# Transient Cosmological Quasiparticles

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Based on 2405.XXXX with Jay Hubisz, Seung Lee, Bharath Sambasivam

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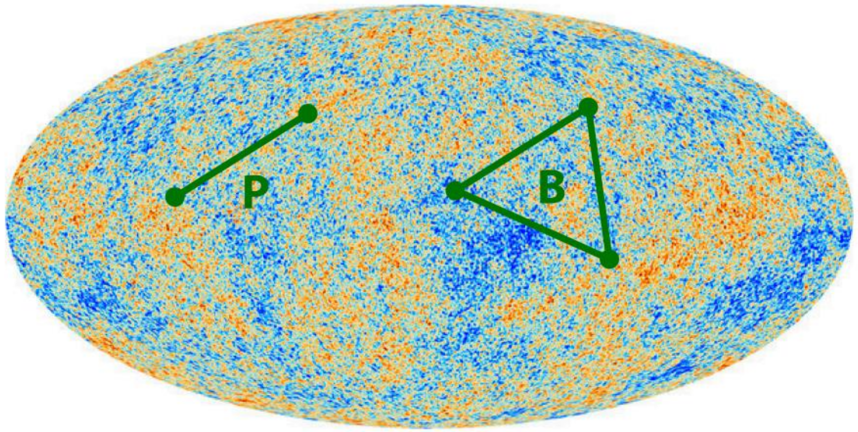
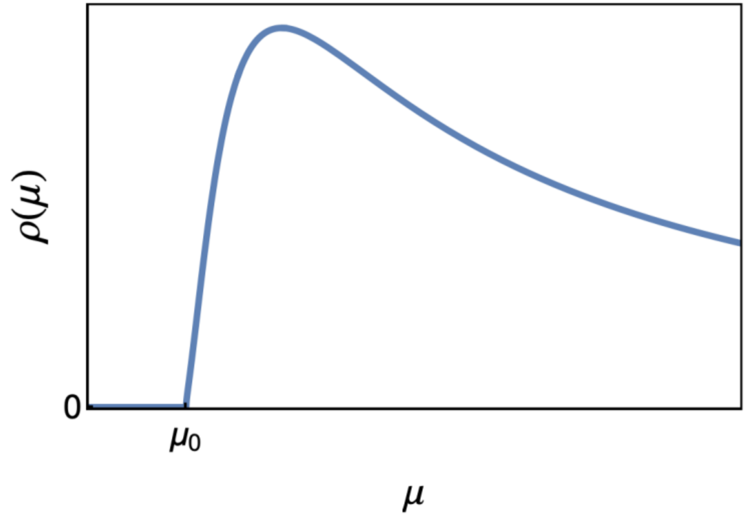
# Elevator Pitch

The spectrum of a scalar operator in a large N CFT in an inflationary background is characterized by a gapped continuum, with the gap set by the Hubble rate of inflation.

In this work, we investigate the non-Gaussian signatures in the CMB bispectrum caused by the interaction of such an operator with the inflaton using Holographic principles.



# Holography

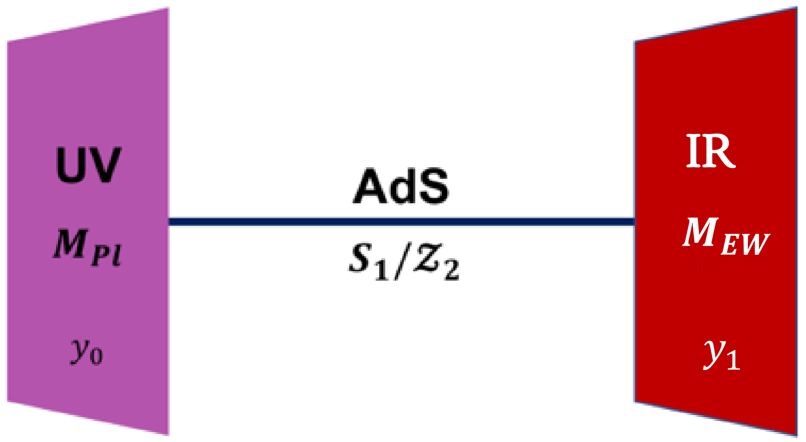
**Hierarchy problem:** Large hierarchy of scales in the standard model ($M_{EW} \sim 10^3 GeV$, $M_{Pl} \sim 10^{19} GeV$); Smallness of Higgs mass ($126\ GeV$)

- Randall-Sundrum models- Elegant geometric solution

$$ds^2 = e^{-2A(y)} dx_4^2 - dy^2$$

- $A(y) = ky \equiv$ pure AdS; $k$ is the inverse-curvature
- **Goldberger-Wise**: Size of extra dimension stabilized by scalar gaining a $\langle \phi \rangle (y)$, deforming AdS geometry
- Spectrum- discrete tower of KK modes with $m \sim f$

Spontaneously broken CFT on boundary

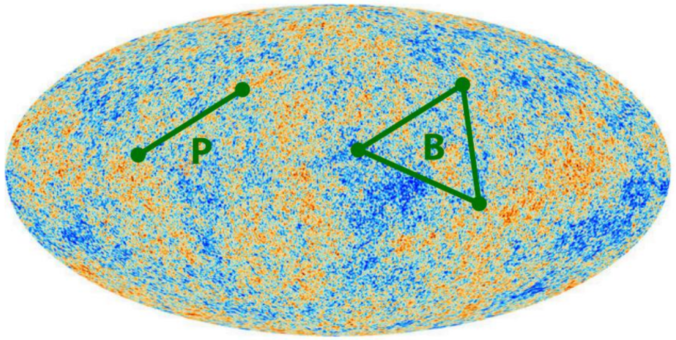


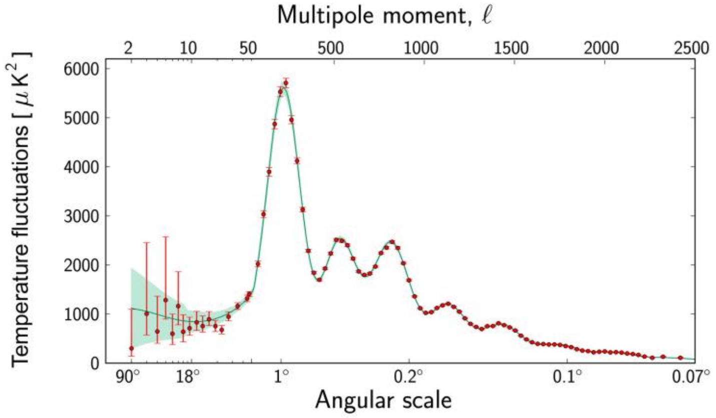
# Inflation

Epoch of dark energy domination leading to exponential expansion of the universe for $\sim 60$ efolds

- Inflation solves the flatness, homogenous & isotropy problems,
  - Curvature and inhomogeneities get stretched away
  - Quantum fluctuations of $(\phi, \sigma, \cdots)$ get stretched, imprinted on superhorizon scales, and reenter horizon to seed fluctuations of CMB and large scale structure formation
- Fluctuations are primordial, approximately scale-invariant, and Gaussian

Non-Gaussianities and beyond the power spectrum?

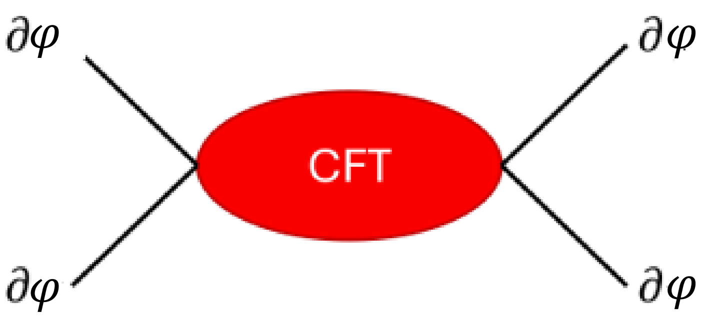


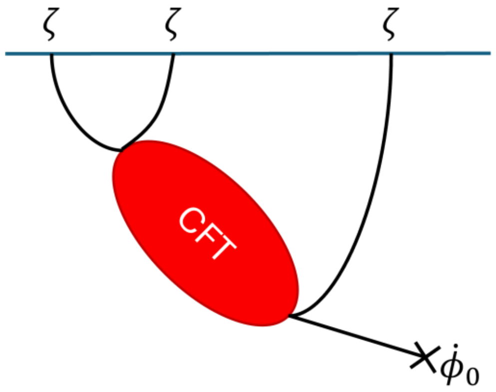



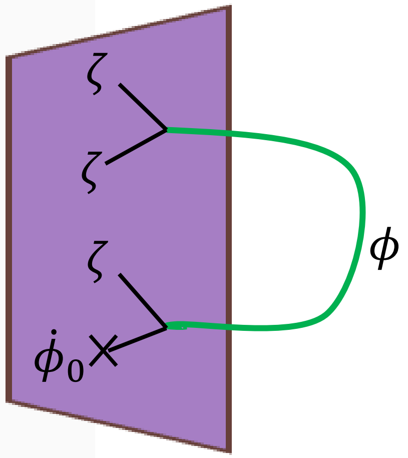

$n_s = 0.9649 \pm 0.0042$

$\Delta T / T \sim 10^{-5}$

# Our Model of Inflation and Spectral Density




$\zeta$: Inflaton on the brane
$\phi$: Bulk scalar field
$\dot{\phi}_0$: background field

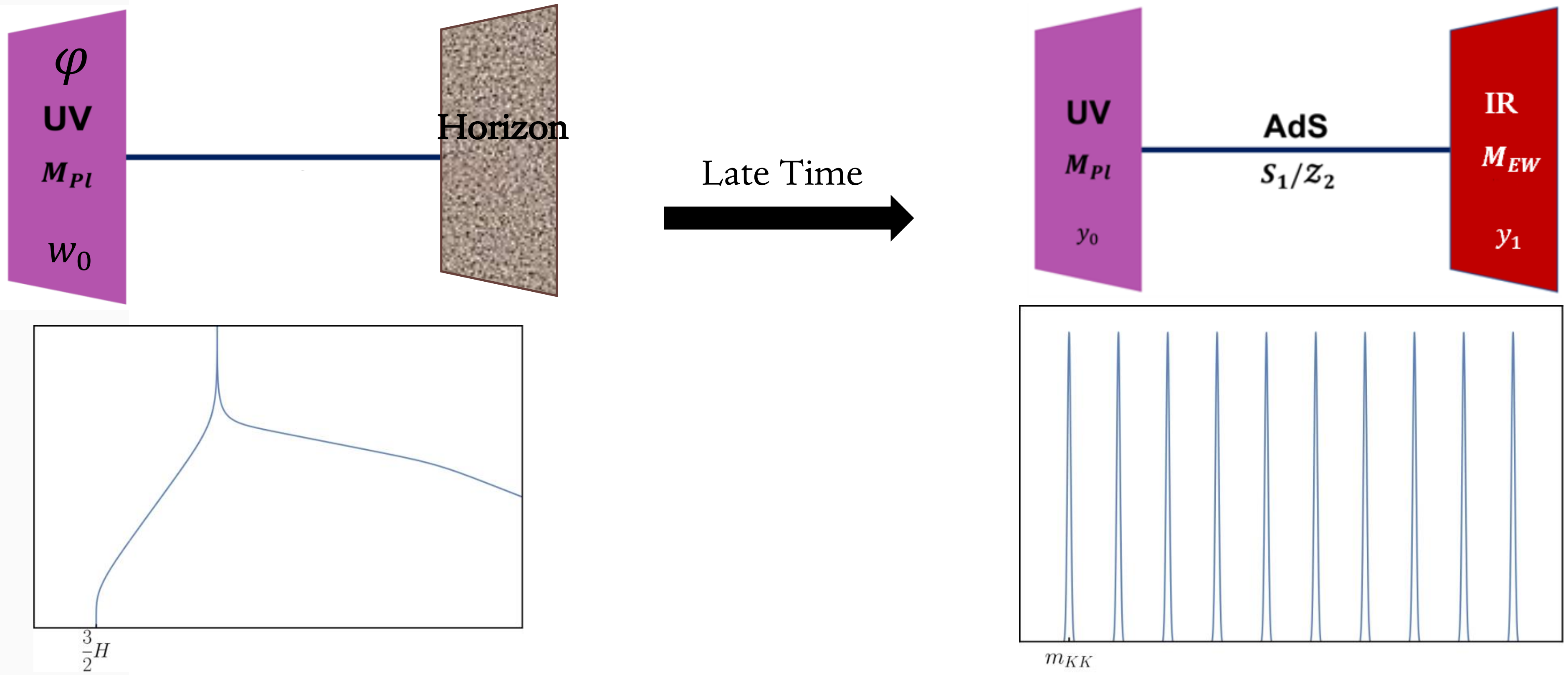
m: Bulk scalar mass
$\nu = \sqrt{4 + m^2}$: Eff mass of bulk scalar
$m_0$: Brane mass

$$\mathcal{L}_{4D} = \mathcal{L}_{inf} + \mathcal{L}_{CFT} + \sum_{i,j} g_{i,j} \mathcal{O}^i_{inf} \mathcal{O}^j_{CFT}$$

Coupling term: $\lambda\phi(\nabla\zeta)^2$

# Our Model of Inflation and Spectral Density

$$ds^2 = e^{-2A(w)}(dt^2 - e^{2Ht}dx^2 - dw^2) \qquad e^{-A(w)} = \frac{H}{k \sinh Hw}$$

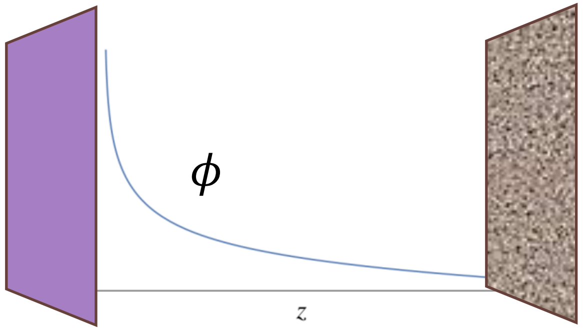



~~CFT~~

Note: the gap is not robust. Coupling with curvature $\xi R\phi^2$ can shift it to H$\sqrt{\frac{9}{4} + 12\xi}$

# UV / IR localized light mode

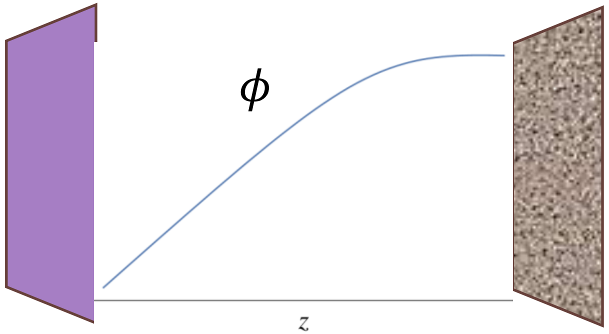
Light mode: discrete mode below the gap




$\nu > 1$, UV localized, exist when H=0

$$\mu^2 = (\nu - 1)\left(m_0^2 - 2(2-\nu)\right) + 2(2-\nu)H^2 + \mathcal{O}(H^4)$$

- Tune brane mass $m_0^2 \approx 2(2-\nu)$
- CFT language: Fundamental bound state in the spectrum mixing with the CFT states; CFT deformation by $H$ backreacts to modify the mass of the particle eigenstate



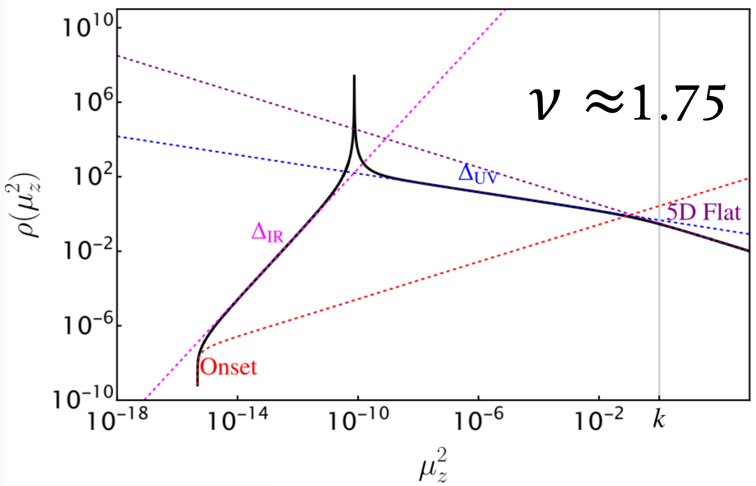

$\nu < 1$, IR localized, not exist when H=0

$$\mu^2 \equiv \text{UV}_{\text{mistune}} + \text{IR piece (H)}$$

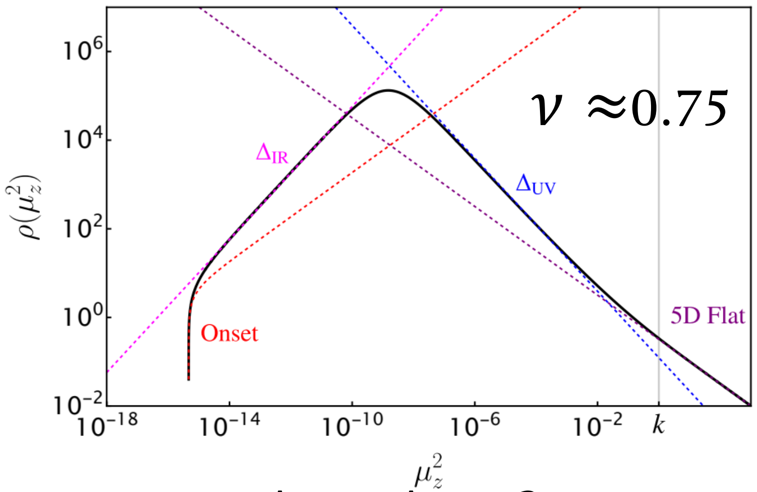
- Analogous to the horizon localized solutions in Schwarzchild geometries for light scalar fields
- CFT language: Mostly composite modes of the near-conformal dynamics. They only exist during the inflationary epoch

# Anatomy of Spectral density and Scaling dimension

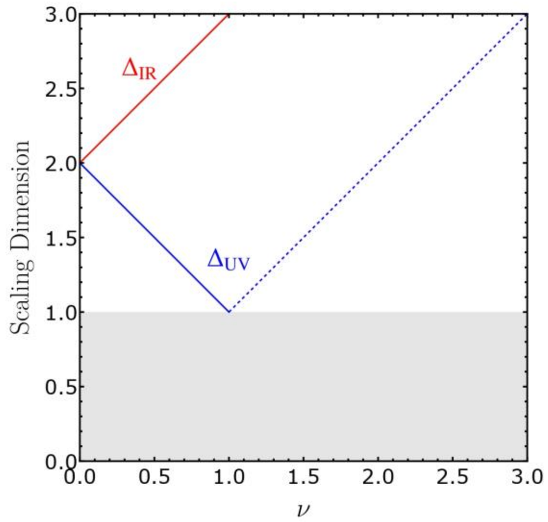
$$\rho(\mu^2) = C(\nu,H)\delta(\mu^2-\mu_*^2) + \rho_c(\nu,m_0,\mu^2,H)\Theta\left(\mu^2-\frac{9}{4}H^2\right)$$




$$\Delta_{IR} = \Delta_+ = 2+\nu$$
$$\Delta_{UV} = 2-\Delta_- = \nu$$




$$\Delta_{IR} = \Delta_+ = 2+\nu$$
$$\Delta_{UV} = \Delta_- = 2-\nu$$



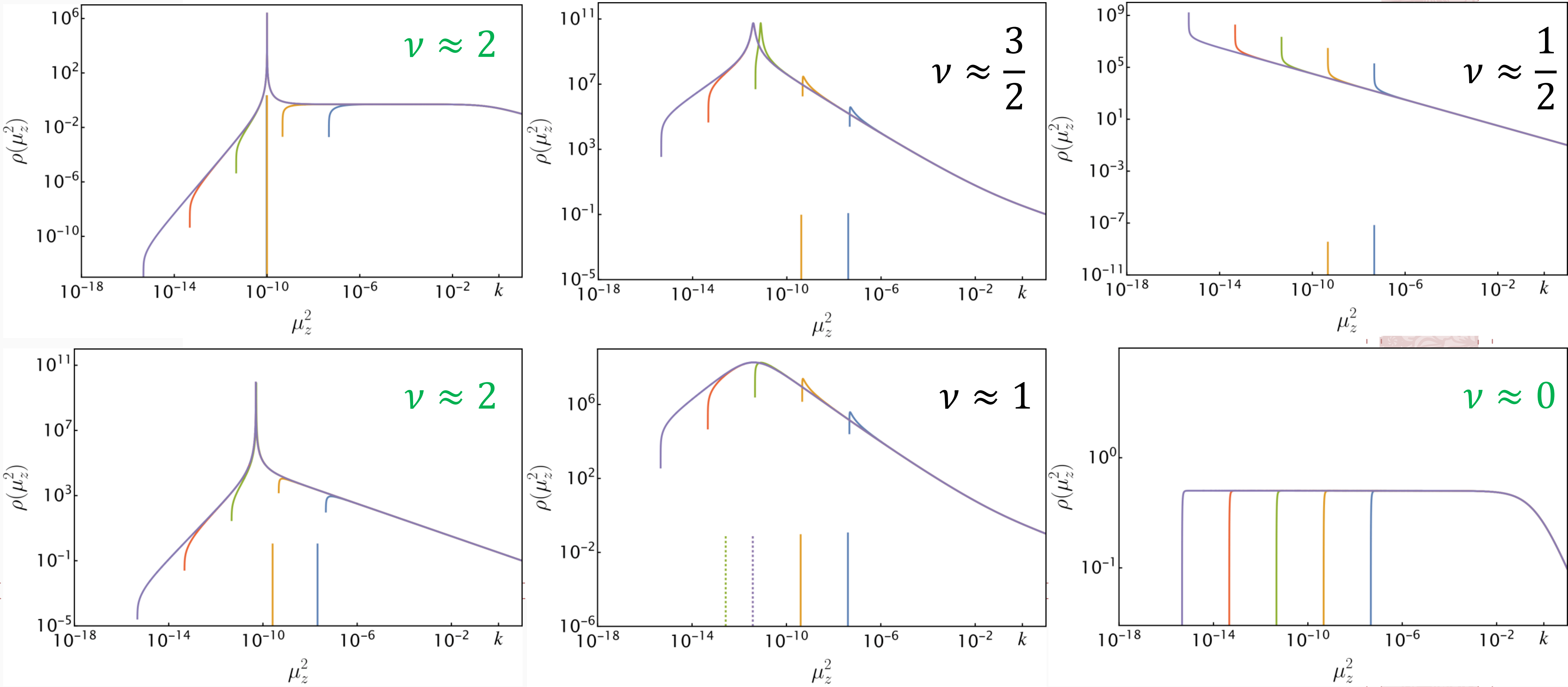

Solutions of 5D scalar equation yield two scaling dimensions:

$$\Delta_\pm = 2\pm\nu = 2\pm\sqrt{4+m^2}$$

We have identified a new UV scaling dimension $\Delta_{UV} = 2-\Delta_-$ when $\nu > 1$

# Spectral Density Plots

$10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$

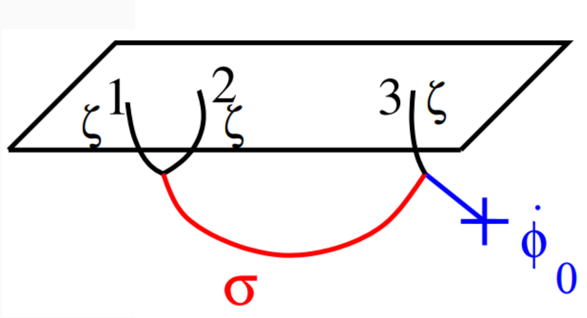


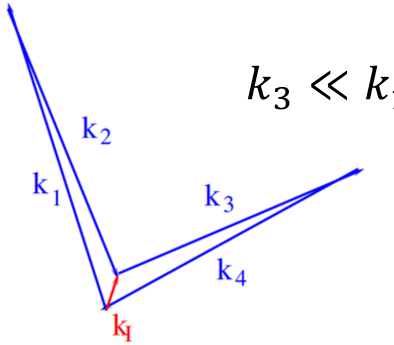
# Cosmological Collider Physics

Higher energy physics ➡ Higher energy collider ➡ Higher cost of money

What about nature's cosmological collider?

Primordial quantum fluctuations(fields interact with inflatons) ➡ Non-Gaussianity from CMB bispectrum(fnl)

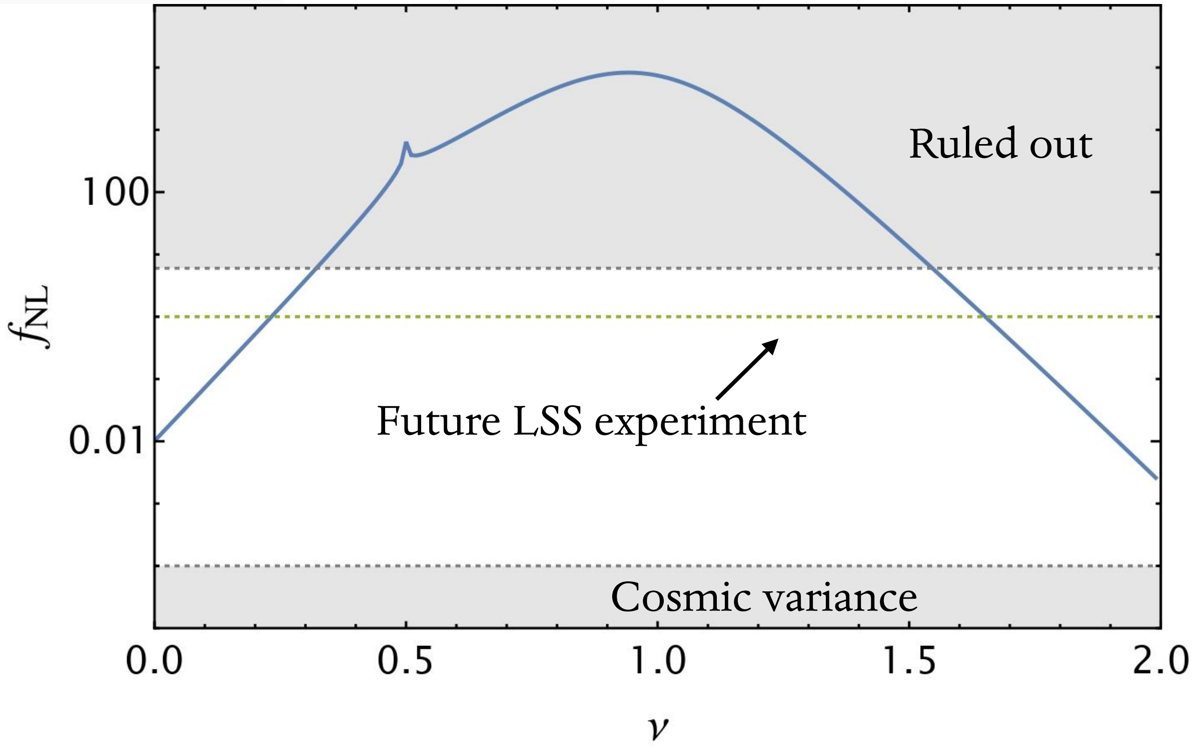


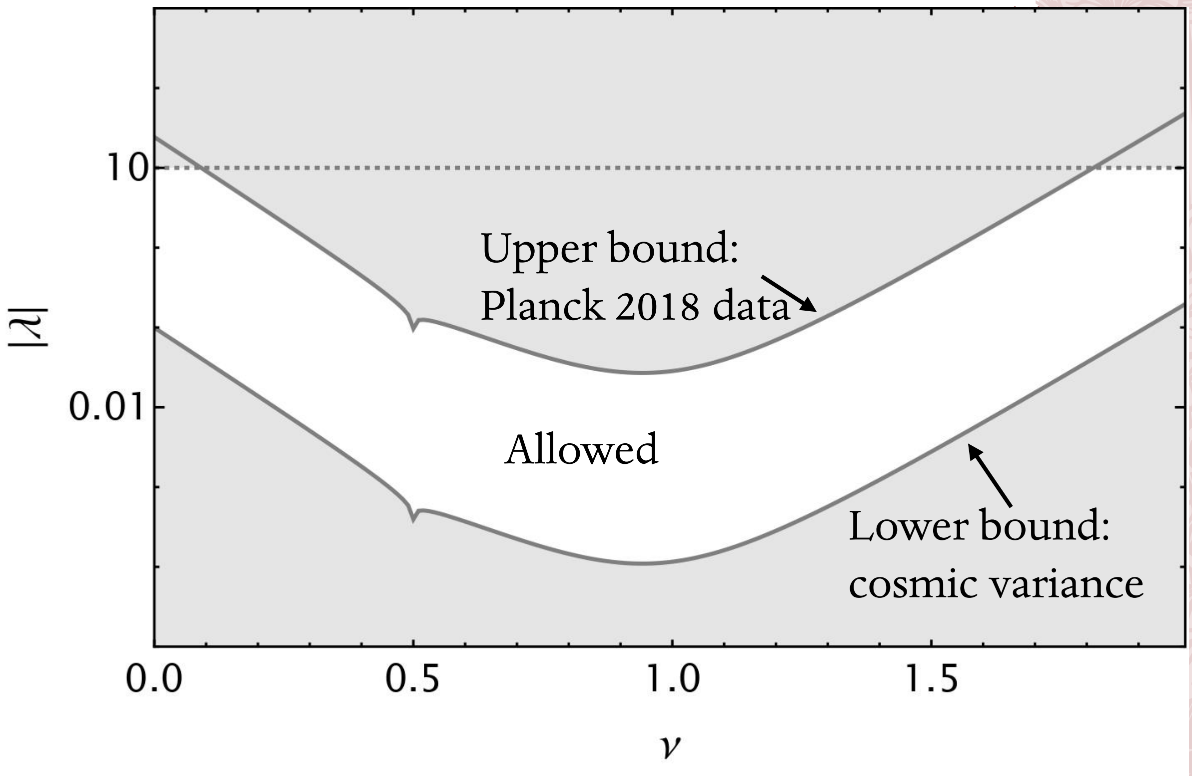




$k_3 \ll k_1$: squeezed limit

$$f_{NL} = \frac{5}{3}\left(\frac{\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle}{4\langle \zeta_{\vec{k}_1}\zeta_{-\vec{k}_1}\rangle\langle \zeta_{\vec{k}_3}\zeta_{-\vec{k}_3}\rangle}\right)_{k_3\to 0} = -\frac{\epsilon M_{Pl}^2\lambda^2}{4\sqrt{\pi}}\frac{\pi^2}{\cosh^2\pi\gamma}\left(\frac{k_3}{k_1}\right)^{\frac{3}{2}} \times \left[A(\gamma)\left(\frac{k_3}{4k_1}\right)^{-i\gamma} + A^*(\gamma)\left(\frac{k_3}{4k_1}\right)^{i\gamma}\right]$$

# Results of non-Gaussianity




$\lambda$=1 (in unit of k, the AdS curvature )
H=10^13 GeV
$\frac{k_3}{k_1} = 0.1$

Coupling term: $\lambda\phi(\nabla\zeta)^2$

Shaded area: Ruled out
Blank: Allowed according to current experiments

# Conclusions and Outlook

- We considered a simple model of inflation in a holographic setup and found the spectrum of a scalar operator in the large N CFT- a gapped continuum
- We find a UV localized light mode when the UV boundary conditions are somewhat tuned
- We also find a normalizable transient cosmological IR localized light mode when $\nu < 1$ localized, that tracks the gap of the spectral density without fine-tuning
- We find a novel scaling dimension in the UV when $\nu > 1$ – Need more work to understand better
- The continuum seems to generate non-Gaussian features that are detectable in future cosmological experiments!
- An extra coupling term $\xi R \phi^2$ of curvature and scalar field can shift the gap

# Thank You!

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# Scalar spectrum

$$ds^2 = \frac{1}{(kz)^2}\left[a^2(\eta)dx_4^2 - \frac{dz^2}{G^2(z)}\right] \qquad a(\eta) = -\frac{1}{H\eta} \qquad G(z) = \sqrt{1+H^2z^2}$$

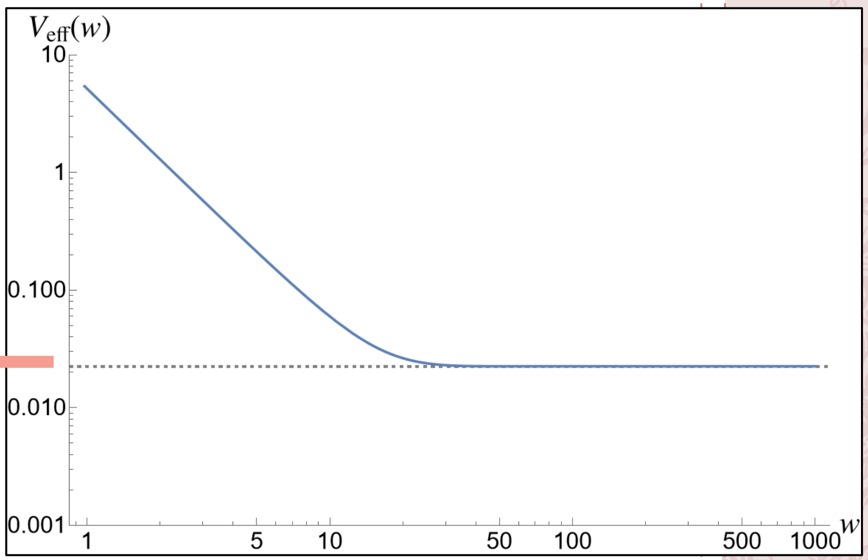
- Scalar EOM in Schrodinger form is

$$-\phi'' + \left[m^2e^{-2A} + \frac{9}{4}A'^2 - \frac{3}{2}A''\right]\phi = -\Box_{dS}\phi \equiv \mu^2\phi$$

- Asymptotics of the effective potential determines the type of spectrum

$$\lim_{w\to\infty} V_{eff}(w) = \frac{9}{4}H^2$$

Gapped continuum!




- After variable separation the solutions are

$$\sigma = \sqrt{\eta}H_\gamma^{(1,2)}(|k\eta|)$$

Only $H_\gamma^{(1)}$ satisfies Bunch-Davies

$$f_\pm = z^{2\pm\nu}2F1\left[\frac{1}{4} - \frac{\gamma}{2} \pm \frac{\nu}{2}, \frac{1}{4} + \frac{\gamma}{2} \pm \frac{\nu}{2}, 1\pm\nu, -H^2z^2\right]$$

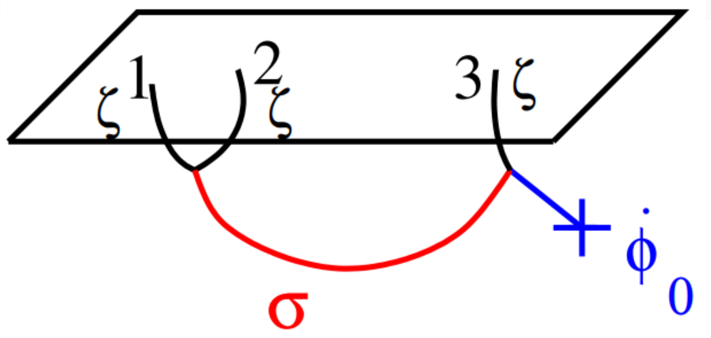
$$f = N(f_+ + \alpha f_-)$$

- BC: $\left(\frac{f'}{f}\right)_{UV} = \frac{1}{2(kz)G}m_0^2$ , regularity at the horizon

$$\gamma = \sqrt{\frac{9}{4} - \left(\frac{\mu^2}{H^2}\right)} \qquad \nu = \sqrt{4+m^2}$$

# Bispectrum

Goal: To find the bispectrum due to an interaction of the inflaton and a massive scalar field of the form $\lambda\int(\nabla\phi)^2\sigma$



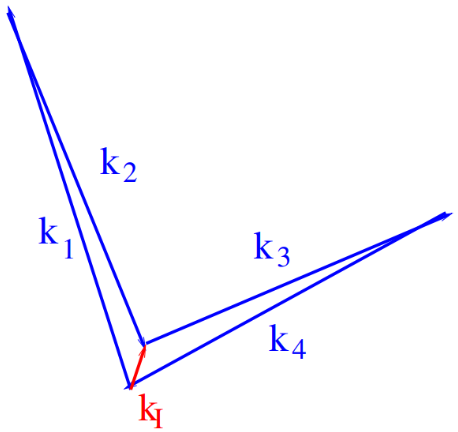

- Currently, let us focus on the non-local contributions in position space, i.e., terms that are non-analytic in $k$

$$\left\langle \phi_{\vec{k}}(\eta)\phi_{-\vec{k}}(\eta')\right\rangle \supset \frac{(\eta\eta')^{\frac{3}{2}}}{4\pi}\left[\Gamma(-i\gamma)^2\left(\frac{k^2\eta\eta'}{4}\right)^{i\gamma}+\Gamma(i\gamma)^2\left(\frac{k^2\eta\eta'}{4}\right)^{-i\gamma}\right]$$

- To find the bispectrum, we find the 4-point correlator and set one of the legs to the background

$$\left\langle \phi_{\vec{k}_1}(\eta_0)\cdots\phi_{\vec{k}_4}(\eta_0)\right\rangle \supset \frac{\eta_0^4 2^2\lambda^2}{16k_1k_2k_3k_4}(I_{++}+I_{+-}+I_{-+}+I_{--})$$

$$I_{\pm\pm} = (\pm i)(\pm i)\int_{-\infty}^{0}\frac{d\eta}{\eta^2}e^{\pm ik_{12}\eta}\int_{-\infty}^{0}\frac{d\eta'}{\eta'^2}e^{\pm ik_{34}\eta'}\left\langle\sigma_{\vec{k}_I}(\eta)\sigma_{-\vec{k}_I}(\eta')\right\rangle_{\pm\pm}$$




- Fluctuations of the inflaton $\phi(t,x)=\phi_0(t)+\xi(t,x)$ can be related to the curvature fluctuation

$$\zeta = -\frac{H}{\dot{\phi}_0}\xi$$

$$f_{NL} = \frac{5}{3}\left(\frac{\left\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\right\rangle}{4\left\langle\zeta_{\vec{k}_1}\zeta_{-\vec{k}_1}\right\rangle\left\langle\zeta_{\vec{k}_3}\zeta_{-\vec{k}_3}\right\rangle}\right)_{k_3\to 0} = -\frac{\epsilon M_{Pl}^2\lambda^2}{4\sqrt{\pi}}\frac{\pi^2}{\cosh^2\pi\gamma}\left(\frac{k_3}{k_1}\right)^{\frac{3}{2}}\times\left[A(\gamma)\left(\frac{k_3}{4k_1}\right)^{-i\gamma}+A^*(\gamma)\left(\frac{k_3}{4k_1}\right)^{i\gamma}\right]$$

# In-In Formalism- Review

- In particle physics, the main observable is the S-matrix
$$\langle out|S|in\rangle = \langle out(+\infty)|in(-\infty)\rangle$$
- Asymptotic states are vacuum states of the free Hamiltonian $H_0$
- In cosmology, we want to find n-point correlations of operators at the same time.
- There are only initial conditions when $\lambda \ll \frac{1}{H}$ (Bunch-Davies)
$$\langle Q(\tau)\rangle = \langle in|Q(\tau)|in\rangle$$
- Work in the interaction picture to evolve $Q(\tau)$ back to $\tau_i$
$$\langle Q(\tau)\rangle = \left\langle 0 \left| \bar{T} e^{i\int_{-\infty(1-i\epsilon)}^{\tau} H_{int}^I(\tau')d\tau'} Q^I(\tau) T e^{-i\int_{-\infty(1+i\epsilon)}^{\tau} H_{int}^I(\tau'')d\tau''} \right| 0 \right\rangle$$
- Expand the exponentials to compute correlation function perturbatively in $H_{int}^I$
$$\langle Q(\tau)\rangle = -i\int_{-\infty}^{\tau} d\tau' \langle 0|[Q^I(\tau), H_{int}^I(\tau')]|0\rangle$$