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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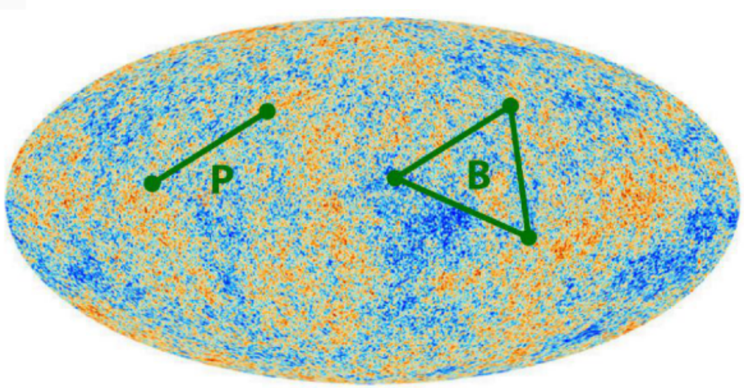
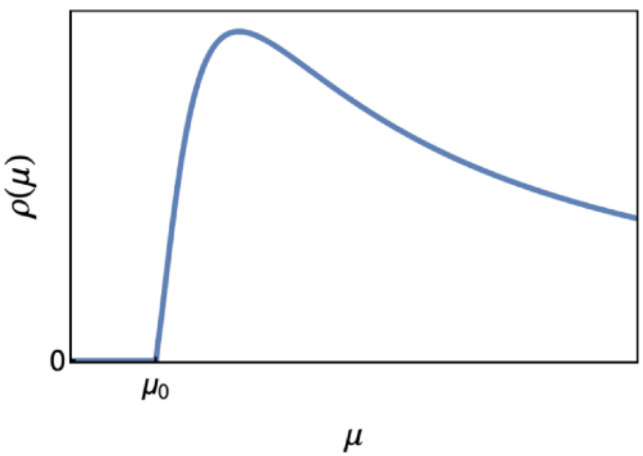
- Conformal Dark Matter production from Inflaton fields?

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.



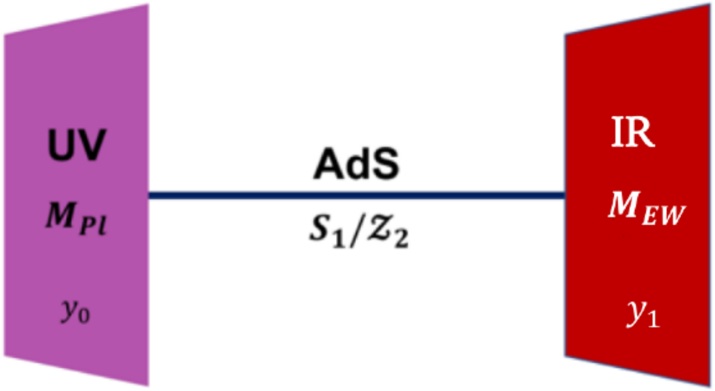


Holography

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

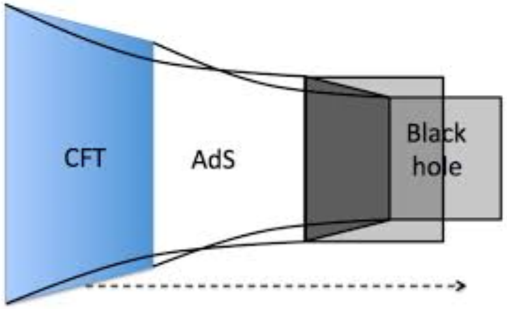


- AdS/CFT: 5D gravity ↔ 4D conformal gauge theory.
- RS1 and RS2 models as duals of large-N CFTs.
- Conformal symmetry breaking is essential for phenomenology.

AdS/CFT

$$\left\langle e^{\int d^4x \phi_0(x)\mathcal{O}(x)} \right\rangle_{\rm CFT} \approx e^{S_{\rm 5Dgravity}[\phi(x,z)|_{z=0}=\phi_0(x)]}$$

$$ds^2 = \frac{R^2}{z^2}\left(dx_\mu^2 - dz^2\right)$$



$\mathcal{O} \subset \mathrm{CFT} \leftrightarrow \phi$ AdS_5 field

AdS/CFT

$$ds^2 = \frac{R^2}{z^2}\left(dx_\mu^2 - dz^2\right)$$

$$z > \epsilon$$

$$S_{bulk} = \frac{1}{2}\int d^4x dz \sqrt{g}(g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi + m^2\phi^2)$$

$$\phi(p, z) = az^2 J_\nu(pz) + bz^2 J_{-\nu}(pz)$$

$$\Delta[\mathcal{O}] = 2 \pm \nu = 2 \pm \sqrt{4 + m^2 R^2}$$

$$< \mathcal{O}(p)\mathcal{O}(p) > \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2}(p^2)^{\Delta-2}$$

Witten, Klebanov 99’

AdS/CFT

CFT completely specified by 2-point function - rest vanish

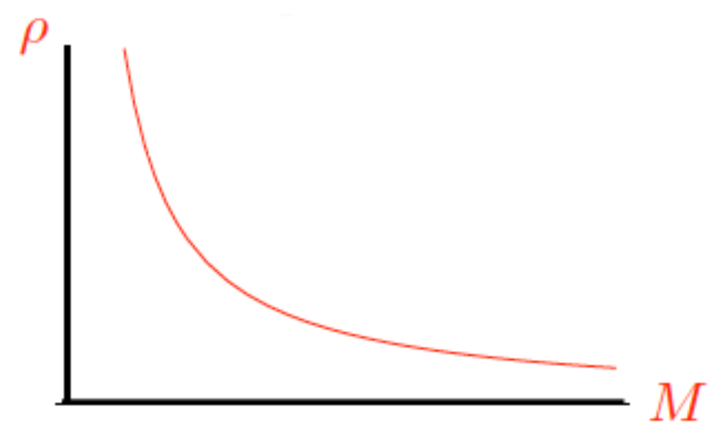
Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$

Can be generated from: $\mathcal{L}_{\mathrm{GFF}} = -\mathcal{h}^\dagger \left(\partial^2\right)^{2-\Delta} \mathcal{h}$

Georgi
hep-ph/070326

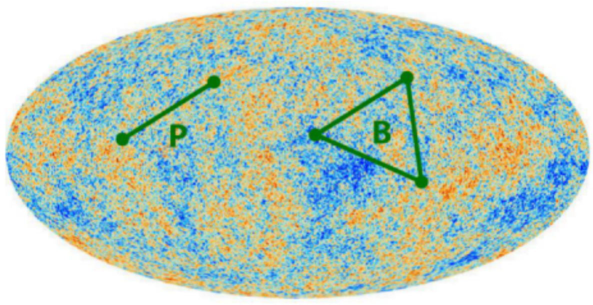
Branch cut starting at origin - spectral density purely a continuum:

$$G(p) \sim \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$

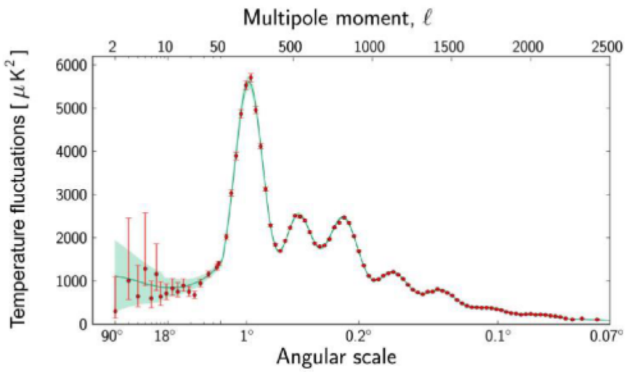


Inflation

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

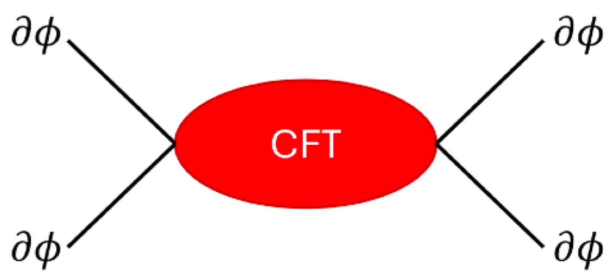


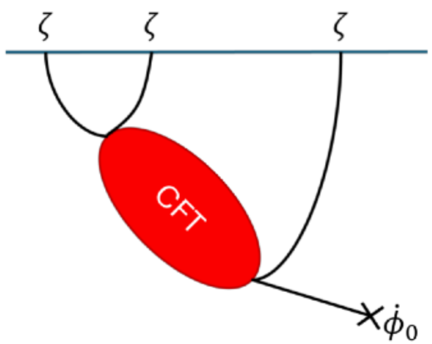
Non-Gaussianities and beyond the power spectrum?

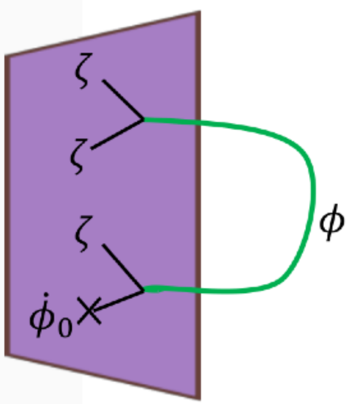
$n_s = 0.9649 \pm 0.0042$
$\Delta T/T \sim 10^{-5}$

- 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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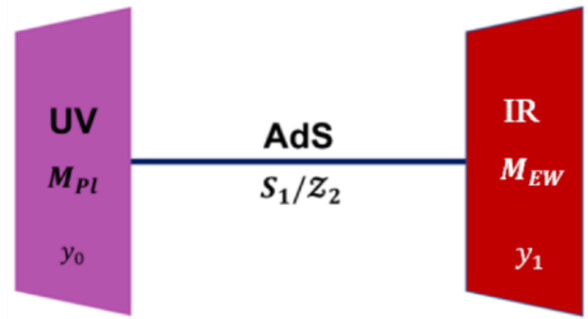
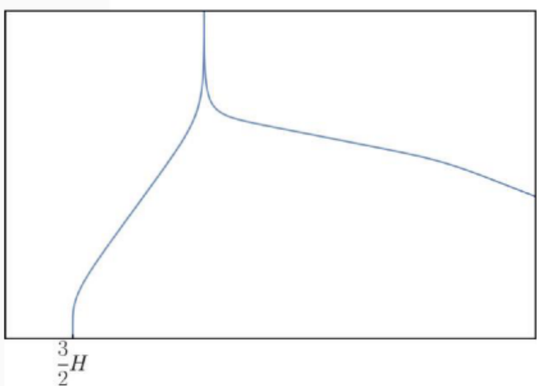
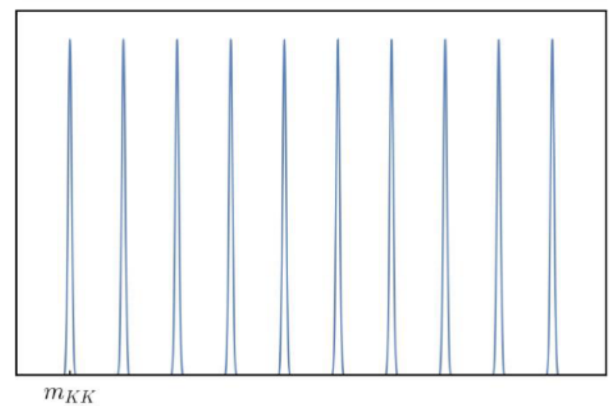
$$ds^2 = e^{-2A(w)}(dt^2 - e^{2Ht}dx^2 - dw^2)$$

$$e^{-A(w)} = \frac{H}{k \sinh Hw}$$

Late Time







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:

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

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

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

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:

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

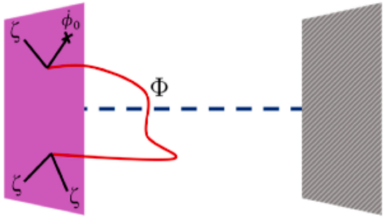
$$G(z) = \sqrt{1 + H^2 z^2}.$$

The metric has a singularity at $z \to \infty$, 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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Bulk scalar eom: $-\phi'' + 3A'\phi' + m^2 e^{-2A(w)}\phi = -\Box_{dS_4}\phi \equiv \mu^2\phi.$

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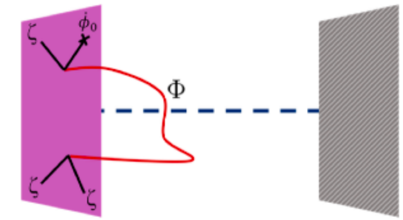

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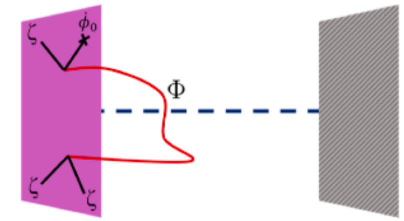

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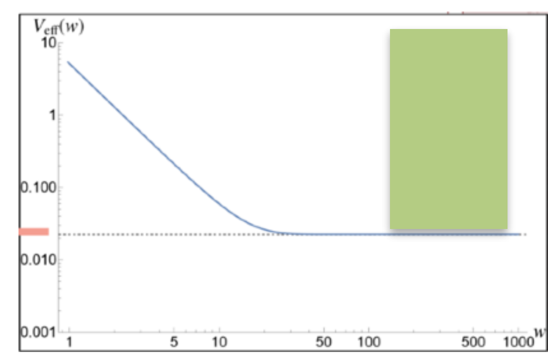

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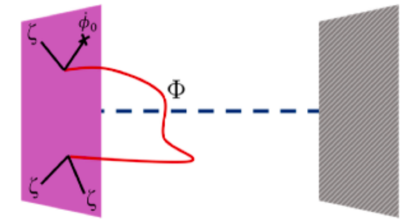

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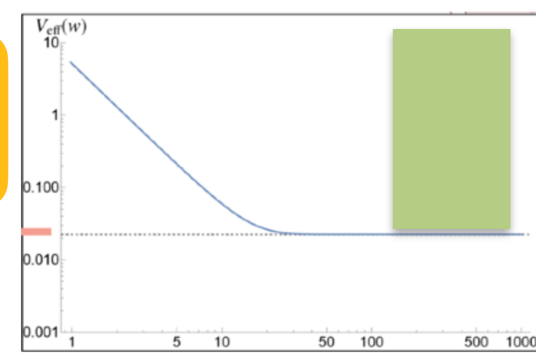
if $V \xrightarrow[w\to\infty]{} \mu_0^2$ = finite => Continuum with Mass Gap! 1D QM problem



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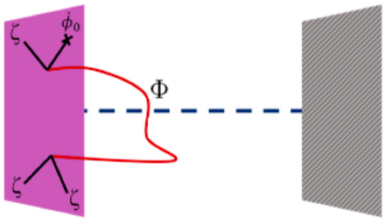

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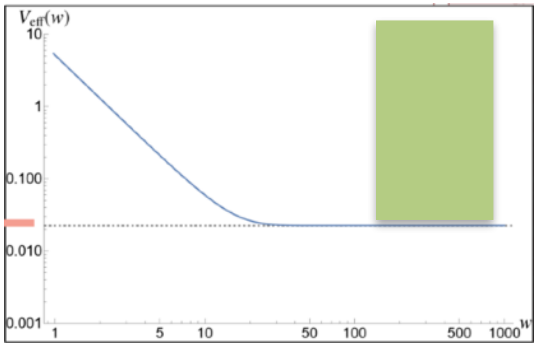

$V(w) \to \frac{9}{4}H^2$ as $w \to \infty$.

=> continuum begins at: $\mu_0 = (3/2)*H$ for $\xi=0$

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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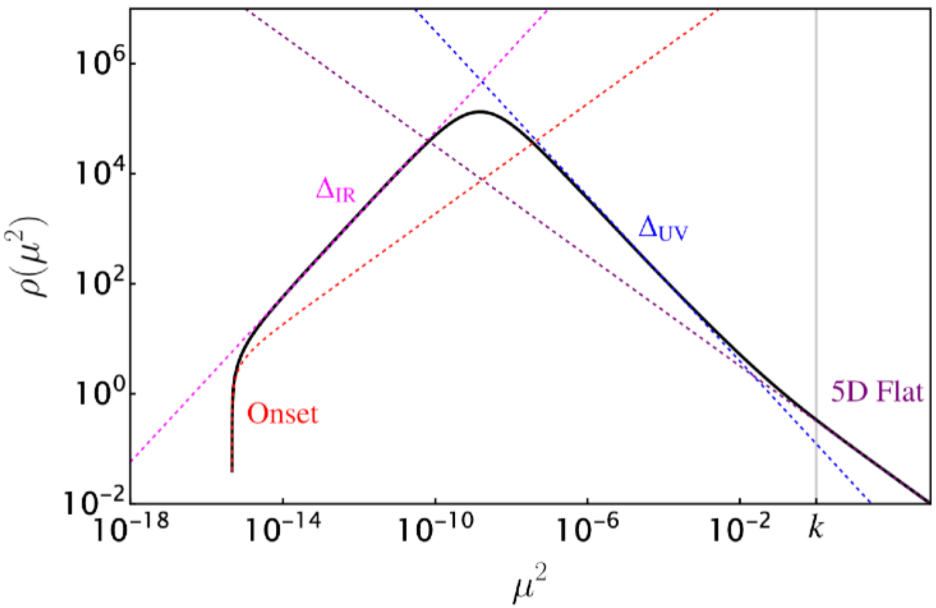

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$\Delta_{UV} = \nu$, rather than $\Delta_{UV} = \Delta_- = 2 - \nu$

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

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

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

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

unitarity bound, $\Delta \geq 1$

- For RS type of model: $m^2 > -3$ becomes interesting (less studied)

  $\Delta_{UV} = \Delta_-$ scaling is prohibited by unitarity constraints: $\Delta \geq 1$

Two possibilities:

1. Conformal invariance is completely broken at high scales where the theory would have followed the $\Delta_- < 1$ scaling law
2. theory is still conformal, but exhibits a scaling law that differs from the prediction

$\Delta_{UV} = \nu$, rather than $\Delta_{UV} = \Delta_- = 2 - \nu$

- 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

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

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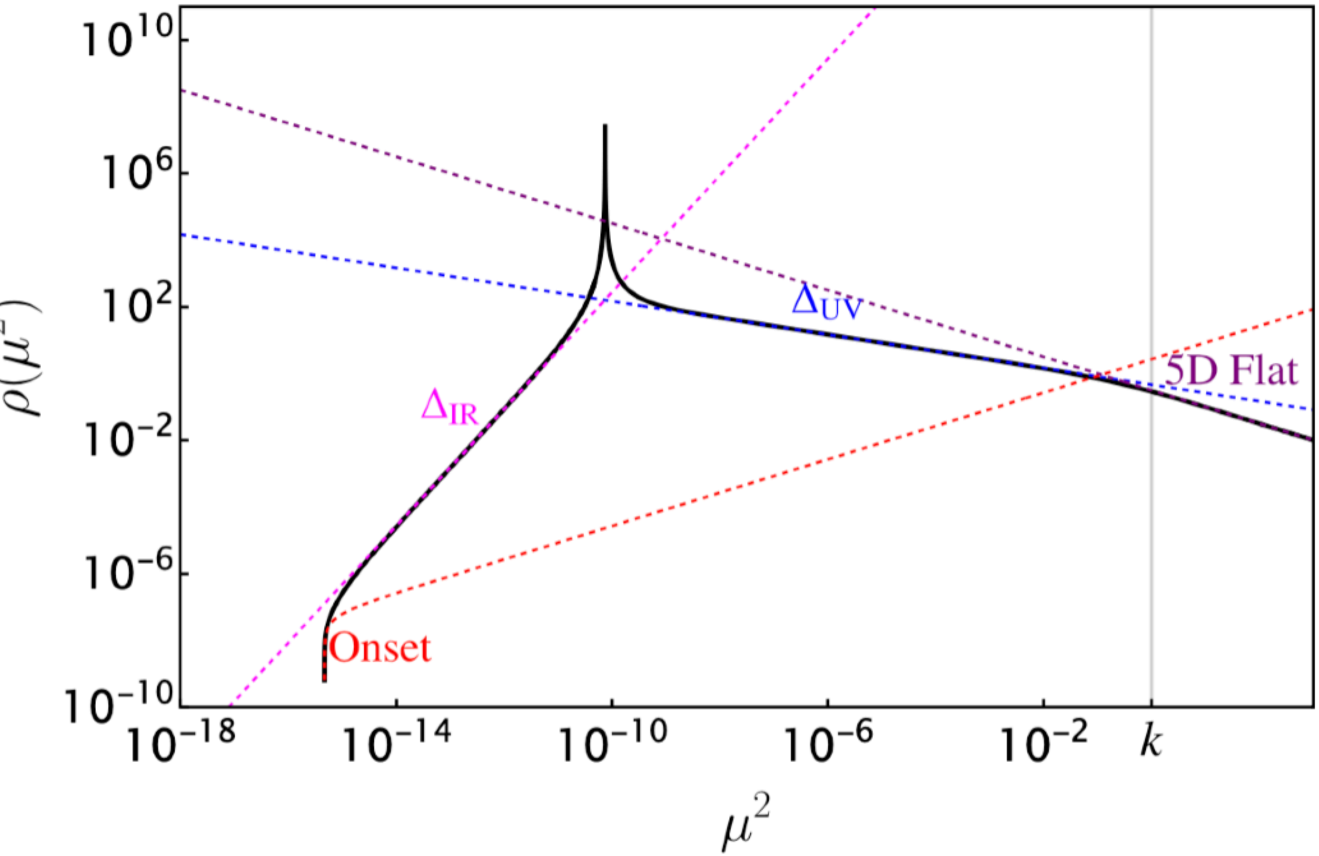

- Emergence of Particle:

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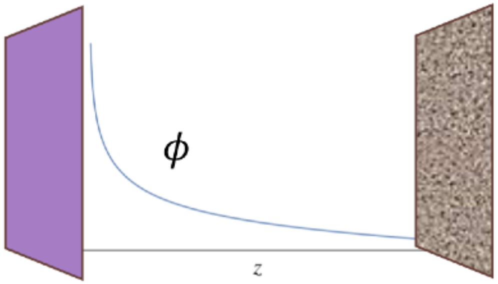
UV / IR localized light mode

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

Light mode: discrete mode below the gap



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

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

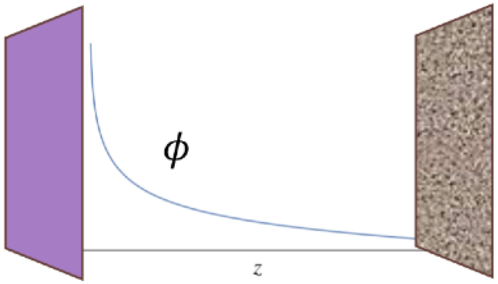
- Tune brane mass $m_0^2 \approx 2(2-\nu)$
- CFT language: Fundamental bound state in the spectrum mixing with the CFT states; CFT deformation by H backreacts to modify the mass of the particle eigenstate

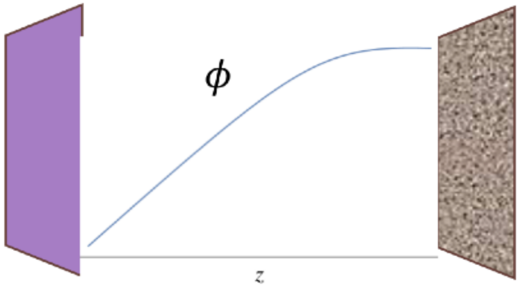
Quasiparticles

UV / IR localized light mode

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

Light mode: discrete mode below the gap





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

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

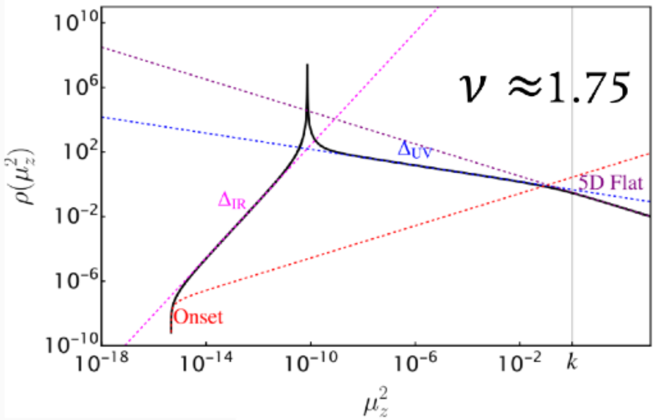
- Analogous to the horizon localized solutions in Schwarzchild geometries for light scalar fields
- CFT language: Mostly composite modes of the near-conformal dynamics. They only exist during the inflationary epoch

Quasiparticles

Cosmological Quasiparticles:

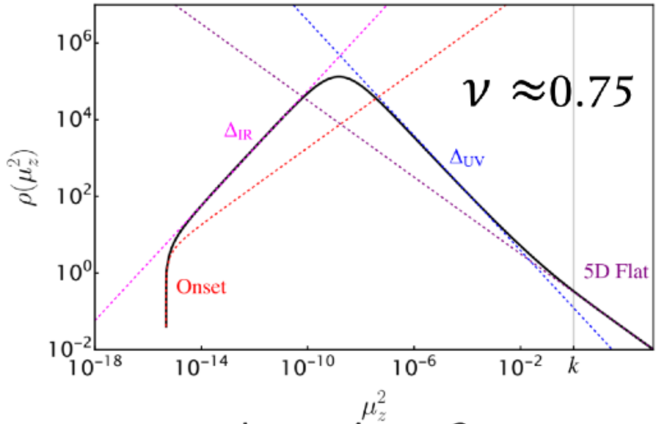
Anatomy of Spectral density and Scaling dimension

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



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

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



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

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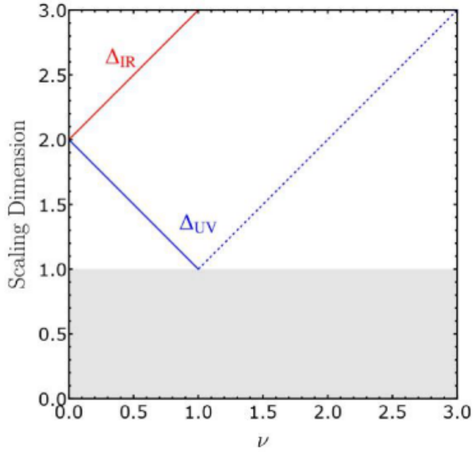


Solutions of 5D scalar equation yield two scaling dimensions:

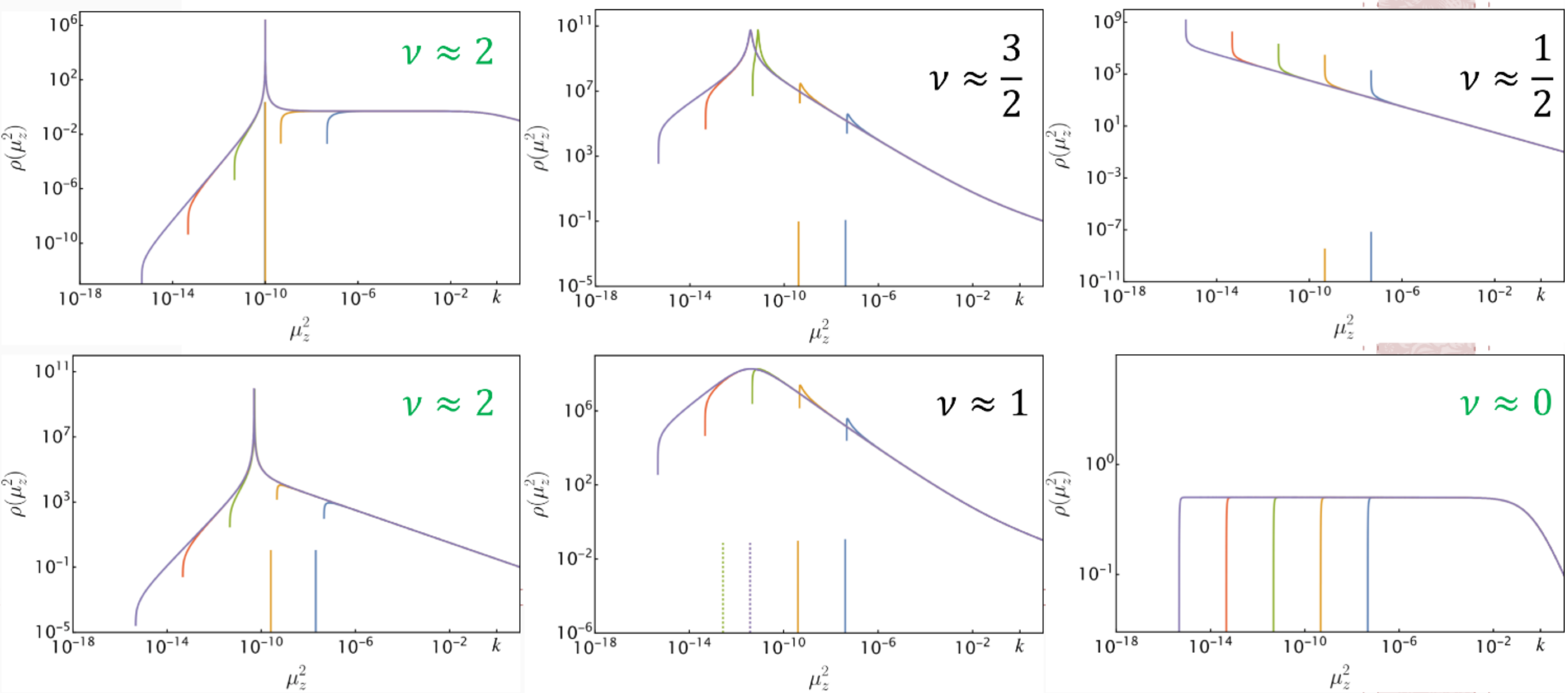
$$\Delta_\pm = 2 \pm \nu = 2 \pm \sqrt{4 + m^2}$$

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

Spectral Density Plots

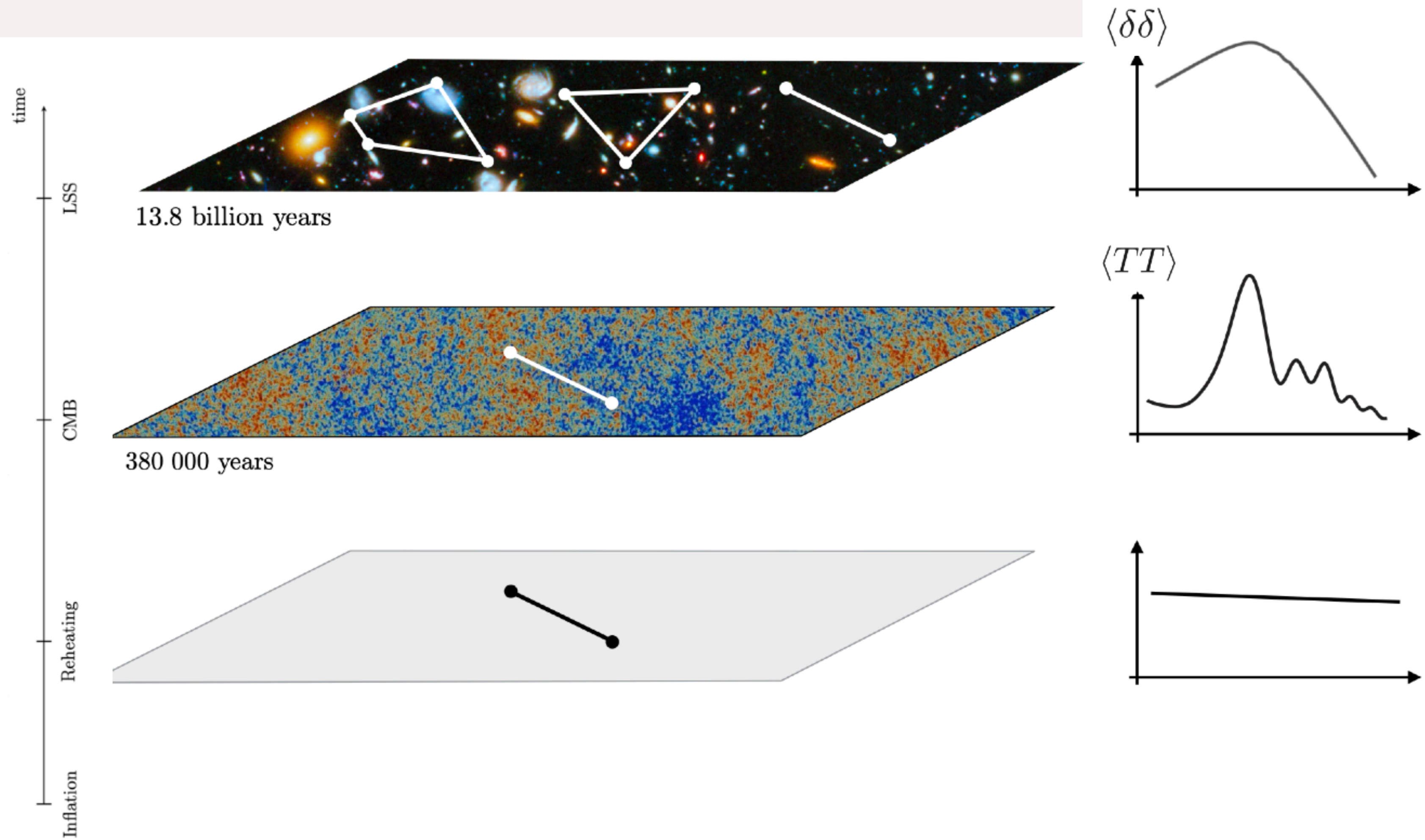
$\delta \equiv m_0^2 - 2(2-\nu)$

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



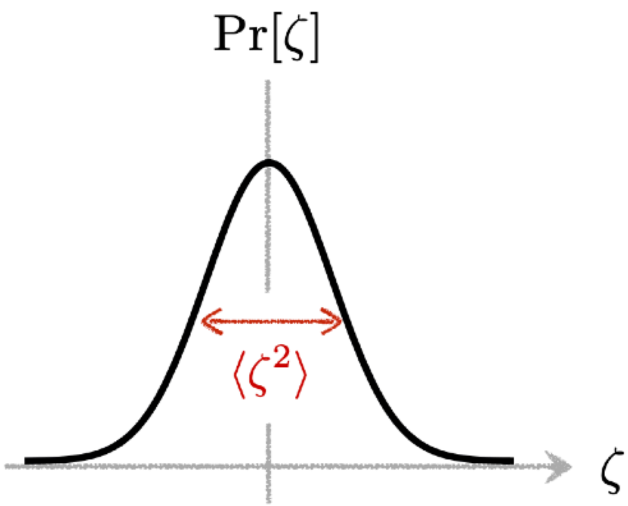
Cosmological Collider Physics (Basic review)

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.

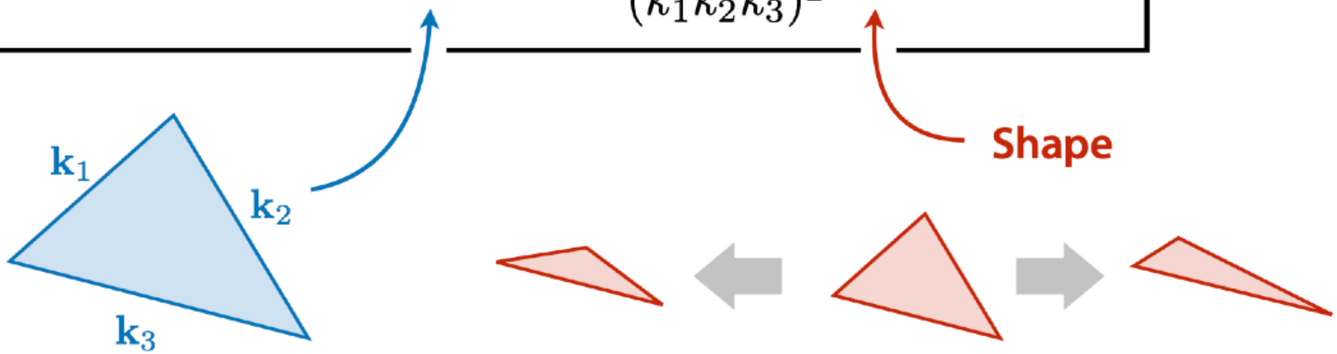
So far, we have only studied the free theory.

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:

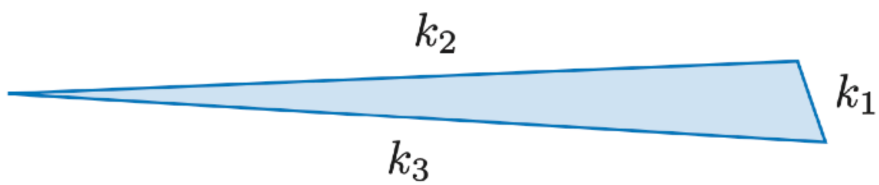
$$F_{\rm NL}(k) \equiv \frac{5}{18} \frac{B_\zeta(k,k,k)}{\Delta_\zeta^3(k)}$$

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

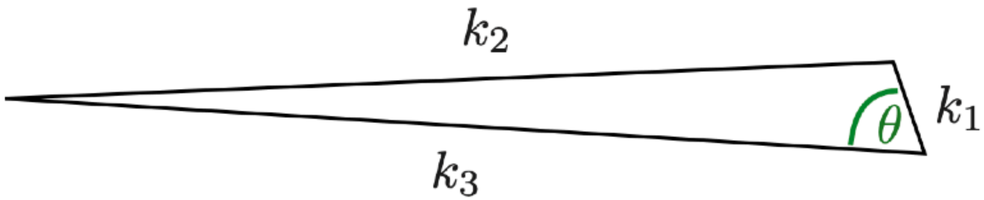
Maldacena [2003]
Creminelli and Zaldarriaga [2004]

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 signal depends on the masses and spins of the new particles:



$$\lim_{k_1 \to 0} \langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \propto \begin{cases} \left(\frac{k_1}{k_3}\right)^{\Delta} & m < \frac{3}{2}H \\ \left(\frac{k_1}{k_3}\right)^{3/2} \cos\left[\mu \ln \frac{k_1}{k_3}\right] & m > \frac{3}{2}H \end{cases}$$

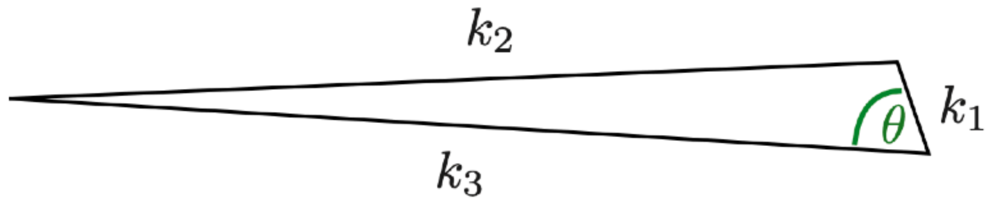
$$\propto \quad P_J(\cos\theta)$$

spin

Arkani-Hamed and Maldacena [2015]

Cosmological Collider Physics (Basic review)

The signal depends on the masses and spins of the new particles:



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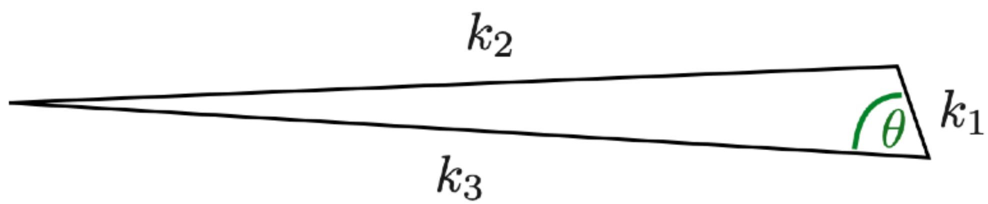

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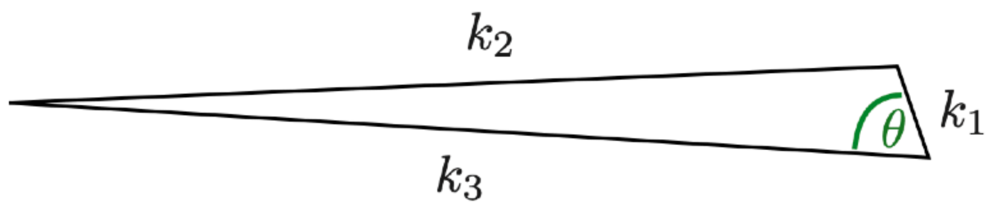

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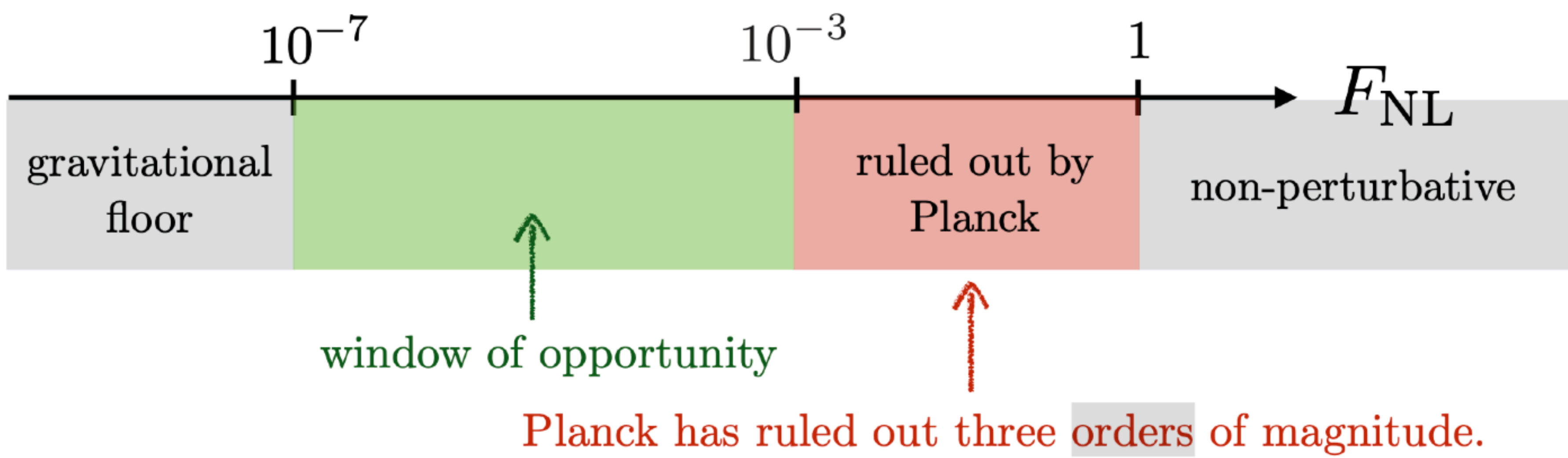
$$\propto \quad P_J(\cos\theta)$$

spin

Arkani-Hamed and Maldacena [2015]

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

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

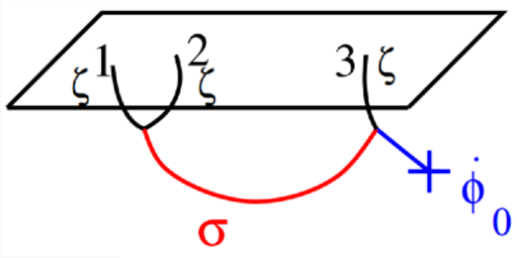
$$\zeta = -\frac{H}{\dot{\phi}_0}\xi$$

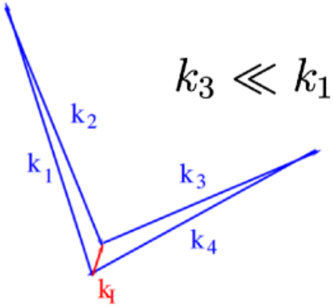
Cosmological Collider Physics

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)





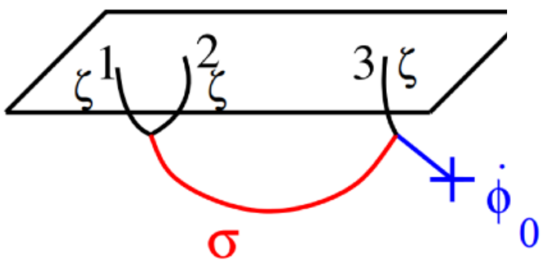
$k_3 \ll k_{1,2}$: squeezed limit

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

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

Bispectrum

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



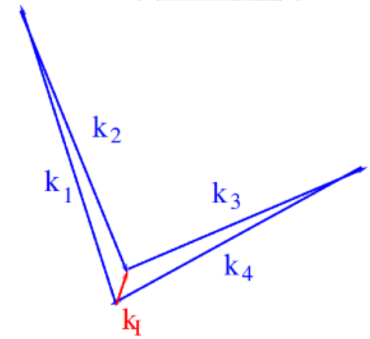
- Currently, let us focus on the non-local contributions in position space, i.e., terms that are non-analytic in k

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

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

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

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

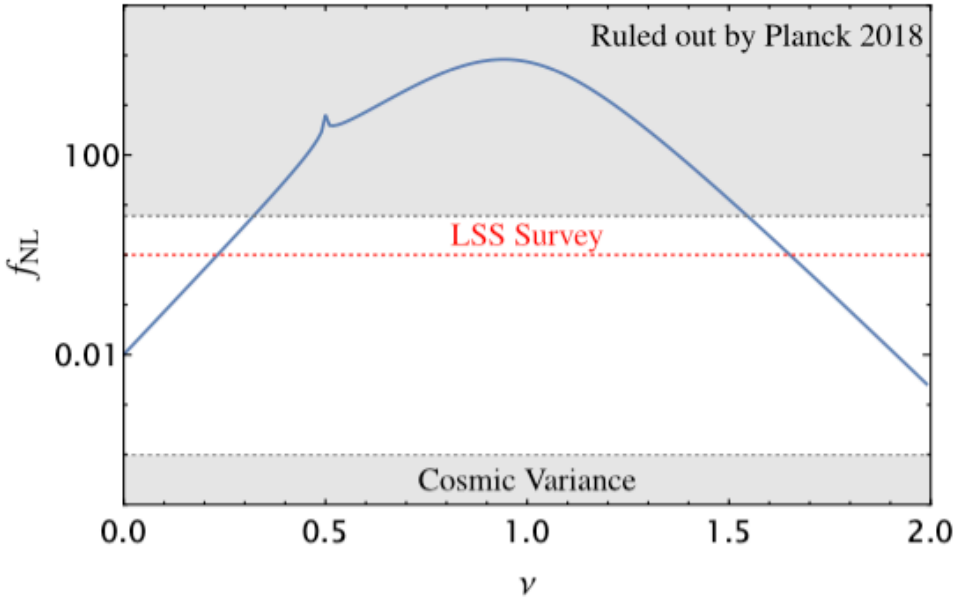


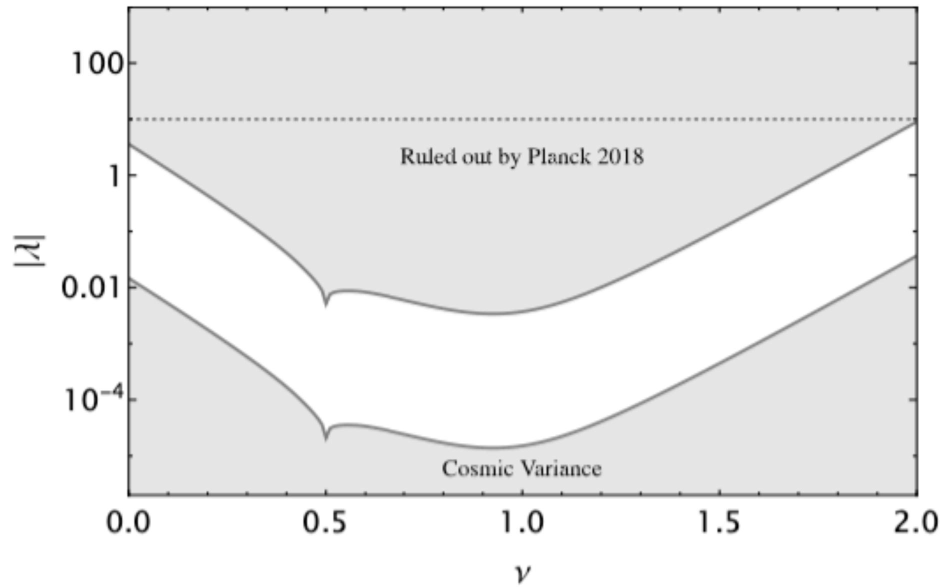
- Fluctuations of the inflaton $\phi(t,x)=\phi_0(t)+\xi(t,x)$ can be related to the curvature fluctuation

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

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

Results of non-Gaussianity





λ=1 (in unit of k, the AdS curvature)

H=10^13 GeV

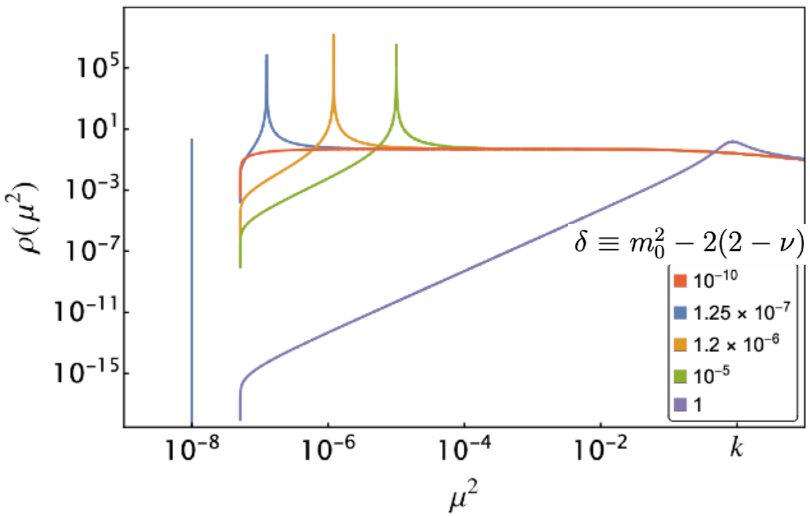
$\frac{k_3}{k_1} = 0.1$

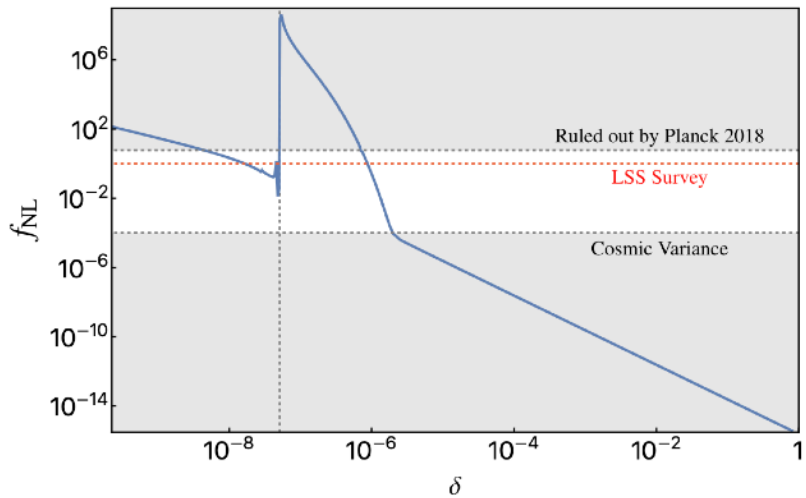
Coupling term: $\lambda\phi(\nabla\zeta)^2$

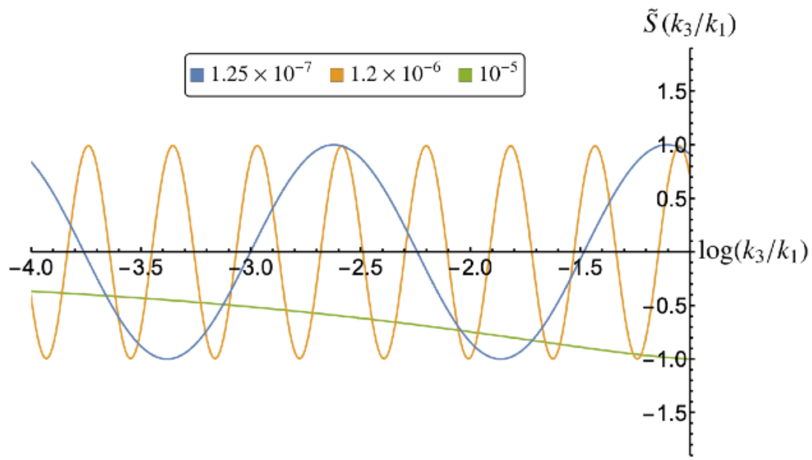
Shaded area: Ruled out

Blank: Allowed according to current experiments nearly marginal, runs slowly. Confinement thus occurs through a form of dimensional transmutation, stabilizing the Planck-Weak hierarchy

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







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

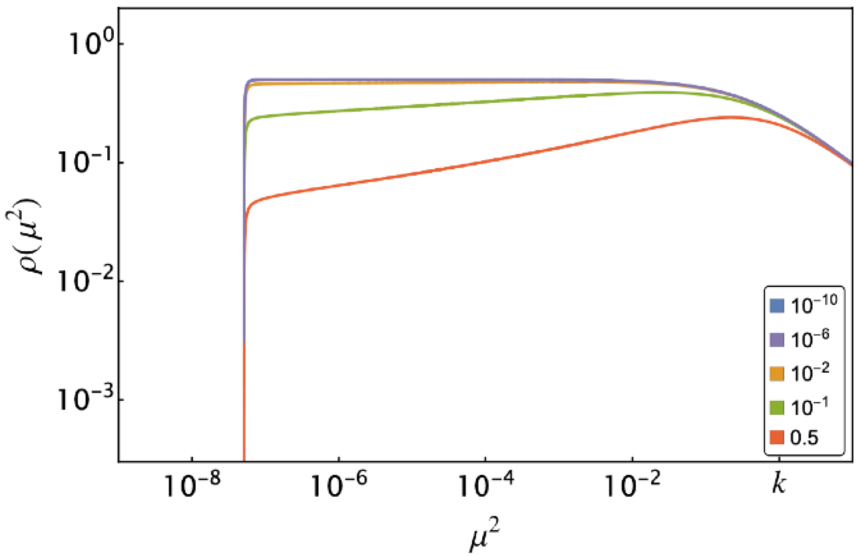
$$F_{\rm NL}(k_3/k_1) = f_{\rm NL}\left(\frac{k_3}{k_1}\right)^{3/2}\widetilde{S}(k_3/k_1),$$

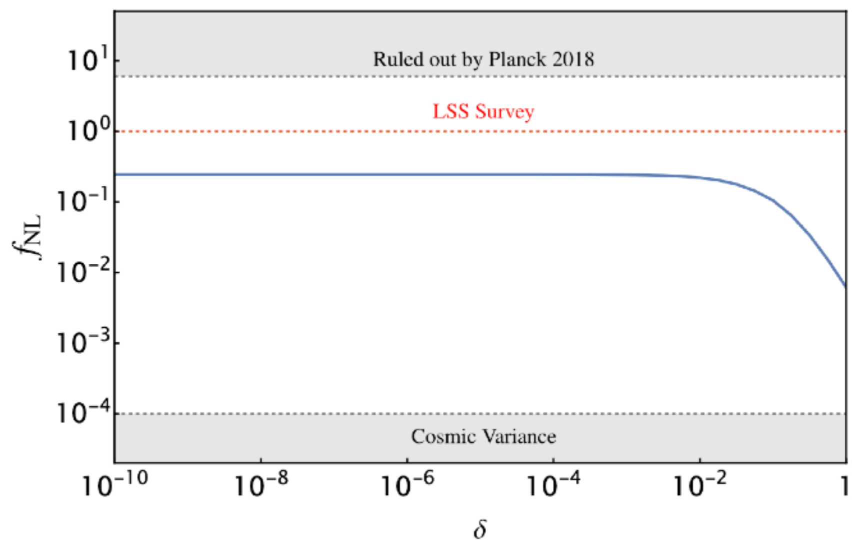
The spectral densities and f_{NL} when the scalar bulk mass $m^2 \sim 0$ for various values of UV brane mistunes, δ. We also show some of the shape functions, which exhibit clear oscillatory behavior when there is a particle slightly above the critical mass, $3/2H$.

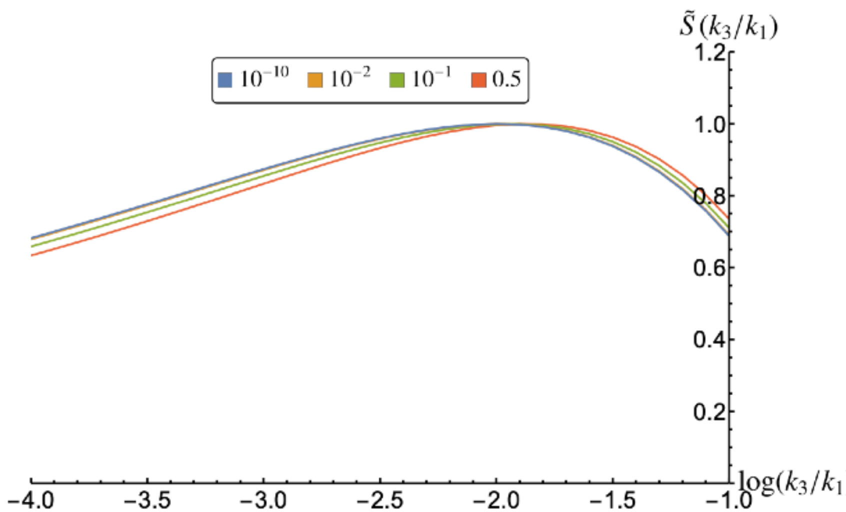
Small Bulk Mass: $m^2 \approx -4$ $L \ni \lambda O^\dagger O$ with $[O] \sim 2$ $\beta = -\lambda^2$

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

-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!