Still

Looking for Evidence of Scalar/Tensor Entanglement in the Cosmological Initial State

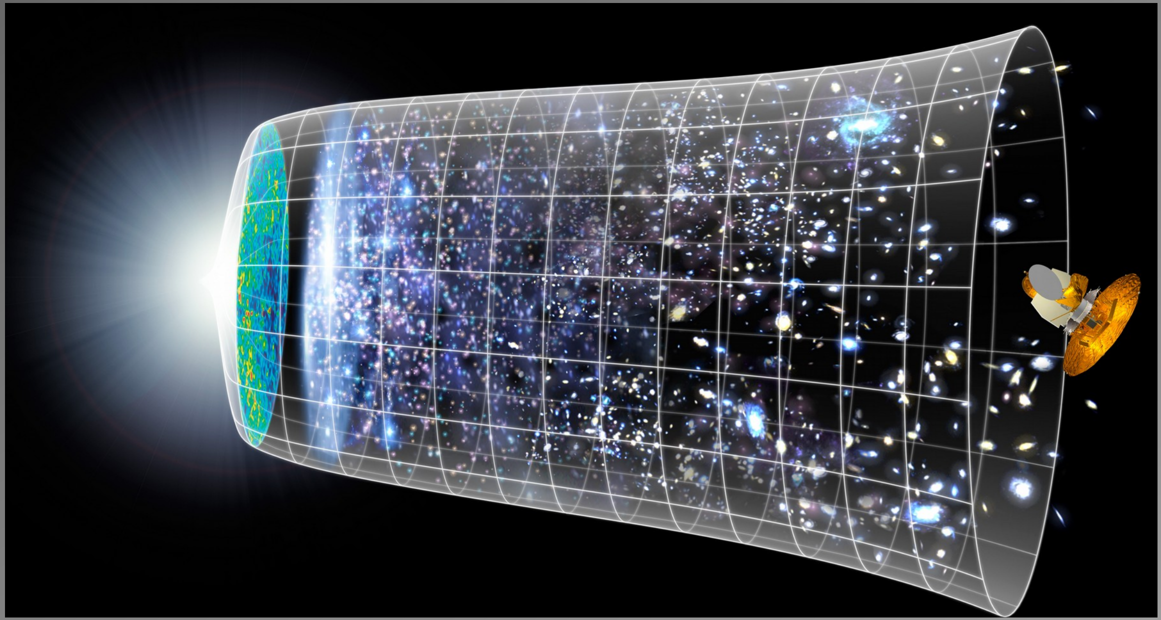


Image Credit: NASA/WMAP

Andrew Arrasmith, Nadia Bolis, Andreas Albrecht

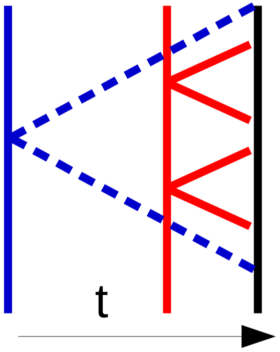
Outline

- Tuning in Initial States in Cosmology
- Bunch-Davies State
- Model for Entangled Initial States
- Our Approach
- Wrap-Up

Tuning in Cosmology:

Inflation is Motivated by Tuning!

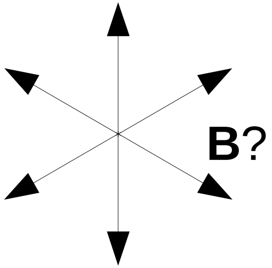
- Horizon Problem



- Flatness Problem

K=0 ? ← Unstable Equilibrium!

- Magnetic Monopoles



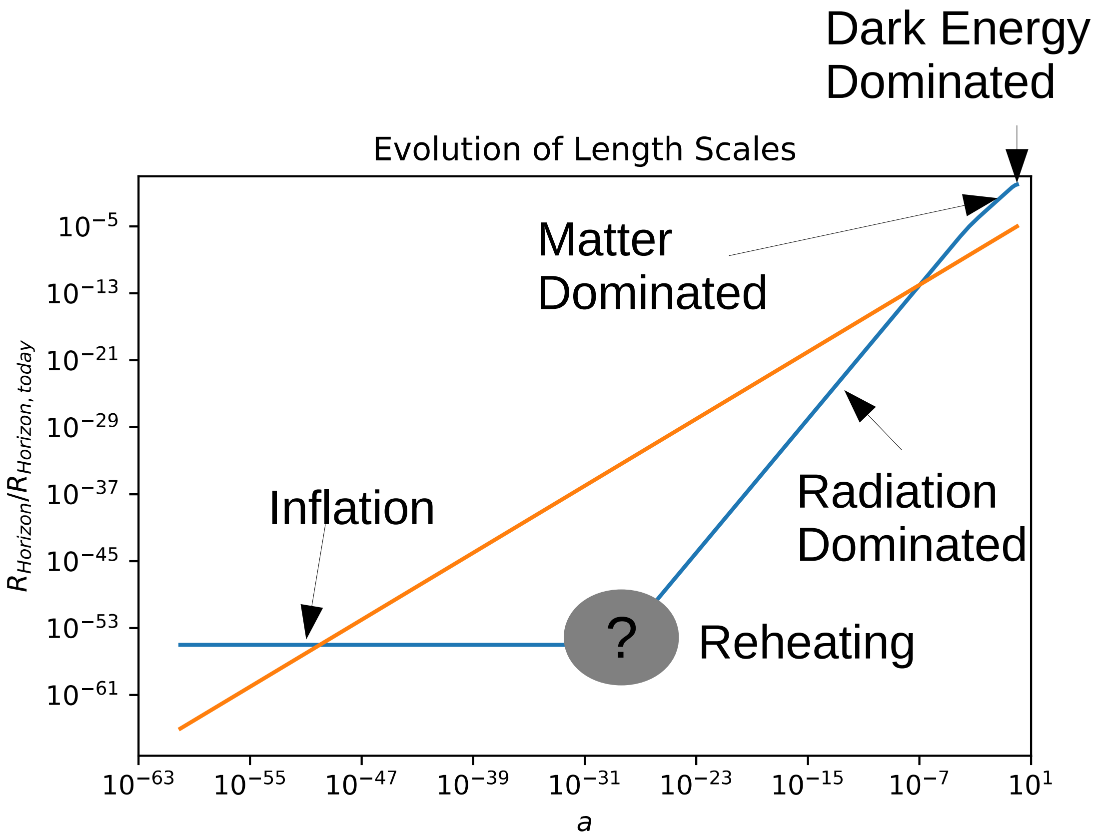
All early universe cosmology is motivated by a rejection of unnatural seeming initial states!

Tuning in Inflation?

Broad strokes of inflation's predictions hold for a wide range of effective inflaton potentials. (That is, it is fairly easy to get reasonable values for n_s and r even with simple models.)

However, inflation makes predictions that depend on UV structure in the early universe.

Boltzmann Brains?



The Bunch-Davies State: Vacuum?

The Bunch-Davies state is usually referred to as the Bunch-Davies vacuum in cosmology, and this can be a point of confusion.

However, the Bunch-Davies state only works as a vacuum in true de Sitter space, not the quasi-de Sitter FLRW space expected during inflation.
(Paul R. Anderson, Emil Mottola, and Dillon H. Sanders, Phys. Rev. D 97, 06501, March 2018)

It is therefore reasonable to expect that deviations from Bunch-Davies will generically be part of a complete treatment of inflation.

Standard Lore: The Bunch-Davies State

Describes the scalar and tensor gauge invariant metric perturbations used in standard inflationary calculations.

Basic idea:
In the short distance limit space is flat→ match solution to wave equations in de Sitter space to flat space vacuum mode functions in that limit

Use this choice to define the Fock space vacuum.

Deals with UV sensitivity with the assumption that the modes are in this vacuum.

Bunch-Davies: Schrödinger Functional Approach

Alternative approach: Schrödinger functional field theory

$$\Psi_{BD}\left[\{\zeta_{\vec{k}}\},\{h^{+}_{\vec{k}}\},\{h^{\times}_{\vec{k}}\},\tau\right]=\prod_{\vec{k}}\psi_{BD\vec{k}}\left[\zeta_{\vec{k}},h^{+}_{\vec{k}},h^{\times}_{\vec{k}},\tau\right]$$

In the absence of coupling between the modes we can write:

$$\psi_{BD\vec{k}}\left[\zeta_{\vec{k}},h^{+}_{\vec{k}},h^{\times}_{\vec{k}},\tau\right]=\sqrt(N_k(\tau))$$
$$exp\Big[-\frac{1}{2}\Big(A_k(\tau)\zeta_{\vec{k}}\zeta_{-\vec{k}}$$
$$+B_k(\tau)\left(h^{\times}_{\vec{k}}h^{\times}_{-\vec{k}}+h^{+}_{\vec{k}}h^{+}_{-\vec{k}}\right)\Big)\Big]$$

Relationship to standard BD modes:

$$\mathrm{iA}_k=a^2\epsilon\left(\frac{v'_k}{v_k}-\frac{(a\sqrt{\epsilon})'}{a\sqrt{\epsilon}}\right)$$

Entangled Initial State Model: Motivations

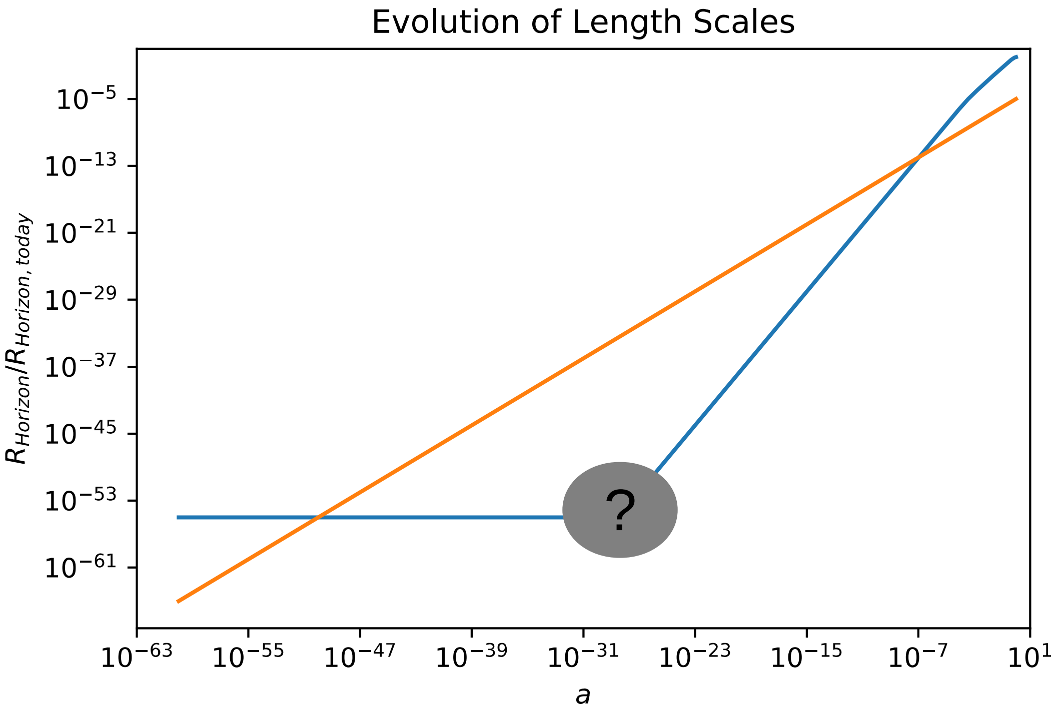
One simple alternative to the BD state is to just add entanglement between the scalar and tensor modes.

Potential to reveal pre-inflation dynamics for short inflation:

- Emergence of EFT
- Tunneling Events (Bubble nucleation)

Additionally, such a model has the potential to break rotational symmetry, possibly giving rise to large scale signatures in the CMB.

(Nadia Bolis, Andreas Albrecht, R. Holman, JCAP 161 (2016) 011)

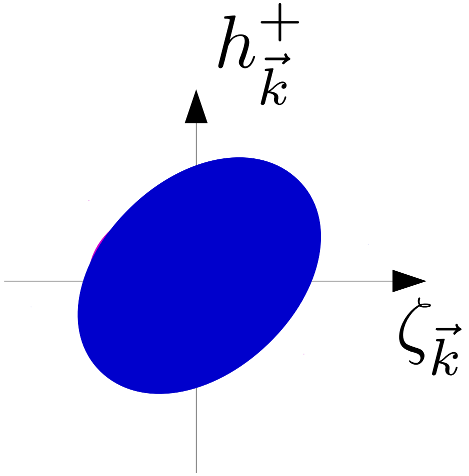


Entangled Initial State Model: Schrödinger Functional Approach

Just as with the case of the BD state, we can express this entangled state as a product of Gaussians

$$\Psi\left[\{\zeta_{\vec{k}}\},\{h^{+}_{\vec{k}}\},\{h^{\times}_{\vec{k}}\},\tau\right]=\prod_{\vec{k}}\psi_{\vec{k}}\left[\zeta_{\vec{k}},h^{+}_{\vec{k}},h^{\times}_{\vec{k}},\tau\right]$$

$$\psi_{\vec{k}}\left[\zeta_{\vec{k}},h^{+}_{\vec{k}},h^{\times}_{\vec{k}},\tau\right]=\sqrt{(N_k(\tau))}exp\Big[-\frac{1}{2}\Big(A_k(\tau)\zeta_{\vec{k}}\zeta_{-\vec{k}} + \sum_{i,j=+,\times}B_{k;i,j}h^{i}_{\vec{k}}h^{j}_{-\vec{k}}. + \sum_{i=+,\times}C_{k;i}(h^{i}_{\vec{k}}\zeta_{-\vec{k}}+h^{j}_{-\vec{k}}\zeta_{\vec{k}})\Big)\Big]$$



Entangled Initial State Model: Entanglement Parameters

With this formalism we have added four new complex parameters (per mode) to the initial state:

- b_1
- b_3
- C_+
- C_x

Since the matrix **B** is symmetric, we have b_2=0

$$\psi_{\vec{k}}\left[\zeta_{\vec{k}}, h^{+}_{\vec{k}}, h^{\times}_{\vec{k}}, \tau\right] = \sqrt{(}N_k(\tau))exp\Big[-\frac{1}{2}\Big(A_k(\tau)\zeta_{\vec{k}}\zeta_{-\vec{k}} + \sum_{i,j=+,\times} B_{k;i,j}(\tau)h^{i}_{\vec{k}}h^{j}_{-\vec{k}}. + \sum_{i=+,\times} C_{k;i}(\tau)(h^{i}_{\vec{k}}\zeta_{-\vec{k}} + h^{j}_{-\vec{k}}\zeta_{\vec{k}})\Big)\Big]$$

$$\mathrm{B}_k = b_{0k}\mathbf{I_{2x2}} + b_{1k}\sigma_{\mathbf{x}} + b_{3k}\sigma_{\mathbf{z}}$$

The Bunch-Davies State: Constraints on Deviations

Measured constraints on the initial state (under the assumption of single field slow roll):

- Non-Gaussianity f_{NL}

$$f_{NL} = 2.5 \pm 5.7$$

- Number of e-foldings

$$N \sim 60$$

- Tensor/scalar ratio r

$$r < 0.072$$

Entangled Initial State Model: Normalization Conditions

Our state for each mode is Gaussian with inverse covariance Re(**M**):

For this state to be normalizable, all three eigenvalues of Re(**M**) must be positive.

This then gives us the following conditions (in addition to the standard BD conditions for A and b_0):

$$\mathrm{M}= \begin{bmatrix} \boldsymbol{A} & \boldsymbol{C_+} & \boldsymbol{C_\times} \\ \boldsymbol{C_+} & \boldsymbol{b_0+b_3} & \boldsymbol{b_1} \\ \boldsymbol{C_\times} & \boldsymbol{b_1} & \boldsymbol{b_0-b_3} \end{bmatrix}$$

$$\begin{aligned} Det(Re(M)) = {} & Re(A)(Re(b_0)^2 - Re(b_1)^2 Re(b_3)^2) \\ & - Re(C_\times)^2(Re(b_0)+Re(b_3)) \\ & - Re(C_+)^2(Re(b_0)-Re(b_3)) \\ & + 2Re(C_+)Re(C_\times)Re(b_1) > 0 \end{aligned}$$

$$\begin{aligned} Re(C_+)^2 + Re(C_\times)^2 - Re(A)Tr(Re(B)) \\ - Det(Re(B)) < 0 \end{aligned}$$

Entangled Initial State Model: Asymmetric Tensor Perturbations

- Standard BD treatment: $P^{xx}(k)=P^{++}(k)$.
- Entangled model: these power spectra can be different!
- This leads to unusual behavior of the angular CMB spectrum:
- Note that for the standard model there is no even/odd alteration, so this reduces to the standard result.

$$\mathrm{C}_\ell^{XX'} = 4\pi \int \frac{\mathrm{d}k}{k}\Big[\Delta^X_{\ell,0}(k)\Delta^{X'}_{\ell,0}(k)P^{00}(k) + \Delta^X_{\ell,2}(k)\Delta^{X'}_{\ell,2}(k)\Big(P^{++}(k)(1+(-1)^\ell) + P^{xx}(k)(1-(-1)^\ell)\Big)\Big].$$

$$XX' \in \{TT, TE, EE\}$$

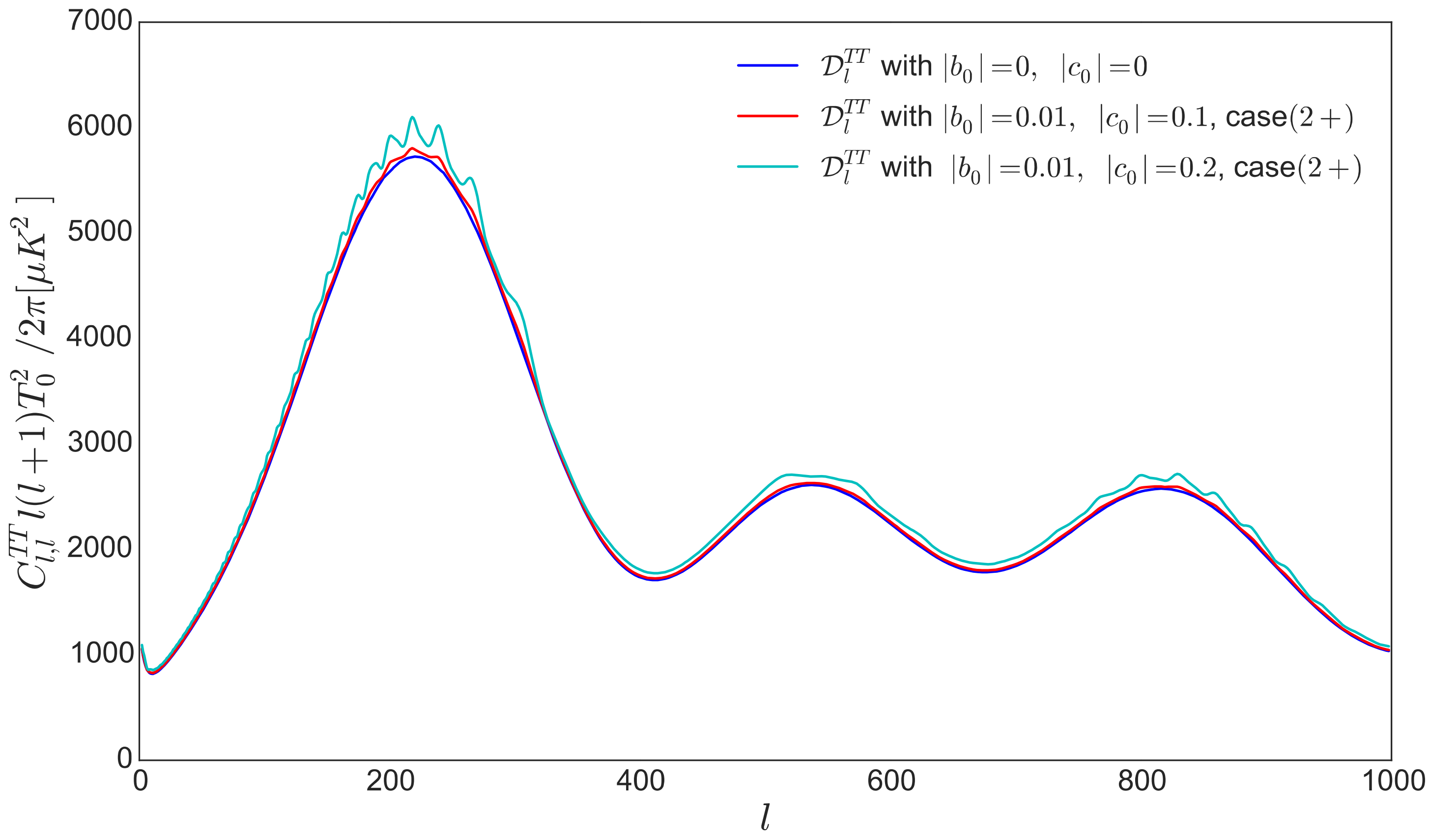
$$\mathrm{C}_\ell^{BB} = 4\pi \int \frac{\mathrm{d}k}{k}\Big[\Delta^B_{\ell,0}(k)\Delta^B_{\ell,0}(k)P^{00}(k) + \Delta^B_{\ell,2}(k)\Delta^B_{\ell,2}(k)\Big(P^{++}(k)(1-(-1)^\ell) + P^{xx}(k)(1+(-1)^\ell)\Big)\Big].$$

Entangled Initial State Model: Effect on CMB

Generic Predictions:

- Additional oscillations
- Slightly enhanced power

(Nadia Bolis, Andreas Albrecht, R. Holman, JCAP 1612 (2016) 011)



Our Approach

We are analyzing this model in the context of the data from the Planck Collaboration.

In particular, we are working with their un-binned CMB temperature and polarization likelihood code.

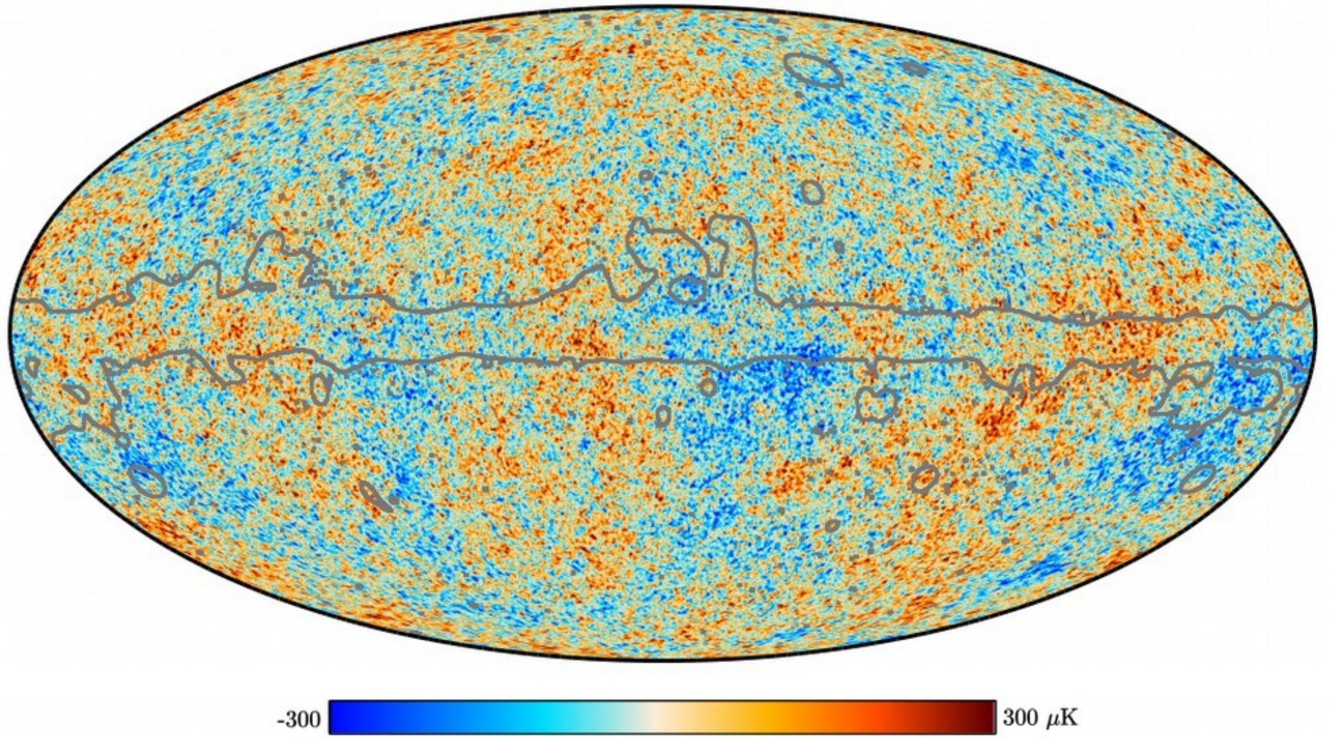


Image credit: ESA/Planck Collaboration

Our Approach

For this investigation, we are working with a modified version of CLASS: Cosmic Linear Anisotropy Solving System
(Diego Blas, Julien Lesgourgues, and Thomas Tram, JCAP 2011, July 2011)

Modified to compute the power spectrum for the entangled case, with the background evolution given by the Hubble slow roll parameters, as well as to compute the spectra without symmetry between the + and x tensor polarizations.

Our Approach: Status and Goals

Current Status:

- Code modification completed, but I believe there is some error that is stopping the oscillations from appearing.

Upcoming work:

- Perform parameter estimation and evidence integrations comparing the BD and entangled initial states, allowing a varying inflationary background

Wrap-up

- Inflationary Basics
- Bunch-Davies State
- Model for Entangled Initial States
- Our Approach

Questions?

Thank You!