Model building aspects of cosmological collider

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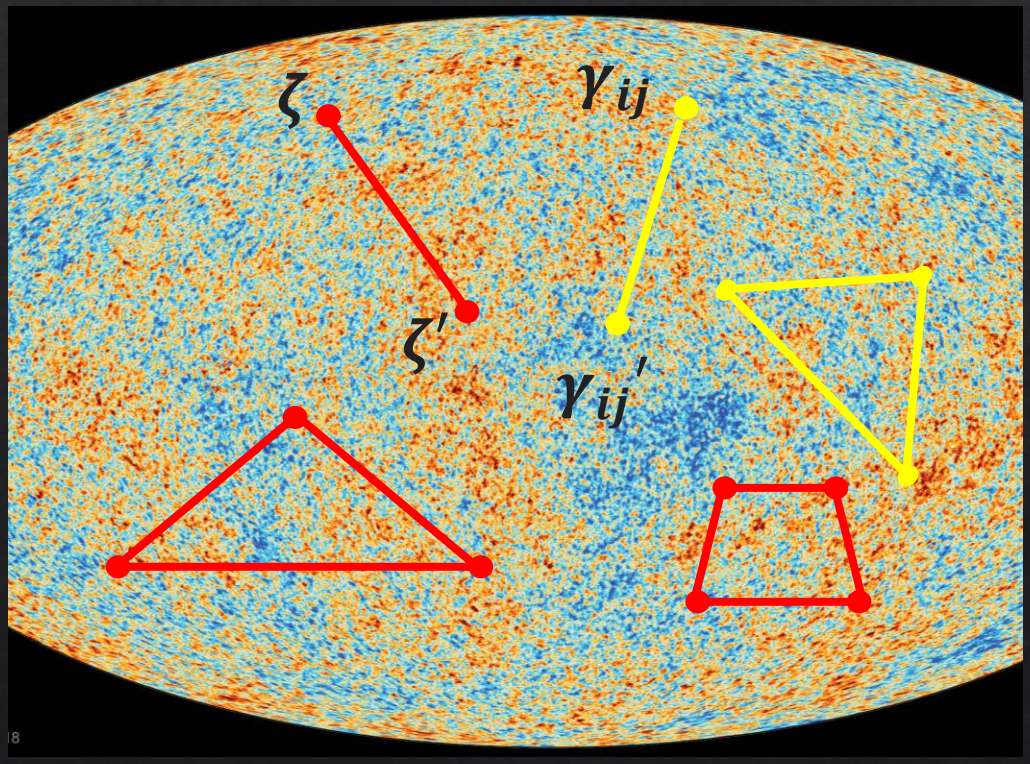
Observable in CMB
= Cosmological correlators

- ζ: scalar, γ: tensor
- Probably created by inflation

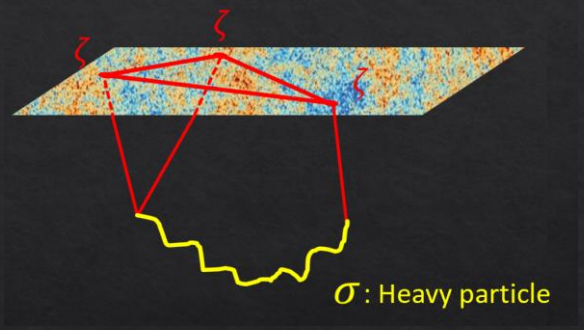


Correlators ⊃ Many information of early universe

- $\langle\zeta\zeta\rangle$: fixed by CMB ⇒ $\dot{\phi}^{1/2}/H_{\rm inf} \sim 60$
- $\langle\gamma\gamma\rangle$: not observed yet (maybe in future) ⇒ $H_{\rm inf}/M_{\rm PL} \sim$?
- $\langle\zeta\zeta\zeta\rangle$, $\langle\zeta\zeta\zeta\zeta\rangle$: non-Gaussianity
  - not observed yet (consistent with 0)
  - strong constraints on inflation models

Non-Gaussianity as particle detector

- $\langle \zeta^3 \rangle$ with heavy particles σ ($m_\sigma \sim H_{\rm inf}$)



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

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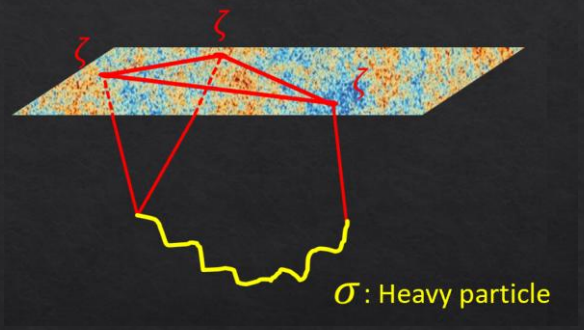

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- σ leaves specific imprints on $\langle\zeta^3\rangle$

$$\langle\zeta^3\rangle\big|_{k_L\ll k_S} \sim e^{-\pi\mu}\left(\frac{k_L}{k_s}\right)^{\frac{3}{2}}\cos\left[\mu\log\left(\frac{k_L}{k_s}\right)+\delta(\mu)\right]P_s(\cos\theta)$$

$\mu \sim m_\sigma/H$: mass

spin

"Cosmological Collider"

Today

- Towards application to BSM (model building aspects)
  - Conditions for large signal?
  - Dominant diagram?

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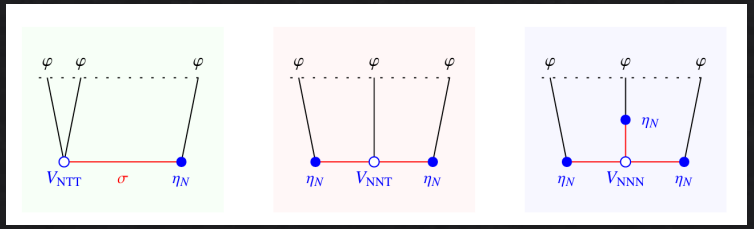
  - Conditions for large signal?
  - Dominant diagram?

- Target & Assumption
  - $\langle \zeta^3 \rangle$
  - Inflation scenario
  - Tree >> Loop
  - Scalar exchange



What determines couplings

- Setup: two scalars ϕ^a $(a = 1,2)$

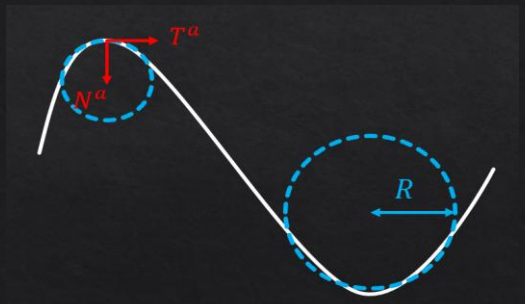
$$S = \int d^4x\sqrt{|\det g|}\left[-\frac{\bar{M}_{\rm Pl}^2}{2}R + \frac{K_{ab}(\phi)}{2}(\partial_\mu\phi^a)(\partial^\mu\phi^b) - V(\phi)\right]$$

- Perturbation for fluctuation $\delta\phi^a = \varphi T^a + \sigma N^a$ $(\varphi{\sim}\zeta)$

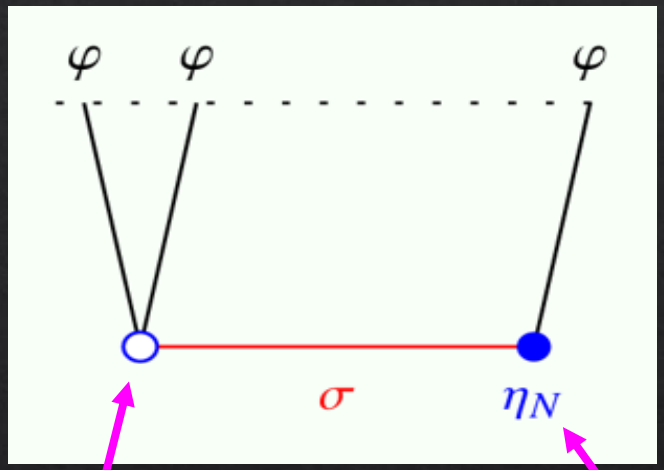
$$\mathscr{L}^{(2)} \approx (\text{free } {\sim}\text{massless } \varphi) + (\text{free massive } \sigma) + 2\eta_N H\sigma\dot{\varphi}.$$

$\varphi \Leftrightarrow \sigma$

- turn rate : $\eta_{\rm N} = \frac{d\phi}{dN} \times \kappa$
  κ: curvature of trajectory



Understanding so far



What determines couplings

- Many cubic, dominated by potential couplings

$$\mathscr{L}^{(3)} \sim \underbrace{V_{TTT}\varphi^3}_{\text{small}} + V_{NTT}\sigma\varphi^2 + V_{NNT}\sigma^2\varphi + V_{NNN}\sigma^3 + \cdots$$

Maldacena '03

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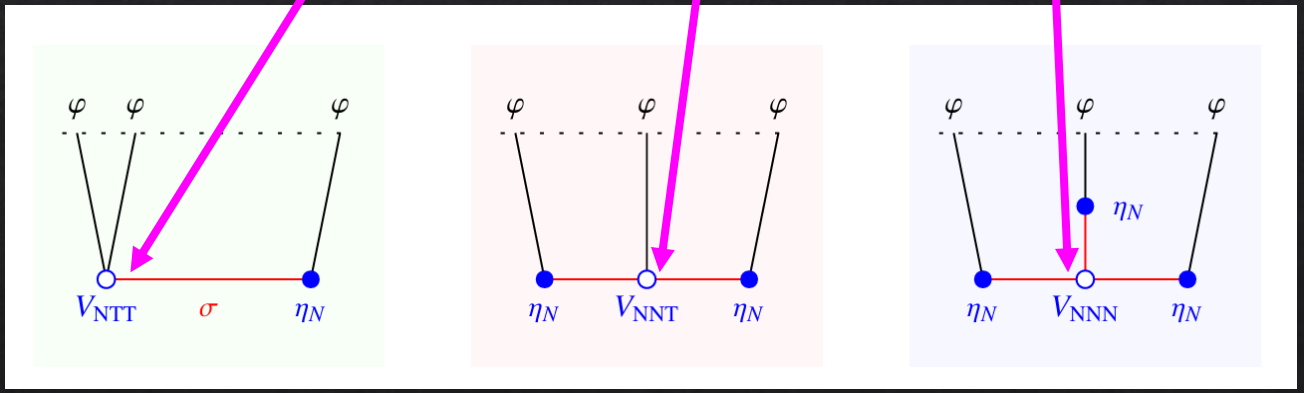
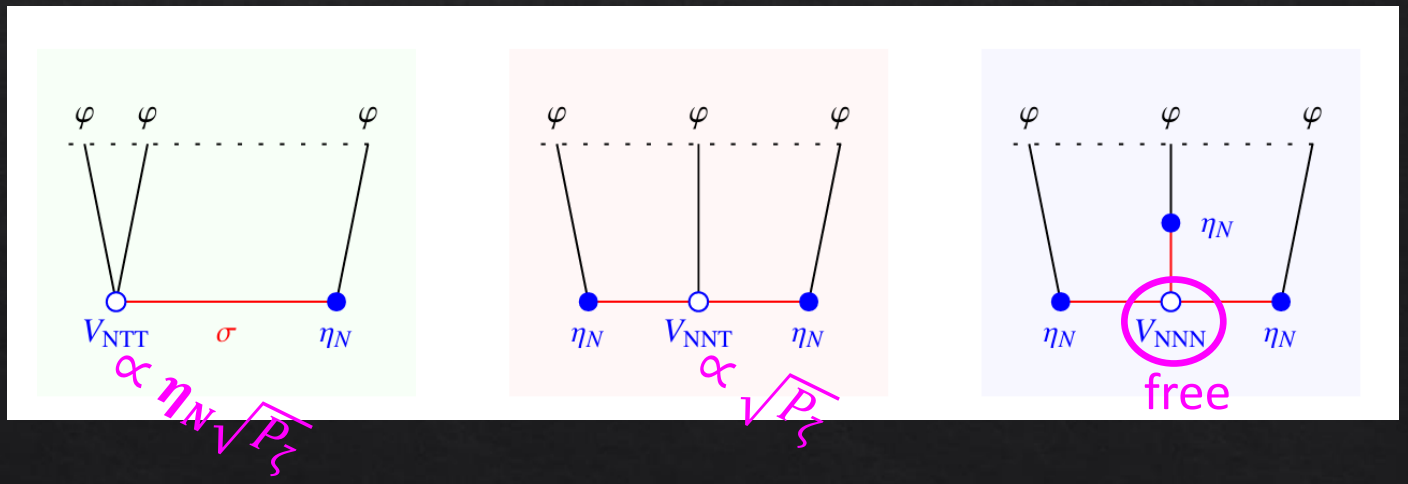
Maldacena '03

- Dominant diagrams



Remark

- Potential derivatives along T-direction (inflaton) are not independent
  - $V_{NTT}/H \sim \eta_N \times \sqrt{P_\zeta}$ with $\sqrt{P_\zeta} \sim 10^{-5}$
  - $V_{NNT}/H \sim \sqrt{P_\zeta}$
- However, V_{NNN} is not constrained (free parameter) in general
- η_N determines almost everything



For large signal

- Large turn rate. Remember $\eta_{\mathrm{N}} = \frac{d\phi}{dN} \times \kappa = \sqrt{2\epsilon} M_{\mathrm{PL}} \times \kappa$
  ⇒ Large κ ⇒ sub-Planckian physics

- Large V_{NNN} "Quasi single field inflation" Chen, Wang, '10

Check by concrete model

- Scalar ϕ + R^2 (scalaron)

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{1}{2} f(\phi) R + \frac{R^2}{6 f_0^2} + \sum_{\phi} \frac{(D_\mu \phi)(D^\mu \phi)}{2} - V_{\rm J}(\phi) \right]$$

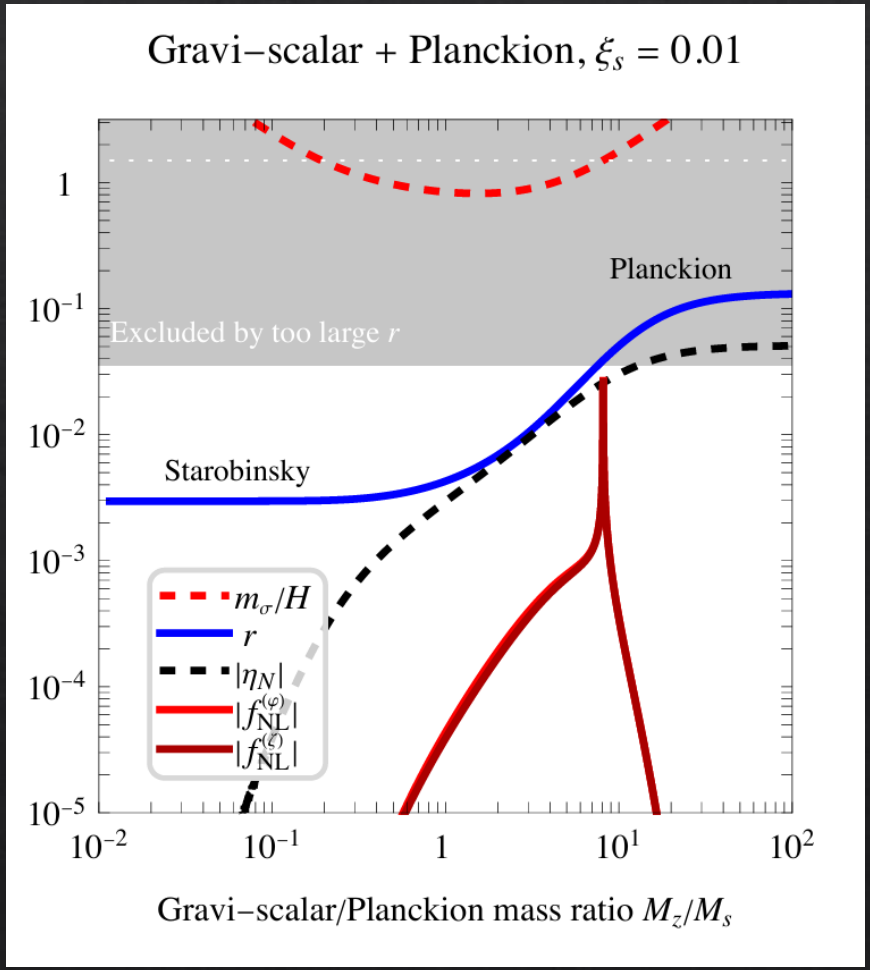
A) $f = \xi\phi^2, V_J = \lambda(\phi)\phi^4/4 \Rightarrow$ dilaton + R^2 Kannike et al, '15,...

B) $f = M_{\rm PL}^2 + \xi\phi^2, V_J = \lambda\phi^4/4 \Rightarrow$ Higgs + R^2 Salvio, Mazumdar '15, Ema '17, ...

- Interpolate ϕ-like inflation and Starobinsky inflation
  $\Rightarrow$ CC signal $= 0$ in two extreme limits, but $\neq 0$ in mixed regime

- Only scale $\sim M_{\rm PL} \Rightarrow \kappa \propto 1/M_{\rm Pl} \Rightarrow \eta_{\rm N} \propto \sqrt{\epsilon}$: Small turn !!

CC signal from dilaton + R^2



Summary

- CC offers a powerful way to probe new physics via cosmology.
- However, the conditions for a large signal remain unclear and are sometimes incorrectly estimated.

- Model building aspects of CC with tree level scalar exchange

  - Need big turn rate (sub-Planckian physics) and/or big V_{NNN} for large signal
  - Confirmed by motivated models: dilaton-R^2 & Higgs-R^2

- interesting to apply other BSM with large turn

Thank you!!

E-frame action

- E-frame

$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{\bar{M}_{\rm Pl}^2}{2} R + \frac{6\bar{M}_{\rm Pl}^2}{z^2} \frac{(\partial_\mu z)^2 + \sum_\phi (D_\mu \phi)^2}{2} - V(\phi, z) \right]$$

$$V = \left(\frac{6\bar{M}_{\rm Pl}^2}{z^2} \right)^2 \left[V_{\rm J}(\phi) + \frac{3}{8} f_0^2 \left(f + \xi_z z^2 \right)^2 \right]. \qquad \xi_z = -1/6,$$

- $V_J \gg f_0^2$: Starobinsky-like inflation. Potential is minimized by $\phi = \text{const.}$ $\rightarrow$ vanishing turn rate
- $V_J \ll f_0^2$: ϕ-like inflation. Potential is minimized by $f(\phi) = -\zeta_z z^2$ $\rightarrow z = z(\phi) \rightarrow$ non-zero turn rate
- $V_J \sim f_0^2$: Mixed regime