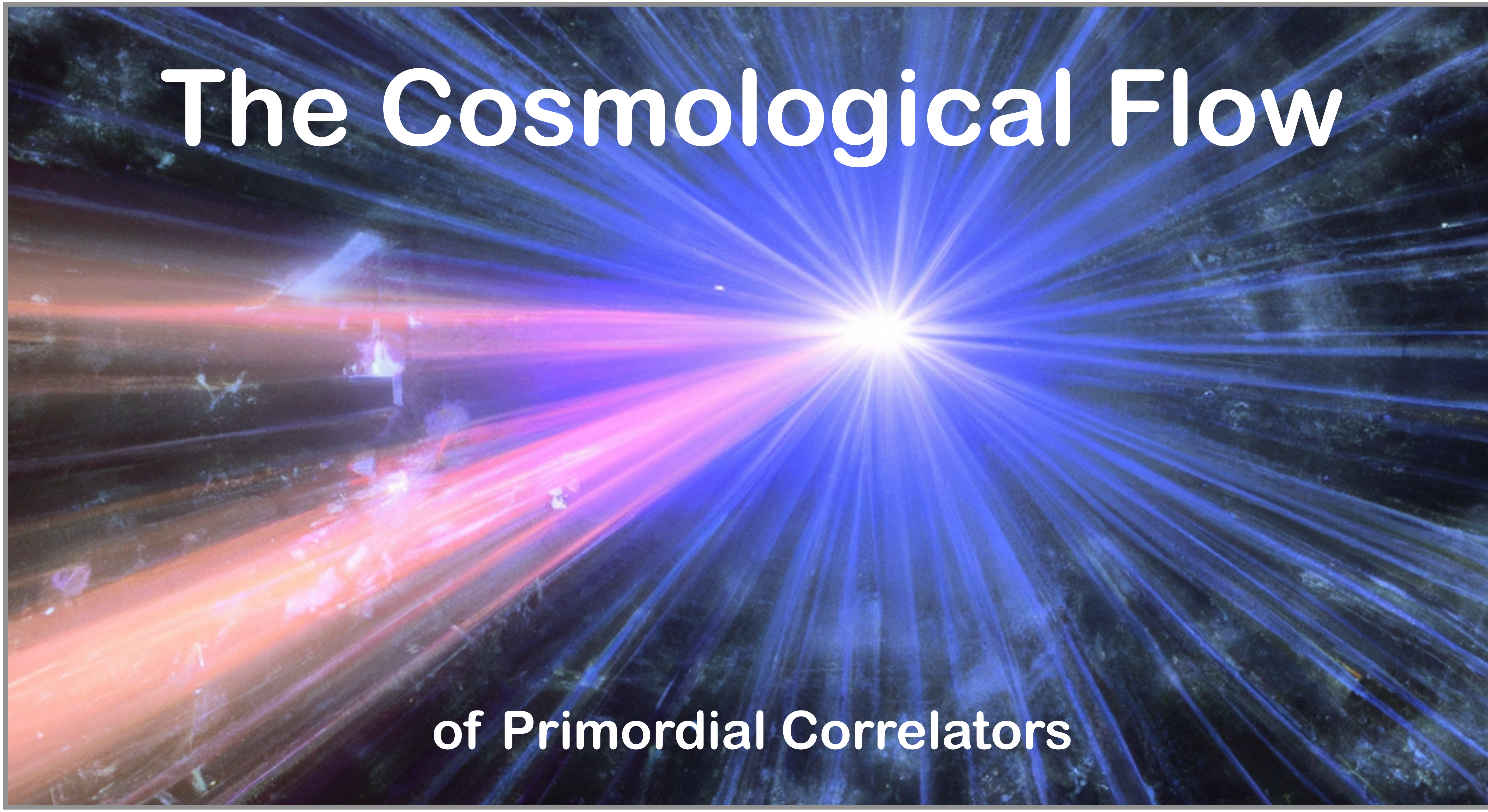
The Cosmological Flow

of Primordial Correlators



Cosmology From Home 2023

Denis Werth

Based on: ArXiv:2302.00655 (short paper)

ArXiv:2305.xxxxx (long paper)

with Lucas Pinol and Sébastien Renaux-Petel

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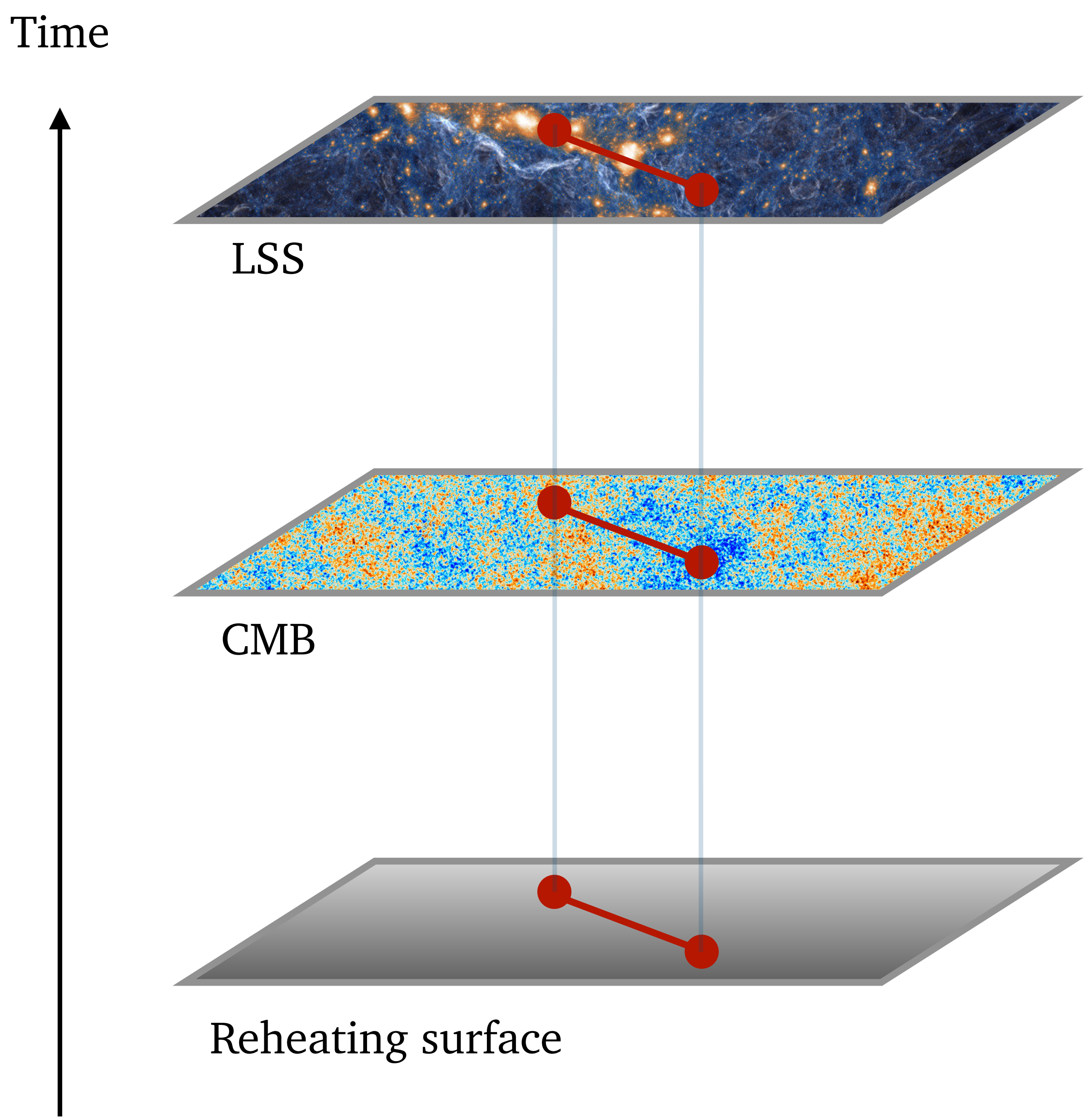
Cosmology: A History of Time

Cosmological fluctuations are **correlated** on large scales



Transfer function

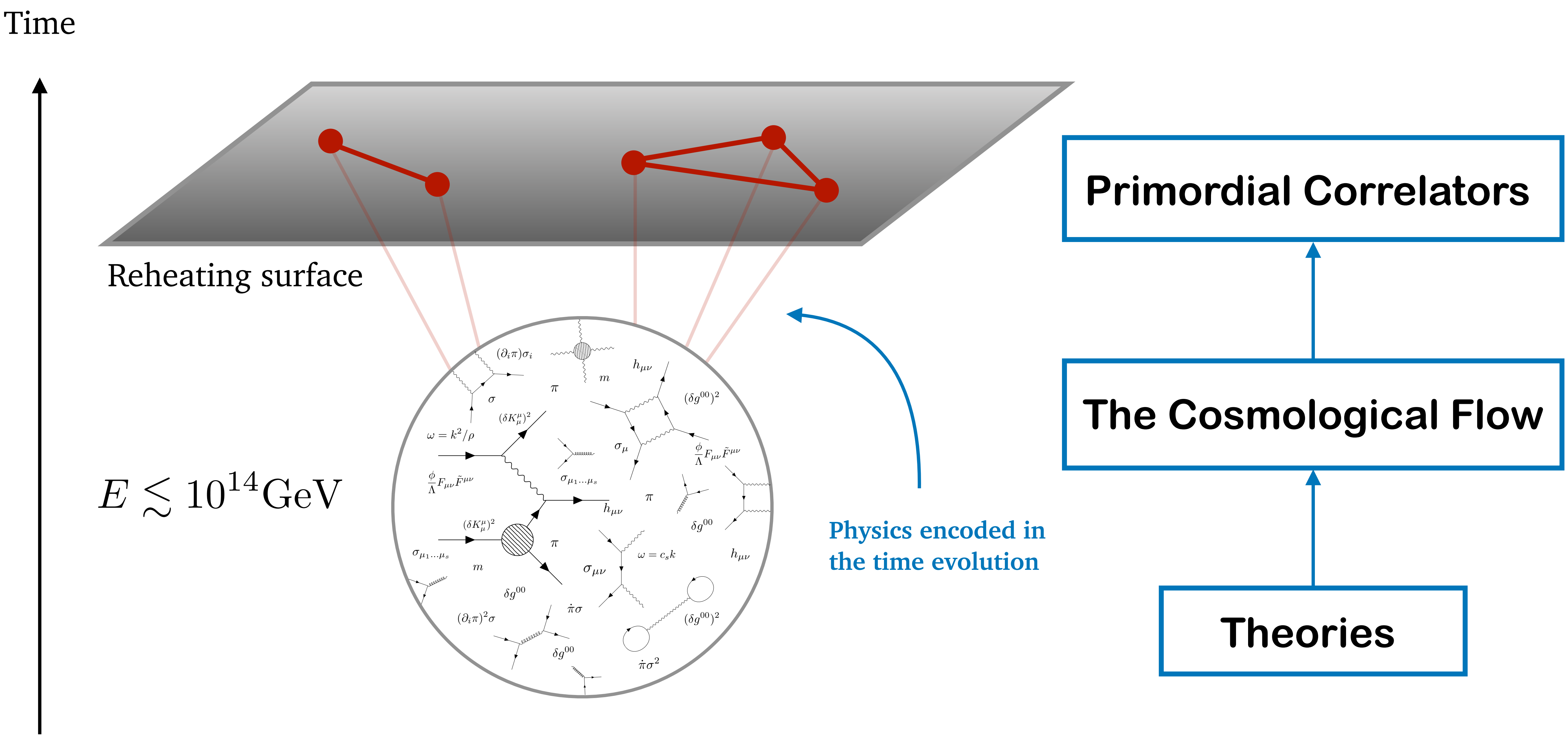
$$\langle X^2(\boldsymbol{k},t)\rangle = \mathbf{T}^2(\boldsymbol{k};t,t_0)\langle X^2(\boldsymbol{k},t_0)\rangle$$

- Linear clustering
- Dark matter, photons, baryons
- …

The physics is encoded in the **time evolution** of these fluctuations

The Cosmological Flow Philosophy

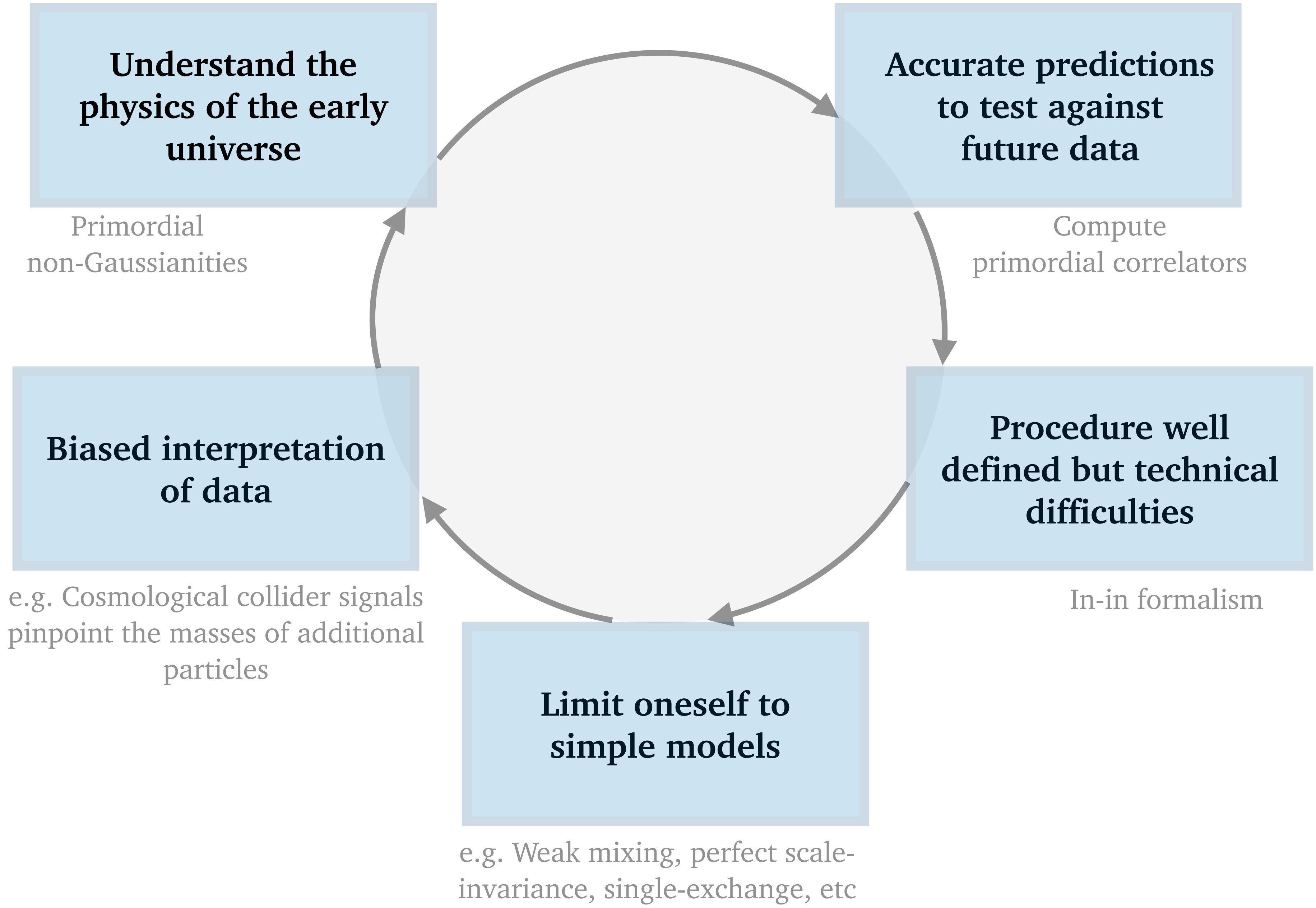
Inflation is a unique probe of the physics
at the highest reachable energies



Follow the **time evolution** of primordial fluctuations from their origin as **quantum vacuum fluctuations** to the reheating surface

Why the Cosmological Flow ?

The **Cosmological Flow** is an **efficient** and **systematic** approach to compute primordial correlators

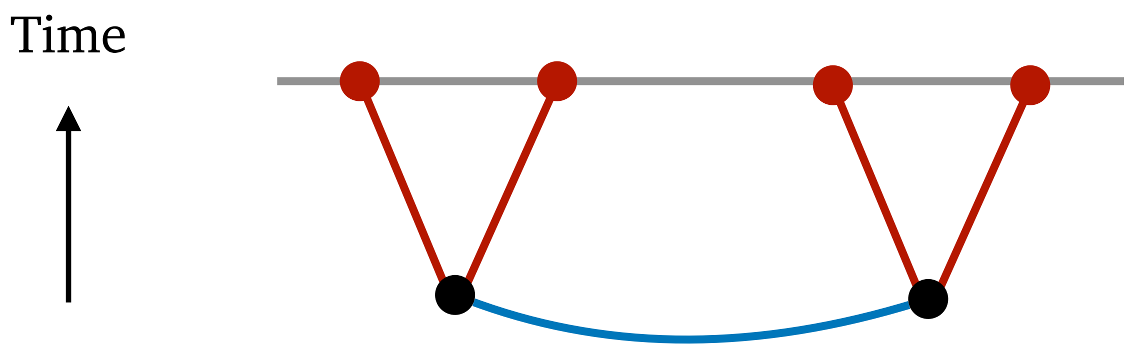


The Cosmological Flow

Primordial Correlators

Well-established Procedure but Technical Difficulties

In practice, we compute Feynman-Witten **diagrams**



$$\langle \boldsymbol{X}^4 \rangle = \int_{-\infty}^{0} \mathrm{d}t\, \mathrm{d}t' V(t) V(t')\, K(k_1, t) K(k_2, t) \mathcal{G}(k_{12}, t, t') K(k_3, t') K(k_4, t')$$

Late-time correlators receive contributions from all times

Nested time integrals

Hankel functions
(or even more complicated functions, e.g. chemical potential)

Quadratic theory not exactly solvable in generic theories

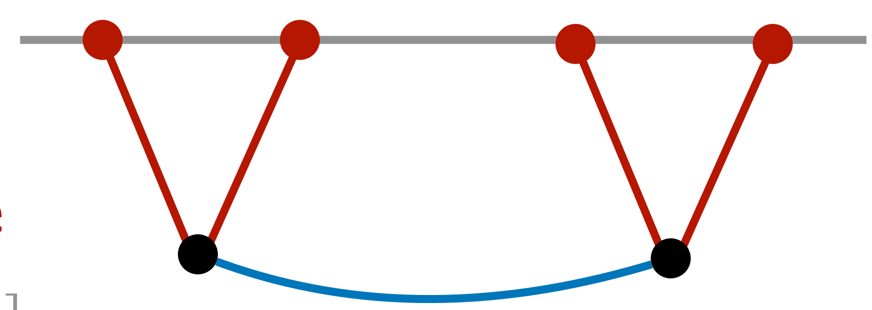
Recent Analytical Developments

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]

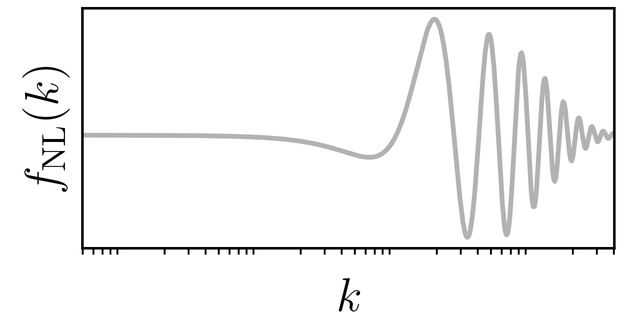
Limitations of Analytical Methods

Weak Quadratic Mixing

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

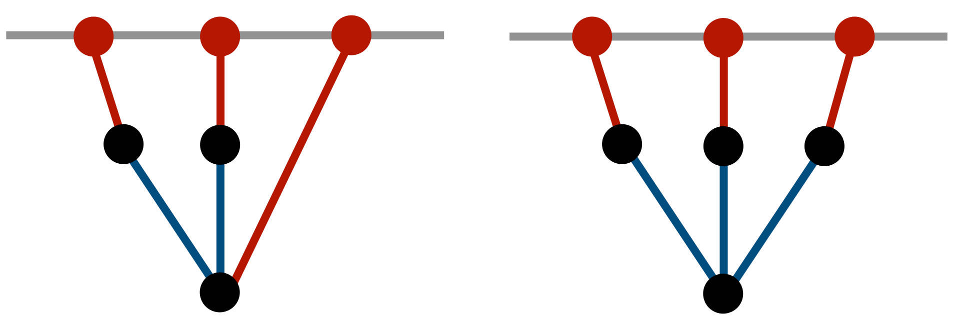
treated perturbatively

(Near) Scale-Invariance

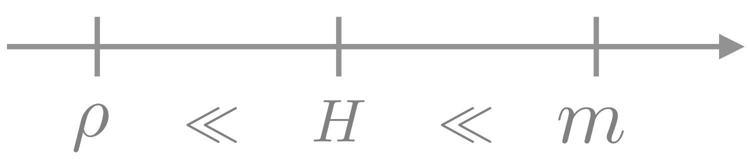


features

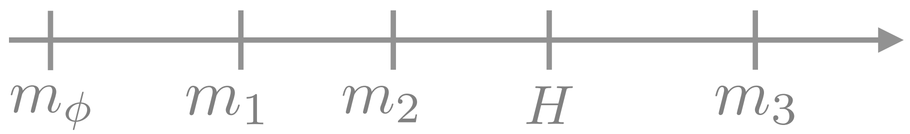
Only Single-Exchange Diagram



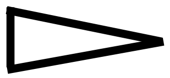
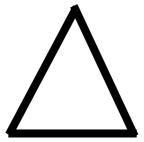
Large hierarchy of masses/couplings but not the intermediate regimes



Often only 1 or 2 Fields



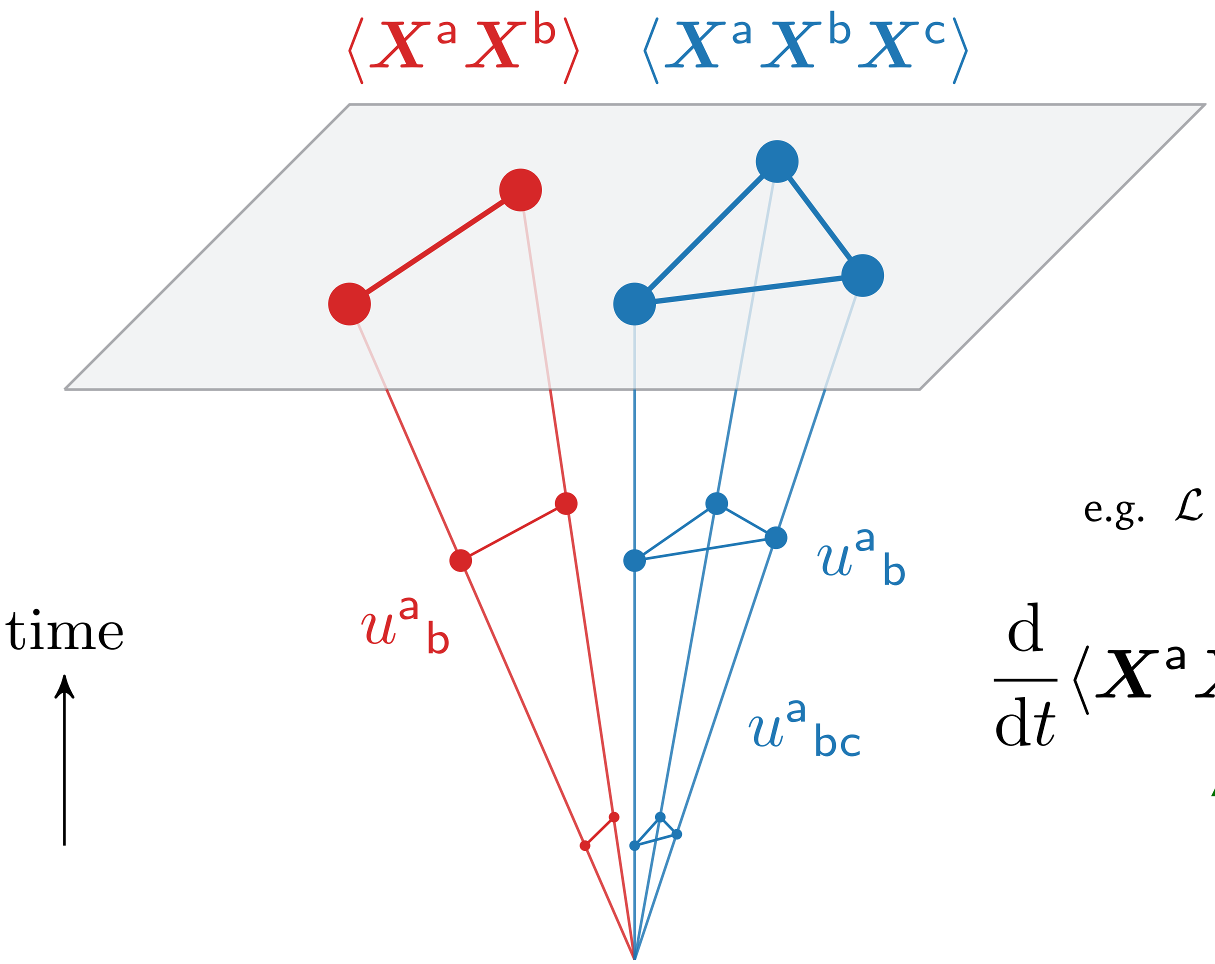
Treatment of Equilateral and Squeezed Configurations Separately

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

Aside from isolated examples…

The Cosmological Flow

From first principles, the time evolution of primordial correlators is encoded in the **flow equations** (Ehrenfest theorem)



$$\frac{d}{dt}\langle \boldsymbol{X}^a \boldsymbol{X}^b \rangle = u^a{}_c \langle \boldsymbol{X}^c \boldsymbol{X}^b \rangle + u^b{}_c \langle \boldsymbol{X}^a \boldsymbol{X}^c \rangle$$

Theory dependence (any time/momentum dependence)

e.g. $\mathcal{L} = g(t)(\partial_i \phi)^2 \sigma$ implies $u^\sigma_{\phi\phi} = g(t)\, \boldsymbol{k}_\phi \cdot \boldsymbol{k}_\phi$

$$\frac{d}{dt}\langle \boldsymbol{X}^a \boldsymbol{X}^b \boldsymbol{X}^c \rangle = u^a{}_d \langle \boldsymbol{X}^d \boldsymbol{X}^b \boldsymbol{X}^c \rangle + u^a{}_{de} \langle \boldsymbol{X}^b \boldsymbol{X}^d \rangle \langle \boldsymbol{X}^c \boldsymbol{X}^e \rangle$$

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

We have converted the problem of computing nested time integrals to **solving a set of coupled differential equations**

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

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

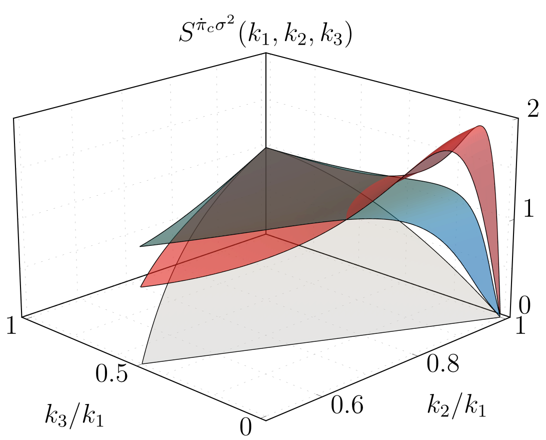
Probing High-Energy Aspects of Inflation

The Cosmological Flow offers new possibilities for **studying**, **exploring** and **understanding** inflationary physics

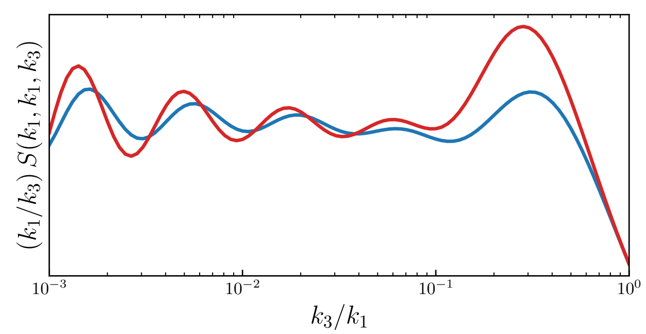
Numerical code **CosmoFlow** soon available

The Cosmological Flow

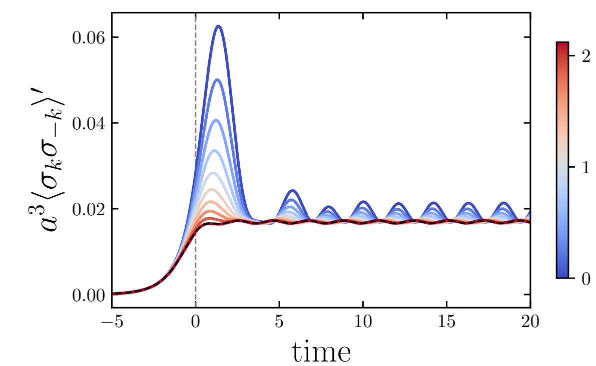
Shapes of non-Gaussianities



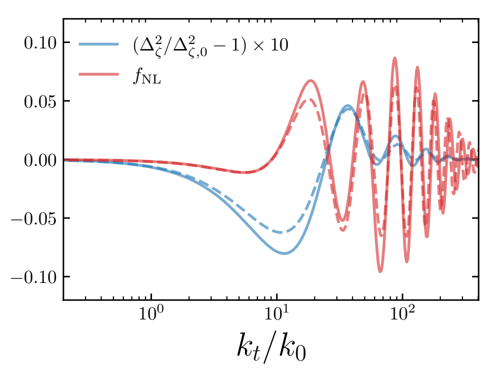
Cosmological Collider Physics



Dynamical aspects of cosmological correlators



Primordial **Features**

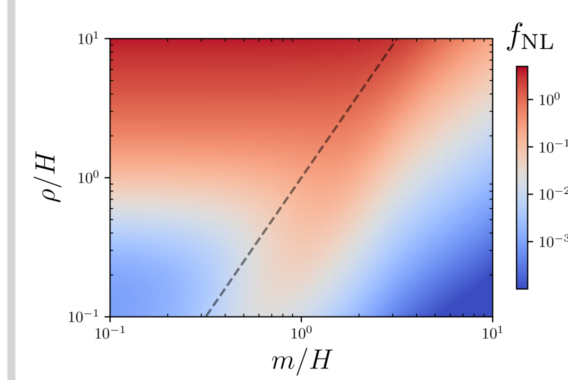


New **templates** for upcoming surveys

$$S = (k_3/k_1)^{\frac{1}{2}+n-\nu}\mathcal{A}\cos(\mu_c \log(k_3/k_1) + \varphi)$$

$$S = (k_3/k_1)^{\frac{1}{2}+n}\sum_{\pm}\mathcal{A}_\pm \cos[(\mu \pm \mu_c)\log(k_3/k_1) + \varphi_\pm]$$

Size of non-Gaussianities



Applications

EFT of Inflationary Fluctuations

We couple the **Goldstone boson** to an additional **massive scalar field**

$$\zeta = -H\pi$$

linear mixing (broken Lorenz invariance)

π quadratic sector

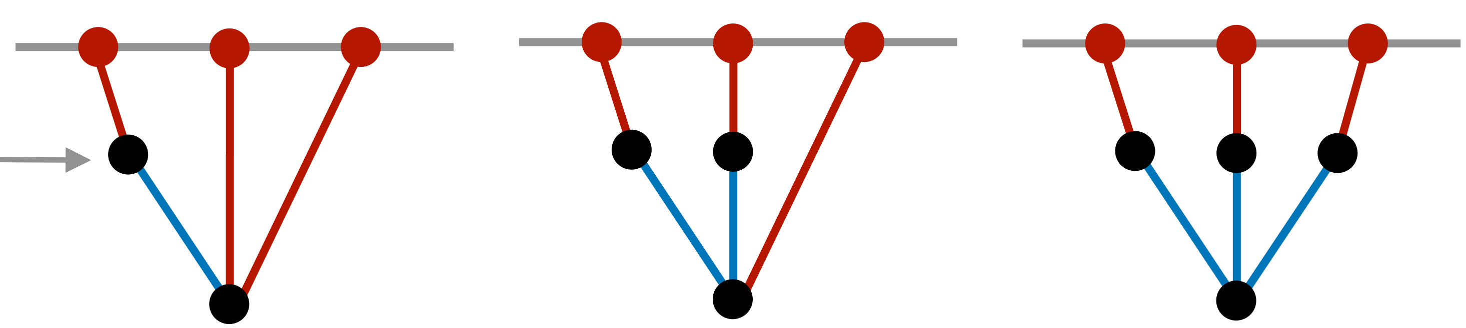
σ quadratic sector

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

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

Cubic interactions

Assuming weak mixing



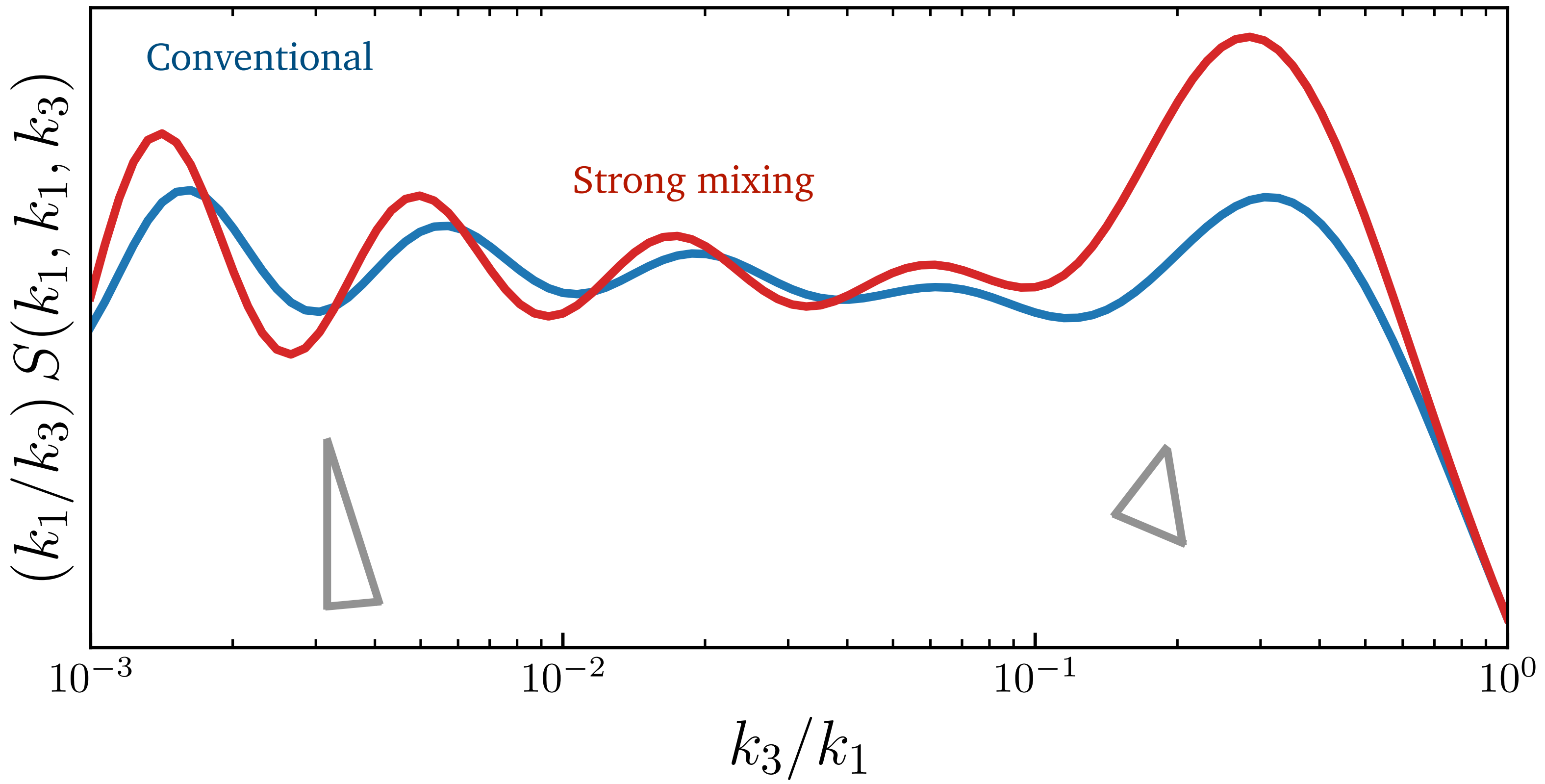
Relax assumptions: beyond weak mixing, time-dependent mixing

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

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

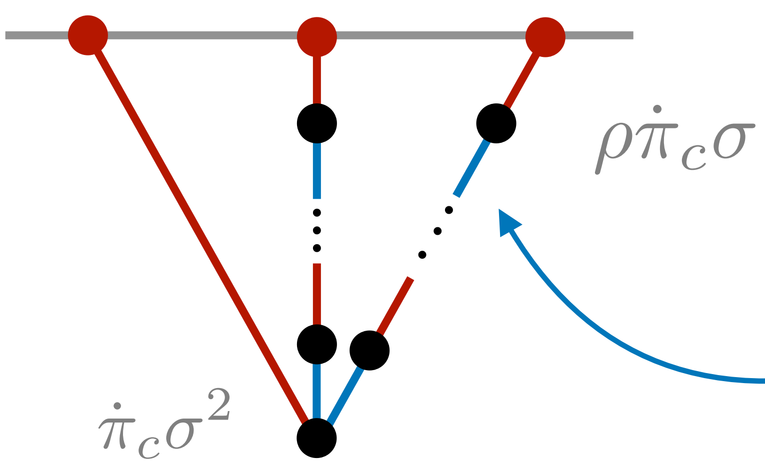
Cosmological Collider Signal at Strong Mixing

The cosmological collider signal of **heavy but weakly mixed** particle oscillates at the same frequency than that of a **light but strongly mixed** particle



<u>Frequency</u>

$$\mu_{\rm eff}^2 = m_{\rm eff}^2/H^2 - 9/4$$



Effective mass for the heavy field

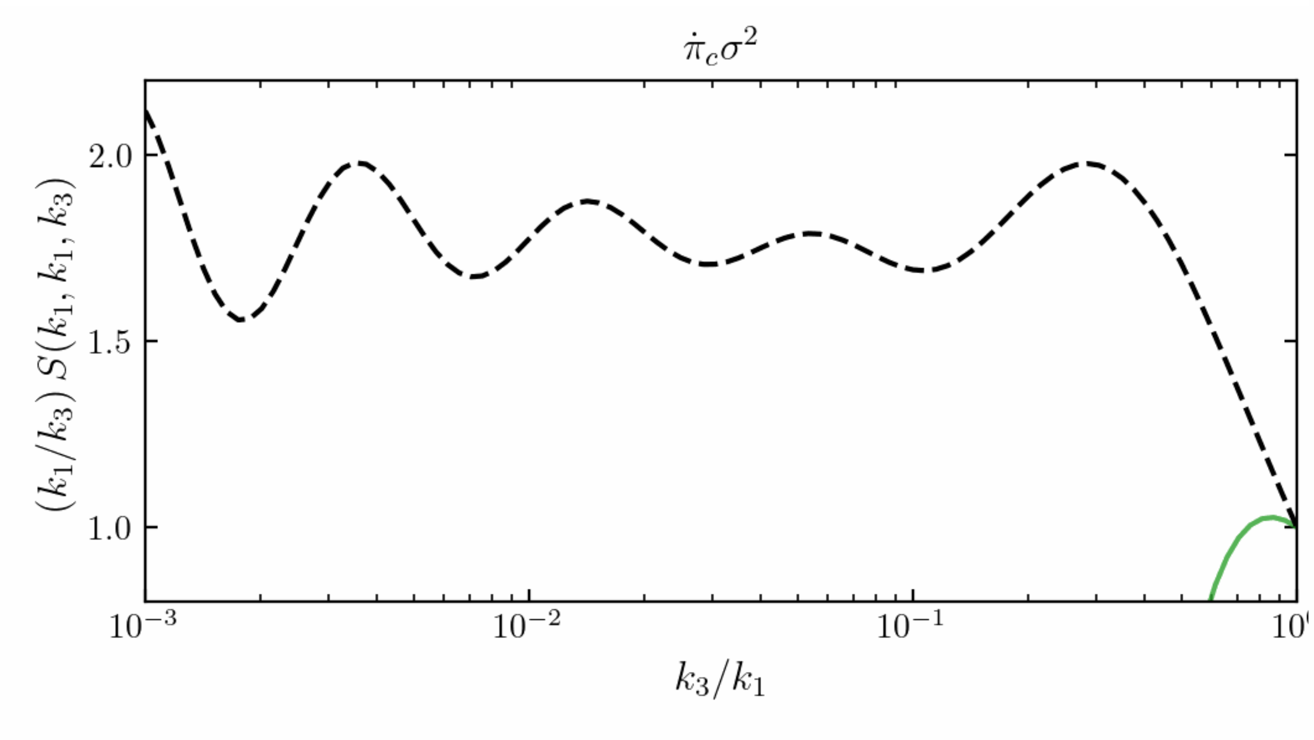
$$m^2 \to m_{\rm eff}^2 = m^2 + \rho^2$$

Resummation of quadratic mixings

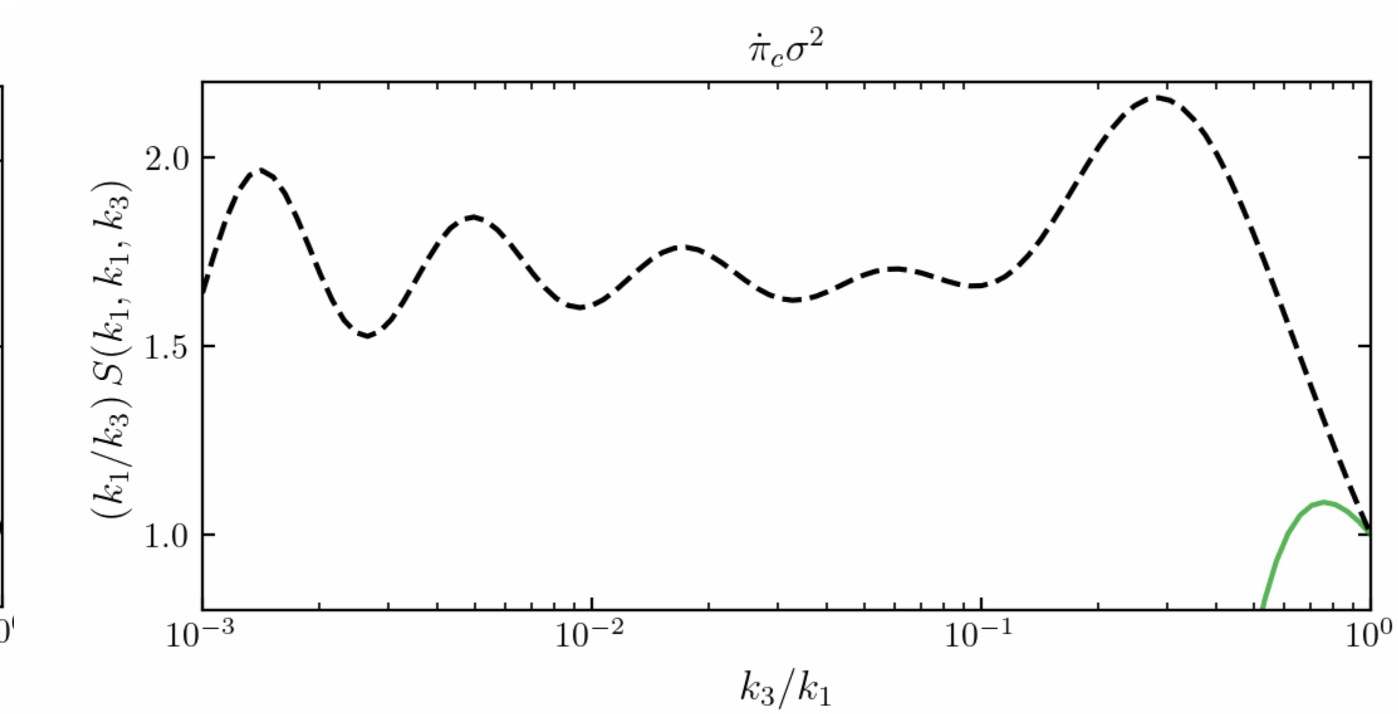
Werth, Pinol, Renaux-Petel [2023 a, b]
Castillo, Koch, Palma [2014]
An, McAneny, Ridgway, Wise [2018]
Iyer, Pi, Wang, Wang, Zhou [2018]

The Cosmological Collider Flow

The Cosmological Flow enables us to access the **time evolution** of primordial correlators and to identify **characteristic time scales**



Weak mixing



Strong mixing

github.com/deniswerth/Cosmological-Collider-Flow

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

Cosmological Collider Signal with Features

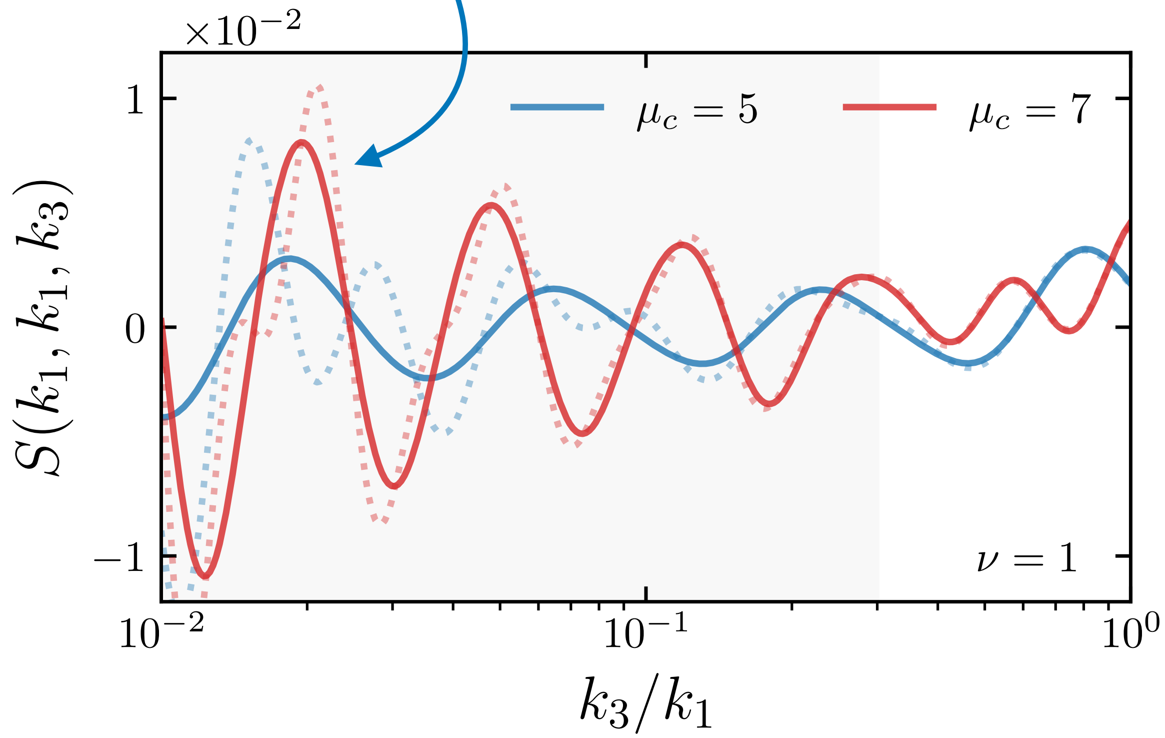
The cosmological collider signal of an **oscillating linear mixing** exhibits new features

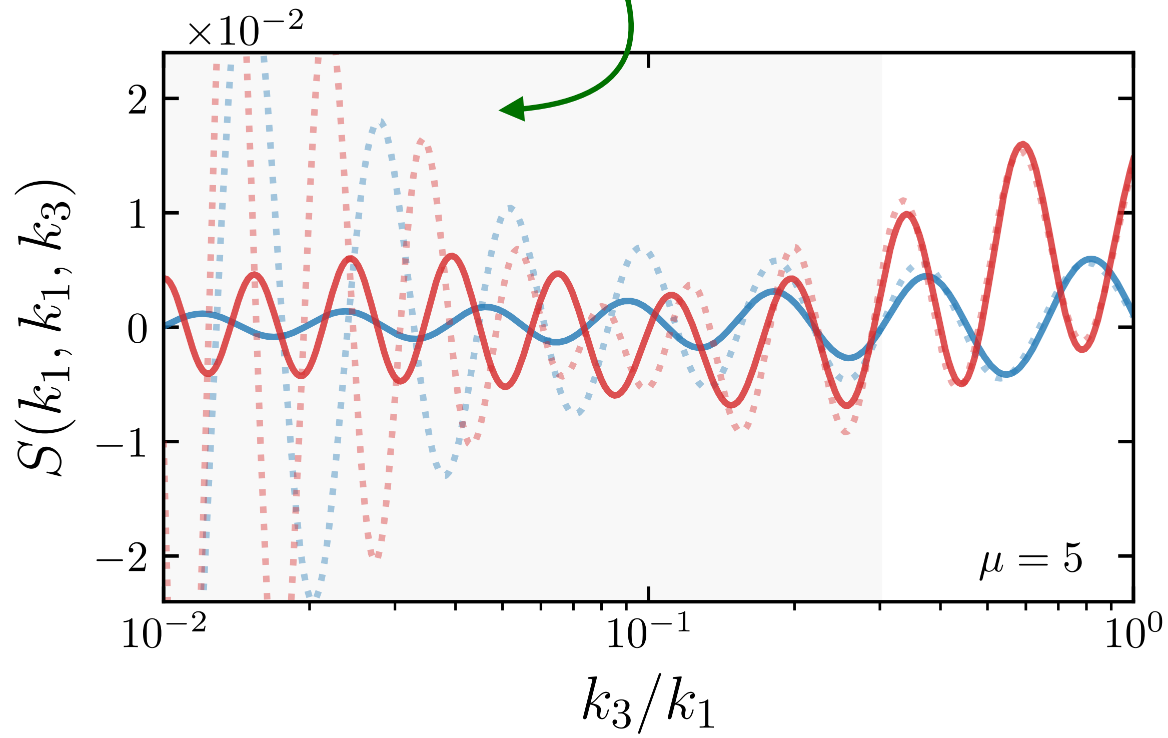
$$\rho(t) = \rho_0 (a_0/a)^n \sin[\omega_c(t - t_0)]$$

Expected distinctive oscillations in the **scale-dependent galaxy bias**

Unobservable effects subtracted

$\mu^2 = m^2/H^2 - 9/4$
$\mu_c = \omega_c/H$





$$S = (k_3/k_1)^{\frac{1}{2}+n-\nu} \mathcal{A} \cos(\mu_c \log(k_3/k_1) + \varphi)$$

$$S = (k_3/k_1)^{\frac{1}{2}+n} \sum_{\pm} \mathcal{A}_{\pm} \cos[(\mu \pm \mu_c) \log(k_3/k_1) + \varphi_{\pm}]$$

New templates

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

Conclusions and Take-Home Messages

Primordial **non-Gaussianities** to understand the **physics of inflation**, primary target for future missions

Cosmological Collider: probe the laws of physics at the highest reachable energies with new templates and complete predictions

The Cosmological Flow

Concentrating on **exploring** and **understanding** the physics in motivated scenarios **in full generality**

Efficient and **systematic** approach to compute inflationary correlators, avoiding technical difficulties

We have only scratched the tip of the iceberg …

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Thank you