Cosmological Phonon Collider

Sadra Jazayeri

Institut d'Astrophysique de Paris

Disclaimer: incomplete references

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SJ, S Renaux-Petel 2022

SJ, S Renaux-Petel, D Werth 2023

SJ, S Renaux-Petel, X Tong, D Werth, Y Zhu 2023

Sébastien Renaux-Petel (IAP)

Denis Werth (IAP)

Xi Tong (DAMTP)

Yuhang Zhu (IBS)

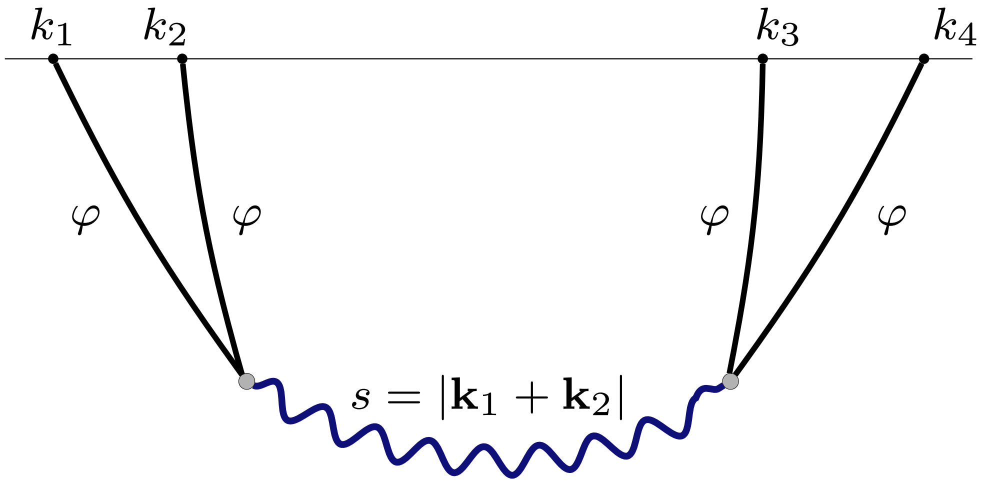
- Correlators as Particle Detectors
- Cosmological Phonon Collider
- Non-Local EFT for Phonons
- Correlators from the Non-Local EFT
- Future Outlook

Correlators as Particle Detectors

- EFT and particle production in de Sitter

$$\langle \phi(\mathbf{k}_1)\,\phi(\mathbf{k}_2)\,\phi(\mathbf{k}_3)\,\phi(\mathbf{k}_4)\rangle \;=\; \underbrace{\textit{analytic in } \{s, k_i\}}_{\text{I}} + \exp(-\pi m/H) \times \underbrace{\textit{non-analytic}}_{\text{II}}$$

Massless field



Fixed by dS isometries and analyticity

Arkani-Hamed et al 2018

Correlators as Particle Detectors

- EFT and particle production in de Sitter

$$\langle \phi(\mathbf{k}_1)\,\phi(\mathbf{k}_2)\,\phi(\mathbf{k}_3)\,\phi(\mathbf{k}_4)\rangle \;=\; \textit{analytic in } \{s, k_i\} + \exp(-\pi m/H) \times \textit{non-analytic}$$

I

- Corresponds to the EFT expansion

$$\sum_n \frac{c_n}{m^{2n}} \partial^{2n} \phi^4$$

- Unlike the 2-to-2 amplitude, **the expansion in** $1/m^2$ **is asymptotic**

$$\langle \phi^4 \rangle \sim \sum_n \frac{n!}{m^{2n}} \frac{\mathrm{Poly}_{2n+2}(k_i, s)}{k_T^{2n-1}}$$

II

- Encodes non-perturbative pp in dS

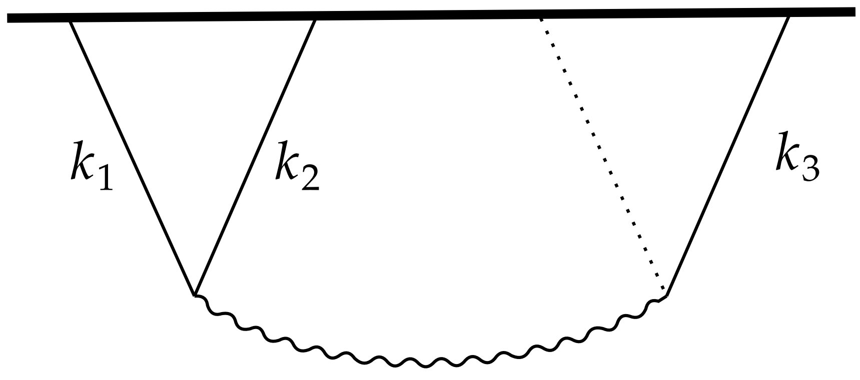
$$\frac{i}{\sqrt{2k}} \frac{1}{a(t)} \exp\left(i \int_{-\infty}^{t} dt' \omega(t')\right)$$

Bunch-Davies vacuum

$$\to \alpha_k \frac{1}{a(t)^{3/2}} \exp(imt) + \beta_k \frac{1}{a(t)^{3/2}} \exp(-imt)$$

Particle Production

- Characteristic oscillations in the bispectrum

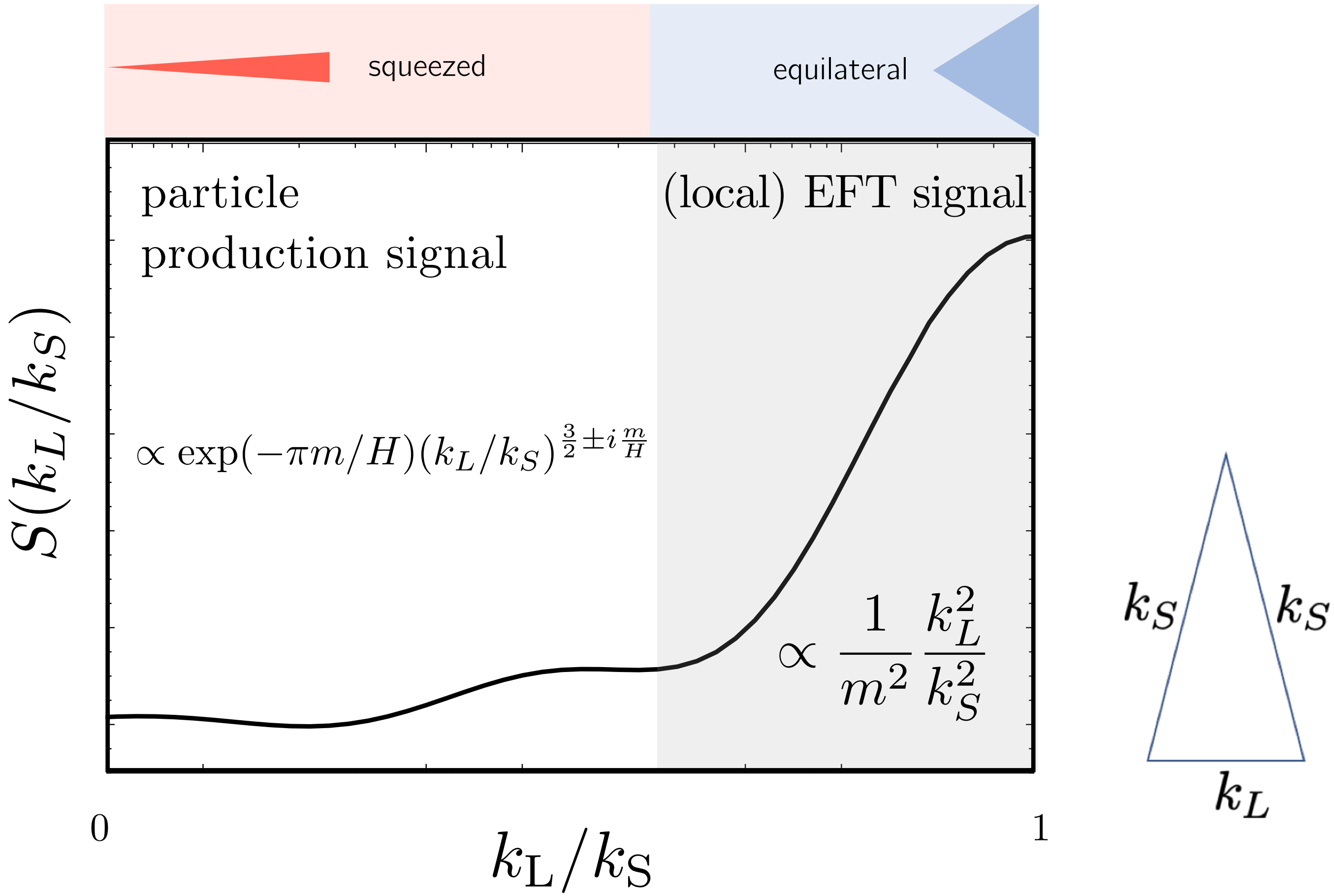


curvature perturbations

$$\langle \zeta(\mathbf{k}_1 \zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle' = (2\pi)^3 \frac{1}{(k_1 k_2 k_3)^2} \underbrace{S(k_1, k_2, k_3)}_{\text{non-Gaussian shape}} .$$

<u>Arkani-Hamed, Maldacen 2014</u>
<u>Lee, Baumann, Pimentel 2016</u>

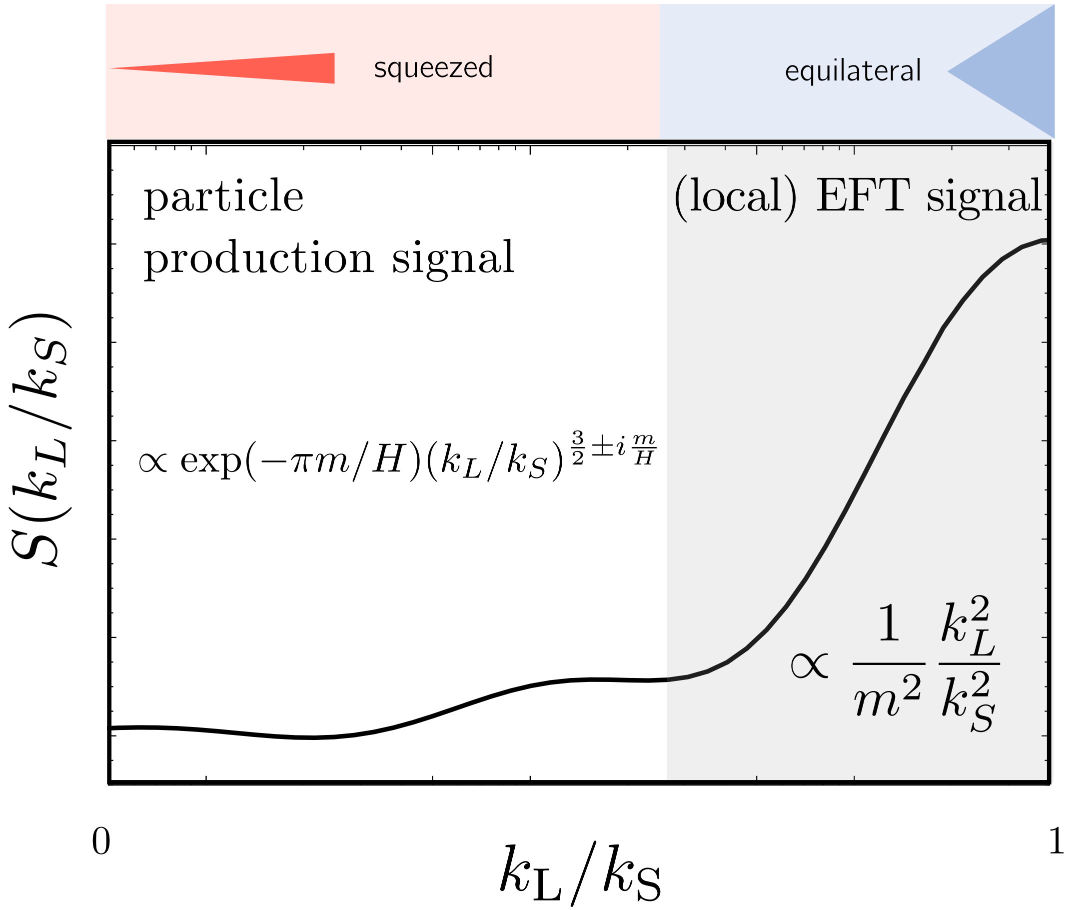
- Characteristic oscillations in the bispectrum

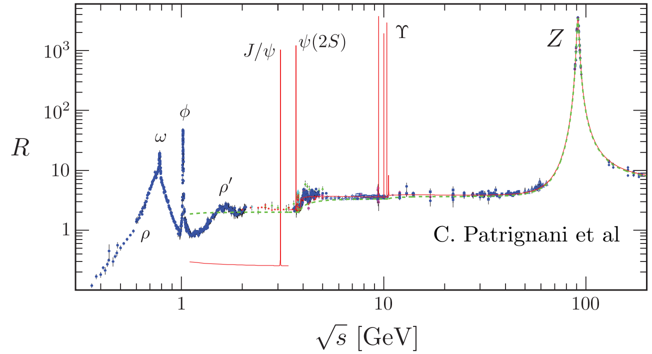


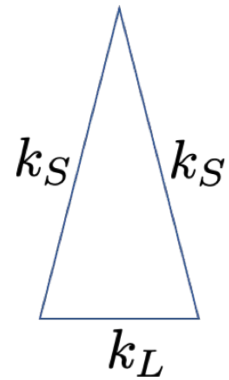
- Characteristic oscillations in the bispectrum

Cosmological Collider

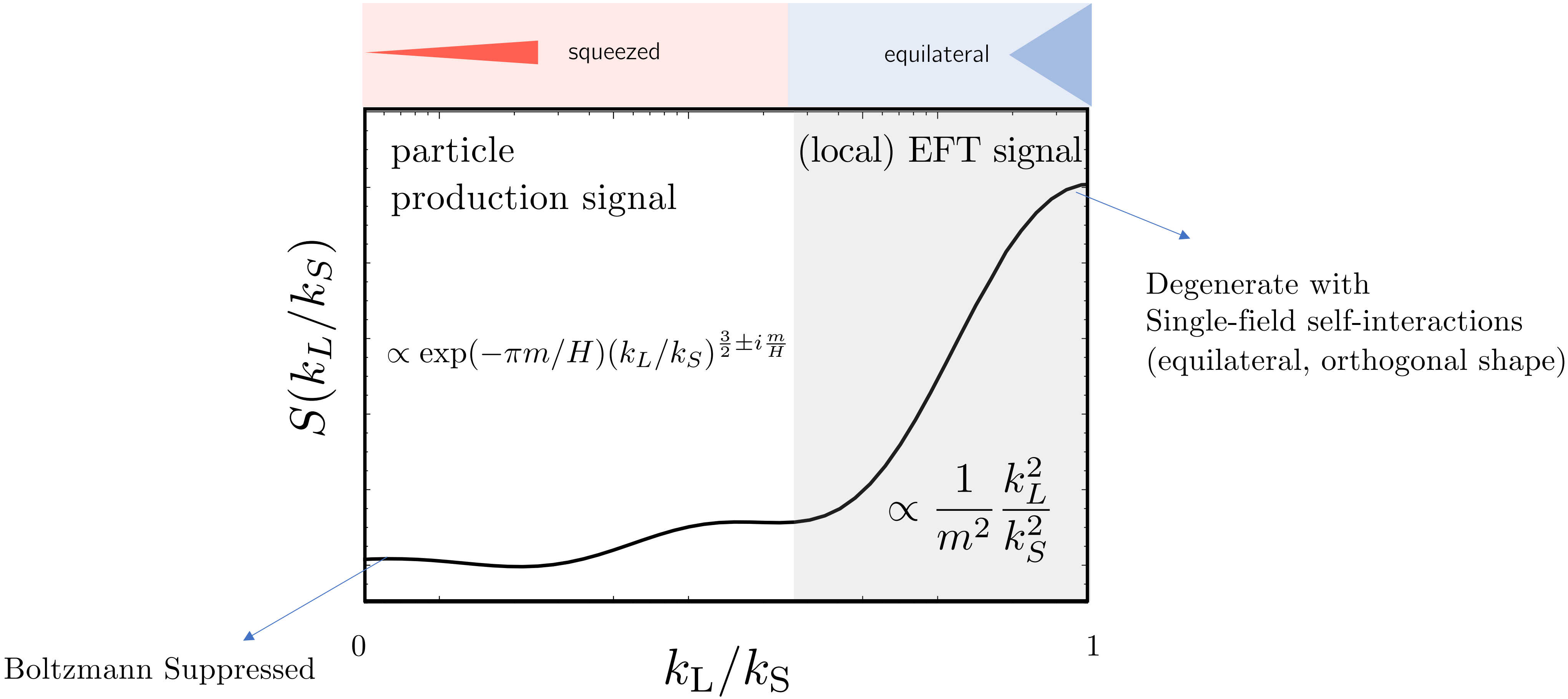
$H \sim 10^{14}$Gev







- Characteristic oscillations in the bispectrum



“You're good, Spaniard, but you're not that good. You could be magnificent”

Gladiator 2000

"You're good, Spaniard, but you're not that good. You could be magnificent"

Gladiator 2000

Break de Sitter boosts!

Cosmological Phonon Collider

- During inflation **time translation symmetry** is spontaneously broken. The long wavelength fluctuations of the system can be described with the associated **Goldstone boson**

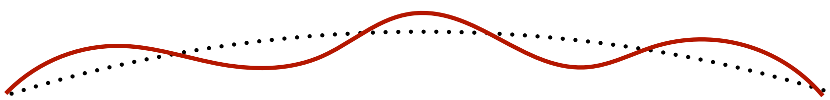
$$\phi = t + \pi(t, \mathbf{x}) \qquad\qquad \zeta \sim -H\pi$$

<u>Cheung et al 2007</u>

$$S_\pi = \int d\eta\, d^3\mathbf{x}\, a^2 \epsilon H^2 M_{\rm Pl}^2 \left[\frac{1}{c_s^2} \left(\pi'^2 - c_s^2 (\partial_i \pi)^2 \right) - \frac{1}{a} \left(\frac{1}{c_s^2} - 1 \right) \left(\pi' (\partial_i \pi)^2 + \frac{A}{c_s^2} \pi'^3 \right) + \dots \right]$$

(speed of sound) (large boost breaking interactions)

$\pi(x, t)$ fluctuation of the clock field



$\phi(t)$

$c_s \geq 0.021$

Planck 2018

Cosmological Phonon Collider

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(speed of sound) (large boost breaking interactions)

$$S_\sigma^{(2)} = \int d\eta d^3\boldsymbol{x}\, a^2 \left(\frac{1}{2}\sigma'^2 - \frac{1}{2}(\partial_i \sigma)^2 - \frac{1}{2} m^2 a^2 \sigma^2\right)$$

(unit sound speed)

- Colliding phonons

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Effective field theory of dark matter direct detection with collective excitations

Tanner Trickle,[1] Zhengkang Zhang,[1,2] and Kathryn M. Zurek[1]

[1] *Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*

[2] *Department of Physics, University of California, Santa Barbara, California 93106, USA*

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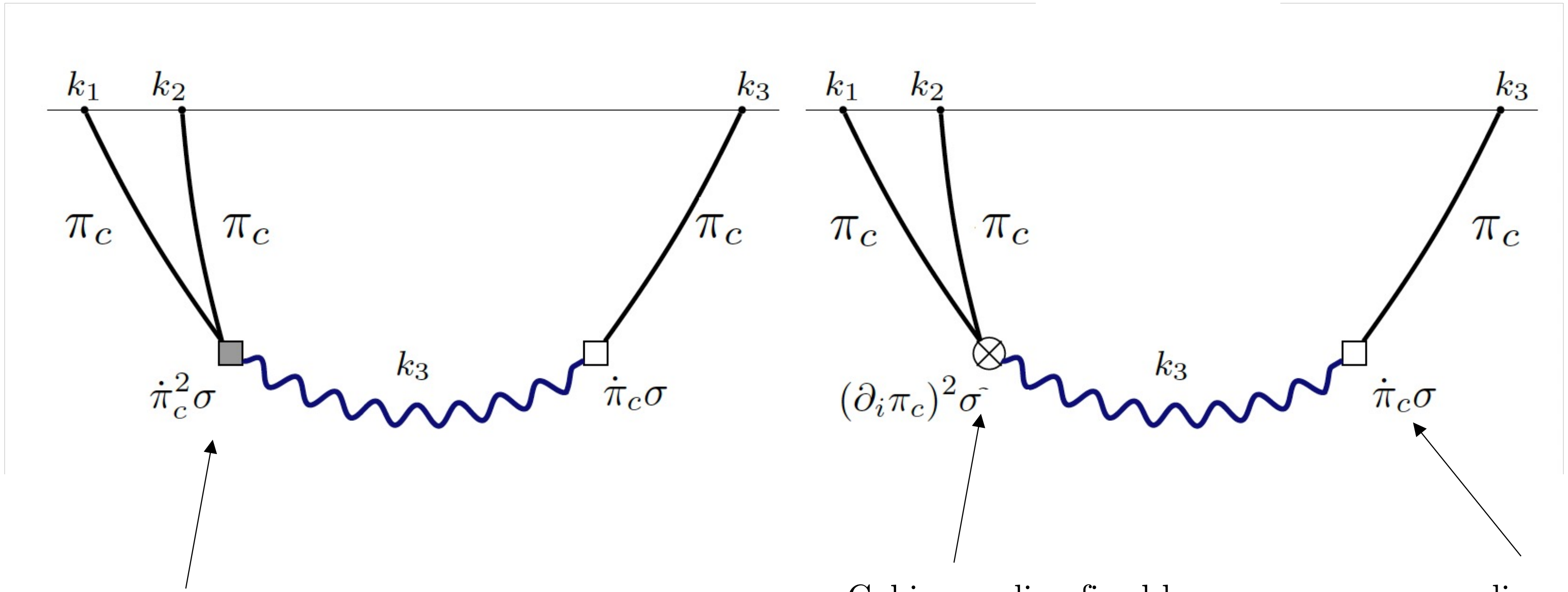
- Colliding phonons

$$S_{\pi\sigma} = \int d\eta d^3\mathbf{x}\, a^2 \left(\rho a \pi_c' \sigma + \frac{1}{\Lambda_1} \pi_c'^2 \sigma + \frac{c_s^2}{\Lambda_2} (\partial_i \pi_c)^2 \sigma \right) \qquad \pi_c = \sqrt{2\epsilon} H M_{\rm Pl} c_s^{-1} \pi$$



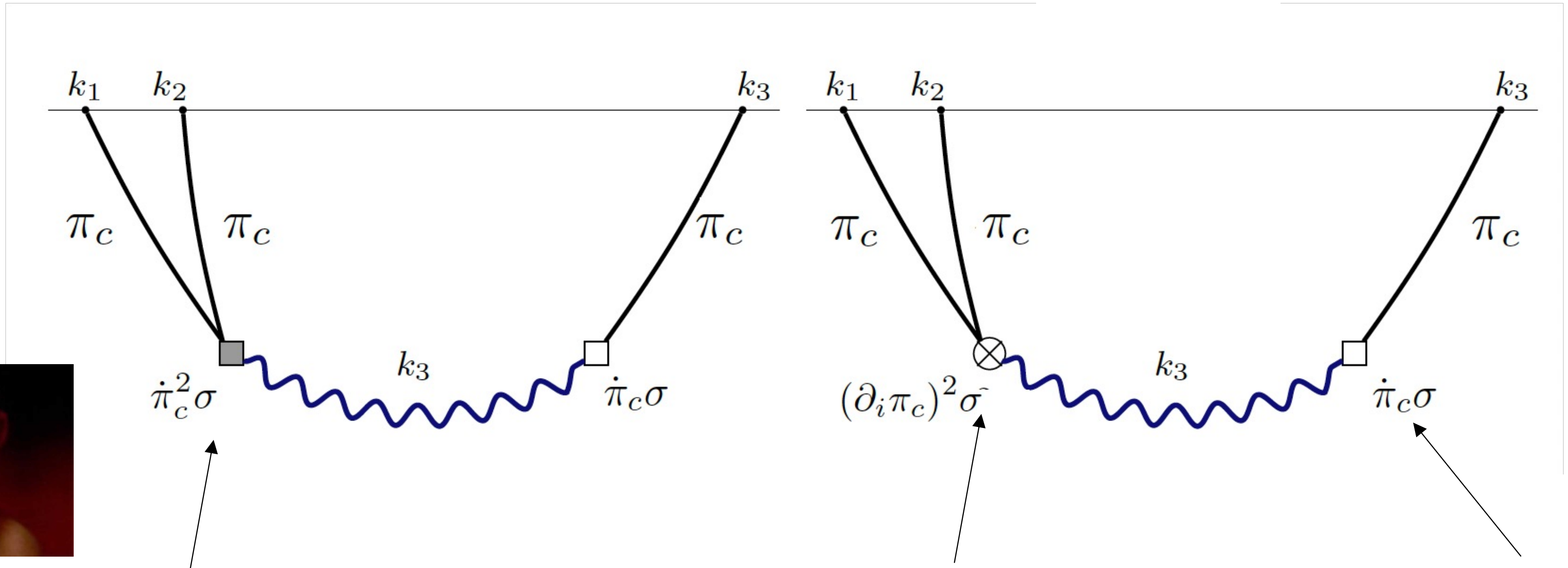
Cubic coupling with free coef.

Cubic coupling fixed by non-linearly realized diffs

linear mixing

- Colliding phonons

$$S_{\pi\sigma} = \int d\eta d^3\mathbf{x}\, a^2 \left(\rho a \pi_c' \sigma + \frac{1}{\Lambda_1} \pi_c'^2 \sigma + \frac{c_s^2}{\Lambda_2} (\partial_i \pi_c)^2 \sigma \right) \qquad \pi_c = \sqrt{2\epsilon} H M_{\rm Pl} c_s^{-1} \pi$$



Wolfram *Mathematica*

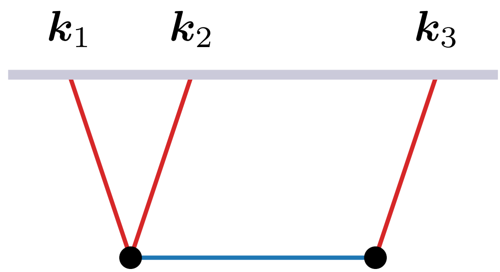
Cubic coupling with free coef.

Cubic coupling fixed by non-linearly realized diffs

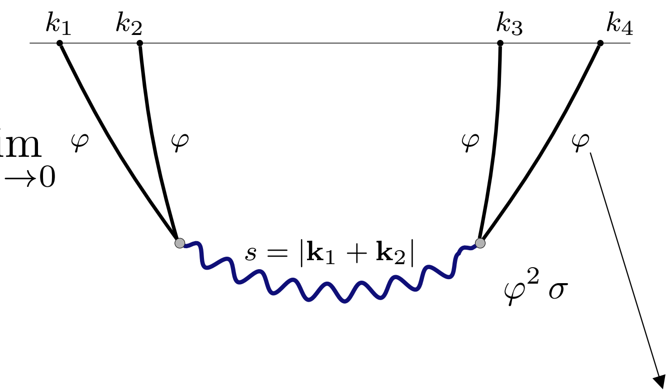
linear mixing

- All single-exchange diagrams can be mapped onto a seed four-point through bespoke weight-shifting operators and appropriate soft limits

SJ, Renaux-Petel 2022
Arkani-Hamed, Baumann, Lee, Pimentel, 2018
Baumann, Duaso Pueyo, Joyce, Pimentel 2019



$$= \hat{W}(k_1, k_2, k_3, \partial_{k_i}) \lim_{k_4 \to 0}$$



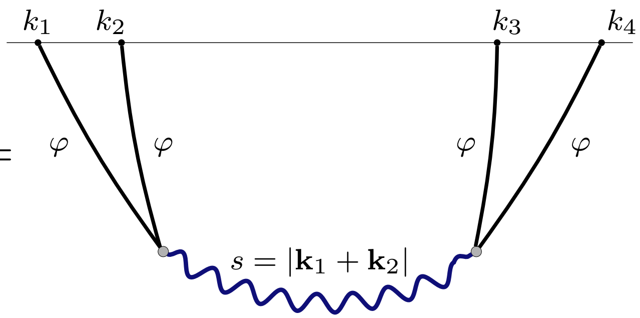
$$\varphi_+ = -\frac{H}{\sqrt{2c_s k}}\eta\, \exp(+ic_s\, k\eta)$$

$$m_\varphi^2 = 2H^2$$

See Wang, Pimentel 2022 for a different approach

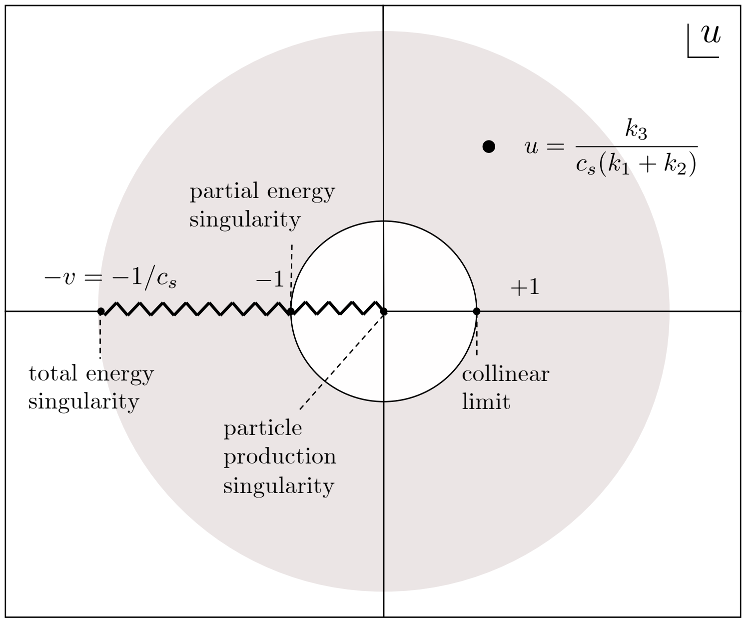
- Despite breaking boosts this four-point function can be derived from the **analytical continuation of the de Sitter four-point outside the unit disk**

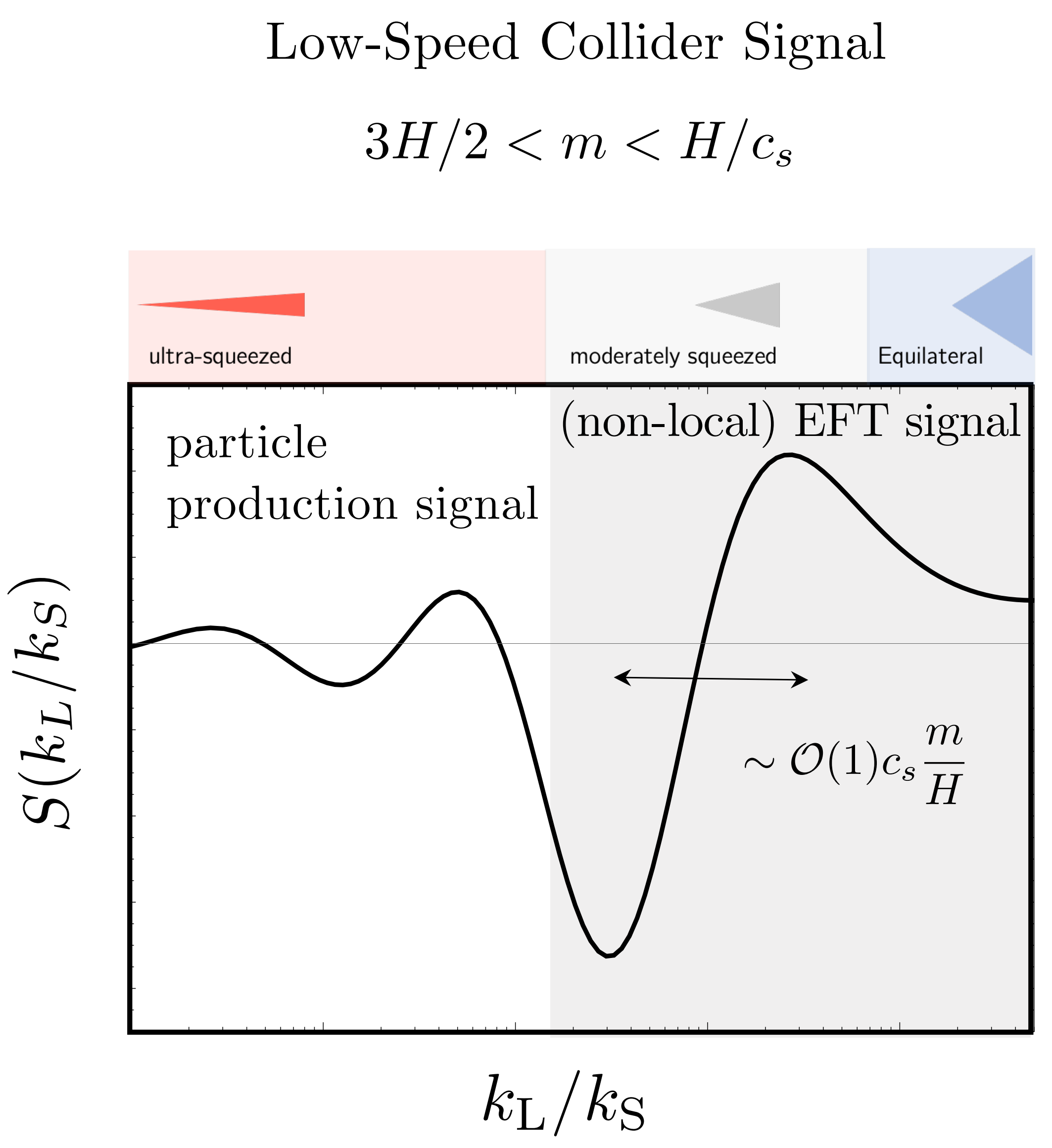
$$F_4(u, v) =$$



$$u = \frac{s}{k_1 + k_2} \leq 1$$

$$v = \frac{s}{k_3 + k_4} \leq 1$$





Low-Speed Collider Signal
$3H/2 < m < H/c_s$
ultra-squeezed
moderately squeezed
Equilateral
particle production signal
(non-local) EFT signal
$\sim \mathcal{O}(1) c_s \frac{m}{H}$
$S(k_L/k_S)$
$k_\mathrm{L}/k_\mathrm{S}$

Non-Local Effective Field Theory

- When $c_s \ll c_\sigma = 1$, the following hierarchy of scales emerges

$$\frac{c_s}{H} \ll \frac{1}{m} \ll \frac{1}{H}$$

Sound Horizon
(Freezing scale)

Compton Scale

Hubble Horizon
(background expansion)

Non-Local Effective Field Theory

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$$\frac{c_s}{H} \ll \frac{1}{m} \ll \frac{1}{H}$$

Sound Horizon (Freezing scale)

Compton Scale

Hubble Horizon (background expansion)

The heavy particle mediates non-local interactions between phonons

Non-Local Effective Field Theory

- When $c_s \ll c_\sigma = 1$, the following hierarchy of scales emerges

$$\frac{c_s}{H} \ll \frac{1}{m} \ll \frac{1}{H}$$

Sound Horizon
(Freezing scale)

Compton Scale

Hubble Horizon
(background expansion)

The heavy field is effectively non-dynamical
(the non-locality is only spatial)

Non-Local Effective Field Theory

- When $c_s \ll c_\sigma = 1$, the following hierarchy of scales emerges

$$\frac{c_s}{H} \ll \frac{1}{m} \ll \frac{1}{H}$$

Sound Horizon
(Freezing scale)

Compton Scale

Hubble Horizon
(background expansion)

Particle creation is negligible
(no on-shell heavy field decay)

Non-Local Effective Field Theory

- When $c_s \ll c_\sigma = 1$, the following hierarchy of scales emerges

$$\frac{c_s}{H} \ll \frac{1}{m} \ll \frac{1}{H}$$

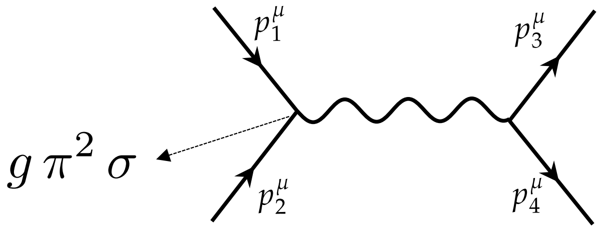
Sound Horizon (Freezing scale) — Compton Scale — Hubble Horizon (background expansion)

- In this limit, the time derivative of the *off-shell* heavy fields are small compared to its gradient

$$|\dot{\sigma}| \ll |\partial_i \sigma|$$

- A simple illustration of this limit: consider a toy model in flat space and the associated 2-to-2 scattering of phonons through the single-exchange process

$$p_i^\mu = (c_s|\mathbf{p}_i|, \mathbf{p}_i)$$



$$= \frac{-g^2}{E_\sigma^2 - \mathbf{k}_\sigma^2 - m^2} = \frac{-g^2}{c_s^2(|\mathbf{p}_1| + |\mathbf{p}_2|)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 - m^2}$$

- For generic momentum configurations we can approximate this amplitude by

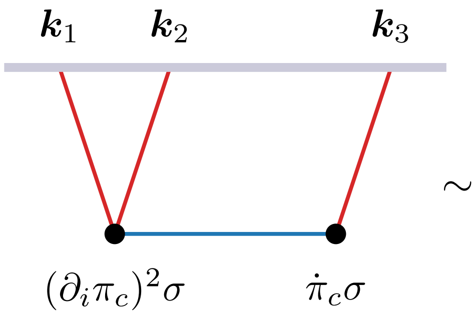
$$\mathcal{A}_4 \sim \frac{g^2}{(\mathbf{p}_1 + \mathbf{p}_2)^2 + m^2} \quad \Longleftrightarrow \quad D_{\mathrm{F}}(\boldsymbol{x}, t; \boldsymbol{y}, t') \to \delta(t - t')\, \frac{e^{-m|\boldsymbol{x}-\boldsymbol{y}|}}{4\pi|\boldsymbol{x} - \boldsymbol{y}|}$$

- In this regime, the heavy field can be solved as an auxillary field, resulting in a non-local effective action for the phonons

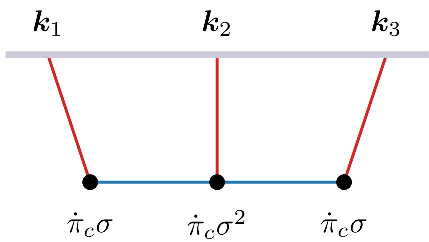
$$(\partial_i \sigma)^2 + g\dot{\pi}^2\sigma \to \frac{1}{2} g^2 \dot{\pi}^2 \frac{1}{\nabla^2 + m^2} \dot{\pi}^2$$

Correlators from the Non-Local EFT

- Similar simplification occurs for cosmological correlators induced by the exchange of the heavy field



$\sim\ (\partial_i\pi)^2\,\mathcal{D}^{-1}\,\dot{\pi}$

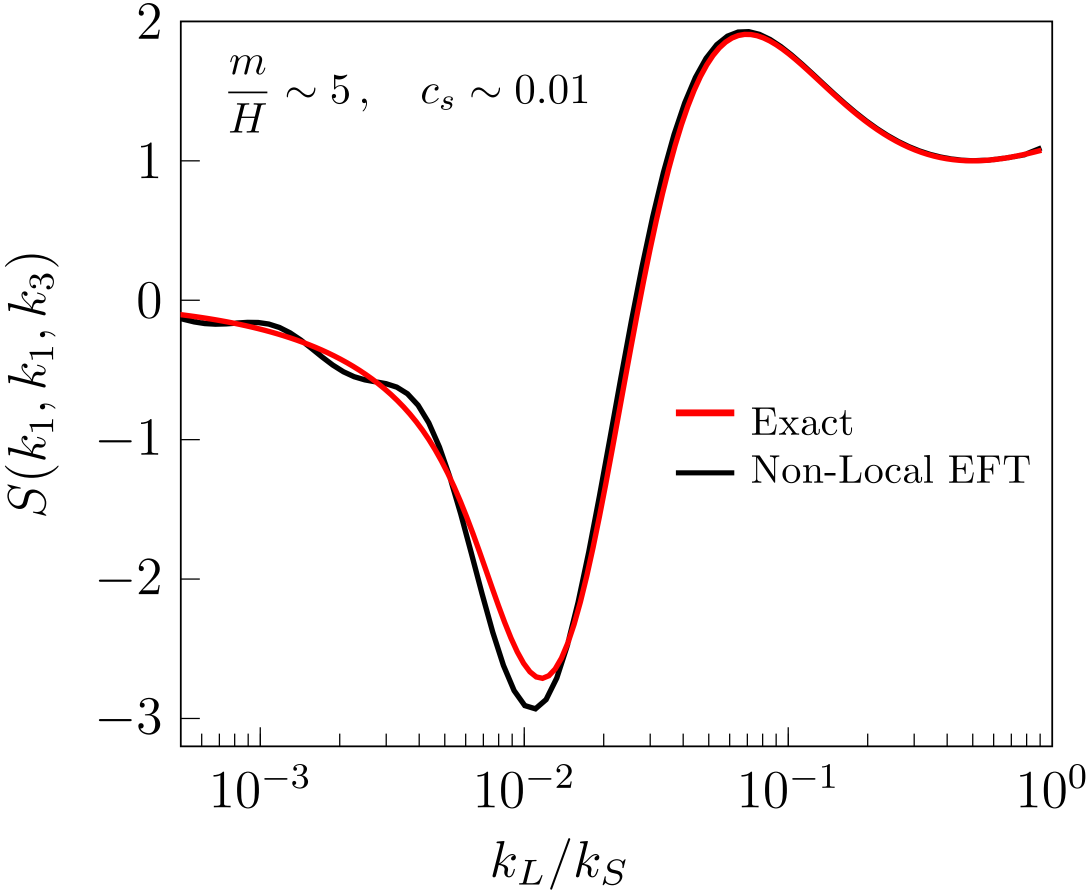


$\sim\ \ \dot{\pi}\,\mathcal{D}^{-1}\dot{\pi}\,\mathcal{D}^{-1}\dot{\pi}$

$$\mathcal{D}^{-1} = \frac{1}{a^{-2}(t)\nabla^2 + m^2}$$

- **Retardation effects** can be treated perturbatively by adding operators with higher order time derivatives

$$\mathcal{D}^{-1} = \frac{1}{a^{-2}(t)\nabla^2 + m^2}\sum_n (-1)^n\ \left[(\partial_t^2 + 3H\partial_t)(a^{-2}(t)\nabla^2 + m^2)^{-1}\right]^n\ .$$



<u>SJ, Renaux-Petel, Werth 2023</u>

- ✓ Full analysis of the bispectrum shape and its size (single-, double- and triple- exchange diagrams)
- ✓ Non-perturbative treatment of the linear mixing $\rho\,\dot{\pi}\sigma$ $(\rho > m)$
- ✓ Factorized template for the low-speed collider signal as a function of

  $\alpha = c_s m/H$
- ✓ Analysis of the full bispectrum shape including the contamination with the standard equilateral non-Gaussianity induced by

  $\dot{\pi}(\nabla\pi)^2$

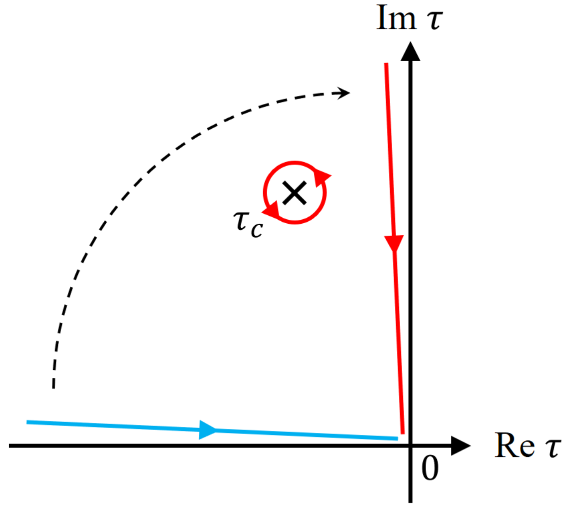
- An interesting application: parity violation in the scalar trispectrum

Unitarity, locality, Bunch Davis, Scale invariance	➡	No tree-level contribution to parity-odd single-field four-point
$g\,\epsilon_{ijk}\partial^n\pi^4$	➡	Changes the quartic wavefunction Coefficient but not the correlator 4pt

Cabass, SJ, Stefanyszyn, Pajer 2022
Liu, Tong, Wang, Xianyu 2019

- An interesting application: parity violation in the scalar trispectrum

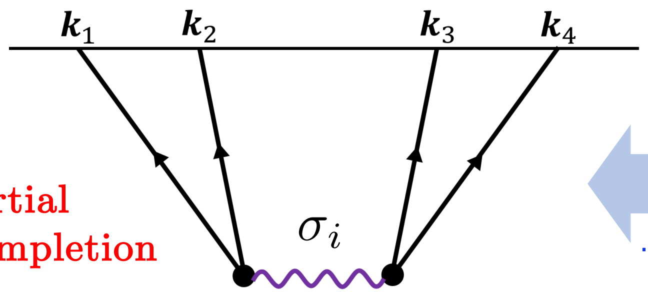
$$B_4^{PO} \propto \mathrm{Im}\left(\int_C d\eta\, F(\mathbf{k}_i,\eta) \prod_{i=1}^{4} \partial_\eta^{n_i}\pi_+(k_i,\eta)\right)$$



$$\pi_+ = \frac{H}{\sqrt{2k^3}}(1 - ik\eta)\exp(ik\eta)$$ bulk-to-boundary propagator

e.g. $$F \sim \frac{1}{(s^2\eta^2 + m^2)^2 - 4\mu^2 s^2\eta^2}$$

Parity violating term



Partial UV Completion

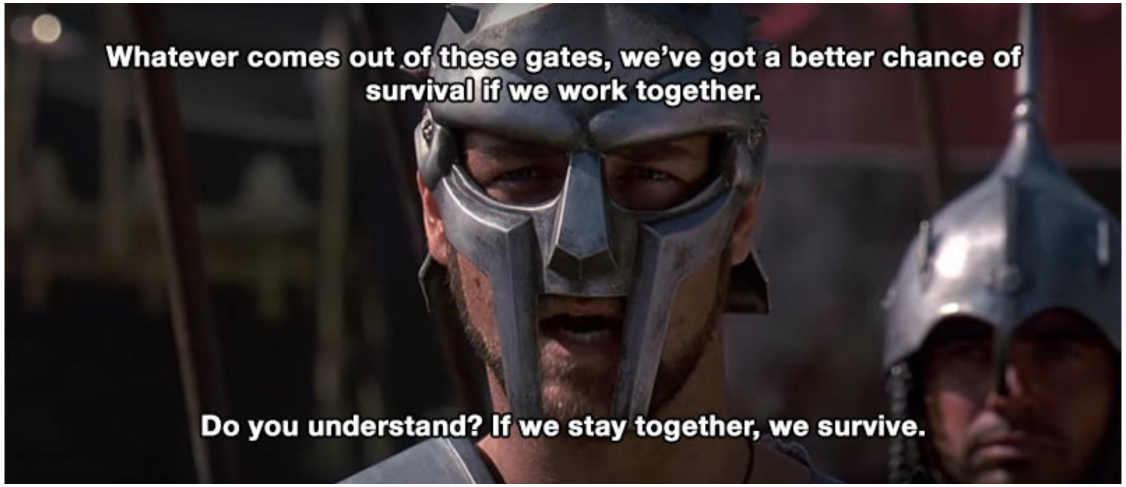
$$S_\sigma = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{4}F_{\mu\nu}^2 - \frac{m^2}{2}\sigma_\mu^2 + \frac{\kappa t}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

$$\frac{a^{-2}}{\bar{\Lambda}^3}\ddot{\pi}_c\partial_i\dot{\pi}_c\sigma_i$$ cubic mixing

Future Outlook

Maximus: “Whatever comes out of these gates,
we've got a better chance of survival if we work together.”

Gladiator 2000



Future Outlook

- Cosmological Collider Physics: beyond weakly coupled massive fields? What is the appropriate EFT?
- Non-local EFT: integrating out at one-loop level. Relevance: e.g. fermionic fields. Same low-speed collider signal?
- Constructing non-local EFT from bottom up?