

# Continuous spectrum on cosmological collider

**Shuntaro Aoki**

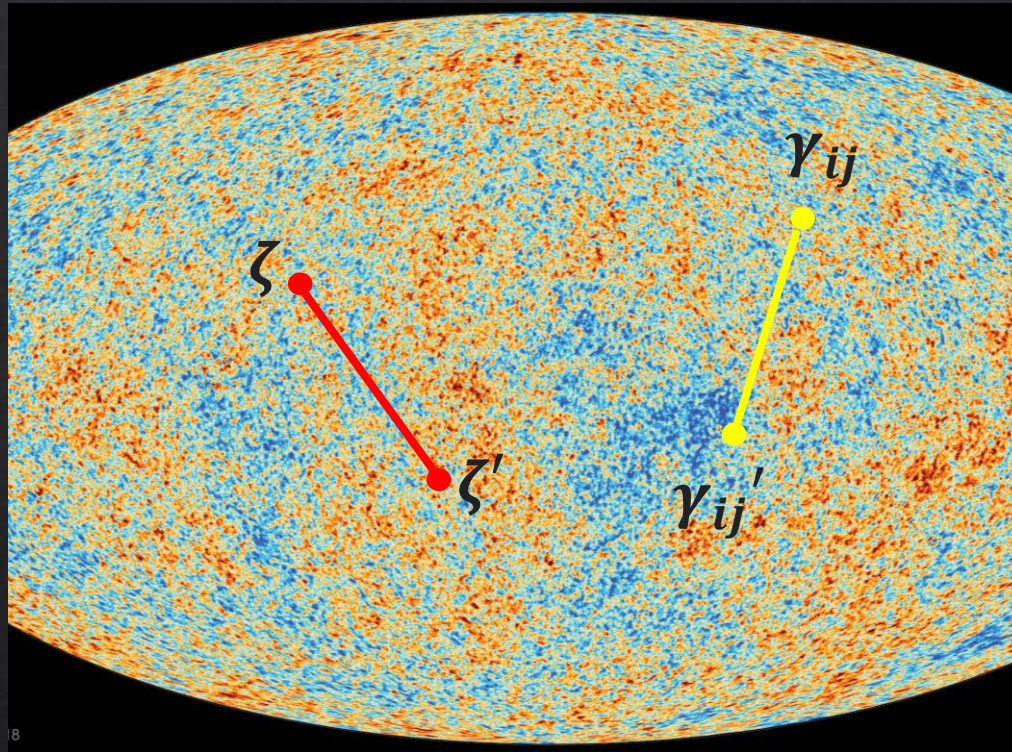
(Chung-Ang University)

based on [2301.07920](#)



CAU BSM workshop  
23/2/2023

# Inflationary observable



scalar power spectrum:  $P_\zeta \sim \langle \zeta \zeta' \rangle$

tensor power spectrum:  $P_\gamma \sim \langle \gamma \gamma' \rangle$

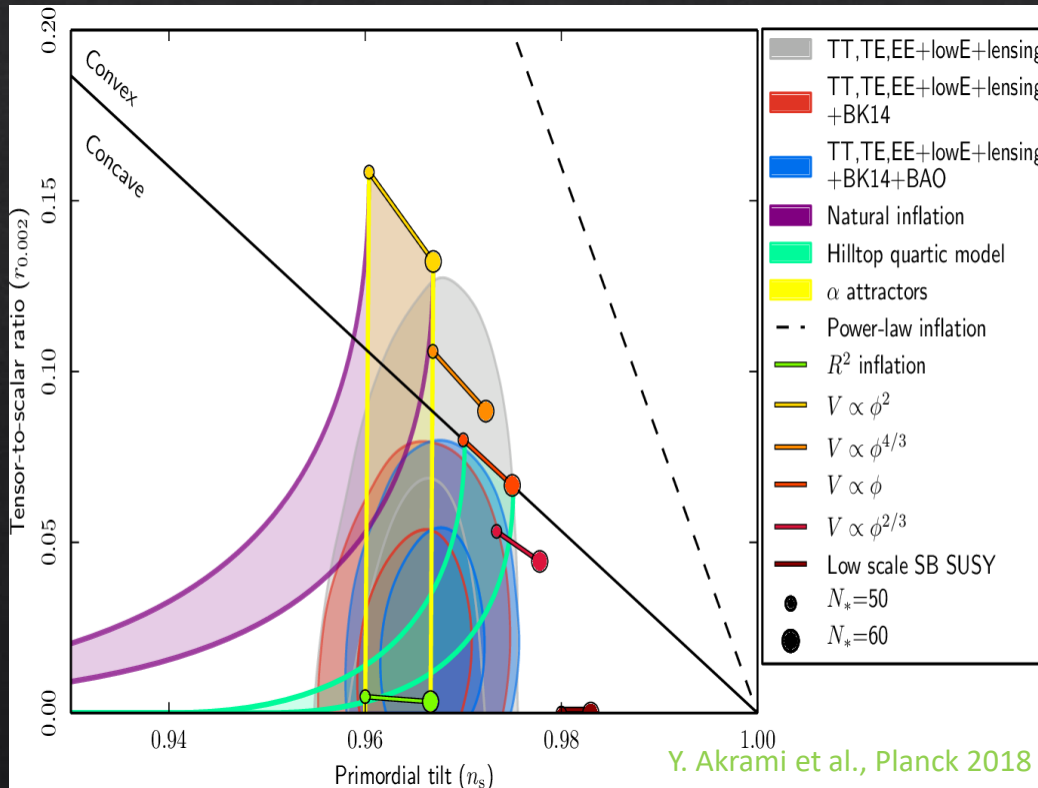
spectral tilt:  $n_s - 1 = \frac{d \ln P_\zeta}{d \ln k}, \dots$

# Restrictions on inflaton potential

$$n_s - 1 = \frac{d \ln P_\zeta}{d \ln k} = -3 \left( \frac{V'}{V} \right)^2 + 2 \frac{V''}{V}$$

$$r = \frac{P_\gamma}{P_\zeta} = 8 \left( \frac{V'}{V} \right)^2$$

$r$

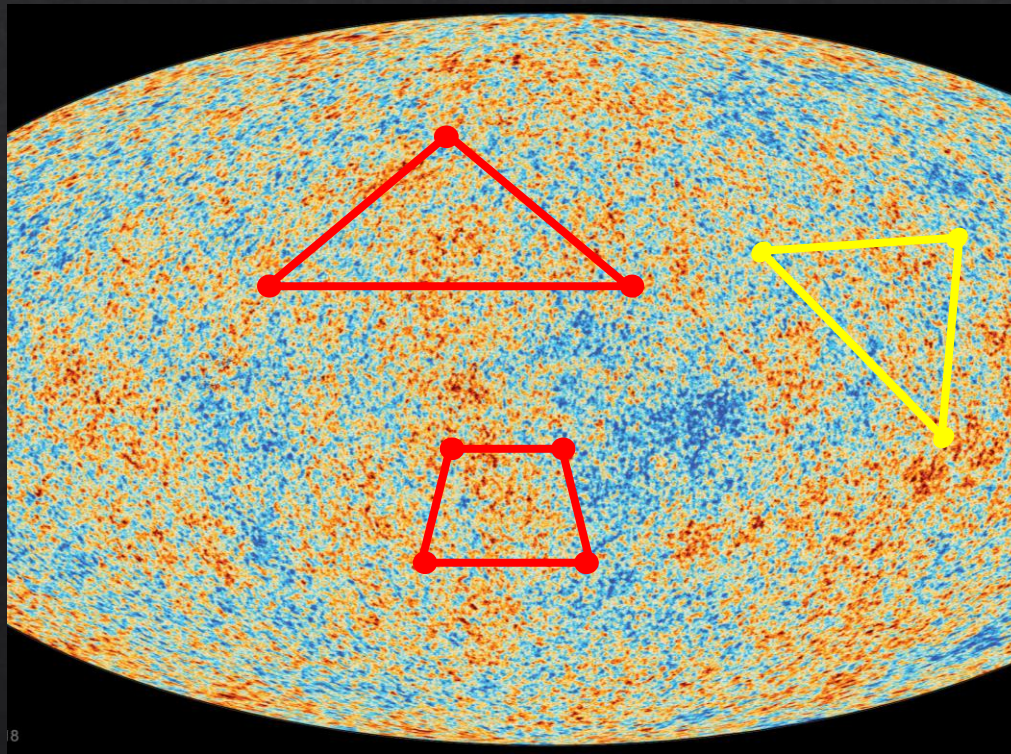


Y. Akrami et al., Planck 2018

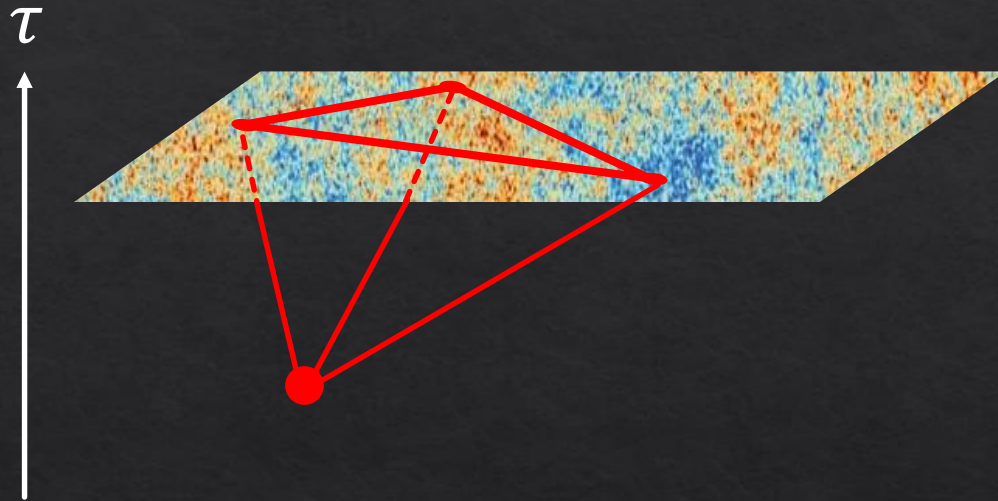
$n_s$

# Beyond 2-pt. function: non-Gaussianity (NG)

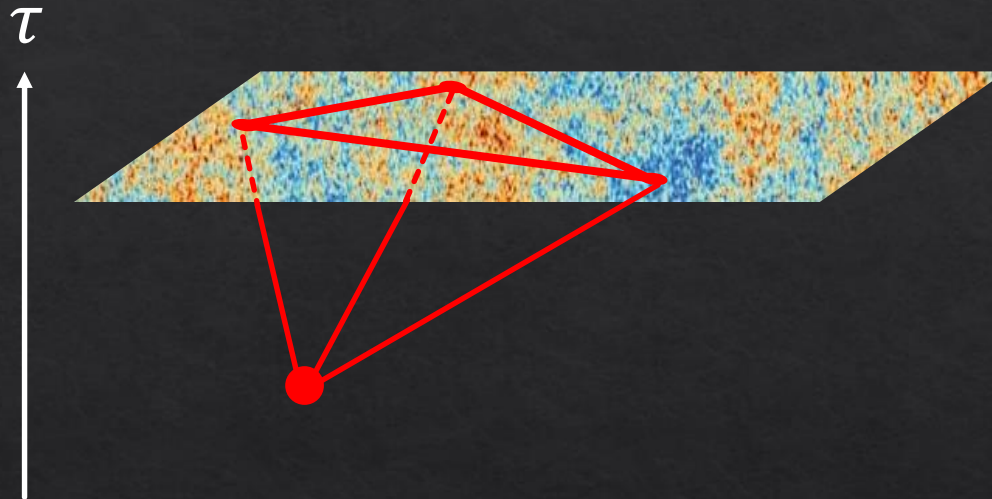
$\langle \zeta^3 \rangle$  : Bispectrum,  $\langle \zeta^4 \rangle$  : trispectrum, ...



# NG from self-interaction



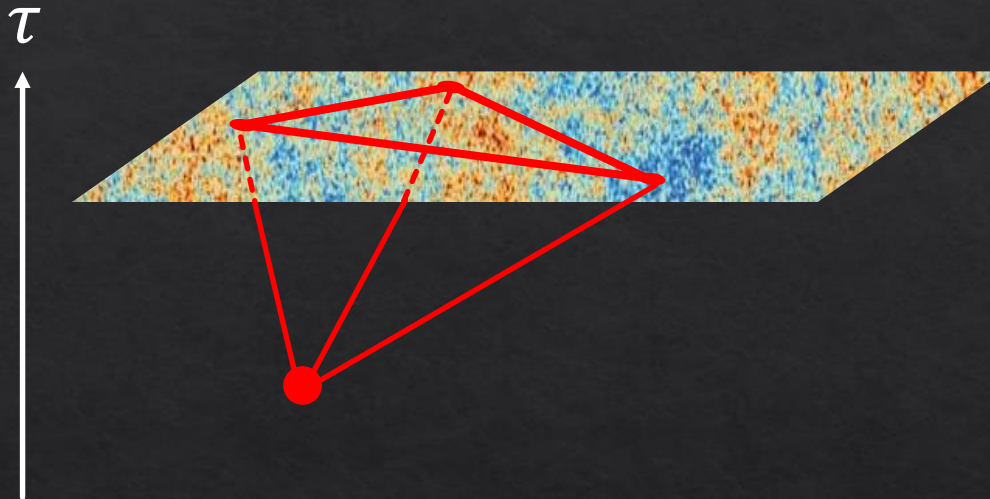
# NG from self-interaction



- $f_{\text{NL}} \sim \mathcal{O}(\epsilon)$  for simple model Maldacena '03

simple : single scalar + Einstein gravity + canonical kinetic term + slow-roll

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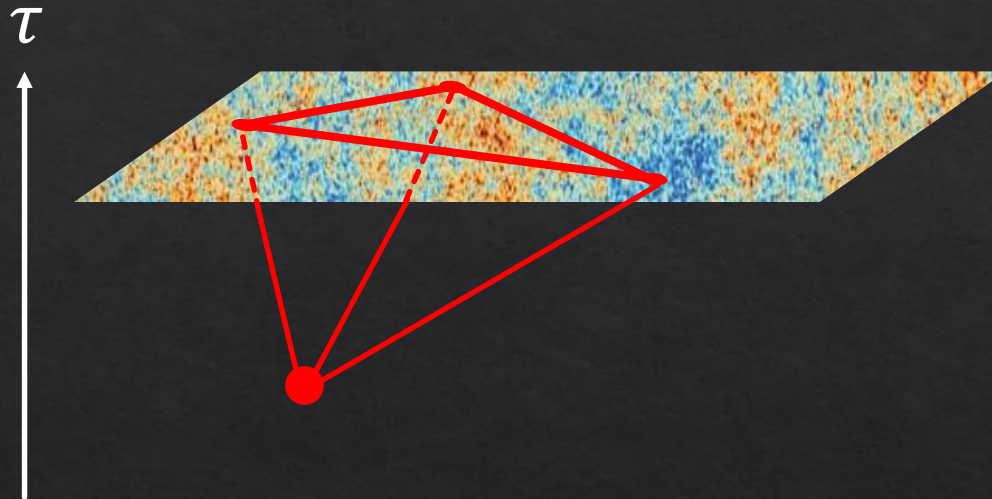


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- $f_{\text{NL}} \gg 1$  for more general class of inflation models

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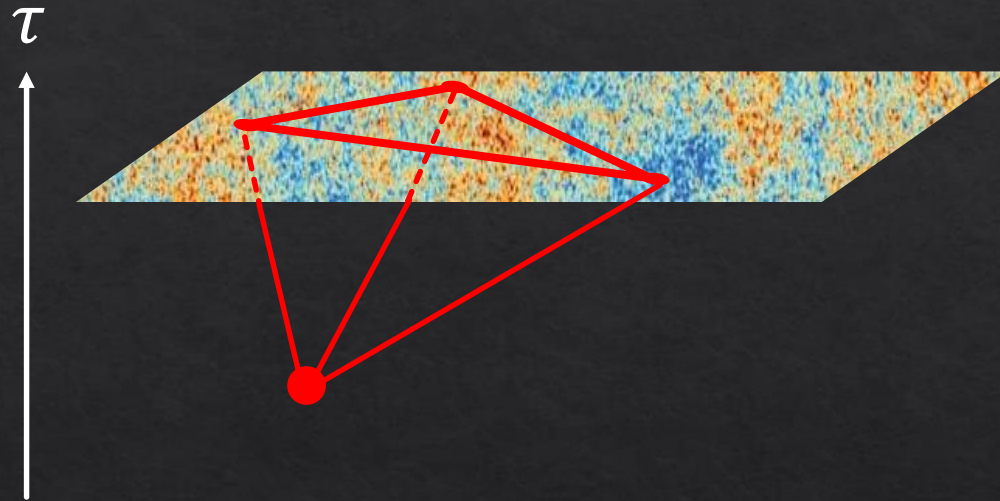
- $f_{\text{NL}} \gg 1$  for more general class of inflation models
- Observational constraints :

$$f_{\text{NL}}^{\text{local}} = 2.7 \pm 5.8, f_{\text{NL}}^{\text{equil}} = -42 \pm 75, \text{ and } f_{\text{NL}}^{\text{ortho}} = -25 \pm 39$$

From Shellard's slide

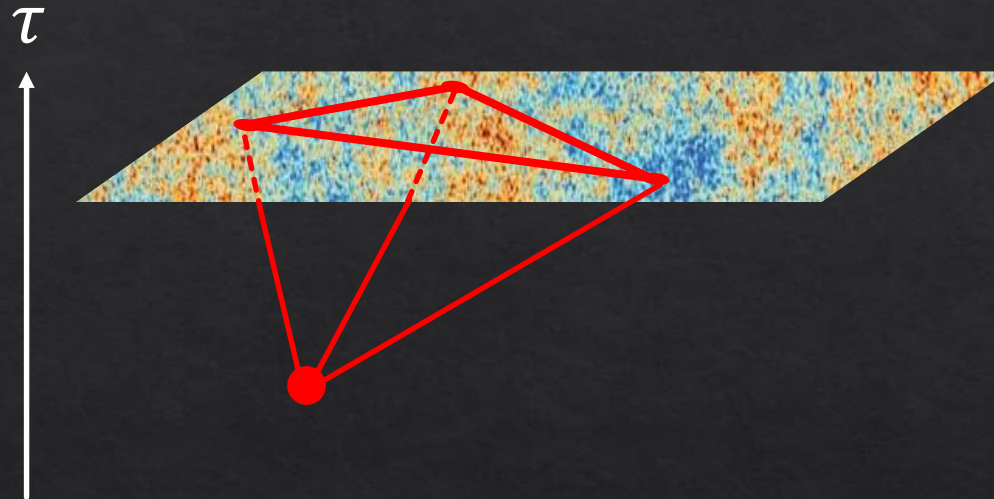


# NG from self-interaction



NG  $\rightarrow$  strong restrictions on inflation models

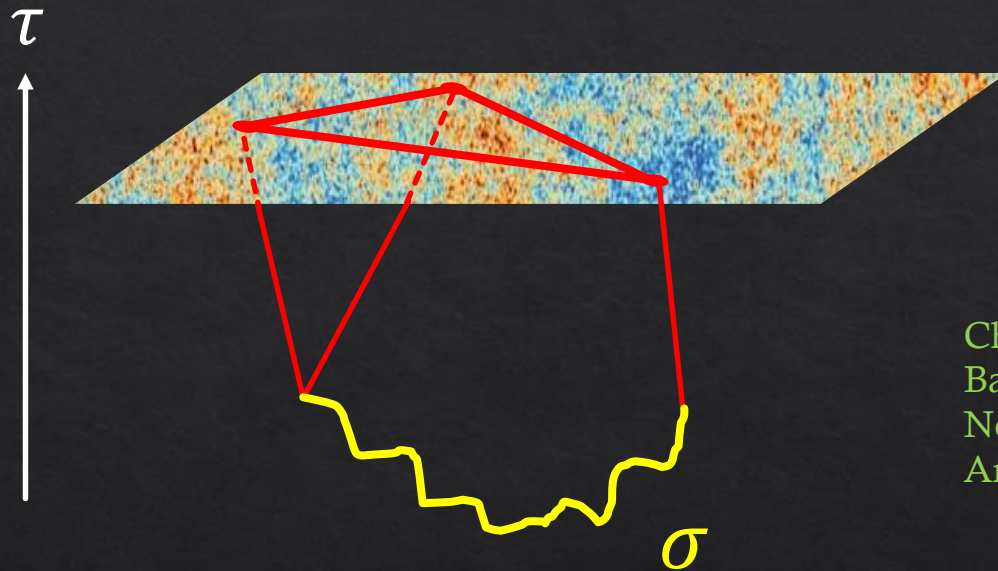
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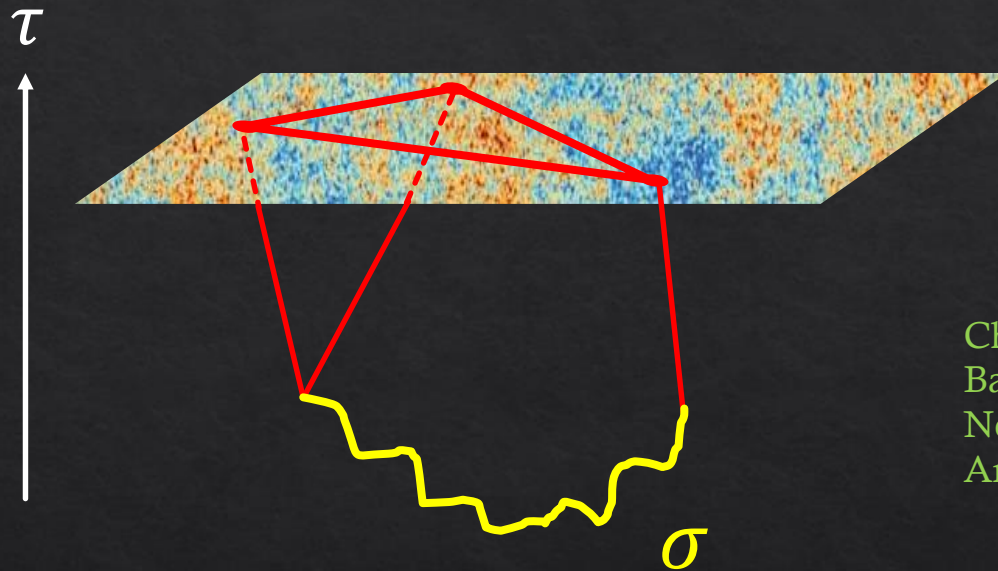
There's more: Cosmological collider (CC)

# Cosmological collider (CC)



Chen, Wang, '10  
Baumann, Green, '12  
Noumi, Yamaguchi, Yokoyama, '13  
Arkani-Hamed, Maldacena, '15

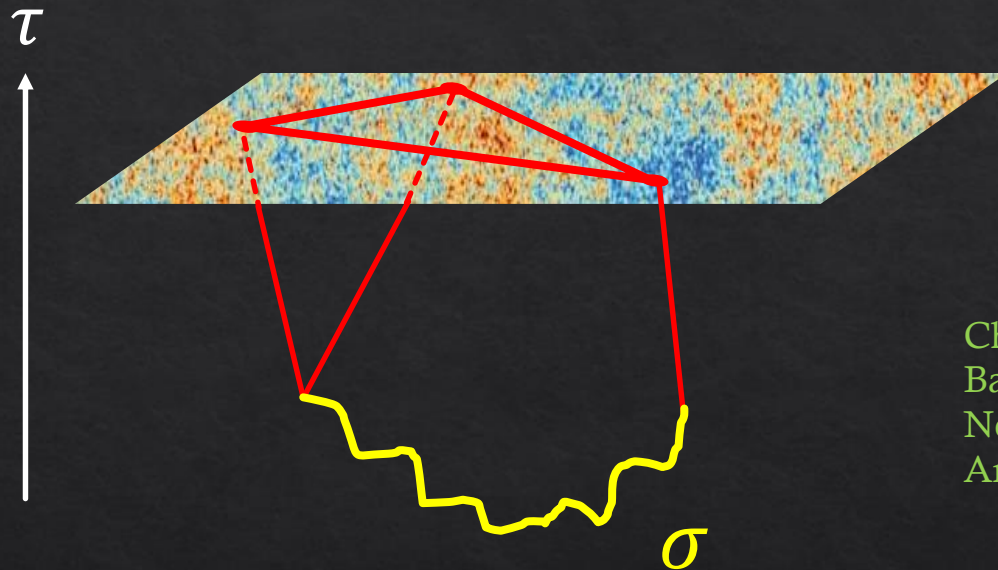
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- NG can contain information of heavy (new) particle  $\sigma$  with specific **oscillation** signal

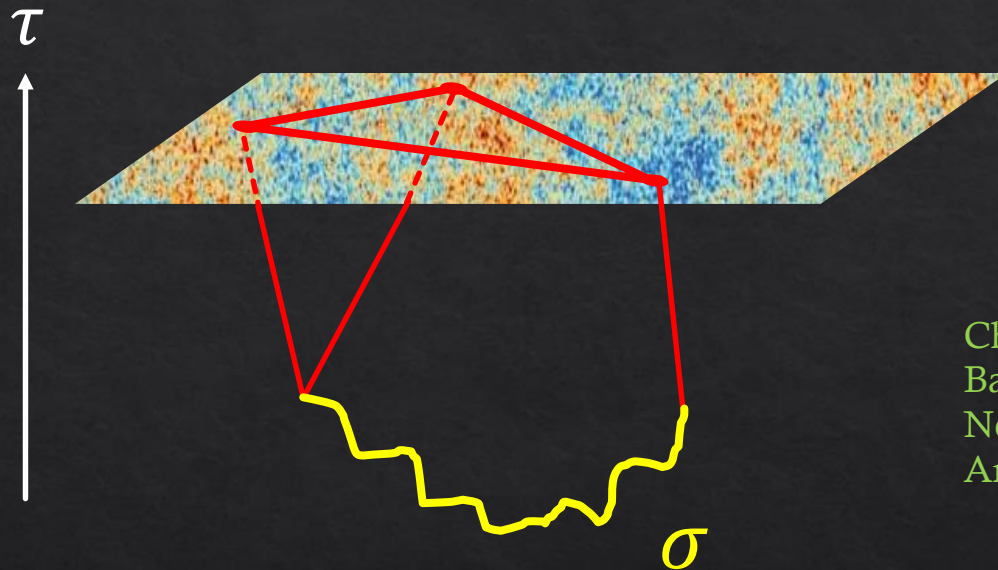
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- $m_\sigma \sim H \sim 10^{13} (\text{GeV}) \gg$  energy scale of terrestrial experiment

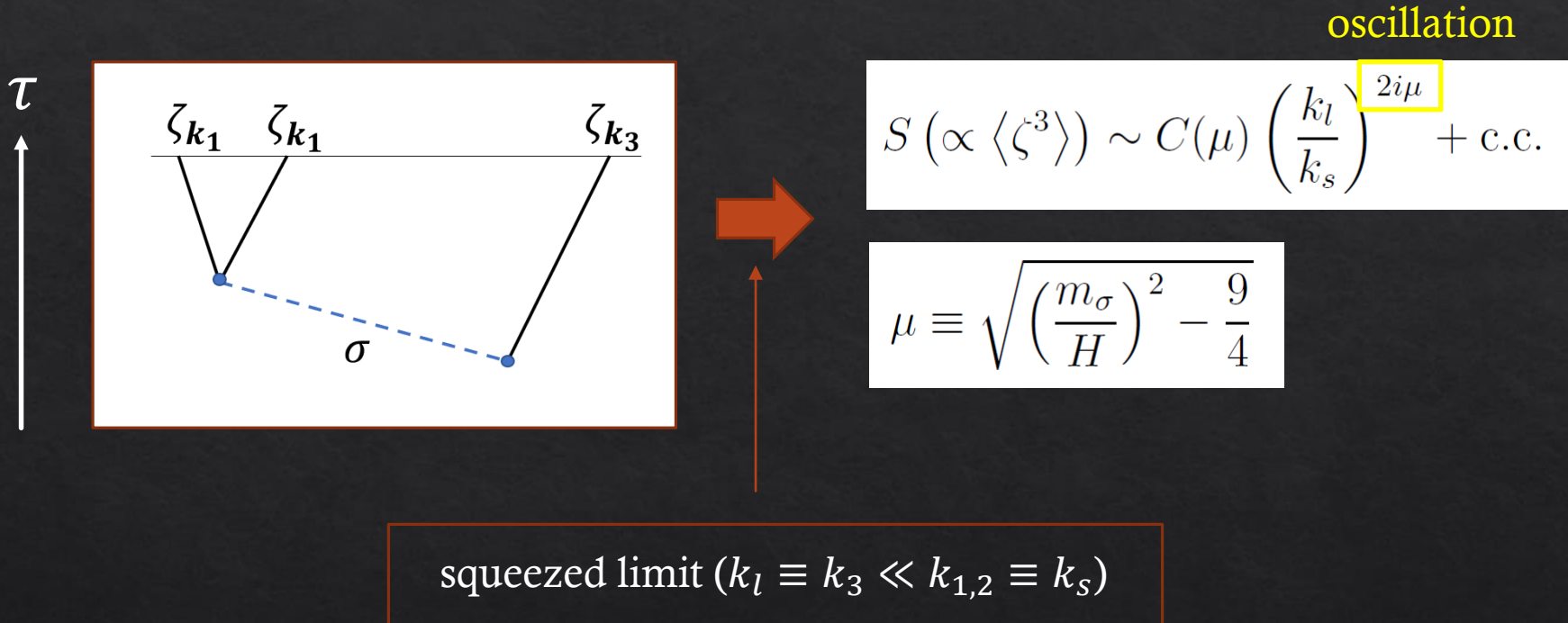
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- NG can contain information of heavy (new) particle  $\sigma$  with specific **oscillation** signal
- $m_\sigma \sim H \sim 10^{13} \text{ (GeV)} \gg$  energy scale of terrestrial experiment
- Signal can be large!!

# Example: scalar $\sigma$



Can read off the mass of a new particle from frequency

# Many works

## On search for new physics

- ✓ SUSY (Baumann, Green, '12)
- ✓ General interactions for a massive scalar by EFT approach (Noumi, Yamaguchi, Yokoyama, '13)
- ✓ Higher spin (H. Lee, D. Baumann, and G. L. Pimentel, '16)
- ✓ Standard model particles, Neutrino (Chen, Wang, Xianyu, '16)
- ✓ Leptogenesis (Cui, Xianyu '21)
- ✓ GUT (Maru, Okawa, '21)
- ...

## Bootstrapping approach

Arkani-Hamed, Baumann, Lee, Pimentel '18, ...

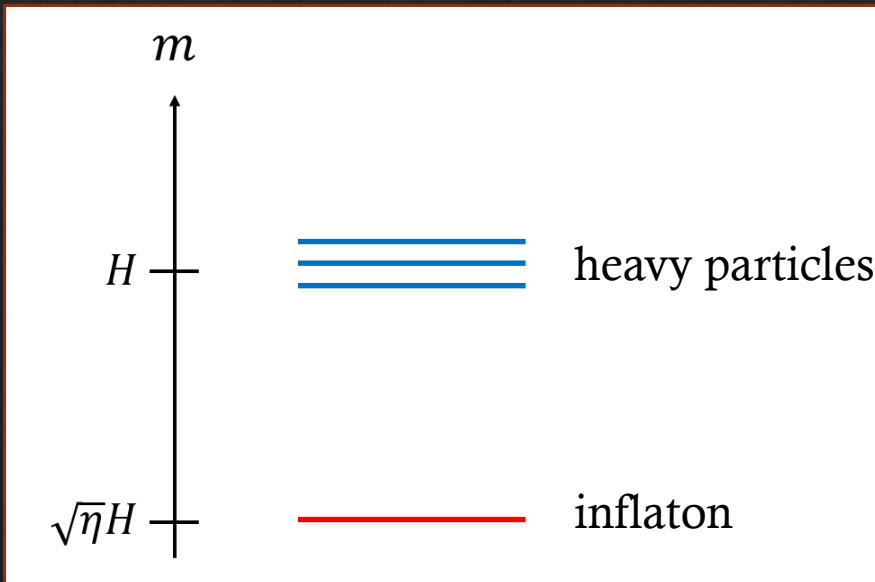


# Question

✓ **single** particle with a definite mass and spin



Q. What about **multiple** particles case?



Natural setup for UV theory  
(e.g., soft masses  $\sim H$  in  
supergravity)

# Multifiled on CC

- ✓ Whole signal is governed by lightest particle due to Boltzmann suppression  $\sim e^{-\pi m/H}$
- ✓ Non-trivial signal for (almost) degenerate masses

SA, M. Yamaguchi, JHEP 04 (2021) 127

L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi, 2112.05710

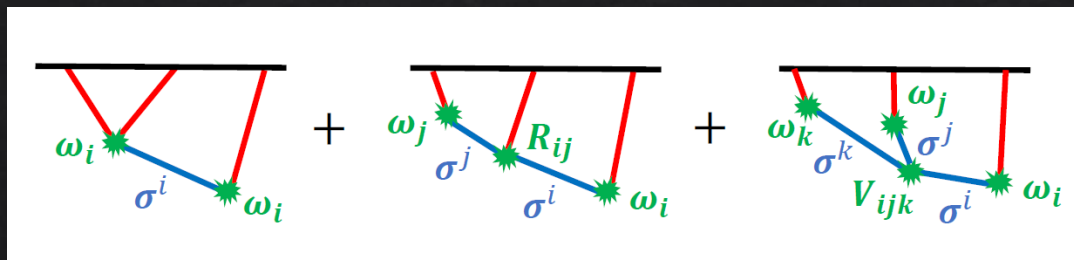
# Multifield on CC

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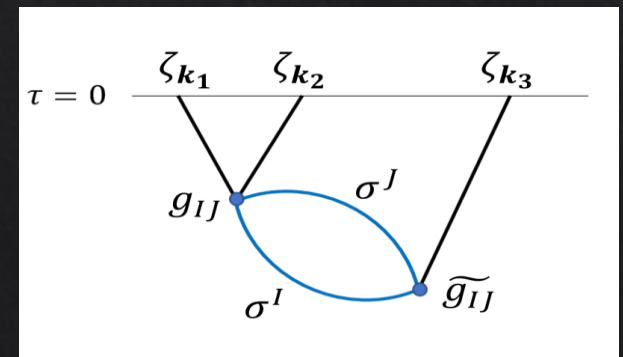
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tree level



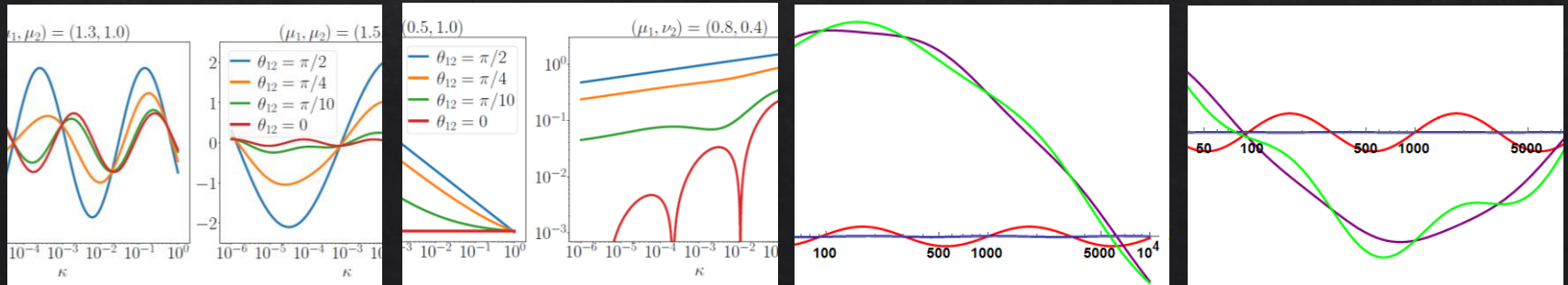
loop level

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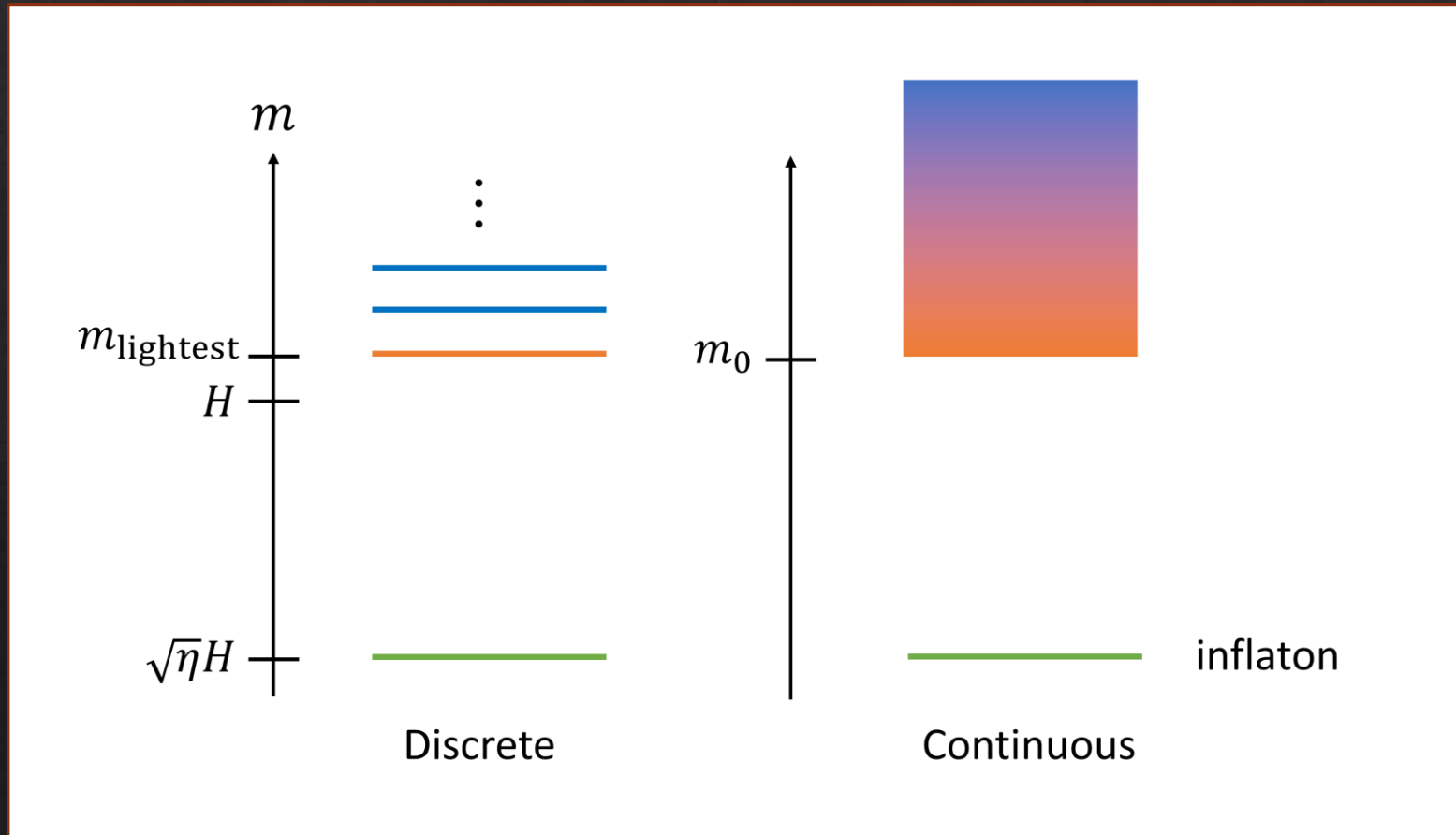


Specific signal by superposition

e.g., wavelength with  $1/|m_1 - m_2|$

# Today: what about continuous spectrum?

Motivated by some extra-dimension model



$m_0$ : gap scale

# Setup

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} f(\sigma) (\partial_\mu \phi)^2 - \frac{1}{2} (\partial_\mu \sigma)^2 - V(\phi) - U(\sigma) \right]$$

$\phi$ : inflaton

$\sigma$ : field with continuous spectrum

# Setup

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} f(\sigma) (\partial_\mu \phi)^2 - \frac{1}{2} (\partial_\mu \sigma)^2 - V(\phi) - U(\sigma) \right]$$

$\phi$ : inflaton

$\sigma$ : field with continuous spectrum

Quantization of fluctuations

$$\delta\phi = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \left( u_k a_{\mathbf{k}} + u_k^* a_{-\mathbf{k}}^\dagger \right) e^{i\mathbf{k}\cdot\mathbf{x}},$$

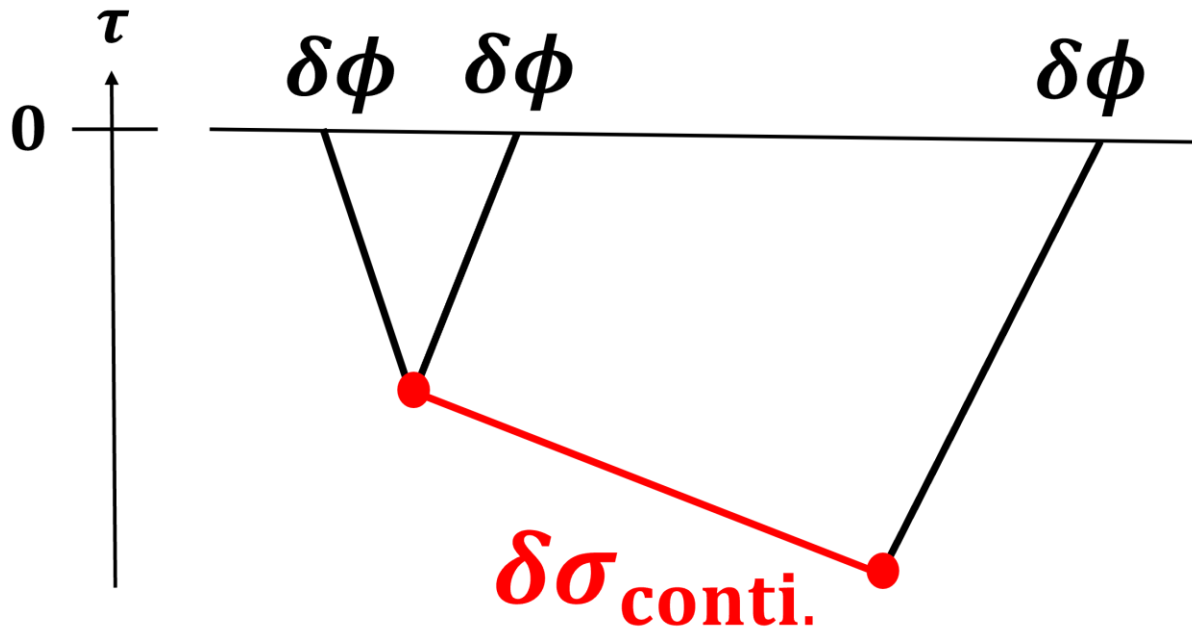
$$\delta\sigma = \int \frac{dm^2}{2\pi} \sqrt{\rho(m^2)} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \left( v_{k,m} b_{\mathbf{k},m} + v_{k,m}^* b_{-\mathbf{k},m}^\dagger \right) e^{i\mathbf{k}\cdot\mathbf{x}},$$

$\rho(m^2)$ : spectral density

# Interactions

$$\mathcal{L}_{2,\text{int}} = a^3 f_\sigma \dot{\phi}_0 \delta\sigma \delta\dot{\phi},$$

$$\mathcal{L}_{3,\text{int}} = \frac{a^3}{2} f_\sigma \delta\sigma \left( (\delta\dot{\phi})^2 - \frac{1}{a^2} (\partial\delta\phi)^2 \right),$$





# Observable:

Curvature perturbation  $\zeta \sim -\frac{H}{\dot{\phi}_0} \delta\phi$

def. of shape function ( $\sim f_{\text{NL}}$ )

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = (2\pi)^7 P_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) S(k_1, k_2, k_3)$$

# Result

Result in squeezed limit ( $\kappa \equiv k_1/k_3 \gg 1$ )

$$S = -\frac{\pi}{4} M_{\text{Pl}}^2 \epsilon \left(\frac{f_\sigma}{f}\right)^2 \kappa^{-1/2} \int_{m_0^2}^{\infty} \frac{dm^2}{2\pi} \rho(m^2) e^{-\pi\mu} \text{Im} \left\{ \left(\frac{1}{\kappa}\right)^{-i\mu} J_-(i\mu) + \left(\frac{1}{\kappa}\right)^{i\mu} J_+(i\mu) \right\}$$

↑  
New !!

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

coefficient (analytic expression)

$$J_+(i\mu) = -\frac{\sqrt{\pi} 2^{-1-2i\mu} (e^{\pi\mu} - i) \Gamma(i\mu + \frac{7}{2}) (\text{csch}(\pi\mu) + \text{sech}(\pi\mu))}{(2\mu - i) \Gamma(i\mu + 1)},$$

$$J_-(i\mu) = J_+(-i\mu) e^{2\pi\mu}.$$

# Result

$$S = -\frac{\pi}{4} M_{\text{Pl}}^2 \epsilon \left( \frac{f_\sigma}{f} \right)^2 \kappa^{-1/2} F_{\text{conti.}}$$

Continuous case:

$$F_{\text{conti.}} = \int_{m_0^2}^{\infty} \frac{dm^2}{2\pi} \rho(m^2) e^{-\pi\mu} \mathcal{A}(\mu) \sin(\mu \log \kappa + \varphi(\mu))$$

$$\mathcal{A}(\mu) = [\{\text{Im}J_-(i\mu) + \text{Im}J_+(i\mu)\}^2 + \{\text{Re}J_-(i\mu) - \text{Re}J_+(i\mu)\}^2]^{1/2},$$

$$\varphi(\mu) = \arctan \left( \frac{\text{Im}J_-(i\mu) + \text{Im}J_+(i\mu)}{\text{Re}J_-(i\mu) - \text{Re}J_+(i\mu)} \right).$$



Usual case  
(single particle with  
definite mass):

$$F_{\text{particle}} = e^{-\pi\mu_\sigma} \mathcal{A}(\mu_\sigma) \sin(\mu_\sigma \log \kappa + \varphi(\mu_\sigma))$$

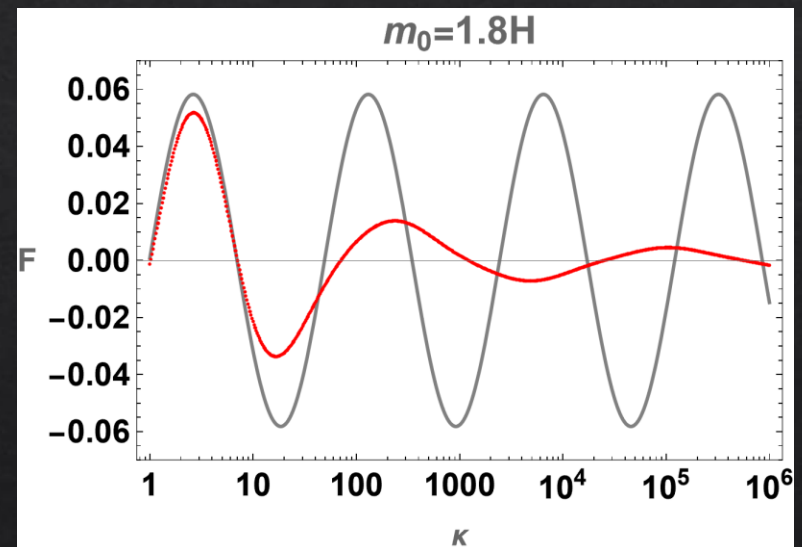
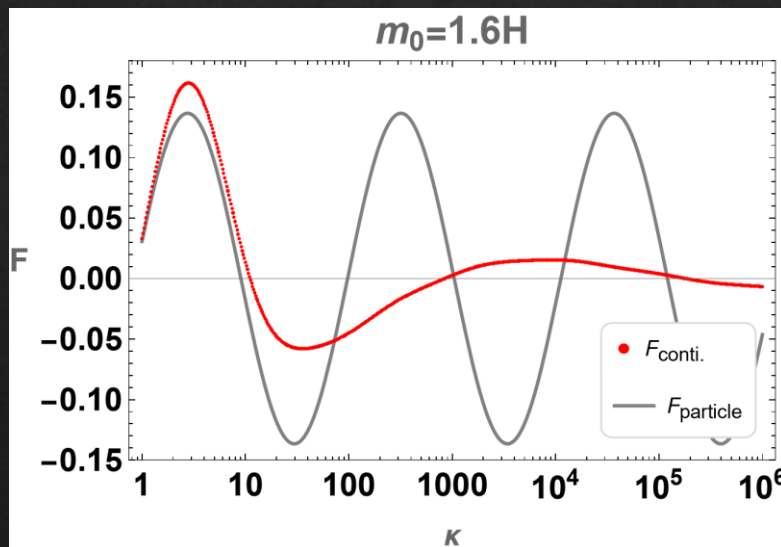
# Result

choose a specific spectral density

$$\rho(m^2) = \frac{2\pi}{m_0^2} \sqrt{\frac{m^2}{m_0^2} - 1},$$

E. Megias, M. Quirós, '19

C. Csaki, S. Hong, G. Kurup, S. J. Lee, M. Perelstein, W. Xue, '22



- ✓ Damping amplitude = signal of continuous spectrum
- ✓  $\int dm \sin(m\kappa) \rightarrow 1/\kappa$  factor (consequence of integration)

# Summary

- ◇ Cosmological collider (CC) is a new attractive tool for exploring high energy
- ◇ Multiple field signature on CC (motivated by e.g., supergravity)
  - ✓ non-trivial superposition for almost degenerate masses
- ◇ Continuous spectrum on CC (motivated by some extra dimensional models)
  - ✓ damping effects in deep squeezed limit
- ◇ These signals cannot be mimicked by single particle with a definite mass → Strong evidence of multi particles & continuous spectrum
- ◇ Interesting to think about embedding into concrete UV setup

Thank you for your attention !!