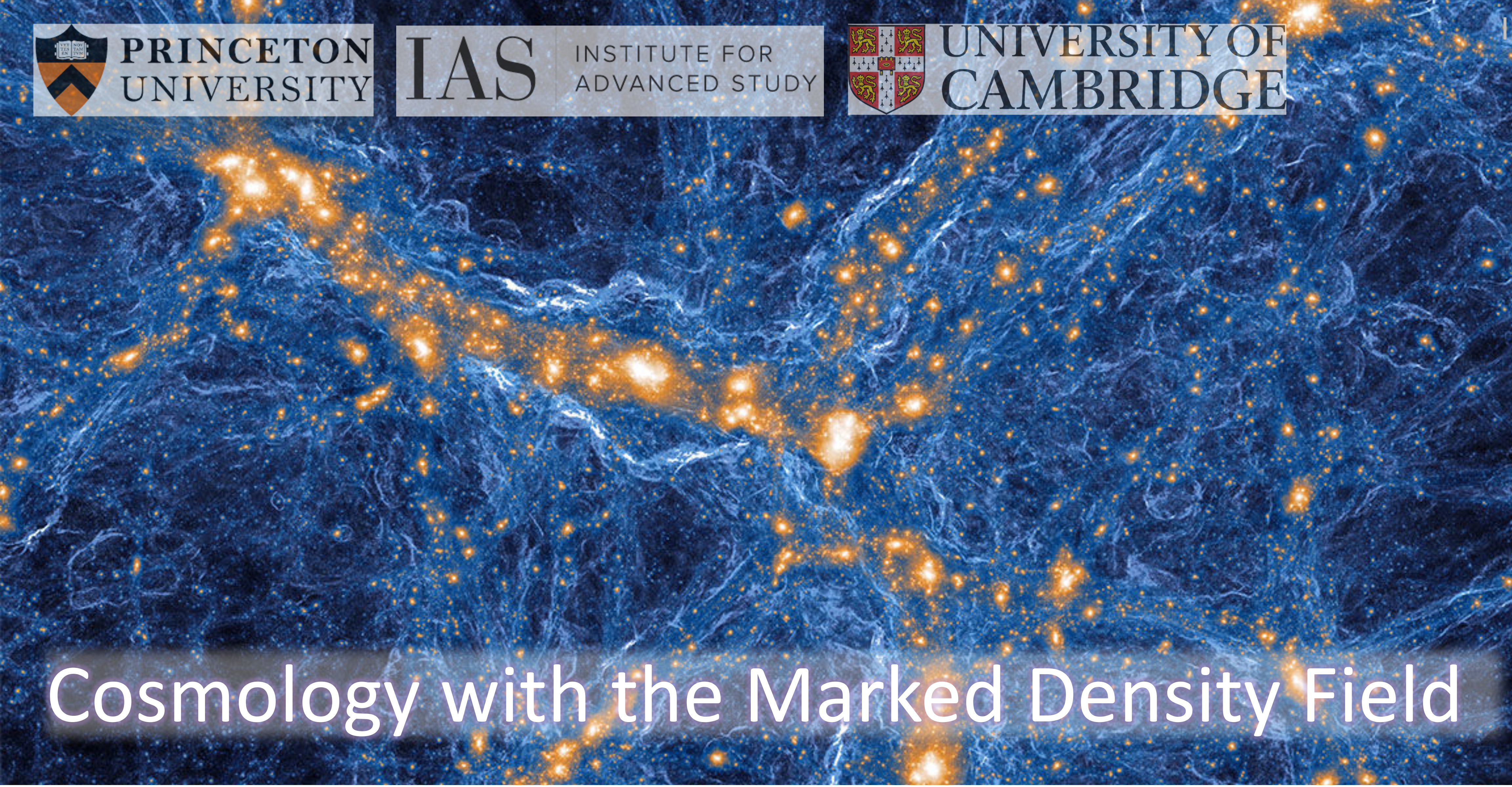


Cosmology with the Marked Density Field

Oliver Philcox (Princeton)

Eisenstein Group Meeting, CfA

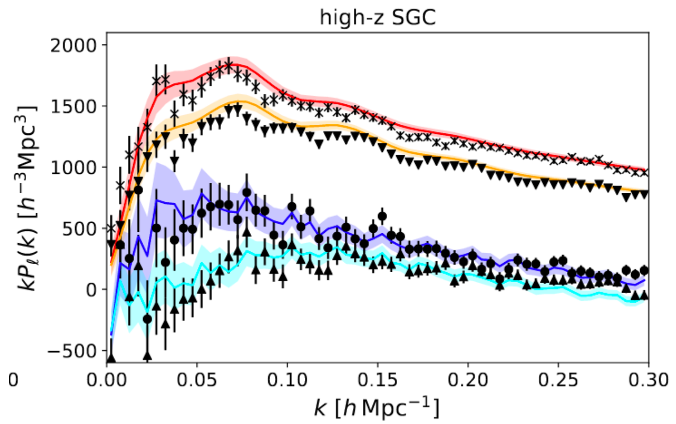
Based on:

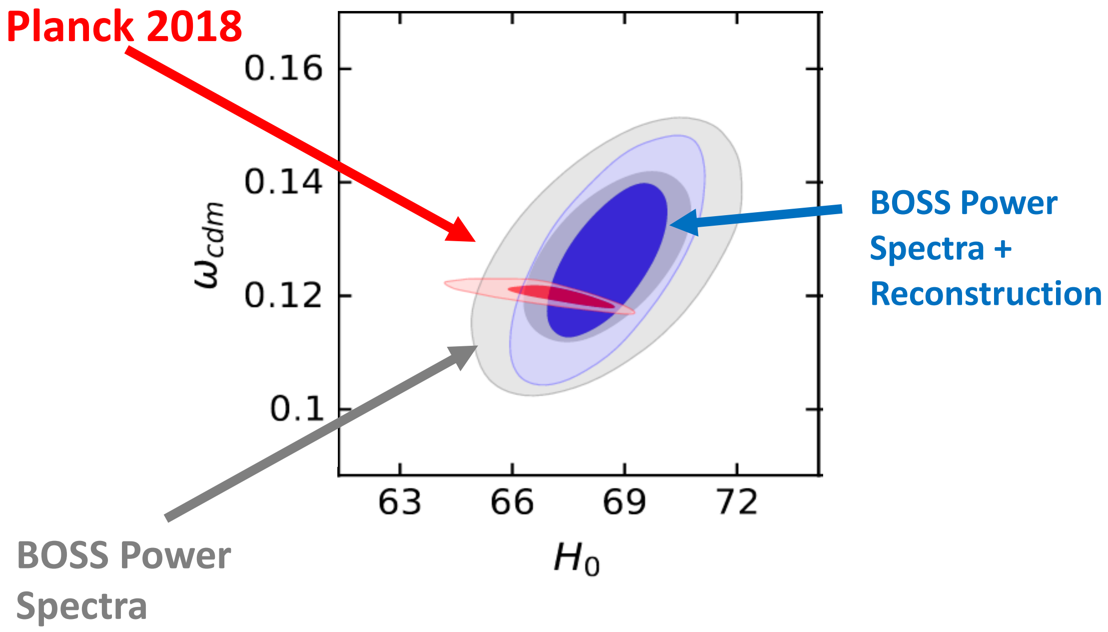
- *Philcox, Massara & Spergel (2020, arXiv: 2004.09515)*
- *Philcox, Aviles & Massara (in prep., arXiv: 2010.XXXXX)*

Cosmology from Large Scale Structure

- Large Scale Structure gives **comparable** constraints to the **CMB**
- Major probe: statistics of galaxy positions from spectroscopic surveys
- Usually measure galaxy **power spectra**, which encodes:
  - **B**aryon **A**coustic **O**scillations
  - Equality Scale

And thus $\Omega_m, \omega_b, n_s, H_0, \sum m_\nu$, etc.





Philcox, Ivanov, Simonovic, Zaldarriaga'20

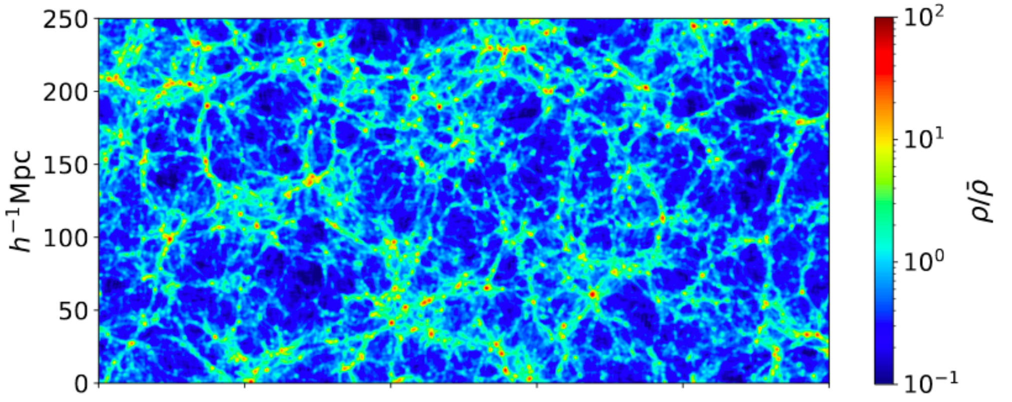
Beyond the Density Field

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

- If the Universe is Gaussian, the power spectrum of δ contains **all** cosmological information

- For a **non-Gaussian** universe, **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

Massara+20

The Marked Density Field

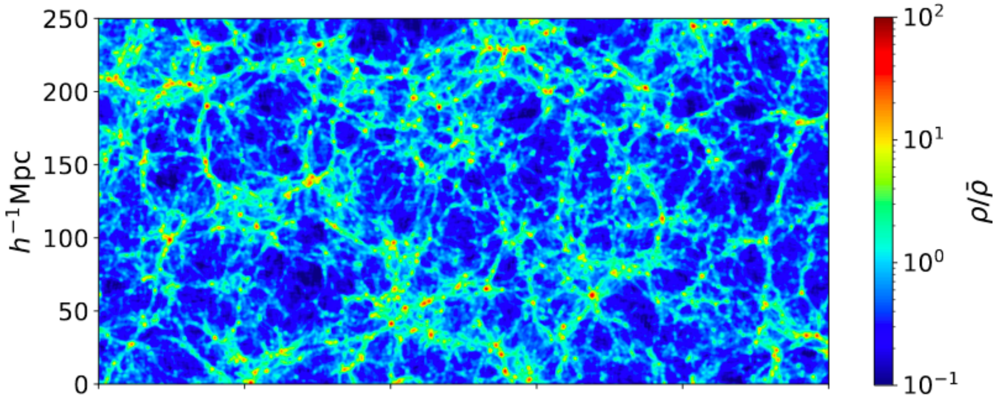
- Define a new density field by **weighting** by the **mark**

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

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

depending on **smoothed** overdensity $\delta_R(\mathbf{x})$

- Controlled by **mark parameters:**
  - Exponent p ($p > 0$ to upweight low-density regions)
  - Cut-off δ_s
  - Smoothing scale, R



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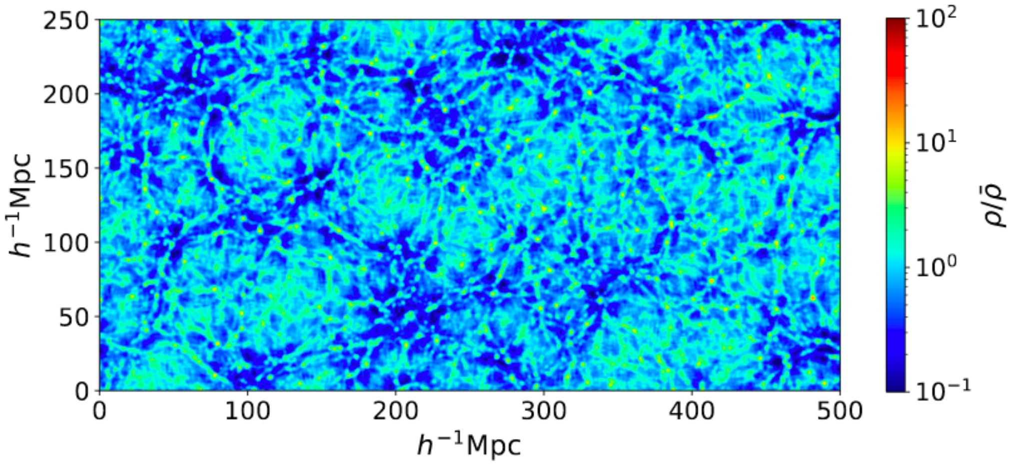

Marked Density Field

Massara+20

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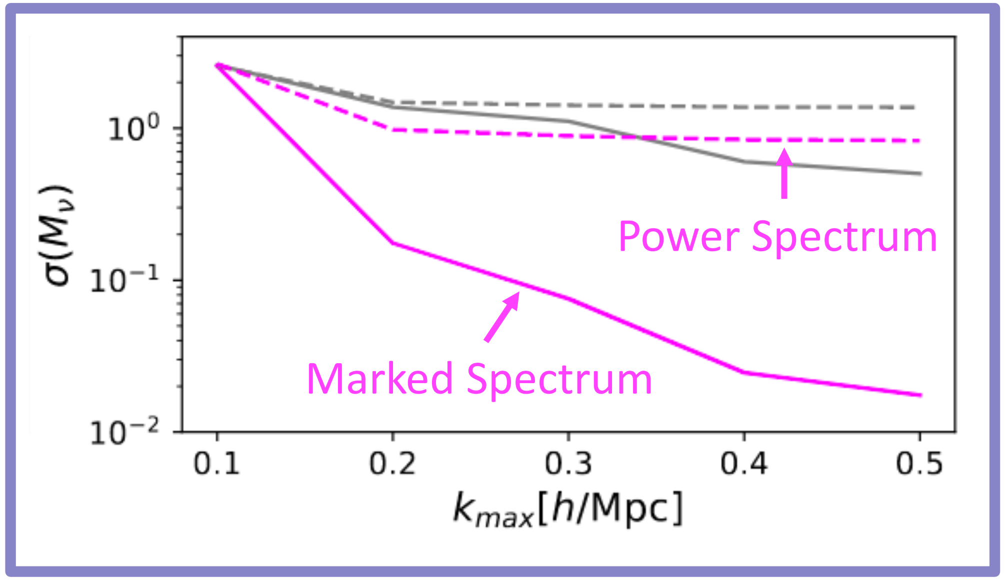
- Shown to give a **significant** increase in cosmological information for **real-space matter**, particularly:
  - **Neutrino masses** [Massara+20]
  - **Modified gravity** [White 16]



Fisher Matrix Constraints on Neutrino Mass

Massara+20

EFT of LSS: A Lightning Introduction

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

- Treat the Universe as an **imperfect** fluid, including **viscosity** etc.
- Expansion variable: **smoothed** overdensity field $\delta_\Lambda(\boldsymbol{x})$

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

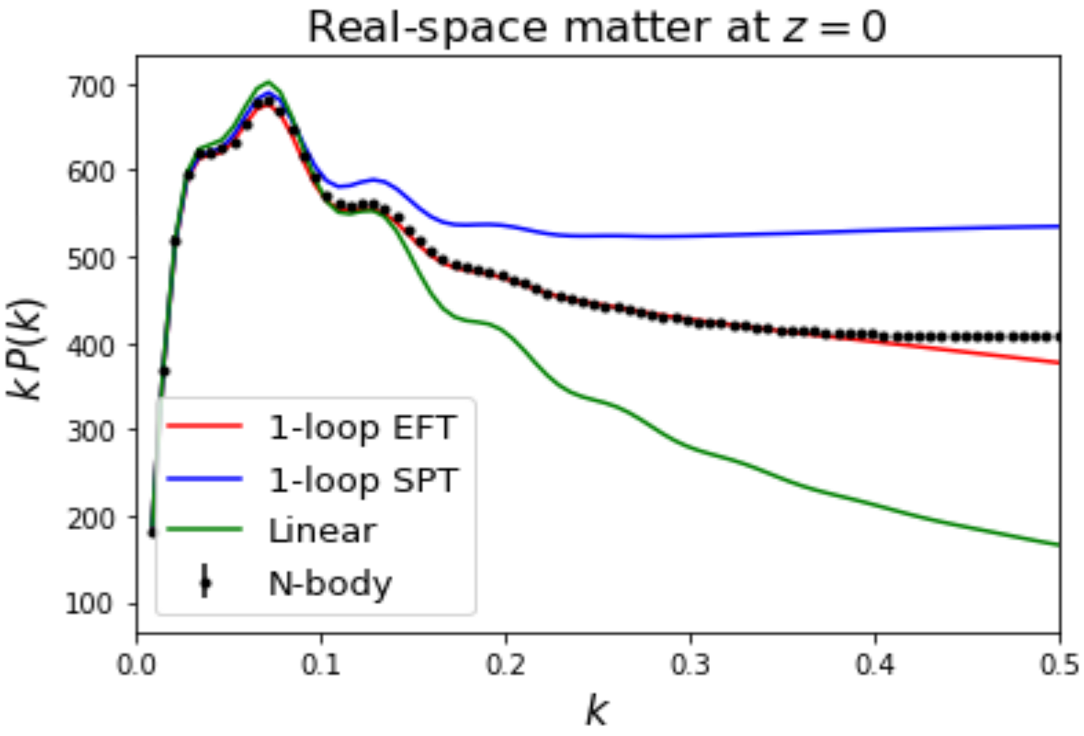
Theory is an **expansion** in terms of non-Gaussian **loop** corrections:

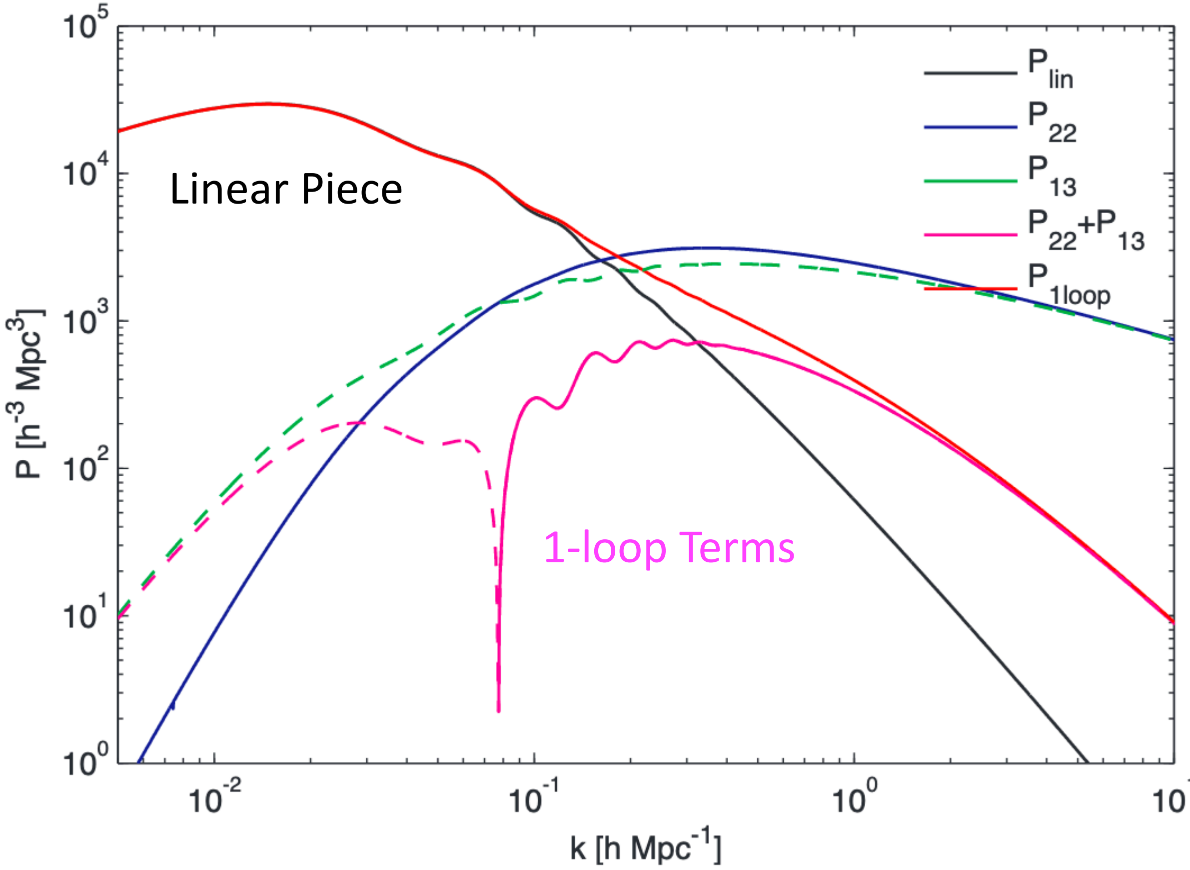
$$P(k) = \underbrace{P_{\rm lin}(k)}_{\text{Linear}} + \underbrace{P_{22,\Lambda}(k) + 2P_{13,\Lambda}(k)}_{\text{1-loop }(\sim P_L^2(k))} - \underbrace{2c_{s,\Lambda}^2 k^2 P_{\rm lin}(k)}_{\text{Counterterm}}$$

Counterterm encodes **backreaction** of **small-scale** physics on **large-scale** modes via **free parameter** $c_{s,\Lambda}^2$

EFT of LSS: Predicting P(k) for Matter

- EFT provides **accurate** models of the **matter** power spectrum up to wavenumbers $k \approx 0.15h/\mathrm{Mpc}$ at $z = 0$





EffectiveHalos & Baldauf Adv. Cosm

EFT of LSS: Predicting M(k) for Matter

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

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

- 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:

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

- This gives a straightforward 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 ($\sim P_L(k)$)

1-loop ($\sim P_L^2(k)$)

Counterterms ($\sim k^2 P_L(k)$)

Philcox+20

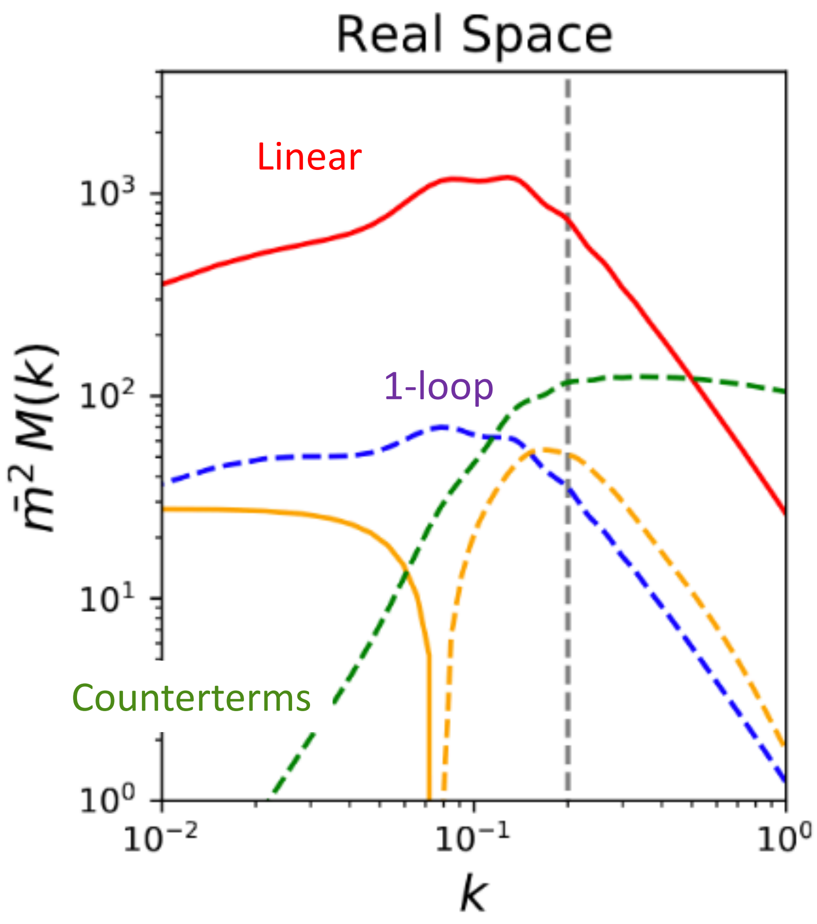
EFT of LSS: Predicting M(k) for Matter

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

Linear Theory ($\sim P_L(k)$)

1-loop SPT ($\sim P_L^2(k)$)

Counterterms ($\sim k^2 P_L(k)$)



- One-loop terms have unusual behavior on large-scales:
  - **Power Spectrum:** $P_{1-\text{loop}}(k) \sim k^2 P_L(k)$
  - **Marked Spectrum:** $M_{1-\text{loop}}(k) \sim P_L(k)$ or $M_{1-\text{loop}}(k) \sim \text{const.}$
- Higher loops do **not** decay on large scales

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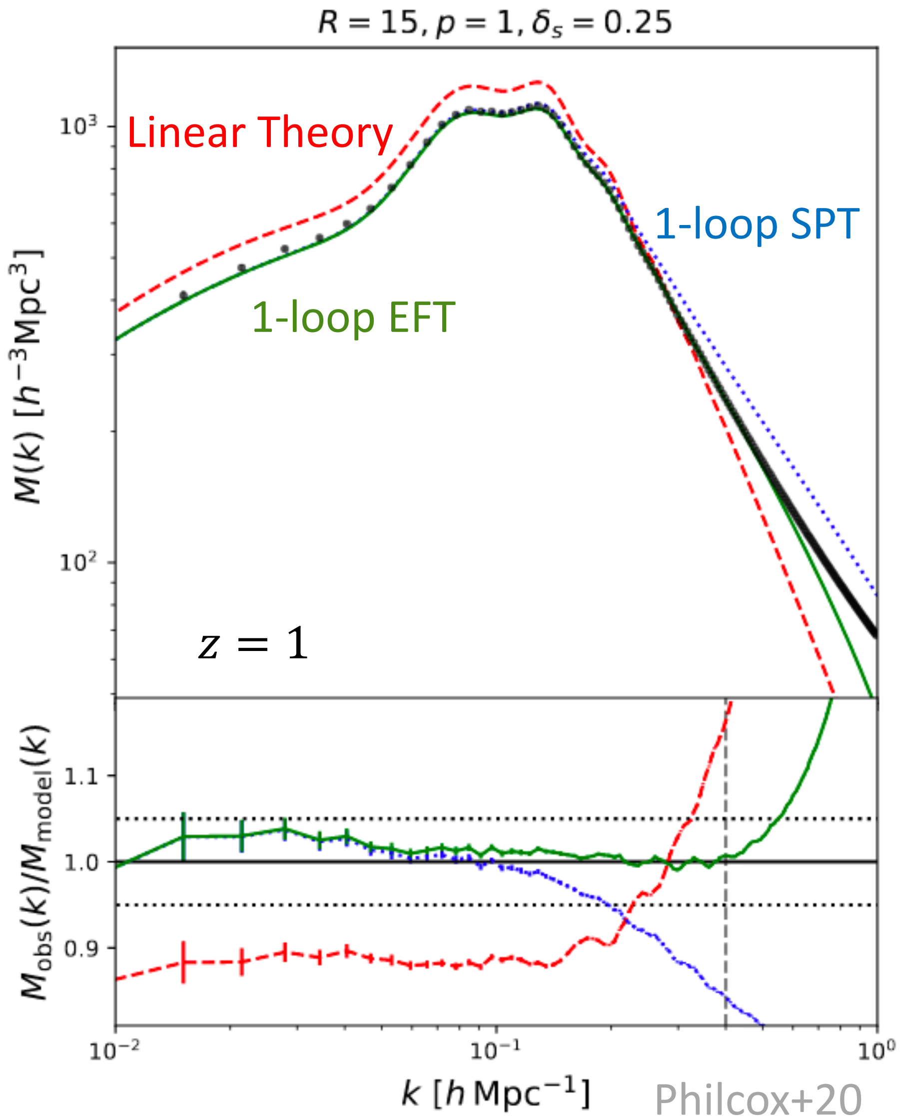
Results: Matter in Real Space

- Linear theory ($\sim \delta_L^2$) fails at **all** scales
  - The one-loop terms ($\sim \delta_L^4$) **cannot** be neglected

- The EFT model works quite well *iff*:
  - Redshift is not too low
  - Smoothing (to define the mark) is moderately large

- 1-loop EFT fails when **higher** order terms become non-negligible



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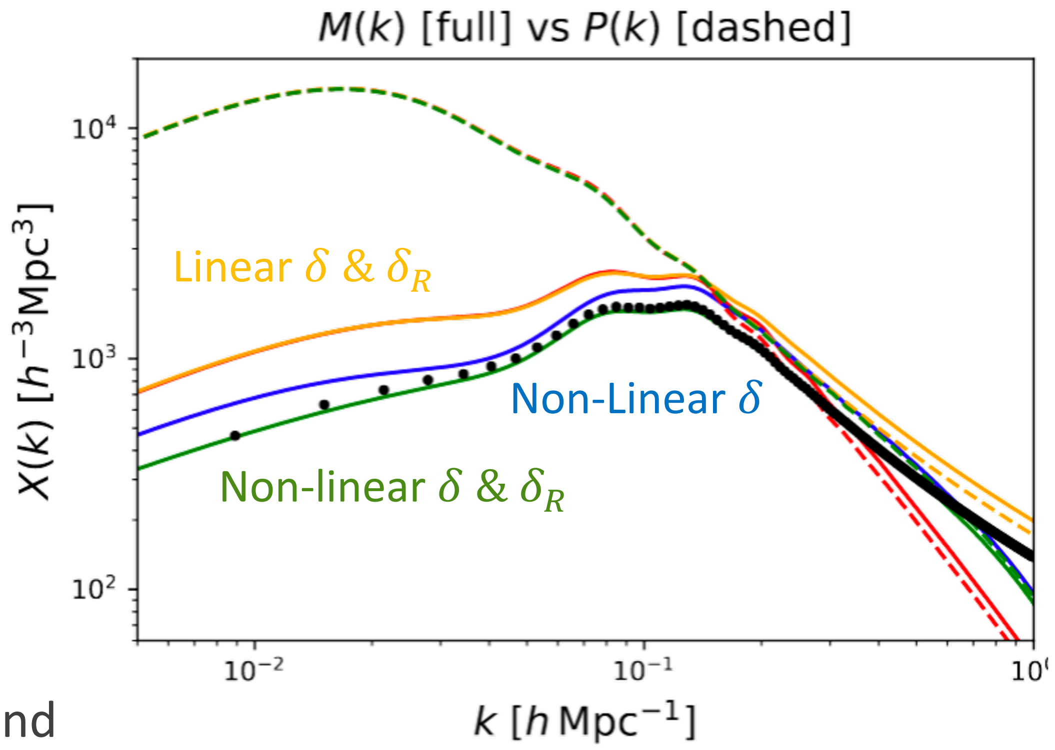
What can we learn from EFT?

- Higher order terms are sourced by **two** effects:
  1. Non-linearities in the **mark**
  2. Non-linearities in the **density field**

- **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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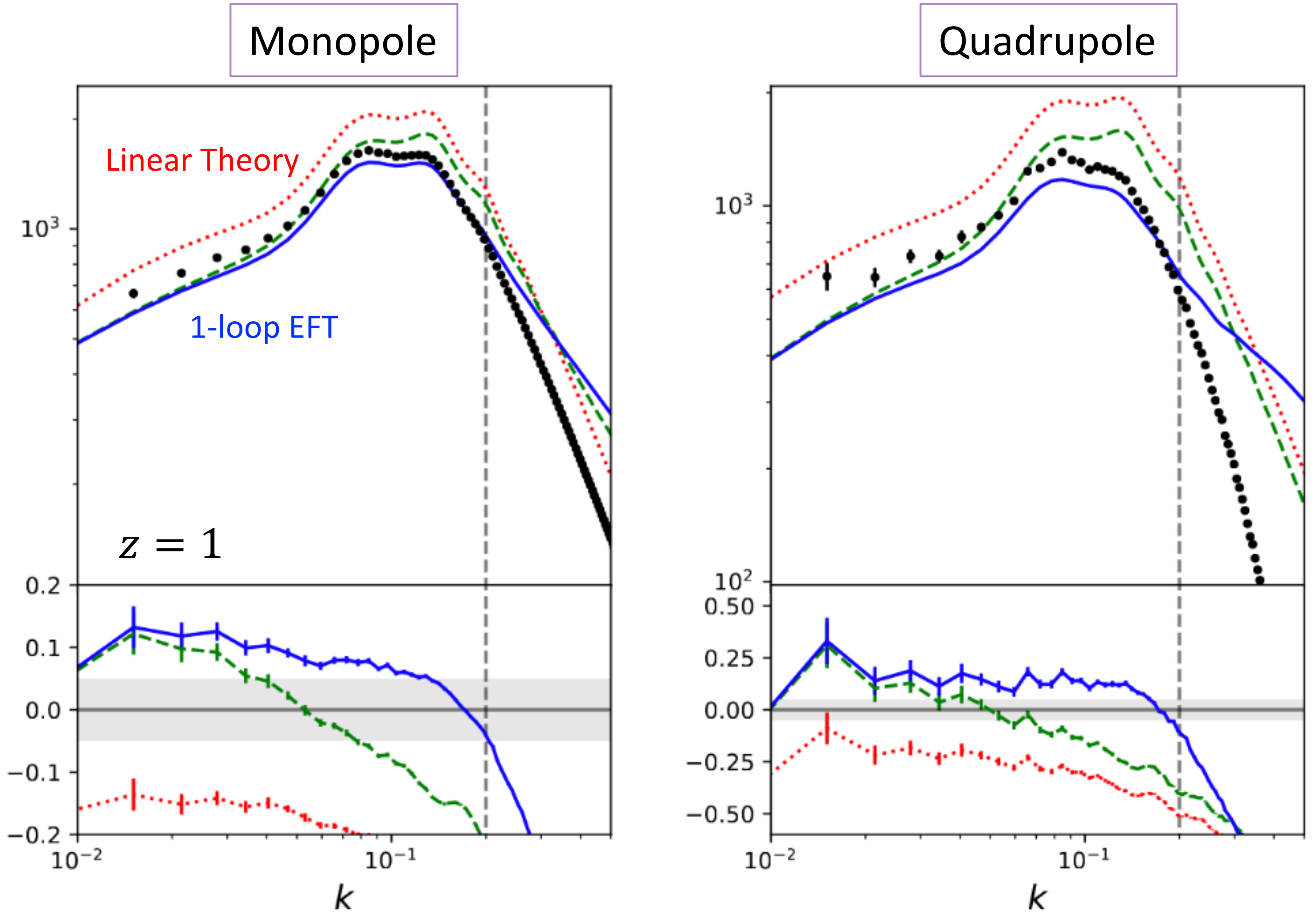
Results: Matter in Redshift Space

- We can extend the modeling to the **redshift-space** multipoles using EFT
- The theory includes:
  - **R**edshift-**S**pace **D**istortions
  - **F**ingers-**o**f-**G**od
- The Taylor series is **less** well convergent
  - **Higher-order terms are even more important!**



Philcox+ (in prep.)

How can we do better?

- Model breaks down due to significant contributions from higher-loop terms on large scales

- Can we **re-organize** the theory into a (formally) convergent series?

$$\bar{m}^2 M^{\mathrm{reorg}}(\boldsymbol{k}) = M^{r,0}(\boldsymbol{k}) + M^{r,1}(\boldsymbol{k}) + \ldots,$$

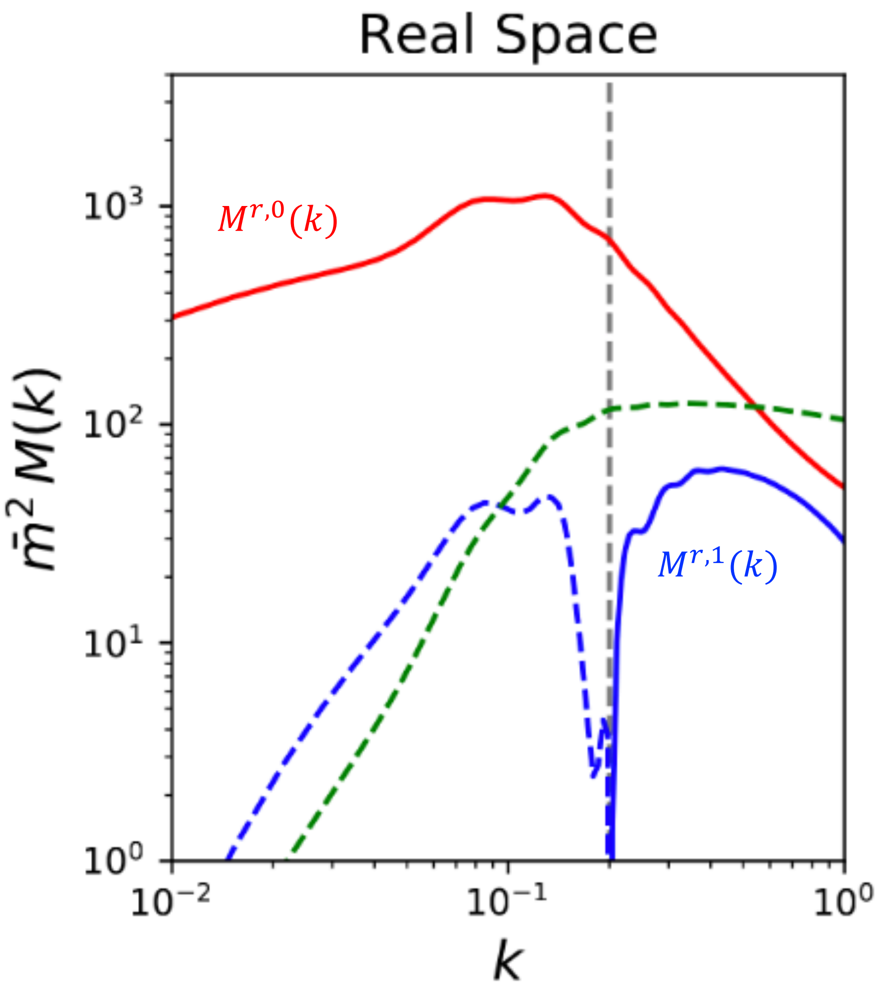
$\sim P_L(k)$ $\qquad$ $\sim k^2 P_L(k)$

- Now **all** large-scale information is encoded in $M^{r,0}$, but this depends on **all higher loops!**

- ***Ansatz:***

Free parameters

$$M^{r,0}(\boldsymbol{k})\big|_{\infty-\mathrm{loop}} \approx [C_0 - C_1 W_R(k)]^2 \left\{(\tilde{a}_0 + \tilde{a}_1\mu^2)P_L(k) + \tilde{b}_0\right\}$$



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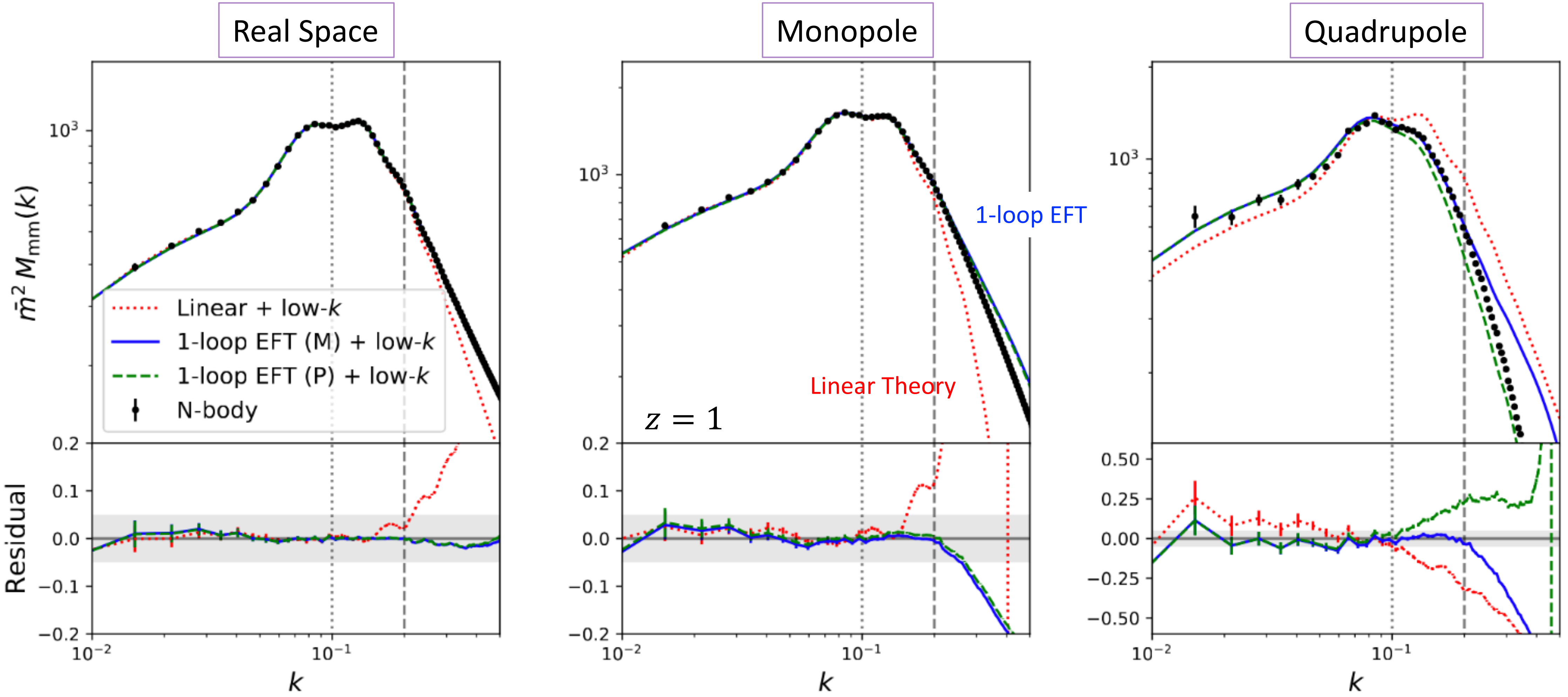
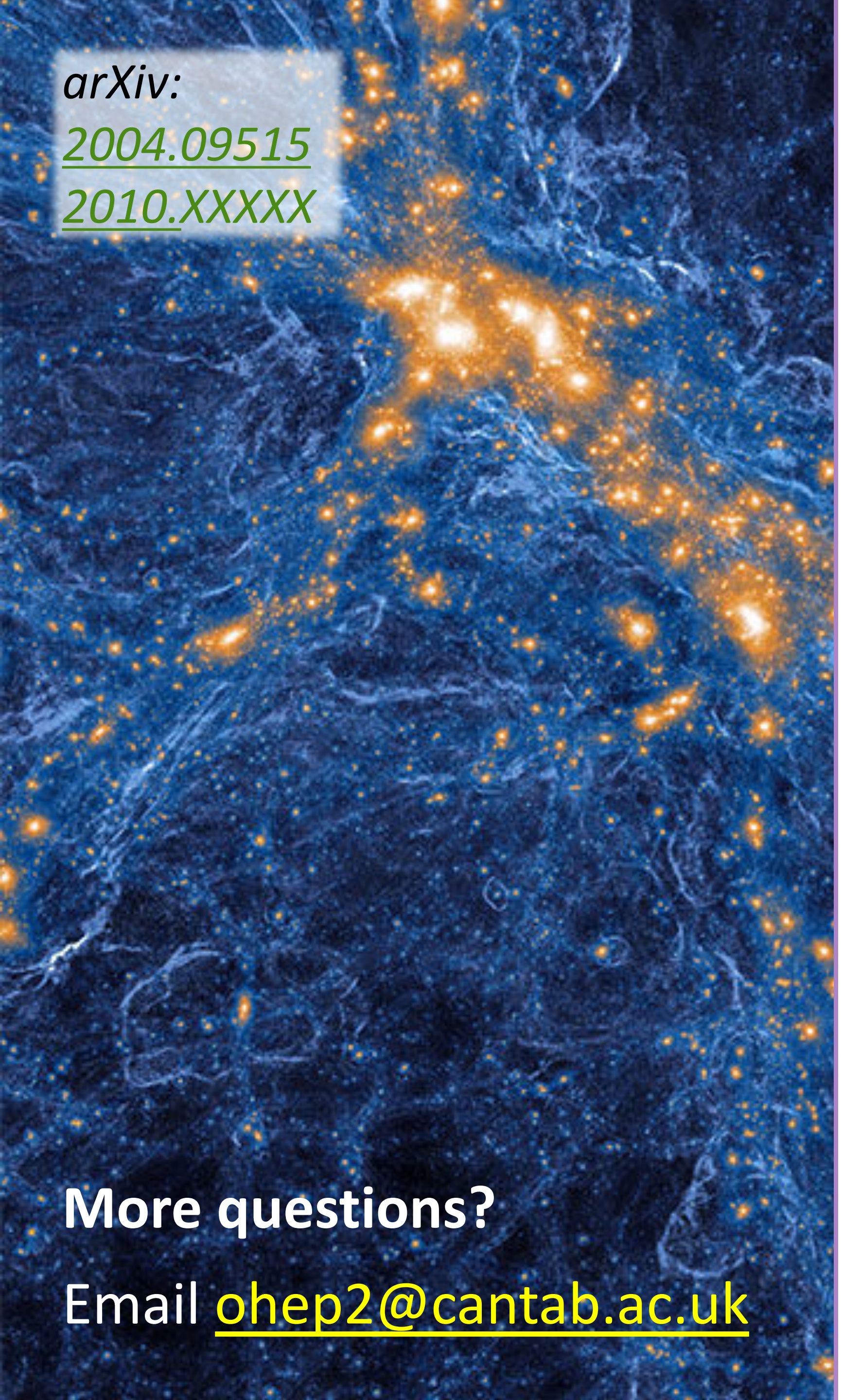
Results: Matter at ∞-loop



Adding a large scale ∞-loop **correction term** gives an **accurate** theory!

Philcox+ (in prep.)



arXiv:
2004.09515
2010.XXXXX

More questions?

Email ohep2@cantab.ac.uk

Conclusions

- The **marked** density field can place **strong** constraints on cosmological parameters
- It can be modeled using Effective Field Theory but:
  - The large-scale theory depends on **all** loops contributions!
- Adding in a **free** correction term improves the theory!

- Do the **free** parameters destroy the **information** content?
- Is the marked field still useful for **biased** tracers?
- Should we worry about **baryonic** effects?

Backup Slides