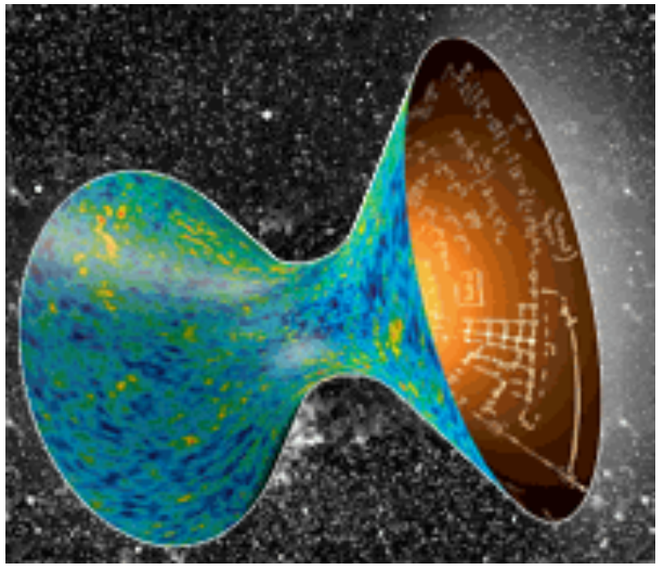
Holographic methods for cosmology

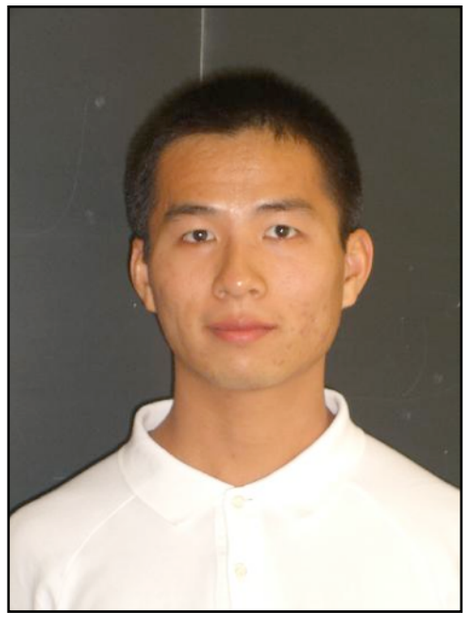


Gonzalo Torroba
Stanford University

Observations and Theoretical Challenges in Primordial Cosmology
KITP, UCSB, April 2013

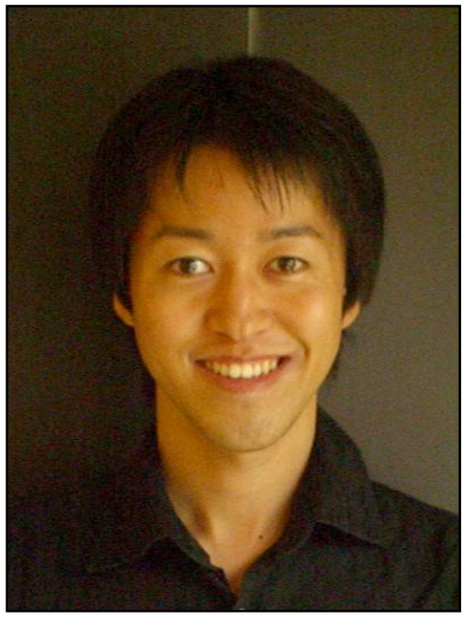
Members of the collaboration

Matt Dodelson

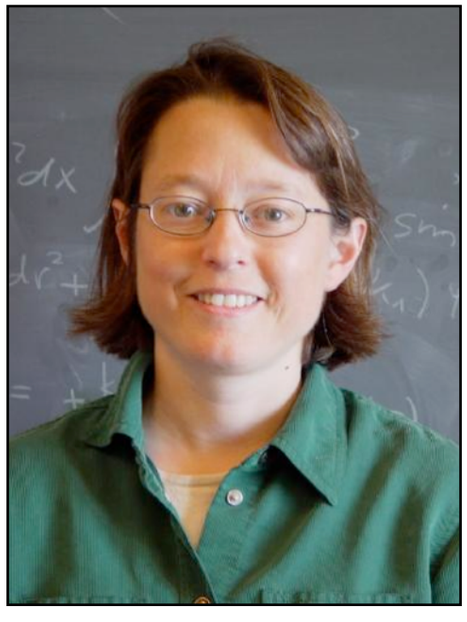


Xi Dong

Bart Horn



Shunji Matsuura

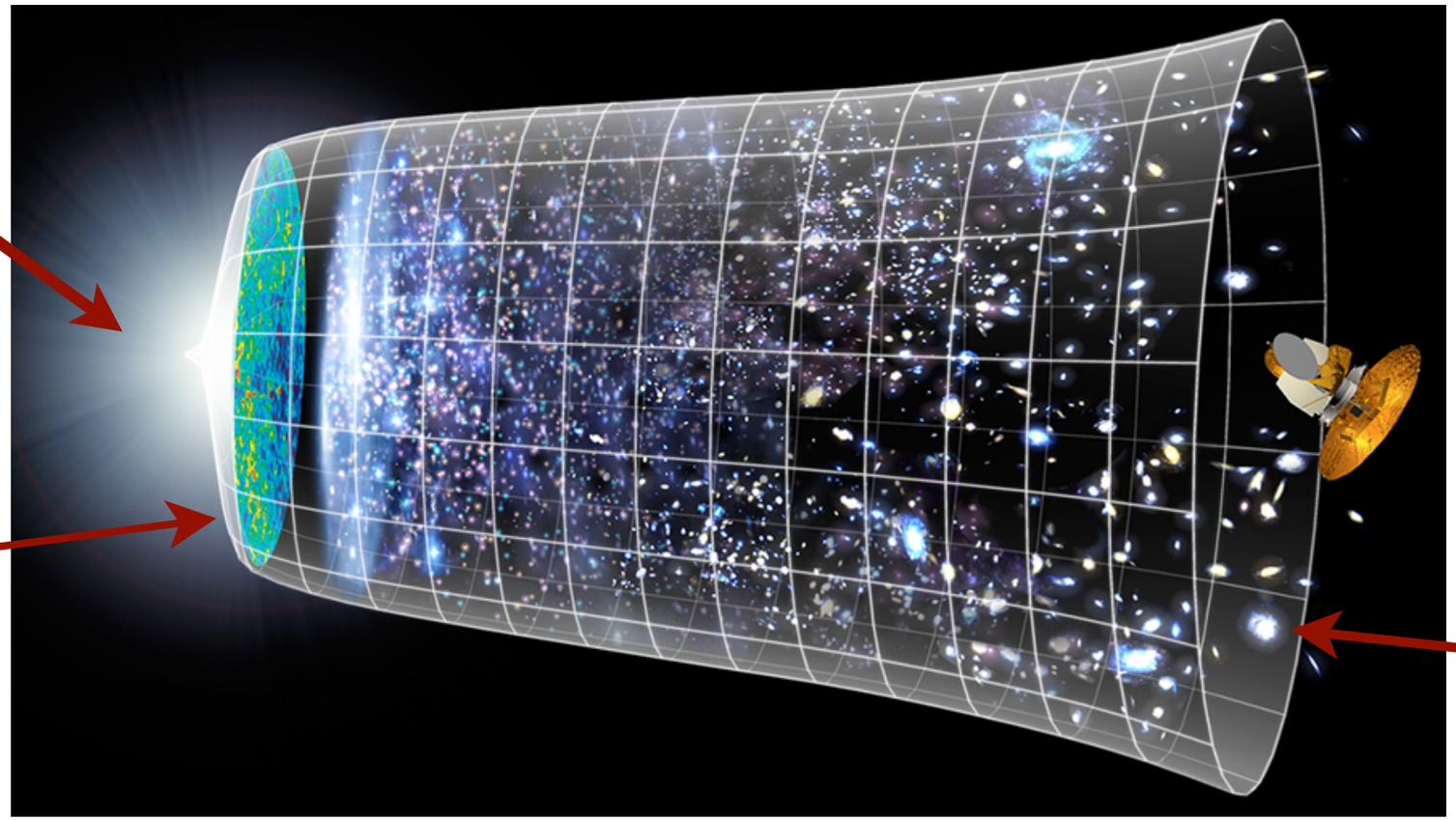


Eva Silverstein

During the last century, Cosmology has seen some of the most spectacular discoveries in the history of Physics

big bang

inflation



Dark energy
Accelerated expansion

Accelerating universe, both in the far past and future

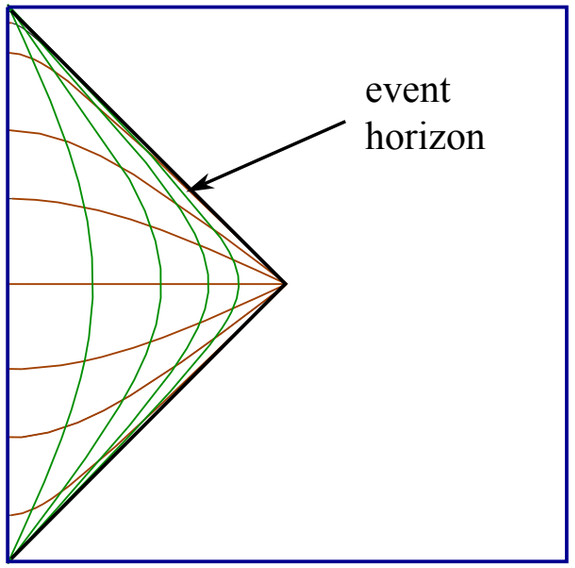
Simplest example: **de Sitter universe** , $a \propto \exp(Ht)$

de Sitter (1917) ←

Fascinating properties of accelerating cosmologies:

- Event horizons
- Thermodynamic laws

Hawking, Bekenstein, Gibbons,... (70's)



$$T = H^{-1} \quad , \quad \mathcal{S} = \frac{\text{Area}}{4G_N}$$

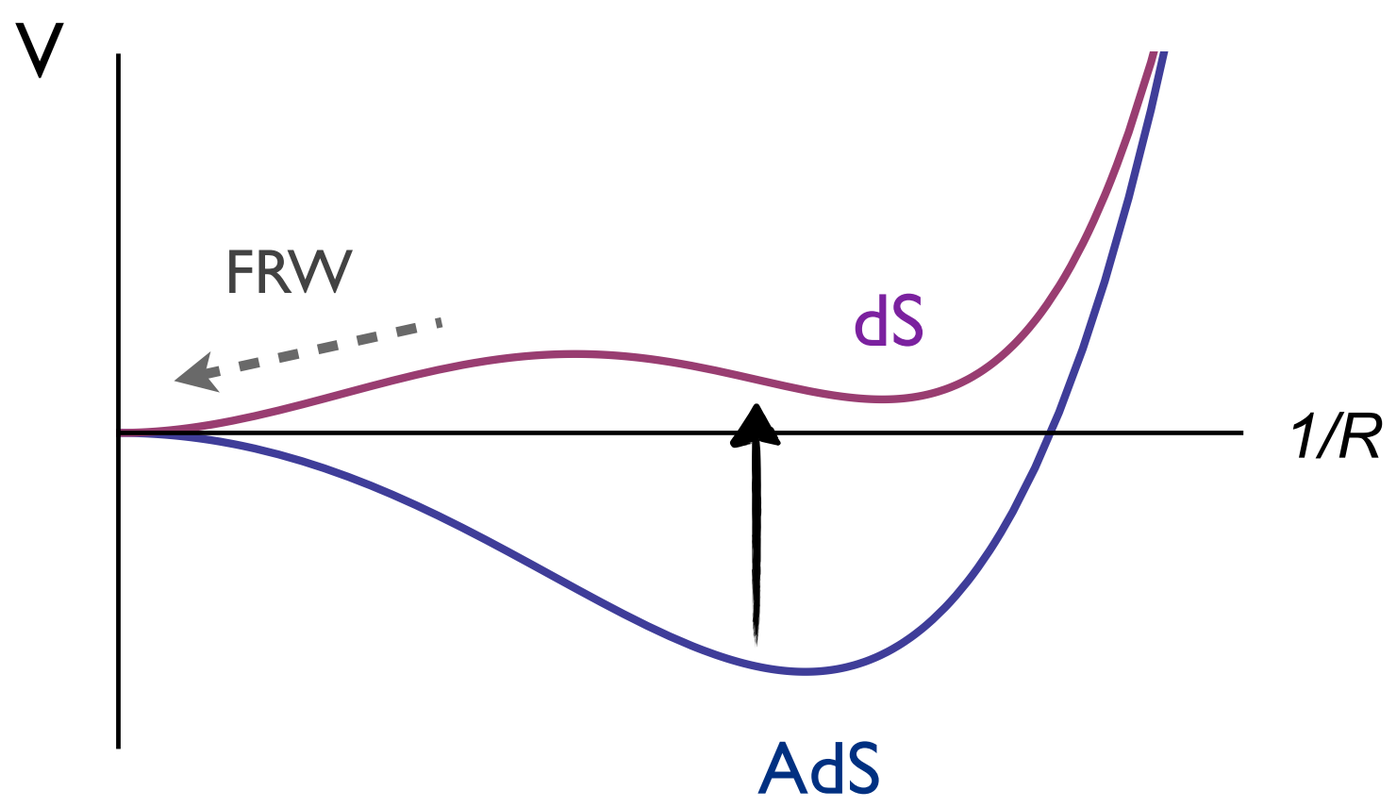
- Lead to deep questions in theoretical cosmology:
  - ➡ microscopic origin of thermodynamic properties?
  - ➡ UV complete framework for calculating observables?

Formulate quantum gravity on cosmological spacetimes?!

Our approach:

formulate cosmology holographically and determine the degrees of freedom that build up cosmological spacetimes

- Strategy: generalize AdS/CFT to cosmology



Organization of the talk

A. Macroscopic holography

B. Uplifting AdS/CFT to cosmology

C. General features of QFT duals

A. Macroscopic holography

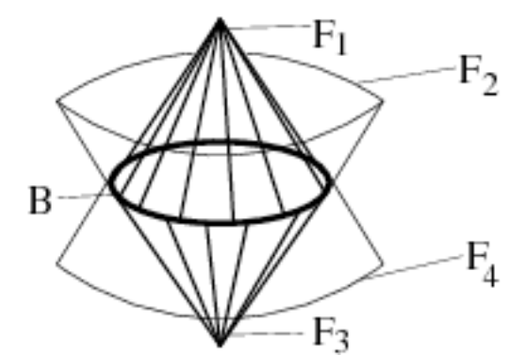
Why a holographic formulation of cosmology?

✓ Gibbons-Hawking entropy for de Sitter

✓ more general idea of holographic principle 't Hooft, Susskind

- relates spacetime geometry to number of quantum states

covariant entropy bound $\mathcal{N} \leq e^{A(B)/4}$

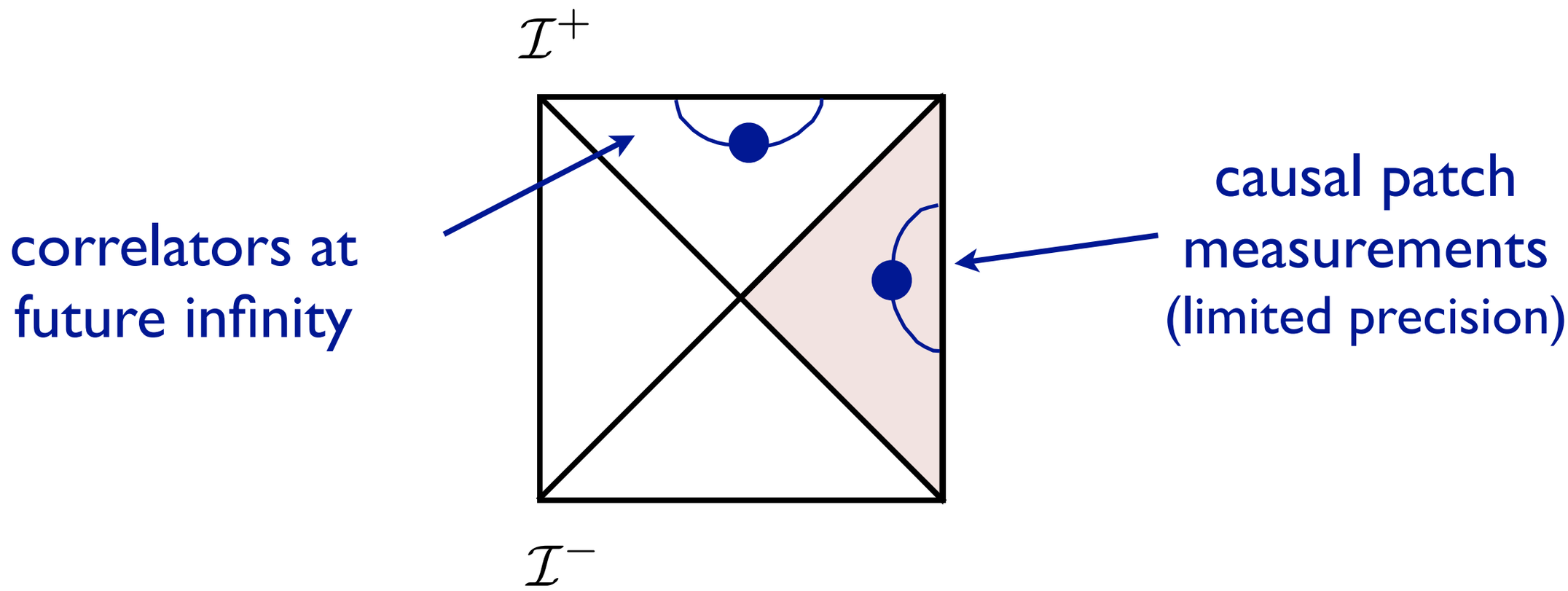


Bousso

✓ basic mechanism responsible for AdS/CFT also in dS

✓ string theory constructions provide dS and FRW holographic duals

Observables in dS



Structure of correlators at $\mathcal{I}^+$

- "metaobservers" (useful for inflation)
- dS symmetries $\Rightarrow$ conformal transf. of boundary
- Suggests $dS_{d+1} \Leftrightarrow$ euclidean CFT_d

Strominger;Witten; Maldacena

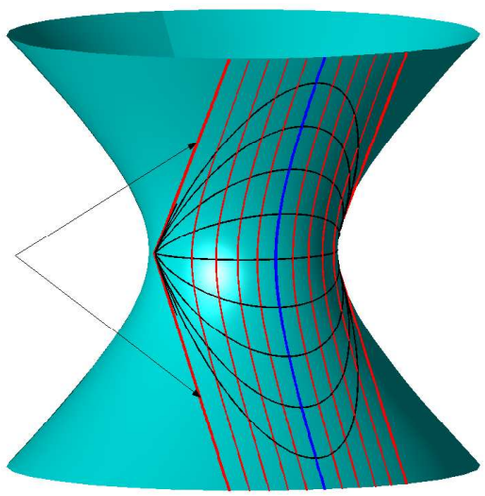
$$\langle F(f) \rangle = \int \mathcal{D}f \; F(f) |\Psi(f)|^2$$

Causal patch holography

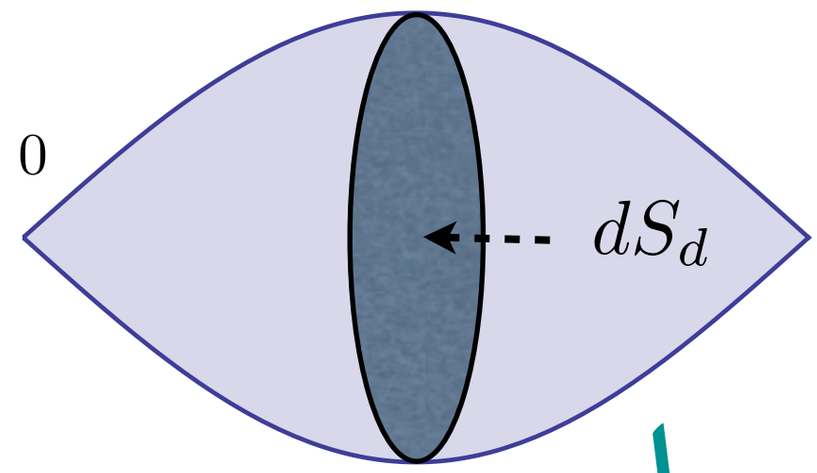
Alishahiha, Karch,
Silverstein, Tong

dS_{d+1}/dS_d

$$ds^2_{d+1} = dr^2 + \sin^2(\frac{r}{R})ds^2_{dS_d}$$

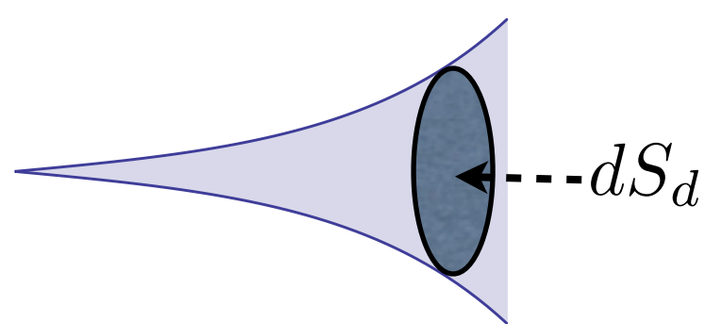


$$E_{loc} \sim \frac{r}{R}E_{pr} \to 0$$



two AdS throats deformed and glued near central slice

Compare to AdS/dS

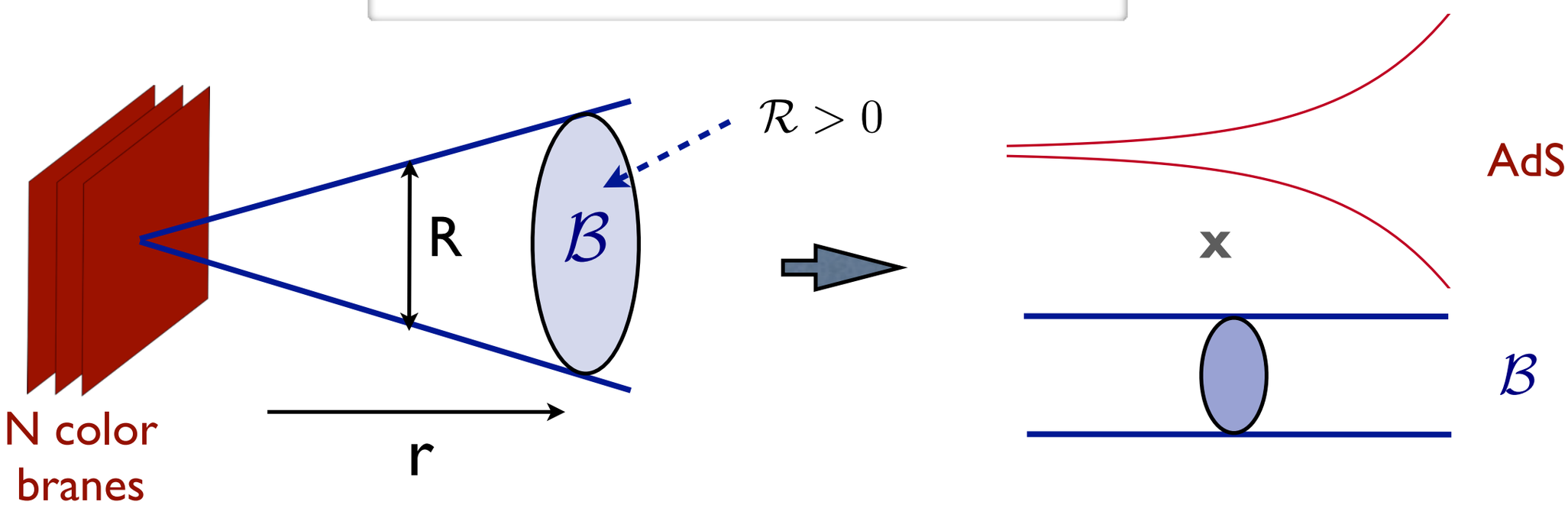


Causal patch of dS_{d+1} $\Leftrightarrow$ Two coupled QFTs on dS_d with dynamical gravity

B. Uplifting AdS/CFT to cosmology

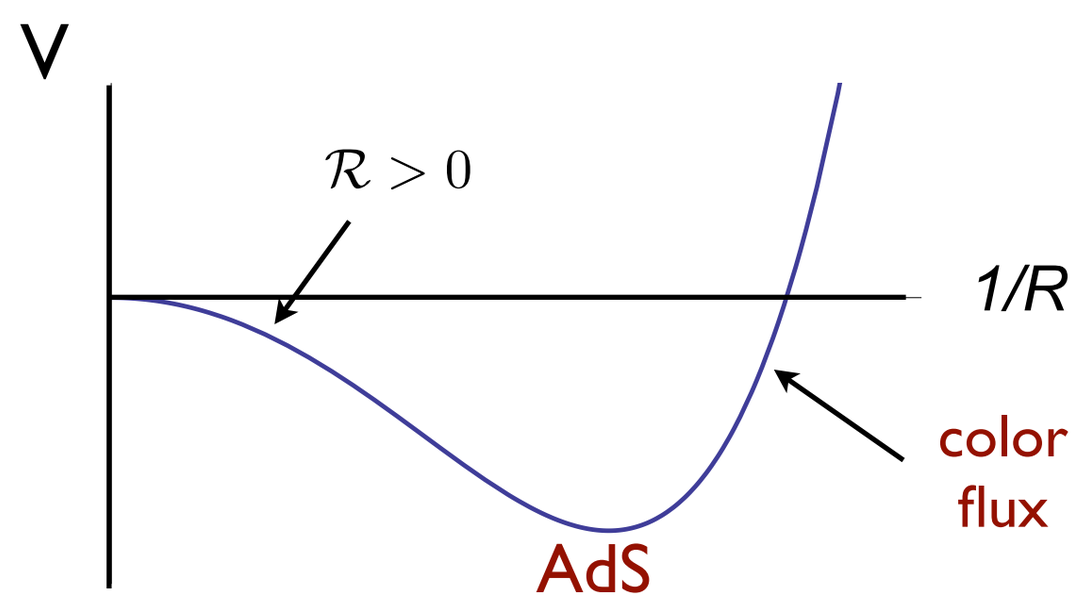
Dong, Horn, Silverstein, GT

AdS/CFT duality



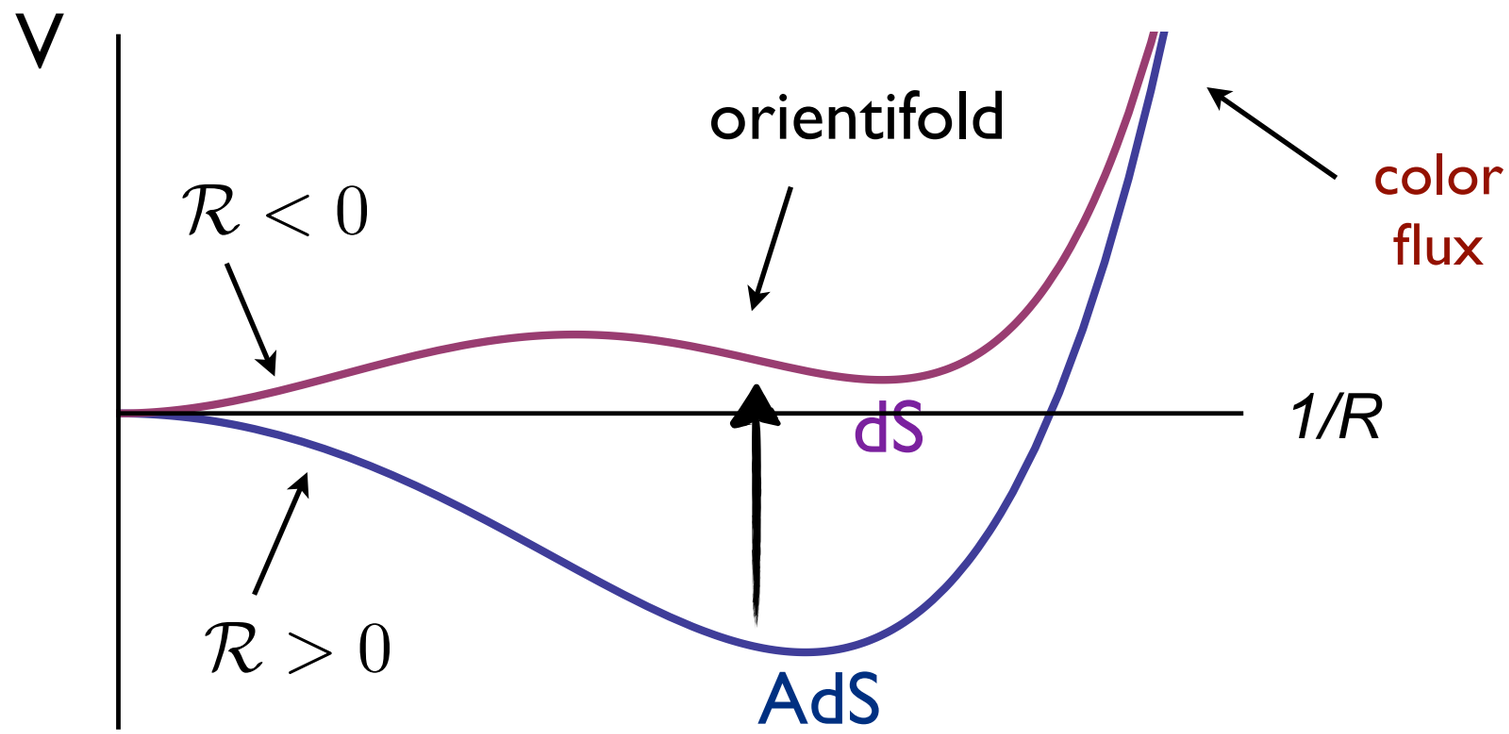
$$\frac{(dR/dr)^2}{R^2} = +\frac{1}{R^2} - g_s^2 \left(\frac{N}{R^n}\right)^2$$

$\mathcal{R} > 0$ color flux



Uplifting AdS/CFT

no hard c.c.!



✓ Internal space of negative curvature obtained by adding magnetic flavor branes

✓ Orientifolds provide negative tension for the intermediate term in the potential

✓ With other ingredients in place to stabilize all light fields

... can lead to metastable de Sitter solutions

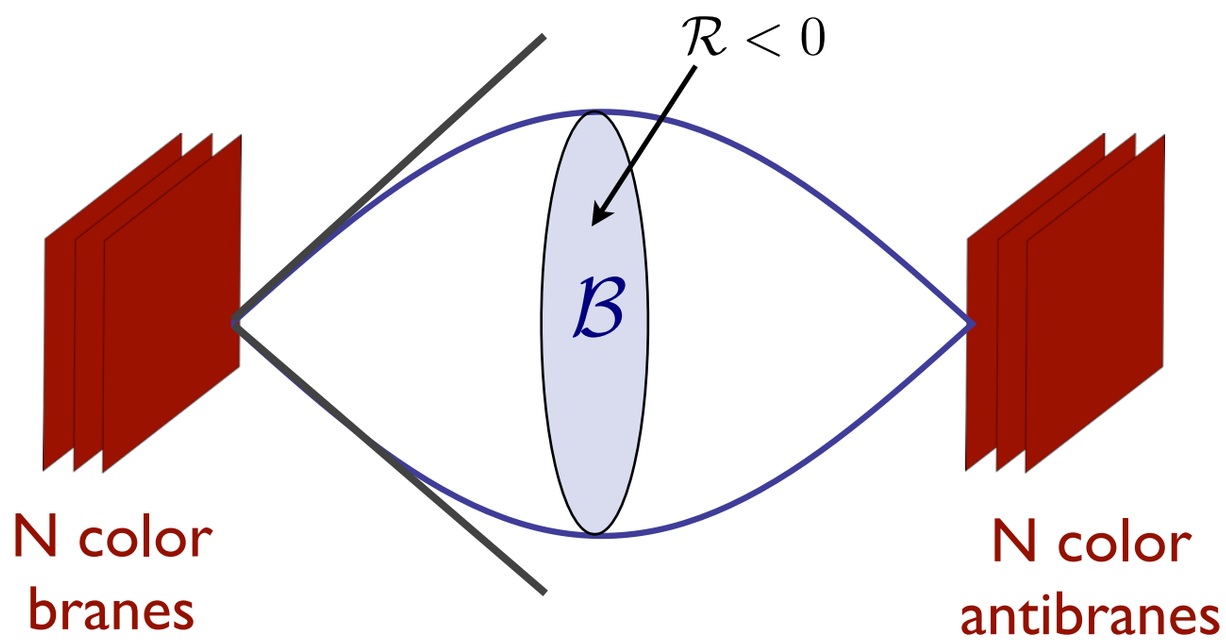
Concrete brane construction given in Dong, Horn, Silverstein, GT arXiv:1005.5403

Brane construction

Background internal geometry:

$$\frac{(dR/dr)^2}{R^2} = -\frac{1}{R^2} + \frac{\text{const}}{R^{d_\perp}}$$

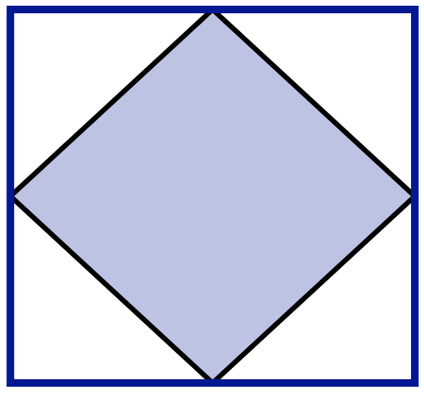
$\mathcal{R} < 0$ orientifold



- The cone of AdS/CFT now becomes compact
- Two tips; place color branes at one and antibranes at the other

$dS_{d+1} \times \mathcal{B} \equiv$ Two large N QFTs on dS_d plus Gravity_d

Agrees w/ macroscopics!



dS/dS

Properties of the duality

- Two large N gauge theories with dyonic flavors living on dS
- Framework for calculating observables in causal patch

$$\langle F(\phi)\rangle \;\leftrightarrow\; \int D\phi\, Z_{(1)}[\phi] Z_{(2)}[\phi] F(\phi)$$

- Semiholographic: lower dimensional dynamical gravity. But screened by large N matter sector

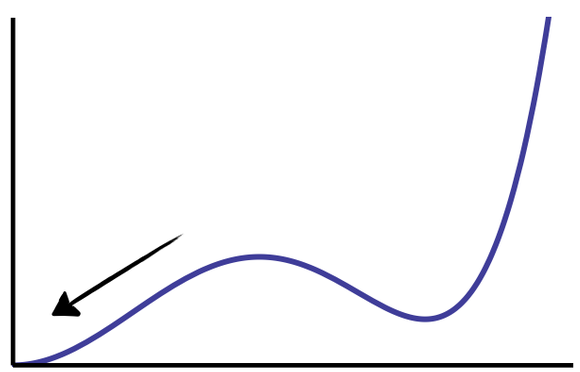
❖ Microscopic explanation of thermodynamic properties

$$\left(\begin{array}{c}\text{Area of dS}\\ \text{horizon}\end{array}\right) \cong \left(\begin{array}{c}\text{Thermal entropy of}\\ \text{large N matter sector}\end{array}\right)$$

❖ FRW decays

Dong, Horn, Matsuura
Silverstein, GT

arXiv:1108.5732
arXiv:1203.1680



- Dual to two t-dep QFTs
- Precise duality at late times!

$$S \to \infty \;\;,\;\; GR_d \text{ decouples}$$

C. RG structure of dS dual

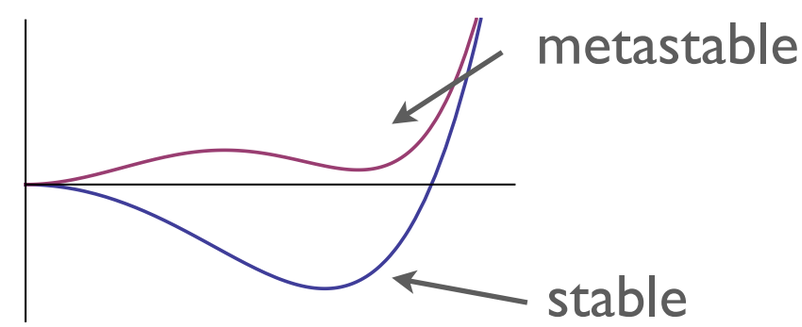
arXiv:1209.5392 Dong, Horn, Silverstein, GT

Conditions on a QFT so that it can describe holographically an observer patch of de Sitter?

From gravity side, both AdS and dS look very special ...

✓ maximal symmetry $\Rightarrow \begin{cases} ds^2_{d+1} = dr^2 + a(r)^2 ds^2_{dS_d} \\ a(r) = \sin(\mathrm{h})(r) \ \text{ for } (\mathrm{A})\mathrm{dS} \end{cases}$

✓ moduli stabilization $V'(\phi) = 0$



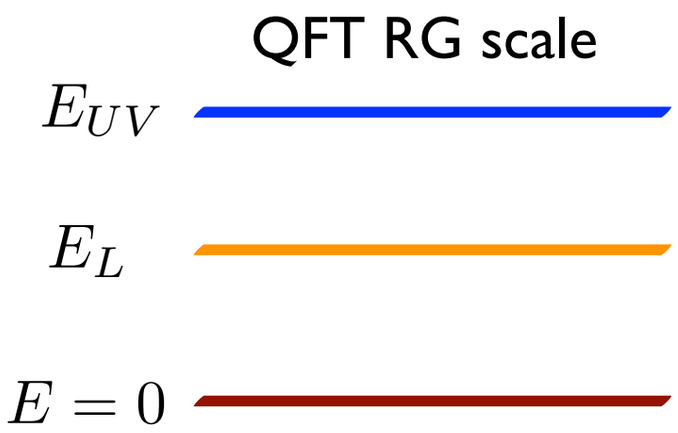
For AdS, properties should be equivalent to having a CFT

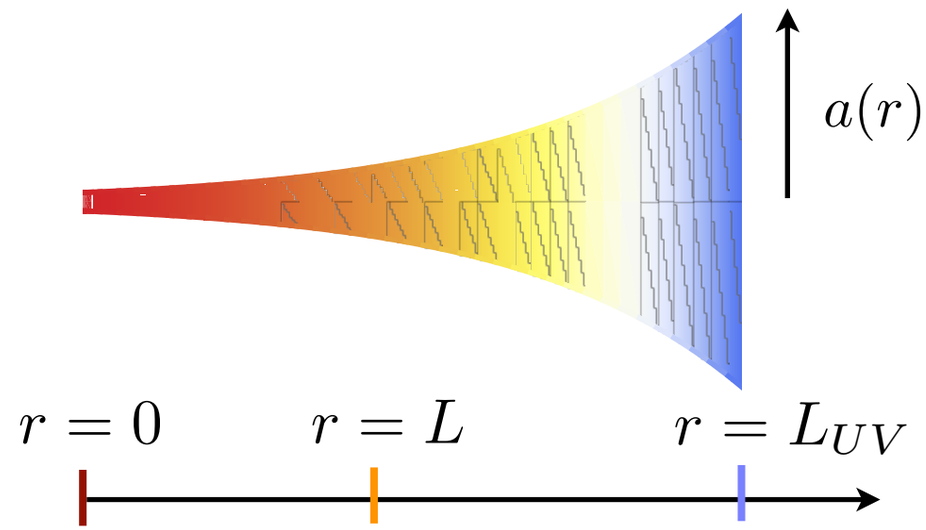
Features of dS dual that encode max. sym. and stabilization?

de Boer, Verlinde, Verlinde;
Henningson, Skenderis ...

Holographic RG

Energy-Radius relation: $ds^2 = dr^2 + a(r)^2 \hat{g}_{\mu\nu} dx^\mu dx^\nu \quad \Rightarrow \quad E_{\rm loc} = a(r) E_{\rm proper}$





$$Z_{\rm QFT} = \int \mathcal{D}M \, e^{-S_{QFT}} = \qquad\qquad Z_{\rm bulk} = \int \mathcal{D}\phi \, e^{-\mathcal{S}} =$$

$$\int \mathcal{D}M|_{E<E_L} \underbrace{\left(\int \mathcal{D}M_{E>E_L} e^{-S_{QFT}} \right)}_{e^{-S_{\rm eff}(E_L)}} \cong \int \mathcal{D}\tilde{\phi} \underbrace{\left(\int \mathcal{D}\phi|_{r<L} \, e^{-\mathcal{S}|_{r<L}} \right)}_{\Psi_{IR}(L,\tilde{\phi})} \underbrace{\left(\int \mathcal{D}\phi|_{r>L} \, e^{-\mathcal{S}|_{r>L}} \right)}_{\Psi_{UV}(L,\tilde{\phi})}$$

Heemskerk
Polchinski

Postulate: $\Psi_{IR}(L,\tilde{\phi}) = \int \mathcal{D}M|_{E<E_L} \, e^{-S_0(M) + \int d^d x \sqrt{g} \, \tilde{\phi} \, \mathcal{O}}$

$$e^{-S_{\rm eff}(E_L)} = e^{-S_0} \int \mathcal{D}\tilde{\phi} \, e^{\int d^d x \sqrt{g} \, \tilde{\phi} \, \mathcal{O}} \, \Psi_{UV}(L,\tilde{\phi})$$

Consequences of moduli stabilization

Bulk scalar sitting at (local) minimum: $V'(\phi_*) = 0$

$$\mathcal{S} = -\int d^{d+1}x\,\sqrt{g}\left((\partial\phi)^2 + V(\phi) + \ldots\right)\,,\;\; V(\phi) = V_* + \frac{1}{2}V_*''(\phi-\phi_*)^2 + \ldots$$

Ψ_{UV} dominated by classical trajectory $\phi(L_{UV}) = \phi_* \;\;\rightarrow\;\; \phi(L) = \tilde{\phi}$

$\Rightarrow\; \log\,\Psi_{UV}$ has no linear term in $\tilde{\phi} - \phi_*$

Wilson action $S_{\text{eff}} = S_0(M) + g_1\mathcal{O} + \frac{1}{2}g_2(L)\mathcal{O}^2 + \ldots$

1. Single trace couplings do not run, $\partial_L g_1 = 0$
2. Iterative structure of RG: $\partial_L g_n$ only depends on $g_{m\leq n}$

Strong simplification of RG evolution

Suggests new way of organizing the QFT path integral

Partial moduli stabilization

work in progress
Dodelson et al

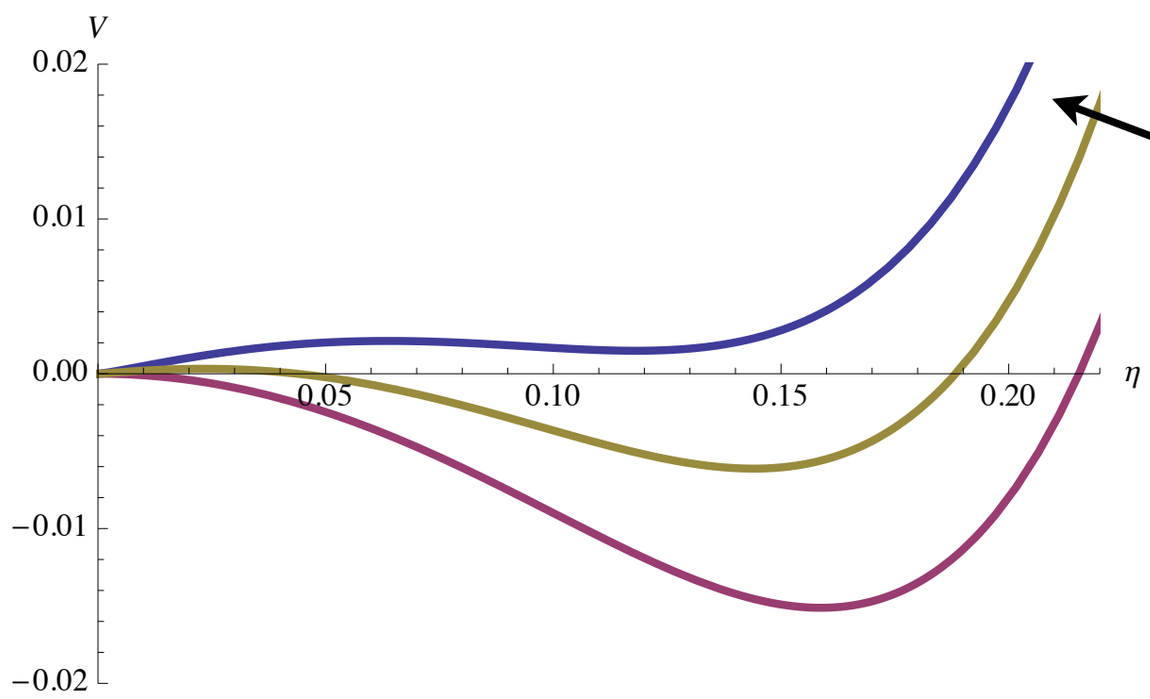
➡ Apply lessons from holographic RG to construct dual QFTs

$$\beta_{\text{single trace}} = 0$$ for each metastabilized scalar

Explicit UV complete model for uplifting?

➡ Simpler construction that uplifts AdS/CFT but doesn't stabilize all moduli

$$\text{D3 gauge theory} + \overline{9 - 9} \text{ flavors} + \text{orbifold}$$



uplift : $\frac{N_f}{N_c} \sim \frac{1}{\lambda^{3/2}}$

changes VEV and dimension of $\mathrm{tr}\left(F_{\mu\nu}^4\right)$

May also be useful for holographic dual of inflation

D. Summary and future directions

- dS and FRW dual to two large N gauge theories plus gravity with enough magnetic flavors for uplifting.
- Explains thermodynamic properties and provides a framework for calculating observables

Nontrivial agreement between micro and macroscopic results indicates a consistent framework for holographic cosmology

- Develop more string theory constructions of dS, FRW and models of inflation
- Explicit description of matter content and couplings of dual QFTs. Flesh out more explicitly holographic dictionary
- Is uplifting the only mechanism for obtaining a dS dual? Relation to global dS/CFT description?