On Vacuum Transitions and the String Landscape

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CERN TH Colloquium
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Recent detailed reviews:
M.Cicoli, J. Conlon, A. Maharana, S. Parameswaran, FQ, I. Zavala 2303.04819 Phys Reports 1059 (2024) 1-155
L. McAllister, FQ (Handbook on Quantum Gravity) 2310.20559

Recent work on vacuum transitions:
S. Cespedes, S. de Alwis, F. Muia, FQ 2307.13614, *Phys.Rev.D* 104 (2021) 2, 026013 2011.13936 also work with V. Pasquarella

‘Standard Model of Cosmology’

ΛCDM

Λ: Cosmological constant

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 0$$

$\Lambda = 0$ Minkowski spacetime

$\Lambda > 0$ de Sitter spacetime

$\Lambda < 0$ Anti-de Sitter spacetime

$$\Lambda \simeq +10^{-120} M_{Planck}^4$$

$$M_{Planck} = \sqrt{\frac{\hbar c}{G}} \simeq 10^{19} \text{GeV}$$

CDM: Cold dark matter

New kind of Matter ≠ quarks, leptons

Dark: Electrically neutral

Cold: v<<c

Gravitationally (weakly?) interactive

Open Problems in Theoretical Cosmology

- **Big bang**
- **Origin of inflation (or alternatives)**
- **Dark energy** $\Lambda \simeq +10^{-120} M^4_{Planck}$ $w_{DE,0} = -1.028 \pm 0.032\,.$
- **Dark matter**
- **Baryogenesis…**
- **Lack of underlying theory**

Strings and Cosmology

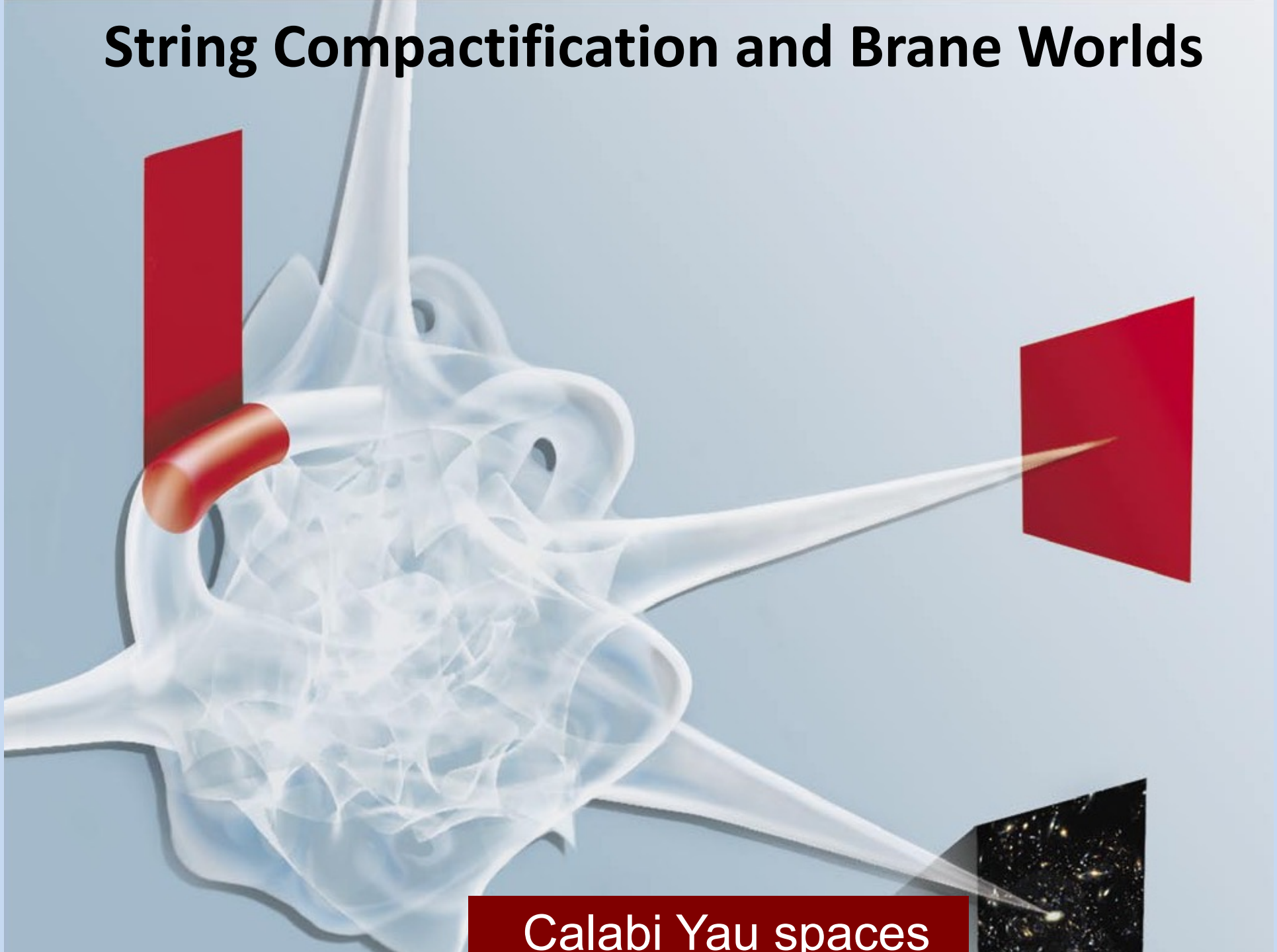
- Big Bang? (before inflation?)
- Inflation or alternatives
- After Inflation ((P)Reheating, dark matter, baryogenesis,…)
- Today (dark energy)
- Future?

Low energy states in string 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 !

String Compactification and Brane Worlds



Calabi Yau spaces

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

What are the moduli fields?

e.g. 10D metric

$$g_{MN} = \begin{pmatrix} g_{\mu\nu} & g_{\mu n} \\ g_{n\nu} & g_{mn} \end{pmatrix}$$

4D metric

4D vectors

4D scalars

M,N = 0,…,9

μ, ν = 0,1,2,3

m,n = 4,…,9

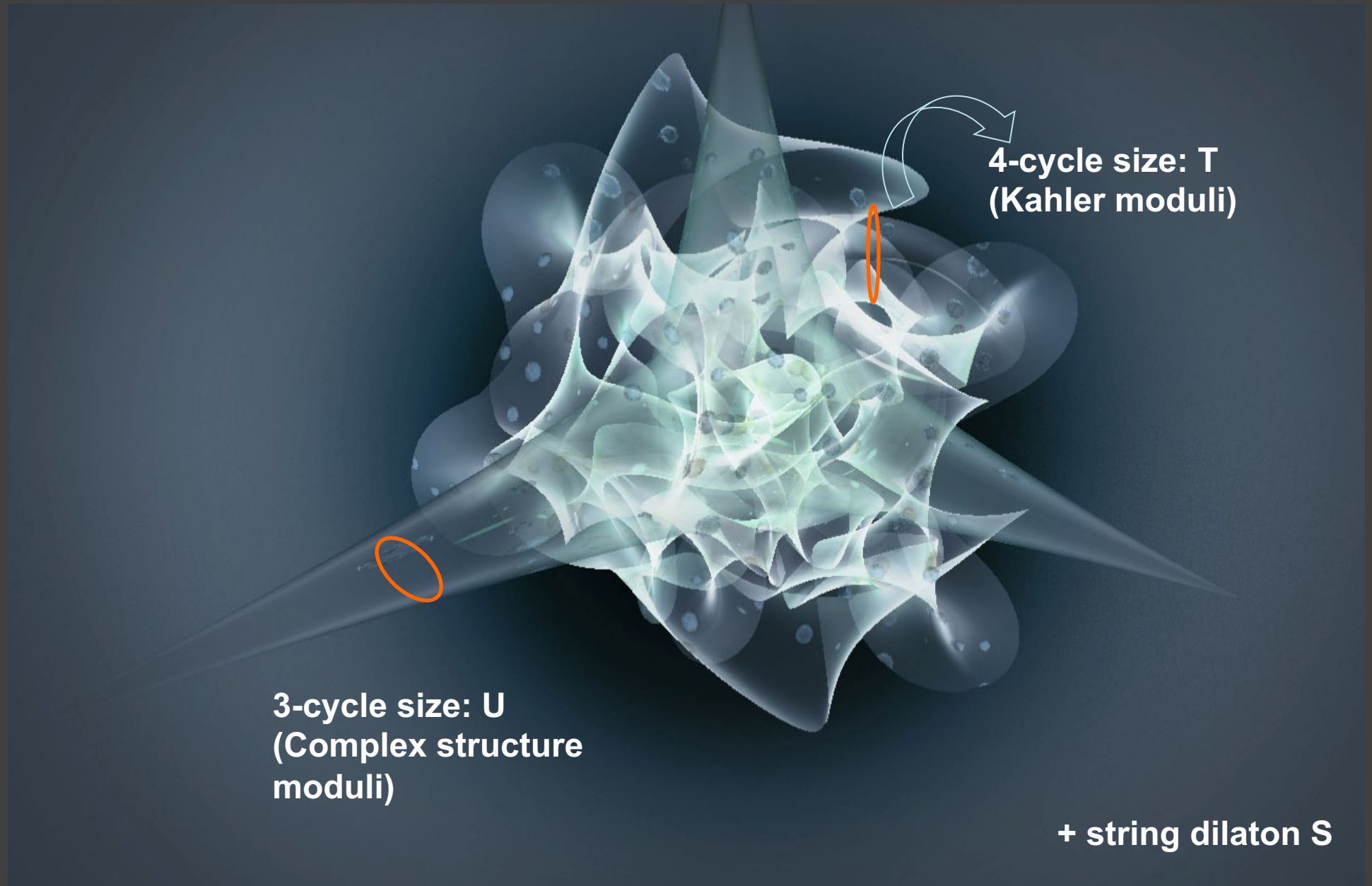
Measure size and shape of extra dimensions

The String Landscape

Moduli Stabilisation

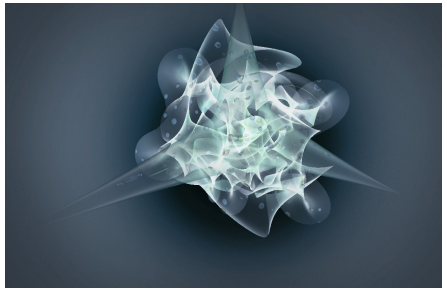
Review: McAllister, FQ e-Print: 2310.20559 [hep-th]

Status of moduli stabilisation

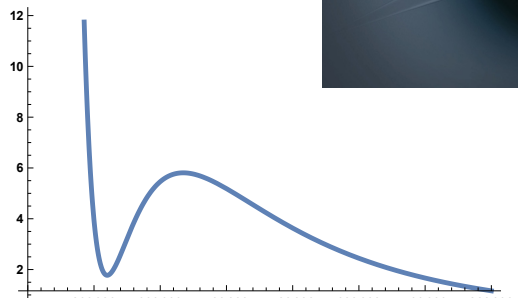


Three related questions

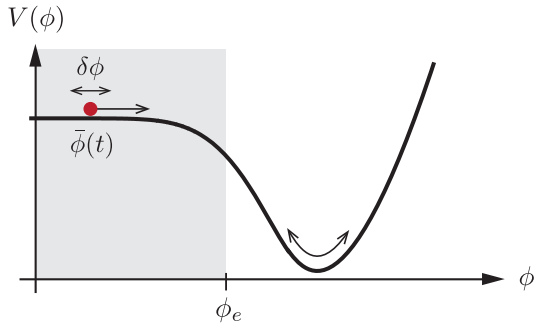
- **Moduli stabilization**



- **De Sitter**



- **Inflation**



Sources of moduli potentials

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

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

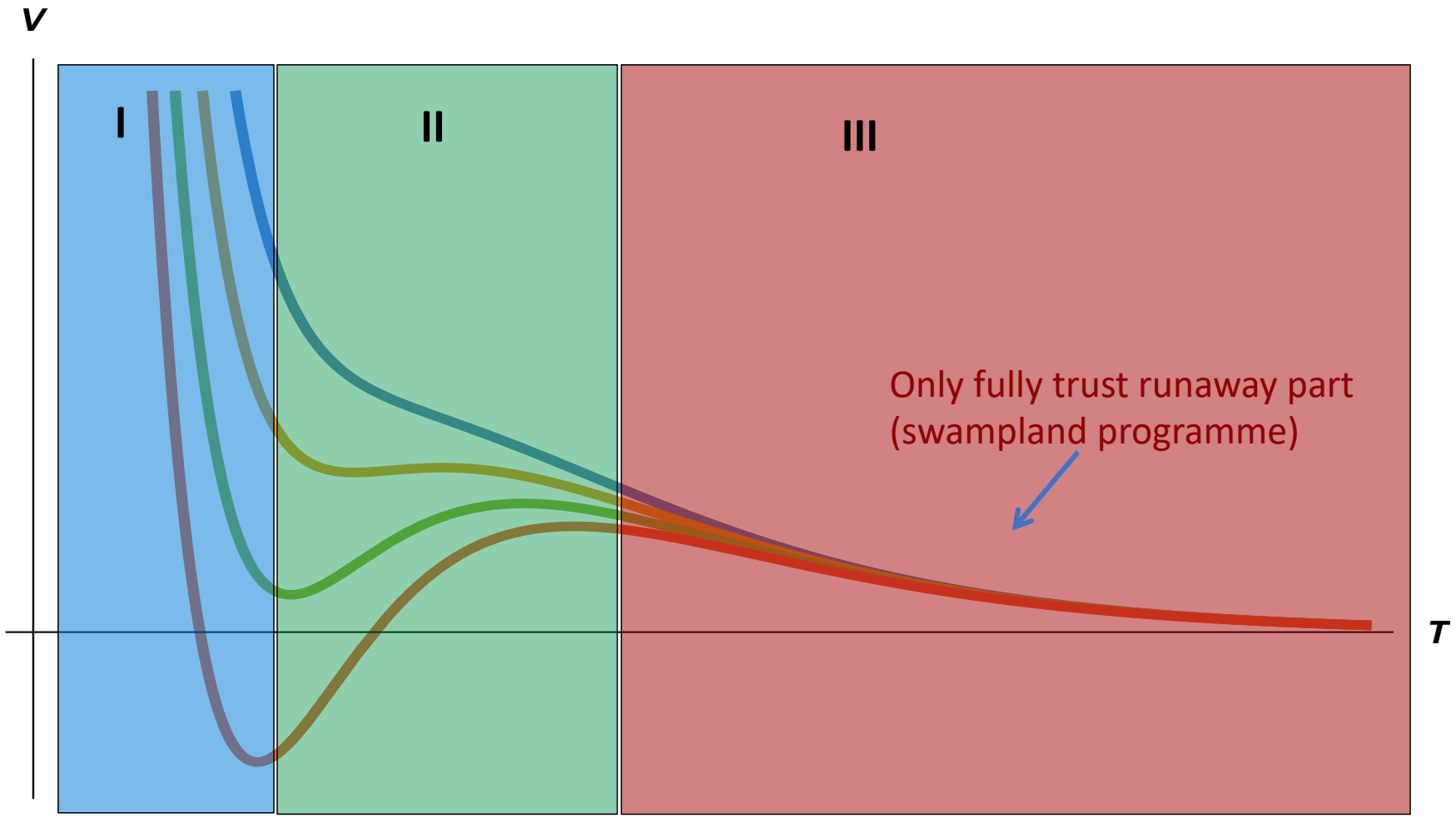
Curvature $V(R) \propto \frac{1}{R^8},$

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

R: typical scale of extra dimensions

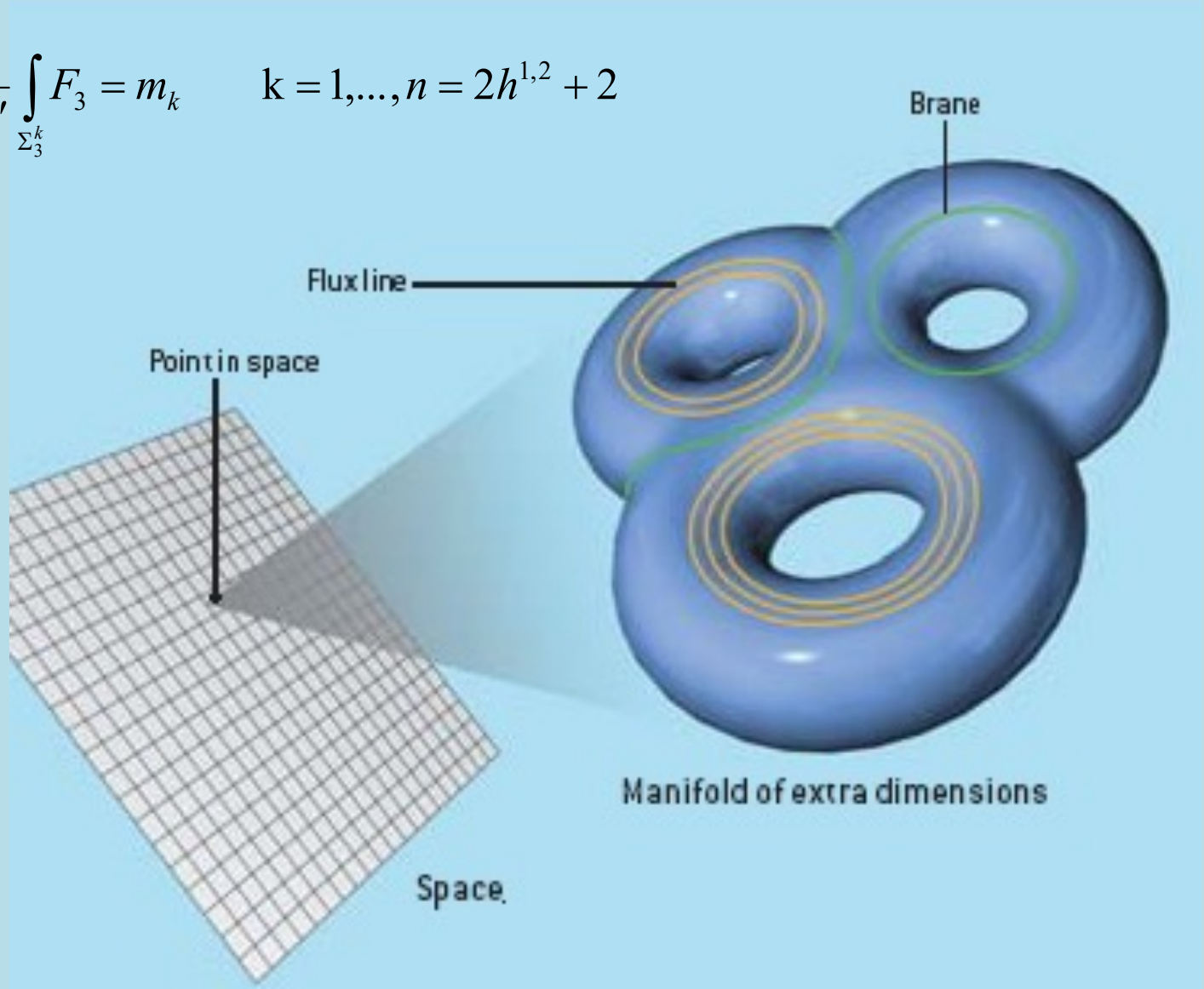
Dine Seiberg Problem

Dine, Seiberg 1985

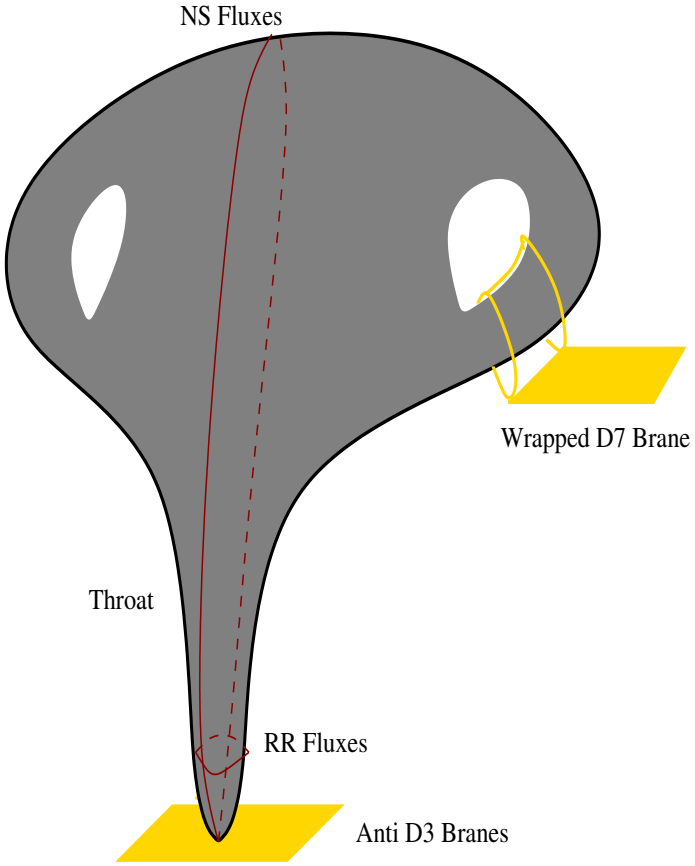


Flux compactifications

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



e.g. KKLT/LVS Scenarios



Warning: The control status of these approaches is under heated debate !

Century old Moduli Problem

Q: Why we do not see the extra dimensions? Kaluza, Klein 1920s

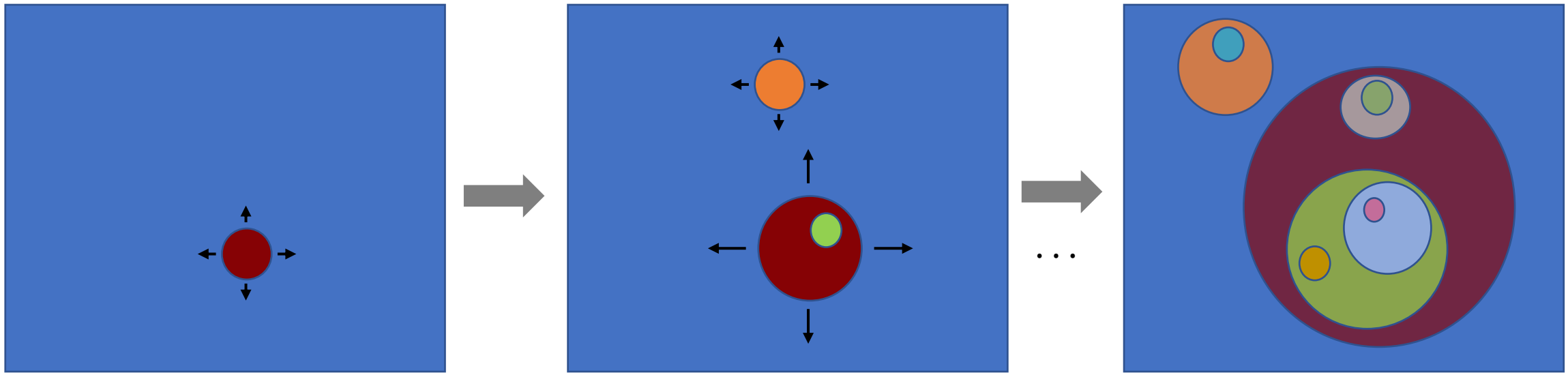
A: Because they are too small to be seen

Q: Why are they so small?

A1: We don't know! (20^{th} century)

A2: A combination of fluxes and quantum corrections fix the moduli and/or we may live on a 'brane' (21^{st} century)

The multiverse



Bubble nucleation

Expanding bubbles within bubbles

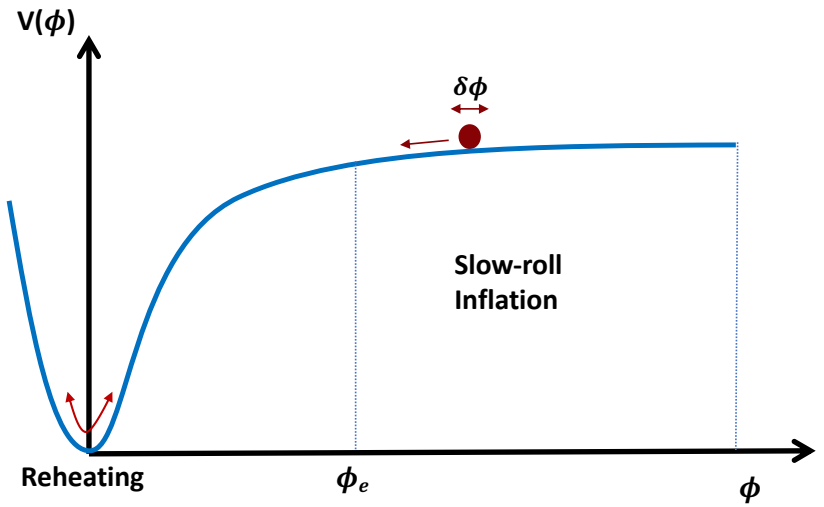
Our universe = one of many bubbles

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!!!

String Inflation



String Inflation

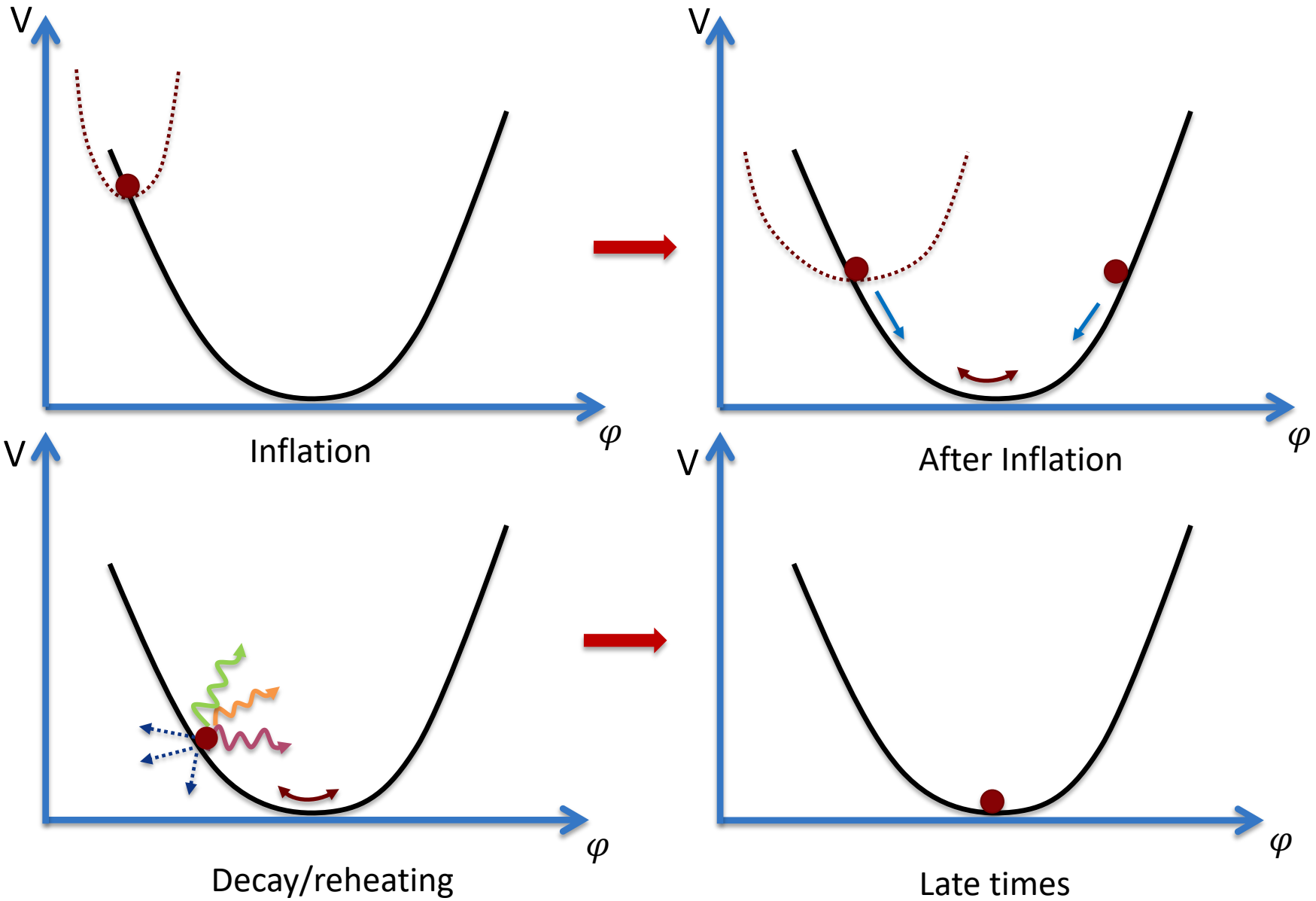
String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N-Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$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

Planck/BICEP 2021 $r_{0.05} < 0.036$ at 95% confidence $n_s = 0.965 \pm 0.004$

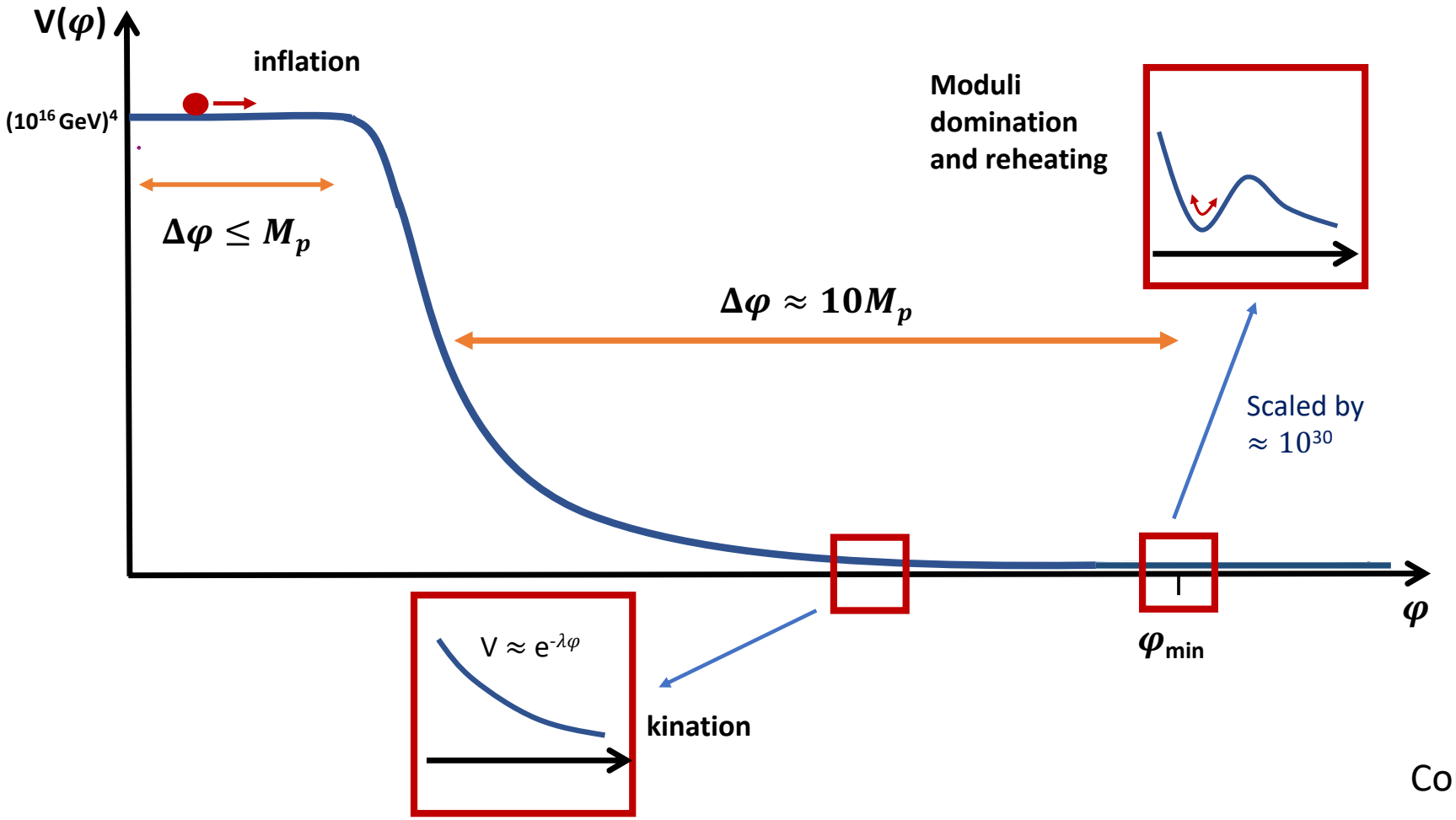
Challenges: eta problem, scales (KL problem), moduli stabilisation, observations?

After String Inflation

Moduli Domination



Kination: Kinetic Domination?

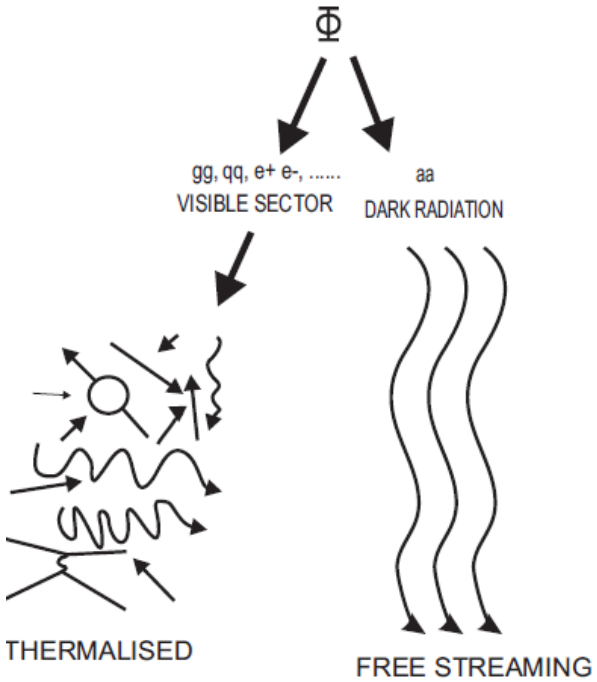


Conlon et al.

Dark Matter ?

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

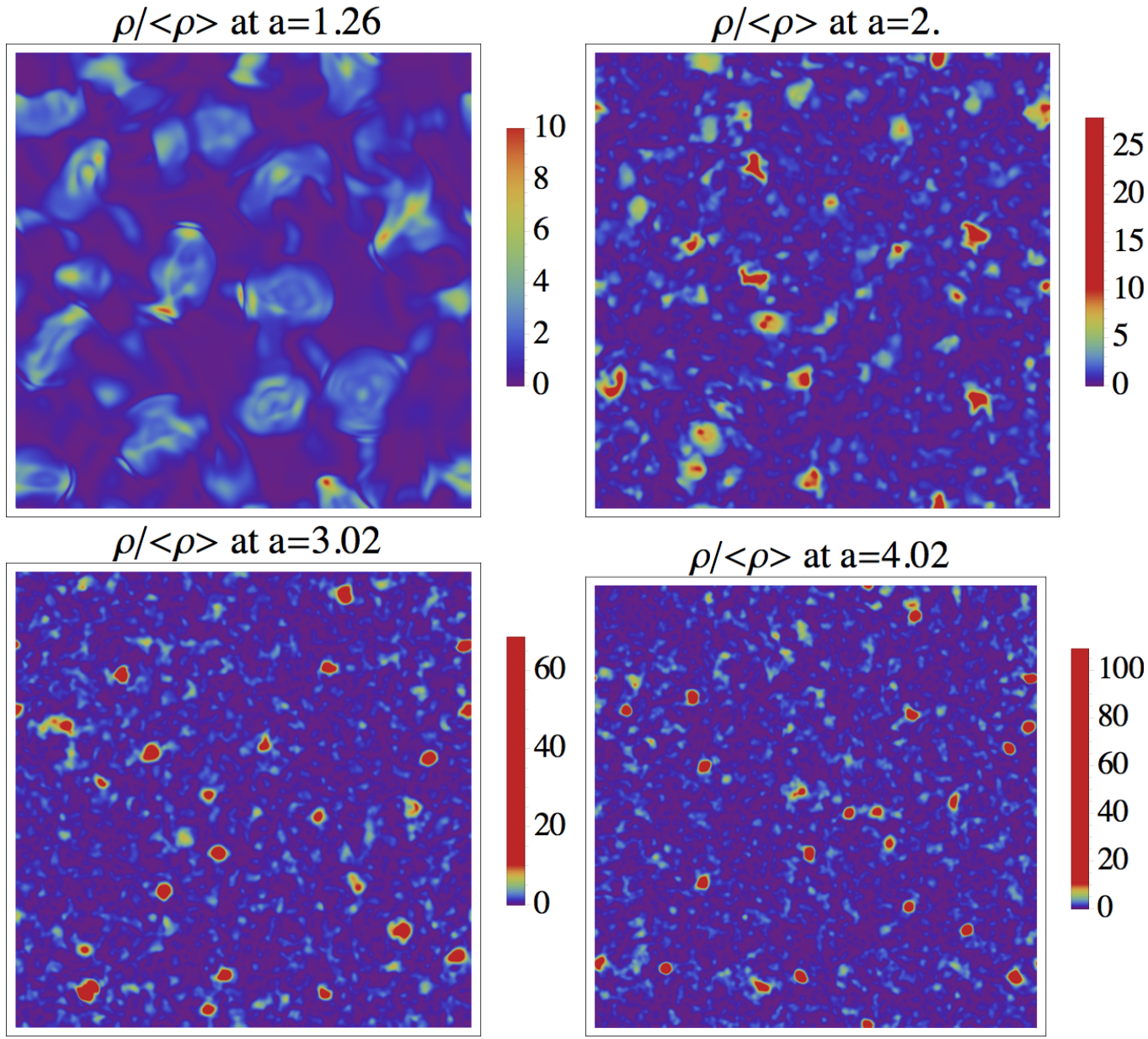
Dark Radiation ?



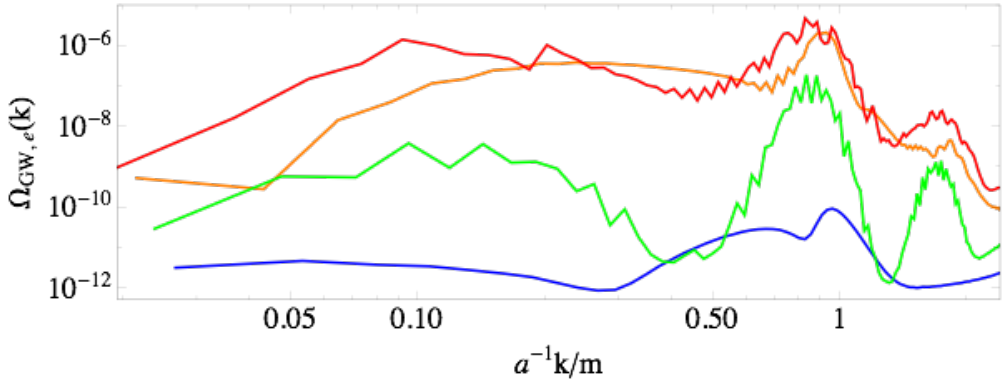
- Axions (ultra light)
- Hidden sector much constrained !!!

$\Delta N_{eff} < 0.2$!

Oscillons/Oscillatons



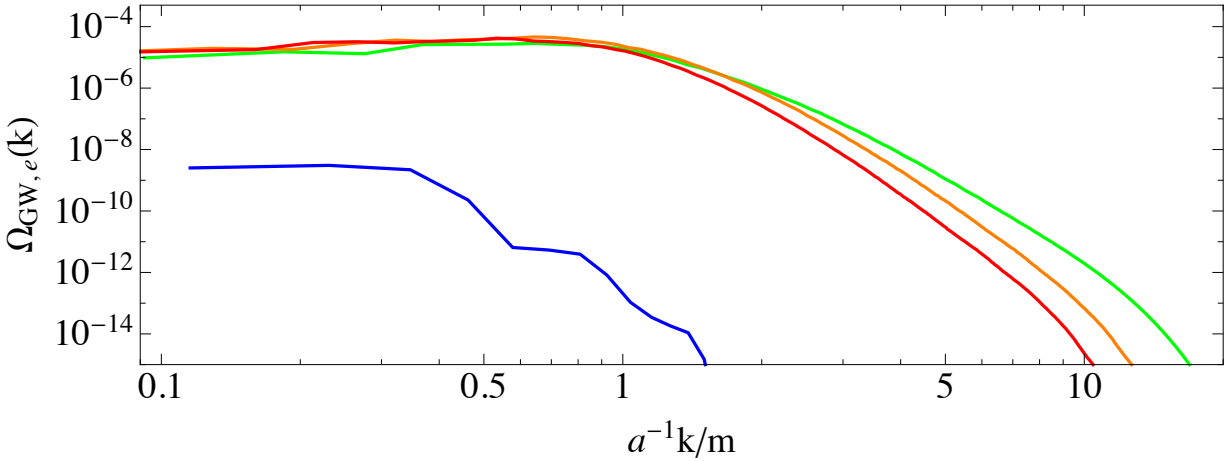
GW spectrum: KKLT



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

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

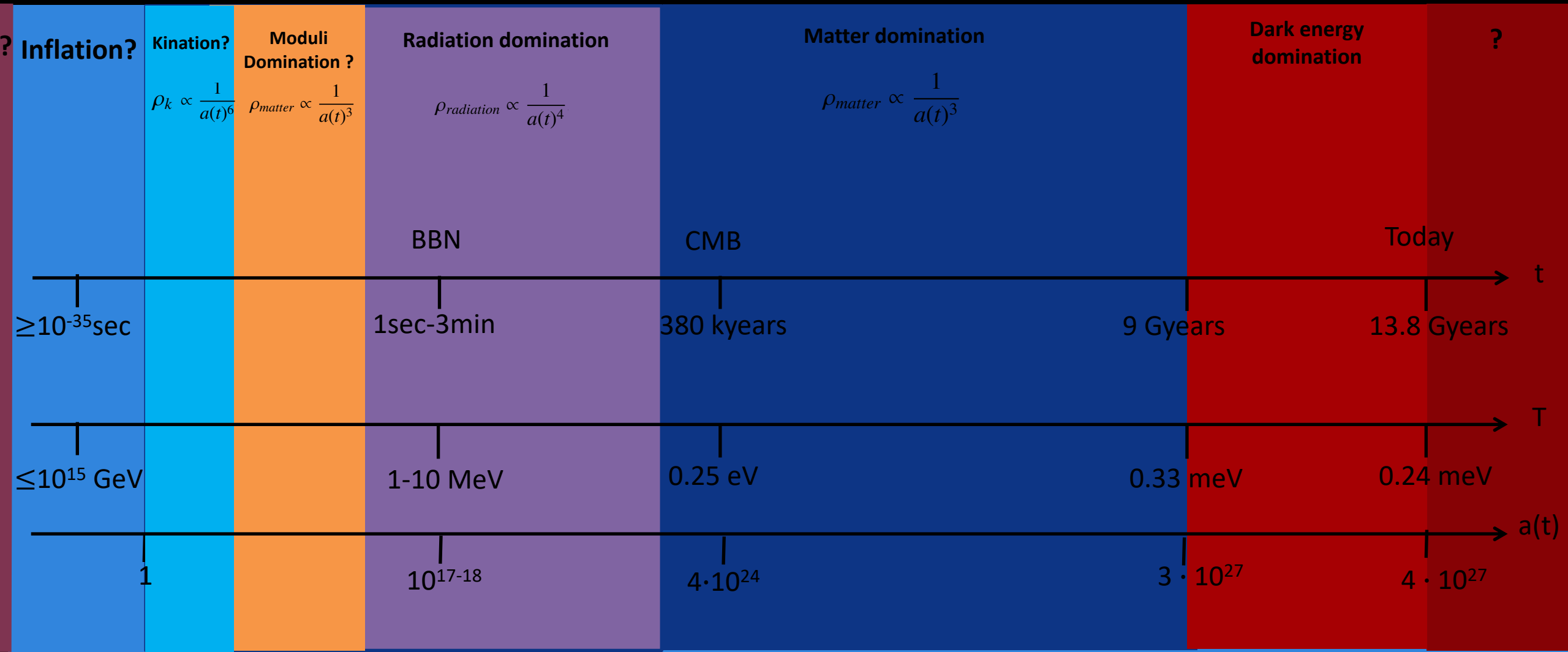
GW spectrum: Blow-up LVS



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

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

Alternative Histories of the Universe?



Before Inflation?

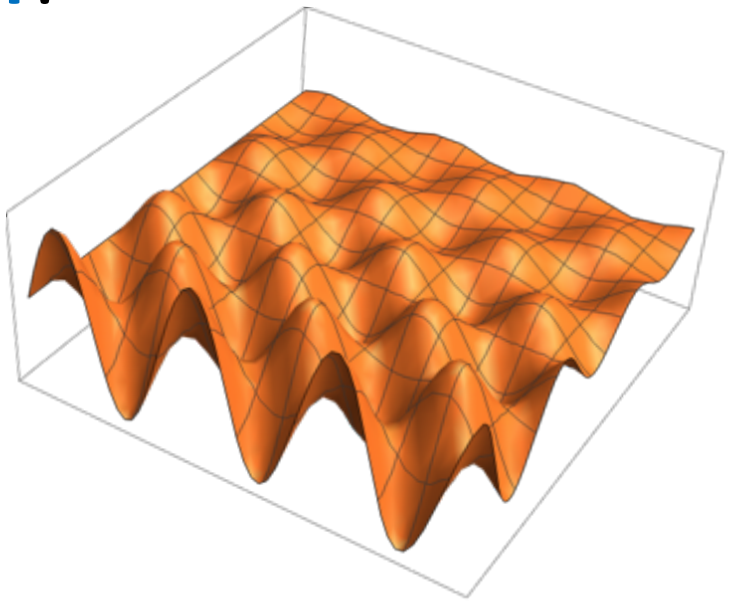
Vacuum Transitions in the Landscape?

Early History

- Coleman de Luccia (false vacuum decay 1980)
- Witten (bubble of nothing 1981)
- Vilenkin + Hartle-Hawking (‘creation from nothing’ 1982-3)
- Brown-Teitelboim (bubble nucleation 1987)
- Farhi-Guth-Guven (creation of universe from the lab 1990)
- Fischler-Morgan-Polchinski (Hamiltonian approach 1990)

Predictions from the landscape?

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



Wave functions of the universe

Mini-superspace

$$ds^2 = -N^2(t)dt^2 + a^2(t)(dr^2 + \sin^2 r d\Omega_2^2)$$

Hartle-Hawking vs Vilenkin (tunneling to dS from nothing)

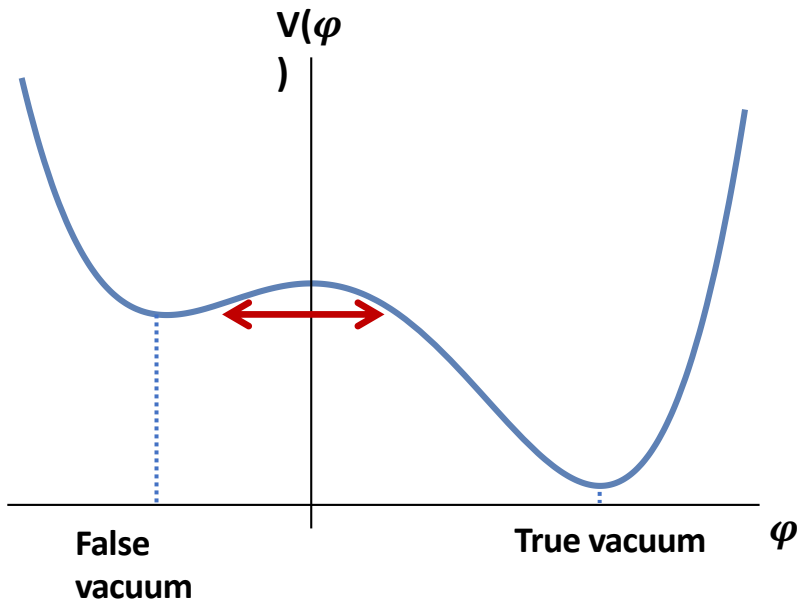
$$\mathcal{P}_{\rm HH}(\text{Nothing} \to \text{dS}) = \left\|\Psi_{\rm HH}\left(\text{H}_{\rm dS}\right)\right\|^2 \propto e^{\frac{\pi}{GH^2_{\rm dS}}} = e^{+S_{\rm dS}}$$

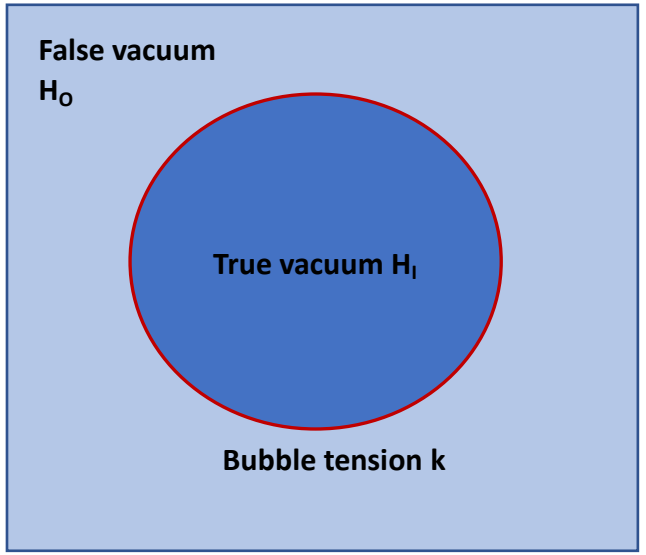
$$\mathcal{P}_{\rm T}(\text{Nothing} \to \text{dS}) = \left\|\Psi_{\rm T}\left(\text{H}_{\rm dS}\right)\right\|^2 \propto \text{e}^{-\frac{\pi}{\text{GH}^2_{\rm dS}}} = e^{-S_{\rm dS}}$$

entropy

Vacuum Transitions

Coleman
1970's-1980s



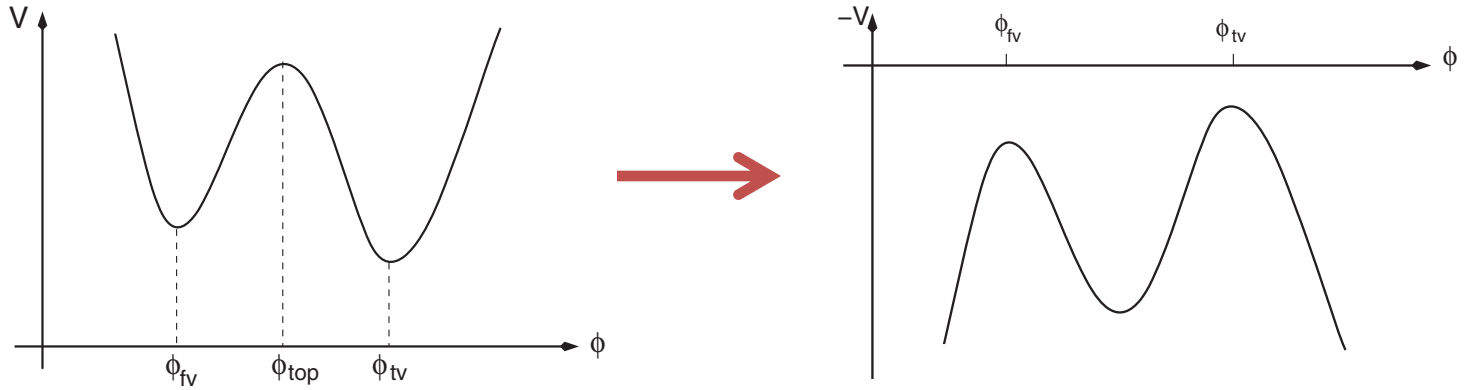


Bubble nucleation

The beginning and end of our universe?

Euclidean Approach

Coleman et al. (Field theory (and Gravity?)



O(4) Instanton (bounce)

$$\xi^2 = |x|^2 + \tau^2$$

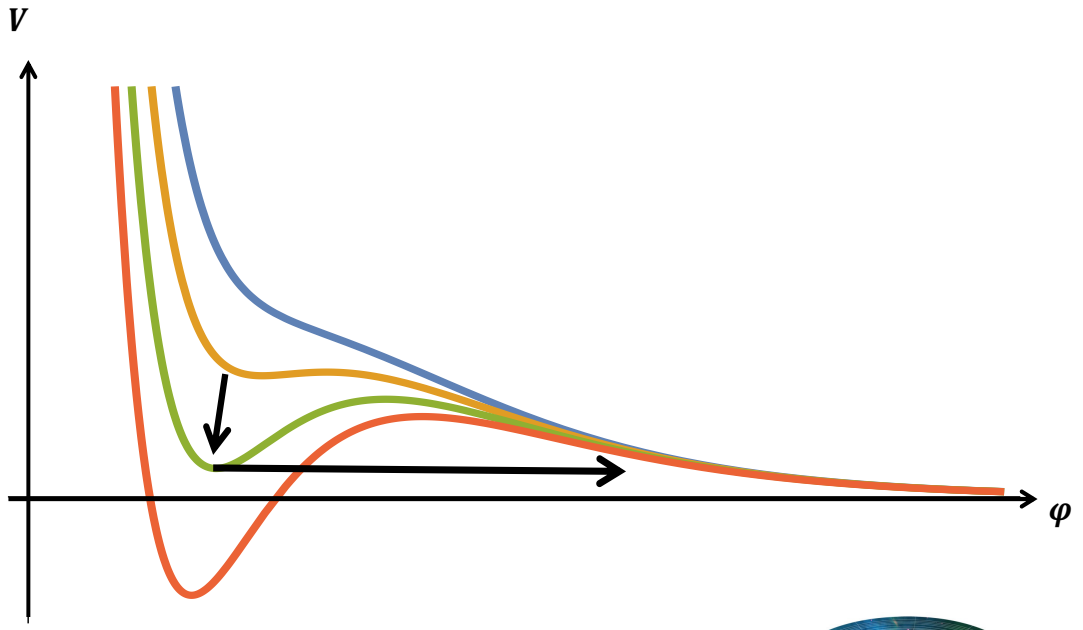
$$ds^2 = d\xi^2 + \rho^2(\xi)(d\psi^2 + \sin^2\psi d\Omega_2^2)$$

Analytic continuation O(3,1)

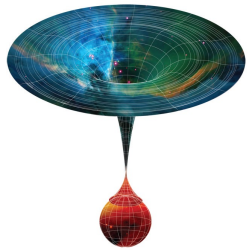
$$ds^2 = -dt^2 + \rho^2(-i\xi)(d\chi^2 + \sinh^2\chi d\Omega_2^2).$$

Open FLRW geometry!

Transitions in the landscape



1. **Flux transitions** (induced by D5/NS5 nucleation)



Brown-Teitelboim 87

2. **Decompactification**

Coleman-De Luccia 1980

$$\Gamma_{\text{flux}} \ll \Gamma_{\text{decompactification}} \qquad e.g. \qquad \Gamma_{\text{flux}} \sim e^{-\mathcal{V}^2}\Gamma_{\text{decompactification}}$$

(In LVS)

dS to dS

Euclidean approach (Coleman-de Luccia, Lee-Weinberg, Brown-Teitelboim) :

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

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

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

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

Up-Tunneling and Minkowski limit

Detailed balance

$$\Gamma_{\rm up} = \Gamma_{\rm down} \exp\left[\frac{\pi}{G}\left(\frac{1}{H_{\rm I}^2} - \frac{1}{H_{\rm O}^2}\right)\right] = \Gamma_{\rm CDL} \exp\left(S_{\rm I} - S_{\rm O}\right)$$

entropies

For HH sign only!

De Sitter to Minkowski ?

$$H_I \to 0, \qquad \Gamma_{\rm down} \to \exp\left[-\frac{\pi}{2G}\frac{\kappa^4}{H_O^2\left(H_O^2+\kappa^2\right)^2}\right]$$

$$H_O \to 0, \qquad \Gamma_{\rm up} \to 0$$

Guth et al. : possible but need singular instantons.

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

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

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

$$S_{\rm mat} = -4\pi\int dtdr\,LN_tR^2\,\rho(r)\,,$$

$$\rho = \Lambda_{\rm O}\,\theta(r-\hat{r}) + \Lambda_{\rm I}\,\theta(\hat{r}-r)$$

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

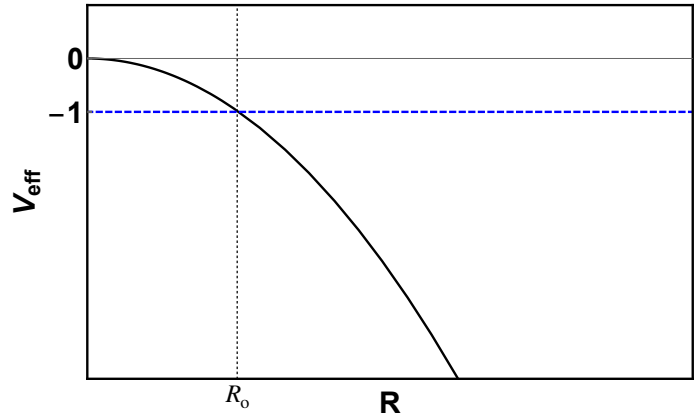
$$\mathcal{H} = \mathcal{H}_g + 4\pi LR^2\rho(r) + \delta(r-\hat{r})E = 0\,,$$

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

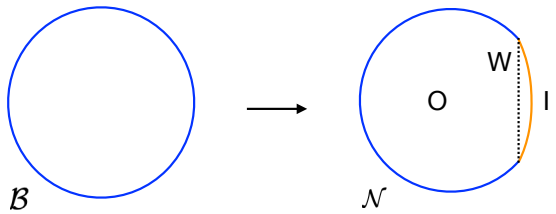
$$E = \sqrt{\frac{\hat{p}^2}{\hat{L}^2} + m^2}\,, \qquad m = 4\pi\sigma\hat{R}^2\,, \qquad \hat{p} = \partial\mathcal{L}/\partial\dot{\hat{r}}$$

De Sitter to de Sitter

$$\mathcal{P}(\mathrm{dS} \to \mathrm{dS}/\mathrm{dS} \oplus \mathrm{W}) = \frac{|\Psi(\mathrm{dS}/\mathrm{dS} \oplus \mathrm{W})|^2}{|\Psi(\mathrm{dS})|^2}$$



$$V = -\frac{1}{4\kappa^2}\hat{R}^2\left[(H_{\mathrm{O}}^2 - H_{\mathrm{I}}^2)^2 + 2\kappa^2(H_{\mathrm{O}}^2 + H_{\mathrm{I}}^2) + \kappa^4\right]$$



$$A_{\mathrm{O}} = 1 - H_{\mathrm{O}}^2 R^2\,, \qquad A_{\mathrm{I}} = 1 - H_{\mathrm{I}}^2 R^2$$

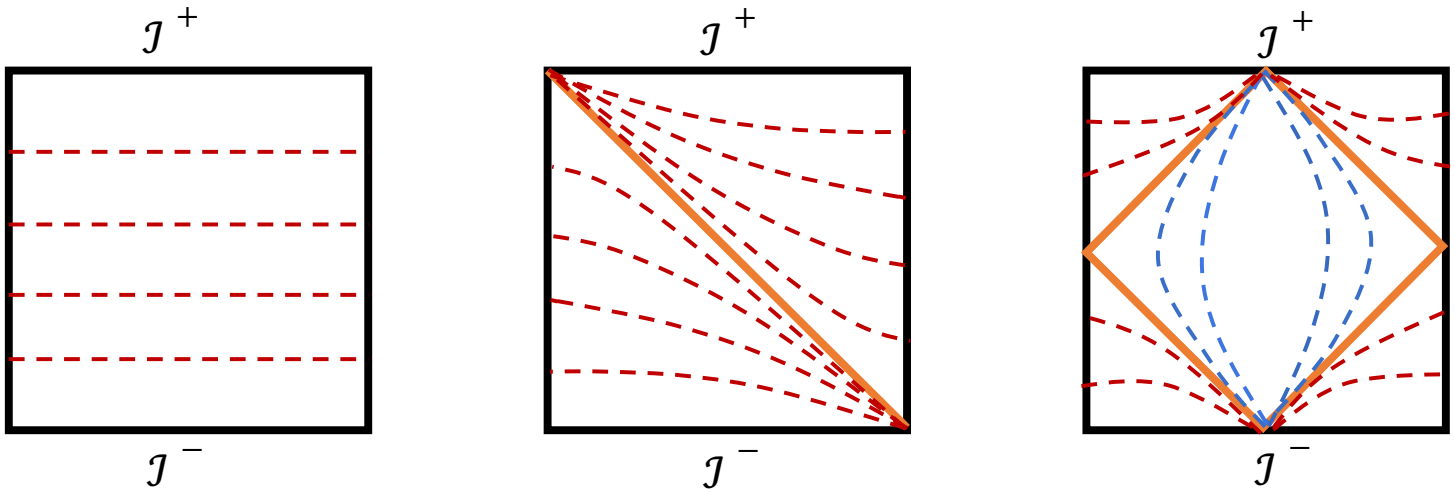
$$I_{\mathrm{tot}}\Big|_{\mathrm{tp}} - \bar{I} = -\frac{\eta\pi}{G}\left[\frac{\left[(H_{\mathrm{O}}^2 - H_{\mathrm{I}}^2)^2 + \kappa^2(H_{\mathrm{O}}^2 + H_{\mathrm{I}}^2)\right] R_{\mathrm{o}}}{8\kappa H_{\mathrm{O}}^2 H_{\mathrm{I}}^2} - \frac{1}{4}\left(H_{\mathrm{I}}^{-2} - H_{\mathrm{O}}^{-2}\right)\right]$$

Same result as Euclidean approach

$\eta = +1$ **Background Hartle-Hawking**

$\eta = -1$ **Background Vilenkin**

De Sitter Slicings



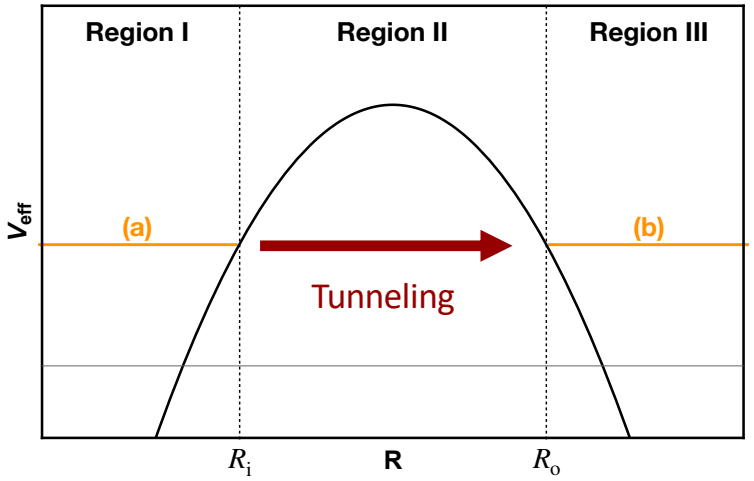
Closed **Flat** **Open**

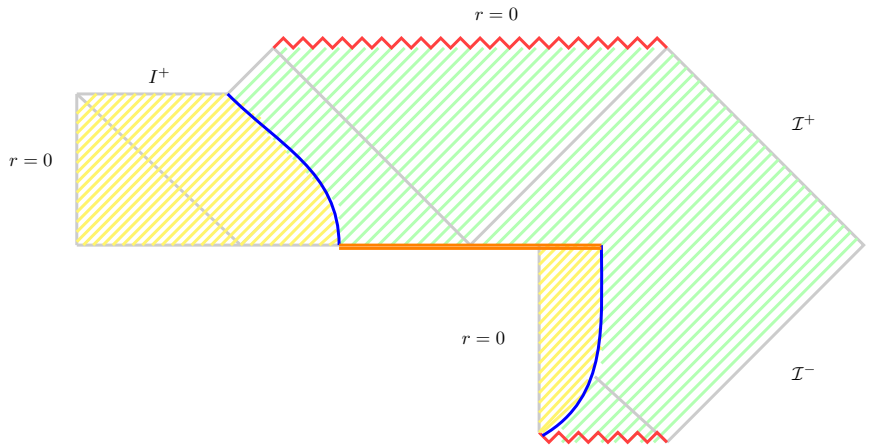
From Hamiltonian approach: O(3) symmetry, closed slicing.
Universe inside the bubble is closed for global slicing.

Schwarzschild to de Sitter

(H_O=0)

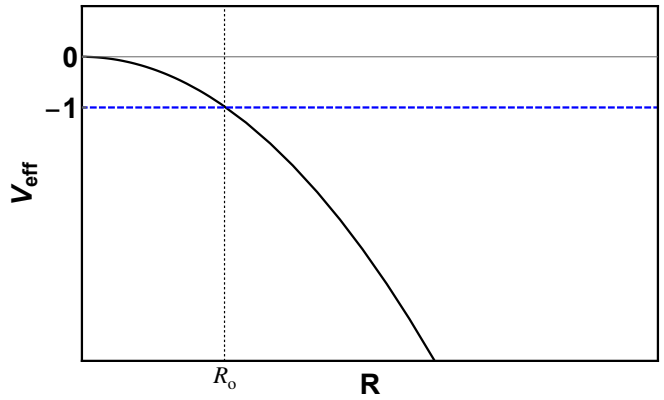
Farhi,Guth, Guven (Euclidean) + Fischler, Morgan, Polchinski (Hamiltonian)





Zero Schwarzschild mass limit

(Minkowski ≈ Schwarzschild in the M=0 limit)



$$V = -\frac{\left(H^2+\kappa^2\right)^2}{4\kappa^2}\hat{R}^2$$

$$\mathcal{P}(\mathcal{M} \to \mathcal{M}/\mathrm{dS} \oplus \mathrm{W}) = \exp\left[\frac{\eta\pi}{GH^2}\left(1 - \frac{\kappa^4}{(H^2+\kappa^2)^2}\right)\right]$$ **Up-tunneling**

$$\mathcal{P}(\mathrm{dS} \to \mathrm{dS}/\mathcal{M} \oplus \mathrm{W}) = \exp\left[\frac{\eta\pi}{GH^2}\left(-\frac{\kappa^4}{(H^2+\kappa^2)^2}\right)\right]$$ **Down-tunneling**

Detailed Balance

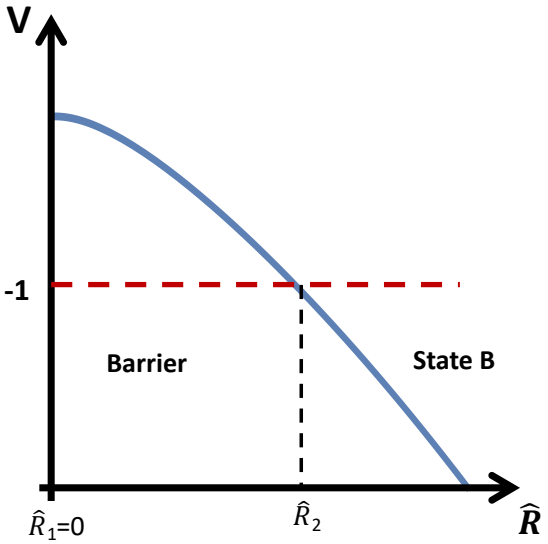
$$\frac{\mathcal{P}(\mathcal{M} \to \mathcal{M}/\mathrm{dS} \oplus \mathrm{W})}{\mathcal{P}(\mathrm{dS} \to \mathrm{dS}/\mathcal{M} \oplus \mathrm{W})} = \exp\left[\eta\frac{\pi}{G}\frac{1}{H^2}\right]$$

Entropy

M=0 Schwarzschild≠ H=0 de Sitter

(Difference on background wave function)

AdS to AdS



$$\kappa < \left|\sqrt{|H_I^2|} - \sqrt{|H_O^2|}\right|, \qquad \text{or} \qquad \kappa > \left|\sqrt{|H_I^2|} + \sqrt{|H_O^2|}\right|,$$

$$B = -\frac{\eta\pi}{2G}\left[\frac{\left(|H_I^2| - |H_O^2|\right)^2 - \kappa^2\left(|H_I^2| + |H_O^2|\right)}{2\kappa|H_I^2||H_O^2|}R_0 - \left(\frac{1}{|H_O^2|} - \frac{1}{|H_I^2|}\right)\right]$$

$$\mathcal{P}_{\text{up}}^{\text{AdS}\to\text{AdS}} = \mathcal{P}_{\text{down}}^{\text{AdS}\to\text{AdS}},$$

Detailed balance if Entropy of AdS = 0 !

AdS to dS

$$B^{\mathrm{AdS}->\mathrm{dS}} = \frac{\eta\pi}{G}\left\{\frac{\left\{(|H_B^2|+H_A^2)^2+\kappa^2(-|H_B^2|+H_A^2)\right\}R_{\mathrm{o}}}{4\kappa|H_B^2|H_{\mathrm{A}}^2}+\frac{1}{2}\left(\frac{1}{H_A^2}-\frac{1}{|H_B^2|}\right)\right\},$$

$$\frac{P^{\mathrm{AdS}->\mathrm{dS}}}{P^{\mathrm{dS}->\mathrm{AdS}}} = \frac{e^{B^{\mathrm{AdS}->\mathrm{dS}}}}{e^{B^{\mathrm{dS}->\mathrm{AdS}}}} = \frac{\exp\left(\frac{\eta\pi}{2G}\frac{1}{H_A^2}\right)}{\exp\left(-\frac{\eta\pi}{2G}\frac{1}{H_A^2}\right)} = e^{\eta(S_{\mathrm{dS}}-(S_{\mathrm{AdS}}=0))},$$

Detailed balance if AdS entropy=0!

Minkowski limit from dS blows-up but from AdS is finite!?

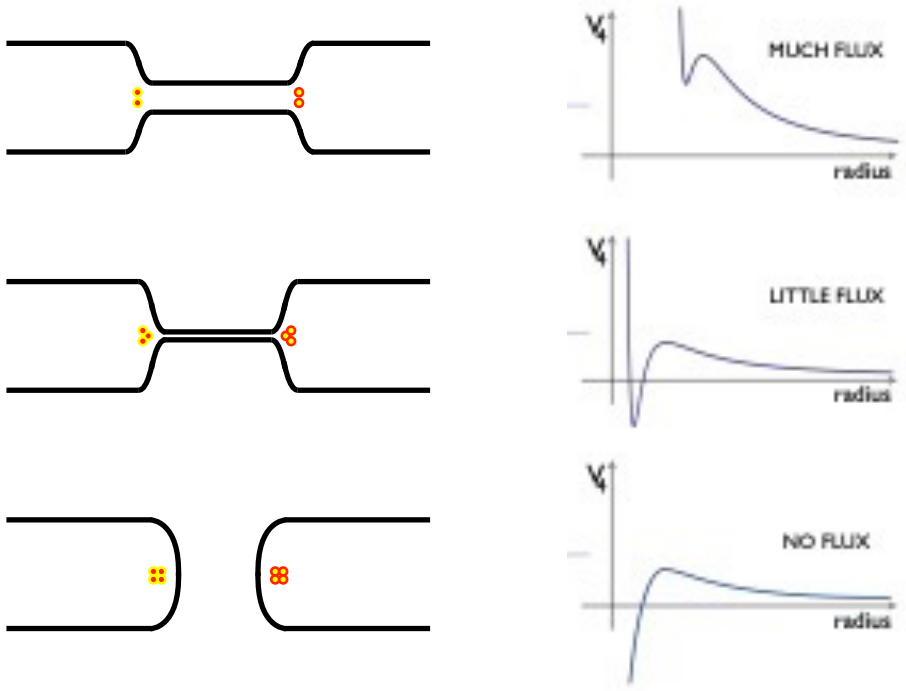
To Nothingness and Back?

For SAdS to dS $H_{\rm O} \gg H_{\rm I}, M$,

$$B^{\rm AdS->dS} \to \frac{\eta\pi}{G}\left\{\frac{\{(|H_B^2|)^2\}\,2\kappa/|H_B^2|}{4\kappa|H_{\rm B}^2|H_A^2}+\frac{1}{2}\left(\frac{1}{H_A^2}+0\right)\right\}=\frac{\eta\pi}{2G}\frac{1}{H_A^2}.$$

The same as Vilenkin, Hartle-Hawking wave functions!

≈ Brown-Dahlen:
Nothing as AdS $H_{\rm O} \to \infty$



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!?)

Summary of transitions

- Schwarzschild M=0 to dS allowed
- AdS Schwarschild M=0 to (A)dS also allowed
- Entropy of Minkowski/AdS is 0 or ∞?
- Transition from $\Lambda \to -\infty$ to dS same as HH/Vilenkin universe from nothing!
- Universe after transition open or closed?!
- Hamiltonian approach very limited!

Conclusions

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

SAdS to dS

$$I_{\rm B}\Big|_{\rm tp} \equiv I_{\rm B}\Big|_{R_{\rm I}}^{R_{\rm O}} = \begin{cases} \frac{\eta\pi}{2G}(R_{\rm O}^2 - R_{\rm I}^2)\,, & M > M_{\rm S}\,, \\ \frac{\eta\pi}{2G}(R_{\rm O}^2 - R_{\mathcal{S}}^2)\,, & M_{\rm S} > M > M_{\rm D} \\ \frac{\eta\pi}{2G}(R_{\rm dS}^2 - R_{\mathcal{S}}^2)\,, & M_{\rm D} > M\,. \end{cases}$$

$$M_{\rm S} = \frac{H_{\rm O}^2 + H_{\rm I}^2 + \kappa^2}{2G\left(H_{\rm I}^2 + \kappa^2\right)^{3/2}}, \qquad M_{\rm D} = \frac{H_{\rm O}^2 + H_{\rm I}^2 - \kappa^2}{2GH_{\rm I}^3}$$

Need numerical estimates for wall contribution but the transition is allowed however detailed balance is OK only for M_D>M (?)

$$\frac{P^{\rm AdS->dS}}{P^{\rm dS->AdS}} = \frac{e^{B^{\rm AdS->dS}}}{e^{B^{\rm dS->AdS}}} = \frac{\exp\left(\frac{\eta\pi}{2G}\frac{1}{H_A^2}\right)}{\exp\left(-\frac{\eta\pi}{2G}\frac{1}{H_A^2}\right)} = e^{\eta(S_{\rm dS} - (S_{\rm AdS}=0))},$$