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# The Effective Field Theory of Cosmological Large Scale Structures

# A data driven subject



#### Limits in terms of parameters of a Lagrangian

$$S_{\pi} = \int d^4 \sqrt{-g} \left[ \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} \left( \dot{\pi}^2 - c_s^2 (\partial_i \pi)^2 \right) + \frac{\dot{H} M_{\rm Pl}^2}{c_s^2} \left[ \dot{\pi} (\partial_i \pi)^2 + \tilde{c}_3 \, \dot{\pi}^3 \right] \right]$$

with Cheung, Creminelli, Fitzpatrick and Kaplan, JHEP 2008



- These are contour plots of parameters of a fundamental Lagrangian
- Same as in particle accelerator Precision Electroweak Tests. see Barbieri, Giudice, Isidori, ...
- Thanks to the EFT: A qualitatively new (and superior) way to use the cosmological data

#### What has Planck done to theory?

- Planck improve limits wrt WMAP by a factor of ~3.
- Since  $NG \sim \frac{H^2}{\Lambda^2} \implies \Lambda^{\min, Planck} \sim \sqrt{3} \Lambda^{\min, WMAP}$
- Given the absence of known or nearby threshold, this is not much.
- Planck was great

-but CMB did not have enough modes

• Planck was an opportunity for a detection, not much an opportunity to change the theory in absence of detection

–We crossed the tilt-threshold (luckily WMAP had a tilt a 2.5  $\sigma$  , so we got to  $6 \sigma$  )

• On theory side, little changes

-contrary for example to LHC, which was crossing thresholds

• Any result from LHC is changing the theory

#### Cosmology, after Planck, has changed

- Tremendous progress has been made through observation of the primordial fluctuations
- We are probing a statistical distribution:
  - -In order to increase our knowledge of Inflation, we need more modes:
    - like a luminosity experiment

- $\Delta$ (everything)  $\propto \frac{1}{\sqrt{N_{\text{modes}}}}$
- Planck has just observed ~all the modes from the CMB
- and now what?
- I will assume we are not lucky
  - -no B-mode detection
- Unless we find a way to get more modes, cosmology as we are used to is over
- Large Scale Structures offer the only medium-term place for hunting for more modes
  - -but we are compelled to understand them
    - I do not think, so far, we understand them well enough

# Some things already done

• Baryon Acoustic Oscillations in Galaxies distribution



## What is next?

• Euclid, LSST and Chime are the next big missions: this is our only next chance

-we need to understand how many modes are available

- -Need to understand short distances
- -Similar as from LEP to LHC



#### The EFTofLSS: A well defined perturbation theory

• Non-linearities at short scale



Idea of the Effective Field Theory

## Consider a dielectric material

- Very complicated on atomic scales  $d_{\text{atomic}}$
- On long distances  $d \gg d_{\text{atomic}}$

-we can describe atoms with their gross characteristics

• polarizability  $\vec{d}_{\text{dipole}} \sim \alpha \vec{E}_{\text{electric}}$  : average response to electric field

-we are led to a uniform, smooth material, with just some macroscopic properties

- we simply solve dielectric Maxwell equations, we do not solve for each atom.
- The universe looks like a dielectric



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Dielectric Fluid



## With this



#### The Theory of the Universe

- Useful or not, this is the correct description of the long distance universe
  - as we describe water as a fluid, and not a set of molecules hitting each other



• similarly the universe *is* the system I am going to describe

# Normal Approach: numerics

• Just simulate the full universe (such as water molecules to simulate ocean waves)



even though successful in the past, now numerics is showing its limitations

–and to make further progress, high precision is required

Construction of the Effective Field Theory

## The Effective ~Fluid

–In history of universe Dark Matter moves about  $1/k_{\rm NL} \sim 10 \,{\rm Mpc}$ 

- it is an effective fluid-like system with mean free path ~  $1/k_{\rm NL} \sim 10 \,{
  m Mpc}$
- it interacts with gravity so matter and momentum are conserved
- Skipping subtleties, the resulting equations are equivalent to fluid-like equations

$$\nabla^2 \Phi_l = H^2 \frac{\delta \rho_l}{\rho}$$
$$\partial_t \rho_l + H \rho_l + \partial_i \left( \rho_l v_l^i \right) = 0$$
$$\dot{v}_l^i + H v_l^i + v_l^j \partial_j v_l^i = \frac{1}{\rho} \partial_j \tau_{ij}$$

with Baumann, Nicolis and Zaldarriaga JCAP 2012 with Carrasco and Hertzberg JHEP 2012 with Porto and Zaldarriaga JCAP1405

-short distance physics appears as a non trivial stress tensor for the long-distance fluid

$$\tau_{ij} \sim \delta_{ij} \rho_{\text{short}} \left( v_{\text{short}}^2 + \Phi_{\text{short}} \right)$$

# Dealing with the Effective Stress Tensor

• Take expectation value over short modes (integrate them out)

$$\langle \tau_{ij} \rangle_{\text{long-fixed}} \sim \delta_{ij} \left[ p_0 + c_s \,\delta \rho_l + \mathcal{O}\left(\frac{\partial}{k_{\text{NL}}}, \partial_i v_l^i, \delta \rho_l^2, \ldots\right) + \Delta \tau \right]$$

• We obtain equations containing only long-modes

$$\nabla^{2} \Phi_{l} = H^{2} \frac{\delta \rho_{l}}{\rho}$$

$$\partial_{t} \rho_{l} + H \rho_{l} + \partial_{i} \left(\rho_{l} v_{l}^{i}\right) = 0$$

$$\dot{v}_{l}^{i} + H v_{l}^{i} + v_{l}^{j} \partial_{j} v_{l}^{i} = \frac{1}{\rho} \partial_{j} \tau_{ij}$$

$$\langle \tau_{ij} \rangle_{\text{long-fixed}} \sim \delta_{ij} \left[ p_{0} + c_{s} \delta \rho_{l} + \mathcal{O} \left( \frac{\partial}{k_{\text{NL}}}, \partial_{i} v_{l}^{i}, \delta \rho_{l}^{2}, \dots \right) + \Delta \tau \right]$$



- This is call `integrating out' short modes
- How many terms to keep?
  - $\boldsymbol{k}$ • each term contributes as an extra factor of  $\delta_{01}$

$$\frac{\delta \rho_l}{\rho} \sim \frac{\kappa}{k_{\rm NL}}$$

• we keep as many as required precision

• 
$$\Rightarrow$$
 manifest expansion in  $\frac{k}{k_{\rm NL}} \ll 1$ 

## A subtlety: non-locality in Time

#### This EFT is non-local in time

• For local EFT, we need hierarchy of scales.

-In space we are ok





-In time we are not ok: all modes evolve with time-scale of order Hubble



with Carrasco, Foreman and Green **1310** Carroll, Leichenauer, Pollak **1310** Mirbabahi, Schmidt, Zaldarriaga **1412** 

•  $\Rightarrow$  The EFT is local in space, non-local in time

$$\langle \tau_{ij}(\vec{x},t) \rangle_{\text{long fixed}} \sim \int^t dt' \ K(t,t') \ \delta\rho(\vec{x}_{\text{fl}},t') + \dots$$

A Non-Renormalization Theorem (for a SUSY conference)

## A non-renormalization theorem

• Can the short distance non-linearities change completely the overall expansion rate of the universe, possibly leading to acceleration without  $\Lambda$ ?



- In terms of the short distance perturbation, the effective stress tensor reads  $\tau_{00} \sim (\text{mass} + \text{kinetic energy} + \text{gravity potential energy})$  $\tau_{ii} \sim (2 \text{ kinetic energy} + \text{gravity potential energy})$
- when objects virialize, induced pressure vanish  $\langle \rho_S \left( 2v_S^2 + \Phi_S \right) \rangle_{\text{virialized}} \to 0$

-ultraviolet modes do not contribute (like in SUSY!)

• In the EFT we can solve iteratively  $\delta_{\ell}, v_{\ell}, \Phi_{\ell} \ll 1$ 

$$\nabla^{2} \Phi_{l} = H^{2} \frac{\delta \rho_{l}}{\rho}$$
  

$$\partial_{t} \rho_{l} + H \rho_{l} + \partial_{i} \left( \rho_{l} v_{l}^{i} \right) = 0$$
  

$$\dot{v}_{l}^{i} + H v_{l}^{i} + v_{l}^{j} \partial_{j} v_{l}^{i} = \frac{1}{\rho} \partial_{j} \tau_{ij}$$
  

$$\langle \tau_{ij} \rangle_{\text{long-fixed}} \sim \delta_{ij} \left[ p_{0} + c_{s} \,\delta \rho_{l} + \mathcal{O} \left( \frac{\partial}{k_{\text{NL}}}, \partial_{i} v_{l}^{i}, \delta \rho_{l}^{2}, \ldots \right) + \Delta \tau \right]$$

• Since equations are non-linear, we obtain convolution integrals (loops)

$$\delta^{(n)} \sim \int \text{GreenFunction} \times \text{Source}^{(n)} \left[ \delta^{(1)}, \delta^{(2)}, \dots, \delta^{(n-1)} \right]$$
  
$$\Rightarrow \quad \delta^{(2)}(k_l) \sim \int d^3k_s \ \delta^{(1)}(k_s) \ \delta^{(1)}(k_l - k_s) \ , \quad \Rightarrow \quad \langle \delta_l^2 \rangle \sim \int d^3k_s \ \langle \delta_s^{(1)2} \rangle^2$$



## A subtlety: non-locality in Time

#### Consequences of non-locality in time

- The EFT is non-local in time  $\implies \langle \tau_{ij}(\vec{x},t) \rangle_{\text{long fixed}} \sim \int^t dt' \ K(t,t') \ \delta \rho(\vec{x}_{\text{fl}},t') + \dots$
- Perturbative Structure has a decoupled structure

$$\delta\rho(x,t') = D(t')\delta\rho(\vec{x})^{(1)}(t) + D(t')^2\delta\rho(\vec{x})^{(2)}(t) + \dots$$

• A few coefficients for each counterterm:

$$\Rightarrow \langle \tau_{ij}(\vec{x},t) \rangle_{\text{long fixed}} \sim \int^t dt' \ K(t,t') \ \left[ D(t')\delta\rho(\vec{x})^{(1)} + D(t')^2\delta\rho(\vec{x})^{(2)} + \dots \right] \\ \simeq c_1(t) \ \delta\rho(\vec{x})^{(1)}(t) + c_2(t) \ \delta\rho(\vec{x})^{(2)}(t) + \dots$$

• where  $c_i(t) = \int dt' K(t,t') D(t')^i$ 

- Difference: Time-Local QFT:  $c_1(t) \left[ \delta \rho(\vec{x})^{(1)}(t) + \delta \rho(\vec{x})^{(2)}(t) + \ldots \right]$ Non-Time-Local QFT:  $c_1(t) \ \delta \rho(\vec{x})^{(1)}(t) + c_2(t) \delta \rho(\vec{x})^{(2)}(t) + \ldots$ 
  - More terms, but not a disaster

• Since equations are non-linear, we obtain convolution integrals (loops)

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• Regularization and renormalization of loops (no-scale universe)  $P_{11}(k) = \frac{1}{k_{\rm NL}^3} \left(\frac{k}{k_{\rm NL}}\right)^n$ -evaluate with cutoff:

$$P_{1-\text{loop}} = c_1^{\Lambda} \left(\frac{\Lambda}{k_{\text{NL}}}\right) \left(\frac{k}{k_{\text{NL}}}\right)^2 P_{11} + c_1^{\text{finite}} \left(\frac{k}{k_{\text{NL}}}\right)^3 P_{11} + \text{subleading in } \frac{k}{k_{\text{NL}}}$$

- divergence (we extrapolated the equations where they were not valid anymore)

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- we need to add effect of stress tensor  $\tau_{ij} \supset c_s^2 \, \delta \rho$

$$P_{11, c_s} = c_s \left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}$$
, choose  $c_s = -c_1^{\Lambda} \left(\frac{\Lambda}{k_{\rm NL}}\right) + c_{s, \text{finite}}$ 

$$\implies P_{1-\text{loop}} + P_{11, c_s} = c_{s, \text{finite}} \left(\frac{k}{k_{\text{NL}}}\right)^2 P_{11} + c_1^{\text{finite}} \left(\frac{k}{k_{\text{NL}}}\right)^3 P_{11} + \text{subleading in } \frac{k}{k_{\text{NL}}}$$

-we just re-derived renormalization

-after renormalization, result is finite and small

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## Lesson from Renormalization

• Each loop-order L contributes a finite, calculable term of order

$$P_{\rm L-loops} \sim \left(\frac{k}{k_{\rm NL}}\right)^L$$

-each higher-loop is smaller and smaller

-crucial difference with all former approaches

• This happens after canceling the divergencies with counterterms

$$P_{\rm L-loops; without counterterms} = \left(\frac{\Lambda}{k_{\rm NL}}\right)^L \frac{k^2}{k_{\rm NL}^2} P(k)$$

• each loop contributes the same

- $c_1^{\text{finite}} k^3 P(k)$  is non-analytic, and so non-degenerate with counterterms
  - calculable within EFT
  - analogous to  $\beta \log(E/\mu)$

## Connecting with the Eulerian Treatment

• When we solve iteratively these equations in  $\delta_{\ell}, v_{\ell}, \Phi_{\ell} \ll 1$ ,

-this corresponds to expanding in three parameters:

$$\epsilon_{\text{tidal}}(k) \sim \int^{k} d^{3}q \ P(q)$$
  
$$\epsilon_{\text{long displacement}}(k) \sim k^{2} \int^{k} d^{3}q \ \frac{P(q)}{q^{2}}$$

Effect of Long Overdensities

Effect of Long Displacements



## Perturbation Theory in our Universe

• In a no-scale universe  $P_{11}(k) = \frac{1}{k_{\text{NL}}^3} \left(\frac{k}{k_{\text{NL}}}\right)^n$ ,

 $\epsilon_{\text{tidal}} \sim \epsilon_{\text{long displacement}} \sim \epsilon_{\text{short displacement}} \sim \left(\frac{k}{k_{\text{NL}}}\right)^{3+i}$ 

• But our universe has features. It has more than one scale.



 $\epsilon_{\text{long displacement}}$  is of order one for low k's, but being IR dominated, its contribution can be treated non-perturbatively

Since displacements displace (they do not deform) effect is kinematical and not dynamical (so conceivable to resum)

• After IR-resummation, and after renormalization, each loop goes as power of

 $(\epsilon_{\rm tidal})^L$ 

with Zaldarriaga JCAP1502

## **Results for Dark Matter**

## EFT of Large Scale Structures

- Loop contributions from non-linear modes give non-sense results: we need to correct for them: renormalization (make the calculation UV-insensitive)
- At 1-loop one counterterm is enough  $\partial^2 \tau_{ij} \sim c_s \ k^2 \delta(k)$
- At 2-loops, consider  $\partial^2 \tau_{ij} \sim c_1 \ k^2 [\delta^2](k) + c_4 \ k^4 \delta(k)$



Estimate size of counterterms

by requiring cutoff independent result  $P_{2 \text{ loop}}^{(\text{UV-safe},\Lambda=\infty)}$ + counterterms)/ $P_{2 \text{ loop}}^{(\text{UV-safe}, \Lambda=2)}$ 1.6 ---  $c_1^{(\text{UV})} = c_4^{(\text{UV})} = c_{\text{stoch}}^{(\text{UV})} = 0$ 1.4 ----- best-fit values for  $c_1^{(UV)}, c_4^{(UV)}, c_{stoch}^{(UV)}$ 1.2 1.0 0.8 0.6 0.4 0.2 0.0 0.4 0.6 0.8 1.0with Foreman and Perrier 1507  $k [h \text{ Mpc}^{-1}]$ 

•  $\Rightarrow$  At two-loops, with precise data, 3 counterterms are needed, and we estimate size

• The fact that this works is another proof that the EFTofLSS is correct



- k-reach pushed to  $k \sim 0.34 \, h \, {\rm Mpc}^{-1}$ , cosmic variance  $\sim 10^{-3}$
- Order by order improvement  $\left(\frac{k}{k_{\rm NL}}\right)^L$
- Huge gain wrt former theories
- Theory error estimated, high precision

with Carrasco, Foreman and Green JCAP1407 with Zaldarriaga JCAP1502 with Foreman and Perrier 1507 see also Baldauf, Shaan, Mercolli and Zaldarriaga 1507, 1507 In the EFTofLSS we need parameters. Let us measure them from small N-body Simulations!

with Carrasco and Hertzberg JHEP 2012

## Measuring parameters from N-body sims.

- The EFT parameters can be measured from small N-body simulations, using UV theory –similar to what happens in QCD: lattice sims
- We measure  $c_s$  using the dark matter particles:



- Lattice running
- Agreement with fitting from Power Spectrum directly

$$\frac{d c_s}{d\Lambda} = \frac{d}{d\Lambda} \int^{\Lambda} d^3k \ P_{13}(k)$$

with Carrasco and Hertzberg **JHEP 2012** see also McQuinn and White **1502** 

## Other Observables

## **Other Observables**

-Since this is a theory and not a model

-prediction for other observables from same parameters

-3point function

-very non-trivial function of three variables!

with Angulo, Foreman and Schmittful **1406** see also Baldauf et al. **1406** 

-Momentum

-They all work as they should

with Carrasco, Foreman and Green JCAP 1407 Baldauf, Mercolli and Zaldarriaga 1507

-Vorticity Spectrum

with Carrasco, Foreman and Green JCAP1407

-agrees with most accurate measurements in simulations

Pueblas and Scoccimarro **0809** Hahn, Angulo, Abel **1404** 



#### Analytic Prediction of Baryon Effects

with Lewandowski and Perko JCAP1502

## Baryonic effects

• When stars explode, baryons behave differently than dark matter



• They cannot be reliably simulated due to large range of scales

# Baryons

- Main idea for EFT for dark matter:
  - since in history of universe Dark Matter moves about  $1/k_{\rm NL} \sim 10 \,{
    m Mpc}$ 
    - $\implies$  it is an effective fluid-like system with mean free path  $\sim 1/k_{\rm NL}$
- Baryons heat due to star formation, but they do not move much:
  - indeed, from observations in clusters, we know that they move

 $1/k_{\rm NL(B)} \sim 1/k_{\rm NL} \sim 10 \,{\rm Mpc}$ 

•  $\Rightarrow$  it is an effective fluid with similar mean free path

-Universe with CDM+Baryons  $\implies$  EFTofLSS with 2 species

• The effective force on baryons: expand force in long-wavelength fields:

$$\partial^2 \tau_b + \partial \gamma_b \sim c_s^2 \,\partial^2 \delta_l + c_\star \,\partial^2 \delta_l + \dots$$

gravity-induced pressure

star formation-induced pressure

#### Baryons



-and it seems to work as expected

## Galaxies Power and Bispectrum



# Galaxies in the EFTofLSS

- Similar considerations apply to biased tracers:
  - Galaxy density depends on all long fields evaluated on past history on past path

$$\delta_{M}(\vec{x},t) \simeq \int^{t} dt' \ H(t') \left[ \bar{c}_{\partial^{2}\phi}(t,t') \ \frac{\partial^{2}\phi(\vec{x}_{\mathrm{fl}},t')}{H(t')^{2}} \right]$$
Senatore **1406**  
Mirbabahi, Schmidt, Zaldarriaga **1412**  
$$+ \bar{c}_{\partial_{i}v^{i}}(t,t') \ \frac{\partial_{i}v^{i}(\vec{x}_{\mathrm{fl}},t')}{H(t')} + \bar{c}_{\partial_{i}\partial_{j}\phi\partial^{i}\partial^{j}\phi}(t,t') \ \frac{\partial_{i}\partial_{j}\phi(\vec{x}_{\mathrm{fl}},t')}{H(t')^{2}} \frac{\partial^{i}\partial^{j}\phi(\vec{x}_{\mathrm{fl}},t')}{H(t')^{2}} + \dots \right]$$

- all terms allowed by symmetries
- this generalizes and completes McDonald and Roy 0902
- this correctly parametrizes assembly bias
- Obtain only 7 parameters for
  - at 1-loop power spectrum
  - tree level bispectrum

## Halos in the EFTofLSS with

- We compare  $P_{hh}^{1-\text{loop}}$ ,  $P_{hm}^{1-\text{loop}}$ ,  $B_{hhh}^{\text{tree}}$ ,  $B_{hhm}^{\text{tree}}$ ,  $B_{hmm}^{\text{tree}}$  using 7 bias parameters
  - Fit works up to  $k \simeq 0.3 \, h \text{Mpc}^{-1}$  for 1-loop and  $k \simeq 0.15 \, h \text{Mpc}^{-1}$  at tree-level (for low bins, with large theory uncertainties): as it should



• the 3pt function measures very well the bias coefficients (there is a lot of data)

• Similar formulas just worked out for redshift space distortions

with Zaldarriaga 1409



- A manifestly well-defined perturbation theory  $\left(\frac{k}{k_{\rm NL}}\right)^L$
- we match until  $k \sim 0.34 \, h \, \text{Mpc}^{-1}$ , as where we should stop fitting -there are  $\sim 10^2$  more quasi linear modes than previously believed! -huge impact on possibilities, for ex:  $f_{\text{NL}}^{\text{equil., orthog.}} \lesssim 1$ , neutrinos, dark energy.
- This is an huge opportunity and a challenge for us.

# Conclusions

- The EFTofLSS: a novel and powerful way to analytically describe Large Scale Structures
  - -It describes something true, the real universe: many application for astrophysics
  - -It uses novel techniques that come from particle physics
    - Loops, divergencies, counterterms, renormalization & non-ren., IR divergencies
    - Measurements in Simulations (lattice) and lattice-running
- Many calculations and verifications to do (huge opportunity for particle physicists)
- Huge opportunity for complementarity with simulations
  - -Maybe do simulations focused to convey the EFT parameters?!
- If success continues, revolution in our expectations for next generation experiments



### Make Peace and no War

• Let us not fight between Simulations and Perturbation Theory



## Perturbation Theory and Simulations

• There is room for everybody: the two approaches are *complementary* 

Short Wavelengths: Simulations







• Hopefully, in this way, we can make LSS interesting for the Big Bang!

#### **IR-resummation**

with Zaldarriaga 1404

#### The Effect of Long-modes on Shorter ones

• In Eulerian treatment



- Add a long `trivial' force (trivial by GR)
- This tells you that one can resum the IR modes: this is the Lagrangian treatment



• Two effects

$$\vec{\pi}(\vec{x}) \rightarrow \vec{\pi}_{\text{inertial}}(\vec{\tilde{x}}) = \vec{\pi}(\vec{x}(\vec{\tilde{x}})) + \rho(\vec{\tilde{x}}) \vec{v}(\vec{\tilde{x}})$$
  
-Shift in coordinates

-Shift in field

• Two effects

$$\vec{\pi}(\vec{x}) \rightarrow \vec{\pi}_{\text{inertial}}(\vec{\tilde{x}}) = \vec{\pi}(\vec{x}(\vec{\tilde{x}})) + \rho(\vec{\tilde{x}}) \vec{v}(\vec{\tilde{x}})$$
  
-Shift in coordinates  
-Shift in field

• Two effects



• For fields that are scalar, this naively implies, by GR, that there are no IR effects in Fourier space at equal time correlators

-both modes are shifted the same way



with Frieman and Scoccimarro 1996

with Carrasco, Foreman and Green **1304** used to find the so-called consistency conditions in GR

Creminelli, Norena, Simonovic 1309



 $\mathcal{X}$ 

- The universe has features!
- Even on equal time correlators, IR modes of order the BAO scale do not cancel!

peak located at  $\lambda_{\text{long}}$ 

- -There is no Fermi Frame with BAO and no displacements shorter than peak
- To compute the width, IR modes up to the peak are relevant
- But they just do kinematics, so we can resum them!



- All former theories, RPT, LPT,.... differ from SPT just by the IR-resummation
- $\implies$  by GR, IR-modes cancel in P(k), so cannot change broad k-reach of the theory
  - they just change the BAO, which are 2% oscillations in k-space
    - if you doubt this, please ask me questions

#### Precision at low k's



- Precision at low k's is also important and great
- Look where linear theory fails by 1% at  $k \sim 0.03 h \,\mathrm{Mpc}^{-1}!$
- we can see that order by order, at low k's, the EFT converges!
  - former techniques and N-body sims *do not* converge to this accuracy

# Comments on Precise Power Spectrum



- Are we overfitting?
  - Fitting procedure constructed in order not to overfit
  - Size of counterterms compatible with expectations from UV-insensitivity
  - Theory error estimated by imposing  $1\sigma$  compatibility of measurement of parameters as we increase  $k_{\text{fit}}$
  - If we set  $P_{2\text{-loop}} = 0$ , then fit to data is very bad





• In former two-loop EFT calculation, the k-reach had been estimated to potentially reach  $k \sim 0.4 - 0.6 h \,\mathrm{Mpc}^{-1}$  with only the  $c_s$  parameter.

• Using Coyote-emulator data, 2% sys. error bars



• More precise data show that the  $c_s$  parameter is 30% different than from Coyote

reduces the k-reach a bit more than expected (not by much though) Baldauf, Shaan, Mercolli and Zaldarriaga 1507, 1507, with Foreman and Hideki 1507
It is compulsory that with more precise data (0.1%), the k-reach is decreased (look linear theory failing at k ~ 0.03 h Mpc<sup>-1</sup>!) and more counterterms are needed:

• k-reach makes sense as concept only after specifying the precision of the data

• The story *has not* been changing apart for better measurement of the parameters

## The EFTofLSS at high-z

with Foreman **1503** with Foreman and Perrier **1507** 

#### All redshifts



#### Results 2-loop IR-resummed

- UV reach improves at high-z 1.02 1.01 • Theory error gets smaller 1.00 0.99 z = 00.98 1.02 1.01 $P_{\text{theory}}/P_{\text{NI}}$ 0.99 z = 10.98 1.02 1.01 1.00 0.99 z = 20.98 0.5 1.5 0.0  $k [h \text{ Mpc}^{-1}]$
- The gain wrt former techniques is huge
- Time dependence of  $C_s$ ,  $C_1$ ,  $C_4$  is measured (only 12 parameters for all z's)
  - size compatible with UV expectations
- $\Rightarrow$  we can do CMB lensing analytically up to high ell.
  - and similarly galaxy lensing
  - $C_s$  detected detected with high sensitivity by upcoming CMB experiments