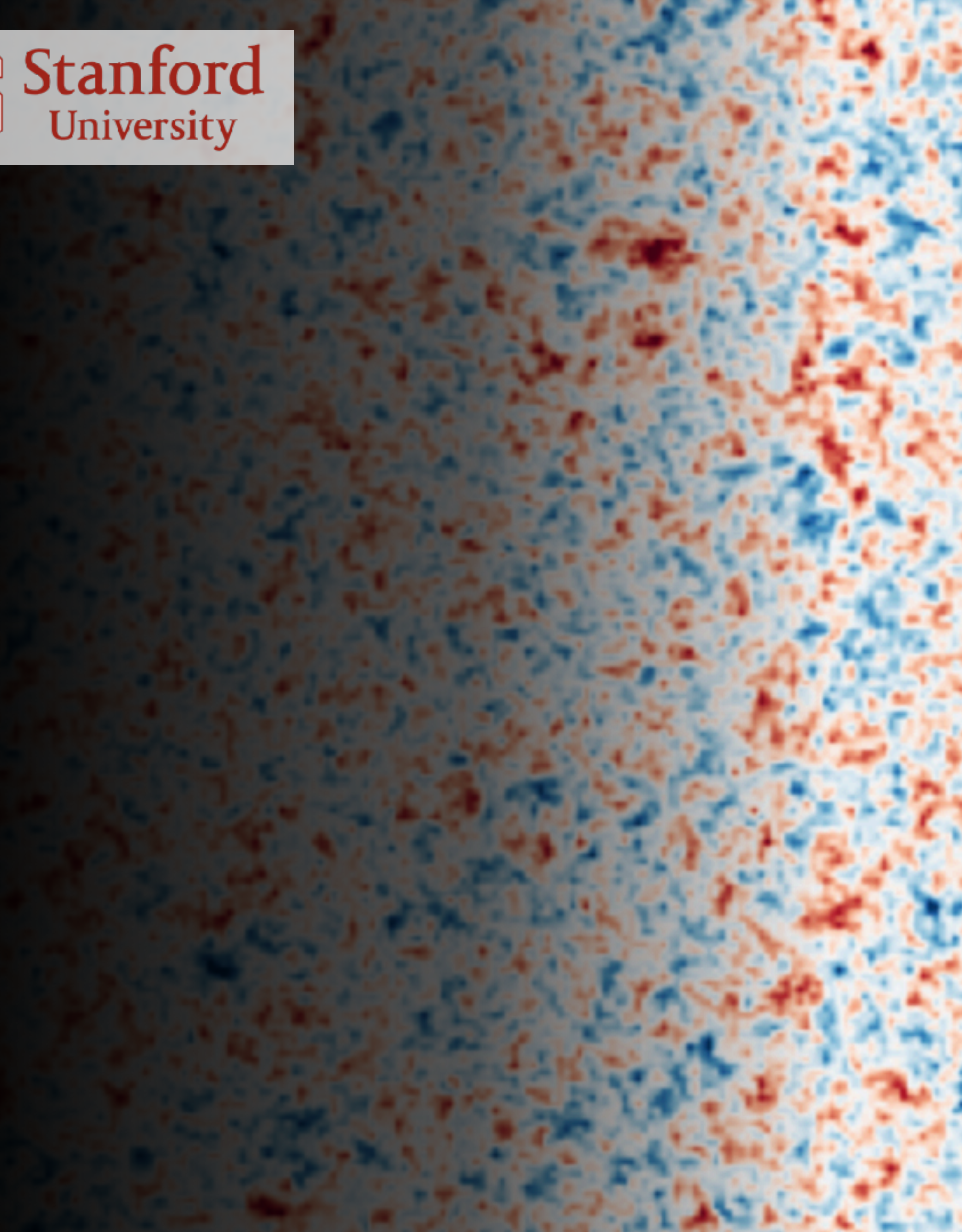
SIMONS FOUNDATION

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Stanford University

Particle Colliders in the Sky

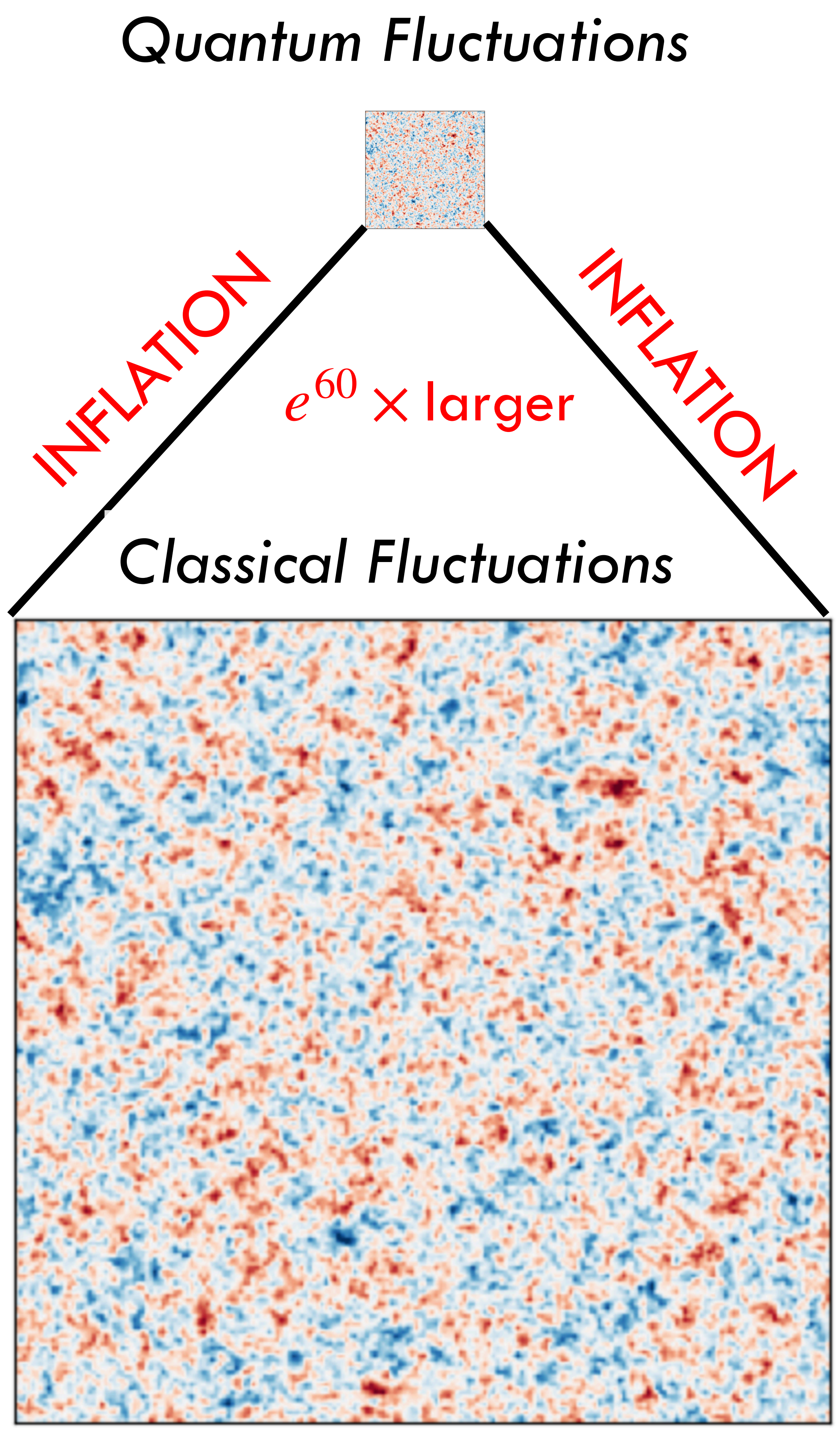
Learning $10^{13}\,\mathrm{TeV}$ physics with $10^{-16}\,\mathrm{TeV}$ data



Oliver H. E. Philcox
Junior Fellow @ Simons Foundation
Postdoc @ Columbia
Assistant Prof @ Stanford [from September]

Roadmap of this Talk

What do we think we know about inflation?



Background

- Almost ***exponential*** expansion of spacetime

  $\Rightarrow$ Solves flatness / horizon / monopole problems

Perturbations

- **Quantum** vacuum fluctuations sourced **classical** perturbations in the curvature, $\zeta(\mathbf{x})$

  $\Rightarrow$ The distribution of ζ should be Gaussian!

$$\zeta(\mathbf{k}) \sim \mathrm{Normal}[P_\zeta(k)], \qquad P_\zeta(k) \sim \langle \zeta(\mathbf{k})\zeta^*(\mathbf{k})\rangle$$

(k = Fourier-space momentum)

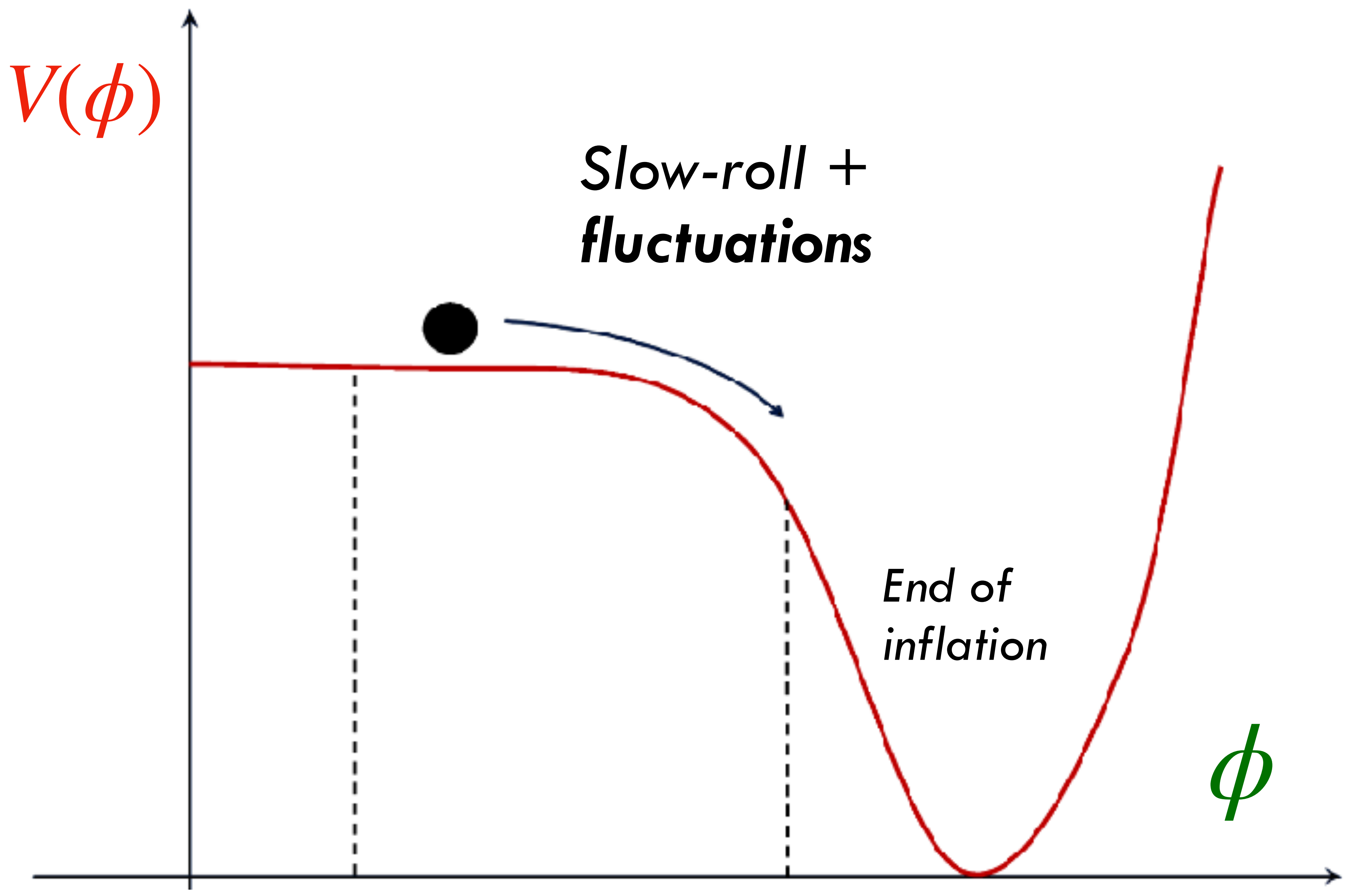
COBE, WMAP, Planck, Linde, Guth, Starobinsky, …

What do we think we know about inflation?

Simplest (phenomenological) model

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

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



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

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 $\delta\phi$

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

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? ⟶ $\phi \to \phi, \chi, \psi_u, \cdots$
- Did the fields **interact**? ⟶ Lagrangian $\supset \dot{\phi}^3 + \cdots$

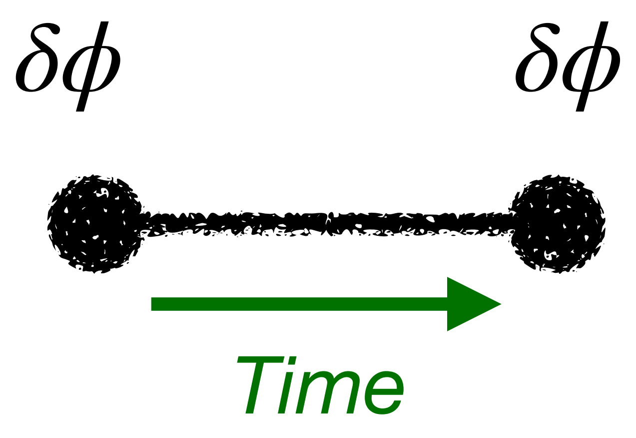
Linde, Guth, Starobinsky, Lyth, Mukhanov, Sasaki, …

Two-Point Functions

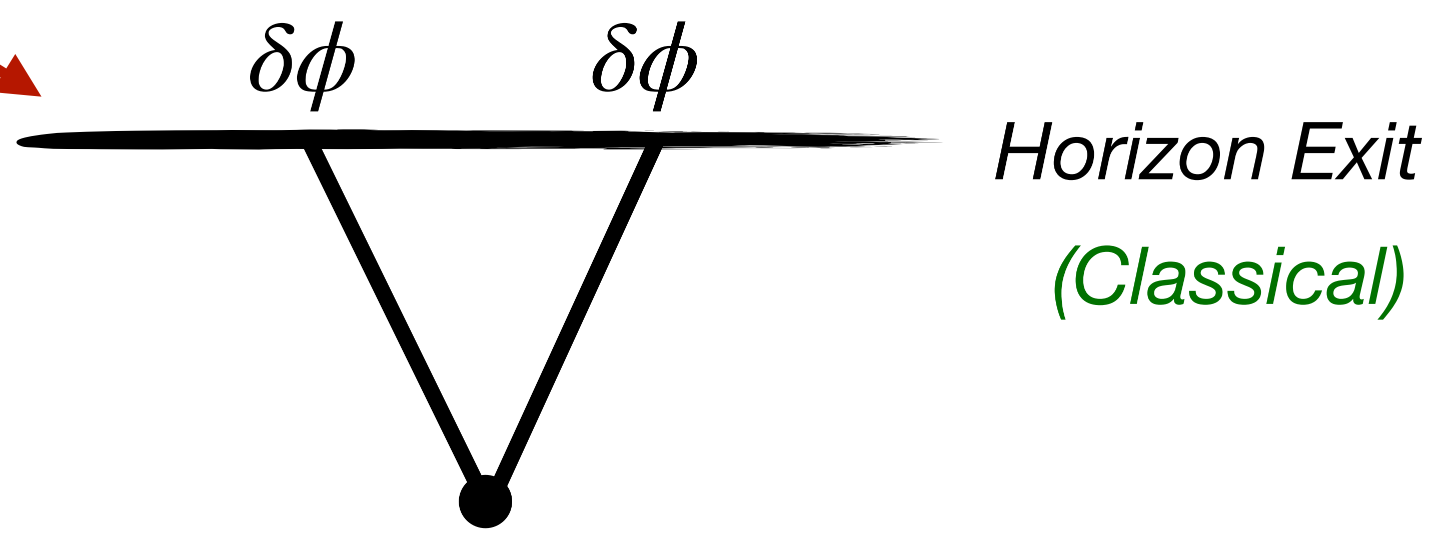
- Let's assume we have just a **single field** ϕ in inflation (the "inflaton")

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

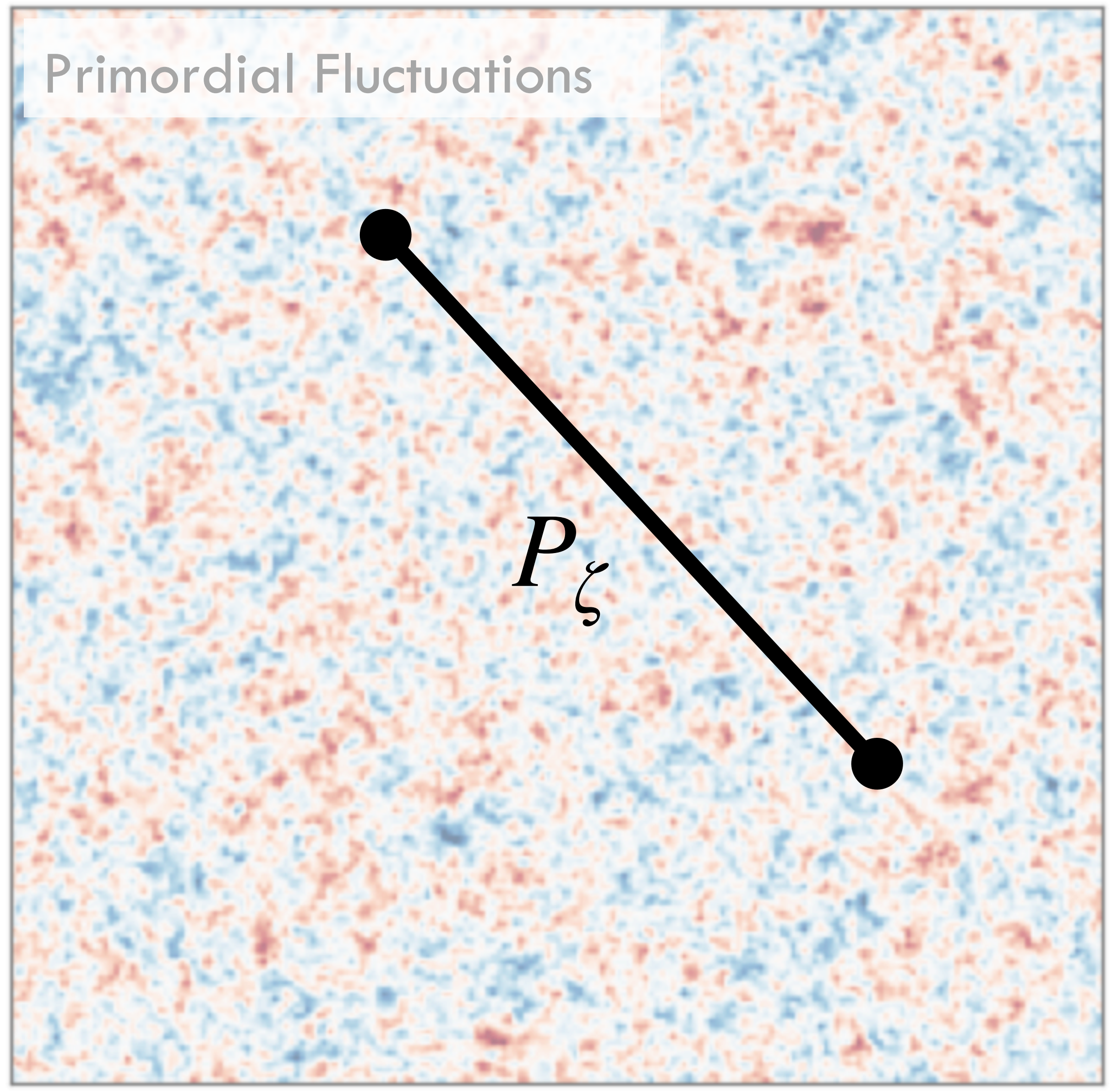
$$\mathscr{L} \sim \delta\dot{\phi}^2 - c_s^2(\partial\phi)^2$$



Flat-Space



de Sitter



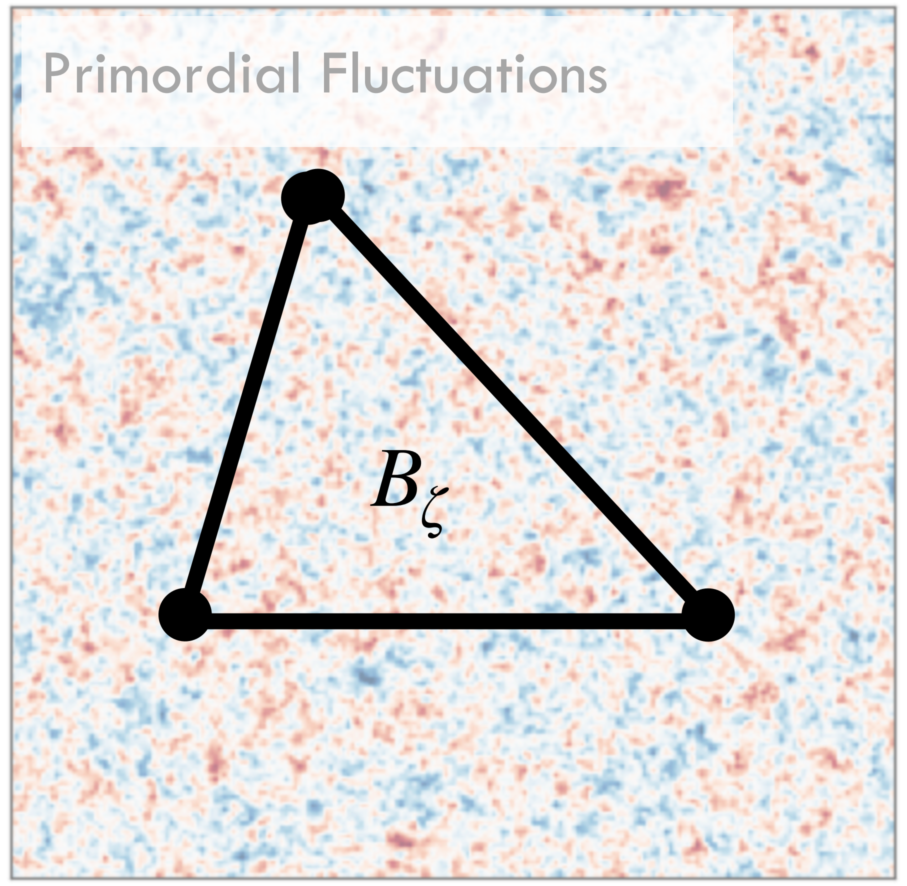
- Since $\delta\phi$ sources **curvature** ζ**,** we get a **two-point** function at the end of inflation:

$$P_\zeta(k) = \langle \zeta(\mathbf{k})\zeta(-\mathbf{k}) \rangle \sim k^{n_s - 4}$$

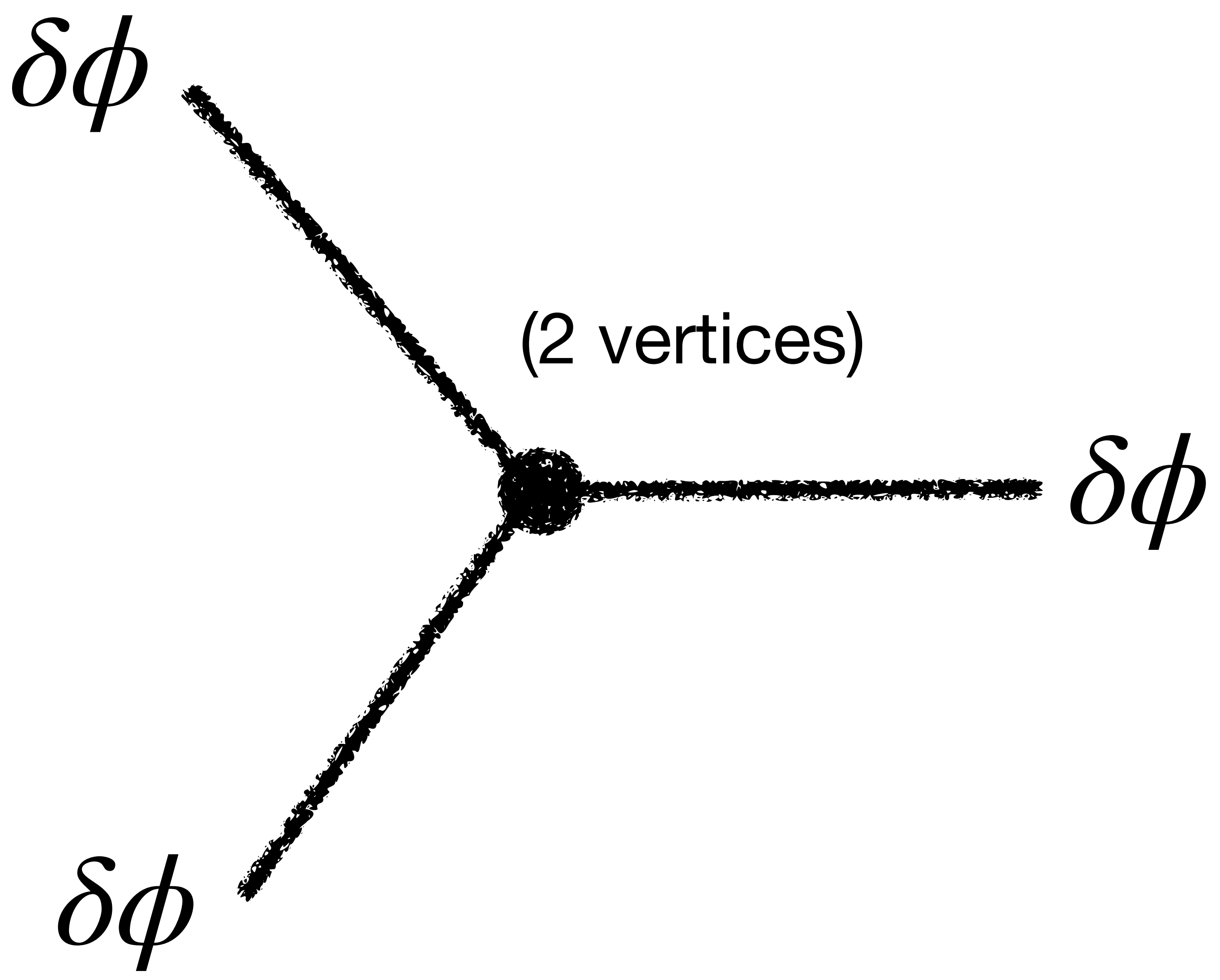
Maldacena, Arnold, Deser, Misner, …

Three-Point Functions (Contact)

- We could add **cubic** terms to the action



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



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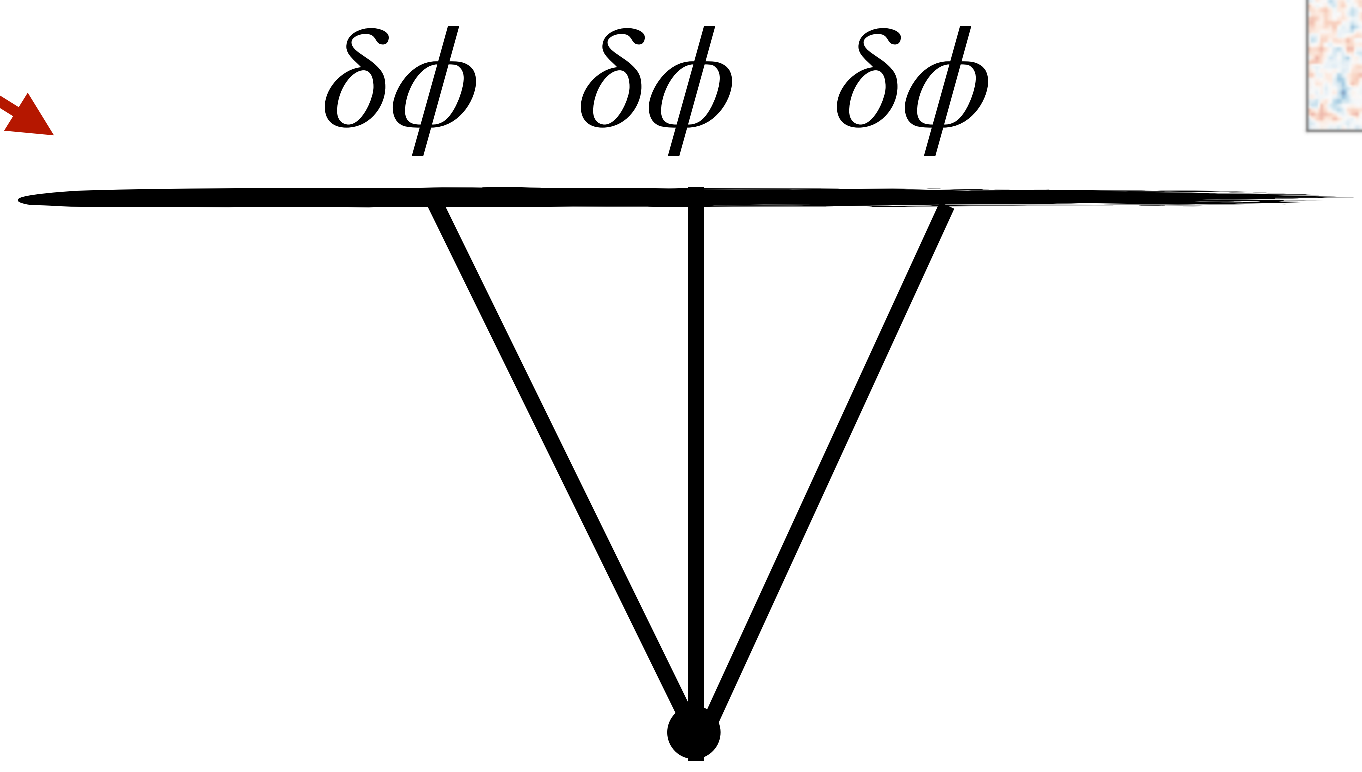


de Sitter

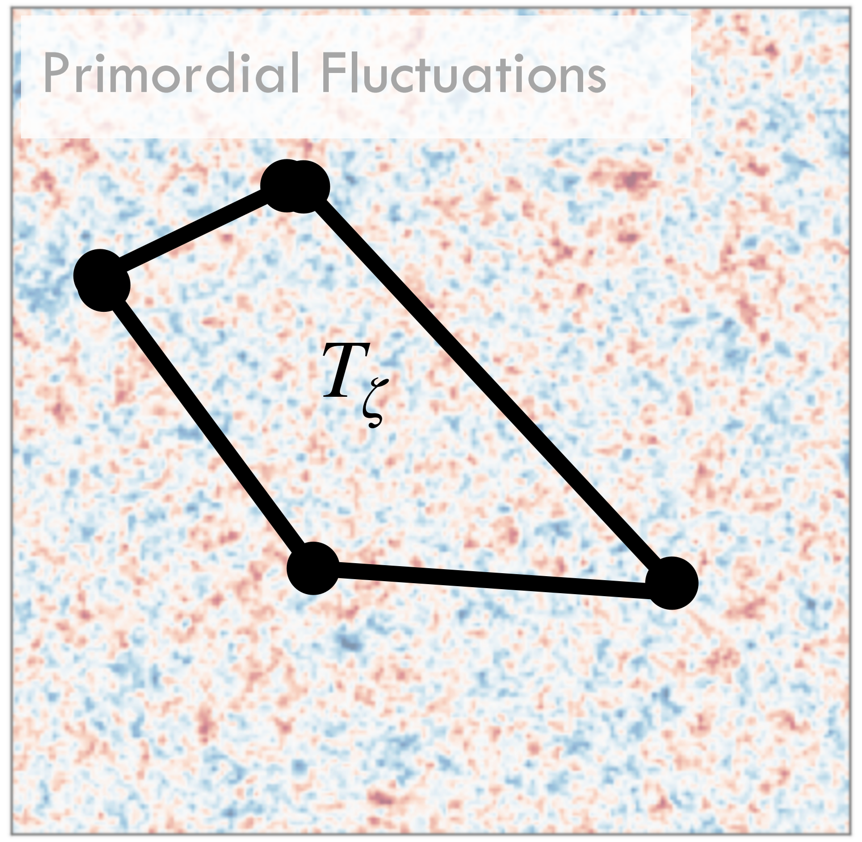
These lead to curvature **bispectra:** $\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\rm NL} \times$ shape

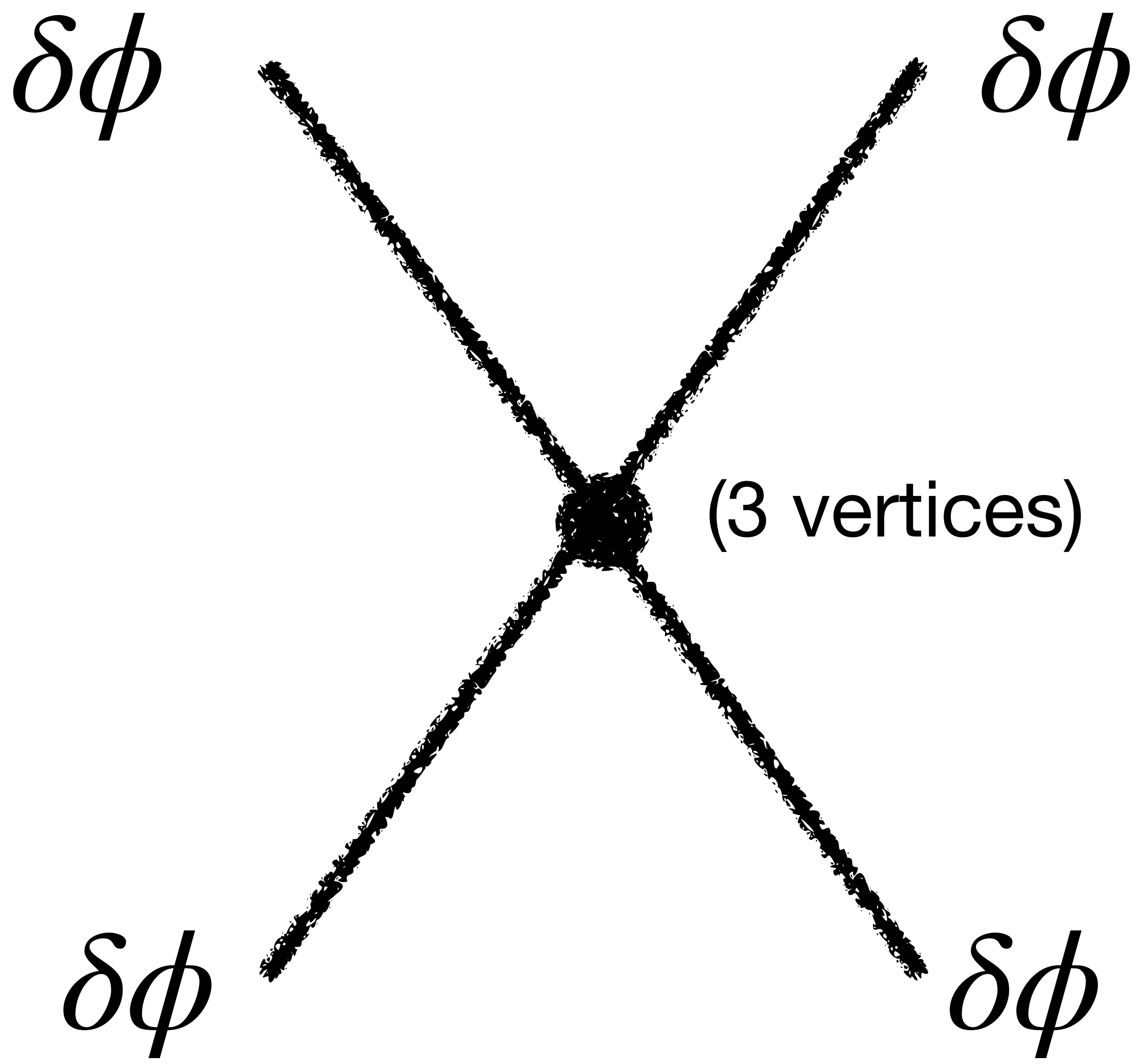
See the Effective Field Theory of Inflation (Senatore, Zaldarriaga, Creminelli, Baumann, …)

Four-Point Functions (Contact)

- We could also add **quartic** terms to the action

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





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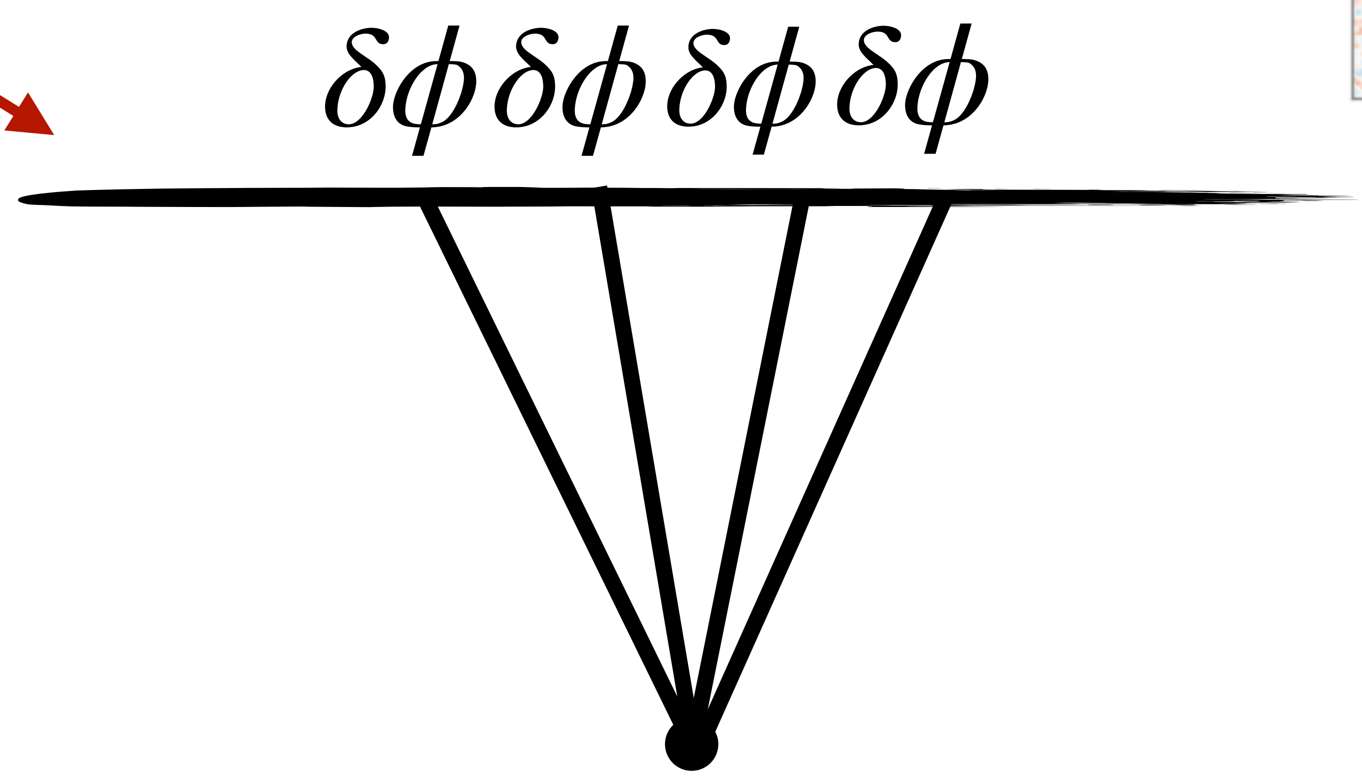


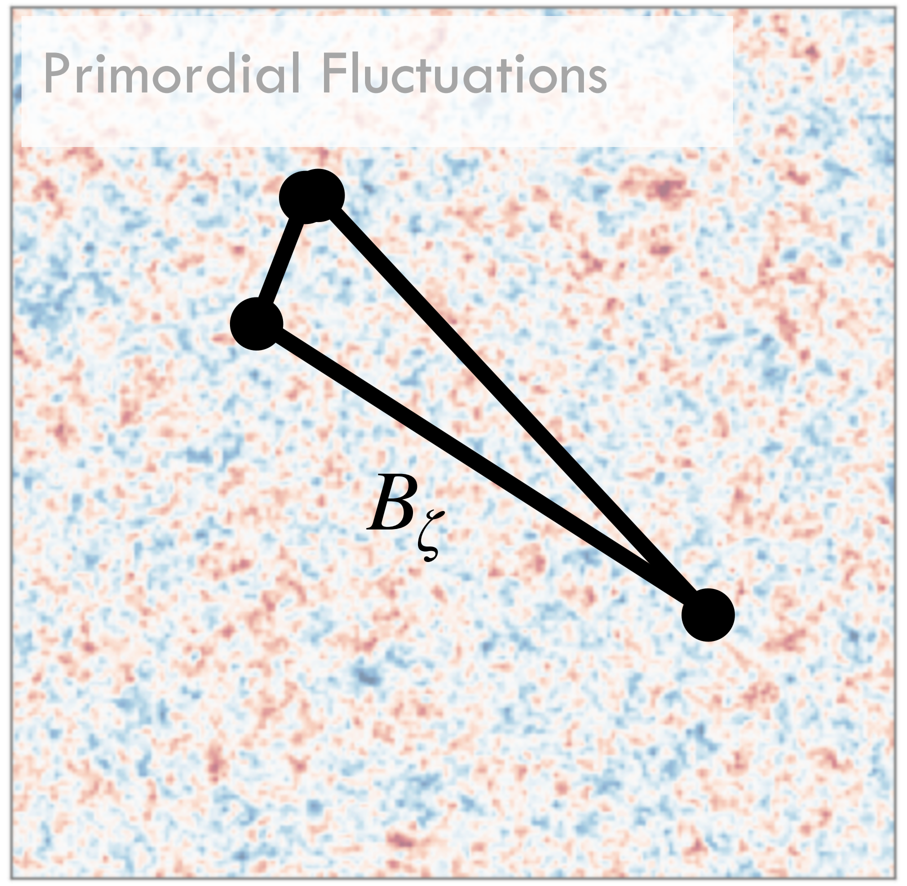
de Sitter

(**Note**: $\delta\dot{\phi}^2(\partial\phi)^2, (\partial\phi)^4$ are suppressed in single-field inflation)

These lead to curvature **trispectra** $\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle \sim g_{\rm NL} \times$ shape

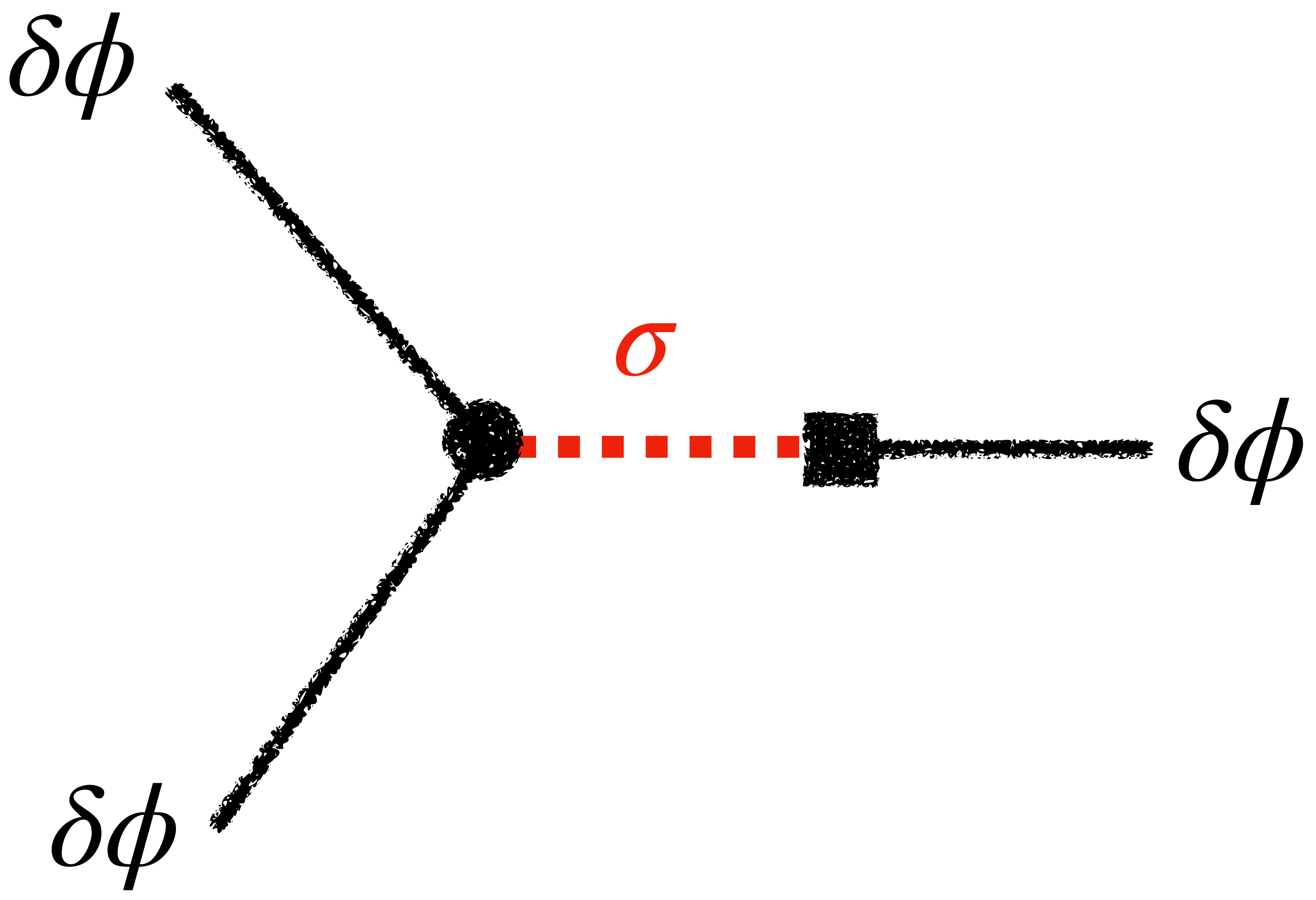
See the Effective Field Theory of Inflation (Senatore, Zaldarriaga, Creminelli, Baumann, ...)

Three-Point Functions (Exchange)



- We could also introduce an extra **light field** σ

$$\mathscr{L} \supset \delta\dot{\phi}\sigma, \delta\dot{\phi}^2\sigma, (\partial\phi)^2\sigma$$



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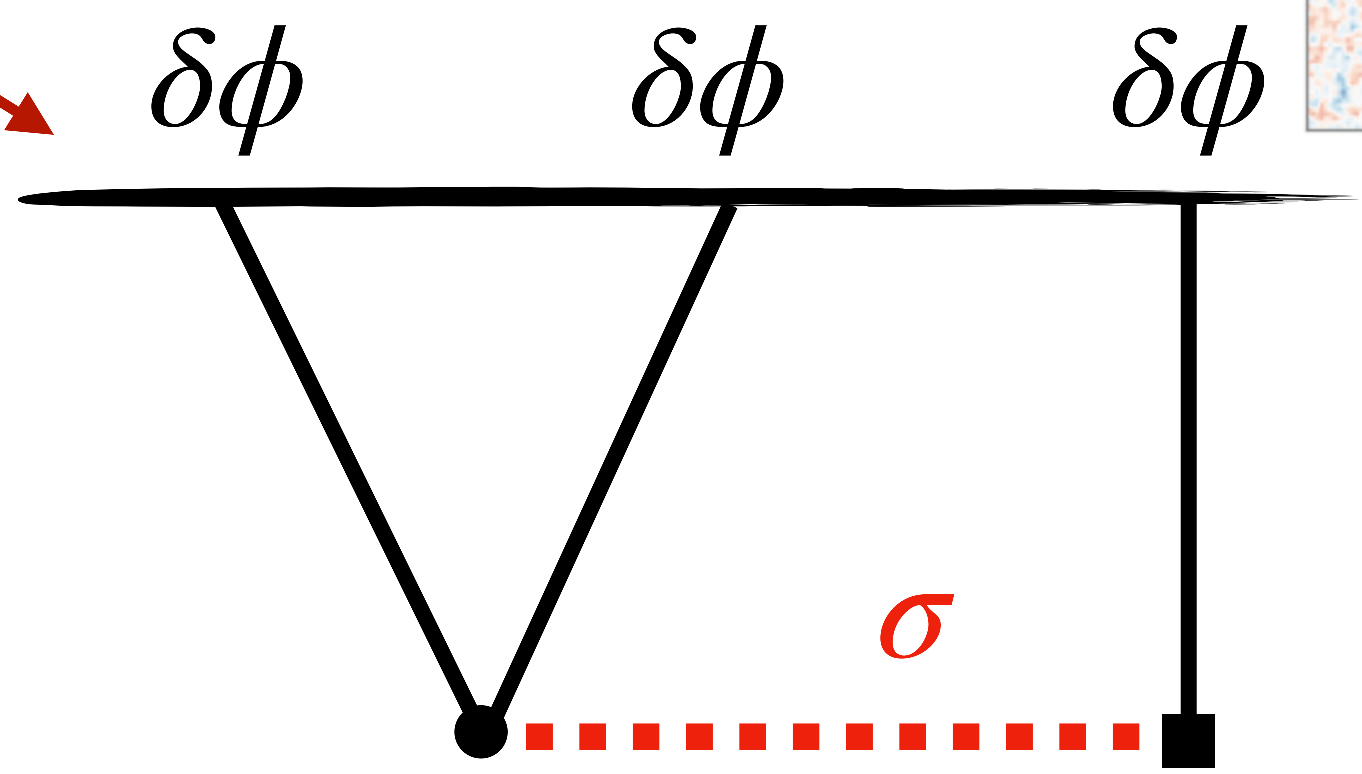
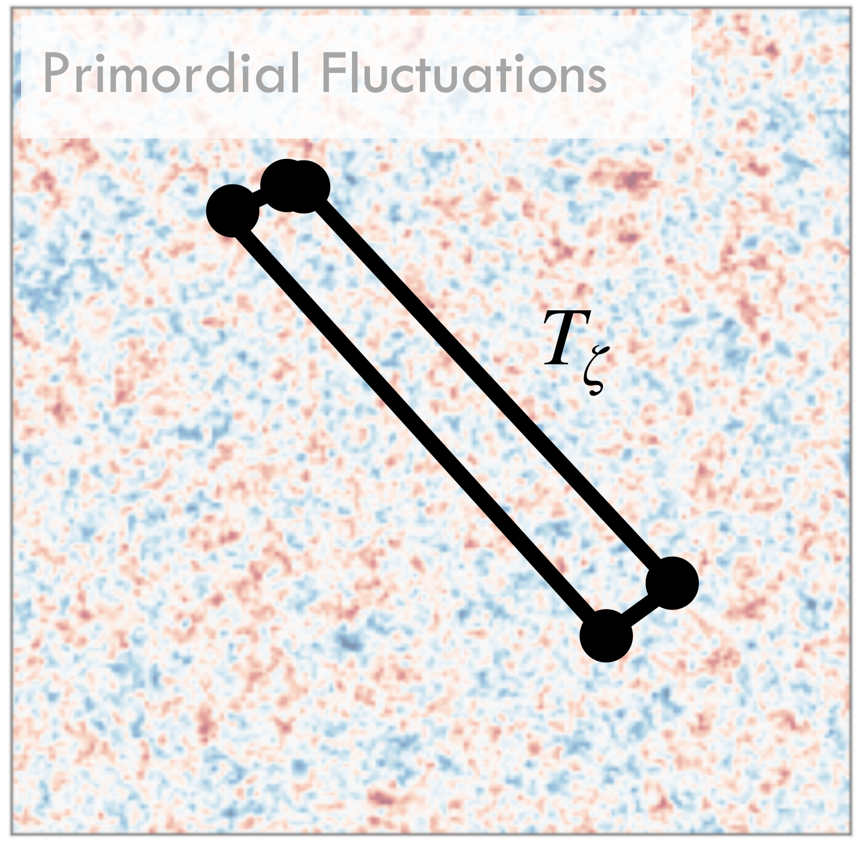


de Sitter

These lead to curvature **bispectra** $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\mathrm{NL}}^{\mathrm{local}} \times$ shape

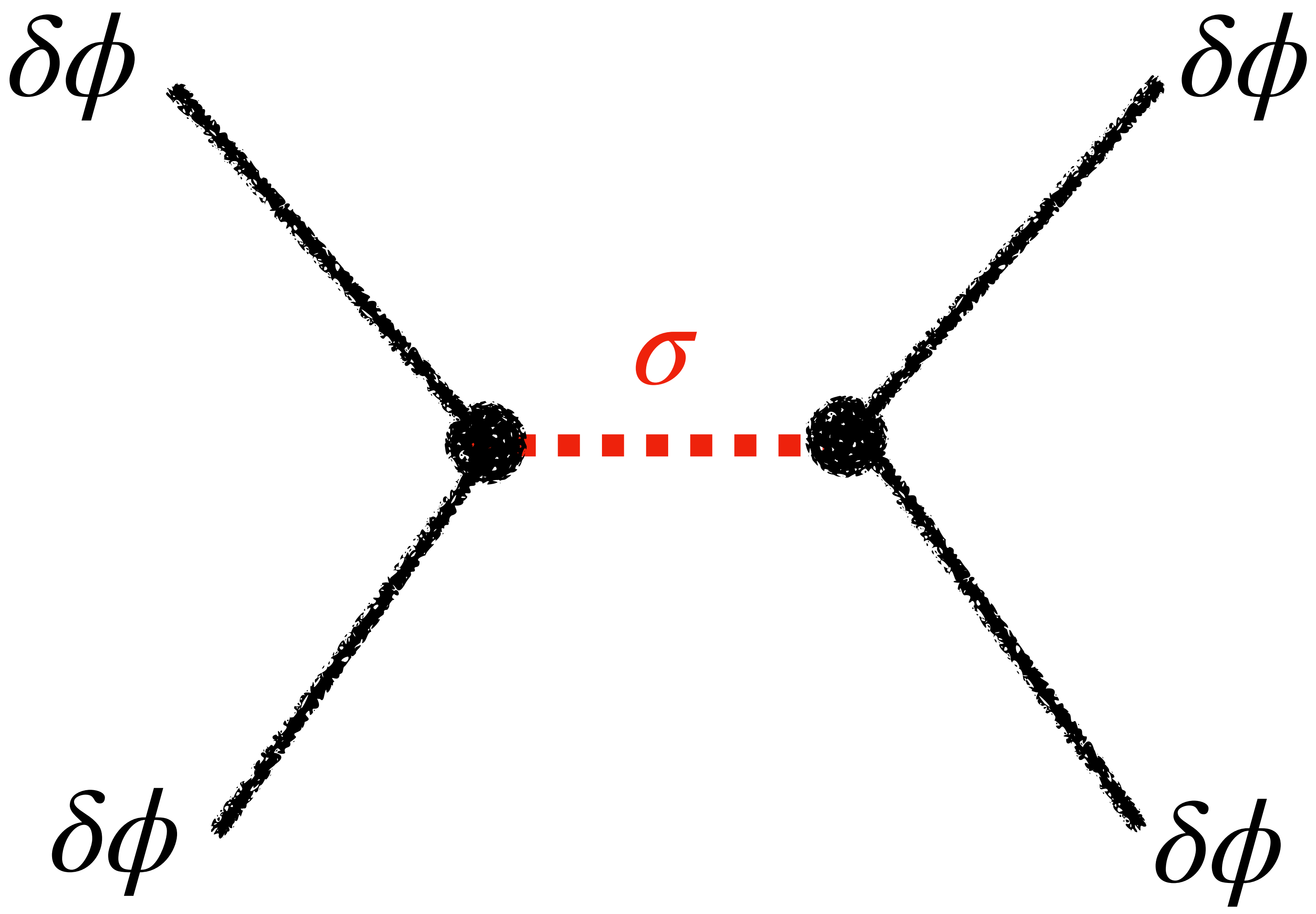
See the Effective Field Theory of Inflation (Senatore, Zaldarriaga, Creminelli, Baumann, …)

Four-Point Functions (Exchange)



- We can also get **quartic** terms from σ

$$\mathscr{L} \supset \delta\dot{\phi}^2\sigma, (\partial\phi)^2\sigma$$



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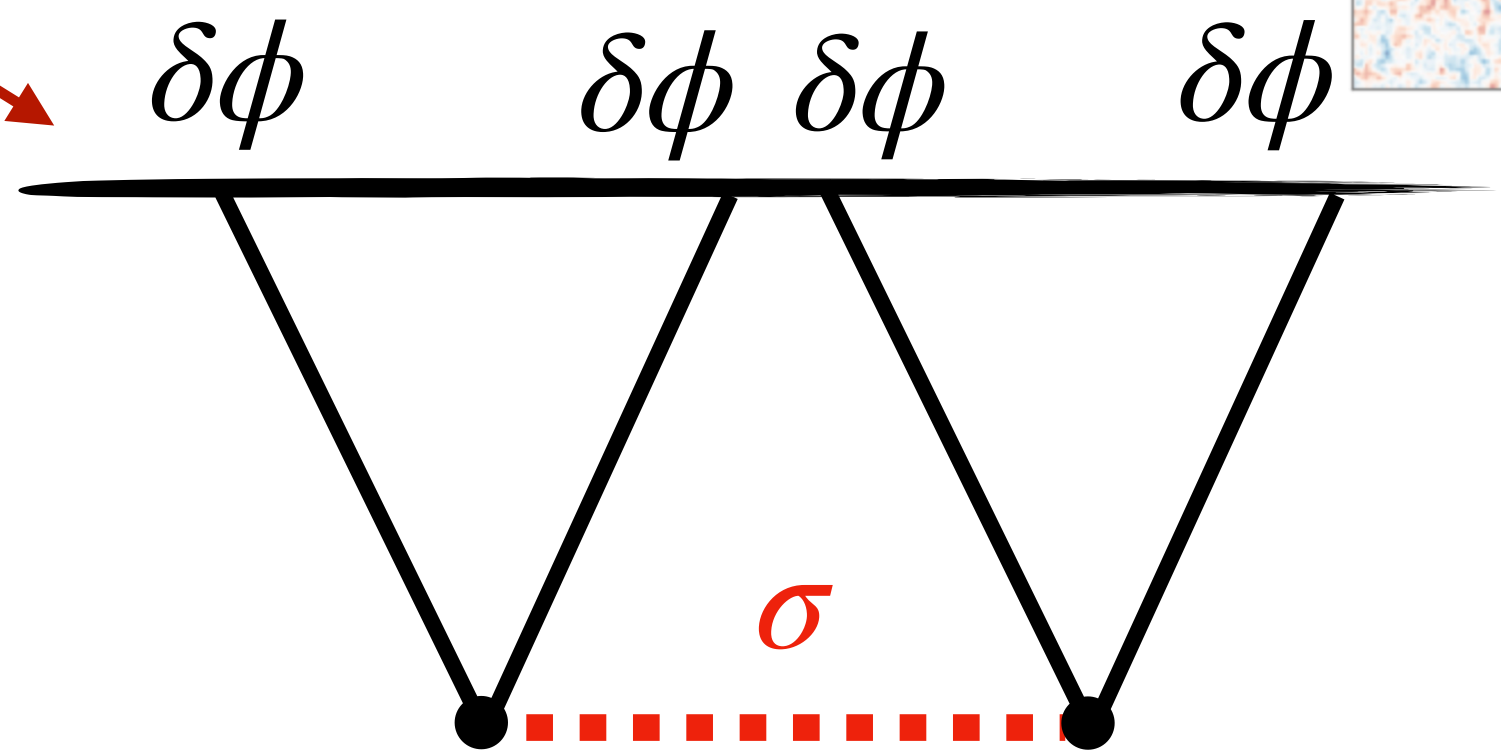


de Sitter

These lead to curvature **trispectra** $\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle \sim \tau_{\rm NL}^{\rm local} \times$ 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 $s = 0,1,2,\cdots$

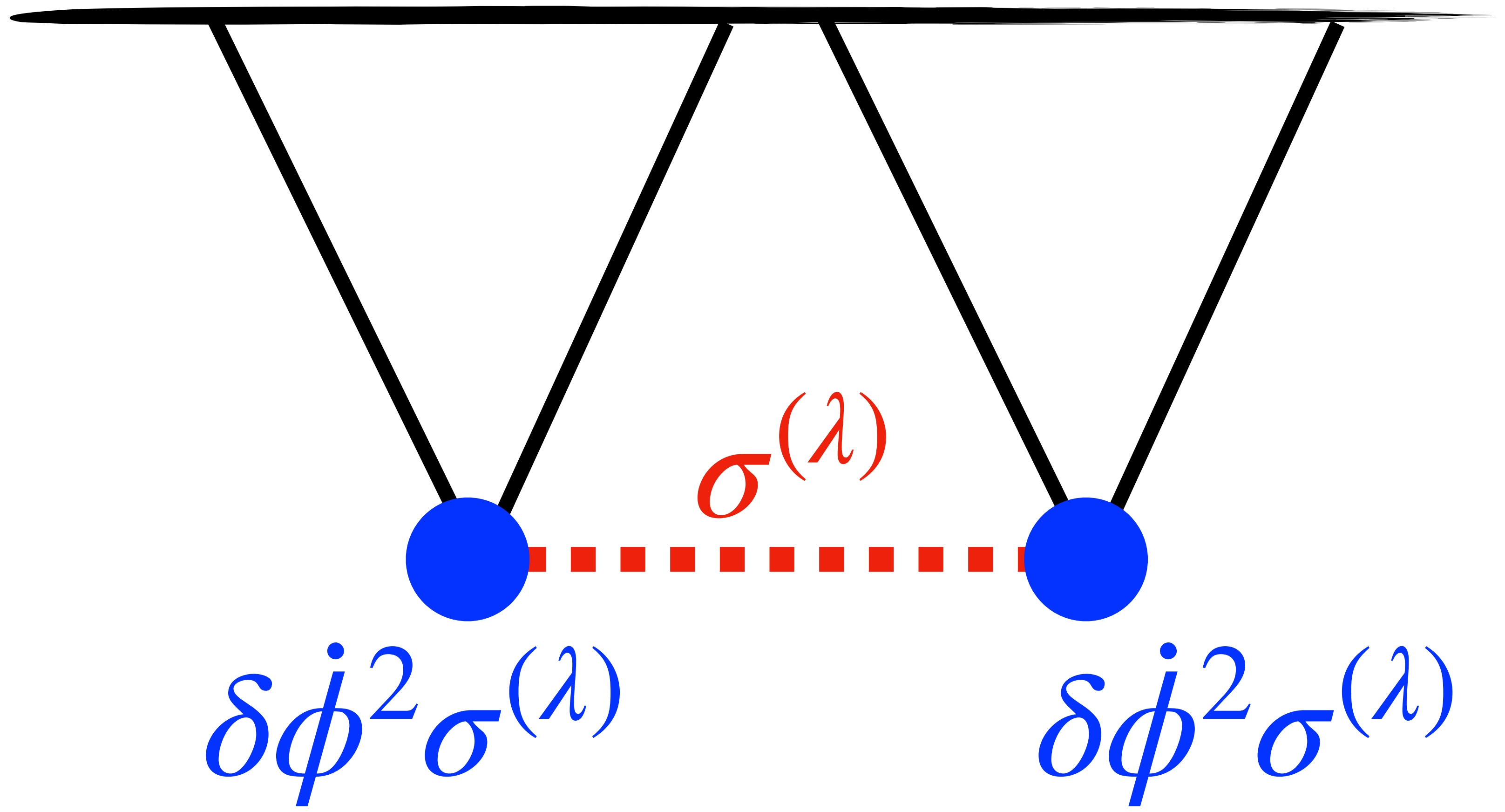
- This depends on the **power spectrum** of σ, including all its **helicity states, $\sigma^{(\lambda)}$**

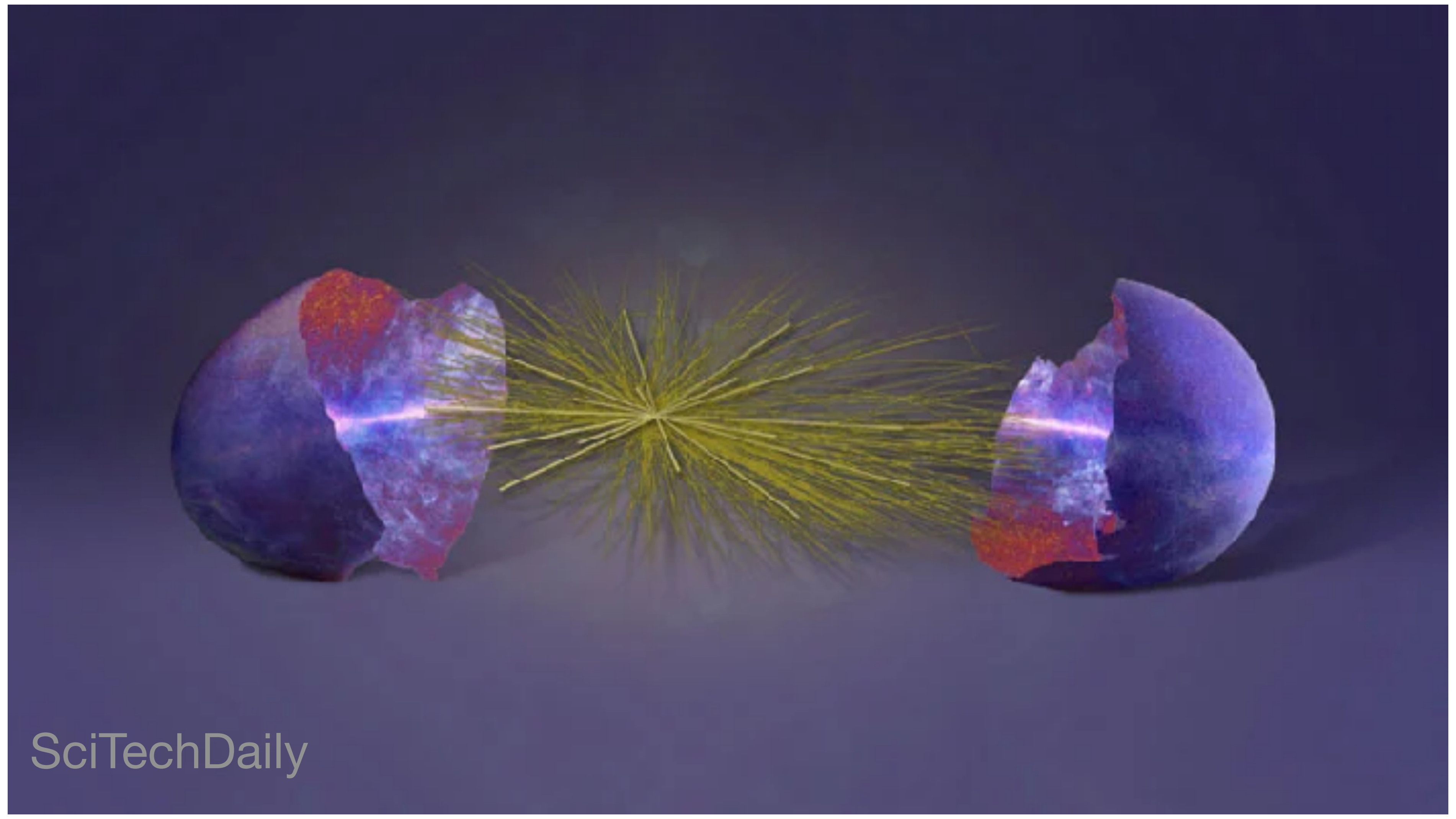
$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle \sim \sum_\lambda P_\zeta(k_1)P_\zeta(k_3)P_{\sigma^{(\lambda)}}(K) \times \text{coupling}$$

- 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!

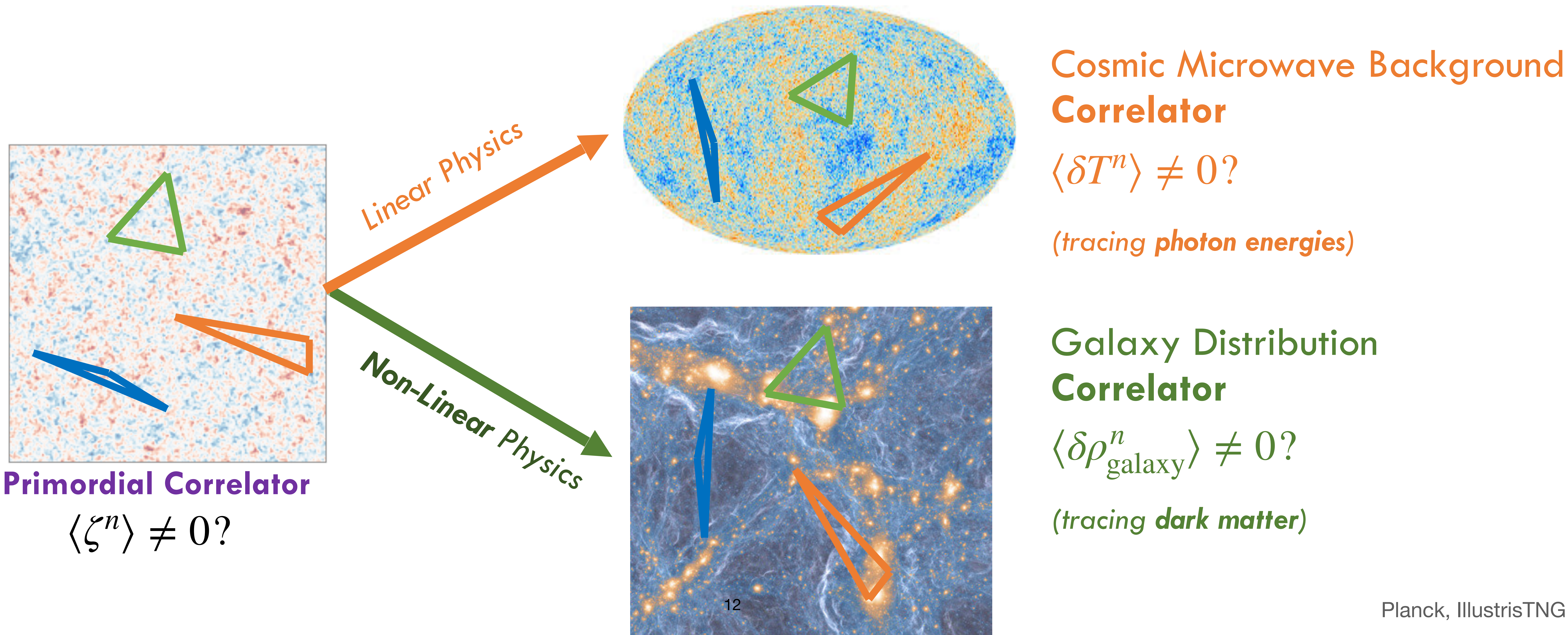




Maldacena, Arkani-Hamed, Jazayeri, Pajer, Zaldarriaga, Lee, Moradinezhad, Cabass, Baumann, …

How to Measure Primordial Non-Gaussianity

- The **curvature perturbation** ζ sets the **initial conditions** for the late Universe!



Planck, IllustrisTNG

Observational Constraints

- Previous CMB experiments have placed **strong** constraints on **three-point** functions across **many** scenarios (self-interactions, light fields, colliders, …)
- So far, there have been **no detections**: $10^{-5}\,|f_{\rm NL}| \ll 1$

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

Yes!

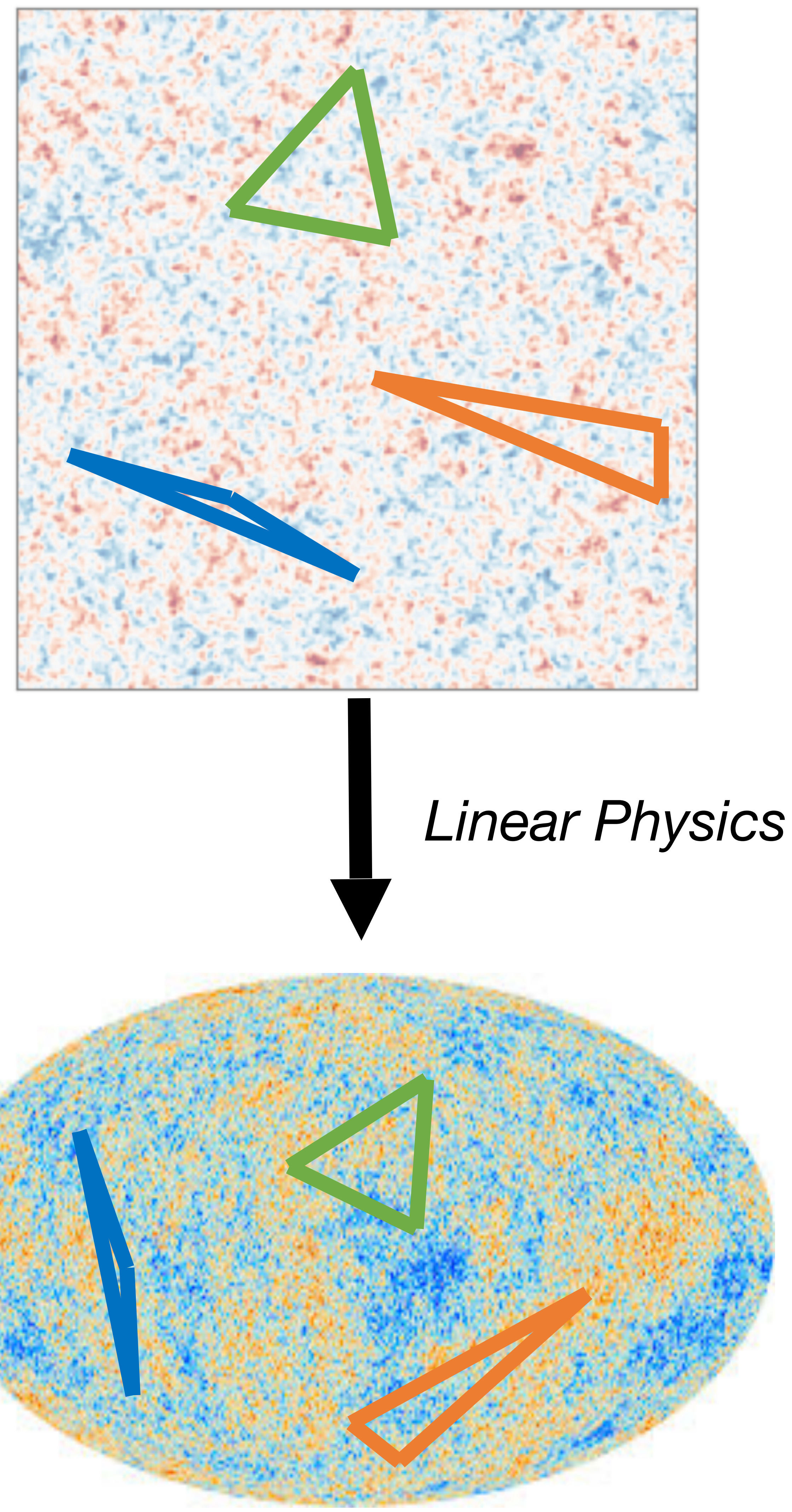
- Cubic-terms in the Lagrangian could be **protected** by symmetry

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

(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**



[13] Planck 2018, Smith+, Senatore+, Maldacena, Creminelli, Fergusson+, Shellard+, Sohn+

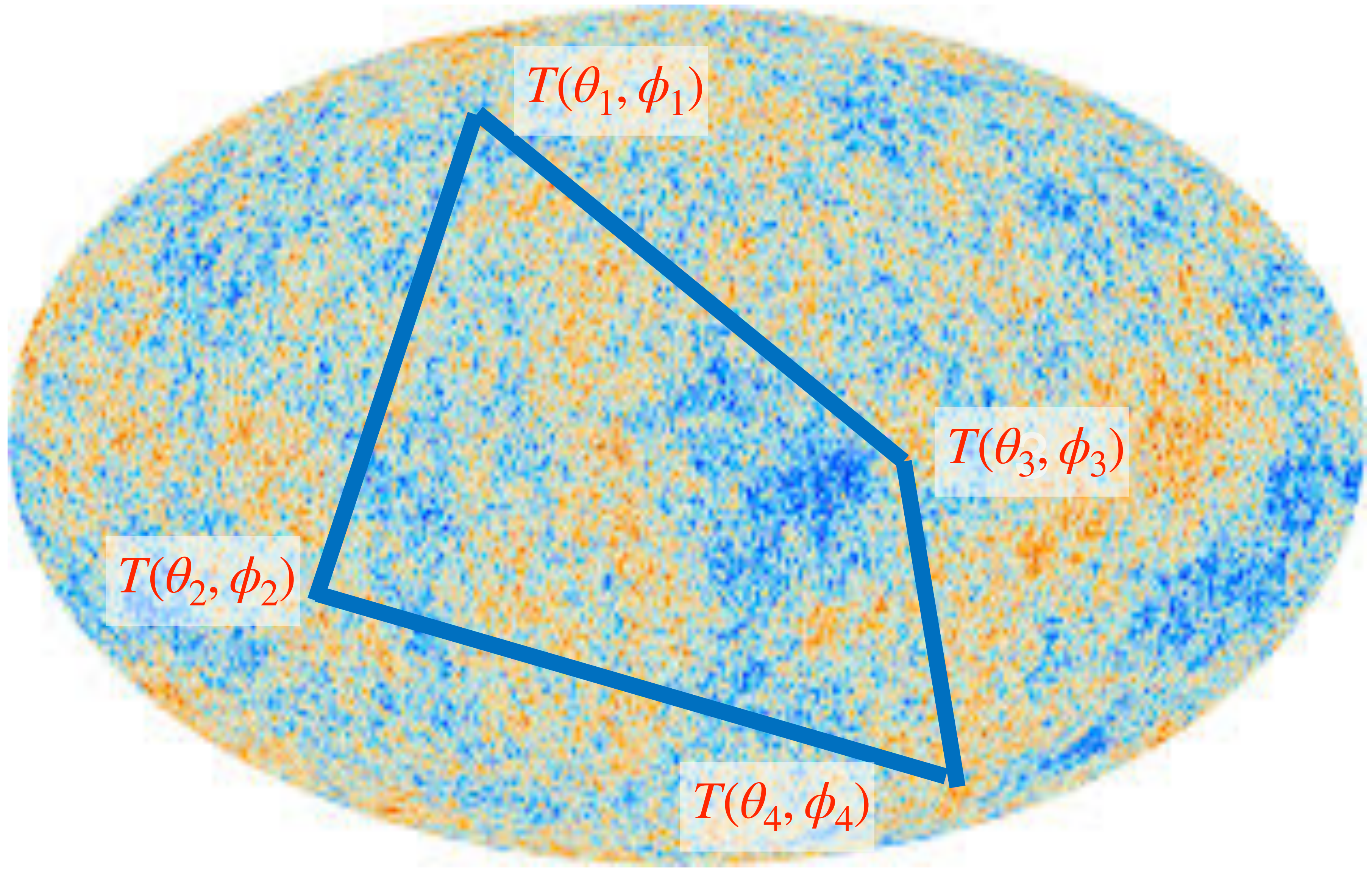
How to Measure a Four-Point Function

- 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?!

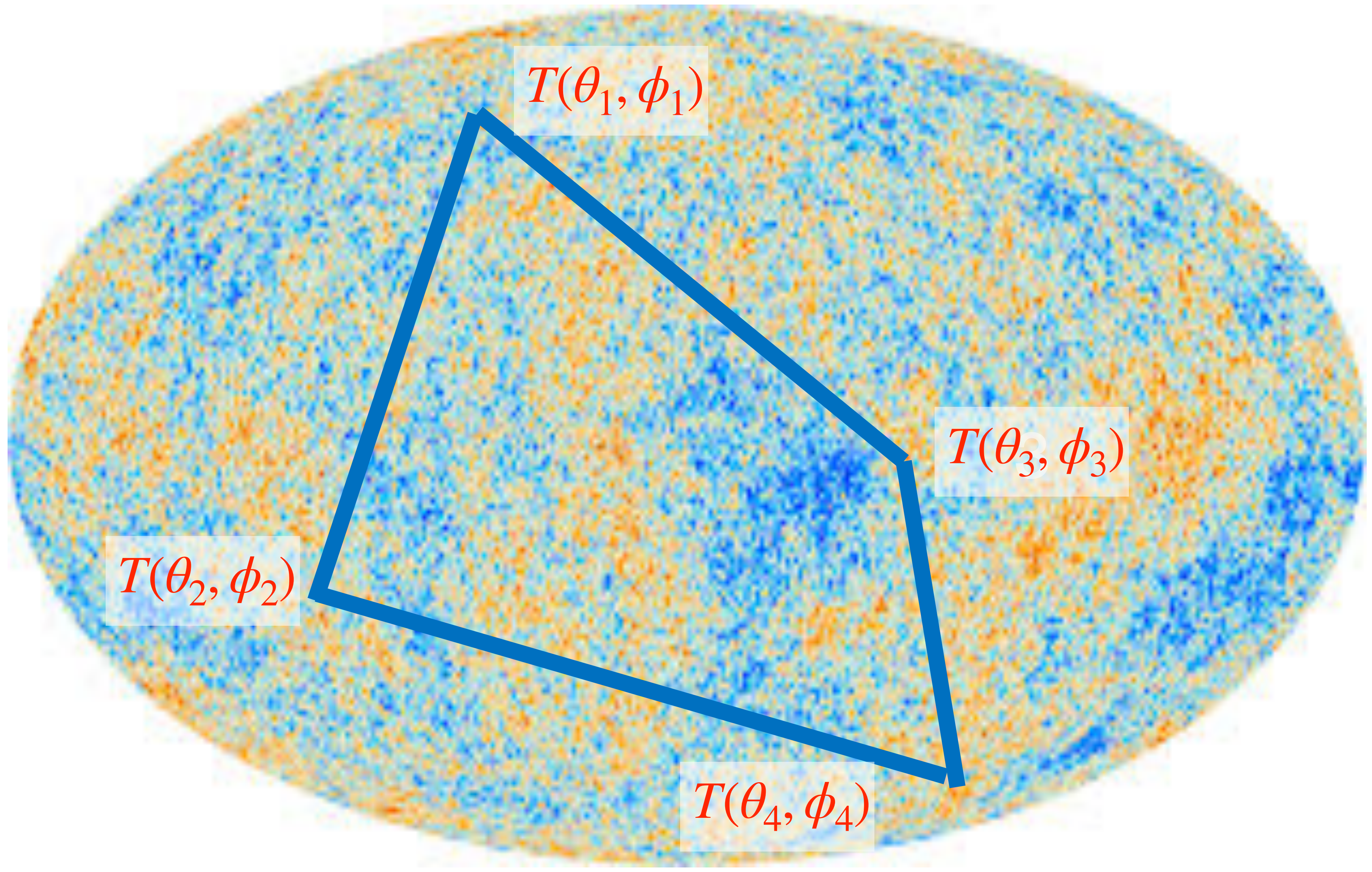
Planck 2018

Optimal Trispectrum Analyses

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

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

Model Data



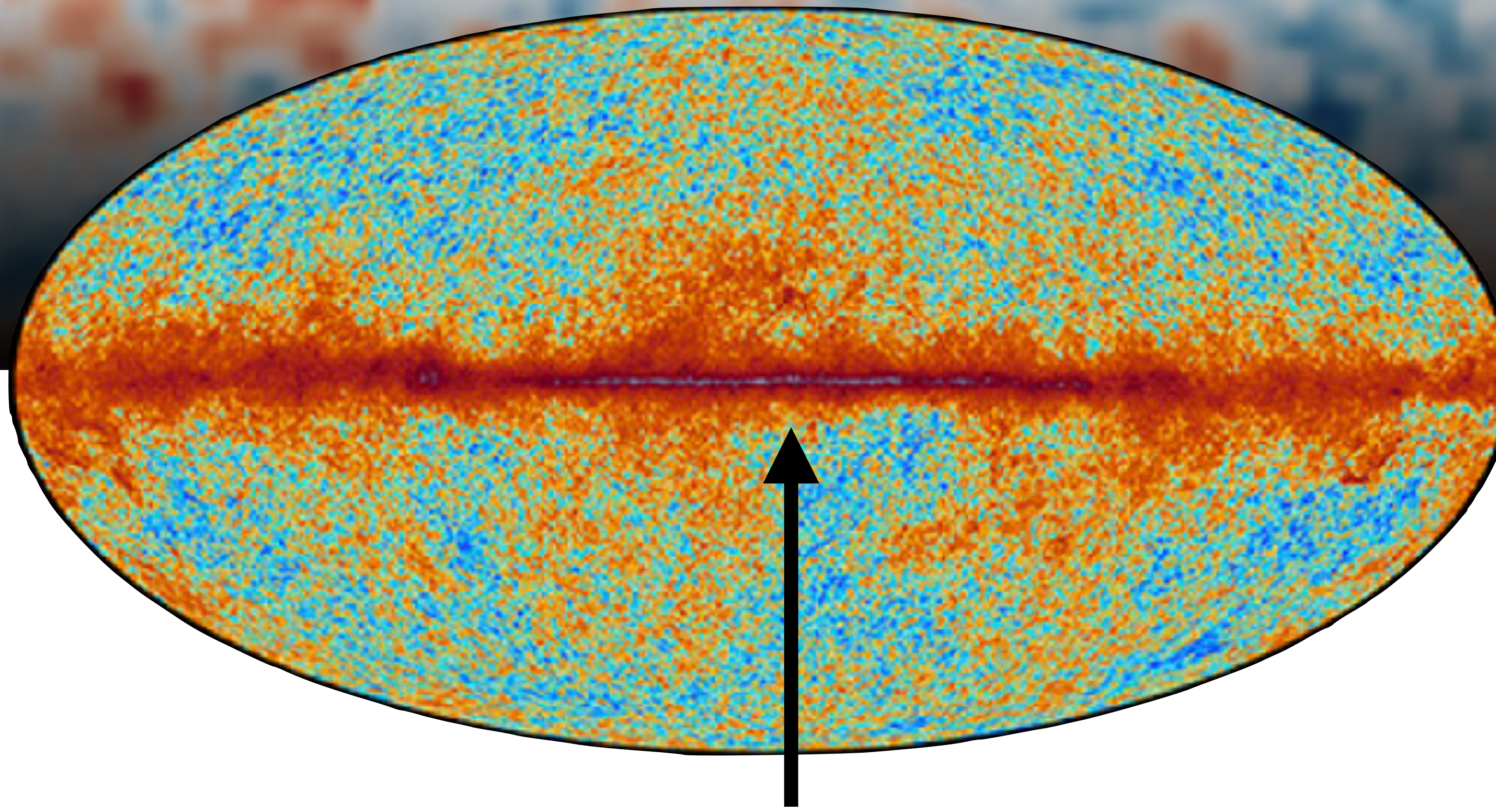
- We compress all 10^{28} elements into a **single** number!

- This encodes the **amplitude** of a specific model, e.g., τ_{NL}, which traces the **microphysics** of inflation

- This depends on a **theory model** which can be easily computed from the primordial prediction, $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4) \rangle$

Sekiguchi+13, Smith+15, **Philcox** 25a

Optimal Trispectrum Analyses



Need to remove Galactic dust

In practice, we have to be a bit careful:

1. This estimator is **biased** even in a perfectly Gaussian universe!
    - We need to **subtract off** the Gaussian contribution!

$$\widehat{A} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3 \ell_4 m_4} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle^{\dagger}_{\rm theory} \times \left[a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} - \langle a_{\ell_1 m_1} a_{\ell_2 m_2} \rangle \langle a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle + \cdots \right]$$

2. We need to add a **normalization** to make sure we get out the right value!

$$\text{normalization} \sim \sum_{\ell_i m_i} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle^{\dagger}_{\rm theory} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle_{\rm theory}$$

(More complex with beams & masks)

3. We need to carefully **weight** the data and remove the **galaxy**

$$a_{\ell m} \to \text{weight}(a)_{\ell m}$$

Sekiguchi+13, Smith+15, **Philcox** 25a

Optimal Trispectrum Analyses

We **still** have a problem!!

- These estimators require summing over $\mathcal{O}(\ell_{\max}^8)$ components (with $\ell_{\max} \sim 2000$)

$$\widehat{A} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3 \ell_4 m_4} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle^{\dagger}_{\text{theory}} \times \left[a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} + \cdots \right]$$

- If the underlying trispectrum can be **separated:**

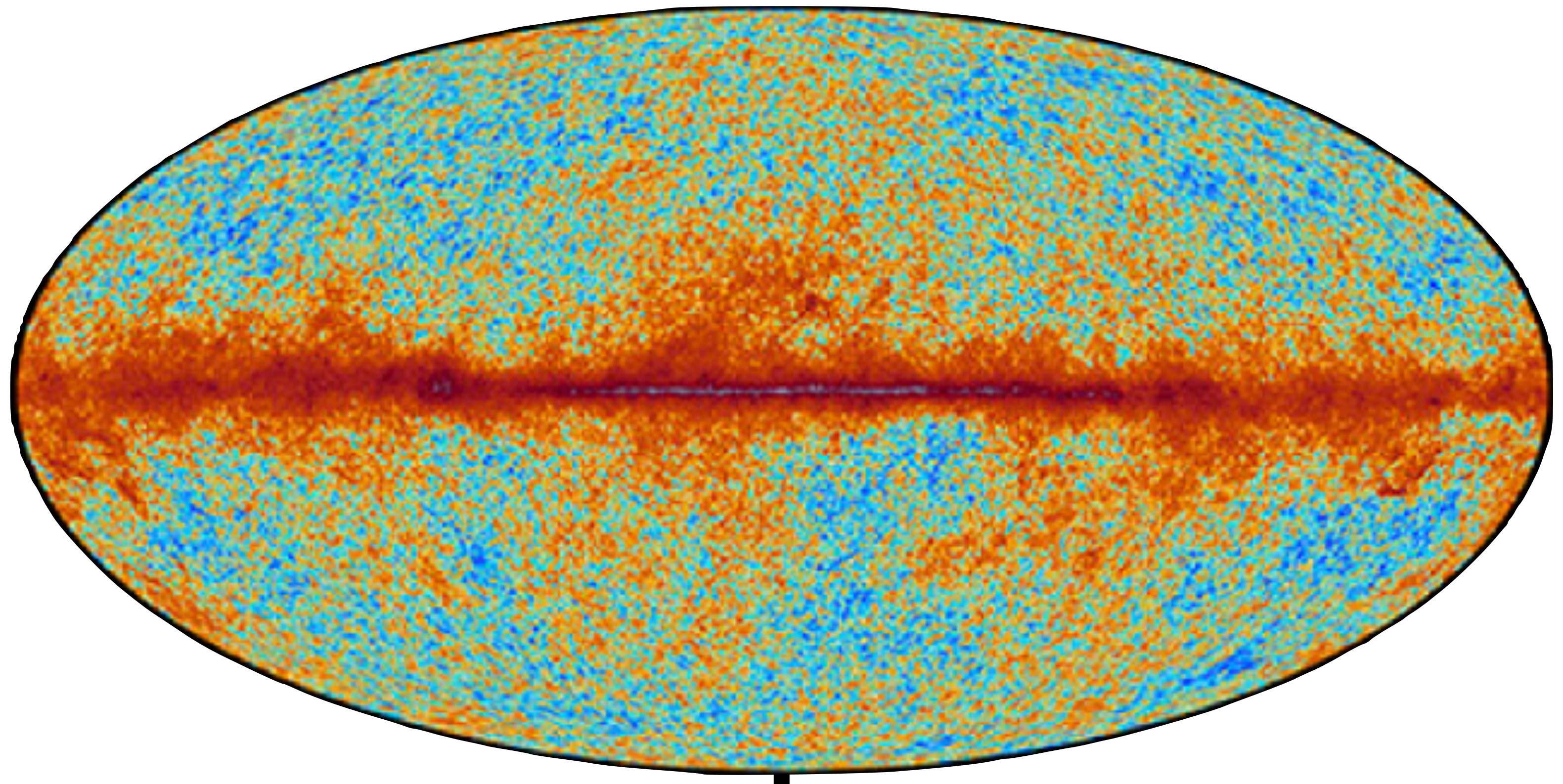
$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4) \rangle \to \sum f(k_1) f(k_2) f(k_3) f(k_4) F(s),$$

(Possibly including ∫ or ∫∫)

we can **rewrite** the estimator in terms of **low-dimensional integrals**, *harmonic transforms*, and **Monte Carlo summation:**

$$\widehat{A} \sim \sum_{i=1}^{N_{\text{pixels}}} \int dr \left(\sum_{\ell m} a_{\ell m} f_{\ell}(r, i) \right)^4$$

- This reduces the computational costs to just $\mathcal{O}(\ell_{\max}^2 \log \ell_{\max})$!



inflation parameters

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

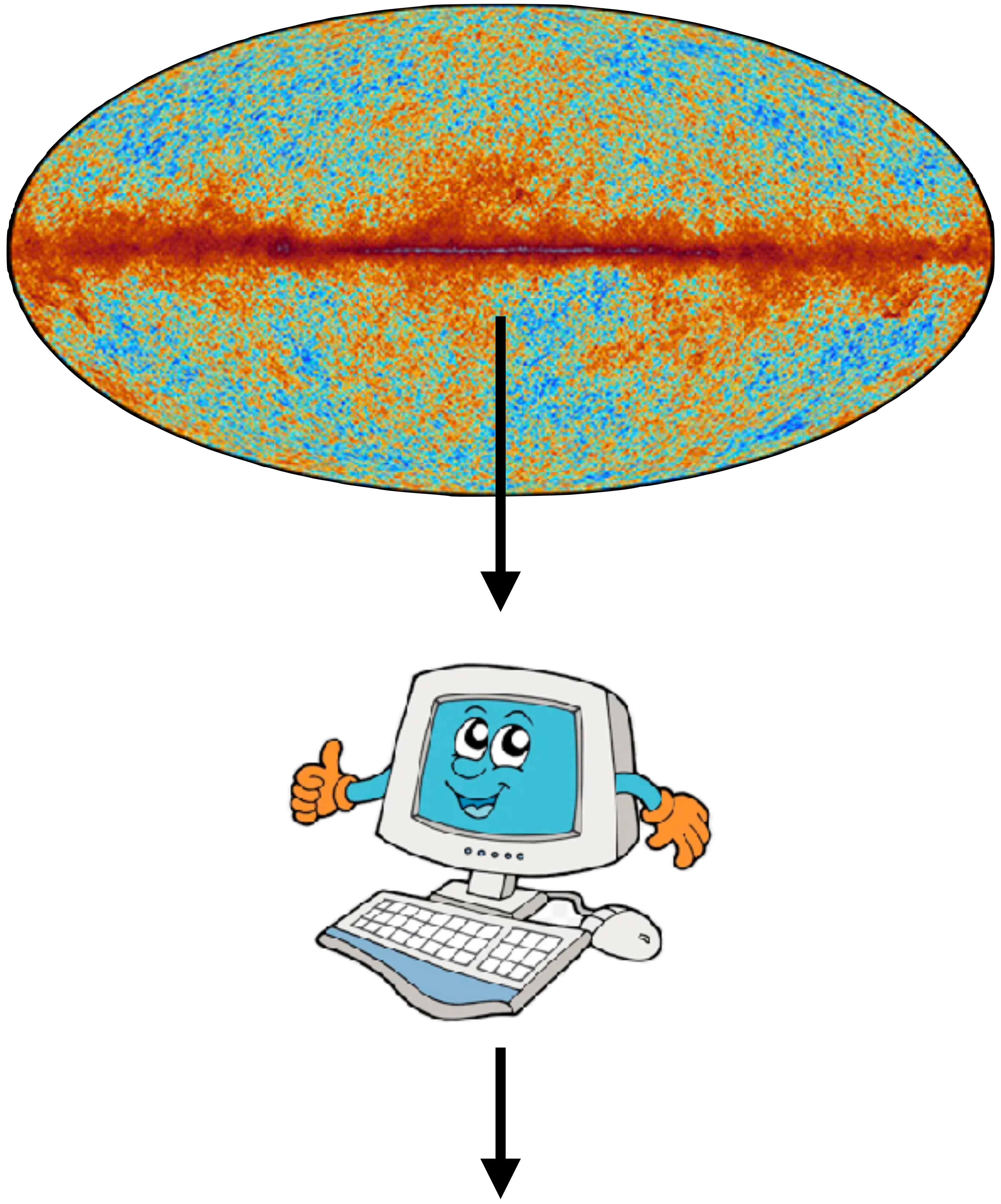
Optimal Trispectrum Analyses

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 model included so far)

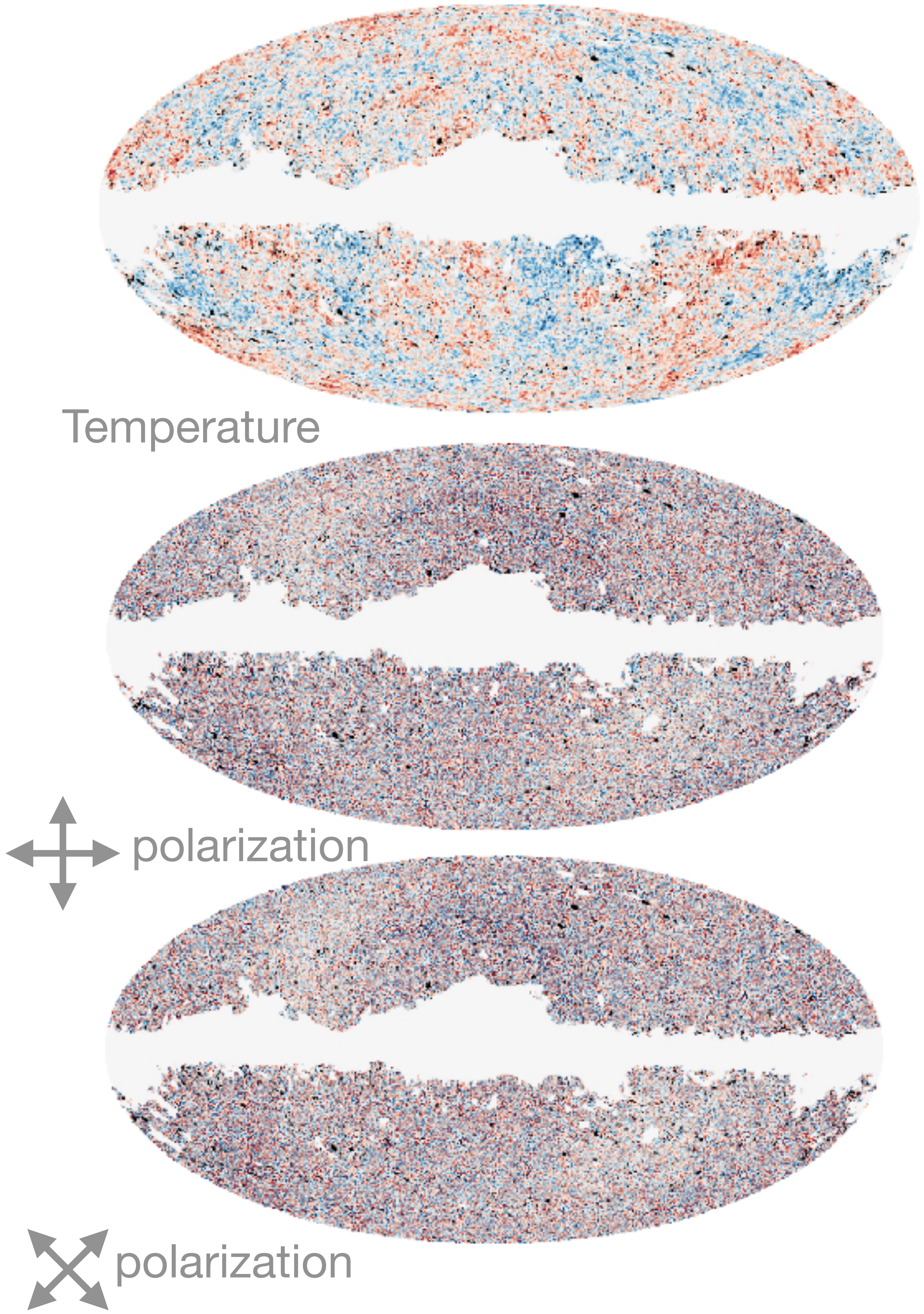
Public at **https://github.com/oliverphilcox/PolySpec**



inflation parameters

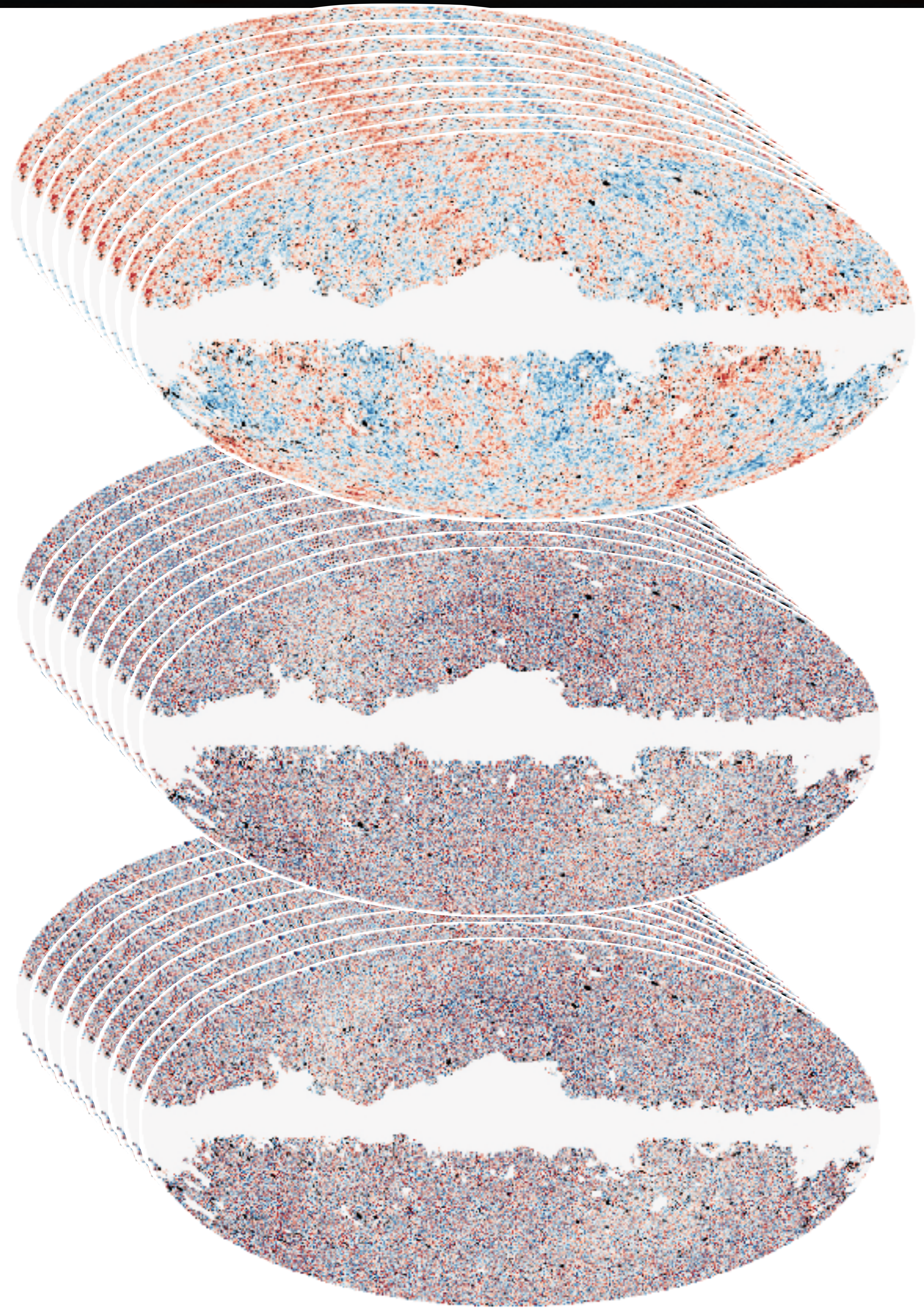
Philcox 25ab

The *Planck* Trispectrum



Planck PR4/NPIPE data

+



100 FFP10 simulations

+ Optimal Weighting

+ Beam & Mask

+ Transfer Functions

(+ many systematics tests)

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

Results: Local Non-Gaussianity

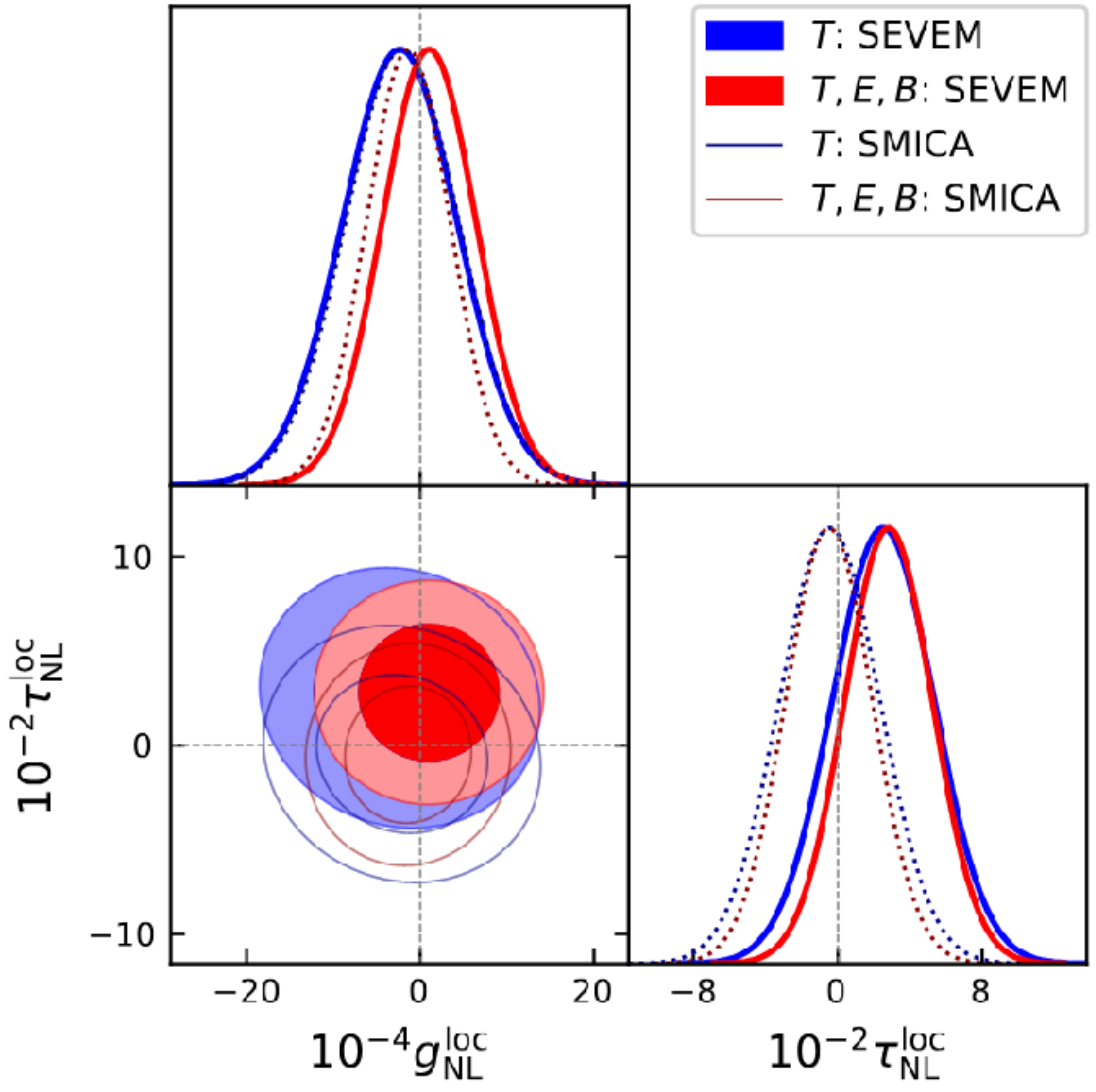
Model: non-linear effects + light particles ($m_\sigma \to 0$)

- Constrains inflationary effects such as:
  - **Curvatons** (perturbations sourced by a second light field)
  - **Bouncing / ekpyrotic** universes
  - New particles **uncorrelated** with the inflaton

Outcome: Consistent with zero!

- $(30-40\%)$ better than any previous constraints

T+Pol > T-only



Cubic Quadratic^2

Planck 2013, Marzouk+22, **Philcox** 25c

Results: Local Non-Gaussianity

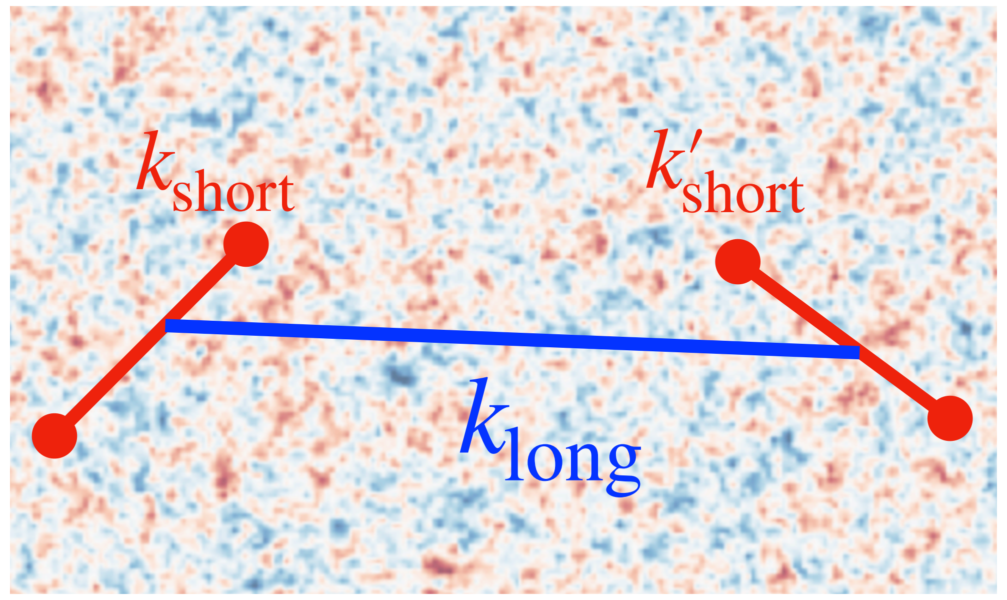
Model: non-linear effects + light particles ($m_\sigma \to 0$)

$$\langle \zeta^4 \rangle \sim P_\zeta(k_{\rm short})P(k'_{\rm short})P_\zeta(k_{\rm long})$$

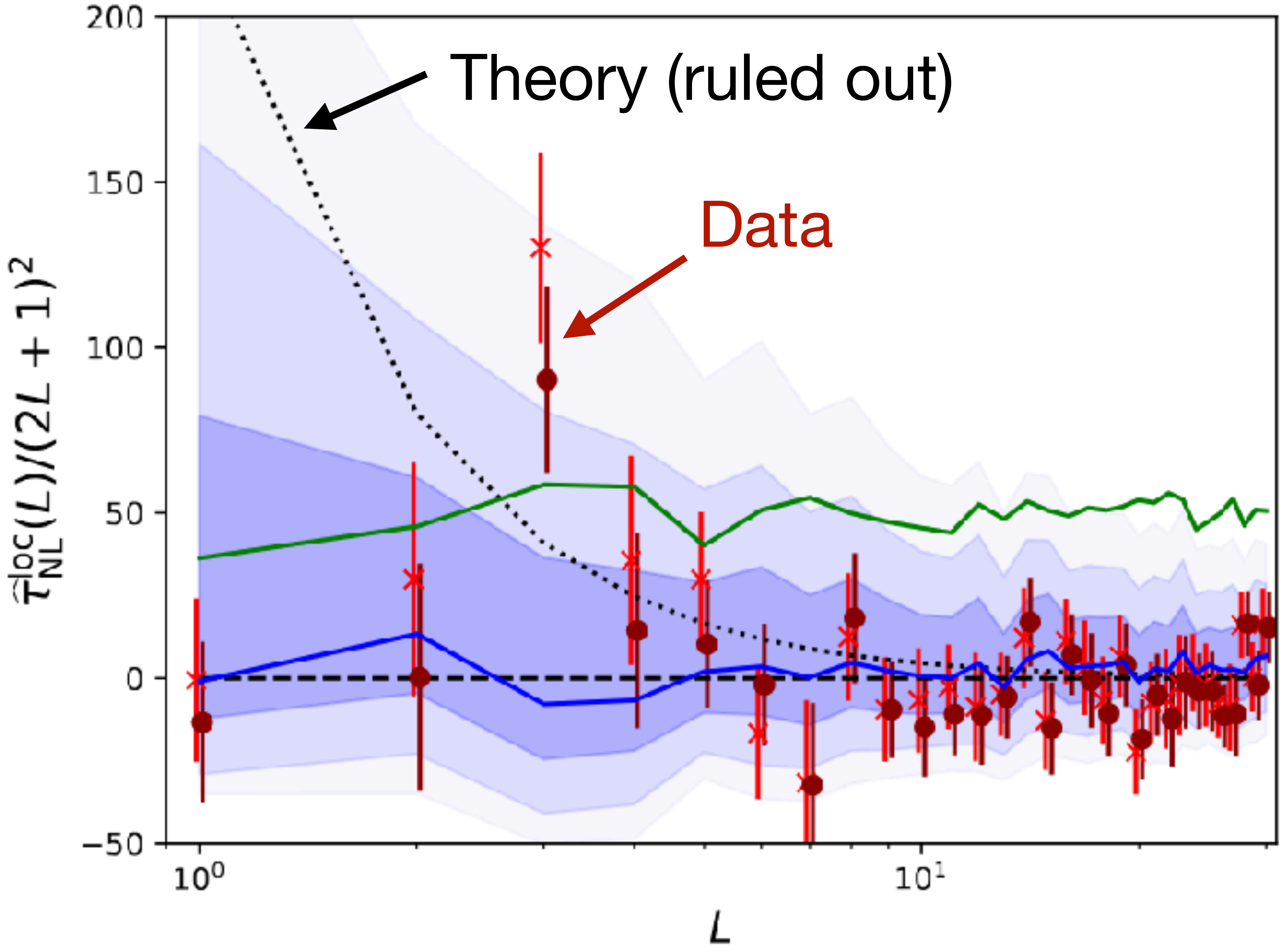
- Constrains inflationary effects such as:
  - **Curvatons** (perturbations sourced by a second light field)
  - **Bouncing / ekpyrotic** universes
  - New particles **uncorrelated** with the inflaton

Outcome: Consistent with zero!

- $(30 - 40\%)$ better than any previous constraints



"Power spectrum of the power spectrum"



Planck 2013, Marzouk+22, **Philcox** 25c

Results: Equilateral Non-Gaussianity

Model: *self-interactions* in inflation

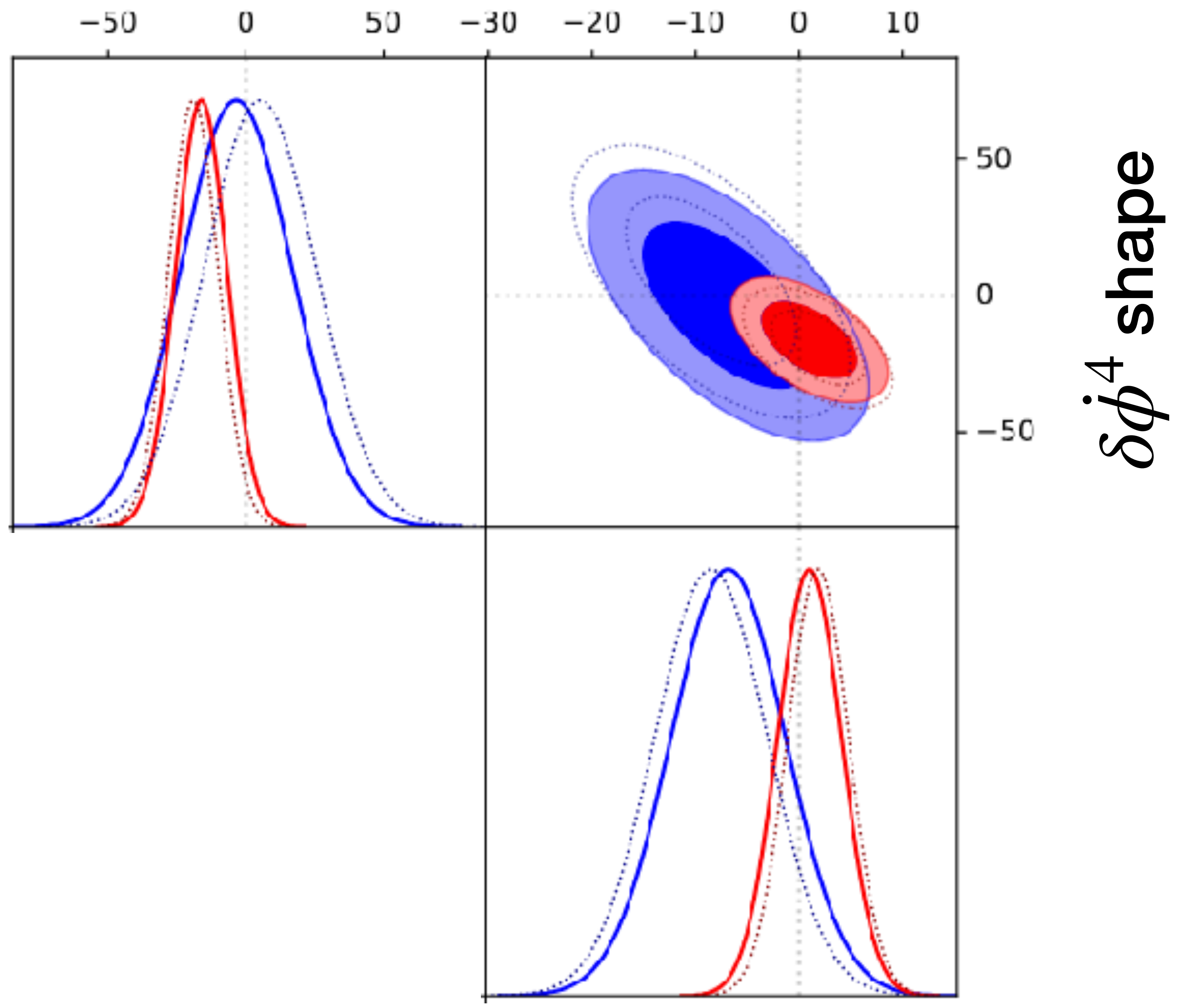
- Constrains models such as:
  - **Effective Field Theory** couplings
  - **DBI** inflation (*string theory* + *small sound-speed*)
  - **Generic** single-field inflation (including *Lorentz Invariant* models)
  - **Ghost** inflation**, k**-inflation, and beyond…

Outcome: Consistent with zero!

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

T+Pol $\gg$ T-only

$\delta\dot{\phi}^4$ shape $\quad (\partial\phi)^4$ shape



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]

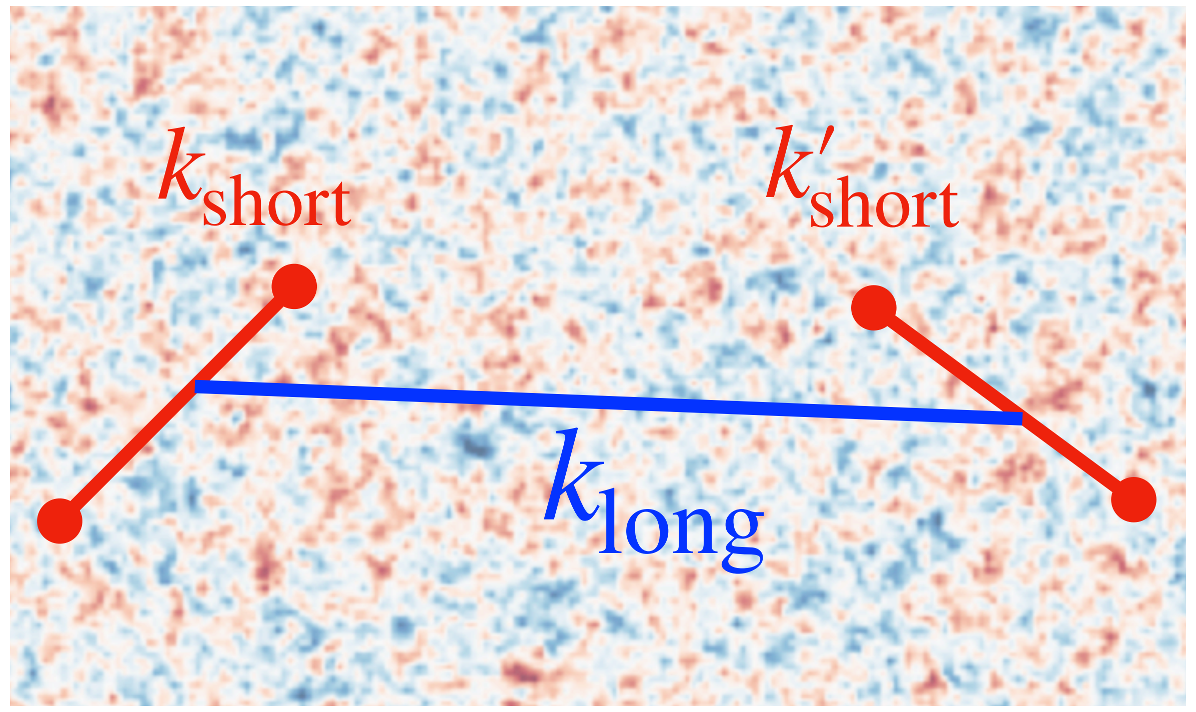
Smith+15, Planck 2015, Planck 2018, **Philcox** 25c

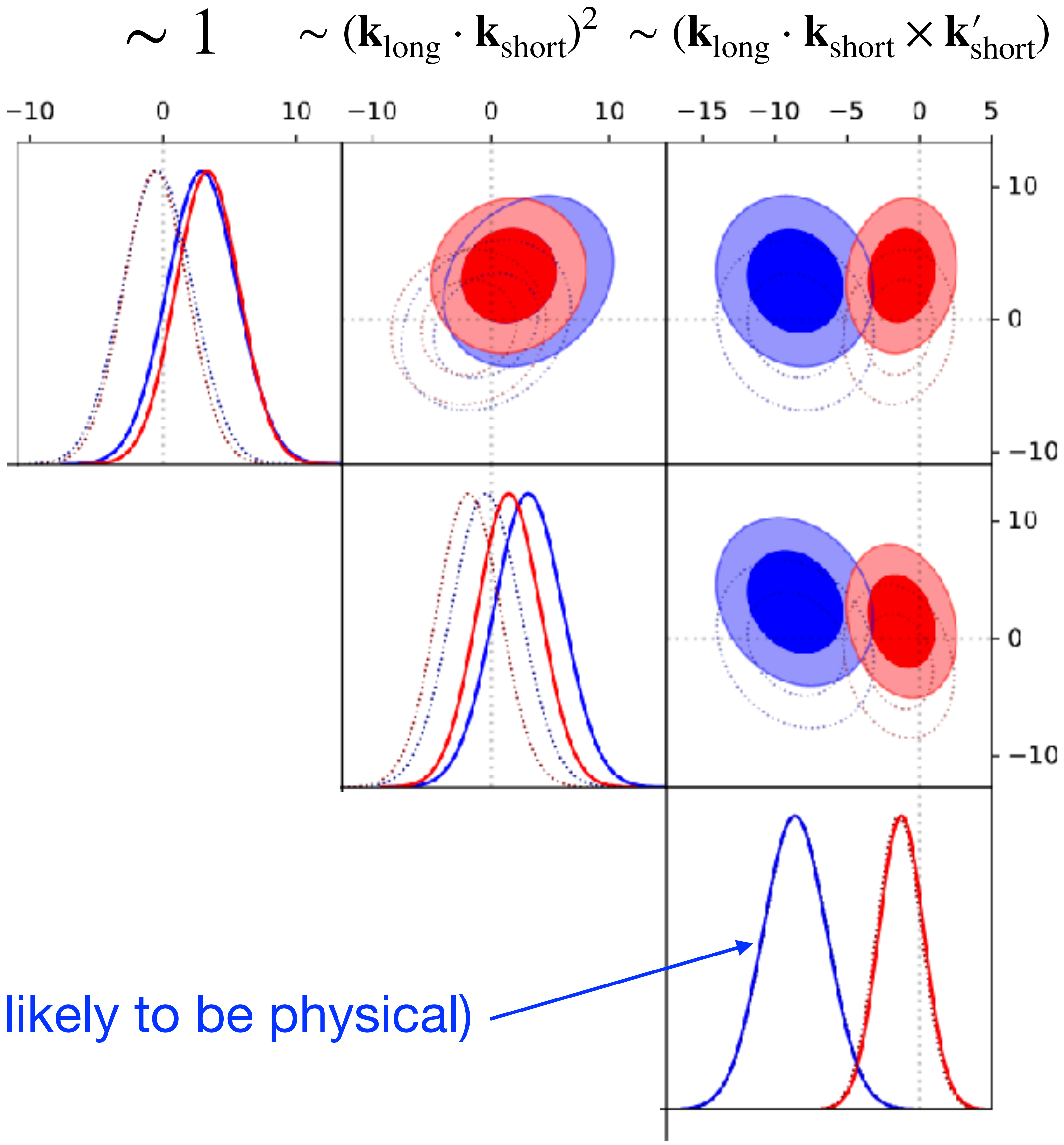
Results: Direction-Dependent Non-Gaussianity

Model: *local effects with **angle-dependence***

$$\langle\zeta^4\rangle \sim P_\zeta(k_{\rm short})P(k'_{\rm short})P_\zeta(k_{\rm long}) \times \text{AngleFunction}(\hat{\mathbf{k}}_{\rm short}, \hat{\mathbf{k}}'_{\rm short}, \hat{\mathbf{k}}_{\rm long})$$

- Constrains models such as:
  - **Solid Inflation**
    (*driven by triplet of vector fields*)
  - **Gauge Fields**
    (*coupled to inflation, e.g.* $f(\phi)F\tilde{F}$)
  - **Parity-Violation** (*chiral couplings*)





(Unlikely to be physical)

Outcome: (Mostly) consistent with zero!

- **First constraints from data!**

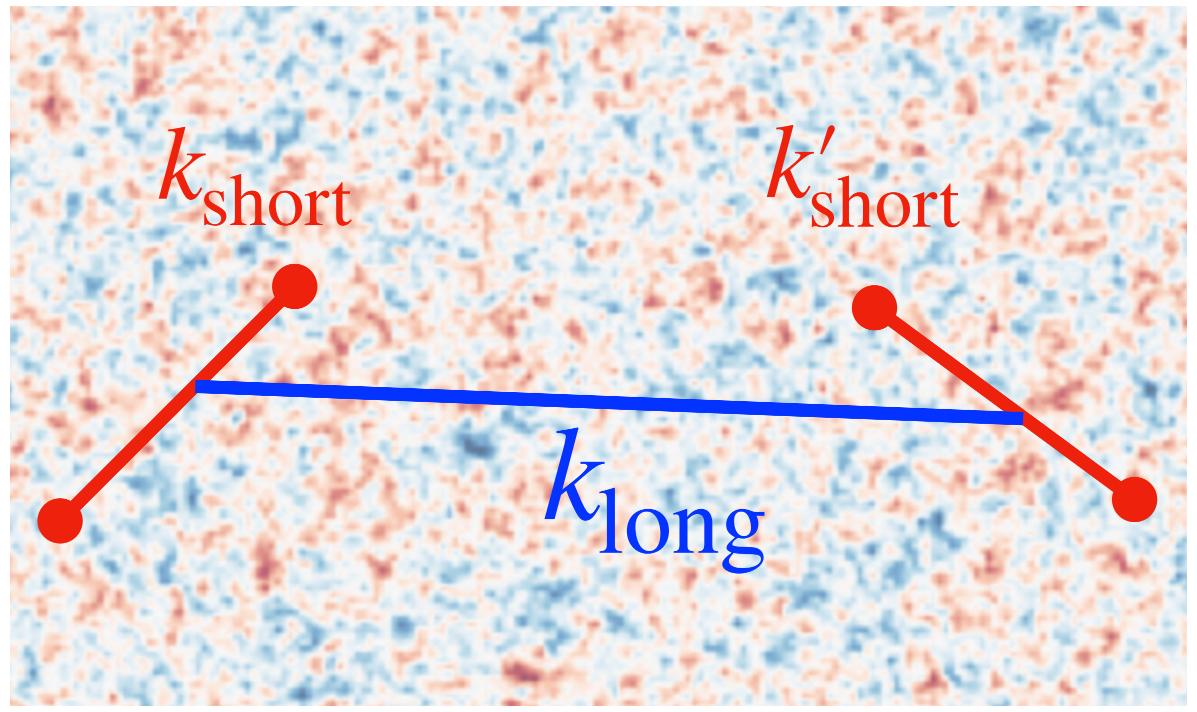
Shiraishi+, Bartolo+, Cabass+, **Philcox** 25c

Results: Cosmological Collider

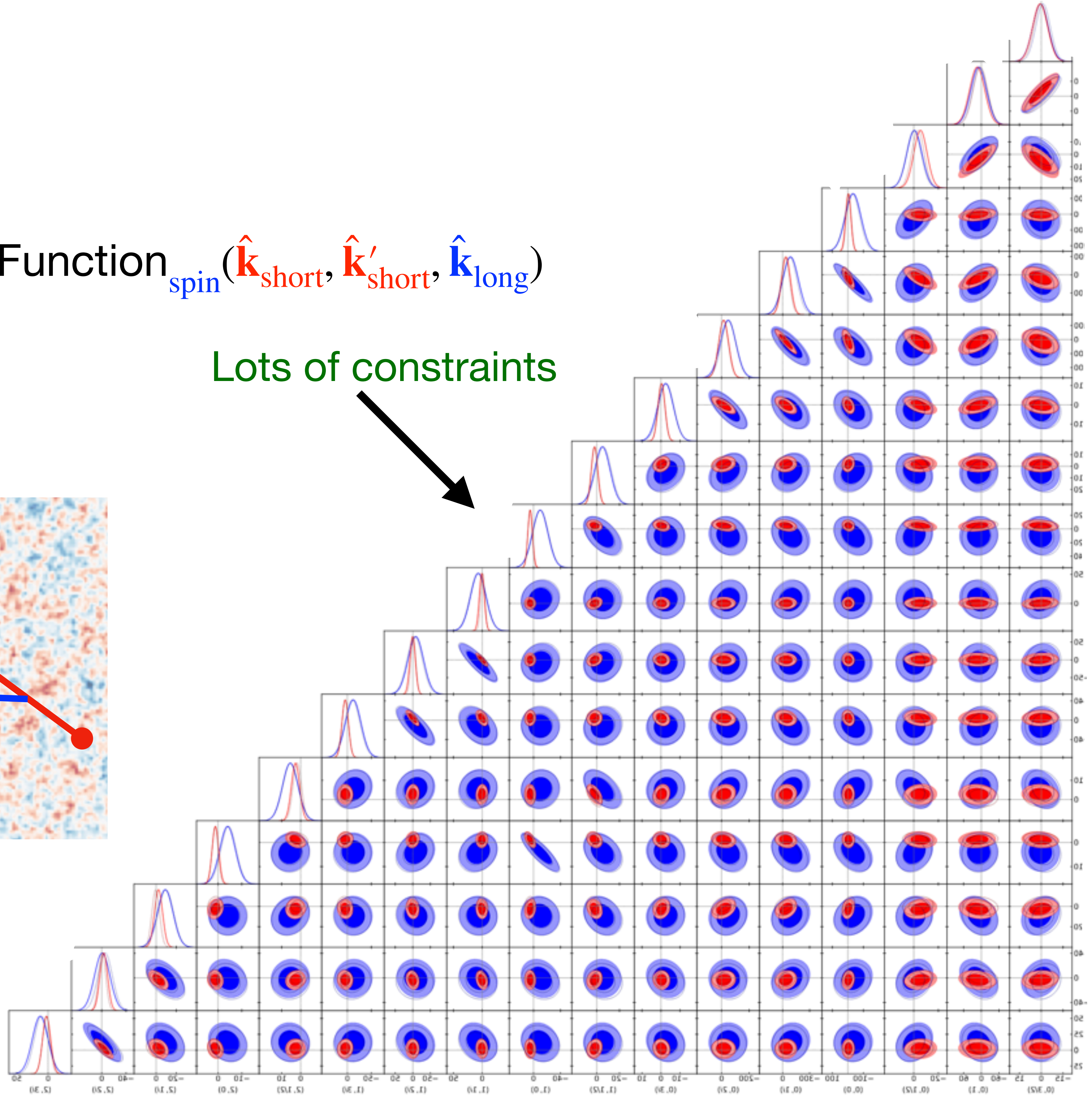
Model: *inflationary* ***massive*** *and* ***spinning*** *particles*

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

- 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



Outcome: Consistent with zero!

- **First constraints from data!**

Philcox 25c

Results: Cosmological Collider

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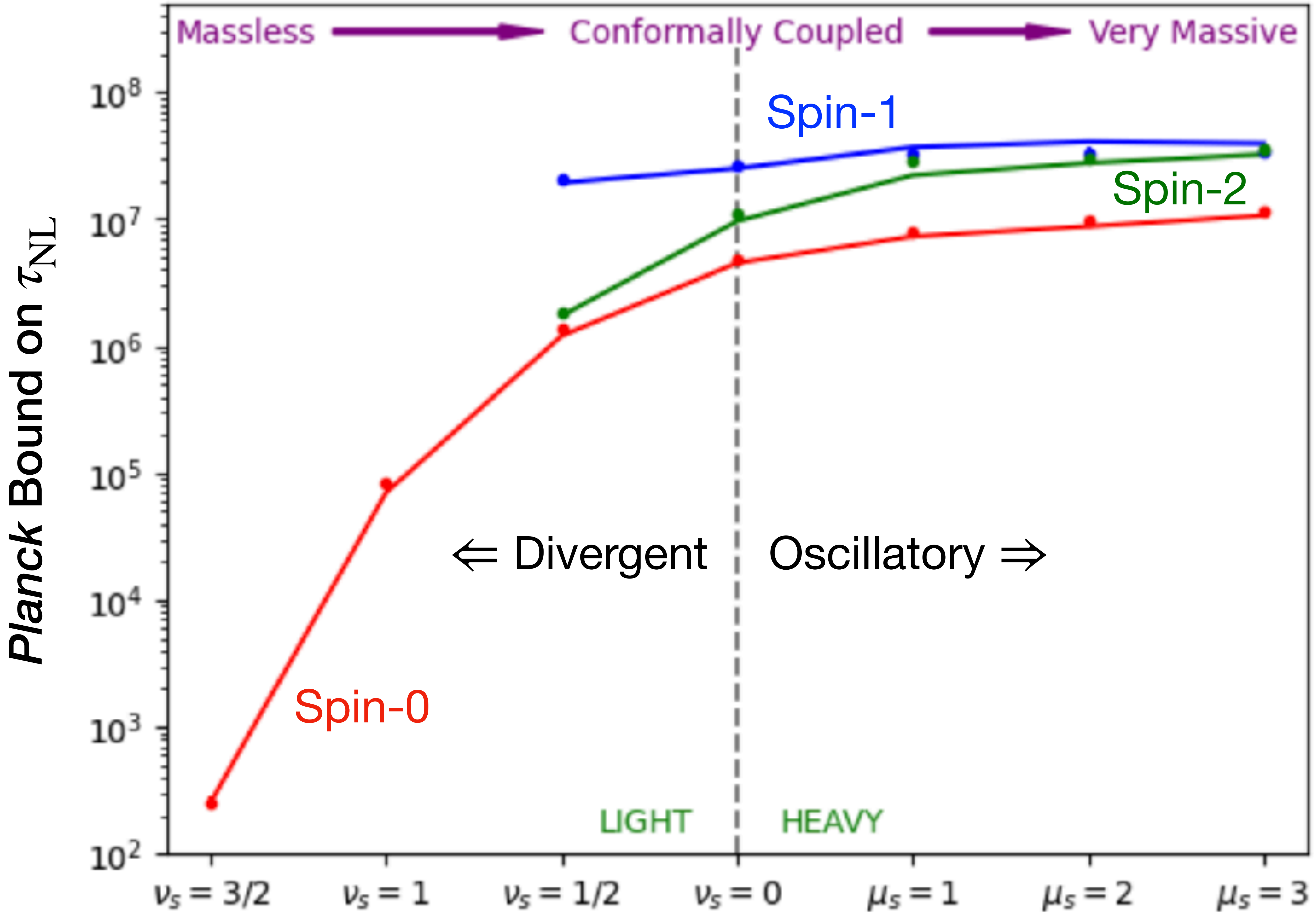
    $m_\sigma \gtrsim 3H/2$

- As expected, **light fields** are easiest to constrain since their trispectrum ***diverges***

- Odd-spins are **hard** to constrain due to cancellations!



Philcox 25c, Moradinezhad+, Schmidt+

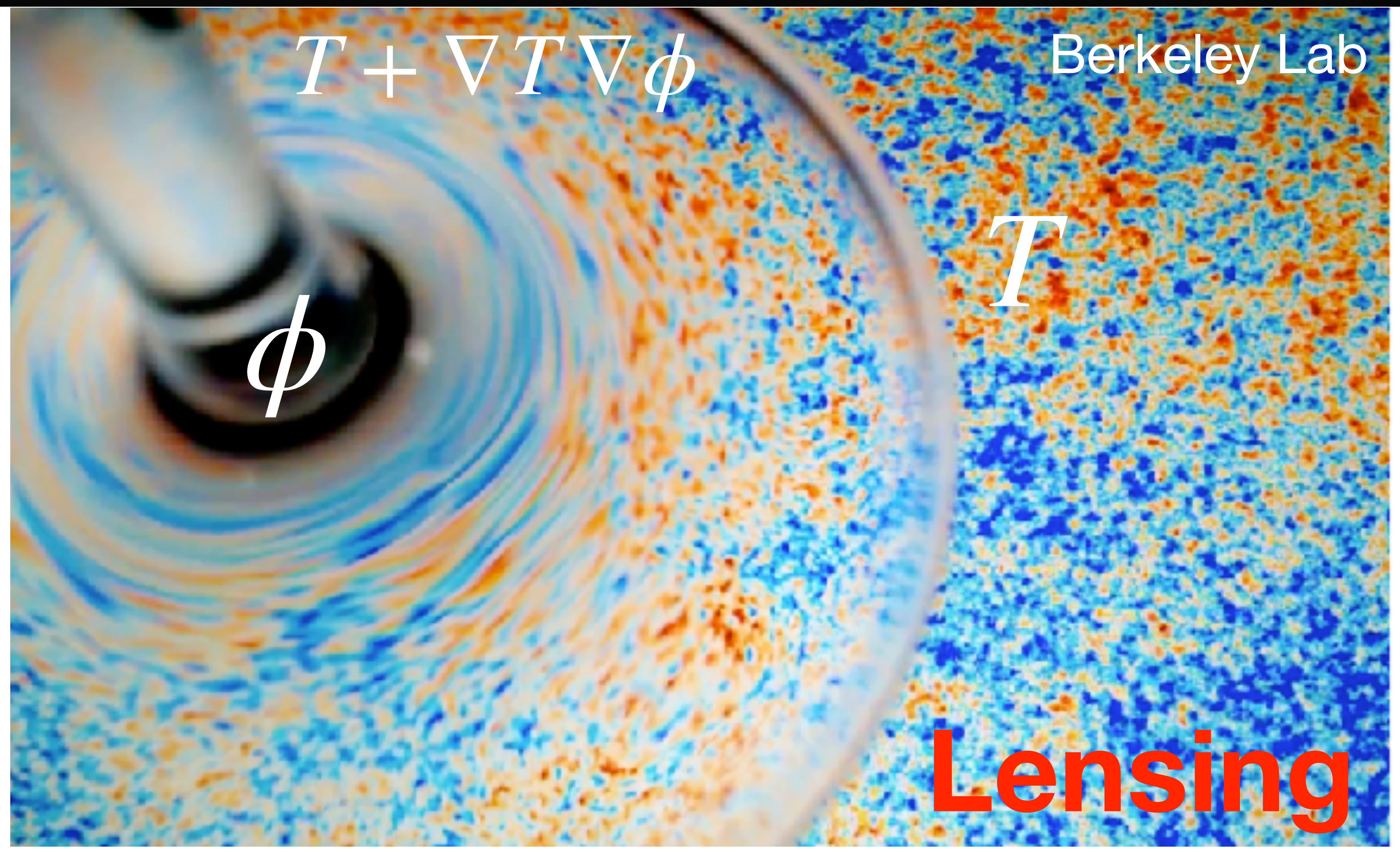
Results: Gravitational Lensing

Gravitational lensing also induces a **four-point** function:

$$T_{\rm CMB} \to T_{\rm CMB} + \nabla T \nabla \phi$$

$$\langle T^4_{\rm CMB} \rangle \sim \langle T \nabla T \rangle^2 \langle \nabla \phi \nabla \phi \rangle$$

$\nabla^2 \phi \sim \int$ dark matter



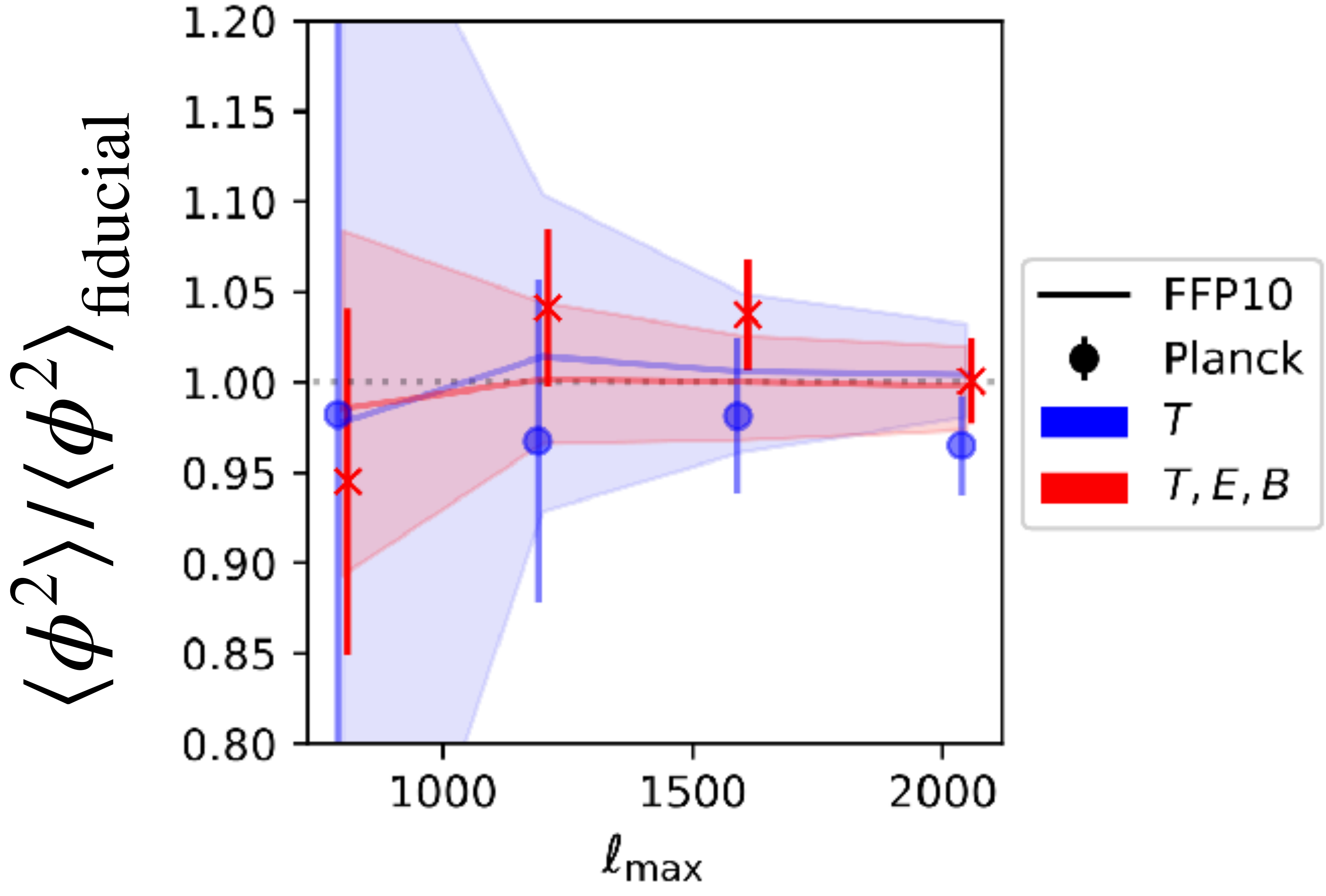
- The estimators are (almost) equivalent to the standard forms

(Including realization-dependent noise, N^0 bias, N^1 bias, but adding mask-dependent normalization and optimal filtering)

- We detect *Planck* lensing at 43σ!
  - This is **consistent** with the standard model

$$\langle \phi^2 \rangle / \langle \phi^2 \rangle_{\rm fiducial} \sim C_L^{\phi\phi} / C_L^{\phi\phi,\rm fid} = 0.979 \pm 0.023$$

  - It's the **joint strongest** constraint yet!



cf. Hu, Okamoto, Lewis, Challinor, …, Carron+22, ACT+24, **Philcox** 25c

What's Next For the Trispectrum?

There are *many* ways to extend.

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

    - ACT, SPT, Simons Observatory, CMB-S4, CMB-HD will provide data down to **much** smaller scales!

    - The **polarization** will be particularly useful and could benefit from **delensing**

2. More **Models**

    - Lighter particles? Heavier particles?

    - Collider physics **beyond** the collapsed limit?

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

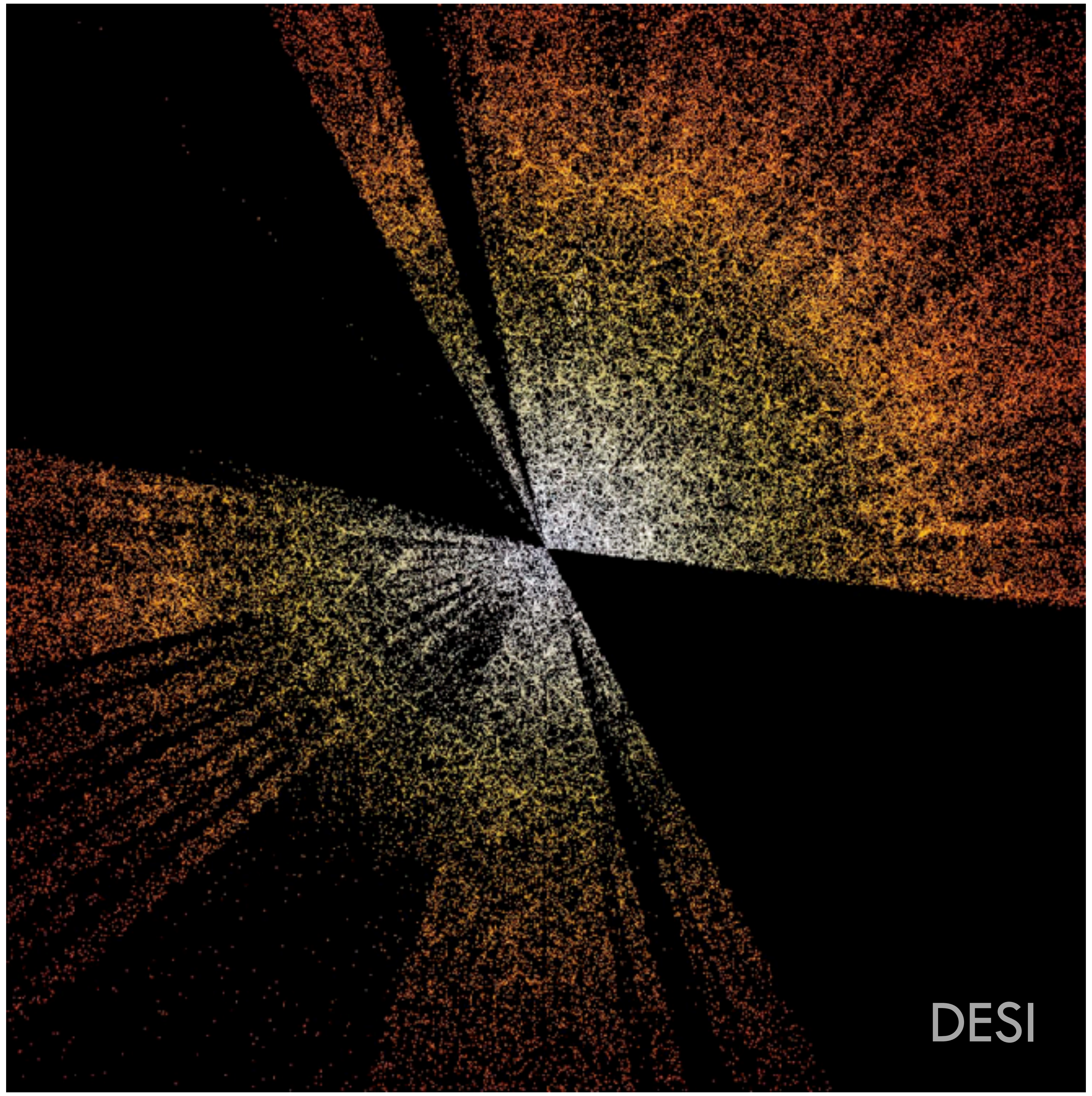
    - Scale-dependence? Isocurvature? Primordial magnetic fields?

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

The Future of Non-Gaussianity

- Future **CMB** experiments will improve bounds by $\lesssim 10\times$
  - This is a **two-dimensional** field
  - We're running out of modes to look at!
  - Small-scales are **hard**
- What about **galaxy surveys**?
  - This is a **three-dimensional** field
  - Legacy surveys map **a million** galaxies [BOSS]
  - New surveys map $\sim 100\times$ more! [DESI, Euclid, Rubin, Roman, …]

Density of galaxies, $\rho_{\rm gal}$



Inflation from Galaxy Surveys

- Modern galaxy surveys map of the distribution of galaxies in three-dimensions: $\delta_g(\mathbf{x}, z)$

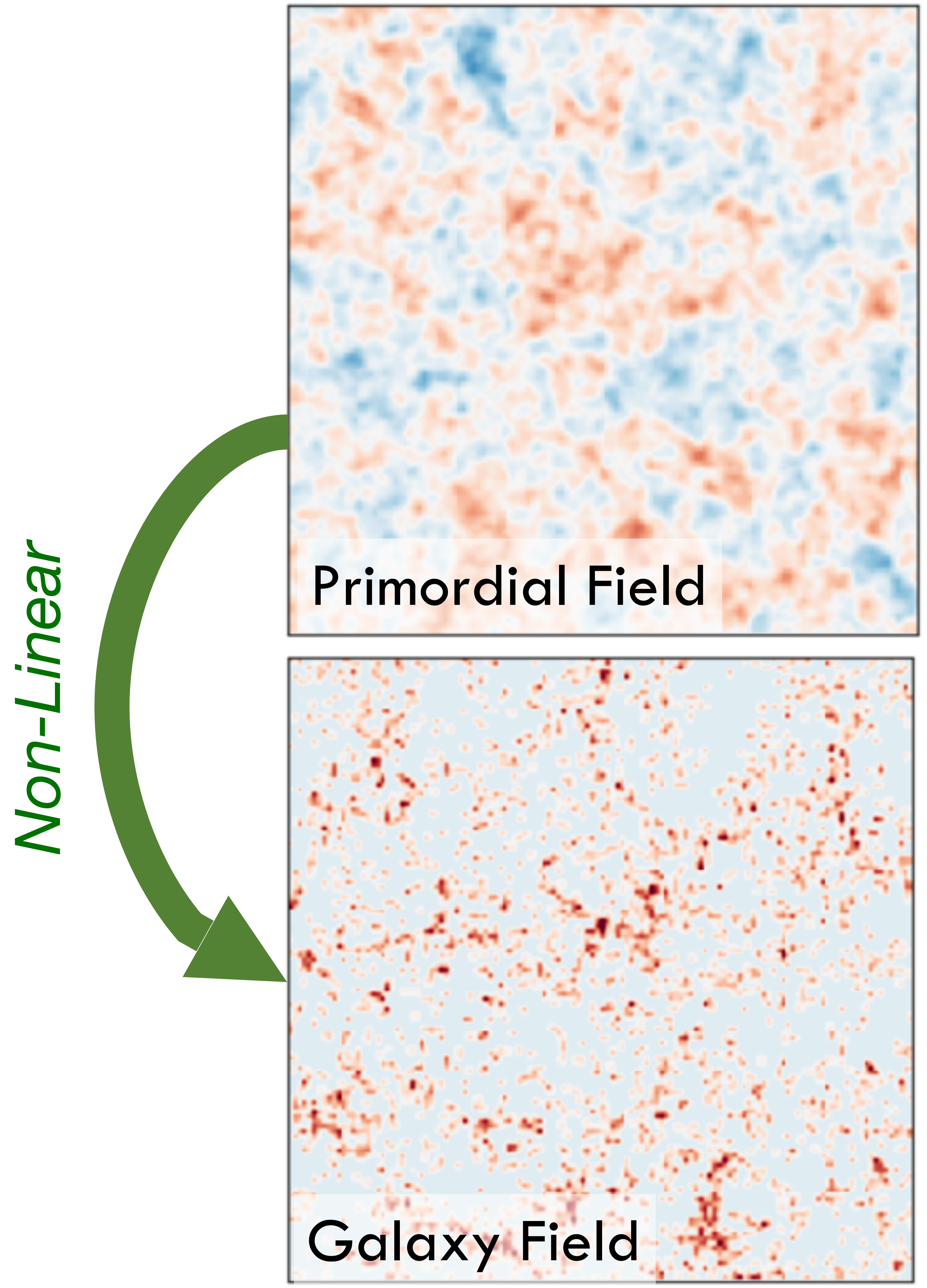
- This **traces dark matter** evolution and the **initial conditions**

- 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:

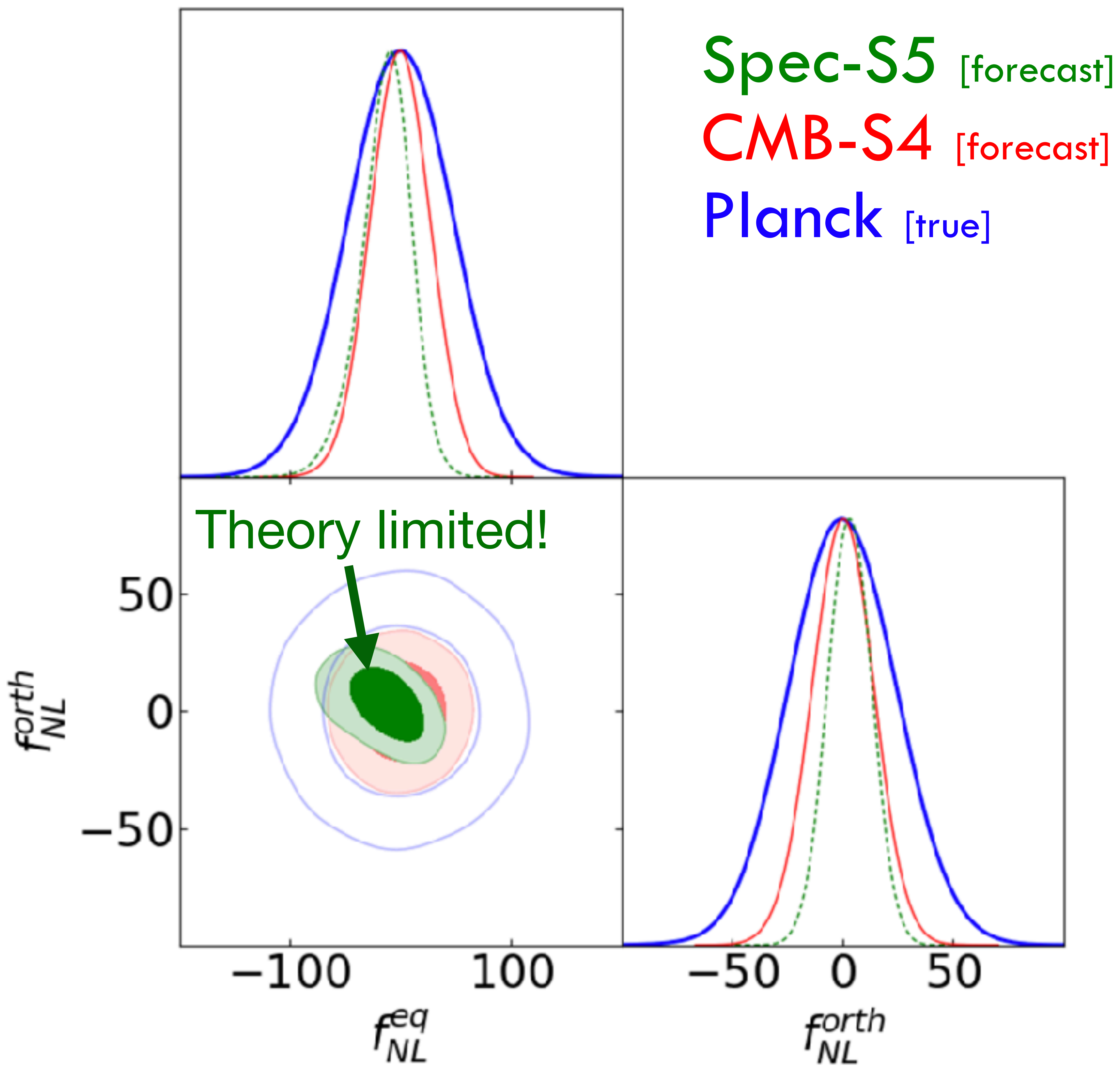
Effective Field Theory** of **Large Scale Structure (EFTofLSS)



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

Inflation from Galaxy Surveys

- Recent works have constrained:
  - **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
  - **Collider** three-point functions from the exchange of massive scalar fields
- For now, the constraints are **much** worse than the CMB $(5-20\times)$ – this will change soon!
- There's lot's more to explore, including the **four-point function** and the **full collider scenario**!



Self-Interaction Forecast

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

SIMONS FOUNDATION

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Stanford University

arXiv

2502.06931
2502.05258
2502.04434
2407.08731
2404.01894
2204.01781
2201.07238

Summary

- Thanks to new developments in theory and analysis, we can now *directly* constrain inflationary four-point functions and the **cosmological collider**

- This probes $10^{13}\,\mathrm{TeV}$-scale physics using low-energy data!

- New data from the **CMB** and **galaxy surveys** will *significantly* enhance our knowledge of inflation!

Contact: *ohep2@cantab.ac.uk*


The Cosmological Collider has been switched on!