_R - L\pi_L'.$$

Constraints

$$\mathcal{H} = \mathcal{H}_g + 4\pi LR^2 \rho(r) + \delta(r - \hat{r})E = 0,$$

$$P = P_g - \delta(r - \hat{r})\hat{p} = 0,$$

$$E = \sqrt{\frac{\hat{p}^2}{L^2} + m^2}, \quad m = 4\pi\sigma \hat{R}^2, \quad \hat{p} = \partial\mathcal{L}/\partial\dot{\hat{r}}$$

e.g. dS to dS

Hamiltonian approach=Euclidean approach :

$$\Gamma \sim e^{-B}, \quad B = S[\text{instanton}] - S[\text{background}]$$

$$B = \frac{\pi}{2G} \left[\frac{[(H_0^2 - H_1^2)^2 + \kappa^2(H_0^2 + H_1^2)] R_0}{4\kappa H_0^2 H_1^2} - \frac{1}{2} (H_1^{-2} - H_0^{-2}) \right]$$

$$R_0^2 = \frac{4\kappa^2}{(H_0^2 - H_1^2)^2 + 2\kappa^2(H_0^2 + H_1^2) + \kappa^4}$$

Analytic continuation from Euclidean to Lorentzian implies open universe but just a “guess” (O(4) symmetry)

Transitions: Standard Lore

M_1 to M_2	Anti de Sitter	Minkowski	de Sitter
Anti de Sitter	Yes (bound on wall tension)	No	No
Minkowski	Yes	–	No
de Sitter	Yes	Yes	Yes

Bubble Universe is open!

From Hamiltonian Approach

M_1 to M_2	Anti de Sitter	Minkowski	de Sitter
Anti de Sitter	Yes (bound on wall tension)	Yes?	Yes?
Minkowski	Yes	–	Yes ?
de Sitter	Yes	Yes	Yes

Bubble Universe is open, closed!
(‘nothing’ of bubble of nothing = ‘nothing’ of creation out of nothing!?)

Conclusions

- **Moduli fields: low energy remnants from string compactifications**
- **Inflaton candidates**
- **Change post-inflation cosmology**
- **Source string landscape: dark energy**
- **Vacuum transitions in landscape rich subject**
- **Ultra high frequency gravitational waves: the future!**
- **Many open questions (EFT of alternatives to inflation, Hamiltonian approach to vacuum decay, fully trustable de Sitter, spatial curvature of our universe...)**