UNIVERSITY OF CAMBRIDGE

The Stephen Hawking Centre for Theoretical Cosmology

Bootstrapping Multi-Field Inflation:

non-Gaussianities from light scalars revisited

with Guilherme Pimentel, Ana Achucarro

arXiv: 2212.14035

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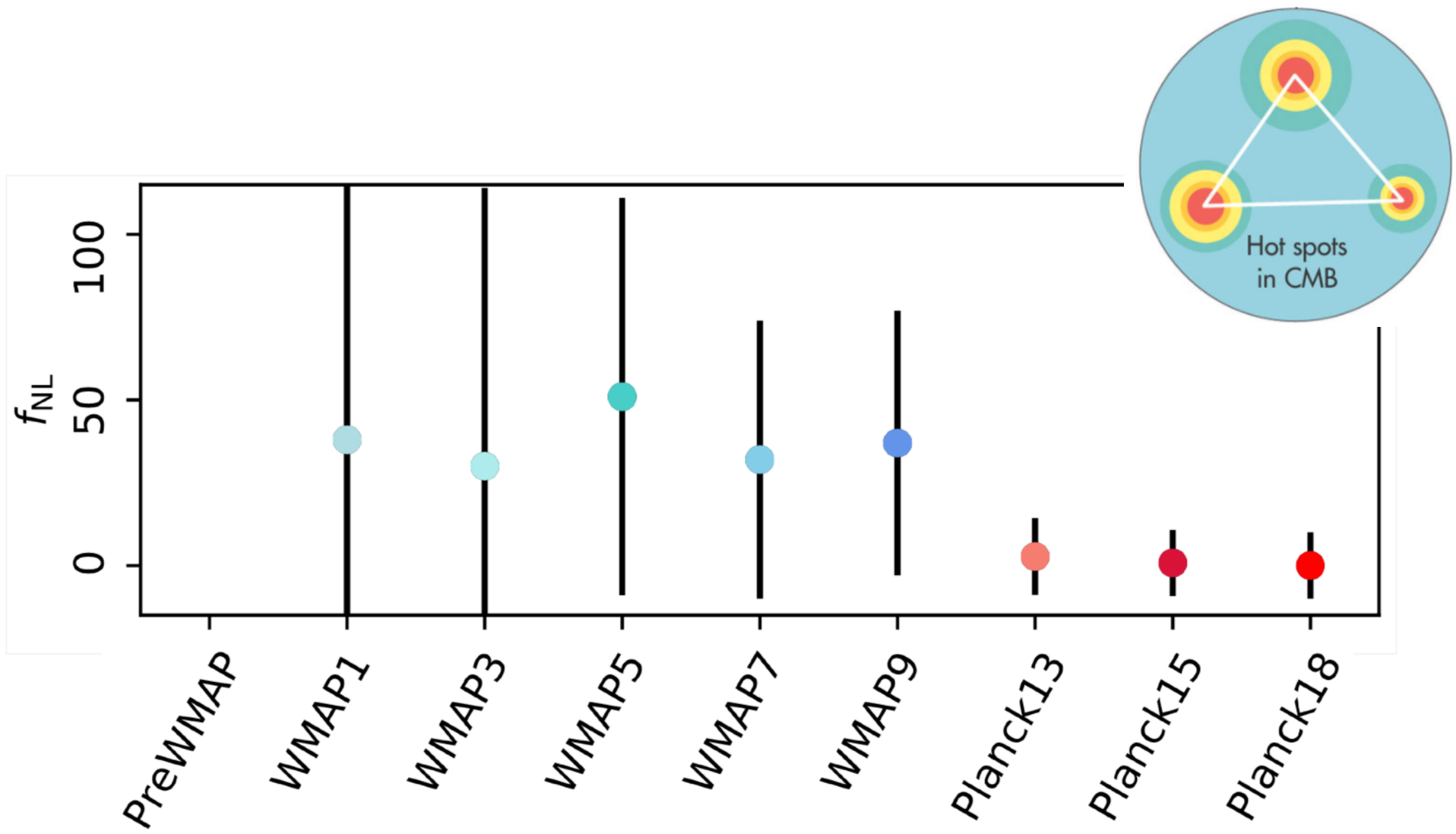
Cosmology From Home 2023

If we enter a data-oriented conference on non-Gaussianity...

$$S^{\rm local} = \frac{k_1^3 + k_2^3 + k_3^3}{k_1^3 k_2^3 k_3^3}$$

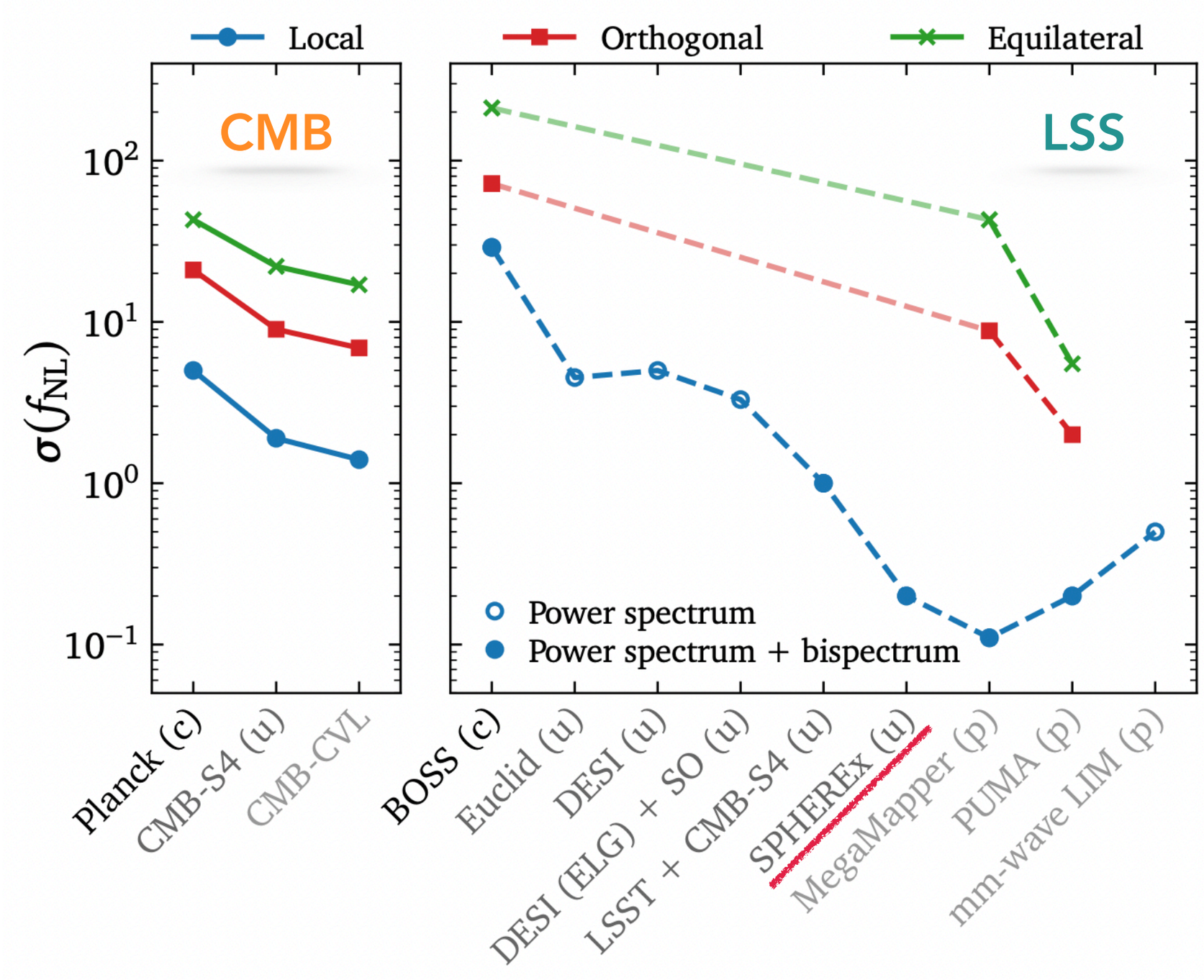
Multi-Field Inflation

Tracing local non-Gaussianity in CMB



Latest CMB constraint from Planck satellite: $f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$

Huge improvements are under way!



Picture from 2203.08128 — Snowmass White Paper on Inflation

Bootstrapping Multi-Field Inflation

DGW, Pimentel, Achucarro 2022

- The ***true*** "local" shape from multi-field inflation

  What was missed in previous computations?

- Classification of multi-field non-Gaussianities

  New shapes!

Plan of the Talk

- **Bootstrap Recap in 2 mins:**

  basic ideas & the pheno frontier

- **IR Divergences in Cosmological Bootstrap**

  anomalous Conformal Ward Identities

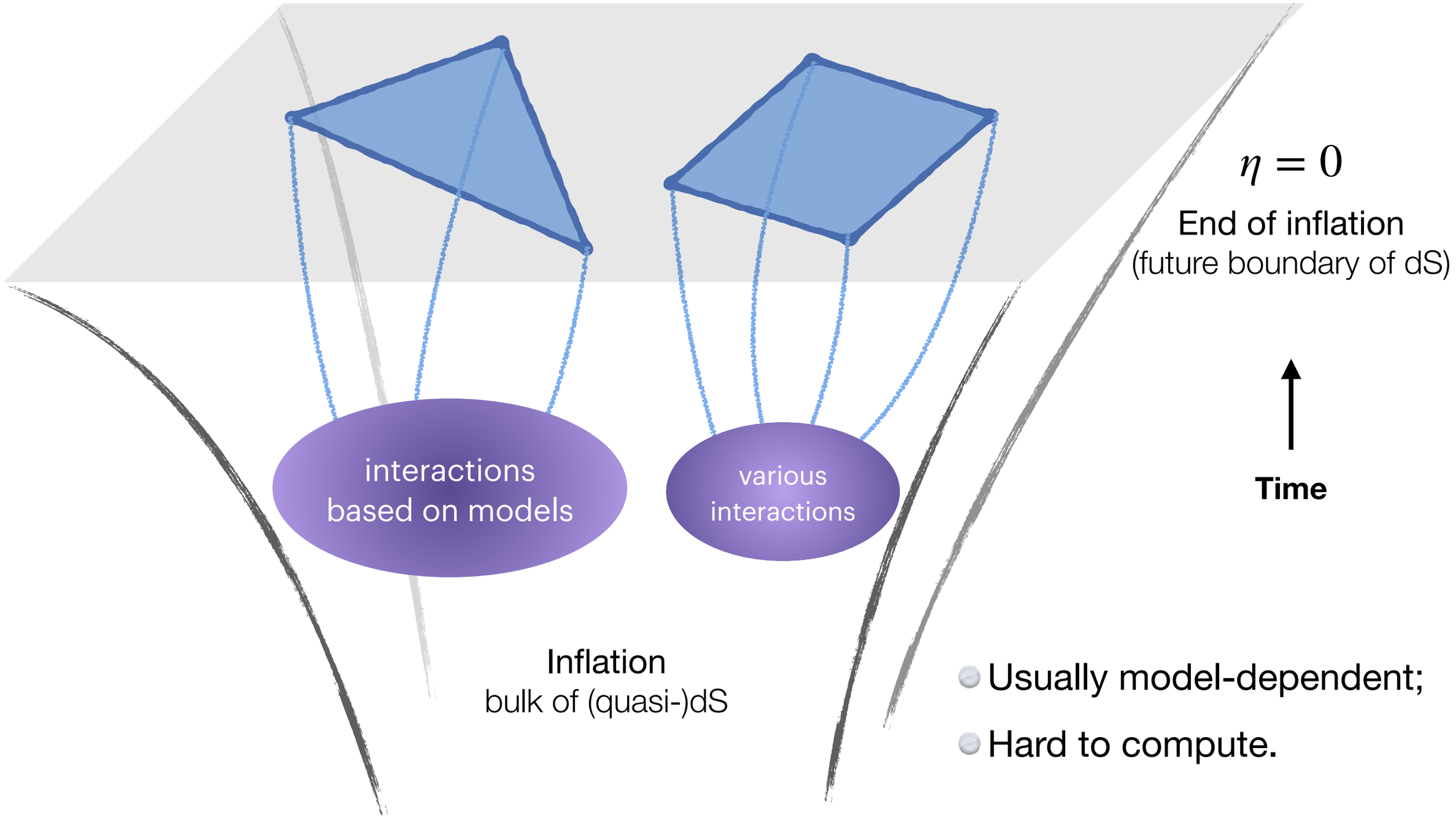
- **Classification of multi-field non-Gaussianities**

  true form of the local shape & new pheno

- **Summary & Outlook**

The traditional approaches towards cosmological correlators

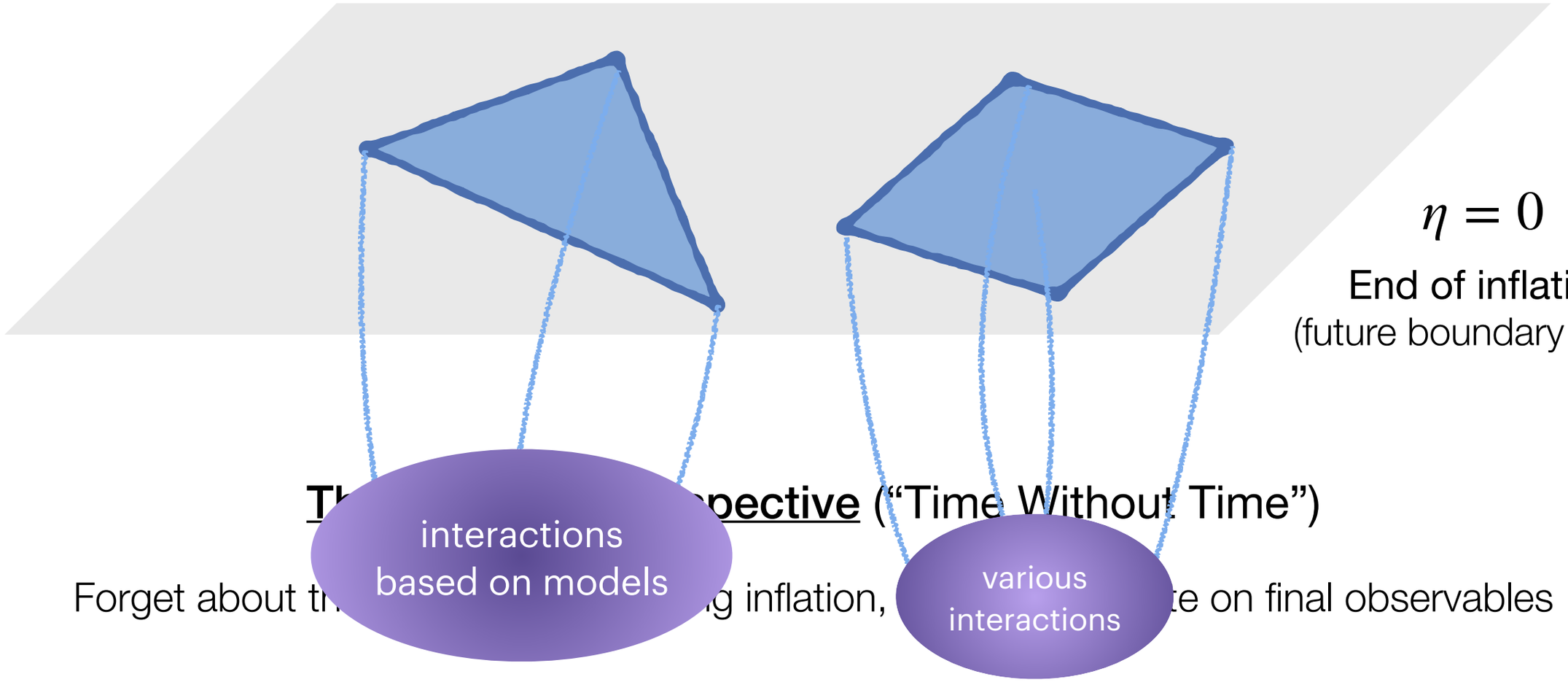
(the in-in formalism, δN formalism, transport method, etc)



- Usually model-dependent;
- Hard to compute.

Cosmological Bootstrap:

Correlators from Symmetries, Locality & Unitarity



Th **pective** ("Time Without Time")

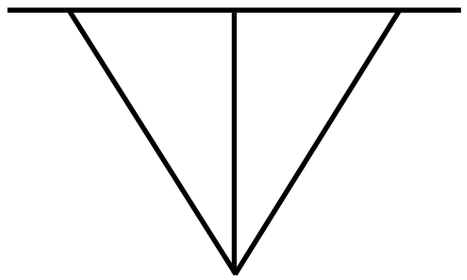
Forget about t g inflation, te on final observables

- Model-independent;
- Powerful computational tools.

See talk videos on ***CfH 21*** by G. Pimentel; and on ***CfH 22*** by H. Goodhew, G. Lee, S. Renaux-Petel&S. Jazayeri, A. Thavanesen, and DGW

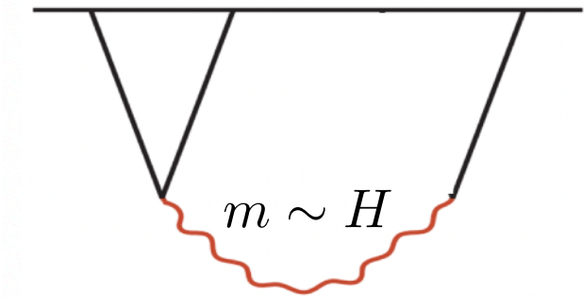
Classification of Primordial Non-Gaussianities

single field inflation



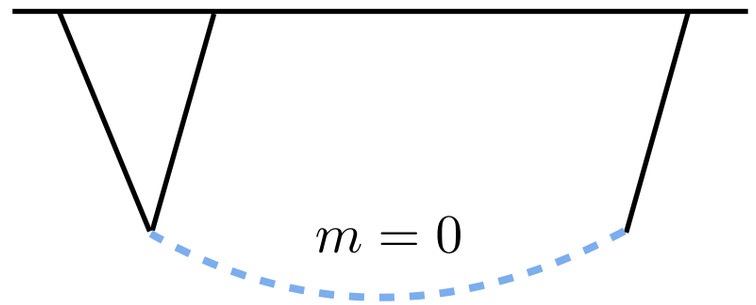
contact

cosmological collider



massive exchange

multi-field inflation



additional light scalars

Assuming:

1) (nearly) scale-invariance; 2) weakly coupled (tree-level LO).

Primordial bispectrum: the Fourier transf. of the 3-point correlation function

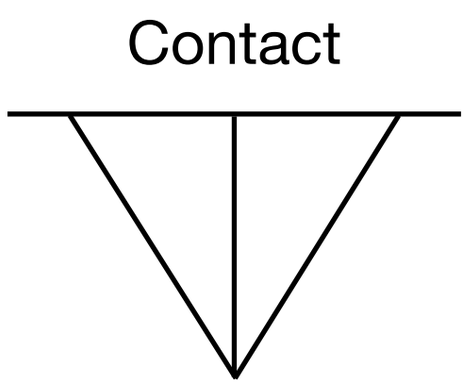
$$\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle \sim f_{\rm NL} S(k_1, k_2, k_3) P_\zeta^2$$

How easy/hard to be detected

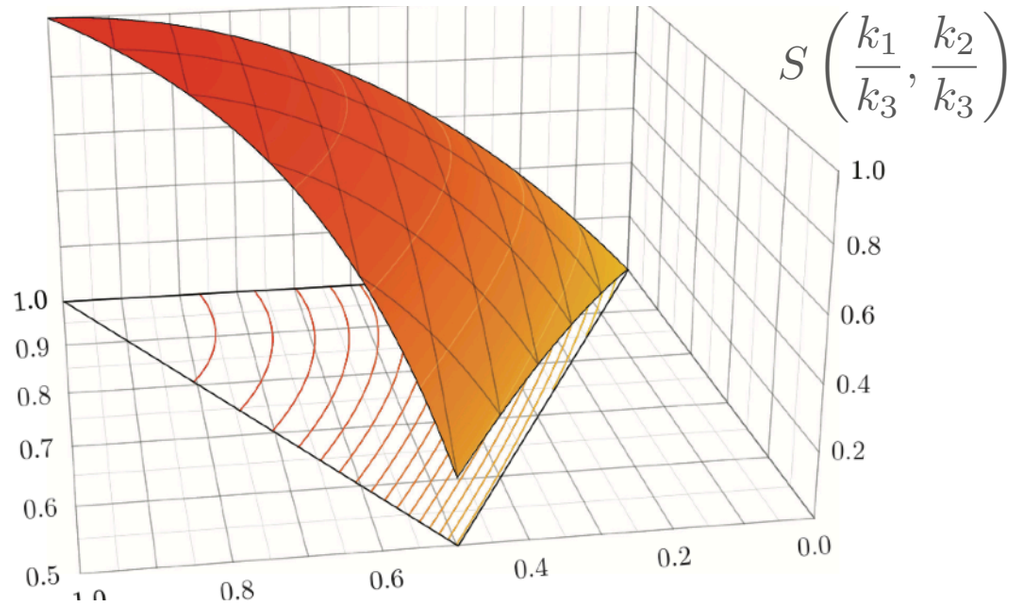
size

shape

Pheno Frontier of the Bootstrap Program



Equilateral non-Gaussianity



Single Field Inflation

Boostless Bootstrap

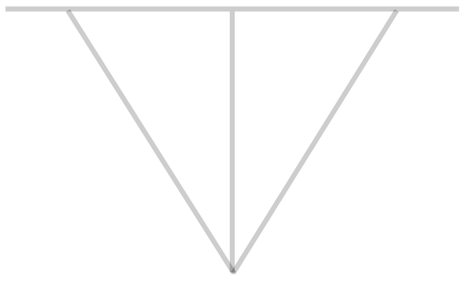
Pajer, Stefanyszyn, Supeł 2020; Pajer 2020
Jazayeri, Pajer, Stefanyszyn 2021
Bonifacio, Pajer, DGW 2021; ….

captures models such as P(X), DBI inflation with small sound speed

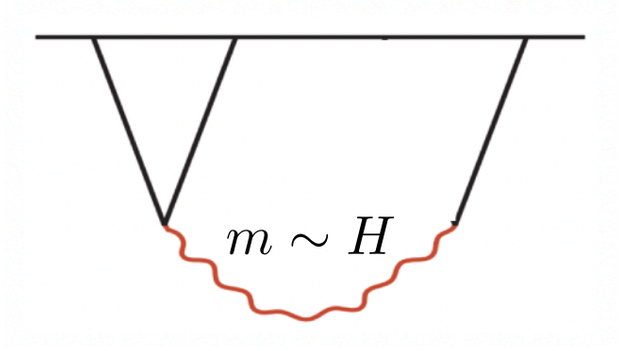
- boost-breaking => large signals
- a complete menu of scalar bispectra from single field inflation

Pheno Frontier of the Bootstrap Program

Contact

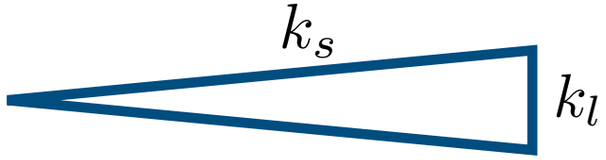


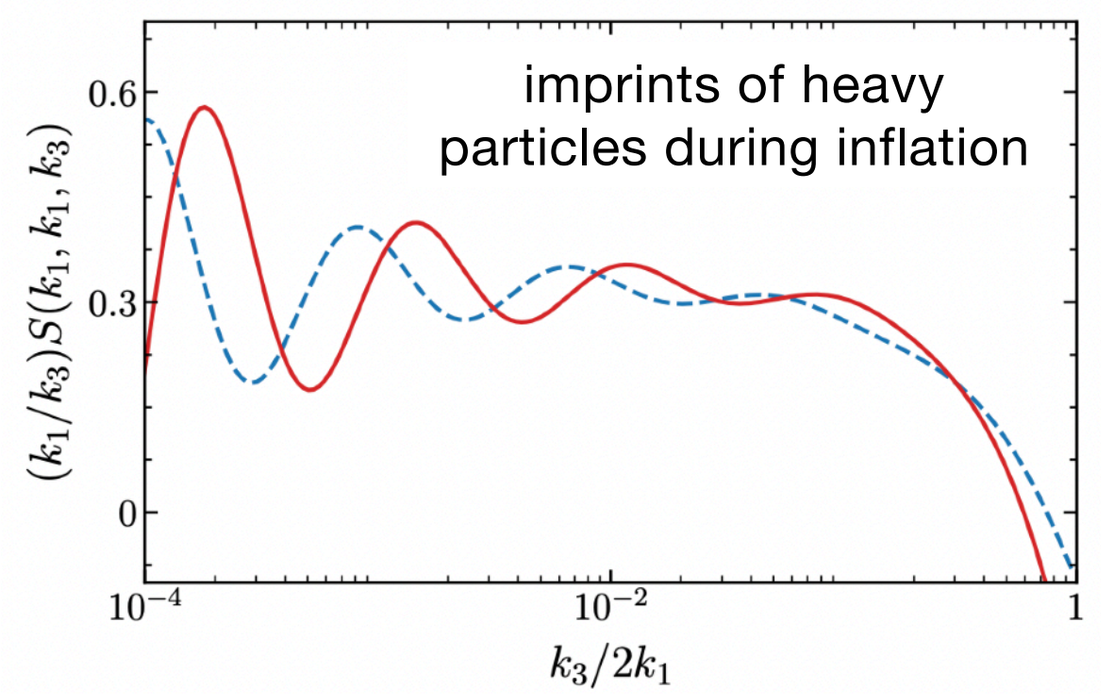
Massive Exchange



Massless Exchange

Cosmological Colliders





Boostless Cosmological Collider Bootstrap

Pimentel, DGW 2022

- ☑ full analytical shapes of **cosmo collider** bispectra for ***any*** mass, spin, interactions
- ☑ new pheno: *the equilateral collider shape*

[See more in my last years' talk on CfH 22 and also the talk by Renaux-Petel&Jazayeri]

Pheno Frontier of the Bootstrap Program

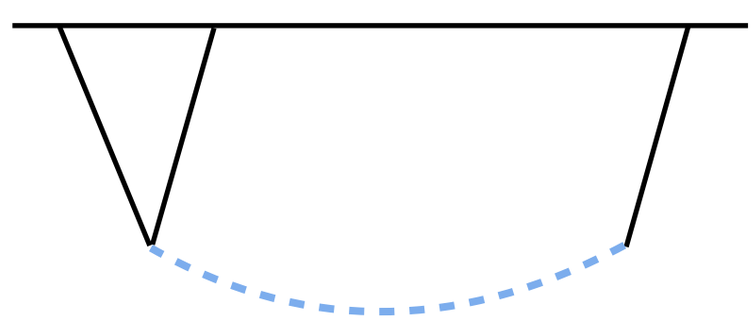
Single Field Inflation

Contact

Cosmological Collider

Massive Exchange

Multi-Field Inflation



Massless Exchange

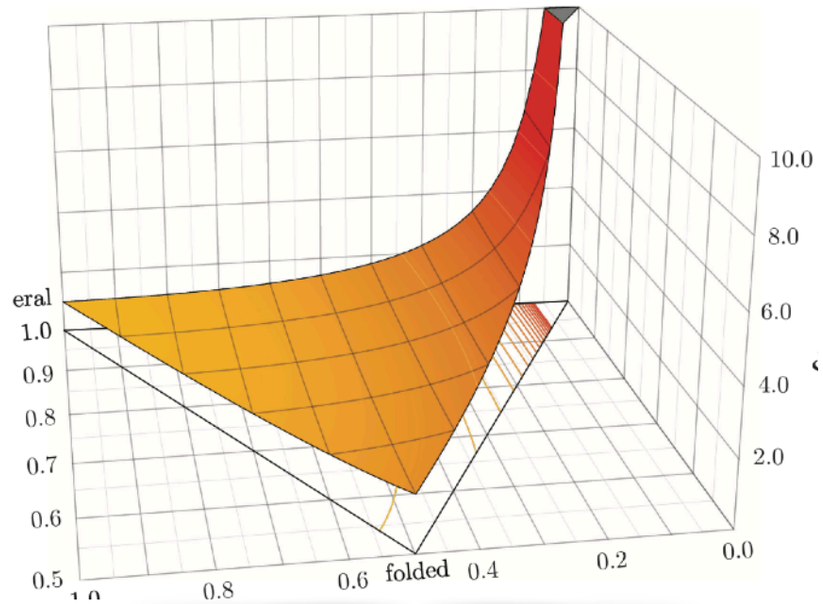
Traditional approach:

separate universe approximation

(δN formalism)

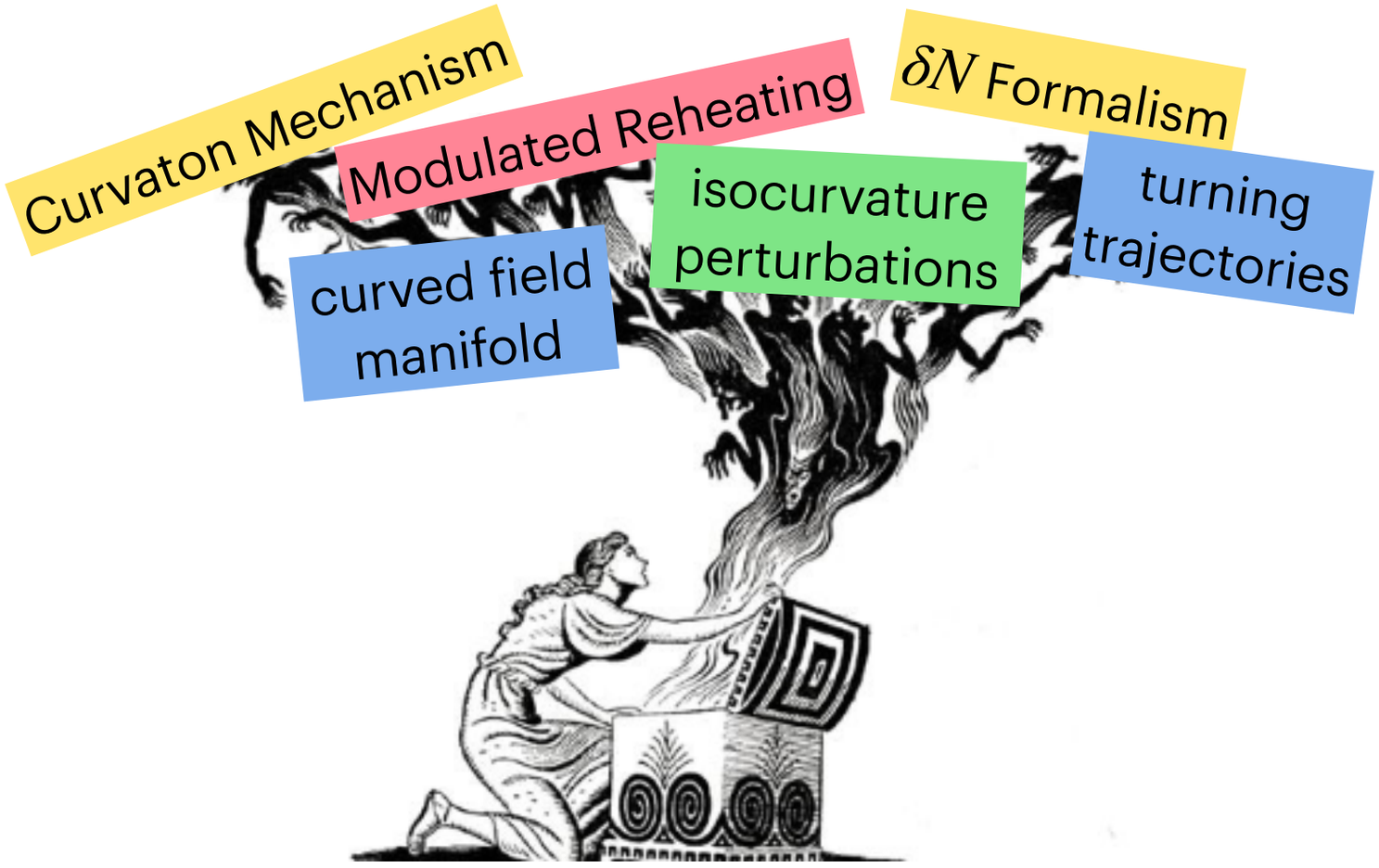
Lyth, Seery, Wands, Sasaki, Komatsu,… 2003/2004

Is this computation complete?



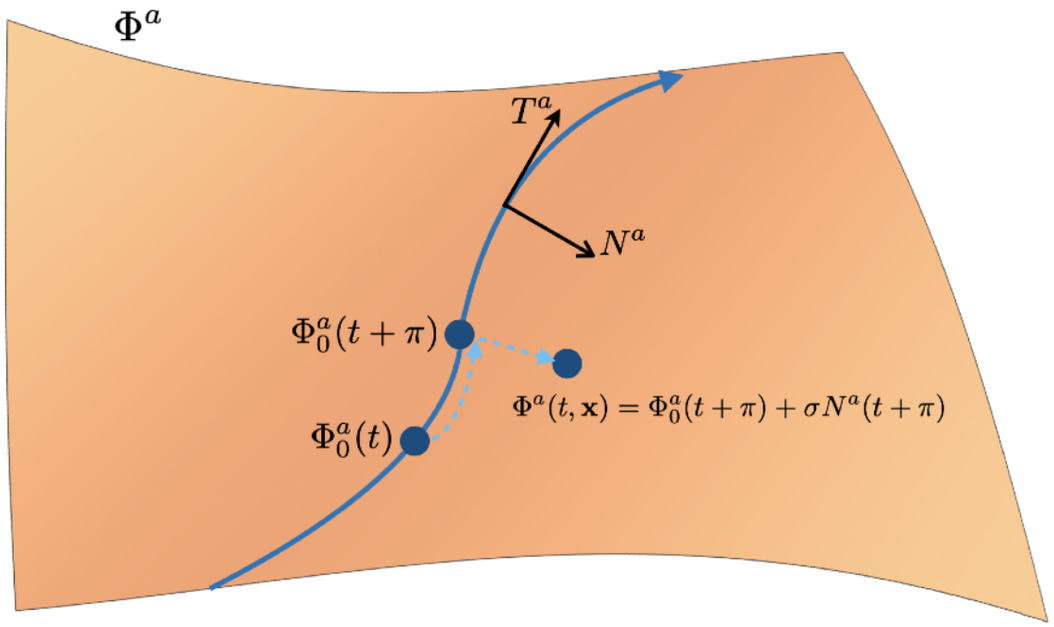
Local non-Gaussianity

When we talk about multi-field inflation…



- Too many possibilities explored in the past 30 years;
- Normally model dependent;
- Lacking a unifying theme… :(

Multi-Field Conversion = IR Divergences



Conversion from Interactions

adiabatic modes: ϕ

the inflaton fluctuations

isocurvature modes: σ

the additional light scalars $m \ll H$

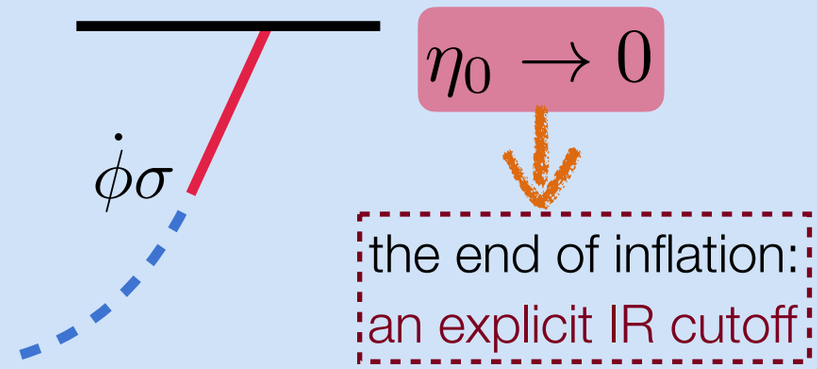
$$\mathcal{L}^{\rm int} = -\lambda\dot{\phi}\sigma - g(\partial_\mu\phi)^2\sigma$$

Superhorizon Conversion $\dot{\zeta} \propto \lambda\sigma$

super-horizon growth of ζ by the multi-field conversion

$$\zeta \propto Ht$$

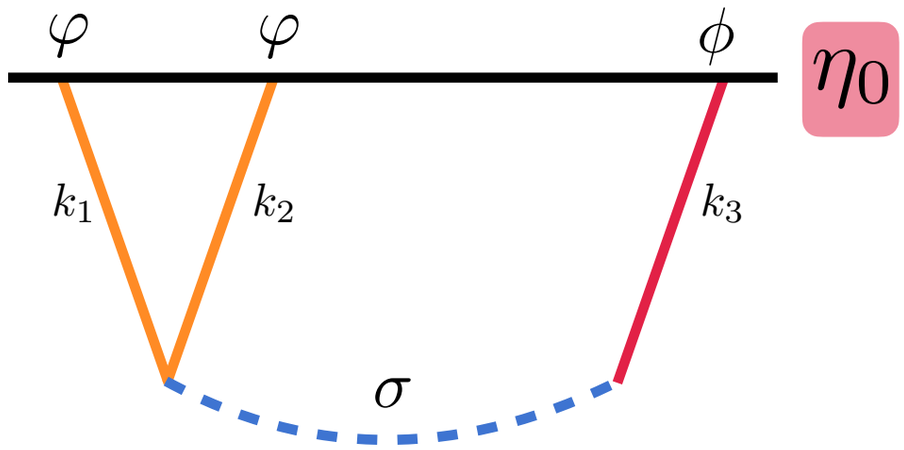
IR singular behaviour $\mathcal{K} \propto \log(k\eta_0)$



IR Divergences in Cosmological Bootstrap

Three-Point Scalar Seed

$$\langle \varphi_{k_1} \varphi_{k_2} \phi_{k_3} \rangle \sim$$



$$\sim \hat{\mathcal{I}}(u, \eta_0)$$

$$u \equiv \frac{k_3}{k_1 + k_2}$$

- σ is massive → **IR-finite** correlator

Arkani-Hamed, Baumann, Lee, Pimentel 2018
Pimentel, DGW 2022

Conformal Ward Identities

$$\left(\Delta_u - 2 + \frac{m^2}{H^2}\right) \hat{\mathcal{I}} = \frac{u}{1+u}$$

with $\Delta_u \equiv u^2(1-u^2)\partial_u^2 - 2u^3\partial_u$

- σ is massless → **IR-divergent** correlator

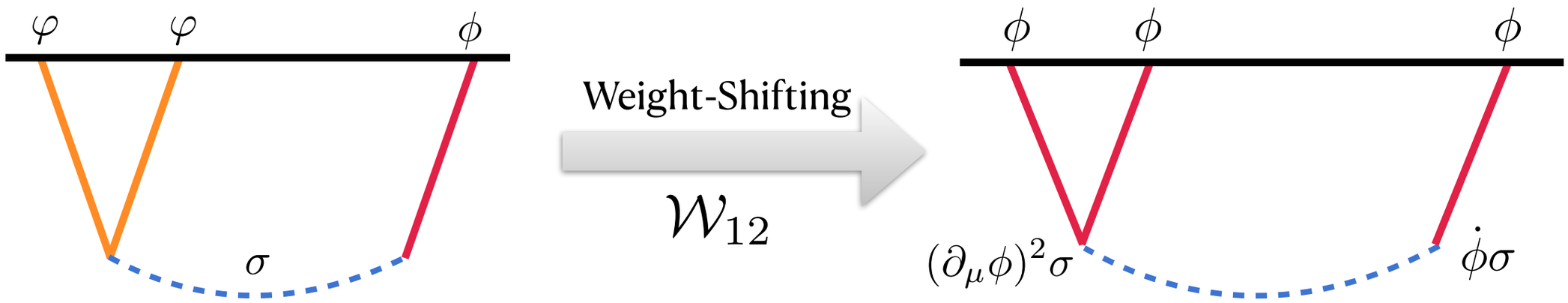
DGW, Pimentel, Achucarro 2022

Anomalous Conformal Ward Identities

$$(\Delta_u - 2)\hat{\mathcal{I}}(u, \eta_0) = \frac{u}{1+u} + \frac{6}{u}\hat{\mathcal{K}}(k\eta_0)$$

an extra source term caused by the IR cutoff

The true "local" shape from dS bootstrap



massless exchange:
the minimal setup for multi-field inflation

Here is the full shape:

logarithmic k_t-pole:
from the cubic vertex

$$S(k_1,k_2,k_3) \propto \frac{1}{k_1^3k_2^3k_3^3}\Big[\,(\gamma_E-3-\log(-k_t\eta_0))\,(k_1^3+k_2^3+k_3^3)+k_te_2-4e_3$$
$$+(k_2^3+k_3^3)\log(-2k_1\eta_0)+(k_1^3+k_3^3)\log(-2k_2\eta_0)+(k_1^3+k_2^3)\log(-2k_3\eta_0)\Big]$$

$$S^{\rm local}=\frac{k_1^3+k_2^3+k_3^3}{k_1^3k_2^3k_3^3}$$

logarithmic k_n-pole: from the linear mixing

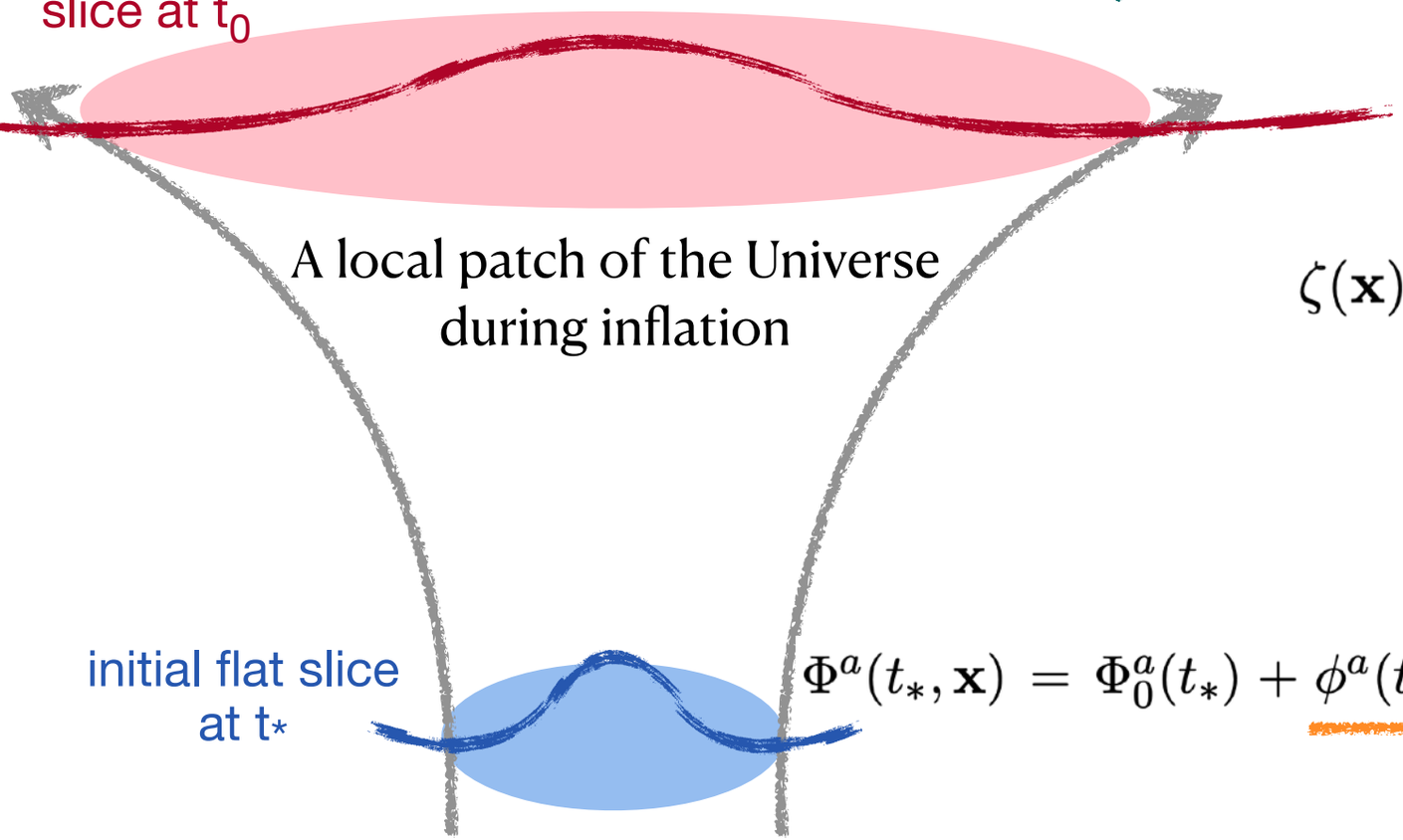
$$k_t\equiv k_1+k_2+k_3 \qquad e_2=k_1k_2+k_1k_3+k_2k_3 \text{ and } e_3=k_1k_2k_3$$

What was missed in the δN / transport approach?

previous

comoving slice at t_0

$$N(t_*, \mathbf{x}) = N(\Phi^a)$$



$$\Phi^a(t_*, \mathbf{x}) = \Phi_0^a(t_*) + \phi^a(t_*, \mathbf{x})$$

Initial field fluctuations are defined at t* right after horizon exit

Curvature Perturbation as the differences in the local efolds

$$\zeta(\mathbf{x}) = N(\Phi_0^a + \phi^a) - N(\Phi_0^a)$$

$$= N_a \phi^a + \frac{1}{2} N_{ab} \phi^a \phi^b + \frac{1}{6} N_{abc} \phi^a \phi^b \phi^c + \ldots$$

Are they just *free* scalars? Actually not in multi-field inflation!

As an example, even ***before*** horizon-exit,

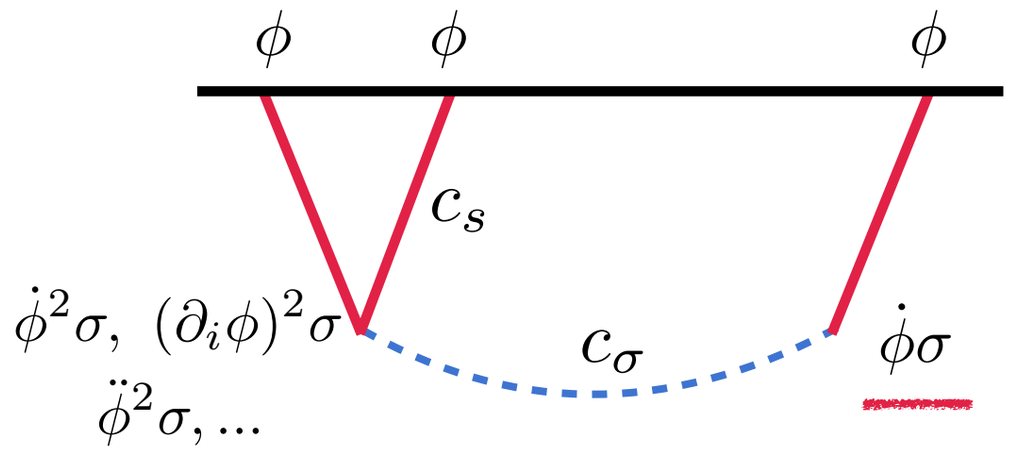
the $\dot{\phi}\sigma$ interaction already deformed the Bunch-Davies mode function

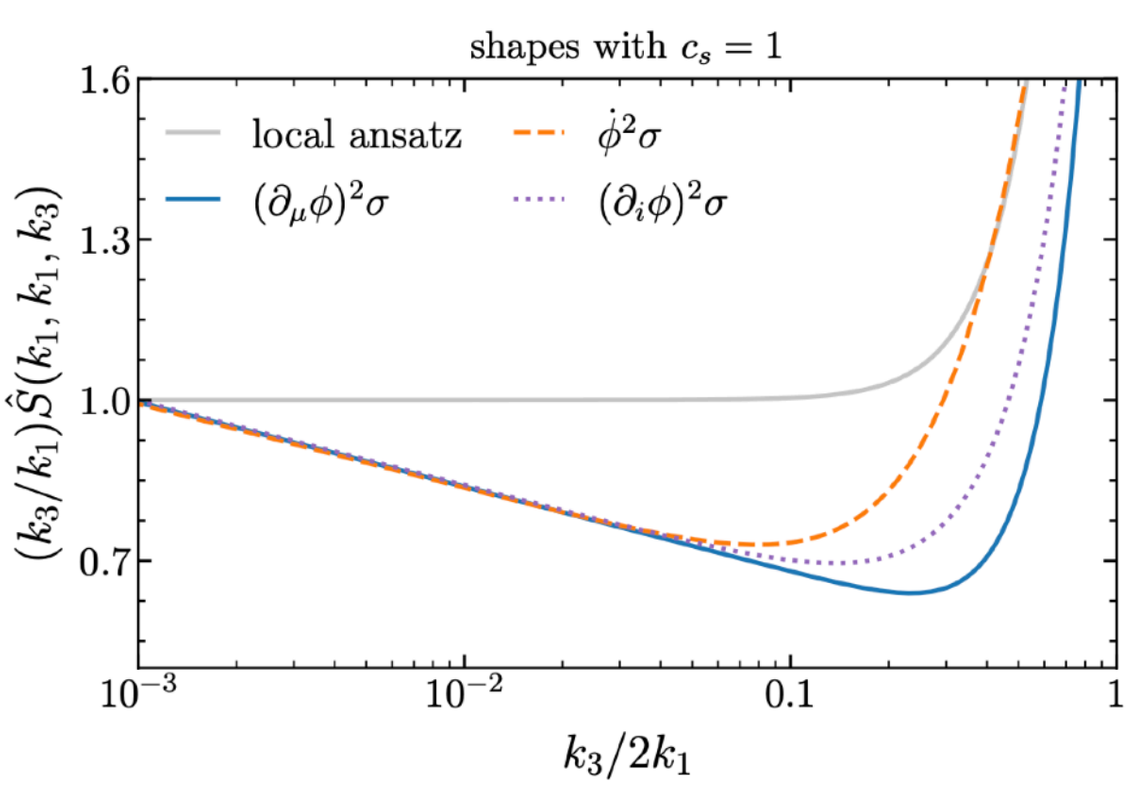
$$\text{for} \quad -k\eta > 1, \qquad \mathcal{K} \to \eta e^{ik\eta} \log(-k\eta)$$

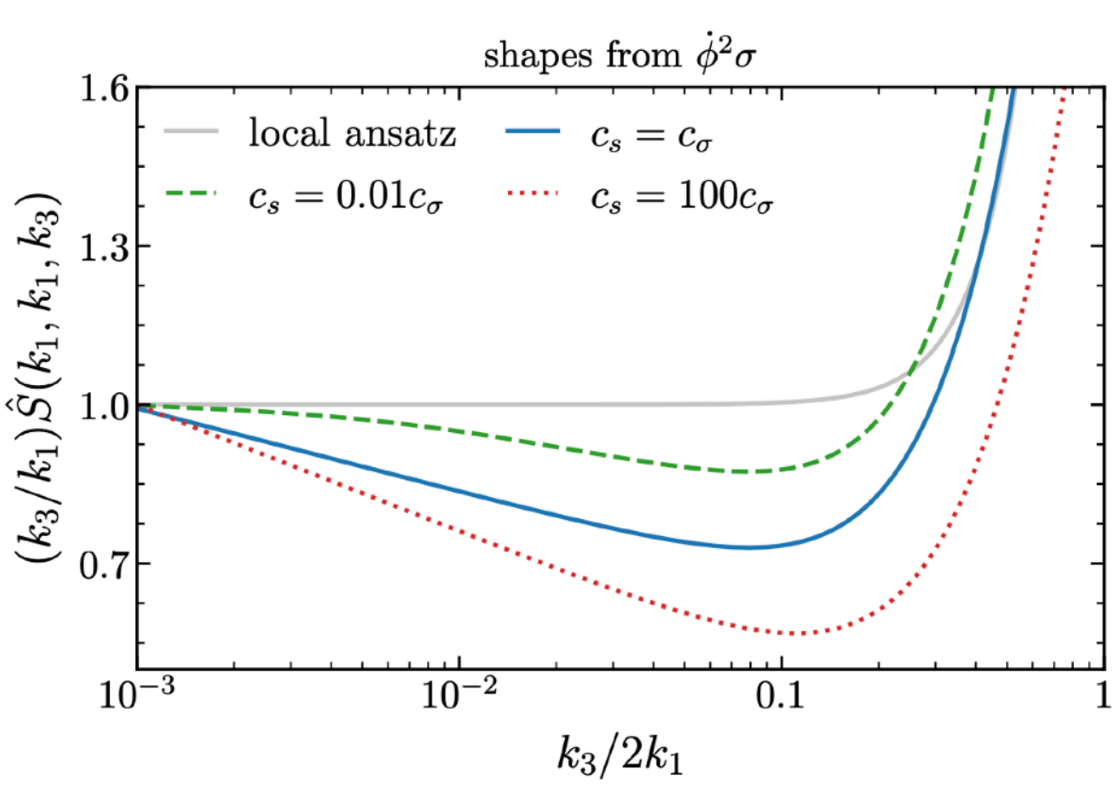
one concrete example for comparison: Achucarro, Copeland, Iarygina, Palma, DGW, Welling 2019

IR divergence => local-type non-Gaussianity

massless exchange with arbitrary interactions:

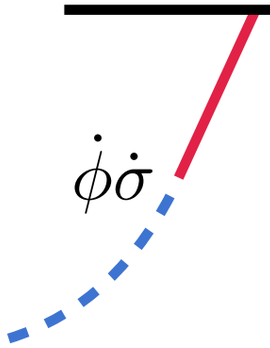






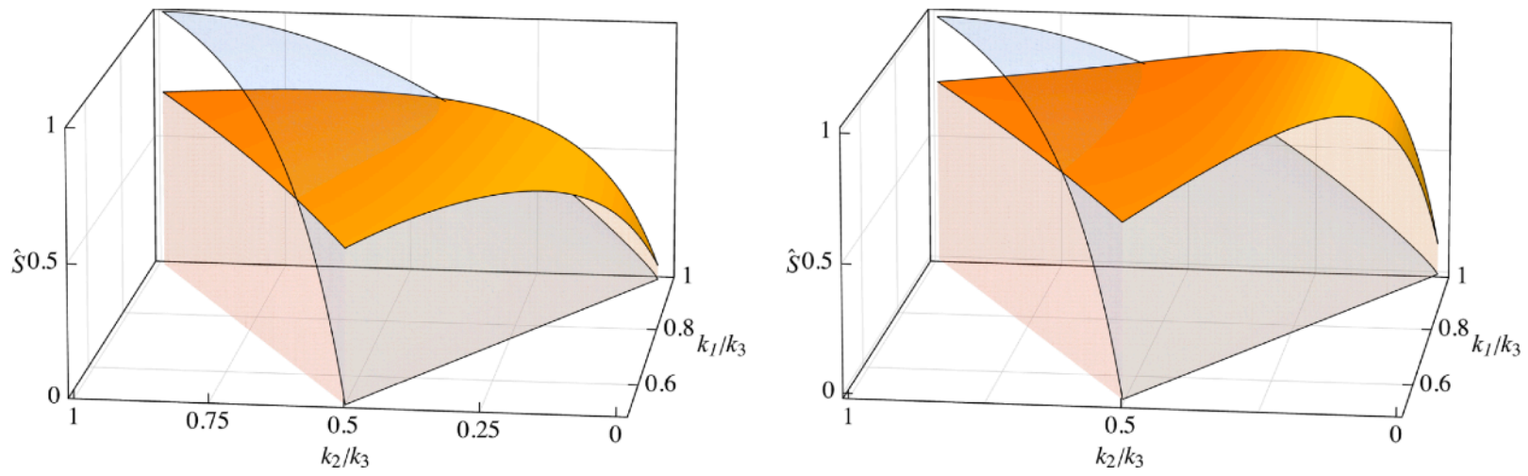
New Pheno: *Multi-Speed Non-Gaussianity*

Linear mixing with **higher derivatives** $\ddot{\phi}\sigma,\ \dot{\phi}\partial_i^2\sigma,$ etc. → **IR-finite** correlators

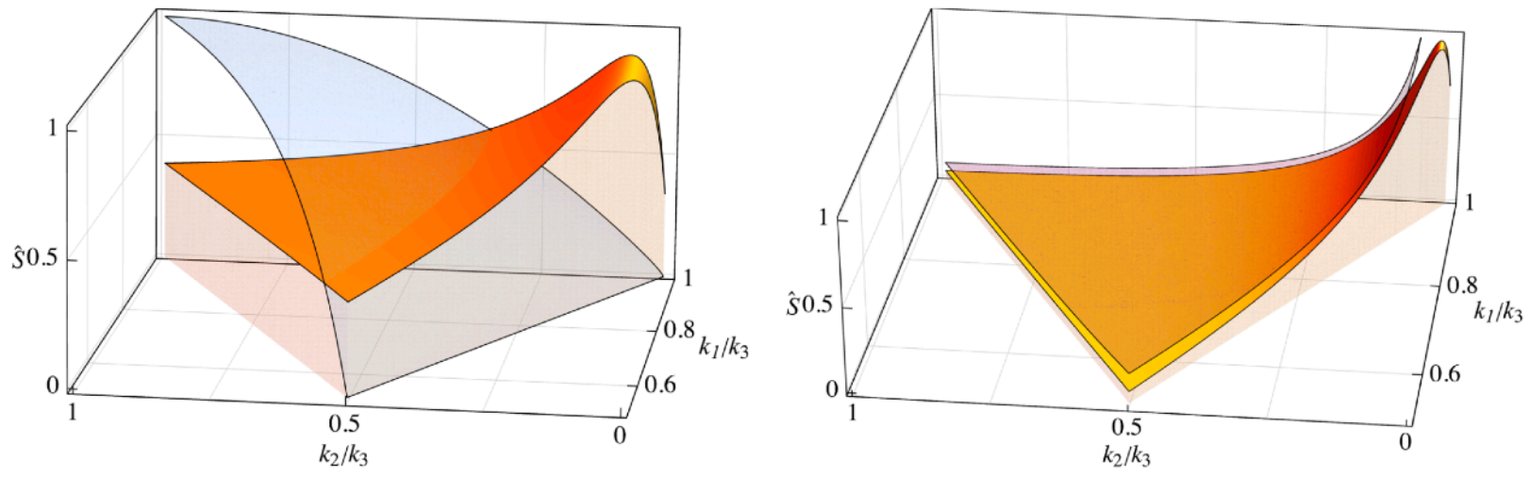


$$\mathcal{K}_+^{c_\sigma}(c_\sigma k,\eta)=\frac{H^2\eta}{2c_\sigma k}e^{ic_\sigma k\eta}$$

$$\hat{S}^{\text{multi}-c_s}(k_1,k_2,k_3)=\frac{k_1k_2k_3}{(c_1k_1+c_2k_2+c_3k_3)^3}+5\ \text{perms}$$



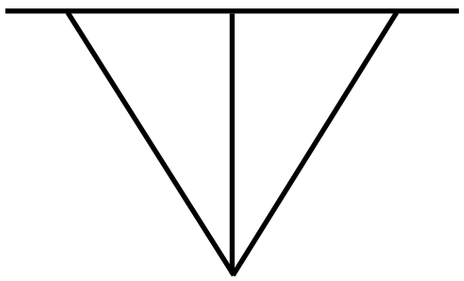
(a) $c_1=c_2=0.8,\ c_3=1$ (b) $c_1=0.3,\ c_2=0.4,\ c_3=1$



(c) $c_1=0.5,\ c_2=0.2,\ c_3=1$ (d) $c_1=c_2=0.05,\ c_3=1$

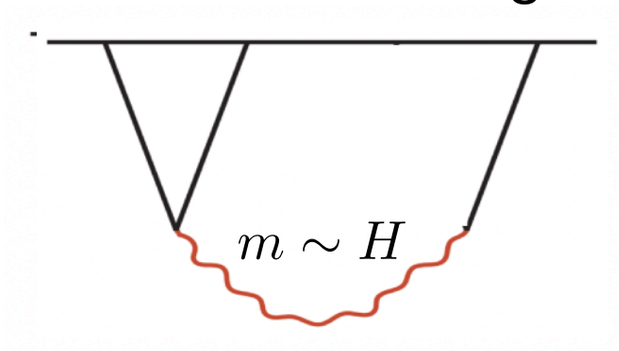
Bootstrap our way towards inflationary new physics

Contact



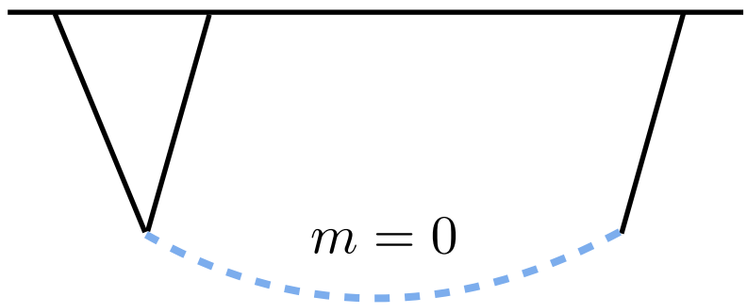
self-interaction of the inflaton

Massive Exchange



intermediate massive particles

Massless Exchange



additional light scalars

Boostless Bootstrap

- ☑ all the possible **equilateral-type** non-Gaussianity from single field inflation

Boostless Cosmological Collider Bootstrap

- ☑ a complete set of **cosmo collider** bispectra with full analytic shapes
- ☑ new pheno: *the equilateral collider shape*

multi-field Bootstrap

- ☑ the full **"local" shapes** from multi-field inflation and more
- ☑ new pheno: *the multi-speed non-Gaussianity*

Exciting Progresses. Stay tuned!