Title: Cutting rule on cosmological correlators and its applications

Speakers: Yohei Ema

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Abstract:

We derive a cutting rule for equal-time in-in correlators, including cosmological correlators based on Keldysh r/a basis, which decomposes diagrams into fully retarded functions and cut-propagators consisting of Wightman functions. Our derivation relies only on basic assumptions such as unitarity, locality, and the causal structure of the in-in formalism. We apply the cutting rule to simplify the extraction of non-local cosmological collider signals, and prove the absence of one-loop scale-invariant corrections from enhanced small-scale perturbations to superhorizon curvature and tensor perturbations.

Cutting rule for cosmological correlators and its applications

Yohei Ema

University of Florida

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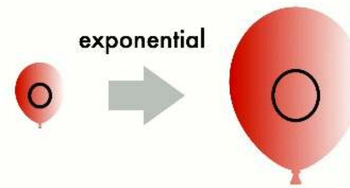
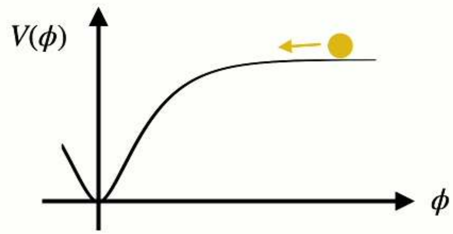
Based on 2409.07521, 2506.15780, 2603.01961
with Muzi Hong, Ryusuke Jinno, Kyohei Mukaida

Cosmic inflation

- Early universe exponentially expanded = cosmic inflation.

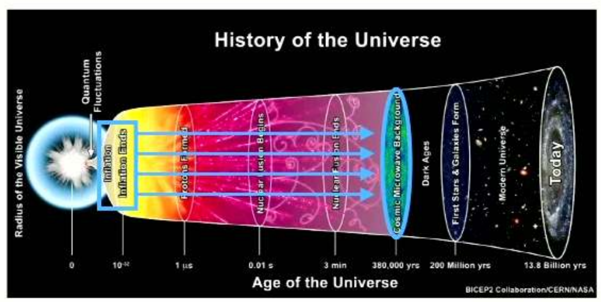


- Inflation driven by inflaton potential:



$$H^2 = \frac{\dot{a}^2}{a^2} \simeq \frac{V(\phi)}{3M_P^2}$$ where $V(\phi)$: inflaton potential.

- Inflationary dynamics imprinted in cosmological perturbations.



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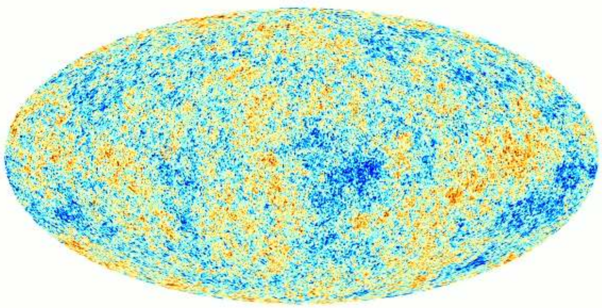
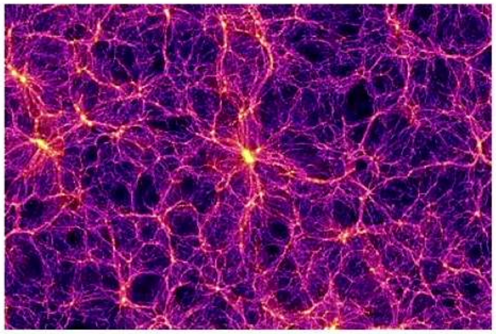
Cosmological correlators

- Structures of the universe originate from cosmic inflation.



[Planck collaboration]



[https://wwwmpa.mpa-garching.mpg.de/galform/data_vis/]

- Initial conditions provided by "cosmological correlators"

$$\langle \phi_{\vec{k}_1} \phi_{\vec{k}_2} \cdots \phi_{\vec{k}_n} \rangle$$: generated during inflation.

➡ Correlators encode: inflaton potential, couplings to other particles, etc.

- No time translation invariance → calculations quite involved in general.

➡ QFT technique to simplify/classify calculations?

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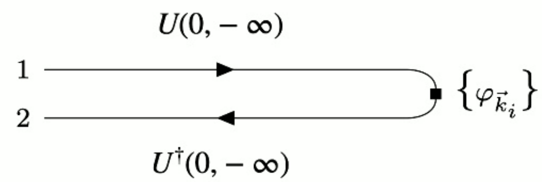
Outline

1. In-in formalism and cutting rule
2. Application 1: non-local CC signals
3. Application 2: one-loop correction to soft mode
4. Summary

In-in formalism

- Cosmological correlators: evaluated at end of inflation with initial condition fixed.

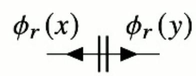
  "in-in" formalism: $\langle \varphi_{\vec{k}_1} \cdots \varphi_{\vec{k}_n} \rangle = \langle 0 | U^\dagger(0,-\infty) \varphi_{\vec{k}_1} \cdots \varphi_{\vec{k}_n} U(0,-\infty) | 0 \rangle$.



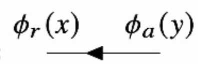
- Two types of fields: $\phi_1(x)$ from $U(0,-\infty)$ and $\phi_2(x)$ from $U^\dagger(0,-\infty)$.

- Keldysh basis : $\phi_r = \frac{1}{2}(\phi_1 + \phi_2), \quad \phi_a = \phi_1 - \phi_2.$ [Keldysh 64]

$$G_{rr}(x,y) = \frac{1}{2}\left[G_>(x,y) + G_<(x,y)\right] =$$



$$G_{ra}(x,y) = \theta(x_0 - y_0)\left[G_>(x,y) - G_<(x,y)\right] =$$



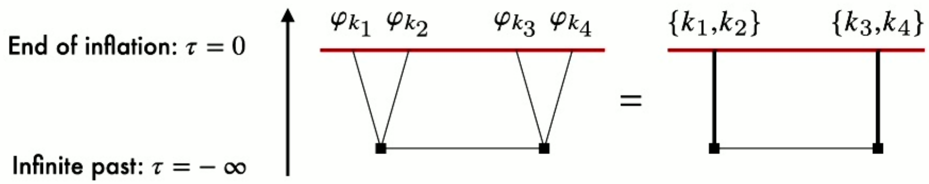
Arrow: causal flow $a \to r$.

$$G_{aa}(x,y) = 0$$

where $G_>(x,y) = G_<(y,x) = \langle \phi(x)\phi(y) \rangle$.

In-in Feynman diagram

- In-in correlators: expressed by "in-in Feynman" diagrams.



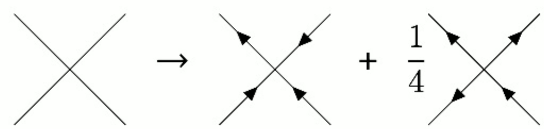
- $1/2$ vertices have opposite overall sign:

$$e^{iW[J_1,J_2]} = \int \mathscr{D}\phi \, e^{i(S[\phi_1] - S[\phi_2] + J_1\cdot\phi_1 - J_2\cdot\phi_2)}$$

- Odd # of arrows out-going from each vertex:

$$e^{iW[J_1,J_2]} = \int \mathscr{D}\phi \, e^{i(S[\phi_1] - S[\phi_2] + J_1\cdot\phi_1 - J_2\cdot\phi_2)}$$ ➡ Odd under $\phi_1 \leftrightarrow \phi_2$ or $\phi_a \to -\phi_a$.

E.g. $\frac{\lambda}{4}\phi^4 \;\to\; \frac{\lambda}{4}(\phi_1^4 - \phi_2^4) = \lambda\left(\phi_r^3\phi_a + \frac{1}{4}\phi_r\phi_a^3\right)$:



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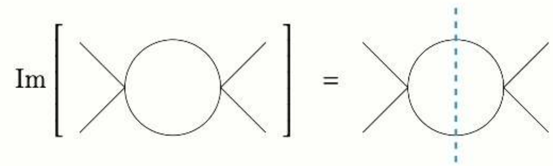
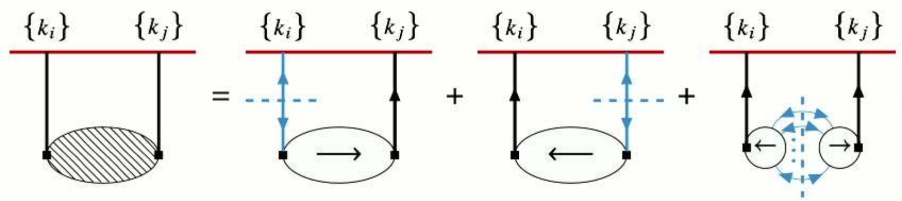
Cutting rule for in-in correlators

- Optical theorem for S-matrix = in-out formalism: $\mathrm{Im}\,\mathscr{M} \sim \sigma$.

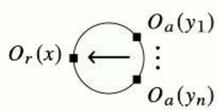
  ➡ Expressed as "cutting rule" in QFT:



- A general cutting rule exists for in-in correlators: [YE, Mukaida 24]



where blue cut : average of $G_>(x,y)$ and $G_<(x,y)$,



$= \langle O_r(x) O_a(y_1) \cdots O_a(y_n) \rangle$: fully retarded function

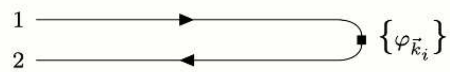
with a straightforward generalization to n-pt bulk correlators.

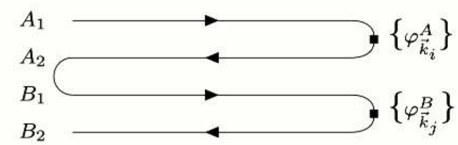
- The proof proceeds as 2 steps:

  1. Duplicate in-in contours as "A" and "B".
  2. Show that isolated A/B islands vanishes.

Sketch of proof

1. Duplicate the in-in contour (See also [Caron-Huot 07]):

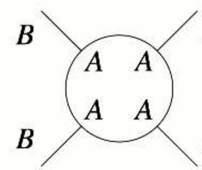




$$\langle 0 | \underbrace{U^\dagger(0,-\infty)}_{\text{"2"}} \varphi_{\vec{k}_1} \cdots \varphi_{\vec{k}_n} \underbrace{U(0,-\infty)}_{\text{"1"}} | 0 \rangle$$

$$\langle 0 | \underbrace{U^\dagger}_{\text{"}B_2\text{"}} \varphi_{\vec{k}_1} \cdots \varphi_{\vec{k}_i} \underbrace{UU^\dagger}_{\text{"}B_1 + A_2\text{"}} \varphi_{\vec{k}_j} \cdots \varphi_{\vec{k}_n} \underbrace{U}_{\text{"}A_1\text{"}} | 0 \rangle$$

2. Show that ''isolated islands'' of A/B vertices vanish:



$= 0.$

Each diagram has a boundary of A/B regions connected to $\{\varphi^{A/B}_{\vec{k}_i}\}$ = cut.

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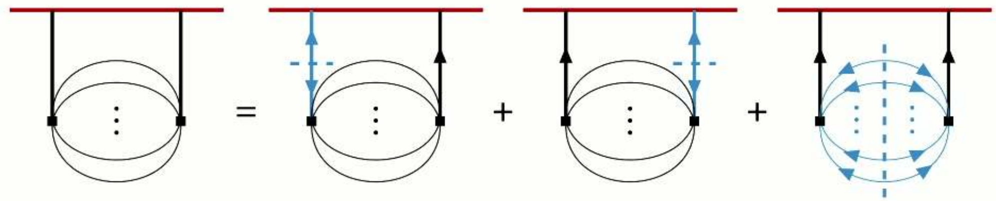
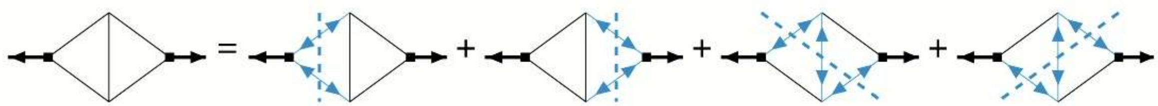
Cutting rule: examples

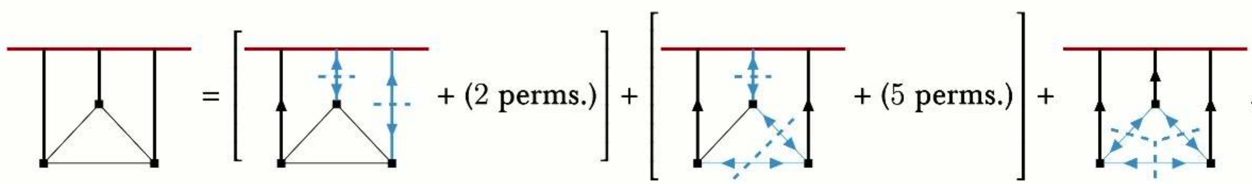
- "Melon" diagrams:



- A two-loop diagram:



- One-loop 3pt diagram:



Outline

1. In-in formalism and cutting rule
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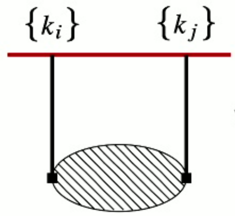
Cosmological collider

- Cosmological collider (CC) = "particle production" signals

$$\langle \phi_{\vec{k}_1}\phi_{\vec{k}_2}\cdots\phi_{\vec{k}_n}\rangle =$$  with $\sum_i k_i = k_L, \sum_j k_j = k_R, \left|\sum \vec{k}_i\right| = k_s$

CC signals: $\langle \phi_{\vec{k}_1}\phi_{\vec{k}_2}\cdots\phi_{\vec{k}_n}\rangle \propto \left[\frac{k_s}{k_{L/R}}\right]^{\pm\nu}, \left[\frac{k_L}{k_R}\right]^{\pm\nu}$, non-analytic in momentum $\left(\nu \sim \frac{im}{H}\right)$.

"non-local" "local"

[Chen, Wang 09;...; Arkani-hamed, Maldacena 15; ...]

Non-analytic = particle production

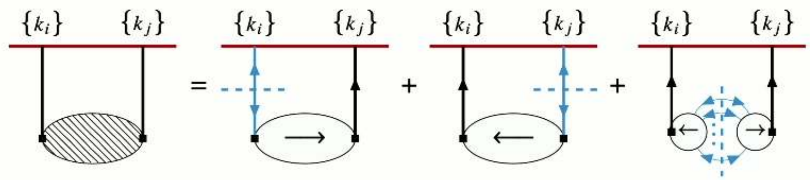
- Higher dimensional operators: analytic in momentum.

$$\mathscr{L} \sim (\partial\phi)^{2n} \sim k^{2n}\phi^{2n}$$ with n : integer for higher dimensional operators.

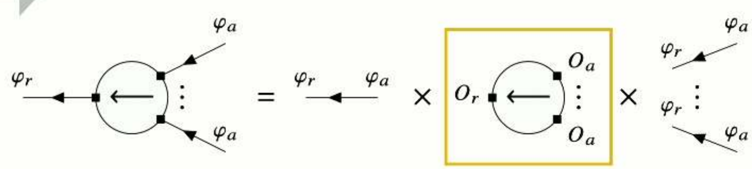
- No time translation invariance → calculations quite involved in general.

Cutting rules for cosmological correlators simplify?

Fully retarded function

- Cutting rule: 

"Fully retarded function" is fundamental



$= \mathscr{V}_{ra\cdots a}(x, y_1, \cdots, y_n) = \langle \mathcal{O}_r(x)\mathcal{O}_a(y_1)\cdots\mathcal{O}_a(y_n)\rangle .$

- Microcausality: fully retarded functions satisfy

$\mathscr{V}_{ra\cdots a}(x, y_1, \cdots, y_n) = 0$ if y_i is outside past light-cone of x.

<u>E.g. 2pt:</u> $\mathscr{V}_{ra}(x, y) = \theta(x^0 - y^0)\langle[\mathcal{O}(x), \mathcal{O}(y)]\rangle$ ➡ microcausality directly applicable.

Generalizable to multi-pt functions by mathematical induction.

Cutting rule: non-local CC

- Fully retarded function has a finite support in its spatial arguments:

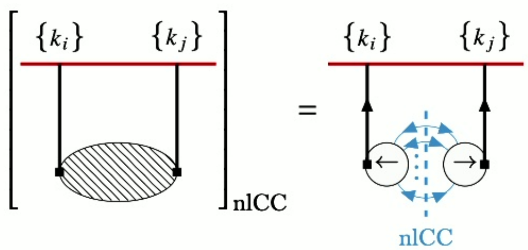
$$\mathscr{V}_{ra\cdots a}(x, y_1, \cdots, y_n) = 0 \ \text{ if } |\vec{x} - \vec{y}_i|^2 > (x^0 - y_i^0)^2 : \text{FT analytic in spatial momentum } \vec{k}_i.$$

"Paley-Wiener theorem"

- Non-local CC: non-analytic dependence on spatial momentum.

Non-local CC arises solely from cut-propagators

[YE, Mukaida 24]



Time integrals factorized, simplify calculations.

(See also [Tong+ 21] for tree-level, [Qin, Xianyu 23,24] for loops but with explicit forms of propagators)

Non-local CC: example

- Consider $\mathscr{L} = \lambda_3 a^2 \varphi'^2 \sigma$ with massless φ and massive σ :

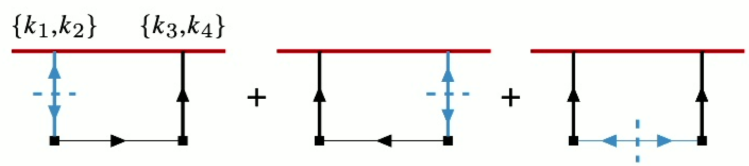
$$\begin{cases} \varphi : \Delta_>(k;\tau_1,\tau_2) = \dfrac{H^2}{2k^3}(1+ik\tau_1)(1-ik\tau_2)e^{-ik(\tau_1-\tau_2)}, \\ \sigma : G_>(k;\tau_1,\tau_2) = \dfrac{\pi}{4Ha_1^{3/2}a_2^{3/2}} H_\nu^{(1)}(-k\tau_1)H_\nu^{(2)}(-k\tau_2), \quad \nu = \sqrt{\dfrac{9}{4} - \dfrac{m^2}{H^2}} \,. \end{cases}$$

$$G_{ra}(k;\tau_1,\tau_2) = \frac{i\pi\theta(\tau_1-\tau_2)}{2Ha_1^{3/2}a_2^{3/2}} \left[\frac{J_\nu(-k\tau_1)J_{-\nu}(-k\tau_2)}{\sin(\pi\nu)} + (\nu \to -\nu) \right]$$: analytic in k.

$J_\nu(e^{2i\pi}z) = e^{2i\pi\nu}J_\nu(z)$

- Tree-level "s-channel" process:

$$\langle \varphi_{\vec{k}_1}\varphi_{\vec{k}_2}\varphi_{\vec{k}_3}\varphi_{\vec{k}_4}\rangle\Big|_s =$$



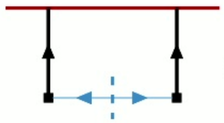
$$= -\frac{\lambda_3^2 H^4}{2k_1k_2k_3k_4} \int_{-\infty}^{0} d\tau_L \int_{-\infty}^{\tau_L} d\tau_R \sin(k_{12}\tau_L)\cos(k_{34}\tau_R)G_{ra}(k_s;\tau_L,\tau_R),$$

nested but no non-local CC

where $k_{ij} = k_i + k_j$, and $k_s = |\vec{k}_1 + \vec{k}_2| = |\vec{k}_3 + \vec{k}_4|$.

Non-local CC: example

- "Bulk-cut" diagram has factorized time integrals.

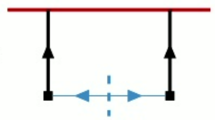


$$= \frac{\lambda_3^2 H^4}{2k_1k_2k_3k_4}\int_{-\infty}^{0} d\tau_L \int_{-\infty}^{0} d\tau_R \sin(k_{12}\tau_L)\sin(k_{34}\tau_R)G_{rr}(k_s;\tau_L,\tau_R),$$

where $G_{rr} \sim J_{\pm\nu}(-k_s\tau_L)J_{\pm\nu}(-k_s\tau_R)$.

- Factorized time integrals simplify the calculation, in particular

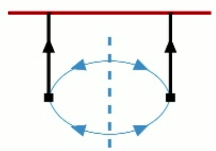
$$\langle \varphi_{\vec{k}_1}\varphi_{\vec{k}_2}\varphi_{\vec{k}_3}\varphi_{\vec{k}_4}\rangle\Big|_{s,\text{nlCC}} =$$



$$= \frac{\lambda_3^2 H^6[1+\sin(\pi\nu)]\Gamma^2[-\nu]\Gamma^2\left[\frac{5}{2}+\nu\right]}{8\pi k_1k_2k_3k_4 k_{12}^{5/2}k_{34}^{5/2}}\left[\frac{k_s^2}{4k_{12}k_{34}}\right]^{\nu} {}_2F_1\left[\begin{matrix}\frac{5+2\nu}{4},\frac{7+2\nu}{4}\\ 1+\nu\end{matrix};\frac{k_s^2}{k_{12}^2}\right] {}_2F_1\left[\begin{matrix}\frac{5+2\nu}{4},\frac{7+2\nu}{4}\\ 1+\nu\end{matrix};\frac{k_s^2}{k_{34}^2}\right] + (\nu \to -\nu)\,.$$

non-local CC

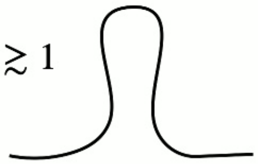
- Can be extended to loops:



Motivation

- Enhanced scaler perturbations to produce primordial black holes.

$$\frac{\delta\rho}{\rho} \gtrsim 1$$



Claims on *scale-invariant* corrections to large scale perturbations.

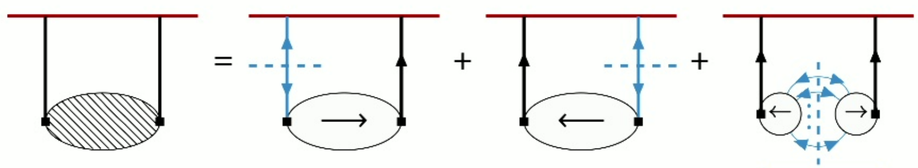
Scalar: [Kristiano, Yokoyama 22,23], tensor: [Ota, Sasaki, Wang 22a, 22b]

- Inconsistent with expectation from gauge invariance.

e.g. corrections to soft tensor mode → no derivative = graviton mass: $h_{\mu\nu}h^{\mu\nu}$.

How to make symmetry structures manifest in actual calculations?

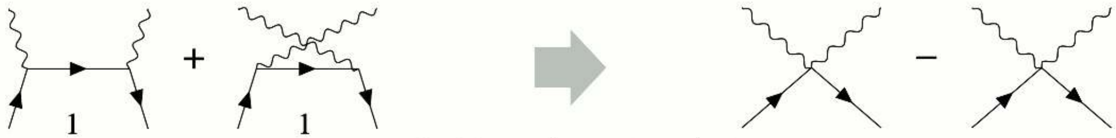
- Cutting-rule classification:



Causal production of GW $\sim k^3$

"Shrinking" structure

- QED example:

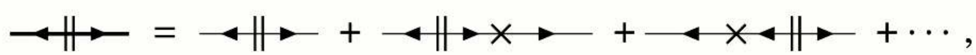


$\frac{1}{t - m_e^2}$ $\qquad$ $\frac{1}{u - m_e^2}$ $\qquad$ $q^\mu \Gamma_\mu(q) = S^{-1}(p+q) - S^{-1}(p)$

- Similar "shrinking" structure for cosmological correlators: [YE, Hong, Jinno, Mukaida 25, 26]

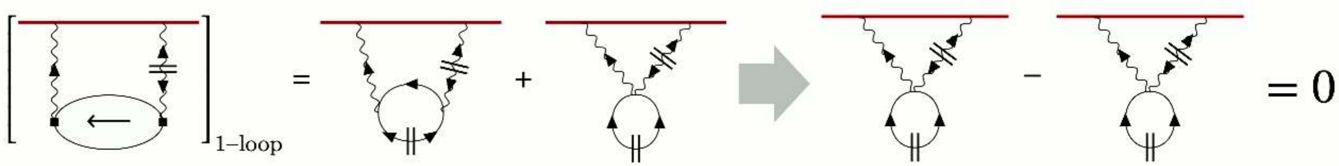
$$S = \frac{1}{2}\int d^{d-1}x d\tau\, f^2(\tau)\left[\left(\frac{d\chi}{d\tau}\right)^2 - c_s^2(\tau)(1+\epsilon)^2(\partial_i\chi)^2 - m_\chi^2(\tau)\chi^2\right]$$

Include ϵ to full order v.s. treat ϵ perturbatively



$\frac{\partial}{\partial \log l} G_{rr} \sim G_{ra} \times G_{rr}$: reduce number of propagators = "shrinking"

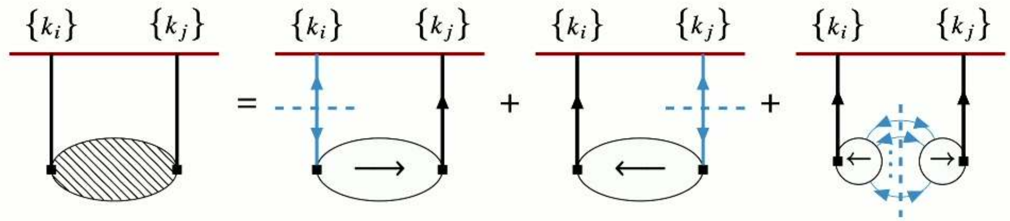
- As a result, one-loop correction to soft tensor mode cancels out:



[Ota, Sasaki, Wang 22a, 22b] didn't solve the mode equation with a given background consistently.

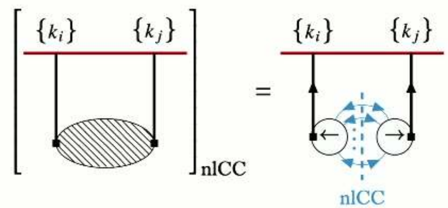
Summary

- A general cutting rule exists for in-in correlators:



- Several applications to classify/simplify calculations:

    1. Factorization of non-local cosmo-collider signal:



    2. Cancellation of one-loop correction to large scale perturbations: