Galaxy Surveys:

A Precision Probe of Inflation

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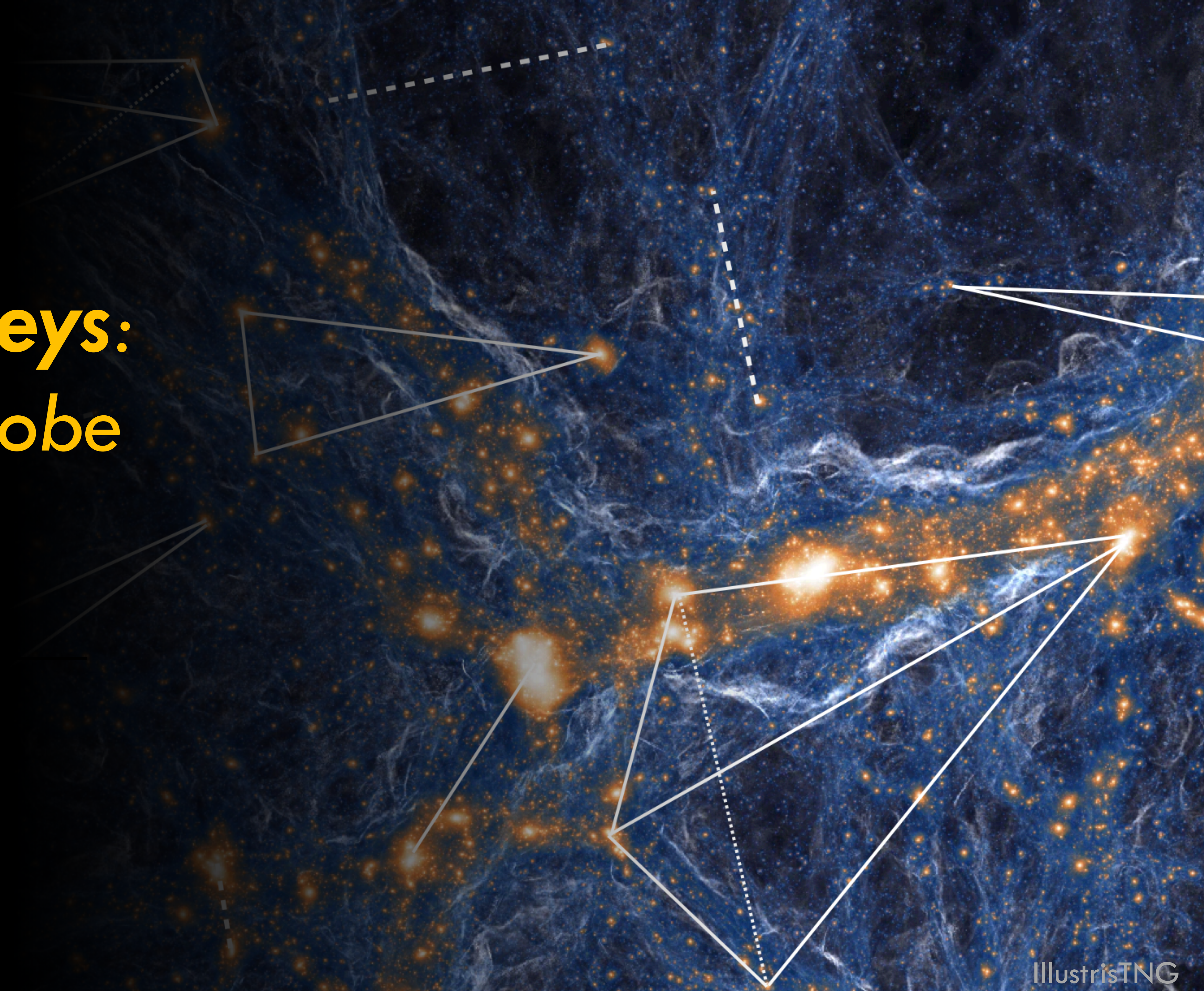
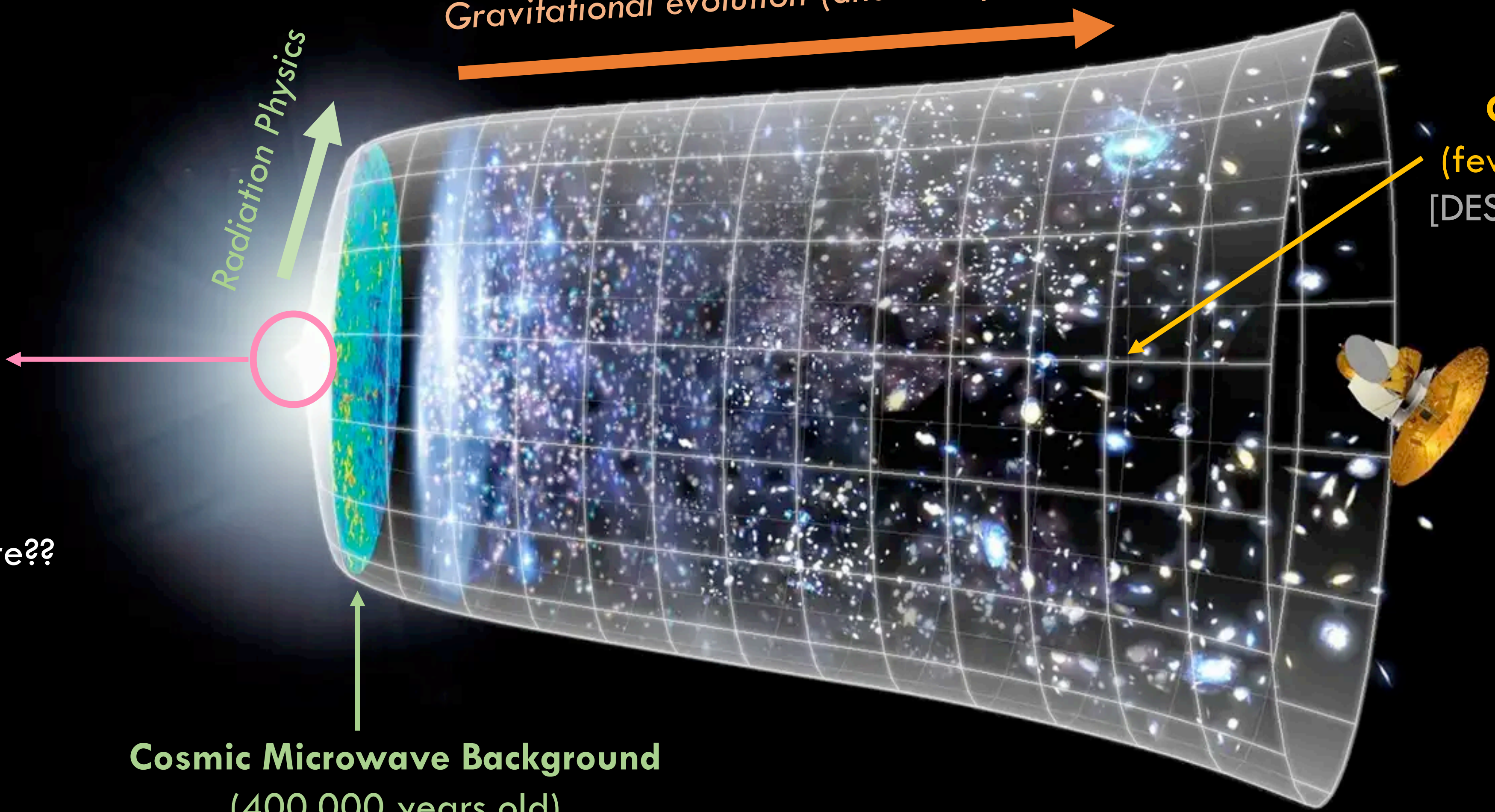
Simons Foundation



IllustrisTNG

Our View of the Universe



Gravitational evolution (and astrophysics)

Radiation Physics

Inflation
($\sim 10^{-34}$s old)

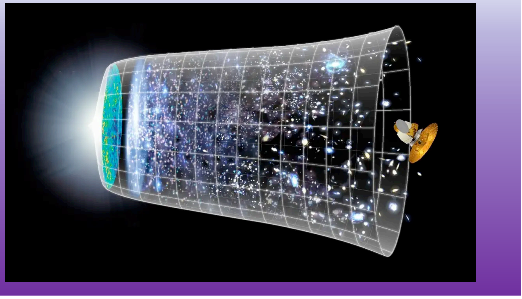
What happened here??

Cosmic Microwave Background
(400,000 years old)
[Planck, WMAP]

Galaxy Surveys
(few billion years old)
[DESI, Euclid, BOSS, …]

NASA/WMAP

What Do We Know About Inflation?



Background

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

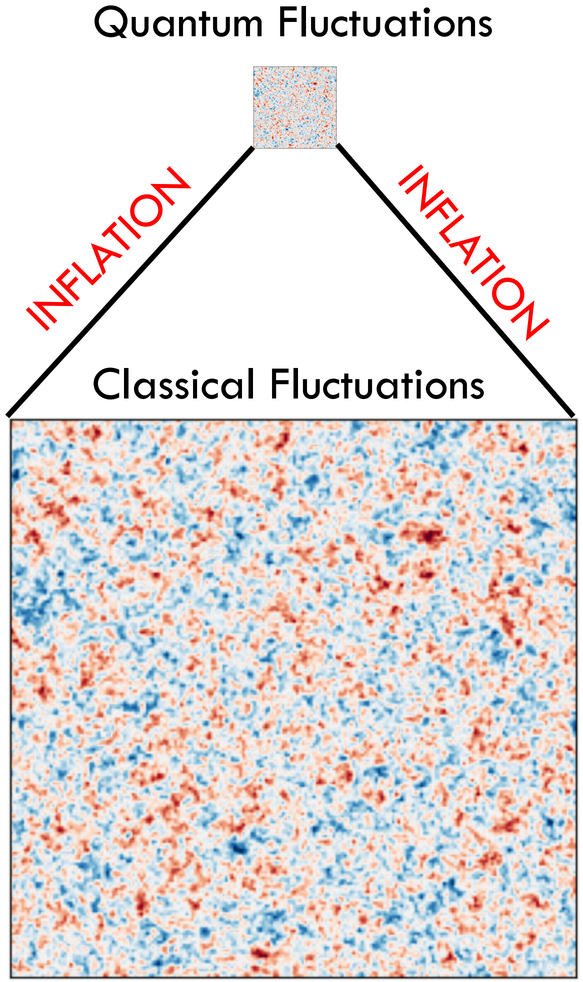
→ **Scale-free**

Perturbations

- **Quantum** vacuum fluctuations sourced **classical** curvature perturbations

→ *(Almost)* **Gaussian** distribution of fluctuations

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

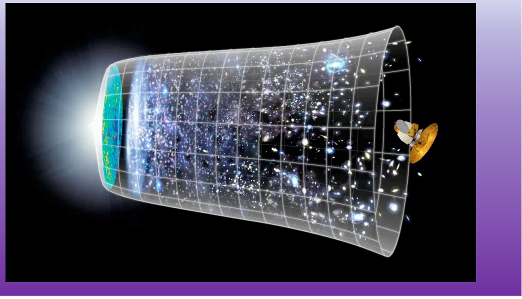


Quantum Fluctuations

Classical Fluctuations

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

What Do We Know About Inflation?



Simplest model

- Caused by a *single field* evolving along an *(almost)* flat potential [Single Field Slow Roll]

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

But:

- What is the **energy scale** of inflation?

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

- What was the **potential**?

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

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

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

- Did the fields **interact**?

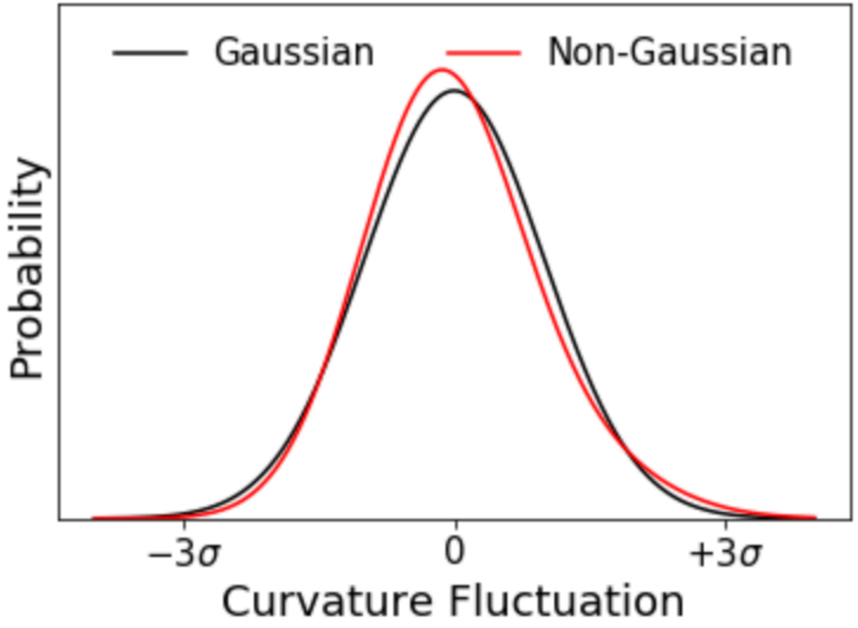
$$\mathcal{L}_{\text{inf}} \supset \dot{\phi}^3 + \cdots$$

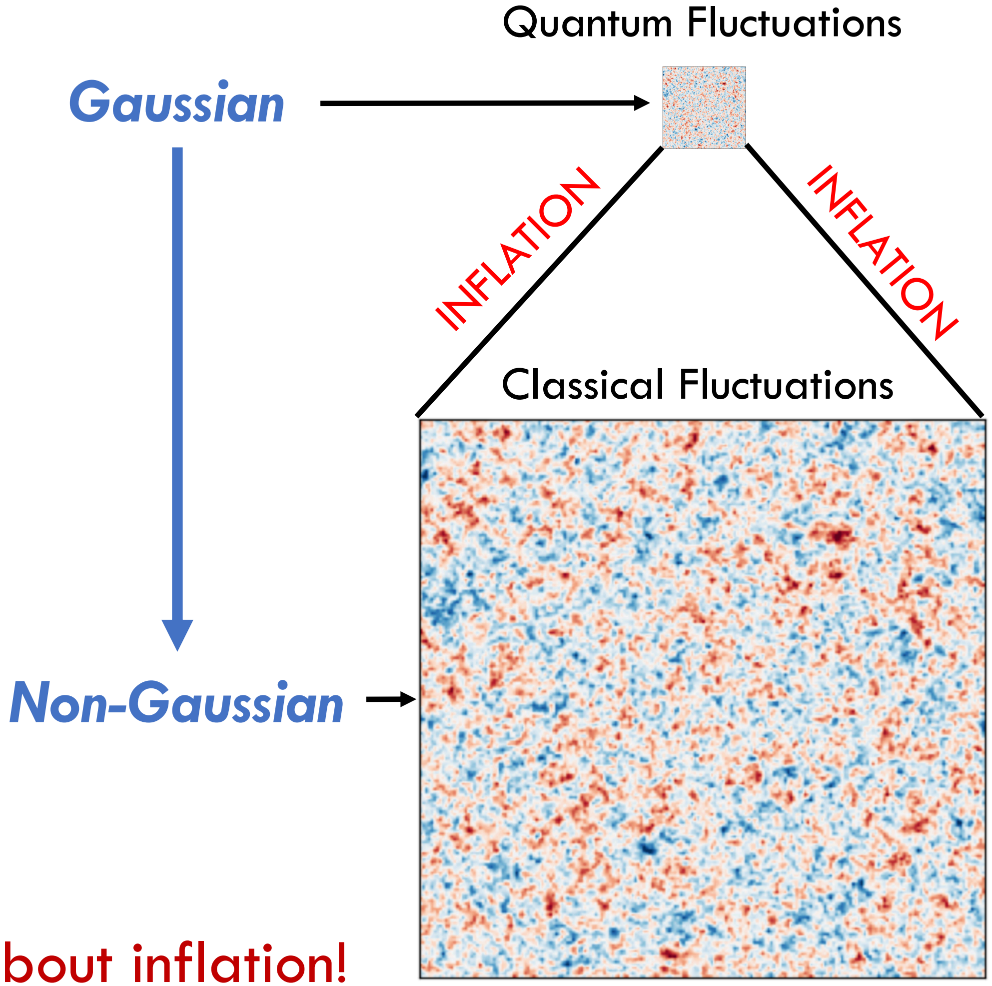
Guth, Linde, Starobinsky, Lyth, Mukhanov, Sasaki, …

How to Probe Inflation

New physics in inflation

→ **non-Gaussian** fluctuations





Quantum Fluctuations

Gaussian

INFLATION

INFLATION

Classical Fluctuations

Non-Gaussian

By measuring the non-Gaussianity, we can learn about inflation!

Maldacena, Arkani-Hamed, Zaldarriaga, Creminelli, ++

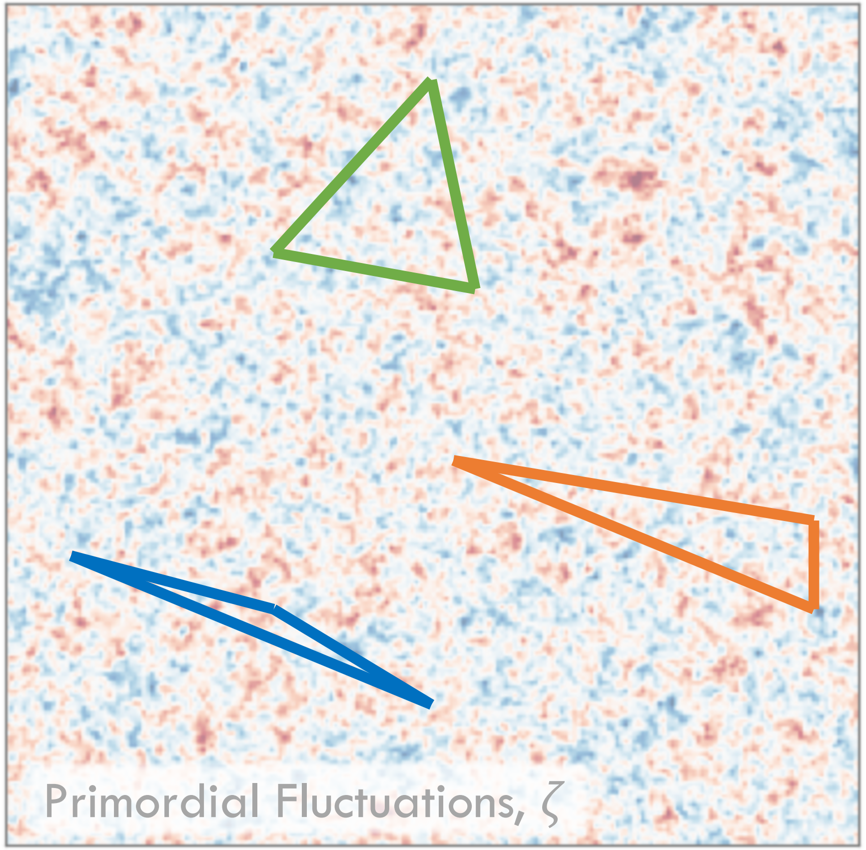
What Does non-Gaussianity Look Like?

- 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:
  - Equilateral triangles: **self-interactions**
  - Squeezed triangles: **new light fields**
  - Folded triangles: **new vacuum states**

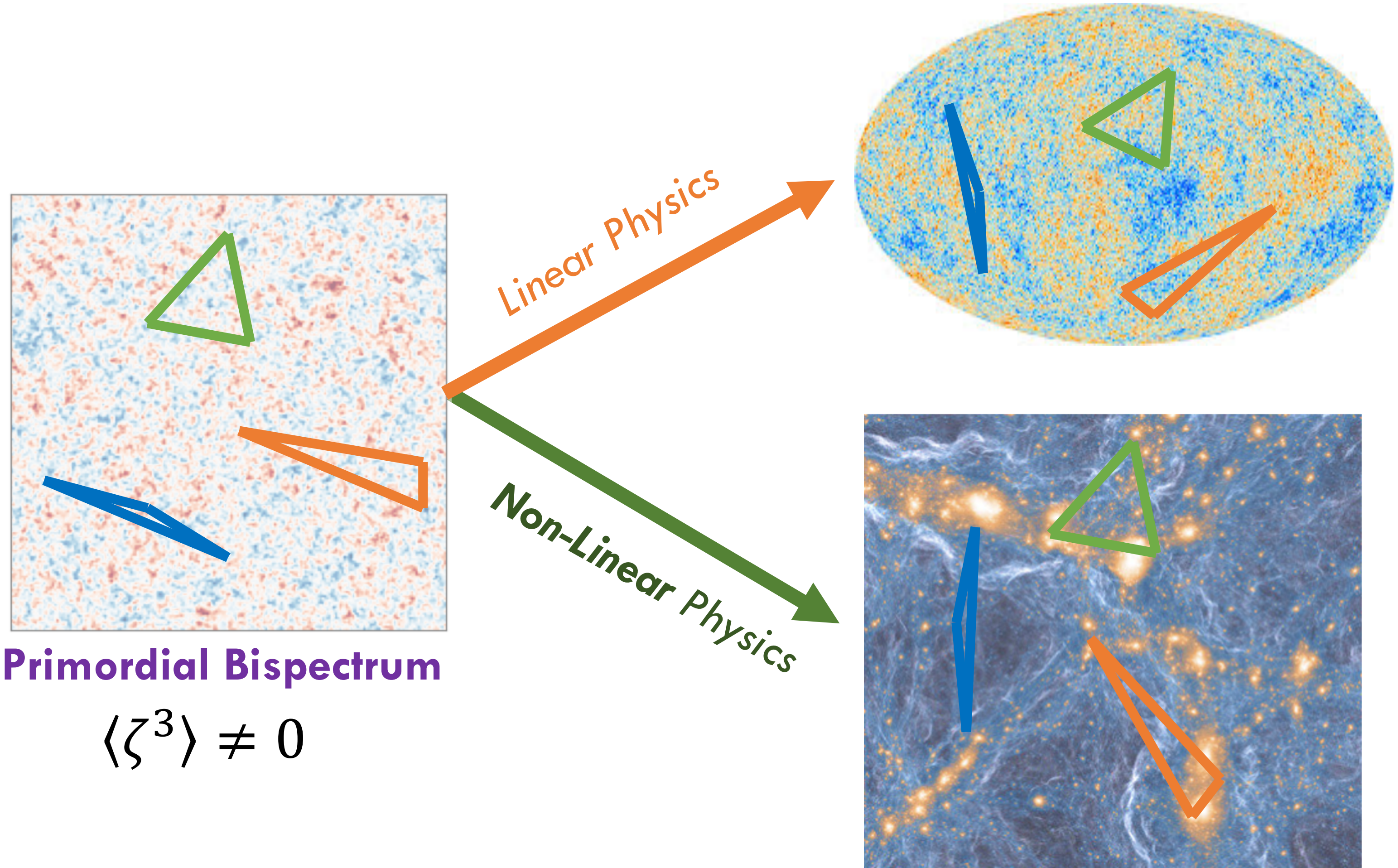
$$\boxed{\zeta \sim \mathrm{Edgeworth}[P(k), B(k_i), T(k_i), \dots]}$$



Maldacena, Arkani-Hamed, Zaldarriaga, Creminelli, ++

Measuring non-Gaussianity

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



Primordial Bispectrum

$\langle \zeta^3 \rangle \neq 0$

Cosmic Microwave Background

Bispectrum

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

Galaxy Distribution

Bispectrum

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

Planck, IllustrisTNG

CMB Non-Gaussianity

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

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

Planck 2018

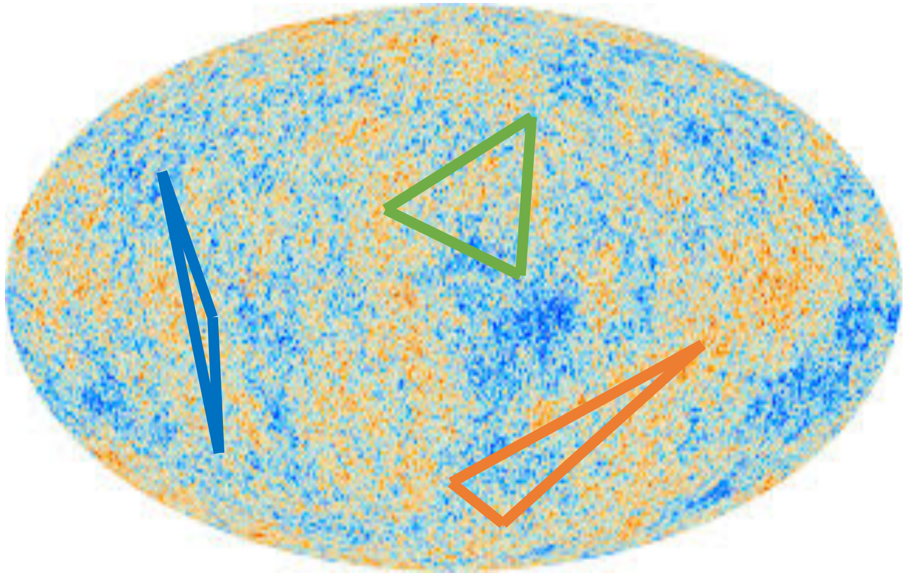
f_{NL}	Local	6.7 ± 5.6
	Equilateral	6 ± 66
	Orthogonal	-38 ± 36

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

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

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

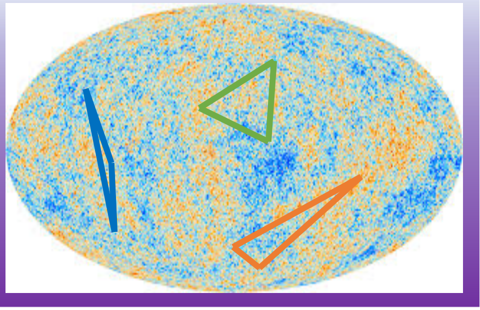
Can we do better in the future?



Cosmic Microwave Background

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

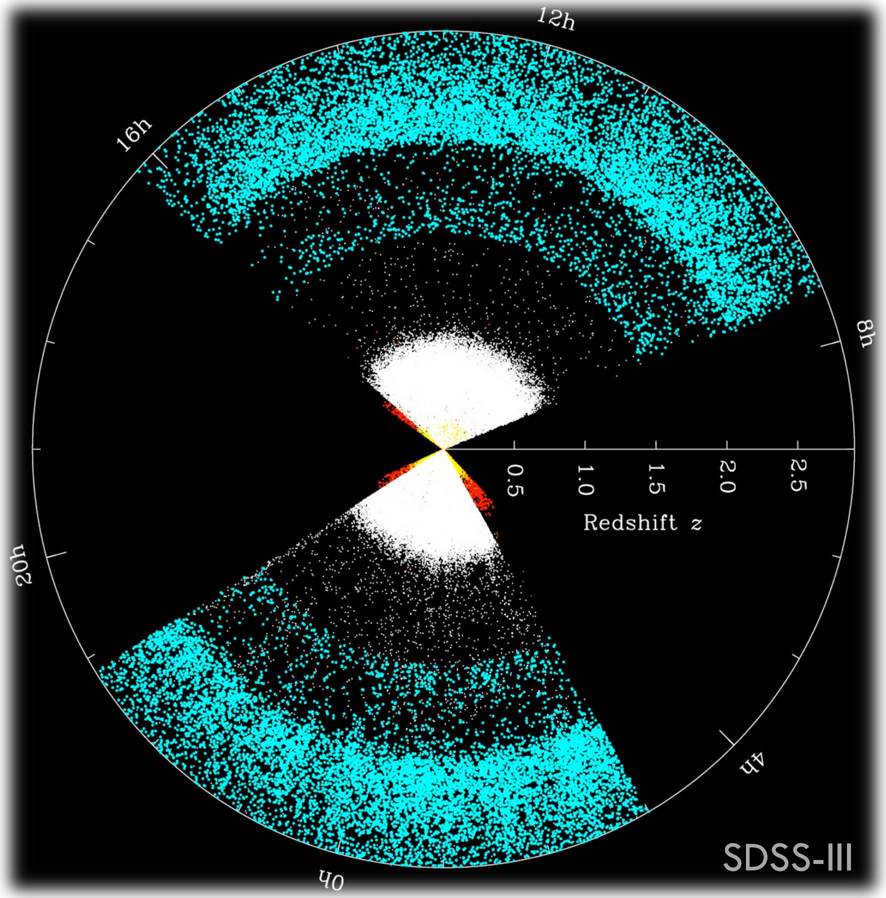
The Future of Non-Gaussianity



- Future **CMB** experiments will improve bounds by $\mathcal{O}(2\times)$
  - We're running out of modes to look at!
  - Small-scales are **hard**

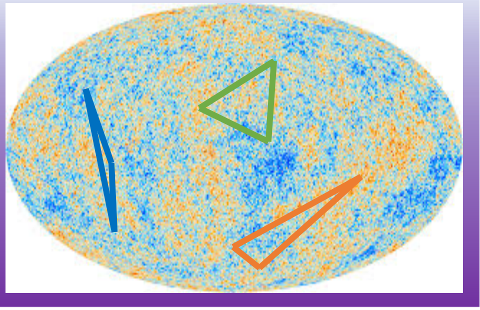
- What about **galaxy surveys**?
  - Legacy surveys map **a million** galaxies

[BOSS: 2010s]



CMB-S4, SDSS-III

The Future of Non-Gaussianity



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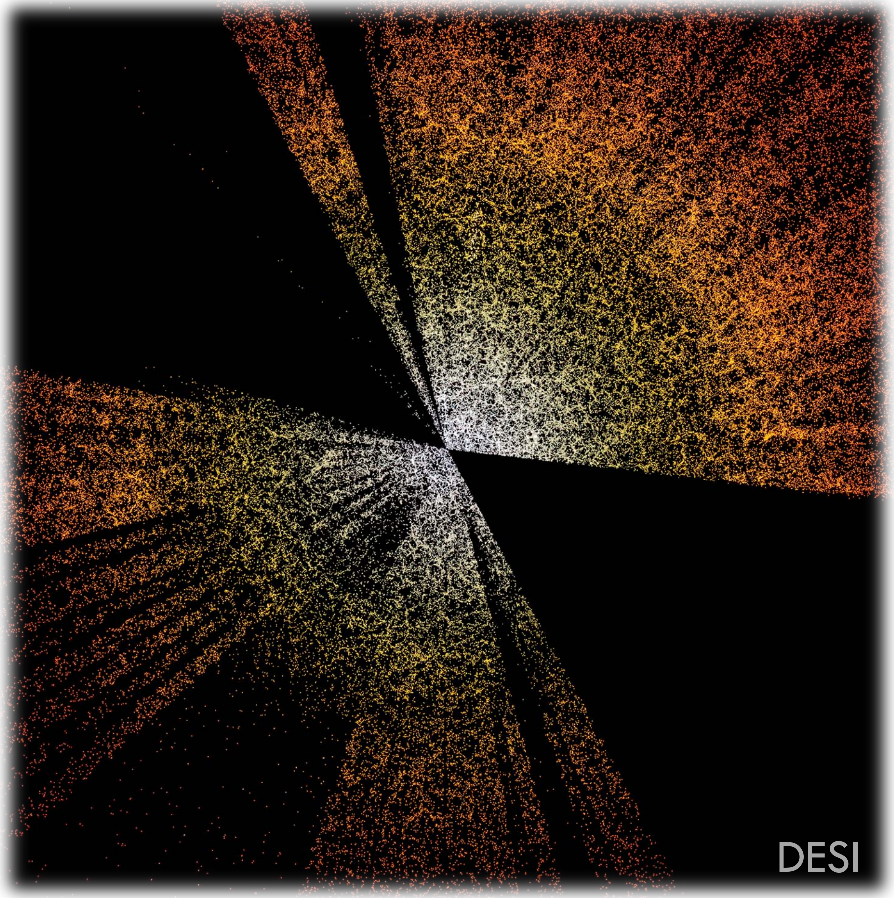
- What about **galaxy surveys**?
  - Legacy surveys map **a million** galaxies

    [2010s: BOSS]
  - New surveys map $\approx \mathbf{100}\times$ more!

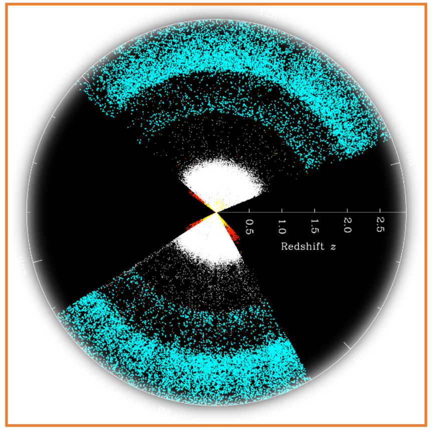
    [2020s: Euclid, DESI, SPHEREx, Rubin, …]

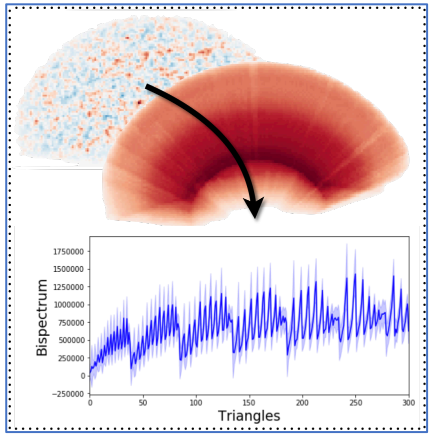


Let's make **galaxy surveys** a tool for **inflationary cosmology**!

CMB-S4, DESI

Roadmap: From Public Data to New Physics





$$
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&\quad + (f\mu_{123}q_{123})\left[\frac{\mu_{12}}{q_{12}}K_1 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_3}{q_3}K_2(\boldsymbol{q}_1,\boldsymbol{q}_2)\right]\\
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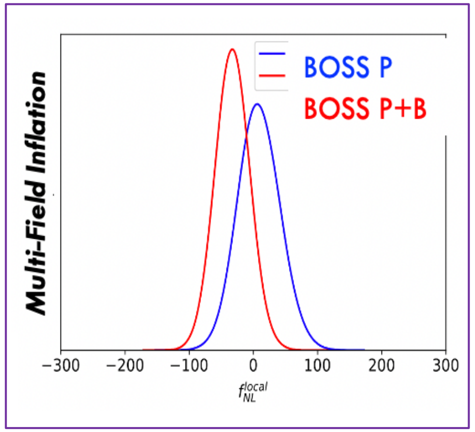
&\qquad\qquad \left. + 2\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}K_1 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}K_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^3}{6}\left[3\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}\frac{\mu_4}{q_4}G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3}K_1\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^4}{24}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3}\frac{\mu_4}{q_4},
\end{aligned}
$$



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

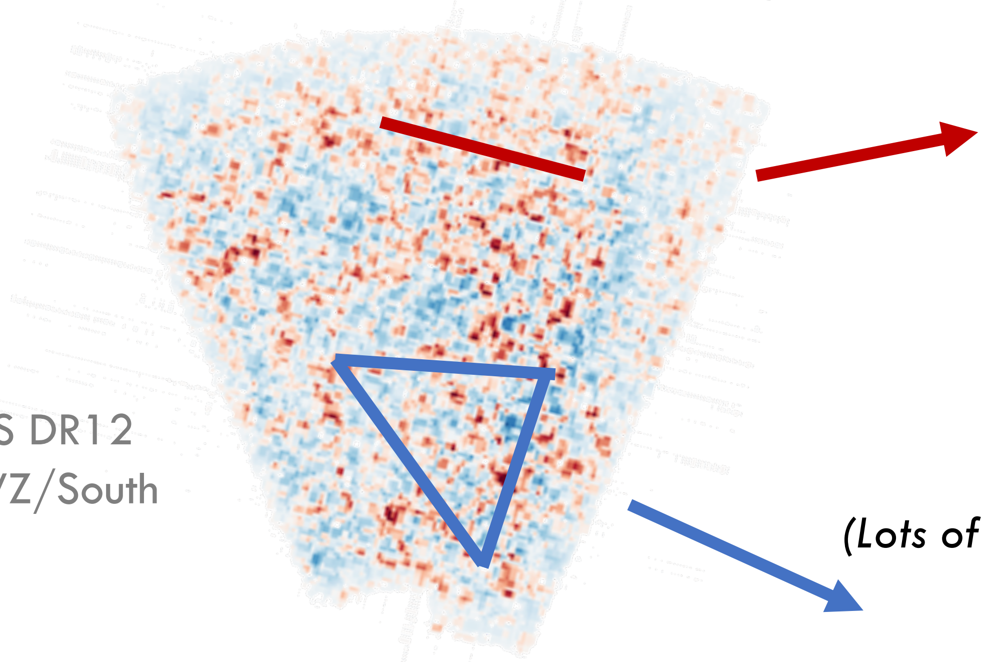
All with **public code!**

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

Philcox+19-24

How to Analyze a Galaxy Survey

Galaxy Density Field, n_{gal}



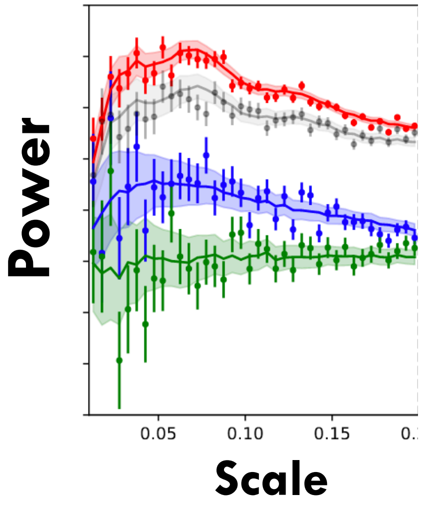
BOSS DR12
LOWZ/South

The Standard Approach

Power Spectrum

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

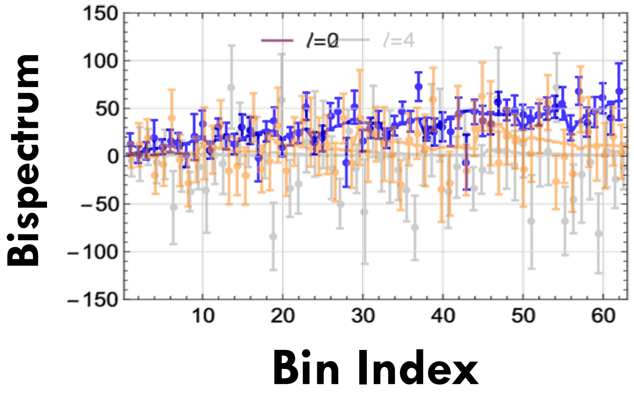
Use this to learn about dark energy



(Lots of fun estimation problems here!)

Bispectrum

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



GitHub: spectra-without-windows, PolyBin3D

SDSS-III, **Philcox**+21

Predicting Galaxy Statistics

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

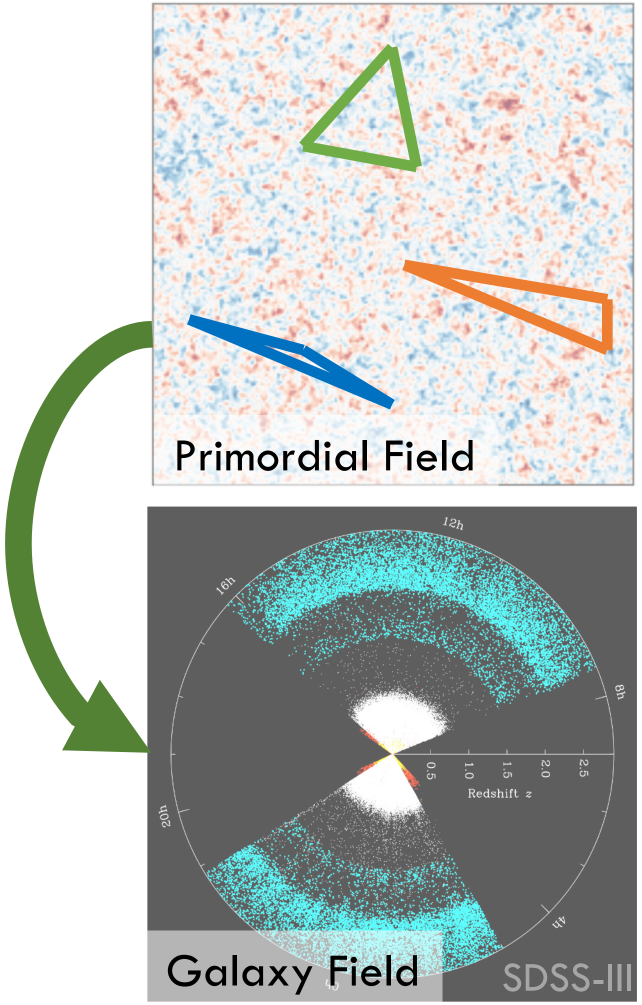
- For the CMB, the physics is **linear:**

$$\langle \delta T^3 \rangle \sim \text{Primordial Bispectrum} \sim f_{\mathrm{NL}}$$

- For the galaxy distribution, the physics is **non-linear:**

$$\langle \delta n_{\mathrm{gal}}^3 \rangle \sim \text{Primordial Bispectrum} + \text{Gravity}$$

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

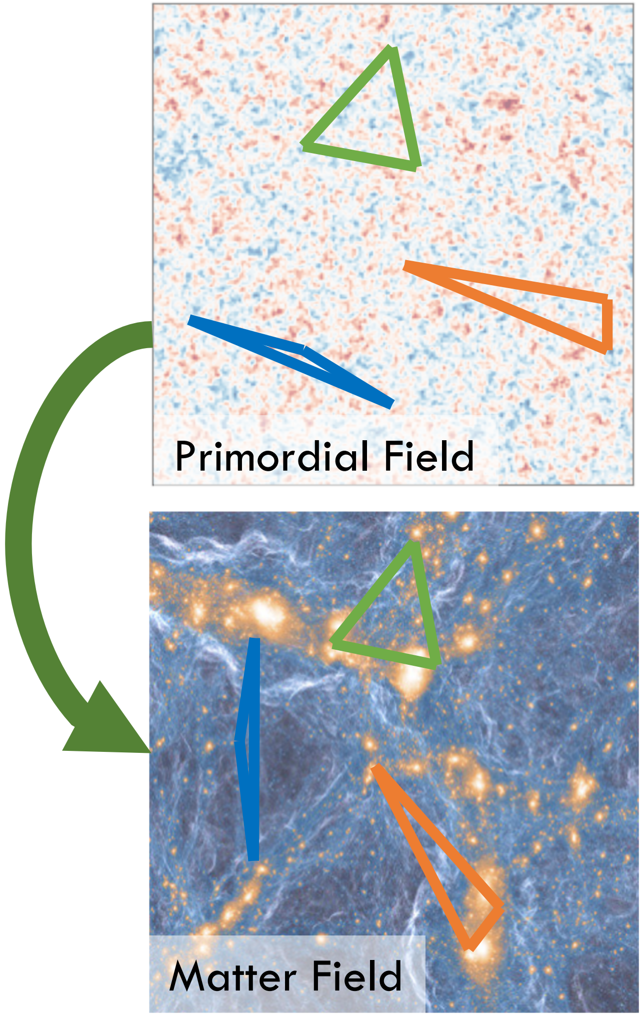


Cabass, **Philcox**+22, Assasi+15

Matter x Effective Field Theory

State-of-the-art method:

Effective Field Theory of Large Scale Structure (EFTofLSS)



- **Analytic** model for the distribution of matter, solving the **non-ideal** fluid equations given initial conditions

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

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

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

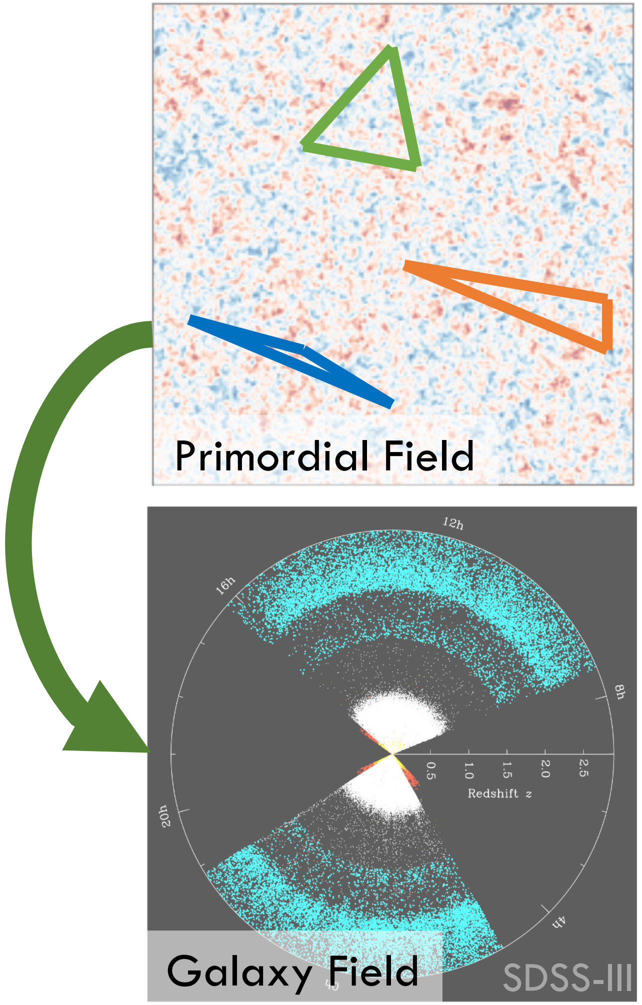
e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, **Philcox**, etc.

Galaxies x Effective Field Theory

Incorporate galaxies via **symmetries:**

$$\delta n_{\mathrm{gal}} \sim b_1\,\delta\rho + b_2\delta\rho^2 + b_s\left[\left(\frac{\partial^i\partial^j}{\partial^2} - \delta_K^{ij}\right)\delta\rho\right]^2 + \cdots$$

- A **perturbative expansion** in all operators allowed by:
  - *Translation invariance*
  - *Rotation invariance*
  - *Galilean invariance*
- Free amplitudes are Wilson coefficients encoding **hydrodynamics, baryons,** and **galaxy formation**
- <u>*Highly accurate*</u> on scales $k < k_{\mathrm{NL}}$



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

Galaxies x Effective Field Theory

I use EFTofLSS to predict galaxy **power spectra** and **bispectra**:

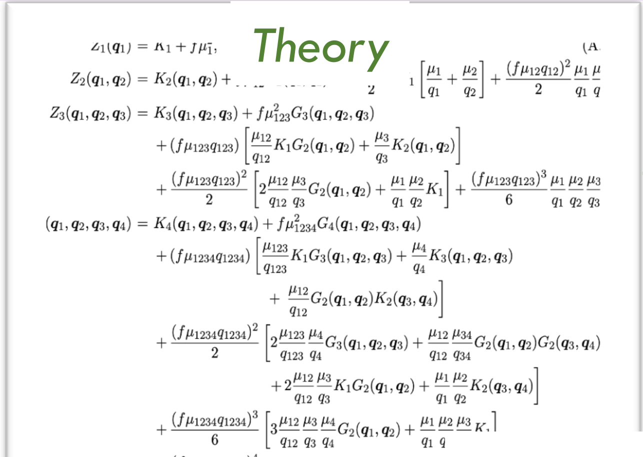
$$P_{\mathrm{gal}} = P_{\mathrm{gal}}(k, \mathrm{cosmology}, \mathrm{bias}, \ldots)$$

$$B_{\mathrm{gal}} = B_{\mathrm{gal}}(k_1, k_2, k_3, \mathrm{cosmology}, \mathrm{bias}, \ldots)$$

This works:

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

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



Theory

$$Z_1(\boldsymbol{q}_1) = K_1 + f\mu_1^2,$$

$$\begin{aligned}
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\end{aligned}$$

$$\begin{aligned}
(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) &= K_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) + f\mu_{1234}^2 G_4(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3,\boldsymbol{q}_4) \\
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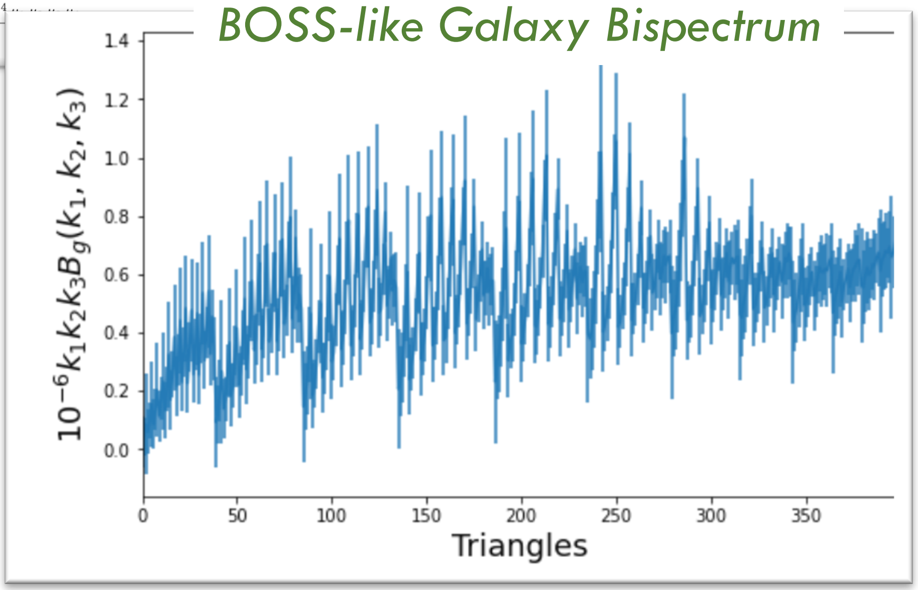
\end{aligned}$$

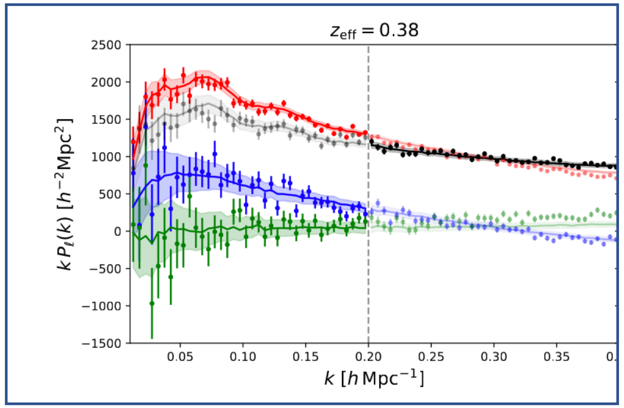


BOSS-like Galaxy Bispectrum

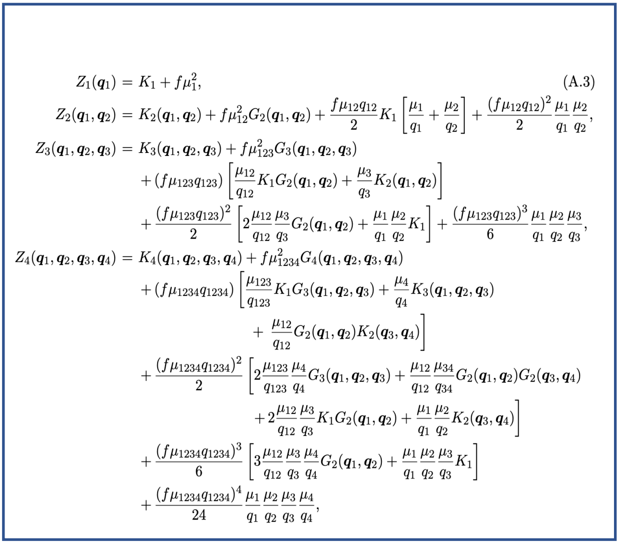
Ivanov, **Philcox**+20,21, **Philcox**+22, Cabass, **Philcox**+22

Constraining Inflation from BOSS Galaxies

Statistics



Theory Model



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&\qquad\qquad \left. + \frac{\mu_{12}}{q_{12}}G_2(\boldsymbol{q}_1,\boldsymbol{q}_2)K_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^2}{2}\left[2\frac{\mu_{123}}{q_{123}}\frac{\mu_4}{q_4}G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + \frac{\mu_{12}}{q_{12}}\frac{\mu_{34}}{q_{34}}G_2(\boldsymbol{q}_1,\boldsymbol{q}_2)G_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right.\\
&\qquad\qquad \left. + 2\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}K_1 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}K_2(\boldsymbol{q}_3,\boldsymbol{q}_4)\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^3}{6}\left[3\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}\frac{\mu_4}{q_4}G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3}K_1\right]\\
&\quad + \frac{(f\mu_{1234}q_{1234})^4}{24}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3}\frac{\mu_4}{q_4},
\end{aligned}$$

Spectra-Without-Windows

CLASS-PT

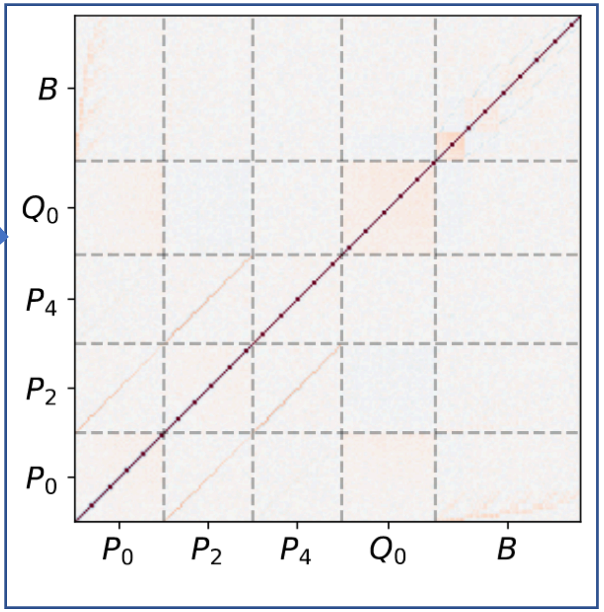
Gaussian likelihood

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

MCMC

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

Covariance Matrices



Analysis takes O(few) CPU-hours!

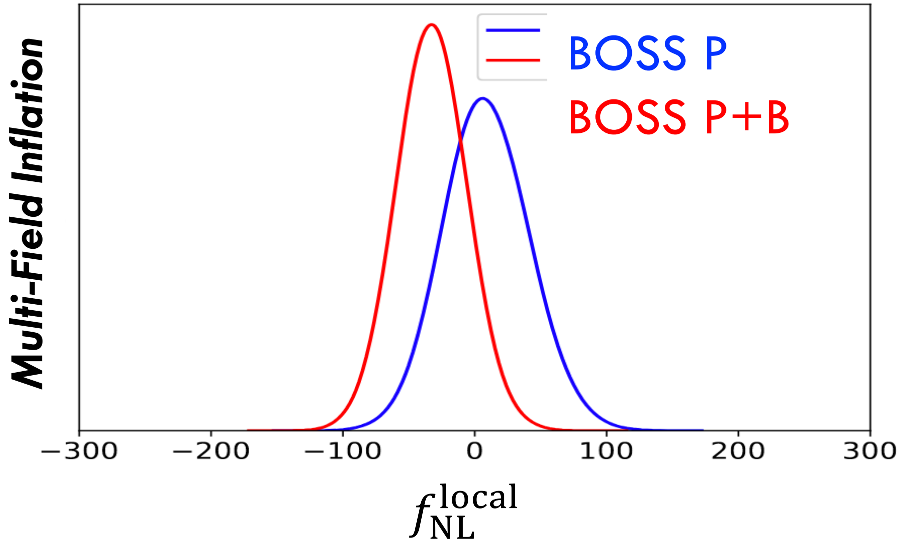
Philcox+19-24, Ivanov+, Cabass+, etc.

Constraining Inflation from BOSS Galaxies

Two main analyses:

1. **Local** non-Gaussianity

  - Probes **light fields** $(m \ll H)$ in inflation or non-linear physics **after** inflation
  - **First** analysis to feature the bispectrum
  - No evidence for multi-field inflation!
  - 30% improvement from the **bispectrum**



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

(CMB: ± 6, Target: ± 1)

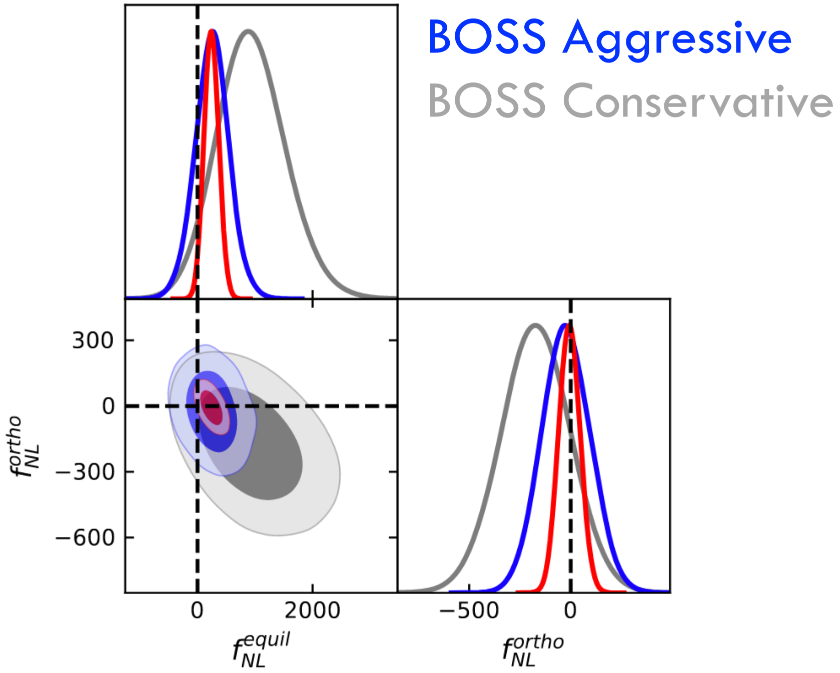
Cabass, **Philcox**+22 (see also d'Amico+22)

Constraining Inflation from BOSS Galaxies

Two main analyses:

1. **Local** non-Gaussianity
2. **Non-local** non-Gaussianity

- Probes **dynamics** of inflation: $10^5 f_{\rm NL} \sim (H/\Lambda)^2$
- **First** non-CMB analysis
- No evidence for self-interactions in inflation!
- Only possible with the bispectrum!



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

(CMB: $\pm 50, \pm 25$*, Target:* ± 1*)*

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

Constraining Inflation from BOSS Galaxies

Two main analyses:

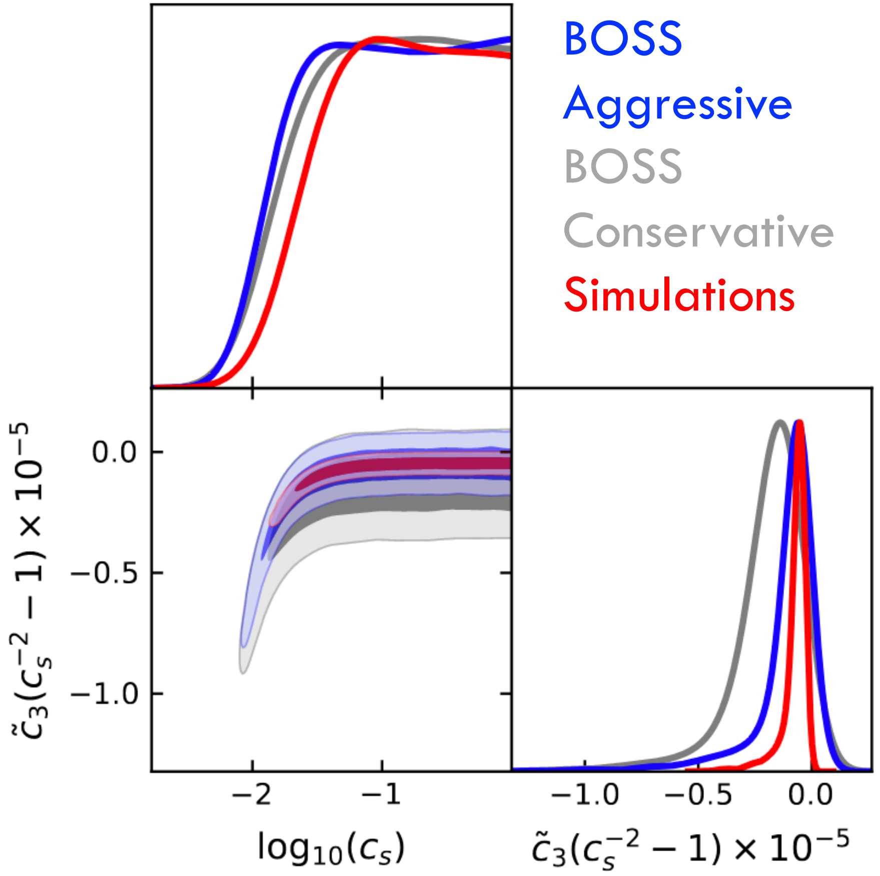
1. **Local** non-Gaussianity
2. **Non-local** non-Gaussianity

- This is related to **microphysics** in the Effective Field Theory of inflation

$$S_{\mathrm{EFT}} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{M_{\mathrm{P}}^2\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2\frac{(\nabla\pi)^2}{a^2}\right)\right. \left. + \boxed{\frac{M_{\mathrm{P}}^2\dot{H}}{c_s^2}(1-c_s^2)\left(\frac{\dot{\pi}(\nabla\pi)^2}{a^2} - \left(1+\frac{2}{3}\frac{\tilde{c}_3}{c_s^2}\right)\dot{\pi}^3\right)}\right]$$

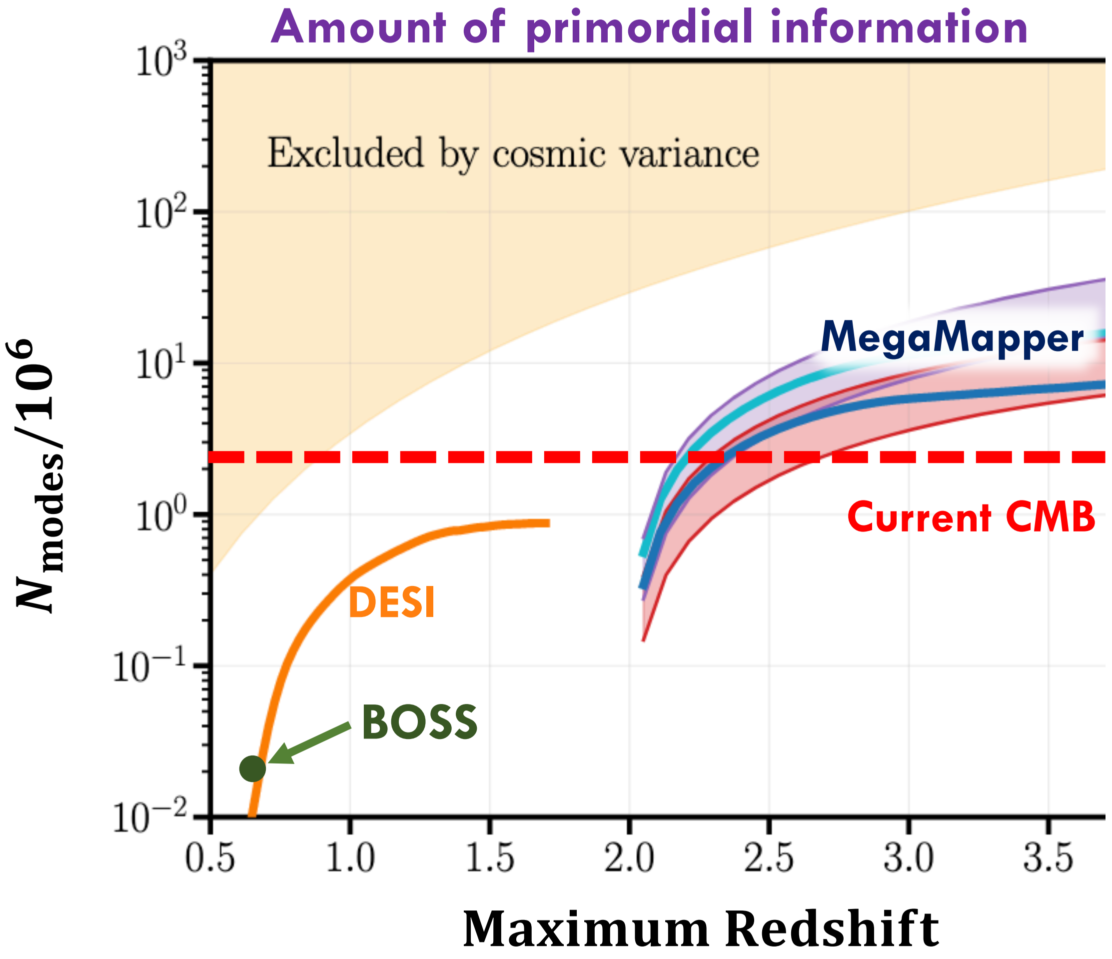
New physics is here!

- We constrain the sound-speed $c_s^2 \geq 0.013$ (95% CL)



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

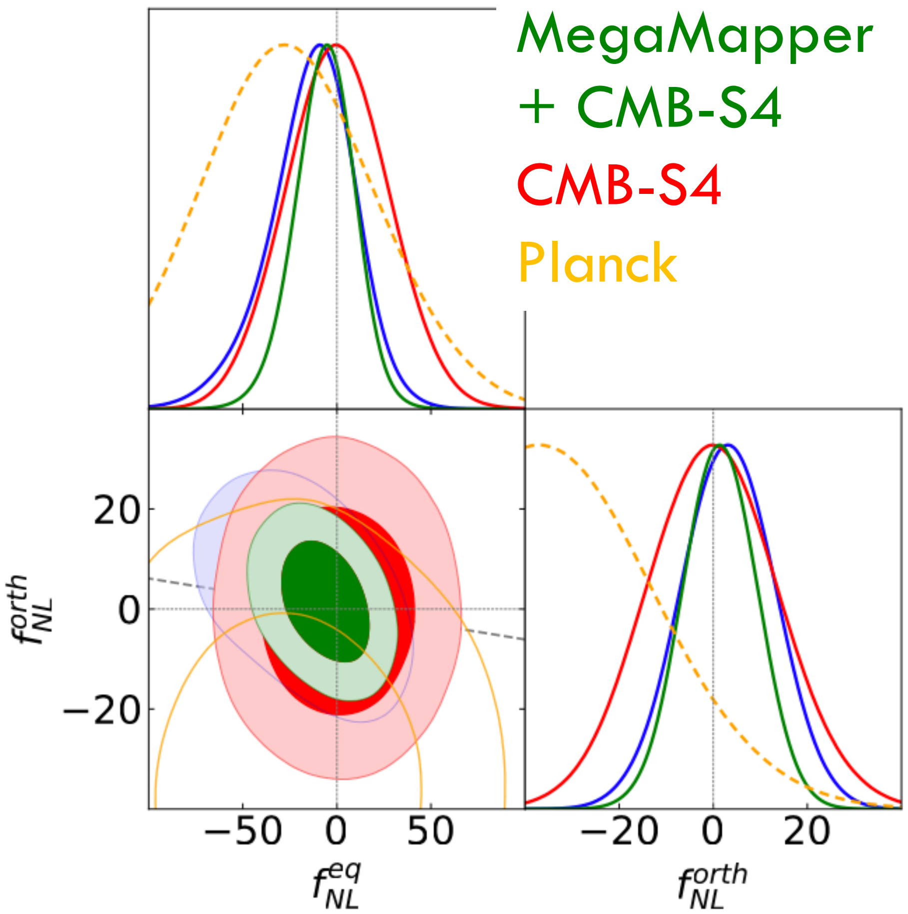
The future of f_{NL}



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

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

The future of $f_{\rm NL}$

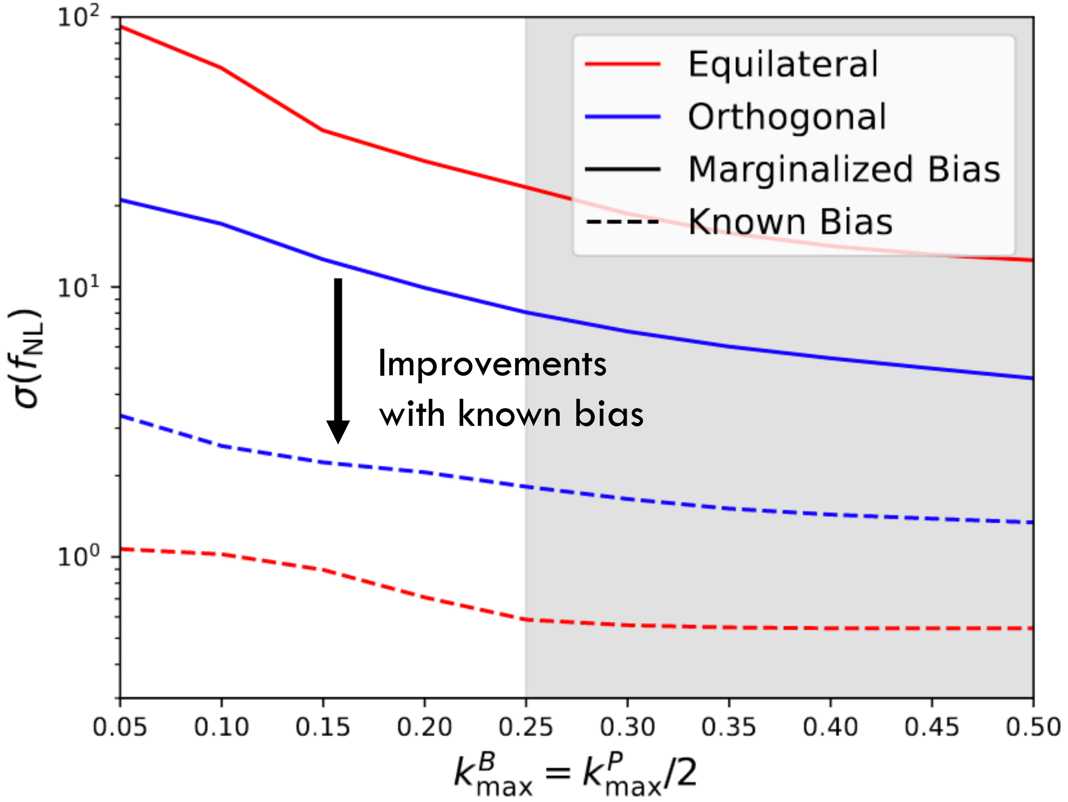


MegaMapper > CMB-S4!

- For now, the CMB gives **stronger constraints** than galaxy surveys
- This makes sense: the CMB measures **much more** of the Universe
- By Stage-V surveys like **MegaMapper**, **galaxies** will place the **strongest** constraints on inflationary physics
- ***Can we do better still?***

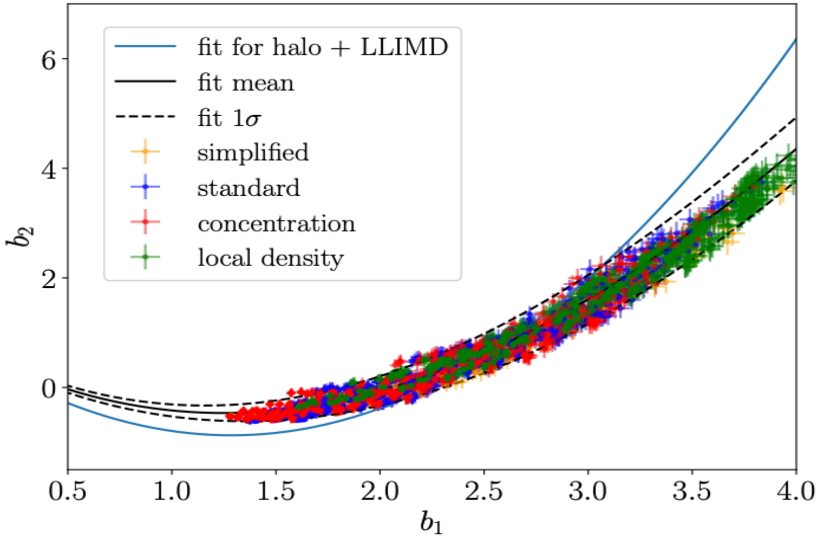
Cabass, **Philcox**+22b, Sailer+22, Ferraro+22

The future of f_{NL}



MegaMapper forecast

- Limiting factor in primordial analyses is knowledge of **galaxy formation**
- Can we calibrate with simulations or semi-analytic models?



Cabass, **Philcox**+22b, Akitsu, **Philcox**+ (in prep.)

Beyond f_{NL}

There's lots more to explore:

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

Hard in the CMB!

*Much of this will need the galaxy **trispectrum**!*

Cosmological Collider

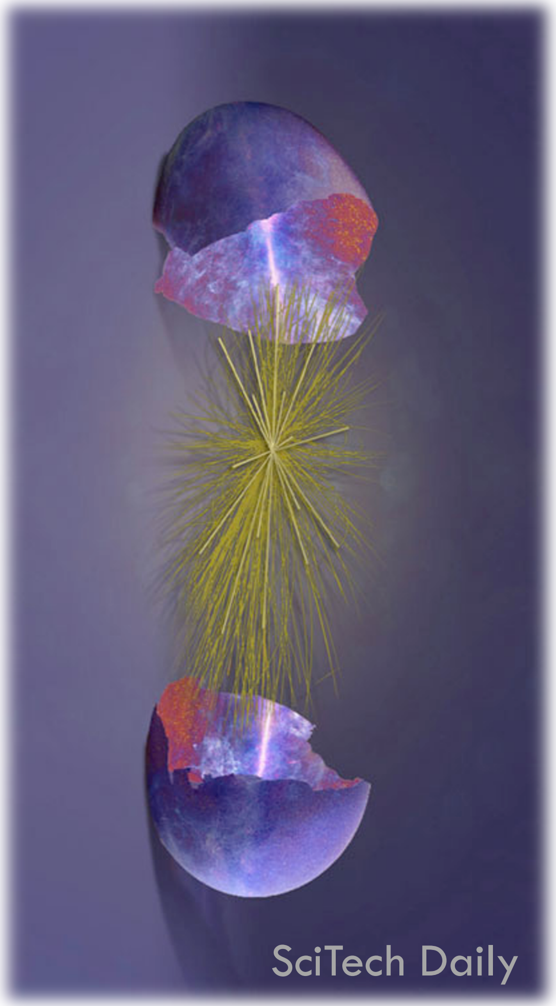
Low-energy remnants
[curvature fluctuations]

↑

High-energy physics
[particle scattering]

↓

Low-energy remnants
[curvature fluctuations]



SciTech Daily

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

Beyond Perturbation Theory

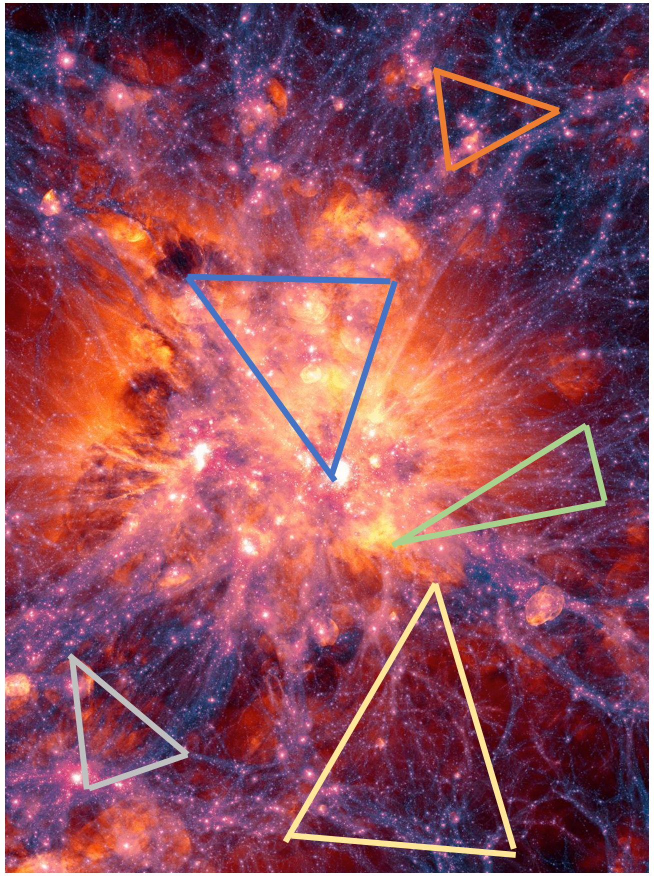
- All the above analyses assume **perturbativity:**

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

What symmetries can we use?

1. Galiliean invariance

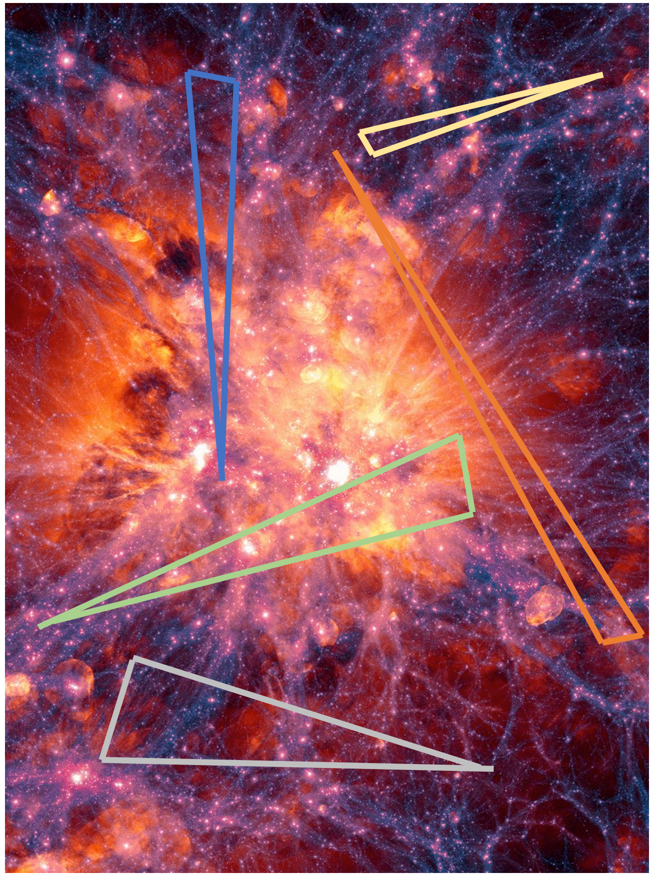
$$\mathbf{x} \to \mathbf{x} + \mathbf{s}(t), \qquad \mathbf{v} \to \mathbf{v} - \dot{\mathbf{s}}(t), \qquad \phi \to \phi + \Delta\phi$$

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

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

- This **consistency relation** is **violated** by local $f_{\rm NL}$

We can measure local $f_{\rm NL}$ from **highly non-linear** scales



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

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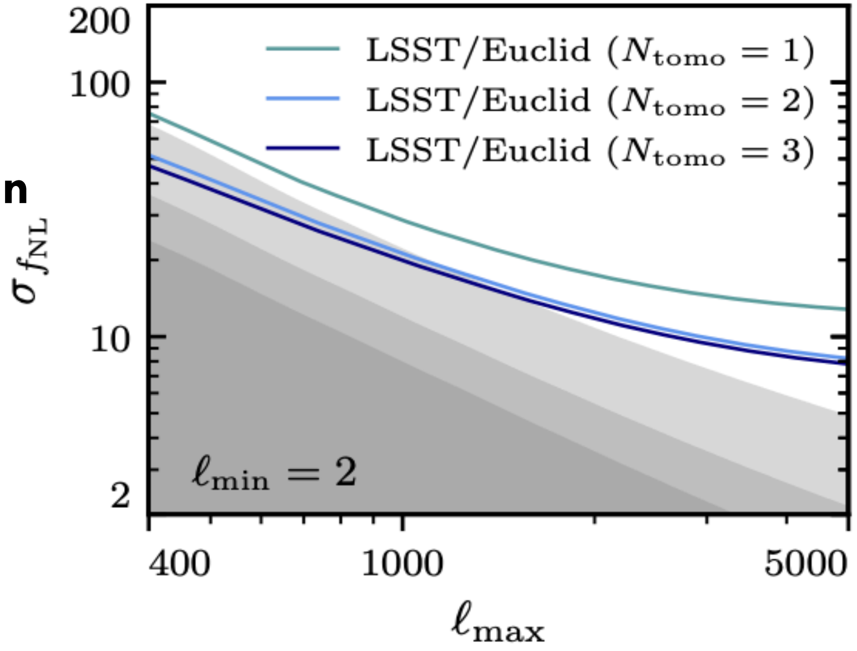
Non-linear weak lensing constraints



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

Beyond Perturbation Theory

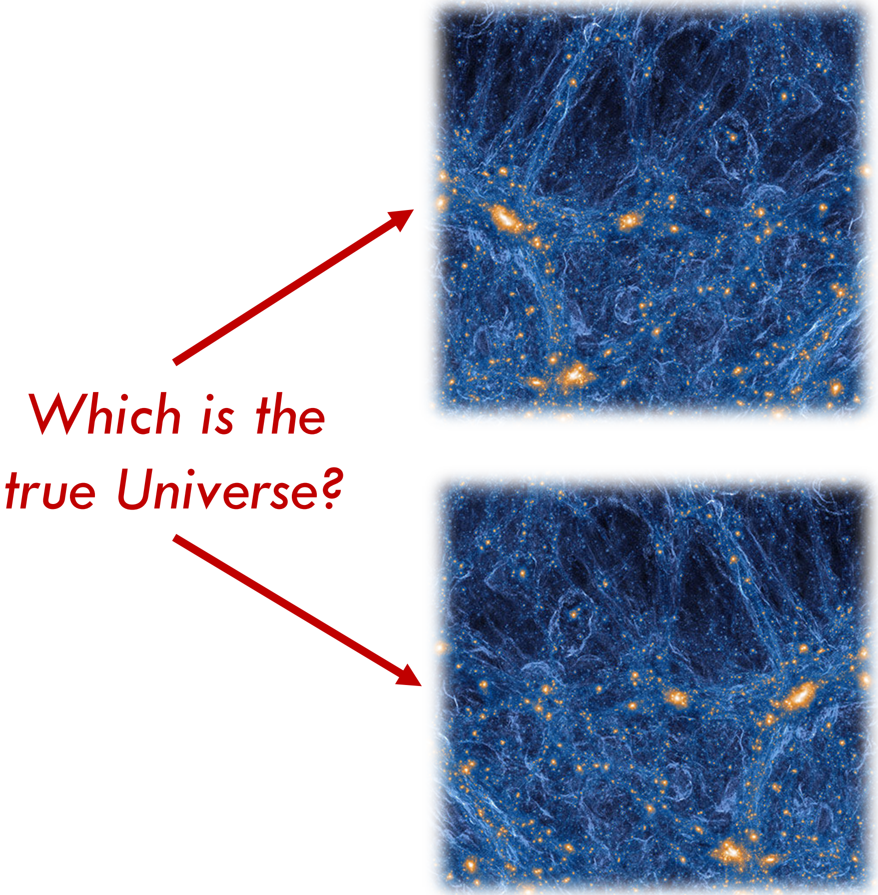
What symmetries can we use?

1. Galiliean 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?

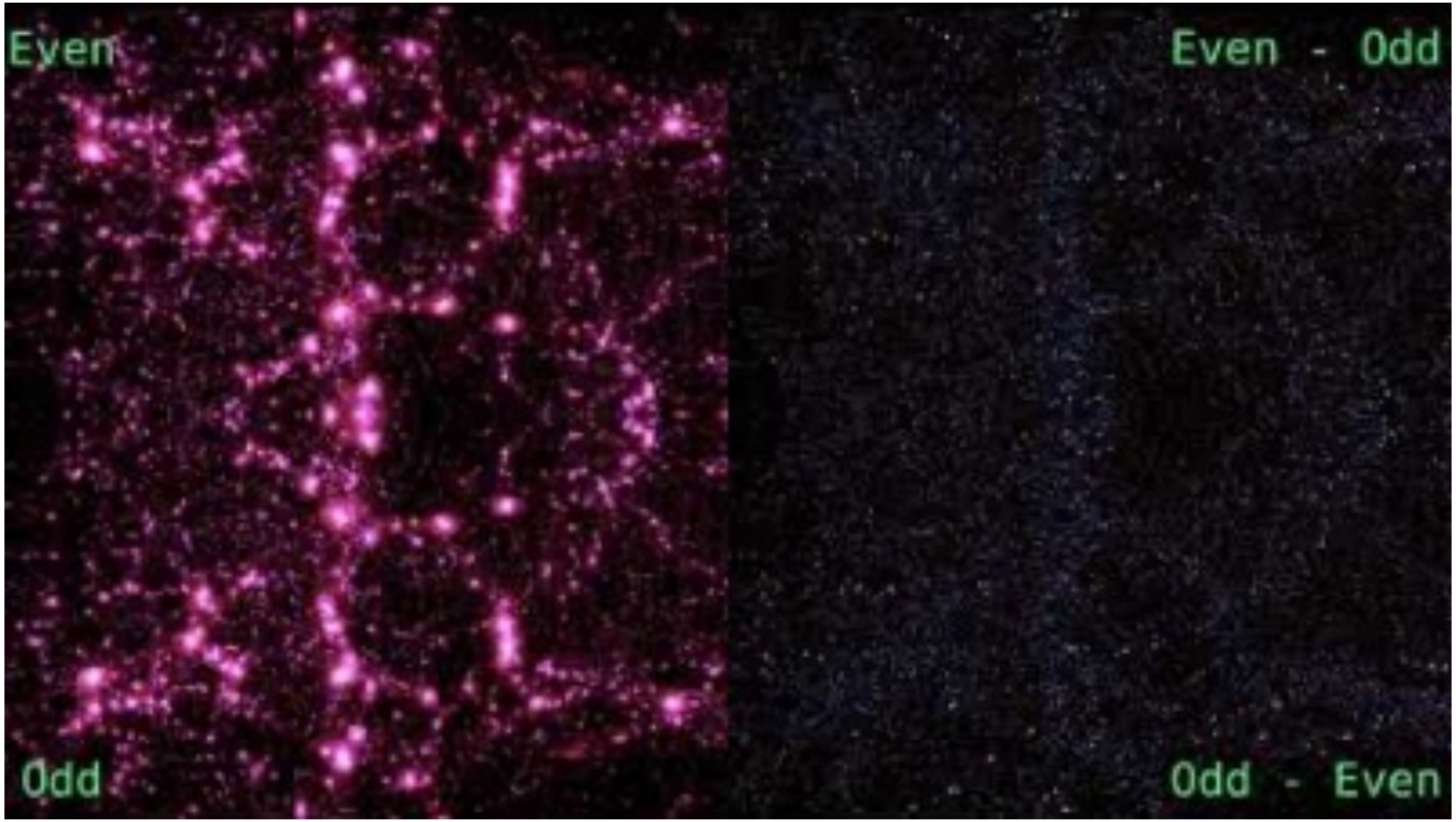


Which is the true Universe?

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

A Parity-Violating Universe

QUIJOTE-Odd: 1000 simulated universes with parity-violating **initial conditions**



Coulton, **Philcox**+23

How To Search for Parity-Violation

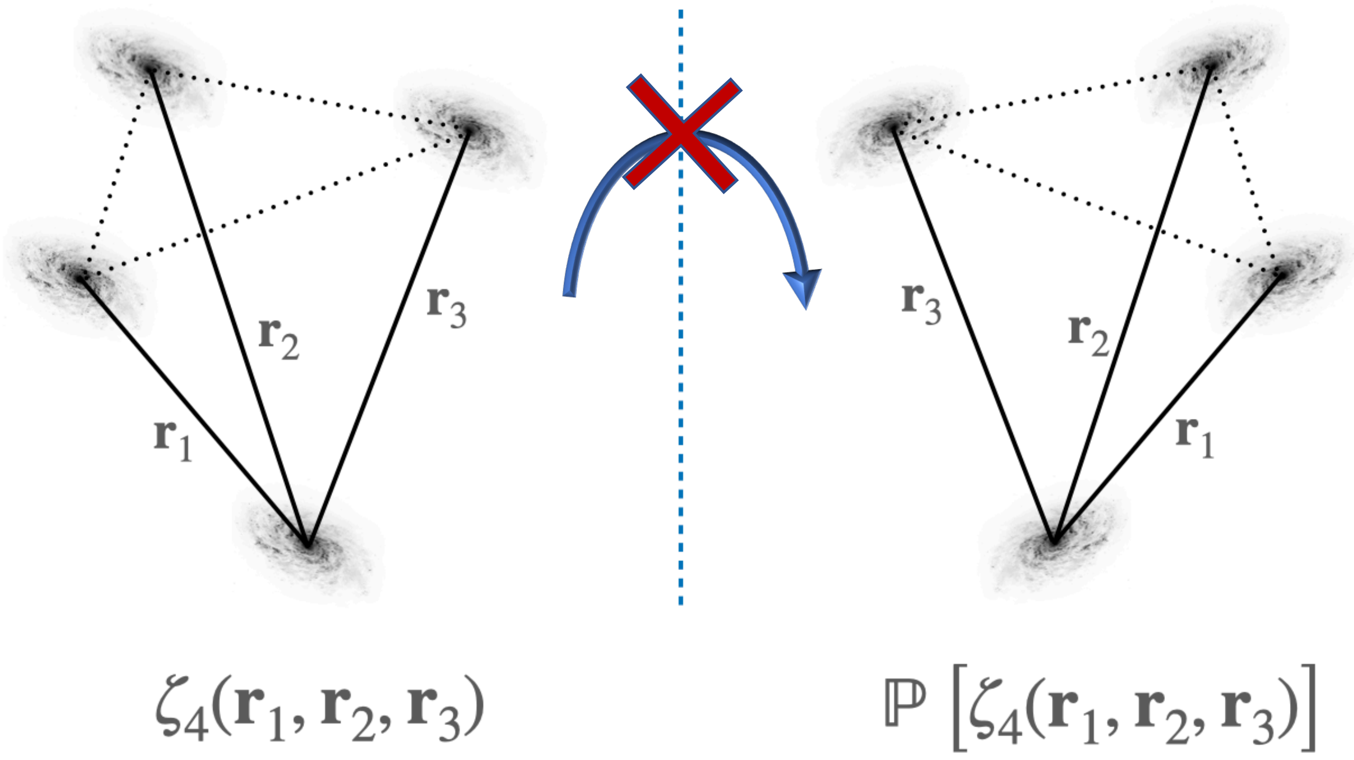
Scalar observables:

- Galaxy density
- CMB fluctuations

We need a **triple product:** $\mathbf{r}_1 \cdot \mathbf{r}_2 \times \mathbf{r}_3$

Statistics:

- **Four-point** correlation function
- **Trispectrum**

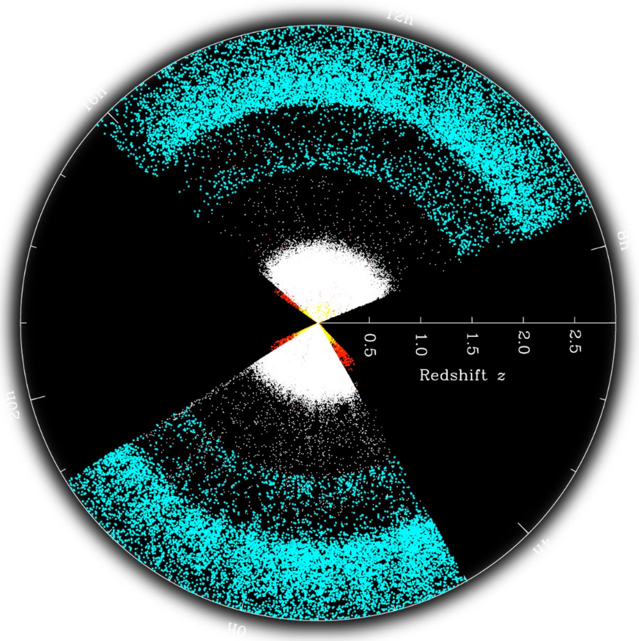


Lue+99, Gluscevic+10, Liu+20, Cahn+21, **Philcox** 22, Coulton, **Philcox**+23

How To Search for Parity-Violation

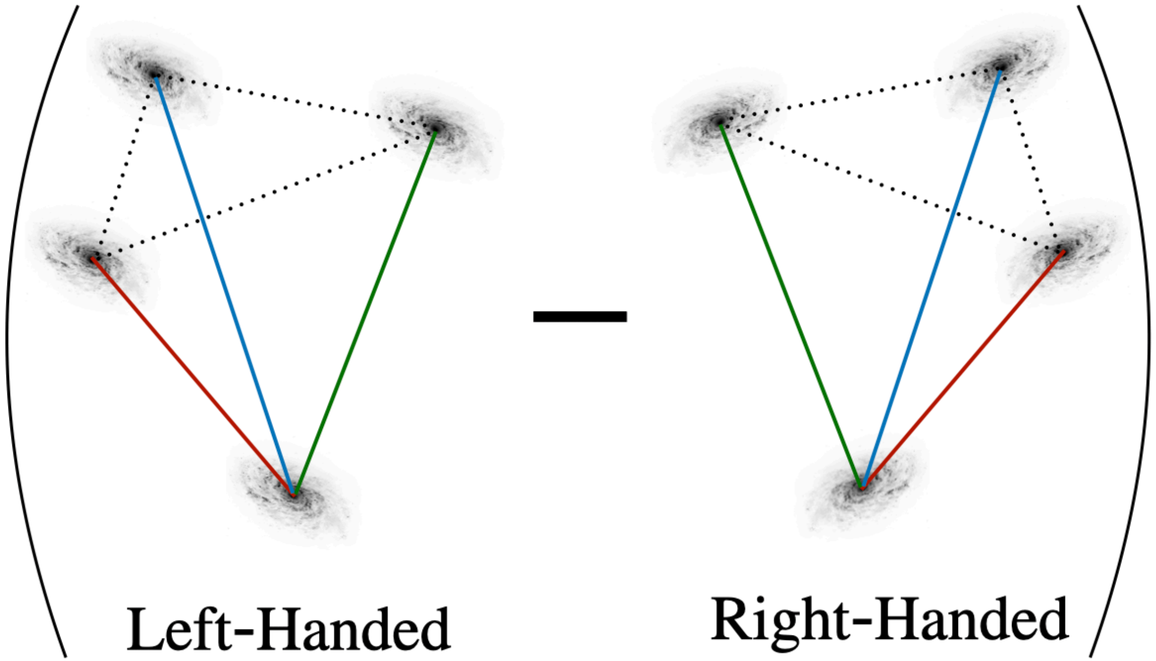
Measure the four-point function from 10^6 BOSS galaxies

Zero without parity-violation!



BOSS Galaxy Sample

ENCORE Code



$\mathbf{r}_1 \cdot \mathbf{r}_2 \times \mathbf{r}_3 > 0$

$\mathbf{r}_1 \cdot \mathbf{r}_2 \times \mathbf{r}_3 < 0$

GitHub: encore, Parity-Odd-4PCF

Philcox 22, Philcox+24, Hou+22

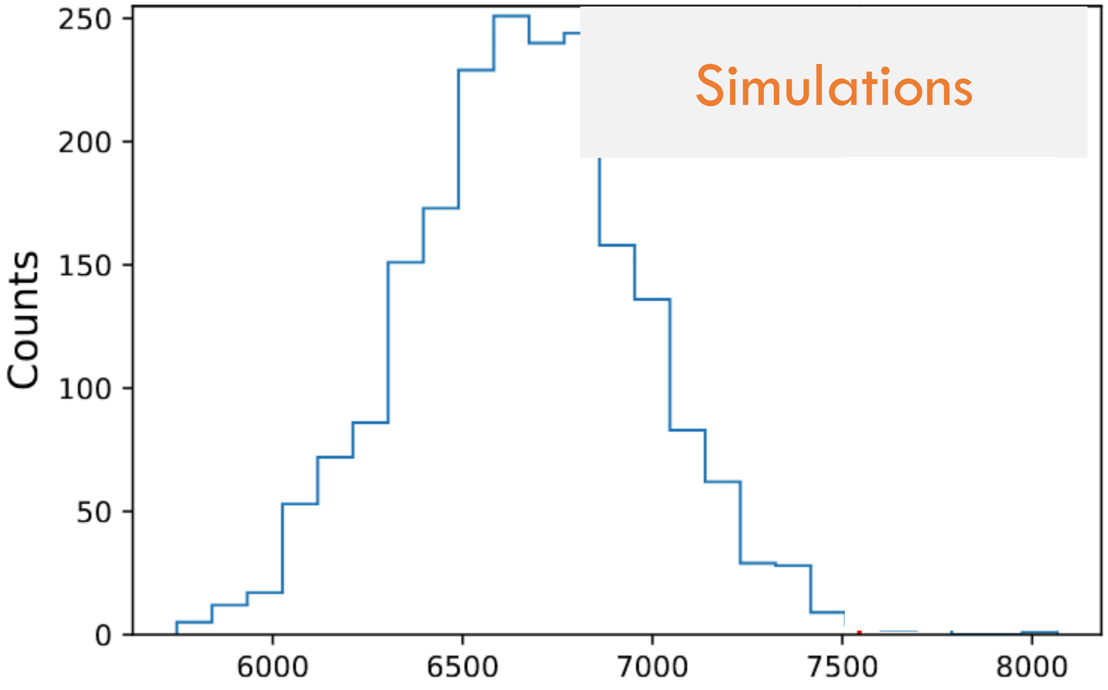
How To Search for Parity-Violation

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

- We need the **covariance** of a 4-point function
- Need to model an **8**-point function down to (mildly) **non-linear** scales

Perform a **simulation-based** χ^2 analysis of the observed data

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



Galaxy Parity-Violating Probability

Philcox 22, Philcox+24, Hou+22

Detecting Parity-Violation?

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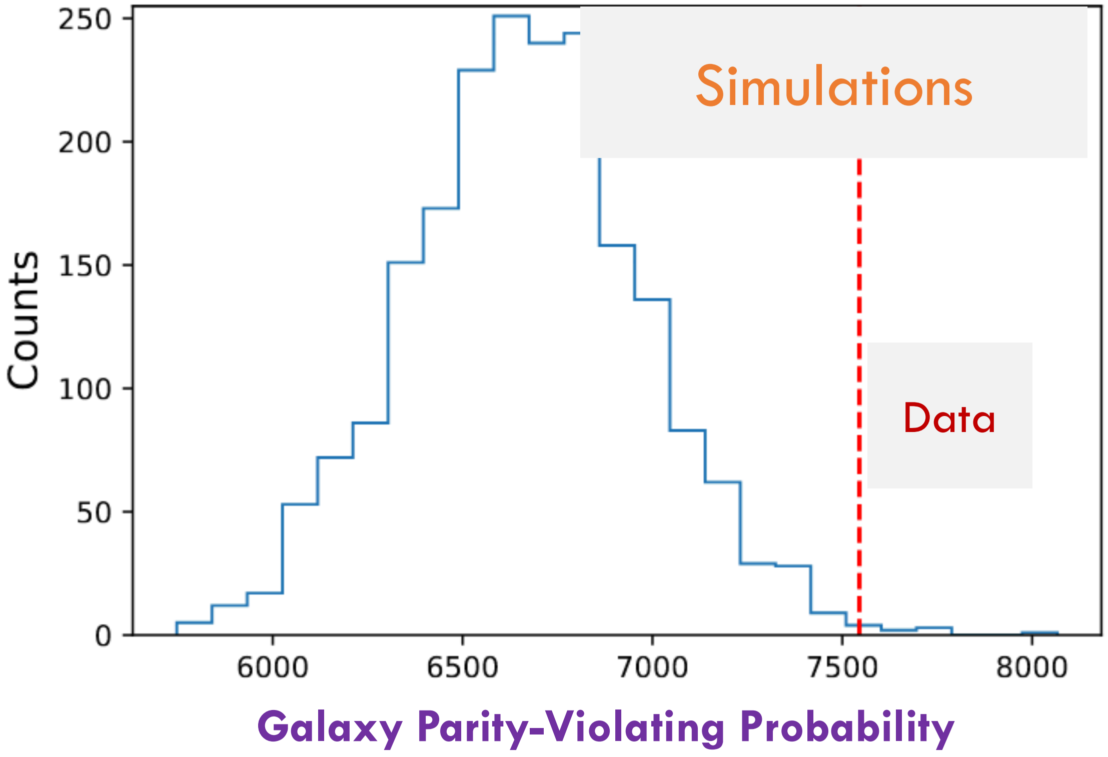
Perform a **simulation-based** χ^2 analysis of the observed data

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

BOSS Rank: 2040/2048 (99.6%)



3σ detection of parity-violation??

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

Detecting Parity-Violation?

COSMOLOGY

Asymmetry Detected in the Distribution of Galaxies

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ting details of

COLUMBIA NEWS

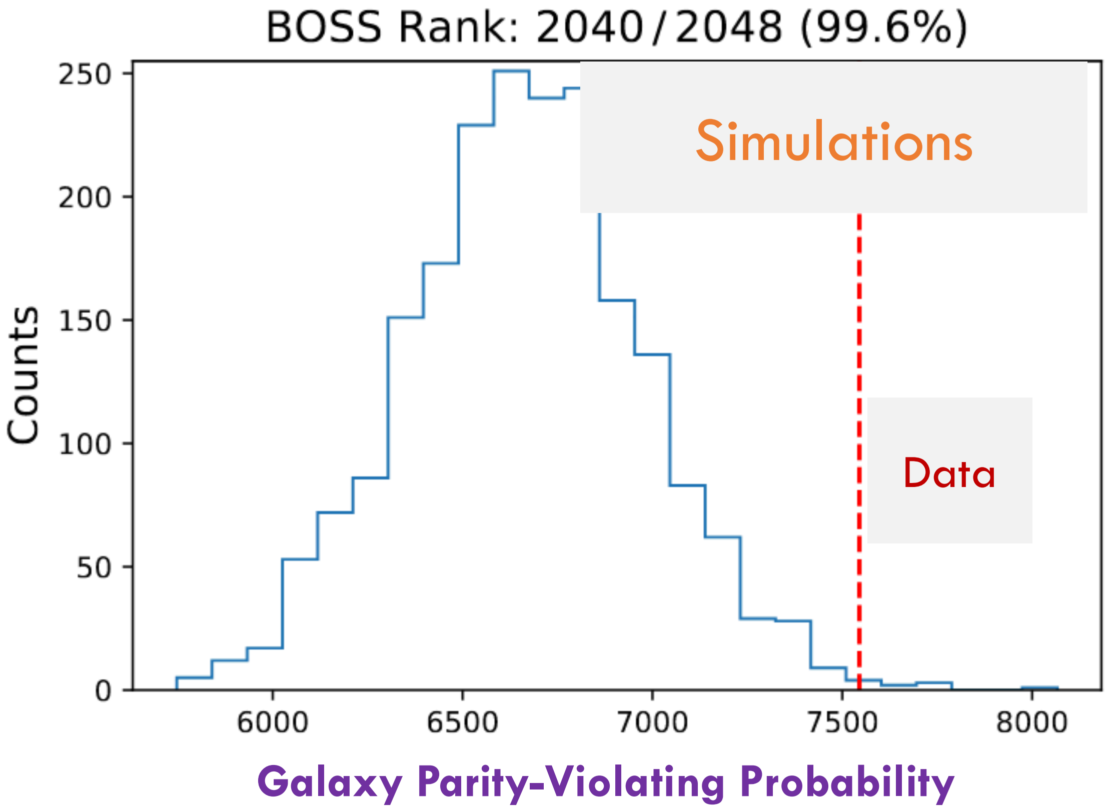
Is the Universe Asymmetrical?

The universe is surprisingly lopsided and we don't know why

Two analy

symmetri

universe a



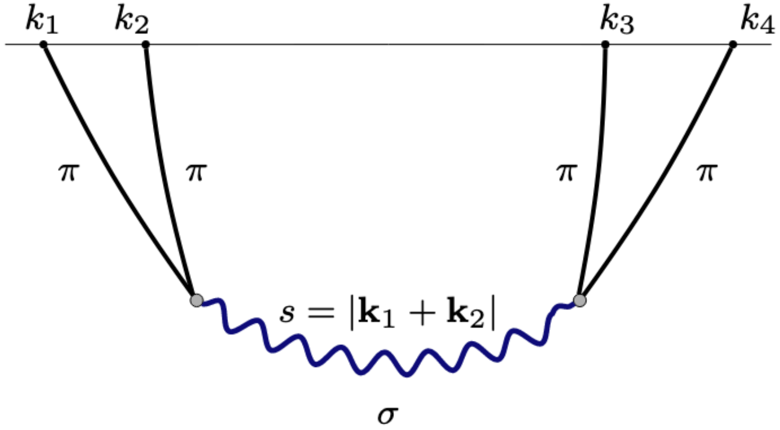
3σ detection of parity-violation??

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

Detecting Parity-Violation?

Many ways to violate parity in inflation:

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



Spinning particles in inflation

Ghost inflation

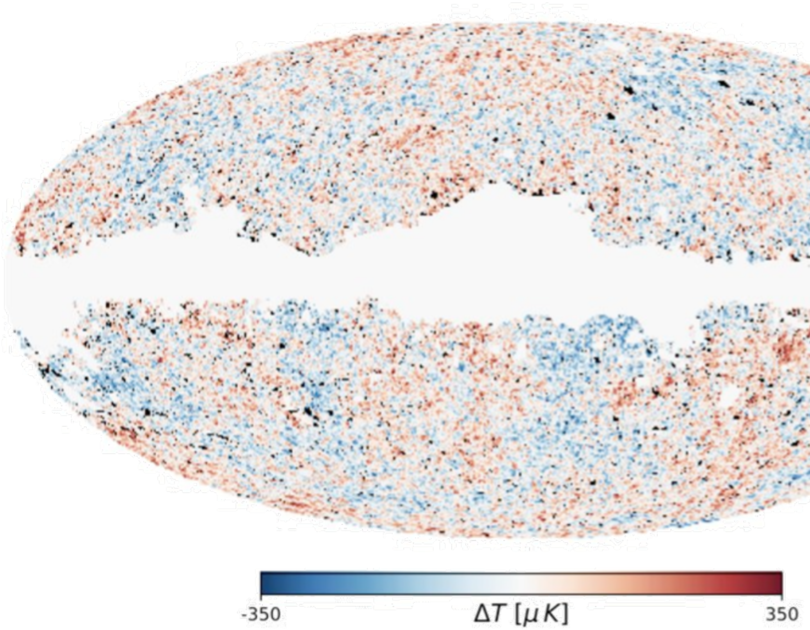
Chern-Simons inflation

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

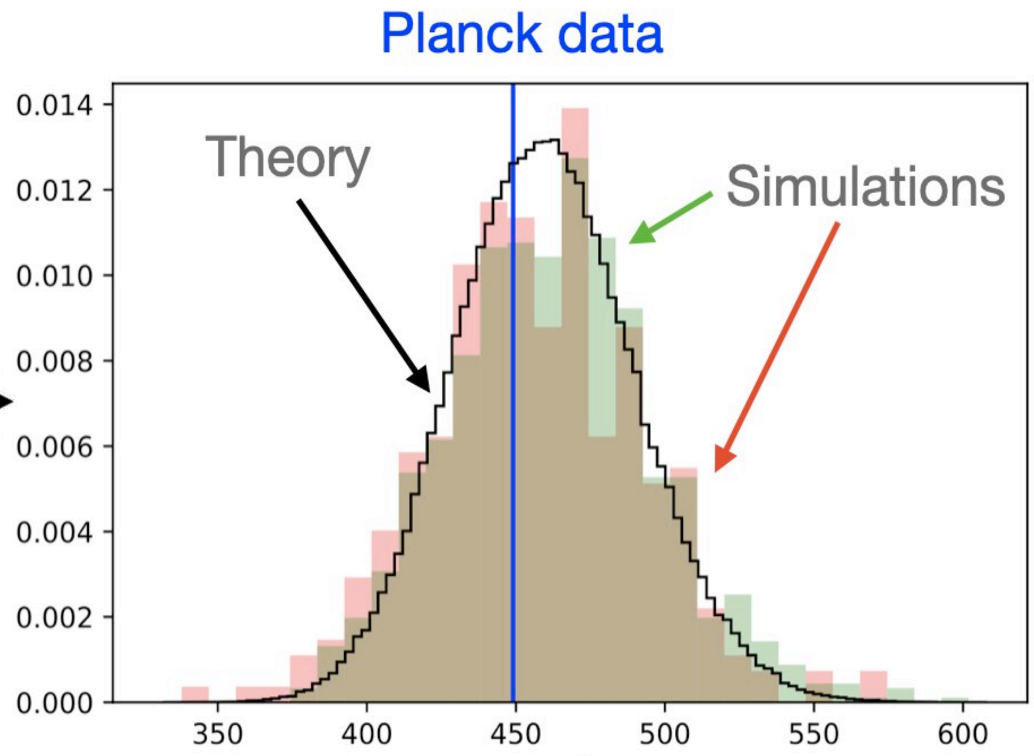
Cabass+22, Cabass, **Philcox**+22, Creque-Sarbinowski, **Philcox** 23, **Philcox**+23

*Un*detecting Parity-Violation

***Planck* Temperature and Polarization**



PolyBin



CMB Parity-Violating Probability

$< 0.5\sigma$ **detection with 250x more modes**

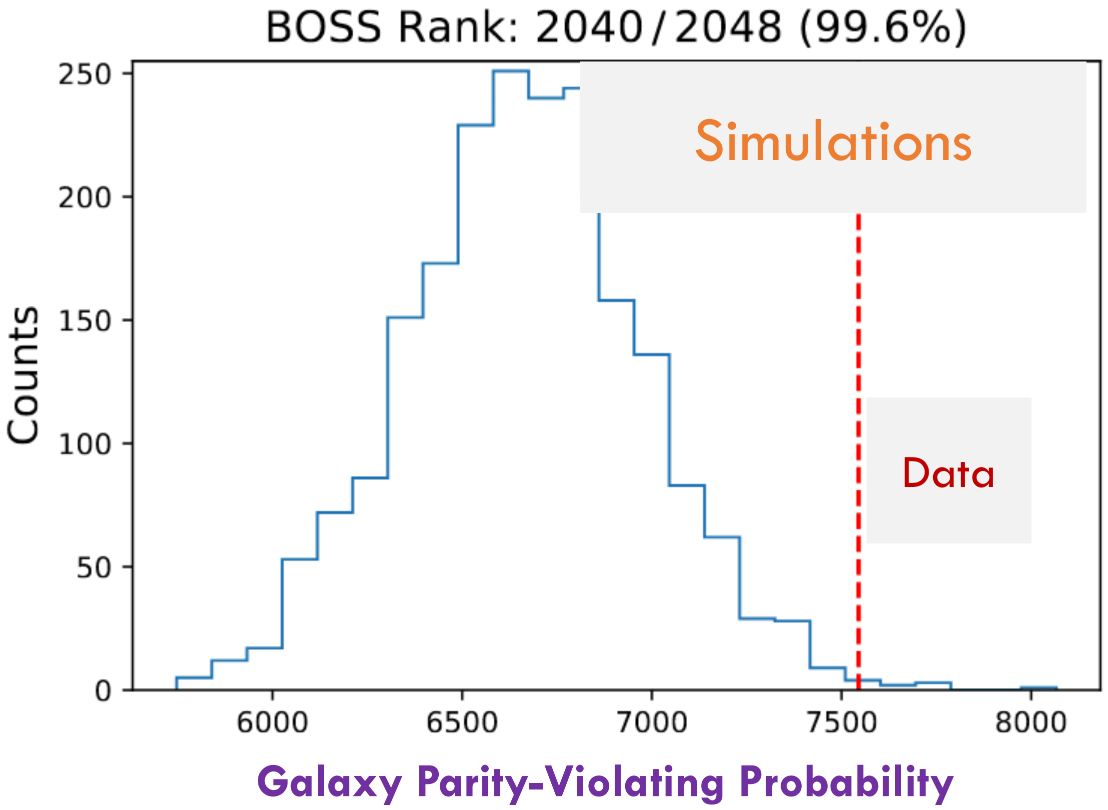
GitHub: PolyBin

Philcox 23, **Philcox**+23

What Was Responsible for the Galaxy Signal?

Cosmological options

- 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?

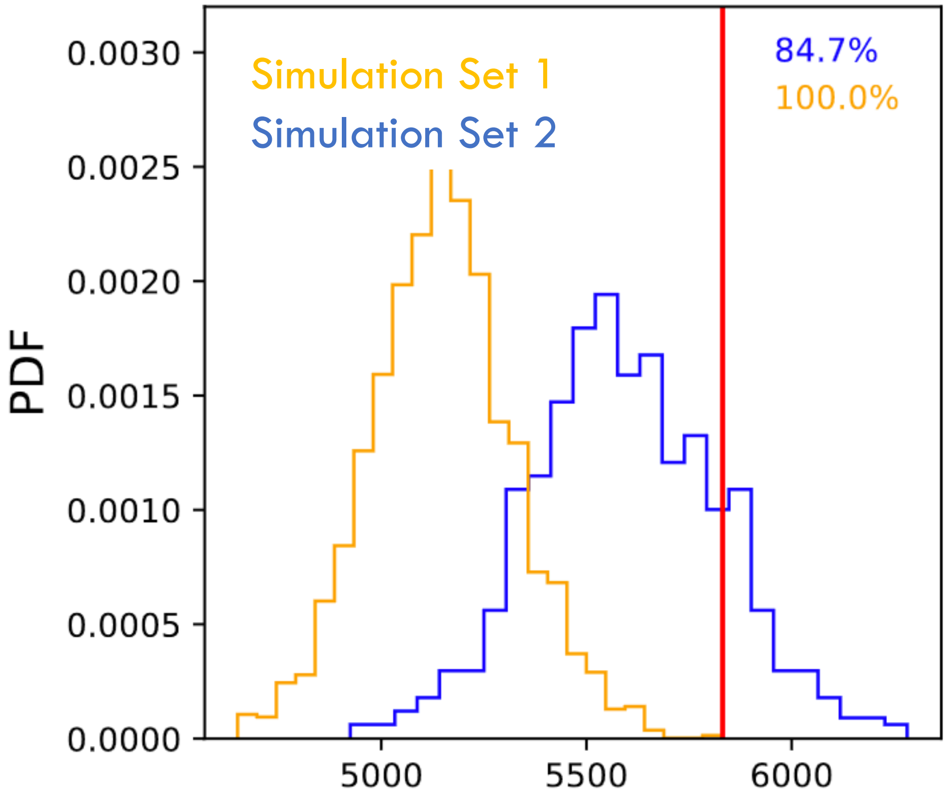
Cosmological options

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

Non-cosmological options

- Systematics in **data**
- Systematics in **analysis**

Are the simulations reliable?



Galaxy Parity-Violating Probability

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

Does the Universe Violate Parity?

BOSS galaxy survey:

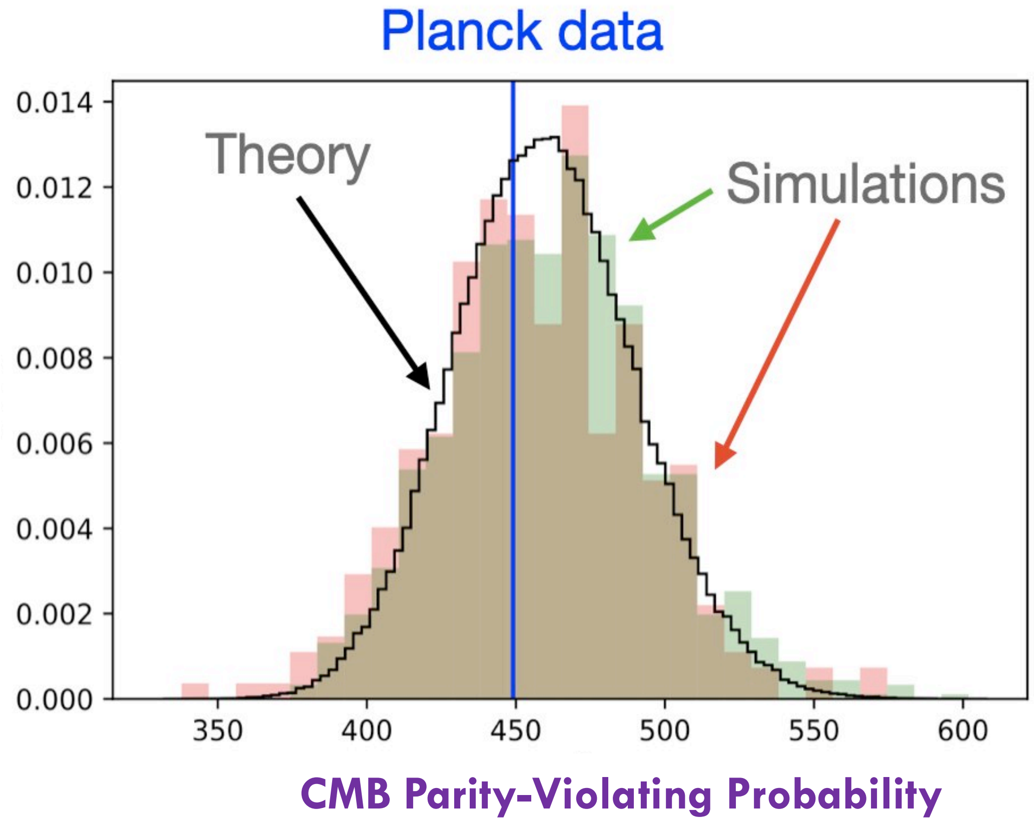
Yes! $\mathbf{3\sigma}$ detection of parity-violation

***Planck* Cosmic Microwave Background:**

No! $< \mathbf{0.5\sigma}$ detection of parity-violation

- Possible explanation: inaccurate **simulations**

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



Philcox 23, **Philcox**+23

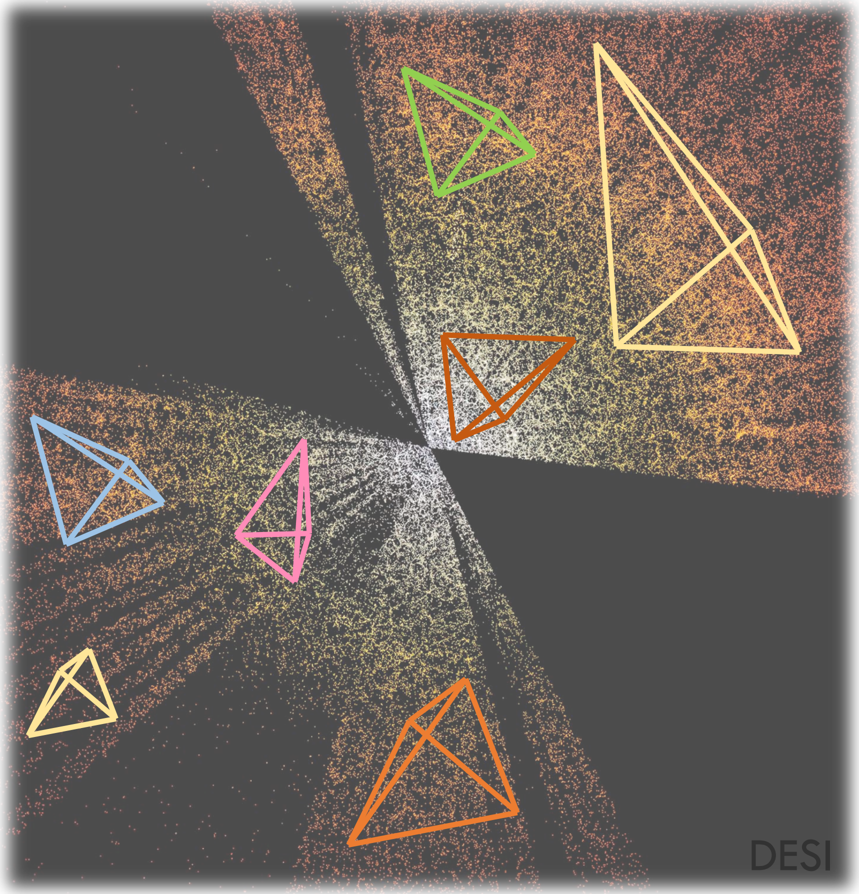
The Future

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

- We have a unique opportunity to pin down **inflationary particle physics**

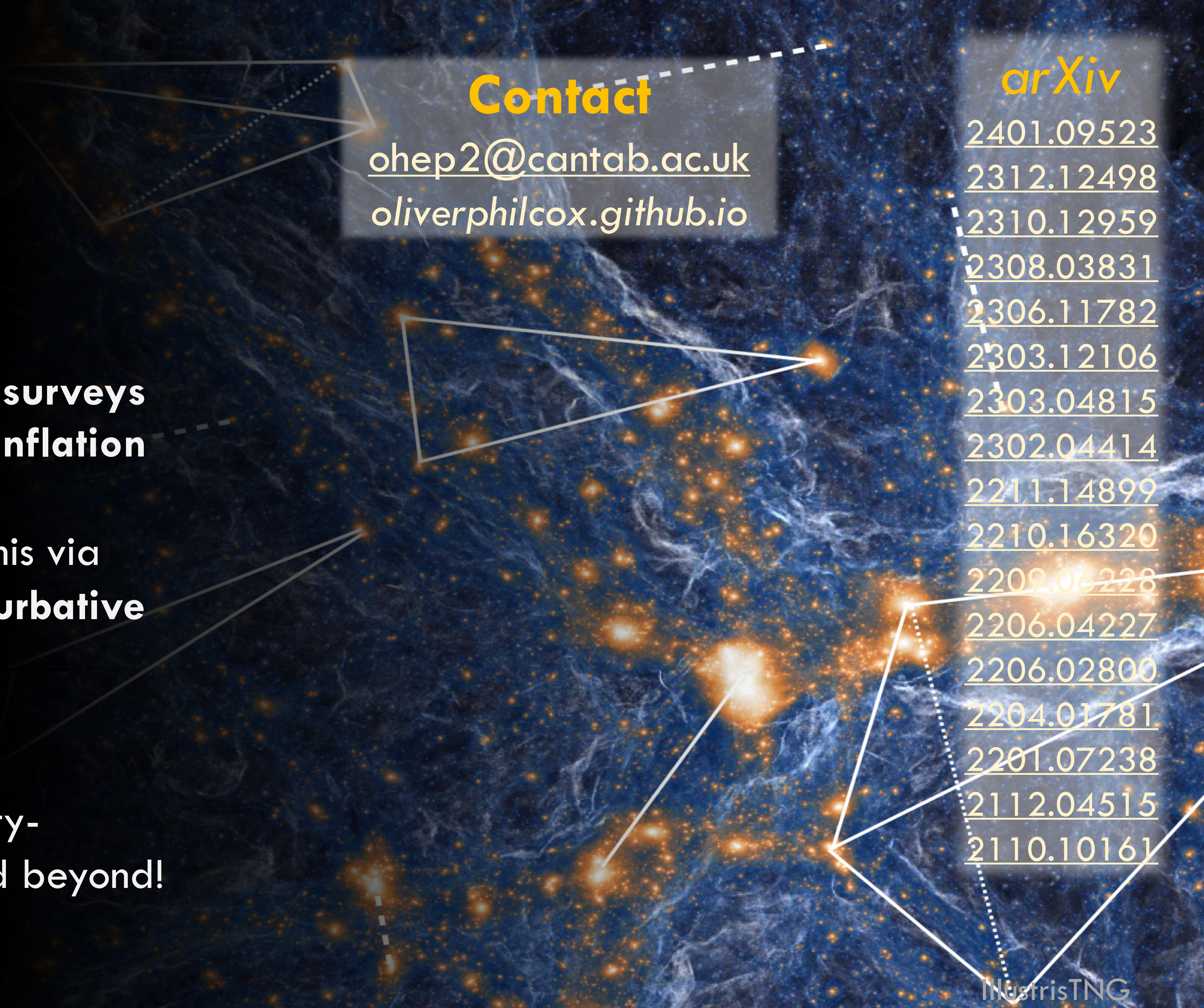
- This will require:
  - High-resolution **data** [DESI, Euclid, …]
  - Robust **statistics** [Bispectra, Trispectra, ...]
  - Accurate **theoretical** models [perturbative, symmetries, …]

We have already developed a lot of the technology to do this!



Summary

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



IllustrisTNG

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arXiv

2401.09523
2312.12498
2310.12959
2308.03831
2306.11782
2303.12106
2303.04815
2302.04414
2211.14899
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