The 5th Asian-European-Institutes Workshop for BSM

09/29/2025

Cosmological Quasiparticles and the Cosmological Collider

KIAS

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In collaboration with

Jay Hubisz, He Li, and Bharath Sambasivam: ArXiv:2408.08951

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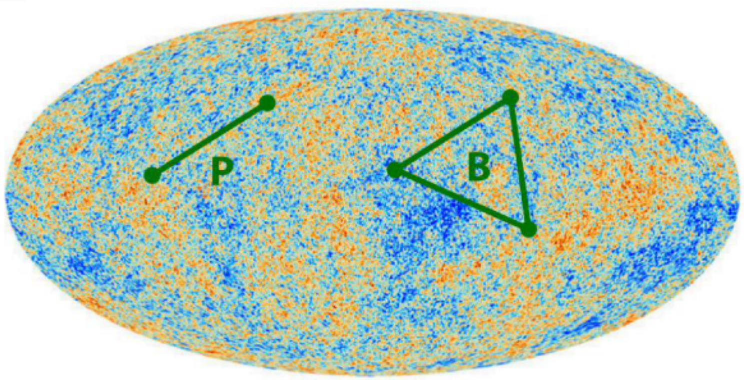
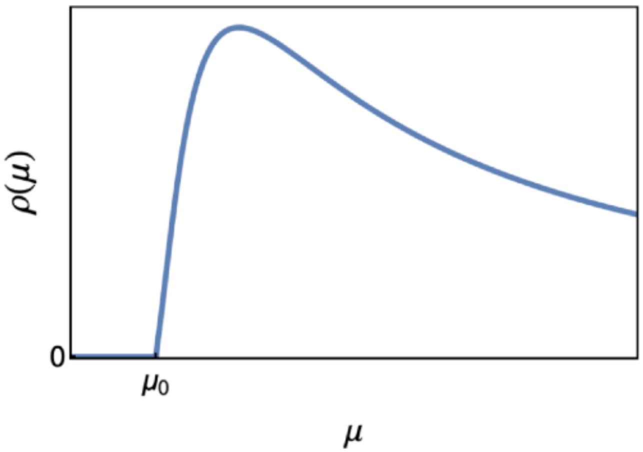
- We can consider, for example, a CFT operator O with scaling dimension Δ, and ask what sort of contribution it gives to the power spectrum as a function of its boundary conditions and Δ.
- We can utilize the AdS/CFT dictionary, and study the quantum fluctuations of a 5D scalar field in AdS-dS

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.



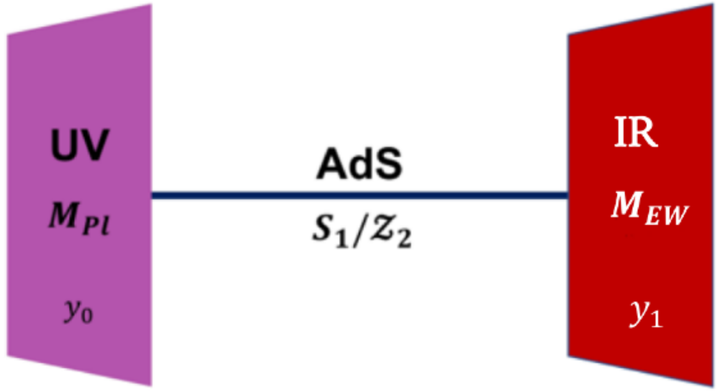


Holography

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

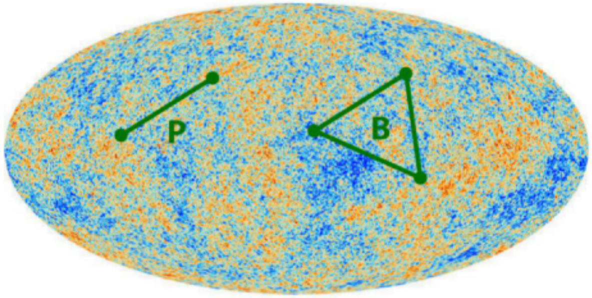


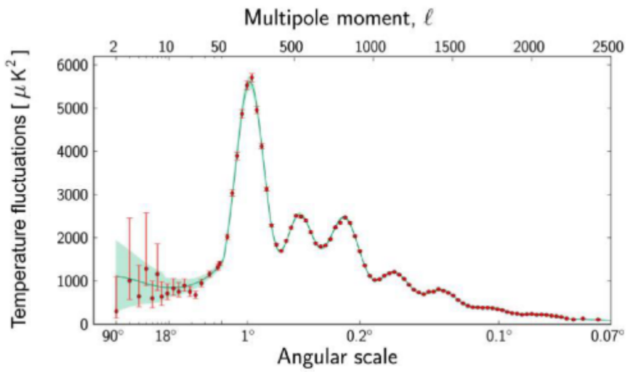
- AdS/CFT: 5D gravity ↔ 4D conformal gauge theory.
- RS1 and RS2 models as duals of large-N CFTs.
- Conformal symmetry breaking is essential for phenomenology.

Inflation

Epoch of dark energy domination leading to exponential expansion of the universe for ~ 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





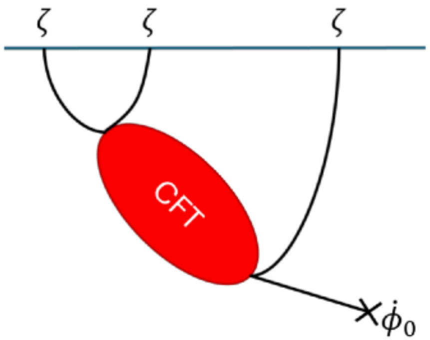
Non-Gaussianities and beyond the power spectrum?

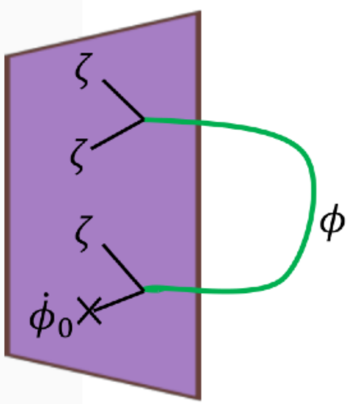
$n_s = 0.9649 \pm 0.0042$

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

- Inflaton localized on UV brane.
- Bulk scalar coupled to inflaton field.
- AdS-dS geometry: Hubble scale introduces IR cutoff.

Our Model of Inflation and Spectral Density





ζ: Inflaton on the brane
ϕ: 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: $\lambda\phi(\nabla\zeta)^2$

$$\langle\phi(x)\phi(x')\rangle \propto \int \frac{d^4p}{(2\pi)^4} e^{ip(x-x')} \frac{i}{(p^2+i\epsilon)^{2-\Delta}} = i\int \frac{d^4p}{(2\pi)^4} e^{ip(x-x')} \int_0^\infty d(\mu^2) \frac{\rho(\mu^2)}{(p^2-\mu^2+i\epsilon)}$$

$$\rho(\mu^2) = \frac{C(\Delta)}{(\mu^2)^{2-\Delta}}$$

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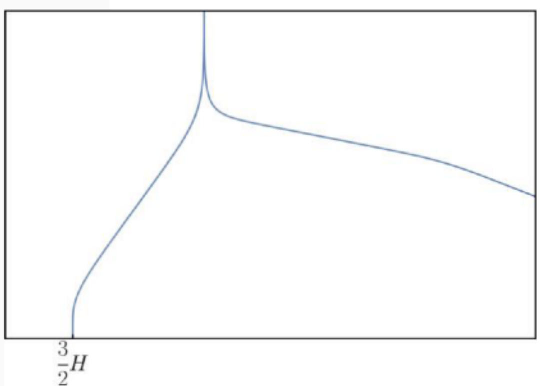
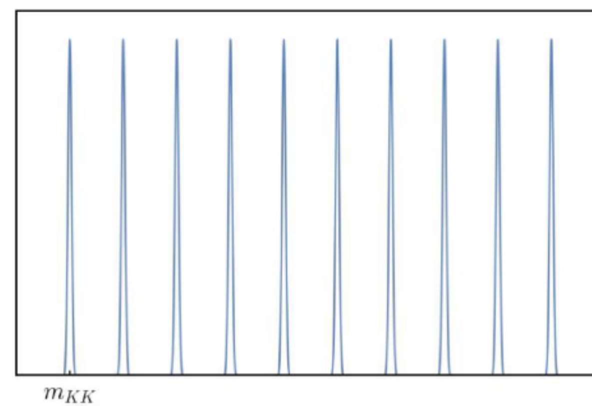
$$ds^2 = e^{-2A(w)}(dt^2 - e^{2Ht}dx^2 - dw^2) \qquad e^{-A(w)} = \frac{H}{k \sinh Hw}$$





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

~~CFT~~

5D inflationary set-up

$$\mathcal{L} = \mathcal{L}_{\text{inf}} + \mathcal{L}_{\text{CFT}} + \sum_{ij} g_{ij} \mathcal{O}^i_{\text{inf}} \mathcal{O}^j_{\text{CFT}}$$

5D Einstein-Hilbert action on a space with one brane, and a scalar field action on UV brane:

$$S = -\int d^5x\sqrt{g}\left[\Lambda + \frac{1}{2\kappa^2}R\right] + \int d^4x\sqrt{g_0}\left[\frac{1}{2}(\partial\varphi)^2 - \lambda(\varphi)\right] \qquad \Lambda = -\frac{6k^2}{\kappa^2}$$

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{\partial\lambda(\varphi)}{\partial\varphi} = 0$$

FLRW equation on the UV brane:

$$H^2 + \frac{1}{2}\dot{H} = \frac{\kappa^4}{36}\lambda^2(\varphi)\left(1 - \frac{\dot{\varphi}^2}{\lambda(\varphi)}\right)\left(1 + \frac{\dot{\varphi}^2}{2\lambda(\varphi)}\right) + \frac{\kappa^2}{6}\Lambda. \qquad H^2 \approx \frac{\kappa^4}{36}\lambda^2(\varphi) - k^2.$$

5D metric:

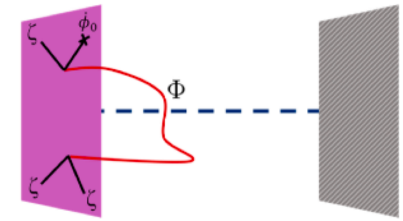
$$ds^2 = \frac{1}{(kz)^2}\left(dt^2 - e^{2Ht}d\vec{x}^2 - \frac{dz^2}{G^2(z)}\right) \qquad G(z) = \sqrt{1 + H^2z^2}.$$

The metric has a singularity at $z \to \infty$, corresponding to a horizon, and the length of the extra dimension is

$$L = \int_{1/k}^{\infty} \frac{1}{kzG}dz = k^{-1}\sinh^{-1}\frac{k}{H} \approx k^{-1}\log\frac{2k}{H}.$$

The finite size of the observable universe, H^{-1}, acts as an infrared cutoff for the geometry

Continuum in Inflationary 5D geometry



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$$ds^2 = e^{-2A(w)}\left[dt^2 - e^{2Ht} - dw^2\right], \text{ with } e^{-A(w)} = \frac{H}{k \sinh Hw}$$

Bulk scalar eom: $$-\phi'' + 3A'\phi' + m^2 e^{-2A(w)}\phi = -\Box_{dS_4}\phi \equiv \mu^2\phi.$$

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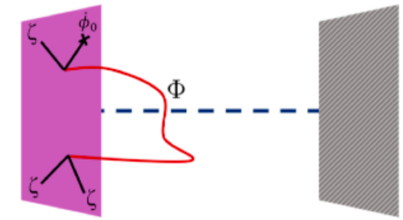

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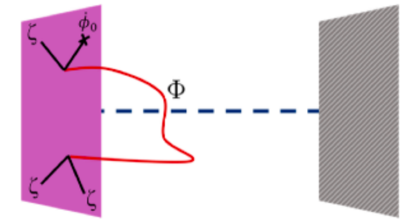

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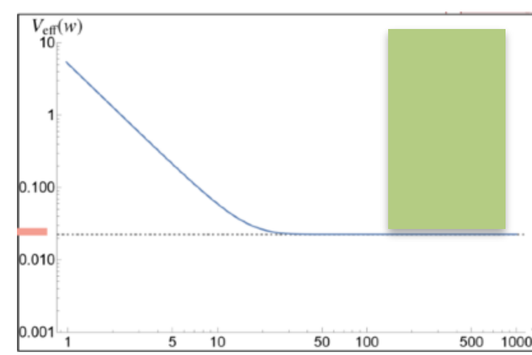

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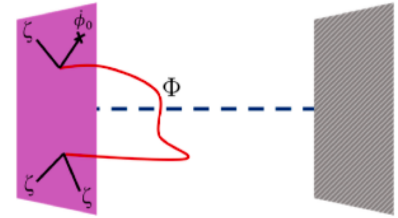

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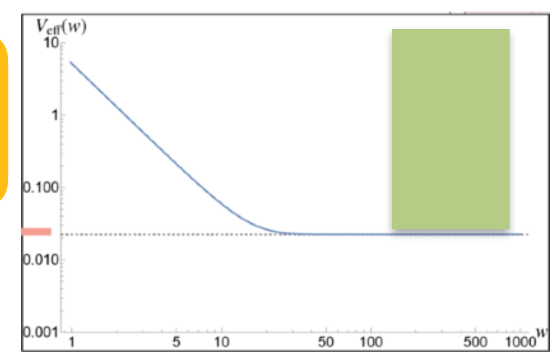
if $V \xrightarrow[w\to\infty]{} \mu_0^2$ = finite => Continuum with Mass Gap! 1D QM problem



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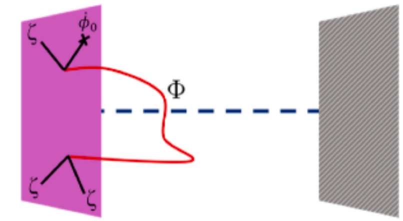

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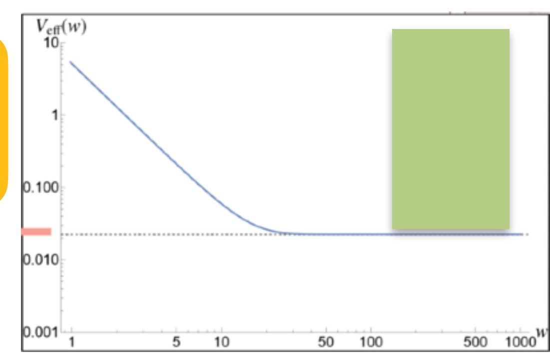

V(w)→ $\frac{9}{4}H^2$ as $w \to \infty$.

=> continuum begins at: μ_0= (3/2)*H for ξ=0

Correlation functions and the Spectral Density (From AdS/CFT)

$$\rho(\mu^2) \; = \; C(\Delta)(\mu^2)^{\Delta-2}$$

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

unitarity bound, $\Delta \geq 1$

- For CFT (UV brane at the AdS boundary):

both $\Delta_{\pm}$ solution works for: $-4 \leq m^2 \leq -3$

describes two CFT's, with each of them associated with a different choice of boundary action for the scalar field

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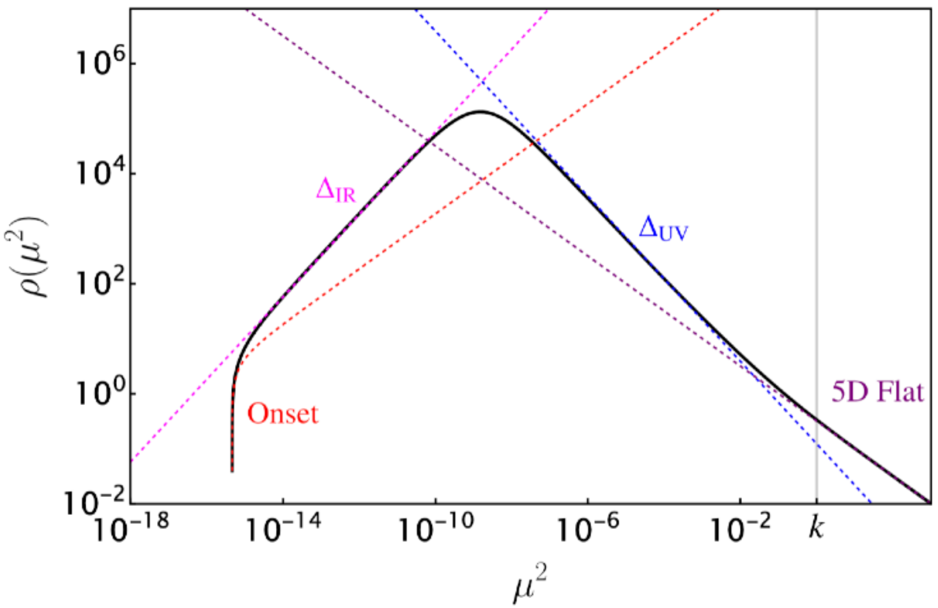

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- Emergence of Particle:

  As the theory transitions between the usual IR scaling, $\Delta_{IR} = \Delta_+$, and $\Delta_{UV} = \nu$ there is typically a sharp particle-like feature in the spectral density separating the two regions of distinct scalings

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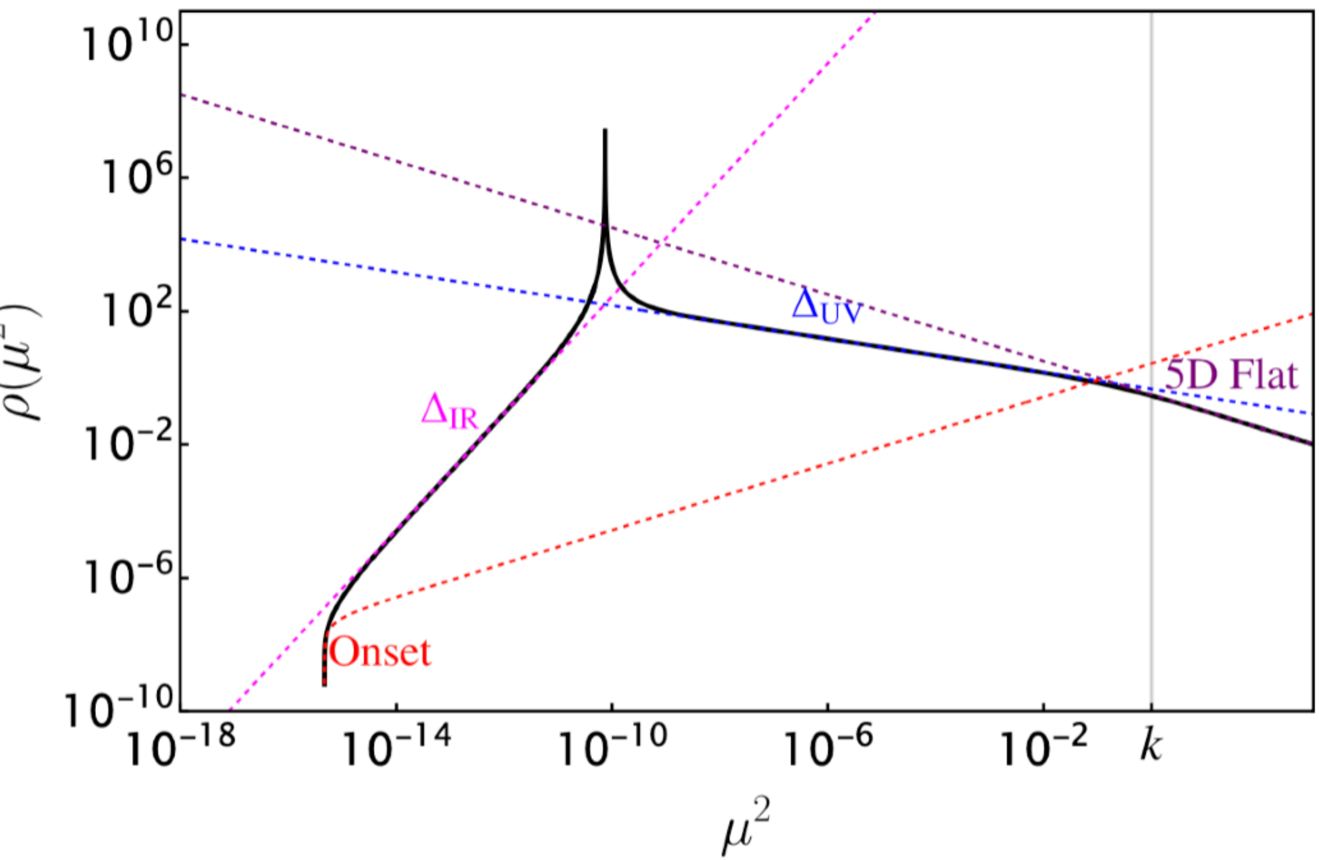

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UV / IR localized light mode

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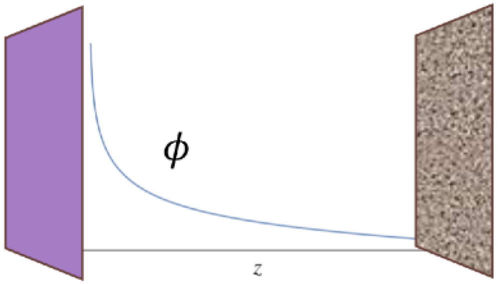
Light mode: discrete mode below the gap



$\nu > 1$, 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

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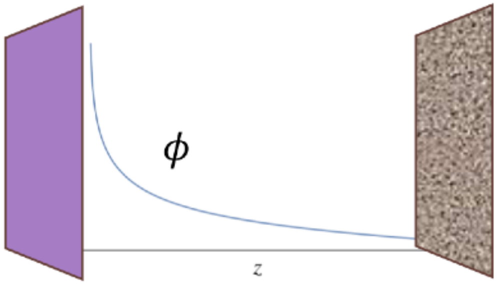

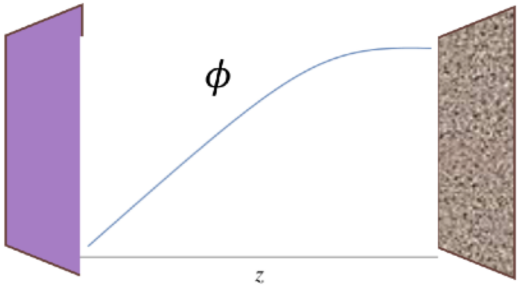

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$\nu < 1$, IR localized, not exist when H=0

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

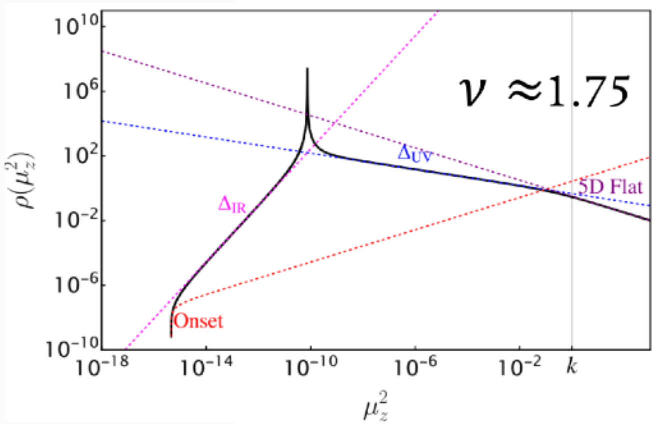
- Analogous to the horizon localized solutions in Schwarzchild geometries for light scalar fields
- CFT language: Mostly composite modes of the near-conformal dynamics. They only exist during the inflationary epoch

Quasiparticles

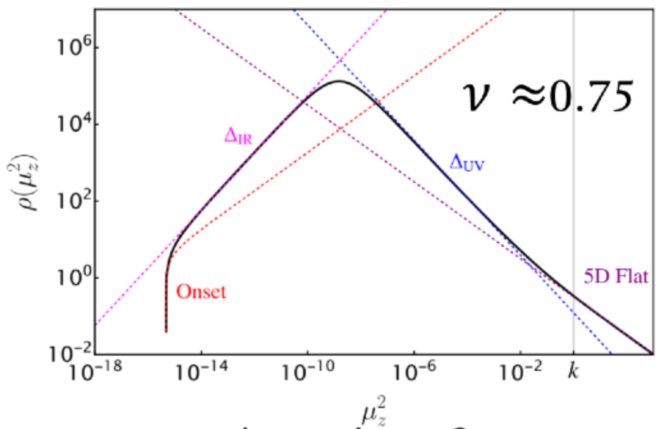
Cosmological Quasiparticles:

Anatomy of Spectral density and Scaling dimension

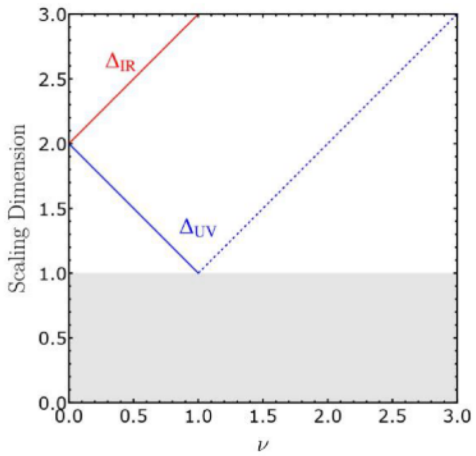
$$\rho(\mu^2) = C(\nu, H)\delta(\mu^2 - \mu_*^2) + \rho_c(\nu, m_0, \mu^2, H)\Theta\left(\mu^2 - \frac{9}{4}H^2\right)$$



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



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

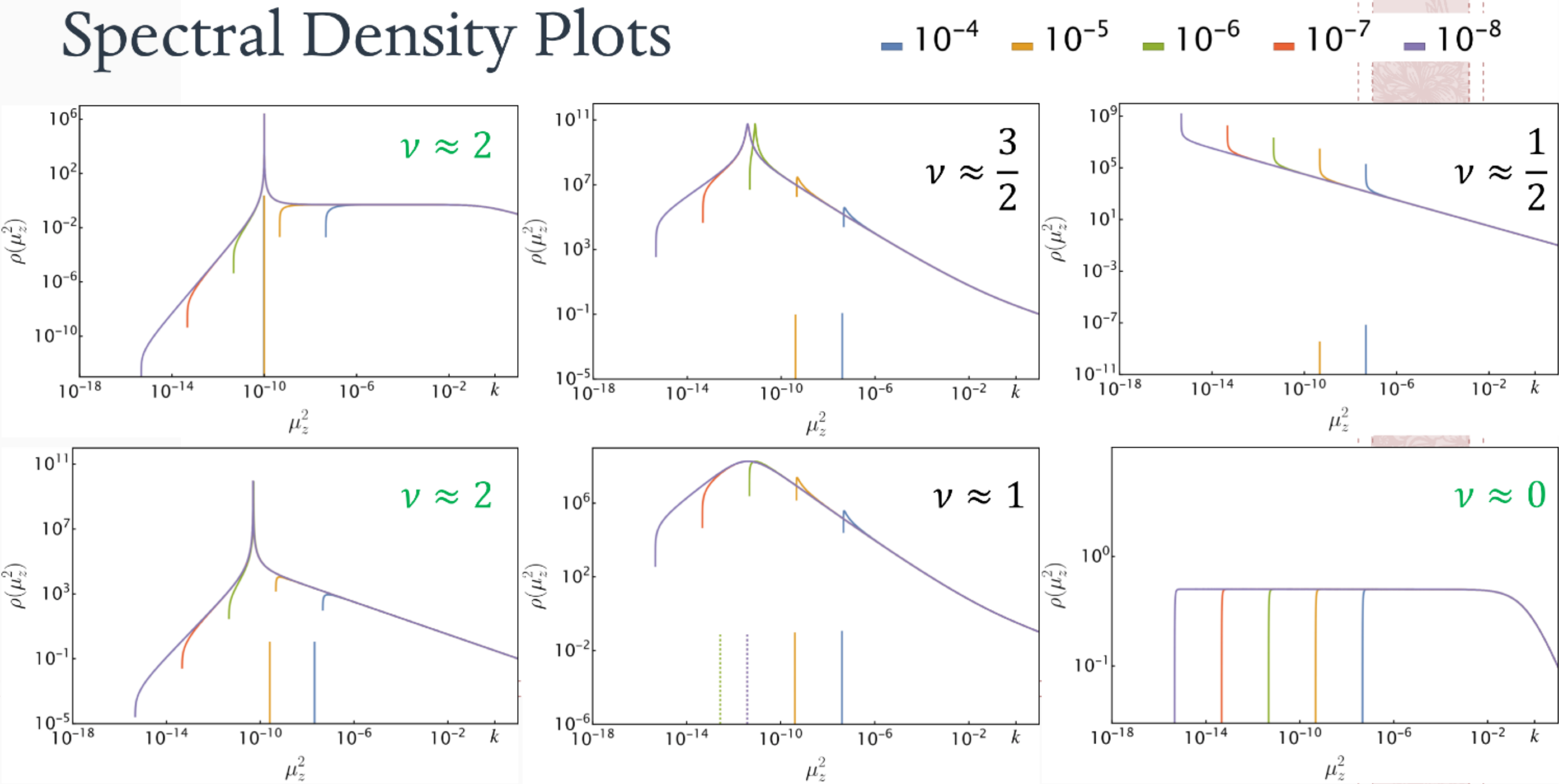


Solutions of 5D scalar equation yield two scaling dimensions:

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

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

Spectral Density Plots



UV brane localized

scalar inflaton

$\phi(t, x) = \phi_0(t) + \xi(t, x)$

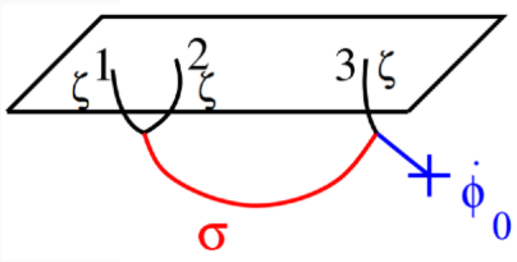
$$\zeta = -\frac{H}{\dot{\phi}_0}\xi$$

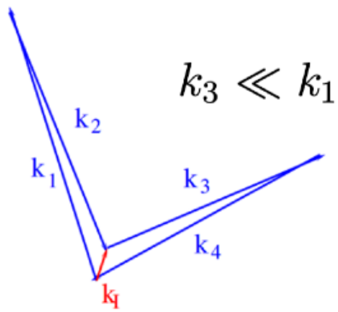
Cosmological Collider Physics

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)

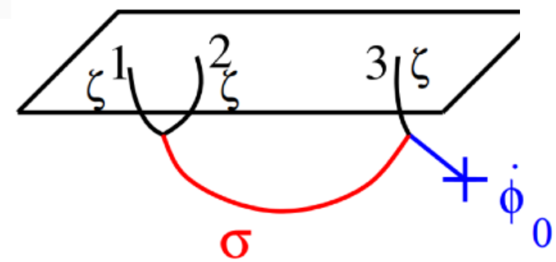




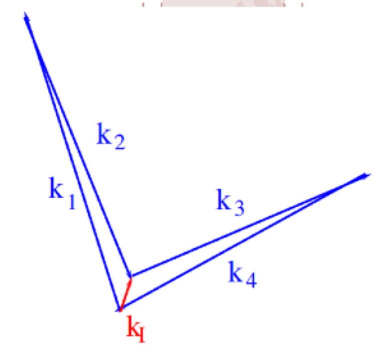
$k_3 \ll k_{1,2}$: squeezed limit

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

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

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

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

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

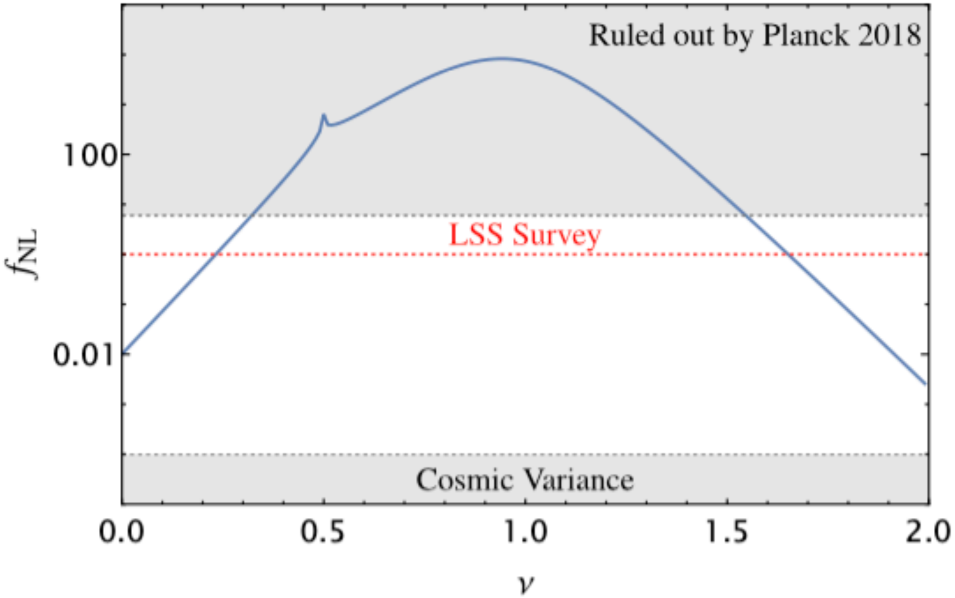
$$I_{\pm\pm}=(\pm i)(\pm i)\int_{-\infty}^{0}\frac{d\eta}{\eta^2}e^{\pm ik_{12}\eta}\int_{-\infty}^{0}\frac{d\eta'}{\eta'^2}e^{\pm ik_{34}\eta'}\left\langle\sigma_{\vec{k}_I}(\eta)\sigma_{-\vec{k}_I}(\eta')\right\rangle_{\pm\pm}$$

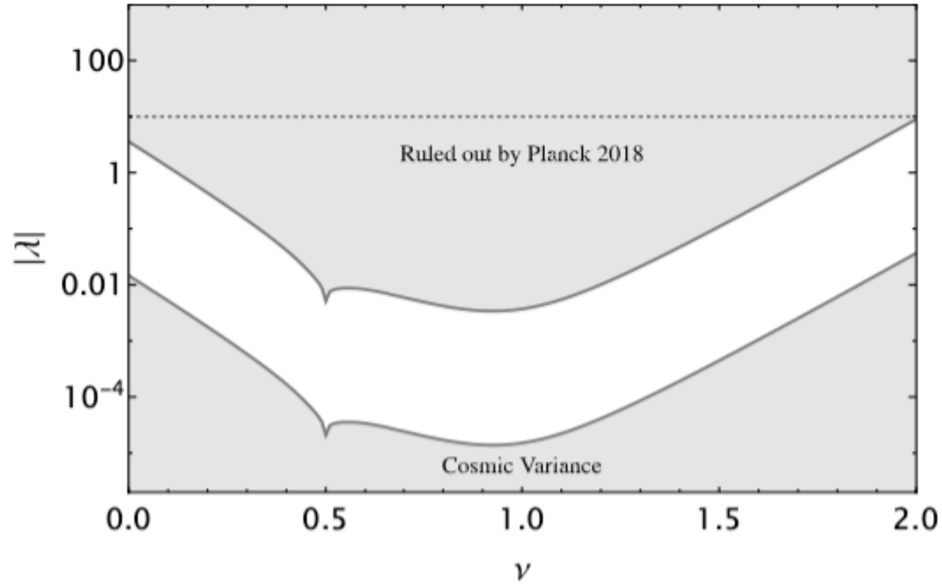
- Fluctuations of the inflaton $\phi(t,x)=\phi_0(t)+\xi(t,x)$ can be related to the curvature fluctuation

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

$$f_{NL}=\frac{5}{3}\left(\frac{\left\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\right\rangle}{4\left\langle\zeta_{\vec{k}_1}\zeta_{-\vec{k}_1}\right\rangle\left\langle\zeta_{\vec{k}_3}\zeta_{-\vec{k}_3}\right\rangle}\right)_{k_3\to0}=-\frac{\epsilon M_{Pl}^2\lambda^2}{4\sqrt{\pi}}\frac{\pi^2}{\cosh^2\pi\gamma}\left(\frac{k_3}{k_1}\right)^{\frac{3}{2}}\times\left[A(\gamma)\left(\frac{k_3}{4k_1}\right)^{-i\gamma}+A^*(\gamma)\left(\frac{k_3}{4k_1}\right)^{i\gamma}\right]$$

Results of non-Gaussianity



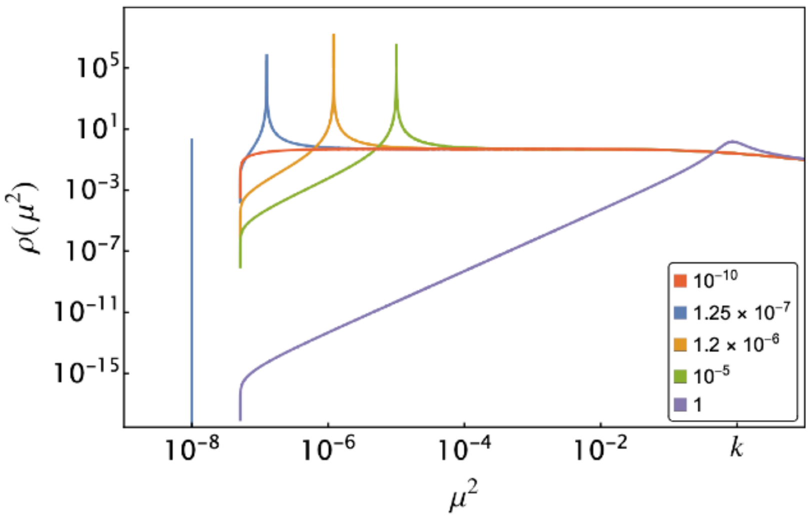


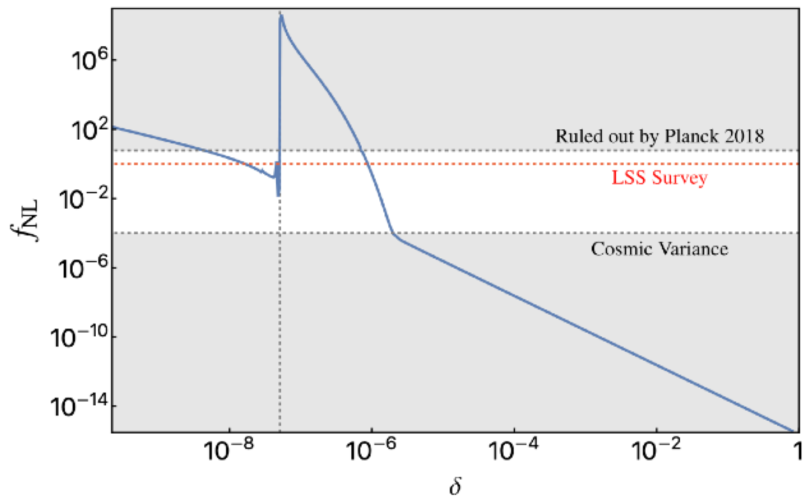
λ=1 (in unit of k, the AdS curvature)
H=10^13 GeV
$\frac{k_3}{k_1} = 0.1$

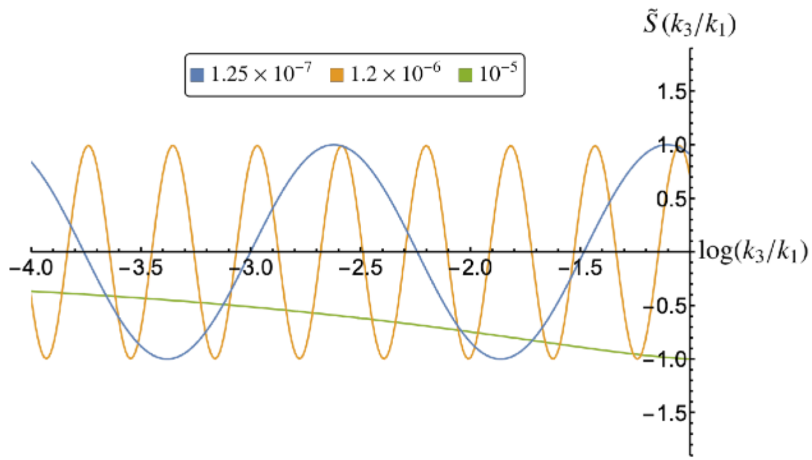
Coupling term: $\lambda\phi(\nabla\zeta)^2$

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

Small Bulk Mass: $m^2 \approx 0$ $\quad L \ni \lambda O$ with $[O]\sim 4$







$$\delta \equiv m_0^2 - 2(2-\nu)$$

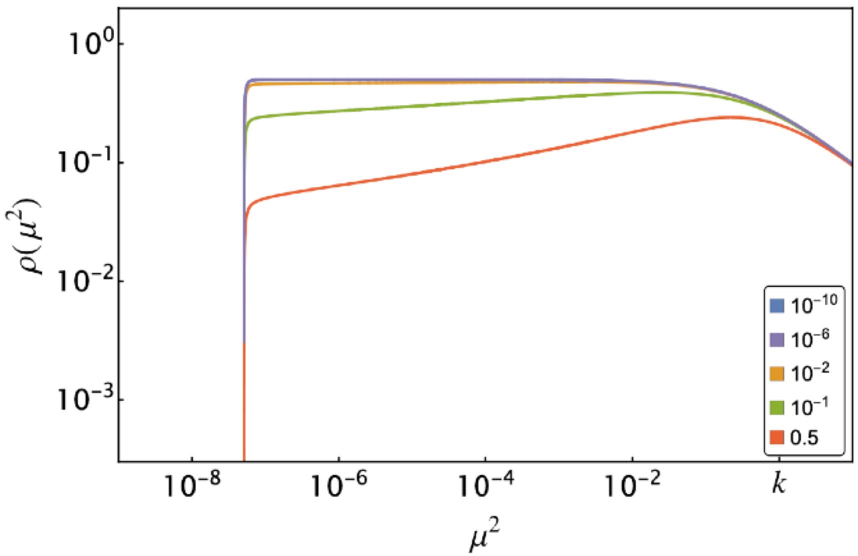
$$F_{\rm NL}(k_3/k_1) = f_{\rm NL}\left(\frac{k_3}{k_1}\right)^{3/2}\widetilde{S}(k_3/k_1),$$

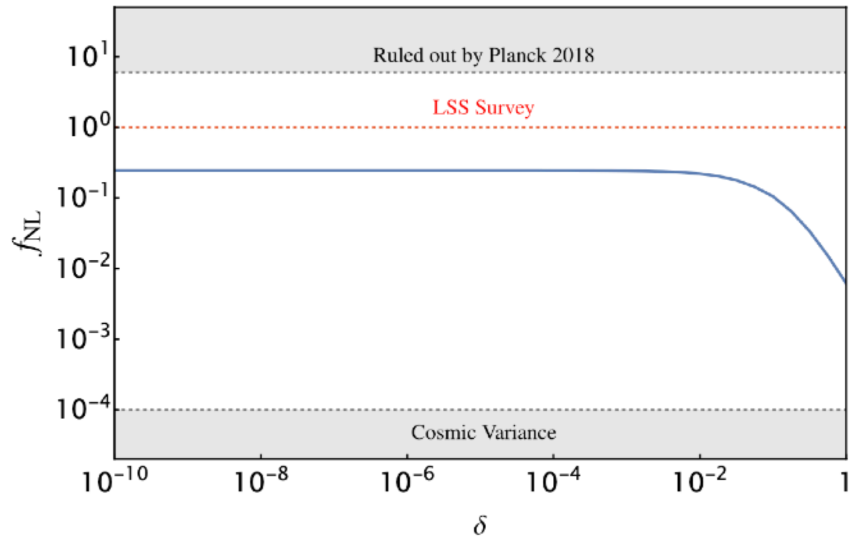
The spectral densities and f_{NL} when the scalar bulk mass $m^2 \sim 0$ for various values of UV brane mistunes, δ. We also show some of the shape functions, which exhibit clear oscillatory behavior when there is a particle slightly above the critical mass, $3/2H$.

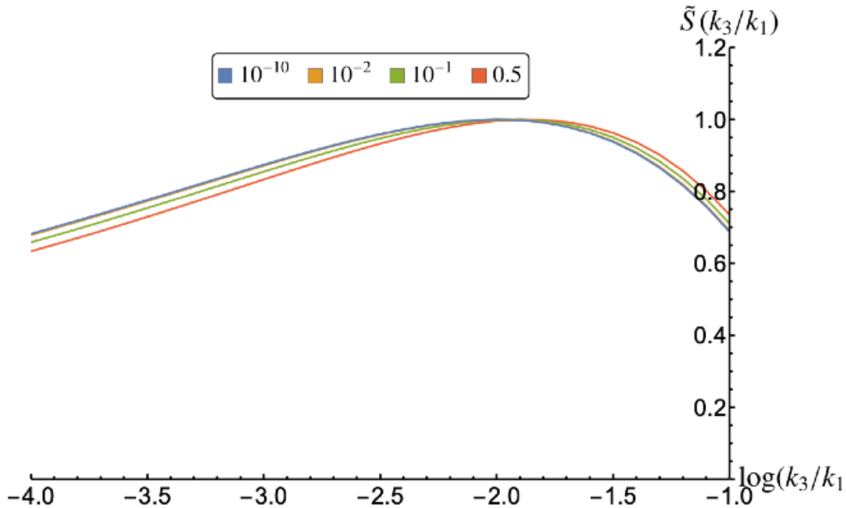
Small Bulk Mass: $m^2 \approx -4$ $L \ni \lambda O^\dagger O$ with $[O]\sim 2$ $\beta = -\lambda^2$

$\nu \approx 0$ $\delta = 2(\nu - \lambda)$

-can lead to an IR localized state that is near to the horizon, producing a “cosmological quasiparticle”







$$\delta \equiv m_0^2 - 2(2-\nu)$$

$$F_{\rm NL}(k_3/k_1) = f_{\rm NL}\left(\frac{k_3}{k_1}\right)^{3/2}\widetilde{S}(k_3/k_1),$$

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 $\nu > 1$.
- The non-analytic particle-like feature can rise above the continuum contributions, giving the "smoking gun" oscillatory features in the shape function for F_{NL}
- 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!