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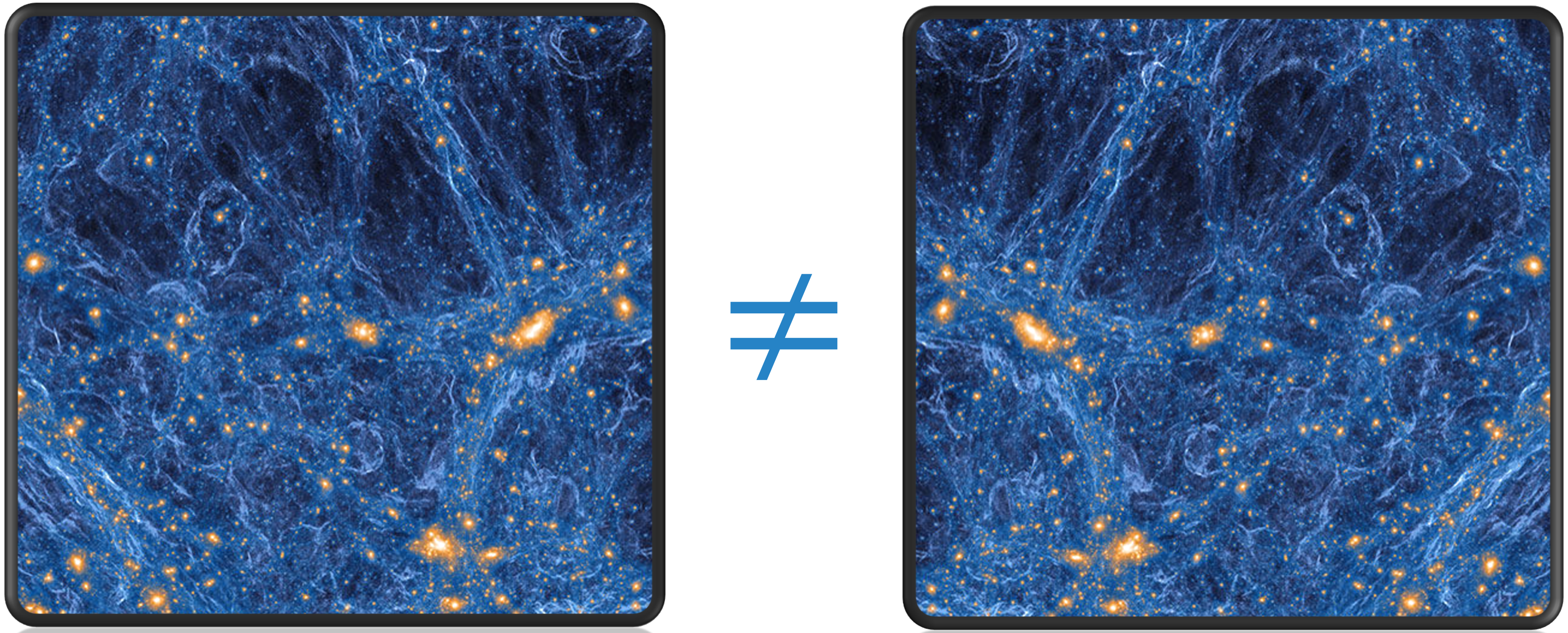

Hints of Cosmological Parity Violation

Oliver Philcox (Columbia / Simons Foundation)

Johns Hopkins, February 2023

November 2020

Parity-Violation from the CMB?

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A Hint of New Physics Observed in Polarized Radiation From the Early Universe

June 2022

Parity-Violation from Galaxies?

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COSMOLOGY

Asymmetry Detected in the Distribution of Galaxies

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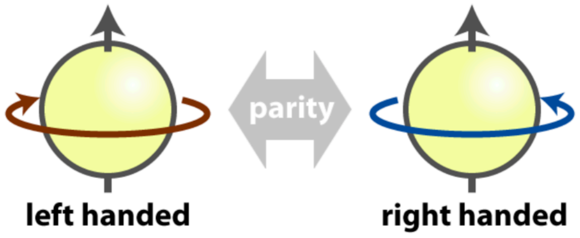
The universe is surprisingly lopsided and we don't know why

Minami+20, **Philcox** 22, Hou+22

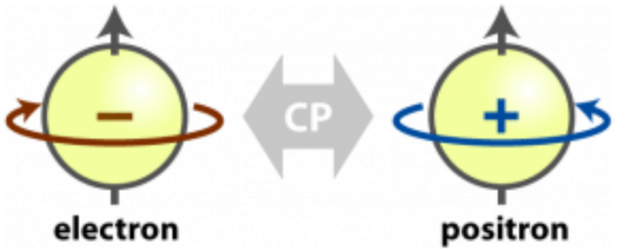
PARITY SYMMETRY IN PHYSICS

- Parity symmetry = symmetry under **point reflection**



$$\mathbb{P}[f(\mathbf{x}_1, \mathbf{x}_2, \dots)] = f(-\mathbf{x}_1, -\mathbf{x}_2, \dots)$$

- Physics obeys **C**harge-**P**arity-**T**ime symmetry:



(+ reverse time)

$$f^+(\mathbf{x}, t) = f^-(-\mathbf{x}, -t)$$

Luders & Pauli 1954

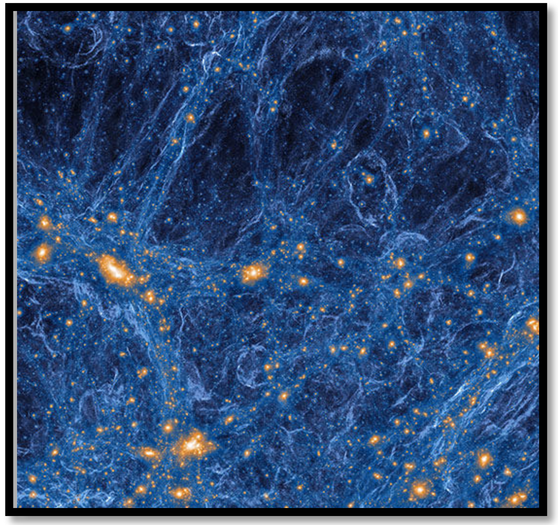
PARITY SYMMETRY IN COSMOLOGY

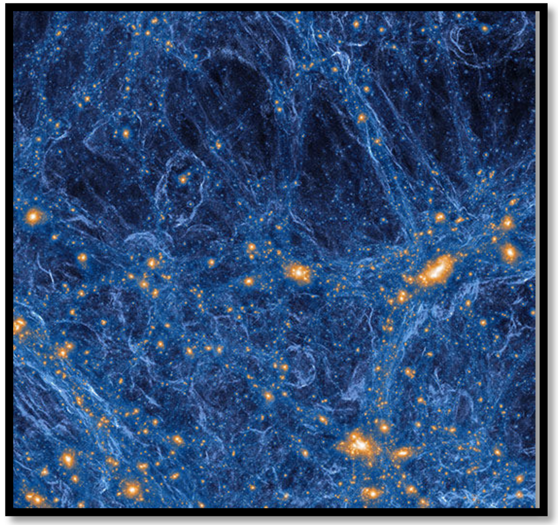
Large-scale cosmology is controlled by **GR**:

- No dependence on **charge**
- **Time** reversable

⇒ Cosmology should be **parity-symmetric**

$$\mathbb{P}[f(\mathbf{x}_1, \mathbf{x}_2, \ldots)] = f(\mathbf{x}_1, \mathbf{x}_2, \ldots)$$

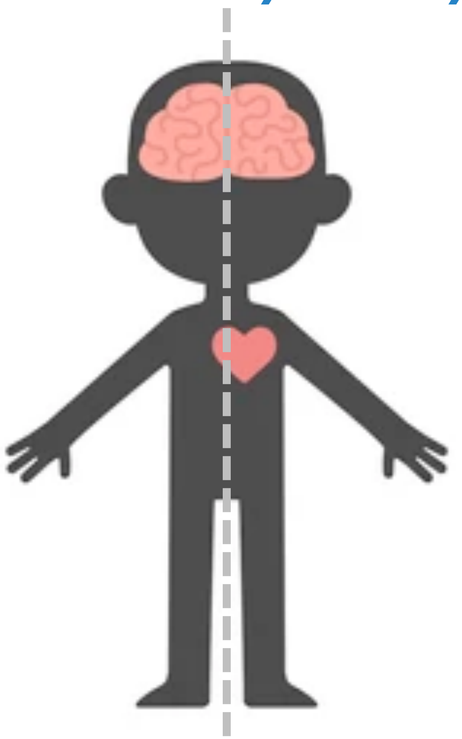




These should be **statistically indistinguishable!**

PARITY-VIOLATION EXISTS IN NATURE

- Human-scale physics is **not** parity-symmetric
  - Chemistry is controlled by the weak force!



- **Baryogenesis** violates charge-parity symmetry

$$n_{\text{Baryon}} \neq n_{\text{Anti-Baryon}}$$

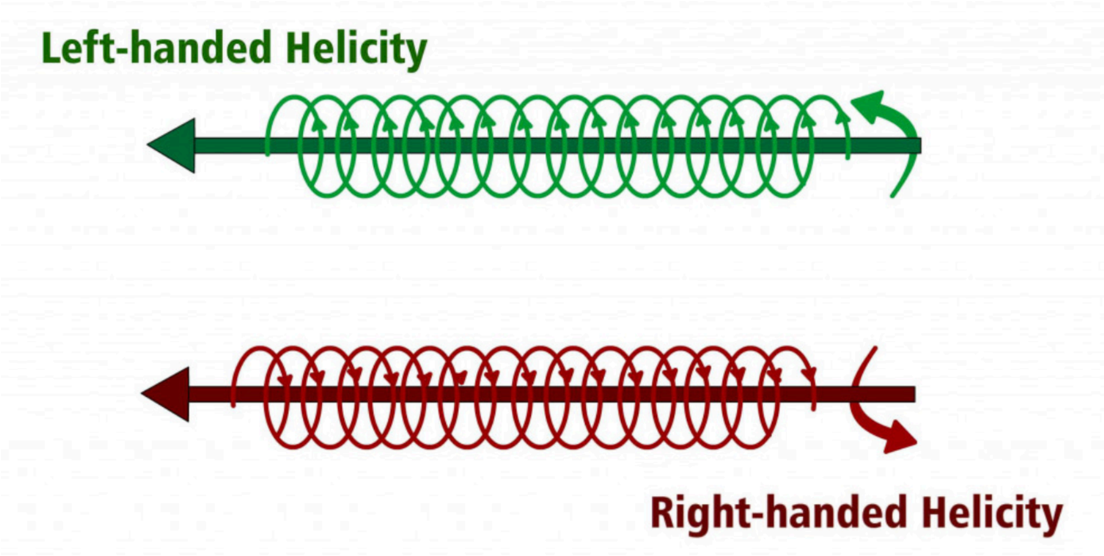
Non-Gravitational physics **can** break parity invariance!

Sakharov 67

PARITY-VIOLATION IN COSMOLOGY

Where could parity-violation come from?

- Cosmic Inflation
- Exotic late-time physics



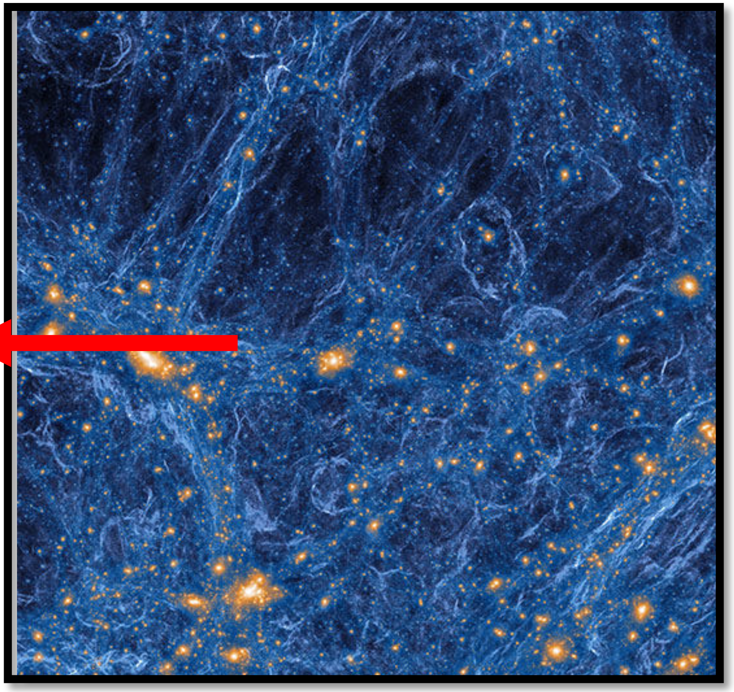
Usually, this requires vectors / tensors!

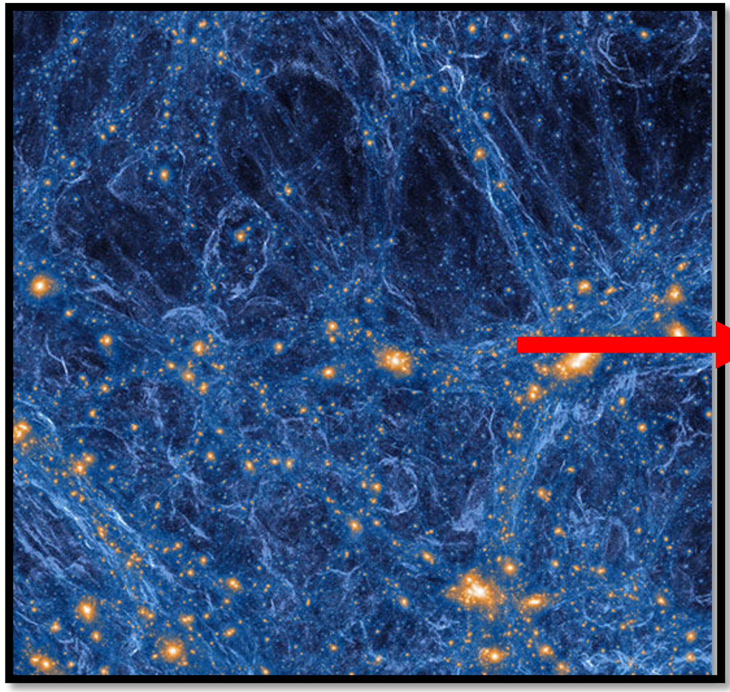
$$\mathbf{v}(\mathbf{x}) = v_L \boldsymbol{e}_L(\mathbf{x}) + v_R \boldsymbol{e}_R(\mathbf{x}) \qquad \mathbb{P}\left[\boldsymbol{e}_{L/R}\right] = \boldsymbol{e}_{R/L}$$

Lue+99, Cabass+22

HOW TO SEARCH FOR PARITY VIOLATION

$P(\mathbf{k})$
$B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$
$T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$
…





$\mathbb{P}[P(\mathbf{k})]$
$\mathbb{P}[B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)]$
$\mathbb{P}[T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)]$
…

Which statistics are sensitive to parity?

$X - \mathbb{P}[X] = ?$

SEARCHING FOR <u>SCALAR</u> PARITY VIOLATION

Let's start with **scalar** observables, e.g.:

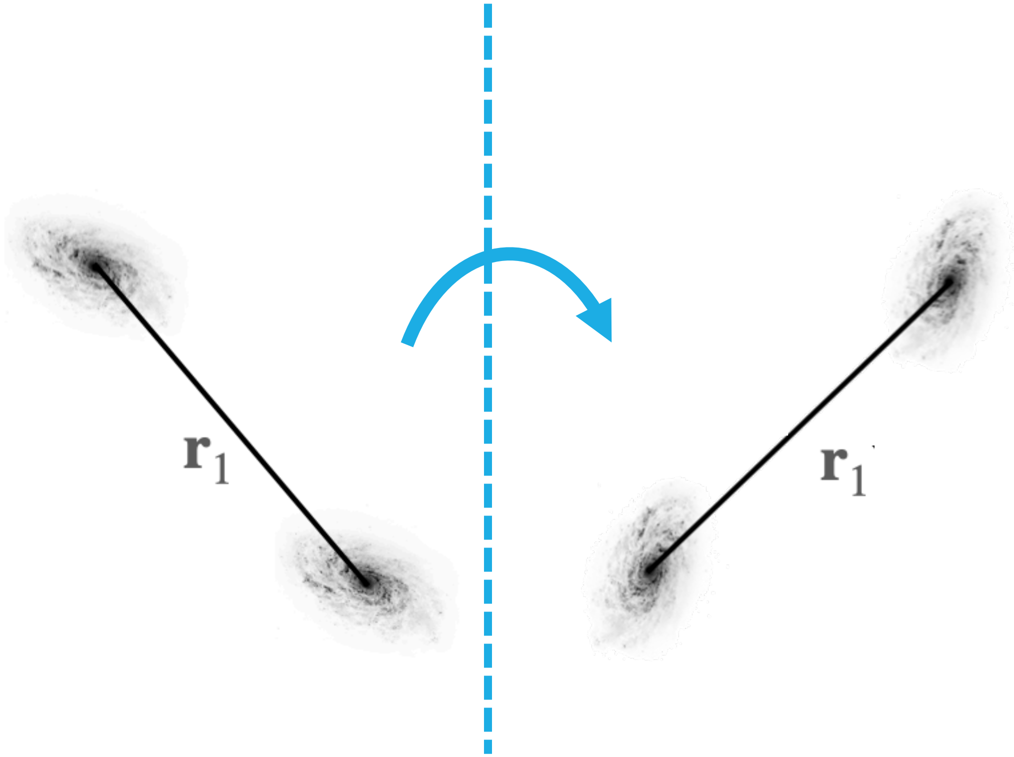
- Galaxy **overdensity** [δ_g]
- CMB **temperature** [T]

<u>Simplest observable</u>

Power Spectrum / 2-Point Function (2PCF)

But *parity inversion = rotation*

⇒ No signal!



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

SEARCHING FOR SCALAR PARITY VIOLATION

Let's start with **scalar** observables, e.g.:

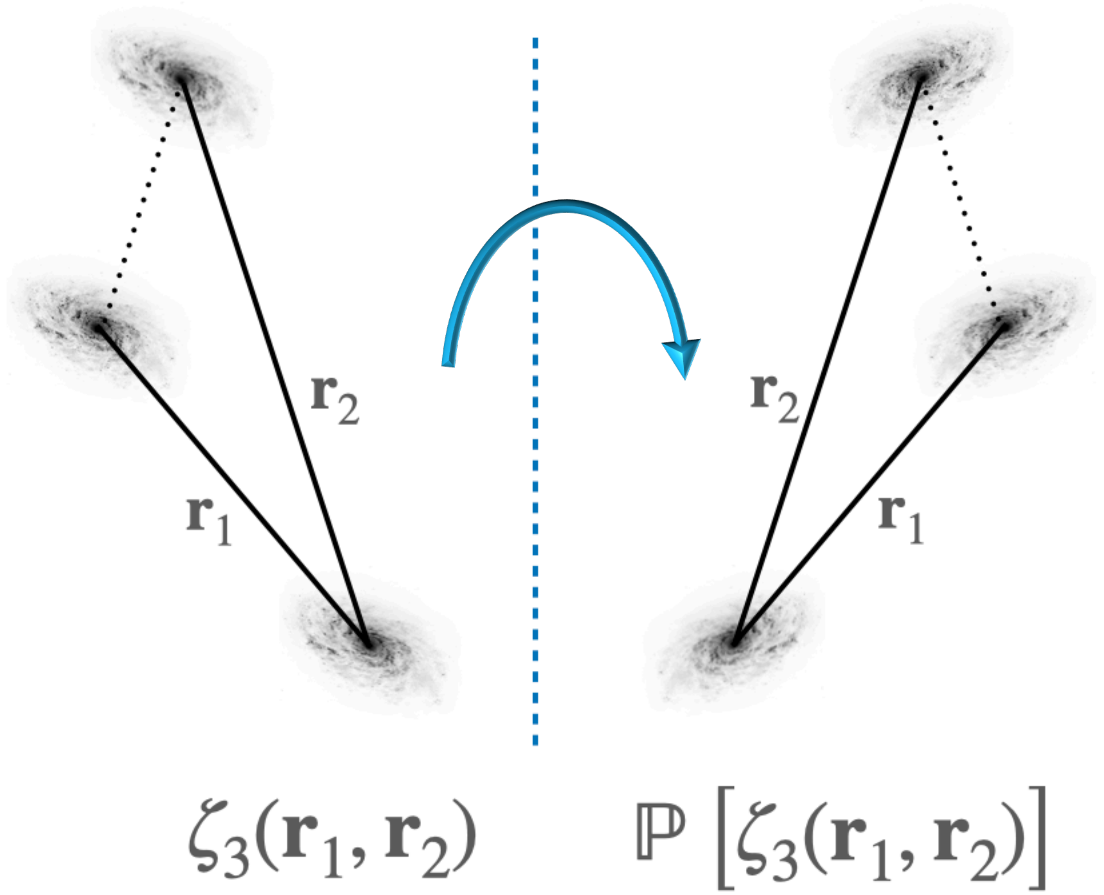
- Galaxy **overdensity** [δ_g]
- CMB **temperature** [T]

Next observable

Bispectrum / 3-Point Function (3PCF)

Still *parity inversion = rotation*

⇒ No signal!



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

SEARCHING FOR SCALAR PARITY VIOLATION

Let's start with **scalar** observables, e.g.:

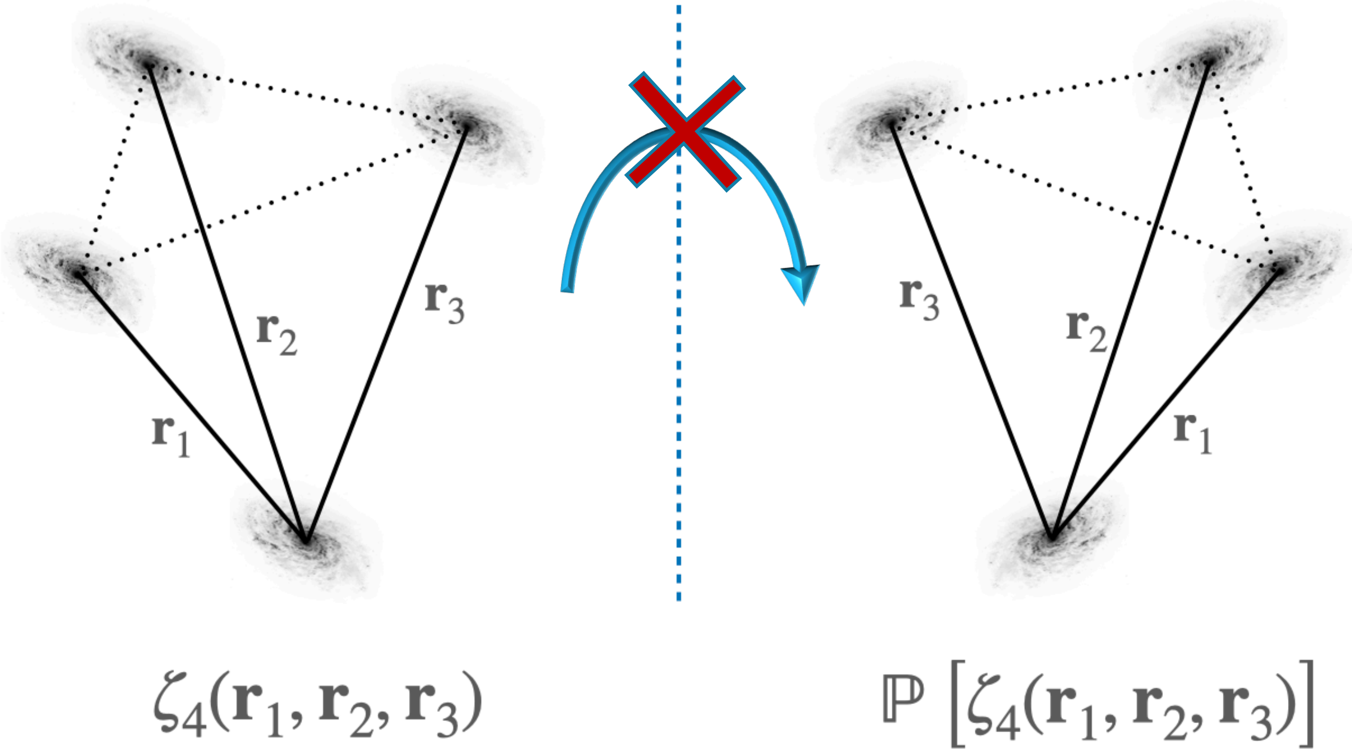
- Galaxy **overdensity** [δ_g]
- CMB **temperature** [T]

Next next observable

Trispectrum / 4-Point Function (4PCF)

Finally *parity inversion ≠ rotation*

⇒ We can get a signal!



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SEARCHING FOR TENSOR PARITY VIOLATION

For **vector/tensor** observables, e.g.:

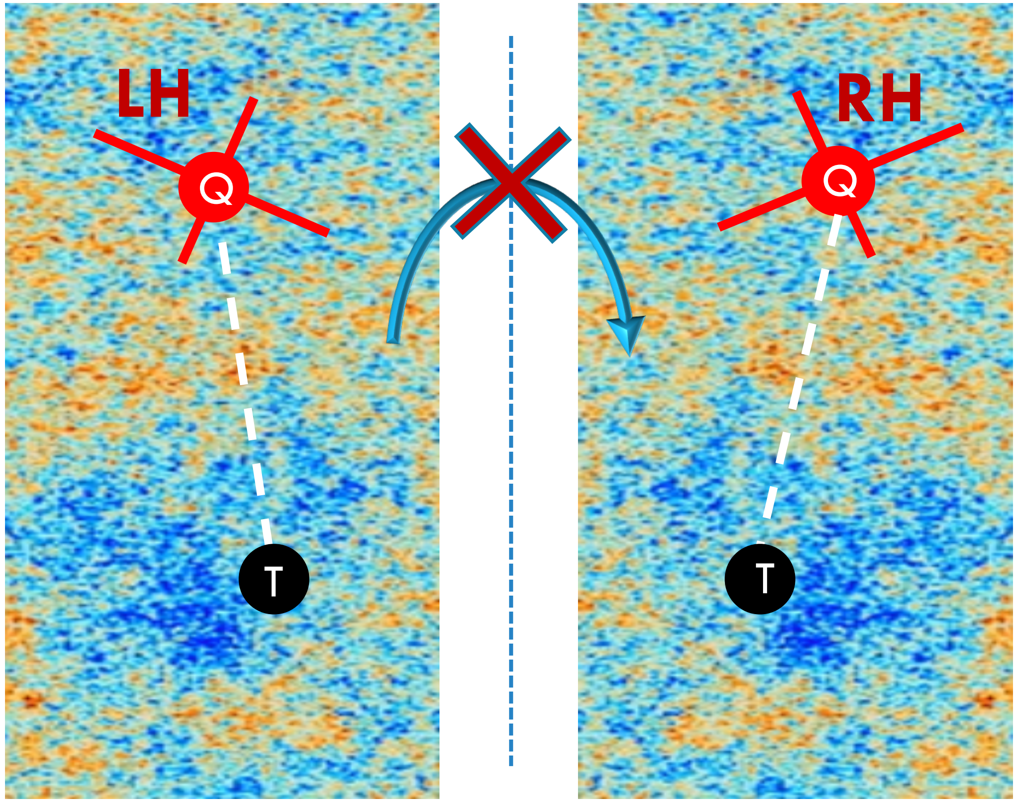
- CMB **polarization** $[E, B]$
- Galaxy **shear** $[\gamma^{E,B}]$
- Galaxy **spins**

Simplest observable

Power Spectrum / 2-Point Function (2PCF)

Parity inversion ≠ rotation

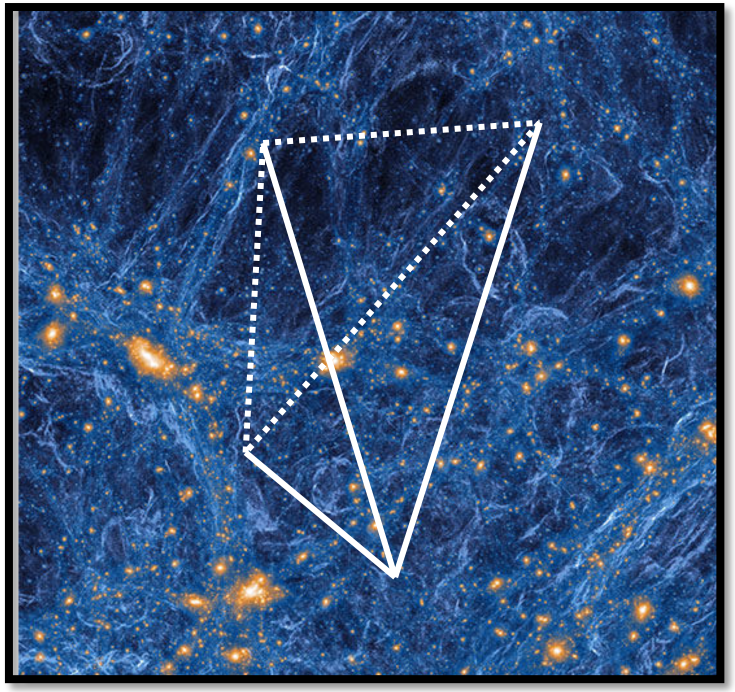
⇒ We can get a signal!



$$C_\ell^{TB} \neq 0$$

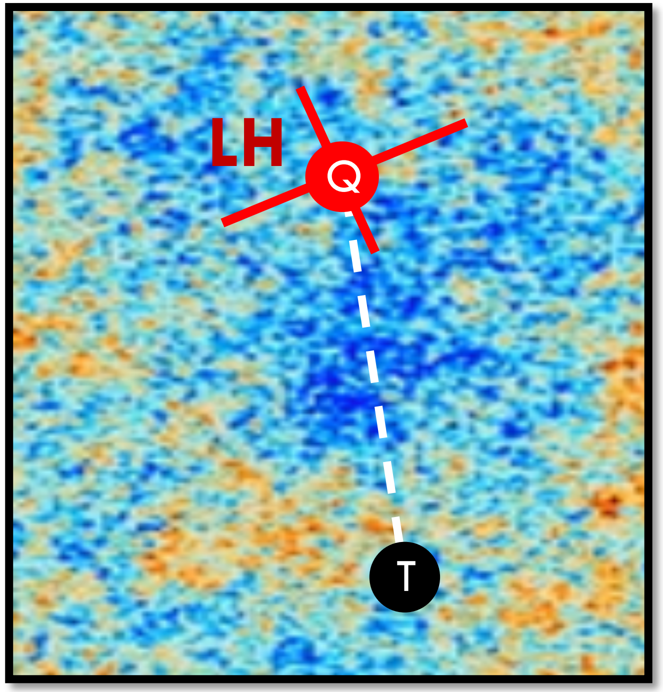
Lue+99, Gluscevic+10, Liu+20, Cahn+21, **Philcox 22**

PARITY SENSITIVE OBSERVABLES



Scalars: $\zeta_4 - \mathbb{P}[\zeta_4]$

Look in galaxy surveys or the CMB!



Tensors: $C_\ell^{TB}, C_\ell^{EB}, B_{\ell_1\ell_2\ell_3}^{TTB}, \ldots$

Look in the CMB and cosmic shear!

OBSERVATION #1: COSMIC BIREFRINGENCE

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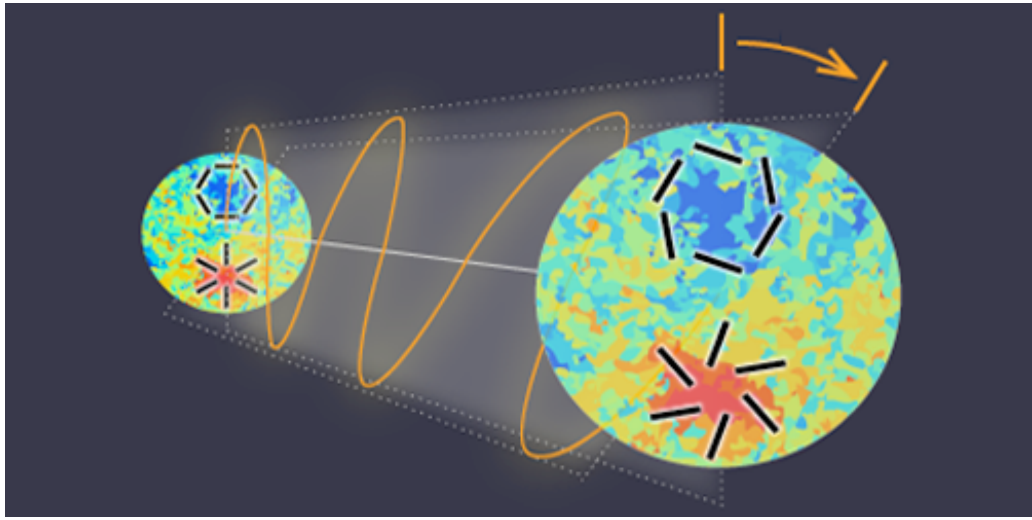
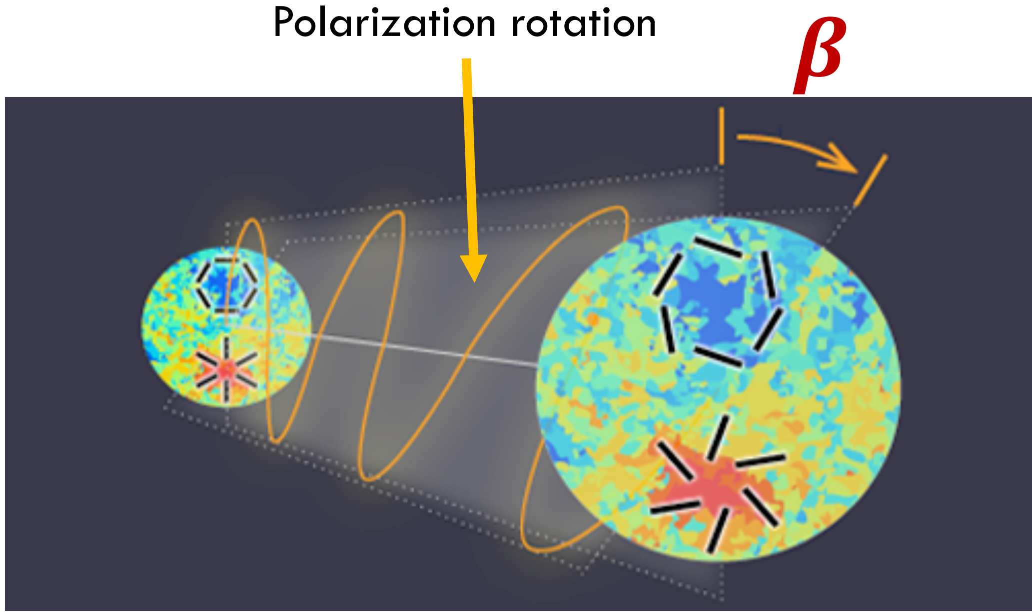


Minami+20, Clark+21, Fujita+22, Diego-Palazuelos+22

OBSERVATION #1: COSMIC BIREFRINGENCE

Hypothesis:

- Emitted CMB is parity-symmetric ($C_\ell^{EB} = 0$)
- Photon polarization plane ***rotated*** at late times
- **E-modes** transformed into **B-modes**
- Observed CMB is ***not*** parity symmetric ($C_\ell^{EB} \neq 0$)



$$C_\ell^{EB} = \frac{1}{2} \sin 4\beta \, (C_\ell^{EE} - C_\ell^{BB})$$

Rotation angle $\boldsymbol{\beta = (0.30 \pm 0.11)^\circ}$ **[2.7σ]**

Minami+20, Clark+21, Fujita+22, Diego-Palazuelos+22

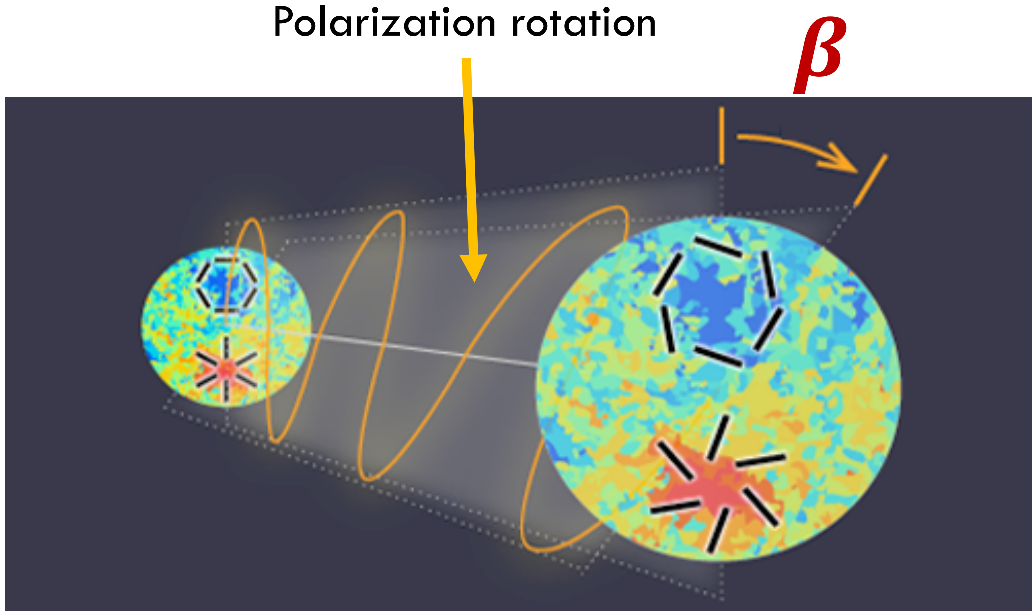
OBSERVATION #1: COSMIC BIREFRINGENCE

CMB photons could be coupled to **axion-like particles** via a **Chern-Simons** coupling

Photon

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Axion



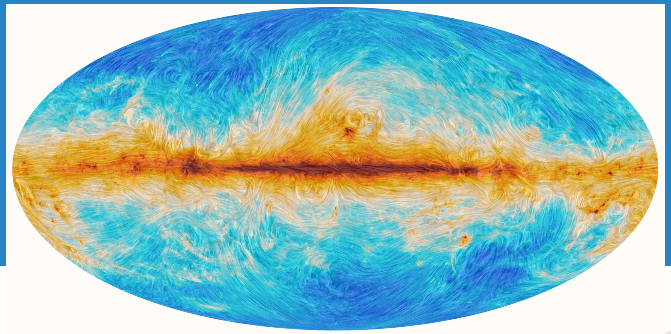
$$C_\ell^{EB} = \frac{1}{2} \sin 4\beta \, (C_\ell^{EE} - C_\ell^{BB})$$

Axion interactions rotate the polarization plane!

$$\beta \propto g_{\phi\gamma} \int \mathrm{d}t \, \dot{\phi} \quad \Rightarrow \quad g_{\phi\gamma} \neq 0 \, ?$$

Minami+20, Turner+88

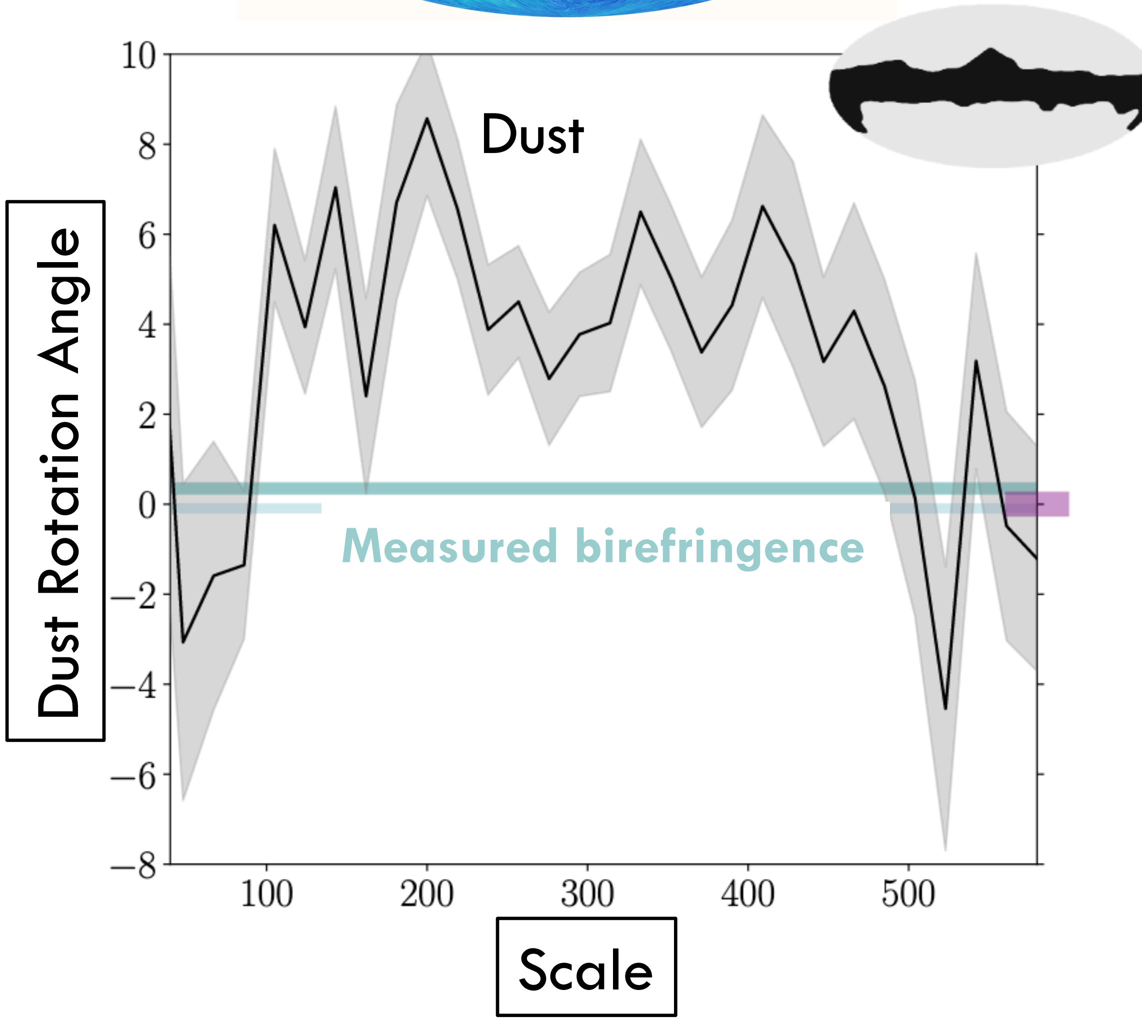
BUT: WHAT ABOUT DUST?



- ▷ Polarized dust emission can **break** parity-symmetry
- ▷ Signal could just be from dust!

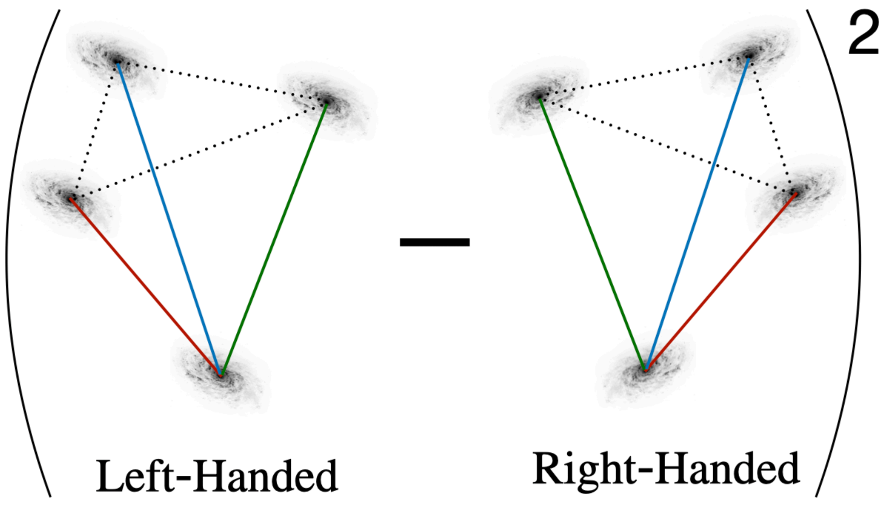
Not resolved yet:

> ***"High-precision CMB data** and a **characterization of dust** beyond the modified blackbody paradigm are needed to obtain a **definitive measurement**…"*
>
> *- Diego-Palazuelos+22*

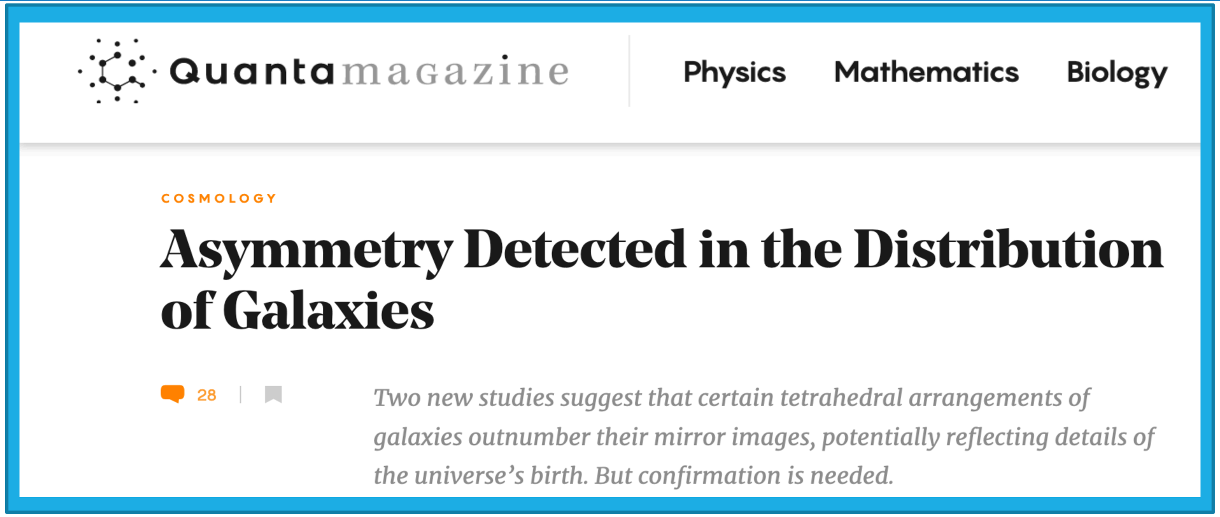


Clark+21, Diego-Palazuelos+22

OBSERVATION #2: GALAXY FOUR-POINT FUNCTIONS



$\zeta_4 - \mathbb{P}[\zeta_4] \neq 0$ in BOSS!


Quantamagazine Physics Mathematics Biology

COSMOLOGY

Asymmetry Detected in the Distribution of Galaxies

28

Two new studies suggest that certain tetrahedral arrangements of galaxies outnumber their mirror images, potentially reflecting details of the universe's birth. But confirmation is needed.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The universe is surprisingly lopsided and we don't know why

Two analyses of a million galaxies show that their distribution may not be symmetrical, which may mean that our understandings of gravity and the early universe are incorrect

Hou+22, **Philcox 22**

THE GALAXY 4-POINT FUNCTION

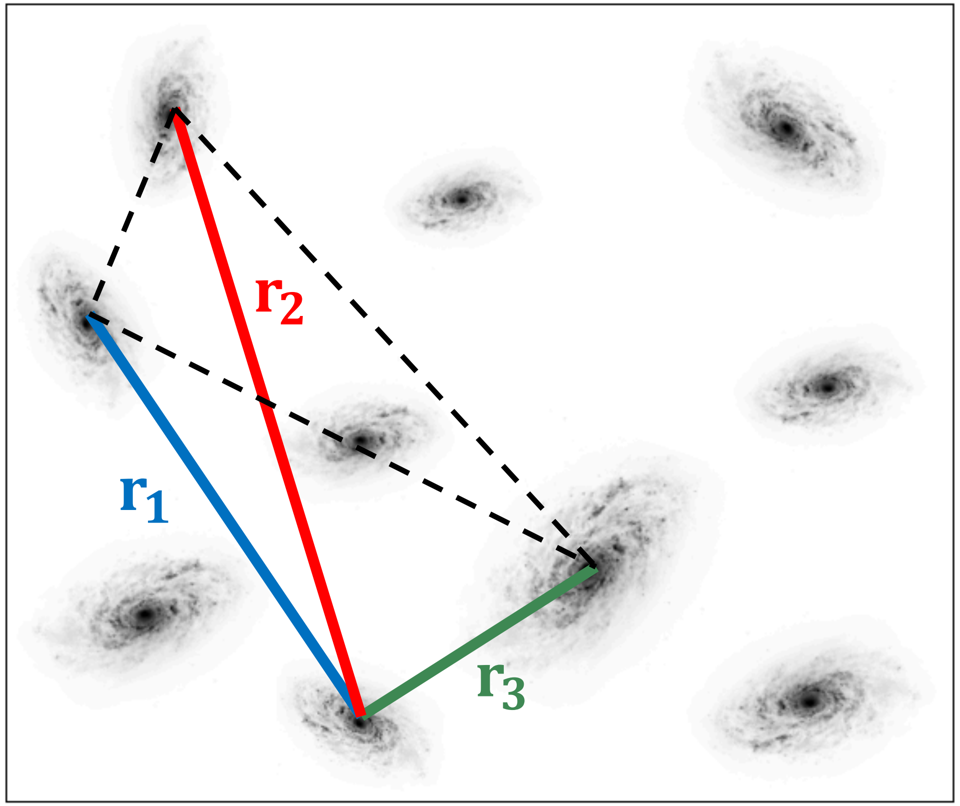
Four-point correlation function (4PCF)

=

Probability of finding a galaxy **tetrahedron** of a given shape

$$\zeta_4(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) = \langle \delta_g(\mathbf{x}) \delta_g(\mathbf{x} + \mathbf{r}_1) \delta_g(\mathbf{x} + \mathbf{r}_2) \delta_g(\mathbf{x} + \mathbf{r}_3) \rangle_c$$

New methods allow this to be computed efficiently!

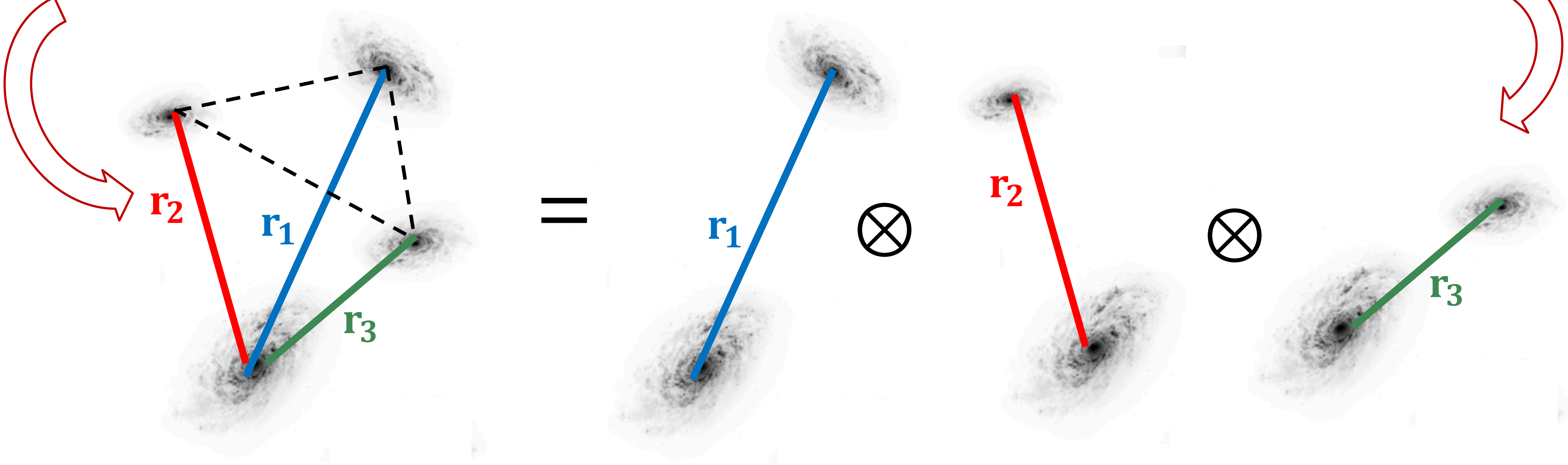


ENCORE, **Philcox**+21ab

ONE TETRAHEDRON = THREE VECTORS

Count up 10^{24} sets of **four** galaxies

Count up 10^{12} sets of **two** galaxies



3 lengths + 3 angles

1 length + 1 direction

1 length + 1 direction

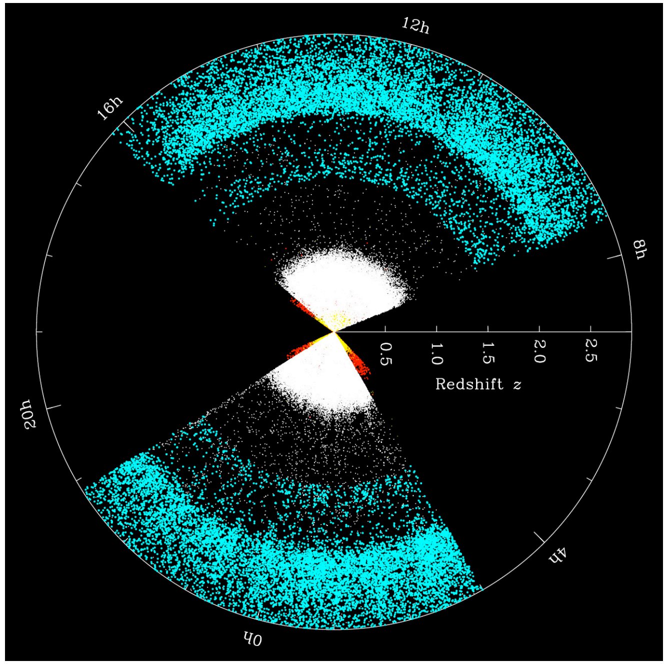
1 length + 1 direction

See GitHub.com/oliverphilcox/encore, GitHub.com/oliverphilcox/NPCFs.jl

ENCORE, **Philcox**+21ab

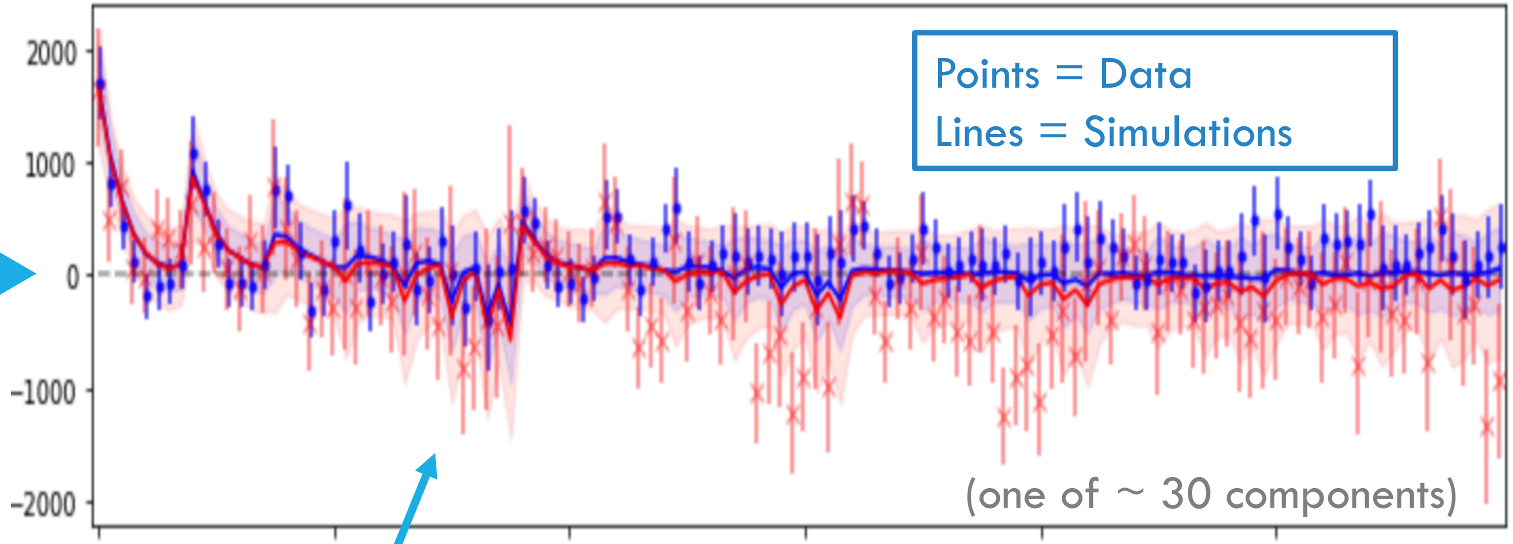
THE OBSERVED FOUR-POINT FUNCTION

We measure the 4PCF from $\approx 10^6$ BOSS CMASS galaxies



Galaxy Positions

Parity-Even Contribution, $\zeta_4 + \mathbb{P}[\zeta_4]$



Increasing Size (20 – 160 Mpc/h)

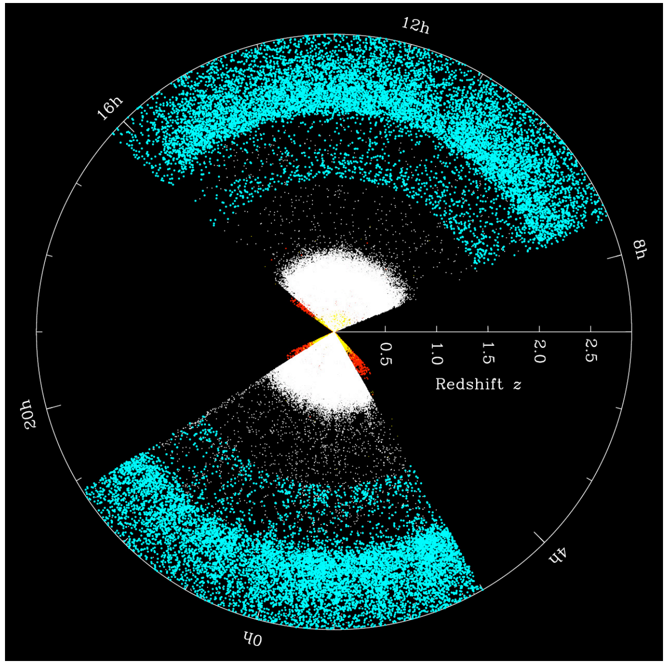
Parity-even gravity contribution!

github.com/oliverphilcox/Parity-Even-4PCF

Philcox+21

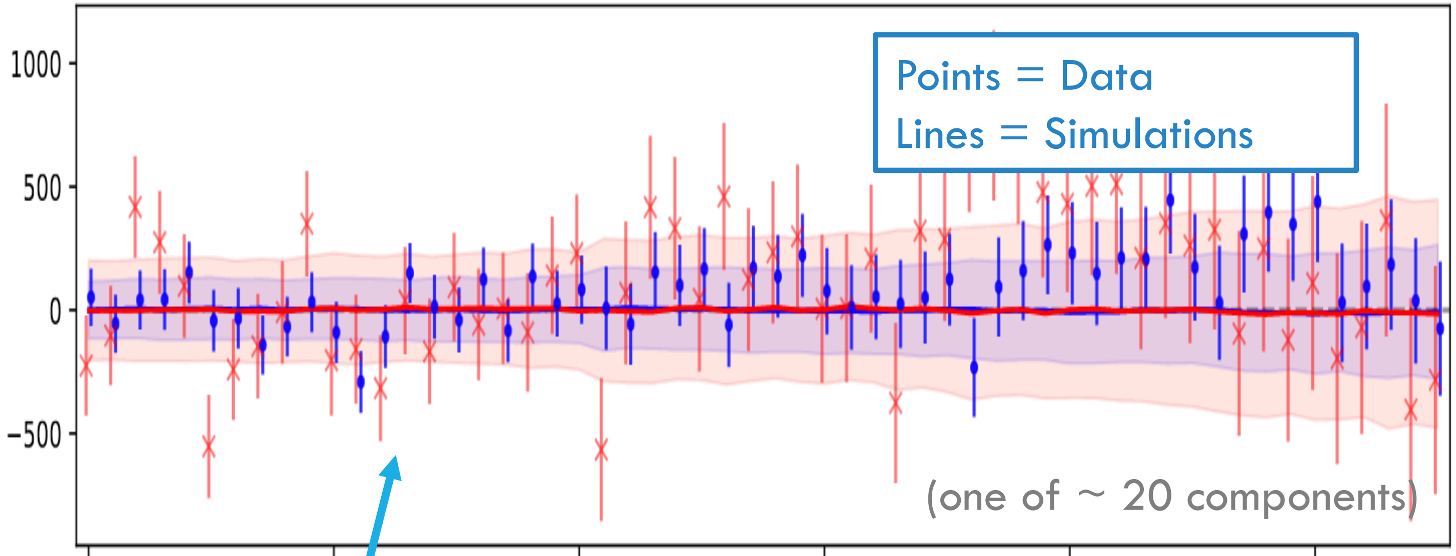
THE OBSERVED FOUR-POINT FUNCTION

We measure the 4PCF from $\approx 10^6$ BOSS CMASS galaxies



Galaxy Positions

Parity-Odd Contribution, $\zeta_4 - \mathbb{P}[\zeta_4]$



Increasing Size (20 – 160 Mpc/h)

Are parity-odd contributions zero??

github.com/oliverphilcox/Parity-Odd-4PCF

Philcox 22, Hou+22

ANALYZING THE 4PCF

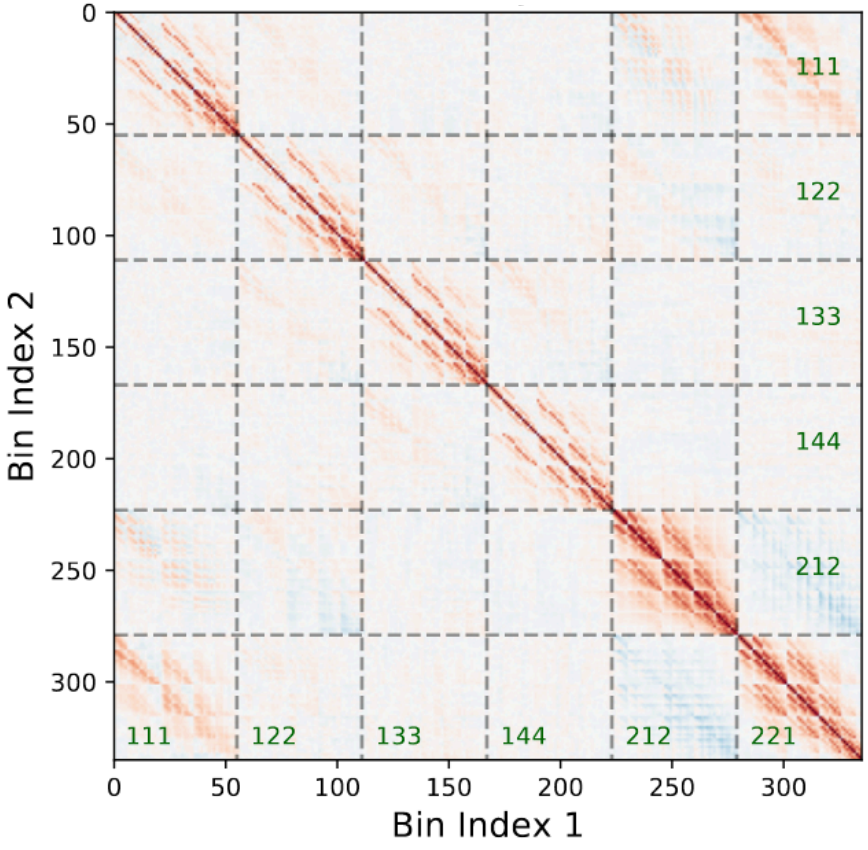
$$\zeta^{\text{odd}} = \frac{1}{2}(\zeta_4 - \mathbb{P}[\zeta_4])$$

- The 4PCF is a **high-dimensional** object with $\sim 10^3$ **correlated** bins

Compute the **detection significance** with a χ^2 test

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

Correlation Matrix



Philcox 22, Hou, **Philcox**+21, Hou+22

ANALYZING THE 4PCF

$$\zeta^{\rm odd} = \frac{1}{2}(\zeta_4 - \mathbb{P}[\zeta_4])$$

- The 4PCF is a **high-dimensional** object with $\sim 10^3$ **correlated** bins

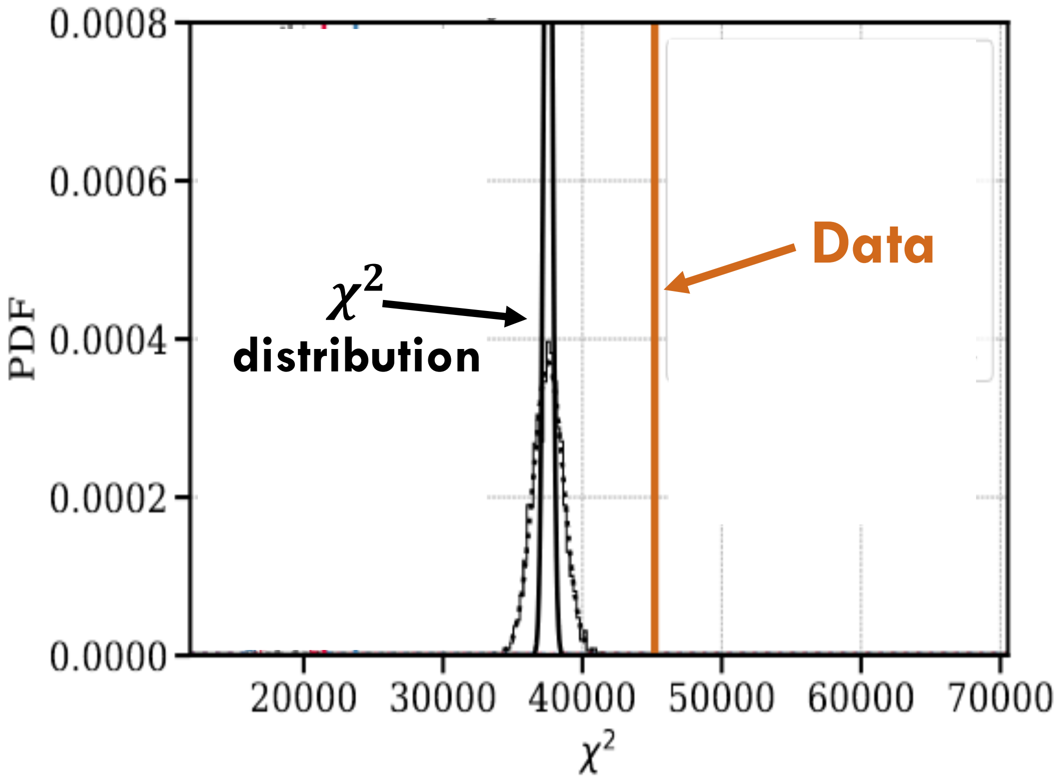
Compute the **detection significance** with a χ^2 test

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

Assumptions

- **Theoretical** covariance matrix is accurate
- Likelihood is **Gaussian**

7.1σ detection???



Hou, **Philcox**+21, Hou+22

ANALYZING THE 4PCF

$$\zeta^{\mathrm{odd}} = \frac{1}{2}(\zeta_4 - \mathbb{P}[\zeta_4])$$

- The 4PCF is a **high-dimensional** object with $\sim 10^3$ **correlated** bins

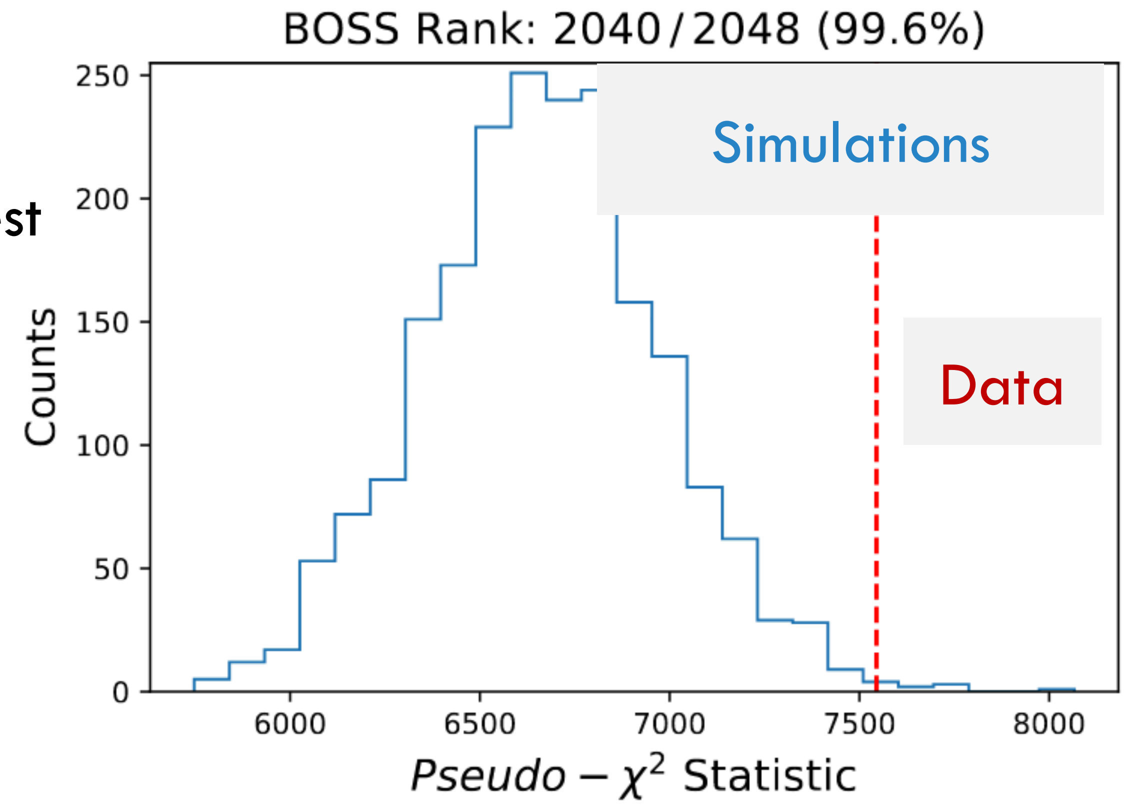
Compute the **detection significance** with a χ^2 test

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

Assumptions

- **Simulation** covariance matrix is accurate
- Likelihood is based on **simulations**

2.9σ detection???



Philcox 22

WHAT CAUSES THE DIFFERENCES?

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

Two analysis of the **same** data at the **same** time get **very** different results

- **Covariance** modelling may be inadequate?

[linear theory, no RSD, no window, imprecise mocks]

- Likelihood might not be **Gaussian**?

[high-dimensional data]

<u>But</u>, both seem to agree there is a signal!

7.1σ detection???

Astrophysics > Cosmology and Nongalactic A...

arXiv:2206.03625 (astro-ph)

[Submitted on 8 Jun 2022]

Measurement of Parity-Odd Modes in the Large-Scale 4-Point Correlation Function of SDSS BOSS DR12 CMASS and LOWZ Galaxies

Jiamin Hou, Zachary Slepian, Robert N. Cahn

2.9σ detection???

Astrophysics > Cosmology and Nongalactic Astrophysics

arXiv:2206.04227 (astro-ph)

[Submitted on 9 Jun 2022 (v1), last revised 29 Jul 2022 (this version, v2)]

Probing Parity-Violation with the Four-Point Correlation Function of BOSS Galaxies

Oliver H. E. Philcox

Philcox 22, Hou+22

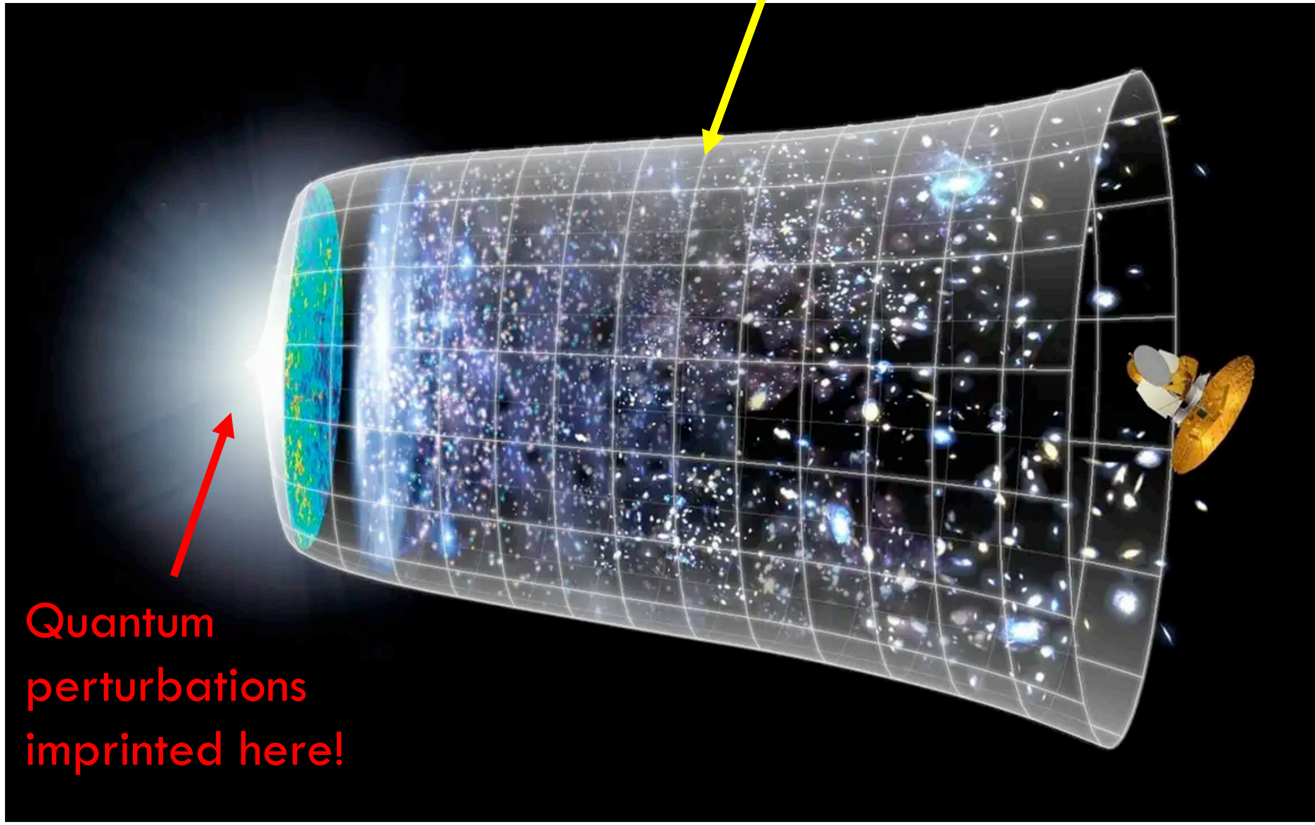
SOURCES OF PARITY VIOLATION

The 4PCF could be sourced

1. **Early:** non-standard inflation?

2. **Late:** modified gravity?

Galaxies have only moved ~ 20 Mpc/h since inflation, so **early** is a more likely scenario!



Cabass, **Philcox**+22

PRIMORDIAL PARITY-VIOLATION

Parity **conservation** if

1. **Scale-invariant** (*i.e.* exact dS)

and

2. **Scalar** fields (or massless spin fields)

and

3. **Bunch-Davies** vacuum

Parity **violation** if

▷ **Not scale-invariant** (*Chern-Simons gravity*)

or

▷ **Massive spinning** fields (*cosmological collider*)

or

▷ **Non-Bunch-Davies** vacuum (*ghost condensate*)

(and many other scenarios)

Cabass+22

PRIMORDIAL PARITY-VIOLATION: GHOSTS

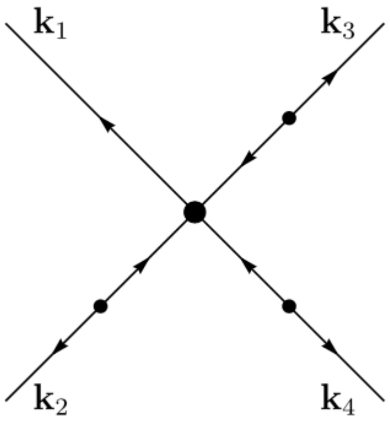
If the inflaton has a **quadratic** dispersion relation, $\omega \propto k^2$

Inflaton

$$S_{\pi\pi} = \int \mathrm{d}^3x\mathrm{d}\eta\, a^4(\eta)\left[\frac{\Lambda^4}{2}\frac{\pi'^2}{a^2(\eta)} - \frac{\tilde{\Lambda}^2}{2}\frac{(\nabla^2\pi)^2}{a^4(\eta)}\right]$$

+ *interactions*

We generate a parity-odd trispectrum!



$$T_\zeta(k_1,k_2,k_3,k_4) \sim \frac{\Lambda^5 H^{\frac{3}{2}}}{\Lambda_{\mathrm{PO}}^2\,\tilde{\Lambda}^{\frac{9}{2}}}\left(\Delta_\zeta^2\right)^3(\mathbf{k_1}\cdot\mathbf{k_2}\times\mathbf{k_3})\ \dots$$

Arkani-Hamed+03, Cabass, **Philcox**+22

PRIMORDIAL PARITY-VIOLATION: COSMOLOGICAL COLLIDER

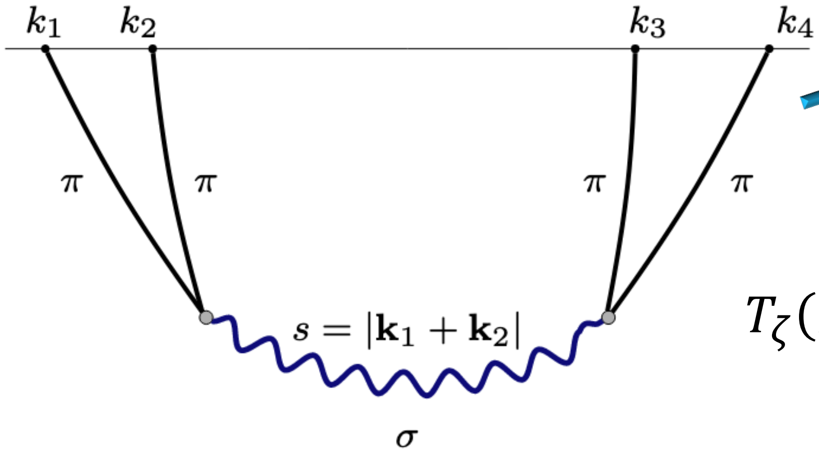
If we **exchange** a **spin-1 particle** during inflation

New Particle

$$S_{\pi\pi\sigma} = \int \mathrm{d}^3x\mathrm{d}\eta \left[\lambda_1 \partial_i \pi' \partial_i \partial_j \pi \sigma^j + \ldots\right.$$

Inflaton

We generate a parity-odd trispectrum!



$$T_\zeta(k_1, k_2, s) \sim c_s^4 \frac{\lambda_1\lambda_3}{H} P_\zeta(k_1) P_\zeta(k_2) P_\sigma(s) (\Delta_\zeta^2) \sin[\pi(\nu + 0.5)] (\mathbf{k_1} \cdot \mathbf{k_2} \times \mathbf{k_3}) \ldots$$

Baumann+10, Cabass+22, Cabass, **Philcox**+22, Creque-Sarbinowski, **Philcox**+ (in prep.)

PRIMORDIAL PARITY-VIOLATION: DYNAMICAL CHERN-SIMONS GRAVITY

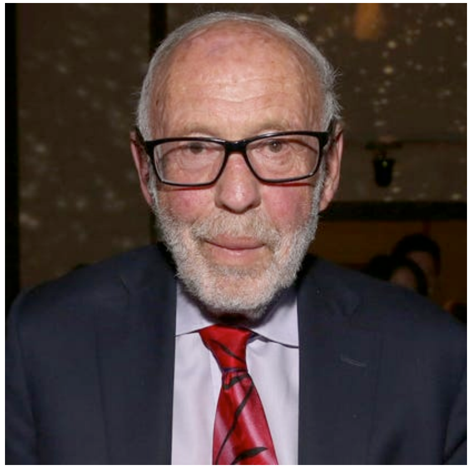
If we **exchange** a **gravitational wave** during inflation

$$S = S_{\rm GR} + \frac{1}{4f}\int d^4x\sqrt{-g}\,\phi\,{}^*RR$$

Gravity

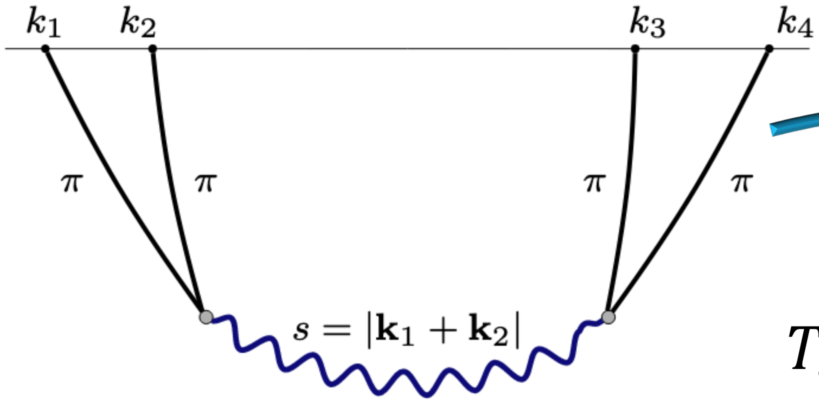
Inflaton

CS Coupling



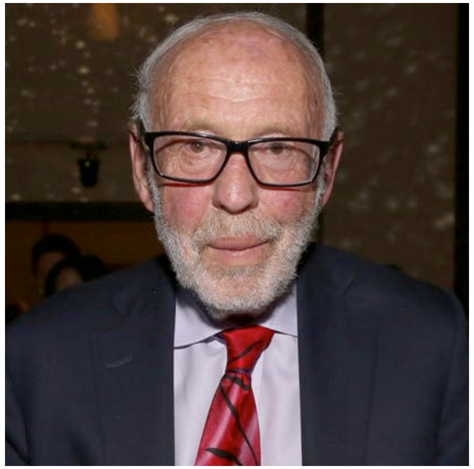
NB:
Jim is remarkably parity-symmetric

We generate a parity-odd trispectrum!



Gravitational Wave

$$T_\zeta(k_1, k_2, s) \sim \frac{1}{f}\, P_\zeta(k_1) P_\zeta(k_2) [r\, P_\zeta(s)]\, \ldots$$



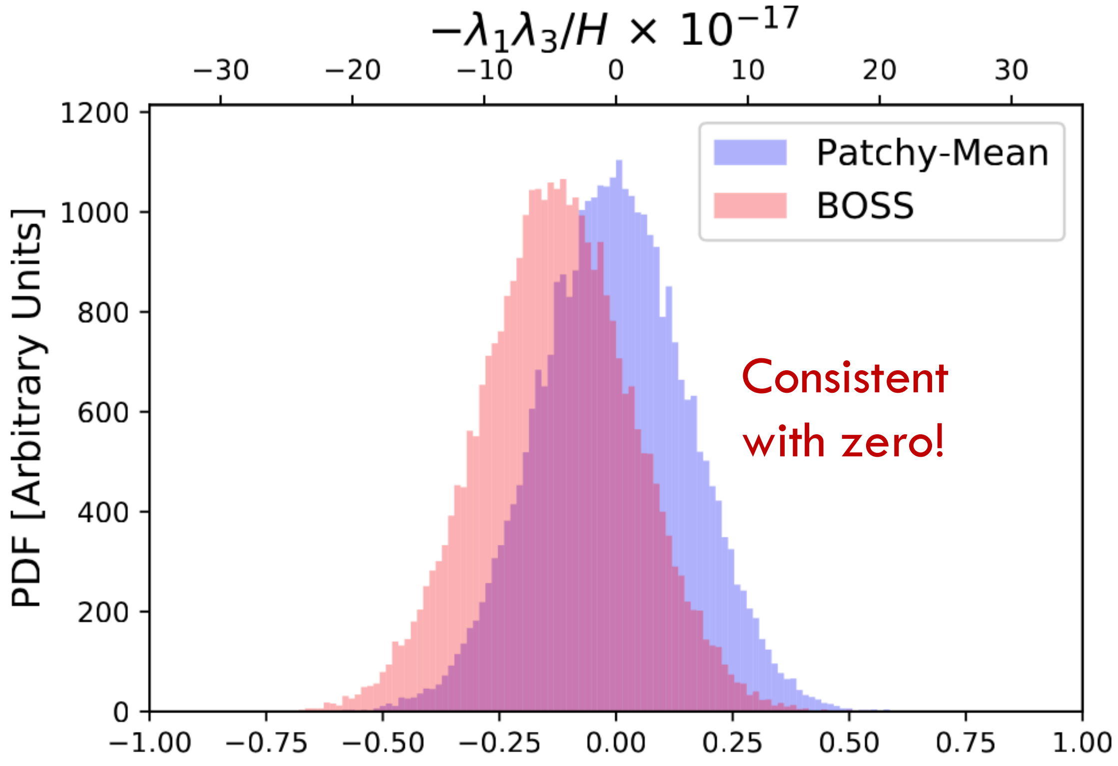
Creque-Sarbinowski, **Philcox**+ (in prep.)

ARE THESE RESPONSIBLE FOR THE PARITY-ODD SIGNAL?

- We can **predict** the galaxy 4PCF from the **primordial trispectrum***

- Does this match the BOSS signal?

No evidence for an inflationary source from the 18 models we tried…



Collider Amplitude

Consistent with zero!

*with lots of effort. Note we ignore non-linear effects + bias…

Baumann+10, Cabass, **Philcox**+22

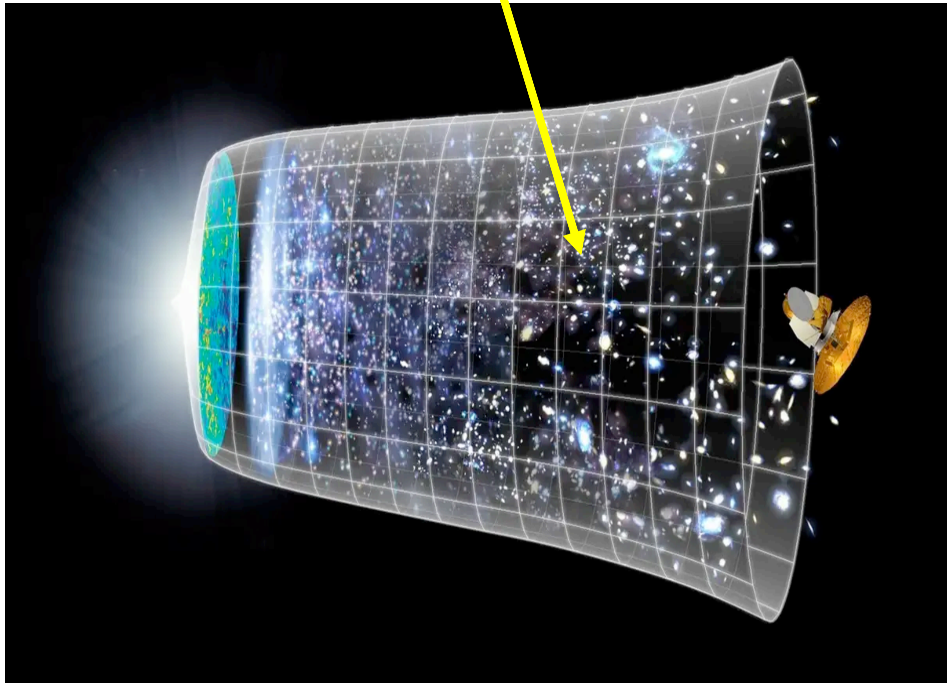
LATE-TIME PARITY VIOLATION

Non-linear gravitational evolution here!

Could the **same** physics be responsible for **birefringence** and **4PCFs**?

- **Unlikely!**
- Chern-Simons couplings affect photon **polarization**
- We observe galaxy **intensity,** which **isn't** affected

In general, **late-time** sources would mainly affect **small scales** – but our signal is at $r > 20$ Mpc/h



Cabass, **Philcox**+22

WHAT'S RESPONSIBLE FOR THE SIGNAL?

Cosmological options

- Some other model of inflation
- Late-time physics with **large** characteristic scale

Non-cosmological options

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

Errors in the mask?
[mocks are unbiased]

Errors in the fiber collisions?
[mocks are unbiased]

Errors in the selection function?
[shouldn't violate parity]

Other systematics?
[very possible]

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

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

Errors in the covariance?
[analytic modeling insufficient?]

Errors in the likelihood?
[non-Gaussianity is likely!]

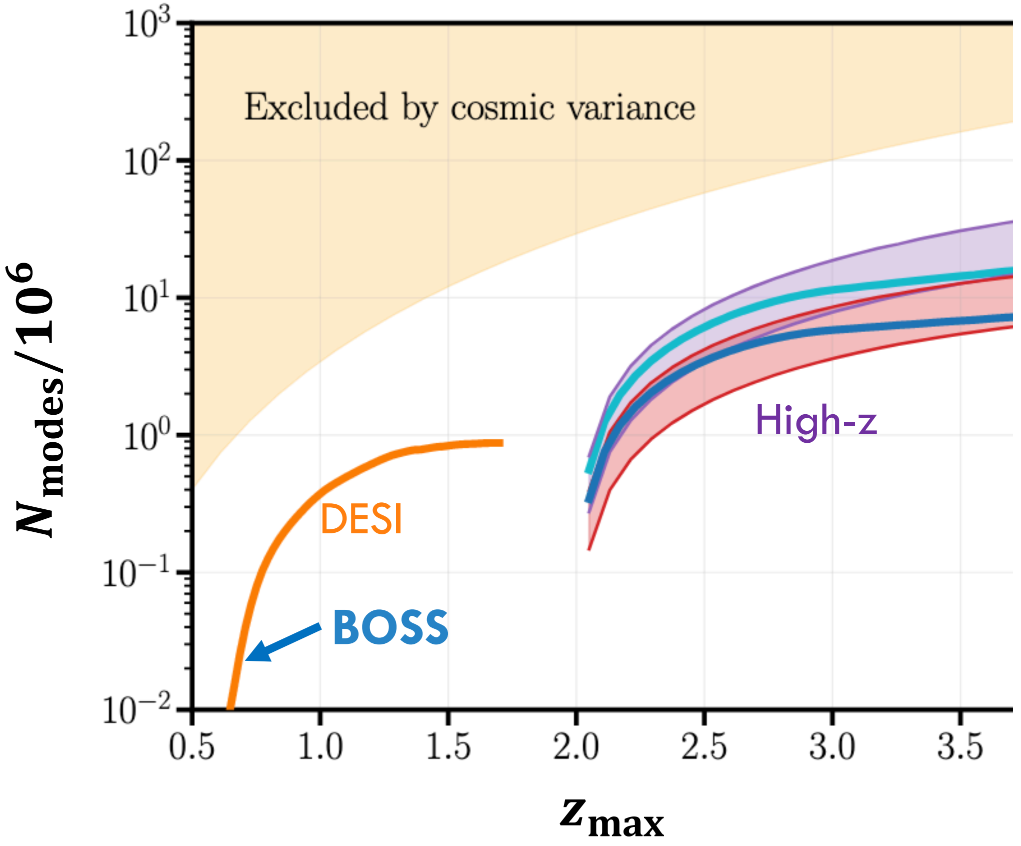
Errors in the simulations?
[do our mocks reproduce the noise properties of the data?]

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

WHAT'S NEXT? (LSS)

- New data from DESI, SPHEREx, Euclid, etc. will **significantly** reduce error-bars

- ***<u>But</u>* systematics might not go away!**



Ferraro+19

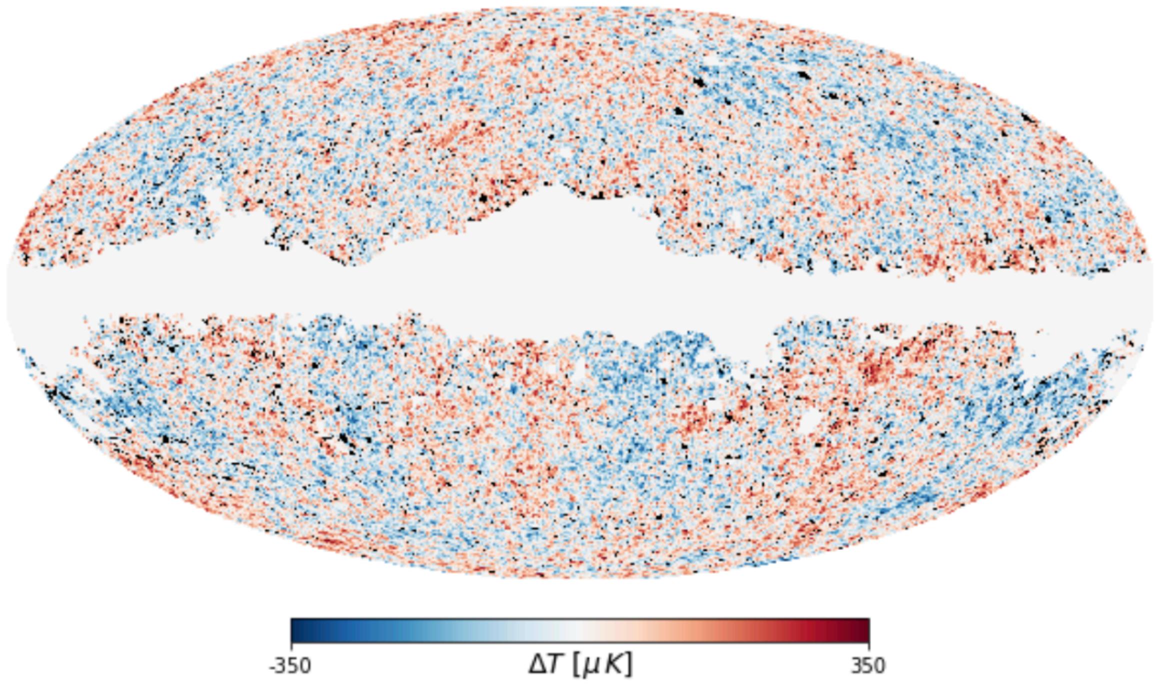
WHAT'S NEXT? (CMB)

The CMB can also probe scalar parity-violation

- Constrain with the large-scale ($\ell < 500$) **temperature trispectrum**

$$t^{\ell_1\ell_2}_{\ell_3\ell_4}(L) \sim \left\langle \prod_{i=1}^{4} a_{\ell_i m_i} \right\rangle^{\text{odd}}$$

- Measure this from **Planck**!



Philcox (in prep. x2)

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Advantages of the CMB

- Gaussian statistics
- More modes [for now]
- More linear
- No galaxy bias
- Better simulations

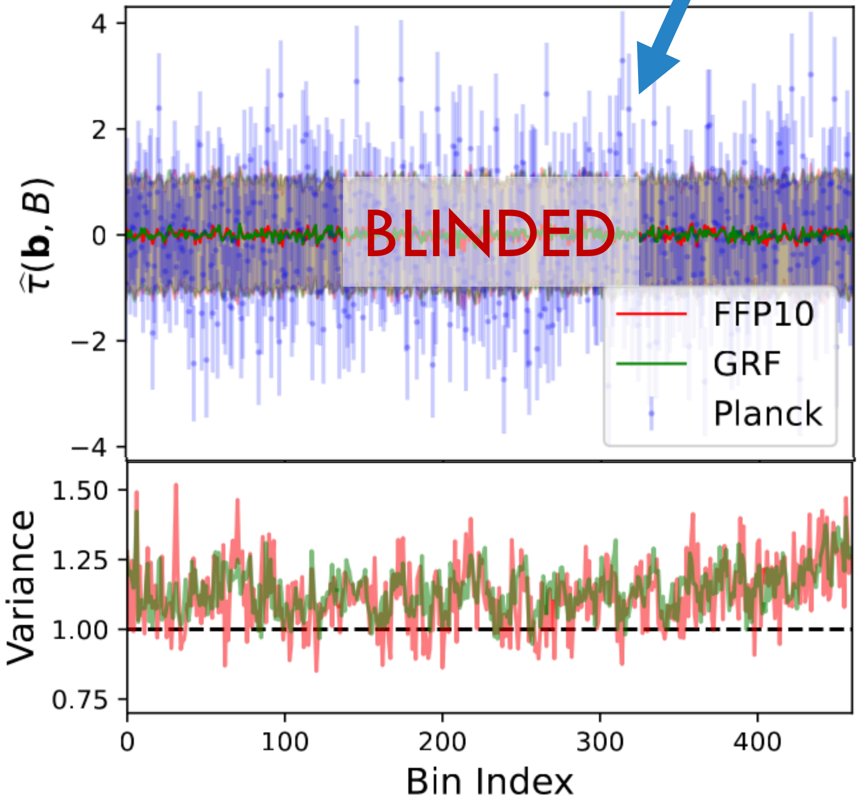
Philcox (in prep. x2)

CMB PARITY VIOLATION

▷ The CMB measures the *reduced trispectrum*

$$\left\langle \prod_{i=1}^{4} a_{\ell_i m_i} \right\rangle_c \equiv \sum_{LM} (-1)^M w^{L(-M)}_{\ell_1\ell_2 m_1 m_2} w^{LM}_{\ell_3\ell_4 m_3 m_4} t^{\ell_1\ell_2}_{\ell_3\ell_4}(L) + 23 \text{ perms.} \quad (1)$$

▷ Extract this with new **optimal** estimators with **Fisher matrix** weighting



Very close to optimal!

Philcox (in prep. x2) Regan+10

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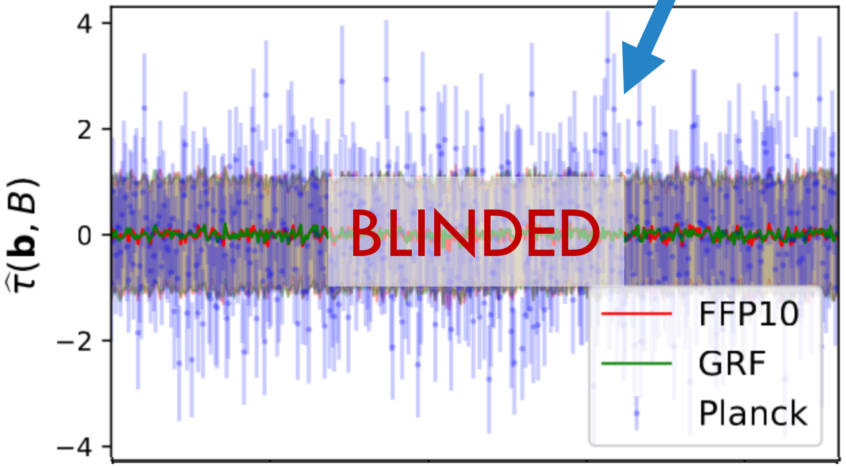
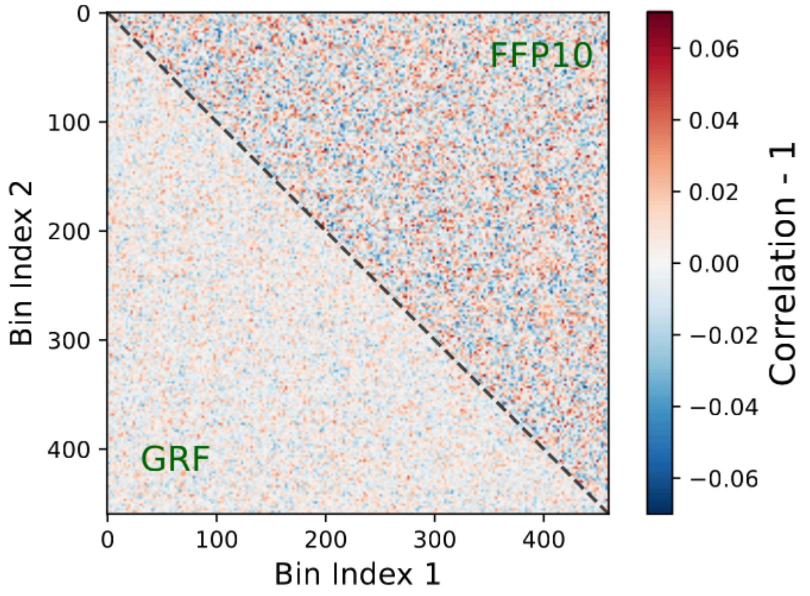
- Extract this with new **optimal** estimators with **Fisher matrix** weighting
  - Rescaled covariance is almost perfectly diagonal!





Philcox (in prep. x2) Regan+10

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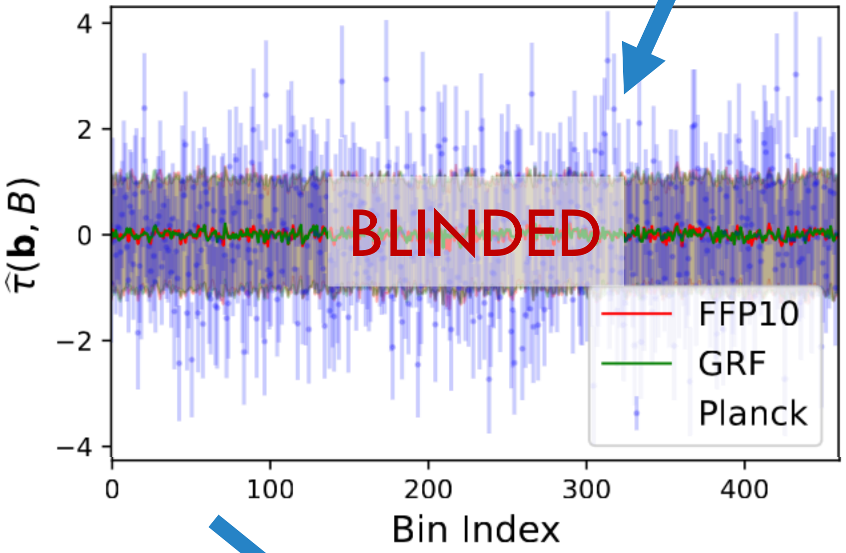
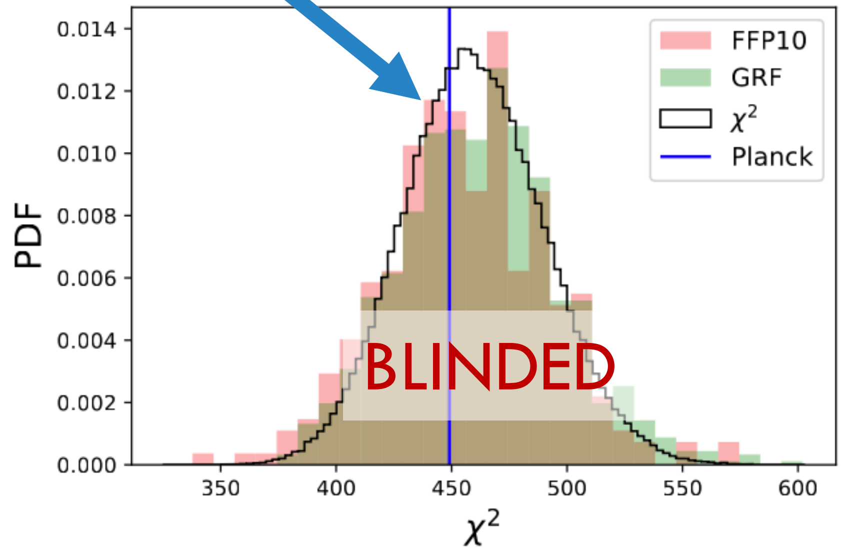
- Extract this with new **optimal** estimators with **Fisher matrix** weighting
  - Rescaled covariance is almost perfectly diagonal!
- Do we detect parity violation?

Wait and see…





Philcox (in prep. x2) Regan+10

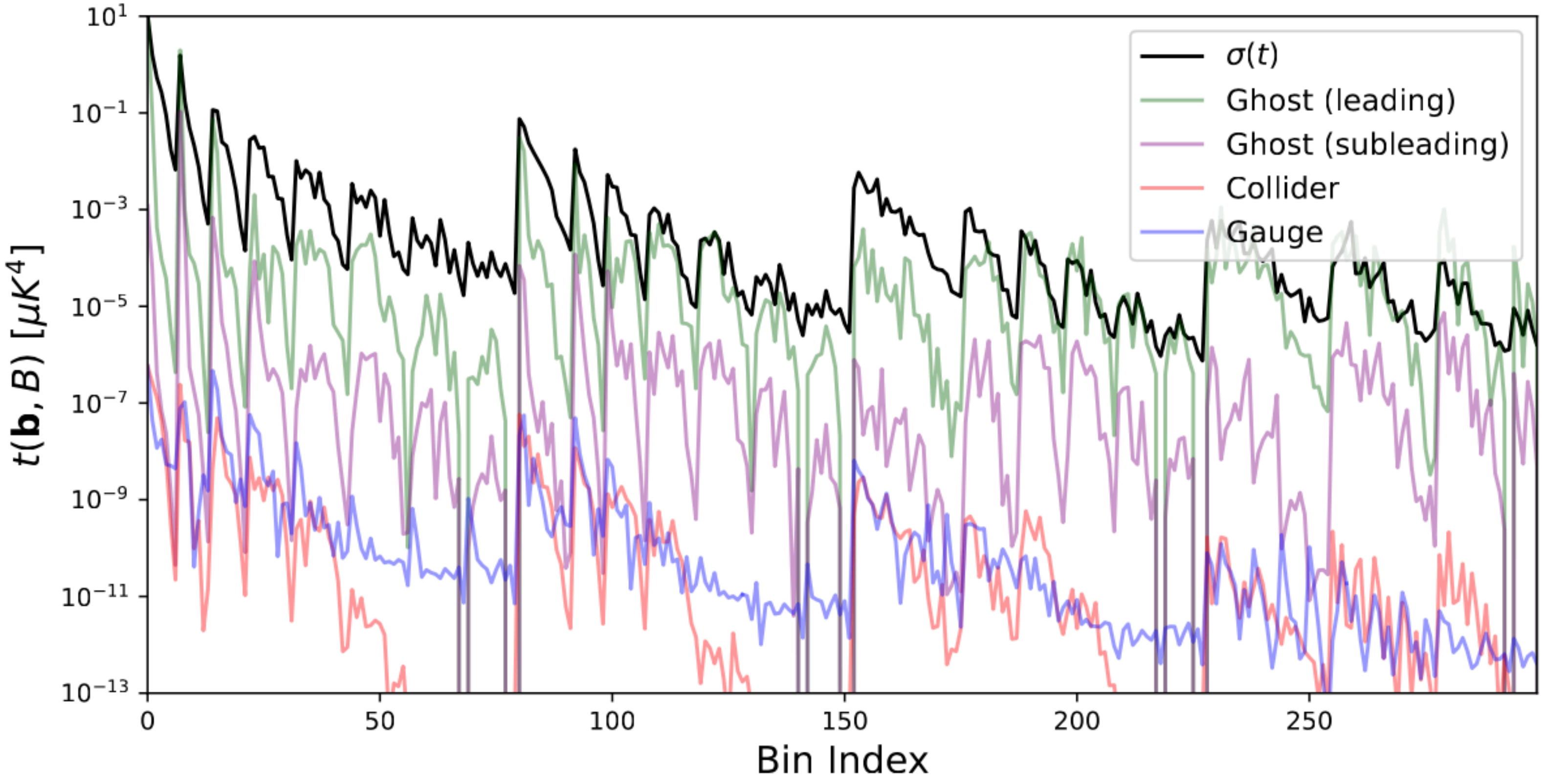
MODEL CONSTRAINTS

Observation

Theoretical models can be constrained as for LSS:

$$\left\langle \prod_{i=1}^{4} a_{\ell_i m_i} \right\rangle_c = (4\pi)^4 \left[\prod_{i=1}^{4} i^{\ell_i} \int_{\mathbf{k}_i} \mathcal{T}_{\ell_i}(k_i) Y^*_{\ell_i m_i}(\hat{\mathbf{k}}_i)\right] (4)$$
$$\times T_\zeta(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)(2\pi)^3 \delta_D(\mathbf{k}_{1234}),$$

Theory



Philcox (in prep.)

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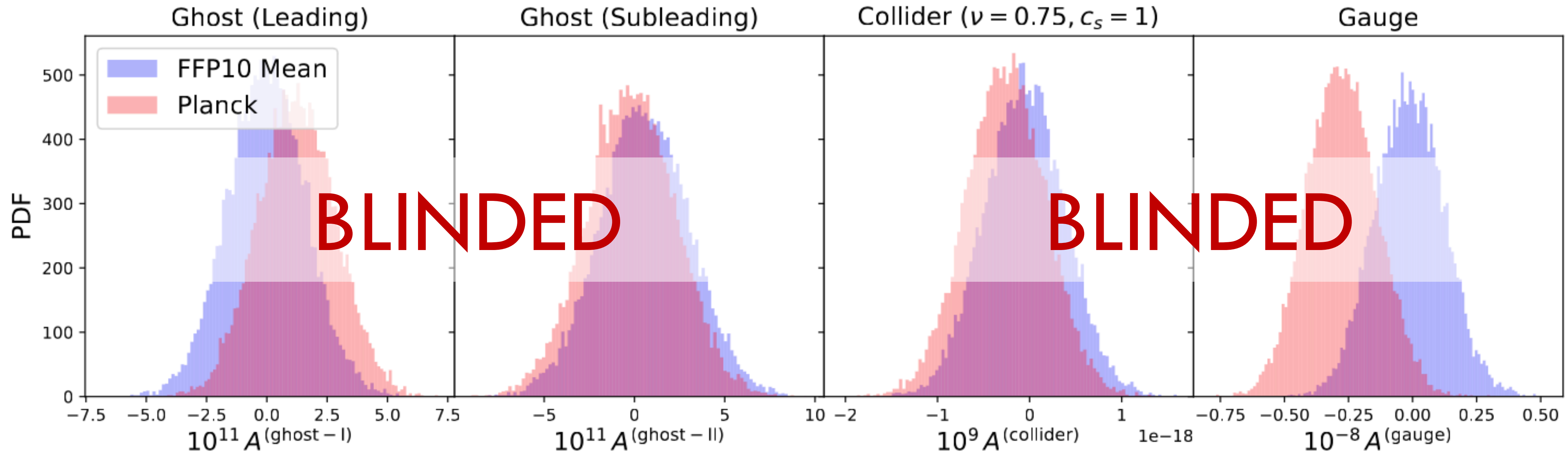
Theory



Philcox (in prep.)

arXiv

2011.11254

2210.07655

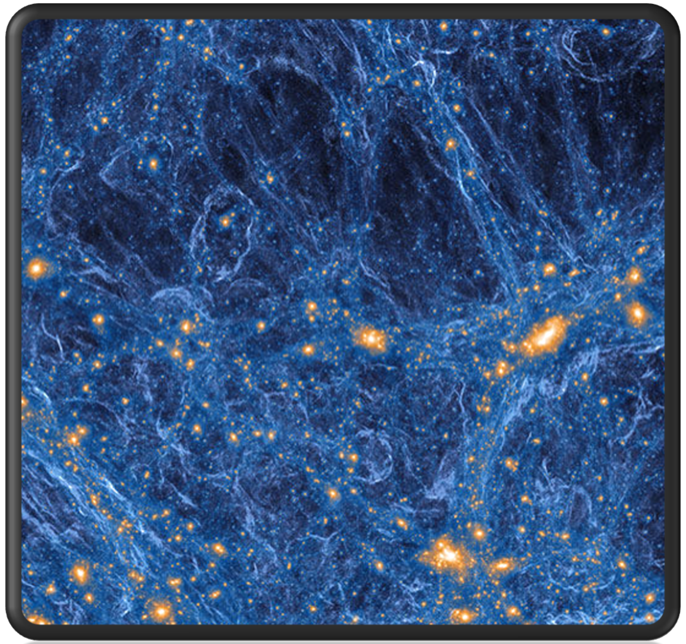
2206.04227

2206.03625

2210.02907

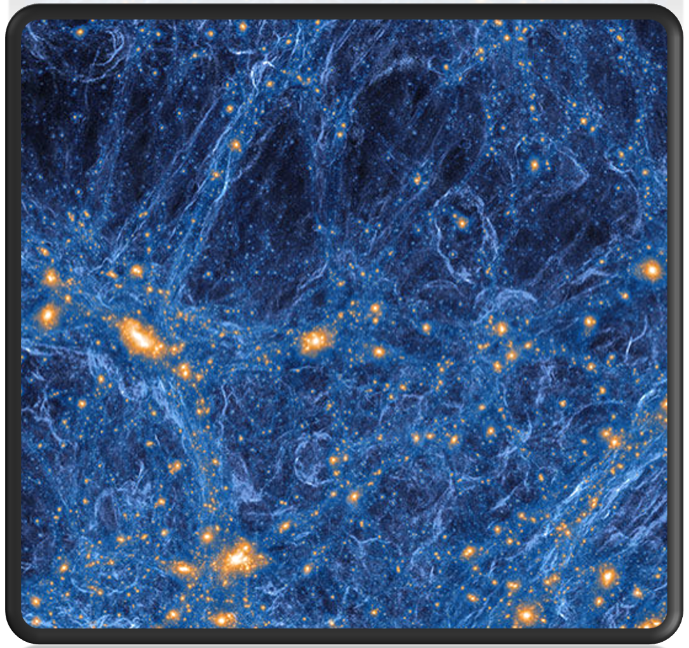
Coming soon (x3)

CONCLUSIONS



- New observations may hint at **parity-violation** in the Universe
- If true, this would imply **new physics** in **inflation** and/or the **late Universe**
- But, could also be explained by **dust** and **imperfect analyses.**

New CMB results coming soon!



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