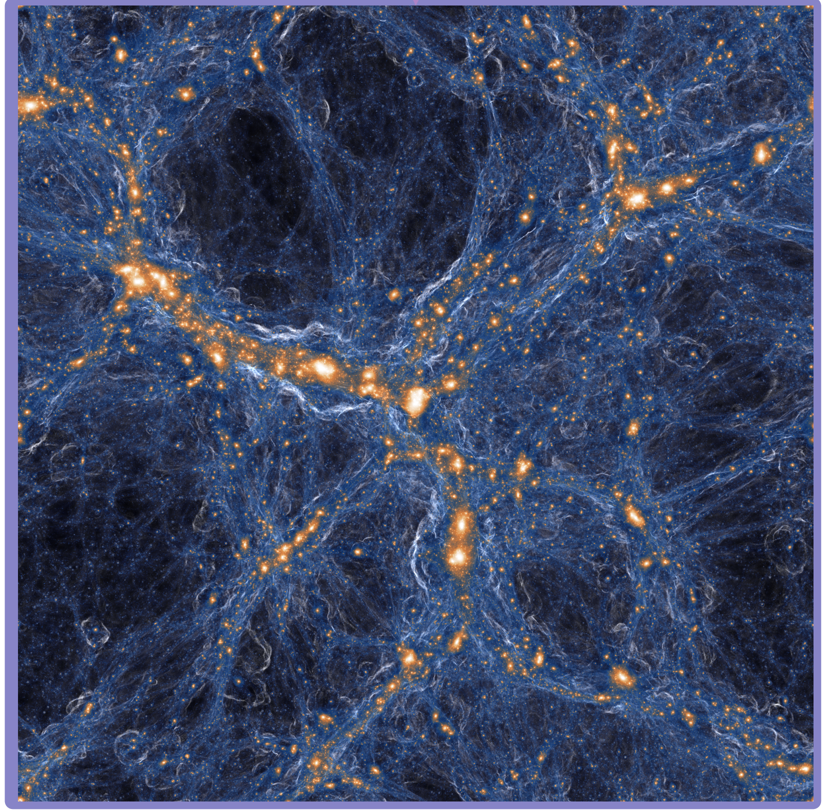
$$P_{\rm gg}(z,k) = b_1^2(z)(P_{\rm lin}(z,k) + P_{\text{1-loop, SPT}}(z,k)) + b_1(z)b_2(z)\mathcal{I}_{\delta^2}(z,k) + 2b_1(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\mathcal{G}_2}(z,k) + \left(2b_1(z)b_{\mathcal{G}_2}(z) + \frac{4}{5}b_1(z)b_{\Gamma_3}(z)\right)\mathcal{F}_{\mathcal{G}_2}(z,k) + \frac{1}{4}b_2^2(z)\mathcal{I}_{\delta^2\delta^2}(z,k) + b_{\mathcal{G}_2}^2(z)\mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\delta^2\mathcal{G}_2}(z,k) + P_{\nabla^2\delta}(z,k) + P_{\epsilon\epsilon}(z,k)\,,$$

???



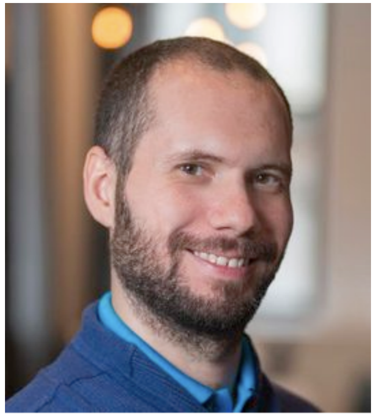
What's Next for the EFTofLSS*?

*Effective Field Theory of Large Scale Structure

OLIVER PHILCOX
(PRINCETON)

June 30, 2020

Elena Massara



Francisco Villaescusa-Navarro

David Spergel

Mikhail Ivanov

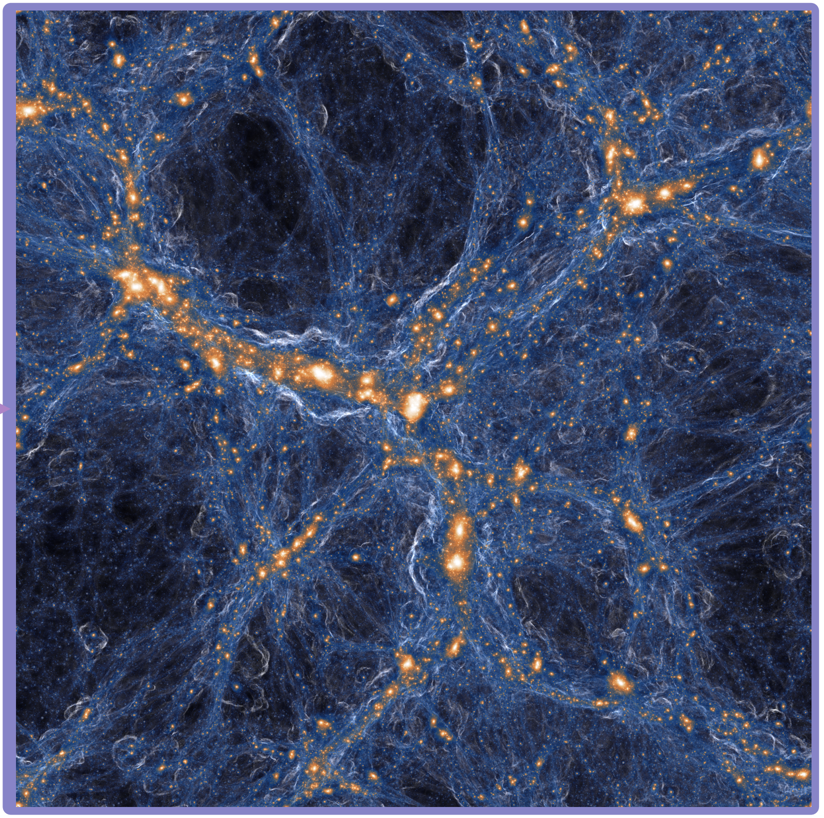
Marcel Schmittfull

Marko Simonovic

Matias Zaldarriaga

$$
\begin{aligned}
P_{\rm gg}(z,k) = {} & b_1^2(z)(P_{\rm lin}(z,k) + P_{\text{1-loop, SPT}}(z,k)) + b_1(z)b_2(z)\mathcal{I}_{\delta^2}(z,k) \\
& + 2b_1(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\mathcal{G}_2}(z,k) + (2b_1(z)b_{\mathcal{G}_2}(z) + \frac{4}{5}b_1(z)b_{\Gamma_3}(z))\mathcal{F}_{\mathcal{G}_2}(z,k) \\
& + \frac{1}{4}b_2^2(z)\mathcal{I}_{\delta^2\delta^2}(z,k) + b_{\mathcal{G}_2}^2(z)\mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\delta^2\mathcal{G}_2}(z,k) \\
& + P_{\nabla^2\delta}(z,k) + P_{\epsilon\epsilon}(z,k)\,,
\end{aligned}
$$

???



I. What is EFT?

Standard Perturbation Theory 101

- Describes the evolution of structure on **quasi-linear** scales

- Observables are density field, $\delta(\vec{x}) = \frac{\rho(\vec{x})}{\bar{\rho}} - 1$ and velocity field $\vec{v}(\vec{x})$

- Treat the cosmic matter as a **pressureless**, **Newtonian fluid**

- This must obey the **fluid equations**

$\dot{\delta} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0,$	Continuity Equation
$\dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\mathcal{H}\boldsymbol{v} - \nabla\phi,$	Euler Equation
$\nabla^2\phi = 4\pi G a^2 \bar{\rho}\delta,$	Poisson Equation

$\mathcal{H}(a) = aH(a)$, $\phi =$ gravitational peculiar potential
$\dot{y} = \partial y / \partial \tau$, $\tau =$ conformal time

e.g. Bernardeau+02

Standard Perturbation Theory 101

- In Fourier space:

$$\delta'(\boldsymbol{k}) + \theta(\boldsymbol{k}) = -\int \frac{\mathrm{d}^3 q}{(2\pi)^3}\frac{\mathrm{d}^3 q'}{(2\pi)^3}(2\pi)^3 \delta^{(\mathrm{D})}(\boldsymbol{k} - \boldsymbol{q} - \boldsymbol{q}')\alpha(\boldsymbol{q}, \boldsymbol{q}')\theta(\boldsymbol{q})\delta(\boldsymbol{q}'),$$

$$\theta'(\boldsymbol{k}) + \mathcal{H}\theta(\boldsymbol{k}) + \frac{3}{2}\Omega_{\mathrm{m}}(a)\mathcal{H}^2\delta(\boldsymbol{k}) = -\int \frac{\mathrm{d}^3 q}{(2\pi)^3}\frac{\mathrm{d}^3 q'}{(2\pi)^3}(2\pi)^3 \delta^{(\mathrm{D})}(\boldsymbol{k} - \boldsymbol{q} - \boldsymbol{q}')\beta(\boldsymbol{q}, \boldsymbol{q}')\theta(\boldsymbol{q})\theta(\boldsymbol{q}').$$

where $\theta = \nabla \cdot v$ is the velocity divergence and α, β are dimensionless kernels.

- At linear order, these are easily solved:

$$\delta^{(1)}(\mathbf{k}, \tau) = D(\tau)\delta_L(\mathbf{k}), \quad \theta^{(1)}(\mathbf{k}, \tau) = -\mathcal{H}(\tau)f(\tau)D(\tau)\delta_L(\mathbf{k})$$

where $\delta_L(\mathbf{k})$ is the initial **linear** density field, and $f(\tau), D(\tau)$ are the growth factors.

e.g. Bernardeau+02

Standard Perturbation Theory 101

- Beyond linear order, we expand **perturbatively** assuming $\delta_L(\mathbf{k})$ is small:

$$\delta(\mathbf{k},\tau) = D(\tau)\delta^{(1)}(\mathbf{k}) + D^2(\tau)\delta^{(2)}(\mathbf{k}) + D^3(\tau)\delta^{(3)}(\mathbf{k}) + \ldots$$

$$\theta(\mathbf{k},\tau) = -\mathcal{H}(\tau)f(\tau)\left[D(\tau)\theta^{(1)}(\mathbf{k}) + D^2(\tau)\theta^{(2)}(\mathbf{k}) + D^3(\tau)\theta^{(3)}(\mathbf{k}) + \ldots\right]$$

- The n-th order solution involves n powers of the linear density field:

$$\delta^{(n)}(\boldsymbol{k}) = \prod_{m=1}^{n}\left\{\int \frac{\mathrm{d}^3 q_m}{(2\pi)^3}\delta^{(1)}(\boldsymbol{q}_m)\right\} F_n(\boldsymbol{q}_1,\ldots,\boldsymbol{q}_n)(2\pi)^3\delta^{(\mathrm{D})}(\boldsymbol{k}-\boldsymbol{q}|_1^n)$$

$$\tilde{\theta}^{(n)}(\boldsymbol{k}) = \prod_{m=1}^{n}\left\{\int \frac{\mathrm{d}^3 q_m}{(2\pi)^3}\delta^{(1)}(\boldsymbol{q}_m)\right\} G_n(\boldsymbol{q}_1,\ldots,\boldsymbol{q}_n)(2\pi)^3\delta^{(\mathrm{D})}(\boldsymbol{k}-\boldsymbol{q}|_1^n)$$

Linear Solution Coupling kernels (set by the fluid equations)

e.g. Bernardeau+02

Standard Perturbation Theory 101

- Using these, it's straightforward to compute the matter power spectrum:

$$(2\pi)^3\delta_D(\mathbf{k}+\mathbf{k}')P(\mathbf{k},\tau) = \langle\delta(\mathbf{k},\tau)\delta(\mathbf{k}',\tau)\rangle$$

$$P(\mathbf{k},\tau) = P_L(\mathbf{k},\tau) + P_{22}(\mathbf{k},\tau) + 2P_{13}(\mathbf{k},\tau) + \ldots$$

for linear power spectrum $P_L(\mathbf{k},\tau) = D^2(\tau)P_L(\mathbf{k})$ and **one-loop** terms

$$\begin{aligned} P_{22}(\mathbf{k}) &= \int \frac{d^3q}{(2\pi)^3} P_L(\mathbf{q})P_L(\mathbf{k}-\mathbf{q})|F_2(\mathbf{q},\mathbf{k}-\mathbf{q})|^2 \\ P_{13}(\mathbf{k}) &= 3P_L(\mathbf{k})\int \frac{d^3q}{(2\pi)^3} P_L(\mathbf{q})F_3(\mathbf{k},\mathbf{q},-\mathbf{q}) \end{aligned}$$

- Higher order statistics can be computed similarly, and we can extend to 2+ loops

e.g. Bernardeau+02

Problems with SPT

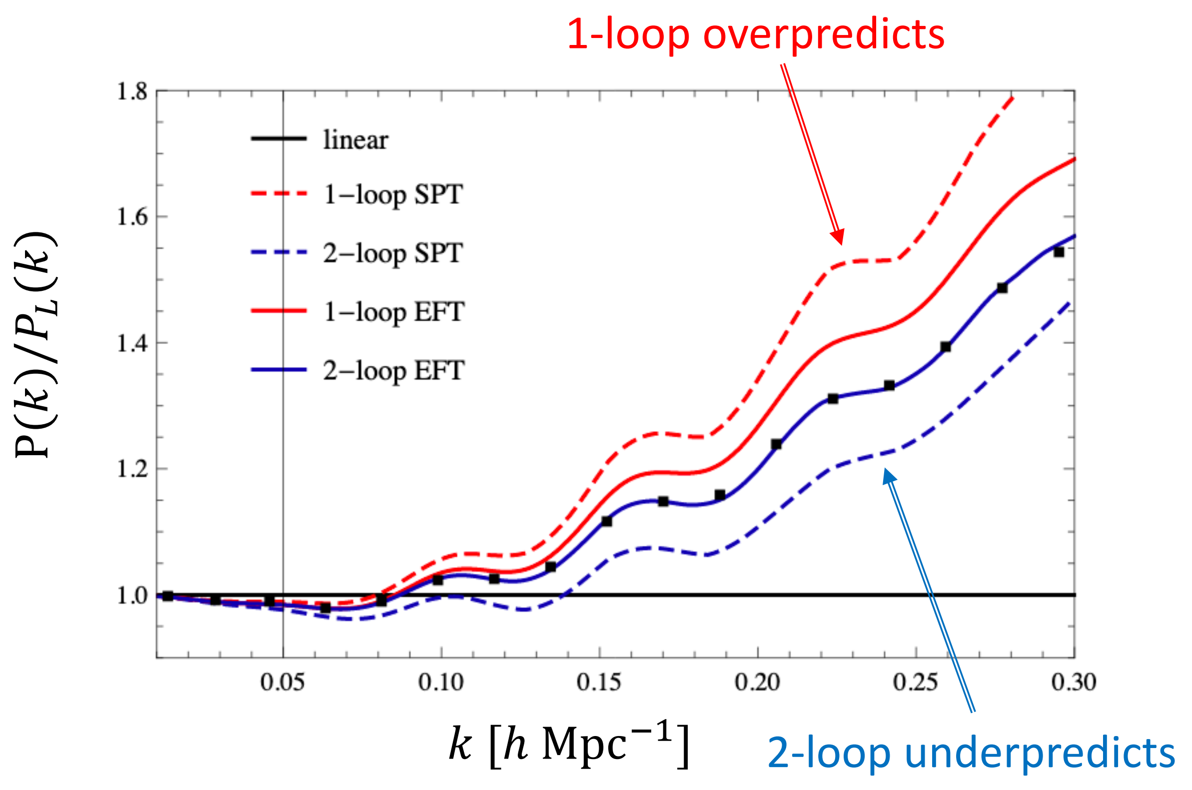
1. Is there a good **expansion parameter**?

   The overdensity is **large** on small scales, so the series diverges

2. Is matter really a **perfect fluid**?

3. The loop integrals can **diverge**

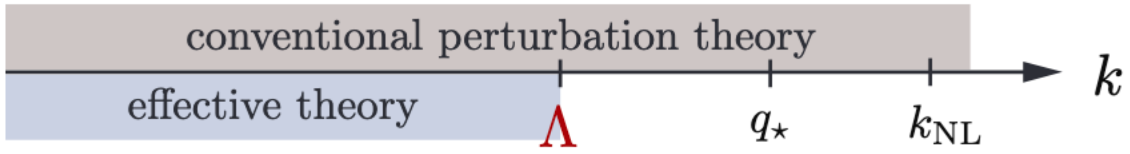
4. The theory doesn't **converge** to the truth!



Baldauf, Adv. Cosm.

The Effective Field Theory of LSS

- Standard Perturbation Theory (SPT) is assumed to work on **all scales**.



- **Effective Field Theory (EFT)** explicitly restricts to scales $k < \Lambda$

- Using **symmetry**, we can parametrize the corrections from a short scale $q_* > \Lambda$ mode on the **large-scale** modes, $k < \Lambda$. We can *integrate out* the small-scale physics

- Free parameters can be **fit** from simulations or data

Baumann+12
Carrasco+12

The Smoothed Fluid Equations

- Start from the fluid equations, but **smooth** on scale Λ

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

- The new term is the **effective stress tensor**, which can be written in terms of e.g. density gradients, viscocity, sound-speed etc.

- We now have a **well-defined** expansion parameter δ_Λ which is guaranteed to be **small** everywhere

Baumann+12
Carrasco+12

The Smoothed Fluid Equations

- Including this in the perturbation theory gives a new term:

$$\delta(\boldsymbol{k},\tau) = \delta^{(1)}(\boldsymbol{k},\tau) + \delta^{(2)}(\boldsymbol{k},\tau) + \delta^{(3)}(\boldsymbol{k},\tau) - k^2 c_{\rm s}^2(\tau)\delta^{(1)}(\boldsymbol{k},\tau) + \dots$$

- This depends on the **effective sound speed** $c_s^2(\tau)$ which incorporates **small scale physics** and must be **fit from data**.

- For the power spectrum:

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

The 1-loop **counterterm**

Baumann+12
Carrasco+12

Renormalizing Perturbation Theory

- The new one-loop power spectra are integrated only up to $q_{\max} = \Lambda$

$$\text{e.g. } P_{13,\Lambda}(\mathbf{k}) = 3P_L(\mathbf{k}) \int_0^\Lambda q^2 dq P_L(q) \times \dots$$

- These seem to **explicitly** depend on the cut-off Λ

$$P_{13,\Lambda}(\mathbf{k},\Lambda) = P_{13,\infty}(\mathbf{k}) - f(\Lambda)k^2 P_L(k)$$

- But the **cut-off** dependence can be **absorbed** by the $-c_{s,\Lambda}^2 k^2 P_L(k)$ counterterm!

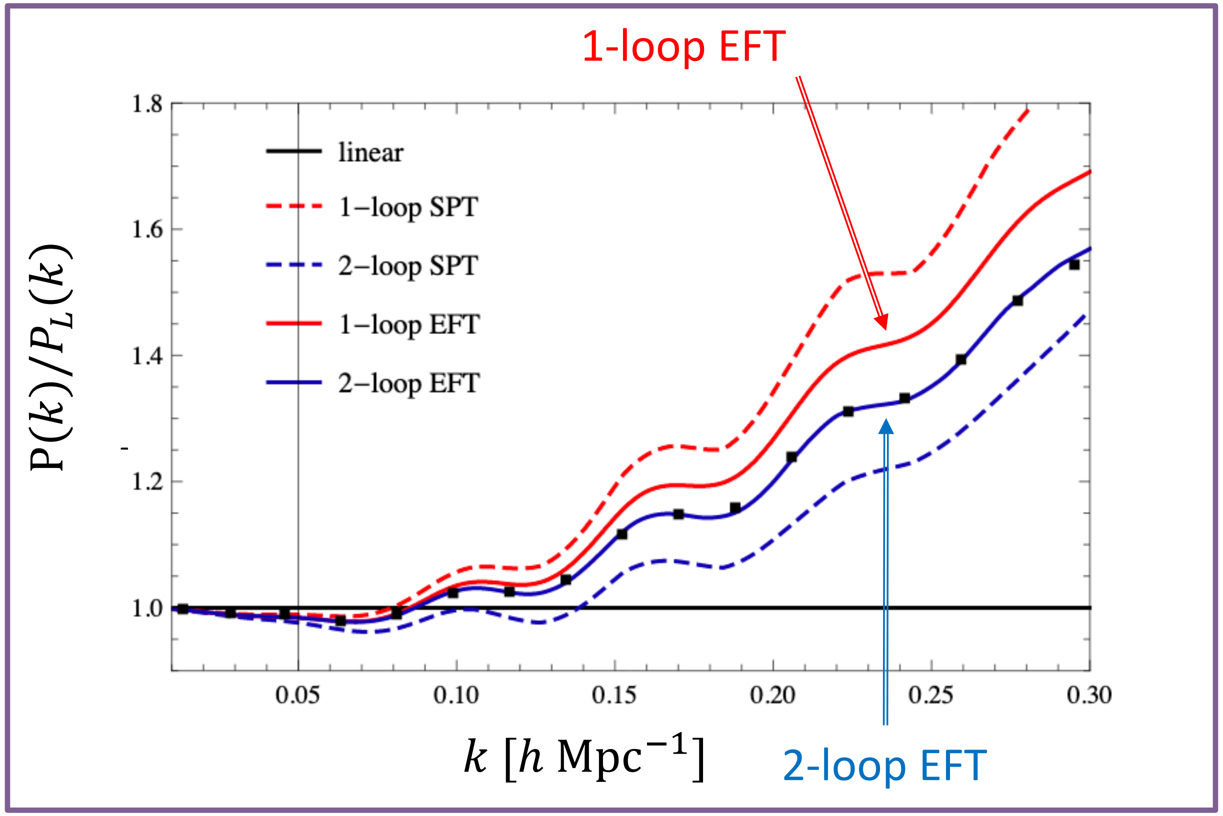
- The resulting theory is **independent** of the cut-off scale

$$\boxed{P(k) = P_{11}(k) + P_{22}(k) + 2P_{13}(k) - 2c_{s^2,\infty}k^2 P_{11}(k)}$$

The one-loop Effective Field Theory of matter

Baumann+12
Carrasco+12

The EFT of LSS: Matter



EFT Provides an Accurate Fit on quasi-linear scales

Baldauf, Adv. Cosm.

The EFT of Biased Tracers

- The **EFT** of **LSS** can be extended to biased tracers, e.g. halos and galaxies

- First let's expand the galaxy overdensity, $\delta_g(\mathbf{x})$ in terms of the matter overdensity:

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

- Does $\delta_g(\mathbf{x})$ depend on anything else?
  - What about tidal effects?
  - What about time dependence?
  - What about non-local operators?
  - What about stochasticity?

e.g. McDonald+Roy 09

The EFT of Biased Tracers

- **The EFT approach:** Write down all possible operators in the bias expansion and give each a free parameter.
- At third order:

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

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

- All these can be expressed in terms of the linear density field $\delta^{(1)}(\mathbf{x})$ (or a stochastic variable), and lead to new terms in the power spectrum.
- We can also have new **counterterms** catching the cutoff-dependence (UV sensitivity) of the new operators.

e.g. Senatore+15, Mirbabayi+15, Angulo+15

Moving to Redshift Space

- Real space ($\mathbf{x}$) and redshift space ($\mathbf{s}$) are related by

$$\mathbf{s} = \mathbf{x} + \frac{\hat{z}\cdot\mathbf{v}}{aH}\hat{z}$$

where $\hat{z}$ is the line-of-sight direction.

- By conservation of mass

$$[1+\delta_{g,s}(\mathbf{s})]\,d^3s = [1+\delta_g(\mathbf{x})]\,d^3x$$

giving

$$\begin{aligned}\delta_{g,s}(\mathbf{k}) &= (2\pi)^3\delta_D(\mathbf{k}) + \int d^3x\left[e^{-i\frac{k_z}{aH}v(\mathbf{x})} - 1\right](1+\delta_g(\mathbf{x}))\\ &= \delta_g(\mathbf{k}) - i\frac{k_z}{aH}v_z(\mathbf{k}) + \ldots\end{aligned}$$

e.g. Senatore+14, Perko+16

- This gives an **extra** dependence of $\delta_{g,s}$ on the **velocity** field, and **new counterterms**.

The EFT of Biased Tracers in Redshift Space

- Putting it all together, we can write

$$\delta_{g,s}(\mathbf{k}) = \delta_g^{(1)}(\mathbf{k}) + \delta_g^{(2)}(\mathbf{k}) + \delta_g^{(3)}(\mathbf{k}) + \delta_g^{(\mathrm{ct})}(\mathbf{k}) + \delta_g^{(\mathrm{stoch})}(\mathbf{k})$$

where:

-$\delta_g^{(n)}$ are convolutions of n density fields with kernels Z_n

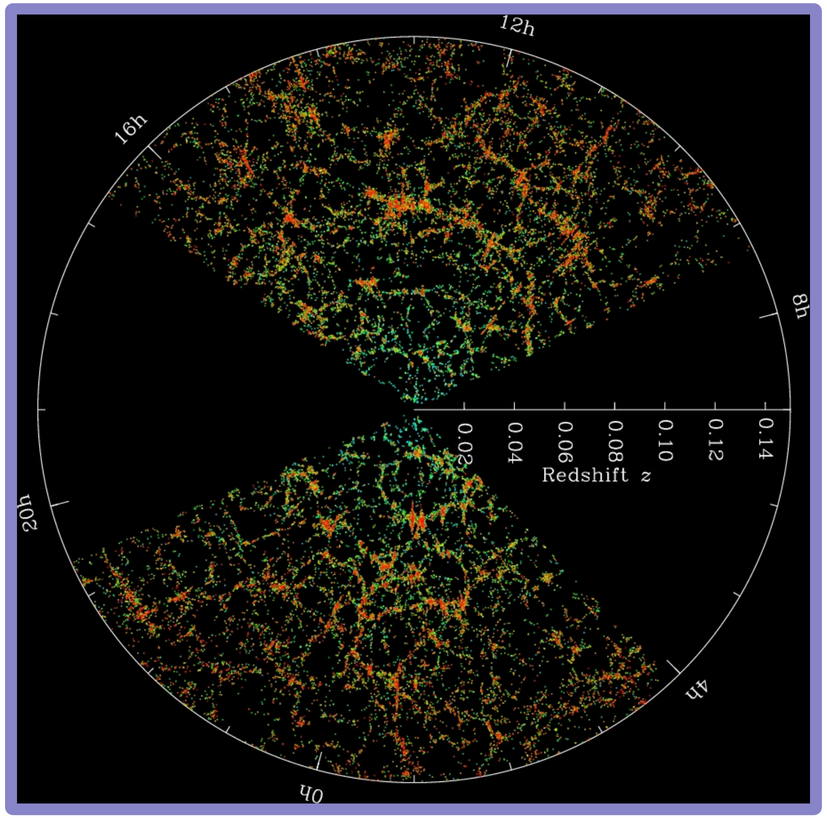
- $\delta_g^{(\mathrm{ct})}$ are appropriate counterterms

-$\delta_g^{(\mathrm{stoch})}$ are stochastic contributions

$$\begin{aligned}
Z_1(\mathbf{k}) &= b_1 + f\mu^2\,,\\
Z_2(\mathbf{k}_1,\mathbf{k}_2) &= \frac{b_2}{2} + b_{\mathcal{G}_2}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - 1\right) + b_1F_2(\mathbf{k}_1,\mathbf{k}_2) + f\mu^2G_2(\mathbf{k}_1,\mathbf{k}_2)\\
&\quad + \frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}(b_1+f\mu_2^2) + \frac{\mu_2}{k_2}(b_1+f\mu_1^2)\right)\,,
\end{aligned}$$

$$\begin{aligned}
Z_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) &= 2b_{\Gamma_3}\left[\frac{(\mathbf{k}_1\cdot(\mathbf{k}_2+\mathbf{k}_3))^2}{k_1^2(\mathbf{k}_2+\mathbf{k}_3)^2} - 1\right]\left[F_2(\mathbf{k}_2,\mathbf{k}_3) - G_2(\mathbf{k}_2,\mathbf{k}_3)\right]\\
&+ b_1F_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) + f\mu^2G_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) + \frac{(f\mu k)^2}{2}(b_1+f\mu_1^2)\frac{\mu_2}{k_2}\frac{\mu_3}{k_3}\\
&+ f\mu k\frac{\mu_3}{k_3}\left[b_1F_2(\mathbf{k}_1,\mathbf{k}_2) + f\mu_{12}^2G_2(\mathbf{k}_1,\mathbf{k}_2)\right] + f\mu k(b_1+f\mu_1^2)\frac{\mu_{23}}{k_{23}}G_2(\mathbf{k}_2,\mathbf{k}_3)\\
&+ b_2F_2(\mathbf{k}_1,\mathbf{k}_2) + 2b_{\mathcal{G}_2}\left[\frac{(\mathbf{k}_1\cdot(\mathbf{k}_2+\mathbf{k}_3))^2}{k_1^2(\mathbf{k}_2+\mathbf{k}_3)^2} - 1\right]F_2(\mathbf{k}_2,\mathbf{k}_3) + \frac{b_2f\mu k}{2}\frac{\mu_1}{k_1}\\
&+ b_{\mathcal{G}_2}f\mu k\frac{\mu_1}{k_1}\left[\frac{(\mathbf{k}_2\cdot\mathbf{k}_3)^2}{k_2^2k_3^2} - 1\right]\,,
\end{aligned}$$

e.g. Perko+16, Ivanov+20



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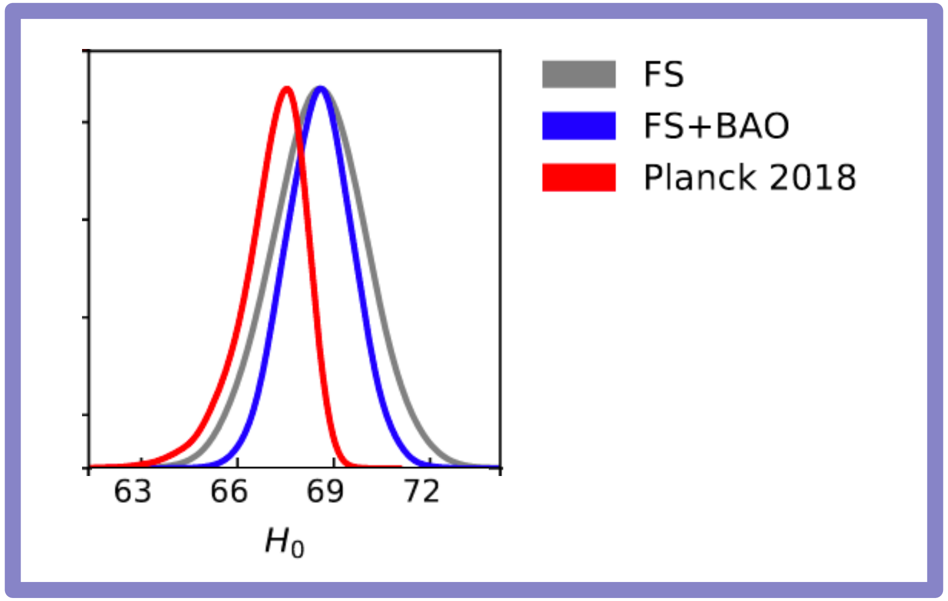


Philcox+20a

II. Can we Apply EFT to Data?

Fitting Galaxy Power Spectra

- How can we use EFT to analyze large scale structure data?
- Conventional analyses just use the position of the **BAO** and the ratio $P_2(k)/P_0(k)$ to calibrate cosmology
- Is there information in the **full shape** of the power spectra? We now have an **accurate** and **rigorous** model with which to probe this!

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

Linear Theory | 1-loop SPT | Stochastic Terms | Counterterms

Ivanov+19a,b, d'Amico+19, Nishimichi+20

Data

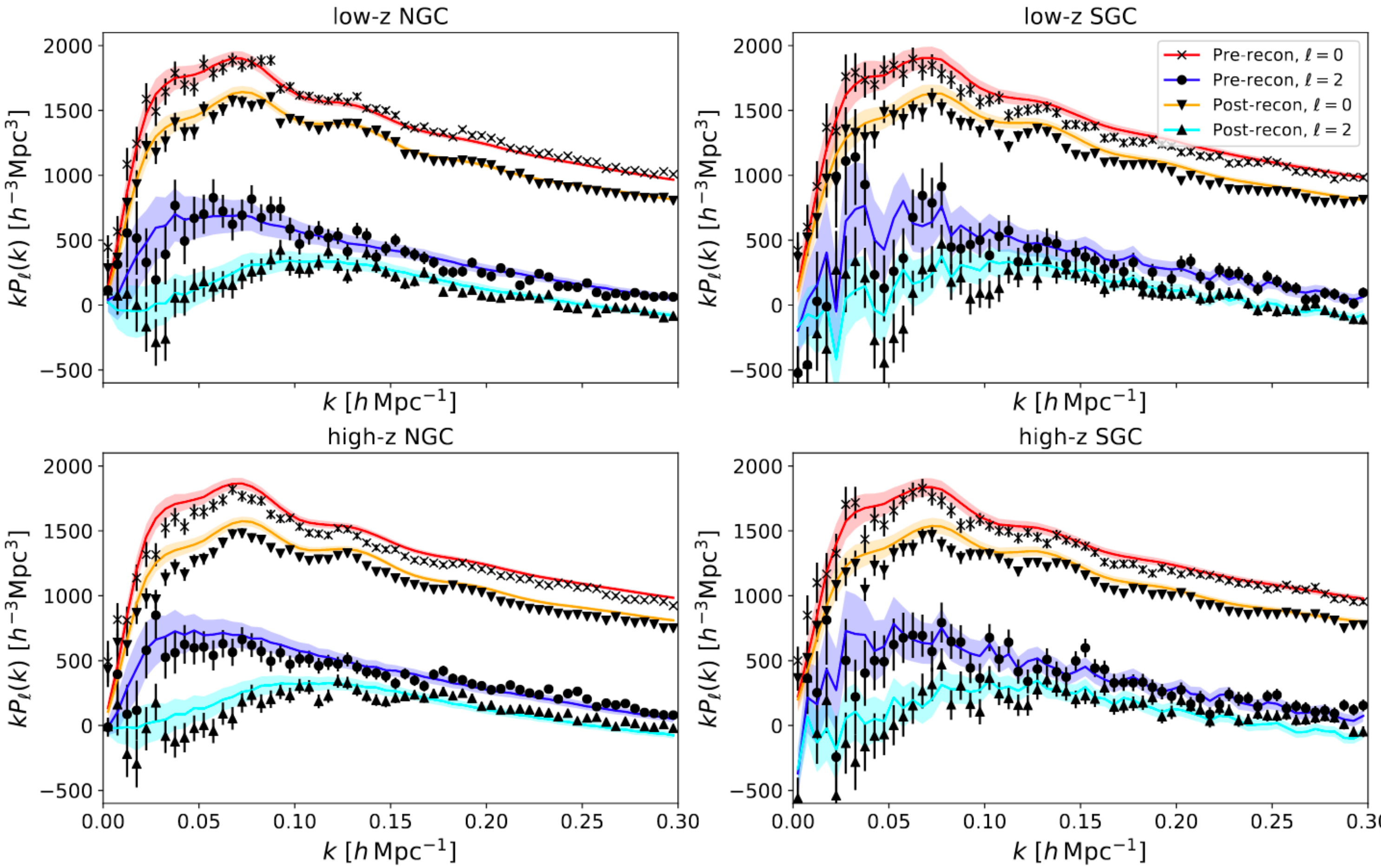
From **BOSS DR12**

Two sky patches (NGC + SGC)

Two redshifts $z_{\mathrm{eff}} \in \{0.38, 0.61\}$

Total volume $V_{\mathrm{eff}} = 2.4\ (h^{-1}\mathrm{Gpc})^3$

All **publicly** available



Points: Observed Spectra, Lines: Mock Spectra

Ivanov+19a,b, d'Amico+19, Philcox+20

github.com/michalychforever/lss_montepython

Galaxy Spectrum Pipeline

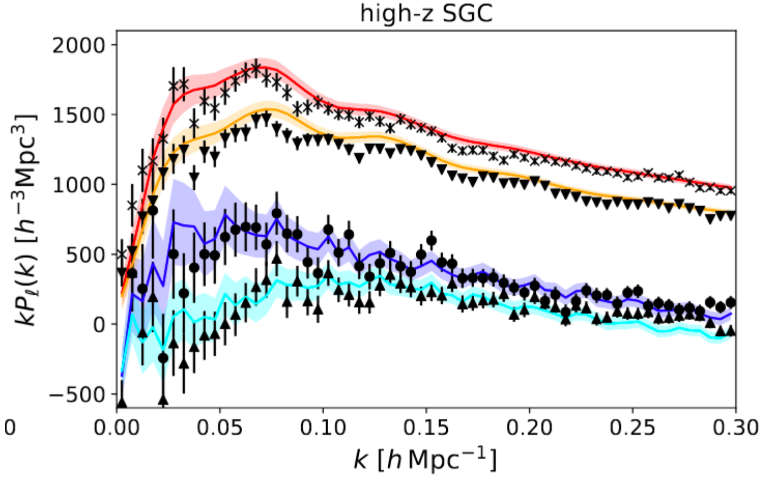
Benefits:
- Publicly Available (CLASS-PT)
- Works with any CLASS parameters
- Fast! (~ 0.05s to evaluate likelihood)

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

EFT Model

Window Function

BOSS DR12 Data



MCMC → *Cosmological Parameters*

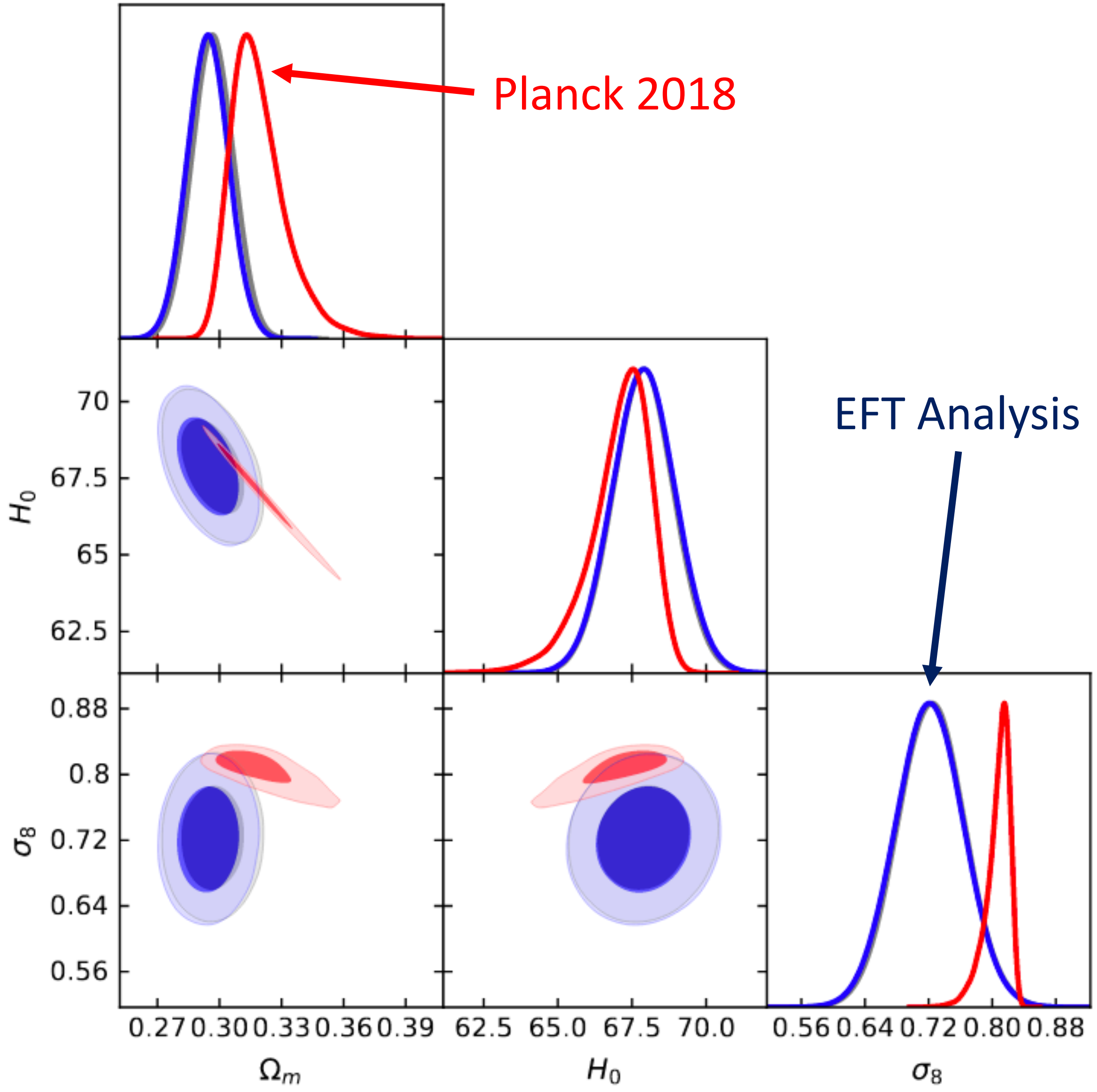
$$\{\omega_b, \omega_{cdm}, h, A_s, \sum m_\nu, n_s\}$$

(+ 7 nuisance parameters)

Ivanov+19a,b, d'Amico+19, Nishimichi+20

Results

- EFT analysis gives **competitive** constraints on cosmology
- Combining with CMB gives **sharper** constraints due to **degeneracy breaking**
- But these are **not** much stronger than simple BAO constraints?
  - We don't use BAO information
  - BOSS is small



BAO Reconstruction

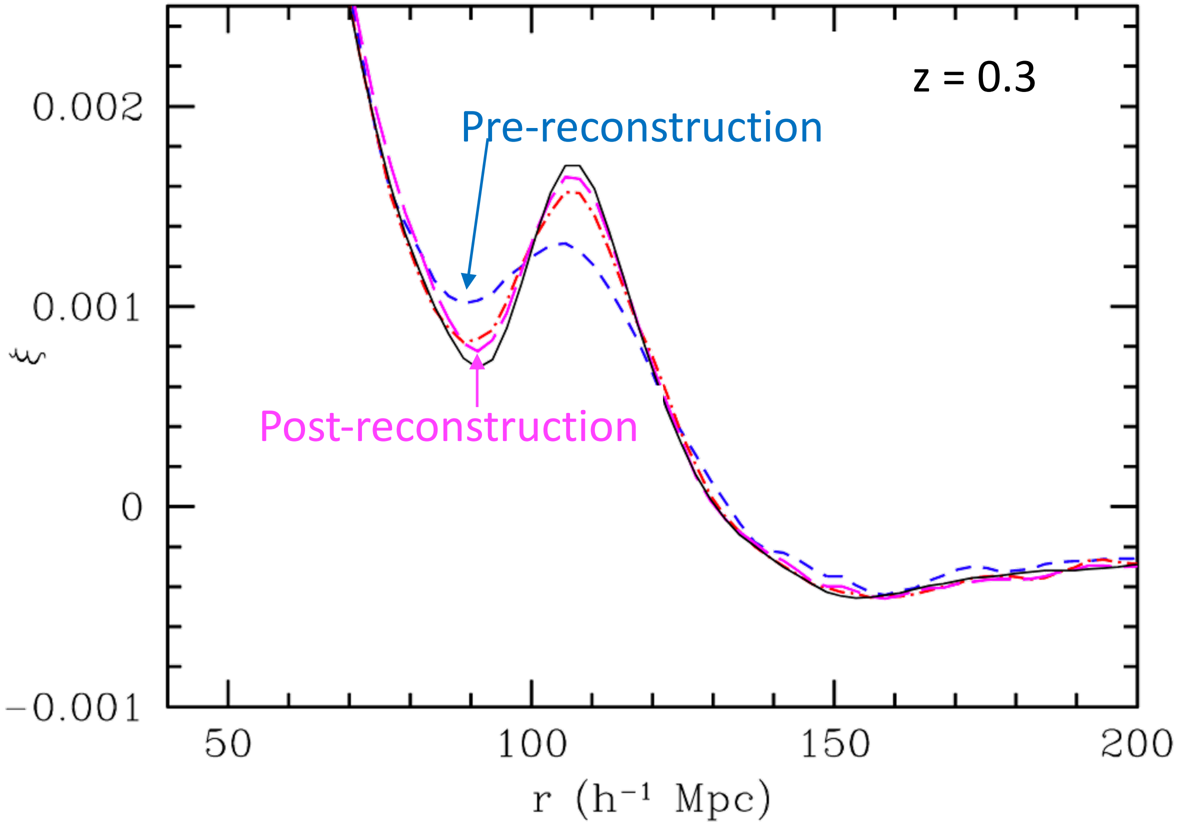
- When measuring the **BAO** position, we normally **reconstruct** the power spectrum

- This **undoes** long-wavelength displacements by estimating the velocity field

$$\nabla \cdot \mathbf{v} \approx -\delta_{\rm smooth}$$

- The reconstructed power spectra have **sharper** BAO features, but **much** more complex broadband shape [Hikage+17,19]

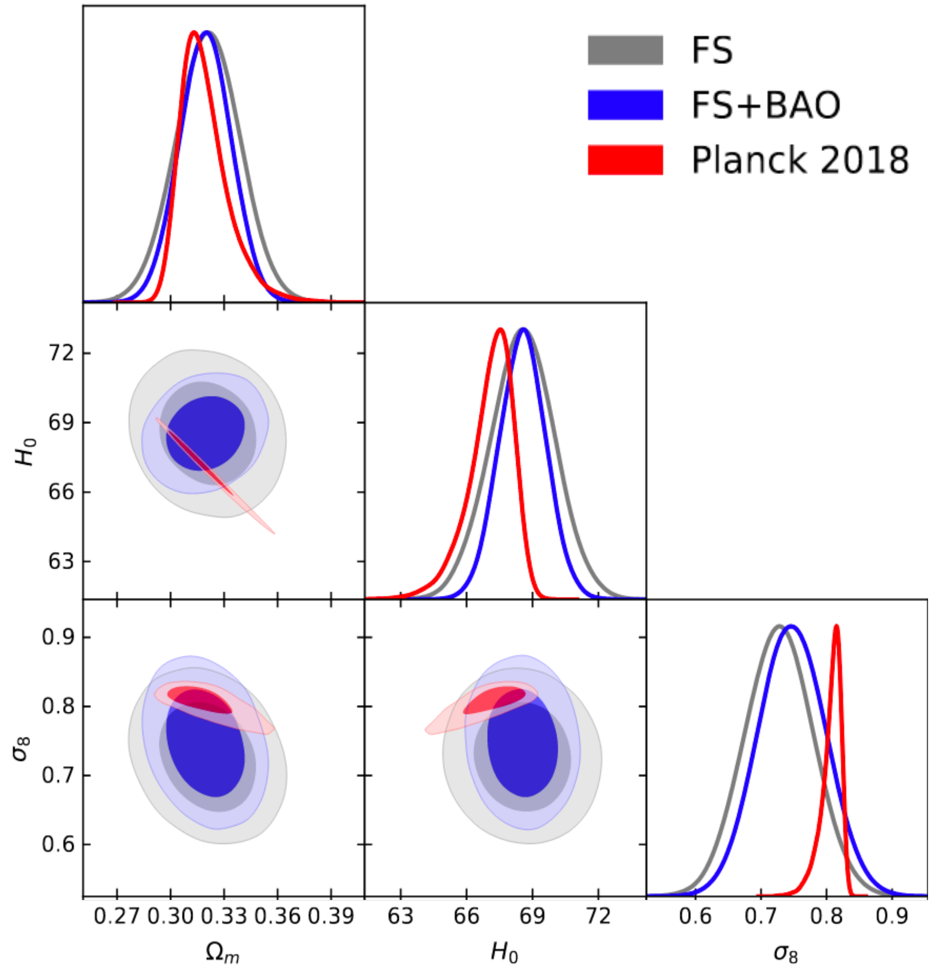
Galaxy Correlation Function



Eisenstein+06, Padamanbhan+12

A Joint Analysis

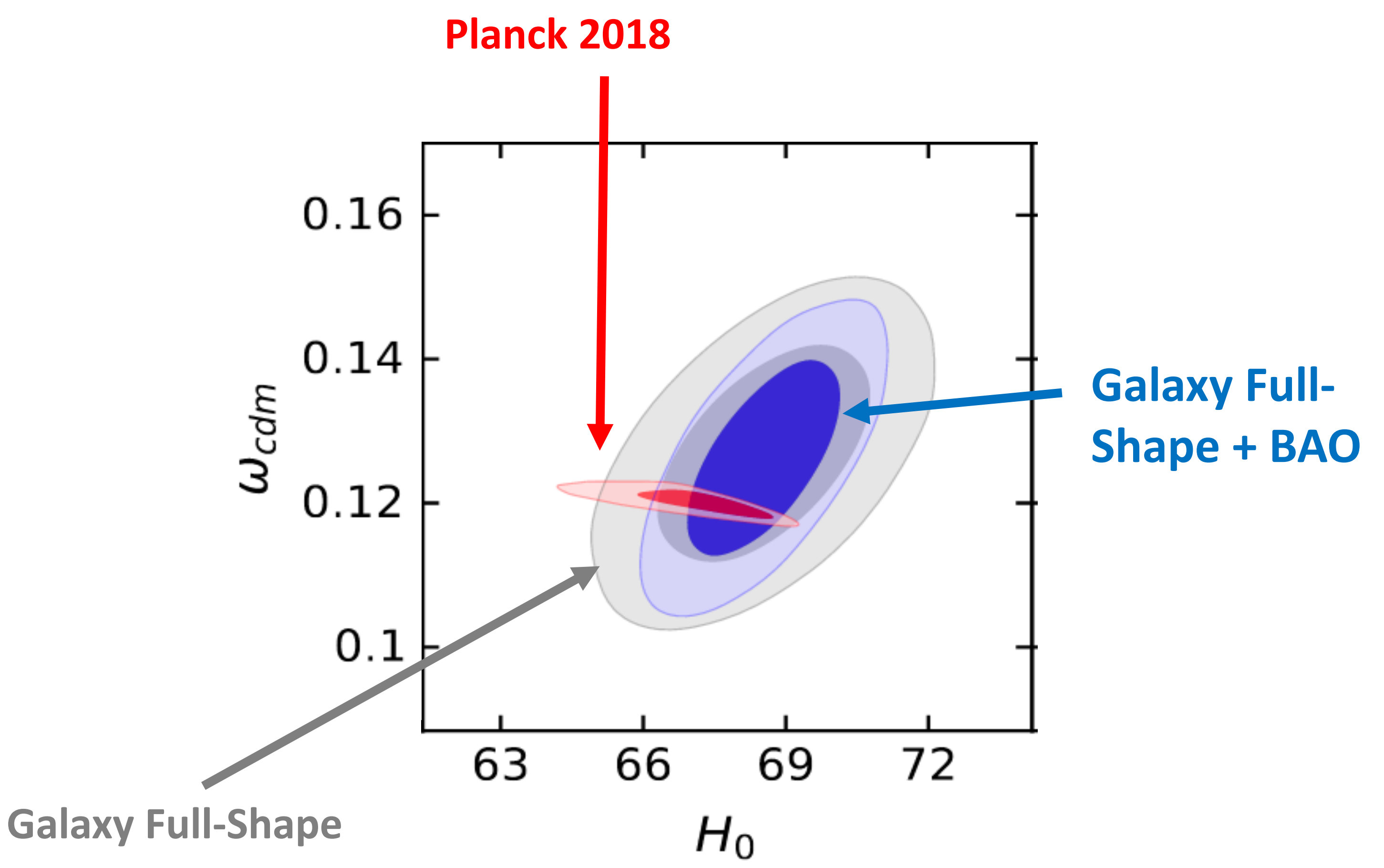
1. Measure the **BAO** position from the **reconstructed** power spectra.
2. Find the **covariance** of the **BAO** parameters with the **unreconstructed** spectra
3. Run the EFT analysis on the **combined f**ull shape (FS) + BAO data-vector.



Philcox+ 2020a

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

40% gain from combining FS+BAO



(Free n_s + BBN prior on Ω_b)

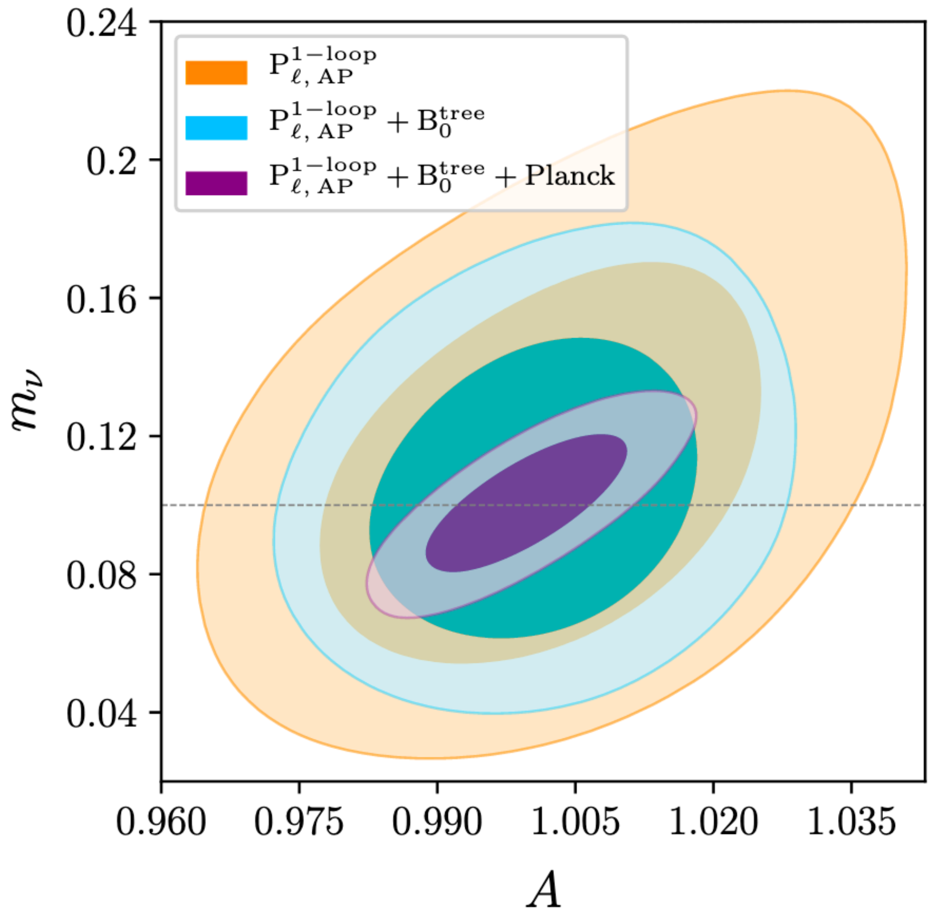
Philcox+ 2020a

What's Next?

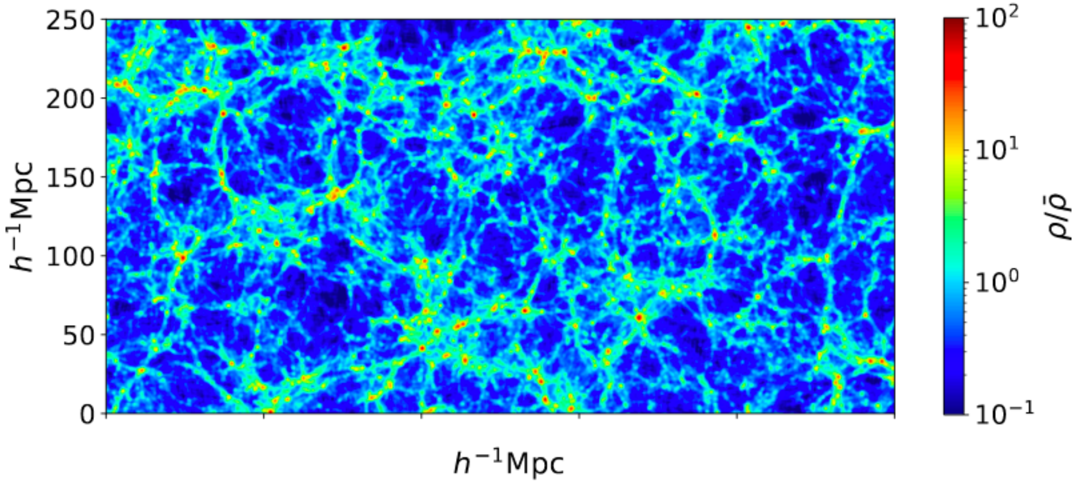
- Other EFT analyses are possible:
  - Tree-level **Bispectrum** [d'Amico+19]
  - One-loop **Bispectrum**
  - Two-loop **Power Spectrum**

and many more…

EFT Forecasts for Euclid

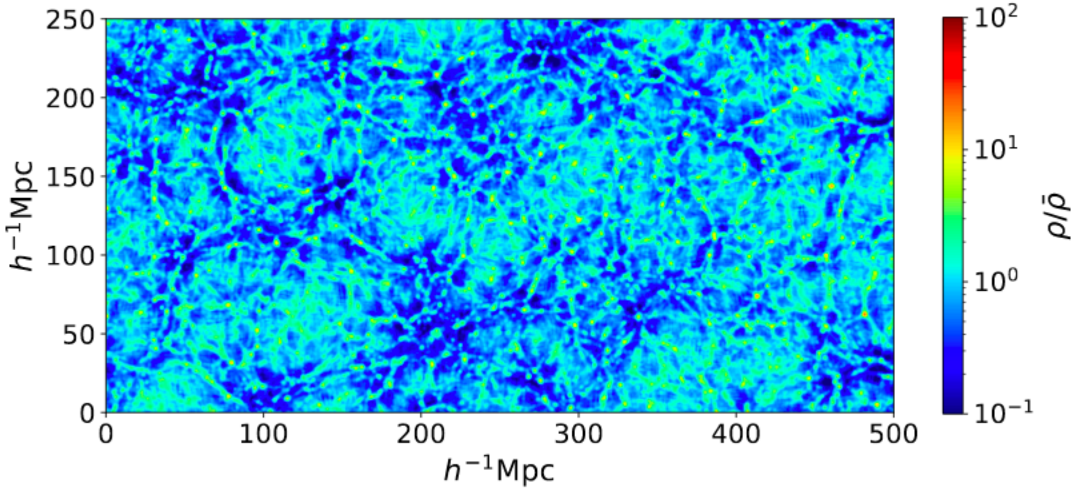


Chudaykin & Ivanov 19



Density Field

???



Marked Density Field

Massara+20

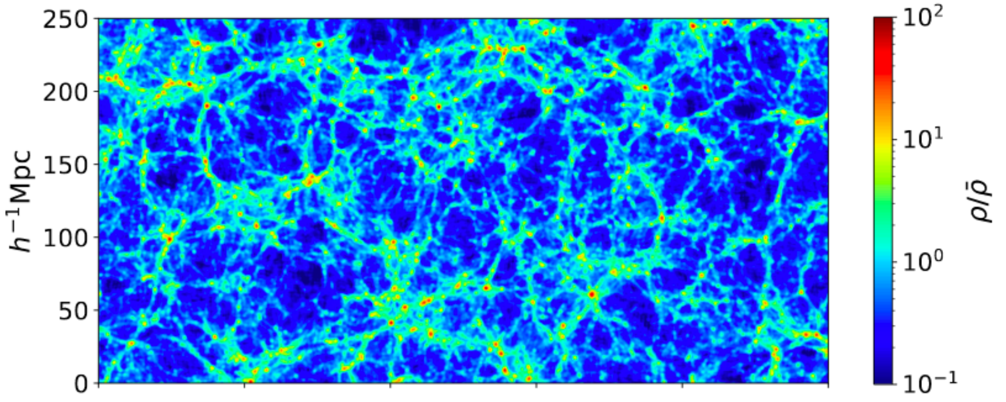
III. Alternative Density Statistics

Beyond the Density Field?

- Most conventional statistics involve the n-point correlation functions of the **overdensity** field, δ

- However, we know that **low-density regions** carry a lot of cosmological information, and contribute little to δ [e.g. Pisani+19]

- Various alternative statistics have been proposed:
  - Reconstructed Density Fields [e.g. Eisenstein+07]
  - Log-normal Transforms [Neyrinck+09, Wang+11]
  - Gaussianized Density Fields [Weinberg 92, Neyrinck+17]
  - **Marked Density Fields** [Stoyan 84, White 16, Massara+20]



Overdensity Field

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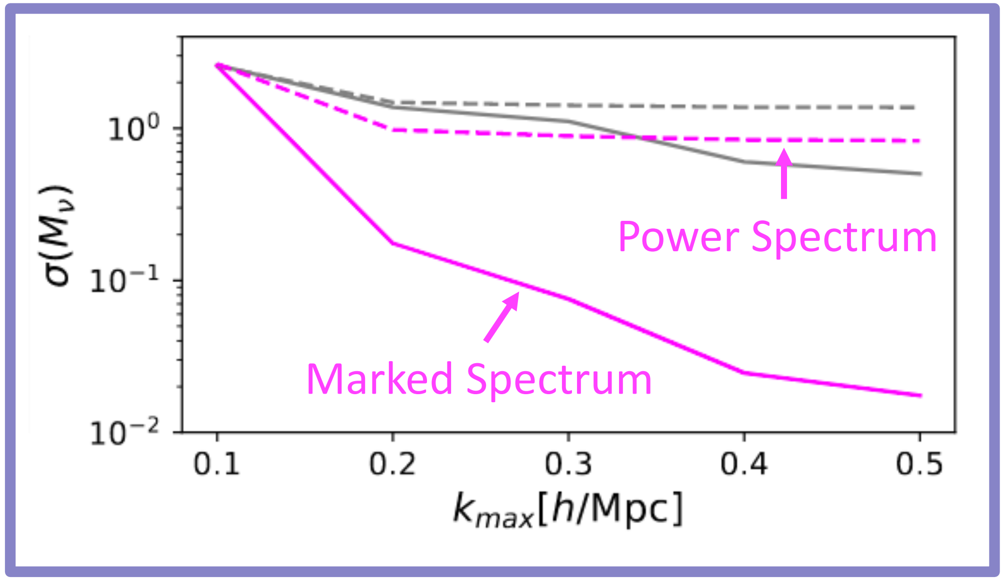


Fisher Matrix Constraints on Neutrino Mass

White 16, Massara+20

The Marked Density Field

- Shown to give **strong** constraints on cosmology, especially on **neutrinos** [Massara+20]

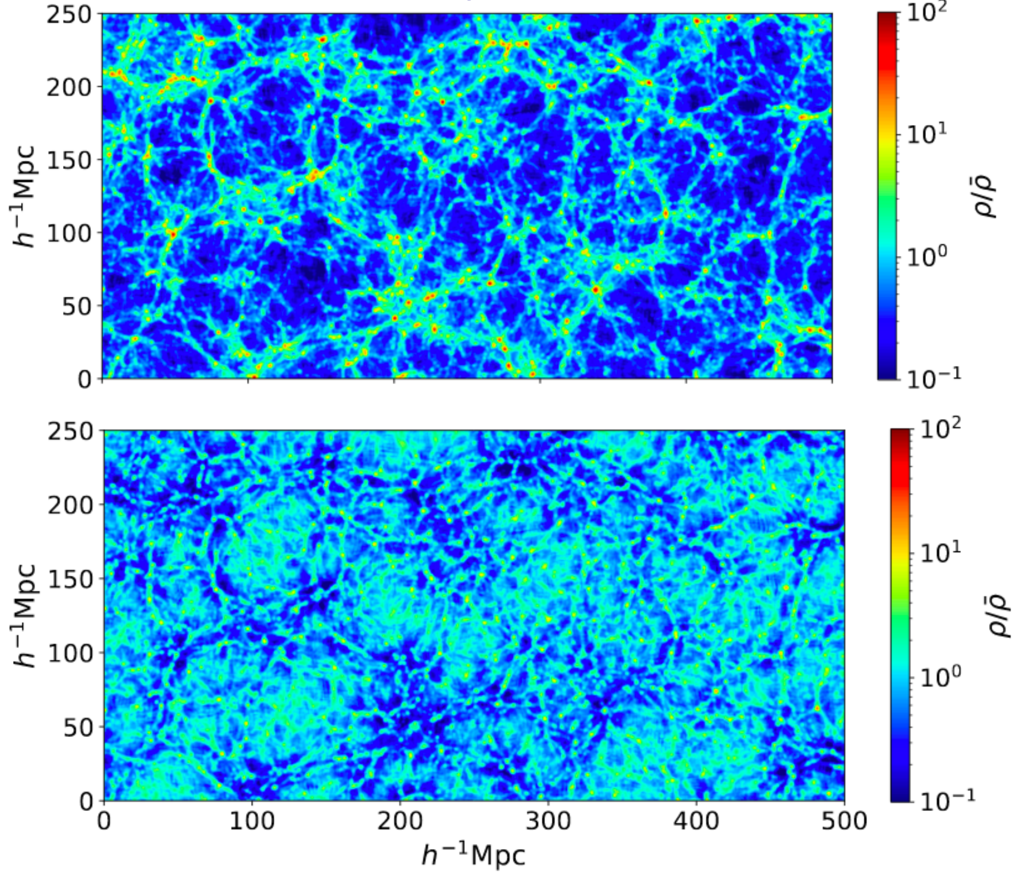
- Defined as a **local-overdensity** weighted density field:

$$m(\mathbf{x}) = \left(\frac{1+\delta_s}{1+\delta_s+\delta_R(\mathbf{x})}\right)^p$$

$$\rho_M(\mathbf{x}) = m(\mathbf{x})n(\mathbf{x}) = m(\mathbf{x})\bar{n}\left[1+\delta(\mathbf{x})\right]$$

where $p > 0$ upweights low-density regions.

Density Field



Marked Density Field

EFT of the Marked Density Field

- Start by Taylor expanding the mark $m(\mathbf{x})$:

$$\delta_M(\mathbf{x}) = \frac{\rho_M(\mathbf{x})-\bar{\rho}_M}{\bar{\rho}_M} = \frac{1}{\bar{m}}\left[1+\delta(\mathbf{x})\right]\left[1 - C_1\delta_R(\mathbf{x}) + C_2\delta_R^2(\mathbf{x}) - C_3\delta_R^3(\mathbf{x})\right] - 1 + \mathcal{O}\left(\delta^4\right)$$

Marked Overdensity

Smoothed Overdensity

- Now create a perturbative solution:

$$\delta_M(\mathbf{x}) \equiv \left(\frac{1}{\bar{m}} - 1\right) + \frac{1}{\bar{m}}\left(\delta_M^{(1)}(\mathbf{x}) + \delta_M^{(2)}(\mathbf{x}) + \delta_M^{(3)}(\mathbf{x}) + \delta_M^{(ct)}(\mathbf{x})\right)$$

- Each order depends on $\delta^{(n)}(\mathbf{x})$ **and** $\delta_R^{(n')}(\mathbf{x})$, and we can write down coupling kernels:

$$\delta_M^{(n)}(\mathbf{k}) = \int_{\mathbf{p}_1\ldots\mathbf{p}_n} H_n(\mathbf{p}_1,\ldots,\mathbf{p}_n)\delta^{(1)}(\mathbf{p}_1)\ldots\delta^{(1)}(\mathbf{p}_n)\delta_D(\mathbf{p}_1+\ldots+\mathbf{p}_n-\mathbf{k})$$

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EFT of the Marked Density Field

- This gives a simple theory:

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

Linear Theory   1-loop SPT   Counterterms

- Since the mark only involves the **smoothed** density field, the new terms are well-behaved for large loop momenta

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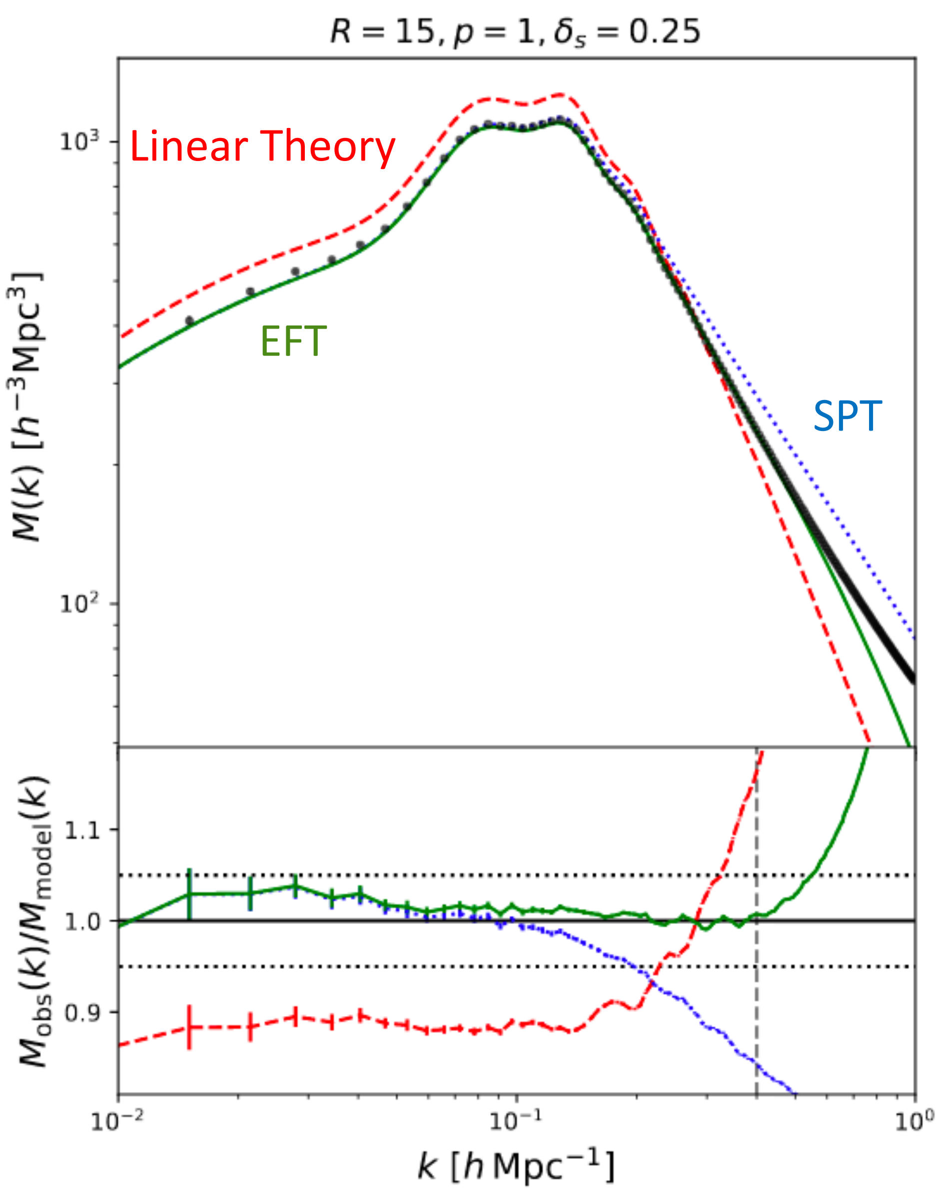
Results

- At moderate redshift, and intermediate smoothing, EFT works well!

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

- We have **big contributions** from one-loop terms at large-scales.



(b) $z = 1$

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Results

- At moderate redshift, and intermediate smoothing, EFT works well!
- This theory is unusual:
  - Linear theory fails on **all** scales
  - At low redshifts, EFT fails on **all** scales
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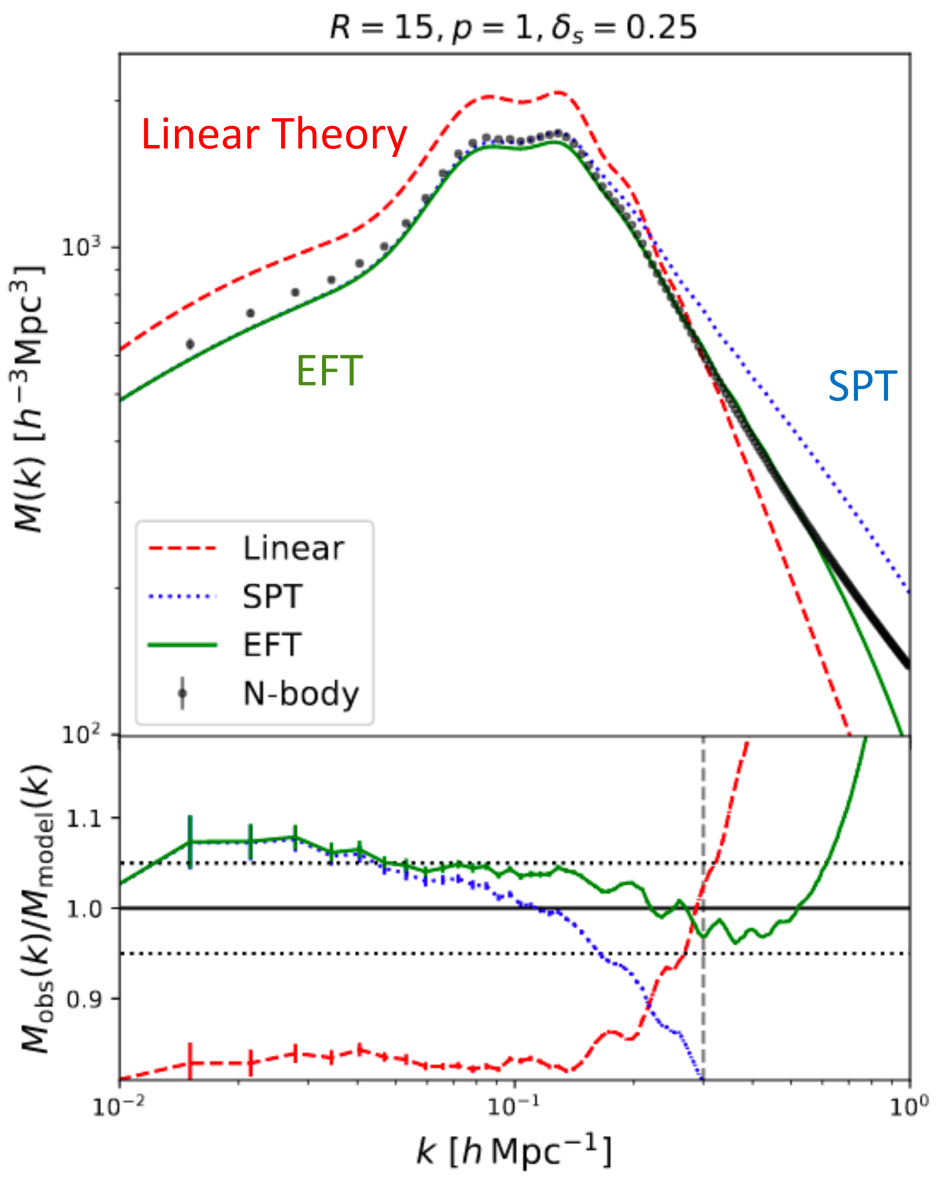

(a) $z = 0.5$

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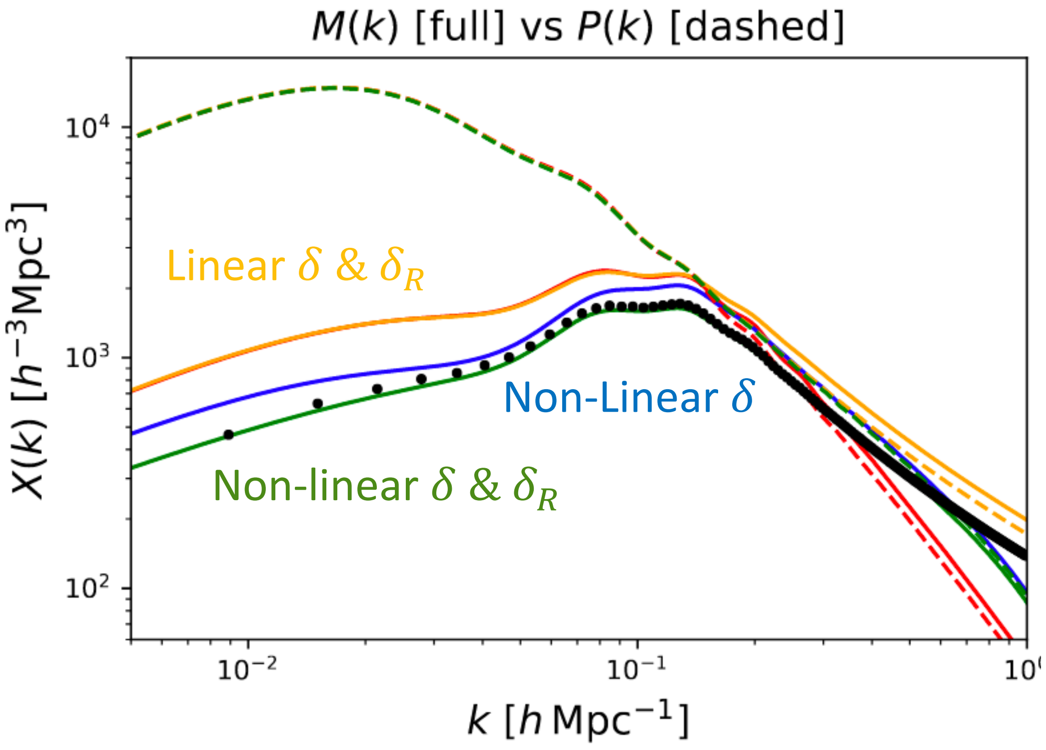
What can we learn from EFT?

- The EFT model allows us to understand where the **cosmological information** is coming from!
- The mark **suppresses** linear terms on large 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



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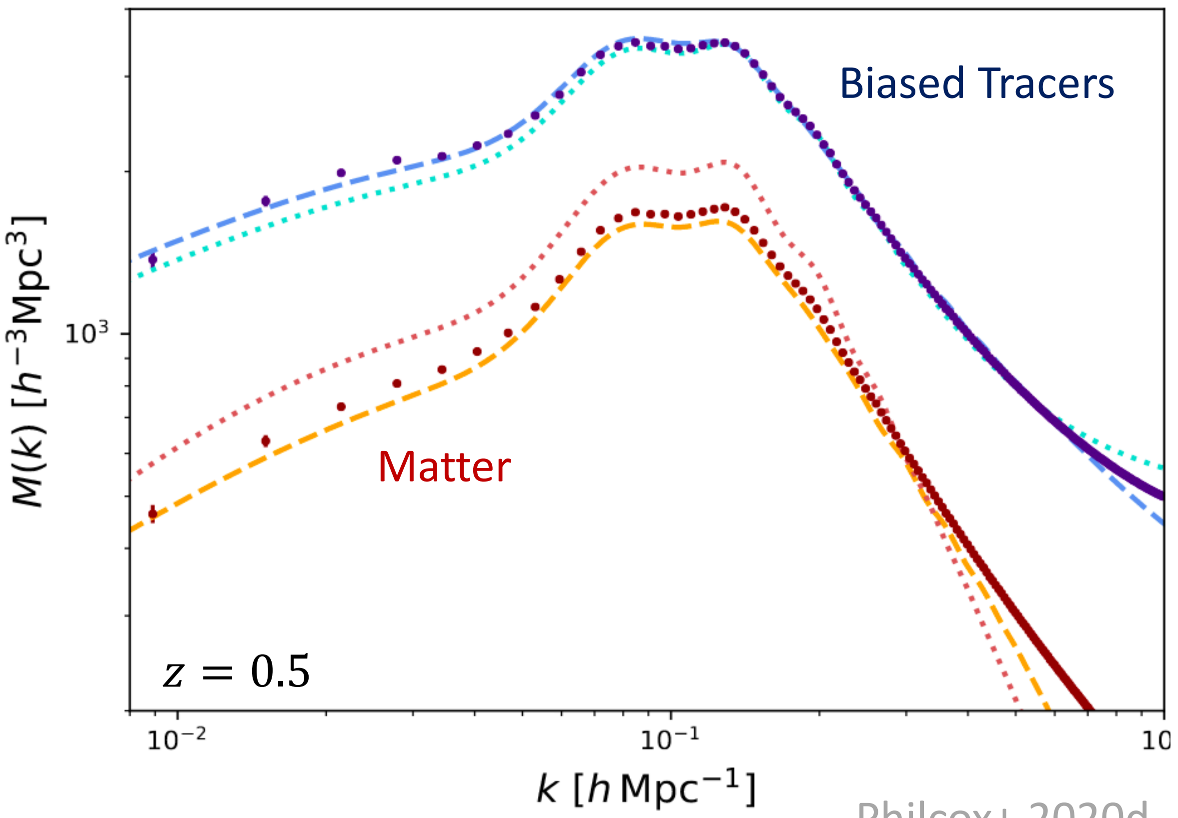
What's Next for the Mark?

- Before we can apply it to data, we must consider **biased tracers**, and **redshift-space.**
- Preliminary results for bias look promising:
- But does it still have constraining power?
- And do we couple in **baryonic effects?**



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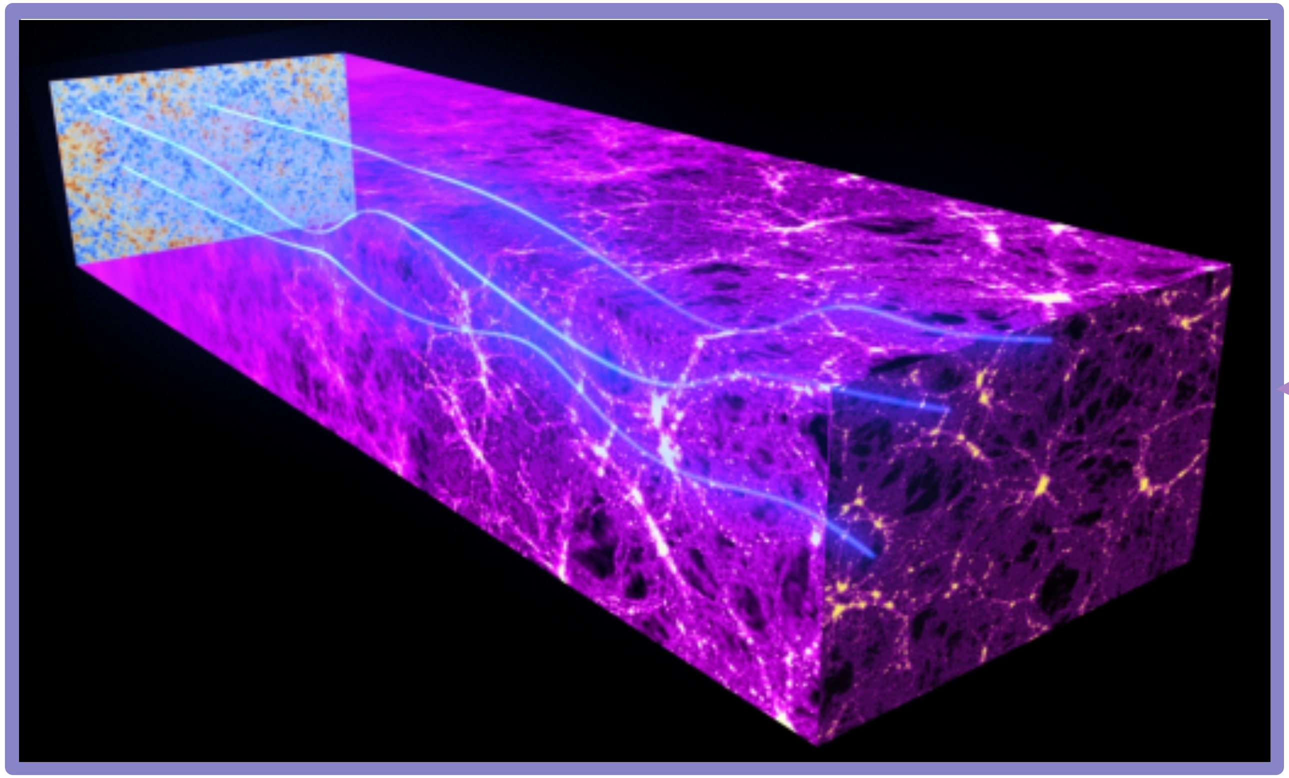

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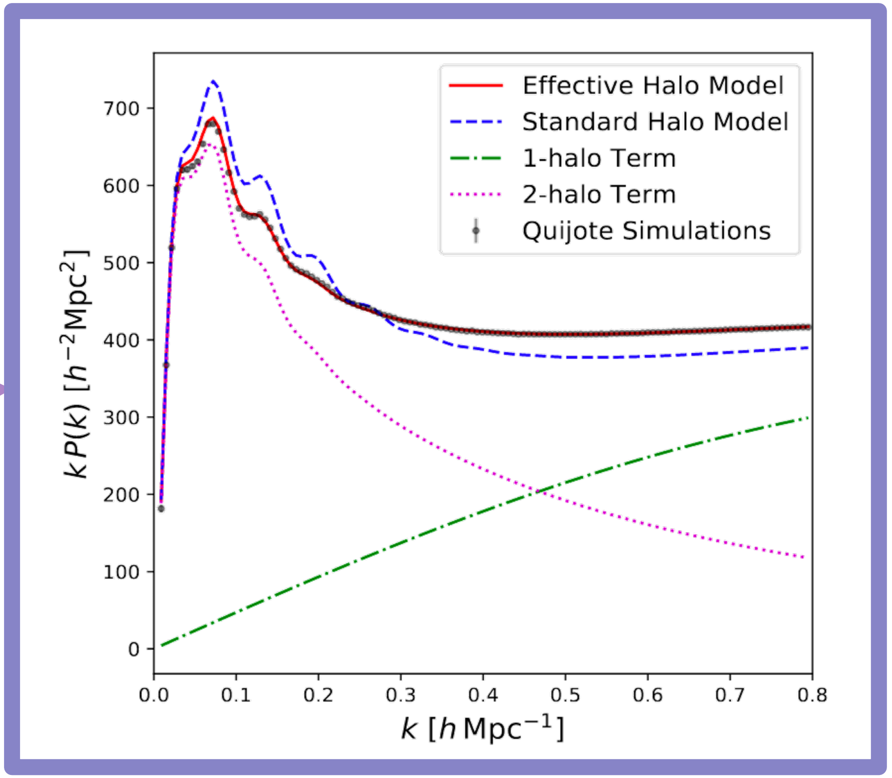

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IV. EFT for Weak Lensing?

Weak Lensing

- Weak lensing spectra are just integrals over the matter power spectrum:

$$C_\ell^{ij} = \int dz\, \frac{c}{H(z)} \frac{W^i(\chi(z))W^j(\chi(z))}{\chi^2(z)} \times P\left(k = \frac{\ell+1/2}{\chi(z)}, z\right)$$

where $\chi(z)$ is comoving distance, and W^i, W^j are probe-specific window functions.

- So we can compute an EFT for weak lensing by integrating the matter EFT?

- It's **not** that simple. C_ℓ gets contributions from a **broad** range of scales, so we need a model for P(k) for *all* k.

See also Foreman & Senatore 15

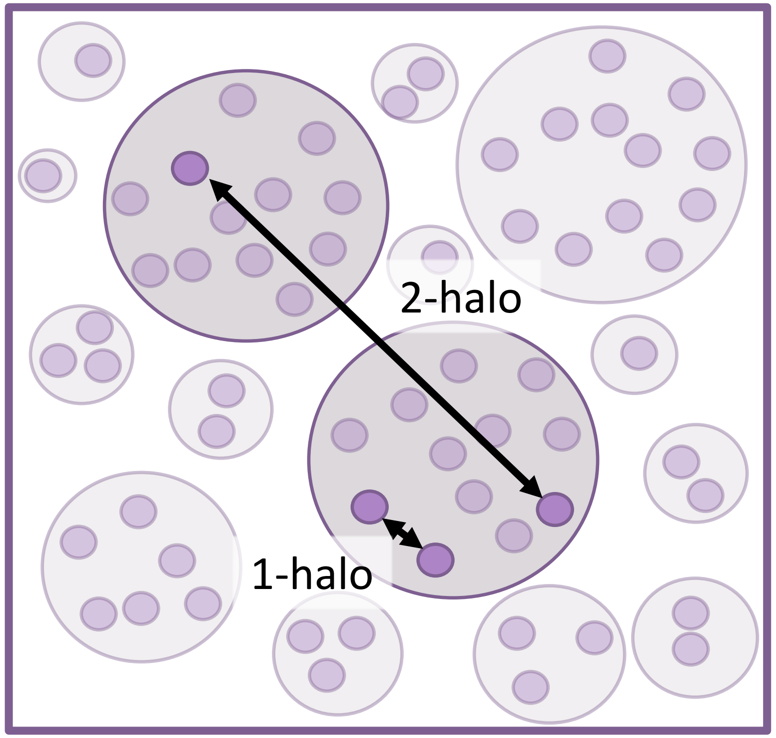
The Effective Halo Model: A Model for P(k)

- This combines the matter **EFT** with the **halo model**.

- In the **usual** halo model:

$$P(k) = \overbrace{\left[I_1^1(k)\right]^2 P_{\mathrm{L}}(k)}^{\text{2-halo}} + \overbrace{I_2^0(k)}^{\text{1-halo}}$$

Mass Integrals   Linear Power



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The Effective Halo Model: A Model for P(k)

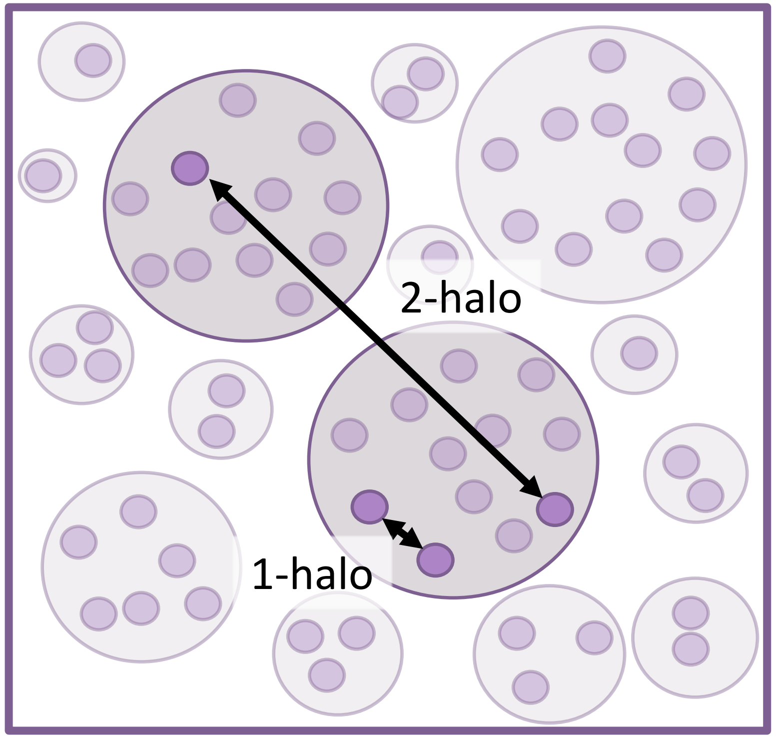
- This combines the matter **EFT** with the **halo model**.

- In the **effective** halo model:

Smoothing Function

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

Mass Integrals EFT Power



EffectiveHalos.rtfd.io

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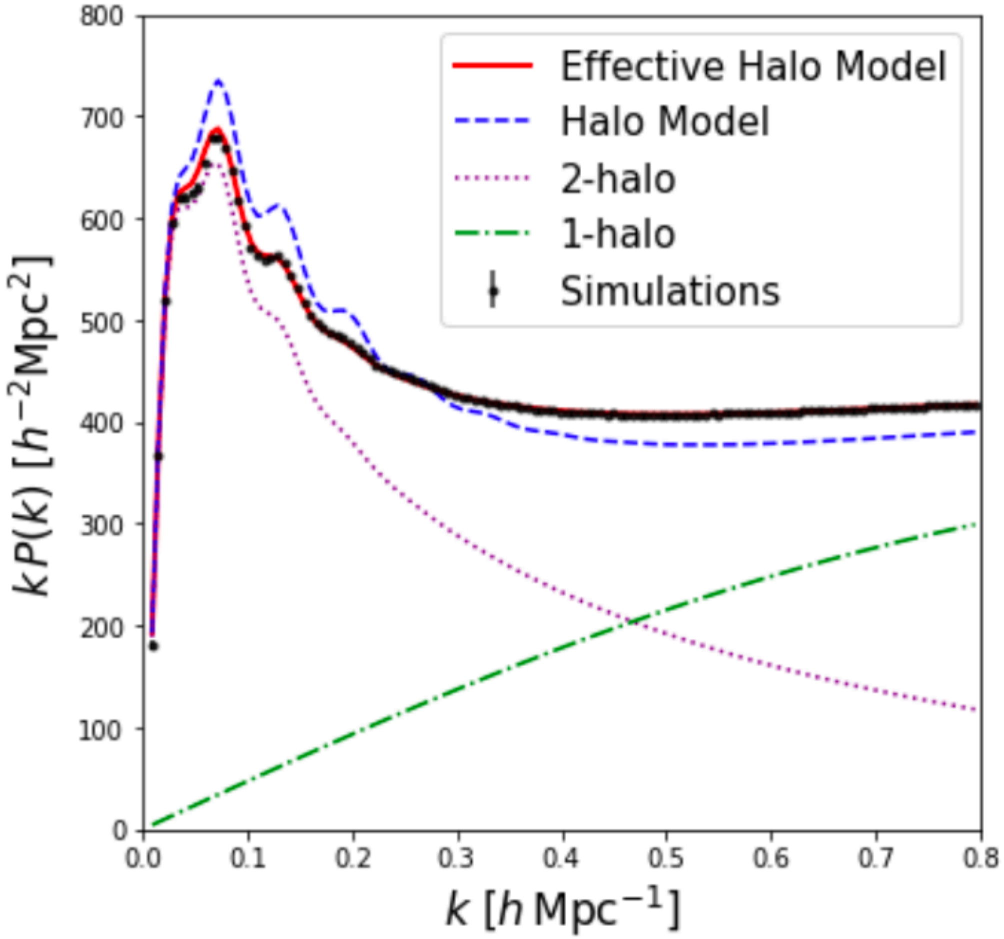
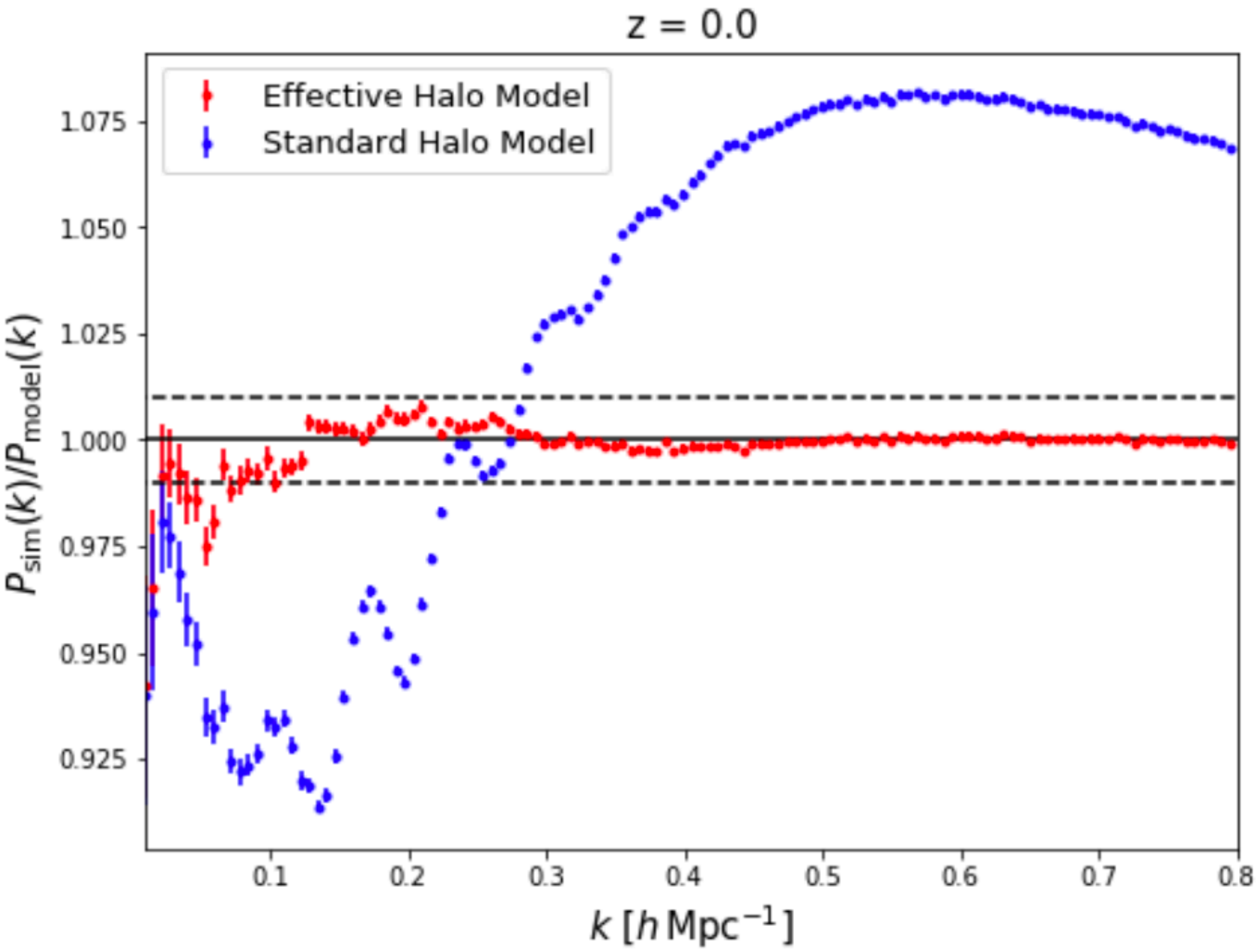
Power Spectra



Ratio of Simulation and Model Power



Using 100 N-body simulations from Quijote [Villaescusa-Navarro+19]

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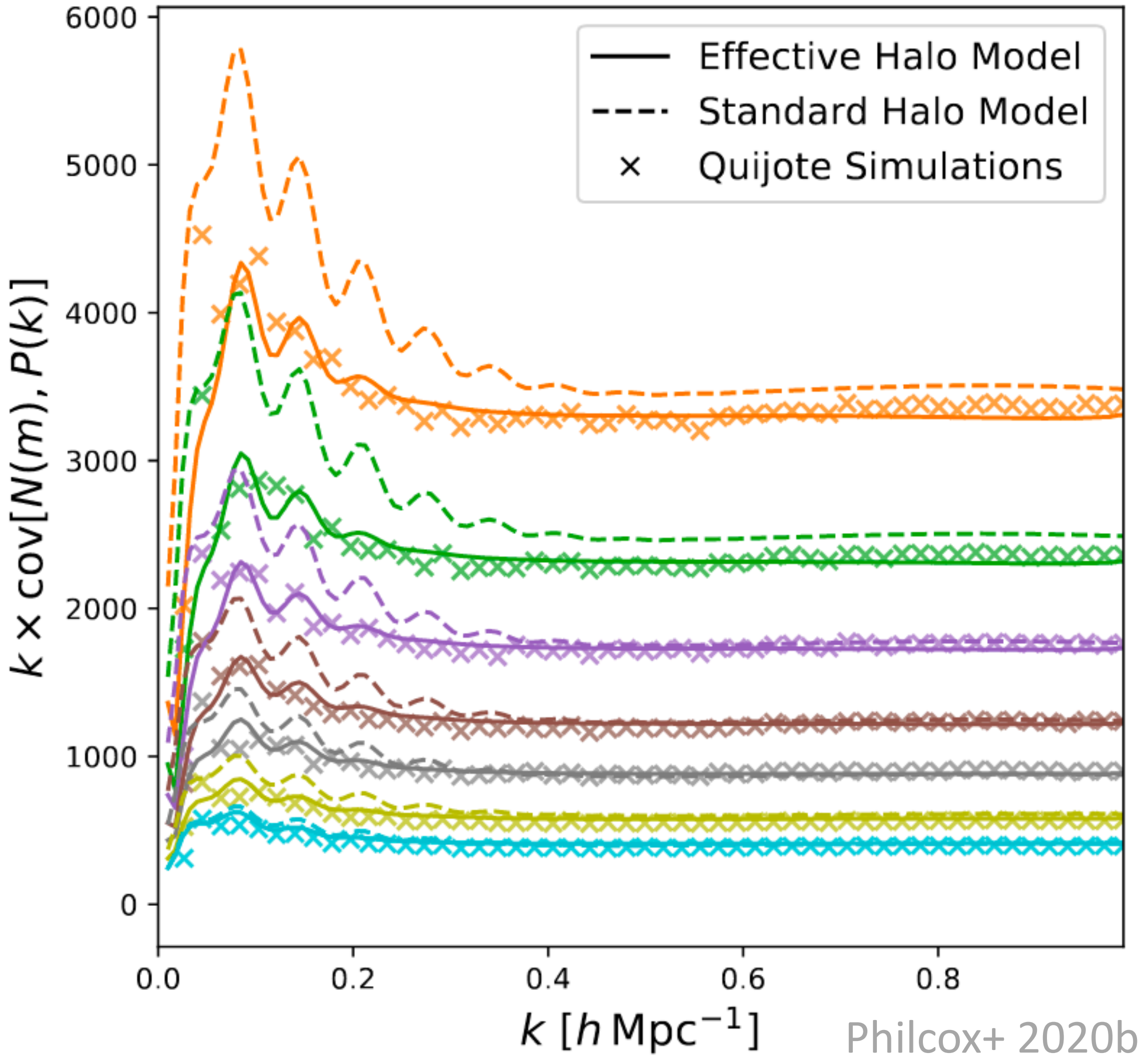
Applications of EHM?

- 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 will be used to compute projected spectra e.g.
  - **Weak Lensing** (WL)
  - Joint analysis of WL and **thermal SZ**

Covariance of Halo Counts and P(k)



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Conclusions

More questions?

Email ophilcox@princeton.edu

- The *Effective Field Theory of Large Scale Structure* provides **accurate** models for density correlators on **quasi-linear** scales

- It allows for **parameter inference** in galaxy **full-shape** analyses, shedding light on the H_0 tension

- It can be applied to **alternative** density statistics, e.g. the **marked** power spectrum and used to **understand** them

- By combining EFT with the **halo model**, we will be able to construct models for projected statistics e.g. weak lensing