SIMONS FOUNDATION

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

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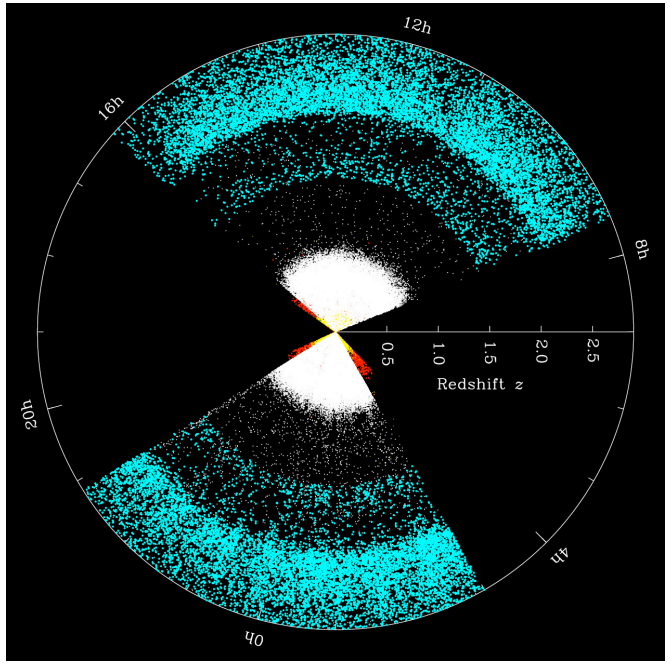
What can galaxy surveys teach us about inflation?

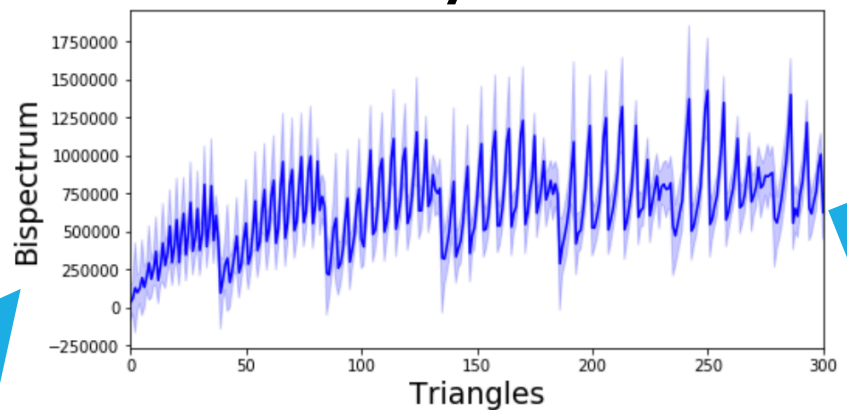
Oliver Philcox

FROM GALAXY SURVEYS TO INFLATION



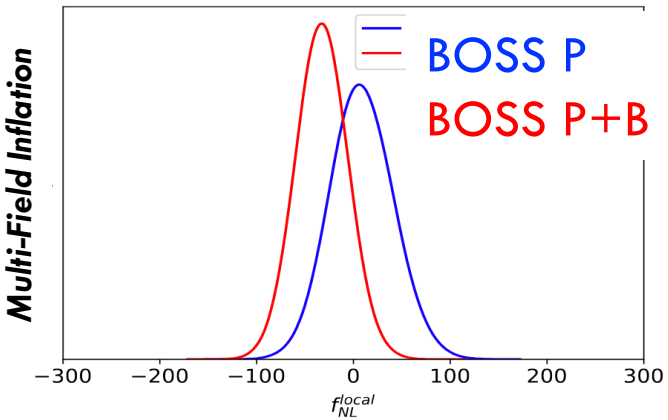
Raw data

Summary statistics



Theory model

$$
\begin{aligned}
Z_1(\boldsymbol{q}_1) &= K_1 + f\mu_1^2, \qquad \text{(A.3)}\\
Z_2(\boldsymbol{q}_1,\boldsymbol{q}_2) &= K_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + f\mu_{12}^2 G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{f\mu_{12}q_{12}}{2}K_1\left[\frac{\mu_1}{q_1}+\frac{\mu_2}{q_2}\right] + \frac{(f\mu_{12}q_{12})^2}{2}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2},\\
Z_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) &= K_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + f\mu_{123}^2 G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3)\\
&\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]\\
&\quad + \frac{(f\mu_{123}q_{123})^2}{2}\left[2\frac{\mu_{12}}{q_{12}}\frac{\mu_3}{q_3}G_2(\boldsymbol{q}_1,\boldsymbol{q}_2) + \frac{\mu_1}{q_1}\frac{\mu_2}{q_2}K_1\right] + \frac{(f\mu_{123}q_{123})^3}{6}\frac{\mu_1}{q_1}\frac{\mu_2}{q_2}\frac{\mu_3}{q_3},\\
Z_4(\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)\\
&\quad + (f\mu_{1234}q_{1234})\left[\frac{\mu_{123}}{q_{123}}K_1 G_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3) + \frac{\mu_4}{q_4}K_3(\boldsymbol{q}_1,\boldsymbol{q}_2,\boldsymbol{q}_3)\right.\\
&\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 \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}
$$



Inflation constraints

SDSS-III, **Philcox**+22abc
Cabass, **Philcox**+22abc

WHAT CAN WE LEARN ABOUT INFLATION?

$$P_\zeta(k) \sim A_s\, k^{n_s-1}$$

Energy scale of inflation?

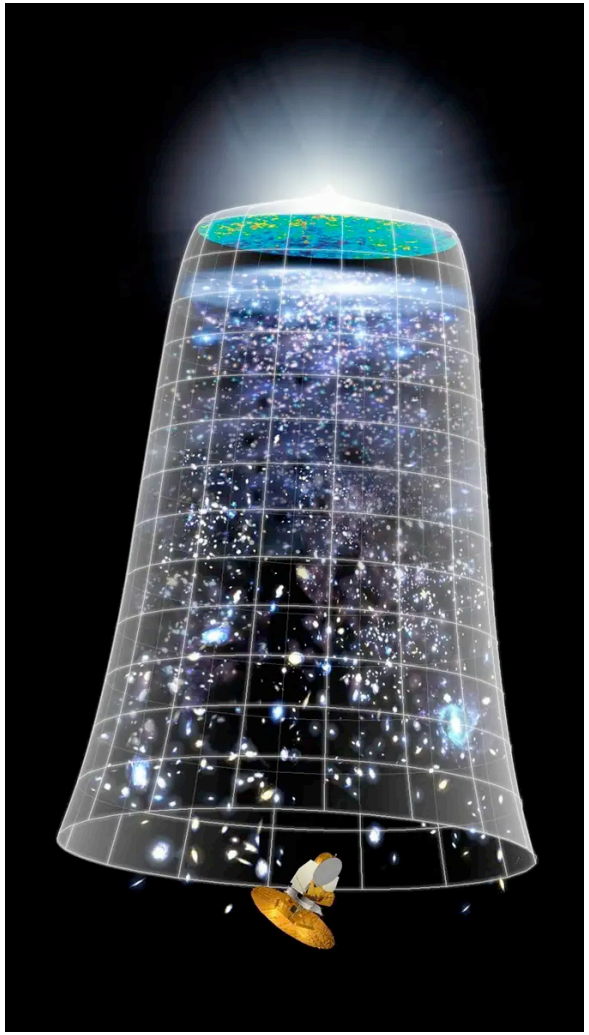
- ▷ Primordial GWs!

Number of fields in inflation?

- ▷ Local primordial non-Gaussianity

Interactions in inflation?

- ▷ Non-local primordial non-Gaussianity



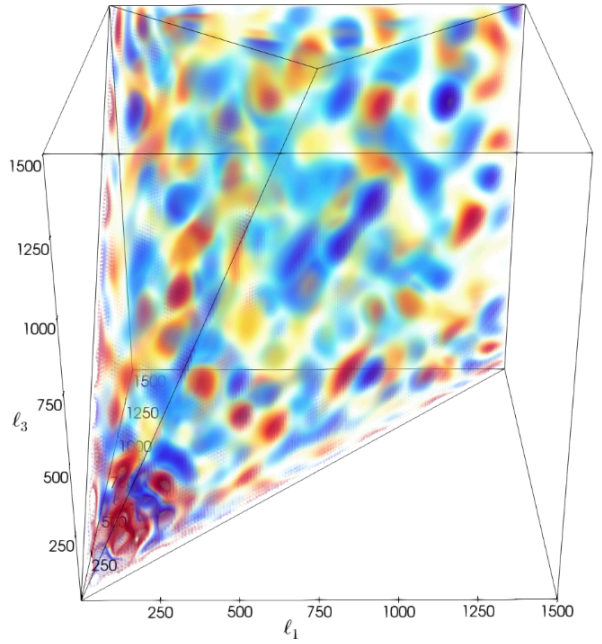
Inflation

New Scientist

HOW CAN WE LEARN ABOUT INFLATION?

1. **CMB non-Gaussianity**

Planck Bispectrum



≈ 2× better with CMB-S4!

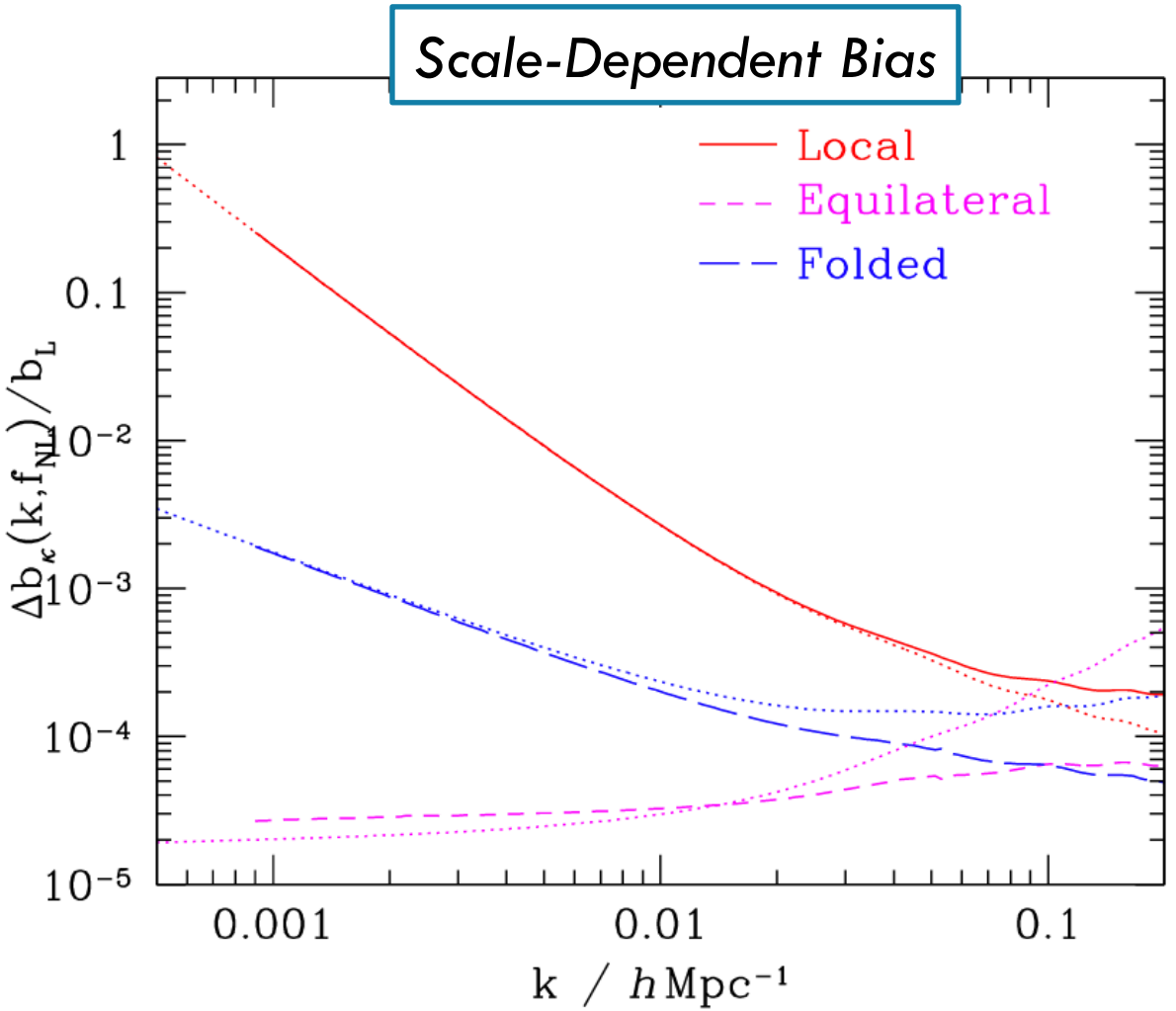
f_{NL} Constraints

Local	6.7 ± 5.6
Equilateral	6 ± 66
Orthogonal	-38 ± 36

Planck 2018 IX

HOW CAN WE LEARN ABOUT INFLATION?

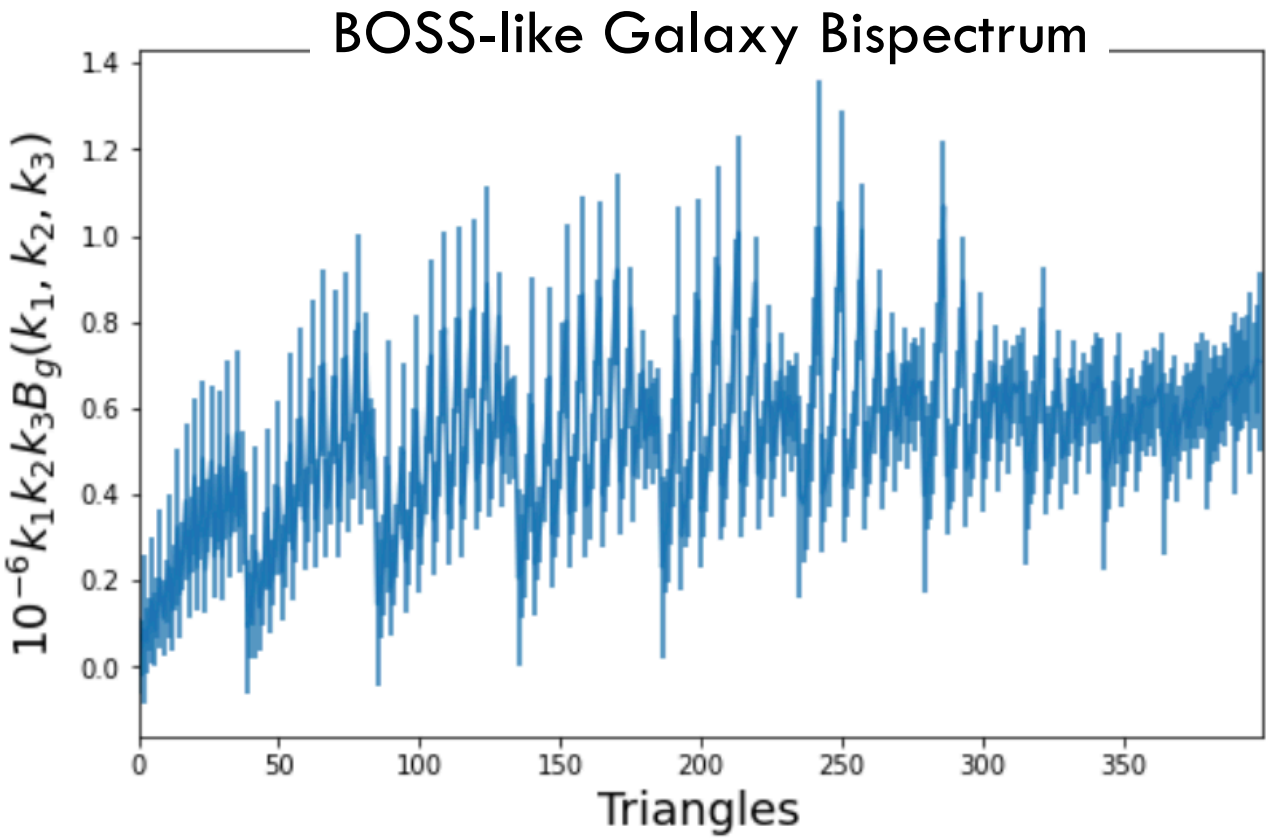
1. CMB non-Gaussianity
2. **Galaxy Bias**



Desjacques & Seljak 10, eBOSS 21

HOW CAN WE LEARN ABOUT INFLATION?

1. CMB non-Gaussianity
2. Galaxy Bias
3. **Galaxy non-Gaussianity**



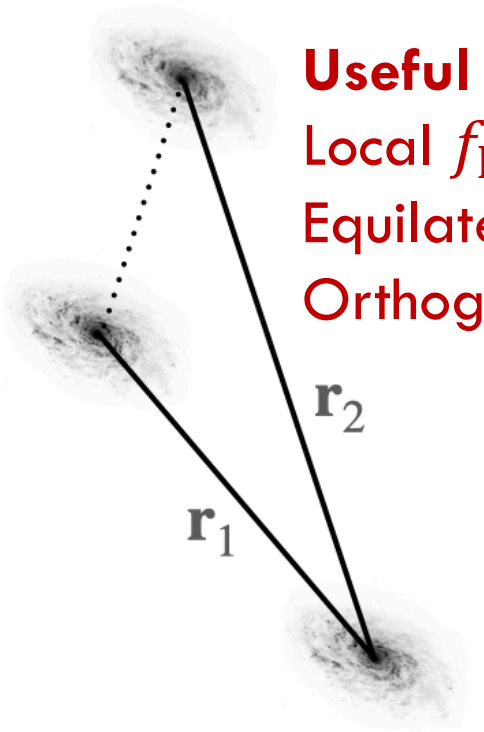
What statistics should we use?

Philcox+21, Cabass, **Philcox**+22ab

NON-GAUSSIAN STATISTICS

Standard choices:

1. Galaxy **bispectrum** / three-point function $\langle \delta_g \delta_g \delta_g \rangle$



Useful for:
Local $f_{\rm NL}$
Equilateral $f_{\rm NL}$
Orthogonal $f_{\rm NL}$

Measure with window-free Fourier-space estimators

$$\zeta_3(\mathbf{r}_1, \mathbf{r}_2)$$

https://github.com/oliverphilcox/Spectra-Without-Windows

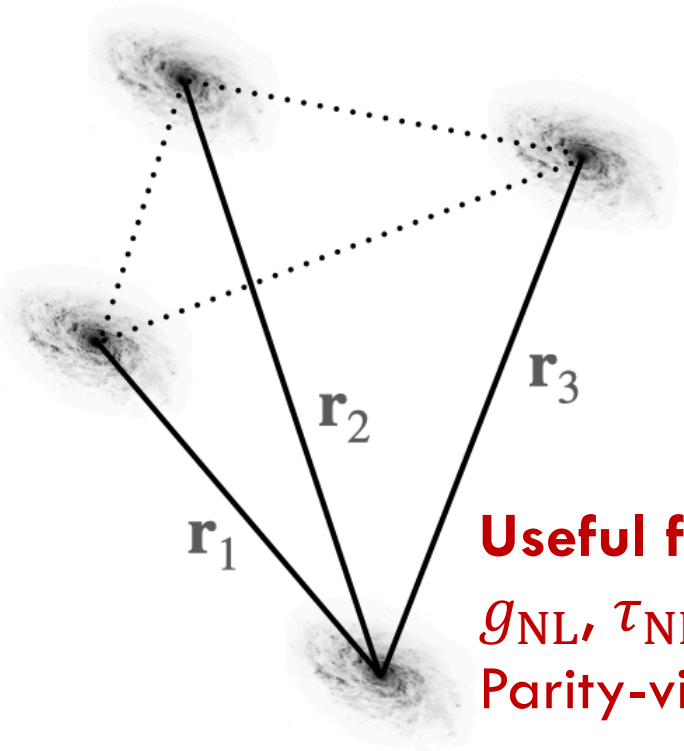
Philcox+21, **Philcox** 22

NON-GAUSSIAN STATISTICS

Standard choices:

1. Galaxy **bispectrum** / three-point function $\langle \delta_g \delta_g \delta_g \rangle$

2. Galaxy trispectrum / **four-point function** $\langle \delta_g \delta_g \delta_g \delta_g \rangle$



Useful for:

$g_{\rm NL}$, $\tau_{\rm NL}$

Parity-violation

Measure with efficient real-space estimators

$$\zeta_4(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$$

https://github.com/oliverphilcox/encore

Philcox+21, **Philcox** 22

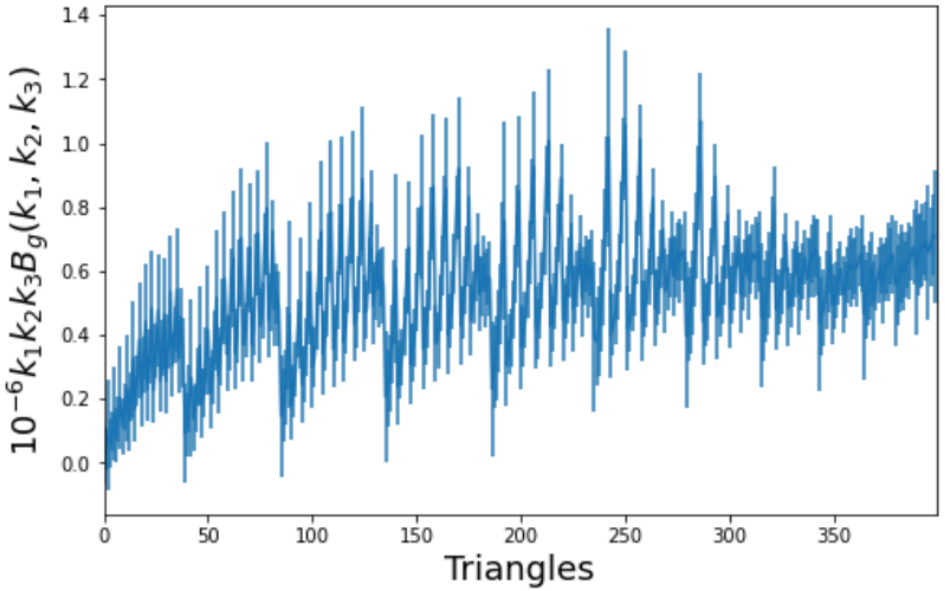
MODELING GALAXY SURVEYS

We need to model *both* inflation and late-time behavior

Initial Conditions: $A_s, \omega_{cdm}, \omega_b, n_s, f_{\rm NL}, \ldots$

Gravity: $\Omega_m, \gamma, w, \ldots$

Statistics



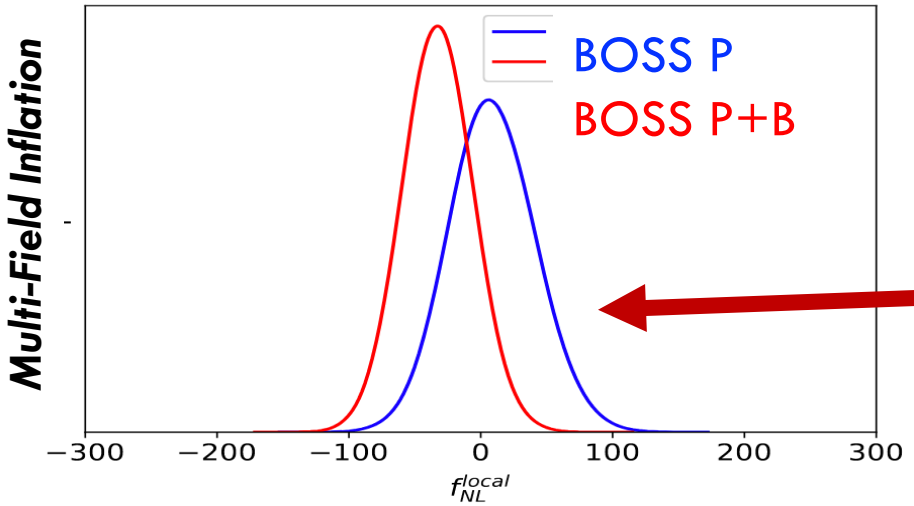
Tool: the **Effective Field Theory** of LSS

- **Analytic** theory for $\delta(\mathbf{x})$, based on the non-ideal **fluid equations**

- **Major Ingredient:** *Back-reaction* of small-scale physics on large-scale modes

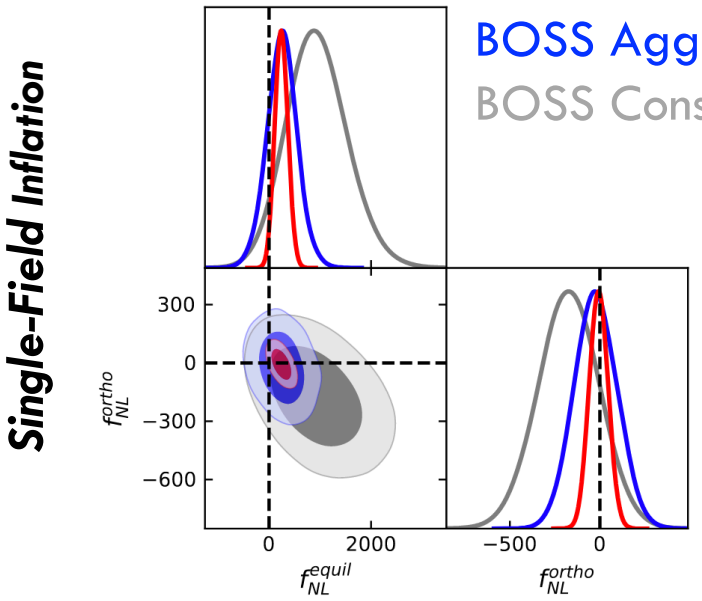
e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, etc.

CONSTRAINTS ON $f_{\rm NL}$



BOSS Power Spectrum + Bispectrum

$$f_{\rm NL}^{\rm local} = -33 \pm 28$$ *(Actually measuring $b_\phi f_{NL}$)*



$$f_{\rm NL}^{\rm equil} = 260 \pm 300$$

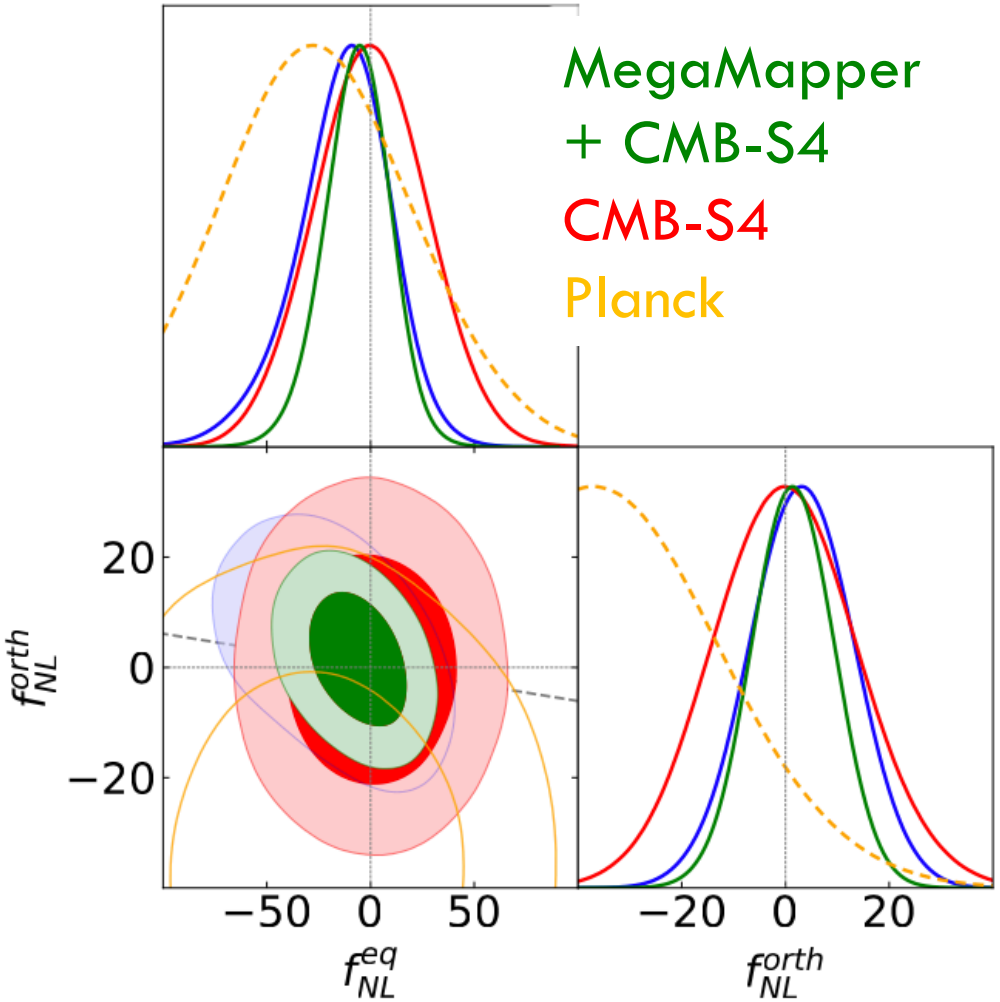
$$f_{\rm NL}^{\rm orth} = -23 \pm 120$$

First measurement without CMB!

All analysis is public:
github.com/oliverphilcox/full_shape_likelihoods

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

CONSTRAINTS ON $f_{\rm NL}$



- Future surveys will do **much** better for primordial non-Gaussianity

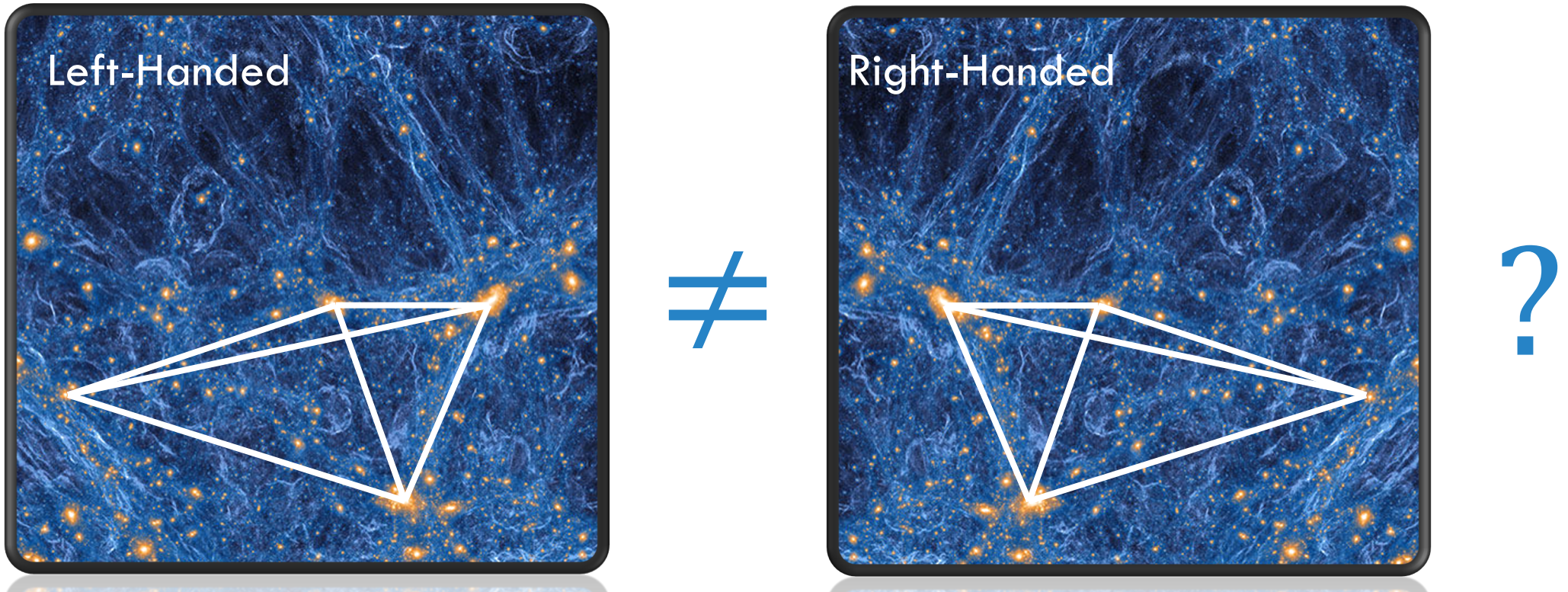
Cabass, **Philcox**+22b

COSMOLOGICAL PARITY-VIOLATION

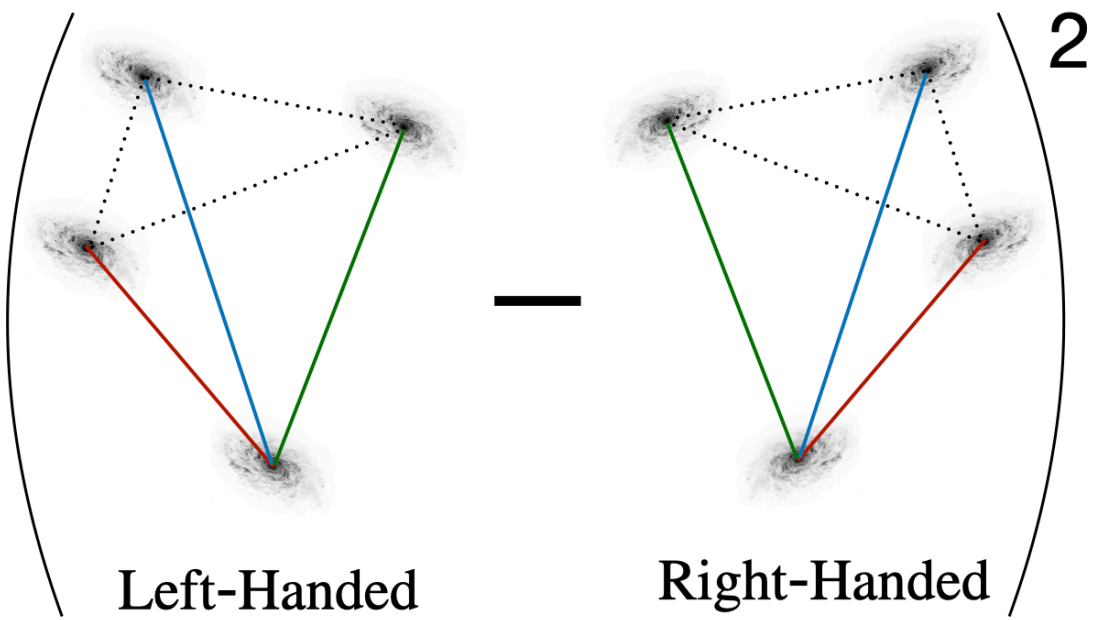
The primordial Universe could contain **mirror asymmetry**

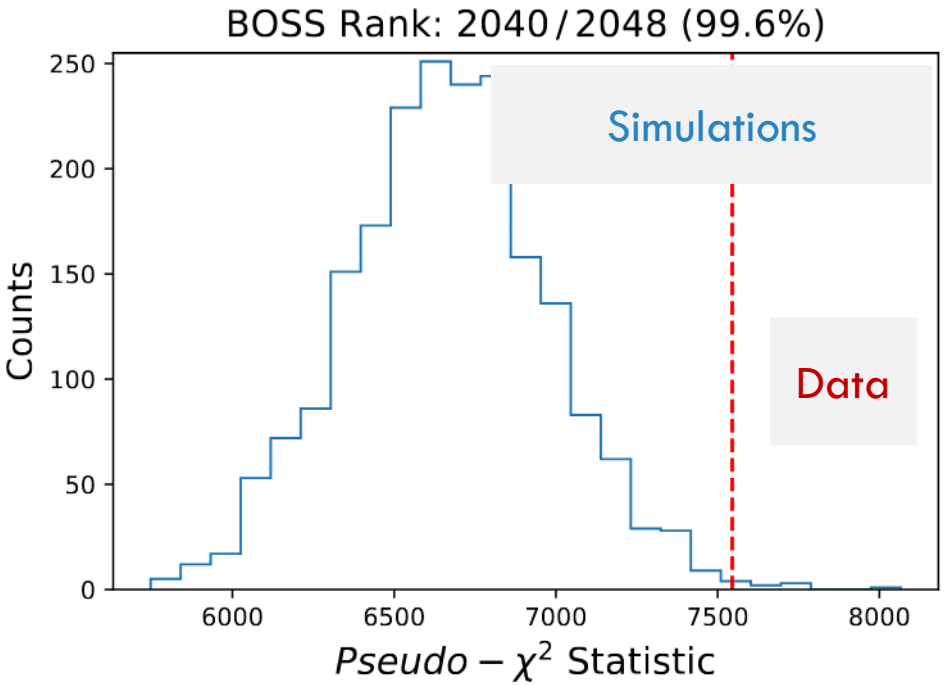
Search for in the **four-point function!**

- Not constrained by the CMB (yet)

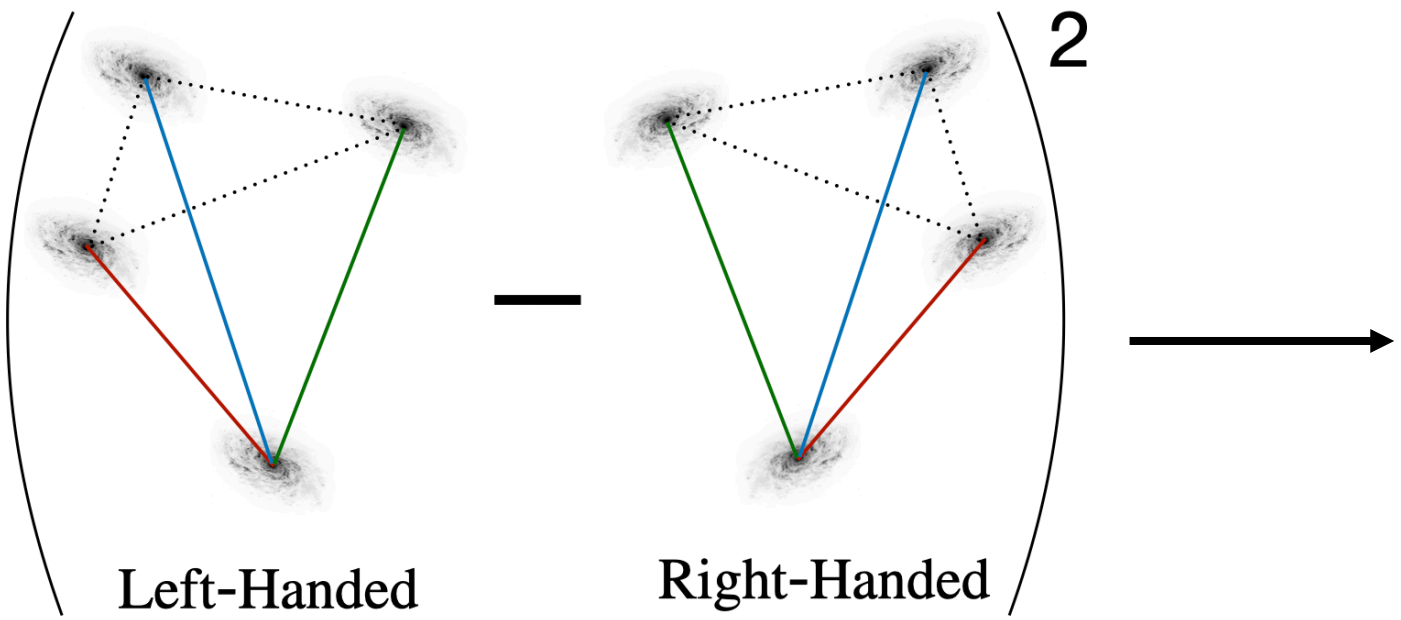


PARITY-ODD 4-POINT FUNCTIONS





PARITY-ODD 4-POINT FUNCTIONS



Conclusions

- Simulations do not capture noise properties of the data
- ***Or*** we have detected *parity-violating inflation* at 3σ???

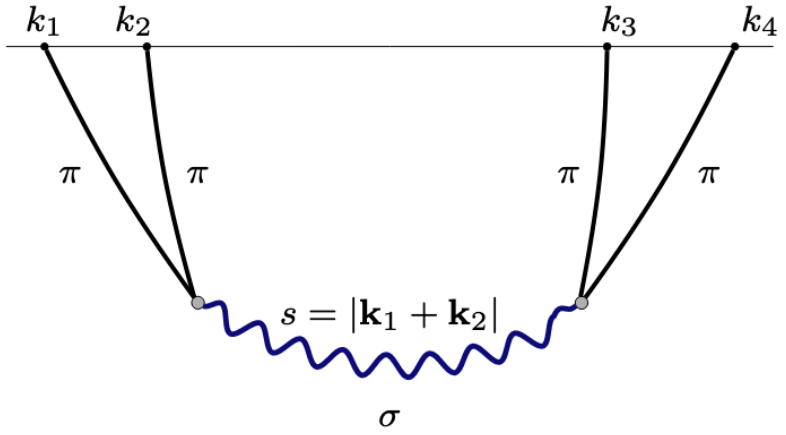
INFLATIONARY PARITY-VIOLATION

Possible models:

1. Inflationary particle exchange?
2. Ghost inflation?
3. Dynamical Chern-Simons inflation?

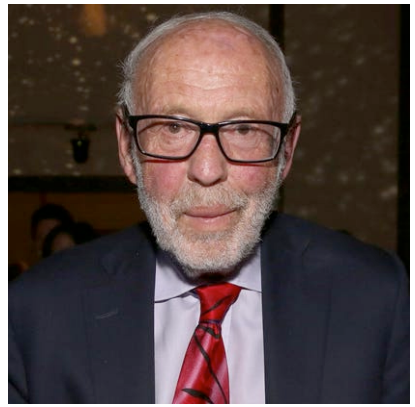
No evidence for any models so far!

Stay tuned for CMB results…



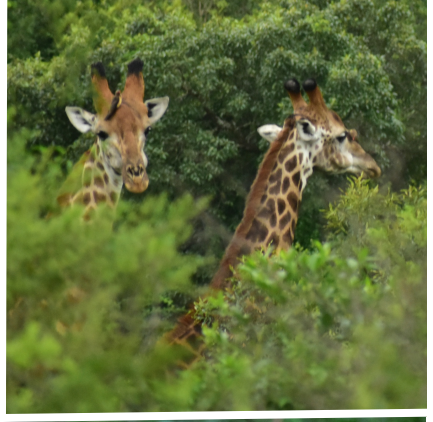
Spinning particles!

Ghost inflation!



Chern-Simons inflation

Cabass+22, Cabass, **Philcox**+22c, Creque-Sarbinowski, **Philcox** (in prep x2.)


CONCLUSIONS

Contact
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- Galaxy surveys can measure the Universe's **initial conditions**
- Safaris are an excellent place for cosmology
- Constraints are (mostly) **weak** compared to the CMB but will get much stronger soon!