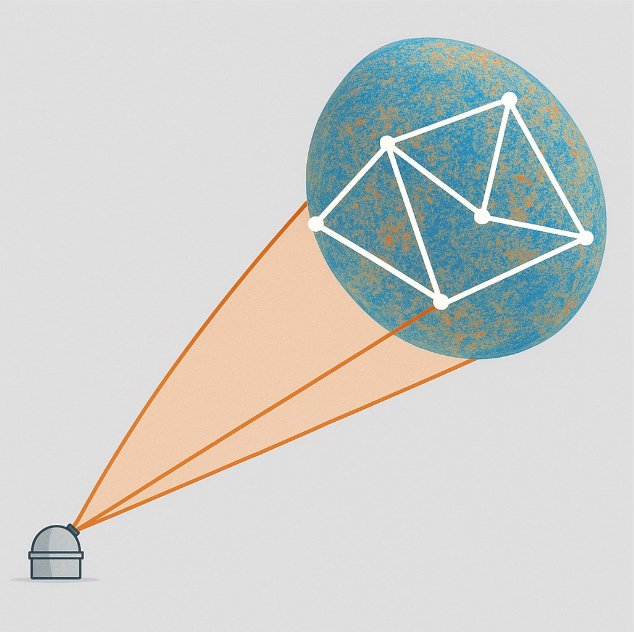
Soft Gravitons during inflation



Kshitij Gupta
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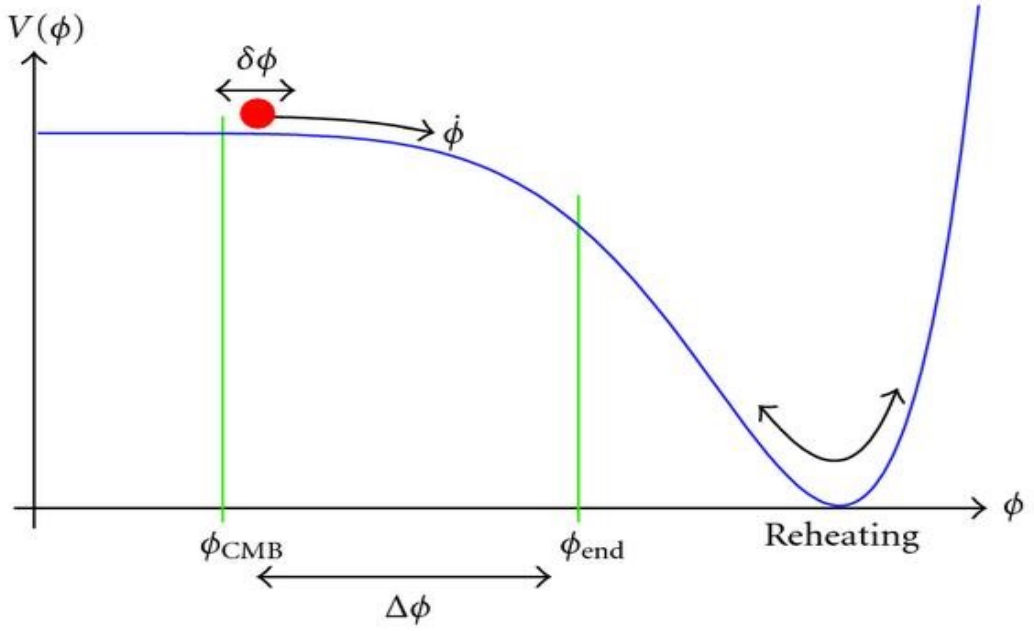
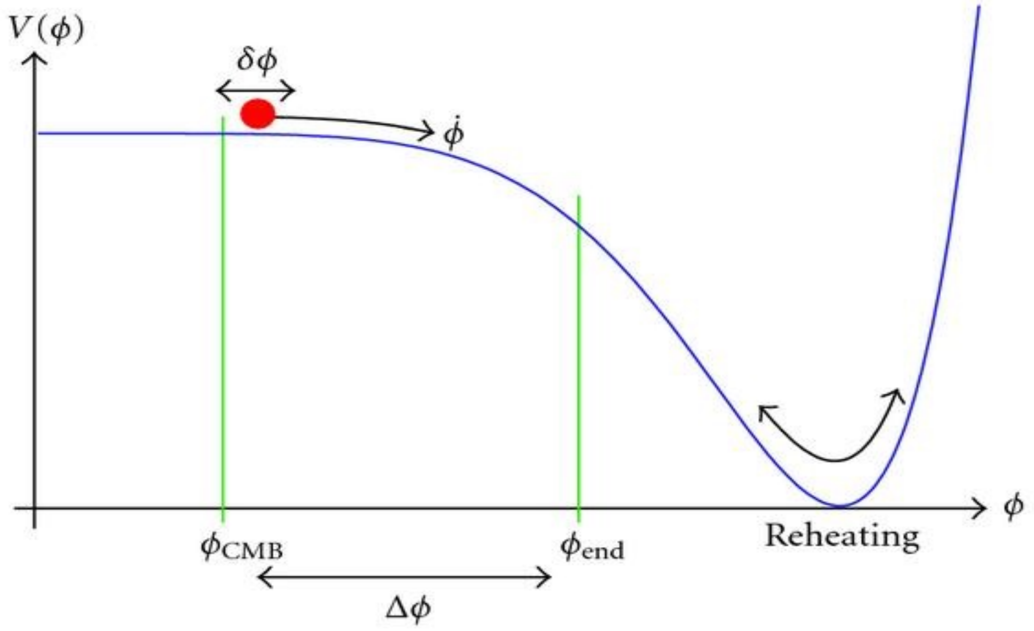
Review of inflationary perturbations

- We have this classic picture of inflation – a ball rolling down the hill



Review of inflationary perturbations

- The slow rolling of the field describes the quasi de Sitter expansion of the Universe



Review of inflationary perturbations

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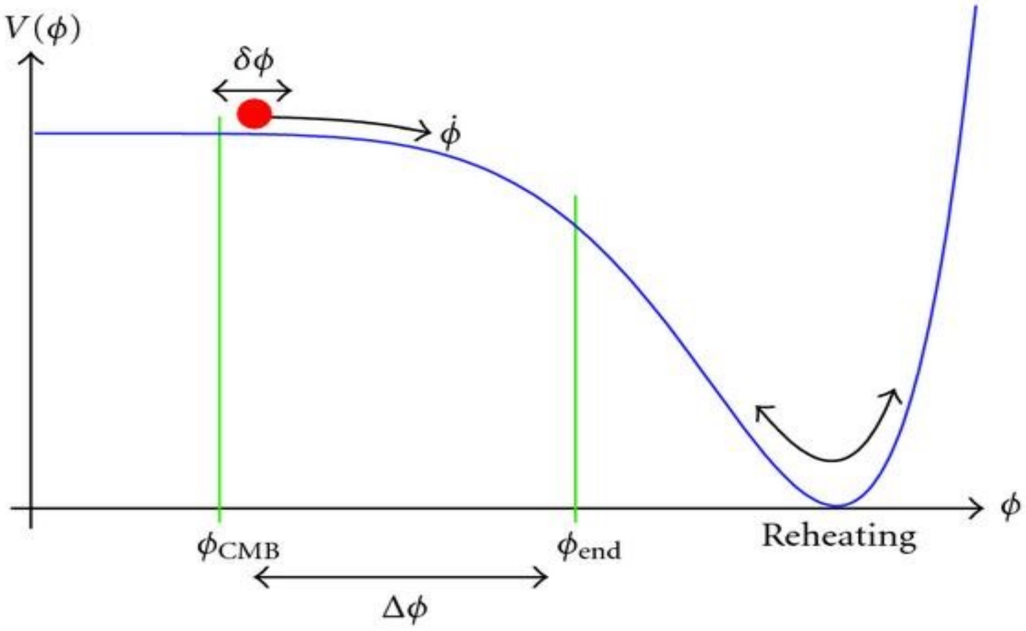
$$g_{ij} = a^2(t)\delta_{ij}$$
$$a(t) = e^{Ht}$$



Broken symmetry

- During slow roll, we have that $\dot{\phi}$ approximately constant, and hence

$\phi =$ 

- Due to presence of the clock, we have that time translations are broken spontaneously.

- This is the starting point behind the EFT of Inflation.

Cheung et al. (2007)

EFT of Inflation

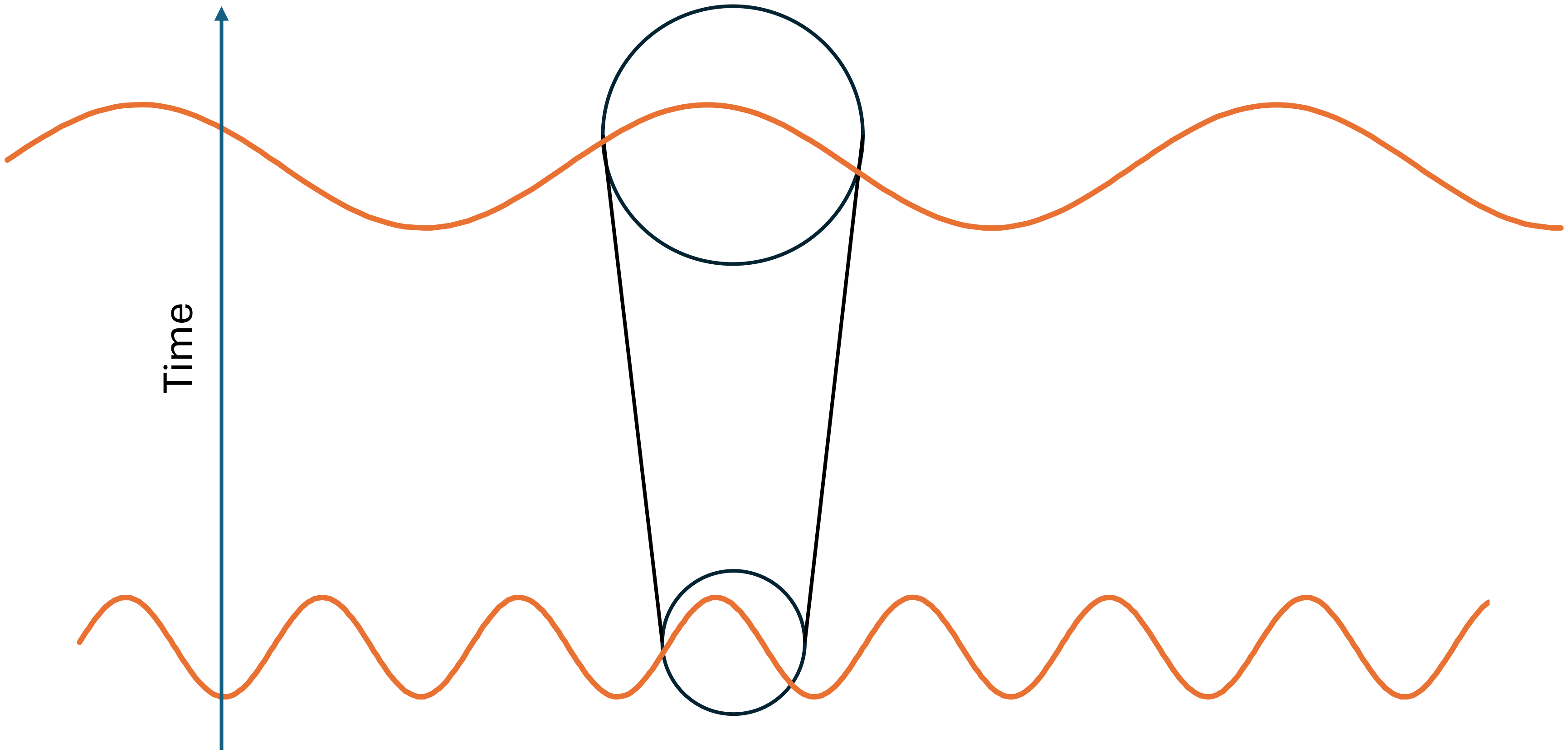
- EFT of Inflation describes the fluctuations of a spontaneously broken time translation symmetry on a background de Sitter

- We construct it in analogy to SSB of gauge theories, and it shares common features.

- At high energies, we expect the Goldstone boson to decouple from the gauge boson (gravity) Green, Huang, **KG** (2023)

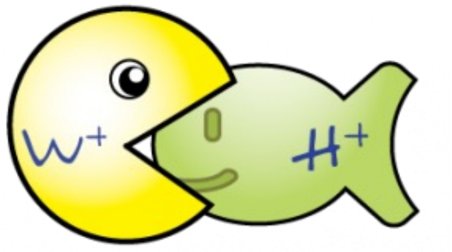
Modes redshift

- We are usually interested in properties of soft fluctuations, because expansion continuously redshifts modes.



Low Energies = Unitary gauge

- At low energies, gauge fields eats the Goldstone to become a massive gauge boson



- Similarly, we want to describe the fluctuations in a gauge where gravity has eaten the Goldstone boson:

$$g_{ij} = a^2(t)e^{2\zeta(x,t)}\delta_{ij}$$

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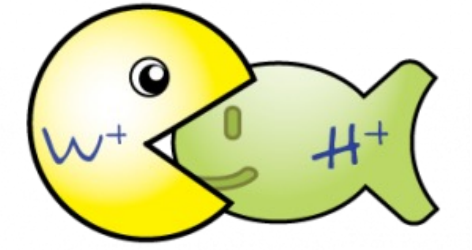

- Similarly, we want to describe the fluctuations in a gauge where gravity has eaten the Goldstone boson:

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Note that we are suppressing the transverse modes!

Symmetries of ζ

- The advantage of ζ is that it is completely fixed by its symmetries (dilation and SCTs), which it realizes non-linearly

$$\zeta(x) \to \zeta(xe^{\lambda}) - \lambda$$

- By using Ward identities, it satisfies soft theorems. The most useful one relates the 3 point functions to the 2 point functions,

$$\lim_{k_1\to 0}\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle = -(2\pi)^3\delta^3(\sum_i \vec{k}_i)P_{k_1}P_{k_3}\frac{d\log k_3^3 P_{k_3}}{d\log k_3}\ , \quad \langle \zeta_{\vec{k}_i}\zeta_{\vec{k}_j}\rangle = (2\pi)^3\delta^3(\vec{k}_i+\vec{k}_j)P_{k_i}$$

Maldacena (2002)

Are symmetries protected?

- The symmetries are equivalent to requiring that ζ is massless to all orders. The important question is :

Do Symmetries
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Do Symmetries Hold with Loops?

Senatore and Zaldarriaga (2009)

⋮

Kahaya et al. (2010)

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Diagrammatic Arguments

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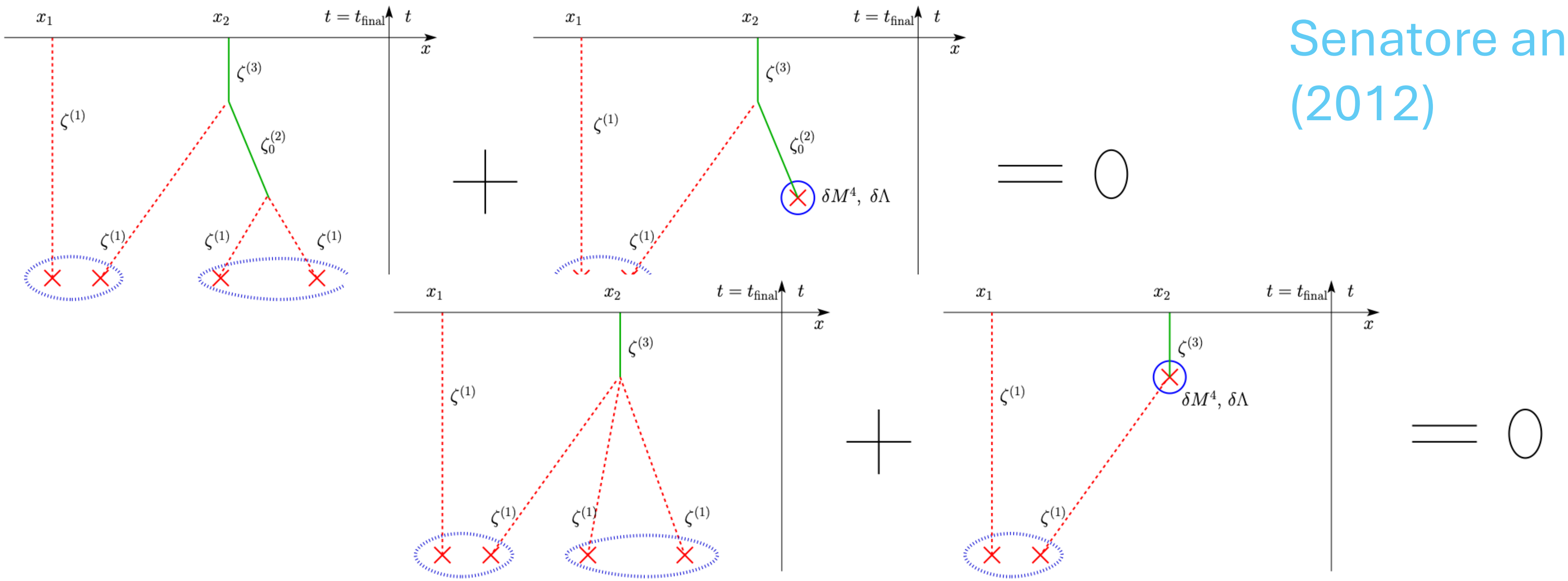

Senatore and Zaldarriaga (2012)

Why the issue?

- Two main issues – didn’t have a better technical understanding of the soft structure of de Sitter theory.

- Also, calculating loops in de Sitter has been plagued with different choices of regulators, which muddles up the the situation more

Soft de Sitter EFT

- I have worked on understanding the soft structure of inflation from an EFT approach, using Soft de Sitter EFT. Cohen and Green (2020)

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- From power counting and symmetries, we can write down the action and analyze the soft structure directly.

- We can also regulate loops unambiguously in the EFT in a dim reg manner

What we get?

- We can use RG analysis without complicated diagrammatics to show that to all orders the symmetries of ζ are preserved.

- We can prove that the transverse tensor modes are also massless.

- We can also verify that in the presence of additional heavy spectator fields, our results still hold.

Green and **KG** (2024)

Conclusion

- de Sitter has been plagued with issues and constant disagreements over IR behavior of fields, primarily due to lack of an organizing principle.
- Using Soft de Sitter EFT, we can unify a variety of different methods that reached the same answer in a clean framework.
- These tools will help us give deeper insights into further IR problems of de Sitter (eternal inflation, tails of distribution etc.)