Continuous spectrum on cosmological collider

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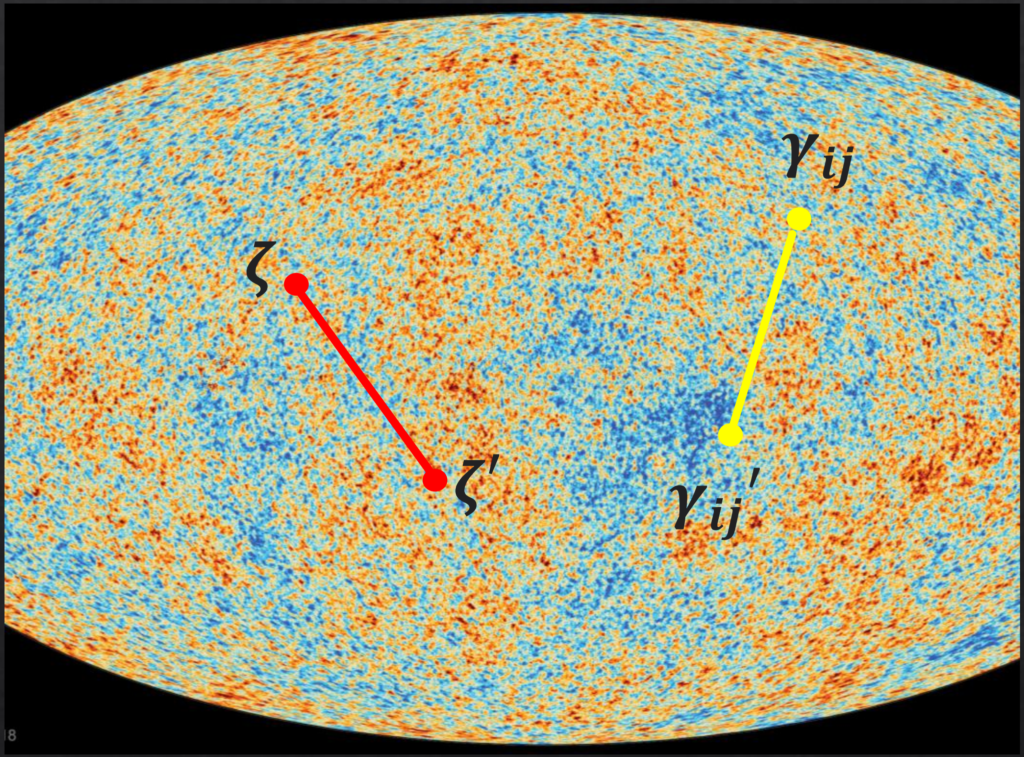
(Chung-Ang University)

based on 2301.07920

PPC 2023 6/12

Inflationary observable



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

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

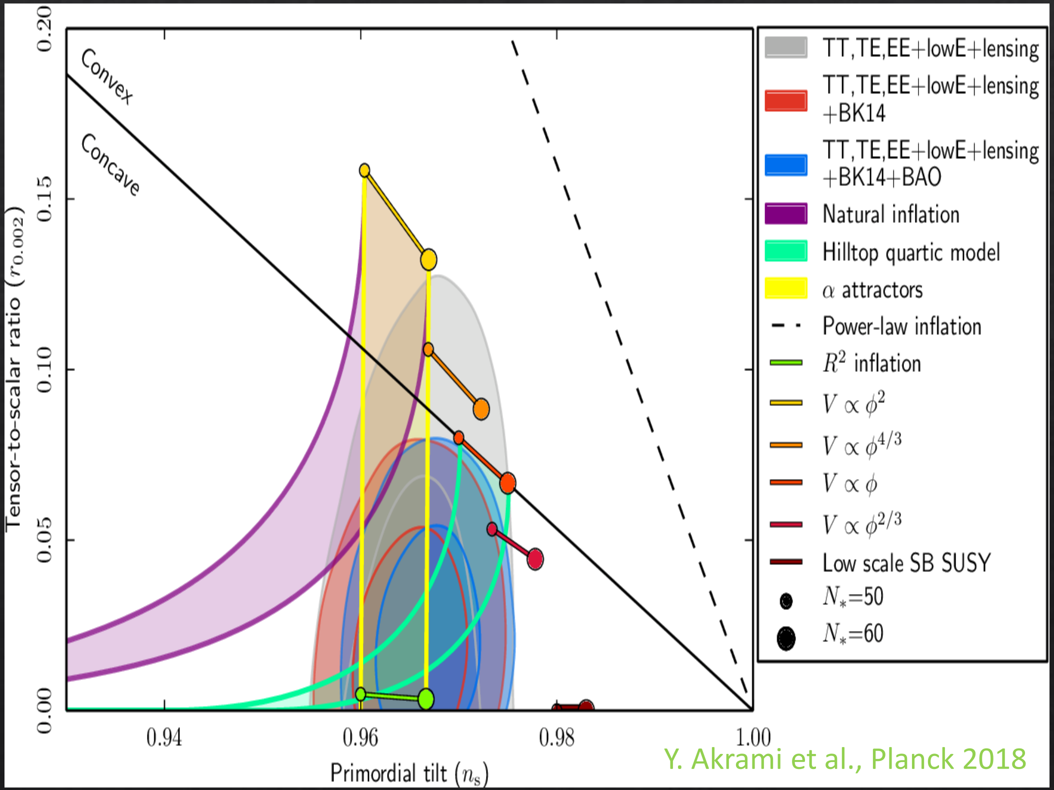
spectral tilt: $n_s - 1 = \frac{d \ln P_\zeta}{d \ln k}, \ldots$

Restrictions on inflaton potential

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

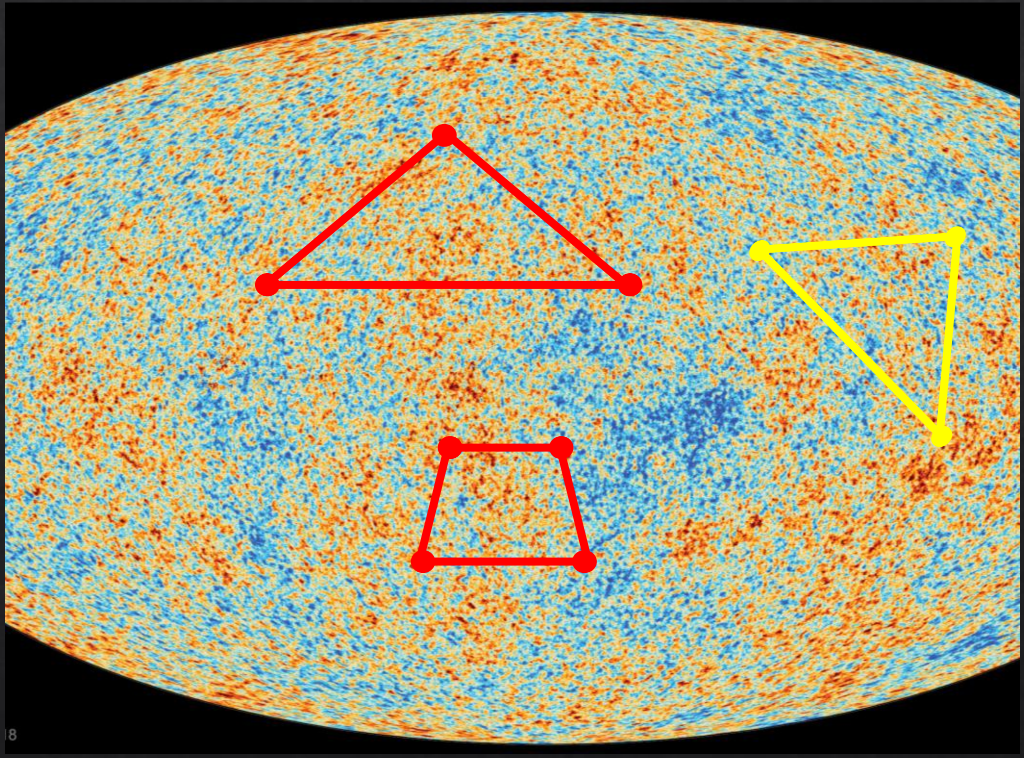
$$r = \frac{P_\gamma}{P_\zeta} = 8\left(\frac{V'}{V}\right)^2$$

r

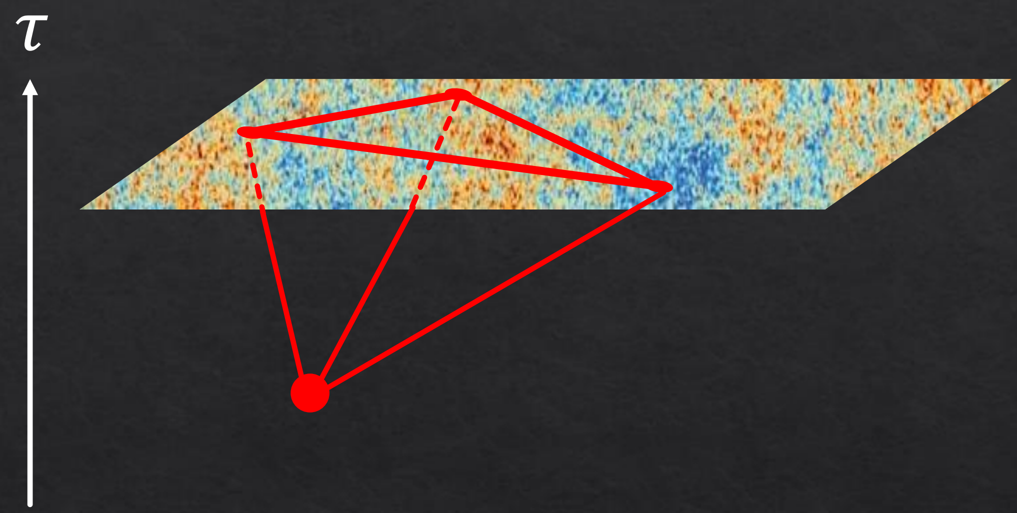


n_s

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



NG from self-interaction



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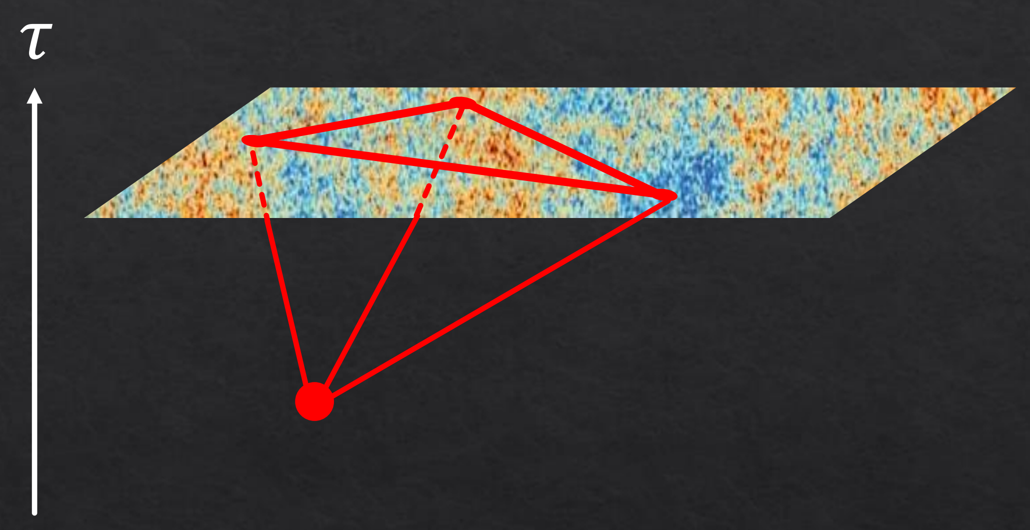

- $f_{\rm NL} \sim O(\epsilon)$ for <u>simple</u> model   Maldacena '03

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

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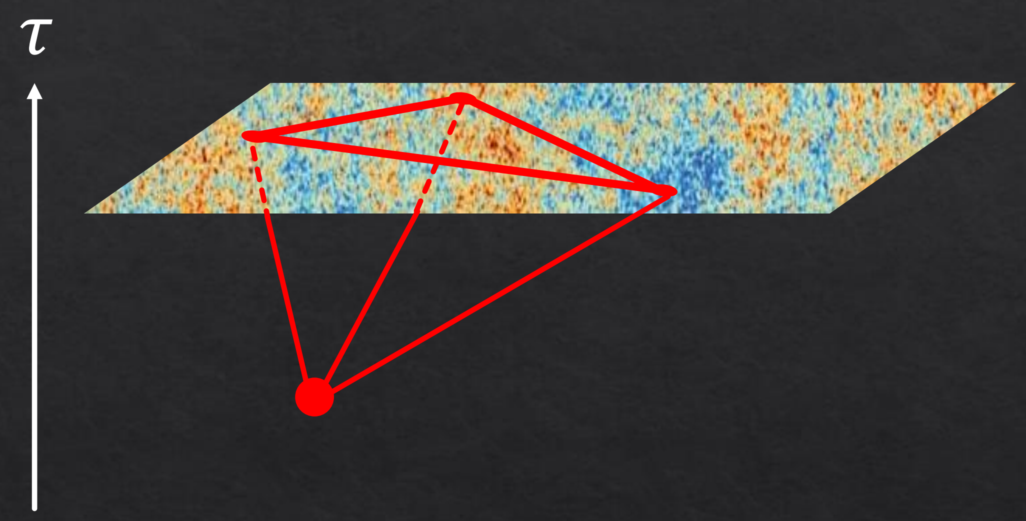

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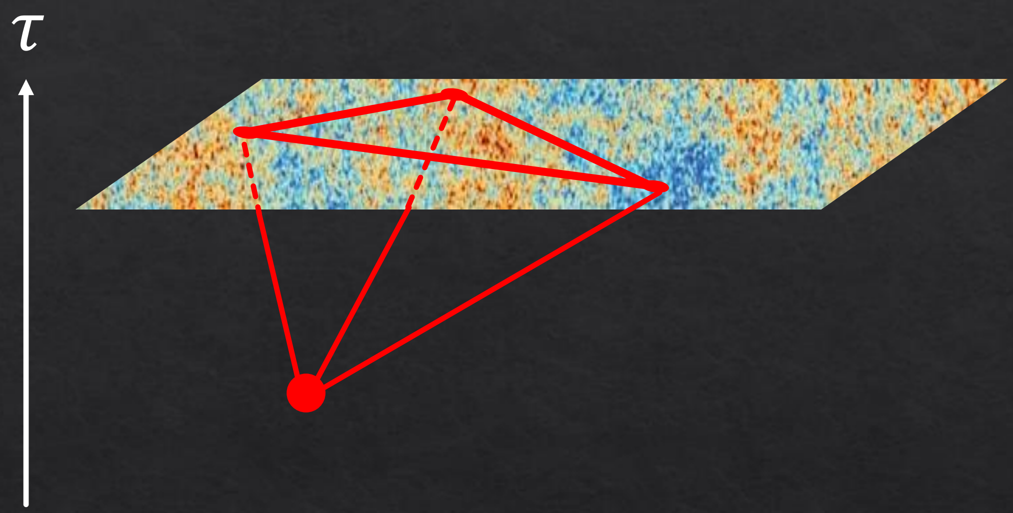

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  simple : single scalar + Einstein gravity + canonical kinetic term + slow-roll

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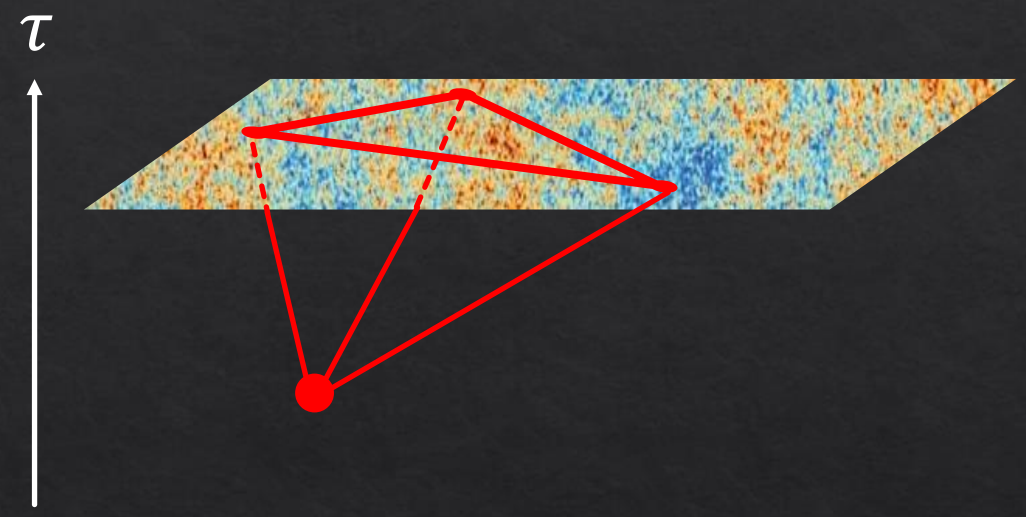
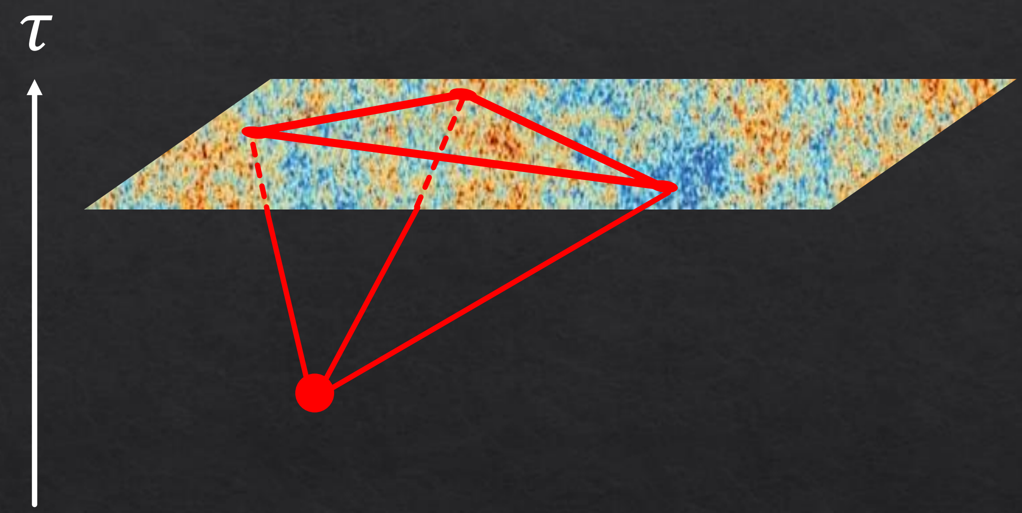
- Maldacen's consistency relation, Suyama-Yamaguchi bound, …

NG from self-interaction



NG → strong restrictions on inflation models

NG from self-interaction



NG $\rightarrow$ strong restrictions on inflation models

There's more: Cosmological collider (CC)

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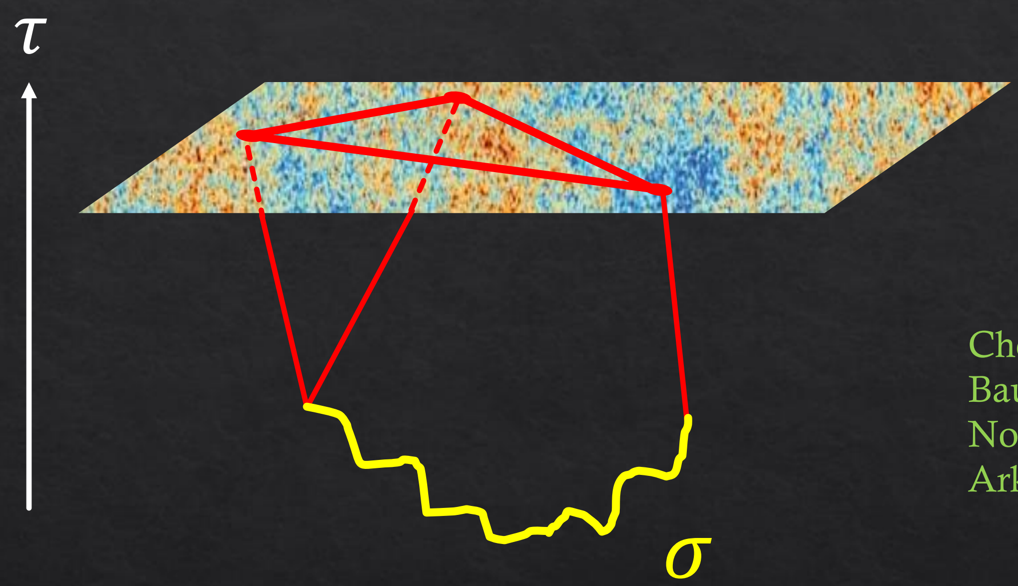

Chen, Wang, ’10
Baumann, Green, ’12
Noumi, Yamaguchi, Yokoyama, ’13
Arkani-Hamed, Maldacena, ’15

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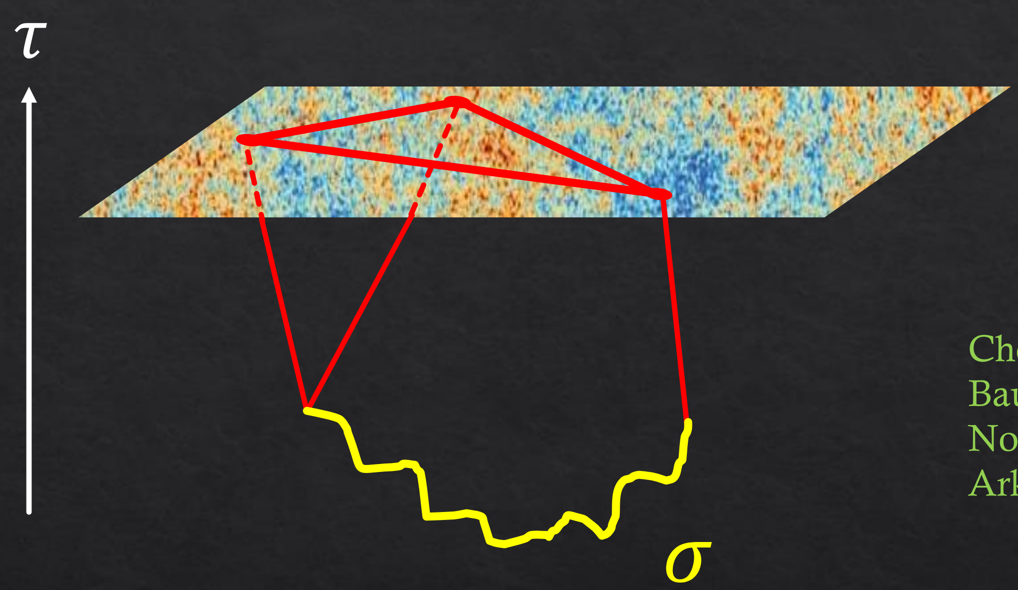

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- NG can contain information of heavy (new) particle σ with specific oscillation signal (frequency = m_σ)

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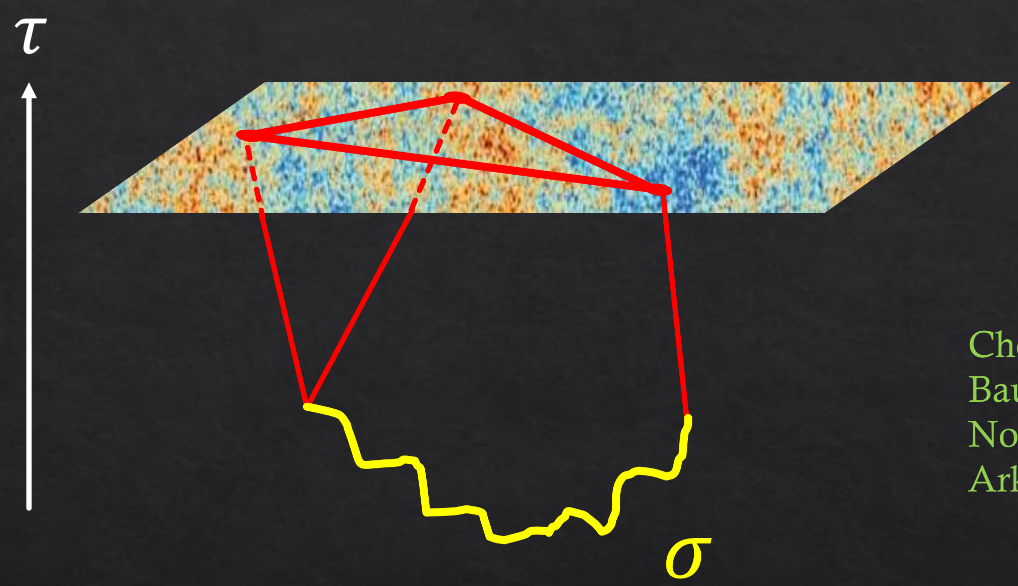

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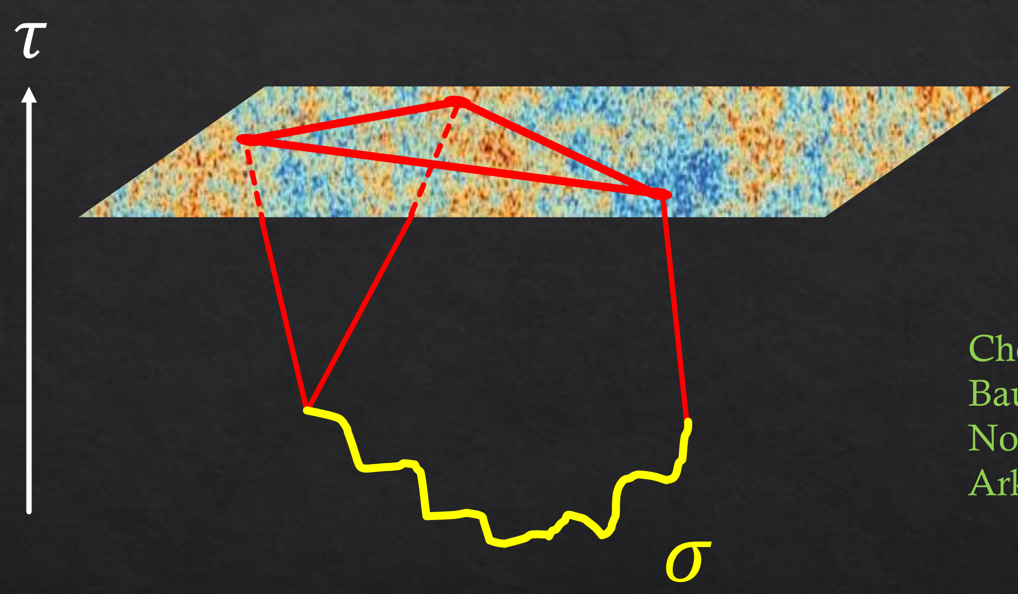

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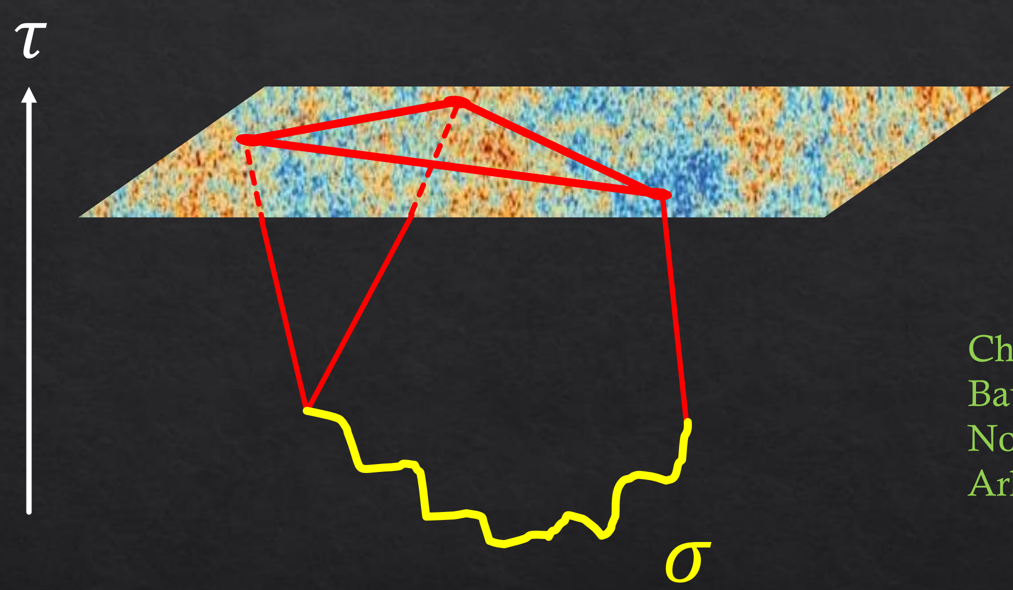

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- NG can contain information of heavy (new) particle σ with specific oscillation signal (frequency = m_σ)
- $m_\sigma \sim H \sim 10^{13}$(GeV) $\gg$ energy scale of terrestrial experiment
- Signal can be large!!
- CC = new tool for searching high energy physics

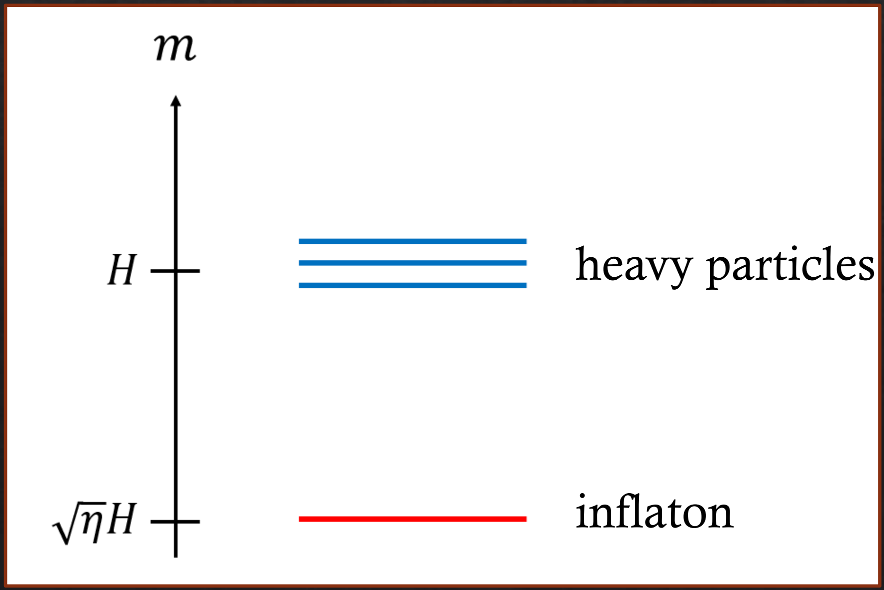
Many applications

✓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)
✓Multifield signature (SA, M. Yamaguchi, ’20, L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi, ’21)
✓Leptogenesis (Cui, Xianyu ’21)
✓GUT (Maru, Okawa, ’21)
…

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 $\sim e^{-\pi m/H}$

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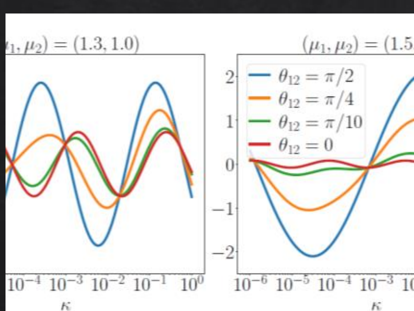
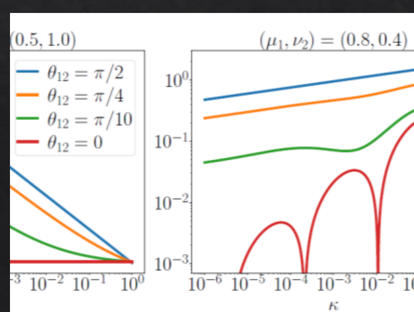
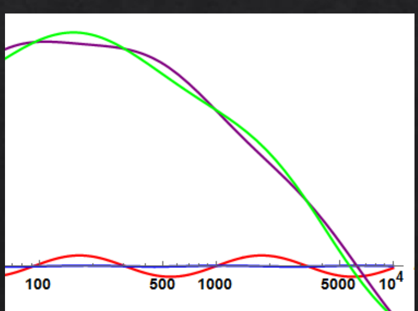
✓ Whole signal is governed by lightest particle due to Boltzmann suppression $\sim e^{-\pi m/H}$

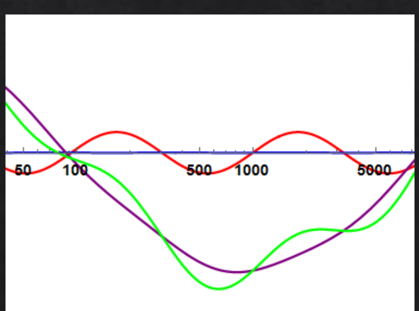
✓ Non-trivial signal for (almost) degenerate masses

SA, M. Yamaguchi, JHEP 04 (2021) 127
L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi, 2112.05710



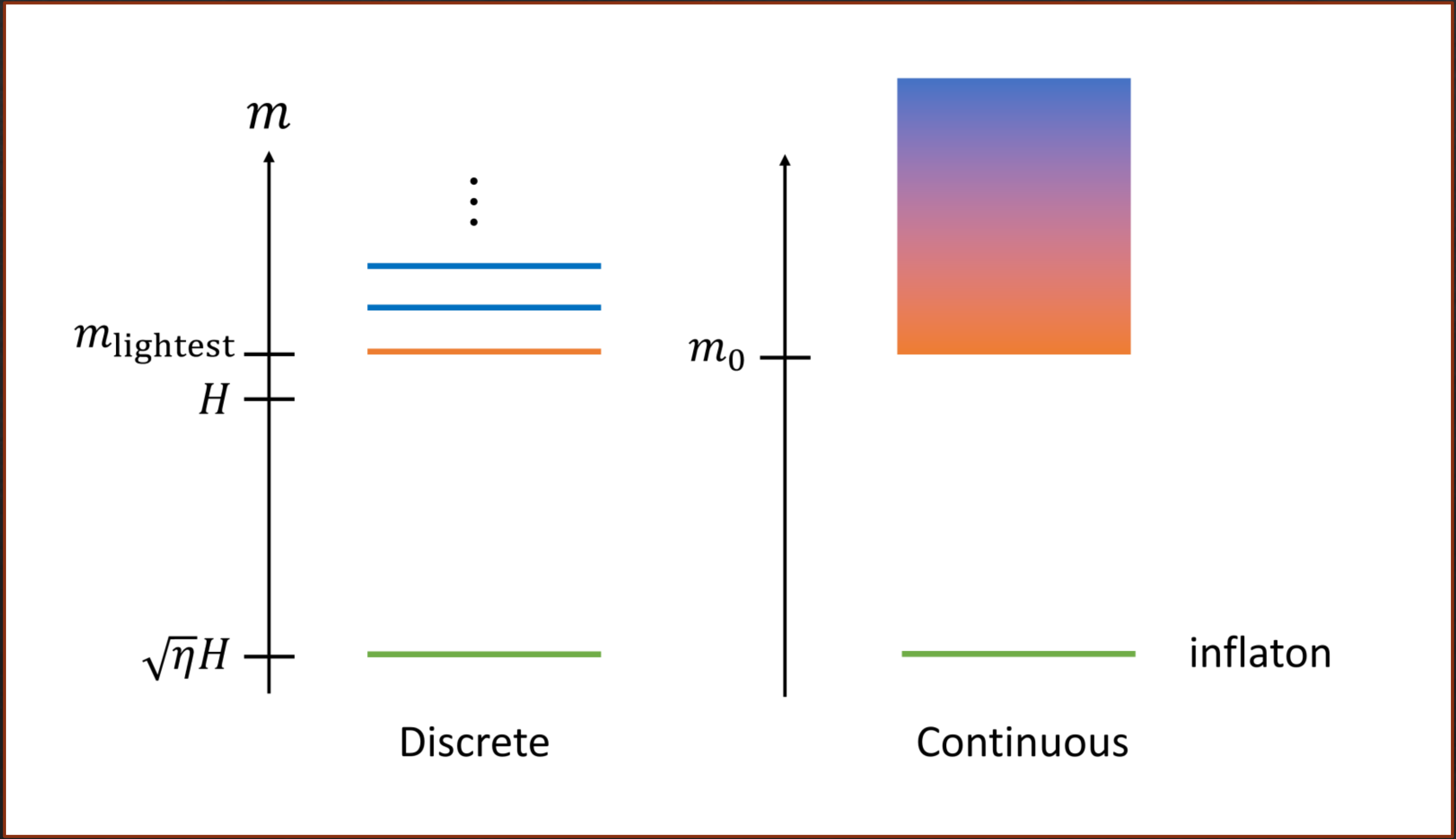






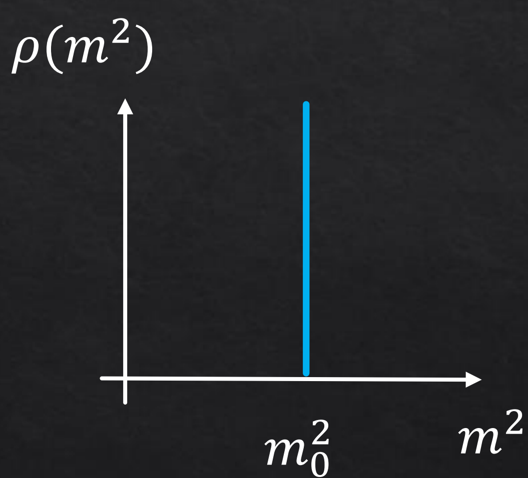
Today: what about continuous spectrum?

Motivated by some extra-dimension models

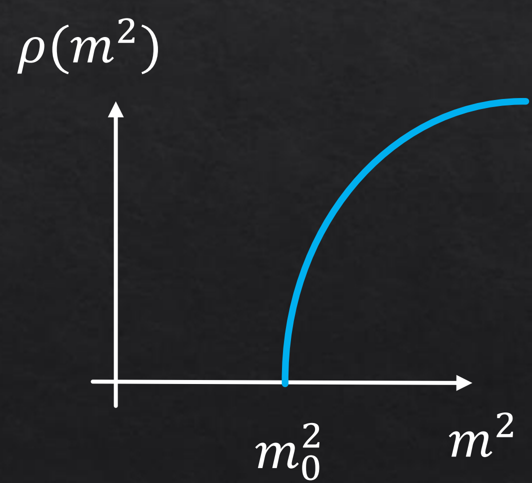


Setup

ϕ: inflaton
σ: field with continuous spectrum
characterized by spectral density $\rho(m^2)$

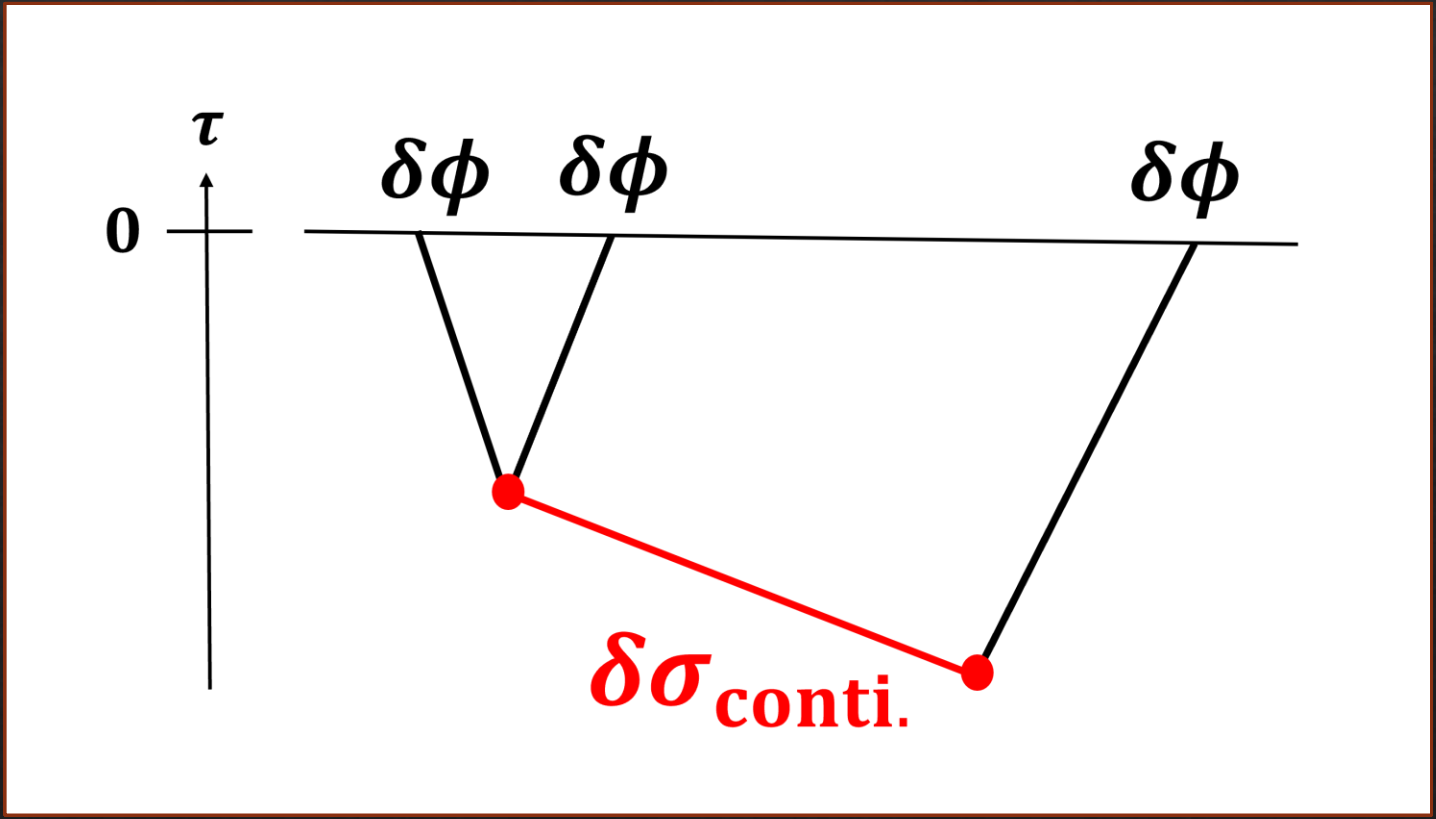


Discrete



Continuous

Interactions



Observable:

$$\langle \delta\phi^3 \rangle|_{\kappa \equiv k_{1,2}/k_3 \gg 1} \propto F$$

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Usual case
(single particle with definite mass):

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

$$\mu_\sigma = \sqrt{\left(\frac{m_\sigma}{H}\right)^2 - \frac{9}{4}}$$

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Continuous case:

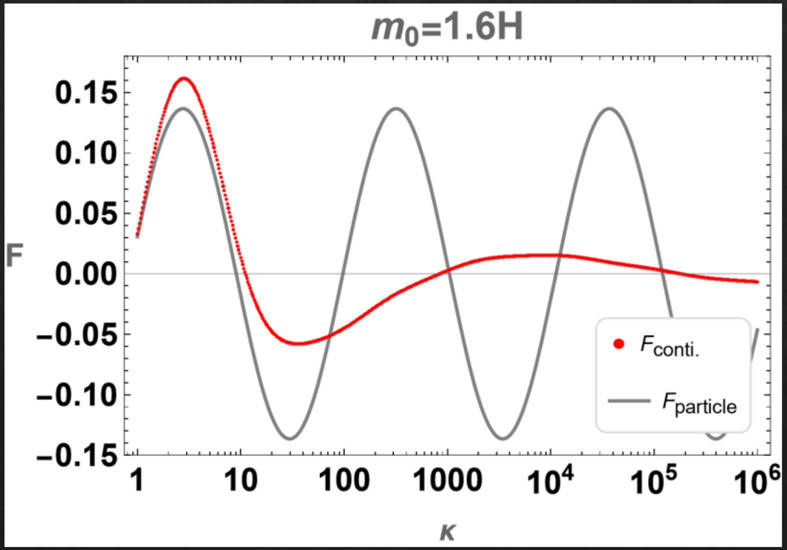
$$F_{\text{conti.}} = \int_{m_0^2}^{\infty} \frac{dm^2}{2\pi}\rho\left(m^2\right) e^{-\pi\mu}\mathcal{A}(\mu)\sin\left(\mu\log\kappa + \varphi(\mu)\right)$$

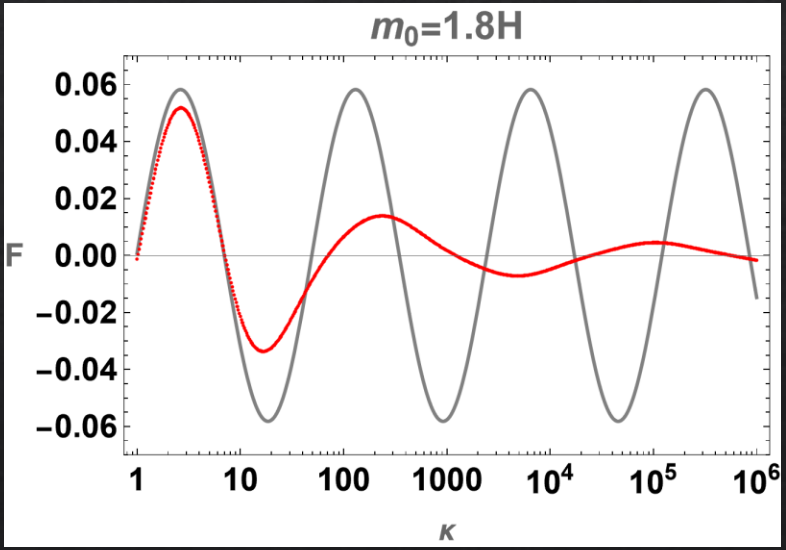
$$\mu = \sqrt{\left(\frac{m}{H}\right)^2 - \frac{9}{4}}.$$

Result

choose a specific spectral density $\rho\left(m^2\right) = \frac{2\pi}{m_0^2}\sqrt{\frac{m^2}{m_0^2} - 1},$

E. Megıas, M. Quirsos,'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
- Continuous spectrum on CC (motivated by some extra dimensional models)

  ✓ damping effects in deep squeezed limit
- Universal feature independently of $\rho(m^2)$
- The signal cannot be mimicked by single particle with a definite mass $\rightarrow$ Strong evidence of continuous spectrum
- Interesting to think about embedding into concrete UV setup

Thank you for your attention !!

Details

Setup

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

ϕ: inflaton
σ: field with continuous spectrum

Quantization of fluctuations

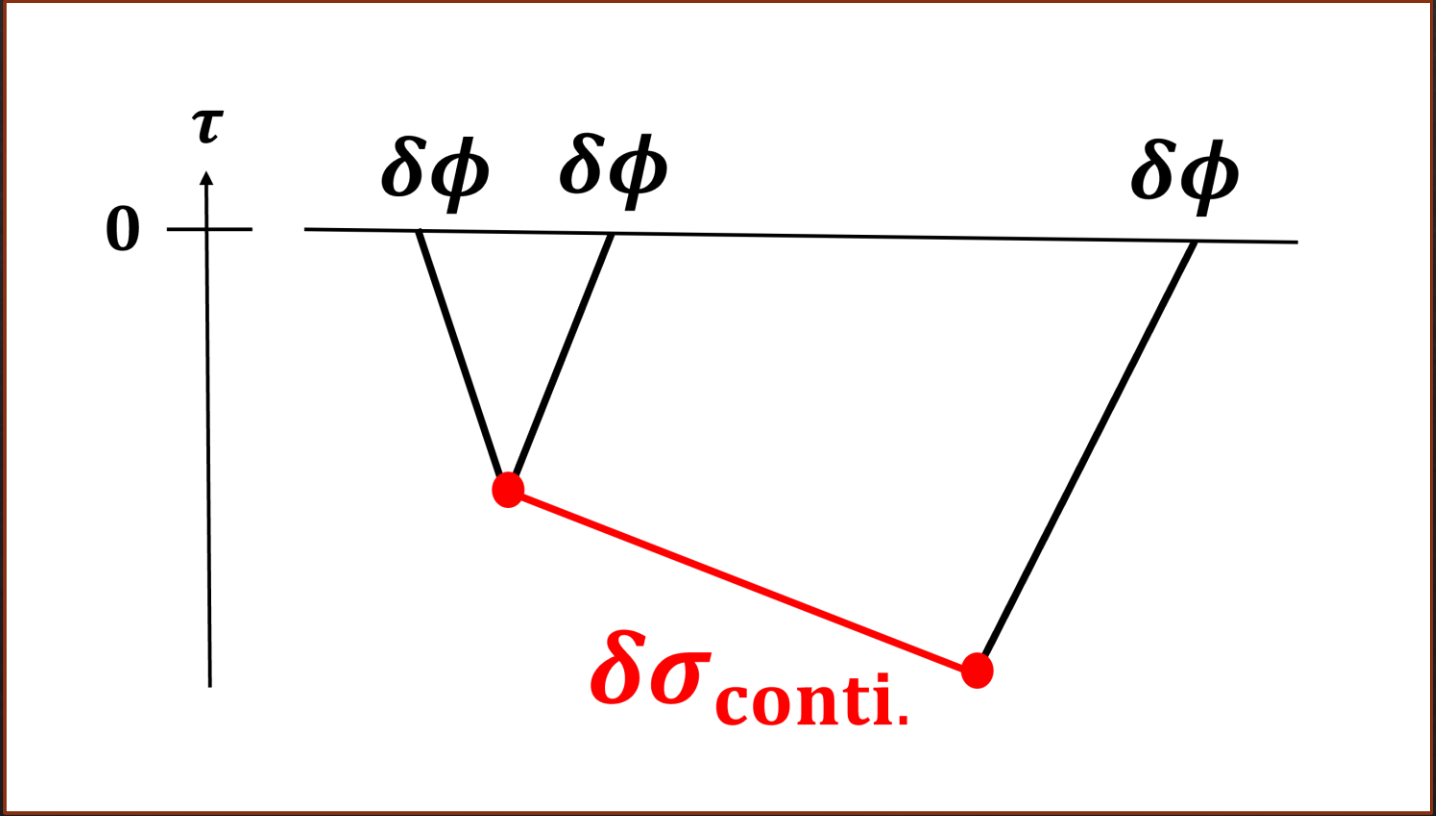
$$\delta\phi = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \left(u_k a_{\boldsymbol{k}} + u_k^* a_{-\boldsymbol{k}}^\dagger \right) e^{i\boldsymbol{k}\cdot\boldsymbol{x}},$$

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

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

Interactions

$$\mathcal{L}_{2,\mathrm{int}} = a^3 f_\sigma \dot{\phi}_0 \delta\sigma \delta\dot{\phi},$$
$$\mathcal{L}_{3,\mathrm{int}} = \frac{a^3}{2} f_\sigma \delta\sigma \left((\delta\dot{\phi})^2 - \frac{1}{a^2}(\partial\delta\phi)^2 \right),$$



Observable:

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

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

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

Result

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

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

New !!

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

coefficient (analytic expression)

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

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

Result

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

Continuous case:

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

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

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

↕

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