Boostless Cosmological Collider Bootstrap
~ of Tensor Bispectra ~

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SCUOLA
NORMALE
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YITP
Nov 2025

Outline

$$\overbrace{\text{Boostless}}^{3.}\quad \overbrace{\text{Cosmological Collider}}^{2.}\quad \overbrace{\text{Bootstrap}}^{4.}$$

$$\text{of}\quad \underbrace{\text{Tensor Bispectra}}_{1.}$$

5. Some results
6. Conclusions

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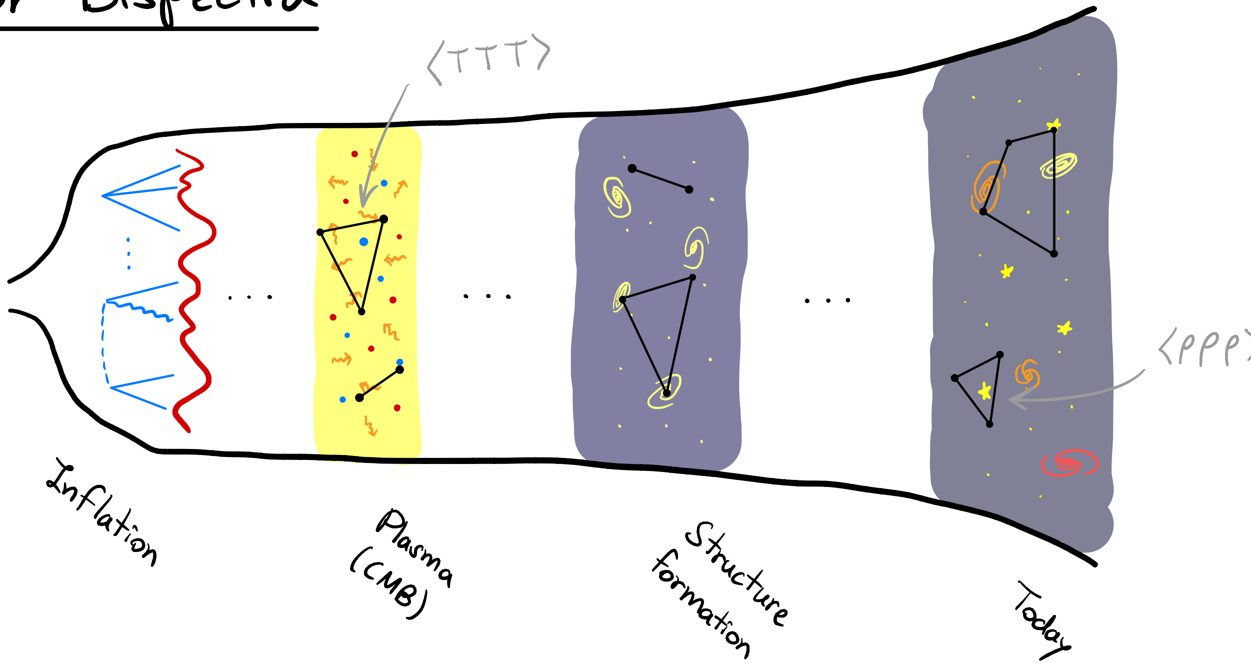
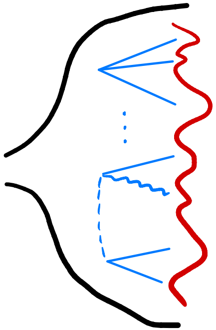
Tensor Bispectra



The primordial perturbations generated during inflation seeded the late time structure

Tensor Bispectra



Inflation

Primordial perturbations...

... can be scalar (ζ) or tensor (γ_{ij})

... are small:

$$\Delta_\zeta^2 \sim 10^{-9} \qquad \text{Planck '23}$$

$$\Delta_\gamma^2 \lesssim 0.03\,\Delta_\zeta^2 \qquad \text{BICEP/Keck '18}$$

3-pt. functions (bispectra) encode the dynamics

$$\langle \zeta\zeta\zeta \rangle \qquad \boxed{\langle \gamma\zeta\zeta \rangle \quad \langle \gamma\gamma\zeta \rangle \quad \langle \gamma\gamma\gamma \rangle} \qquad \text{Tensor bispectra}$$

Tensor Bispectra

Current constraints from CMB:

Model		T+E+B
Tensor-Tensor-Tensor		
Squeezed	$(\times 10^{-1})$	$\mathbf{4 \pm 8}$
Equilateral	$(\times 10^{-2})$	$\mathbf{-0 \pm 3}$
$W^3\,(n_{\rm NL} = +1)$	$(\times 10^{-3})$	$\mathbf{6 \pm 4}$
$W^3\,(n_{\rm NL} = 0)$	$(\times 10^{-2})$	$\mathbf{4 \pm 4}$
$W^3\,(n_{\rm NL} = -1)$	$(\times 10^{0})$	$\mathbf{3 \pm 15}$
$\widetilde{W}W^2\,(n_{\rm NL} = +1)$	$(\times 10^{-3})$	$\mathbf{-4 \pm 7}$
$\widetilde{W}W^2\,(n_{\rm NL} = 0)$	$(\times 10^{-2})$	$\mathbf{-2 \pm 5}$
$\widetilde{W}W^2\,(n_{\rm NL} = -1)$	$(\times 10^{0})$	$\mathbf{5 \pm 17}$
$\widetilde{F}F$	$(\times 10^{-2})$	$\mathbf{3 \pm 6}$
Tensor-Tensor-Scalar		
$\widetilde{W}W$	$(\times 10^{-2})$	$\mathbf{6 \pm 10}$
Tensor-Scalar-Scalar		
Squeezed	$(\times 10^{0})$	$\mathbf{11 \pm 11}$

Philcox, Shiraishi '24

- Future improvements:

$$\sigma\left(f_{NL}^{\gamma\zeta\zeta}\right) \sim \mathcal{O}(0.1-1)$$

$$\sigma\left(f_{NL}^{\gamma\gamma\zeta}\right) \sim \mathcal{O}(10)$$

$$\sigma\left(f_{NL}^{\gamma\gamma\gamma}\right) \sim \mathcal{O}(1)$$

LiteBird
CMB-S4

- Only 11 models have been constrained, many more to explore!

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3. Boostless
2. Cosmological Collider
4. Bootstrap
1. of Tensor Bispectra

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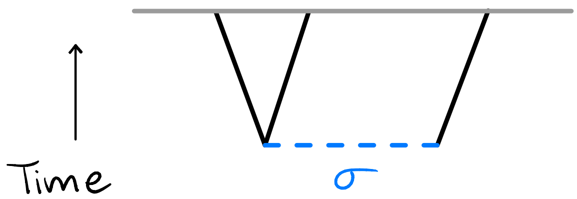
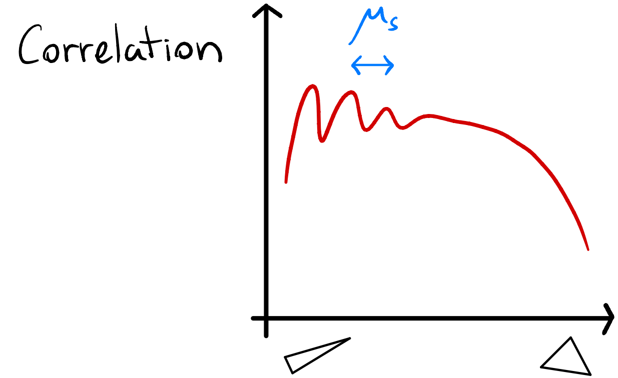
Cosmological collider

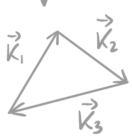


$\left\{ \begin{array}{l} \text{mass } m > H \\ \text{spin } s \end{array} \right.$



$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle \xrightarrow[k_3 \ll k_1 = k_2]{\text{Squeezed limit}} P_s(\hat{k}_1 \cdot \hat{k}_3) \cdot \left(\frac{k_3}{k_1}\right)^{3/2} \cdot \cos\left[\mu_s \cdot \log\left(\frac{k_3}{k_1}\right) + \text{ph.}\right]$$

Mom. conservation



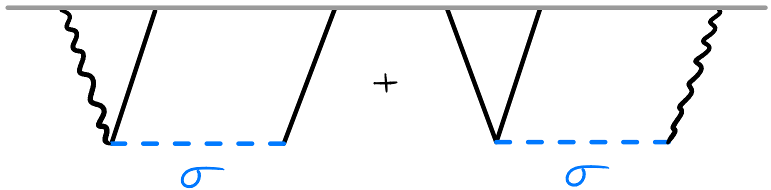
$$\mu_s \equiv \sqrt{\frac{m^2}{H^2} - \left(s - \frac{1}{2}\right)^2}$$

Arkani-Hamed, Maldacena '15
Baumann, Lee, Pimentel '16
Pimentel, Wang '22
Jazayeri, Renaux-Petel '22

Cosmological collider tensor bispectra

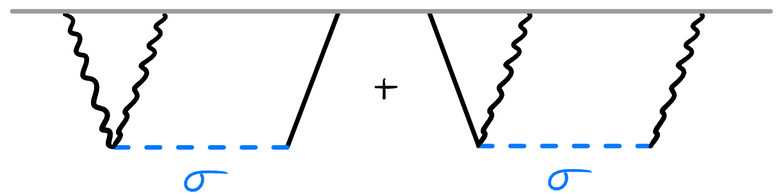
We want to compute:

$\langle \gamma \zeta \zeta \rangle =$

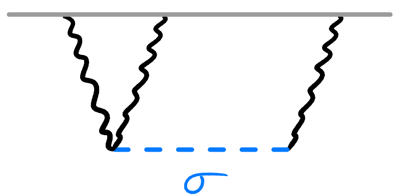


Baumann, Lee, Pimentel '16
(squeezed limit)

$\langle \gamma \gamma \zeta \rangle =$



$\langle \gamma \gamma \gamma \rangle =$



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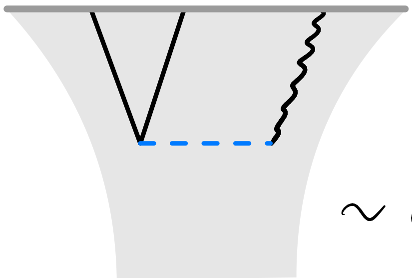
Boostless



$\sim$ de Sitter

dS isometries

Spatial translations
Spatial rotations
Dilatation
~~dS boosts~~

Observed

- Free theory: dS mode functions with sound speed

$$0 < c_\varphi \leq 1 \ , \quad c_\sigma \leq 1 \ , \quad c_\gamma = 1 \ \text{(w.l.o.g.)}$$

- Interactions: We use the EFT of inflation framework

Cheung et al. '07

$$\mathcal{L}(\pi, \gamma_{ij}, \sigma^{\mu_1 \cdots \mu_s}) \subset \dot{\pi}\, \partial_i \pi\, \sigma_i , \ \dot{\gamma}_{ij} \sigma_{ij} , \ \dots$$

Outline

3. 2. 4.

Boostless Cosmological Collider Bootstrap

of Tensor Bispectra

1.

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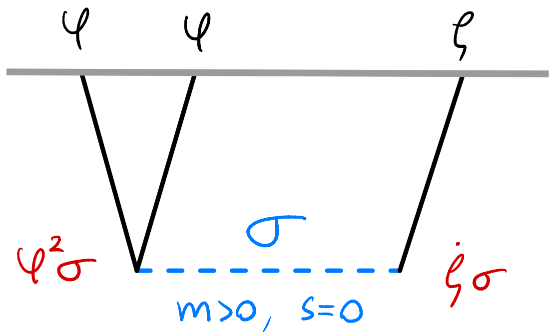
Bootstrap

Start from a basic "seed" correlator of scalars:

$\hat{I}(k_1, k_2, k_3) =$ 

φ: Conformally coupled scalar

It obeys a boundary diff. eq.:

$$\left[\Delta_u + \left(\mu^2 + \frac{1}{4}\right)\right]\hat{I}(u) = i\,\frac{u}{1+u}$$

with

$$\begin{cases} \Delta_u = u^2(1-u^2)\partial_u^2 - 2u^3\partial_u \\ u = \dfrac{k_3}{k_1+k_2} \\ \mu = \sqrt{\dfrac{m^2}{H^2} - \dfrac{9}{4}} \end{cases}$$

Pimentel, Wang '22

Bootstrap

$$\left[\Delta_u + \left(\mu^2 + \frac{1}{4}\right)\right] \hat{I}(u) = i\,\frac{u}{1+u}$$

with

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Analytical solution:

$$\hat{I}(u) = \underbrace{i\sum_{n=0}^{\infty} C_n \cdot u^{n+1}}_{\substack{\text{Particular sol.}\\ \text{(EFT)}}} - \underbrace{\frac{i}{2}\sum_{\pm} C_\pm \left(\frac{iu}{2\mu}\right)^{\frac{1}{2}\pm i\mu} \cdot {}_2F_1\left[\frac{1}{4} \pm \frac{i\mu}{2}, \frac{3}{4} \pm \frac{i\mu}{2}; 1\pm i\mu; u^2\right]}_{\substack{\text{Homogeneous sol.}\\ \text{(Particle production)}}}$$

Boundary cond.: match the bulk integral in the squeezed limit

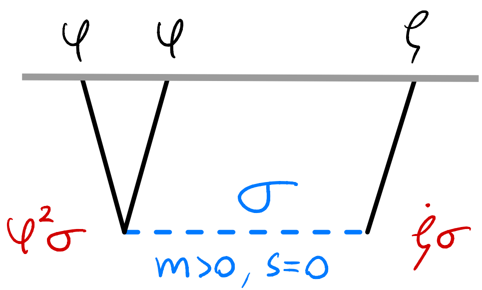
$\Downarrow$

Fixes $C_\pm$

Pimentel, Wang '22

Bootstrap

Then use momentum differential ops. to get tensor bispectra, e.g. $\langle \gamma \zeta \zeta \rangle$:



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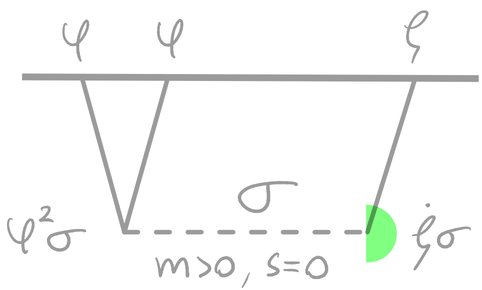
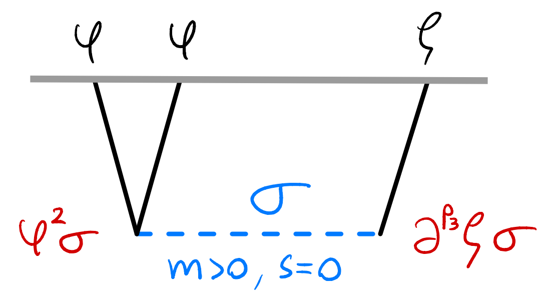
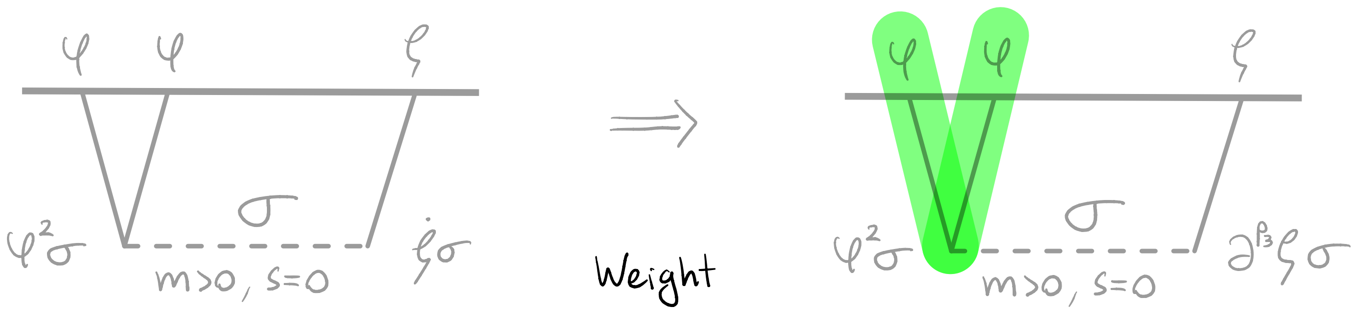


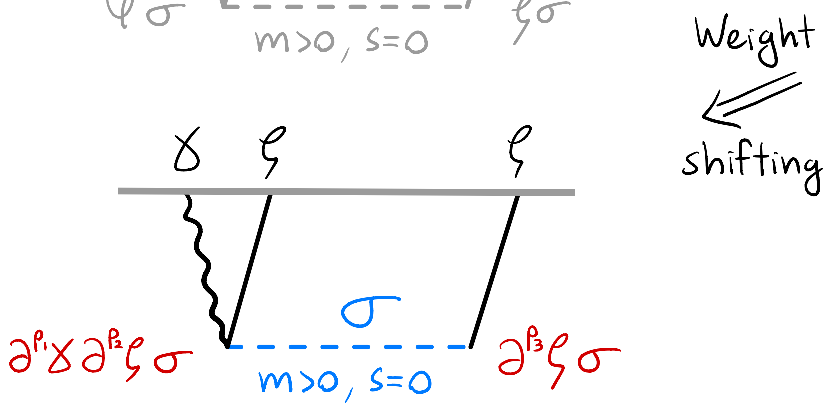
Generalised
$\Longrightarrow$
seed



Bootstrap

Then use momentum differential ops. to get tensor bispectra, e.g. $\langle \gamma\zeta\zeta \rangle$:



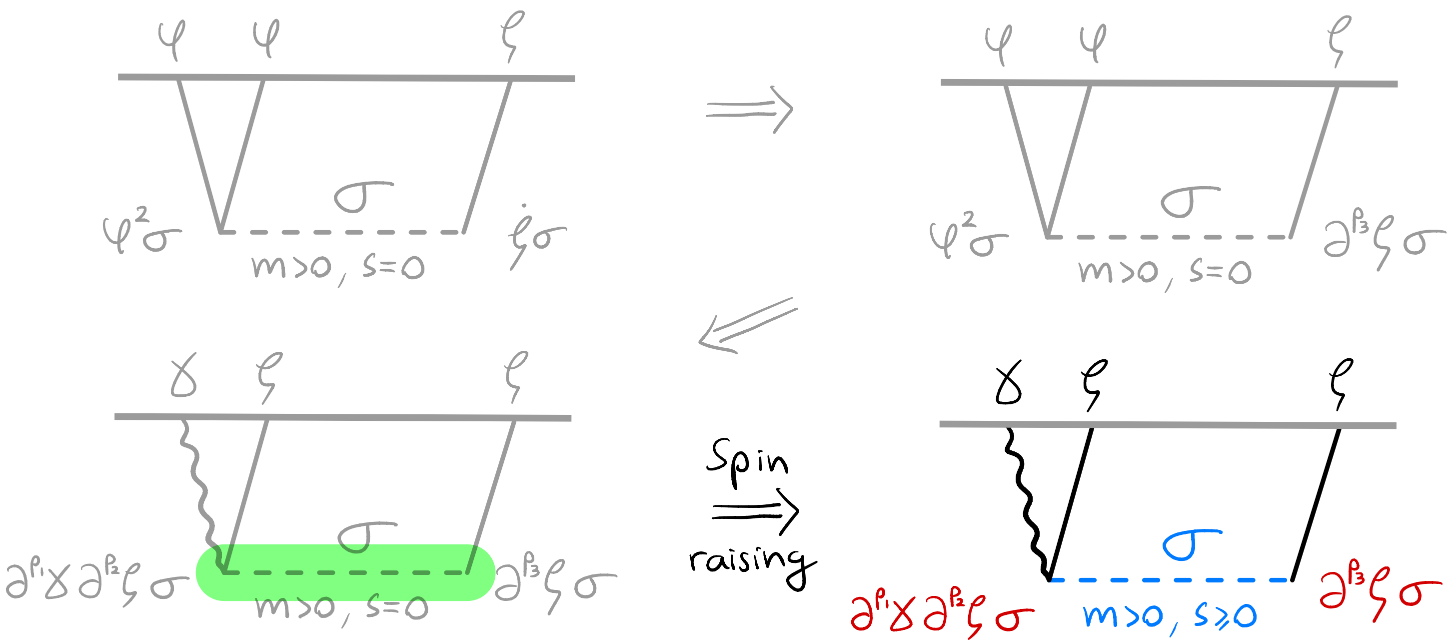


Simple example:

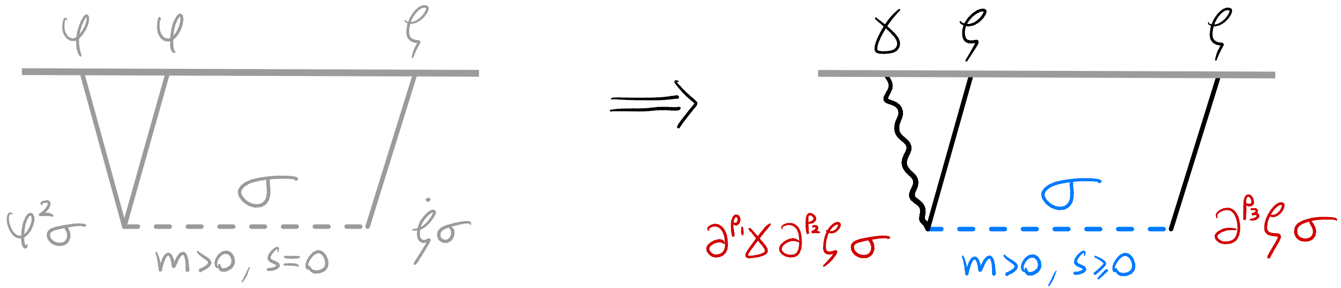
$$\partial_t^p \hat{K}_\zeta(\vec{k},\eta) = \underbrace{k^{p-1}(1-p-k\partial_k)}_{\text{Diff. op.}} \hat{K}_\varphi(\vec{k},\eta)$$

Bootstrap

Then use momentum differential ops. to get tensor bispectra, e.g. $\langle \gamma\zeta\zeta \rangle$:



Bootstrap



Polarization struc.

Weight shifting

$$\boxed{\langle \gamma^{\lambda}_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = \mathcal{E}^{\lambda}(\hat{k}_1 \cdot \hat{k}_3) \cdot \mathcal{U}_s \cdot \mathcal{W} \cdot \hat{\mathcal{I}}^{(n)}(u)}$$

Spin raising

Generalised seed

... and similarly for $\langle \gamma\gamma\zeta \rangle$ & $\langle \gamma\gamma\gamma \rangle$

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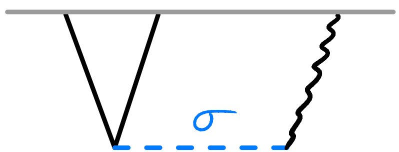


Only even $s \geq 2$

Spin 2 observable if:

- $m \lesssim \text{few} \times H$
- $c_\varphi \lesssim 0.4$
- $r \gtrsim 0.01$

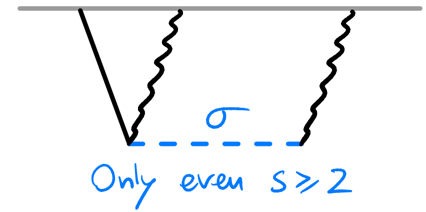
(assumming $c_\sigma \simeq 1$)

$$\lim_{k_3 \ll k_1 = k_2} \langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \gamma^{\lambda}_{\vec{k}_3} \rangle_{\text{n.l.}} \sim P_s^{\lambda}(\hat{k}_1 \cdot \hat{k}_3) \cdot \left(\frac{k_3}{k_1}\right)^{3/2} \cdot \cos\left[\mu_s \cdot \log\left(\frac{k_3}{k_1}\right) + \text{ph.}\right]$$

$$\lim_{k_3 \ll k_1 = k_2} \langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \gamma^{\lambda}_{\vec{k}_3} \rangle_{\text{l.}} \sim P_s^{\lambda}(\hat{k}_1 \cdot \hat{k}_3) \cdot \left(\frac{k_3}{k_1}\right)^{s}$$

Coincides with Baumann, Lee, Pimentel '16, but now we have the full solution!

Some results



$$\lim_{k_3 \ll k_1 = k_2} \langle \zeta_{\vec{k}_1} \gamma^{\lambda_2}_{\vec{k}_2} \gamma^{\lambda_3}_{\vec{k}_3} \rangle_{\text{n.l.}} \sim \mathcal{E}_s^{\lambda_2 \lambda_3}(\hat{k}_1 \cdot \hat{k}_3) \cdot \left(\frac{k_3}{k_1}\right)^{3/2} \cdot \cos\left[\mu_s \cdot \log\left(\frac{k_3}{k_1}\right) + \text{ph.}\right]$$

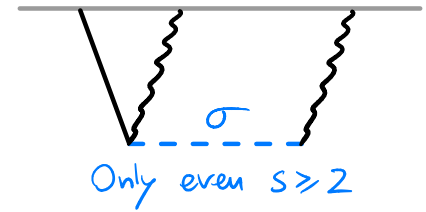
$$\lim_{k_3 \ll k_1 = k_2} \langle \zeta_{\vec{k}_1} \gamma^{\lambda_2}_{\vec{k}_2} \gamma^{\lambda_3}_{\vec{k}_3} \rangle_{\text{l.}} \sim \mathcal{E}_s^{\lambda_2 \lambda_3}(\hat{k}_1 \cdot \hat{k}_3) \cdot \left(\frac{k_3}{k_1}\right)^{0} \longleftarrow \text{Dominates!}$$

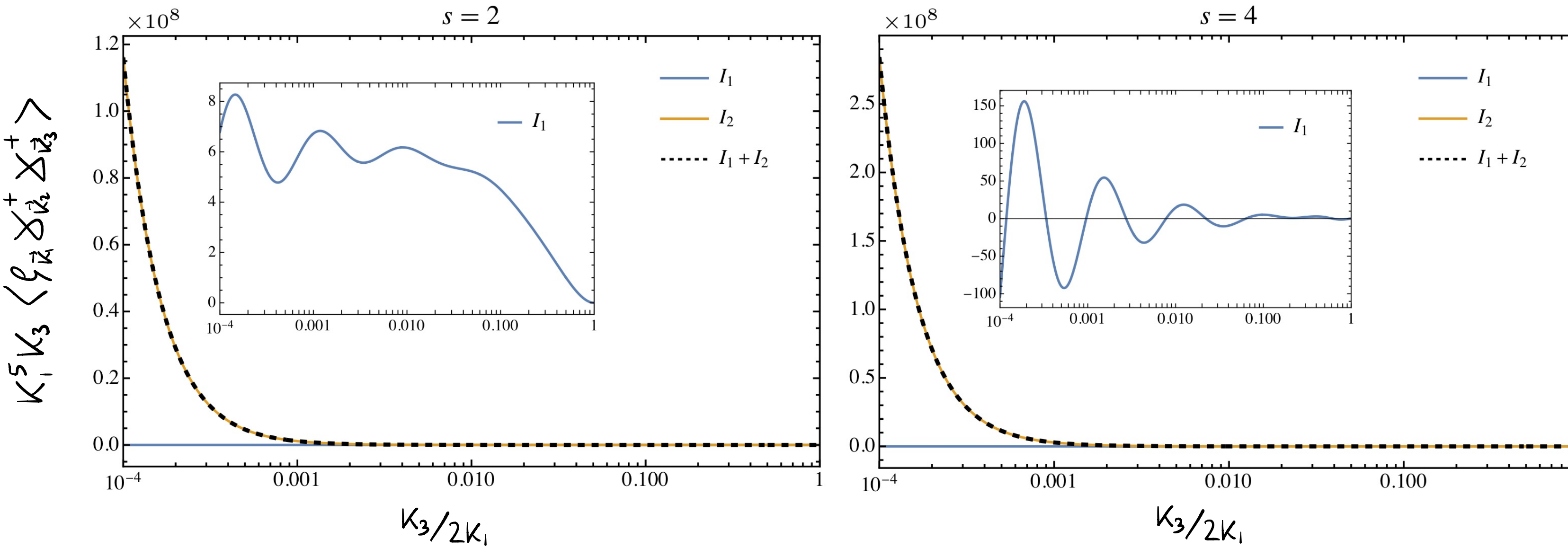
The oscillations are not visible, the EFT part dominates

Some results

I_1 = non-local part

I_2 = local part





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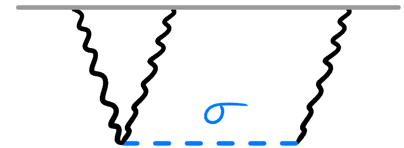


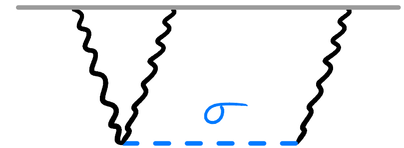
Only even $s \geq 2$

$$\lim_{K_3 \ll K_1 = K_2} \langle \gamma^{\lambda_1}_{\vec{K}_1} \gamma^{\lambda_2}_{\vec{K}_2} \gamma^{\lambda_3}_{\vec{K}_3} \rangle_{n.l.} \sim \mathcal{Q}_s^{\lambda_1 \lambda_2 \lambda_3}(\vec{K}_1, \vec{K}_2, \vec{K}_3) \cdot \left(\frac{K_3}{K_1}\right)^{3/2} \cdot \cos\left[\mu_s \cdot \log\left(\frac{K_3}{K_1}\right) + \text{ph.}\right]$$

$$\lim_{K_3 \ll K_1 = K_2} \langle \gamma^{\lambda_1}_{\vec{K}_1} \gamma^{\lambda_2}_{\vec{K}_2} \gamma^{\lambda_3}_{\vec{K}_3} \rangle_{l.} \sim \mathcal{Q}_s^{\lambda_1 \lambda_2 \lambda_3}(\vec{K}_1, \vec{K}_2, \vec{K}_3) \cdot \left(\frac{K_3}{K_1}\right)^{0}$$

Extra momentum dependence

Some results



Only even $s \geq 2$

$$\lim_{k_3 \ll k_1 = k_2} \langle \gamma^{\lambda_1}_{\vec{k}_1}\gamma^{\lambda_2}_{\vec{k}_2}\gamma^{\lambda_3}_{\vec{k}_3}\rangle_{\text{n.l.}} \sim Q_s^{\lambda_1\lambda_2\lambda_3}(\vec{k}_1,\vec{k}_2,\vec{k}_3)\cdot\left(\frac{k_3}{k_1}\right)^{3/2}\cdot\cos\left[\mu_s\cdot\log\left(\frac{k_3}{k_1}\right)+\text{ph.}\right]$$

$$\lim_{k_3 \ll k_1 = k_2} \langle \gamma^{\lambda_1}_{\vec{k}_1}\gamma^{\lambda_2}_{\vec{k}_2}\gamma^{\lambda_3}_{\vec{k}_3}\rangle_{\text{l.}} \sim Q_s^{\lambda_1\lambda_2\lambda_3}(\vec{k}_1,\vec{k}_2,\vec{k}_3)\cdot\left(\frac{k_3}{k_1}\right)^{0}$$

The oscillations are not visible in some helicity configurations:

$s=2$

$+++$	$-++$	$+-+$	$++-$
✓	✗	✗	✗

$s \geq 4$

$+++$	$-++$	$+-+$	$++-$
✓	✓	✗	✗

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Conclusions

- We bootstrap the cosmological collider contributions to

$$\langle \gamma\zeta\zeta \rangle, \quad \langle \gamma\gamma\zeta \rangle, \quad \langle \gamma\gamma\gamma \rangle,$$

- ... coming from exchange of massive spinning fields
- ... with non-trivial sound speeds and boost-breaking interactions
- We start from simple scalar seeds and build weight- & spin-shifting operators that act on them
- The c.c. signal from $h=2$ exchange is not visible for $\langle \gamma\gamma\zeta \rangle$ and some helicity choices of $\langle \gamma\gamma\gamma \rangle$
- Other diagrams, f_{NL} estimates, angular and sound-speed dependence soon!

Thank you!