Sharpening cosmological constraints with EFT methods

Kudos to Rafael Porto

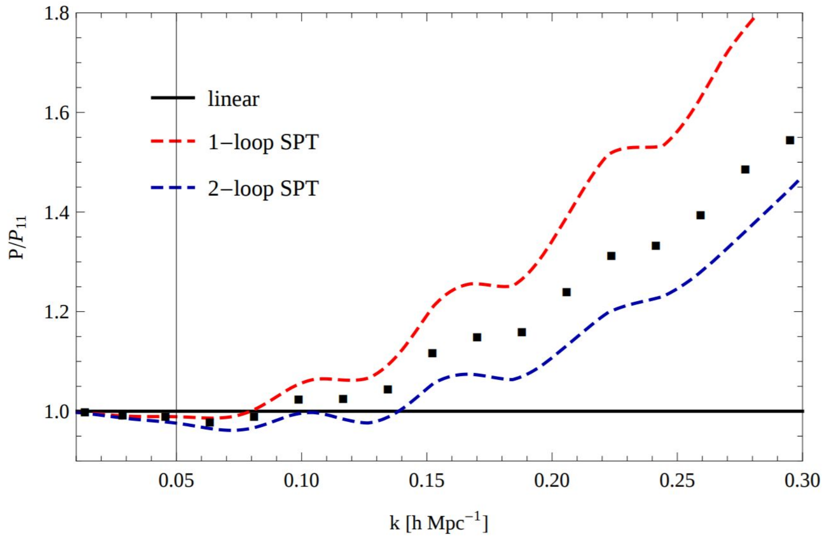
Nick Kokron (KIPAC/Stanford)
w/ Jérôme Gleyzes, Pierre Zhang, Leonardo Senatore, Dida Markovic,
Florian Beutler, Héctor Gil-Marín, others

EFT?

- *Effective Field Theory* (EFT for short) is a general paradigm
  - Valid when hierarchy between length scales exists
- Wild success in particle theory, condensed matter/stat mech, biophysics, gravitational waves, physics of inflation, hydrodynamics
- Baumann et al. (2010) proposed using EFT to study dark matter as a cosmological fluid
  - E.g., Large-scale structure formation should not depend on the microphysics of stellar structure
- Allows us to import particle theory technology into cosmology
- Provides an "analytic", physically well motivated, approach to computing quasilinear corrections to cosmological observables
  - This is a good thing.

Doesn't SPT do this already?

- Other approaches to cosmological perturbation theory have the same objective
- Several have pitfalls
  - For example, SPT gives formally infinite answers already at one loop
- EFT is as an extension of SPT
  - Uses the tools of particle theory to control for these infinities
- Also consistently includes:
  - Tracer biasing from gravitational physics
  - Stochastic biases
  - Higher-order RSD
  - "IR-resummation", for BAO purposes
  - Baryons



"Practical aspects of the EFT of LSS" - Baldauf

Whirlwind explanation of how this is done

- Normally the first and second moments of the collisionless Boltzmann eqn. are solved sequentially:

$$\nabla^2 \phi = \frac{3}{2} H_0^2 \Omega_m \frac{\delta}{a}$$

(Poisson equation)

$$\dot{\delta} = -\frac{1}{a} \vec{\nabla} \cdot ((1+\delta)\vec{v})$$

(Continuity equation)

= 0 in SPT

$$\dot{\vec{v}} + H\vec{v} + \frac{1}{a}\left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} + \frac{1}{a}\vec{\nabla}\phi = -\frac{1}{a\rho}\cancel{\partial_i \tau^{ij}}$$

(Euler equation)

Whirlwind explanation of how this is done

- Not zero in EFT, expanded in combinations of large-scale quantities allowed by Galilean + rotational symmetry
- Higher order contributions are always smaller, due to the scale hierarchy mentioned above
    - Like a matryoshka doll! (I told you it was relevant)
- Explicitly:

$$\begin{aligned}\tau^{ij} =& p_b\delta^{ij} + \rho\left[c_s^2\delta^{ij}\delta - \frac{c_{bv}^2}{Ha}\delta^{ij}\vec{\nabla}\cdot\vec{v} - \frac{3}{4}\frac{c_{sv}^2}{Ha}\left(\partial_j v^i + \partial^i v^j - \frac{2}{3}\delta^{ij}\partial_k v^k\right)\right] \\ &+ \Delta\tau^{ij} + \cdots\end{aligned}$$

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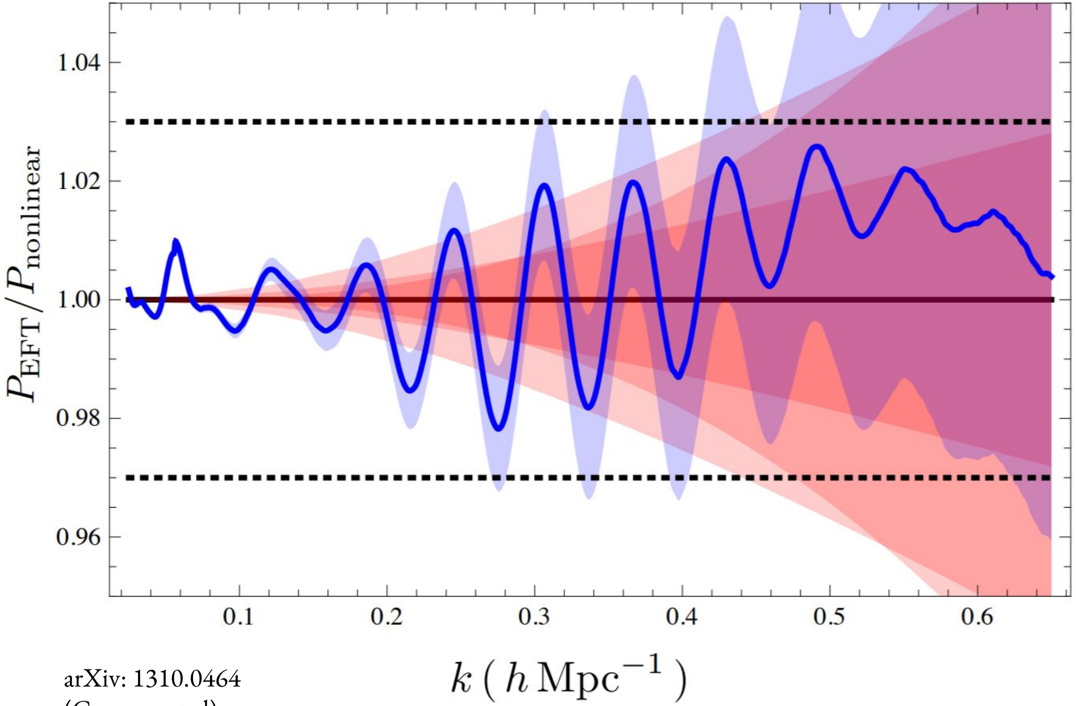
- Combined into one free parameter, correction will look like:

$$P_{\rm ct}(k) = -\tilde{c}_s^2\frac{k^2}{k_{\rm NL}^2}P_{\rm lin}(k)$$

Whirlwind explanation of how this is done

- Quality of fit improves dramatically by fitting for this sound speed simultaneously



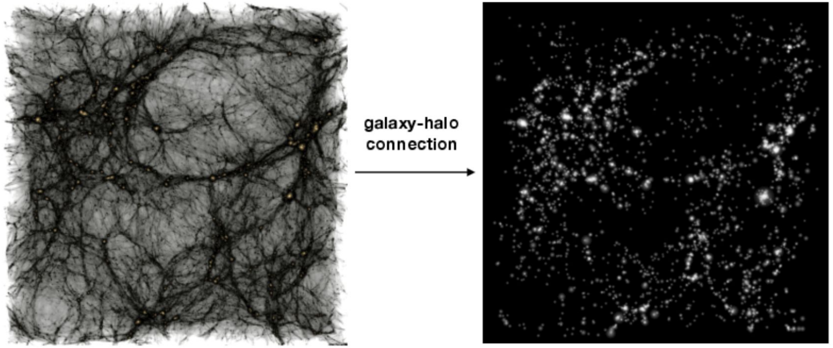
arXiv: 1310.0464
(Carrasco et al)

The Universe isn't "Fair and Balanced"™: Some bias required

- Formalism so far only treats dark matter density
- We observe galaxies, which trace DM
  - DM halos themselves are biased tracers of the dark matter density
- EFT principles guide us in how to describe biasing procedure
  - Desjacques, Jeong & Schmidt 2018 is the most comprehensive review on this
- Biasing can be split into two contributions:

$$\left.\begin{aligned}\delta_h = {} & b_1\delta + b_{\nabla^2\delta}\nabla^2\delta \\ & + \frac{1}{2}b_2\delta^2 + b_{K^2}\left(K_{ij}\right)^2 \\ & + \frac{1}{6}b_3\delta^3 + b_{\delta K^2}\delta\left(K_{ij}\right)^2 + b_{K^3}\left(K_{ij}\right)^3 + b_{td}O_{td}^{(3)}\end{aligned}\right\}\text{Deterministic}$$

$$+\varepsilon + \varepsilon_\delta\delta + \varepsilon_{\delta^2}\delta^2 + \varepsilon_{K^2}\left(K_{ij}\right)^2 \longrightarrow \text{Stochastic}$$



Wechsler & Tinker 2018

Including RSD

- We don’t observe physical radial positions of galaxies

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- Mapping between real-space and redshift space

$$\vec{x}_r = \vec{x} + \frac{\hat{z} \cdot \vec{v}}{aH}\hat{z}$$

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$$\vec{x}_r = \vec{x} + \frac{\hat{z} \cdot \vec{v}}{aH} \hat{z}$$

- Density contrast will transform as

$$\delta_r(\vec{k}) = \delta(\vec{k}) + \int d^3x e^{-i\vec{k}\cdot\vec{x}} \left(\exp\left[-i \frac{k_z}{aH} v_z(\vec{x}) \right] - 1 \right) (1 + \delta(\vec{x}))$$

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- To cubic order, will give

$$\delta_r(\vec{k}) = \delta(\vec{k}) + \mu^2 \frac{\dot{\delta}(\vec{k})}{H} - \epsilon^{zij} \frac{\mu\, k_i}{k} \frac{\pi_{V,j}}{H} - \frac{1}{2} \left(\frac{k\,\mu}{aH} \right)^2 \left([v_z^2]_{\vec{k}} + [v_z^2 \delta]_{\vec{k}} \right) + \frac{i}{6} \left(\frac{k\,\mu}{aH} \right)^3 [v_z^3]_{\vec{k}}$$

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$$+ \frac{c_1}{2}\mu^4 \left(\frac{k}{k_{\rm NL}} \right)^2 \frac{\theta(\vec{k})}{aH} - \frac{(c_1 + c_2)}{2}\mu^2 \left(\frac{k}{k_{\rm NL}} \right)^2 \delta(\vec{k}) - \frac{c_3}{2}\mu^4 \left(\frac{k}{k_{\rm NL}} \right)^2 \delta(\vec{k})$$

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Jump forward in time ~4 years (and around 30 papers)

"(…) long-wavelength statistics that are routinely observed in LSS surveys can be finally computed in the EFTofLSS. This formalism thus is ready to start to be compared directly to observational data."

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Jump forward in time another 2 years (10 more papers)

A model fit for a survey I: A cornucopia of free parameters

- With the tools outlined above we may write a model for the anisotropic power spectrum at one loop (third order in δ, v)
- It looks like this

$$
\begin{aligned}
P_g(k,\mu) &= Z_1(\mu)^2 P_{11}(k) \\
&+ 2\int d^3q\, Z_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)P_{11}(q) + 6Z_1(\mu)P_{11}(k)\int d^3q Z_3(\boldsymbol{q},-\boldsymbol{q},\boldsymbol{k})P_{11}(q) \\
&+ 2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm NL}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm M}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm M}^2}\right) + \frac{1}{\bar{n}_g}\left(c_{\epsilon,1} + c_{\epsilon,2}\frac{k^2}{k_{\rm M}^2} + c_{\epsilon,3} f\mu^2\frac{k^2}{k_{\rm M}^2}\right)
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There are actually 12 bias parameters a priori. They can be re-cast into a basis of four less-degenerate parameters.

A model fit for a survey II: window functions and likelihoods

- Window functions in 3D surveys are applied in real space
  - EFT predictions diverge at large k. This is a bad thing.

$$P_\ell(k) \overset{\text{FFTlog}}{\rightarrow} \xi_\ell(r) \quad \rightarrow \quad \xi_\ell^{(W)}(r) = Q_{\ell,\ell'}(r) \cdot \xi_\ell(r) \quad \overset{\text{FFTlog}}{\rightarrow} \quad P_\ell^{(W)}(k)$$

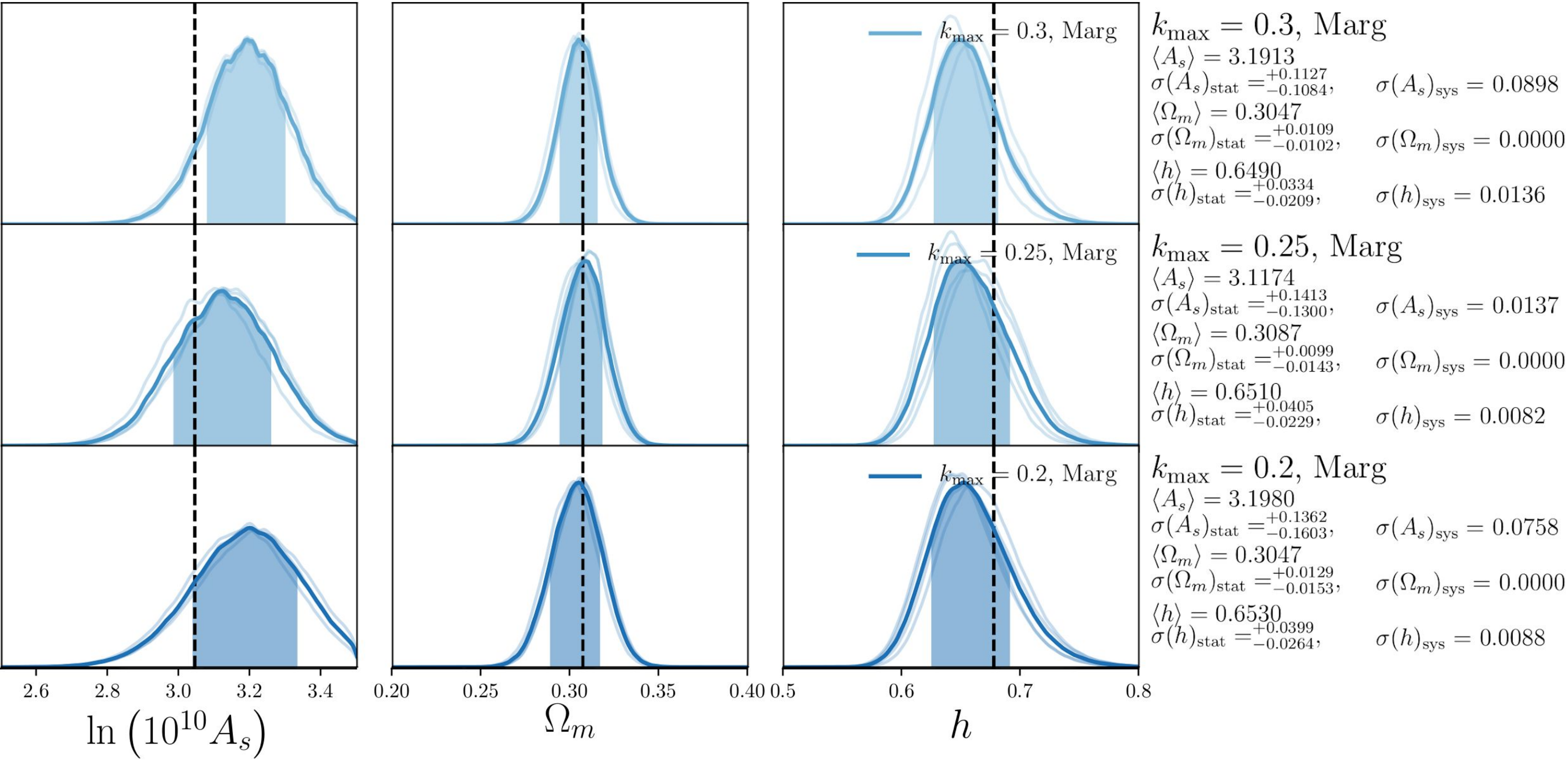
- Lessons from CMB: mode-coupling window functions à la pseudo-Cl

$$P_\ell^W(k) = \sum_{k',\ell'} W_{\ell,\ell'}(k,k') P_{\ell'}^W(k')$$

- 6 of the 10 bias parameters only enter linearly in the prediction
  - They factor quadratically in the likelihood
- Analytically marginalized, leading to only 3+3 parameters being varied
  - Strong, physical priors can be used on marginalized params

Validating on simulations

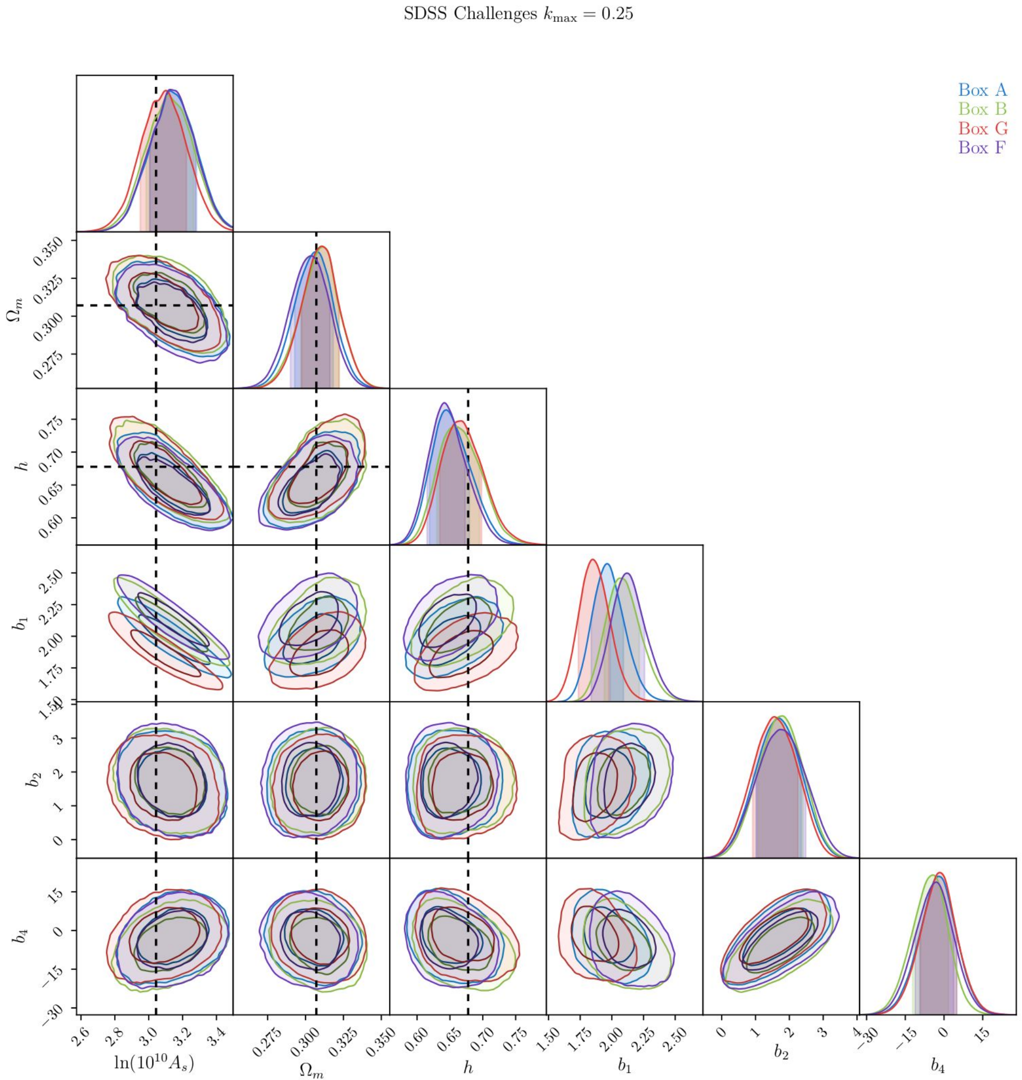
- Extensive validation across various numerical suites of simulations
  - You can ask me for a list
- Of specific interest are 'Lettered Challenge Boxes' from Hand et al. (2017)
  - (Their model has 13 free parameters)
- High resolution, varying HODs for each catalog
  - Covariance matrices scaled to BOSS DR12 volume



$k_{\rm max} = 0.3$, Marg
$k_{\rm max} = 0.25$, Marg
$k_{\rm max} = 0.2$, Marg
$\ln\left(10^{10}A_s\right)$
Ω_m
h
$k_{\rm max} = 0.3$, Marg
$\langle A_s\rangle = 3.1913$
$\sigma(A_s)_{\rm stat} =^{+0.1127}_{-0.1084}$, $\sigma(A_s)_{\rm sys} = 0.0898$
$\langle \Omega_m\rangle = 0.3047$
$\sigma(\Omega_m)_{\rm stat} =^{+0.0109}_{-0.0102}$, $\sigma(\Omega_m)_{\rm sys} = 0.0000$
$\langle h\rangle = 0.6490$
$\sigma(h)_{\rm stat} =^{+0.0334}_{-0.0209}$, $\sigma(h)_{\rm sys} = 0.0136$
$k_{\rm max} = 0.25$, Marg
$\langle A_s\rangle = 3.1174$
$\sigma(A_s)_{\rm stat} =^{+0.1413}_{-0.1300}$, $\sigma(A_s)_{\rm sys} = 0.0137$
$\langle \Omega_m\rangle = 0.3087$
$\sigma(\Omega_m)_{\rm stat} =^{+0.0099}_{-0.0143}$, $\sigma(\Omega_m)_{\rm sys} = 0.0000$
$\langle h\rangle = 0.6510$
$\sigma(h)_{\rm stat} =^{+0.0405}_{-0.0229}$, $\sigma(h)_{\rm sys} = 0.0082$
$k_{\rm max} = 0.2$, Marg
$\langle A_s\rangle = 3.1980$
$\sigma(A_s)_{\rm stat} =^{+0.1362}_{-0.1603}$, $\sigma(A_s)_{\rm sys} = 0.0758$
$\langle \Omega_m\rangle = 0.3047$
$\sigma(\Omega_m)_{\rm stat} =^{+0.0129}_{-0.0153}$, $\sigma(\Omega_m)_{\rm sys} = 0.0000$
$\langle h\rangle = 0.6530$
$\sigma(h)_{\rm stat} =^{+0.0399}_{-0.0264}$, $\sigma(h)_{\rm sys} = 0.0088$

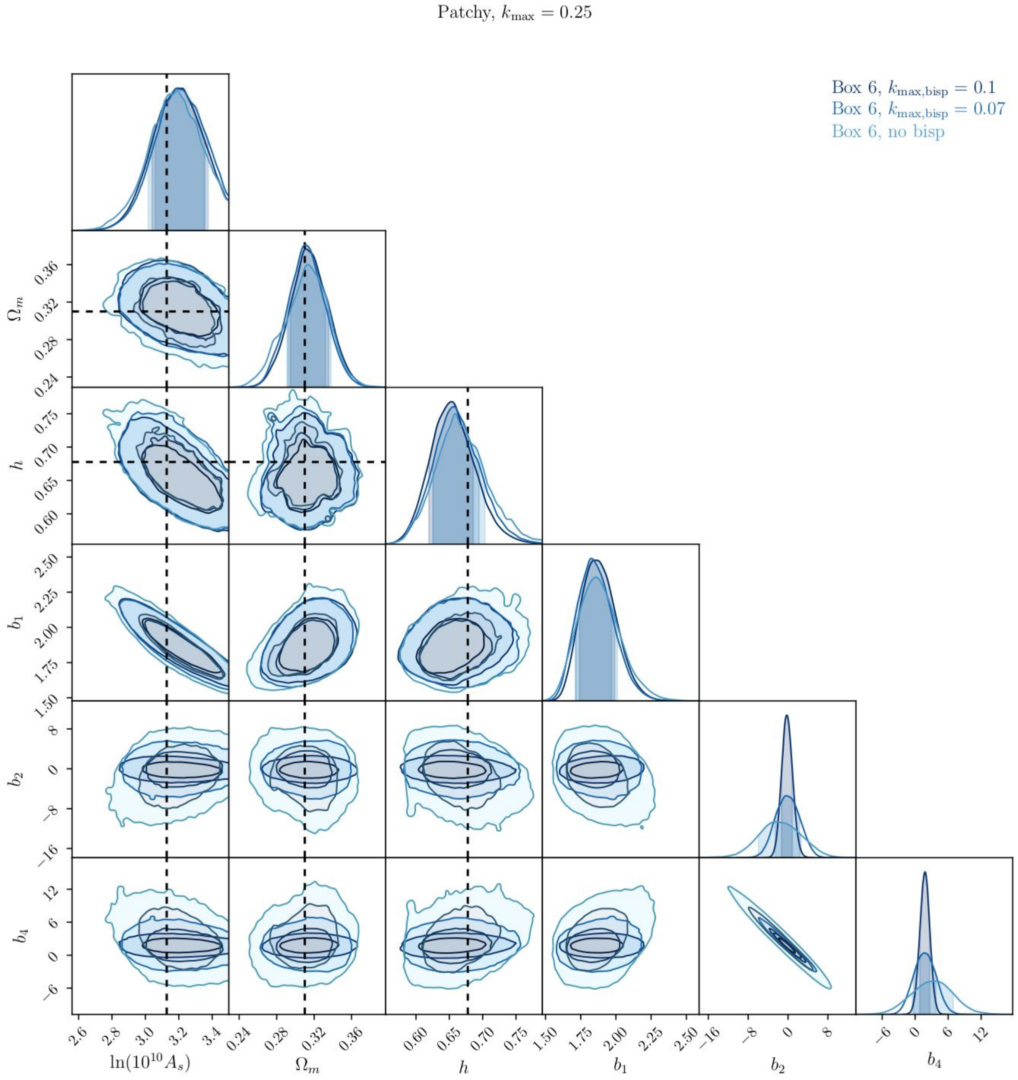
Validating on simulations

- Errors decrease well as we increase kmax
- Posteriors contain the truth within 1σ, normally
  - Looking at product of posteriors reveals slight biases in A_s and h, ~0.5σ
- Looking at bias contours reveals we can tell the HOD apart
  - Without significantly affecting the cosmology



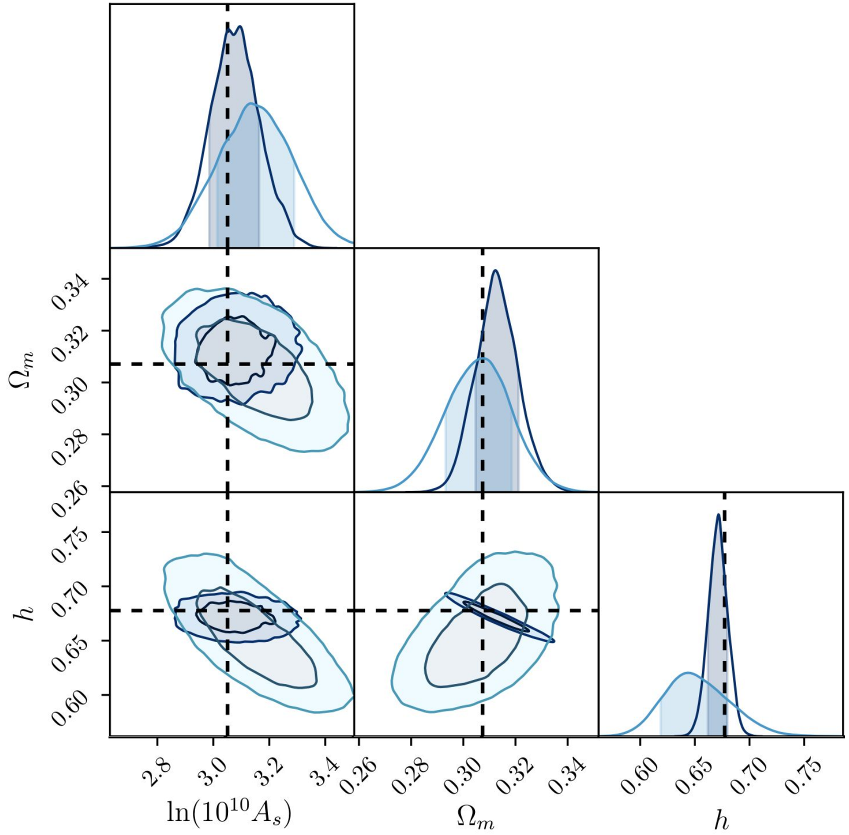
Validating on simulations

- Other suites show similar results
  - Modulo their quality at small scales
- Our model can also self-consistently includes bispectrum predictions
  - Apparently not much cosmology improvement
- Are the simulations to blame?



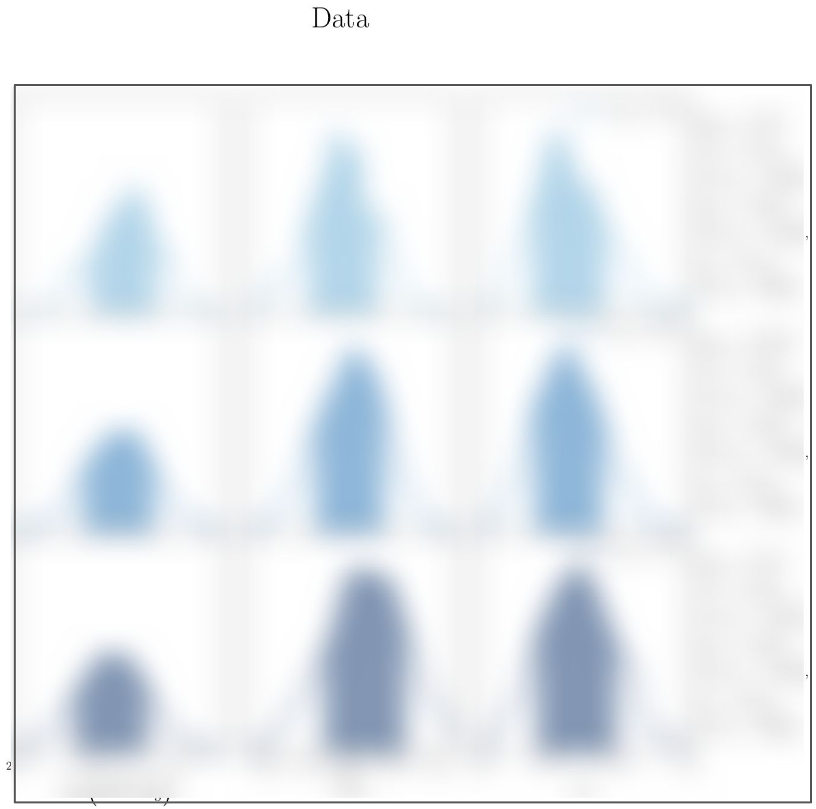
Validating on simulations: a heavenly anchor

- A "light" way to combine with CMB information: sound horizon at decoupling
- r_d is set by early universe physics
  - Imposes strong constraints on $h - \Omega_m$ plane.
- Constraints aren't biased by this prior



Onto data!

- Confident in our validation we take another look at BOSS DR12
- Simulated constraints are already exciting
  - ~Plank 13 for data released in 2015!
- Error bars in data comparable to simulated chains
- Stay tuned. arXiv: 1812.XXXX
  - hopefully



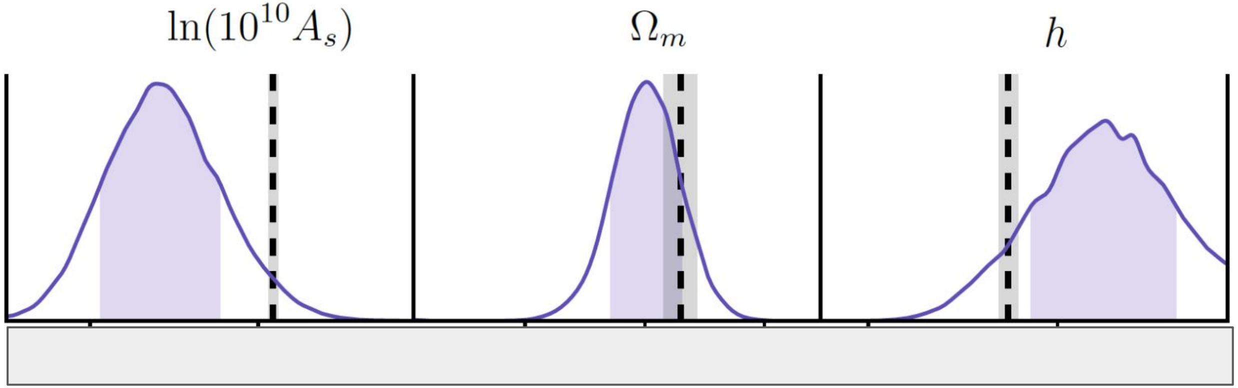
An aside

- Barriers exist between community working on this and survey cosmologists
- Sociology aside, I think these techniques can be valuable for DES/DESI/LSST
  - Please don’t shoot the messenger
- We now have (moderately) fast codes and analysis pipelines set up to do this for spectroscopic surveys
- Extending to photometric observables is feasible
  - We can push the modelling harder for lensing with no additional parameters

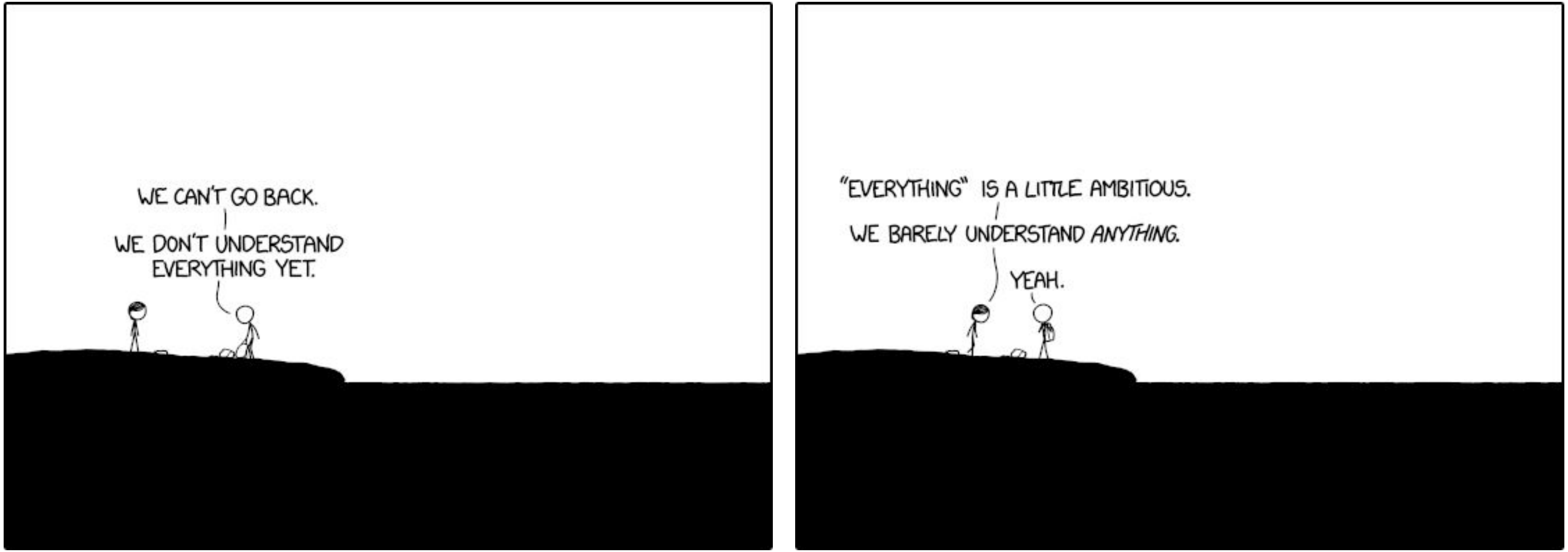
Wrapping up

- Extensive tests of EFT modelling for the anisotropic power spectrum have been performed
- We can wring out even more constraining power from existing data
- Combining these techniques with survey data is tantalizing
- Or perhaps we should just go to the field level as Marko explained earlier? :)

Spoilers (outdated):



Thank you for your time!



Time, XKCD

An extra slide: planck shift