Magnetic and Axionic Wormholes as seeds for Higgs Inflation

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Work in collaboration with O. Papadoulaki
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and
arXiv:2412.03639 + I. Gialamas

Cosmological Frontiers in Fundamental Physics 2025

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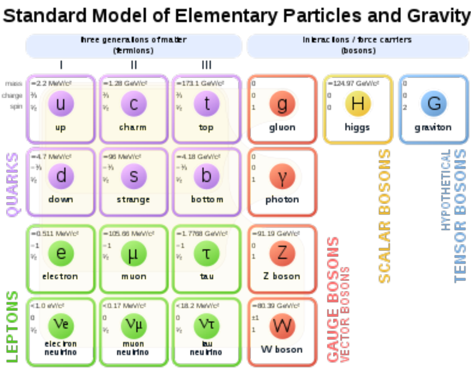
QFT - the success of the Standard Model

- QFT is a framework that incorporates all known particles and forces we observe - "Standard model"
- Still many input parameters and "hierarchy/fine tuning problems" (SM is an EFT)
- Detection of classical gravitational waves [LIGO ...] Possible to perturbatively quantise small gravitational ripples (graviton)

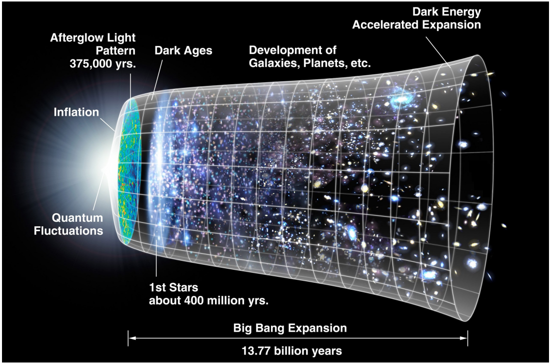


- When we add Gravity into the game:
  Planck scale $M_{Pl} \simeq 1.22 \times 10^{19} GeV$ as the highest energy scale

- The frontier lies in combining QFT and gravity beyond the perturbative regime (Quantum Gravity?) $\Rightarrow$ A theory of Black Holes and Cosmology

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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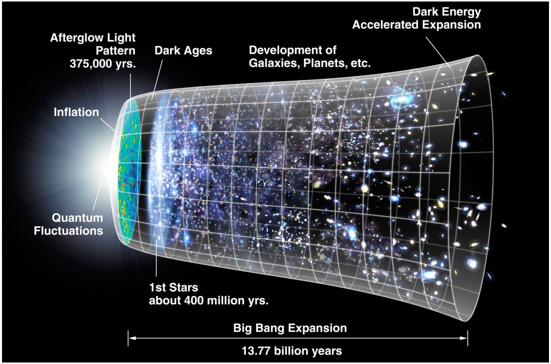
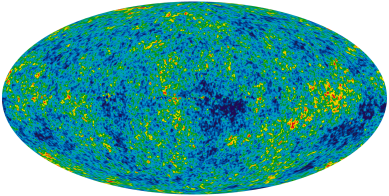


But how did it all start?
(physics before CMB production)



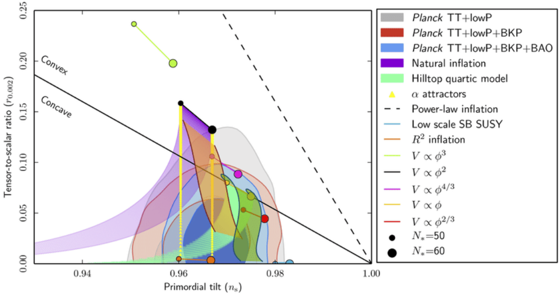
Features of the cosmic evolution

- 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

$$\mathcal{P}_{\mathcal{R}} = A_{\mathcal{R}} \left(\frac{k}{k_*}\right)^{n_s - 1} , \qquad n_s \simeq 0.96$$

The success of Inflationary theory

- Inflation is a theory that incorporates all these features
- The cosmological constant is promoted to a potential $V(\phi)$
  - ϕ a (new?) scalar particle: the Inflaton
- Various models consistent with all these + additional observational data (i.e. Tensor to Scalar ratio)



- Very hard though to embed Inflation in a UV complete model such as string theory (latter prefers anti-de Sitter vacua with $V_{min}(\phi_{min}) < 0$)

A minimal model for Inflation: Higgs Inflation

[Bezrukov - Shaposhnikov ...]

- The Higgs boson is the only experimentally observed scalar particle in nature and could perhaps also play the role of the inflaton

- This leads to a class of models of inflation that conform very well to observations: "Higgs Inflation" [Bezrukov - Shaposhnikov ...]

$$\mathcal{S}_J^E = \int \mathrm{d}^4x\sqrt{g_E}\left[-\frac{1}{2\kappa}R - \frac{\xi\phi^2}{2}R + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi) + \mathcal{L}_{\mathrm{rad}} + \mathcal{L}_{\mathrm{matter}}\right]$$

where $\kappa \equiv 1/M_{Pl}^2$

- 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 "ξ-attractors")

- Such terms typically appear when considering loop corrections to the effective action and therefore required for renormalization
[Callan-Coleman-Jackiw, Salopek-Bond-Bardeen ...]

Classical analysis: Weyl rescaling

- Perform a Weyl transformation to pass to the Einstein frame

$$g_{\mu\nu} \to \Omega^{-2}(\phi) g_{\mu\nu}\,, \qquad \text{with} \qquad \Omega^2(\phi) = 1 + \kappa\xi\phi^2$$

$$\mathcal{S}_J^E = \int \mathrm{d}^4x\sqrt{g_E}\left(-\frac{R}{2\kappa} + \left(\frac{1+(1+6\xi)\kappa\xi\phi^2}{(1+\kappa\xi\phi^2)^2}\right)\frac{\partial_\mu\phi\partial^\mu\phi}{2} + \frac{V(\phi)}{(1+\kappa\xi\phi^2)^2}\right)$$

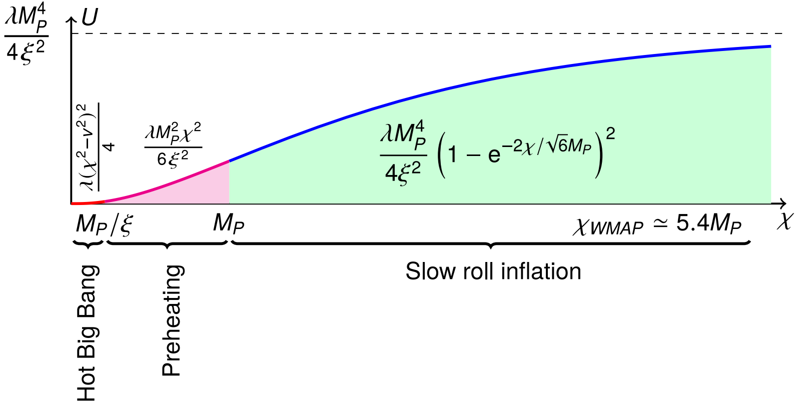
- Perform a scalar redefinition $\chi(\phi)$ to get a canonical kinetic term

$$\mathcal{S}_{EF}^E = \int \mathrm{d}^4x\sqrt{g_E}\left(-\frac{R}{2\kappa} + \frac{\partial_\mu\chi\partial^\mu\chi}{2} + U(\chi)\right)$$

$$U(\chi) = \frac{V(\phi(\chi))}{(1+\kappa\xi\phi^2(\chi))^2} \simeq \begin{cases} \frac{\lambda}{4}(\chi^2 - v_{\rm ew}^2)^2\,, & \text{if } \chi \ll \mathcal{M}_{Pl}/\xi \\ \frac{\lambda}{4\kappa^2\xi^2}\left(1 - e^{-\sqrt{2\kappa/3}\chi}\right)^2\,, & \text{if } \chi \gg \mathcal{M}_{Pl}/\xi \end{cases}$$

- In the last formula we used the standard (tree-level) Higgs potential $V(\phi) = \lambda(\phi^2 - v_{\rm ew}^2)^2/4$

Tree level potential in EF: Different stages of the Universe



Consistency with the CMB

- For $N_\star = 60$ e-folds of inflation we obtain (pivot scale $k_\star \simeq 0.05 Mpc^{-1}$)

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

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

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

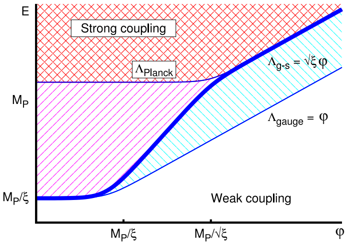
- The value of $A_s^\star$ leads to $\xi_\star/\sqrt{\lambda_\star} \simeq 47000$
- The potential on the inflationary plateau region is approximately $U(\chi_\star) \simeq \lambda_\star/(4\kappa^2\xi_\star^2) \simeq 10^{-10} M_{Pl}^4$

Scales and issues (tree level analysis)

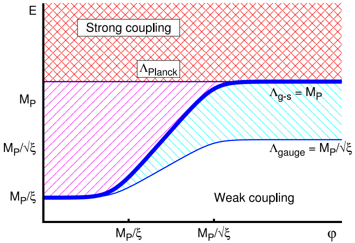
Tree level couplings assumed to be constants $g = g_\star$ with $\star$ the inflationary scale

- This model does suffer from some issues...
- Tree level Unitarity is violated at $\Lambda_{tree} \simeq M_{Pl}/\xi$
- The Hubble scale at Inflation is $H \simeq \lambda_\star^{1/2} M_{Pl}/\xi_\star$ (quite close to Λ_{tree} if $\lambda_\star \simeq O(1)$)
- $M_{Pl}/\xi < T_{Reheat} < M_{Pl}/\sqrt{\xi}$
- Quite subtle Pre/Re-heating processes and issues [Bezrukov, Gorbunov, Shaposhnikov, + many others ...] (No discussion today ...)
- The upshot: Need a proper treatment of quantum effects and/or UV completion
- Caveat: scales and cutoffs are background and frame dependent

Jordan frame (φ)



Einstein frame $(\chi(\varphi))$



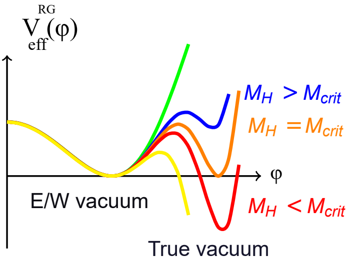
Relation between cut-offs in different frames: $\Lambda_{\text{Jordan}} = \Lambda_{\text{Einstein}}\Omega$

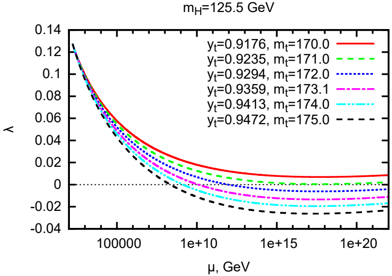
- This leads to two prescriptions (renormalization schemes) when computing quantum effects and to different UV completions
- I) Fixed (field independent cutoff) in EF (related to demanding quantum scale invariance at high energies)
- II) Field independent cutoff in the original Jordan frame (standard prescription for loop corrections from an EFT perspective)

RG (loop) corrections change the Higgs potential

No Gravity

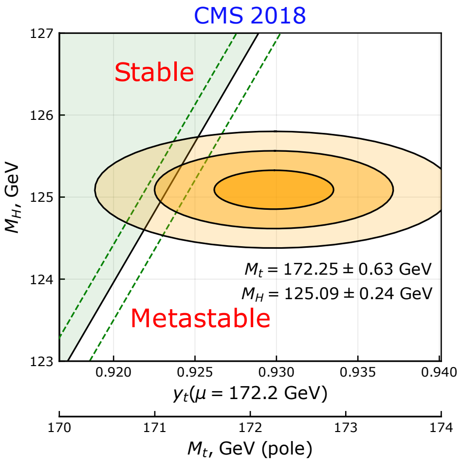
- The shape of the Higgs potential is very sensitive to quantum (loop) corrections and the values of the Higgs and top quark mass





- There are cases of both stability/metastability
- In the latter case the true vacuum has negative energy
- All these results are sensitive to the UV completion of the SM ("dessert"? SUSY? additional particles/fields?)

Experiment: We seem to be in the critical/metastable regime



- This is assuming no important gravitational corrections and a “dessert” when extrapolating RG to higher energies

Gravitational corrections are small

- Include gravity as an EFT: Write the GR effective action in a derivative expansion

$$S_{GR} = \int \mathrm{d}^4x\sqrt{g_E}\left(-\kappa_1 R + \alpha_1 R^2 + \alpha_2 R_{\mu\nu}R^{\mu\nu} + \alpha_3 R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} + \ldots\right)$$

together with couplings to matter/Higgs

$$S[\phi] = \int \mathrm{d}^4x\sqrt{g_E}\left(\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi) - \frac{\xi}{2}\phi^2 R + \ldots\right)$$

and finally compute the RG running of the couplings $g_i(\mu)$

- One can check that for the cosmological scales of interest the gravitational curvature corrections are small and can be neglected for most processes $\Rightarrow$ keep lower derivative terms

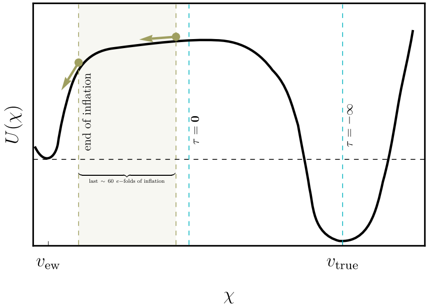
- The couplings $\xi(\mu)$, $\lambda(\mu)$ do run appreciably though, especially in the case of metastability where $\lambda(\mu) < 0$ in a certain (high) energy window

Our model (SM + GR)

[P.B. - I. Gialamas - O. Papadoulaki (24)]

- Assume that we are in the metastability regime with a negative minimum above the inflationary scale (this is also corroborated from string theory expectations/models with better UV behaviour)

The Higgs effective potential $U(\chi)$ in the EF



- The precise shape of the potential at high energies does depend on the UV completion - (The details turn out not to be so important)
- In order to have successful Inflation, we need as initial condition to start high up in the hilltop (a generic issue of Infl. models)

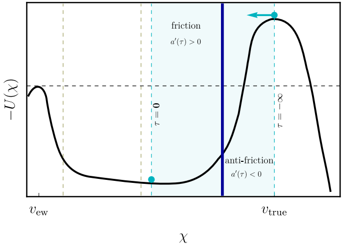
Pertinent Questions

- What gave rise to the initial conditions/state of inflation?
  i.e. Why to start high up in the inflaton potential?
- Tracing back Lorentzian evolution: Initial singularity/Planck scale?
  - Our physical laws cease to work
- Do we really need a complete theory of quantum gravity to surpass these problems?

- We will show that it is possible to obtain a semi-classical understanding for the "birth/nucleation of the Universe" (i.e. Lorentzian Inflationary evolution that starts high up in the Inflaton potential, even if the global minimum is AdS - no singularity)
- This involves semi-classical instanton/bounce like Euclidean techniques
  For a Wheeler-DeWitt/Holographic perspective: [PB - Papadoulaki (24)]

An obvious objection?

- There is an obvious objection to this idea: Assumed that the global minimum of the scalar potential is negative, is our spacetime inevitably anti-de Sitter?
- We do not wish (and cannot have in our model) a completely stable eternal de-Sitter Cosmology
- We want a (non-perturbative) instanton or bounce-like process that allows a nucleation of the Universe with right initial conditions high up in the Inflaton potential, that then follows a Lorentzian slow roll trajectory
- We show that solutions of this kind do exist, since the Euclidean evolution (used in such processes in QM) proceeds in $-U(\chi)$



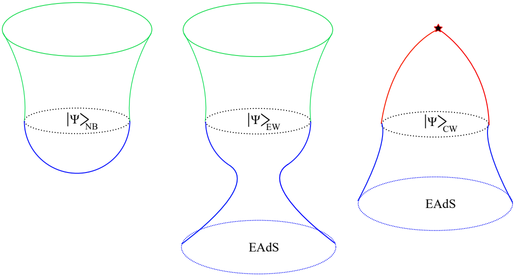
Euclidean geometries that prepare initial states

- Euclidean geometries have interesting connections to Lorentzian geometries upon analytic continuation

- Euclidean geometries with Z_2 reflection symmetry can be sliced in half to define initial $t = 0$ states/wavefunctions of the Lorentzian evolution

- Similarly to bubble nucleation, this can be used to define the initial state the "birth/nucleation" of a small Universe ($L_U > 10^4 L_{Pl}$)

- An impressionistic version of examples:



- We shall focus in the middle picture: A "wineglass" (half) - wormhole

"Wineglass" AdS wormholes: Generalities

- We shall call (half of) our geometries "wineglass" AdS (half) wormholes
  Assume a (homogeneous/isotropic) E-FRLW ansatze

$$ds^2 = d\tau^2 + a^2(\tau) d\Sigma_3^2 \,, \qquad \phi(\tau)$$

- 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 (in Euclidean)

- These are also good initial conditions for a subsequent inflationary Lorentzian evolution (since $t = i\tau \;\Rightarrow \dot{a}(0) = \dot{\phi}(0) = 0 \,,\; \ddot{a}(0) > 0$)

- To obtain such solutions: A scalar potential that takes both positive and negative values, and some form of negative Euclidean energy that supports their throat from collapsing

Models for "wineglass" AdS wormholes

- Consider a general GR-inflaton-radiation-matter EFT ($\kappa \equiv M_{Pl}^{-2}$)

$$S_{EFT} = \int d^4x\sqrt{g_E}\left(-\frac{1}{2\kappa}R + \frac{1}{2}\nabla^\mu\chi\nabla_\mu\chi + U(\chi) + \mathcal{L}_{rad.} + \mathcal{L}_{matter}\right)$$

and the spherically symmetric and homogeneous ansatze

$$ds^2 = d\tau^2 + a^2(\tau)d\Omega_3^2\,, \quad \phi(\tau)\,,$$

The Einstein and inflaton EOMs reduce to

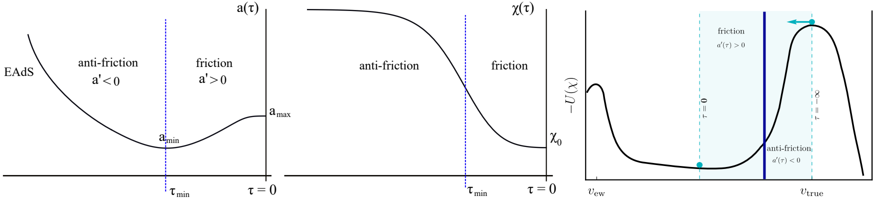
$$\frac{a'^2}{a^2} - \frac{1}{a^2} + \frac{\kappa}{3}\left(U(\chi) - \frac{\chi'^2}{2}\right) + \frac{\rho_{axion}}{a^6} - \frac{\rho_{rad.}}{a^4} - \frac{\rho_{matter}}{a^3} = 0\,,$$

$$\chi'' + 3\frac{a'\chi'}{a} - \frac{dU}{d\chi} = 0\,,$$

- "Wineglass" Wormholes can be supported by axions [PB - Papadoulaki (23)] or magnetic radiation [PB - Papadoulaki - Gialamas 24]
- Magnetic radiation/fluxes lead to $\rho_{rad.} < 0$ (i.e. $T^E_{\tau\tau} \sim E^2 - B^2$)

The physics of Wormhole solutions

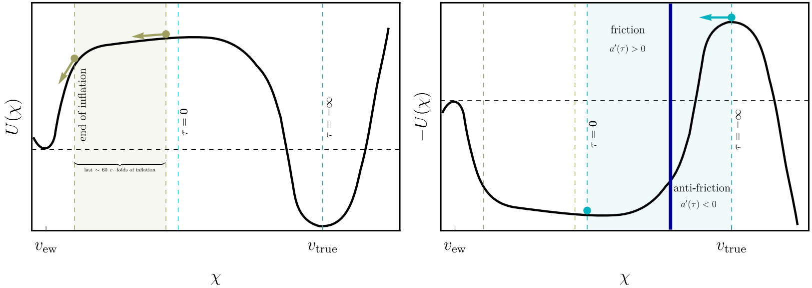
- Gravity wants to shrink the scale factor $(-1/a^2)$, while axions/magnetic fluxes try to expand it $(\rho_{axion}/a^6 - \rho_{rad.}/a^4\ ,\ \rho_{rad.} < 0)$
- The (Euclidean) EOM for the scalar field describes a particle moving in the potential $-U(\chi)$ with an (anti)-friction term $3a'\chi'/a$
- The Euclidean evolution of the scale factor and the scalar field in $-U(\chi)$



- The Euclidean manifold initially shrinks ($a' < 0$/gravitational dominance) and then expands ($a' > 0$/flux dominance) causing the χ particle to first accelerate ($a' < 0$/anti-friction) and then to stop ($a' > 0$/friction) at χ_0.
  (Desirable to stop near the minimum of $-U(\chi)$...)

Subsequent Lorentzian evolution

- The Euclidean trajectory describes the nucleation of the Universe at χ_0, high up in the potential with $\dot{a}(0) = \dot{\chi}(0) = 0$. It then follows the slow roll trajectory to the E/W vacuum



- Our proposal in the context of Higgs inflation is consistent with the experimental constraints on inflation ex. [Planck, BICEP] etc.

- It predicts a dominant magnetic radiation and/or axionic component in the very early Universe (we give precise numbers/bounds)

- They both get diluted to an enormous degree during inflation

Further properties and the need for UV completion

- While $\xi_\star \simeq 47.000\sqrt{\lambda_\star}$ is an inflationary condition, $\lambda_{E/W} \gg \lambda_\star$ (in our proposal), so $\xi(\mu_\star^+)$ can be quite small and Unitarity violation at M_{Pl}/ξ is pushed at higher energy scales

- Moreover the Hubble scale at Inflation $H_\star \simeq \lambda_\star^{1/2} M_{Pl}/\xi_\star$ is driven to smaller values than the Unitarity violation scale

- To precisely fix these values, we would like to understand the shape of the potential quantitatively up to the UV scale of the global AdS minimum

- The road to UV completion - various levels of sophistication: $SM + GR$ EFT $\ll$ GUTs/SUGRA EFT $\ll$ String theory (ℓ_s) $\ll$ microscopic D-brane Holography

- We momentarily change gears, before discussing a more UV complete picture for our proposal

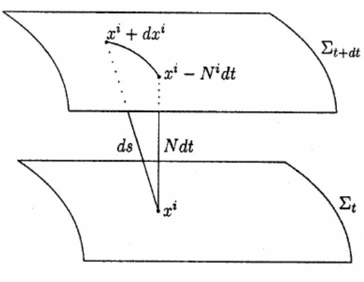
A (WDW) Wavefunction perspective

- To understand the properties of the inflationary wavefunction for the Universe: Pass to a canonical formalism of GR

- Use the [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", N^i is the "shift" vector and g_{ij} is the spatial metric on a slice Σ



Canonical formalism and constraints

- Start from the Einstein Hilbert (+ matter) action

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

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 (i.e. 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" ansatze/truncation that is better defined and leads to ODEs/PDEs

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

- The WDW equation simplifies in the reduced minisuperspace ansatze

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

- 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
- There is also an alternative [Linde - Vilenkin] Tunelling (T) proposal as well as our EAdS Wormhole proposal when $V(\phi)$ contains both signs
- We can compute relative probabilities for specific "histories"/realisations of the inflating Universe, via ratios $r_{i/j} = P_i/P_j = |\Psi_\Sigma(i)|^2/|\Psi_\Sigma(j)|^2$
- We can compute perturbations of the fields: $\Psi_\Sigma(a + \delta a(\Omega), \phi + \delta\phi(\Omega))$.

No Boundary/Tunneling and slow roll inflation

Reviews: [Halliwell - Lehners - Maldacena]

- In the slow roll approximation for the potential $V(\phi)$ one finds the semi-classical (WKB) No Boundary/Tunneling wavefunctions ($\kappa = 8\pi\hbar G_N \to 0$)

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

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

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

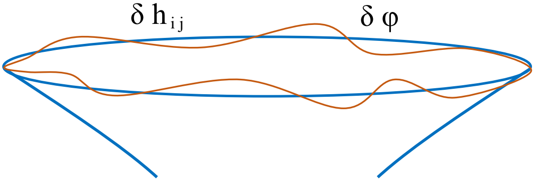
- S_E is the on-shell action of Euclidean de-Sitter (sphere)
  S_L is the action in the Lorentzian-oscillatory region when the scale factor is large $a^2 > 3/\kappa V(\phi)$

- Derivation: Solve WDW semiclassically in the Euclidean/Lorentzian regions and perform WKB matching for the value of the inflaton/size of the sphere at "first horizon crossing" $(\phi_*, a_*)\,, H(\phi_*)a_*(\phi_*) \simeq 1$
  i.e. near the "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

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

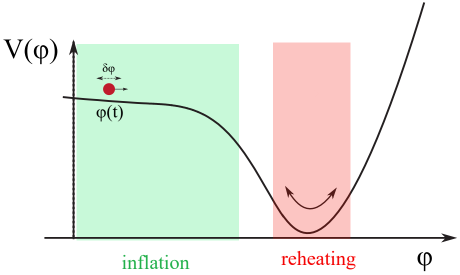
It describes a Cosmological analogue of the "vacuum" [Bunch-Davies ...]

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

An exponential (hierarchy) problem

- Remember the current cosmological constant problem

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



- There is an exponentially worse problem with the No Boundary proposal!

$$P_{NB}(\phi) \simeq e^{-S_E(\phi)} = \exp\left(\frac{M_P^4}{V(\phi)}\right), \quad r_{i/j} \simeq \exp\left(\frac{M_P^4}{V(\phi_i)} - \frac{M_P^4}{V(\phi_j)}\right)$$

- It gives an overwhelming probability/ratio ($P_{NB} \gg 1$) 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

AdS wormholes evade the issue of the No Boundary proposal

[PB - Papadoulaki (24)]

- 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

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

  ($p = 3,\ 1$ for axion, radiation)

- 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 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

Summary and Future Directions

Summary

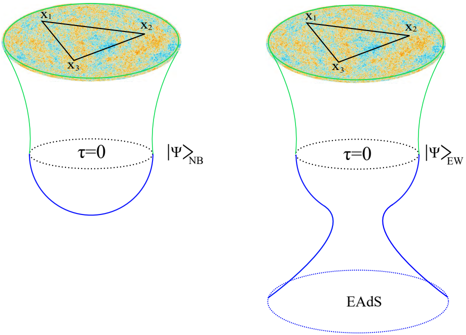
- We proposed a new type of saddle/wavefunction for the universe computed from the gravitational path integral, with asymptotically $EAdS$ boundary conditions
- In the semiclassical limit, it describes a Euclidean AdS (half)-wormhole geometry. If the scale factor acquires a local maximum at the surface of reflection (Z_2) symmetry, it gives rise to a Lorentzian expanding universe
- Our 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)
- Our proposal 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

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

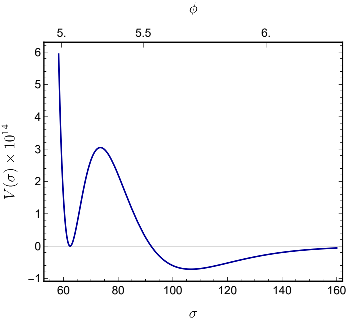


- We are currently studying Cosmological correlators in our setup and comparing them with the No-Boundary proposal `[In progress]`

- No leading deviations, since the metric resembles EdS near the throat, as long as one chooses the vacuum state in the $EAdS$ asymptotic regions (subleading corrections?)

SUGRA constructions

- It is possible to construct appropriate SUGRA models, with the needed ingredients for our mechanism to work [In progress, PB , Gialamas, Papadoulaki]



- Examples exist in racetrack type of (super)-potentials $W = W_0 + Ae^{aT} + Be^{bT}$ $(T = \sigma + ia)$ 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.]

- What about a clean string theoretic embedding?

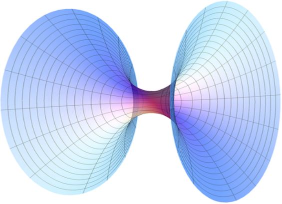
String (inspired) SUGRA models

See the review by [Conlon - Quevedo et al. (23)]

String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N-Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$ Inflation	0.968	10^{-7}
Inflection Point Inflation	0.923	10^{-6}
D3-D7 Inflation	0.981	10^{-6}
Racetrack Inflation	0.942	10^{-8}
Volume Inflation	0.965	10^{-9}
DBI Inflation	0.923	10^{-7}

- We do not yet know if we can realize our scenario and at the same time get realistic $N_\star$, n_s , $r_\star$ in string/SUGRA models (Non minimal couplings?)

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

Question

- Are there Microscopic UV complete models of Euclidean Wormholes? In AdS/CFT? (we ultimately want to understand string theory on target space wormhole backgrounds)
- This question is closely related to the factorization problem in its original incarnation: [Maldacena Maoz (04)]

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

  Proposals: (Statistical) Averaging [low-dim ...] vs. Interactions

  [PB - Kiritsis - Papadoulaki (19-21)] [Van Raamsdonk et. al. (20-22)]

Other Future Directions

- Important to run RG equations for various scenarios ("dessert" / SUSic etc.) to quantitatively fix the shape of the effective Higgs potential
- Check the details of these scenarios (perturbations, consistency with data etc.)
- Our model predicts the presence of primordial magnetic fields and/or axions
- Check whether there exist mechanisms that can sustain the former during the inflationary dilution (seeds for the galactic dynamo?)
- The latter have interesting connections to BSM phenomenology. Perhaps they can also explain current observational data on Dark Energy/Matter
- Develop a Holographic picture (at least bottom up) for our EFT model
- If gravity and axions arise from a strongly coupled hidden QFT_N sector, what should its properties be to realize our setup?

Thank you!

Axion like particles (ALPs)

- Axion-like particles (ALPs) are omnipresent in physics beyond the SM
- They were introduced to solve the strong CP problem: $\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\langle\theta\rangle \approx 0$ (approximate CP symmetry) - promote $\theta \to a(x)$
- The shift symmetry of axions $\alpha \to \alpha + C$ broken by non-perturbative QCD effects (instantons)
- The weak effective potential leads to $\langle\alpha\rangle = 0$ [Vafa-Witten]
- Because of the protection rendered by approximate Peccei-Quinn (PQ) symmetry, proposals to serve as dark matter, dark energy, or drive inflation
- They are ubiquitous in string theory and typical vacua have hundreds of ALPs
- In [Anastastopoulos, PB, Bianchi, Consoli, Kiritsis (18)] studied emergent/composite axions dual to "hidden sector" instanton densities

Further effects of gravity

- Global symmetries are expected to be violated in gravity ($U(1)$ PQ quality problem). Wormholes can indeed be one such source of violation
- When hidden sector holographic: This is the bulk gravitational counterpart to the "hidden sector" QFT_N non-perturbative effects that break PQ
- A non-minimal coupling $\xi > 10^3$ alleviates the quality problem [Hamaguchi, Kanazawa, Nagata ...] - AdS asymptotics achieve this with even smaller ξ
- It would be interesting to understand if ALPs from a strongly coupled (holographic) hidden sector can play the role of a (weakly) time dependent Dark Energy, consistently with the recent results of [DESI]
- Two birds with one stone: Data explanation and strengthening our model and its potential Holographic UV completion

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

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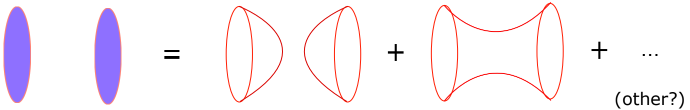
The factorisation problem: $Z(J_1, J_2) \neq Z_1(J_1)Z_2(J_2)$

[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 [...]

  Is this is what happens in our Cosmology?

No factorisation problem due to interactions?

[PB - Kiritsis - Papadoulaki (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
- It is actually quite subtle!: "Why to have a disconnected pair of boundaries and not a single one?" $\Rightarrow$ UV soft - IR strong cross-interactions (reminiscent of confinement...)
- 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

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

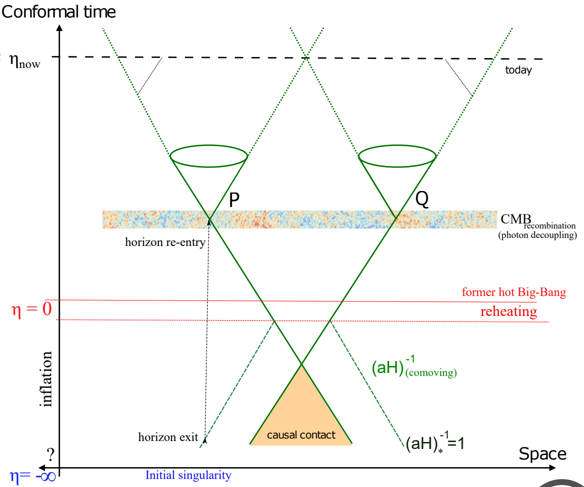
in a single unitary/reflection positive system? (S some "sector")
[PB - Kiritsis - Papadoulaki (21)] ($S \equiv R$ - $U(N)$ representations)

The inflationary paradigm

- Consider an FRW metric

$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2 = a^2(\eta)[-d\eta^2 + d\vec{x}^2], \quad \eta = \int \frac{dt}{a(t)} = \int \frac{d\log a}{(aH)}$$

- The conformal time elapsed η depends on the comoving Hubble radius $(aH)^{-1} = (da/dt)^{-1}$
- Inflation: Comoving Hubble radius was initially decreasing $\equiv d^2a/dt^2 > 0$ (after reheating it increases $\equiv d^2a/dt^2 < 0$)
- This means that superhorizon scales entering the present universe, actually started from a small region where local microphysics established homogeneity and isotropy (thermal equilibrium)



Future Directions

- We would like to perform a thorough WKB analysis of the two-parameter (a, ϕ) WDW equation (turning points, caustics etc...)

- It is important to understand whether the resulting (half)-wormhole wavefunction is normalisable or not

- Analyse the spectrum of fluctuations around such wormholes

- Embed our setup in holography. A UV complete microscopic model of Euclidean wormholes? [PB - Papadoulaki - Kiritsis, Van Raamsdonk ...]

- Understand what our (half)-wormholes correspond to from a dual field theory perspective

- A related simpler question [PB - Gaddam - Papadoulaki ...]: What does opening up a hole in the center of EAdS and fixing bcs there mean for the holographic CFT?

WDW equation and normalizability of the wavefunction

- Issue II: The No-Boundary wavefunction is non-normalizable
- Our WDW equation is ($A = \log a$ avoids normal ordering issues)

$$\left[\frac{\partial^2}{\partial A^2} - \frac{\partial^2}{\partial \tilde{\phi}^2} + \left(\frac{12\pi^2}{\kappa}\right)^2 \left(e^{6A}\tilde{V}(\tilde{\phi}) - e^{4A} + \tilde{Q}^2\right)\right]\Psi = 0$$

with $\tilde{\phi} = \phi/M_{Pl}$, $\tilde{V} = \kappa V/3\,, \tilde{Q}^2 = \kappa Q^2/3$)

- Unfortunately we cannot solve this equation in closed form, but the work of [Hawking - Page] showed that a similar equation admits a discrete set of normalisable solutions/states
- Their idea is that semi-classical (half)-wormhole solutions are superpositions of these elementary states [Hawking - Page]
- If true this would mean that our (half)-wormholes would be described by a normalisable WDW wavefunction in contrast with the No Boundary wavefunction, but this remains to be checked

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])