Colliders in the Sky

Constraining Primordial Non-Gaussianity with CMB and LSS Observations

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Primordial non-Gaussianity

Single-field, slow-roll inflation, with Bunch-Davies vacuum

↑

Vanilla inflation ⇒ **Gaussian** fluctuations in ζ

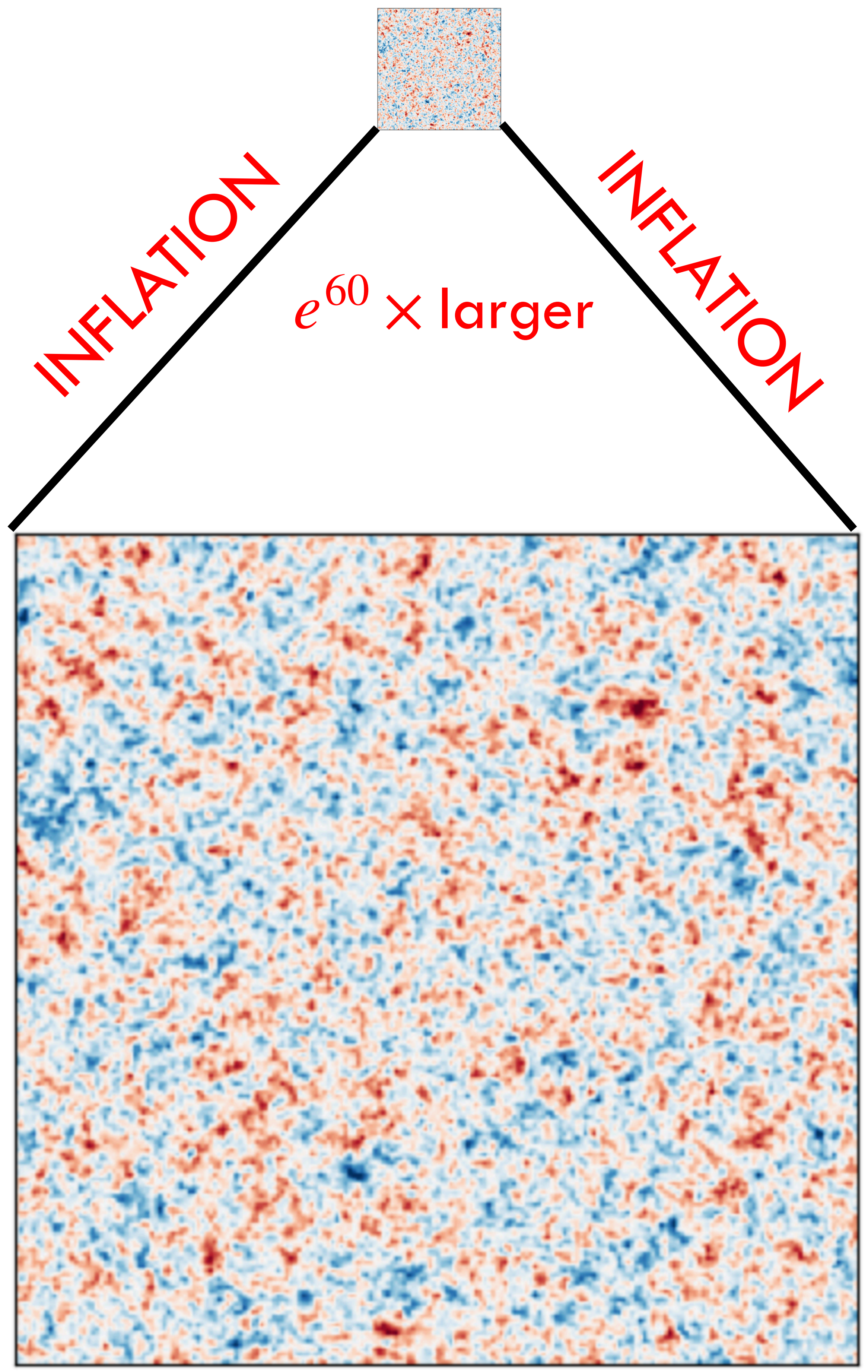
New physics ⇒ **non-Gaussian** fluctuations in ζ

↓

Self-interactions, new fields, new vacuum states, thermal dissipation, …

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

START: Quantum Fluctuations in Inflaton ϕ



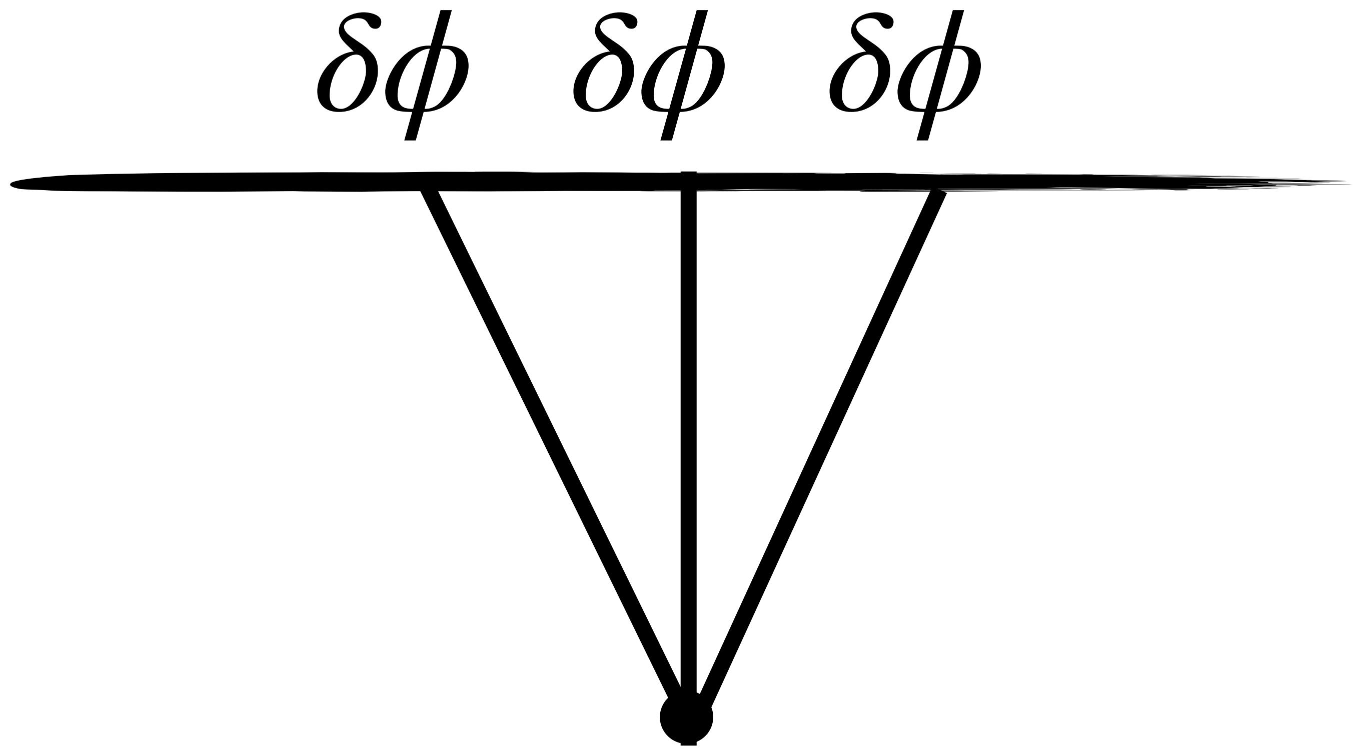
END: Classical Fluctuations in Curvature ζ

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

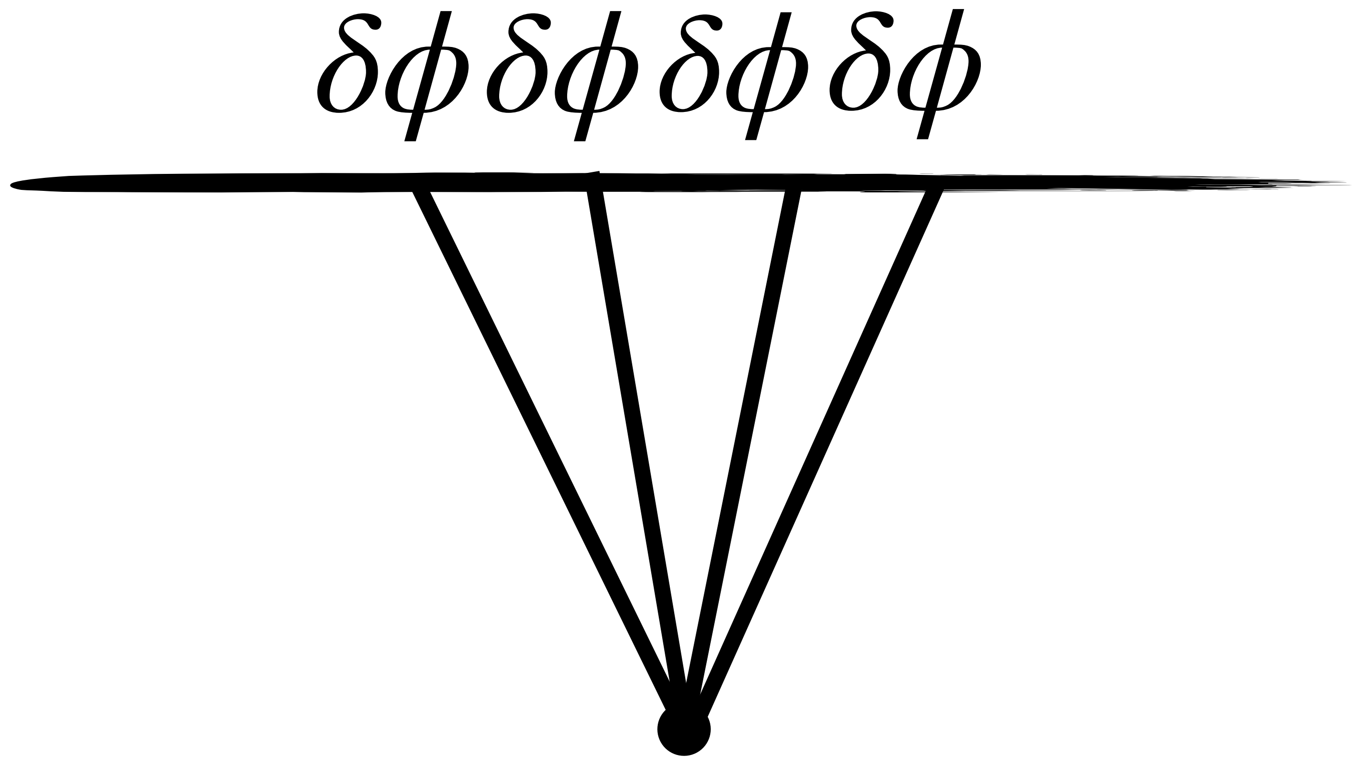
Self-Interactions

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

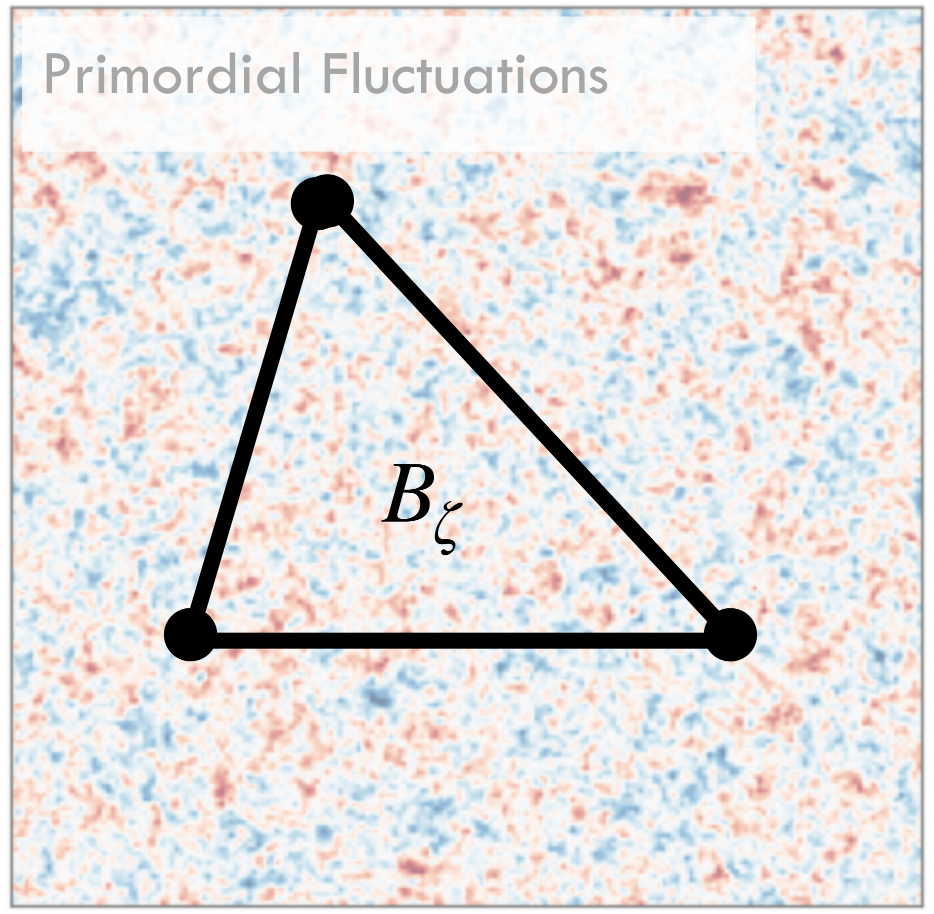
$$\mathscr{L} \supset \delta\dot\phi^3, \quad \delta\dot\phi(\partial\phi)^2, \quad \delta\dot\phi^4, \quad \cdots$$

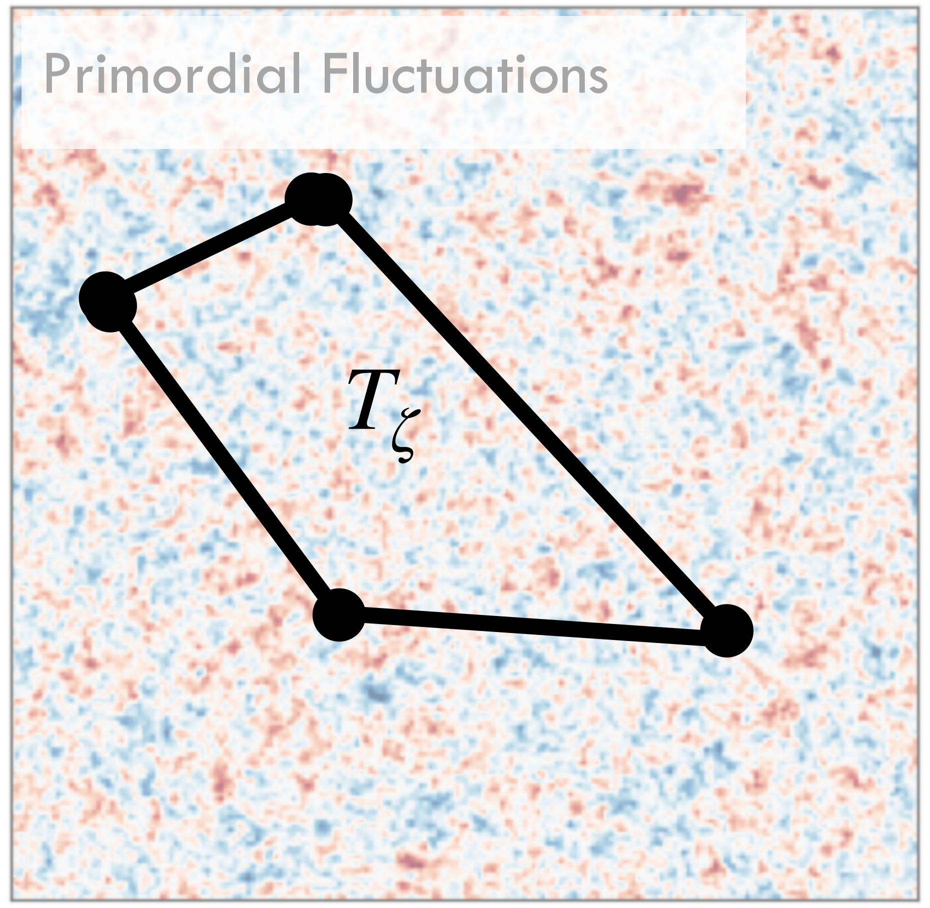


Cubic $\sim f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}$



Quartic $\sim g_{\rm NL}^{\rm eq}\,(\times 3)$





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

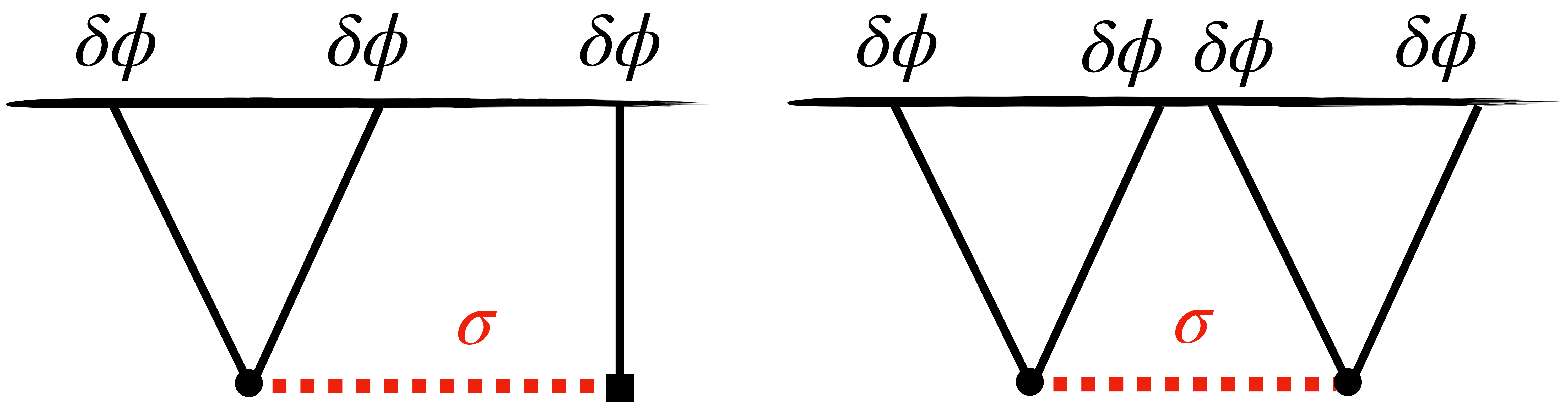
e.g. $\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\rm NL}^{\rm eq} \times$ shape

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

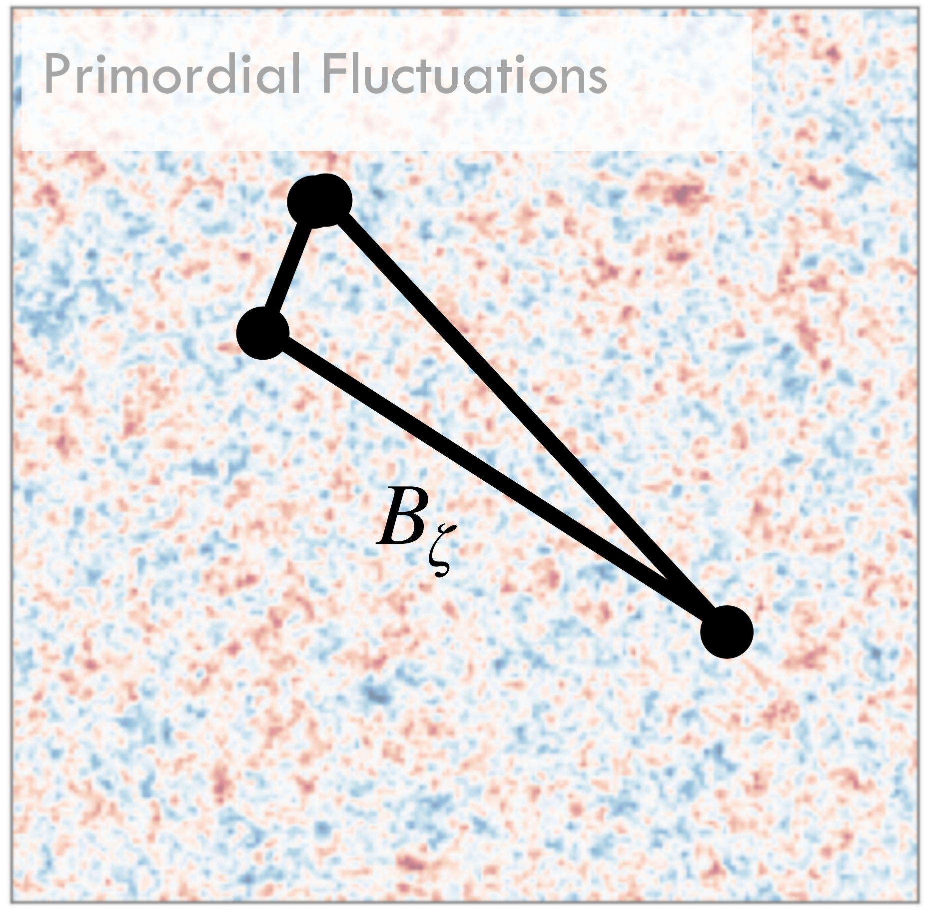
~~Self~~-Interactions

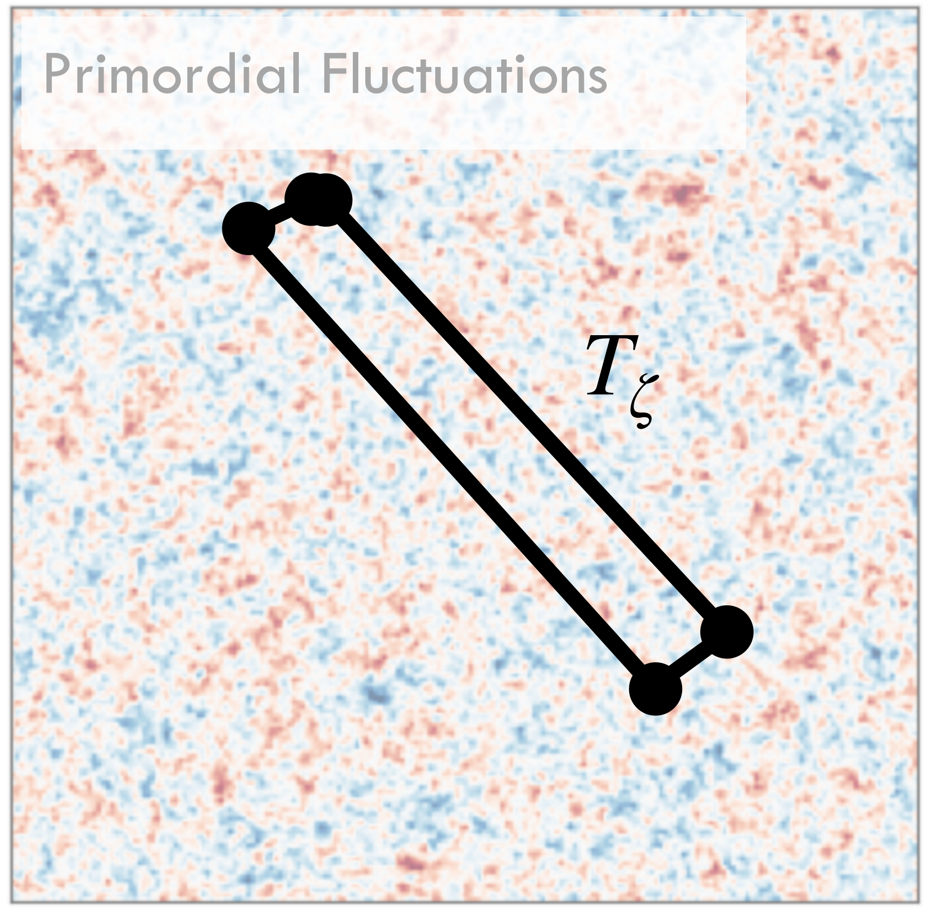
- Other models feature **new particles**, σ**:**

$$\mathscr{L} \supset \delta\dot{\phi}\sigma, \quad \delta\dot{\phi}^2\sigma, \quad \delta\dot{\phi}^3\sigma, \cdots$$



Linear-Quadratic $\sim f_{\rm NL}^{\rm loc}$ *Quadratic*^{2} $\sim \tau_{\rm NL}^{\rm loc}$ (+ linear-cubic, $\sim g_{\rm NL}^{\rm loc}$)





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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 **three-** and **four-point** functions track the **exchange** of a particle $\sigma_{\mu_1 \cdots \mu_s}$ of mass $m_\sigma \sim H$ and spin $s = 0,1,2,\cdots$

- In the **collapsed limit** (low exchange momentum), the inflationary signatures are set by **symmetry** and depend **only** on the mass m_σ, the spin, s, and the speed c_σ

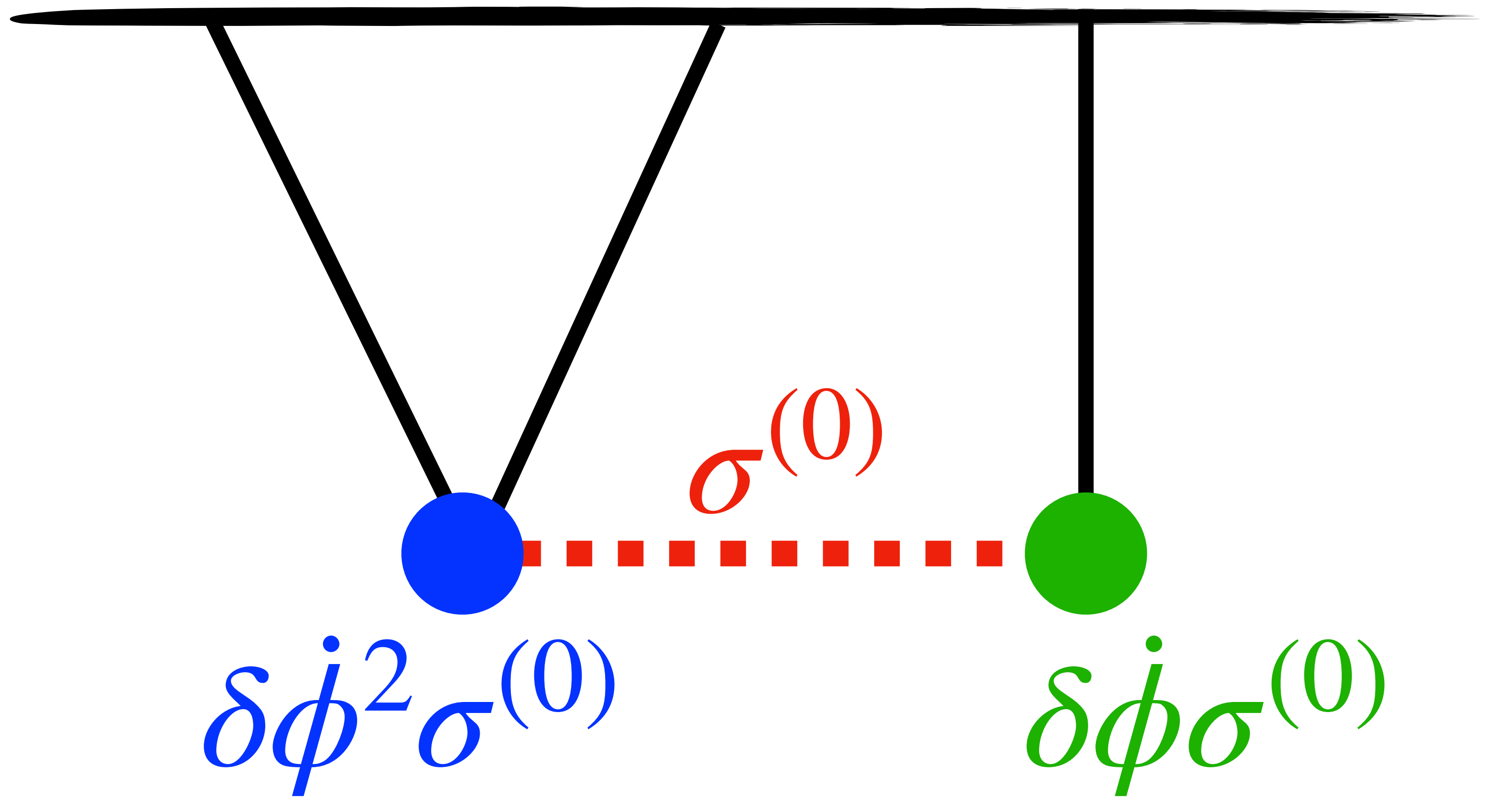
$$\langle \zeta^4 \rangle \sim \tau_{\rm NL} \times \frac{1}{k_1^3 k_3^3 k_{12}^3} \left[\left(\frac{k_{12}}{k_1 k_3} \right)^{3/2+i\mu_s} + \left(\frac{k_{12}}{k_1 k_3} \right)^{3/2-i\mu_s} \right] \mathscr{L}_s(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_3)$$

Amplitude $\sim e^{-m_\sigma/H}$ — Shape (mass dependent) — Angle (spin-dependent)

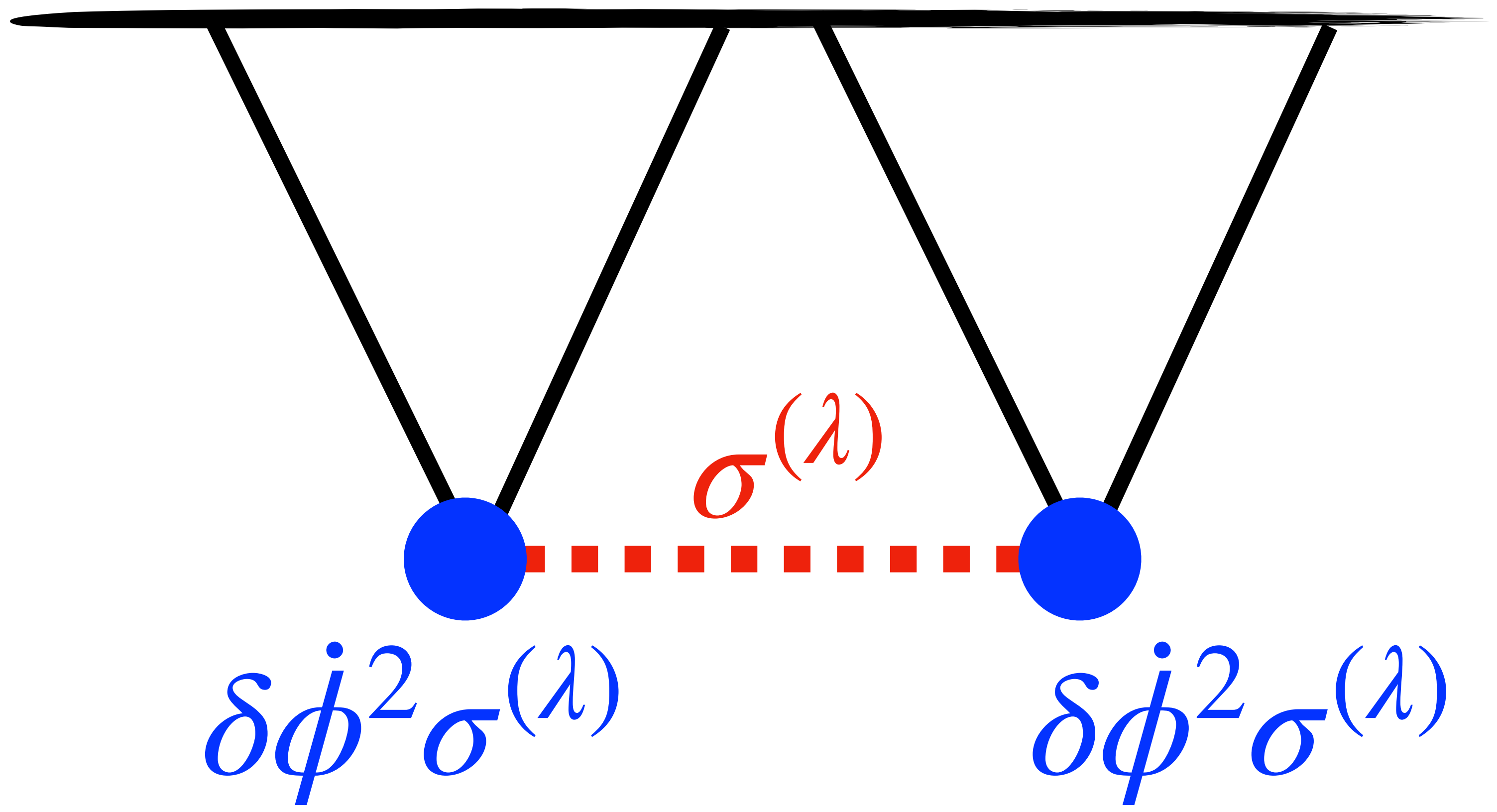
for mass parameter $\mu_s = \sqrt{m_\sigma^2/H^2 - 9/4}$

- We get **oscillations** for particles with $m_\sigma \gtrsim H$

Three-Point

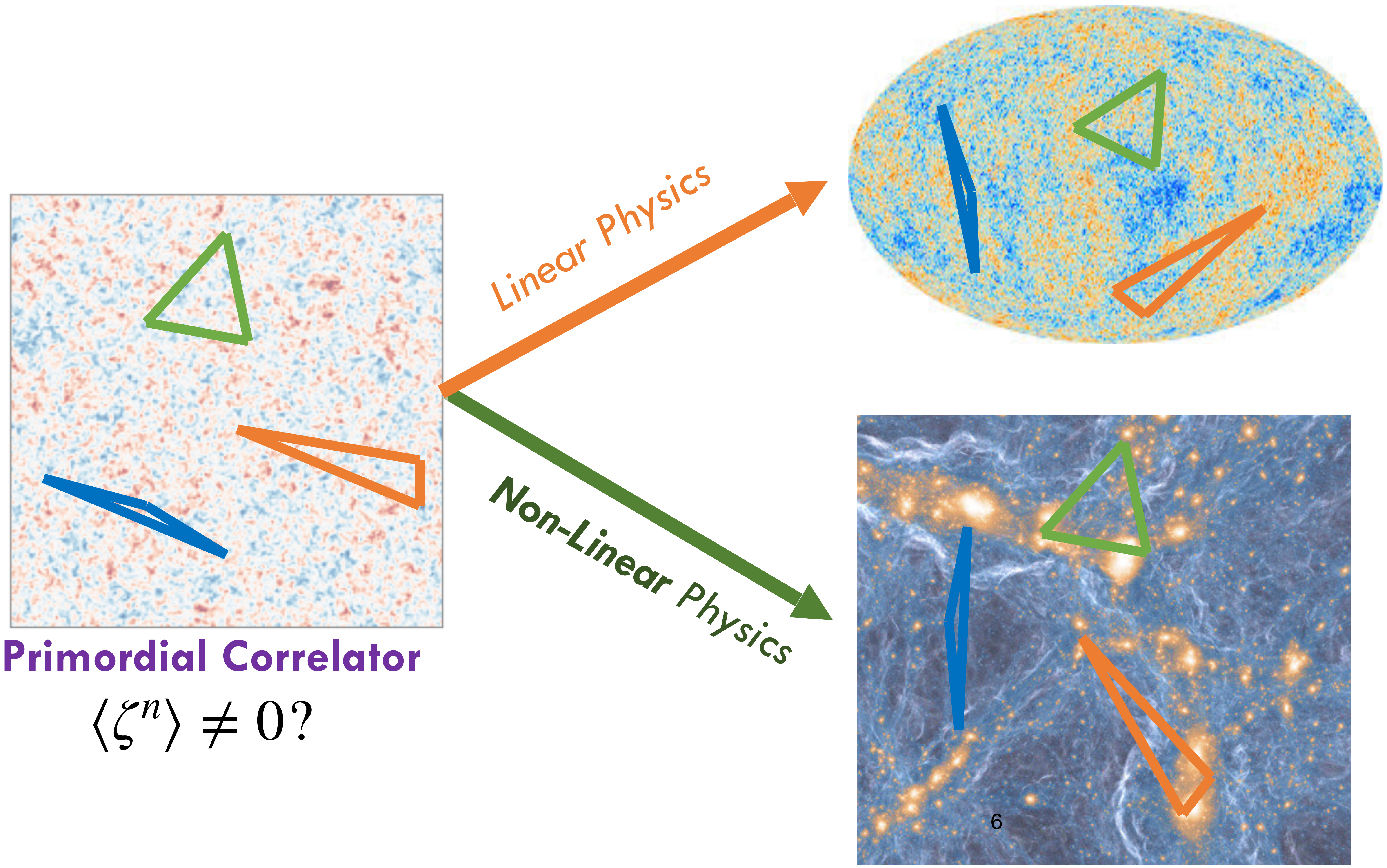


Four-Point



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

How to Measure Primordial Non-Gaussianity



Primordial Correlator

$\langle \zeta^n \rangle \neq 0?$

Cosmic Microwave Background Correlator

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

Galaxy Distribution Correlator

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

Planck, IllustrisTNG

How to Measure a Three-Point Function

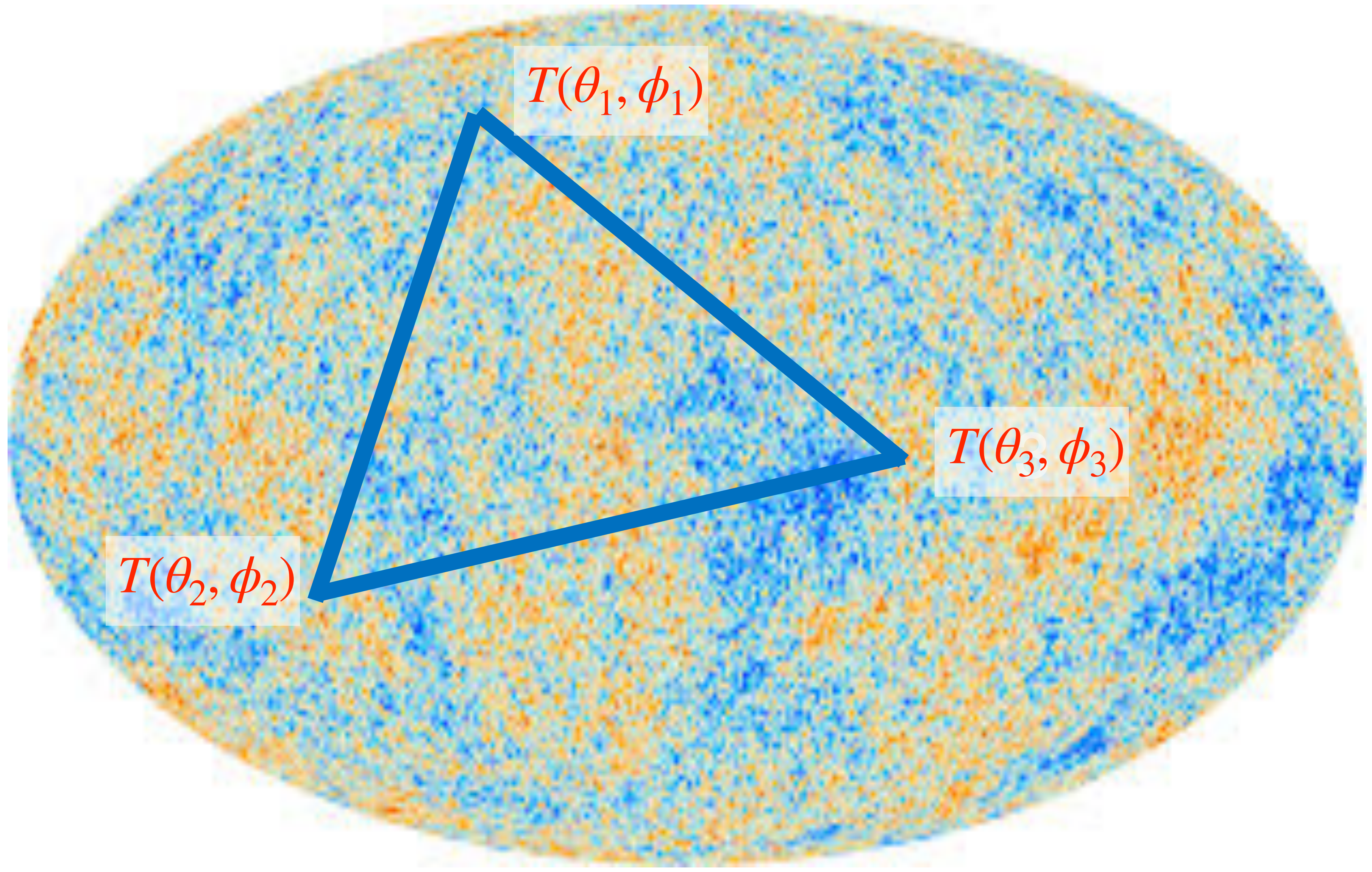
- CMB experiments measure the **temperature** and **polarization** across the whole sky

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

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

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

- This is computationally **expensive:**
  - The bispectrum is **3-dimensional** [after symmetries]
  - There's $N^3_{\mathrm{pix}} \sim 10^{21}$ combinations of points!



Planck 2018

How to Measure a Three-Point Function

Most CMB analyses use two tricks:

1. **Compression:**

- We compress all 10^{21} elements into a single number, encoding the amplitude of a specific model, e.g., $f_{\rm NL}^{\rm loc}$

$$\widehat{f_{\rm NL}^{\rm loc}} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle^{\dagger}_{\rm theory} \times (C^{-1}a)_{\ell_1 m_1} (C^{-1}a)_{\ell_2 m_2} (C^{-1}a)_{\ell_3 m_3}$$

Model　　　　Data

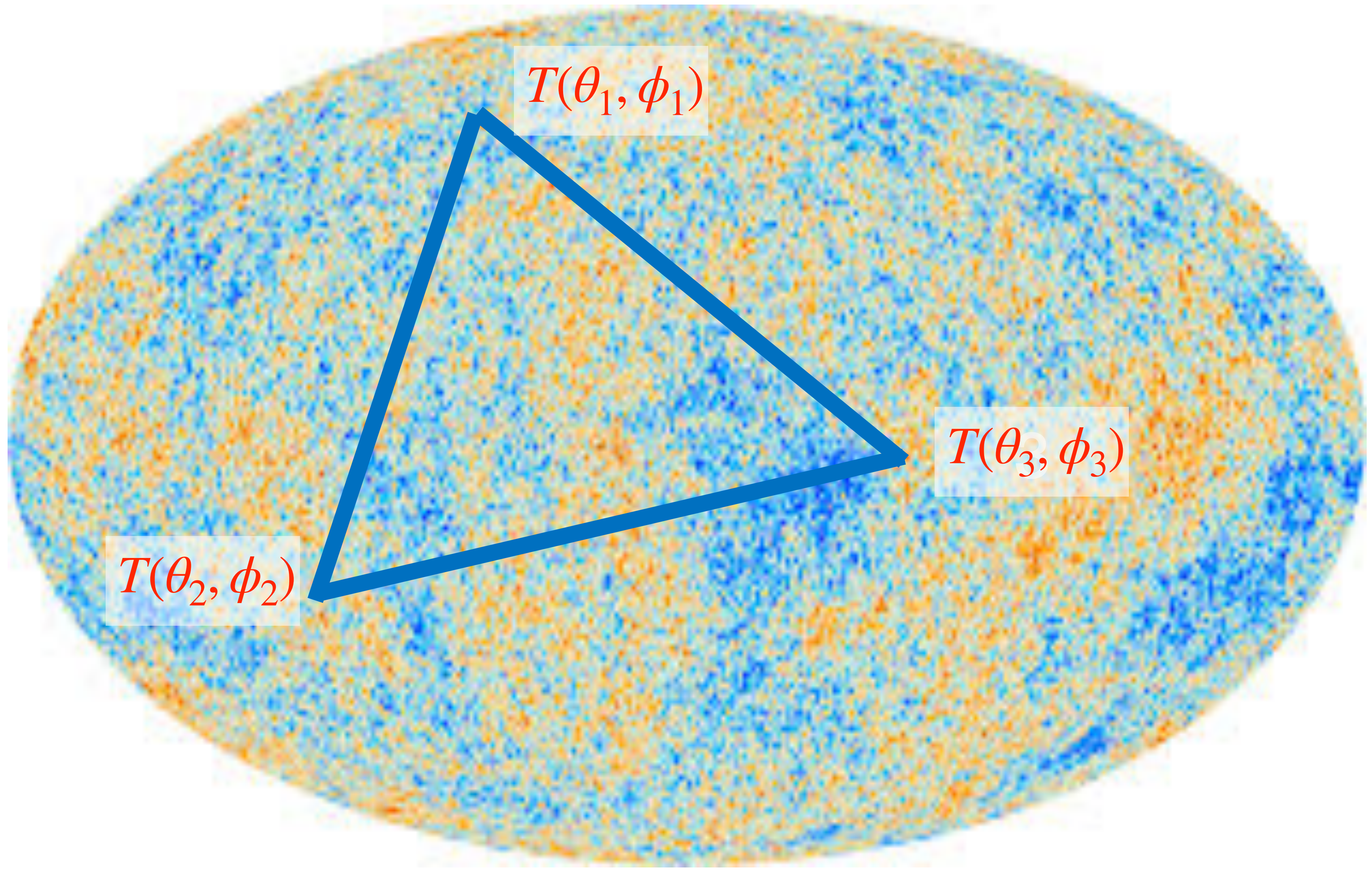
- This is an **optimal estimator** for $f_{\rm NL}$, *i.e.* it is **lossless**

2. **Separability:**

- If the **theory model** is **separable**, we can rewrite the ℓ, m sum using spherical harmonic transforms!

$$B_\zeta(k_1, k_2, k_3) \sim \sum_n \alpha_n(k_1)\beta_n(k_2)\gamma_n(k_3)$$

- This reduces the complexity from $\mathcal{O}(N_{\rm pix}^3)$ to $\mathcal{O}(N_{\rm pix} \log N_{\rm pix})$



(**Note**: binned/modal analyses use a similar trick, but compress to a lower-dimensional basis, rather than a single amplitude)

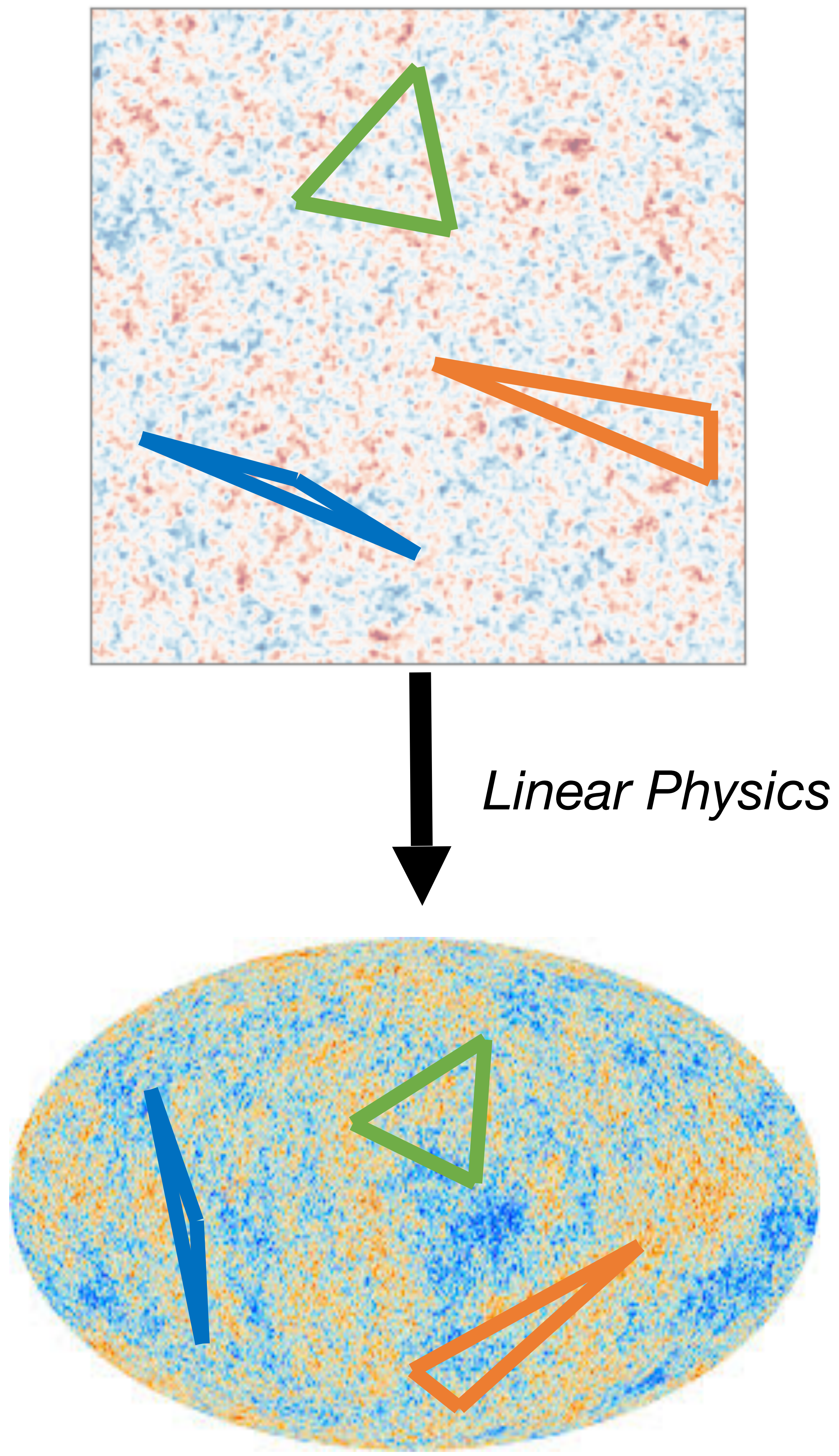
Komatsu, Spergel, Wandelt, Smith+13

CMB Bispectrum Constraints

- *Planck* placed **strong** constraints on scalar **three-point** functions, e.g.,

Planck 2018		
Local	−0.9 ± 5.1	← *New light scalars*
Equilateral	−26 ± 47	← *Self-interactions*
Orthogonal	−38 ± 24	← *Self-interactions*

  - These span **many** phenomenological templates
  - *Planck* uses both **separable** shapes and **modal/binned** approximations
  - Recent work has also constrained **tensor** three-point functions, e.g., $\langle\zeta\zeta h\rangle$ and **cosmological collider** bispectra



Conclusion: Scalar primordial non-Gaussianity is **small:** $10^{-5}\,|f_{\rm NL}| \ll 1$

However, we are still far from the (rough) theory targets: $\sigma(f_{\rm NL}) \sim 1$

Planck 2013, 2015, 2018, Jung+24, Sohn+24, **Philcox**, Shiraishi 23, 24, Wang, Shellard, Fergusson, Smith, Senatore, Maldacena, Creminelli, …

What's Next for PNG?

1. **More models**
   - Folded NG? Excited states? Slow colliders? Strongly-mixed colliders?
2. **Higher-orders**
   - Four-point functions? Five-point functions? Non-perturbative effects?
3. **Other datasets**
   - Next-generation CMB? Galaxy clustering? Weak lensing? 21cm observations?

The CMB Trispectrum

Very few previous works have considered **four-point** functions!
- Are they worth investigating?

Yes!
- **Cubic-terms** in the Lagrangian could be protected by **symmetry**

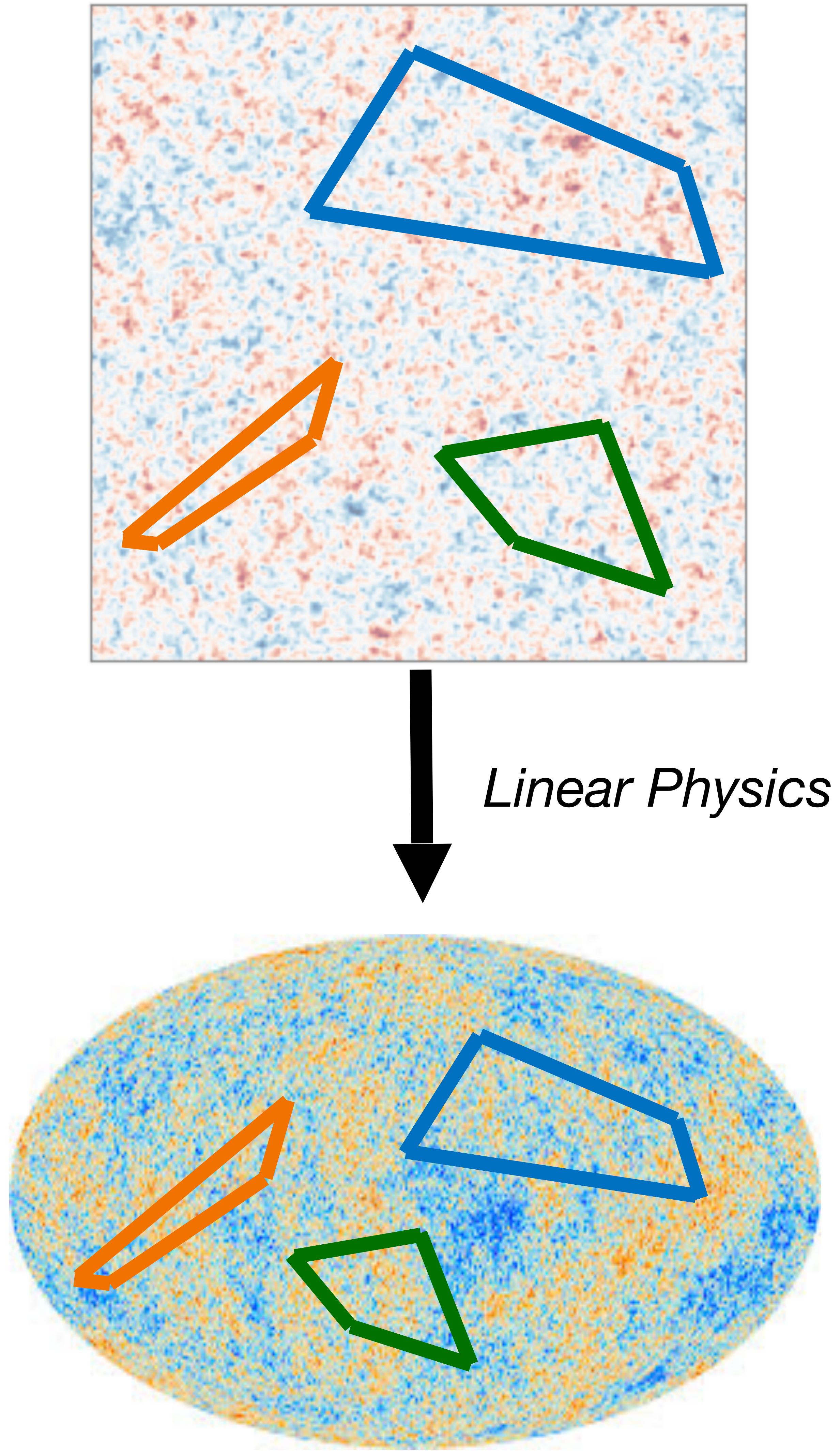
$$\mathscr{L} \sim \frac{1}{2}(\partial\sigma)^2 + \cancel{\dot{\sigma}^3} + \dot{\sigma}(\cancel{\partial\sigma})^2 + \delta\sigma^4 + \cdots$$

(for a general light scalar σ, ignoring coupling amplitudes)

Killed by $\mathbb{Z}_2$ symmetry ($\sigma \to -\sigma$), or some supersymmetries

- Four-point functions can reveal **hidden particle physics**, e.g, **helicities**
- Collider trispectra *don't* require a **linear mixing** with the inflaton

- 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: $g_{\rm NL}^{\rm eq} \times 3$)



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

How to Measure a Four-Point Function

Measuring the CMB trispectrum is a challenge!

- The trispectrum is **five-dimensional** [after symmetries] and depends on 10^{28} sets of points!

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

- We can use **compression** as for the bispectrum:

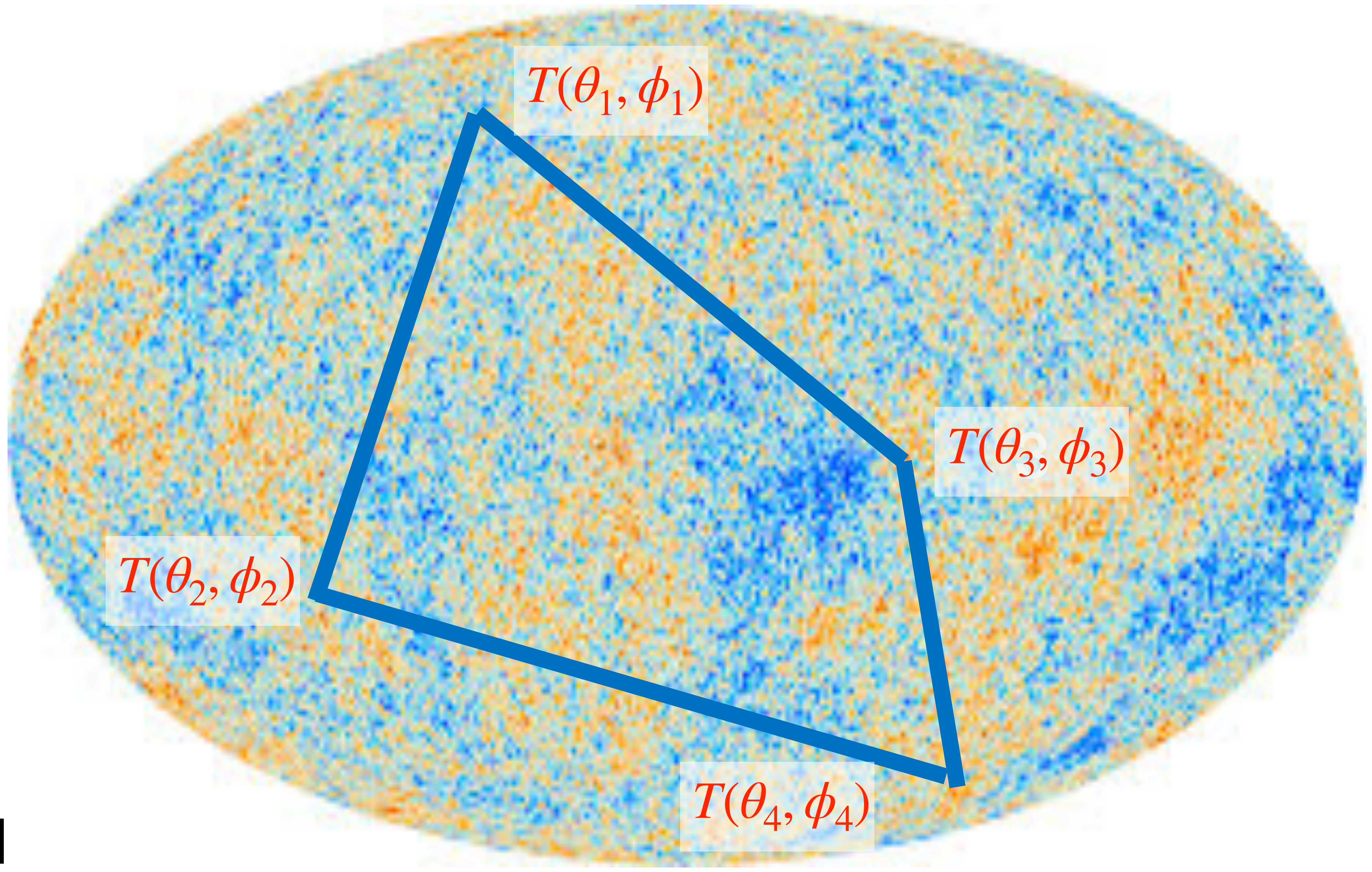
$$\widehat{g_{\rm NL}} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3 \ell_4 m_4} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4}\rangle^\dagger_{\rm theory} \times (C^{-1}a)_{\ell_1 m_1}(C^{-1}a)_{\ell_2 m_2}(C^{-1}a)_{\ell_3 m_3}(C^{-1}a)_{\ell_4 m_4}$$

Model Data

- To **compute** the ℓ, m sum we use a variety of tricks, including low-dimensional integrals, harmonic transforms, and Monte Carlo summation

$$T_\zeta(k_1,k_2,k_3,k_4,s,t,u) \sim F(k_1)G(k_2)H(k_3)I(k_4)J(s^{1/2}) + \cdots$$

- If the trispectrum can be (integral-)**factorized**, this reduces the complexity from $\mathcal{O}(N_{\rm pix}^4)$ to $\mathcal{O}(N_{\rm pix}\log N_{\rm pix})$



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

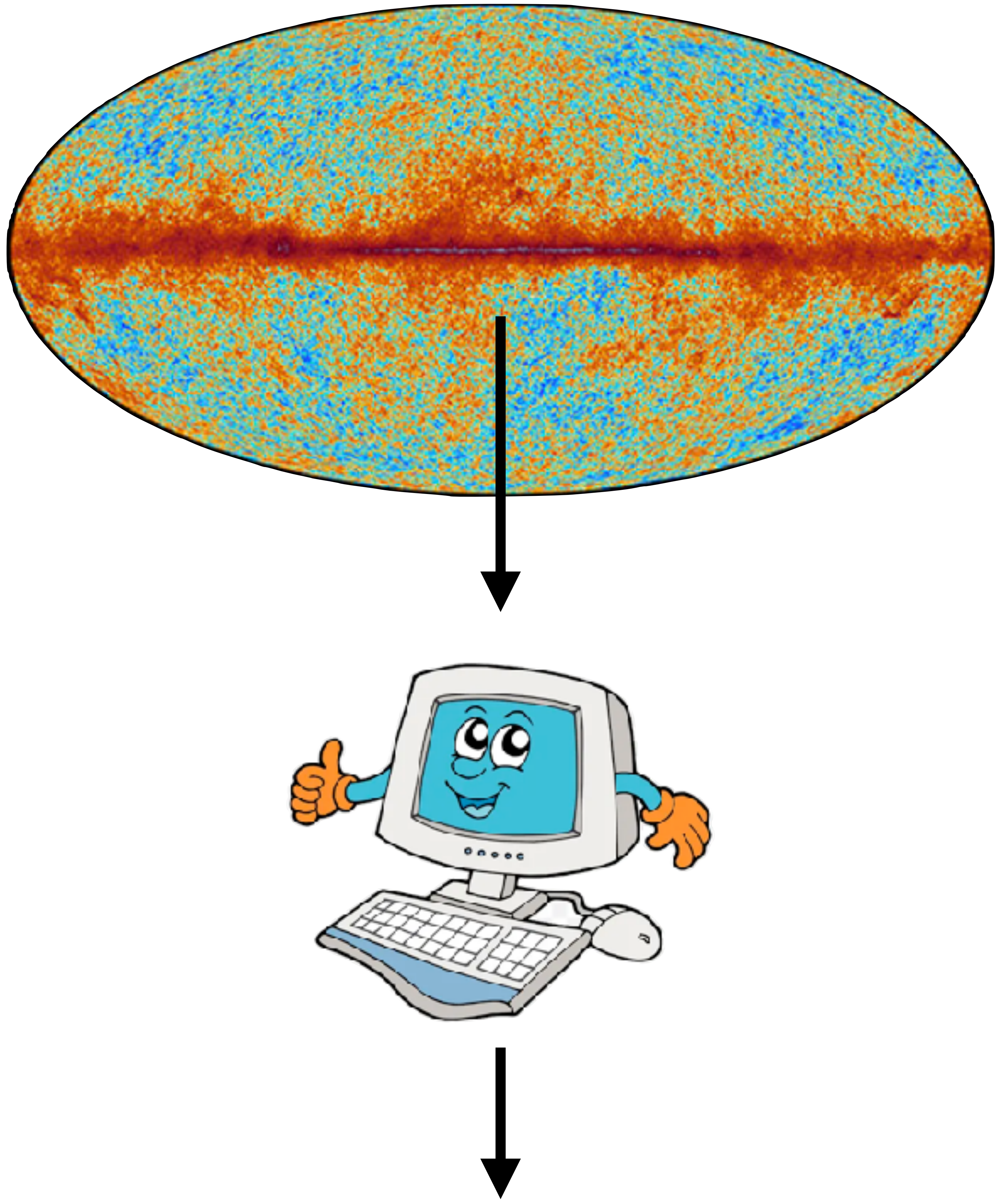
Optimal Trispectrum Analyses

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 **factorizable** model included so far)

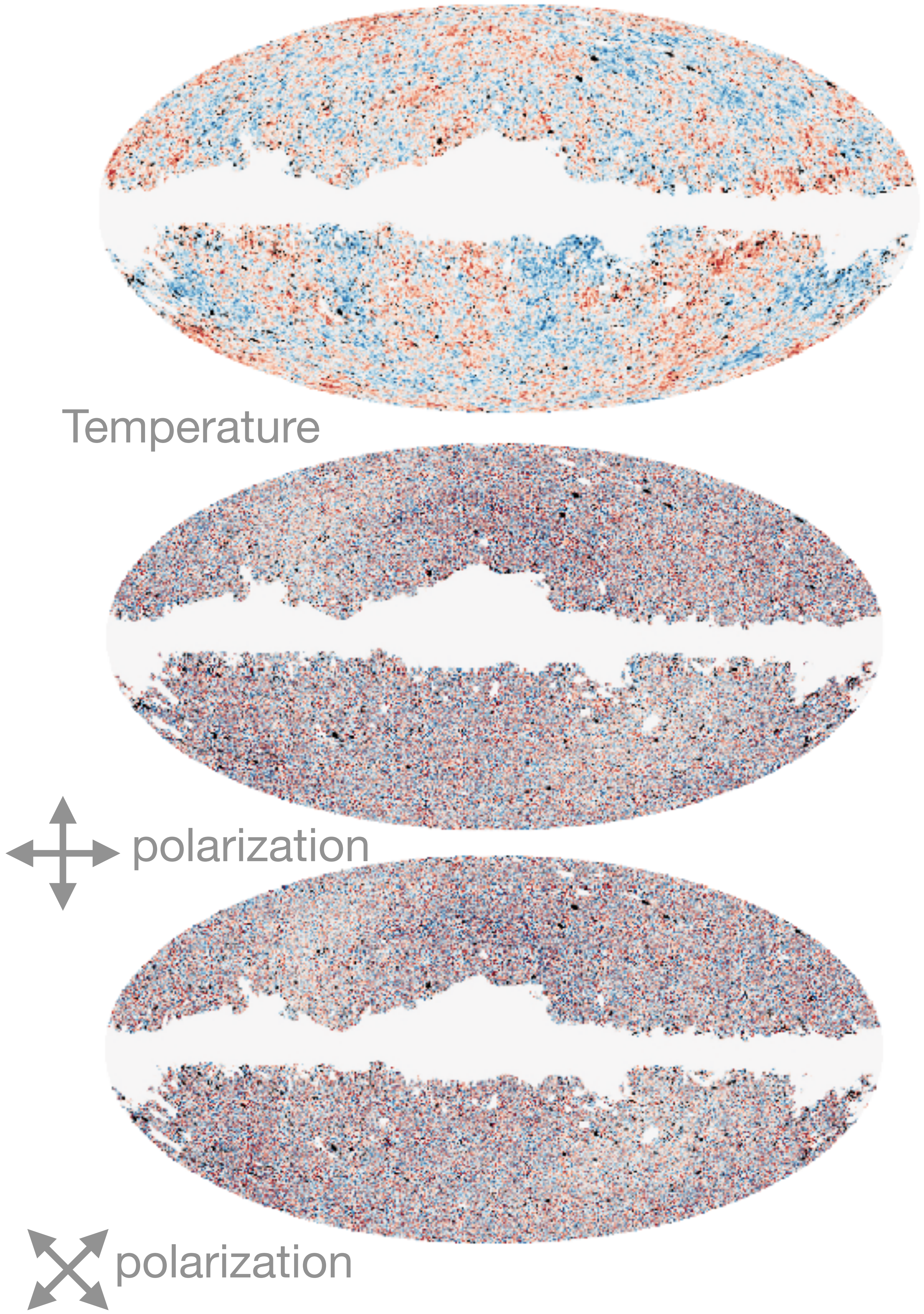
Public at **https://github.com/oliverphilcox/PolySpec**



inflation parameters

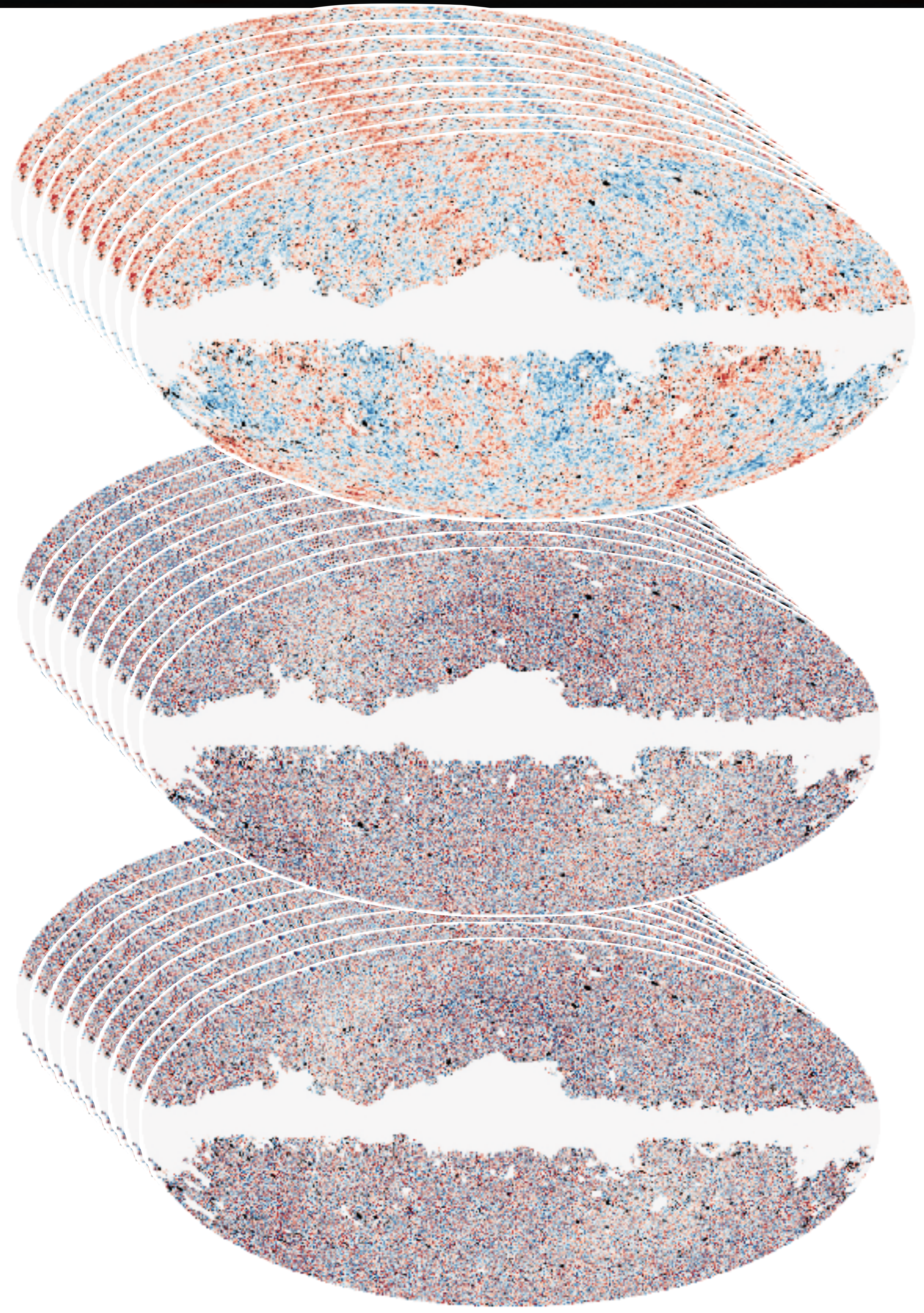
Philcox 25ab

The *Planck* Trispectrum



***Planck* PR4/NPIPE data**

+



100 FFP10 simulations

+ Optimal Weighting

+ Beam & Mask

+ Transfer Functions

(+ many systematics tests)

$$= g_{\rm NL}^{\rm loc}, g_{\rm NL}^{\rm eq}, \tau_{\rm NL}^{\rm loc}, \cdots$$

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 [non-analytic part]
7. Weak **Gravitational Lensing**
8. Unresolved **Point-Sources**
9. ISW-lensing **Trispectra**

All of these can be integral-factorized!

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

Detecting Non-Gaussianity?

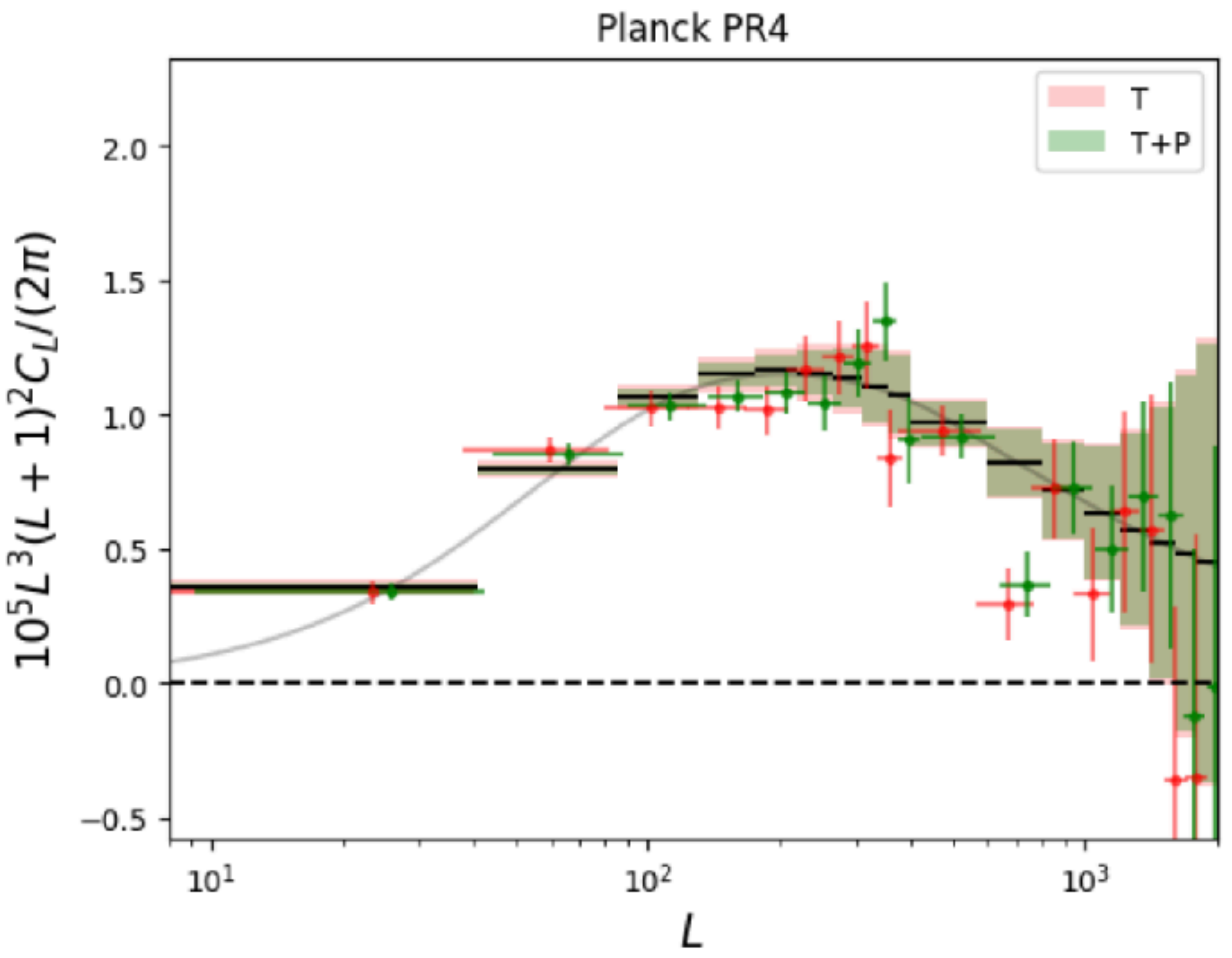
PolySpec

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 [non-analytic part] — No ($\times 17$)
7. Weak **Gravitational Lensing** — Yes!!!
8. Unresolved **Point-Sources** — No
9. ISW-lensing **Trispectra** — No

All of these can be integral-factorized!



Gravitational Lensing

(43σ, but not a new detection)

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

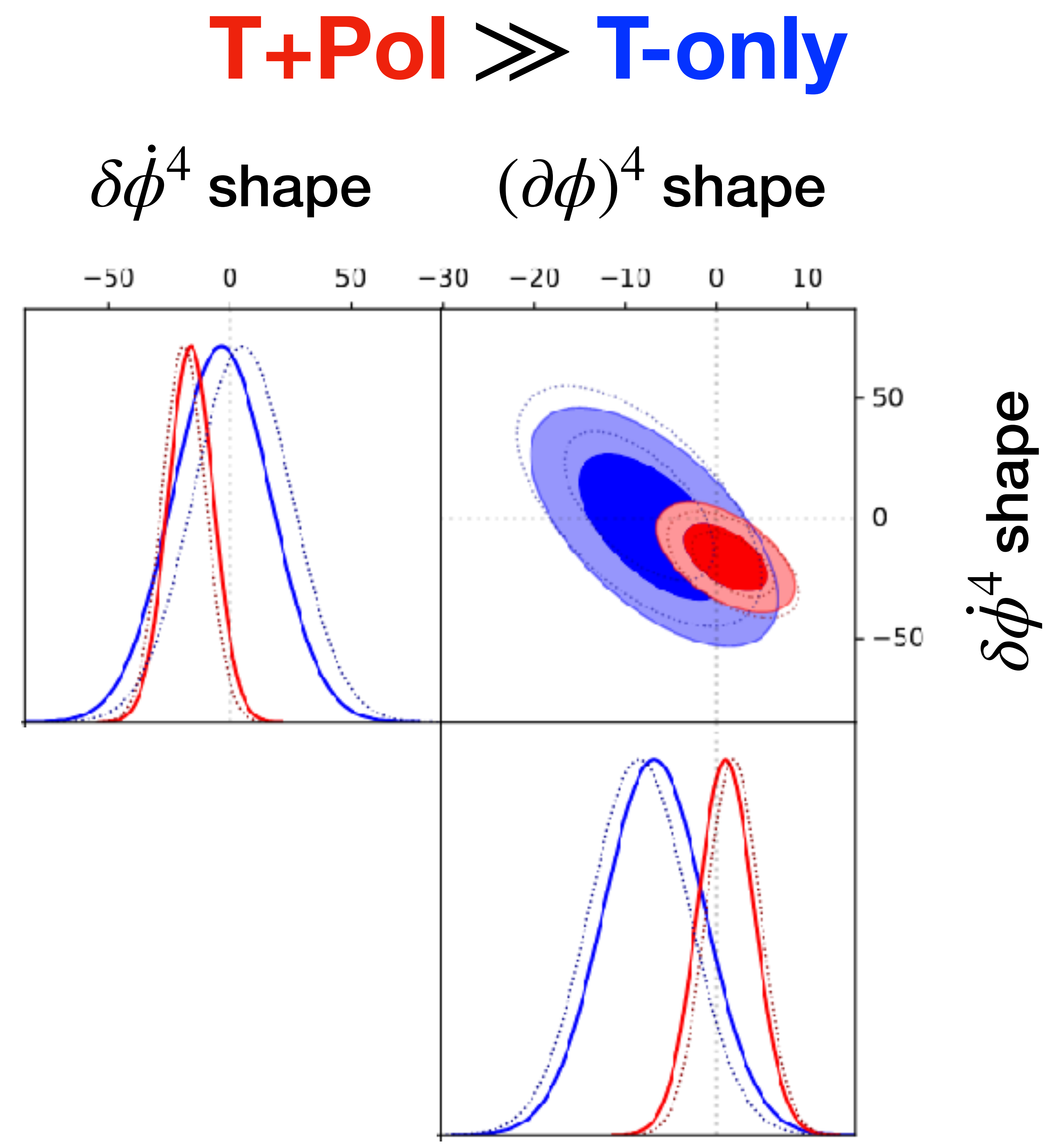
Equilateral Non-Gaussianity

We can constrain cubic *self-interactions* in inflation

- Constrains models such as:
    - **Effective Field Theory** couplings
    - **DBI** inflation (*string theory* + *small sound-speed*)
    - **Generic** single-field inflation (including *Lorentz Invariant* models)
    - **Ghost** inflation**, k**-inflation, and beyond…

Outcome: Consistent with zero!

- $(50-150\%)$ better than any previous constraints!



The third shape — $\delta\dot\phi^2(\partial\phi)^2$ — is very correlated, so we don't plot it [but we don't detect it]

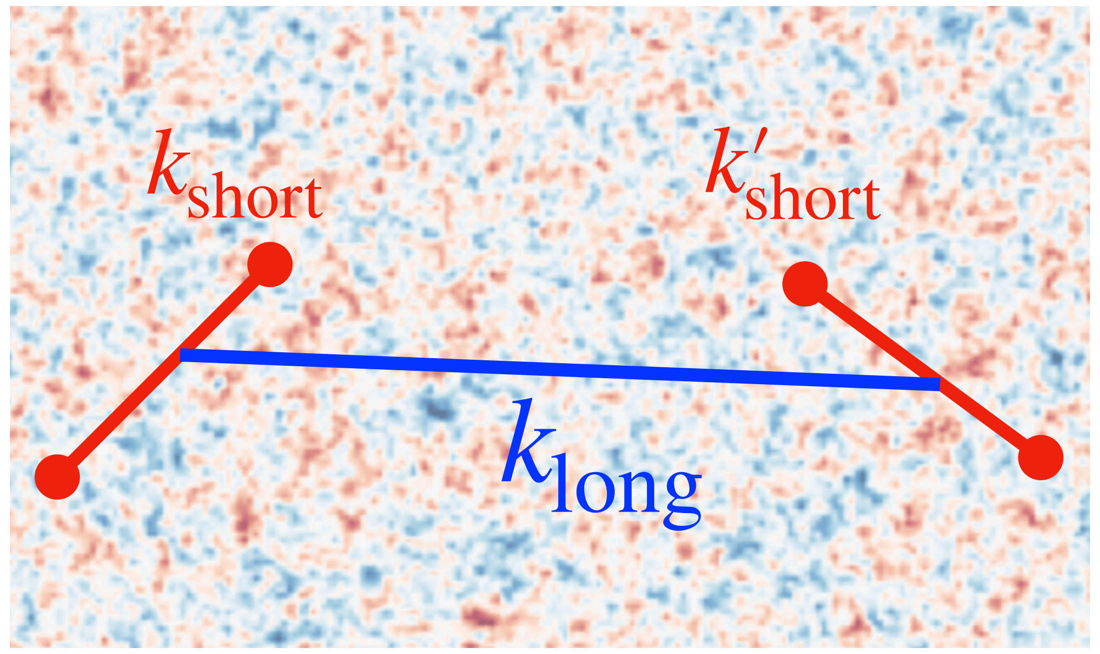
Smith+15, Planck 2015, Planck 2018, **Philcox** 25c

Cosmological Colliders

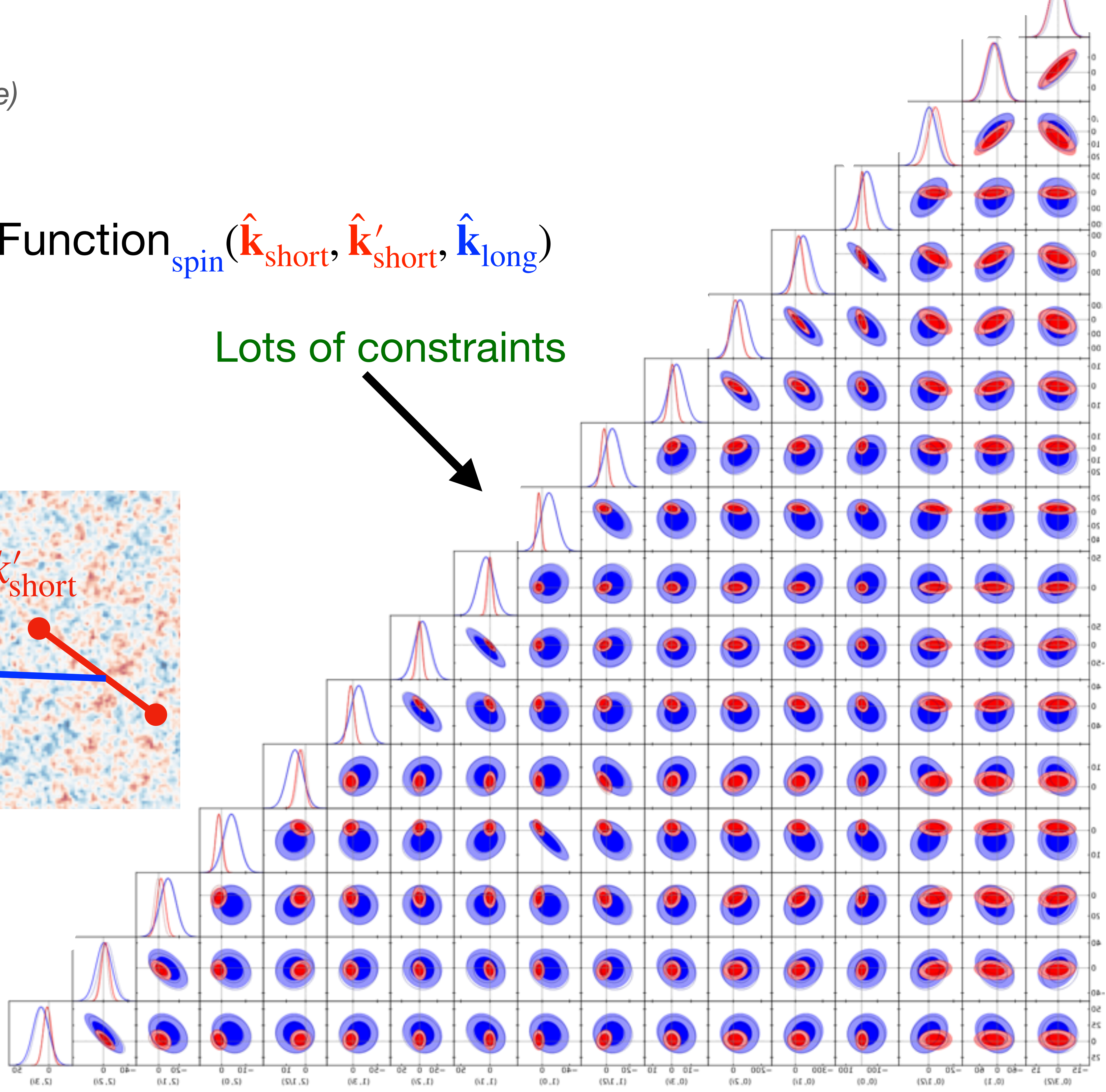
We can search for **massive** and **spinning** particles *(non-analytic piece)*

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

- 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

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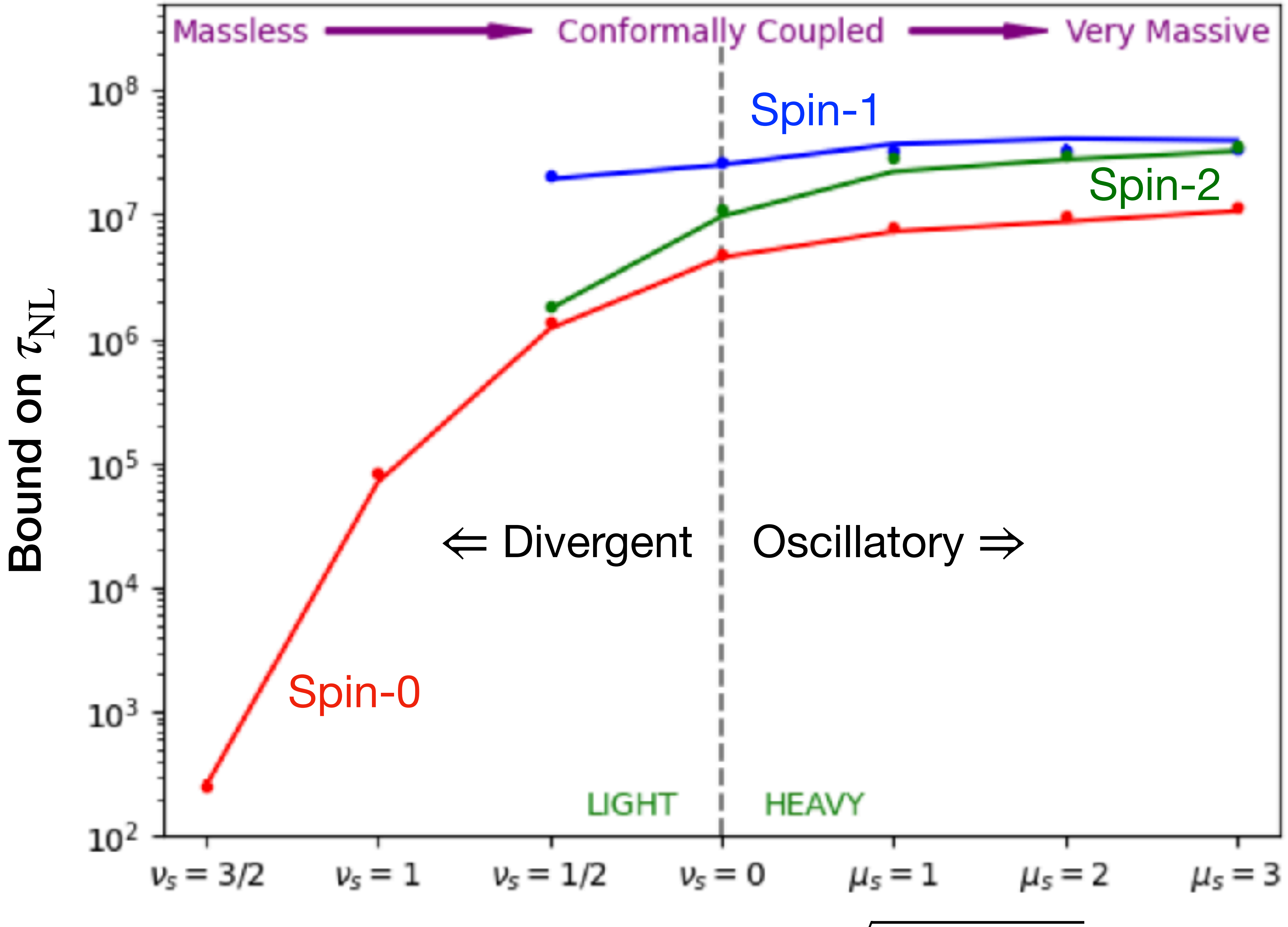
  - **Heavy** Fields (Principal Series): $m_\sigma \gtrsim 3H/2$

- As expected, **light fields** are easiest to constrain since their trispectrum ***diverges***
- Odd-spins are **hard** to constrain due to cancellations!
- **Note**: many of the collider signals are **orthogonal** to the standard templates! [Suman+25, Sohn+24]



Mass parameter: $\mu_0 = i\nu_0 = \sqrt{m^2/H^2 - 9/4}$

Philcox 25c, Moradinezhad, Schmidt, Suman, Wang, Sohn, Fergusson, Shellard…

What's Next For the Trispectrum?

There are *many* ways to extend.

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

   - ACT, SPT, Simons Observatory, LiteBird, CMB-HD, … 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? Unparticles?

   - Tensor non-Gaussianity?

   - Collider physics beyond the collapsed limit?

   - Thermal baths? Higher-spin particles? Modified sound speeds? Loops? Fermions?

   - Scale-dependence? Isocurvature? Primordial magnetic fields?

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

Separable Inflationary Correlators

- Efficient **bispectrum** and **trispectrum** analyses require **factorizable** primordial signals.
  - Separable N-point function → $\mathcal{O}(N_{\rm pix}\log N_{\rm pix})$ algorithm
  - Non-separable N-point function → $\mathcal{O}(N_{\rm pix}^N)$ algorithm

$$B_\zeta(k_1,k_2,k_3) \sim F(k_1)G(k_2)H(k_3)$$

$$T_\zeta(k_1,k_2,k_3,k_4,s,t,u) \sim F(k_1)G(k_2)H(k_3)I(k_4)J(s^{1/2}) + \cdots$$

- Many models of interest are **not separable**
  - Some require complex oscillatory integrals (via *in-in*)
  - Others cannot be expressed analytically (e.g., *numerical methods*)

$$B_\zeta(k_1,k_2,k_3) \sim \frac{k_1k_2k_3}{(k_1+k_2+k_3)^3}$$

- To analyze these models, we have two options:
  1. **Bin the statistic** [lossy, and expensive to compute theory predictions!]
  2. Create a **separable approximation** [e.g., modal decompositions]

Philcox, Zhong, Samuele Sirletti (2025), Komatsu, Spergel, Wandelt, Regan, Shellard, Fergusson, Sohn, Wang, Suman…

Separable Inflationary Bispectra

- **Modal approach**: represent the bispectrum as a **sum** of **polynomials**:

$$(k_1k_2k_3)^2B_\zeta(k_1,k_2,k_3) \sim \sum_{p+q+r=0} \alpha_{pqr}k_1^pk_2^qk_3^r$$

(or Legendre polynomials)

  - Given a **target** bispectrum, the coefficients α_{pqr} are computed with **linear algebra**
  - Each term is **factorizable**, so we can build an efficient CMB estimator!
  - *However*, this basis is **big** (≈ 5000 terms used in the *Planck* collider analysis) and does not represent all shapes of interest.

- **Alternative approach**: **learn** the basis from the **theory** itself

$$(k_1k_2k_3)^2B_\zeta(k_1,k_2,k_3) \sim \sum_n w_n\alpha_n(k_1)\beta_n(k_2)\gamma_n(k_3) + \text{perms.}$$

  - Given a **target** bispectrum, the **functions** $\alpha_n, \beta_n, \gamma_n$ and **weights** w_n are computed using **machine learning**
  - By carefully choosing the loss function, we can **optimize** the decomposition for the task of interest, e.g., *Planck* CMB analysis
  - This typically requires **far fewer terms** ($N \lesssim 3$) to compute the bispectra!

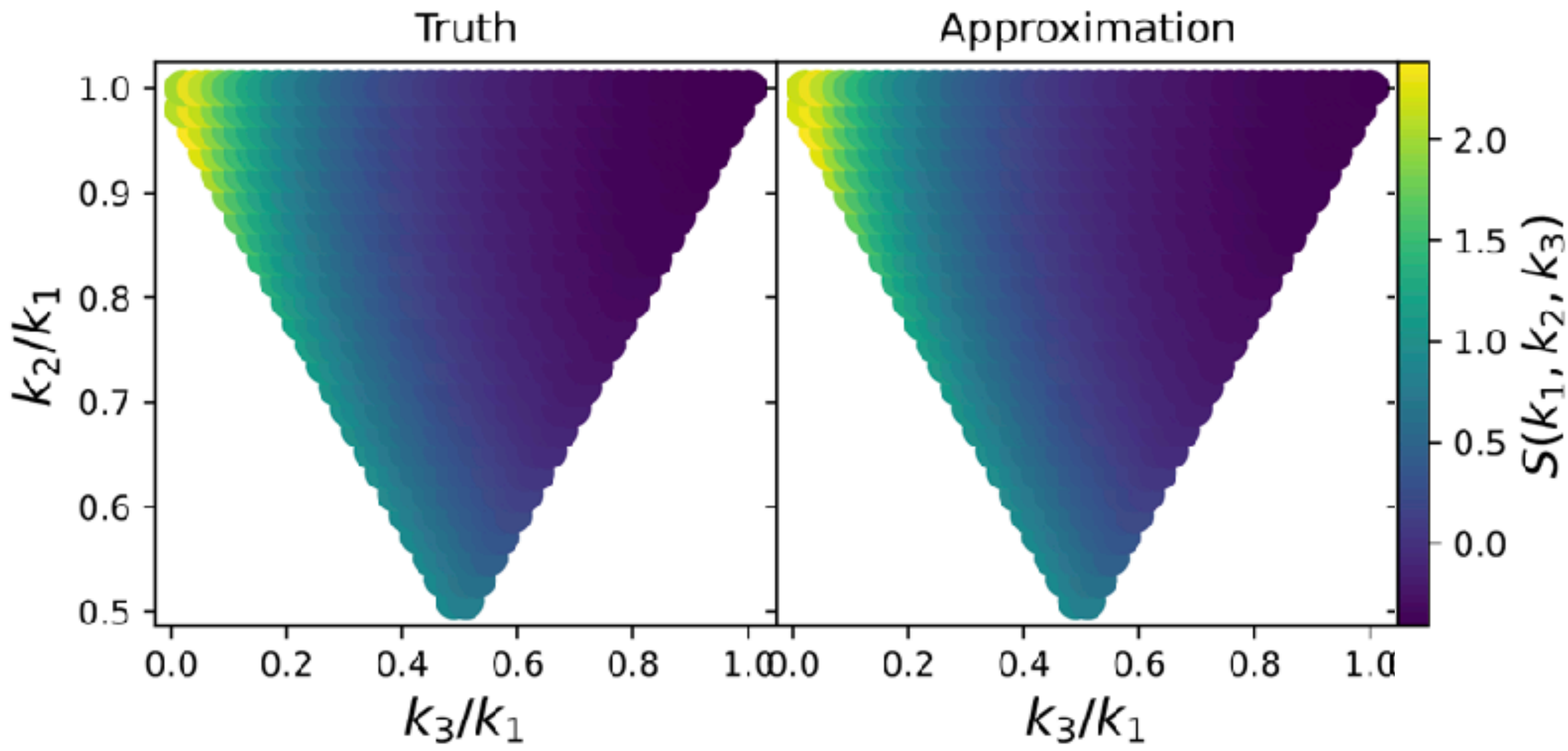
Philcox, Zhong, Samuele Sirletti (2025), Komatsu, Spergel, Wandelt, Regan, Shellard, Fergusson, Sohn, Wang, Suman…

Separable Bispectra in Practice

- This is implemented in the `separable_bk` code, which includes:
  - Simple **neural network** architecture, supplemented with permutation symmetries
  - Training with **stochastic gradient descent**
  - Fast `pytorch` implementation, giving basis functions in $\mathcal{O}(\text{minutes})$
- We test `separable_bk` using **numerical** bispectra obtained with the **CosmoFlow** code
  - We use a **strongly-mixed** collider shape that **cannot** be computed analytically
  - With just **three** terms, we find approximations with $> 99.9\,\%$ accuracy!

Available at https://github.com/KunhaoZhong/separable_bk

$$(k_1k_2k_3)^2B_\zeta(k_1,k_2,k_3) \sim \sum_n w_n\alpha_n(k_1)\beta_n(k_2)\gamma_n(k_3) \text{ + perms.}$$



Collider bispectrum shape

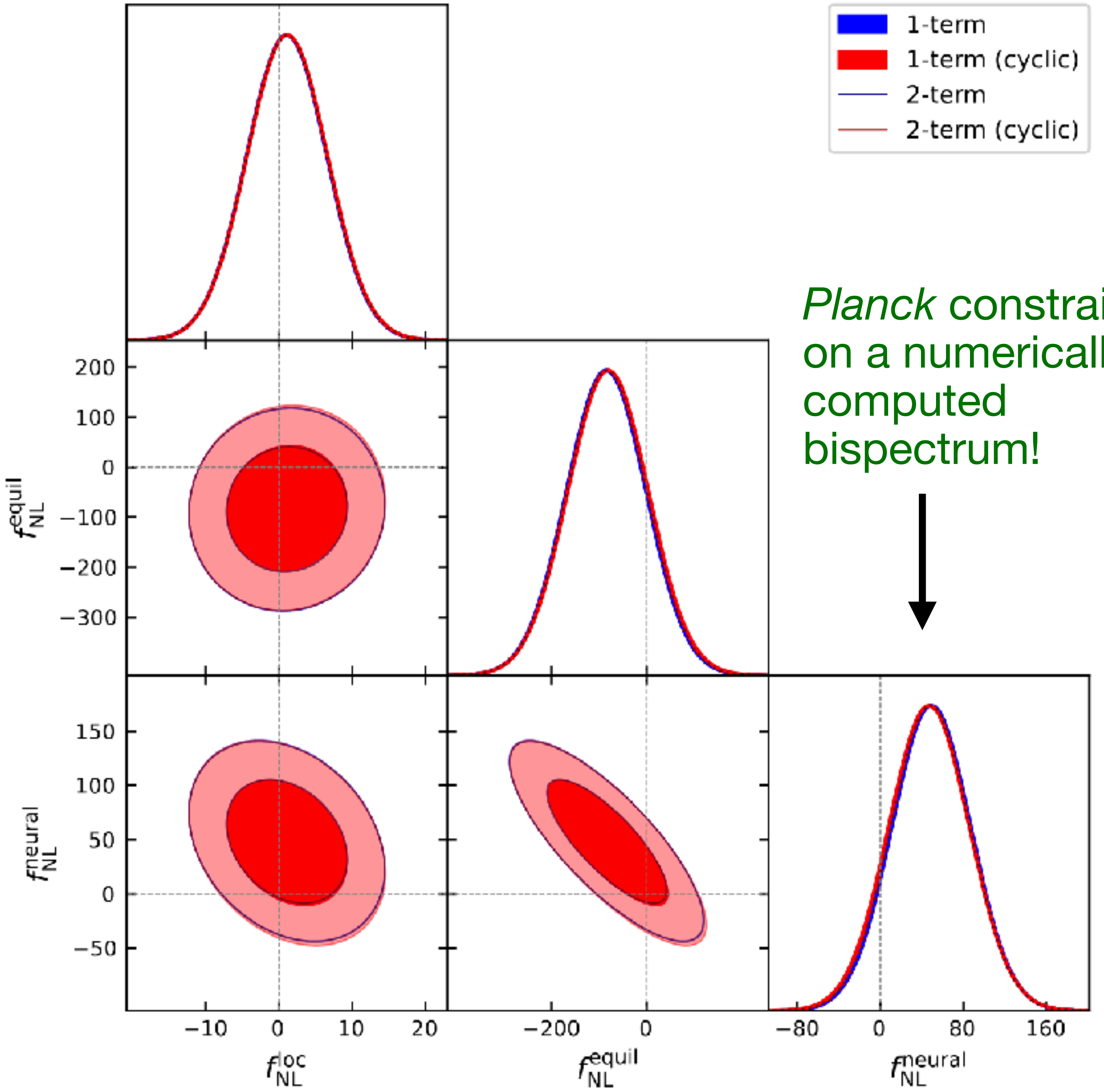
(deprojecting equilateral piece)

Philcox, Zhong, Samuele Sirletti (2025), Werth, Pinol, Renaux-Patel 2024, 2025, Jazayeri …

Separable Bispectra in Practice

- The output of `separable_bk` is a set of **basis functions** describing a particular primordial bispectrum.
- These can be interfaced with the ***PolySpec*** code to compute $f_{\rm NL}$ bounds, e.g., from *Planck*
- Since the number of separable terms is **small**, we can analyze **collider** bispectra in similar computation time to standard shapes, such as local and equilateral!
- This will allow us to constrain **arbitrary** primordial bispectra, including those that can only be computed numerically.
- There is **lots** to explore, e.g., analysis of strongly-mixed colliders, and extension to trispectra

Available at https://github.com/KunhaoZhong/separable_bk



Planck constraint on a numerically computed bispectrum!

Philcox, Zhong, Samuele Sirletti (2025), Werth, Pinol, Renaux-Patel 2024, 2025, Jazayeri …

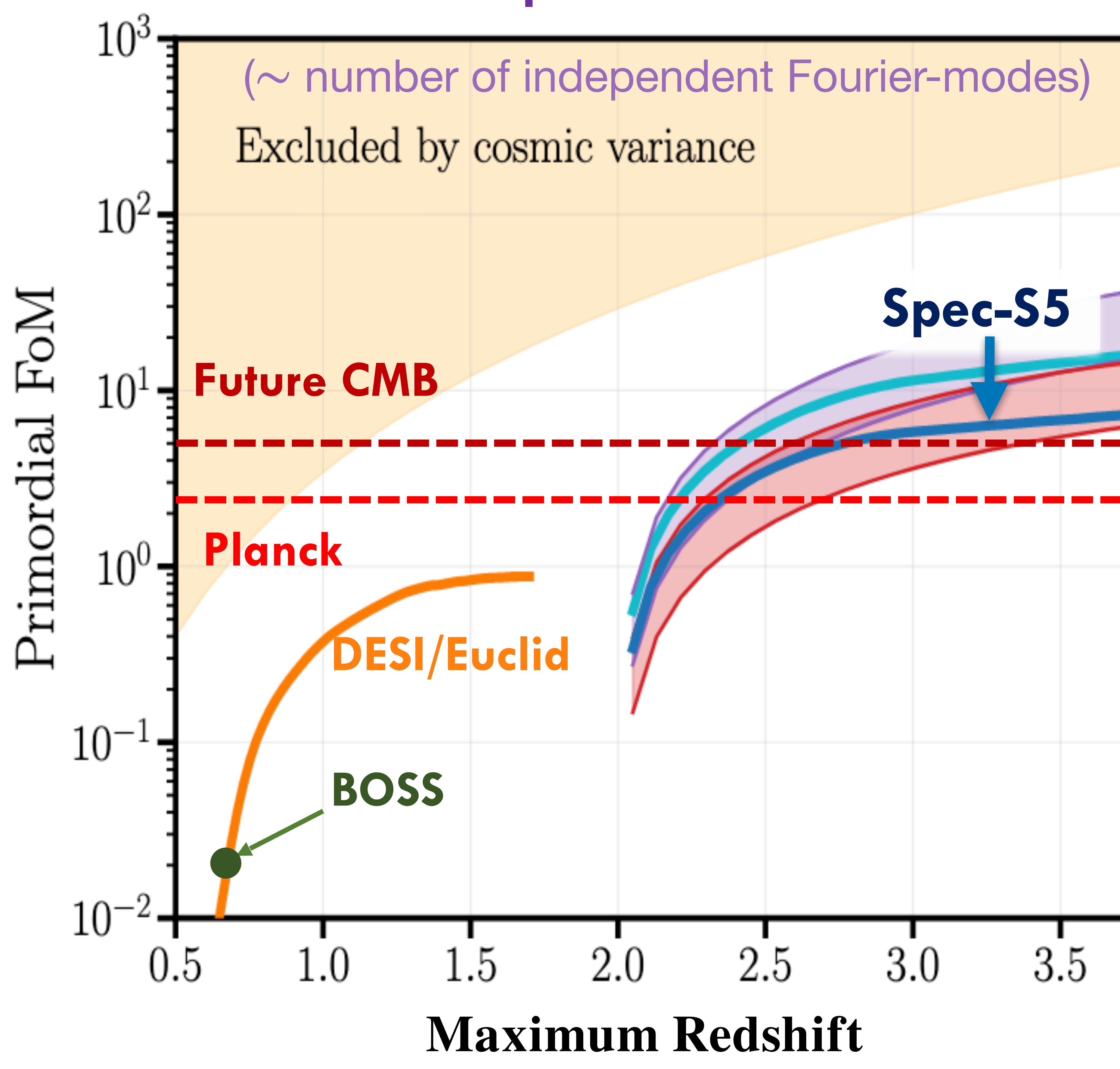
The Future of Non-Gaussianity

- Future **CMB** experiments will improve bounds on PNG by $\lesssim 3\times$
  - This is a **two-dimensional** field
  - We're running out of modes to look at
    - Large-scales are **cosmic-variance-limited**
    - Small-scales are limited by **secondaries** and **Silk damping**

- What about **galaxy surveys**?
  - The data precision is **rapidly increasing**
    - Legacy surveys map **a million** galaxies [BOSS]
    - New surveys map $\sim 100\times$ more! [DESI, Euclid, Rubin, Roman, SphereX,…]
  - This is a **three-dimensional** field
    - We aren't limited by **projection effects**
  - There are new observables e.g., galaxy **shapes,** kSZ cross-correlations, …

Amount of primordial information

(~ number of independent Fourier-modes)

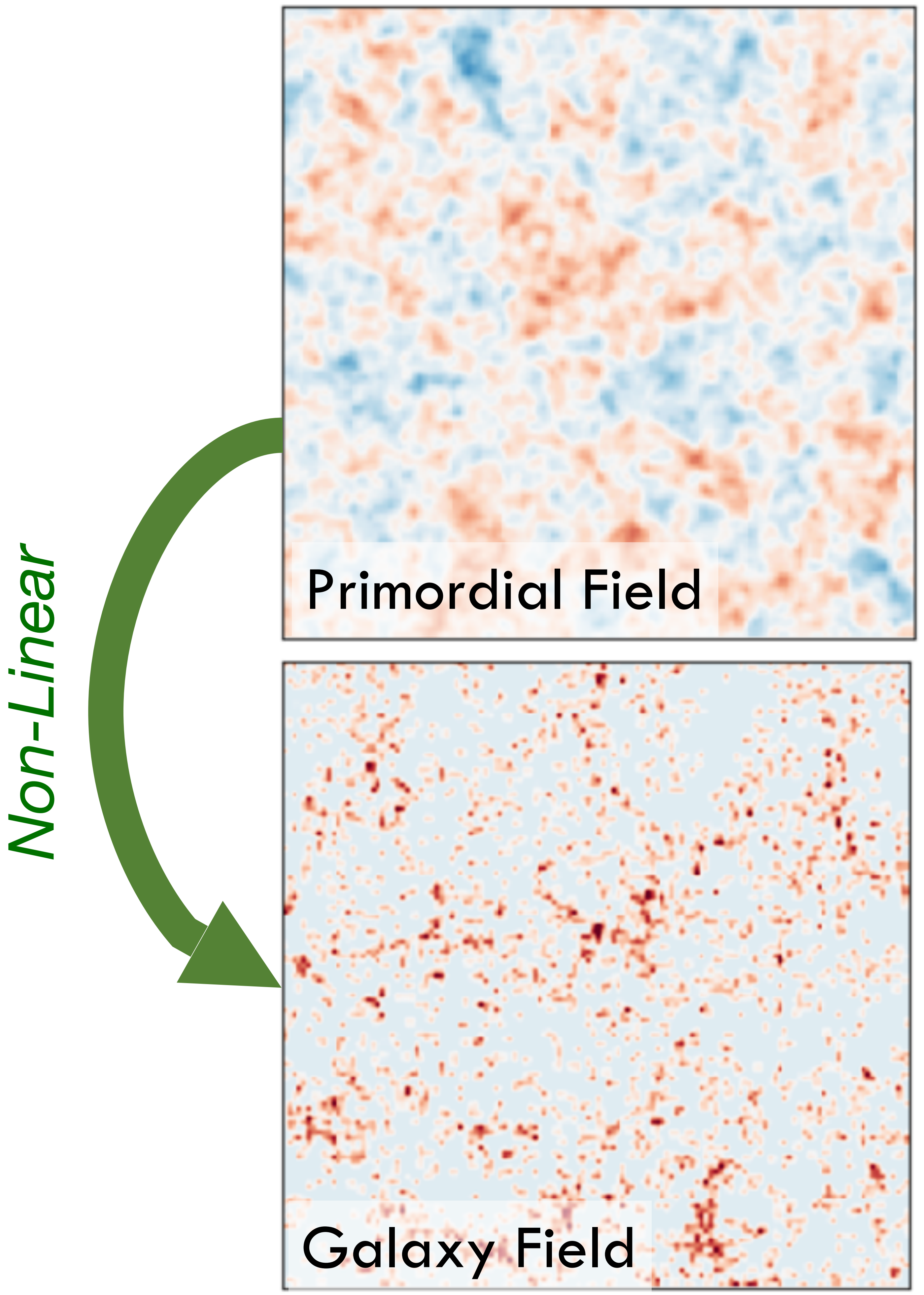


Simons Observatory, Sailer+, Ferraro+

Inflation from Galaxy Surveys

- Modern galaxy surveys map of the distribution of galaxies in three-dimensions: $\delta_g(\mathbf{x}, z)$
- This **traces dark matter** evolution and the **initial conditions**
- To extract **inflationary information**, we need a **joint** model of all effects:

$$\langle \delta_g \delta_g \delta_g \rangle \sim \text{Primordial Physics} + \text{Gravity} + \text{cross-terms}$$



State-of-the-art method:

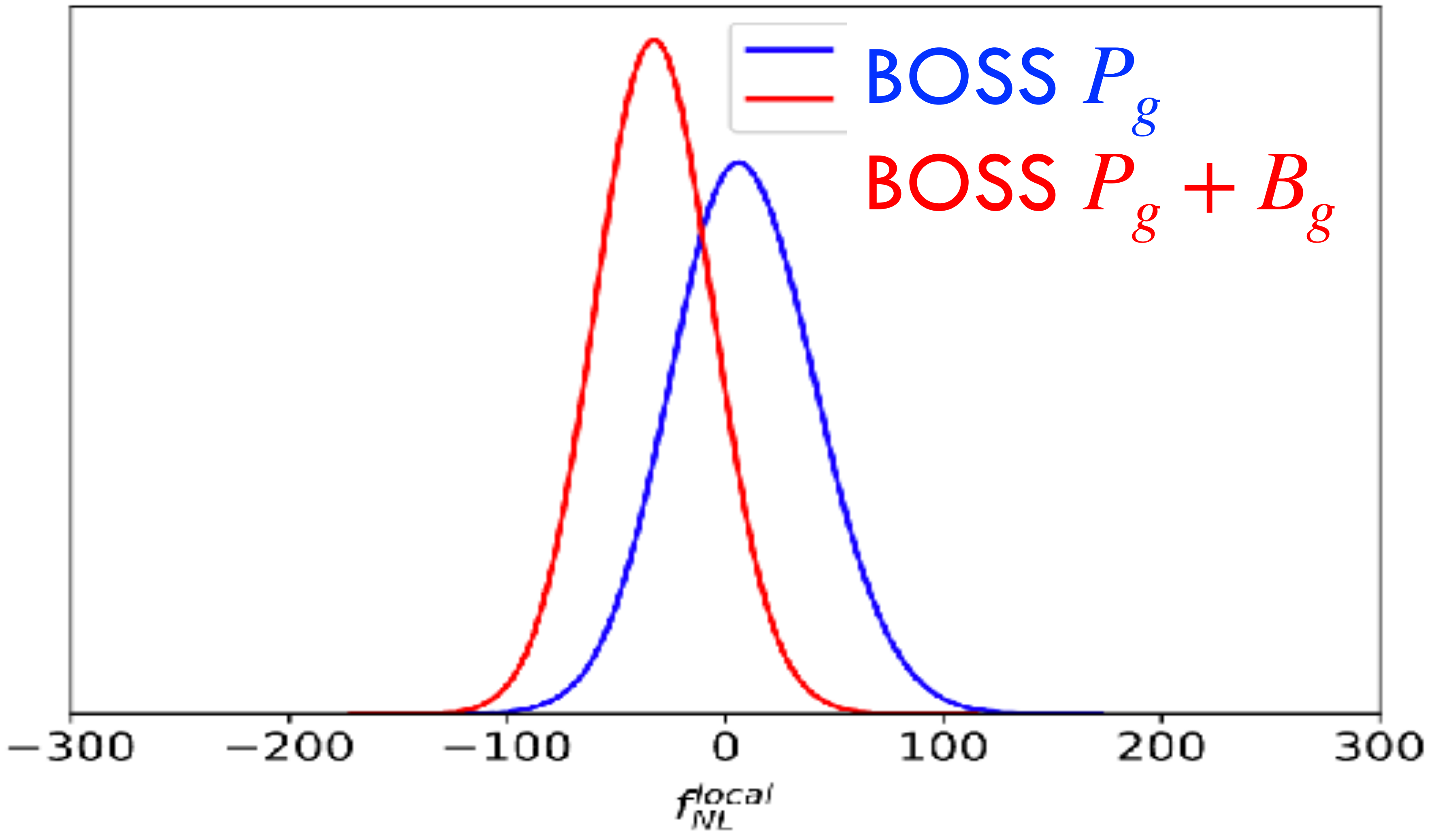
Effective Field Theory** of **Large Scale Structure (EFTofLSS)

Cabass+, **Philcox**+, Chen+, d'Amico+, Assassi, Zaldarriaga, Senatore, …

Inflation from Galaxy Surveys

- Recent works have constrained inflationary **bispectra** with **legacy galaxy survey** data (SDSS-BOSS):
  - $f_{\rm NL}^{\rm loc}$: **Local** three-point functions from additional **light fields**
  - $f_{\rm NL}^{\rm eq,orth}$: **Equilateral** three-point functions from cubic interactions in single-field inflation
  - $f_{\rm NL}^{\rm coll}(m_\sigma, c_\sigma)$: **Collider** three-point functions from the exchange of massive scalar fields

Light Field Constraints



- For now, the constraints are **much** worse than the CMB $(5-20\times)$

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

(CMB: ± 5, Target: ± 1)

- ***Much better data is coming soon!***

Cabass, **Philcox**, Ivanov, Zaldarriaga, Simonovic, Chen, d'Amico+ …

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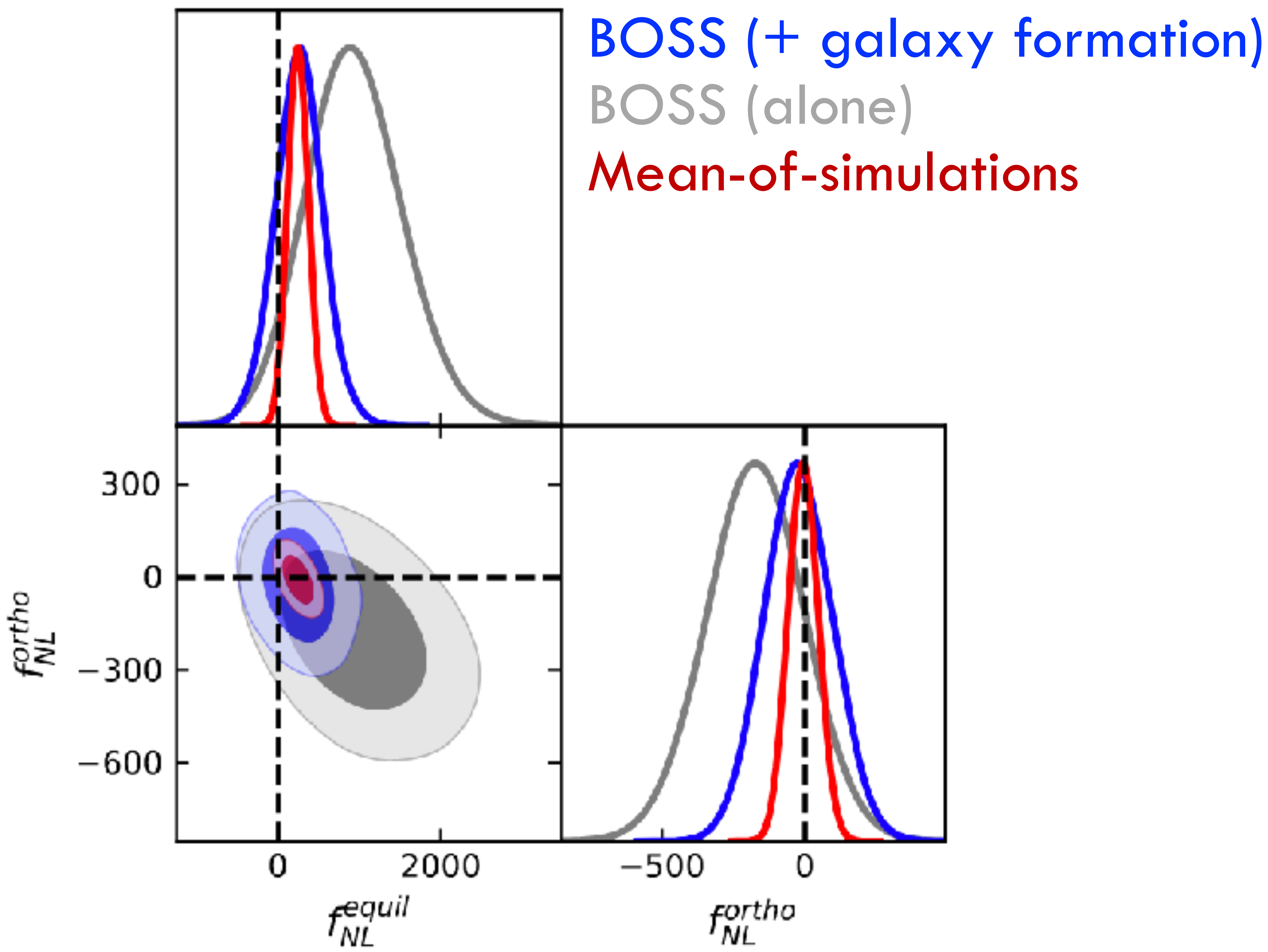
Self-Interaction Constraints



$f_{\rm NL}^{\rm eq} = 940 \pm 600, f_{\rm NL}^{\rm orth} = -170 \pm 170$

(CMB: $\pm 50, \pm 25$, Target: ± 1)

Cabass, **Philcox**, Ivanov, Zaldarriaga, Simonovic, Chen, d'Amico+ …

Inflation from DESI

The first year of DESI data is now public!

- We have developed an **independent** pipeline for analyzing the **power spectrum** and **bispectrum**
- This has been used to constrain: ΛCDM (Ω_m, H_0, σ_8), dark energy ($w_0 w_a$), curvature (Ω_k), neutrino masses ($\sum m_\nu$)

Chudaykin, Ivanov, **Philcox** 2025a, 2025b, 2025 (in prep.), DESI, Chaussidon+24

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New constraints on inflation!

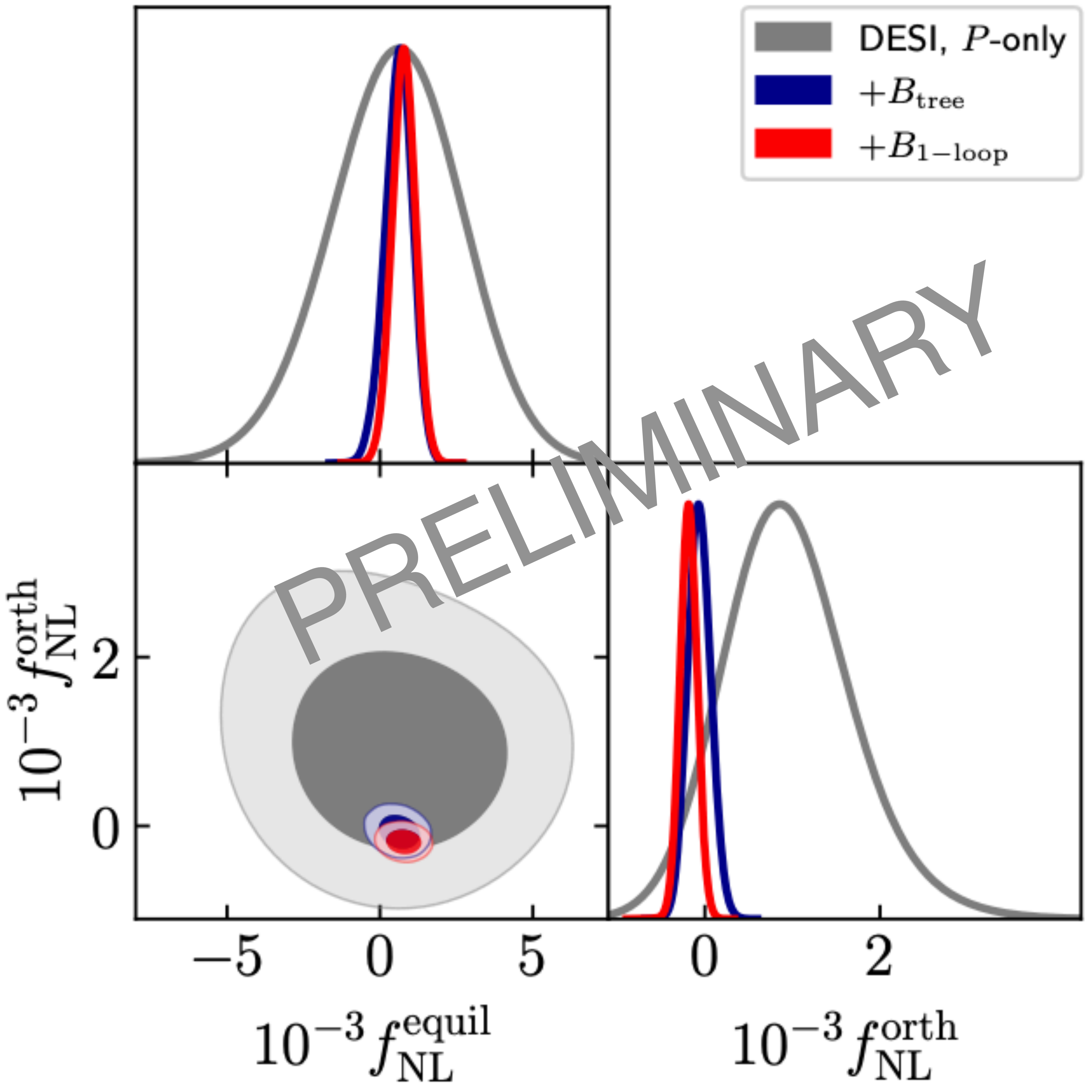
- **Multi-field**: $f_{\rm NL}^{\rm loc} = 0 \pm 7$
- **Single-Field**: $f_{\rm NL}^{\rm eq} = 200 \pm 230, f_{\rm NL}^{\rm orth} = -24 \pm 86$

Compare to official DESI results:
$f_{\rm NL}^{\rm loc} = -2 \pm 10$

(Using the DESI DR1 one-loop power spectrum and bispectrum, plus the high-z quasar sample)

- Adding **Planck**, we obtain the **tightest** constraint on local PNG yet!!

$$f_{\rm NL}^{\rm loc} = 0 \pm 4$$



Chudaykin, Ivanov, **Philcox** 2025a, 2025b, 2025 (in prep.), DESI, Chaussidon+24

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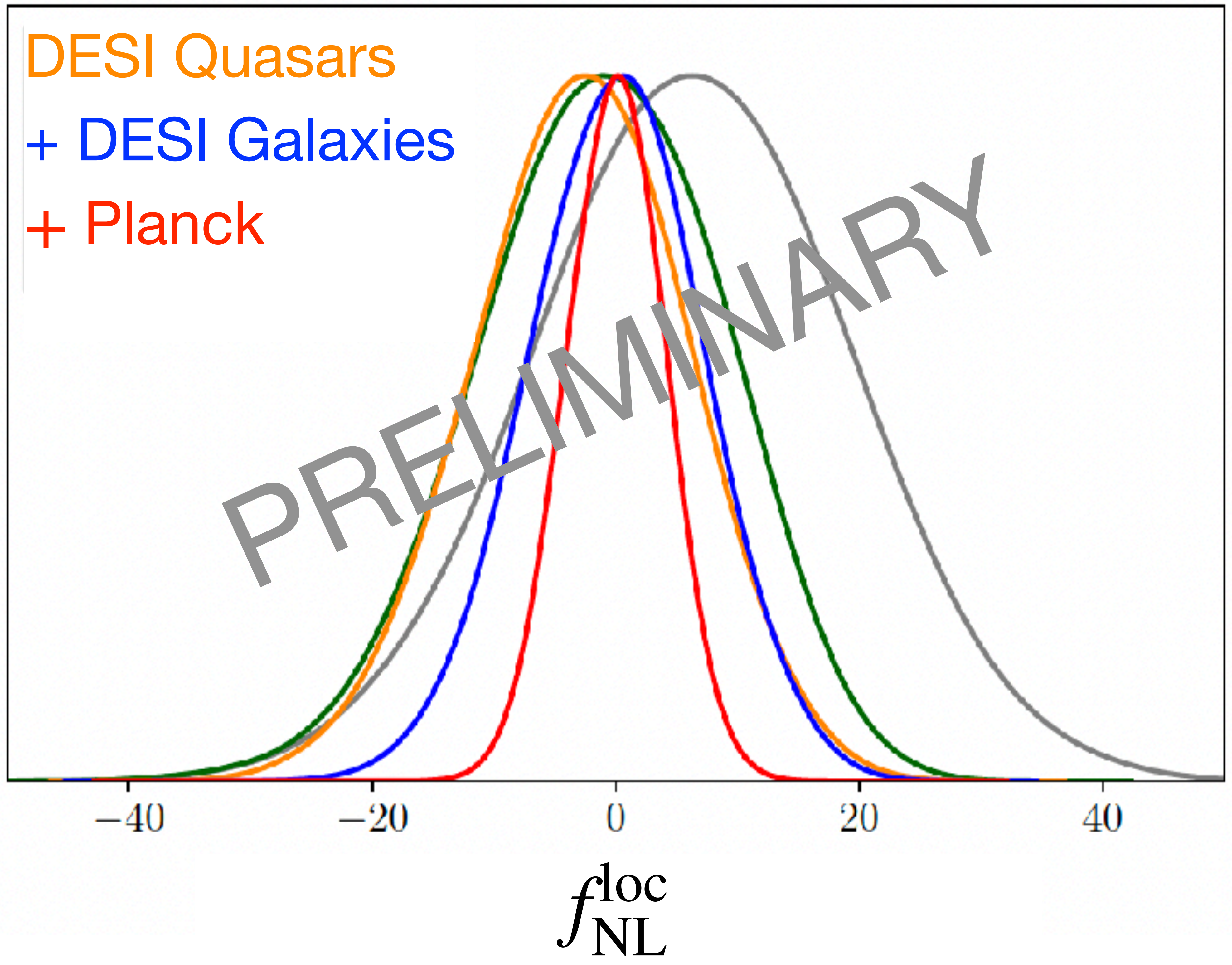

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Summary

PNG analysis is a very active field!

- We can now constrain inflationary four-point functions in the CMB, including the **cosmological collider**!
- We can probe **arbitrary** non-separable bispectrum models with CMB data and **machine-learning**
- **Galaxy surveys** are providing exciting new insights into inflation and are starting to rival the CMB

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