Some directions for The future of primordial non-Gaussianities

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European Research Council
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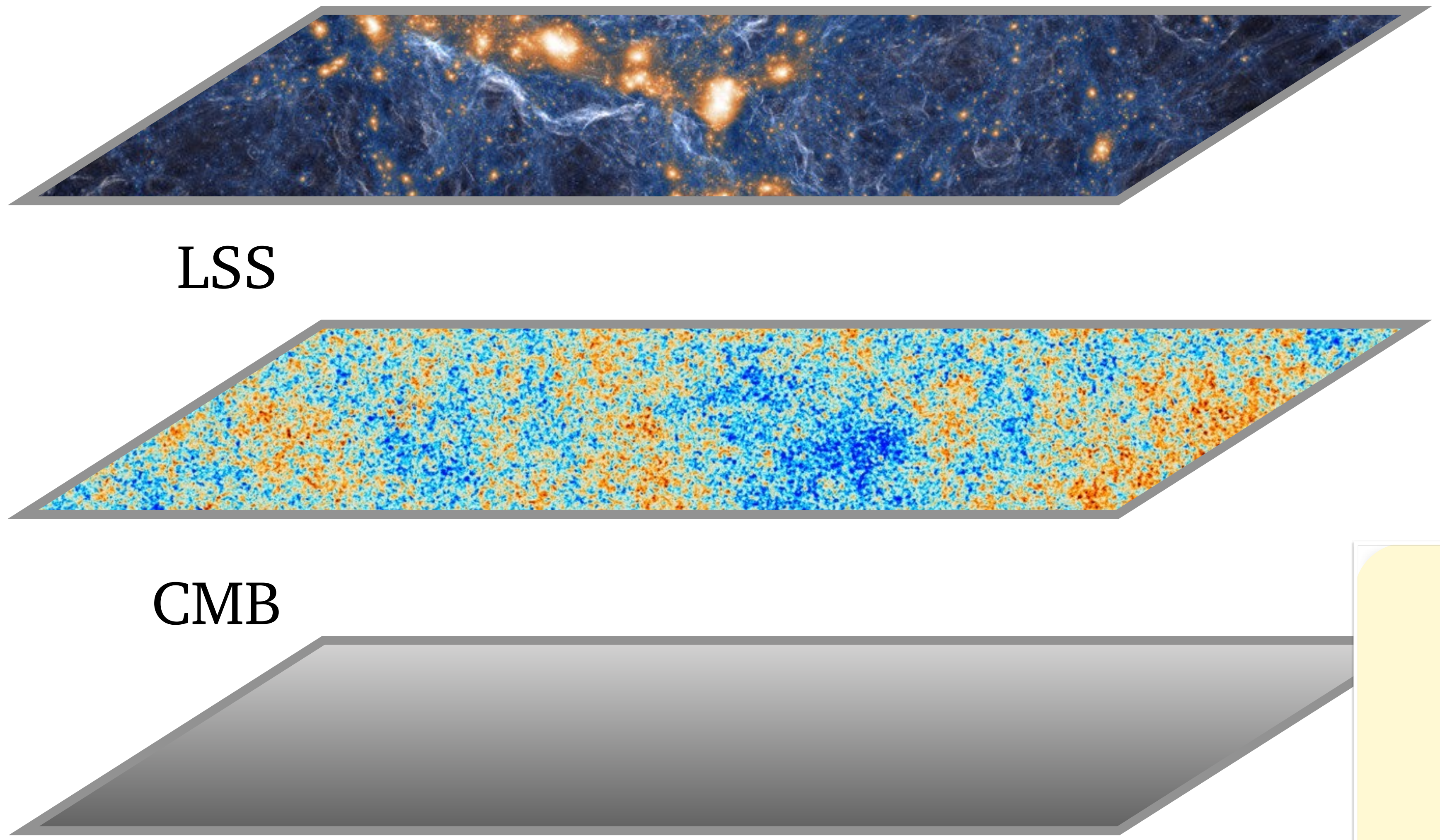
GEODESI

A detective's work

Time



LSS

CMB

Reheating surface

Observations

observational data

Statistical properties

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

Physics of inflation?

theoretical data

"Data! data! data!"

Outline

I. The Physics of Inflation and non-Gaussianities

II. The Cosmological Flow

III. The Cosmological Collider

IV. The Low Speed Collider

I. The Physics of Inflation and non-Gaussianities

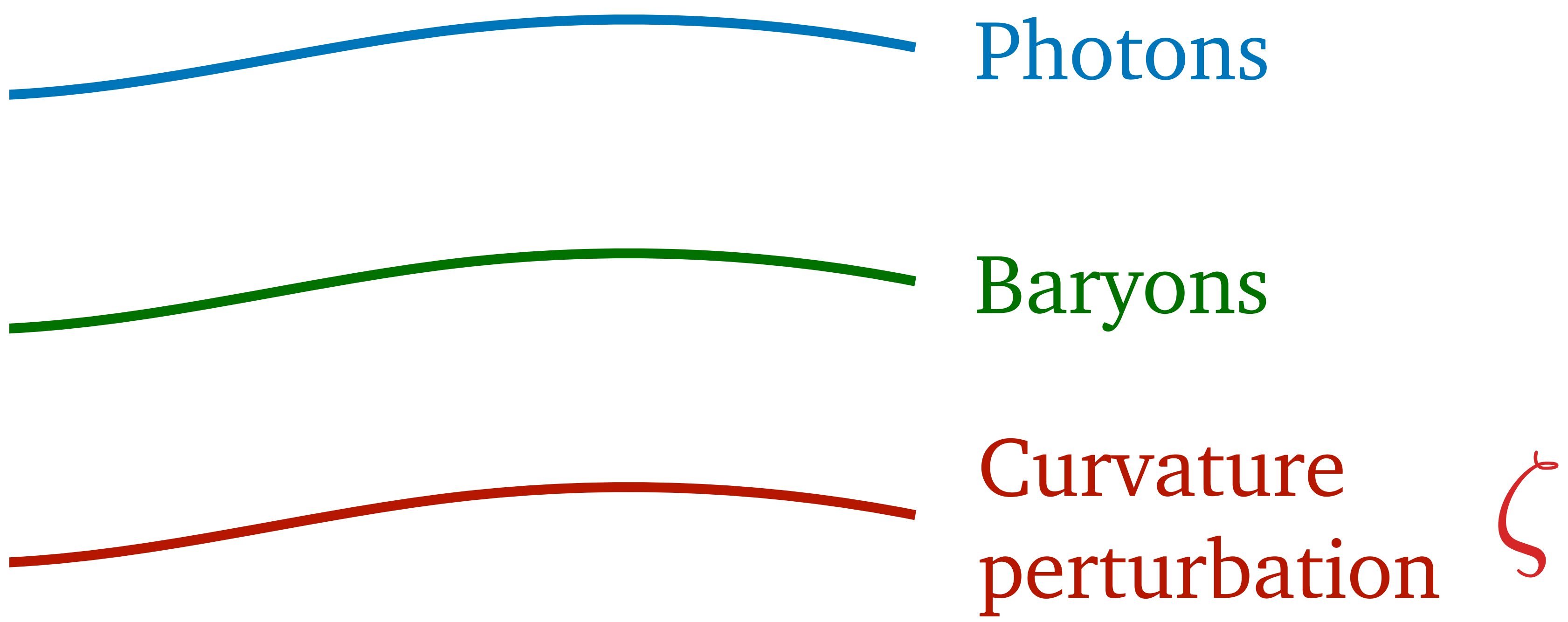
- Basics of Inflation from Observations
- Effective Field Theory of Inflationary fluctuations
- Imprints of extra fields

Clues so far

Planck [2018]

Adiabatic

$$\delta_X(\boldsymbol{x}) \propto \delta_Y(\boldsymbol{x})$$

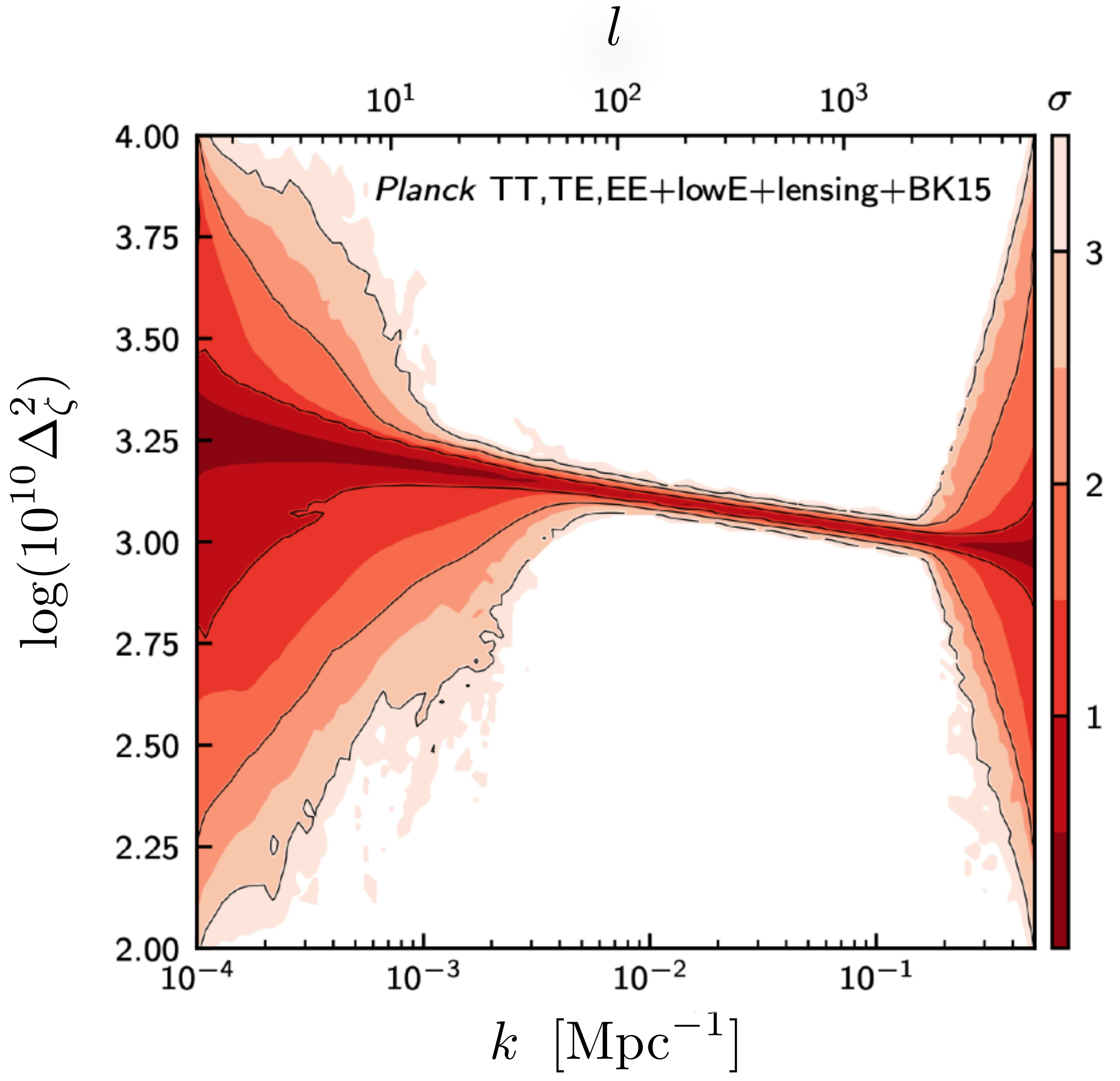


$$g_{ij} = a^2 e^{2\zeta}\delta_{ij}$$

Single fluctuating scalar degree of freedom left over

Almost scale-invariant

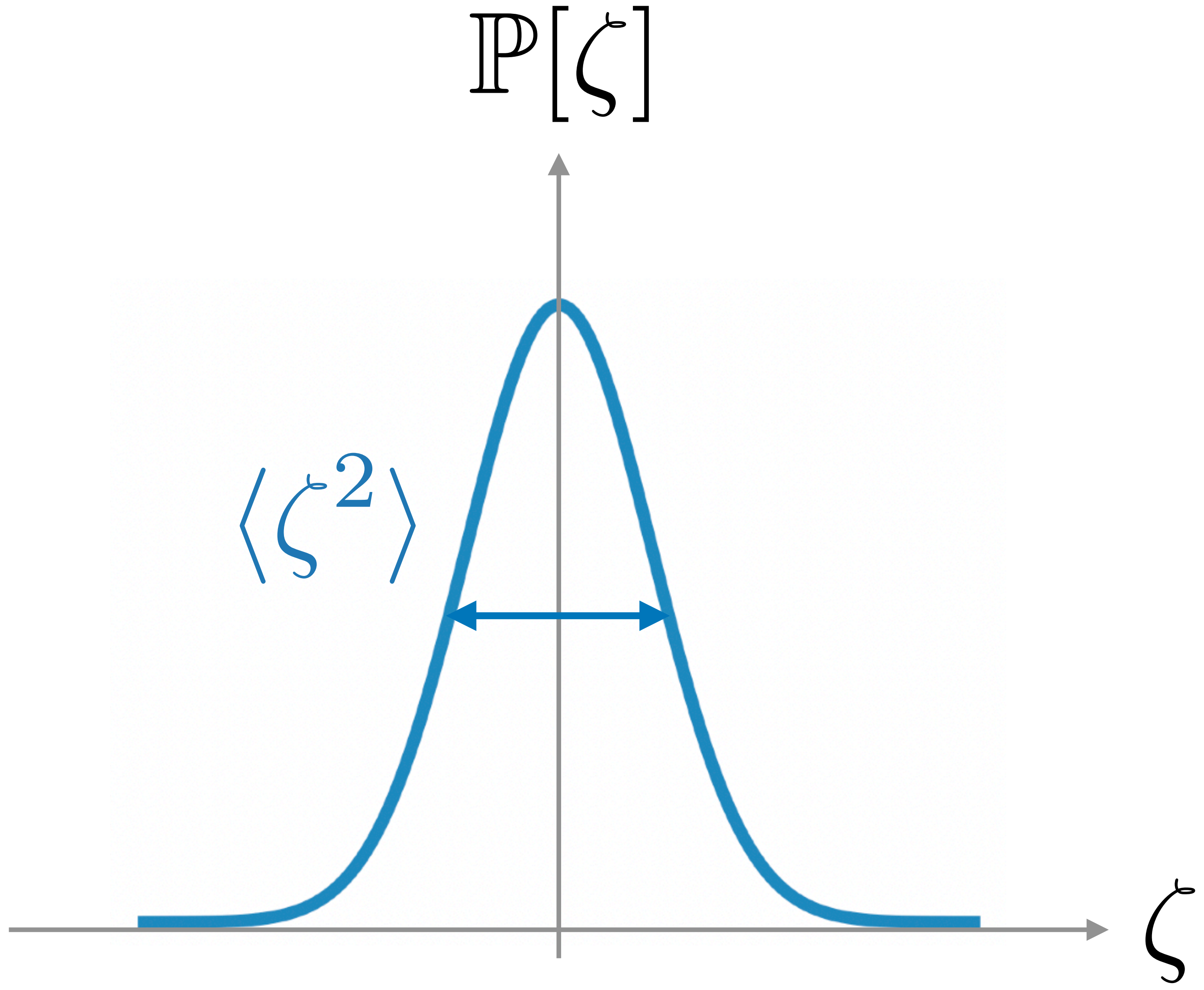
$$\Delta^2_\zeta = \frac{k^3}{2\pi^2}\langle \zeta_{\boldsymbol{k}}\zeta_{-\boldsymbol{k}}\rangle' = A_s\left(\frac{k}{k_\star}\right)^{n_s-1}$$



$$n_s = 0.9652 \pm 0.0042$$

Approximate time-translation invariance

Very gaussian



$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} < 10^{-3}$$

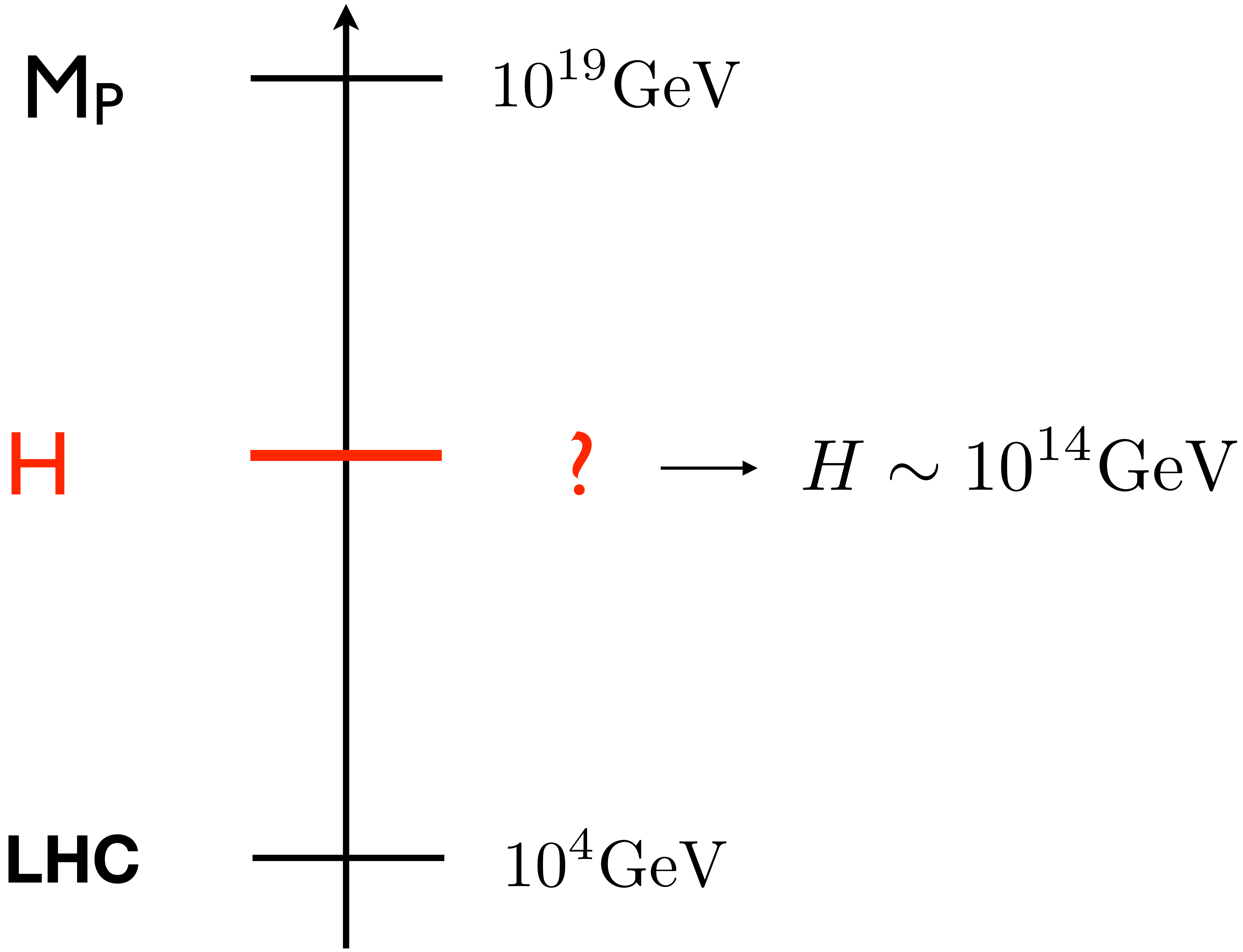
Weakly coupled theory

Clues so far

Planck [2018]

Primordial gravitational waves
from B-modes polarization of CMB

$$\frac{\langle h_{ij}h^{ij}\rangle}{\langle\zeta\zeta\rangle} \lesssim 10^{-2}$$



Detection would be spectacular
(hint about gravity at Planck scale)

No useful theoretical lower bound:
B-modes may be forever out of reach

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

Effective Field Theory of Inflationary Fluctuations

Formulation of theories
straight at the level of fluctuations

motivates

informs

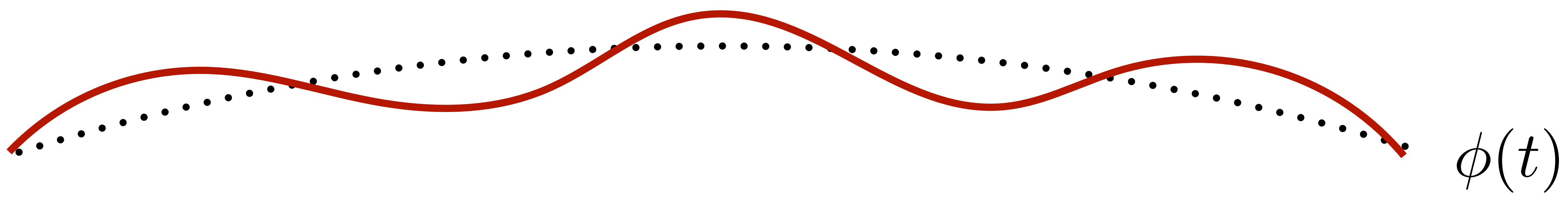
Source of inflation

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



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

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

Effective Field Theory of Inflationary Fluctuations

Action in unitary gauge (preferred foliation) invariant only under spatial diff

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\underline{\frac{1}{2}M_{\rm pl}^2 R + M_{\rm pl}^2\dot{H}g^{00} - M_{\rm pl}^2(3H^2+\dot{H})} + \sum_{n=2}^{\infty}\frac{M_n^4(t)}{n!}\left(\delta g^{00}\right)^n + \dots\right]$$

single-field slow-roll in disguise

Restoring time diff invariance by Stuckelberg trick $\quad t \to t + \pi(\boldsymbol{x}, t)$

Decoupling limit: unperturbed metric is enough $\quad \delta g^{00} \to -2\dot{\pi} - \dot{\pi}^2 + (\partial_i\pi)^2/a^2$

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

Non-linearly realised symmetry

Effective Field Theory of Inflationary Fluctuations

Action in unitary gauge (preferred foliation) invariant only under spatial diff

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non-perturbative background (DBI)
or effect of heavy fields (gelaton)

Restoring time diff invariance by Stuckelberg trick $\quad t \to t + \pi(\boldsymbol{x}, t)$

Decoupling limit: unperturbed metric is enough $\quad \delta g^{00} \to -2\dot{\pi} - \dot{\pi}^2 + (\partial_i\pi)^2/a^2$

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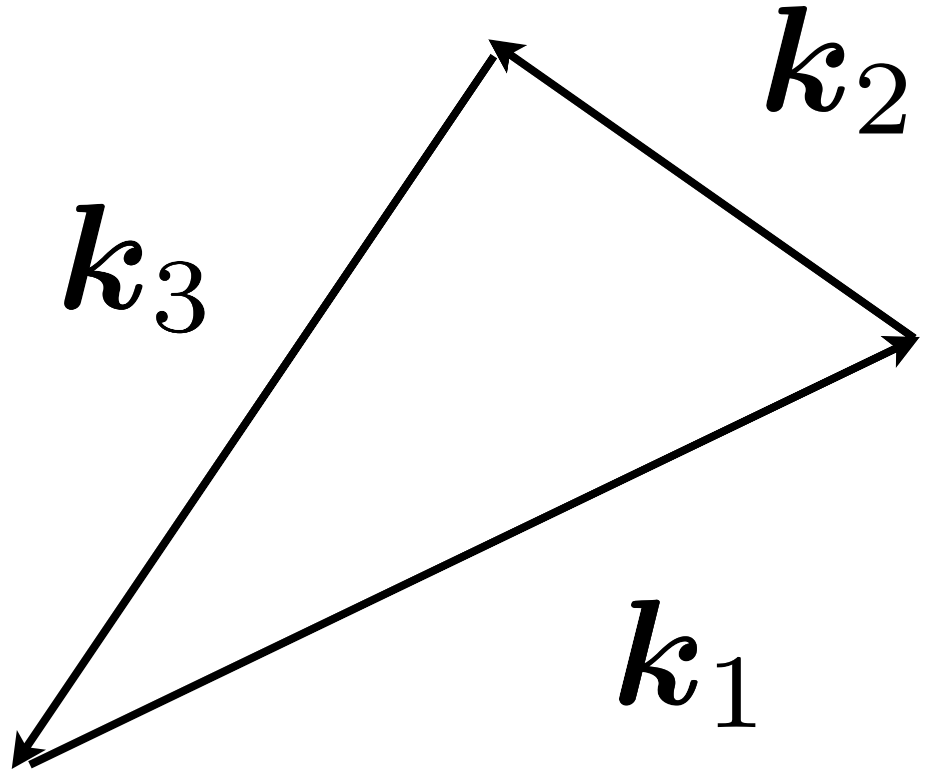
Non-linearly realised symmetry

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 $S \sim f_{\mathrm{NL}}$

Scale-dependence (overall size)

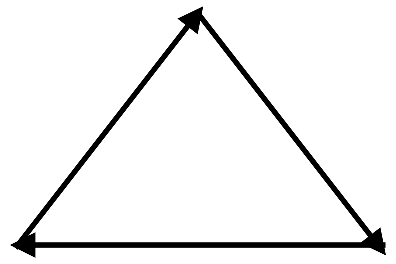
Shape dependence (configuration of triangles)

Equilateral/orthogonal non-Gaussianities

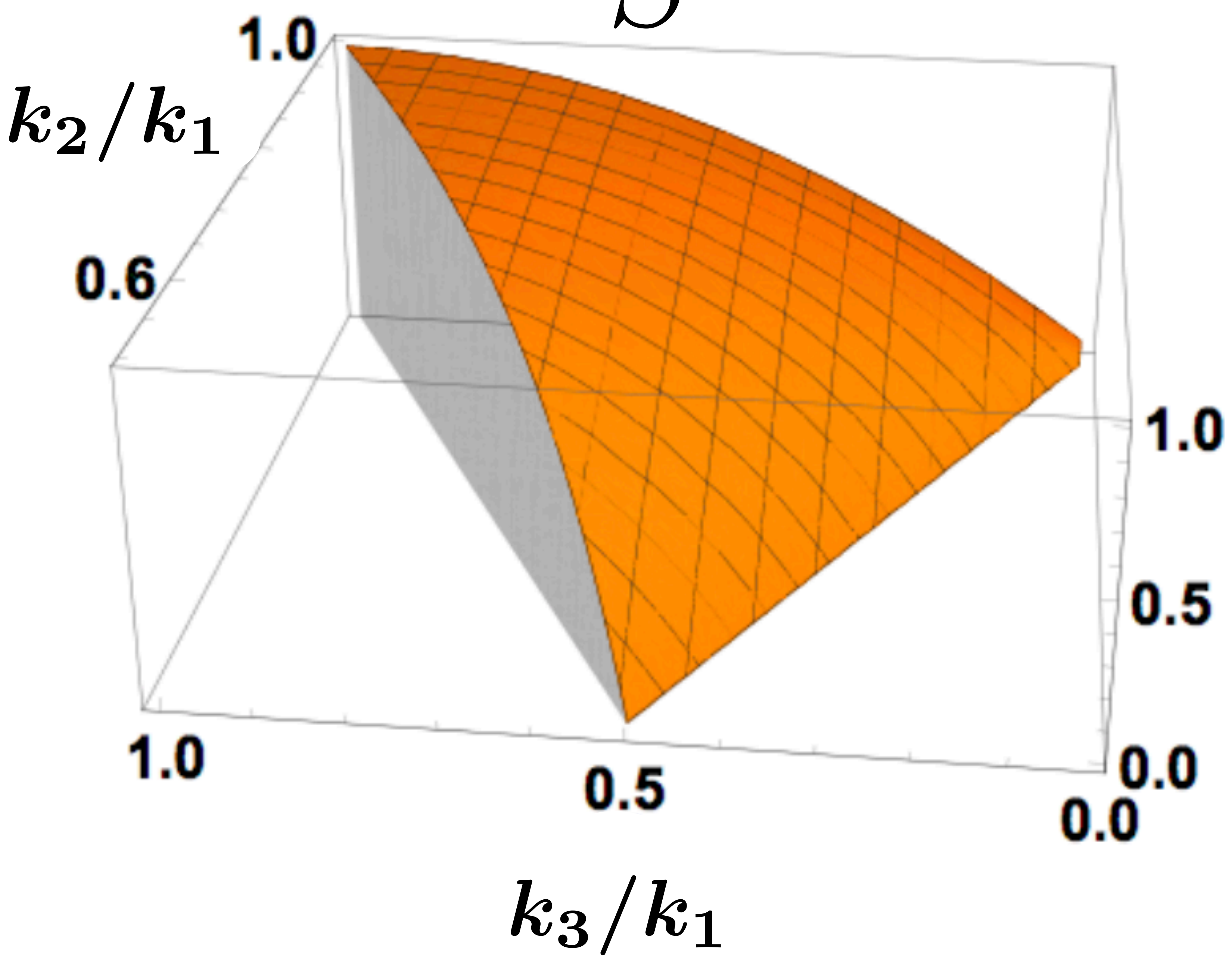
$$\mathcal{L}_\pi/a^3 = \frac{M_{\rm pl}^2|\dot H|}{c_s^2}\left[\dot\pi^2 - c_s^2\frac{(\partial_i\pi)^2}{a^2} + (1-c_s^2)\left(\dot\pi^3 - \dot\pi\frac{(\partial_i\pi)^2}{a^2}\right) - \frac{4}{3}M_3^4\frac{c_s^2}{M_{\rm pl}^2|\dot H|}\dot\pi^3\right]$$

Non-linearly realised symmetry

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



$S^{\rm eq}$



$$f_{\rm NL}^{\rm eq} = -26 \pm 47$$

$$f_{\rm NL}^{\rm orth} = -38 \pm 24$$

(68% CL)

Planck 2018

$$c_s \geq 0.021$$

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

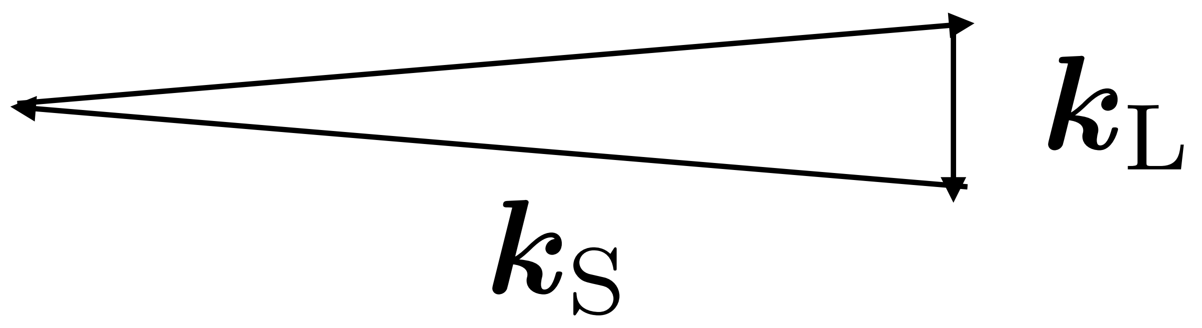
$f_{\rm NL} = \mathcal{O}(\epsilon,\eta) \sim 10^{-2}$ gravitational floor Maldacena (03)

Imprints of additional degrees of freedom

$$S[\pi] \overset{?}{+} S[\text{mixing}] + S[\text{other}]$$

Ubiquitous in string theory, supergravity …

Probed in squeezed limit



$$\kappa = k_{\mathrm{L}}/k_{\mathrm{S}} \ll 1$$

Observable squeezed limit in single-clock inflation

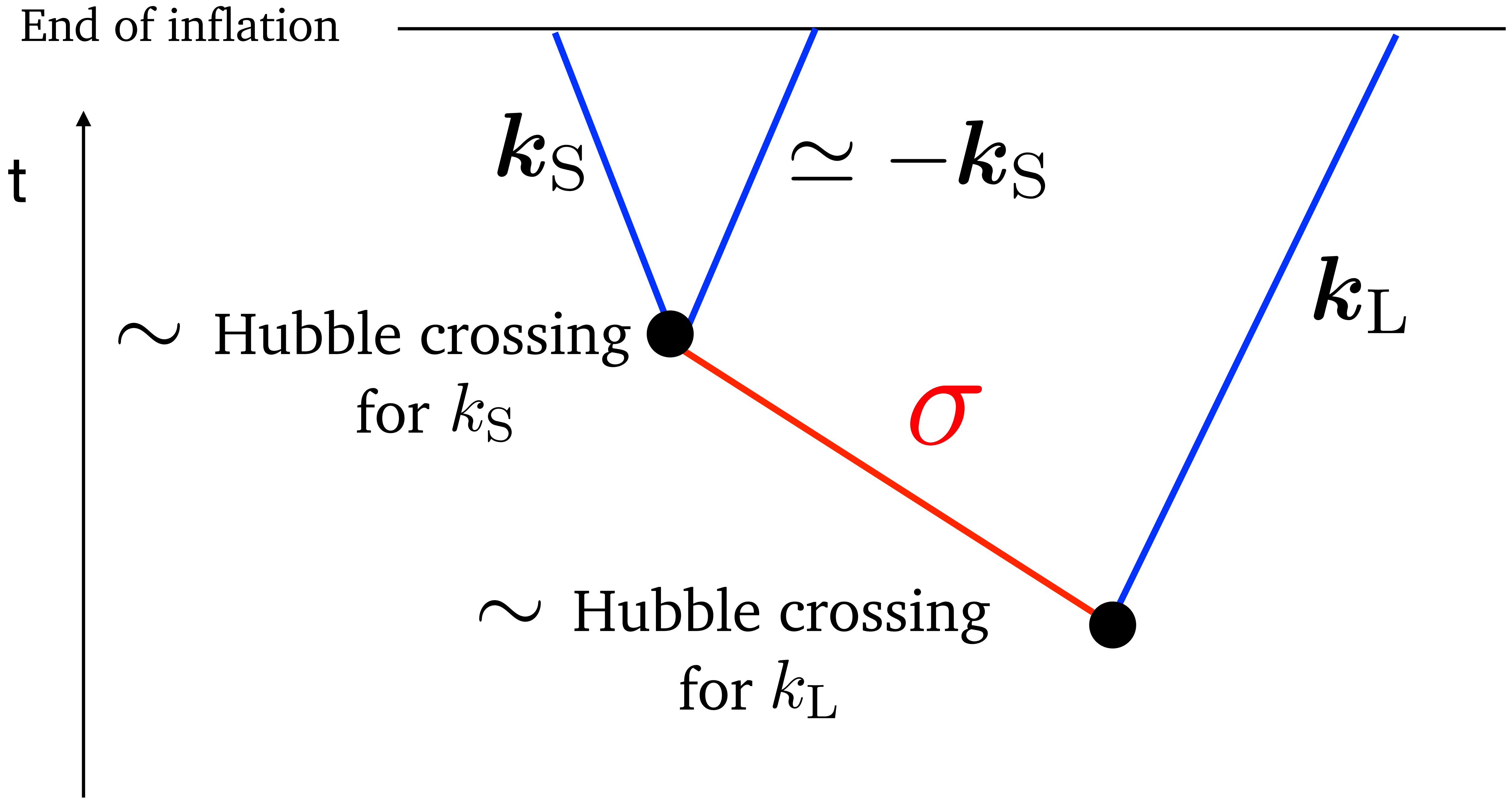
$$\underset{\kappa \ll 1}{S \propto \kappa}$$

Maldacena, Creminelli, Zaldarriaga, Tanaka, Urakawa, Pajer, Schmidt …

Imprints of additional degrees of freedom

Example: $$S_{\pi-\sigma} = -\int \mathrm{d}^4x\sqrt{-g}\tilde{M}_1^3\delta g^{00}\sigma \qquad S_\sigma = -\int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}m^2\sigma^2 + \ldots\right]$$

$$\dot{\pi}\sigma \qquad (\partial_i\pi)^2\sigma$$



Hierarchies of scales

↓

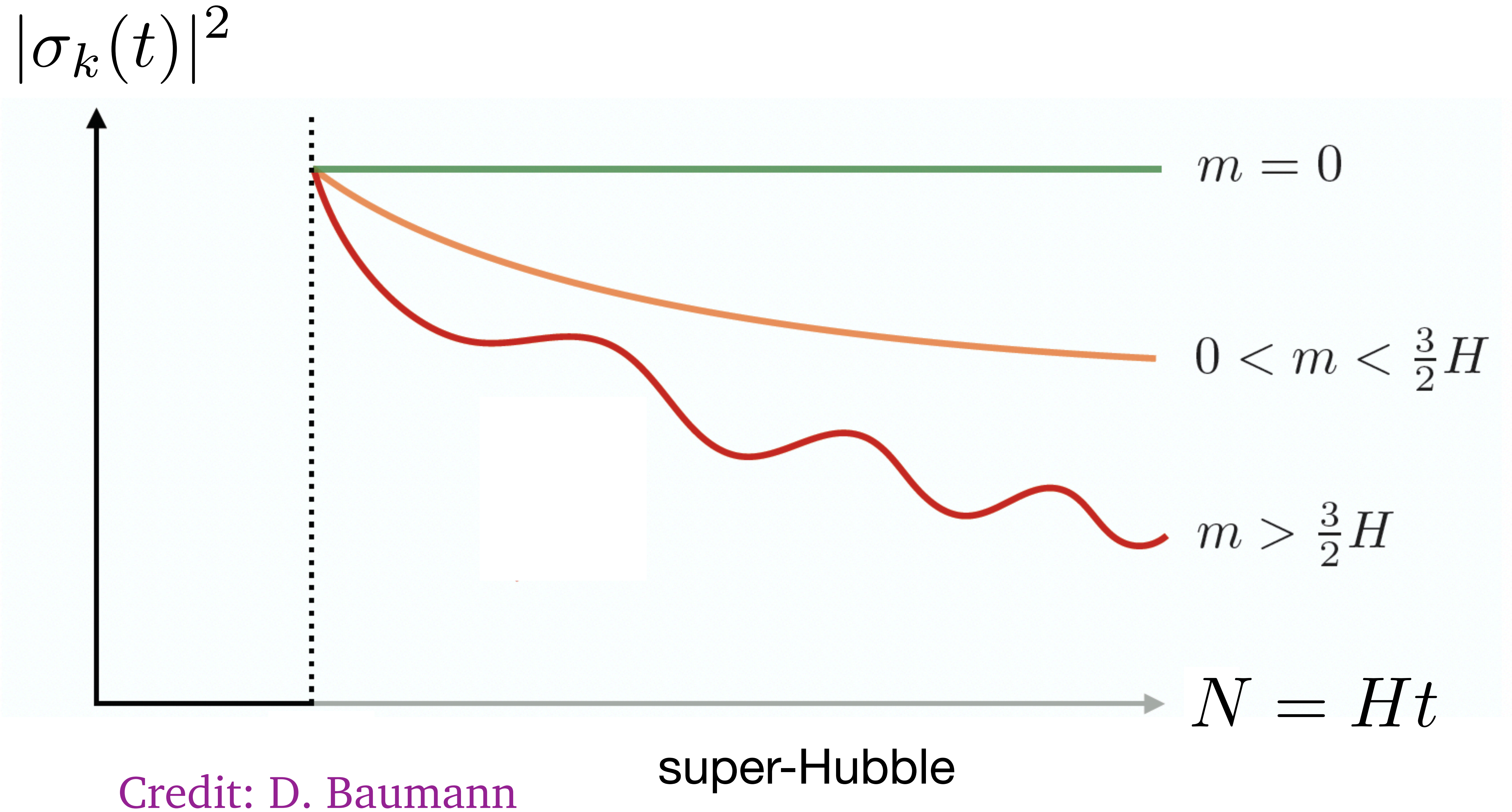
Hierarchies of times

↓

Probe evolution of extra dof on super-Hubble scales

Imprints of additional degrees of freedom

$$\ddot{\sigma}_k + 3H\dot{\sigma}_k + m^2\sigma_k \simeq 0$$



Credit: D. Baumann

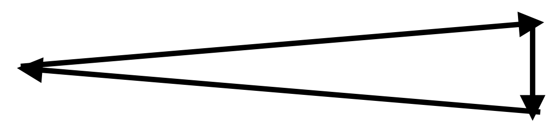
$$\boxed{S \propto \kappa^{1/2-\nu}}$$

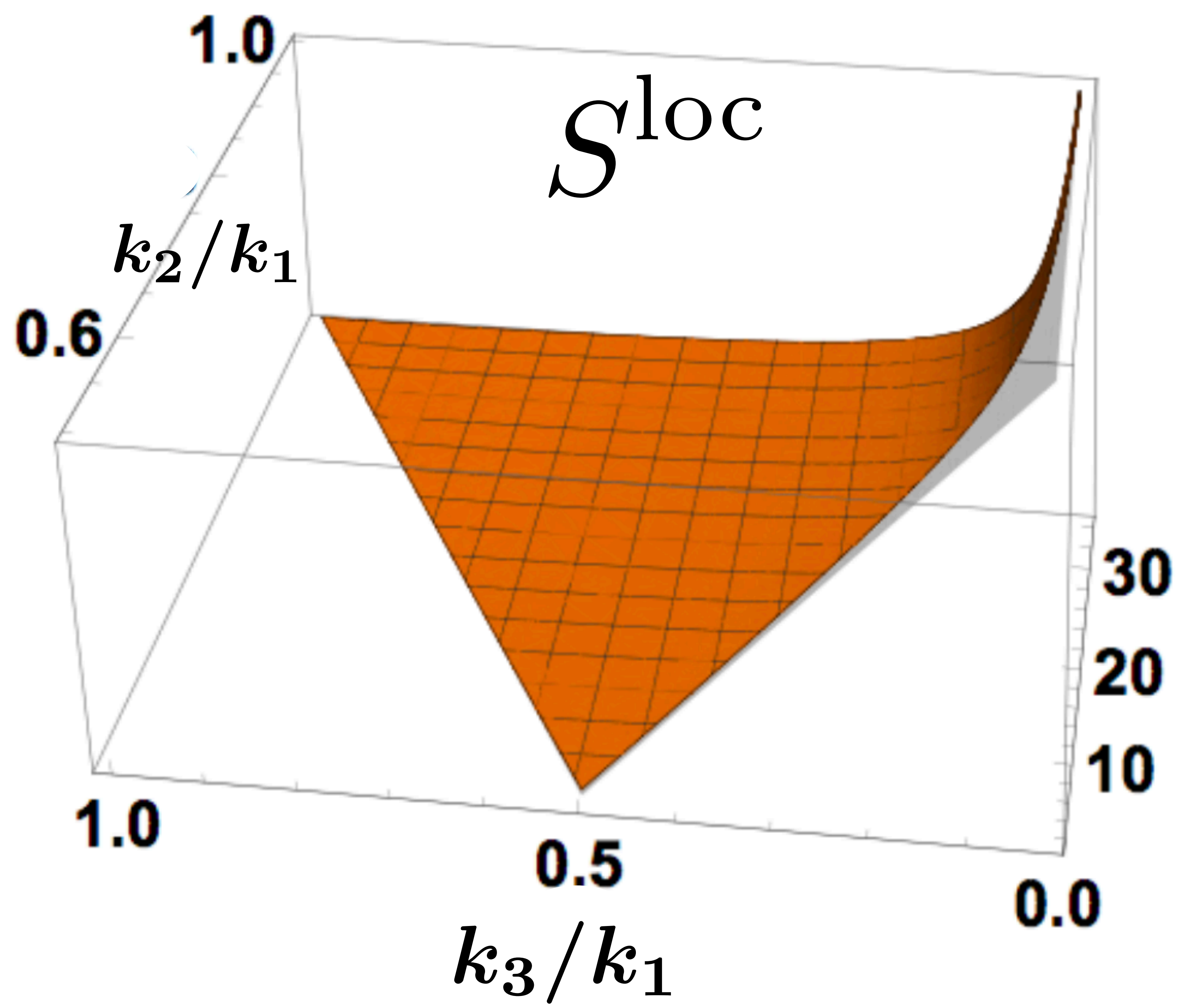
$$\sigma \propto \frac{1}{a^{\frac{3}{2}-\nu}} \qquad \nu = \sqrt{9/4 - m^2/H^2}$$

$$\sigma \propto \frac{\cos(\mu N + \phi)}{a^{\frac{3}{2}}} \qquad \mu = \sqrt{m^2/H^2 - 9/4}$$

$$\boxed{S \propto \kappa^{1/2}\cos(\mu\log(\kappa) + \varphi)}$$

Local shape





$$f_{\text{NL}}^{\text{loc}} = -0.9 \pm 5.1$$

Not possible in single-clock inflation

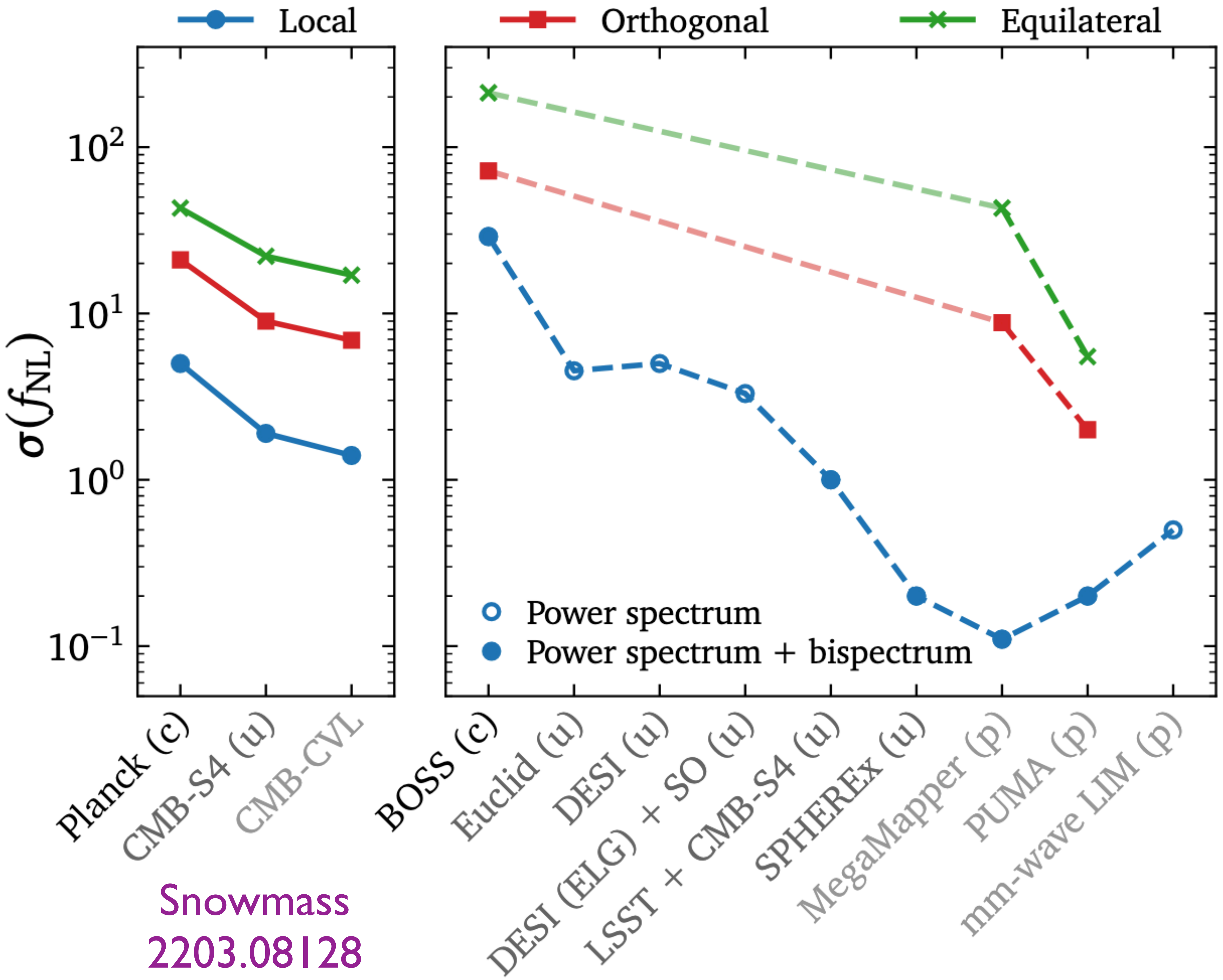
Special role of massless fields
they do not decay

Detection via scale-dependent bias

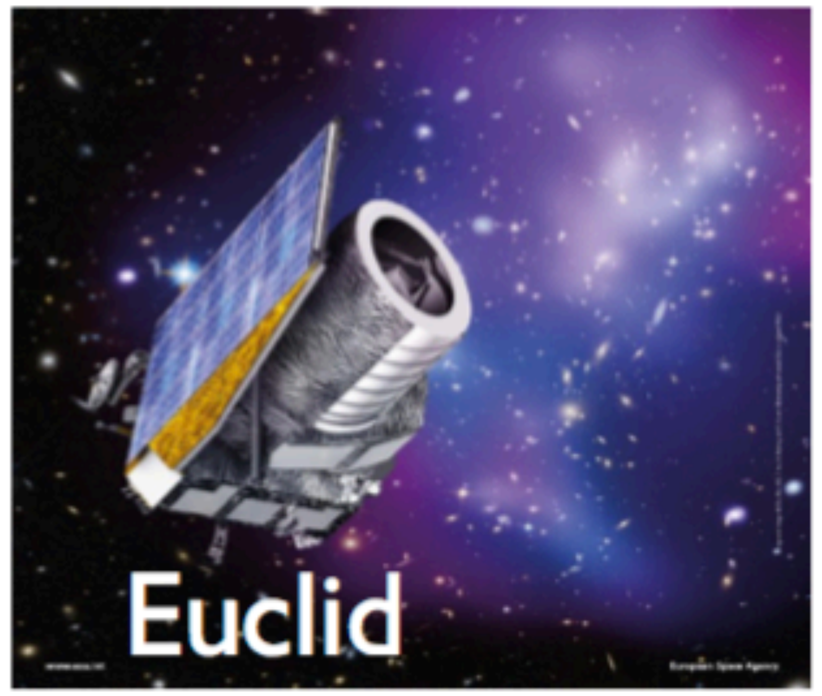
Dalal et al [2008]

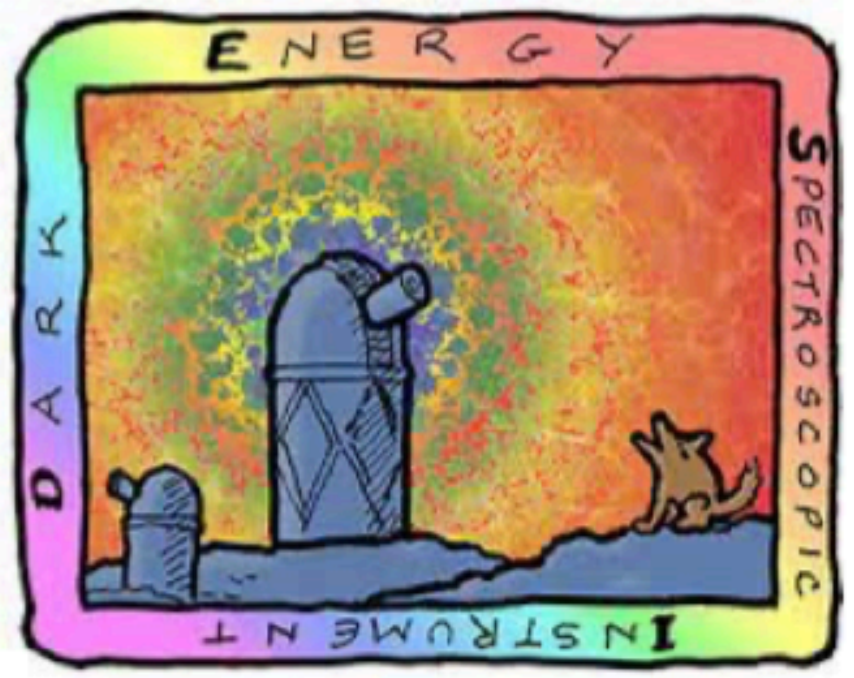
Prospects

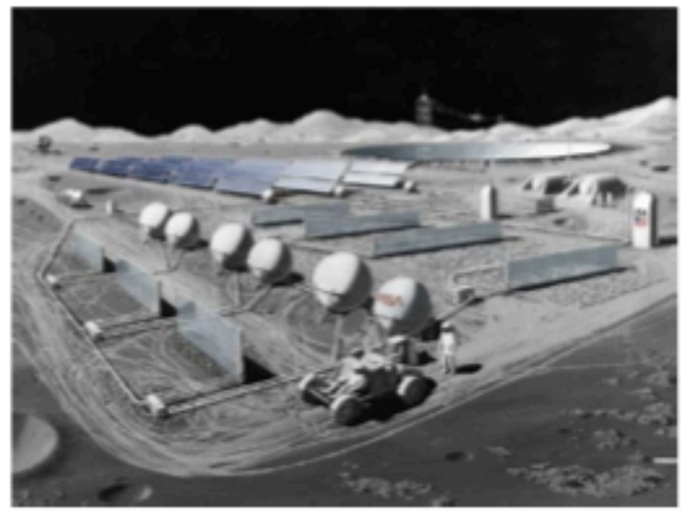
Huge efforts with CMB-S4 &
large-scale structure surveys
(scale-dependent bias, EFT of LSS,
position space maps, simulation based inference etc)



Snowmass
2203.08128



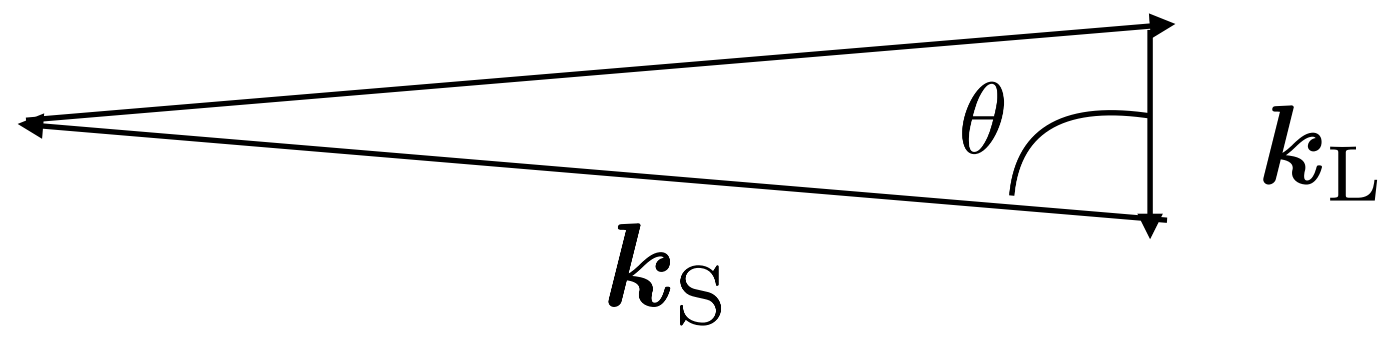




Long-term: 21cm radio-astronomy
from the far side of the moon!
(dark ages)

Cosmological collider physics

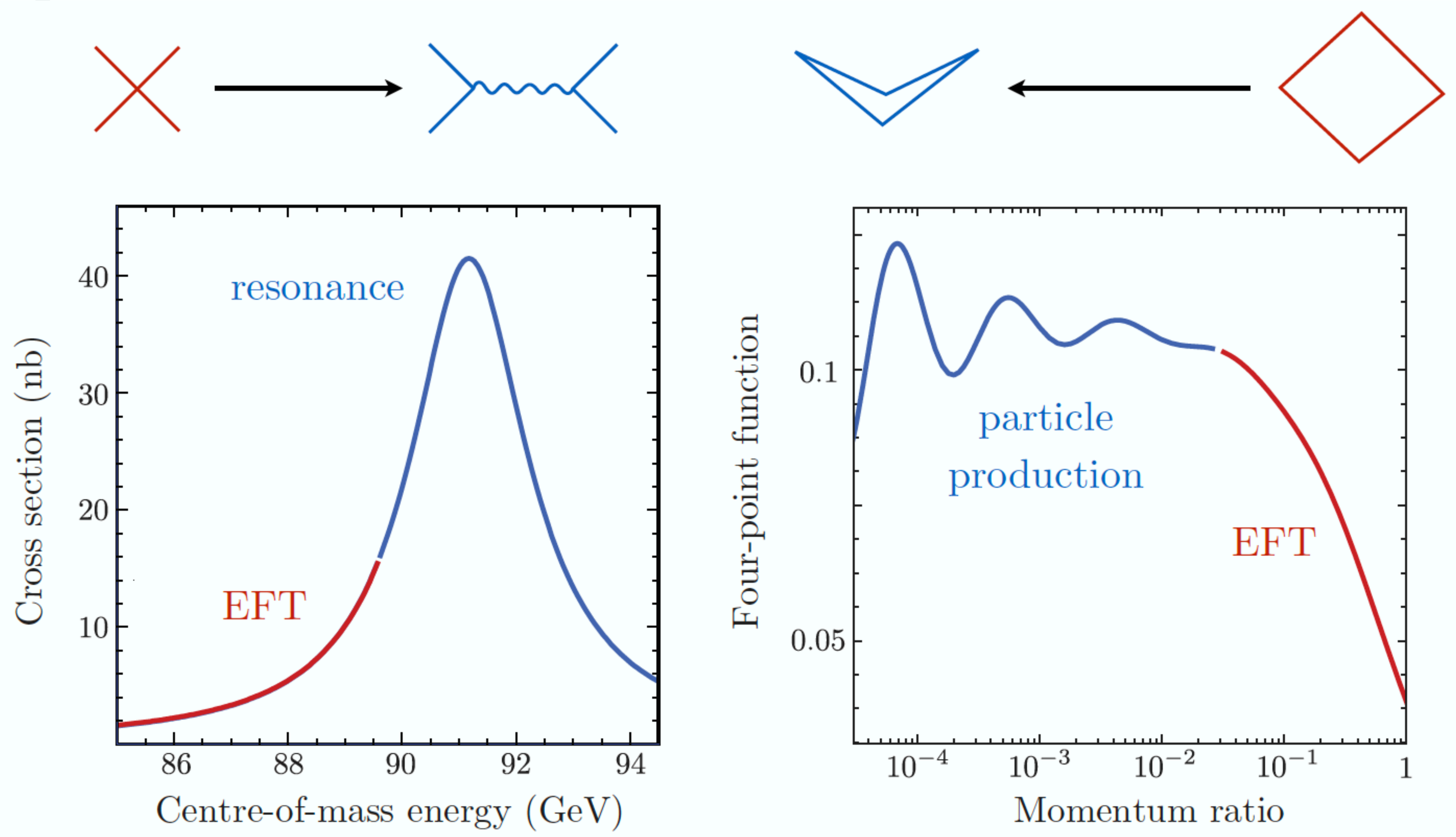
3pt



$$S \propto \kappa^{1/2} e^{-\pi\mu} \cos(\underline{\mu \log(\kappa)} + \varphi) \underline{P_S(\cos\theta)}$$

Mass & Spin of heavy particle

4pt



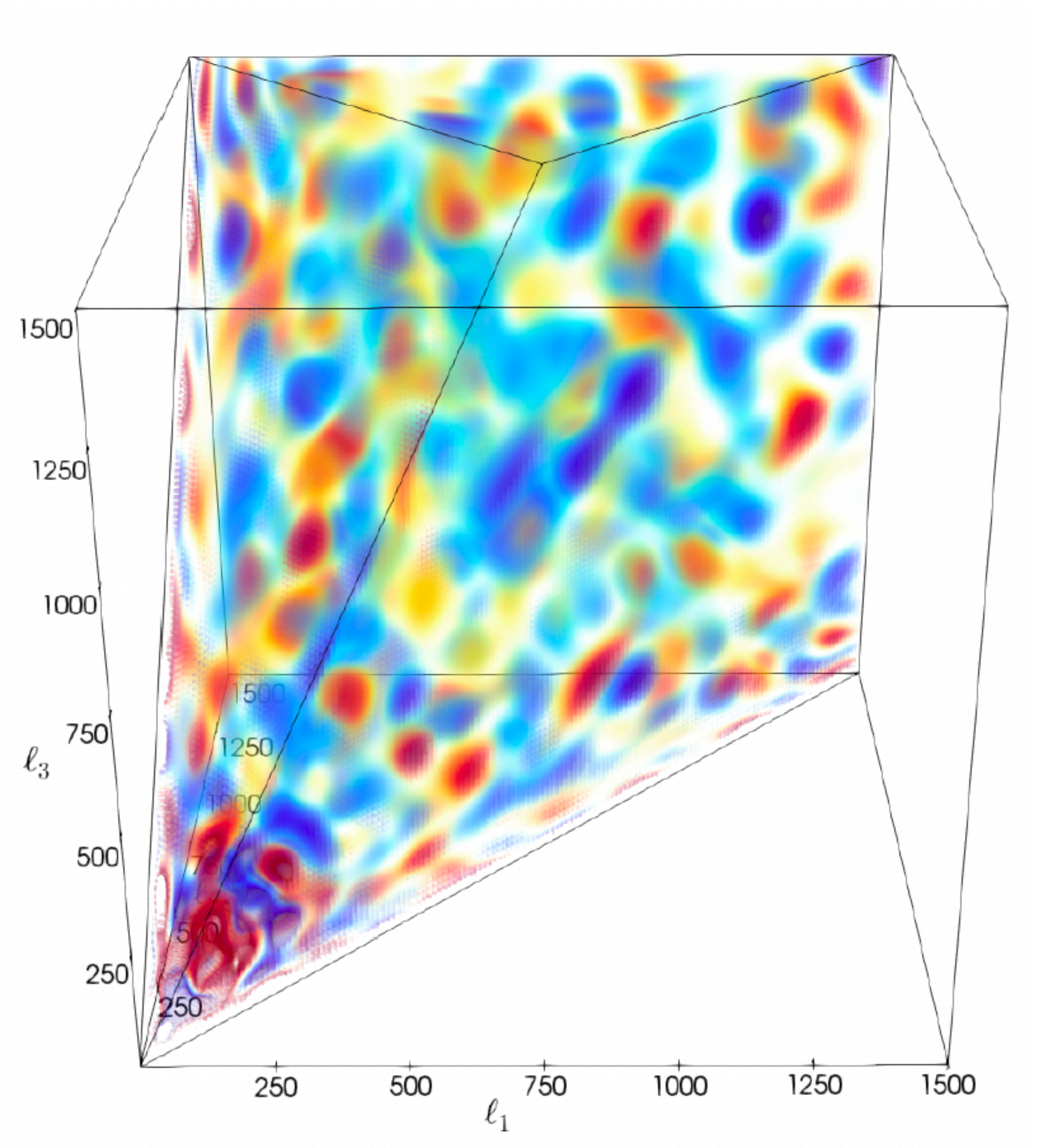
From 1811.00024

Chen, Wang 2009
Noumi, Yamaguchi, Yokohama 2012
Arkani-Hamed, Maldacena 2015
Lee, Bauman, Pimentel 2016
+ many works

Is that it for theorists?

Beyond what I said: features, excited states …

The Planck team constrained a high number of shapes



Fergusson, Shellard
modal decomposition

Physics of inflation?

Statistical properties

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

Theorists' task

Building dictionary

Identifying targets worth measuring

Is the dictionary complete?!

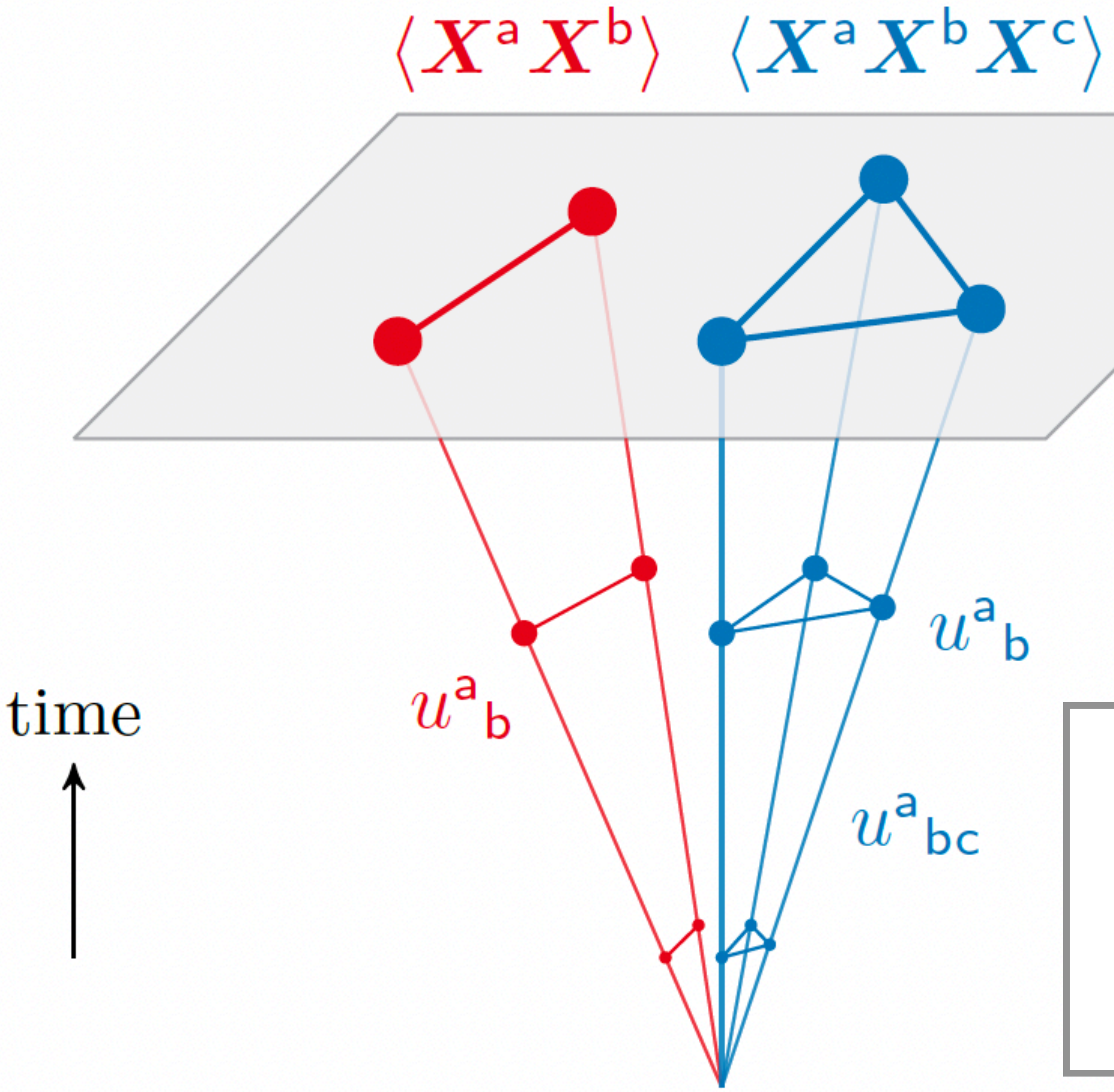
Interesting targets not yet identified?!

II. The Cosmological Flow

- Limitations of current methods create theoretical bias
- The Cosmological Flow Approach

Werth, Pinol, Renaux-Petel [2023 a,b]

The Cosmological Flow in a nutshell



Follow the **time evolution** of correlators during inflation

Theories formulated at level of **EFT of inflationary fluctuations**

Any theory: # dofs, couplings, time-dependence, sound speeds, masses, etc → **Cosmological Flow** → **Primordial correlators**

Shift from technical considerations to unbiased exploration

Generate theoretical data

Assist theoretical understanding

Well-established procedure (in-in)...

$$\boxed{\langle\Omega|\,\mathcal{O}(\boldsymbol{X}^a)\,|\Omega\rangle = \langle 0|\left[\bar{\mathrm{T}}\,e^{i\int_{-\infty^+}^{t} H_{\mathrm{I}}(t')\mathrm{d}t'}\right]\mathcal{O}(X^a)\left[\mathrm{T}\,e^{-i\int_{-\infty^-}^{t} H_{\mathrm{I}}(t')\mathrm{d}t'}\right]|0\rangle}$$

Weinberg 2005

$$\boldsymbol{X}^a \equiv (\boldsymbol{\varphi}^\alpha, \boldsymbol{p}^\beta)$$

Interaction-picture fields
evolve with free Hamiltonian

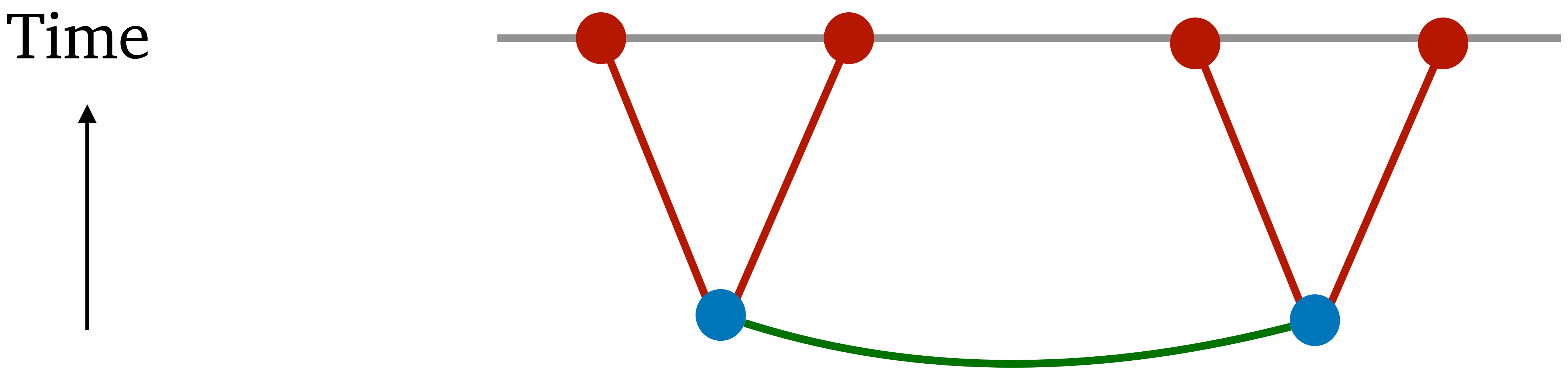
Hamiltonian $\quad H(\boldsymbol{X}^a) = H_0(\boldsymbol{X}^a) + H_I(\boldsymbol{X}^a)$

Free

Interacting

… but technical difficulties

In practice, we compute Feynman-Witten **diagrams** involving complicated time integrals



$$\langle \boldsymbol{X}^4 \rangle = \int \mathrm{d}t \int \mathrm{d}t' V(t) V(t') \mathcal{G}(k_{12}, t, t') K(k_1, t) K(k_2, t) K(k_3, t') K(k_4, t')$$

- Background is time-dependent
- Algebraic complexity
- Starts from solvable free theory
- …

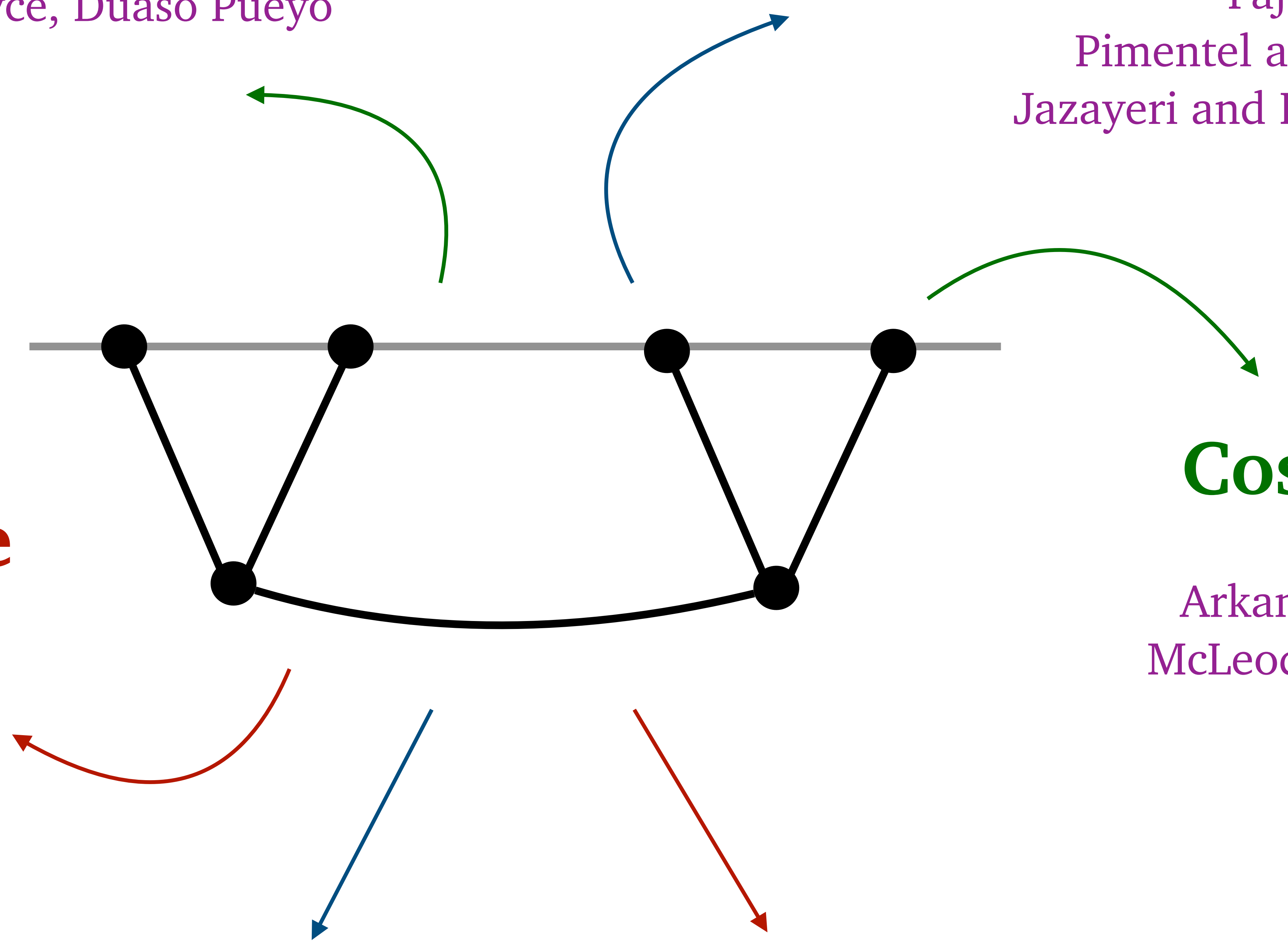
Recent Analytical Developments

dS Cosmological Bootstrap

Arkani-Hamed, Baumann, lee, Pimentel, Joyce, Duaso Pueyo
[2019, 2020, 2022]

Boostless Cosmological Bootstrap

Pajer [2020]
Pimentel and Wang [2022],
Jazayeri and Renaux-Petel [2022]



AdS-inspired Mellin Space

Sleight and Taronna [2019, 2021,2022]

Cosmological Potytopes

Arkani-Hamed, Benincasa, Postnikov,
McLeod [2017, 2018, 2019, 2020 2022]

Fundamental Principles (Unitarity & Locality)

Pajer, Stefanyszyn, Supeł, Goodhew, Jazayeri, Melville, Gordon
Lee, Bonifacio, Wang [2020, 2021, 2022]

Partial Mellin-Barnes Representation

Qin and Xianyu [2022]

+ Several other approaches and authors

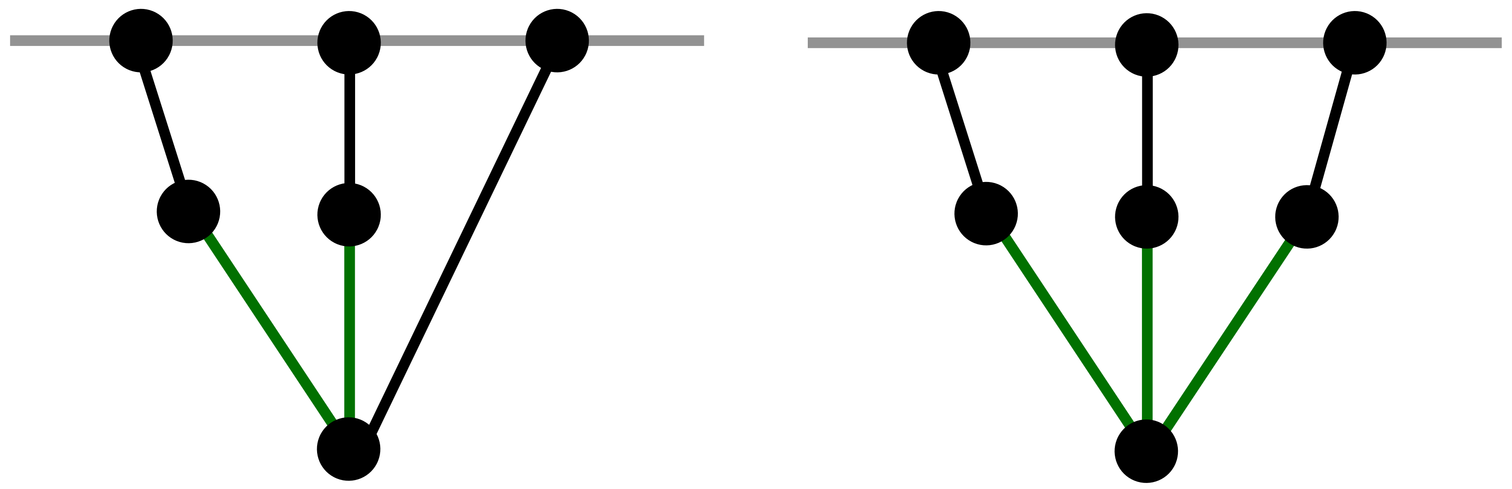
Limitations of Analytical Methods

Weak Quadratic Mixing

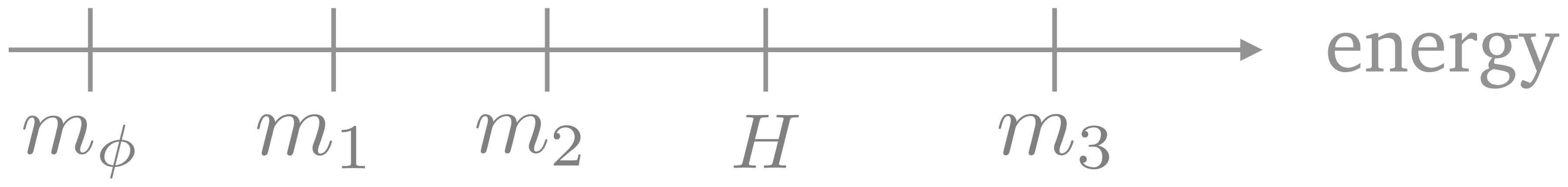
$$\mathcal{L}^{(2)} \supset \rho \dot{\pi} \sigma$$

treated perturbatively

Only Single-Exchange Diagram

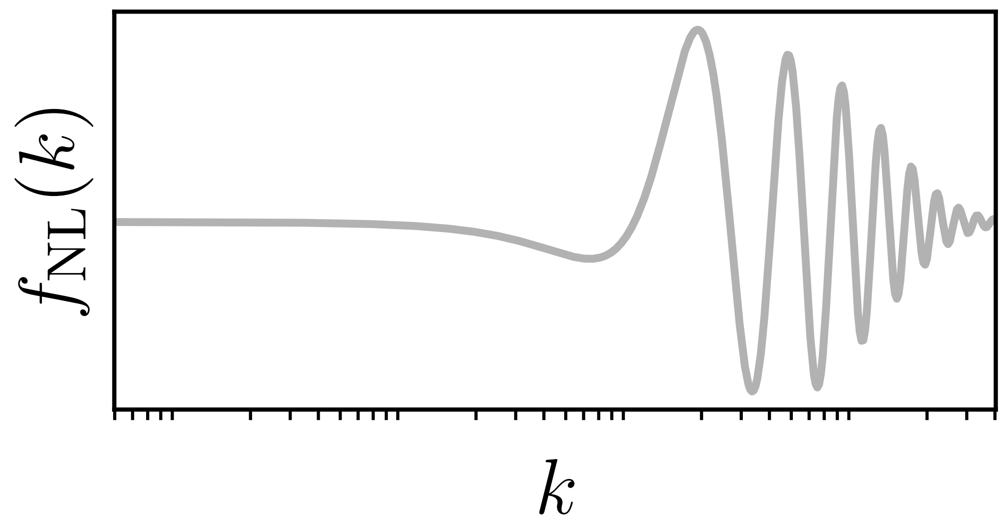


Often only 1 or 2 Fields



Aside from isolated examples…

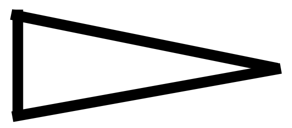
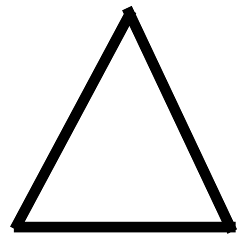
(Near) Scale-Invariance



features

Large hierarchy of masses/couplings but not the intermediate regimes

Treatment of Equilateral and Squeezed Configurations Separately

 $\sim e^{-\pi\mu}$  $\sim \frac{1}{\mu^2}$

Why the Cosmological Flow: Break the Vicious Circle

Understand the physics of the early universe

We want to make accurate predictions to test against future data

Procedure well defined but technical difficulties

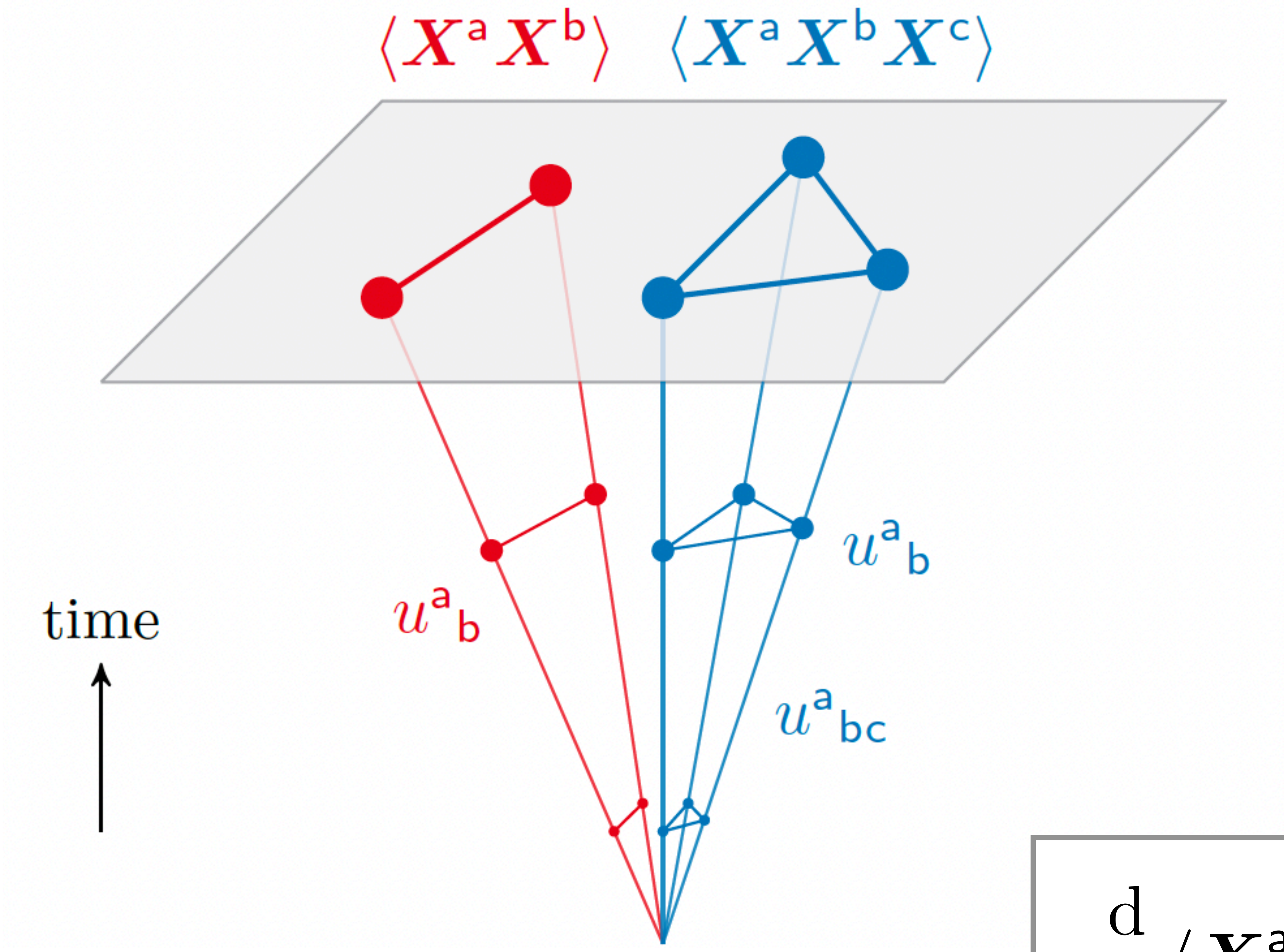
Limit oneself to simple models

Biased interpretation of data

The Cosmological Flow

Efficient and systematic approach without resorting to approximations

The flow of (tree-level) correlation functions



Ehrenfest theorem $\dfrac{d}{dt}\langle A \rangle = i\langle [H, A] \rangle$

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}\langle \boldsymbol{X}^{a} \boldsymbol{X}^{b} \rangle = u^{a}{}_{c}\langle \boldsymbol{X}^{c} \boldsymbol{X}^{b} \rangle + u^{b}{}_{c}\langle \boldsymbol{X}^{a} \boldsymbol{X}^{c} \rangle}$$

Theory dependence
(read off from action)

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}\langle \boldsymbol{X}^{a} \boldsymbol{X}^{b} \boldsymbol{X}^{c} \rangle = u^{a}{}_{d}\langle \boldsymbol{X}^{d} \boldsymbol{X}^{b} \boldsymbol{X}^{c} \rangle + u^{a}{}_{de}\langle \boldsymbol{X}^{b} \boldsymbol{X}^{d} \rangle\langle \boldsymbol{X}^{c} \boldsymbol{X}^{e} \rangle + (2 \text{ perms})}$$

First used for particular background mechanisms

Dias, Fazer, **Mulryne, Seery**, Ronayne
[2010, 2011, 2012, 2013, 2015, 2016, 2018]

Initial conditions automatically known for
Bunch-Davies (or make your own choice)

Resumming Quadratic Mixings

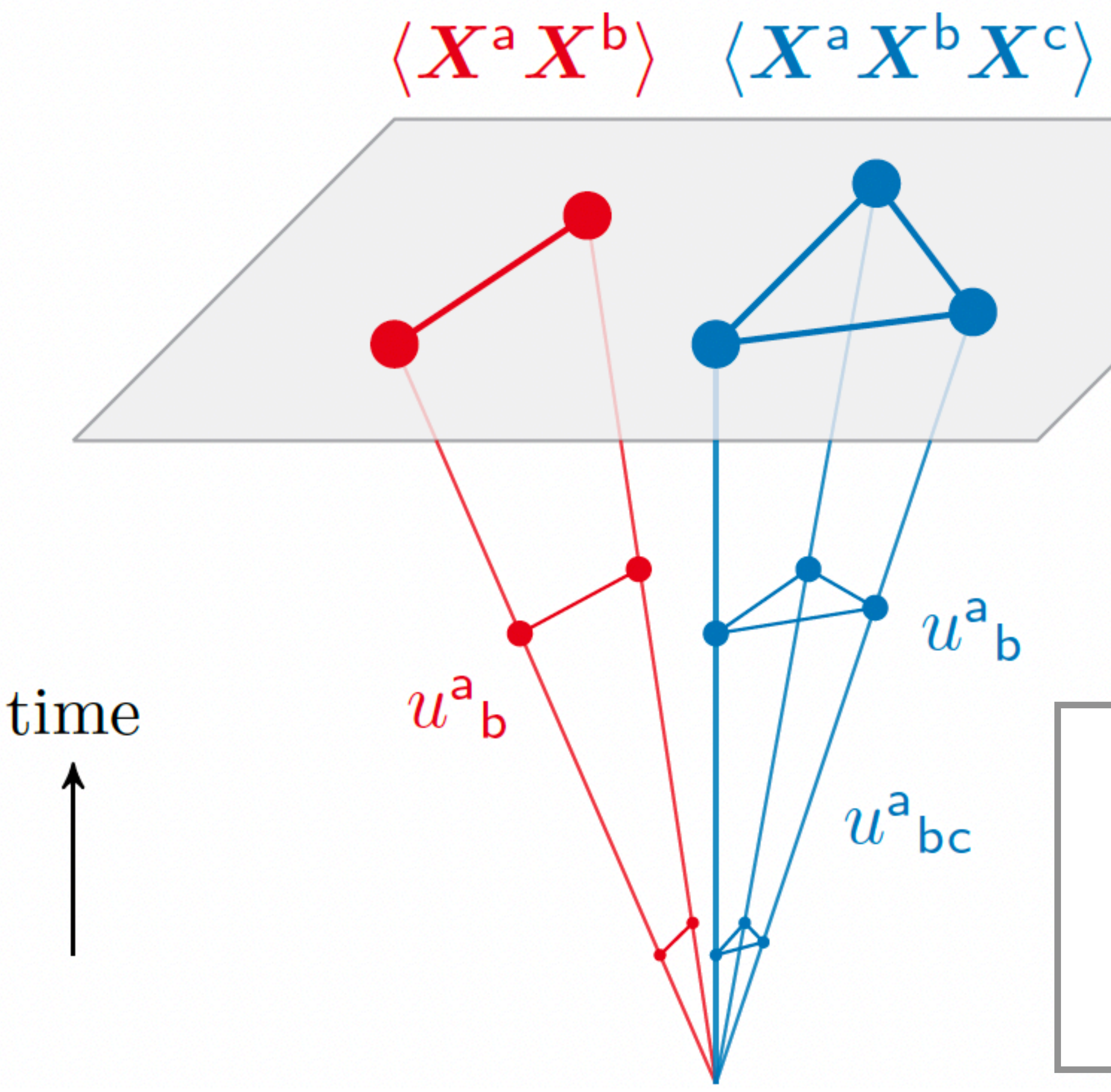
Exact treatment of quadratic «interactions»

Comparing to conventional split

$$\mathcal{L}^{(2)} = \mathcal{L}^{(2)}_{\text{diag}} + \mathcal{L}^{(2)}_{\text{mix}}$$

CosmoFlow

with Denis Werth and Lucas Pinol
soon publicly available



Follow the **time evolution** of correlators during inflation

Theories formulated at level of **EFT of inflationary fluctuations**

Any theory: # dofs, couplings, time-dependence, sound speeds, masses, etc ⟶ **Cosmological Flow** ⟶ **Primordial correlators**

Shift from technical considerations to unbiased exploration

Generate theoretical data

Assist theoretical understanding

III. The Cosmological Collider

- With Flavor Oscillations
- At Strong Mixing
- With Time-Dependent Mixing

Cosmological collider: « a robust probe of field content of inflation »?

$$S \propto \kappa^{1/2} e^{-\pi\mu} \cos(\underline{\mu \log(\kappa)} + \varphi) \underline{P_S(\cos\theta)}$$

As robust probe as assumptions are restrictive:
unique additional dof, weakly mixed, scale-invariant

Observed π ← mixing → Hidden sector

Observed π

Dispersion relation

mixing

Type

Strength

Time-dependence

Hidden sector

Several dofs

Mass and spin

Interactions

Time-dependence…

Cosmological collider: « a robust probe of field content of inflation »?

$$S \propto \kappa^{1/2} e^{-\pi\mu} \cos(\underline{\mu \log(\kappa)} + \varphi) \underline{P_S(\cos\theta)}$$

As robust probe as assumptions are restrictive:
unique additional dof, weakly mixed, scale-invariant

Observed π

Dispersion relation

↓

Lee, Baumann, Pimentel [2018]
Wang, Pimentel [2022]
Jazayeri, Renaux-Petel [2022]

← **mixing** →

Type

Strength

Time-dependence

Hidden sector

Several dofs

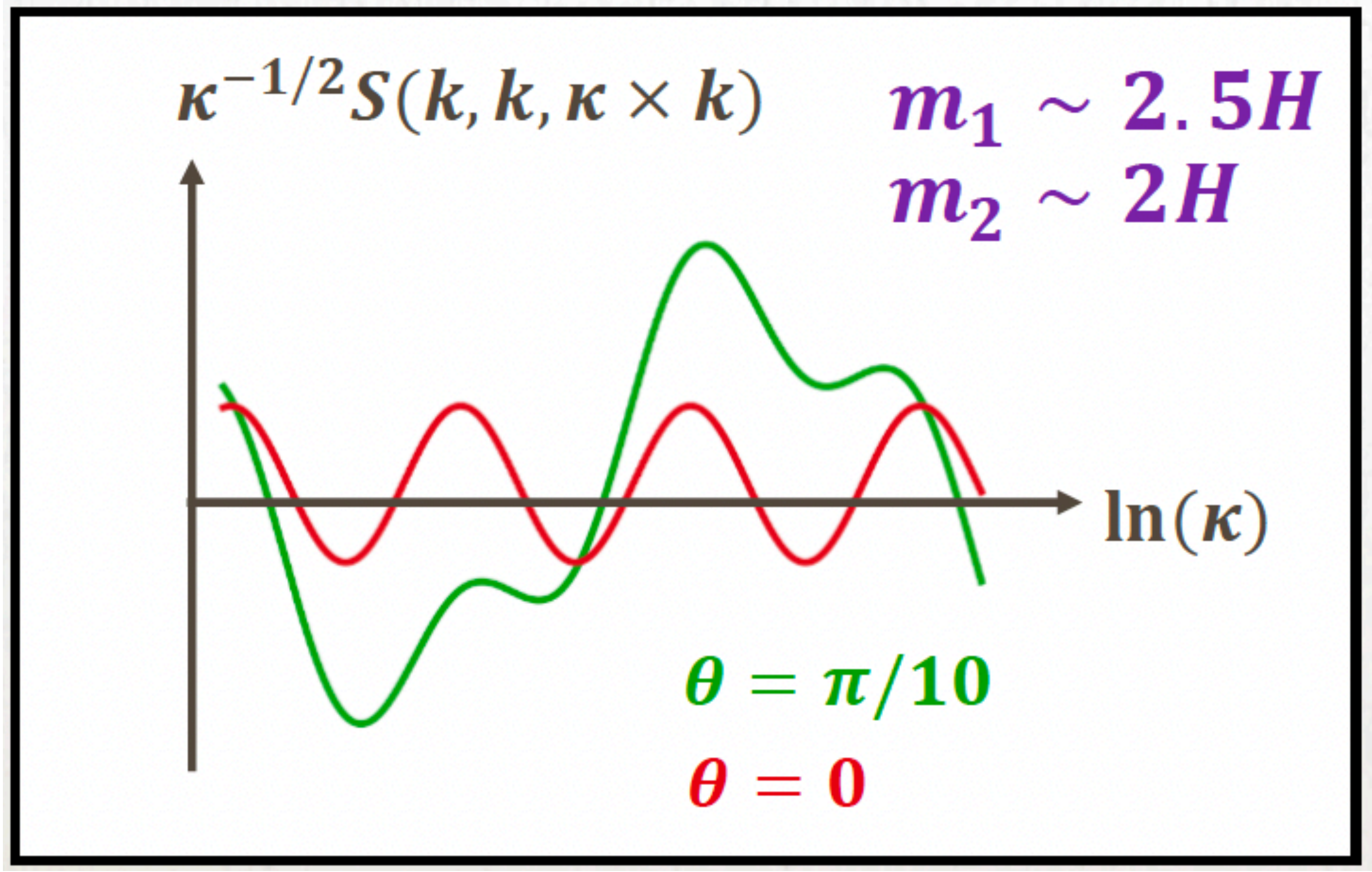
Mass and spin

Interactions

Time-dependence… → Wang [2019]

Cosmological collider signatures beyond restrictive assumptions

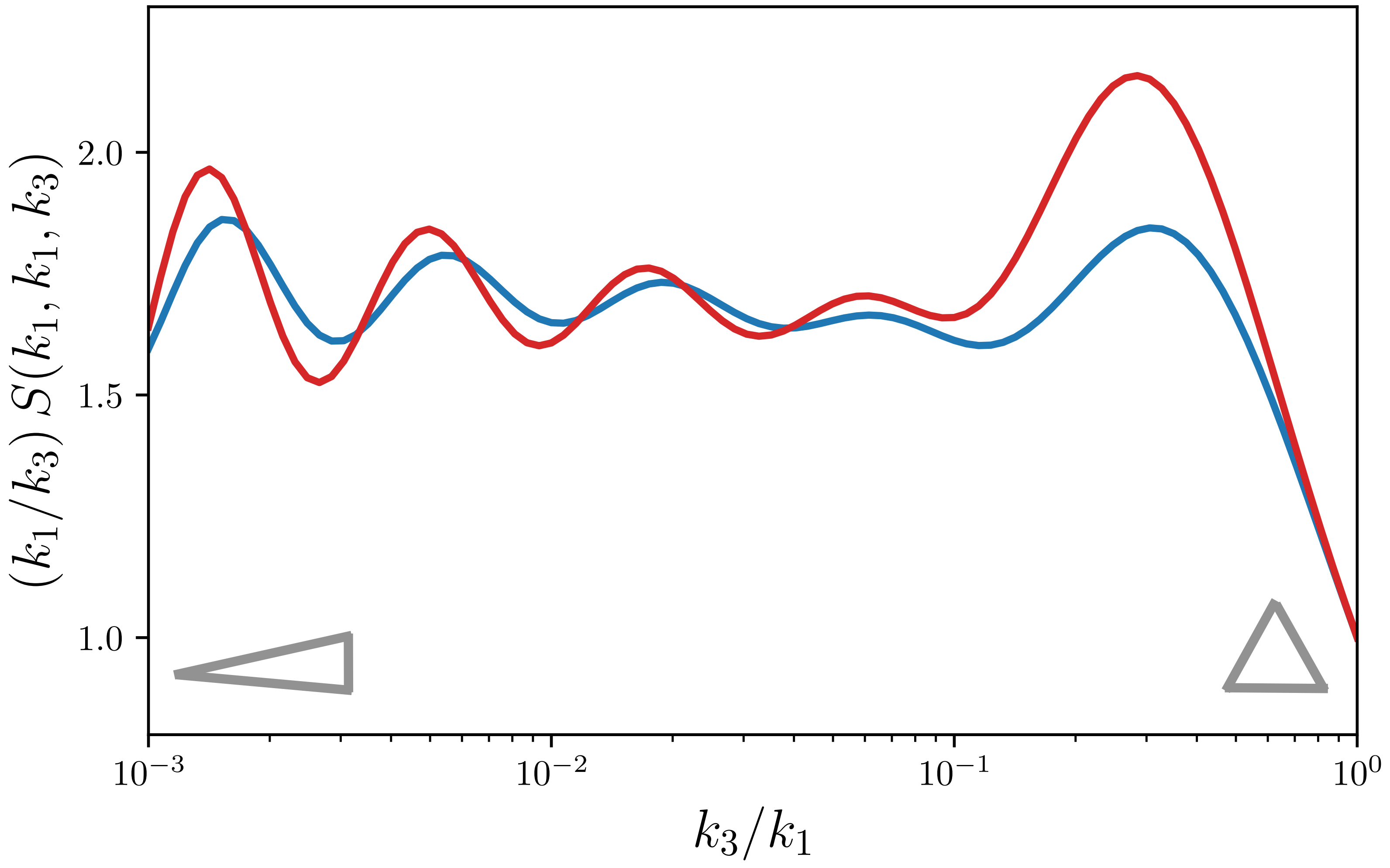
Mass mixing



Inflationary flavor oscillations

Pinol, Aoki, Renaux-Petel, Yamaguchi [2021]

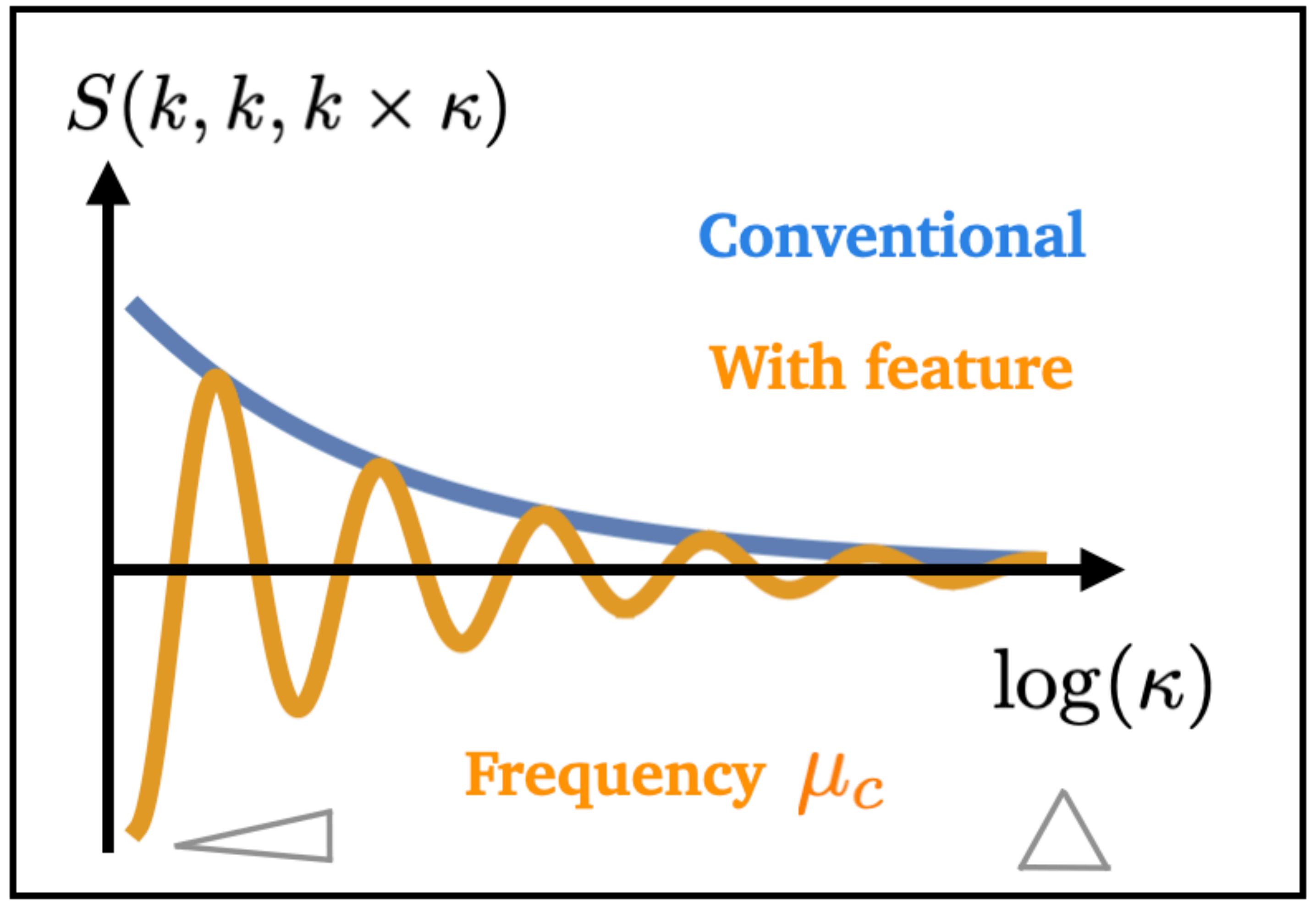
Strong mixing



Breaking degeneracies weak/strong mixing

Werth, Pinol, Renaux-Petel [2023 a,b]

Time-dependent mixing



Soft limits complementary to equilateral to diagnose features

Werth, Pinol, Renaux-Petel [2023 a,b]

Goldstone Boson coupled to Massive Field

π quadratic sector

canonically normalised

σ quadratic sector

quadratic mixing

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

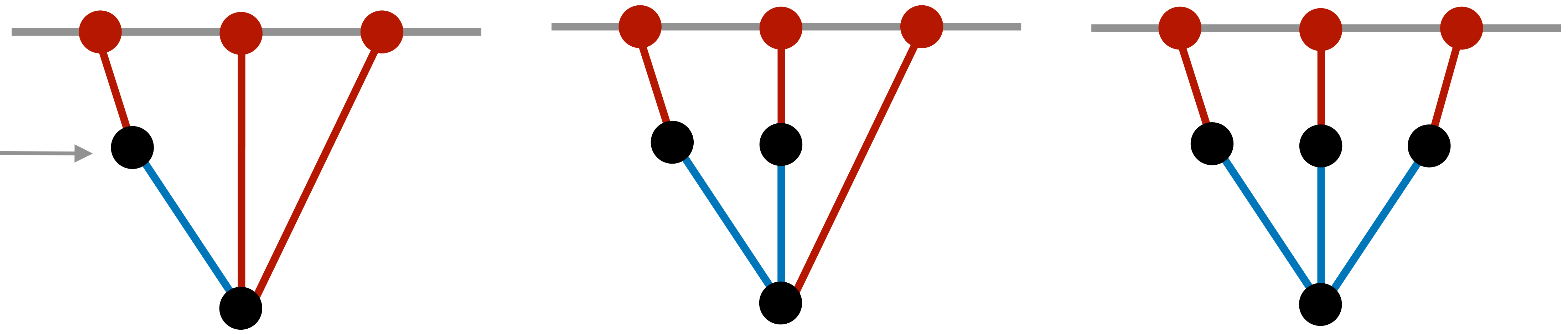
$$-\lambda_1\dot{\pi}_c\frac{(\partial_i\pi_c)^2}{a^2} - \lambda_2\dot{\pi}_c{}^3 - \mu\sigma^3 - \lambda\dot{\pi}_c\sigma^2 - \frac{1}{\Lambda_1}\frac{(\partial_i\pi_c)^2}{a^2}\sigma - \frac{1}{\Lambda_2}\dot{\pi}_c{}^2\sigma$$

Non-linearly realised symmetry

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

Self-interactions

Assuming weak mixing



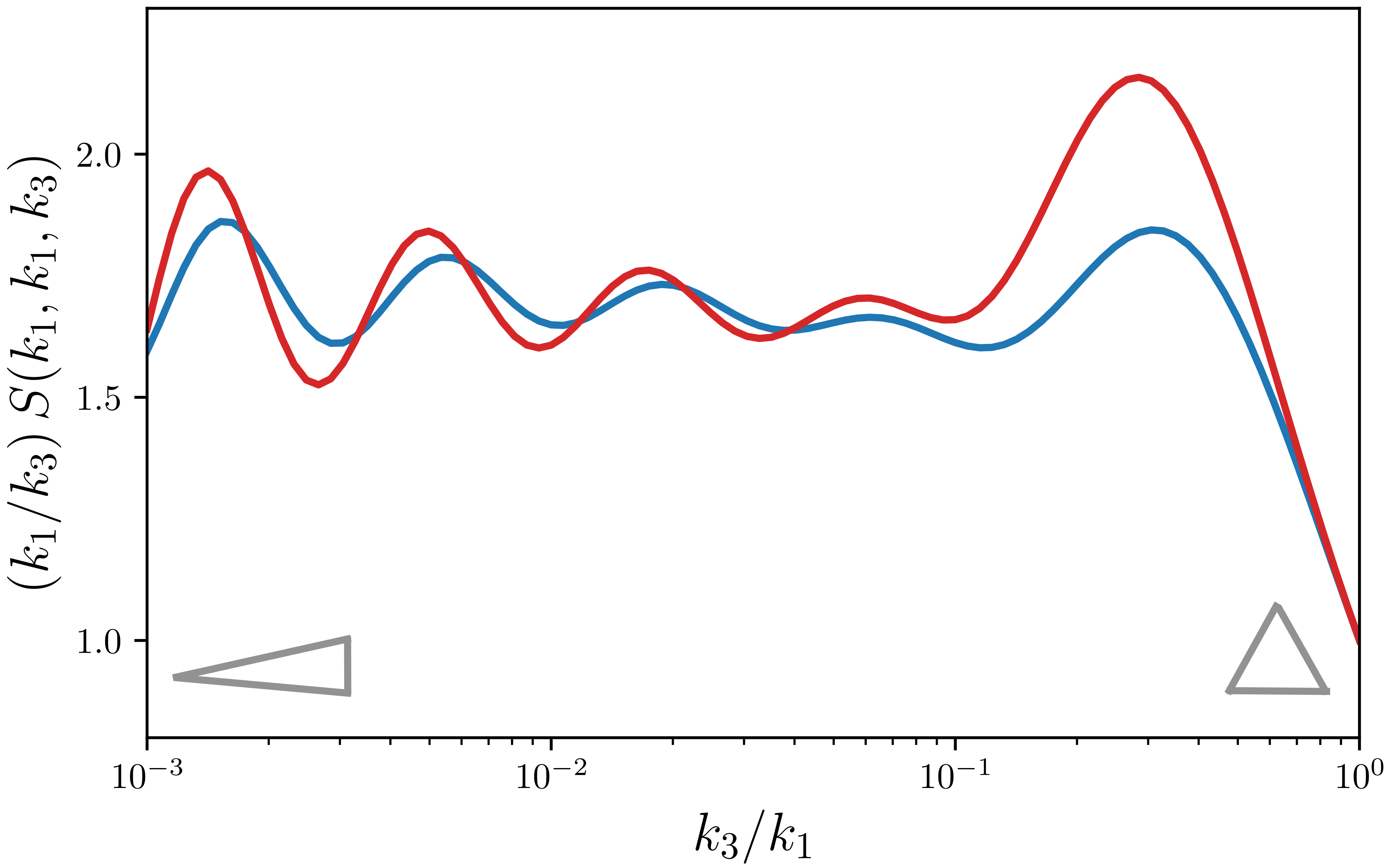
CosmoFlow

Correlators for all interactions

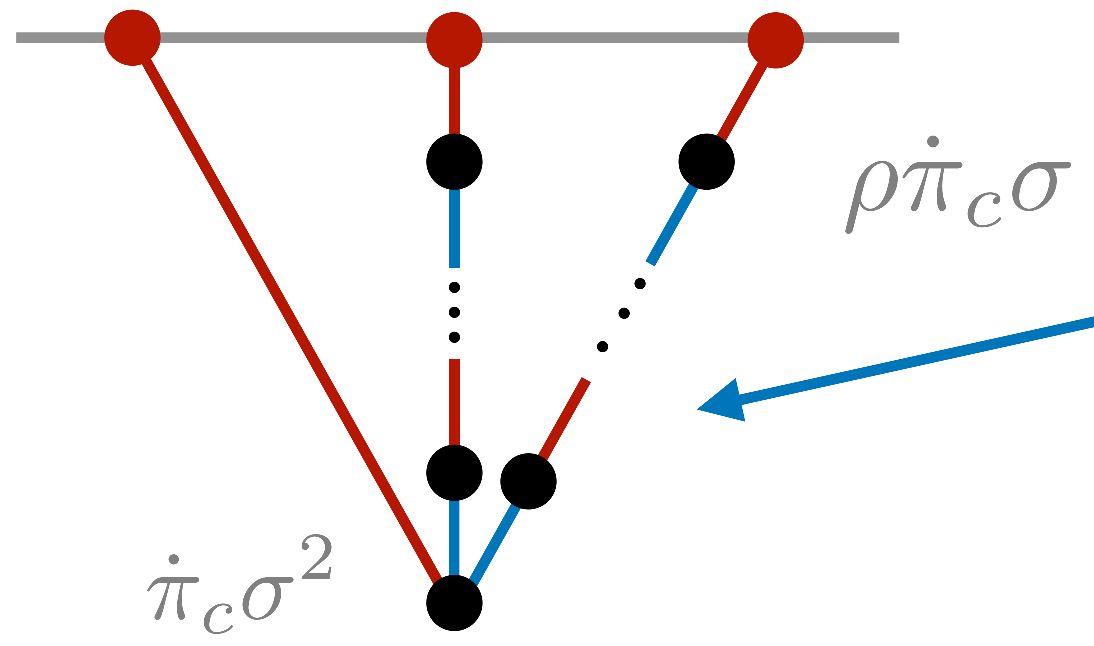
Beyond weak mixing and single exchange

Cosmological Collider Signal at Strong Mixing

Super-Hubble behaviour governed by **effective mass** $m^2 \to m^2_{\text{eff}} = m^2 + \rho^2$ An et al, Iyer et al 2017



Same frequency of cosmological collider for **heavy but weakly mixed** and **light but strongly mixed** field



Resummation of quadratic mixings

<u>Frequency</u> $\mu^2_{\text{eff}} = m^2_{\text{eff}}/H^2 - 9/4$

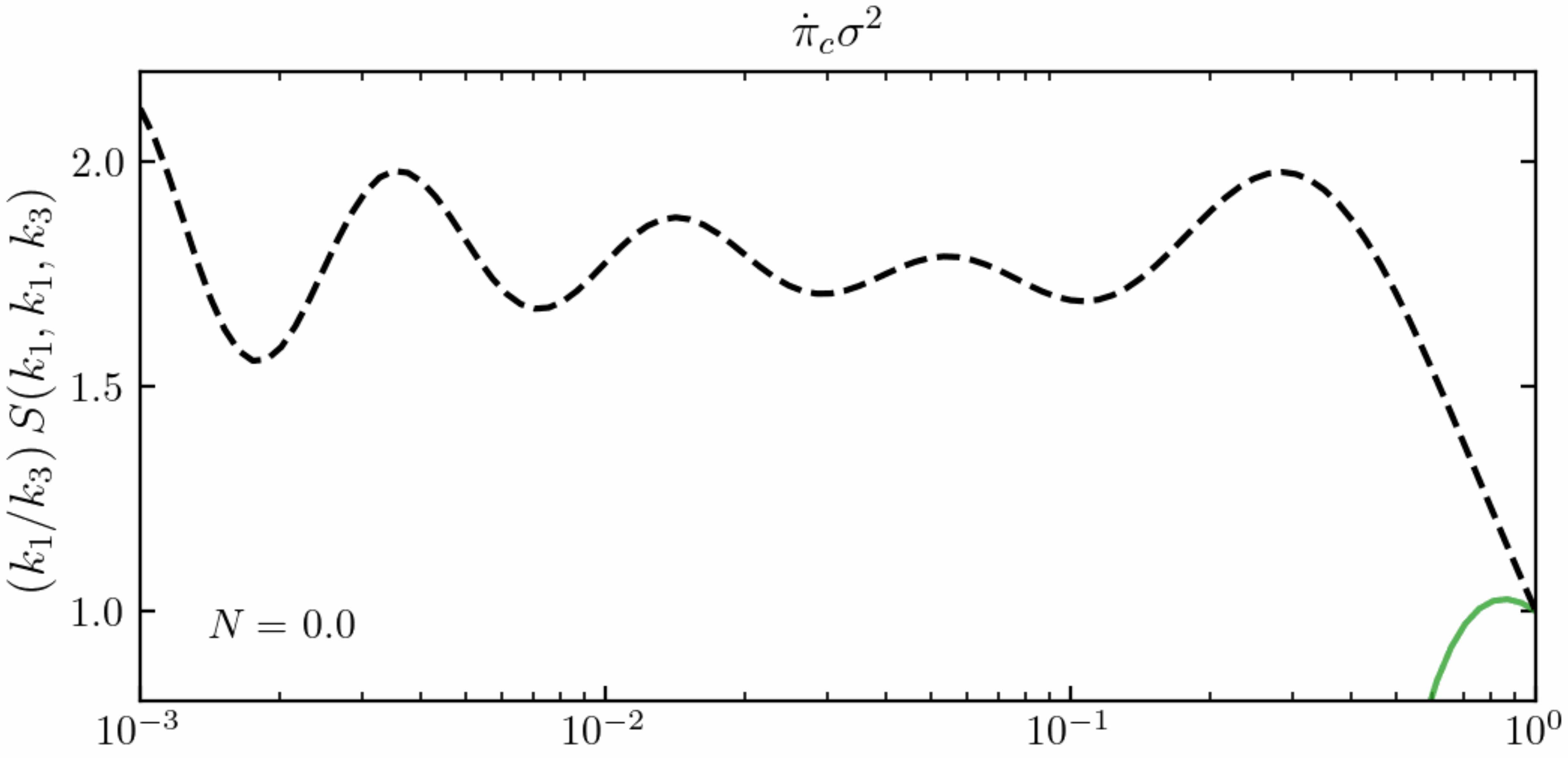
Werth, Pinol, Renaux-Petel [2023 a,b]

CosmoFlow allows complete predictions. Necessary to break degeneracies

Cosmological Collider Flow

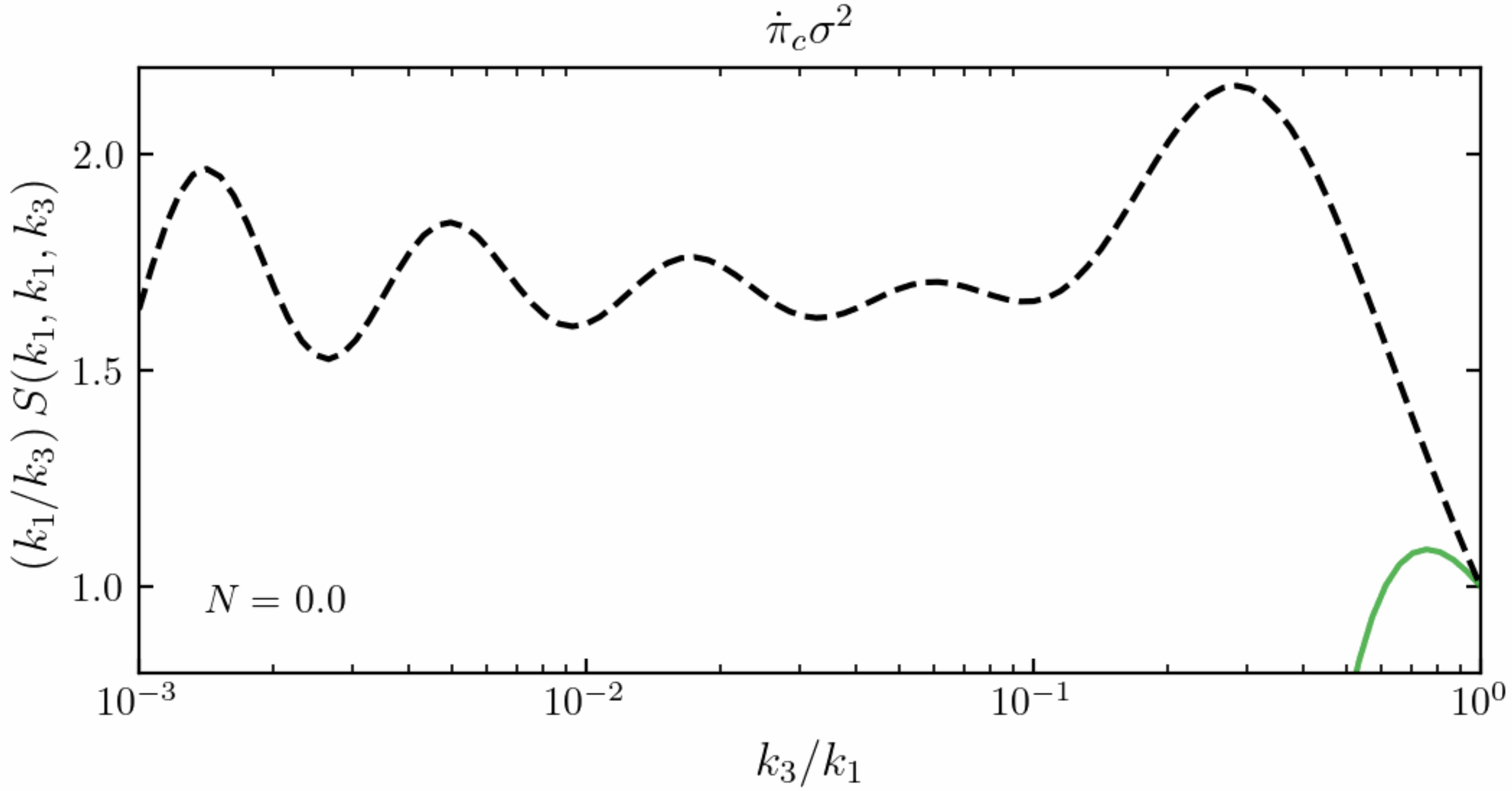
Weak mixing

$\mu_{\text{eff}} = 5, \rho/H = 0.1$



Strong mixing

$\mu_{\text{eff}} = 5, \rho/H = 5$



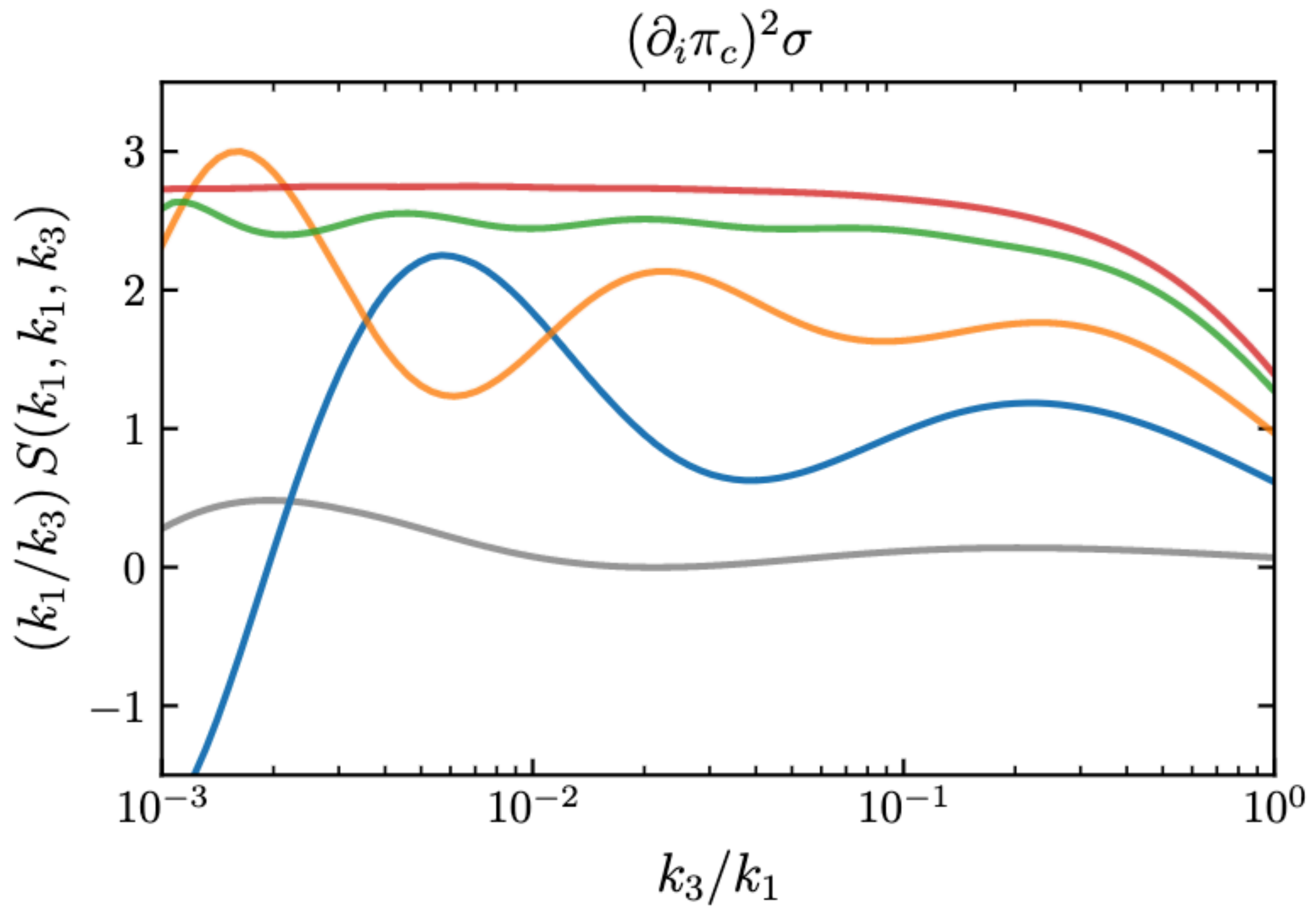
Flow of pi correlators

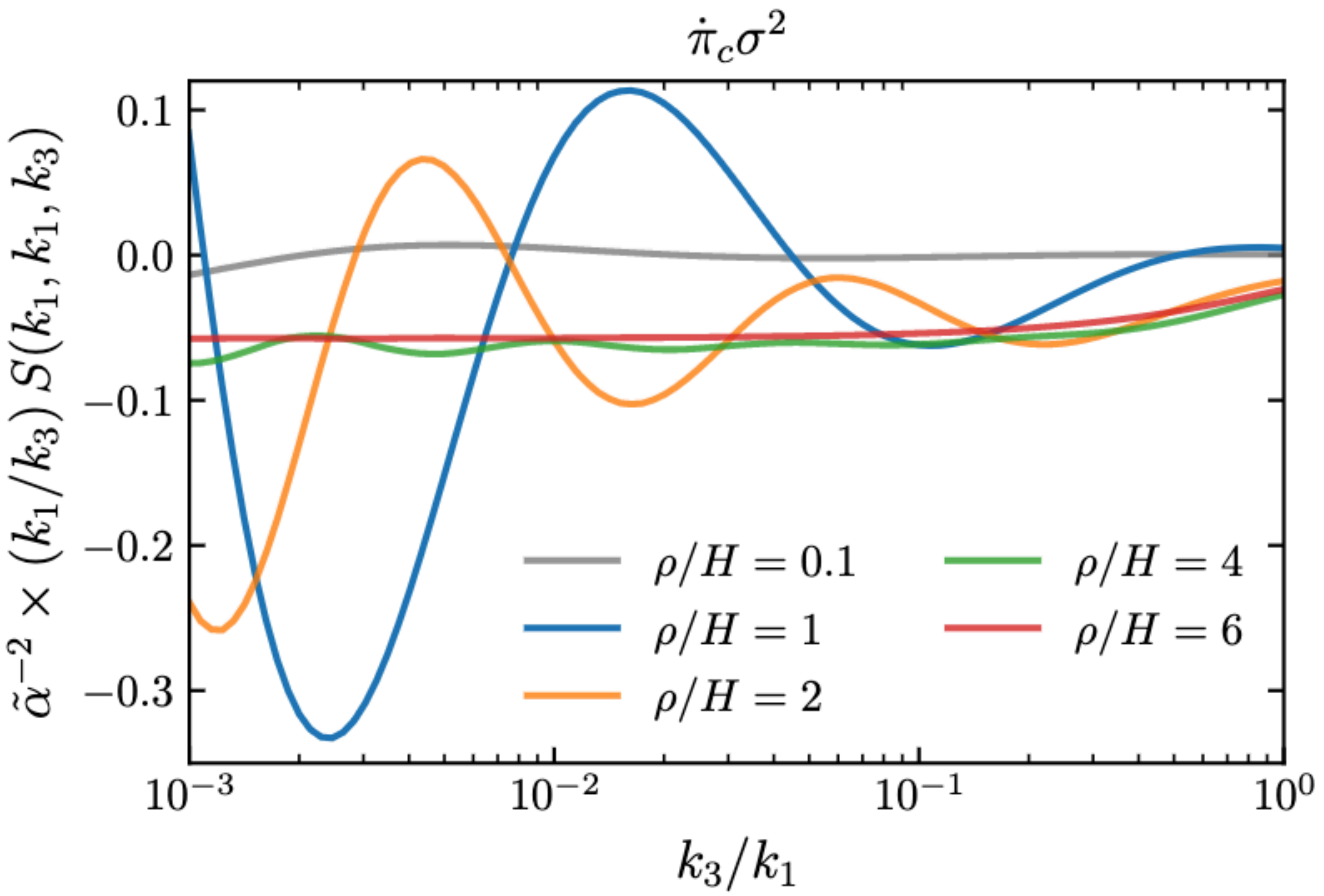
Identification of characteristic times

Assist theoretical understanding

Werth, Pinol, Renaux-Petel [2023 a,b]

Larger cosmological collider signal allowed at Strong Mixing!





Fixed mass $m = 2H$

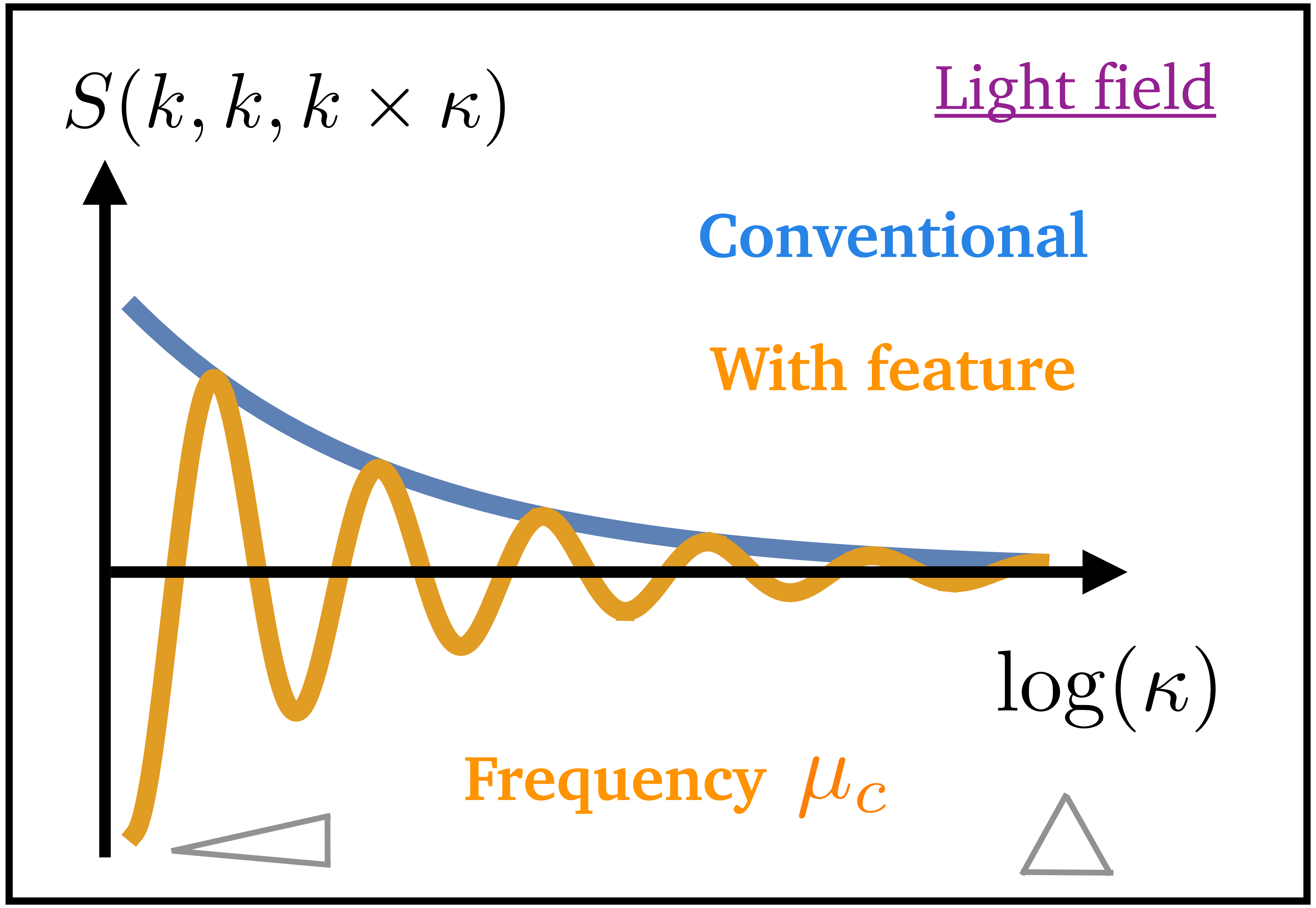
Amplitude ρ/H of mixing varies

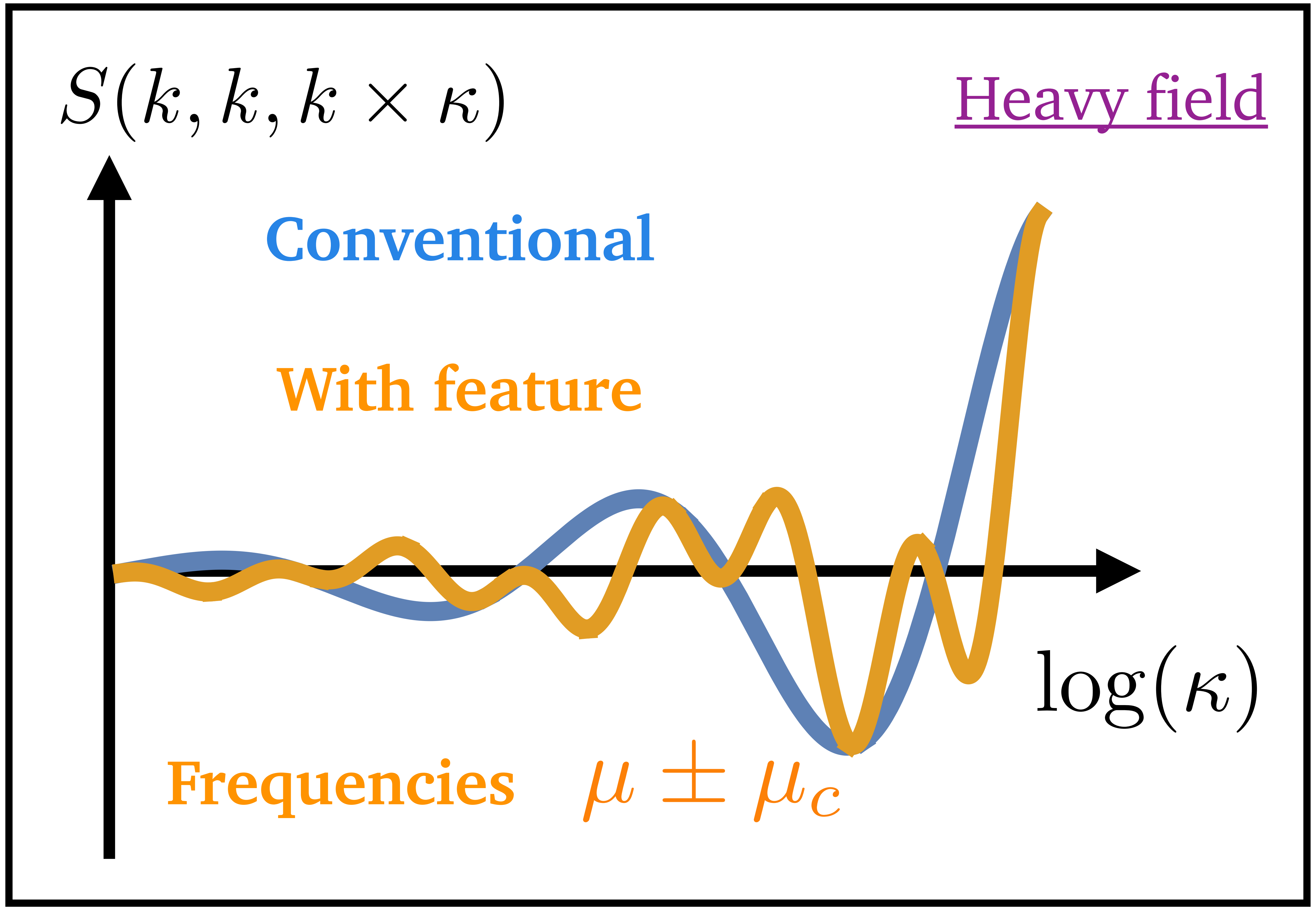
Cosmological Collider with Features

Werth, Pinol, Renaux-Petel [2023 a,b]

Motivated example: $$\rho(t) = \rho_0 \left(\frac{a_0}{a}\right)^n \sin\left[\omega_c(t - t_0)\right]$$

Frequency $\mu_c = \frac{\omega_c}{H}$



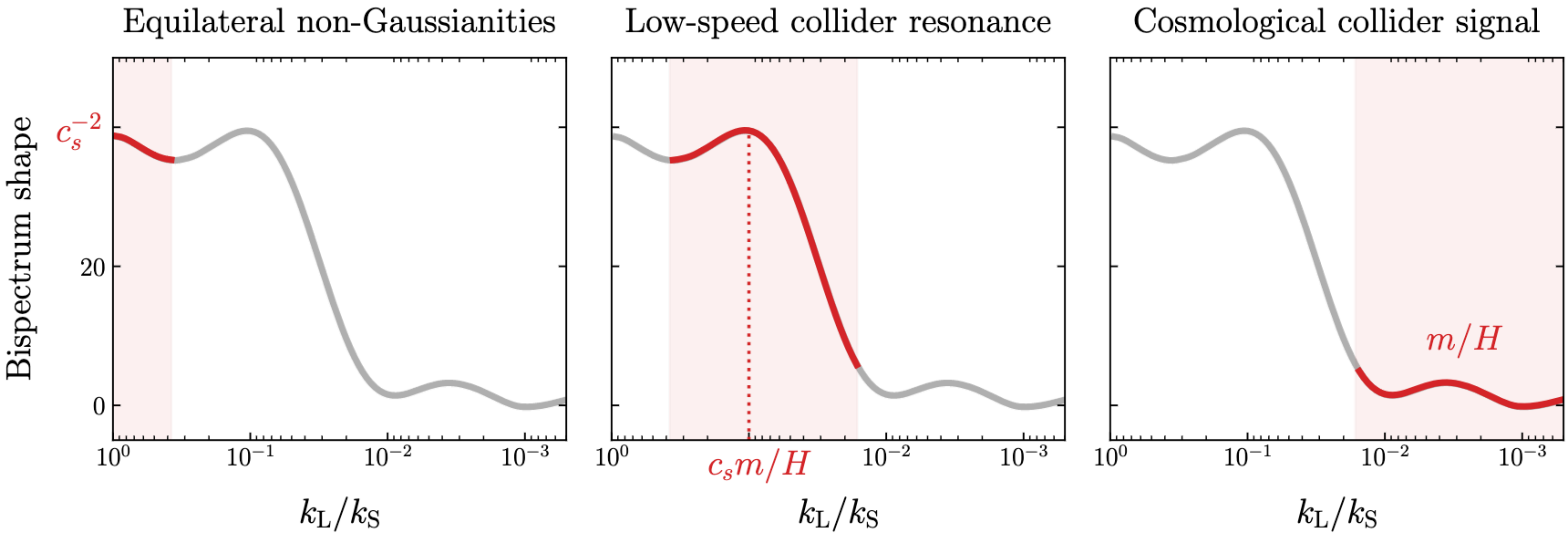


IV. The Low Speed Collider

- Motivation
- Non-local single-field EFT
- Low speed collider at strong mixing

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

Detection of large Equilateral NG, what is the next target?



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

(only possibility anyway)

Goldstone Boson coupled to Massive Field

π quadratic sector

canonically normalised

σ quadratic sector

quadratic mixing

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

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

Non-linearly realised symmetry

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

Self-interactions

Bootstrap results in simplest situation

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

+ **Cosmological Flow** in all situations

But transparent physical understanding with non-local single-field EFT

Non-local single-field EFT

$$(\cancel{\partial_t^2 + 3H\partial_t} - \tilde{\partial}_i^2 + m^2)\sigma = \rho\dot{\pi}_c$$

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

$\xrightarrow{c_s^2 \ll 1}$

$$\sigma_{\mathrm{EFT}} = \rho\mathcal{D}^{-1}\dot{\pi}_c$$

$$\mathcal{D}^{-1} = (-\tilde{\partial}_i^2 + m^2)^{-1}$$

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

Low sound speed $\longrightarrow$ Instantaneous response of supersonic field to dynamics of π $\longrightarrow$ Single-field EFT

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

Non-local in space

$\downarrow$

Interactions delocalized in time

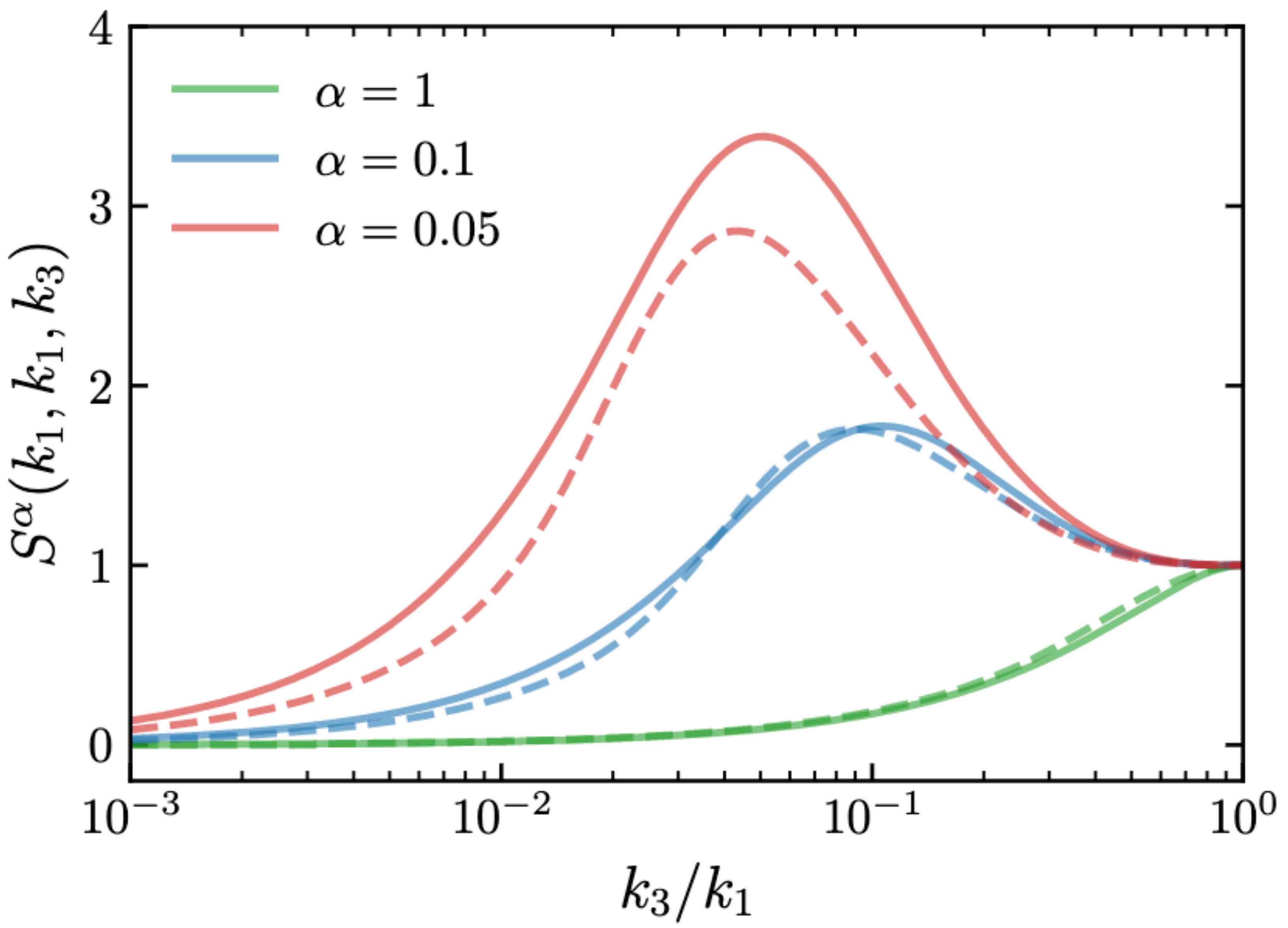
Weak mixing

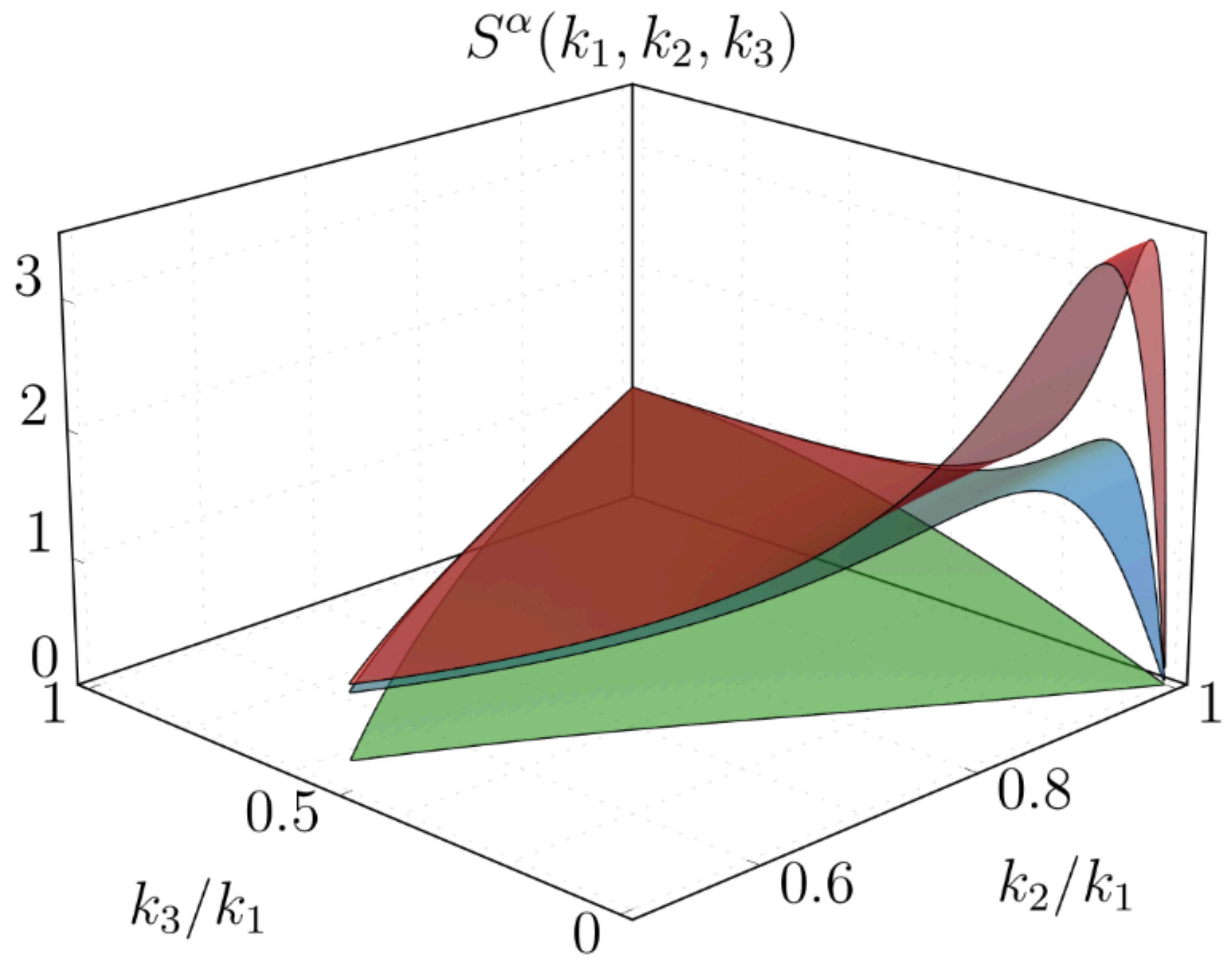
Jazayeri, Renaux-Petel [2022]
Jazayeri, Renaux-Petel, Werth [2023]

All interactions contact $\longrightarrow$ Simple analytical results for all interactions

Simple factorizable template

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





Resonance comparable to self-interactions when pushing

$$\rho \sim m$$

$\downarrow$

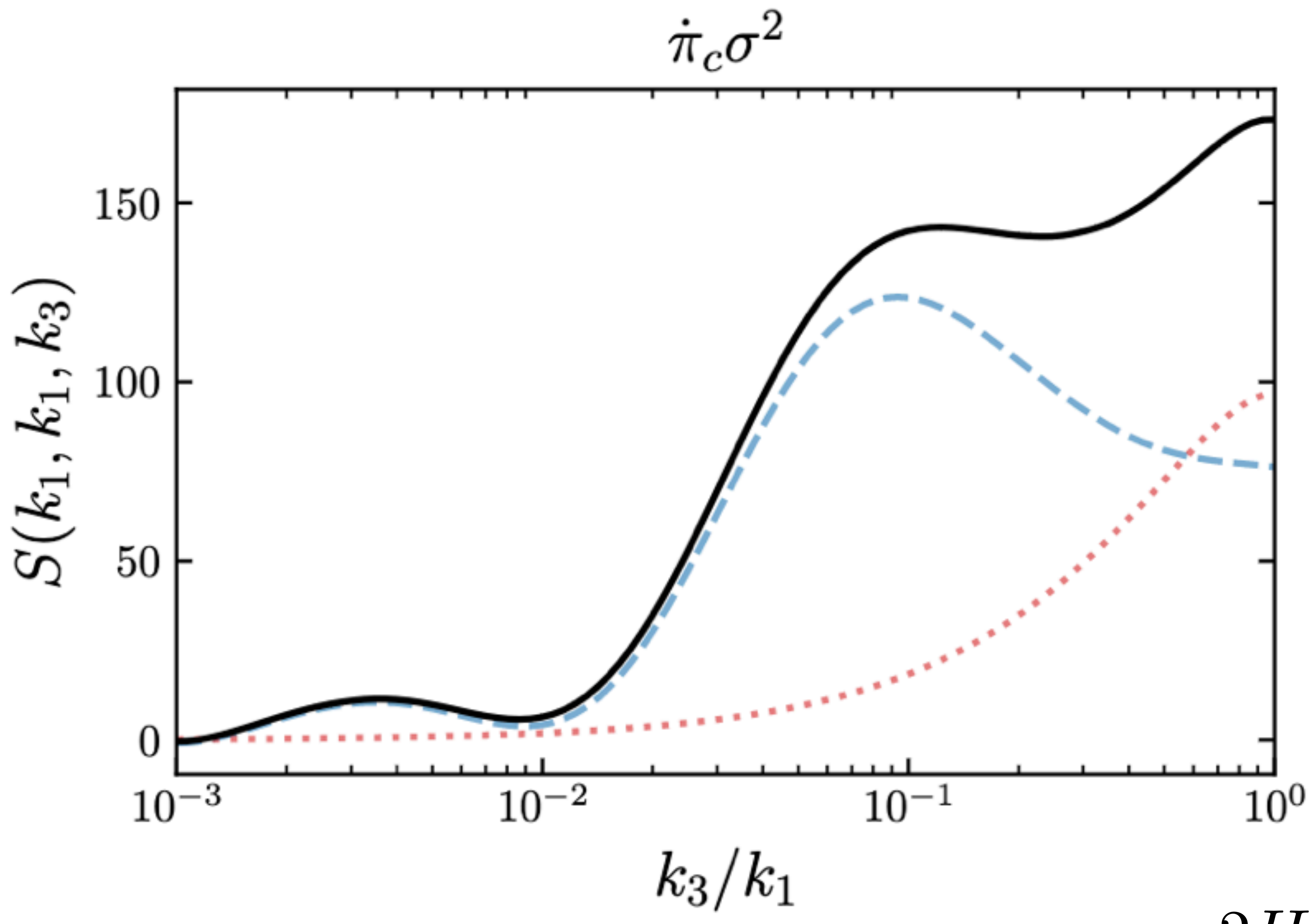
Non-perturbative treatment of mixing required

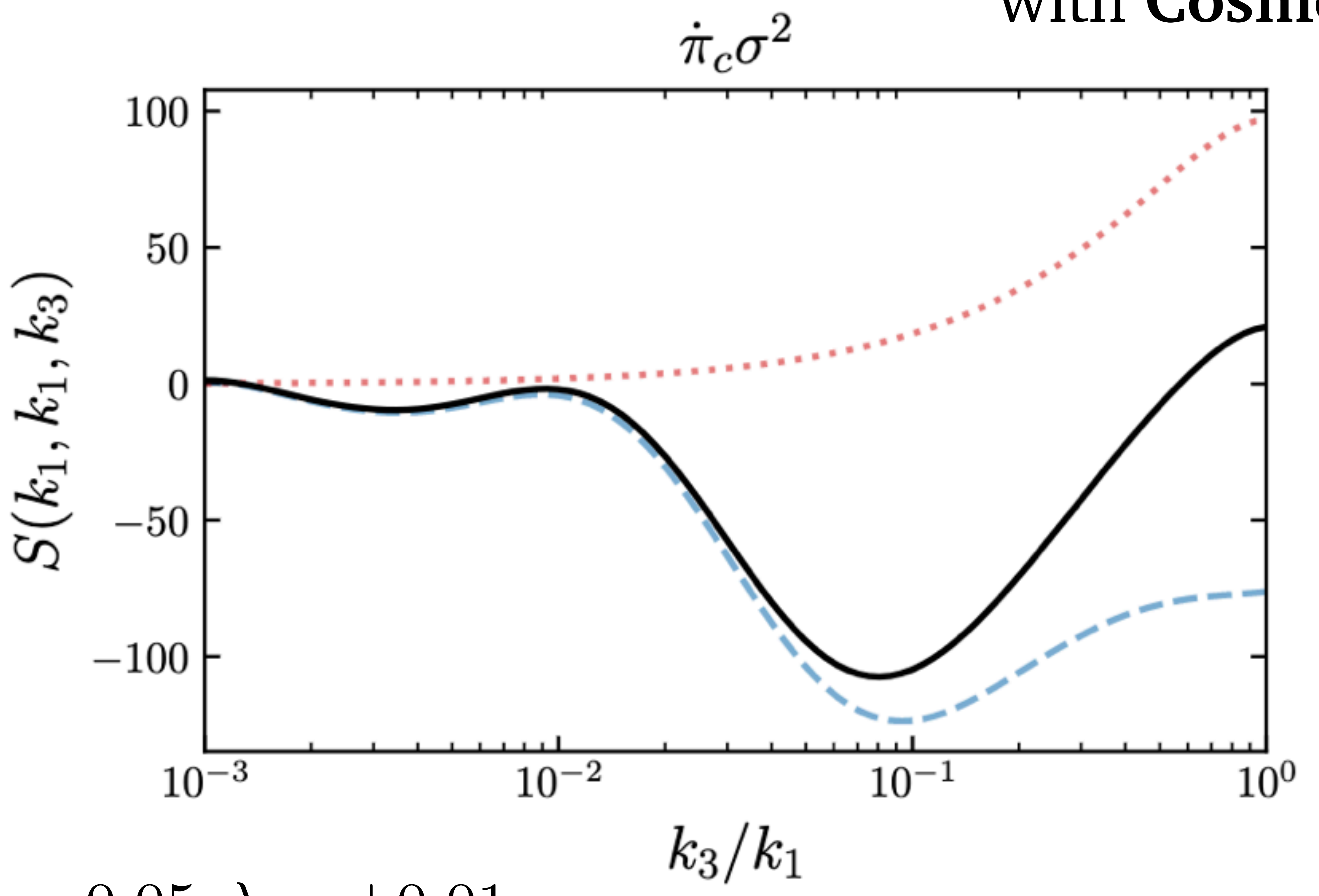
Strong mixing

Jazayeri, Renaux-Petel [2022]
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

Conclusions

- Cosmological collider beyond vanilla models: several new motivated signals when restrictive assumptions are released

- Next target after equilateral NG discovery(?): low speed collider resonance

- NG is a mature field but limited and biased by technical difficulties

Cosmological Flow program

Efficient and systematic

Generate theoretical data to explore rich physics of inflation

Assist theoretical understanding

Outlook

Natural extensions:

Spinning fields

Higher-point correlators

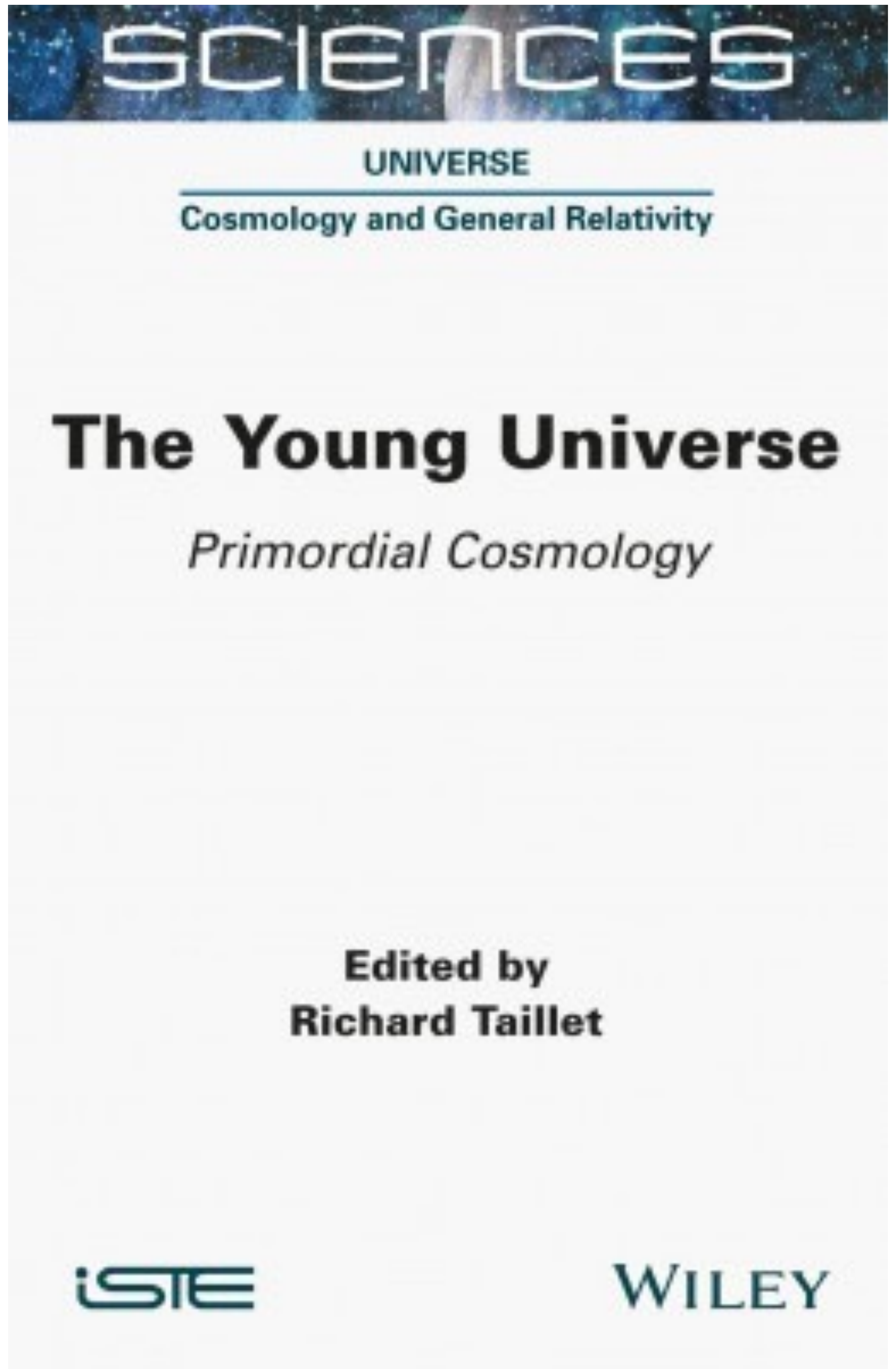
The Cosmological Flow

Wavefunction

Loop level
(not straightforward)

Path integral formulation

Thank you!



Oct 22, 348 pages

undergraduate & graduate textbook, 4 authors :

1. A Thermal History of the Universe and Primordial Nucleosynthesis, Pierre Salati.

2. Cosmological Microwave Background, Julien Lesgourgues.

3. Cosmological Inflation, Sébastien Renaux-Petel.

4. Dark Matter, Richard Taillet.