Colliders in the Sky

Constraining High-Energy Physics with CMB and LSS Observations

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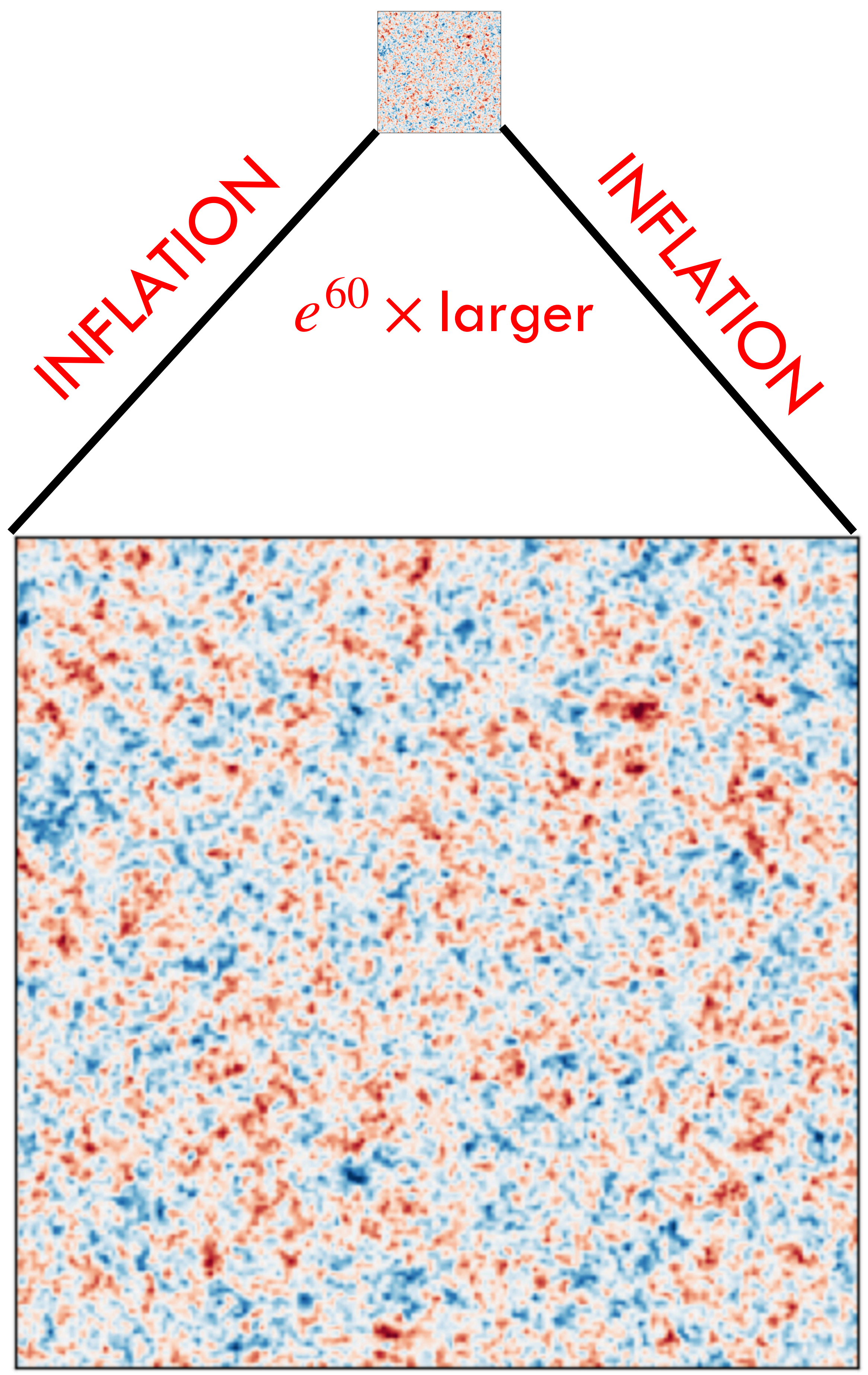
Outline of this Talk

What do we know about the early Universe?

<u>Background</u>

- Almost **exponential** expansion of spacetime

  ⇒ Explains the Universe's **flatness, uniformity**, and (lack of) **monopoles**



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

What do we know about the early Universe?

<u>Background</u>

- Almost **exponential** expansion of spacetime

  $\Rightarrow$ Explains the Universe's **flatness, uniformity**, and (lack of) **monopoles**

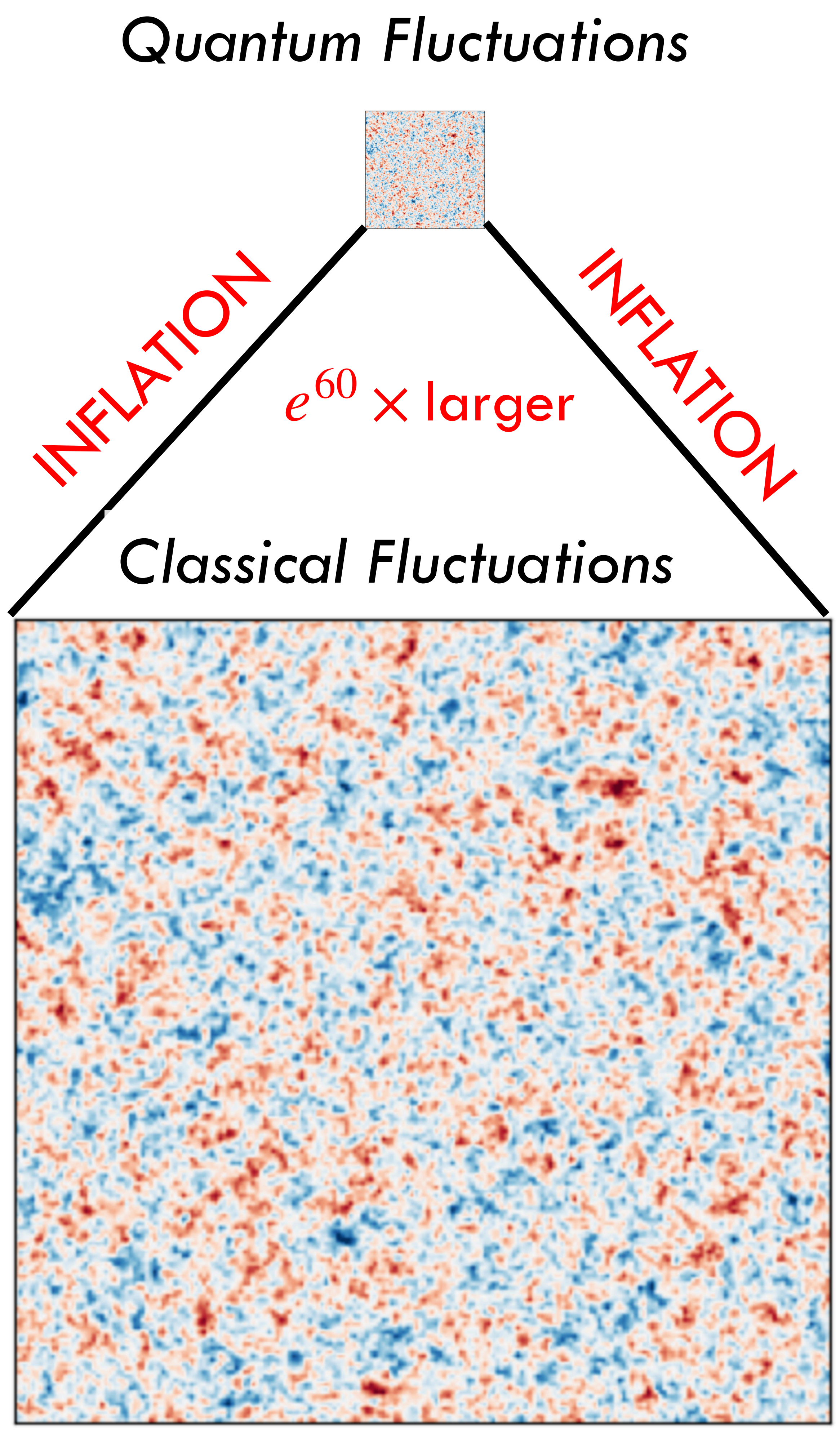
<u>Perturbations</u>

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

  $\Rightarrow$ Predicts that the distribution of ζ should be **Gaussian**!

$$\zeta(\mathbf{k}) \sim \mathrm{Normal}[0, P_\zeta(k)], \qquad P_\zeta(k) \sim \langle \zeta(\mathbf{k})\zeta^*(\mathbf{k})\rangle$$

(k = Fourier-space momentum)



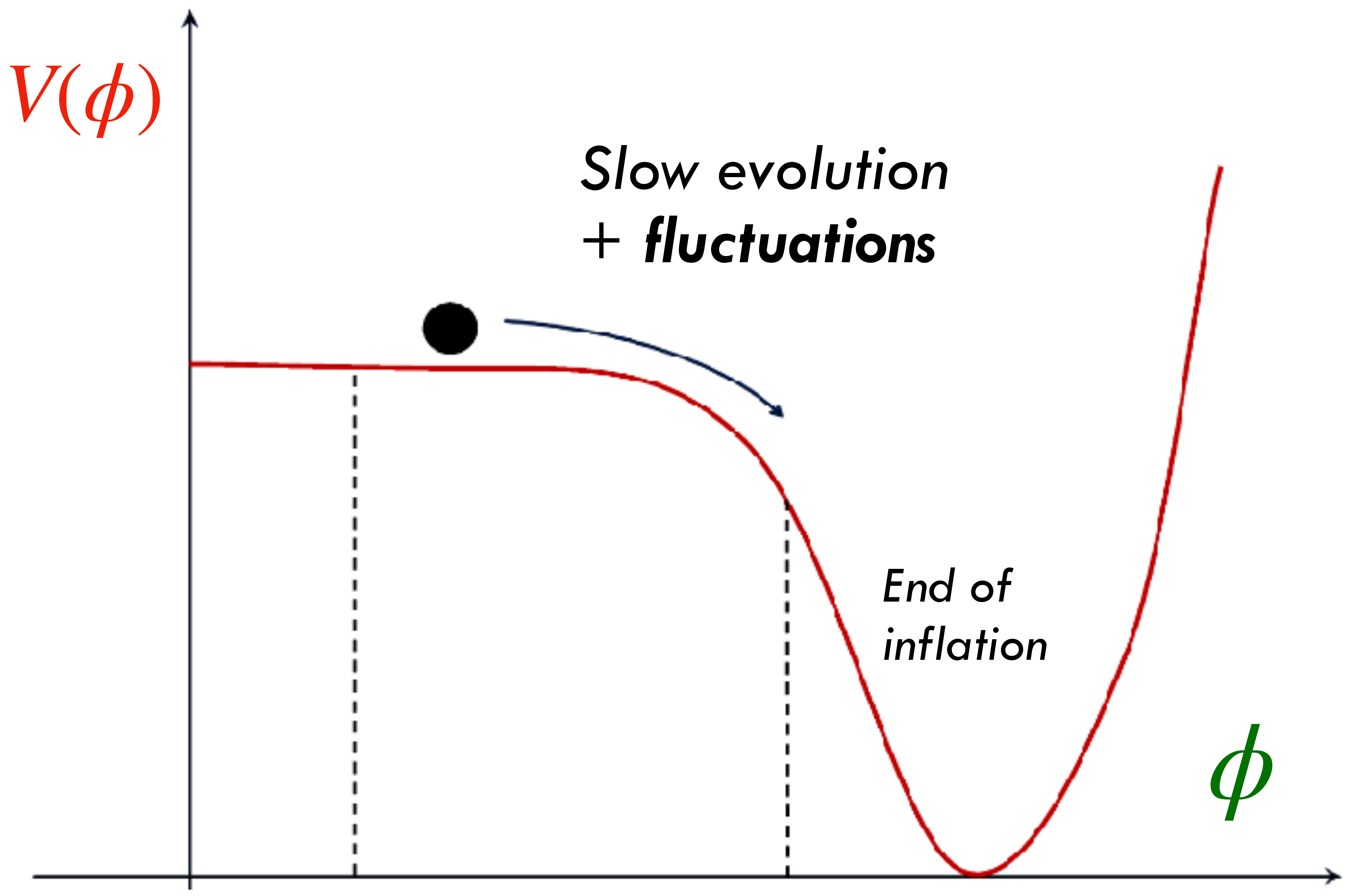
COBE, WMAP, Planck, Linde, Guth, Starobinsky, …

What do we know about the early Universe?

Simplest (phenomenological) model

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

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



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

What do we want to know about the early Universe?

Simplest (phenomenological) model

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

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

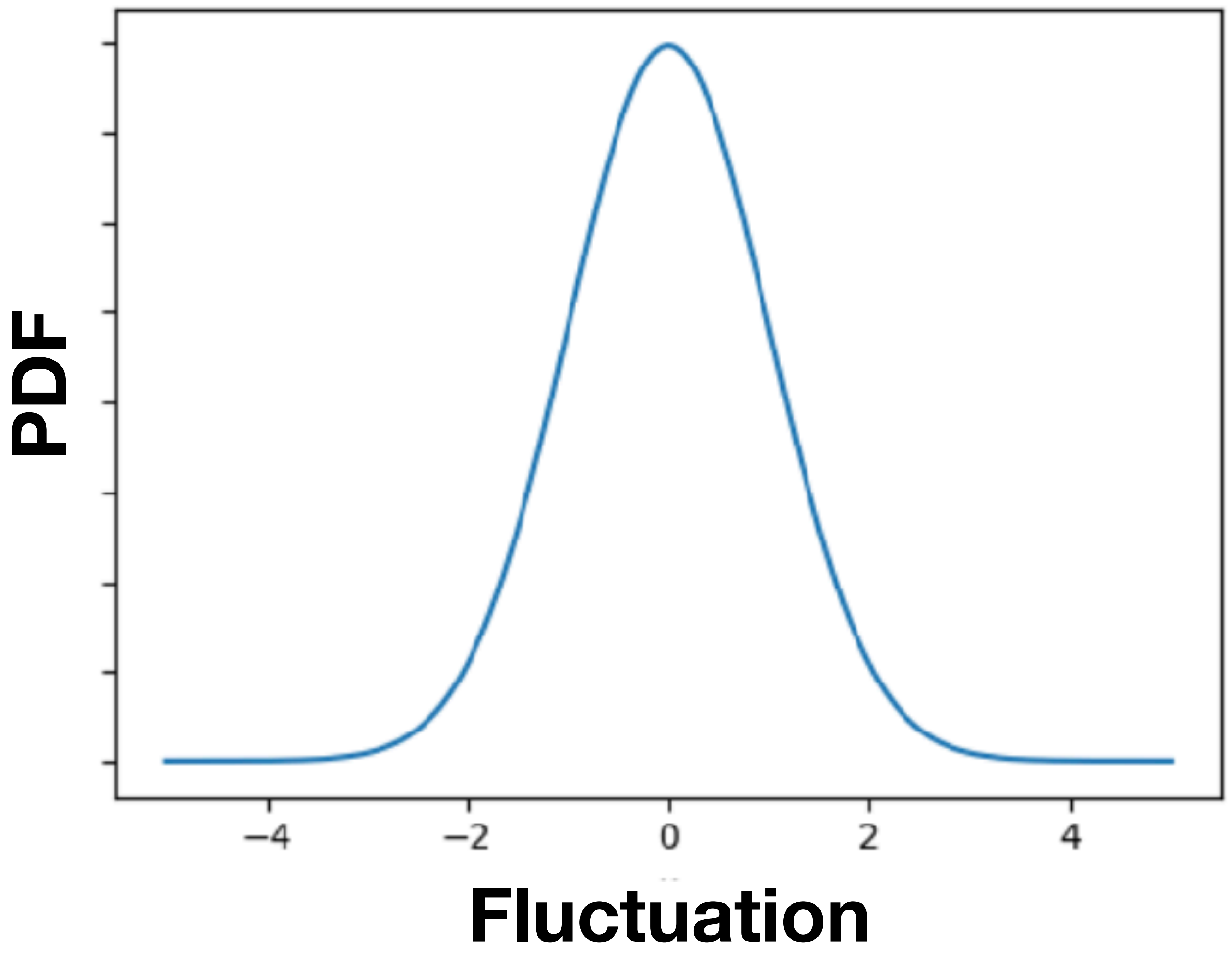
HOWEVER:

- What is the **energy scale** of inflation? $\longrightarrow$ $E \lesssim 10^{13}\mathrm{TeV}$
- What sets the **potential**? $\longrightarrow$ $V(\phi) = ???$
- Were there **other fields** during inflation? $\longrightarrow$ $\phi \to \phi, \chi, \psi_u, \cdots$
- Did the fields **interact**? $\longrightarrow$ Lagrangian $\supset \dot{\phi}^3 + \cdots$

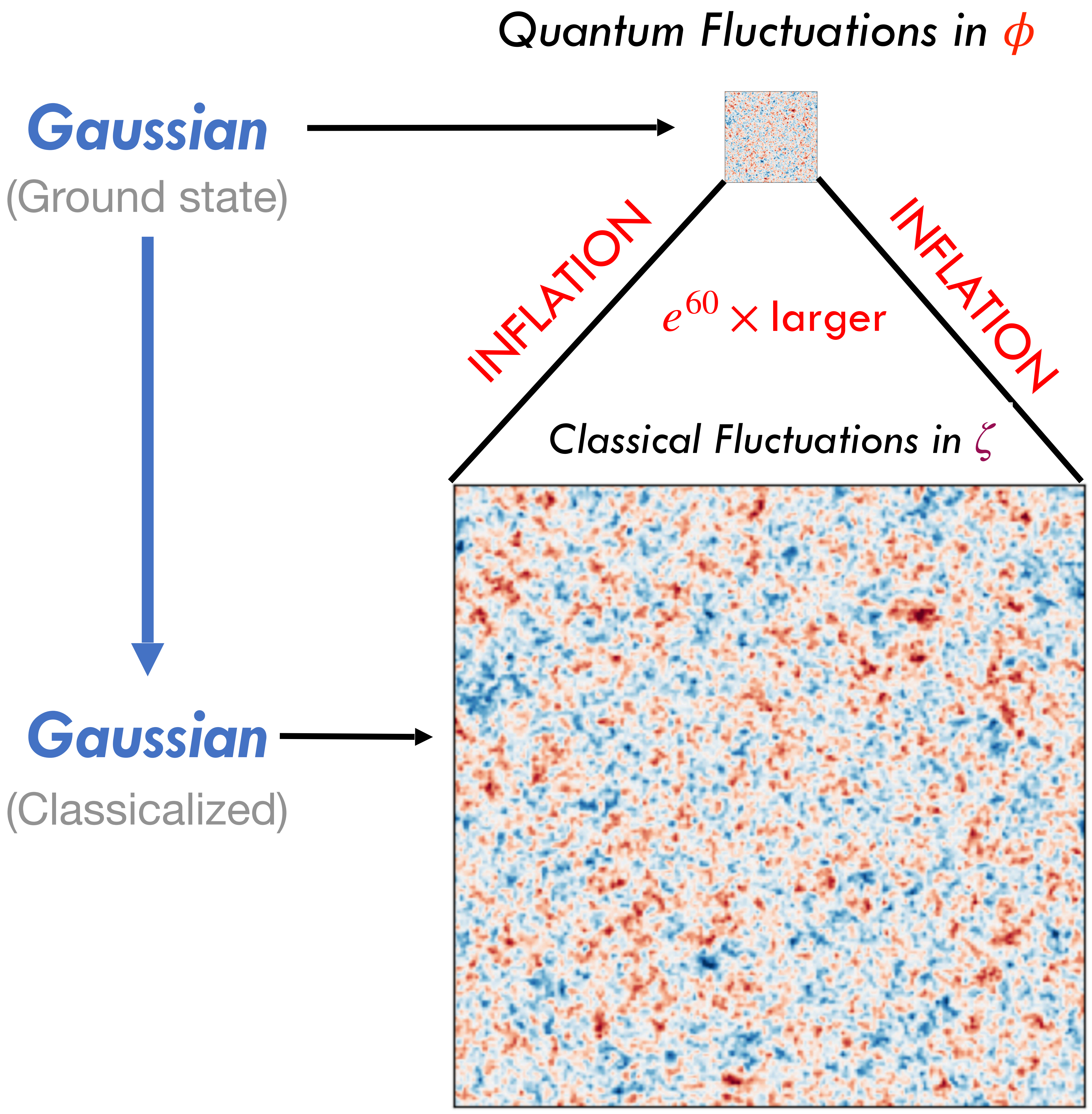
Linde, Guth, Starobinsky, Lyth, Mukhanov, Sasaki, …

Statistics of Inflation

Simplest inflationary models ⇒ **Gaussian** fluctuations in ζ



$$\mathscr{P}(\zeta) \sim e^{-\frac{1}{2}\zeta^2/P_\zeta}$$

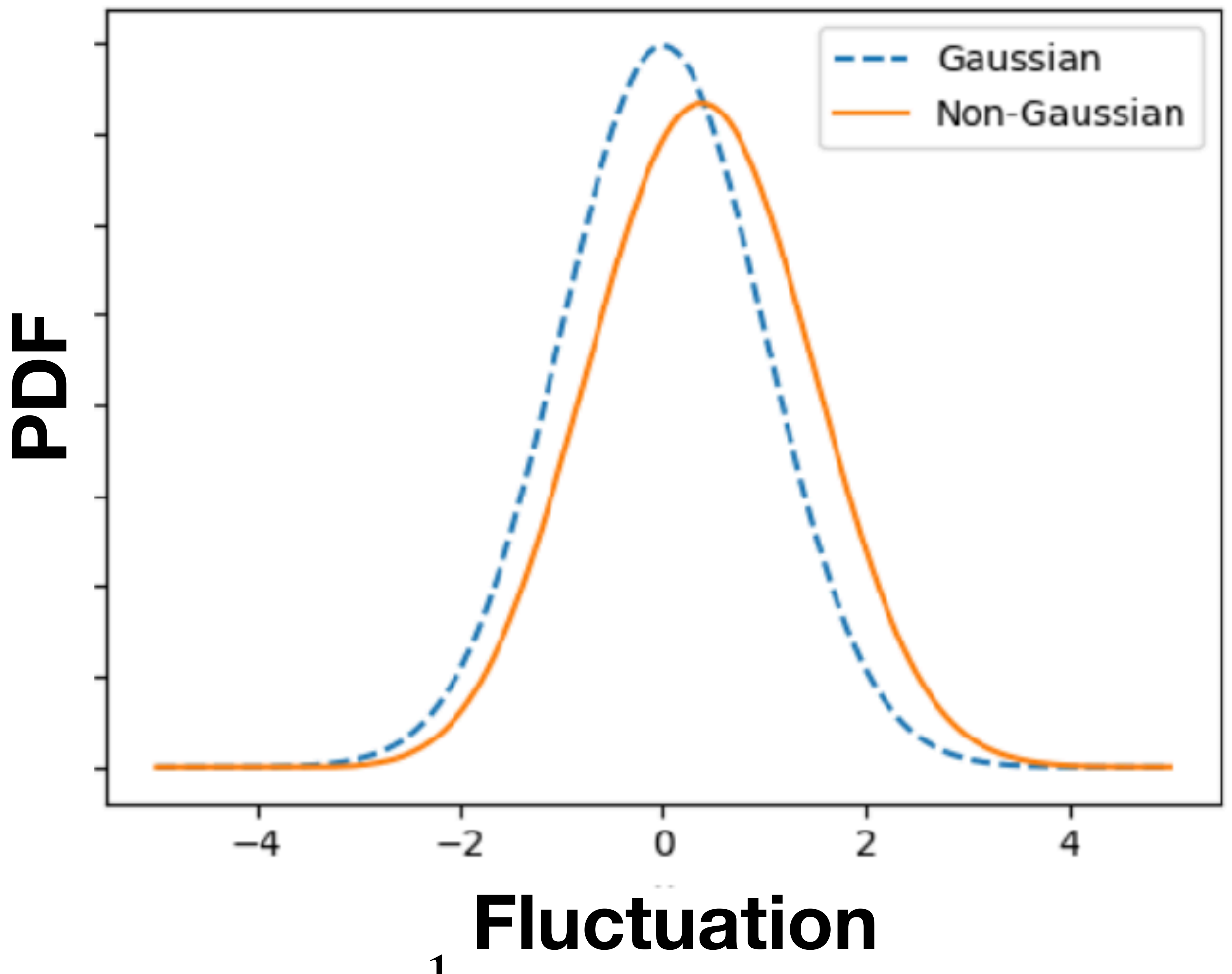


COBE, WMAP, Planck, Linde, Guth, Starobinsky, …

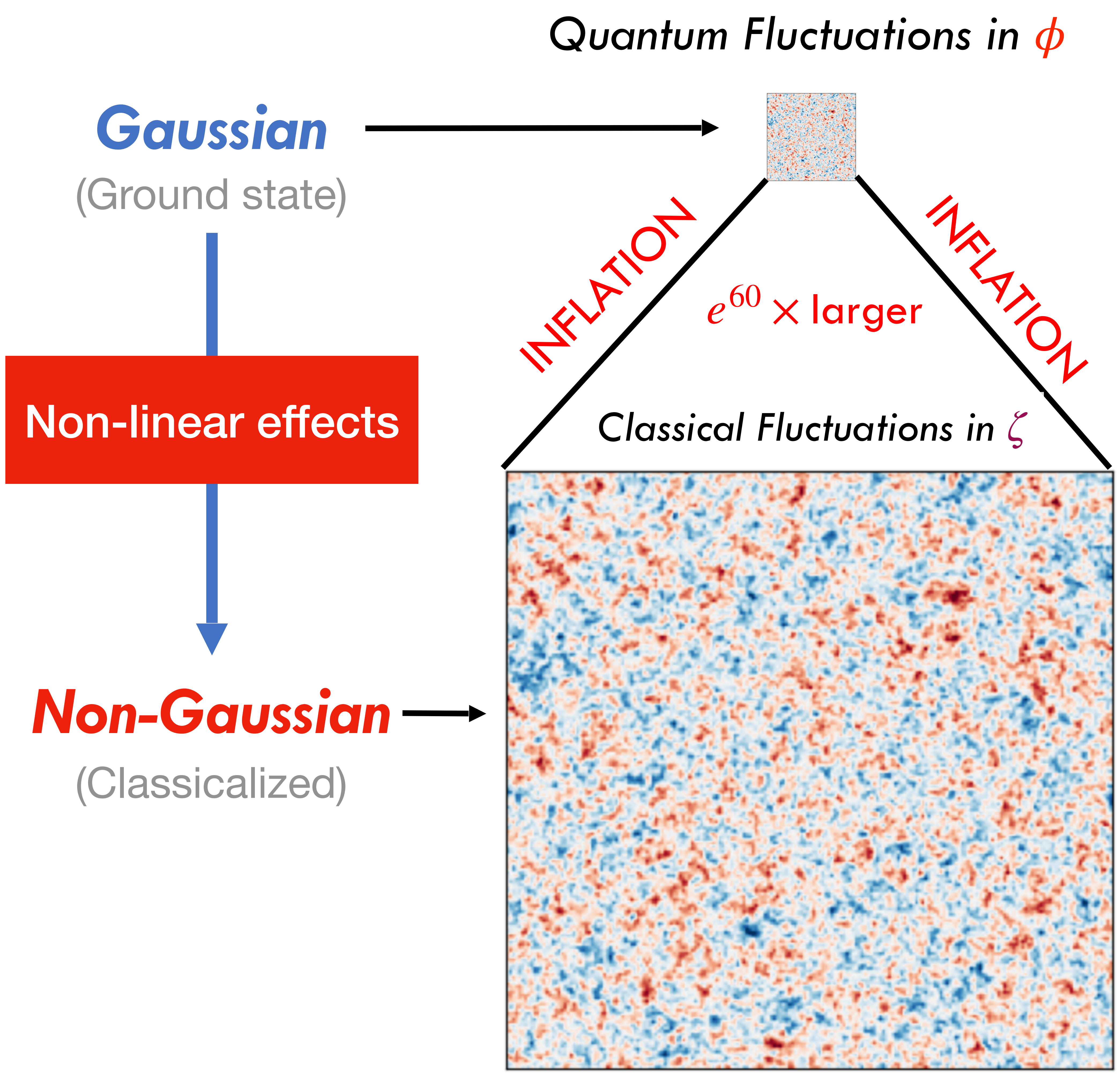
Statistics of Inflation

Simplest inflationary models ⇒ **Gaussian** fluctuations in ζ

Non-linear effects ⇒ **Non-Gaussian** fluctuations in ζ



$$\mathscr{P}(\zeta) \sim e^{-\frac{1}{2}\zeta^2/P_\zeta}\left(1+\zeta^3 B_\zeta+\zeta^4 T_\zeta+\cdots\right)$$



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

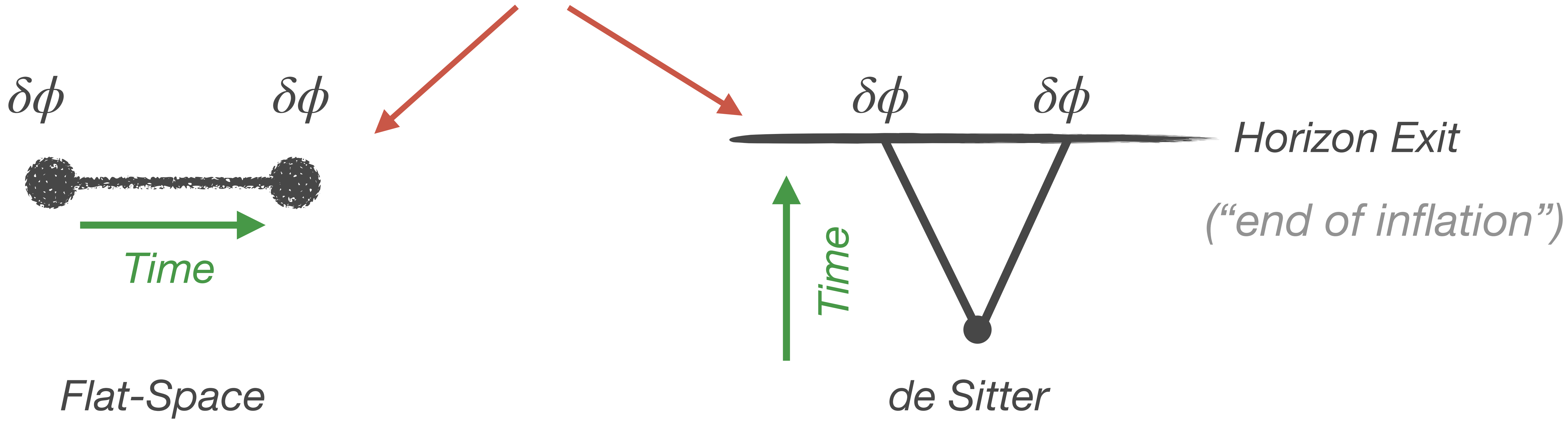
COBE, WMAP, Planck, Linde, Guth, Starobinsky, …

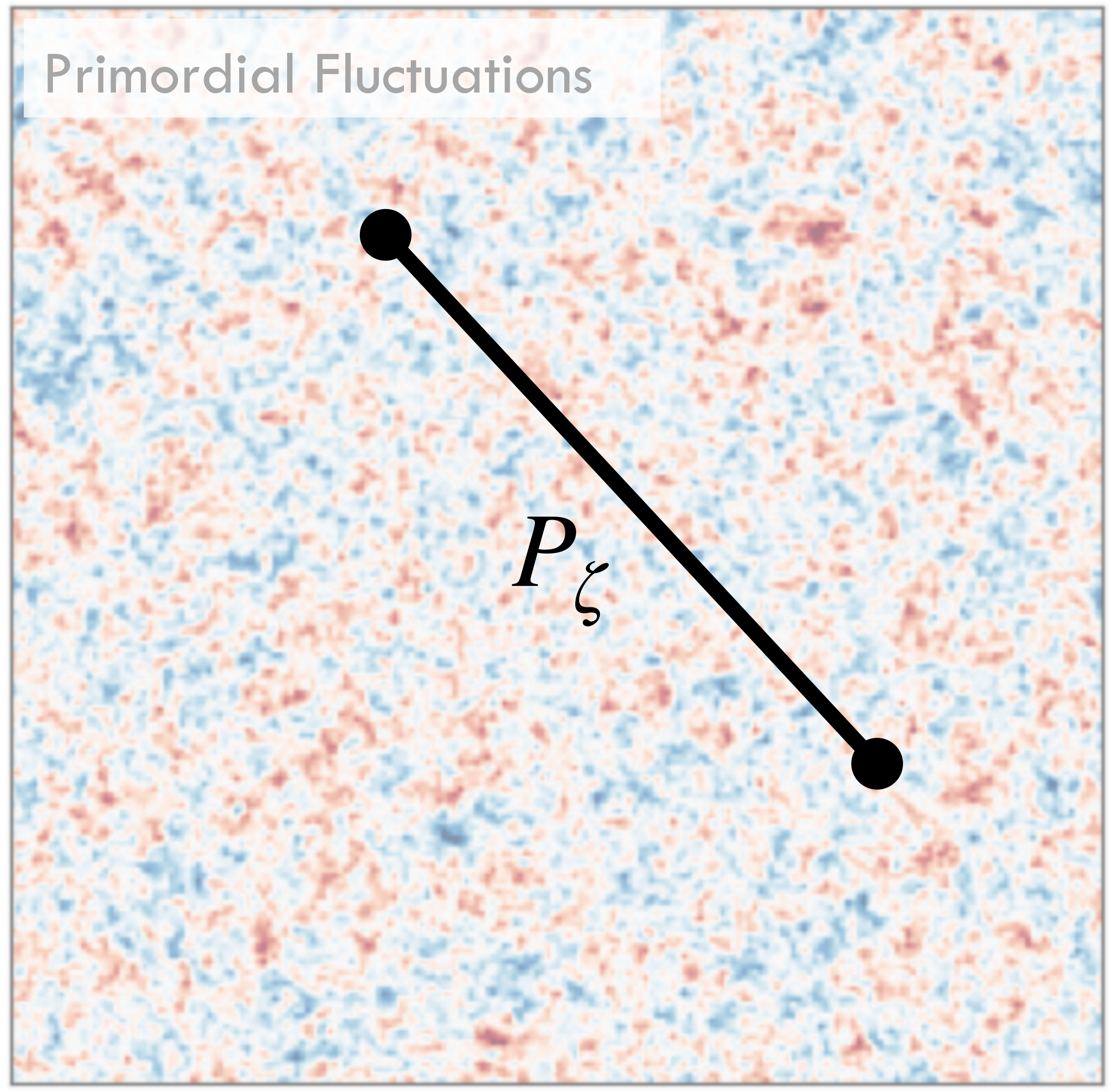
Vanilla Inflation

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

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

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





- This correlates the curvature at **two points** in space

$$P_\zeta(k) = \langle \zeta(\mathbf{k})\zeta(-\mathbf{k}) \rangle \sim k^{-3-\epsilon}$$

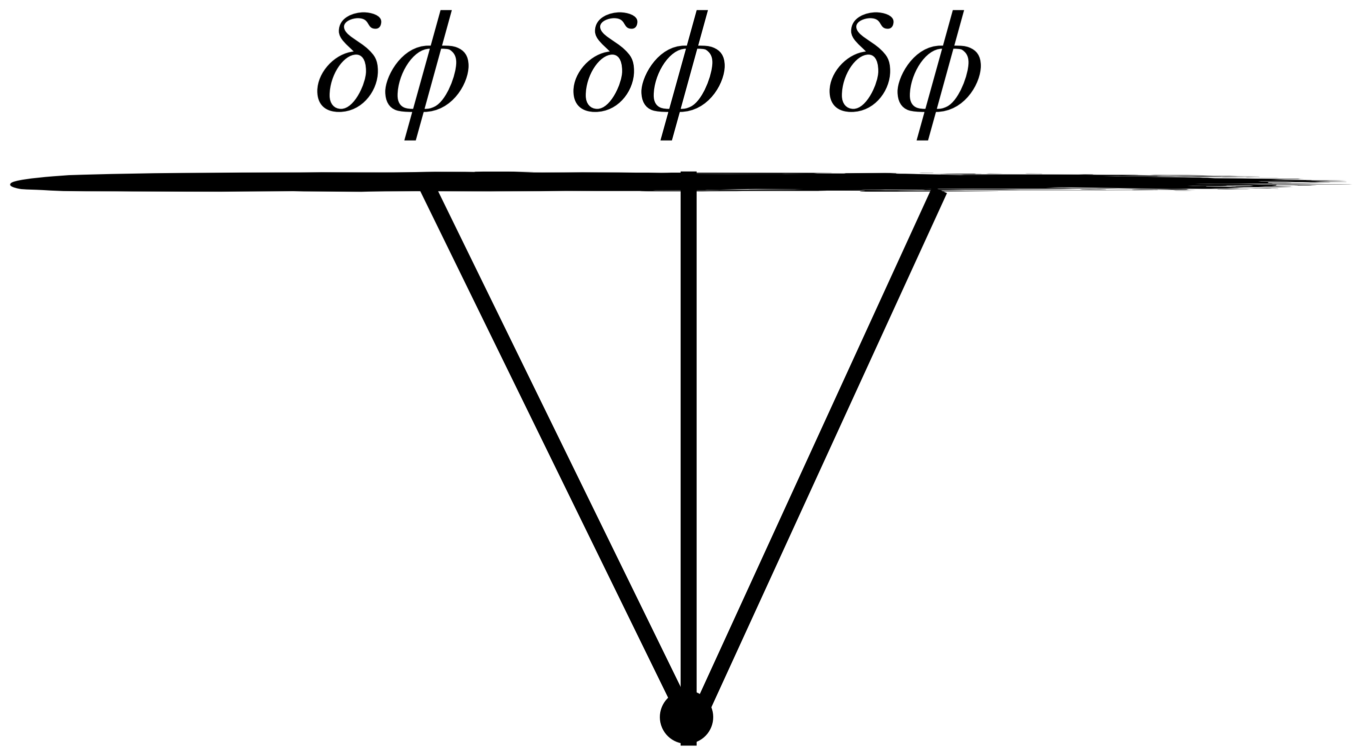
(*This could be an effective degree of freedom, *i.e.* the Goldstone mode of broken time translations)

Maldacena, Arnold, Deser, Misner, …

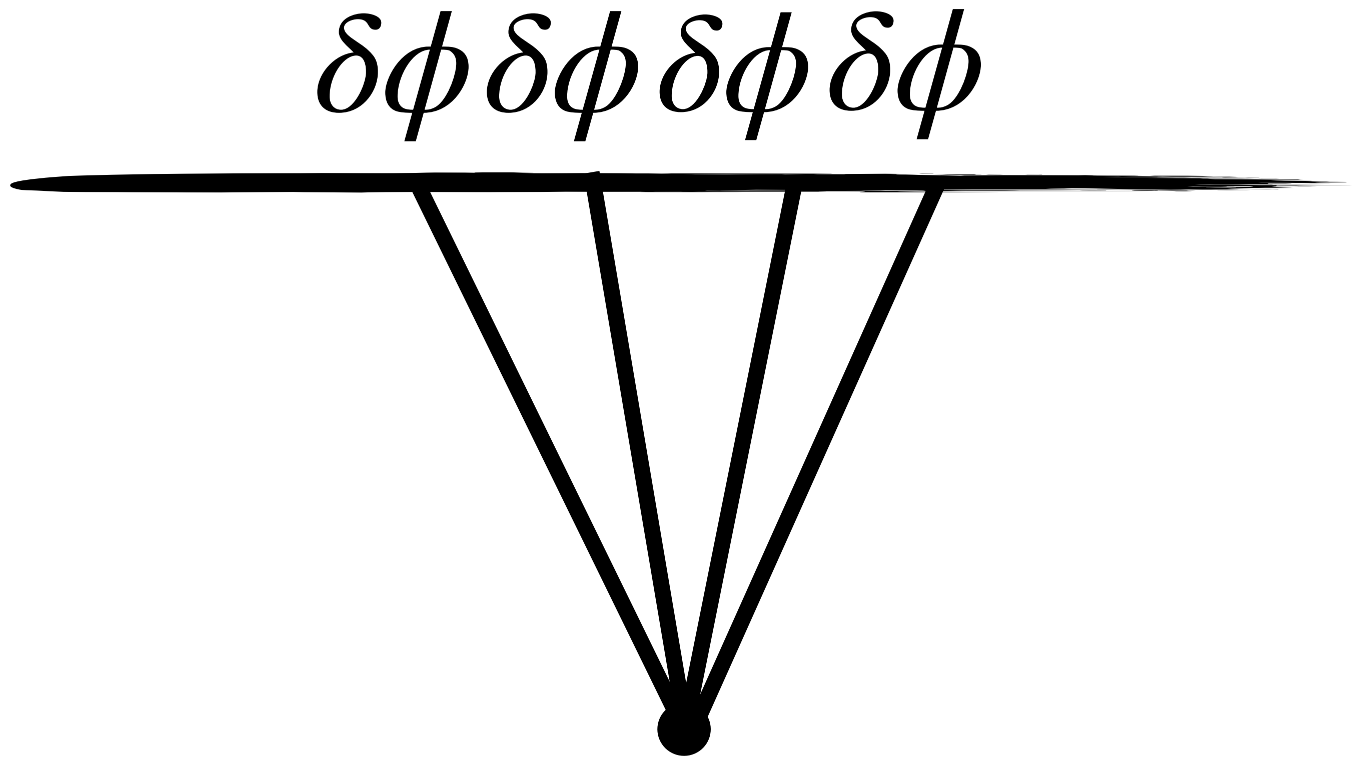
Self-Interactions

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

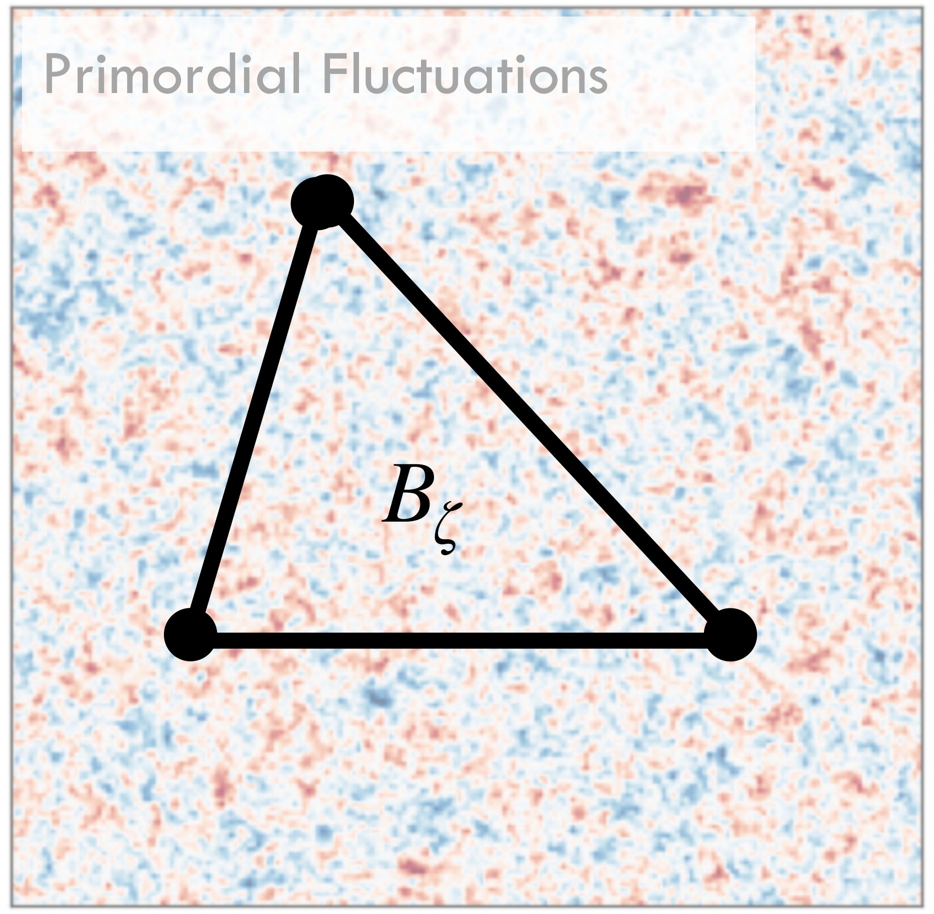
$$\mathscr{L} \supset \delta\dot{\phi}^3, \quad \delta\dot{\phi}(\partial\phi)^2, \quad \delta\dot{\phi}^4, \quad \cdots$$

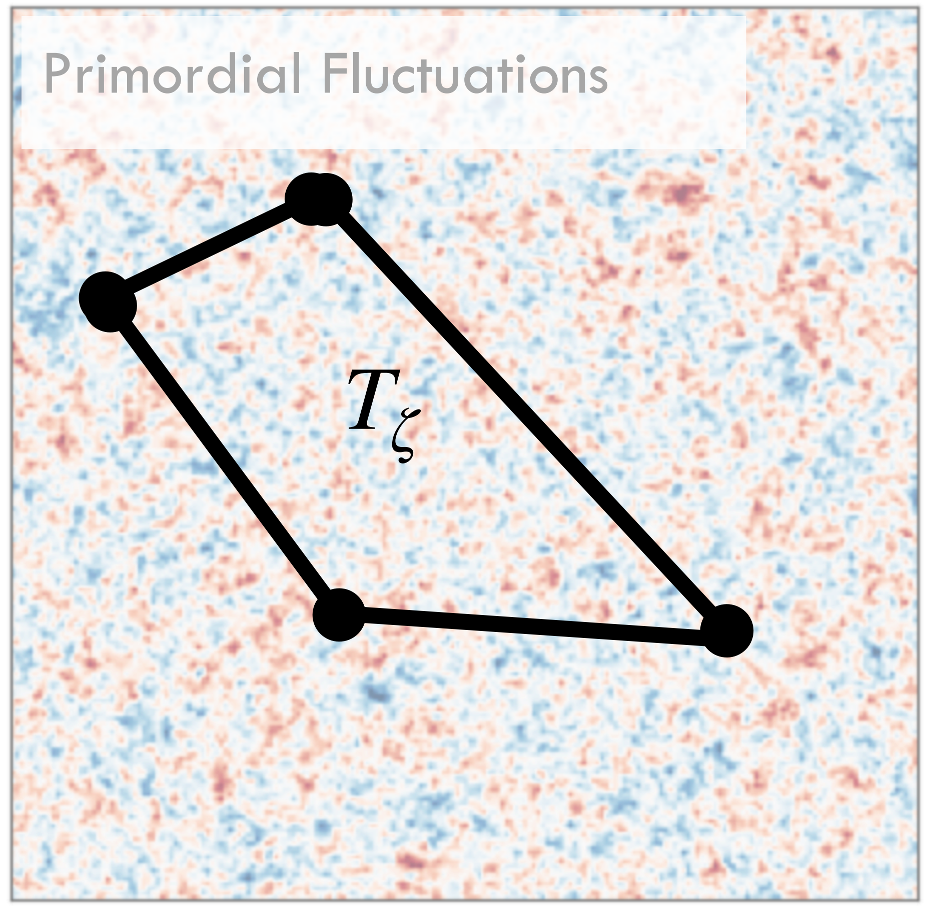


Cubic $\sim f_{\rm NL}^{\rm eq}$



Quartic $\sim g_{\rm NL}$





- These lead to **three**- and **four**-point functions at the end of inflation

- The **shape** encodes the vertex, the **amplitude** encodes the microphysics

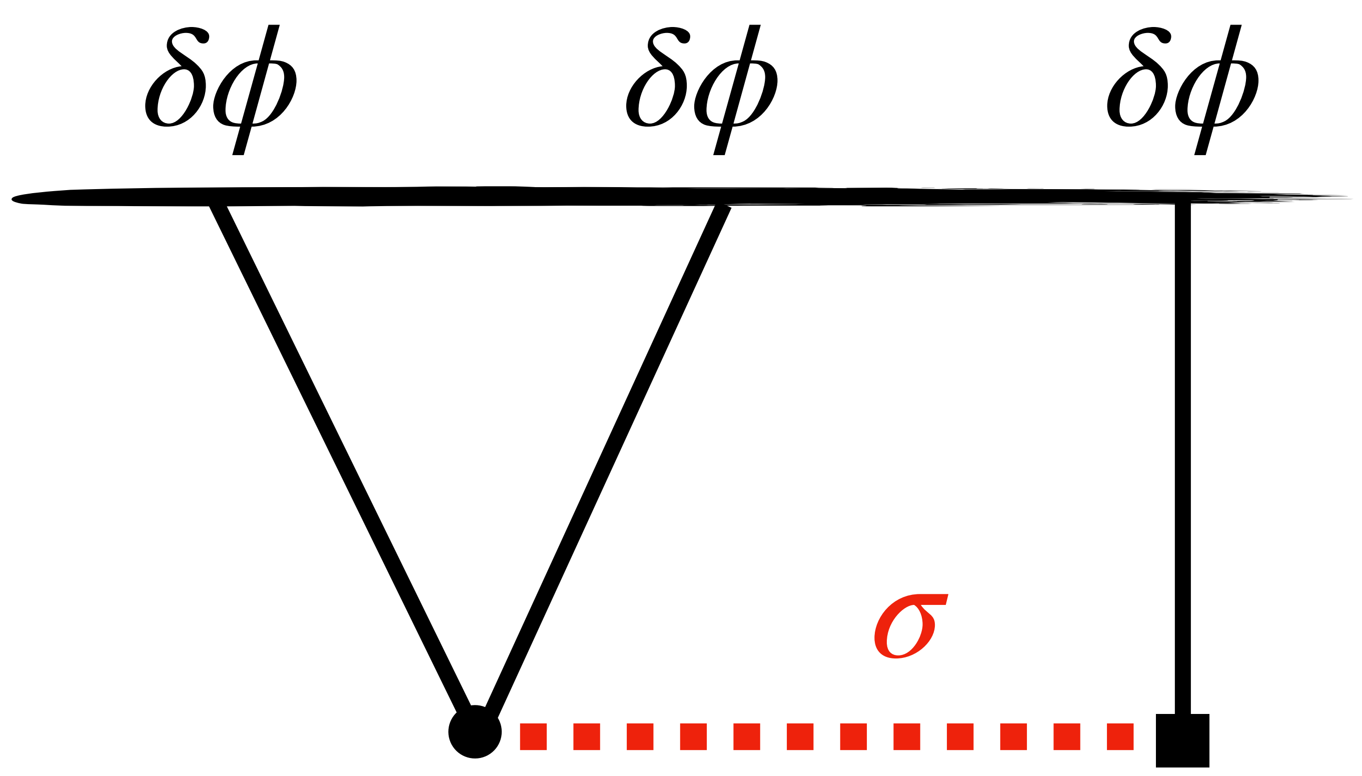
e.g. $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \sim f_{\rm NL}^{\rm eq} \times$ shape

Senatore, Zaldarriaga, Creminelli, Baumann, …

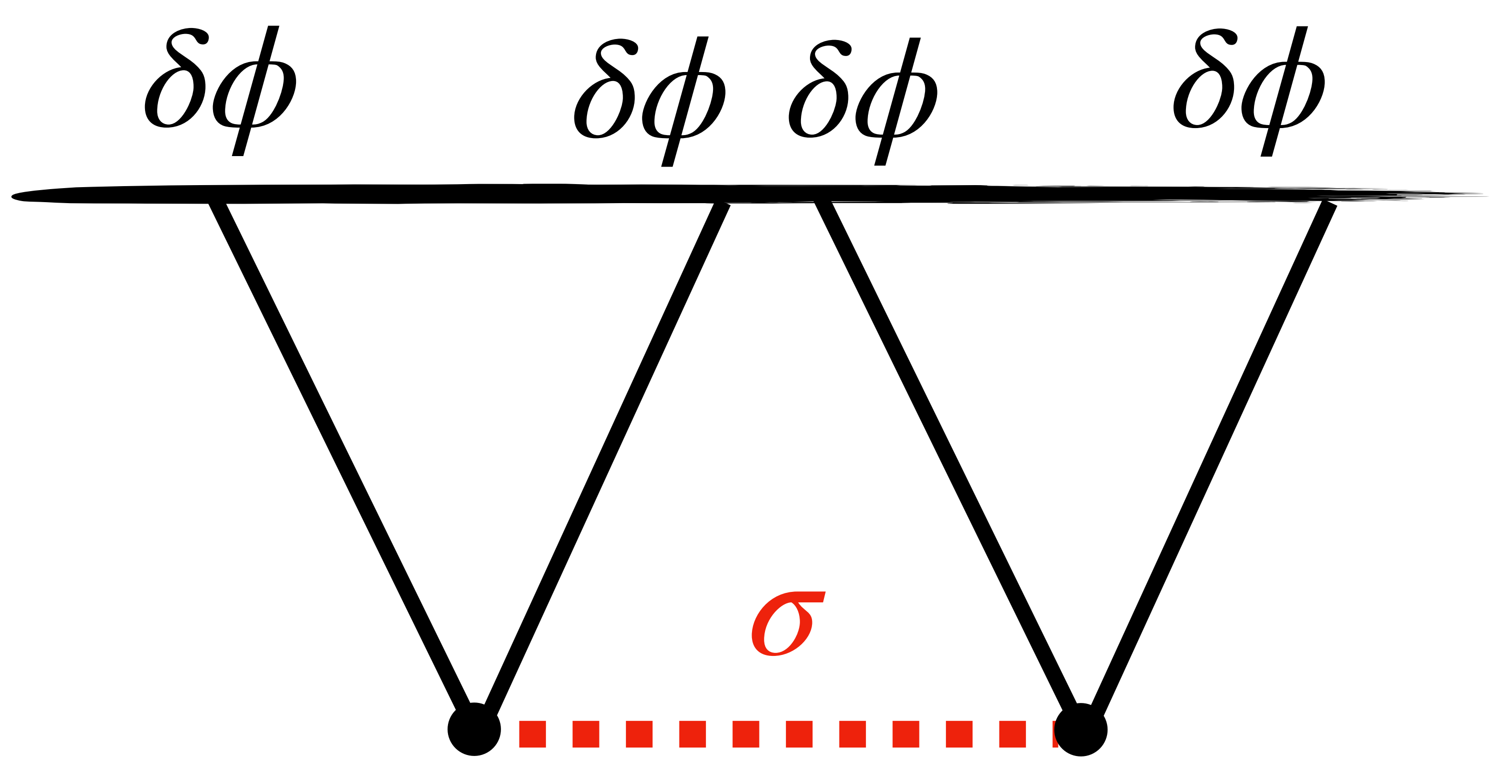
Multi-Field Inflation

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

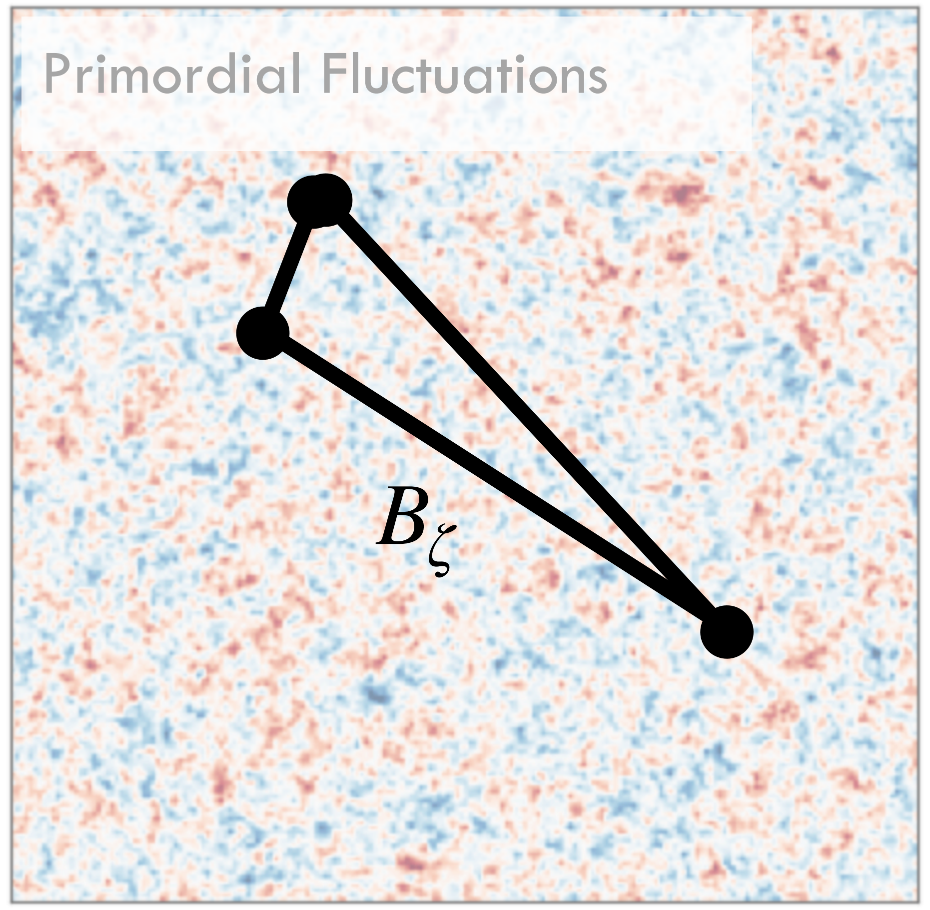
$$\mathscr{L} \supset \delta\dot{\phi}\sigma, \quad \delta\dot{\phi}^2\sigma, \quad \cdots$$

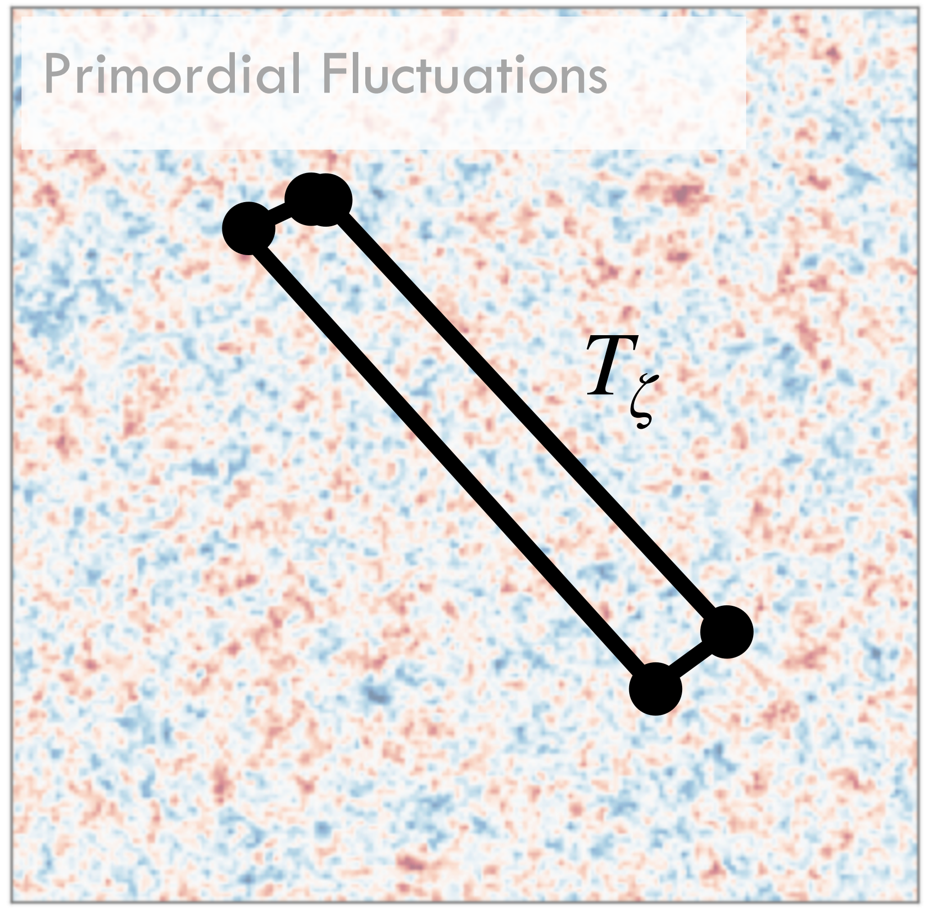


Linear-Quadratic $\sim f_{\mathrm{NL}}^{\mathrm{loc}}$



Quadratic^2 $\sim \tau_{\mathrm{NL}}$





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

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

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

The Cosmological Collider

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

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle_{k_1 \ll k_3} \sim f_{\rm NL}(m_\sigma, s)$$

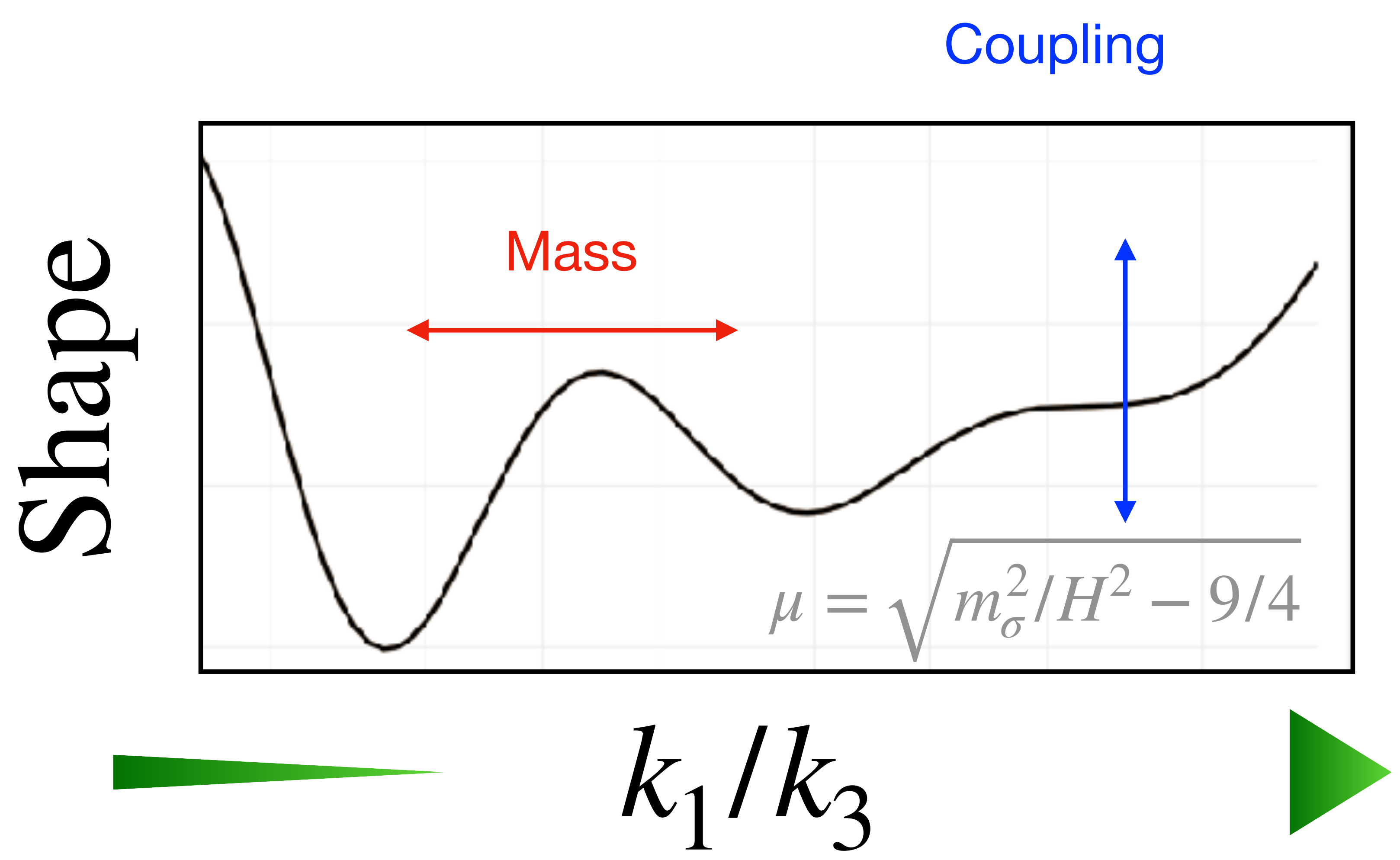
Amplitude $\sim e^{-\pi\, m_\sigma/H}$

$$\times \frac{1}{k_1^3 k_3^3}\left[\left(\frac{k_1}{k_3}\right)^{3/2+i\mu} + \left(\frac{k_1}{k_3}\right)^{3/2-i\mu}\right]$$

Shape (mass dependent)

$$\times \mathscr{L}_s(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_3)$$

Angle (spin-dependent)

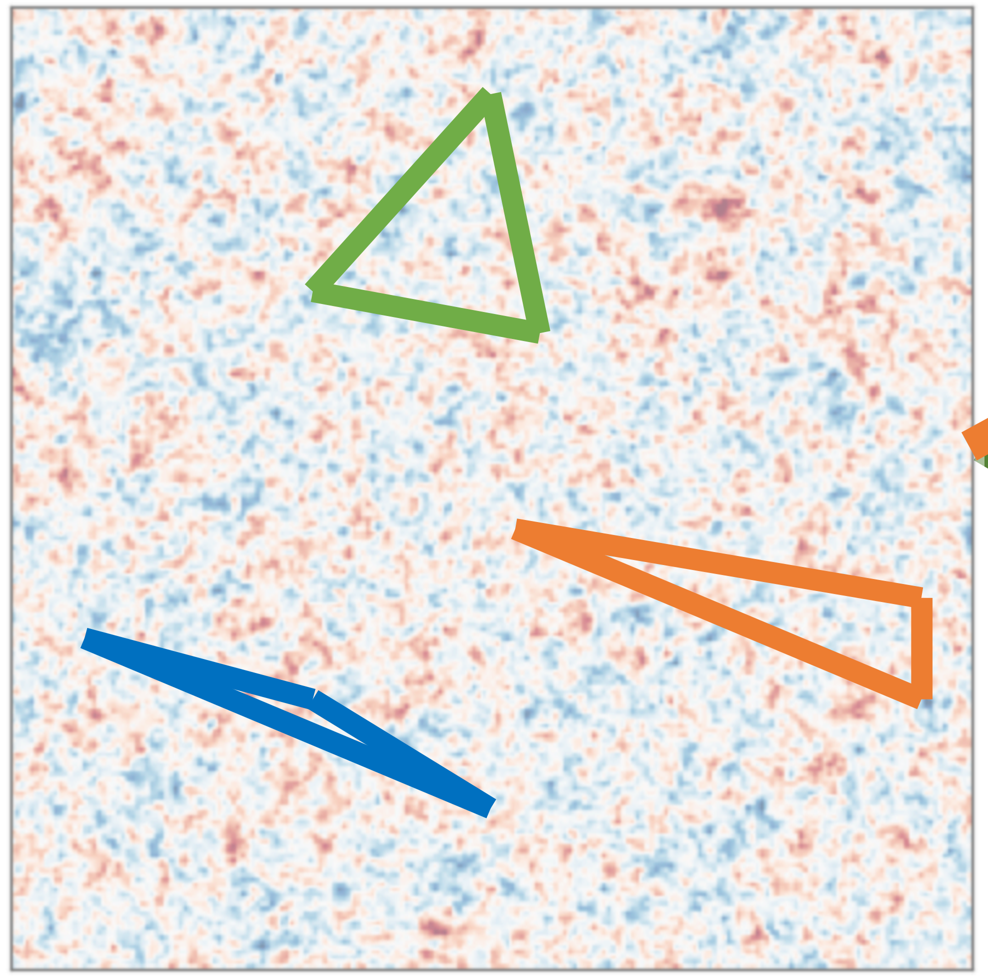


- These **oscillations** are a **smoking-gun** for new physics at $m_\sigma \sim H$!

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

How to Measure Primordial Non-Gaussianity

The **curvature fluctuations** set the **initial conditions** for the late Universe!

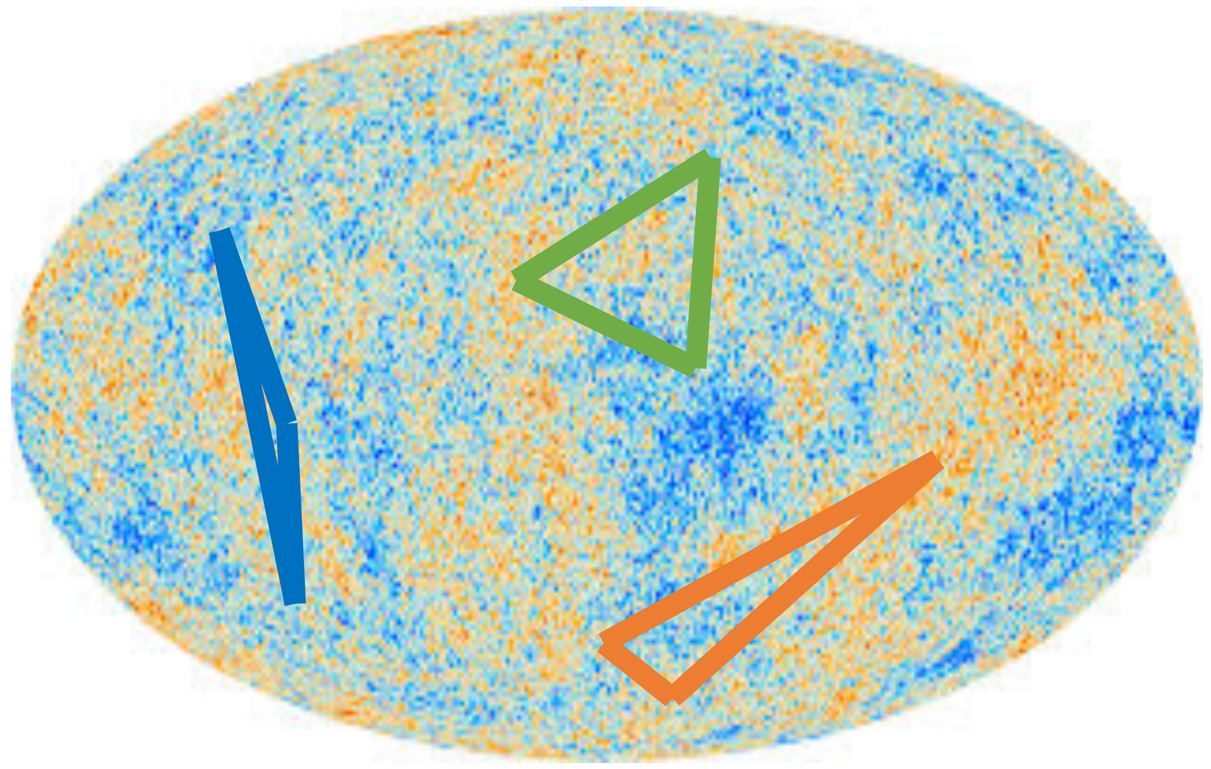


Primordial Curvature

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

Linear Physics

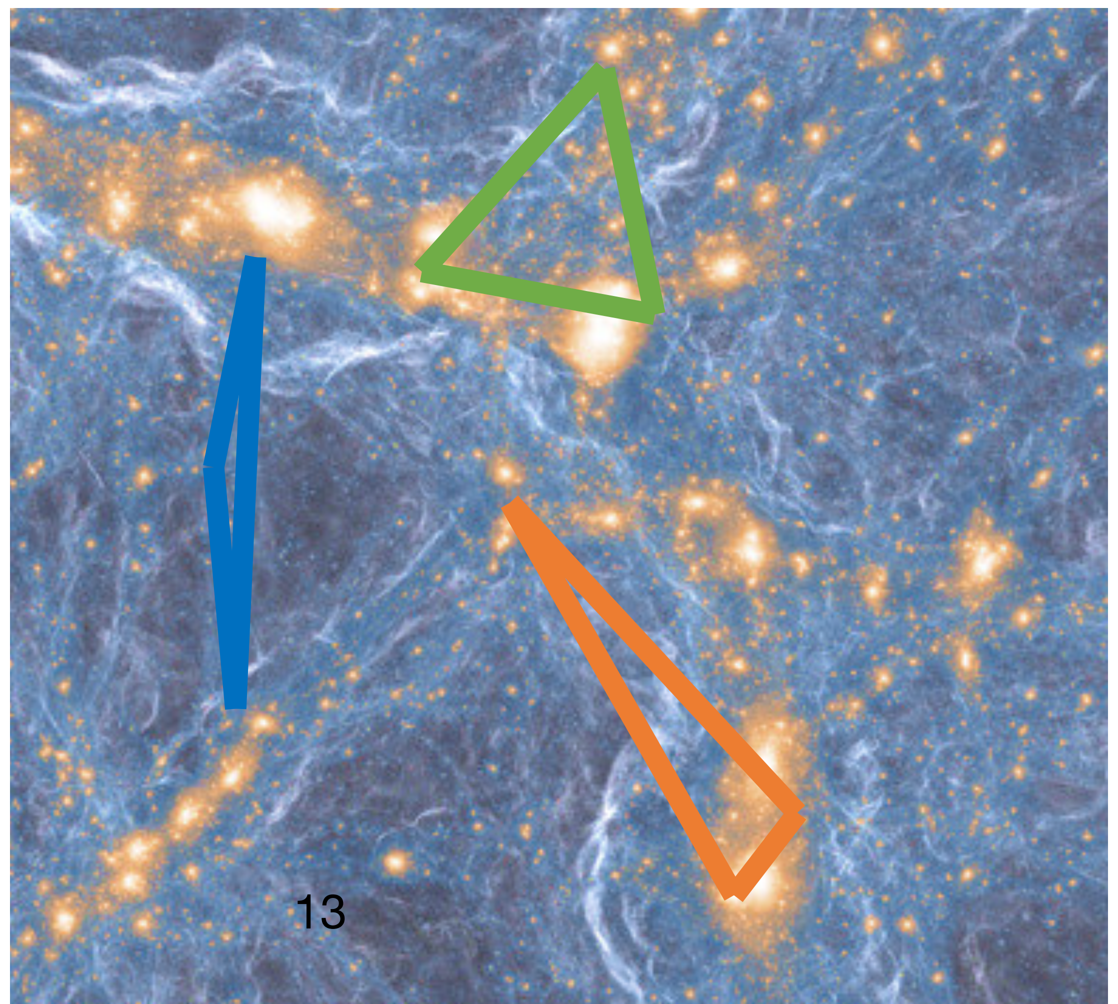
Non-Linear Physics



Fluctuations in CMB **temperature**

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

*(tracing **photon energies**)*



Fluctuations in **galaxy number density**

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

*(tracing **dark matter**)*

Planck, IllustrisTNG

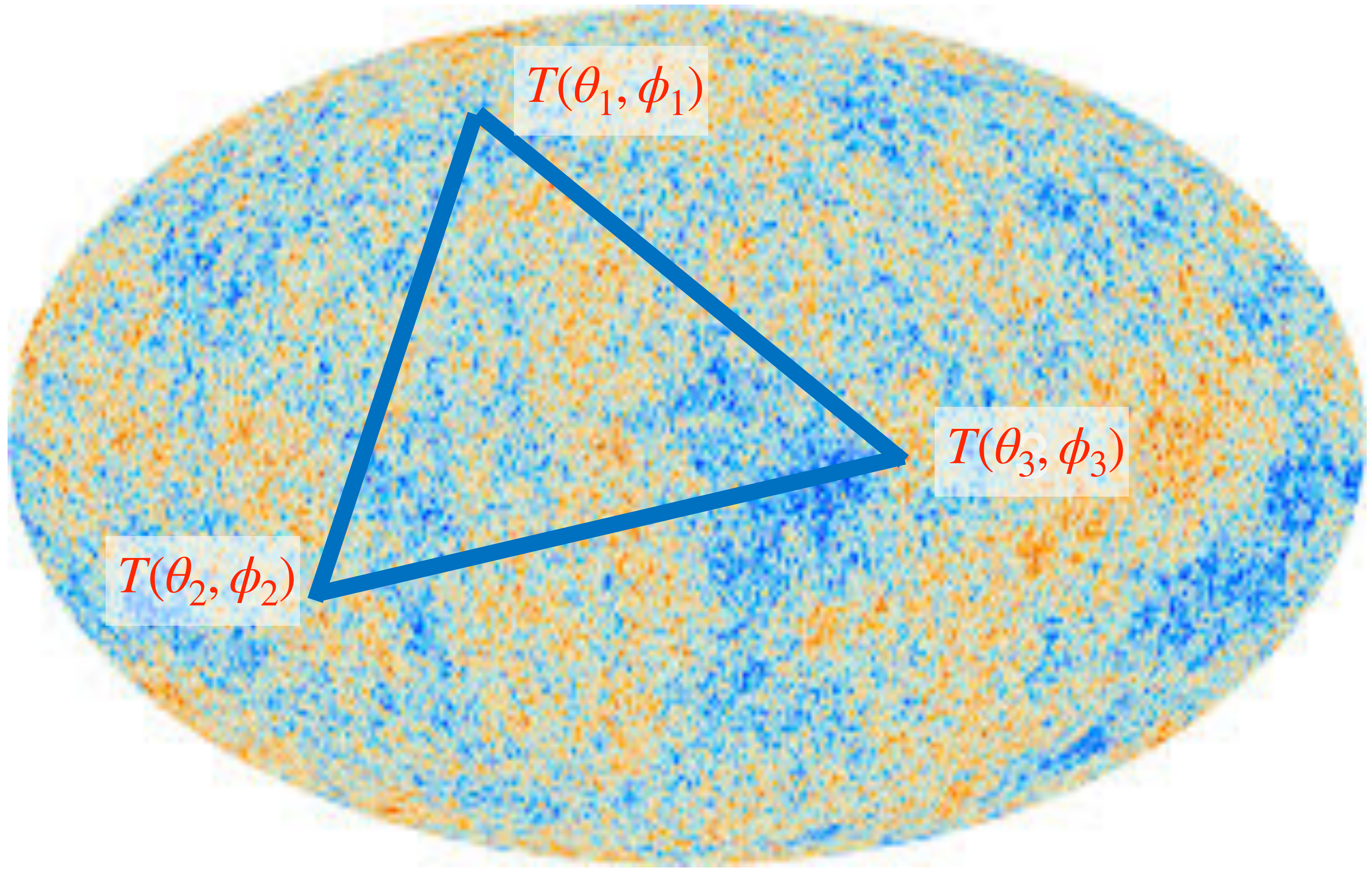
How to Measure a Three-Point Function

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

$$T(\theta, \phi)$$

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

$$\langle T(\theta_1, \phi_1) T(\theta_2, \phi_2) T(\theta_3, \phi_3) \rangle$$



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

Planck 2018, Komatsu, Spergel, Wandelt, Shellard, Fergusson, Sohn, Bucher, **Philcox**, …

How to Measure a Three-Point Function

- We can **compress** the data, using techniques from **signal processing**:

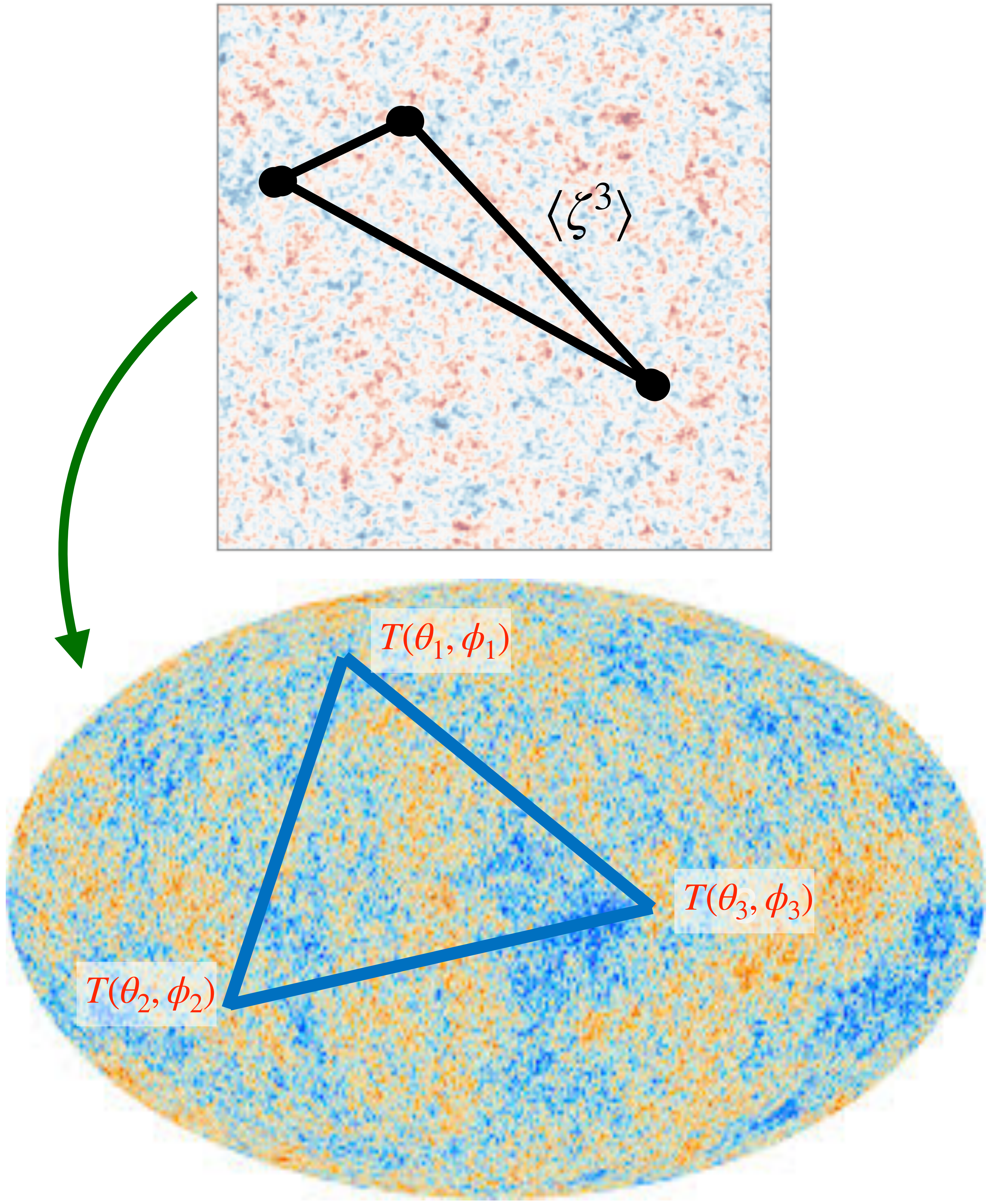
$$\hat{f}_{\mathrm{NL}} \sim \sum_{10^{21}\ \text{combinations}} \text{Model} \times T_1 T_2 T_3$$

- We measure the **amplitude of a specific model**, which traces the **microphysics** of inflation

- This depends on a **theory model** which can be computed from the primordial prediction

- Using **many** numerical tricks we can do the calculation in $\mathcal{O}(N_{\mathrm{pix}} \log N_{\mathrm{pix}})$ time instead of $\mathcal{O}(N_{\mathrm{pix}}^3)$
  - This requires a **simple** and **factorizable** theory model!

$$B_\zeta(k_1, k_2, k_3) \rightarrow a(k_1) b(k_2) c(k_3)$$



Planck 2018, Komatsu, Spergel, Wandelt, Shellard, Fergusson, Sohn, Bucher, **Philcox**, …

CMB Constraints (2019 edition)

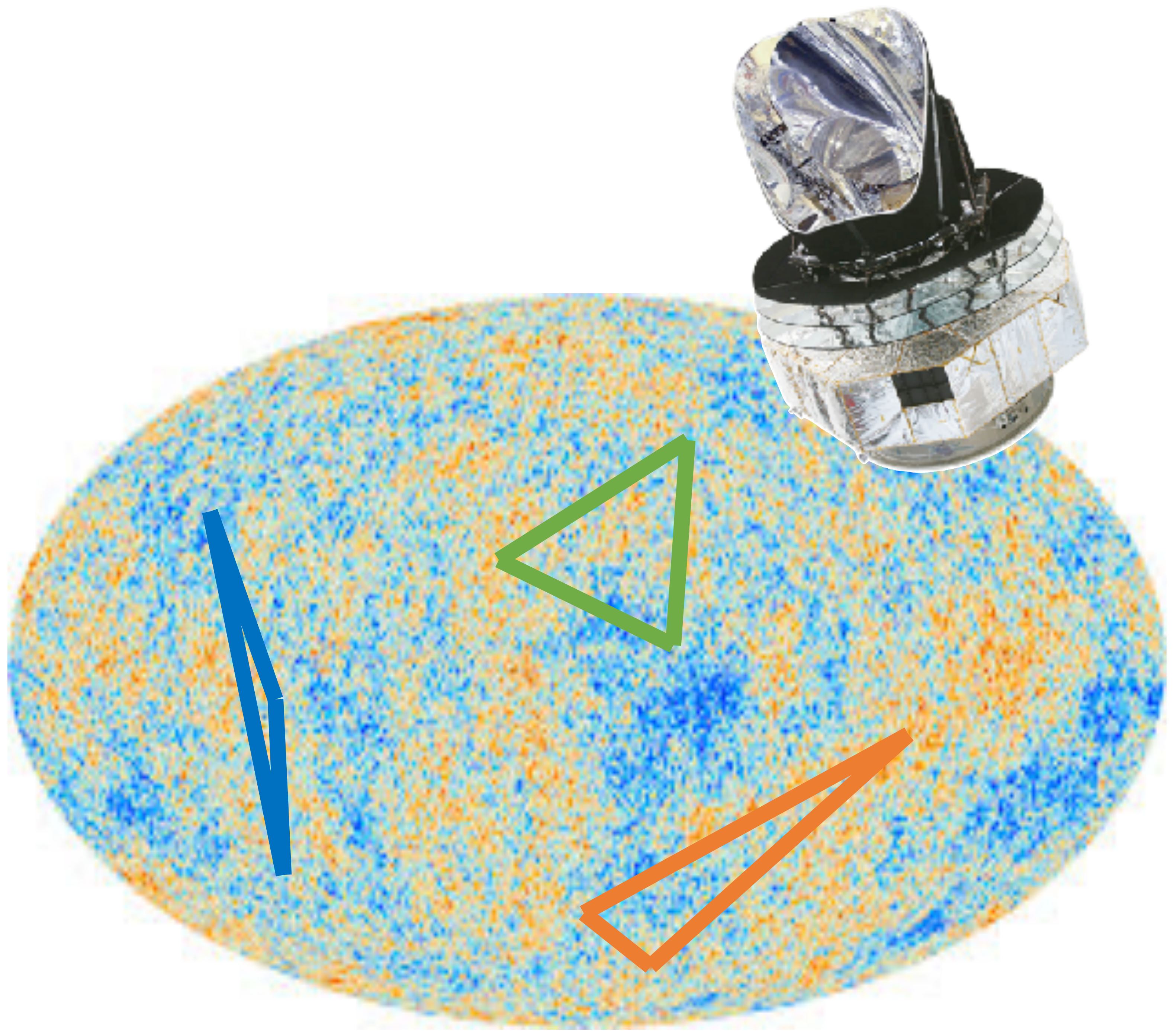
The *Planck* collaboration placed strong constraints on simple **phenomenological** three-point functions, e.g.,

$$\langle \delta T^3 \rangle \sim \langle \zeta^3 \rangle \sim f_{\mathrm{NL}} \times \text{Shape}$$

Planck 2018			
	Local	-0.9 ± 5.1	≈ Light field exchange
	Equilateral	-26 ± 47	≈ Self interaction (v1)
	Orthogonal	-38 ± 24	≈ Self interaction (v2)

[Note: $f_{\mathrm{NL}} = 10^5$ is $\mathcal{O}(1)$ non-Gaussianity]

Planck



Conclusion: The distribution of curvature is **Gaussian** to $\lesssim 0.1\,\%$

However, we are far away from the theory **targets**

$$f_{\mathrm{NL}} \sim 1$$

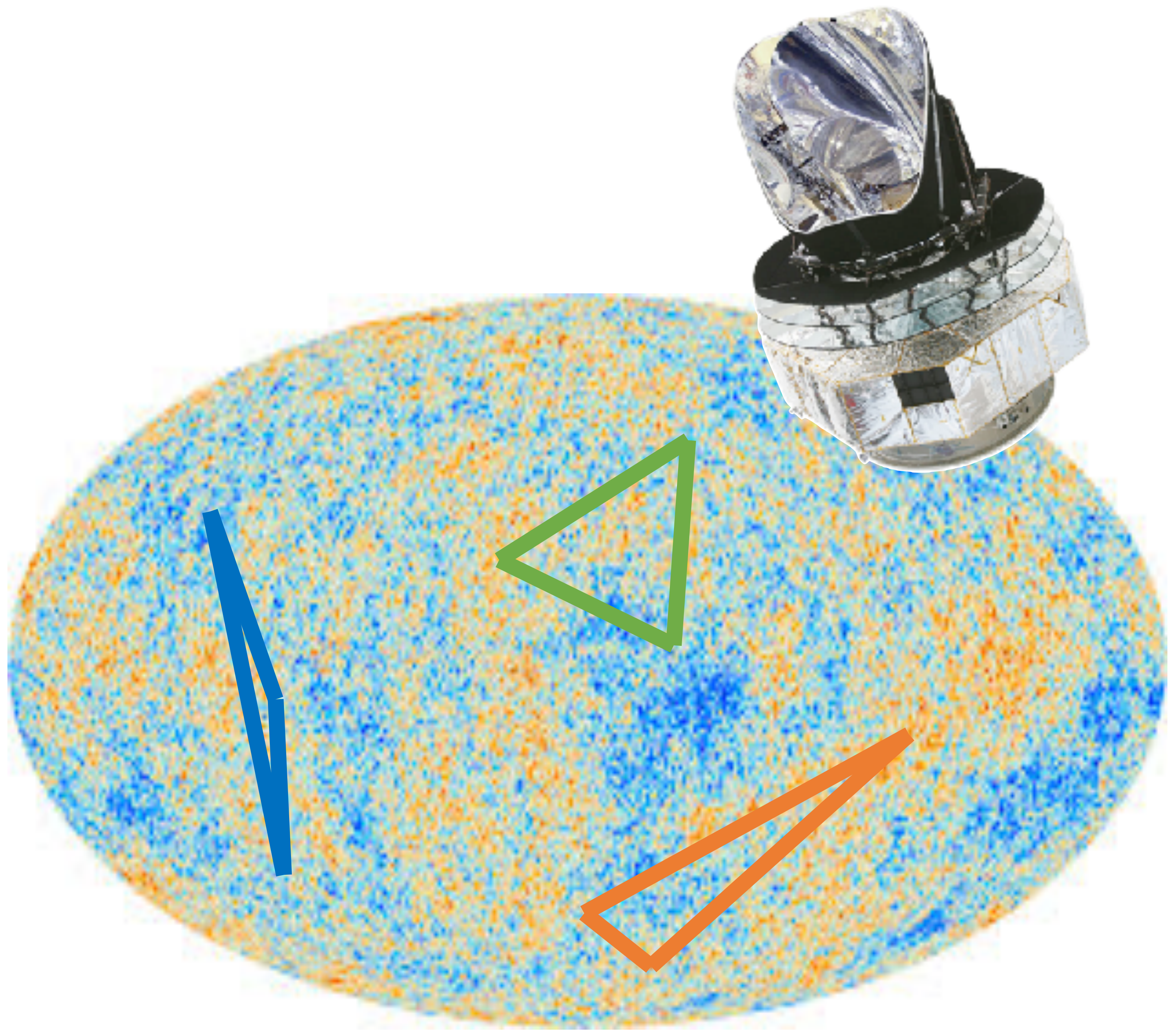
Planck 2018, Smith+, Senatore+, Maldacena, Creminelli, Fergusson, Shellard

CMB Constraints (2026 edition)

We can now analyze **realistic** inflationary models *(not just simple templates!)*

- Correlations with **gravitational waves** [**Philcox** & Shiraishi 24, 25]
- Exchange of **massive** particles with $m_\sigma \sim H$ [**Philcox**+25, **Philcox** 26 (see also Suman+, Sohn+, Kumar+)]
- Exchange of **strongly-coupled** conformal field theories [**Philcox**+26]
- Oscillations induced by **spinning** particles $s = 1,2,\ldots$ [**Philcox** 26 (see also Sohn+, Kumar+, Suman+)]

Planck



These have benefited from novel **techniques**

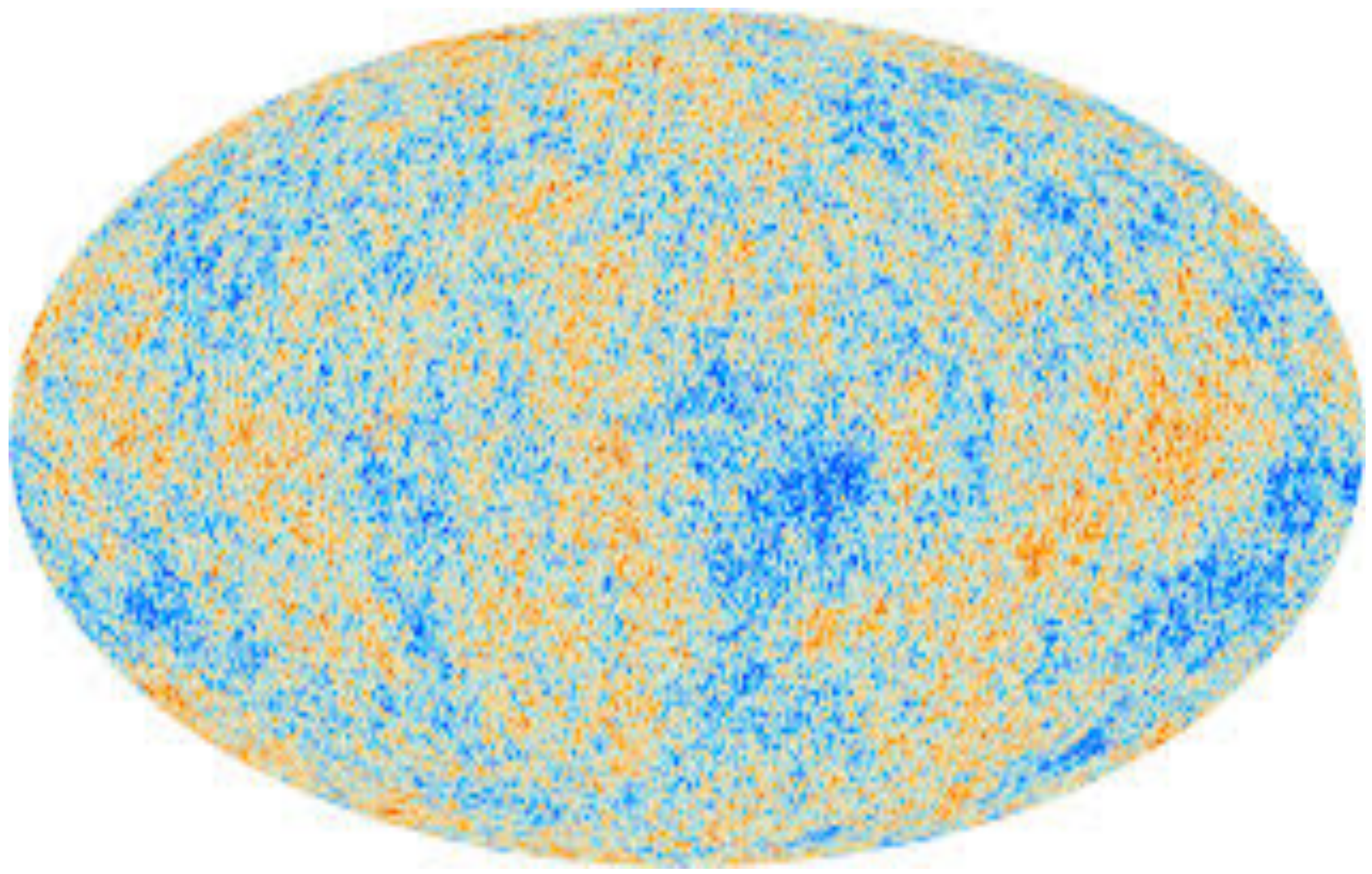
- Clever **basis decompositions** [modal bases, machine learning]
- Advances in inflationary **predictions** [bootstraps and numerical methods]

So far, there have been no detections!

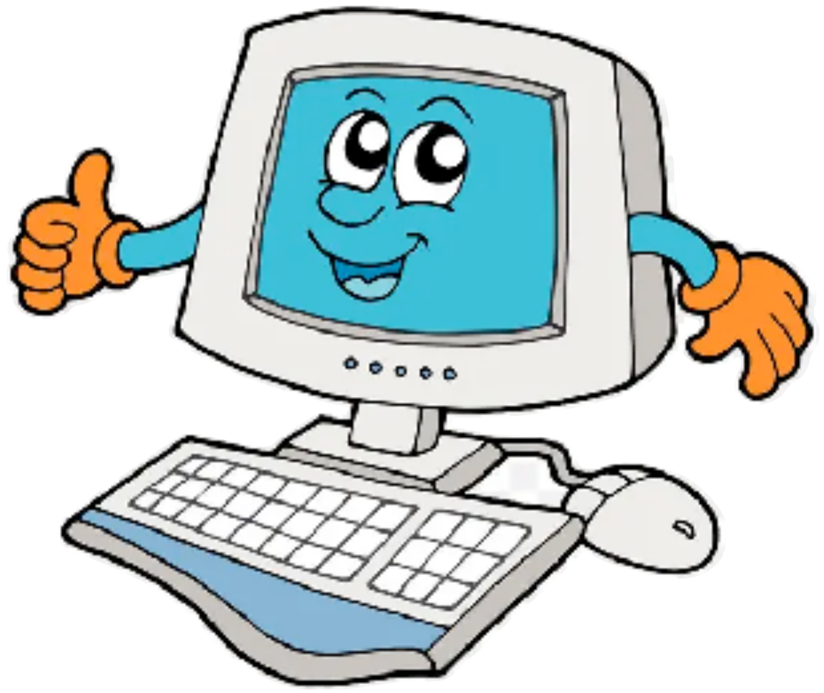
e.g., **Philcox,** Sohn, Suman, Wang, Yang, Shellard, Fergusson, Pimentel, Baumann, Arkani-Hamed, Lee, Werth, Pinol, Renaux-Petel, Sirletti, Zhong, Green, Shiraishi, Qu, Xianyu, Kumar…

How to Constrain Inflation

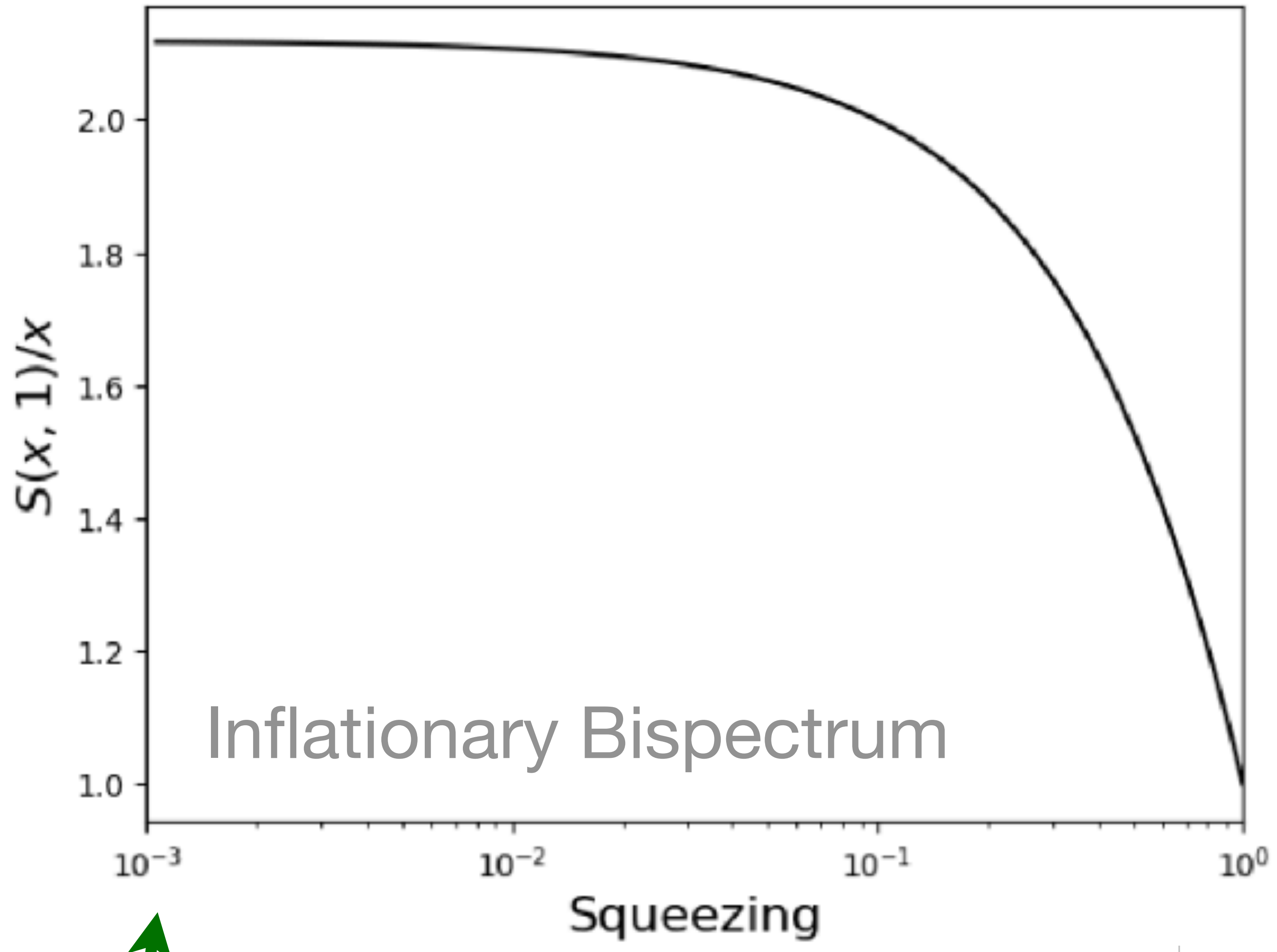
Data

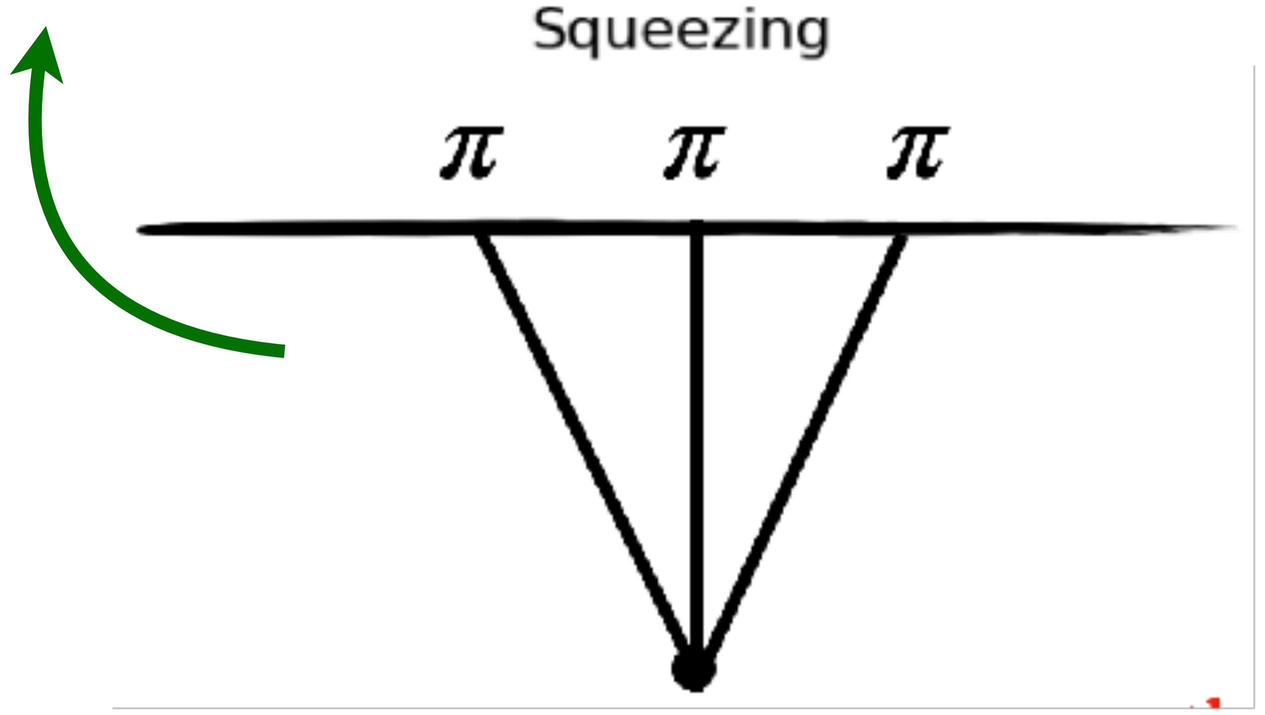


CMB Fluctuations



Theoretical Shape





f_{NL}

Amplitude

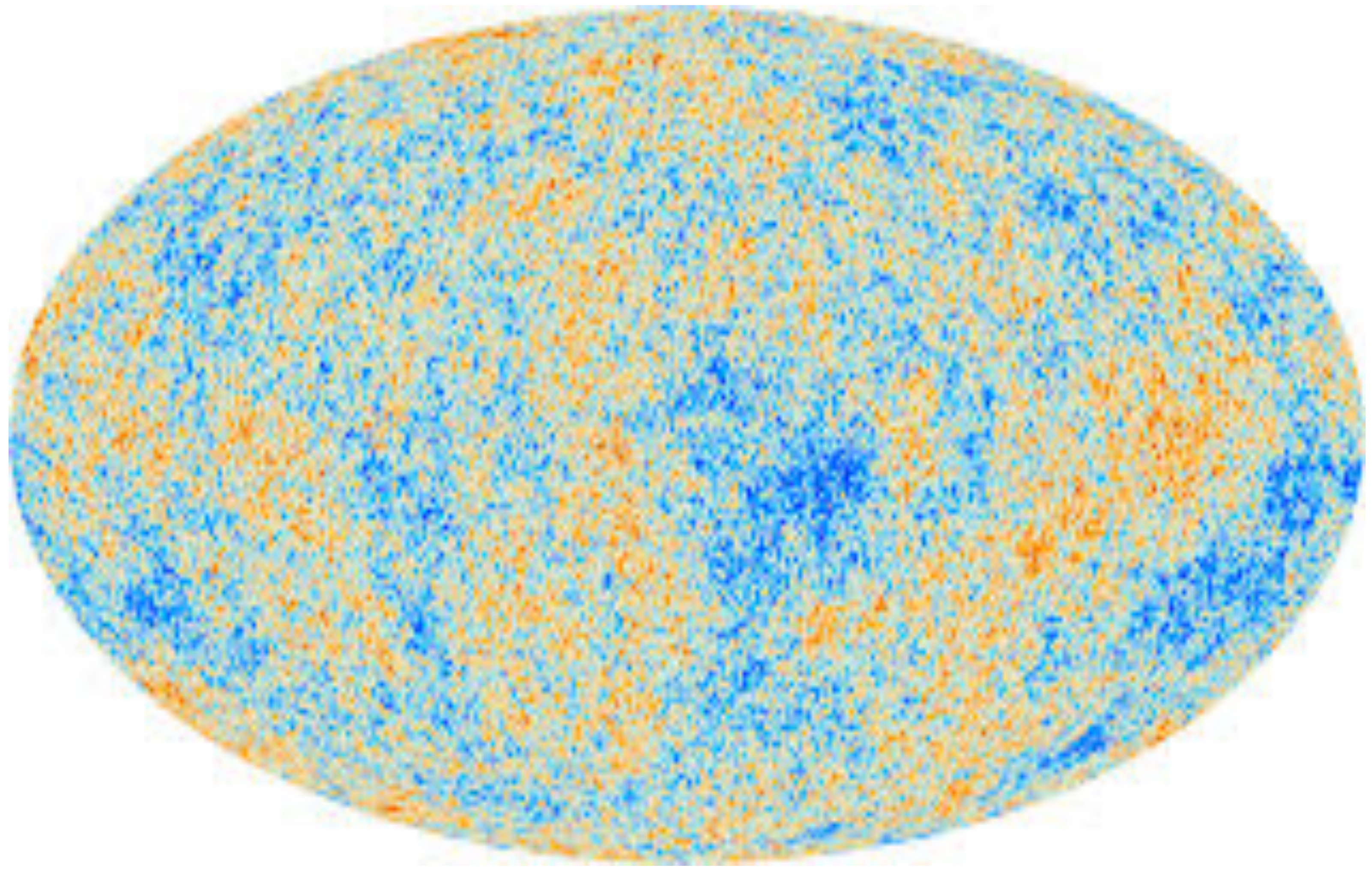
This is **hard**

- Efficient computation requires **simple** theory models
- Every model needs a **dedicated** analysis

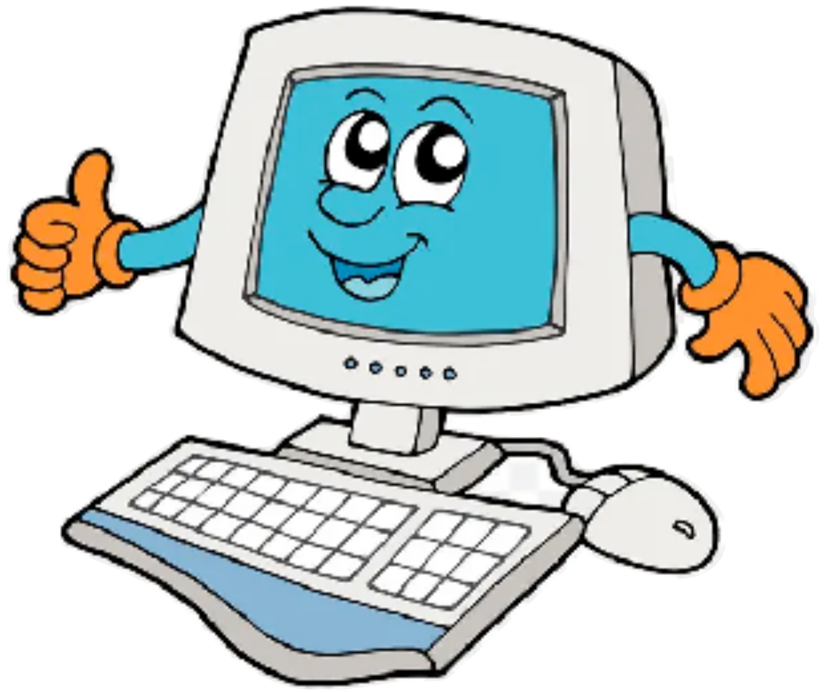
Komatsu, Spergel, Wandelt, **Philcox**, Zhong, Sirletti, Smith, Zaldarriaga, Senatore, …

How to Constrain Inflation

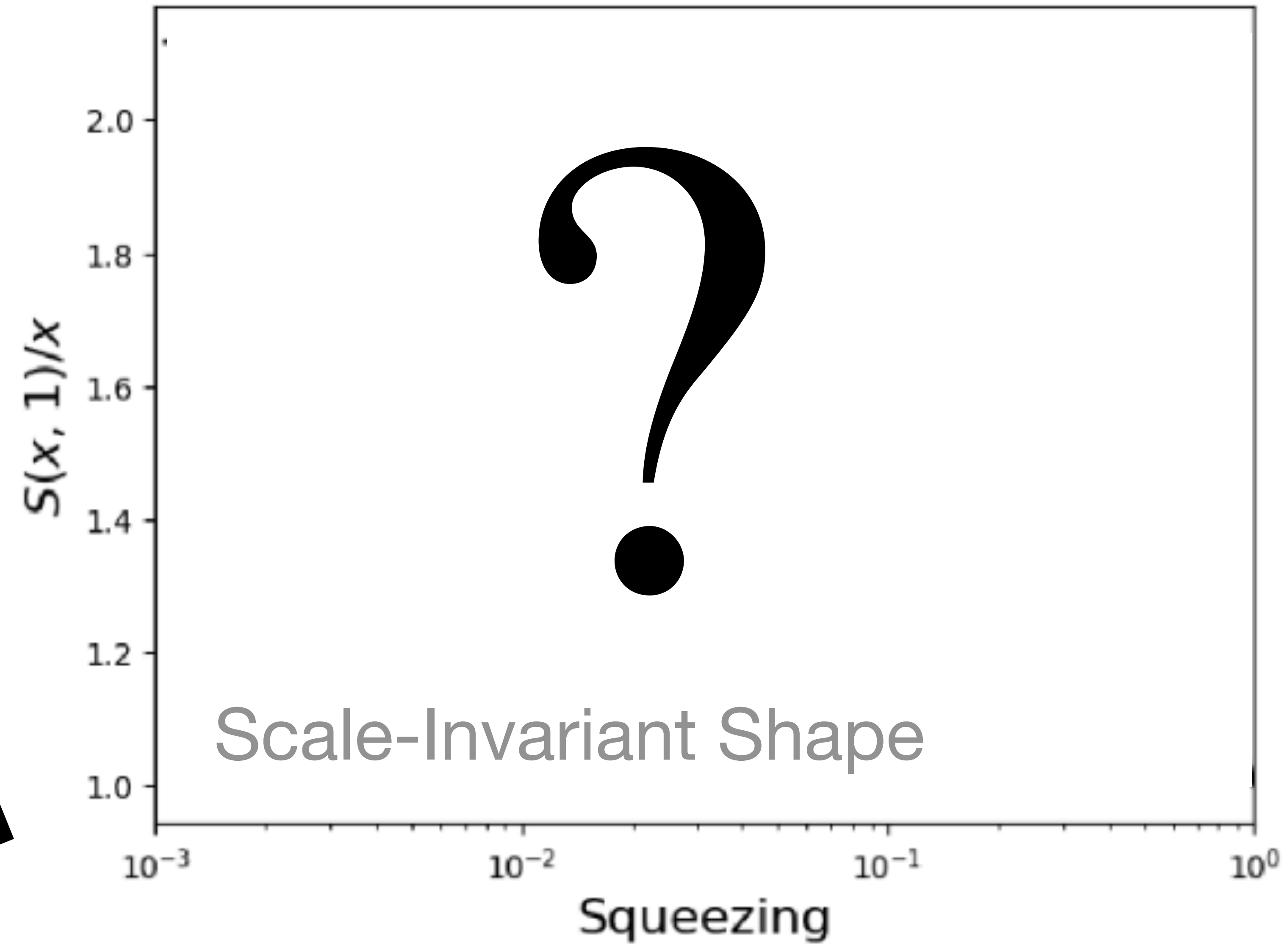
Data



CMB Fluctuations



Observed Shape



$f_{\rm NL}$

Amplitude

(See also modal decompositions)

This is **easy**

- We can analyze *any* shape
- The analysis is (almost) **free**

Philcox 26 (see also Fergusson+, Shellard+, Sohn+, Suman+…)

What Shape is the Bispectrum?

Can we **reconstruct** the inflationary bispectrum?

$$B(\ell_1,\ell_2,\ell_3) \sim \int dk_1 dk_2 dk_3 dr\, B_\zeta(k_1,k_2,k_3) j_{\ell_1}(k_1 r) j_{\ell_2}(k_2 r) j_{\ell_3}(k_3 r)\cdots$$

Observer-friendly — *Theory-friendly*

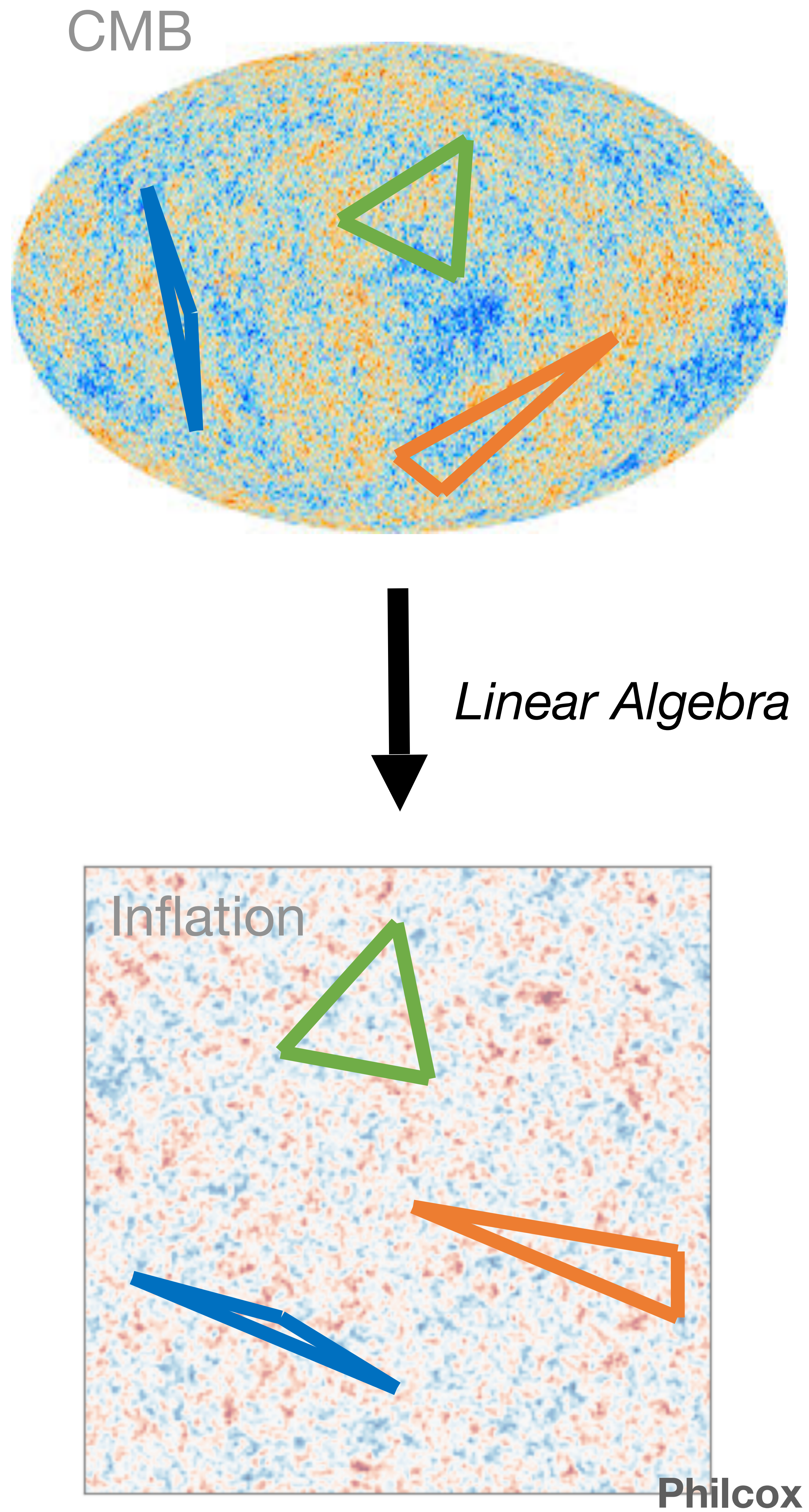
- Let's assume **scale-invariance** (*i.e.* dilatation invariance) ⇒ we have a 2D **shape function**

$$B_\zeta(k,k,k) \sim k^{-6} \qquad S(x=k_1/k_3, y=k_2/k_3) \propto (k_1k_2k_3)^2 B_\zeta(k_1,k_2,k_3)$$

- Build a **binned estimator** for $S(x,y)$ from the CMB!

$$\widehat{S(x,y)} \sim \sum_{\ell_1 m_1 \ell_2 m_2 \ell_3 m_3} \frac{\partial \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}\rangle^\dagger_{\text{theory}}}{\partial S(x,y)} \times (C^{-1}a)_{\ell_1 m_1}(C^{-1}a)_{\ell_2 m_2}(C^{-1}a)_{\ell_3 m_3}$$

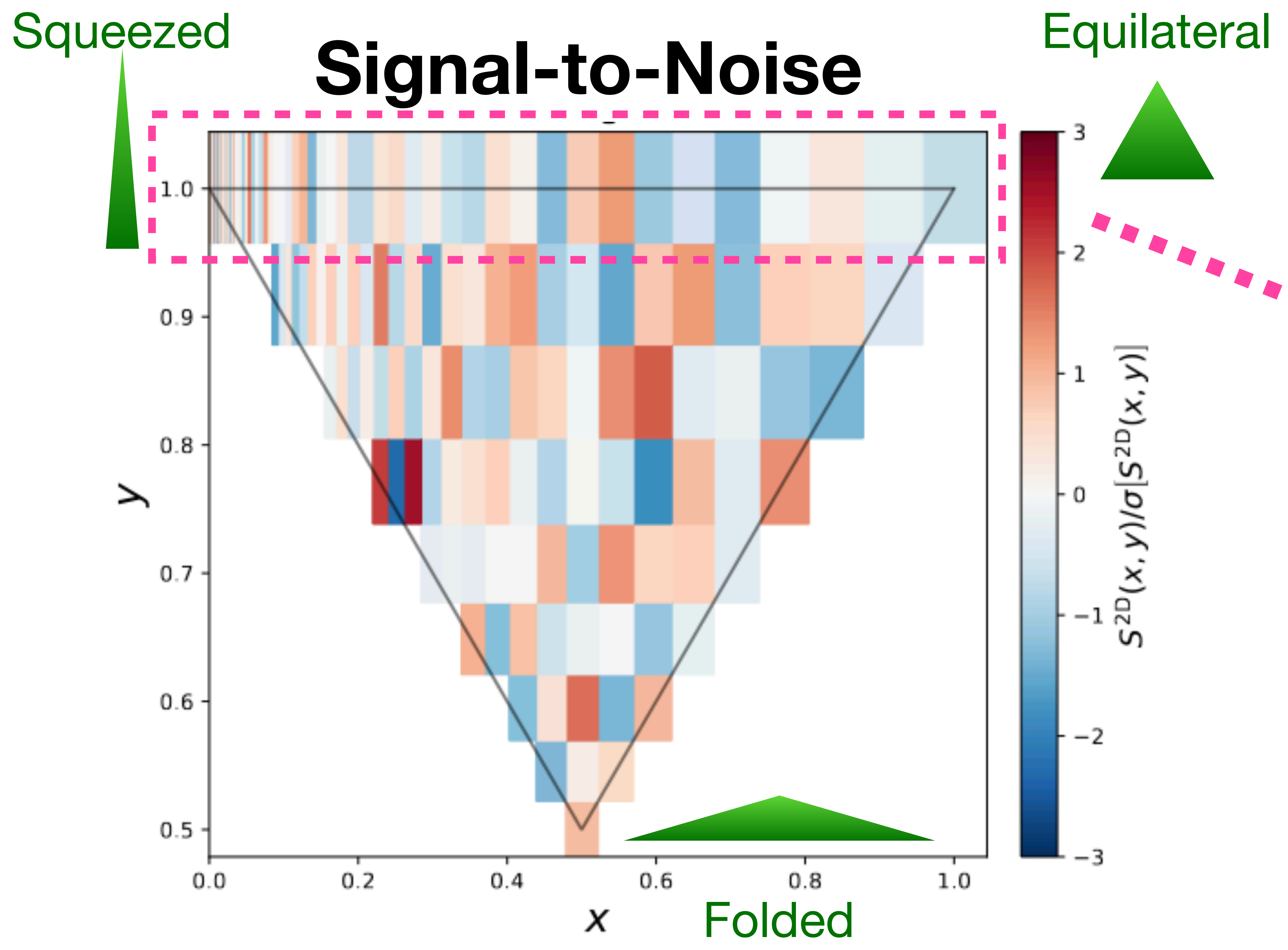
(In practice, build a 3D estimator binned in $\log k$, then linearly transform to $\log x/\log y$ bins)

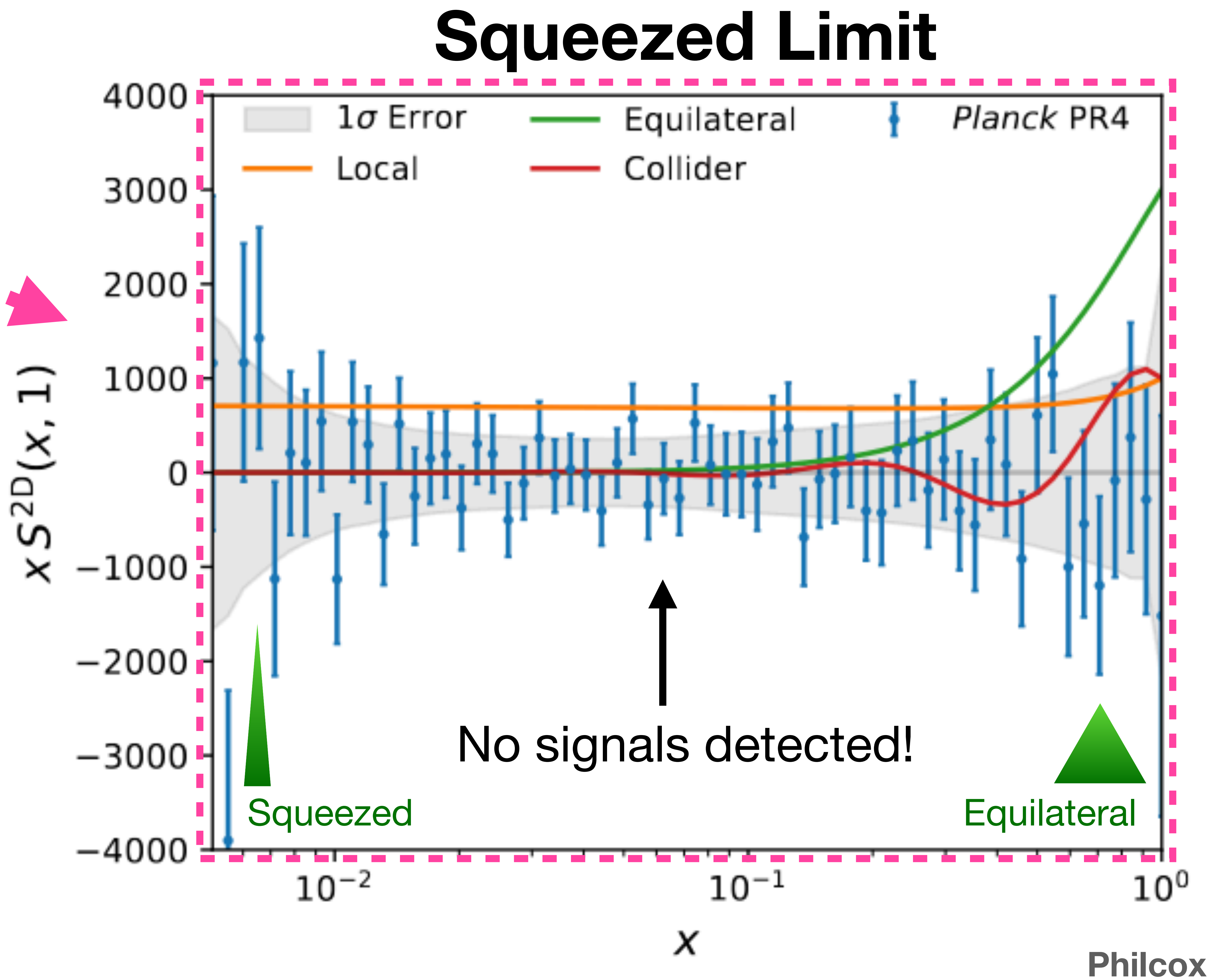


The *Observed* Inflationary Bispectrum

We can **reconstruct** *scale-invariant* inflationary signals using observational data from *Planck*

This compresses 10^{21} combinations of pixels into 171 numbers!

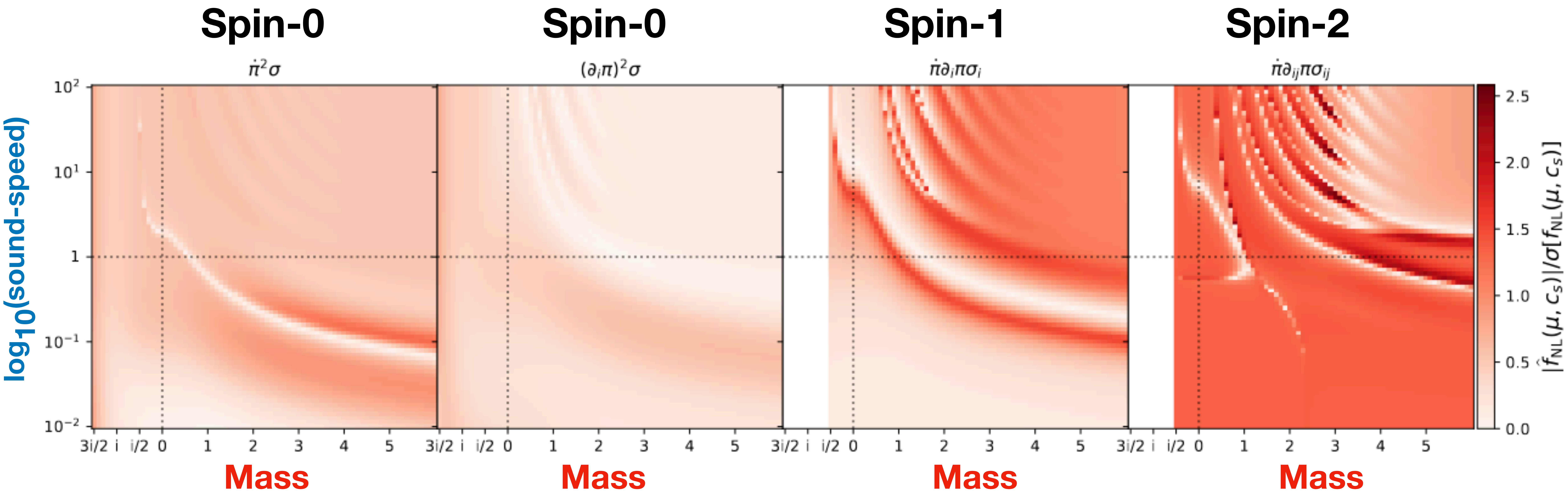




Planck PR4, T+E, $\ell \in [2,2048]$, $\chi^2/\mathrm{dof} = 174/171$

Searching for Massive Particle Exchange

We can use the reconstruction to search for new particles as a function of **mass**, **spin**, and **sound-speed**



Signal-to-Noise

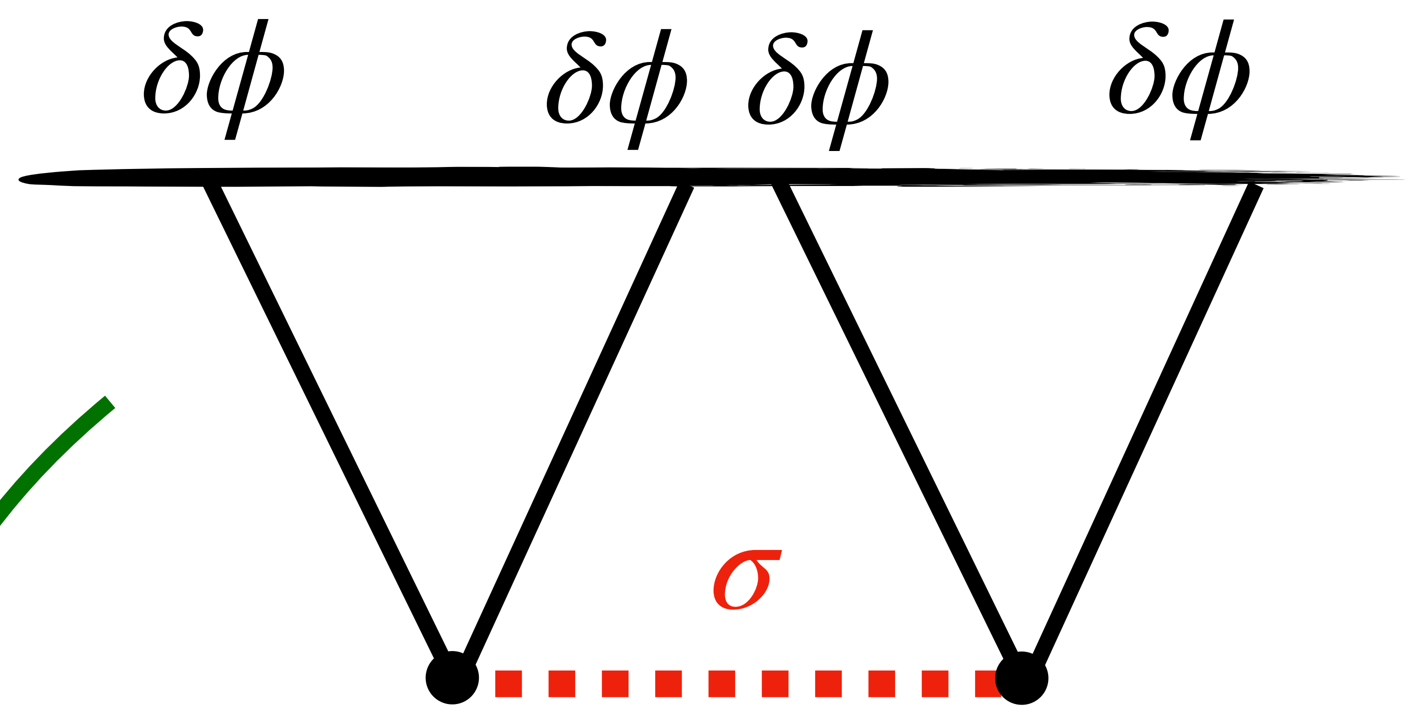
This takes 0.6 seconds!

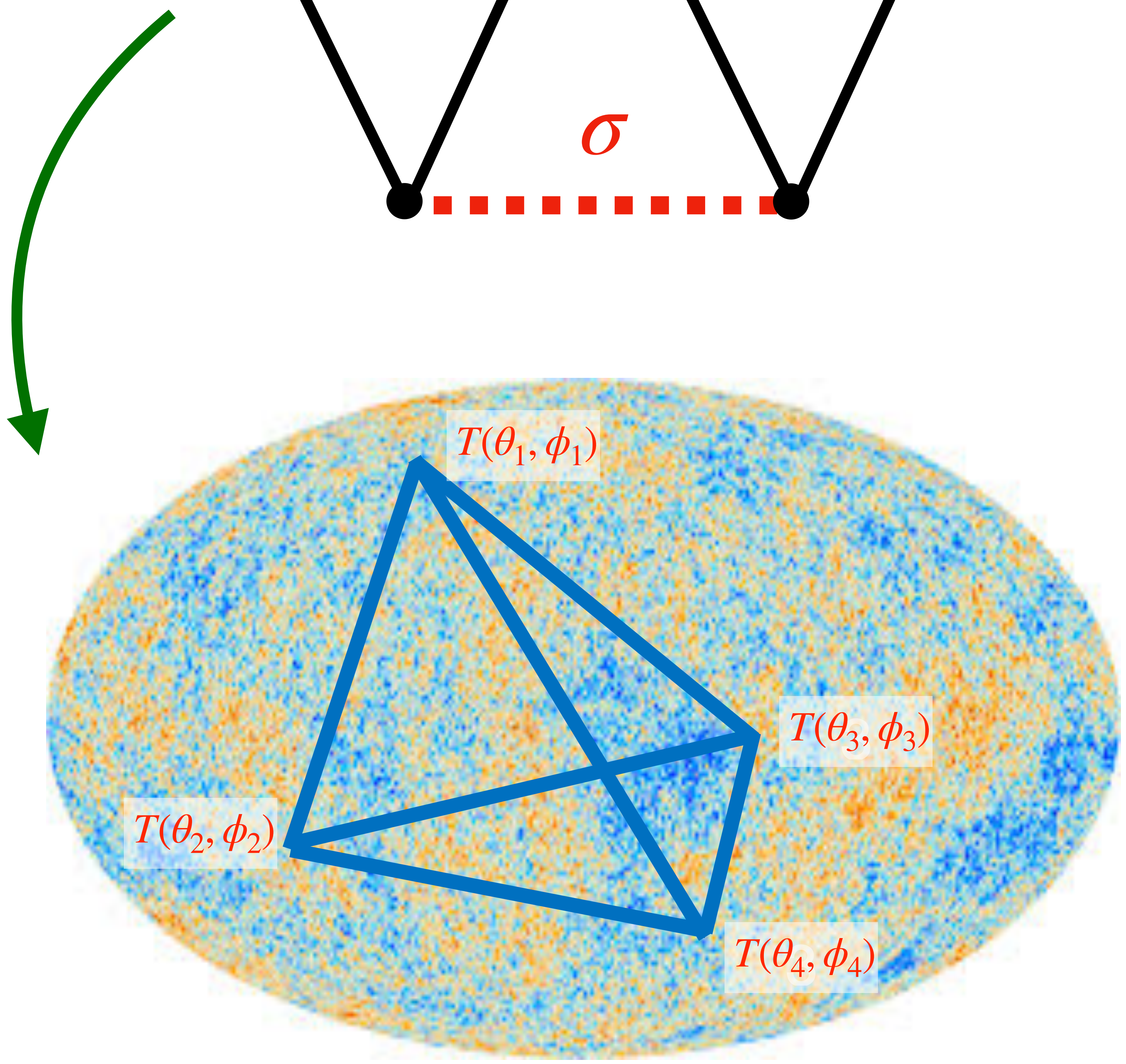
What About Higher-Orders?

- The **three-point** function (bispectrum) has been **extensively** analyzed
- The **four-point** function (trispectrum) has **almost never** been analyzed

Is the **four-point** function worth looking at?

- Many interactions **only** enter at higher order!
- Four-point functions can reveal **hidden particle physics**





Let's search for primordial physics in the CMB trispectrum!

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

How to Measure a Four-Point Function

- We can **compress** the data, using techniques from **signal processing**:

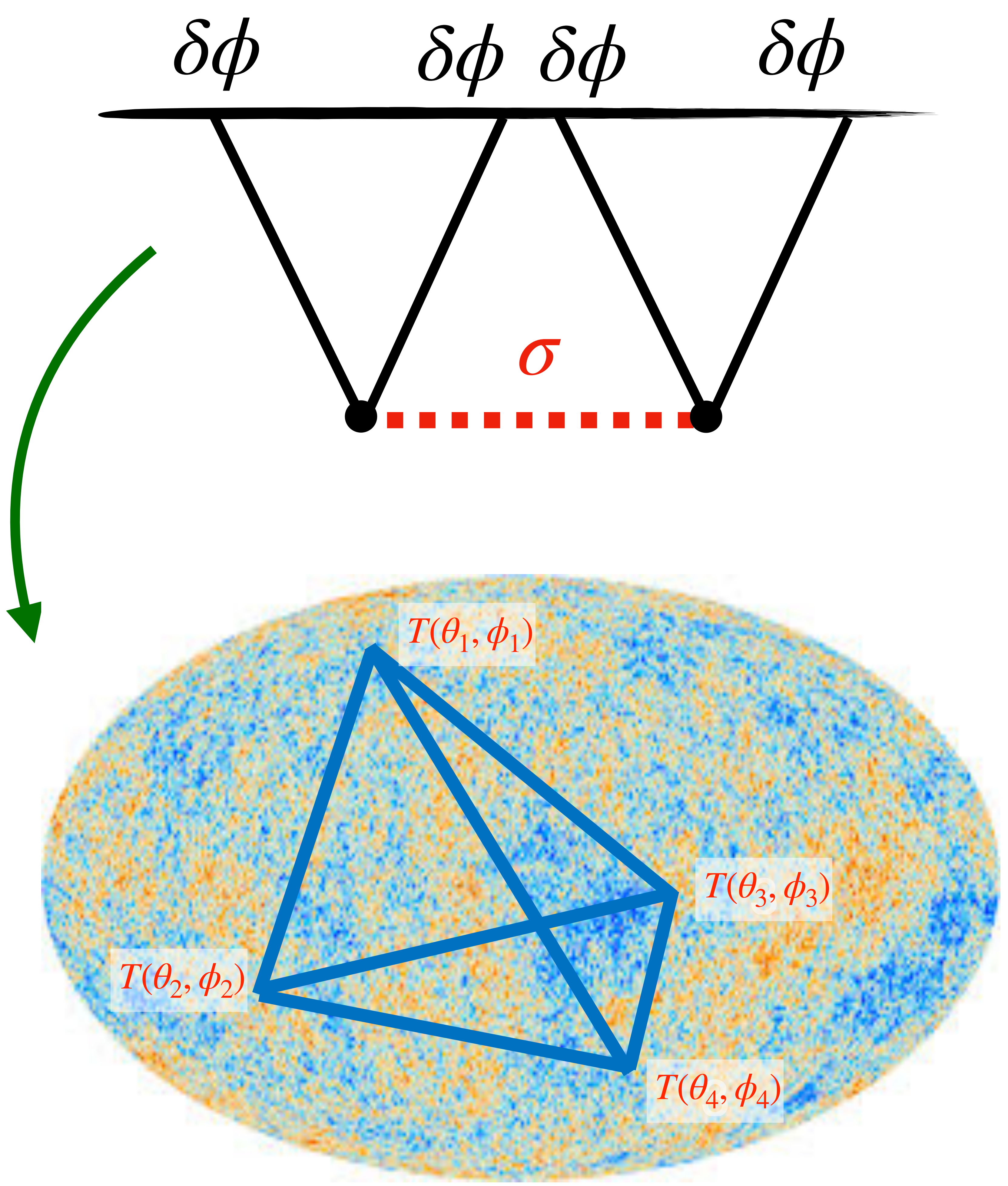
$$\hat{g}_{\rm NL} \sim \sum_{10^{28}\ \text{combinations}} \text{Model} \times T_1 T_2 T_3 T_4$$

- We measure the **amplitude of a specific model**, which traces the **microphysics** of inflation

- This depends on a **theory model** which can be easily computed from the primordial prediction

- Using **many** numerical tricks we can do the calculation in $\mathcal{O}(N_{\rm pix} \log N_{\rm pix})$ time instead of $\mathcal{O}(N_{\rm pix}^4)$
  - This requires a **simple** and **factorizable** theory model!

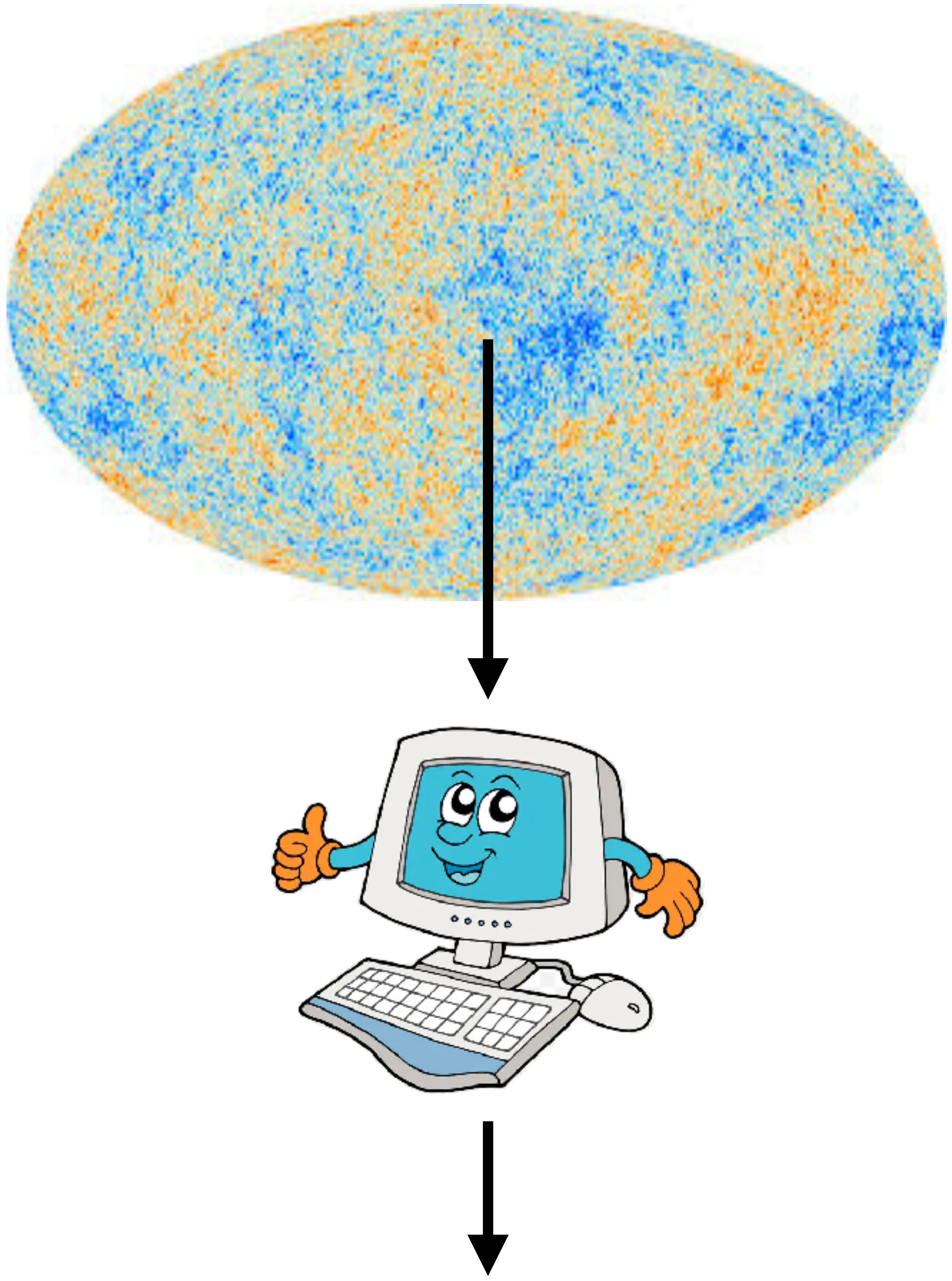
$$T_\zeta(k_1, k_2, k_3, k_4, |\mathbf{k}_1 + \mathbf{k}_2|) \to a(k_1)b(k_2)c(k_3)d(k_4)e(|\mathbf{k}_1 + \mathbf{k}_2|)$$



Smith & Zaldarriaga 15, **Philcox** 25abc, **Philcox** & Hill 25

Optimal Trispectrum Analyses

For factorizable shapes, we can **quickly** estimate four-point amplitudes!



inflation parameters

The estimators are

- ***Unbiased*** (by observational effects and noise)
- ***Efficient*** (limited by spherical harmonic transforms)
- ***Optimal*** (they achieve *minimum variance*)
- ***Open-Source*** (entirely written in Python/Cython)
- ***General*** (20+ types of model included so far)

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

Philcox 25ab

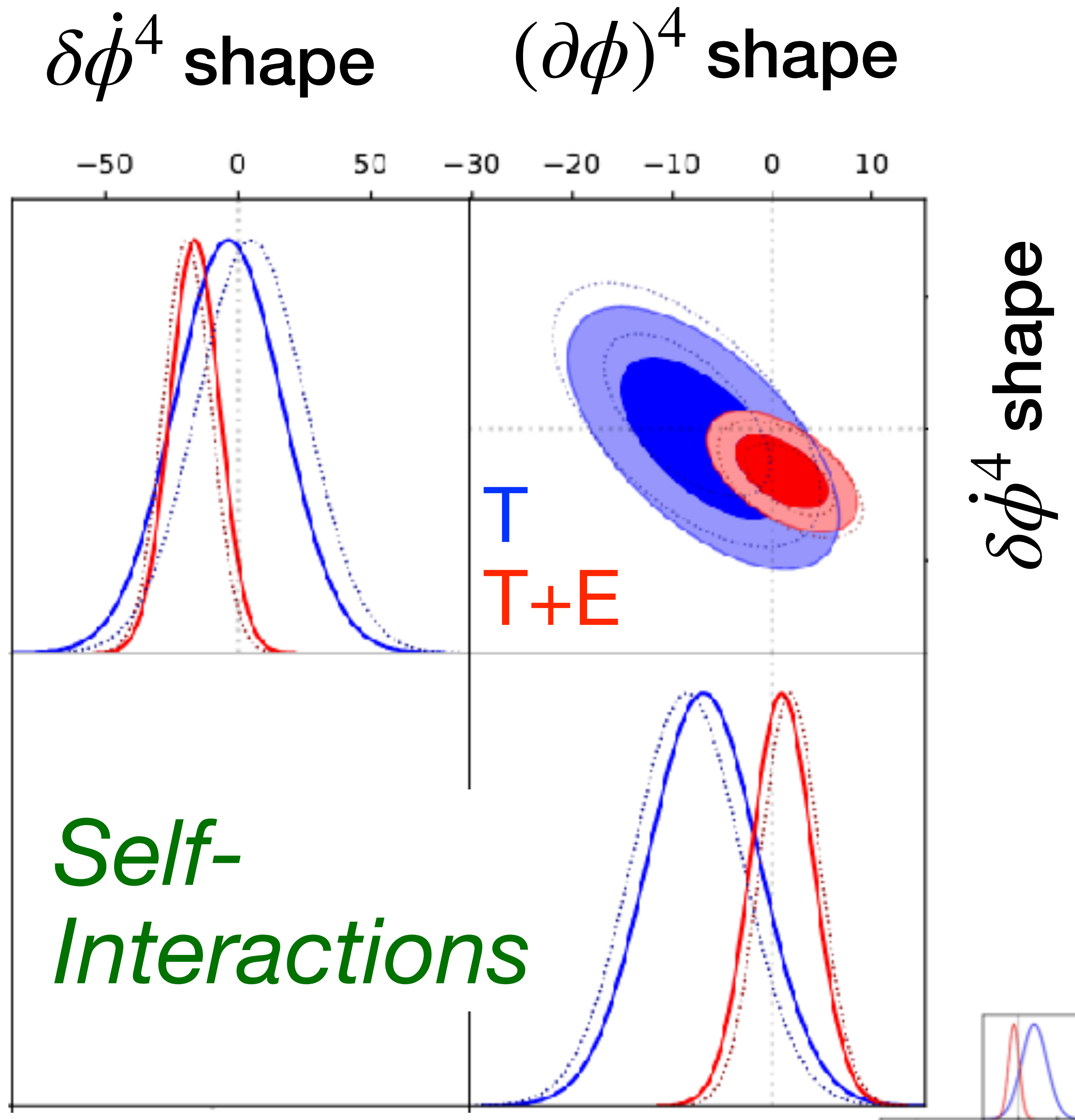
Results from the Four-Point Function

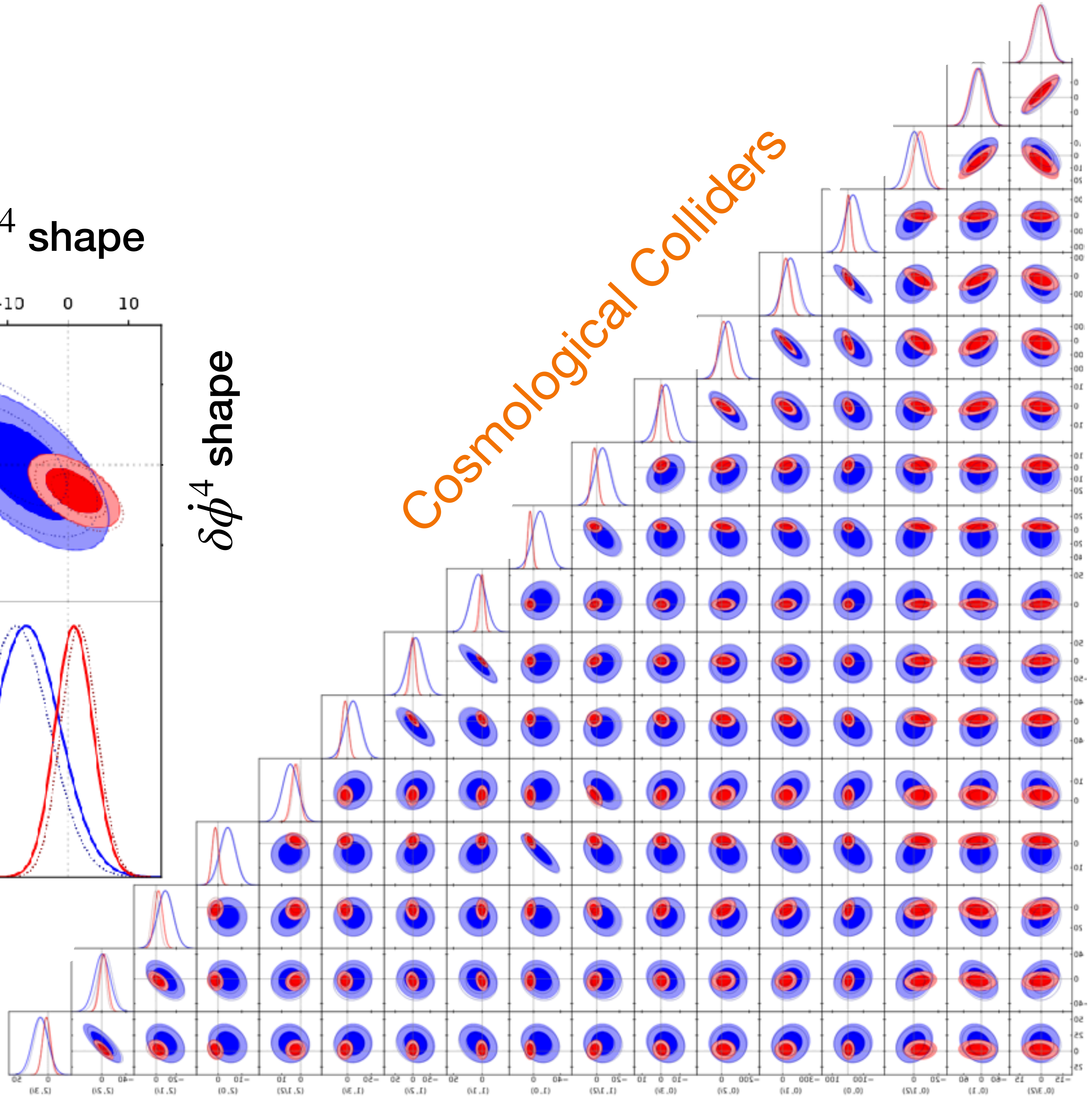
Using *Planck* data, we performed an **extensive** search for the inflationary **four-point function**!

We place bounds on **many** models:

- **Non-linear** effects [$g_{\rm NL}, \tau_{\rm NL}$]
- **Self-interactions** [EFT of inflation]
- Extra **light** fields
- Extra **heavy** fields
- Extra **spinning** fields
- Gravitational **lensing**

(and many more…)





Philcox 25abc, **Philcox** & Hill 25

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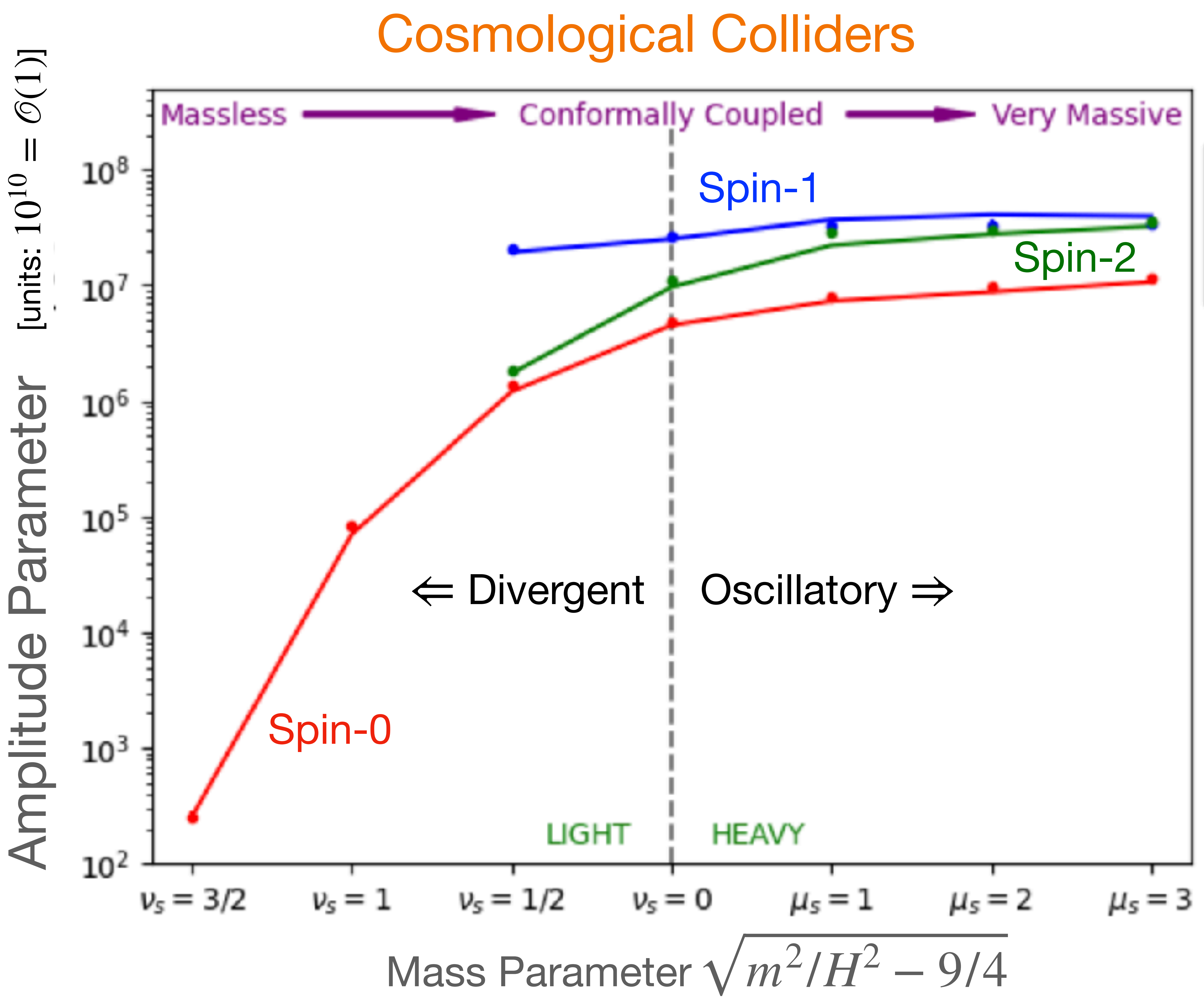

Philcox 25abc, **Philcox** & Hill 25

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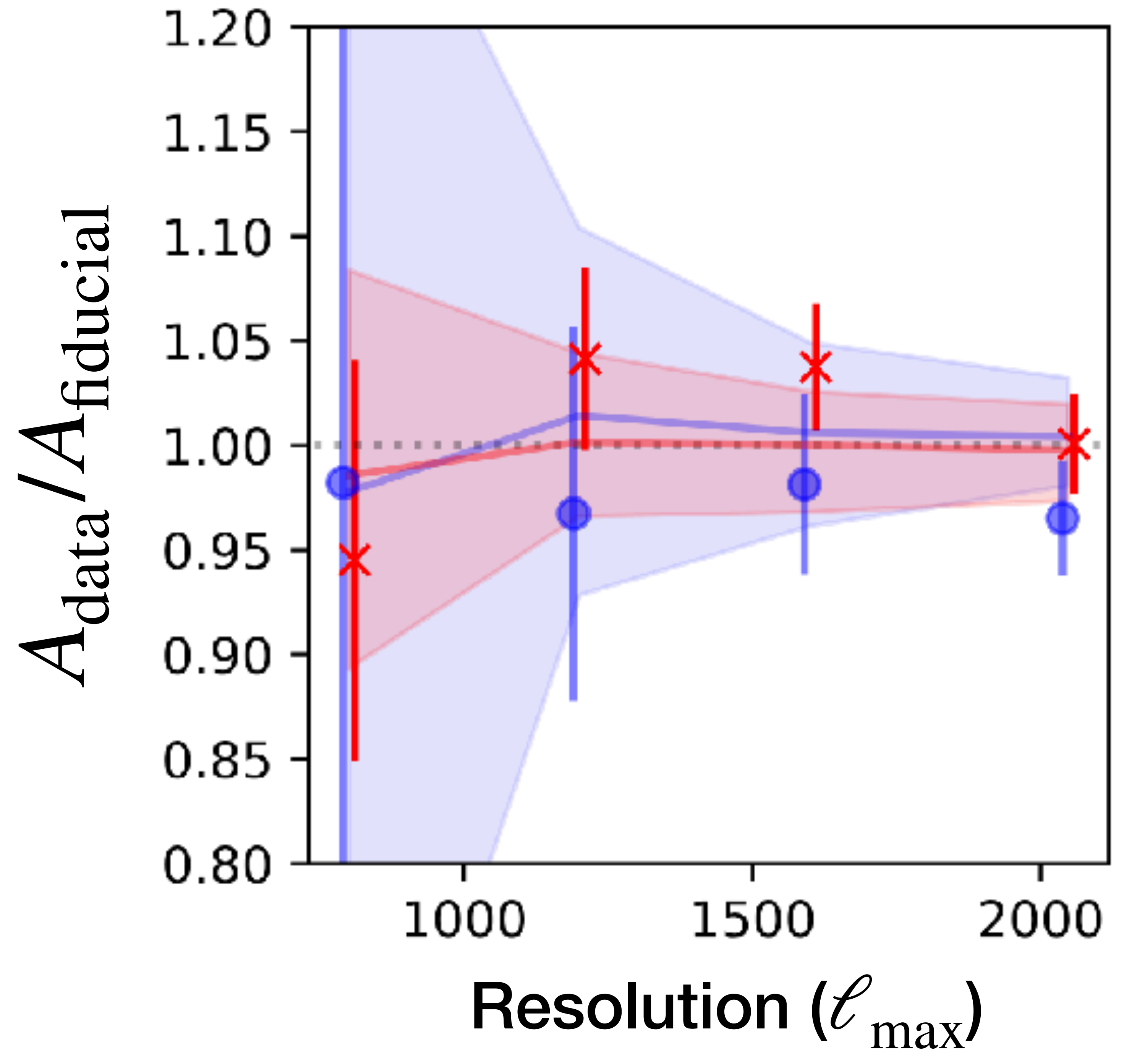
- Gravitational **lensing**

(and many more…)

All consistent with zero!

Detected at 43σ

Lensing matches theory to $(98 \pm 2)\,\%$!



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

The Future of Non-Gaussianity

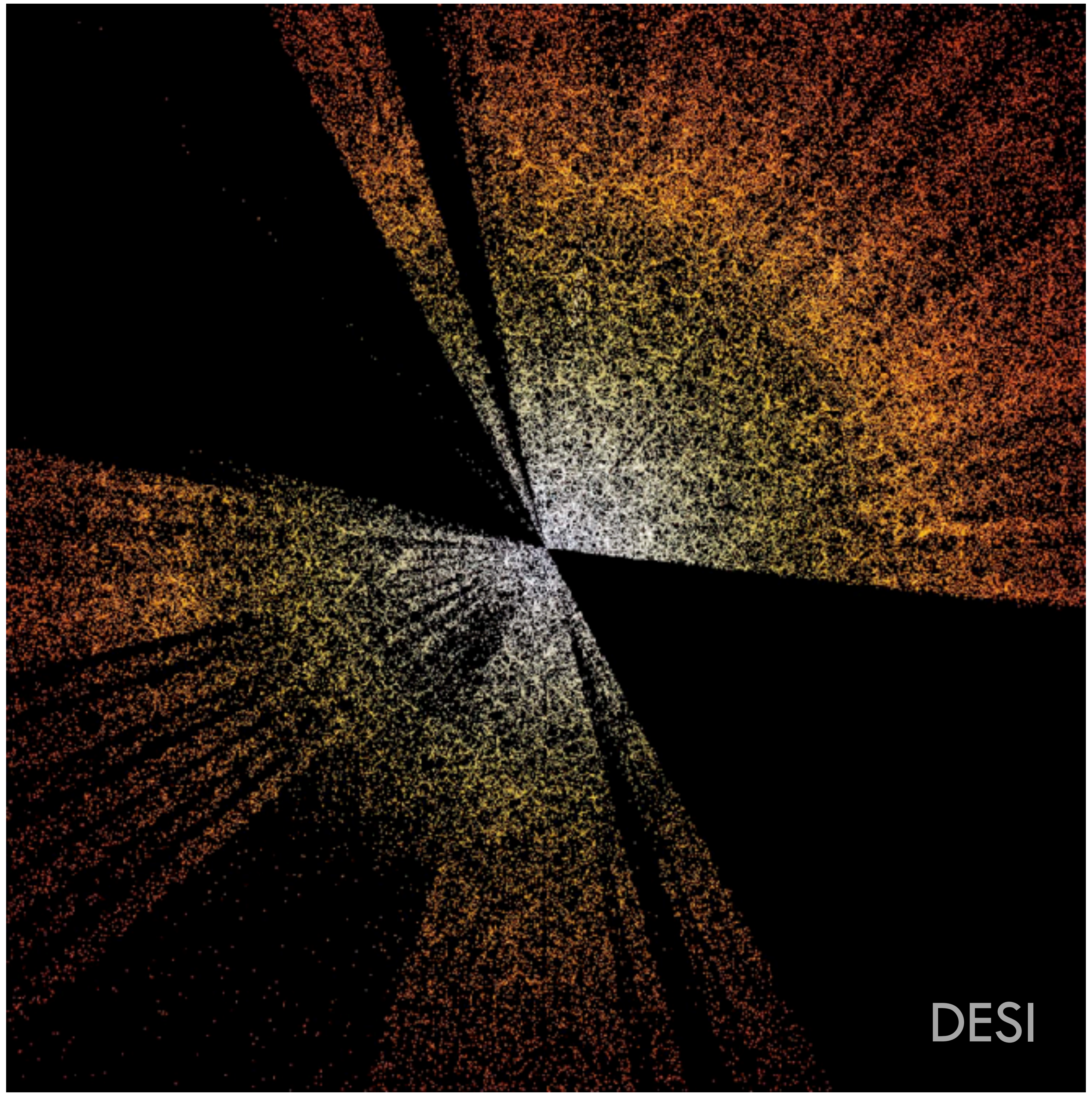
- Current experiments **confirm** that the primordial Universe is **close-to-Gaussian**
    - This strongly constrains the physics of inflation
    - *But*, there could still be could signals hiding under the noise
- **Future experiments** will tighten the bounds on many inflationary models!
    - However, we're running out of CMB to look at!
    - Constraints will only improve by $\lesssim (2-5)\times$

The Future of Non-Gaussianity

- **CMB experiments** provide a **2D** map of the Universe at age $380{,}000\,\mathrm{yr}$

- **Galaxy surveys** provide a **3D** map of the Universe at age $\sim 10^9 - 10^{10}\mathrm{yr}$
  - Legacy surveys have mapped a **million** galaxies [BOSS]
  - New surveys map $\sim 100\times$ more! [DESI, Euclid, Rubin, Roman, SPHEREx, …]

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



Can we use galaxy surveys to learn about inflation?

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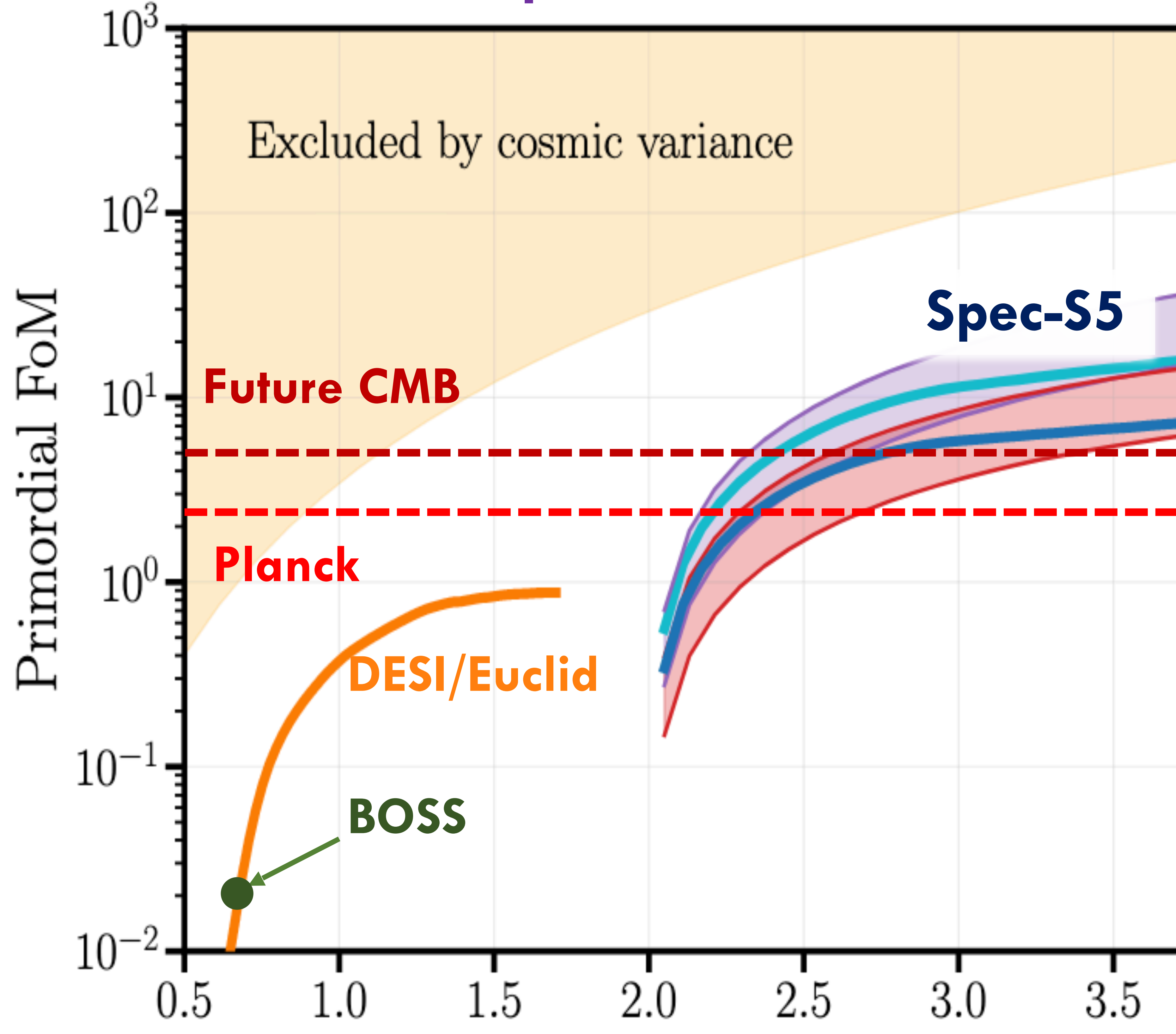
Amount of primordial information

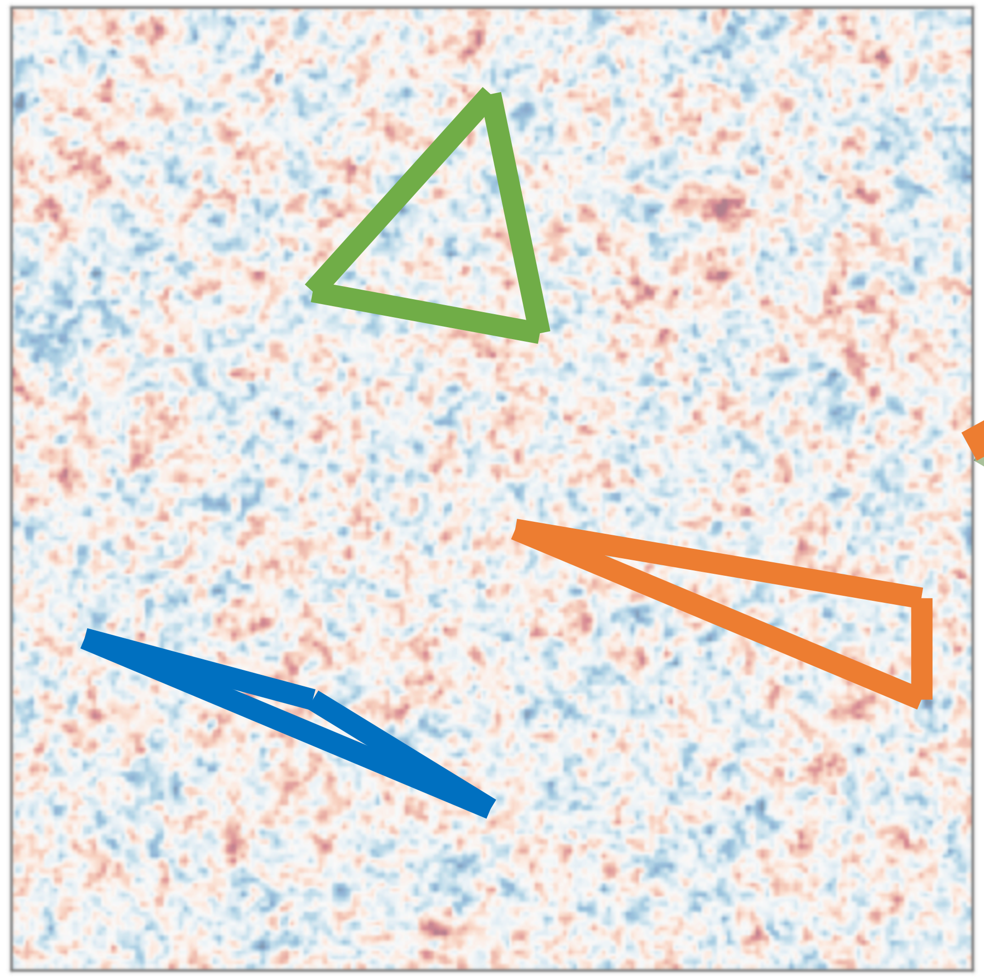


Maximum redshift

Sailer+, Ferraro+

How to Measure Primordial Non-Gaussianity

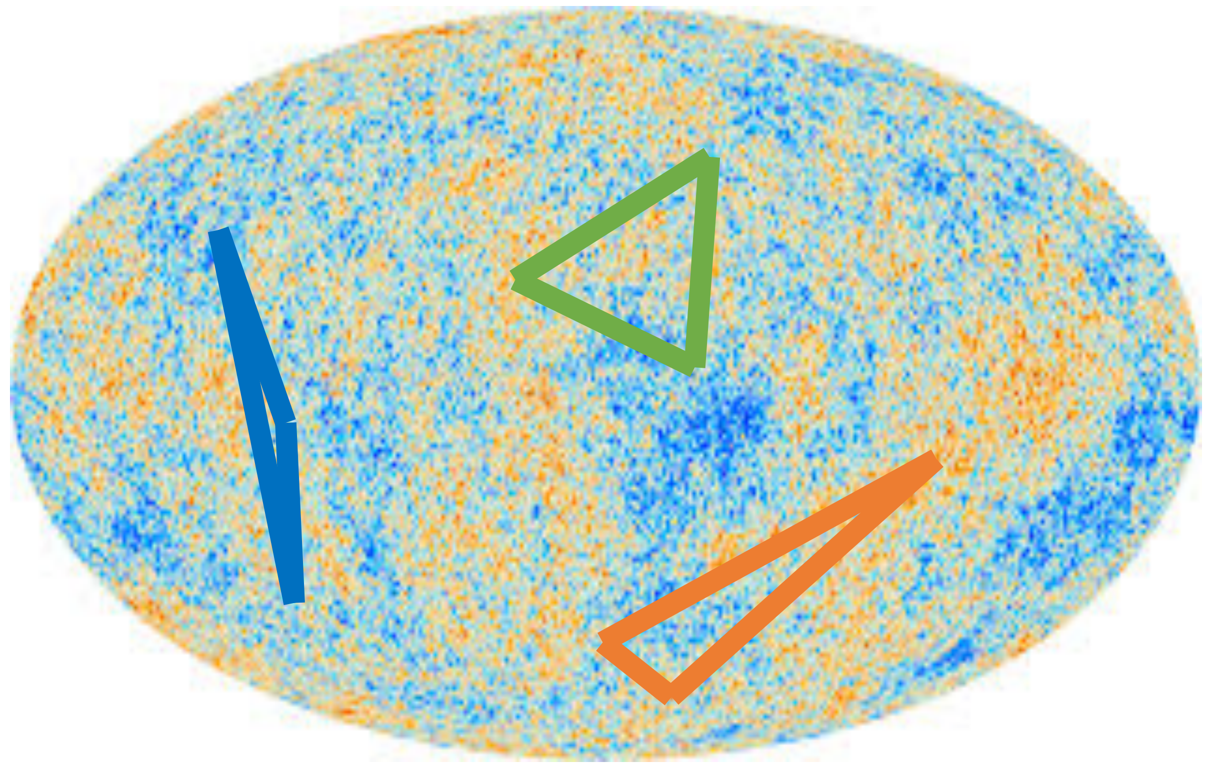
The **curvature fluctuations** set the **initial conditions** for the late Universe!



Primordial Curvature

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

Linear Physics

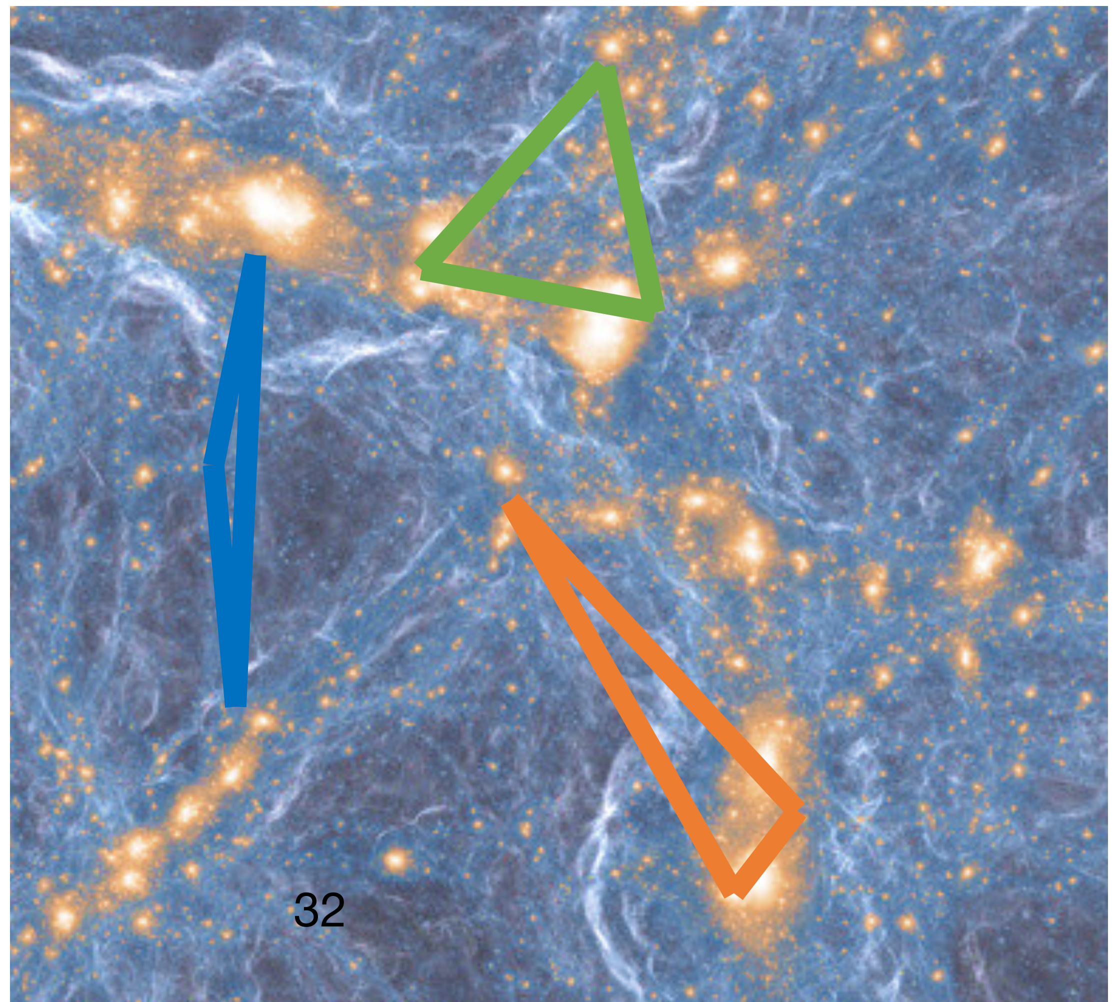


Fluctuations in CMB **temperature**

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

*(tracing **photon energies**)*

Non-Linear Physics



Fluctuations in **galaxy number density**

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

*(tracing **dark matter**)*

Planck, IllustrisTNG

Inflation from Galaxy Surveys

- The distribution of galaxies traces the **initial conditions**, the evolution of **dark matter**, and the physics of **galaxy formation**

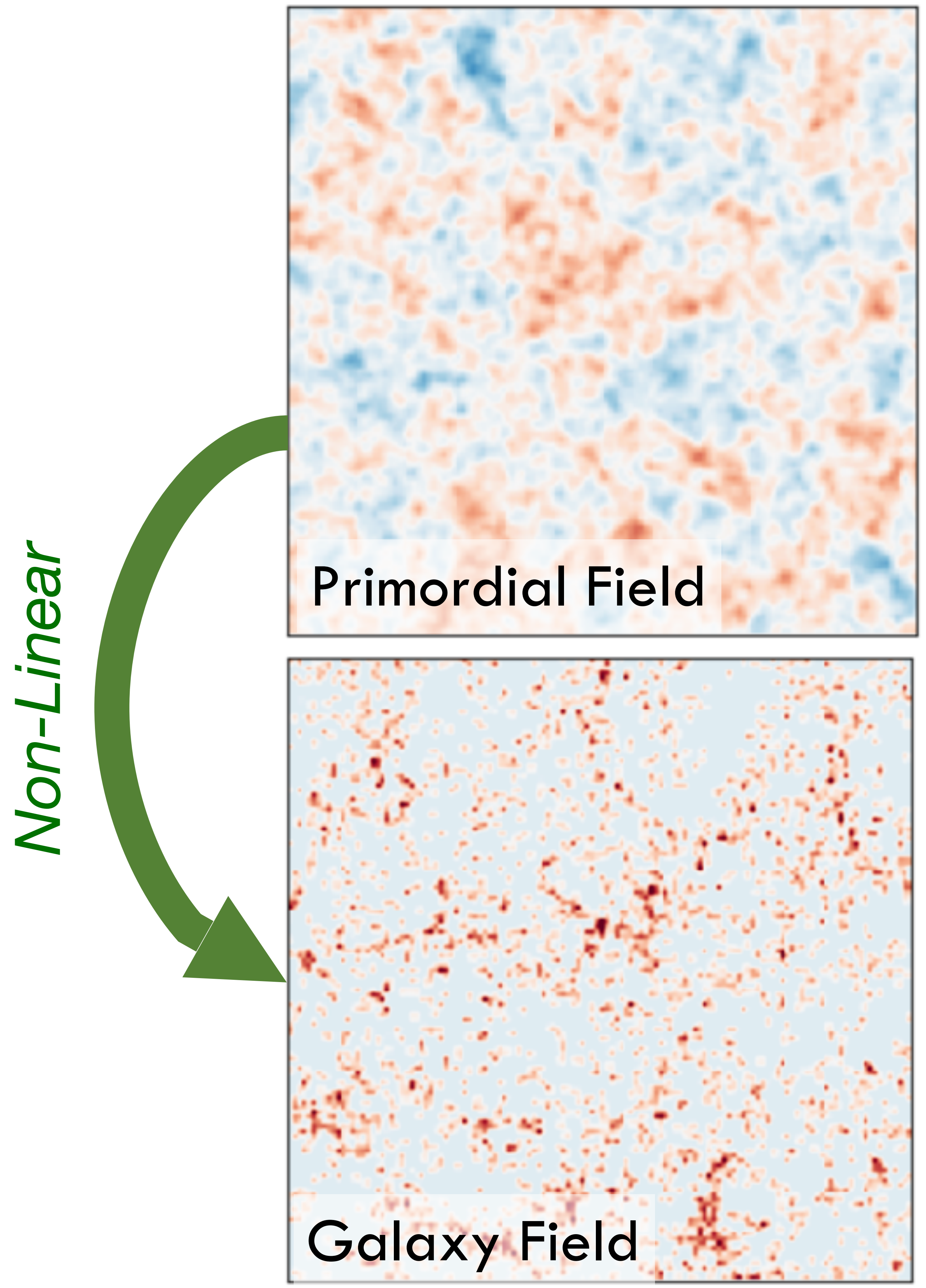
- To extract **inflationary information**, we need a **joint** model of all effects:

Galaxy Correlators ~ Primordial Physics + Gravity + cross-terms

State-of-the-art method:

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

$$\rho_{\text{galaxy}} = F_1[\zeta] + F_2[\zeta, \zeta] + F_3[\zeta, \zeta, \zeta] + \cdots$$



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

How to Model Galaxies

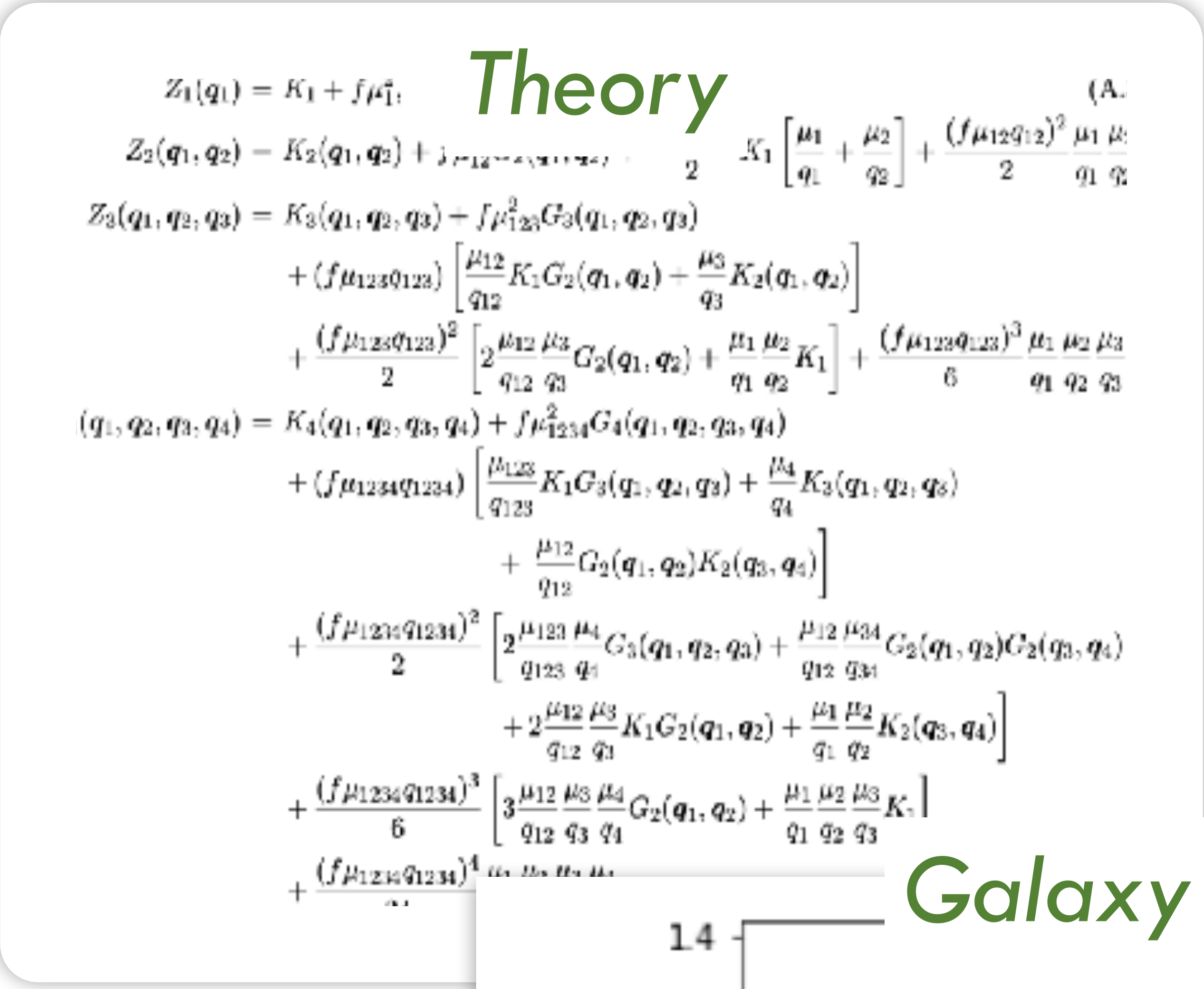
- Using the EFT of LSS, we can model the **two-** and **three-point** correlation functions of galaxies using **loop integrals**

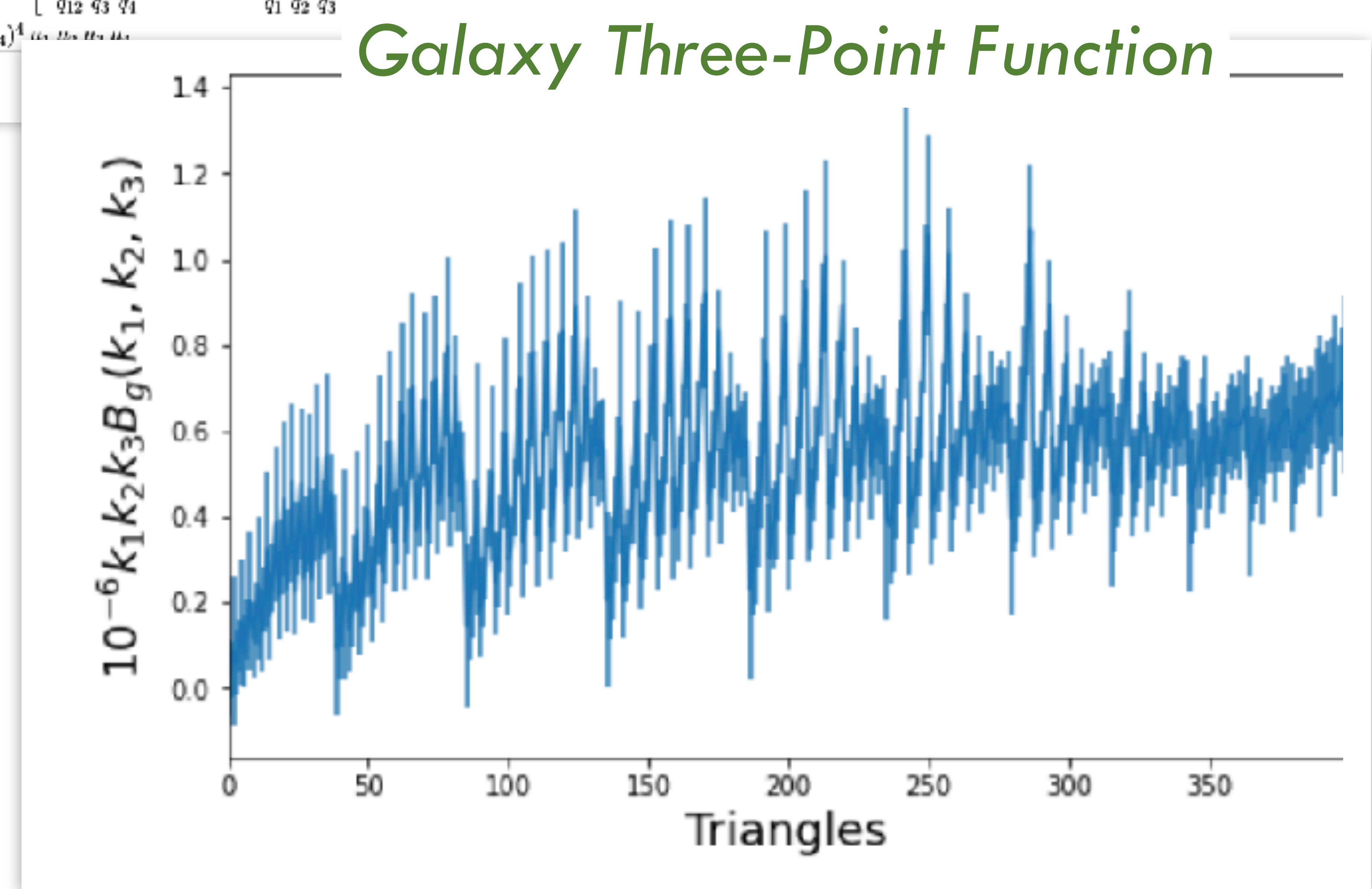
$$P_{gg}(k) \sim P_\zeta + \int P_\zeta^2 + \cdots$$

- With efficient tools like CLASS-PT, we can predict the statistics in $\lesssim 1$s at next-to-leading-order.

- The results depend on **cosmological**, **inflationary** and **bias** parameters
  - These can be **constrained** using data!

- These techniques are a **core** part of modern galaxy survey analyses!





Ivanov, **Philcox**+20,21, **Philcox**+22, Cabass, **Philcox**+22,24 (see also d'Amico+)

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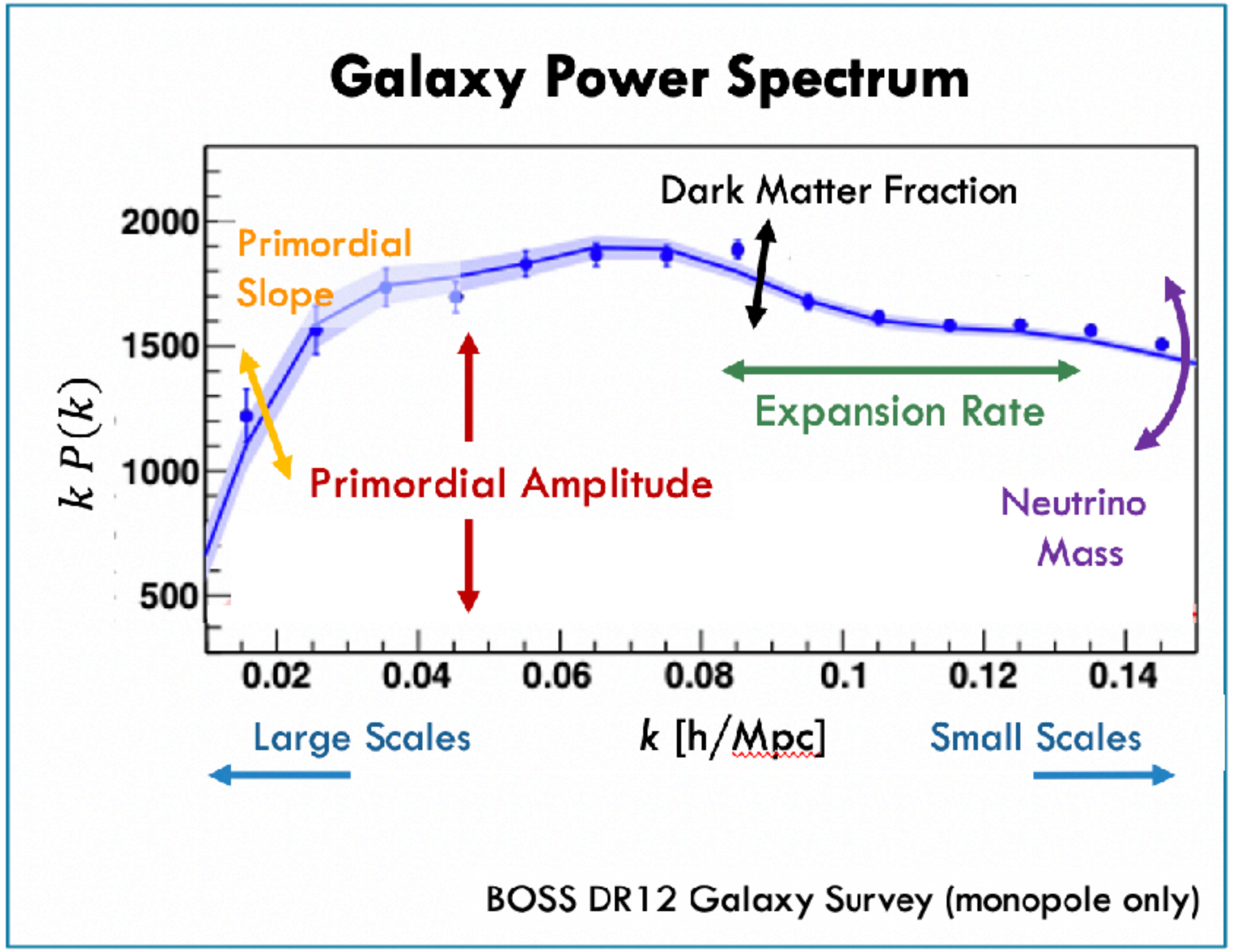


Ivanov, **Philcox**+20,21, **Philcox**+22, Cabass, **Philcox**+22,24 (see also d'Amico+)

Inflation from Galaxy Surveys

$$P_{gg}(k) \sim P_{gg,\mathrm{fid}}(k) + f_{\mathrm{NL}} \Delta P_{gg}(k)$$

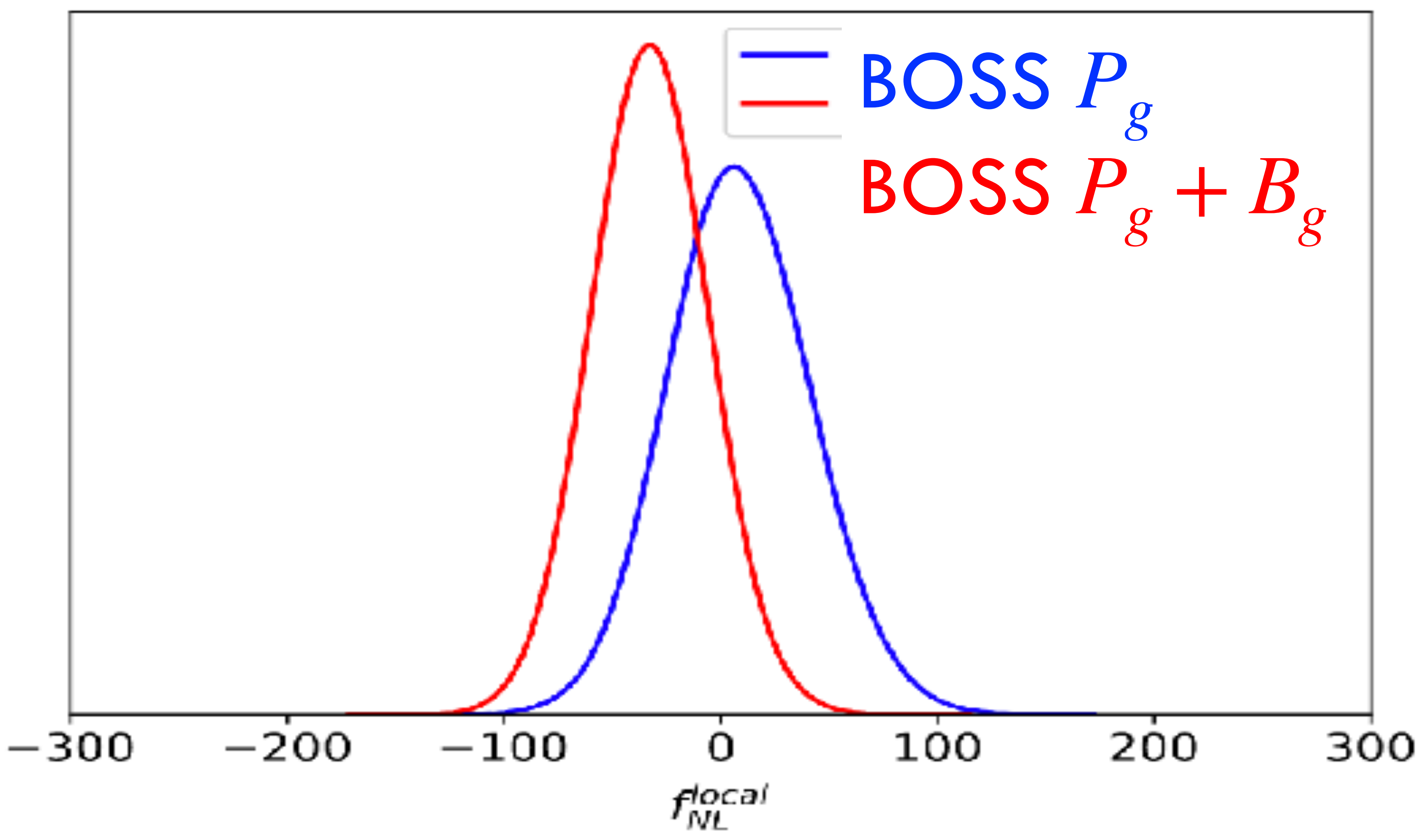
$$B_{ggg}(k) \sim B_{ggg,\mathrm{fid}}(k) + f_{\mathrm{NL}} \Delta B_{ggg}(k)$$

Recent works have constrained inflationary **bispectra** with **legacy galaxy survey** data (SDSS-BOSS):

- $f_{\mathrm{NL}}^{\mathrm{loc}}$: **Local** $\Rightarrow$ extra **light fields**
- $f_{\mathrm{NL}}^{\mathrm{eq,orth}}$: **Equilateral** $\Rightarrow$ cubic self-interactions
- $f_{\mathrm{NL}}^{\mathrm{coll}}(m_\sigma, c_\sigma)$: **Collider** $\Rightarrow$ exchange of massive ($m_\sigma \gtrsim H$) and massive-ish ($m_\sigma \lesssim H$) fields

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

Light Field Constraints



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

(CMB: ± 5, Target: ± 1)

Cabass, **Philcox**, Wallisch, Green, Guo, Han, Ivanov, Zaldarriaga, Simonovic, Chen, d'Amico+ …

Reanalyzing DESI

The first year of DESI data is now public!

See Anton Chudaykin's talk!

- We have developed an **independent** pipeline for analyzing the DESI catalogs!

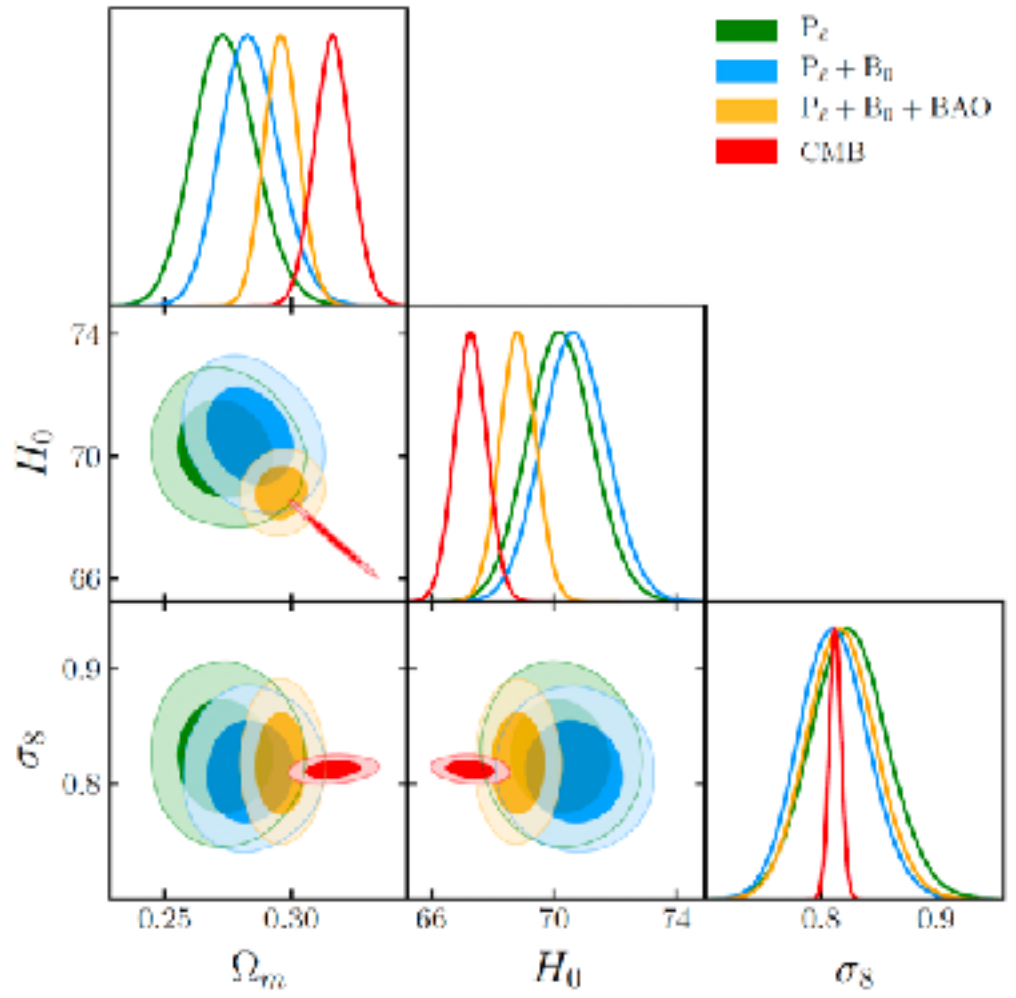
Our full dataset includes….

- **Power spectra,** $P_\ell(k), \quad (\ell = 0,2,4, \quad k \leq 0.2\,h\mathrm{Mpc}^{-1})$
- **Bispectra**, $B_\ell(k_1, k_2, k_3), \quad (\ell = 0,2, \quad k \leq 0.15\,h\mathrm{Mpc}^{-1})$
- **Baryon Acoustic Oscillations** $\alpha_\parallel, \alpha_\perp$
- **Lensing cross-correlations** $C_\ell^{\kappa g}$
- **Photometric galaxies** C_ℓ^{gg}

… all analyzed consistently with **Effective Field Theory** (at one-loop)

Excerpt from DESI Data Release 1

TARGETID int64	Z float64	NTILE int64	RA float64	DEC float64	...
39627540901396844	0.42060841162467566	1	159.30684159361635	-10.155757636765902	...
39627546836338876	0.8668980715716706	1	158.44667596279407	-9.962760066342906	...
39627546840531340	0.9348172077800124	1	158.4799294702238	-9.880343166939232	...
39627546840533707	0.7646678553759423	1	158.65071160360105	-9.900898173028425	...
39627546840534067	0.88129590000311	1	158.67878216902403	-9.91791308567385	...
39627546840534396	0.6646155566176719	1	158.70027052890555	-9.885818986284596	...
39627546844725593	0.7619120932610688	1	158.72751630870823	-10.011383569041937	...
39627546844726132	0.8129116729090922	1	158.75343950179967	-9.912671320450734	...
39627546844726593	0.835471640017949	1	158.79898500886574	-9.952788127324665	...
39627546848921194	0.8148312339778753	1	159.052157885943	-9.992428612452807	...
39627546848922139	0.7200341373651288	1	159.10202657806508	-9.938566366253678	...
39627546848922621	0.7606337242857438	1	159.1309146297404	-10.02377942401391	...
39627546848922874	0.7198972751282844	1	159.1462785833043	-9.950181865635432	...
39627546848923188	0.7210857282186207	1	159.16399100631358	-9.912947332242044	...
39627546848923381	0.569430729151765	1	159.17802210549974	-9.97892860399317	...
39627546848923415	0.8891288789150124	1	159.18008439182032	-10.072752528866118	...
39627546848923493	0.9513285375888253	1	159.1840389390485	-9.910321824120278	...
39627546848923519	0.7212784017696859	1	159.1860701777553	-9.944737378735352	...
39627546853114634	0.8131126675553368	1	159.25137421856687	-10.058275905081851	...
39627546853115304	0.5559672054059013	1	159.28855963426028	-9.955979493106813	...
39627546853115470	0.7147216867384578	1	159.2970230990033	-10.012836906791499	...
39627546853115682	0.9274570688680336	1	159.30835543527493	-10.106935803496164	...
...	...	...	...	...	...



ΛCDM Constraints

Chudaykin, Ivanov, **Philcox** 2025abc / 2026ab, DESI, Chaussidon+24

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- We have developed an **independent** pipeline for analyzing the DESI catalogs!

So far, we have constrained…

- ΛCDM parameters $(\Omega_m, H_0, \sigma_8)$
- Dark energy equation-of-state (w_0, w_a)
- Curvature (Ω_k)
- Neutrino masses $(\sum m_\nu)$
- Inflation $(f_{\rm NL})$

… both alone and in combination with the CMB!

There are many more models to constrain!

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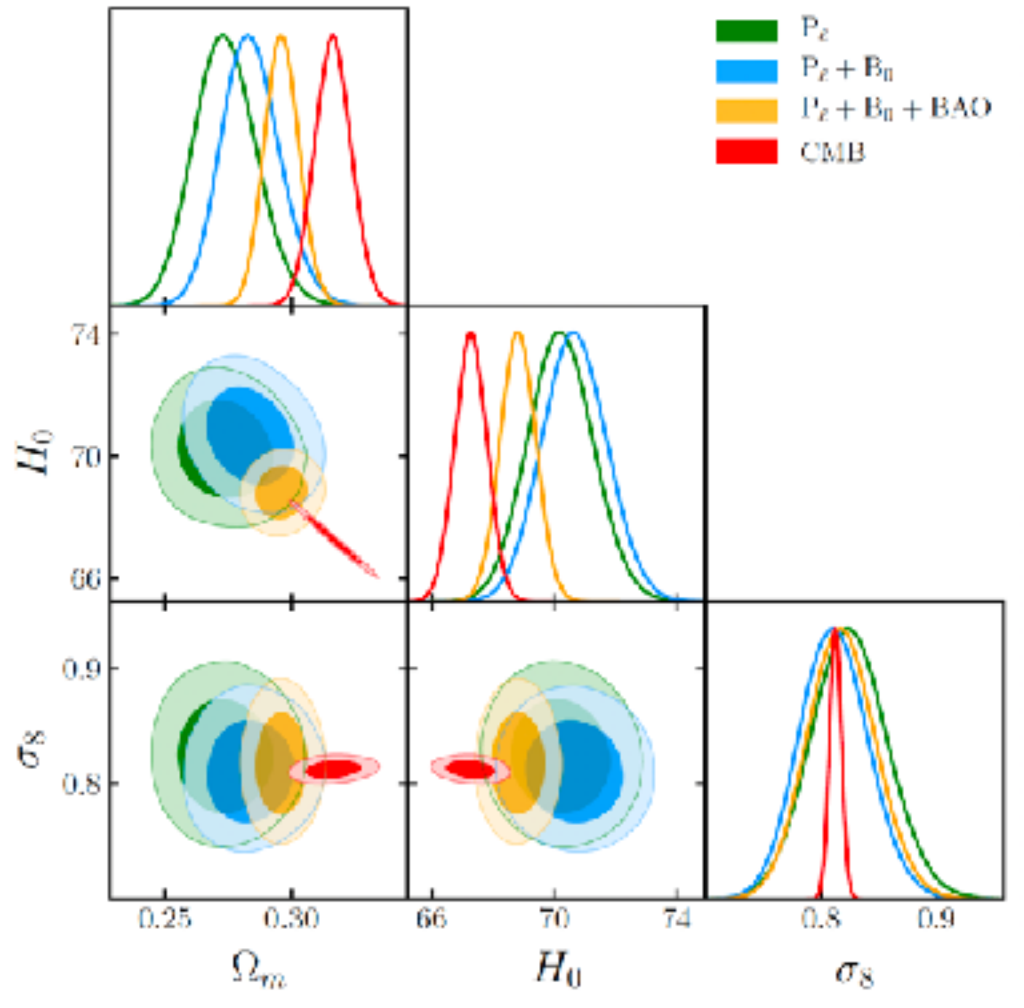


ΛCDM Constraints

Chudaykin, Ivanov, **Philcox** 2025abc / 2026ab, DESI, Chaussidon+24

Inflation from DESI

The first year of DESI data is now public!

See Anton Chudaykin's talk!

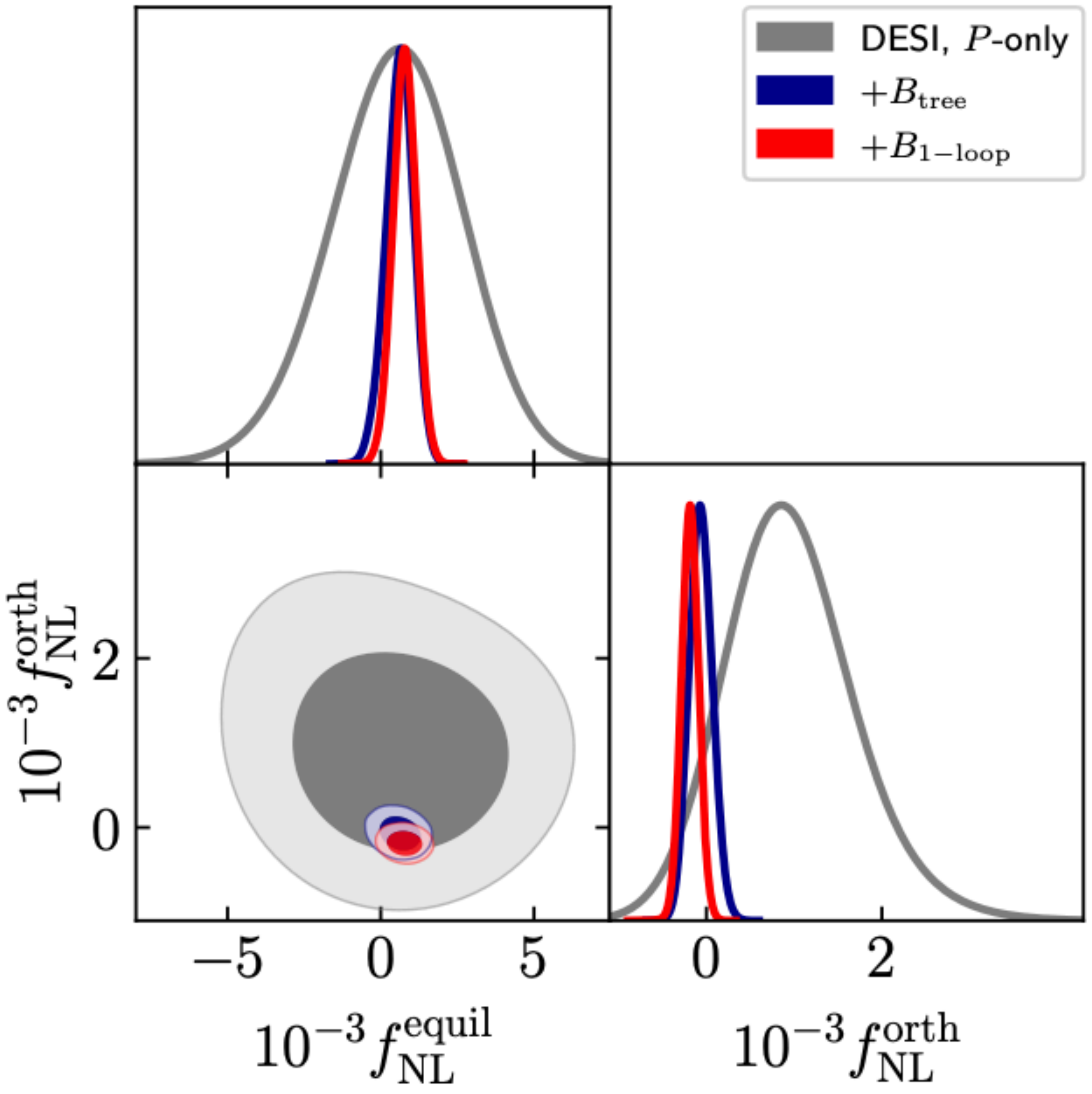
- We have developed an **independent** pipeline for analyzing the DESI catalogs!

We place strong constraints on inflation…

- **Single-Field (v1)**: $f_{\rm NL}^{\rm eq} = 200 \pm 230$
- **Single-Field (v2):** $f_{\rm NL}^{\rm orth} = -24 \pm 86$
- **Multi-field**: $f_{\rm NL}^{\rm loc} = -0.1 \pm 7.4$

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

… and there's many more scenarios to explore!



Chudaykin, Ivanov, **Philcox** 2025abc / 2026ab, DESI, Chaussidon+24

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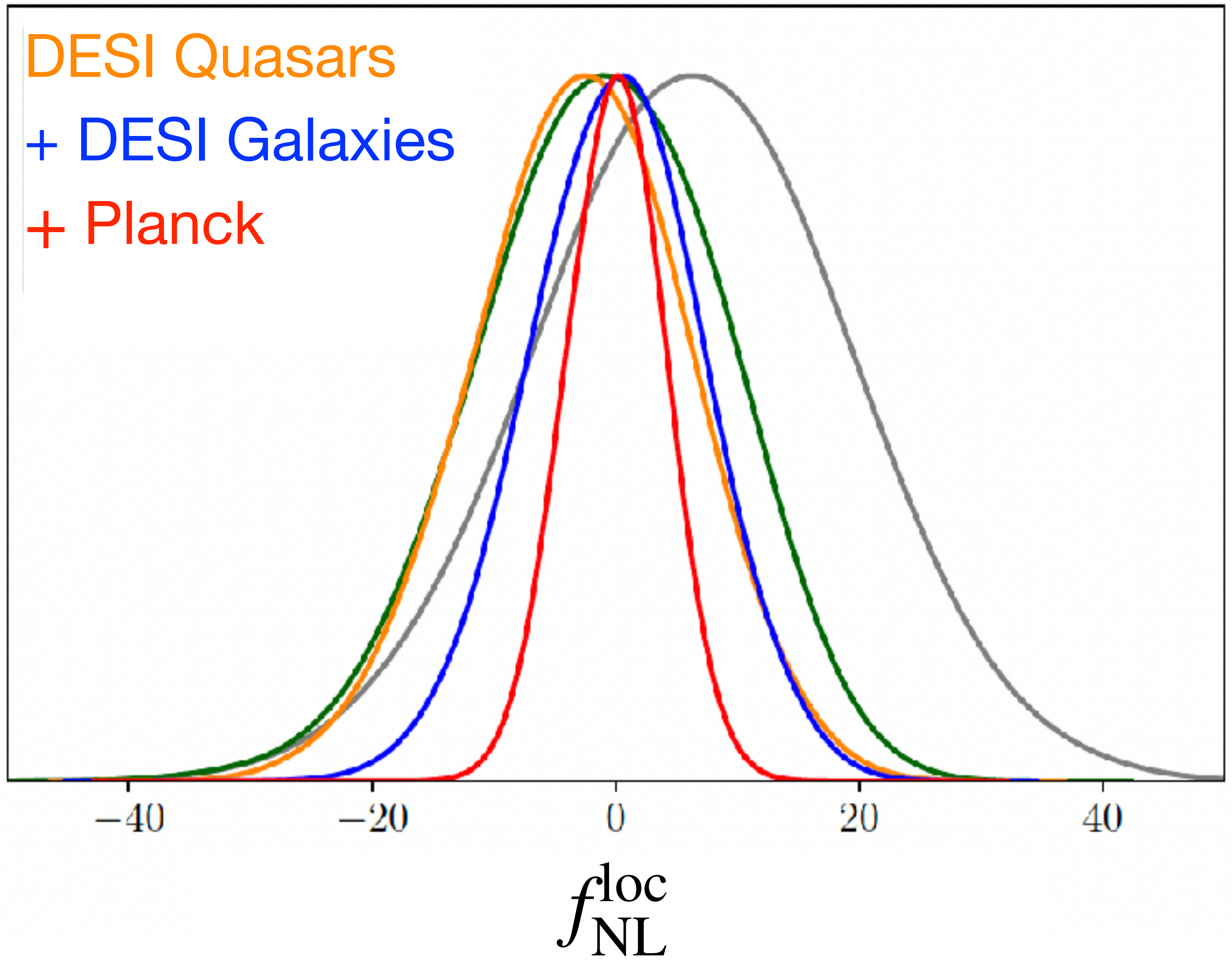


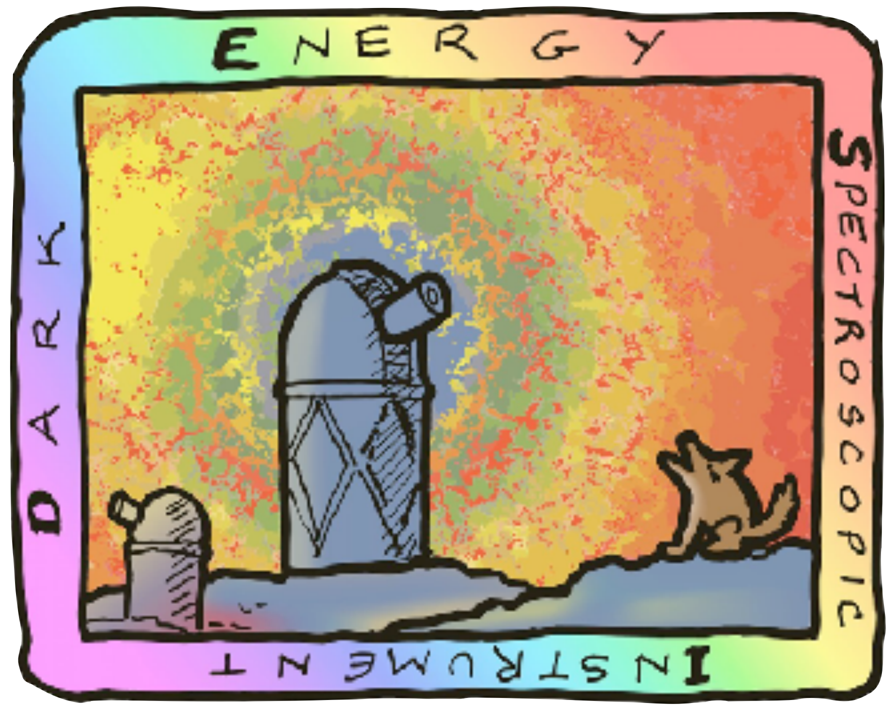
By combining with ***Planck***, we obtain the **tightest** constraint on local PNG yet!

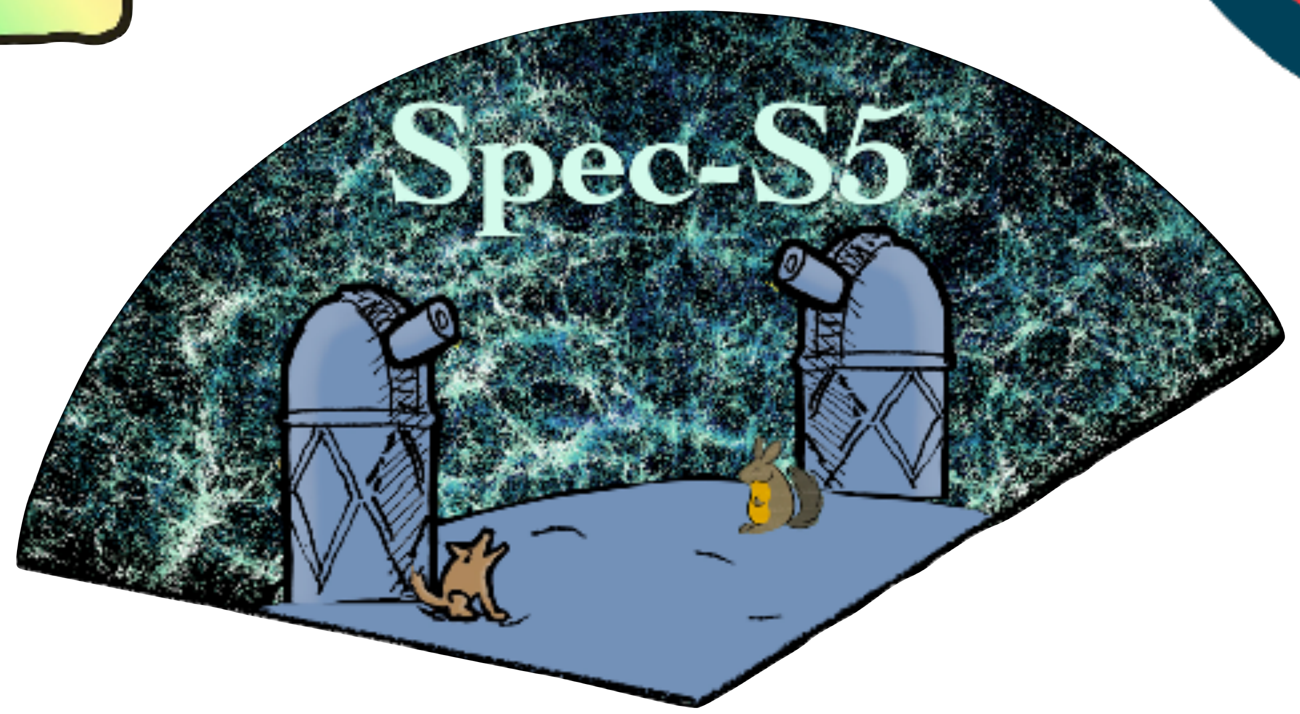
$$f_{\rm NL}^{\rm loc} = 0.0 \pm 4.1$$

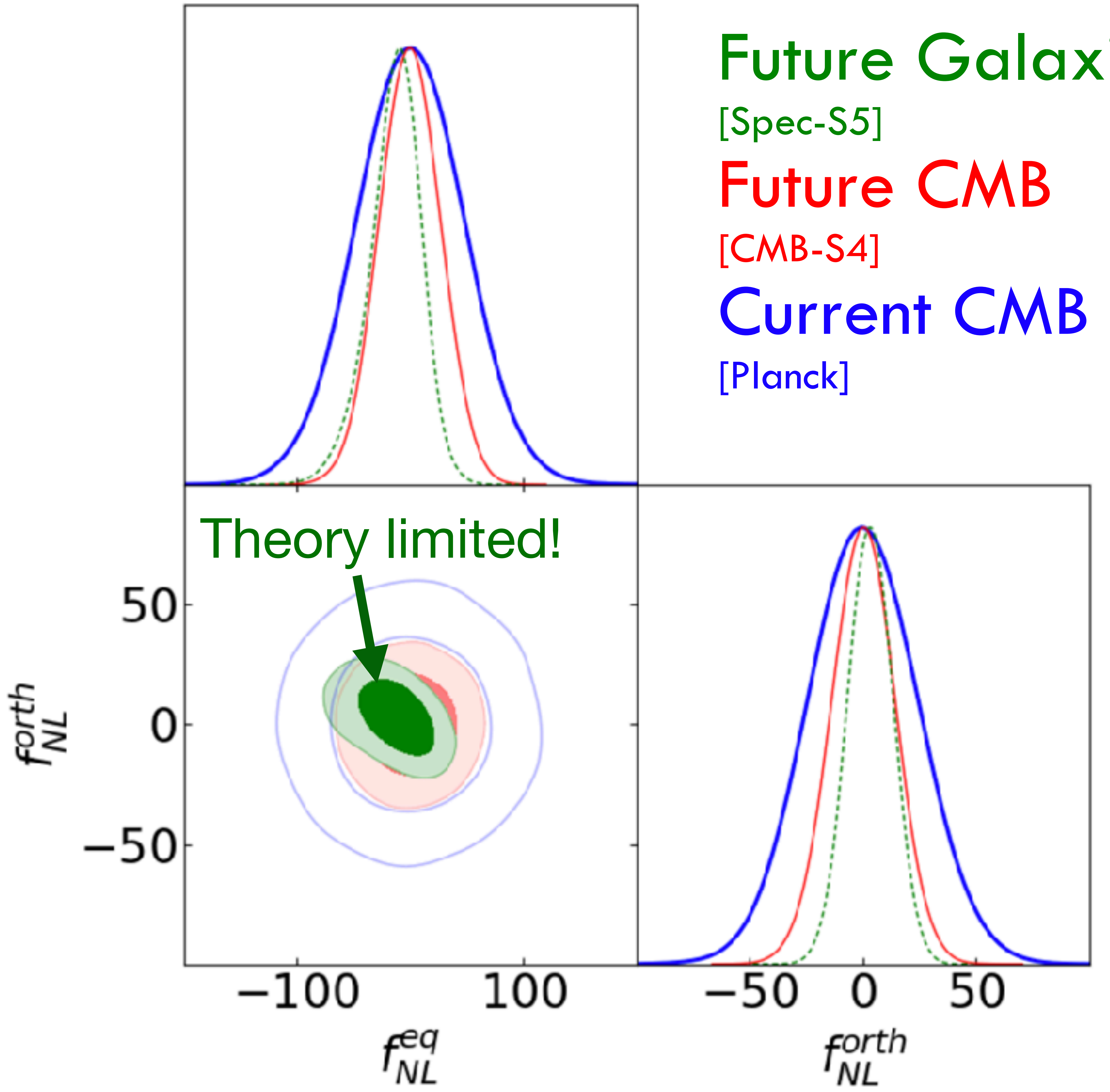
Chudaykin, Ivanov, **Philcox** 2025abc / 2026ab, DESI, Chaussidon+24

Inflation beyond DESI

Even better experiments are coming soon!







Future Galaxies
[Spec-S5]
Future CMB
[CMB-S4]
Current CMB
[Planck]

Self-Interaction Forecast

Within a decade, galaxy clustering will be the **best** probe of the inflationary Universe!

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

Stanford University

KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

LEINWEBER INSTITUTE FOR THEORETICAL PHYSICS

Summary

- **Particle interactions** in inflation leave remnants in the CMB and galaxy distributions
- Searching for these signatures probes $\lesssim 10^{16}\mathrm{GeV}$-scale physics using low-energy data
- By combining new data with new methods we will **significantly** enhance our knowledge of inflation

Contact: ophilcox@stanford.edu