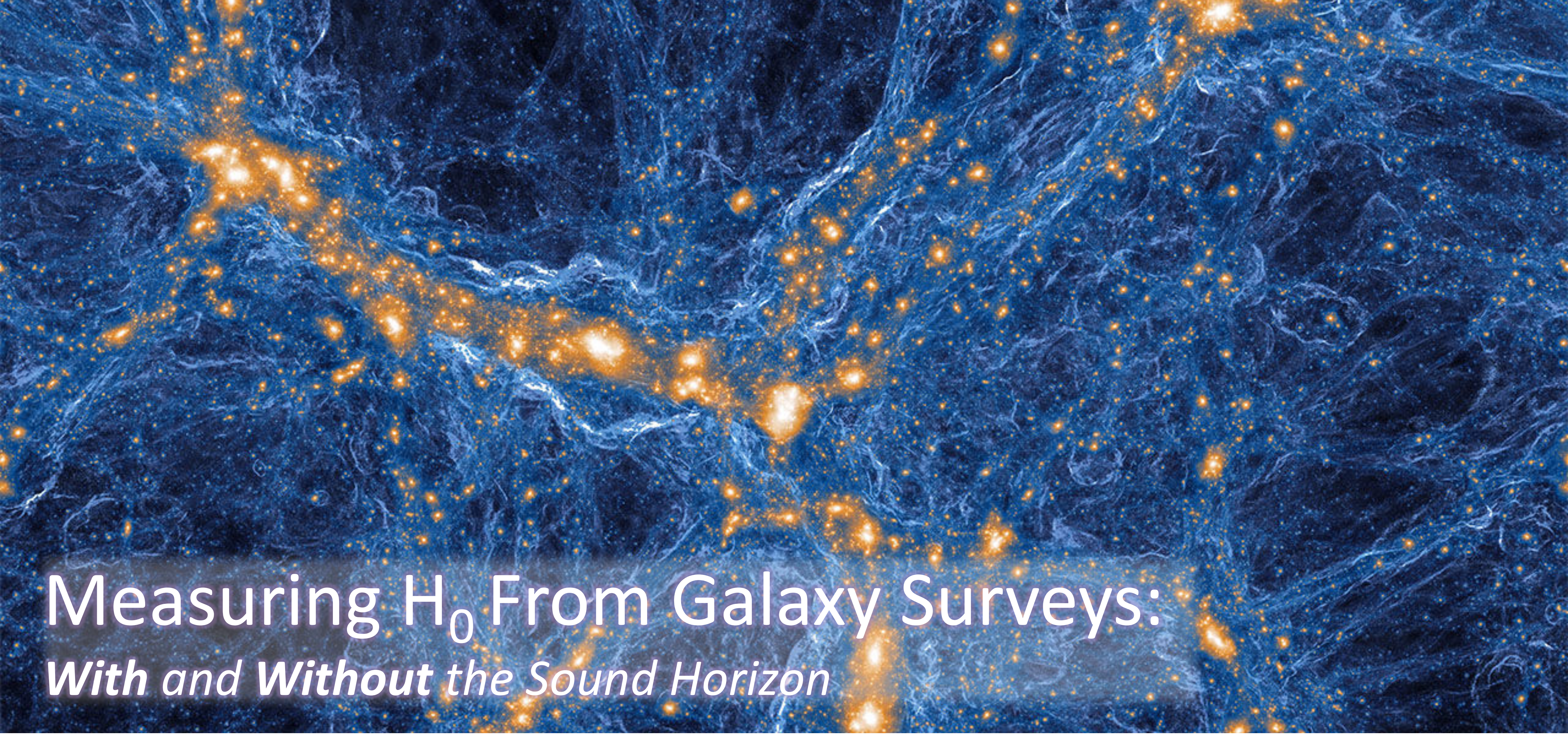


Measuring H_0 From Galaxy Surveys:

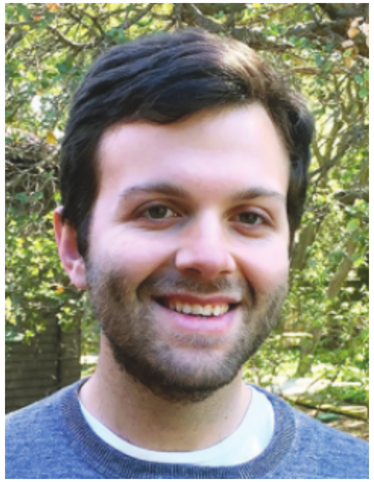
With *and* ***Without*** *the Sound Horizon*

Oliver Philcox (Princeton)

Cosmology From Home 2020

Based on:

- *Philcox, Ivanov, Simonovic, Zaldarriaga (2020, arXiv: 2002.04035)*
- *Philcox, Sherwin, Farren, Baxter (to appear)*



Blake Sherwin

Gerrit Farren

Eric Baxter

Mikhail Ivanov

Marko Simonovic

Matias Zaldarriaga

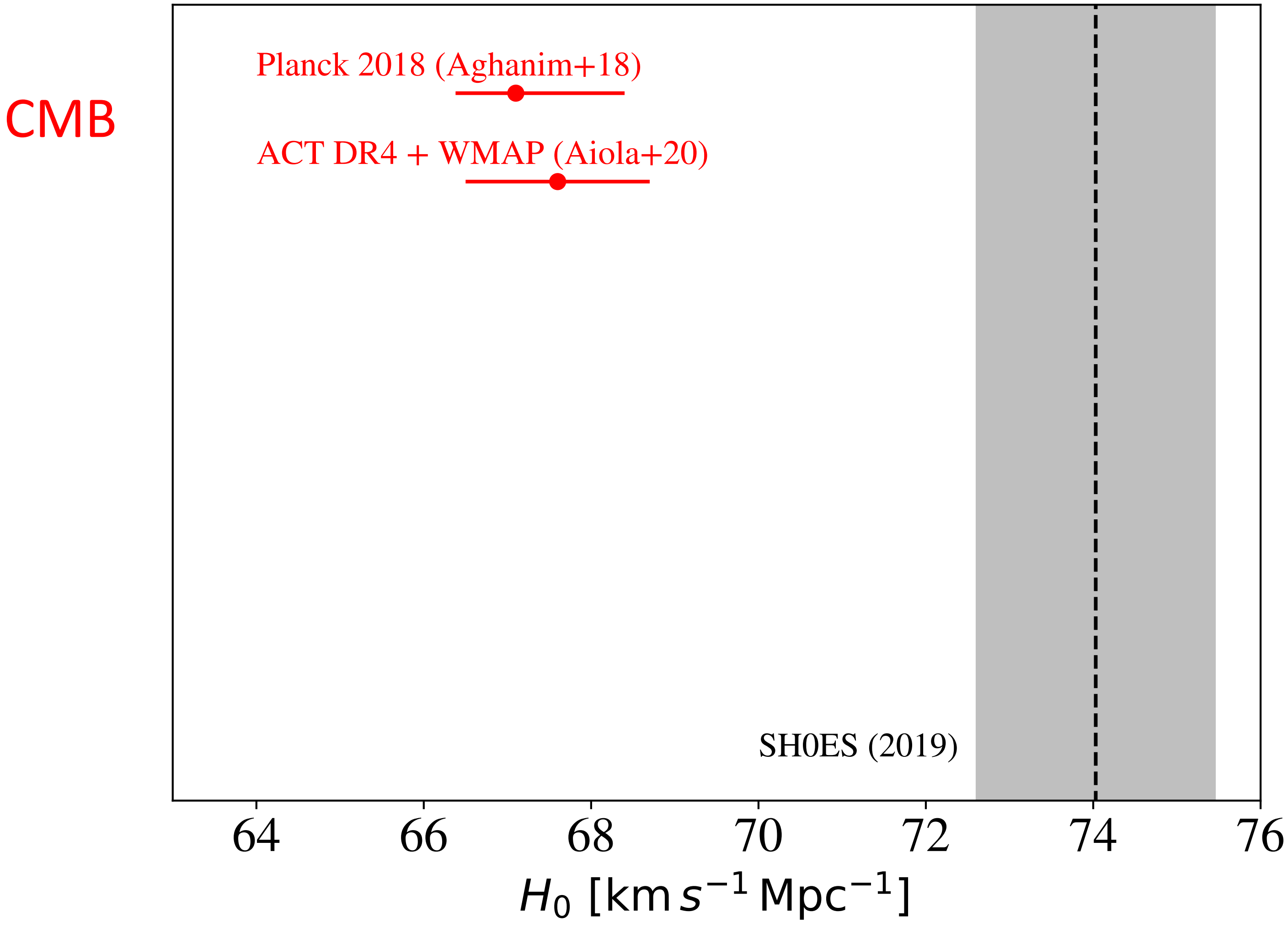
Indirect H_0: No Longer Just the CMB

- Two types of measurements:

  1. **Indirect**
     - Require a **cosmological model**

  2. **Direct**
     - No model required!
     - e.g. distance ladders, strong lensing, …

- Historically **indirect** H_0 constraints are from the CMB



Disclaimer: 1σ errors do not fully represent non-Gaussian posteriors.

Indirect H_0: No Longer Just the CMB

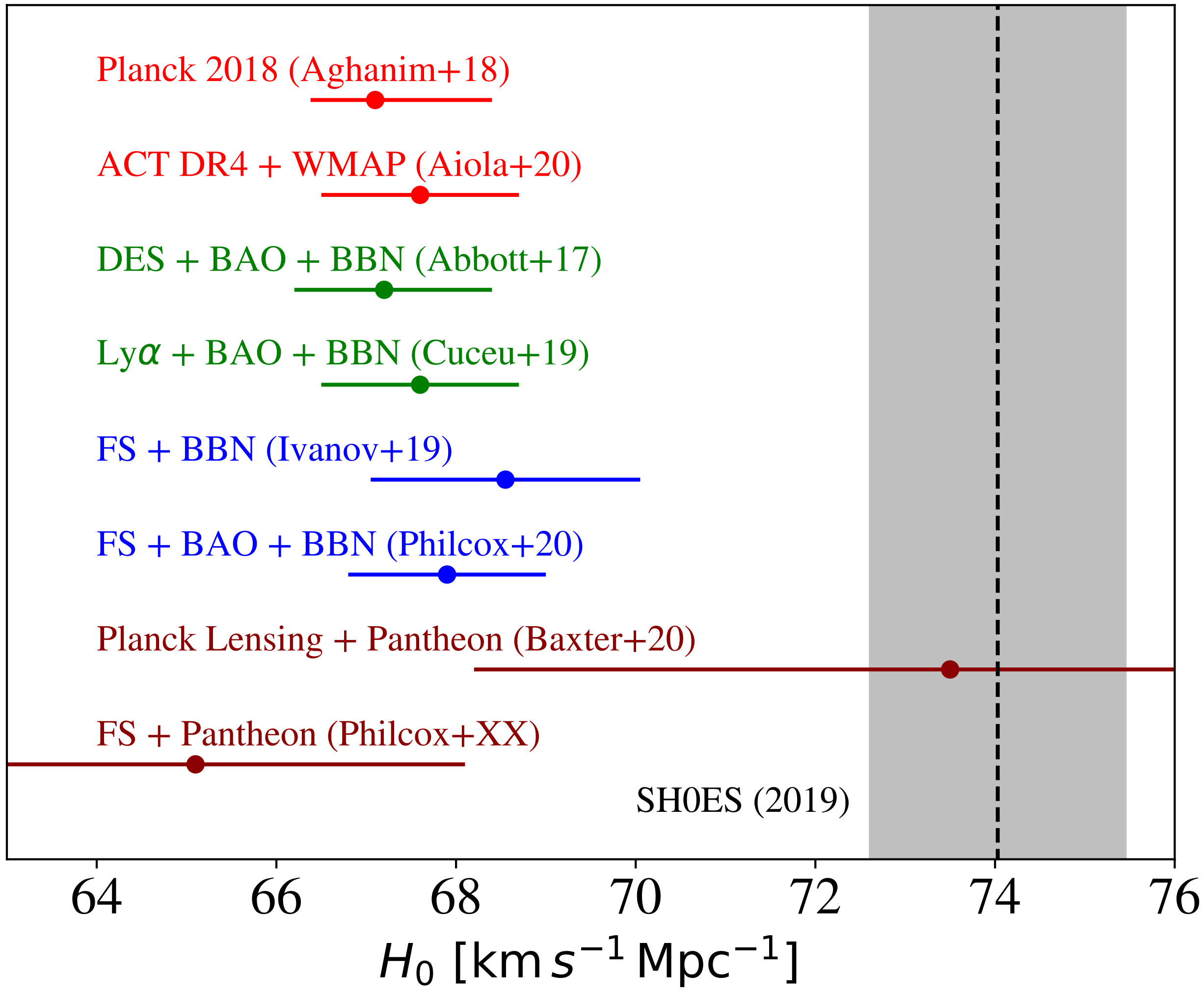
- Two types of measurements:
  1. **Direct**
     - Require a **cosmological model**
  2. **Indirect**
     - No model required!
     - e.g. distance ladders, strong lensing, …
- Historically **indirect** H_0 constraints are from the CMB
- **Large Scale Structure** comparable to the CMB!

CMB

BOSS BAO

BOSS FS

Equality



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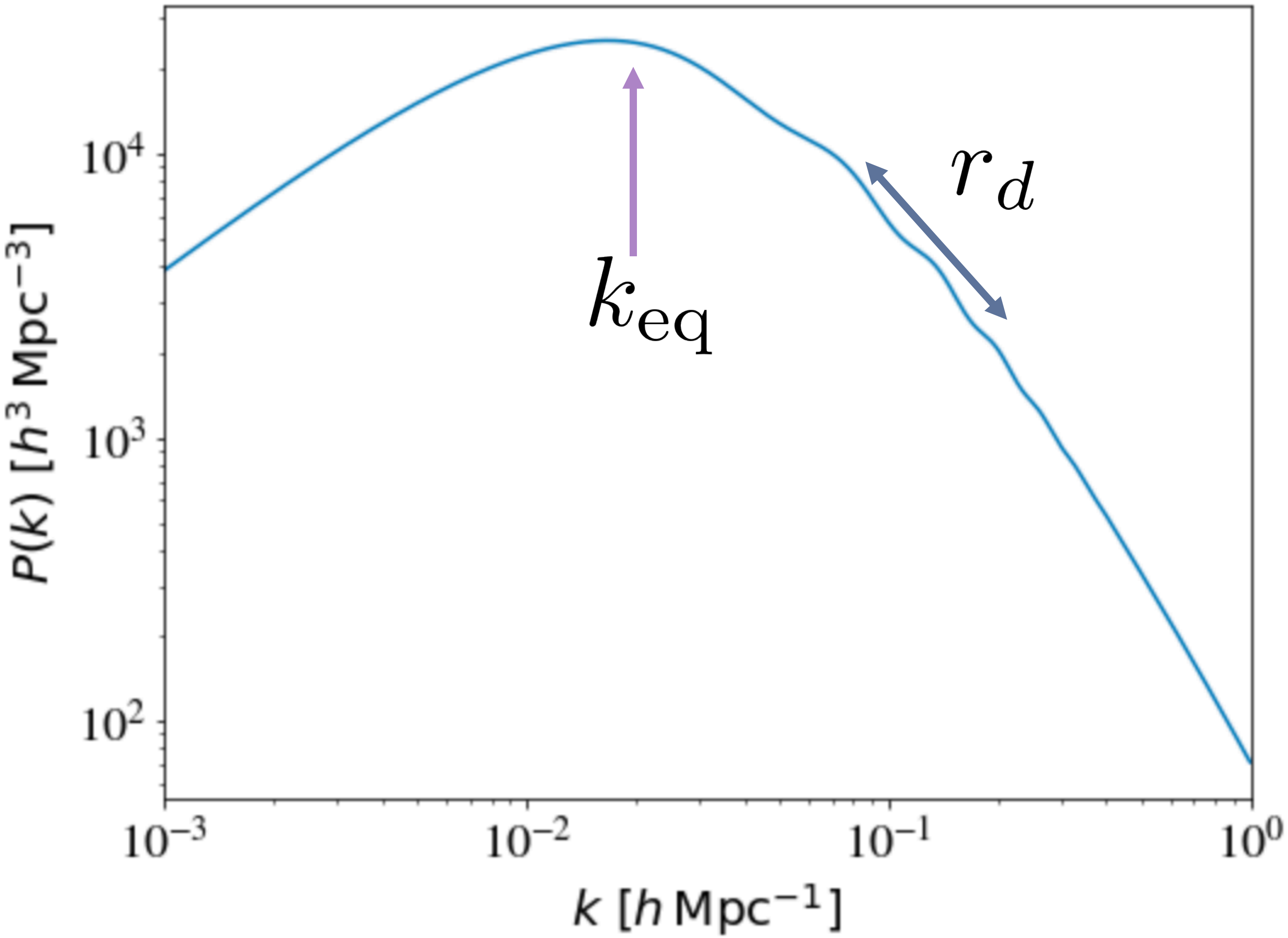
Two Scales in the Matter Power Spectrum



1. The Equality Scale: $k_{\rm eq}^{-1}$
   - The **horizon** at radiation-matter equality ($z \sim 3600$)
   - Sets the **peak** and overall shape
2. The Sound Horizon: r_d
   - The **sound horizon** at baryon drag ($z \sim 1100$)
   - Sets the **BAO** frequency

These are **standard rulers**

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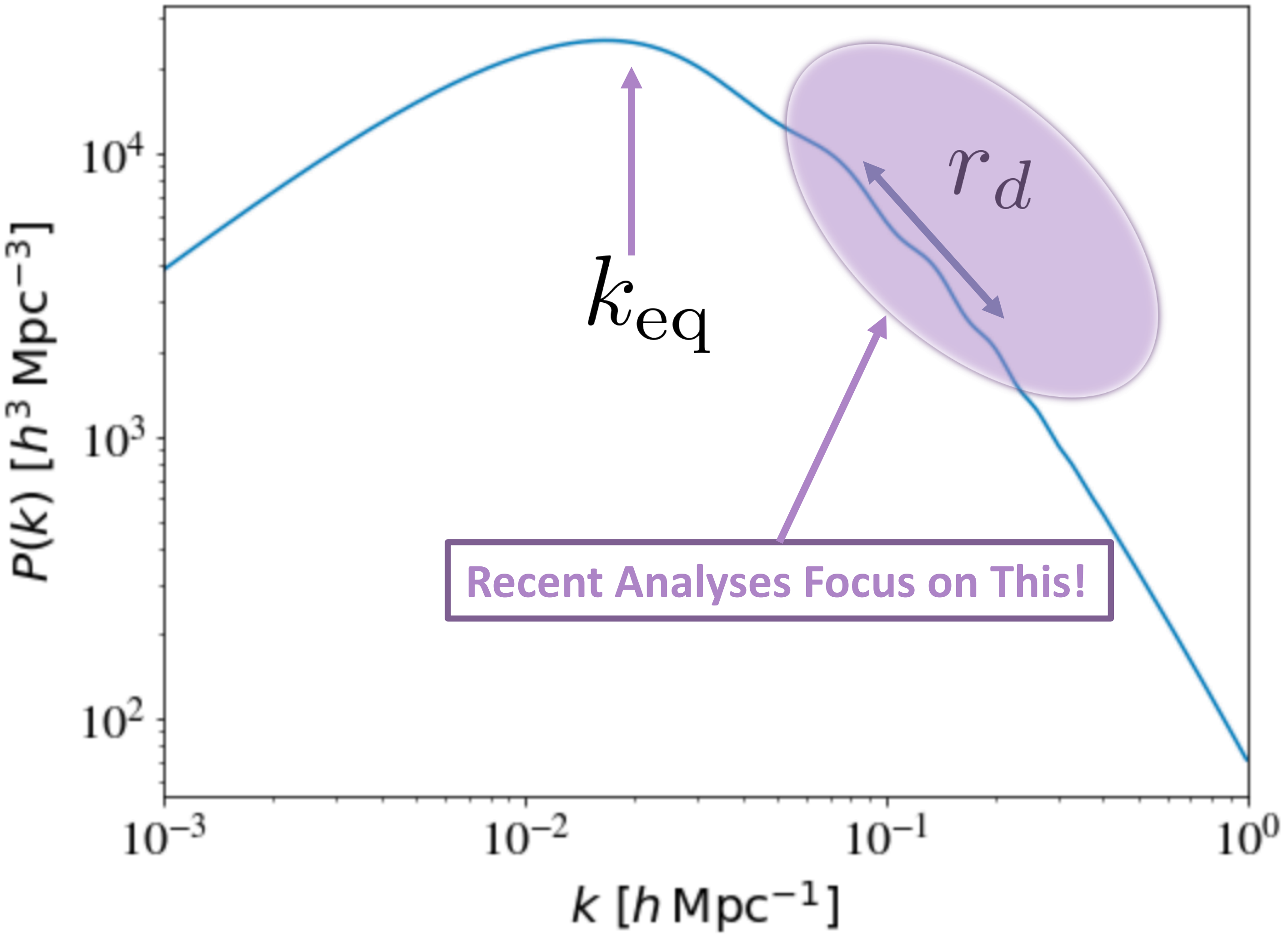

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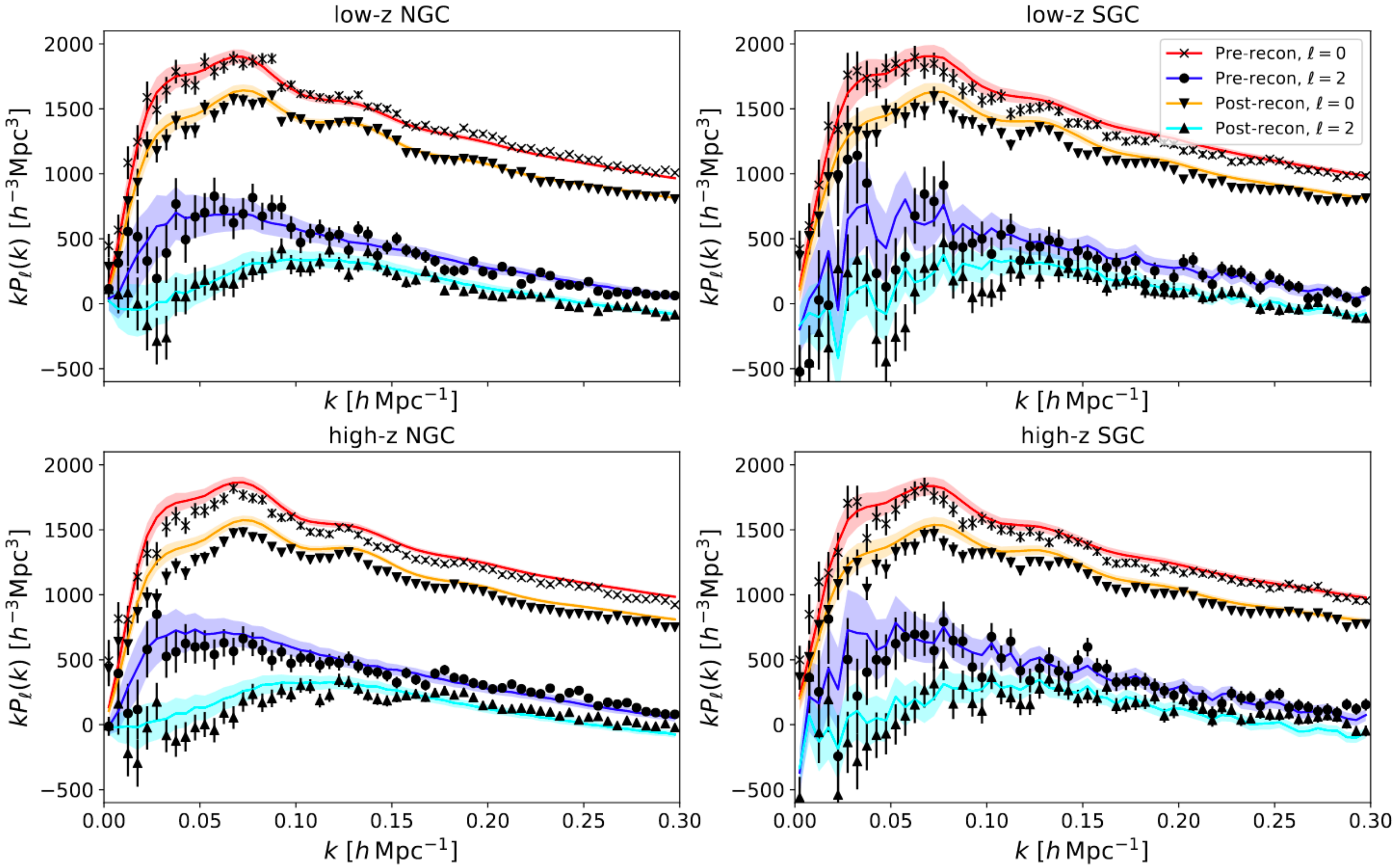
1. H_0 From the Sound Horizon

BOSS Power Spectra



BOSS DR12 [Alam+16]

- Two sky **patches**: NGC + SGC
- Two **redshifts**: $\{0.38, 0.61\}$
- Total **volume** $5.8\ (h^{-1}\mathrm{Gpc})^3$
- **Much** more coming soon…

Philcox+20

Galaxy Surveys: Measuring BAO

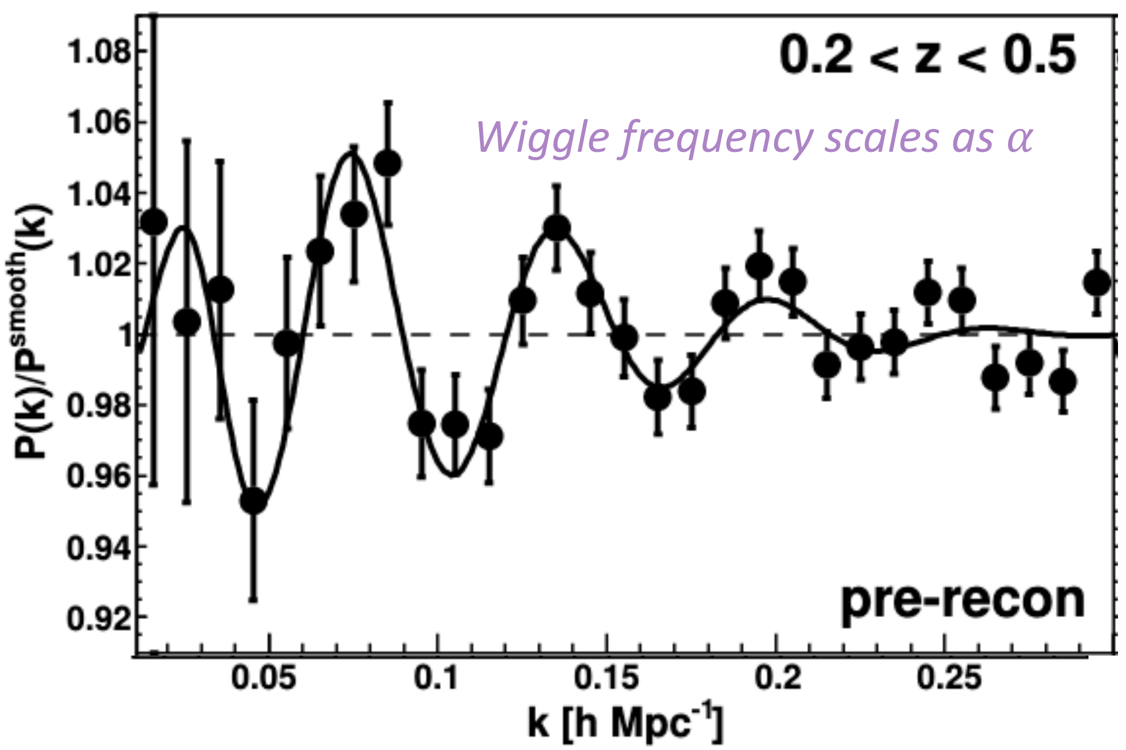
- Recent surveys measure 3 parameters:
  1. Radial Alcock-Paczynski parameter: $\boldsymbol{\alpha}_{\parallel}$
  2. Tangential Alcock-Paczynski parameter: $\boldsymbol{\alpha}_{\perp}$
  3. Ratio of quadrupole and monopole: $\boldsymbol{f\sigma_8}$

- These encode **cosmology:**

$$\alpha_{\parallel} \propto \frac{1}{H(z)r_d}$$

$$\alpha_{\perp} \propto \frac{D_A(z)}{r_d}$$

- To constrain $\boldsymbol{H_0}$ we need to know $\boldsymbol{r_d}$
  - Fix from *Planck* or use priors from BBN



BOSS DR12 Power Spectra

Beutler+16

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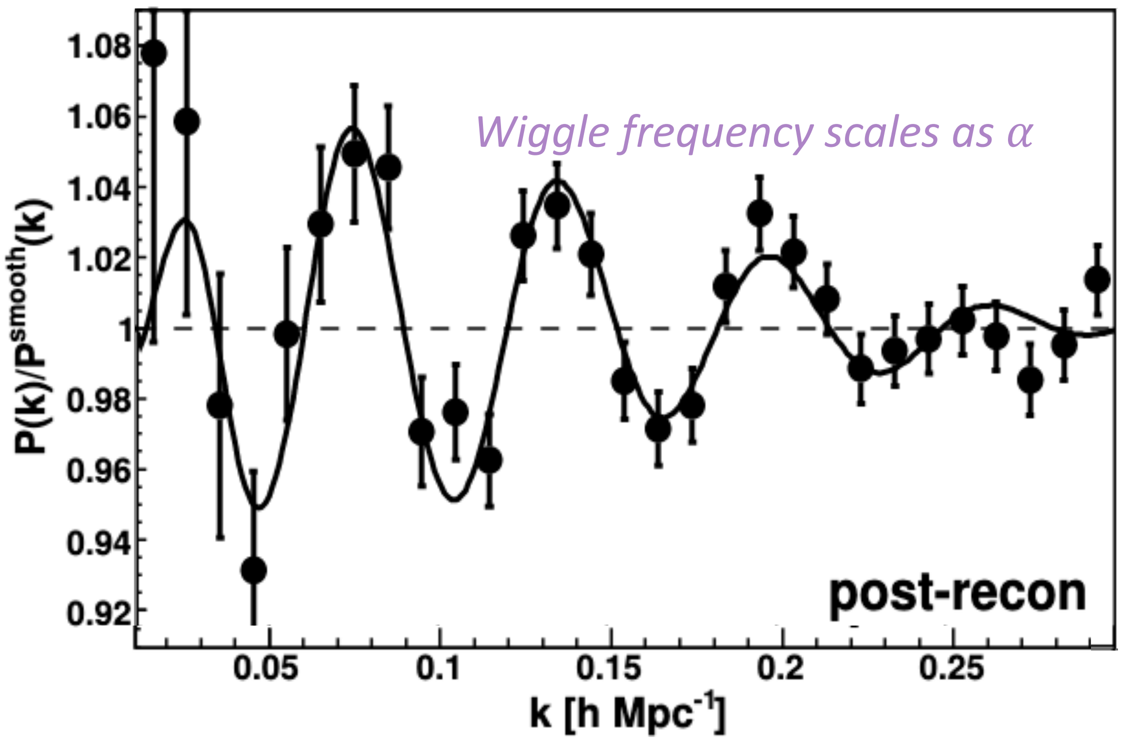
- Results are improved by **reconstruction**



BOSS DR12 Power Spectra

Beutler+16

Galaxy Surveys: Beyond the BAO

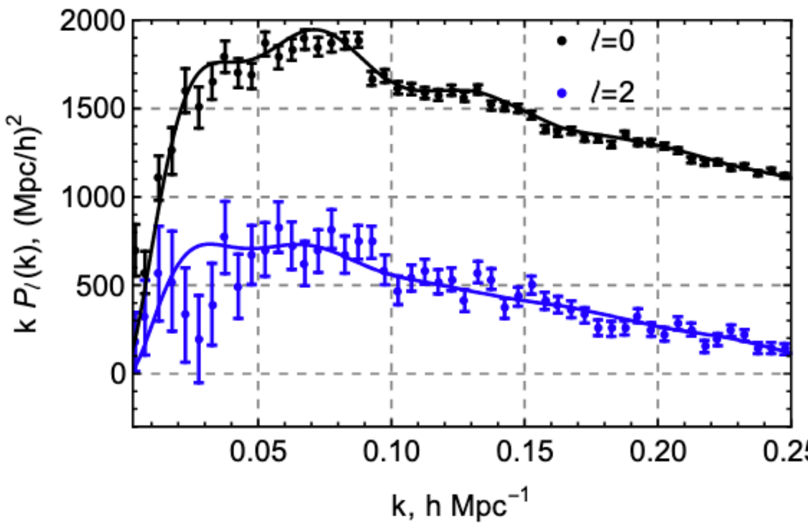
- Can we constrain cosmological information from **full shape** of the **unreconstructed** power spectrum?
- Model with the **Effective Field Theory of Large Scale Structure,** [Ivanov+19,20; d'Amico+19] including:
  - **One-loop** perturbation theory
  - Non-linear **bias**
  - **Stochastic** contributions (shot-noise)
  - UV **counterterms**
  - IR **resummation**

$$P_{g,\ell}(k) = P_{g,\ell}^{\text{tree}}(k) + P_{g,\ell}^{1-\text{loop}}(k) + P_{g,\ell}^{\text{noise}}(k) + P_{g,\ell}^{\text{ctr}}(k)$$

Linear Theory 1-loop PT Shot-noise Counterterms

- This has been tested on **huge** volume simulations [Nishimichi+20]

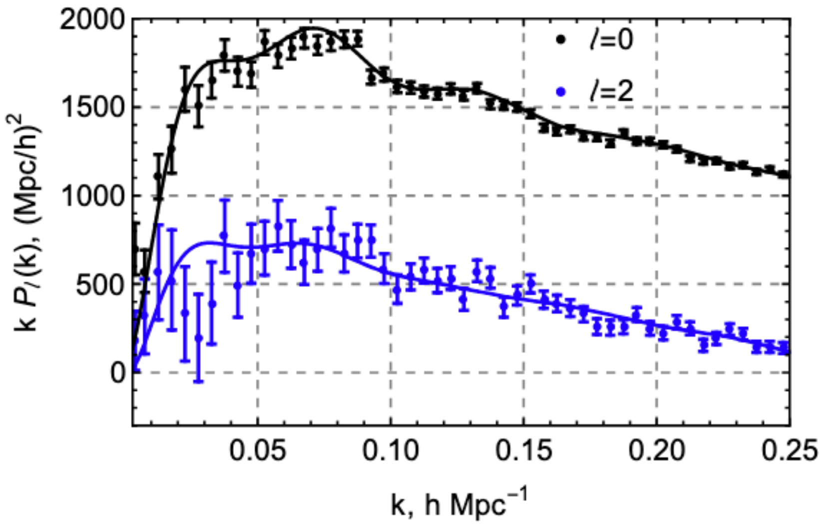
BOSS DR12 Spectra



Ivanov+19

Galaxy Surveys: Beyond the BAO

BOSS DR12 Spectra

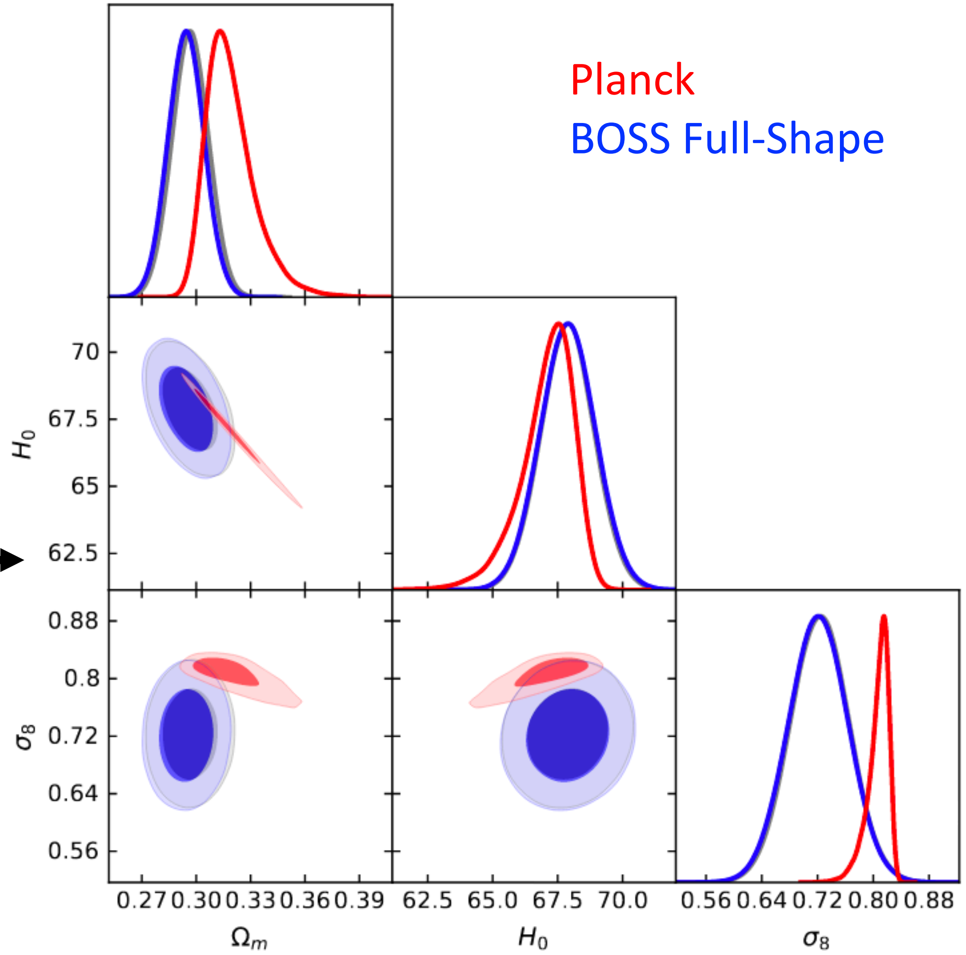


$$P_{g,\ell}(k) = P_{g,\ell}^{\rm tree}(k) + P_{g,\ell}^{1-{\rm loop}}(k) + P_{g,\ell}^{\rm noise}(k) + P_{g,\ell}^{\rm ctr}(k)$$

Linear Theory | 1-loop PT | Shot-noise | Counterterms

EFT Model

MCMC



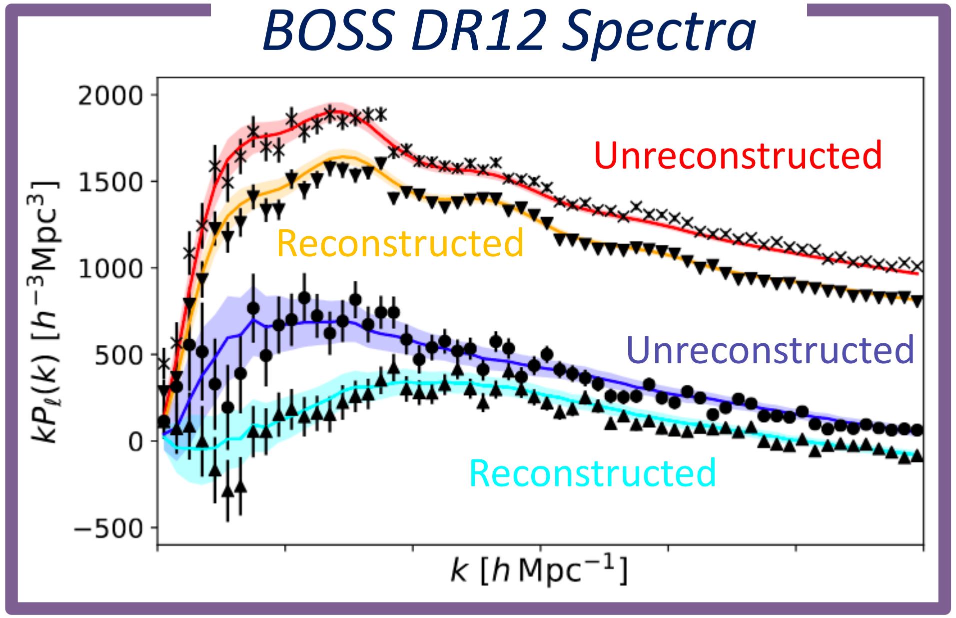
Including a BBN prior on ω_b

Ivanov+19

Galaxy Surveys: Bringing back the BAO

- What about the **reconstructed** spectrum?

- This is **difficult** to model: [Hikage+17,19, Chen+19]
  - Broadband is distorted
  - Distortion depend on reconstruction schemes
  - Depends on modeling assumptions [Sherwin+19]



Philcox+20

Galaxy Surveys: Bringing back the BAO

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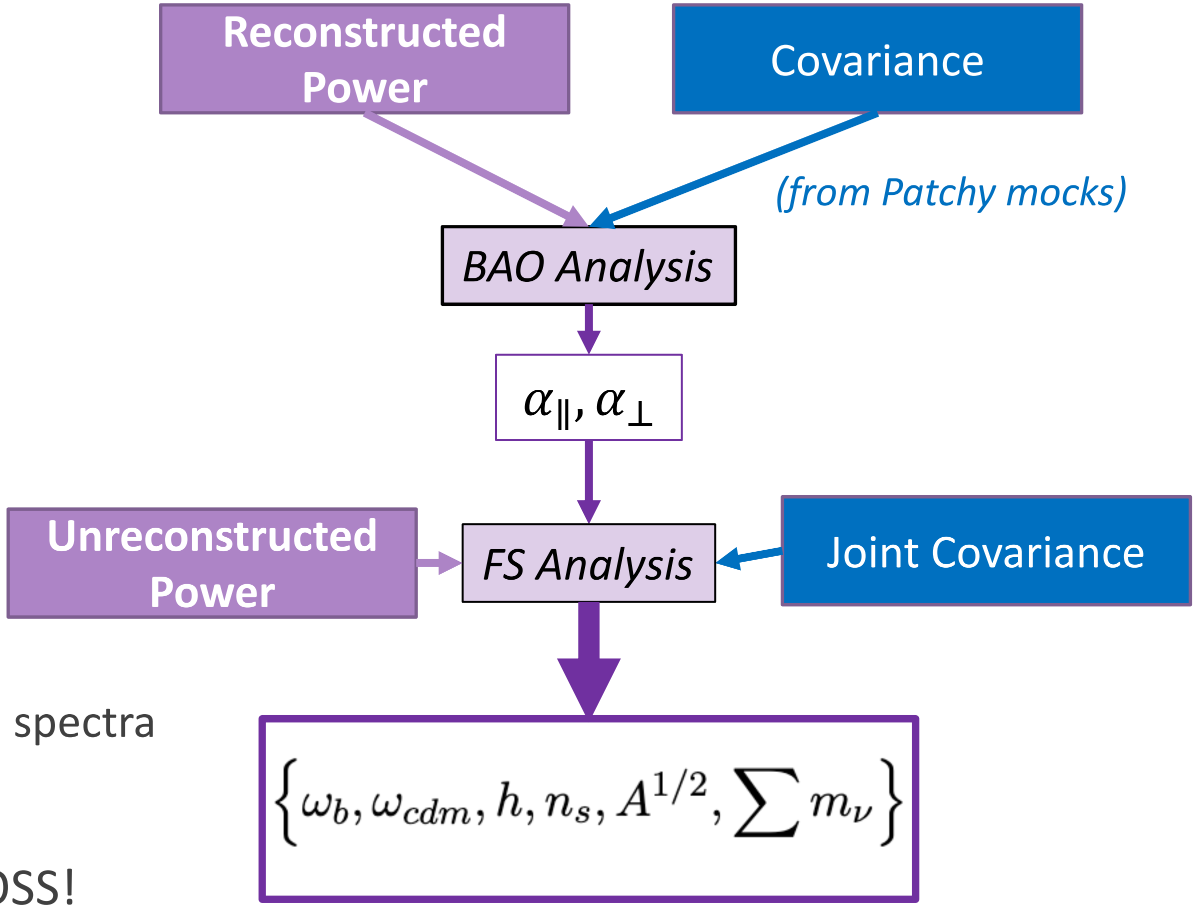
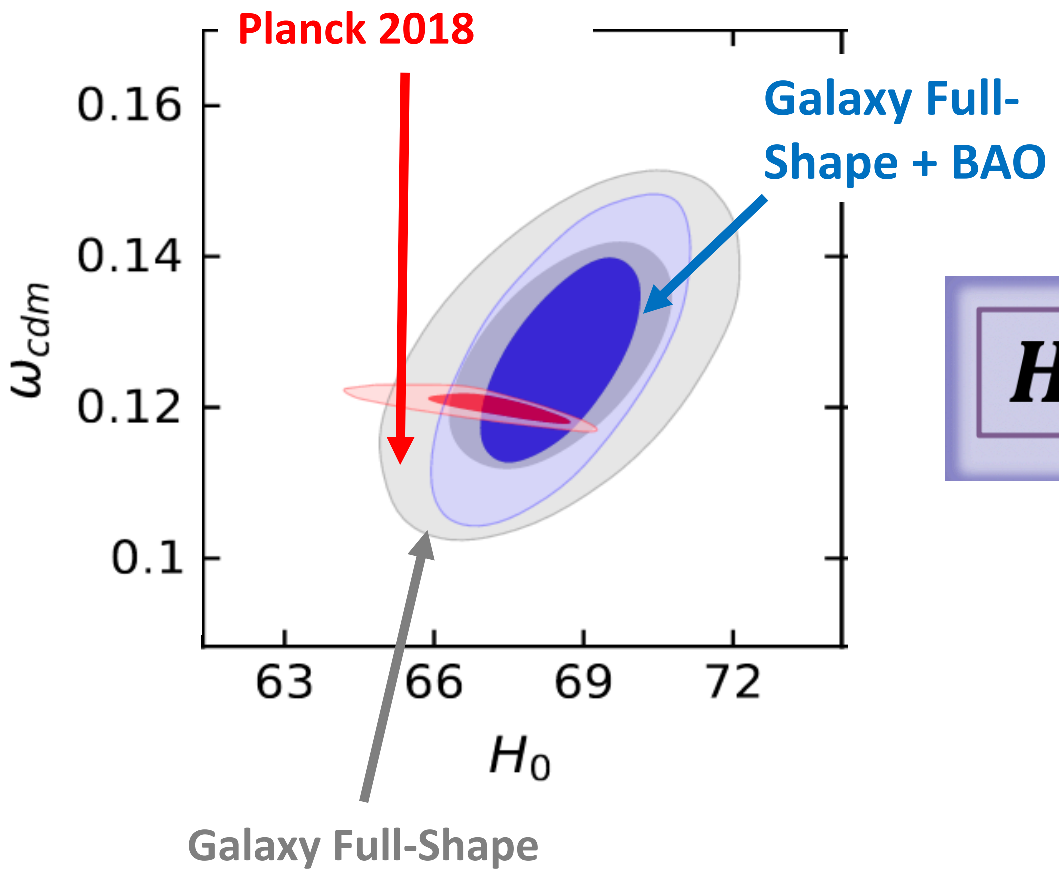
- **Solution**:
  1. Measure **BAO parameters** from **reconstructed** spectra
  2. Combine with **full-shape** likelihood for **unreconstructed** spectra

- This allows **more information** to be extracted from BOSS!



Philcox+20

Galaxy Surveys: Bringing back the BAO

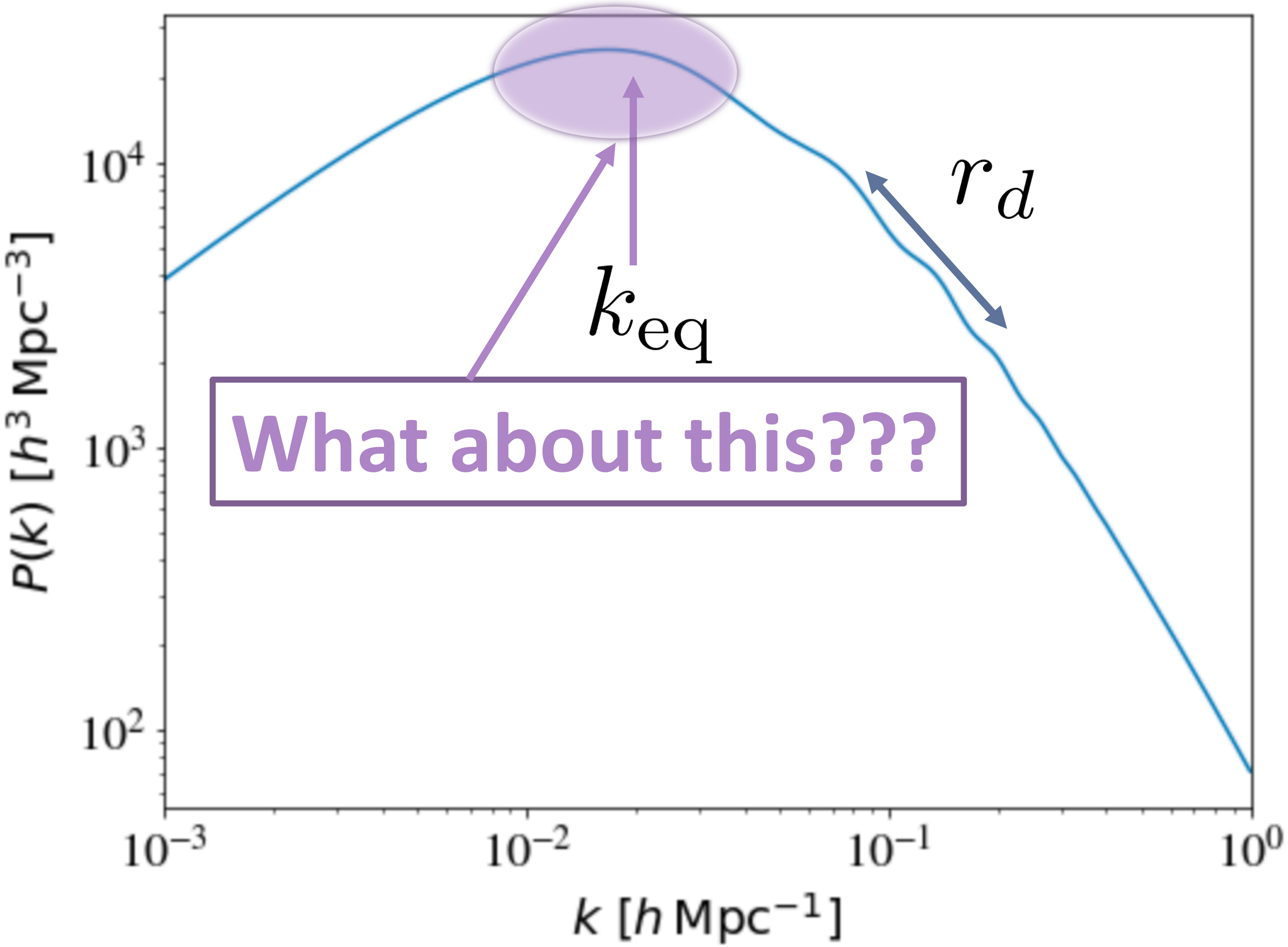


H_0	Full-Shape only	Full-Shape + BAO	Planck 2018
	68.55 ± 1.5	67.9 ± 1.1	$67.1^{+1.3}_{-0.72}$

Philcox+20

2. H_0 Without the Sound Horizon

Two Scales in the Matter Power Spectrum



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These are **standard rulers**

The Equality Scale: A (New) Probe of H0?

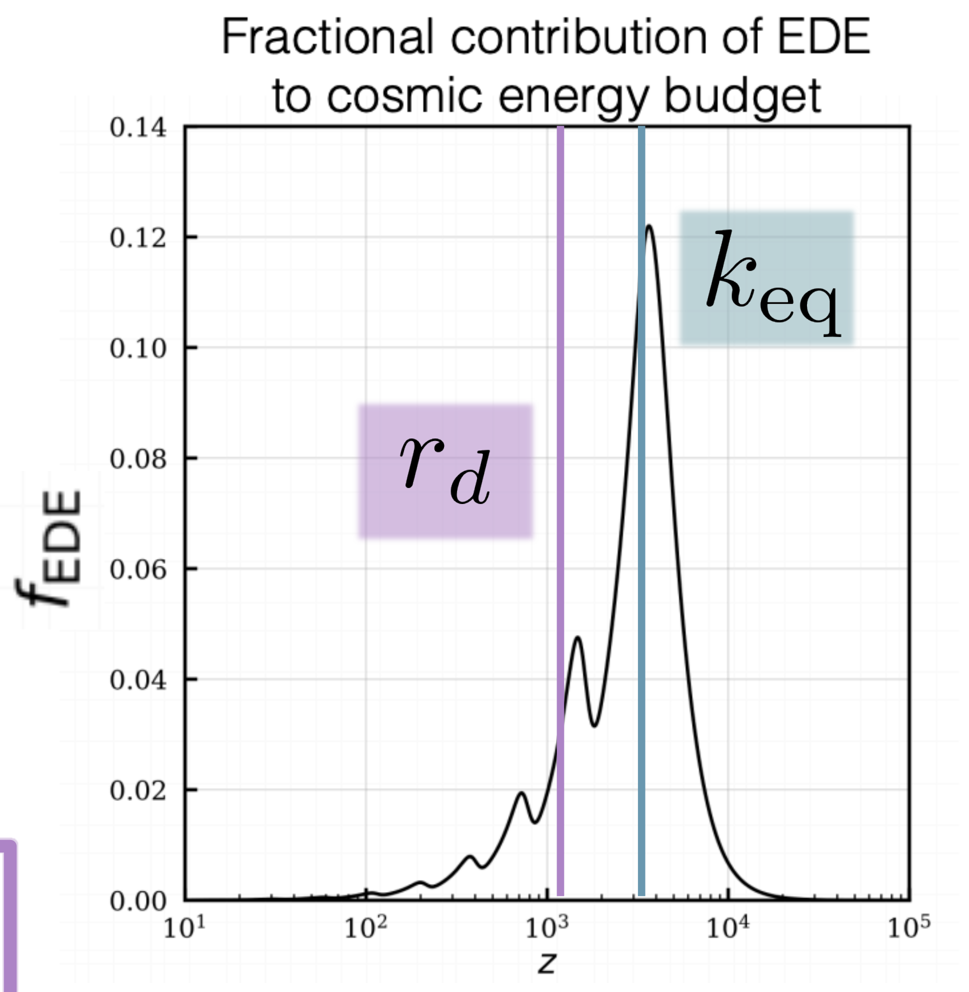
- The **equality scale** acts contains H_0 information

$$k_{\rm eq} \propto \Omega_{cb} H_0^2 T_{\rm CMB}^{-2}$$

- Measuring it in $h\ \mathrm{Mpc}^{-1}$ units probes $\boldsymbol{\Omega_{cb} H_0}$

- Given a probe of $\boldsymbol{\Omega_{cb}}$ (or Ω_m) we can **constrain** H_0!

- This is a measurement of H_0 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**

Baxter & Sherwin 2020, Hill+19,20

The Equality Scale: A (New) Probe of H0?

- The **equality scale** was measured decades ago, through the **shape parameter** Γ [e.g. Percival+01]

- **Baxter & Sherwin** (2020) recently showed this could be measured from *Planck* lensing and Pantheon SNe, via

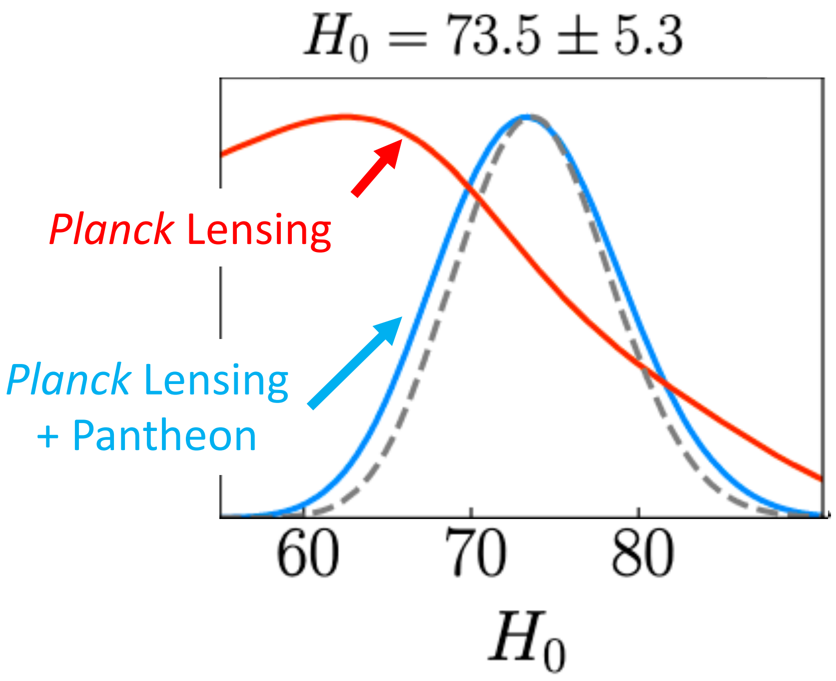
$$L_{\rm eq} \equiv k_{\rm eq}\chi_* \sim \Omega_m^{0.6} h$$

giving

$$H_0 = 73.5 \pm 5.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

independent of sound horizon physics

- Can we do the same for galaxy surveys?



Baxter & Sherwin 2020

Extracting Equality

- We can't see the equality scale directly in BOSS.
- It can be probed from the power spectrum **shape**:

$$P_g(k > k_{\rm eq}) \approx b_1^2 A_s \left(c + \log \frac{k}{k_{\rm eq}}\right)^2 \left(\frac{k}{k_{\rm eq}}\right)^{n_s - 4}$$

- This is helped by knowledge of $b_1^2 A_s$ from **loops** and **redshift-space distortions**
- Adding information about Ω_m from **Pantheon** or **uncalibrated BAO** breaks the $\boldsymbol{\Omega_{cb} - \mathrm{H}_0}$ **degeneracy**

Ansatz: Analyzing the full-shape BOSS data **without** a restrictive prior on $\boldsymbol{\omega_b}$ will measure H_0 from the **equality scale**

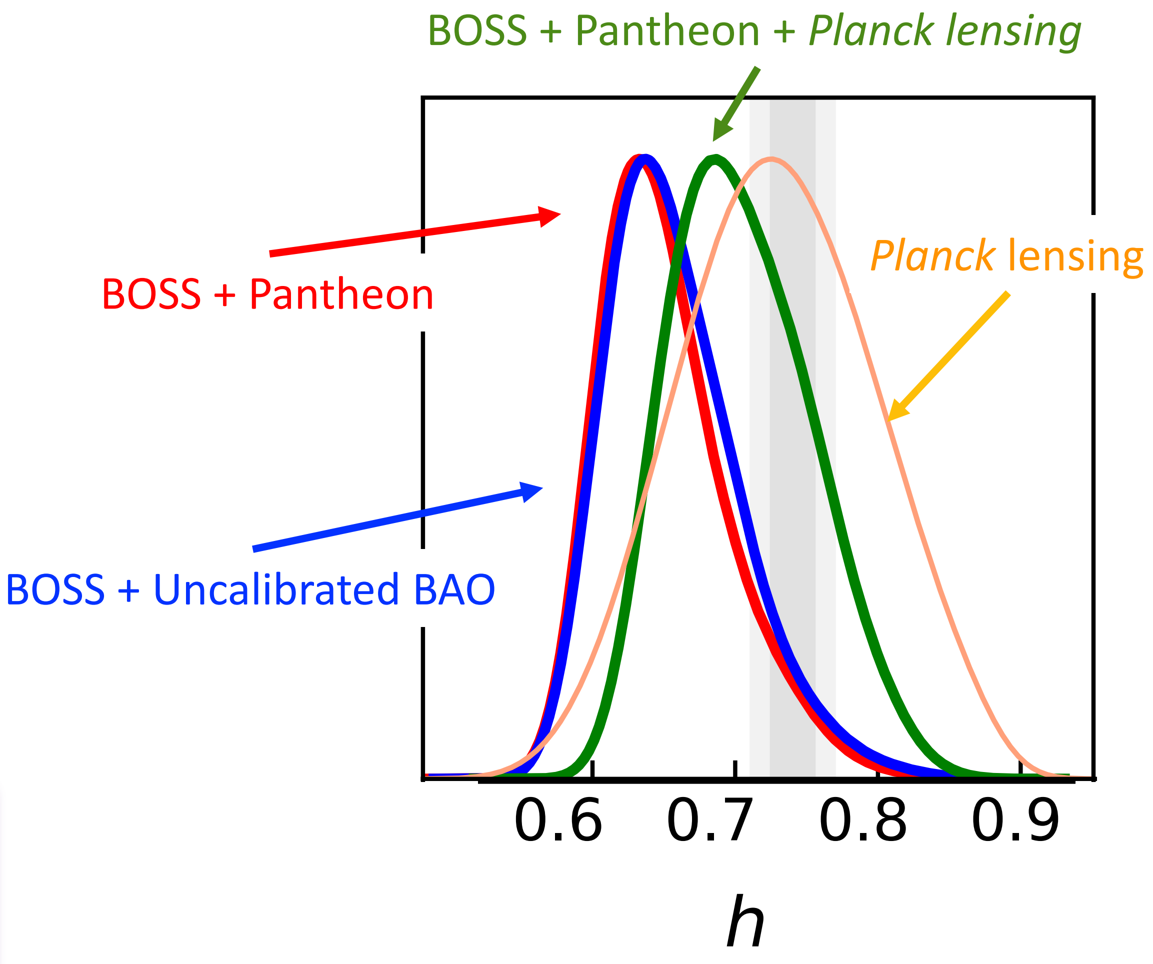
H_0 Constraints from Equality

- MCMC results*:

Dataset	H_0 (mean $\pm 1\sigma$) [$\mathrm{km\ s^{-1}\ Mpc^{-1}}$]
BOSS + Pantheon	$65.1^{+3.0}_{-5.4}$
BOSS + Uncalibrated BAO	$65.6^{+3.4}_{-5.5}$
BOSS + Pantheon + Planck Lensing	$70.6^{+3.7}_{-5.1}$

95% of the baseline **BOSS + Pantheon** posterior is **below** the SH0ES best-fit, even without the **sound horizon**!

* $\{h, \omega_b, \omega_{cdm}, A_s, n_s, \sum m_\nu\}$ + 28 nuisance parameters are varied in the likelihood



Philcox+20, Baxter & Sherwin (2020)

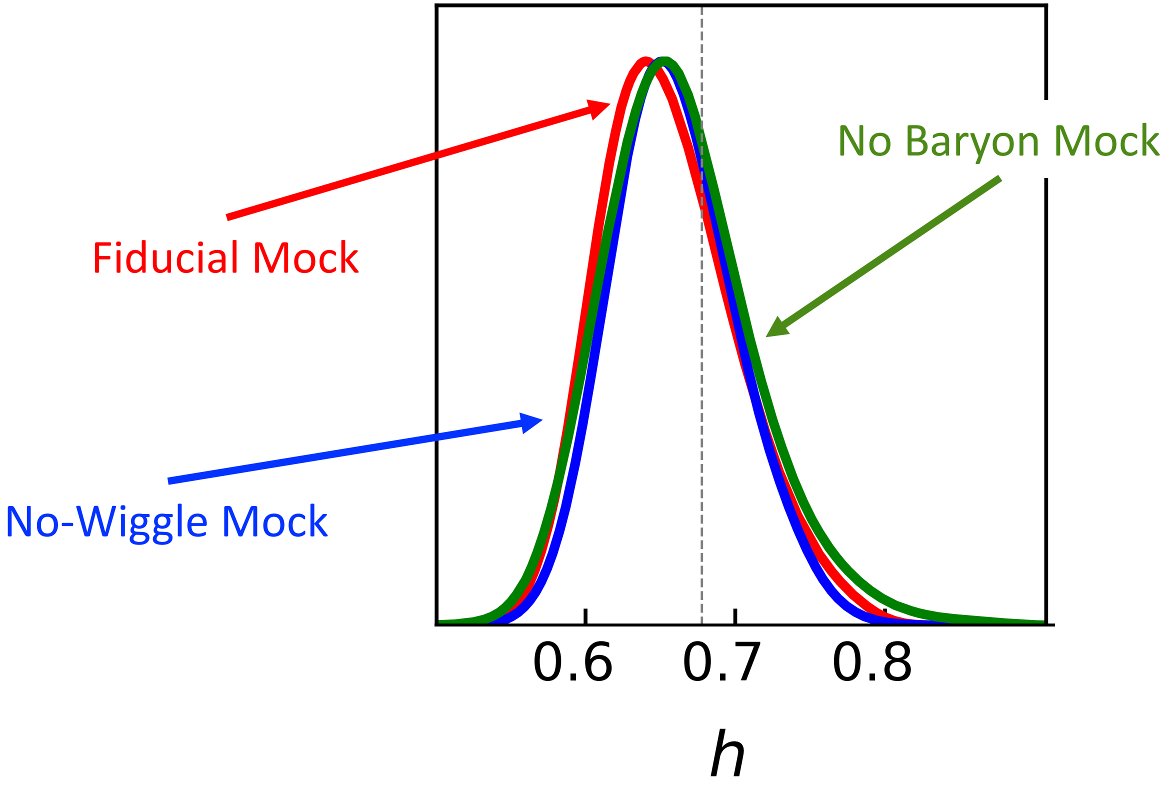
Sound-Horizon Independence (I)

- Test on mock data:

  1. Matching BOSS DR12
  2. With suppressed **BAO wiggles**
  3. With 10x **less baryons**

- No significant change to H_0 constraints

- Information is **not** coming from the sound horizon!



Philcox+20

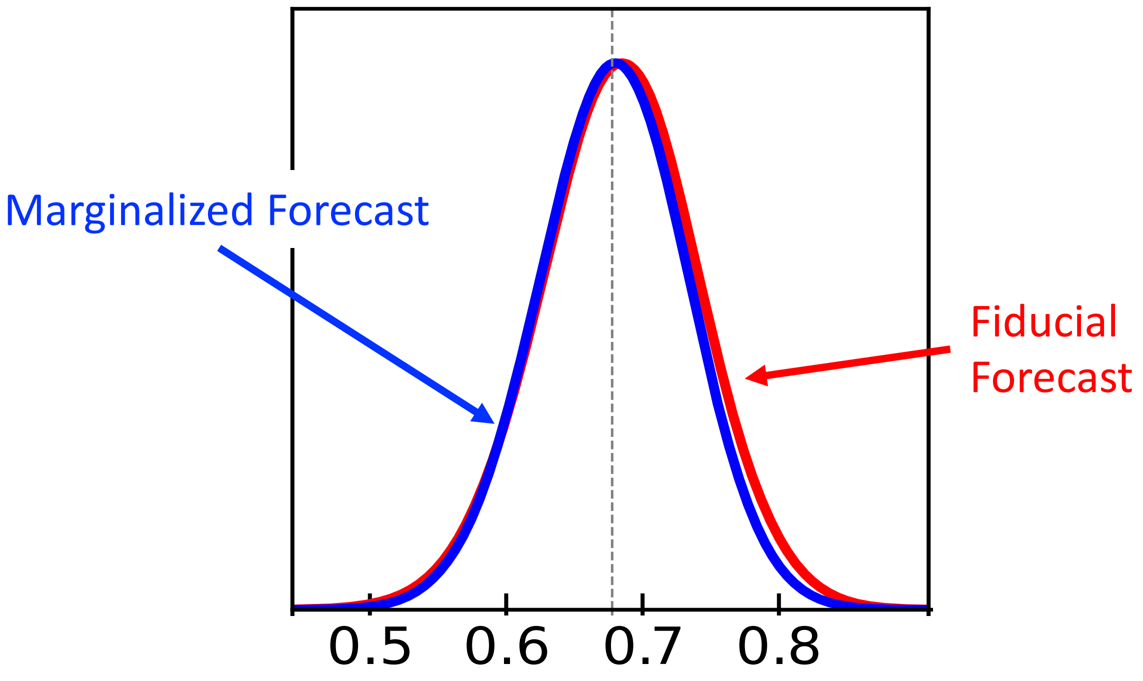
Sound-Horizon Independence (II)

- Perform a **Fisher forecast** with an Eisenstein-Hu transfer function:

  1. Emulating BOSS DR12
  2. Marginalizing over r_d

- No significant change to H_0 constraints

- Information is **not** coming from the sound horizon!



Philcox+20

Cosmological Implications

- **BAO Constraints:** Probe H_0 around $z \sim 1100$
- **Equality Constraints:** Probe H_0 around $z \sim 3600$

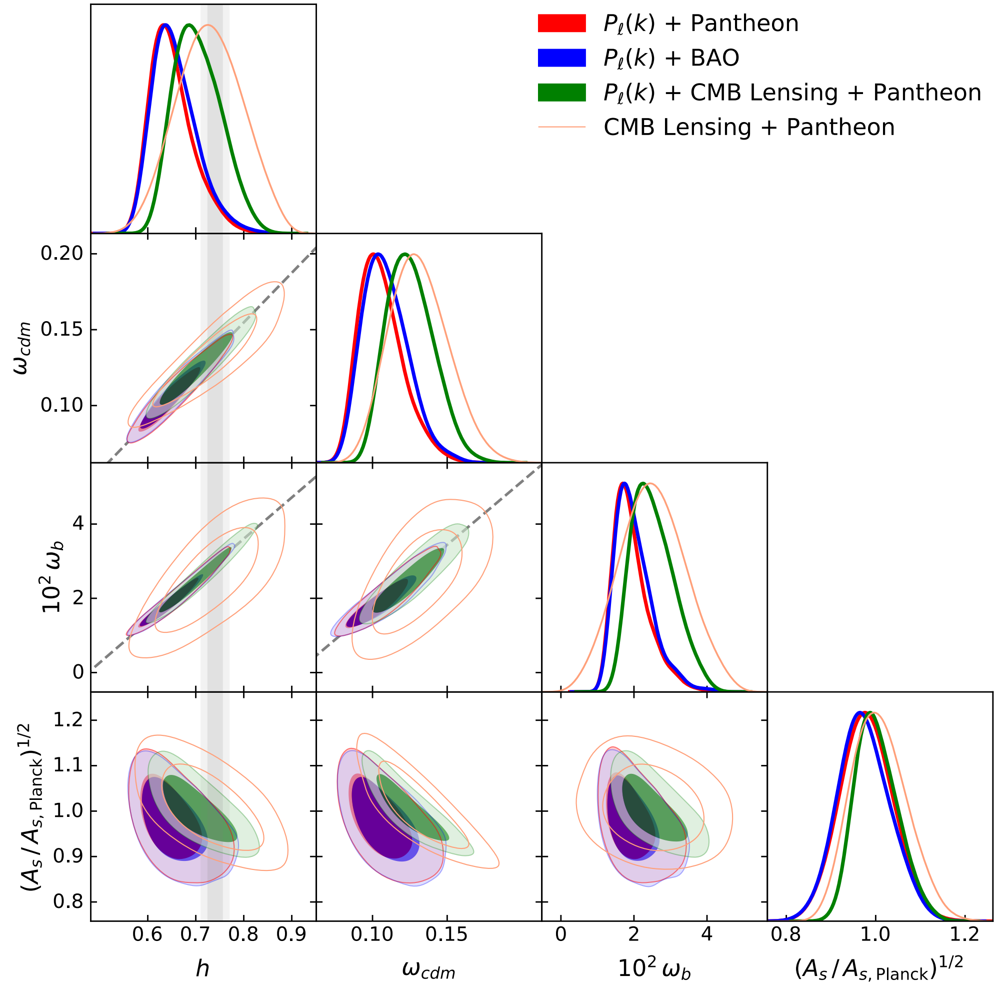
- Discrepancy of H_0 measurements could indicate **new physics** around recombination

- Consistency of H_0 measurements would make some **beyond-ΛCDM** solutions to the **Hubble tension** difficult

- A simple forecast for **Euclid** shows that

$$\sigma_{H_0} \sim 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

will soon be possible



Philcox+20

Conclusions

- **Galaxy Surveys** can place **strong constraints** on H_0, **not** just from the **BAO**

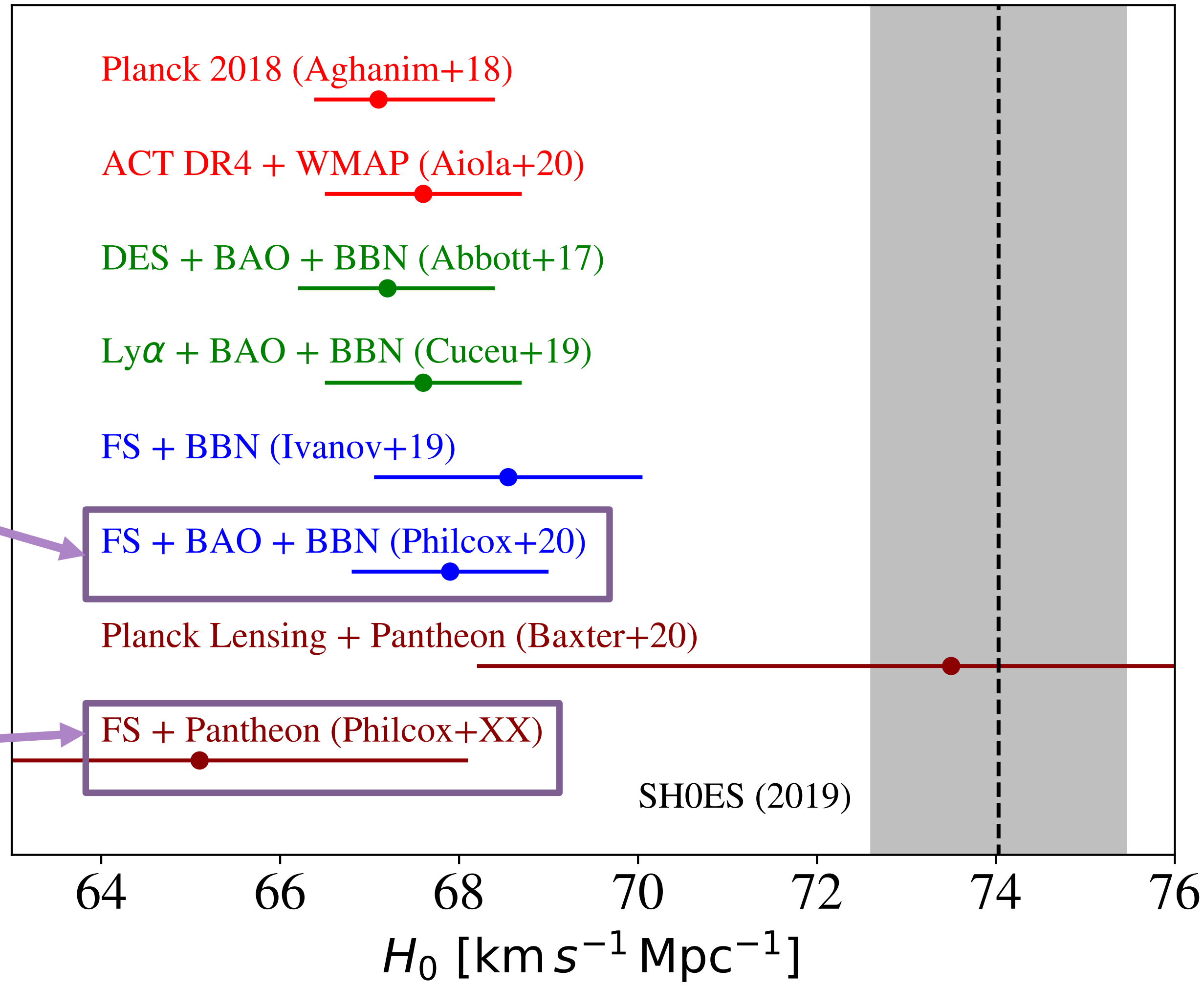
- Combining **BAO** and **Full-Shape** data (with BBN priors on ω_b) gives

$$H_0 = 67.9 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- Using **Full-Shape** data (and Pantheon priors on Ω_m) gives

$$H_0 = 65.1^{+3.0}_{-5.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

independent of sound horizon physics!



Philcox+20

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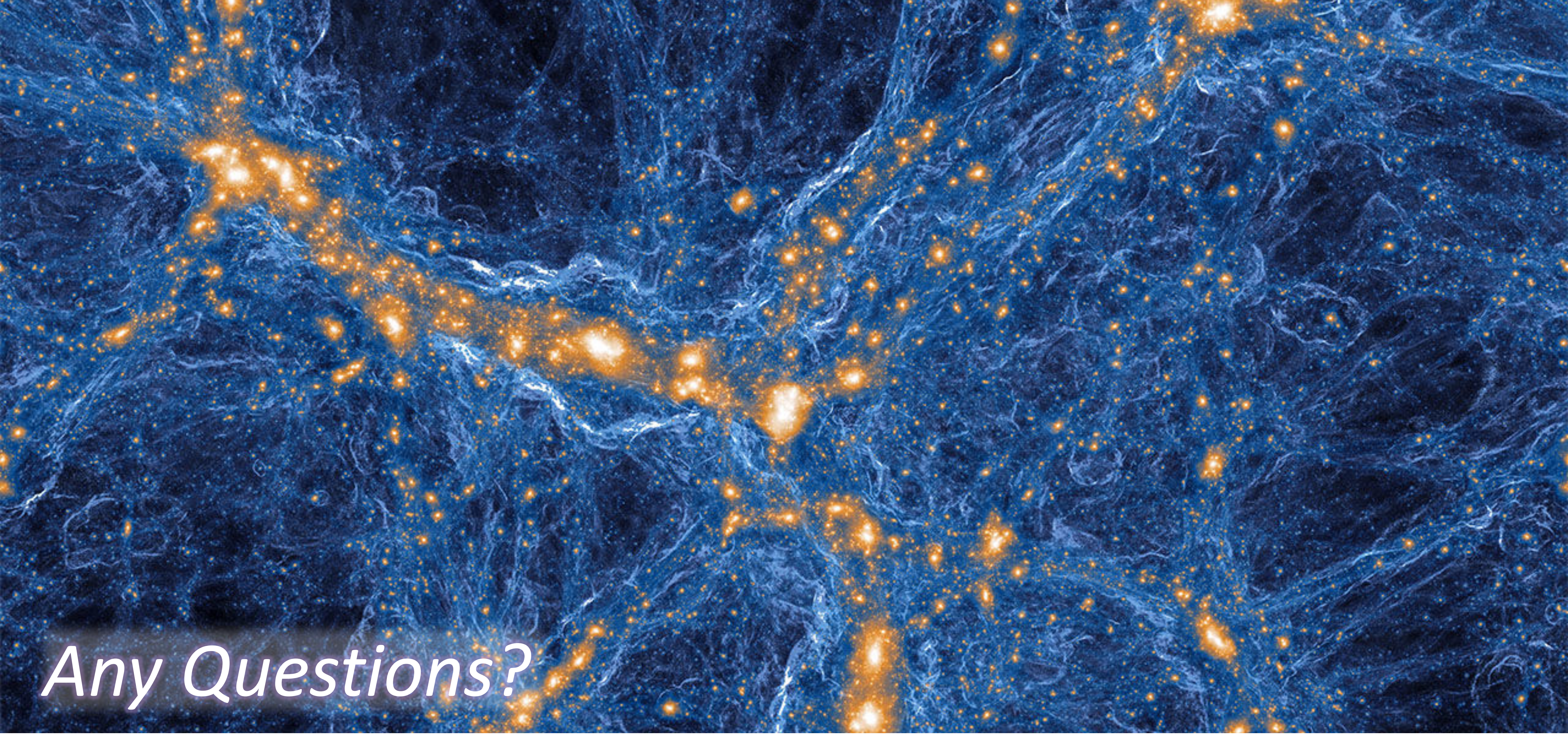

Any Questions?

Email: ohep2@cantab.ac.uk

Want to Read More?

- *Philcox, Ivanov, Simonovic, Zaldarriaga (2020, arXiv: 2002.04035)*
- *Philcox, Sherwin, Farren, Baxter (to appear)*