Review on the No-Boundary Proposal and its Alternatives

Olga Papadoulaki

CNRS, CPHT, Ecole Polytechnique

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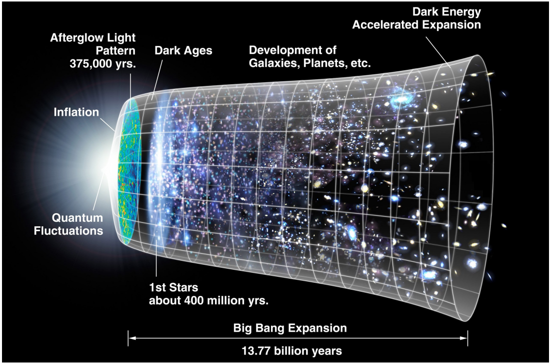
The History of our Universe

- Our Universe is currently expanding
- It is "Hot" ($T \simeq 2.73$ K)
- Extremely uniform at large scales $\delta T/T \sim 10^{-5}$



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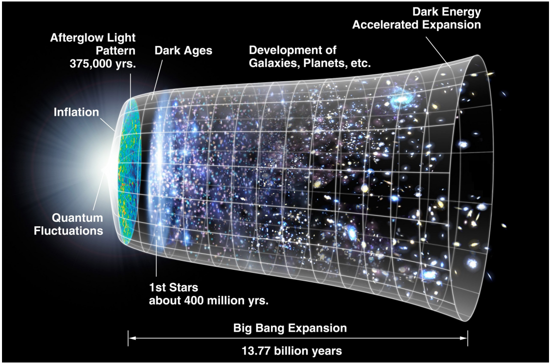
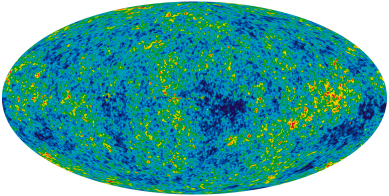
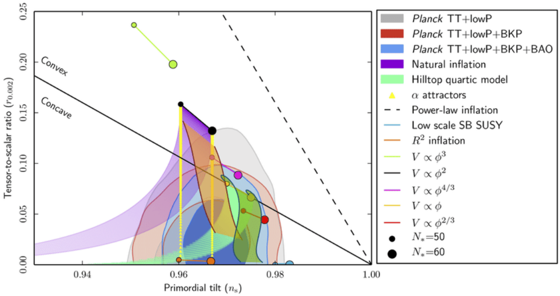


But how did it all start?



Features of the cosmic evolution

- Flatness "problem" - Universe is nearly flat, homogeneous and isotropic
- Horizon "problem" - causally disconnected regions of spacetime very similar
- Monopole "problem" - No exotic relics (ex: monopoles) around
- Production of primordial perturbations that are nearly scale invariant
- Inflation is a theory that can adequately explain these features (+more)



Pre-inflationary issues

Pertinent Questions

- What gave rise to the initial conditions/state of inflation?
- Initial singularity/Planck scale - Our physical laws cease to work
- Do we really need a complete theory of quantum gravity to understand these problems?
- Is there any (approximate) way to compute (estimate) probabilities and features of the early universe Cosmology?

The Wheeler - DeWitt equation and "Quantum Cosmology"

- Hartle and Hawking gave one such appealing proposal for computing the "Wavefunction of the Universe"
- Based on the so called [Wheeler DeWitt] (WDW) equation
- In this approach one uses the canonical (Hamiltonian) formalism of general relativity and promotes the constraints expressing diffeomorphism invariance to quantum operators annihilating the wavefunction

Canonical formalism and constraints

- The basic idea is that the spacetime is foliated into a family of spacelike surfaces Σ_t at each time coordinate t, and the coordinates on each slice are x_i
- The dynamic variables are: the metric tensor of three-dimensional spatial slices g_{ij} and their conjugate momenta π_{ij}
- Using these variables it is possible to define a Hamiltonian, and thereby write the equations of motion for general relativity in the form of Hamilton's equations
- Use the ADM [Arnowitt-Deser-Misner] decomposition of the metric

$$ds^2 = -N^2 dt^2 + g_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

- N is called the "lapse" and encodes the proper time evolution
- N^i is the "shift" vector and encodes how spatial coordinates change between hypersurfaces
- g_{ij} is the spatial metric on a slice Σ_t

- Start from the Einstein Hilbert (+ matter) action

$$S = \frac{1}{2\kappa}\int d^4x\,\sqrt{|g|}\,R^{(4)} \;+\; S^{matter}$$

In ADM parametrization, the canonical Hamiltonian can be written in the form

$$H_c = \int_\Sigma d^3x\sqrt{g}\,(NH + N^i H_i)$$

$$H = 2\kappa g^{-1}\left(g_{ik}g_{jl}\pi^{kl}\pi^{ij} - \frac{1}{2}(g_{ij}\pi^{ij})^2\right) - \frac{1}{2\kappa}R^{(3)} + H^{matter}$$

$$\pi^{ij} = \frac{\delta S}{\delta \dot{g}_{ij}}\,, \qquad H_i = -2g_{ij}D_k\frac{\pi^{jk}}{\sqrt{g}} + H_i^{matter}$$

where D_i is the g_{ij} covariant derivative and we indicate possible additional matter contributions

Constraints and the Wheeler DeWitt equation

- Diffeomorphism invariance $\Rightarrow$ The physical states/configurations are independent of the choice of lapse and shift (N, N^i)
- This leads to constraints [Dirac] $\Rightarrow H,\ H_i = 0$
- Let us also consider as matter a scalar field ϕ (that will play the role of the inflaton)
- At the quantum level one has to impose the constraints, acting as operators on the wavefunctions

$$\widehat{H}_{WDW}(\pi_{ij}, g_{ij}; \pi_\phi, \phi)\,\Psi_\Sigma(g_{ij}, \phi) = 0\,, \quad \widehat{H}_i(\pi_{ij}, g_{ij}; \pi_\phi, \phi)\,\Psi_\Sigma(g_{ij}, \phi) = 0$$

$$\hat{\pi}_{ij}\Psi_\Sigma(g_{ij}, \phi) = -i\frac{\delta}{\delta g_{ij}}\Psi_\Sigma(g_{ij}, \phi)\,, \qquad \hat{\pi}_\phi\Psi_\Sigma(g_{ij}, \phi) = -i\frac{\delta}{\delta \phi}\Psi_\Sigma(g_{ij}, \phi)$$

- These (functional differential) equations are not really well defined
$\Rightarrow$ There exists a "minisuperspace" ansatz/truncation that is better defined and leads to ODEs/PDEs

  Fortunately the isotropy and homogeneity of the universe makes this ansatze physically relevant

Minisuperspace and the No Boundary Proposal

- The WDW equation makes sense in the reduced minisuperspace ansatz

$$ds^2 = -N^2(t)dt^2 + a^2(t)d\Omega_\Sigma^2\,, \quad \phi = \phi(t)$$

- In this case $\widehat{H}_i \Psi_\Sigma(a,\phi) = 0$ automatically and $\widehat{H}_{WDW}\Psi_\Sigma(a,\phi) = 0$ becomes a well defined PDE
- One has to supplement appropriate "boundary" conditions
- The [Hartle - Hawking] No Boundary (NB) proposal posits that one has to make an excursion to Euclidean signature and consider compact metrics with no boundary at early times
- The resulting state/wavefunction corresponds to the [Bunch - Davies] or Euclidean vacuum (the analogue of the Minkowski vacuum in a Cosmological setting i.e. $\Lambda > 0$)
- There is also an alternative [Linde - Vilenkin] Tunelling (T) proposal (defined via probability influx/outflux in the superspace boundaries)

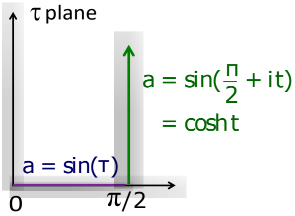
The simplest example: Empty de Sitter

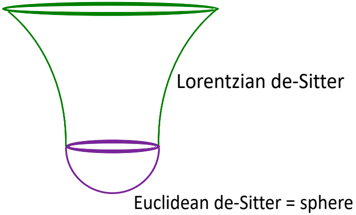
Consider the Einstein Hilbert action with positive cosmological constant

$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}\,(R-2\Lambda)\,, \qquad \Lambda > 0$$

that admits an empty de Sitter solution

The [Hartle - Hawking] proposal classically describes a (complex) metric
- half of Euclidean de-Sitter glued to half of Lorentzian de-Sitter -





$$ds^2 = d\tau^2 + \sin^2\tau\, d\Omega_3^2 \longrightarrow ds^2 = -\,dt^2 + \cosh^2 t\, d\Omega_3^2$$

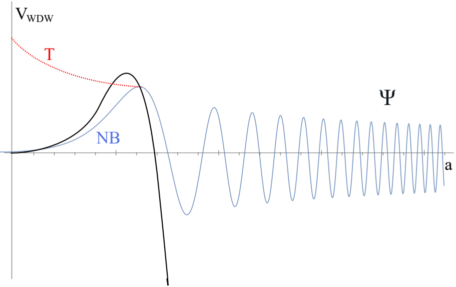
Semi-classics and WKB of minisuperspace WDW

- The minisuperspace WDW equation (positive cc./no matter) reads

$$\left(\widehat{\pi}_a^2 + a^2 - \frac{\Lambda}{3}a^4\right)\Psi_\Sigma(a) = 0 \qquad \widehat{\pi}_a = -i\kappa\frac{d}{da}$$

- To understand its semi-classical properties - convenient to employ a "WKB" ansatze ($\kappa = 8\pi G_N \hbar \to 0$)

$$\Psi_\Sigma^L(a) = A_L e^{iS_L/\kappa} + B_L e^{-iS_L/\kappa}\,, \qquad \Psi_\Sigma^E(a) = A_E e^{S_E/\kappa} + B_E e^{-S_E/\kappa}$$

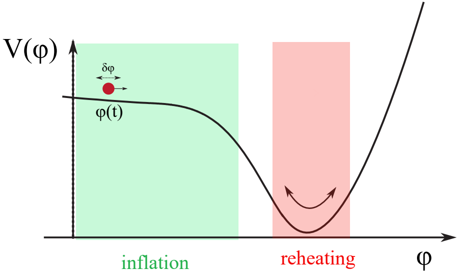


- For large a the wavefunction is oscillatory (Lorentzian), while for small a it has an exponential increasing/decreasing behaviour (Euclidean)
- The No Boundary proposal selects the increasing branch and the wavefunction vanishes at zero a - The Tunneling/[Vilenkin] proposal selects the decreasing branch

WDW and slow roll inflation

- One can include the presence of the scalar inflaton field ϕ
- We assume a slow roll approximation for the potential $V(\phi)$ in the inflationary region

$$\epsilon_V \equiv \frac{M_P^2}{16\pi}\left(\frac{V_\phi}{V}\right)^2 \ll 1\,, \quad \eta_V \equiv \frac{M_P^2}{8\pi}\frac{V_{\phi\phi}}{V} \ll 1$$



- The WDW wavefunction now depends on two arguments i.e. $\Psi_\Sigma(a, \phi)$
- Given the wavefunction, we can compute the probability for a specific "history"/realisation of the inflating Universe, via its norm $P = |\Psi|^2$

No Boundary/Tunneling and slow roll inflation

- In the slow roll approximation for the potential $V(\phi)$ one finds the semi-classical (WKB) No Boundary/Tunneling wavefunctions $(\kappa = 8\pi G_N)$

$$\Psi_{NB}(a,\phi) \simeq P_{NB}^{1/2}\,\Re\left(e^{iS_L(a,\phi)}\right)\,, \quad P_{NB} = e^{-S_E(\phi)}$$

$$\Psi_T(A,\phi) \simeq P_T^{1/2}\left(e^{-iS_L(a,\phi)}\right)\,, \quad P_T = e^{+S_E(\phi)}\,,$$

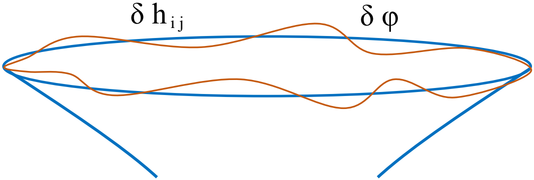
$$S_E(\phi) = -\frac{24\pi^2}{\kappa^2 V(\phi)}\,, \quad S_L(a,\phi) \simeq \frac{24\pi^2(a^2\kappa V(\phi)/3-1)^{3/2}}{\kappa^2 V(\phi)}$$

- S_E is the on-shell action of Euclidean de-Sitter (sphere)
- S_L is the on-shell action in the Lorentzian-oscillatory region when the scale factor is large $a^2 > 3/\kappa V(\phi)$
- The value of the inflaton/size of the sphere is typically set at horizon crossing during inflation $(\phi_*, a_*)\,, H(\phi_*)a_*(\phi_*) = 1$
  i.e. "beginning of inflation"

No Boundary and slow roll inflation: Fluctuations

[Halliwell - Hawking ...]

- It is also possible to describe (inhomogeneous) fluctuations of the fields $\phi(\Omega) = \phi_* + \delta\phi(\Omega)\,,\; g_{ij}(\Omega) = g^*_{ij} + \delta h_{ij}(\Omega)$ etc.



- The No Boundary proposal predicts the correct spectrum of primordial perturbations with a Gaussian suppression factor

$$|\Psi_{NB}(\phi)|^2 \sim e^{-S_E(\phi_*)} \prod_{modes} \exp\left(-\delta\phi_{mode}\, C_{mode}\, \delta\phi_{mode}\right)$$

(it describes the analogue of a Cosmological "vacuum")

- In the Tunneling proposal such fluctuations are unsuppressed $(- \leftrightarrow +)$...

The No Boundary proposal and Stochastic Inflation

[Starobinskii, Goncharov-Linde-Mukhanov ...]

- Assume a slow roll inflationary scenario and split the evolution of a scalar field into UV and IR modes (wtr Hubble scale H)

- The IR physics at scales $\Delta t \sim 1/H$, $\Delta L \gg 1/H$ is governed by an effective stochastic equation

$$\dot{\phi} = -\frac{V'}{3H} + \xi(t)\,, \qquad \langle \xi(t)\xi(t') \rangle = \frac{H^3}{4\pi^2}\delta(t-t')$$

  and a Fokker-Planck equation for the probability $P(t,\phi)$ that the field has the value ϕ at time t

$$\partial_t P + \partial_\phi J = 0\,, \quad J = -\frac{V'}{3H}P - \partial_\phi\left(\frac{H^3}{8\pi^2}P\right)$$

- For a potential bounded from below $V(\phi) \geq V_{min} > 0$, one finds an equilibrium $(J=0)$ distribution consistent with the No Boundary proposal

$$P_{eq.}(\phi) \sim \exp\left(\frac{24\pi^2}{\kappa^2 V(\phi)}\right) \sim P_{NB}(\phi) \qquad H^2 \sim \kappa V/3$$

Issues with the No Boundary proposal

- Given the wavefunction, we can also compute the probability for a specific "history"/realisation of the Universe, via its norm $P = |\Psi|^2$

$$P_{NB} = |\Psi_{NB}(\phi)|^2 \simeq \exp\left(-S_E(\phi)\right) = \exp\left(\frac{M_P^4}{V(\phi)}\right)$$

- This comes from the leading semi-classical piece of the wavefunction and indicates that the wavefunction is non-normalizable

- Perhaps this is not a deep problem due to the minisuperspace and (WKB) approximations involved

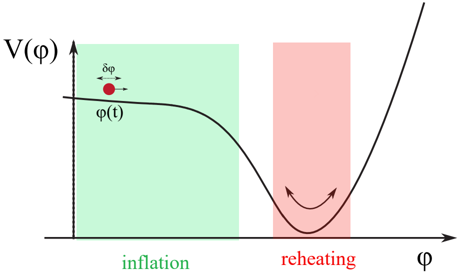
- Since the stochastic description is just an effective description of the IR sector, which the No Boundary proposal seems to describe correctly, perhaps there is no fundamental reason to demand its normalizability

- Nevertheless, even using it in this restricted sense, there is a more acute problem for the No Boundary proposal in the context of inflation (See the reviews by [Lehners, Maldacena])

An exponential (hierarchy) problem

- Remember the current cosmological constant problem

$$\frac{M_P^4}{V(\phi_{now})} \simeq 10^{120}$$



- The problem with the No Boundary proposal is exponentially worse!

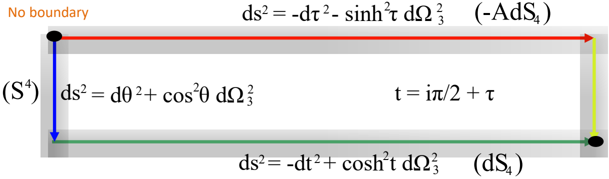
$$P_{NB} = |\Psi_{NB}(\phi_*)|^2 \simeq \exp\left(-S_E(\phi_*)\right) = \exp\left(\frac{M_P^4}{V(\phi_*)}\right)$$

- It gives an overwhelming probability ($P_{NB} \gg 1$) for an empty cold universe, with the smallest allowed number for the cosmological constant
- In the inflationary context it predicts the least number of e-folds
- The issue stems from the fact that the on-shell action for the positively curved Euclidean de-Sitter is negative

Ideas to evade this problem

- The Tunneling wavefunction [Linde - Vilenkin] evades this issue ($P_T \simeq e^{+S_E}$), but does not describe correctly the cosmological fluctuations beyond minisuperspace (they get enhanced)
- Selection rule or anthropic reasoning
  [Linde, Hartle - Hawking - Hertog ...]
- The gravitational path integral is not very well defined - non-renormalizability and the conformal mode problem - Understand it in a Picard-Lefschetz fashion and define an appropriate (steepest descend) contour in field space.
  [Halliwell-Louko, Hartle-Hawking-Hertog, Lehners, ...]
- Quantum effects (loops): It is possible that the (non-perturbative!?) wavefunction has a very different behaviour than its naive semi-classical expansion
  (seen in $2d$ models [Betzios-OP (20), Anninos (24)])
- Change entirely the assumptions/setup giving rise to our Cosmology?

- Alternative contours to the [Hartle-Hawking] one?
- One of them seems to connect cosmology with a $(-)AdS$ space [Hartle-Hawking-Hertog (11), Maldacena-Turiaci-Yang (19), ... Betzios-OP (20)]



No physically transparent meaning...

- Another approach: Domain-wall/Cosmology correspondence [Skenderis - Townsend] (Multiple analytic continuations...)
- But what if one wish to retain a clear understanding of the Lorentzian/Euclidean sections related with a simple $t = i\tau$

No-boundary density matrix

[Ivo - Li - Maldacena ('24)]

- The no boundary proposal assumes that we make observations to a whole spatial slice Σ_3
- But an observer can only see a part of it $\Rightarrow$ more realistic to consider the part of the spatial slice that an observer has access to, in order to make predictions
- Thus one needs to define a density matrix for the observable portion of the universe

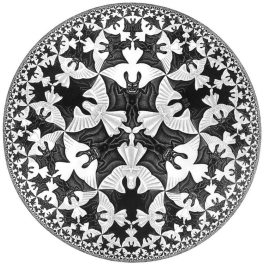
$$\rho\left[\Phi_{in}^{-}(\vec{x}), \Phi_{in}^{+}(\vec{x})\right] = \int \mathcal{D}\Phi_{out}\, \Psi^{*}\left[\Phi_{in}^{-}, \Phi_{out}\right] \Psi\left[\Phi_{in}^{+}, \Phi_{out}\right]$$
$$\sim \Psi^{*}\left[\Phi_{in}^{-}, \Phi_{out}^{s}\right] \Psi\left[\Phi_{in}^{+}, \Phi_{out}^{s}\right]$$

- Where $\Phi_{in}^{\pm}$ are data on the bra and ket sides and Φ_{out} are data one traces over in the unobserved region.
- In the semiclassical limit it is computed via a saddle point approximation $\Rightarrow$ It corresponds to evaluating the density matrix on a specific field configuration Φ_{out}^{s}.
- Even in this case the usual problems associated with the no-boundary proposal (non-renormalisability, preference for a small universe) remain

The No Boundary proposal and AdS/CFT

There is a case where the analogue of the No Boundary proposal works perfectly well: The AdS/CFT correspondence ($Z_{QGR}^{AdS} = Z_{CFT}^{\partial AdS}$)

- ex: Global $EAdS_4$ and the S^3 partition function (regular interior $\leftrightarrow$ N.B.)



$$ds^2_{H_4} = L^2_{AdS}(d\tau^2 + \sinh^2\tau d\Omega_3^2)$$

$$e^{-S_E(H_4)} \sim Z_{CFT}(S^3)\,, \quad S_E = \frac{L^2_{AdS}}{2G_N}$$

- Both sides can be computed and agree. For example in ABJM (finite-N) [Kapustin-Willet-Yaakov, Drukker-Marino-Putrov ...]
- Here it is crucial that the on-shell action of AdS is positive (after performing holographic renormalization)
- No direct relation to Cosmology (with a simple $\tau = it$)

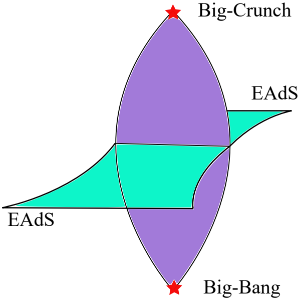
Euclidean Wormholes and Bang-Crunch Cosmologies

AdS/CFT context: [Maldacena-Maoz (04), Betzios-Gaddam-OP (17) + Kiritsis (19-21), Van Raamsdonk et. al. (20-23) ...]

- In AdS/CFT there is an example that gives rise to FRW cosmologies: Two boundary Euclidean AdS wormholes ($' = d/d\tau$)

$$ds^2 = d\tau^2 + a^2(\tau) d\Omega_3^2 \,, \quad a''(0) > 0 \,, \, a'(0) = 0 \,, \, a(\tau \to \pm\infty) \sim e^{H|\tau|}$$

- Euclidean Wormholes are NOT related to Black Holes (horizons) via analytic continuation - Instead:



- Their analytic continuation $\tau = it$ gives rise to Bang - Crunch Cosmologies (Remember that Λ is negative)

$$ds^2 = -dt^2 + a^2(t) d\Omega_3^2$$
$$\ddot{a}(0) < 0 \,, \quad \dot{a}(0) = 0$$

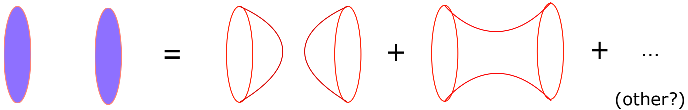
Symmetries and correlators of local operators

[Betzios - Kiritsis - OP (19), Betzios - OP (23)]

- Euclidean Wormholes are very puzzling from a holographic point of view
- No obvious entanglement as for Lorentzian wormholes (BH horizons)
- Global symmetries for the boundary theories? $\leftrightarrow$ A common Bulk "Gauss Law constraint" and gauge field
- Symmetries are broken to their diagonal part: $\mathcal{G}_1 \times \mathcal{G}_2 \to \mathcal{G}_{diag.}$
- One might have expected: different decoupled EQFTs on $\partial\mathcal{M} = \cup_i \partial\mathcal{M}_i$ $\Rightarrow$ Cross correlators are zero or $Z(J_1, J_2) = Z_1(J_1) Z_2(J_2)$
- Wormhole Bulk dictates otherwise $\Rightarrow$ What gives rise to the peculiar properties of the cross-correlators?

The factorisation problem: $Z(J_1, J_2) \neq Z_1(J_1)Z_2(J_2)$

`[Maldacena - Maoz (2004) ...]`

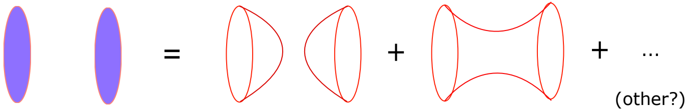


Possible resolutions:

- The QGR path integral corresponds to an average: $\langle Z(J_1)Z(J_2)\rangle \Rightarrow$ Several options `[...]`
- Explicit averaging over ensembles of CFT's - (Unitarity crisis)
- In canonical AdS/CFT there is a single theory with fixed parameters
- Approximate statistical averaging ("ETH" - "Quantum Chaos") $\Rightarrow$ "Statistical wormholes" from complicated/almost random Hamiltonians `[...]`

No factorisation problem due to interactions?

[Betzios - Kiritsis - OP (19 - 21)], see also related work by [Van Raamsdonk et. al. (20-22)] and [Bachas - Lavdas (18)]



A potentially microscopic understanding of wormhole saddles?:

- Interactions between holographic QFT's
- UV soft - IR strong cross-interactions
- Wormhole cross correlators - no short distance singularities
  $\Rightarrow$ averages of lower point correlators in individual subsystems
- I.e. can the exact Schwinger functional acquire an "averaged" form

$$Z_{system}(J_1, J_2) = \sum_S e^{w(S)} Z_S^{(QFT1)}(J_1) Z_S^{(QFT2)}(J_2)$$

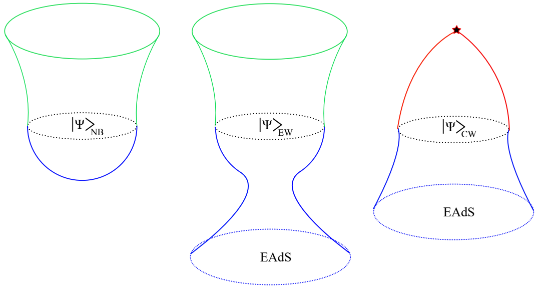
in a single unitary/reflection positive system (S some"sector")
[Betzios - Kiritsis - OP (21)] ($S \equiv R$ - $U(N)$ representations)

A new proposal for the wavefunction of the Universe

- An issue with these geometries is that upon analytic continuation they inevitably crunch and do not allow for a period of inflation

- Our idea [Betzios - OP (24)] : Combine features of both anti-de Sitter and de-Sitter - we need a Euclidean wormhole geometry that is asymptotically EAdS that transitions into EdS near its throat

- By cutting it in half we can "glue" to it an expanding Lorentzian Universe



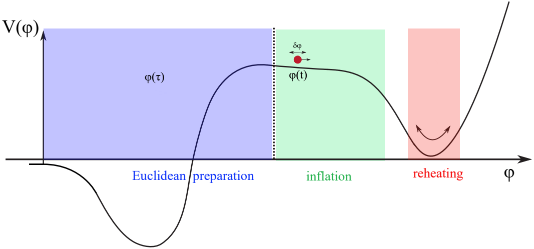
"Wineglass" AdS wormholes

- We shall call (half of) these geometries "wineglass" AdS (half) wormholes (Asymptotically flat analogues [Lavrelashvili-Rubakov-Tinyakov, Lehners])
- Their defining properties: They should asymptote to a EAdS space: $a(\tau \to \pm\infty) \sim \exp(H_{AdS}|\tau|)$ and in addition

$$a''(0) < 0\,, \quad a'(0) = 0\,, \quad a(0) = a_{\mathsf{max}}\,, \quad \phi'(0) = 0$$

  so that a_{max} is a local maximum of the scale factor

- These are also good initial conditions for a subsequent inflationary evolution (since $\ddot{a}(0) > 0$)
- An example of a scalar potential that can support such solutions



A model for "wineglass" AdS wormholes

- A simple model: Consider an Einstein-scalar-axion system ($\kappa \equiv M_{Pl}^{-2}$)

$$S_E = \int d^4x \sqrt{g_E} \left(-\frac{1}{2\kappa} R + \tfrac{1}{2} \nabla^\mu \phi \nabla_\mu \phi + V(\phi) + \frac{1}{12 f_\alpha^2} H_{\mu\nu\rho} H^{\mu\nu\rho} \right)$$

  and the spherically symmetric and homogeneous ansatz (q is a constant axion charge)

$$ds^2 = d\tau^2 + a^2(\tau) d\Omega_3^2 \,, \quad \phi(\tau) \,, \quad H_{ijk} = q \epsilon_{ijk}$$

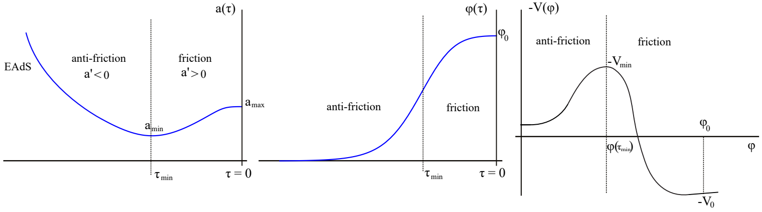
  One finds the two independent EOMs ($Q^2 \equiv q^2/2f_\alpha^2$)

$$\frac{a'^2}{a^2} - \frac{1}{a^2} + \frac{\kappa}{3} \left(V(\phi) - \frac{\phi'^2}{2} \right) + \frac{\kappa Q^2}{3a^6} = 0 \,,$$
$$\phi'' + 3 \frac{a' \phi'}{a} - \frac{dV}{d\phi} = 0 \,,$$

- The EOM for the scalar field describes a particle moving in the potential $-V(\phi)$ with an (anti)-friction term $3a'\phi'/a$

Wormhole solution

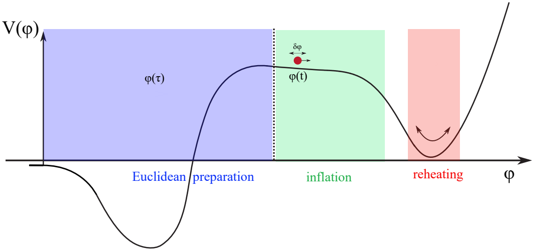
- We consider a potential $V(\phi)$ with a local maximum at $\phi = 0$ i.e. $V(\phi) \sim -1 + m^2\phi^2/2$ with $m^2 < 0$
- This leads to a renormalization group flow driven by a relevant operator with conformal dimension $\Delta = 3/2 + \sqrt{9/4 + m^2} < 3$
- The Euclidean evolution of the scale factor and the scalar field in $-V(\phi)$



- The Euclidean manifold initially shrinks ($a' < 0$/anti-friction) and then expands ($a' > 0$/friction) causing the ϕ particle to first accelerate and then stop at ϕ_0.

Subsequent Lorentzian evolution

- The potential should also contain a slow roll region for $\phi > \phi_0$, so that the Universe can subsequently inflate/expand in Lorentzian time



- Our proposal can accommodate various options consistent with the latest experimental constraints on inflation ex. [Planck] - incorporated in the shape of the potential

Evading the issue of the No Boundary proposal

- To compute the semi-classical probability and compare with the No-Boundary proposal ($P = |\Psi|^2 \simeq e^{-S_E}$)

  $\Rightarrow$ evaluate the Euclidean wormhole on-shell action

$$S_E^{\text{on-shell}} = 4\pi^2 \int_{UV}^{0} d\tau \left(\frac{2Q^2}{a^3} - a^3 V(\phi) \right) + S_{GH}^{UV} + S_{c.t.}^{UV} \,,$$

- The EAdS UV boundary contains the Gibbons-Hawking S_{GH}^{UV} as well as boundary counterterms $S_{c.t.}^{UV}$ that one needs to add in order to perform holographic renormalization

- Either numerically or analytically using thin/thick wall approximations one typically finds a positive on-shell action for the wormhole

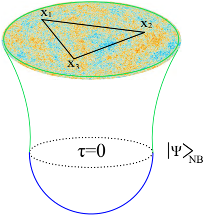
- As in other Holographic examples, due to the AdS asymptotics we have a well defined probability ($P \simeq e^{-S_E} < 1$) and the issue of the No Boundary proposal can be evaded : The Universe prefers to "nucleate" high up in the potential and then follows the slow roll trajectory

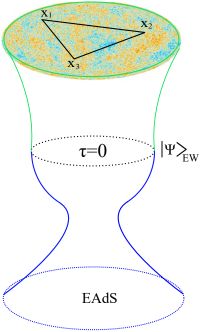
Cosmological Correlators

- Bulk correlators at $\tau = 0$ can be computed from the wavefunction using

$$\int D\phi \, |\Psi_{\tau=0}|^2 \, \phi(0, \vec{x}_1)...\phi(0, \vec{x}_n)$$

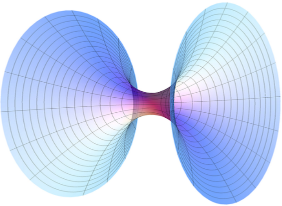
Later time/Cosmological correlators are computed using the in/in formalism `[Weinberg ...]` or evolving the wavefunction in Lorentzian





- Study Cosmological correlators in our setup and compare them with the No-Boundary proposal
- No leading deviations, since the metric resembles EdS near the throat, as long as one chooses the vacuum state in the $EAdS$ asymptotic regions

Holographic (AdS/CFT) embedding



- Our construction is amenable to a possible Holographic interpretation and embedding due to the $EAdS$ boundaries
- This relies on understanding the Holographic dual(s) of Euclidean wormholes

Pertinent Question

- Are there Microscopic UV complete models of Euclidean Wormholes? In AdS/CFT? (we want to understand string theory on target space wormhole backgrounds)
- This question is closely related to the factorization problem:

  Entanglement "holds up the throat" of a two sided eternal black hole, but it is not clear what is the analogue for Euclidean wormholes

SUGRA constructions

- It is possible to construct appropriate SUGRA models, with the needed ingredients for our mechanism to work [In progress, Betzios , Gialamas, OP]
- Examples exist in racetrack type of (super)-potentials $W = W_0 + Ae^{aT} + Be^{bT}$ i.e. [Kallosh-Linde ...] model
- Usually in [KKLT] and related models one uplifts the whole potential to positive values, it is much more natural to uplift only a part of it (for small field values - better control).
  Other groups are also working in similar directions [Quevedo et. al.]
- We do not yet know how to realize our scenario and at the same time get realistic $N_\star\,,\, n_s\,,r_\star$ in SUGRA models
- What about a clean string theoretic embedding?

A model consistent with experimental data (SM + GR)

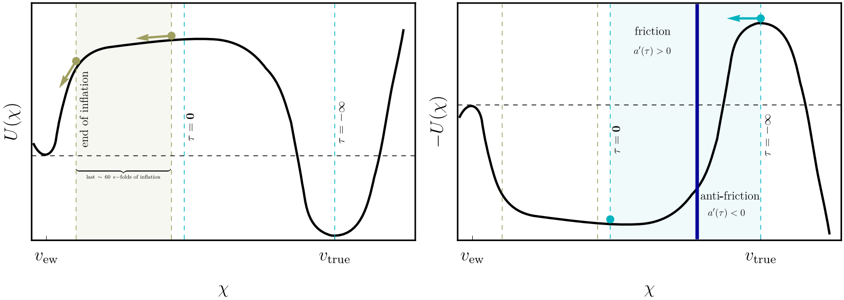
[P. Betzios - I. Gialamas - O. P. (24)]

- The Higgs boson is the only experimentally observed scalar particle in nature and could perhaps also play the role of the inflaton
- A class of models of inflation that conform very well with observations: "Higgs Inflation" [Bezrukov - Shaposhnikov ...]
- These models include a non-minimal coupling term $\sim \xi\phi^2 R$ to the Einstein-Higgs action (Jordan-frame action)
  (The [Starobinskii] R^2 model is a $\xi \to \infty$ limit of these models)
- Such terms typically appear when considering loop corrections to the effective action [Callan-Coleman-Jackiw ...]
- Central experimental values of the Higgs and Top mass [PDG ...] favor SM metastability $\Rightarrow$ the Higgs effective potential turns negative at high energies/field values (incl. loop corrections)

A model consistent with experimental data (SM + GR)

- Going back to Einstein Frame ($g_{\mu\nu} = e^{2\Omega}\tilde{g}_{\mu\nu}$) and to a canonically normalised scalar field $\chi(\phi)$, one finds a potential: of the Higgs type at small χ, of the slow roll type at inflationary χ and with a negative true minimum at very high energies/field values

The one-loop Higgs effective potential $U(\chi)$ in EF



- Our particular Higgs Inflation model also admits EAdS "wineglass wormhole" solutions as long as there is a dominant magnetic radiation component in the early Universe

A model consistent with experimental data (SM + GR)

[P.Betzios - I. Gialamas - O. P. (24)]

- The potential on the inflationary plateau region is approximately $U(\chi_\star) \simeq \lambda_\star/(4\kappa^2\xi_\star^2) \simeq 10^{-10} M_{Pl}^4$
- For $N_\star = 60$ e-folds of inflation we obtain

$$A_s^\star \simeq \frac{N_\star^2 \lambda_\star}{72\pi^2 \xi_\star^2}\,, \qquad n_s^\star \simeq 1 - \frac{2}{N_\star} \approx 0.9667\,, \qquad r_\star \simeq \frac{12}{N_\star^2} \approx 0.0033$$

- These are very good values for the spectral index and tensor/scalar ratio, close to (Planck/BICEP-Keck/BAO)

$$\begin{aligned} A_s^\star &= (2.10 \pm 0.03) \times 10^{-9}\,, && 68\%\ \text{CL} \\ n_s^\star &= 0.9649 \pm 0.0042\,, && 68\%\ \text{CL} \\ r_\star &< 0.036\,, && 95\%\ \text{CL}\,. \end{aligned}$$

- Our proposal can be realised in a phenomenological model consistent with current experimental/observational data, both from high energy and cosmological/astrophysical experiments

Summary

Summary

- The no-boundary proposal is an appealing proposal to define the wave-function of the universe
- Attractive features: Integrating over geometries without boundaries then there is no reason to impose a boundary condition at the big-bang singularity
- The same time it has been demonstrated that it gives non-sensical probabilities as well as it predicts an empty cold universe
- There are various alternatives but those too exhibit different issues
- The no-boundary proposal works nicely in the case of an asymptotically AdS spacetime (important that the CC is negative)

Summary

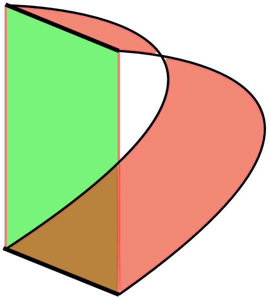
- Maybe a new type of wavefunction for the universe computed from the gravitational path integral, with asymptotically $EAdS$ boundary conditions is a better choice
- In the semiclassical limit, it describes a Euclidean AdS (half)-wormhole geometry. If the scale factor acquires a local maximum at the surface of reflection (Z_2) symmetry, it gives rise to an expanding universe upon analytic continuation to Lorentzian signature
- This proposal can be realised with a non-trivial scalar potential $V(\phi)$ that takes both positive and negative values (i.e. in the SM + GR: $\phi \equiv$ Higgs)
- It evades some issues of the No Boundary proposal, leading to a well defined probability $P \simeq e^{-S_E} < 1$. It can also favor a long-lasting period of inflation - (for certain scalar potentials)
- It also raises the interesting possibility of describing the physics of inflating cosmologies and their perturbations within the context of holography (Duals of EAdS Wormholes?)

Thank you!

Tripartite BQFT construction

[van Raamsdonk (20) - (22)], [Betzios - Kiritsis - OP (21)]

- Two d-dim (holographic) BQFT's on Σ coupled through a $d+1$-dim intermediate ("messenger") theory on $I \times \Sigma$



- Consider a system for which $c_{d+1} \ll c_d$
- We would like the system to flow to a gapped/confining theory in the IR
- The geometric idea: The dual bulk gravity can localise on $d+1$-dim EOW branes that bend and connect in the IR [van Raamsdonk]

- We focus in the case where the messenger theory is (quasi) topological ($TQFT_{d+1}$) $\Rightarrow$ No contamination from $d+2$ bulk perturbative modes, natural gap in the IR ... [Betzios - Kiritsis - OP]
- Integrate out $TQFT_{d+1}$ $\Rightarrow$ The Schwinger functional does become

$$Z_{system} = \sum_S e^{w(S)} Z_S^{(BQFT_1)}(J_1) Z_S^{(BQFT_2)}(J_2)$$

A model consistent with experimental data (SM + GR)

In progress [Betzios - Gialamas - OP]

- Replace the contribution of the axion, with radiation density $\sim 1/a^4$ arising from the experimentally observed SM gauge fields
- The Higgs boson is the only experimentally observed scalar particle in nature and could perhaps also play the role of the inflaton
- A class of models of inflation that conform very well with experimental data : "Higgs Inflation" [Bezrukov - Shaposhnikov ...]
- These models include a non-minimal coupling term $\sim \xi\phi^2 R$ to the Einstein-Higgs action (Jordan-frame action)
- Such terms typically appear when considering loop corrections to the effective action
- The [Starobinskii] R^2 model is a $\xi \to \infty$ limit of these models
- Going back to Einstein frame ($g_{\mu\nu} = e^{2\Omega}\tilde{g}_{\mu\nu}\,,\ \phi(\chi)$) one finds a potential of the slow roll type at large χ and of the Higgs type at small χ

A model consistent with experimental data (SM + GR)

In progress [Betzios - Gialamas - OP]

- Current experimental data of the Higgs and Top mass [PDG ...] favor SM metastability $\Rightarrow$ the Higgs effective potential turns negative at high energies/field values!

- We obtain a phenomenological model (consistent with current experimental data) that can realise our proposal

The one-loop Higgs effective potential $U(\chi)$