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Workshop: Eternal Inflation

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A bit about de Sitter

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A bit about de Sitter

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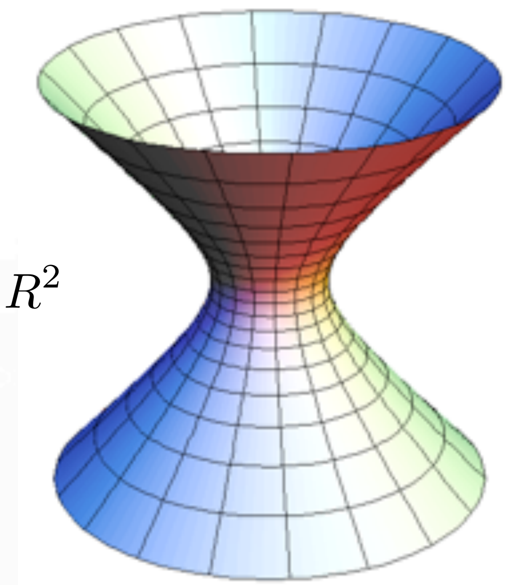
Introduction

QG/EFT in (quasi-) de Sitter is key to understanding eternal inflation

$$-X_0^2 + X_1^2 + X_2^2 + X_3^2 + X_4^2 = R^2$$



- No global timelike Killing vector
- Horizon, gravitational entropy
- Breakdown of EFT in de Sitter

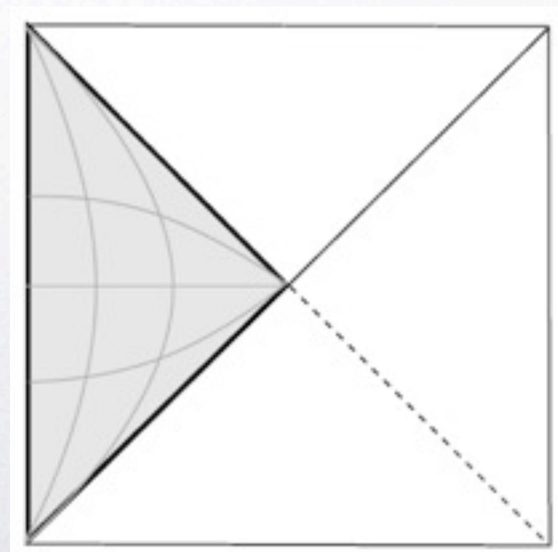
N. Arkani-Hamed, S. Dubovsky, A. Nicolis, E. Trincherini and G. Villadoro, 0704.1814 [hep-th]

Free-falling observers: static coordinates

$$ds^2 = -(1 - H^2 r^2) dt^2 + (1 - H^2 r^2)^{-1} dr^2 + r^2 d\Omega^2$$

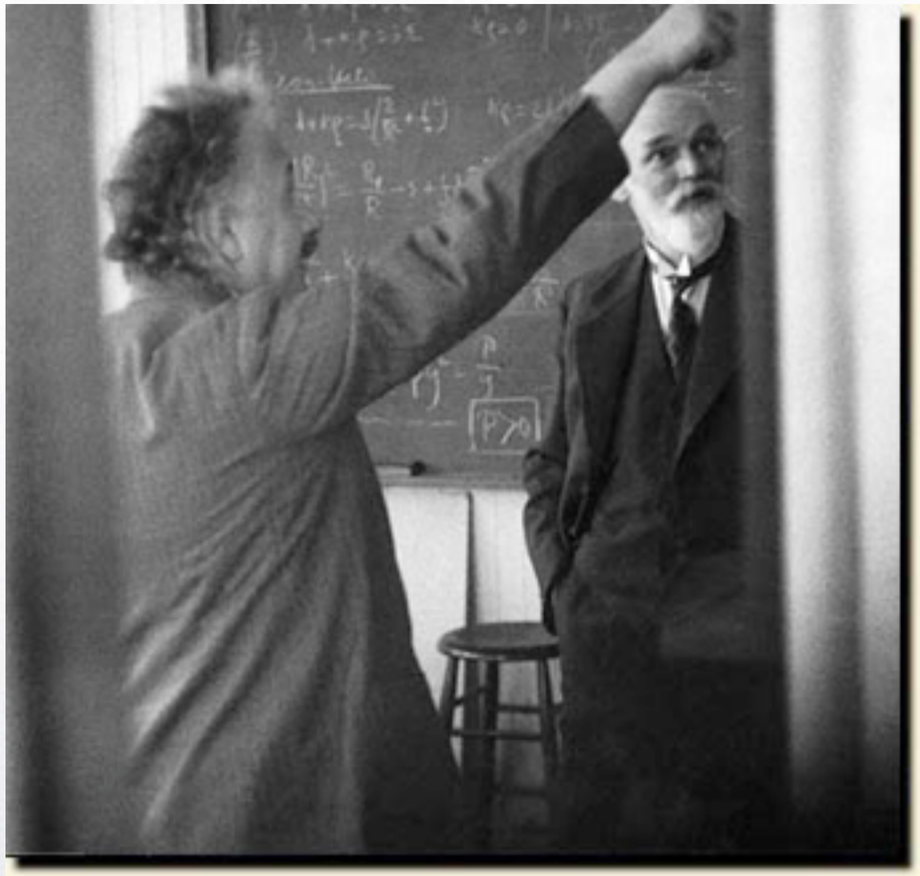
$$T_{GH} = \frac{H}{2\pi}$$

$$S = \frac{A}{4G} \propto \frac{M_{Pl}^2}{H^2}$$



Outline

- De Sitter and black holes
- Tunneling and backreaction
- Complementarity in de Sitter
- Concluding remarks

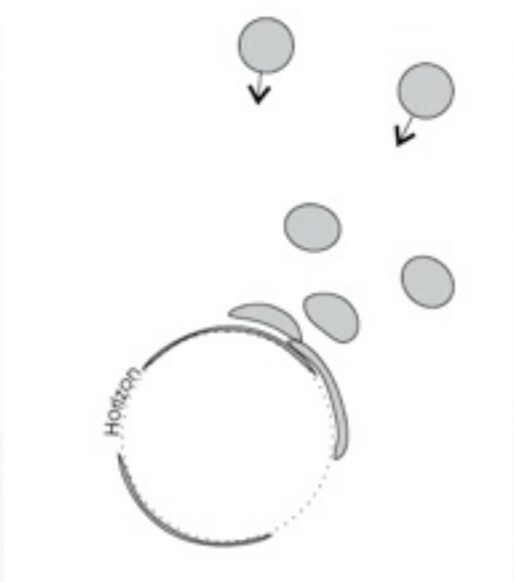


de Sitter and Einstein, 1932

De Sitter and black holes

Similarities and differences: horizon physics

- Locally, near horizon: Rindler space
- Black hole: distinction infalling and external observers
- De Sitter: horizon is observer dependent (dS symmetry)
- Black holes evaporate: sharpens information paradox
- No S-matrix in de Sitter (observables?)
- Black hole singularity



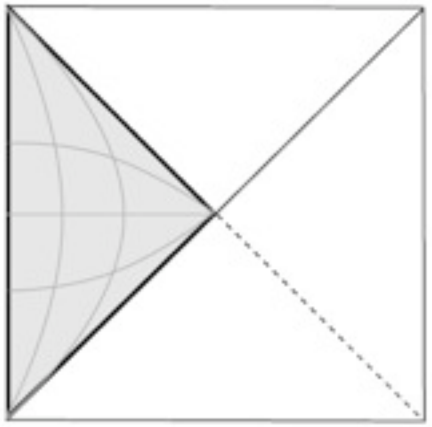
$$T_H = \frac{\hbar\kappa}{2\pi}$$

$$S_{BH} = \frac{A}{4G\hbar}$$

However: horizon properties seem universal

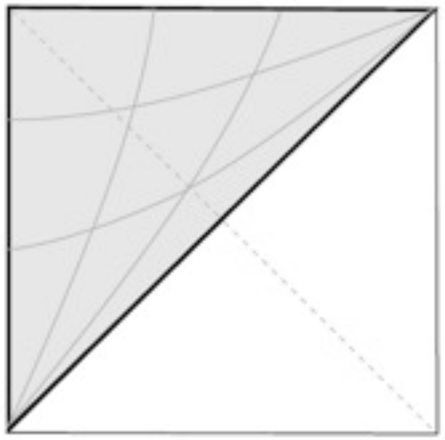
De Sitter vacua

Relation between the static and BD state:



$$ds^2 = -(1 - H^2 r^2)dt^2 + (1 - H^2 r^2)^{-1} dr^2 + r^2 d\Omega^2$$

$b_k|S\rangle = 0$ → $T_{GH} = \frac{H}{2\pi}$ thermal to all other (outgoing) observers



Formal `lightlike observer' limit of static vacuum state : BD vacuum

De Sitter invariant

$$ds^2 = -dt^2 + e^{2Ht}dx^2 = \frac{1}{(H\eta)^2}\left(-d\eta^2 + d\rho^2 + \rho^2 d\Omega^2\right)$$

$$u_k(\eta, \vec{x}) = N_k\,(1 + ik\eta)\,e^{-ik\eta + i\vec{k}\cdot\vec{x}}$$

$$\frac{\partial}{\partial\eta} u_k(\eta, \vec{x}) = -iku_k(\eta, \vec{x})$$

$$\eta \rightarrow -\infty$$

Tunneling and backreaction

Applies universally (BH's and dS)

Painleve coordinates: $ds^2 = -\left(1 - H^2 r^2\right) dt^2 - 2Hr\, dr\, dt + dr^2 + r^2\, d\Omega^2$

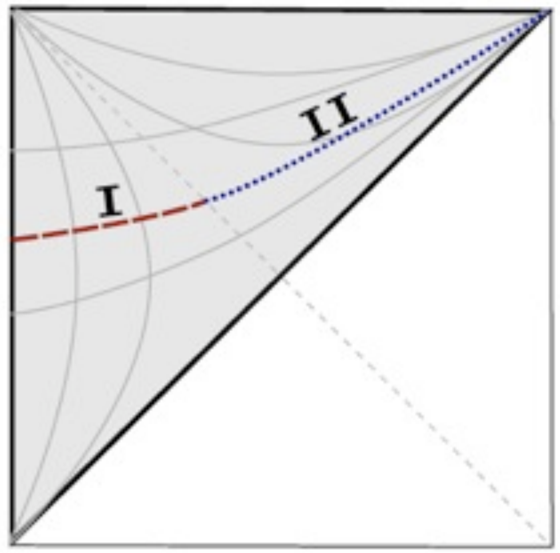
- Finite at horizon
- Planar flat slicing
- Stationary

$$\Gamma \sim \exp(-2\ \mathrm{Im}\ I/\hbar) \sim \exp(\Delta S) = \exp\left[\frac{\pi}{G}(r_f^2 - r_i^2)\right]$$

$$r_i = H^{-1}$$

$$\frac{e^{S_{\rm final}}}{e^{S_{\rm initial}}} = \exp(\Delta S)$$

s-waves only



After emission of the spherical shell: SdS spacetime

$$ds^2 = -(1 - H^2 r^2 - 2G\omega/r)dt^2 + (1 - H^2 r^2 - 2G\omega/r)^{-1} dr^2 + r^2 d\Omega^2$$

$G\omega H \ll 1$ →

$$\Gamma \approx \exp\left[-\frac{2\pi}{H}\omega\left(1 + \frac{\omega H}{8\pi M_p^2}\right)\right]$$

$$\left|\frac{\langle \mathrm{out}|\, b_k\, b_{-k}\, |\mathrm{BD}'\rangle}{\langle \mathrm{out}|\mathrm{BD}'\rangle}\right|^2 = e^{\Delta S(\omega_k)}$$

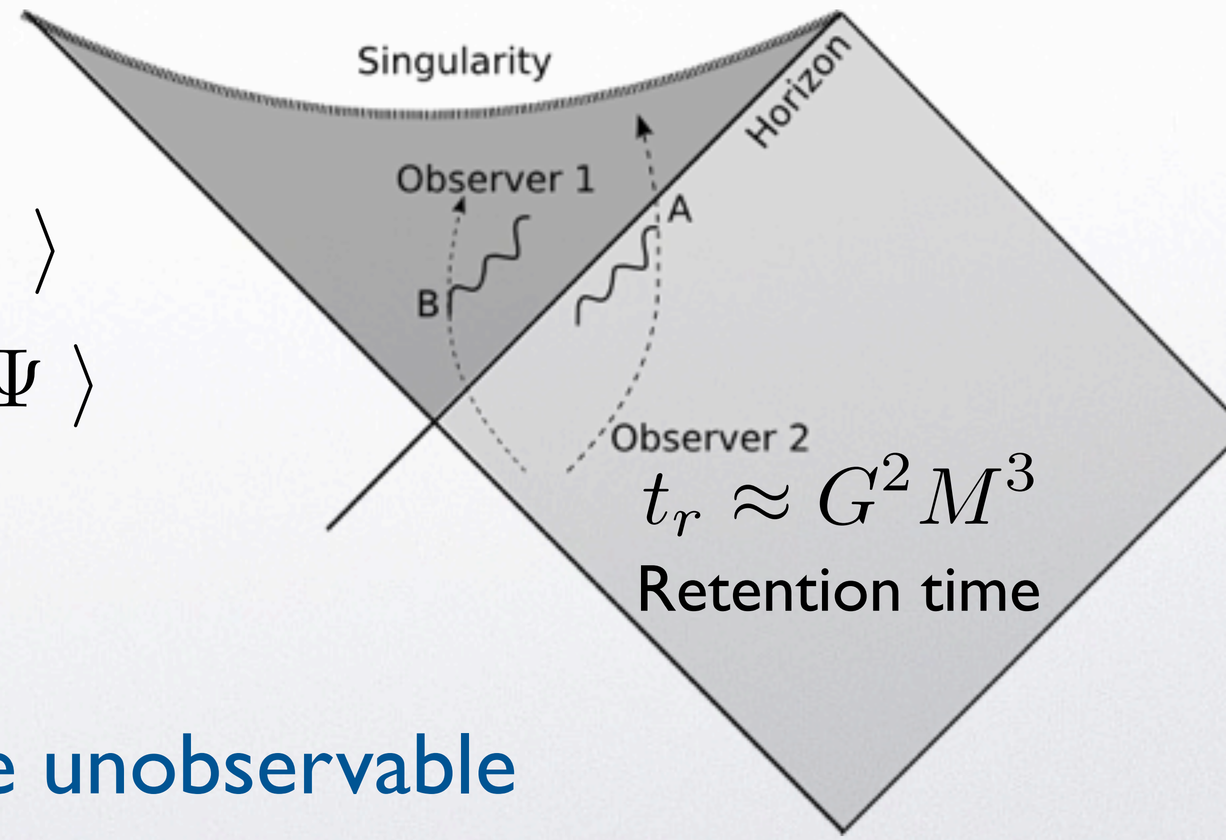
Universal correction to BD

M. Parikh, hep-th/0204107
B. Greene, M. Parikh and JPvdS, hep-th/0512243

Black hole complementarity

1. Observer 1 jumps in carrying a single bit (spin)
2. At point A observer 2 reads the bit in the Hawking radiation
3. Observer 2 then jumps in to see same bit twice
4. At point B observer 1 sends the bit to observer 2

- Unitarity $|\Psi_{\text{out}}\rangle = S|\Psi_{\text{in}}\rangle$
- Linearity $|\Psi\rangle \not\rightarrow |\Psi\rangle \otimes |\Psi\rangle$
- Equivalence principle



Complementarity: violations should be unobservable

Entanglement and information

Information: $$I = S_{\text{maximal}} - S_{\text{actual}}$$

Consider two subsystems of a total system in a pure state and let the smaller subsystem have a Hilbert space of dimension m<n, where n is the Hilbert space dimension of the other subsystem

$$S = -\mathrm{Tr}\,\rho \log \rho$$

The entanglement entropy, averaged over all pure states, reads

$$\langle S \rangle = \sum_{k=n+1}^{k=mn} \frac{1}{k} - \frac{m-1}{2n}$$

$$\langle I_{m,n} \rangle = \ln m - \langle S \rangle \approx \frac{m}{2n}$$

Typically the subsystem contains no information (thermal) until it reaches at least half the size of the whole system

$$t_r \approx G^2 M^3$$

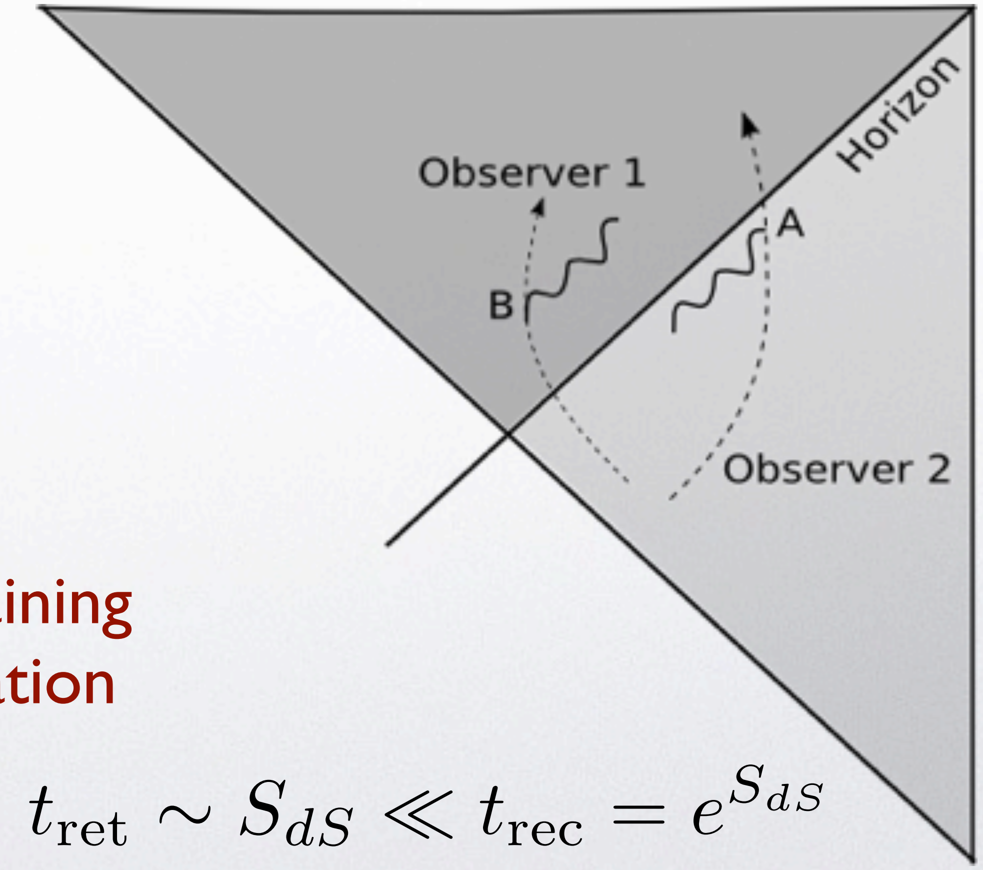
Page, gr-qc/9305007

Complementarity in de Sitter

1. Observer 1 jumps in carrying a single bit (spin)
2. At point A observer 2 reads the bit in the Hawking radiation
3. Observer 2 then jumps in to see same bit twice
4. At point B observer 1 sends the bit to observer 2

Observer 2:

$$S = \frac{A}{4G} \propto \frac{M_{Pl}^2}{H^2}$$



- Unitarity $|\Psi_{\rm out}\,\rangle = S|\Psi_{\rm in}\,\rangle$
- Linearity $|\Psi\,\rangle \not\to |\Psi\,\rangle \otimes |\Psi\,\rangle$
- Equivalence principle

Observer 2 collects Hawking radiation, but before obtaining a single bit the (maximal) entropy of the collected radiation should at least be 1/2 the dS entropy [Page]

$$t_{\rm ret} \sim S_{dS} \ll t_{\rm rec} = e^{S_{dS}}$$

Maximal information storage

In de Sitter, the most entropic subsystem consists of the largest black hole that will fit, the Nariai solution.

In D dimensions this reads $\frac{A_{D-2} r_H^{D-2}}{4G}$ with $H r_H = \left(\frac{D-3}{D-1}\right)^{1/2}$

$$\frac{S_{\rm subsystem}}{S_{\rm dS}} \leq \left(\frac{D-3}{D-1}\right)^{(D-2)/2} < \frac{1}{e} \qquad = \tfrac{1}{3} \text{ in } D = 4$$

R. Bousso, hep-th/0205177

No observer will ever be able to register a single bit, because backreaction will have interfered. Saves complementarity, but applies more generally

M. Parikh and JPvdS, 0804.0231[hep-th]

Causal patch holography?

No observer in de Sitter can register even a single bit of information in the Hawking radiation

- Holography: all information stored in dS causal region
- Information might be there, but cannot be accessed
- Localized detectors have a finite number of states
- No information about the landscape can be retrieved through Hawking radiation (assuming asymptotic dS)

Final remarks

Be careful using EFT in an eternal inflation context

- Many black hole results/puzzles generalize to dS
- Crucial role played by backreaction
- Could imply breakdown of EFT, possibly at macroscopically large distance scales
- Fundamental obstruction to recover information
- Practical meaning of holography in causal region?