Moduli Stabilisation and String Cosmology

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Puzzles in Quantum Gravity Landscape
Perimeter Institute
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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

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

$$G_3 := F_3 - \tau H_3 \qquad F_3 := \mathrm{d}C_2\,, \qquad H_3 := \mathrm{d}B_2\,,$$

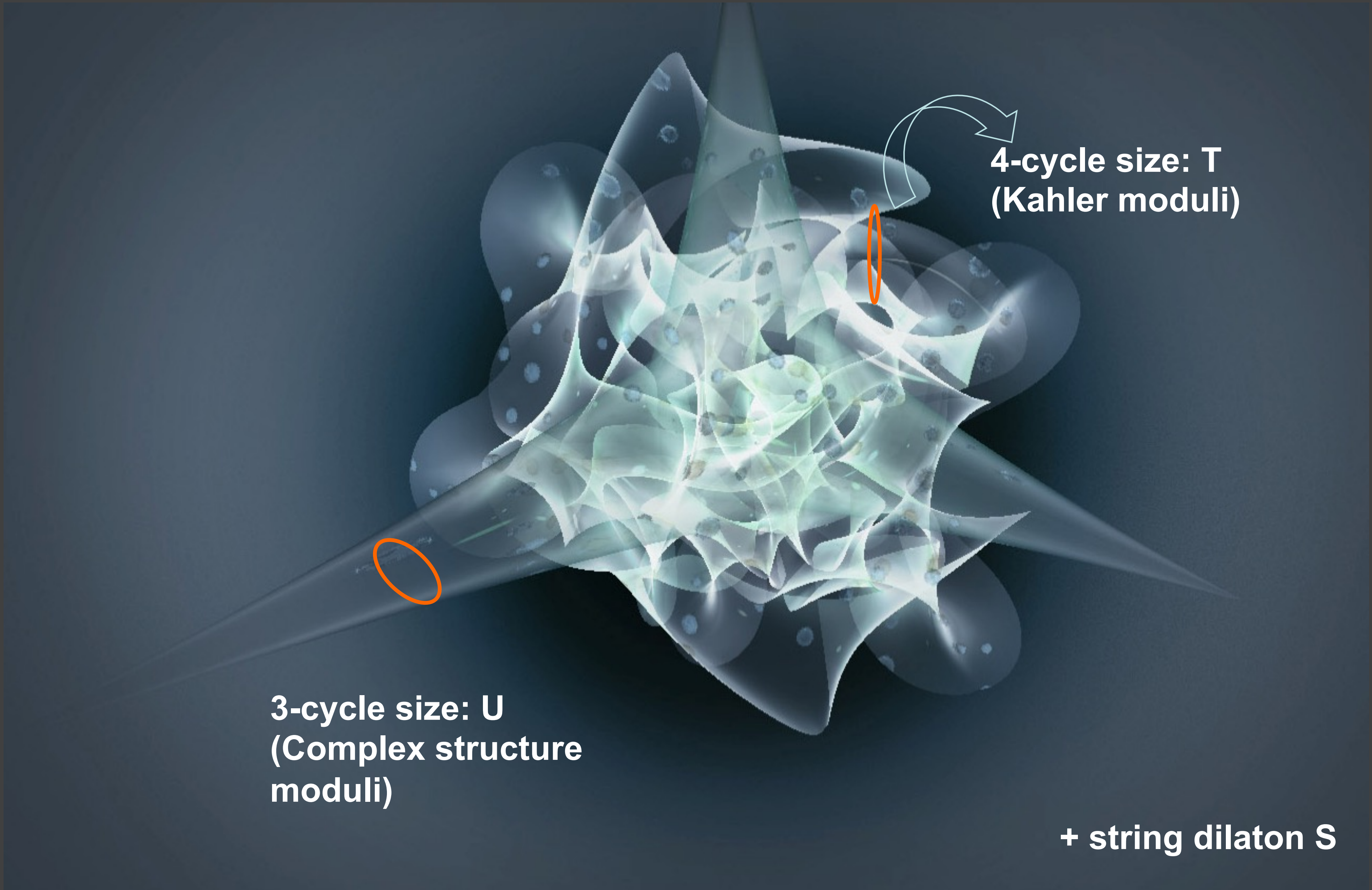
$$\tilde{F}_5 := \mathrm{d}C_4 + \frac{1}{2}B_2\wedge F_3 - \frac{1}{2}C_2\wedge H_3\,, \qquad \tau := C_0 + ie^{-\phi}\,.$$

4D Compactifications

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

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

Status of moduli stabilisation



IIB: 4D Moduli

10D massless spectrum:

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

$C_p \leftarrow\rightarrow$ (p-1) and (7-p) D-Branes

Compactification to 4D: moduli

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

$$T_i = \tau_i + i\, b_i\ , \quad \tau_i = \mathrm{Vol}(D_i), \quad b_i = \int_{D_i} C_4, \quad i = 1, \dots, h_{1,1},$$

Sources of moduli potentials

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

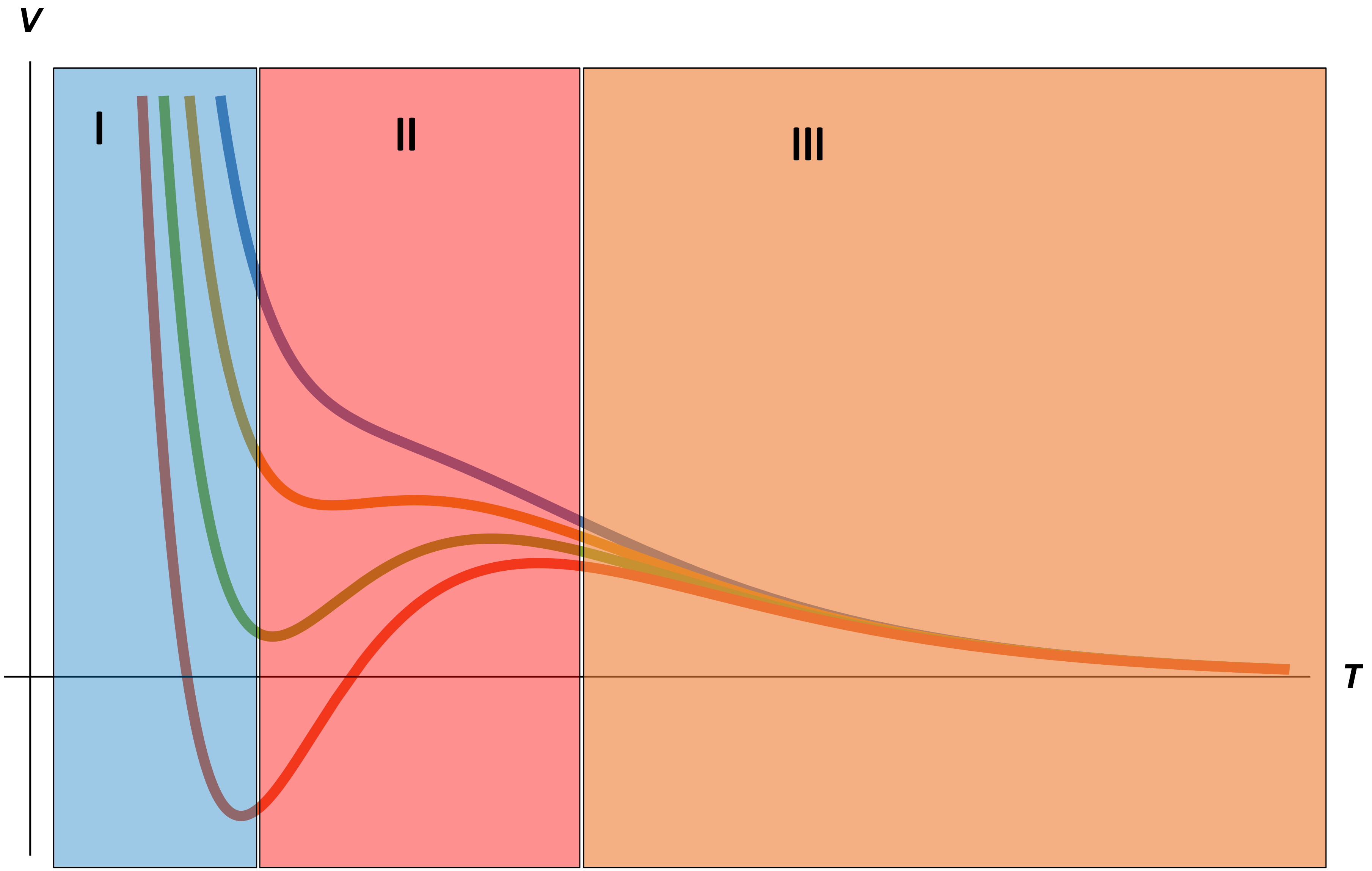
p-branes, Op-planes $$V(R) \propto T_p R^{p-15},$$

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:**

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

- **Tree-level superpotential**:

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

- **Flux quantisation:**

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

$\Rightarrow$ **free parameters** (n_k, m_k)

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

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

Can fix all U and S ($\mathrm{S} \sim m/n \gg 1$)

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

String Landscape

Moduli Stabilisation in IIB String Theory

- **S,U,T Moduli**

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

$$W_{\rm tree} = W_{\rm flux}(U,S) \qquad K^{-1}_{i\bar{j}} K_i K_{\bar{j}} = 3$$

No-scale

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

Fix S,U but T flat!

- **Quantum corrections** $\delta V \propto W_0^2 \delta K + W_0 \delta W$

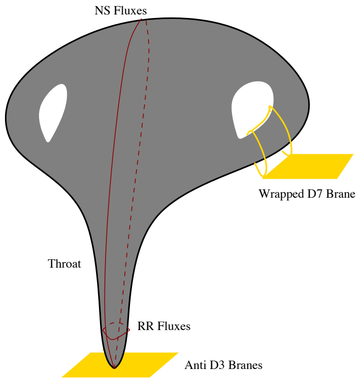
- **Three options:** **(i)** $W_0 \gg \delta W \quad \delta K \gg \delta W$ **Perturbative Runaway: Dine-Seiberg problem…?**

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

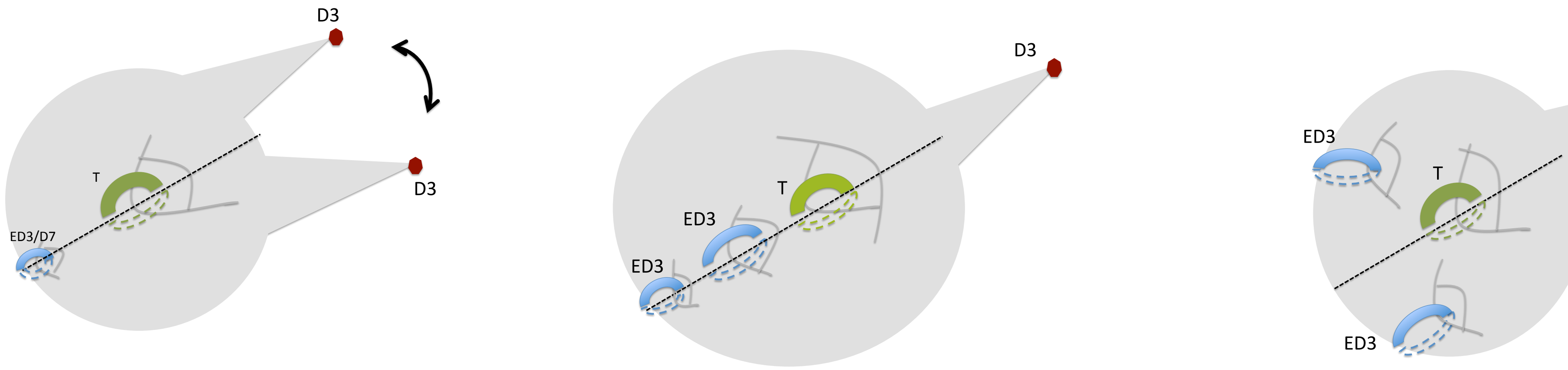
$W_0 \ll 1$ **Fix T-modulus: KKLT**

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

$\delta K \sim 1/\mathcal{V}$ and $\delta W \sim e^{-a\tau}$ **Fix T-moduli: LVS**



Embedding in CY compactification with Standard Model brane



Cicoli et al 2017,2021

De Sitter + … from String Theory !!

Active debate for many years: ‘full control’?

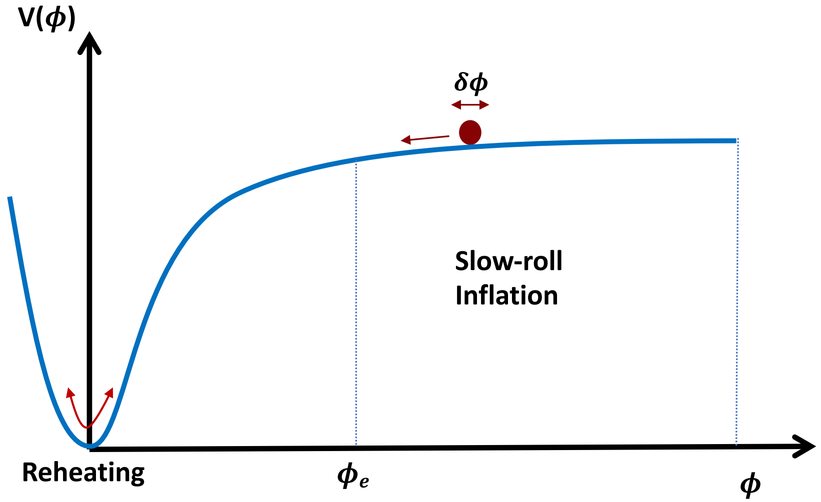
The String Landscape and Dark Energy

- 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



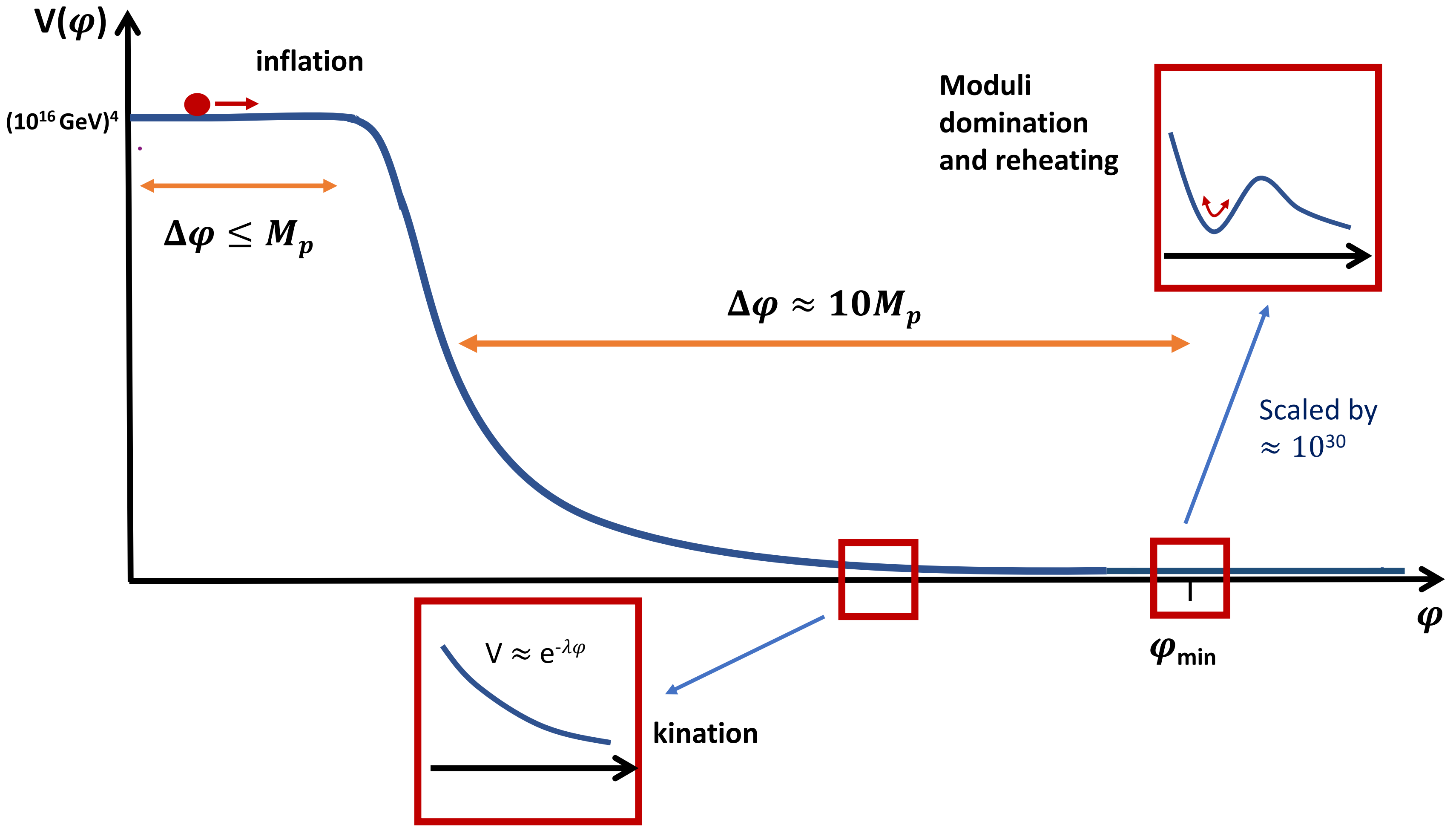
String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N-Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$ 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 $\quad n_s = 0.965 \pm 0.004$ $\quad$ Planck/BICEP 2021

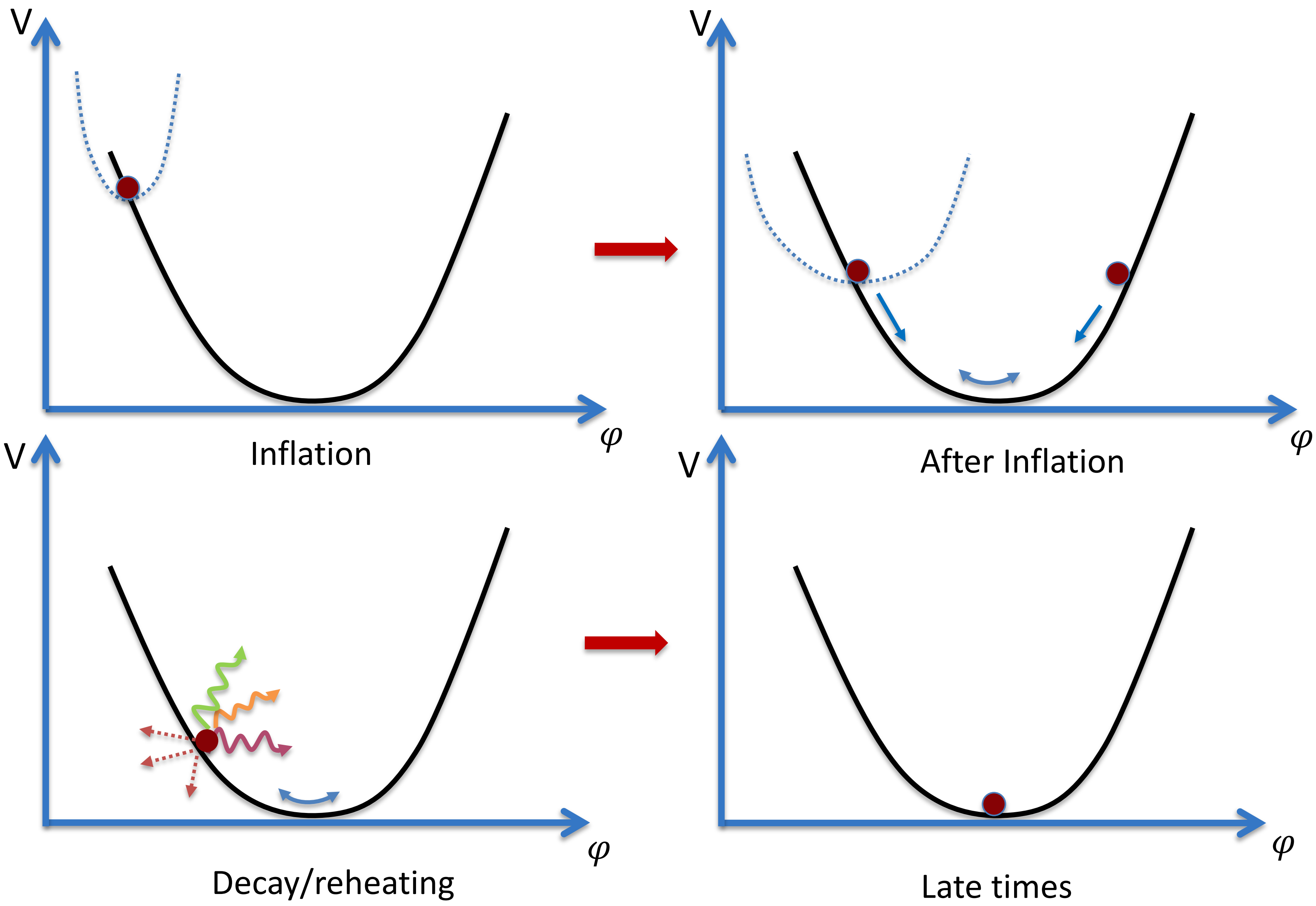
Challenges: **eta problem, scales (KL problem), moduli stabilisation, observations?**

After String Inflation

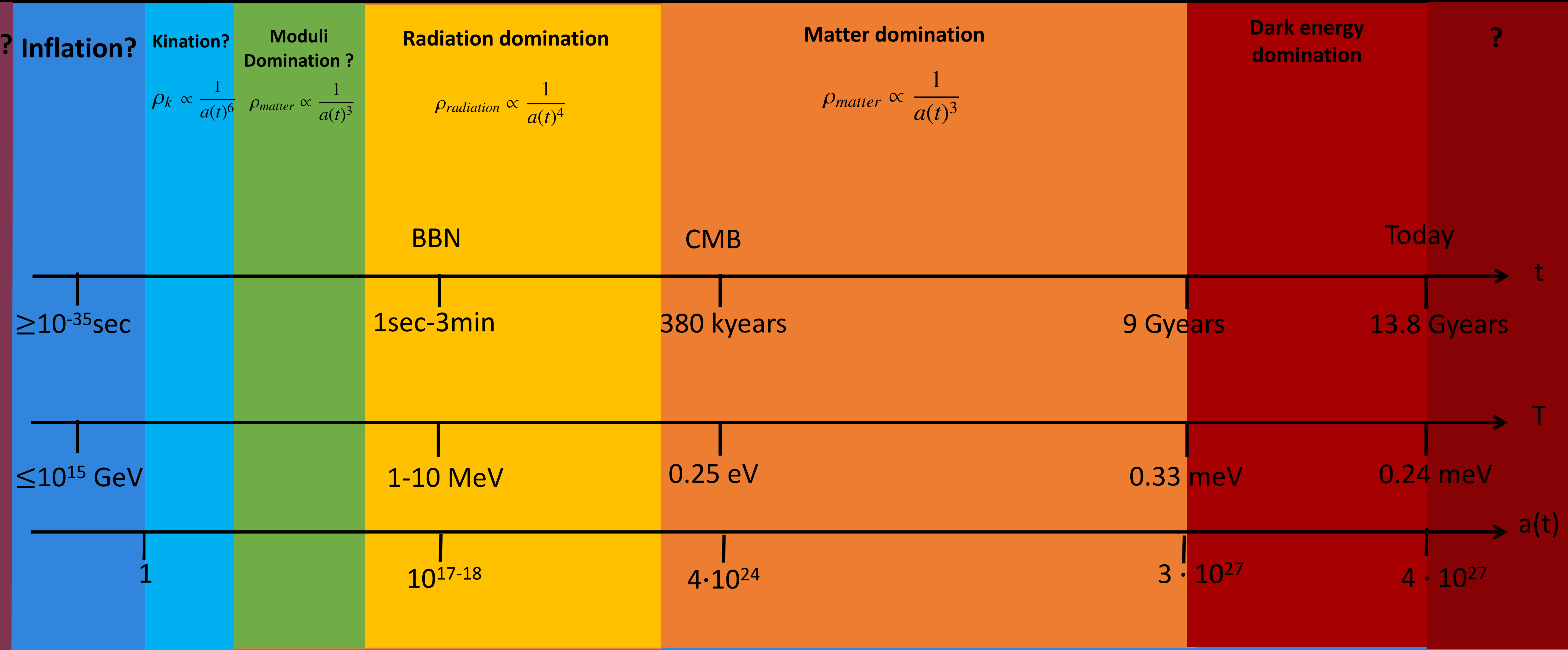
Kination: Kinetic Domination?



Moduli Domination



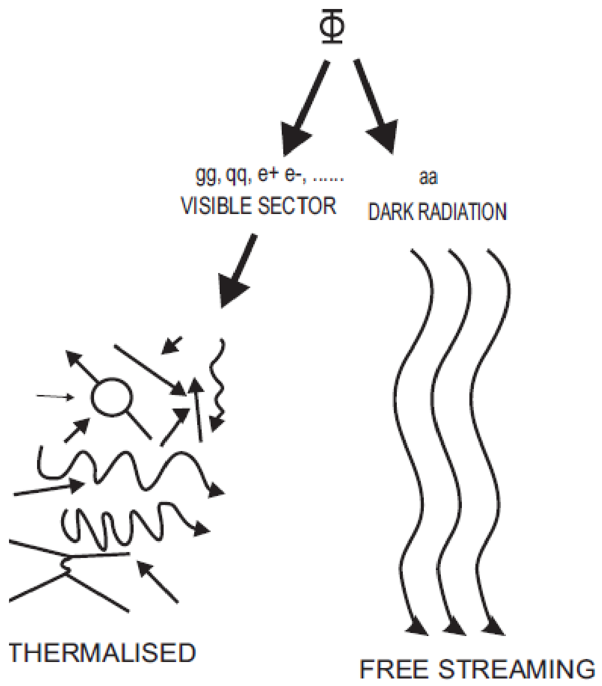
Alternative Histories of the Universe?



Dark Matter ?

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

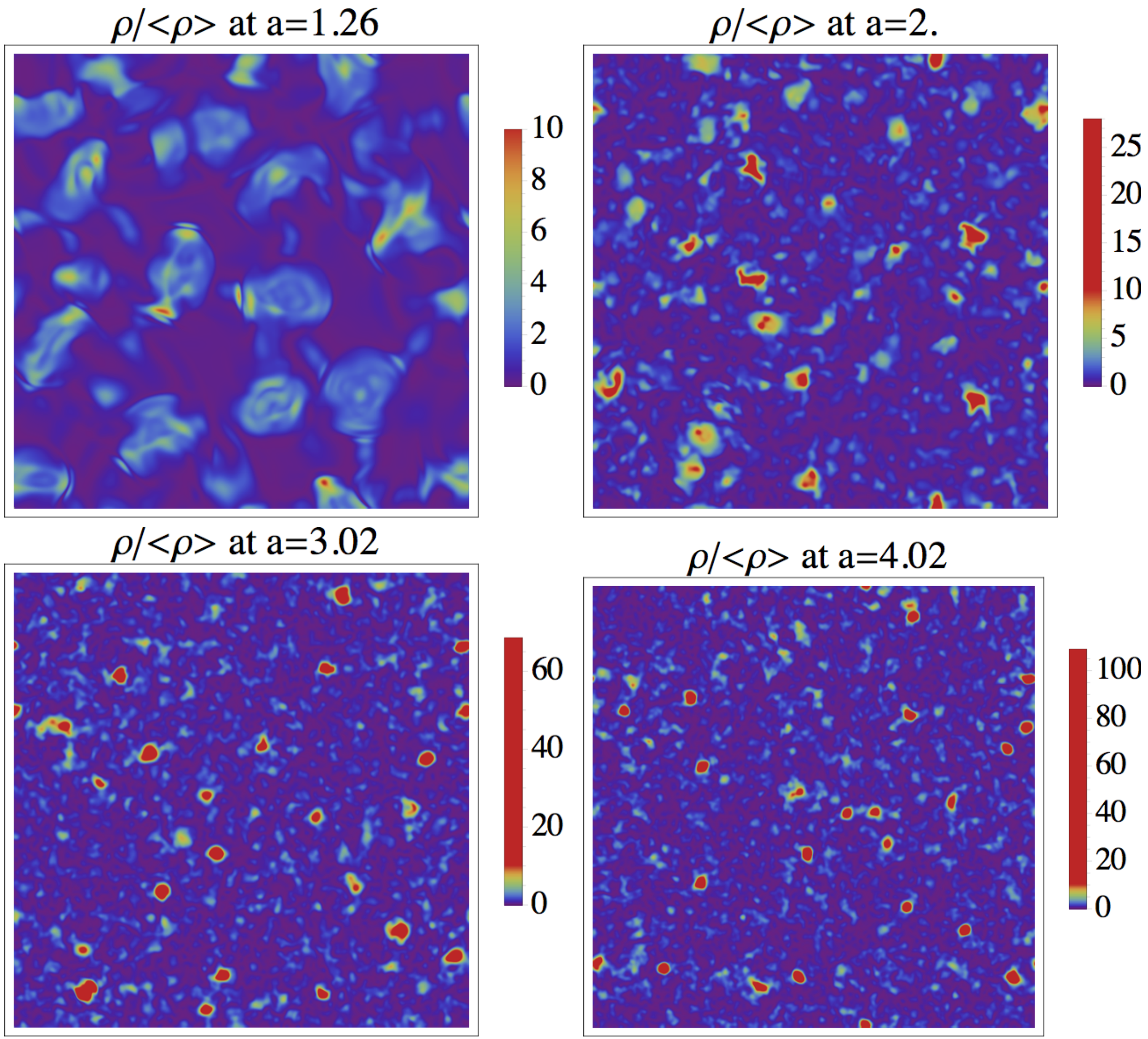
Dark Radiation ?



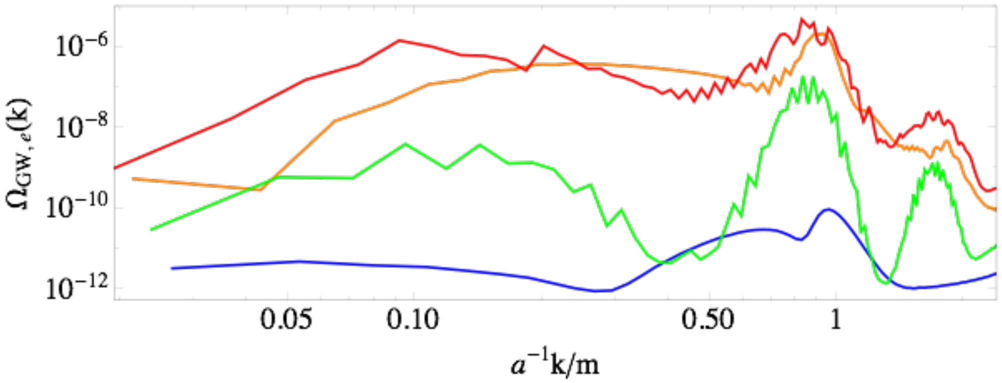
- Axions (ultra light)
- Hidden sector much constrained !!!

$\Delta N_{eff} < 0.2$!

Oscillons/Oscillatons



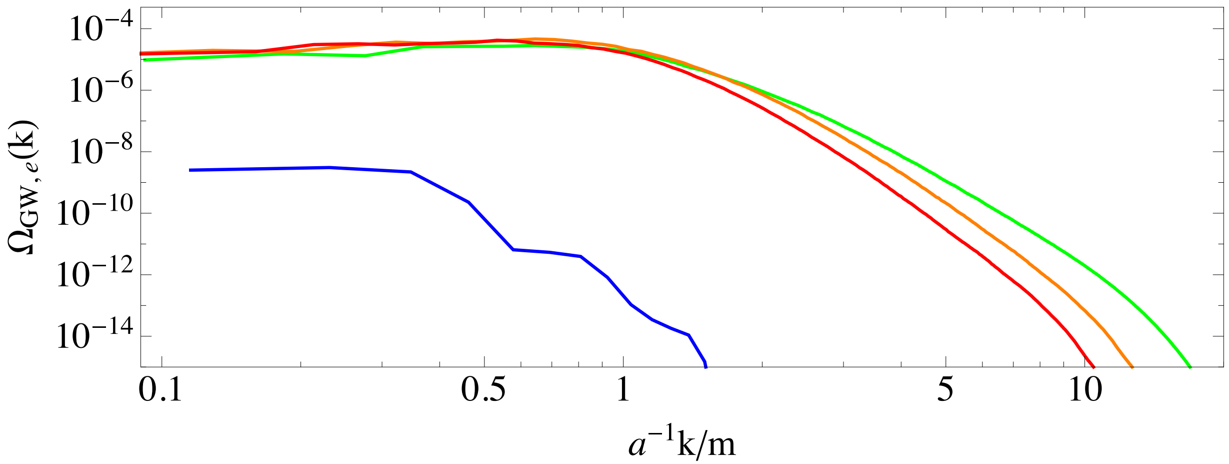
GW spectrum: KKLT



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

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

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

See also:

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

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

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

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

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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.

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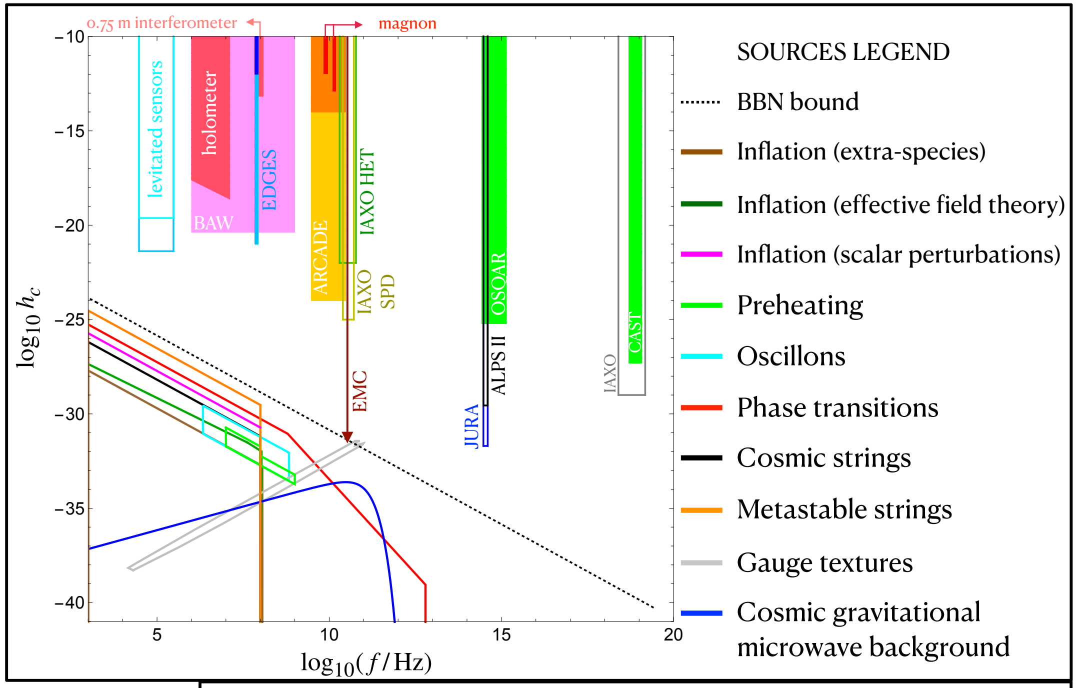
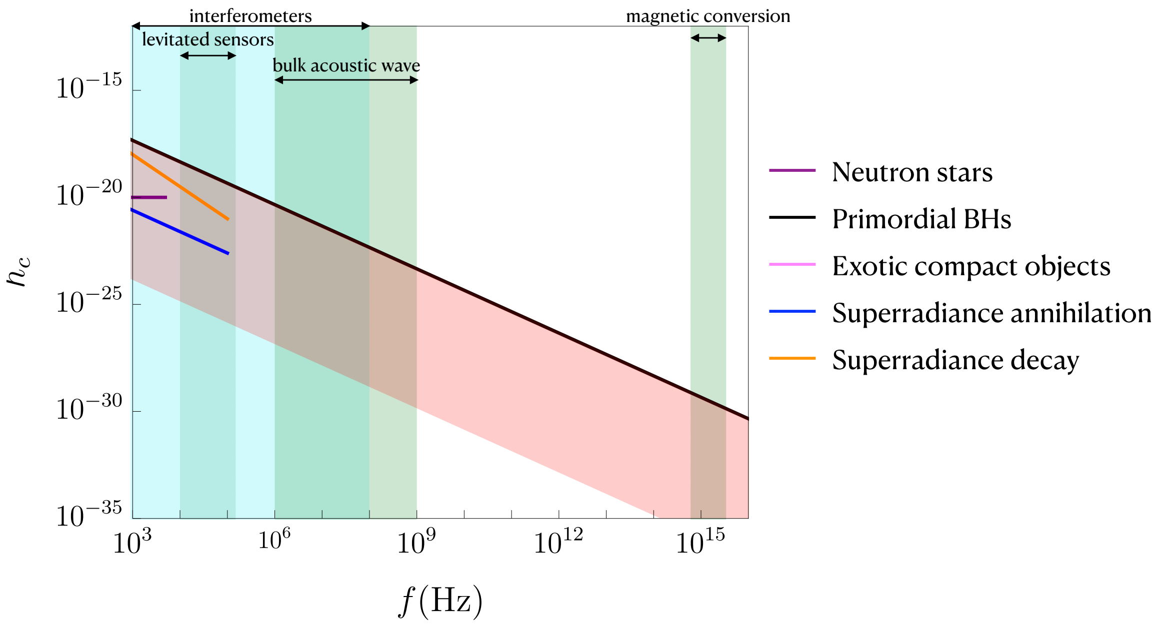
Cosmological sources of stochastic High Frequency Gravitational Waves



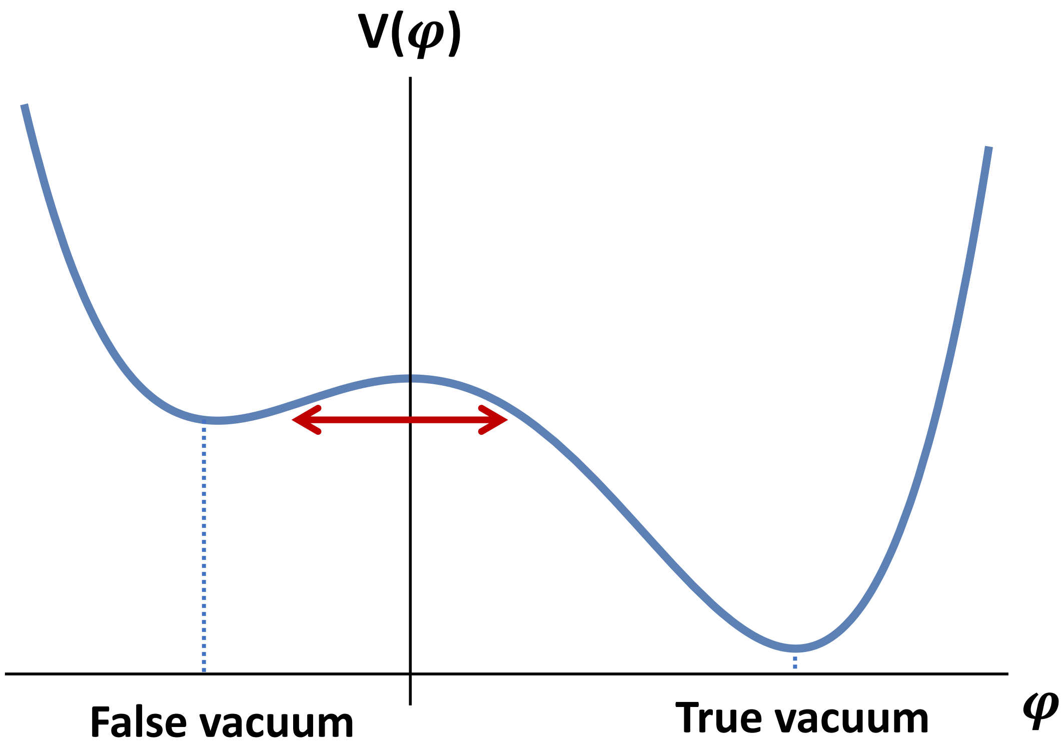
Sources of Coherent Gravitational Waves

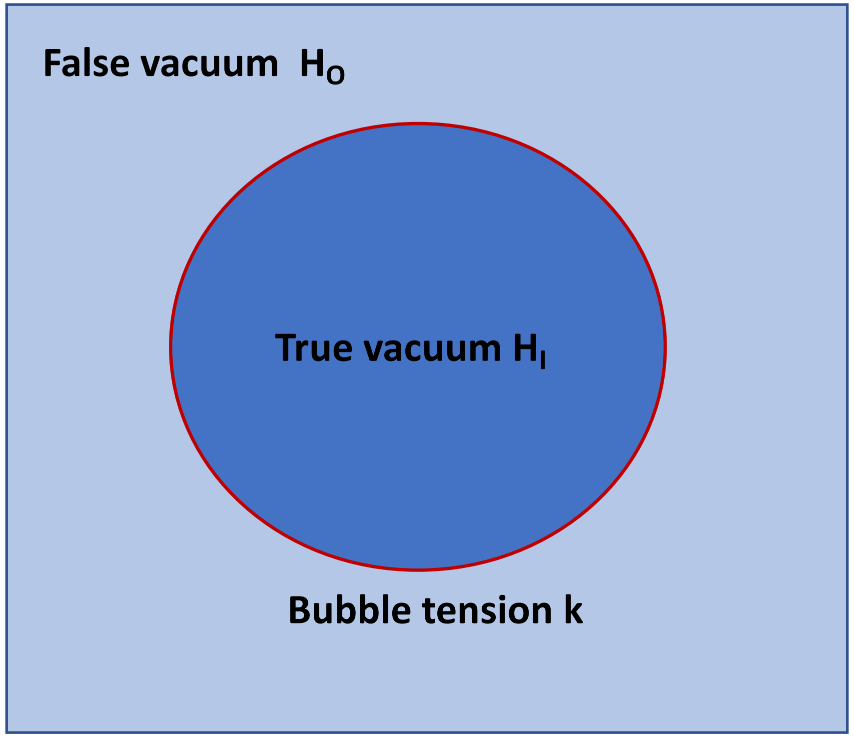


Vacuum Transitions in the Landscape?

Vacuum Transitions


Coleman
1970's-1980s





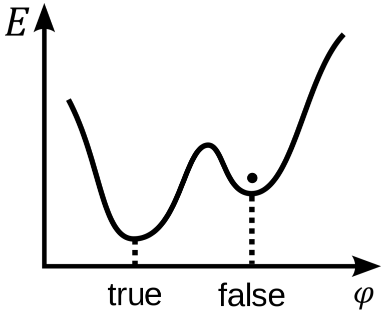
Bubble nucleation

The beginning and end of our universe?

Vacuum transitions in the Landscape

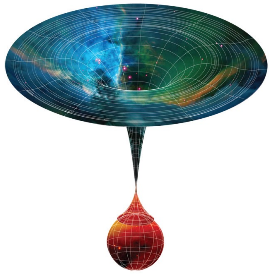
1. **Transition between two minima of scalar potential**

   Coleman-De Luccia 1980

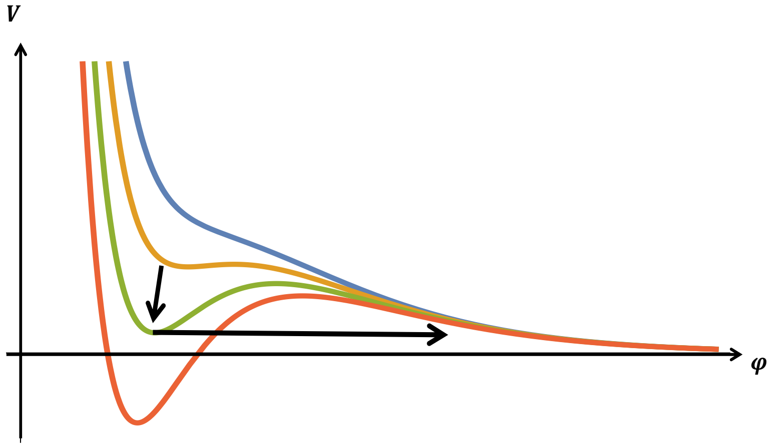


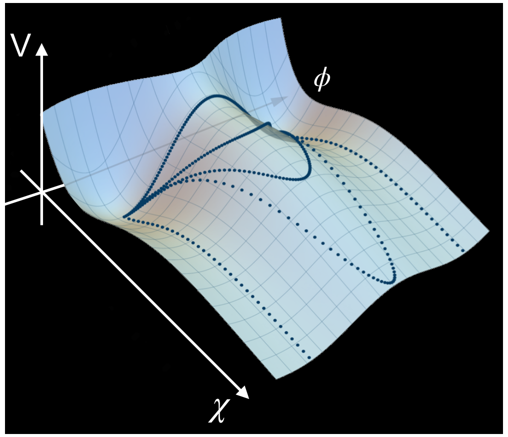
2. **No scalar field: M_1 to M_1+Wall+M_2**

   Brown-Teitelboim 87



Both realised in string landscape

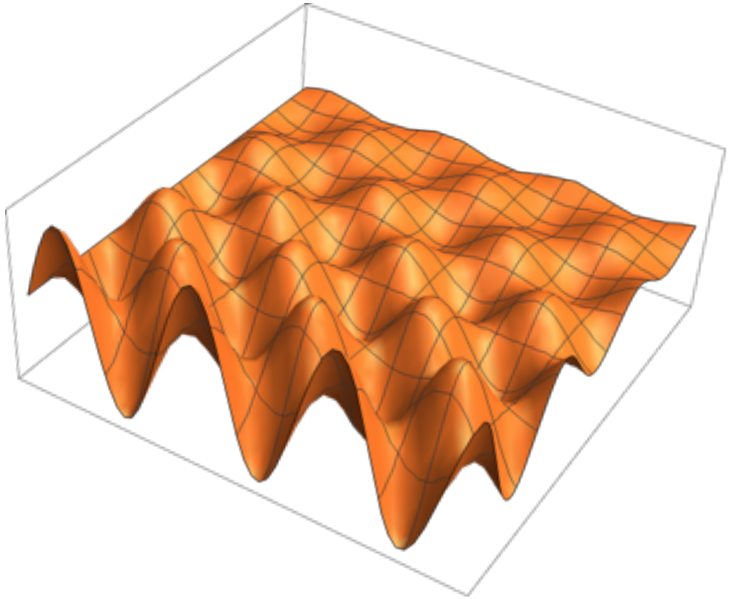




Approximate picture

Predictions from the landscape?

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



Early History

- Coleman de Luccia **(1980)**
- Witten **(1981)**
- Vilenkin + Hartle-Hawking **(1982-3)**
- Brown-Teitelboim **(1987)**
- Farhi-Guth-Guven **(1990)**
- Fischler-Morgan-Polchinski **(1990)**

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

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

$$S_{\rm W} = -4\pi\sigma\int dtdr\,\delta(r-\hat{r})[N_t^2 - L^2(N_r + \dot{\hat{r}})^2]^{1/2}$$

$$S_{\rm mat} = -4\pi\int dtdr\,LN_tR^2\,\rho(r)\,, \quad \boxed{\rho = \Lambda_{\rm O}\,\theta(r-\hat{r}) + \Lambda_{\rm I}\,\theta(\hat{r}-r)}$$

Conjugate variables

$$\pi_L = \frac{N_rR' - \dot{R}}{GN_t}R, \qquad \pi_R = \frac{(N_rLR)' - \partial_t(LR)}{GN_t}\,,$$

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

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

Constraints

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

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

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

e.g. dS to dS

Hamiltonian approach=Euclidean approach :

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

$$B = \frac{\pi}{2G}\left[\frac{\left[(H_{\rm O}^2 - H_{\rm I}^2)^2 + \kappa^2(H_{\rm O}^2 + H_{\rm I}^2)\right] R_{\rm o}}{4\kappa H_{\rm O}^2 H_{\rm I}^2} - \frac{1}{2}\left(H_{\rm I}^{-2} - H_{\rm O}^{-2}\right)\right]$$

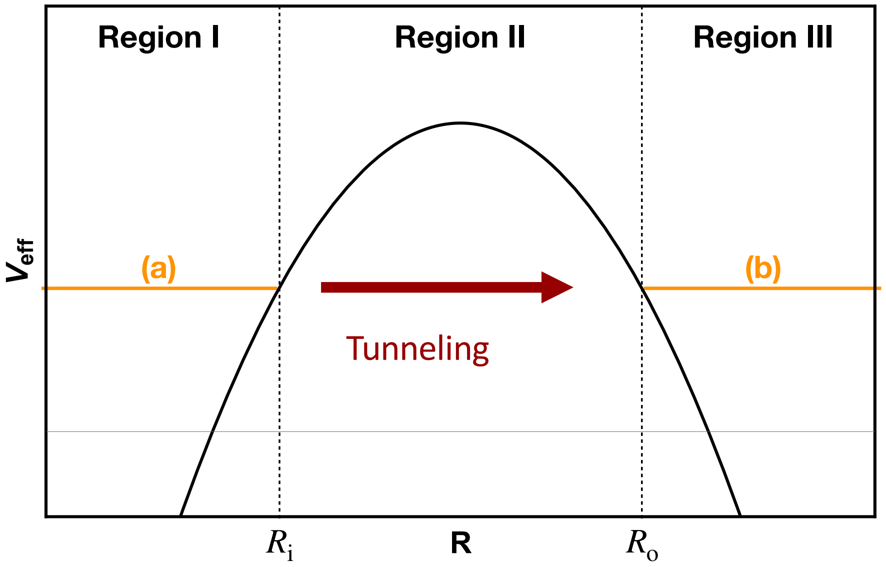
$$R_{\rm o}^2 = \frac{4\kappa^2}{(H_{\rm O}^2 - H_{\rm I}^2)^2 + 2\kappa^2(H_{\rm O}^2 + H_{\rm I}^2) + \kappa^4}$$

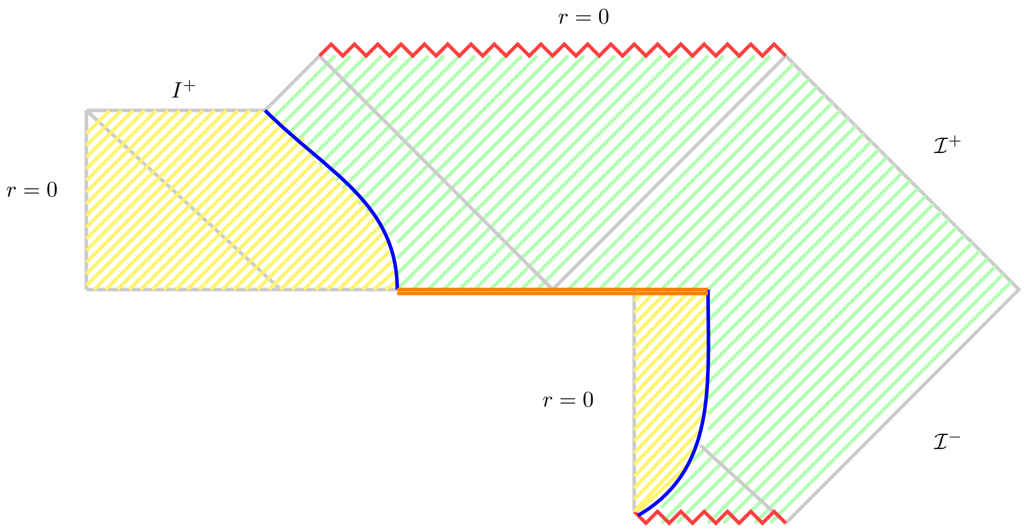
Analytic continuation from Euclidean to Lorentzian implies open universe but just a "guess'' (O(4) symmetry)

e.g. Schwarzschild to de Sitter

(H_O=0)

Farhi, Guth, Guven (Euclidean) + Fischler, Morgan, Polchinski (Hamiltonian)





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…)