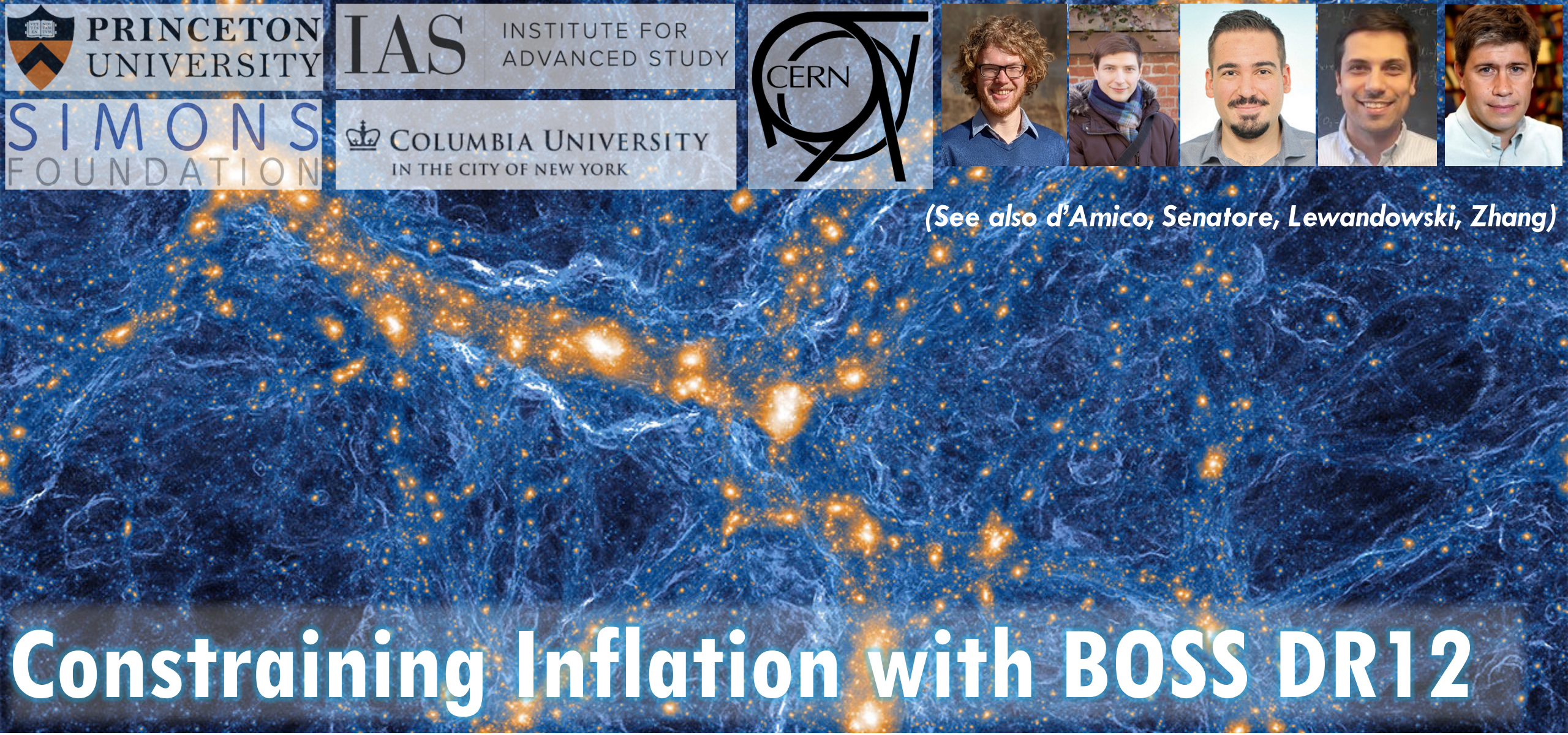


(See also d'Amico, Senatore, Lewandowski, Zhang)

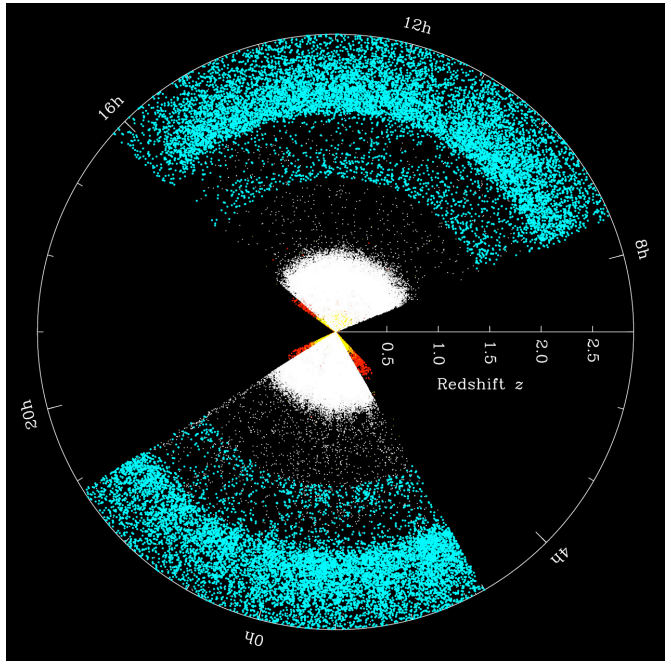
Constraining Inflation with BOSS DR12

Oliver Philcox (Columbia / Simons Foundation)

PNG Workshop, *September 2022*

Collaborators:
Mikhail Ivanov, Giovanni Cabass,
Marko Simonovic, Matias Zaldarriaga

FROM GALAXY SURVEYS TO INFLATION



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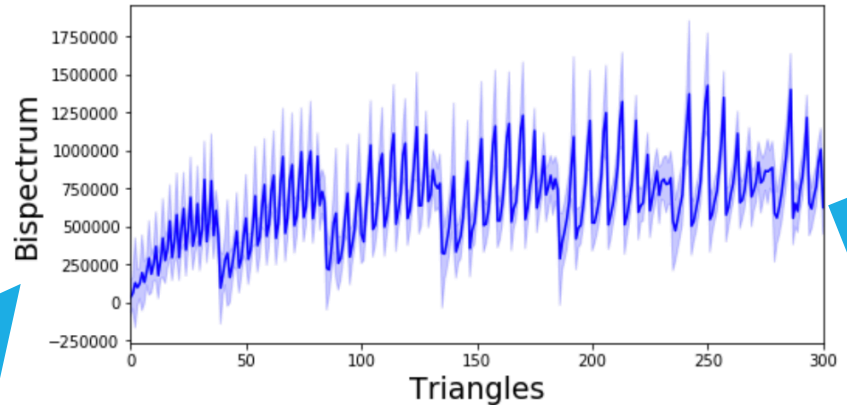

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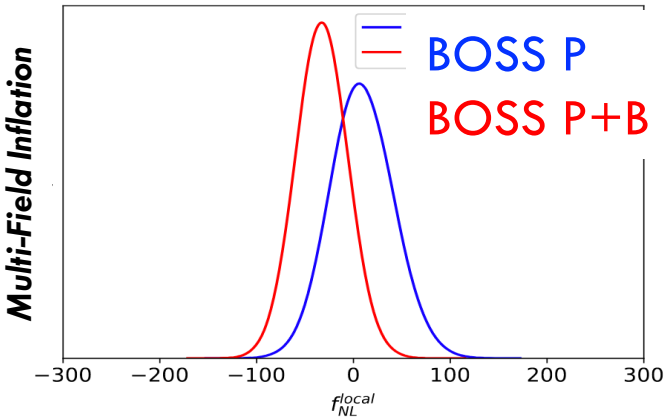


f_{NL} bounds

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

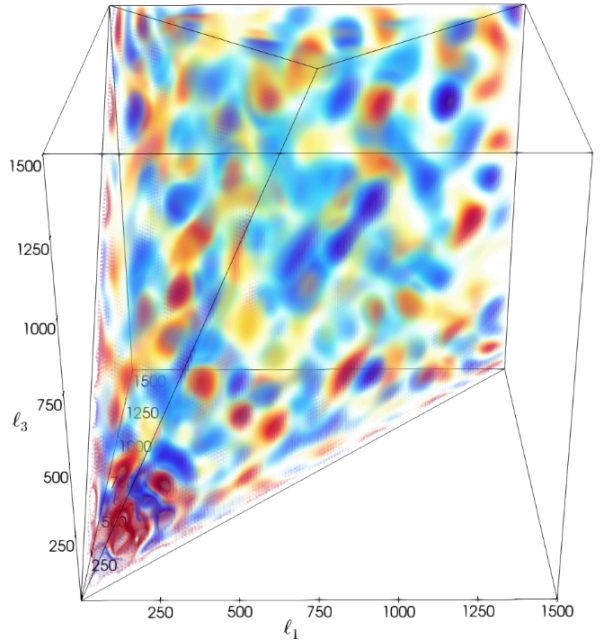
HOW CAN WE MEASURE $f_{\rm NL}$?

$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

1. CMB Bispectrum

See Will's talk!

Planck TTT Bispectrum



≈ 2× better with CMB-S4!

$f_{\rm NL}$ Constraints

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

Planck 2018 IX

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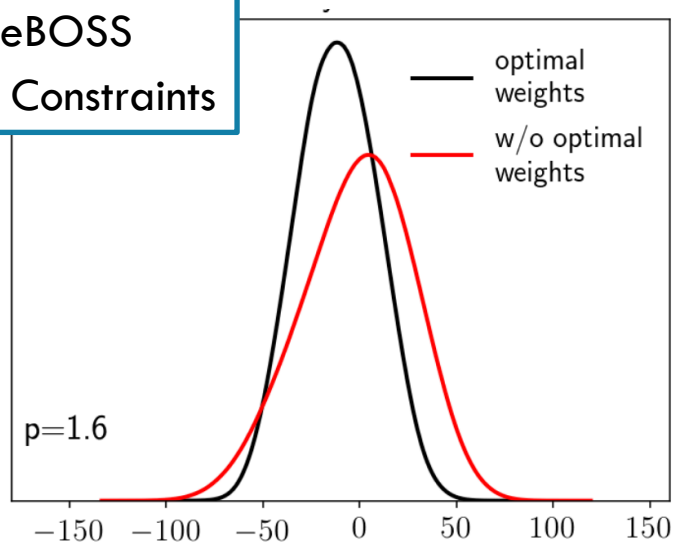
1. CMB Bispectrum

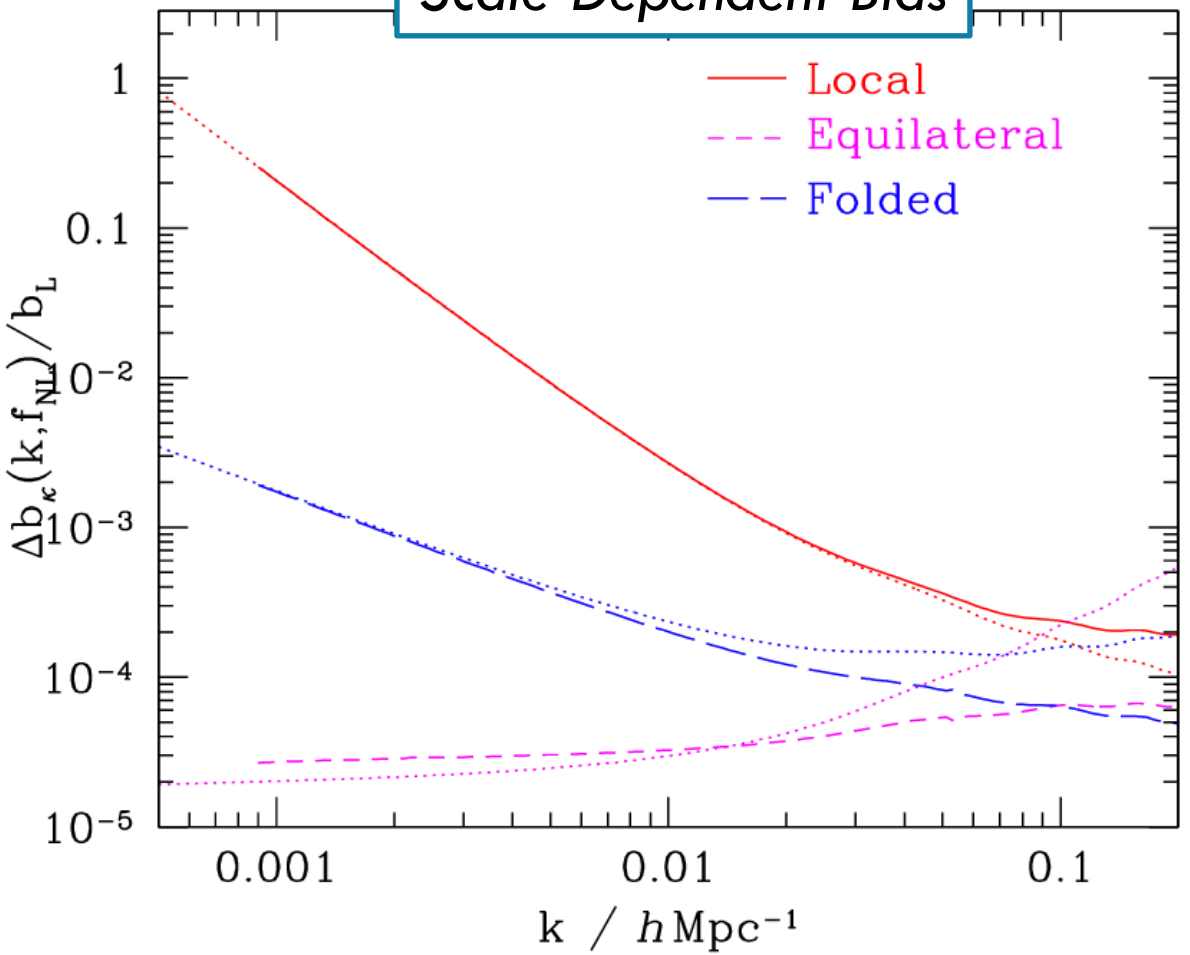
2. **Galaxy Power Spectrum**

See Eva-Maria and others' talks!

eBOSS $f_{\rm NL}^{\rm loc}$ Constraints



Scale-Dependent Bias



Desjacques & Seljak 10, eBOSS 21

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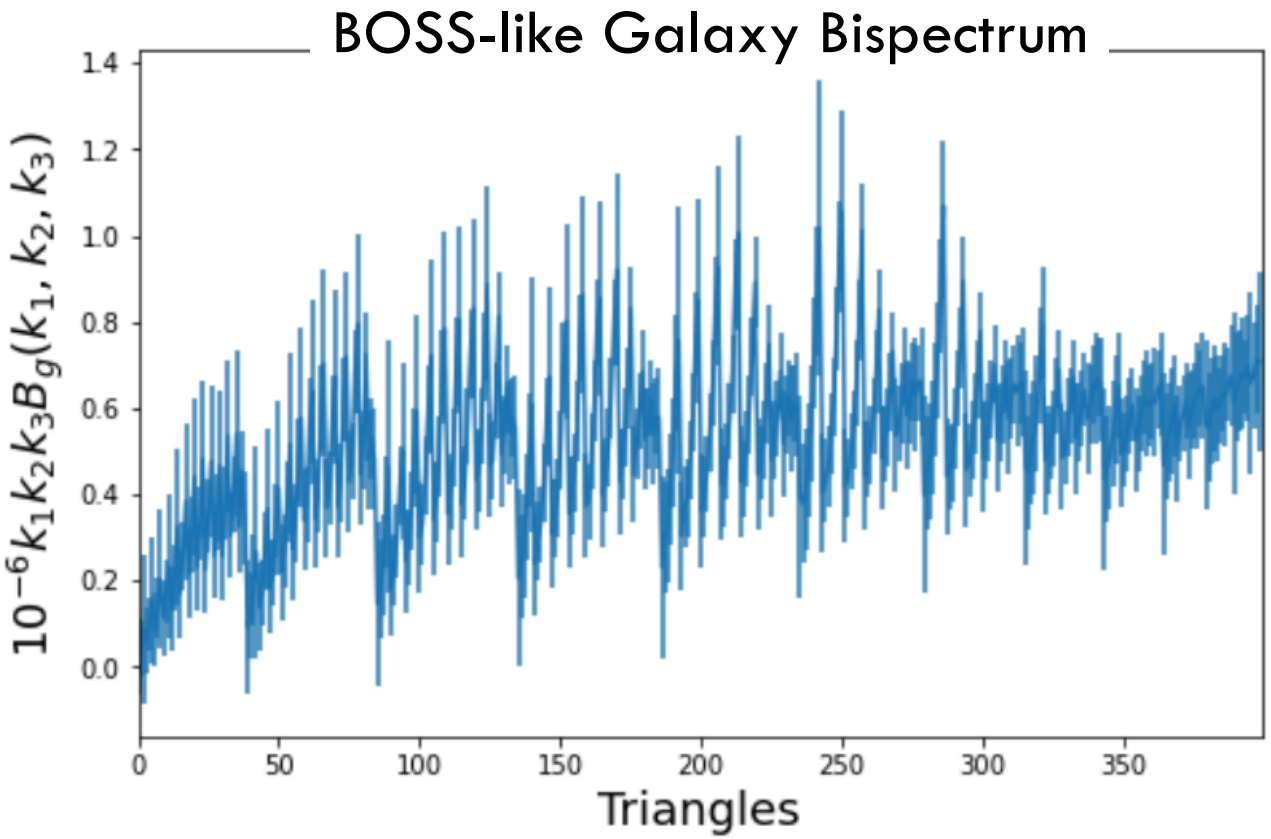
1. CMB Bispectrum
2. Galaxy Power Spectrum
3. **Galaxy Bispectrum**

See also Hector's talk!

We need a good theory model!



Philcox+21, Cabass+21,22

THE EFFECTIVE FIELD THEORY OF LSS

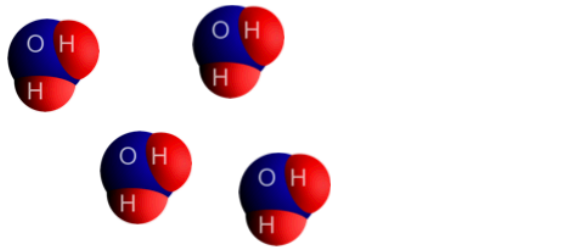
- **Analytic** theory for $\delta(\mathbf{x})$, based on the non-ideal **fluid equations**

$$\dot{v}^i + H v^i + v^j \partial_j v^i = \frac{1}{\rho} \partial_j \tau^{ij}$$

- A <u>controlled</u> **Taylor series** in $k/k_{\rm NL}$

(or $k\sigma_{\rm FoG}$, $kR_{\rm Halo}$)

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



large scales

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

MODELLING PNG

Theory model requires:

- Primordial bispectrum:

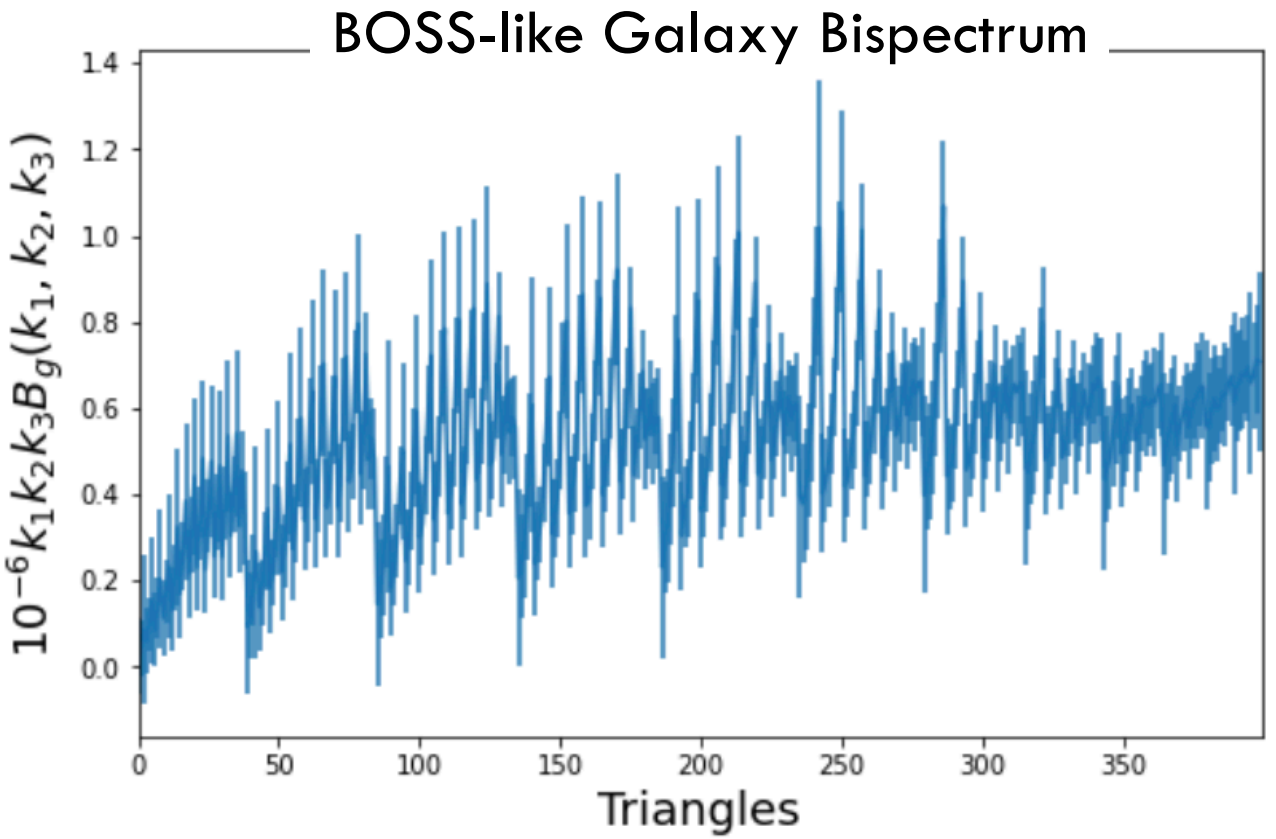
$$\langle \delta^{(1)}\delta^{(1)}\delta^{(1)} \rangle \sim f_{\rm NL} P^2(k)$$

- Scale dependent bias:

$$b_1(f_{\rm NL}) \to b_1 + (b_\phi f_{\rm NL})/k^2$$

- Loop corrections:

$$P_{gg}(\boldsymbol{k}) \to P_{gg}(\boldsymbol{k}) + f_{\rm NL} \int d\boldsymbol{q}\, \alpha\, P(\boldsymbol{q}) P(\boldsymbol{k}-\boldsymbol{q})$$

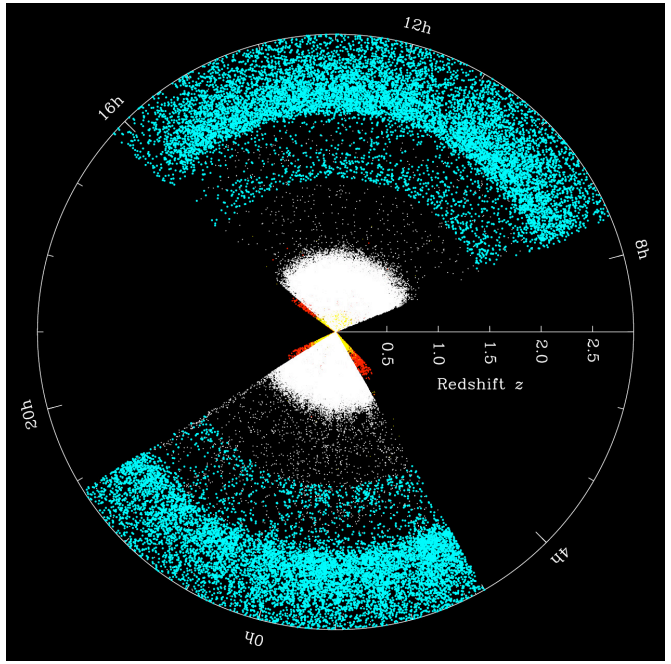


$$B_g = B_g(f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}, f_{\rm NL}^{\rm loc})$$

See GitHub.com/michalychforever/CLASS-PT

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

FROM GALAXY SURVEYS TO INFLATION



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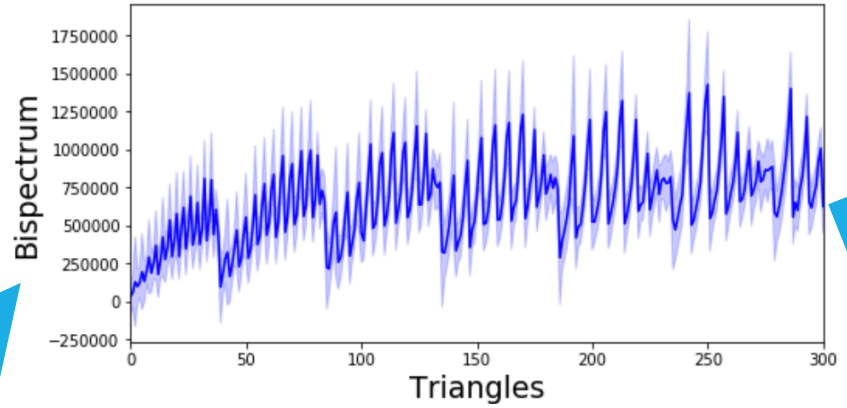

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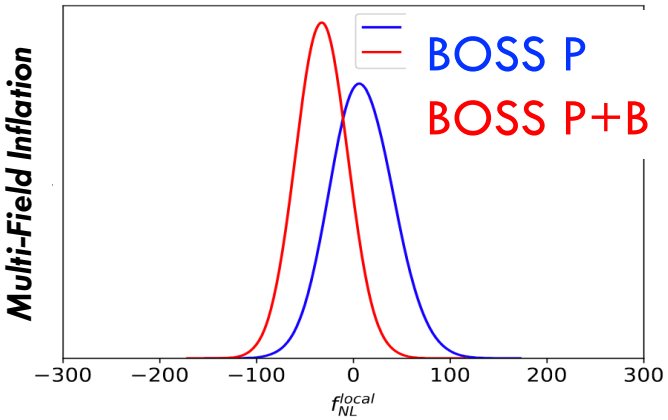


f_{NL} bounds

SDSS-III, Philcox+22, Cabass+22

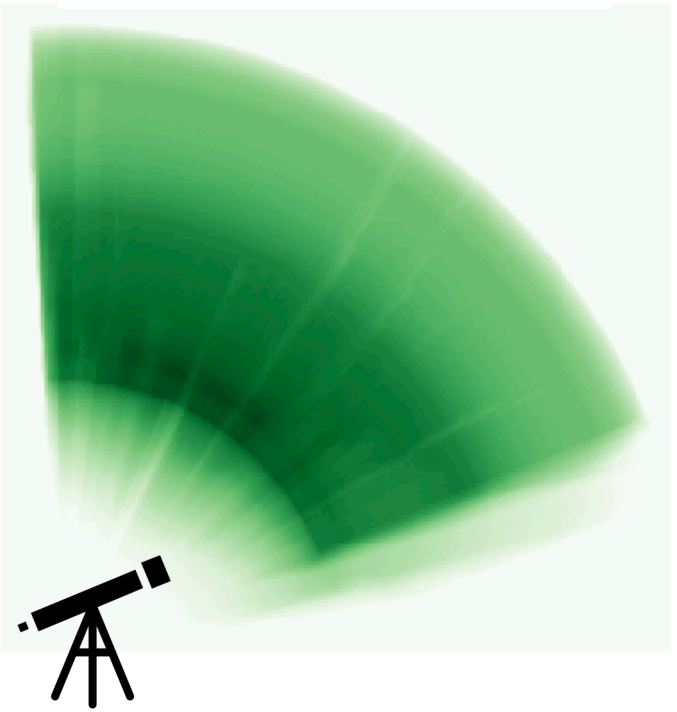
HOW TO MEASURE A BISPECTRUM

We usually measure the **window-convolved** bispectrum

$$B_g(\mathbf{k}_1, \mathbf{k}_2) \to \int_{\mathbf{p}_1 \mathbf{p}_2} W(\mathbf{k}_1 - \mathbf{p}_1) W(\mathbf{k}_2 - \mathbf{p}_2) W(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{k}_1 - \mathbf{k}_2) B_g(\mathbf{p}_1, \mathbf{p}_2)$$

Understanding this is **crucial** for getting robust $f_{\rm NL}$ bounds

Survey Mask, $W(\mathbf{r})$



Gil-Marin 16, **Philcox** 21 (see also Pardede+22)

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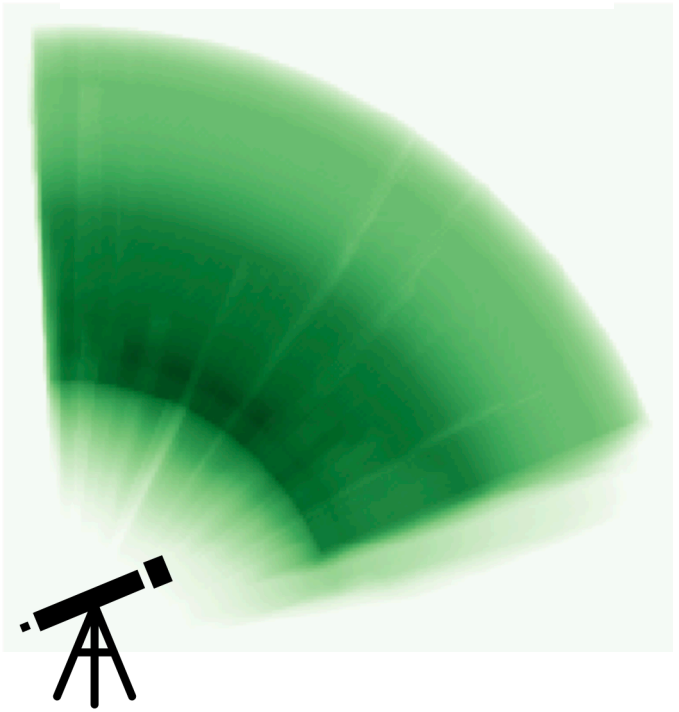


Understanding this is **crucial** for getting robust $f_{\rm NL}$ bounds

Three options:

1. Explicitly perform convolution integral *[very expensive!]*
2. Make approximations *[robust?]*
3. Circumvent the problem!

See Kevin's talk!

Gil-Marin 16, **Philcox** 21 (see also Pardede+22)

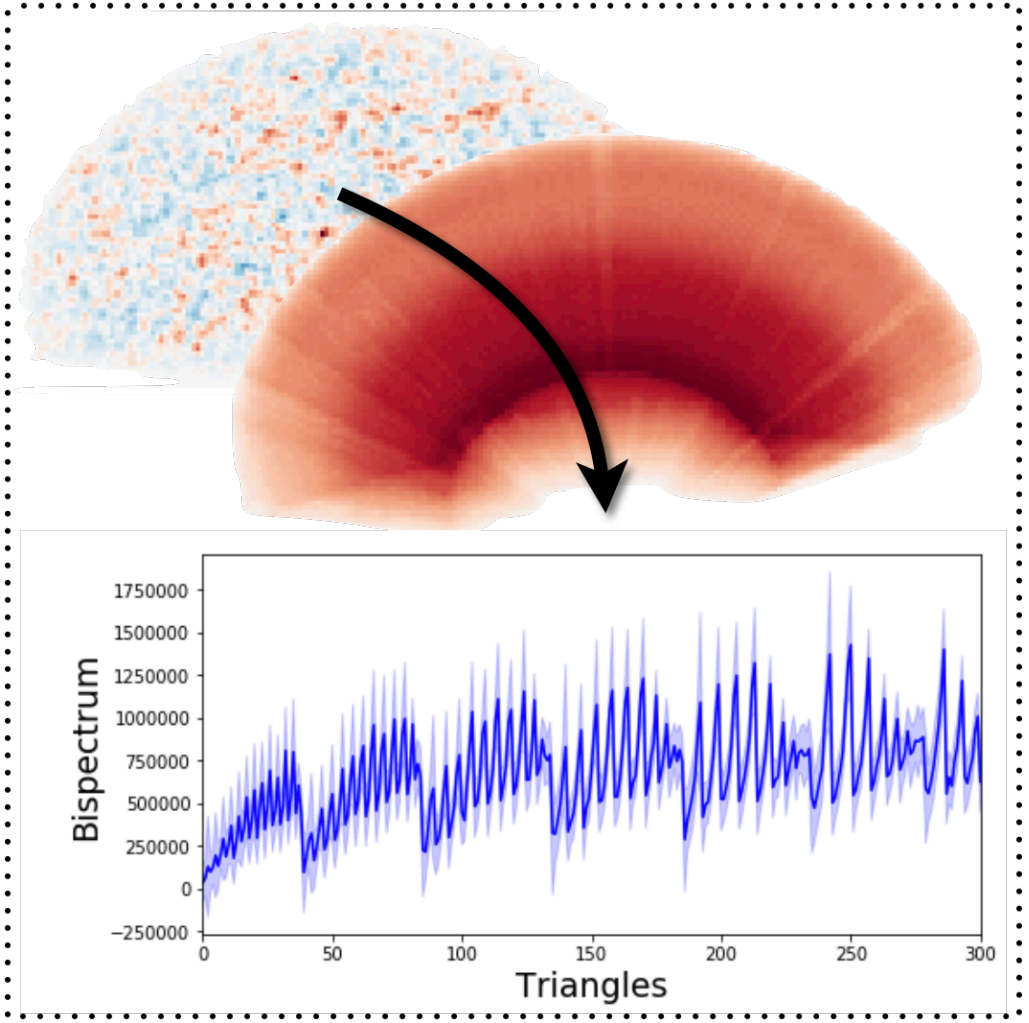
BISPECTRA WITHOUT WINDOWS

Estimate the **unwindowed** bispectrum directly

$$B_g^{\rm win}(\mathbf{k}_1,\mathbf{k}_2) = \int_{\mathbf{p}_1\mathbf{p}_2} W(\mathbf{k}_1-\mathbf{p}_1)W(\mathbf{k}_2-\mathbf{p}_2)W(\mathbf{p}_1+\mathbf{p}_2-\mathbf{k}_1-\mathbf{k}_2)B_g(\mathbf{p}_1,\mathbf{p}_2)$$

We use a **maximum-likelihood** estimator for the **true** bispectrum

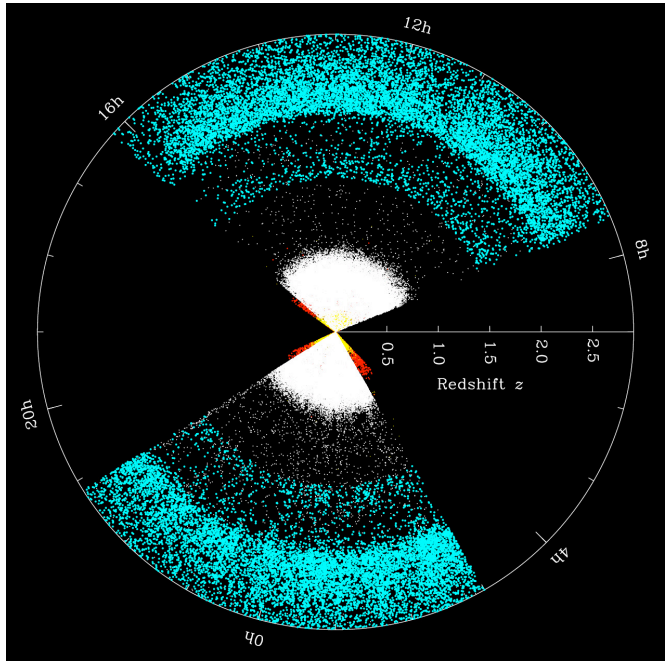
$$\nabla_{B_g} L[\text{data}|B_g] = 0 \quad \Rightarrow \quad \widehat{B}_g = \cdots$$



See GitHub.com/oliverphilcox/Spectra-Without-Windows

Philcox 20, 21

FROM GALAXY SURVEYS TO INFLATION



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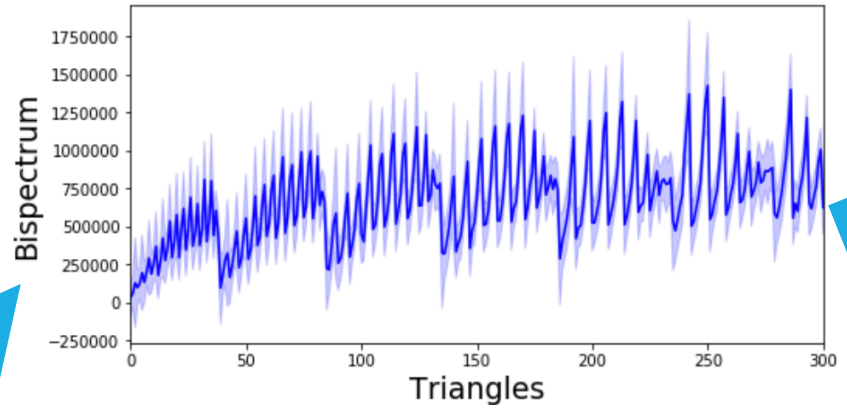

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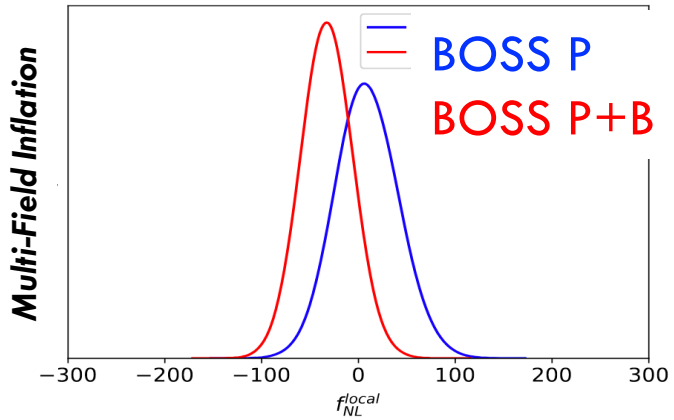
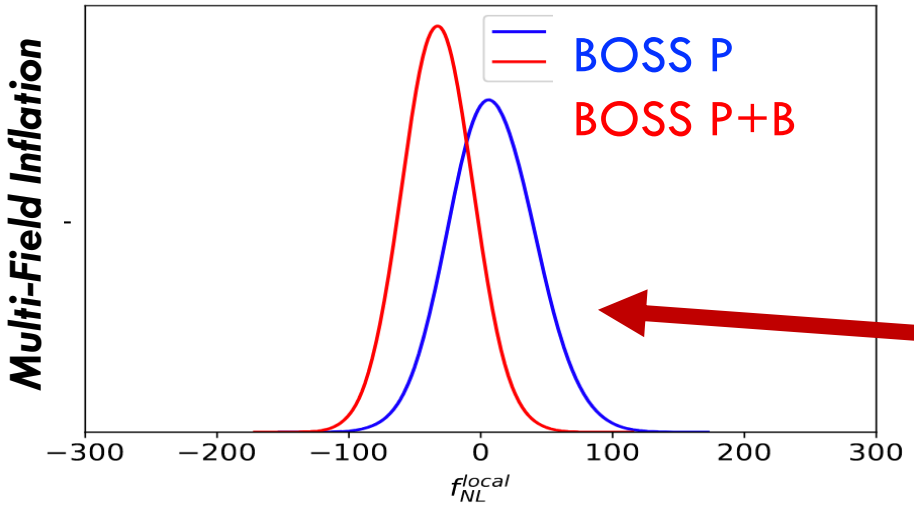


f_{NL} bounds

SDSS-III, Philcox+22, Cabass+22

CONSTRAINTS ON $f_{\rm NL}$



BOSS Power Spectrum + Bispectrum + $O(f_{\rm NL})$ Theory Model

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

Really measuring $b_\phi f_{\rm NL}$ - see Alex's talk!

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

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

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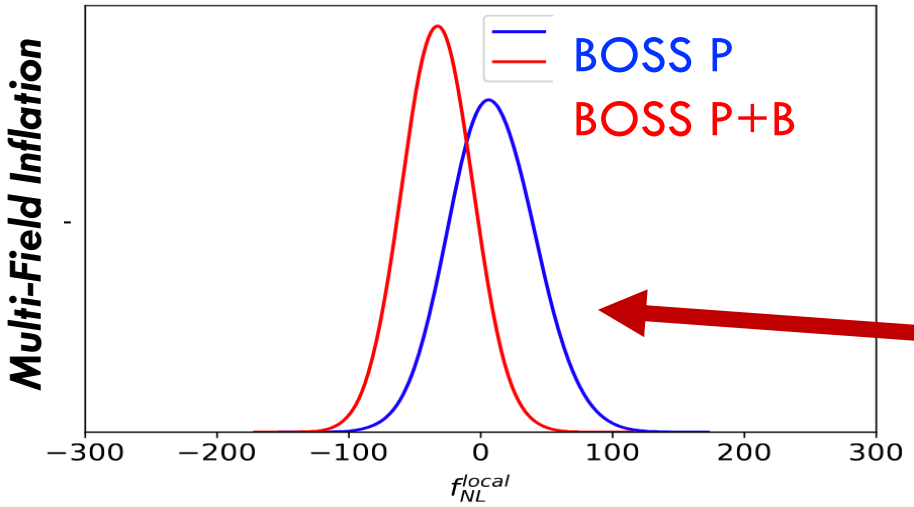

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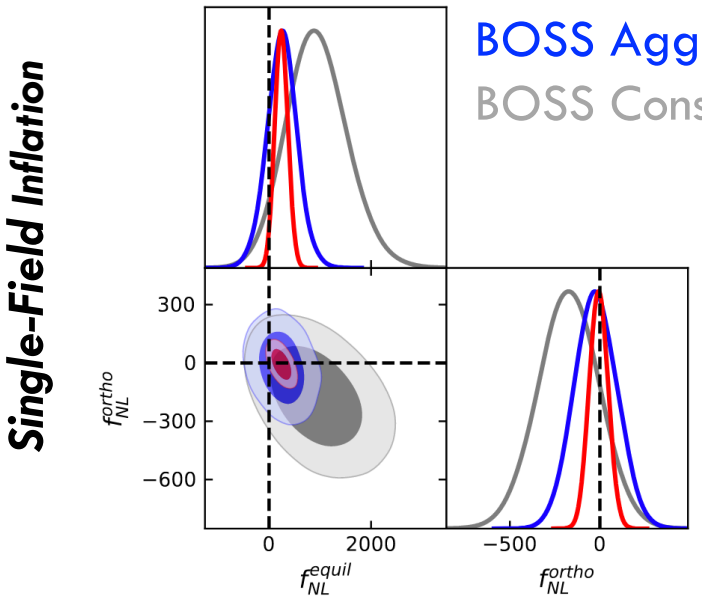


$$f_{\rm NL}^{\rm equil} = 260 \pm 300$$

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

- First measurement without CMB!
- Needs bispectrum!

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

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

CONSTRAINING INFLATION

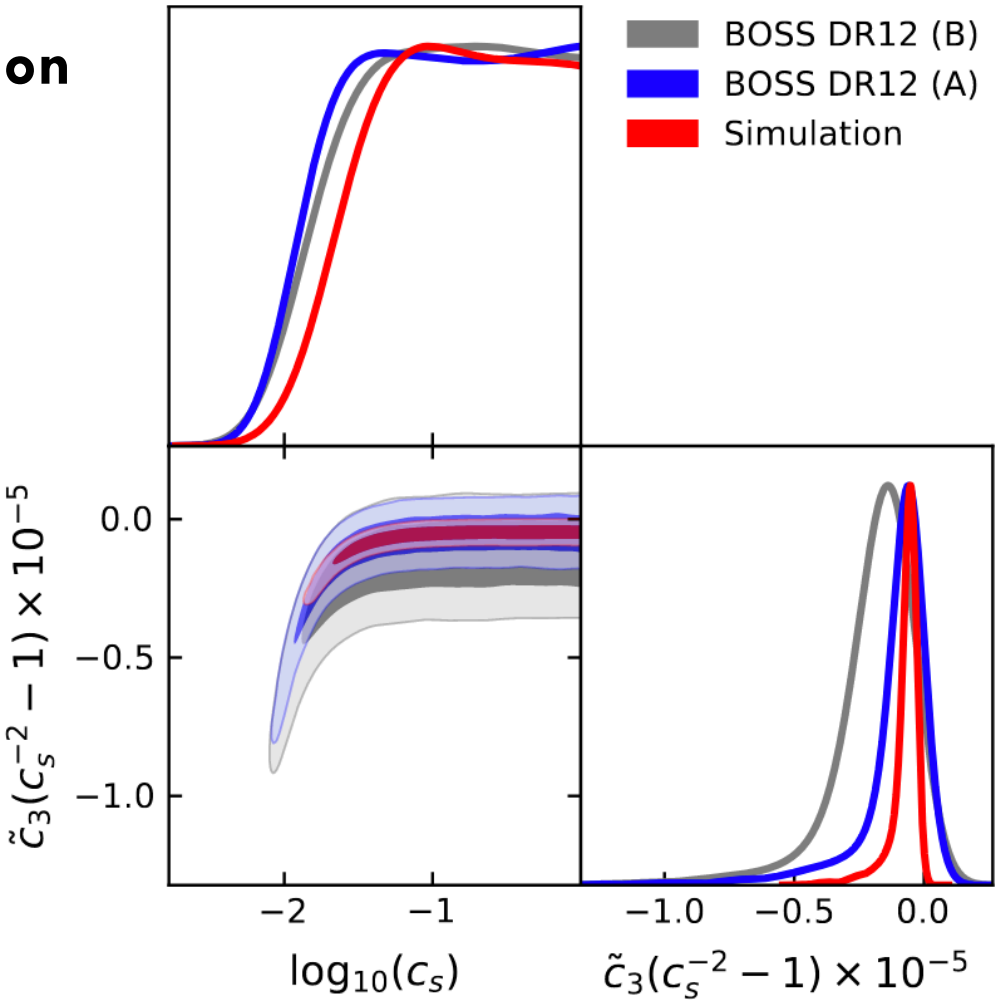
We can relate $f_{\rm NL}$ to the **couplings** in the **EFT of Inflation**

Most general 3rd order single-field action:

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

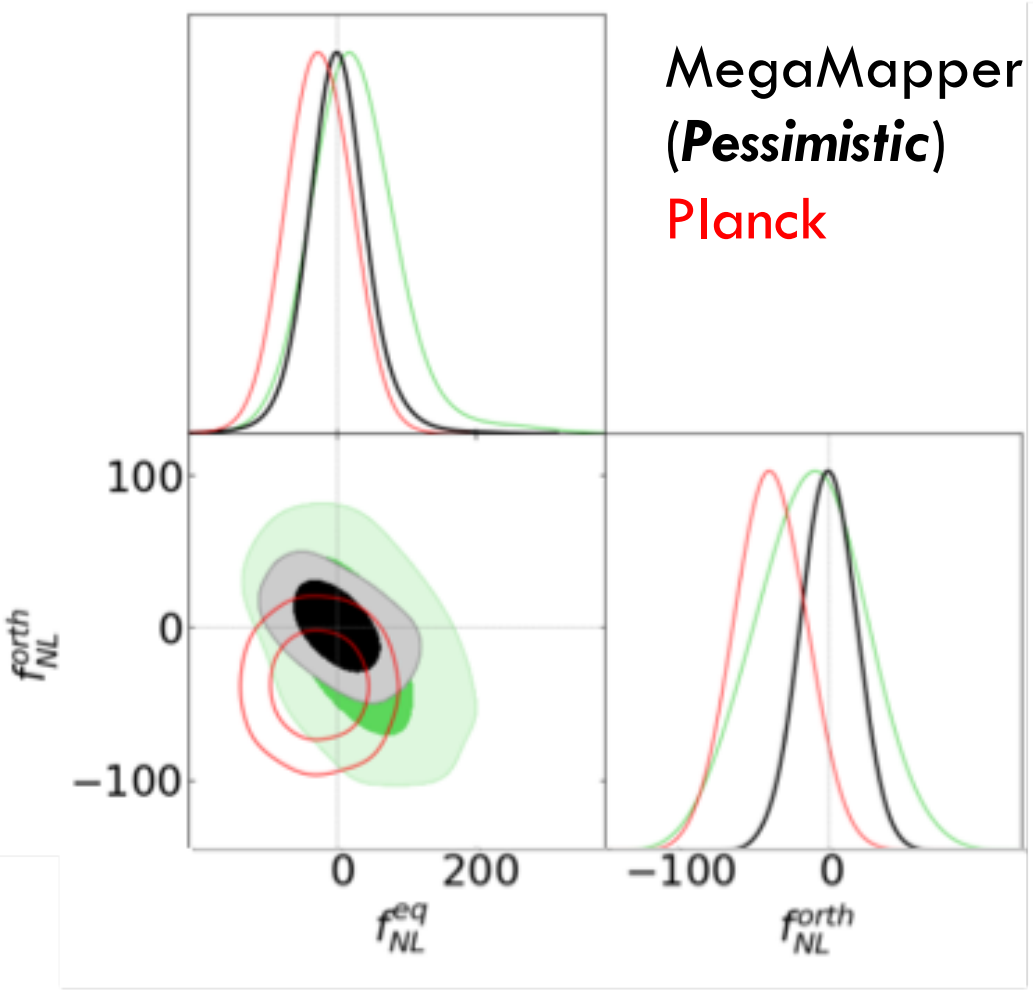
We find $c_s^2 \geq 0.013$ at 95% CL

See Ana's talk!



Senatore+09, Cabass+21

FUTURE PROSPECTS



- MegaMapper gets **better** non-local PNG constraints than *Planck*
- **Actual** constraints will use **higher** k_{max}:
  - Higher redshift
  - Better modelling

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

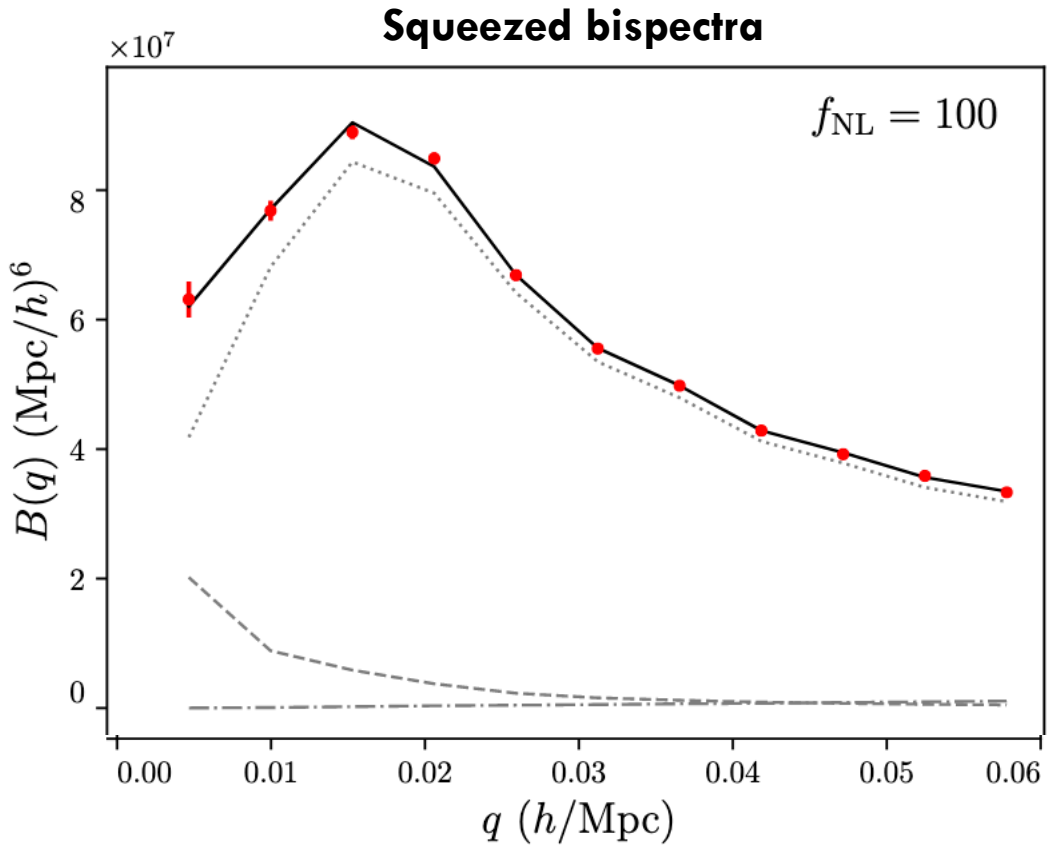
OTHER IDEAS: BEYOND PERTURBATION THEORY

Sam Goldstein

- We can measure **local** $f_{\rm NL}$ from the **non-linear** bispectrum using **consistency relations**

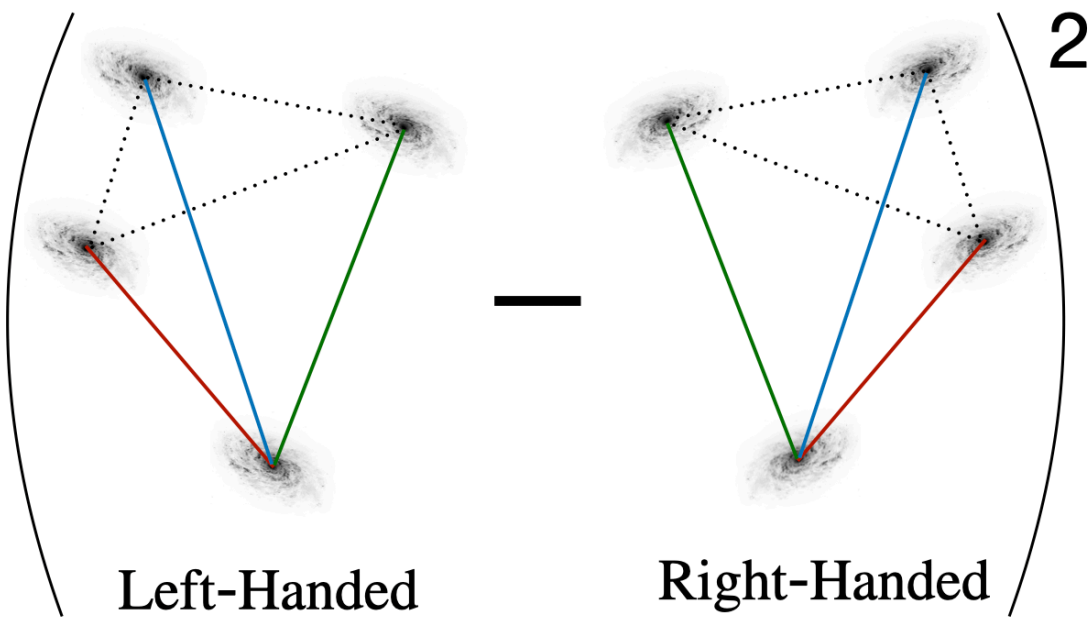
$$B(\boldsymbol{q},\boldsymbol{k}) = \frac{6 f_{\rm NL}\Omega_{m,0}H_0^2}{D_{\rm md}(z)}\,\frac{\partial P(k)}{\partial \log \sigma_8^2}\,\frac{P(q)}{q^2 T(q)} + \mathcal{O}(f_{\rm NL}^2)$$

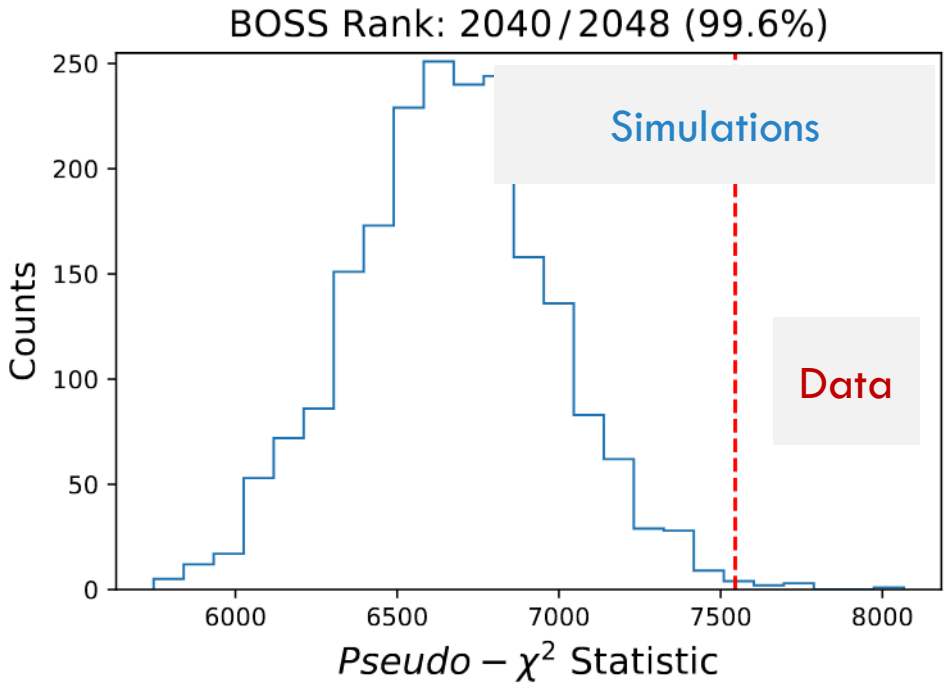
- This gives **accurate** $f_{\rm NL}^{\rm loc}$ constraints for matter at $k = 0.6h/\mathrm{Mpc}$



Goldstein+22

OTHER IDEAS: PARITY-ODD 4-POINT FUNCTIONS

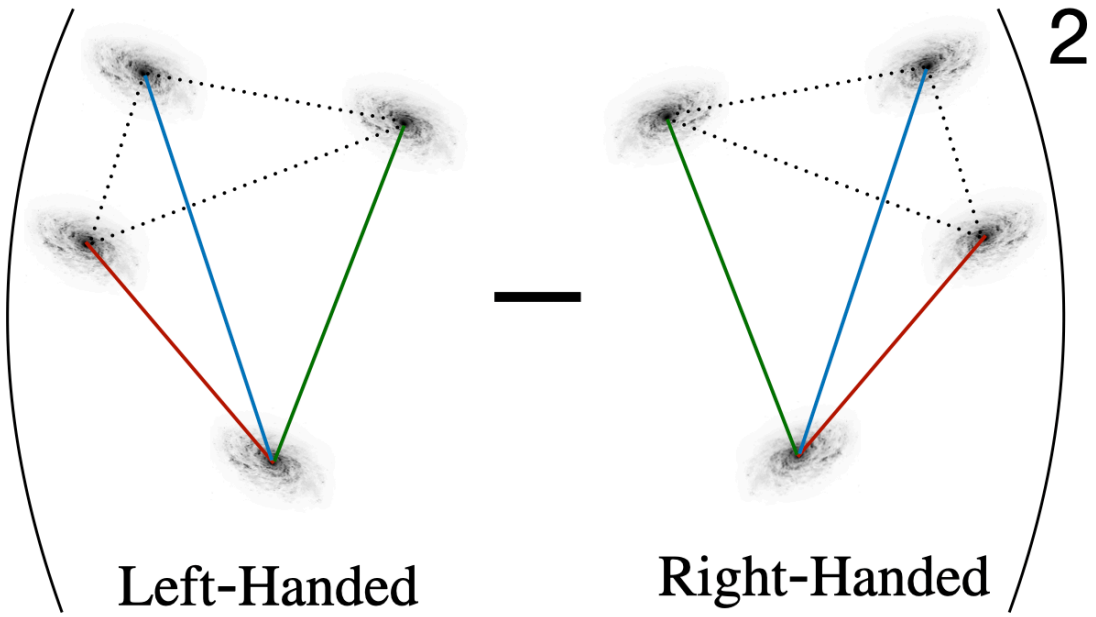




Conclusions

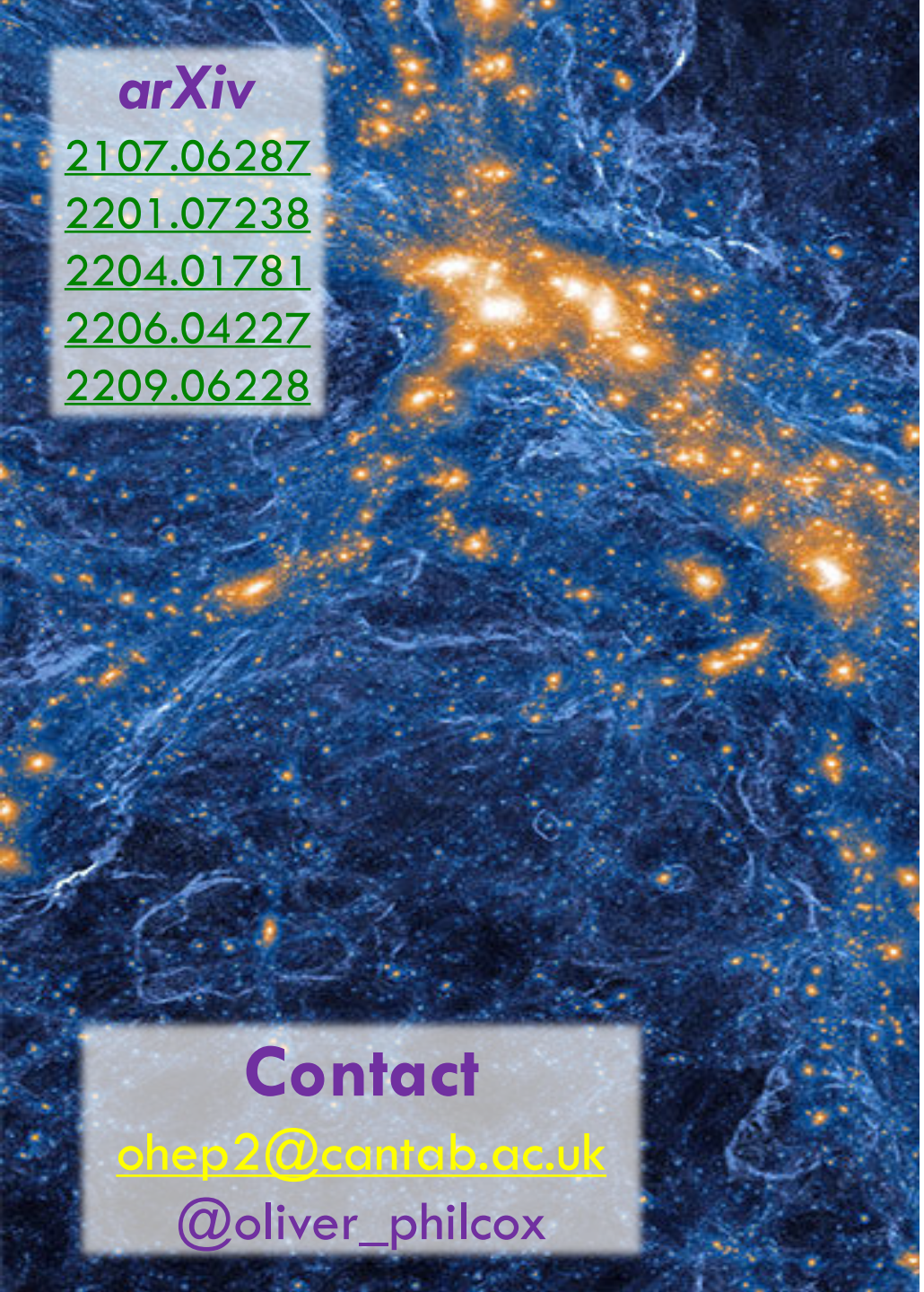
- Simulations do not capture noise properties of the data
- ***Or*** we have detected *parity-violating inflation* at 3σ???

BONUS: PARITY-ODD 4-POINT FUNCTIONS



Conclusions

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



arXiv

2107.06287
2201.07238
2204.01781
2206.04227
2209.06228

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CONCLUSIONS

- We can measure **any** type of 3-point PNG using the galaxy **power spectrum** and **bispectrum**
- Constraints are **weak** compared to the CMB but will get much stronger soon!
- We can learn more from non-perturbative physics and higher-point functions!