UNIVERSITY OF CAMBRIDGE

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# Boostless Cosmological Collider Bootstrap

with Guilherme Pimentel, arXiv:2205.00013

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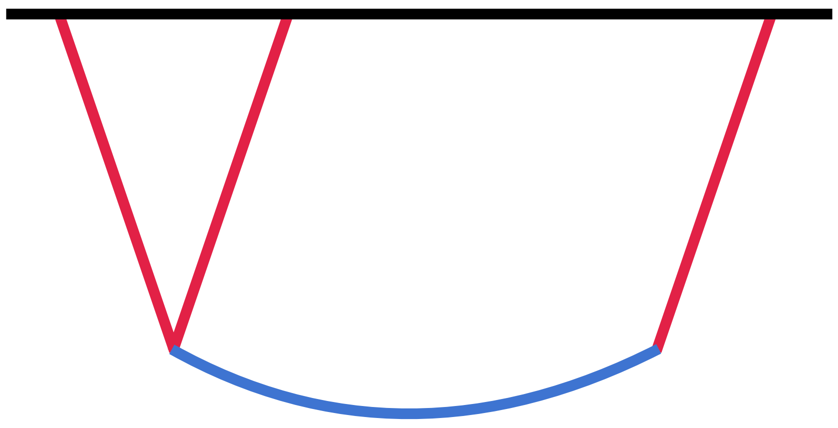
Cosmology from Home 2022

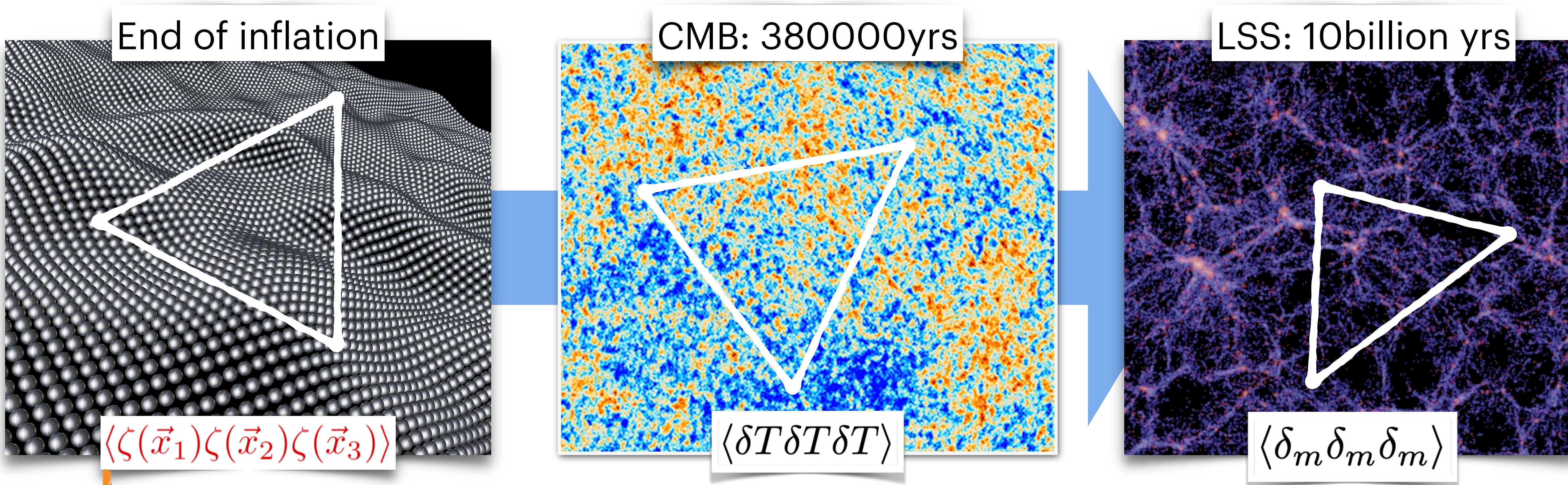
## Goal:

Find all **Cosmological Colliders** using the **Bootstrap** method,
and identify the *large signals* and *new shapes* for upcoming observations.



# Triangles in the Sky

## 3-point correlation function in the primordial perturbations




→ **primordial bispectrum**: the Fourier transf. of the 3pt correlation function

$$\langle\zeta_{\mathbf{k_1}}\zeta_{\mathbf{k_2}}\zeta_{\mathbf{k_3}}\rangle \sim f_{\rm NL} S(k_1, k_2, k_3) P_\zeta^2$$

How easy/hard to be detected ← ***size*** ($f_{\rm NL}$)

***shape*** ($S(k_1, k_2, k_3)$)

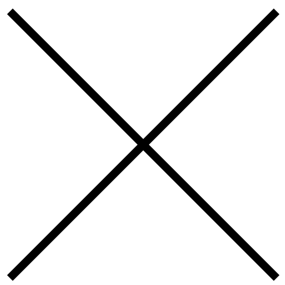
Lots of information;

**Focus of this talk**

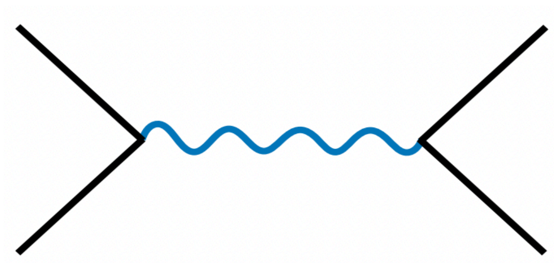
**Major target of CMB, LSS, 21cm..**

# Fantastic New Physics and Where to Find Them

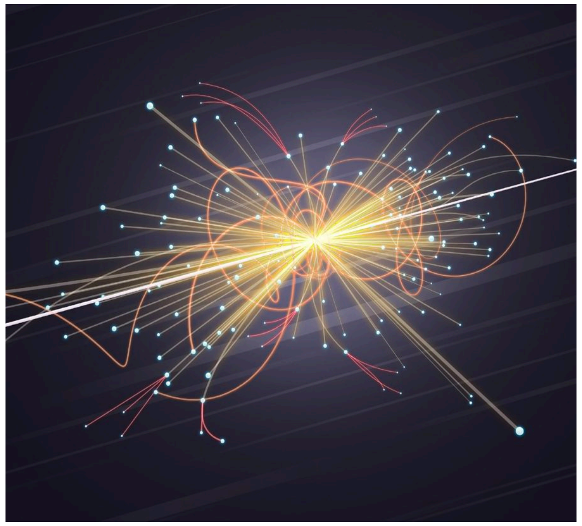
## Scattering Amplitudes



Contact diagram



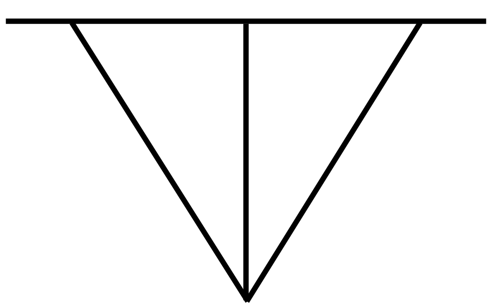
Exchange diagram



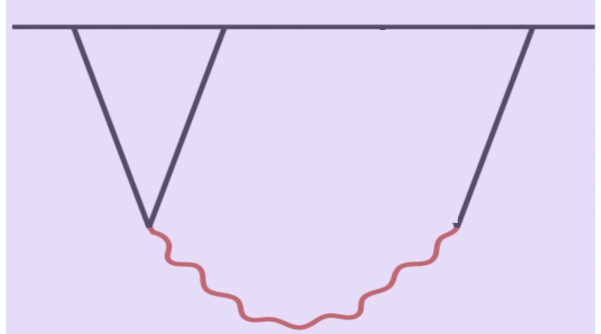
$\sim 1\text{TeV}$

## Cosmological Correlators $\langle \zeta(x_1)\zeta(x_2)\zeta(x_3) \rangle$

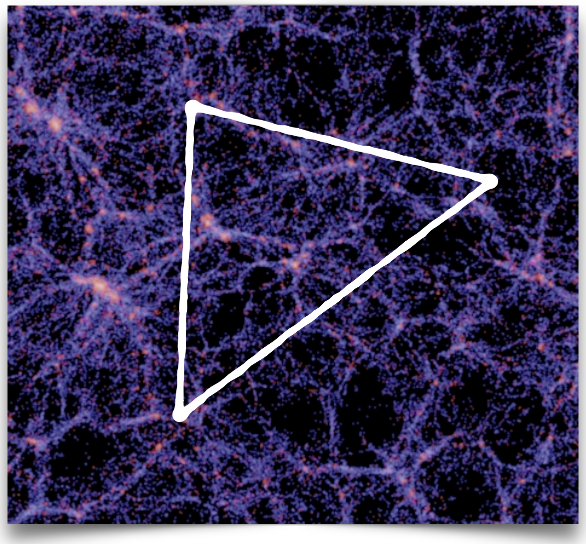
$\eta = 0$



Contact diagram
(Self-interaction of the inflaton)



Exchange diagram
(intermediate extra fields)

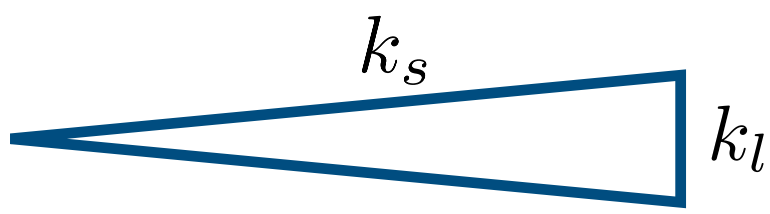


$< 10^{14}\text{GeV}$

# Cosmological Collider Physics

Arkani-Hamed, Maldacena 2015
Chen, Wang 2009
Baumann, Green 2010
Noumi et al 2012

## Squeezed limit of the inflationary bispectrum




contains information of heavy particles in the high energy environment of inflation

$$\lim_{k_l \to 0} \langle \zeta_{\mathbf{k_l}} \zeta_{\mathbf{k_s}} \zeta_{\mathbf{k_s}} \rangle \propto \left( \frac{k_l}{k_s} \right)^{3/2} \cos \left[ \frac{m}{H} \ln \left( \frac{k_l}{k_s} \right) + \delta \right] P_s(\mathbf{k_l} \cdot \mathbf{k_s})$$

**oscillation** measures mass, **angular** dependence measures spin

### A Large Menu of Possibilities

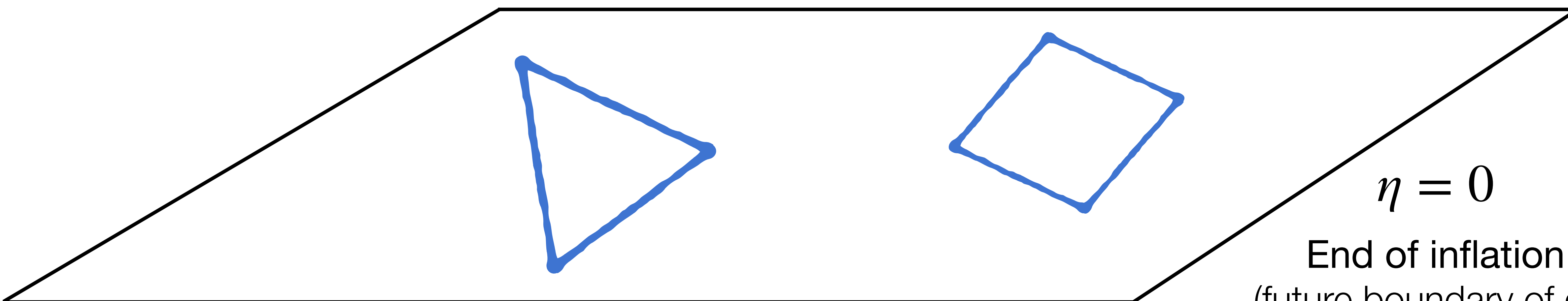
| | |
|---|---|
| EFT of cosmo collider | Lee, Baumann, Pimentel 2016 |
| Standard Model mass spectrum | Chen, Wang, Xianyu 2016 |
| Non-perturbative regimes | An, McAneny, Ridgway, Wise 2017 |
| Gauge theories + GUT | Kumar, Sumdrum 2017; 2018 |
| Chemical Potential | Wang, Xianyu 2019 |
| SM fermions and Higgs | Hook, Huang, Racco 2019 |
| Curved field manifold | **DGW** 2019 |

……

# This Talk:

*Find all Cosmo Collider bispectra via*

## Cosmological Bootstrap



$\eta = 0$

End of inflation

(future boundary of dS)

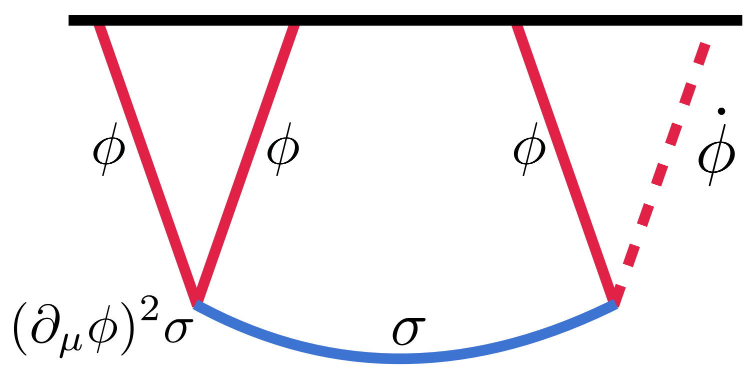
*Cosmological Correlators from Symmetries, Locality & Unitarity*

See **H. Goodhew**'s talk
for general introduction

- Fully model-independent;
- Powerful computational tools.

# De Sitter Bootstrap *v.s.* Boostless Bootstrap

Arkani-Hamed, Baumann, Lee, Pimentel 2018
Baumann, Duaso Pueyo, Joyce, Lee, Pimentel 2019, 2020




### *Pros*

dS symmetries are nicely manifested;

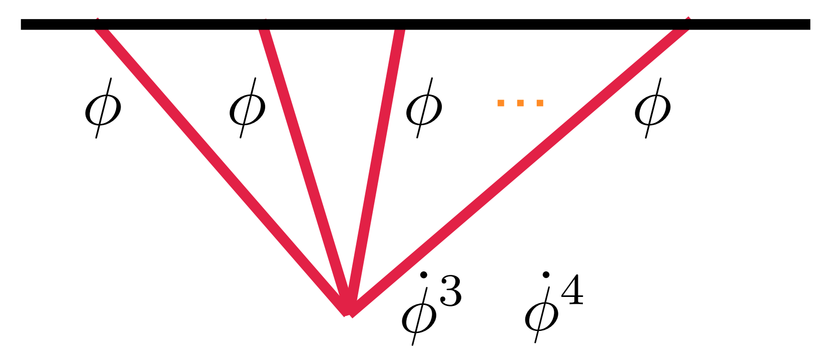
Fully analytical control for correlators;

### *Cons*

Non-Gaussianity signals are ***very small***;

Need 4-pt first, before computing 3-pt.

Pajer 2020
Jazayeri, Pajer, Stefanyszyn 2021
Bonifacio, Pajer, DGW 2021; ….




### *Pros*

Large signals are possible;

A complete set of single field correlators.

### *Cons*

Only for correlators from massless field interactions

See M.H. G. Lee and A. Thavanesan's talks

De Sitter Bootstrap + Boostless Bootstrap

↓

# Boostless Cosmological Collider Bootstrap

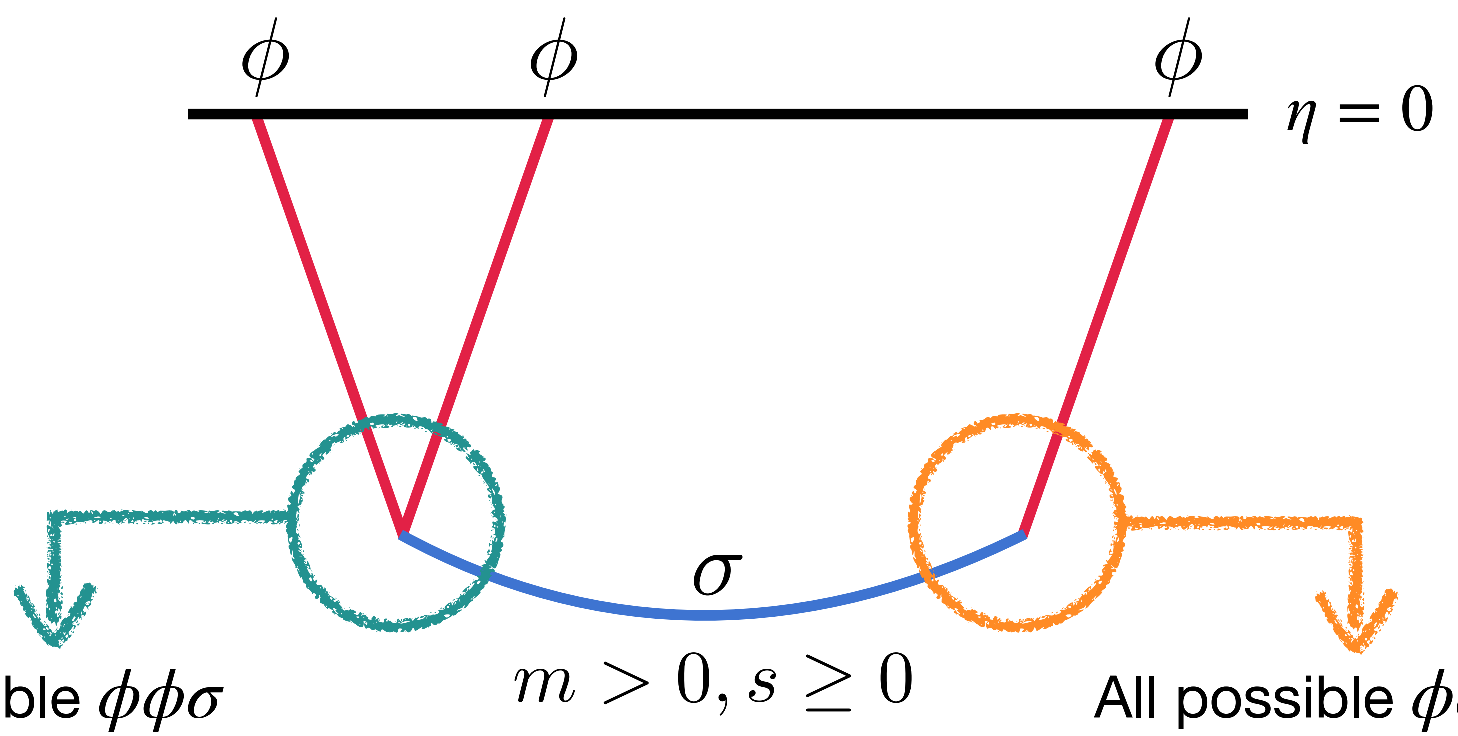
Pimentel, **DGW** 2022

- Large **boost-breaking interactions** with massive particles;
- Bootstrap inflationary **three-point functions** directly;

→ A **complete menu** of possibilities for massive-exchange bispectra.

# To be more specific...

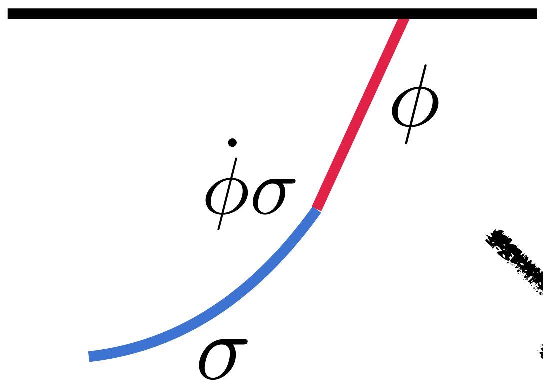
**Inflaton Bispectrum** $\langle \phi_{k_1} \phi_{k_2} \phi_{k_3} \rangle$




| All possible $\phi\phi\sigma$ cubic interactions | | All possible $\phi\sigma$ quadratic interactions |
|---|---|---|
| $\dot{\phi}^2\sigma,\ (\partial_i\phi)^2\sigma,\ \ddot{\phi}^2\sigma, \ldots$ | scalar exchange | $\dot{\phi}\sigma,\ \partial^2\phi\sigma,\ \ddot{\phi}\sigma, \ldots$ |
| $\dot{\phi}\partial_{ij..}\dot{\phi}\sigma_{ij..}, \ldots$ | spinning exchange | $\partial_{ij..}\dot{\phi}\sigma_{ij..}, \ldots$ |

# The Building Blocks of BCCB

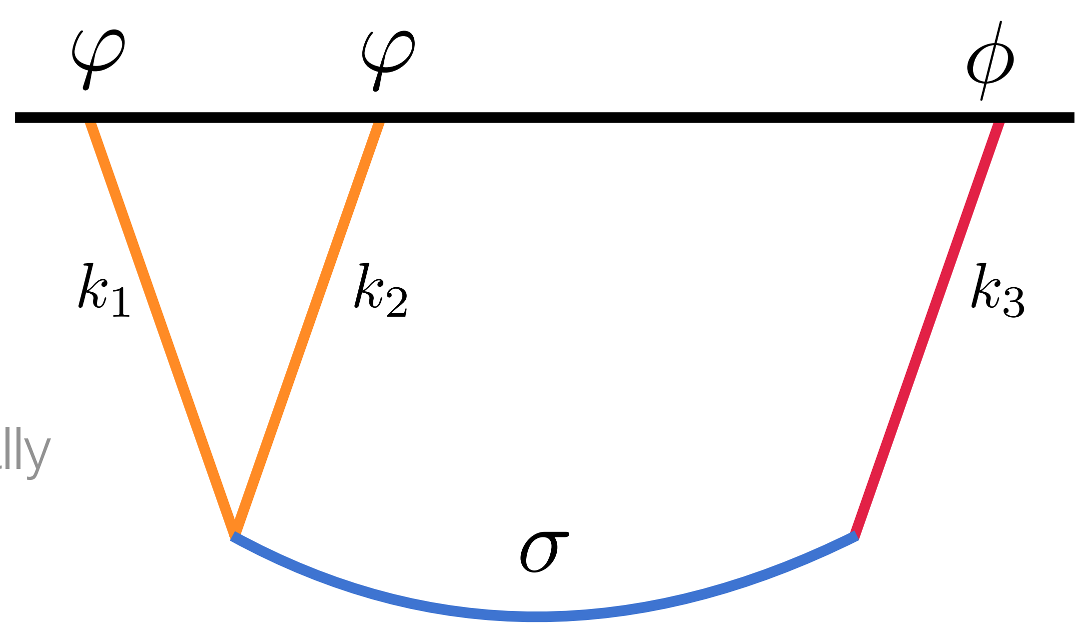
## 0. A Mixed Propagator




the conversion from massive scalar $\boldsymbol{\sigma}$ to the inflaton $\boldsymbol{\phi}$

## I. Three-Point Scalar Seed

$$\langle \varphi_{k_1} \varphi_{k_2} \phi_{k_3} \rangle \sim \hat{\mathcal{I}}(u)$$




$$u \equiv \frac{k_3}{k_1 + k_2}$$

$\varphi$ — conformally coupled scalar

$m^2 = 2H^2$

$m > 0, s = 0$

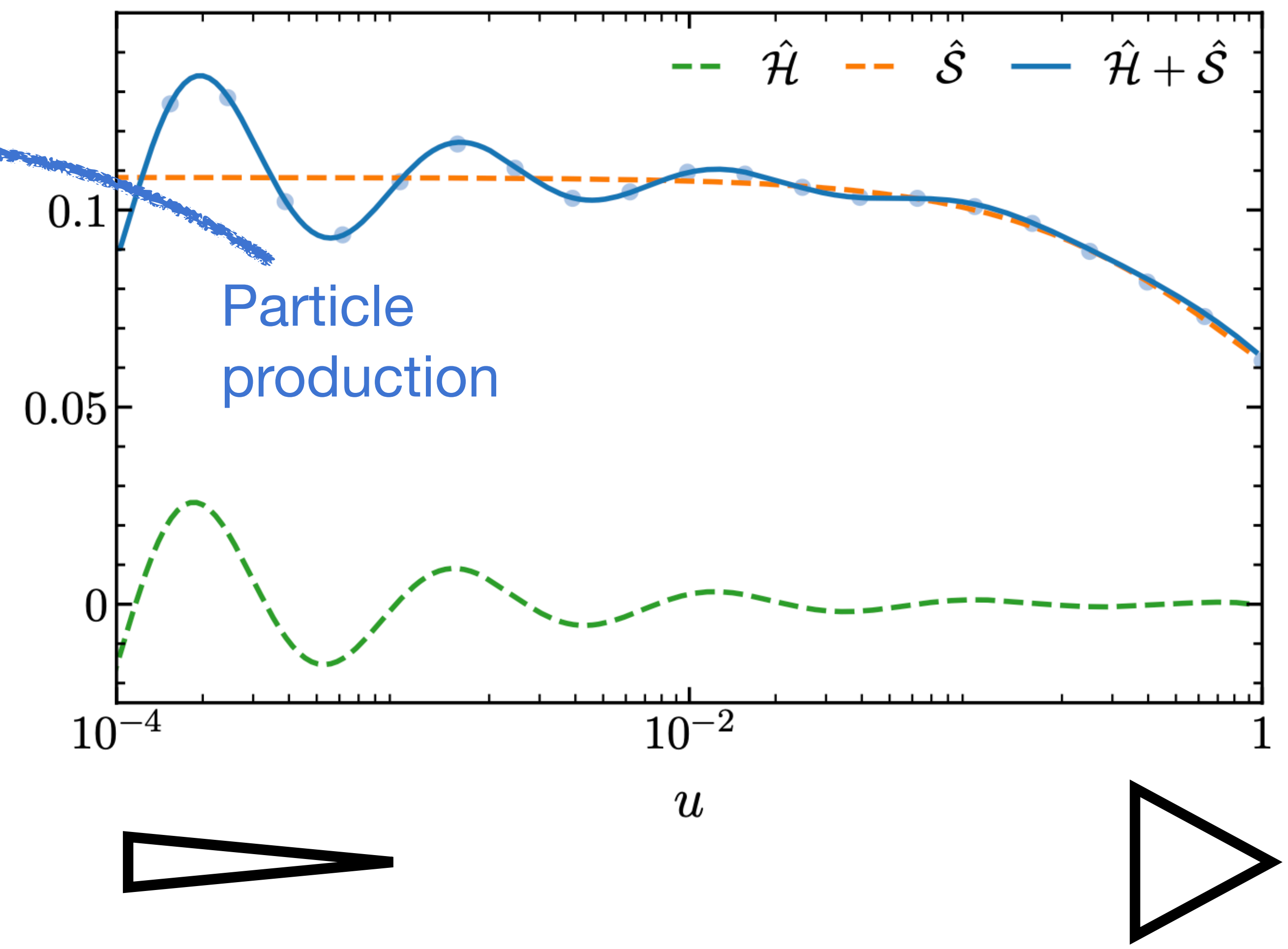
# I. Solving the Scalar Seed

A differential equation for the scalar seed

$$\left(\Delta_u + \frac{m^2}{H^2}\right)\hat{\mathcal{I}} = \frac{u}{1+u} \quad \text{with} \quad \Delta_u \equiv u^2(1-u^2)\partial_u^2 - 2u^3\partial_u, \quad u \equiv \frac{k_3}{k_1+k_2}$$

**Analytical solution:**

$\hat{\mathcal{I}}(u)/u$




The squeezed-limit oscillations caused by massive particles

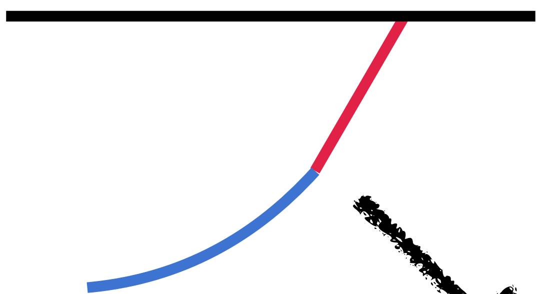
$$\hat{\mathcal{I}}(u\to 0) = -\frac{i}{2}\sum_{\pm} B_{\pm}\left(\frac{u}{2}\right)^{\frac{1}{2}\pm i\mu}$$

$$\propto \sin\left(\frac{M}{H}\log(k_L/k_S)\right)$$

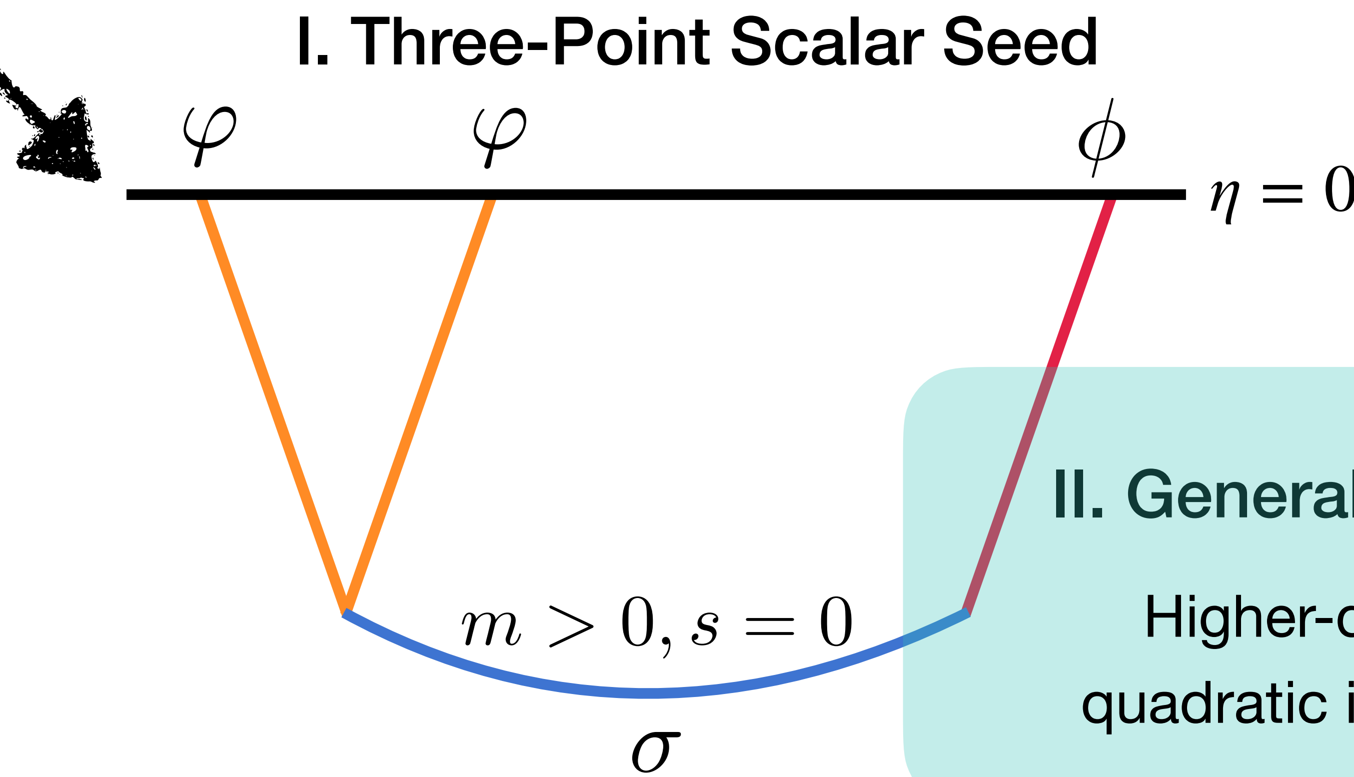
Cosmological Collider Signal

# Strategy of BCCB

## 0. A Mixed Propagator



## I. Three-Point Scalar Seed




## II. Generalized Seeds

Higher-derivative quadratic interactions

$$\dot{\phi}\sigma \;\Rightarrow\; a^{-n_{\partial_i}}\partial_i^{n_{\partial_i}}\left(\partial_t^{n_{\partial_t}}\phi\right)\left(\partial_t^{\tilde{n}_{\partial_t}}\sigma\right)$$

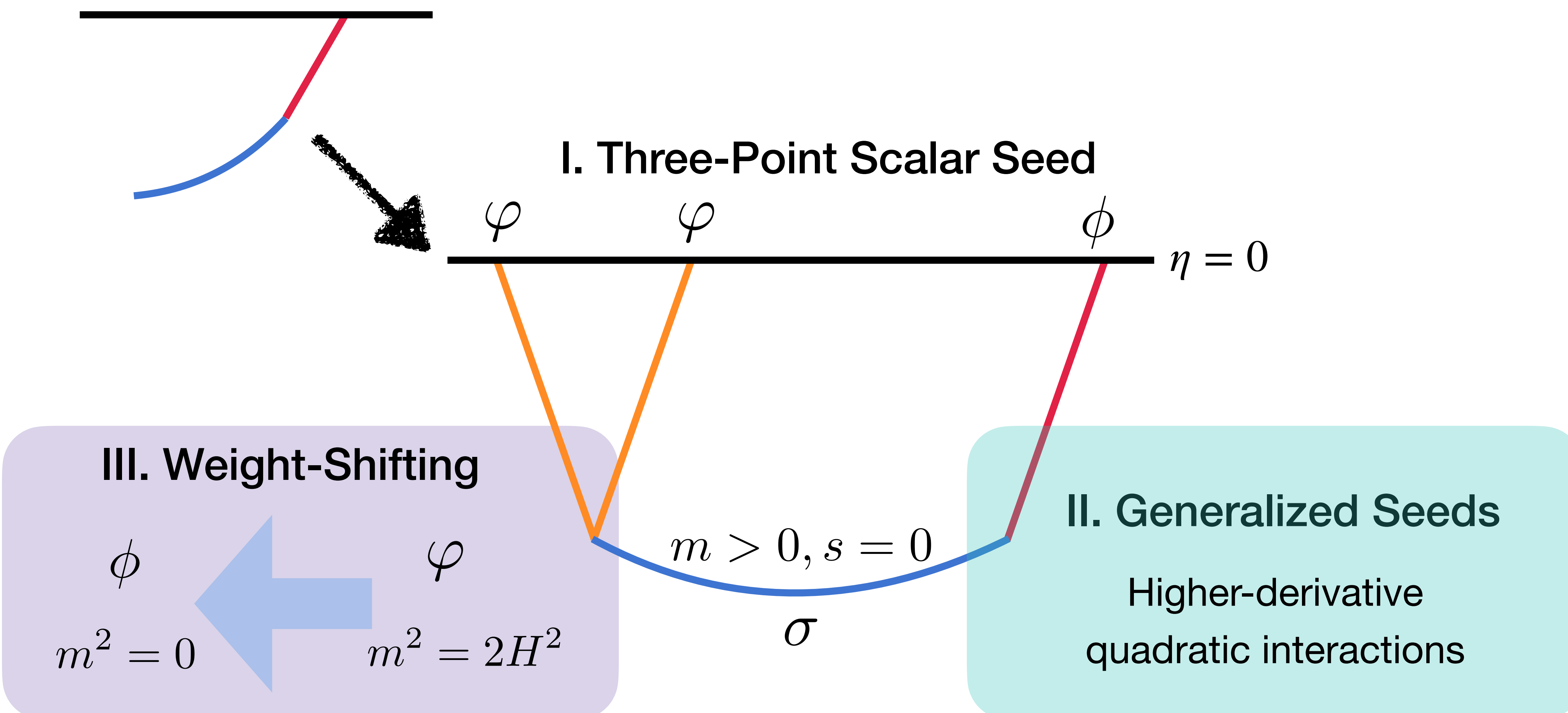
$$\hat{\mathcal{I}}(u) \;\Rightarrow\; \hat{\mathcal{I}}^{(n)}$$

(for any number of time and spatial derivatives)

$$\left(\Delta_u + \frac{m^2}{H^2}\right)\hat{\mathcal{I}}^{(n)} = \left(\frac{u}{1+u}\right)^{n+1}$$

# Strategy of BCCB

0. A Mixed Propagator



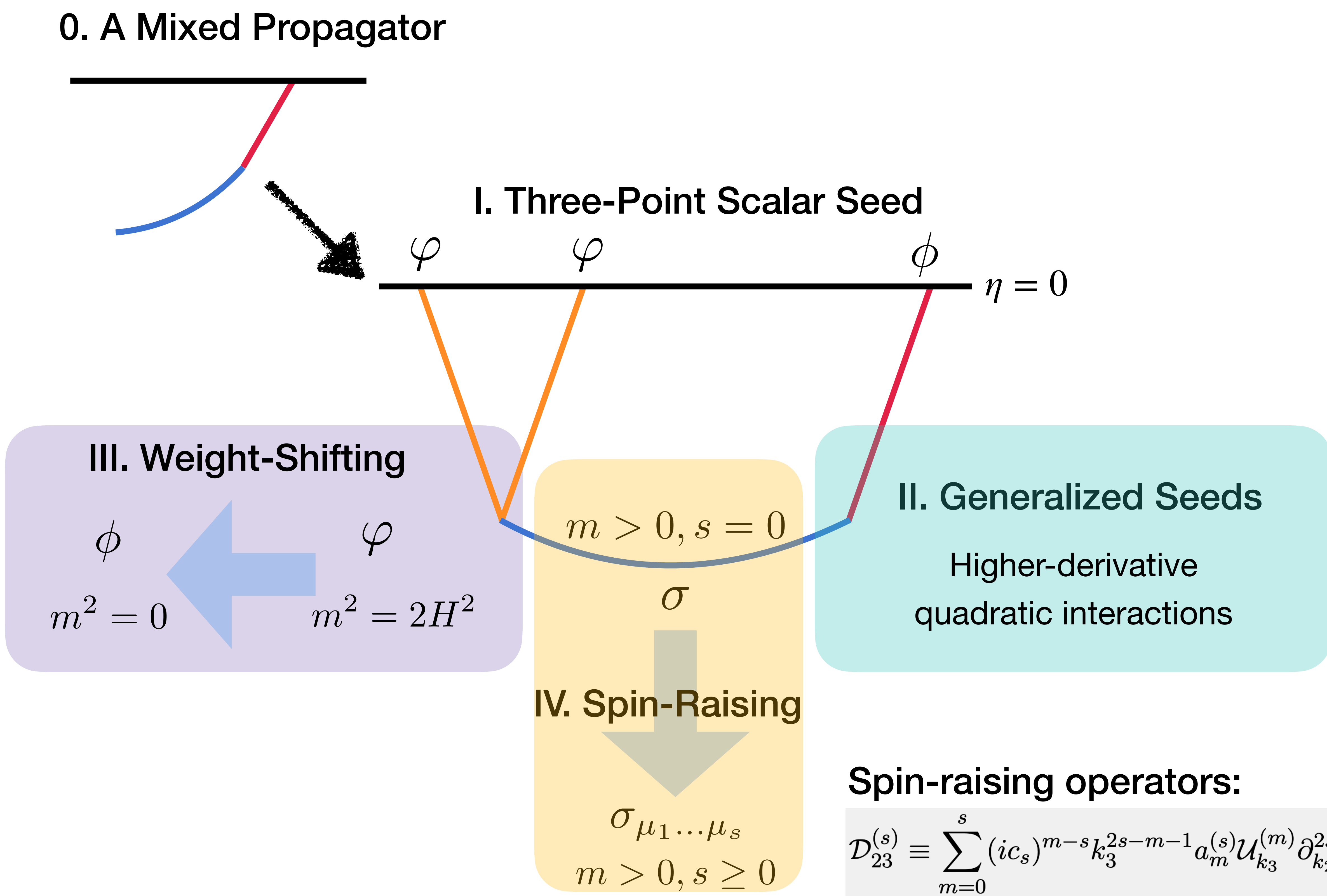

$$\partial_i^{n_s}\left(\partial_t^{n_1}\phi\partial_t^{n_2}\phi\partial_t^{n_3}\sigma\right)$$

Any boost-breaking
cubic interactions

Weight-shifting operators $\langle\phi\phi\phi\rangle = \mathcal{W}\,\langle\varphi\varphi\phi\rangle \sim \mathcal{W}\,\hat{\mathcal{I}}$

$$\mathcal{W}_{12} \equiv -c_s^{2-n_s}(\mathbf{k}_a\cdot\mathbf{k}_b)^{n_s/2}k_1^{n_1-1}k_2^{n_2-1}\left(1-n_1-k_1\partial_{k_1}\right)\left(1-n_2-k_2\partial_{k_2}\right)\partial_{k_{12}}^{\tilde{n}_T-2}$$

# Strategy of BCCB

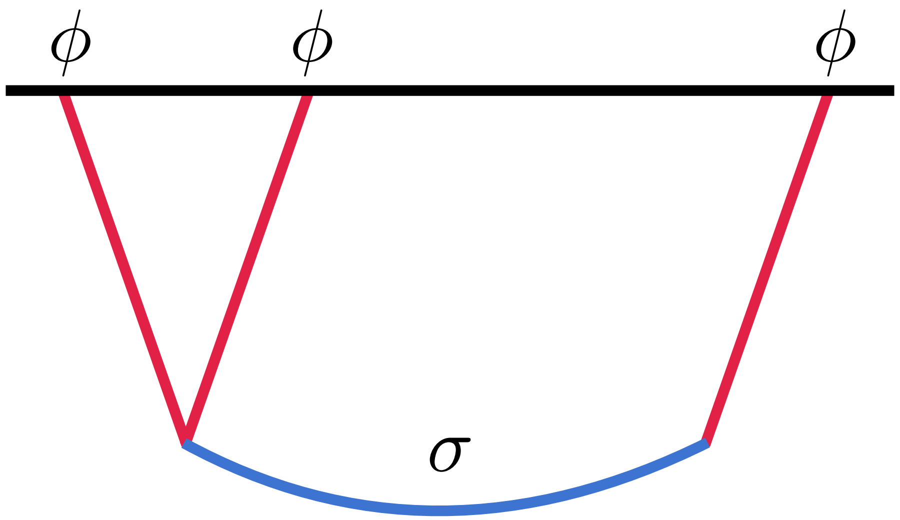



Spin-raising operators:

$$\mathcal{D}_{23}^{(s)} \equiv \sum_{m=0}^{s} (ic_s)^{m-s} k_3^{2s-m-1} a_m^{(s)} \mathcal{U}_{k_3}^{(m)} \partial_{k_2}^{2s-m-1}$$

# One Formula to Find Them All

A complete set of inflationary bispectra from:




$m > 0, s \geq 0$

$$\langle \phi_{k_1} \phi_{k_2} \phi_{k_3} \rangle \sim P_s(\cos\theta) \; \mathcal{W} \cdot \mathcal{U} \cdot \hat{\mathcal{I}}^{(n)}$$

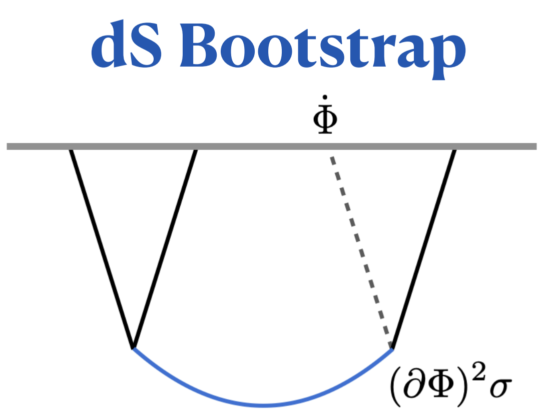
Weight-shifting

Spin-raising

Scalar Seeds

- **Full shapes**
- **Large signals**
- **Richer pheno**

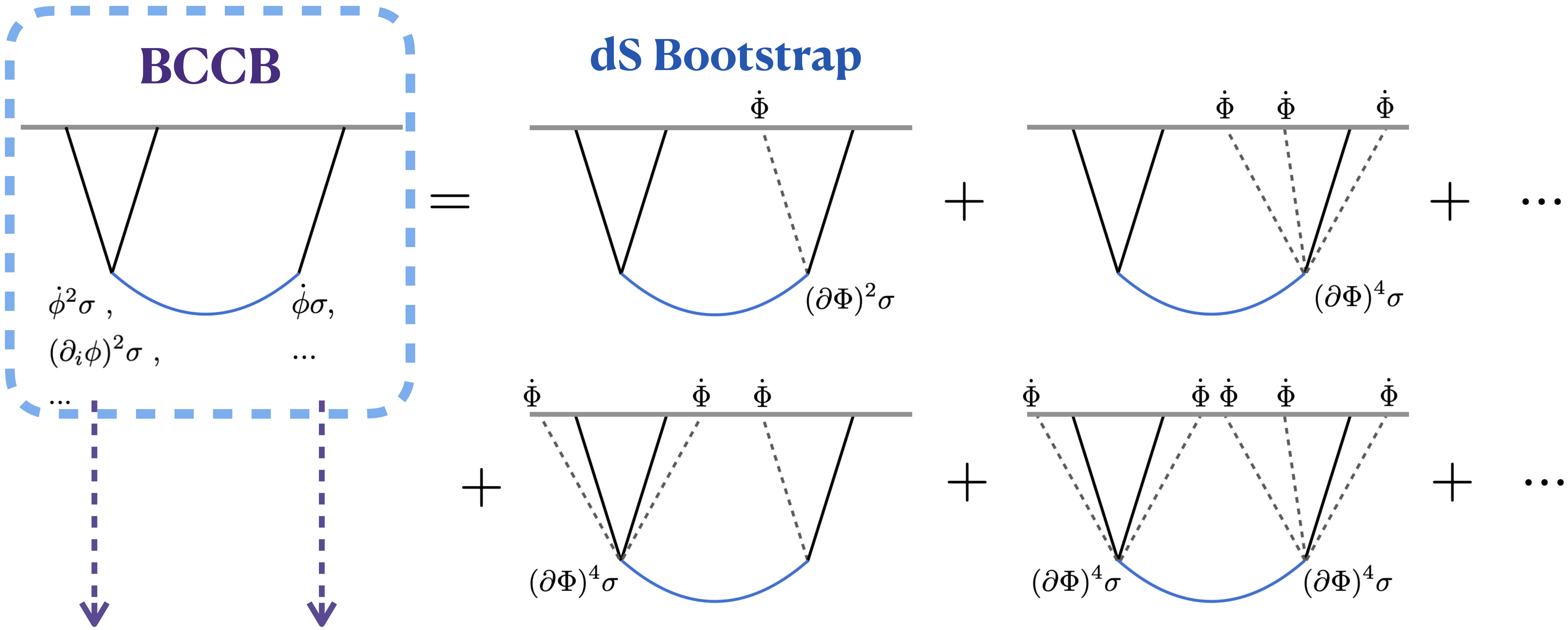
# Why results from dS bootstrap are small?




mild breaking of dS boost symmetries

→ $\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle$ **Slow-roll suppressed ~O($\epsilon$)**

# Signals are boosted in strong boost-breaking scenarios




Cubic & quadratic interactions from the EFT of inflation

Baumann, Lee, Pimentel 2016
Bordin, Creminelli, et al 2018
Pimentel, DGW 2022

## The EFT of Cosmo Collider

$$\langle \zeta_{\mathbf{k_1}}\zeta_{\mathbf{k_2}}\zeta_{\mathbf{k_3}}\rangle \sim f_{\rm NL} S(k_1,k_2,k_3) P_\zeta^2$$

size — $f_{\rm NL}$

*shape* — $S(k_1,k_2,k_3)$

$f_{\rm NL} \lesssim \mathcal{O}(10)$

# Phase of Cosmological Colliders

Oscillatory signals in the squeezed limit of the shape function

$$\lim_{k_3\to 0} S^{(0)}(k_1,k_2,k_3) \sim \left(\frac{k_3}{k_1}\right)^{1/2} \cos\left[\mu \log\left(\frac{c_\sigma k_3}{4c_s k_1}\right) + \delta(\mu)\right]$$

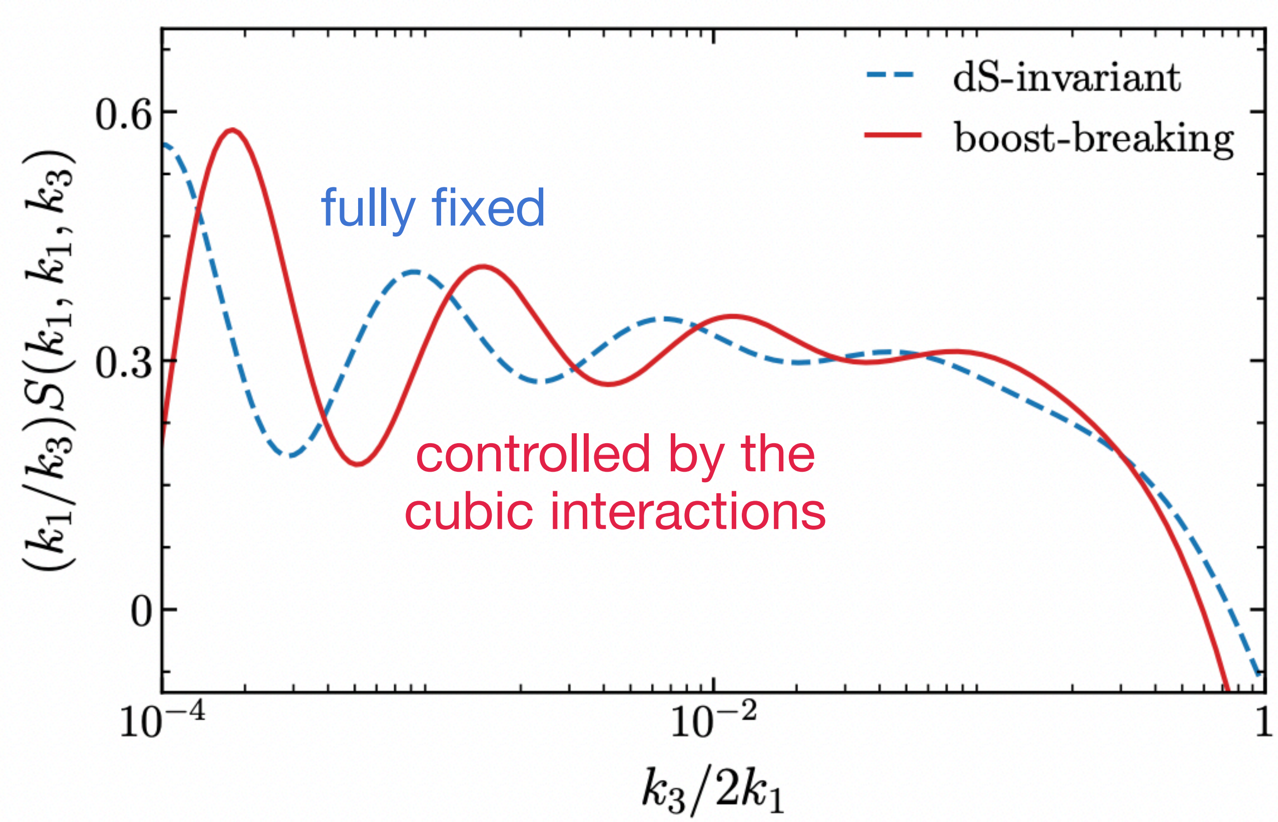
two sound speeds

phase

For dS-invariant theories:

$$c_s = c_\sigma = 1\ ,$$

$$\delta^{\mathrm{dS}}(\mu) = \arg\left[i\frac{\Gamma\left(\frac{7}{2}+i\mu\right)}{\Gamma\left(1+i\mu\right)}\frac{(1+i\sinh\pi\mu)}{\frac{1}{2}+i\mu}\right]$$



# Collider Signals around the Equilateral Limit

One special case:

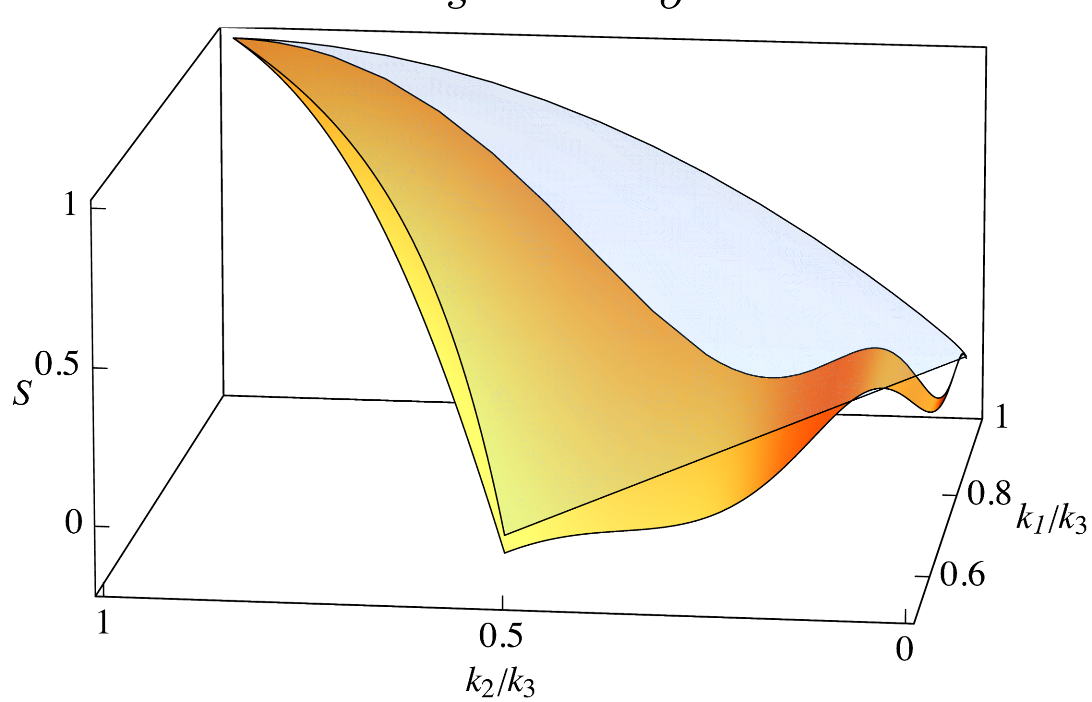
$$c_\sigma \ll c_s$$

Collider signals are shifted outside of the squeezed limit.

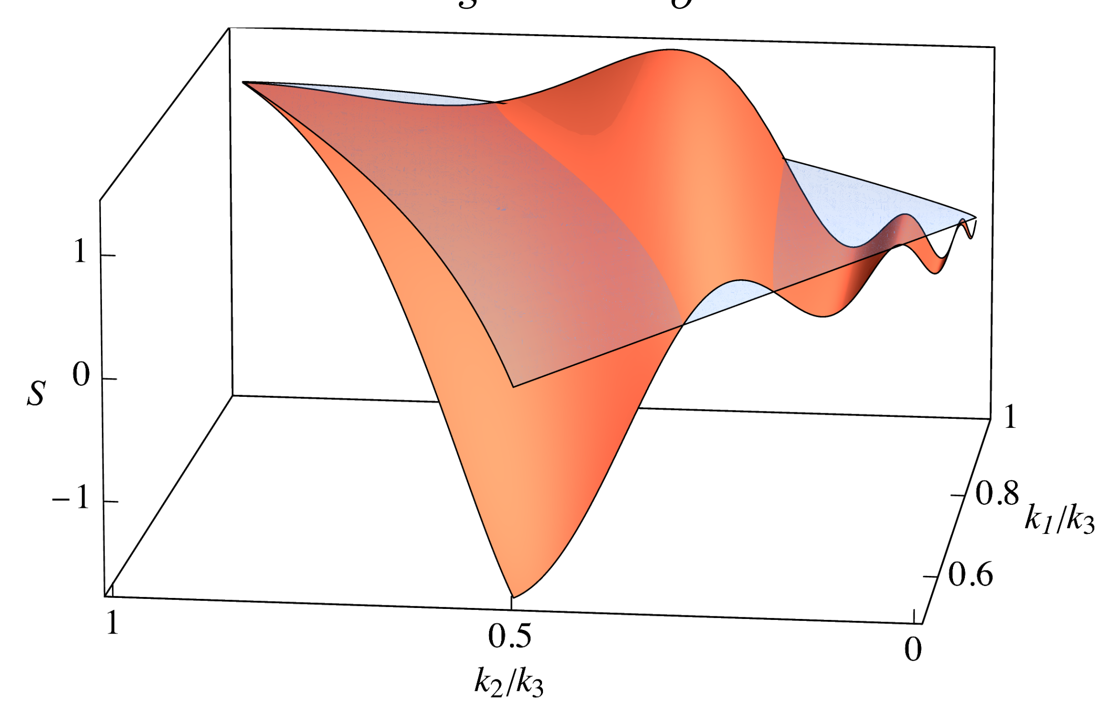
## The Equilateral Collider Shape

$$S^{\text{eq.col.}}(k_1,k_2,k_3) = \frac{k_1 k_2}{(k_1+k_2)^2}\left(\frac{k_3}{k_1+k_2}\right)^{1/2} \cos\left[\mu \log\left(\frac{c_\sigma k_3}{2c_s(k_1+k_2)}\right)+\delta\right] + \text{perms.}$$

$c_s = 10c_\sigma$




$c_s = 20c_\sigma$



# Take-Away Messages

- ☑ A complete set of cosmo collider bispectra, Bootstrapped!!
- ☑ The size of the bispectra can be large, as strong breaking of the dS boosts is allowed in BCCB.
- ☑ New pheno with the <u>phase of cosmo colliders</u> and the <u>equilateral collider shape</u>
- ☑ These bispectra shapes provide theoretically well-motivated (and consistent) **targets for upcoming LSS/CMB/21cm surveys**.

***New formalism. A lot to be done!***

**Looking forward to questions in the discussion session.**