

Title: The Effective Field Theory of Large Scale Structures

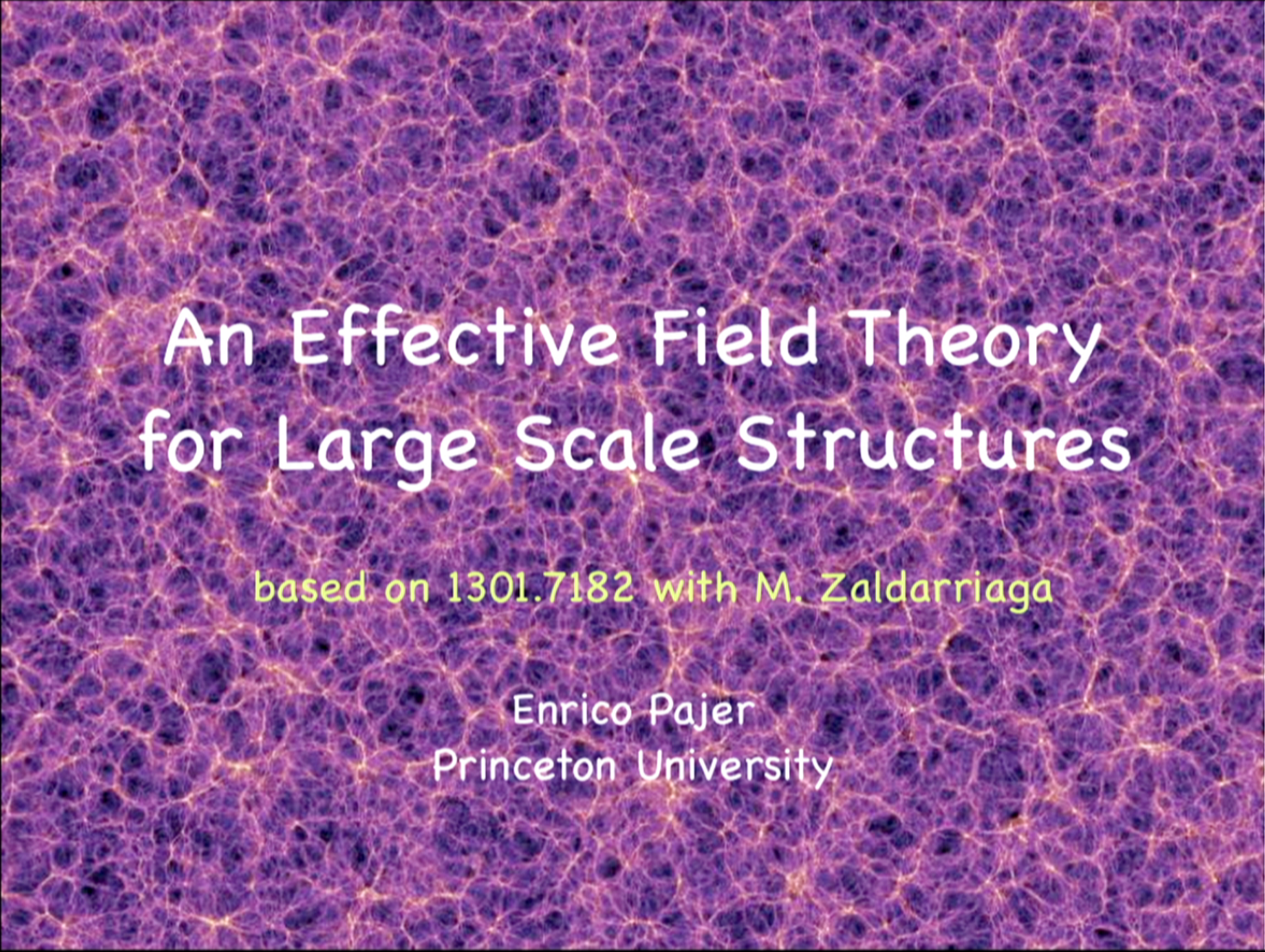
Date: Mar 19, 2013 11:00 AM

URL: <http://pirsa.org/13030110>

Abstract: An analytical understanding of large-scale matter inhomogeneities is an important cornerstone of our cosmological model and helps us interpreting current and future data. The standard approach, namely Eulerian perturbation theory, is unsatisfactory for at least three reasons: there is no clear expansion parameter since the density contrast is not small everywhere; it does not consistently account for deviations at large scales from a perfect pressureless fluid induced by short-scale non-linearities; for generic initial conditions, loop corrections are UV divergent, making predictions cutoff dependent and hence unphysical.

&nbsp;

I will present the systematic construction of an Effective Field Theory of Large Scale Structures and show that it successfully addresses all of the above issues. The idea is to smooth the density and velocity fields on a scale larger than the non-linear scale. The resulting smoothed fields are then small everywhere and provide a well-defined small parameter for perturbation theory. Smoothing amounts to integrating out the short scales, whose non-linear dynamics is hard to describe analytically. Their effects on the large scales are then determined by the symmetries of the problems. They introduce additional terms in the fluid equations such as an effective pressure, dissipation and stochastic noise. These terms have exactly the right scale dependence to cancel all divergences at one loop, and this should hold at all loops.  
I will present a clean example of the renormalization of the theory in an Einstein de Sitter universe with self-similar initial conditions and discuss the relative importance of loop and effective corrections.

A visualization of the cosmic web, showing a dense network of filaments and nodes in shades of purple and orange against a dark background. The filaments form a complex, interconnected web-like structure.

# An Effective Field Theory for Large Scale Structures

based on 1301.7182 with M. Zaldarriaga

Enrico Pajer  
Princeton University



# Outline

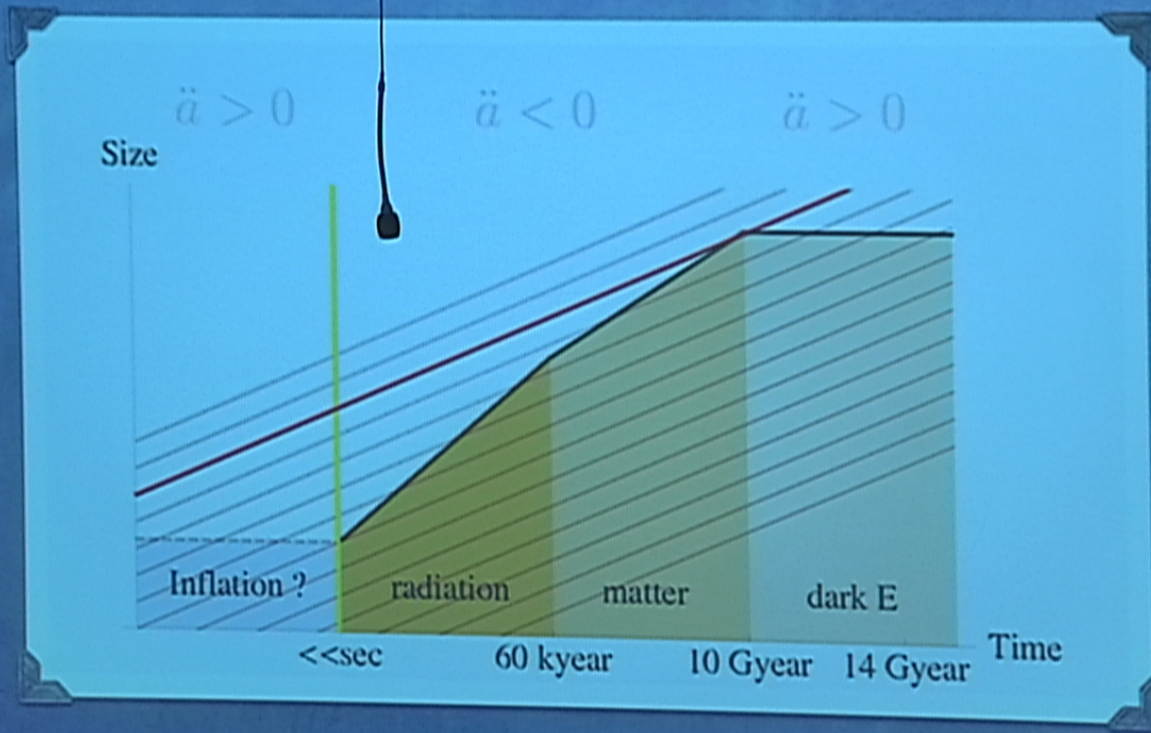
- Motivations
- Standard Perturbation Theory (SPT) and its problems
- Effective Field Theory for Large Scale Structures (EFToLSS)
- Resolution of the SPT problems
- Renormalization of EFToLSS
- Summary and Outlook

# Motivations

- Define Large Scale Structures (LSS)
- LSS teach us about: Dark Matter, Dark Energy, primordial perturbations, modifications of GR, ...
- Why simulate when you can calculate?
- Analytical understanding of LSS is a milestone of our cosmological model



# History of the universe



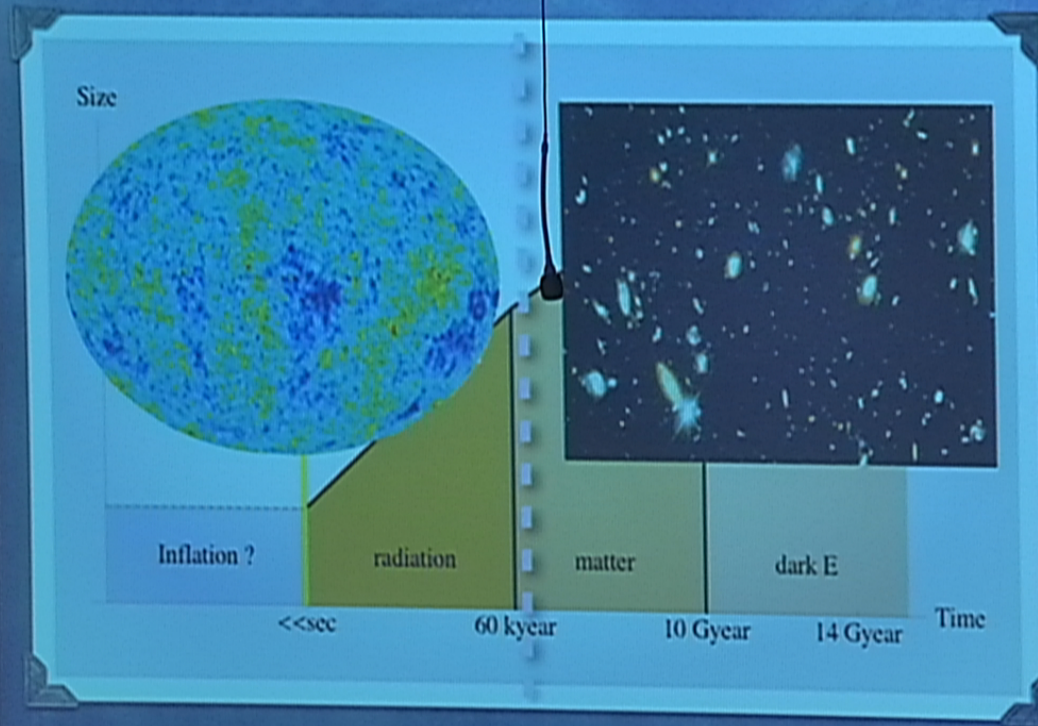
Perimeter Institute

March 19, 2013

Enrico Pajer, Princeton University



# The hard problem

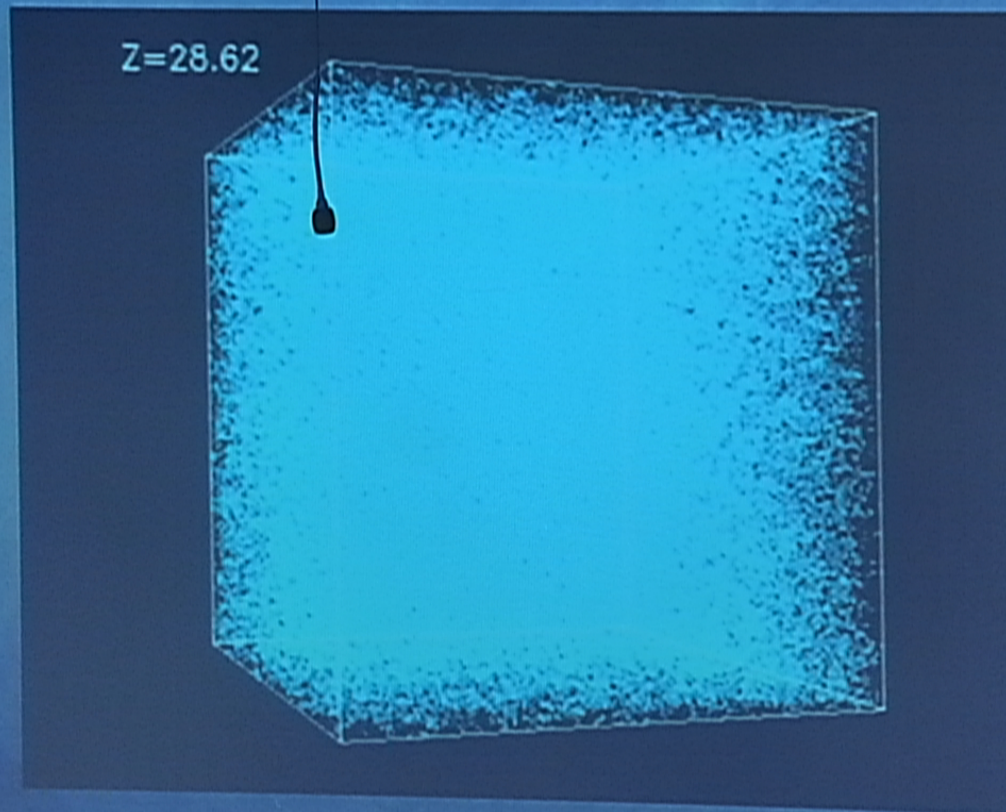


- CMB physics is linear, i.e. the physics of waves
- LSS physics involves large non-linearities

Now we have to deal with the hard problem!



# Structure formation



Perimeter Institute

March 19, 2013

Enrico Pajer, Princeton University



# Challenges for LSS

- **Matter distribution:** follow the non-linear gravitational evolution on large and intermediate scales of the initial condition from the early universe [This talk!]
- **Biasing:** Describe the highly non-linear dynamics of gravitational collapse, the formation of halos and galaxies
- **Redshift space distortion:** relate 3D observations in redshift space to correlators in 3D real space
- **Relativistic corrections:** identify physical observables [Schmidt, EP & Zaldarriaga to appear]



# Challenges for LSS

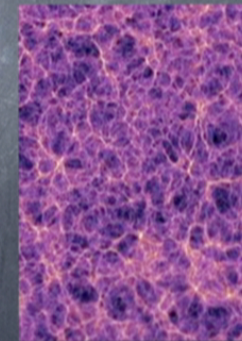
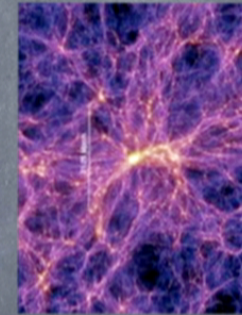
- Matter distribution: follow the non-linear gravitational evolution on large and intermediate scales of the initial condition from the early universe [This talk!]
- Biasing: Describe the highly non-linear dynamics of gravitational collapse, the formation of halos and galaxies
- Redshift space distortion: relate 3D observations in redshift space to correlators in 3D real space
- Relativistic corrections: identify physical observables [Schmidt, EP & Zaldarriaga to appear]



# Large Scale Structures

- The distribution of matter in the universe is very inhomogeneous, with very **dense clumps of matter** (e.g. galaxies) separated by big voids
- On scales much larger than the average galaxy-galaxy distance, i.e.  $O(1)$  Mpc, the density of clumps (e.g. galaxies) is very **homogeneous**
- Large Scale Structures (LSS) have a **small density contrast**

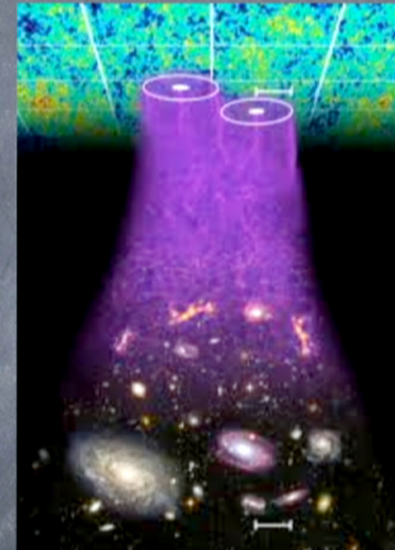
$$\delta(x) = \frac{\rho(x)}{\bar{\rho}} - 1$$





# LSS and Dark Energy

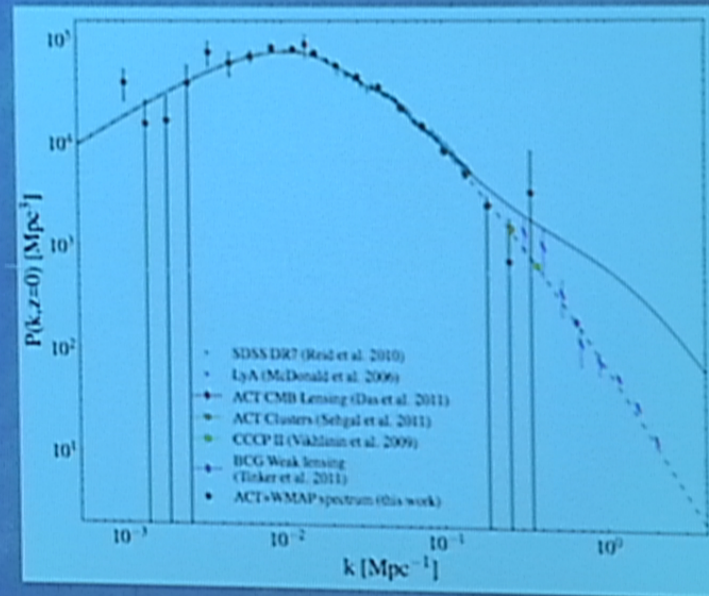
- Dark Energy can be probed studying the **expansion history** of the universe
- The Baryon Acoustic Oscillations (**BAO**) provide a standard ruler of 150 Mpc
- The BAO peak has a width of  $O(10)$  Mpc which gets broaden by **non-linear effects**





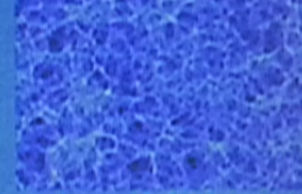
# LSS and primordial perturbations

- Because of the small density contrast, LSS evolve linearly giving us a very clean probe of initial conditions
- LSS are compatible with  $10^{-5}$  perturbations with a scale-invariant initial power spectrum
- Because 3D information is available through redshift, there are many more modes in LSS than in the CMB which is 2D, hence lower cosmic variance





# Simulations



- Numerical simulations of the formation and evolution of structures have become a standard tool in interpreting new data
- Simulations are essential at short scales where the dynamics is highly non-linear
- Simulating accurately large boxes such as the observable universe requires a very large dynamical range, which is very time consuming and resource intensive
- Probing the large-dimensionality parameter space needed for cosmology makes things worse



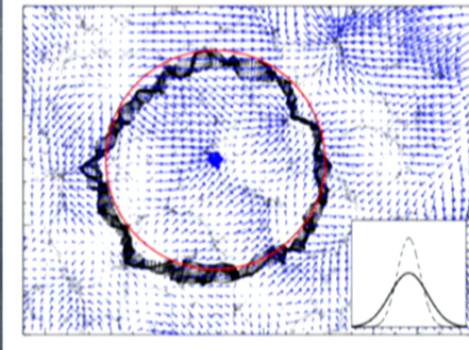
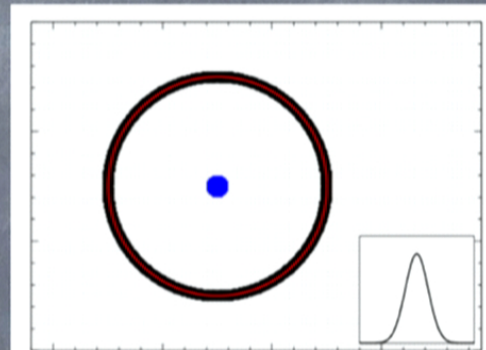
# Analytical description

- Since **LSS evolve almost linearly**, we have powerful analytical tools to describe the physics, e.g. perturbation theory
- Very **general results** can be derived where the dependence on cosmological parameters is explicit
- We can combine analytical result with **simulations on short scales**, which are much less resource intensive
- Obtain a **real understanding** of what's going on



# Mildly non-linear regime

- Below some **non-linear scale**  $k_{NL}$  the density perturbations are strongly coupled and not amenable to analytical computations
- $k \ll k_{NL}$  are **mildly non-linear**, that's where we can make some progress
- These scales are crucial for the (reconstruction of) the **BAO peak**
- The number of independent modes grow with the **cube** of the shortest scale. So **pushing closer to  $k_{NL}$  is essential** to make progress on primordial perturbations



# Standard Perturbation Theory

- A Boltzmann equation for collisionless Dark Matter particles: the **Vlasov equation**
- On large scales (before shell crossing) one can truncate the hierarchy and get the **fluid equations** (Bernardeau et al '01)
- Problem 1: there is no clear **expansion parameter**
- Problem 2: missing deviations from a perfect pressureless fluid
- Problem 3: predictions are **UV-divergent** and hence unphysical



# Vlasov Equation

- Since there is 6 times more DM than baryons, we focus on a system of collisionless DM particles **interacting only gravitationally**
- The corresponding **Boltzmann equation**

$$\frac{\partial f}{\partial t} + \frac{p^i}{ma^2} \frac{\partial f}{\partial x^i} - m \partial_i \phi \frac{\partial f}{\partial p^i} = 0$$

known as the Vlasov Equation, describes the evolution of the phase-space density

$$f(\vec{p}, \vec{x}) = \sum_i \delta^3(\vec{x} - \vec{x}_i) \delta^3(\vec{p} - m\vec{a}_i)$$

- The Poisson's equation determines  $\phi$

# Fluid equations

- Let us define **density** and **velocity**

$$\rho \equiv ma^{-3} \int d^3p f(x, p) \quad \rho v^i \equiv \int d^3p p^i f(x, p)$$

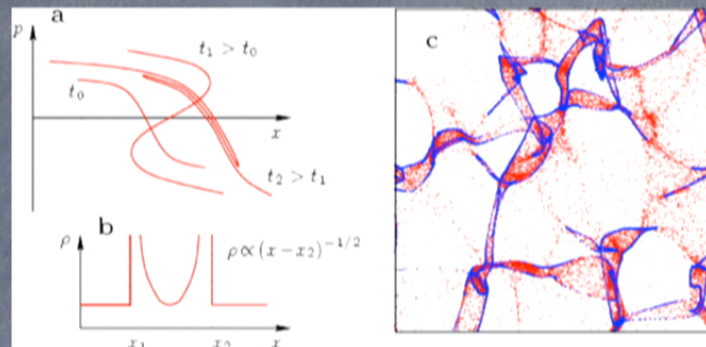
- Taking the first two moment of the Vlasov equation leads the **continuity** and the **Euler equations**

$$\begin{aligned} \partial_\tau \delta + \partial_i [(1 + \delta) v^i] &= 0 \\ \partial_\tau v^i + \mathcal{H}v^i + \partial_i \phi + v^k \partial_k v^i &= 0 \end{aligned}$$

- Can we solve it **perturbatively**?



# Problem 1



- Because of **shell-crossing** the density diverges at short scales
- No clear **expansion parameter** for perturbation theory
- Even when applying to large scales, this makes it hard to estimate the **theoretical errors** in the computation



## Problem 2

- The fluid equations are those of a **perfect pressureless fluid**
- Since the short scales cannot be model correctly, there is no way to exclude non-linear exchanges of energy and/or momentum with the large scales, leading to dissipation
- More generally, there is NO symmetry forbidding a **pressure** term or any higher derivative corrections, e.g. **viscosity**.
- **Why would they not be there?**



# Fluid equations

- Let us define **density** and **velocity**

$$\rho \equiv ma^{-3} \int d^3p f(x, p) \quad \rho v^i \equiv \int d^3p p^i f(x, p)$$

- Taking the first two moment of the Vlasov equation leads the **continuity** and the **Euler equations**

$$\begin{aligned} \partial_\tau \delta + \partial_i [(1 + \delta) v^i] &= 0 \\ \partial_\tau v^i + \mathcal{H}v^i + \partial_i \phi + v^k \partial_k v^i &= 0 \end{aligned}$$

- Can we solve it **perturbatively**?



## Problem 2

- The fluid equations are those of a **perfect pressureless fluid**
- Since the short scales cannot be model correctly, there is no way to exclude non-linear exchanges of energy and/or momentum with the large scales, leading to dissipation
- More generally, there is NO symmetry forbidding a **pressure** term or any higher derivative corrections, e.g. **viscosity**.
- **Why would they not be there?**



# Problem 3

- Perturbation theory as (dubious) expansion in  $\delta$

$$\delta_n \sim \int G\Gamma(k, k')\delta_m(k')\delta_{n-m}(k - k')$$

- Corrections to correlators, e.g. to the power spectrum  $P(k)$ , are organized in loops. E.g. linear and 1-loop:

$$P = P_{lin} + P_{22} + P_{13} + \dots$$
$$\langle \delta\delta \rangle = \langle \delta_1\delta_1 \rangle + \langle \delta_2\delta_2 \rangle + 2\langle \delta_1\delta_3 \rangle + \dots$$

and similarly for  $v$  and higher  $n$ -point functions



# Problem 3

- “Loop” corrections indeed have loop integrals

$$P_{22}(k \rightarrow \infty) \simeq k^4 \int \frac{dq}{q^2} P_{in}^2(q)$$

$$P_{13}(k \rightarrow \infty) \simeq k^2 P_{in}(k) \int dq P_{in}(q)$$

- For generic initial conditions these are UV-divergent, and hence unphysical

$$P_{in} = Ak^n$$

|             | UV div       | IR div      |
|-------------|--------------|-------------|
| $P_{13}$    | $n \geq -1$  | $n \leq -1$ |
| $P_{22}$    | $n \geq 1/2$ | $n \leq -1$ |
| $P_{total}$ | $n \geq -1$  | $n \leq -3$ |



# Effective Field Theory of Large Scale Structures

- Consistently integrate out short-scales (Baumann et al '10)
- Problem 1: smoothed density and velocity are a good expansion parameters
- Problem 2: effective corrections to a perfect pressureless fluid arise (EFT philosophy)
- Problem 3: effective corrections are exactly the needed counterterms to renormalize the theory



# Smoothing

- We **smooth** all fields on a certain scale  $\Lambda \ll k_{NL}$

$$\delta \rightarrow [\delta]_{\Lambda} = \int dx' W_{\Lambda}(x - x') \delta(x')$$

- Short modes can combine to create long-wavelength perturbations
- We can **expand** short modes in the background of long modes

$$(f g)_l = f_l g_l + (f_s g_s)_l + \frac{1}{\Lambda^2} \nabla f_l \nabla g_l + \dots$$

- We get long, **stochastic** and **higher derivative** terms

# Short scales

- We do not know how to describe the short scales, but we can **parameterize our ignorance**

$$(f_s g_s)_l = \langle f_s g_s \rangle_0 + \delta_l \frac{\partial \langle f_s g_s \rangle}{\partial \delta_l} + (f_s g_s) - \langle f_s g_s \rangle + \dots$$

- There are numerical and stochastic unknown coefficients
- These coefficients can be determined by simulations or by **fitting the observations** (Carrasco et al '12, Hertzberg '12)
- As always in EFT, the theory becomes **predictive** once we have more observables than parameters



# Effective corrections

- Smoothing the Vlasov equation leads to

$$\partial_\tau \delta + \partial_i [(1 + \delta) v_l^i] = 0,$$

$$\begin{aligned} \partial_\tau v_l^i + \mathcal{H} v_l^i + \partial_i \phi + v_l^k \partial_k v_l^i = & -c_s^2 \partial^i \delta + (c_{sv}^2 + c_{bv}^2) \frac{\partial^2 v_l^i}{\mathcal{H}} \\ & + \frac{c_{sv}^2}{\mathcal{H}} \partial^i \partial_j v_l^j - \Delta J^i \dots \end{aligned}$$

- A **pressure**, **viscosity** and a **stochastic** terms, plus (infinitely many) higher derivatives
- These are **all the terms allowed by the symmetries** of the problem, as in the EFT philosophy

# Effective corrections

- Smoothing the Vlasov equation leads to

$$\partial_\tau \delta + \partial_i [(1 + \delta) v_l^i] = 0,$$

$$\begin{aligned} \partial_\tau v_l^i + \mathcal{H} v_l^i + \partial_i \phi + v_l^k \partial_k v_l^i = & -c_s^2 \partial^i \delta + (c_{sv}^2 + c_{bv}^2) \frac{\partial^2 v_l^i}{\mathcal{H}} \\ & + \frac{c_{sv}^2}{\mathcal{H}} \partial^i \partial_j v_l^j - \Delta J^i \dots \end{aligned}$$

- A **pressure**, **viscosity** and a **stochastic** terms, plus (infinitely many) higher derivatives
- These are **all the terms allowed by the symmetries** of the problem, as in the EFT philosophy



# Problems 1 & 2

- Every field is now smoothed on a scale  $\Lambda \ll k_{NL}$  therefore  $\delta, v \ll 1$  providing good expansion parameters
- The short scales are now consistently accounted for, through the effective terms
- Collisionless dark matter on large scales shows indeed deviations from a perfect pressureless fluid, that vanish as  $k$  goes to 0
- What about perturbation theory?



# Renormalization

- For generic initial conditions, SPT predictions are **UV-divergent** and hence unphysical (Friemann & Scoccimarro '96)
- The effective coefficients induced by integrating out the short scales (neglected in SPT) are exactly the **counterterms** needed to cancel the UV-divergencies
- EFToLSS, rather than SPT, is the theoretically consistent way to do perturbation theory
- **Einstein deSitter** (EdS) is a simple, realistic and very instructive example



# Perturbation theory

- For simplicity let us focus just on  $\delta$

$$\square\delta \simeq -c_s^2 k^2 \delta - J + \int F(k, q) \delta(k - q) \delta(q)$$

- $F$  is the usual interaction kernel in SPT, while  $J$  and  $c_s$  are the **new effective terms**
- The terms on the rhs are treated **perturbatively**

$$\delta_J = \int G J \quad \delta_{c_s} = \int G c_s^2 k^2 \delta_1$$

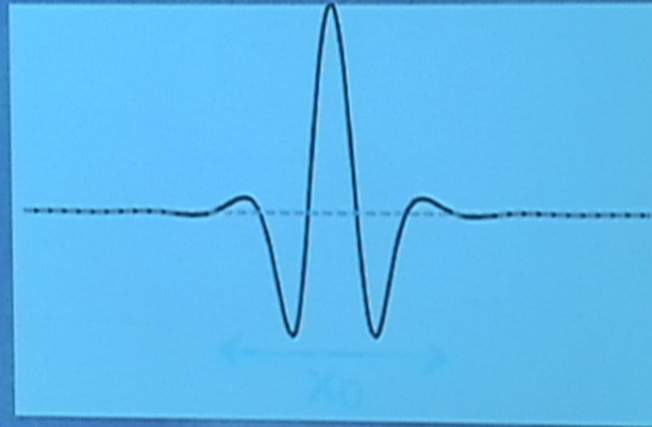
- **New corrections** to the correlators, e.g. power spectrum

$$\langle \delta_1 \delta_{c_s} \rangle \equiv P_{c_s} \quad \langle \delta_J \delta_J \rangle \equiv P_J$$



# Stochastic term

- Mass and momentum conservation restrict the effects of short scales on large scales [Peebles]



$$\begin{aligned}\delta(k) &= \int d^3x \delta(x) e^{ikx} \\ &\simeq \int_0^{x_0} d^3x \delta(x) (1 + ikx - kx^2) \\ &\propto (kx_0)^2 \Rightarrow \langle JJ \rangle \sim k^4 + \mathcal{O}(k^5)\end{aligned}$$



# Regularization

- The smoothing has regularized the theory. For  $P = k^n$

$$P_{22}(k \rightarrow \infty) \simeq k^4 \int \frac{dq}{q^2} P_{in}^2(q) \sim k^4 \Lambda^{2n-1}$$

$$P_{13}(k \rightarrow \infty) \simeq k^2 P_{in}(k) \int dq P_{in}(q) \sim k^2 P_{in}(k) \Lambda^{n-1}$$

- But now we have extra (counter)terms

$$P_J = \langle JJ \rangle(\Lambda) \sim k^4 f(\Lambda)$$

$$P_{c_s^2} = c_s^2(\Lambda) k^2 P_{in}(k)$$

- Precisely the right  $k$ -dependence to cancel the  $1/\epsilon$ -divergences



# Cancellation of UV-divergences

- Although we show it just at one loop the cancellation of divergences takes place at all loops
- This is ensured by the EFT construction: if all terms compatible with the symmetries are included, there is always a term with the same structure as the UV-divergences
- The cancellation ensures that the result is independent of the cutoff  $\Lambda$ , and hence physically meaningful (unlike for SPT)



# Einstein de Sitter

- During  $3300 < z < 1$  our universe was matter dominated
- To first approximation most structures formed in a universe with  $\Omega_m = 1$ , i.e. an Einstein deSitter (EdS) universe
- The (non-relativistic) SPT fluid equations have a scaling symmetry in EdS

$$\tilde{\delta}(x, \tau) = \delta(\lambda_x x, \lambda_\tau \tau)$$

because there is no velocity in the problem

- This simple but realistic example teach us a lot about the structure of perturbation theory



# Self-similarity

- For the rescaled solution to belong to the same cosmology as the original one, one needs

$$\Delta^2(k, \tau) \equiv \frac{k^3 P(k, \tau)}{2\pi^2} \quad \Delta^2(k, \tau) = \Delta^2(k/\lambda_x, \lambda_\tau \tau)$$

- This happens only for a self-similar (no-scale) initial power spectrum  $P = A a^2 k^n$
- Only one scale in the problem, e.g. the non-linear scale

$$k_{NL}^{3+n} \equiv \frac{2\pi^2}{Aa^2} \propto \tau^{-4} \quad \Delta_{lin}^2 = \left( \frac{k}{k_{NL}} \right)^{n+3}$$

- Everything must be function of  $k/k_{NL}$



# Self-similarity

- For the rescaled solution to belong to the same cosmology as the original one, one needs

$$\Delta^2(k, \tau) \equiv \frac{k^3 P(k, \tau)}{2\pi^2} \quad \Delta^2(k, \tau) = \Delta^2(k/\lambda_x, \lambda_\tau \tau)$$

- This happens only for a self-similar (no-scale) initial power spectrum  $P = A a^2 k^n$
- Only one scale in the problem, e.g. the non-linear scale

$$k_{NL}^{3+n} \equiv \frac{2\pi^2}{Aa^2} \propto \tau^{-4} \quad \Delta_{lin}^2 = \left( \frac{k}{k_{NL}} \right)^{n+3}$$

- Everything must be function of  $k/k_{NL}$



# Self-similarity

- For the rescaled solution to belong to the same cosmology as the original one, one needs

$$\Delta^2(k, \tau) \equiv \frac{k^3 P(k, \tau)}{2\pi^2} \quad \Delta^2(k, \tau) = \Delta^2(k/\lambda_x, \lambda_\tau \tau)$$

- This happens only for a self-similar (no-scale) initial power spectrum  $P = A a^2 k^n$
- Only one scale in the problem, e.g. the non-linear scale

$$k_{NL}^{3+n} \equiv \frac{2\pi^2}{Aa^2} \propto \tau^{-4} \quad \Delta_{lin}^2 = \left( \frac{k}{k_{NL}} \right)^{n+3}$$

- Everything must be function of  $k/k_{NL}$



# Power spectrum

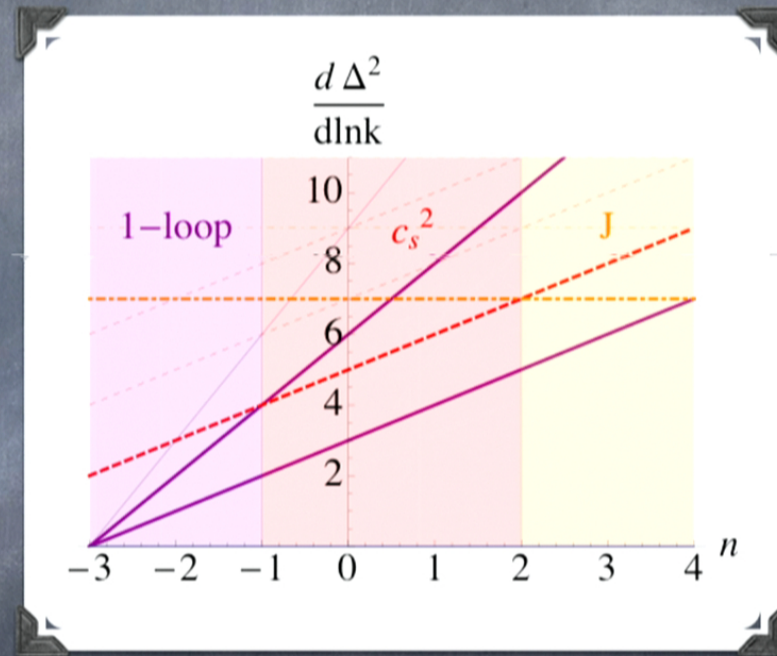
- Because of self-similarity, knowing the  $k$ -dependence of every term fixed the form of all correlators.
- E.g. the power spectrum is

$$\Delta^2 = \left(\frac{k}{k_{NL}}\right)^{3+n} + \beta(n) \left(\frac{k}{k_{NL}}\right)^{5+n} + \gamma(n) \left(\frac{k}{k_{NL}}\right)^7 \\ + \left(\frac{k}{k_{NL}}\right)^{2(3+n)} \left[ \alpha(n) + \tilde{\alpha}(n) \ln \left(\frac{k}{k_{NL}}\right) \right] + \dots$$



## Relative importance of corrections

- Relative importance of terms as  $k \rightarrow 0$  depends on  $n$
- For our universe  $n = 1.5$  hence  $c_s^2$  is more important than 2-loops  $\mathcal{J}$  is less important than 3-loops
- This shows which terms can be consistently included





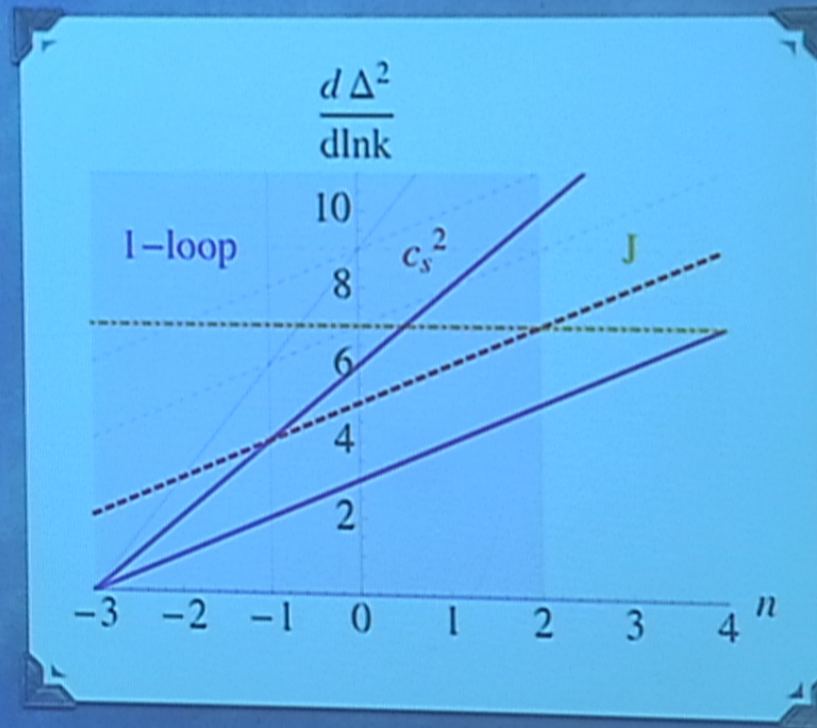
# Dimensional regularization

- $\beta$  and  $\gamma$  are  $n$ -dependent fitting parameters, that can be determined comparing with observations or simulations (e.g. Carrasco et al '12, Hertzberg '12)
- $\alpha$  and  $\tilde{\alpha}$  are  $n$ -dependent numbers predicted by perturbation theory. They are most easily computed in dimensional regularization (dim reg)
- Dim reg preserved the scaling symmetry (unlike the cutoff regularization) of EdS, hence no violation of self-similarity appears anywhere in the computation

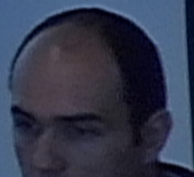


# Relative importance of corrections

- Relative importance of terms as  $k \rightarrow 0$  depends on  $n$
- For our universe  $n = 1.5$  hence  $c_s$  is more important than 2-loops  $J$  is less important than 3-loops



- This shows which terms can be consistently included





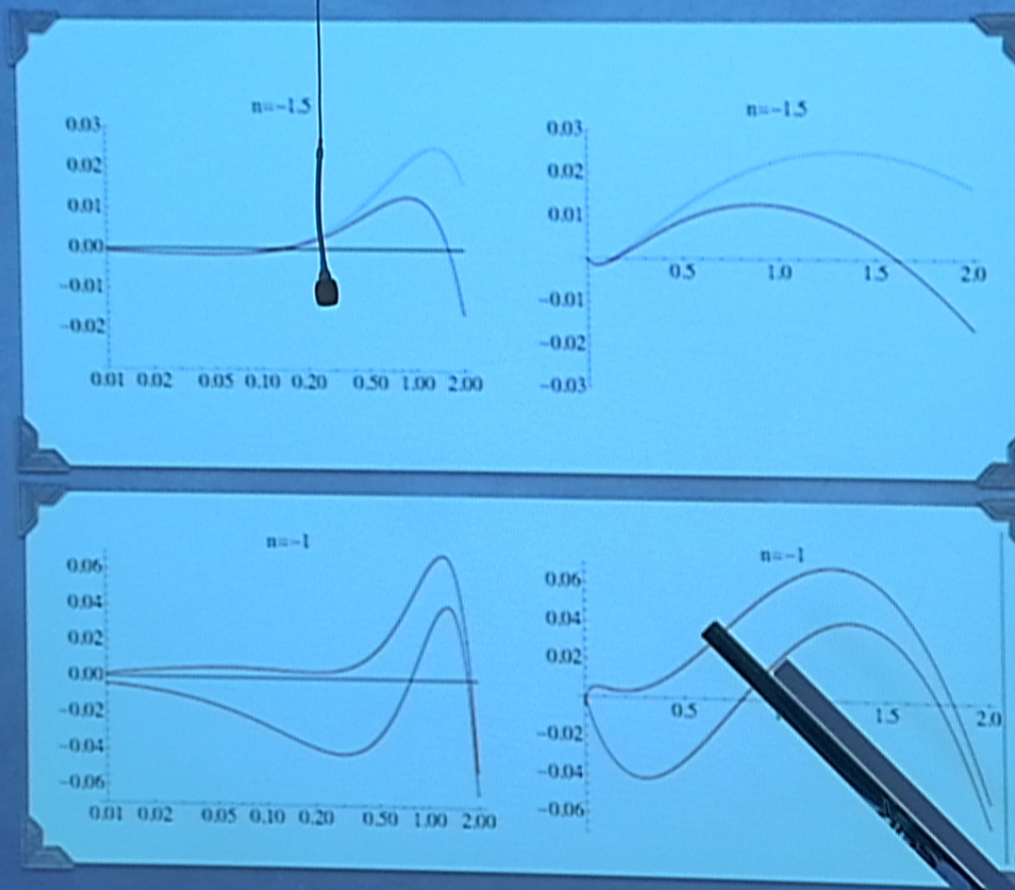
# Dim reg computation

$$\begin{aligned}
 P_{22}(k, \tau) = & \left( \frac{\Gamma[4 - \frac{d}{2} - n]\Gamma^2[(-4 + d + n)/2]}{2\Gamma^2(2 - n/2)\Gamma[-4 + d + n]} + \frac{3\Gamma[3 - \frac{d}{2} - n]\Gamma[(-4 + d + n)/2]\Gamma[(-2 + d + n)/2]}{\Gamma[1 - n/2]\Gamma[2 - n/2]\Gamma[-3 + d + n]} \right. \\
 & + \frac{29\Gamma[2 - \frac{d}{2} - n]\Gamma^2[(-2 + d + n)/2]}{4\Gamma^2[1 - n/2]\Gamma[-2 + d + n]} - \frac{11\Gamma[2 - \frac{d}{2} - n]\Gamma[(-4 + d + n)/2]\Gamma[(d + n)/2]}{4\Gamma[2 - n/2]\Gamma[-n/2]\Gamma[-2 + d + n]} \\
 & - \frac{15\Gamma[1 - \frac{d}{2} - n]\Gamma[(-4 + d + n)/2]\Gamma[(2 + d + n)/2]}{2\Gamma[-1 - n/2]\Gamma[2 - n/2]\Gamma[-1 + d + n]} + \frac{15\Gamma[1 - \frac{d}{2} - n]\Gamma[(-2 + d + n)/2]}{2\Gamma[1 - n/2]\Gamma[-n/2]} \\
 & \times \frac{\Gamma[(d + n)/2]}{\Gamma(-1 + d + n)} - \frac{25\Gamma[-d/2 - n]\Gamma[(-2 + d + n)/2]\Gamma[(2 + d + n)/2]}{\Gamma[-1 - n/2]\Gamma[1 - n/2]\Gamma[d + n]} + \frac{25\Gamma[-d/2 - n]}{4\Gamma[-2 - n/2]} \\
 & \times \left. \frac{\Gamma[(-4 + d + n)/2]\Gamma[(4 + d + n)/2]}{\Gamma[2 - n/2]\Gamma[d + n]} + \frac{75\Gamma[-\frac{d}{2} - n]\Gamma^2[(d + n)/2]}{4\Gamma^2[-n/2]\Gamma[d + n]} \right) \frac{A^2 a^{4(d-2)}}{49} \frac{1}{8\pi^{3-d/2}} \\
 & \times k^{2n+d}, \tag{A.7}
 \end{aligned}$$

$$\begin{aligned}
 P_{13}(k, \tau) = & \Gamma[-1 + d/2] \left( - \frac{\Gamma[(4 - d - n)/2]\Gamma[(-2 + d + n)/2]}{84\Gamma(1 - n/2)\Gamma[-2 + d + n/2]} - \frac{19\Gamma[-(d + n)/2]\Gamma[(2 + d + n)/2]}{84\Gamma(-1 - n/2)\Gamma(d + n/2)} \right. \\
 & + \frac{\Gamma[-(2 + d + n)/2]\Gamma[(4 + d + n)/2]}{12\Gamma[-2 - n/2]\Gamma[1 + d + n/2]} + \frac{5\Gamma[(2 - d - n)/2]\Gamma[(d + n)/2]}{28\Gamma[-1 + d + n/2]\Gamma[-n/2]} \\
 & \left. - \frac{\Gamma[(-4 + d + n)/2]\Gamma[(6 - d - n)/2]}{42\Gamma[2 - n/2]\Gamma[-3 + d + n/2]} \right) \frac{1}{8\pi^{3-d/2}} A^2 a^{4(d-2)} k^{2n+d}. \tag{A.8}
 \end{aligned}$$



# Comparison with simulations



Perimeter Institute

March 19, 2013

Enrico Pajer, Princeton University



# Conclusions

- SPT is unsatisfactory for at least three reasons
  1. there is no clear expansion parameter
  2. deviation from perfect pressureless fluid are missing
  3. predictions are UV-divergent and hence unphysical
- The EFT approach is to consistently integrate out the short scales. This addresses all the above problems
  1. smoothed fields are small everywhere
  2. pressure, dissipation and stochastic noise arise as fitting parameters
  3. counterterms cancel UV-divergences and make the theory predictive



# Outlook

- Generalize to velocity correlators and higher  $n$ -point function. The relative importance of operators is the same!
- The effective coefficients have been estimated (Carrasco et al '12, Hertzberg '12) fitting the power spectrum. But there is more information in each individual realization
- Lagrangian perturbation theory (LPT) improves SPT accounting for bulk flow (Tassev & Zaldarriaga '12). Develop an EFT of LPT