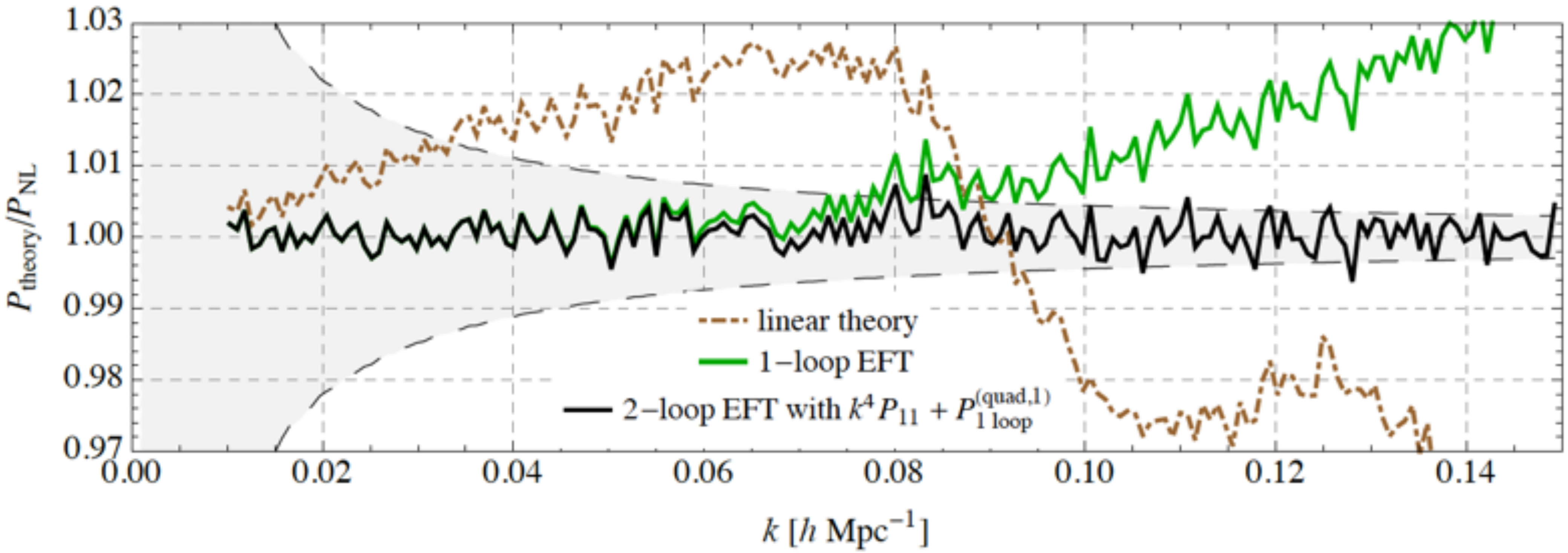
Leonardo Senatore (Stanford)

Aspects of the Effective Field Theory of Large Scale Structures

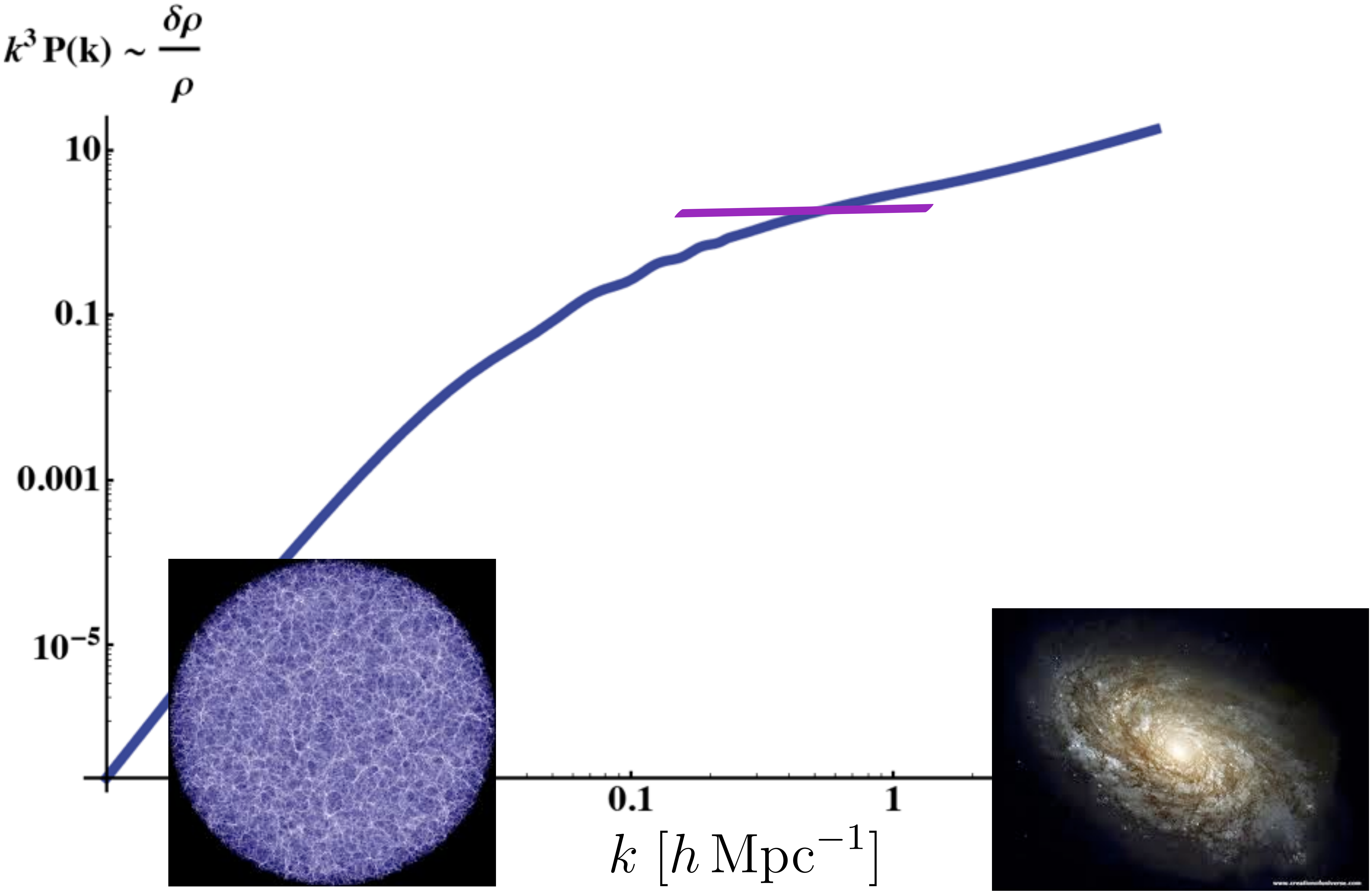
Leonardo Senatore (Stanford)

Making of
Large Scale Structures Science
a
High Precision Science

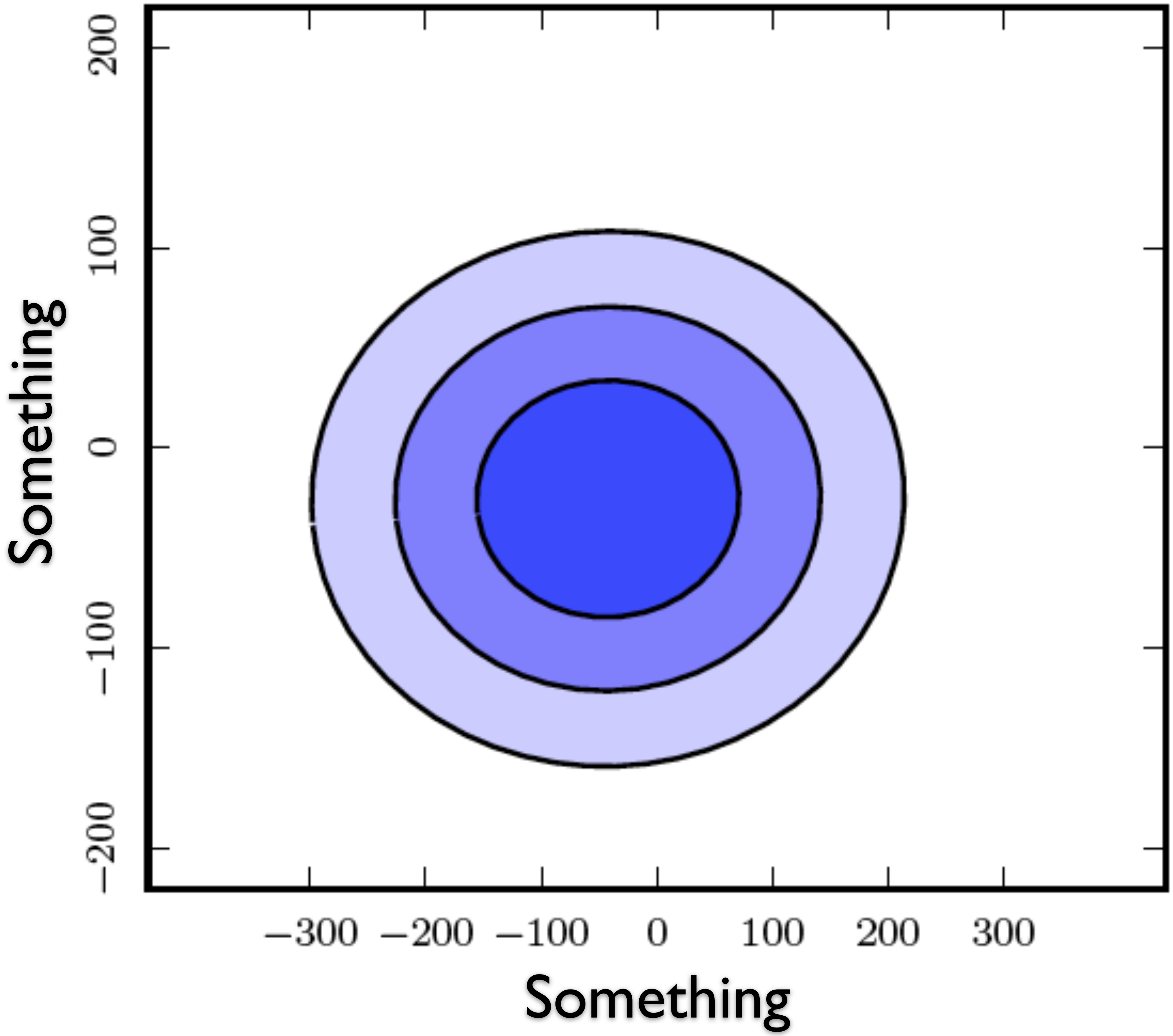


The EFTofLSS: A well defined perturbation theory

- Non-linearities at short scale



With this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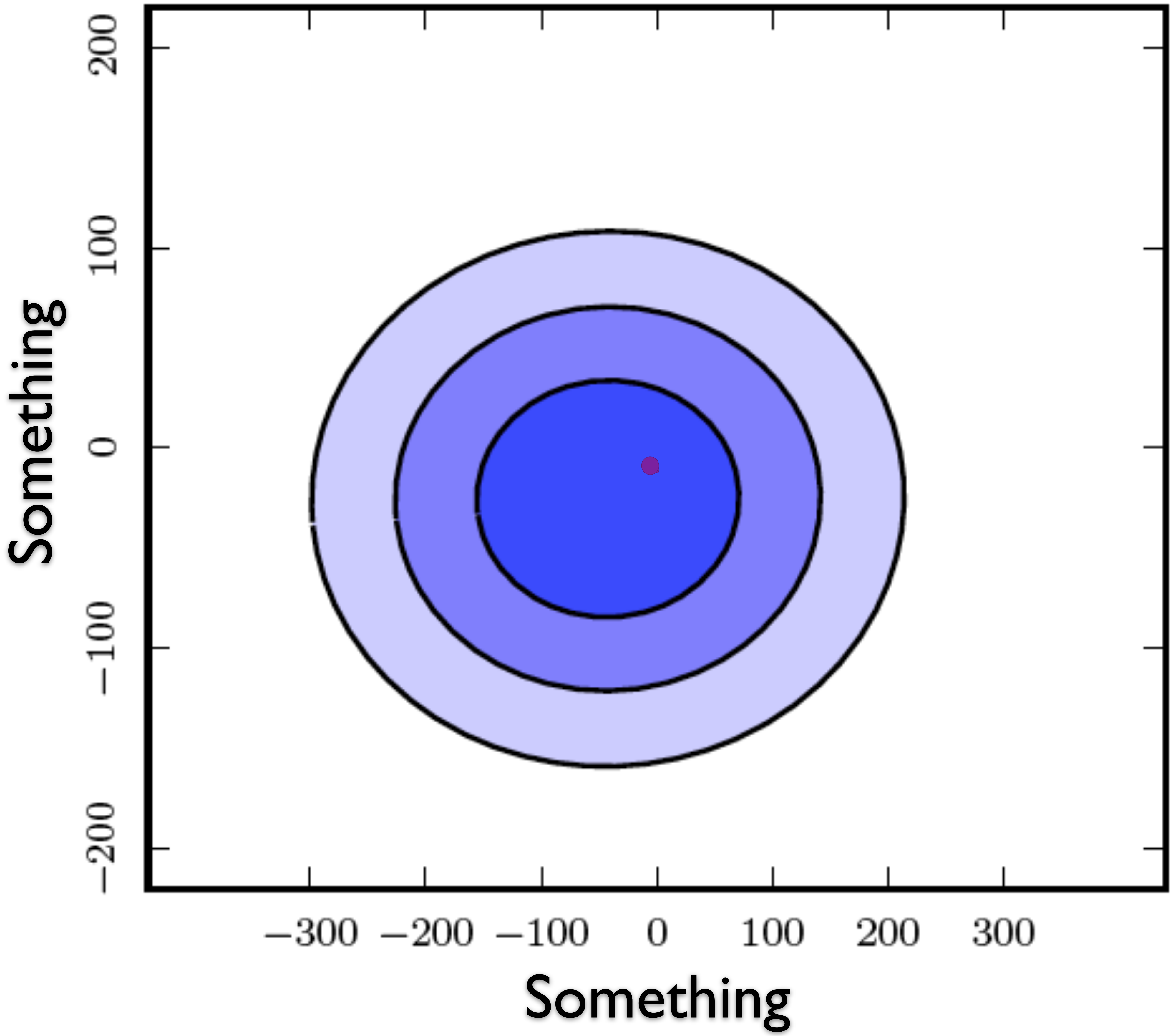
With this



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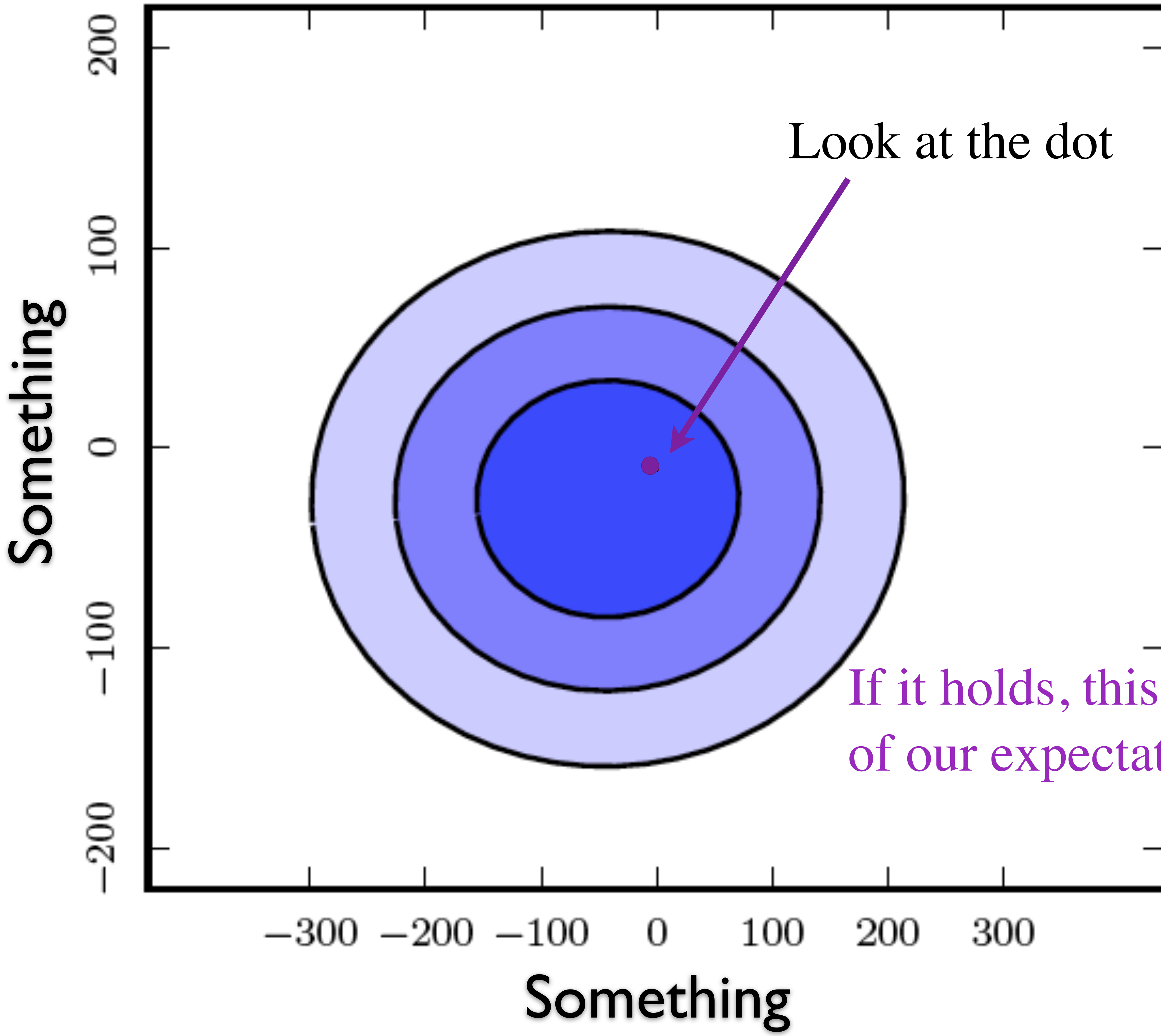
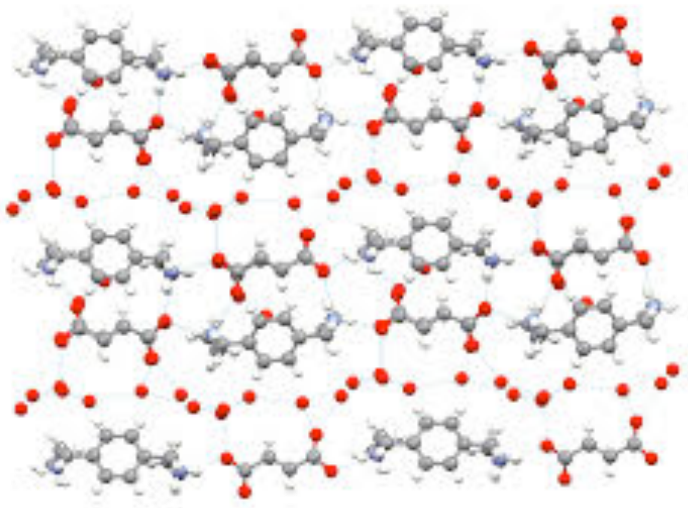
With this

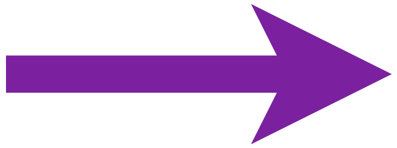


If it holds, this is a revolution
of our expectations

The Theory of the Universe

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

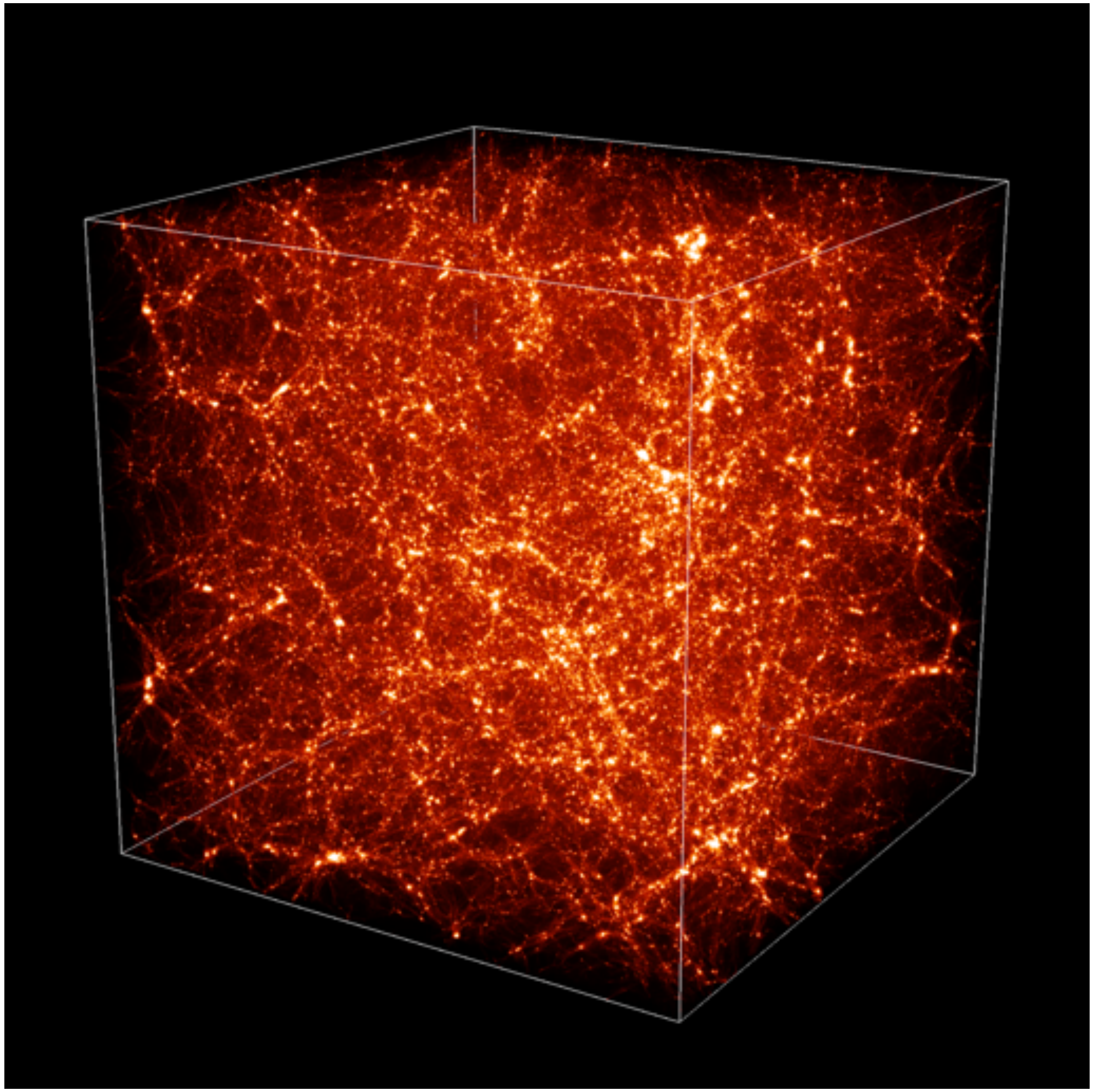




- similarly the long distance universe *is* the system described by the EFTofLSS

Normal Approach: numerics

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



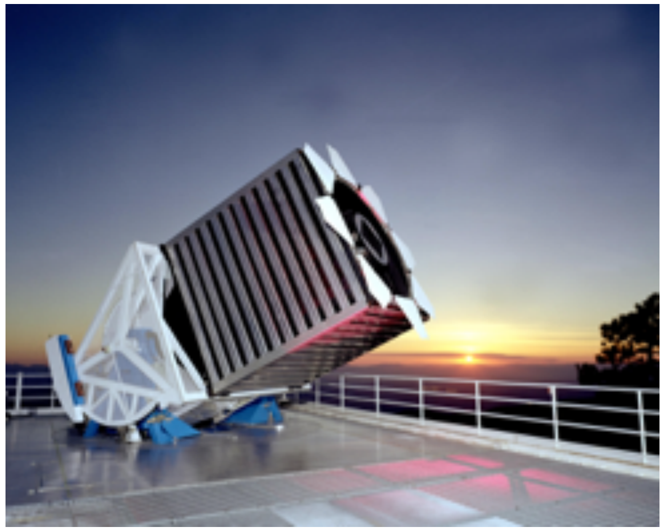
Why numerics are not enough

- they do not give the simple description of the system
- In principle, we can simulate the clustering of dark matter with N-body sims
- But
  - simulations with dark matter are very slow
    - systematic error of order 1$\%$

A. Schneider, R. Teyssier, … V. Springel *et al*. **1503**

  - we cannot simulate baryons: we can only `model' them

– As a proof, SDSS stops analyzing data at $k \simeq 0.1\, h\mathrm{Mpc}^{-1}$



Numerics have been great

- Do not misunderstand me:
  - numerical simulations have provided some of the most beautiful history-making discoveries:
    - dark matter is cold
    - structures form from small to big
    - …

many due to Simon White here!

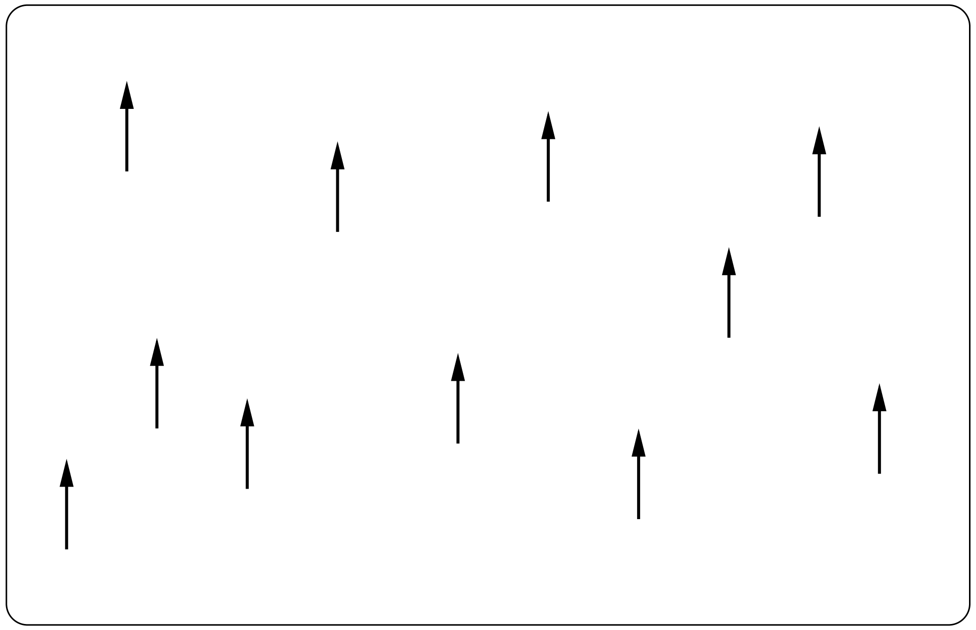
- But I believe, after these giants, we live in hard times
  - and to make further progress, high precision is required
    - N-body sims do not seem, to me, the only appropriate tool.

Idea of the
Effective Field Theory

Consider a dielectric material

- Very complicated on atomic scales d_{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

Dielectric Fluid



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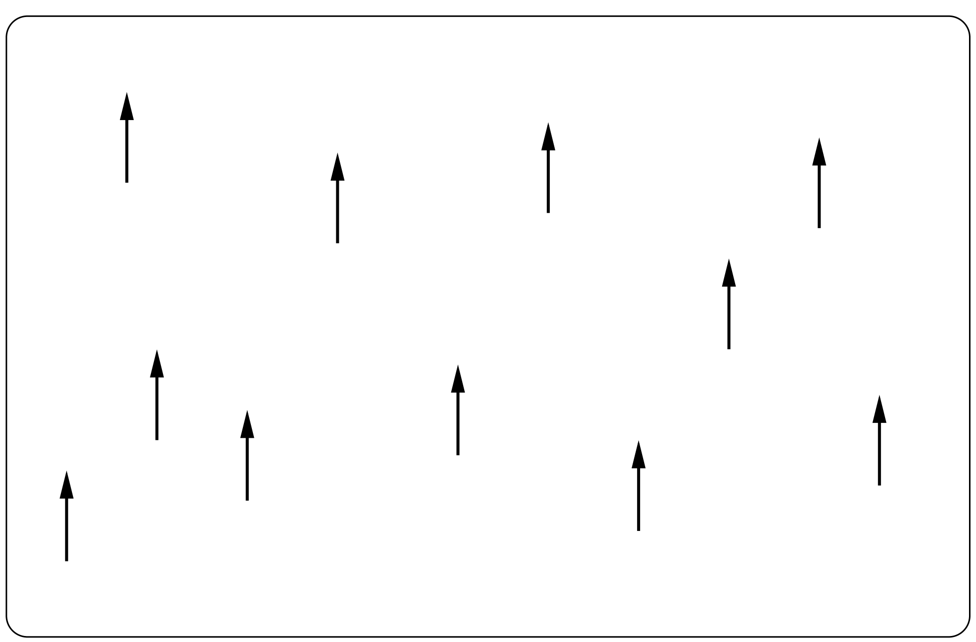
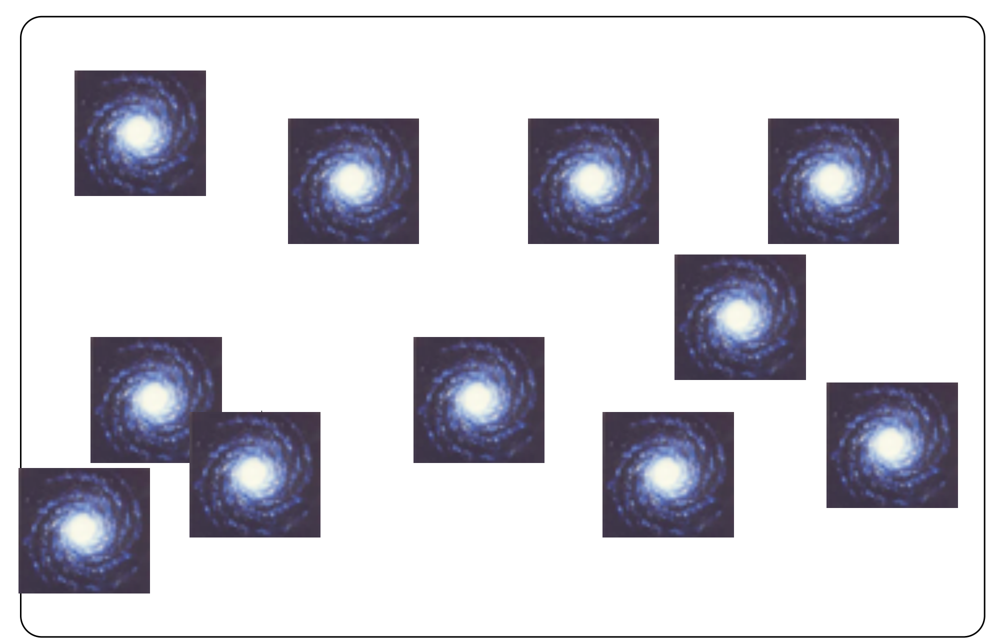
- The universe looks like a dielectric

$$\text{EM} \quad \longrightarrow \quad \text{GR}$$

Dielectric Fluid



Dielectric Fluid



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 ~ $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

 – 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**

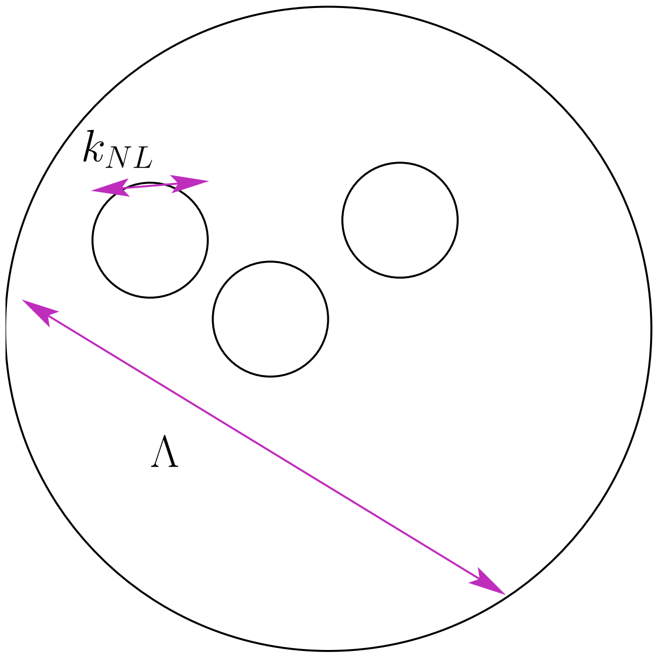
– short distance physics appears as a non trivial stress tensor for the long-distance fluid

$$\tau_{ij} \sim \delta_{ij}\,\rho_{\rm short}\,\left(v^2_{\rm short} + \Phi_{\rm short}\right)$$

Dealing with the Effective Stress Tensor

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

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



- We obtain equations containing only long-modes

$$\nabla^2 \Phi_l = H^2 \frac{\delta\rho_l}{\rho}$$

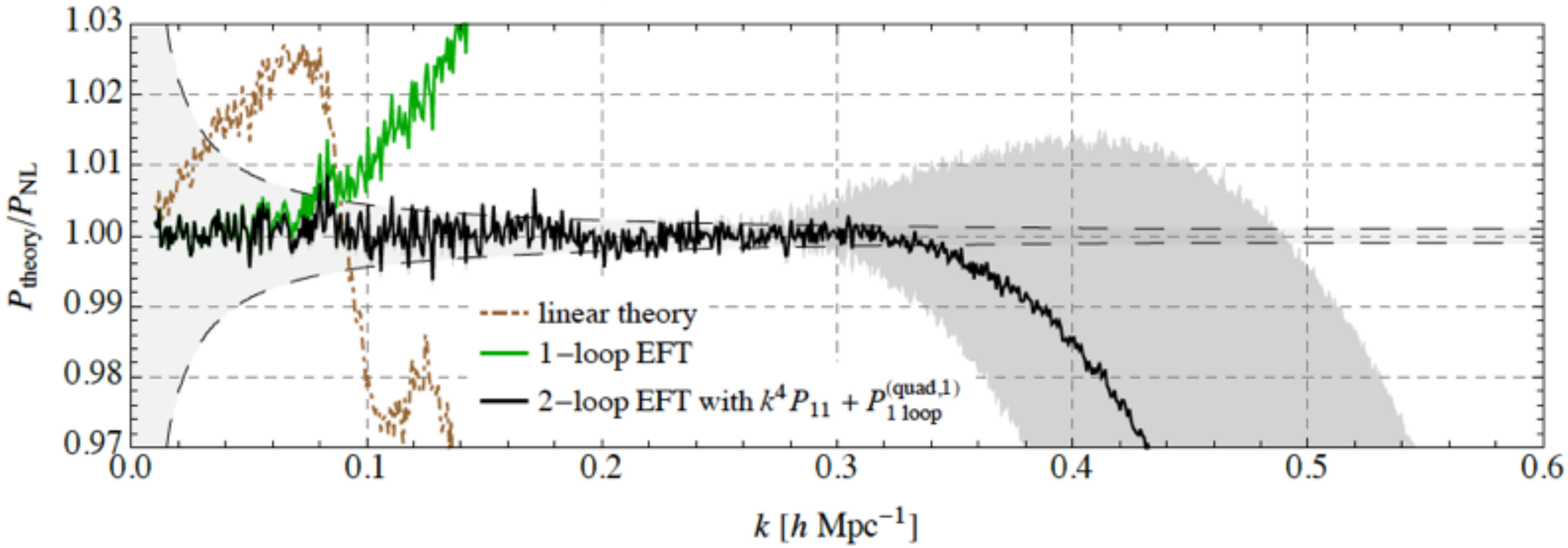
$$\partial_t \rho_l + H\rho_l + \partial_i \left(\rho_l v_l^i \right) = 0$$

$$\dot{v}_l^i + H v_l^i + v_l^j \partial_j v_l^i = \frac{1}{\rho} \partial_j \tau_{ij}$$

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

- How many terms to keep?
  - –each term contributes as an extra factor of $\frac{\delta\rho_l}{\rho} \sim \frac{k}{k_{\rm NL}}$
    - we keep as many as required precision
    - $\Longrightarrow$ manifest expansion in $\frac{k}{k_{\rm NL}} \ll 1$

A theory, and not a model



- The EFTofLSS is a *theory* and not a *model*
  - no guess-work, no intuition
  - It Taylor expands in well defined, small parameters
    - Order by order improvement
    - We can estimate the theory error
    - We can compute the next order and the result will improve
  - Several observables are connected
    - all of this does not happen for a model

How do we know the EFTofLSS is right?

- The EFTofLSS is *the* theory of the long distance universe
  - By using only the symmetries of the problem, the Effective Field Theory correctly describes the LSS
    - in this sense, it is manifestly correct
    - this is not presumption
- History of physics have thought us that this is possible
  - GR is the EFT of a spin-2 particle
  - E&M for dielectrics is an EFT
  - The Chiral Lagrangian is an EFT
  - …
    - All these theories have free parameters, but these parameters are guaranteed to make the theory approach the truth order by order in a perturbative expansion

Perturbation Theory with the EFT

Perturbation Theory within the EFT

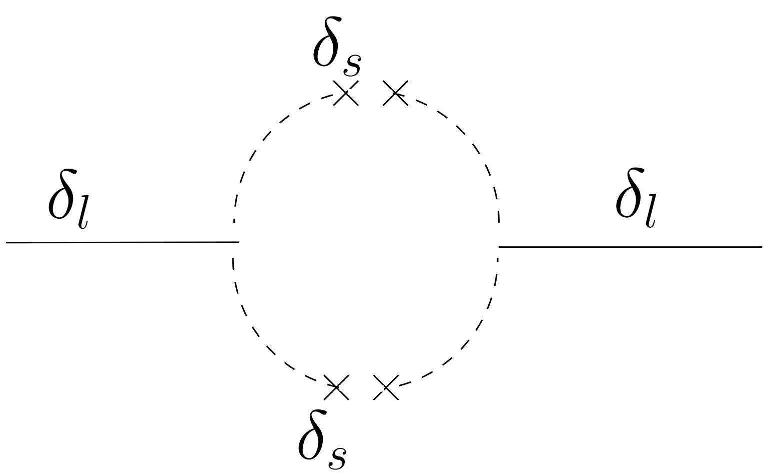
- In the EFT we can solve iteratively $\delta_\ell, v_\ell, \Phi_\ell \ll 1$

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

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

–need to renormalize

- as loops with short-distance mode not under control:



- crucial difference wrt former techniques

Connecting with the Eulerian Treatment

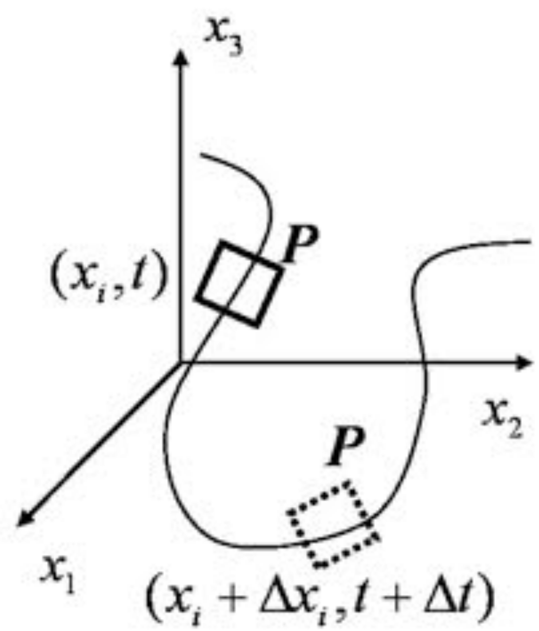
- When we solve iteratively these equations in $\delta_\ell, v_\ell, \Phi_\ell \ll 1$,
  - this corresponds to expanding in two parameters:

$$\epsilon_{\rm tidal}(k) \sim \int^k d^3q\ P(q)$$

Effect of Long Overdensities

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

Effect of Long Displacements

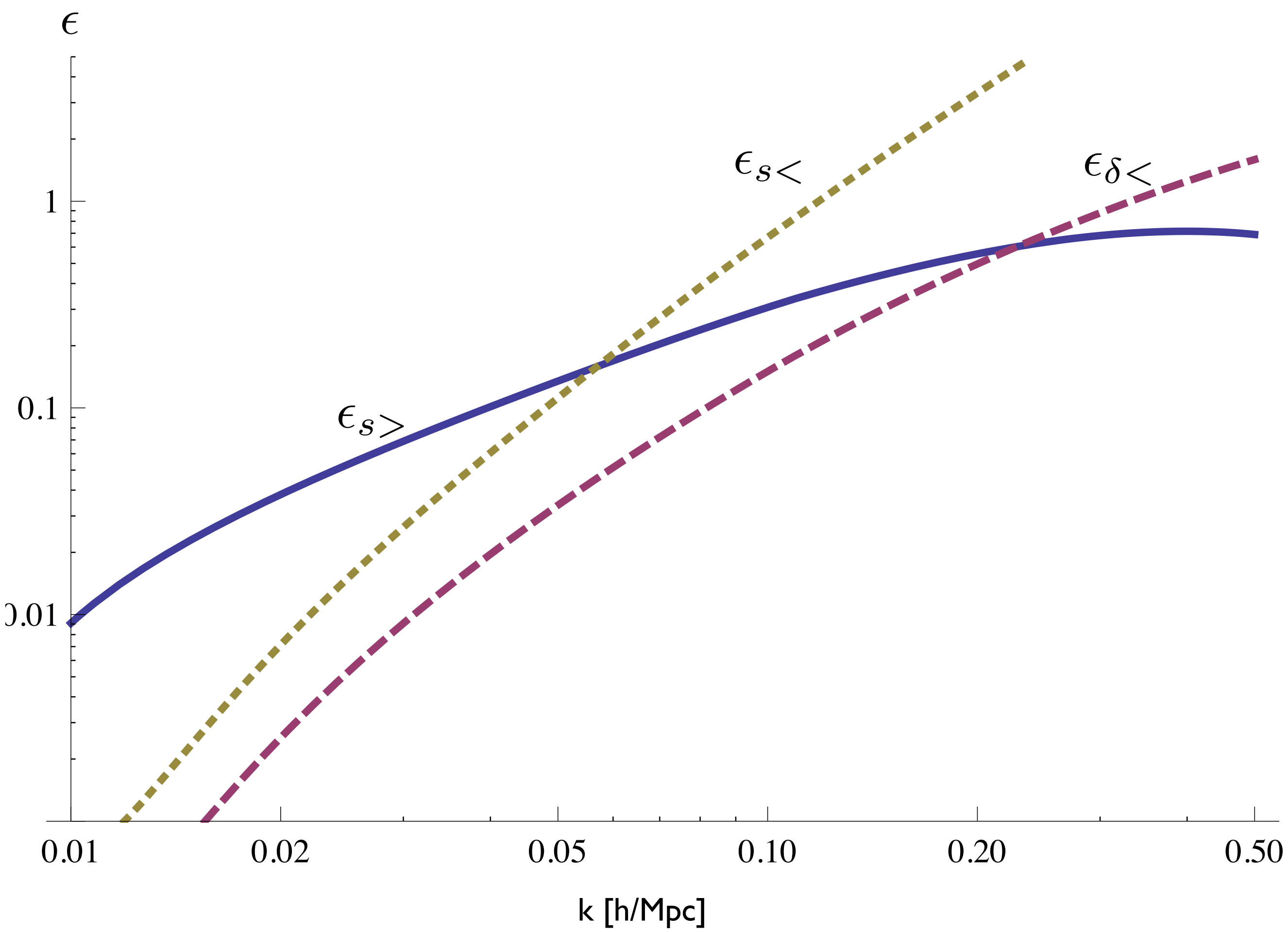


- Displacement from long modes, longer than the BAO, cancel in $P(k)$ by GR
- $\Longrightarrow$ they are important only for the BAO

with Zaldarriaga **JCAP1502**
see originally Scoccimarro and Frieman **9609047**

Perturbation Theory in our Universe

- Our universe has more than one scale: parameters scale differently.



$\epsilon_{\text{long displacement}}$ 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)

with Zaldarriaga **JCAP1502**

- After IR-resummation, and after renormalization, each loop goes as power of $\left(\epsilon_{\text{tidal}}\right)^L$

Was the IR-resummation already done by Zeldovich?

You are reinventing the wheel

– assessment from a famous theorist

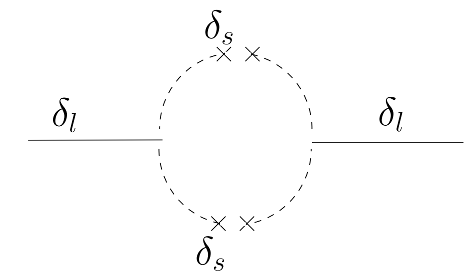
- Zeldovich had already `guessed' a way to get a solution by non-expanding in $\epsilon_{\text{long displacement}}$
- *But*:
  - –Zeldovich approximation is an approximation in ϵ_{tidal}
    - It is just a super-clever, awesome, humbling.... approximation
    - but it does not tell us how to include the next correction in ϵ_{tidal}, it ignores it
      - two decades of failing in making Lagrangian PT work demonstrate this
- Our IR-resummation goes beyond Zeldovich, because it allows us to go to arbitrary order in ϵ_{tidal}
  - this is what I would call to understand the problem

with Zaldarriaga **JCAP1502**

Results for Dark Matter

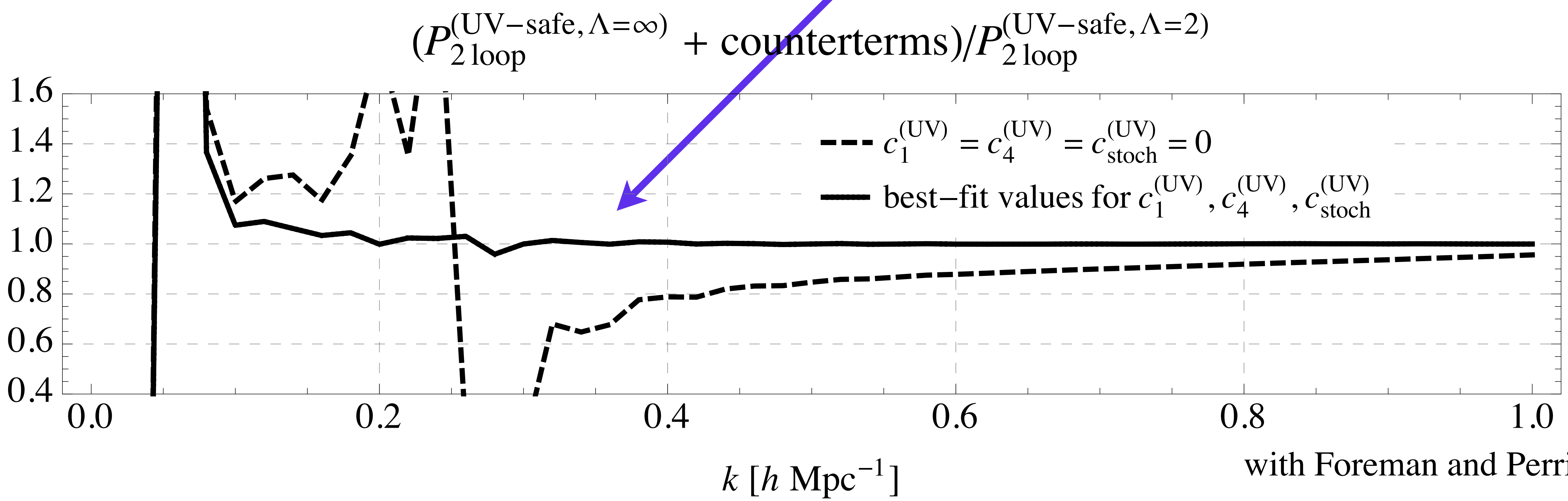
EFT of Large Scale Structures

- 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 $\partial^2 \tau_{ij} \sim c_s\, k^2 \delta(k)$
- 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



with Foreman and Perrier **1507**

- $\Longrightarrow$ 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

EFT of Large Scale Structures

with Foreman and Perrier **1507**

- At 2-loops, we need speed of sound & quadratic & higher-derivative counterterm:

$$\partial^2 \tau_{ij} \sim c_s \, k^2 \delta(k) + c_1 \, k^2 [\delta^2](k) + c_4 \, k^4 \delta(k)$$

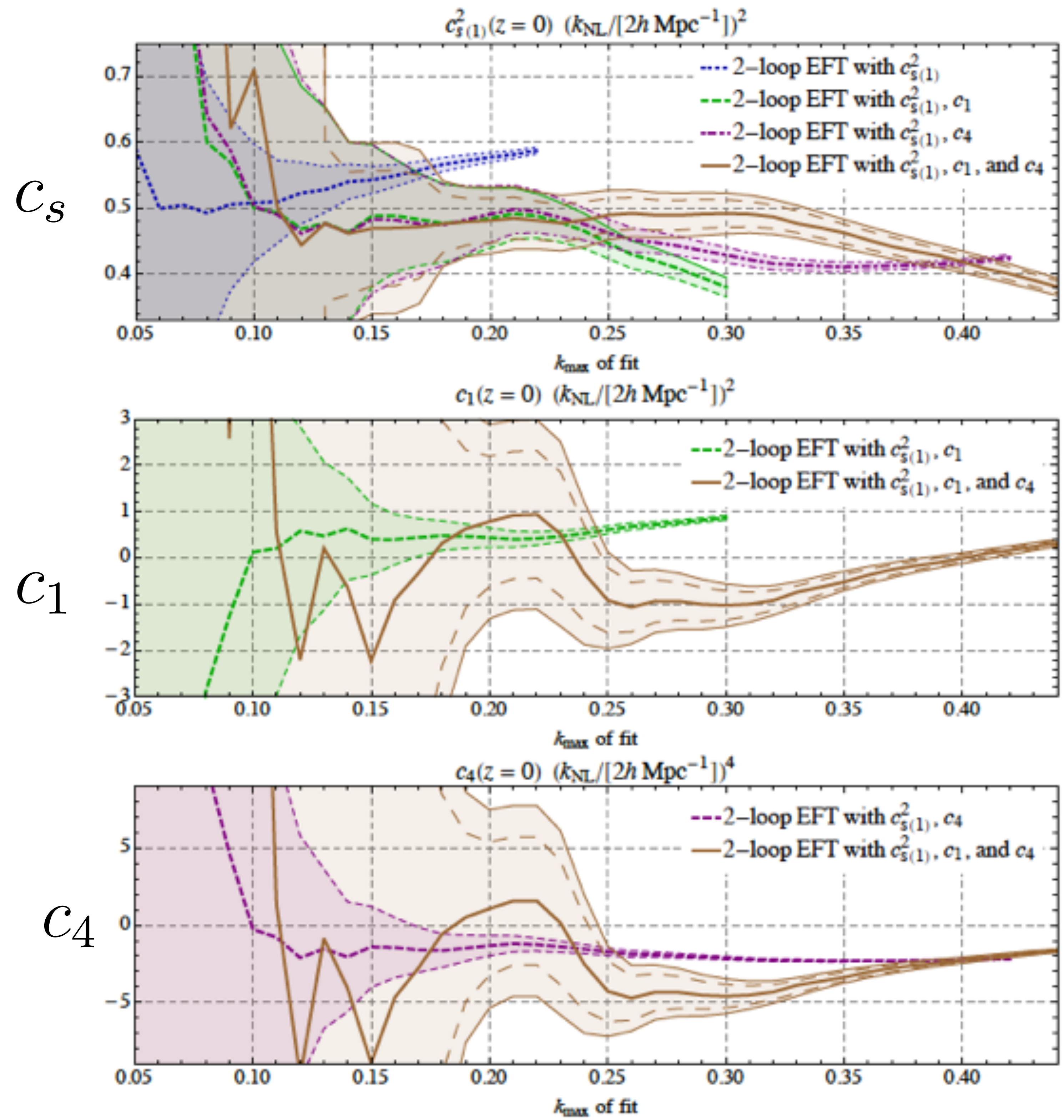
- How to choose for them?
  - Fit them to data
  - How to get sure we do not overfit?
    - As data increase, the improved measurement of parameters should be compatible with measurement with less data

EFT of Large Scale Structures at Two Loops

$$\partial^2 \tau_{ij} \sim c_s\, k^2 \delta(k) + c_1\, k^2 [\delta^2](k) + c_4\, k^4 \delta(k)$$

- As data increase, the improved measurement of parameters should be compatible with measurement with less data

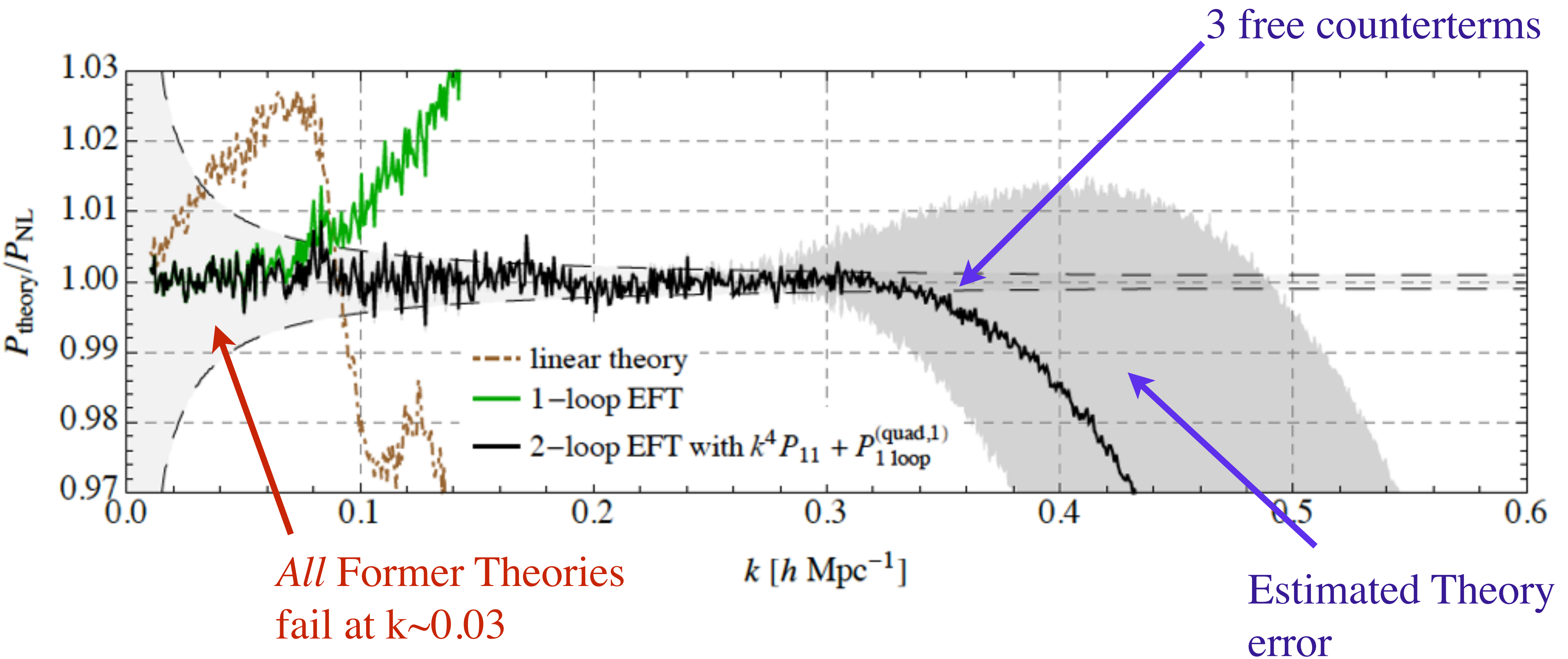
- If we fit until $k \sim 0.32\, h\, \mathrm{Mpc}^{-1}$ we are not overfitting



with Foreman and Perrier **1507**

EFT of Large Scale Structures at Two Loops

- $\partial^2\tau_{ij} \sim c_s\, k^2\delta(k) + c_1\, k^2[\delta^2](k) + c_4\, k^4\delta(k)$



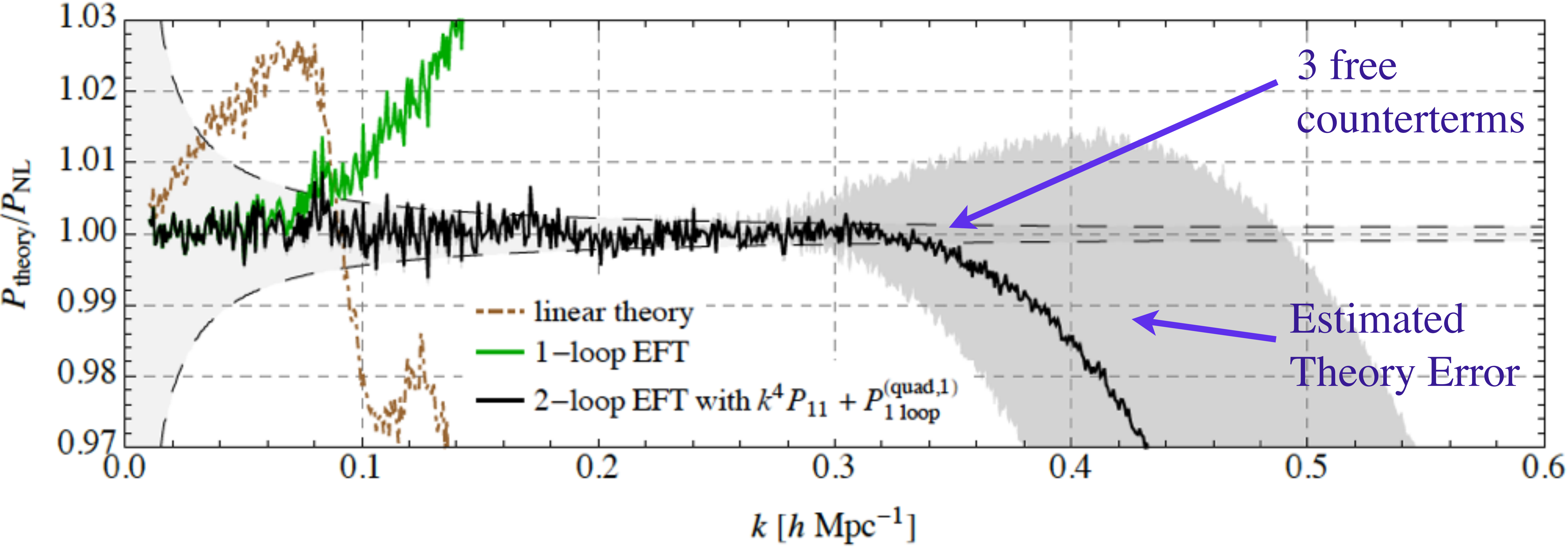
- k-reach pushed to $k \sim 0.34\, h\, {\rm Mpc}^{-1}$, cosmic variance $\sim 10^{-3}$
- Order by order improvement $\left(\frac{k}{k_{\rm NL}}\right)^L$
- Huge gain wrt former theories

with Carrasco, Foreman and Green **JCAP1407**
with Zaldarriaga **JCAP1502**
with Foreman and Perrier **1507**

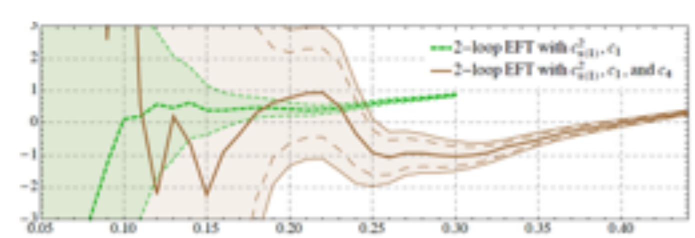
EFT of Large Scale Structures at Two Loops

with Foreman and Perrier **1507**

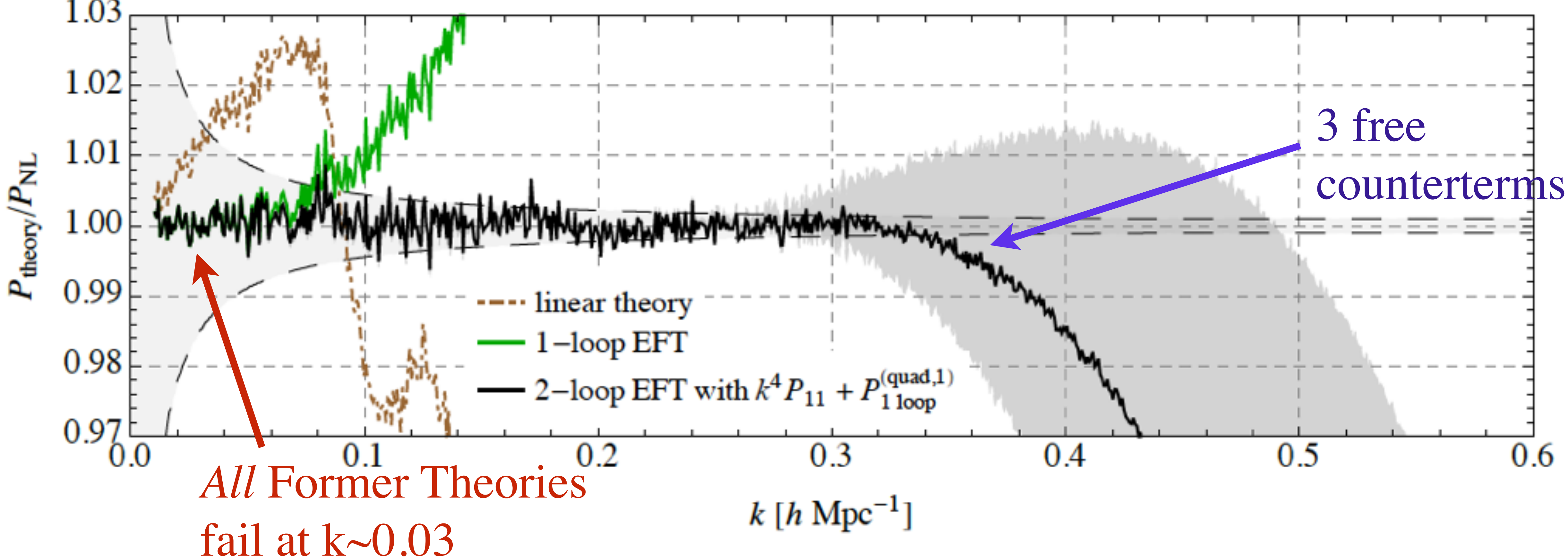
$$\partial^2 \tau_{ij} \sim c_s \, k^2 \delta(k) + c_1 \, k^2 [\delta^2](k) + c_4 \, k^4 \delta(k)$$



- 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 1σ compatibility of measurement of parameters as we increase $k_{\rm fit}$
  - If we set $P_{\text{2-loop}} = 0$, then fit to data is very bad

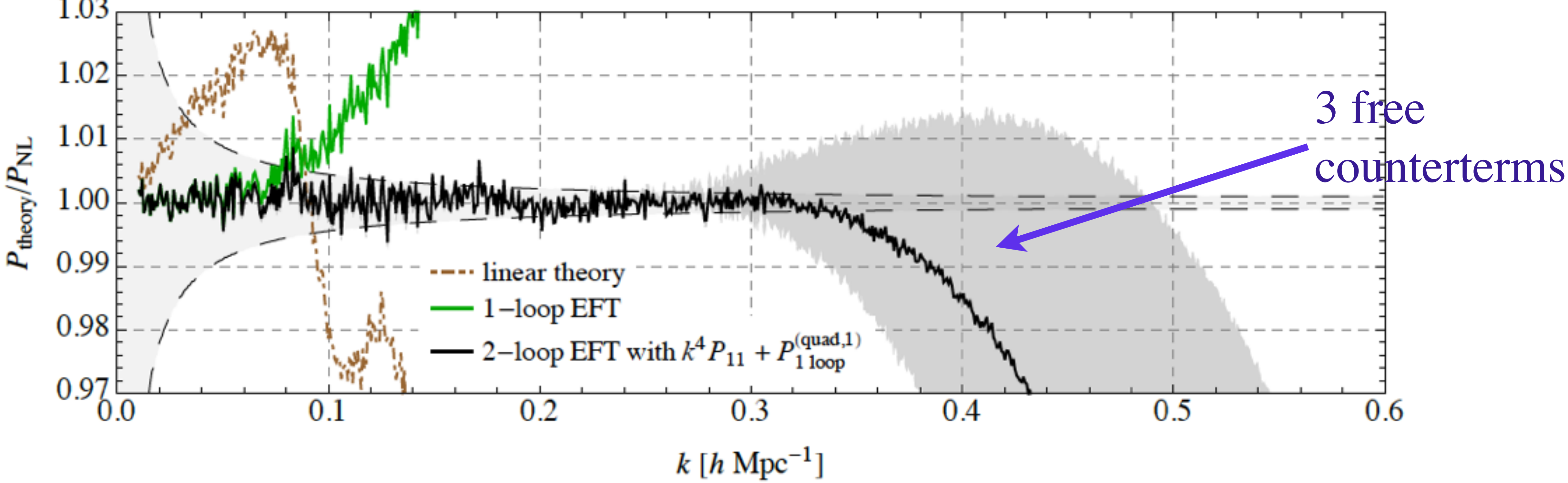


EFT of Large Scale Structures at Two Loops

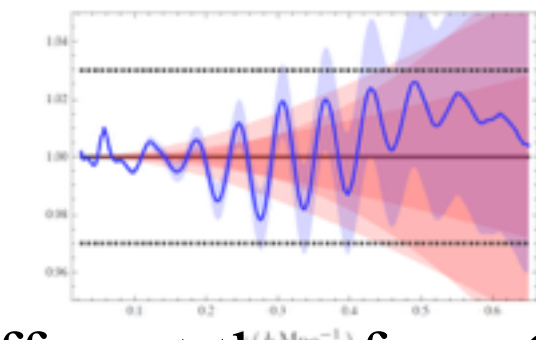


- All former theories, RPT, LPT,…. differ from SPT just by the IR-resummation
- $\Longrightarrow$ by GR, IR-modes cancel in $P(k)$, so cannot change the UV-reach of the theory
  - they just change the BAO, which are 2% oscillations in k-space
- So, if you see plots where RPT is improving the UV-reach wrt SPT, it is not *just* IR-resummation, but something else which, to me, is physically not derived nor justified
  - at this point, you can call RPT as you wish (fitting function? ansatz?…you choose)
    - it does not seem to me a well defined theory.

EFT of Large Scale Structures at Two Loops



- 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.

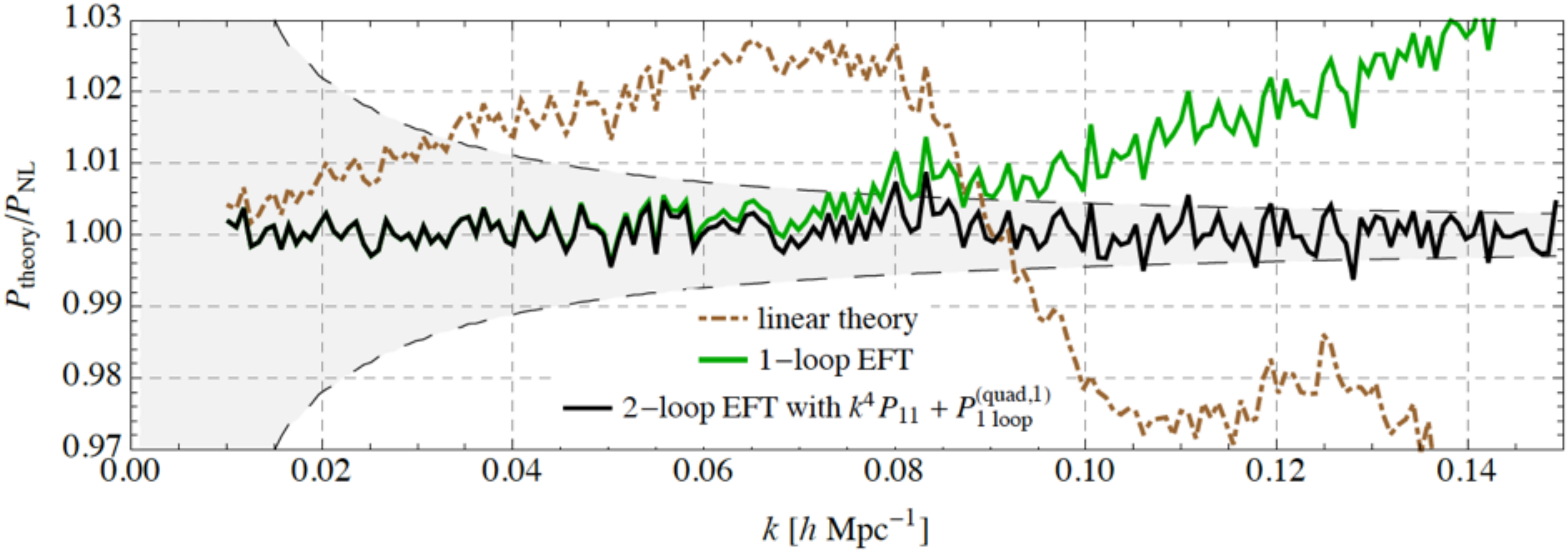


  - Using Coyote-emulator data, 2% sys. error bars
- More precise data show that the c_s parameter is 30% different than from Coyote
  - reduces the k-reach a bit more than expected (not by much though)

Baldauf 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 $k \sim 0.03\, h\, \mathrm{Mpc}^{-1}$!) 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

Precision at low k's



- k-reach is not everything. Precision at low k's is also important and great
  - no matter the k-reach, at low k's very fast convergence.
- Look where linear theory fails!, $k \sim 0.03\, h\, \mathrm{Mpc}^{-1}$, and these are Euclid-like error bars!
- 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

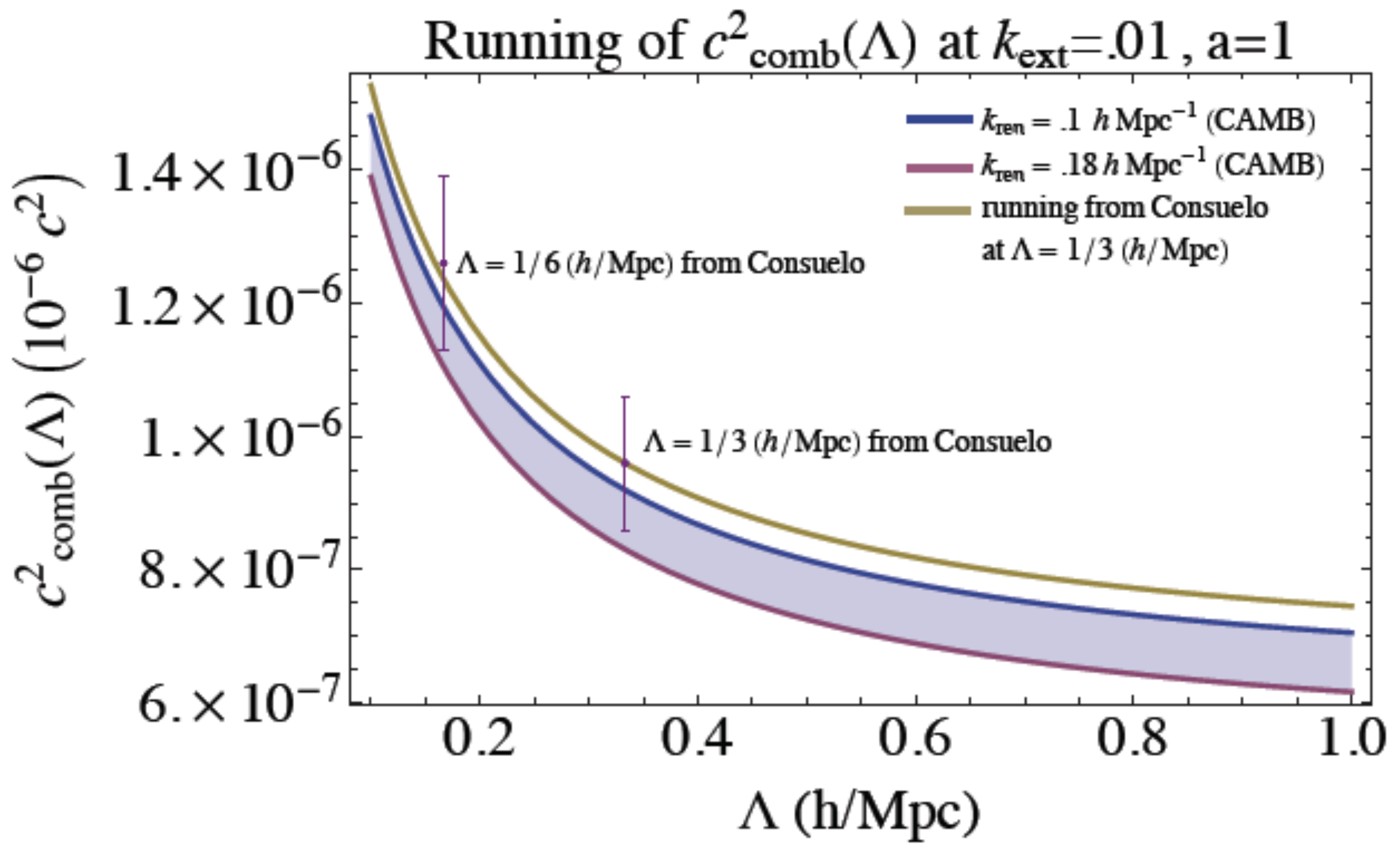
In the EFTofLSS we need parameters.
Let us measure them from
small N-body Simulations!

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:

$$\tau_{ij} \sim \sum_i m_i \left(v_i^2 + \phi_i\right)$$



- Agreement with fitting from Power Spectrum directly

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

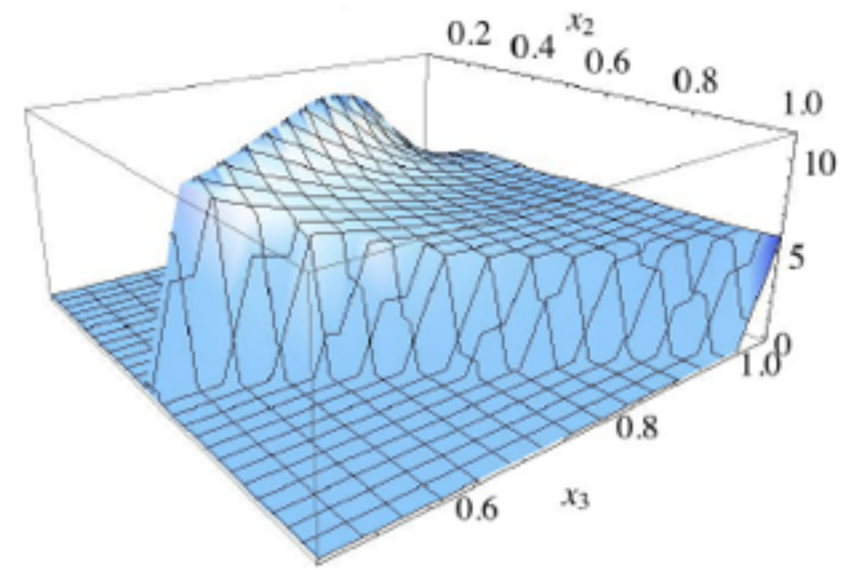
with Carrasco and Hertzberg **JHEP 2012**

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 **JCAP1407**

- Vorticity Spectrum with Carrasco, Foreman and Green **JCAP1407**
  - agrees with most accurate measurements in simulations

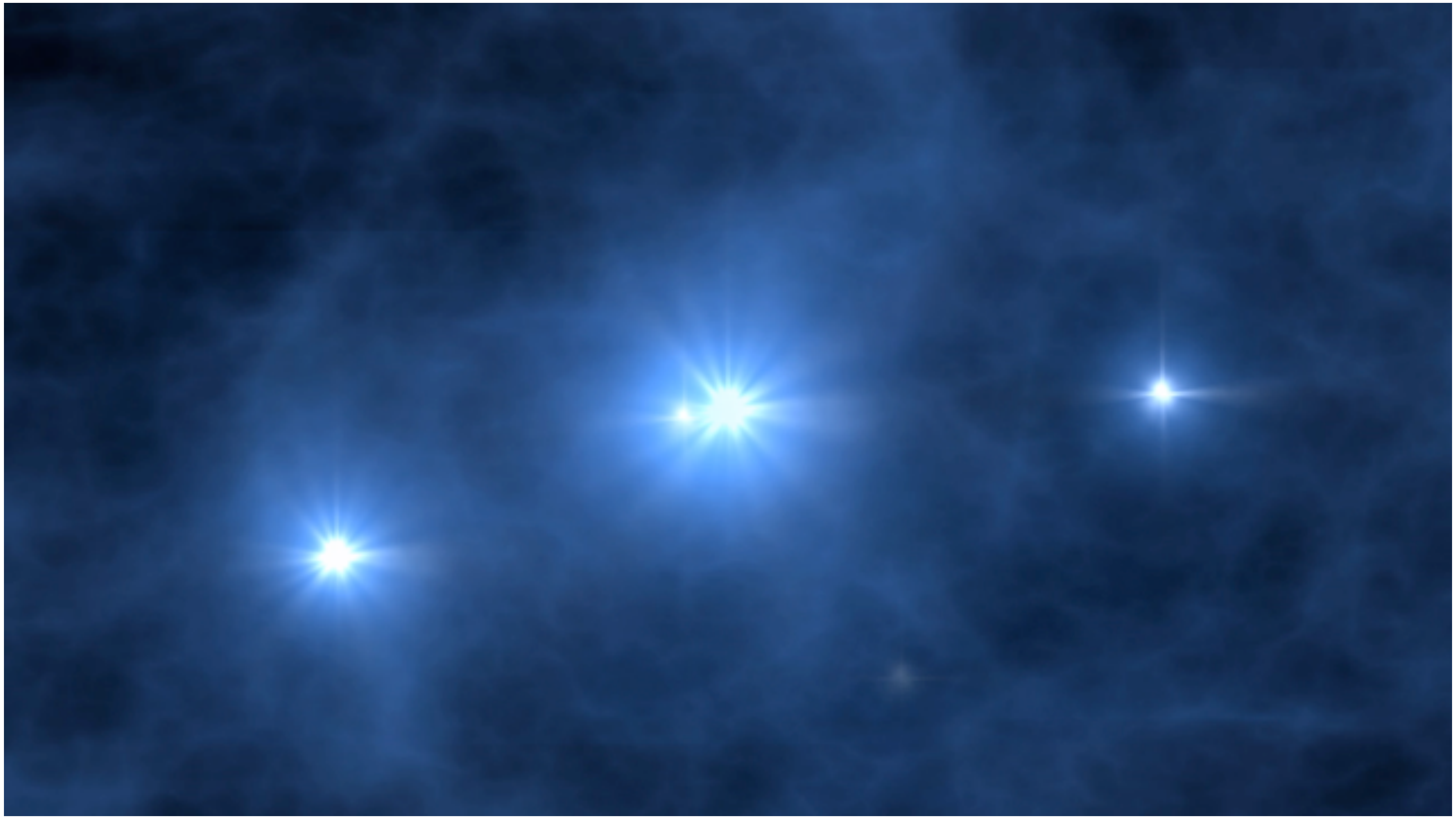
Pueblas and Scoccimarro **0809**
Hahn, Angulo, Abel **1404**

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 $1/k_{\rm NL} \sim 10\,{\rm Mpc}$
    - $\Longrightarrow$ 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

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

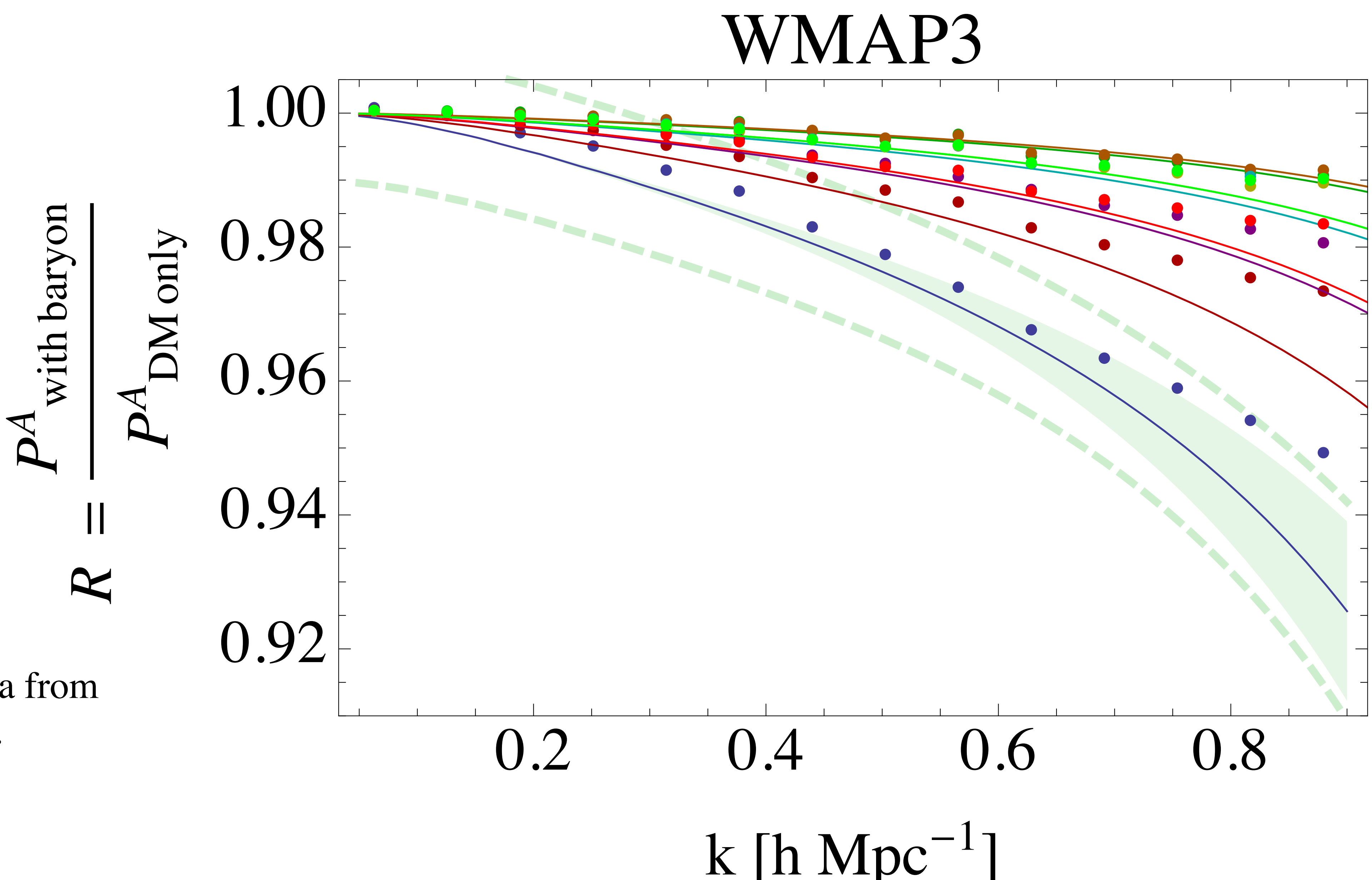
    - $\Longrightarrow$ it is an effective fluid with similar mean free path
  - Universe with CDM+Baryons $\Longrightarrow$ EFTofLSS with 2 species
- The effective force on baryons: expand force in long-wavelength fields:

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

gravity-induced pressure

star formation-induced pressure

Baryons



Simulation data from
J. Schaye et al.

– Analytic form of effect known: $\Delta P_b(k) \simeq c_\star^2 \left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}^A(k)$

– and it seems to work as expected

Halos Power and Bispectrum

Senatore (alone) **1406**
with Angulo, Fasiello and Vlah **1503**

Halos in the EFTofLSS

- Similar considerations apply to biased tracers:
  - Halo formation depends on fields evaluated on past history on past path

$$\delta_M(\vec{x},t) \simeq \int^t dt'\; H(t')\; \left[\bar{c}_{\partial^2\phi}(t,t')\, \frac{\partial^2\phi(\vec{x}_{\rm fl},t')}{H(t')^2}\right.$$
$$\left. + \bar{c}_{\partial_i v^i}(t,t')\, \frac{\partial_i v^i(\vec{x}_{\rm fl},t')}{H(t')} + \bar{c}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\, \frac{\partial_i\partial_j\phi(\vec{x}_{\rm fl},t')}{H(t')^2}\frac{\partial^i\partial^j\phi(\vec{x}_{\rm fl},t')}{H(t')^2} + \dots\right].$$

Senatore **1406**
Mirbabahi, Schmidt, Zaldarriaga **1412**

    - this generalizes and completes McDonald and Roy **0902**
    - this correctly parametrizes assembly bias

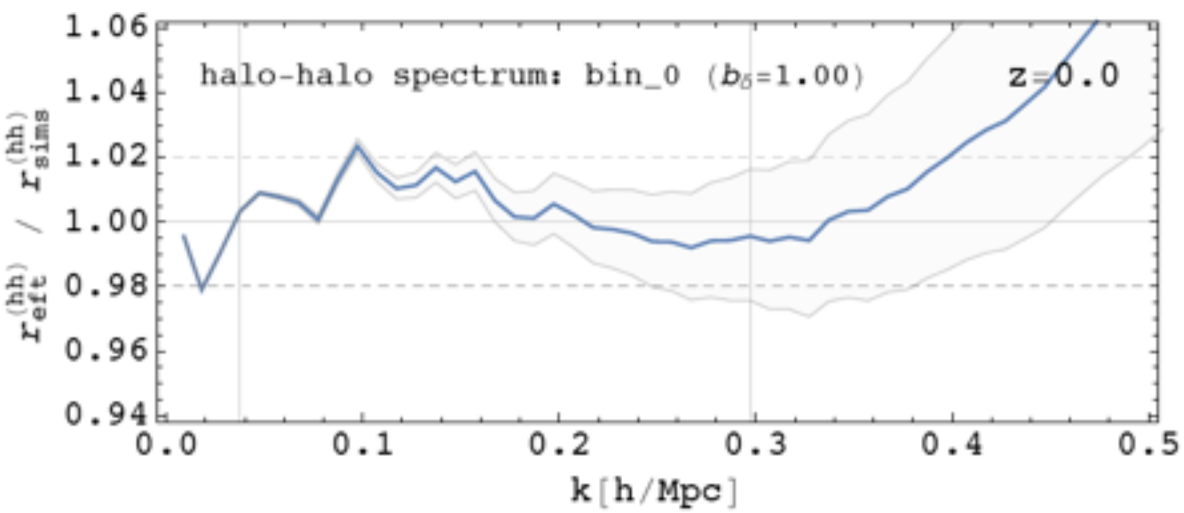
- Since evolution is k-independent, we can formally evaluate the integrals, to obtain only 7 parameters for
  - at 1-loop power spectrum
  - tree level bispectrum
  - tree level trispectrum

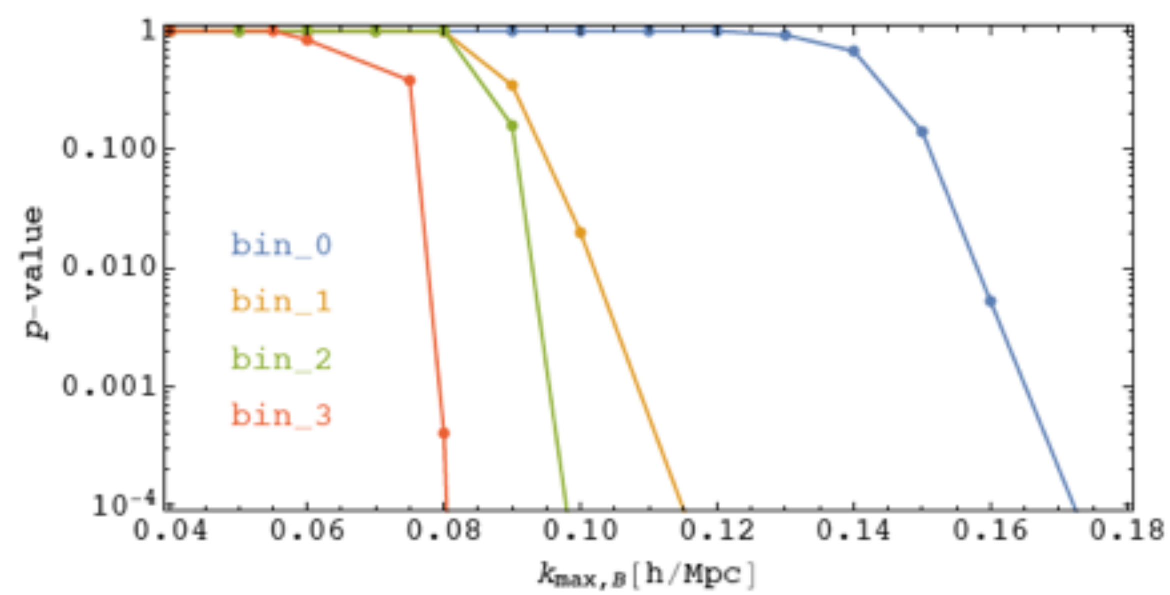
Halos in the EFTofLSS

with Angulo, Fasiello, Vlah **1503**

- We compare $P_{hh}^{1-\mathrm{loop}}$, $P_{hm}^{1-\mathrm{loop}}$, B_{hhh}^{tree}, B_{hhm}^{tree}, B_{hmm}^{tree} using 7 bias parameters

  - Fit works up to $k \simeq 0.3\, h\mathrm{Mpc}^{-1}$ for 1-loop and $k \simeq 0.15\, h\mathrm{Mpc}^{-1}$ at tree-level (for low bins, with large theory uncertainties): as it should

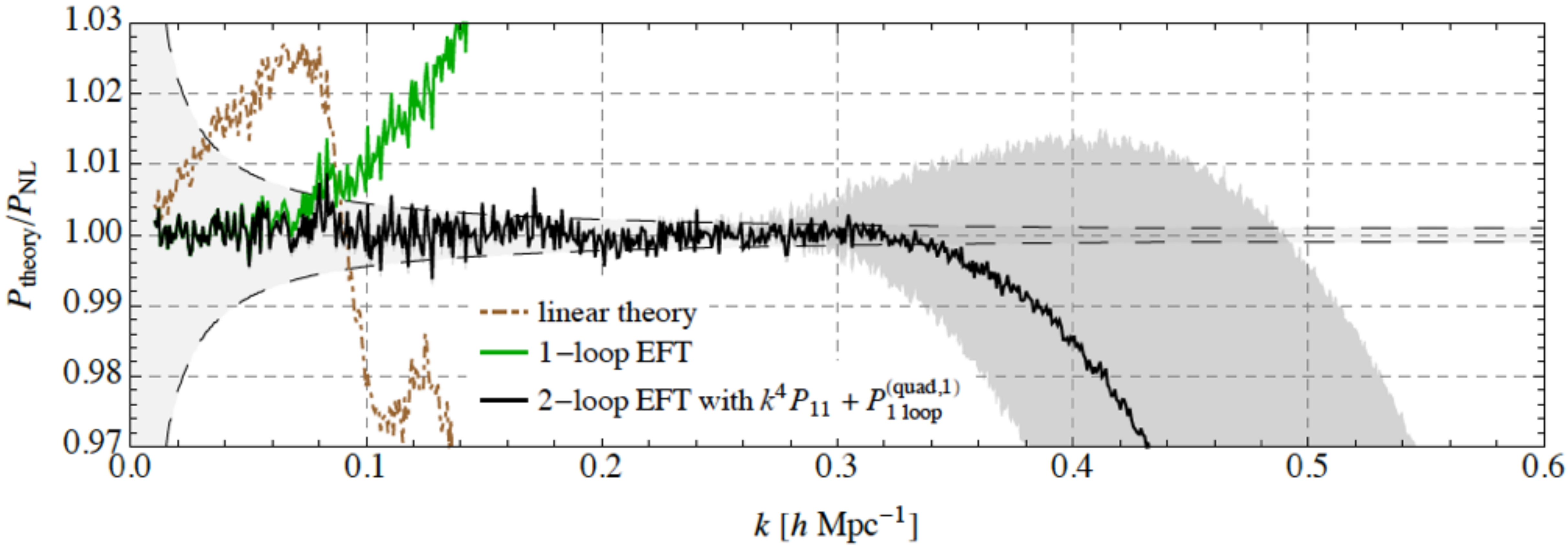




- the 3pt function measures very well the bias coefficients (there is a lot of data)
  - 4pt function is predicted
- Similar formulas just worked out for redshift space distortions

with Zaldarriaga **1409**

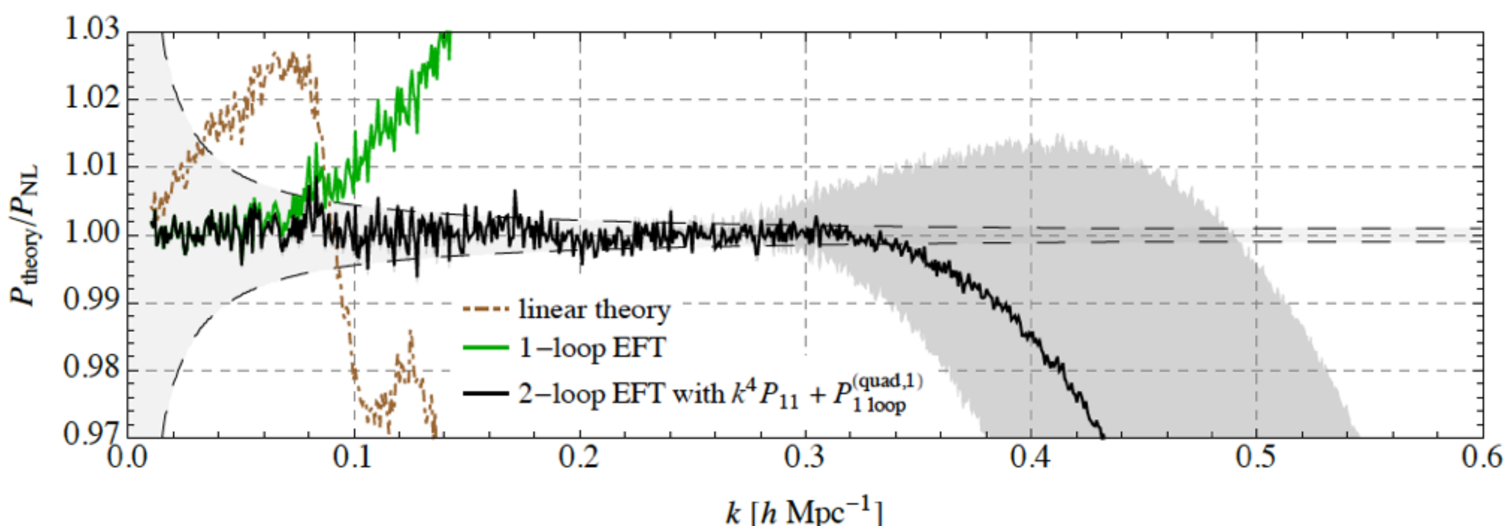
The EFT of Large Scale Structures



- 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 ~10^2 more quasi linear modes than previously believed!
  - –huge impact on possibilities, for ex: $f_{\rm NL}^{\text{equil., orthog.}} \lesssim 1$, 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 and renormalization, IR divergencies
    - Measurements in Simulations (lattice) and lattice-running
- Many calculations and verifications to do
- Huge opportunity for complementarity with simulations
  - Maybe do simulations focussed to convey the EFT parameters?!
- If success continues, revolution in our expectations for next generation experiments
  - on primordial cosmology

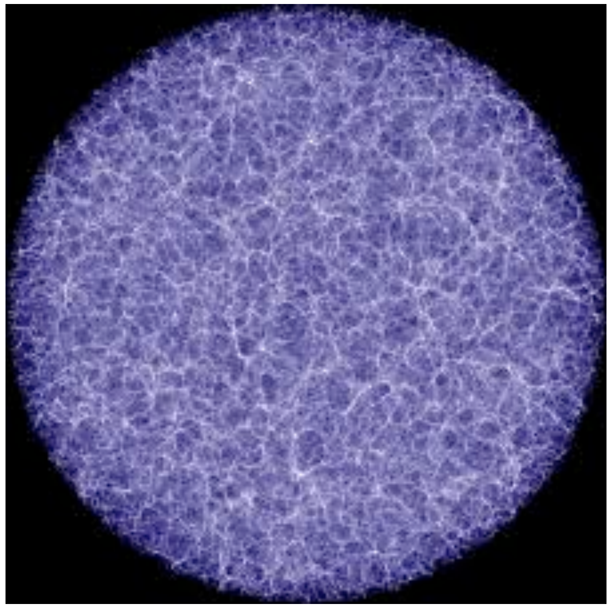


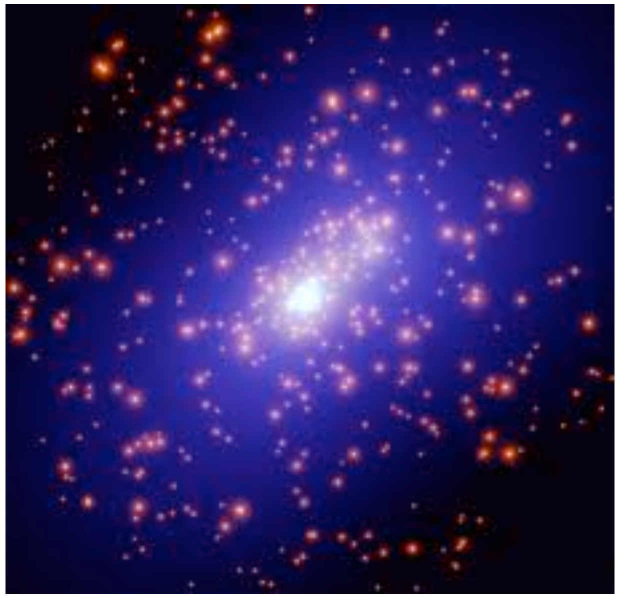
Extra

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**

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

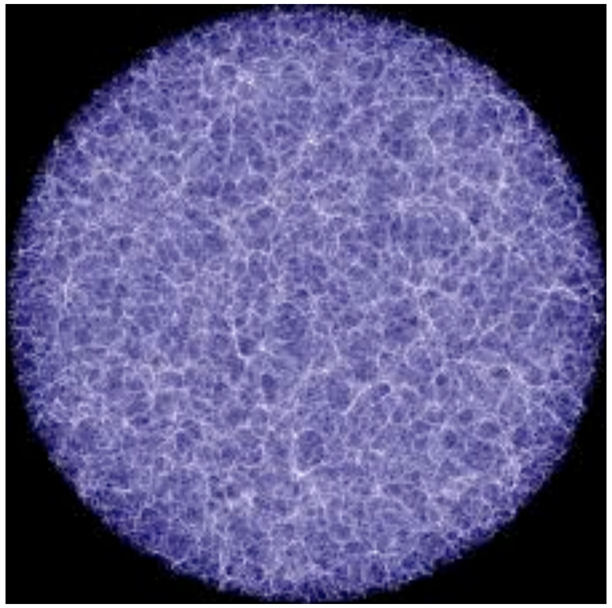
$$\langle \tau_{ij} \rangle_{\delta_l} \sim \int dt' \; K(t,t') \; \partial^2 \phi(x_{\rm fl}, t')$$

  - Technically it does not affect much because the linear propagator is local in space

A Non-Renormalization Theorem

A non-renormalization theorem

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



- 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)

- The backreaction is dominated by modes at the virialization scale

$$\tau_{l,\,ij} \sim \partial_t^2 \left(x^2 \tau_{l,\,00}\right) \sim \frac{H^2}{{k_{\rm NL}}^2} \tau_{l,\,00} \sim 10^{-5} \tau_{l,\,00} \qquad \Rightarrow \qquad w_{\rm induced} \sim 10^{-5}$$

with Baumann, Nicolis and Zaldarriaga **JCAP 2012**

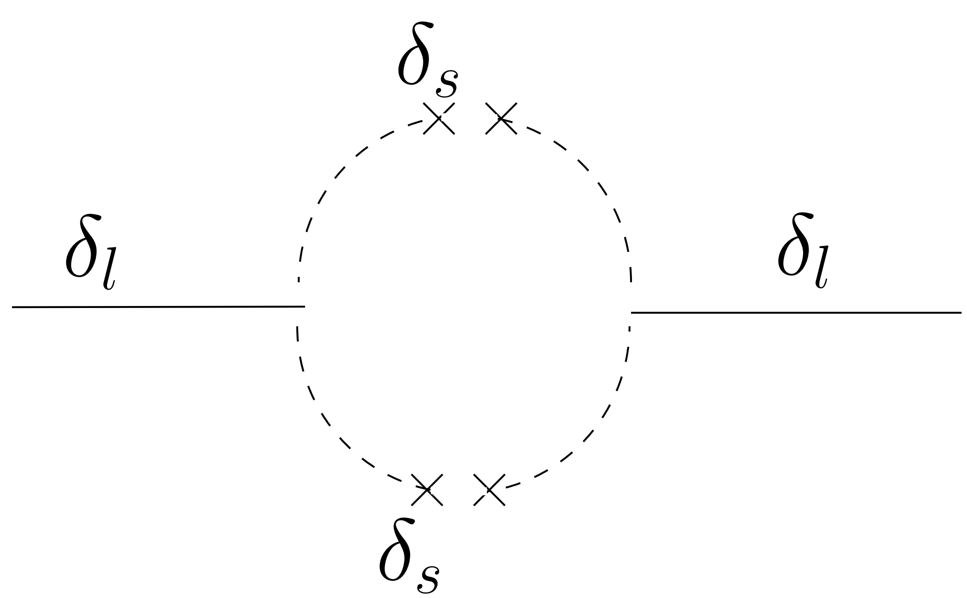
Perturbation theory

Perturbation Theory within the EFT

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

$$\delta^{(n)} \sim \int \mathrm{GreenFunction} \, \times \, \mathrm{Source}^{(n)} \left[\delta^{(1)}, \delta^{(2)}, \ldots, \delta^{(n-1)}\right]$$

$$\Rightarrow \quad \delta^{(2)}(k_l) \sim \int d^3k_s \, \delta^{(1)}(k_s) \, \delta^{(1)}(k_l - k_s) \ , \quad \Rightarrow \quad \langle \delta_l^2 \rangle \sim \int d^3k_s \, \langle \delta_s^{(1)2} \rangle^2$$



Perturbation Theory within the EFT

- 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:

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

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

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

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

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

–we just re-derived renormalization

–after renormalization, result is finite and small

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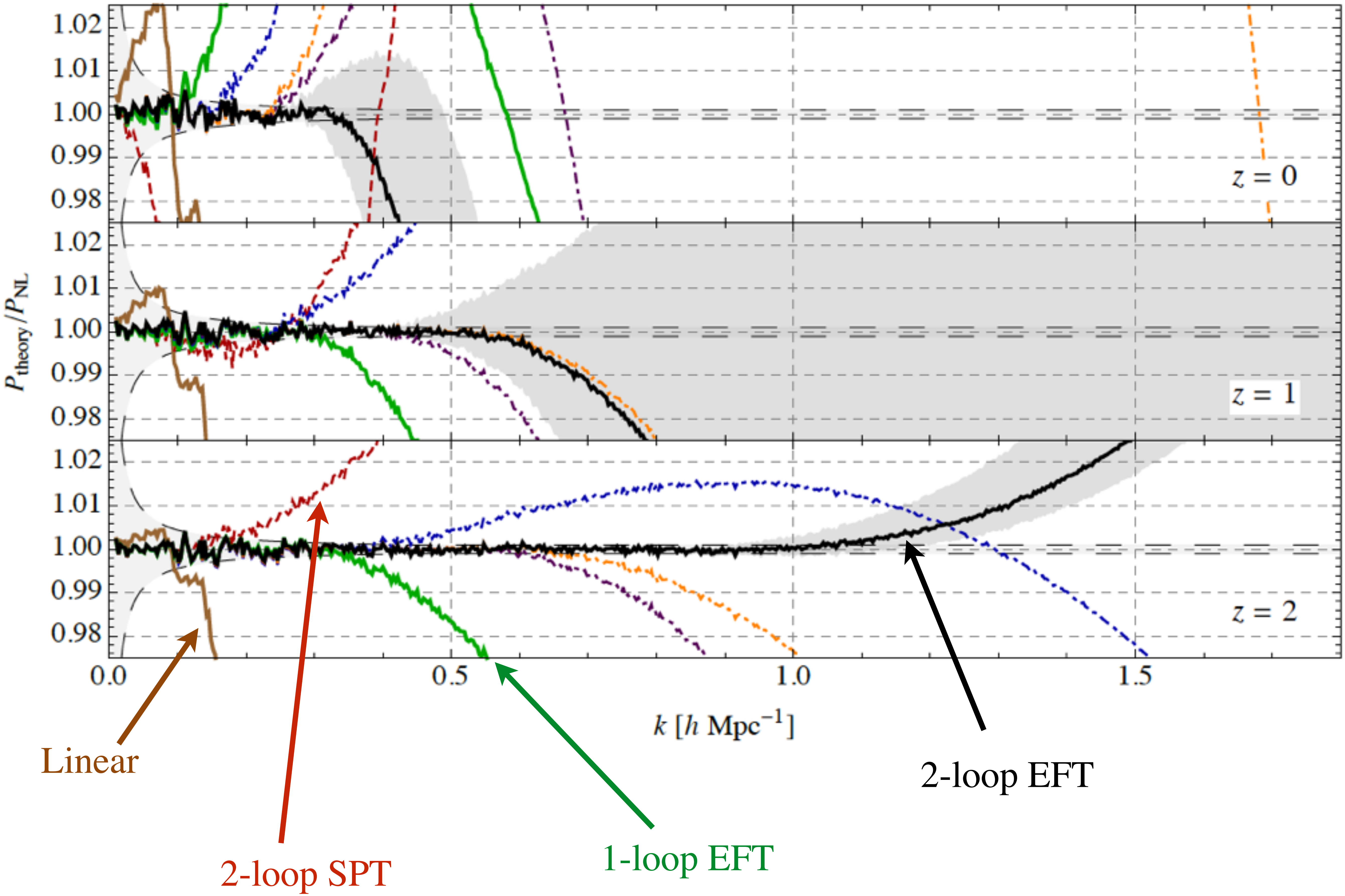
The EFTofLSS at high-z

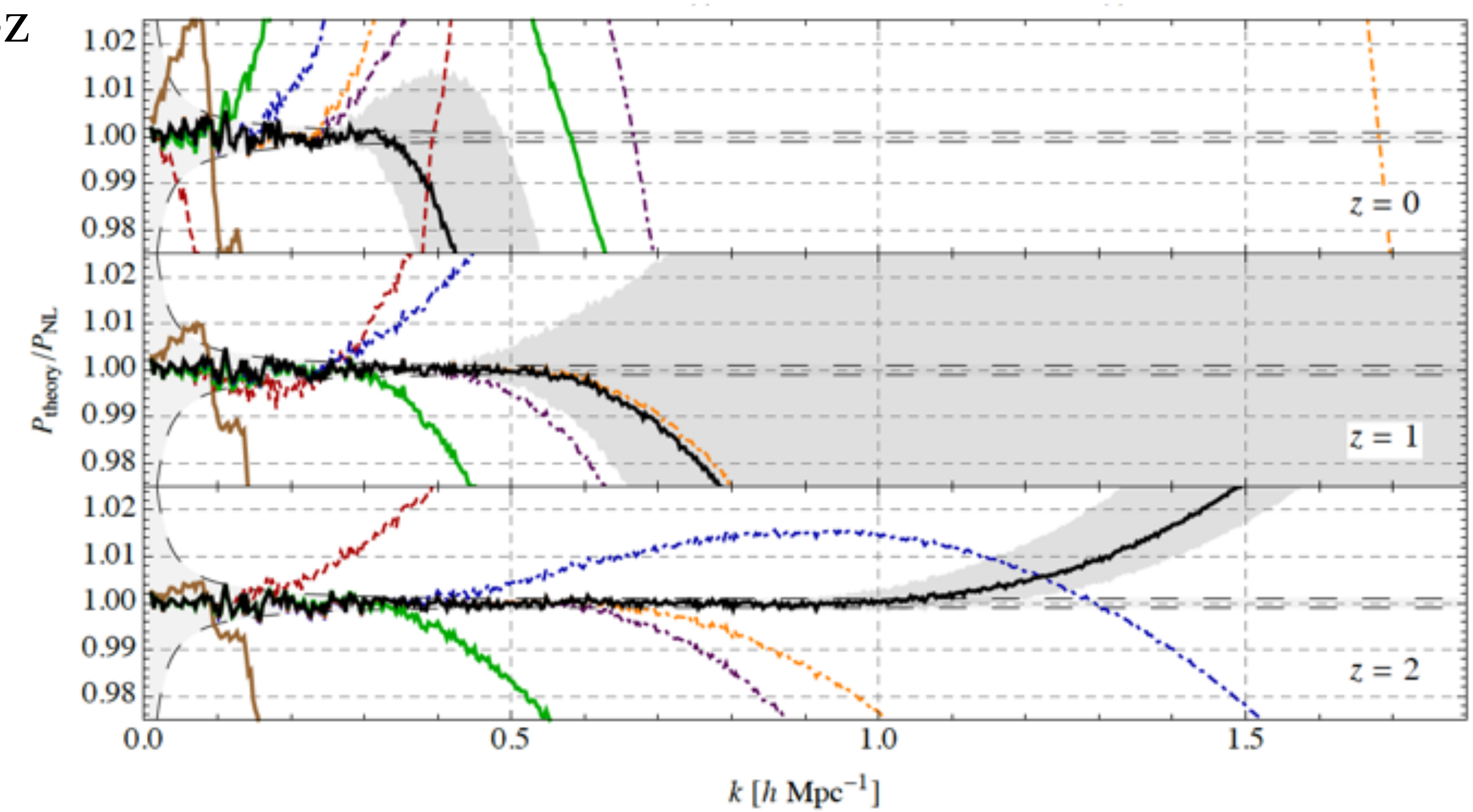
with Foreman **1503**
with Foreman and Perrier **1507**

All redshifts



Results 2-loop IR-resummed

- UV reach improves at high-z
- Theory error gets smaller

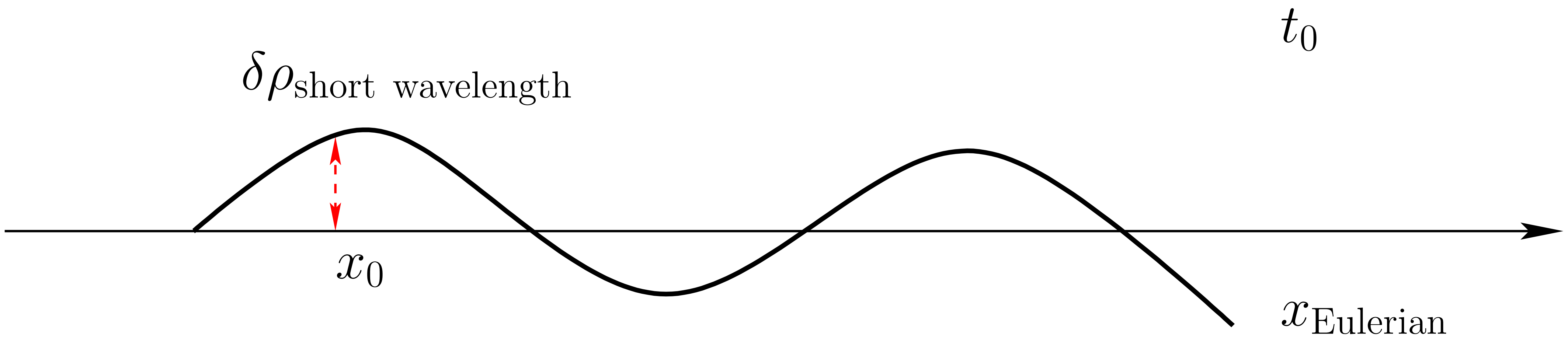


- The gain wrt former techniques is huge
- Time dependence of c_s , c_1 , c_4 is measured (only 12 parameters for all z's)
  - size compatible with UV expectations
- $\Rightarrow$ we can do CMB lensing analytically up to high ell.
  - and similarly galaxy lensing
  - c_s detected detected with high sensitivity by upcoming CMB experiments

IR-effects

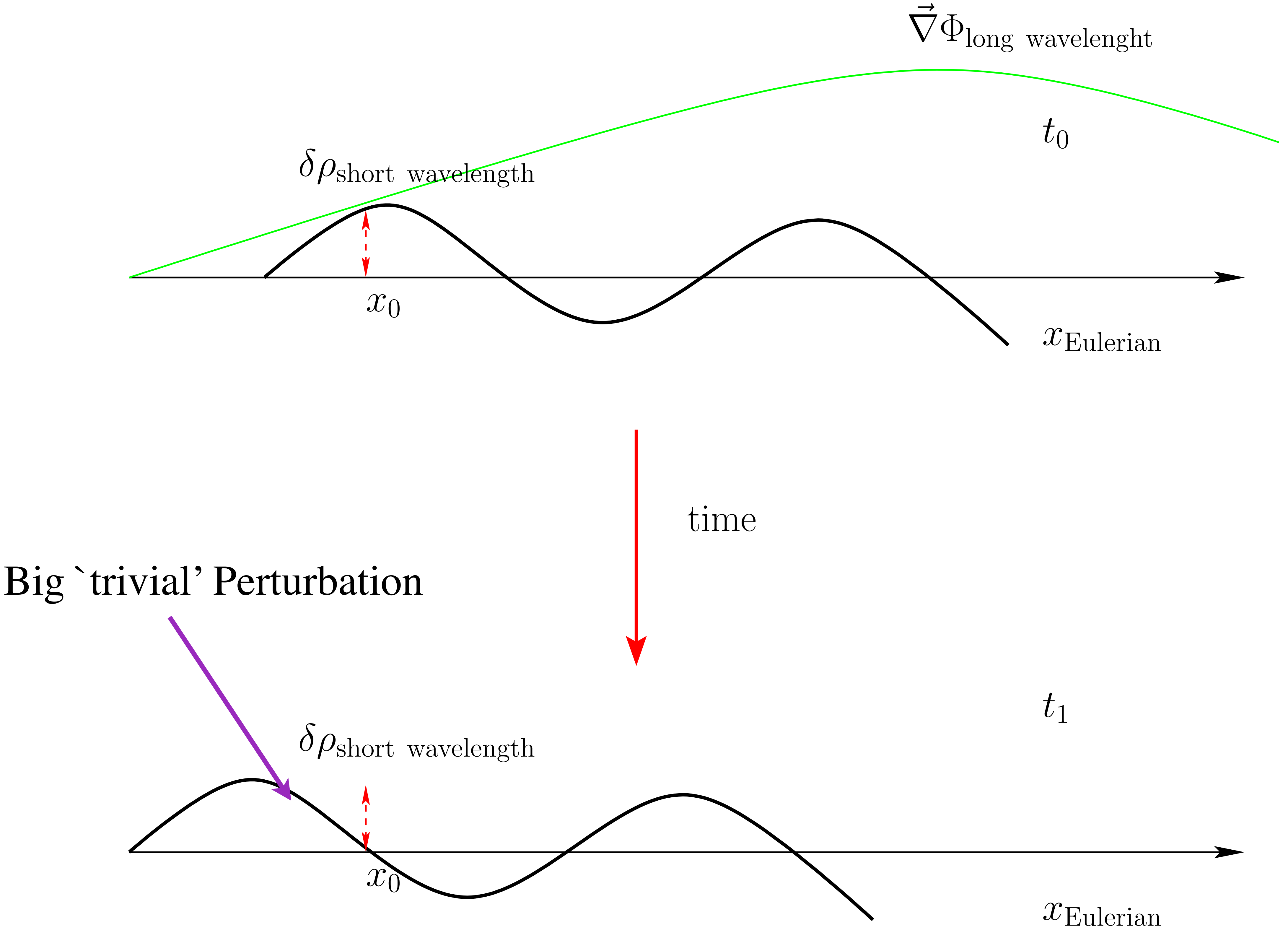
The Effect of Long-modes on Shorter ones

- In Eulerian treatment



The Effect of Long-modes

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



Baryons

Baryons

- The two species conserve mass, but exchange momentum (through gravity):

$$\nabla^2\phi = \frac{3}{2}H_0^2\frac{a_0^3}{a}(\Omega_c\delta_c + \Omega_b\delta_b)$$

$$\dot{\delta}_c = -\frac{1}{a}\partial_i((1+\delta_c)v_c^i)$$

$$\dot{\delta}_b = -\frac{1}{a}\partial_i((1+\delta_b)v_b^i)$$

$$\partial_i\dot{v}_c^i + H\partial_i v_c^i + \frac{1}{a}\partial_i(v_c^j\partial_j v_c^i) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_c^i + \frac{1}{a}\partial_i(\gamma)_c^i \ ,$$

$$\partial_i\dot{v}_b^i + H\partial_i v_b^i + \frac{1}{a}\partial_i(v_b^j\partial_j v_b^i) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_b^i + \frac{1}{a}\partial_i(\gamma)_b^i \ ,$$

$$(\partial\tau_\rho)_\sigma^i = \frac{1}{\rho_\sigma}\partial_j\tau_\sigma^{ij} \ , \qquad (\gamma)_c^i = \frac{1}{\rho_c}V^i \ , \qquad (\gamma)_b^i = -\frac{1}{\rho_b}V^i \ .$$

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Source of gravity

$$\dot{\delta}_c = -\frac{1}{a}\partial_i((1+\delta_c)v_c^i)$$

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Each-species' mass conservation

$$\partial_i\dot v_c^i + H\partial_i v_c^i + \frac{1}{a}\partial_i(v_c^j\partial_j v_c^i) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_c^i + \frac{1}{a}\partial_i(\gamma)_c^i\ ,$$

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Stress tensor like term:
two derivatives from momentum conservation

$$(\partial\tau_\rho)_\sigma^i = \frac{1}{\rho_\sigma}\partial_j\tau_\sigma^{ij}\ , \qquad (\gamma)_c^i = \frac{1}{\rho_c}V^i\ , \qquad (\gamma)_b^i = -\frac{1}{\rho_b}V^i\ .$$

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No Stress-tensor-like term:
only one derivative term,
it cancel in the sum (overall momentum cons.)

$$\dot\delta_c = -\frac{1}{a}\partial_i((1+\delta_c)v_c^i)$$

$$\dot\delta_b = -\frac{1}{a}\partial_i((1+\delta_b)v_b^i)$$

$$\partial_i\dot v_c^i + H\partial_i v_c^i + \frac{1}{a}\partial_i(v_c^j\partial_j v_c^i) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_c^i + \frac{1}{a}\partial_i(\gamma)_c^i\ ,$$

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