Leonardo Senatore (Stanford)

The Effective Field Theory
of
Cosmological Large Scale Structures

What has Planck done to theory?

- Planck improve limits wrt WMAP by a factor of ~3.
- We can think of Inflation as being characterized by higher dimension opt.s $\frac{\dot{\pi}^3}{\Lambda_U^2}$
- Since $\mathrm{NG} \sim \frac{H^2}{\Lambda_U^2} \quad \Rightarrow \quad \Lambda_U^{\mathrm{min,\,Planck}} \simeq \sqrt{3}\, \Lambda_U^{\mathrm{min,\,WMAP}}$
- Given the absence of known or nearby threshold, this is not much.
- Planck is great
- but Planck is not good enough
  - not Plank's fault, but Nature's faults
    - Please complain with Nature
- Planck was an opportunity for a detection, not much an opportunity to change the theory in absence of detection
- On theory side, little changes
  - contrary for example to LHC, which was crossing thresholds
    - Any result from LHC is changing the theory

What has Planck done to theory?

- In order to increase our knowledge of Inflation, we need more modes.
- Large Scale Structures offer the ideal place for hunting for more modes
  - I will show results that, if verified and extended to all observable, can increase limits to

$$f_{\rm NL}^{\rm equil,\, orthog,\;\; loc.} \lesssim 1$$

  - We can argue that absence of detection of NG up to this level implies observational proof of slow-roll inflation
    - This is learning even without detection

- This also offers us a way to study the large scale structures of the univrse
  - which are nice
- Implications for dark energy, neutrinos, light species, etc.

What is next in Cosmology?

- Plank will increase by a factor of less than 2.
- Next are Large Scale Structures
- Like moving from LEP to LHC:
  - much dirtier, but much more potential

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The Effective Field Theory of Cosmological Large Scale Structures

The IR-resummed Effective Theory of Large Scale Structure — with Zaldarriaga **to appear**

The Lagrangian-space Effective Theory of Large Scale Structure — with Porto and Zaldarriaga **1311**

The Effective Theory of Large Scale Structure at 2-loops — with Carrasco, Foreman and Green **1310**

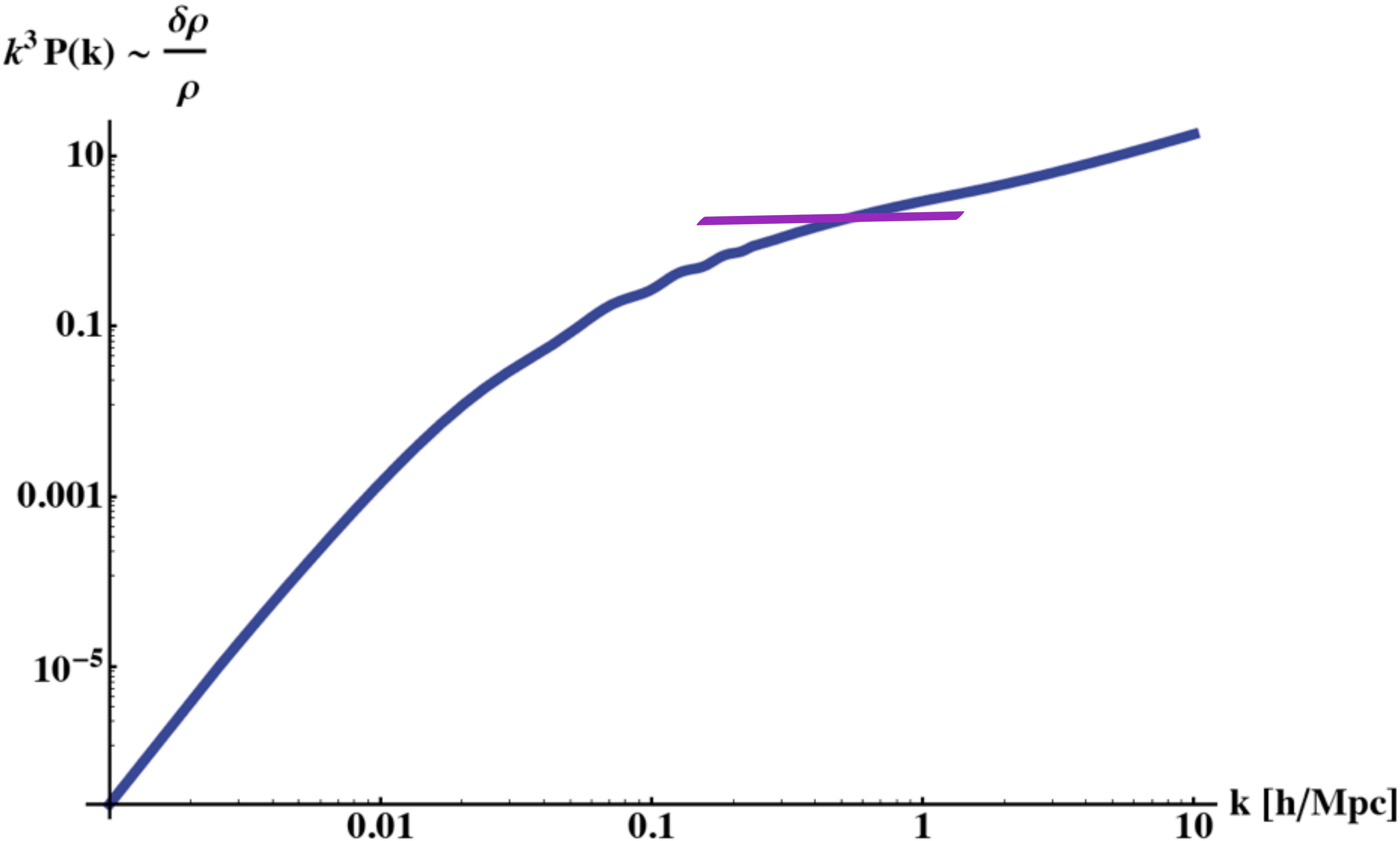
The 2-loop power spectrum and the IR safe integrand — with Carrasco, Foreman and Green **1304**

The Effective Theory of Large Scale Structure — with Carrasco and Hertzberg **JHEP 2012**

Cosmological Non-linearities as an Effective Fluid — with Baumann, Nicolis and Zaldarriaga **JCAP 2012**

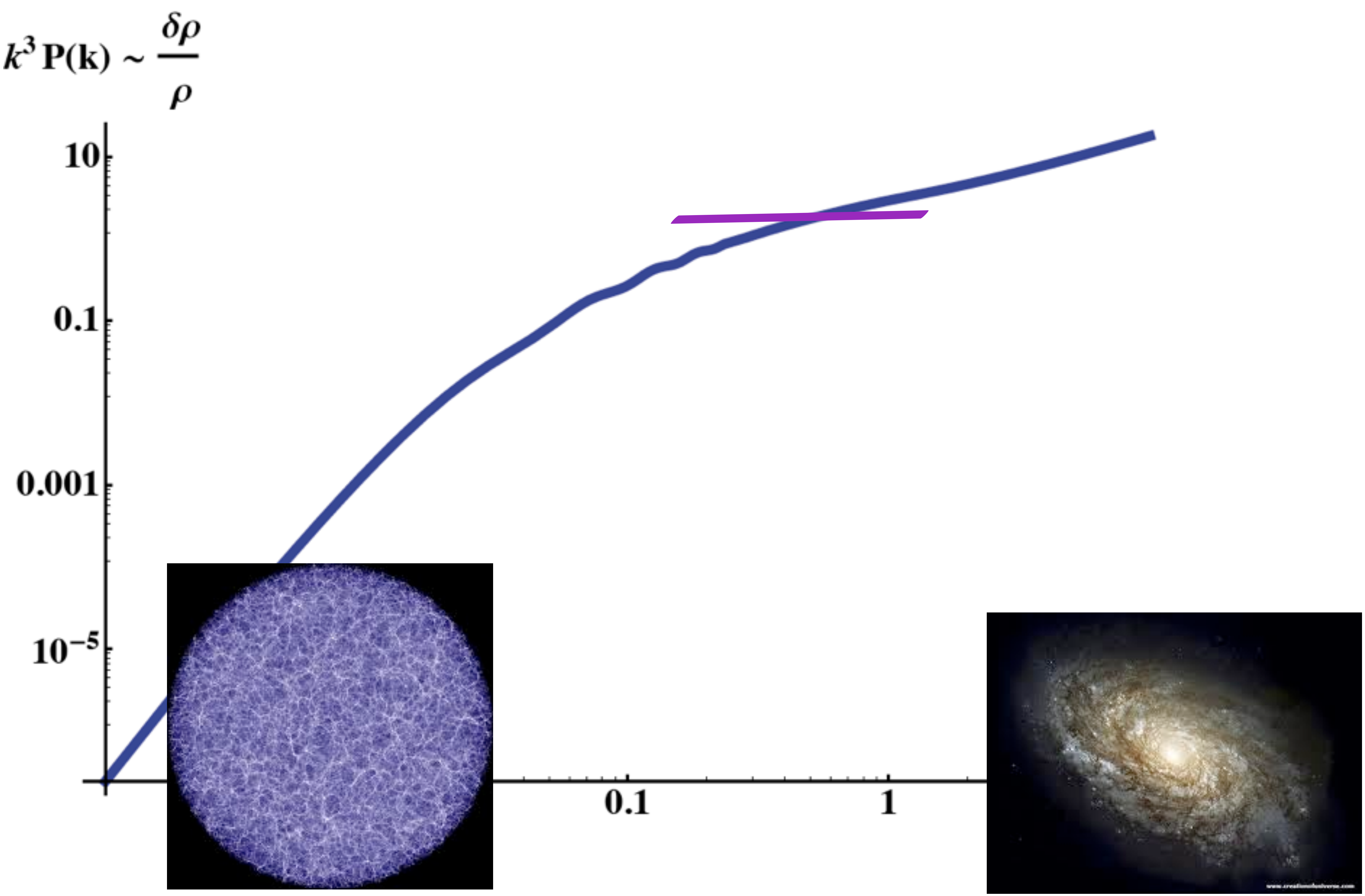
A well defined perturbation theory

- Non-linearities at short scale



A well defined perturbation theory

- Non-linearities at short scale



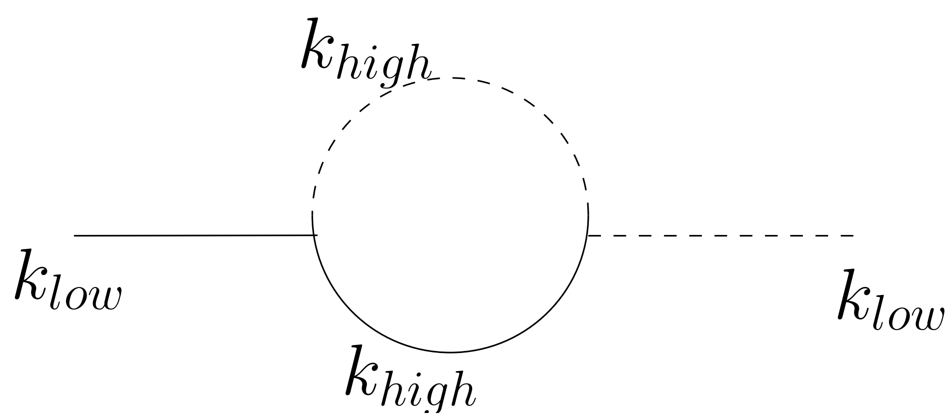
A well defined perturbation theory

- Standard perturbation theory is not well defined
- Standard techniques
  - perfect fluid $\dot{\rho} + \partial_i \left(\rho v^i\right) = 0 \ ,$
  - expand in $\delta \sim \dfrac{\delta\rho}{\rho}$ and solve iteratively

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

$$\Rightarrow \quad \langle \delta_k^{(2)} \delta_k^{(2)} \rangle \sim \int d^3k' \ \langle \delta_{k-k'}^{(1)} \delta_{k-k'}^{(1)} \rangle \ \langle \delta_{k'}^{(1)} \delta_{k'}^{(1)} \rangle$$

- Perturbative equations break in the UV
  - $\delta \sim \dfrac{k}{k_{NL}} \gg 1 \quad \text{for} \quad k \gg k_{NL}$
  - no perfect fluid if we truncate

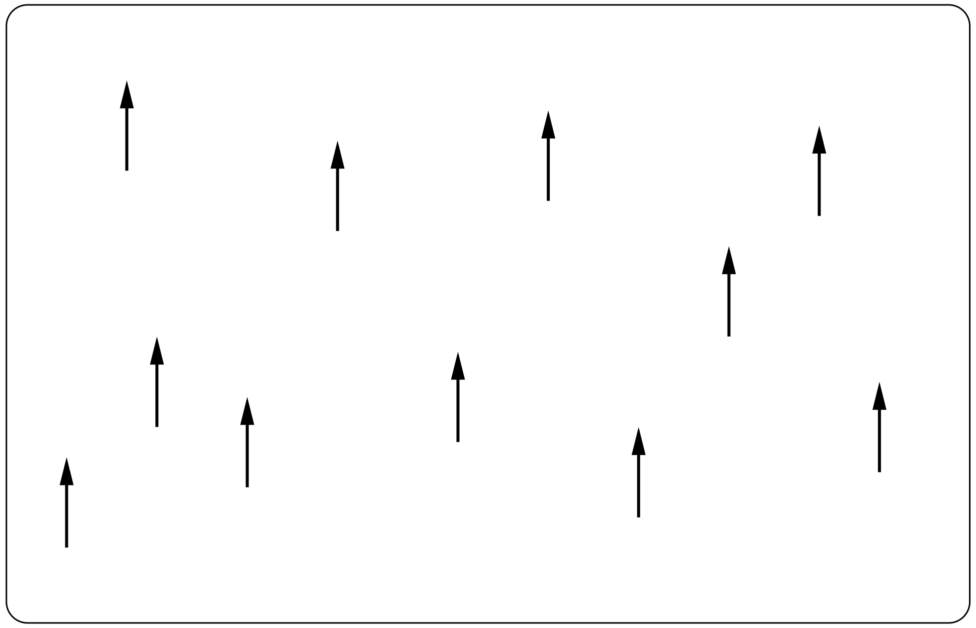


Idea of the
Effective Field Theory

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

Dielectric Fluid



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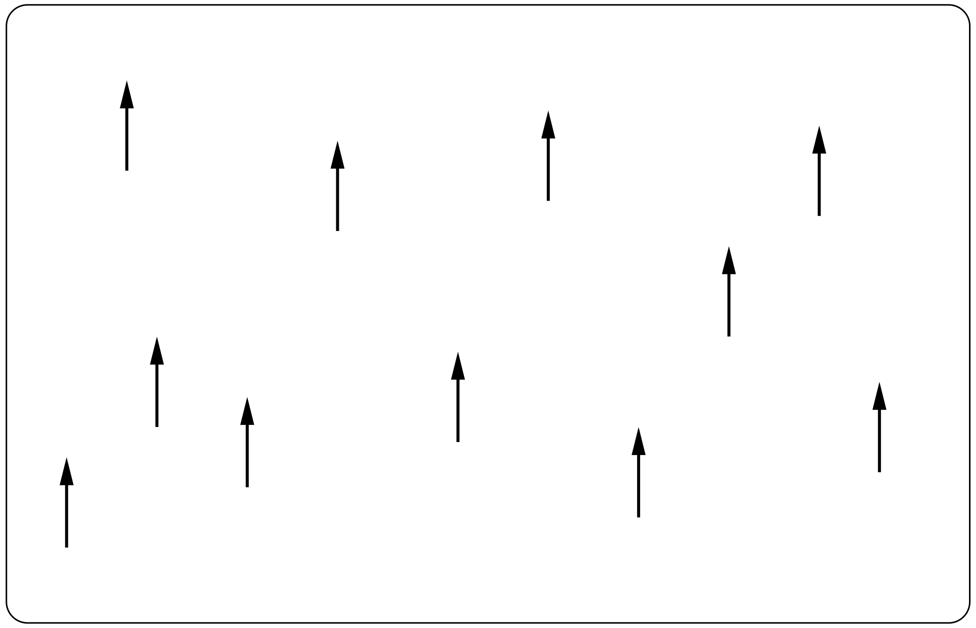
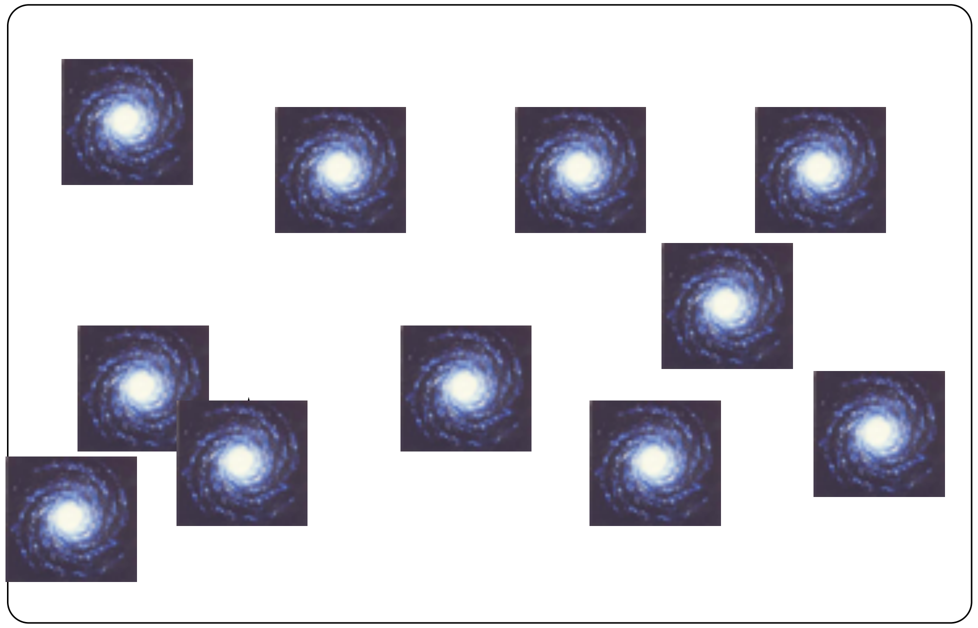
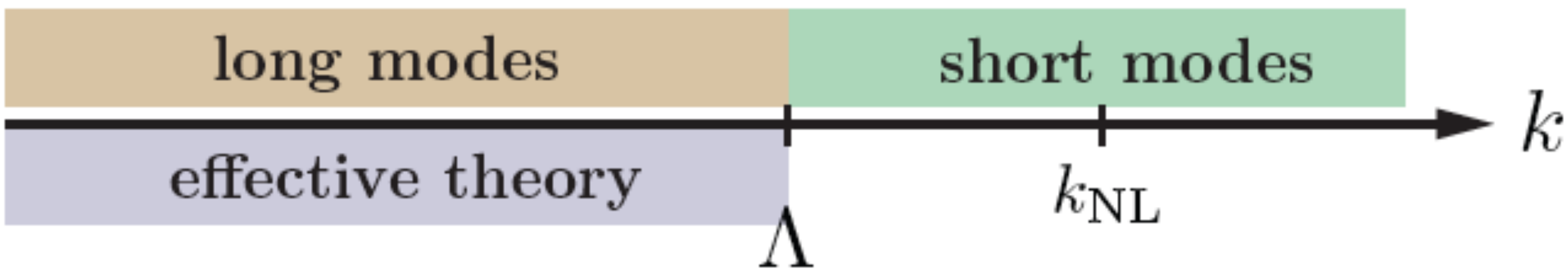


Dielectric Fluid



A well defined perturbation theory

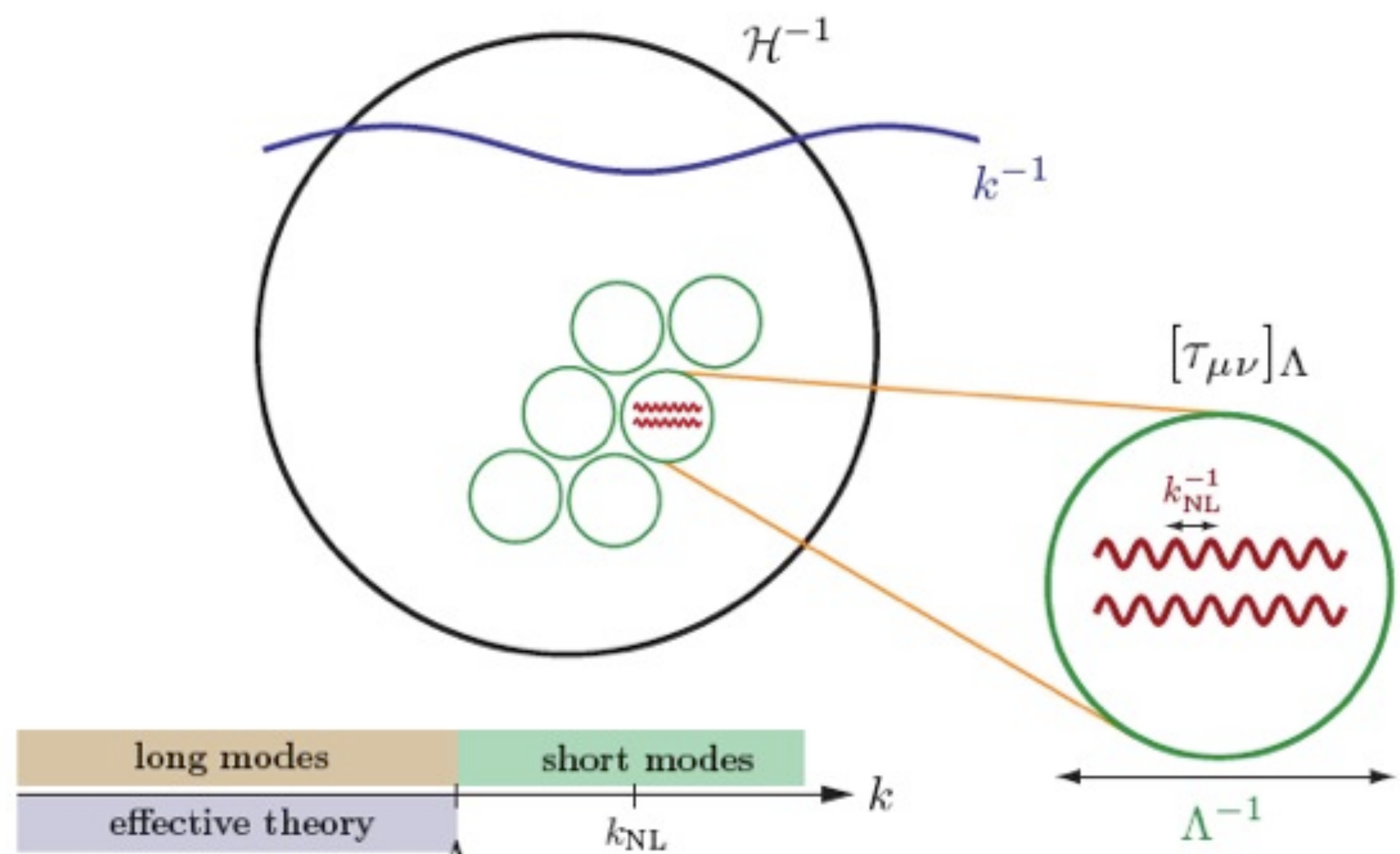
- We will define a manifestly convergent perturbation theory



  - where the ingredient is

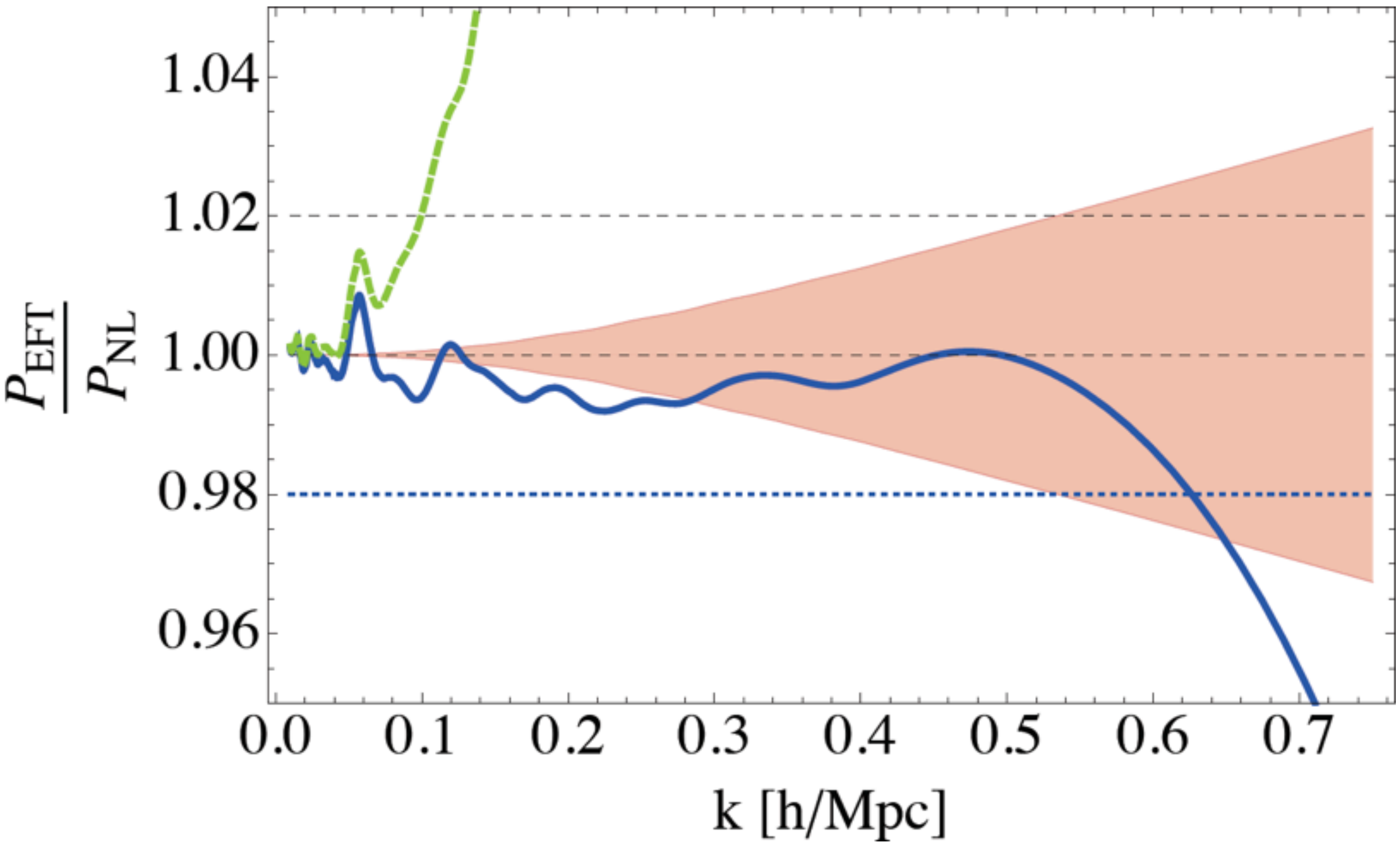
    an fluid-like system with

$$\delta_\ell, v_\ell, \Phi_\ell \ll 1$$



Bottom line result

- 2-loop in the EFT, with IR resummation



- Data go as $k_{\rm max}^3$: factor of 200 more modes than naive

Construction of the Effective Field Theory

Point-like Particle versus Extended Objects

- On short distances, we have point-like particles
  - they move

$$\frac{d^2\vec{z}(\vec{q},\eta)}{d\eta^2}+\mathcal{H}\frac{d\vec{z}(\vec{q},\eta)}{d\eta}=-\vec{\partial}_x\Phi[\vec{z}(\vec{q},\eta)]$$

  - induce overdensities

$$\begin{aligned}1+\delta(\vec{x},\eta) &= \int d^3\vec{q}\;\delta^3(\vec{x}-\vec{z}(\vec{q},\eta))\\ &= \left[\det\left(\frac{\partial z^i}{\partial q^j}\right)\right]^{-1}=\left[\det\left(1+\frac{\partial s^i}{\partial q^j}\right)\right]^{-1}\end{aligned}$$

  - Source gravity

$$\partial_x^2\Phi(\vec{x},\eta) = \frac{3}{2}\mathcal{H}^2\Omega_m\delta(\vec{x},\eta)$$

Point-like Particle versus Extended Objects

- But we cannot describe point-like particles: we need to focus on long distances.
  - We deal with Extended objects
    - they move differently:

$$\frac{d^2\vec{z}(\vec{q},\eta)}{d\eta^2}+\mathcal{H}\frac{d\vec{z}(\vec{q},\eta)}{d\eta}=-\vec{\partial}_x\Phi[\vec{z}(\vec{q},\eta)]$$

Point-like Particle versus Extended Objects

- But we cannot describe point-like particles: we need to focus on long distances.
  - We deal with Extended objects
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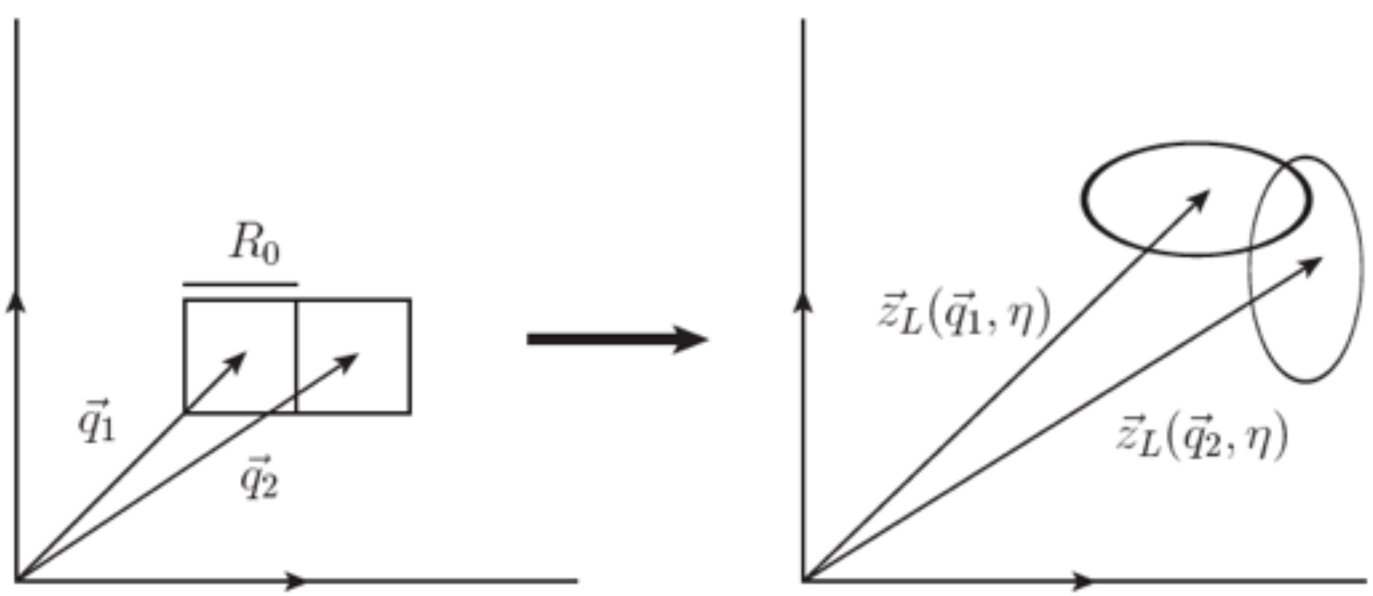
$$\frac{d^2\vec{z}_L(\vec{q},\eta)}{d\eta^2}+\mathcal{H}\frac{d\vec{z}_L(\vec{q},\eta)}{d\eta} = -\vec{\partial}_x\left[\Phi_L[\vec{z}_L(\vec{q},\eta)]+\frac{1}{2}Q^{ij}(\vec{q},\eta)\partial_i\partial_j\Phi_L[\vec{z}_L(\vec{q},\eta)]+\cdots\right]+\vec{a}_S(\vec{q},\eta)$$

- the center of mass moves from force on center of mass, but also from tidal force proportional to quadrupole of mass distribution
  - there is also a force that comes when regions overlap.



Point-like Particle versus Extended Objects

- But we cannot describe point-like particles: we need to focus on long distances.
  - We deal with Extended objects
    - they induce number over-densities and real-space multipole moments

$$1+\delta_{n,L}(\vec{x},\eta) \equiv \int d^3\vec{q}\;\delta^3(\vec{x}-\vec{z}_L(\vec{q},\eta))\;,$$
$$\mathcal{Q}^{i_1\ldots i_p}(\vec{x},\eta) \equiv \int d^3\vec{q}\;Q^{i_1\ldots i_p}(\vec{q},\eta)\delta^3(\vec{x}-\vec{z}_L(\vec{q},\eta))$$

    - they source gravity with the overall mass

$$\partial_x^2\Phi_L=\frac{3}{2}\mathcal{H}^2\Omega_m\left(\delta_{n,L}(\vec{x},\eta)+\frac{1}{2}\partial_i\partial_j\mathcal{Q}^{ij}(\vec{x},\eta)-\frac{1}{6}\partial_i\partial_j\partial_k\mathcal{Q}^{ijk}(\vec{x},\eta)+\cdots\right)\equiv\frac{3}{2}\mathcal{H}^2\Omega_m\delta_{m,L}(\vec{x},\eta)$$

    - These equations can be derived from smoothing the point-particle equations
      - but actually these are the assumption-less equations

How do we treat the new terms?

- Similar to treatment of material polarizability: $\vec{d}_{\rm dipole} \sim \vec{d}_{\rm intrinsic} + \alpha\, \vec{E}$
- Take moments:

$$Q^{ij} = \langle Q^{ij} \rangle_S + Q^{ij}_{\mathcal{S}} + Q^{ij}_{\mathcal{R}}$$

- Expectation value

$$\langle Q^{ij} \rangle_{\mathcal{S}} = l_S^2(\eta)\delta_{ij}$$

- Response (non-local in time) $Q^{ij}_{\mathcal{R}}(\vec{q},\eta) = \int d\eta' \; A^{ij,lk}(\eta;\eta')\partial_l\partial_k\Phi_L(\vec{z}_L(\vec{q},\eta'))$
- Stochastic noise

$$\langle Q_{\mathcal{S}} \rangle = 0 \qquad \langle Q_{\mathcal{S}} Q_{\mathcal{S}} \ldots \rangle \neq 0$$

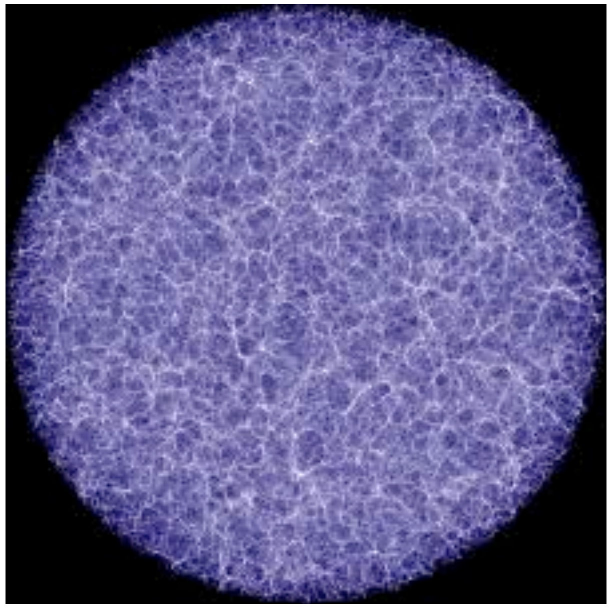
- Overall

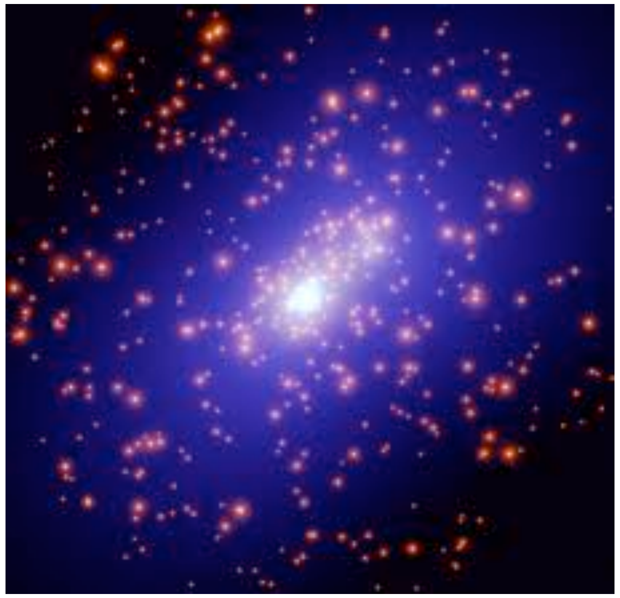
$$Q_{ij} = l_0^2\, \delta_{ij} + l_1^2\, \partial_i\partial_j \Phi_L + \ldots + Q_{ij,\mathcal{S}}$$

- In summary: we obtain an expression just in terms of long-wavelength variables

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

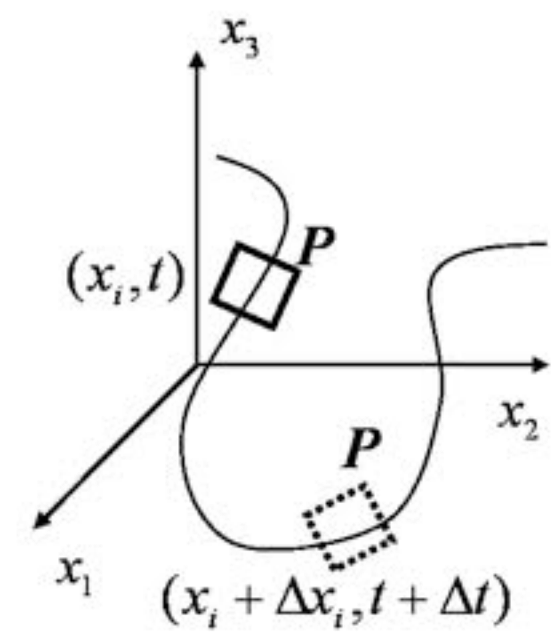
When do we stop?

- Similar to treatment for material polarizability: $\vec{d}_{\text{dipole}} \sim \alpha\, \vec{E}_{\text{electric}}$, $Q_{ij}^{\text{electric}} = c\, E_i E_j$, ...
- Short distance physics is taken into account by expectation value, response, and noise
- Force equation breaks when $\Phi_L[\vec{z}_L(\vec{q},\eta)] \sim Q^{ij}(\vec{q},\eta)\partial_i\partial_j\Phi_L[\vec{z}_L(\vec{q},\eta)]$
  – force on center of mass ~ force from tidal forces
- Poisson equation breaks when $\delta_{n,L}(\vec{x},\eta) \sim \partial_i\partial_j \mathcal{Q}^{ij}(\vec{x},\eta)$
  – gravitational potential from quadrupole moment ~ the one from center of mass
- By dimensional analysis, this happens for distances shorter than a critical length
  – the non-linear scale $k \gtrsim k_{\text{NL}}$
  – on long distances, $k \ll k_{\text{NL}}$, write as many terms as precision requires.
    - Manifestly convergent expansion in $$\left(\frac{k}{k_{\text{NL}}}\right) \ll 1$$

Connecting with the Eulerian Treatment

- In the universe, finite-size particles move

$$\vec{z}(\vec{q},t) = \vec{q} + \vec{s}(\vec{q},t)$$



- In Lagrangian space, we do not expand in $\vec{s}(\vec{q},t)$

- In Eulerian, we do: we describe particles from a fixed position

Connecting with the Eulerian Treatment

- If we expand the exponential, we expand in $\vec{k}\cdot\vec{s}_L \ll 1$
  - This means that we describe the motion of the extended object as seen from a fixed point in space
    - We get the Eulerian-point-of-view description of a continuum of particles
    - The resulting equations are equivalent to Eulerian fluid-like equations

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

$$\partial_t\rho + H\rho + \partial_i(\rho v^i) = 0$$

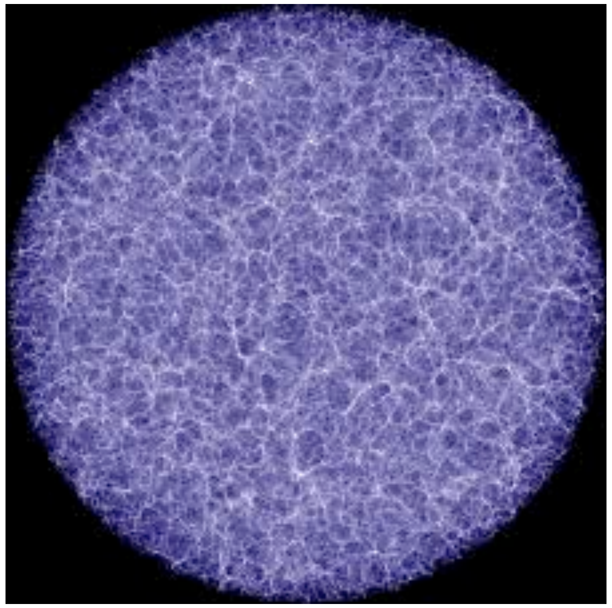
$$\dot{v}^i + Hv^i + v^j\partial_j v^i = \frac{1}{\rho}\partial_j\tau^{ij}$$

– here it appears a non trivial stress tensor for the long-distance fluid

$$\tau_{ij} = p_0\,\delta_{ij} + c_s^2\,\delta_{ij}\,\partial^2\delta\rho + \ldots$$

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

$$\rho_L = \rho_s(v_s^2 + \Phi_s)$$
$$p_L = \rho_s(2v_s^2 + \Phi_s)$$

- when objects virialize, the induced pressure vanish
  - ultraviolet modes do not contribute (like in SUSY)
- The backreaction is dominated by modes at the virialization scale

$$\Rightarrow \quad w_{\text{induced}} \sim 10^{-5}$$

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

Perturbation Theory with the EFT

Perturbation Theory within the EFT

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

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

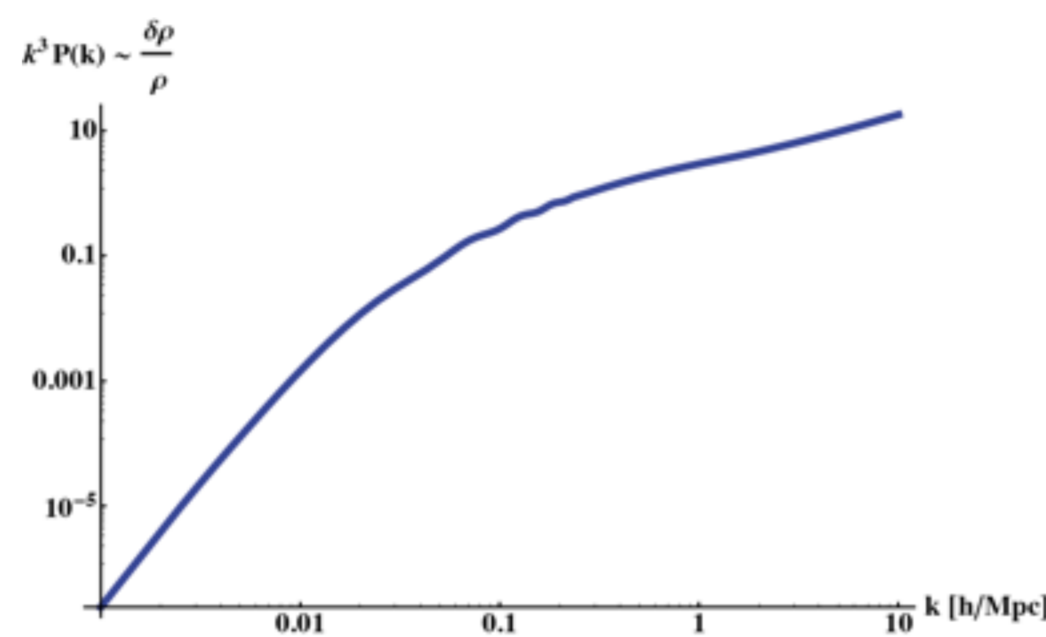
$$\partial_t\rho + H\rho + \partial_i(\rho v^i) = 0$$

$$\dot{v}^i + Hv^i + v^j\partial_j v^i = \frac{1}{\rho}\partial_j\tau^{ij}$$

$$\tau_{ij} = p_0\,\delta_{ij} + c_s^2\,\delta_{ij}\,\partial^2\delta\rho$$

- To estimate
  - Approximate as piecewise scaling universe

$$P_{11}(k) = (2\pi)^3\begin{cases}\frac{1}{k_{\rm NL}^3}\left(\frac{k}{k_{\rm NL}}\right)^{-2.1} & \text{for } k > k_{\rm tr}\ ,\\ \frac{1}{\tilde{k}_{\rm NL}^3}\left(\frac{k}{\tilde{k}_{\rm NL}}\right)^{-1.7} & \text{for } k < k_{\rm tr}\ ,\end{cases}$$



$k_{\rm NL} = 4.6\,h\,{\rm Mpc}^{-1}$ $\qquad k_{\rm tr} = 0.25\,h\,{\rm Mpc}^{-1}$ $\qquad \tilde{k}_{\rm NL} = 1.8\,h\,{\rm Mpc}^{-1}$

Perturbation Theory within the EFT

- Regularization and renormalization of loops (scaling universe)
  - evaluate with cutoff. By dim analysis:

$$P_{11} = \frac{1}{{k_{\rm NL}}^3}\left(\frac{k}{k_{\rm NL}}\right)^{-3/2}$$

$$P^{\rm I}_{\text{2-loop}} = (2\pi)\left[c_0^{\Lambda}\left(\frac{\Lambda}{k_{\rm NL}}\right)^2\left(\frac{k}{k_{\rm NL}}\right)^1 P_{11} + c_1^{\Lambda}\left(\frac{\Lambda}{k_{\rm NL}}\right)^1\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}\right.$$
$$+c_2^{\Lambda}\log\left(\frac{k}{\Lambda}\right)\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + c_1^{\rm finite}\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}$$
$$\left.+c_1^{1/\Lambda}\left(\frac{k}{\Lambda}\right)^1\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + \text{subleading finite terms in } \frac{k}{\Lambda}\right]$$

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$$+ c_2^\Lambda \log\left(\frac{k}{\Lambda}\right)\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + c_1^{\rm finite}\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}$$
$$\left. + c_1^{1/\Lambda}\left(\frac{k}{\Lambda}\right)^1 \left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + \text{subleading finite terms in } \frac{k}{\Lambda}\right]$$

  - absence of counterterm $\tau_{ij} = p_0\,\delta_{ij} + c_s^2\,\delta_{ij}\,\partial^2\delta\rho$

Perturbation Theory within the EFT

- Regularization and renormalization of loops (scaling universe)

$$P_{11} = \frac{1}{{k_{\rm NL}}^3}\left(\frac{k}{k_{\rm NL}}\right)^{-3/2}$$

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$$+c_2^\Lambda \log\left(\frac{k}{\Lambda}\right)\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + c_1^{\rm finite}\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}$$
$$\left.+c_1^{1/\Lambda}\left(\frac{k}{\Lambda}\right)^1\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + \text{subleading finite terms in } \frac{k}{\Lambda}\right]$$

  - absence of counterterm $\tau_{ij} = p_0\,\delta_{ij} + c_s^2\,\delta_{ij}\,\partial^2\delta\rho$
  - One divergent term $\Longrightarrow$

$$P_{\text{2-loop counter}} = (2\pi)c^\Lambda_{\rm counter}\left(\frac{\Lambda}{k_{\rm NL}}\right)\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}$$

$$c^\Lambda_{\rm counter} = -c_1^\Lambda + \delta c_{\rm counter}\left(\frac{k_{\rm NL}}{\Lambda}\right)$$

  - Sum up and $\Lambda \to \infty.$

$$P^{\rm I}_{\text{2-loop}} + P_{\text{2-loop counter}} = (2\pi)\delta c_{\rm counter}\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11} + (2\pi)c_1^{\rm finite}\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}$$

Calculable terms in the EFT

- Has everything being lost?

$$P^{\rm I}_{\text{2-loop}} + P_{\text{2-loop counter}} = (2\pi)\delta c_{\rm counter}\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11} + (2\pi)c_1^{\rm finite}\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11}$$

  – to make result finite, we need to add a counterterm with finite part

    - need to fit to data (like a coupling constant), but cannot fit the power

Calculable terms in the EFT

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$$P^{\mathrm{I}}_{\text{2-loop}} + P_{\text{2-loop counter}} = (2\pi)\delta c_{\mathrm{counter}} \left(\frac{k}{k_{\mathrm{NL}}}\right)^2 P_{11} + (2\pi) c_1^{\mathrm{finite}} \left(\frac{k}{k_{\mathrm{NL}}}\right)^3 P_{11}$$

  – to make result finite, we need to add a counterterm with finite part
    - need to fit to data (like a coupling constant), but cannot fit the power

  – the subleading finite term is not degenerate with a counterterm.
    - it cannot be changed
    - it is calculable by the EFT
      – so it predicts an observation $c_1^{\mathrm{finite}} = 0.044$

Lesson

- Each loop-order L contributed a finite, calculable term of order

$$P^{\rm I}_{\text{L-loops finite}} \sim \left(\frac{k}{k_{\rm NL}}\right)^{(3+n)L} \left(\frac{k}{k_{\rm NL}}\right)^{n}$$

  – each higher-loop is smaller and smaller

- This happen after canceling the divergencies with counterterms

$$P^{\rm I}_{\text{L-loops diverg.}} \sim \left(\frac{\Lambda}{k_{\rm NL}}\right)^{(3+n)L-2} \left(\frac{k}{k_{\rm NL}}\right)^{2} \left(\frac{k}{k_{\rm NL}}\right)^{n} + \text{subleading divergences}$$

  – at each higher loop one needs to adjust the lower order counterterms

    - by this is not a new fit, this is calculable

Example

- At 1-loop, we add a counterterm

$$P_{\text{EFT-1-loop}} = P_{11} + P_{\text{1-loop}} - 2\,(2\pi) c^2_{s(1)} \frac{k^2}{k^2_{\text{NL}}} P_{11}$$

- $c^2_{s(1)}$ is chosen by fitting to data so that

$$P_{\text{1-loop}}(k = k_{\text{ren}})_{\Lambda\to\infty} = P_{\text{NL}}(k_{\text{ren}}) \quad \Rightarrow \quad c^2_{s(1)}(k_{\text{ren}}) = \text{number} = (-3.36 \pm 0.020) \times \frac{1}{2\pi}\left(\frac{k_{\text{NL}}}{h\,\text{Mpc}^{-1}}\right)^2$$

- At 2-loop, there is a divergency that requires the same counterterm.

$$P^{\text{I}}_{\text{2-loop}} = (2\pi)\left[c_1^{\Lambda}\left(\frac{\Lambda}{k_{\text{NL}}}\right)^1\left(\frac{k}{k_{\text{NL}}}\right)^2 P_{11} + c_1^{\text{finite}}\left(\frac{k}{k_{\text{NL}}}\right)^3 P_{11}\right]$$

  – Adjust $c^2_{s(1)} \quad \to \quad c^2_{s(1)} + c^2_{s(2)}$ in a known way (without looking again at the data)

$$c^2_{s(2)}(k_{\text{ren}}) = \frac{P_{\text{2-loop}}(k_{\text{ren}}) + c^2_{s(1)}(k_{\text{ren}}) P^{(c_s)}_{\text{1-loop}}(k_{\text{ren}})}{(k^2_{\text{ren}}/k^2_{\text{NL}}) P_{11}(k_{\text{ren}})} + [c^2_{s(1)}(k_{\text{ren}})]^2 \frac{k^2_{\text{ren}}}{k^2_{\text{NL}}}$$

- Up to 2-loops no additional counterterm is needed

Summary of Procedure

- Do 1-loop calculation

$$P_{\text{EFT-1-loop}} = P_{11} + P_{\text{1-loop}} - 2\,(2\pi) c^2_{s(1)} \frac{k^2}{k^2_{\text{NL}}} P_{11}$$

- Fit $c^2_{s(1)}$
  - we fit in the range $k \sim 0.15 - 0.25\, h\, \text{Mpc}^{-1}$

$$c^2_{s(1)} = (1.62 \pm 0.033) \times \frac{1}{2\pi} \left(\frac{k_{\text{NL}}}{h\, \text{Mpc}^{-1}} \right)^2$$

- Do 2-loop calculation with no additional fitting

$$P_{\text{EFT-2-loop}} = P_{11} + P_{\text{1-loop}} + P_{\text{2-loop}} - 2\,(2\pi)(c^2_{s(1)} + c^2_{s(2)}) \frac{k^2}{k^2_{\text{NL}}} P_{11} + (2\pi) c^2_{s(1)} P^{(c_s,p)}_{\text{1-loop}} + (2\pi)^2 c^4_{s(1)} \frac{k^4}{k^4_{\text{NL}}} P_{11}$$

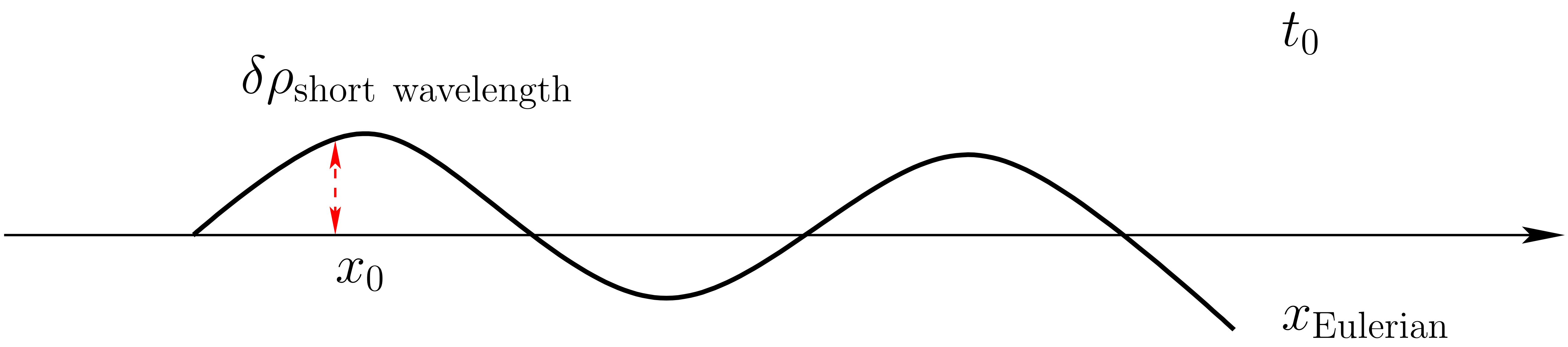
  - just adjust counterterm as calculable

$$c^2_{s(2)} = (-3.36 \pm 0.020) \times \frac{1}{2\pi} \left(\frac{k_{\text{NL}}}{h\, \text{Mpc}^{-1}} \right)^2$$

IR-effects

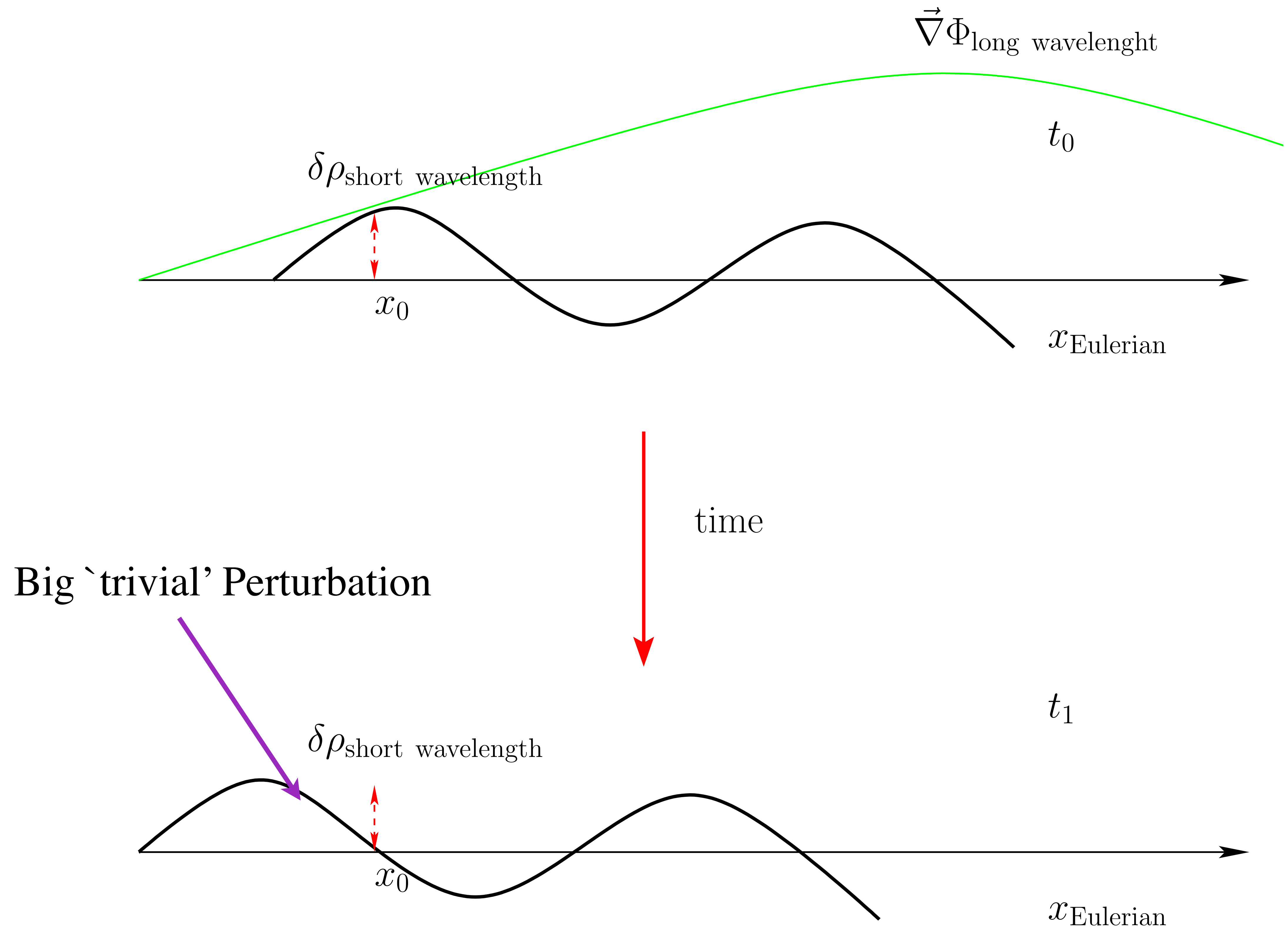
The Effect of Long-modes on Shorter ones

- In Eulerian treatment



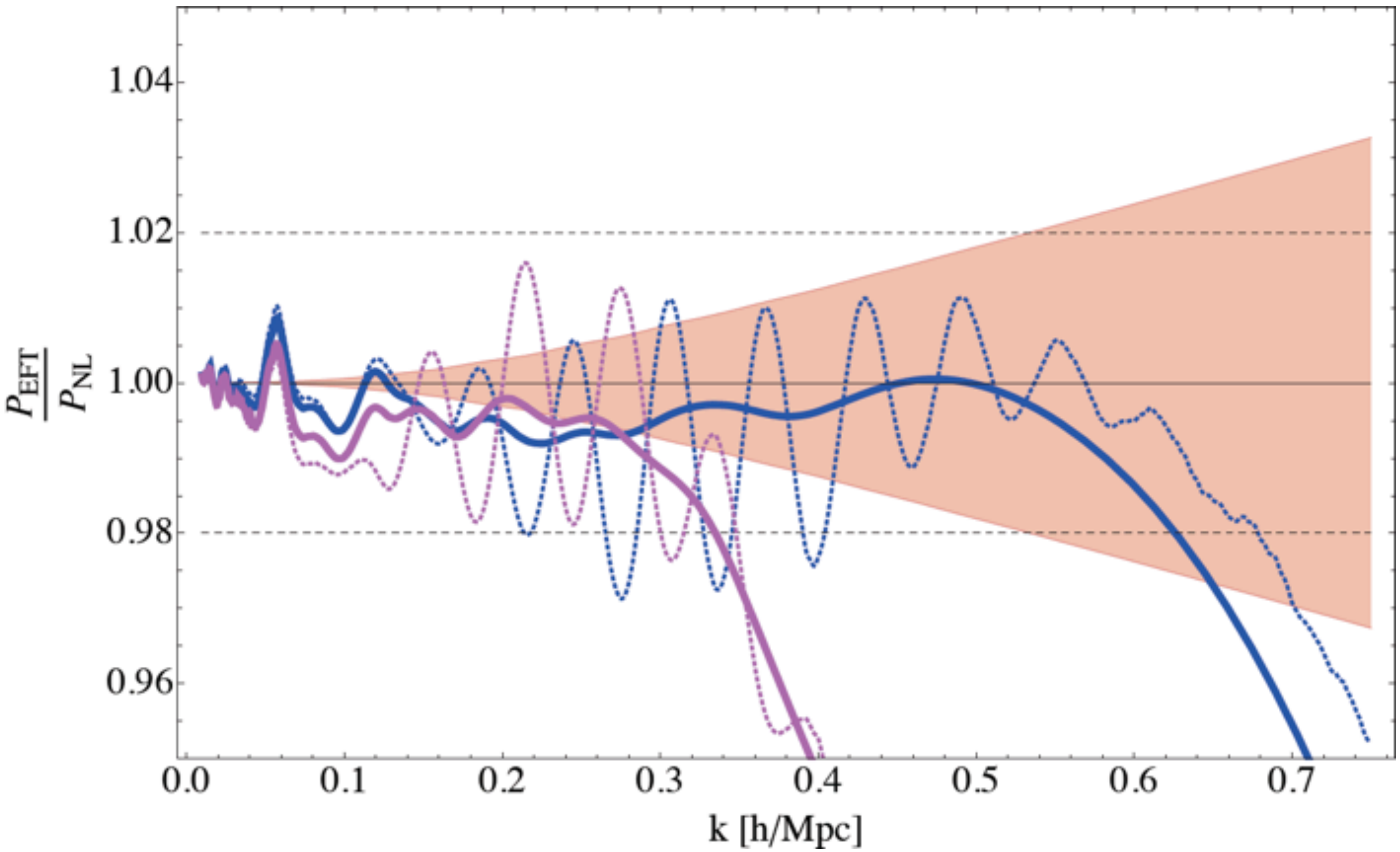
The Effect of Long-modes

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



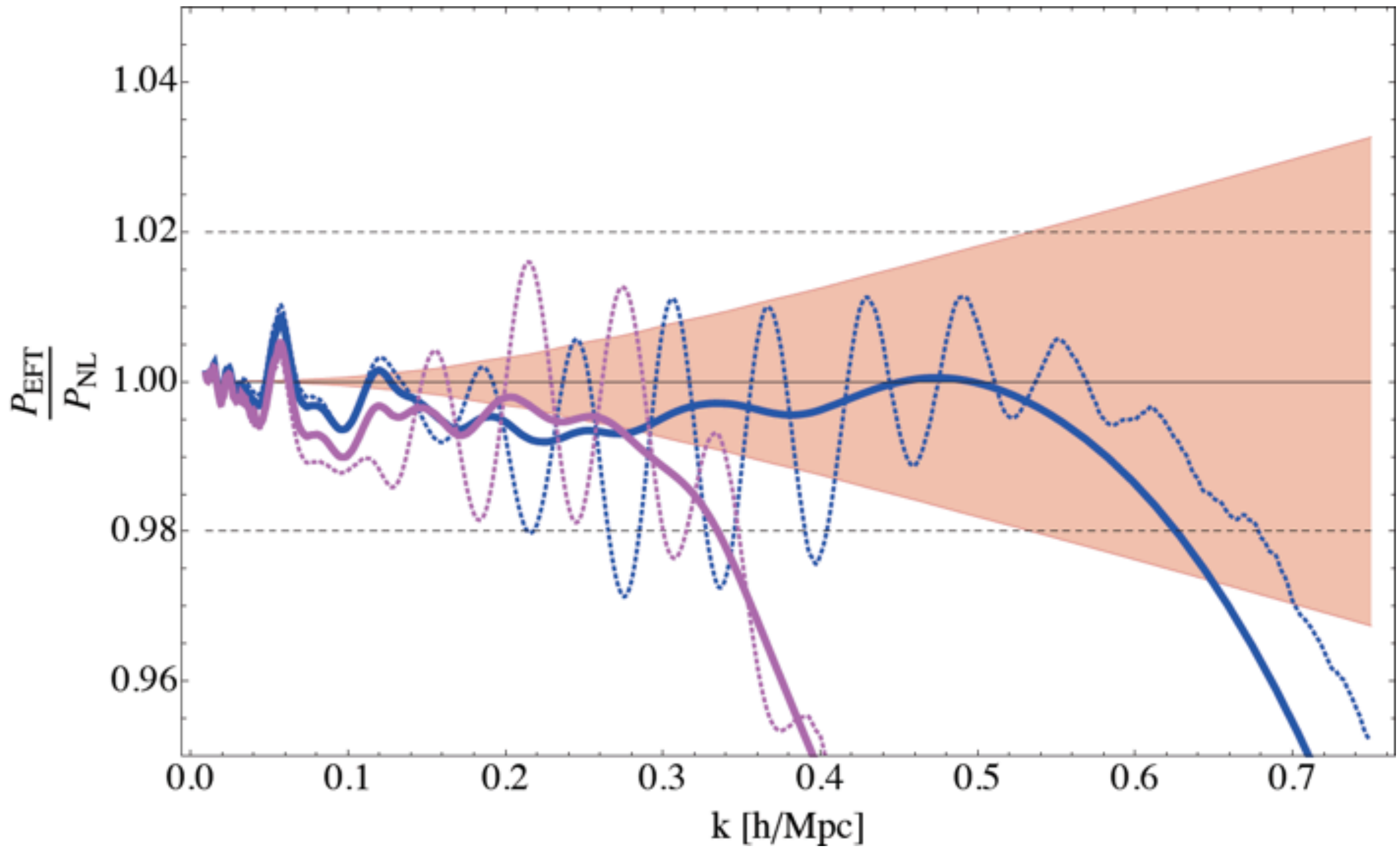
Results

EFT of Large Scale Structures



- Well defined and manif. converg. $\left(\frac{k}{k_{\rm NL}}\right)^L$
- Every perturbative order improves the agreement as it should
- We know when we should fail, and we fail when we should

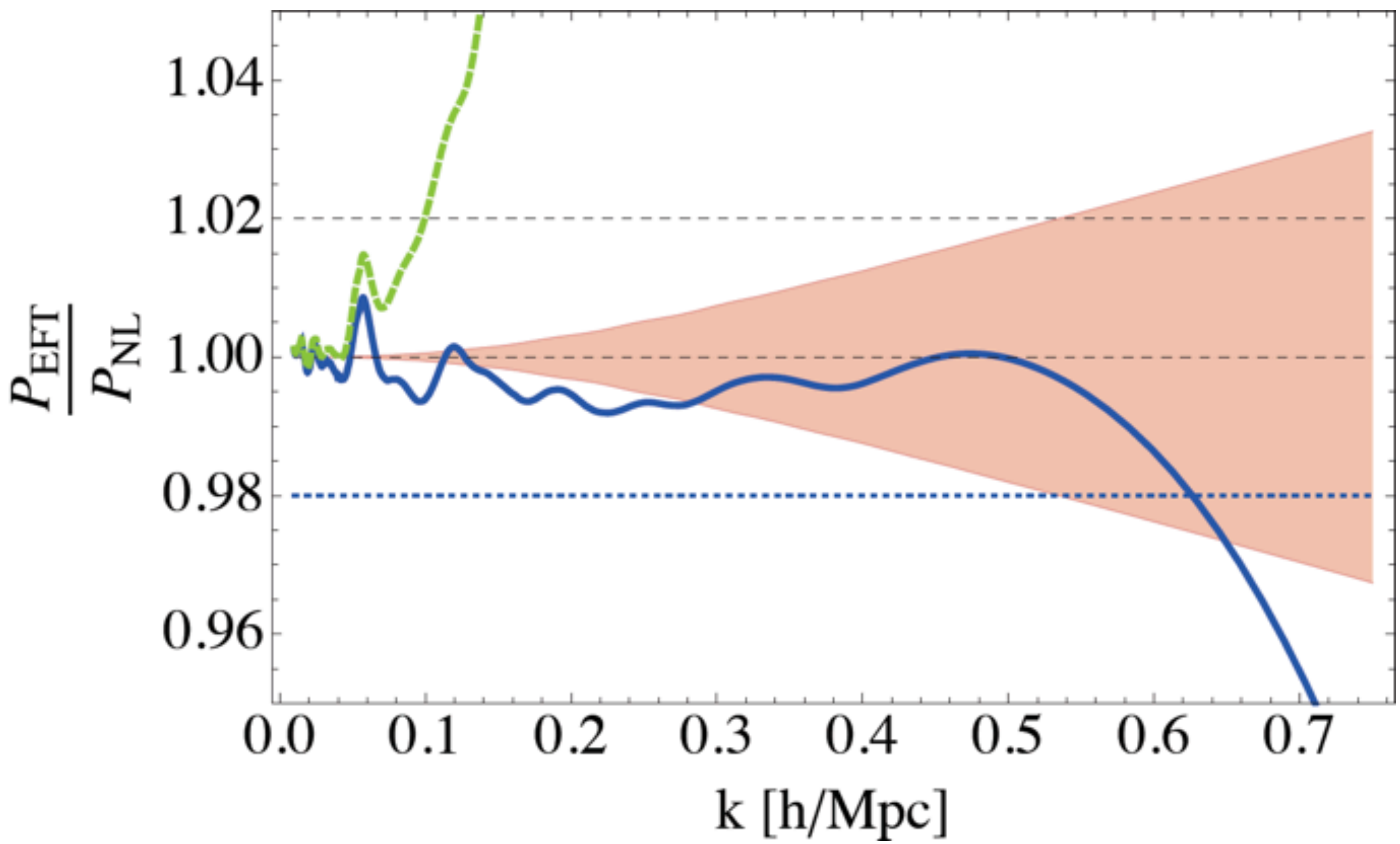
EFT of Large Scale Structures



- The lines with oscillations are obtained without resummation in the IR

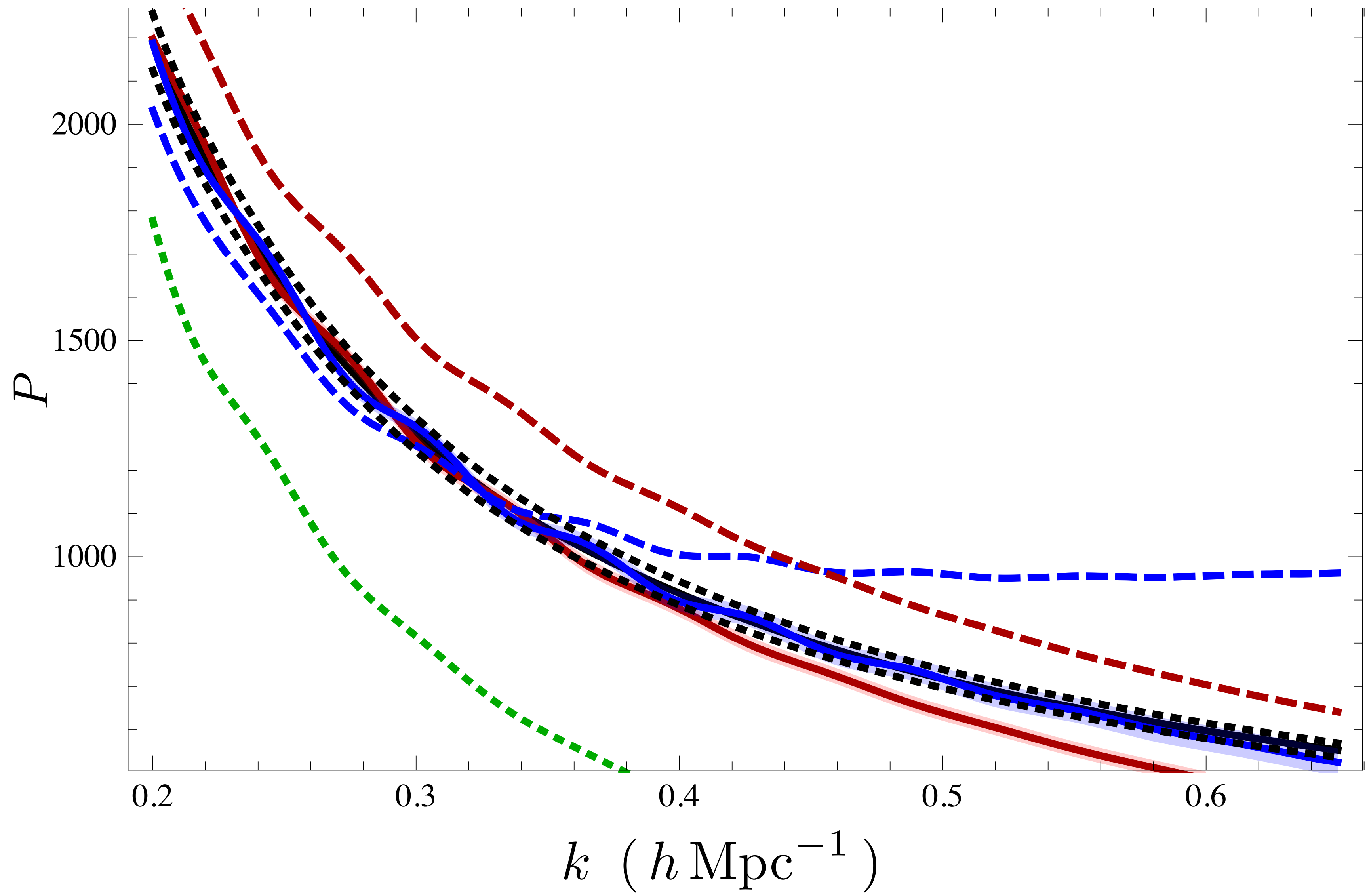
with Carrasco, Foreman and Green **1310**

EFT of Large Scale Structures



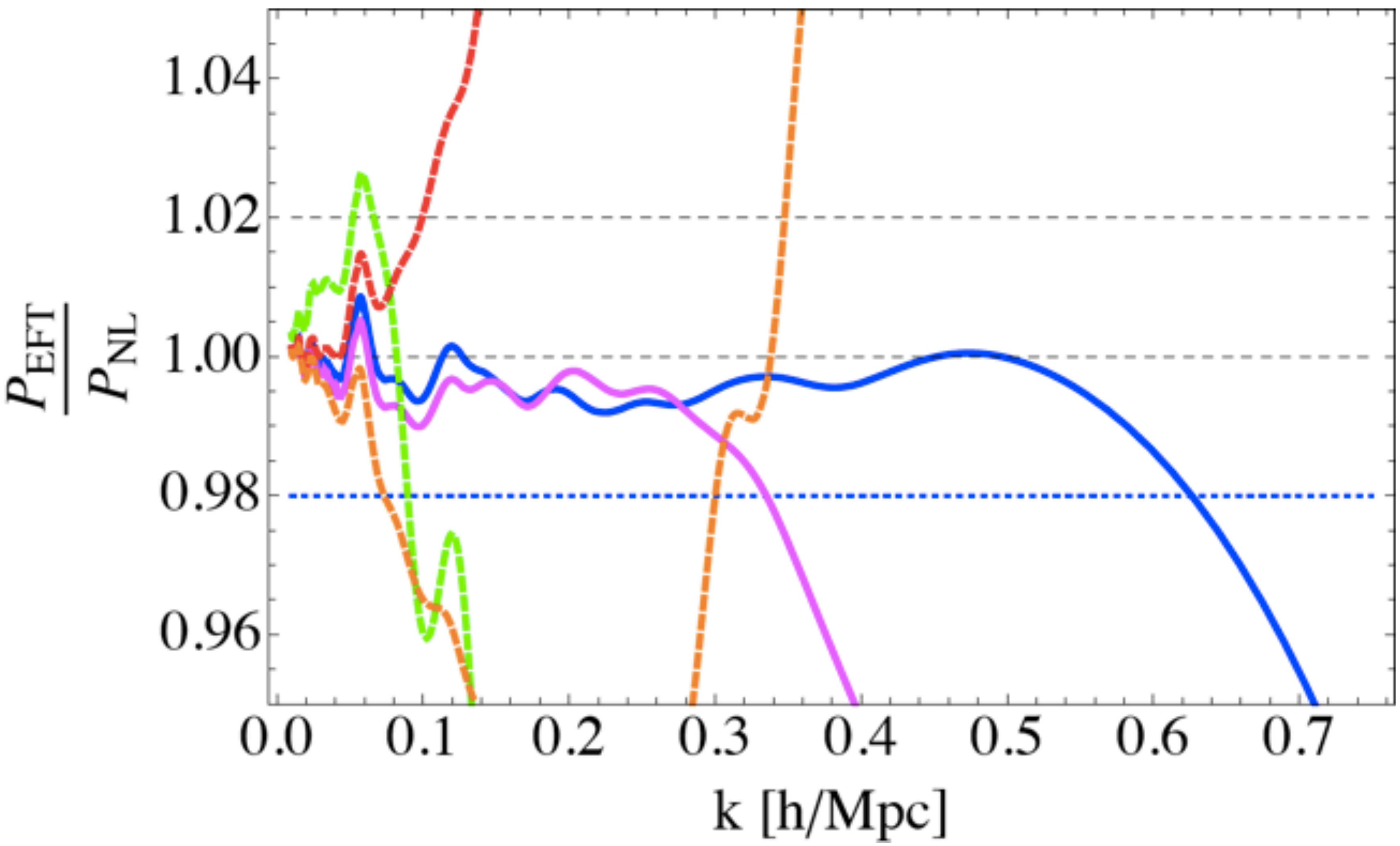
- we fit until $k_{\max} \simeq 0.6\, h\, \mathrm{Mpc}^{-1}$, as where we should stop fitting
  - there are 200 more quasi linear modes than previously believed!

EFT of Large Scale Structures



- The function we are fitting is non-trivial, and made with non-trivial objects

EFT of Large Scale Structures



- Comparison with Standard Treatment

- Fur the EFT, change from 1-loop to 2-loop predicted

$$P_{\text{EFT-2-loop}} = P_{11} + P_{\text{1-loop}} + P_{\text{2-loop}} - 2\,(2\pi)(c^2_{s(1)} + c^2_{s(2)})\frac{k^2}{k^2_{\text{NL}}} P_{11} + (2\pi) c^2_{s(1)} P^{(c_s,p)}_{\text{1-loop}} + (2\pi)^2 c^4_{s(1)} \frac{k^4}{k^4_{\text{NL}}} P_{11}$$

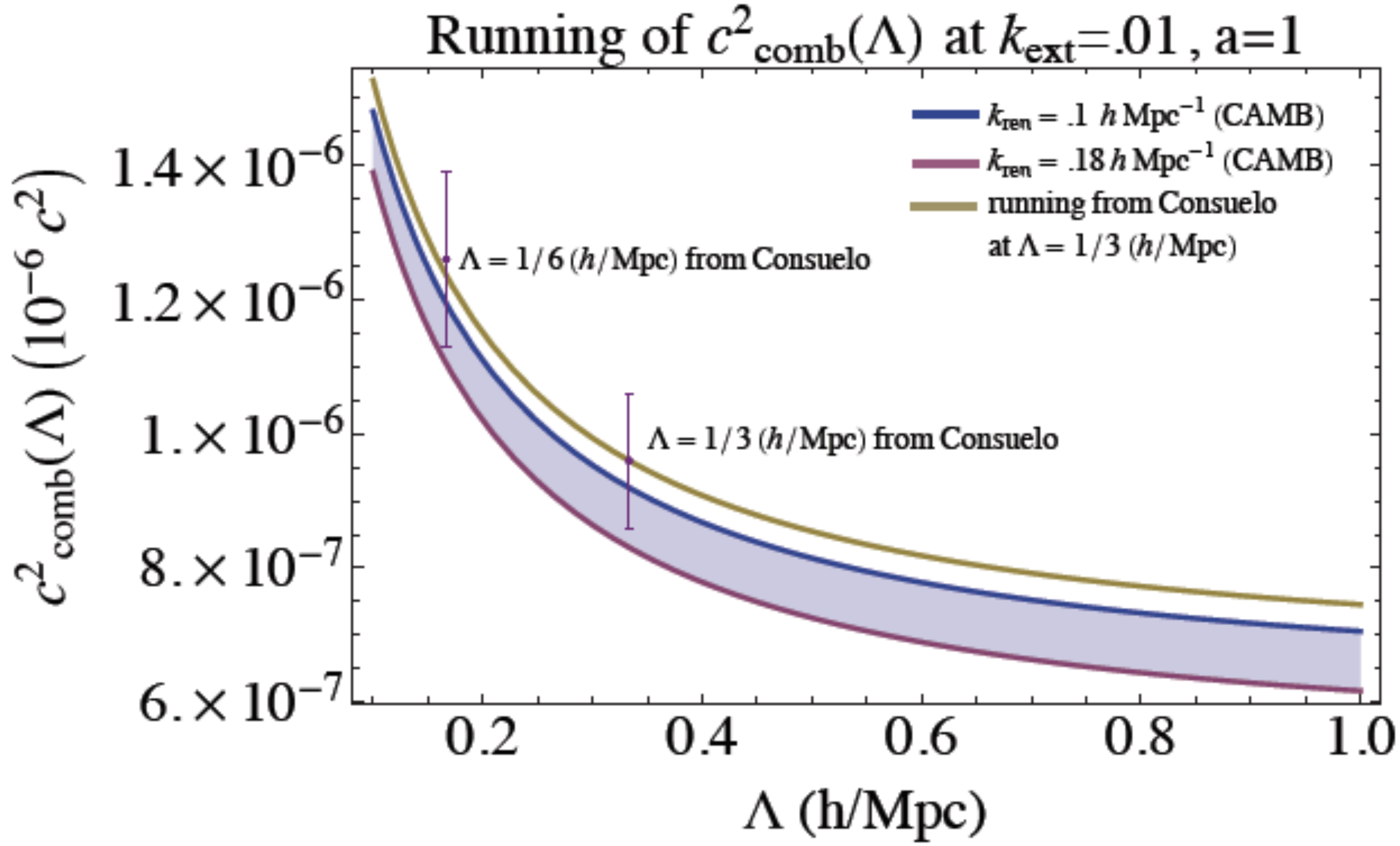
  – the other new terms are clearly important

  – they `conspire' to the right answer

Measuring parameters from N-body sims.

- The EFT parameters can be measured from small N-body simulations
  - similar to what happens in QCD: lattice sims
- As you change smoothing scale, the result changes

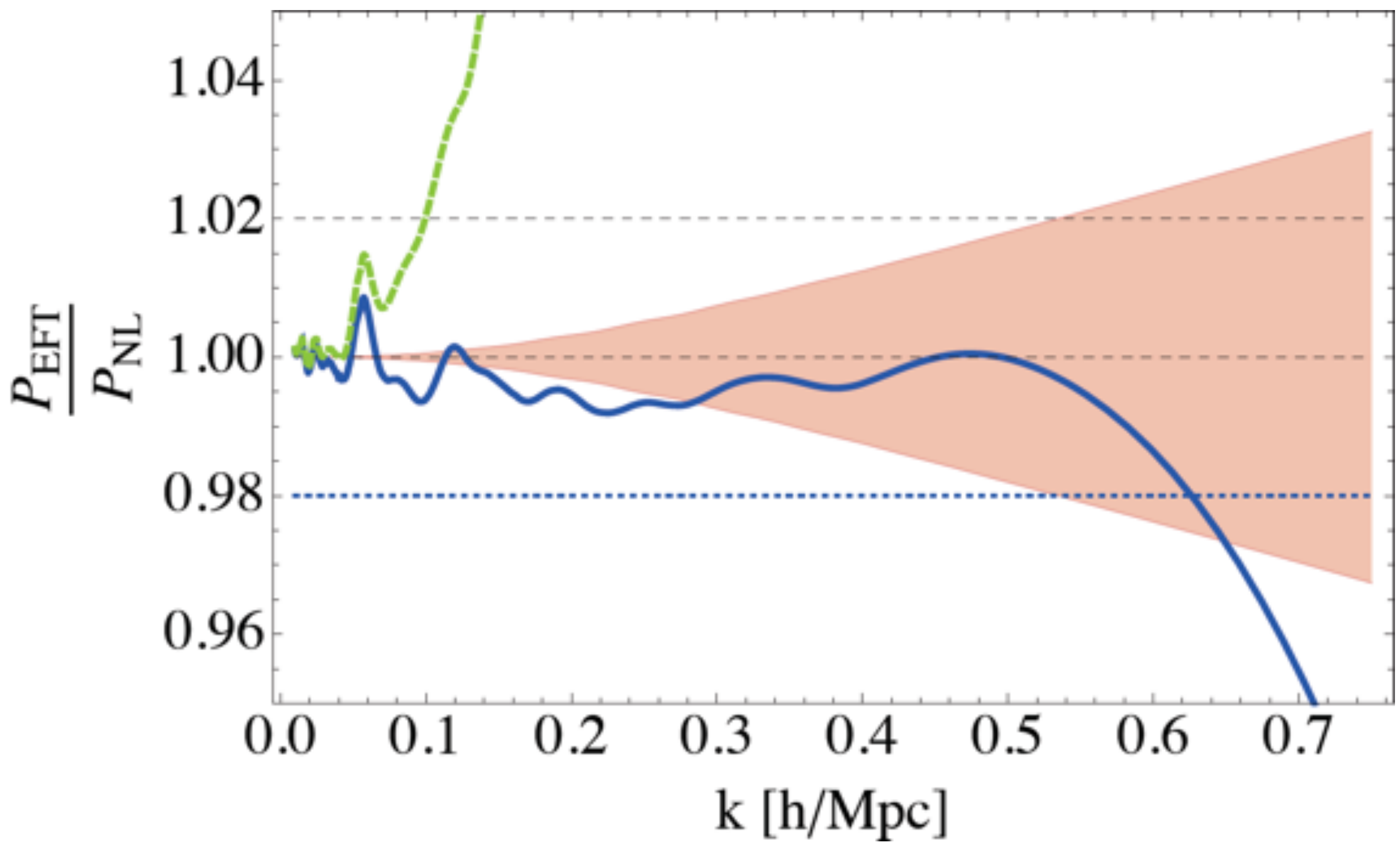
$$\frac{d\,c_s}{d\Lambda} = \frac{d}{d\,\Lambda}\int^{\Lambda} d^3k\ P_{13}(k)$$



- Perfect agreement with fitting at low energies
  - like measuring F_π from lattice sims and $\pi\pi$ scattering

with Carrasco and Hertzberg **JHEP 2012**

EFT of Large Scale Structures



- A manifestly convergent perturbation theory $\left(\frac{k}{k_{\rm NL}}\right)^L$
- we fit until $k_{\rm max} \simeq 0.6\, h\, {\rm Mpc}^{-1}$, as where we should stop fitting
  - there are 200 more quasi linear modes than previously believed!
  - huge impact on possibilities for $f_{\rm NL}^{\rm equil.,\, orthog.} \lesssim 1$
- Can all of us handle it?! This is an opportunity and a challenge for us
  - Primordial Cosmology can still have a bright near future!

Conclusions

- Many (most?) of the features of QFT appear in the EFT of LSS:
  - Loops, divergencies, counterterms and renormalization
  - non-renormalization theorems
  - Calculable and non-calculable terms
  - Measurements in lattice and lattice-running
  - IR-divergencies
- Many calculations and verifications to do:
  - like if we just learned perturbative QCD, and LHC was soon turning on
    - higher n-point functions
    - Validation with simulation
    - Bias, Redshift distortions (similar to hadronization in QCD)
- To me, what is at stake, in the 10 year future of primordial cosmology
- With a growing number of (young) collaborators

EFT of Large Scale Structures

``It would be fantastic to have a perturbation theory that works”

Famous Cosmologist, Trieste, July 2013

EFT of Large Scale Structures

``It would be fantastic to have a perturbation theory that works"

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