Title: Galaxy Surveys: A Precision Primordial Probe

Speakers: Oliver Philcox

Series: Colloquium

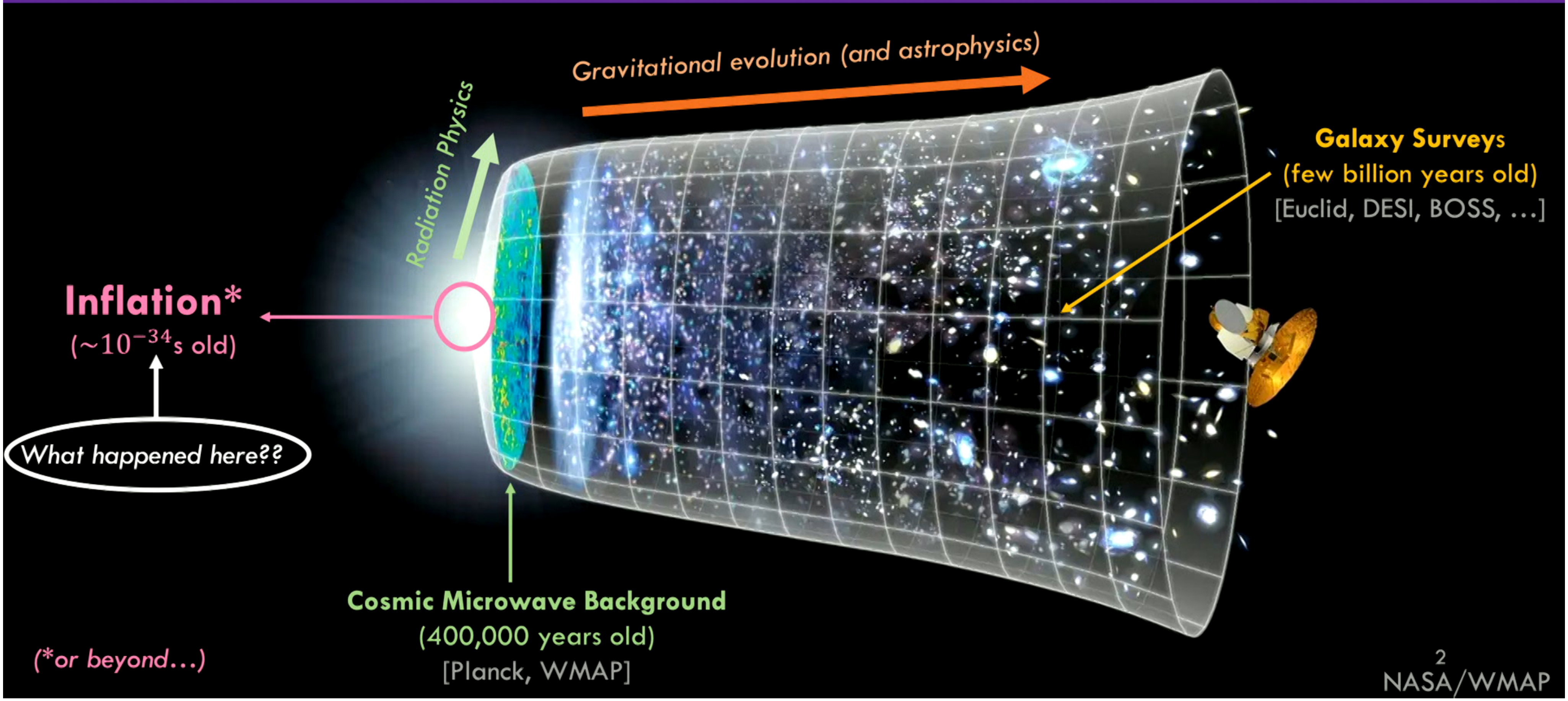
Date: February 14, 2024 - 2:00 PM

URL: https://pirsa.org/24020049

Abstract: What happened in the earliest moments of the Universe? Despite decades of theoretical and observational work, a detailed understanding of the primordial Universe has remained elusive. In this talk, I will show how surveys of millions of galaxies can shed new light on these issues by constraining the statistics of the Universe just after inflation. By combining robust perturbative models with novel numerical techniques, I have placed some of the first (non-Gaussian) constraints on the dynamics and field content of inflation from galaxy surveys; these will sharpen considerably in the next decade as the volume of observational data grows. Through a combination of traditional perturbative approaches and new symmetry-based techniques, I will demonstrate how current and future galaxy surveys can be used to search for a wealth of new physics, including primordial scattering processes and parity violation, opening the door to constraining ultra-high-energy physics with low-energy data.

Zoom link

Our View of the Universe



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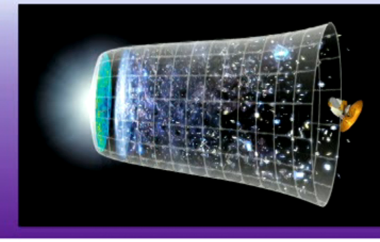
What Do We Think We Know About Inflation?



Background

- *(Almost)* **exponential** expansion of spacetime

*Sources a **flat** Universe with **causal connectivity** and without **monopoles***

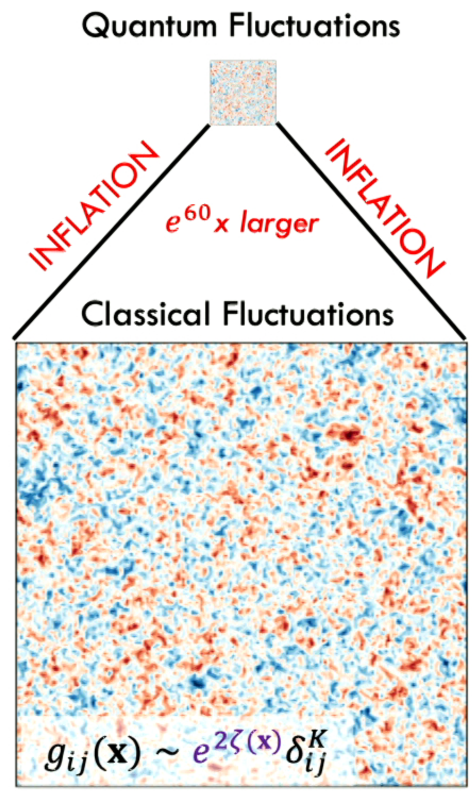
Perturbations

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

→ *(Almost)* **Gaussian** distribution of fluctuations: *observationally supported!*

$$\zeta \sim \text{Gaussian}[P(k)], \qquad P(k) = \langle \zeta(\mathbf{k}) \zeta^*(\mathbf{k}) \rangle'$$

Use Fourier-space, since modes are independent! *($k \sim 1/$distance)*



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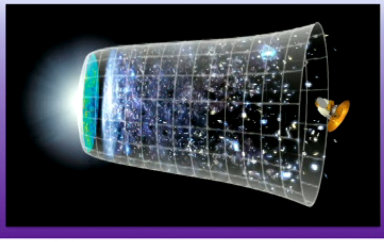
COBE, WMAP, Planck, Guth, Linde, Starobinsky, …

What Do We Think We Know About Inflation?



Simplest model

- A *single field* evolving along an *(almost)* flat potential [Single Field Slow Roll]
- This has **quantum fluctuations**

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

But:

- What is the **energy scale** of inflation? *[Hubble]*

$$H \sim 10^{14}\,\text{GeV}\,?$$

- What was the **potential**?

$$V(\phi) = ???$$

- Were there **other fields** during inflation?

$$\phi \to \phi, \chi, \psi_\mu, \ldots$$

- Did the fields **interact**?

$$\mathcal{L}_{\text{inf}} \supset \dot{\phi}^3 + \cdots$$

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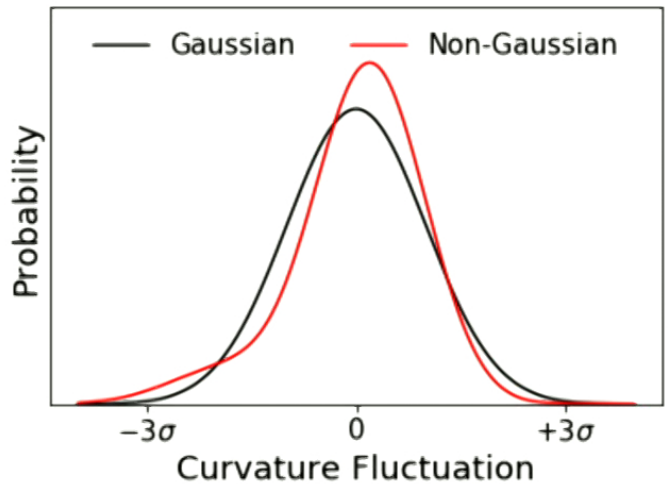
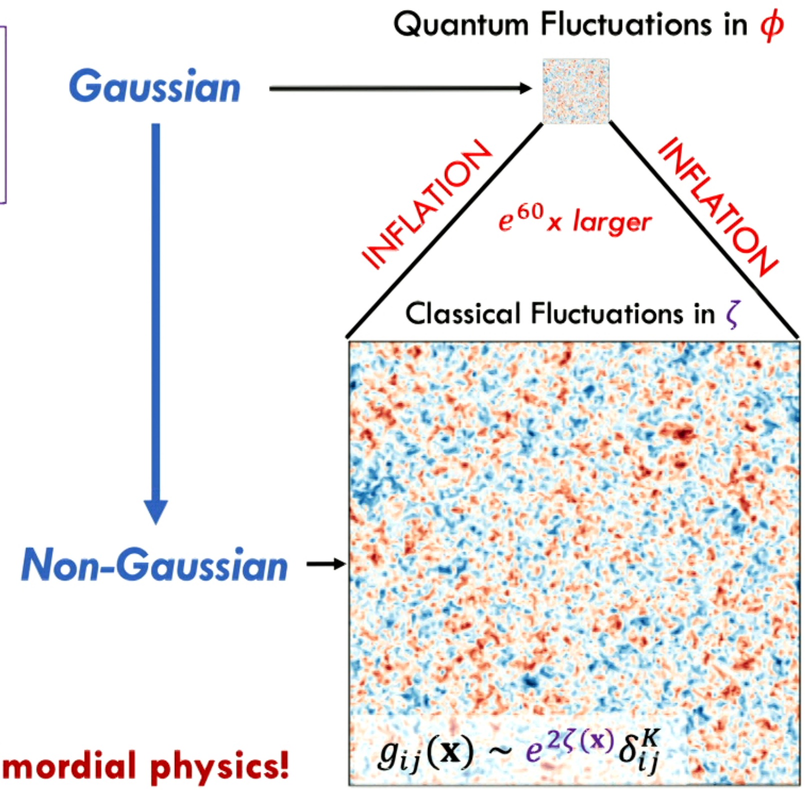
Guth, Linde, Starobinsky, Lyth, Mukhanov, Sasaki, …

Primordial Non-Gaussianity

New physics in the early Universe

→ **non-Gaussian** curvature (ζ) fluctuations





By measuring the non-Gaussianity, we can constrain primordial physics!

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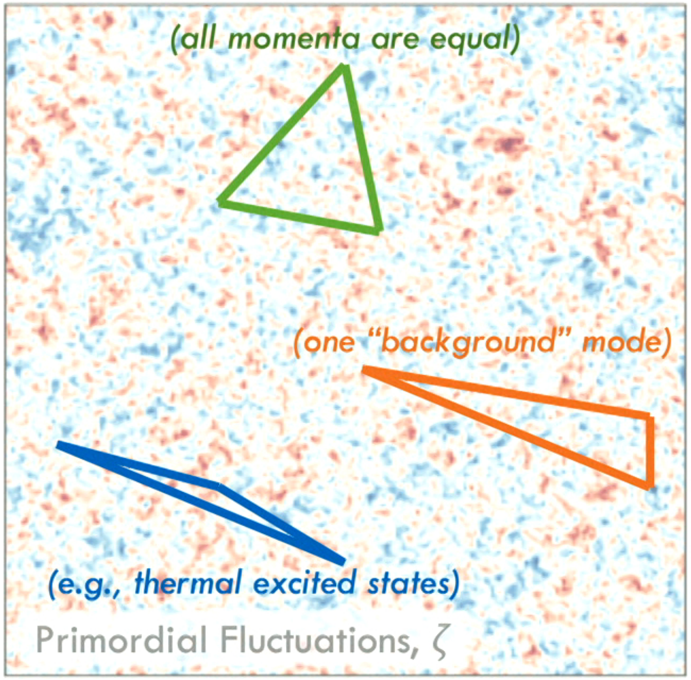
Maldacena, Arkani-Hamed, Zaldarriaga, Creminelli, Afshordi, …

What Does Non-Gaussianity Look Like?

- In 3D, non-Gaussianity is parameterized by **correlation functions** e.g. **bispectra**

$$B(\mathbf{k_1},\mathbf{k_2},\mathbf{k_3}) = \langle\zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3})\rangle \neq 0$$

- Different shapes constrain different physics, e.g.:
  - Equilateral triangles: **self-interactions**
  - Squeezed/local triangles: **new light fields**
  - Folded triangles: **different initial conditions**



$$\zeta \sim \text{Edgeworth}[P(k), B(k_i), T(k_i), \ldots]$$

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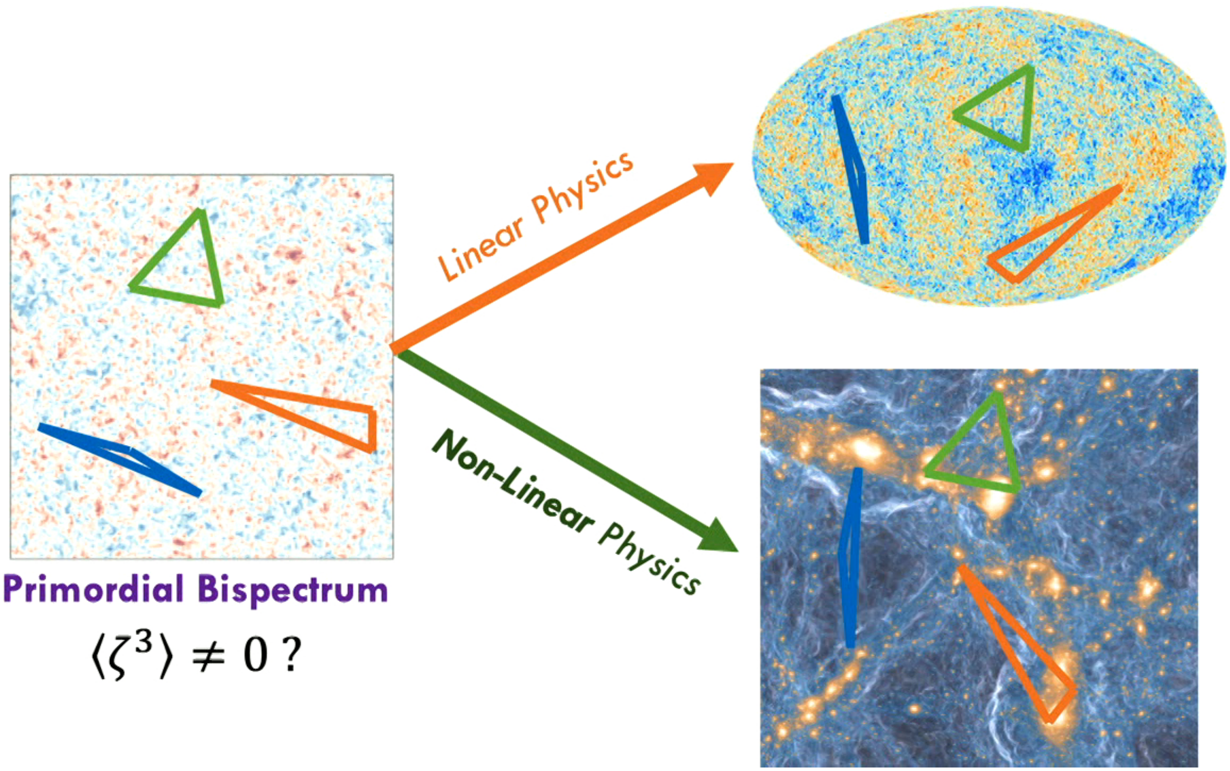
Maldacena, Arkani-Hamed, Zaldarriaga, Creminelli, Afshordi, …

Measuring Non-Gaussianity

- **Late-time** non-Gaussianity traces **primordial** non-Gaussianity



Cosmic Microwave Background
Bispectrum

$\langle \delta T^3 \rangle \neq 0$?

Galaxy Distribution
Bispectrum

$\langle \delta n_{\rm gal}^3 \rangle \neq 0$?

*(tracing **dark matter**)*

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Planck, IllustrisTNG

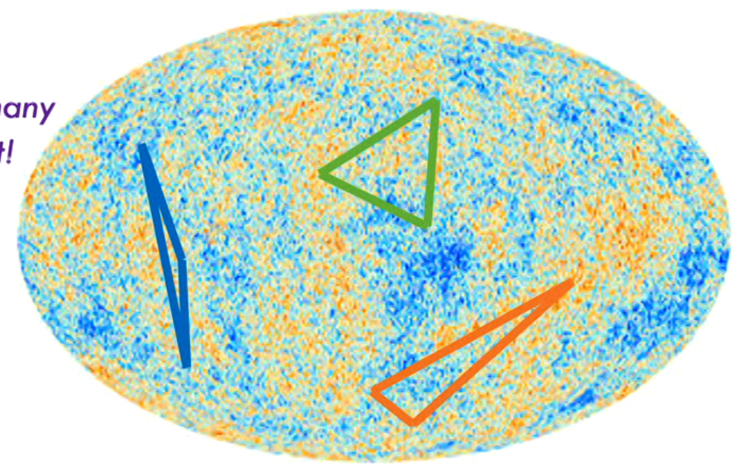
CMB Non-Gaussianity

- **CMB** surveys have constrained **many** phenomenological shapes of non-Gaussianity

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

Planck 2018 f_{NL}		
	Local	-0.9 ± 5.1
	Equilateral	-26 ± 47
	Orthogonal	-38 ± 24

These shapes span many models of interest!



Cosmic Microwave Background

- Primordial non-Gaussianity is **small:**

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

- But theory target is $f_{\mathrm{NL}} \sim \mathcal{O}(1)$…

Can we do better in the future?

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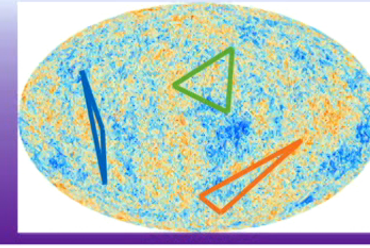
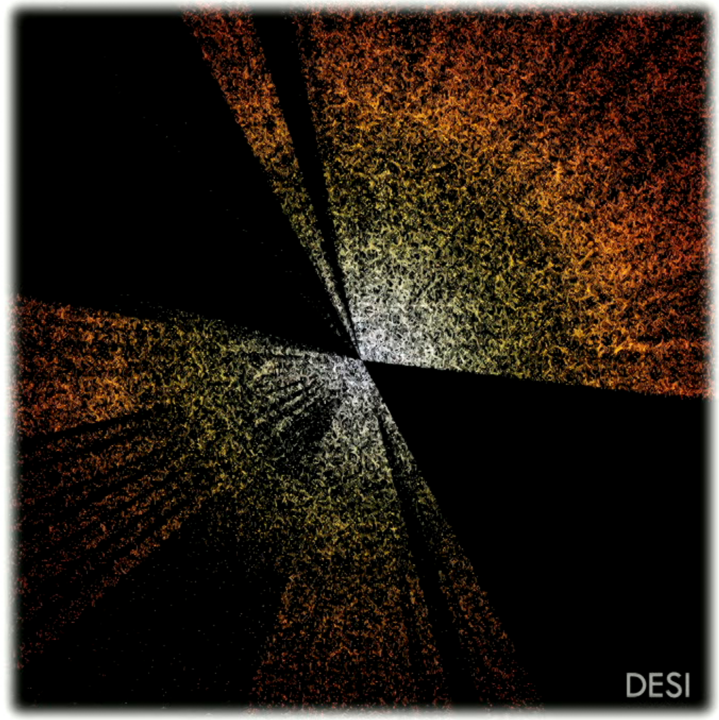
Planck 2018, Smith+06, Senatore+09, Maldacena 03, Creminelli 03, Alvarez+14

The Future of Non-Gaussianity



- Future **CMB** experiments will improve bounds by $\approx 2\times$
  - This is a **two-dimensional** field
  - We're running out of modes to look at!
  - Small-scales are **hard**

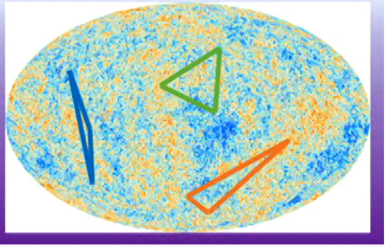
- What about **galaxy surveys**?
  - This is a **three-dimensional** field
  - Legacy surveys map **a million** galaxies
  [2010s: BOSS]
  - New surveys map $\sim \mathbf{100}\times$ more!
  [2020s: Euclid, DESI, SPHEREx, Rubin, …]



CMB-S4: $\sigma\left(f_{NL}^{\rm local}\right) = 3, \sigma\left(f_{NL}^{\rm equil}\right) = 21, \sigma\left(f_{NL}^{\rm orth}\right) = 9$

CMB-S4, Simons Observatory, SDSS-III

The Future of Non-Gaussianity



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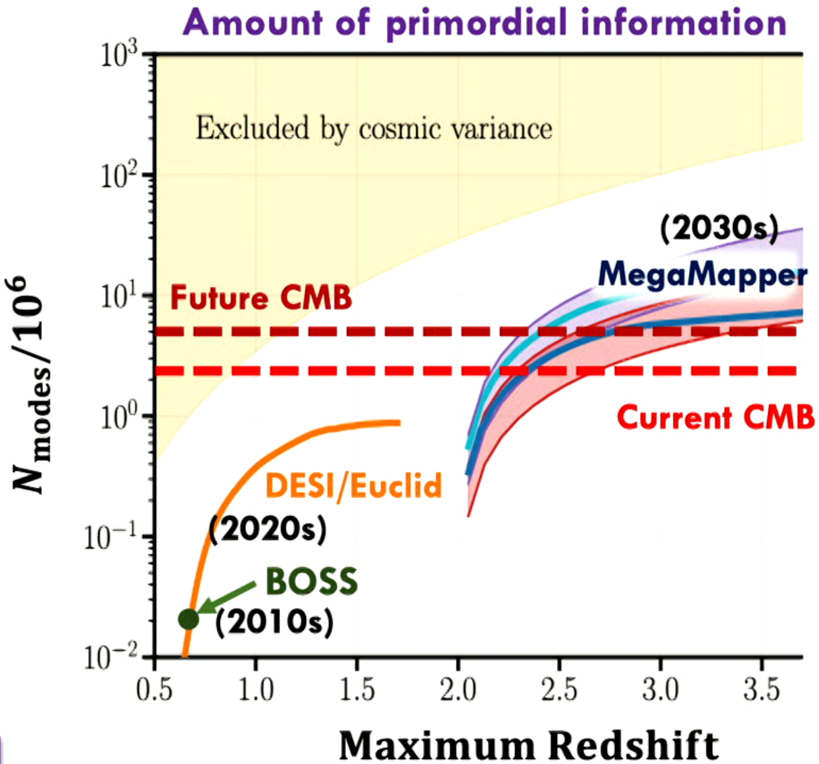
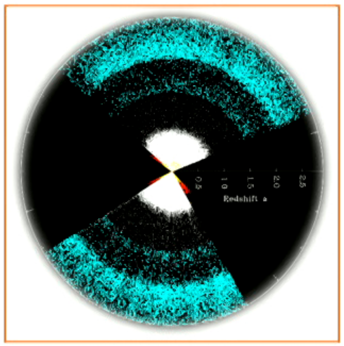
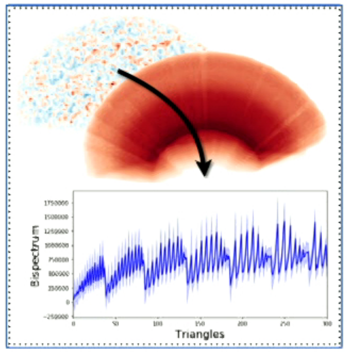


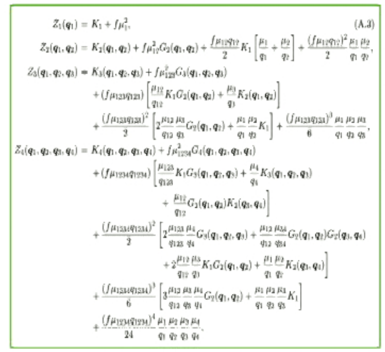
Let's make galaxy surveys a precision probe of inflation!

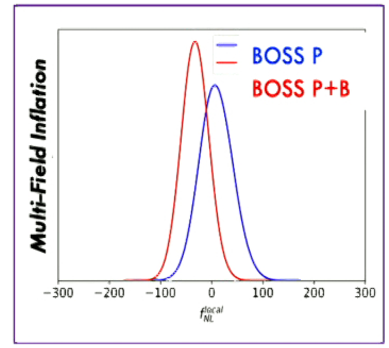
CMB-S4, Simons Observatory, Sailer+22, Ferraro+22

Roadmap: From Public Data to New Physics









Data

- **Galaxy Surveys [BOSS]**
- CMB fluctuations [Planck]

Estimation

- Power spectrum
- **Bispectrum**
- **Trispectrum**

Theory

- **Perturbation theory**
- Inflationary theory
- **Symmetries**

Constraints

- ΛCDM bounds
- H_0 & S_8 tensions
- **Inflationary interactions**
- **Parity-violation**

All with **public code!**

GitHub: CLASS-PT, full-shape-likelihoods, PolyBin

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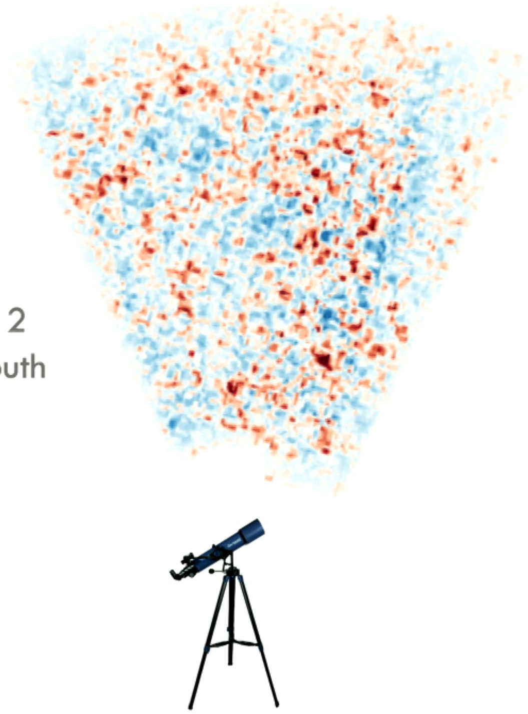
Philcox+19-24

How to Analyze a Galaxy Survey

Galaxy Density Field, $n_{\rm gal}$

BOSS DR12
LOWZ/South



GitHub: *spectra-without-windows*, *PolyBin3D*

SDSS-III, **Philcox**+21

How to Analyze a Galaxy Survey

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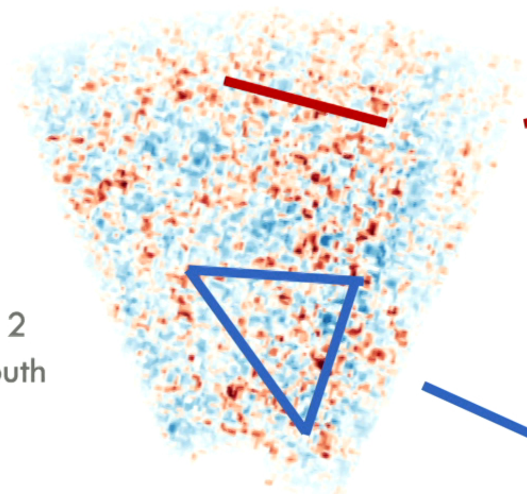
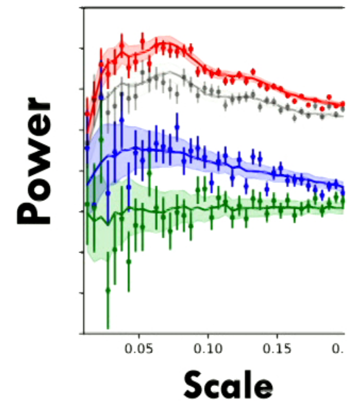


BOSS DR12
LOWZ/South

Power Spectrum

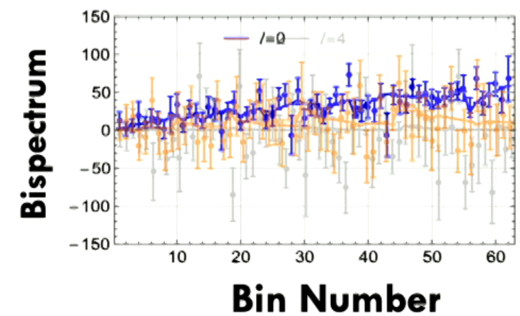
$P(\mathrm{k}) \sim n_{\rm gal}(\boldsymbol{k}) n^*_{\rm gal}(\boldsymbol{k})$



(+ lots of work on robust estimators)

Bispectrum

$B(\mathrm{k}_1, \mathrm{k}_2, \mathrm{k}_3) \sim n_{\rm gal}(\boldsymbol{k}_1) n_{\rm gal}(\boldsymbol{k}_2) n_{\rm gal}(\boldsymbol{k}_3)$



GitHub: spectra-without-windows, PolyBin3D

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SDSS-III, **Philcox**+21, **Philcox** 21, 22, 24

Predicting Galaxy Statistics

- We need a **model** for the observational data

$$P_{\text{gal}} = P_{\text{gal}}(k, \text{cosmology}, \dots)$$

$$B_{\text{gal}} = B_{\text{gal}}(k_1, k_2, k_3, \text{cosmology}, \dots)$$

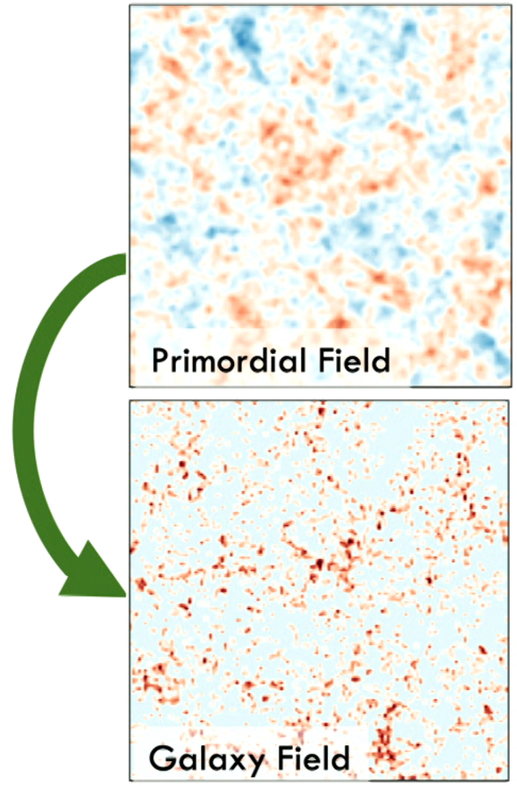
- The physics is **non-linear:**

$$B_{\text{gal}} \sim \text{Primordial Bispectrum} + \text{Gravity}$$

To learn about inflation, we have to **jointly** model **primordial physics** and **gravity/hydrodynamics**

State-of-the-art method:

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



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Cabass, **Philcox**+22, Assasi+15

Matter x Effective Field Theory

The Effective Field Theory of Large Scale Structure is:

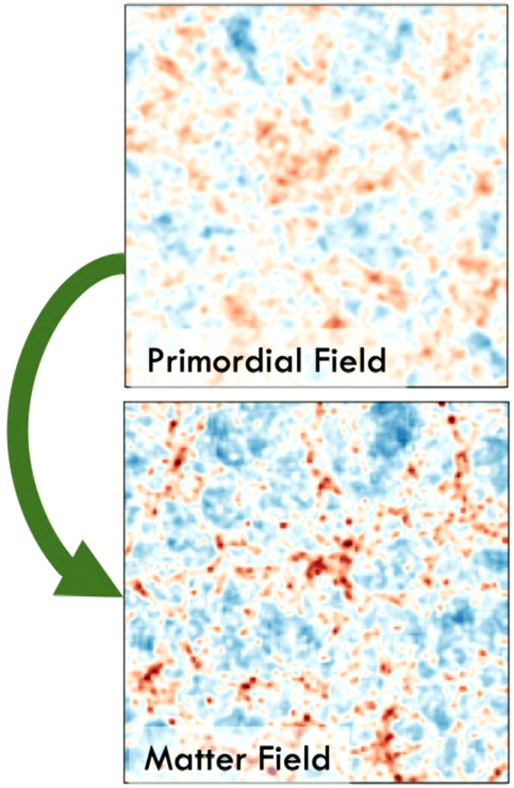
- An **analytic** model for the distribution of matter, solving the **non-ideal** & **smoothed** fluid equations given initial conditions

$$\delta\rho_{\rm matter}(\mathbf{x}) \sim \int d\mathbf{k}\,\zeta(\mathbf{k}) + \int d\mathbf{k}_{1,2}\,\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2) + \cdots$$

- A *low-energy* theory, valid on **large-scales**

$$(k < k_{\rm NL},\quad \text{distance} \gtrsim 15\ \text{Mpc})$$

- A *renormalized* field theory, fully accounting for **back-reaction** of small onto large scales



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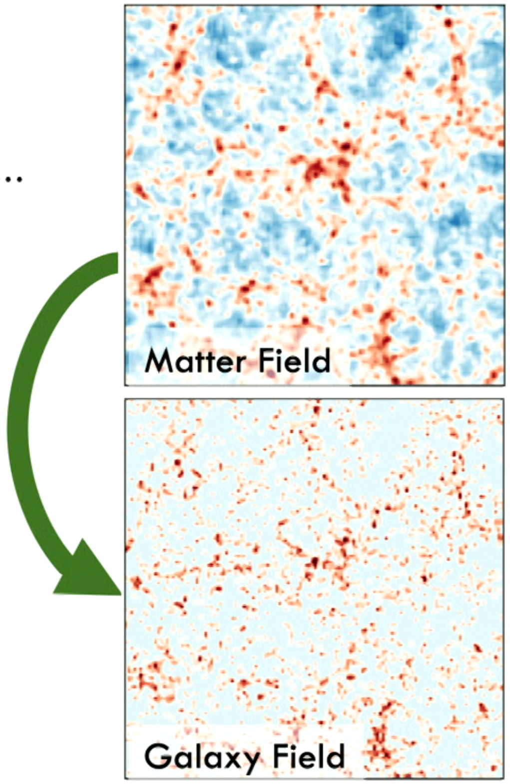
e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, **Philcox**, etc.

Galaxies x Effective Field Theory

Incorporate galaxies via **symmetries:**

$$\delta n_{\text{gal}} \sim b_{\text{linear}}\delta\rho_{\text{matter}} + b_{\text{quadratic}}\delta\rho_{\text{matter}}{}^2 + b_{\text{tidal}}\left[\left(\frac{\partial^i\partial^j}{\partial^2} - \delta_K^{ij}\right)\delta\rho_{\text{matter}}\right]^2 + \cdots$$



- A **perturbative expansion** in all operators allowed by:
  - *Translation invariance*
  - *Rotation invariance*
  - *Galilean invariance*
- Free amplitudes are biases / Wilson coefficients encoding **hydrodynamics, baryons,** and **galaxy formation**

e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, **Philcox**, etc.

Scale-Dependent Bias

Primordial non-Gaussianity adds **new terms** to the expansion:

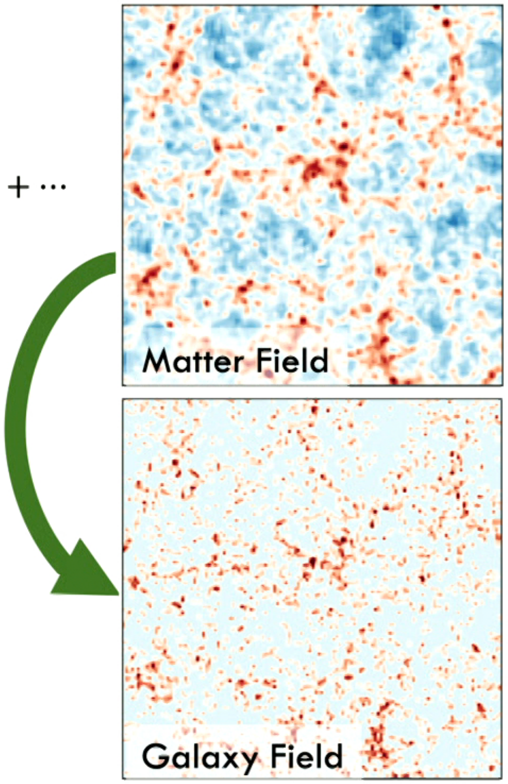
$$\delta n_{\rm gal} \sim \left(b_{\rm linear} + A\frac{f_{\rm NL}^{\rm loc}}{k^2}\right)\delta\rho_{\rm matter} + b_{\rm quadratic}\delta\rho_{\rm matter}{}^2 + b_{\rm tidal}\left[\left(\frac{\partial^i\partial^j}{\partial^2} - \delta_K^{ij}\right)\delta\rho_{\rm matter}\right]^2 + \cdots$$

- This **dominates** on large-scales and allows **local** non-Gaussianity to be measured from the power spectrum *without* the EFTofLSS

***However*:**

- This only works for **some** types of non-Gaussianity! [light particles]
- It's very sensitive to **systematics**

Let's get constraints from the full-theory model!



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Dalal+07, Desjaques+08

Galaxies x Effective Field Theory

$$P_{\text{gal}} = P_{\text{gal}}(k, \text{cosmology}, \dots)$$

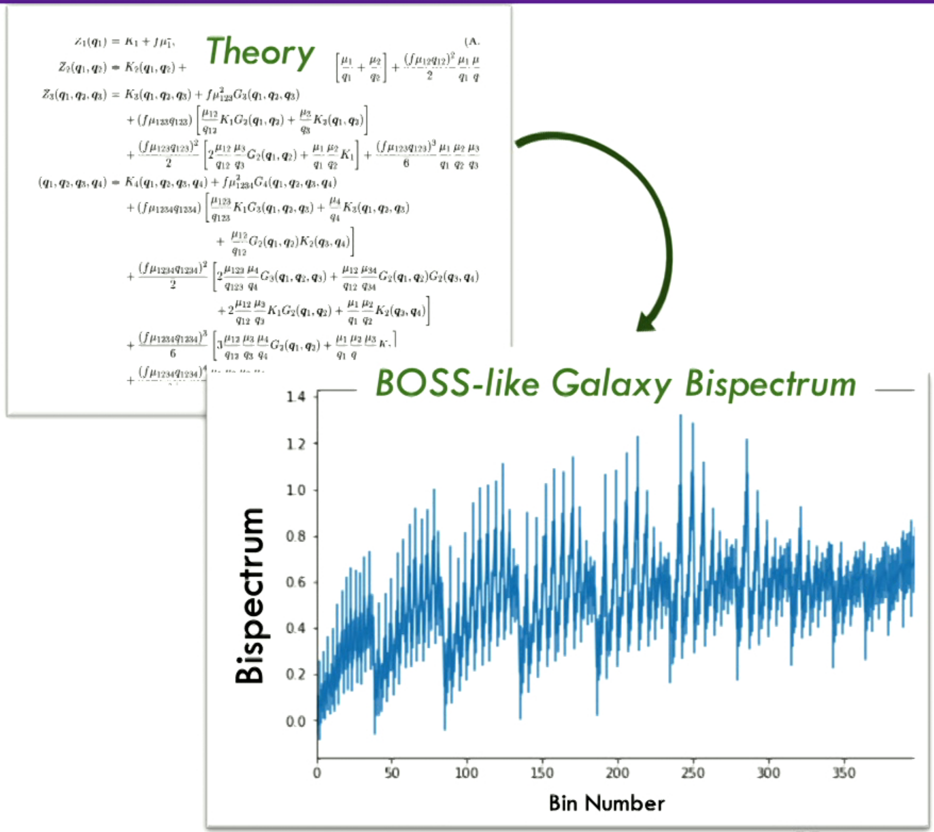
$$B_{\text{gal}} = B_{\text{gal}}(k_1, k_2, k_3, \text{cosmology}, \dots)$$

In practice:

- Efficient C++ implementation [CLASS-PT]
- Full computation in ~ 1 second
- Unbiased parameter recovery for **huge** simulations

Future task: add higher-order calculations!

GitHub: *CLASS-PT*, *full-shape-likelihoods*



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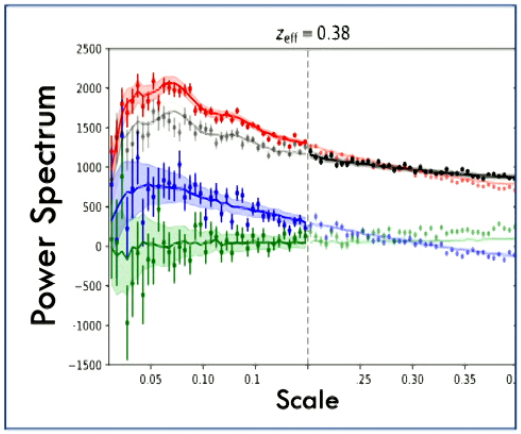
Ivanov, **Philcox**+20,21, **Philcox**+22, Cabass, **Philcox**+22

Constraining Cosmology from BOSS Galaxies

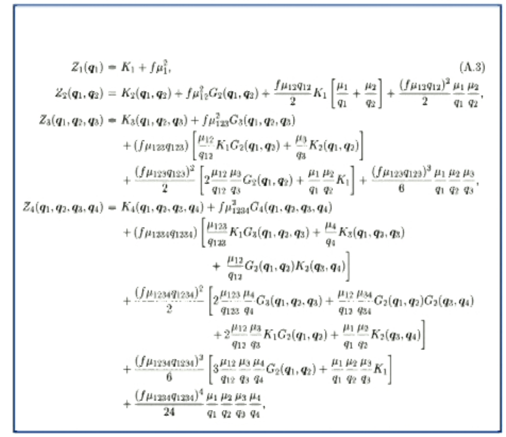
Statistics



+ new (mask-deconvolved) estimators to produce them

Spectra-Without-Windows

Theory Model



+ new code to compute it

CLASS-PT

Gaussian likelihood

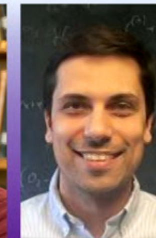
$$-2\log L = (\hat{P} - P_{\text{theory}})C^{-1}(\hat{P} - P_{\text{theory}})$$

MCMC

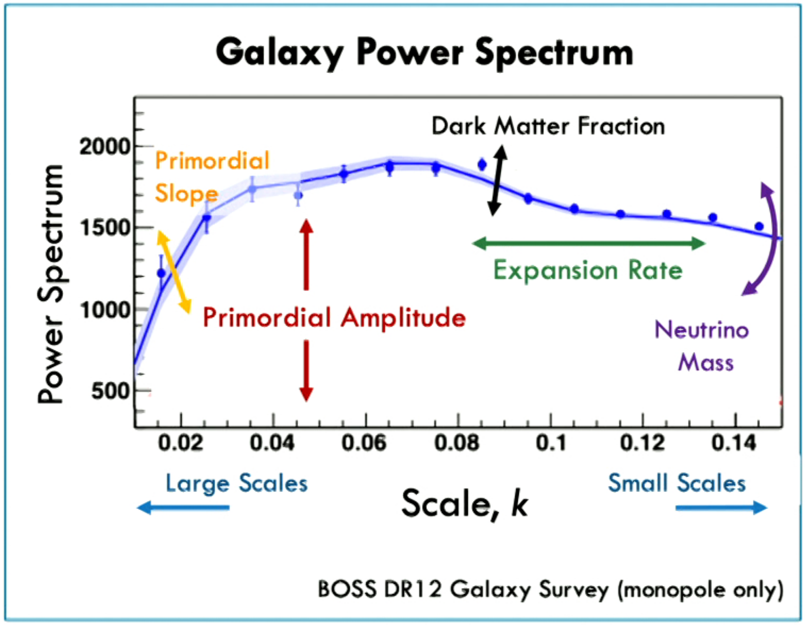
Cosmology Constraints:
(dark matter, dark energy, inflation, …)

Philcox+19-24, Ivanov+, Cabass+, etc.

Aside: Non-Inflationary Cosmology

with Mikhail Ivanov & Marko Simonovic



Use the **power spectrum** and **bispectrum** to measure **any** ingredient of the cosmological model!

Hubble tension:

- No evidence for new physics!
- Agrees with the CMB

S_8 tension:

- No strong evidence!
- Agrees with weak lensing

Old & new physics

- Strong constraints on **dark matter** fraction
- Improved constraints on **axions**
- Robust bounds on **neutrinos**

Community constraints

- Improved bounds on **curvature, dark energy, massive relics, early dark energy, dark sector, …**

Beutler+17, **Philcox**+19-24

Constraining Inflation from BOSS Galaxies

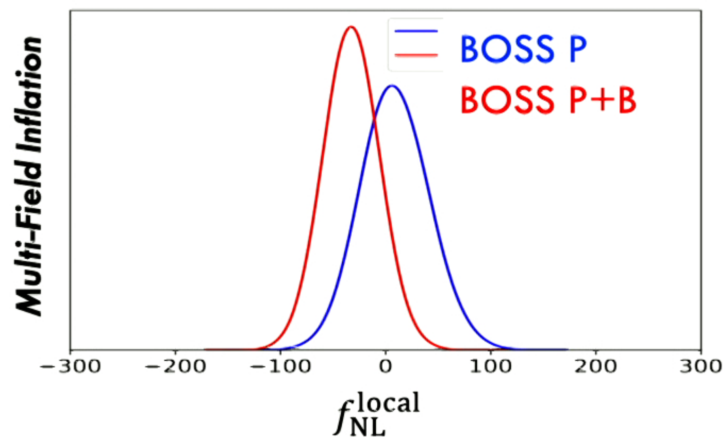
Two main analyses:

1. **Local** non-Gaussianity: $f_{\rm NL}^{\rm local}$

   - Probes **light fields** $(m \ll H)$ in inflation or **non-linear** physics after inflation

   - **Full** EFTofLSS modeling of $P_{\rm gal}(k) + B_{\rm gal}(k)$ improves over standard ***scale-dependent bias*** approach by 20%

   - No evidence for multi-field inflation!



$$f_{\rm NL}^{\rm local} = -33 \pm 28$$

(Without B: $f_{\rm NL}^{\rm local} = 9 \pm 34$)

(*CMB:* ± 5, *Target:* ± 1)

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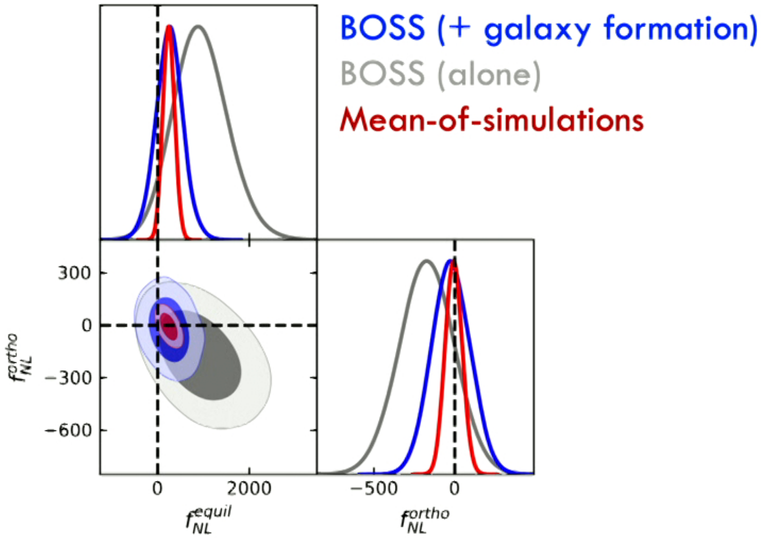
Cabass, **Philcox**+22 (see also d'Amico+22)

Constraining Inflation from BOSS Galaxies

Two main analyses:

1. **Local** non-Gaussianity: $f_{\rm NL}^{\rm local}$
2. **Non-local** non-Gaussianity: $f_{\rm NL}^{\rm equil}$, $f_{\rm NL}^{\rm orth}$

- Probes inflation **interactions:** $10^5 f_{\rm NL} \sim (H/\Lambda)^2$
- **First** non-CMB analysis
- No evidence for self-interactions in inflation
- This **needs** accurate theory models [EFTofLSS] and robust bispectrum estimators [window-free]



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

BOSS Alone:
$f_{\rm NL}^{\rm equil} = 940 \pm 600$
$f_{\rm NL}^{\rm orth} = -170 \pm 170$

(CMB: $\pm 50, \pm 25$, Target: ± 1)

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

Constraining Inflation from BOSS Galaxies

Two main analyses:

1. **Local** non-Gaussianity: $f_{\rm NL}^{\rm local}$
2. **Non-local** non-Gaussianity: $f_{\rm NL}^{\rm equil}, f_{\rm NL}^{\rm orth}$

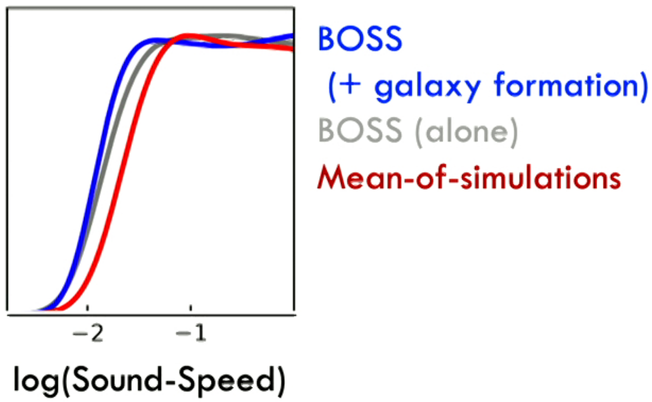
- These amplitudes map to the coefficients of the **leading operators** in the *Effective Field Theory of Inflation*

$$S_{\rm EFT}^{(3)} \sim \int d^4x\sqrt{-g}\left[A\dot{\phi}^3 + B\dot{\phi}(\nabla\phi)^2\right]$$

Inflaton field

- We can use these to constrain the sound-speed of inflaton fluctuations:

  $c_s^2 \geq 0.013$ (95% CL)



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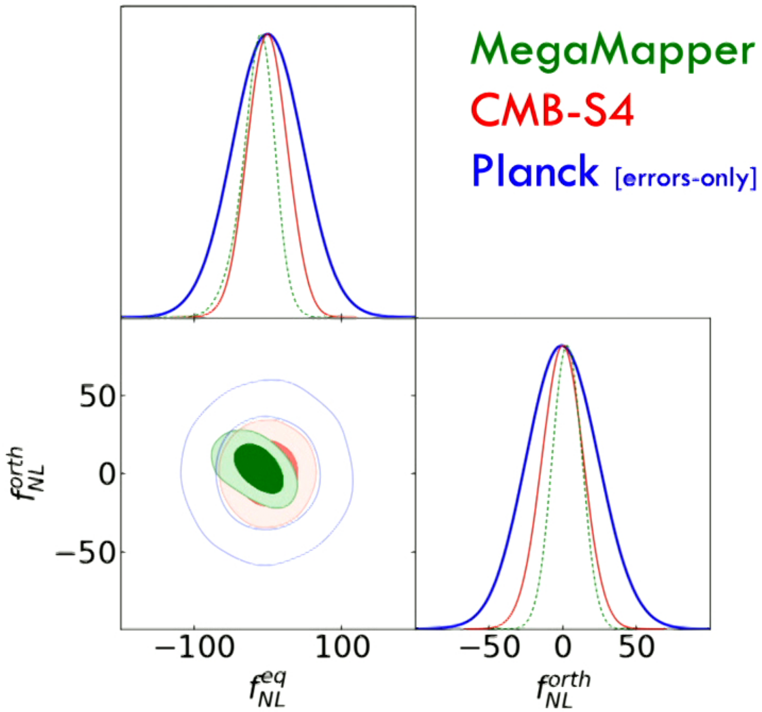
Cabass, **Philcox**+21, Senatore+09

The future of $f_{\rm NL}$



MegaMapper > CMB-S4, Simons Observatory!

- For now, the CMB gives **stronger constraints** than galaxy surveys
- This makes sense: the CMB measures **much more** of the Universe *even in 2D!*
- By Stage-V surveys like **MegaMapper**, **galaxies** will place the **strongest** constraints on inflationary physics

Future tasks

- Add **astrophysics** calibration
- Apply to **future data**!

Cabass, **Philcox**+22b, Sailer+22, Ferraro+22

Beyond (non-)local f_{NL}

There's lots more to explore:

- **Heavy** particles in inflation
  $[m \sim H, m > H]$
- **Spinning** particles in inflation
  $[\mathrm{Bispectrum} \sim \mathrm{Legendre}_{\mathrm{spin}}(\theta)]$
- **Resonant** non-Gaussianity
  $[\mathrm{Bispectrum} \sim \mathrm{oscillations}]$
- **Different** vacuum states
- **Tensor** correlations

Hard in the 2D CMB!

Future task: explore these with the CMB and galaxy **trispectra**!

Cosmological Collider

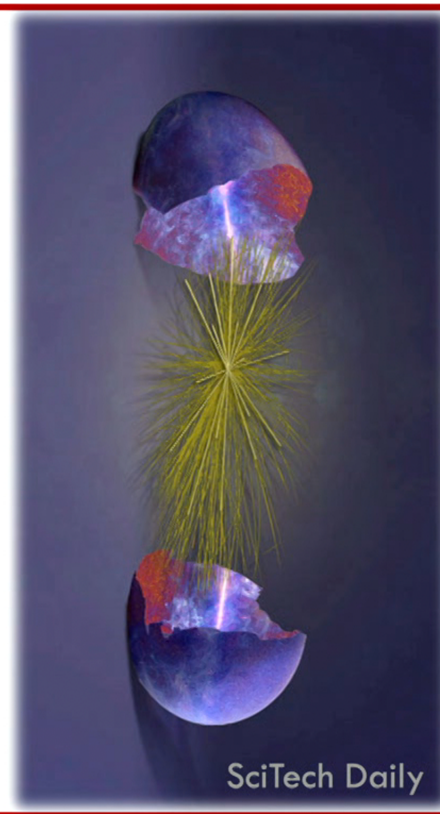
Low-energy remnants
[curvature fluctuations]

↑

High-energy physics
[particle scattering]

↓

Low-energy remnants
[curvature fluctuations]



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Cabass, **Philcox**+ (in prep.), **Philcox**+23, Arkani-Hamed+15

Beyond Perturbation Theory

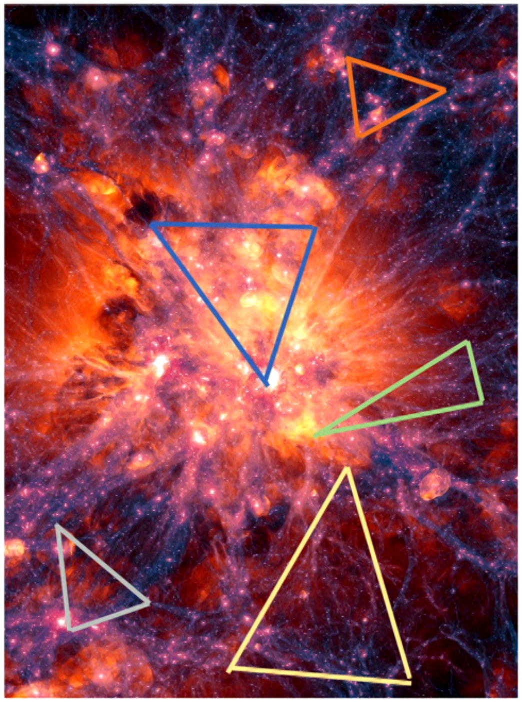
- All the above analyses assume **perturbativity:**

EFTofLSS: A *low-energy* theory, valid on **large-scales** ($k < k_{\rm NL}$)

- Volume of information scales as $k_{\rm max}^3$ → we are **missing** significant information

- This is difficult to **model** explicitly: galaxy formation is hard and already limiting!

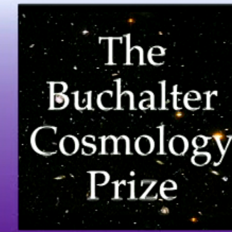
- **Solution:** use *conserved quantities* and *symmetries*



IllustrisTNG

Beyond Perturbation Theory


Sam Goldstein



What symmetries can we use?

1. Galilean invariance

$$\mathbf{x} \to \mathbf{x} + \mathbf{s}(t), \qquad \mathbf{v} \to \mathbf{v} - \dot{\mathbf{s}}(t), \qquad \phi \to \phi + \Delta\phi$$

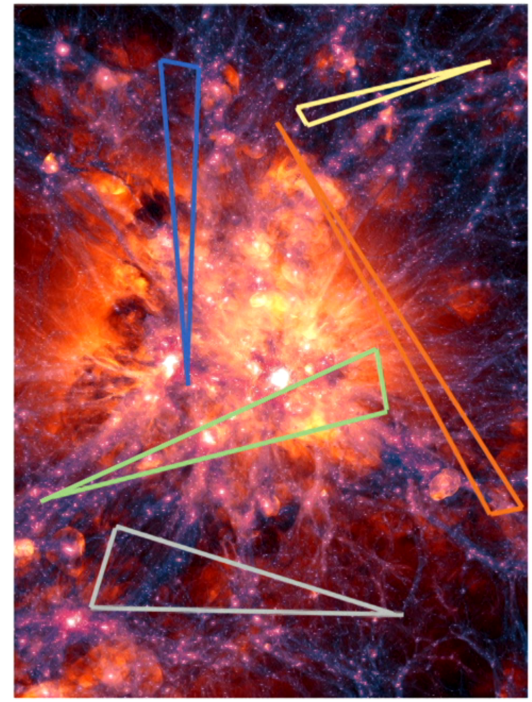
- This is a **non-perturbative** symmetry of the **equations of motion**
- It relates to **Ward Identities** and **Soft Theorems**:

$$\lim_{q \to 0} \frac{q^2 B(\mathbf{q}, \mathbf{k}, \mathbf{k}')}{P(q)} = 0$$

- This **consistency relation** is violated by **multi-field inflation**

We can measure $f_{\rm NL}$ *from* ***highly non-linear*** *scales* $(\sigma(f_{\rm NL}) \sim k_{\rm max}^{3/2})$

Future task: apply this to observational data!



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e.g. Kehagias+, Peloso+, Hui+, Creminelli+, Simonovic+, Giri+23, Goldstein, **Philcox**+22,23

Beyond Perturbation Theory

What symmetries can we use?

1. Galilean invariance

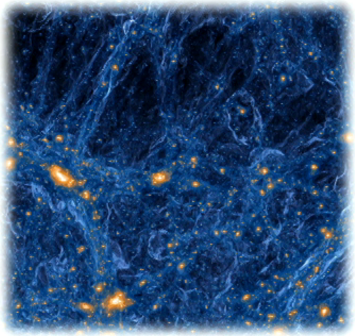
2. Parity symmetry

- Is the Universe invariant under a **point reflection?**

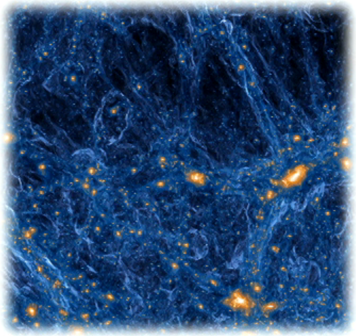
$$f(\mathbf{x}, \mathbf{y}, t) \to f(-\mathbf{x}, -\mathbf{y}, t) = f(\mathbf{x}, \mathbf{y}, t)\,??$$

- **General Relativity** and **hydrodynamics** preserve this symmetry

- Is **inflation** parity-symmetric?



versus

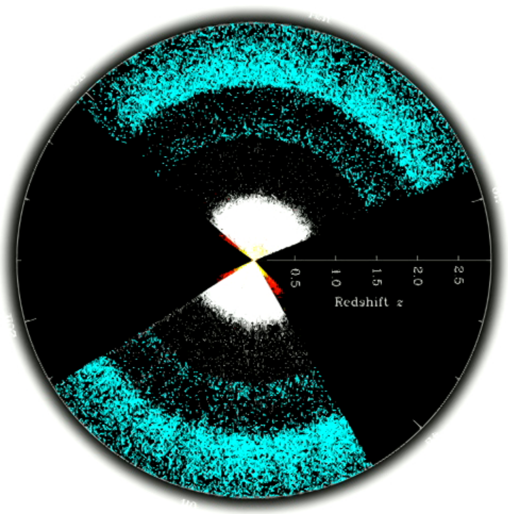


Philcox+22-24, Hou+22, Cabass, Philcox+23, Creque-Sarbinowski, **Philcox**+23

How To Search for Parity-Violation

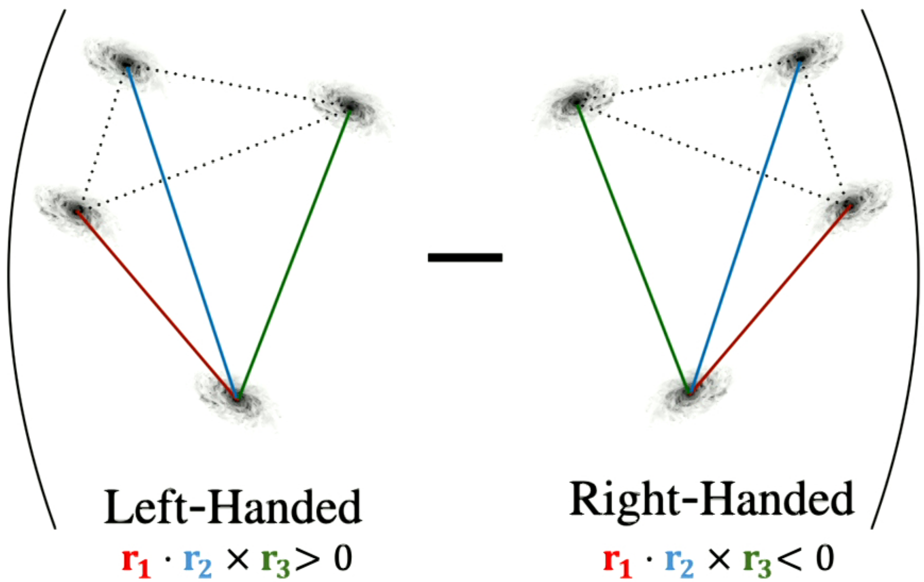
Measure the four-point function from 10^6 BOSS galaxies

Zero without parity-violation!



BOSS Galaxy Sample

ENCORE code



GitHub: *encore*, *Parity-Odd-4PCF*

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Philcox 22, **Philcox**+24, Hou+22

Detecting Parity-Violation?

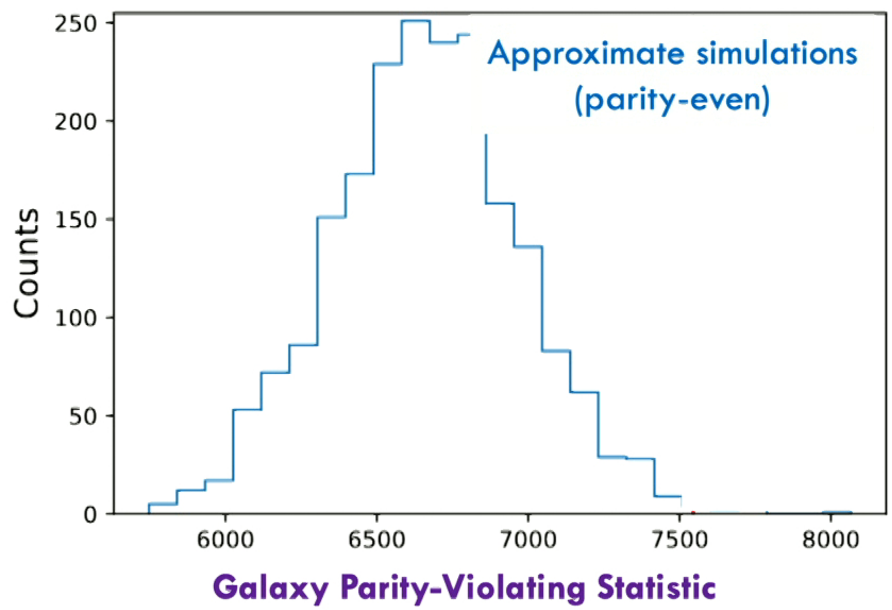
This is **hard** to analyze in practice:

- We need to model the **noise distribution** of the statistic
- This is **very hard** with perturbative methods

Solution: calibrate with a large set of (approximate) galaxy survey **simulations***

$$\chi^2 \equiv \zeta^{\text{odd}} \, \text{Cov}_{\zeta}^{-1} \zeta^{\text{odd}}$$

*Note: this is **not** what we usually use simulations for!*



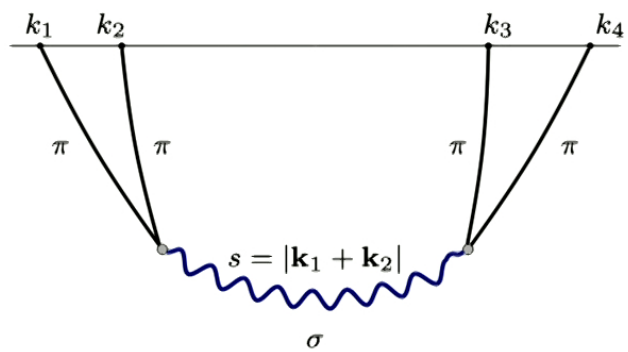
Philcox 22, **Philcox**+24, Hou+22

Detecting Parity-Violation?

Cyril Creque-Sarbinowski

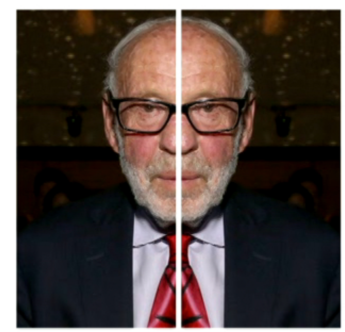
Many ways to violate parity in inflation:

1. Spinning particle exchange?
2. Chern-Simons gravitational waves?
3. Ghost inflation?
4. Gauge fields with loops?



Spinning particles in inflation

Ghost inflation



Chern-Simons inflation

But: *No evidence for an inflationary source from the 18 models we tried!*

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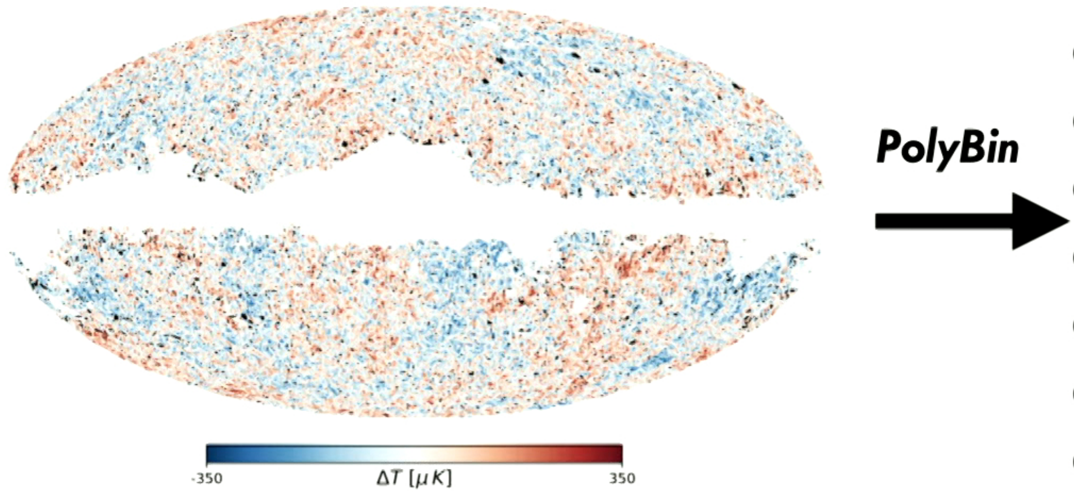
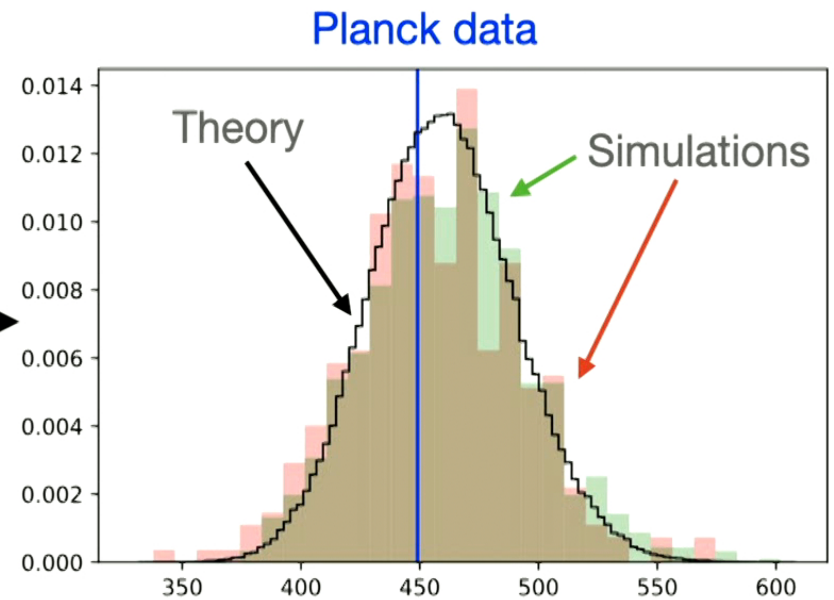
Cabass+22, Cabass, **Philcox**+22, Creque-Sarbinowski, **Philcox** 23, **Philcox**+23

*Un*detecting Parity-Violation

Planck Temperature and Polarization





CMB Parity-Violating Statistic

$< 0.5\sigma$ detection with 250x higher precision

GitHub: *PolyBin*

(Aside: there's lots more interesting non-Gaussianity analyses to do with the CMB!)

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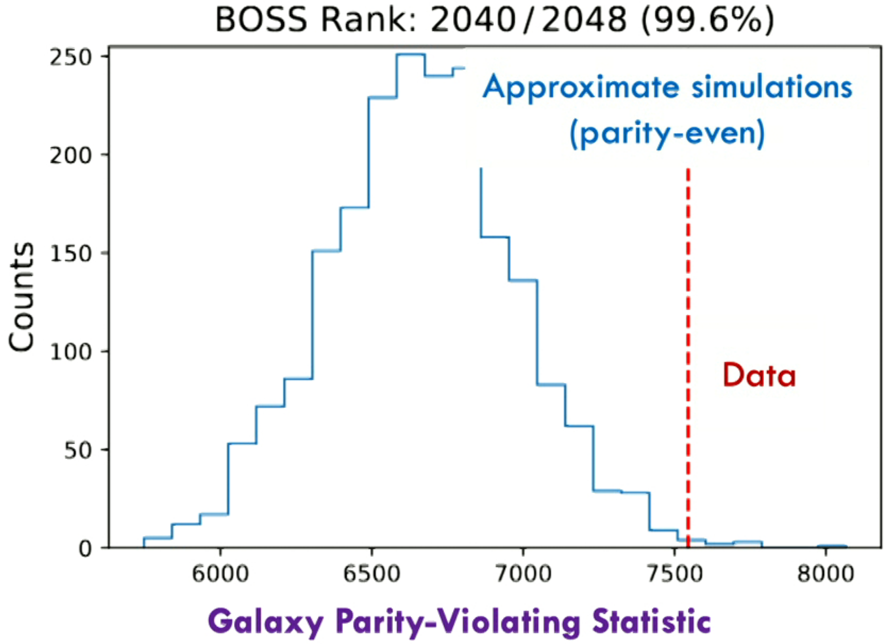
Philcox 23, **Philcox**+23

What Was Responsible for the Galaxy Signal?

A few options remain:

- A **primordial** model that **averages out** in the CMB
- Late-time physics on **large** scales



3σ detection of parity-violation??

Philcox 22, Hou+22, Cabass, **Philcox**+22, Philcox+24

What Was Responsible for the Galaxy Signal?

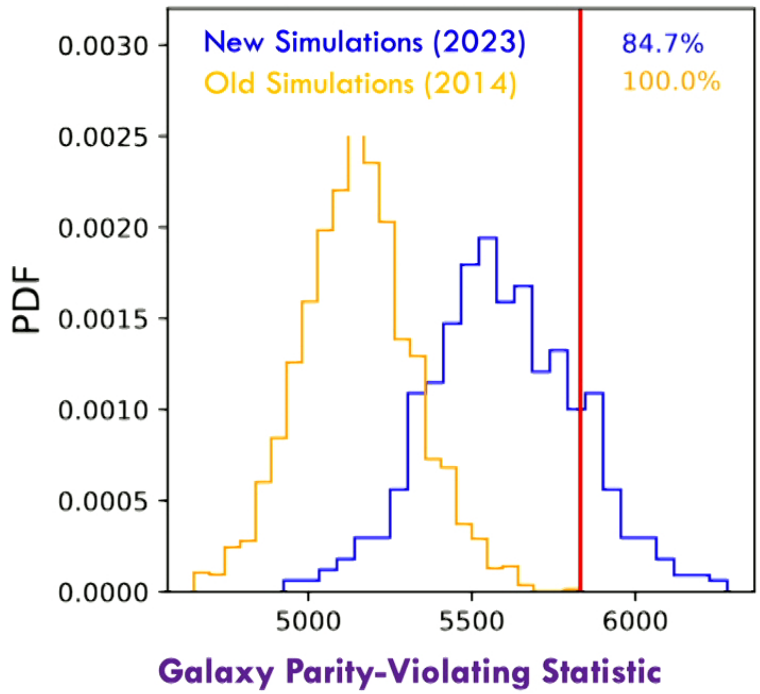
Julia Ereza

A few options remain:

- A **primordial** model that **averages out** in the CMB
- Late-time physics on **large** scales
- **Systematics**

> ***Lesson****: simulation-based analyses are only as good as the simulations!*

Despite the non-detection, this opens up an ***entirely new*** *sector for constraining* ***inflation****!*



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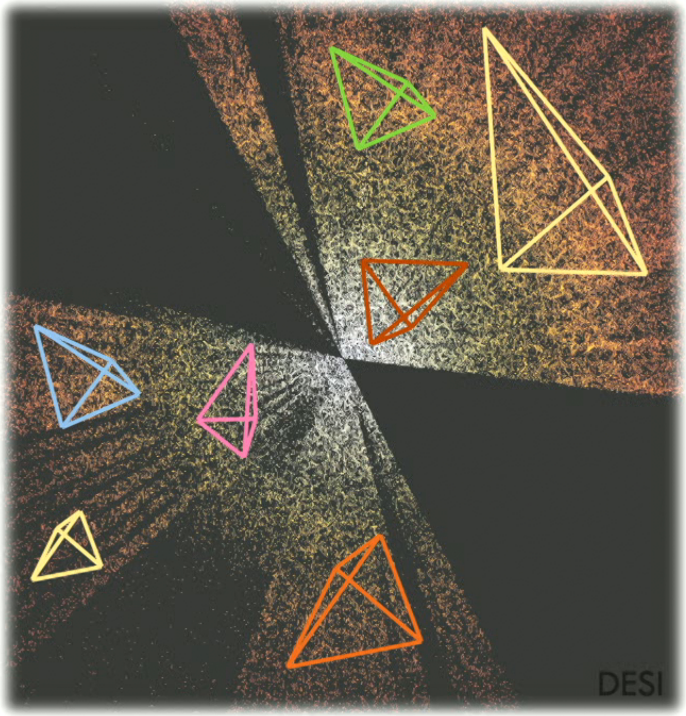
Philcox 22, Hou+22, Cabass, **Philcox**+22, Philcox+24

What's Next?

- The volume of the Universe mapped by galaxy surveys will **increase by** $\approx$ **100**× in the next decade

- This gives a unique opportunity to pin down **inflationary particle physics**



There's much more work to do:

- Develop **theory** and **estimators** for the **galaxy trispectrum**
- Analyze the **cosmological collider** signatures with **perturbative** and **non-perturbative** methods
- Apply to **future data** such as Euclid, DESI & MegaMapper

Summary

- Non-Gaussianity in **galaxy surveys** can probe **new physics** in **inflation**
- We can **directly** constrain this via **perturbative** and **non-perturbative** methods
- **We have a lot to discover:** cosmological colliders, parity-violation, new particles, and beyond!

Contact
ohep2@cantab.ac.uk
oliverphilcox.github.io

arXiv
2401.09523
2312.12498
2310.12959
2308.03831
2306.11782
2303.12106
2303.04815
2302.04414
2211.14899
2210.16320
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