Inflationary Correlators with Dynamical Mass

Shuntaro Aoki (IBS)

arxiv: 2311.XXXX

Collaborators:
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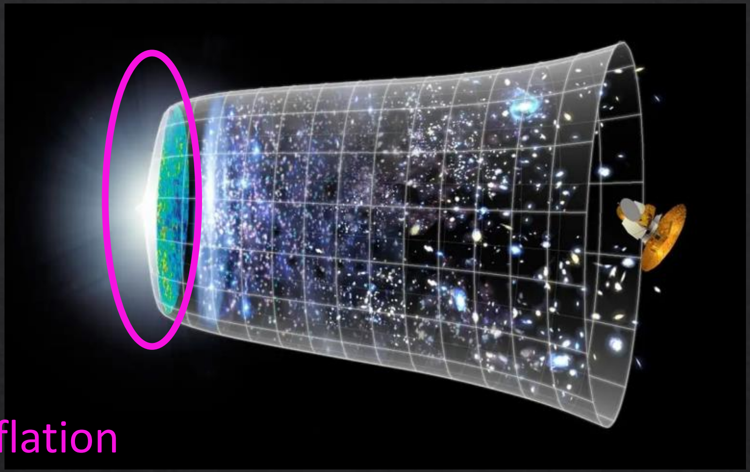
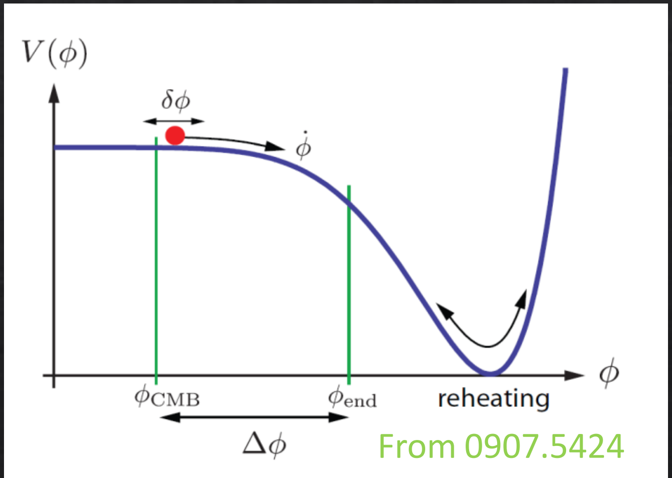
KEK PH 2023
9/11/2023

Cosmic inflation

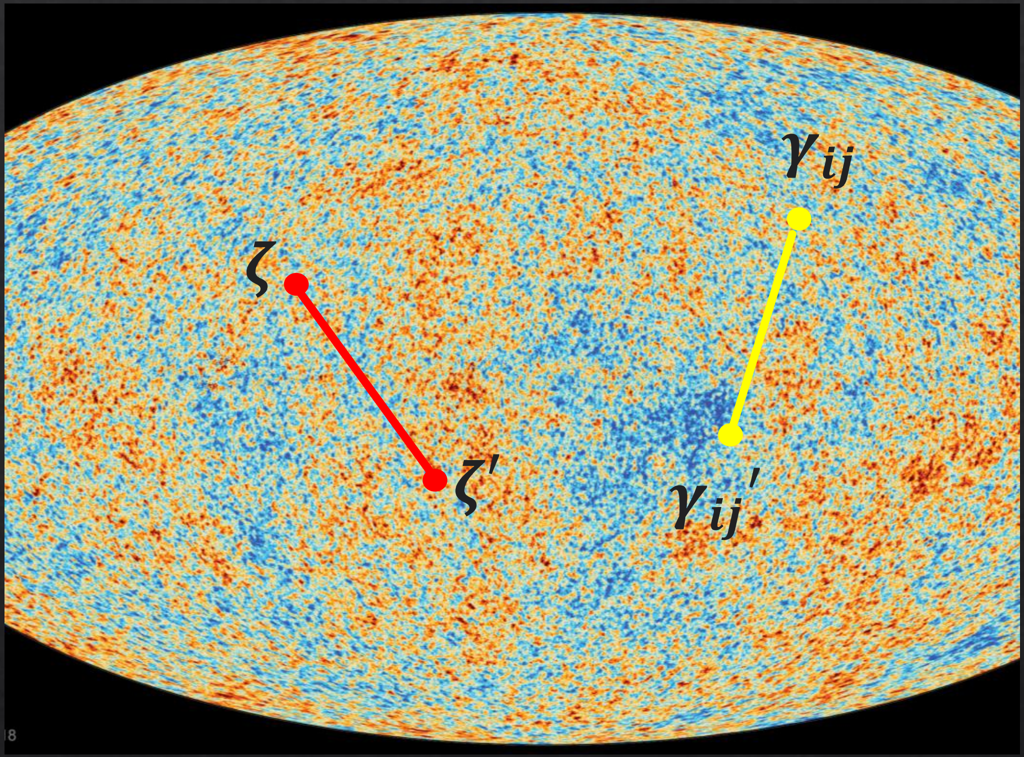


Inflation
- rapid expansion of early universe
- solve initial condition problems (horizon, flatness)



- slow-roll inflation by a scalar field: inflaton
- inflaton fluctuation $\delta\phi \Rightarrow$ scalar mode ζ
- metric fluctuation $\Rightarrow$ tensor mode γ_{ij}

Inflationary observable



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

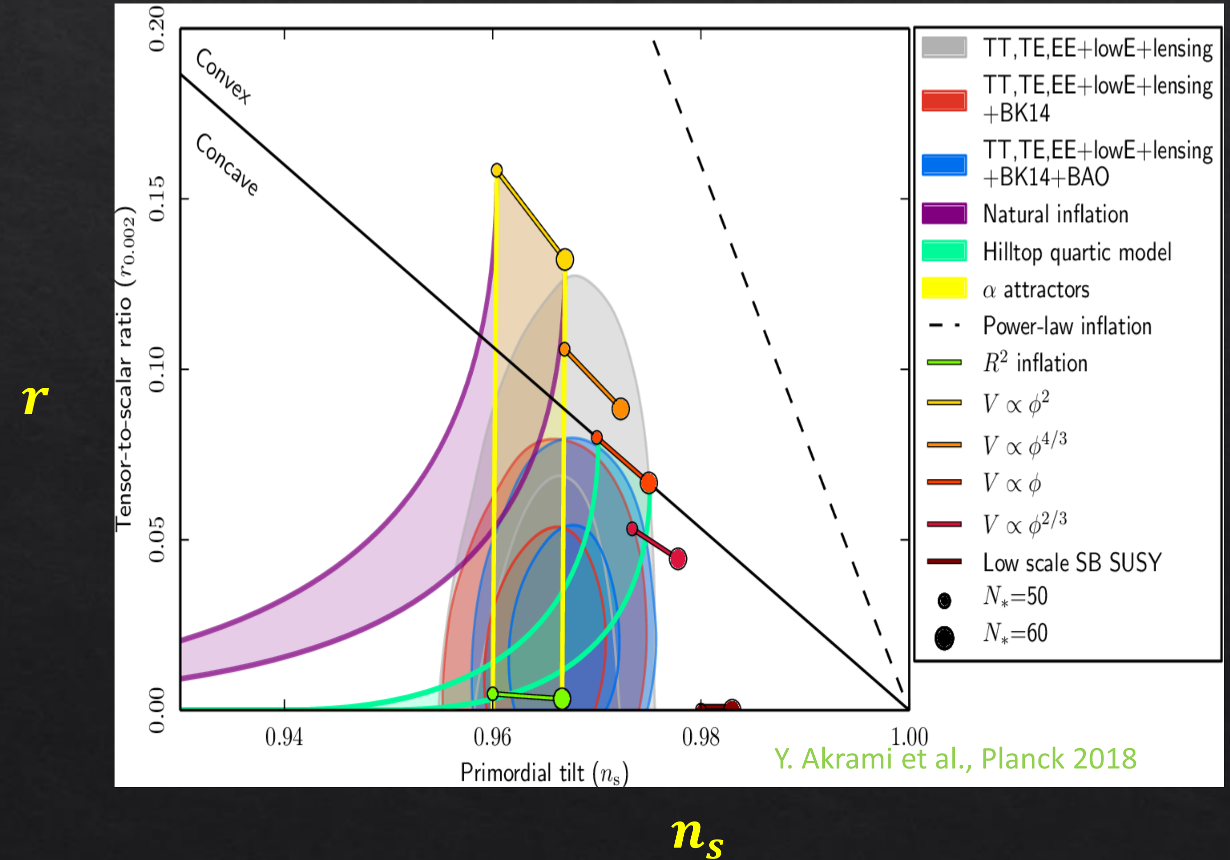
tensor power spectrum: $P_\gamma \sim \langle \gamma \gamma' \rangle$

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

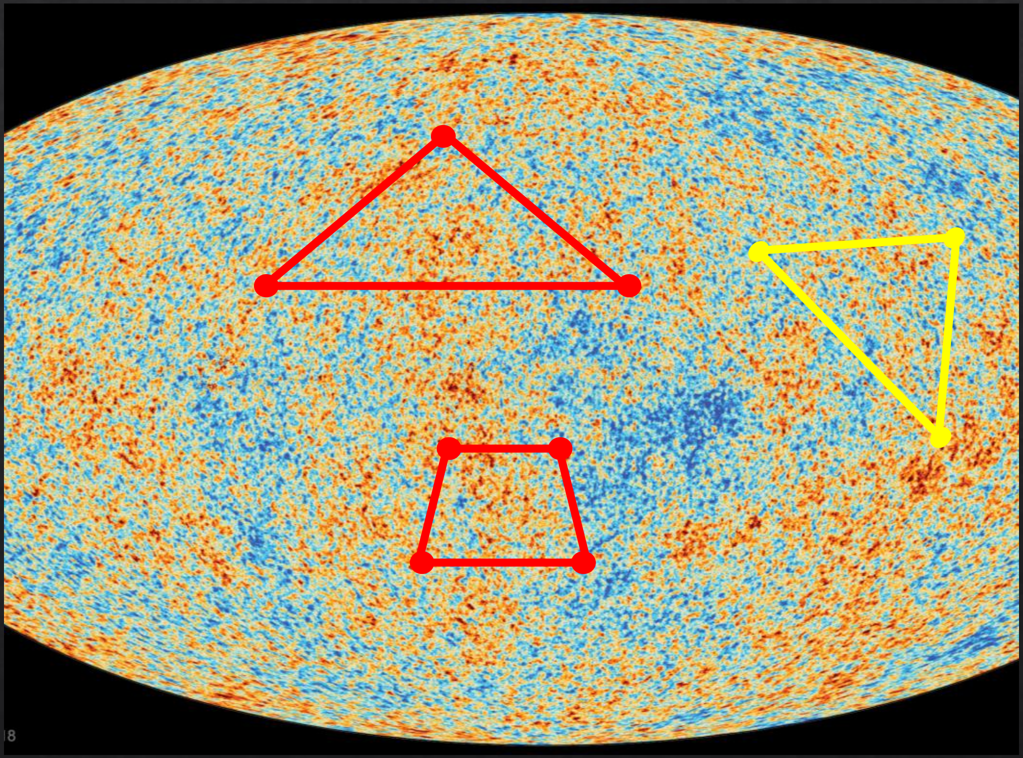
Restrictions on inflaton potential

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

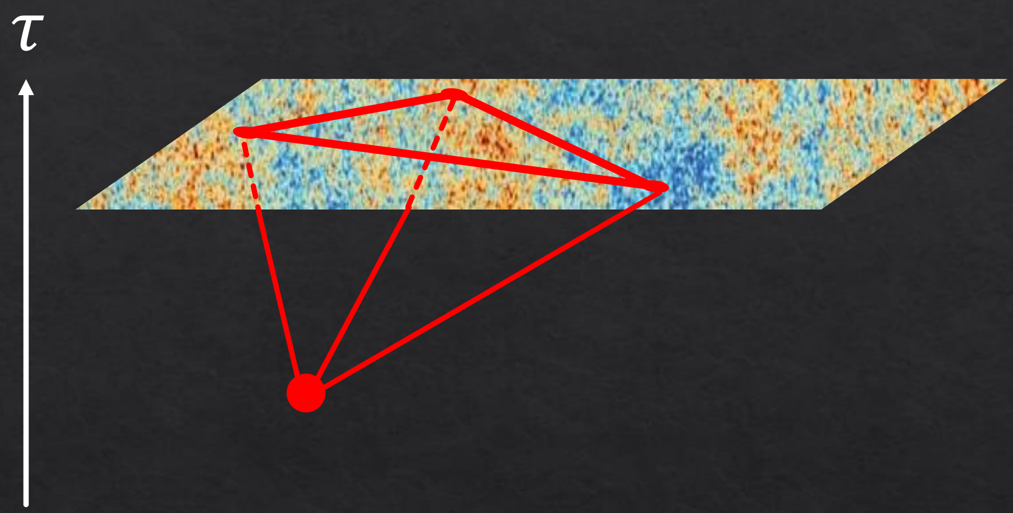
$$r = \frac{P_\gamma}{P_\zeta} = 8\left(\frac{V'}{V}\right)^2$$



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



NG from self-interaction (=gravitational floor)



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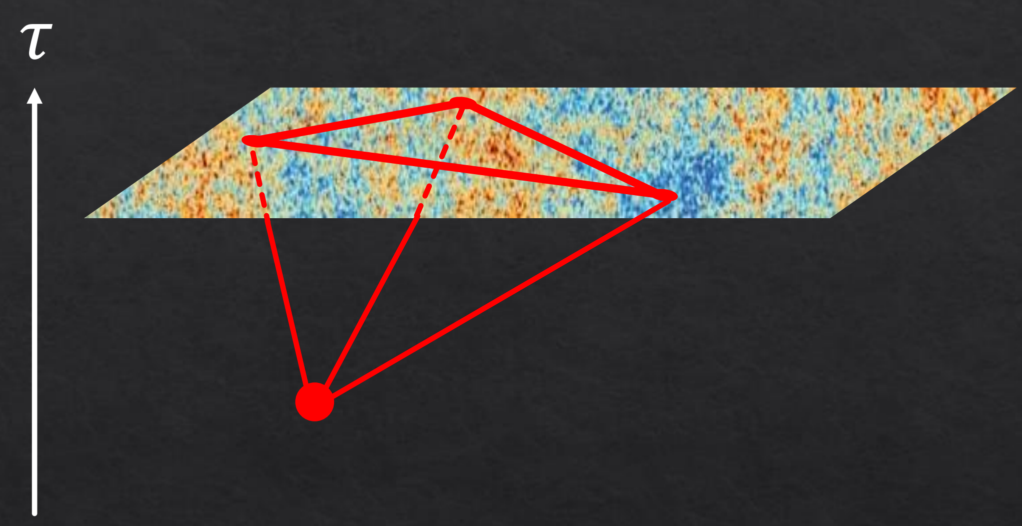

- $f_{\mathrm{NL}} \sim O(\epsilon)$ for simple model   Maldacena '03

  simple : single scalar + Einstein gravity + canonical kinetic term + slow-roll + Bunch–Davies vacuum

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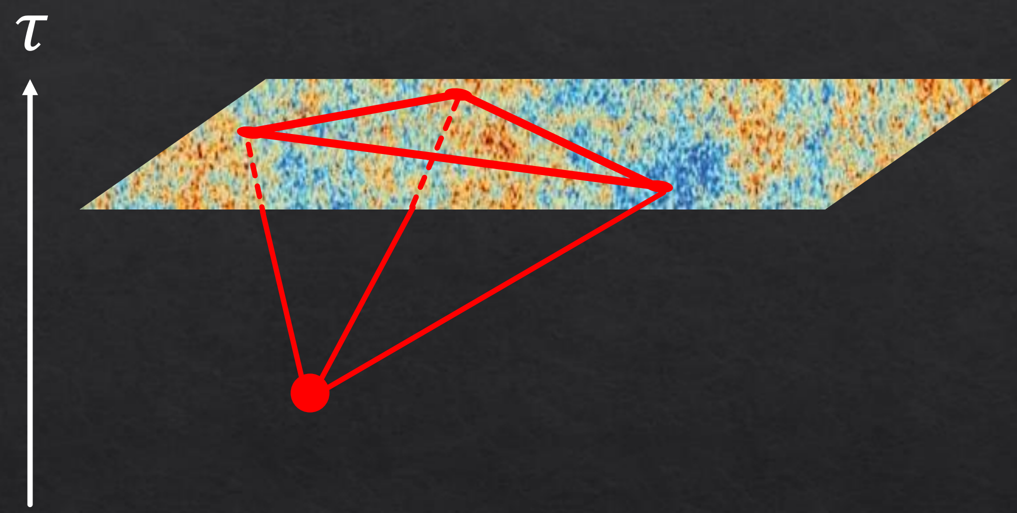

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- $f_{\rm NL} \gg 1$ for more general class of inflation models

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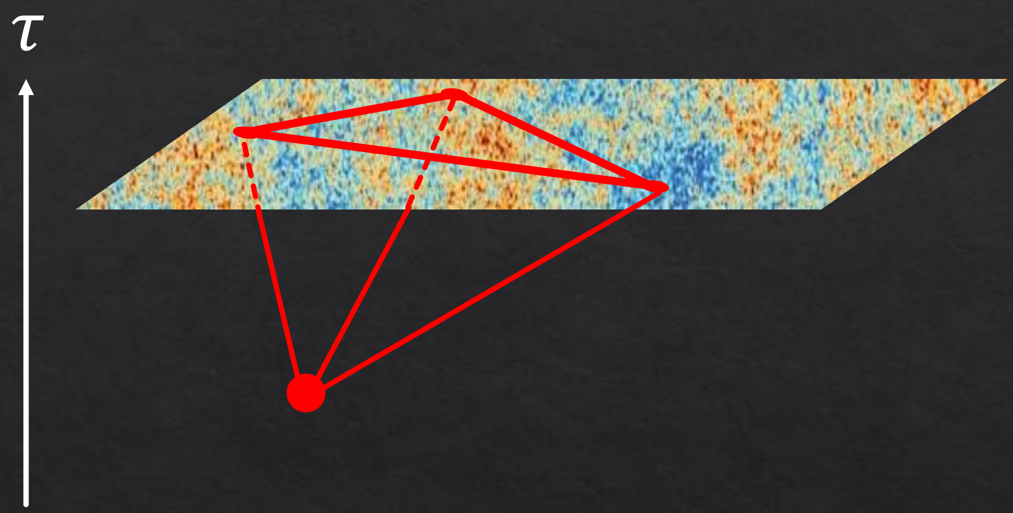

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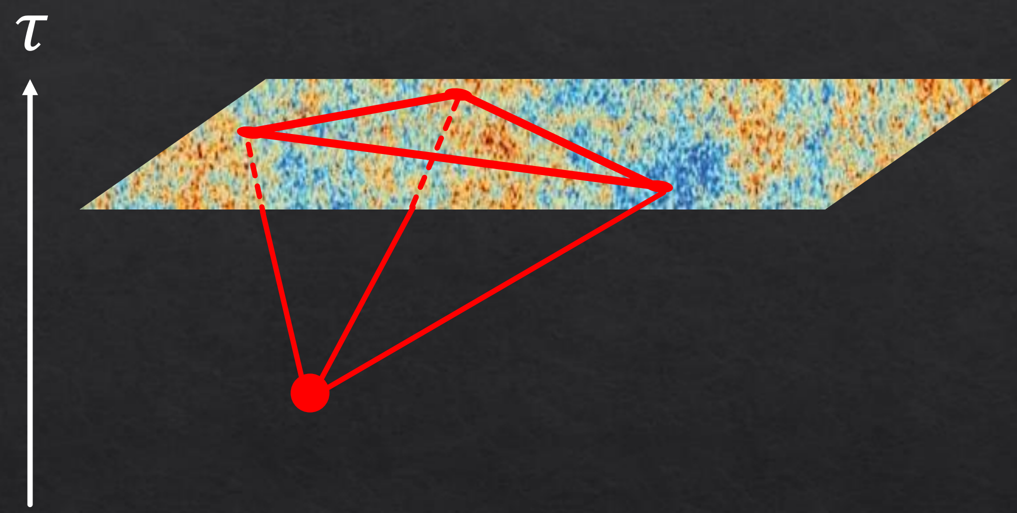
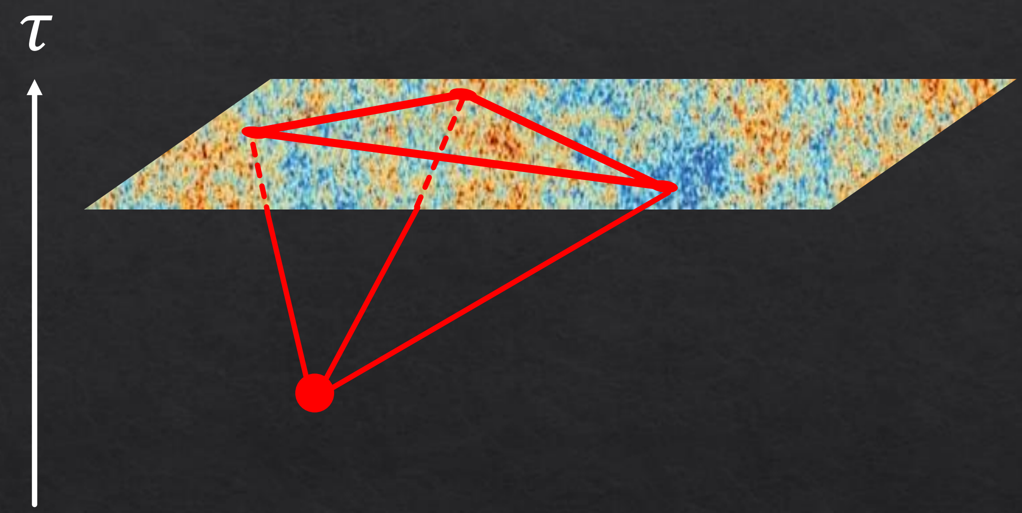
- $f_{\rm NL} \gg 1$ for more general class of inflation models
- Current constraint : $f_{\rm NL} < O(10)$ from Planck, but future observation may reach $O(1?\ 0.1?)$

NG from self-interaction (=gravitational floor)



NG = Nice tool to distinguish inflation models

NG from self-interaction (=gravitational floor)



NG = Nice tool to distinguish inflation models

There's more: Cosmological collider (CC)

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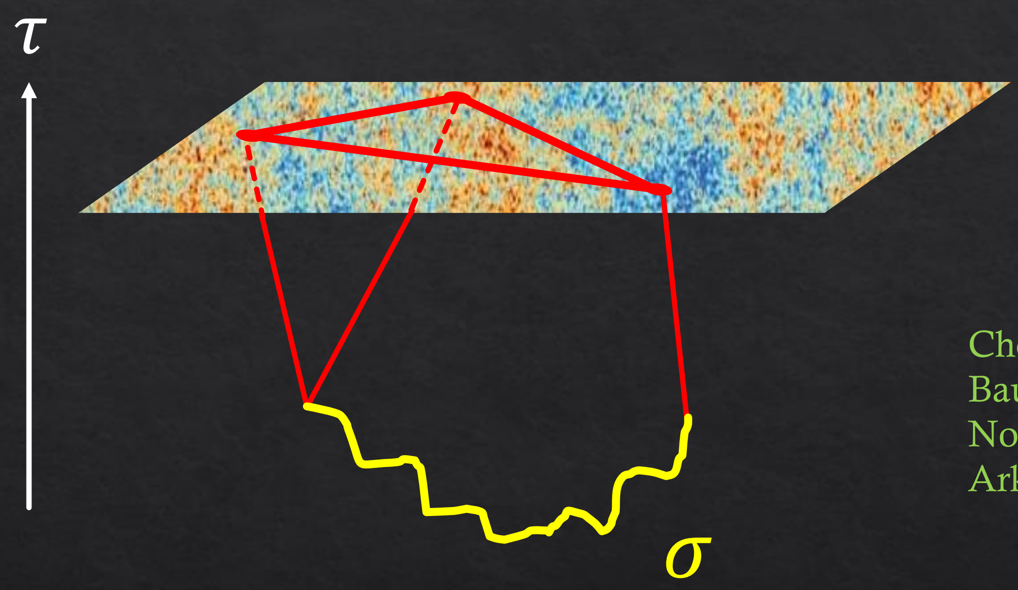

Chen, Wang, '10
Baumann, Green, '12
Noumi, Yamaguchi, Yokoyama, '13
Arkani-Hamed, Maldacena, '15

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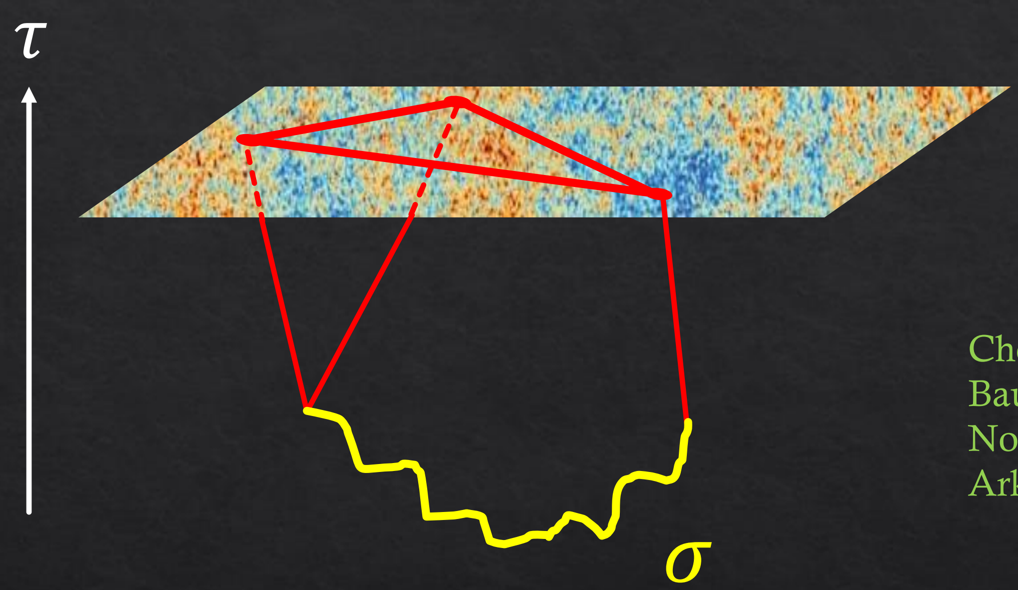

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- NG can contain information of heavy (new) particle σ with specific oscillation signal (frequency = m_σ)

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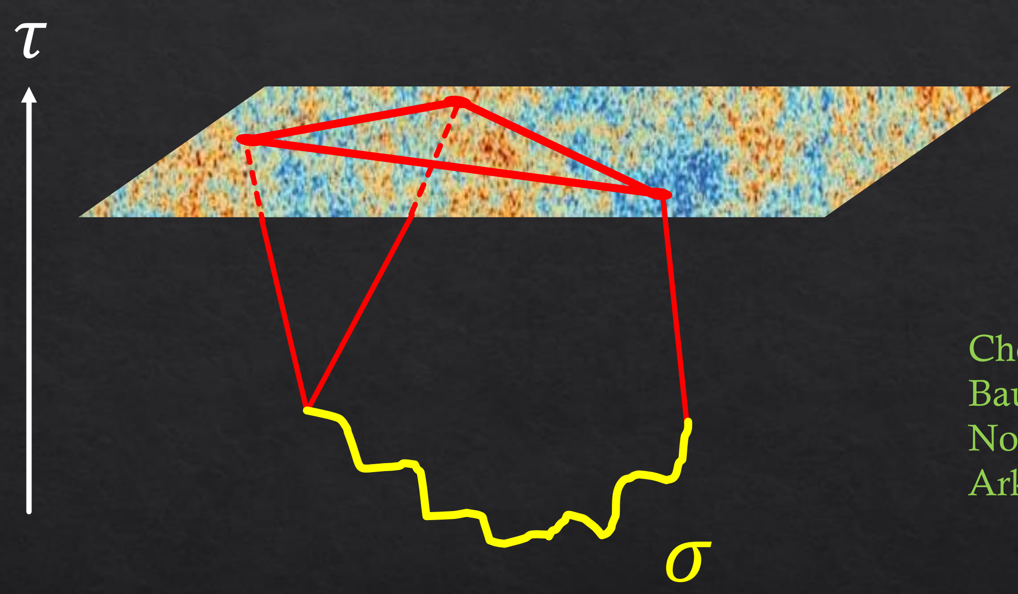

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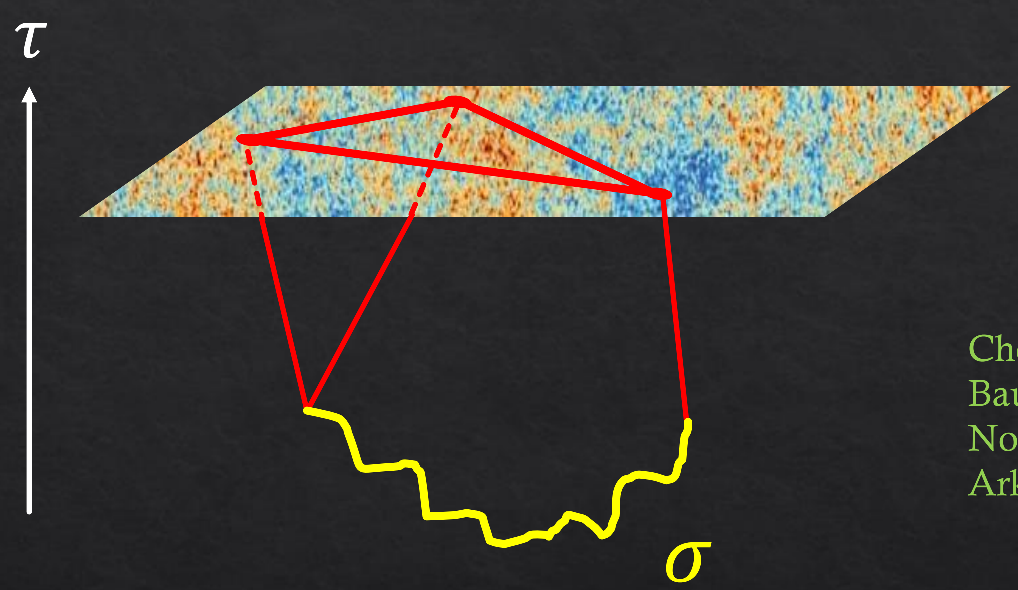

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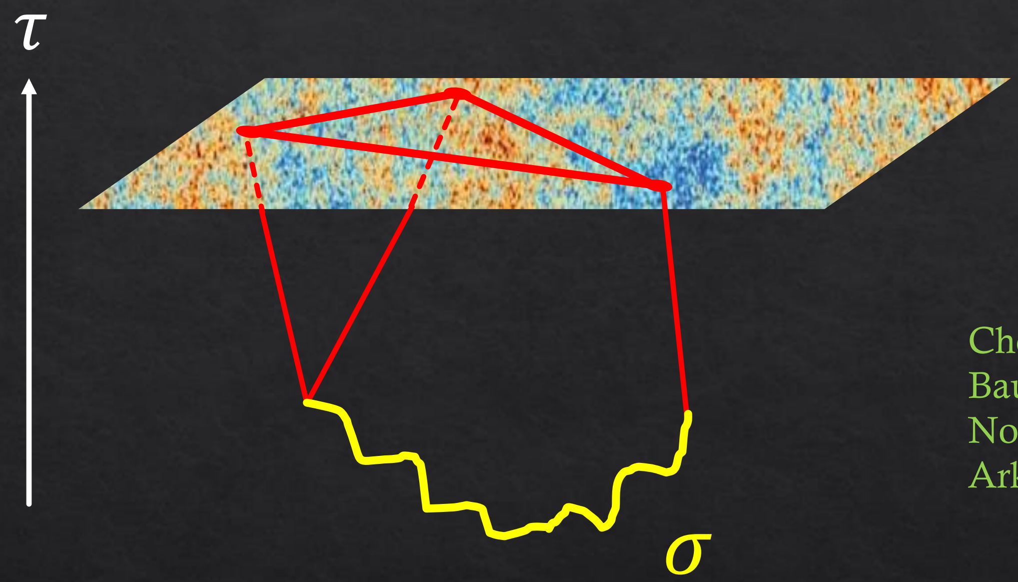
- NG can contain information of heavy (new) particle σ with specific oscillation signal (frequency = m_σ)
- $m_\sigma \sim H \sim 10^{13}$(GeV) $\gg$ energy scale of terrestrial experiment
- Signal can be large!!

Cosmological collider (CC)



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CC = new tool for searching high energy physics

Many works

✓SUSY (Baumann, Green, ’12)
✓EFT approach (Noumi, Yamaguchi, Yokoyama, ’13)
✓Spinning particle (H. Lee, D. Baumann, and G. L. Pimentel, ’16, S. Kim, T. Noumi, K. Takeuchi, Siyi Zhou, ’19, …)
✓Neutrino (Chen, Wang, Xianyu, ’16)
✓Leptogenesis (Cui, Xianyu ’21)
✓GUT (Maru, Okawa, ’21)
…

Today

In general, inflationary background gives a time-dependence to σ-mass

$$\mathcal{L}_{\rm int} \supset -\frac{1}{2}g(\phi)\sigma^2.$$

⇒ $m_{\rm eff}^2 = g(\phi_0)$

Time-dependent mass

⇒ Effects on CC signal??

Today

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Time-dependent mass

⇒ Effects on CC signal??

So far, studied only by numerical simulation

M. Reece, L.T. Wang, Z.Z. Xianyu' 2022

⇒ We tackle this in an analytic way using Bootstrap technique

N. Arkani-Hamed, D. Baumann, H. Lee, G. L. Pimentel '18

Strategy

Linear approximation

$$\phi_0(\tau) = \phi_{0*} - \sqrt{2\epsilon} M_{\rm Pl} \left(1 - \frac{\tau}{\tau_*}\right) + \cdots \,,$$

$$m_{\rm eff}^2(\tau) = g_* - g_{\phi,*} \sqrt{2\epsilon} M_{\rm Pl} \left(1 - \frac{\tau}{\tau_*}\right) + \cdots \,,$$

τ_* : time when a mode k associated with σ crosses the horizon ($k\tau_* = -1$)

→ Mode function of σ can be obtained analytic way

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τ_* : time when a mode k associated with σ crosses the horizon ($k\tau_* = -1$)

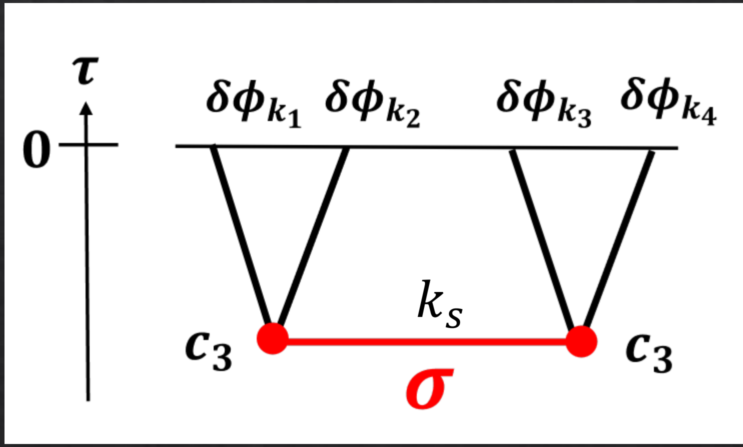
➡ Mode function of σ can be obtained analytic way

Slow-roll approximation $\dot{\phi}_0 \sim$ const.

$$\phi_{0*} = \sqrt{2\epsilon} M_{\rm Pl} \log\left(\frac{\tau_*}{\tau_0}\right) = -\sqrt{2\epsilon} M_{\rm Pl} \log v(k), \quad v(k) \equiv \frac{k}{k_0},$$

➡ additional k-dependence appear

Target



$$\sim \int d\tau_1 d\tau_2\, e^{ik_1\tau_1} e^{ik_2\tau_1} e^{ik_3\tau_2} e^{ik_4\tau_2} D(k_s;\tau_1,\tau_2)$$

Propagator of σ

Performing time-integrations is hard task …

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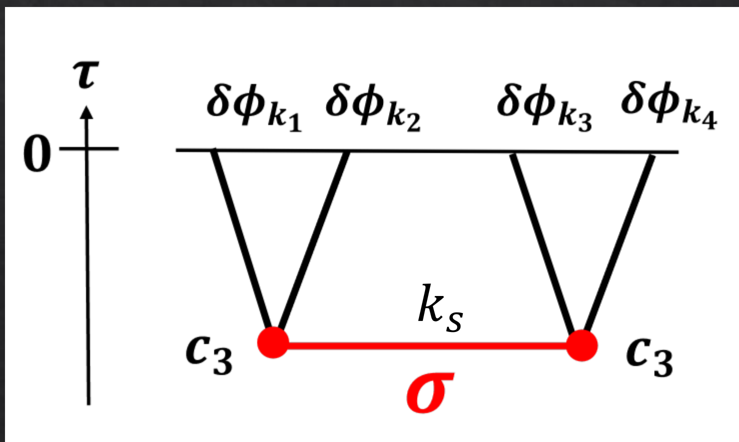

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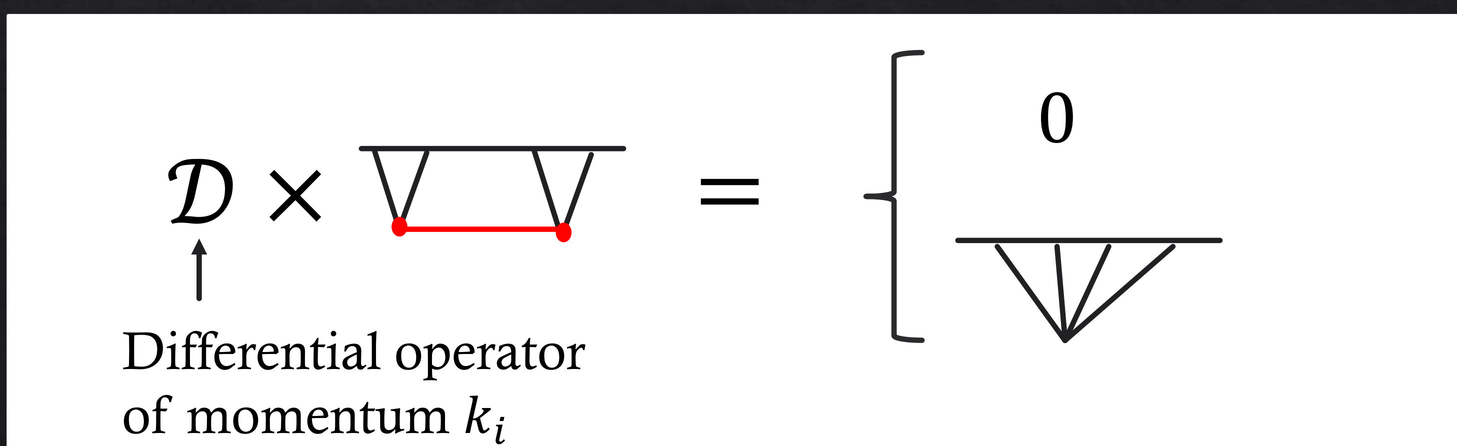
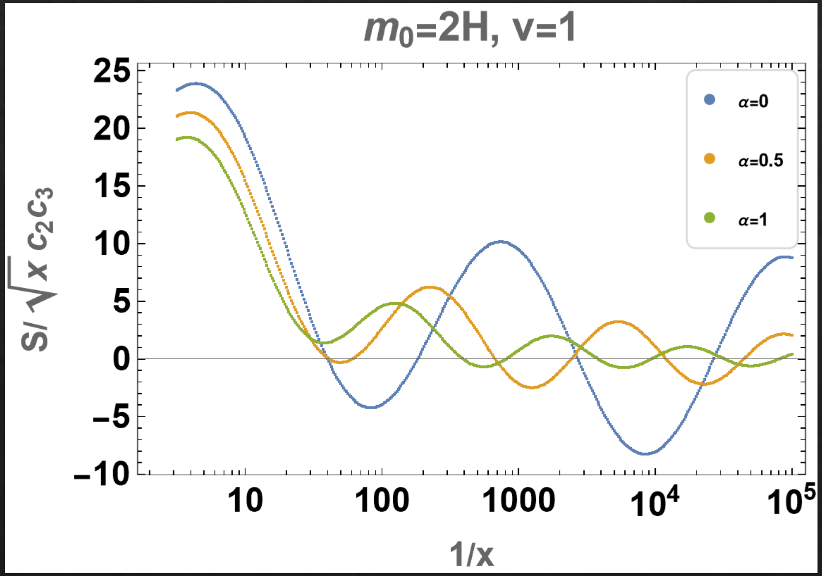
Bootstrap equations



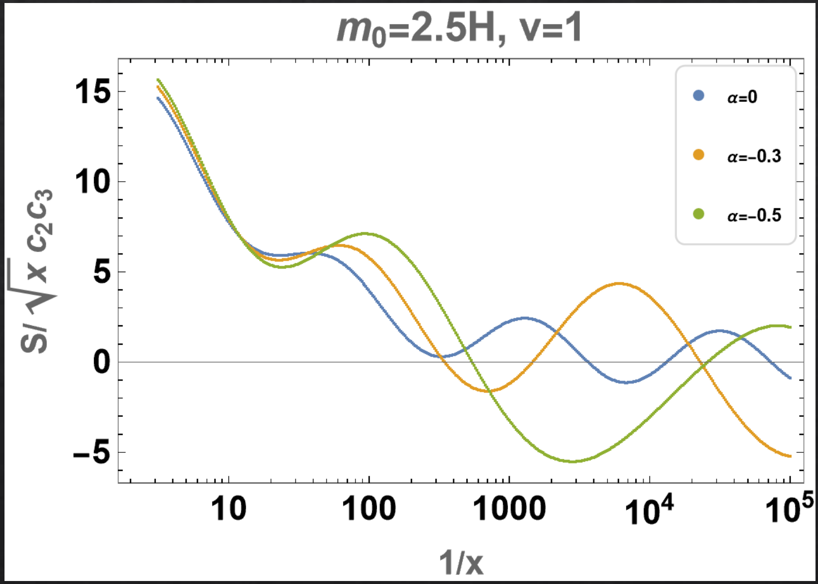
Results (preliminary)

$$g(\phi) = m_0^2 \left(1 + \alpha \frac{\phi}{M_{\rm Pl}}\right)$$

Positive α



Negative α



$x \equiv k_3/k_{1,2}$

Large deviation from standard (constant) mass by scale-dependent Boltzmann suppression

Why??

Squeezed limit:
correlation between a long mode (k_3) and short ones ($k_{1,2}$)

Exit horizon at τ_{early} at τ_{late}

Super-horizon evolution of long mode:

$$v_{k3}(\tau_{\text{late}}) \propto v_{k3}(\tau_{\text{early}}) \times Exp\left\{-\frac{\pi}{2}\frac{m(\tau_{\text{late}}) - m(\tau_{\text{early}})}{H}\right\}$$

enhancement/suppression
depending on sign of α

Distinguish couplings??

Parametrize scale-dependent Boltzmann factor

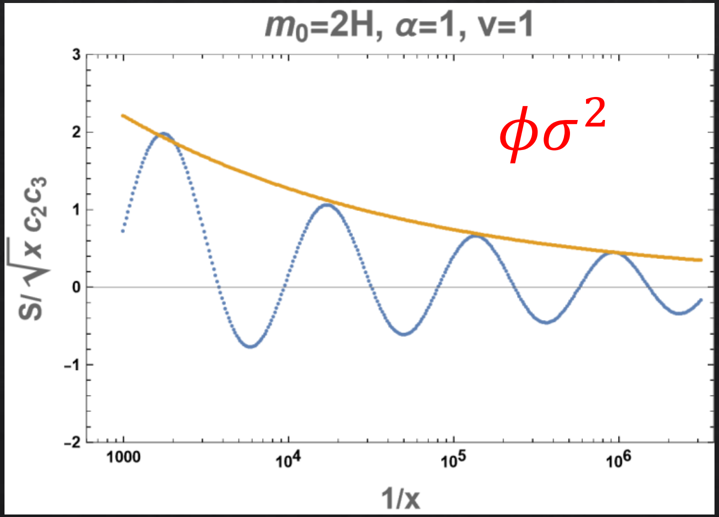
For $g(\phi) = m_0^2 \left(1 + \alpha_{(n)} \frac{\phi^n}{M_{\rm Pl}^n}\right)$

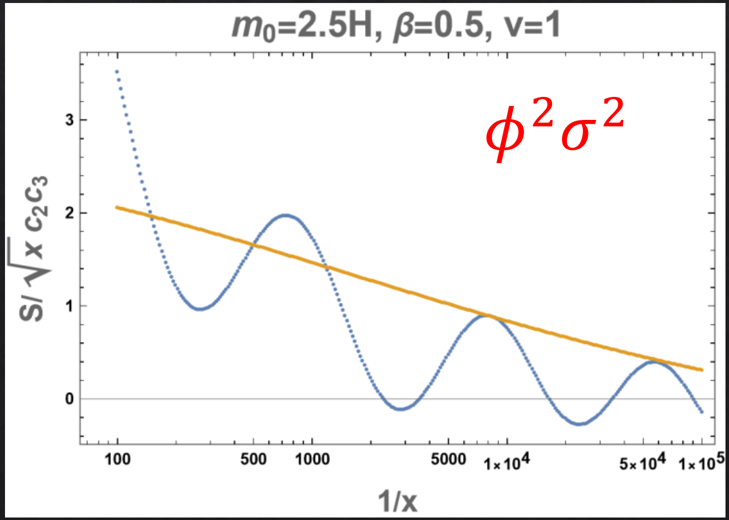
$$e^{-\pi\mu(x)} \sim e^{-\pi m_0/H} \cdot e^{-\pi \frac{m_0}{H} \cdot \frac{\alpha_{(n)}}{2} (-\sqrt{2\epsilon})^n (\log vx)^{n-1} (\log vx + n)},$$

"Suppression tail"

$x \equiv k_3/k_{1,2}$

$v \equiv k_1/k_0.$





Summary

- Cosmological collider (CC)
  is a new attractive tool for exploring high energy

- Time-dependent mass on CC
  (coming from inflaton couplings in general)

- amplitude enhancement/suppression in squeezed limit
  by scale-dependent Boltzmann factor

- From different suppression tails,
  one may distinguish inflaton-sigma couplings

Thank you.

Details

Mode function of heavy field

Linear approximation

$$\phi_0(\tau) = \phi_{0*} - \sqrt{2\epsilon}M_{\rm Pl}\left(1 - \frac{\tau}{\tau_*}\right) + \cdots ,$$

$$m_{\rm eff}^2(\tau) = g_* - g_{\phi,*}\sqrt{2\epsilon}M_{\rm Pl}\left(1 - \frac{\tau}{\tau_*}\right) + \cdots ,$$

τ_* : time when a mode k associated with σ crosses the horizon ($k\tau_* = -1$)

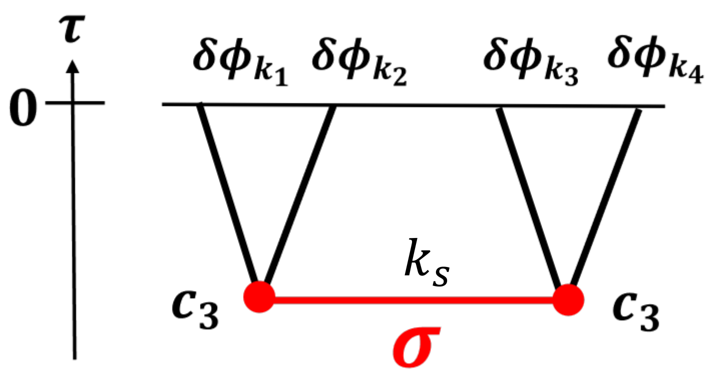
Mode function of σ :

$$v_k = \frac{e^{\pi\kappa/2}}{\sqrt{2k}} H(-\tau) W_{-{\rm i}\kappa,{\rm i}\mu}(2{\rm i}k\tau),$$

$$\mu^2 \equiv \frac{g_*}{H^2}\left(1 - \frac{\sqrt{2\epsilon}g_{\phi,*}M_{\rm Pl}}{g_*}\right) - \frac{9}{4}, \quad \kappa \equiv -\frac{g_*}{2H^2}\frac{\sqrt{2\epsilon}g_{\phi,*}M_{\rm Pl}}{g_*}.$$

Formally, $\kappa = 0$ corresponds to constant mass

Seed integral



$$\propto \sum_{a,b=\pm} I_{ab}^{p_1 p_2}$$

"Seed" integral:

$$\mathcal{I}_{\mathrm{ab}}^{p_1 p_2} \equiv -\mathrm{ab} k_s^{5+p_{12}} \int_{-\infty}^{0} \mathrm{d}\tau_1 \, \mathrm{d}\tau_2 \, (-\tau_1)^{p_1} \, (-\tau_2)^{p_2} \, e^{\mathrm{i a} k_{12}\tau_1 + \mathrm{i b} k_{34}\tau_2} D_{\mathrm{ab}} \left(k_s; \tau_1, \tau_2\right)$$

Propagator of σ

Bootstrap equations

$$\mathcal{D}^{p_1}_{\pm,u_1}\mathcal{I}^{p_1p_2}_{\pm\mp} = 0,$$

$$\mathcal{D}^{p_1}_{\pm,u_1}\mathcal{I}^{p_1p_2}_{\pm\pm} = H^2 e^{\mp \mathrm{i} p_{12}\frac{\pi}{2}}\Gamma(5+p_{12})\left(\frac{u_1u_2}{2(u_1+u_2-u_1u_2)}\right)^{5+p_{12}}$$

$$\mathcal{D}^{p}_{\pm,u} \equiv \left(u^2-u^3\right)\partial_u^2 - \left[(4+2p)u - (1+p\pm \mathrm{i}\kappa)u^2\right]\partial_u + \left[\mu^2 + \left(p+\frac{5}{2}\right)^2\right]$$

$$u_i \equiv \frac{2r_i}{1+r_i}, \quad (i=1,2).$$

$$r_1 \equiv \frac{k_s}{k_{12}}, \quad r_2 \equiv \frac{k_s}{k_{34}},$$

additional scale-dependence is encoded in μ and κ

$$\mu^2 \equiv \frac{g_*}{H^2}\left(1-\frac{\sqrt{2\epsilon}g_{\phi,*}M_{\rm Pl}}{g_*}\right) - \frac{9}{4},$$

$$\kappa \equiv -\frac{g_*}{2H^2}\frac{\sqrt{2\epsilon}g_{\phi,*}M_{\rm Pl}}{g_*}.$$

$$
\begin{aligned}
&\mathcal{I}^{p_1p_2}_{\pm\mp}/H^2 \\
&= \frac{-e^{\mp \mathrm{i}\frac{\pi}{2}\bar{p}_{12}} e^{\pi\kappa}\left[\cosh(2\pi\kappa)+\cosh(2\pi\mu)\right]}{2\sinh^2(2\pi\mu)} \\
&\times \left\{ 2^{\pm \mathrm{i}\mu}\left(\frac{u_1}{2}\right)^{\frac{5}{2}+p_1\pm \mathrm{i}\mu} {}_2\mathcal{F}_1\left[\left.\begin{matrix} \frac{5}{2}+p_1\pm \mathrm{i}\,\mu,\, \frac{1}{2}\mp \mathrm{i}\kappa \pm \mathrm{i}\,\mu \\ 1\pm 2\mathrm{i}\mu \end{matrix}\right| u_1\right] - (\mu\to-\mu)\right\} \\
&\times \left\{ 2^{\pm \mathrm{i}\mu}\left(\frac{u_2}{2}\right)^{\frac{5}{2}+p_2\pm \mathrm{i}\mu} {}_2\mathcal{F}_1\left[\left.\begin{matrix} \frac{5}{2}+p_2\pm \mathrm{i}\,\mu,\, \frac{1}{2}\pm \mathrm{i}\kappa \pm \mathrm{i}\,\mu \\ 1\pm 2\mathrm{i}\mu \end{matrix}\right| u_2\right] - (\mu\to-\mu)\right\},
\end{aligned}
\tag{3.45}
$$

$$
\begin{aligned}
&\mathcal{I}^{p_1p_2}_{\pm\pm}/H^2 \\
&= \frac{\mp \mathrm{i} e^{\mp\frac{\pi}{2}\mathrm{i}p_{12}} e^{\pi\kappa}\pi}{\Gamma\left[\frac{1}{2}\mp \mathrm{i}\kappa-\mathrm{i}\mu,\, \frac{1}{2}\mp \mathrm{i}\kappa+\mathrm{i}\mu\right]\sinh^2(2\pi\mu)} \\
&\times \left\{ \frac{e^{\pi\mu}\cosh\left[\pi(-\mu+\kappa)\right]}{2^{\mp \mathrm{i}\mu}}\left(\frac{u_1}{2}\right)^{\frac{5}{2}+p_1\pm \mathrm{i}\mu} {}_2\mathcal{F}_1\left[\left.\begin{matrix} \frac{5}{2}+p_1\pm \mathrm{i}\,\mu,\, \frac{1}{2}\mp \mathrm{i}\kappa \pm \mathrm{i}\,\mu \\ 1\pm 2\mathrm{i}\mu \end{matrix}\right| u_1\right] - (\mu\to-\mu)\right\} \\
&\times \left\{ 2^{\pm \mathrm{i}\mu}\left(\frac{u_2}{2}\right)^{\frac{5}{2}+p_2\pm \mathrm{i}\mu} {}_2\mathcal{F}_1\left[\left.\begin{matrix} \frac{5}{2}+p_2\pm \mathrm{i}\,\mu,\, \frac{1}{2}\mp \mathrm{i}\kappa \pm \mathrm{i}\,\mu \\ 1\pm 2\mathrm{i}\mu \end{matrix}\right| u_2\right] - (\mu\to-\mu)\right\} \\
&+ \frac{e^{\mp\frac{\pi}{2}\mathrm{i}p_{12}}\Gamma\left(p_{12}+5\right)}{2^{p_{12}+5}} \sum_{n=0}^{\infty} u_1^{n+p_{12}+5}\left(1-\frac{1}{u_2}\right)^n \begin{pmatrix} n+p_{12}+4 \\ n \end{pmatrix} \\
&\times \frac{1}{\mu^2+\left(\frac{5}{2}+n+p_2\right)^2} {}_3\mathrm{F}_2\left[\left.\begin{matrix} 1,3+n+p_2\mp \mathrm{i}\kappa, 5+n+p_{12} \\ \frac{7}{2}+n+p_2-\mathrm{i}\mu,\, \frac{7}{2}+n+p_2+\mathrm{i}\mu \end{matrix}\right| u_1\right],
\end{aligned}
\tag{3.46}
$$