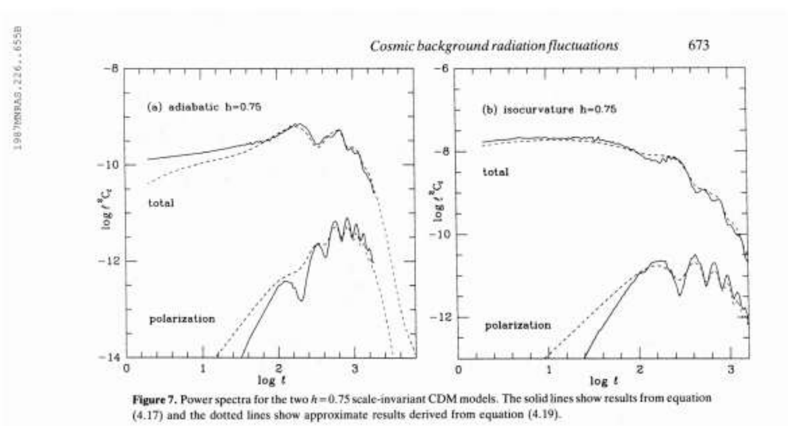
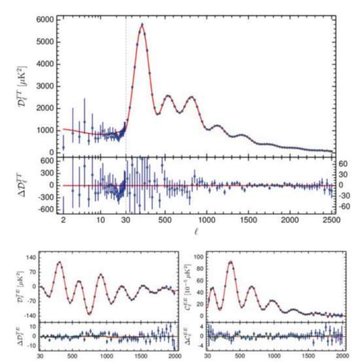
Observational cosmology:

- ΛCDM (dS)
- Precision tests of early U physics, with $\sigma \sim \frac{1}{\sqrt{N_{modes}}} < 10^{-3}$ (CMB & LSS)

  power spectrum (function P(k)) and non-Gaussianities (functional $|\Psi|^2$)
- B modes: primordial GW (large-field inflation), lensing, foregrounds.
- Cosmological info from multi-messenger GW sources etc
- Particle physics (e.g. N_{eff} and neutrinos), dark matter and axion searches, astrophysical measurements,…



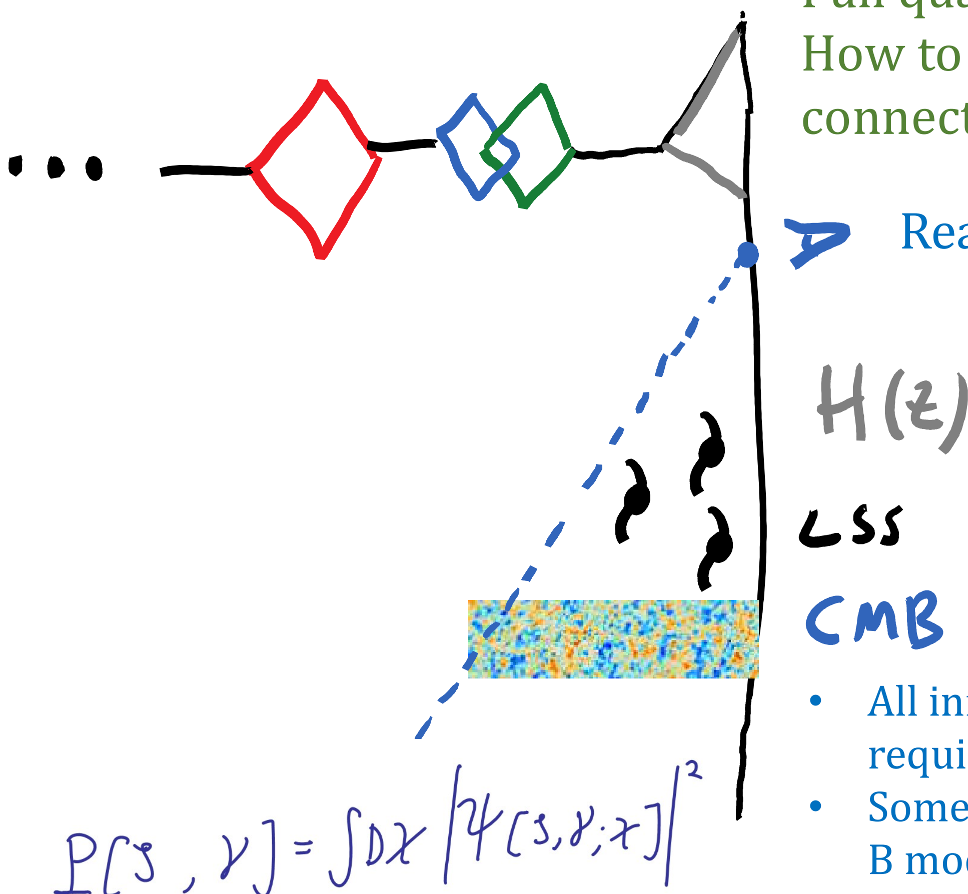
(a) Bond Efstathiou 1987



(b) Planck results: matches the predicted structure of the power spectrum including acoustic oscillations and Silk damping.

Successful theoretical prediction of the origin of structure from quantum fluctuations. Foundation for new precision tests in a UV-sensitive context.

Full quantum gravity framework still in progress. How to make further progress on this and its connection to observables?



Real observations, statistical inferences

- All inflation models UV sensitive, satisfactory theory requires control of QG effects.
- Some testable signatures from string theory mechanisms: B modes, power spectrum features and non-Gaussianity
- Describe/classify perturbations and what we actually measure via bottom up EFT

Or perhaps more globally: $\Sigma_I c_I\ (above \times disconnected\ components)_I$

Basics: structure of the 4d effective scalar potential in perturbative string theory

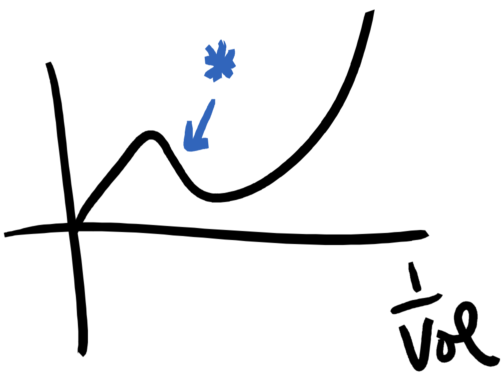
$$S = \frac{1}{2\alpha'^{\frac{D-2}{2}}} \int d^D x \sqrt{g}\, e^{-2\phi_s} \left(\mathcal{R} - \frac{2}{3}\frac{c - c_{\rm crit}}{\alpha'} + 4(\partial\phi_s)^2 \right) + S_{\rm matter}\,.$$

$$S_{matter} = \int d^D x \sqrt{-G}\{ \; - \sum_{n_B} \tau_{n_B} \frac{\delta^{(D-1-n_B)}(x_\perp)}{\sqrt{G_\perp}} + \sum_{n_O} \tau_{n_O} \frac{\delta^{(D-1-n_O)}(x_\perp)}{\sqrt{G_\perp}} + e^{-2\phi_s}|H_3|^2 + \sum_p |\tilde{F}_p|^2 + C.S. + h.d.\}$$

$$\tilde{F}_p = F_p + B \wedge F_{p-2} = dC_{p-1} + B \wedge dC_{p-3} \qquad \tilde{F}_5 = dC_4 - \frac{1}{2}C_2 \wedge H_3 + \frac{1}{2} B \wedge dC_2$$

➔ Flux stabilization typically comes with rolling axions (monodromy). **includes>10 M_p range without strong effects of light fields**.

Reduce to 4d, schematically:



$$\begin{aligned} \frac{V}{M_P^4} \;=\; & g_s^2 \left[\frac{D-10}{L^{D-4}} + \frac{c_h}{L^{D-2}} + \left(\frac{N_3}{L^3}\right)^2 \frac{1}{L^{D-4}} + (NS \ or \ p-q \ branes) \right] \\ + \; & g_s^3 \left[-\sum_O \frac{\hat{\tau}_O L^{n_O}}{L^{2(D-4)}} + \sum_D \frac{\hat{\tau}_D L^{n_D}\sqrt{1+b^2/L^{m_D}}}{L^{2(D-4)}} \right] \\ + \; & g_s^4 \left[\left(\frac{Q_3 - C_0 N_3}{L^3}\right)^2 \frac{1}{L^{D-4}} + \left(\frac{Q_5 - \frac{1}{2}c_2 N_3 + \frac{1}{2} b N_3}{L^3}\right)^2 \frac{1}{L^{D-4}} + \dots \right] \\ + \; & h.d. + warping + quantum \end{aligned}$$

Similar in M theory limits, but no dilaton field. Meta-stability is classic example of **UV sensitivity/dangerous irrelevance.**

4d effective potential

Douglas '09
[Torroba talk]

$$V_{eff}[g^{(D-4)},\ldots] = \frac{\ell_D^{D-2}}{2G_N^2}\frac{\int d^{D-4}y\,\sqrt{g^{(D-4)}}e^{-2\Phi}u^2|_c\left(-R^{(D-4)}-\frac{1}{4}\ell_D^{D-2}T^\mu_\mu-3\left(\frac{\nabla u}{u}\right)^2\Big|_c\right)}{\left(\int d^{D-4}y\sqrt{g^{(D-4)}}e^{-2\Phi}u|_c\right)^2}$$

$$ds^2 = e^{2A(y)}ds^2_{dS_4} + e^{2B(y)}(g_{\mathbb{H}ij}+h_{ij})dy^i dy^j \qquad u(y) = e^{2A(y)}$$

u(y) satisfies GR constraint (its equation of motion):

$$\left(-\nabla^2 - \frac{1}{3}\left(-R^{(D-4)} - \frac{1}{4}\ell_D^{D-2}T^\mu_\mu\right)\right)u = -\frac{C}{6}$$

Like a Schrodinger problem for
$C\ell^2 \sim H^2\ell^2 \ll 1$

$$\Rightarrow \quad V_{eff} = \frac{C}{4G_N} = \frac{R^{(4)}_{\text{symm}}}{4G_N}\,.$$

dS examples:

Reviews of various aspects: Polchinski, Baumann/McAllister, Douglas/Kachru, Denef, Frey, Hebecker; ES TASI '16, ...

- Non-perturbative stabilization

  --GKP '01/KKLT '03 and many followups, e.g.
  --large volume scenario

  Sub-KK scale SUSY breaking

- Power-law stabilization

  --(D-Dc), O-planes, flux, asymmetric orbifold (large-D expansion) '01-'02
  (...other examples...)
  --hyperbolic space, Casimir, flux '21
  Torroba talk
  --including explicit uplifts of AdS/CFT
  [D1-D5 theory -> dS3 '10,
  M2 brane theory -> dS4 '21]

  ≥KK scale SUSY breaking

(Weak-coupling EFT control. Ongoing studies of internal equations of motion in various cases & models, including ones with significant gradients e.g. Cordova et al, ...)

Potential energy **V**(φ_i) in 4d has mostly positive contributions, along with controlled negative sources. Inflation and signatures are sensitive to Planck suppressed operators and to back reaction of heavy fields.

e.g. Many axions ($\sim 2^D$), **generically heavy** in ground state, with flattened large-field inflaton potential, observationally testable with B modes, with residual oscillations. (*model-dependent* tests).

D-10

anti D3 brane

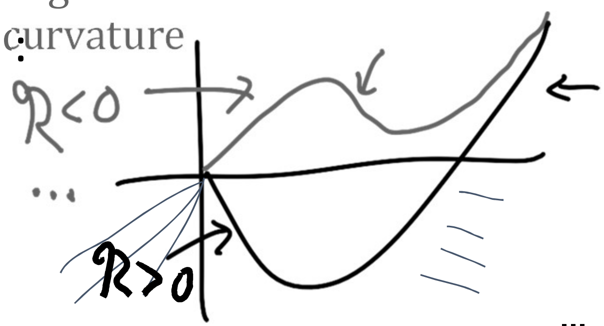
negative

curvature

:

Orientifolds

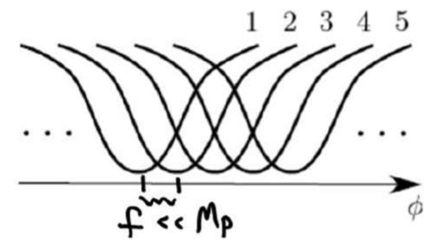
Quantum



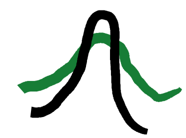
Generalized flux

1/Volume coupling

...



Particle production, **Non-Gaussian** shapes and tails of the distribution



Warped product and/or branes -> other mechanisms with small r, such as slow roll KKLMMT,..., or DBI/trapped/log inflation (testable via non-Gaussianity)

Axion physics:

Review of some aspects: Marsh, ES TASI '16,...

Empirically testable scenarios: axion dark matter, light axions and BH super-radiance, axion (monodromy) inflation (single or multi-field)

- Special case: CY models without flux, brane sources -> light axion phenomenology
  (McAllister et al stats)

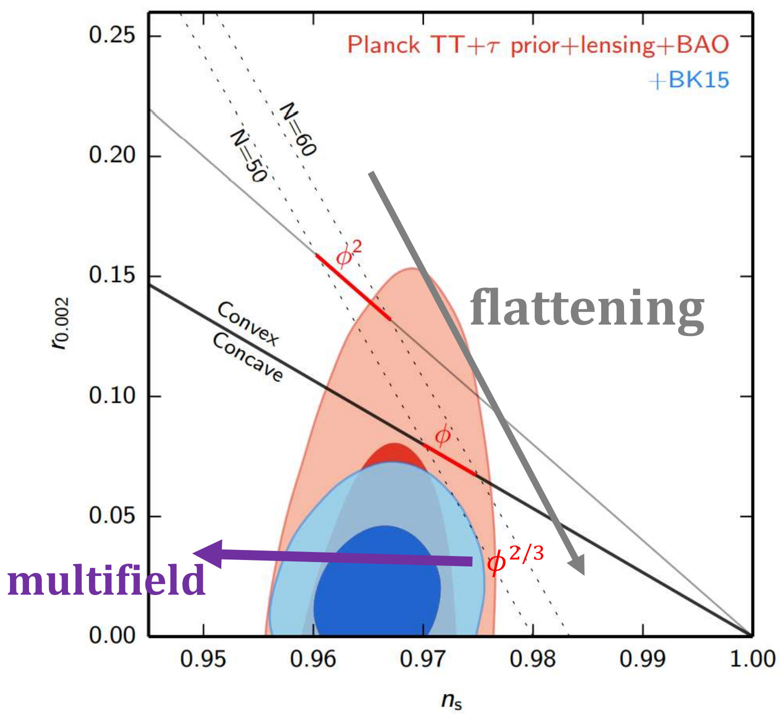
- More generally: 2^D axions (RR), for any D enhanced by internal homology.
  axions dominate the string spectrum

○ NOTE: generically no `saxion': the internal space (generically) breaks SUSY at the KK scale or above. No `universal' saxion back reaction (true back reaction & flattening effects included).

○ NOTE: fluxes and branes (generically) lift the axions, producing a branched large-field potential (flattened at large field range by back reaction of massive fields).

Comments on observables:

r, n_s: flattening and multifield effects



Integrating out heavy fields flattens V (energetics)

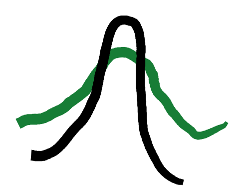
Dong et al, Dimopoulos et al,…,Wenren (before data)

Non-perturbative non-Gaussian tails

$$\mathcal{L}(\zeta(\mathbf{x})|\{\lambda\}) = \int D\chi |\Psi(\zeta(\mathbf{x}),\chi(\mathbf{x});\{\lambda\})|^2.$$

$$e^{W(J)} = \int D\zeta e^{\int J\zeta} \mathcal{L}(\zeta|\{\lambda\})$$

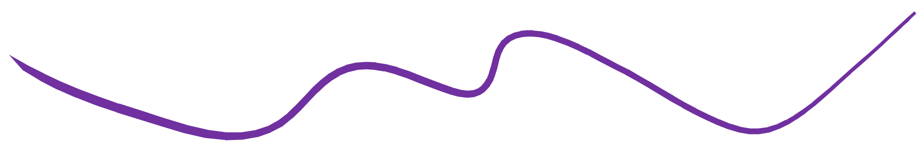
$$\langle \zeta_{\mathbf{k}_1} \dots \zeta_{\mathbf{k}_N} \rangle_C = \frac{\delta^N}{\delta J_{\mathbf{k}_1} \dots \delta J_{\mathbf{k}_N}} W(J) \Big|_{J_{\mathbf{k}_i}=0}$$



Panagopoulos et al '20,
Creminelli et al '21

Novel observational probes & PBH mechanism

The connection between string theory and cosmology is not `all or nothing’ !



Nothing:
`anything goes’
(said nobody)

Truth: landscape is rich but highly structured

Model- and wavefunction-dependent statements

Still, many empirical tests and discriminations

$\Lambda > 0$ demands new framework for QG.

All:
`derive m_e–’
` V' bounded’
`r (un)detectable’
…

Comments on cosmological QG:

(time permitting)

- radial emergence via $T\bar{T} + \Lambda_2$ (static patch, dS/dS)
- other approaches (e.g. EQG) and connections
- (many) questions

Questions and Discussion Topics

Observational

- What are the prospects of future observations?
- What are the main observational challenges?
  Amenable to theoretical contributions (EFT, ML, …)?
- What are key targets for future observations?
- Is the Hubble tension real?

Phenomenological

- What are important effects of the UV completion?
- How do we systematically study non-Gaussianity?
- How to make the most of B-mode measurements?
- How to further test the inflationary framework?

Conceptual

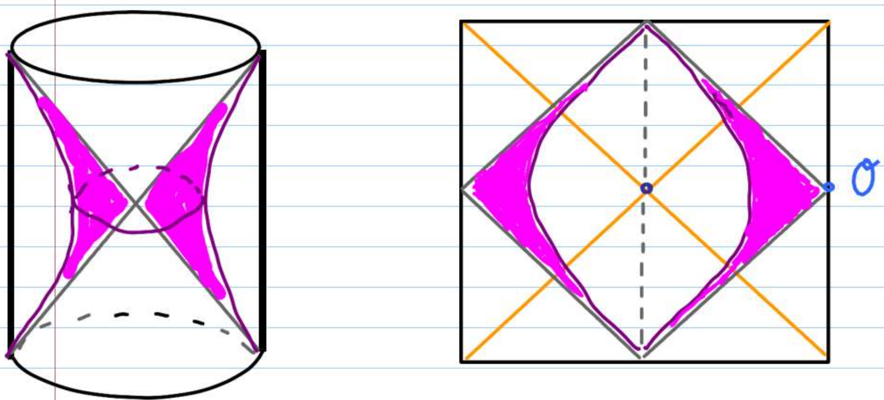
- Do insights from the S-matrix / conformal bootstrap have implications for cosmology?
- How does string theory behave in generic backgrounds?
- Can insights from cosmological holography impact real observables in cosmology?
- Do insights into the BH information paradox have implications for cosmology?
- How do we choose a wavefunction for cosmology?
- Will the nuts and bolts of the string landscape guide us toward a measure?

Comments on cosmological QG

supplementary slides

Renewed traction on holographic framework for metastable dS

$$
\begin{aligned}
ds^2_{(A)dS_{d+1}} &= dw^2 + \sin(h)^2(\frac{w}{\ell_{dS}})ds^2_{dS_d} \\
&= dw^2 + \sin(h)^2(\frac{w}{\ell_{dS}})\left[-d\tau^2 + \ell_{dS}^2 \cosh^2 \frac{\tau}{\ell_{dS}} d\Omega^2_{d-1}\right].
\end{aligned}
$$



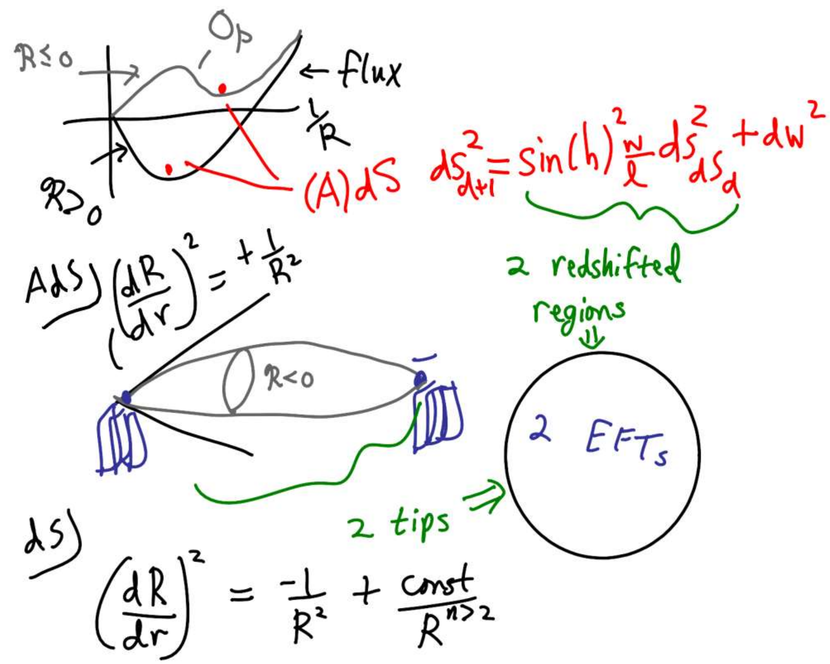
AdS/dS

dS/dS (each point is (d-1)-sphere)

Alishahiha, Karch, ES, Tong '04,…

Uplifting AdS/CFT => 2 sectors

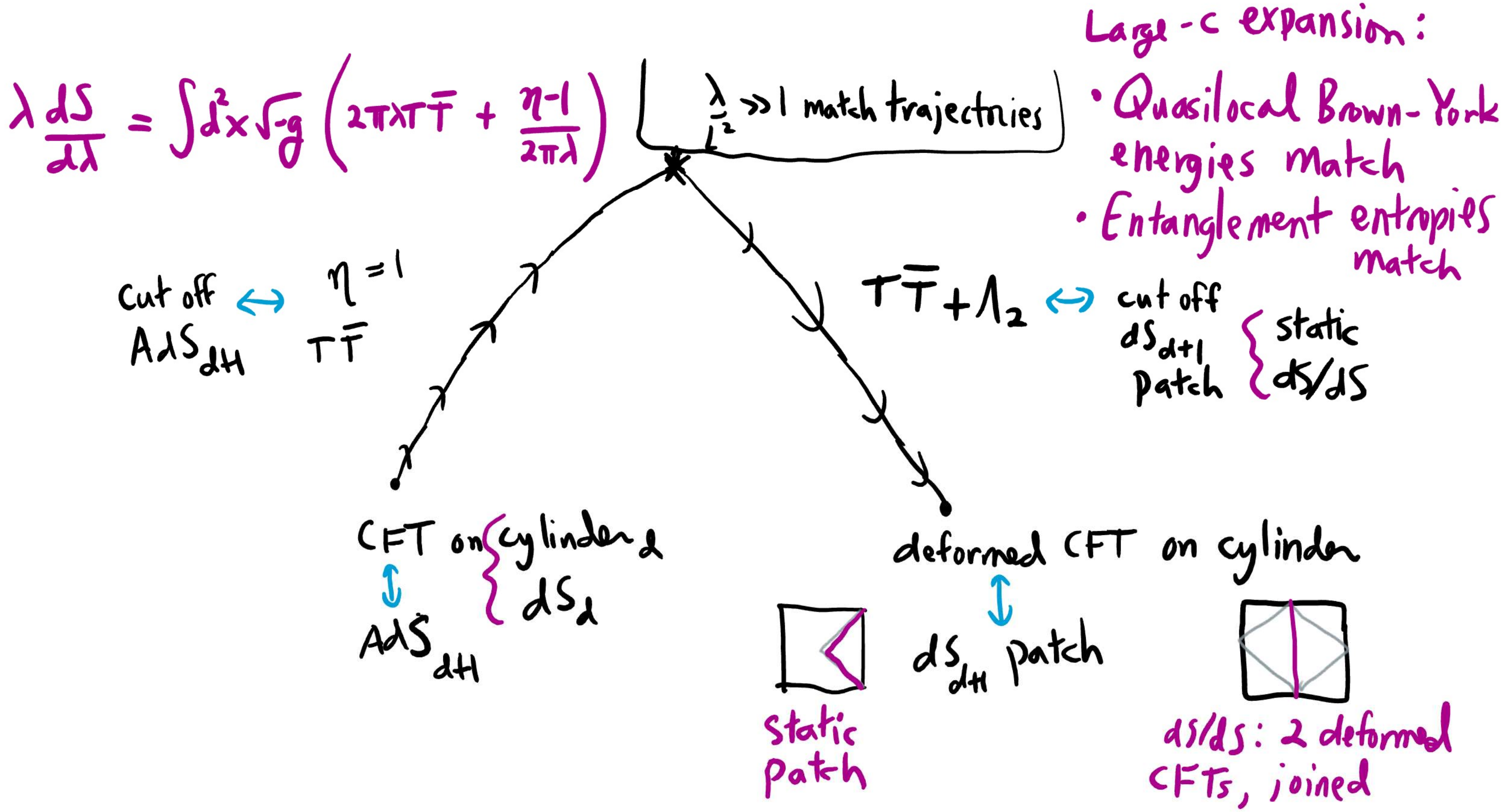
Dong Horn ES Torroba '10



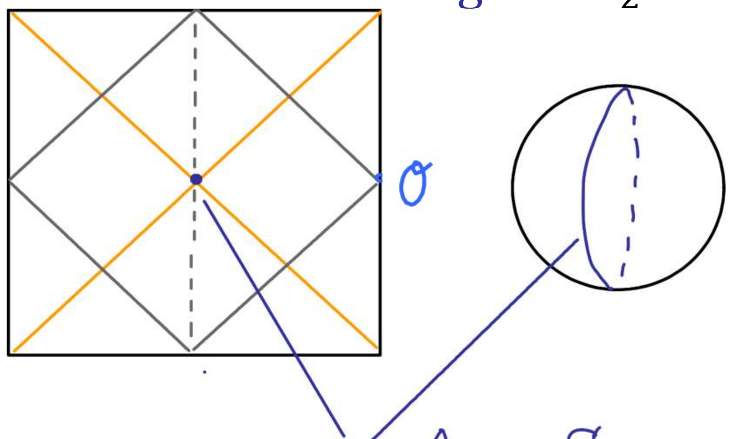
dS vs AdS brane construction: independent derivation of the two sectors because of metastability.

Also true in dS/CFT

Proposed dual contains $T\bar{T} + \Lambda_d$ deformed CFT Gorbenko et al '19



Interpretation of $S_{Gibbons-Hawking}$:
trace out 1 of the 2 identical TTb+… deformed CFTs living on dS_2 saddle.



$$\frac{A}{4G_N} = S_{RT}$$

$$= S_n = S_{VN} = \log \dim H = S^{(\vartheta)}_{G-H}$$

$e^{\pi c/3}$

$e^{\pi c/3}$

Count of dressed energy states:

Anninos et al '20: new calculations of 1-loop correction to entropy, more data to match to in $1/c$ expansion.

LLST '19 dual calculations agree at large c
Shyam '21,… agreement with leading and order $1/c$

Does $S_{Gibbons-Hawking}$ also correspond to a late time limitation on entropy in a region, analogously to switch of saddle dominance in page curve calculations? `West coast paper', Chen et al,…

Depends in part on outcome of bra-ket wormhole calculations, in the full QG (string theory) or in sufficiently faithful toy models.

Does QG provide further guidance/constraints on real observables?

- Role of averaging?
- Wavefunction peaked on certain forms of UV-complete inflation? (combined with principled reason for choosing a particular wavefunction)

For both questions, need accurate accounting of landscape.