Particle Colliders in the Sky

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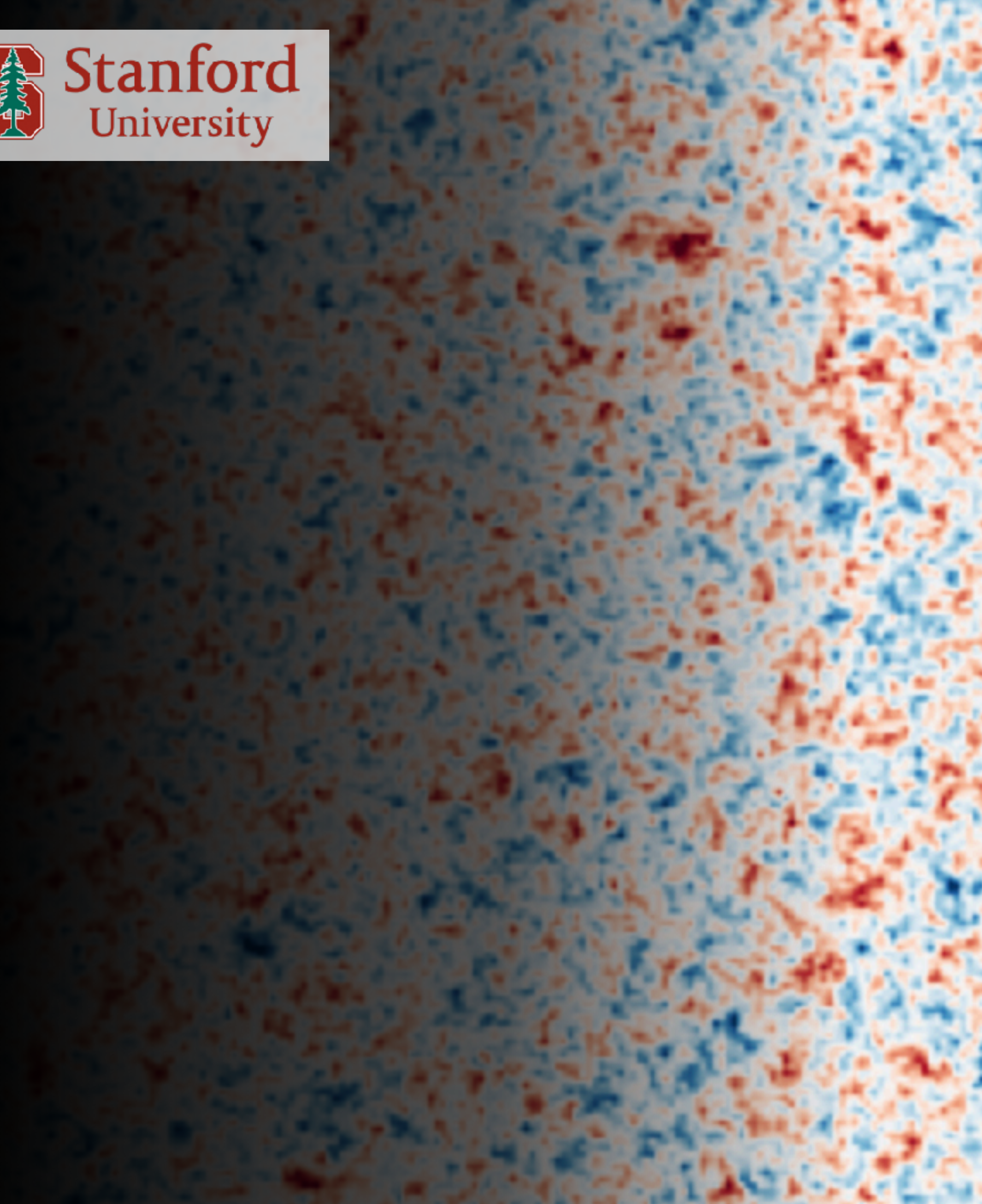
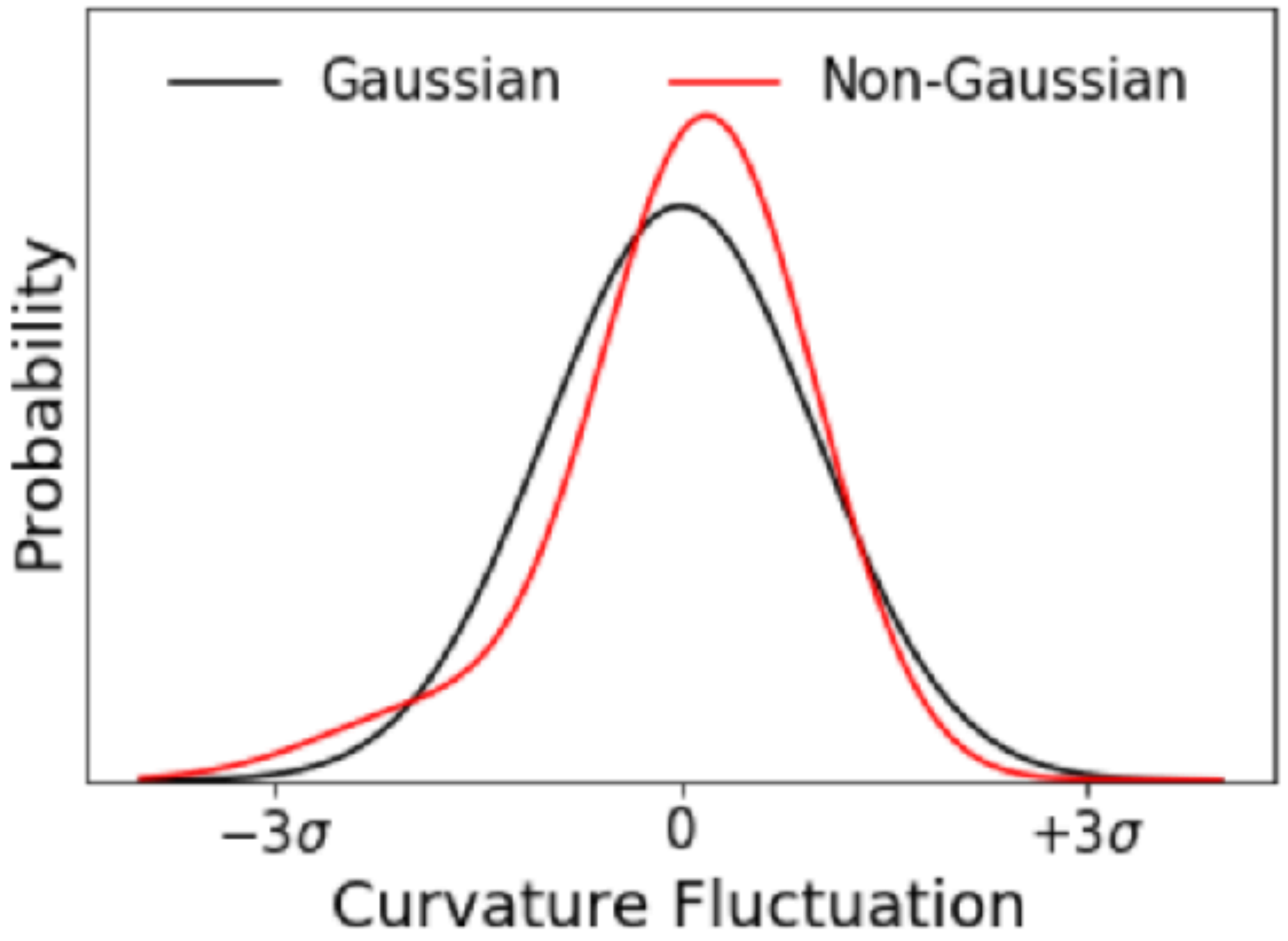
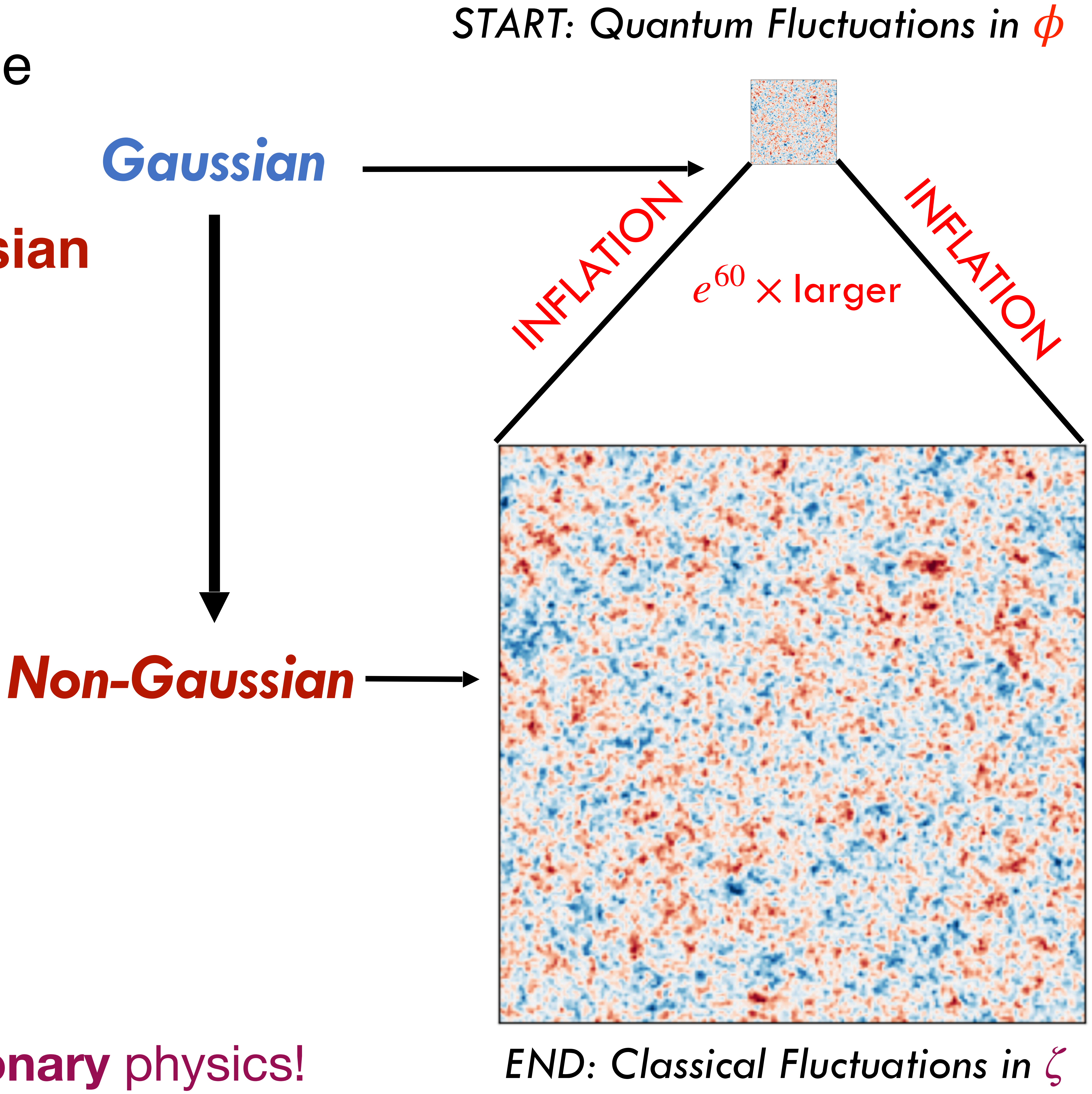


Primordial non-Gaussianity

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

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





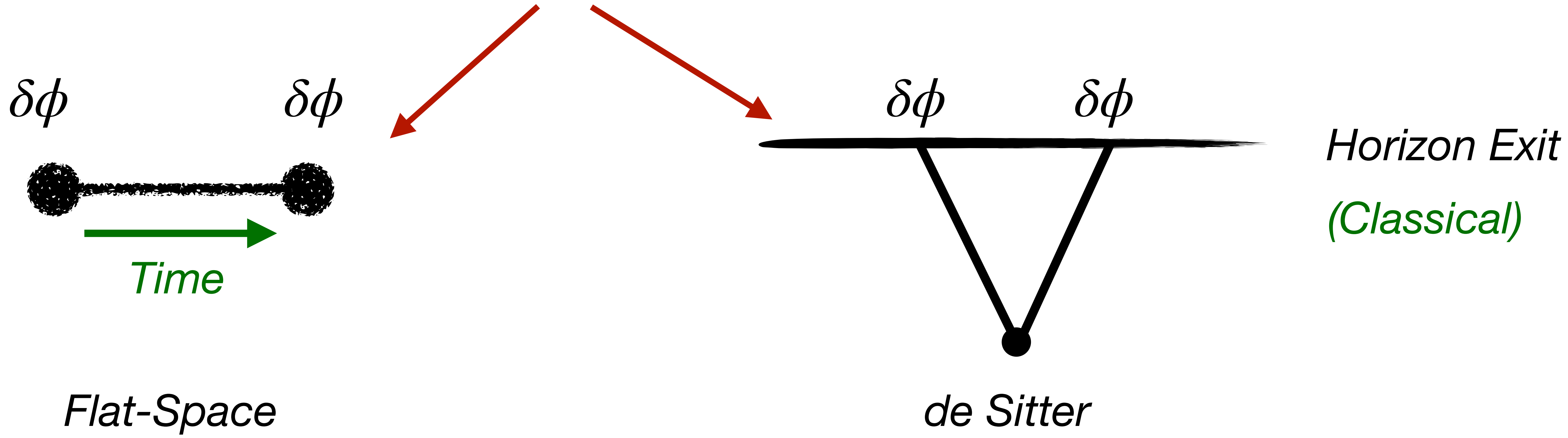
By searching for **non-Gaussianity**, we can constrain **inflationary** physics!

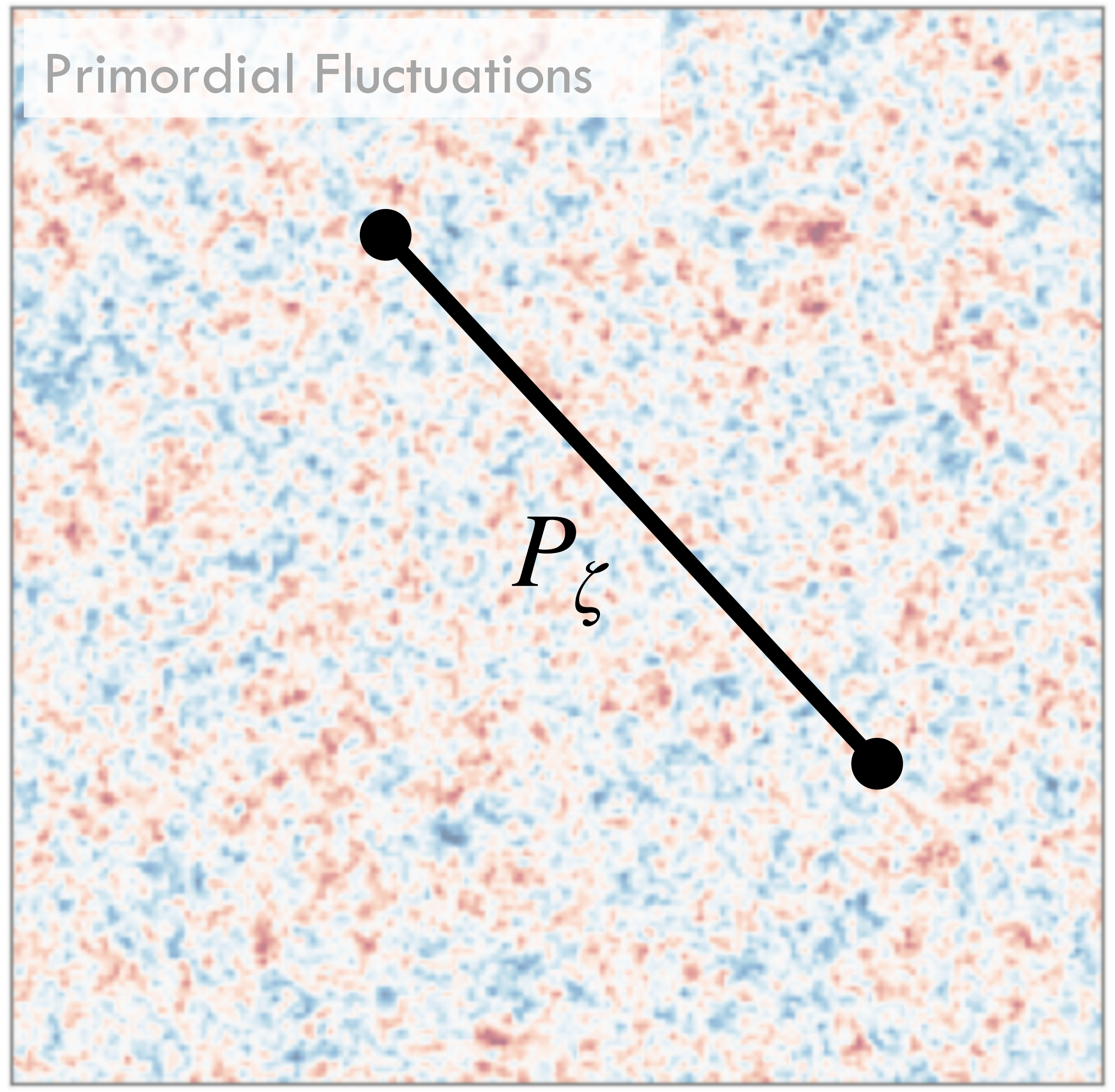
COBE, WMAP, Planck, Linde, Guth, Starobinsky, …

Vanilla Inflation

- In the **simplest** inflationary model, we have a **single field** ϕ (the "inflaton") with a **quadratic Lagrangian:**

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





- This leads to a **two-point** function at the end of inflation

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

- Higher-order correlators are **slow-roll** suppressed

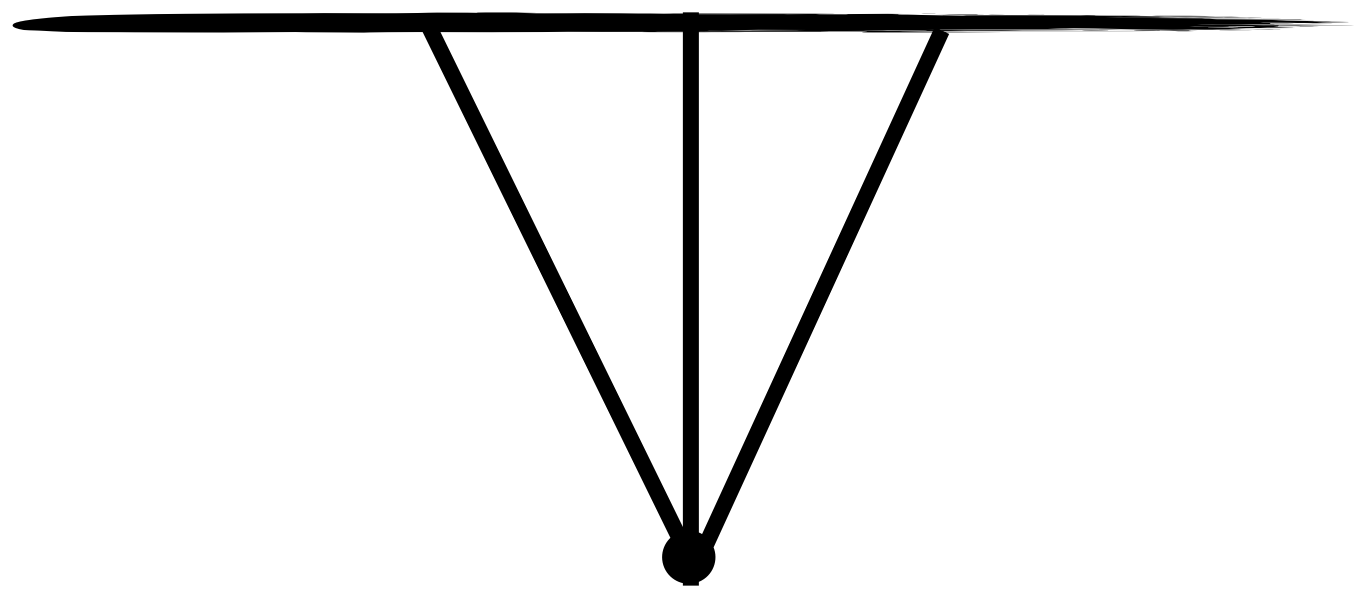
Maldacena, Arnold, Deser, Misner, …

Non-Standard Inflation

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

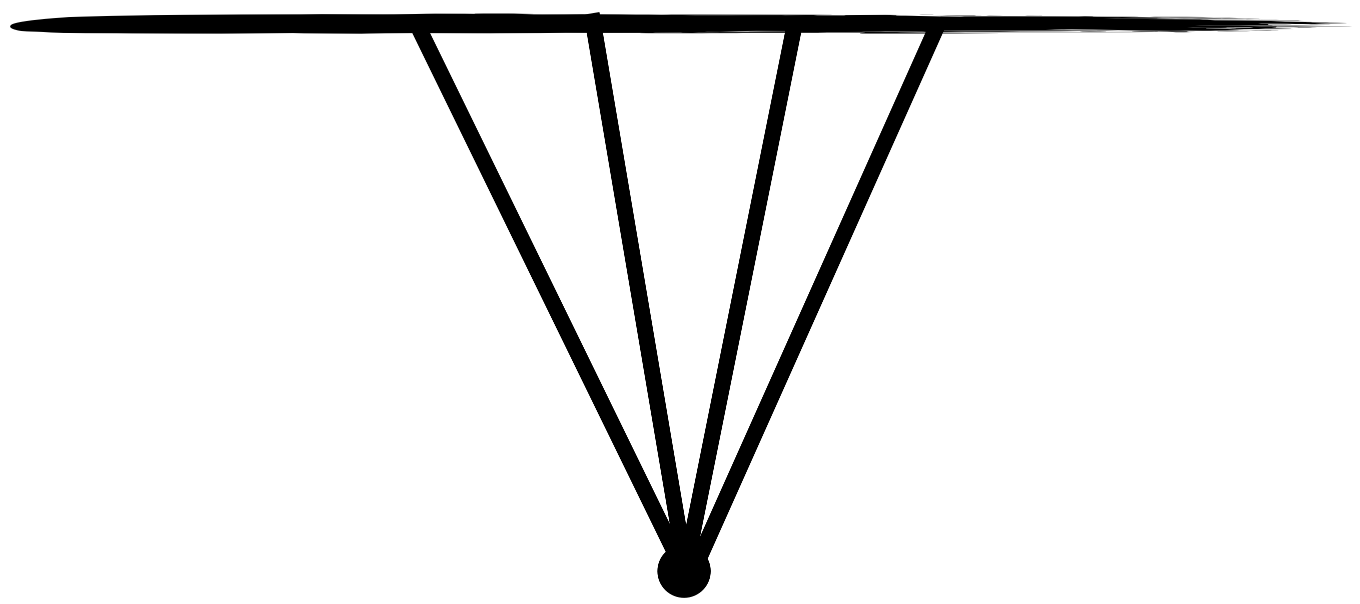
$$\mathscr{L} \supset \delta\dot{\phi}^3, \quad \delta\dot{\phi}(\partial\phi)^2, \quad \delta\dot{\phi}^4, \quad \cdots$$

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

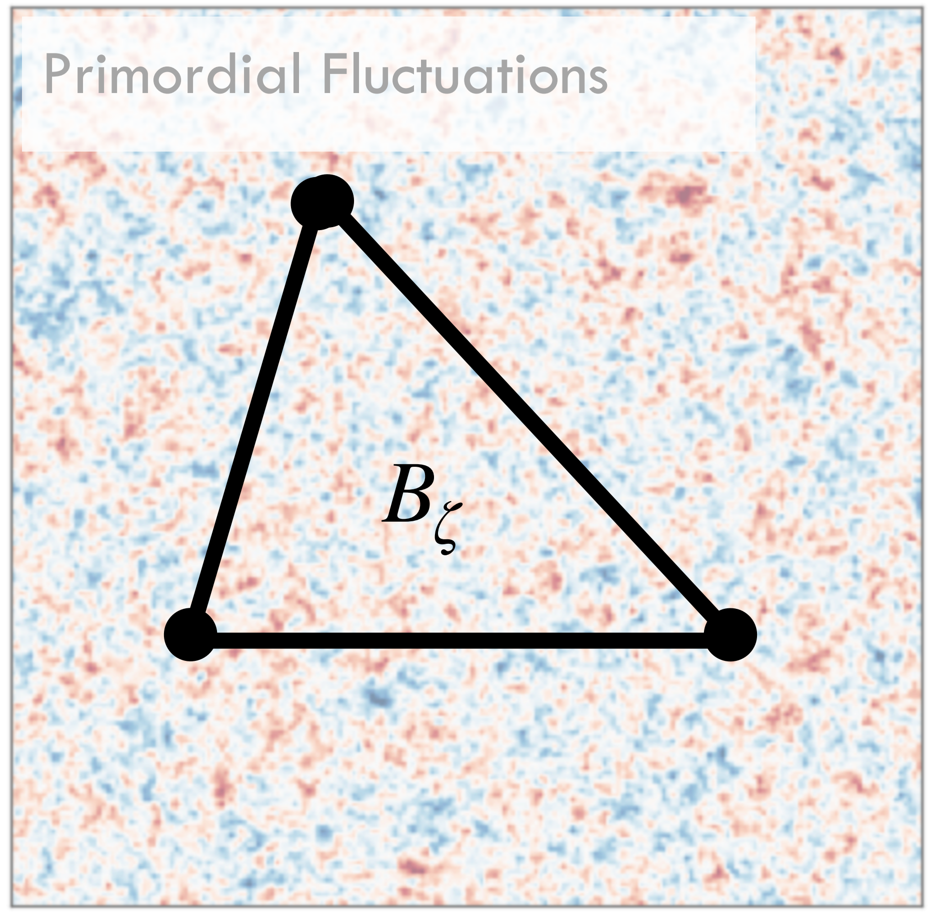


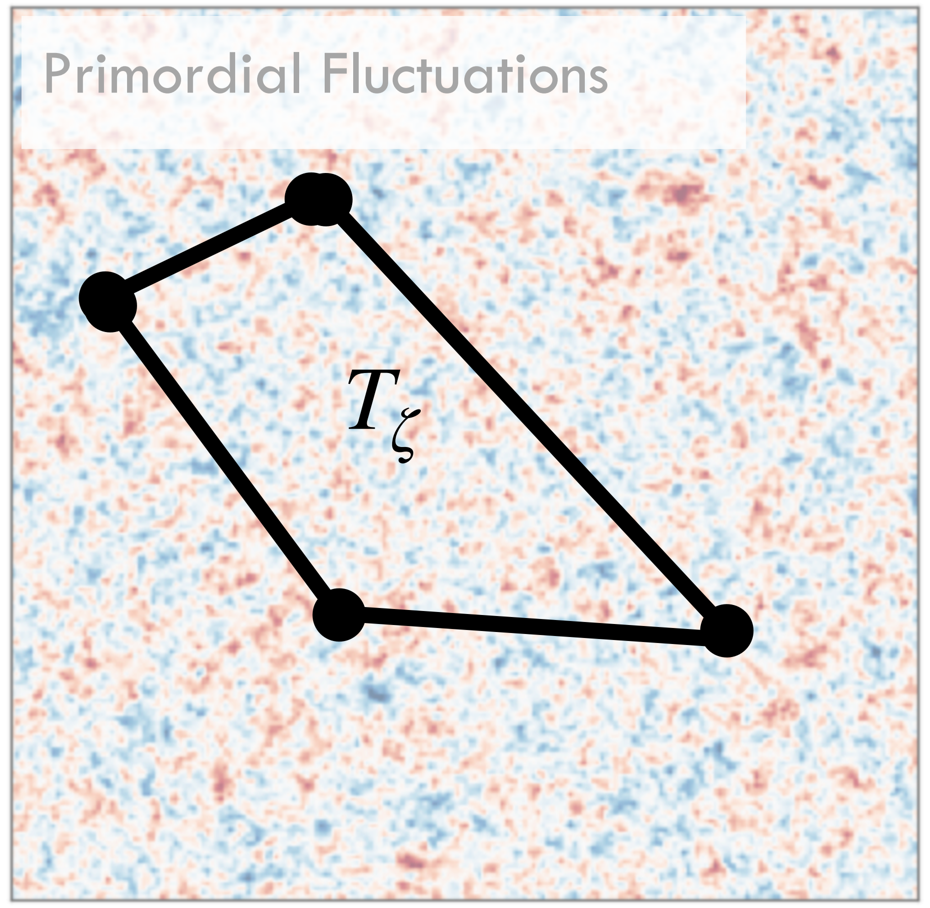
Cubic $\sim f_{\mathrm{NL}}^{\mathrm{eq}}$

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



Quartic $\sim g_{\mathrm{NL}}$





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

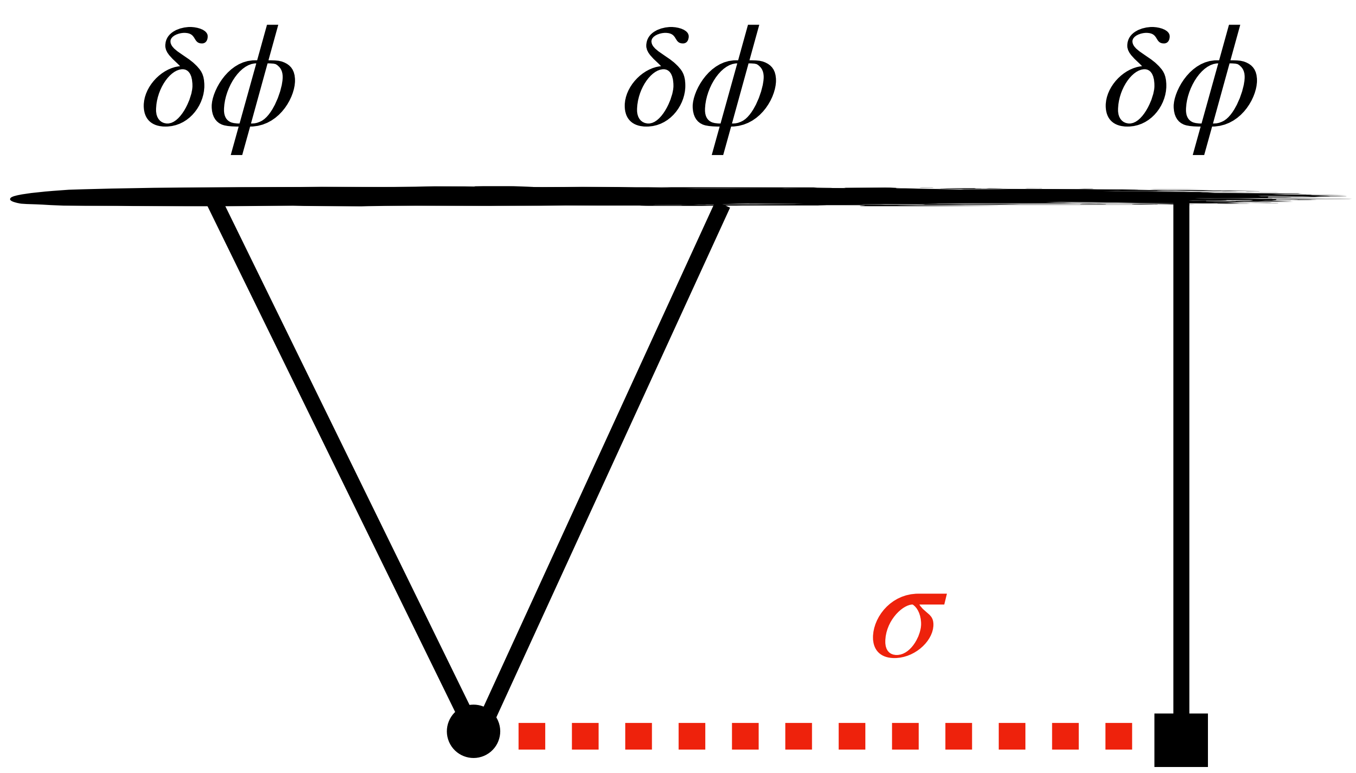
e.g. $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\mathrm{NL}}^{\mathrm{eq}} \times$ shape

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

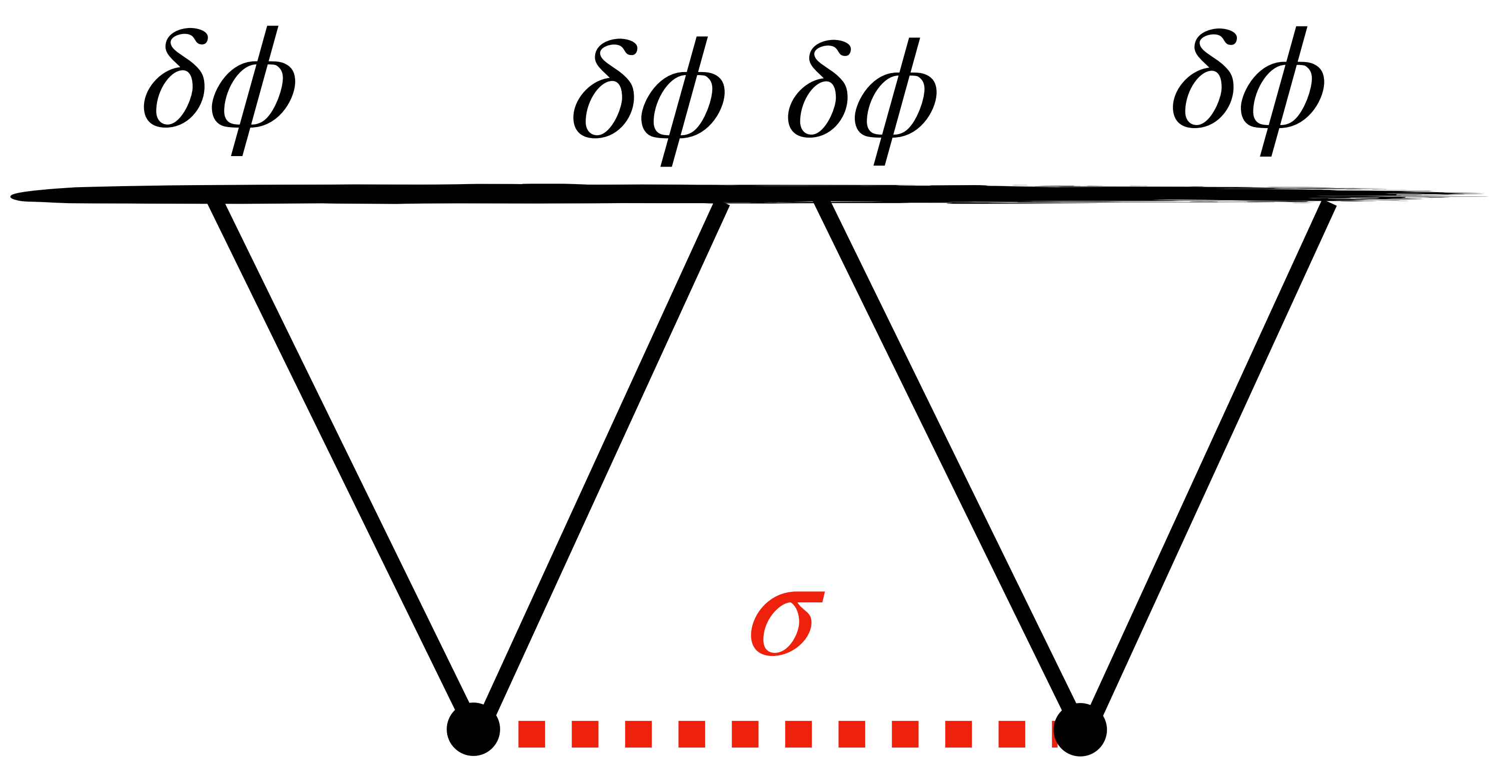
Non-Standard Inflation

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

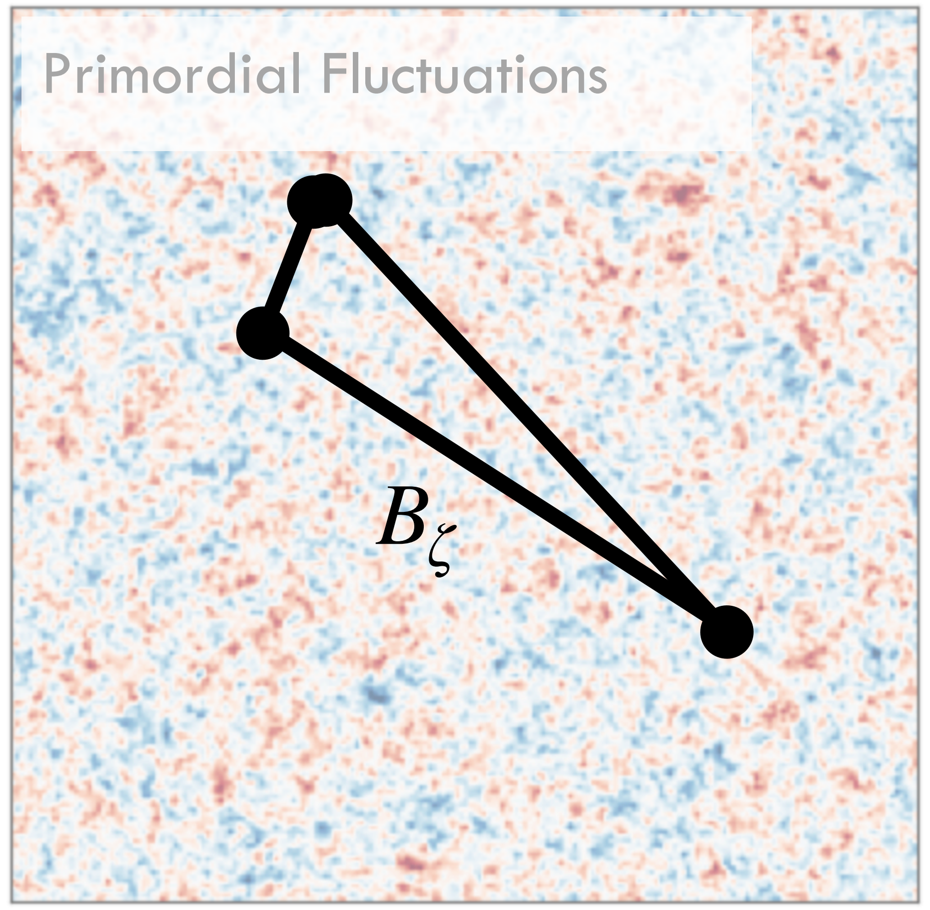
$$\mathscr{L} \supset \delta\dot{\phi}\sigma, \quad \delta\dot{\phi}^2\sigma, \quad \cdots$$

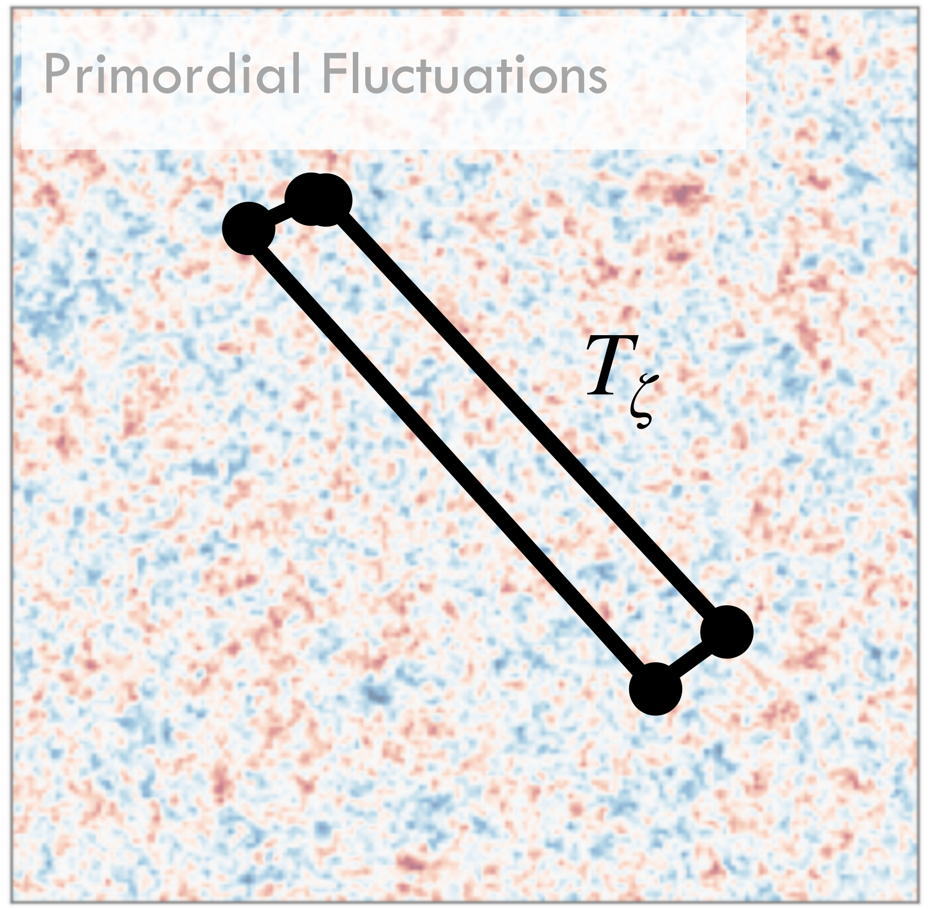


Linear-Quadratic $\sim f_{\rm NL}^{\rm loc}$



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 $s = 0,1,2,\cdots$

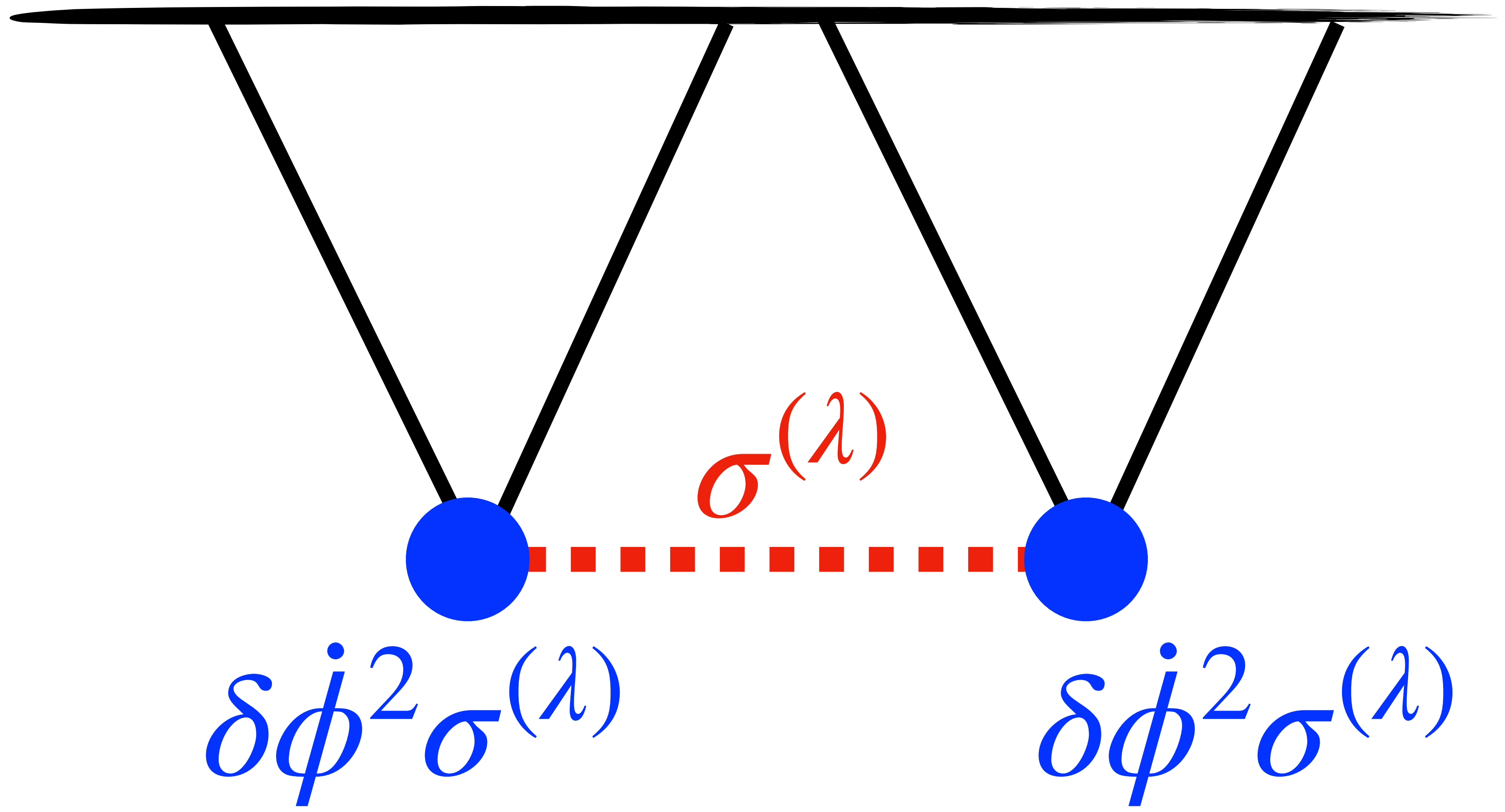
- This depends on the **power spectrum** of σ, including all its **helicity states,** $\sigma^{(\lambda)}$

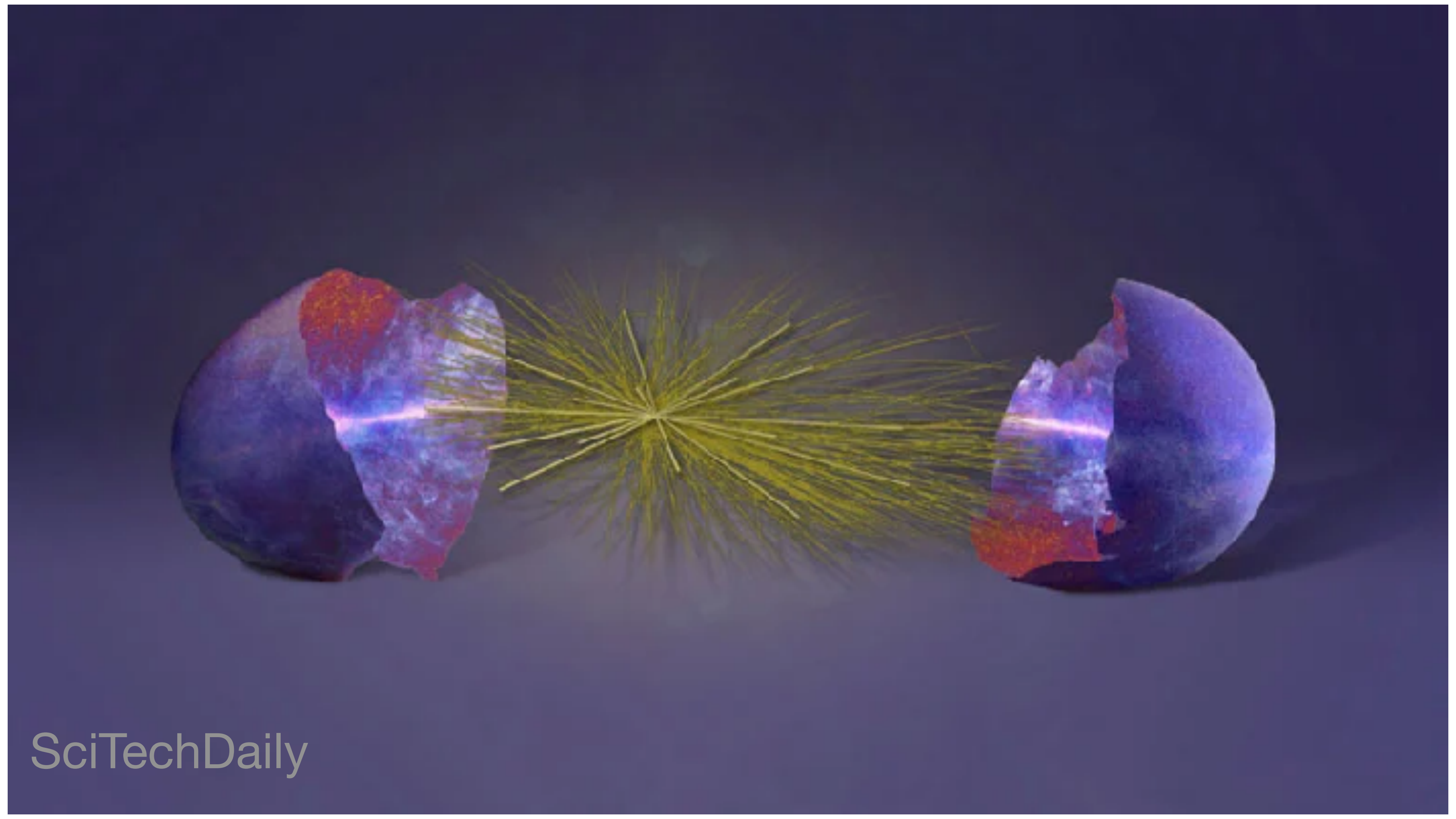
$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle \sim \sum_\lambda P_\zeta(k_1)P_\zeta(k_3)P_{\sigma^{(\lambda)}}(K) \times \text{coupling}$$

- 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!

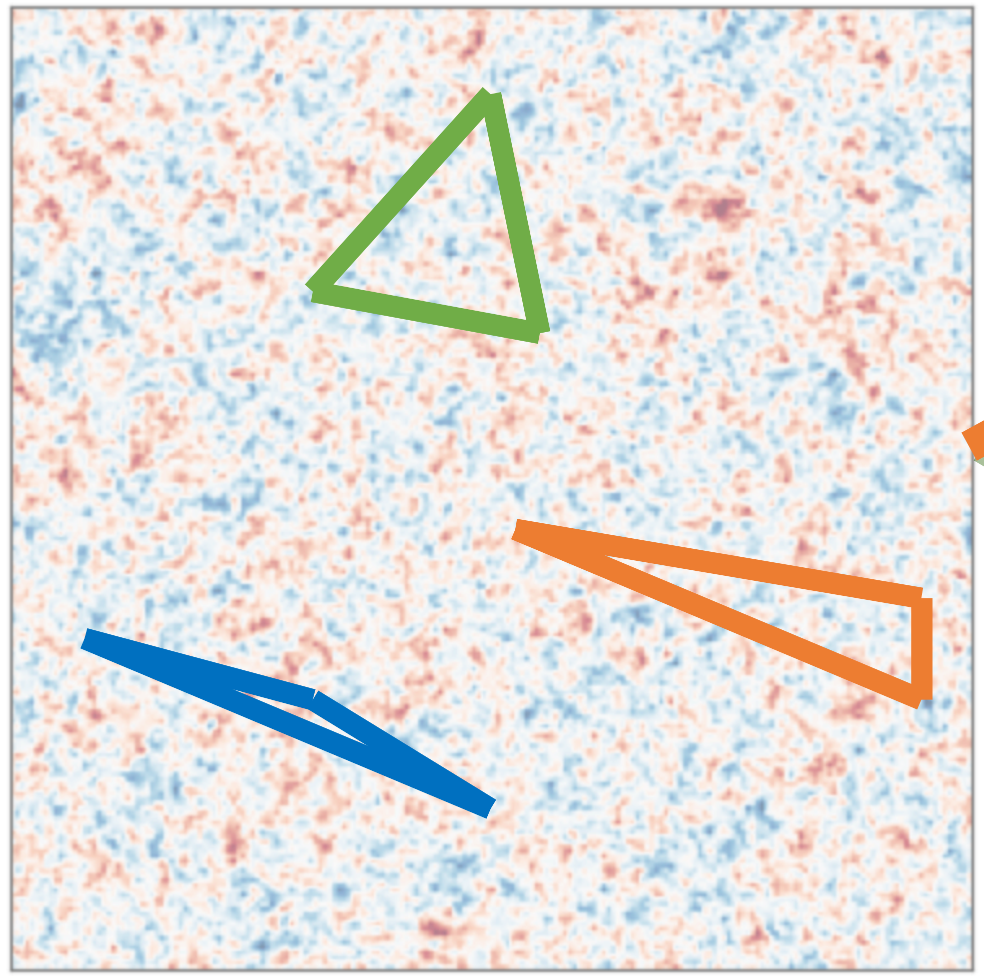




Maldacena, Arkani-Hamed, Jazayeri, Pajer, Zaldarriaga, Lee, Moradinezhad, Cabass, Baumann, …

How to Measure Primordial Non-Gaussianity

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

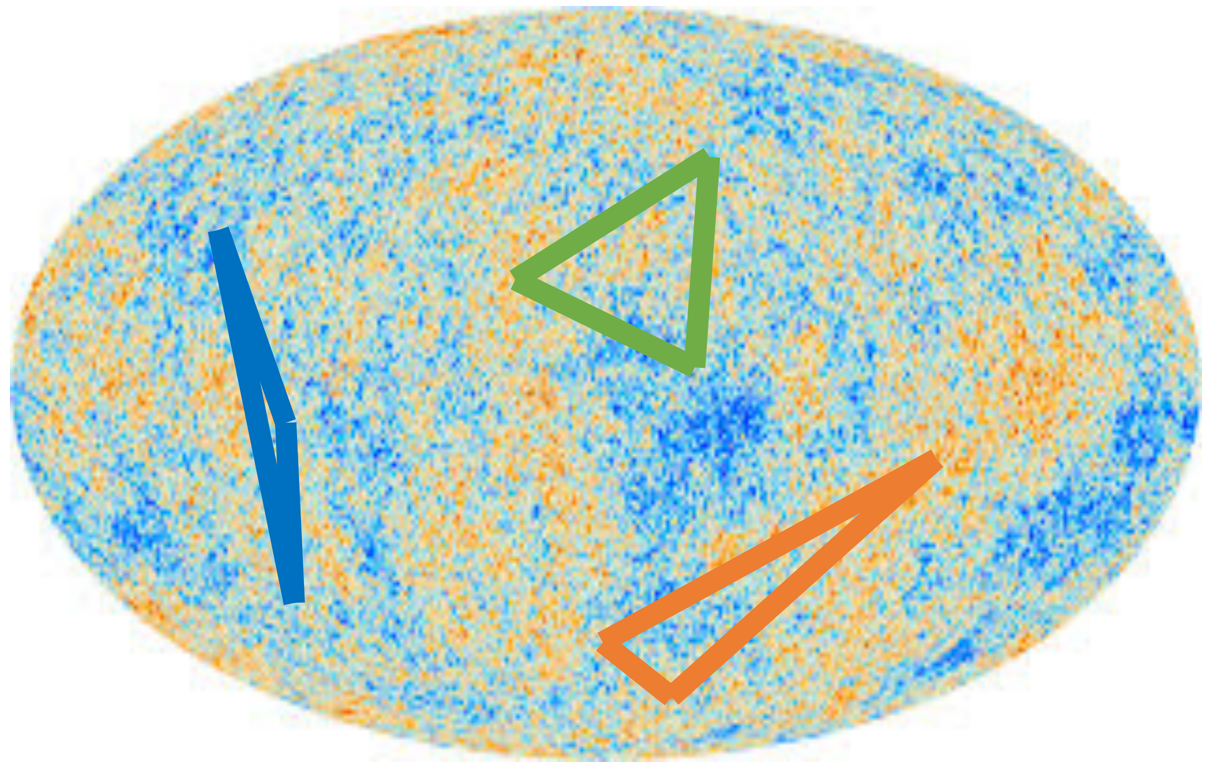


Primordial Correlator

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

Linear Physics

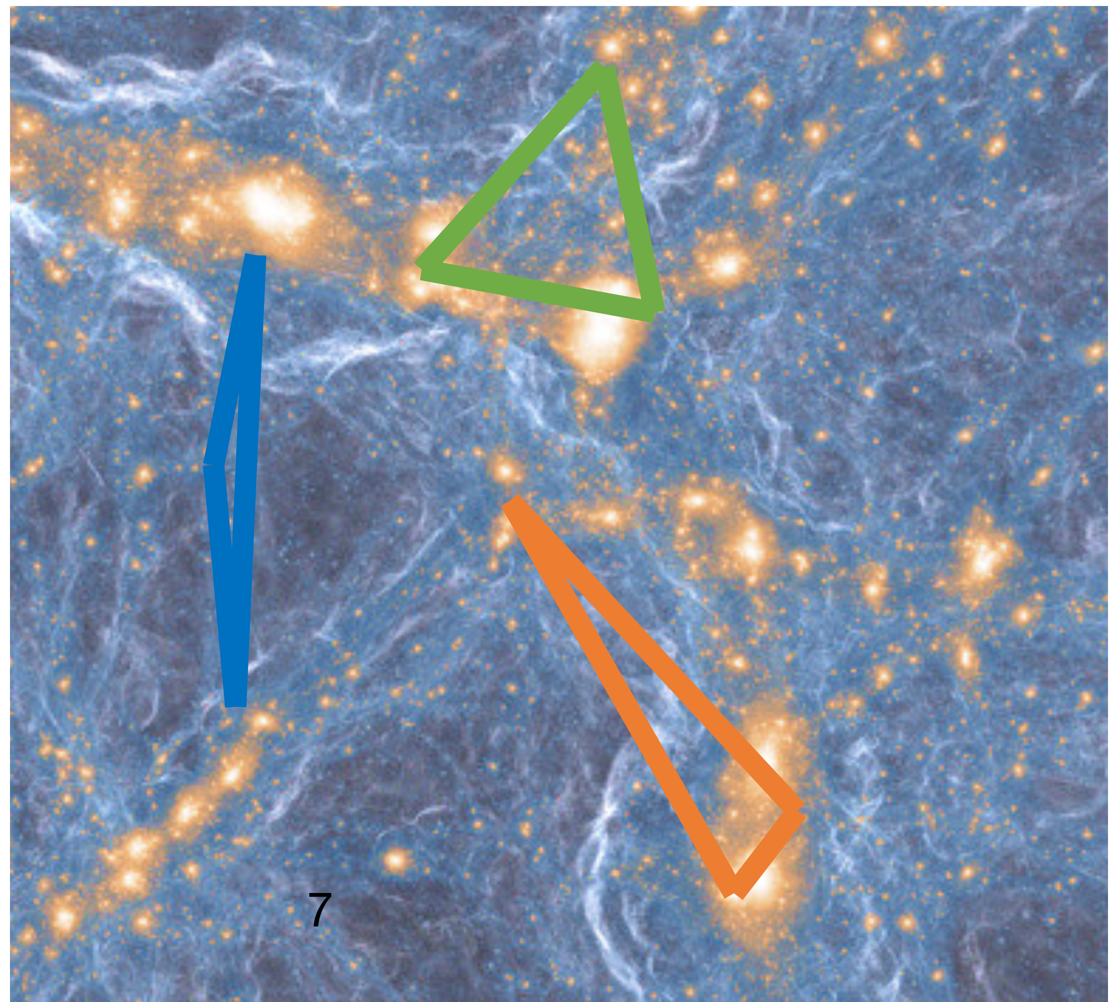
Non-Linear Physics



Cosmic Microwave Background
Correlator

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

(tracing ***photon energies****)*



Galaxy Distribution
Correlator

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

(tracing ***dark matter****)*

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

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

Yes!

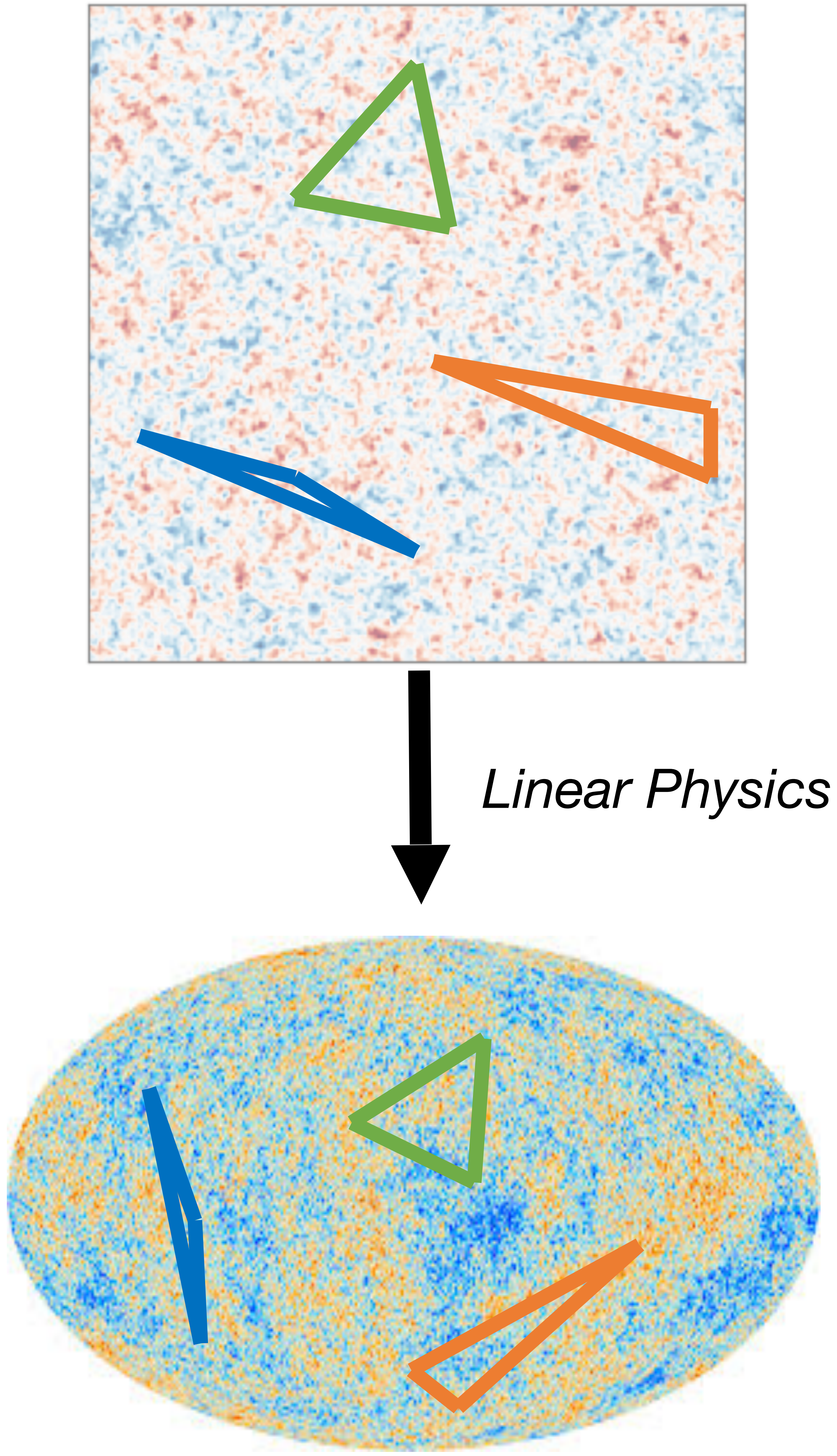
- Cubic-terms in the Lagrangian could be **protected** by symmetry

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

(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**



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

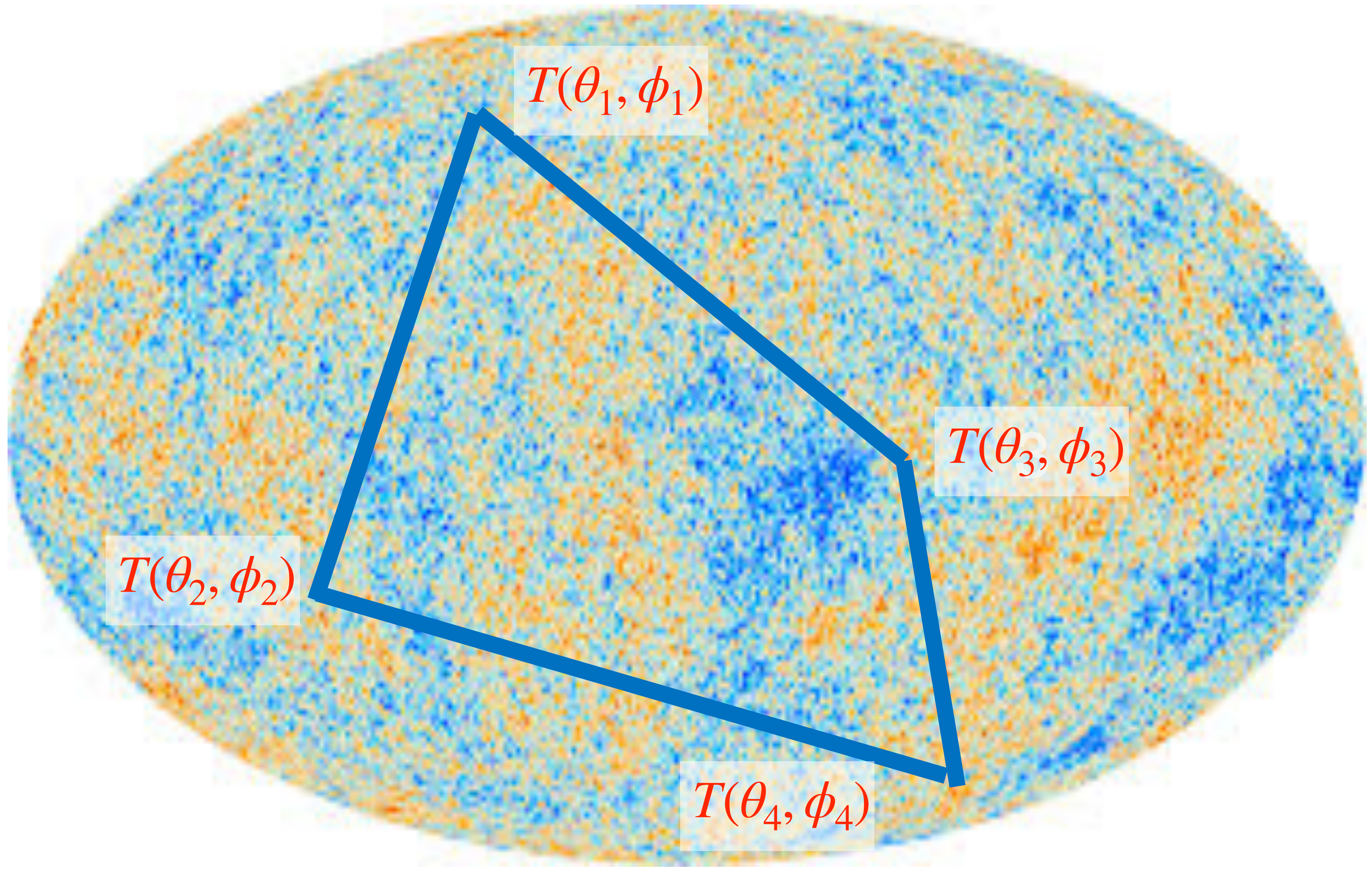
How to Measure a Four-Point Function

- 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?!

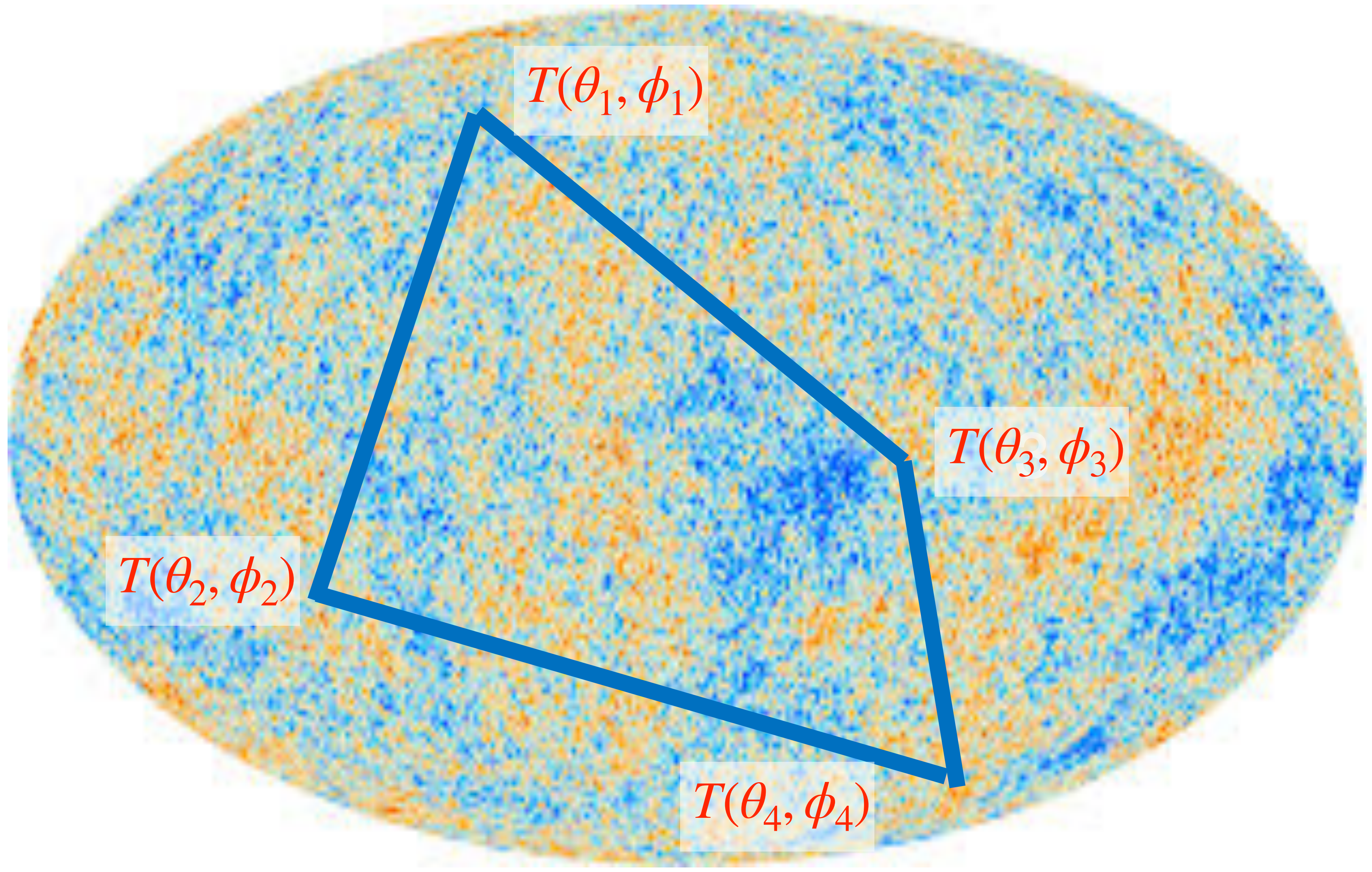
Planck 2018

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., $\tau_{\rm NL}$, 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 $\mathcal{O}(\ell_{\rm max}^2 \log \ell_{\rm max})$

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

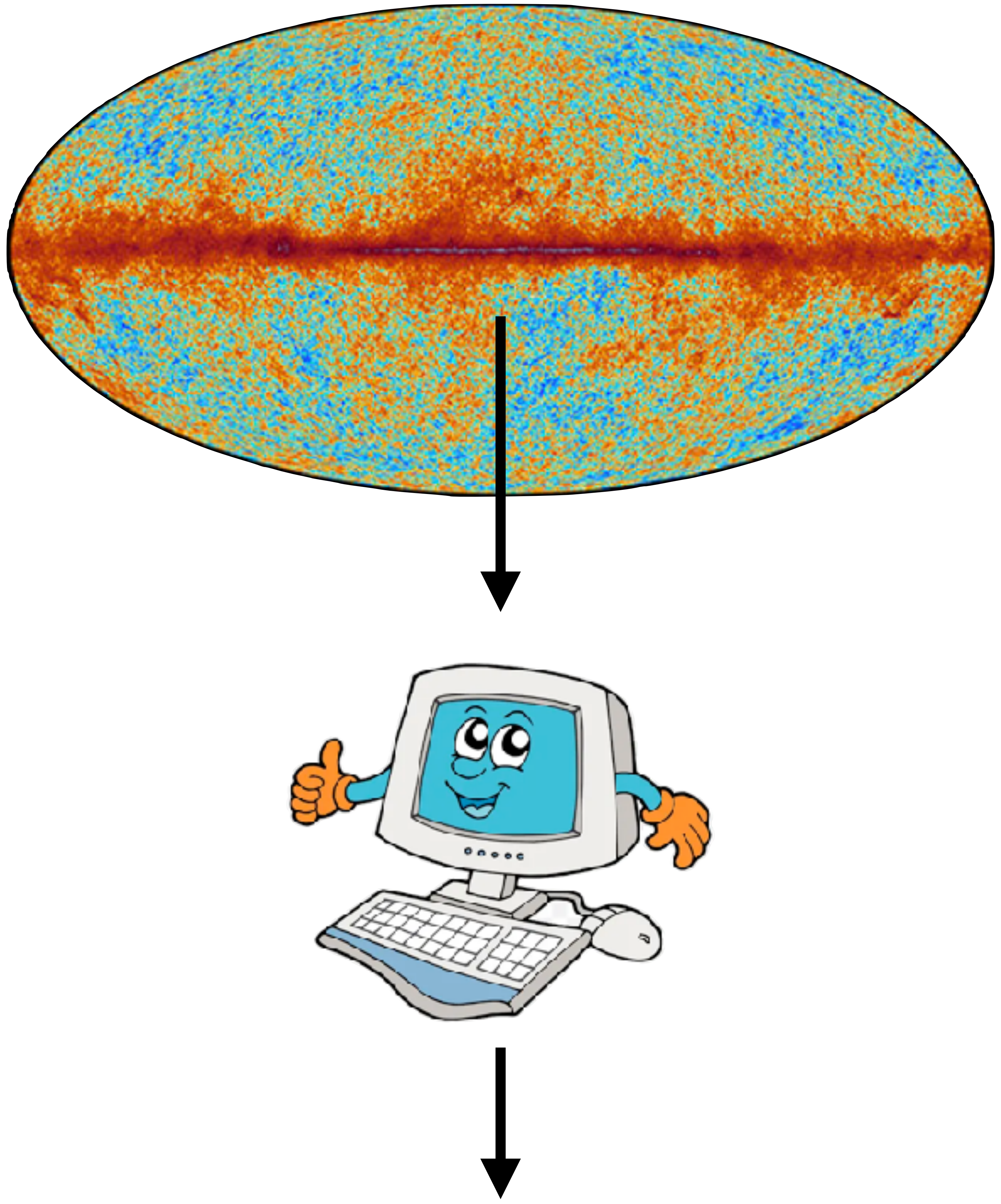
Optimal Trispectrum Analyses

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)

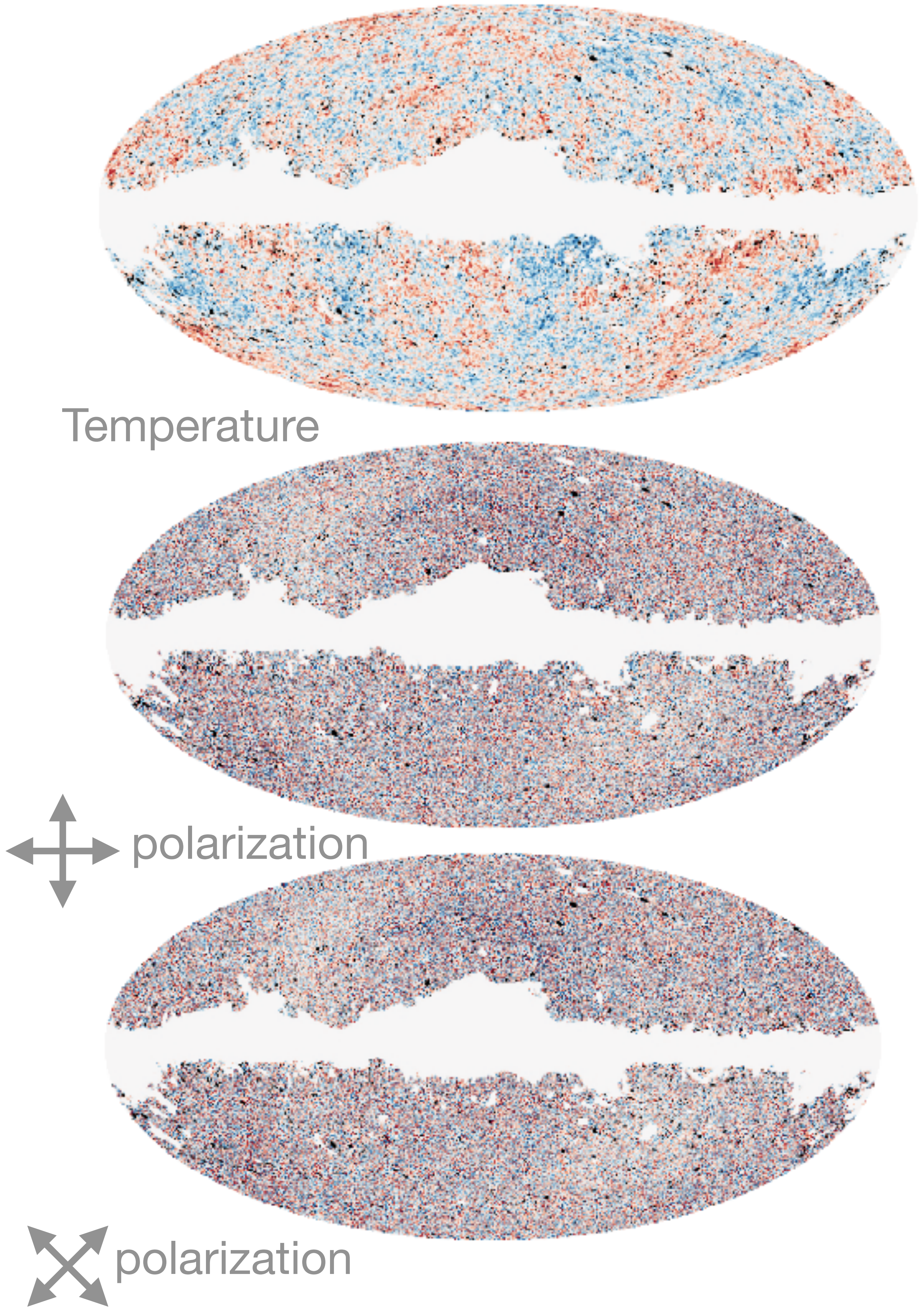
Public at **https://github.com/oliverphilcox/PolySpec**



inflation parameters

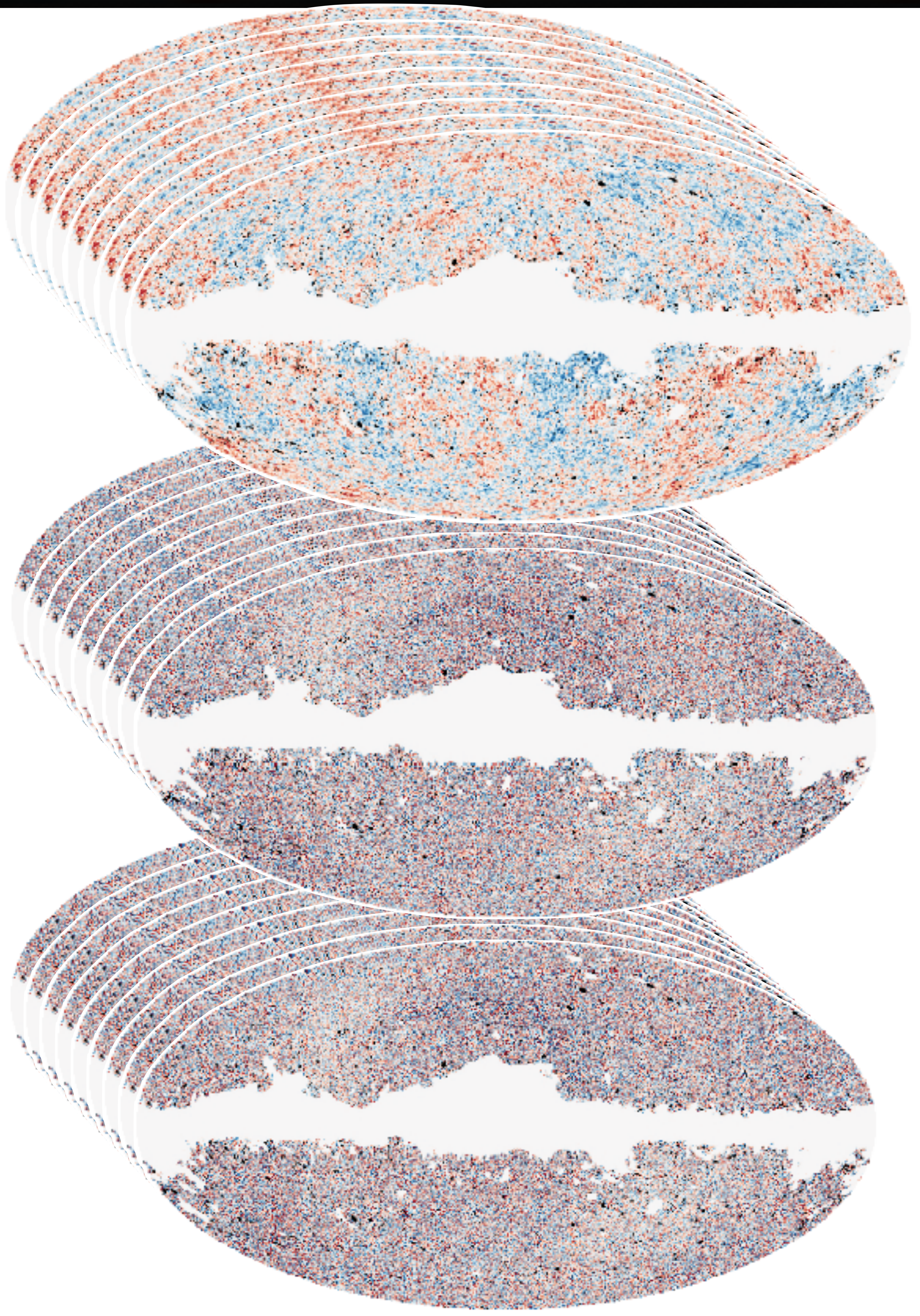
Philcox 25ab

The *Planck* Trispectrum



Planck **PR4/NPIPE data**

+



100 FFP10 simulations

+ Optimal Weighting

+ Beam & Mask

+ Transfer Functions

(+ many systematics tests)

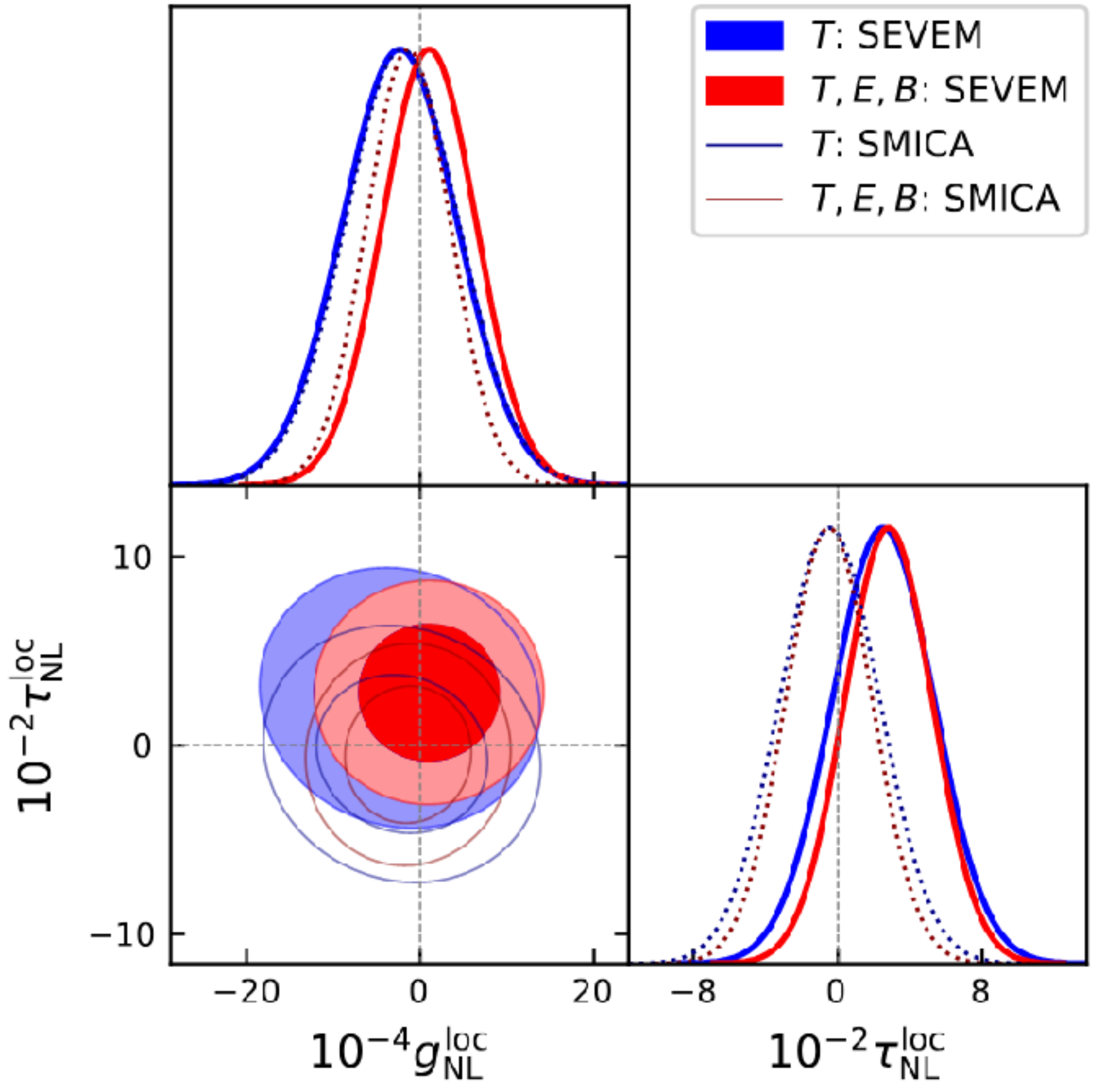
= $g_{\rm NL}, \tau_{\rm NL}$ + 31 others

Results: Local Non-Gaussianity

T+Pol > T-only

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



Cubic Quadratic^2

Outcome: Consistent with zero!

- $(30-40\%)$ improvements from polarization

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

Results: Equilateral Non-Gaussianity

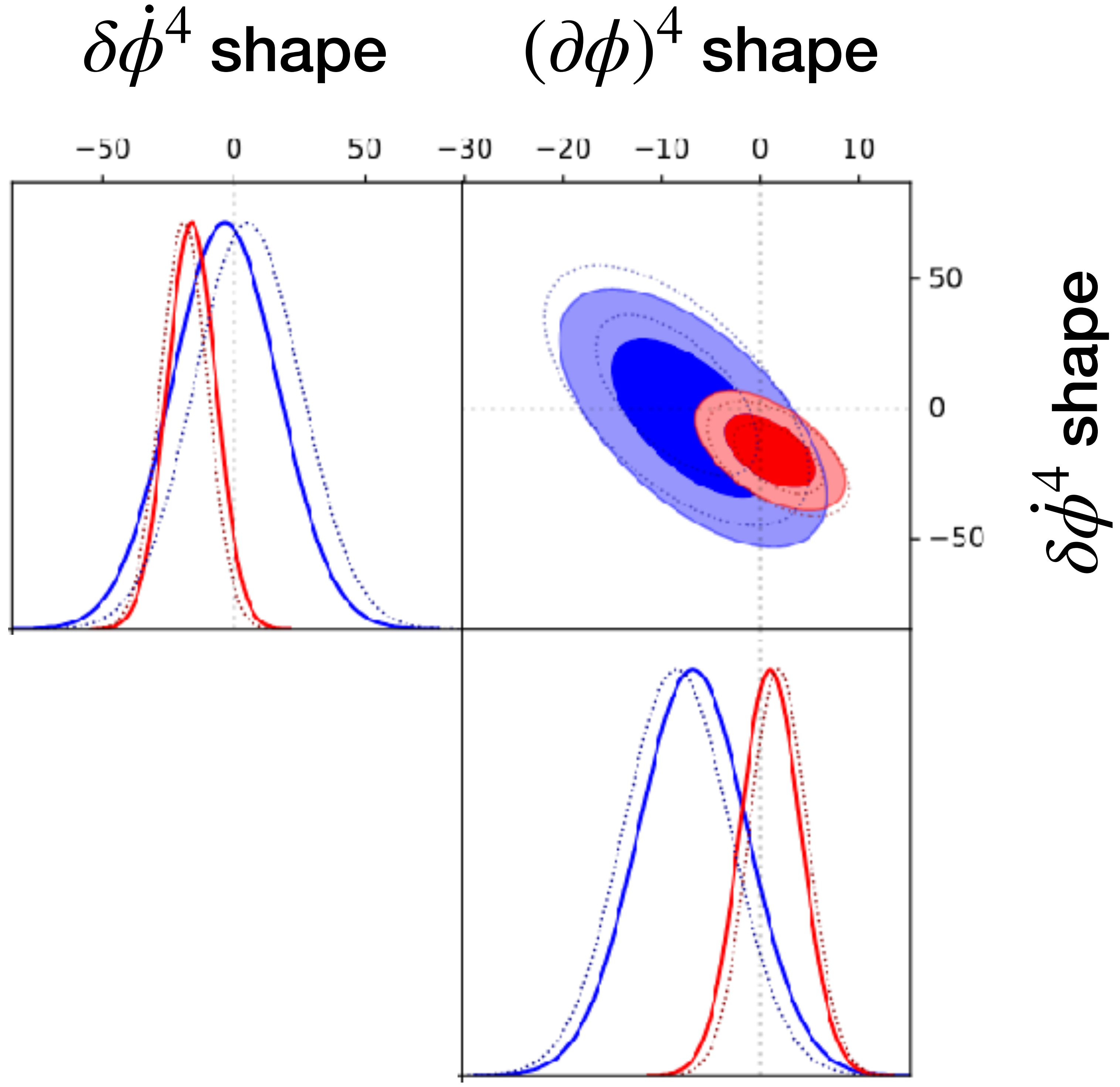
Model: *self-interactions* in inflation

- 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



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]

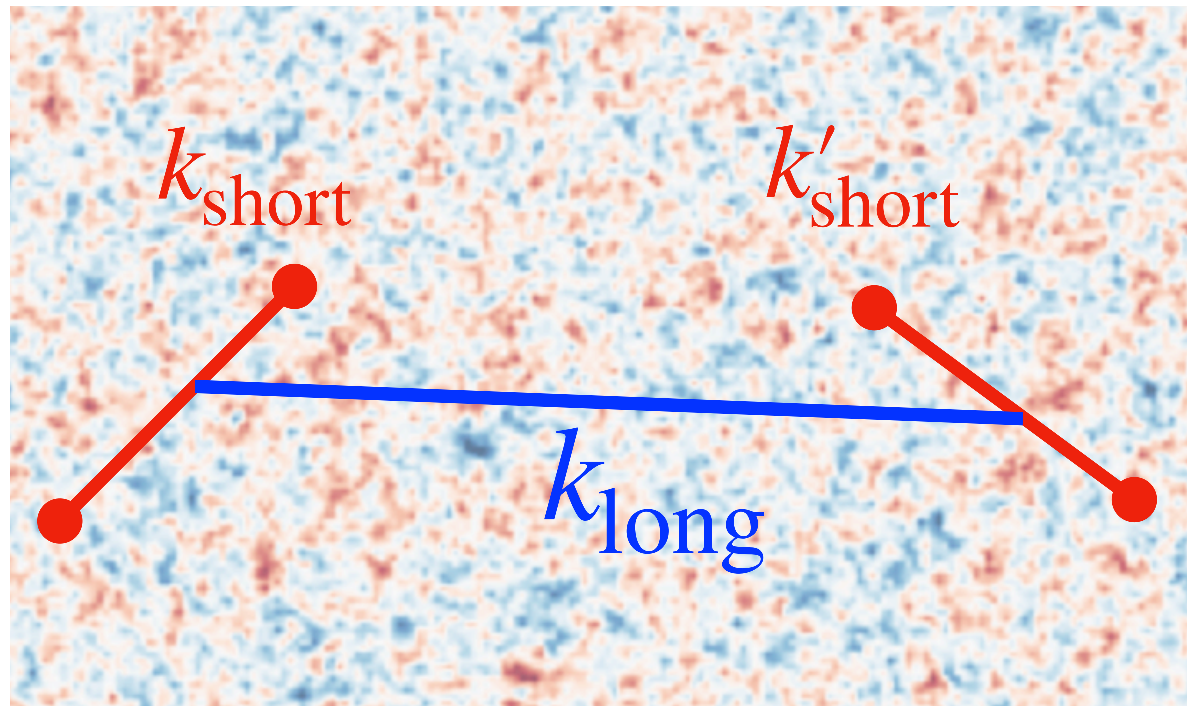
Smith+15, Planck 2015, Planck 2018, **Philcox** 25c

Results: Cosmological Collider

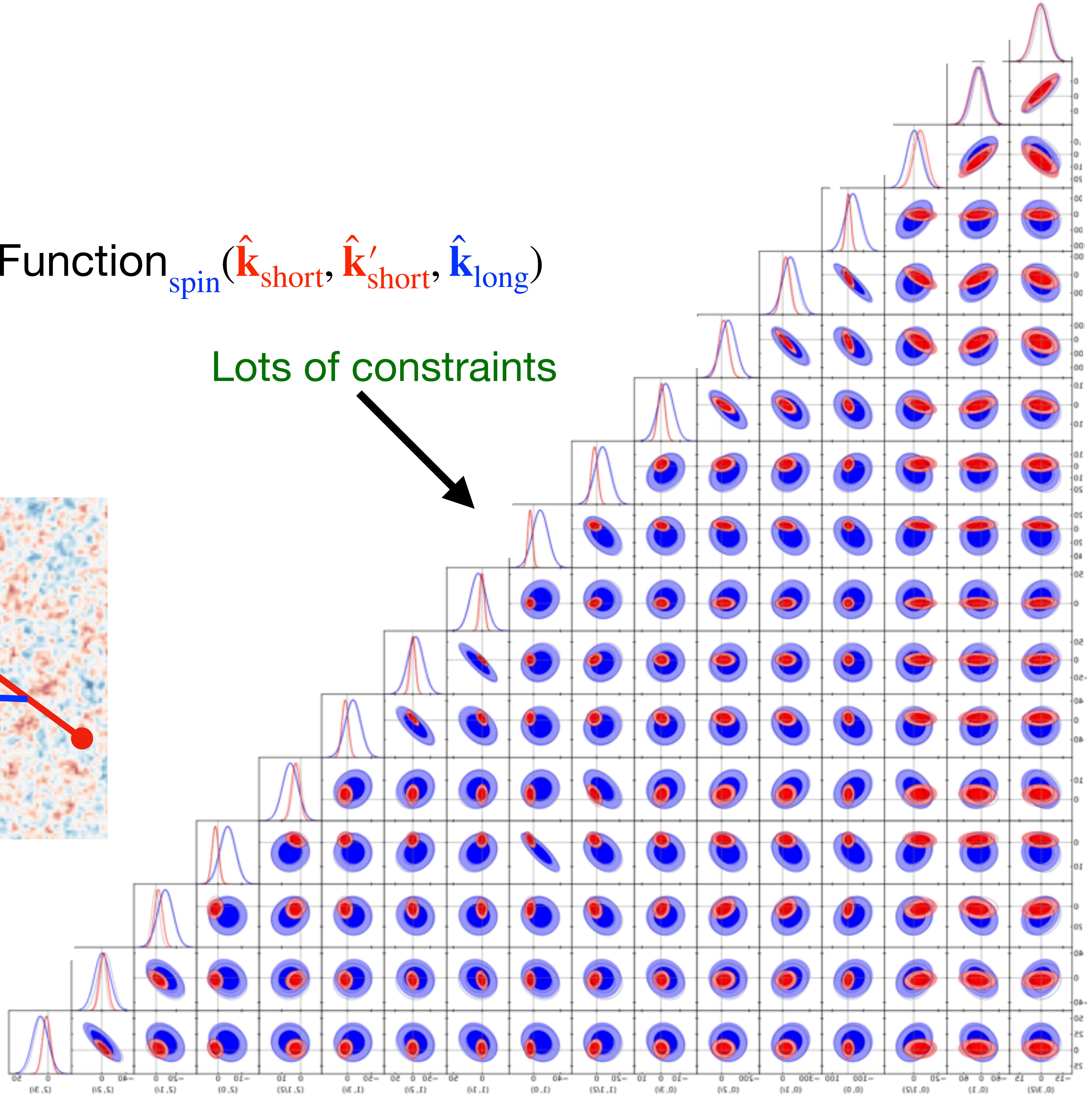
Model: *inflationary **massive** and **spinning** particles*

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

- 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!

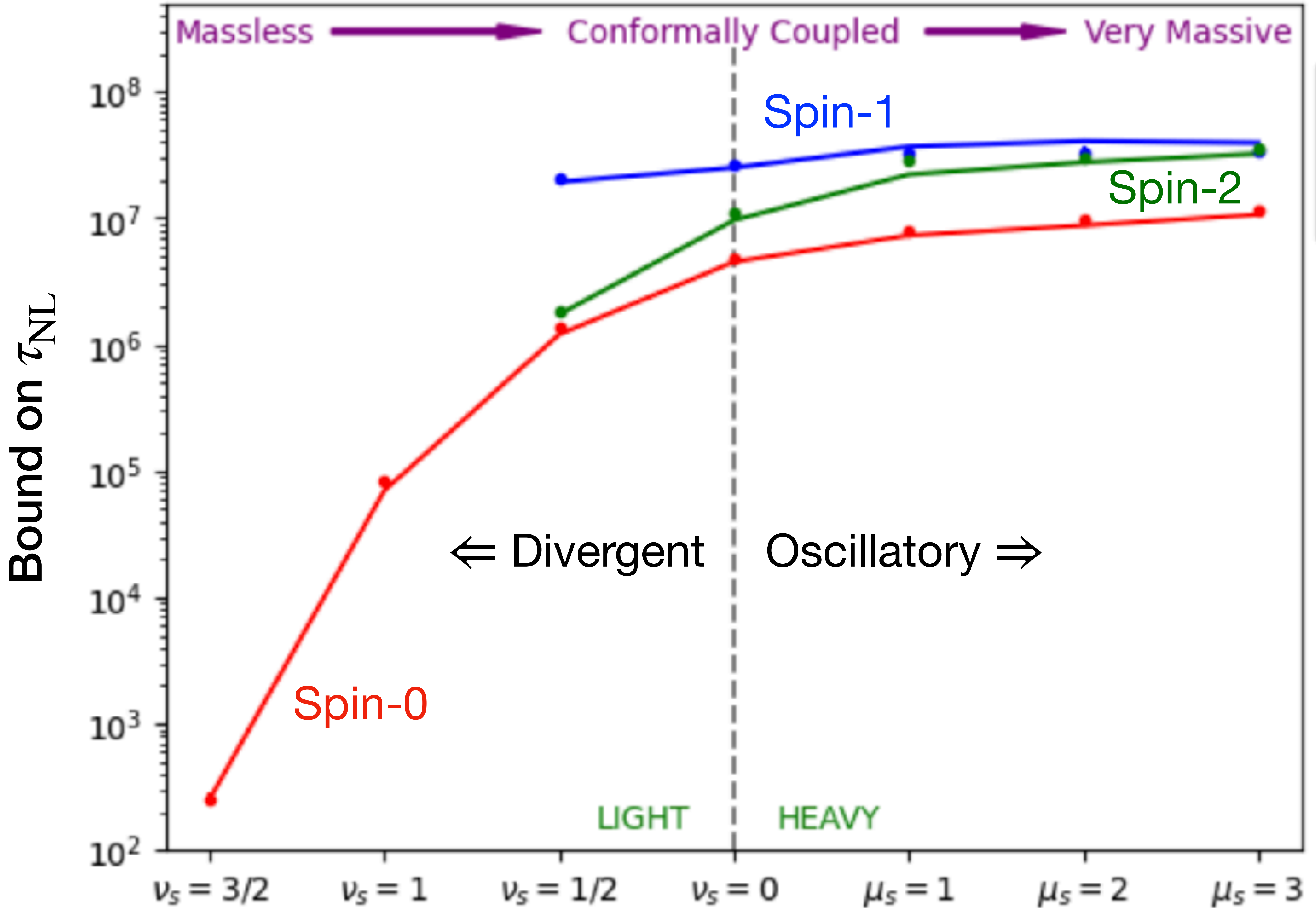
- First constraints from data!

Philcox 25c

Results: Cosmological Collider

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

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

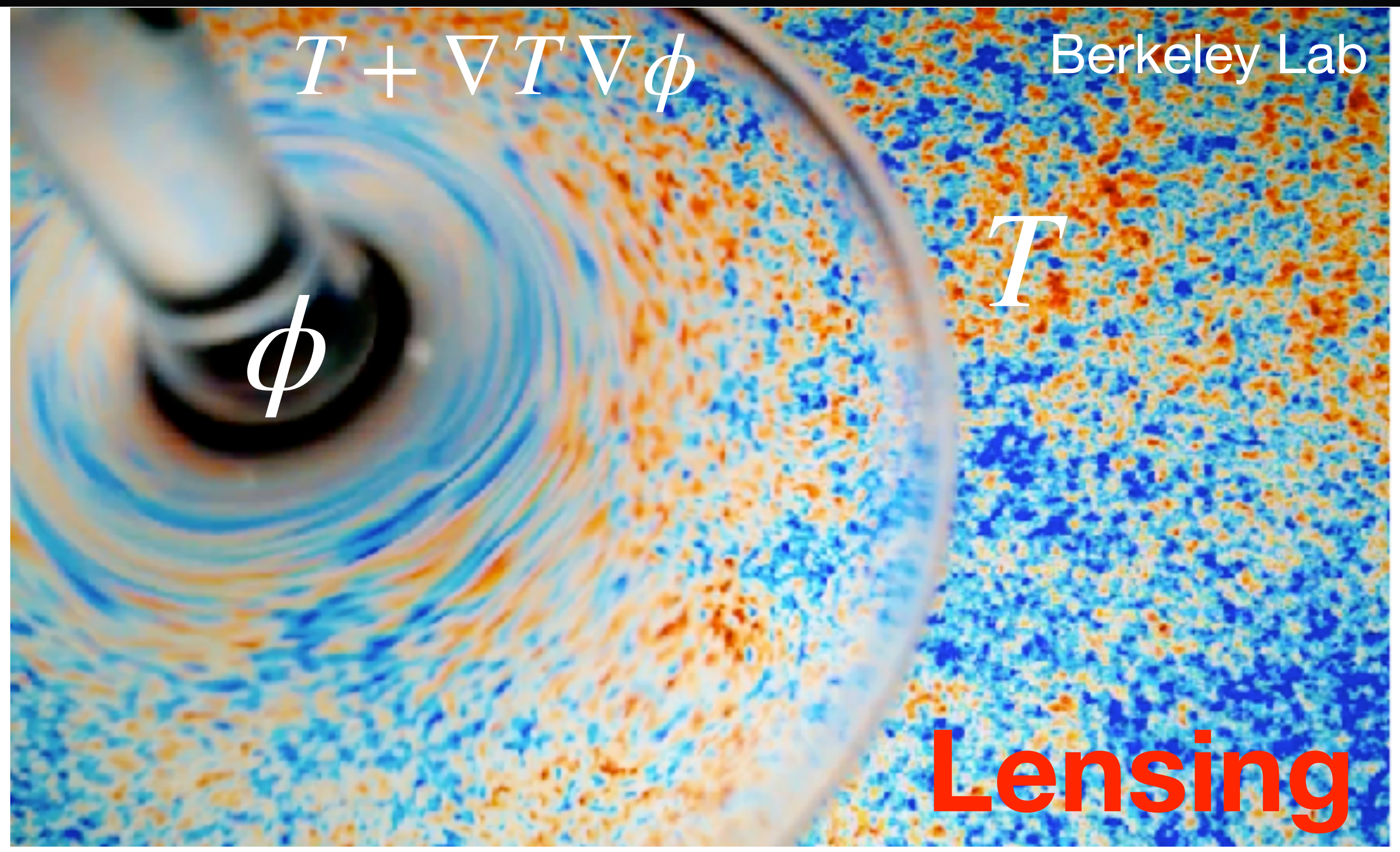
Results: Gravitational Lensing

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

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

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

$$\nabla^2 \phi \sim \int \text{dark matter}$$

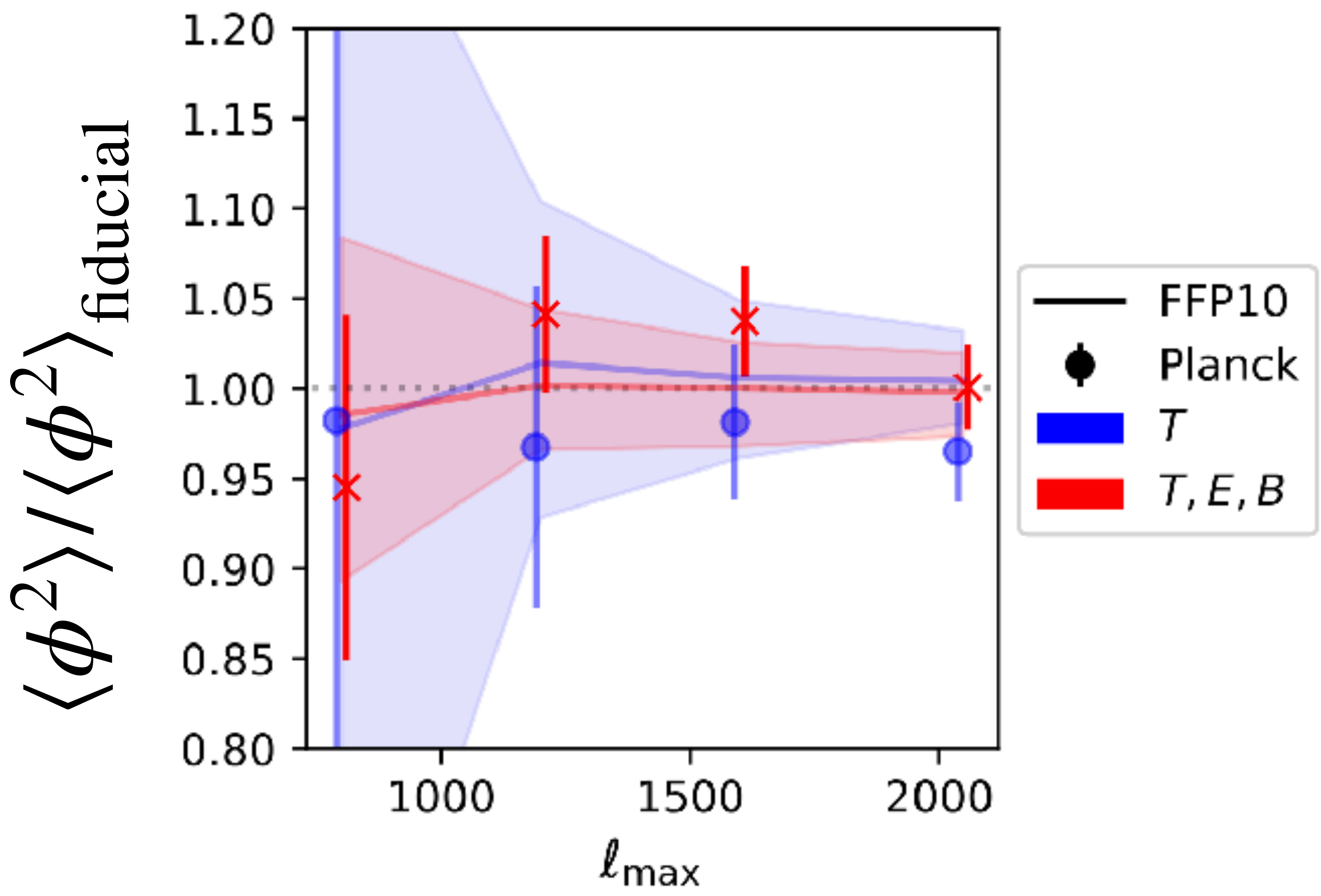


- The estimators are (almost) equivalent to the standard forms

(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

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



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** $\sigma(\tau_{\rm NL}) \sim \ell_{\rm max}^{-2}$

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

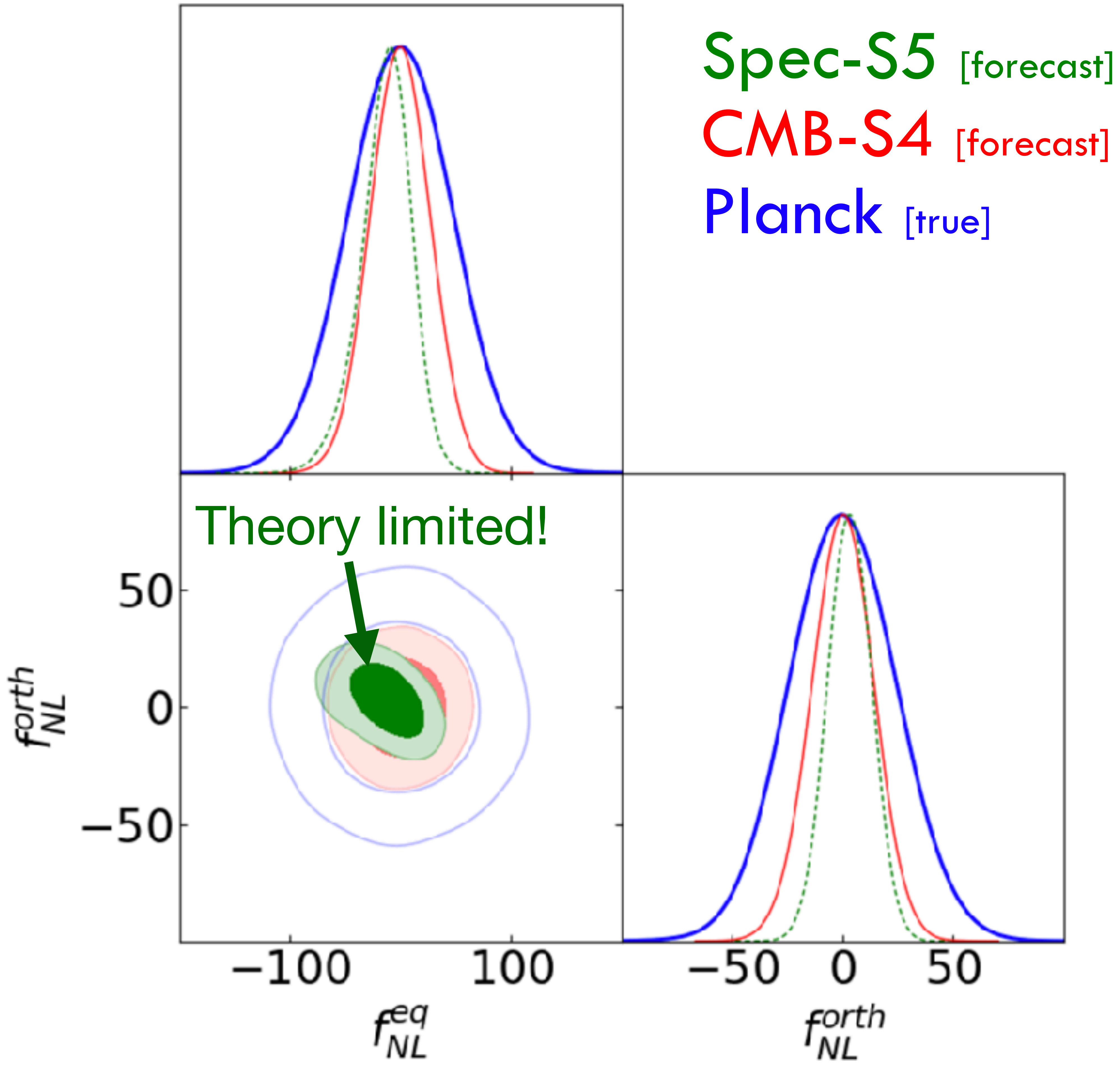
2. More **Models**

   - Lighter particles? Heavier particles?
   - 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 (in 2D) will only improve bounds by $\lesssim 10\times$
- Future **LSS** experiments (in 3D) can place **much** stronger bounds on non-Gaussianity!
- Recent works have constrained several **three-point** function amplitudes, $f_{\rm NL}$ using **Galaxy Surveys**:
  - **Local:** additional **light fields**
  - **Equilateral:** cubic interactions in single-field inflation
  - **Collider:** 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!