Searching for Cosmological Collider in the Planck CMB Data

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Work in collaboration with:
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18 December 2024 @ CMB-France

Arxiv: 2404.07203

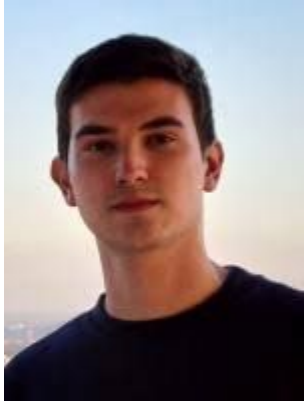
Image credit: Bing image creator

The team

Dong-Gang
Wang

James
Fergusson

Paul
Shellard



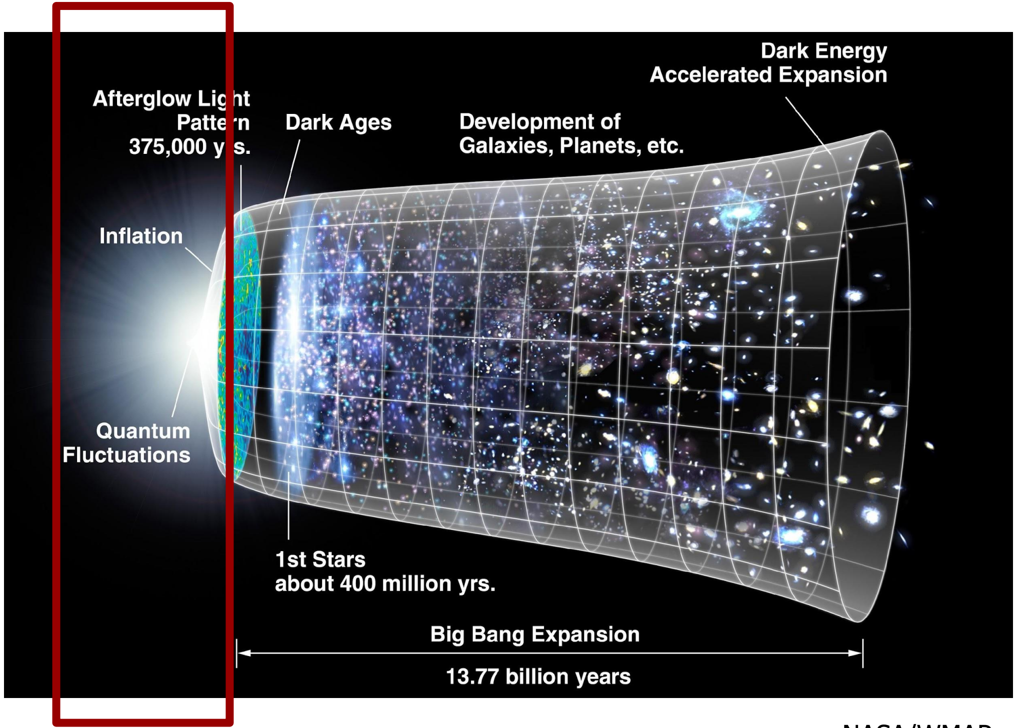
Petar
Suman

DAMTP, University of Cambridge, UK

Work on ArXiv/JCAP: 2404.07203

Inflation

- The leading paradigm of the early universe



NASA/WMAP

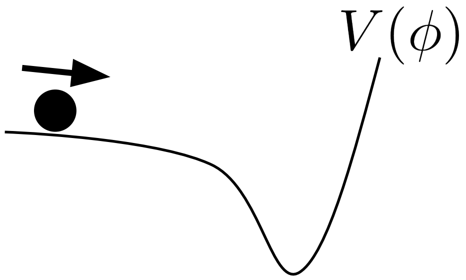
- A period of accelerated expansion ($O(10^{26})$) after the Big Bang

- Solves the horizon, flatness and monopole problems

- What drives inflation?

Simplest model of inflation

- Inflation driven by…
    * single scalar field ϕ
    * slowly rolling down the potential
        + canonical kinetic term, in Bunch-Davies vacua



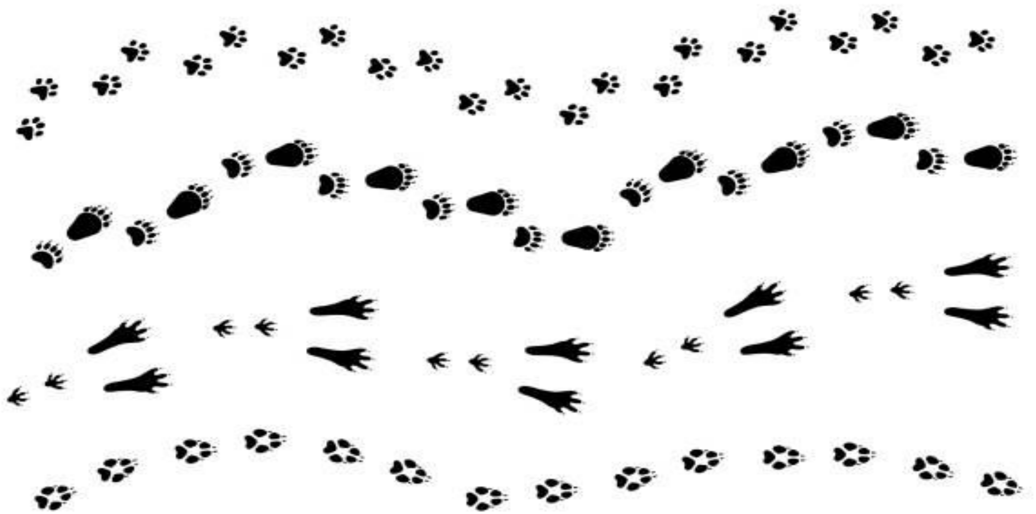
- Successful in explaining:
    ✓ accelerated expansion for 50-60 e-folds
    ✓ seed primordial perturbations which…
    ✓ have near scale-invariant spectra and…
    ✓ are nearly Gaussian

Alternative models of inflation

- Inflation driven by…
    * more than one fields?
    * not necessarily slowly rolling down the potential?
        + non-canonical kinetic term? excited initial states?
- Can also explain:
    ✓ accelerated expansion for 50-60 e-folds
    ✓ seed primordial perturbations which…
    ✓ have near scale-invariant spectra and…
    * observable non-Gaussian signatures! ➡ **Primordial non-Gaussianity!**

Primordial non-Gaussianity (PNG)

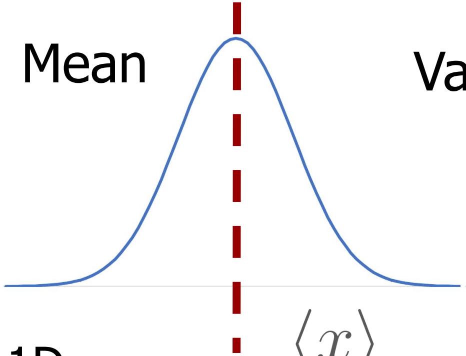
The **size** and **shape** of the PNG let us probe **early universe physics**!



Measuring non-Gaussianity

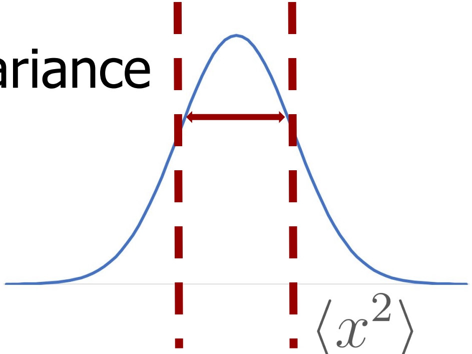
Gaussian statistics

Mean



$\langle x \rangle$

Variance

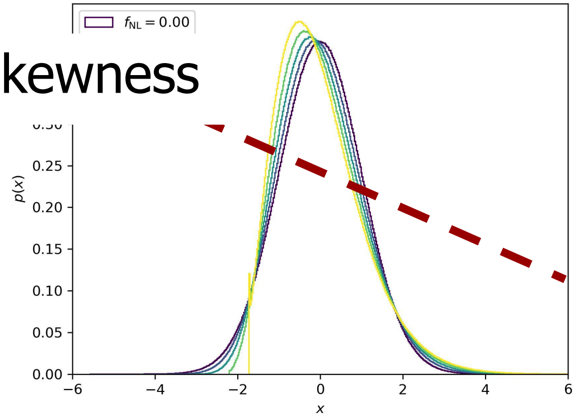


$\langle x^2 \rangle$

1D

non-Gaussian statistics

Skewness



$\langle x^3 \rangle$

Field $\langle \zeta(k) \rangle$

= 0

$\langle \zeta(k_1)\zeta(k_2) \rangle$

Power Spectrum

$\langle \zeta(k_1)\zeta(k_2)\zeta(k_3) \rangle$

Bispectrum

Leading-order NG statistic!

Measuring non-Gaussianity

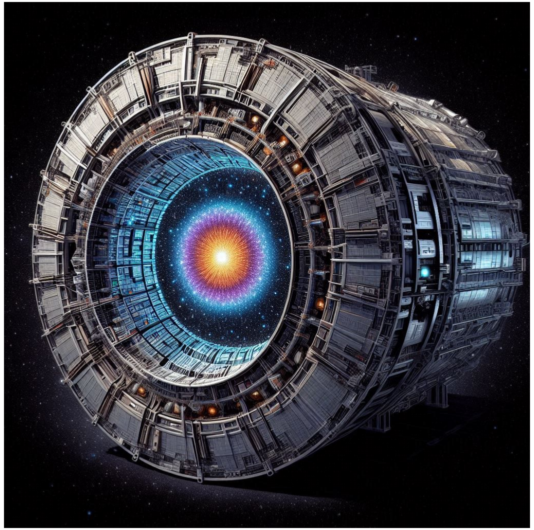
$$\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \propto f_{\mathrm{NL}}\, S(k_1, k_2, k_3)$$

non-linearity parameter

Shape function

Cosmological Colliders

Cosmological (particle) colliders



* AI artist's imagination - unlikely that there were stars during inflation.

Inflationary universe as a particle collider

[Chen & Wang 2010, Baumann & Green 2011, Noumi et al 2012, Arkani-Hamed & Madacena 2015]

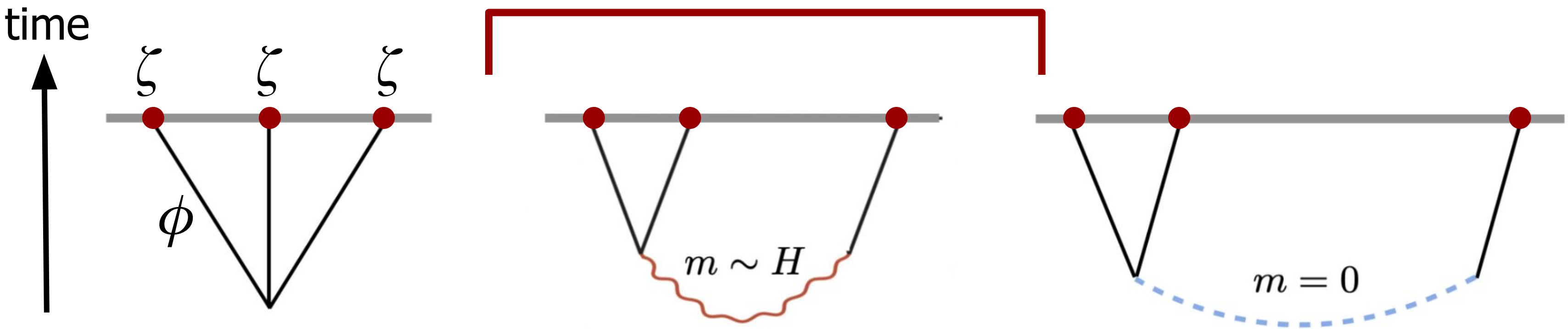
Correlators at the end of inflation can be sensitive to high energy physics

$$\lesssim O(10^{13})\ \mathrm{GeV}$$

during inflation

Inflationary scenarios

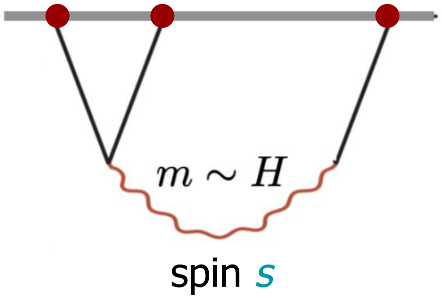
3-point correlations can be sourced by...



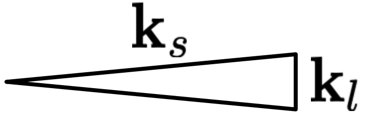
Inflaton self-interactions	Massive exchange	Massless exchange
(Effectively) Single-field	**Cosmological Colliders**	Multi-field

Window for probing **heavy fields** during inflation

Cosmological collider - the squeezed limit



Towards the squeezed limit:



$$S \sim P_s(\hat{\mathbf{k}}_l \cdot \hat{\mathbf{k}}_s) \left(\frac{k_l}{k_s}\right)^{1/2} \cos\left[\mu \ln\left(\frac{k_l}{k_s}\right) + \delta\right]$$

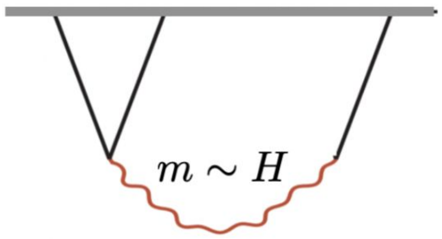
Sensitive to **spin** and **mass**!

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

→ Particle spectroscopy using PNG

[Chen & Wang 2010, Noumi et al 2012, Baumann & Green 2011, Arkani-Hamed & Madacena 2015]

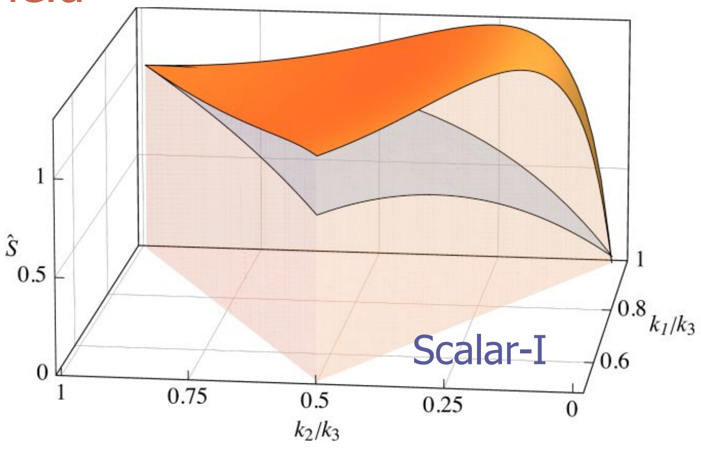
Massive scalar exchange



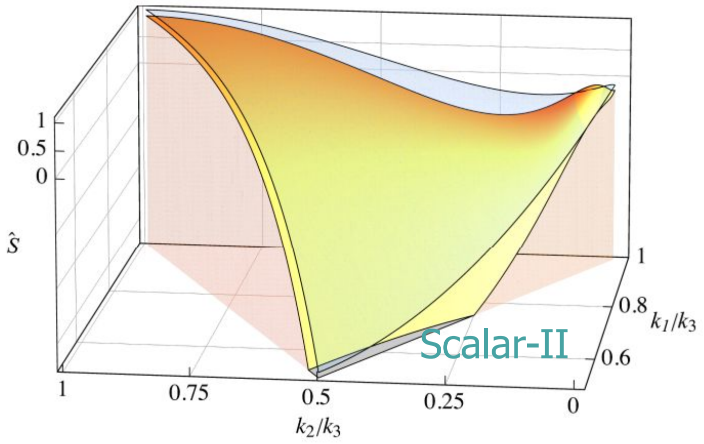
massive scalar field

$0 < m < \frac{3}{2}H$ → Quasi-single-field inflation [Chen & Wang 2010]

$m \geq \frac{3}{2}H$ → Scalar-I, Scalar-II shapes developed using bootstrap techniques in this work



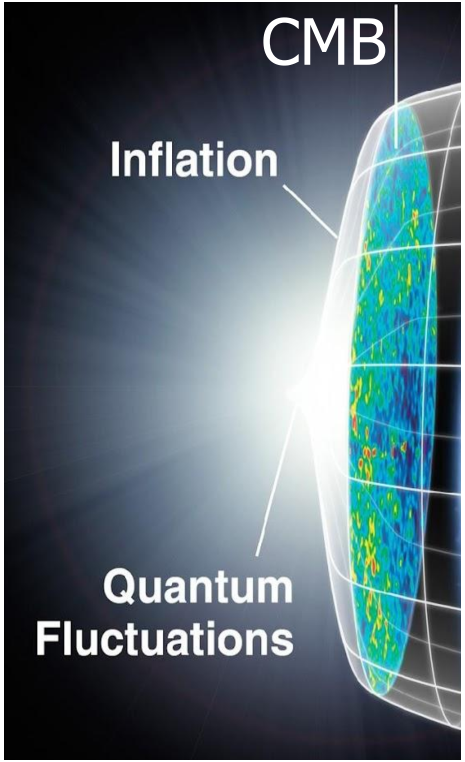
(b) $\mu = 1$



(b) $\mu = 2$

CMB Bispectrum

Cosmic Microwave Background



- Blackbody radiation from 300,000 after the Big Bang

- $O(10^{-5})$ anisotropies in temperature & polarisation, linearly* related to primordial perturbations

$$a_{\ell m} \propto \int d^3\mathbf{k}\, \zeta(\mathbf{k})\, T_{\ell m}(\mathbf{k}) \cdots$$

- CMB bispectrum measures PNG:

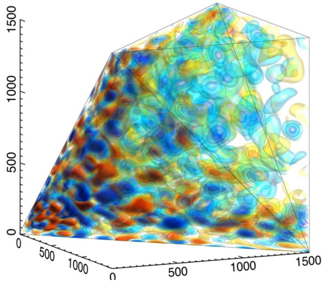
$$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle = f_{\rm NL}\, b_{\ell_1 \ell_2 \ell_3} \cdots$$

Amplitude Shape

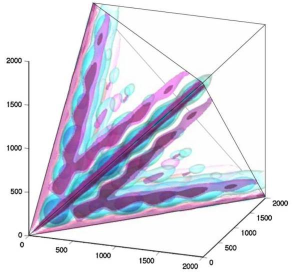
CMB bispectrum estimation

- Bispectrum is noise dominated → Linear template-fitting to estimate $f_{\rm NL}$

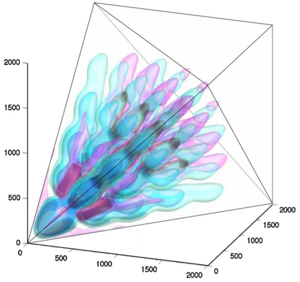
Observed bispectrum



Shape template

$= f_{\rm NL}^{\rm local}$ ()

or

$= f_{\rm NL}^{\rm equil}$ ()

or

⋮

Planck 2018 constraints
(T+E, 68% CL)

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$
$$f_{\rm NL}^{\rm equil} = -26 \pm 47$$
$$f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

Plots from Planck 2015, Phys. Rev. D. 82, 023502 (2010), Planck 2018

CMB-BEST

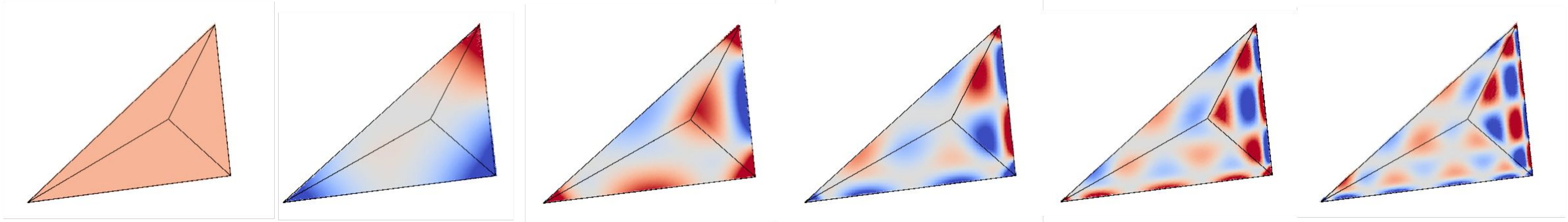
- Public code for CMB Bispectrum ESTimation

  @ https://github.com/Wuhyun/CMB-BEST

- High-resolution, flexible and efficient!

- All heavy-lifting done in HPC clusters and provided as a data file

- Get Planck CMB constraints for arbitrary shapes in seconds!



[WS, Fergusson, Shellard 2211.15139]

CMB-BEST: demo

```python
import cmbbest as best

basis = best.Basis()
model_1 = best.Model("local")
model_2 = best.Model("equilateral")

constraint = basis.constrain_models([model_1, model_2])
constraint.summarize()
```

[3] ✓ 0.9s

1. Create a basis object (type, polarization, …)
2. Create models (bispectrum template shape)
3. Get constraints
4. Output summarised results

Output:

	shape_name	single_f_NL	single_sample_sigma	signal_to_noise
0	local	-1.090533	5.308609	-0.205427
1	equilateral	-21.828939	48.986426	-0.445612

$$f_{\rm NL}^{\rm local} = -1.1 \pm 5.3$$

$$f_{\rm NL}^{\rm equil} = -22 \pm 49$$

Implications of PNG constraints

ex) $f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$ (at 68% CL)

1. Direct bounds on models with similar bispectrum shapes:

   - e.g. A model predicting $f_{\rm NL} = 15$ is ruled out at a 3σ level

   - Multi-field models with $f_{\rm NL} \sim O(1)$ are consistent with the CMB

2. Search for PNG signatures of given shape:

   - The signal-to-noise ratio: $\sigma_{\rm SNR} = 0.9/5.1 = 0.18$

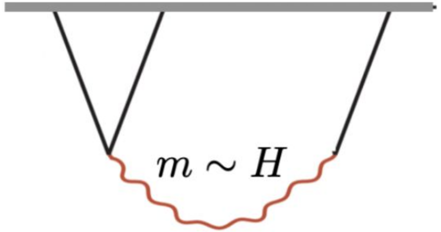
   - If, e.g., $\sigma_{\rm SNR} \geq 3$, this could've been the first detection of PNG

Results

Massive scalar exchange

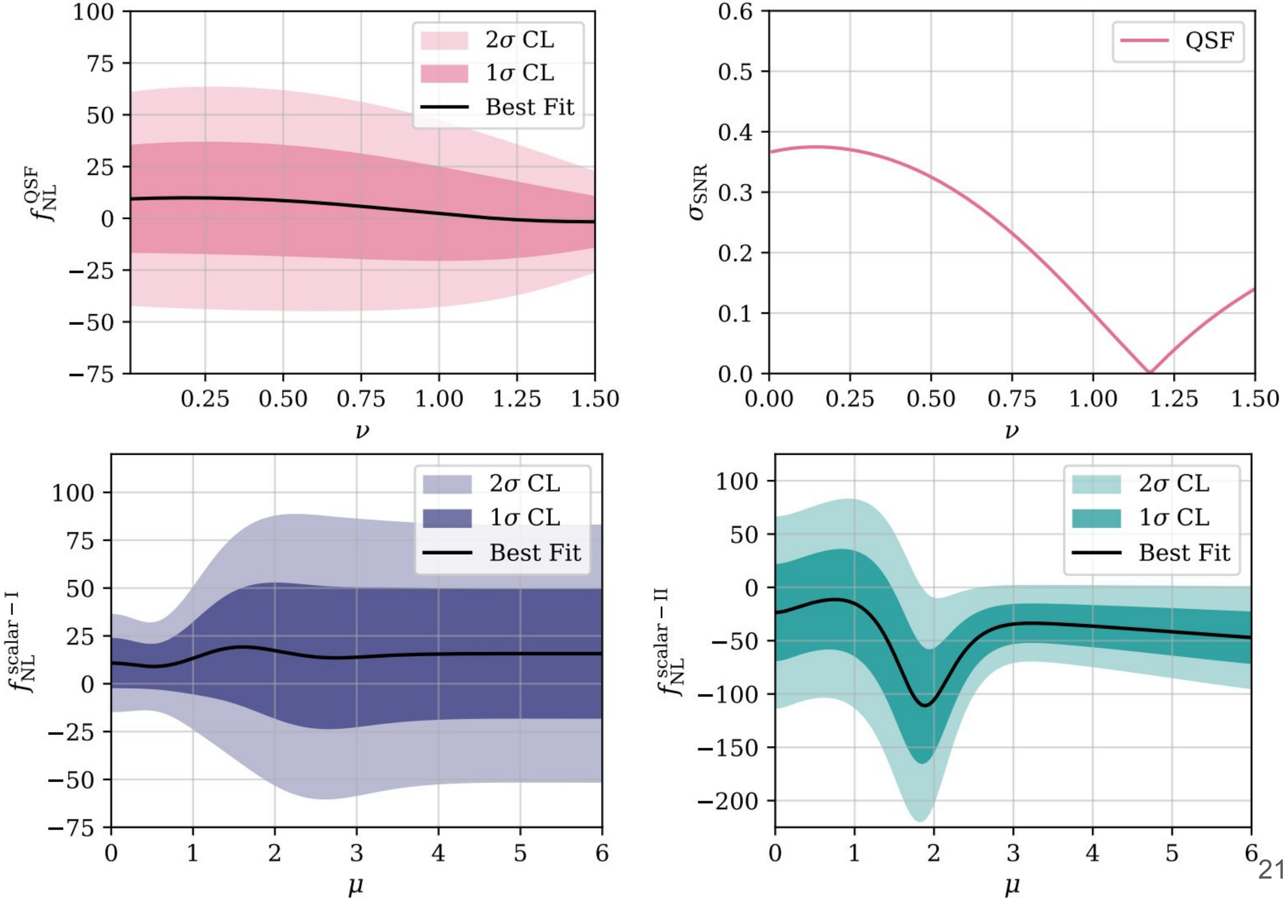
Quasi-single-field

$$0 < m < \frac{3}{2}H$$



Scalar-I, Scalar-II

$$m \geq \frac{3}{2}H$$



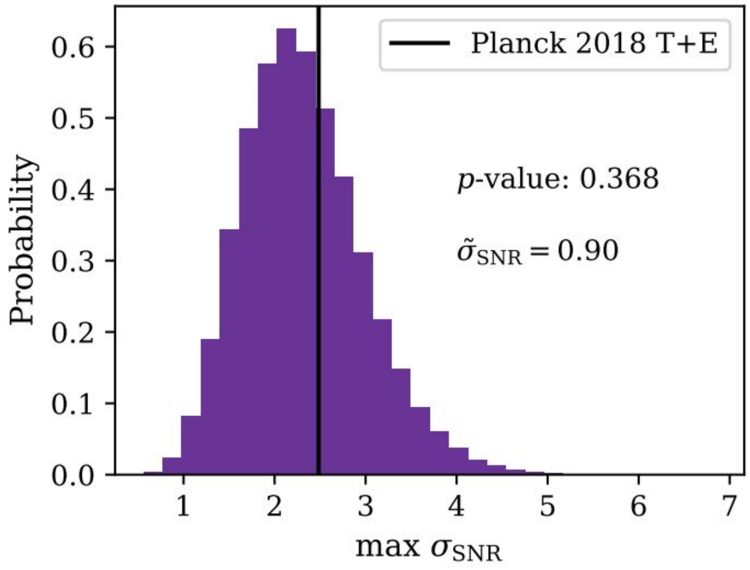
Look-elsewhere effect

- The more independent measurements we make,

  the more likely it is to find a large signal by sheer luck

- To account for this effect,
we draw random correlated samples
from our measurements and
compute the p-value

- Example with equilateral collider:



Adjusted signal-to-noise

Shape	Template	f_{NL} (68% CL)	Raw S/N	Adjusted S/N	Section
Quasi-single field [3]	(2.6)	10 ± 26	0.37	0.12	4.1
Scalar exchange I	(2.15)	11 ± 13	0.86	0.67	4.1
Scalar exchange II	(2.20)	-91 ± 40	2.3	1.8	4.1
Heavy-spin exchange	(2.24)	-59 ± 32	1.9	1.2	4.2
Massive spin-2 exchange	(2.27)	-2.1 ± 1.1	1.9	0.90	4.2
Equilateral collider [59]	(2.32)	-178 ± 72	2.5	0.90	4.3
Low-speed collider [41]	(2.33)	-9 ± 10	0.89	0.29	4.3
Multi-speed PNG [64]	(2.34)	-3.1 ± 2.3	1.3	0.61	4.3

No detection of PNG… yet

Conclusion

Summary

- Extensive data analysis for cosmological colliders using Planck CMB
- Proposed new analytic templates for several scenarios
- Placed the most stringent constraints to date using CMB-BEST.
- No detection of PNG yet, accounting for the look-elsewhere effect
- Analysis pipeline and templates ready to be tested with **future data**!

Thank you!

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FURAX @ SciPol

See **Simon Biquard**'s talk tomorrow (10:20)

- Framework for Unified and Robust data analysis with JAX
- **Modular**, **industry-standard** code for linear algebra in CMB analyses
- Efficient utilisation of CPUs and **GPU**s in parallel
- Code public & continues to be developed…

Github: CMBSciPol/furax

SciPol

Science from the large scale cosmic microwave background polarization structure

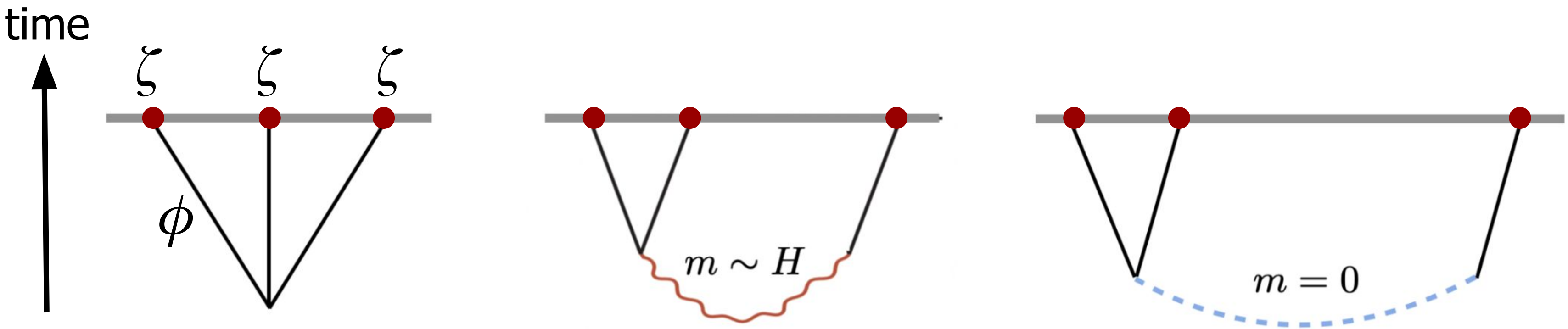
Current Dev Team: Josquin Errard, Artem Basyrov, Benjamin Beringue, Simon Biquard, Pierre Chanial, Wassim Kabalan, Ema Tsang, Amalia Villarubia, WS

Thank you!

Backup slides

Inflationary scenarios - the bootstrap approach

Symmetries, locality & unitarity → the form of correlation functions

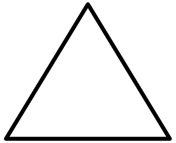


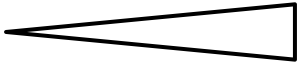
$$S^{\rm eq}(k_1,k_2,k_3) = \frac{\mathrm{Poly}_{p+3}(k_T, e_2, e_3)}{k_1 k_2 k_3 k_T^p}$$

?

$$S^{\rm loc} = (k_1^3 + k_2^3 + k_3^3)/(3k_1k_2k_3)$$

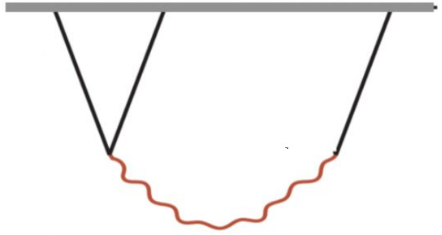
Maximised at
the equilateral limit





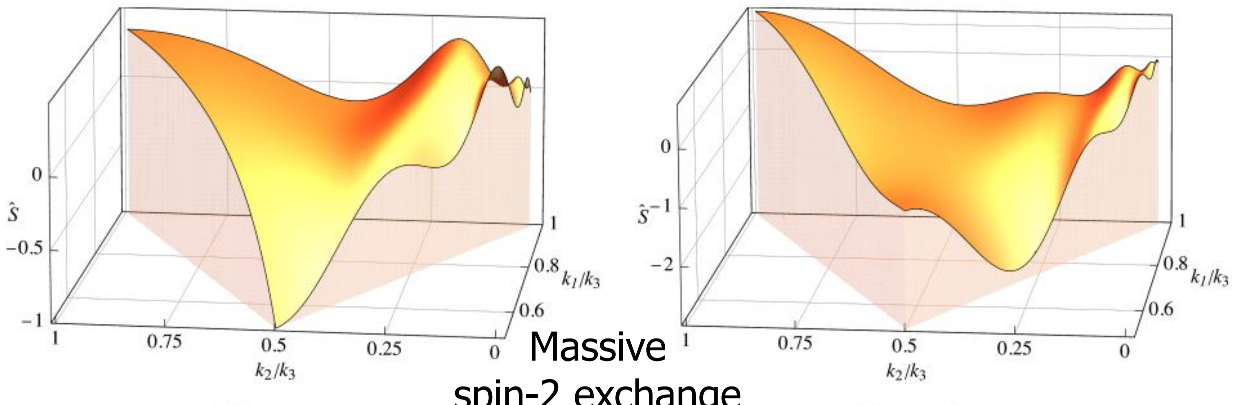
Maximised at
the squeezed limit

Spinning exchange



$m_s \gg H$ → Heavy spin exchange [Dizgah *et al* 2018]

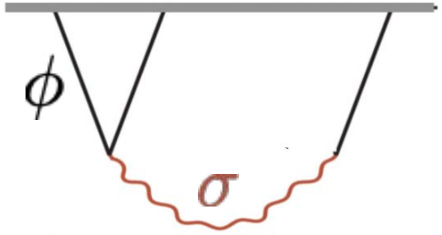
$m_s \sim H$ → Massive spin-2 exchange template developed using bootstrap in this work



(c) $\mu = 4$

(d) $\mu = 5$

Small sound speeds

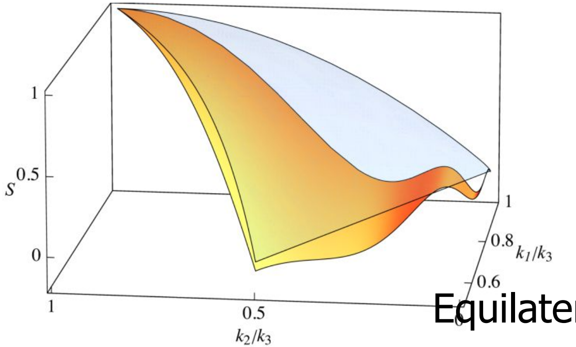


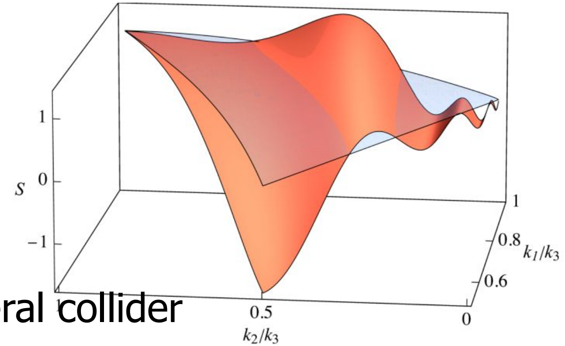
Hierarchy between the sound speeds
c_s, c_σ

$c_\sigma \ll c_s \longrightarrow$ Equilateral collider [Pimentel & Wang 2022]

$c_s \ll c_\sigma \longrightarrow$ Low-speed collider [Jazayeri *et al* 2023]

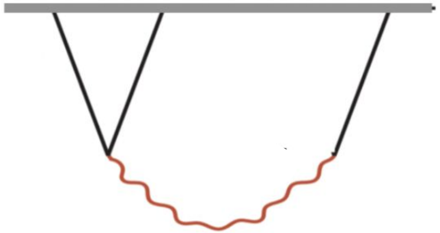
$m = 0, + \cdots \longrightarrow$ Multi-sound-speed non-Gaussianity [Wang *et al* 2023]





Equilateral collider

Spinning exchange



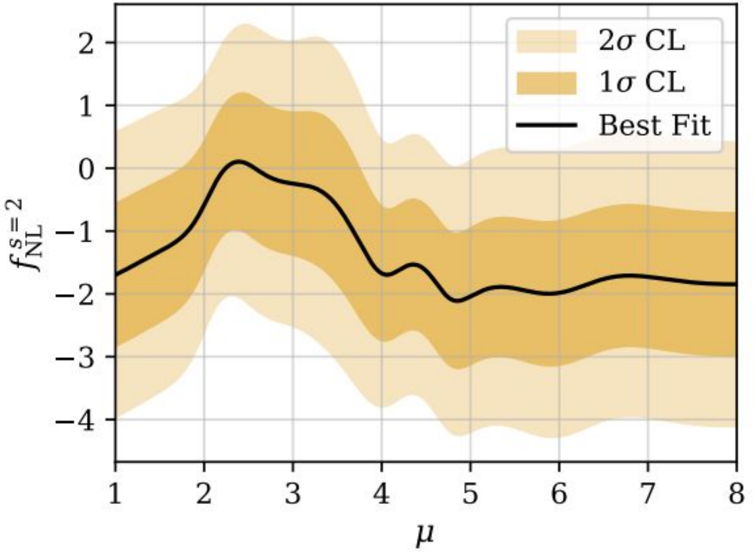
Heavy spin exchange

$$m_s \gg H$$

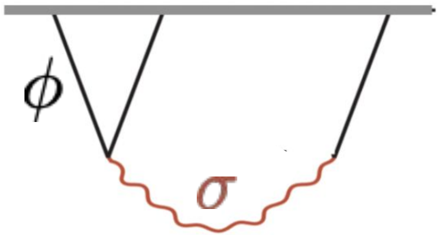
Spin	$f_{\rm NL}$ constraint	Significance
0	-1.5 ± 5.8	0.26
1	-8 ± 45	0.18
2	-18 ± 10	1.8
3	-59 ± 32	1.8
4	-17 ± 16	1.1
6	-1.9 ± 6.7	0.28

Massive spin-2 exchange

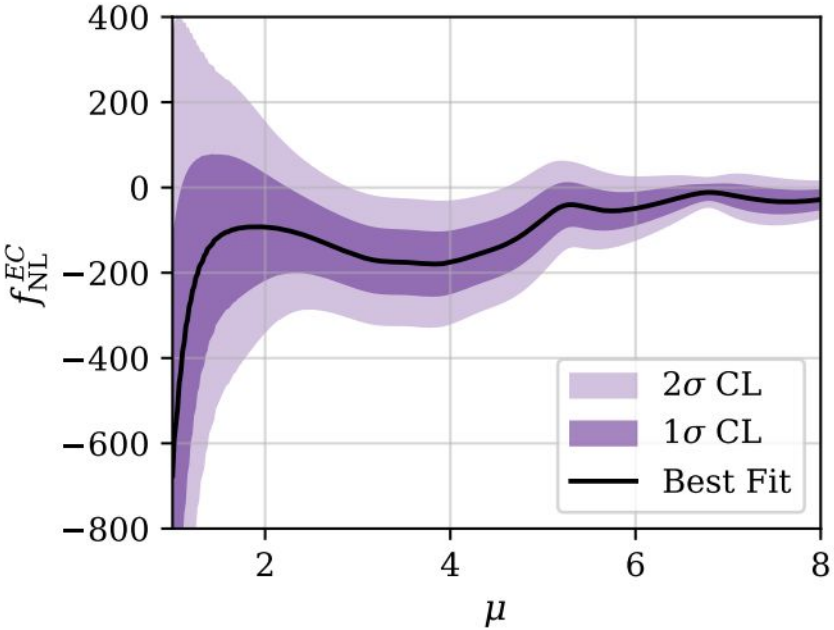
$$m_s \sim H$$

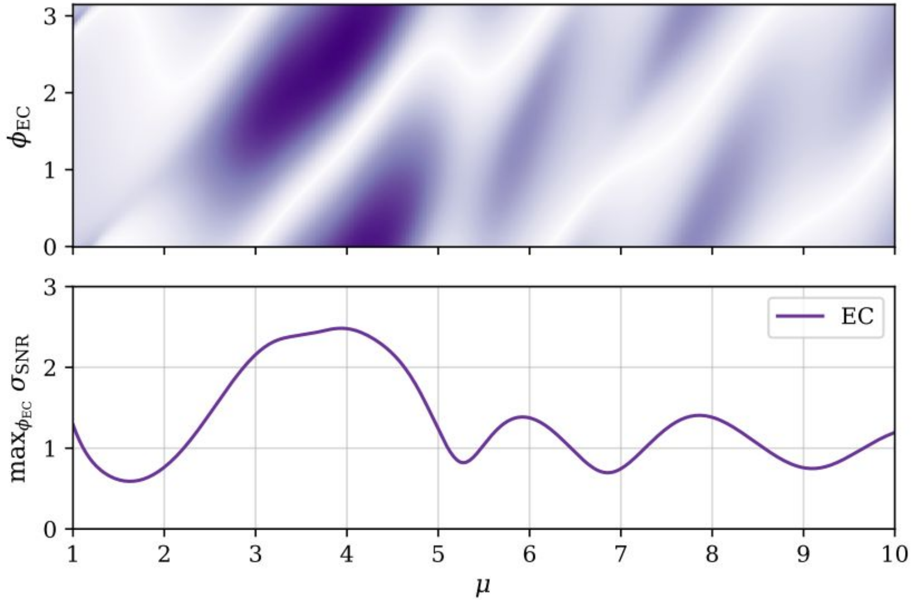


Small sound speeds

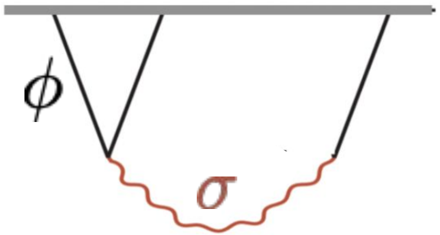


Equilateral collider $\quad c_\sigma \ll c_s$

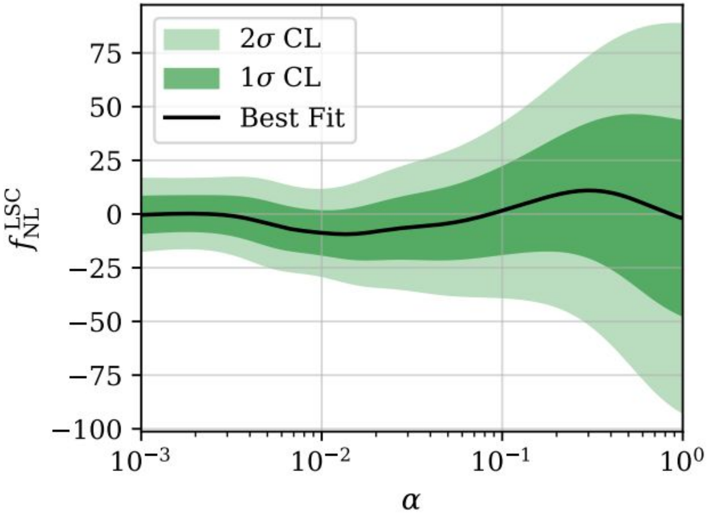


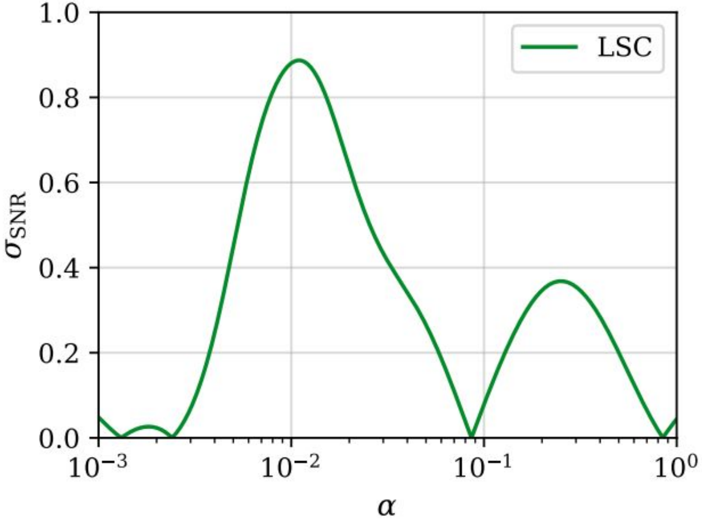


Small sound speeds

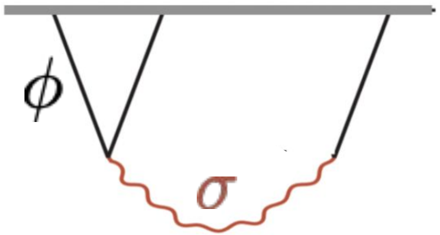


Low-speed collider $c_s \ll c_\sigma$

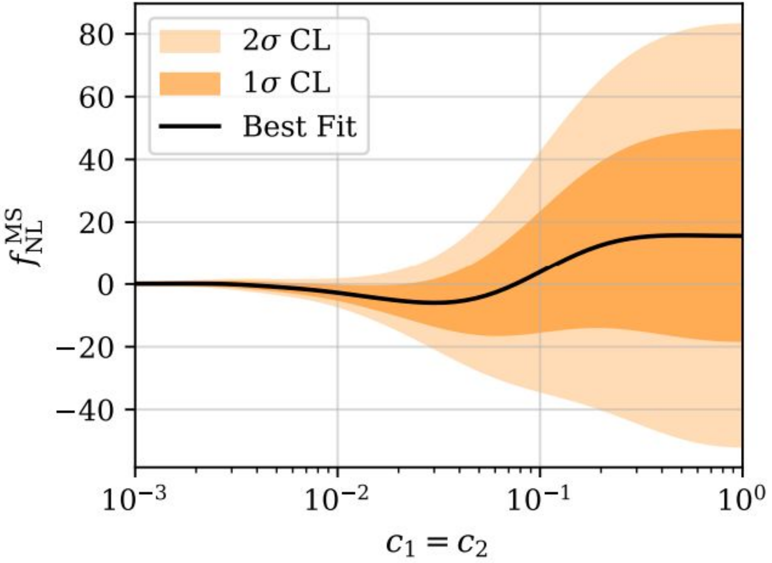


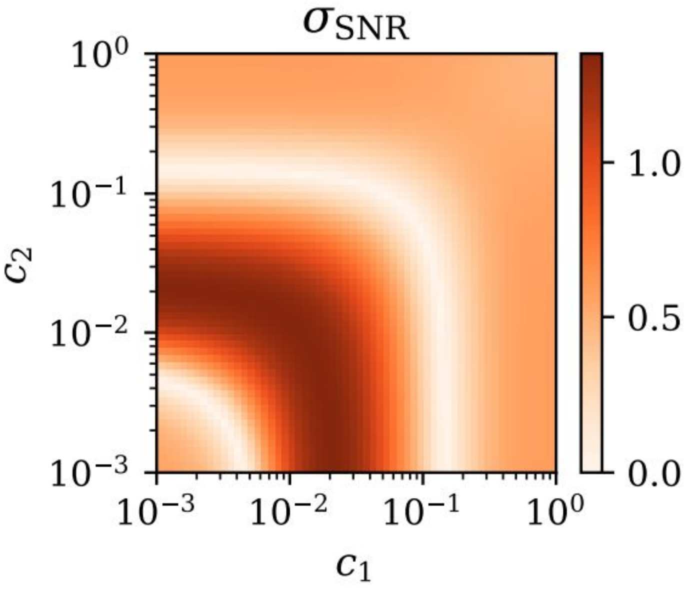


Small sound speeds



Multi-speed non-Gaussianity





Bispectrum and shape function

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \frac{18}{5} f_{\rm NL} \frac{S(k_1, k_2, k_3)}{k_1^2 k_2^2 k_3^2} P_\zeta^2$$

[WS, Fergusson, Shellard 2211.15139]

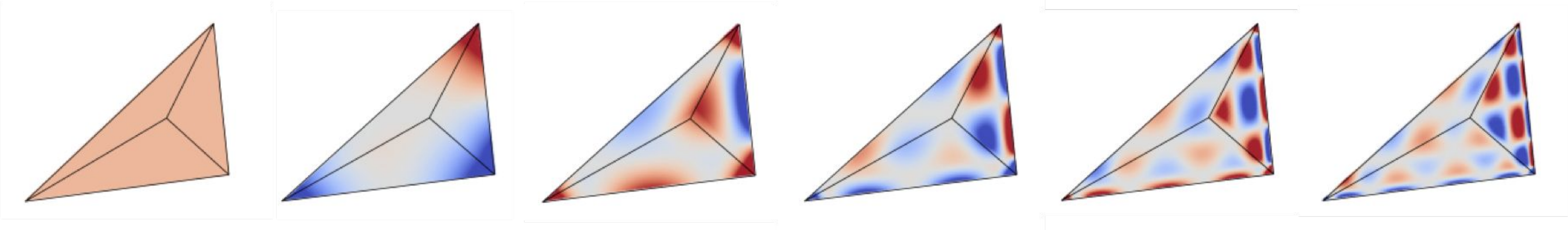
CMB-BEST: core idea

Primordial Bispectrum $B(k_1, k_2, k_3)$ → Project → **Late-time Bispectrum** $b_{l_1 l_2 l_3}$ → Fit → **Estimation** $\hat{f}_{\rm NL}$

$$B(k_1, k_2, k_3) = \sum_{abc} \alpha_{abc}\, q_a(k_1)\, q_b(k_2)\, q_c(k_3) \longrightarrow \hat{f}_{\rm NL}$$

"Separable mode expansion in the primordial space"

Example basis functions in 3D:



[WS, Fergusson, Shellard 2211.15139]

CMB-BEST vs conventional methods

Estimation Accuracy

	Separable templates (e.g. local, equilateral, orthogonal)	**Non-separable** templates (e.g. enveloped oscillations)
KSW [Komatsu et al]	Exact	Does not apply
Modal [Fergusson et al]	As good as the late-time mode expansion	
CMB-BEST (This work)	Exact	As good as the primordial mode expansion

Flexible choice of mode functions & high-resolution

[WS, Fergusson, Shellard 2211.15139]

CMB-BEST vs conventional methods

Computational cost (rough estimate)

	Separable templates (e.g. local, equilateral, orthogonal)	**Non-separable** templates (e.g. enveloped oscillations)
KSW [Komatsu et al]	~1 per model	Does not apply
Modal [Fergusson et al]	~ 30	
CMB-BEST (This work)	~ 10,000	

↓

Thoroughly optimised the algorithm and utilised HPC parallelism

[WS, Fergusson, Shellard 2211.15139]

CMB-BEST vs conventional methods

Can I use the code?

	Separable templates (e.g. local, equilateral, orthogonal)	**Non-separable** templates (e.g. enveloped oscillations)
KSW [Komatsu et al]	Yes! for standard shapes (e.g. AdriJD/ksw)	Does not apply
Modal [Fergusson et al]	Talk to James or Petar...	
CMB-BEST (This work)	Yes! Github: Wuhyun/CMB-BEST	

Get Planck CMB constraints on any input bispectra in seconds!

Primordial bispectrum

- PNG can create non-zero bispectrum:

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\; f_{\rm NL}\; B^{(f_{\rm NL}=1)}(k_1,k_2,k_3)$$

(momentum conservation)

- Models predict distinct amplitude and shape of the bispectrum
- Bispectrum is defined on a 3D 'tetrapyd' domain: