INFLATION

What have we learnt?

What can we learn?

Why should we care?

Oliver H. E. Philcox

What do we want to know about inflation?

Simplest (phenomenological) model

- A **single field,** ϕ evolving along an almost **flat potential**
- Curvature is sourced by **quantum fluctuations** in $\delta\phi$

$$\mathscr{L} \sim \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

HOWEVER:

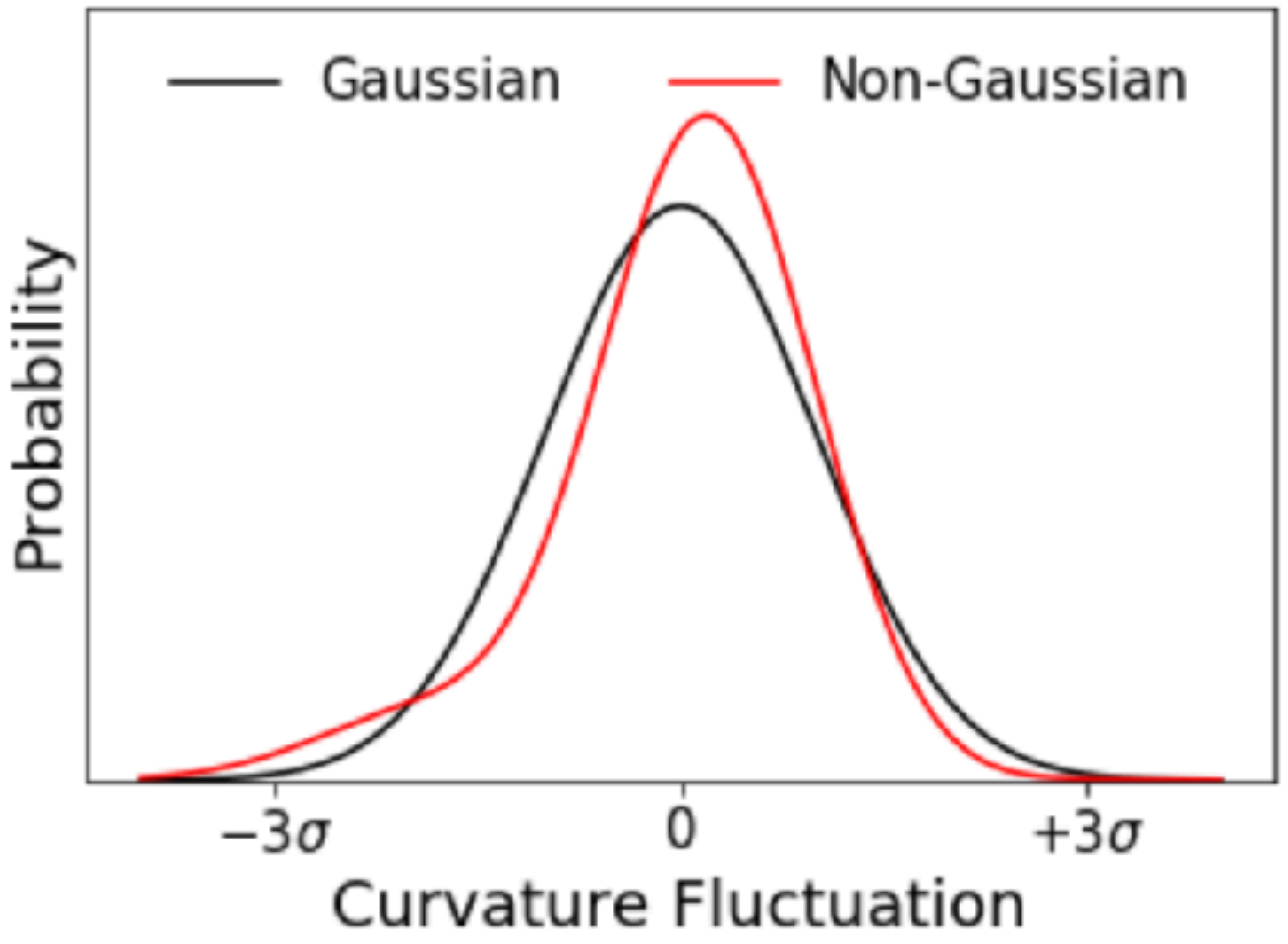
- What is the **energy scale** of inflation? [Hubble] → $H \sim 10^{16}\mathrm{GeV}$
- What sets the **potential**? → $V(\phi) = ???$
- Were there **other fields** during inflation? → $\phi \to \phi, \chi, \psi_\mu, \cdots$
- Did the fields **interact**? → Lagrangian $\supset \dot{\phi}^3 + \cdots$

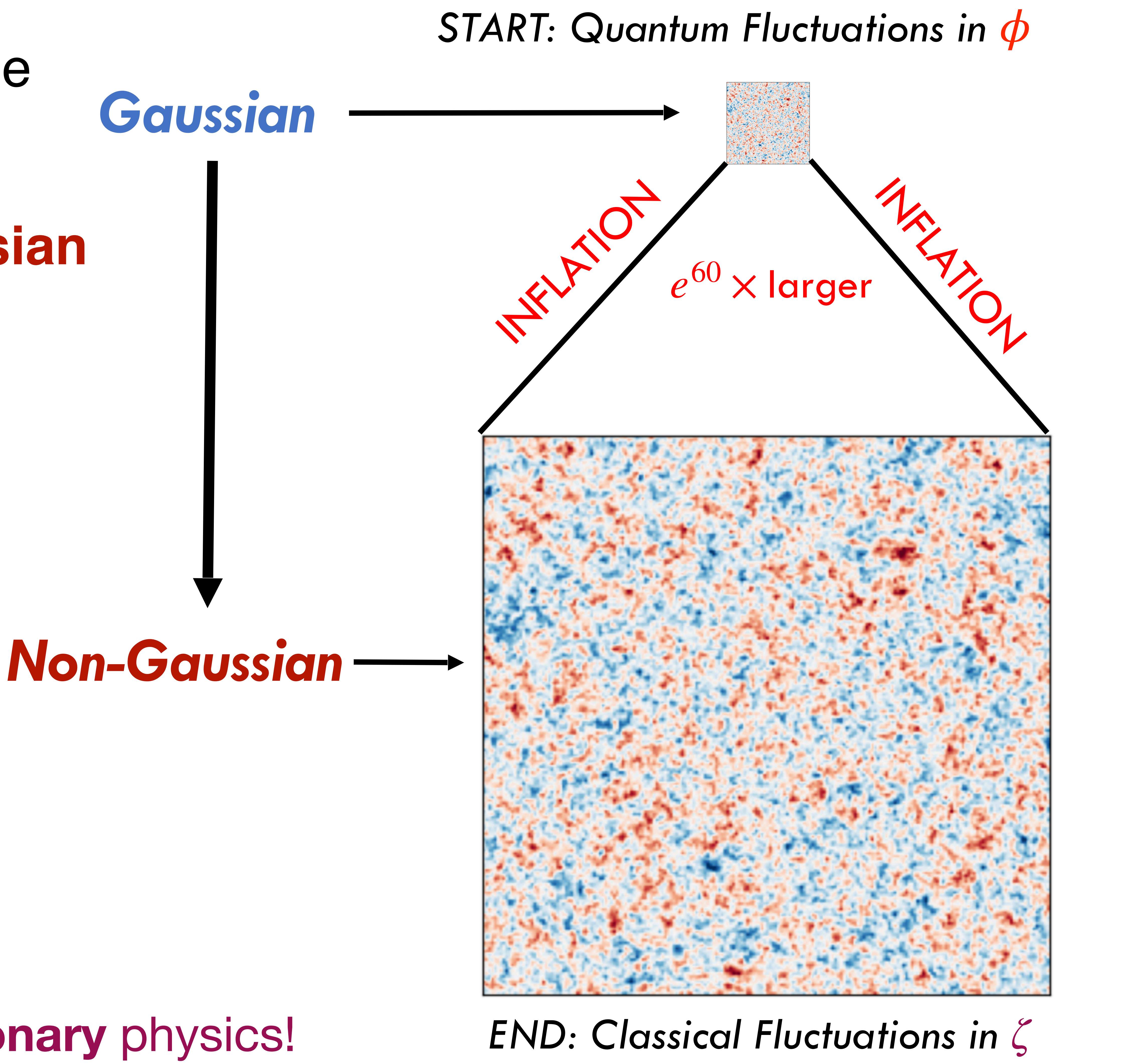
Linde, Guth, Starobinsky, Lyth, Mukhanov, Sasaki, …

How do we learn about inflation?

Vanilla inflation leads to **Gaussian** fluctuations in the primordial curvature perturbations, ζ

New physics in the early Universe gives **non-Gaussian** curvature fluctuations





By searching for **non-Gaussianity**, we can constrain **inflationary** physics!

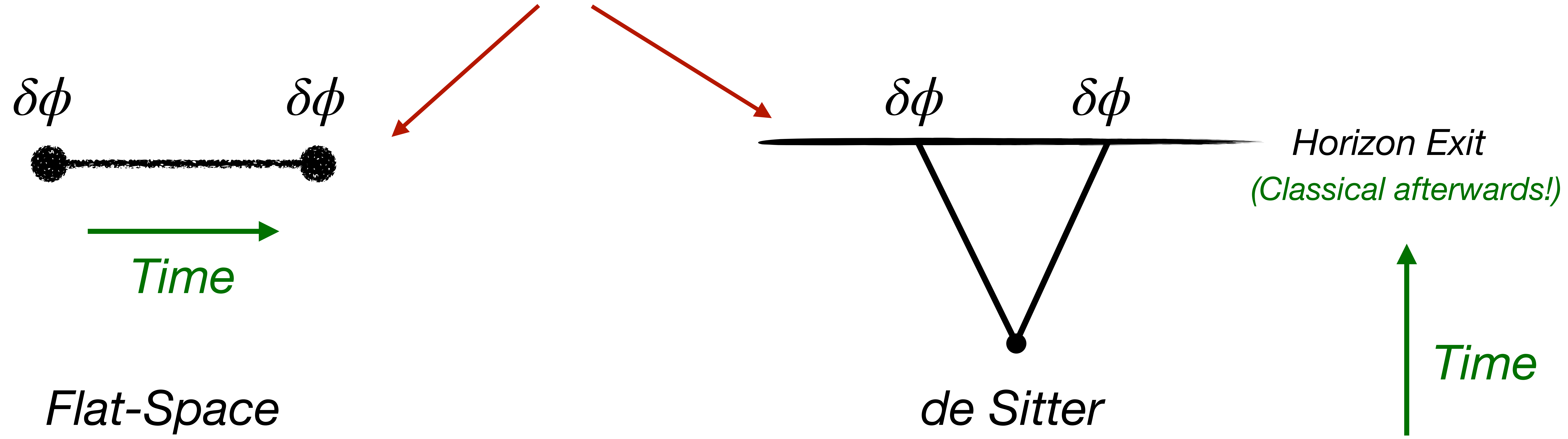
COBE, WMAP, Planck, Linde, Guth, Starobinsky, …

Two-Point Functions

- Let's assume we have just a **single field** ϕ in inflation (the "inflaton")

- The simplest inflationary action is **quadratic in perturbations:**

$$\mathscr{L} \sim \delta\dot{\phi}^2 - c_s^2(\partial\phi)^2$$



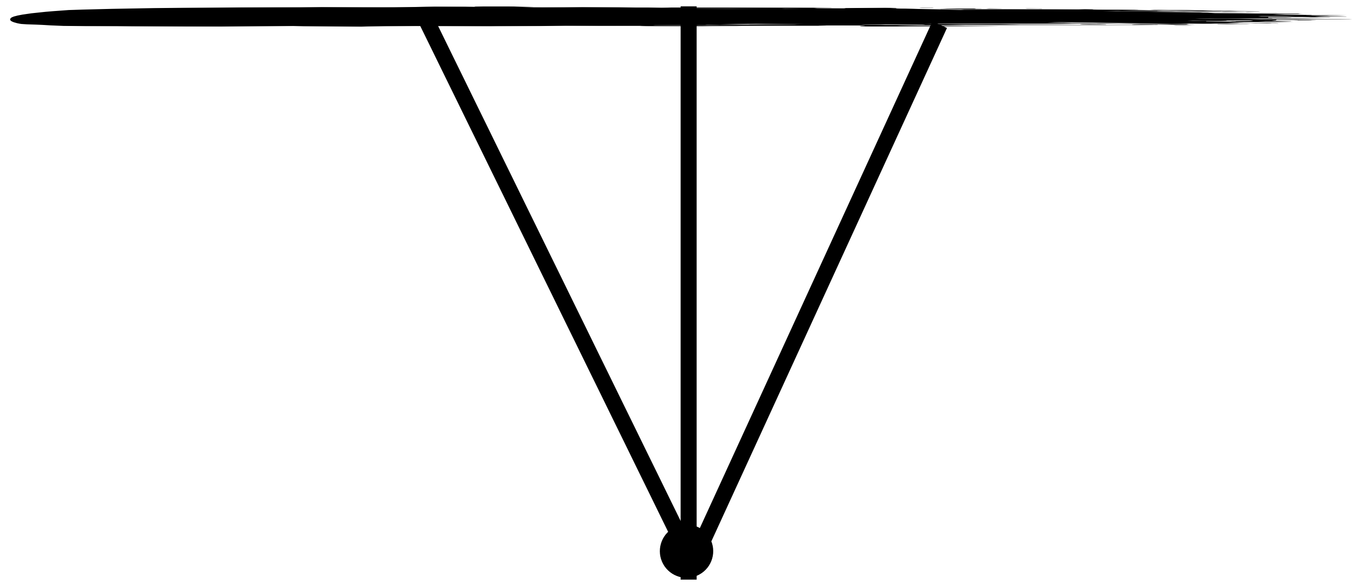
Maldacena, Arnold, Deser, Misner, …

Self-Interactions

- Many models of inflation feature **self-interactions:**

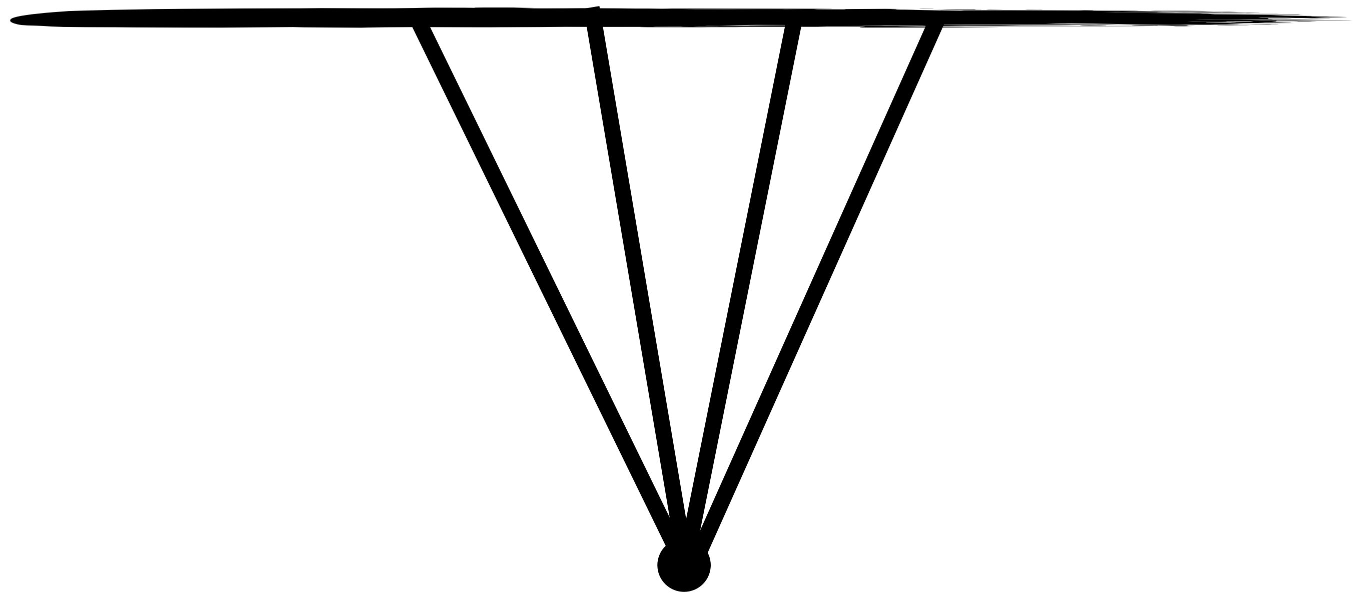
$$\mathscr{L} \supset \delta\dot{\phi}^3, \quad \delta\dot{\phi}(\partial\phi)^2, \quad \delta\dot{\phi}^4, \quad \cdots$$

$\delta\phi \quad \delta\phi \quad \delta\phi$

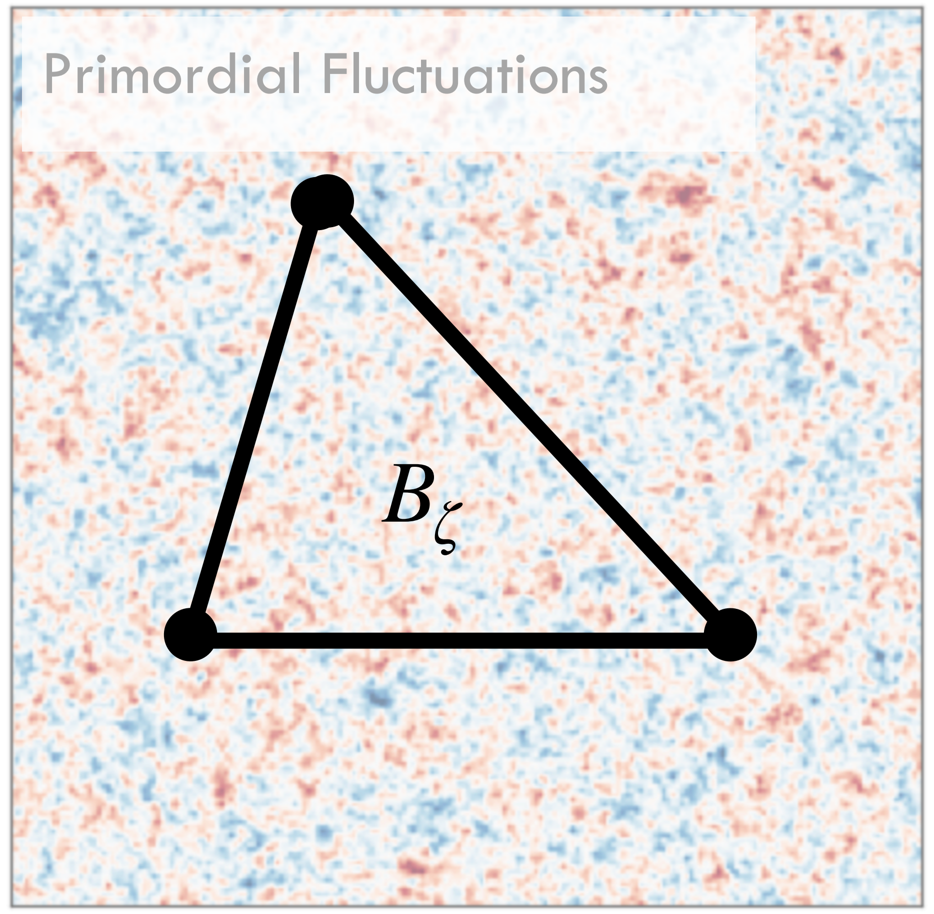


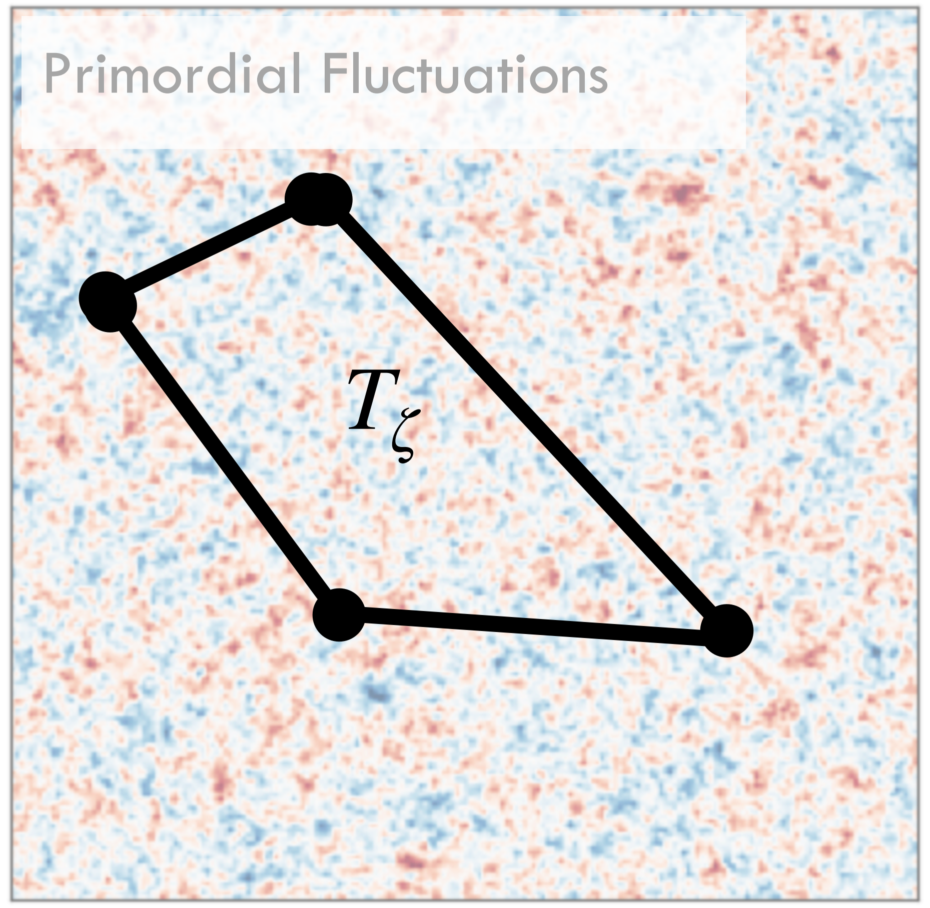
Cubic $\sim f_{\rm NL}^{\rm eq}$

$\delta\phi\,\delta\phi\,\delta\phi\,\delta\phi$



Quartic $\sim g_{\rm NL}$





- This leads to **three**- and **four-point** functions at the end of inflation
- The **shape** encodes the vertex, the **amplitude** encodes the microphysics

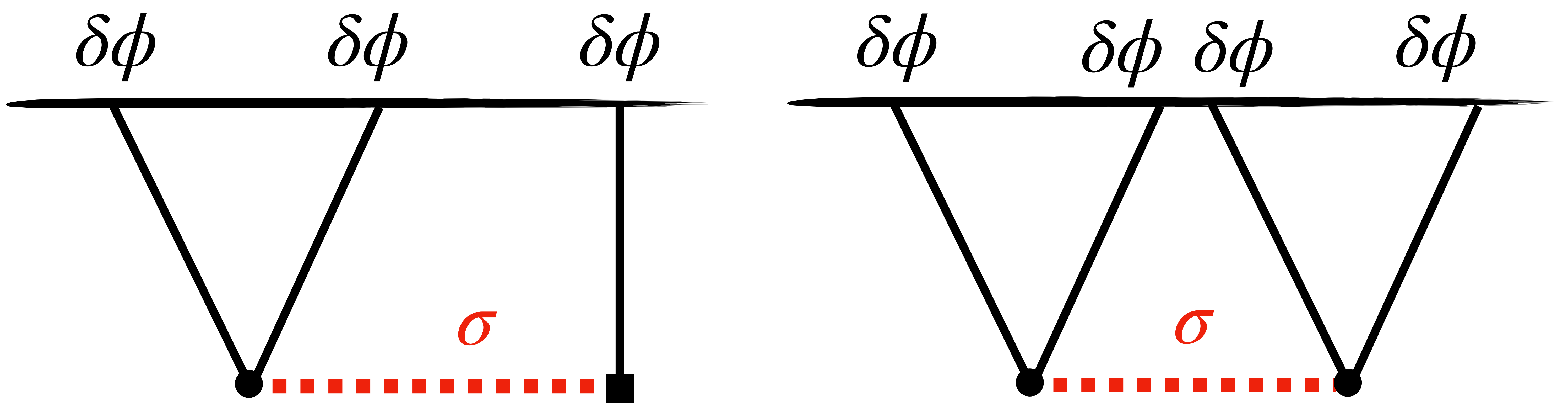
e.g. $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\rm NL}^{\rm eq} \times$ shape

See the Effective Field Theory of Inflation (Senatore, Zaldarriaga, Creminelli, Baumann, …)

~~Self~~-Interactions

- Other models feature **new particles**, σ:

$$\mathscr{L} \supset \delta\dot{\phi}\sigma, \quad \delta\dot{\phi}^2\sigma, \quad \cdots$$



Linear-Quadratic $\sim f_{\rm NL}^{\rm loc}$ *Quadratic*^{2} $\sim \tau_{\rm NL}$

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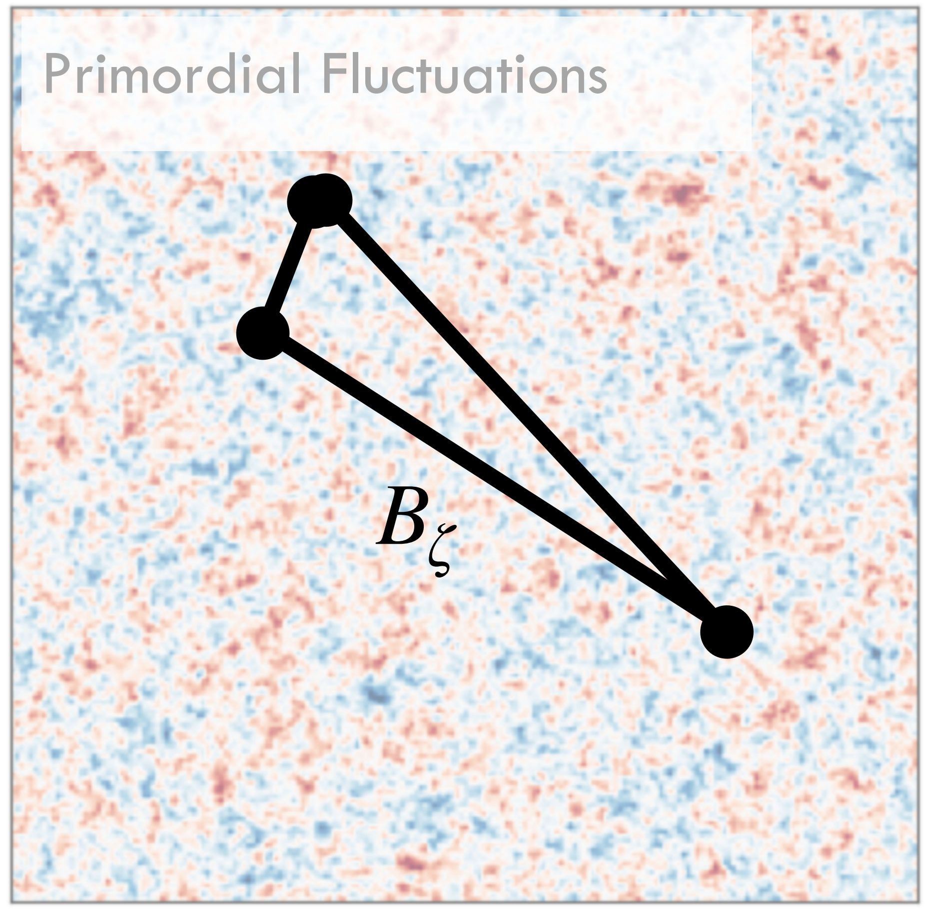
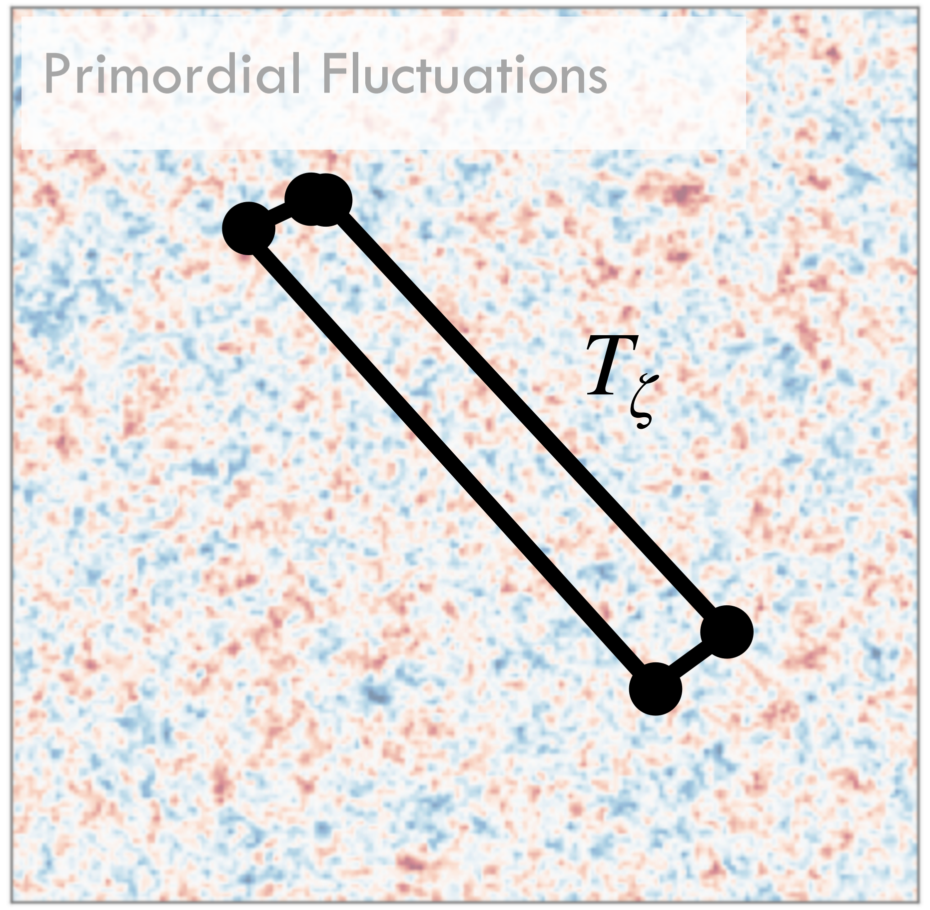
e.g. $\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\rm NL}^{\rm loc} \times$ shape





Arkani-Hamed, Maldacena, Lee, Moradinezhad, Cabass, Pajer, Jazayeri, Baumann…

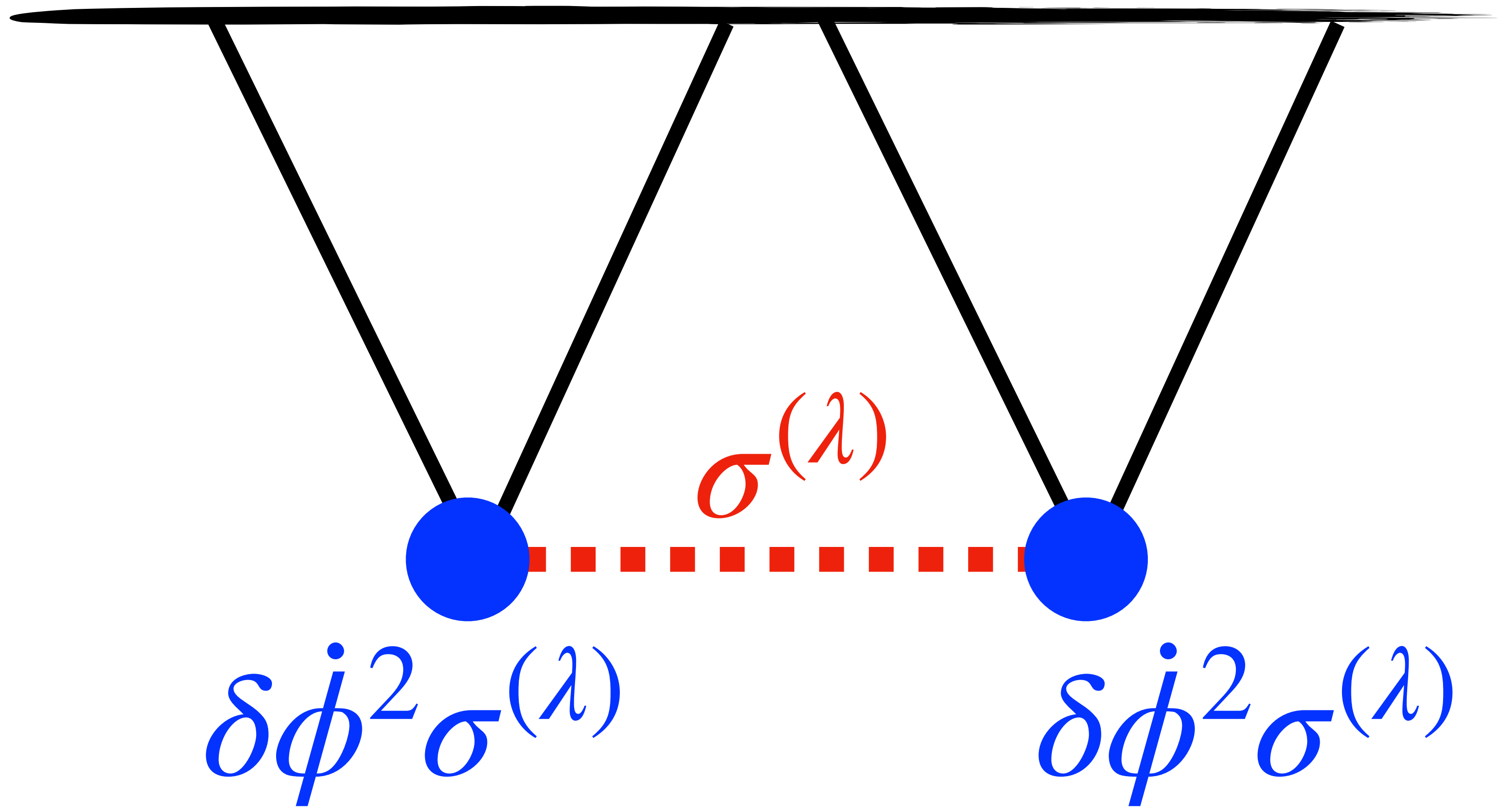
The Cosmological Collider

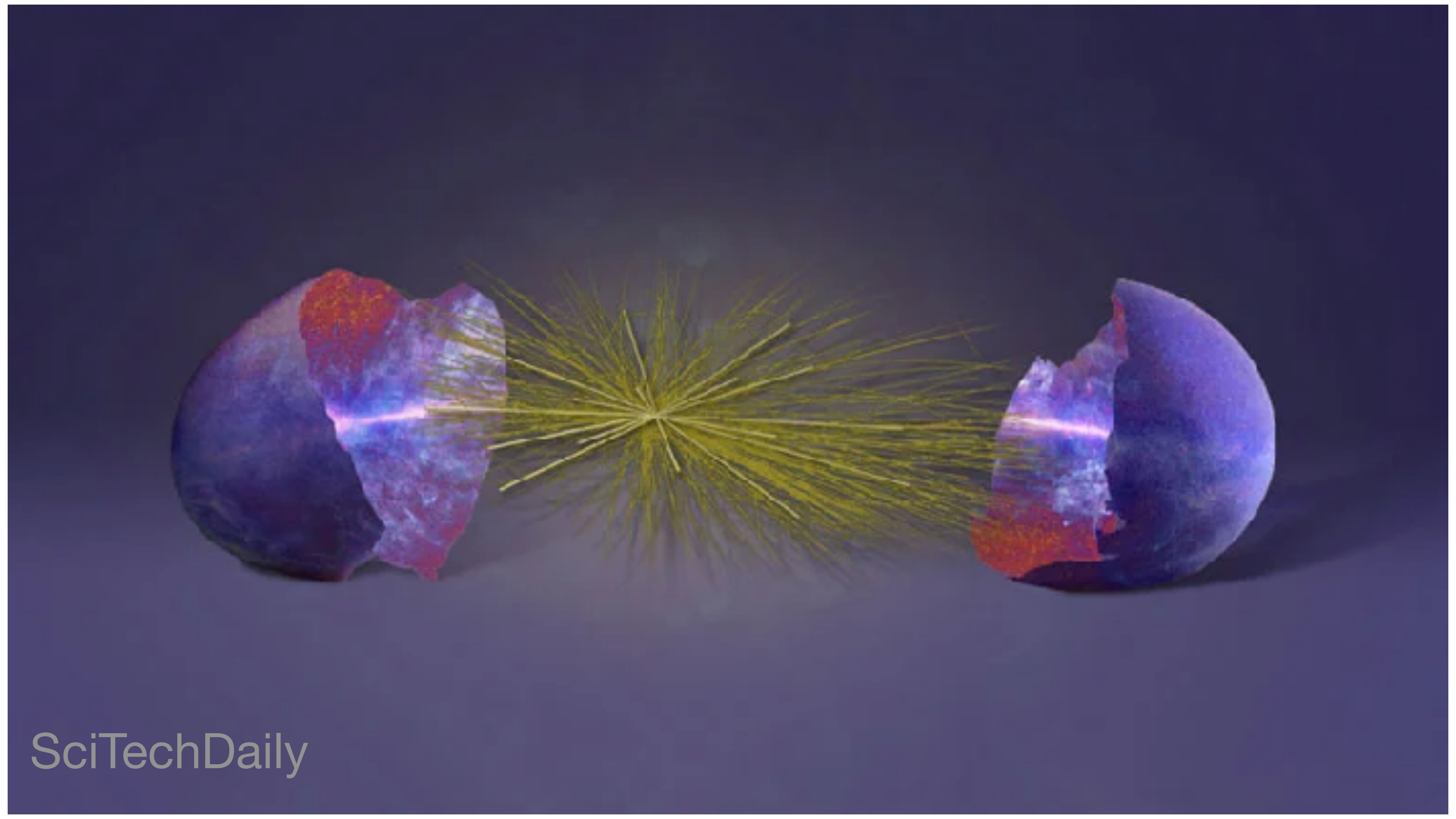
- The four-point function tracks the **exchange** of a particle $\sigma_{\mu_1 \cdots \mu_s}$ of mass $m_\sigma \sim H$ and spin $s = 0,1,2,\cdots$
- This depends on the **power spectrum** of σ, including all its **helicity states, $\sigma^{(\lambda)}$**

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle \sim \sum_\lambda P_\zeta(k_1)P_\zeta(k_3)P_{\sigma^{(\lambda)}}(K) \times \text{coupling}$$

- In the **collapsed limit** (low exchange momentum), the inflationary signatures are set by **symmetry**
- They depend **only** on mass and spin (and the speed) **not** on the microphysical model!

By studying the trispectrum we can probe new particles present during inflation!





Maldacena, Arkani-Hamed, Jazayeri, Pajer, Zaldarriaga, Lee, Moradinezhad, Cabass, Baumann, …

The Cosmological Collider

- The **three-point** function also probes particle-exchange

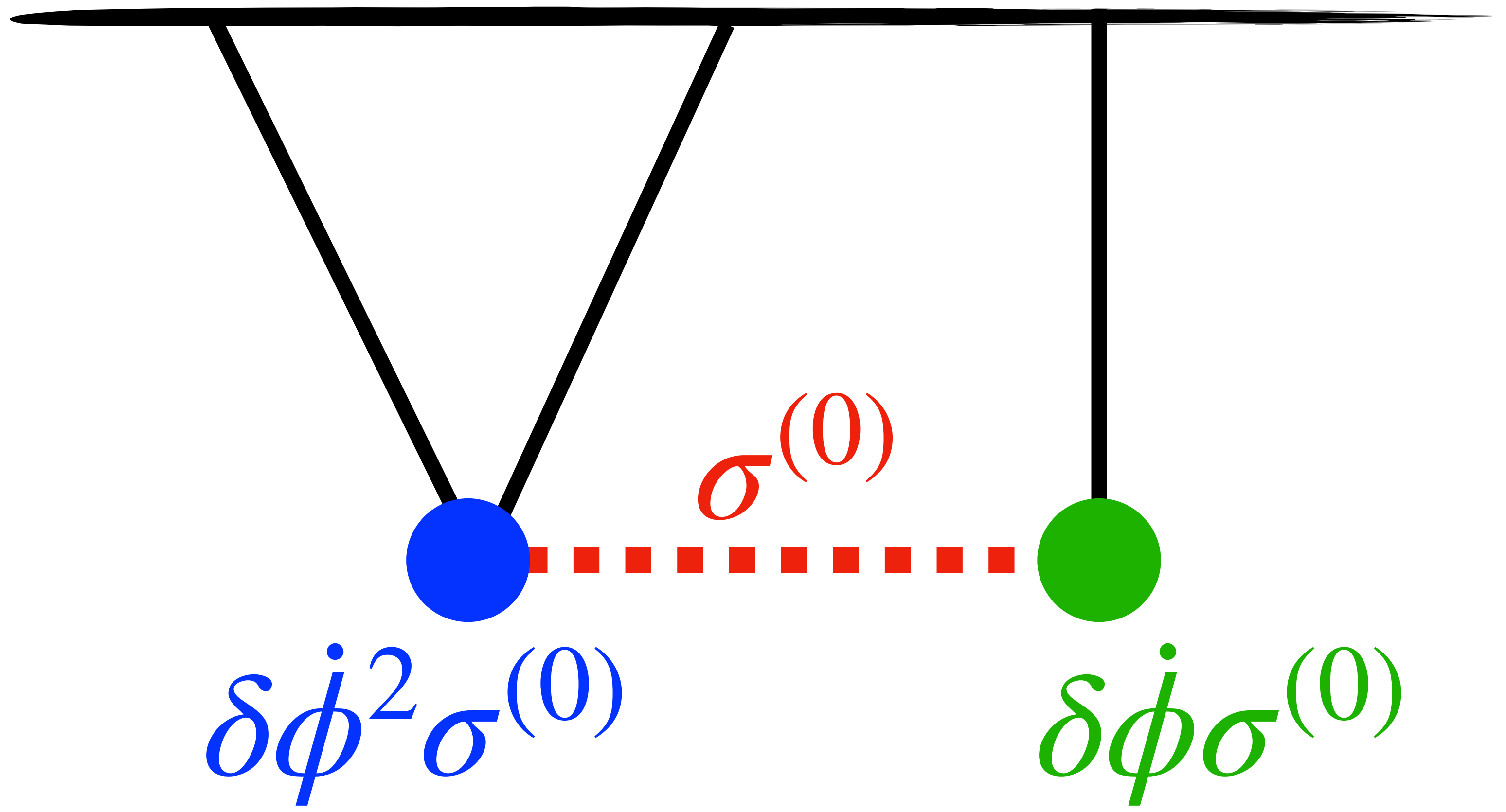
See Sam's talk!

$$B_\zeta(k_1, k_2, k_3) \sim P_\zeta(k_1) P_{\sigma^{(0)}}(k_3) \times \text{coupling}$$

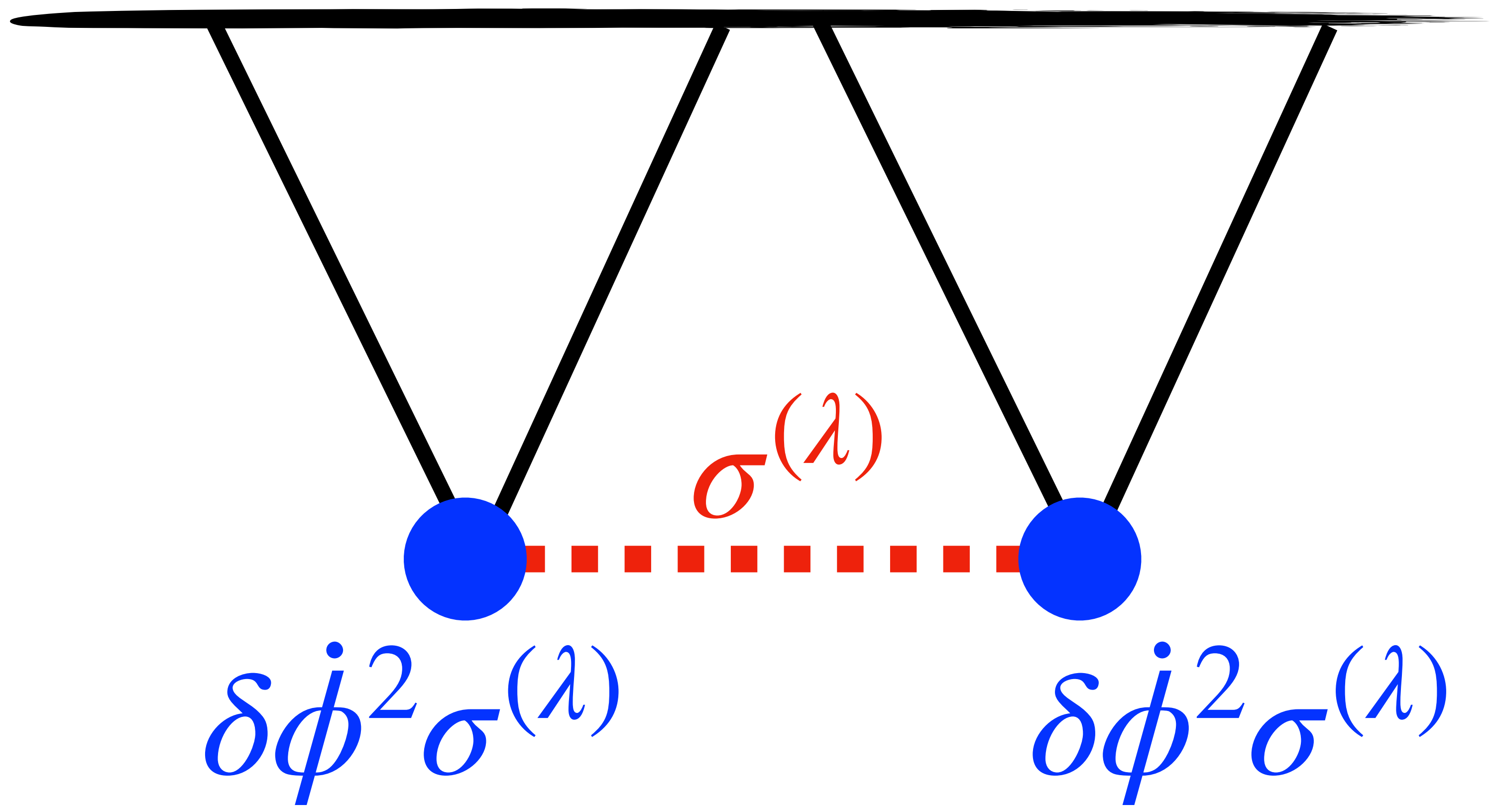
- ***However,***
  - It requires a **quadratic** coupling
    (which could be slow-roll suppressed)
  - It only probes the **longitudinal mode,** $\sigma^{(0)}$
    (which could be subdominant)

- We need the **four-point** function to fully probe collider physics!

Three-Point



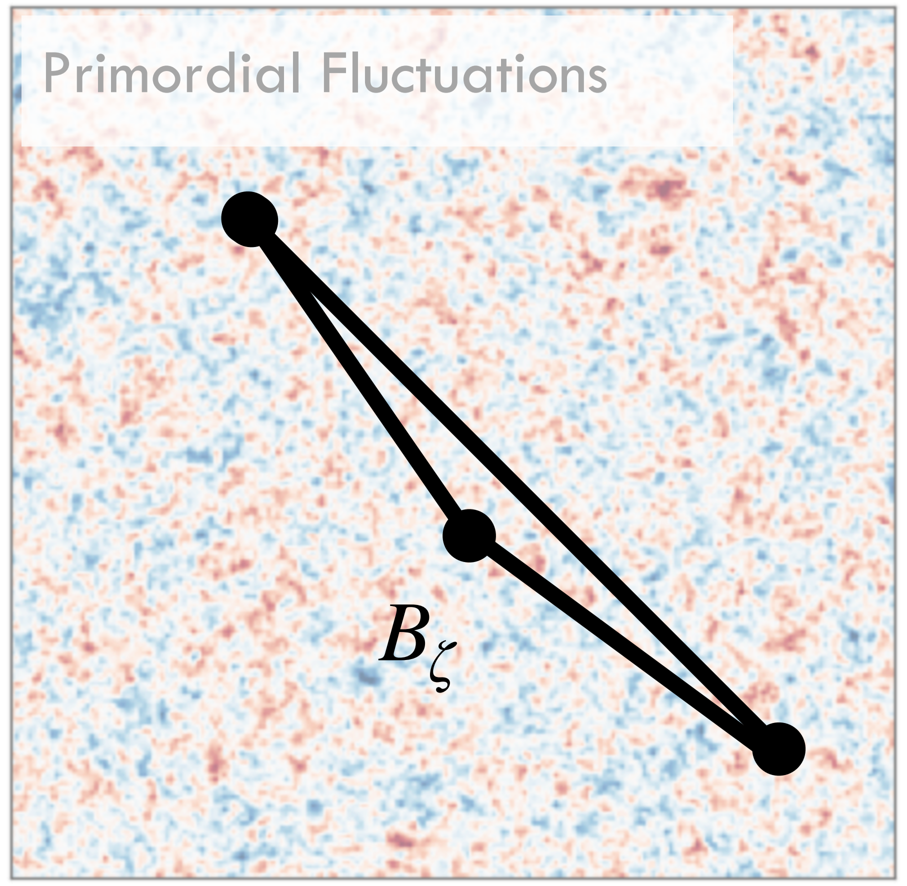
Four-Point

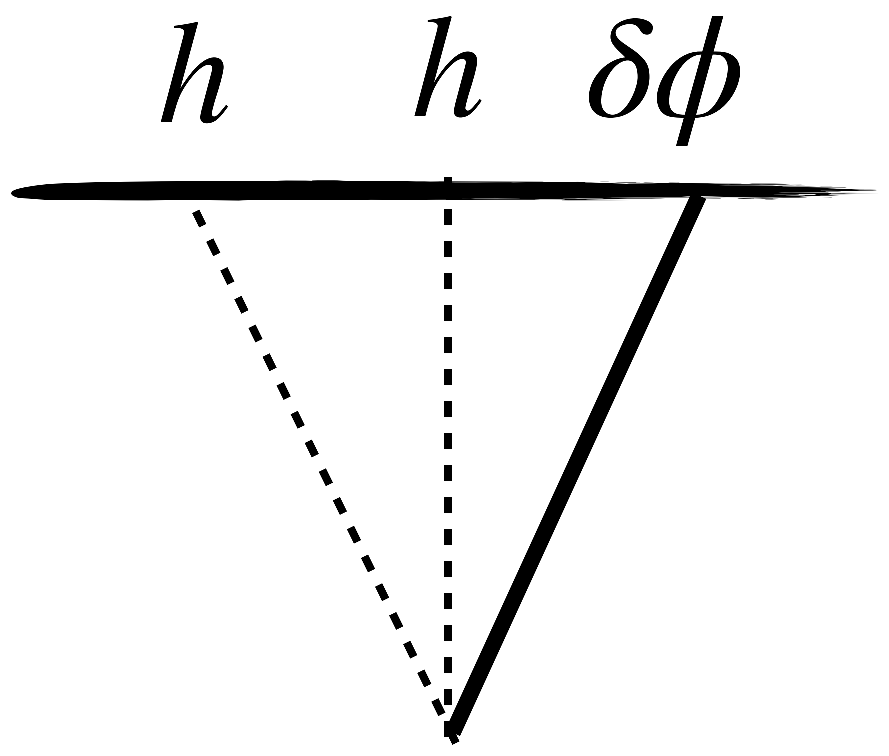


Maldacena, Arkani-Hamed, Jazayeri, Pajer, Zaldarriaga, Lee, Moradinezhad, Cabass, Baumann, …

Other Inflationary Effects

- **Folded** non-Gaussianity?
  - Dissipative effects in inflation
  - Modified initial conditions
- **Oscillatory** effects and **non-perturbativity**?
  - Resonances, axions
  - Very massive particles
- **Tensor** non-Gaussianity?
  - Modified gravity, gauge fields, massive gravity, magnetic fields…

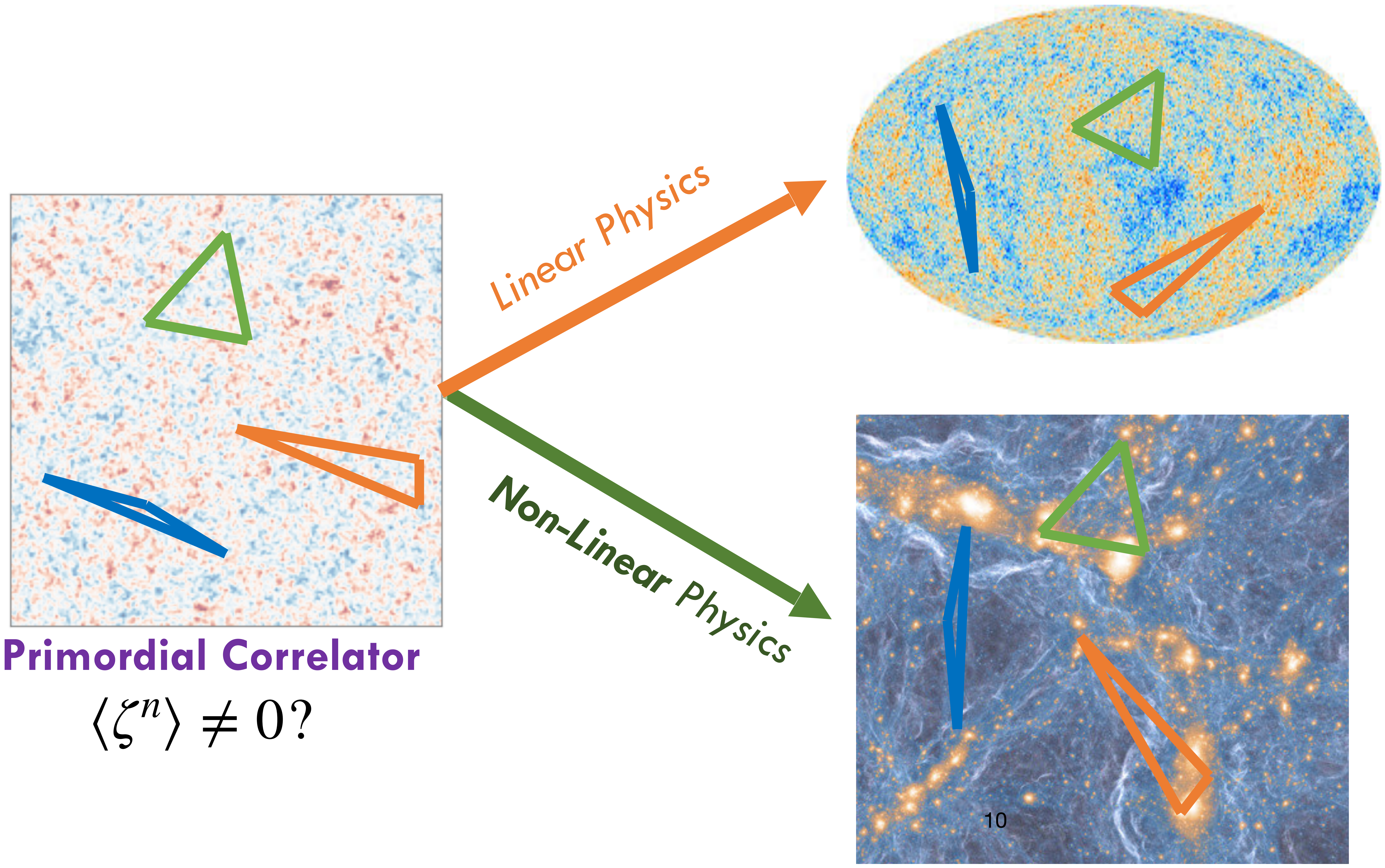




$$\langle h\zeta\zeta\rangle, \langle hh\zeta\rangle, \langle hhh\rangle \neq 0?$$

Pajer, Meerburg, Colas, Salcedo, Creminelli, Shiraishi, **Philcox**…

How to Measure Primordial Non-Gaussianity



Cosmic Microwave Background Correlator

$\langle \delta T^n \rangle \neq 0?$

Galaxy Distribution Correlator

$\langle \delta \rho^n_{\mathrm{galaxy}} \rangle \neq 0?$

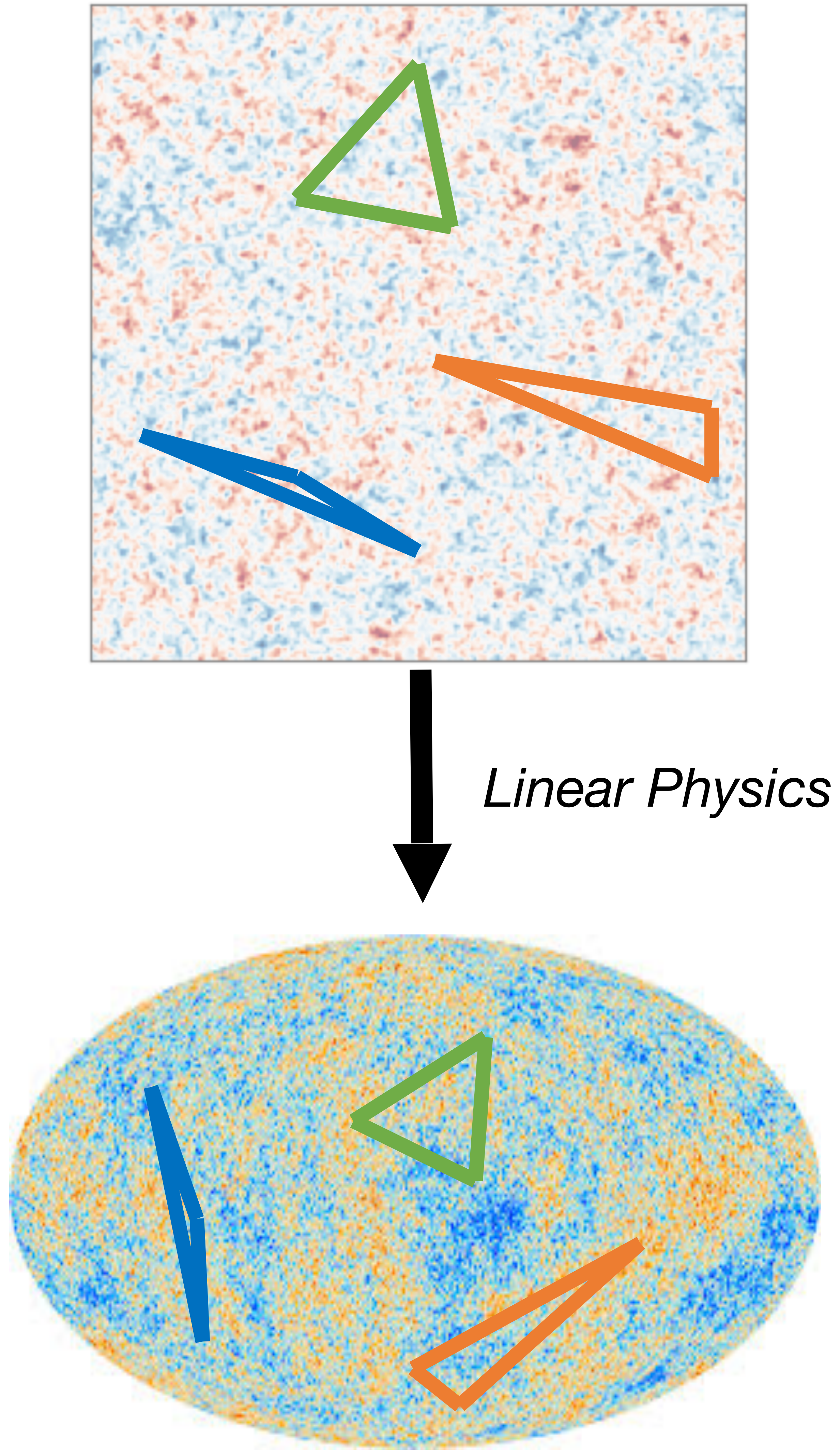
Planck, IllustrisTNG

CMB Constraints (Easyish)

- *Planck* placed **strong** constraints on scalar **three-point** functions

Planck 2018			
	Local	−0.9	± 5.1
	Equilateral	−26	± 47
	Orthogonal	−38	± 24

- These span **many** phenomenological templates
- Recent work by Wuhyun Sohn++ group probed **cosmological collider bispectra**



Conclusion: Scalar primordial non-Gaussianity is **small!**

$$10^{-5}\,|f_{\rm NL}| \ll 1$$

However, we are still far from the (vaguely defined) theory limits

$$\sigma(f_{\rm NL}) \sim 1$$

Planck 2018, Sohn, Wang, Shellard, Fergusson, Smith, Senatore, Maldacena, Creminelli, …

CMB Constraints (Hardish)

- *Planck* can also constrain tensor **three-point** functions

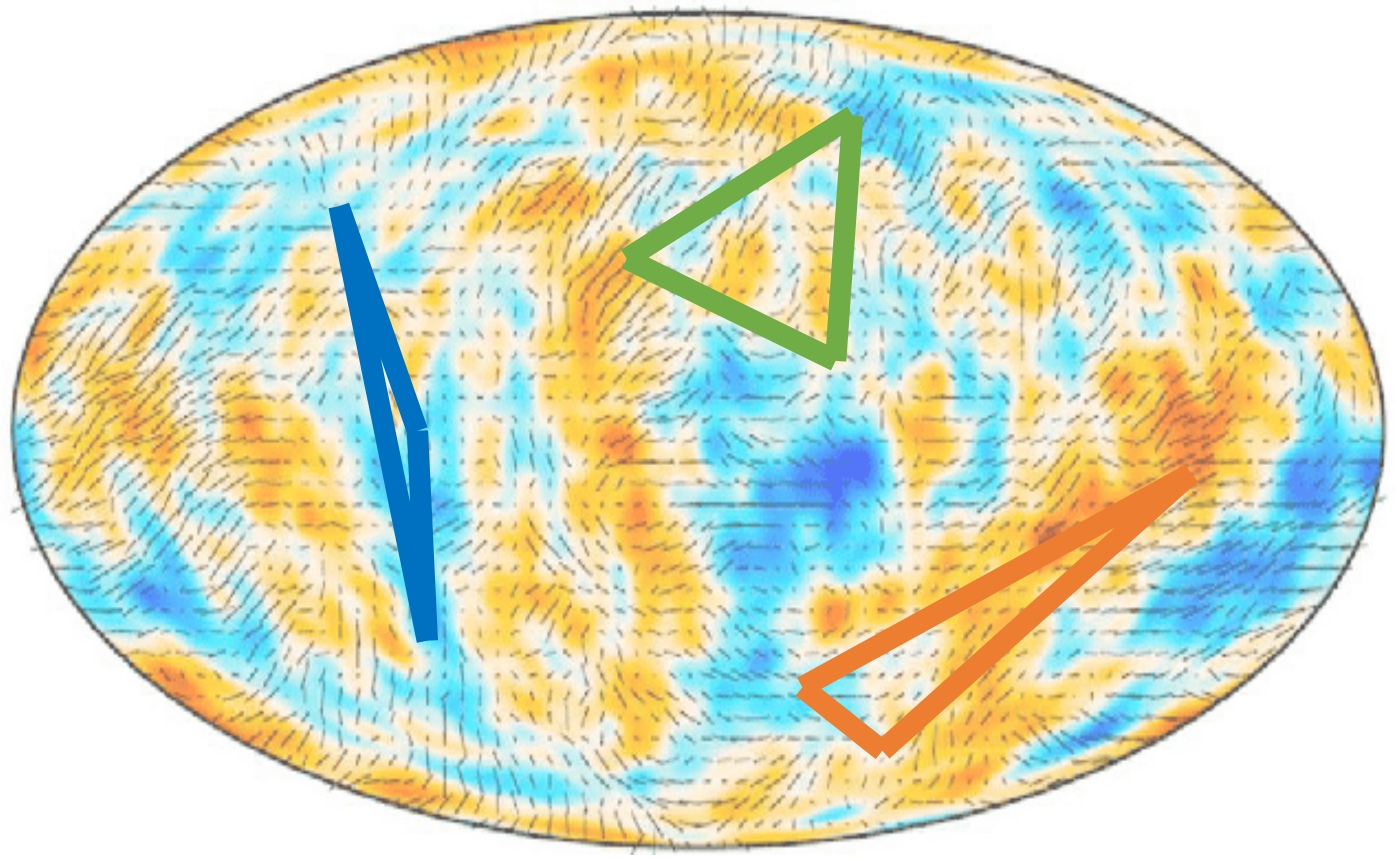
$$\text{e.g.,}\quad \langle TTB \rangle \sim \langle \zeta\zeta(h_+ - h_\times)\rangle$$

- Recent work has constrained several **gravitational wave** templates:
  - Weyl gravity, squeezed bispectra, massive gravity, gauge fields, …

- This uses **binned bispectrum** estimators (not very optimal)
- The signals are mostly on **large scales** due to tensor transfer-functions
- This is limited by **lensing** and **B-mode noise**, not cosmic variance

Conclusion: Tensor primordial non-Gaussianity is **small!**

$$10^{-5}\,|f_{\rm NL}^{\rm tens}| \ll 1$$



Model		*Planck* T	T+E	**T+E+B**
Tensor-Tensor-Tensor				
Squeezed	$(\times 10^{-1})$	51 ± 32	-4 ± 13	$\mathbf{7 \pm 9}$
Equilateral	$(\times 10^{-2})$	-5 ± 13	-3 ± 5	$\mathbf{-0 \pm 3}$
W^3 ($n_{\rm NL} = +1$)	$(\times 10^{-3})$	-63 ± 34	-7 ± 7	$\mathbf{8 \pm 4}$
W^3 ($n_{\rm NL} = 0$)	$(\times 10^{-2})$	-8 ± 14	-4 ± 6	$\mathbf{4 \pm 4}$
W^3 ($n_{\rm NL} = -1$)	$(\times 10^{0})$	-3 ± 41	-7 ± 27	$\mathbf{-6 \pm 15}$
$\widetilde{W}W^2$ ($n_{\rm NL} = +1$)	$(\times 10^{-3})$	61 ± 98	-18 ± 15	$\mathbf{-8 \pm 6}$
$\widetilde{W}W^2$ ($n_{\rm NL} = 0$)	$(\times 10^{-2})$	42 ± 63	-9 ± 11	$\mathbf{-3 \pm 5}$
$\widetilde{W}W^2$ ($n_{\rm NL} = -1$)	$(\times 10^{0})$	136 ± 222	-24 ± 55	$\mathbf{5 \pm 20}$
$\tilde{F}F$	$(\times 10^{-2})$	-16 ± 27	-10 ± 10	$\mathbf{3 \pm 6}$
Tensor-Tensor-Scalar				
$\widetilde{W}W$	$(\times 10^{-2})$	29 ± 460	31 ± 67	$\mathbf{5 \pm 11}$
Tensor-Scalar-Scalar				
Squeezed	$(\times 10^{0})$	-17 ± 31	9 ± 15	$\mathbf{13 \pm 10}$

Shiraishi, **Philcox** 2023, 2024, see also Duivenvoorden, Coulton, etc.

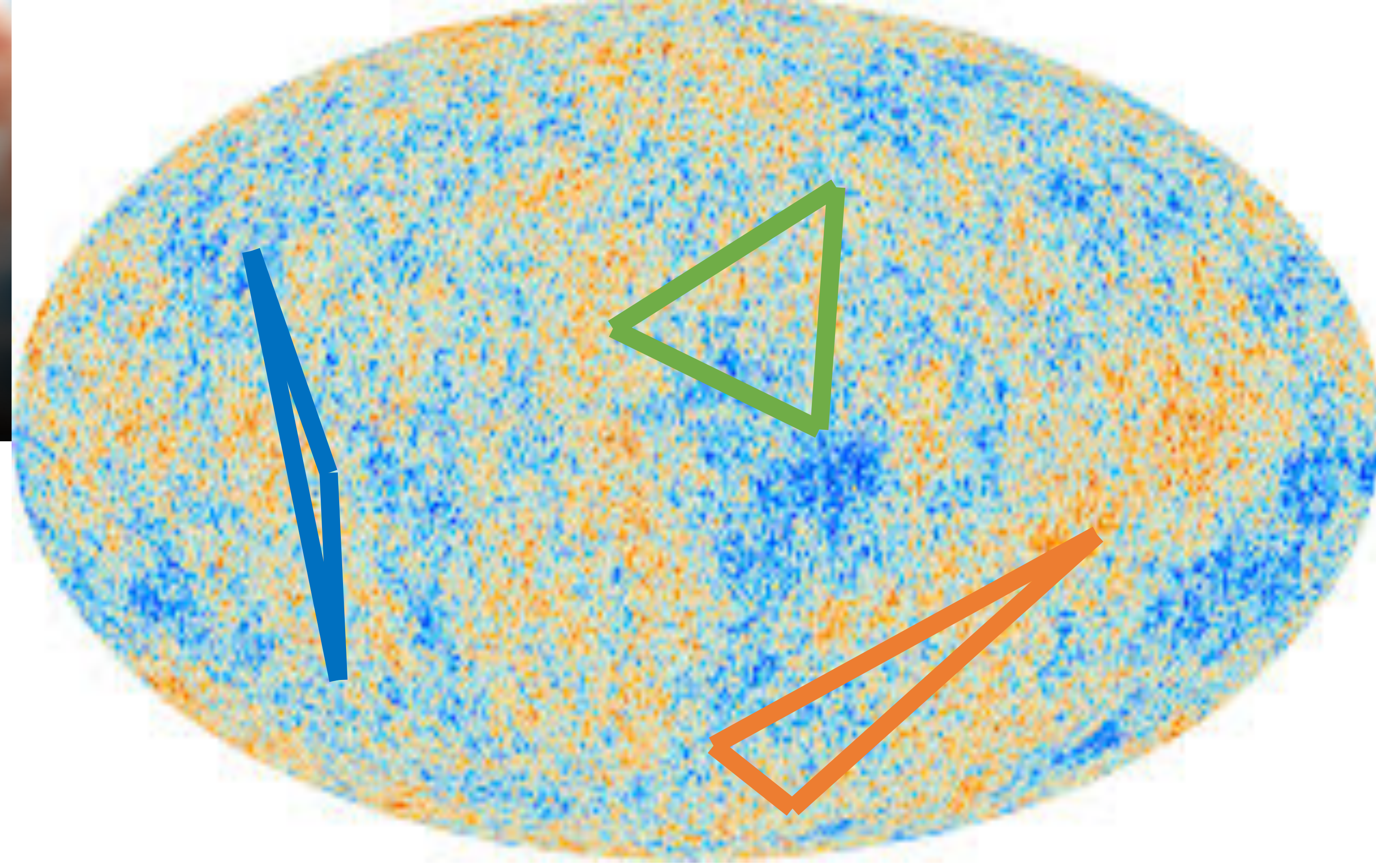
CMB Constraints (Nightmarish)

- ***Very few*** previous works have considered **four-point** functions!

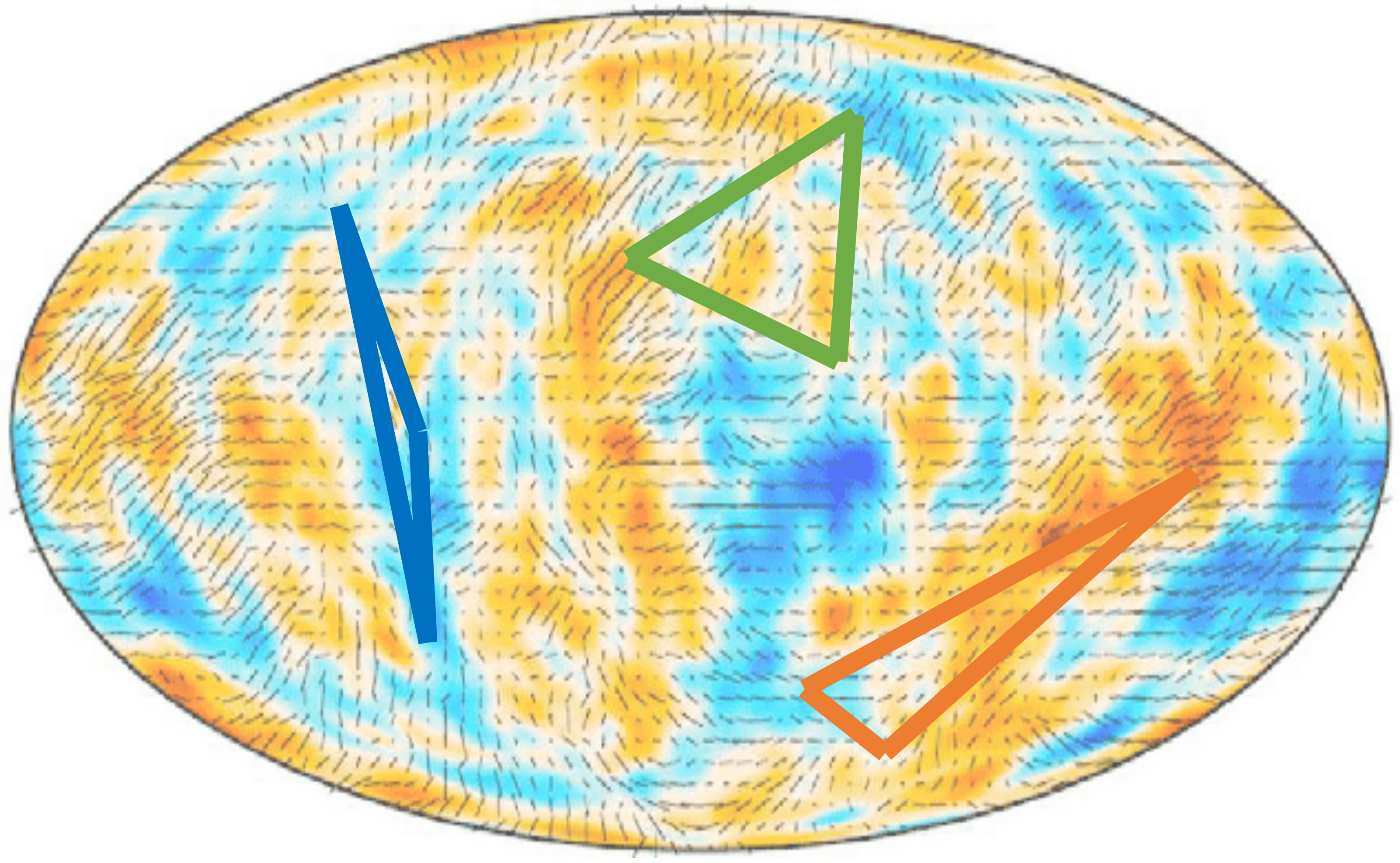
- Until recently, we *only* had constraints on
  - Local effects ($g_{\rm NL}^{\rm loc}, \tau_{\rm NL}^{\rm loc}$)
  - Self-interactions (from the EFT of inflation: $g_{\rm NL}^{\rm equil} \times 3$)

- There's **much** more to learn from the CMB!

Let's search for primordial physics in the CMB four-point function!



Planck CMB Temperature



Planck CMB Polarization

Planck 2018, Carron, Marzouk, Lewis, Smith+, Senatore+, Maldacena, Creminelli, Fergusson+, Shellard+, Sohn+

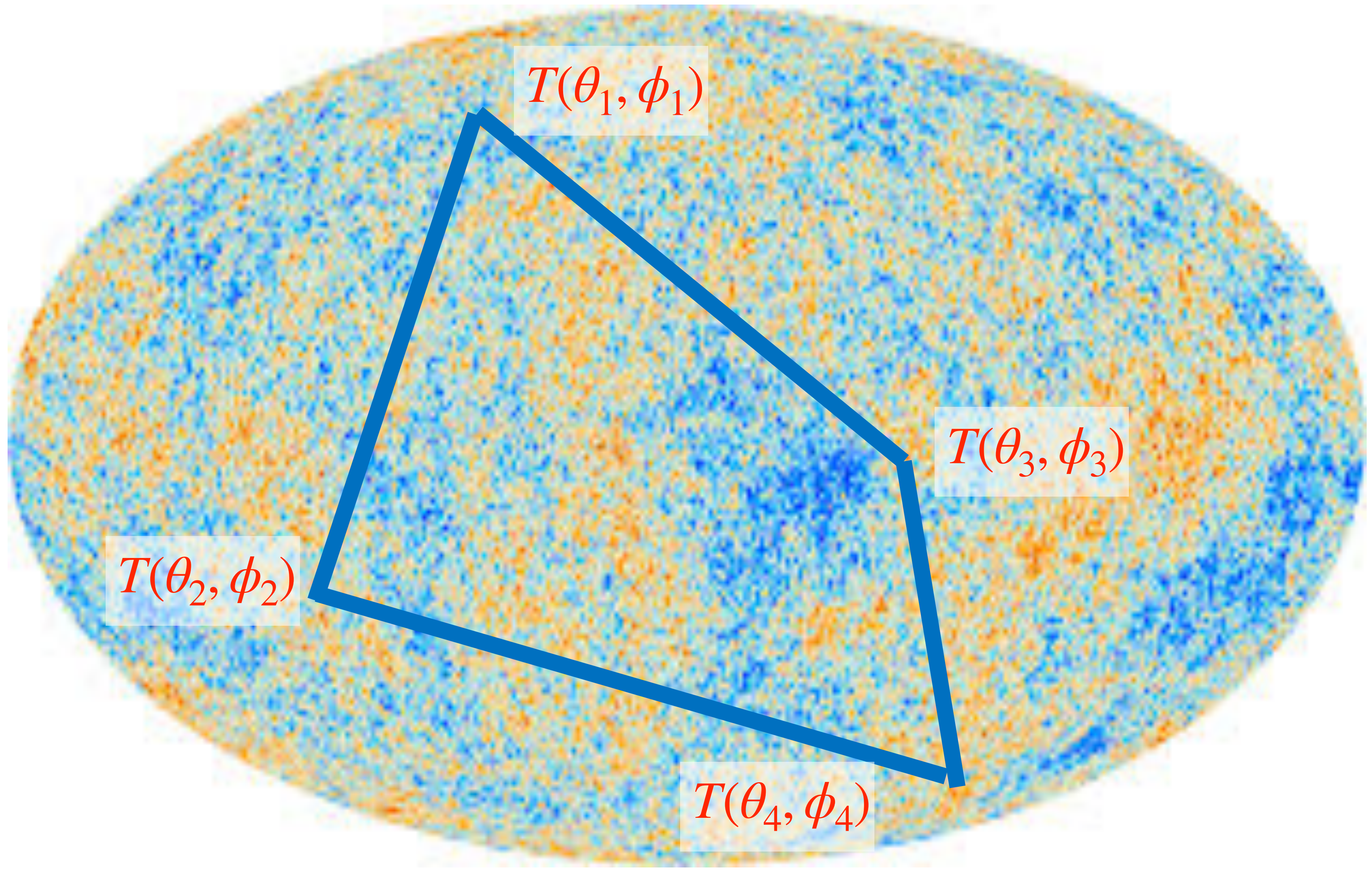
How to Measure a Four-Point Function

- CMB experiments measure the **temperature** and **polarization** across the whole sky

$$T(\theta, \phi), \quad E(\theta, \phi) \quad \leftrightarrow \quad a^T_{\ell m}, \quad a^E_{\ell m}$$

- Since the physics is **linear** we just need to correlate the CMB at **four** angles

$$\langle T(\theta_1, \phi_1) T(\theta_2, \phi_2) T(\theta_3, \phi_3) T(\theta_4, \phi_4) \rangle \leftrightarrow \langle a^T_{\ell_1 m_1} a^T_{\ell_2 m_2} a^T_{\ell_3 m_3} a^T_{\ell_4 m_4} \rangle$$



- **BUT:**
  - The trispectrum is 8-dimensional!?
  - There's 10^{28} combinations of points?!

Planck 2018

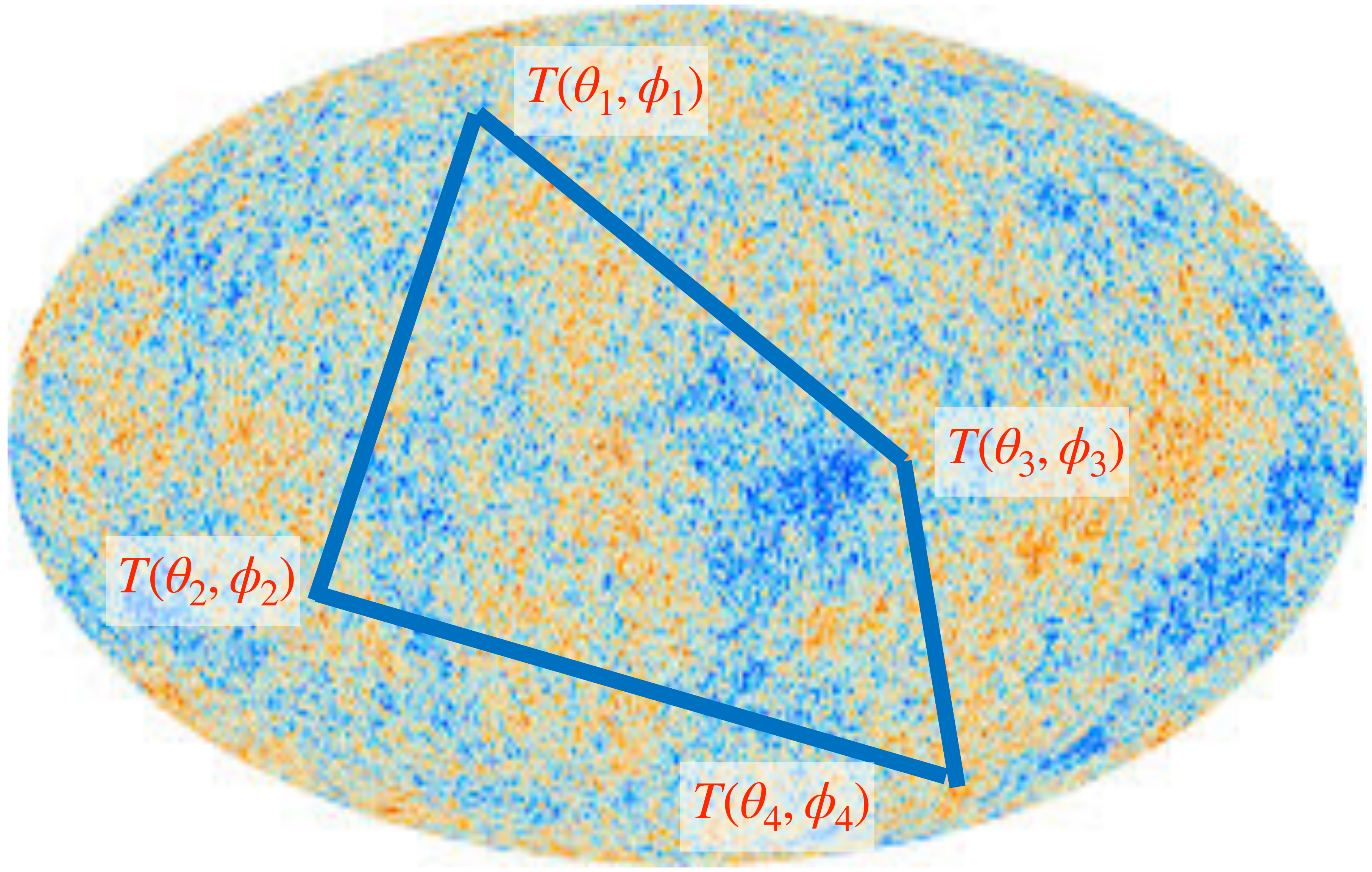
Optimal Trispectrum Analyses

- To **compress** the data, we'll use techniques from **signal processing**

$$\widehat{A} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3 \ell_4 m_4} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle^{\dagger}_{\rm theory} \times (a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4})$$

Model — Data

- We compress all 10^{28} elements into a **single** number!
- This encodes the **amplitude** of a specific model, e.g., $\tau_{\rm NL}$, which traces the **microphysics** of inflation
- To **compute** the ℓ, m sum we use a variety of tricks, including low-dimensional integrals, harmonic transforms, and Monte Carlo summation
- If the trispectrum can be (integral-)**factorized**, this reduces the complexity from $\mathcal{O}(\ell_{\rm max}^8)$ to $\mathcal{O}(\ell_{\rm max}^2 \log \ell_{\rm max})$



Komatsu, Spergel, Wandelt, Munchmeyer, Sekiguchi+13, Smith+15, **Philcox** 25a

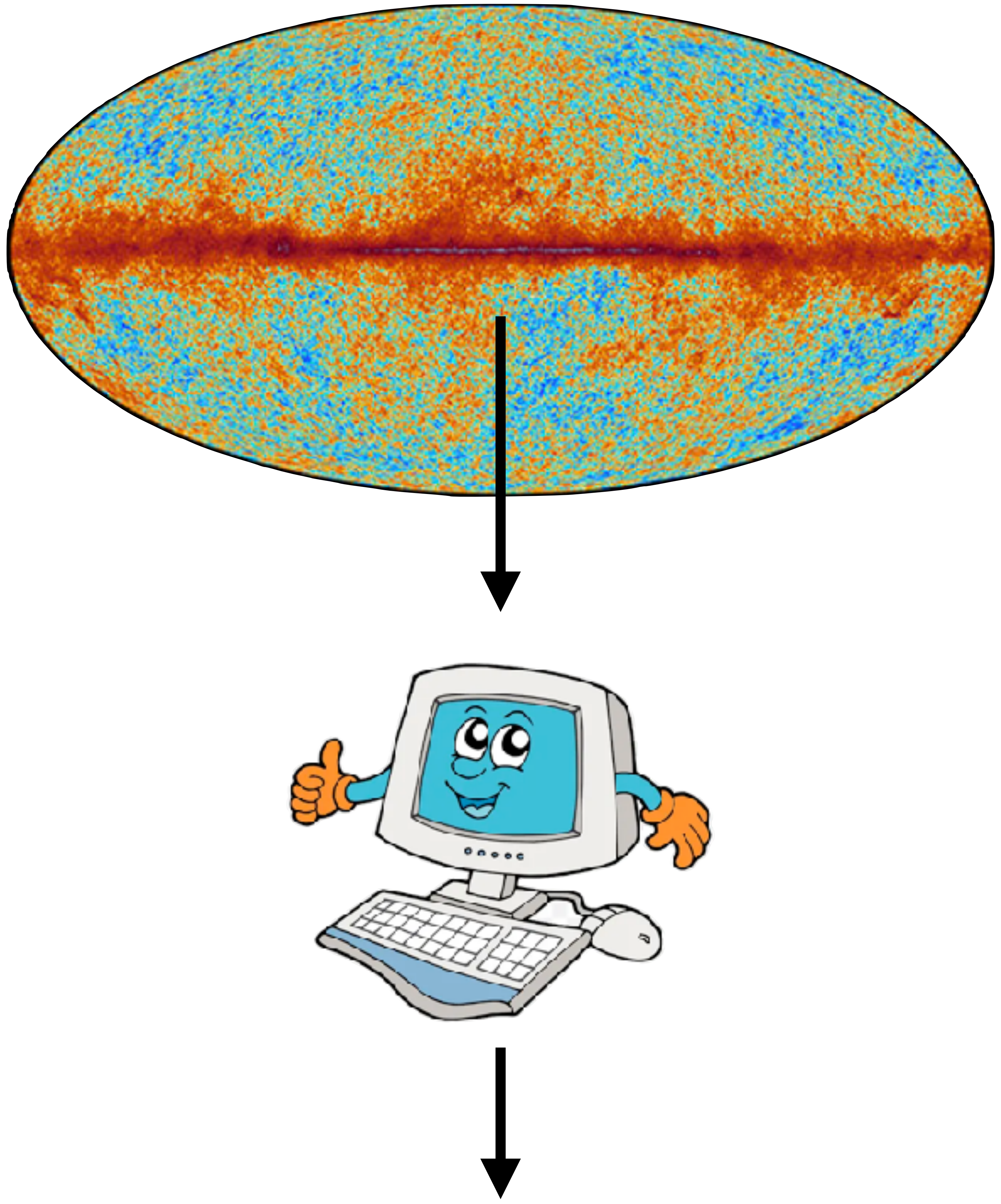
Optimal Trispectrum Analyses

PolySpec

The result: **fast** estimation of four-point amplitudes!

The estimators are

- ***Unbiased*** (by the mask, geometry, beams, lensing, …)
- ***Efficient*** (limited by spherical harmonic transforms)
- ***Minimum-Variance*** (they saturate the Cramer-Rao bound)
- ***Open-Source*** (entirely written in Python/Cython)
- ***General*** (17 classes of model included so far)

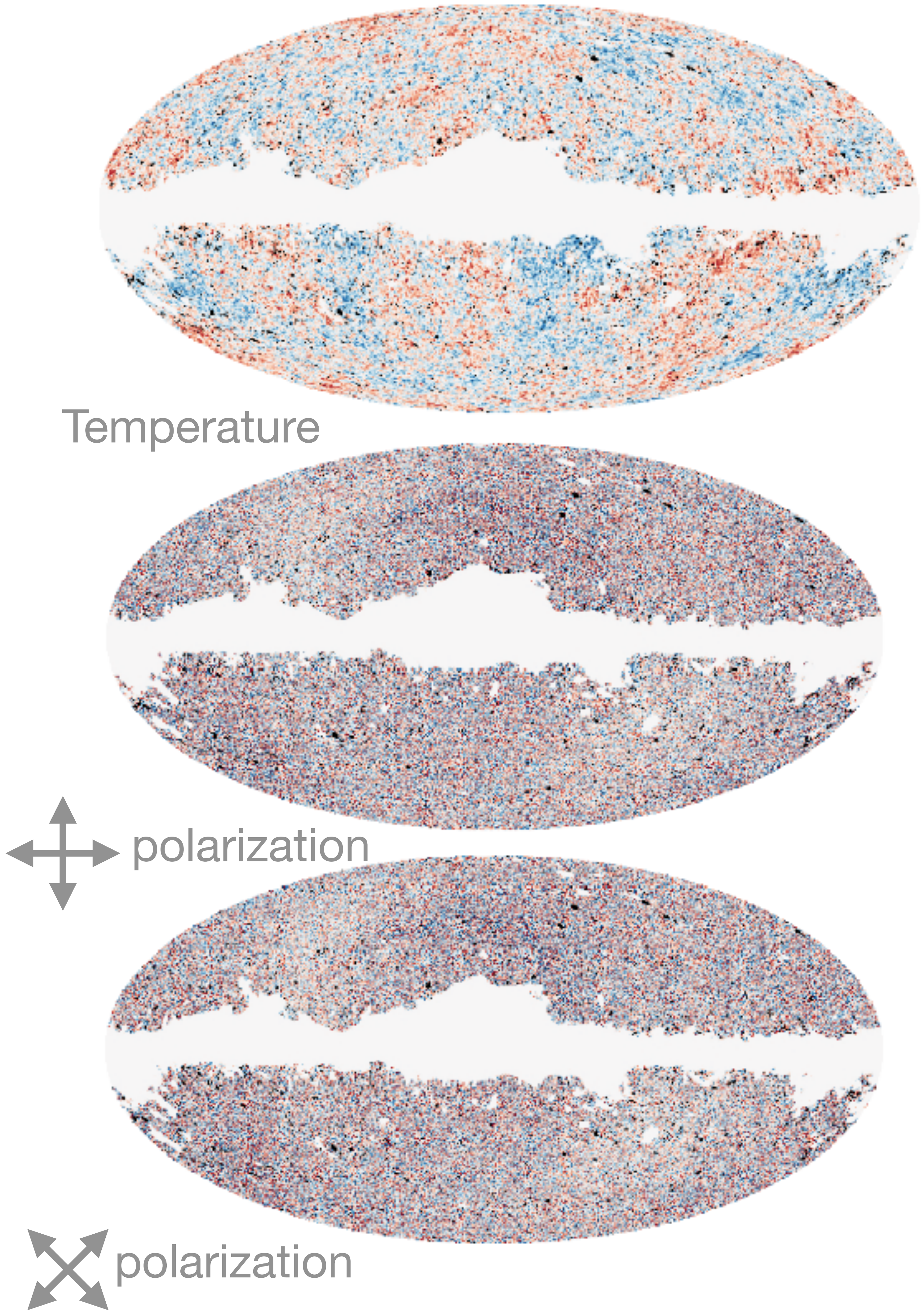


inflation parameters

Public at **https://github.com/oliverphilcox/PolySpec**

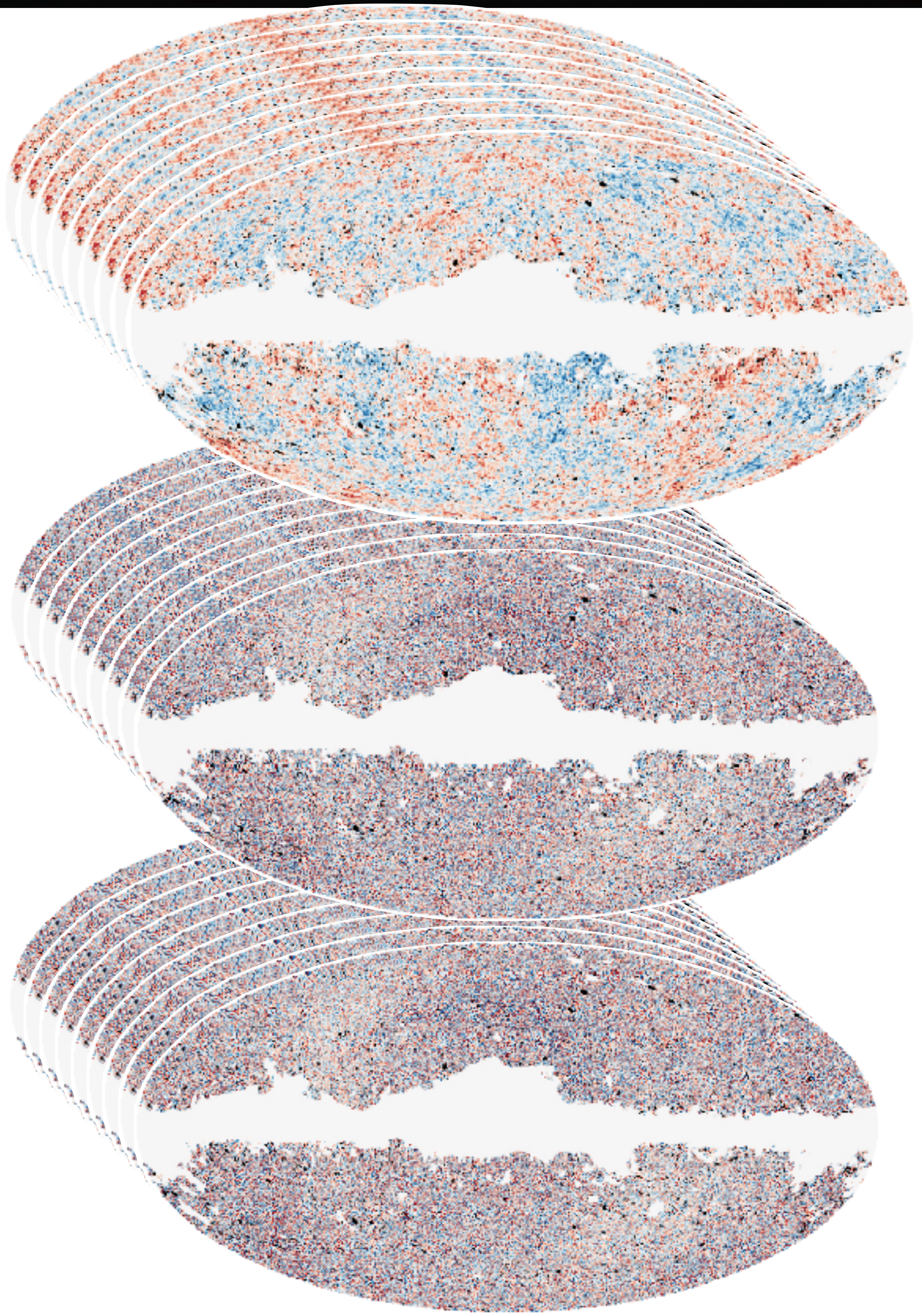
Philcox 25ab

The *Planck* Trispectrum



***Planck* PR4/NPIPE data**

+



100 FFP10 simulations

+ Optimal Weighting

+ Beam & Mask

+ Transfer Functions

(+ many systematics tests)

= $g_{\rm NL}, \tau_{\rm NL}$ + 31 others

Philcox 25c

Detecting Non-Gaussianity?

PolySpec

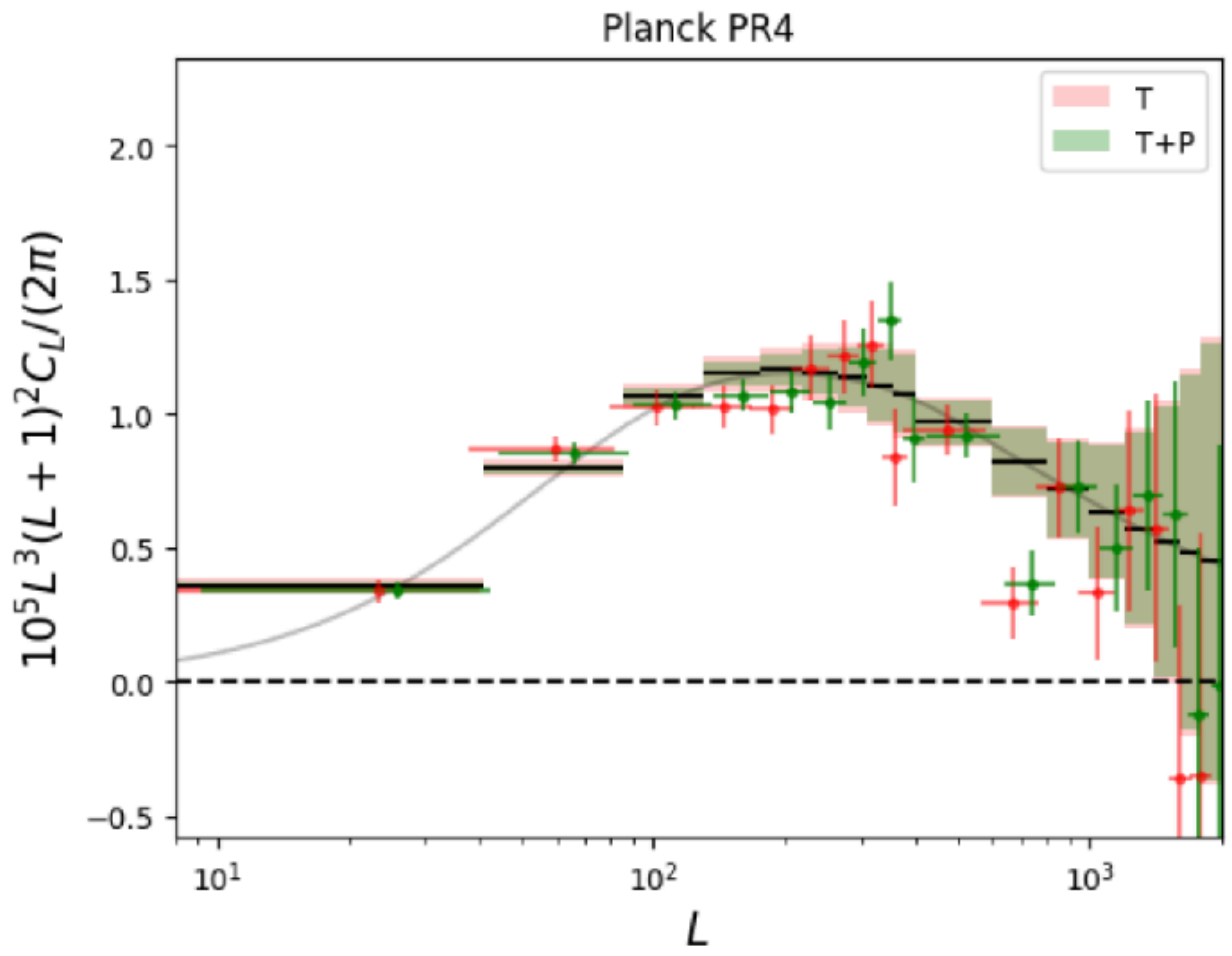
What did we try to detect?

1. **Cubic local** shape ($g_{\rm NL}^{\rm loc}$)
2. **Quadratic**^{2} **local** shape ($\tau_{\rm NL}^{\rm loc}$)
3. **Constant** shape ($g_{\rm NL}^{\rm con}$)
4. **Effective Field Theory of Inflation** shapes ($\times$ 3)
5. **Direction-Dependent** shapes
6. **Cosmological Collider** Shapes
7. Weak **Gravitational Lensing**
8. Unresolved **Point-Sources**
9. ISW-lensing **Trispectra**

Philcox 25abc, **Philcox** & Hill 2025 (see Planck, ACT, SPT, etc. etc.)

Detecting Non-Gaussianity?

What did we try to detect?	Did we detect it?
1. **Cubic local** shape ($g_{\rm NL}^{\rm loc}$)	No
2. **Quadratic^2 local** shape ($\tau_{\rm NL}^{\rm loc}$)	No
3. **Constant** shape ($g_{\rm NL}^{\rm con}$)	No
4. **Effective Field Theory of Inflation** shapes ($\times 3$)	No ($\times 3$)
5. **Direction-dependent** shapes	No ($\times 8$)
6. **Cosmological Collider** shapes	No ($\times 17$)
7. Weak **Gravitational Lensing**	Yes!!!
8. Unresolved **Point-Sources**	No
9. ISW-lensing **Trispectra**	No



OMG! Lensing!
(already detected many times)

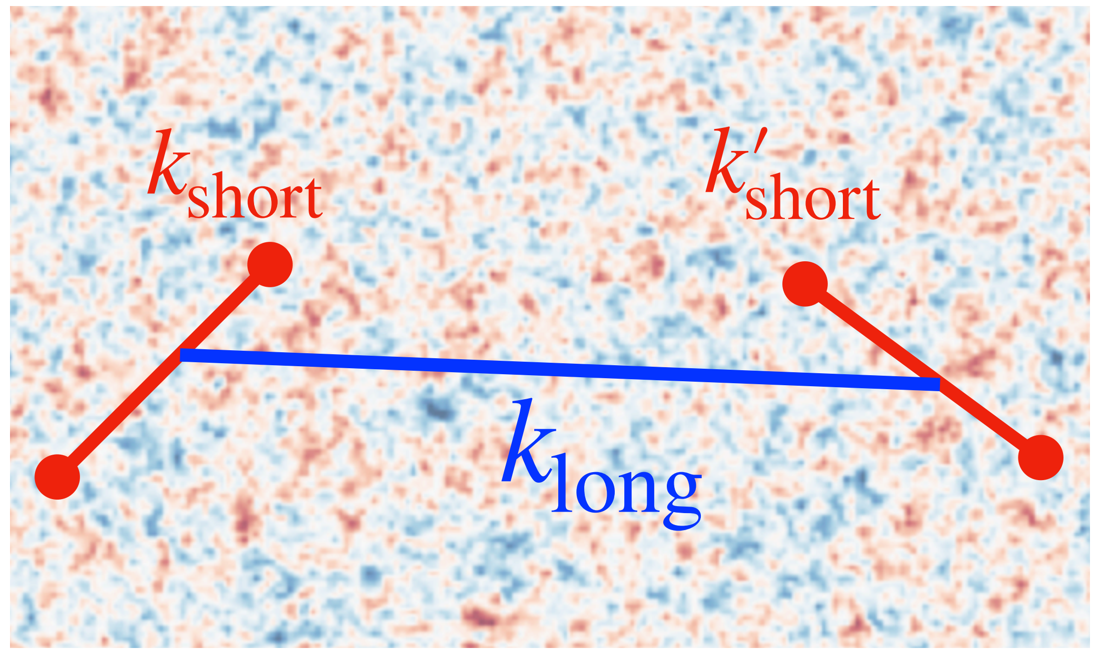
Philcox 25abc, **Philcox** & Hill 2025 (see Planck, ACT, SPT, etc. etc.)

An Example: Cosmological Colliders

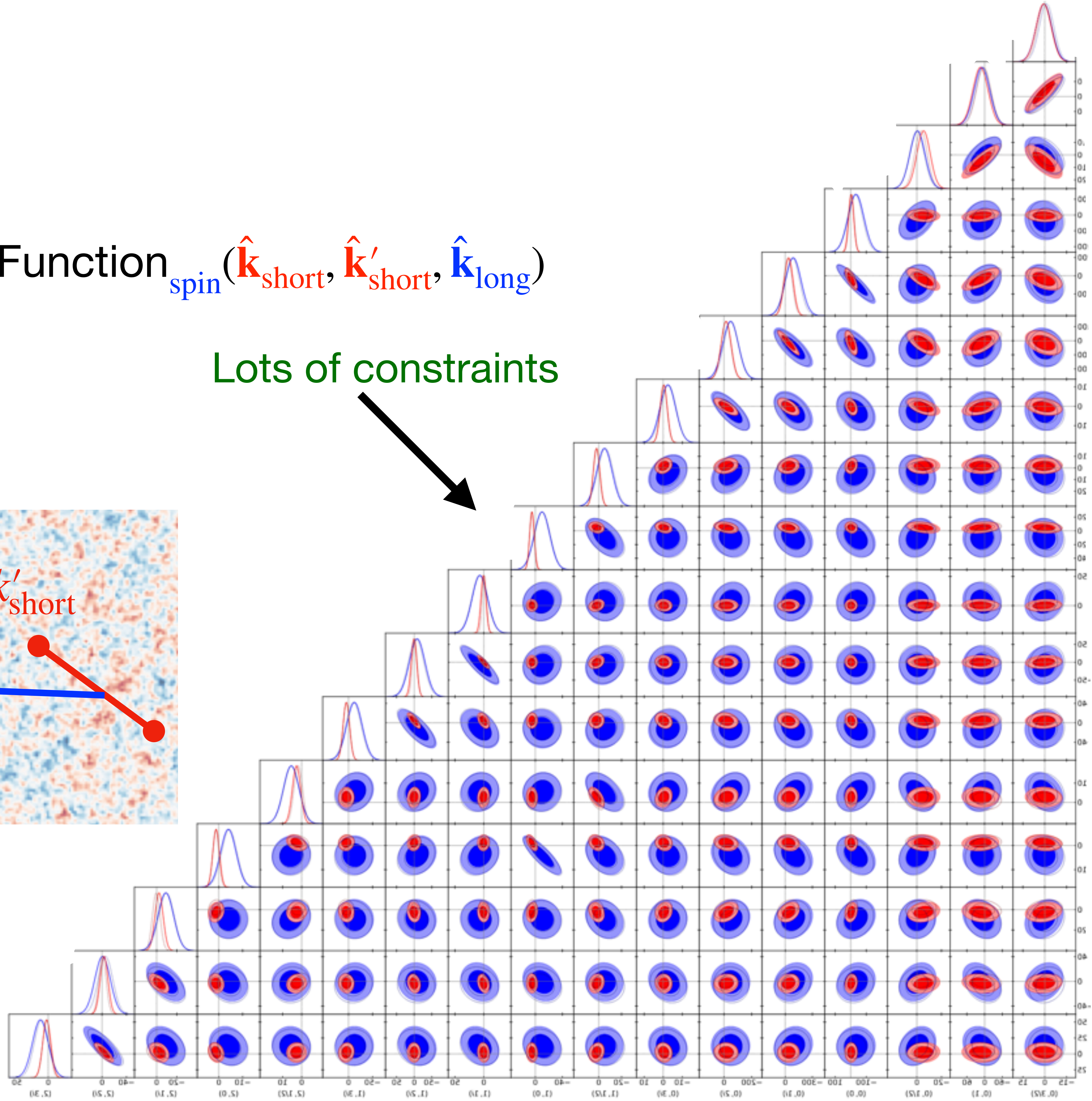
Model: *inflationary* ***massive*** *and* ***spinning*** *particles*

$$\langle \zeta^4 \rangle \sim P_\zeta(k_{\rm short})P(k'_{\rm short})P_\zeta(k_{\rm long}) \times \left(\frac{k_{\rm long}^2}{k_{\rm short}k'_{\rm short}}\right)^{3/2 \pm i\sqrt{m_\sigma^2/H^2 - 9/4}} \quad \text{AngleFunction}_{\rm spin}(\hat{\mathbf{k}}_{\rm short}, \hat{\mathbf{k}}'_{\rm short}, \hat{\mathbf{k}}_{\rm long})$$

- Several regimes, including:
  - **Light** Fields (Complementary Series): $m_\sigma \lesssim 3H/2$
  - **Conformally Coupled** Fields**:** $m_\sigma = 3H/2$
  - **Heavy** Fields (Principal Series): $m_\sigma \gtrsim 3H/2$



Lots of constraints



No detections!

Philcox 25c

What's Next For the Trispectrum?

There are *many* ways to extend.

1. More **Data** $\sigma(\tau_{\mathrm{NL}}) \sim \ell_{\mathrm{max}}^{-2}$

- ACT, SPT, Simons Observatory, LiteBird, CMB-HD, ~~CMB-S4~~ will provide data down to **much** smaller scales!
- **Polarization** will be particularly useful and could benefit from **delensing**

2. More **Models**

- Lighter particles? Heavier particles?
- Tensor non-Gaussianity?
- Collider physics beyond the collapsed limit?
- Thermal baths? Higher-spin particles? Modified sound speeds? Fermions?
- Scale-dependence? Isocurvature? Primordial magnetic fields?

McCulloch+, Baumann+, Lee+, Moradinezhad+, Trivedi+, Jazayeri+, Salcedo+, …, **Philcox** 25abc

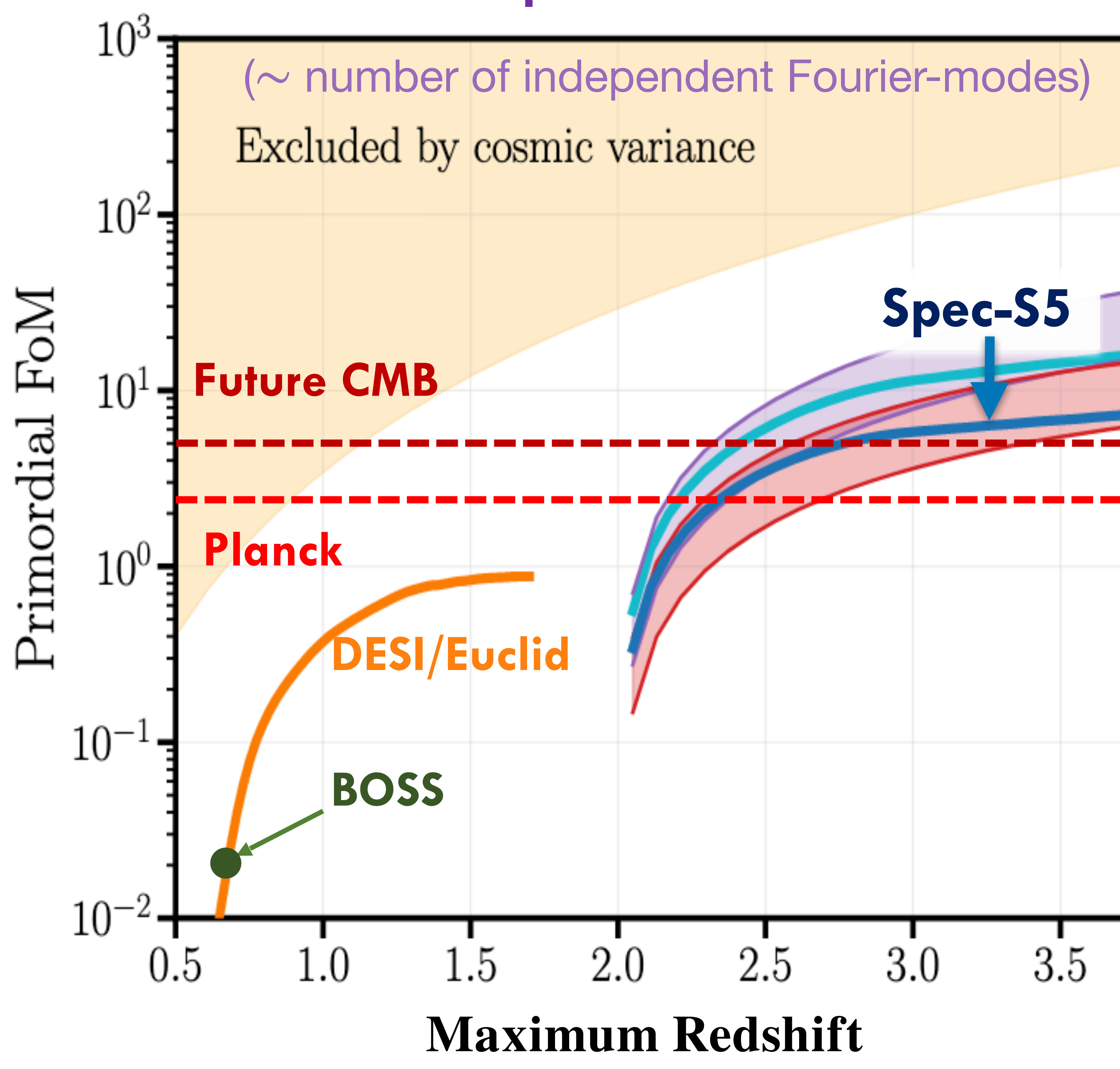
The Future of Non-Gaussianity

- Future **CMB** experiments will improve bounds by $\lesssim 10\times$

  ($f_{\mathrm{NL}}^{\mathrm{loc}}$ might be better)

  - This is a **two-dimensional** field
  - We're running out of modes to look at!
  - Small-scales are **hard**

- What about **galaxy surveys**?
  - The data precision is **rapidly increasing**
  - This is a **three-dimensional** field
    - We aren't limited by **projection effects**
  - There are new observables e.g., galaxy **shapes**



Sailer+, Ferraro+

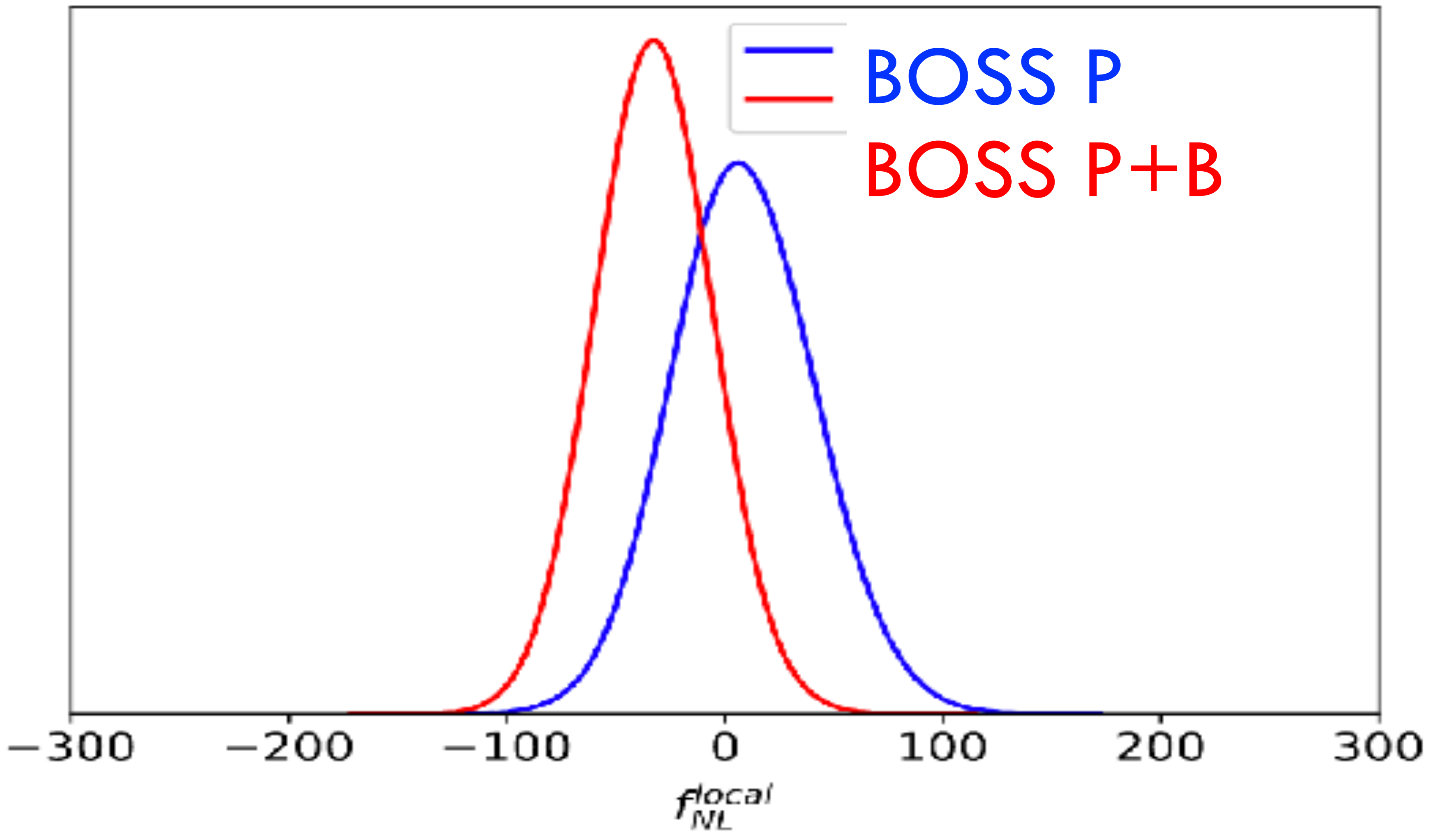
Inflation from Galaxy Surveys

- The **BOSS galaxy survey** has been used to constrain primordial **three-point** functions using the
  - **One-loop** power spectrum: $P_\ell(k) \supset f_{\rm NL} P_{12}$
  - **Tree-level** bispectrum: $B_0(k_1, k_2, k_3) \supset f_{\rm NL} B_{111}$
  - **Skew-spectra**: $P[\delta, \delta \star \delta] \supset f_{\rm NL} B_{111}$

- We have constrained:
  - **Local** three-point functions $f_{\rm NL}^{\rm loc}$ from additional **light fields**

LOCAL

See Dennis' talk for Euclid prospects!
See Marina's talk for eBOSS quasars!



$$f_{\rm NL}^{\rm loc} = -33 \pm 28 \quad (9 \pm 34 \text{ w/o } B_g)$$

(Now better with DESI Quasars: ± 9)

(CMB: ± 5, Target: ± 1)

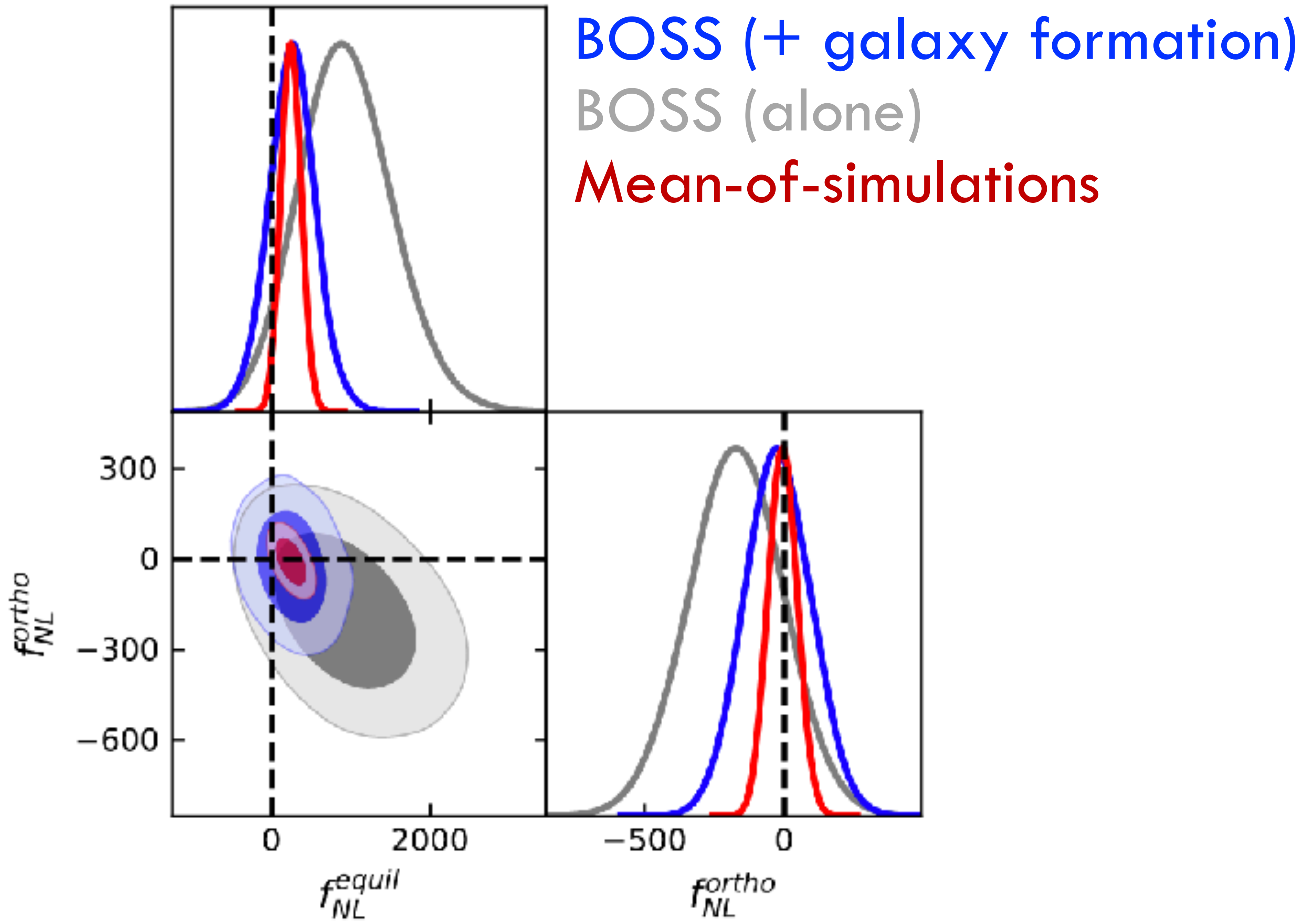
Cabass, **Philcox**, Ivanov, Zaldarriaga, Simonovic, d'Amico, Zhang, Senatore, S. Chen, a different S. Chen, Castorina, Cagliari, Moradinezhad Dizgah, Dvorkin, Chakraborty, Chaussidon, DESI, etc.

Inflation from Galaxy Surveys

- The **BOSS galaxy survey** has been used to constrain primordial **three-point** functions using the
  - **One-loop** power spectrum: $P_\ell(k) \supset f_{\rm NL} P_{12}$
  - **Tree-level** bispectrum: $B_0(k_1, k_2, k_3) \supset f_{\rm NL} B_{111}$
  - **Skew-spectra**: $P[\delta, \delta \star \delta] \supset f_{\rm NL} B_{111}$

- We have constrained:
  - **Local** three-point functions $f_{\rm NL}^{\rm loc}$ from additional **light fields**
  - **Equilateral** three-point functions $f_{\rm NL}^{\rm eq,orth}$ from cubic interactions in single-field inflation

SELF-INTERACTION



$$f_{\rm NL}^{\rm eq} = 260 \pm 300, f_{\rm NL}^{\rm orth} = -23 \pm 120$$

(CMB: $\pm 50, \pm 25$, Target: ± 1)

Cabass, **Philcox**, Ivanov, Zaldarriaga, Simonovic, d’Amico, Zhang, Senatore, S. Chen, a different S. Chen, Castorina, Cagliari, Moradinezhad Dizgah, Dvorkin, Chakraborty, Chaussidon, DESI, etc.

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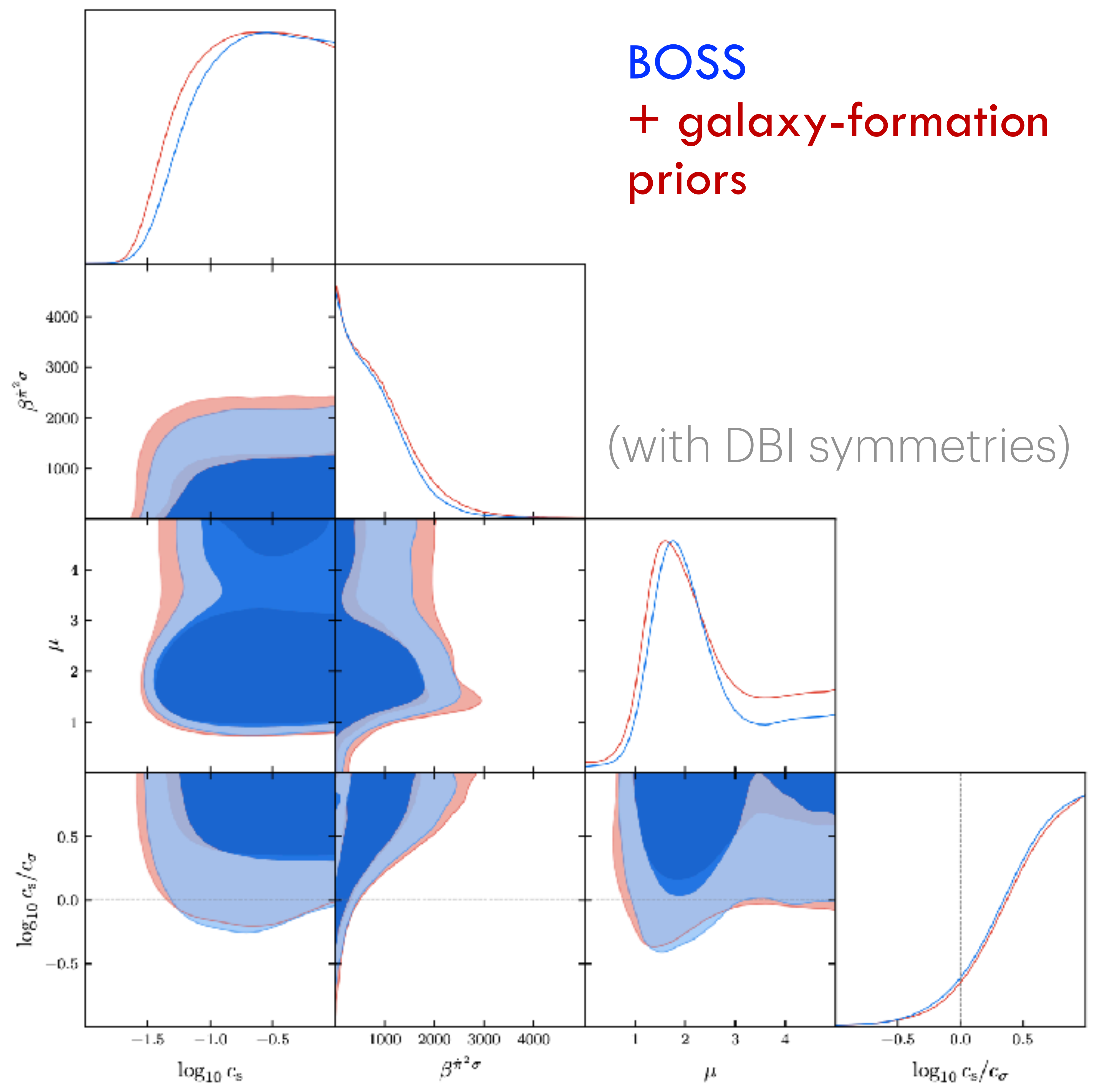
  - **Collider** three-point functions from the exchange of massive *scalar* fields

MASSIVE PARTICLE



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Why are the constraints so bad?

- Current LSS constraints are $\sim 5 - 20 \times$ worse than the CMB, because:
  - **Volume** — BOSS contains fewer modes than Planck
  - **Scale-cuts** — we can't model beyond k_{NL}
  - **Galaxy formation** — few assumptions on non-linear physics
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    - Use **simulations** or *non-linear responses*

    See Sam's talk / Will's talk
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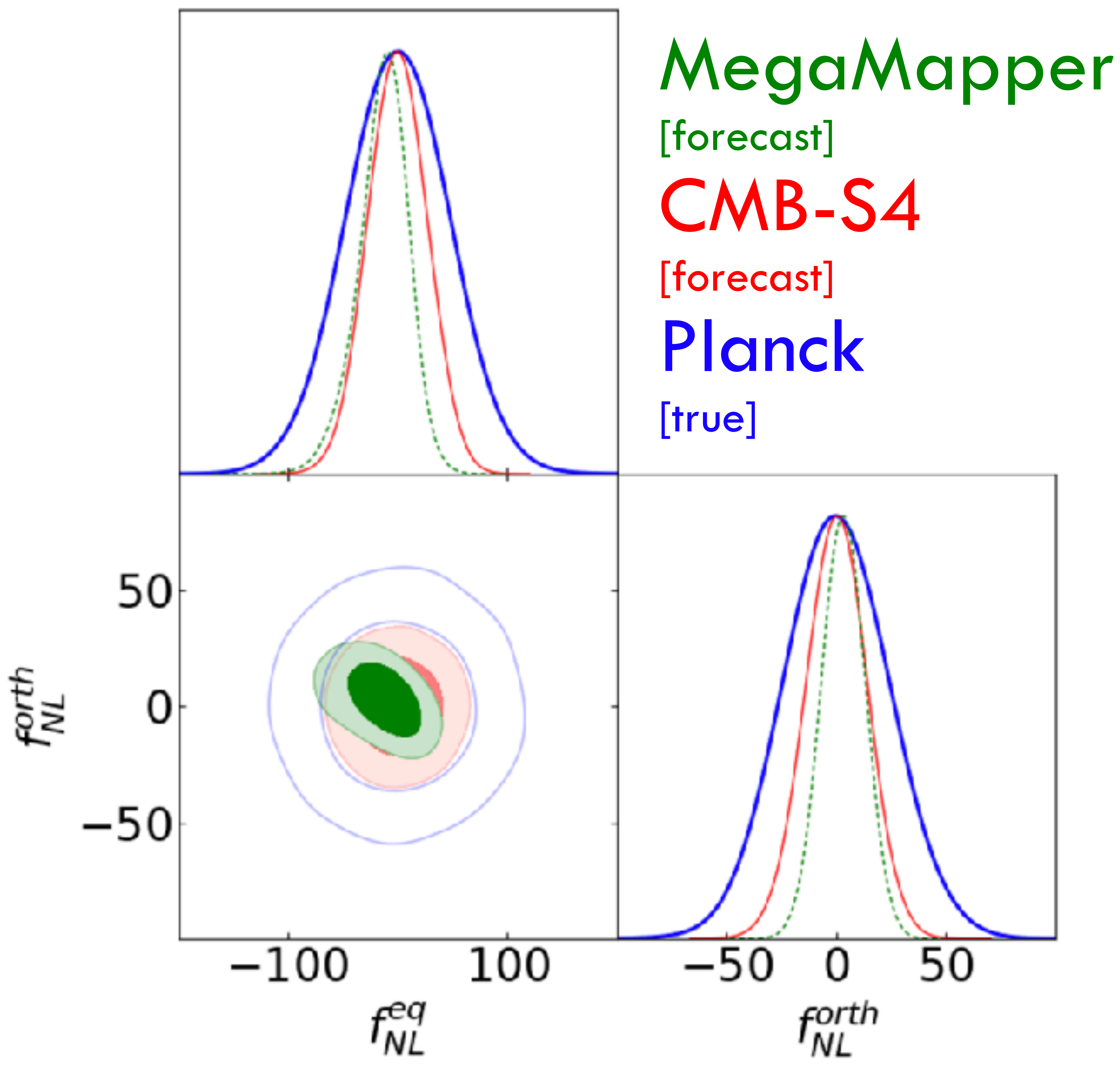
    - Use **new statistics**

Self-Interactions



Cabass, **Philcox** et al. (2023)

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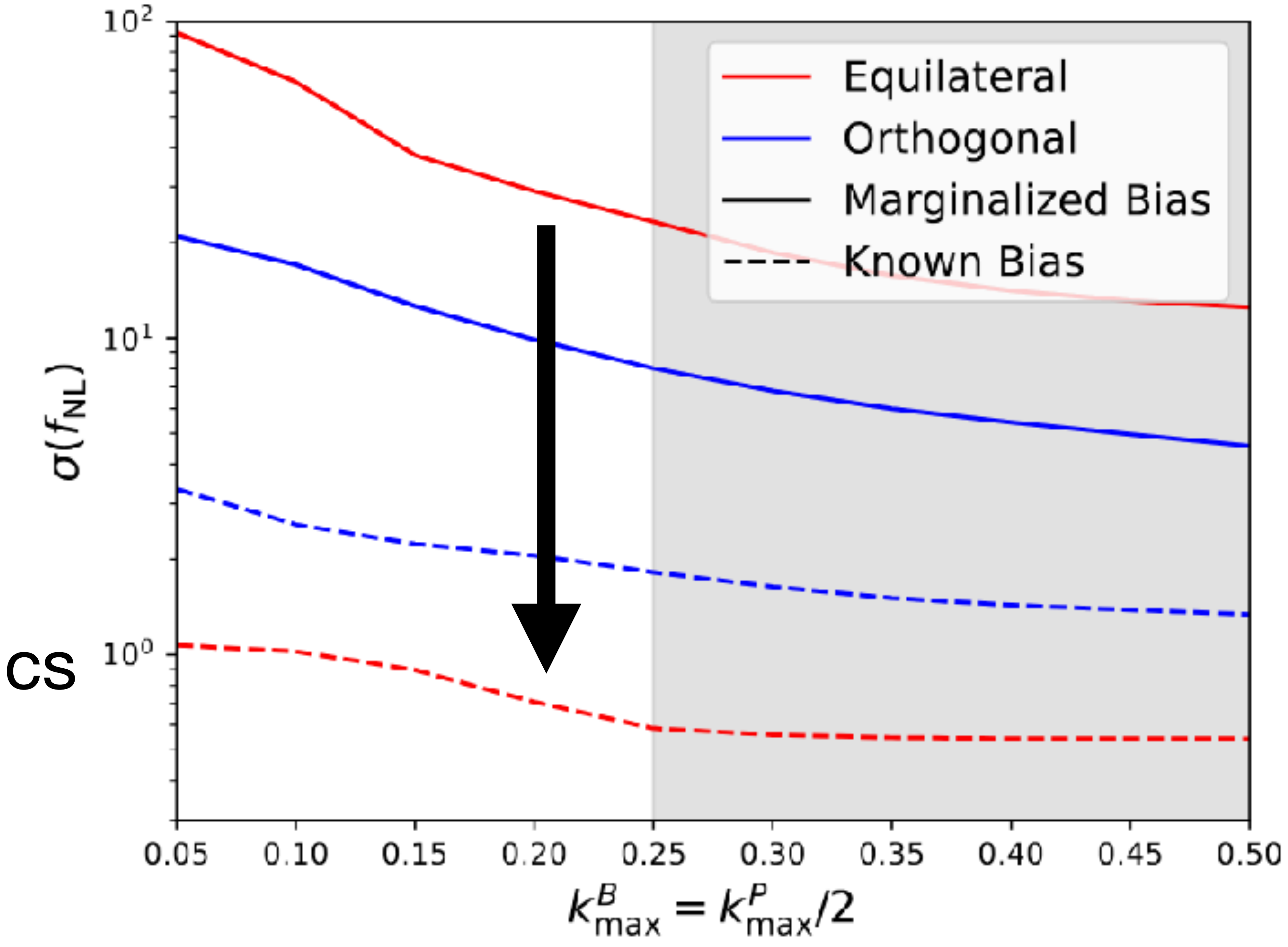
Self-Interaction MegaMapper forecast



(Optimistic $k_{\rm max}$ — see Jamie's talk)

Cabass, **Philcox**, Anbajagane, Lee, Spergel, Alexander, Konig, Kurita, Moradinezhad Dizgah, Schmidt, Dvorkin, Smith, Ferraro, Pen, Akitsu …

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Other observables

Trispectra / kurtospectra

kSZ correlators

CMB lensing correlators

Weak lensing statistics

Galaxy shapes

Galaxy spins

Halo mass functions

(and many others)

Cabass, **Philcox**, Anbajagane, Lee, Spergel, Alexander, Konig, Kurita, Moradinezhad Dizgah, Schmidt, Dvorkin, Smith, Ferraro, Pen, Akitsu …

The Next Generation of LSS

- DESI has already observed **millions** of galaxies across a wide range of redshifts

- So far, this has been used primarily through:
  - **BAO** parameters: $\alpha_{\parallel,\perp} \sim r_d/D_A(z), H(z)r_d$
  - **Power spectra** (galaxies & Ly-α)

- to measure ΛCDM + extensions:
  - $H_0, \Omega_m, \sigma_8, \sum m_\nu$
  - Ω_k, w_0, w_a
  - $f_{\rm NL}^{\rm loc}$

The year one data is now **public** — what else could we measure?

Each blob is a 3D galaxy position!

DESI 2024, 2025, etc. etc. etc.

The Next Generation of LSS

- The first (roughly independent) **re-analyses** of DESI data are being performed!
  - These include **power spectra & bispectra** from all galaxy chunks
- This is **hard**:
  - The public data only contains galaxy **positions** and **weights**
  - There's no **simulations** to use or **covariances**
- There's lots of **systematics** to account for, including:
  - **Fiber collisions**
  - **Bispectrum** window functions
  - **Angular** systematics

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...	...	...	...	...	...

Reanalyzing DESI DR1:
1. ΛCDM Constraints from the Power Spectrum & Bispectrum

Anton Chudaykin,[1,*] Mikhail M. Ivanov,[2,3,†] and Oliver H. E. Philcox[4,5,6,7,‡]

arXiv:2507.13433

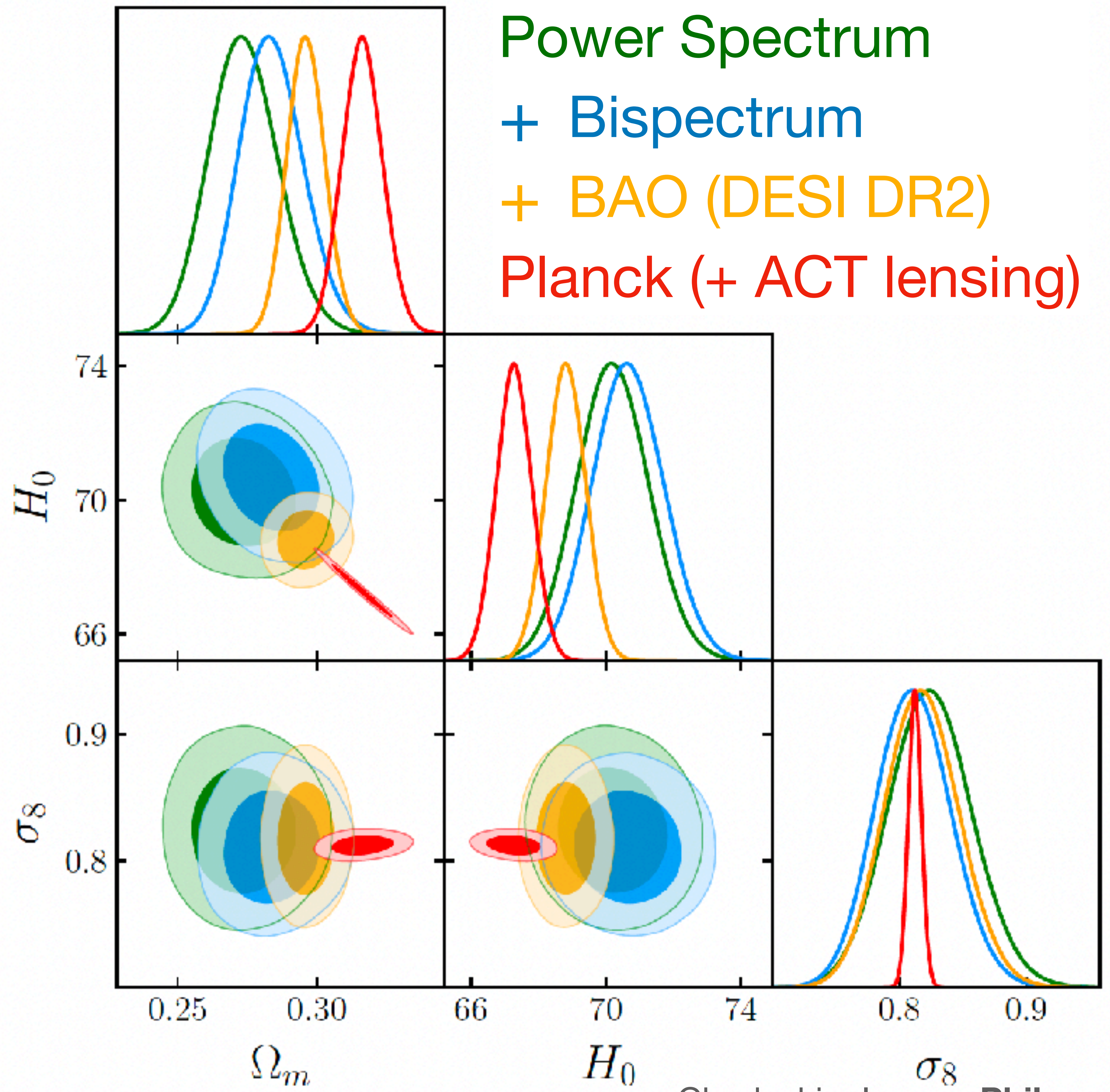
The Next Generation of LSS

- The first (roughly independent) **re-analyses** of DESI data are being performed!
    - These include **power spectra & bispectra** from all galaxy chunks

- So far, we only have published ΛCDM constraints
    - ΛCDM extensions coming soon!

- There's a **lot** more to explore, including:
    - *Bispectrum templates*: $f_{\rm NL}^{\rm loc}, f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}$
    - *Cosmological colliders* (including mass and spin)
    - *Trispectrum templates*: $g_{\rm NL}^{\rm loc}, \tau_{\rm NL}^{\rm loc}, g_{\rm NL}^{\rm eq}, \cdots$

DESI DR1 Constraints



Chudaykin, Ivanov, **Philcox** (2025)

Stanford University

KIPAC

KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

LEINWEBER INSTITUTE FOR THEORETICAL PHYSICS @ STANFORD

DESI (edited)

Summary

- There are many sources of inflationary non-Gaussianity

- The CMB is a **powerful** probe for measuring PNG
(though the results are depressing)

- Galaxies will become a leading probe of PNG
(eventually)

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