Equilateral non-Gaussianities, what is next?
Cosmological correlators beyond locality, weak mixing and parity

the Cosmological Low-Speed Collider

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GEODESI

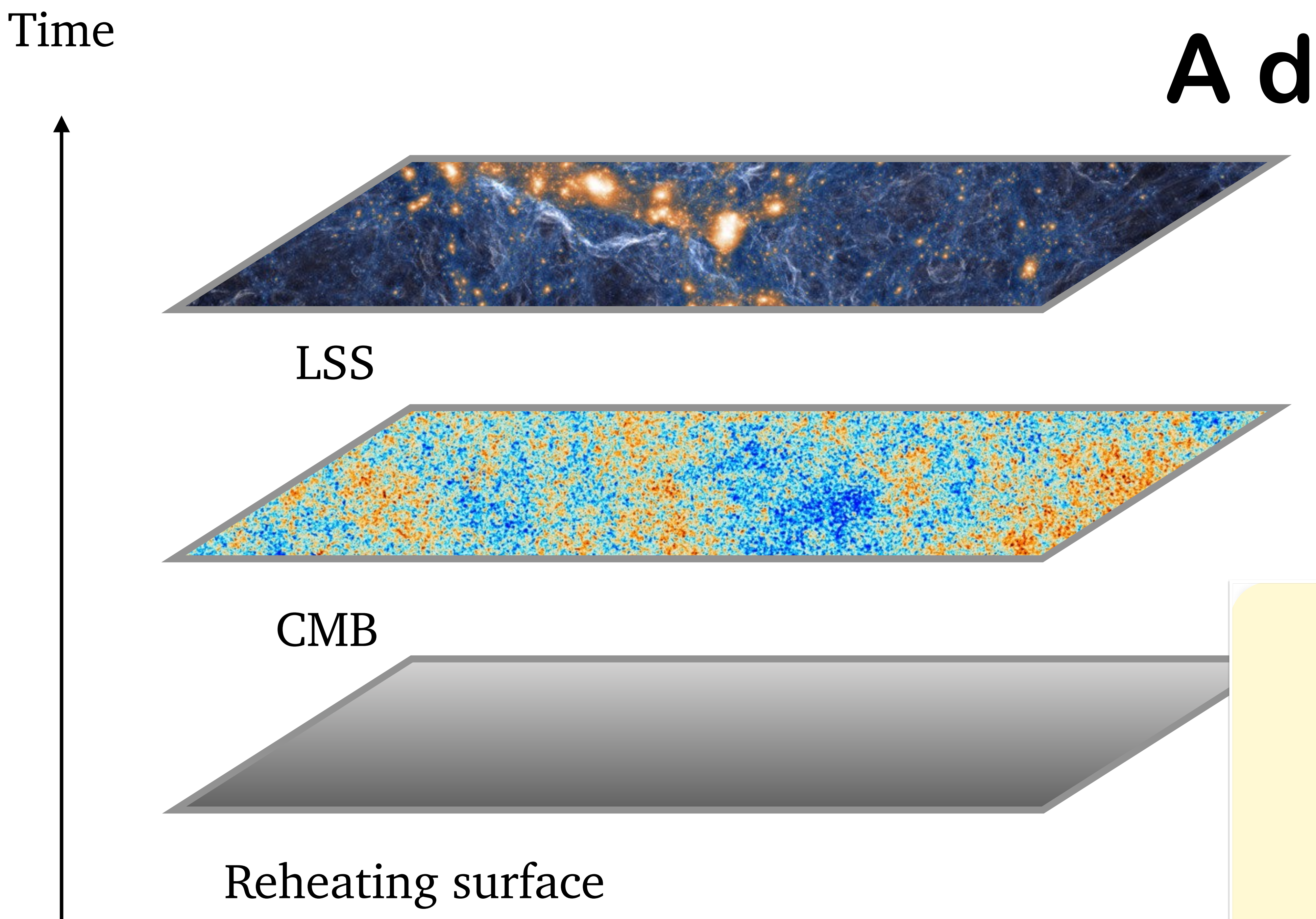
Outline

I. General context and Main Ideas

II. More details

I. General context and Main Ideas

A detective's work



Observations

Statistical properties

$$\mathbb{P}\left(\frac{\delta\rho}{\rho}, h_{ij}\right)$$

observational data

Physics of inflation?

theoretical data

"Data! data! data!"

Primordial non-Gaussianities

Higher-order correlators: beyond free fields ⟶ measure of interactions

Cosmology

Particle physics

Goal: establish a standard model of inflation

Identify degrees of freedom, mass, dispersion relation, spin, interactions

! Additional difficulty compared to particle physics:

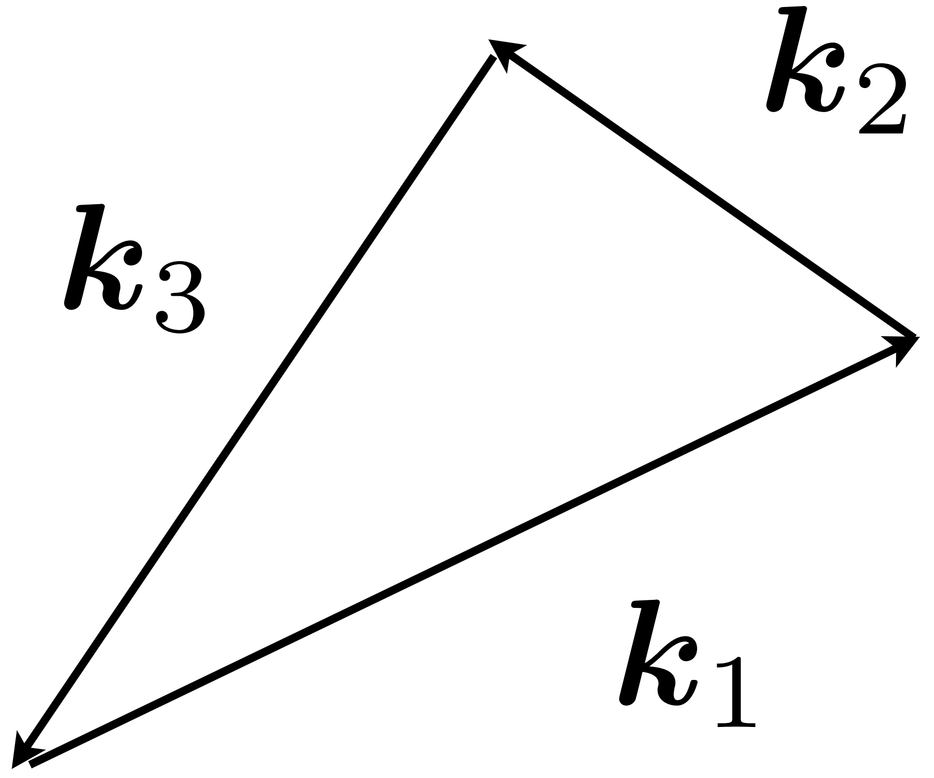
everything is, a priori, time-dependent

Bispectrum

$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle = (2\pi)^3 \delta^{(3)}(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3) B_\zeta(k_1, k_2, k_3)$$

Homogeneity

Isotropy



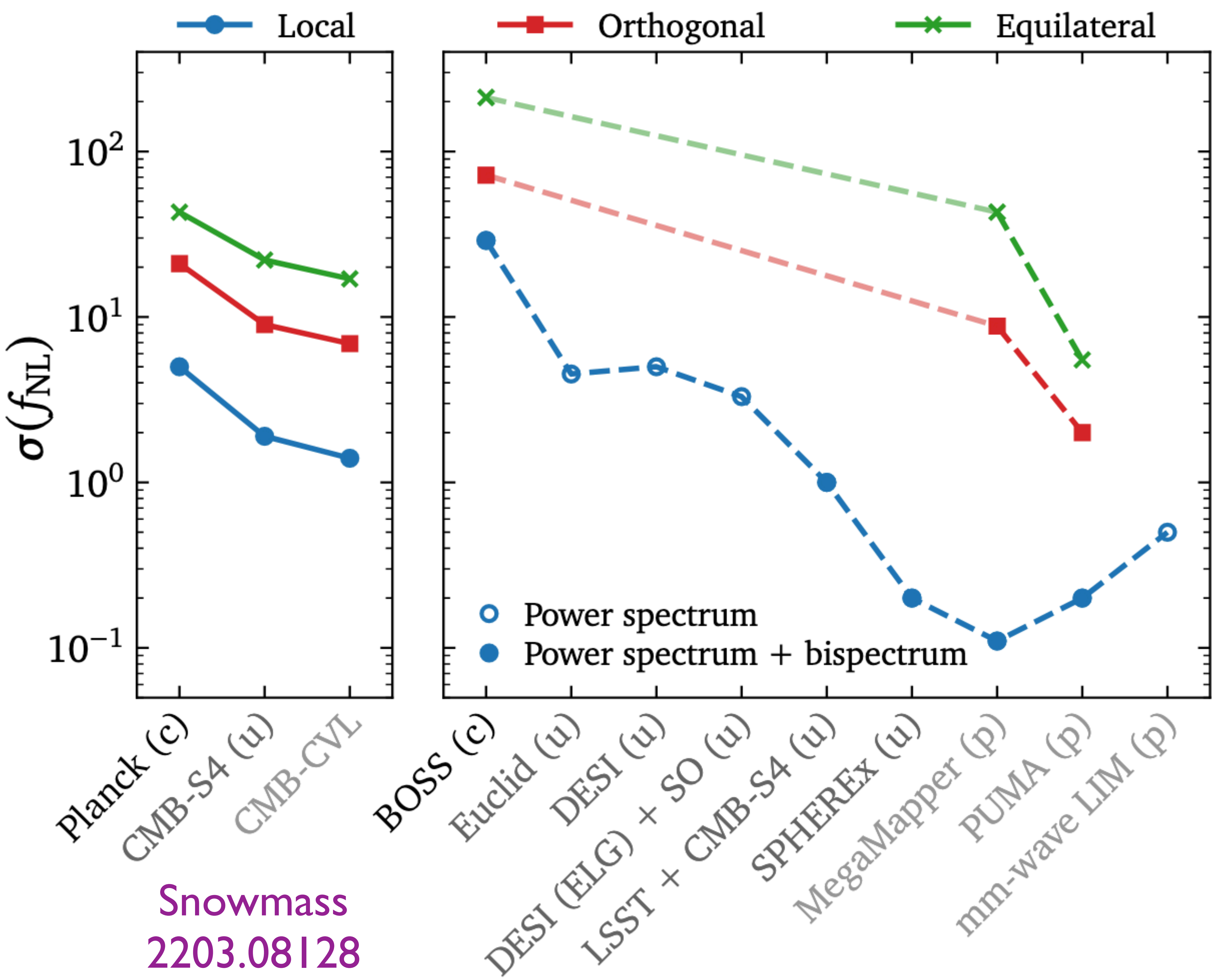
$$B_\zeta \equiv (2\pi)^4 \frac{S(k_1, k_2, k_3)}{(k_1 k_2 k_3)^2} A_s^2$$

Amplitude $S \sim f_{\rm NL}$

Scale-dependence (overall size)

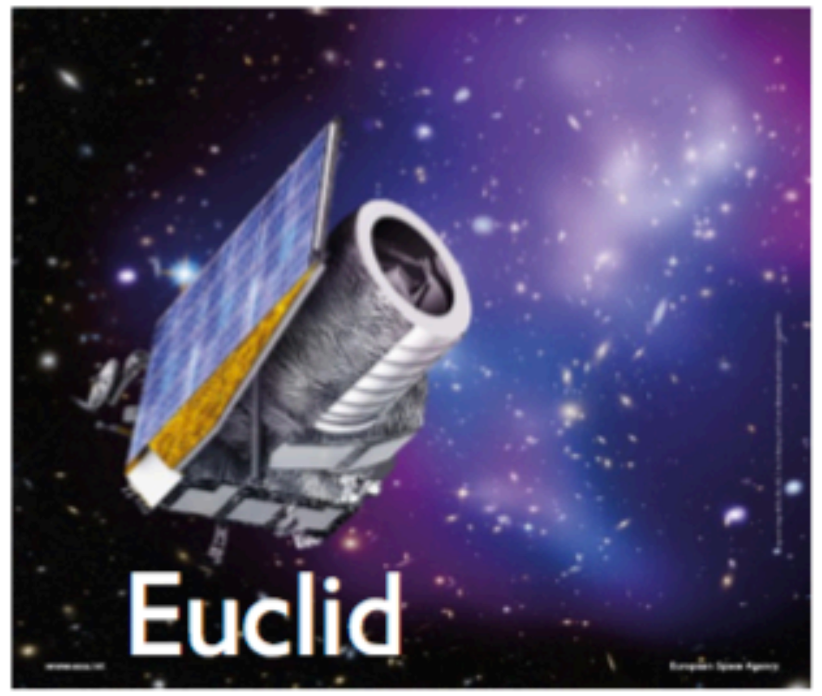
Shape dependence (configuration of triangles)

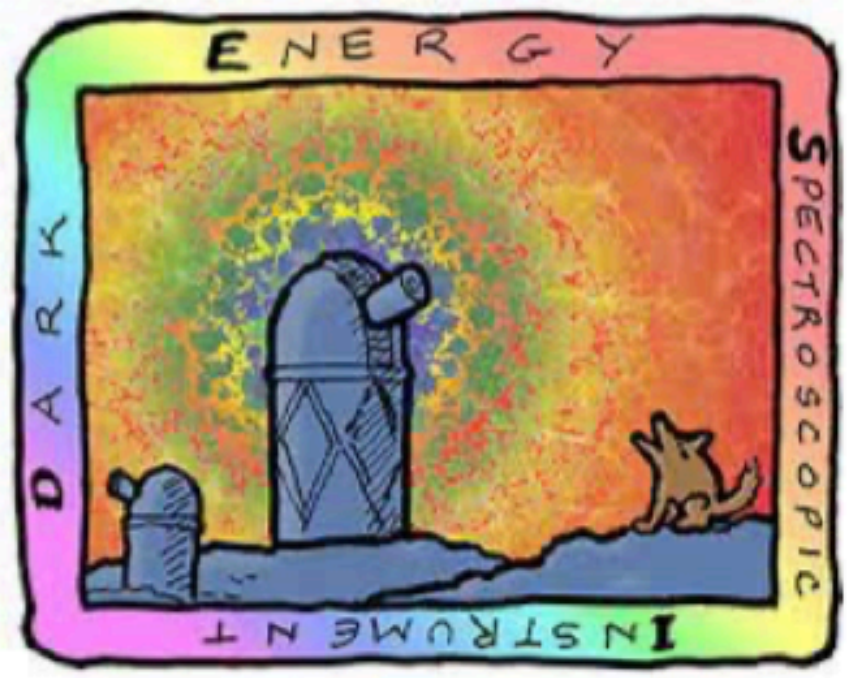
Prospects

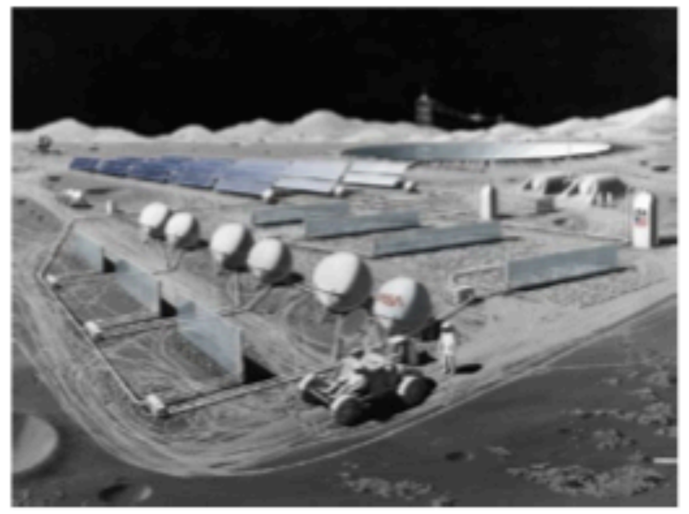


Snowmass
2203.08128

Huge efforts with CMB-S4 & large-scale structure surveys
(scale-dependent bias, EFT of LSS, position space maps, simulation based inference etc)







Long-term: 21cm radio-astronomy from the far side of the moon! (dark ages)

Is it done for theorists?

Physics of inflation?

Statistical properties

$$\mathbb{P}(\zeta)$$

Theorists' task

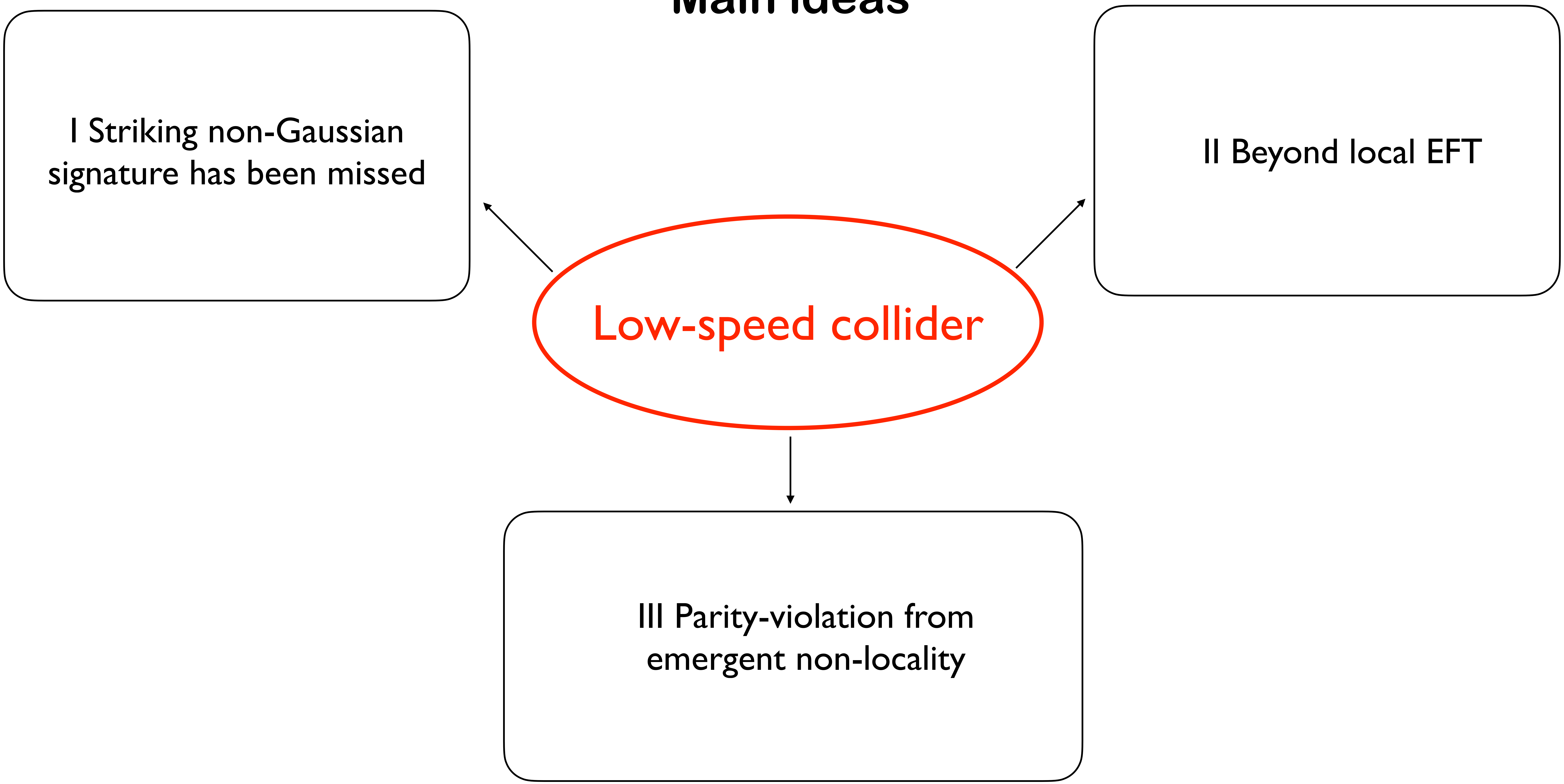
Building dictionary

Identifying targets worth measuring

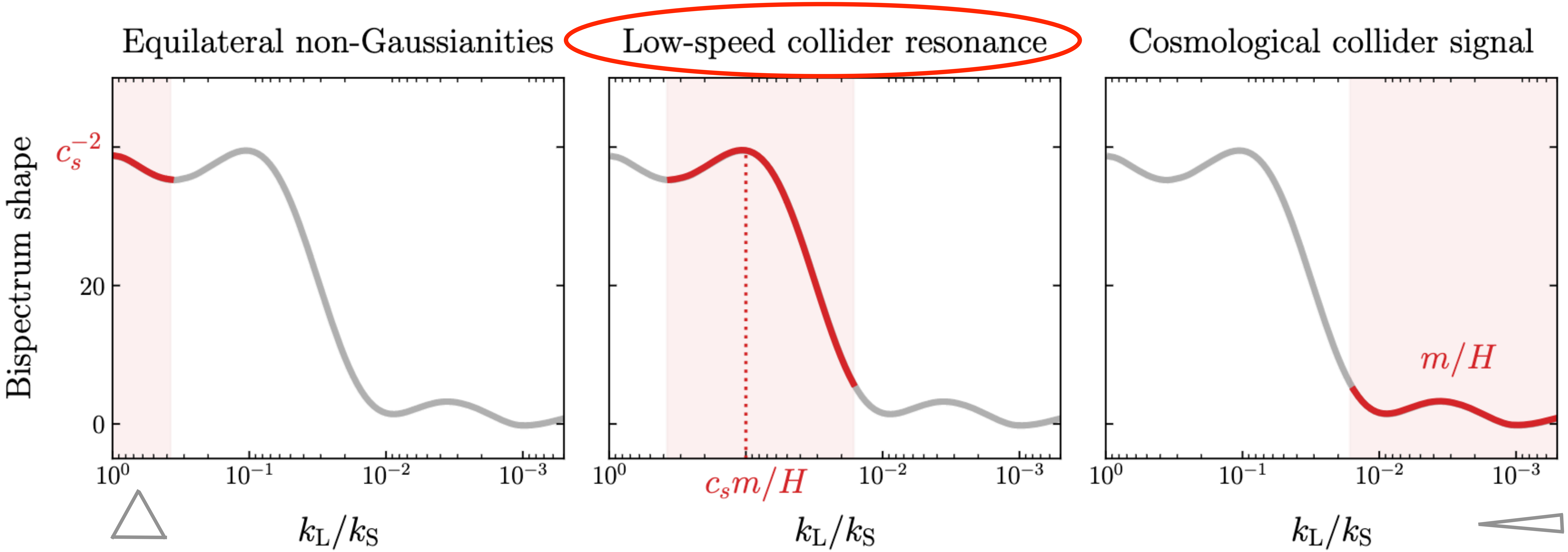
Is the dictionary complete?!

Interesting targets not yet identified?!

Main ideas

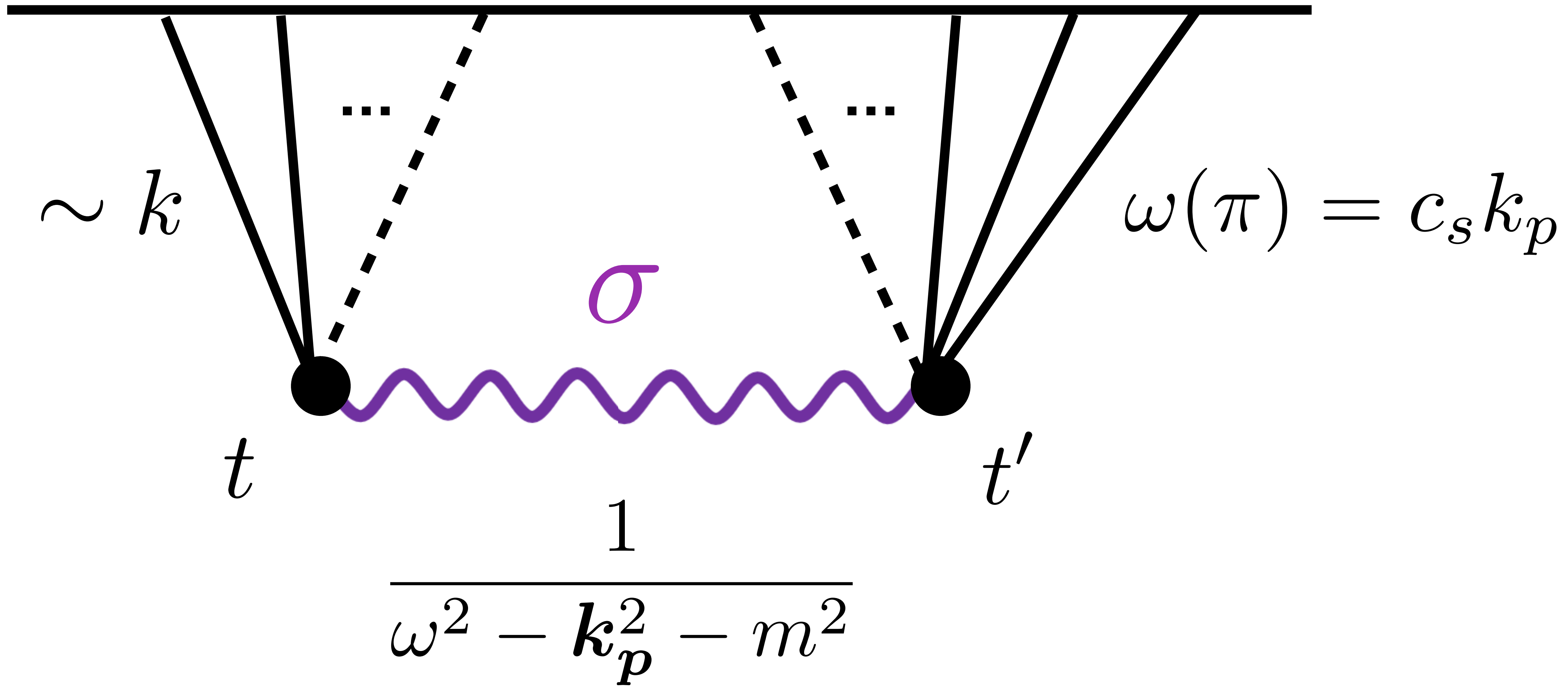

I Striking non-Gaussian signature has been missed
II Beyond local EFT
Low-speed collider
III Parity-violation from emergent non-locality

Idea 1: Detection of equilateral non-Gaussianities, what is the next target?



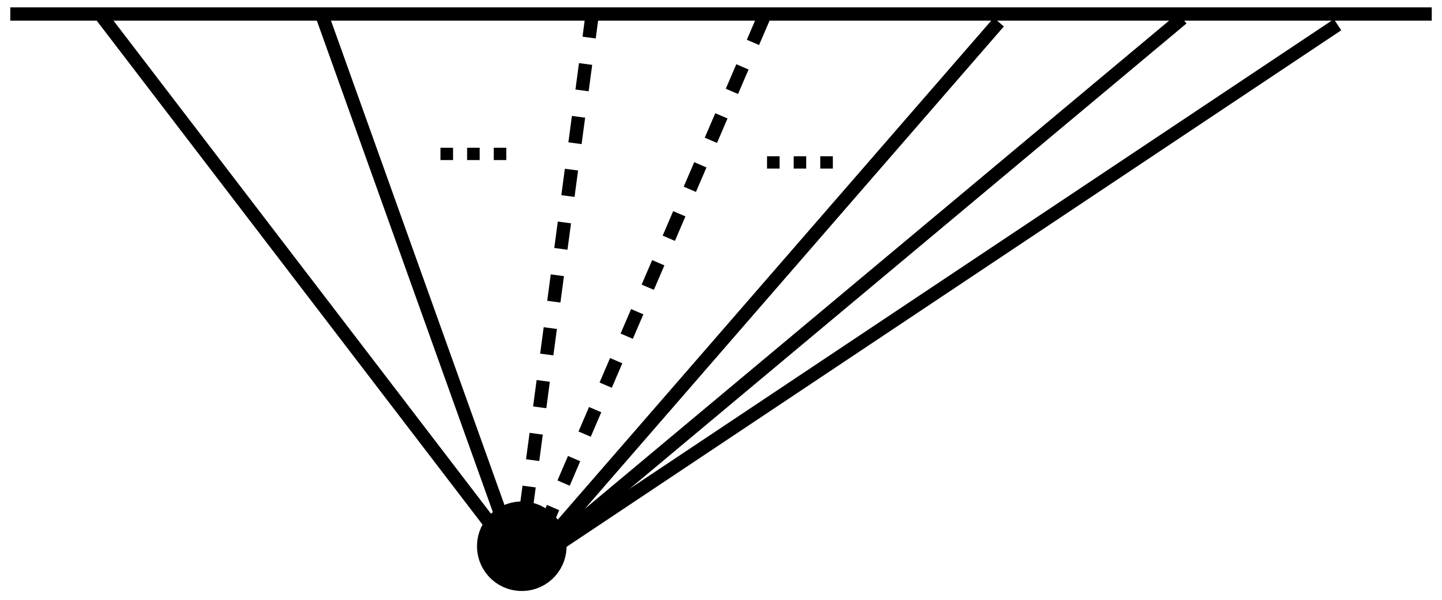
New discovery channel of heavy fields with $m < H/c_s$

Idea 2: Non-local EFT



$c_s^2 \ll 1$ →

Low speed of sound



$$\mathcal{D}^{-1} \sim (k^2/a^2 + m^2)^{-1}$$

Single-field non-local EFT

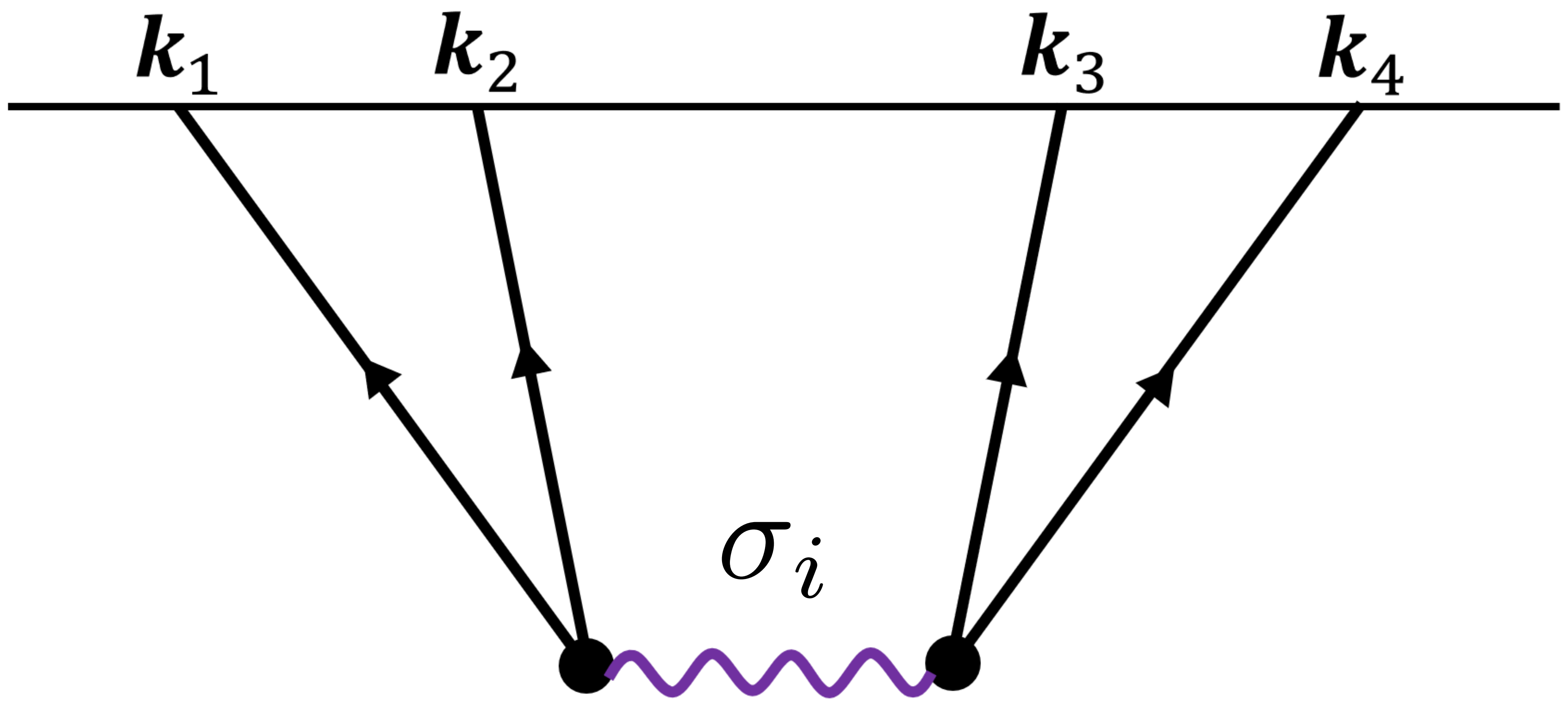
$$D_{\mathrm{F}}(\boldsymbol{x}, t; \boldsymbol{y}, t') \to \delta(t - t')\, \frac{e^{-m|\boldsymbol{x}-\boldsymbol{y}|}}{4\pi|\boldsymbol{x}-\boldsymbol{y}|}$$

Feynmann propagator

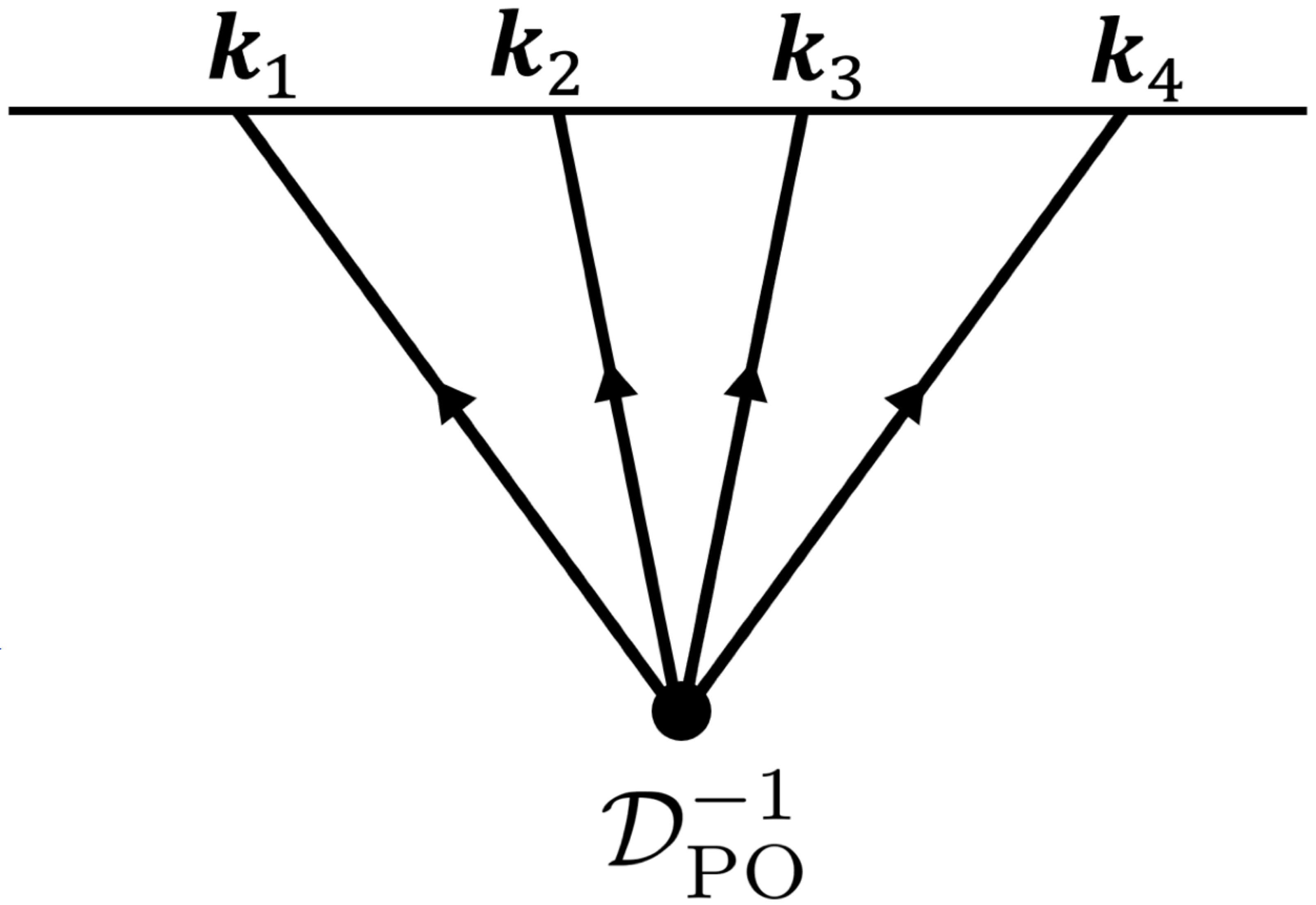
instantaneous propagation of supersonic field

spatial non-locality (mild form, Yukawa-type)

Idea 3: Parity violation from emergent non-locality



$c_s^2 \ll 1$



Massive spin-1
with different helicities

$$\sigma_+ \neq \sigma_-$$

Jazayeri, Renaux-Petel, Tong, Werth, Zhu [2023]

Single-field non-local EFT with parity-odd 4-pt

Low-speed collider resonance
+ new type of oscillatory signal

II. More details

Effective Field Theory of Inflationary Fluctuations

Formulation of theories
straight at the level of fluctuations

motivates ↑ ↓ informs

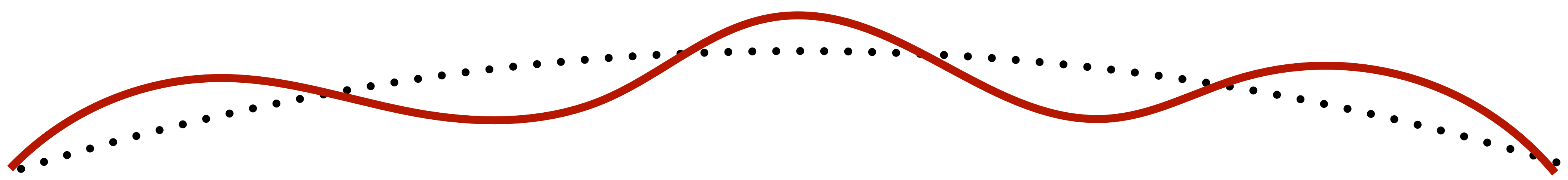
Source of inflation

Systematic, powerful and
direct link with observations

Preferred space-like foliation (existence of clock)
breaks time reparametrization invariance

Guaranteed: Goldstone boson

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



$\phi(t)$

$$\zeta = -H\pi + \dots$$

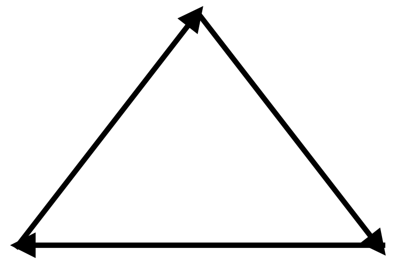
Cheung, Creminelli, Fitzpatrick,
Kaplan, Senatore [2008]

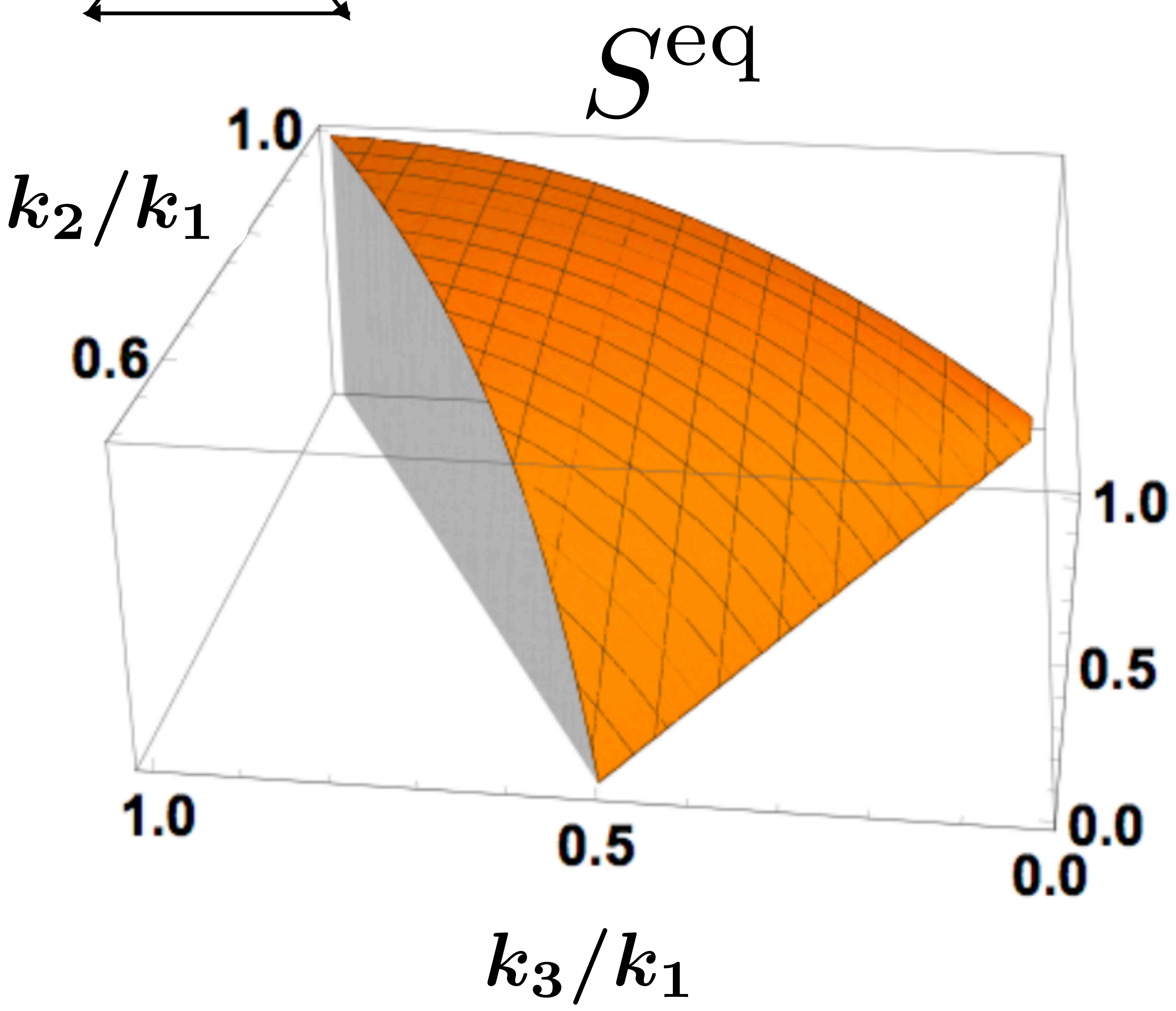
Equilateral/orthogonal non-Gaussianities

Vanilla EFT: $$\mathcal{L}_\pi/a^3 = \frac{M_{\rm pl}^2|\dot H|}{c_s^2}\left[\dot\pi^2 - c_s^2\frac{(\partial_i\pi)^2}{a^2} + (1-c_s^2)\left(\dot\pi^3 - \dot\pi\frac{(\partial_i\pi)^2}{a^2}\right) - \frac{4}{3}M_3^4\frac{c_s^2}{M_{\rm pl}^2|\dot H|}\dot\pi^3\right]$$

Non-linearly realised symmetry

$$f_{\rm NL}^{\rm eq} \sim \frac{1}{c_s^2} - 1$$





$$f_{\rm NL}^{\rm eq} = -26 \pm 47$$
$$f_{\rm NL}^{\rm orth} = -38 \pm 24$$
(68% CL)

Planck 2018

$$c_s \geq 0.021$$

$f_{\rm NL}^{\rm eq} \sim 1$ threshold for slow-roll dynamics

$f_{\rm NL} = \mathcal{O}(\epsilon, \eta) \sim 10^{-2}$ gravitational floor Maldacena (03)

Imprints of Massive Field?

π quadratic sector
canonically normalised

σ quadratic sector

quadratic mixing

$$\mathcal{L}/a^3 = -\frac{1}{2}\left[-\dot{\pi}_c{}^2 + c_s^2\frac{(\partial_i\pi_c)^2}{a^2}\right] - \frac{1}{2}\left[(\partial_\mu\sigma)^2 + m^2\sigma^2\right] + \rho\dot{\pi}_c\sigma$$

Non-linearly realised symmetry

$$H/\Lambda_1 \propto \rho/H$$

$$-\lambda_1\dot{\pi}_c\frac{(\partial_i\pi_c)^2}{a^2} - \lambda_2\dot{\pi}_c{}^3 - \mu\sigma^3 - \lambda\,\dot{\pi}_c\sigma^2 - \frac{1}{\Lambda_1}\frac{(\partial_i\pi_c)^2}{a^2}\sigma - \frac{1}{\Lambda_2}\dot{\pi}_c{}^2\sigma$$

Self-interactions

Bootstrap results in simplest situation

+ **Cosmological Flow** in all situations

Wang, Pimentel [2022]
Jazayeri, Renaux-Petel [2022]

Werth, Pinol, Renaux-Petel [2023]
see Werth's talk

Low-speed limit: transparent physical understanding with non-local single-field EFT

Non-local single-field EFT

$$(\partial_t^2 + 3H\partial_t - \partial_i^2/a^2 + m^2)\sigma = J(\pi_c)$$

$\sim H^2$ $\quad \sim \frac{k^2}{a^2} \sim \frac{H^2}{c_s^2}$

$c_s^2 \ll 1$ →

$$\sigma_{\rm EFT} = \mathcal{D}^{-1} J(\pi_c)$$

$$\mathcal{D}^{-1} = (-\partial_i^2/a^2 + m^2)^{-1}$$

Crucial for $\alpha = c_s \frac{m}{H} < 1$

Low sound speed → Instantaneous response of supersonic field to dynamics of π → Single-field EFT

$$S_{\rm eff} = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{1}{2}\dot{\pi}_c\left[1+\rho^2\mathcal{D}^{-1}\right]\dot{\pi}_c - \frac{c_s^2}{2}(\tilde{\partial}_i\pi_c)^2 - \lambda_1\dot{\pi}_c(\tilde{\partial}_i\pi_c)^2 - \lambda_2\dot{\pi}_c^3 \right.$$
$$\left. - \frac{\rho}{\Lambda_1}(\tilde{\partial}_i\pi_c)^2\mathcal{D}^{-1}\dot{\pi}_c - \frac{\rho}{\Lambda_2}\dot{\pi}_c^2\mathcal{D}^{-1}\dot{\pi}_c - \lambda\rho^2\dot{\pi}_c\left[\mathcal{D}^{-1}\dot{\pi}_c\right]^2 - \mu\rho^3\left[\mathcal{D}^{-1}\dot{\pi}_c\right]^3\right)$$

Non-local in space

↓

Interactions delocalized in time

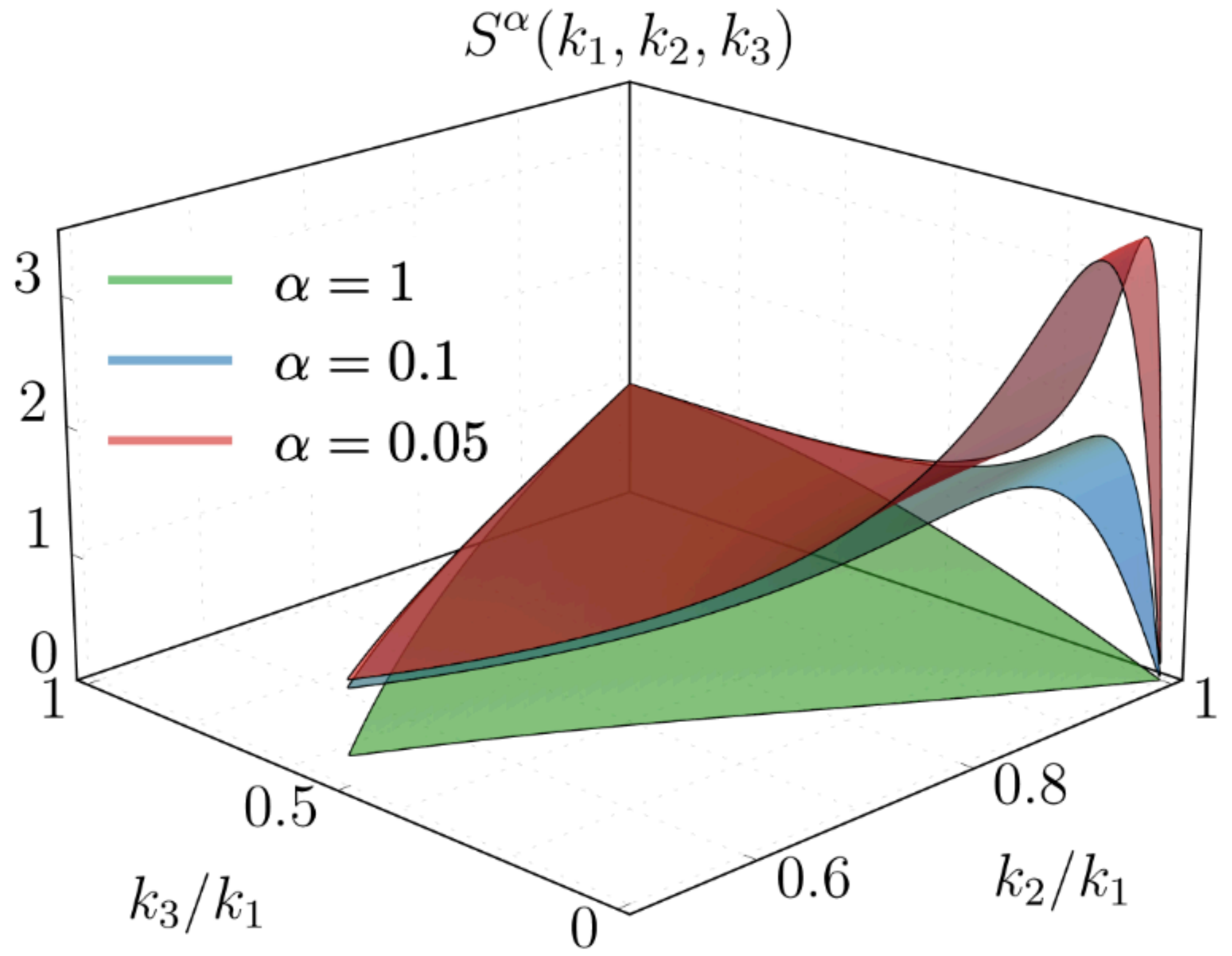
Weak mixing

Jazayeri, Renaux-Petel [2022]
Jazayeri, Renaux-Petel, Werth [2023]

All interactions contact + simple mode functions $\longrightarrow$ Simple analytical results for all interactions

$$S^\alpha(k_1,k_2,k_3) = S^{\rm eq}(k_1,k_2,k_3) + \frac{1}{3}\frac{k_1^2}{k_2k_3}\left[1+\left(\alpha\,\frac{k_1^2}{k_2k_3}\right)^2\right]^{-1} + \ 2 \text{ perms}$$

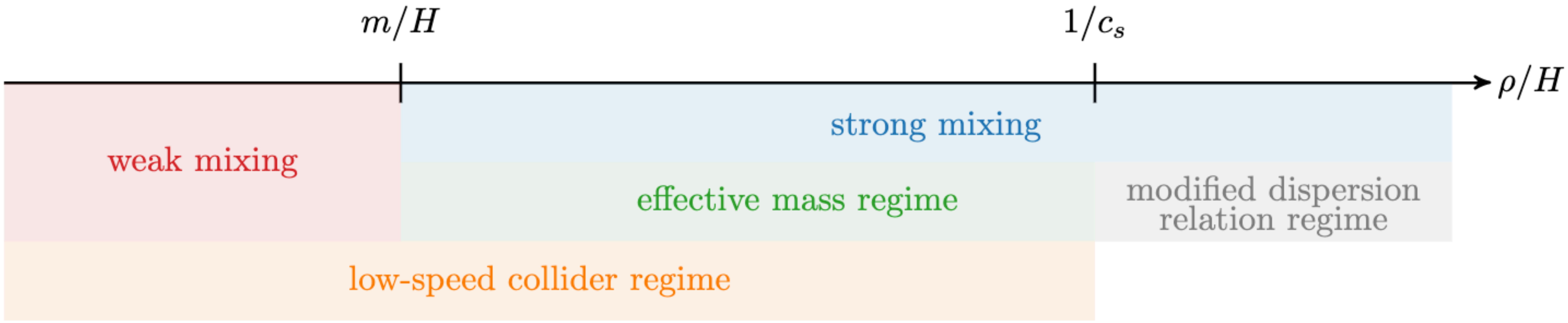
Simple factorizable template for data analysis



Resonance comparable to self-interactions when pushing $\rho \sim m$ $\longrightarrow$ Non-perturbative treatment of mixing required

Strong mixing

Jazayeri, Renaux-Petel, Werth [2023]



Effective mass regime: strong mixing without strong coupling

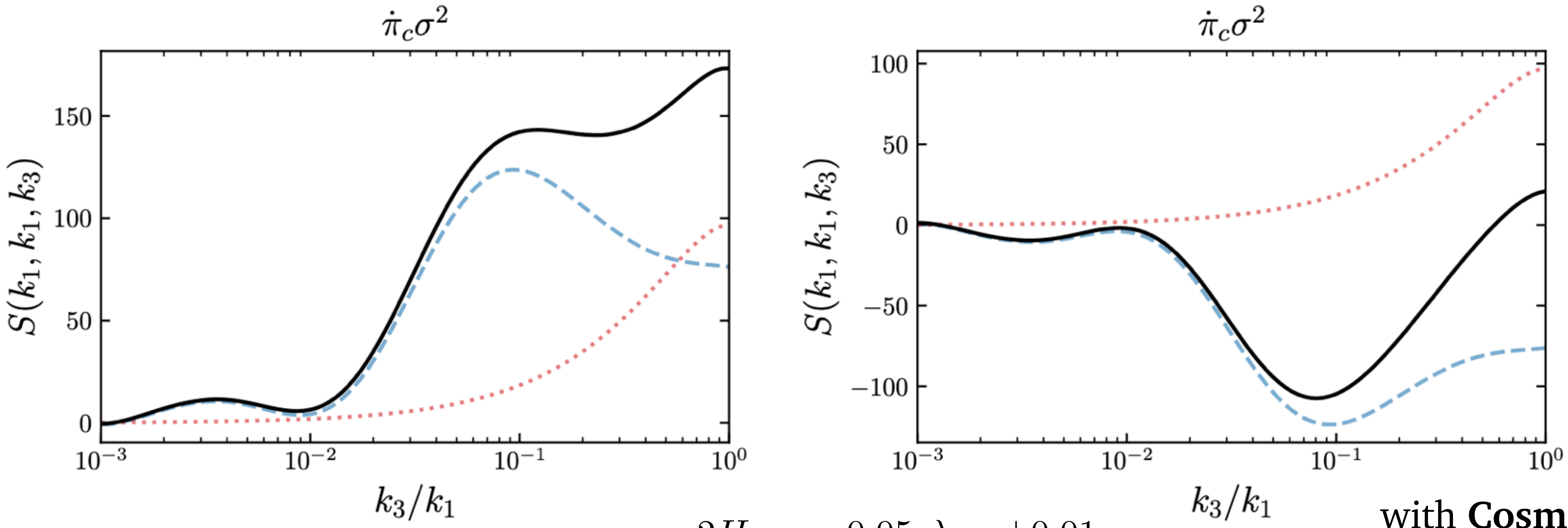
Main effect: unmodified π interacting with σ with effective mass $m_{\text{eff}}^2 = m^2 + \rho^2$

Analytical results and template qualitatively hold with $\alpha \to \alpha_{\text{eff}} = c_s \dfrac{m_{\text{eff}}}{H}$

Strong mixing

Jazayeri, Renaux-Petel, Werth [2023]

Interesting new shapes with large amplitude and perturbative control, e.g.



with **CosmoFlow**

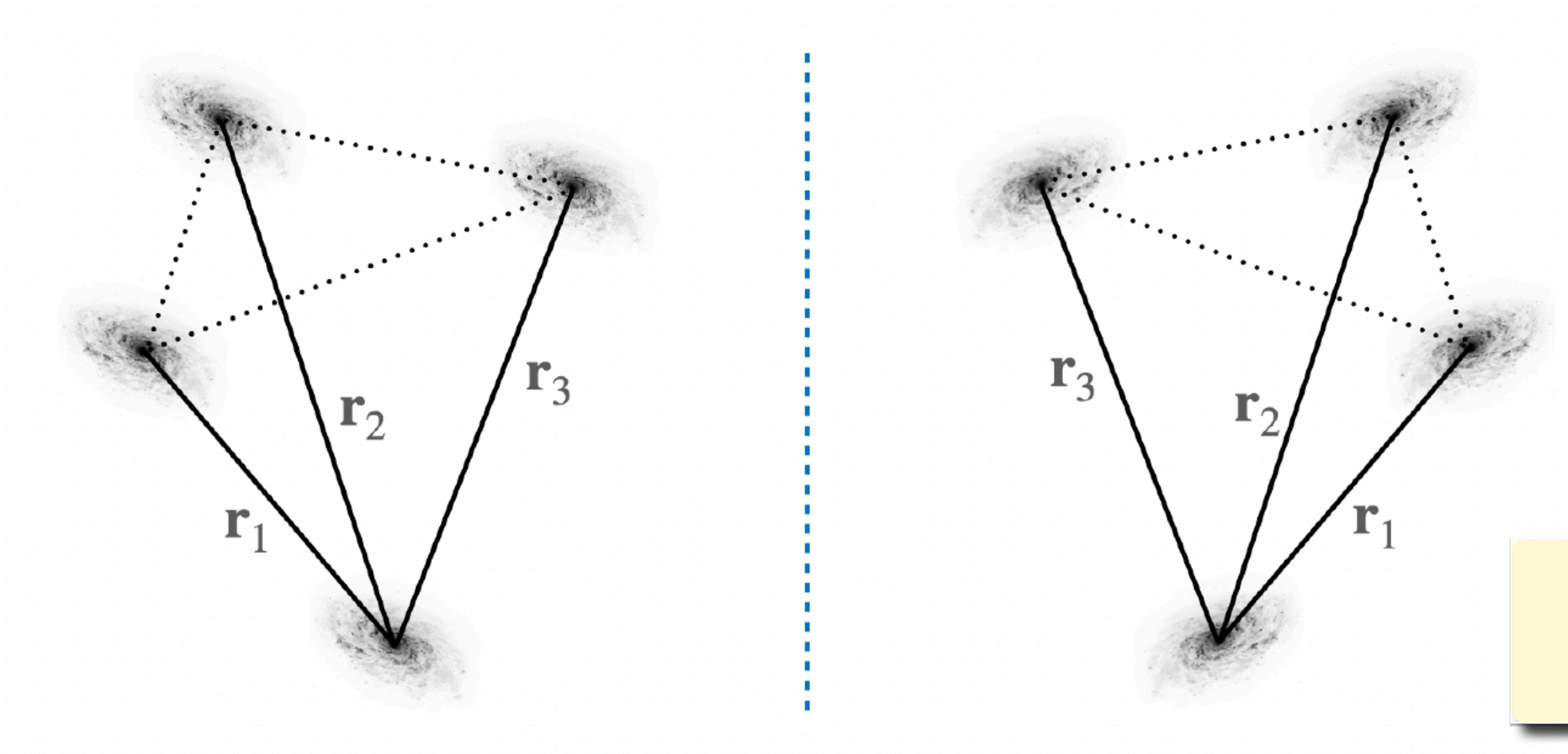
$\rho = m = 2H, c_s = 0.05, \lambda = \pm 0.01$

Self-interactions

Interactions with heavy field

Total shape

Parity violation for density fluctuations



Credit: Philcox, 2206.04227

Tetrahedron and mirror image
not related by rotation
(contrary to 2 and 3 point functions)

First signal of parity violation: 4 pt function

Sum : parity-even 4-pt

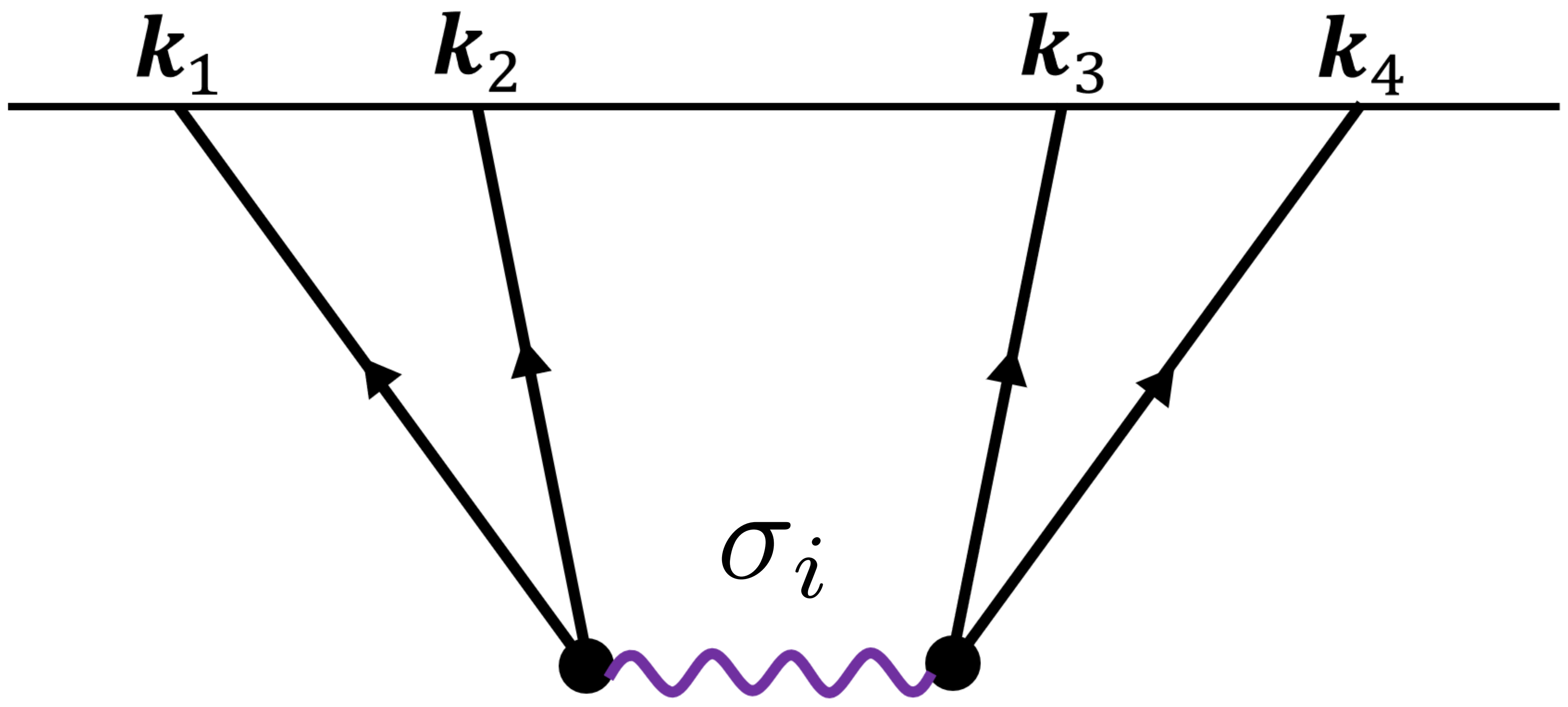
Difference : parity-odd part

→ Fourier space

parity-even: real

parity-odd: purely imaginary

Origin of parity violation: spin-1 with chemical potential



Massive spin-1
with different helicities

$$\sigma_+ \neq \sigma_-$$

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

Proca + Chern-Simons

3 dofs σ_i → longitudinal mode irrelevant for parity violation

3 dofs σ_i → transverse modes, helicity ± 1

$$\sigma''_{\pm,k} + \left[k^2 \pm 2ak\kappa + a^2m^2\right]\sigma_{\pm,k} = 0$$

Parity violation like in axion-gauge field
(but massive field here)

Non-local single-field EFT

$$S = \int \mathrm{d}t\, \mathrm{d}^3x\, a^3 \left[\frac{1}{2}\dot{\pi}_c^2 - \frac{c_s^2}{2}\frac{(\partial_i \pi_c)^2}{a^2} - \frac{1}{2a^2}\sigma_i \left[\delta_{ij}(\partial_t^2 + H\partial_t) + \mathcal{D}_{ij}\right]\sigma_j + \frac{\sigma_i}{a^2} J_i(\pi_c) \right]$$

pi sector | spin-1 sector | coupling

$$J_i(\pi_c) \sim \pi_c \partial_i \pi_c$$

$$\mathcal{D}_{ij} \equiv \left(-\frac{\partial_i^2}{a^2} + m^2\right)\delta_{ij} - 2\kappa \epsilon_{ijl}\frac{\partial_l}{a}$$

parity-odd

Low sound speed $\longrightarrow$

$$S_{\mathrm{EFT}} = \int \mathrm{d}t\, \mathrm{d}^3x\, a^3 \left[\frac{1}{2}\dot{\pi}_c^2 - \frac{c_s^2}{2}\frac{(\partial_i \pi_c)^2}{a^2} + \frac{1}{2a^2} J_i(\pi_c)\mathcal{D}_{ij}^{-1} J_j(\pi_c) - \frac{1}{2a^2} J_i(\pi_c)\mathcal{D}_{il}^{-1}(\partial_t^2 + H\partial_t)\,\mathcal{D}_{lj}^{-1} J_j(\pi_c) + \dots \right]$$

Leading-order EFT | Next-to-Leading-order EFT

Parity violation from emergent non-locality

$$\mathcal{L} \sim \dot{\pi}^2 + \pi\pi\mathcal{D}^{-1}\pi\pi$$

Single-field
+ linear dispersion relation
+ Bunch-Davies

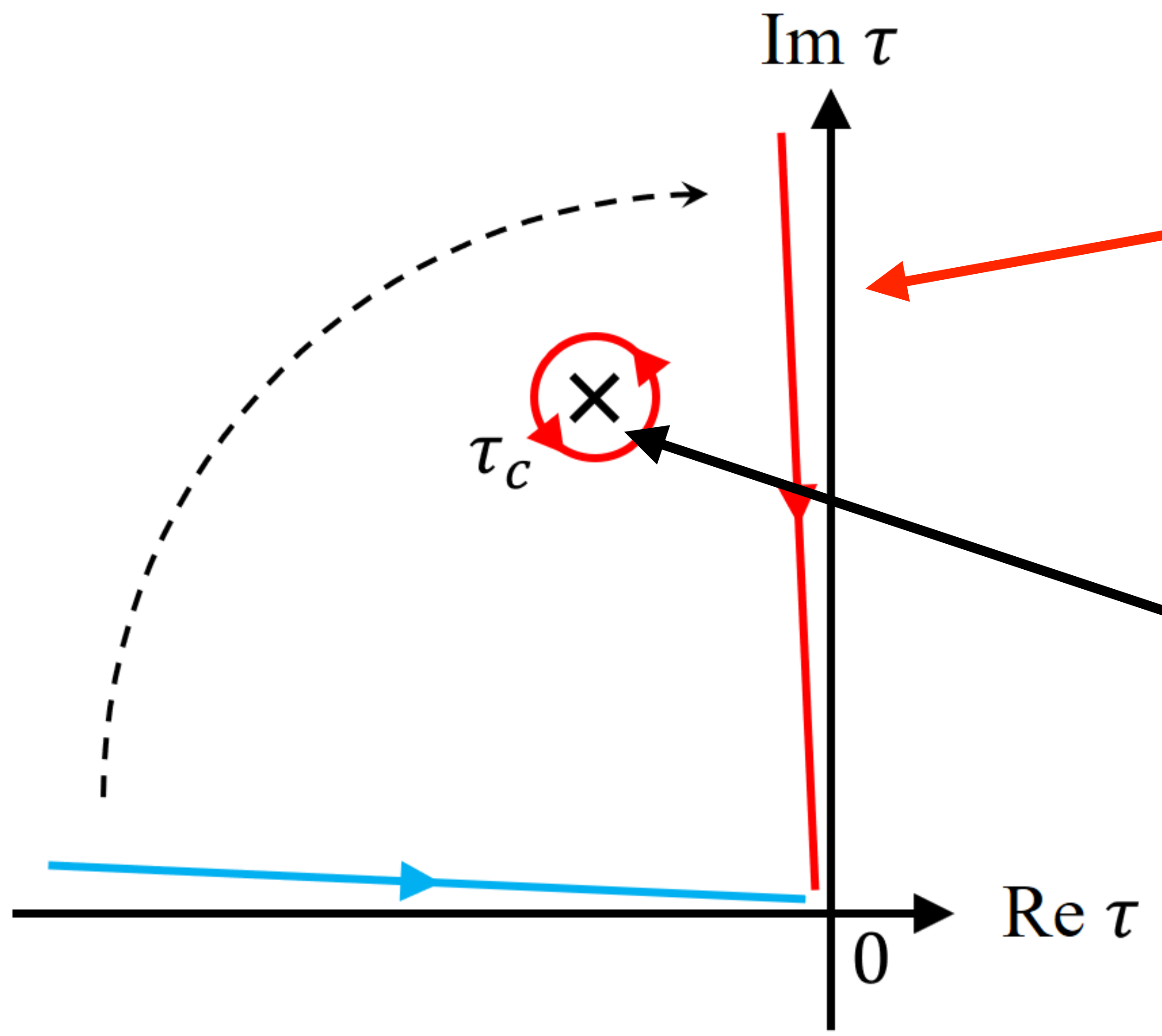
?

→

Liu et al, 1909.01819
Cabass et al, 2210.02907

~~$\langle \pi^4 \rangle_{\rm PO} = 0$~~

no-go theorem does not hold as implicit assumption of locality violated



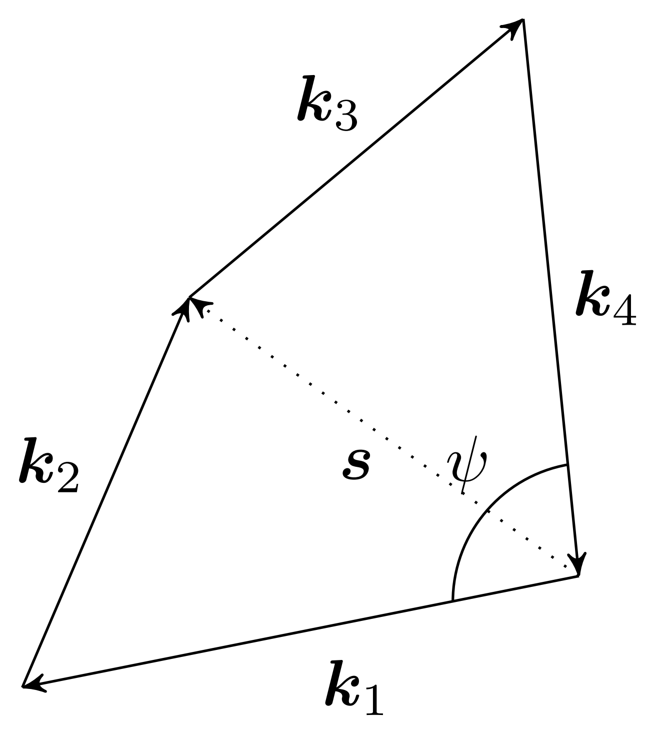
Wick-rotated: zero contribution (usual reason behind no-go theorem)

Pole of $\mathcal{D}^{-1}_{\rm PO}$	non-zero contribution, from emergent non-locality	Simple result and analytical understanding

Jazayeri, Renaux-Petel, Tong, Werth, Zhu [2023]

Main features

$$\langle \zeta^4 \rangle' \sim \frac{\mathcal{P}_\zeta^3}{k^9} \mathcal{T}(\boldsymbol{k_i})$$



Trispectrum: 5d function with scale-invariance

Plot in specific configuration (non-planar)

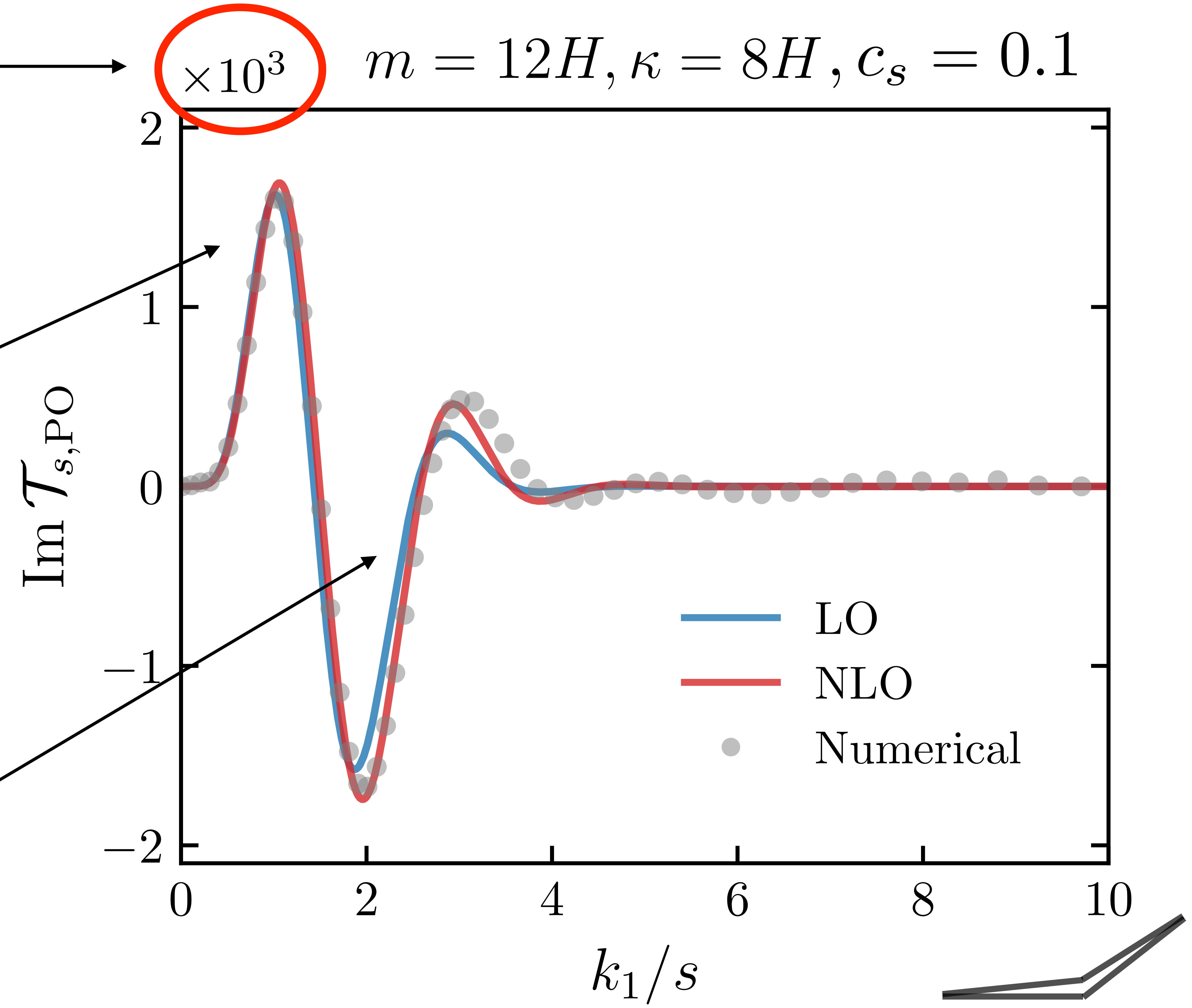
Large signal

Low-speed collider resonance

New oscillatory signal

periodic in k_i/k_j

rather than $\log(k_i/k_j)$



Jazayeri, Renaux-Petel, Tong, Werth, Zhu [2023]

Conclusions

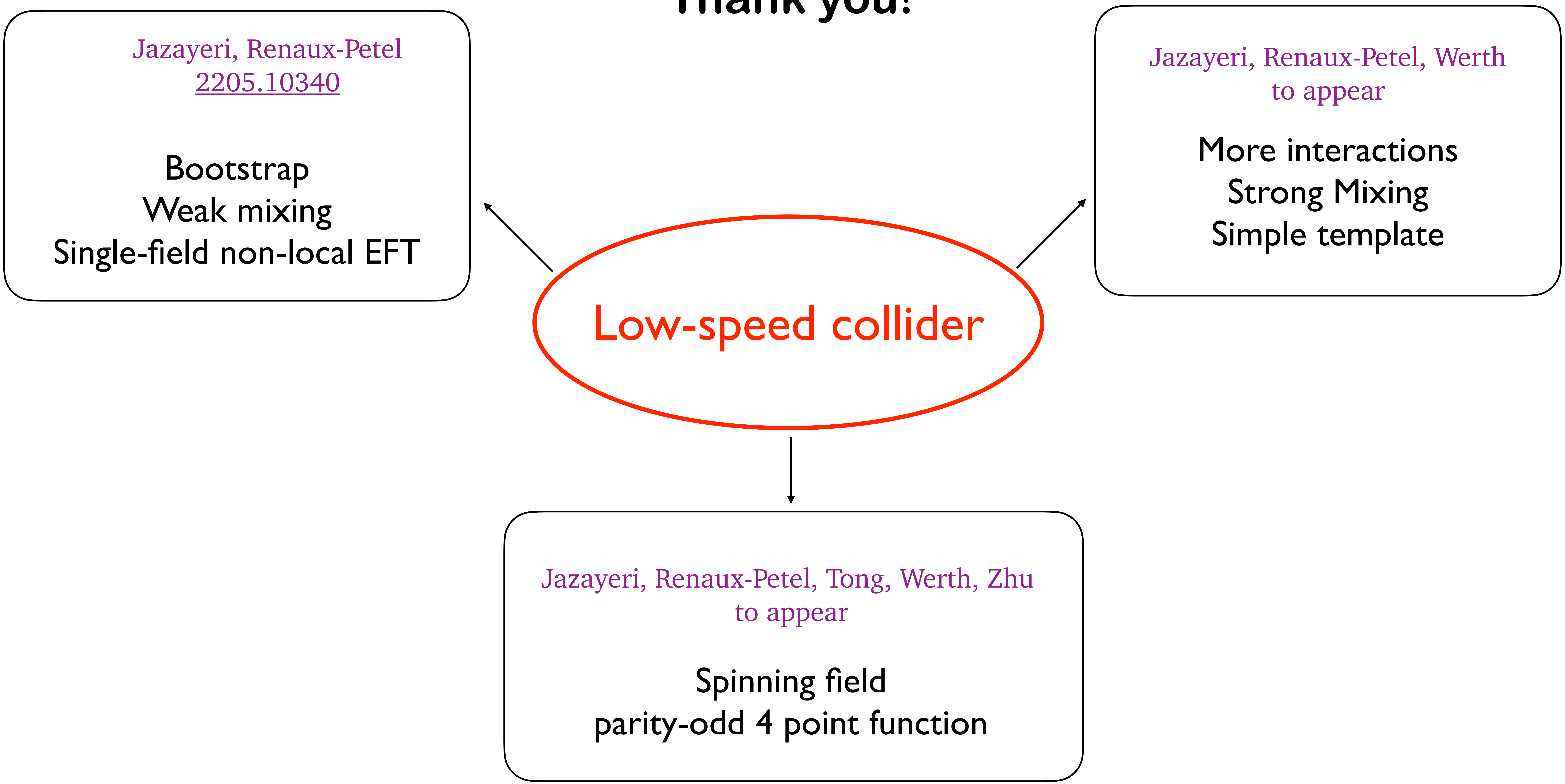
- Striking non-Gaussian signature in motivated minimal framework has been missed: Cosmological Low-Speed Collider. Resonance as discovery channel of heavy fields

- New shape, simple template, interesting strong mixing regime with large amplitude

- Beyond local EFT: interesting by itself, bottom-up constructions?

- Non-local single-field EFT with large parity-odd 4 pt and new signatures

Thank you!



Jazayeri, Renaux-Petel
2205.10340
Bootstrap
Weak mixing
Single-field non-local EFT
Jazayeri, Renaux-Petel, Werth
to appear
More interactions
Strong Mixing
Simple template
Low-speed collider
Jazayeri, Renaux-Petel, Tong, Werth, Zhu
to appear
Spinning field
parity-odd 4 point function