PRINCETON UNIVERSITY

IAS INSTITUTE FOR ADVANCED STUDY

An *Unofficial* BOSS DR12 Analysis:

Cosmology from the Galaxy Power Spectrum and Bispectrum

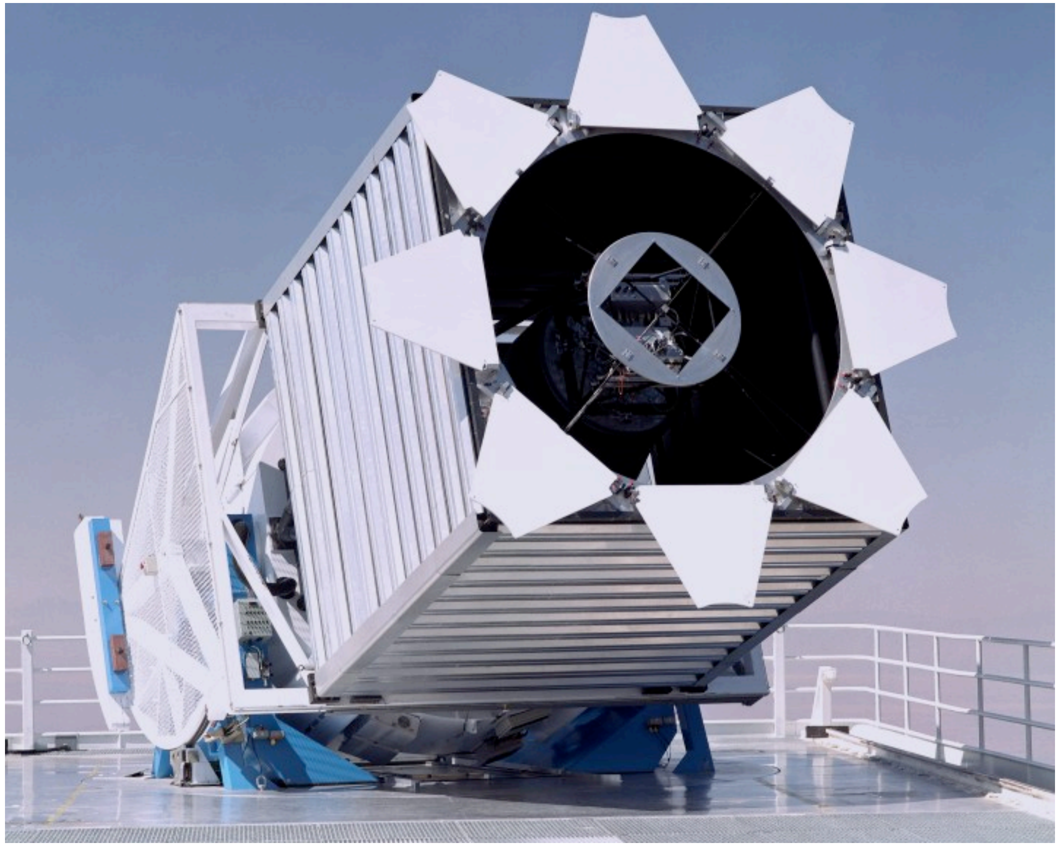
Oliver Philcox (Princeton / IAS)

Misha Ivanov (IAS)

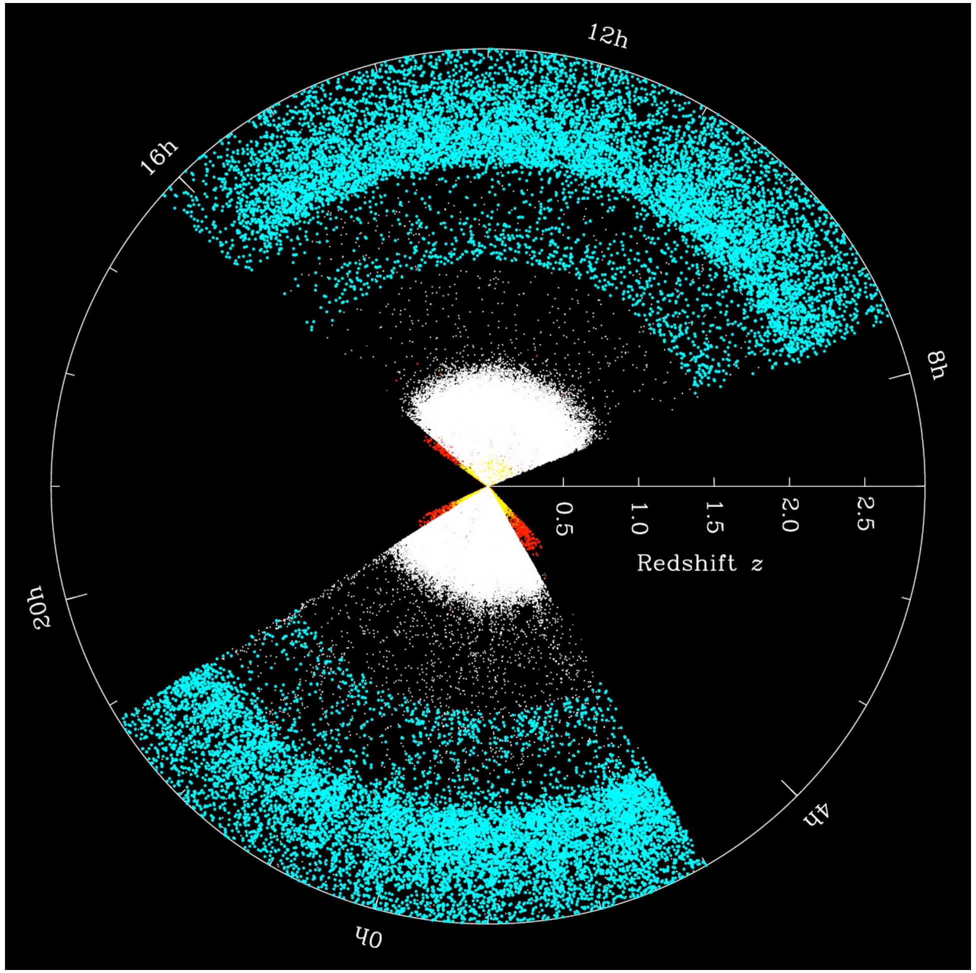
with Giovanni Cabass (IAS), Marko Simonovic (CERN), and Matias Zaldarriaga (IAS)

Tri-State Cosmology Meeting, CCA 18/02/22

COSMOLOGY FROM SPECTROSCOPIC SURVEYS



Big Telescope



10^6 Galaxy Positions

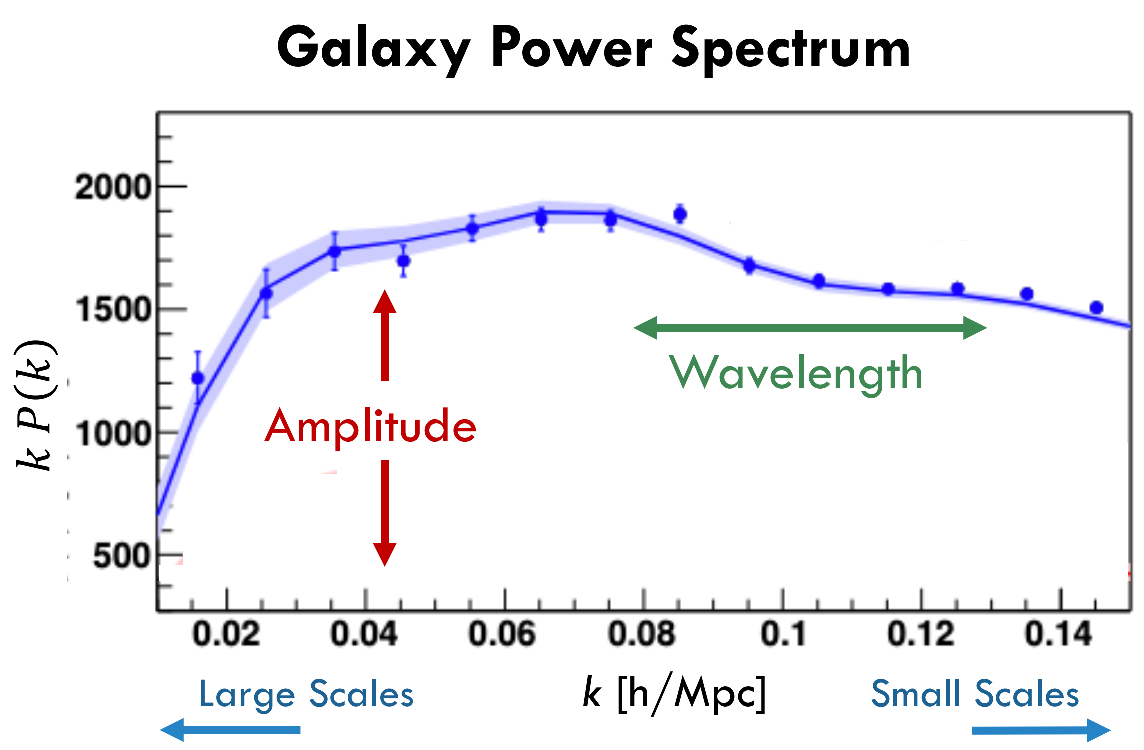
SDSS-III

WHAT DO WE DO WITH THE DATA?

- Compress the 10^6 galaxy positions to a **power spectrum**

- Use a **scaling analysis** to measure:
  - Overall **amplitude** (= primordial amplitude)
  - **Wiggle** positions (= BAO feature)

- Robust way to constrain **growth rate** and **expansion history**, $H(z)$

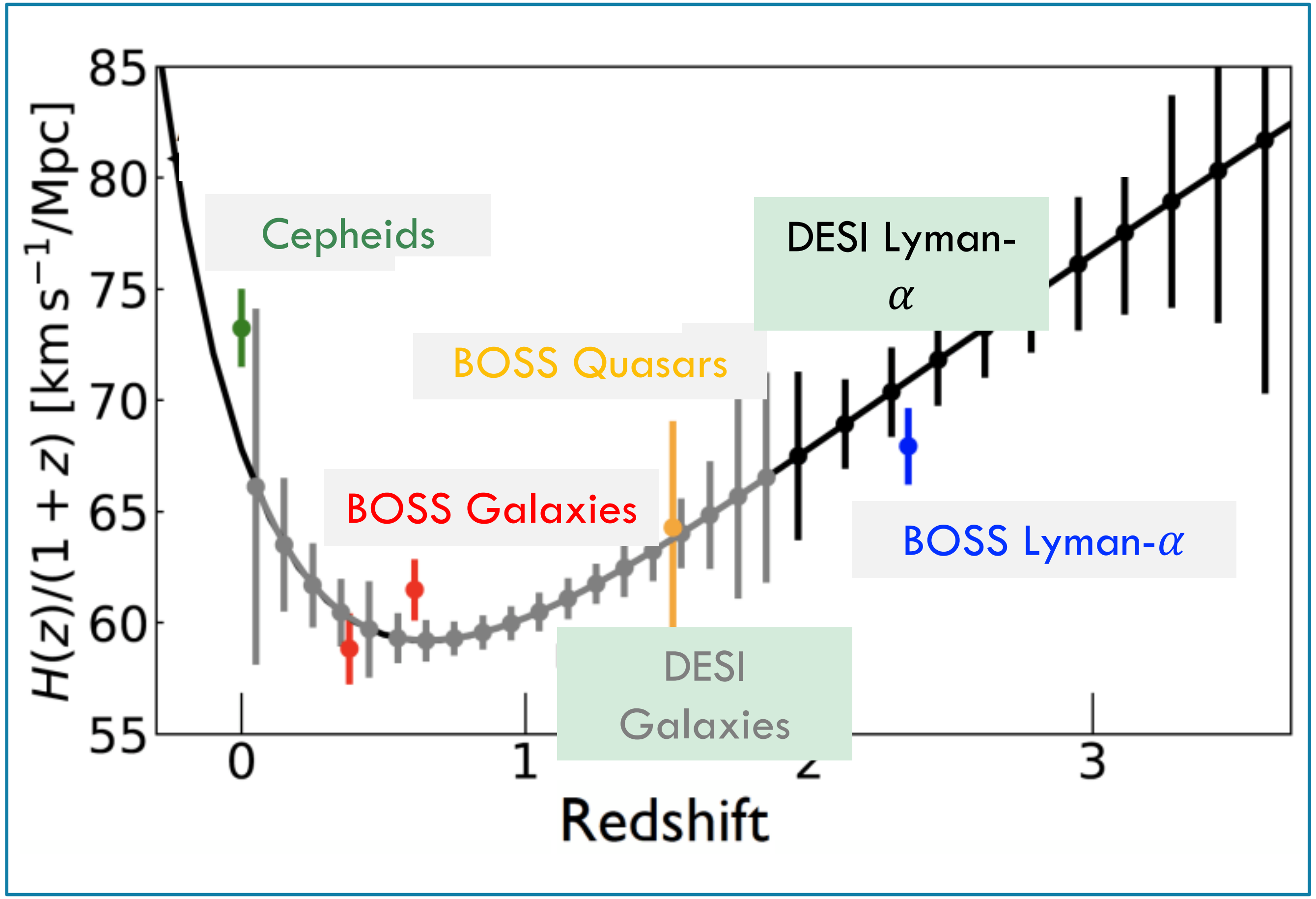


BOSS DR12 Galaxy Survey (monopole only)

e.g. Beutler+17, Gil-Marin+15,17, Alam+20

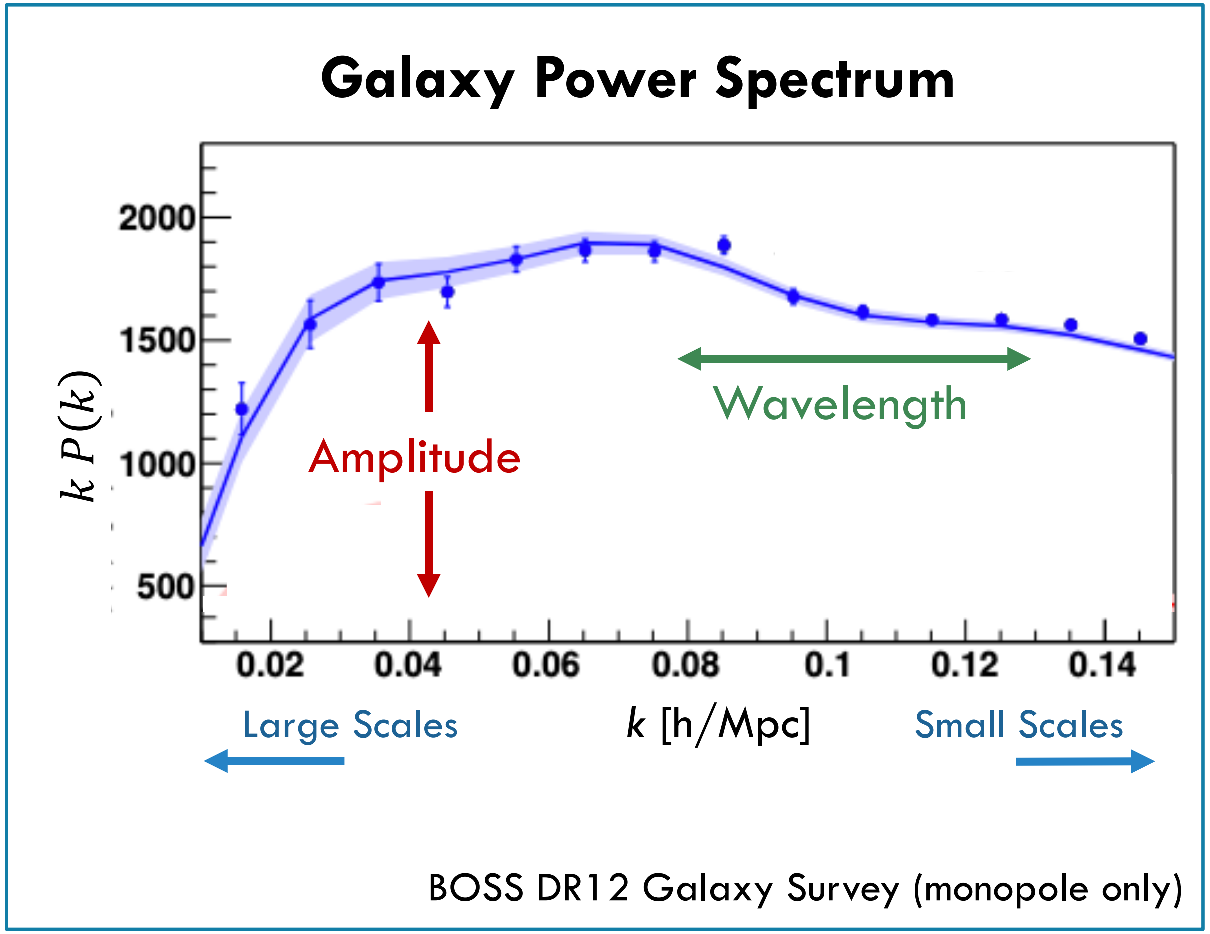
WHAT DO WE DO WITH THE DATA?

- Compress the 10^6 galaxy positions to a **power spectrum**
- Use a **scaling analysis** to measure:
  - Overall **amplitude** (= primordial amplitude)
  - **Wiggle** positions (= BAO feature)
- Robust way to constrain **growth rate** and **expansion history,** $H(z)$



WHAT COULD WE DO WITH THE DATA?

- This is *not* all the available information!



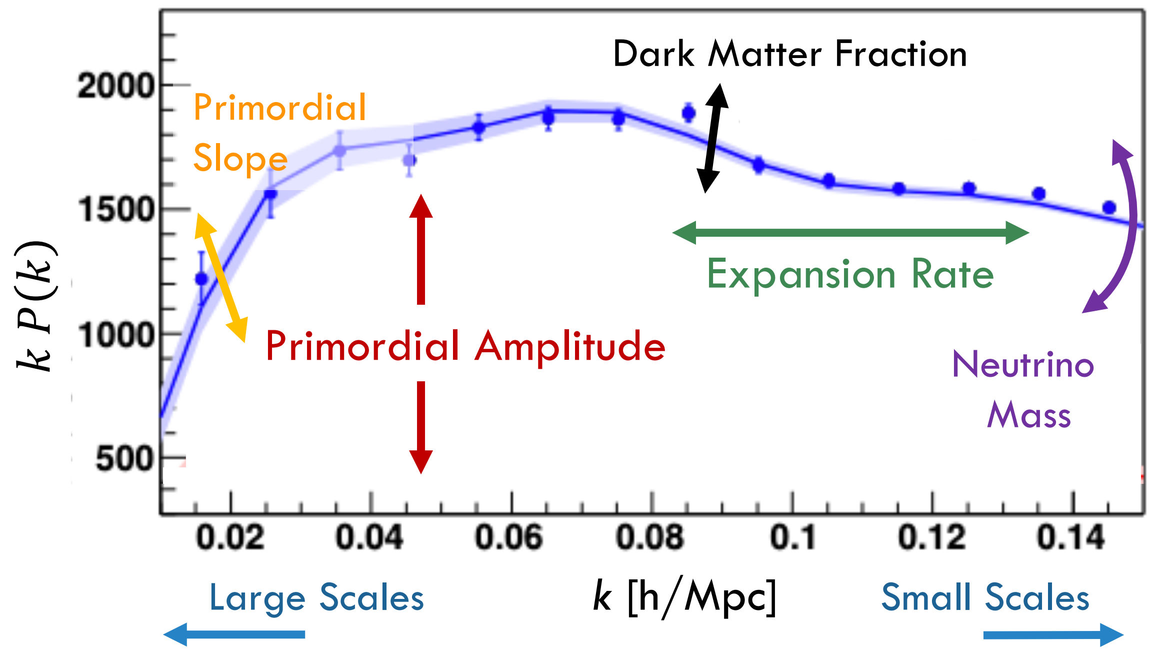
e.g. Beutler+17, Gil-Marin+15,17, Alam+20

WHAT COULD WE DO WITH THE DATA?

- This is *not* all the available information!
- Measure parameters **directly** from the **full shape** of the galaxy power spectrum
- This is just like for the CMB!

This needs an accurate theory model…

Galaxy Power Spectrum



BOSS DR12 Galaxy Survey, Beutler+17

e.g. Ivanov+19,20, d'Amico+19,20, **Philcox**+20ab, Chen+21, Kobayashi+21

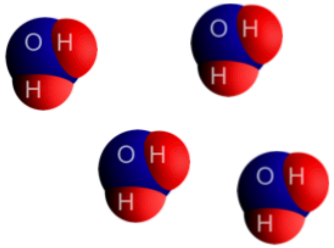
THE EFFECTIVE FIELD THEORY OF LARGE SCALE STRUCTURE

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

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

This includes:

- **Back-reaction** of small-scale physics on large-scale modes
- Long-wavelength displacements
- Galaxy bias
- Redshift-space distortions
- Primordial non-Gaussianity etc.



large scales

Arbitrarily accurate on large scales!

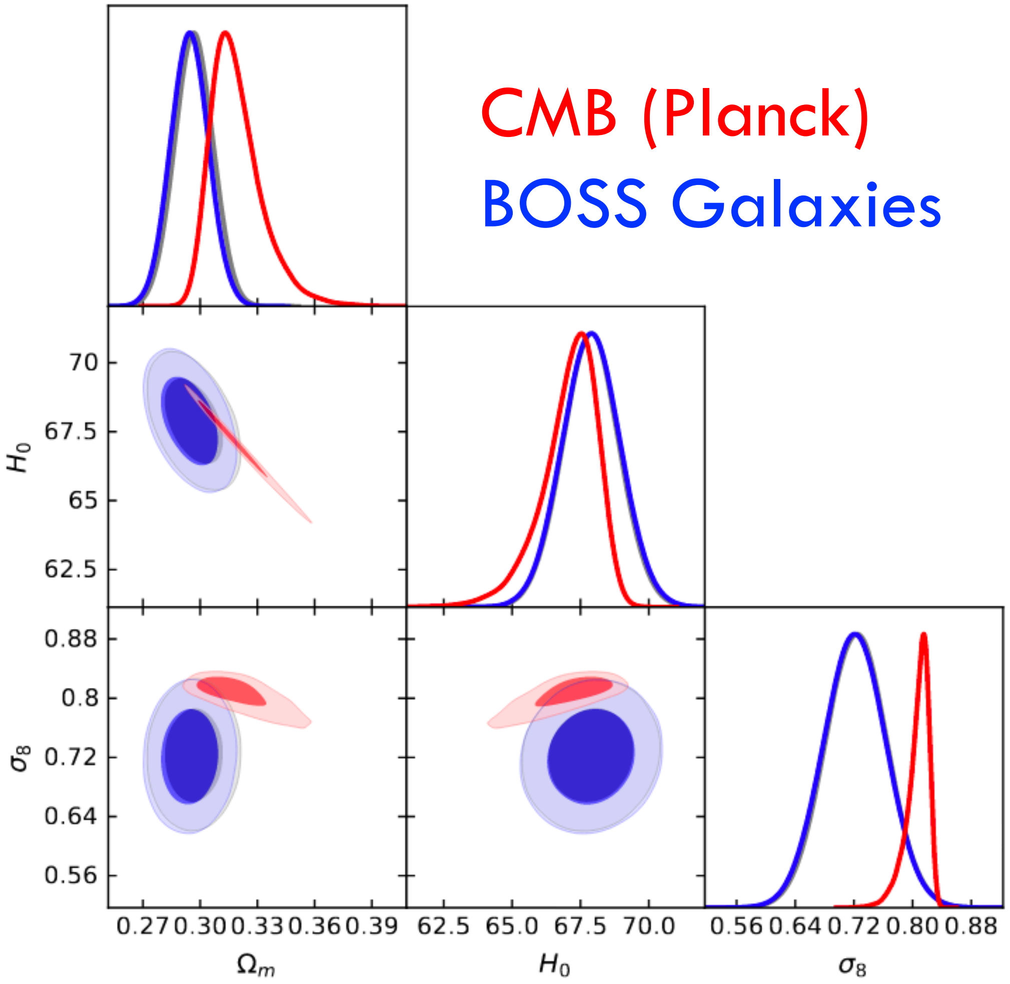
e.g. Baumann, Carrasco, Assassi, Senatore, Zaldarriaga, etc.

WHAT COULD WE DO WITH THE DATA?

- Theory tested at **high precision** in blind mock challenges → it works!

- Applied to **BOSS power spectra**

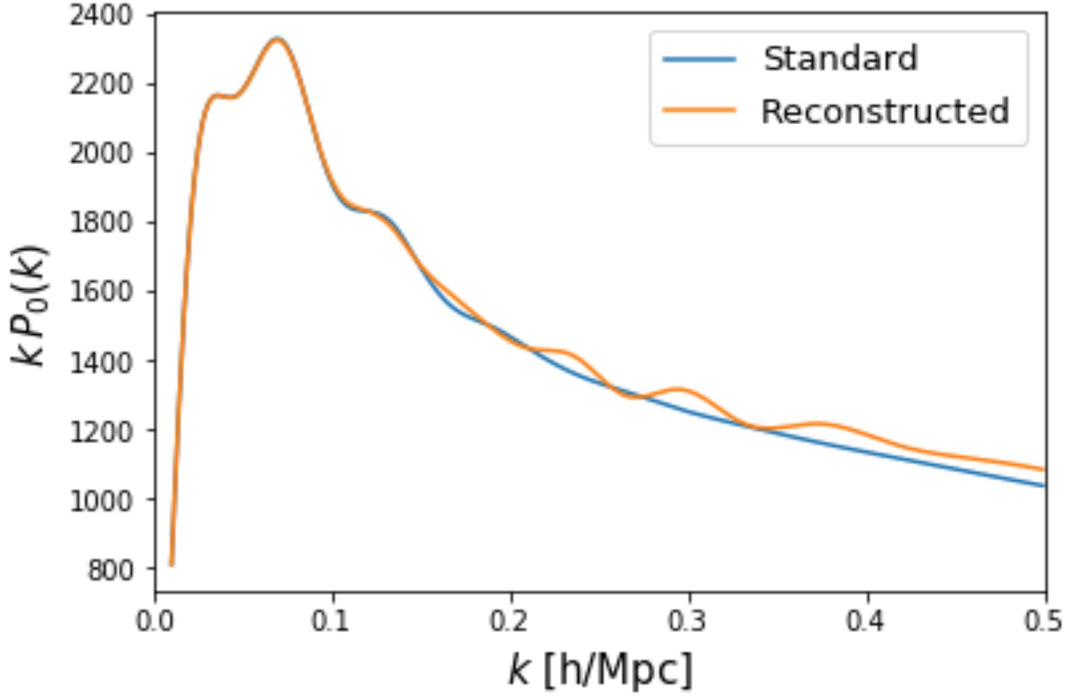
	H_0	Ω_m	σ_8
BOSS 2021	68.8 ± 1.2	0.32 ± 0.01	0.73 ± 0.04
Planck 2018 (TT, TE, EE, low-l, lensing)	67.4 ± 0.5	0.315 ± 0.007	0.811 ± 0.006



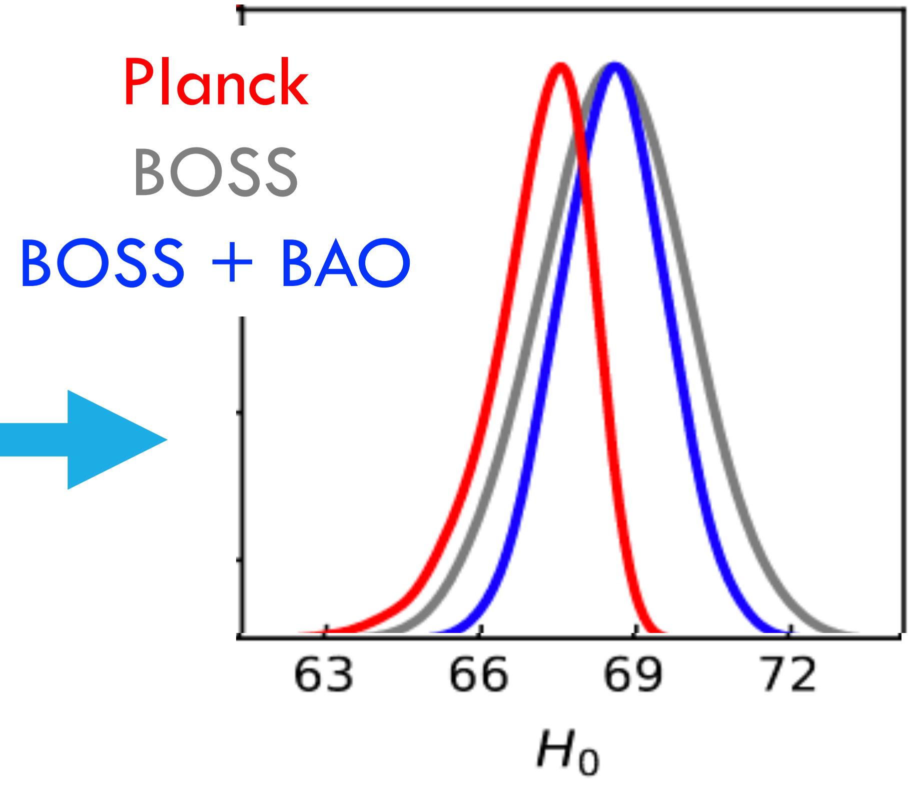
Nishimichi+20, Ivanov+20, **Philcox**+20,21, Planck 18

WHAT ELSE CAN WE DO WITH THE DATA?

Add the **wiggly** information from **baryon acoustic oscillations**



40% better H_0!



Philcox+20 (see also Chen+21, d'Amico+20)

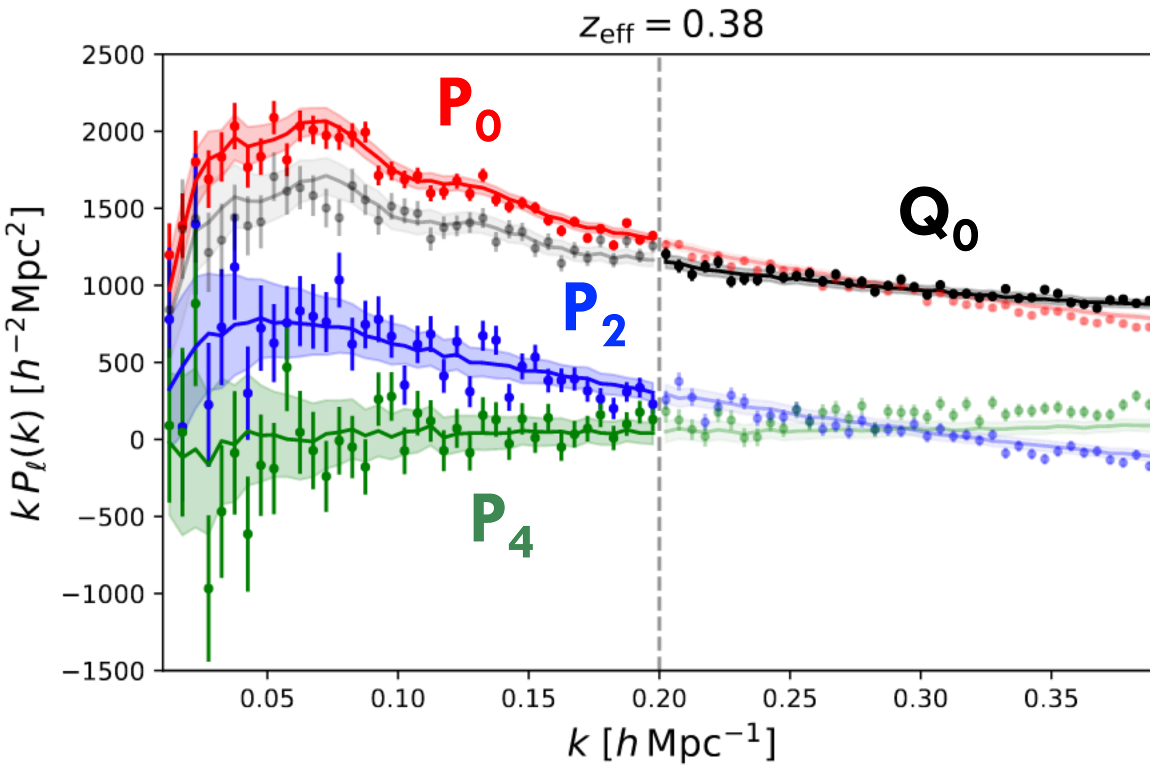
WHAT ELSE CAN WE DO WITH THE DATA?

Add the **real-space** power spectrum

$P_0(k)$
$+$
$P_2(k)$
$+$
$P_4(k)$

$\rightarrow$

$Q_0(k) \approx P(k, \mu = 0)$



- No Fingers-of-God!
- Push to $k_{\rm max} = 0.4h/{\rm Mpc}$
- Constraints improve by (10 – 100)%

Ivanov+21 (see also Tegmark, d'Amico+21)

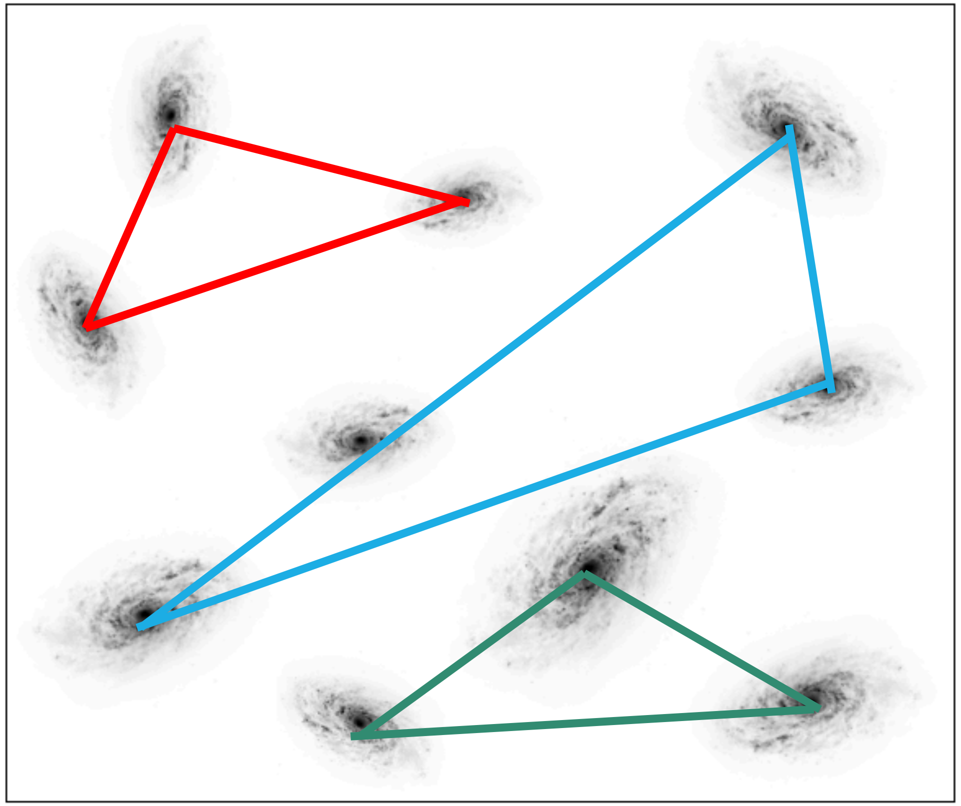
WHAT ELSE CAN WE DO WITH THE DATA?

Add the **galaxy bispectrum:**

$$B_g(k_1, k_2, k_3) = \langle \delta_g(\mathbf{k}_1)\delta_g(\mathbf{k}_2)\delta_g(\mathbf{k}_3)\rangle'$$

This is hard:

- Window functions
- Theory model



Gil-Marin+16, **Philcox** 20, 21, Ivanov+ 21, **Philcox** +21

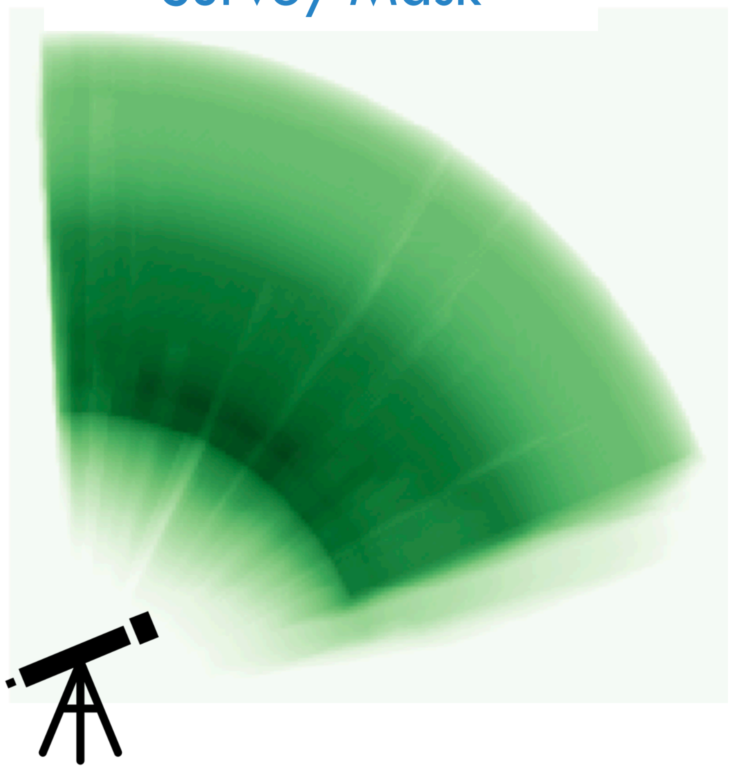
THE MASKED BISPECTRUM

Problem: We don't measure the density field directly.

$$\delta_g(\mathbf{r}) \to W(\mathbf{r})\delta_g(\mathbf{r}) \qquad \delta_g(\mathbf{k}) \to \int \frac{d\mathbf{p}}{(2\pi)^3} W(\mathbf{k}-\mathbf{p})\delta_g(\mathbf{p})$$

Window Function

Survey Mask



The measured bispectrum is a **triple convolution**

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

Solution: Convolve the **theory model** too

This is too expensive to do properly!

BOSS DR12, Gil-Marin 16, **Philcox** 21

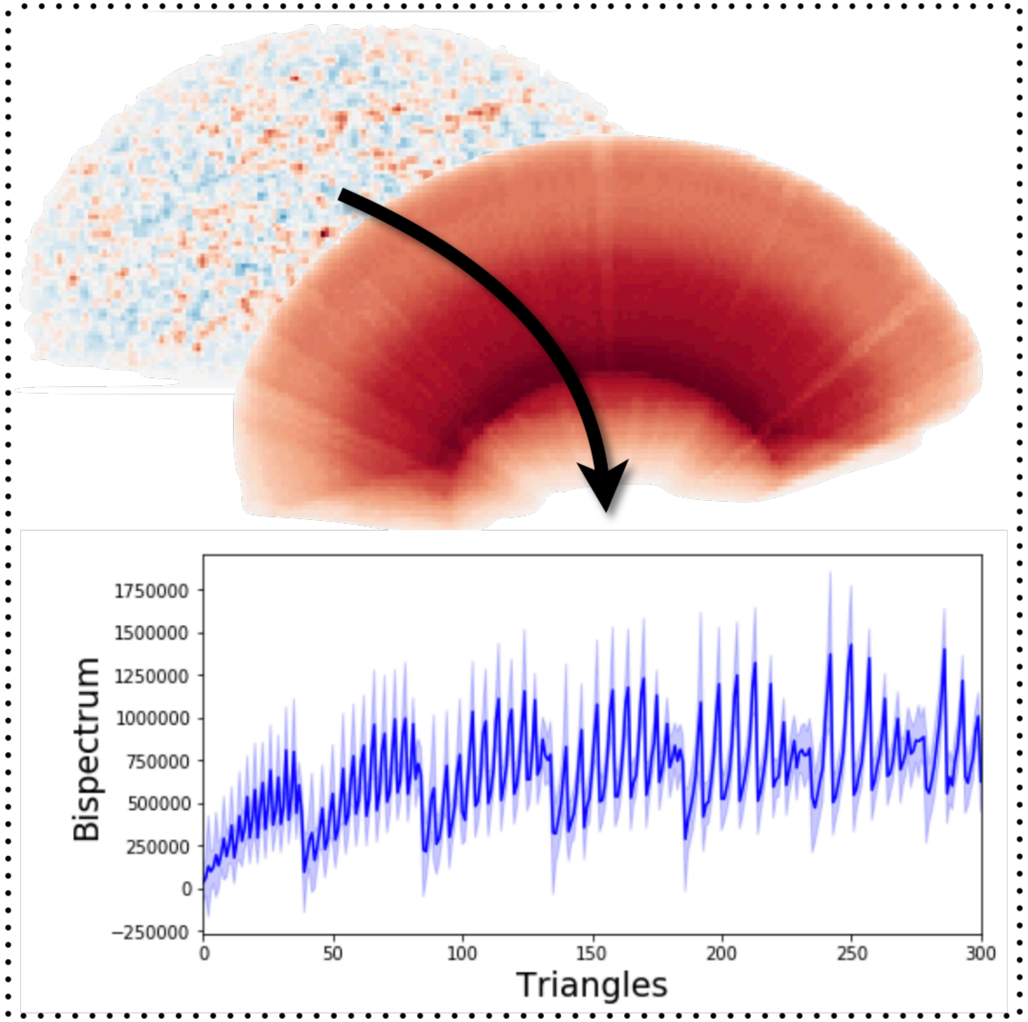
BISPECTRA WITHOUT WINDOWS

Alternatively: estimate the **unwindowed** bispectrum directly

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

- Derive a **maximum-likelihood** estimator for the **true** bispectrum
- Effectively **deconvolves** the window

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



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

Philcox 20, 21

MODELLING THE BISPECTRUM

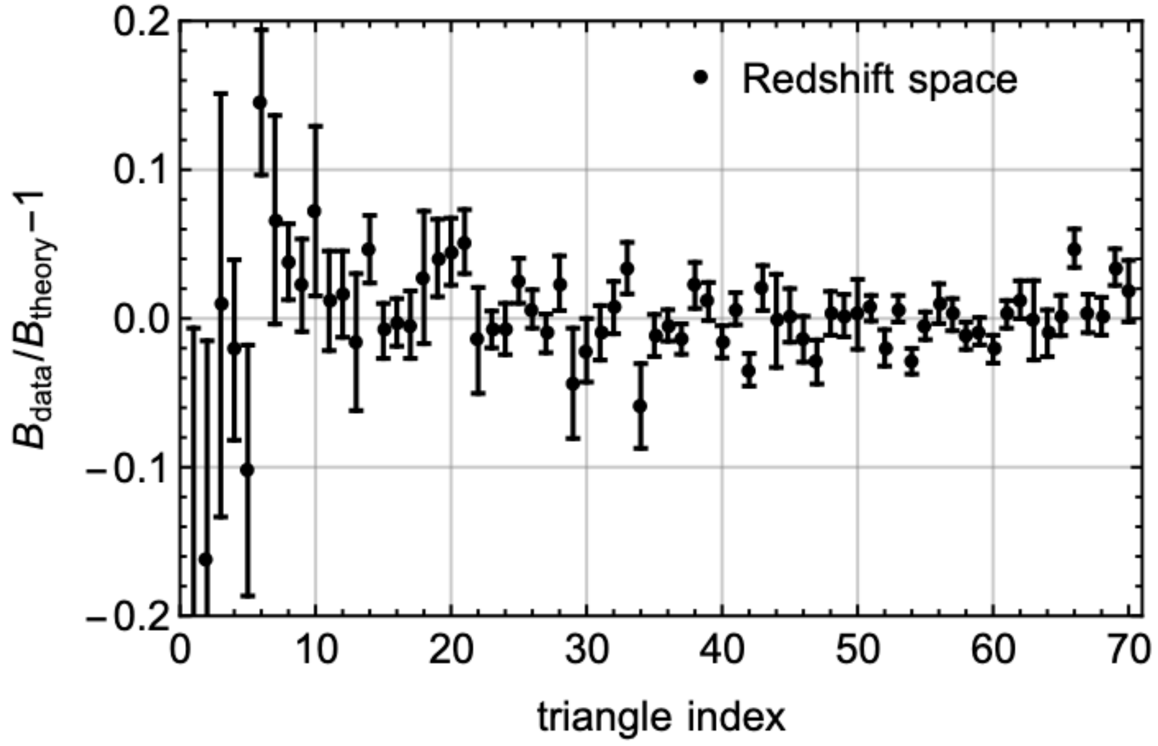
Model:

- Tree-level theory
- Second-order galaxy bias
- Large-scale displacements
- Coordinate transformations
- Fingers-of-God

Tested on $566\ (\mathrm{Gpc/h})^3$ simulations

Accurate up to $k_{max} = 0.08\, h/\mathrm{Mpc}$

Data ÷ Theory −1



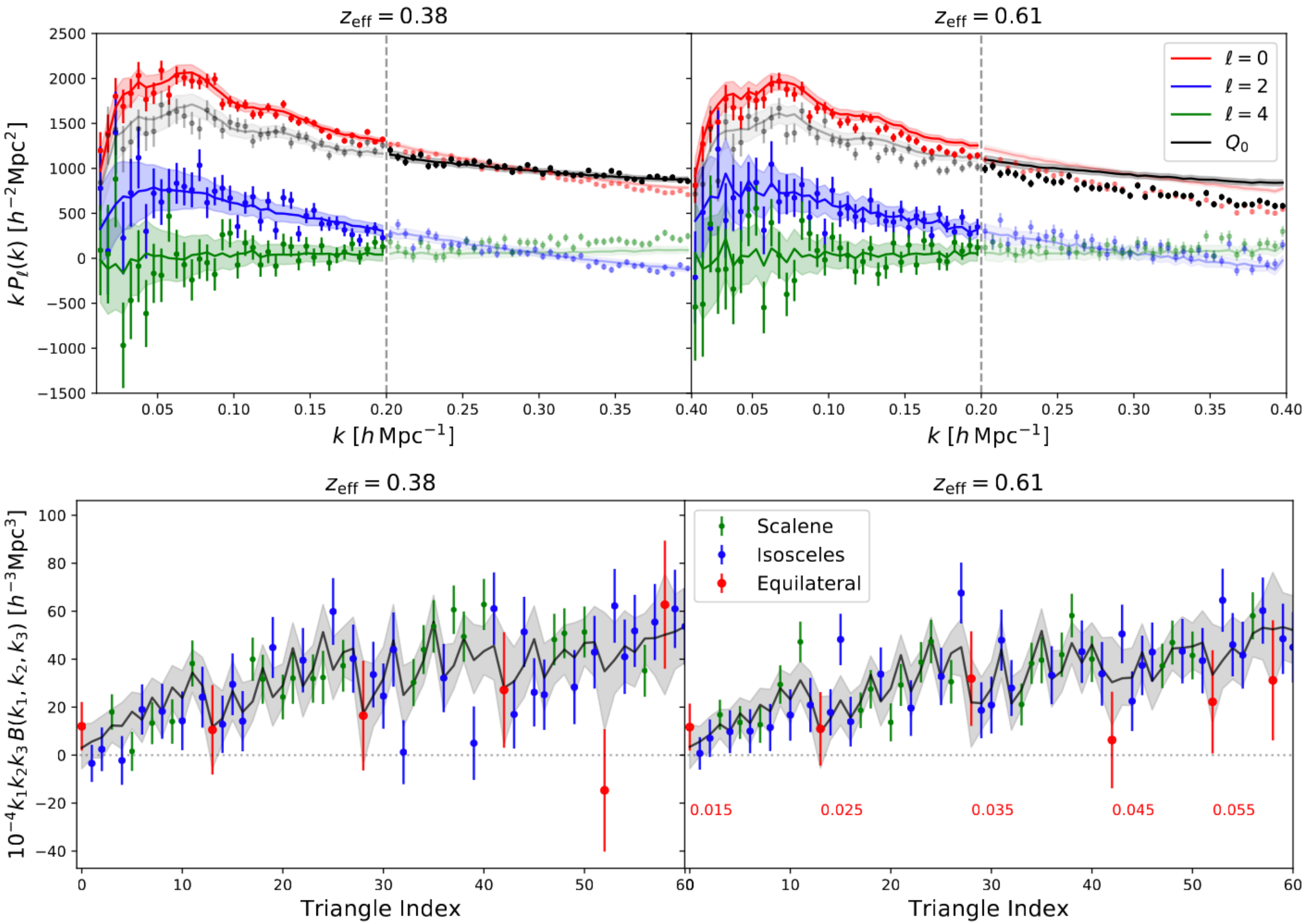
See GitHub.com/michalychforever/CLASS-PT

Ivanov+21

THE UNOFFICIAL BOSS DR12 ANALYSIS

$P_\ell + Q_0$

Bispectrum



Wiggles $(\alpha_{\parallel,\perp})$

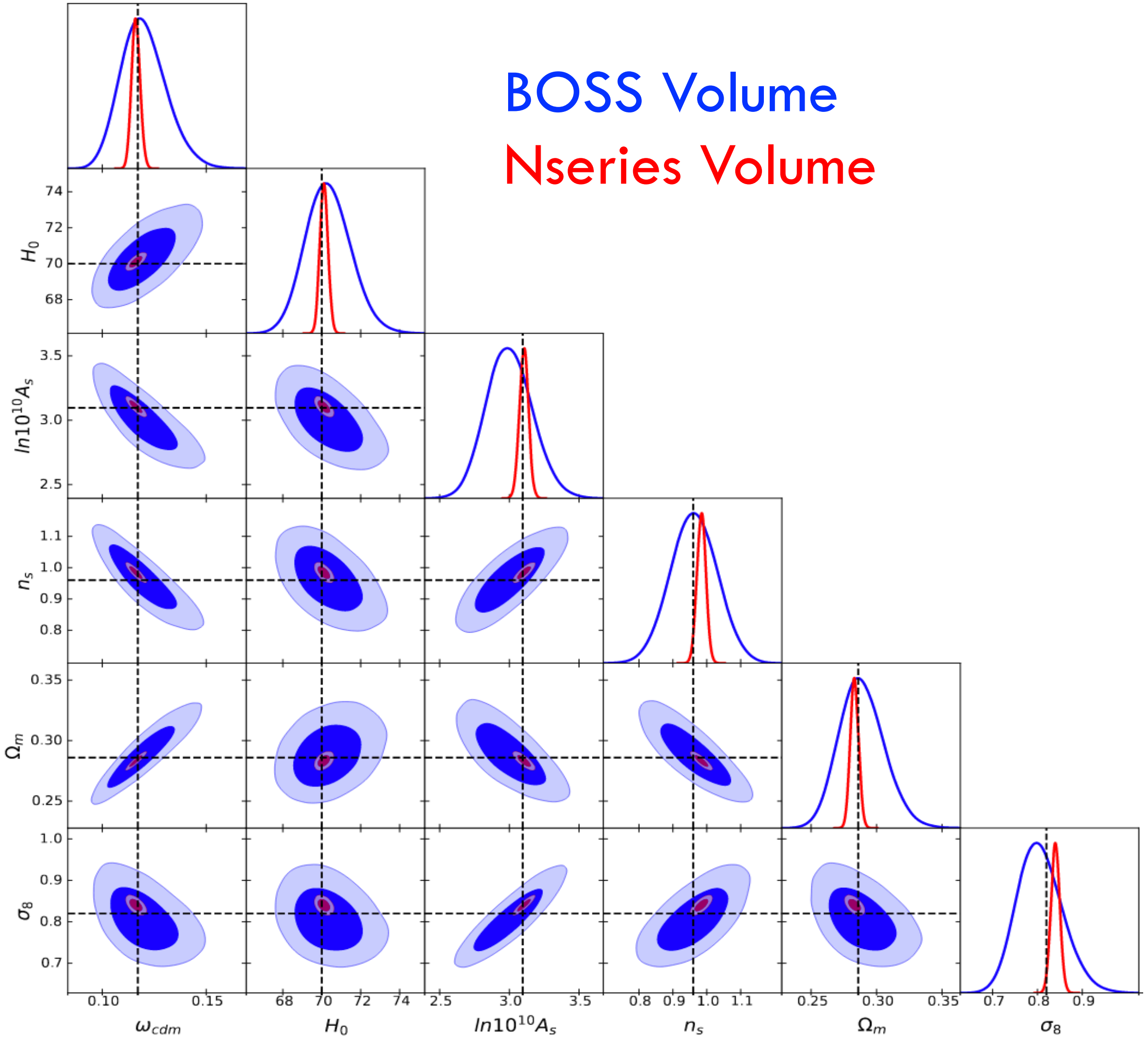
Theory Model

Cosmological Parameters

Ivanov+21

Philcox+21

THE UNOFFICIAL BOSS DR12 ANALYSIS - TESTING



Validate with **Nseries** mocks

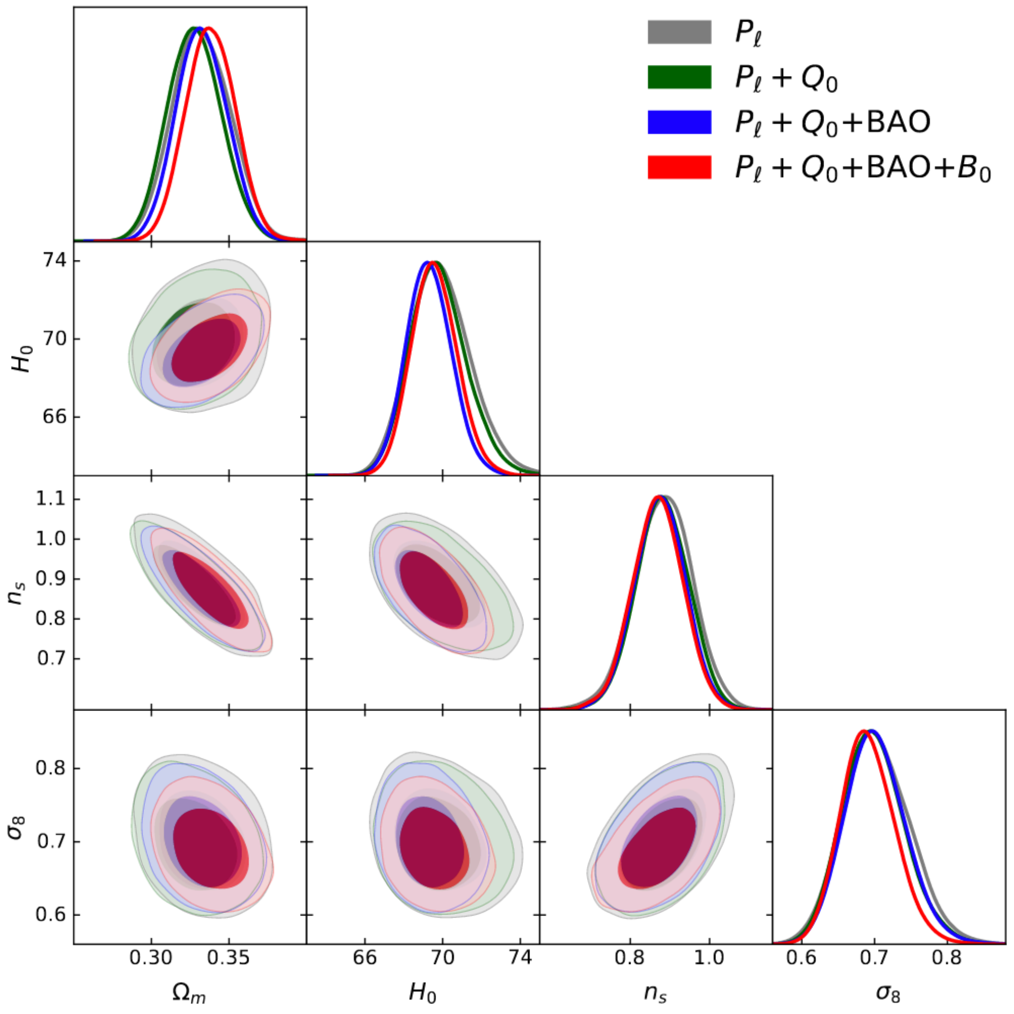
- All parameters recovered at $\ll 1\sigma$
- Theory model works!
- Window function works!
- Fiber collisions work!

Philcox+21

THE UNOFFICIAL BOSS DR12 ANALYSIS - RESULTS

- ΛCDM analysis gives **tight** parameter constraints
- **H_0** agrees with *Planck*
- **S_8** $= 0.75 \pm 0.04$ agrees with weak lensing

	H_0	Ω_m	σ_8
BOSS Pk	68.8 ± 1.2	0.32 ± 0.01	0.73 ± 0.04
BOSS All	$\mathbf{68.3 \pm 0.8}$	$\mathbf{0.32 \pm 0.01}$	$\mathbf{0.72 \pm 0.03}$
Planck 2018 (TT, TE, EE, low-l, lensing)	67.4 ± 0.5	0.315 ± 0.007	0.811 ± 0.006

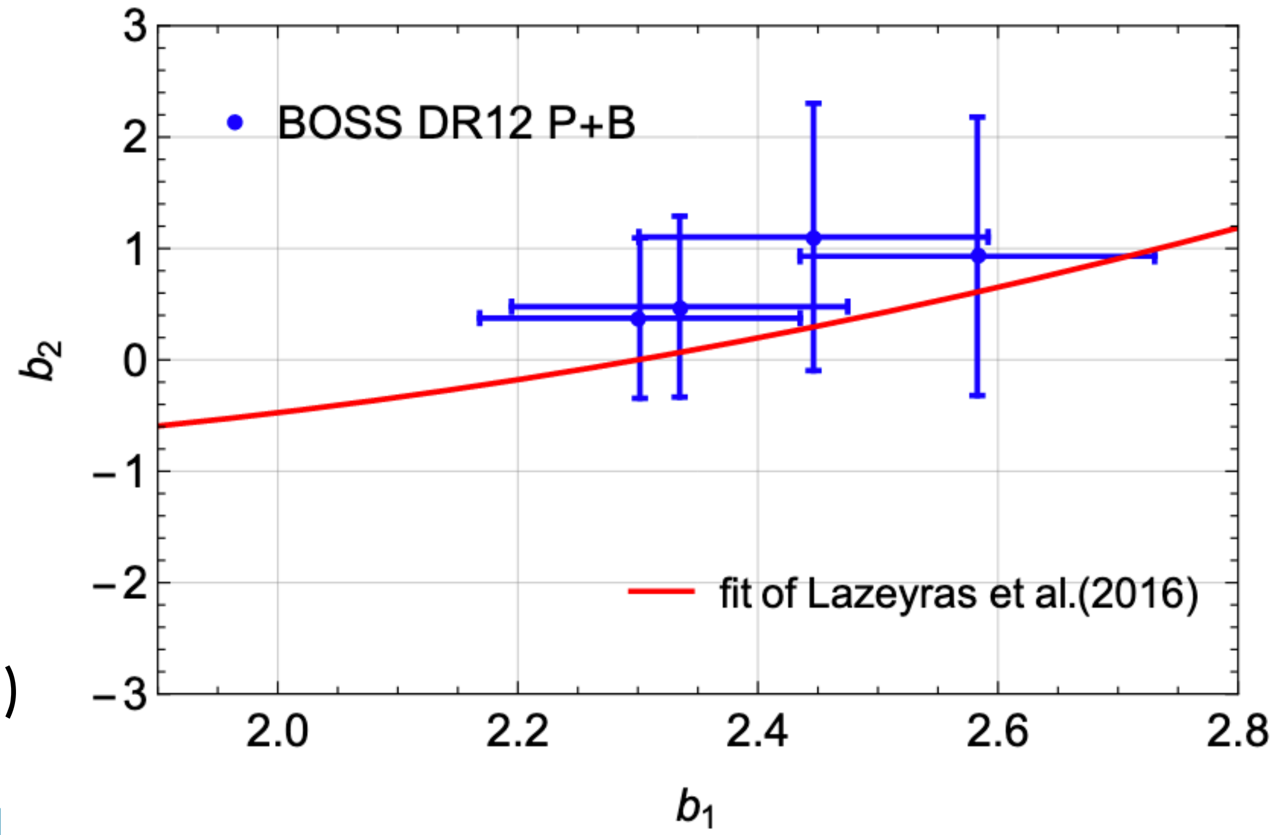


Philcox+21 (see also Chen+21, d'Amico+21)

THE UNOFFICIAL BOSS DR12 ANALYSIS

Can constrain **other** parameters:

- $n_s = 0.87 \pm 0.07$
- Neutrino mass
- Sound-Horizon free H_0 measurements
- Bias relations (3x better with bispectra!)



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

Philcox+21 (see also Chen+21, d'Amico+21)

WHAT'S NEXT?

New / Better Statistics

- **One-Loop** Bispectrum
- Bispectrum **Multipoles**
- Trispectrum
- Correlation Functions?

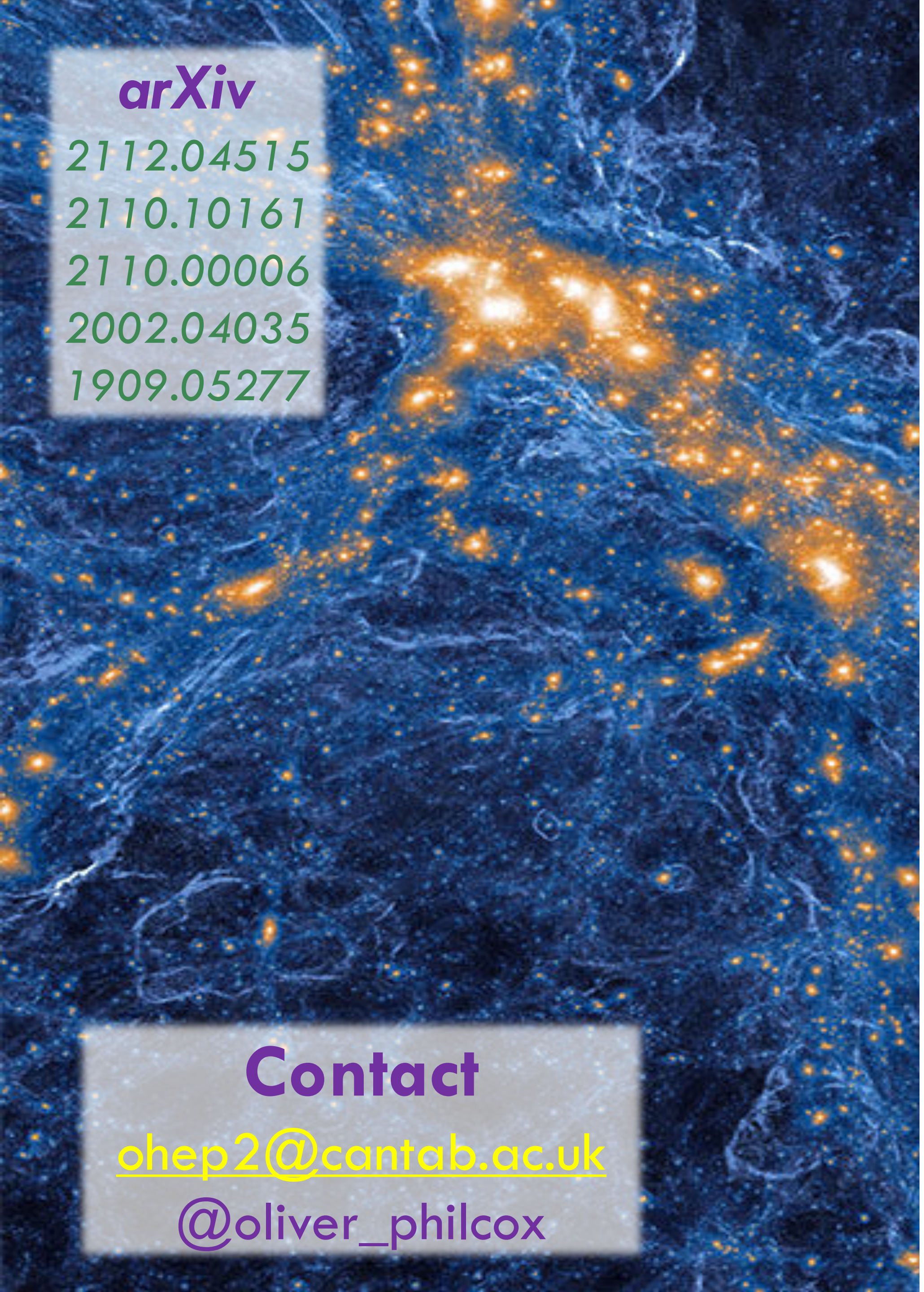
Apply this to DESI?

New Things to Learn

- Primordial Non-Gaussianity (see Misha's talk)
- Ultra-Light Axions
- Early Dark Energy
- Massive Spinning Particles

and much more…

Cabass+22, d'Amico+22, Dizgah+18, Ivanov+20, …



CONCLUSIONS

- We can **directly** extract cosmological parameters from galaxy surveys
- This will (eventually) become stronger than the CMB
- New statistics give **extra** information and can be robustly **measured** & **modelled**