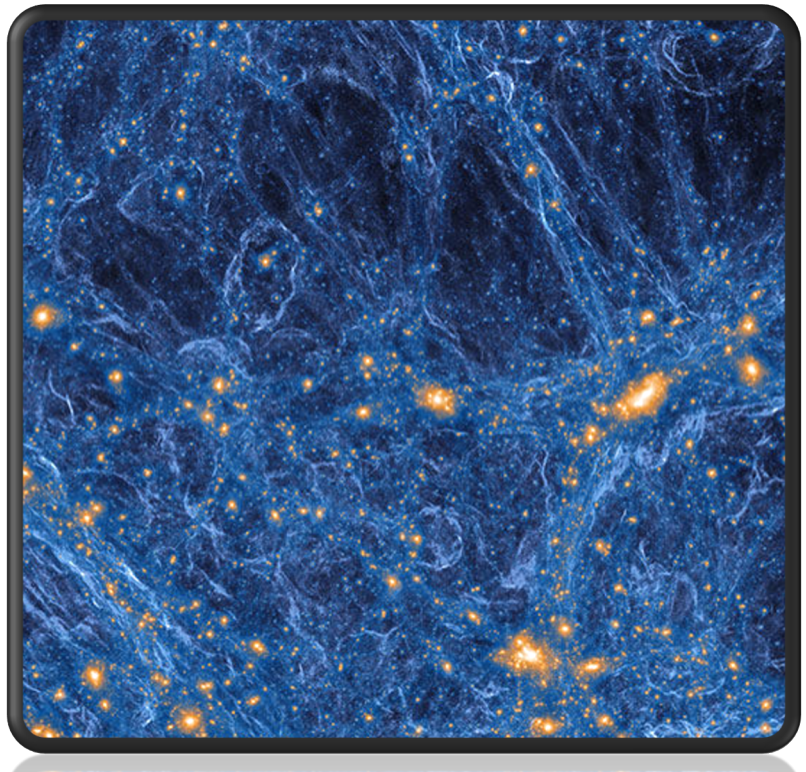
SIMONS FOUNDATION

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



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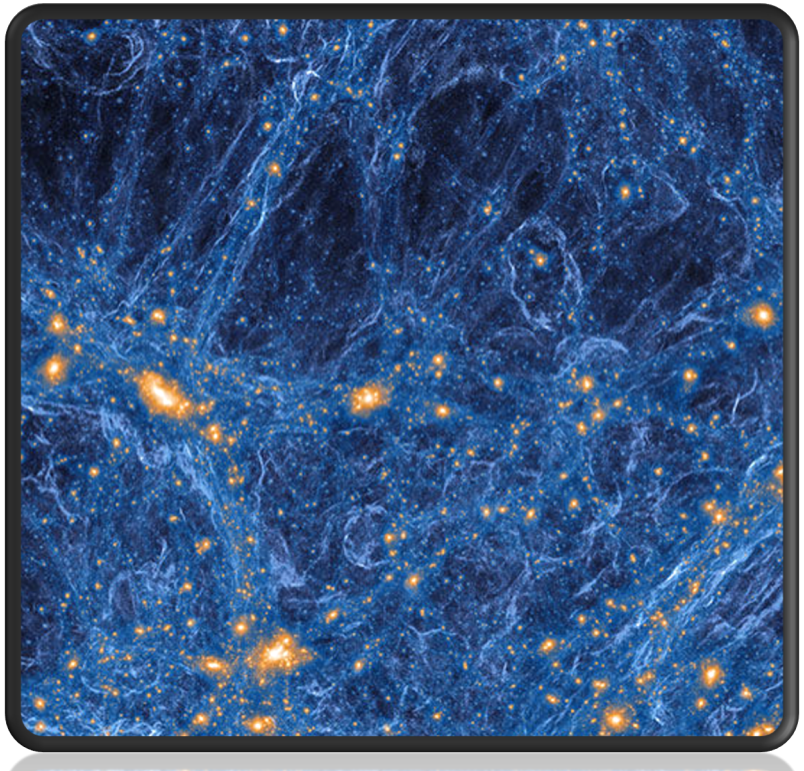


?

Hints of Cosmological Parity Violation

Oliver Philcox (Columbia / Simons Foundation)

HEP/Astro Results Forum, October 2022

November 2020

Parity-Violation from the CMB?

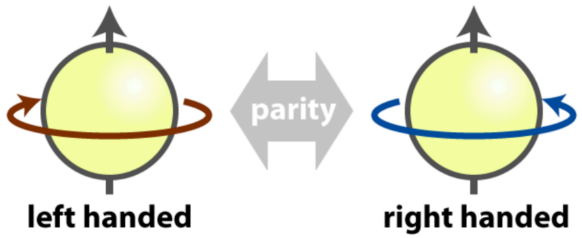
June 2022

Parity-Violation from Galaxies?

Minami+20, Philcox 22, Hou+22

PARITY SYMMETRY IN PHYSICS

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



$$\mathbb{P}[f(x_1, x_2, \dots)] = f(-x_1, -x_2, \dots)$$

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

(+ reverse time)

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

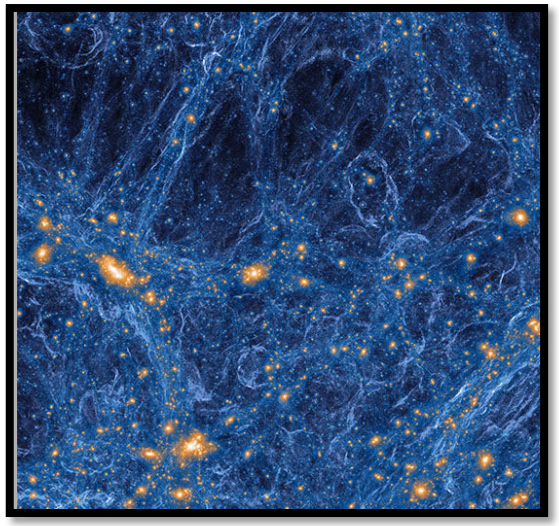
PARITY SYMMETRY IN COSMOLOGY

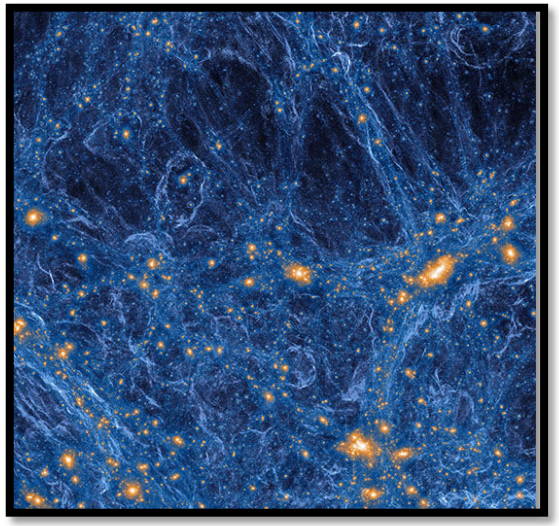
Large-scale cosmology is controlled by **GR:**

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

⇒ Cosmology should be **parity-symmetric**

$$\mathbb{P}[f(x_1, x_2, \dots)] = f(x_1, x_2, \dots)$$



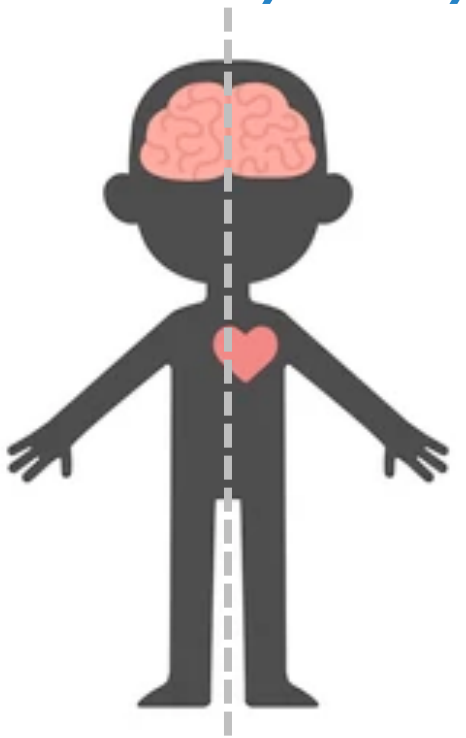


These should be **statistically indistinguishable!**

PARITY-VIOLATION EXISTS IN NATURE

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

No mirror symmetry!



- **Baryogenesis** violates charge-parity symmetry

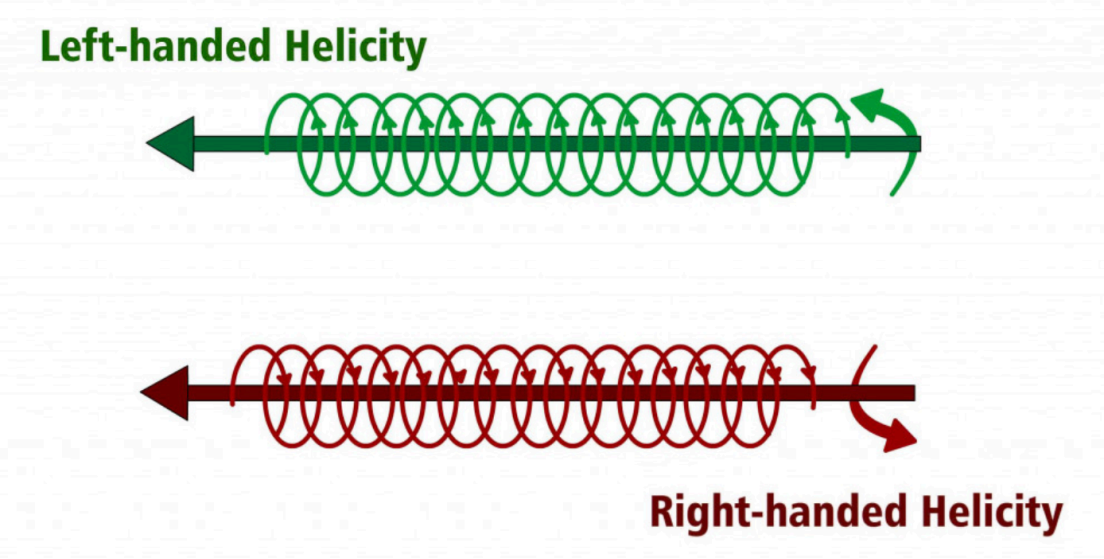
$$n_{\text{Baryon}} \neq n_{\text{Anti-Baryon}}$$

Non-Gravitational Physics can break parity invariance

Sakharov 67

PARITY-VIOLATION IN COSMOLOGY

- **Where could parity-violation come from?**
  - Cosmic Inflation
  - Reheating
  - Exotic late-time physics



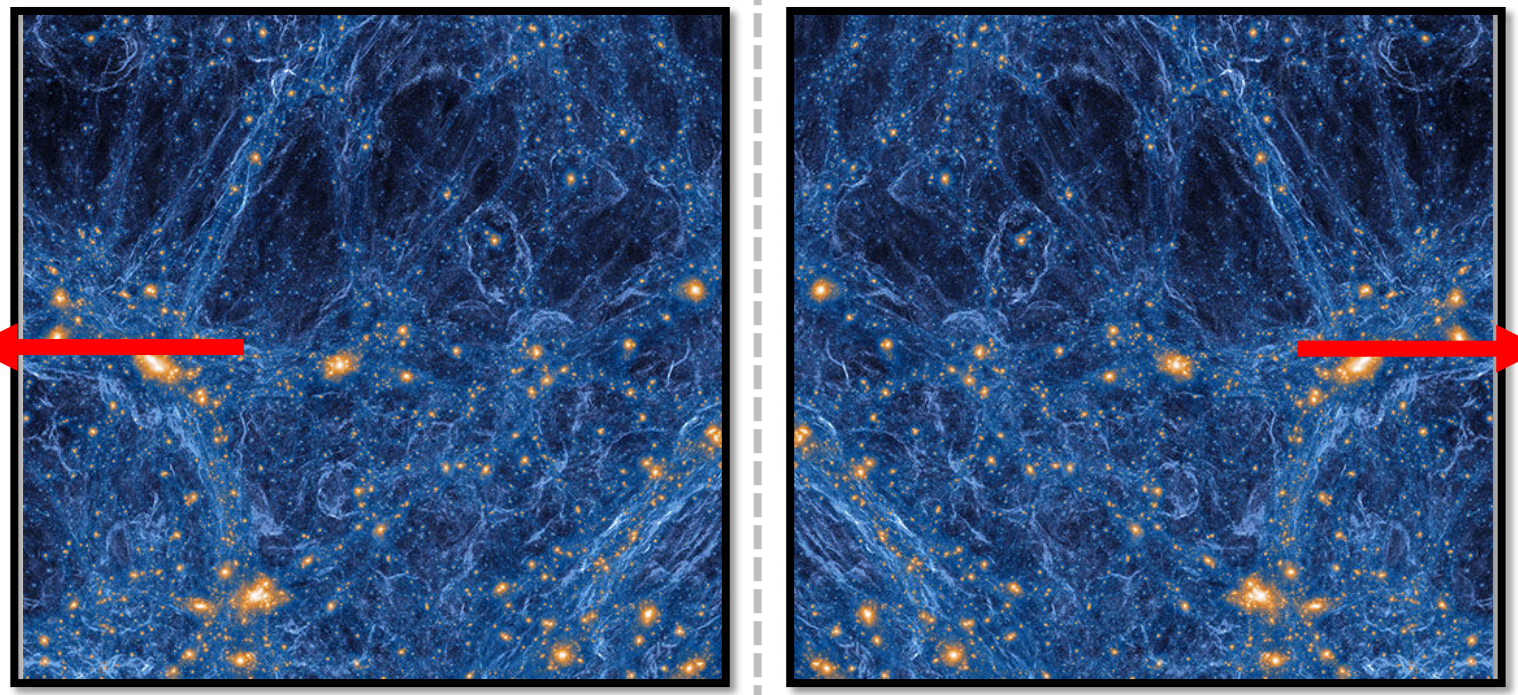
Usually, this requires vectors / tensors!

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

Lue+99, Cabass+22

HOW TO SEARCH FOR PARITY VIOLATION

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



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

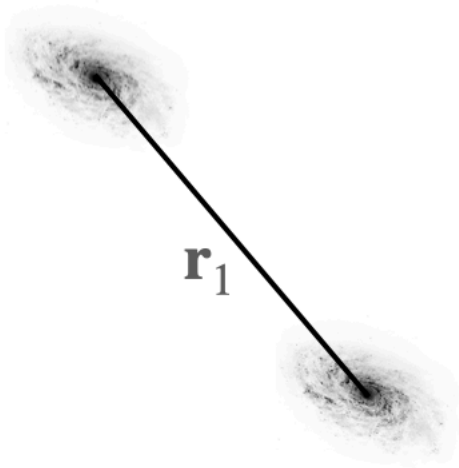
Which statistics are sensitive to parity?

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

SEARCHING FOR SCALAR PARITY VIOLATION

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

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



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

SEARCHING FOR SCALAR PARITY VIOLATION

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- CMB **temperature** [T]

Simplest observable

Power Spectrum / 2-Point Function (2PCF)

But *parity inversion = rotation*

⇒ No signal!

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

SEARCHING FOR SCALAR PARITY VIOLATION

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

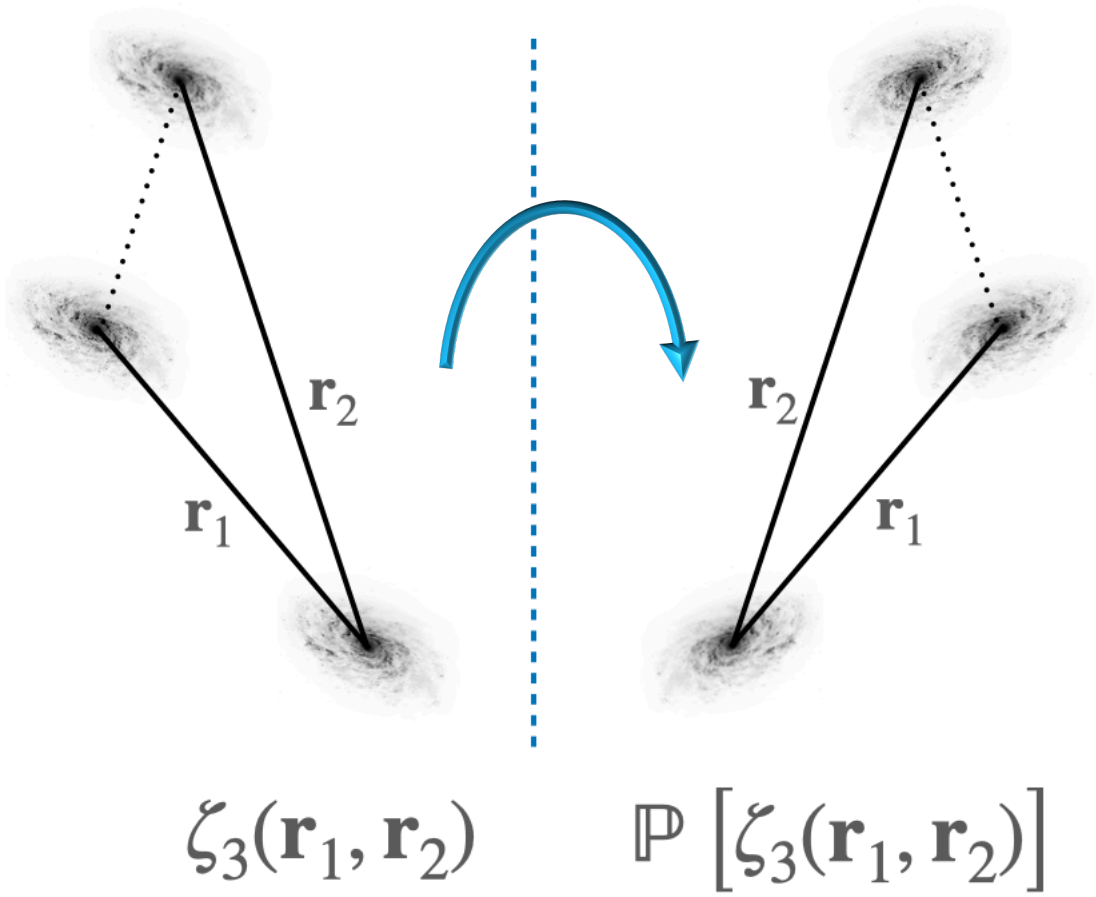
- Galaxy **overdensity** [δ_g]
- CMB **temperature** [T]

Next observable

Bispectrum / 3-Point Function (3PCF)

Still *parity inversion = rotation*

⇒ *No signal!*



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SEARCHING FOR SCALAR PARITY VIOLATION

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

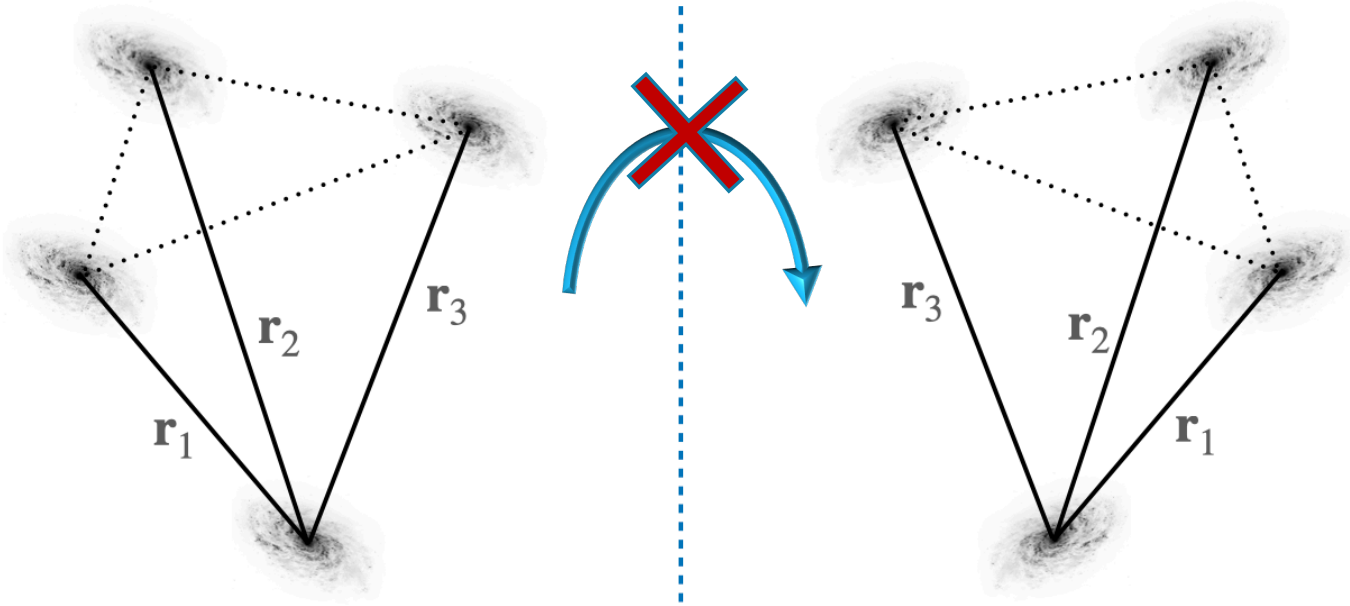
- Galaxy **overdensity** [δ_g]
- CMB **temperature** [T]

Next next observable

Trispectrum / 4-Point Function (4PCF)

Finally *parity inversion ≠ rotation*

⇒ *We can get a signal!*

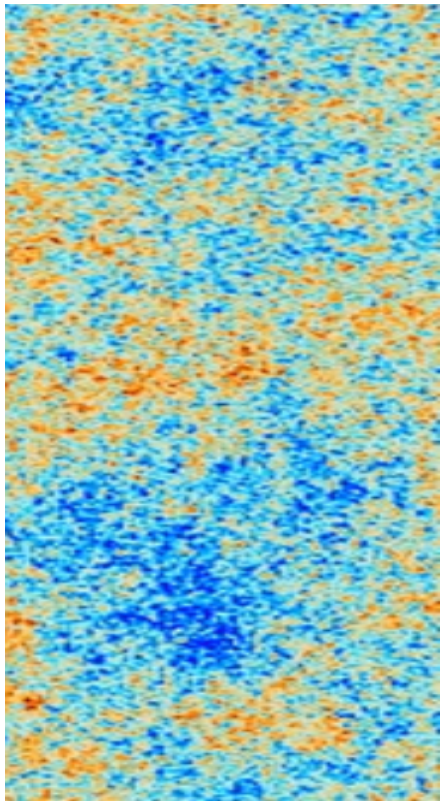


Lue+99, Gluscevic+10, Liu+20, Cahn+21, Philcox 22

SEARCHING FOR TENSOR PARITY VIOLATION

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

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



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- CMB **polarization** $[E, B]$
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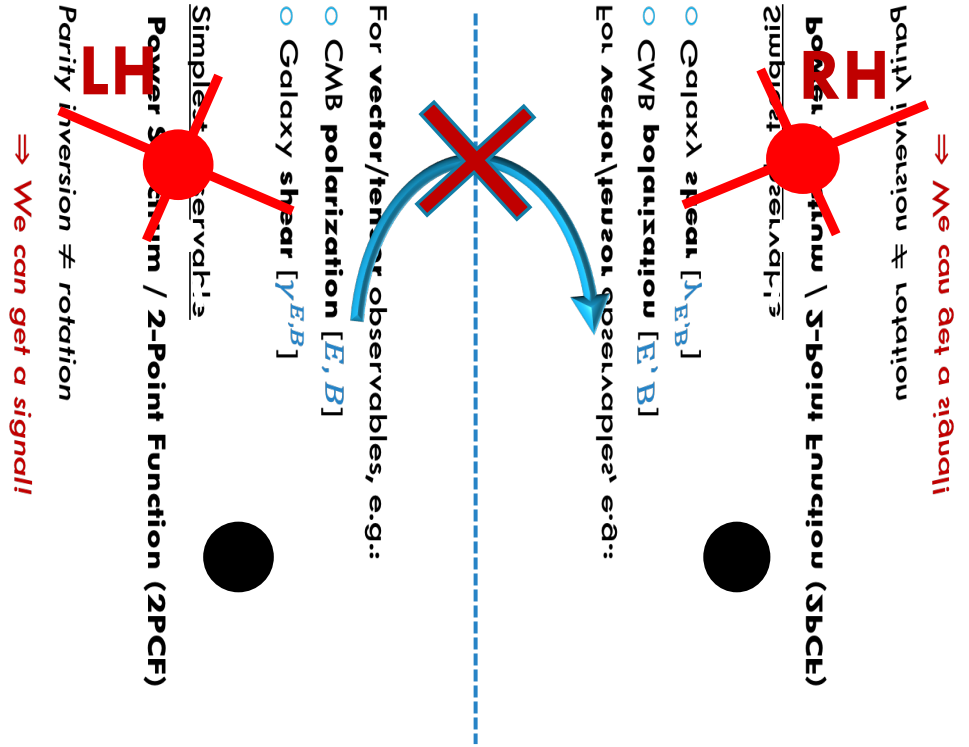
<u>Simplest observable</u>

Power Spectrum / 2-Point Function (2PCF)

Parity inversion ≠ rotation

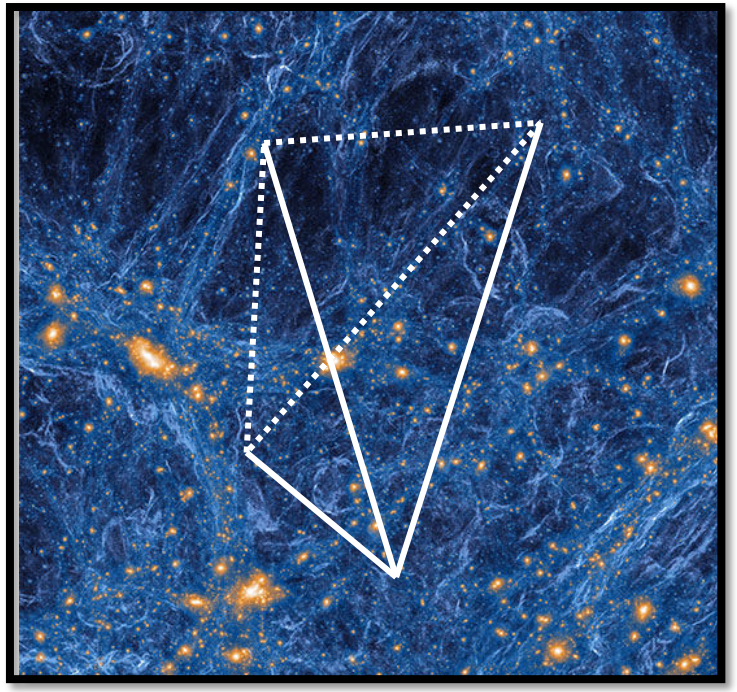
⇒ We can get a signal!



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

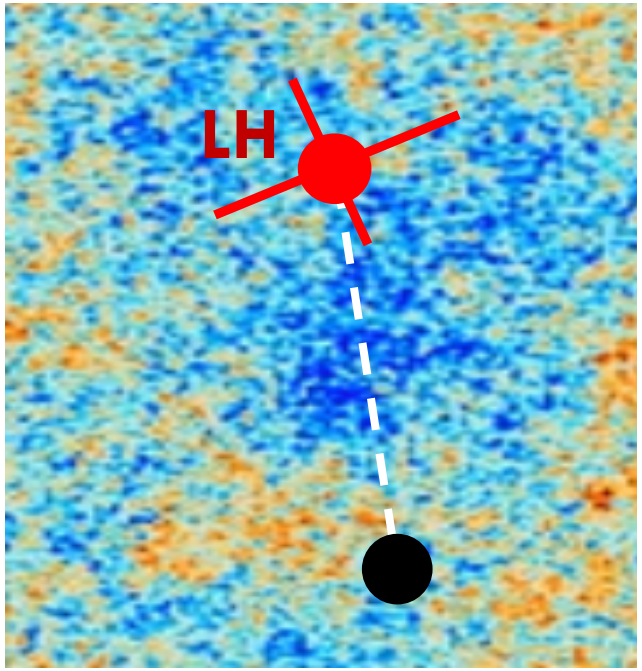
Lue+99, Gluscevic+10, Liu+20, Cahn+21, Philcox 22

PARITY SENSITIVE OBSERVABLES



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

Look in galaxy surveys or 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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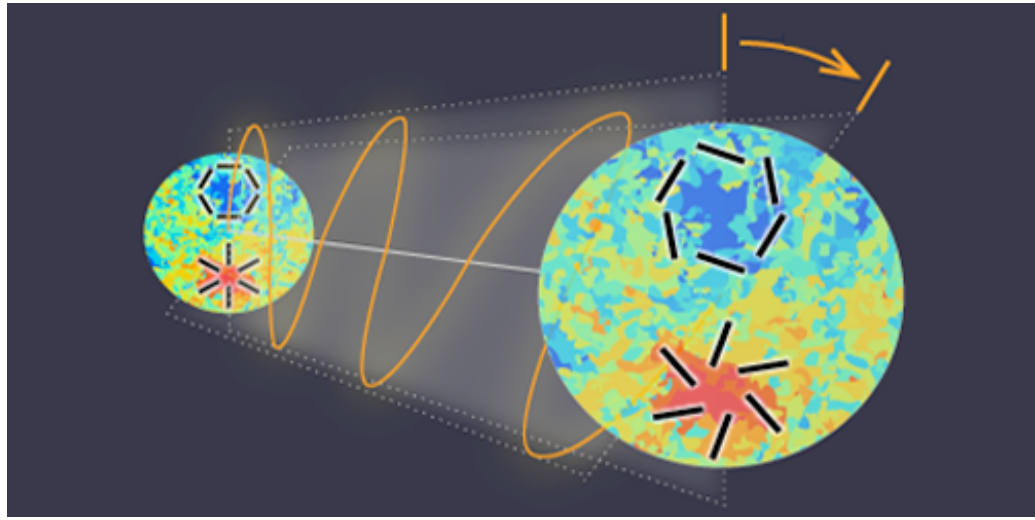
A Hint of New Physics Observed in Polarized Radiation From the Early Universe



$C_\ell^{EB} \neq 0$ in *Planck!*

(after careful correction for calibration errors)

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

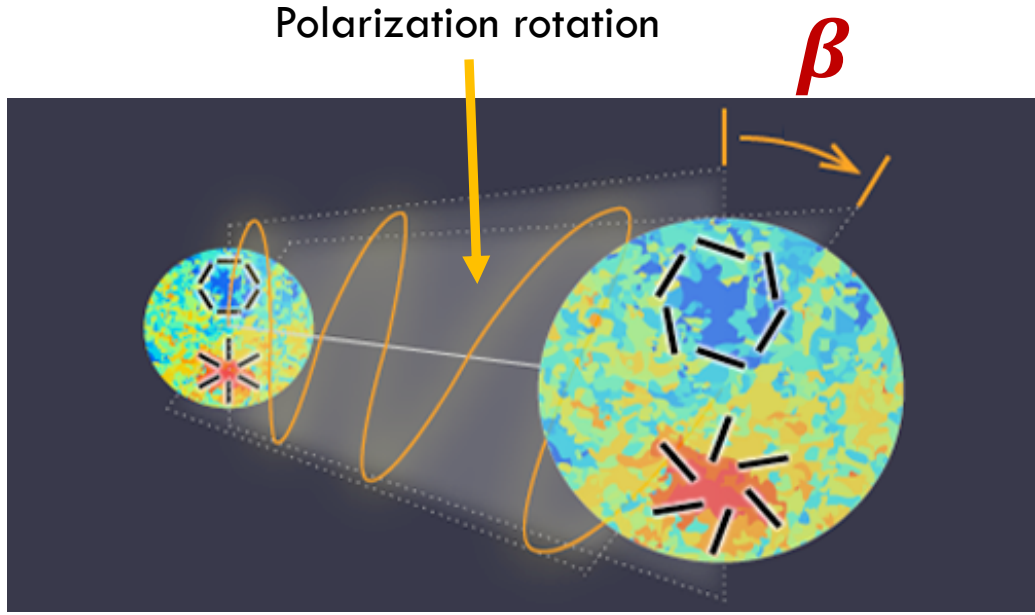
OBSERVATION #1: COSMIC BIREFRINGENCE

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 ($C_\ell^{EB} \neq 0$)

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

[Could also be sourced by inflation, but would give unobserved C_ℓ^{BB} signals]



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

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

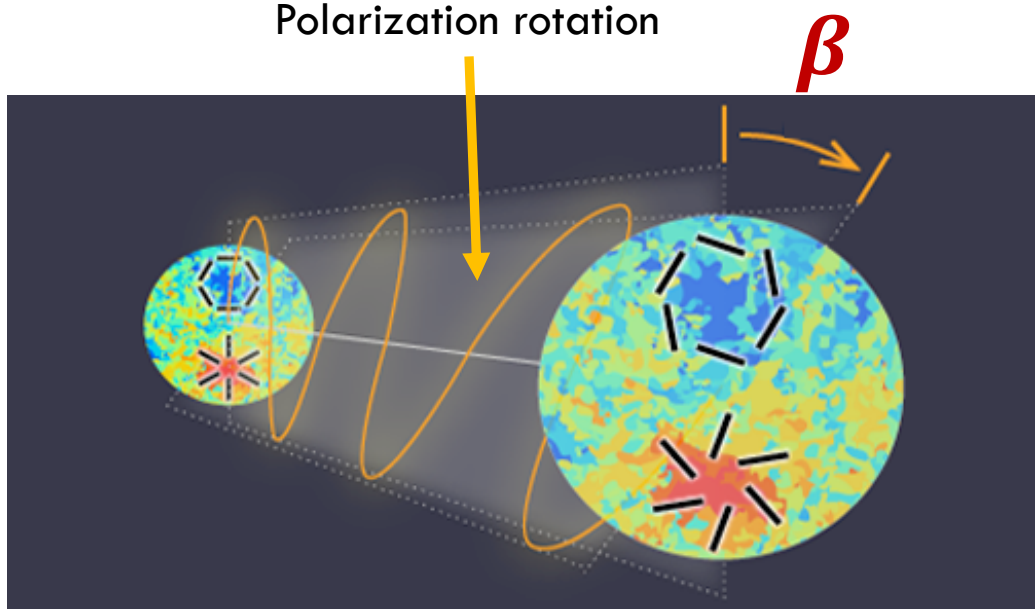
PROPOSED EXPLANATION: AXION-PHOTON COUPLING

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

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

Photon

Axion



Axion interactions rotate the polarization plane!

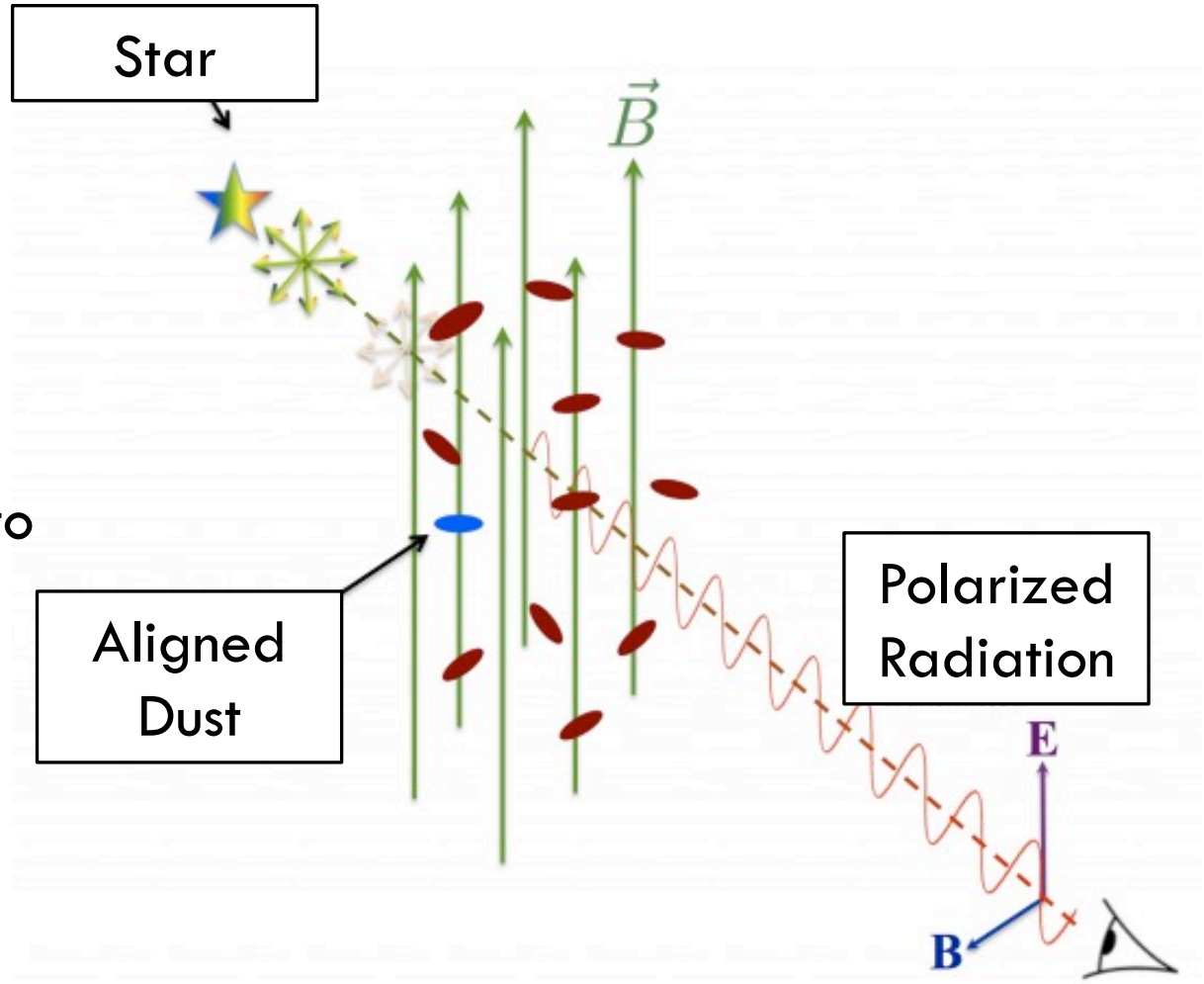
$$\beta \propto g_{\phi\gamma} \int \mathrm{d}t\, \dot{\phi} \quad \Rightarrow \quad g_{\phi\gamma} \neq 0\,?$$

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

Minami+20, Turner+88

BUT: WHAT ABOUT DUST?

- Galactic dust absorbs and emits **stellar radiation**
- Spinning dust grains **align** perpendicular to the Galactic **magnetic field**
- This gives **polarized emission**!



Pasiphae, Clark+21

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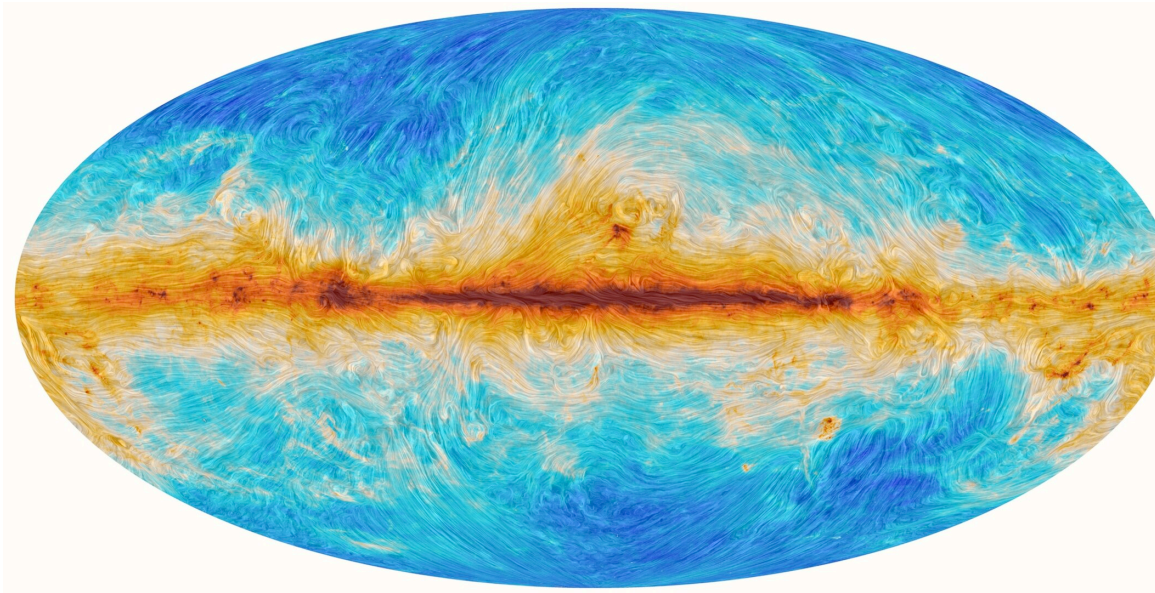


Dust Polarization Map

ESA, Clark+21

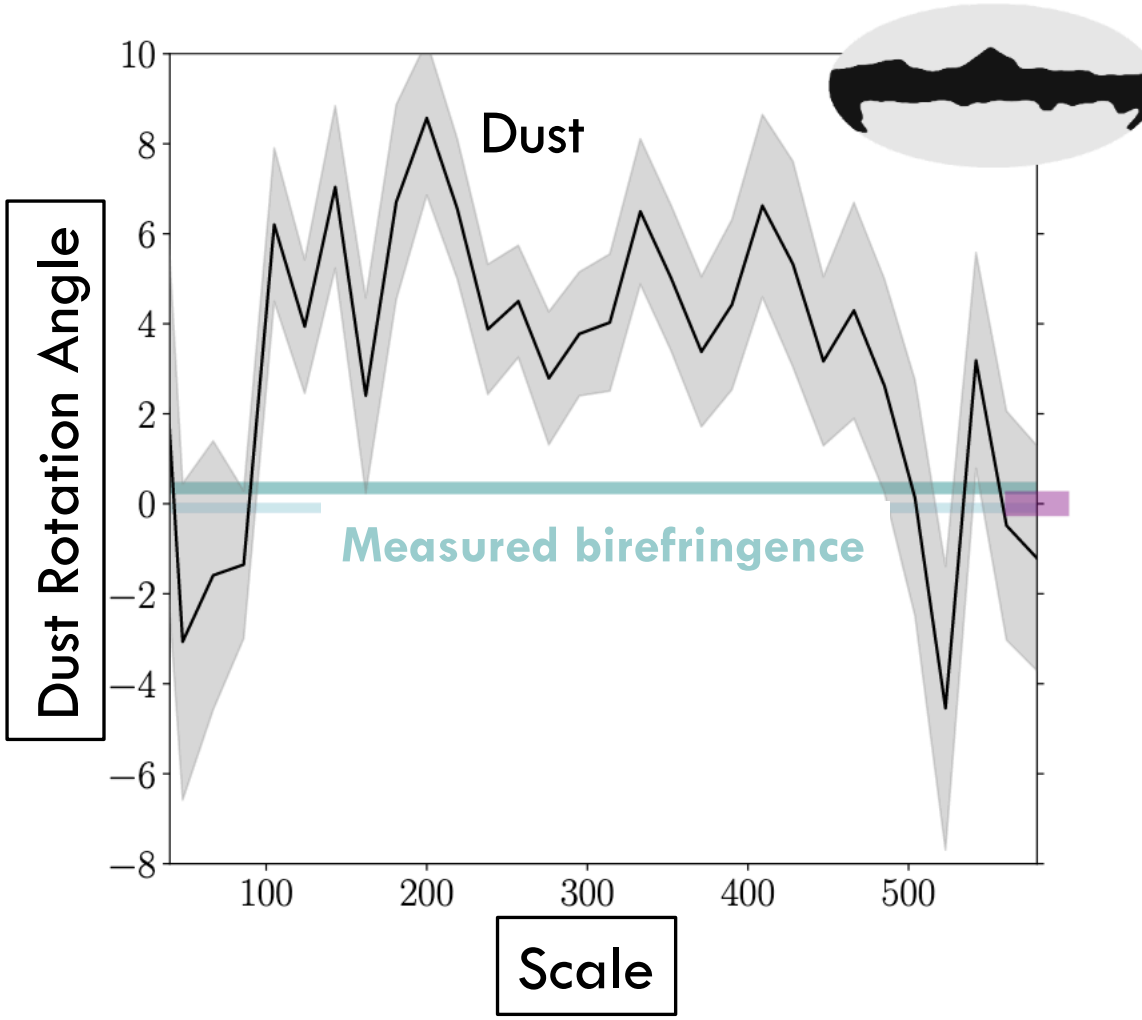
***BUT*: WHAT ABOUT DUST?**

- Since **magnetic fields** are involved, polarized dust emission can **break** parity-symmetry and **generate** C_ℓ^{EB}

- **Dust rotation angle** could explain the observed signal!

- Not resolved yet - most recent paper says:

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



Clark+21, Diego-Palazuelos+22

OBSERVATION #2: GALAXY FOUR-POINT FUNCTIONS

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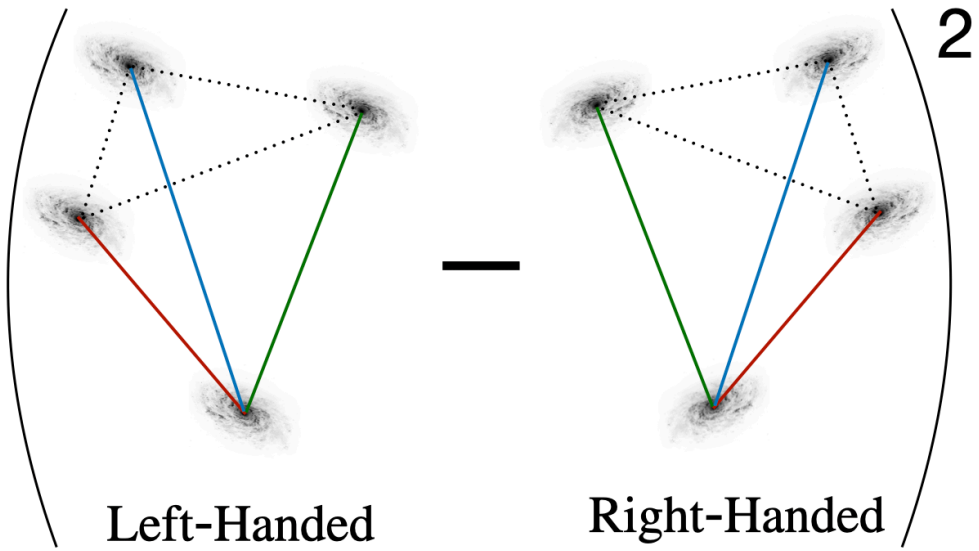
The universe is surprisingly lopsided and we don't know why

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



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

Philcox 22, Hou+22

THE GALAXY 4-POINT FUNCTION

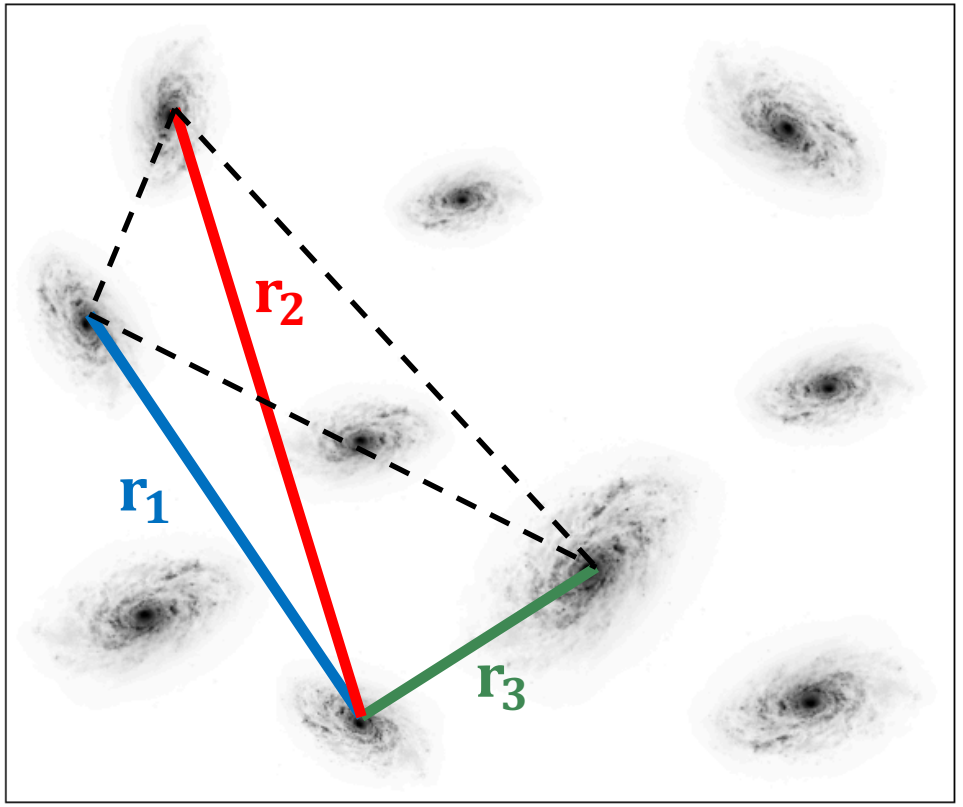
Four-point correlation function (4PCF)

=

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

$$\zeta_4(\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}) = \left\langle \delta_g(\mathbf{x}) \delta_g(\mathbf{x}+\mathbf{r_1}) \delta_g(\mathbf{x}+\mathbf{r_2}) \delta_g(\mathbf{x}+\mathbf{r_3}) \right\rangle_c$$

New methods allow this to be computed efficiently!



ENCORE, Philcox+21

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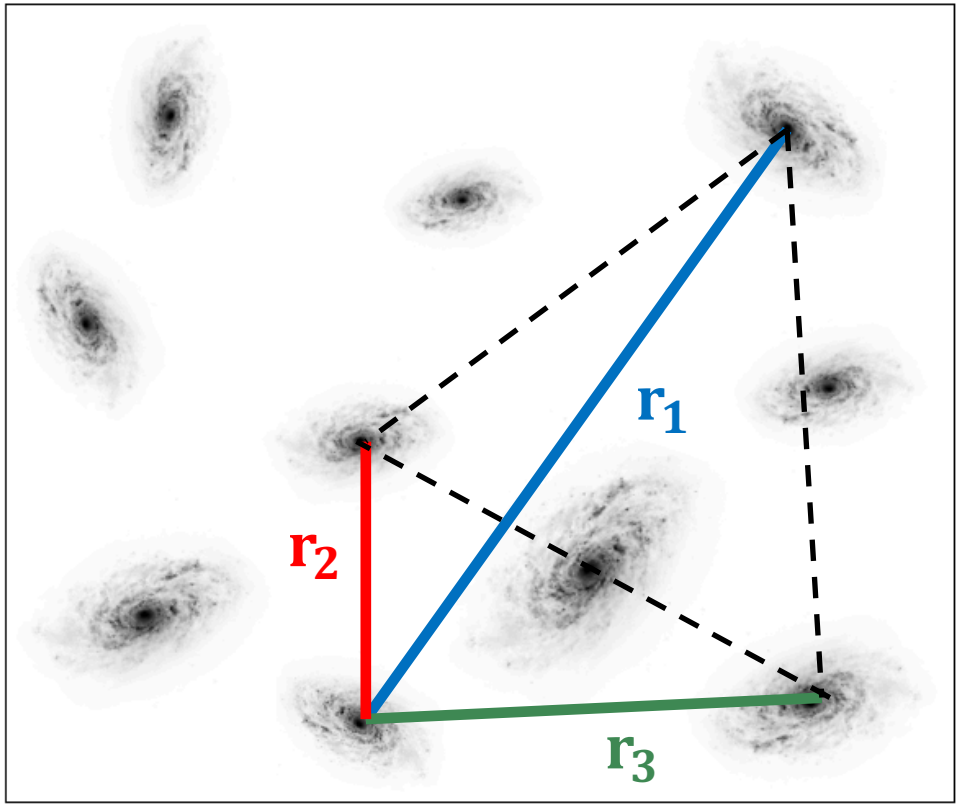

ENCORE, Philcox+21

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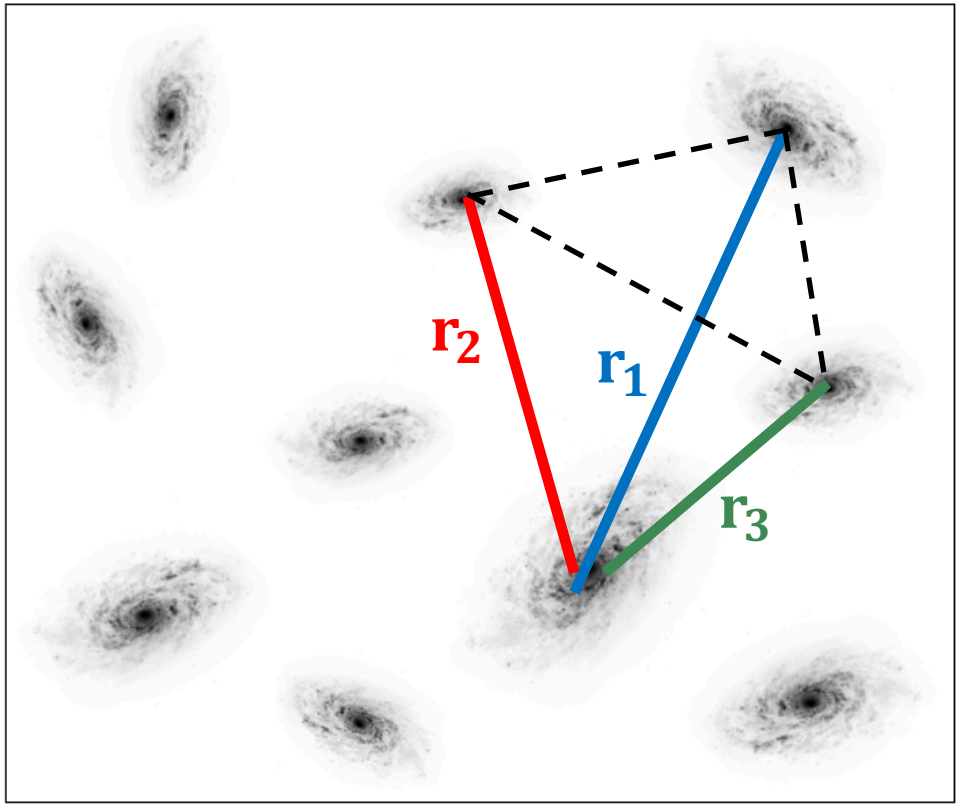
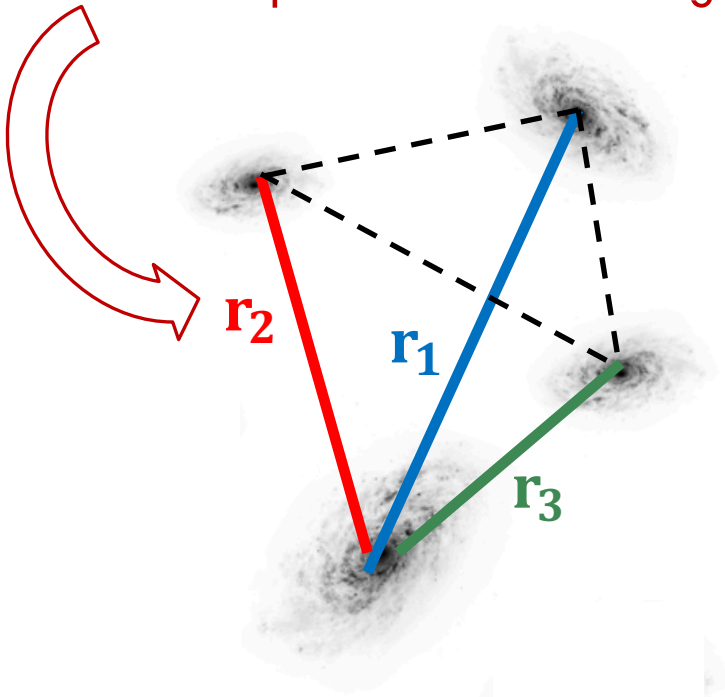


ENCORE, Philcox+21

ONE TETRAHEDRON = THREE VECTORS

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



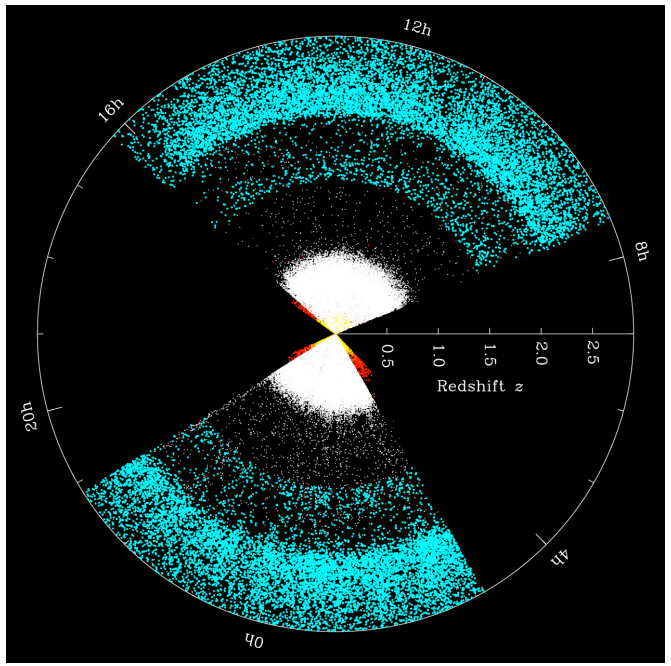
3 lengths + 3 angles

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

Philcox+21

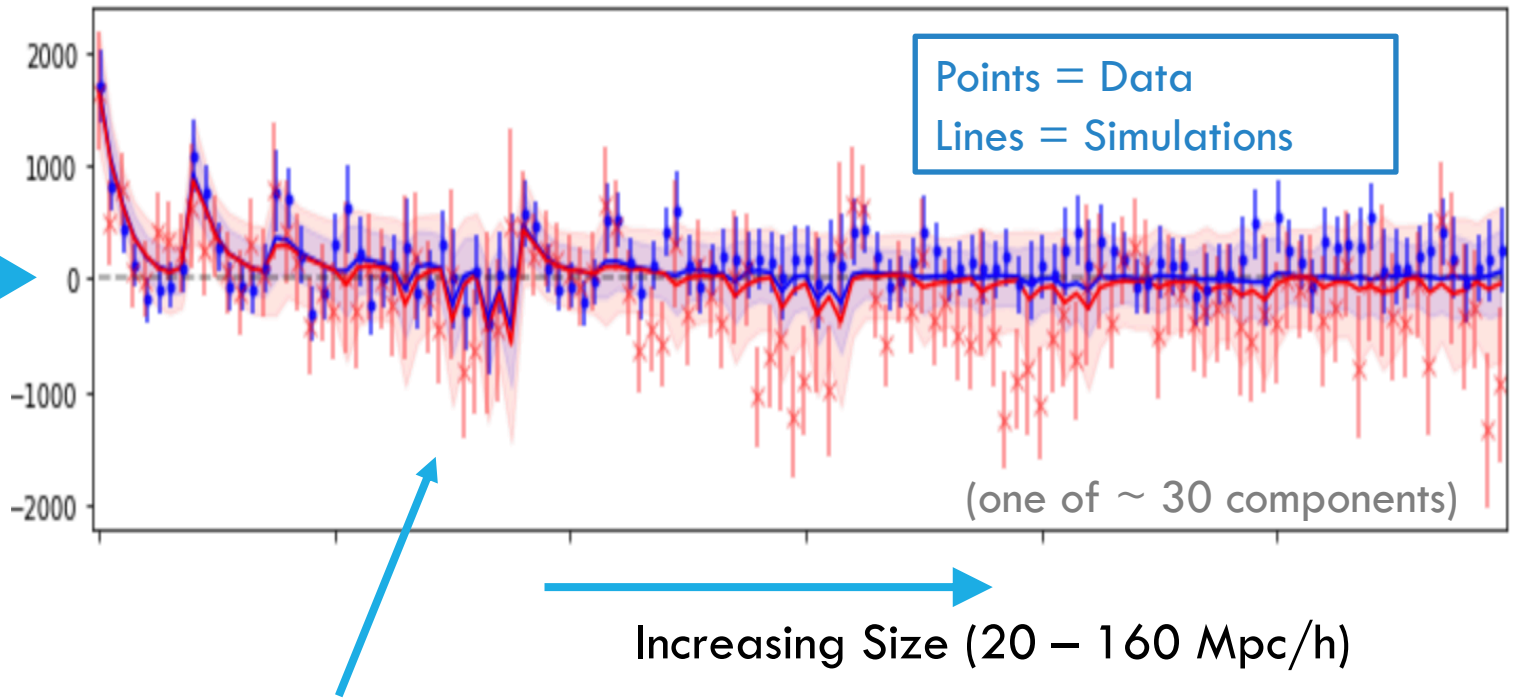
THE OBSERVED FOUR-POINT FUNCTION

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



Galaxy Positions

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



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

Philcox+21

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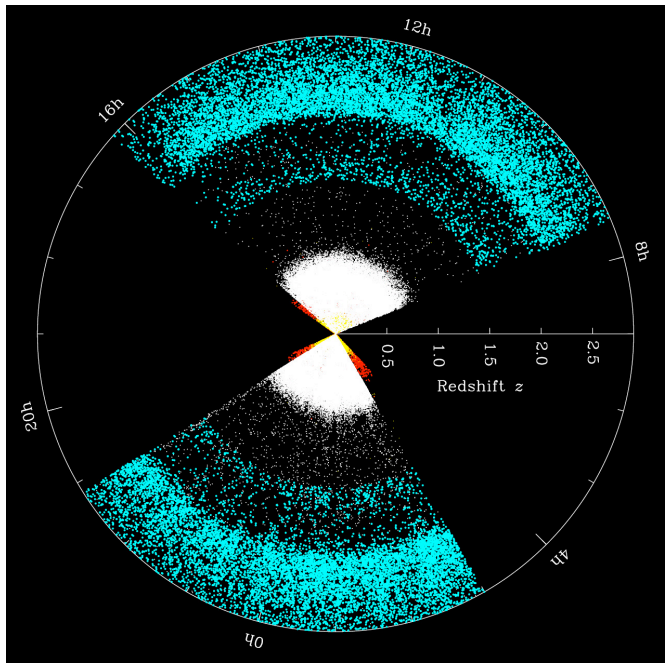
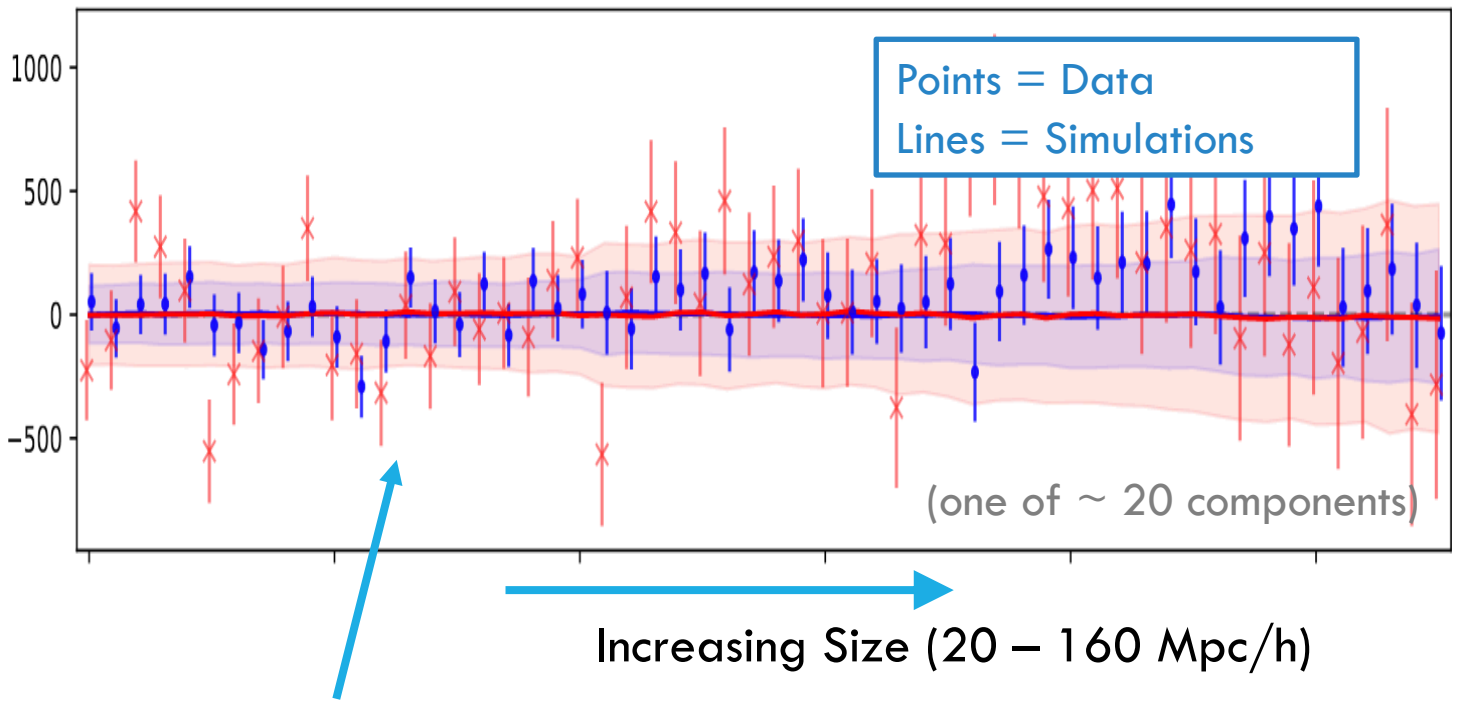


Galaxy Positions

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



Are parity-odd contributions zero??

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

Philcox 22, Hou+22

ANALYZING THE 4PCF

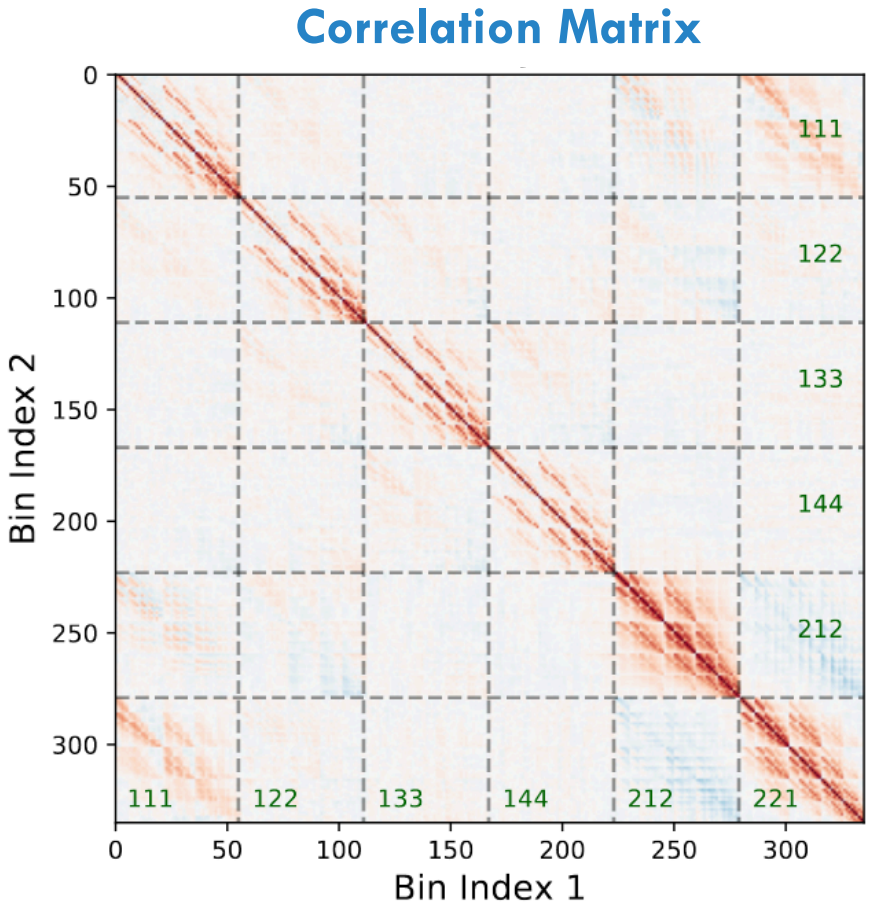
$$\zeta^{\mathrm{odd}} = \frac{1}{2}(\zeta_4 - \mathbb{P}[\zeta_4])$$

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

Standard analysis procedure: look at χ^2

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

- Model **covariance** analytically
- Assume a **Gaussian** likelihood



Philcox 22, Hou+22

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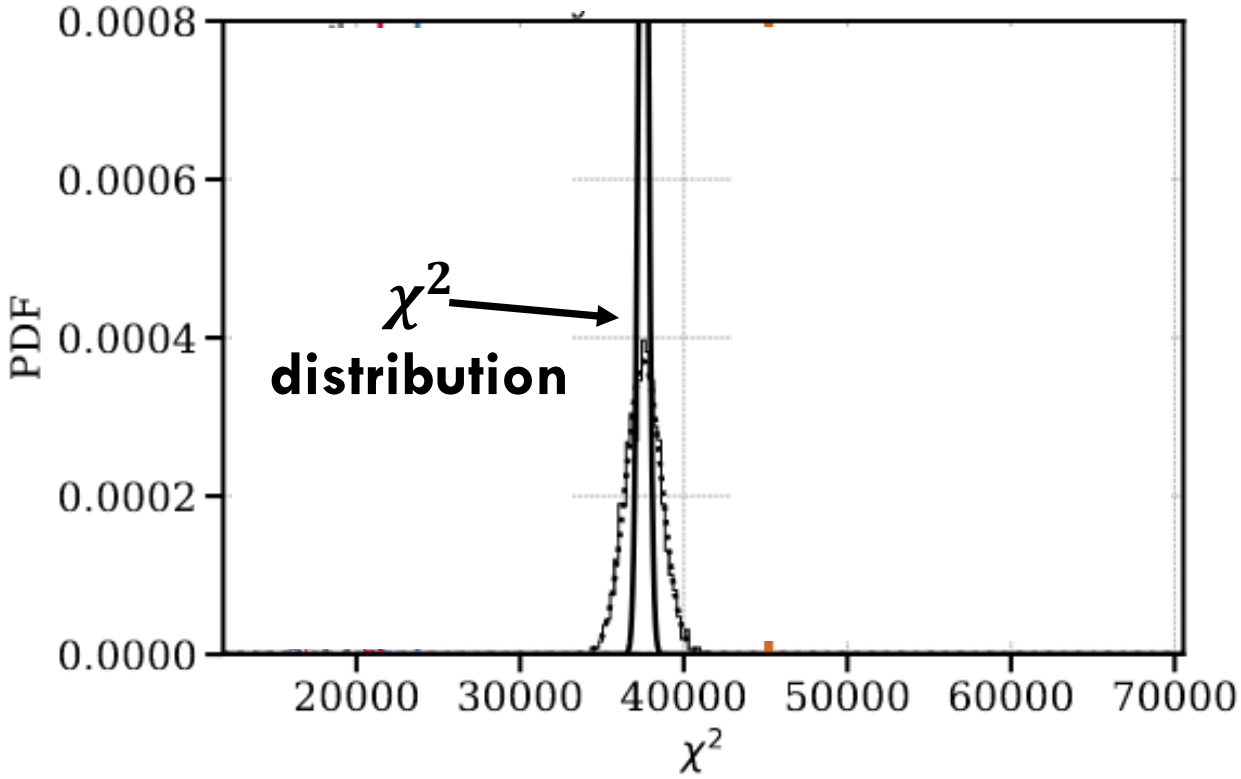

Hou+21,22

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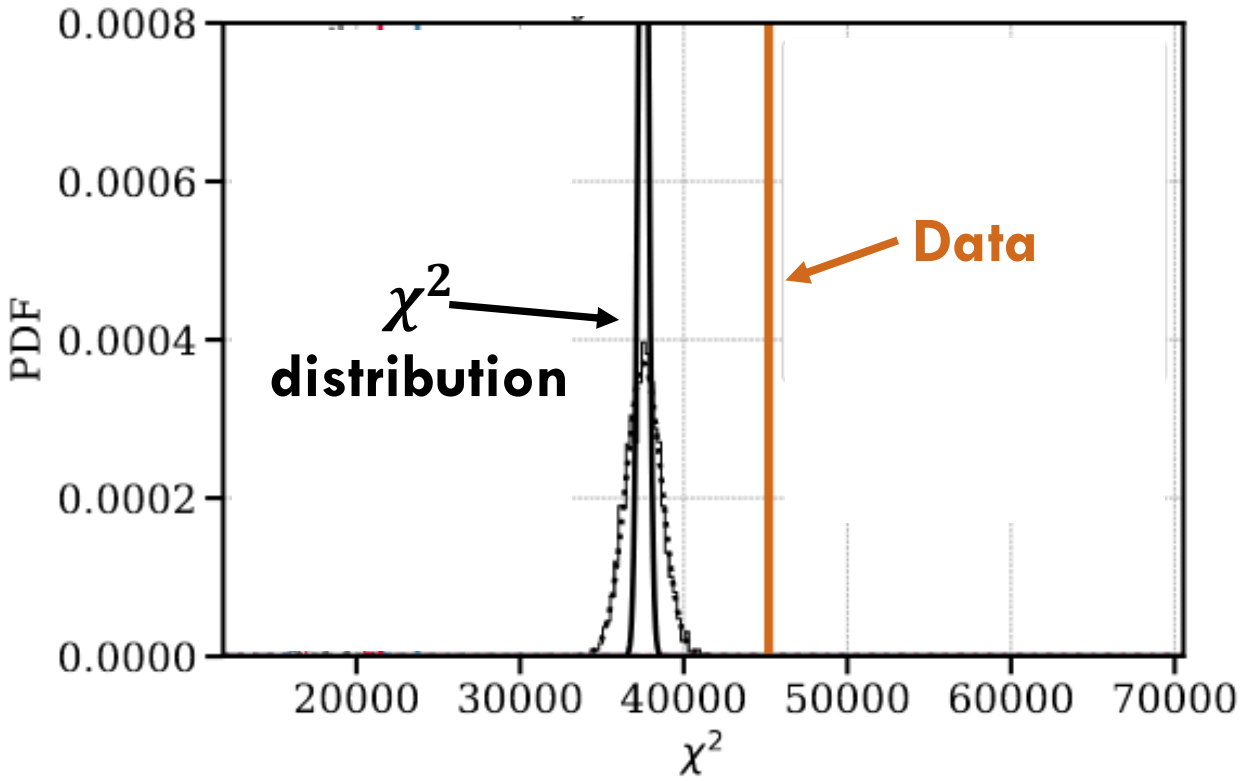
7.1σ detection???



Hou+21,22

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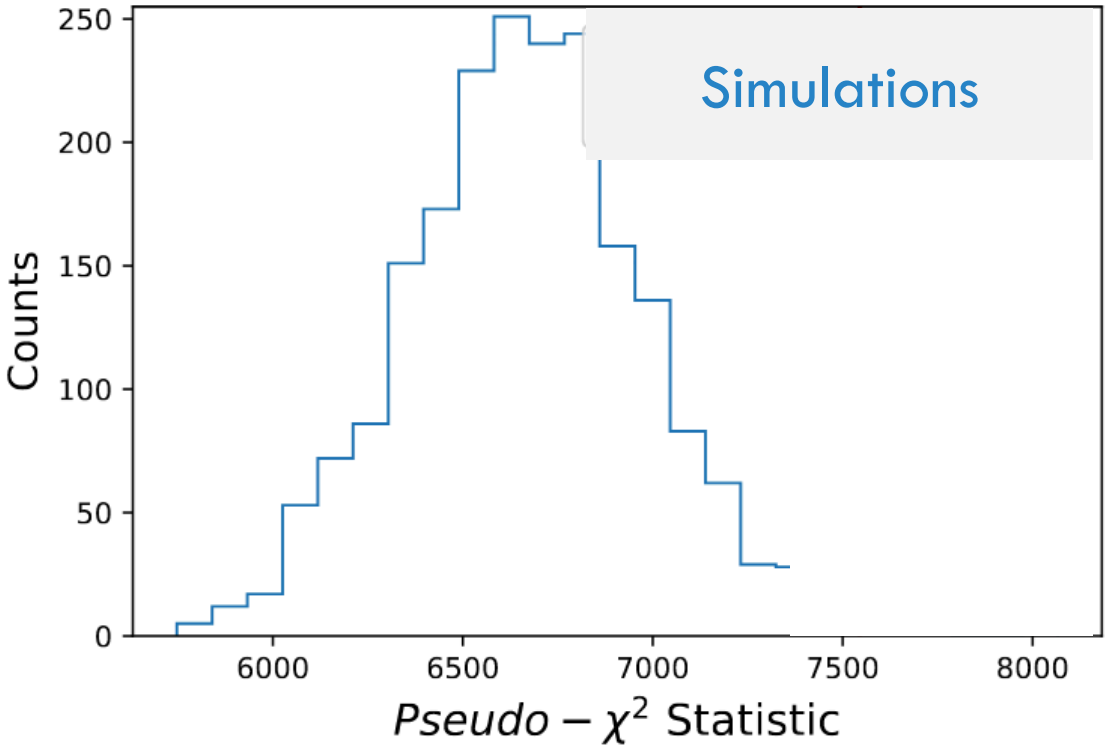
- The 4PCF is a **high-dimensional** object with $\sim 10^3$ **correlated** bins

Alternative analysis procedure

Create **empirical** likelihood based on **simulations**

- No need to assume **Gaussianity**
- **Simulation**-based covariance



ANALYZING THE 4PCF

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

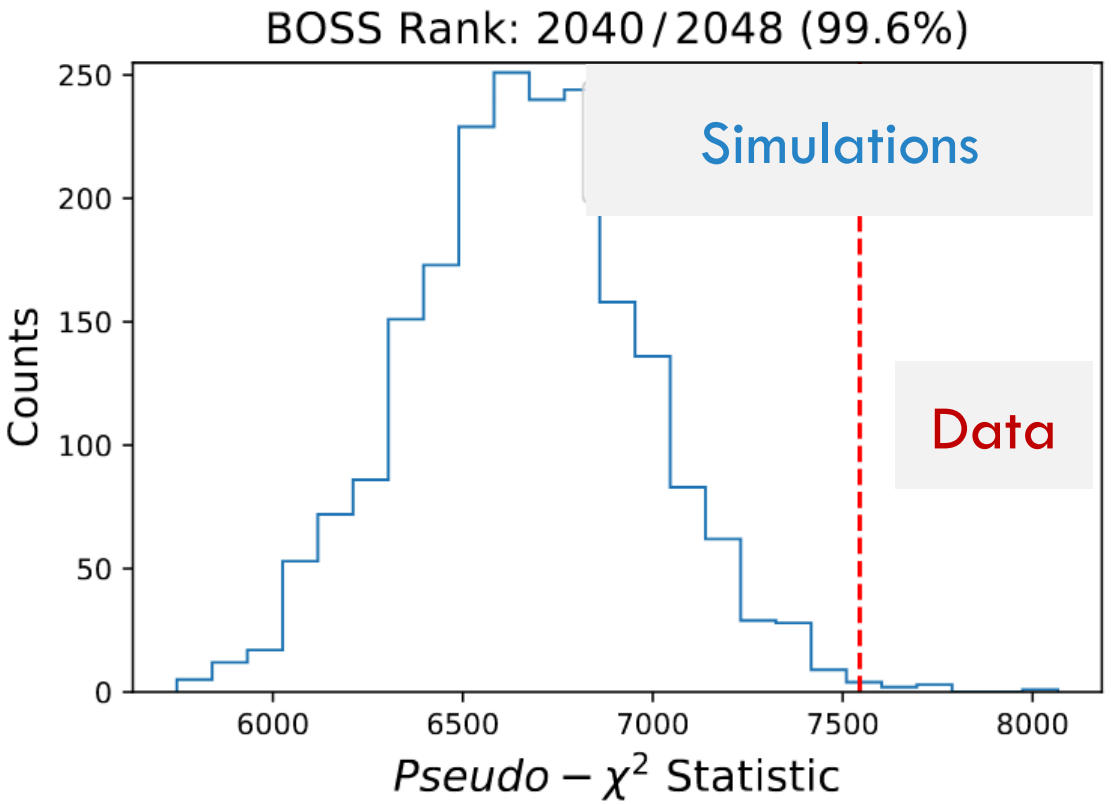
- The 4PCF is a **high-dimensional** object with $\sim 10^3$ **correlated** bins

Alternative analysis procedure

Create **empirical** likelihood based on **simulations**

- No need to assume **Gaussianity**
- **Simulation**-based covariance

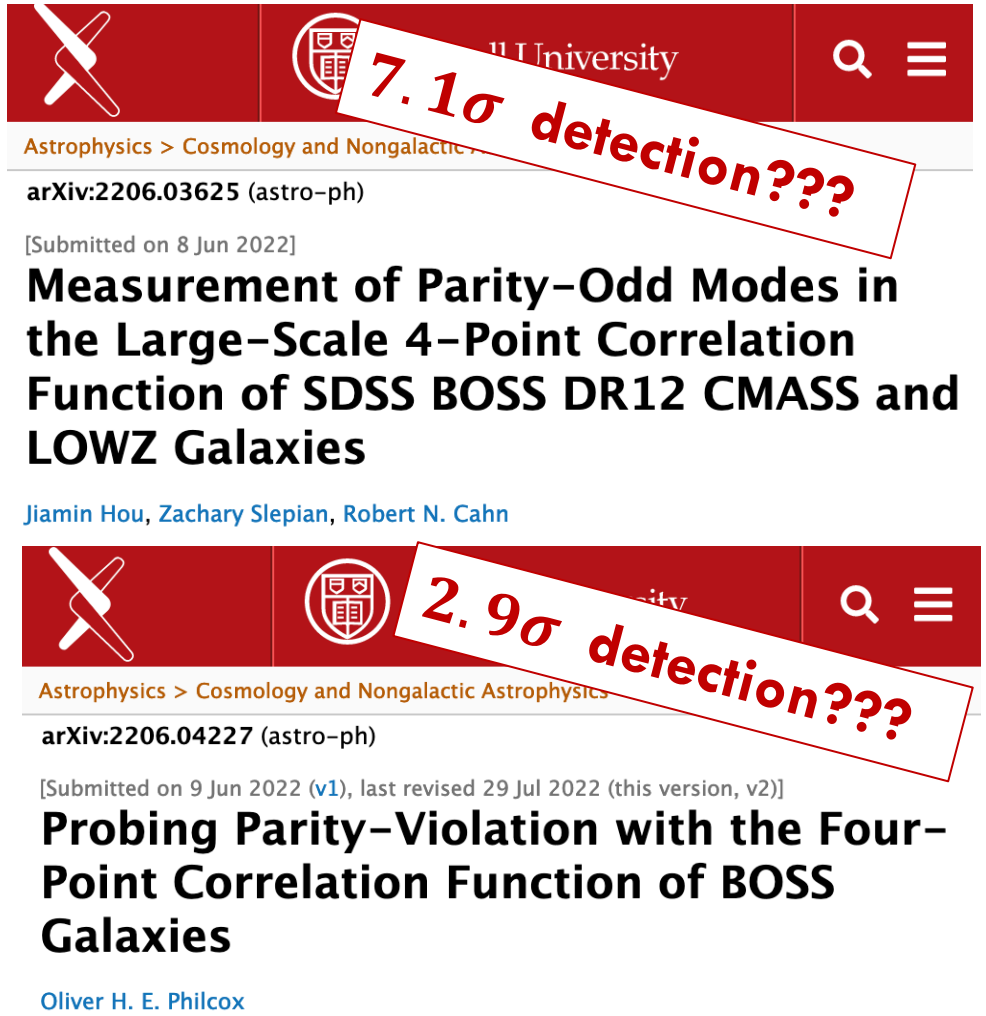
2.9σ detection???



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



Philcox 22, Hou+22

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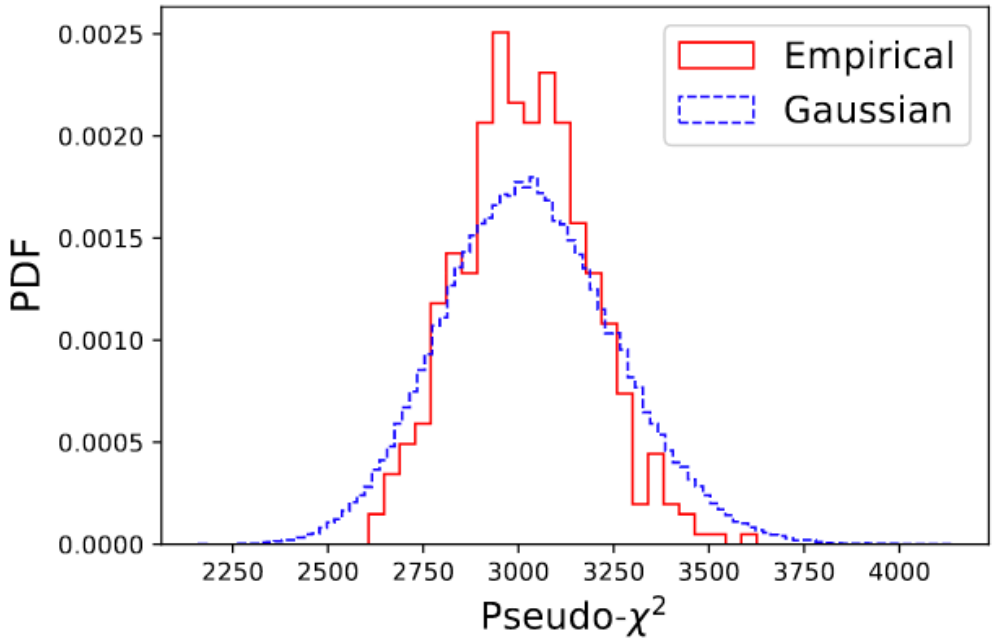
- Likelihood might not be **Gaussian**?
- **Covariance** modelling may be inadequate?

[linear theory, no RSD, no window]



But, both seem to agree there is a signal!

Philcox 22, Hou+22

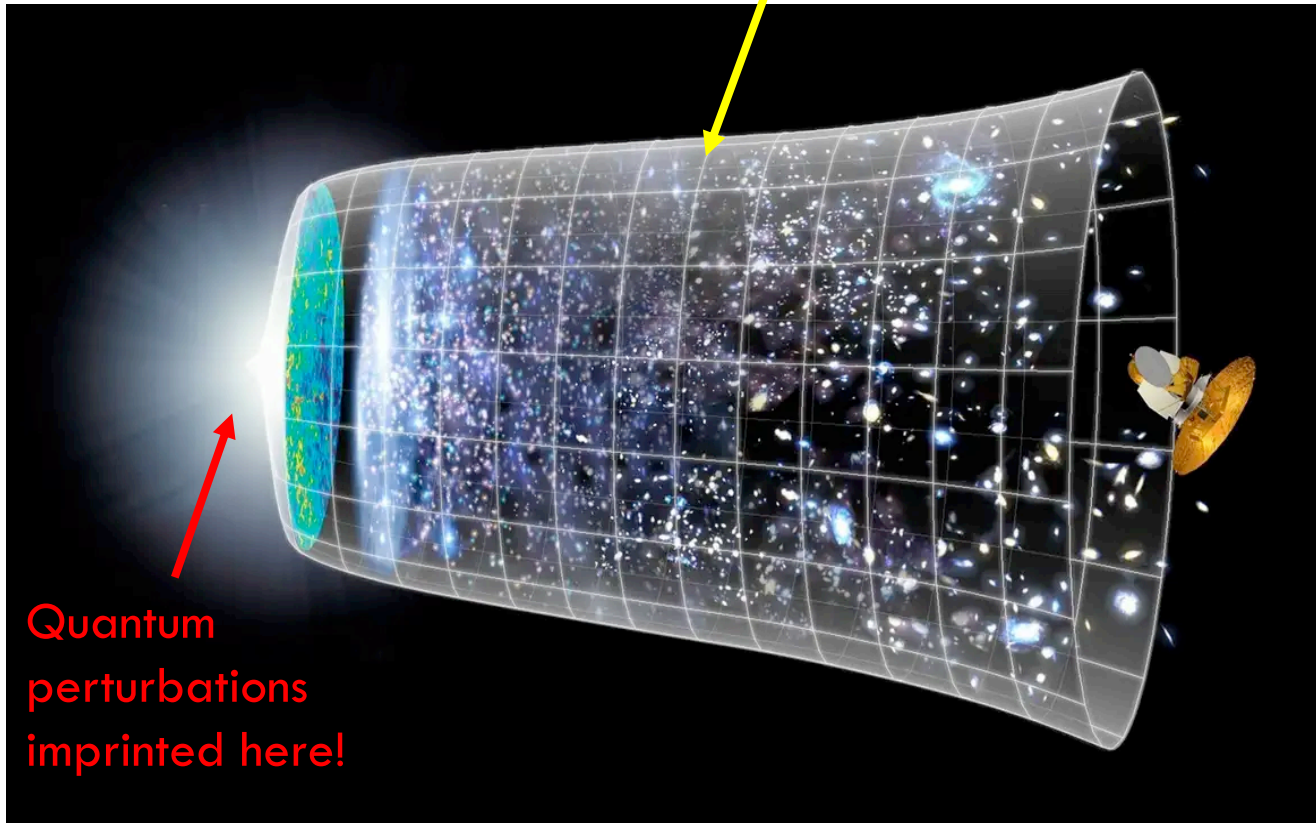
SOURCES OF PARITY VIOLATION

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+22, Philcox+ (in prep.)

PRIMORDIAL PARITY-VIOLATION

There is **no** parity violation in inflation **if**

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

and

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

and

3. **Bunch-Davies** vacuum

Cabass+22

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There **is** parity violation in inflation **if**

▷ **Not scale-invariant** (*time dependent couplings*)

or

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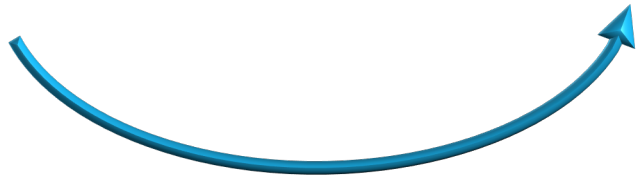
or

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



(and many other scenarios)

Cabass+22

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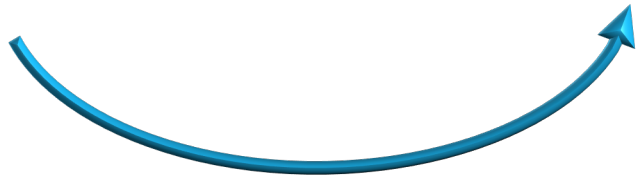


(and many other scenarios)

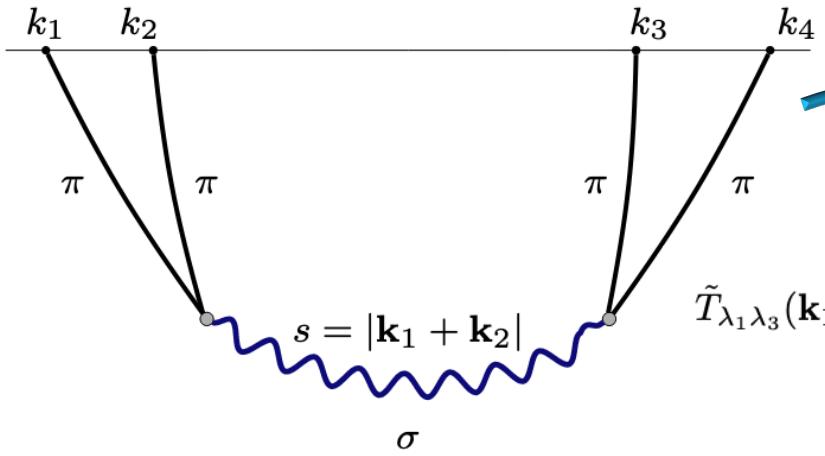
Cabass+22

PRIMORDIAL PARITY-VIOLATION: COSMOLOGICAL COLLIDER

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

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

We generate a parity-odd trispectrum!



$$\tilde{T}_{\lambda_1\lambda_3}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = -ic_s^4\frac{\lambda_1\lambda_3}{8H}(\Delta_\zeta^2)^4 \sin\pi\left(\nu+\frac{1}{2}\right) k_1^{-2}k_2^{-1}k_3^{-1}k_4^{-1}(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)(\hat{\mathbf{k}}_3\cdot\hat{\mathbf{k}}_4)(k_1-k_2)(k_3-k_4)$$
$$\times(\hat{\mathbf{k}}_2\cdot\hat{\mathbf{k}}_3\times\hat{\mathbf{k}}_4)[k_{12}J_3(c_sk_{12},s)+c_sk_1k_2J_4(c_sk_{12},s)][k_{34}J_4(c_sk_{34},s)+c_sk_3k_4J_5(c_sk_{34},s)]$$

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

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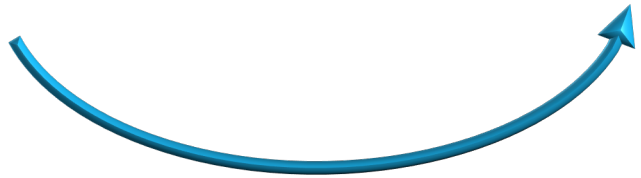


(and many other scenarios)

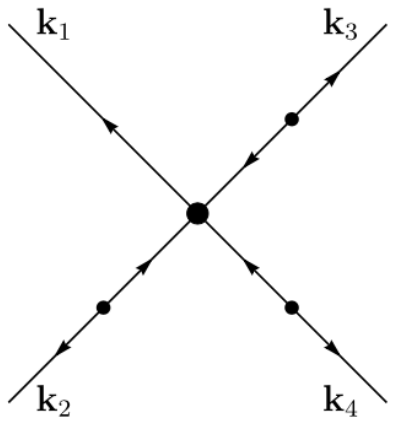
Cabass+22

PRIMORDIAL PARITY-VIOLATION: GHOSTS

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

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

We generate a parity-odd trispectrum!



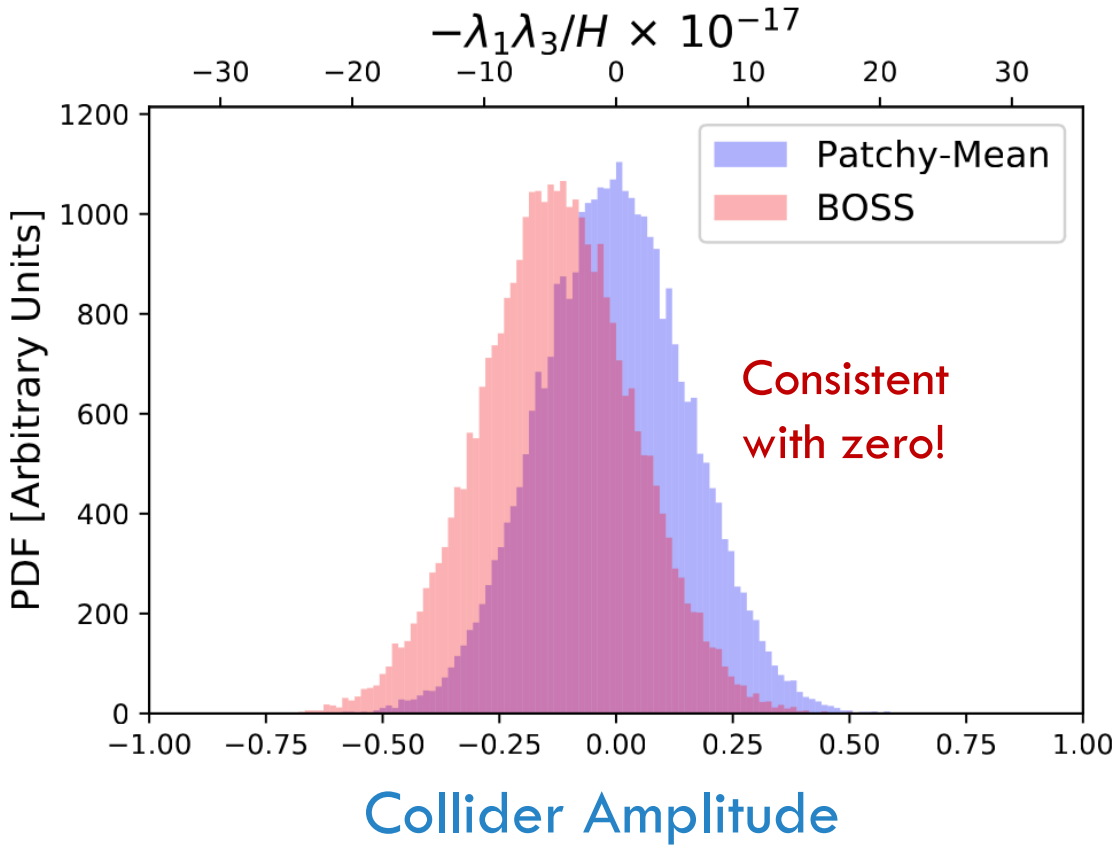
$$\tilde{T}_{\Lambda^2_{\rm PO}}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = \frac{512i\pi^3\Lambda^5(H\tilde{\Lambda})^{3/2}}{\Lambda^2_{\rm PO}\tilde{\Lambda}^6\Gamma(\frac{3}{4})^2}(\Delta^2_\zeta)^3(\mathbf{k}_1\cdot\mathbf{k}_2\times\mathbf{k}_3)(\mathbf{k}_1\cdot\mathbf{k}_2)k_1^{-\frac{3}{2}}k_2^{\frac{1}{2}}k_3^{\frac{1}{2}}k_4^{\frac{1}{2}}\mathcal{T}^{(13)}_{0,0,0,1}(k_1,k_2,k_3,k_4)$$

Arkani-Hamed+03, Cabass+22, Philcox+ (in prep.), DALL-E

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 so far…



*with a lot of effort

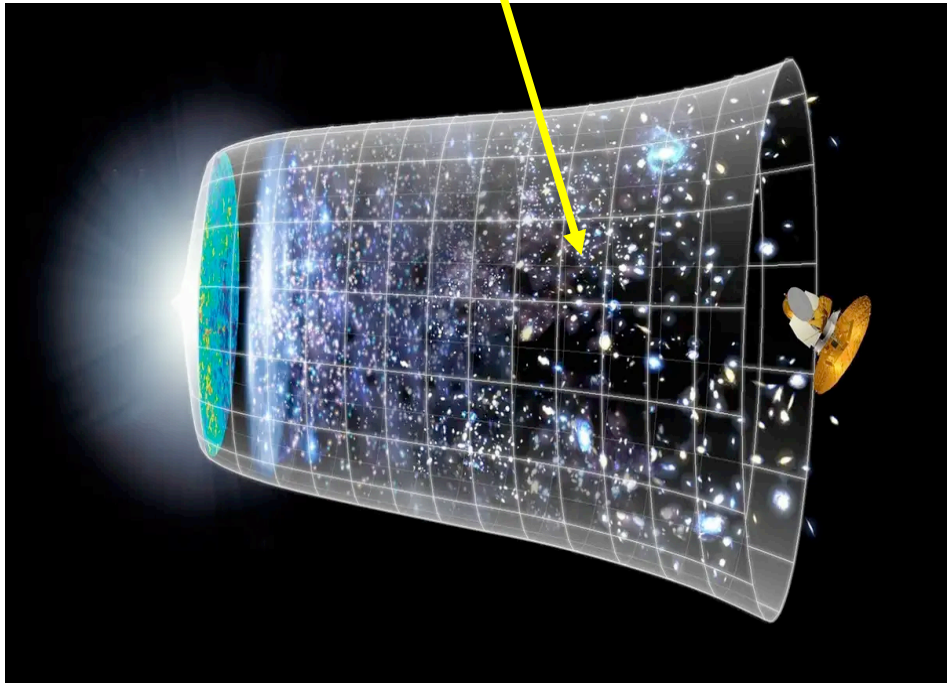
Baumann+10, Cabass+22, Philcox+ (in prep.)

LATE-TIME PARITY VIOLATION

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+22, Philcox+ (in prep.)

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**

Philcox 22, Hou+22, Philcox+ (in prep.)

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- Some other model of inflation
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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, Philcox+ (in prep.)

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 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, Philcox+ (in prep.)

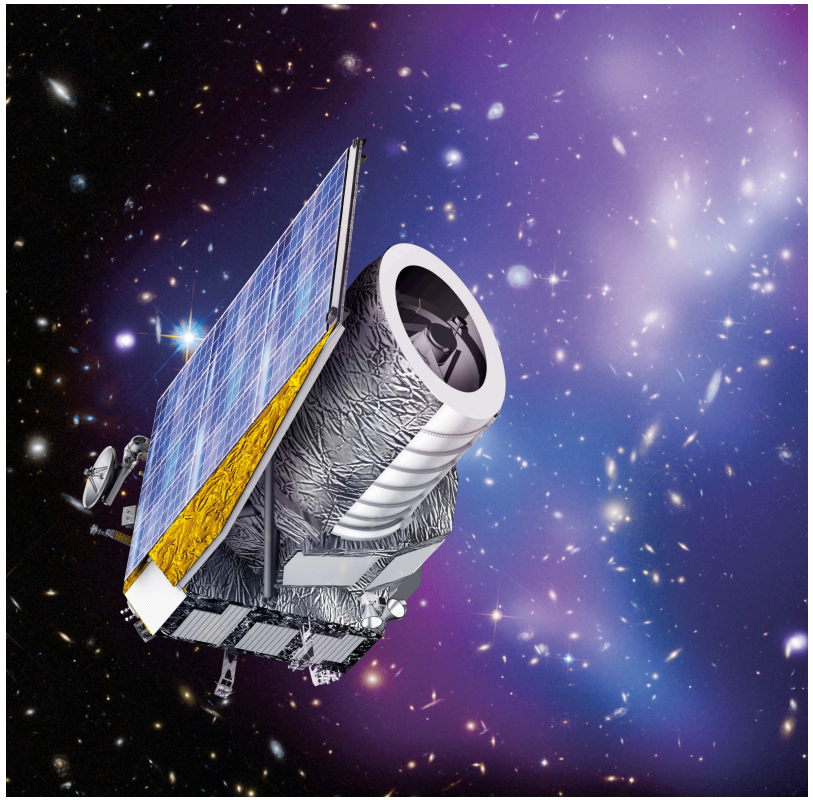
WHAT'S NEXT?

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

- ***But*** **systematics might not go away!**

- We can look at **other datasets**, e.g., the CMB trispectrum

$$\left\langle \prod_{i=1}^{4} a_{\ell_i m_i} \right\rangle^{\text{odd}} = 0??$$



Euclid

CONCLUSIONS

arXiv
2011.11254
2210.07655
2206.04227
2206.03625
2210.02907

- **Birefringence** and the galaxy **4-point function** 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.** There is much more to learn!

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