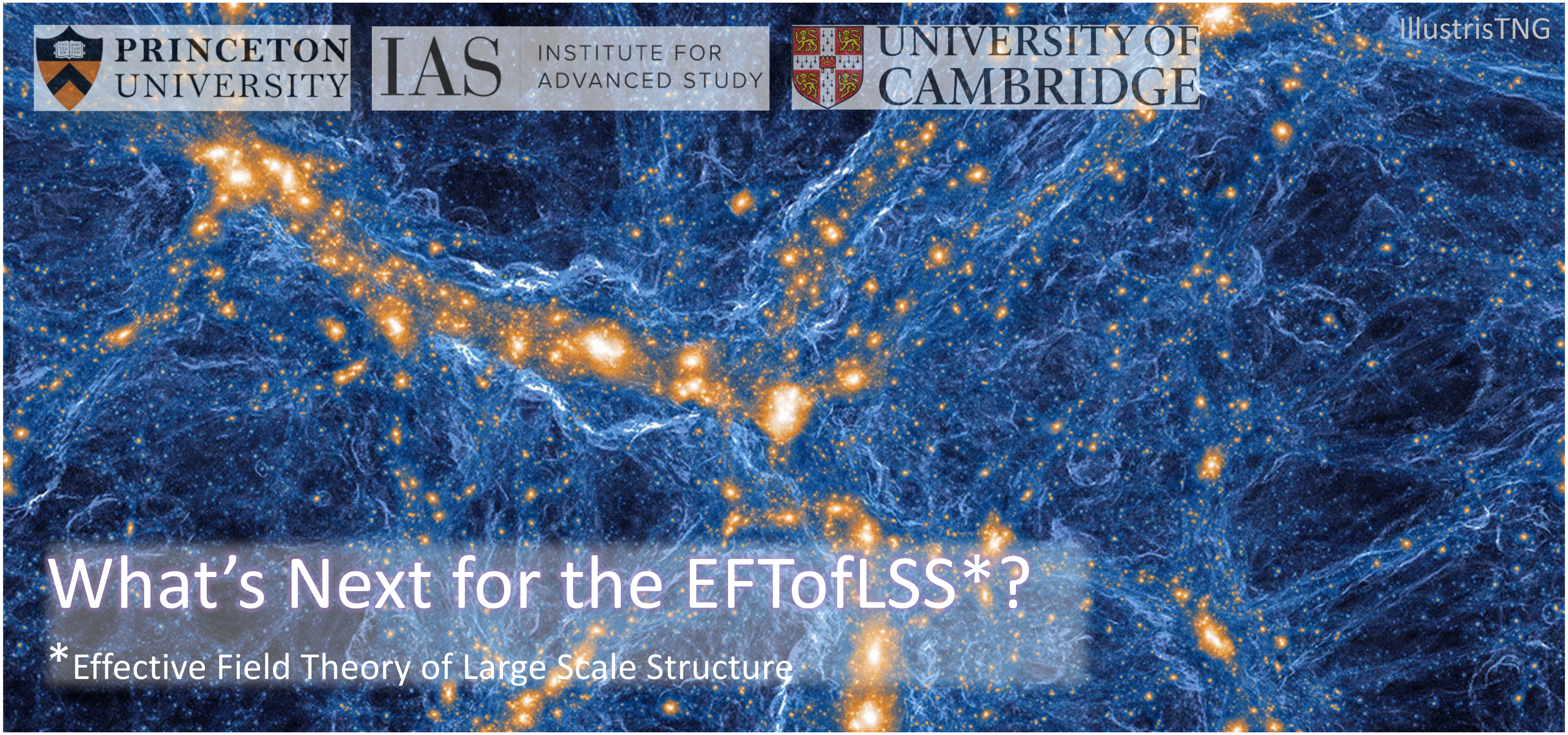


PRINCETON UNIVERSITY

IAS INSTITUTE FOR ADVANCED STUDY

UNIVERSITY OF CAMBRIDGE

What's Next for the EFTofLSS*?

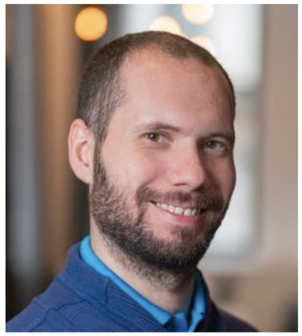
*Effective Field Theory of Large Scale Structure

Oliver Philcox (Princeton)

UK Cosmology Meeting, September 2020

Based on: 2002.04035, 2008.08084, 2004.09515 & 2006.10055

Elena Massara



Francisco Villaescusa-Navarro

David Spergel

Blake Sherwin

Gerrit Farren

Eric Baxter

Mikhail Ivanov

Marcel Schmittfull

Marko Simonovic

Matias Zaldarriaga

EFT of Matter: A Lightning Introduction

Standard Perturbation Theory [e.g. Bernardeau+02]

- Solve the **ideal** fluid equations
- Expansion variable: overdensity field $\delta(\boldsymbol{x})$
- Assume valid on **all** scales

$$\begin{aligned} \dot{\delta}_\Lambda + \nabla \cdot [(1+\delta_\Lambda \mathbf{v}_\Lambda] &= 0 \\ \dot{\mathbf{v}}_\Lambda + (\mathbf{v}_\Lambda \cdot \nabla)\, \mathbf{v}_\Lambda &= -\mathcal{H}\mathbf{v}_\Lambda - \nabla\phi_\Lambda \boxed{- \frac{1}{\rho_\Lambda}\nabla \underline{\underline{\tau}}} \end{aligned}$$

Effective Field Theory [e.g. Carrasco+12, Baumann+12]

- Solve the **non-ideal** fluid equations, including **viscosity** etc.
- Expansion variable: **smoothed** overdensity field $\delta_\Lambda(\boldsymbol{x})$
- Theory **only** valid for $k < \Lambda$

1-loop SPT

$$P(k) = P_{\rm lin}(k) + P_{22,\Lambda}(k) + 2P_{13,\Lambda}(k) - 2c^2_{{\rm s},\Lambda}k^2 P_{\rm lin}(k)$$

1-loop EFT

- EFT includes:
  - Backreaction of small-scale physics on large-scale modes
  - **Controlled** ultraviolet (UV) behavior
  - Proper treatment of **non-perturbative** long-wavelength displacements [e.g. Senatore+14]

At one-loop, EFT adds a **free parameter** c_s^2 encoding **small-scale physics** that must be **fit** to data

EFT of Matter: A Lightning Introduction

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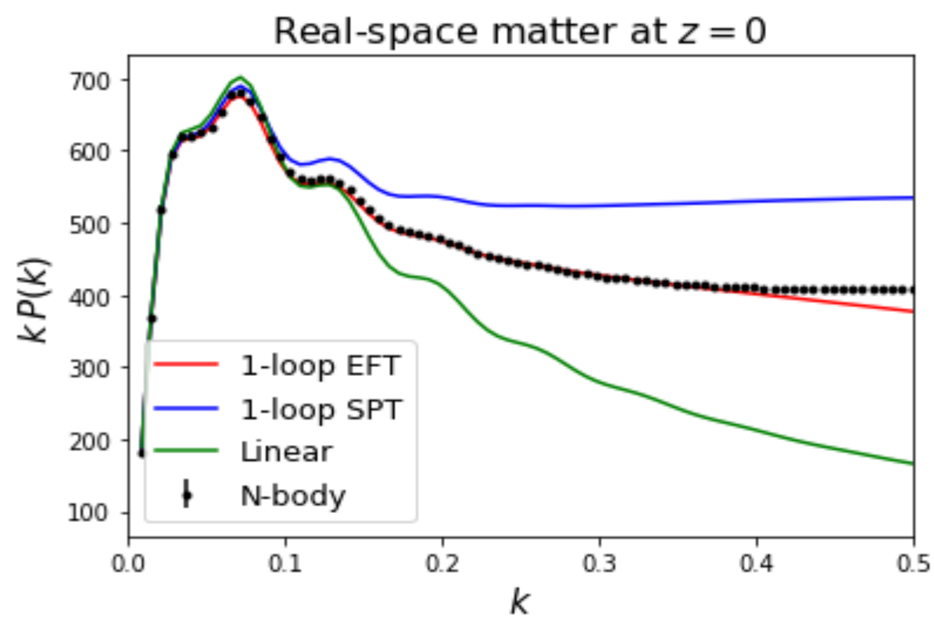

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Biased Tracers

- **Matter** is not observed directly → must predict **galaxy** statistics

- Simple approach: expand the galaxy overdensity in powers of δ:

$$\delta_g(\mathbf{x}) = b_1\delta(\mathbf{x}) + \tfrac{b_2}{2}\delta^2(\mathbf{x}) + \tfrac{b_3}{6}\delta^3(\mathbf{x}) + \ldots$$

- The EFT approach: include all possible parameters allowed by symmetry

$$\delta_g = b_1\delta + \epsilon + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + \frac{b_3}{6}\delta^3 + b_{\delta\mathcal{G}_2}\delta\mathcal{G}_2 + b_{\mathcal{G}_3}\mathcal{G}_3 + b_{\Gamma_3}\Gamma_3 + R_*^2\partial^2\delta$$

with density operators, tidal operators, stochastic operators, and non-local operators (all integrated over a lightcone)

- Also needs **redshift-space** distortions: $\boldsymbol{s} = \boldsymbol{r} + \dfrac{\boldsymbol{v}\cdot\hat{z}}{aH}\ \hat{z}$

Biased Tracers

- Full 1-loop **EFT** model for the **redshift-space** power spectrum of **biased tracers** [e.g. Perko+16]

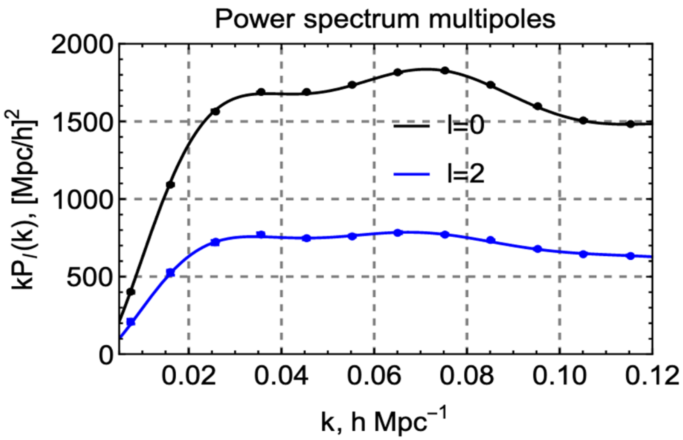
$$P_{g,\ell}(k) = P^{\rm tree}_{g,\ell}(k) + P^{1-{\rm loop}}_{g,\ell}(k) + P^{\rm noise}_{g,\ell}(k) + P^{\rm ctr}_{g,\ell}(k)$$

Linear Theory 1-loop SPT Stochastic Terms Counterterms

- **Seven** nuisance parameters**:**

$$\{b_1, b_2, b_{G_2}, c_{s,0}, c_{s,2}, b_4, P_{shot}\} \times \{\,\omega_b, \omega_{cdm}, h, A_s, \textstyle\sum m_\nu, n_s, \ldots\}$$

- **Sub-percent** accurate on large-scales



Nishimichi+20

Beyond the Blackboard

https://github.com/michalychforever/CLASS-PT

- Can we use EFT to fit the **full-shape** of **observed** galaxy power spectra?

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

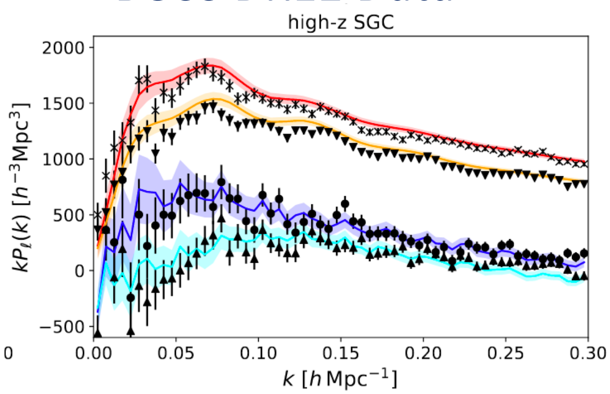
EFT Model (via CLASS-PT)

↓

Window Function

↓

BOSS DR12 Data



→ *MCMC* → *Cosmological Parameters* $\{\omega_b, \omega_{cdm}, h, A_s, \sum m_\nu, n_s\}$

Ivanov+19a,b, d'Amico+19, Chudaykin+20, Philcox+20a https://github.com/michalychforever/class-pt

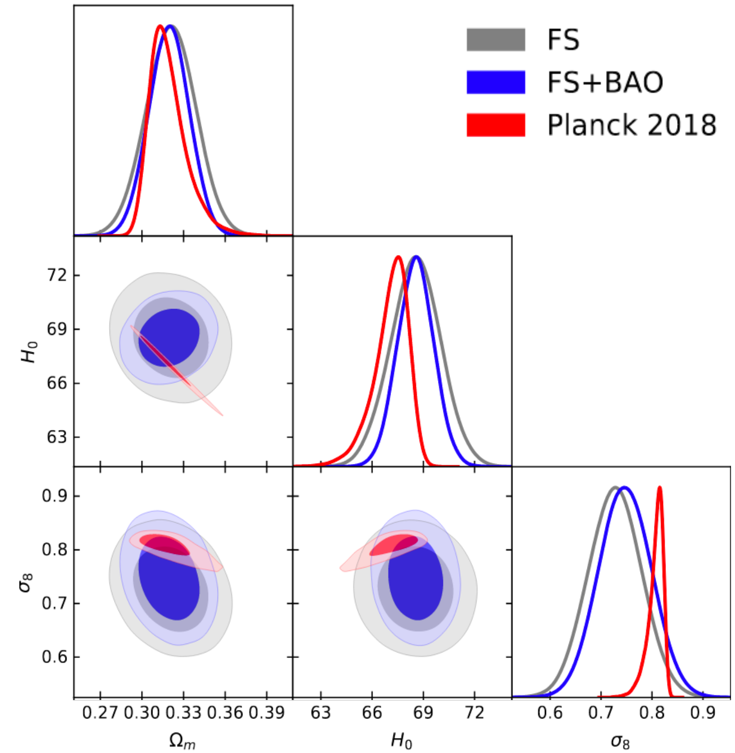
Cosmology from Galaxies + EFT

- Get **competitive** constraints on cosmology from **galaxy** power spectra plus **BBN** [Ivanov+19]

- Constraints are **strengthened** by combining with extra **BAO** information from *reconstruction* [Philcox+20a]

H_0	BOSS FS+BBN	**BOSS FS+BAO+BBN**	Planck 2018
	68.55 ± 1.5	$\mathbf{67.9 \pm 1.1}$	$67.1^{+1.3}_{-0.72}$

- As strong H_0 constraints as *Planck* **without** using CMB data!



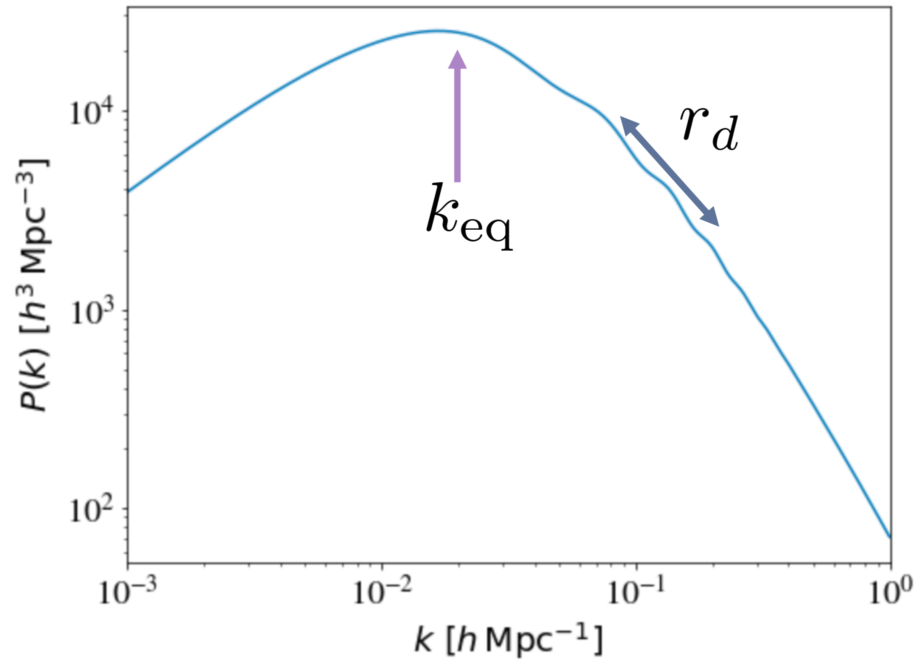
Ivanov+19a, Philcox+20a

H_0 without the Sound Horizon

- H_0 information comes from two **standard rulers**:

    1. Matter-radiation **equality** ($z \sim 3600$)
    2. **B**aryon **A**coustic **O**scillation scale ($z \sim 1100$)

- Can **isolate** the **equality** information by **removing** the BBN prior on ω_b in the EFT analysis



Baxter+20, Philcox+20d

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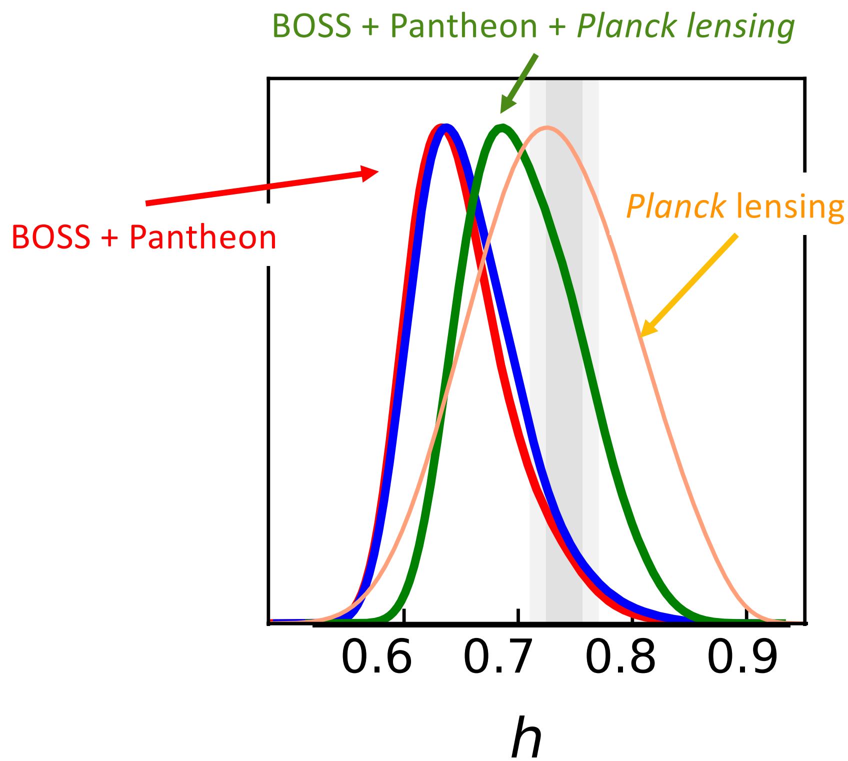
	BOSS + *Pantheon*	+ *Planck* lensing
H_0	$65.1^{+3.0}_{-5.4}$	$70.6^{+3.7}_{-5.1}$

- Galaxy constraints are **independent** of sound-horizon physics, and are $\sim 2\sigma$ below SH0ES

- $\sigma_{H_0} \sim 1.5\ \mathrm{km\ s^{-1} Mpc^{-1}}$ will soon be possible with *Euclid*



Baxter+20, Philcox+20d

Alternative Density Statistics

- **Low-density regions** carry a lot of information but contribute little to δ [e.g. Pisani+19]

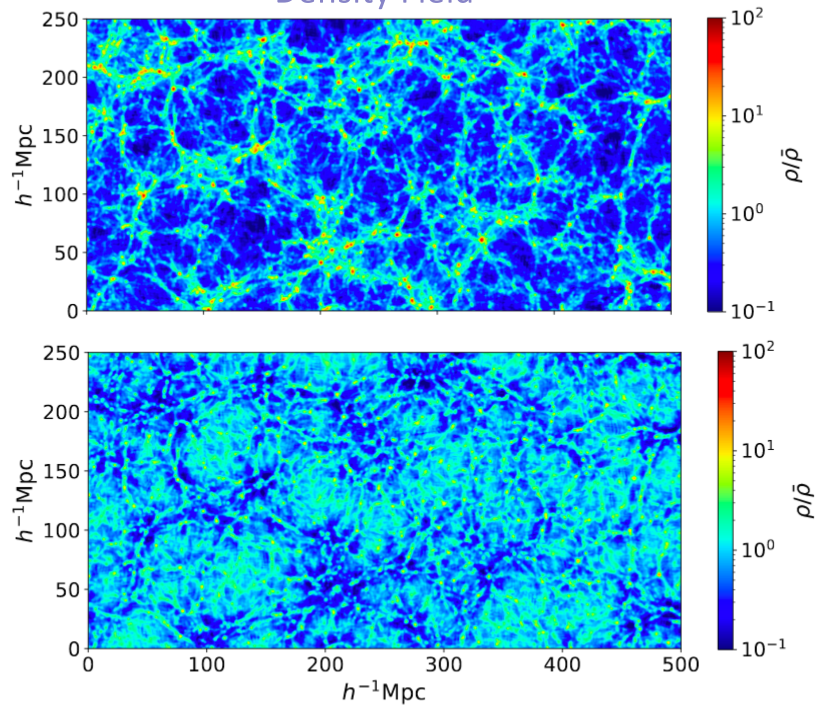
- Alternative statistics can help here, e.g. the **marked** density field [Stoyan 84, White 16, Massara+20]

- This is a **local-overdensity** weighted density field, shown to give strong constraints on the **neutrino** mass [Massara+20]

$$\rho_m(\boldsymbol{x}) \propto \frac{\rho(\boldsymbol{x})}{[c + \rho_R(\boldsymbol{x})]^p}$$

- Can we understand this using EFT?

Density Field



Marked Density Field

White 16, Massara+20

Understanding Marked Statistics

- Write down a **perturbative model** for the **marked** field

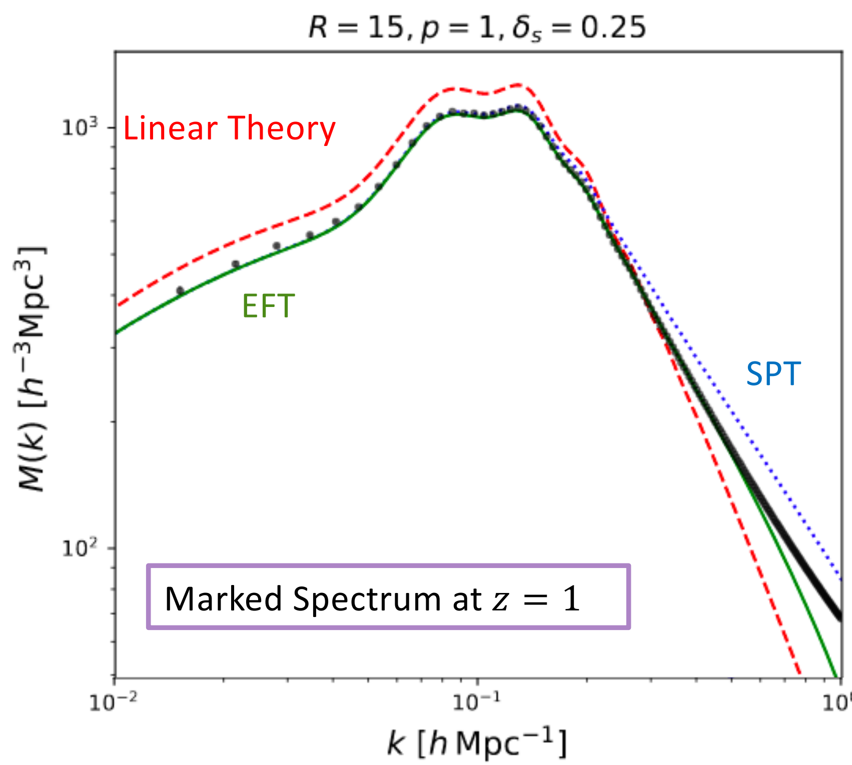
$$M(\mathbf{k}) = |\delta_M(\mathbf{k})|^2 = \frac{1}{\bar{m}^2}\left[M_{11}(\mathbf{k}) + M_{22}(\mathbf{k}) + 2M_{13}(\mathbf{k}) + 2M_{ct}(\mathbf{k})\right]$$

Linear Theory — 1-loop SPT — Counterterms

- This theory is unusual:
  - **Linear** theory fails on **all** scales
  - At low redshifts, **EFT** fails on **all** scales

- **Small-scales** are coupled to **large scales,** through non-linearities and gravitational non-Gaussianities.

- This **shifts** small-scale information, e.g. about neutrinos and n_s, up to **quasi-linear scales**



Philcox+20c, Philcox+ (in prep)

EFT + The Halo Model

- **EFT** gives a highly **accurate** P(k) model at low *k* but **fails** close to the non-linear scale

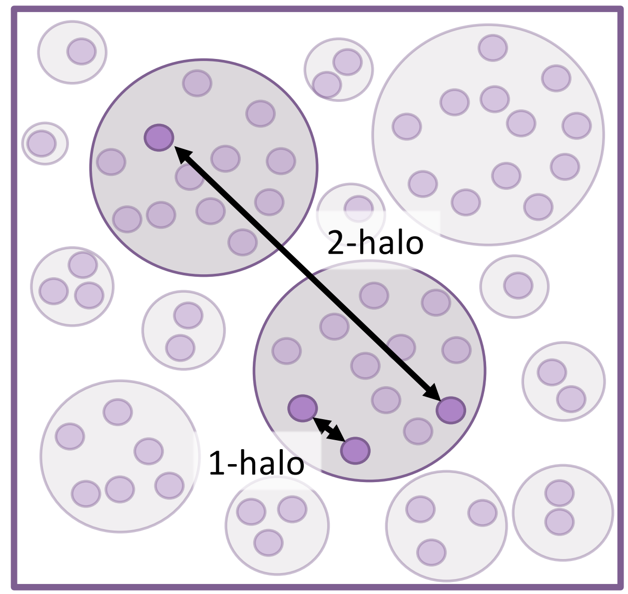
- The **halo model** gives a **rough** model of P(k) up to high *k*

- In **combination,** we can get **accurate** models up to ***high-k***

2-halo 1-halo

$$P(k) = \left[I_1^1(k)\right]^2 P_{\rm L}(k) + I_2^0(k)$$

Mass Integrals Linear Power



Philcox+ 2020b

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Smoothing Function

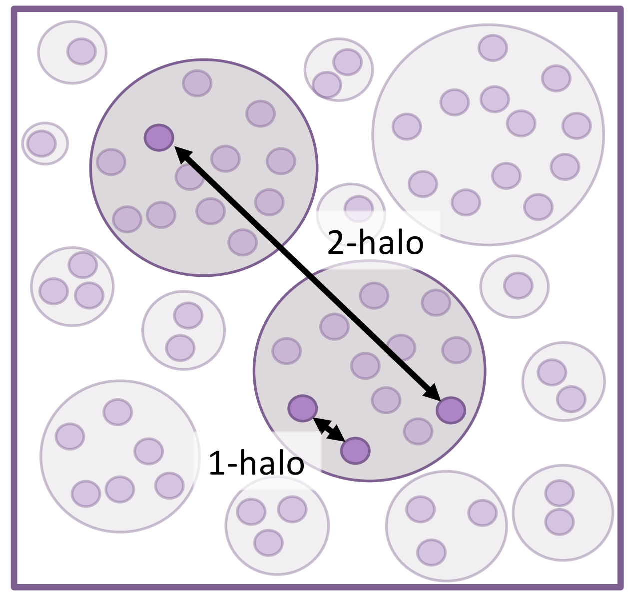
2-halo

1-halo

$$P(k) = \left[I_1^1(k)\right]^2 P_{\rm EFT}(k) W^2(kR) + I_2^0(k)$$

Mass Integrals

EFT Power

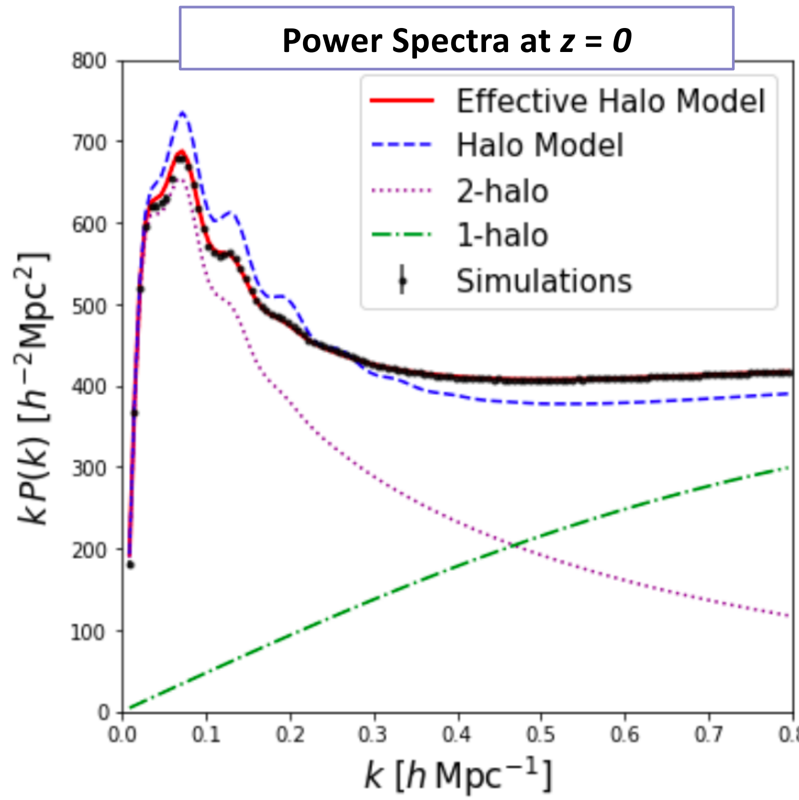


EffectiveHalos.rtfd.io

Philcox+ 2020c

The Effective Halo Model

- The Effective Halo Model is based on **perturbation theory** and is **1% accurate** for a large range of cosmologies.

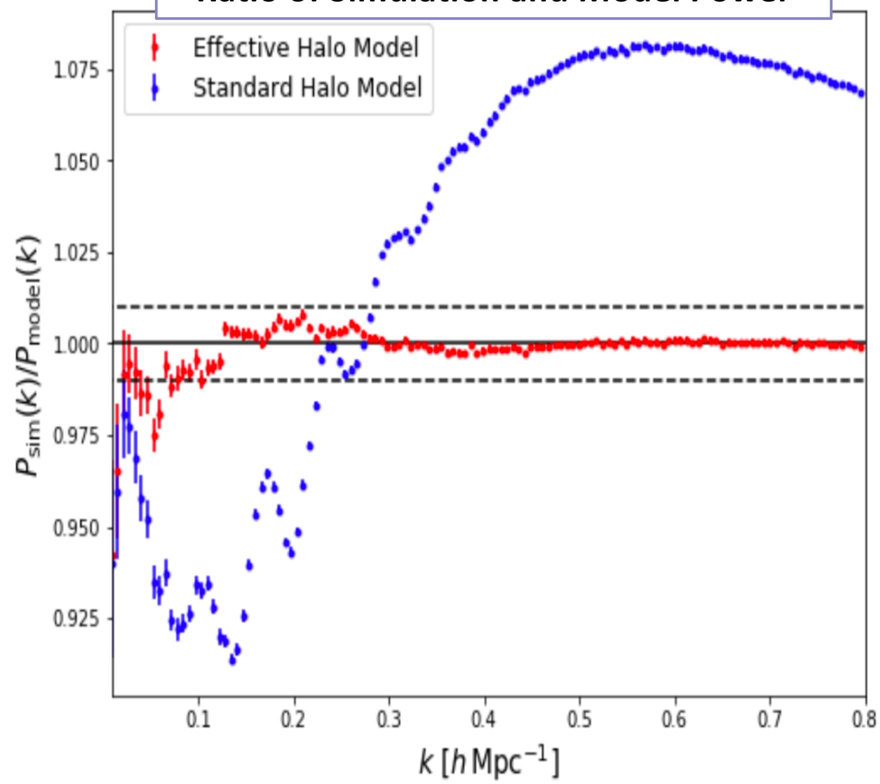


Philcox+ 2020b, Philcox+ (in prep.)

The Effective Halo Model

- The Effective Halo Model is based on **perturbation theory** and is **1% accurate** for a large range of cosmologies.
- We can also predict **covariances** between halo **number counts** and P(k).
- This can be used to compute projected spectra e.g.
  - **Weak Lensing**
  - Joint analysis of lensing and **thermal SZ**

Ratio of Simulation and Model Power



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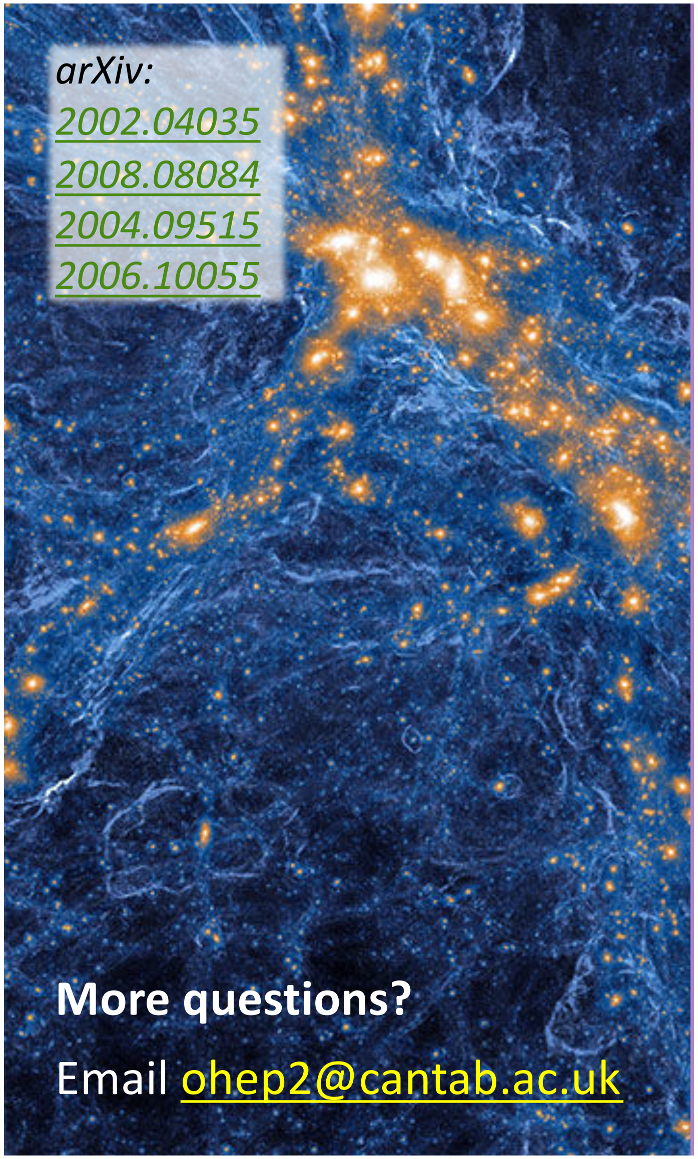

Summary

The *EFTofLSS:*

- Gives **accurate** models for density statistics
- Allows for **parameter inference** shedding light on H_0 tension
- Helps us to **understand** alternative statistics
- Can be combined with the **halo model** to accurately predict **all scales**

Many more possibilities, e.g.:

- Bispectra
- Field-level EFT
- Other statistics
- Weak lensing