Probing New Physics through the Cosmological Collider

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RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program

ASPIRE
Adopting Sustainable Partnerships for Innovative Research Ecosystem

iTHEMS-NCTS Joint Workshop
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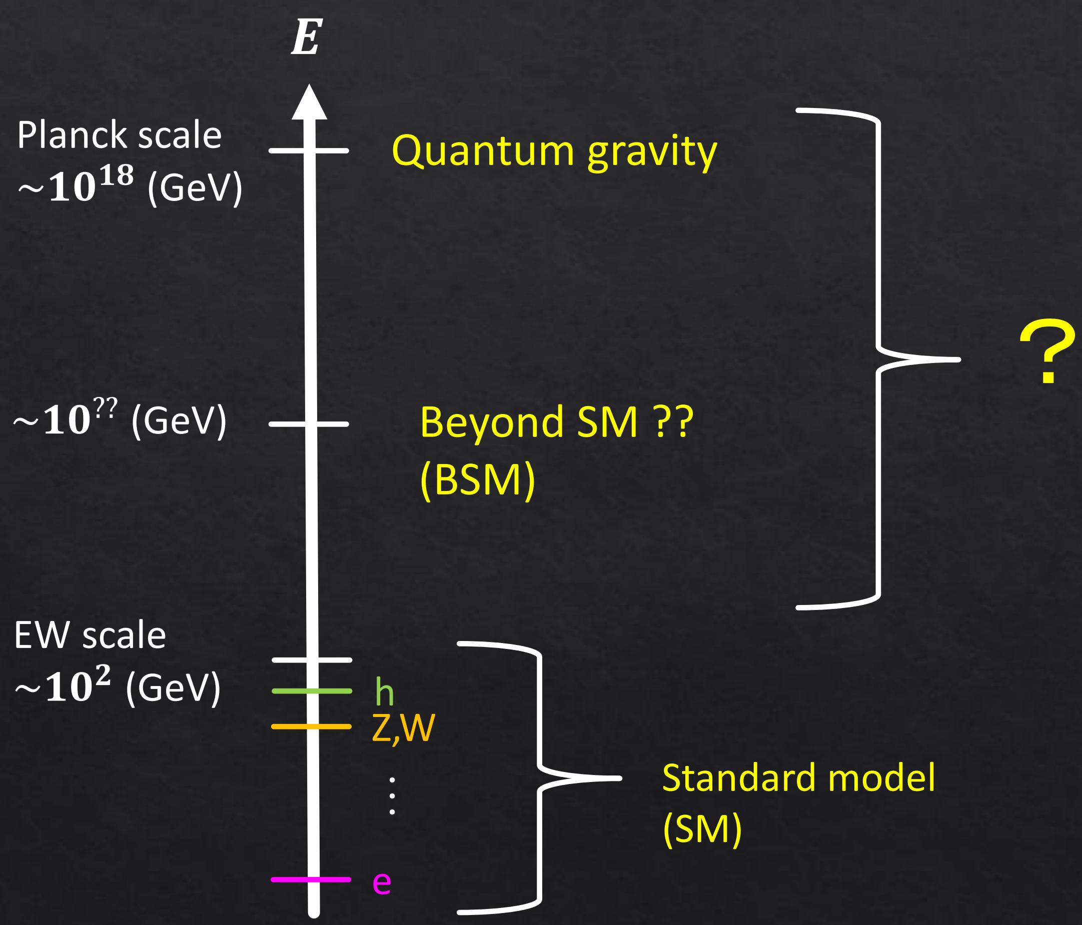
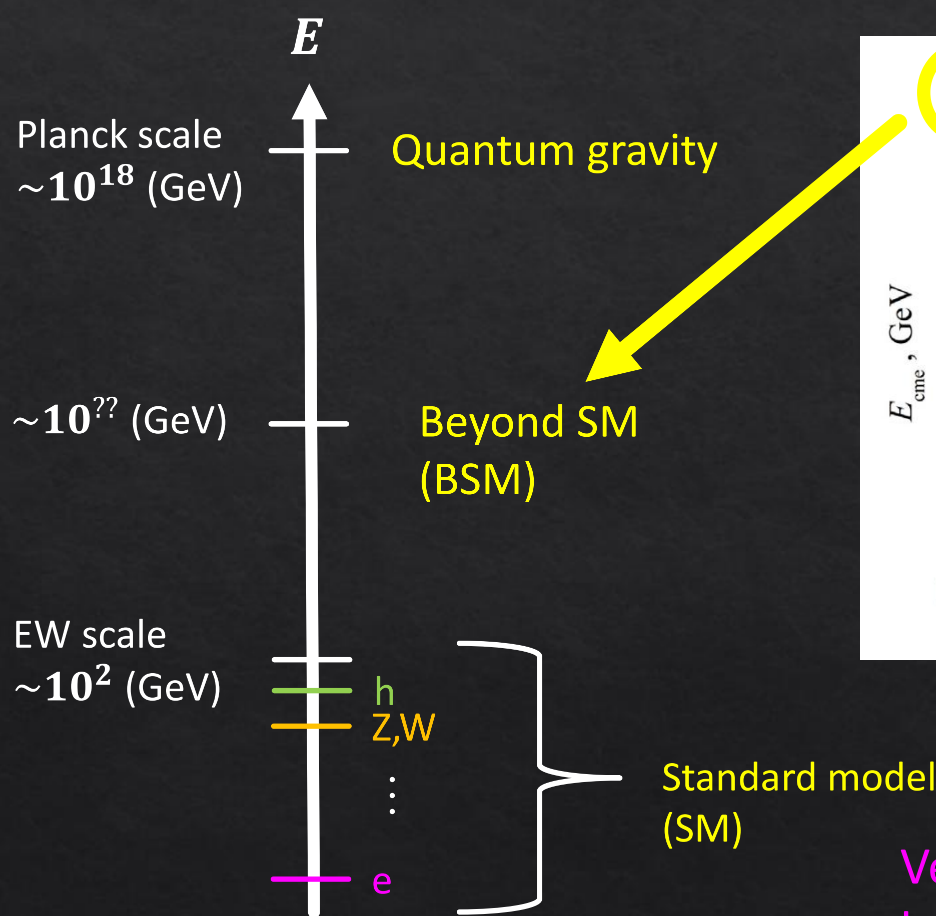
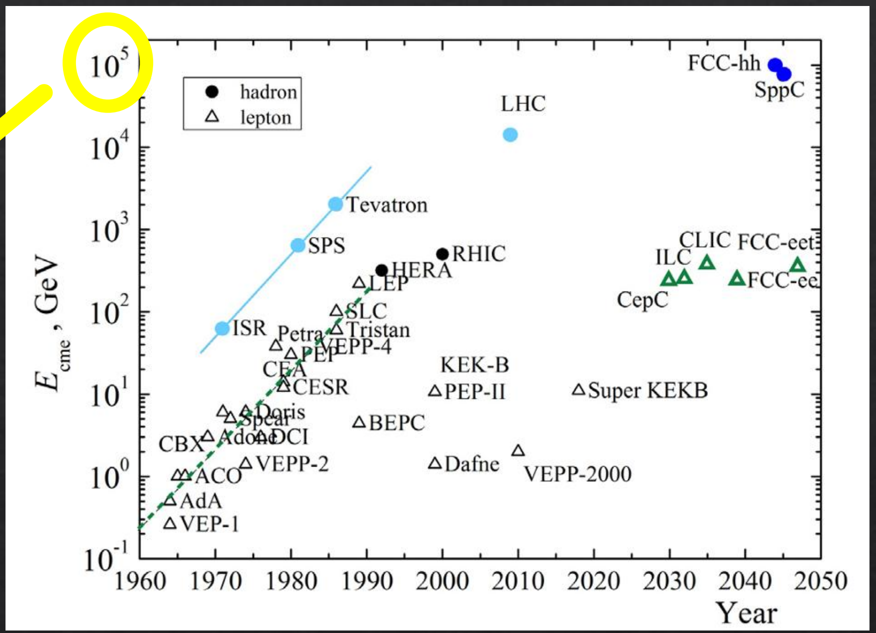
Introduction



Introduction

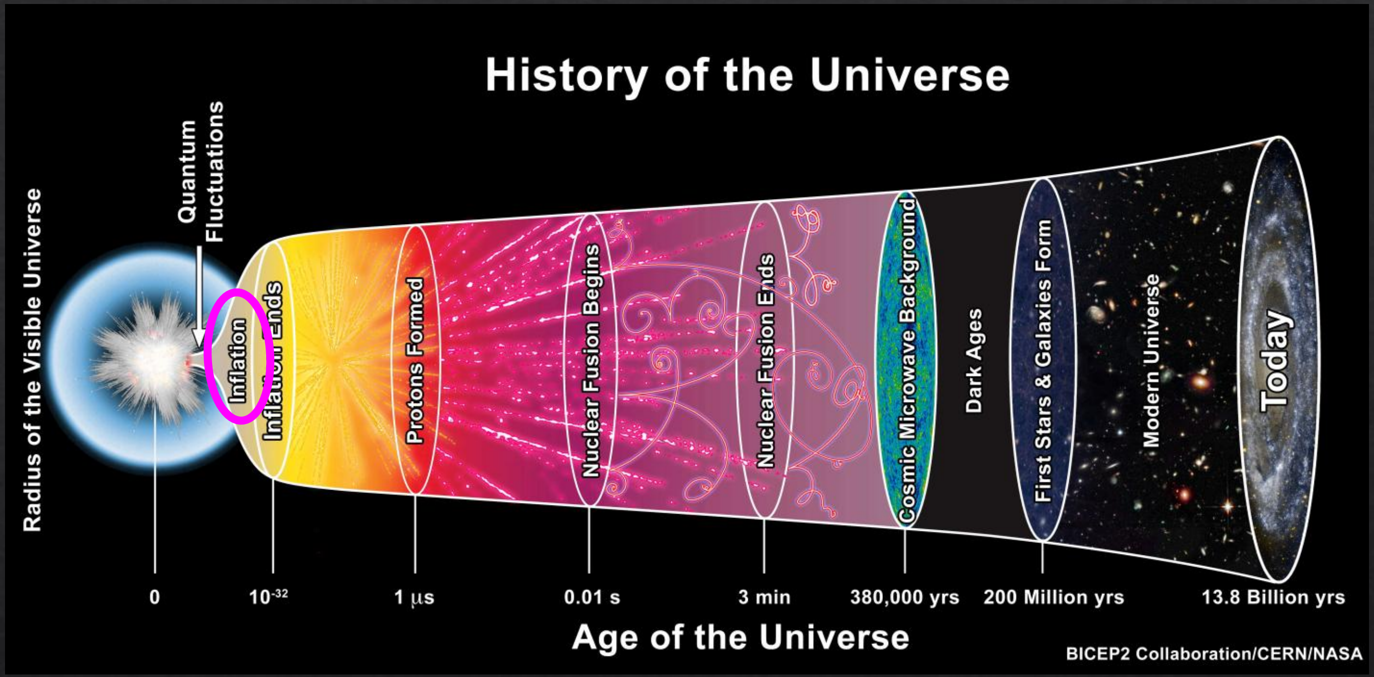


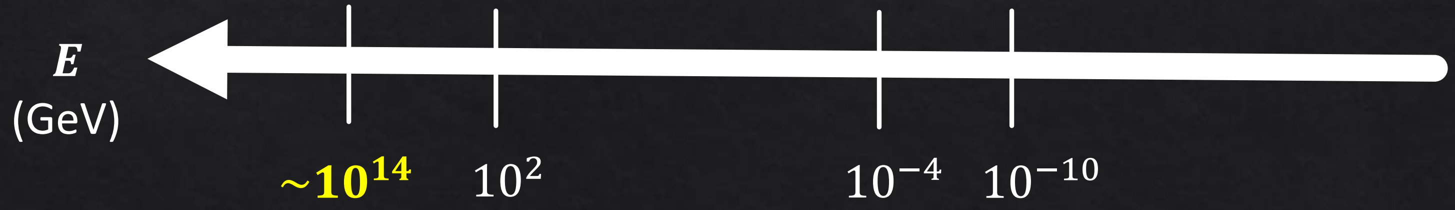


Gray, Future colliders for the high-energy frontier

Very important,
but BSM might appear at higher scale
⇒ Another approach?

Universe as a gigantic accelerator





Idea: probing new physics with inflation energy

Inflation

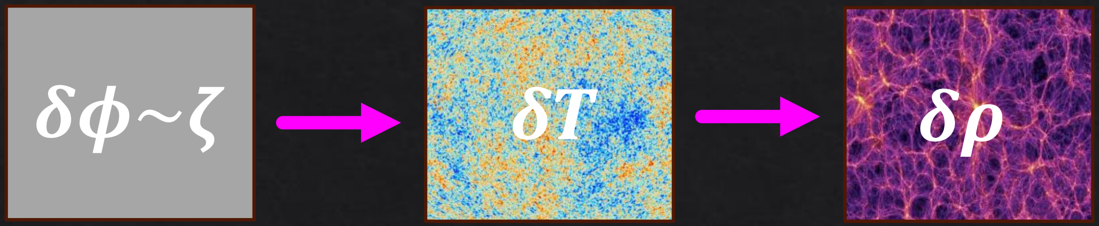
- Inflation = rapid expansion of early universe

Guth, Sato, Starobinsky, Linde,…

- Solve initial condition problems in standard cosmology

- Caused by a scalar ϕ: “inflaton”

- Quantum inflaton fluctuation $\delta\phi \rightarrow$ curvature ζ

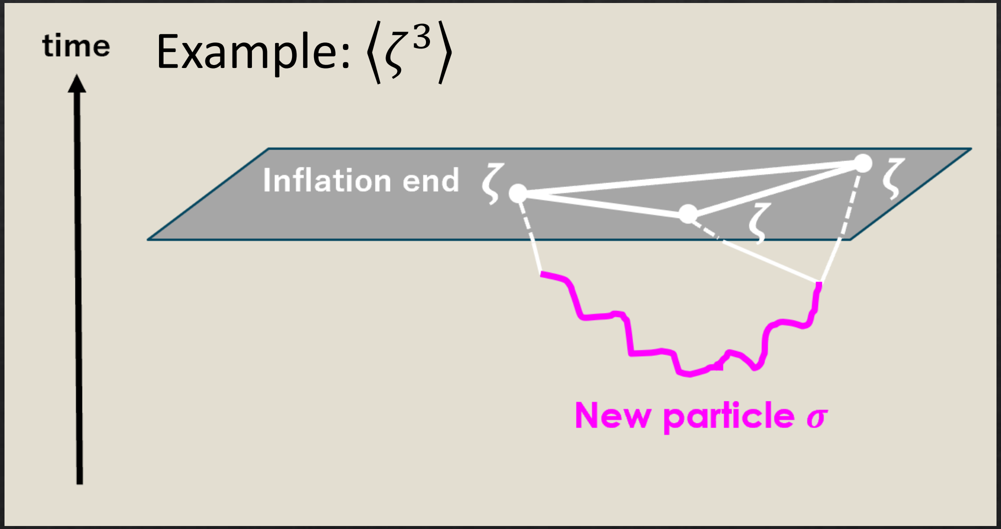


Inflation CMB LSS

Cosmological Collider

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

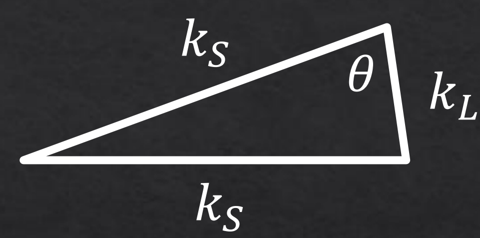
- $\langle \zeta^n \rangle$ can contain information of heavy (new) particle σ



Cosmic expansion creates σ with mass $\sim H$

Cosmological Collider

- Clear signal in squeezed limit of triangle $k_S \gg k_L$



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

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

Boltzmann suppression

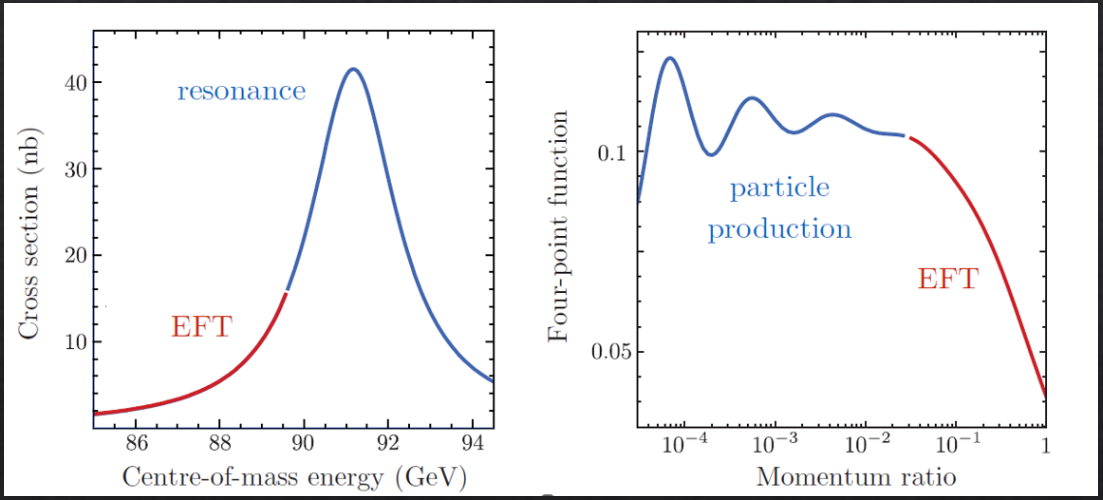
dilution

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

spin

Cosmological Collider

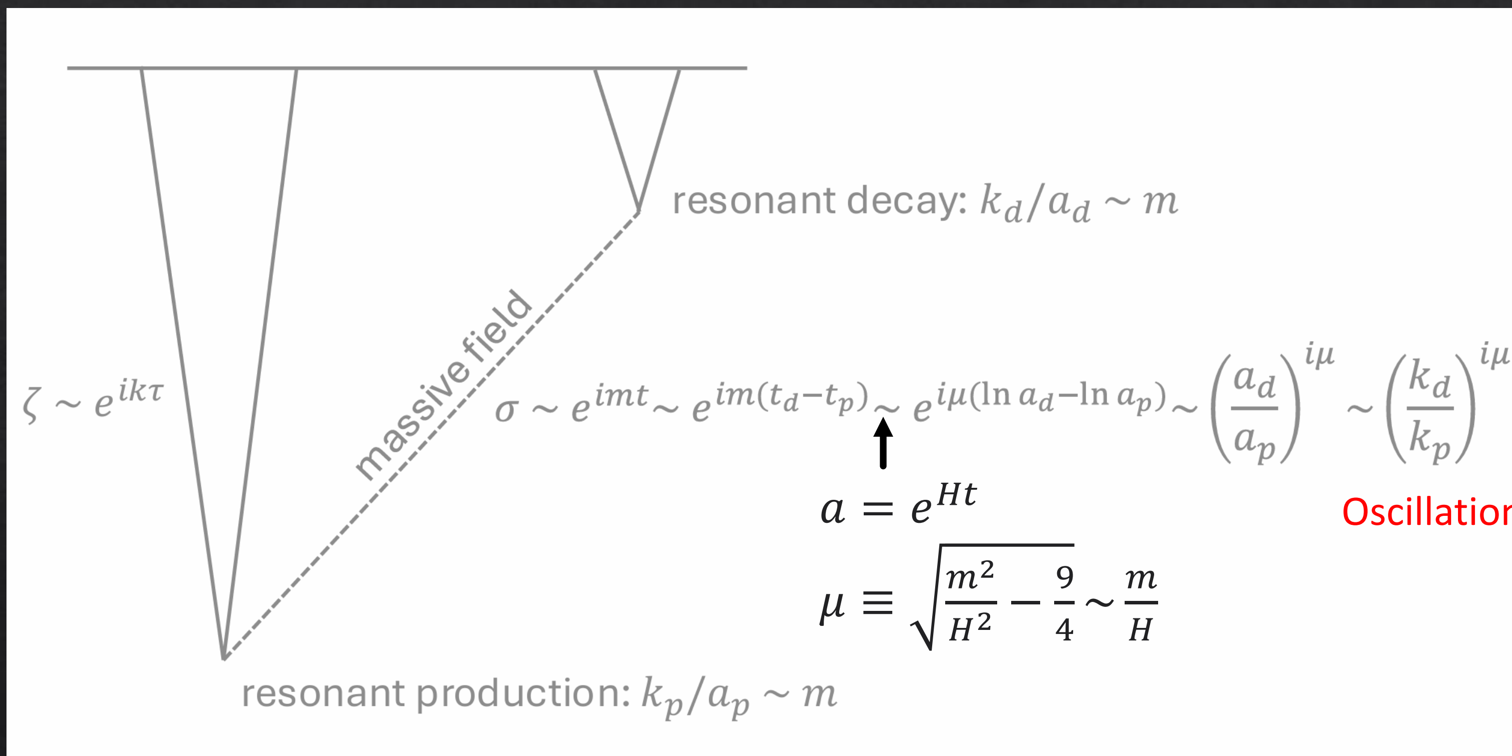
- Particle physics analogy



Baumann, Lectures on The Cosmological Bootstrap

- $m_\sigma \sim H_{\text{inf}} \sim 10^{14}$(GeV) $\gg\gg\gg$ $10^{4,5}$(GeV) ~ collider on earth

Why oscillation??



From Yi Wang's slide

Today

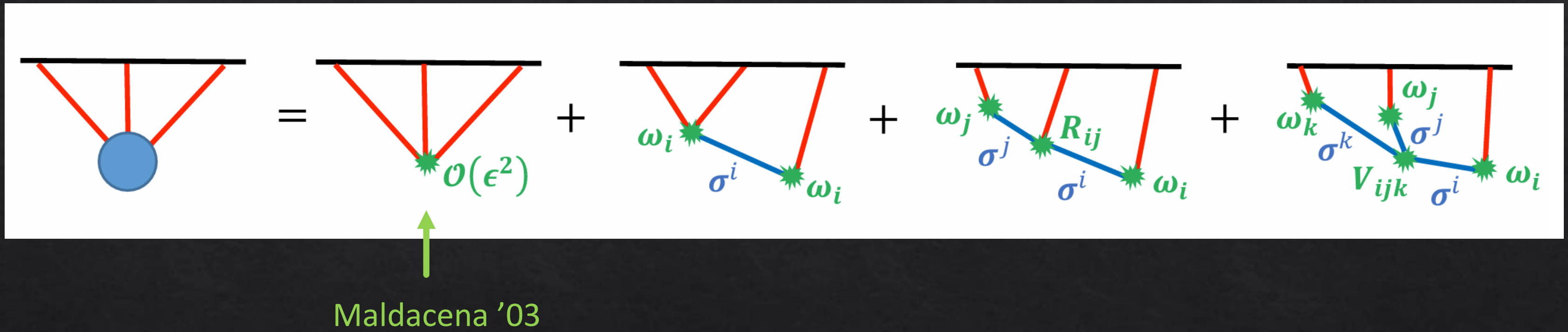
- Multiple massive particle exchange

  SA, L. Pinol, F. Sano, M. Yamaguchi, Y. Zhu, 2404.09547
  See also
  SA, T. Noumi, F. Sano, M. Yamaguchi, 2312.09642
  SA, 2301.07920
  L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi, 2112.05710
  SA, M. Yamaguchi, 2012.13667

- Application to BSM

  SA, A. Ghoshal and A. Strumia, 2408.07069

Multiple Exchange



- Sometimes larger effects than the simple single exchange process
- Rich phenomenology (specific CC signal)

Challenges

- De Sitter makes complexities
    - Mode functions of massive particles (Hankel, Whittacker, …)
    - Nested time integral

Challenges

- De Sitter makes complexities
  - Mode functions of massive particles (Hankel, Whittacker, …)
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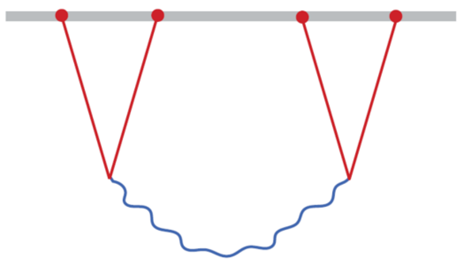
- Structure of correlators
  e.g., $\langle \zeta^4 \rangle$ with tree level single exchange

$F =$

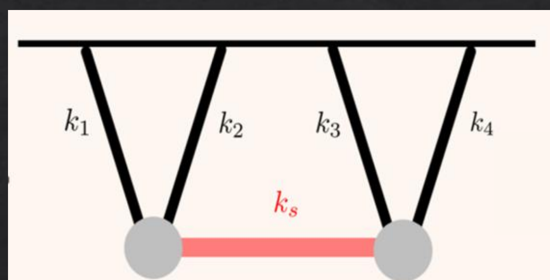


$$\sim -g^2 \int \frac{\mathrm{d}\eta}{\eta^2}\frac{\mathrm{d}\eta'}{\eta'^2}\, \underbrace{e^{i(k_1+k_2)\eta} e^{i(k_3+k_4)\eta'}}_{\text{External line for inflaton}}\, \underbrace{G(|\mathbf{k}_1+\mathbf{k}_2|,\eta,\eta')}_{\text{Propagator of } \sigma \text{ (complicated function)}}\,.$$

Recent development

Arkani-Hamed, Baumann, Lee, Pimentel, 1811.00024

- Correlators satisfy differential equations w.r.t momentum
  $u \equiv k_s/(k_1+k_2)$ & $v \equiv k_s/(k_3+k_4)$



$$\left(\Delta_u + M^2\right) F = uv/(u+v)$$
$$\left(\Delta_v + M^2\right) F = uv/(u+v)$$

$$\Delta_u \equiv u^2(1-u^2)\partial_u^2 - 2u^3\partial_u \,,$$

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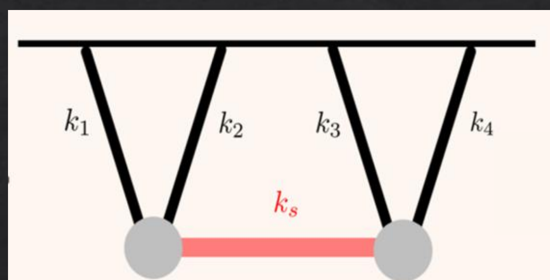

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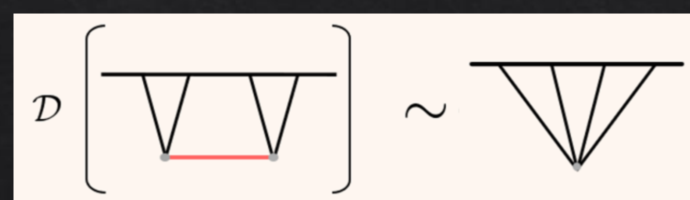
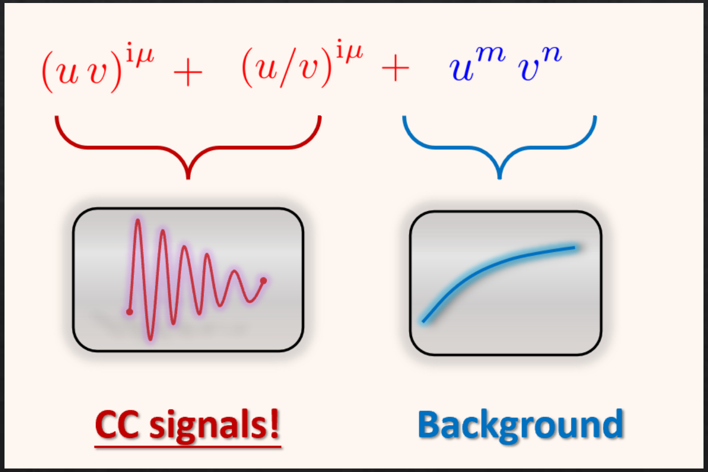
- Schematical expression:

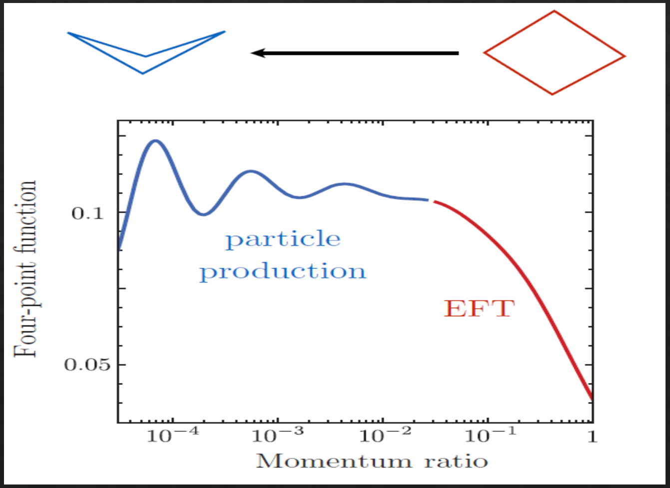


- Related to de Sitter isometry ⇒ WT identity $(\Delta_u - \Delta_v)\, F = 0$

Solutions

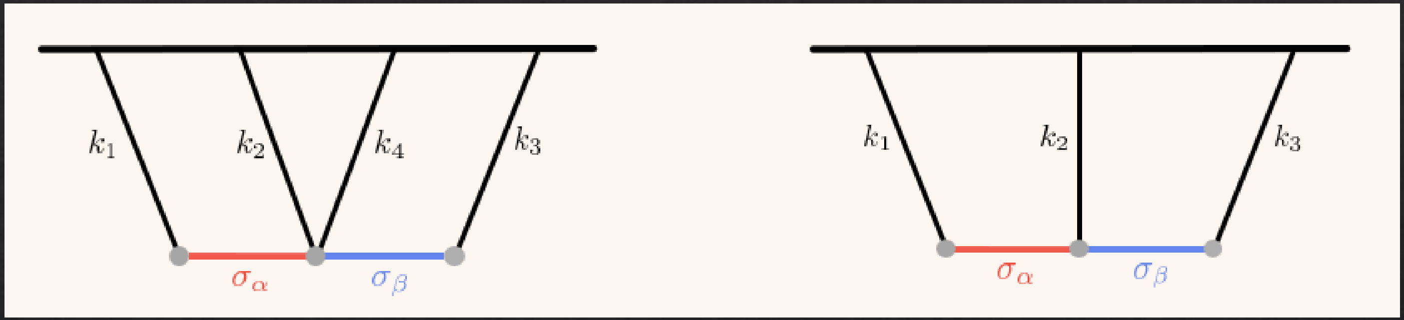
$$\left(\Delta_u + M^2\right) F = uv/(u+v)$$ + B.C.





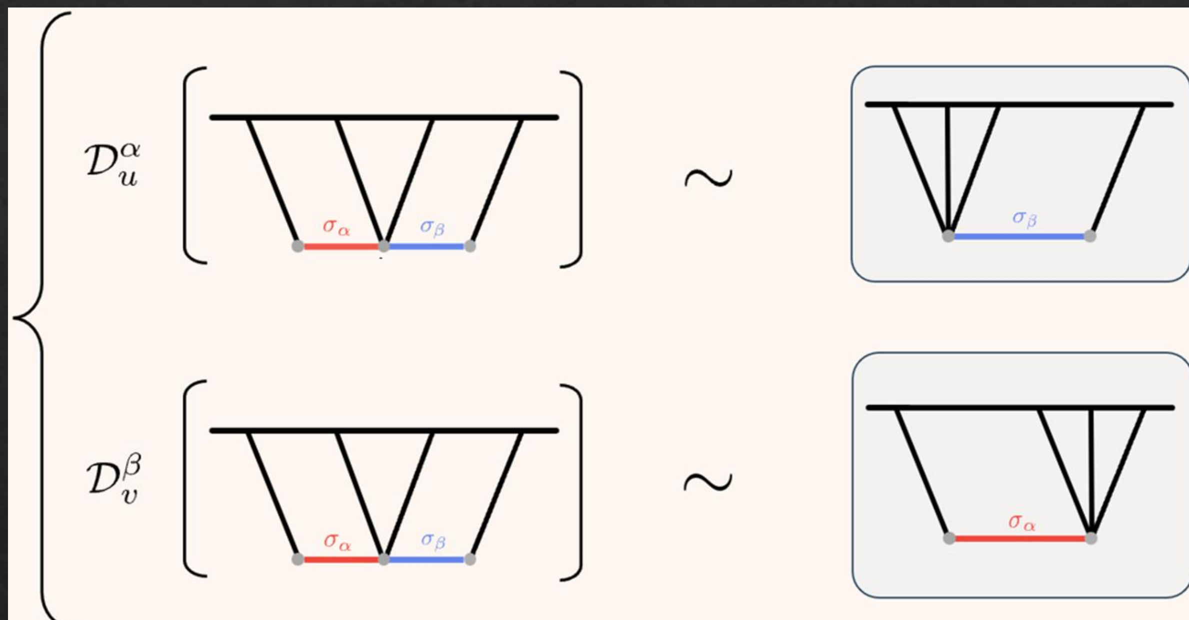
Double exchange

SA, L. Pinol, F. Sano, M. Yamaguchi, Y. Zhu, 2404.09547



$F = F(u, v)$ with $u \equiv \dfrac{k_1}{k_2+k_4}$, $v \equiv \dfrac{k_3}{k_2+k_4}$

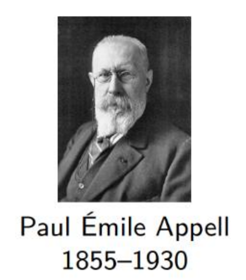
Differential equations



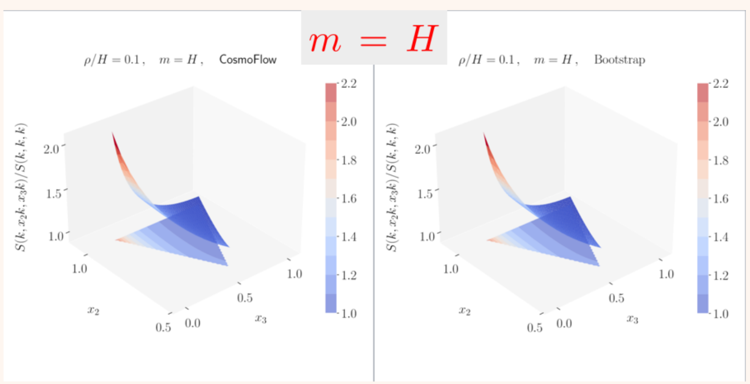
$$\mathcal{D}_u^{\alpha} \equiv u^2\partial_u^2 - 2u\partial_u + \mu_\alpha^2 + \frac{9}{4} - u^2\left(u\partial_u + v\partial_v\right)\left(u\partial_u + v\partial_v - 1\right)$$

Result

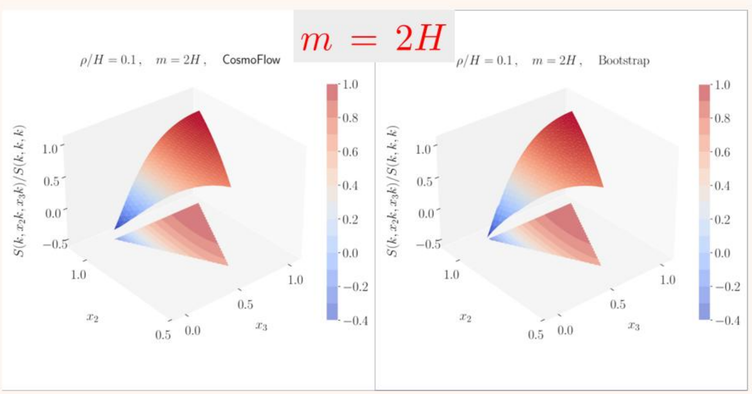
- Analytic solutions (based on Appell series $F_4(u^2, v^2)$)



- valid in any kinematic configuration
- vs Numeric

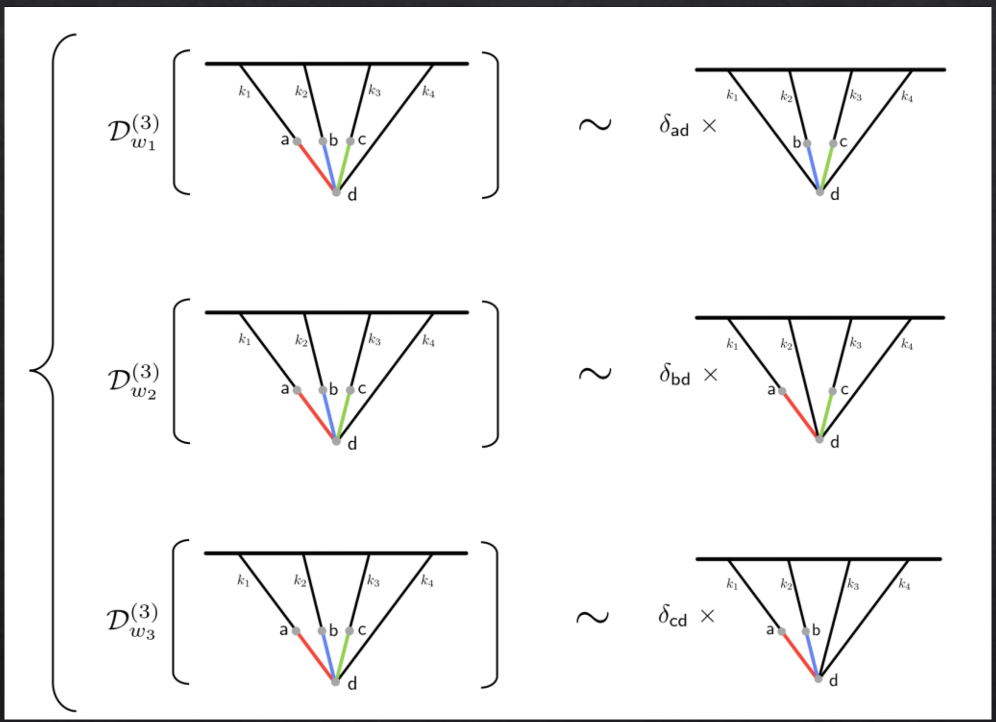


$\sim$ Local



$\sim$ equilateral

Toward triple exchange



$$w_i \equiv \frac{k_i}{k_4}\,, \quad (i = 1, 2, 3)$$

$$\mathcal{D}^{(3)}_{w_i} \equiv w_i^2 \partial_{w_i}^2 - 2 w_i \partial_{w_i} + \mu_i^2 + \frac{9}{4} - w_i^2 \left(\sum_{j=1}^{3} w_j \partial_{w_j} + p_4 + 2 \right) \left(\sum_{j=1}^{3} w_j \partial_{w_j} + p_4 + 1 \right)$$

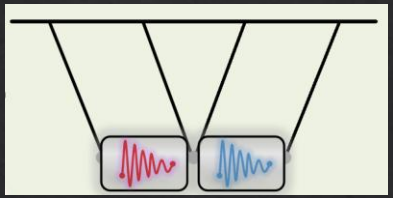
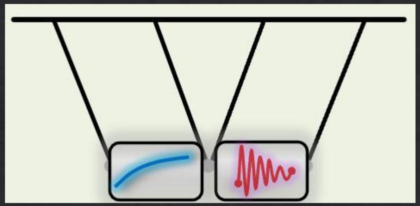
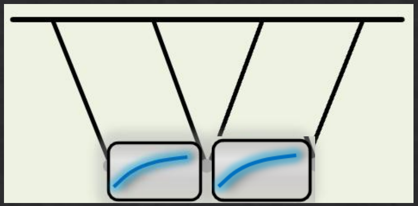
Homogenous solutions:

$$\mathcal{I}^{p_1 p_2 p_3 p_4}_{\text{hom}} \sim \sum_{\mathsf{abc}=\pm} w_1^{\frac{3}{2} - \mathrm{i}\mathsf{a}\mu_1} w_2^{\frac{3}{2} - \mathrm{i}\mathsf{b}\mu_2} w_3^{\frac{3}{2} - \mathrm{i}\mathsf{c}\mu_3}$$
$$\times F_C \left[\begin{matrix} \frac{2p_4 + 11 - 2\mathrm{i}(\mathsf{a}\mu_1 + \mathsf{b}\mu_2 + \mathsf{c}\mu_3)}{4}, \frac{2p_4 + 13 - 2\mathrm{i}(\mathsf{a}\mu_1 + \mathsf{b}\mu_2 + \mathsf{c}\mu_3)}{4} \\ 1 - \mathrm{i}\mathsf{a}\mu_1, 1 - \mathrm{i}\mathsf{b}\mu_2, 1 - \mathrm{i}\mathsf{c}\mu_3 \end{matrix} \middle| w_1^2, w_2^2, w_3^2 \right]$$

Lauricella's hypergeometric function

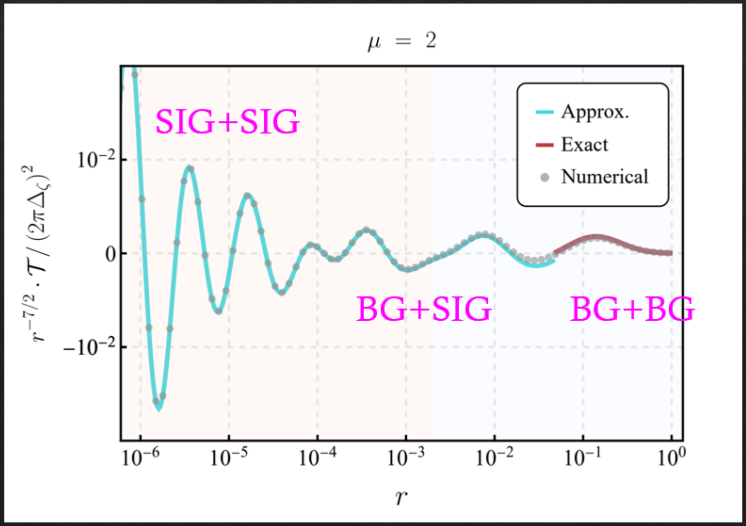
Giuseppe Lauricella
1867–1913

Phenomenological implication

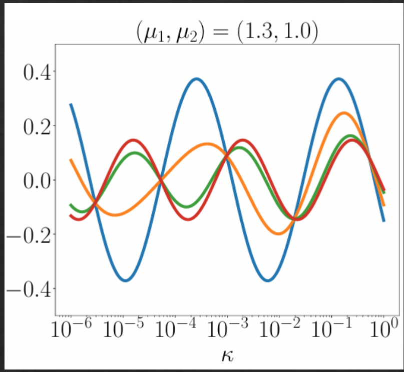
$F =$  $+$  $+$ 

SIG+SIG BG+SIG BG+BG

Specific oscillation signal (change of frequency $\mu \to 2\mu$)
which cannot be mimicked by single exchange

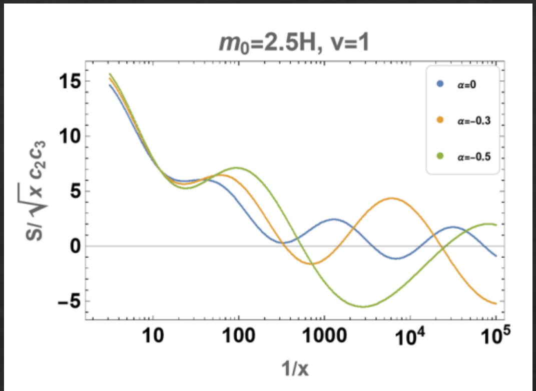


Deviation from the standard signal



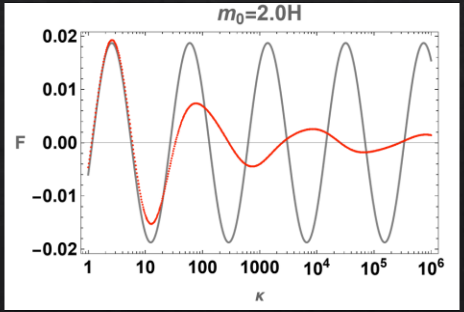
(almost) degenerate masses

L. Pinol, SA, S. Renaux-Petel, M. Yamaguchi, 2112.05710, SA, M. Yamaguchi, 2012.13667



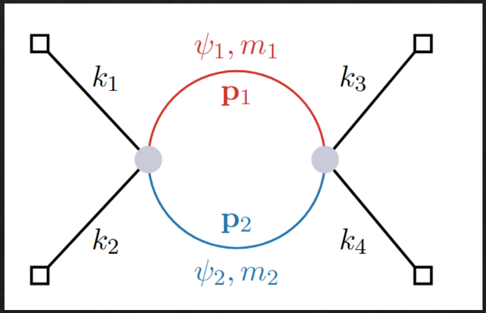
Time-dependent mass

SA, T. Noumi, F. Sano, M. Yamaguchi, 2312.09642



Continuous spectrum

SA, 2301.07920



Fermion loop

SA, Z. Qin, Y. Zhu, M. Yamaguchi, to appear

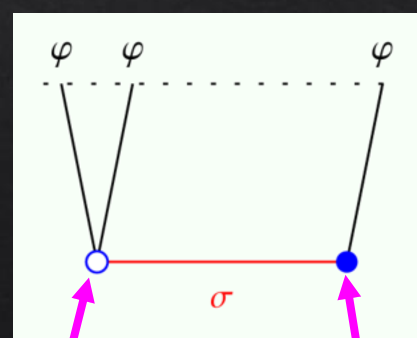
Application to BSM
(Model building aspects of CC)

SA, A. Ghoshal and A. Strumia, 2408.07069

Conditions for large signal??

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

??



??

??

Setup

- two scalars ϕ^a $(a = 1{,}2)$

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

Setup

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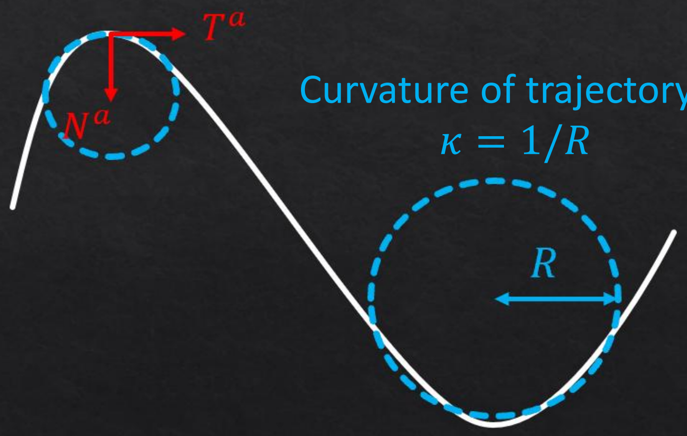
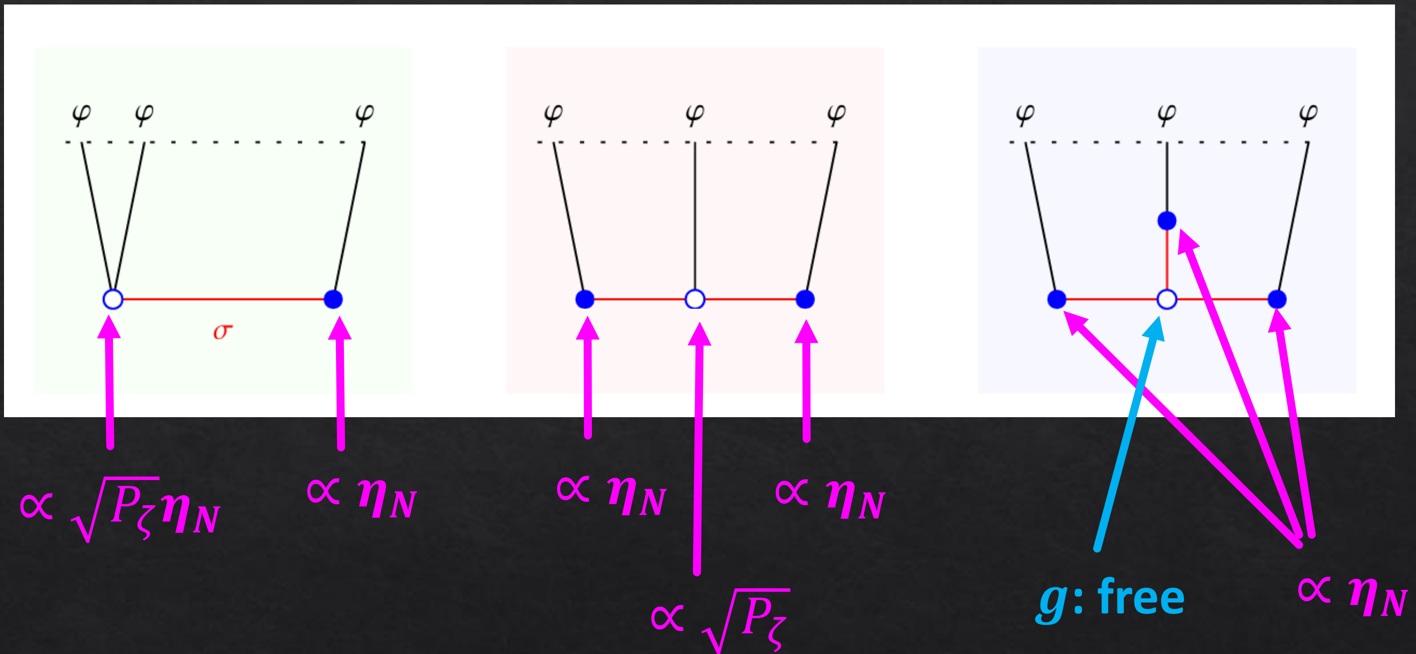


- Perturbation for fluctuation $\delta\phi^a = \varphi T^a + \sigma N^a$
  ($\varphi \sim \zeta$: curvature, σ: isocurvature)
- Turn rate: $\eta_{\rm N} = \frac{d\phi}{d\mathcal{N}} \times \kappa$ (similar to $\omega = v/R$ in Newtonian mechanics)

Three dominant diagram for $\langle \zeta^3 \rangle$

Assuming $m_\sigma \sim H$

$\sqrt{P_\zeta} \sim 10^{-5}$: const



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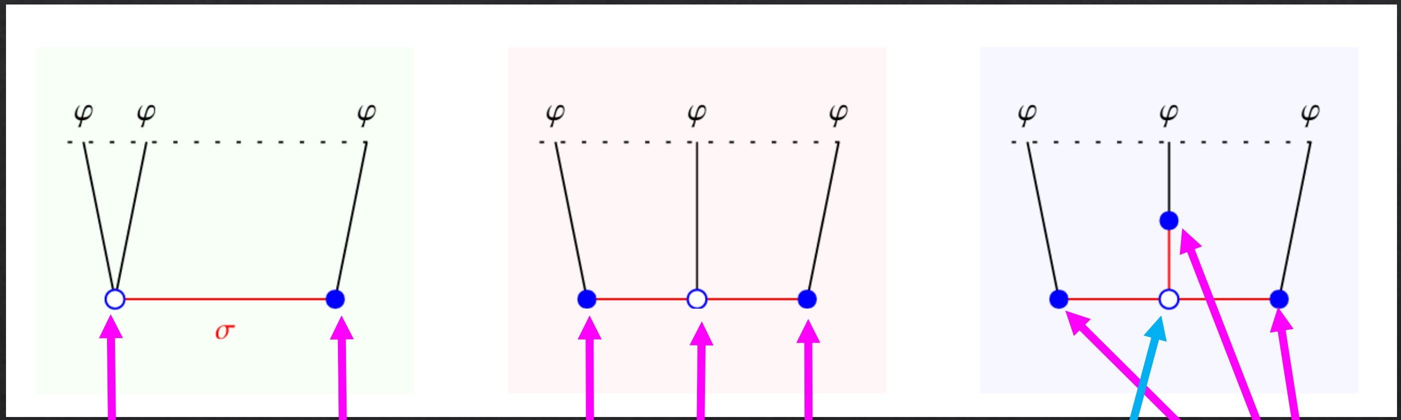


$\propto \sqrt{P_\zeta}\,\boldsymbol{\eta_N}$ $\quad \propto \boldsymbol{\eta_N}$

$\propto \boldsymbol{\eta_N}$ $\quad \propto \boldsymbol{\eta_N}$ $\quad \propto \sqrt{P_\zeta}$

$\boldsymbol{g}$: **free** $\quad \propto \boldsymbol{\eta_N}$

CC signal
$\propto \boldsymbol{\eta_N^2} \times$ oscillation

$\propto \boldsymbol{\eta_N^2}$

$\propto \boldsymbol{\eta_N^3} \times \boldsymbol{g/H}\sqrt{P_\zeta}$

- Triple can be larger than single & double
- η_{N} determines almost everything

Conditions for large signal

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

- Large cubic σ^3 (triple exchange)

  "Quasi single field inflation" Chen, Wang, '10

Check by concrete model

- Scalar ϕ + R^2 (scalaron)

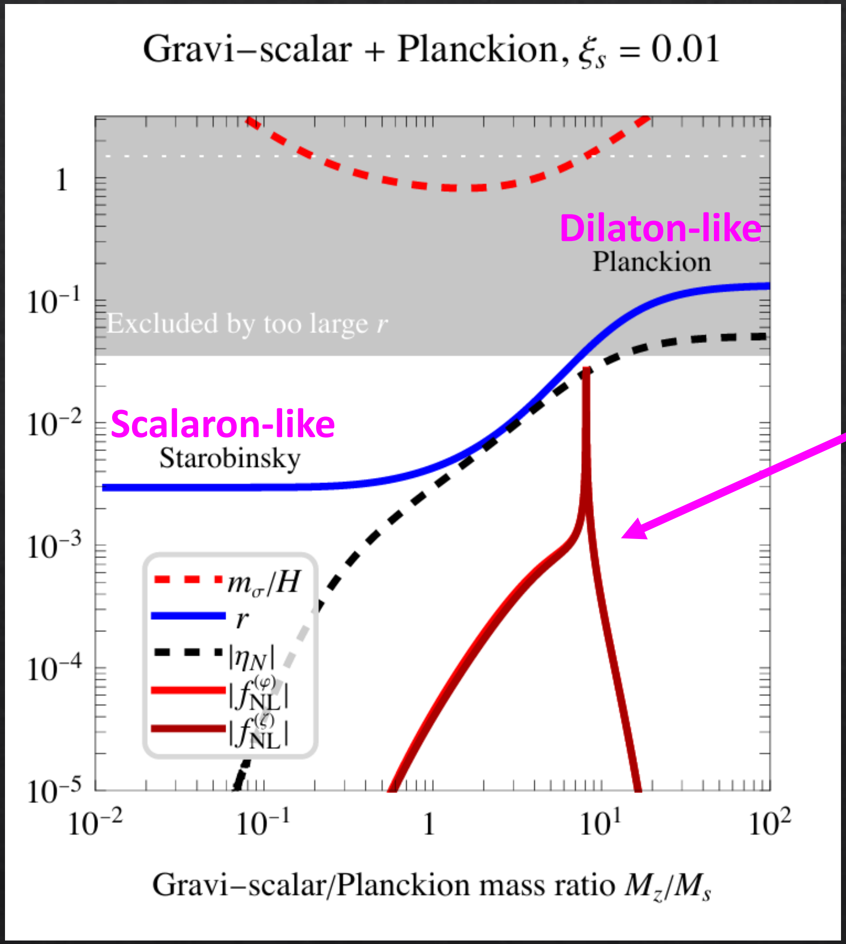
$$S = \int d^4x \sqrt{|\det g|} \left[-\frac{1}{2} f(\phi) R + \frac{R^2}{6 f_0^2} + \sum_{\phi} \frac{(D_\mu \phi)(D^\mu \phi)}{2} - V_{\rm J}(\phi) \right]$$

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, …

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

CC signal from dilaton+R^2



Models with large turn

- Multifield α-attractor
  $\Rightarrow \kappa \propto 1/\alpha M_{Pl}$ for $\alpha \ll 1 \Rightarrow \eta_N^2 \sim \epsilon/\alpha$

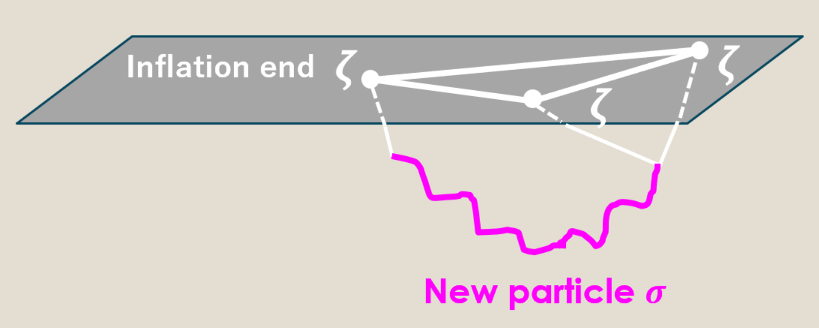
  P. Christodoulidis, D. Roest and E.I. Sfakianakis, 1803.09841.

- Large CC signal & Universal shape of hyperbolic field geometry

  SA, D. Werth, in progress

Summary

➢ CC can probe high-energy physics (mass, spin, couplings of heavy fields)



➢ Recent my work:

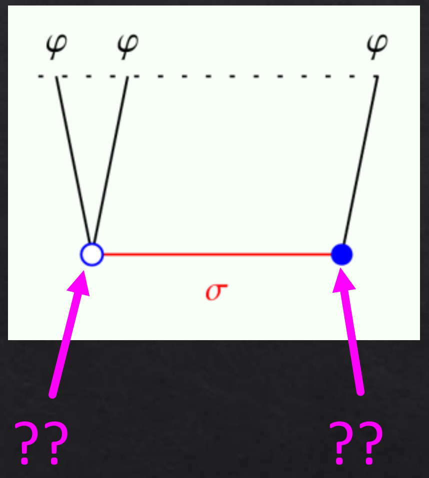
- Analytic expressions of correlators with multiple exchange
- Model building aspects of CC (with tree level scalar exchange)

➢ Future: Making template and compare to observation

Thank you!!

Target & Assumption

- $\langle \zeta^3 \rangle$
- Inflation scenario
- Tree >> Loop
- No chemical potential
- Scalar exchange



E-frame action

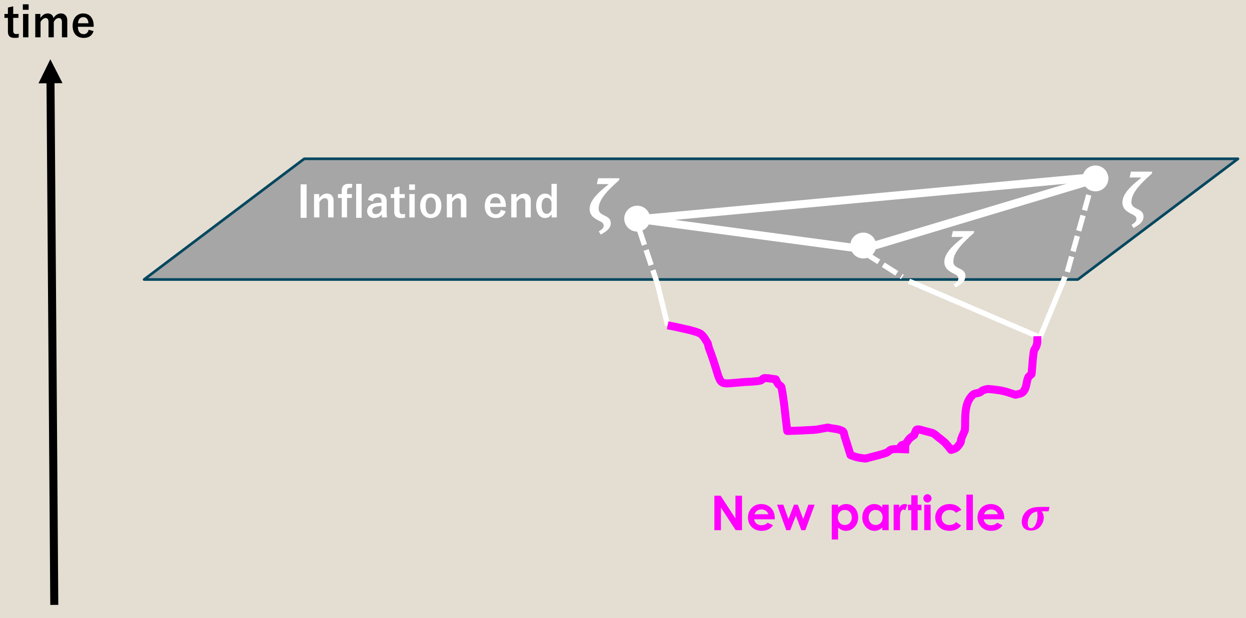
- E-frame

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

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

$$\xi_z = -1/6,$$

- $V_J \gg f_0^2$: 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


time
Inflation end
ζ
ζ
ζ
New particle σ