Comments on the Accelerating Universe and QI

ACP winter conference 2020

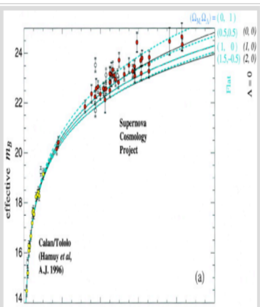
Part I: observations and early universe physics: working toward making the most of the data

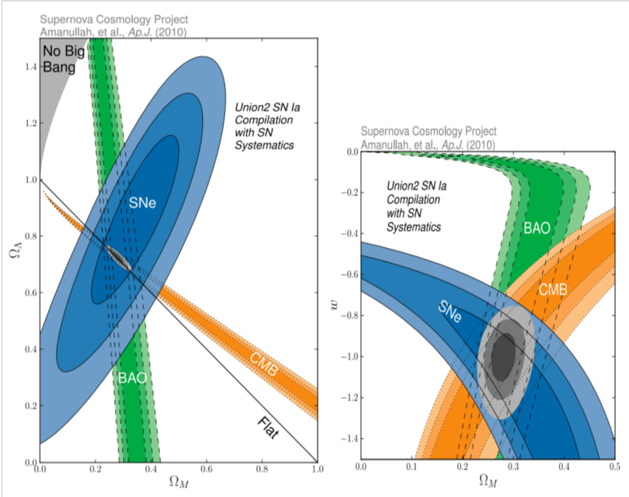
Part II: thought experiments and emergent spacetime

Accelerated expansion

Observationally:

(1) Late Universe





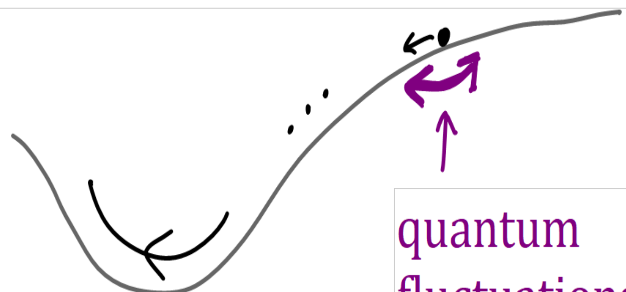
Independent measures of expansion history agree on new parameter Λ

$$\Lambda \sim H^2 \sim 10^{-120} M_P^2$$

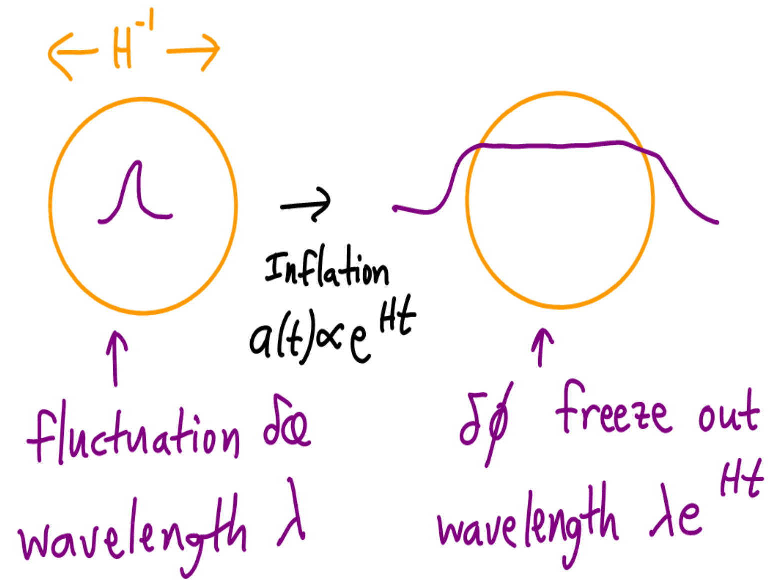
$$M_P \sim 10^{18} GeV \sim 1/\sqrt{G_{Newton}}$$

Strong coupling scale of gravity

(2) Early Universe: leading theory is Inflation, accelerated expansion e.g. driven by scalar field potential energy **V**(ϕ)



quantum fluctuations

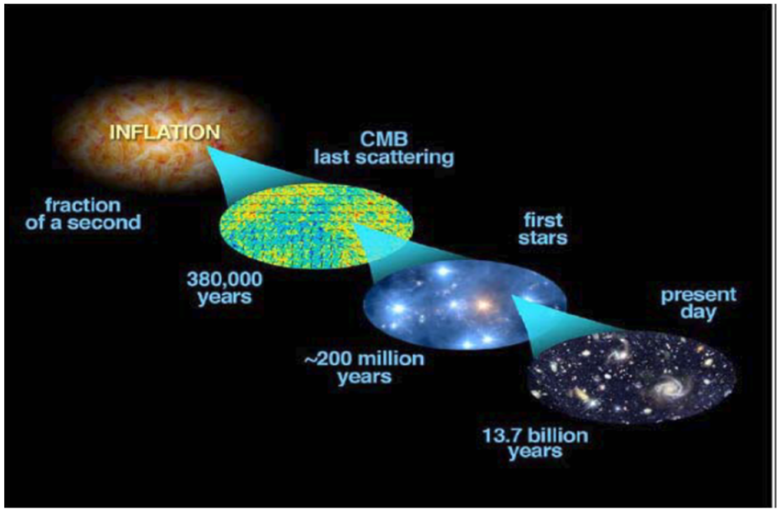


Amplitude fixed by uncertainty principle:

$\delta\phi \sim H$

Quantum seeds for structure:

- Quantum fields obey the Heisenberg uncertainty principle, fluctuate in spacetime.
- For black holes, this leads to their decay (Hawking radiation). Information problem: leading calculation => featureless radiation.
- In cosmology, these quantum fluctuations are seeds for all the observed structure in the universe



Quantum fluctuations from inflaton field as seeds for stucture fits data well: small spectral tilt as expected as H(t) decreases slowly; super-horizon at CMB formation

<δT δT > CMB temperature fluctuations (and polarization, lensing)

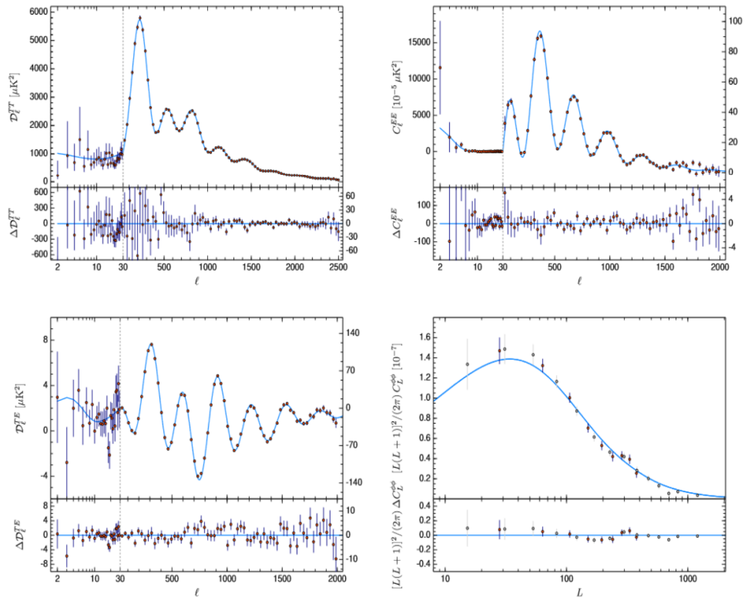
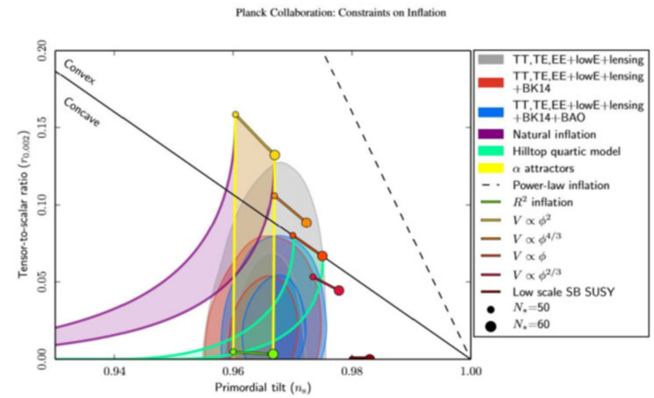


Fig. 1. *Planck* 2018 CMB angular power spectra, compared with the base-ΛCDM best fit to the *Planck* TT,TE,EE+lowE+lensing data (blue curves). For each panel we also show the residuals with respect to this baseline best fit. Plotted are $\mathcal{D}_\ell = \ell(\ell+1)C_\ell/(2\pi)$ for TT and TE, C_ℓ for EE, and $L^2(L+1)^2 C_L^{\phi\phi}/(2\pi)$ for lensing. For TT, TE, and EE, the multipole range $2 \le \ell \le 29$ shows the power spectra from `Commander` (TT) and `SimAll` (TE, EE), while at $\ell \ge 30$ we display the co-added frequency spectra computed from the `Plik` cross-half-mission likelihood, with foreground and other nuisance parameters fixed to their best-fit values in the base-ΛCDM cosmology. For the *Planck* lensing potential angular power spectrum, we show the conservative (orange dots; used in the likelihood) and aggressive (grey dots) cases. Note some of the different horizontal and vertical scales on either side of $\ell = 30$ for the temperature and polarization spectra and residuals.

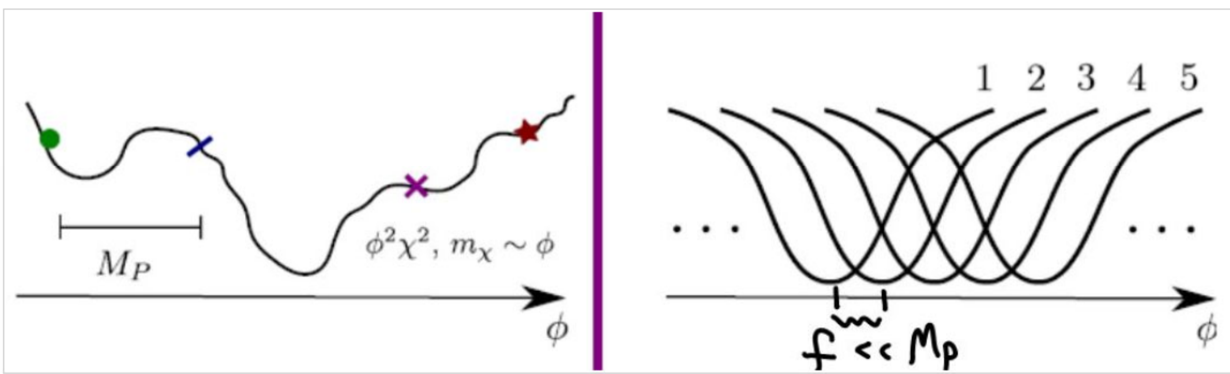
Observational Reach



- Sensitivity to parameters of quantum field theory and even string theory.

$$\epsilon \equiv \frac{M_P V'}{V} \ll 1, \quad \eta \equiv M_P^2 \frac{V''}{V} \ll 1 \;\; \text{but} \;\; \Delta V = V_0(\phi)\frac{(\phi-\phi_0)^2}{M_P^2} \Rightarrow \eta \simeq 1$$

cf Kachru Kallosh Linde Maldacena McAllister Trivedi '03



ES Westphal McAllister; Kaloper Sorbo Lawrence...

Model-dependent* tests; novel signatures

Statistics of the primordial perturbations:

$$\Psi\left[\zeta(\vec{x}),\ \gamma(\vec{x});\ \chi(\vec{x}),\ t\right]$$

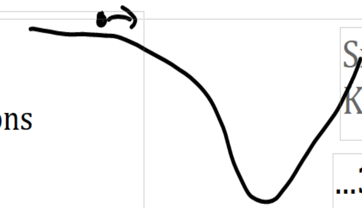
Generically a mixed state

$$P[\zeta,\gamma] = \int D\chi \left|\Psi[\zeta,\gamma;\chi]\right|^2$$

Sensitive to number of fields and their interactions. For free scalar fields, the ground state is Gaussian. Otherwise, non-Gaussian.

Previous Non-Gaussianity Theory

slow roll
V flat =>
small interactions



Srednicki et al,...
Komatsu/Spergel,...

...3pf calc: Maldacena

- Additional fields not so constrained

Curvaton (Mukhanov/Linde...)
Modulated reheating (Dvali/Zaldarriaga, Kofman,...)
(p)reheating dynamics (Bond/Braden/ Frolov et al, Amin...)

- Even for single field, self-interactions on steep potential => larger NG

ES Tong,Alishahiha,Horn,Green,Senatore,...

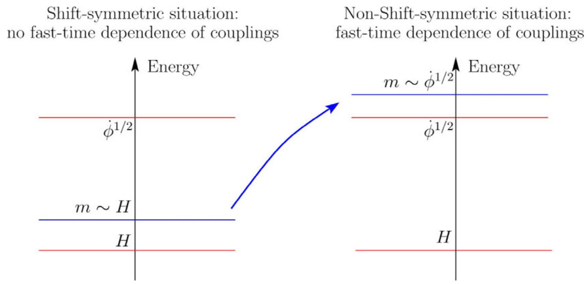
- More systematic EFT

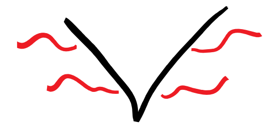
Chen/Huang/Kachru/ Shiu; Senatore et al

- Oscillations (axions), imprints of heavier fields,...

Easther/Lim, Flauger, Peiris et al, McAllister, ES, Westphal, Mirbabayi, Senatore, Chen/Wang, Baumann Green, Arkani-Hamed Maldacena,..

Recent example of this interaction: beyond low point correlators





$$\hat{h}(k\eta_n) = \underbrace{\int_{\eta_n}^{0} \frac{d\eta'}{\eta'}(\sin k\eta' - k\eta' \cos(k\eta'))}_{G(\eta;\,0)} \underbrace{\frac{\delta}{\delta\phi} m_\chi(\phi_0(\eta'))}_{\text{oscillating mass}}$$

Production of particles with mass 100 times H can be detected/constrained. Optimal for the simplest shape **(factorized in momentum space)** is an N>3 point function (or resummed contributions from all N: position space features) Flauger, Mirbabayi, Senatore, ES; cf Bond et al,
Munchmeyer, Smith: optimal estimator and (WMAP) analysis

$$\langle \delta\phi_{\mathbf{k}_1} \ldots \delta\phi_{\mathbf{k}_N} \rangle \sim$$

$$(2\pi)^3 \delta\left(\sum \mathbf{k}_i\right) \frac{\bar{n}_\chi}{H^3} H^{N+3} \sum_n (H\eta_n)^{-3} \prod_{i=1}^{N} \frac{\hat{h}(k_i\eta_n)}{k_i^3}$$

$$\hat{h}_b(k\eta_n) \sim c_b \sqrt{\frac{\omega}{H}} \cos\left(\frac{\omega}{H} \log(-k\eta_n) + \gamma\right)$$

$$\frac{(S/N)_3}{(S/N)_2} \sim c_b \sqrt{\alpha} = c_b \sqrt{\frac{\omega}{H}}$$

Higher N-point function data analysis techniques for heavy particle production and WMAP results

Moritz Münchmeyer[1] and Kendrick M. Smith[1]

[1] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada*

We explore data analysis techniques for signatures from heavy particle production during inflation. Heavy particules can be produced by time dependent masses and couplings, which are ubiquitous in string theory. These localized excitations induce curvature perturbations with non-zero correlation functions at all orders. In particular, Ref. [1] has shown that the signal-to-noise as a function of the order N of the correlation function can peak for N of order $\mathcal{O}(1)$ to $\mathcal{O}(100)$ for an interesting space of models. As previous non-Gaussianity analyses have focused on $N = \{3, 4\}$, in principle this provides an unexplored data analysis window with new discovery potential. We derive estimators for arbitrary N-point functions in this model and discuss their properties and covariances. To lowest order, the heavy particle production phenomenology reduces to a classical Poisson process, which can be implemented as a search for spherically symmetric profiles in the curvature perturbations. We explicitly show how to recover this result from the N-point functions and their estimators. Our focus in this paper is on method development, but we provide an initial data analysis using WMAP data, which illustrates the particularities of higher N-point function searches.

But missing sometimes dominant contributions of different shapes, ones which do not factorize e.g.:

Non-factorizing shapes, e.g. 3 point function in full model

$$\frac{A}{k_1^2k_2^2k_3^2}\sum_{n=n_{min}}^{\infty}\left(\prod_{J=1}^{3}\frac{1}{-\eta_n k_J}\right)\left\{\prod_{I=1}^{3}\cos\left(\tilde{\gamma}_I+\frac{\omega}{H}\log(-k_I\eta_n)\right)\right.$$
$$+C_{34}\frac{k_2k_3}{(k_2+k_3)^2}\cos\left(\gamma_{34}+\frac{\omega}{H}\log(-(k_2+k_3)\eta_n)\right)\cos\left(\tilde{\gamma}_{34}+\frac{\omega}{H}\log(-k_1\eta_n)\right)+\text{permutations}$$
$$\left.+C_5\frac{k_1k_2k_3}{k_T^3}\cos\left(\gamma_5+\frac{\omega}{H}\log(-(k_1+k_2+k_3)\eta_n)\right)\right\}. \tag{3.65}$$

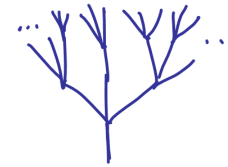
Non-factorized shapes are not practical to test in data because they require too many integrals/sums over momenta.

Could this be sped up by some quantum computing approach?

Could QC speed up generation of fake data (for assessing statistical significance, or as training data for a machine learning approach)?

Somewhat related: could QC simulate reheating effects more completely? (but high occupation numbers -> arguably well done classically after quantum seed).

Large N-point functions (N! enhanced) <-> large tails of the primordial distribution. Solvable example yields heavy (>Gaussian) tails of non-Gaussian distribution from multifield QFT: Panagopoulos ES '19, many PBH works, cf Bond et al



$$\rho(\delta\phi) = \frac{1}{\sqrt{2\pi}} \int d^{N_f}\vec{\chi}\,\rho_G(\vec{\chi})\, e^{-(\delta\phi-\kappa F(\vec{\chi}))^2/2} = \frac{\sqrt{1/2\pi}^{\,N_f}}{\sqrt{2\pi}} \int d^{N_f}\vec{\chi}\, e^{-\vec{\chi}^2/2} e^{-(\delta\phi-\kappa\vec{\chi}^2)^2/2}$$

From evolution by multifield interaction Hamiltonian.

$$|\Psi(t_{exit}+\Delta t)\rangle \simeq e^{-i\Delta t\mathcal{H}}|\Psi\rangle \simeq e^{-i\Delta t\dot{\bar{\phi}}\int d\mathbf{x}\Pi_{\delta\phi}F_{mix}(\chi)}|\Psi\rangle$$

$$|\Psi(t_{exit}+\Delta t)\rangle \simeq e^{-i\Delta t\mathcal{H}}|\Psi\rangle \simeq e^{-i\Delta t\dot{\bar{\phi}}\int d\mathbf{x}\Pi_{\delta\phi}F_{mix}(\chi)}|\Psi\rangle$$

PBH abundance:

$$\beta = \frac{(2\gamma)^{-N_f/2}}{\Gamma(N_f/2)} \int_{\phi_c/\kappa}^{\infty} dy\, y^{N_f/2-1} e^{-y/2\gamma} = \frac{\Gamma(N_f/2, \phi_c/2\kappa\gamma)}{\Gamma(N_f/2)}$$

Heavier tail for hyperbolic target space

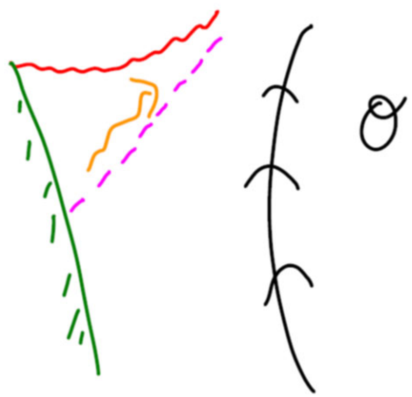
Part I summary:

- The early universe acceleration admits detailed tests of microphysics in principle, sometimes in practice.
- Ongoing developments focused on higher N point functions, tails and rare events; rich QFT dynamics here and during reheating.
- Some tests that we'd like to do even for 3 point functions are not practical with standard methods.
- QI speedup?

General relativity predicts horizons

Black Hole horizon

$$ds^2 = -\left(1-\frac{r_s}{r}\right)dt^2 + \frac{dr^2}{1-\frac{r_s}{r}} + r^2 d\Omega^2$$

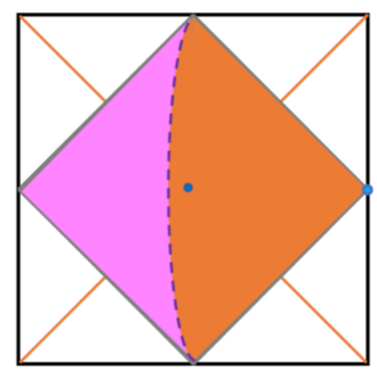


Cosmological horizon

exponentially
expanding
universe

$$ds^2 = -dt^2 + e^{2Ht}(dx^2+dy^2+dz^2)$$

Cosmological constant $\Lambda > 0$



Thought experiments: Classical + Quantum

At semiclassical level, the gravitational system behaves as if it has entropy

S = $Area_{classical\ horizon}/(4G_{Newton})$ + entropy of quantum field fluctuations

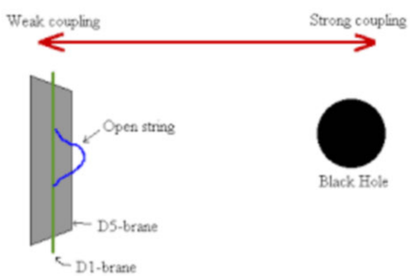
and a temperature, energy and angular momentum like a course-grained thermal system (e.g. a box of gas).

$$dM = \kappa\ dA + \mu\ dQ + \Omega\ dJ \qquad dE = TdS + \mu dN + \cdots$$

$$dA \geq 0 \qquad dS \geq 0$$

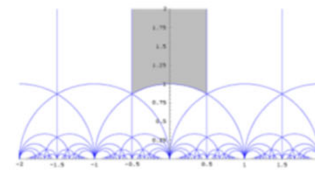
Finite number of available states, discrete quantization of energy levels?

Finite number of available states, discrete quantization of energy levels, with S = log(number of available states)? **Yes…**



Strominger-Vafa

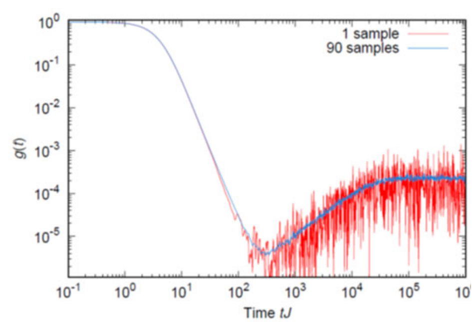
New examples of counts with ties to number theory



$$p(n) = \frac{1}{\pi\sqrt{2}} \sum_{k=1}^{\infty} \sqrt{k}\, A_k(n)\, \frac{d}{dn} \left(\frac{1}{\sqrt{n-\frac{1}{24}}} \sinh\left[\frac{\pi}{k} \sqrt{\frac{2}{3}\left(n - \frac{1}{24}\right)} \right] \right).$$

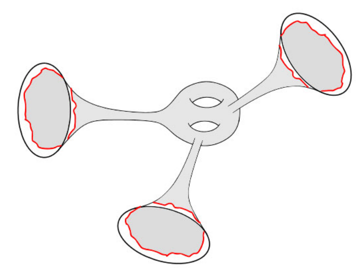
Kachru et al

Within the simplest model with this central question, new calculations with extraordinary quantum gravity precision. Atoms of spacetime! Shenker et al



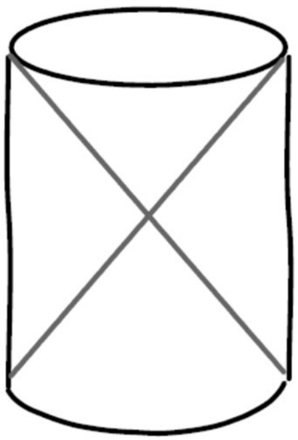
$$\langle Z(\beta + it) Z(\beta - it) \rangle$$

$$Z_{g=2,n=3}(\beta_1, \beta_2, \beta_3) \quad =$$



Holographic duality and spacetime emergence

AdS_{d+1}/CFT_d correspondence formulates $\Lambda < 0$ quantum gravity in terms of non-gravitational dual



AdS:

observables are conformal field theory (CFT) correlation functions

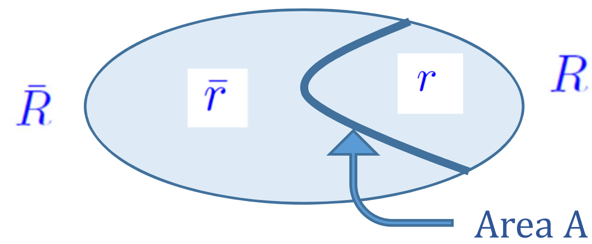
Timelike boundary at infinity pins fields.

Spacetime emerges from more fundamental, strongly interacting degrees of freedom.

- **How exactly?** *Bulk reconstruction, black hole information problem*

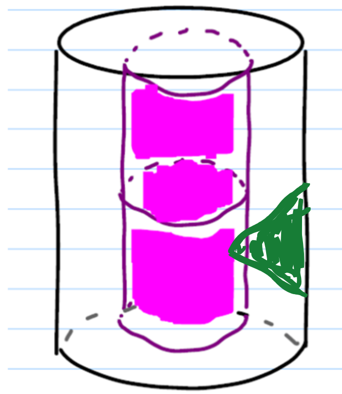
- $\Lambda > 0$. *AdS ($\Lambda < 0$) extremely useful case study. But highly unrealistic, and also highly non-generic in quantum gravity (string theory.)*

Probing the bulk



$$S^{(R,\bar{R})}_{entanglement} \simeq \frac{A}{4G_N} + S^{(r,\bar{r})}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{g^2 N \dot{\phi}^2}{\phi^4}}} = \frac{1}{\sqrt{1 - \frac{v_{d+1}^2}{c^2}}}$$

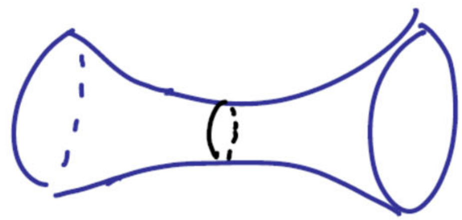


Motion in CFT *field space* is relativistic as a result of strong interactions, maps to causal motion in extra dimension.

The boundary corresponds to high energy (short distance)in the CFT and the middle to low energy (long distance), state more complex.

The entanglement and other properties of the CFT quantum state can be used to reconstruct bulk regions out to the surface between the two endpoints of R, with minimal area A. In fact, the full expression on the right hand side including bulk quantum contributions needs to be minimized.

One theme is that entanglement and other properties of the quantum state are tied to the knitting together of spacetime.

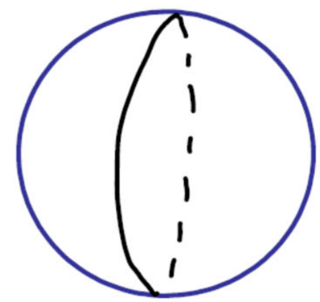


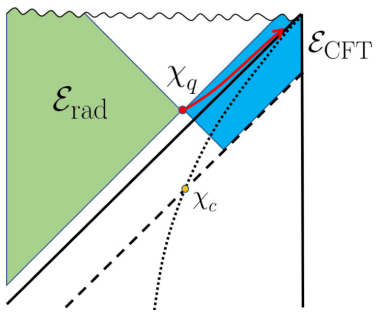
Thermal state of two CFTs (entangled at thermal scale) dual to joined spacetime

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2}|n\rangle|n\rangle\,.$$

``ER=EPR"

Realistic de Sitter case: Entangled state of low energy part of 2 CFTs deformed appropriately (more below).

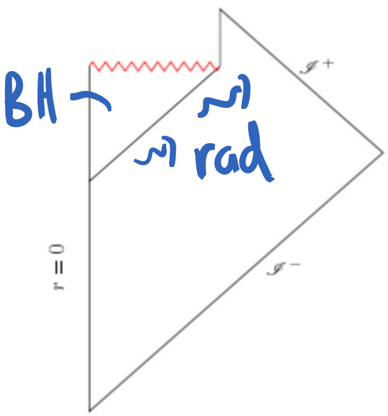


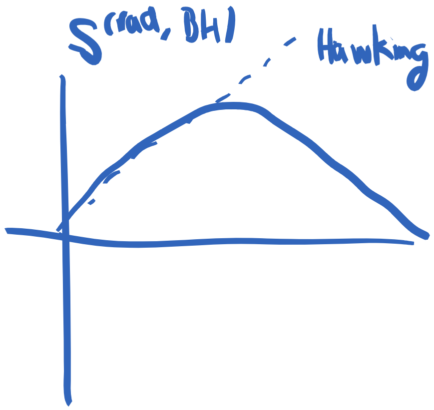


Black Hole Information problem:

Anything could have formed the black hole, but it evaporates into apparently featureless Hawking radiation. Lost that info?

Start with entanglement between radiation and the black hole. If info is to come out, the entanglement must transfer:





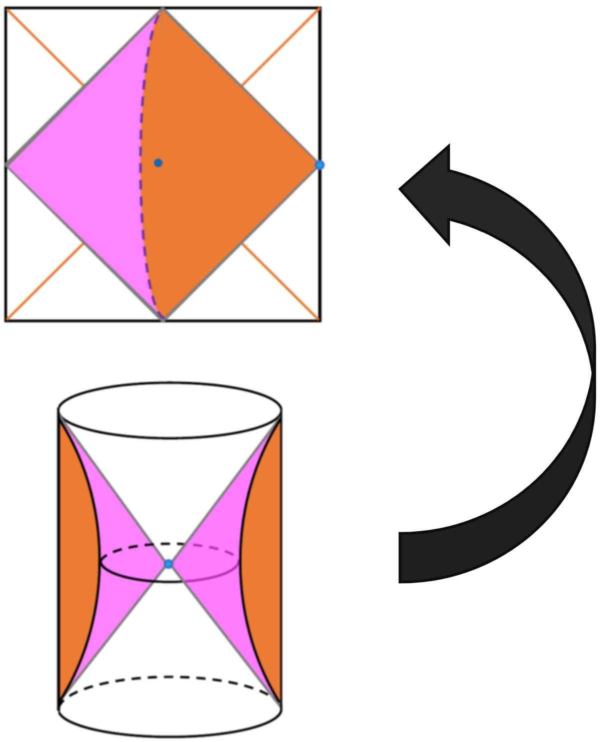
AdS/CFT:

- CFT is unitary so so is BH evaporation.
- ***New:*** the Quantum minimal area surface in entanglement reconstruction confirms that entanglement transfers in AdS/CFT.

G. Penington talk

- Still need detailed mechanism Bousso et al, Harlow et al, … (string theory analysis still in progress: long range effects go beyond quantum field theory calculation of decay; non-equilibrium dynamics and relations to condensed matter; extrapolate to lab systems??).

dS $\Lambda > 0$ /deformed-CFT



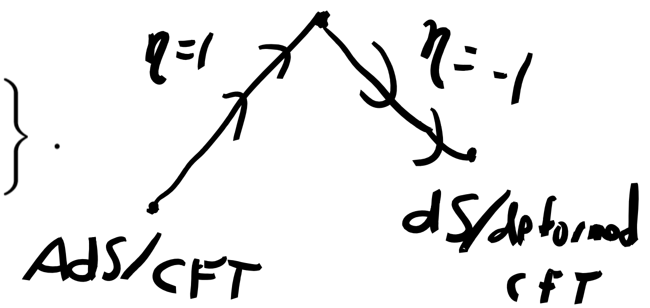
AdS $\Lambda < 0$ /CFT

Recall: the boundary of AdS corresponds to high energy in the CFT and the middle to low energy.

- If we can first deform the CFT so that the high energy part is missing, we remove the unrealistic boundary.
- It turns out that combining this with an equally tractable deformation of the low energy part of the theory yields a bounded patch of **dS** rather than **AdS**, as inferred by agreement of their **energies** and **entropies** in the universal (pure gravity) sector.

$$\delta\mathcal{L} = \delta\lambda \left\{ 2\pi T\bar{T} - \frac{1-\eta}{2\pi\lambda^2} \right\} .$$

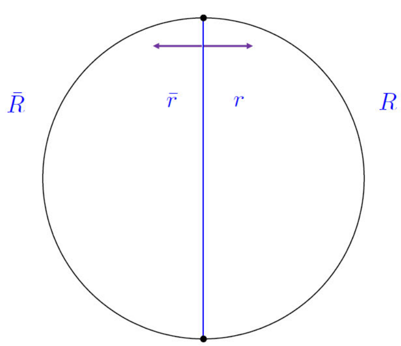
Zamolodchikov,
Cavaglia et al,
Dubovsky et al…

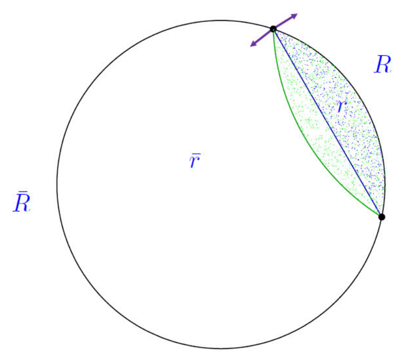


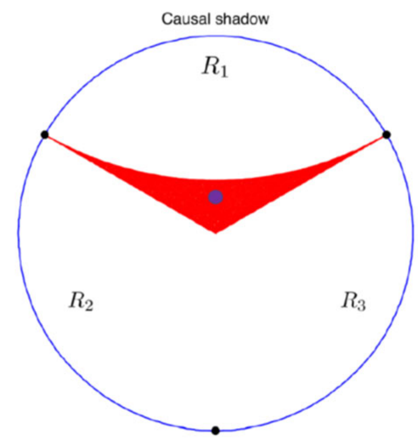
With X. Dong, V. Gorbenko, A. Lewkowycz, J. Liu, G. Torroba;
M. Alishahiha, B. Horn, A. Karch, D. Tong, S. Matsuura,…

Requires additional contributions for local bulk matter effects, for which we can work at level of (perturbations around) large c.

Explicit calculations derive universal (pure gravity) features of the energy spectrum, entanglement entropy, and bulk reconstruction in these deformed-CFT theories which holographically mirror finite spacetime patches, including the case of $\Lambda > 0$.







One interesting aspect is `quantum error correction': bulk points are redundantly encoded in the boundary Almheiri Dong Harlow. This survives in a modified form in the case of $\Lambda > 0$. It exposes new features of operator algebras and of putative tensor network models Swingle et al, Preskill et al

$$\frac{\partial}{\partial \lambda} \log Z = -2\pi \int d^2x \sqrt{g} \, \langle T\bar{T} \rangle + \frac{1-\eta}{2\pi\lambda^2} \int d^2x \sqrt{g}$$

Large $\lambda_{'tHooft}$, large c*: factorization

$$T^a_a = -\frac{c}{24\pi}\mathcal{R}^{(2)} - 4\pi\lambda T\bar{T} - \frac{\eta - 1}{\pi\lambda}$$

$$\nabla^a T_{ab} = 0$$

=> Dressed energies, e.g. on dS_2

$$\langle T^\tau_\tau \rangle = \frac{1}{\pi\lambda}\left(1 \mp \sqrt{\eta + c\frac{\mathcal{R}^{(2)}\lambda}{24} - \frac{C_1\lambda}{L(\tau)^2}}\right) \, , \quad L(\tau) = \ell \cosh\frac{\tau}{\ell}$$

$$\frac{E}{L} = \frac{\mathcal{E}}{L^2} = \frac{1}{\pi\lambda}\left(-1 + \sqrt{\eta + c\frac{\mathcal{R}^{(2)}\lambda}{24} + \frac{(\mathcal{E}^{(0)} - \mathcal{E}_0^{(0)})\lambda}{L^2}}\right)$$

=> Dressed entropies, on replicas

$$L\frac{d}{dL}\tilde{S}_n = -(1 - n\partial_n) \int d^2x \sqrt{g} \, \langle \mathrm{tr}\, T \rangle$$

*For more, see Mazenc, Shyam, Soni '19

AdS/Poincare case study

$$n\partial_n \langle \mathrm{tr}\, T\rangle|_{n\to 1} = \epsilon\, \frac{c}{3}\, \frac{\lambda c}{24\pi}\, \frac{C(\frac{\lambda}{L^2})^2}{\rho\left(\rho^2 + \epsilon\frac{\lambda c}{6}C(\frac{\lambda}{L^2})\right)^{3/2}}\,.$$

$\int \frac{d\rho}{\rho^3}$ div. regulated by λ

$$\begin{aligned} LS'(L) &= 2\times \lim_{n\to 1}(2\pi n)\int_0^{\rho_0 \ll L} \rho d\rho\, n\partial_n \langle \mathrm{tr}\, T\rangle \\ &= \frac{c}{3}C(\frac{\lambda}{L^2})\, \frac{1}{\sqrt{1+\epsilon\frac{\lambda c}{6\rho_0^2}C(\frac{\lambda}{L^2})}}\Bigg|_{\epsilon\to 0} \\ &= \frac{c}{3}C(\frac{\lambda}{L^2})\,. \end{aligned}$$

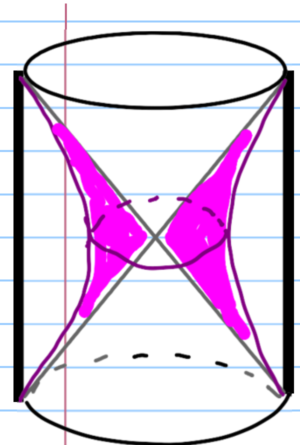
Full non-perturbative (at large c) result from Casini-Heurta-Myers Weyl map => precise match with RT.

$$LS'(L) = \frac{c}{3}\,\frac{1}{\sqrt{1+\frac{\lambda c}{3L^2}}}$$

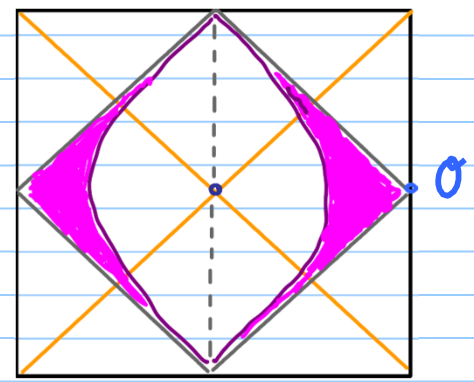
cf Chakraborty et al

Full dS/dS patch is a two-warped-throat Randall-Sundrum system.

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



AdS/dS



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

2 highly redshifted (IR) regions, each ~ IR region of AdS/dS

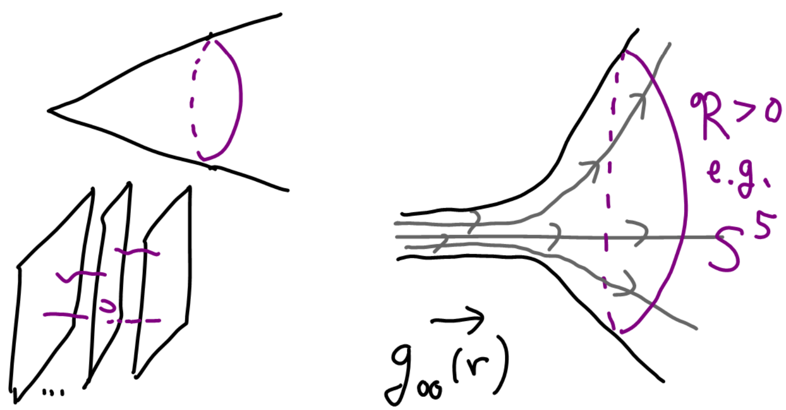
With T-Tbar+Λ_2 first formulate each warped throat, later join

AdS$_{d+1}$/CFT$_d$ correspondence formulates $\Lambda < 0$ quantum gravity in terms of non-gravitational dual

Grew out of black hole thermodynamics:

Area/G_N = Entropy

Brane construction in string theory



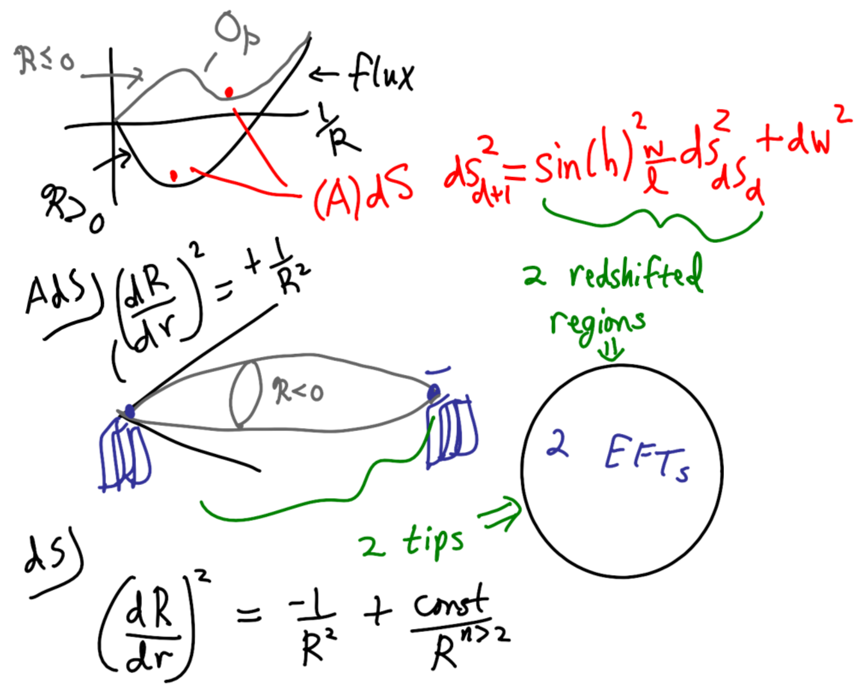
Nc D3-branes Polchinski   Nc flux quanta

Low energy QFT = highly redshifted region

Microscopic dS/dS:

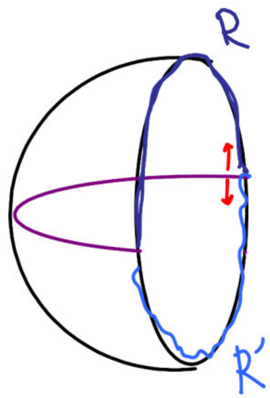
Uplifting AdS/CFT => 2 sectors

Dong Horn ES Torroba '10

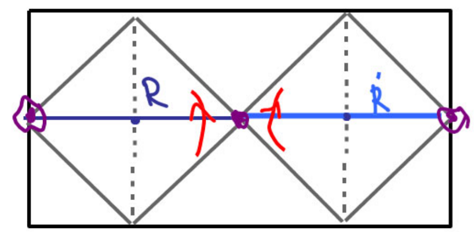


dS vs AdS brane construction: independent derivation of the two sectors because of metastability.

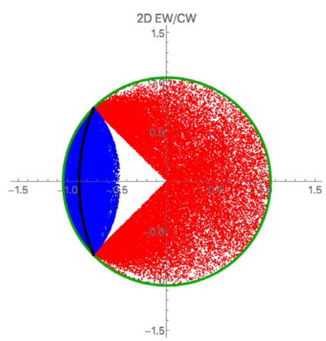
dS/dS case study: again sharp match

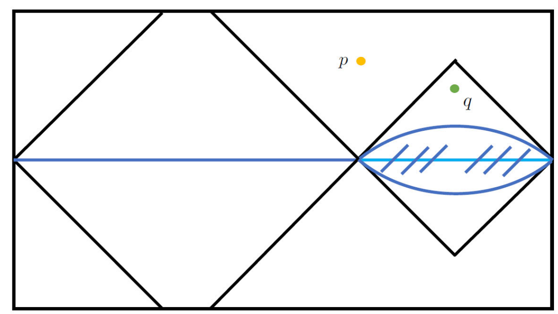


Boundary dS_2



Modular Hamiltonian K_R is local in this case (just Ttt) and modular evolution takes Ops(R)->Ops(D(R)).





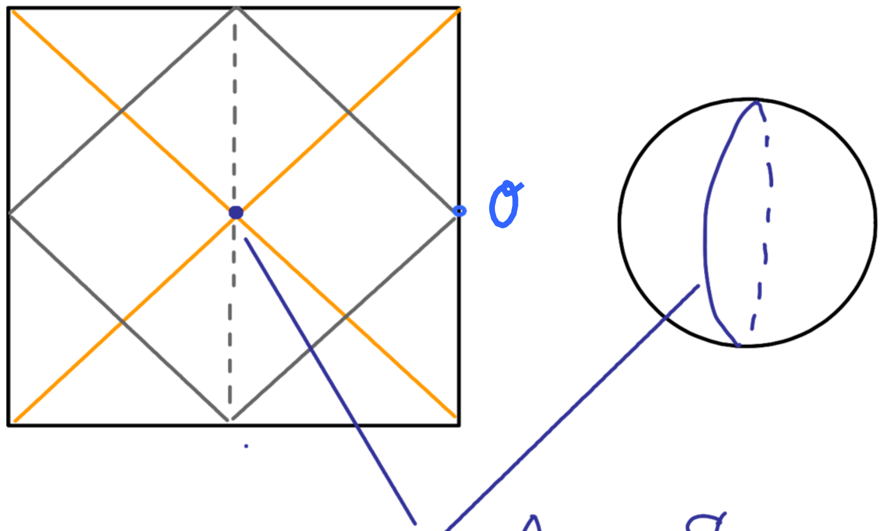
$$\partial_r \log Z_n = -2\pi n r \int_0^\pi d\theta \, \sin\theta \, (T_\theta^\theta + T_\phi^\phi) \, .$$

maximal mixing:

$$S_0(r) = S_1(r) = \frac{\pi c}{6} \quad \text{for} \quad r = \sqrt{\frac{c\lambda}{12}} \, .$$

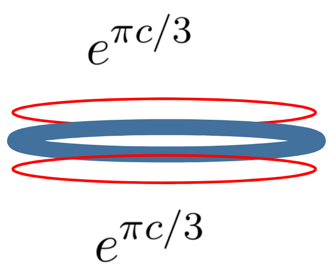
In gravity language, this corresponds to the central slice $w_c = \frac{\pi}{2}\ell$.

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



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

$$= S_n = S_{vN} = \log \dim H = S_{G-H}^{(\theta)}$$



Count of dressed energy states:

Conclusions:

- Cosmological horizons lead to observational consequences (including the quantum origin of all structure!), phenomenological opportunities to test physical parameters in conjunction with more systematically analyzing the QFT dynamics, and major challenges but new tools in quantum gravity.
- On the former, real experimental side, there are well defined signatures with detectable signal/noise that are out of reach due to computing time limitations.
- On the latter, `thought experimental' side, we have renewed traction on emergent space-time thanks to various research directions involving string theory, strongly coupled quantum field theory (and its tractable deformations), and QI ideas.