Spectroscopic Surveys: A Precision Probe of Old & New Physics

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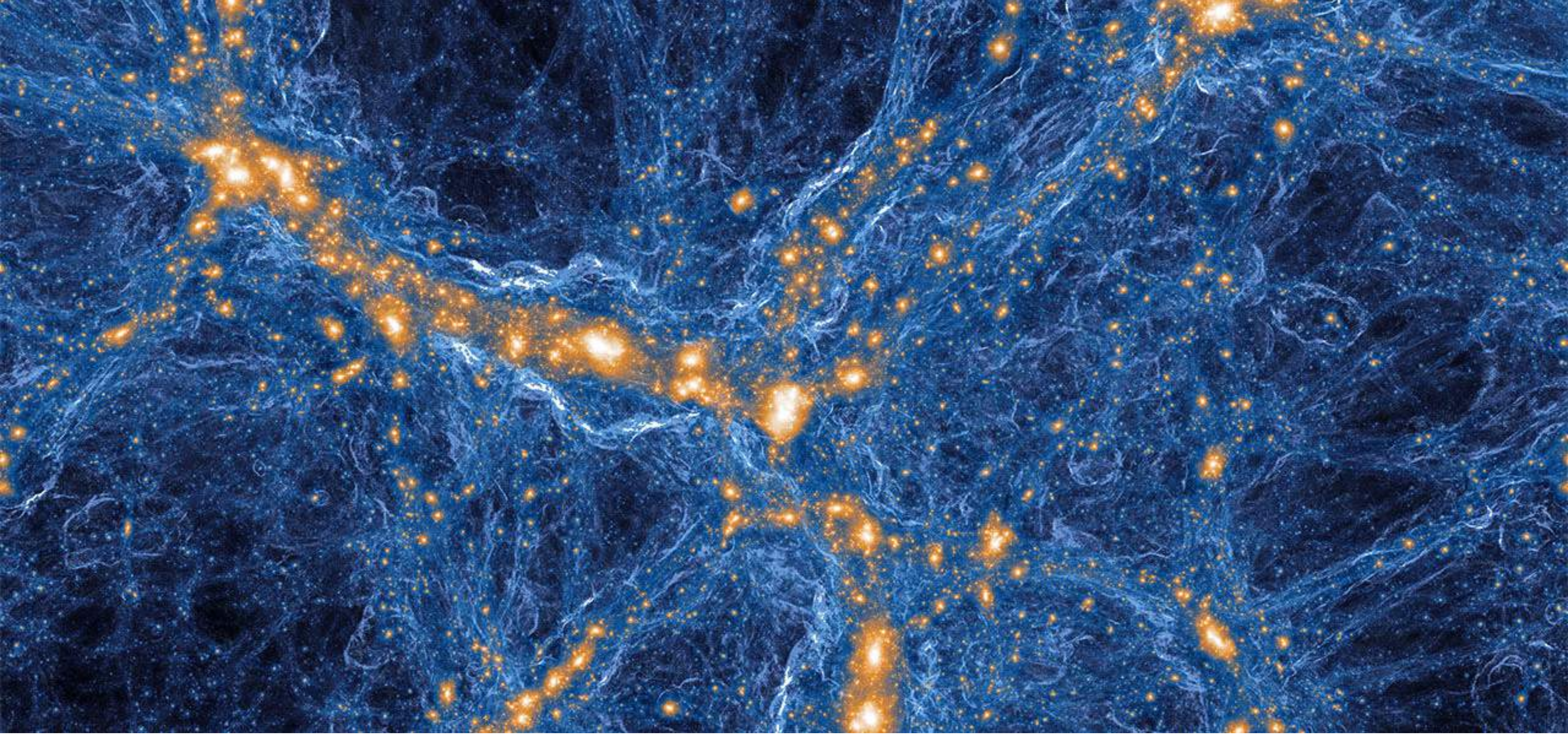
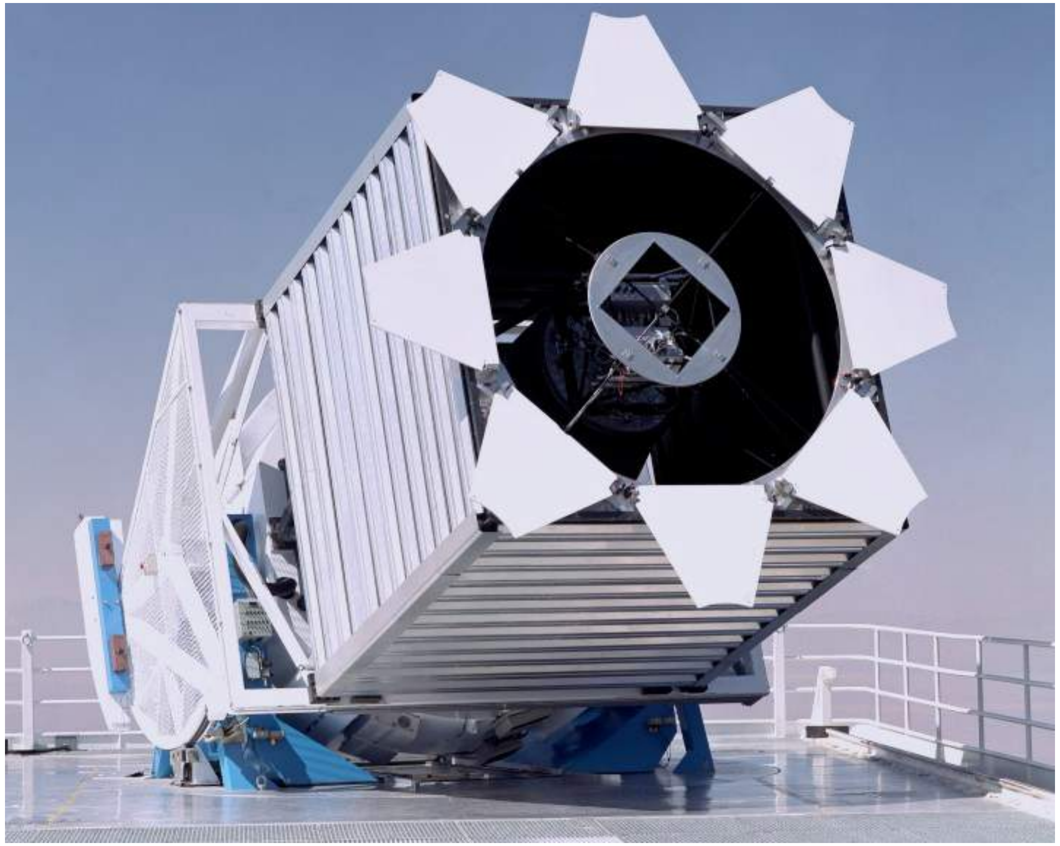
Dark Energy Webinar, *May 2022*

Collaborators: *Mikhail Ivanov, Giovanni Cabass, Marko Simonovic, Matias Zaldarriaga, Takahiro Nishimichi, Masahiro Takada, Blake Sherwin, Gerrit Farren, Eric Baxter, Dillon Brout*

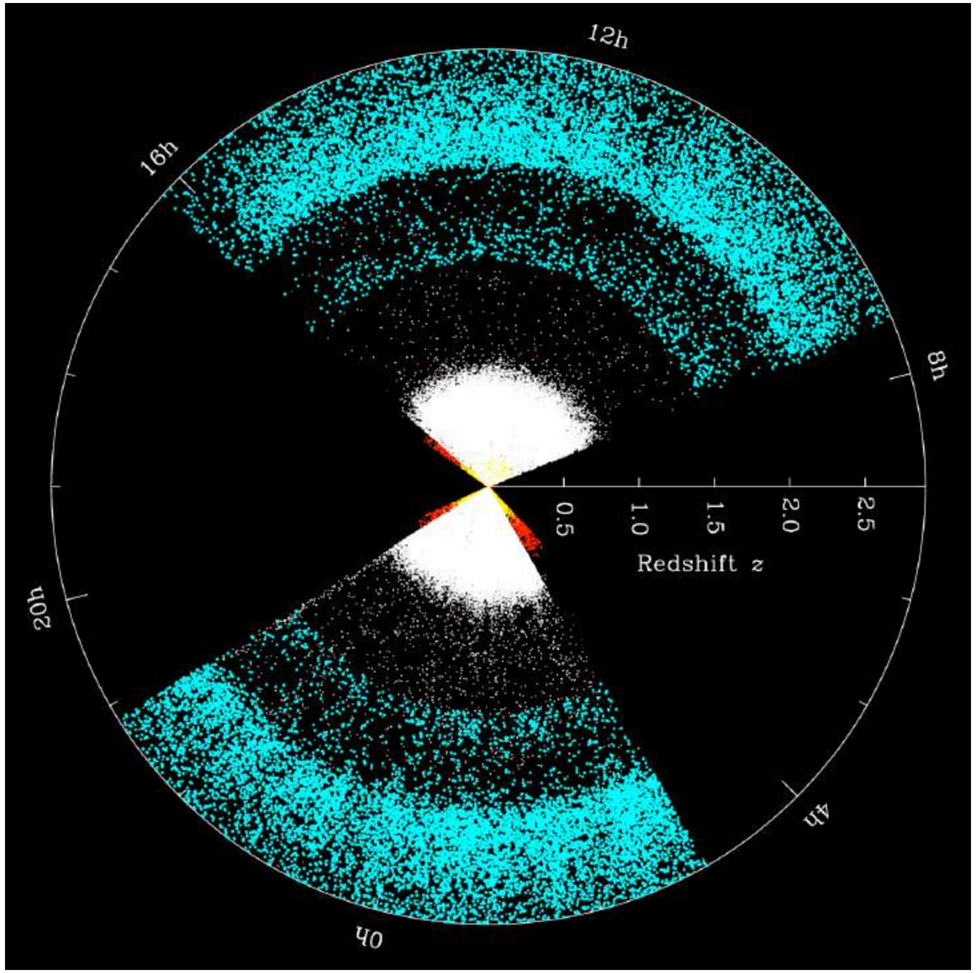


1. What Can We Measure?

COSMOLOGY FROM SPECTROSCOPIC SURVEYS



Big Telescope



10^6 Galaxy Positions

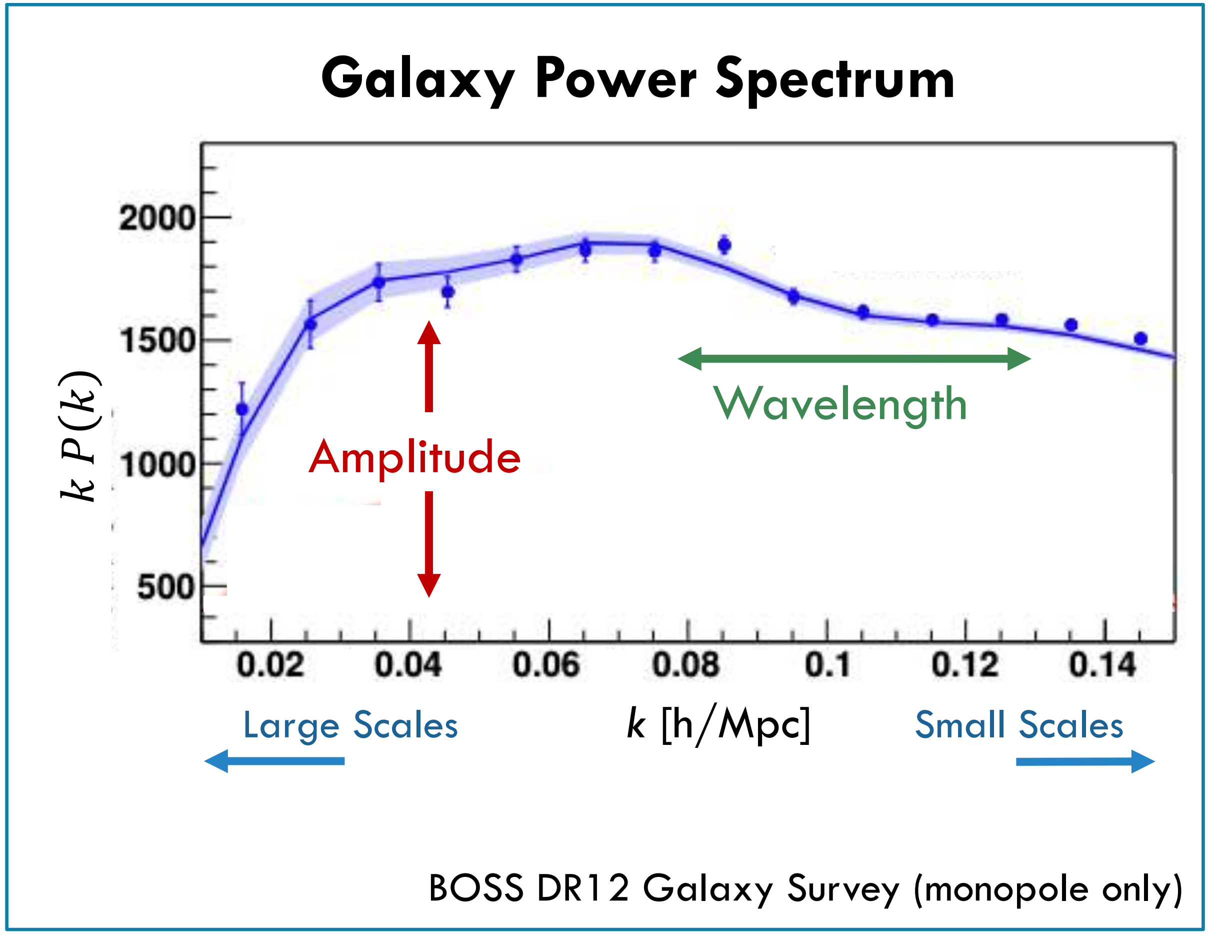
SDSS-III

WHAT DO WE DO WITH THE DATA?

- Compress the 10^6 galaxy positions to a **power spectrum,** $\langle \delta_g(\boldsymbol{k}) \delta_g^*(\boldsymbol{k}) \rangle$

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

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



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

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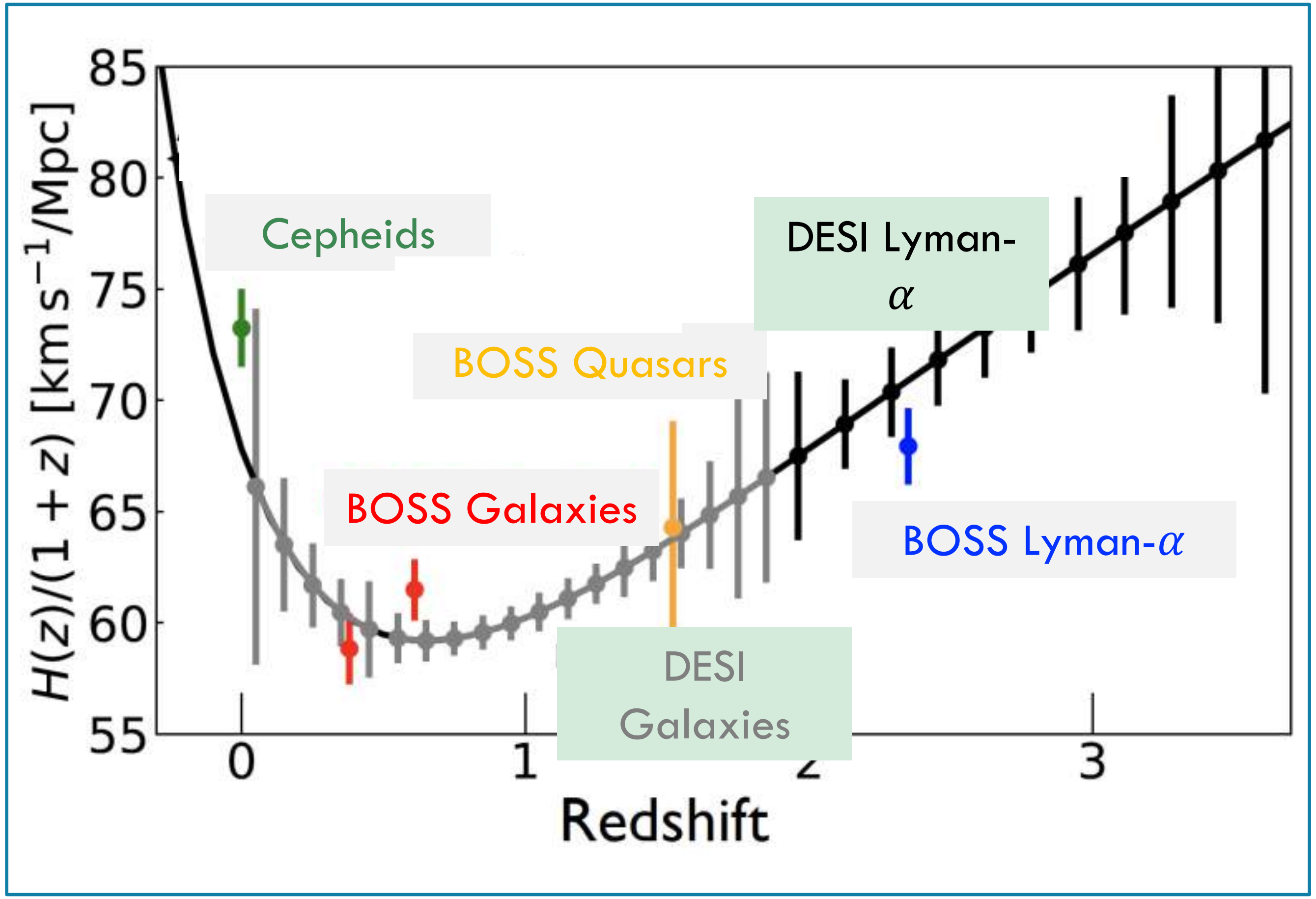
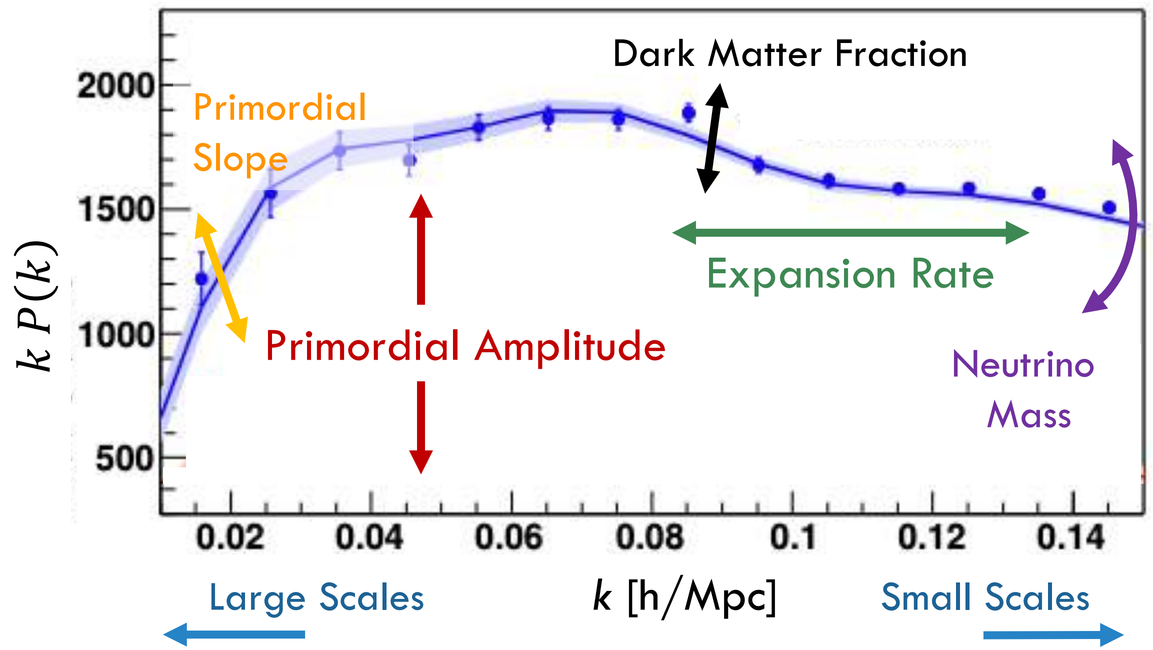


WHAT COULD WE DO WITH THE DATA?

- 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…



BOSS DR12 Galaxy Survey, Beutler+17

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

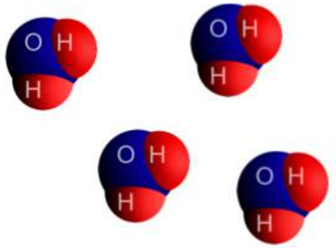
THE EFFECTIVE FIELD THEORY OF LARGE SCALE STRUCTURE

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

- **Also includes**: galaxy bias, long-wavelength displacements, redshift-space distortions, primordial non-Gaussianity, etc.

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

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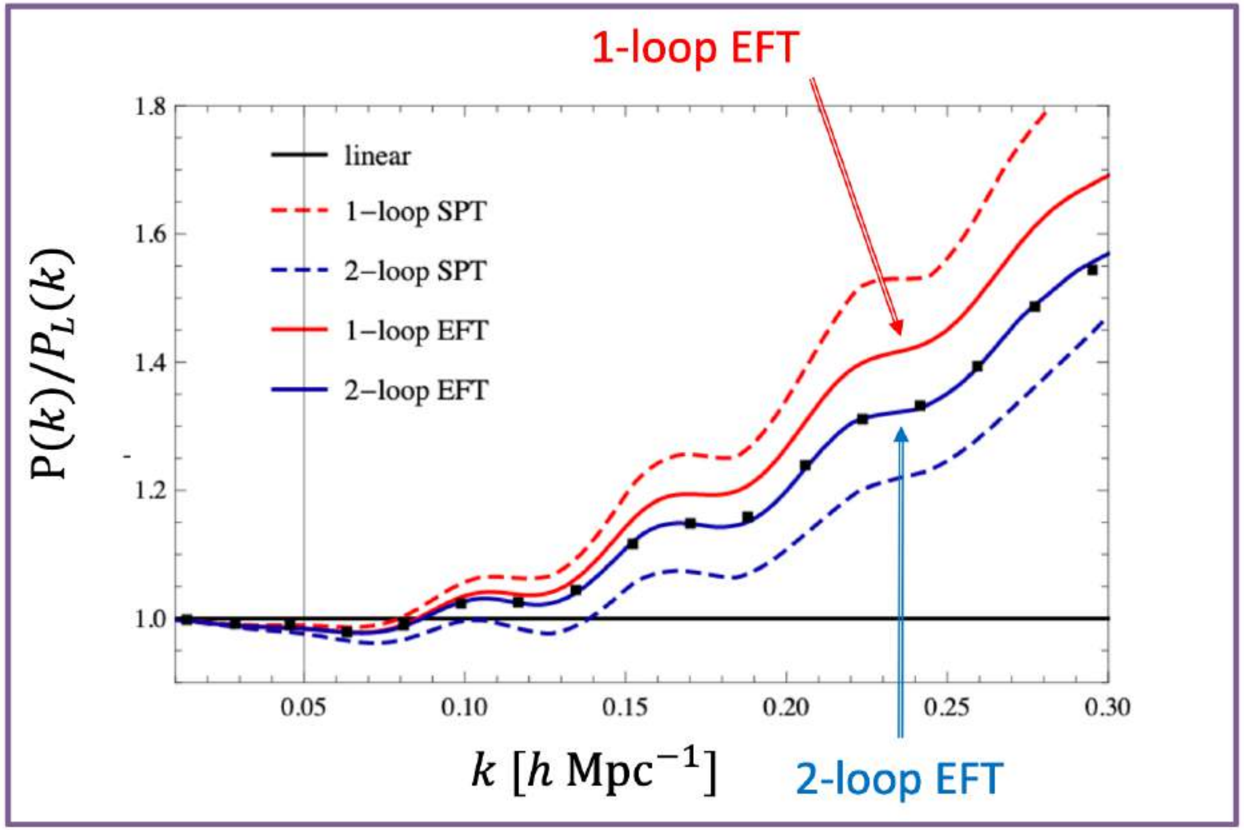
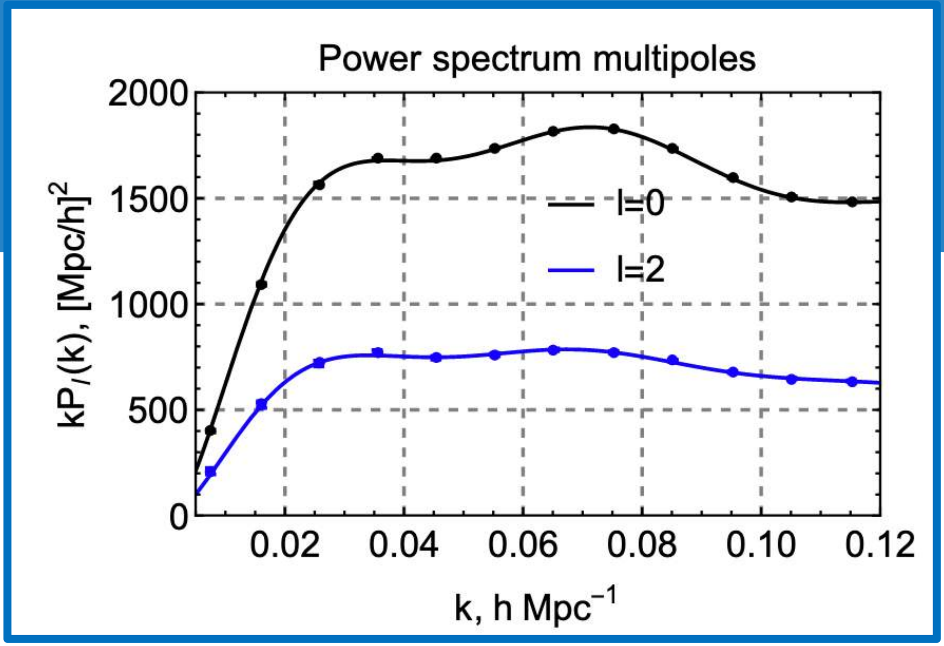
Arbitrarily accurate on large scales!

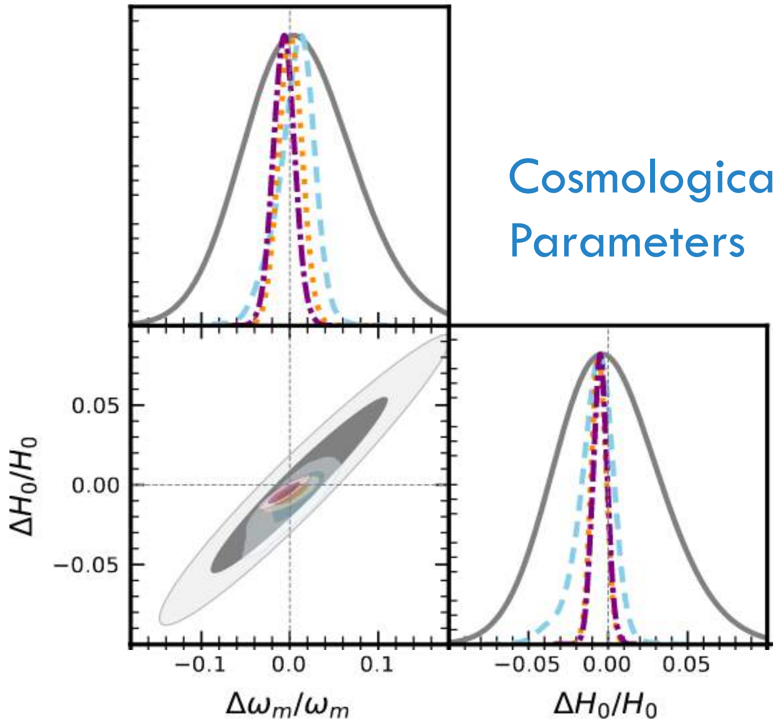


Baldauf, Advanced Cosmology

MODEL VALIDATION

- Compare EFTofLSS model to N-body simulations, comparing $P_{gg}(\boldsymbol{k})$
- Total volume: $566\ (h^{-1}\mathrm{Gpc})^3$
  - *Larger than DESI / Euclid!*
- Fully **blind** analysis
- **Unbiased cosmological parameters!**





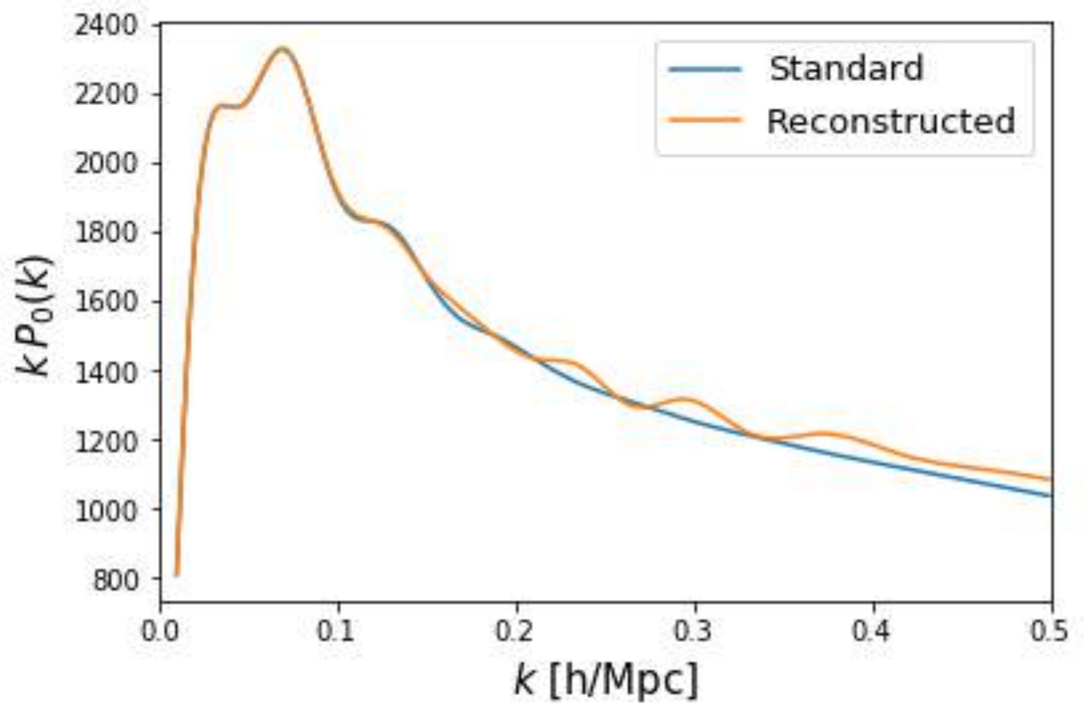
Cosmological Parameters

See GitHub.com/michalychforever/CLASS-PT

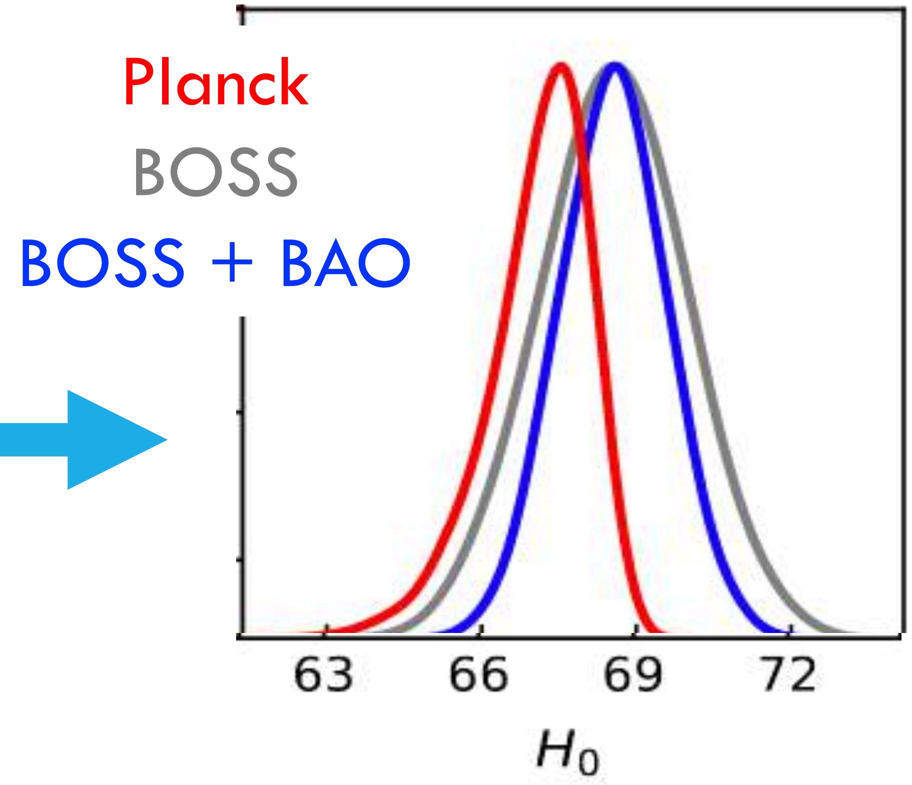
Nishimichi+21

WHAT'S BEYOND THE POWER SPECTRUM? (#1)

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



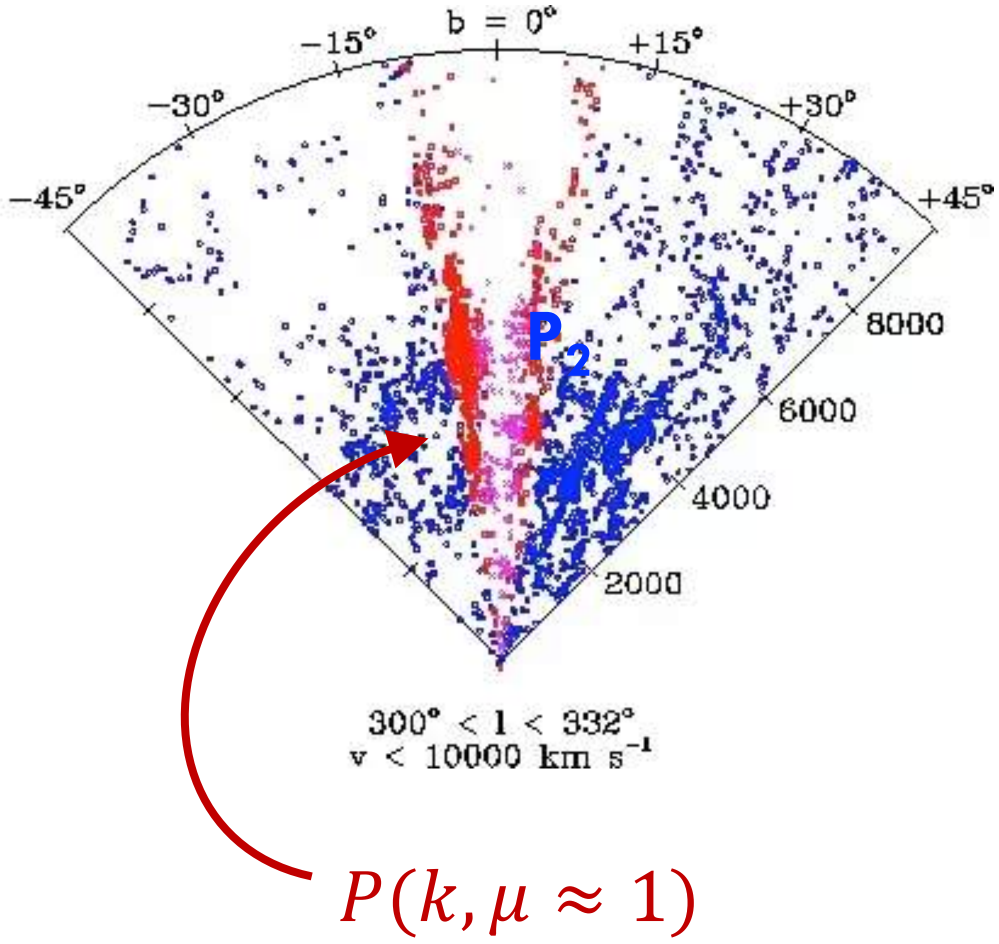
40% better H_0!



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

WHAT'S BEYOND THE POWER SPECTRUM? (#2)

- Fingers-of-God are limiting at high-k
- $k_{\max}$ is lower for radial modes!
- Can we compute $P(k, \mu = 0)$?

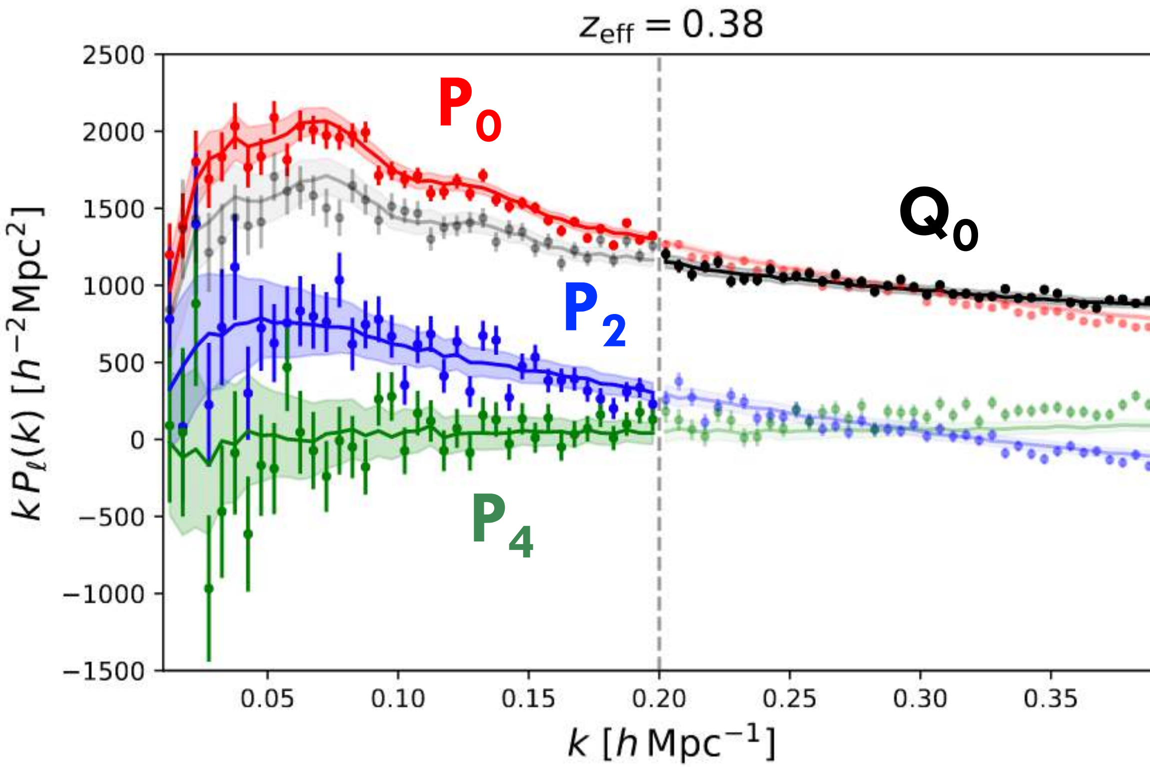


Ivanov+21 (see also Tegmark, d'Amico+21)

WHAT'S BEYOND THE POWER SPECTRUM? (#2)

Compute the **real-space** power spectrum

$P_0(k)$ + $P_2(k)$ + $P_4(k)$ → $Q_0(k) \approx P(k, \mu = 0)$



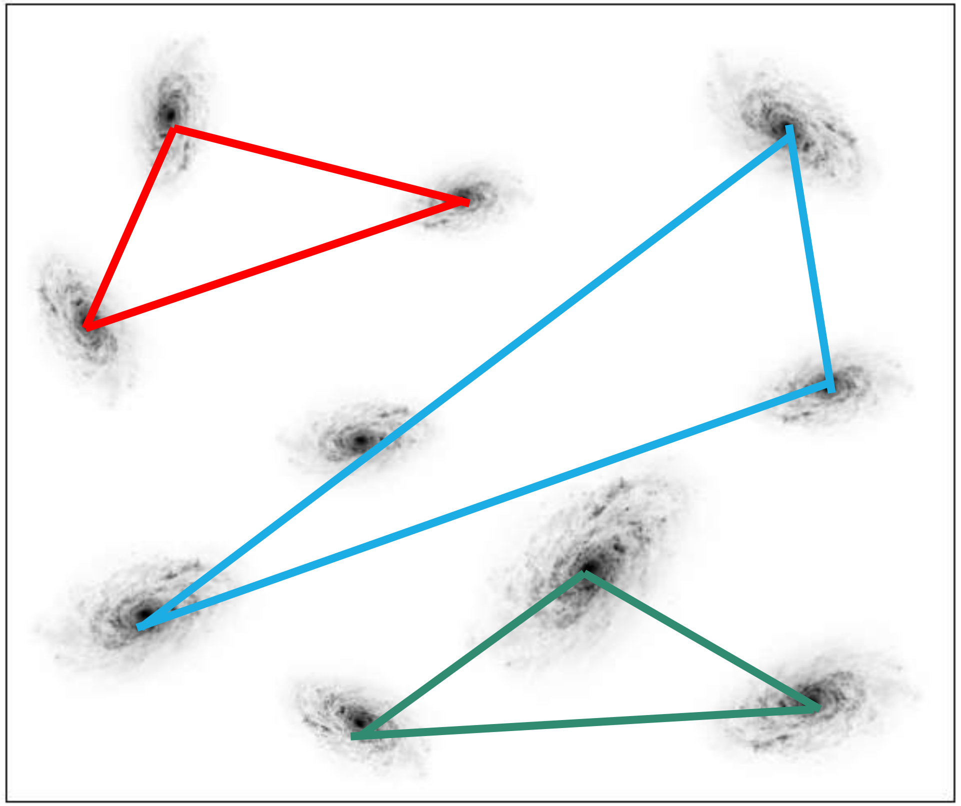
- No Fingers-of-God!
- Push to $k_{\rm max} = 0.4h/{\rm Mpc}$
- Constraints improve by (10 – 100)%

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

WHAT'S BEYOND THE POWER SPECTRUM? (#3)

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 <u>hard</u>:

- 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.

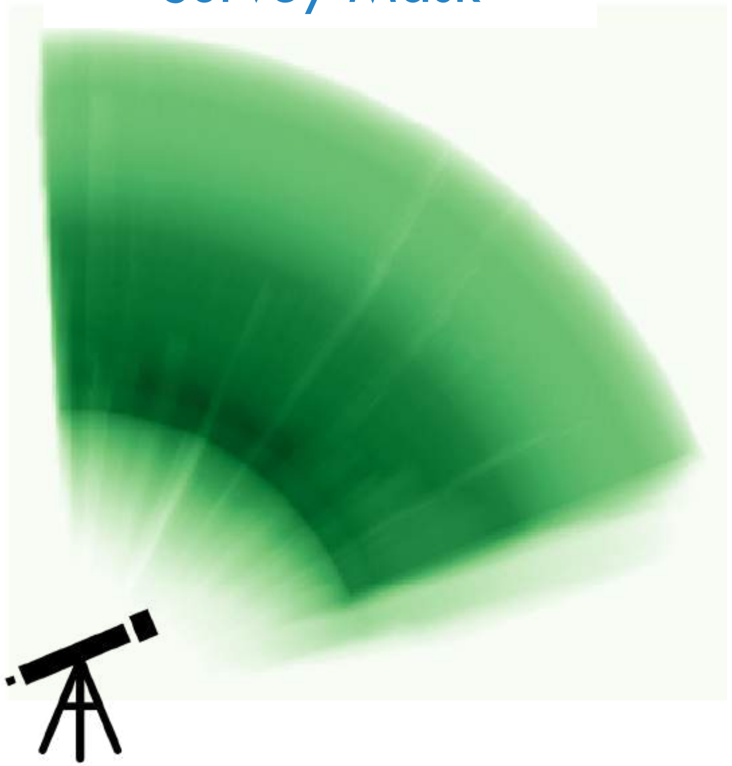
$$\delta_g(\mathbf{r}) \to W(\mathbf{r})\delta_g(\mathbf{r}) \qquad \delta_g(\mathbf{k}) \to \int \frac{d\mathbf{p}}{(2\pi)^3} W(\mathbf{k}-\mathbf{p})\delta_g(\mathbf{p})$$

Window Function

The measured bispectrum is a **triple convolution**

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

Survey Mask



Solution: Convolve the **theory model** too

This is very expensive!

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

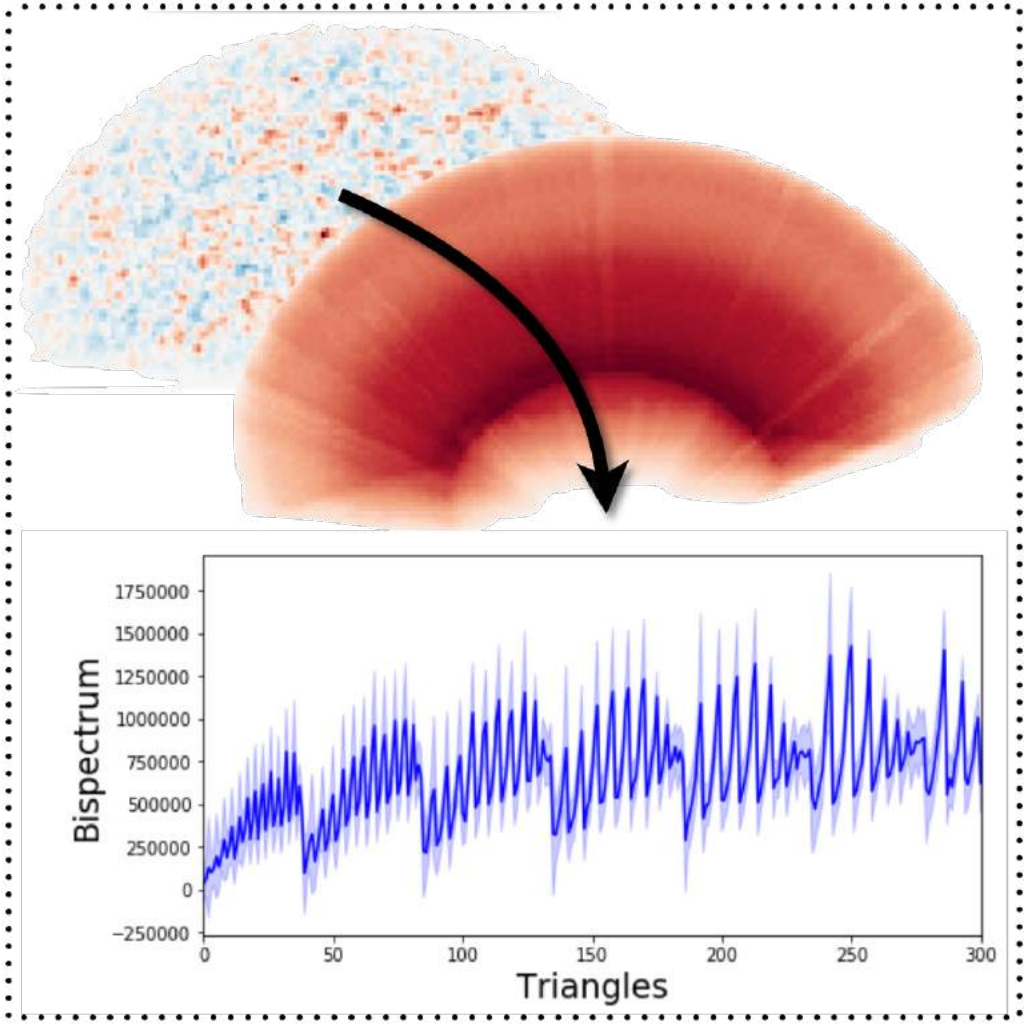
BISPECTRA WITHOUT WINDOWS

Alternatively: estimate the **unwindowed** bispectrum directly

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

- 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/Spectra-Without-Windows

Philcox 20, 21

MODELLING THE BISPECTRUM

1-loop bispectrum coming soon!

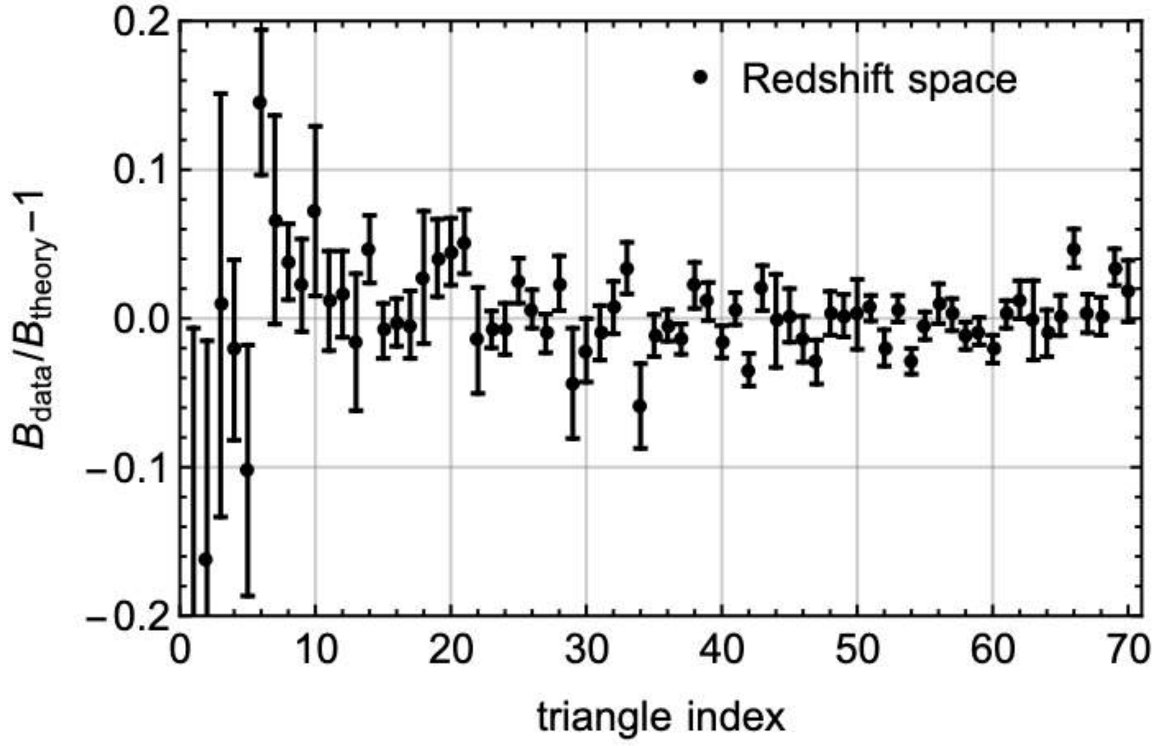
Effective-Field-Theory Model:

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

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

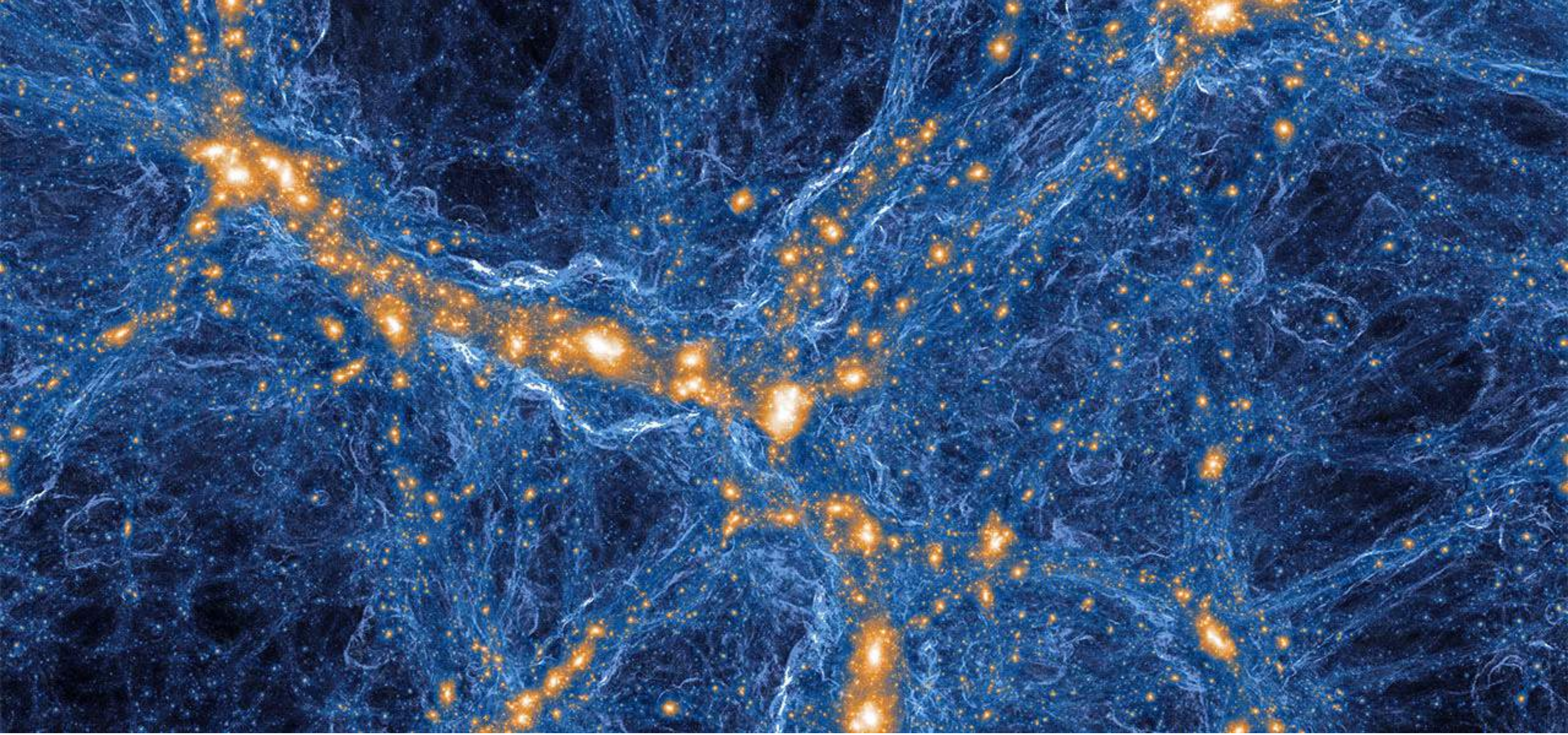
Accurate up to $k_{max} = 0.08\, h/\mathrm{Mpc}$

Data ÷ Theory −1



See GitHub.com/michalychforever/CLASS-PT

Ivanov+21

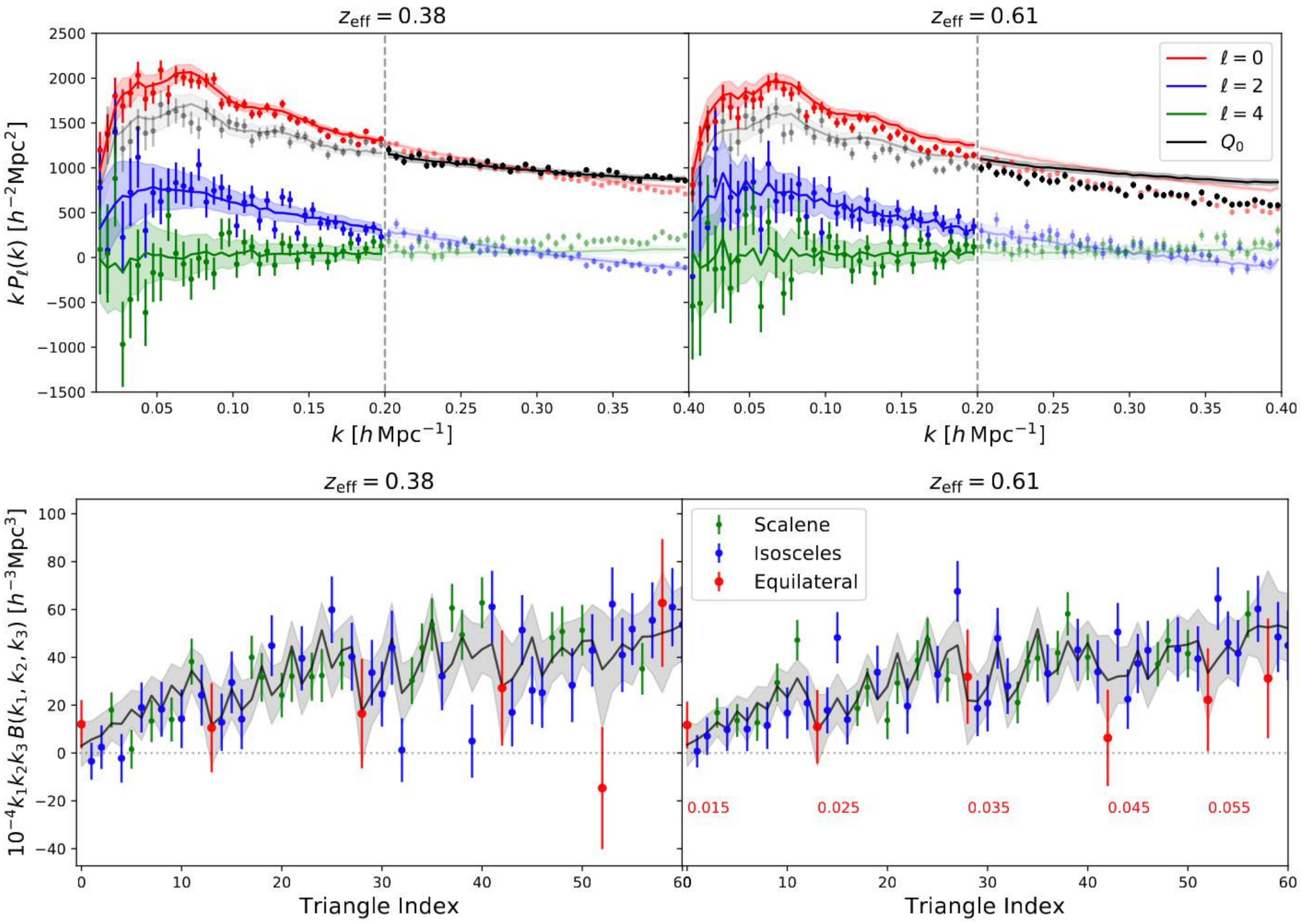


2. What Have We Learnt About ΛCDM?

THE UNOFFICIAL BOSS DR12 ANALYSIS

$P_\ell + Q_0$

Bispectrum



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

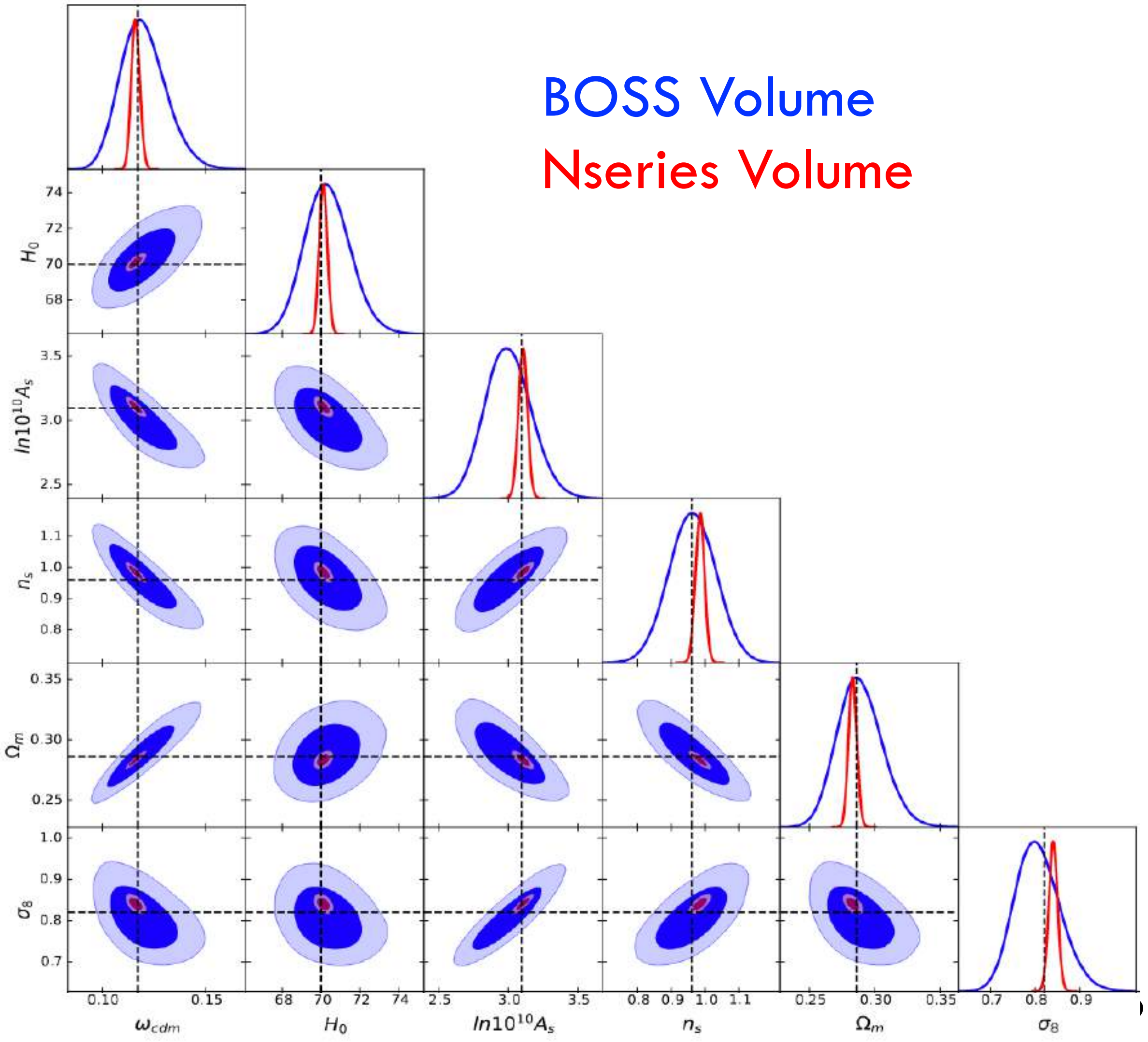
Theory Model

Cosmological Parameters

Ivanov+21

Philcox+21

THE UNOFFICIAL BOSS DR12 ANALYSIS - TESTING



BOSS Volume

Nseries Volume

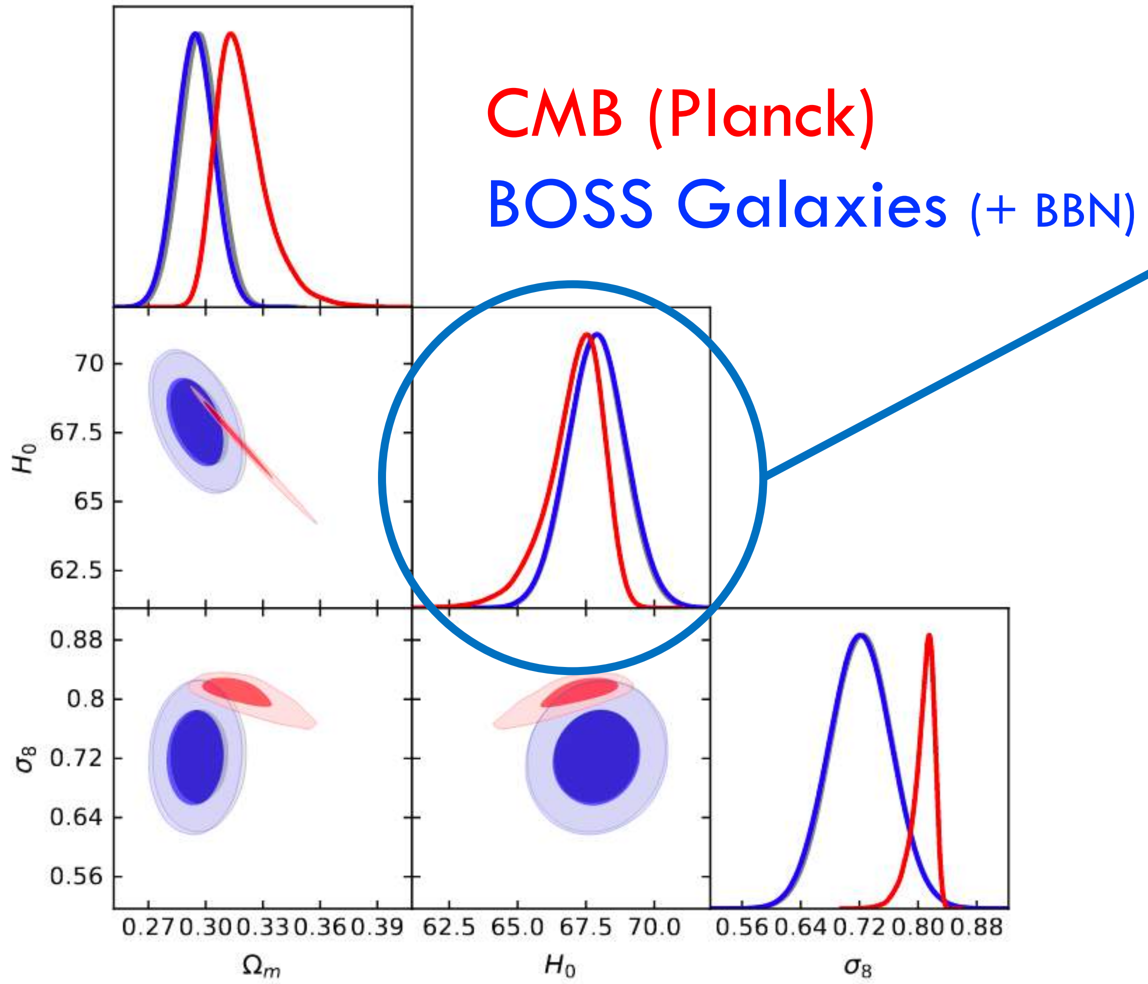
Validate with high-resolution **Nseries** mocks

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

See GitHub.com/oliverphilcox/full_shape_likelihoods

Philcox+21

CONSTRAINTS ON H_0



BOSS Power Spectrum + Bispectrum:

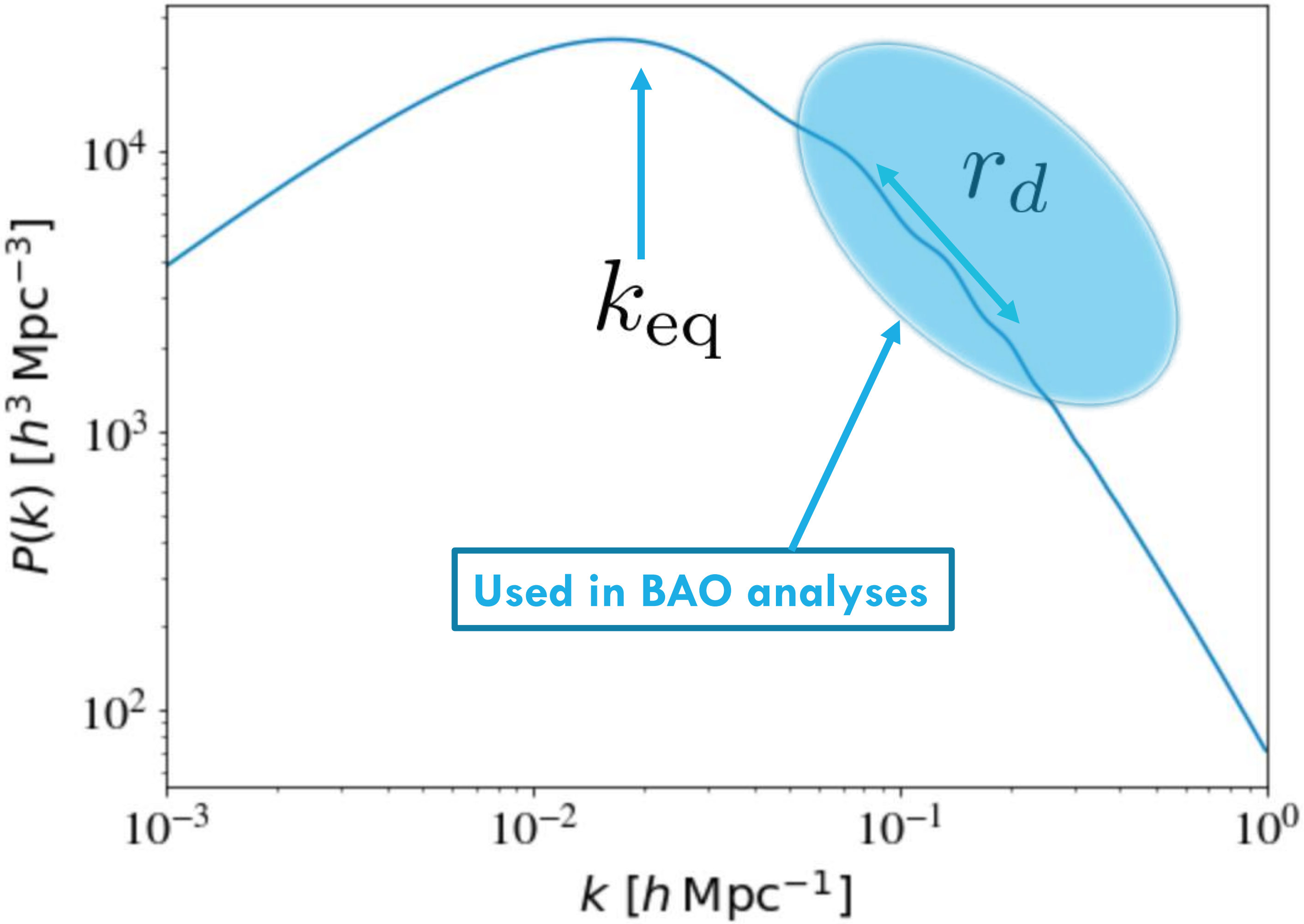
$$H_0 = 68.3 \pm 0.8\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

- H_0 agrees with *Planck*
- 3.7σ *discrepant with SH0ES!*

Where does this information come from?

Philcox+21,2 (also Chen+21, d'Amico+21)

TWO STANDARD RULERS FOR H_0



1. <u>The Sound Horizon</u>: r_d
   - The **sound horizon** at baryon drag ($z \sim 1100$)
2. <u>The Equality Scale</u>: k_{eq}^{-1}
   - The **horizon** at radiation-matter equality ($z \sim 3600$)

***Both** can be used to extract H_0*

Ivanov+21
Philcox+21

THE EQUALITY SCALE: AN (OLD) PROBE OF H_0?

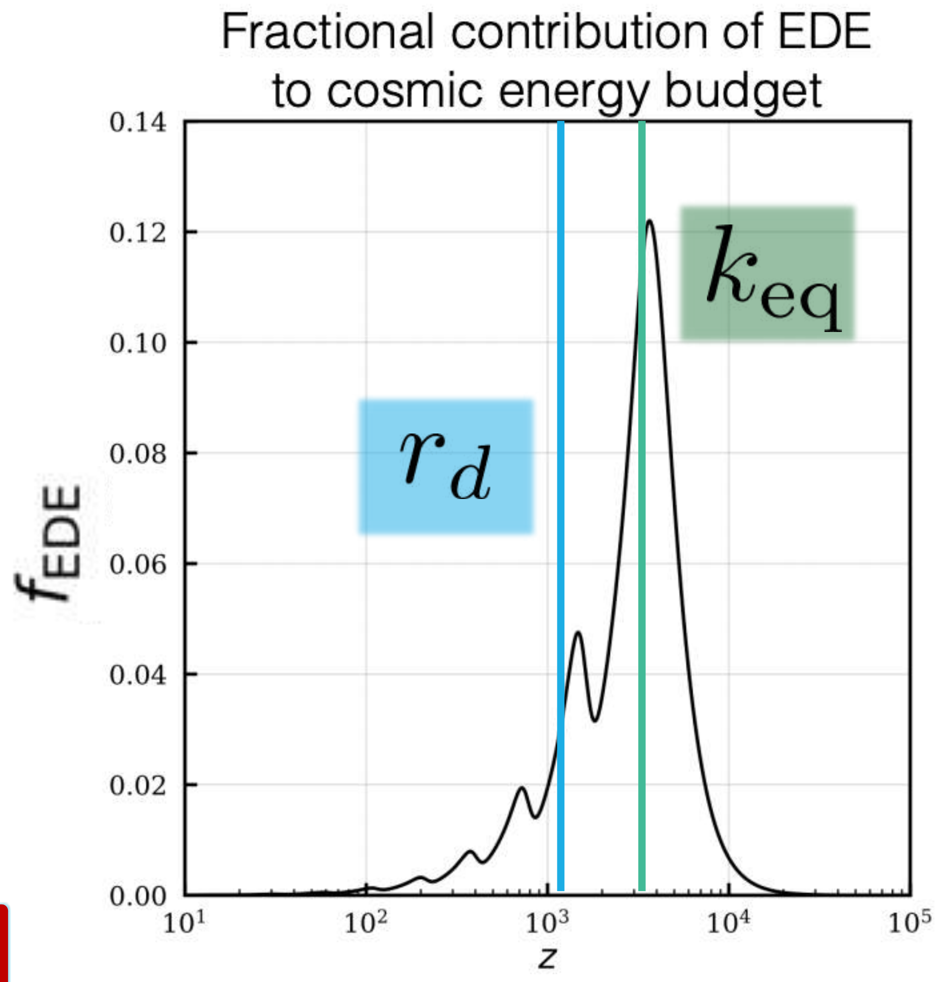
- The **equality scale** contains H_0 information

$$\theta_{\rm eq} \sim k_{\rm eq} {\rm D_A(z)} \propto H_0$$

- This is anchored at $z_{\rm eq} \sim 3600$, **much** before recombination at $z_d \sim 1100$

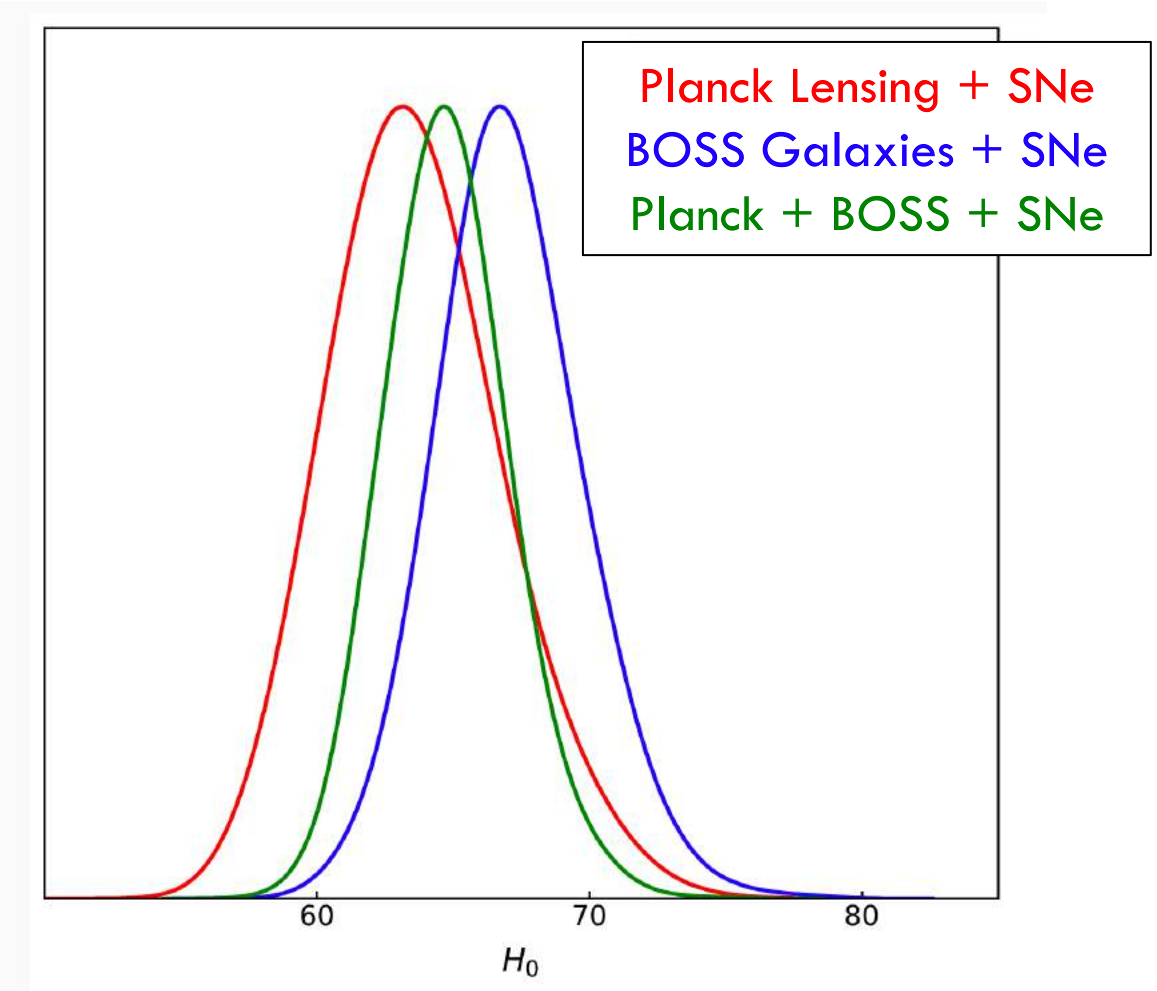
- New physics at $z \sim 10^3$ should affect **BAO** and **equality** H_0 measurements **differently**

$H_0(z_{eq}) - H_0(z_d)$ is a consistency test for ΛCDM



Baxter & Sherwin 2020, Hill+19,20

CONSTRAINTS ON H_0



Sound-Horizon Independent Constraints

BOSS Full Power Spectrum + Bispectrum:

$(z \approx 1100)\quad H_0 = 68.3 \pm 0.8\ \mathrm{km\,s^{-1}Mpc^{-1}}$

BOSS-without-the-sound-horizon:

(using new r_d-marginalized pipeline)

$(z \approx 3500)\quad H_0 = 67.1 \pm 2.7\ \mathrm{km\,s^{-1}Mpc^{-1}}$

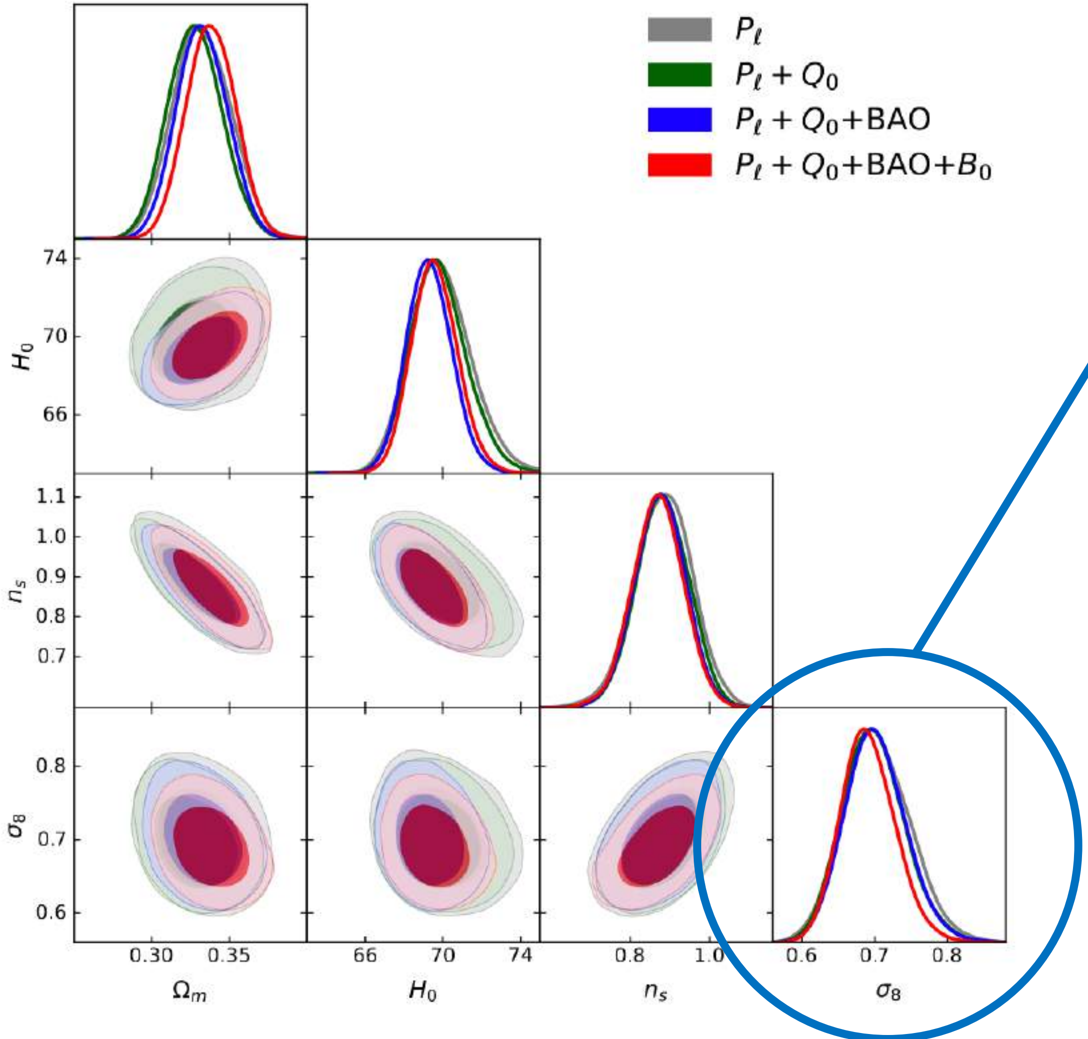
3.0σ *tension with SH0ES!*

Measurements will get **much** tighter with Euclid!

Philcox+21,22, Farren+21

CONSTRAINTS ON σ_8

BOSS (+ BBN) Constraints



BOSS Power Spectrum + Bispectrum:

$\sigma_8 = 0.72 \pm 0.03$ (with *Planck* n_s)

$\sigma_8 = 0.69 \pm 0.04$ (no *Planck*)

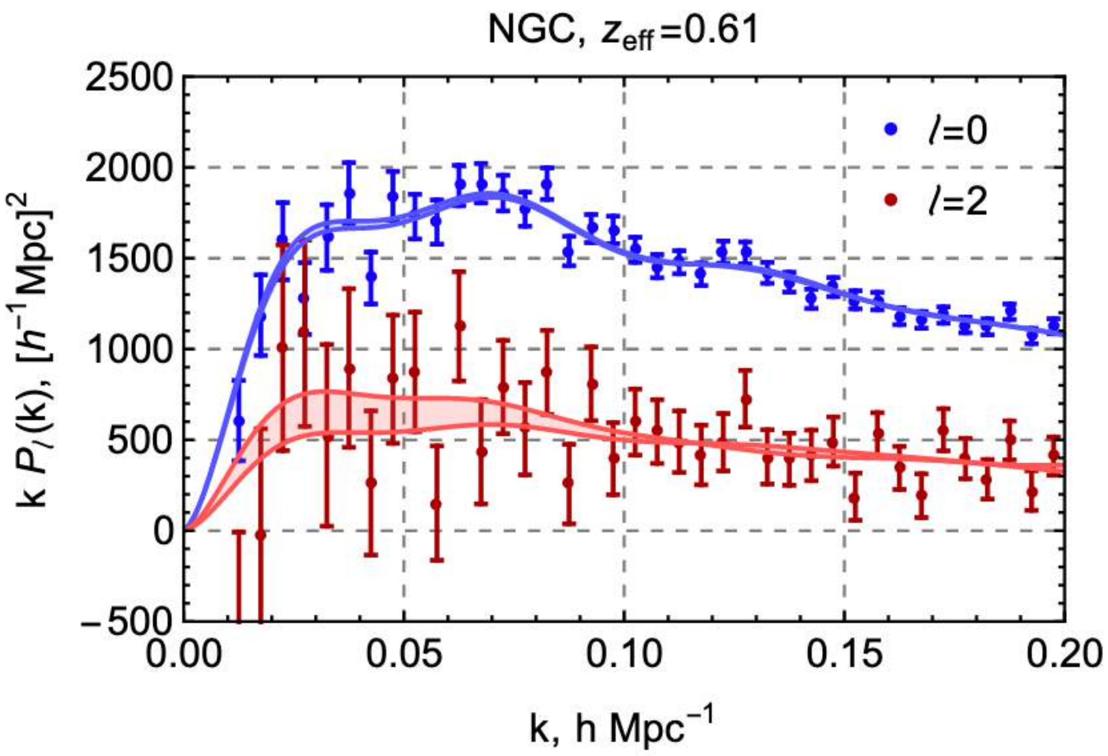
This is consistent with weak lensing, but somewhat lower than *Planck*:

$S_8 = 0.73 \pm 0.04$ (BOSS)

$S_8 = 0.83 \pm 0.01$ (*Planck*)

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

WHERE DOES THE σ_8 INFORMATION COME FROM?



$\boldsymbol{\sigma_8}$ is set by the **large-scale** ($k < 0.1h/\mathrm{Mpc}$) quadrupole

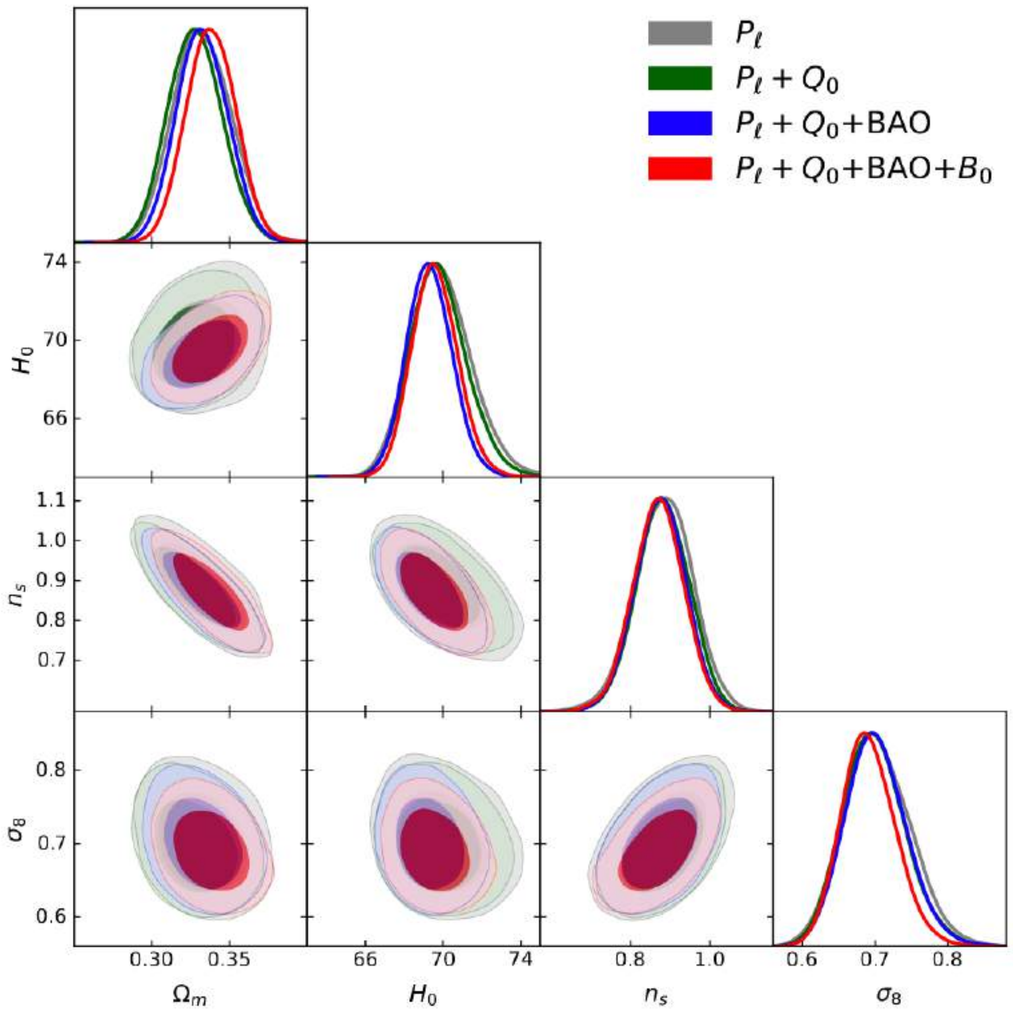
This is hard to change!

- Mostly linear scales
- Bias well understood
- Fingers-of-God suppressed

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

CONSTRAINTS ON OTHER PARAMETERS

BOSS (+ BBN) Constraints



Matter Density:

$$\Omega_m = 0.34 \pm 0.02$$

Consistent with Pantheon+ supernovae!

Spectral Slope:

$$n_s = 0.87 \pm 0.07$$

Consistent with *Planck*

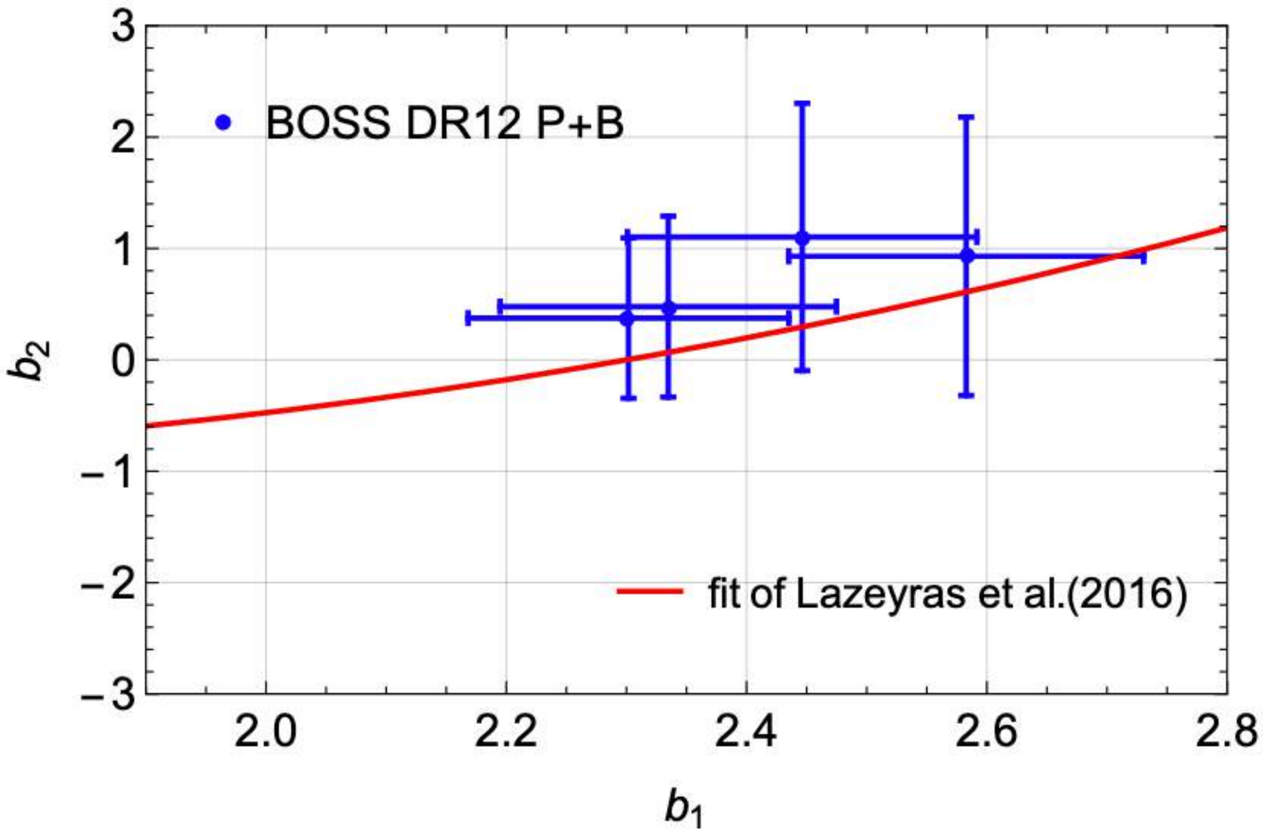
Neutrino Mass:

$$\sum m_\nu < 0.14 \text{ eV } (95\% \text{ CL})$$

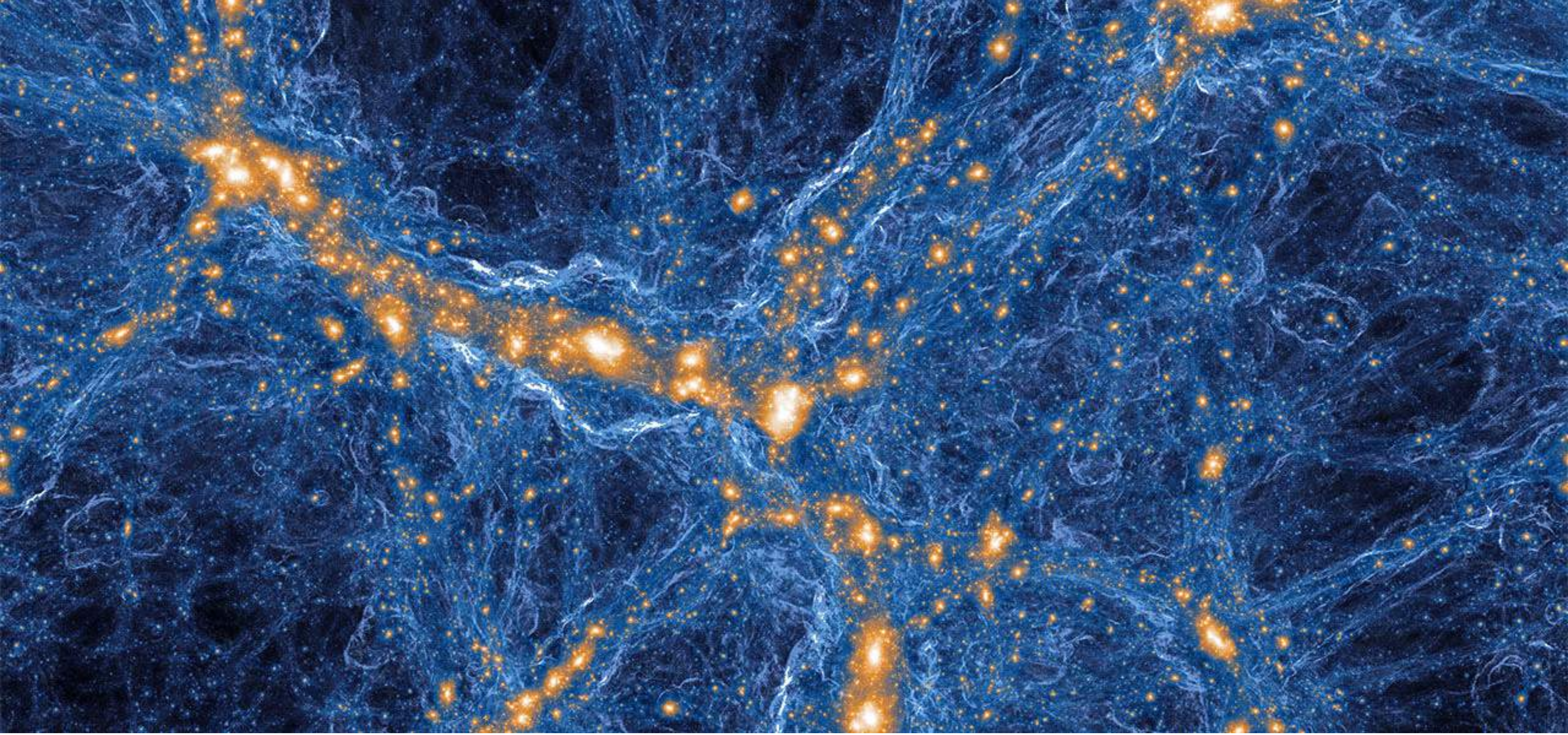
Philcox+20,21 (see also Chen+21, d'Amico+21)

CONSTRAINTS ON ASTROPHYSICS

- Analysis also measures **bias parameters** (especially the bispectrum)
- These encode the physics of galaxy formation
- Consistent with simulation results!



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



3. What Have We Learnt Beyond ΛCDM?

NON-GAUSSIAN INFLATION

Are the primordial perturbations ***Gaussian*** *and* ***adiabatic****?*

In Single-Field Slow-Roll Inflation:

$$f_{\rm NL} \sim (1 - n_s) \ll 1$$

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

Non-standard inflation can beat this:

- Multifield Inflation [Local Bispectrum]
- New Kinetic Terms [Equilateral Bispectrum]
- New Vacuum States [Folded Bispectrum]

Maldacena 03, Creminelli+04

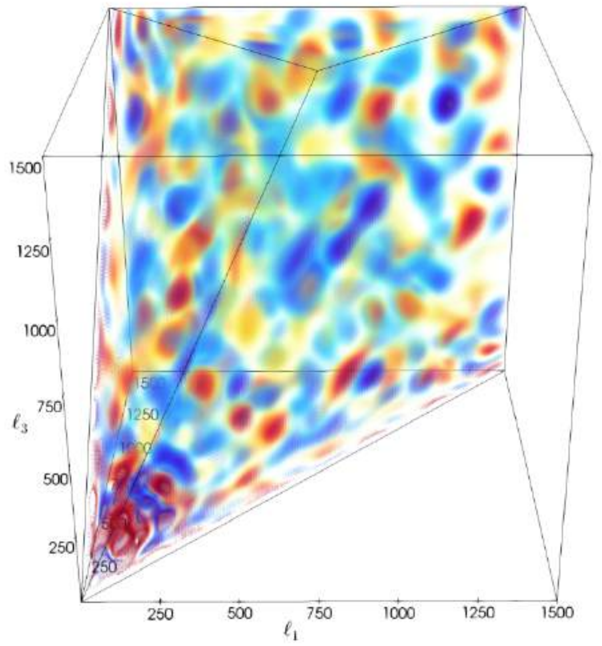
NON-GAUSSIAN INFLATION

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

How do we measure this?

1. **CMB Bispectrum**

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

NON-GAUSSIAN INFLATION

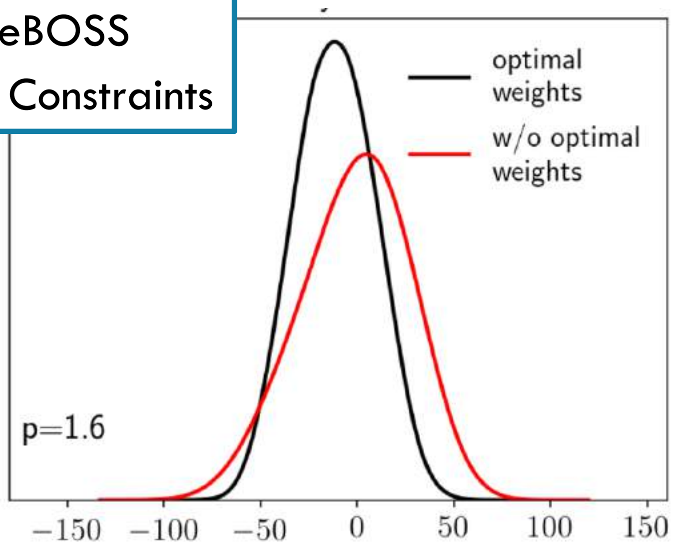
$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

How do we measure this?

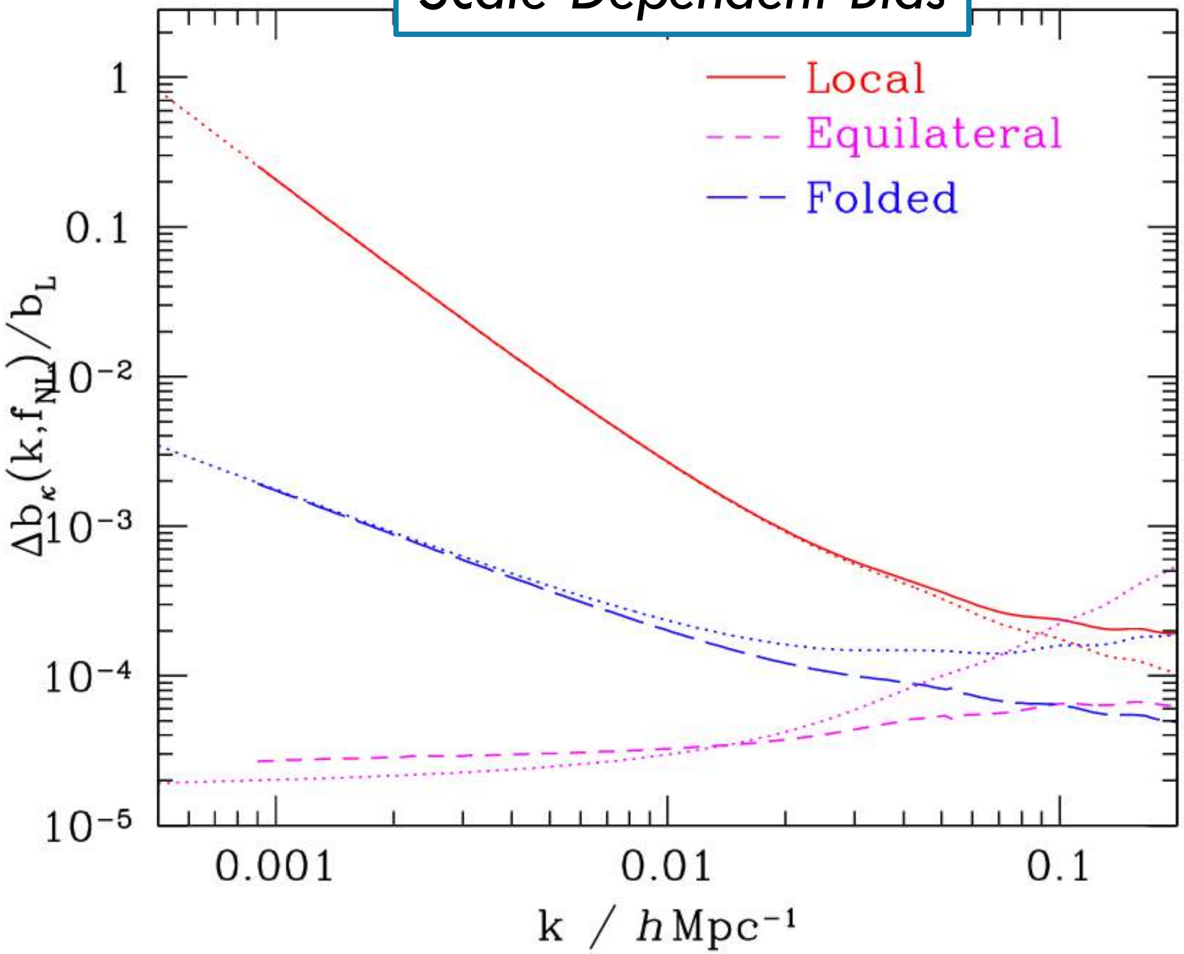
1. CMB Bispectrum

2. **Galaxy Power Spectrum**

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



Scale-Dependent Bias



Desjacques & Seljak 10, eBOSS 21

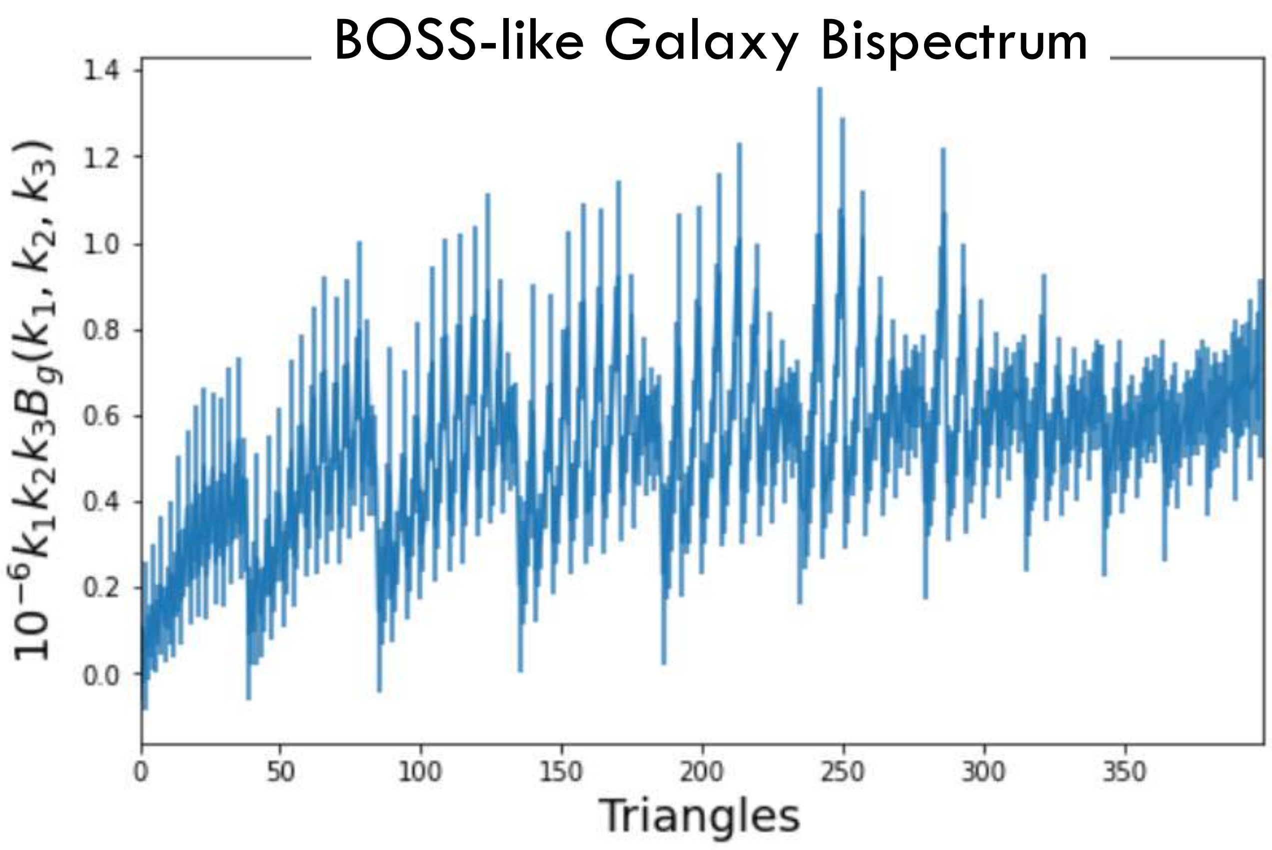
NON-GAUSSIAN INFLATION

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

How do we measure this?

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

Need a good theory model and careful window function treatment!



Philcox+21, Cabass+21,22

MODELING PRIMORDIAL NON-GAUSSIANITIES

Theory model includes:

- Primordial bispectrum:

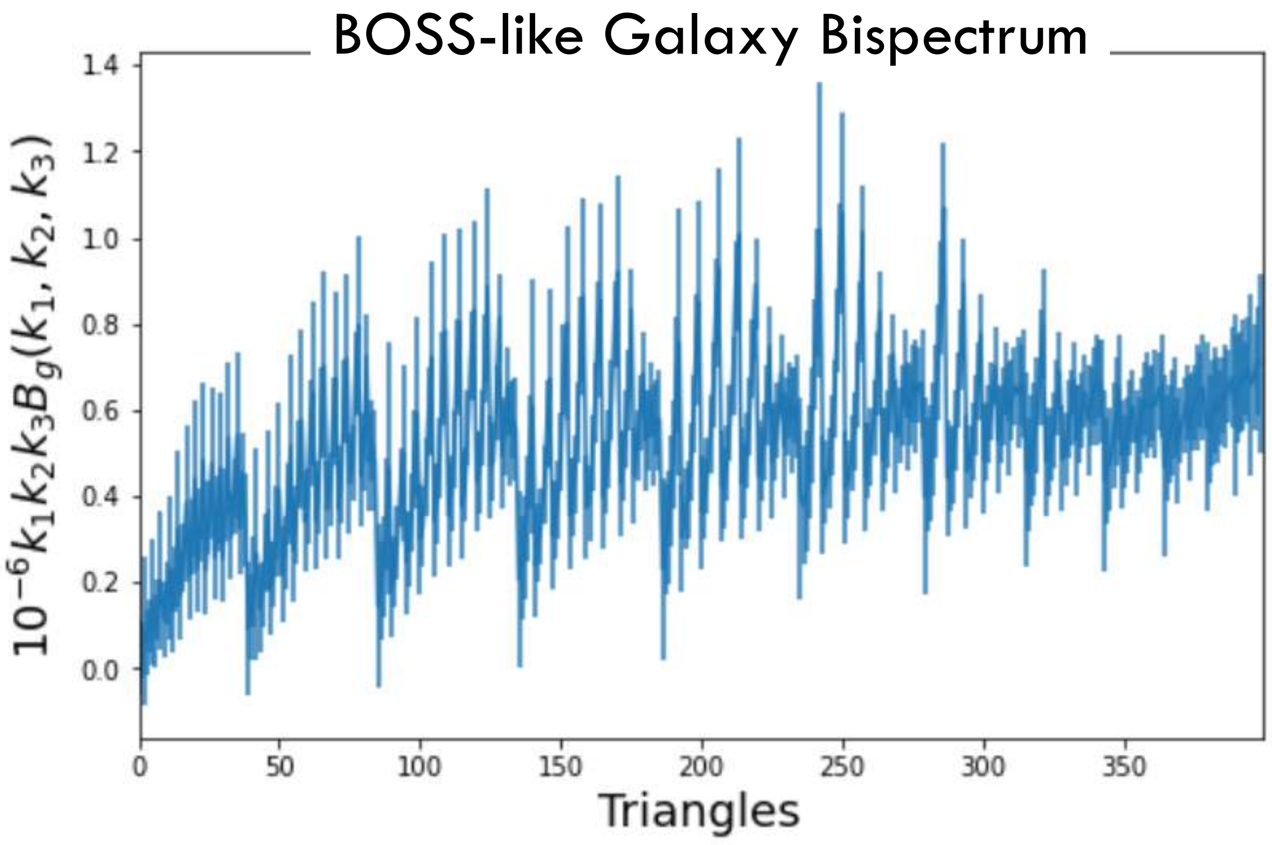
$$\langle \delta^{(1)}\delta^{(1)}\delta^{(1)} \rangle \sim f_{\rm NL} P^2(k)$$

- Scale dependent bias:

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

- Loop corrections:

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



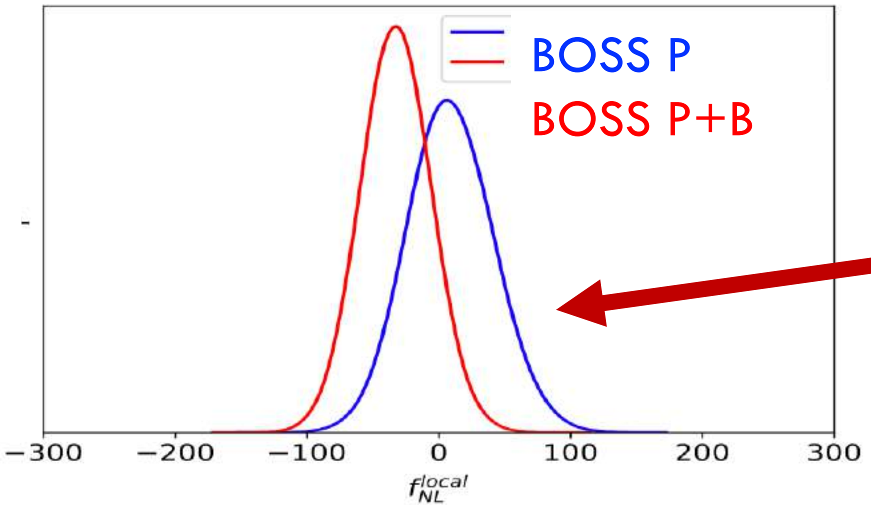
$$B_g = B_g(f_{\rm NL}^{\rm eq}, f_{\rm NL}^{\rm orth}, f_{\rm NL}^{\rm loc})$$

See GitHub.com/michalychforever/CLASS-PT

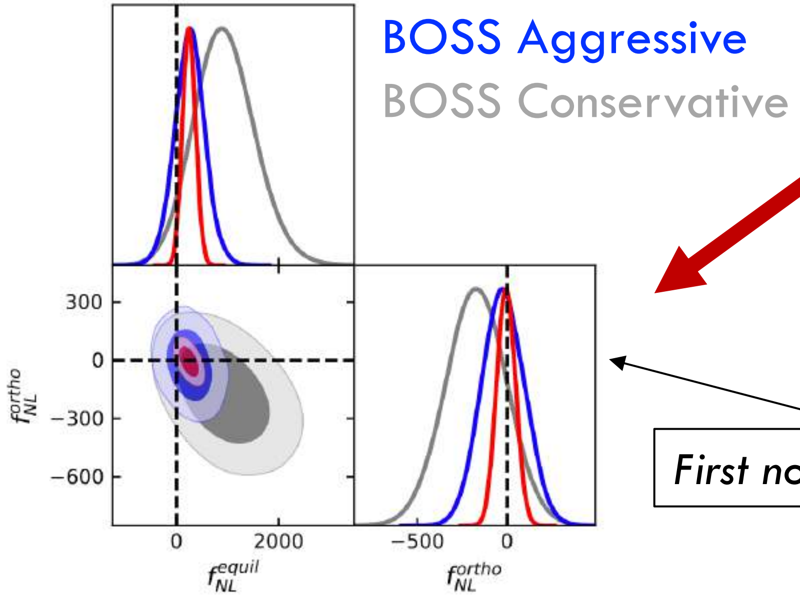
Cabass+21,22 (see also d'Amico+22)

CONSTRAINTS ON $f_{\rm NL}$

Multi-Field Inflation



Single-Field Inflation



First non-CMB measurements!

BOSS Power Spectrum + Bispectrum:

$f_{\rm NL}^{\rm local} = -33 \pm 28$ [fixing b_ϕ]

$f_{\rm NL}^{\rm equil} = 940 \pm 600$

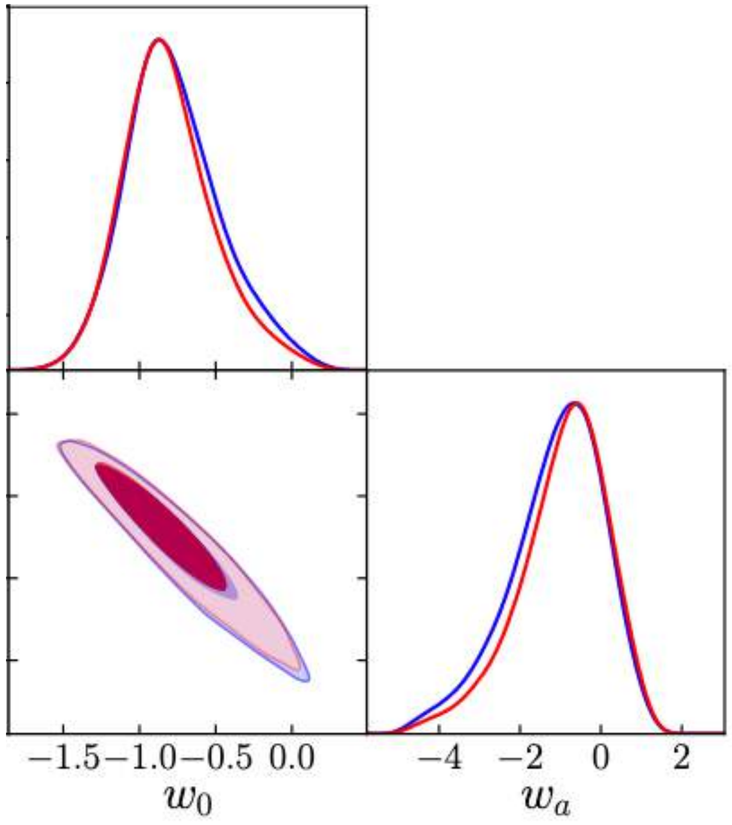
$f_{\rm NL}^{\rm orth} = 170 \pm 170$

This constrains the effective field theory of inflation, e.g., the inflaton sound-speed:

$$c_s \geq 0.013 \text{ (95\% CI)}$$

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

OTHER POST-ΛCDM CONSTRAINTS

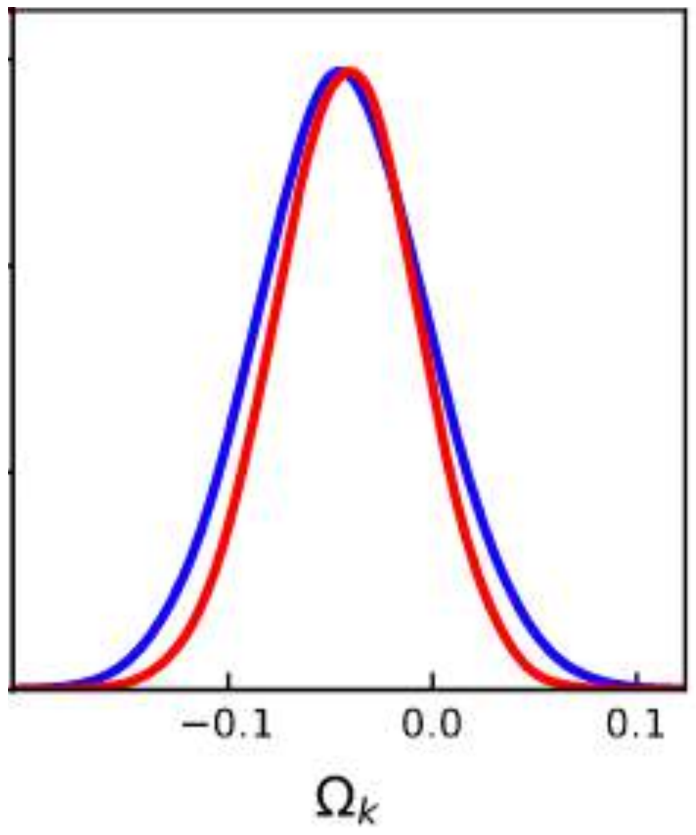


$w_0 = -0.98 \pm 0.01$

$w_a = -0.3 \pm 0.6$

- w_0, w_a consistent with cosmological constant [Chudaykin+20]

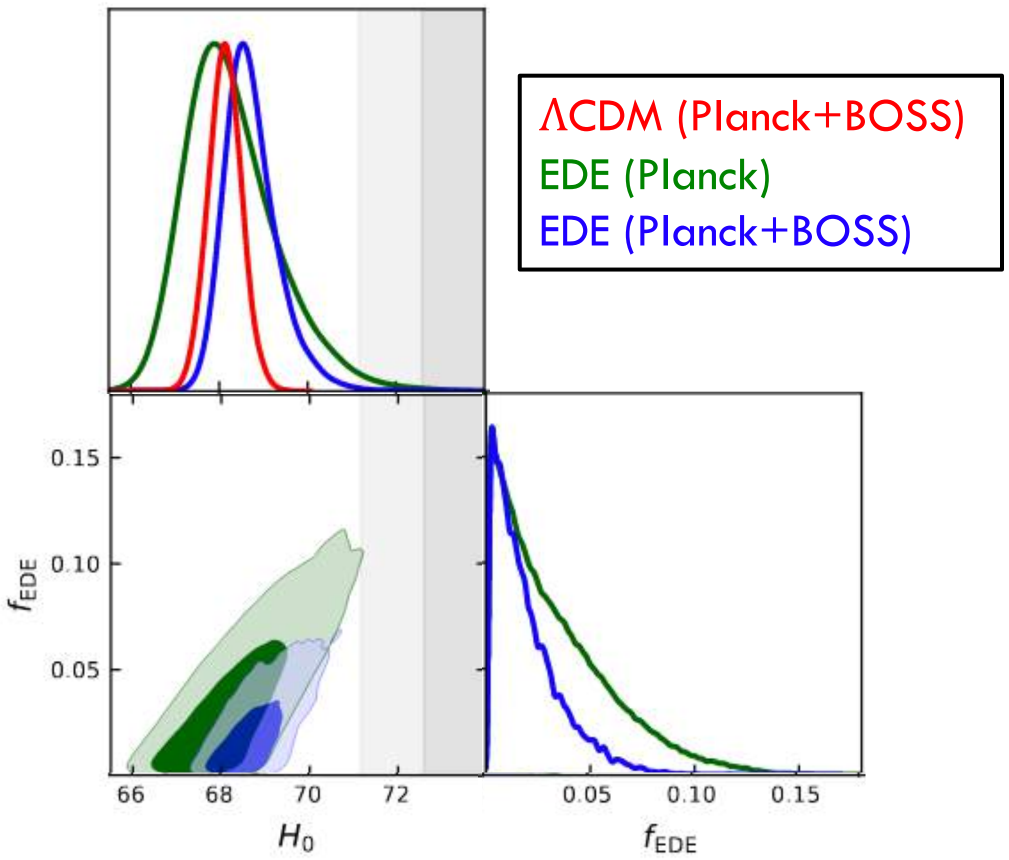
OTHER POST-ΛCDM CONSTRAINTS



$$\Omega_k = -0.04 \pm 0.04$$

- w_0, w_a consistent with cosmological constant [Chudaykin+20]
- Curvature consistent with zero [Chudaykin+20]

OTHER POST-ΛCDM CONSTRAINTS



$f_{\mathrm{EDE}} < 0.053$ (95% CL)

- w_0, w_a consistent with cosmological constant [Chudaykin+20]
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- No evidence for early dark energy [Ivanov+20]

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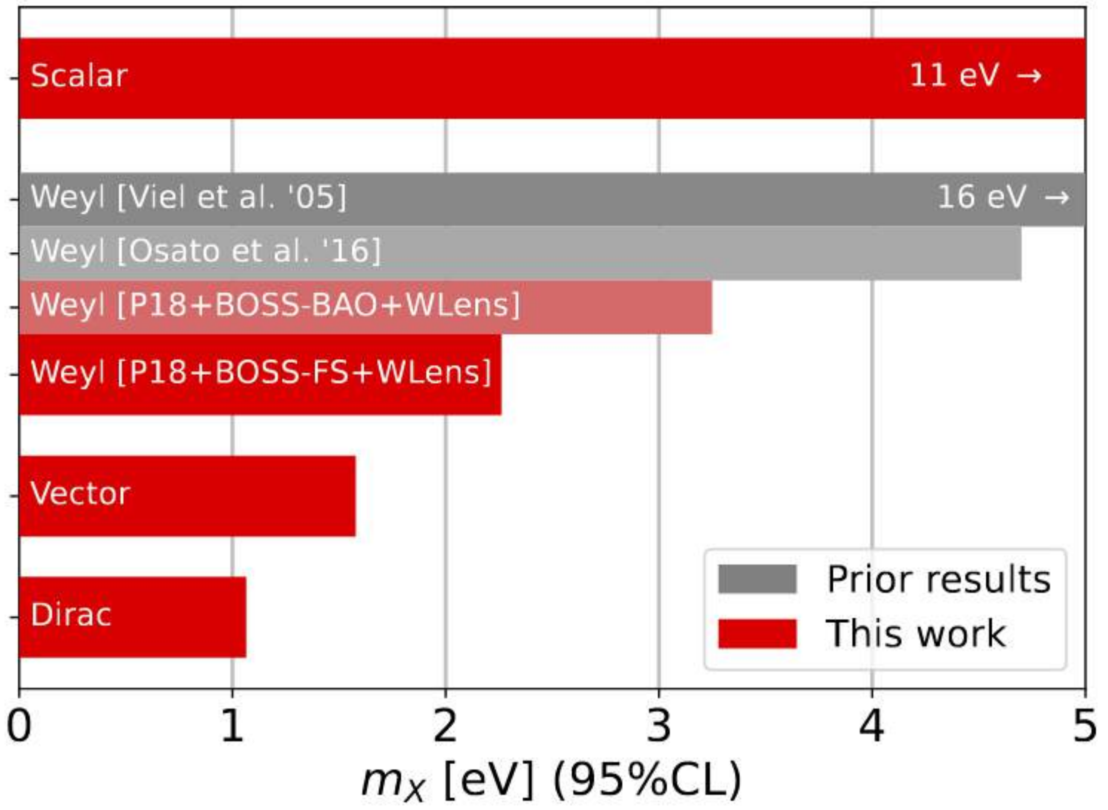

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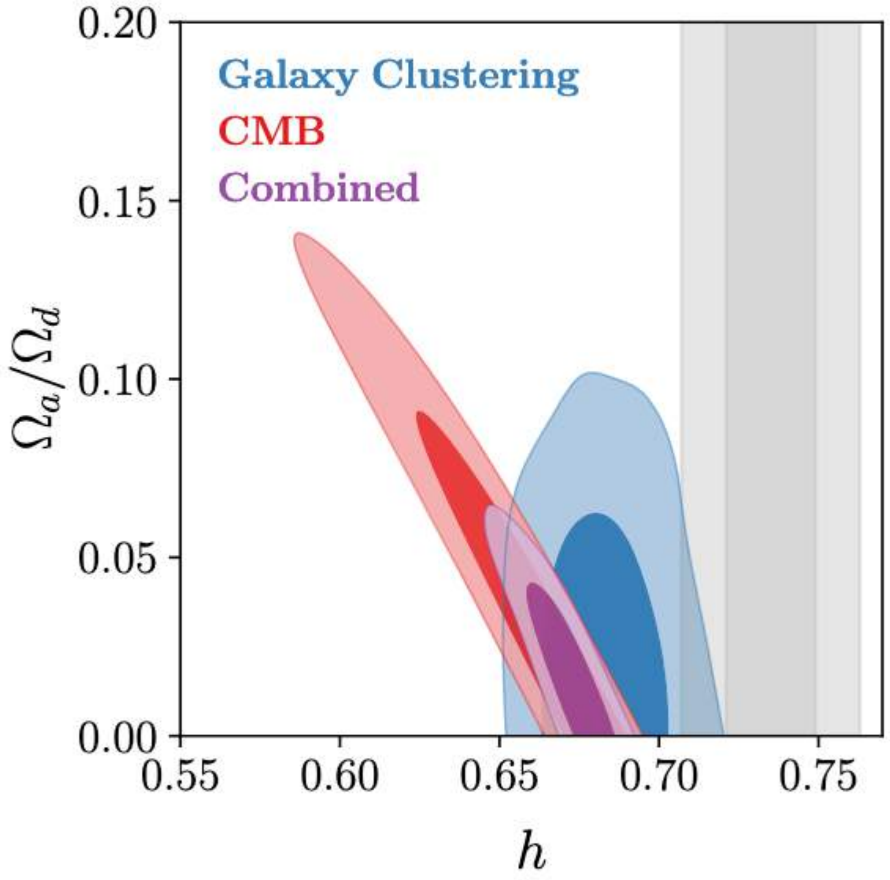

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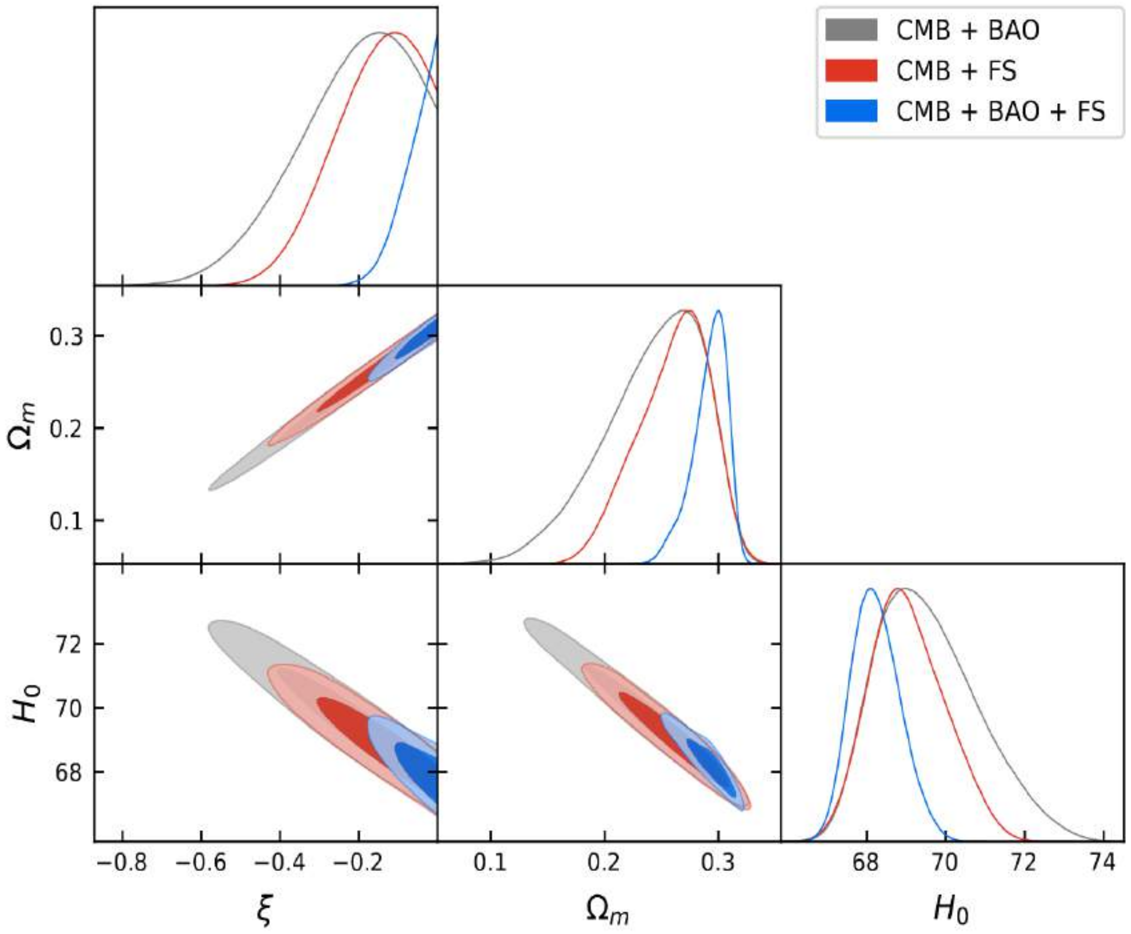

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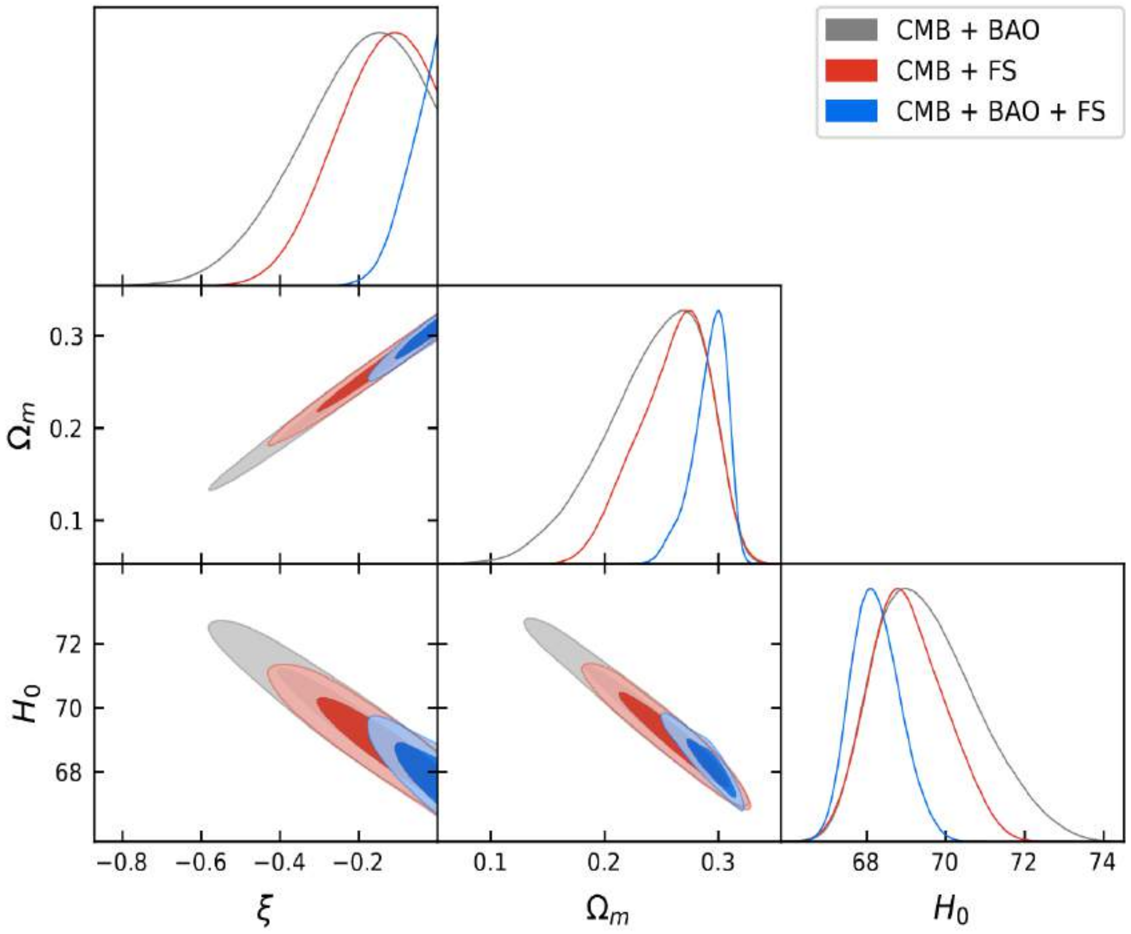

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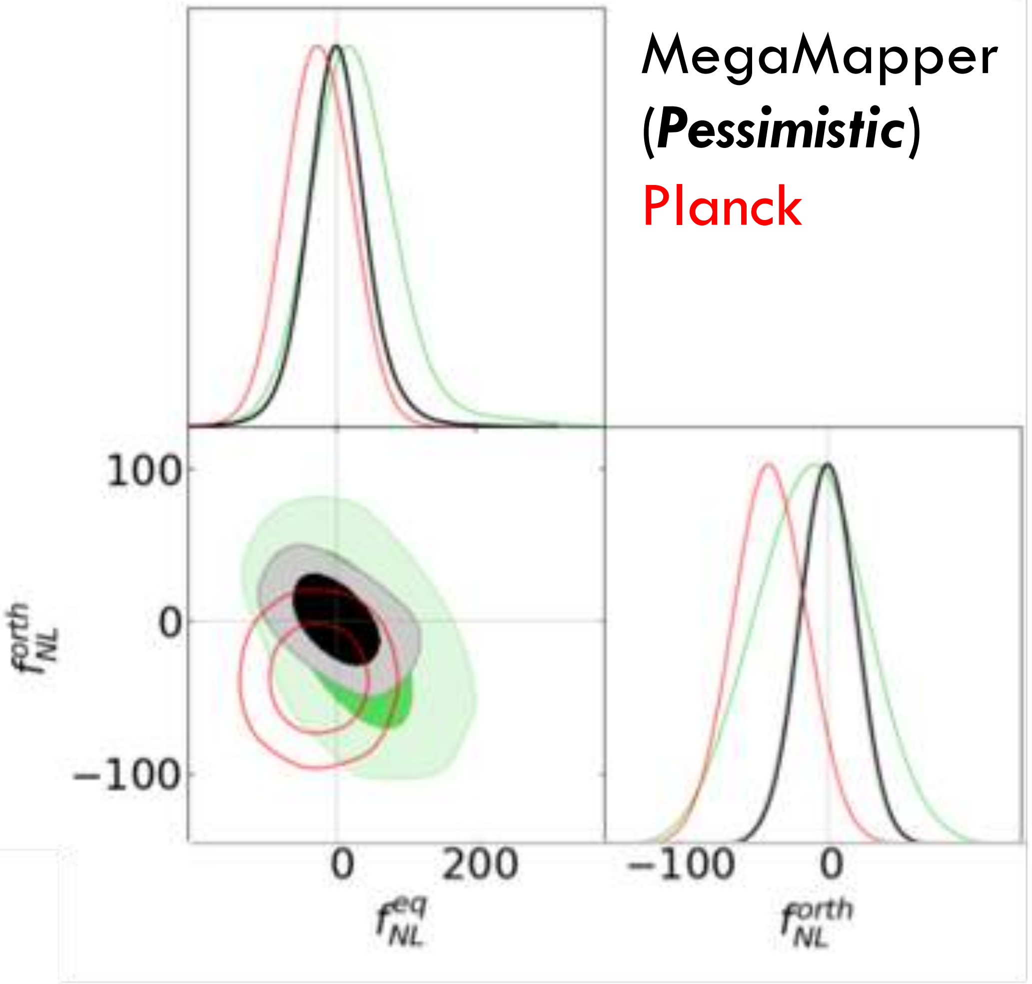
And many more…

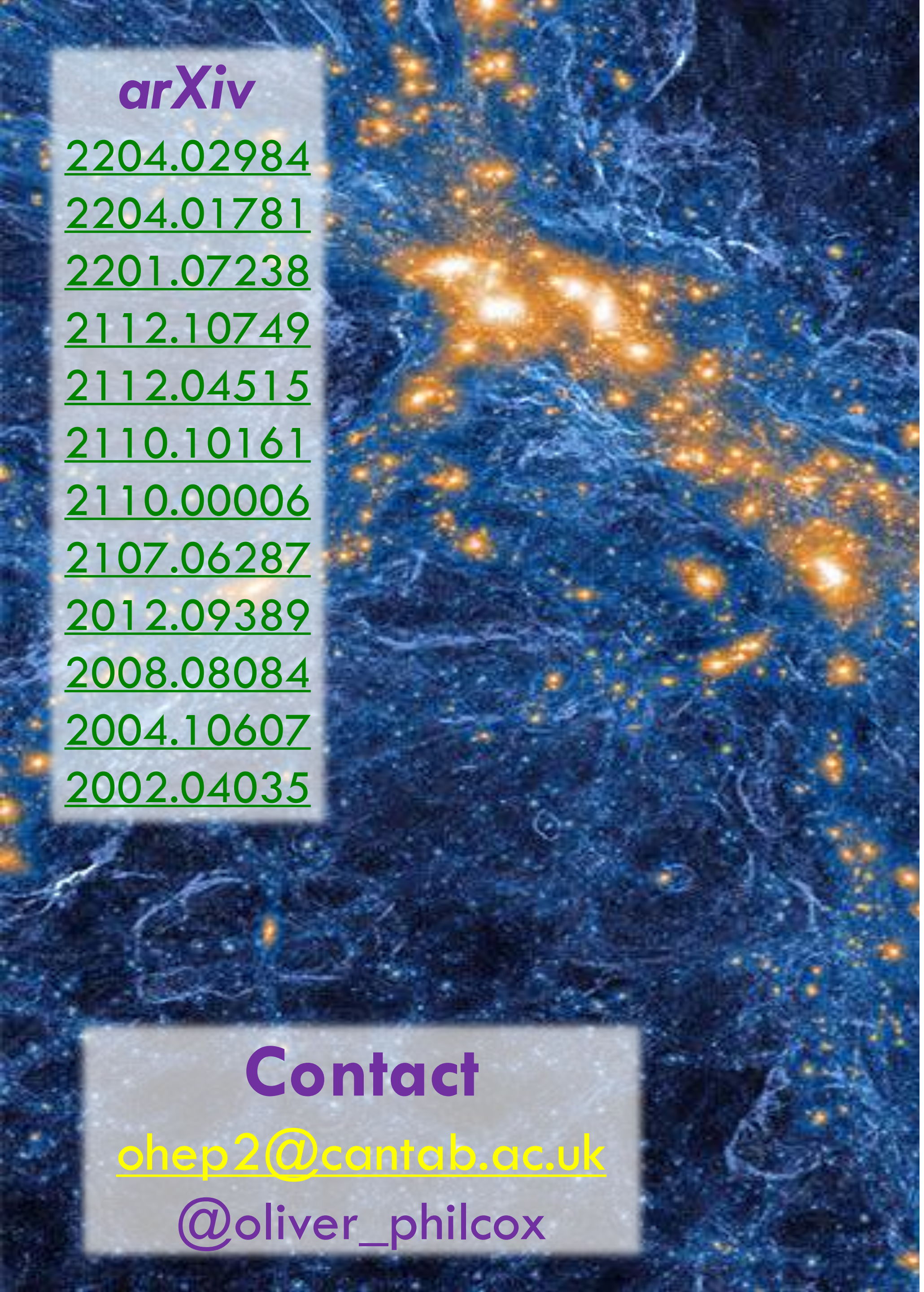
All analysis is public:
github.com/oliverphilcox/full_shape_likelihoods

WHAT'S NEXT?

- **Complete** bispectrum theory model at **one-loop**
- Bispectrum **Multipoles**?
- Trispectrum / correlation functions?
- Other new physics?
- **DESI** / **Euclid** + beyond?

LSS constraints will (eventually) beat the CMB!





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CONCLUSIONS

- We can robustly **measure** and **model** the galaxy power spectrum and bispectrum of survey data
- This allows **direct** extraction of **cosmological parameters** including $H_0, \Omega_m, \sigma_8, f_{\rm NL}, w_0, \Omega_k, f_{\rm EDE}$
- BOSS data is already useful: this will get much better with **Euclid** / **DESI**