Cosmological Quasiparticles and the Cosmological Collider

KIAS

Seung J. Lee

In collaboration with

Jay Hubisz, He Li, and Bharath Sambasivam: ArXiv:2408.08951
Phys.Rev.D 111 (2025) 2

Jay Hubisz, Luis Rufino, and Bharath Sambasivam: work in progress

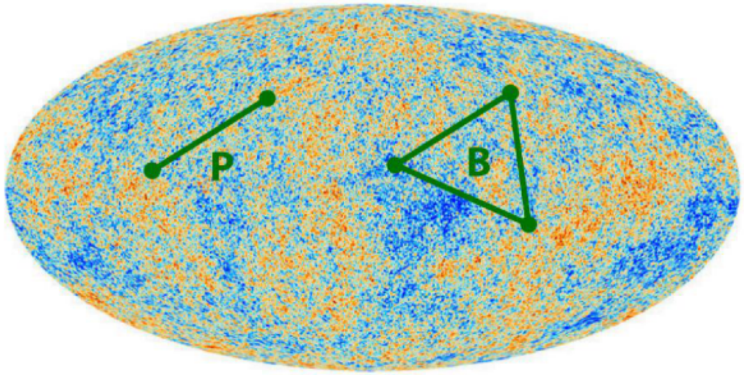
Motivation

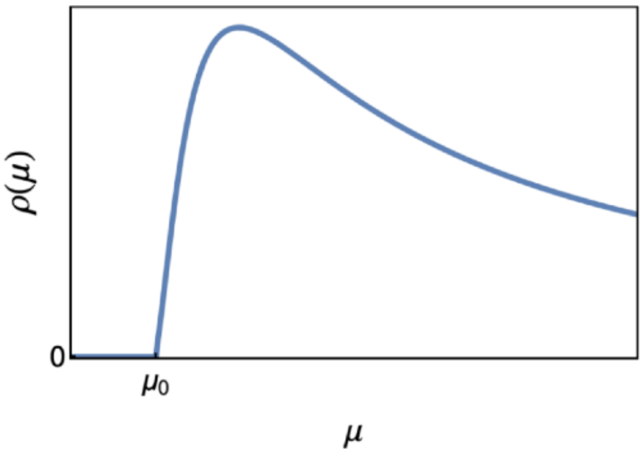
- interested in studying the physics of a strongly coupled conformal sector that is present during the early universe inflationary epoch (connection with some interesting BSM scenarios)

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.



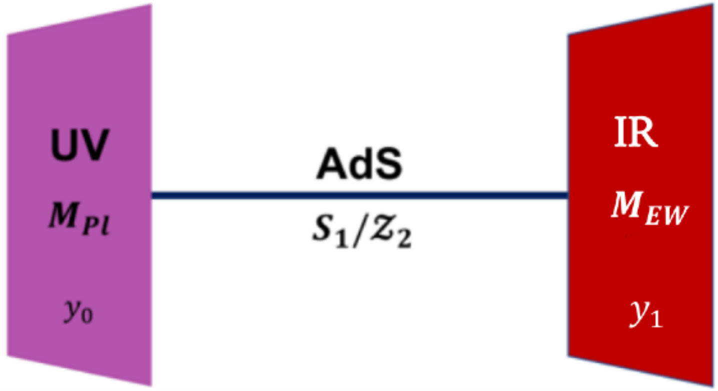


Holography

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 $m \sim f$

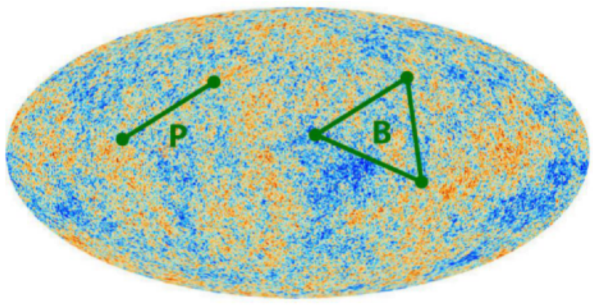
Spontaneously broken CFT on boundary



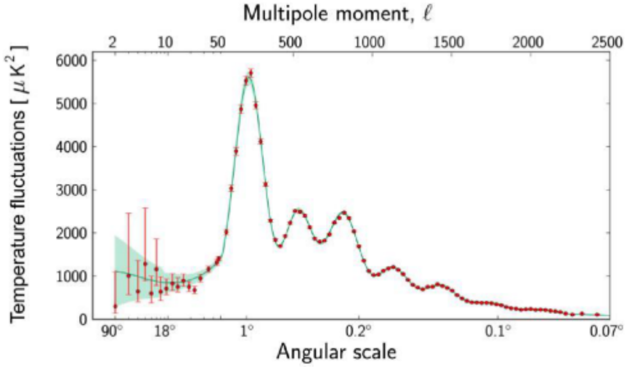
- AdS/CFT: 5D gravity ↔ 4D conformal gauge theory.
- RS1 and RS2 models as duals of large-N CFTs.
- Conformal symmetry breaking is essential for phenomenology.

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



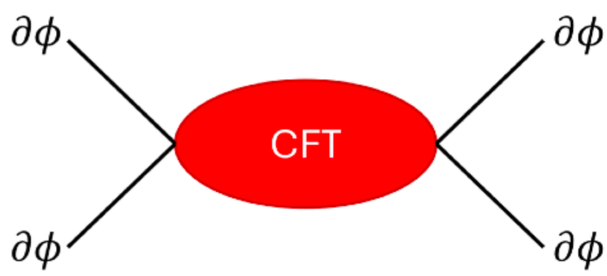
Non-Gaussianities and beyond the power spectrum?

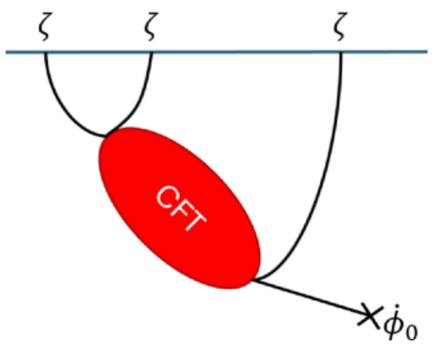
$n_s = 0.9649 \pm 0.0042$

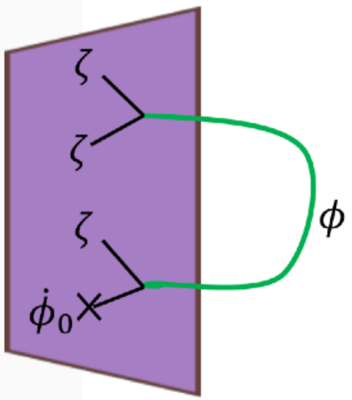
$\Delta T/T \sim 10^{-5}$

- 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

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

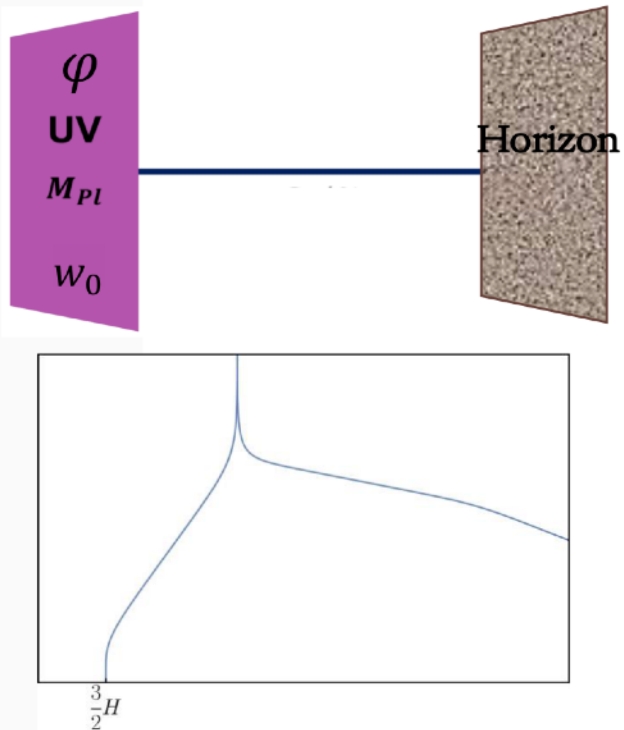
Coupling term: $\lambda\phi(\nabla\zeta)^2$

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

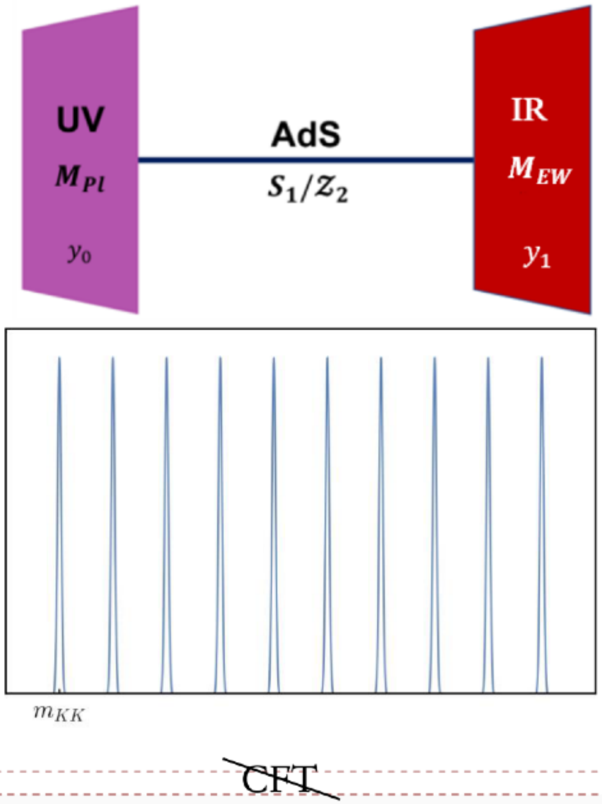
$$\rho(\mu^2) = \frac{C(\Delta)}{(\mu^2)^{2-\Delta}}$$

Our Model of Inflation and Spectral Density

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



Late Time



5D inflationary set-up

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

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

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

$$\Lambda = -\frac{6k^2}{\kappa^2}$$

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

FLRW equation on the UV brane:

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

$$H^2 \approx \frac{\kappa^4}{36}\lambda^2(\varphi) - k^2.$$

5D metric:

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

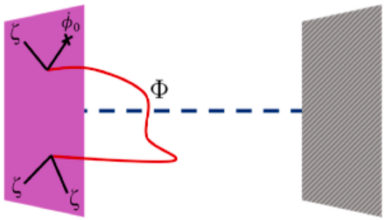
$$G(z) = \sqrt{1 + H^2 z^2}.$$

The metric has a singularity at z → ∞, 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



- Switch to a convenient conformal coordinate:

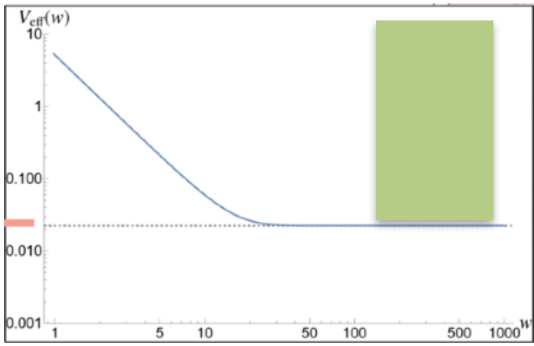
$$ds^2 = e^{-2A(w)}\left[dt^2 - e^{2Ht} - dw^2\right], \text{ with } e^{-A(w)} = \frac{H}{k \sinh Hw}$$

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

Bulk Scalar eom after field rescaling ($\varphi = \tilde{\varphi} e^{3/2\, A(w)}$): $$-\tilde{\phi}'' + \left[m^2 e^{-2A} + \frac{9}{4}A'^2 - \frac{3}{2}A''\right]\tilde{\phi} = \mu^2\tilde{\phi}.$$

"Schrödinger Eqn".: $$-\tilde{\phi}'' + \underbrace{H^2\left[\frac{9}{4}\coth^2(Hw) + \frac{3+2m^2}{2\sinh^2(Hw)}\right]}_{V(w)}\tilde{\phi} = \mu^2\tilde{\phi}$$

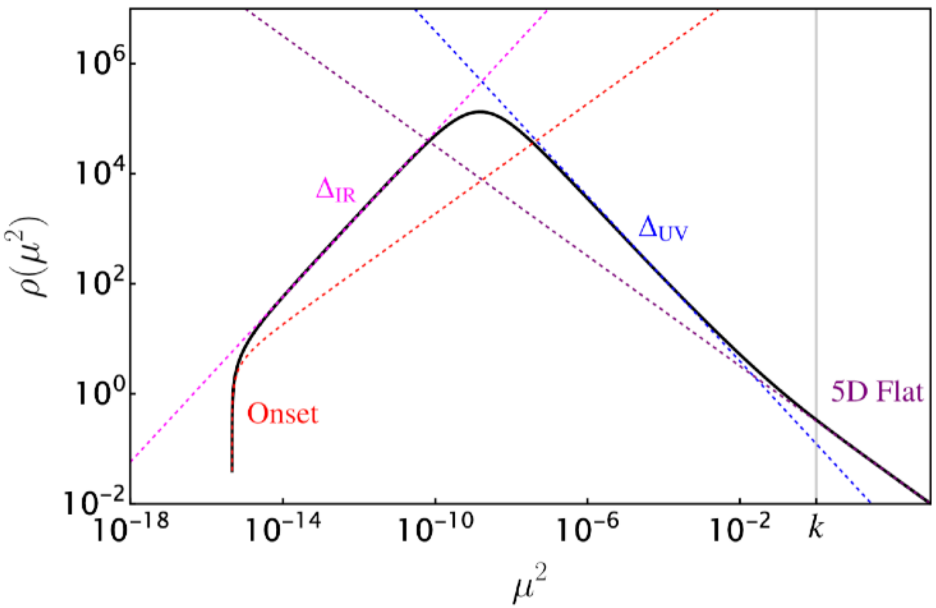
if $V \xrightarrow[w\to\infty]{} \mu_0^2$ = finite => Continuum with Mass Gap! 1D QM problem



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)



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

unitarity bound, $\Delta \geq 1$

ıdary):

n$^2 \leq -3$

associated with a different choice of

- For RS type of model: UV brane is at some high scale (CFT is explicitly broken at that scale:

UV-brane boundary condition for the scalar field then can be interpreted as a β-function that serves to create an RG flow between UV and IR CFT's

Scaling dimension of operator flows from Δ_- in the UV, to Δ_+ in the IR

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

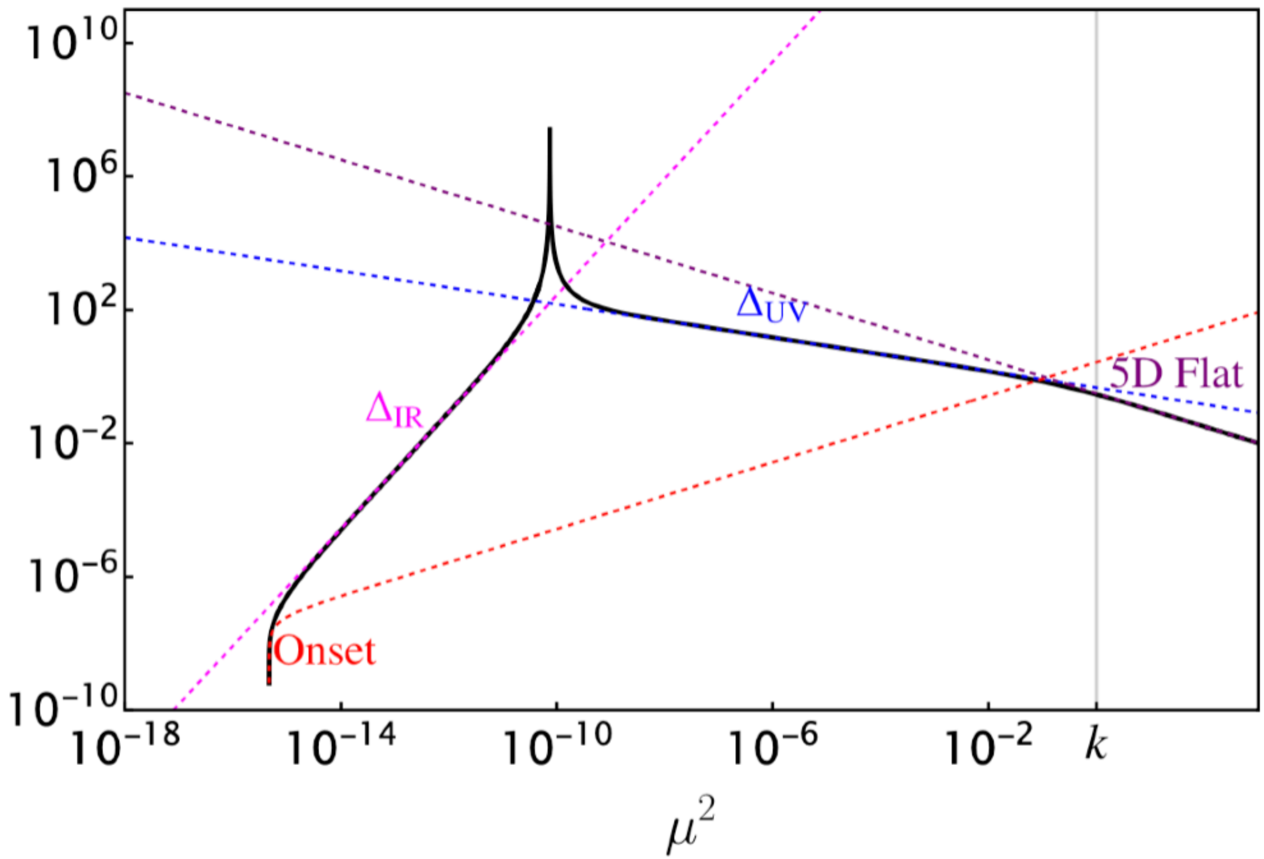
$\rho(\mu^2)$ $\nu^2 = 4 + m^2$

- For I… …ed)

Δ

Two po… …the theory

…rom the



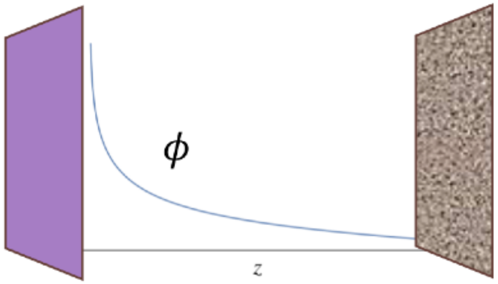
- Emergence of Particle:

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

UV / IR localized light mode

$\nu^2 = 4 + m^2$

Light mode: discrete mode below the gap



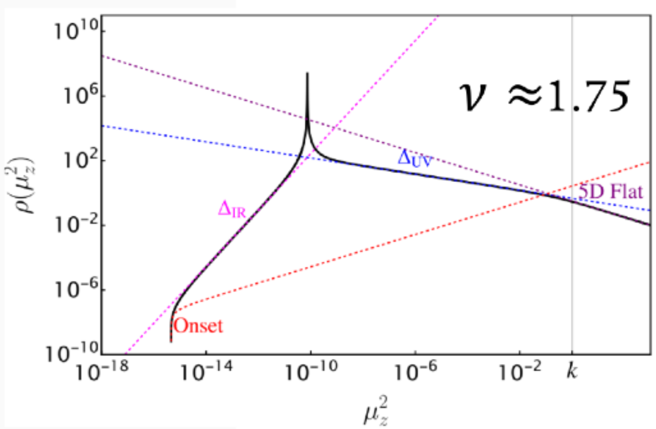
$\nu > 1$, UV localized, exist when H=0

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

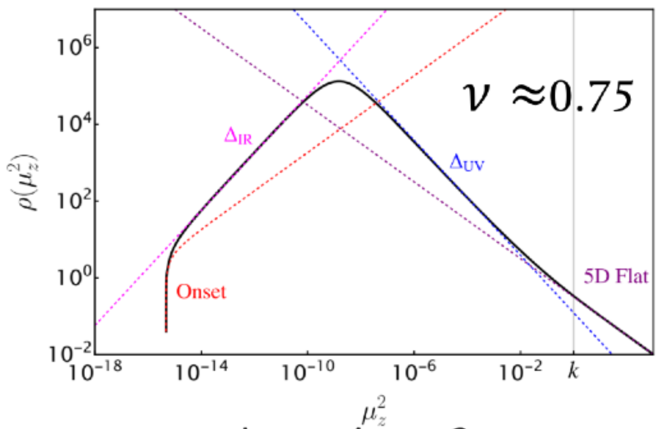
- Tune brane mass $m_0^2 \approx 2(2-\nu)$
- CFT language: Fundamental bound state in the spectrum mixing with the CFT states; CFT deformation by H backreacts to modify the mass of the particle eigenstate

Anatomy of Spectral density and Scaling dimension

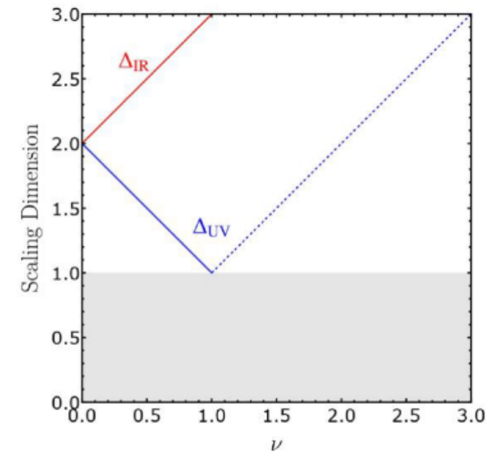
$$\rho(\mu^2) = C(\nu, H)\delta(\mu^2 - \mu_*^2) + \rho_c(\nu, m_0, \mu^2, H)\Theta\left(\mu^2 - \frac{9}{4}H^2\right)$$



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



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



Solutions of 5D scalar equation yield two scaling dimensions:

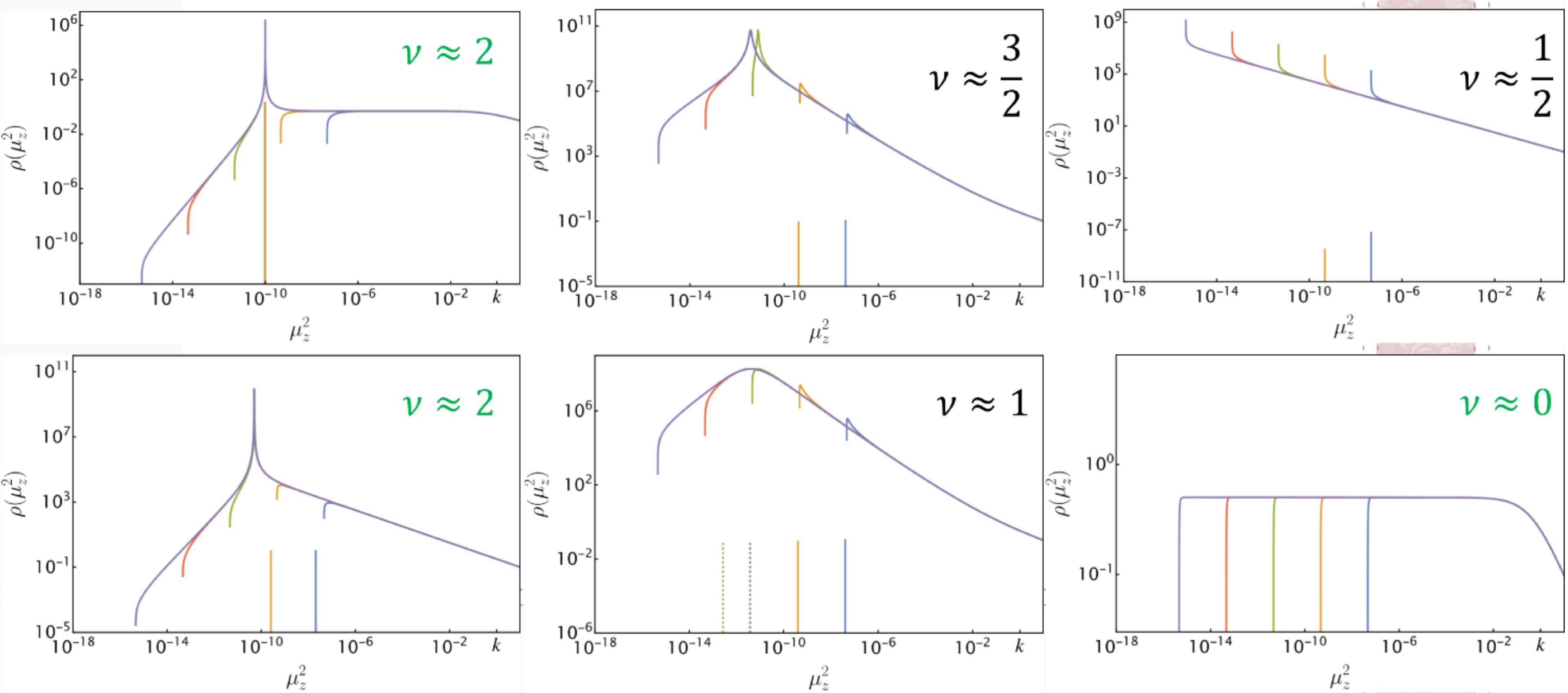
$$\Delta_\pm = 2 \pm \nu = 2 \pm \sqrt{4 + m^2}$$

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

Spectral Density Plots

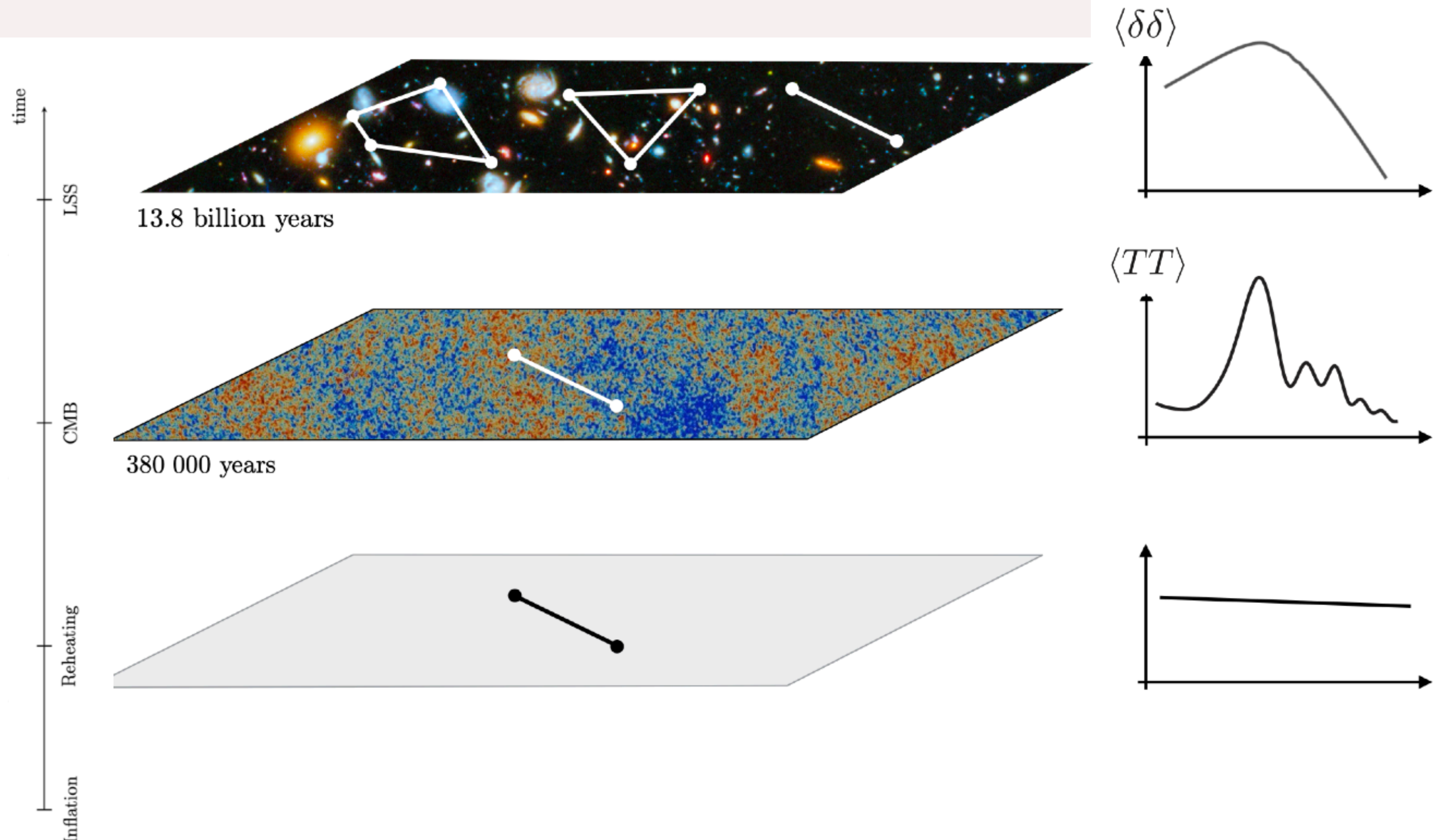
$\delta \equiv m_0^2 - 2(2-\nu)$

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



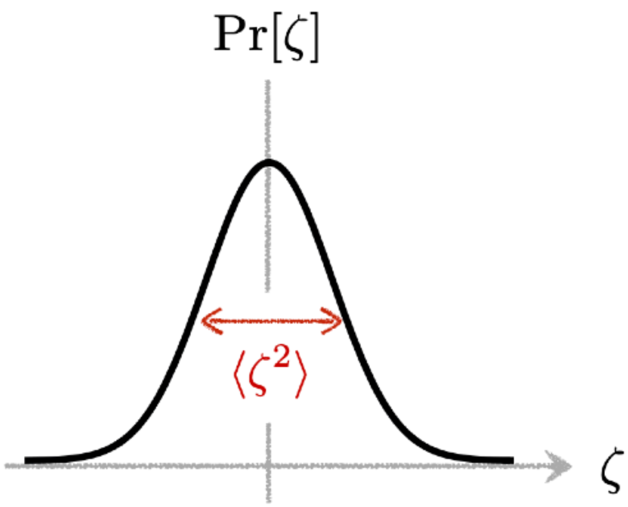
Cosmological Collider Physics (Basic review)

By measuring cosmological correlations, we learn both about the evolution of the universe and its initial conditions



Cosmological Collider Physics (Basic review)

The primordial fluctuations were highly **Gaussian** (as expected for the ground state of a harmonic oscillator):



$$F_{\rm NL} \equiv \frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-3}$$

The universe is more Gaussian than flat.

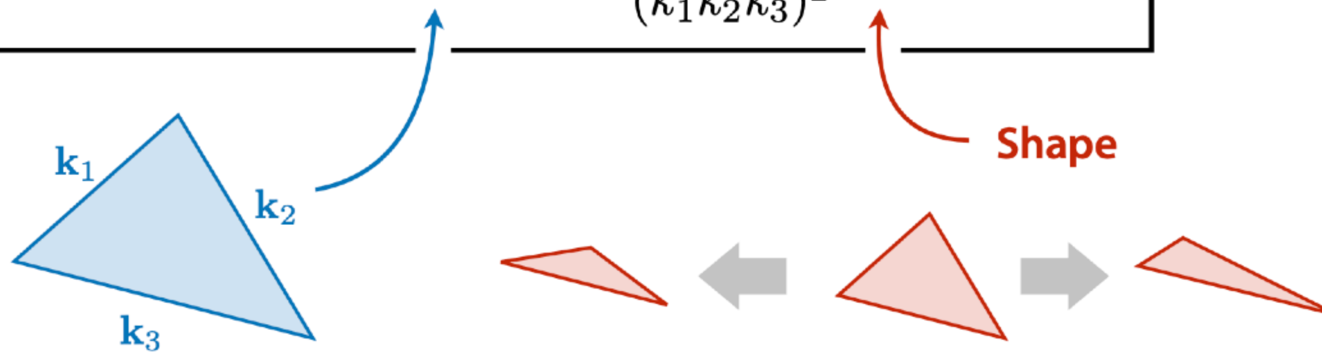
So far, we have only studied the free theory.

Interactions during inflation can lead to **non-Gaussianity**.

Cosmological Collider Physics (Basic review)

The main diagnostic of primordial non-Gaussianity is the **bispectrum**:

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \, \frac{(2\pi^2)^2}{(k_1 k_2 k_3)^2} \, B_\zeta(k_1, k_2, k_3)$$



- The **amplitude** of the non-Gaussianity is defined as the size of the bispectrum in the equilateral configuration:

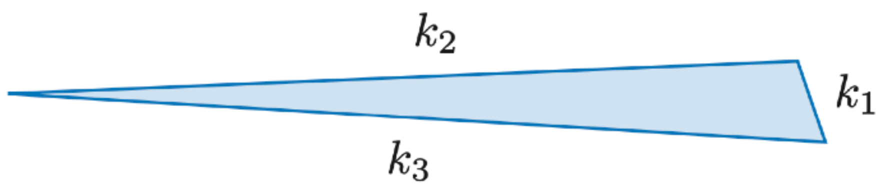
$$F_{\mathrm{NL}}(k) \equiv \frac{5}{18} \frac{B_\zeta(k,k,k)}{\Delta_\zeta^3(k)}$$

Cosmological Collider Physics (Basic review)

Squeezed Non-Gaussianity

In single-field inflation, correlations must vanish in the **squeezed limit**:

$\lim_{k_1 \to 1}$



~ 0

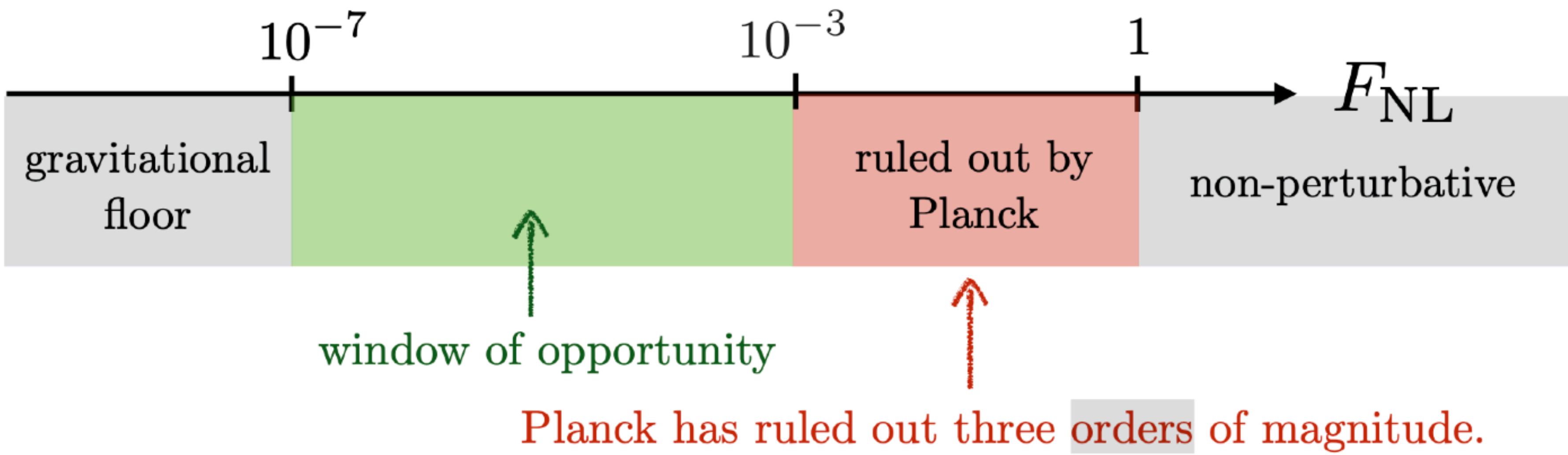
Maldacena [2003]
Creminelli and Zaldarriaga [2004]

The signal in the squeezed limit therefore acts as a **particle detector**.

Chen and Wang [2009]
DB and Green [2011]
Noumi, Yamaguchi andYokoyama [2013]
Arkani-Hamed and Maldacena [2015]
Lee, DB and Pimentel [2016]
DB, Goon, Lee and Pimentel [2017]
Kumar and Sundrum [2018]
Jazayeri and Renaux-Petel [2022]
Pimentel and Wang [2022]

Cosmological Collider Physics (Basic review)

The theoretically interesting regime of non-Gaussianity spans about seven orders of magnitude:



There is still room for new particles to leave their mark.

UV brane localized

scalar inflaton

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

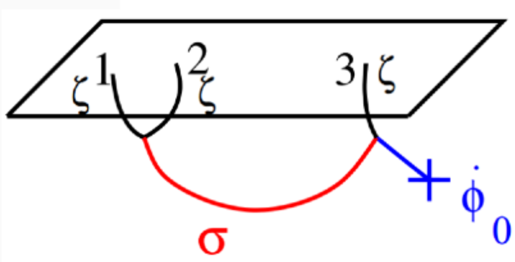
$$\zeta = -\frac{H}{\dot{\phi}_0}\xi$$

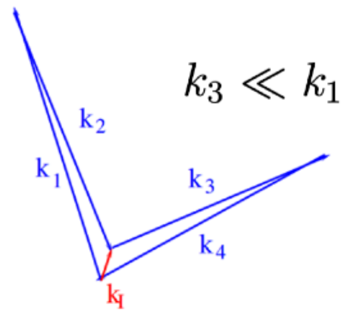
Cosmological Collider Physics

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)





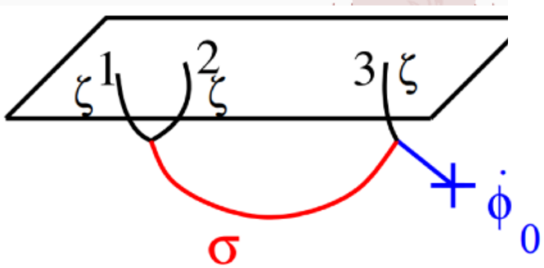
$k_3 \ll k_{1,2}$: squeezed limit

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

$$F_{\rm NL}(k_3/k_1) = f_{\rm NL} \cdot S(k_3/k_1)$$

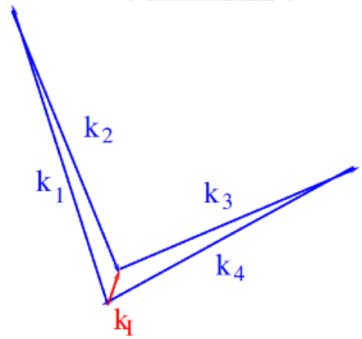
Bispectrum

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

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

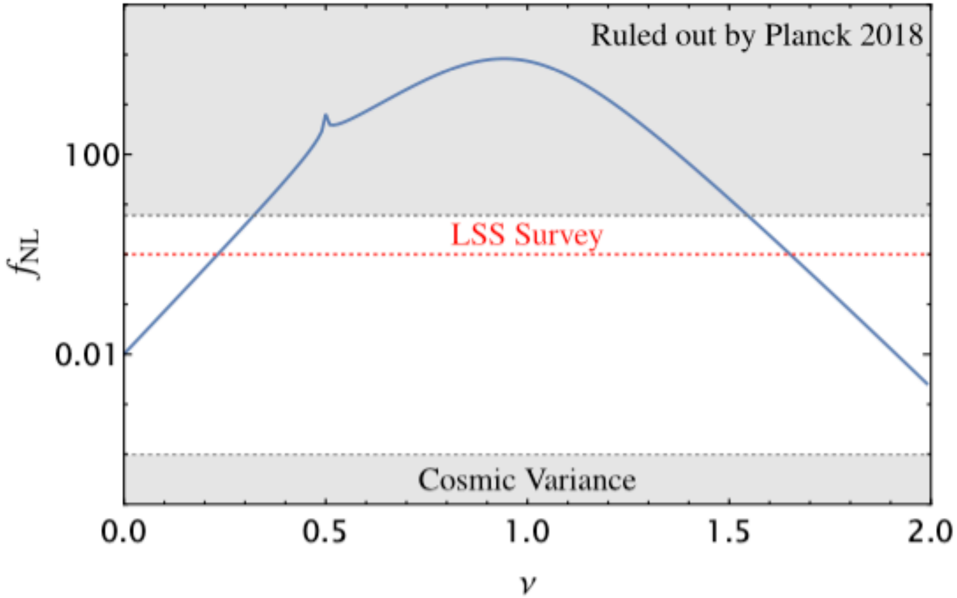
$$I_{\pm\pm} = (\pm i)(\pm i)\int_{-\infty}^{0}\frac{d\eta}{\eta^2}e^{\pm ik_{12}\eta}\int_{-\infty}^{0}\frac{d\eta'}{\eta'^2}e^{\pm ik_{34}\eta'}\left\langle \sigma_{\vec{k}_I}(\eta)\sigma_{-\vec{k}_I}(\eta')\right\rangle_{\pm\pm}$$

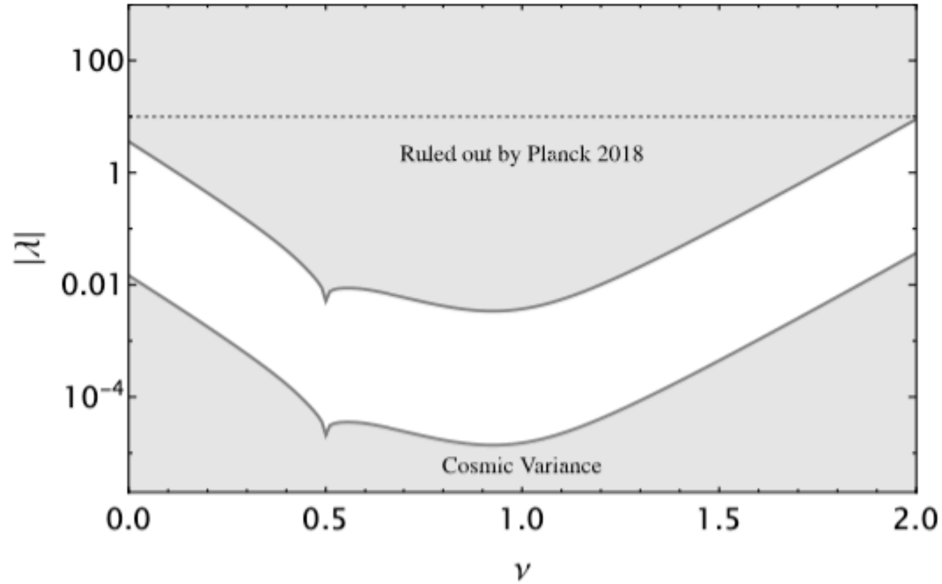
- Fluctuations of the inflaton $\phi(t,x) = \phi_0(t) + \xi(t,x)$ can be related to the curvature fluctuation

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

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

Results of non-Gaussianity





λ=1 (in unit of k, the AdS curvature)

H=10^13 GeV

$\frac{k_3}{k_1} = 0.1$

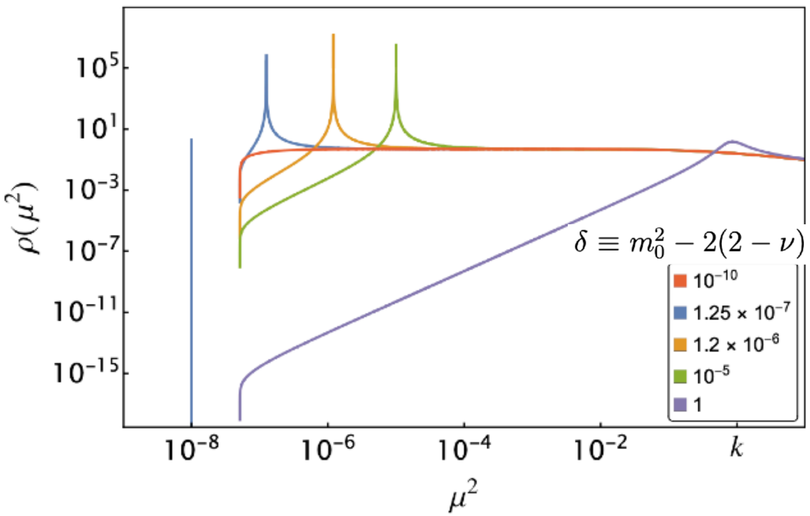
Coupling term: $\lambda\phi(\nabla\zeta)^2$

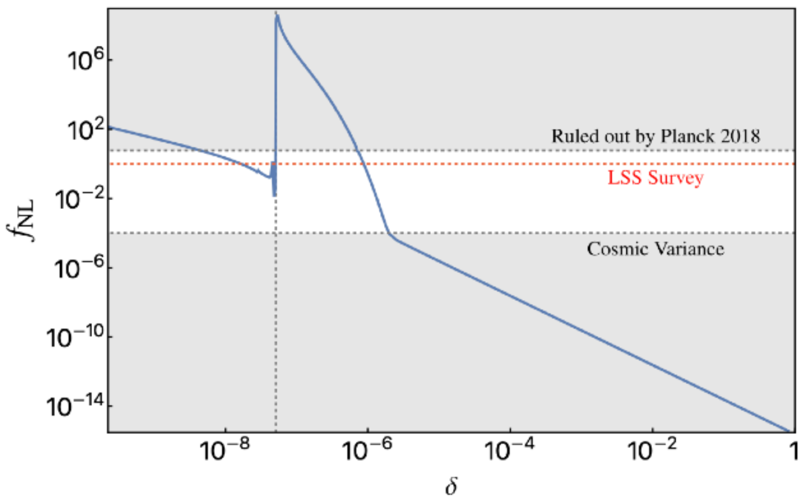
Shaded area: Ruled out

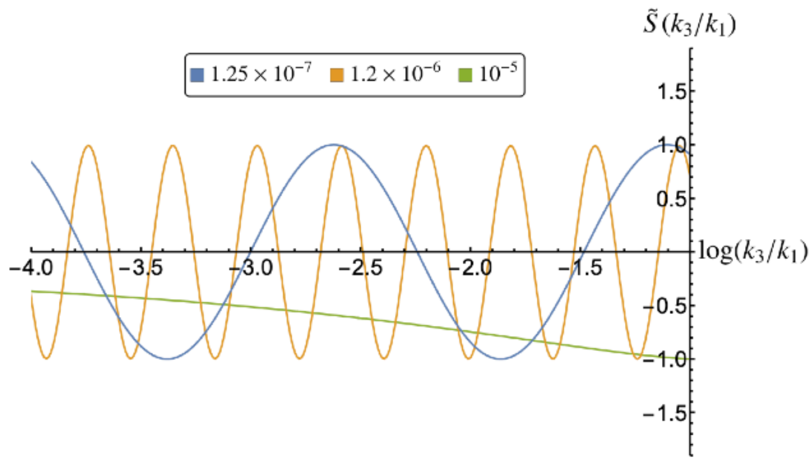
Blank: Allowed according to current experiments

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

nearly marginal, runs slowly. Confinement thus occurs through a form of dimensional transmutation, stabilizing the Planck-Weak hierarchy







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

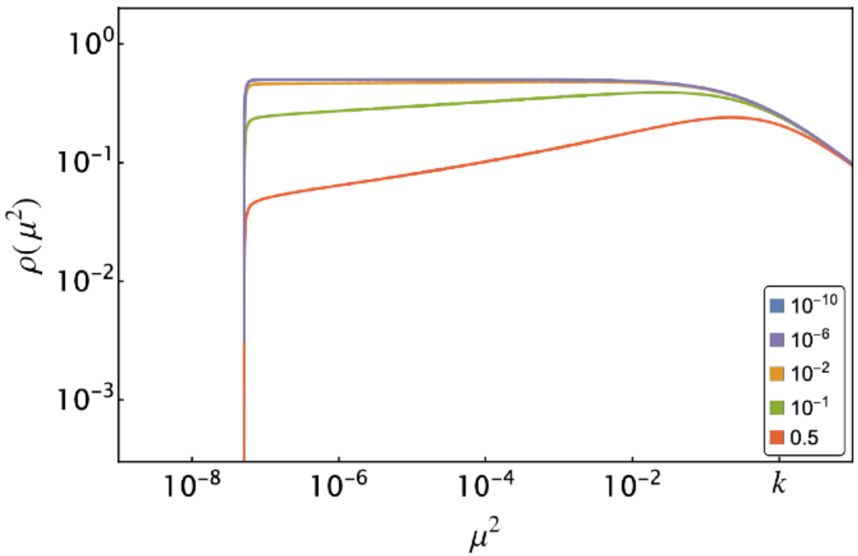
$$F_{\rm NL}(k_3/k_1) = f_{\rm NL}\left(\frac{k_3}{k_1}\right)^{3/2}\widetilde{S}(k_3/k_1),$$

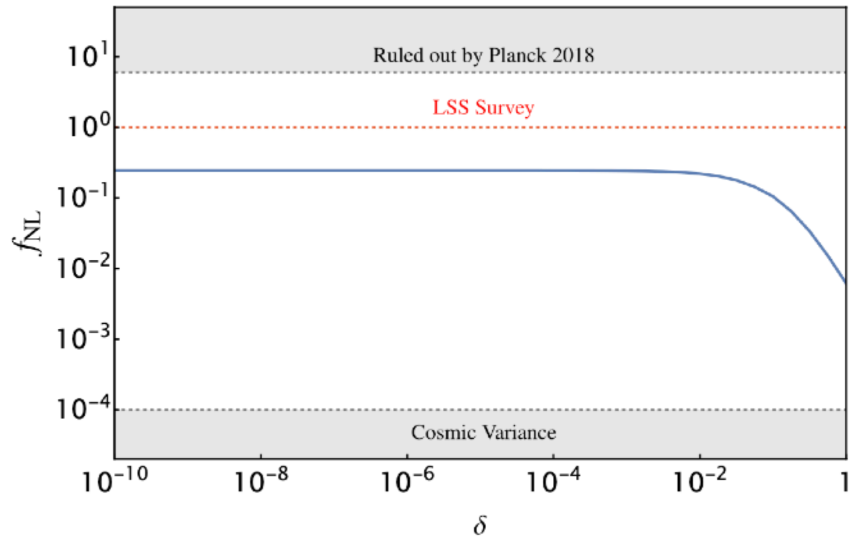
The spectral densities and f_{NL} when the scalar bulk mass $m^2 \sim 0$ for various values of UV brane mistunes, δ. We also show some of the shape functions, which exhibit clear oscillatory behavior when there is a particle slightly above the critical mass, $3/2H$.

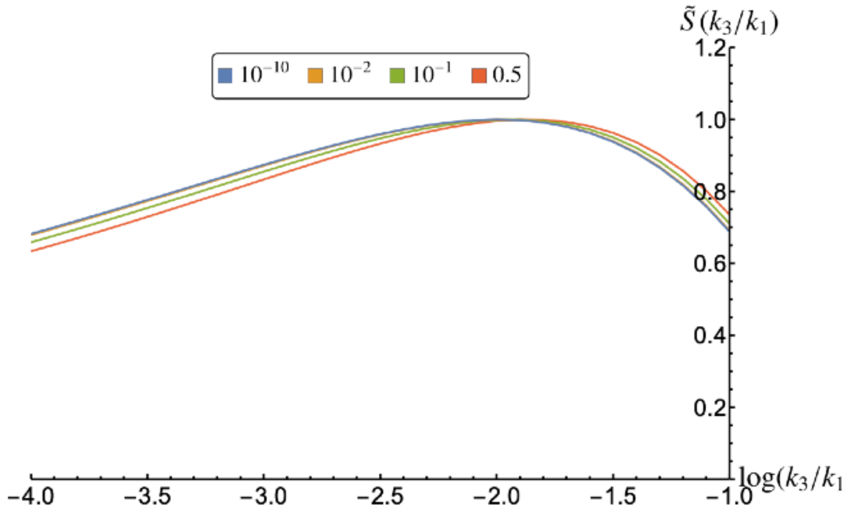
Small Bulk Mass: $m^2 \approx -4$ $L \ni \lambda O^\dagger O$ with $[O]$~2 $\beta = -\lambda^2$

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

-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 t 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!

Thank you!