Leonardo Senatore (Stanford)

The Effective Field Theory of Large Scale Structure

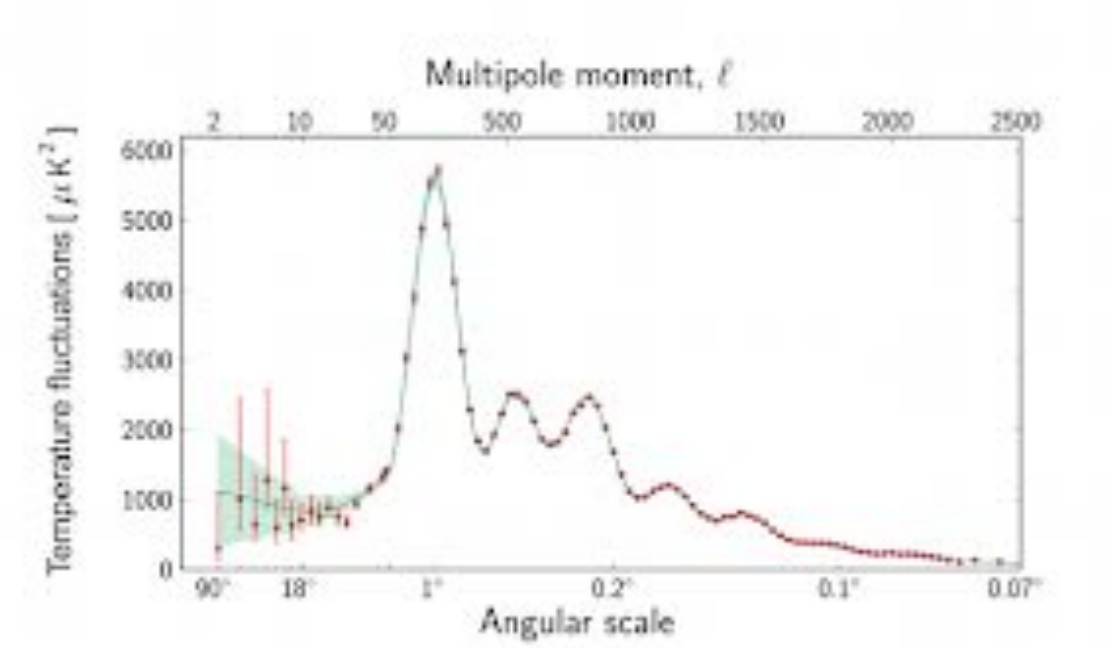
the way to go for inflation

How do we probe inflation

- The only observable we are testing from the background solution is

$$\Omega_K \lesssim 3 \times 10^{-3}$$

- All the rest, comes from the fluctuations



- For the fluctuations
  - –they are primordial
  - –they are scale invariant
  - –they have a tilt $\quad n_s - 1 \simeq -0.04 \sim \mathcal{O}\left(\frac{1}{N_e}\right)$
  - –they are quite gaussian

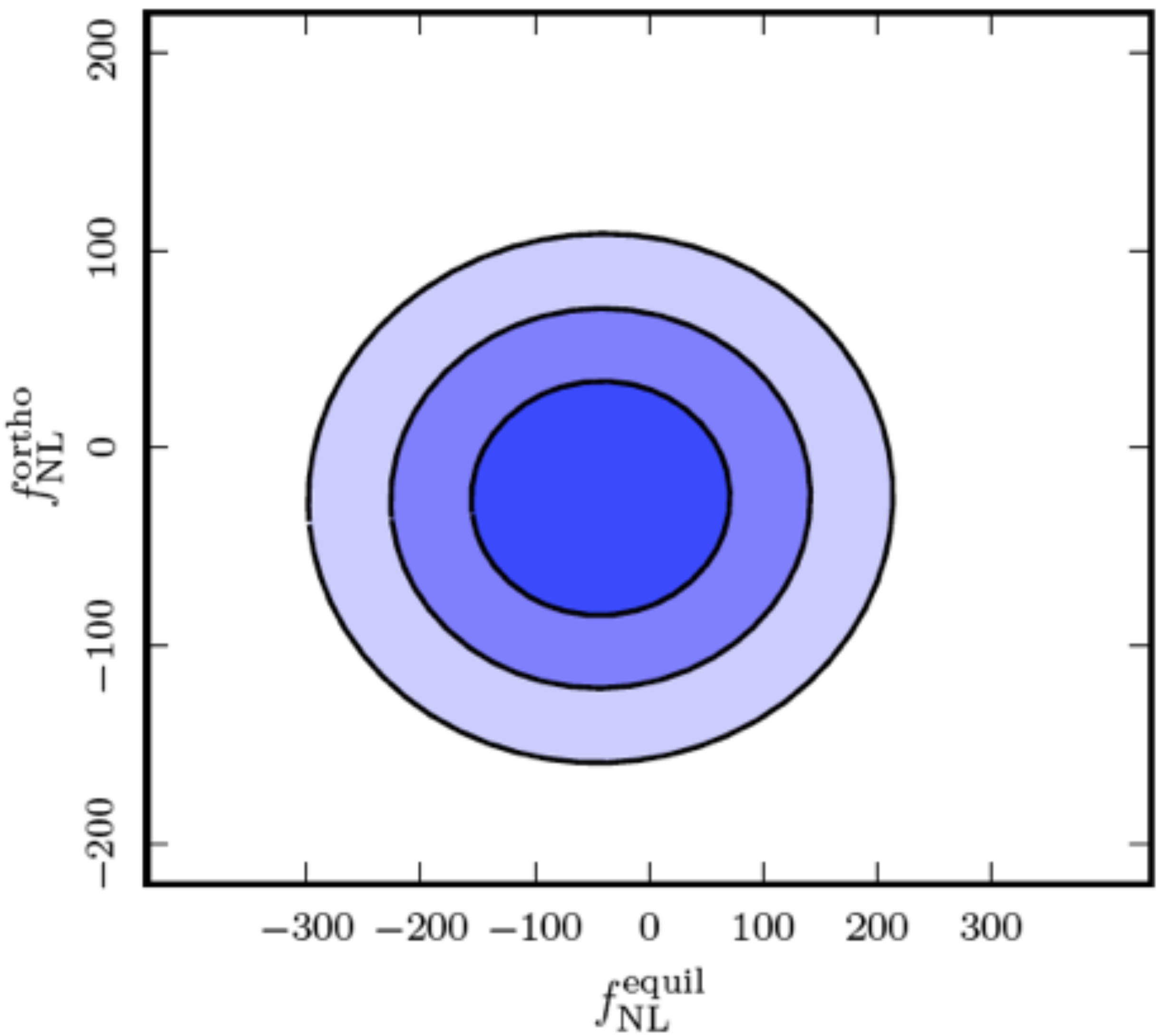
$$\text{NG} \sim \frac{\langle\zeta^3\rangle}{\langle\zeta^2\rangle^{3/2}} \lesssim 10^{-3}$$

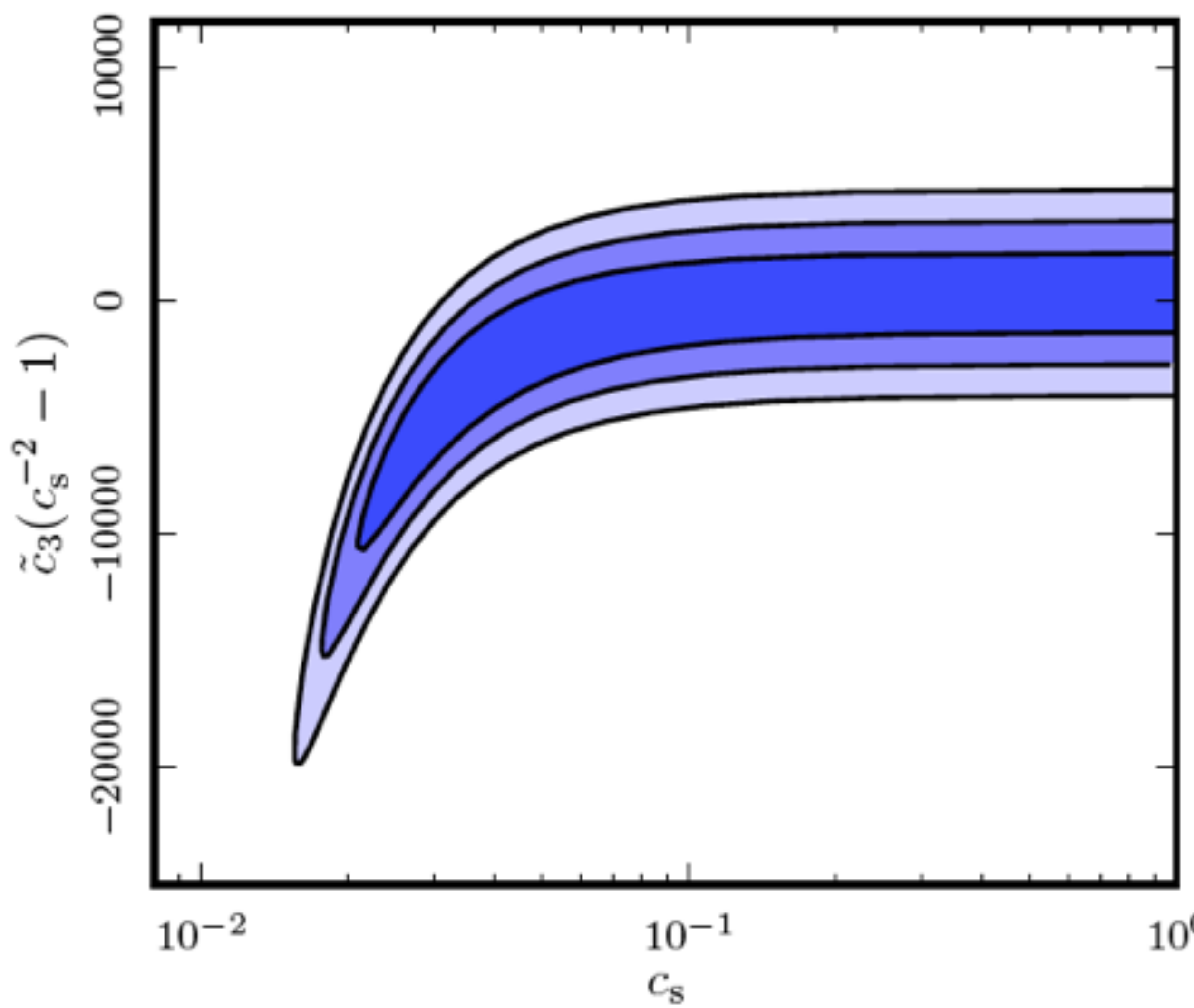
  - –both scalar and maybe tensors

Limits in terms of parameters of a Lagrangian

- $$S=\int d^4x\,\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot H}{c_s^2}\left(\dot\pi^2-c_s^2\frac{(\partial_i\pi)^2}{a^2}\right)+(M_{\rm Pl}^2\dot H)\frac{1-c_s^2}{c_s^2}\left(\frac{\dot\pi(\partial_i\pi)^2}{a^2}+\frac{A}{c_s^2}\dot\pi^3\right)+\cdots\right]$$

with C. Cheung, P. Creminelli, L. Fitzpatrick, J. Kaplan **JHEP 2008**





- these are limits on the cutoff of the theory $\sim\frac{\dot\pi^3}{\Lambda^2}$

with Smith and Zaldarriaga, **JCAP2010**
Planck Collaboration **2013**

The 4-pt function from WMAP

- From EFT of single field inflation

$$S = \int d^4x \, \left[M_{\rm Pl}^2 \dot{H} (\partial_\mu \pi)^2 + {M_4}^4 \left(\dot{\pi}^4 + \dot{\pi}^2 (\partial_\mu \pi)^2 \right) \right]$$

with Zaldarriaga **JHEP 2011**

- From EFT of multifield inflation

$$S_\sigma = \int d^4x \sqrt{-g} \, \left[(\partial_\mu \sigma)^2 + \frac{1}{\Lambda_1^4} \dot{\sigma}^4 + \frac{1}{\Lambda_2^4} \dot{\sigma}^2 (\partial_i \sigma)^2 + \frac{1}{\Lambda_3^4} (\partial_i \sigma)^2 (\partial_j \sigma)^2 + \frac{\mu^4}{\Lambda^4} \sigma^4 + \ldots \right]$$

with Zaldarriaga **JHEP 2011**

- Signal associated to
  - spontaneously broken global symmetries
  - supersymmetry

- 3 independent shapes to analyze

$$(-8.18 \times 10^5) < g_{NL}^{\rm loc} < (0.58 \times 10^5) \qquad (95\% \text{ CL})$$

$$(-9.38 \times 10^6) < g_{NL}^{\dot{\sigma}^4} < (2.98 \times 10^6) \qquad (95\% \text{ CL})$$

$$(-5.26 \times 10^6) < g_{NL}^{(\partial\sigma)^4} < (0.42 \times 10^6) \qquad (95\% \text{ CL})$$

with Smith and Zaldarriaga **to appear**
same code to be applied in Planck, by the collaboration

What has Planck done to theory?

- Planck improve limits wrt WMAP by a factor of ~3.
- Since $$\mathrm{NG} \sim \frac{H^2}{\Lambda_U^2} \quad \Rightarrow \quad \Lambda_U^{\rm min,\, Planck} \simeq 2\, \Lambda_U^{\rm min,\, WMAP}$$
- Given the absence of known or nearby threshold, this is not much.
- Planck was great
- but Planck was 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 (luckily WMAP had a tilt a 2.5 σ, so we got to 6 σ)
- On theory side, little changes
  - contrary for example to LHC, which was crossing thresholds
    - Any result from LHC is changing the theory

Cosmology is going to change in a few months

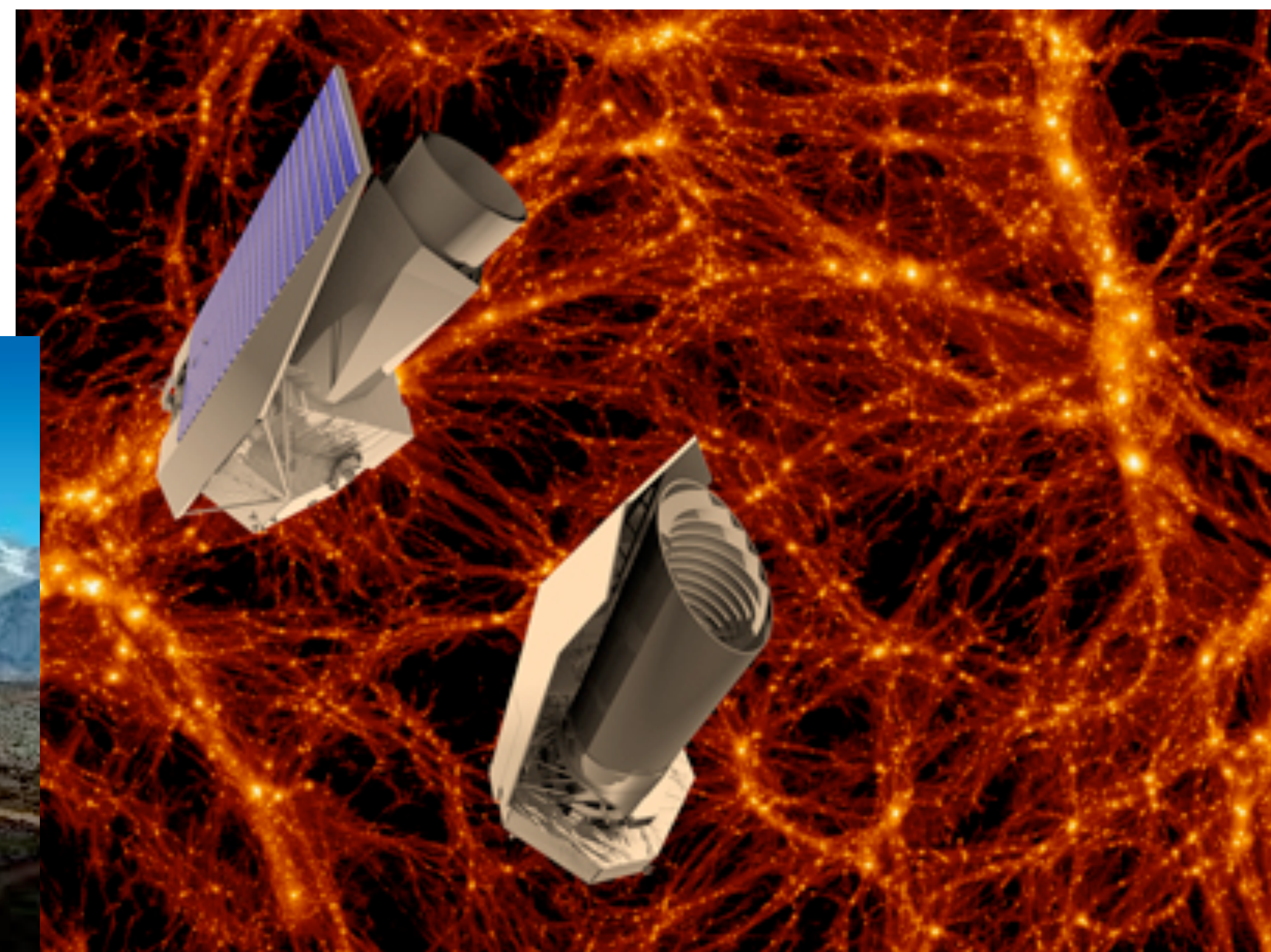
- Tremendous progress has been made through observation of the primordial fluctuations
- In order to increase our knowledge of Inflation, we need more modes
- Planck will soon have observed all the modes from the CMB
- and then what?
- I will assume we are not lucky
  - no B-mode detection
  - no signs from the beginning of inflation
  - no surprises
- Unless we find a way to get more modes, the game 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

What is next?

- Euclid and LSST like: this is our only next chance
  - we need to understand how many modes are available

$$\text{Number of modes} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^3$$

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



The situation is very serious

- Right now, LSS surveys provide information only for those quantities to which the CMB is largely insensitive (such as dark energy)
- To make progress on the early universe, it is not sufficient to do just better that now, we need to beat Planck!
    - this means that log-log plots are not enough, we need percent plots
- We are very far from this level of precision
    - in fact, the community has already kind of given up and focused on dark energy
        - » which theoretically we kind of know is going to be the Cosmological Costant
    - experiments are named and designed for dark energy
        - Dark Energy Survey (DES)
        - Dark Energy Spectroscopic Instrument (DESI)
        - Euclid is very much designed on dark energy
            - » in fact the proposed Sphirex is incredibly cheaper and more powerful

The case for an analytic understanding

- In principle, we can simulate the clustering of dark matter with N-body sims
- But
  - we cannot simulate baryons: we can only `model' them
  - simulations with dark matter are very slow
    - very hard to get 1% precision
      - I have personal experience about this: my group's research program is kind of limited by the availability of precise data from N-body sims.
      - very hard to debug
  - As a proof, SDSS stops analyzing data at $k \simeq 0.1\, h\text{Mpc}^{-1}$
    - this is a very low k for the EFTofLSS
    - and BOSS has been running for 10 years
    - having simulations apparently was not enough to overcome the problems
  - Intellectually: we should have a simple understanding
    - when the regime is quasi-linear

What we should aim for?

- If we push

$$f_{NL} \lesssim 1$$

  - then we rule out all theories of early universe but
    - Single-Field Slow-Roll Inflation
    - As all other theories are more interacting that this
      - all interactions are so small that we are perturbatively close to slow roll inflation
      - or exotic
- Huge discovery without a detection

	$f_{NL}^{\rm loc.} \lesssim 1$	$f_{NL}^{\rm loc.} \gtrsim 1$
$f_{NL}^{\rm equil.,\, orthog.} \lesssim 1$	Only Single-Field Slow-Roll Inflation	Multifield model of early universe
$f_{NL}^{\rm equil.,\, orthog.} \gtrsim 1$	Single-field non-Slow-Roll inflationary model	Multifield model of early universe

- This is what we should aim for

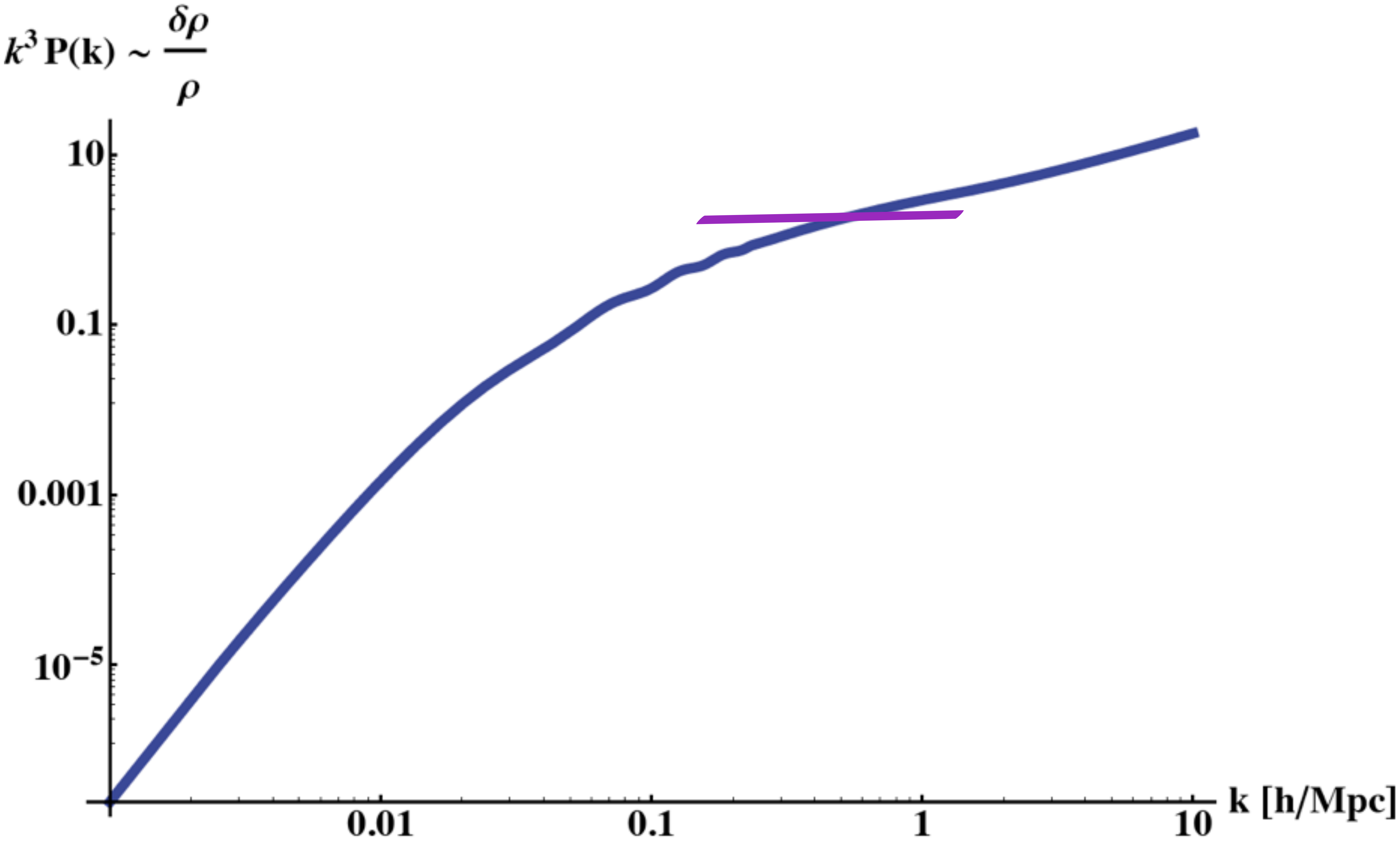
with many authors **1412**

The Effective Field Theory of Cosmological Large Scale Structures

- **The EFTofLSS at high redshift** with Foreman **to appear**
- **Halo Power and Bispectrum from the EFTofLSS** with Angulo, Fasiello and Vlah **to appear**
- **Analytic Prediction of Baryon Effects from the EFTofLSS** with Perko and Lewandowski **1412**
- **Redshift Space distortions in the EFTofLSS** with Zaldarriaga **1409**
- **Bias in the EFTofLSS** me alone **1406**
- **The one-loop bispectrum in the EFTofLSS** with Angulo, Foreman, Schmittful **1406**
  see also Baldauf, Mirbabayi, Mercolli,Pajer **1406**
- **The IR-resummed EFTofLSS** with Zaldarriaga **1404**
- **The Lagrangian-space EFTofLSS** with Porto and Zaldarriaga **JCAP1405**
- **The EFTofLSS at 2-loops** with Carrasco, Foreman and Green **JCAP1407**
- **The 2-loop power spectrum and the IR safe integrand** with Carrasco, Foreman and Green **JCAP1407**
- **The Effective Theory of Large Scale Structure (EFTofLSS)** 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

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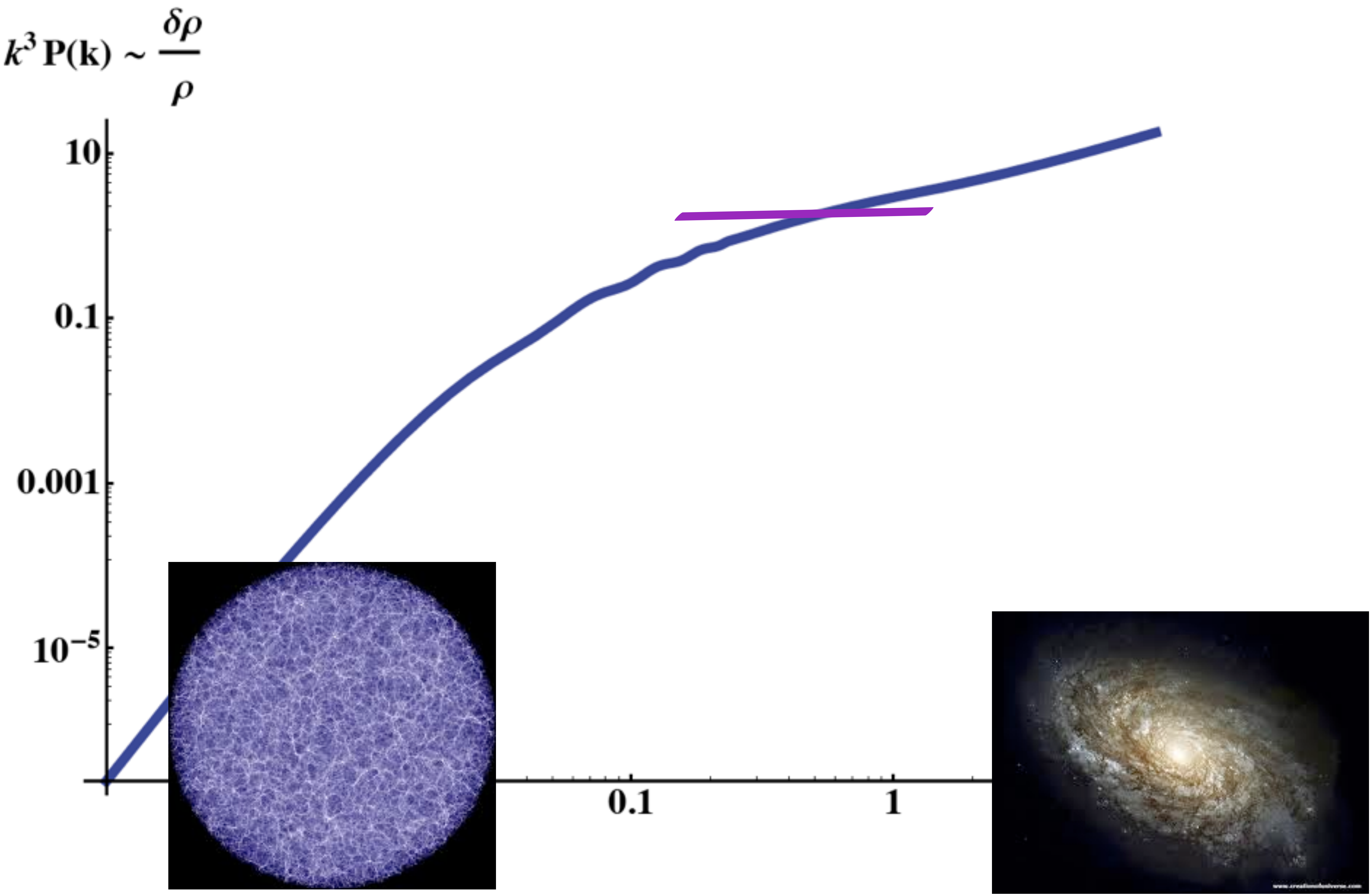


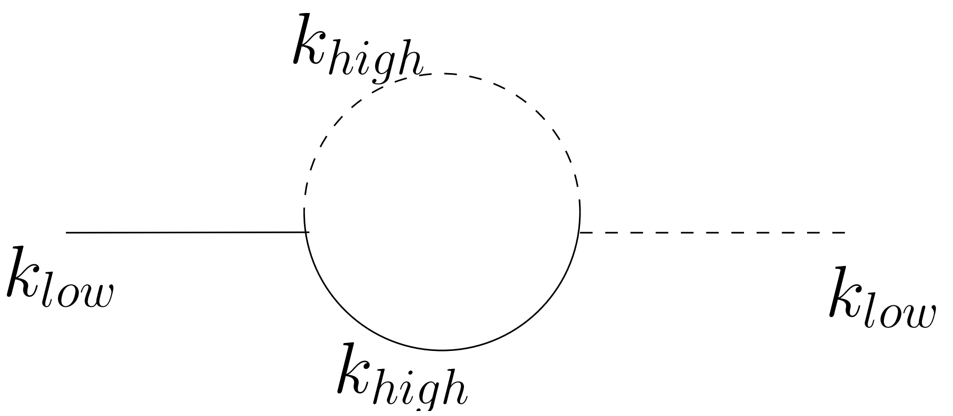
A well defined perturbation theory

- Standard perturbation theory is not well defined
- Standard techniques
  - perfect fluid $\quad \dot{\rho} + \partial_i \left(\rho v^i\right) = 0 \ ,$
  - expand in $\quad \delta \sim \frac{\delta\rho}{\rho}$ 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
  - $\delta \sim \frac{k}{k_{NL}} \gg 1 \quad \text{for} \quad k \gg k_{NL}$
  - no perfect fluid if we truncate



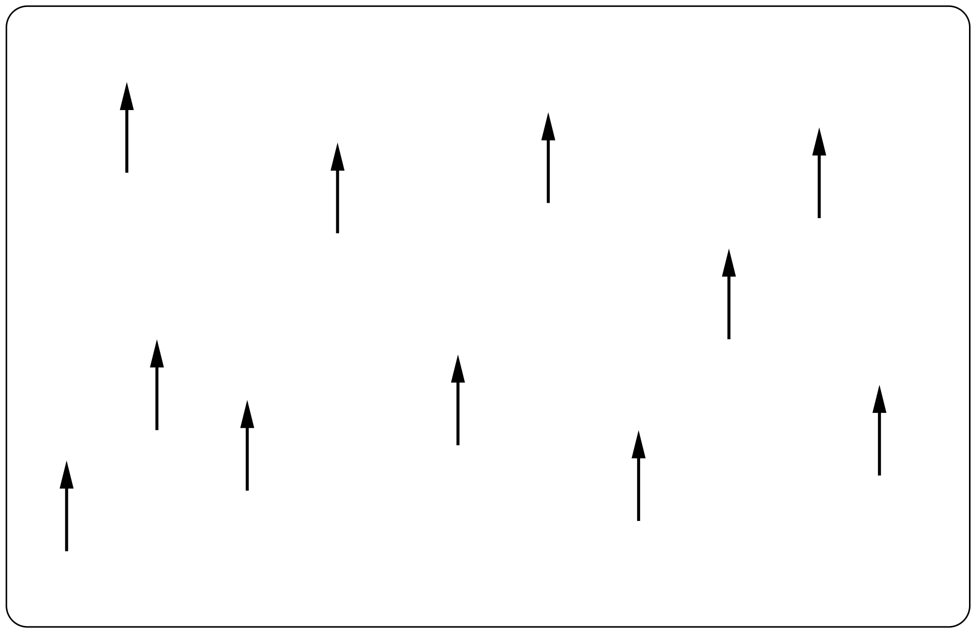
- All available techniques (LPT, RPT,REgPT,…) differ by this only by their treatment of IR modes, not of UV modes. So, all have these problems.

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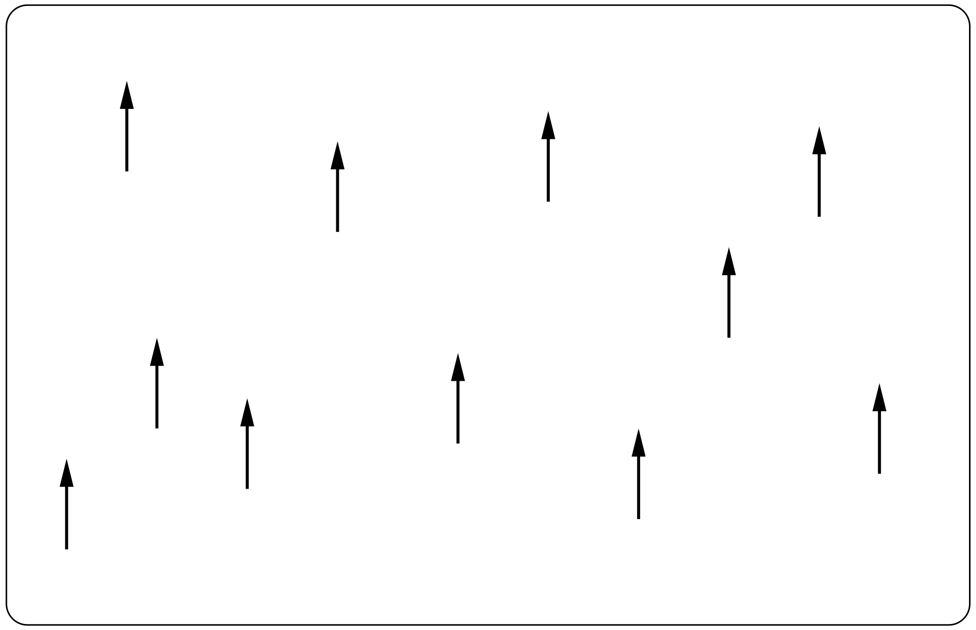
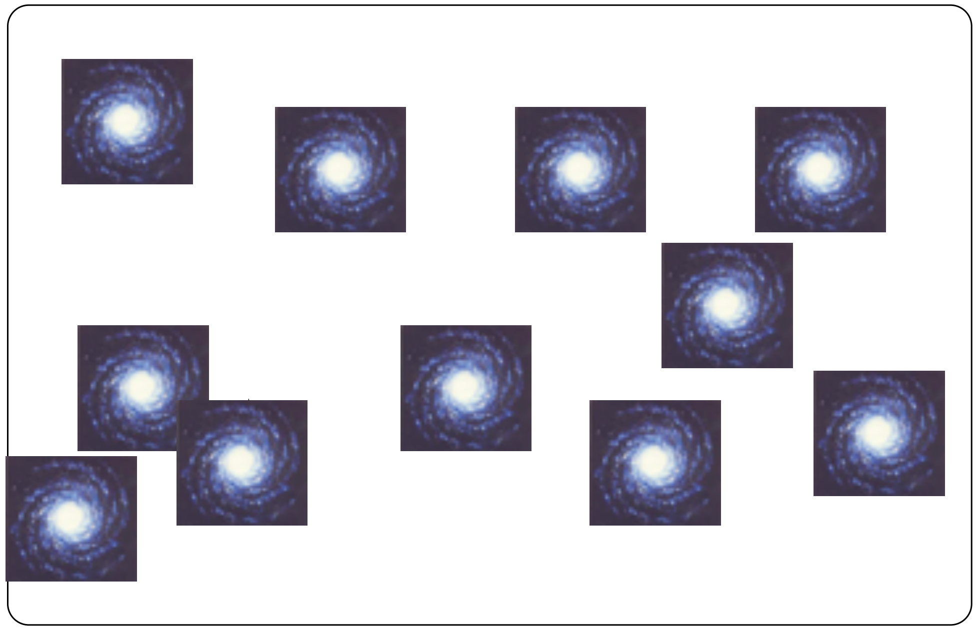
$$\text{EM} \quad \longrightarrow \quad \text{GR}$$

Dielectric Fluid

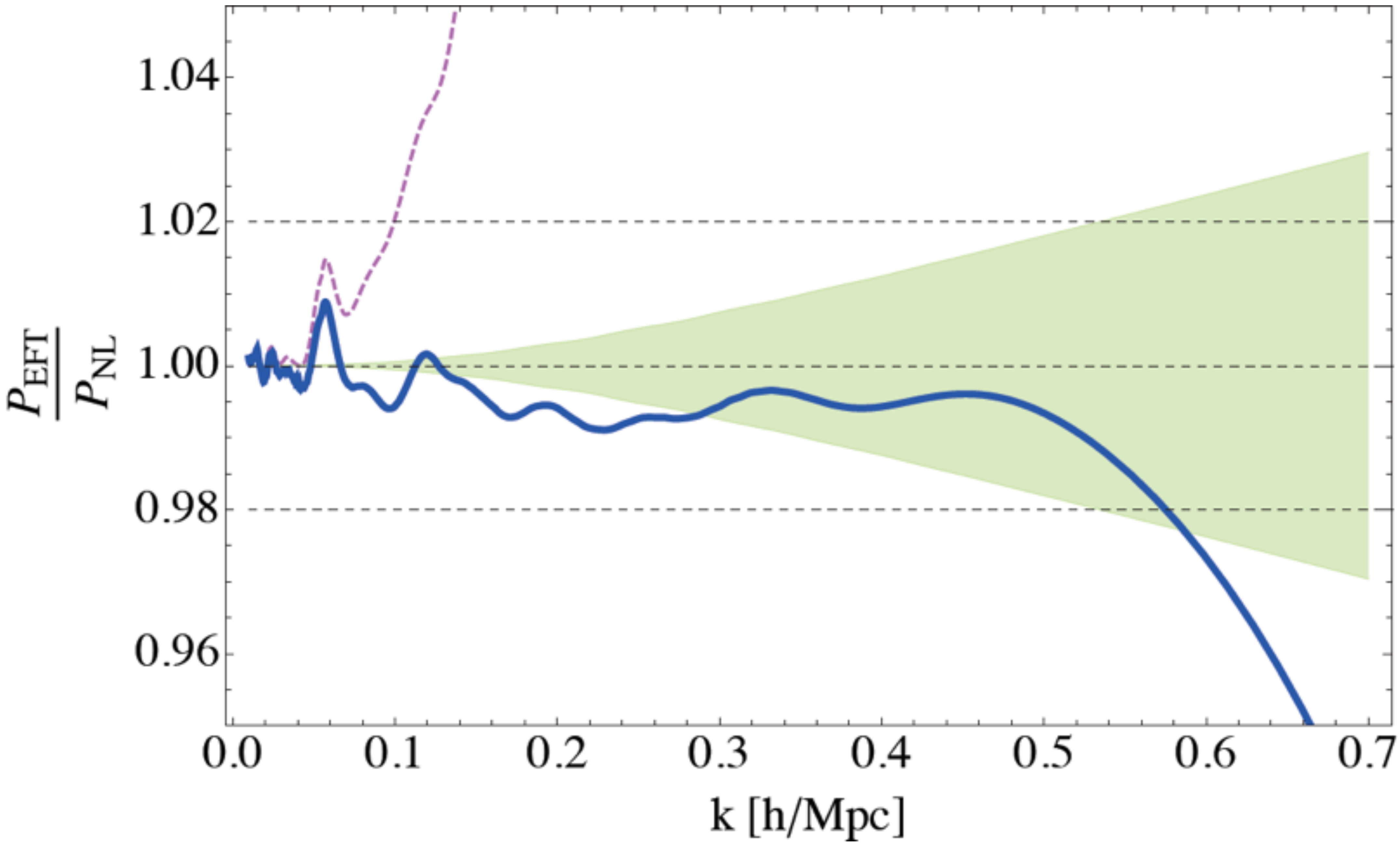


Dielectric Fluid



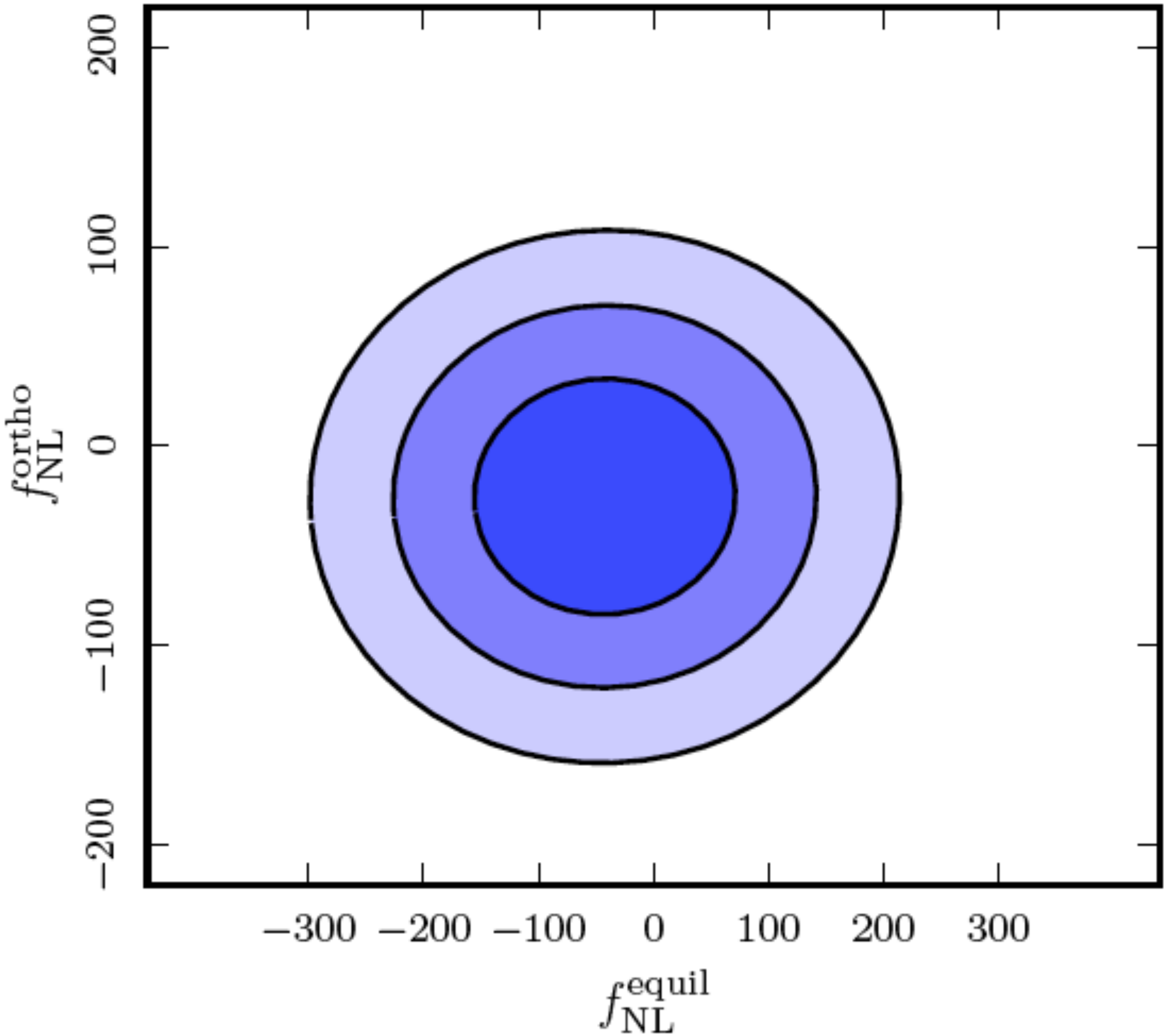
Bottom line result

- A well defined perturbation theory
- 2-loop in the EFT, with IR resummation



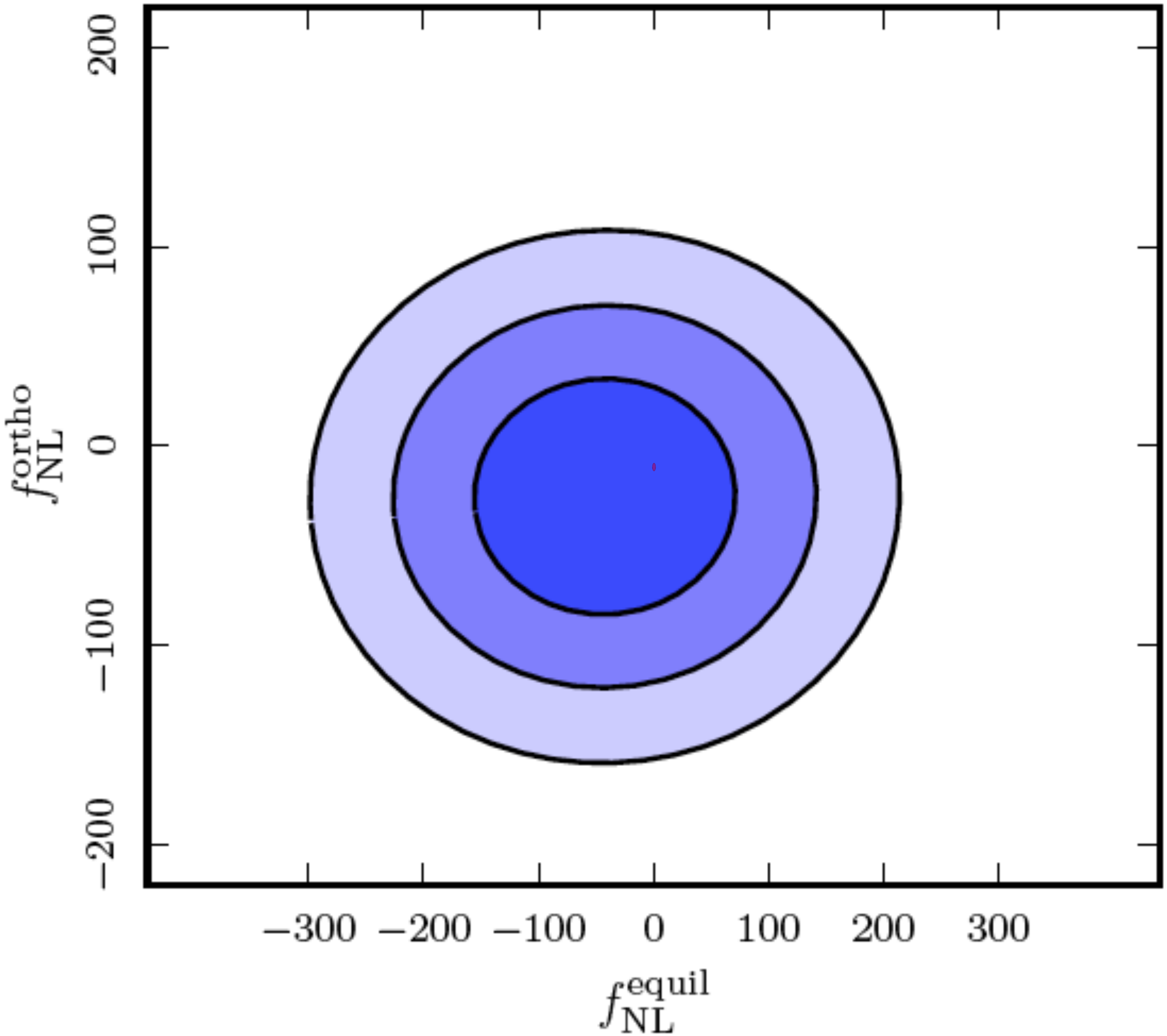
- Data go as $k^3_{\rm max}$: naively factor of 200 more modes than before

With this

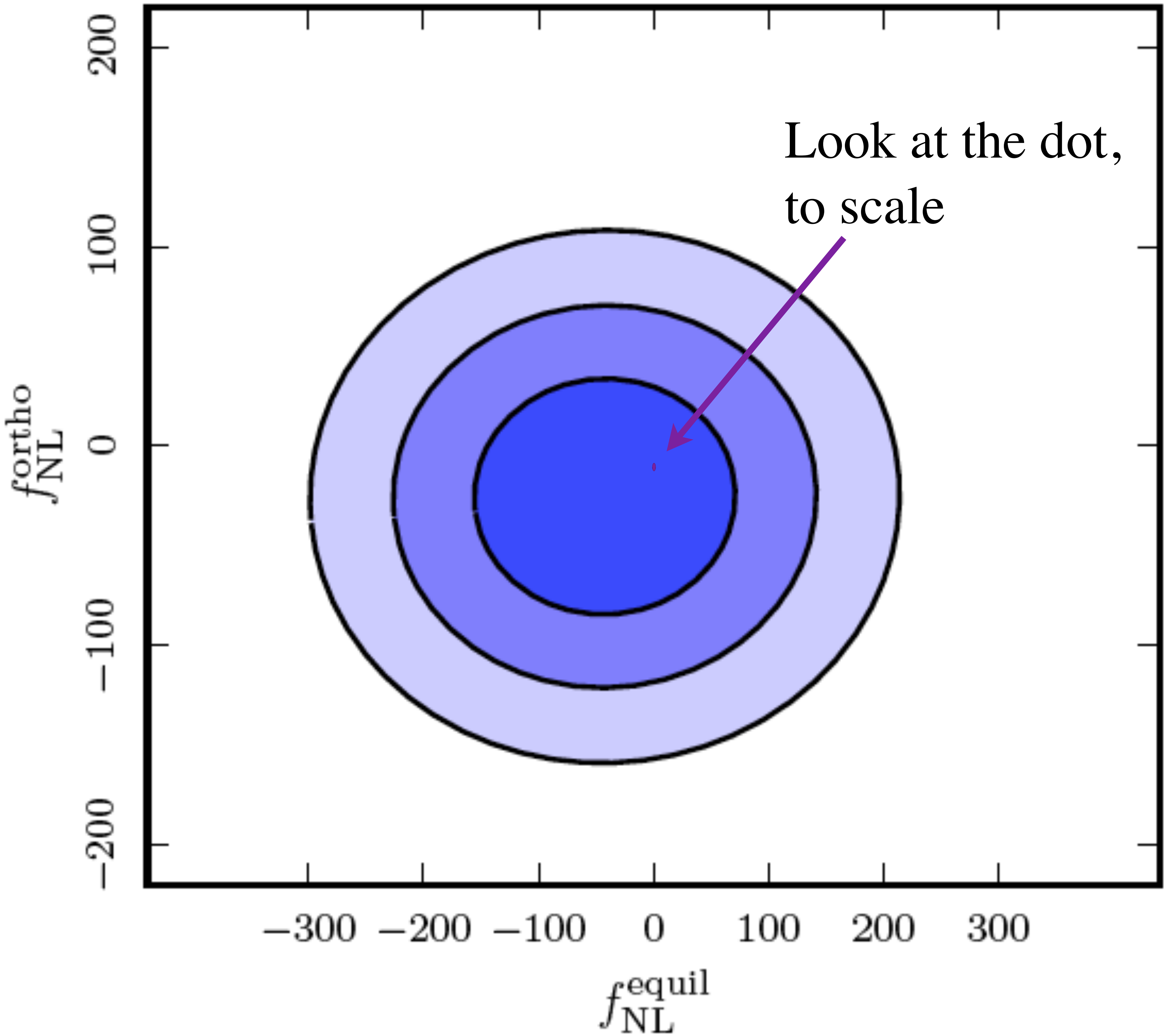


200
100
0
−100
−200
$f_{\rm NL}^{\rm ortho}$
−300
−200
−100
0
100
200
300
$f_{\rm NL}^{\rm equil}$

With this

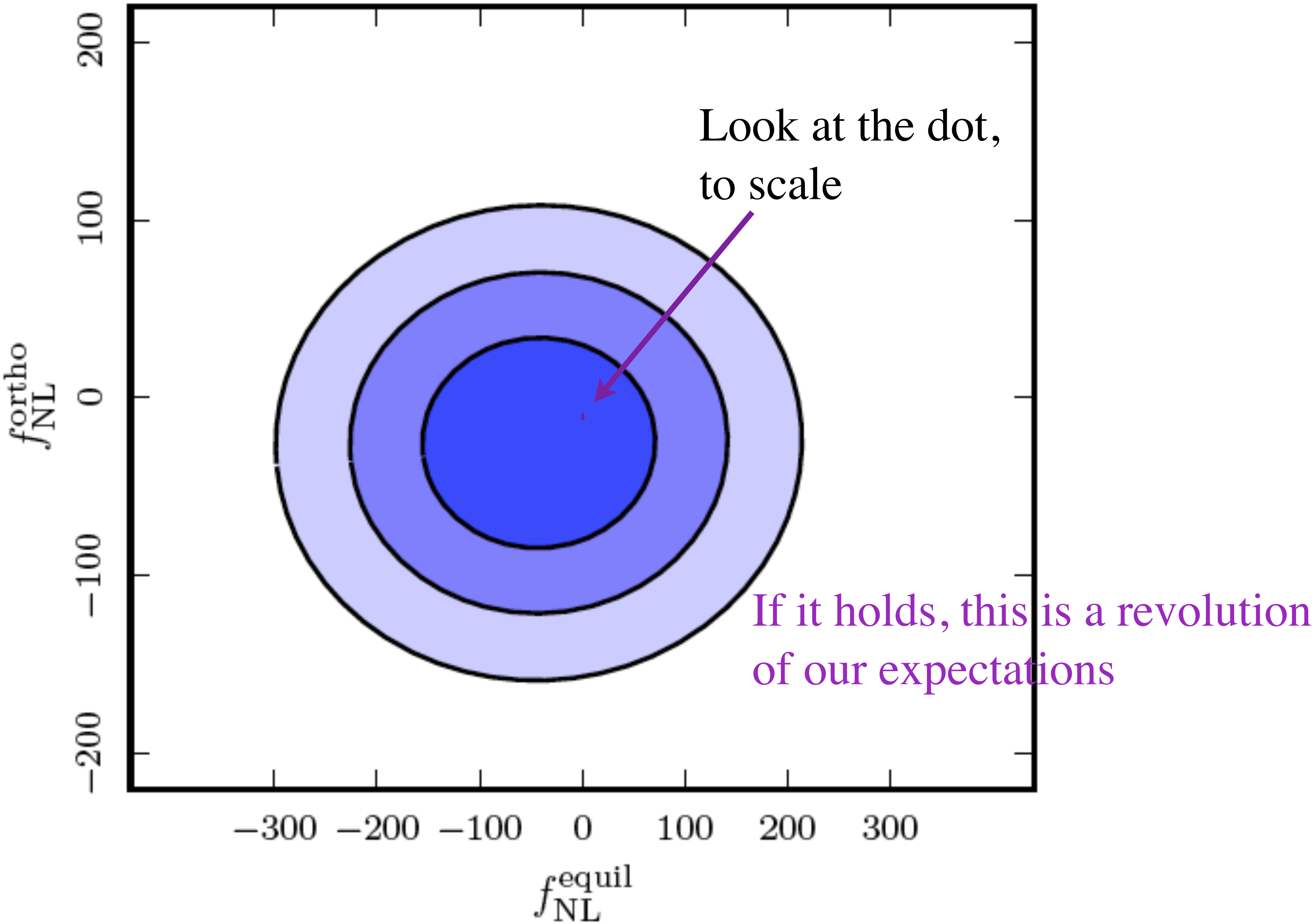


With this

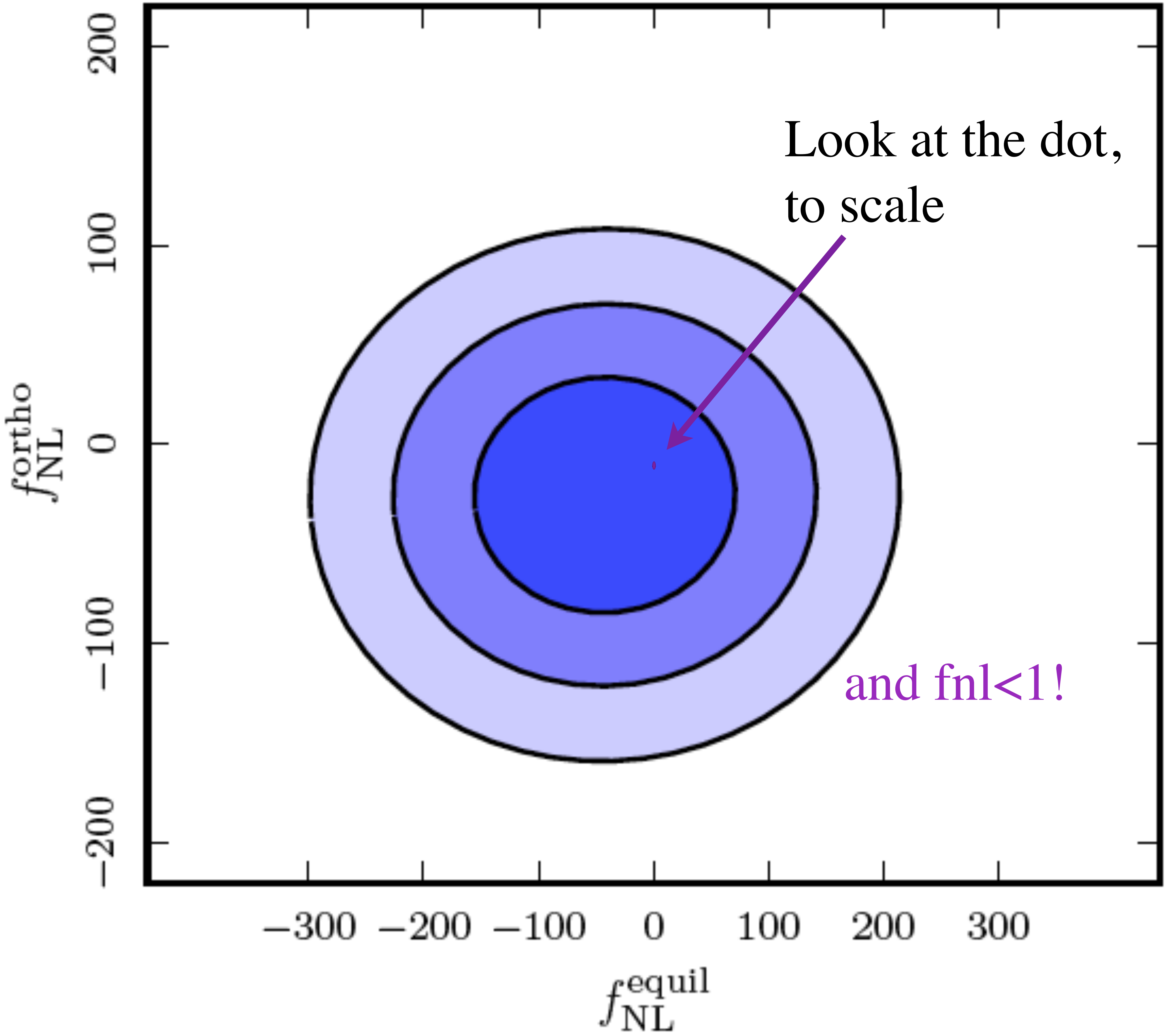


Look at the dot,
to scale
200
100
0
−100
−200
$f_{\rm NL}^{\rm ortho}$
−300
−200
−100
0
100
200
300
$f_{\rm NL}^{\rm equil}$

With this


Look at the dot,
to scale
If it holds, this is a revolution
of our expectations
200
100
0
−100
−200
−300
−200
−100
0
100
200
300
f_{NL}^{ortho}
f_{NL}^{equil}

With this



Look at the dot,
to scale
and fnl<1!
200
100
0
−100
−200
−300
−200
−100
0
100
200
300
f_{NL}^{ortho}
f_{NL}^{equil}

…after constructing the
Effective Field Theory…

Connecting with the Eulerian Treatment

- The resulting equations are equivalent to Eulerian fluid-like equations

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

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

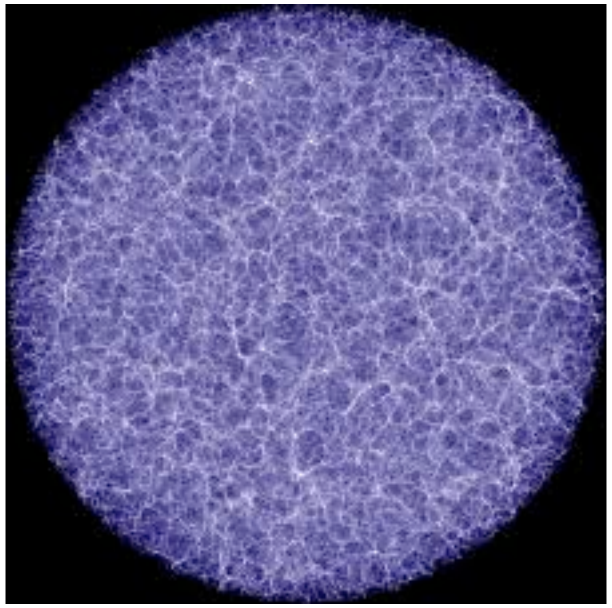
$$\dot{v}^i + Hv^i + v^j\partial_j v^i = \frac{1}{\rho}\partial_j\tau^{ij}$$

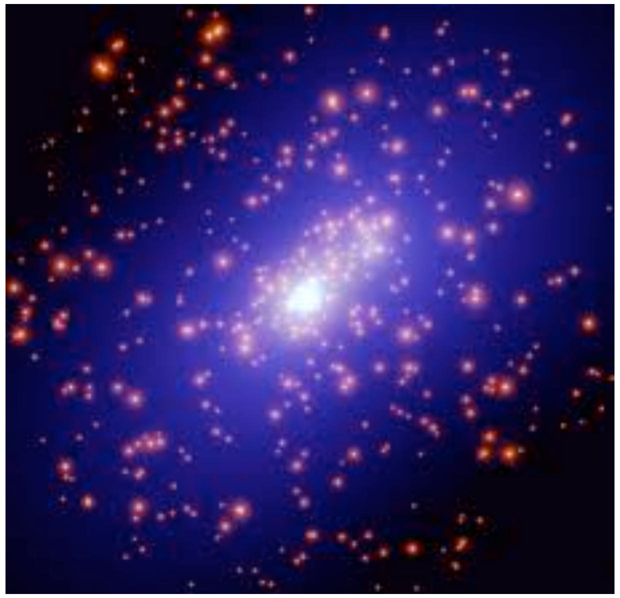
  - here it appears a non trivial stress tensor for the long-distance fluid

$$\tau_{ij} = p_0\,\delta_{ij} + c_s^2\,\delta\rho\,\delta_{ij} + \mathcal{O}\left(\partial, \delta^2, \ldots\right)$$

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

Connecting with the Eulerian Treatment

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

$$\epsilon_{s>} = k^2 \int_k^\infty \frac{d^3k'}{(2\pi)^3} \frac{P_{11}(k')}{k'^2} \ ,$$

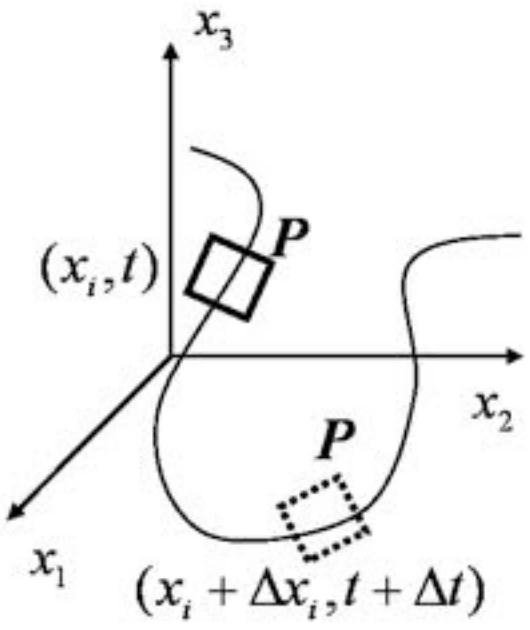
Effect of Short Displacements

$$\epsilon_{\delta<} = \int_0^k \frac{d^3k'}{(2\pi)^3} P_{11}(k') \ ,$$

Effect of Long Overdensities

$$\epsilon_{s<} = k^2 \int_0^k \frac{d^3k'}{(2\pi)^3} \frac{P_{11}(k')}{k'^2} \ ,$$

Effect of Long Displacements



Perturbation Theory with the EFT

Perturbation Theory within the EFT

- Regularization and renormalization of loops (scaling universe) $P_{11}(k) = \frac{1}{{k_{\rm NL}}^3}\left(\frac{k}{k_{\rm NL}}\right)^n$
  - –evaluate with cutoff. By dim analysis:

$$P_{1-\rm loop} = c_0^\Lambda \left(\frac{\Lambda}{k_{\rm NL}}\right)^2 \left(\frac{k}{k_{\rm NL}}\right) P_{11} + c_1^\Lambda \left(\frac{\Lambda}{k_{\rm NL}}\right) \left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}$$
$$+ c_2^\Lambda \log\left(\frac{\Lambda}{k_{\rm NL}}\right) \left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + c_1^{\rm finite} \left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + \text{subleading in } \frac{k}{k_{\rm NL}}$$

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  - absence of counterterm $\tau_{ij} \supset c_s^2\, \delta\rho$

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  - absence of counterterm $\tau_{ij} \supset c_s^2\, \delta\rho$

$$\Rightarrow \quad P_{1-\rm loop,\ counter} = c^\Lambda_{\rm counter}\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}$$

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

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

Lesson from Renormalization

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

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

  – each higher-loop is smaller and smaller

- This happens after canceling the divergencies with counterterms

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

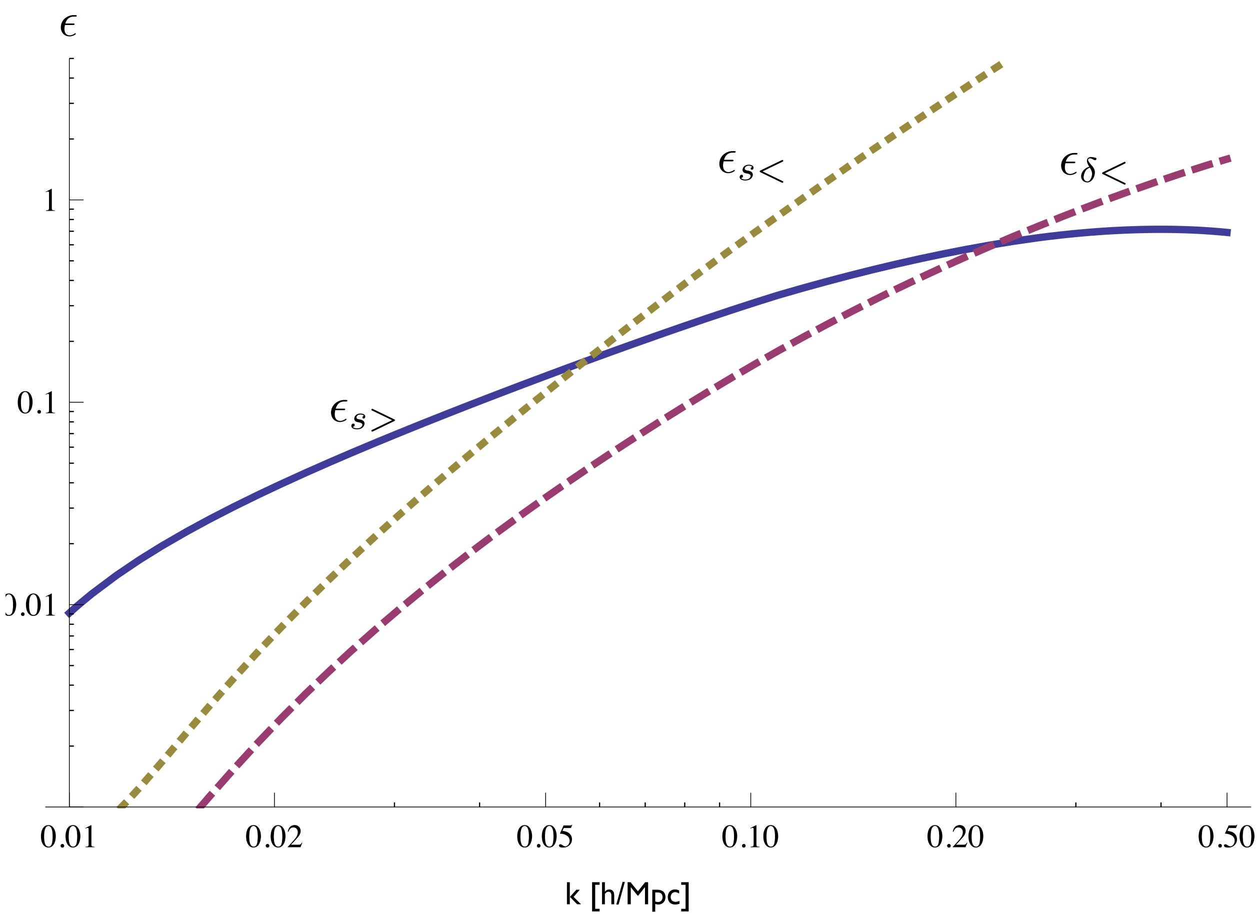
    - each loop contributes the same

- Up to 2-loops, we need only the 1-loop counterterm

Perturbation Theory in our Universe

- In a scaling universe $P_{11}(k) = \frac{1}{{k_{\rm NL}}^3}\left(\frac{k}{k_{\rm NL}}\right)^n$, $\epsilon_{\delta<} \sim \epsilon_{s<} \sim \epsilon_{s>} \sim \left(\frac{k}{k_{\rm NL}}\right)^{3+n}$

- But our universe has features. It is full of scales.



$$\epsilon_{s<} \quad = \quad k^2 \int_0^k \frac{d^3k'}{(2\pi)^3} \frac{P_{11}(k')}{k'^2}$$

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

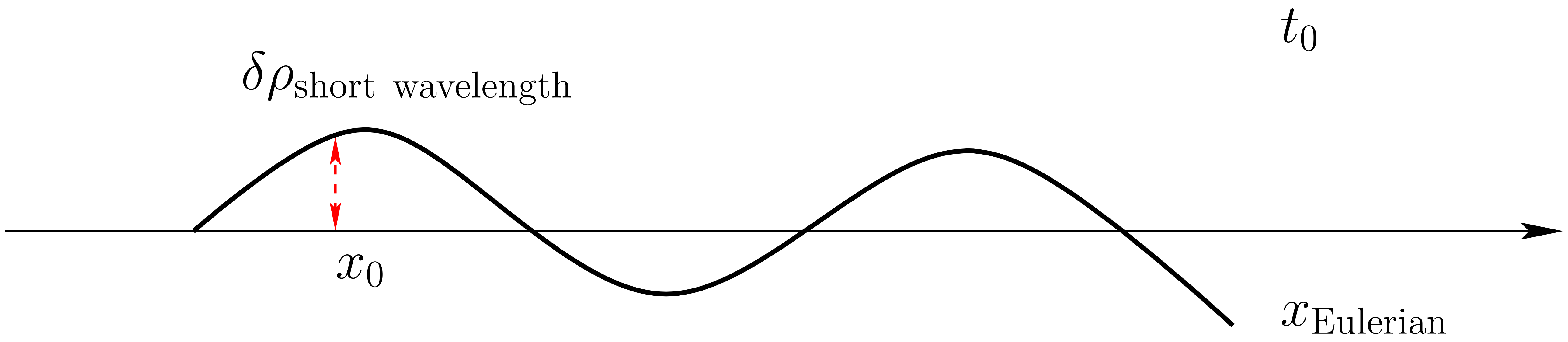
- After IR-resummation, and after renormalization, each loop goes as power of $\left(\epsilon_{\delta<}\right)^L$

IR-resummation

with Zaldarriaga **1404**

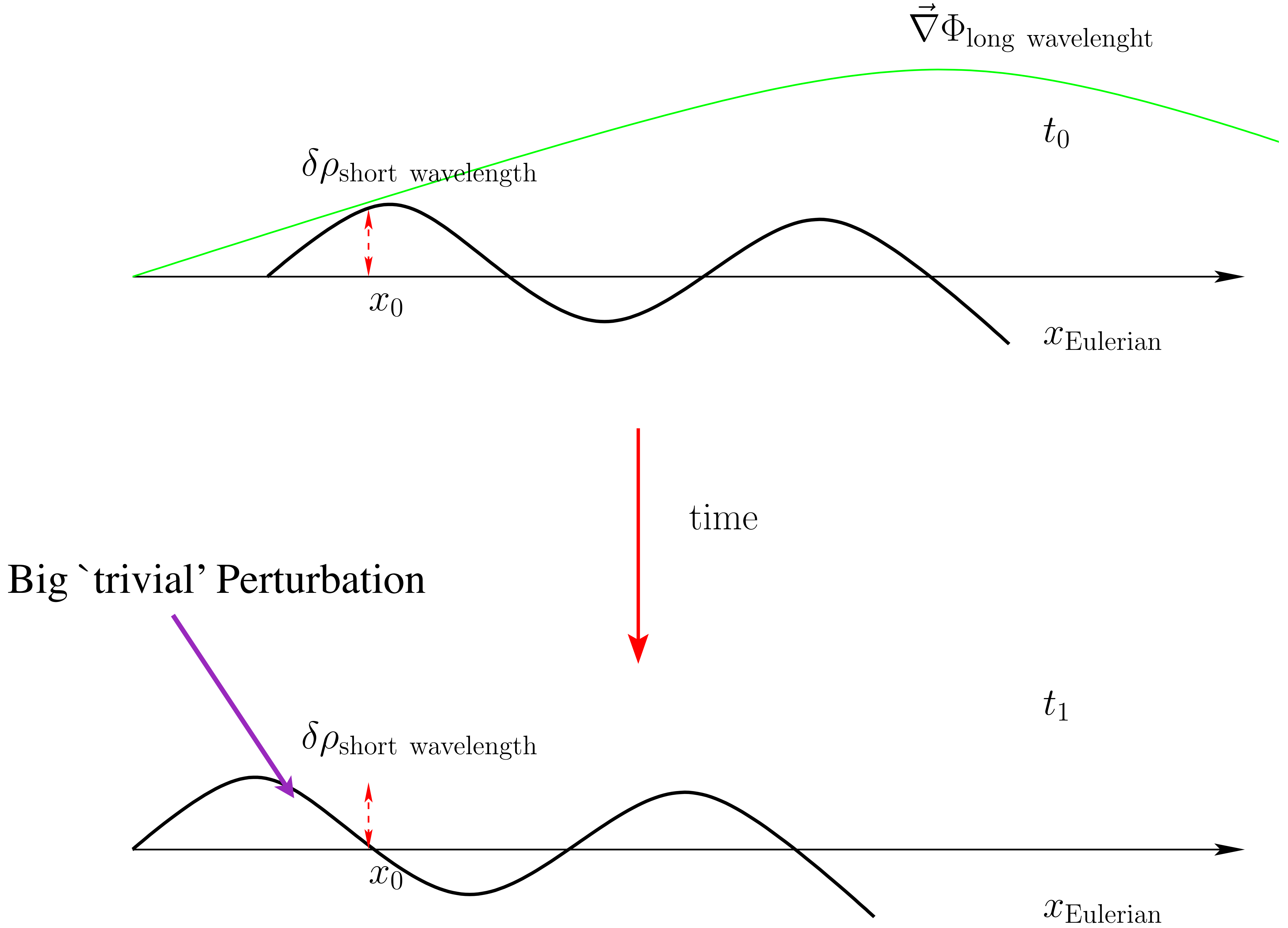
The Effect of Long-modes on Shorter ones

- In Eulerian treatment



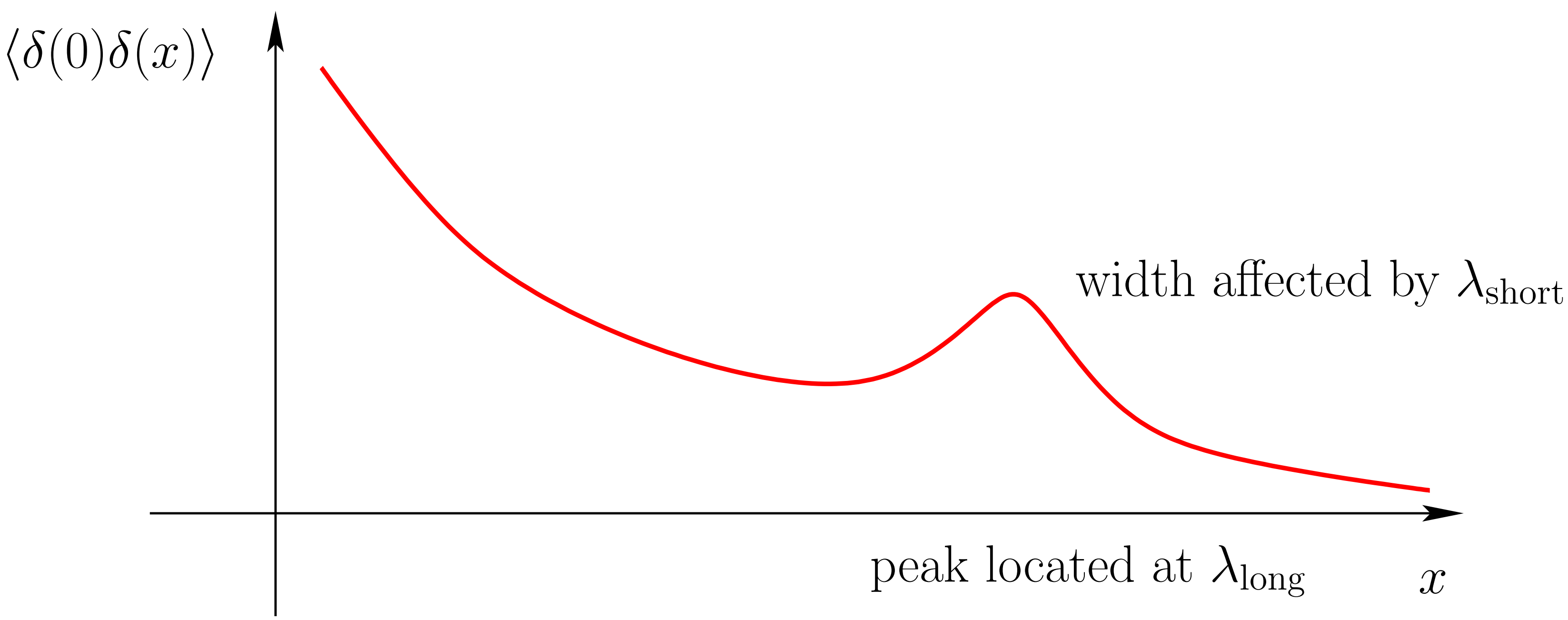
The Effect of Long-modes

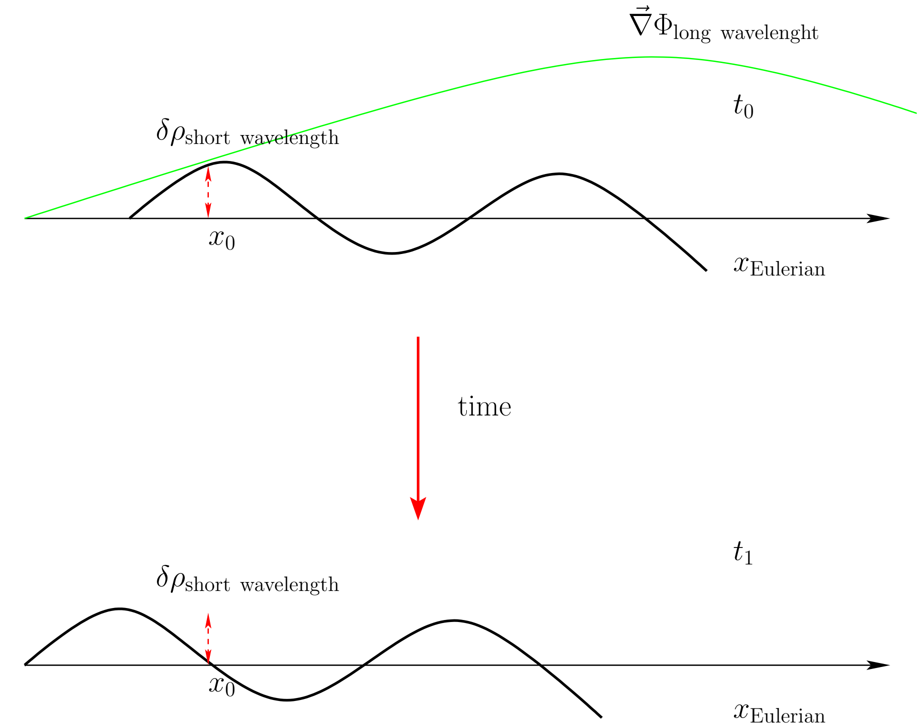
- Add a long `trivial' force (trivial by GR)
- This tells you that one can resum the IR modes: this is the Lagrangian treatment



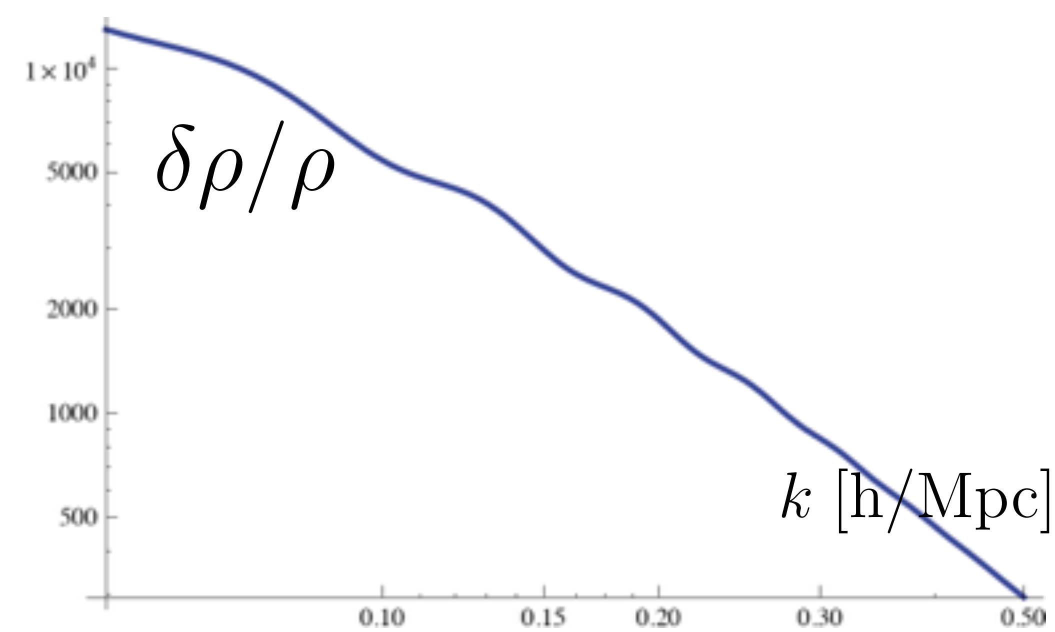
The Effect of Long-modes

with Zaldarriaga **1304**





- For equal time matter correlators, naively no effect from IR displacements
- But the universe has features!
- Even on equal time correlators, IR modes of order the BAO scale do not cancel!
  - –In Fourier space these are the wiggles
- To compute the width, IR-BAO modes are relevant
- But they just do kinematics, so we can resum them!



Non-perturbative treatment

- The derivation is highly technical (so only for close friends or aficionados):

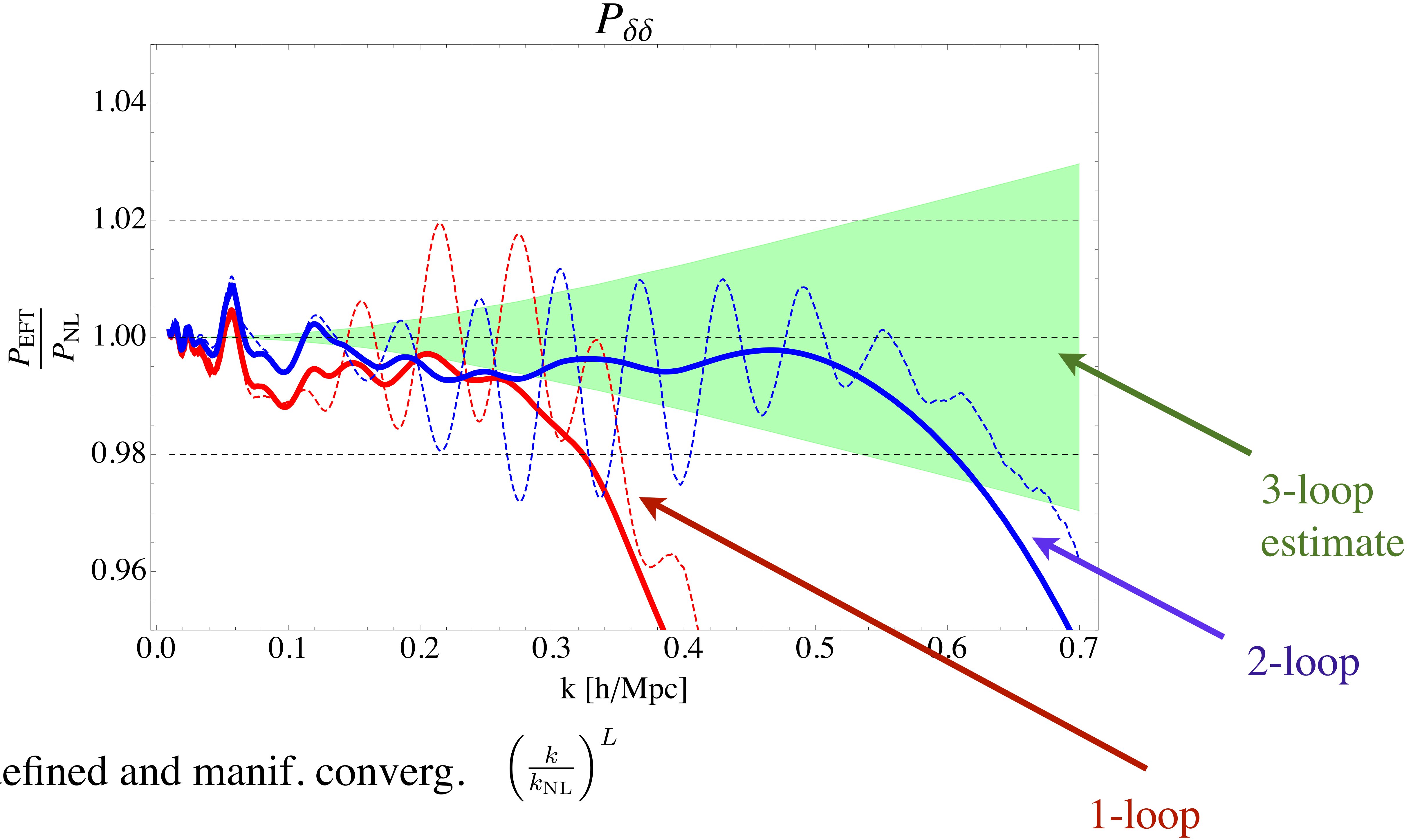
$$P_{\delta\delta}(k;t_1,t_2)|_N = \sum_{j=0}^{N} \int \frac{d^3k'}{(2\pi)^3}\, M_{||_{N-j}}(k,k';t_1,t_2)\; P_{\delta\delta,\,j}(k';t_1,t_2)$$

where $$M_{||_{N-j}}(k,k';t_1,t_2) = \frac{1}{4\pi}\int d^3r\; d^3q\; P_{\mathrm{int}||_0}(r|q;t_1,t_2)\; e^{i\vec{k}\cdot\vec{r}}\; e^{-i\vec{k}'\cdot\vec{q}}$$

- This formula is different from former ones, because it resums the BAO effects without changing the UV behavior of the theory
  - so that the result agrees with the Scoccimarro & Friemann theorem

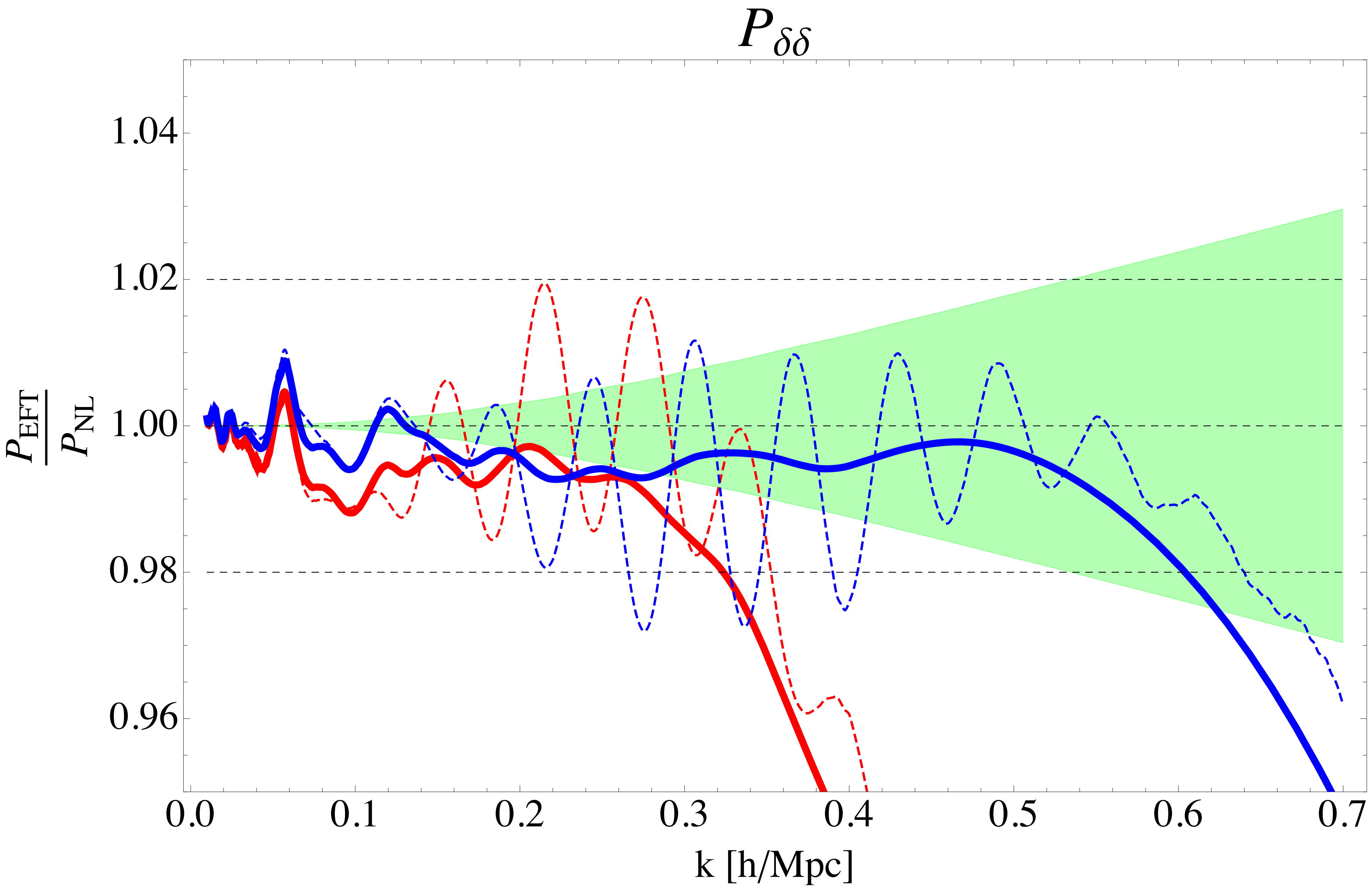
Results for Dark Matter

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

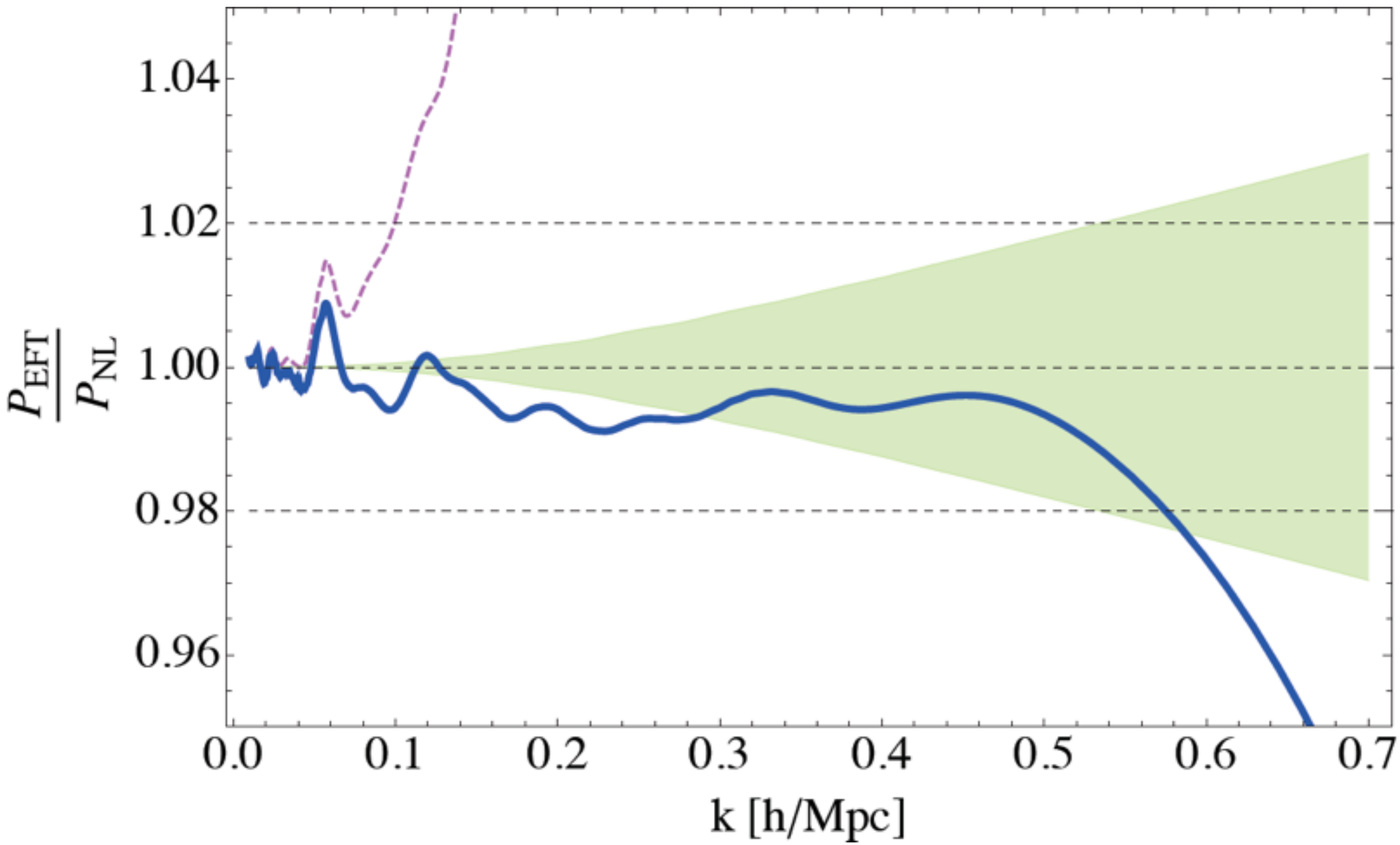
EFT of Large Scale Structures



- The lines with oscillations are obtained without resummation in the IR
  - –Getting the BAO peak wrong

with Carrasco, Foreman and Green **1310**

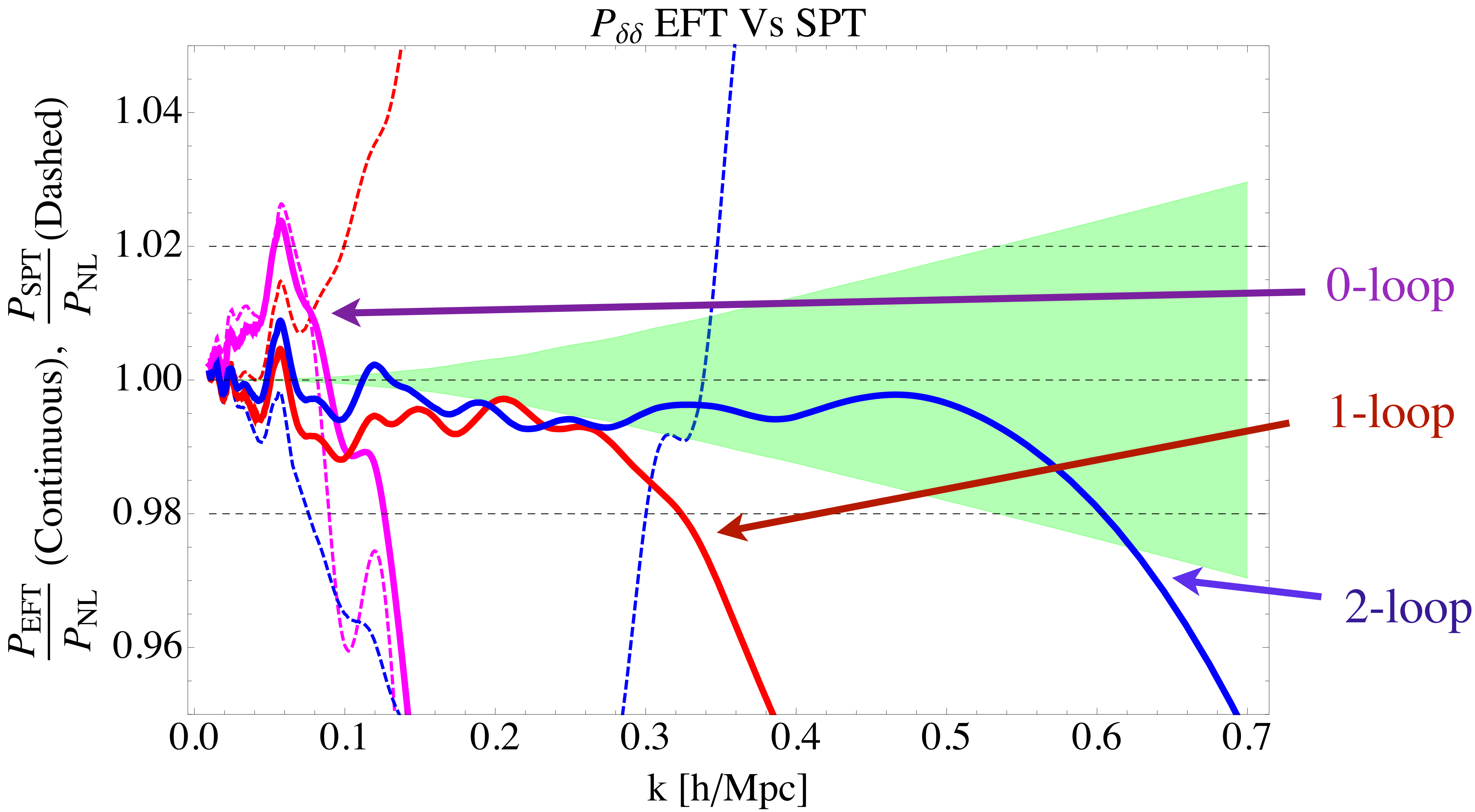
EFT of Large Scale Structures



- 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!

with Zaldarriaga **1404**

EFT of Large Scale Structures



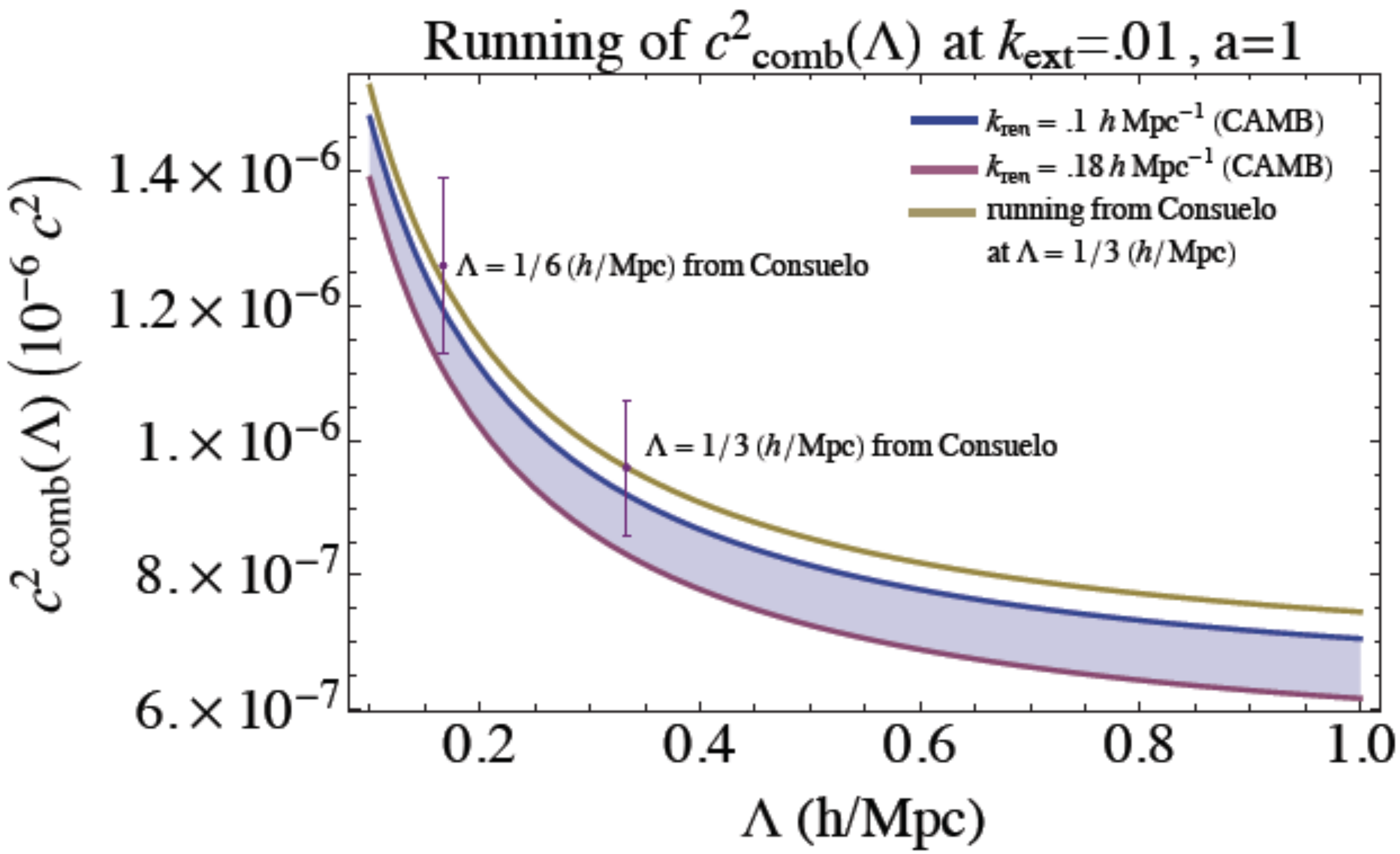
- Comparison with Standard Treatment
  - all other treatments (RPT, RegPT, etc), if done right, have same UV reach as SPT
    - feel free to ask
- Only one parameter used to fit in the EFTofLSS.

Measuring Parameters from small N-body Simulations

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
- 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**

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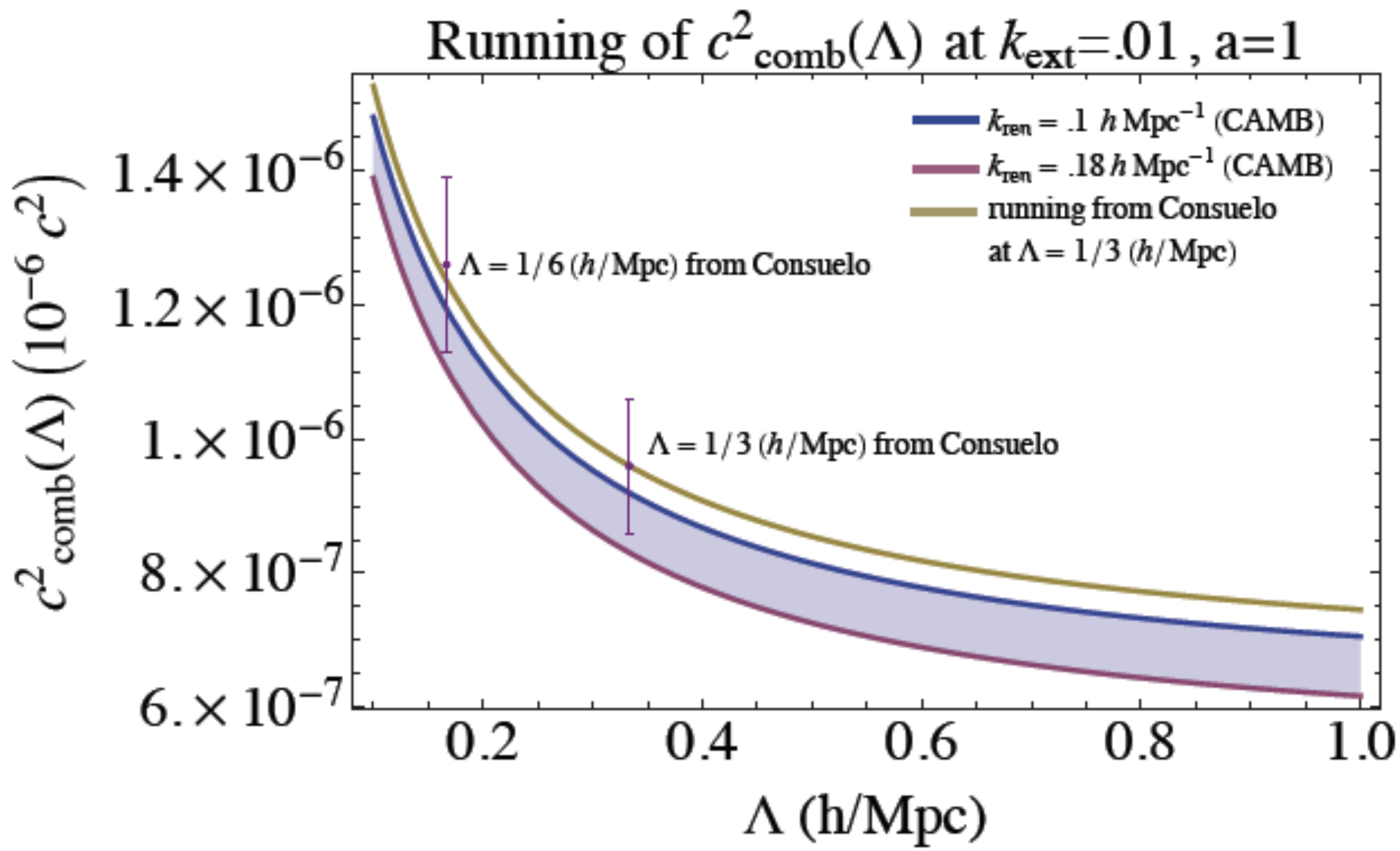


- Perfect agreement with fitting at low energies
  - like measuring F_π from lattice sims and $\pi\pi$ scattering
  - UV dof

$$[\partial_i\partial_j v_k](\vec r) = [\partial_i\partial_j\pi_k](\vec r)/[\rho](\vec r) - [\partial_i\pi_k](\vec r)[\partial_j\rho]/([\rho](\vec r))^2 - [\partial_j\pi_k](\vec r)[\partial_i\rho]/([\rho](\vec r))^2$$
$$- [\pi_k](\vec r)[\partial_i\partial_j\rho](\vec r)/([\rho](\vec r))^2 + 2[\pi_k](\vec r)[\partial_i\rho](\vec r)[\partial_j\rho](\vec r)/([\rho](\vec r))^3$$

arrasco and Hertzberg **JHEP 2012**

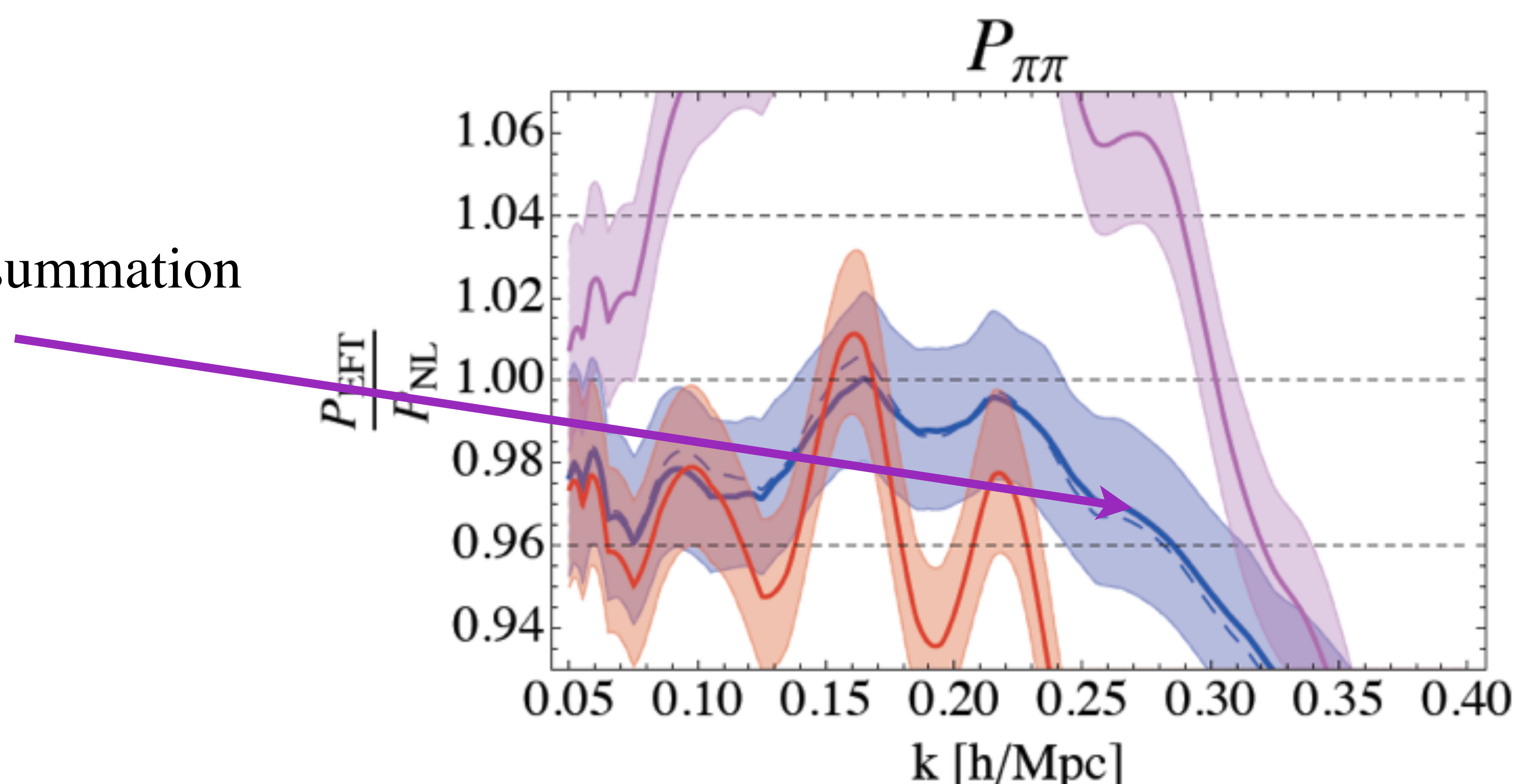
Other Observables

Momentum

with Zaldarriaga **1404**

- Momentum is not IR safe
  - IR-modes do not contribute just for oscillations
  - after IR-resummation
    - with (practically) no additional parameter
      - it works as it should (up to $k \simeq 0.3\, h\mathrm{Mpc}^{-1}$ at one loop)

Blue is with IR-resummation



Bispectrum

with Angulo, Foreman and Schmittful **1406**

– very non-trivial function of two variables!

– use only same counterterm as in power spectrum (so already measured there)

  – because of (2π) counting additional counterterms are smaller than 2-loop terms

    –. $\partial^i\partial^j\tau_{ij} = (2\pi)c_s^2\,\delta + c_2\,\delta^2 + \ldots$

– because of complexity, limit of goodness of fit is very sharp

    – no risk of overfitting

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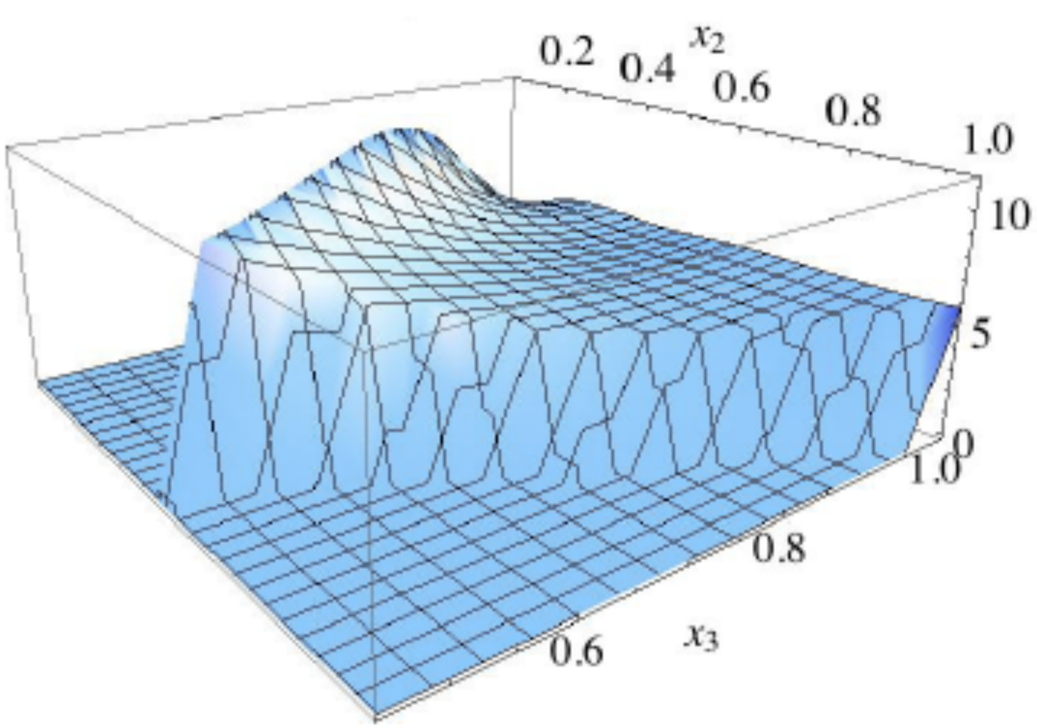

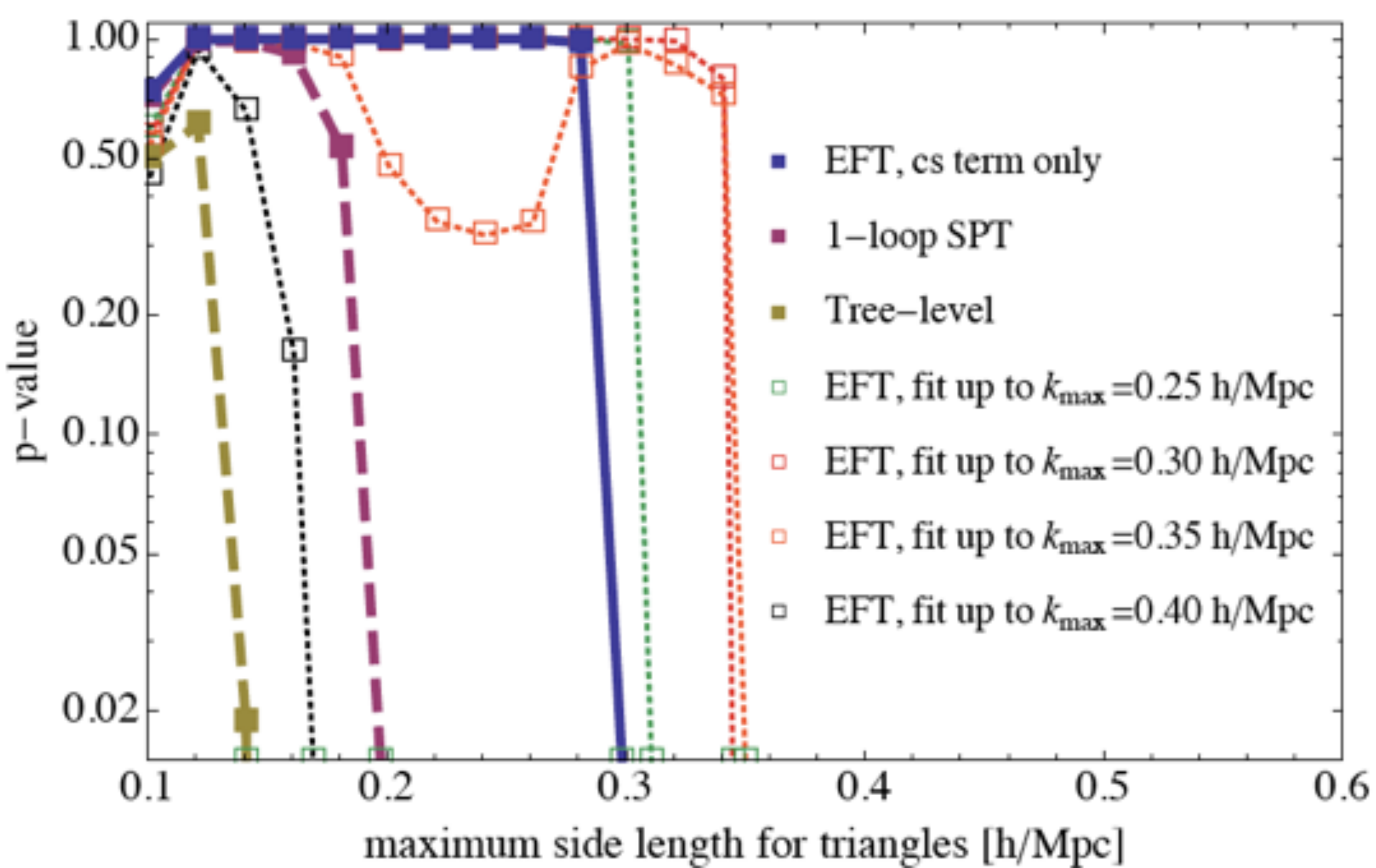

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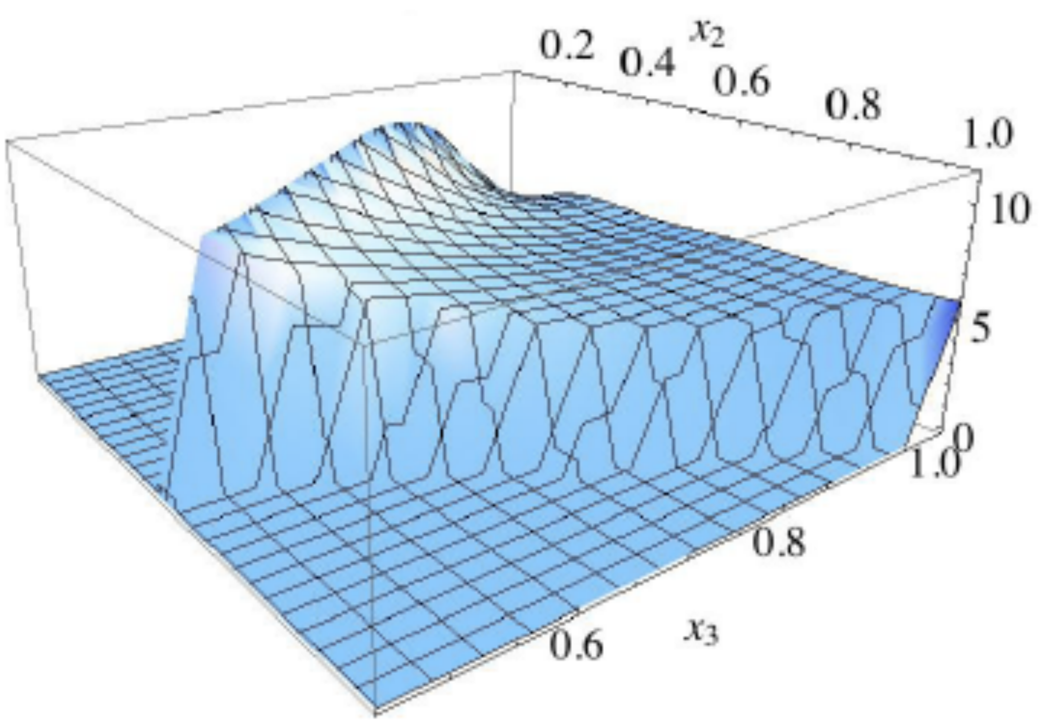

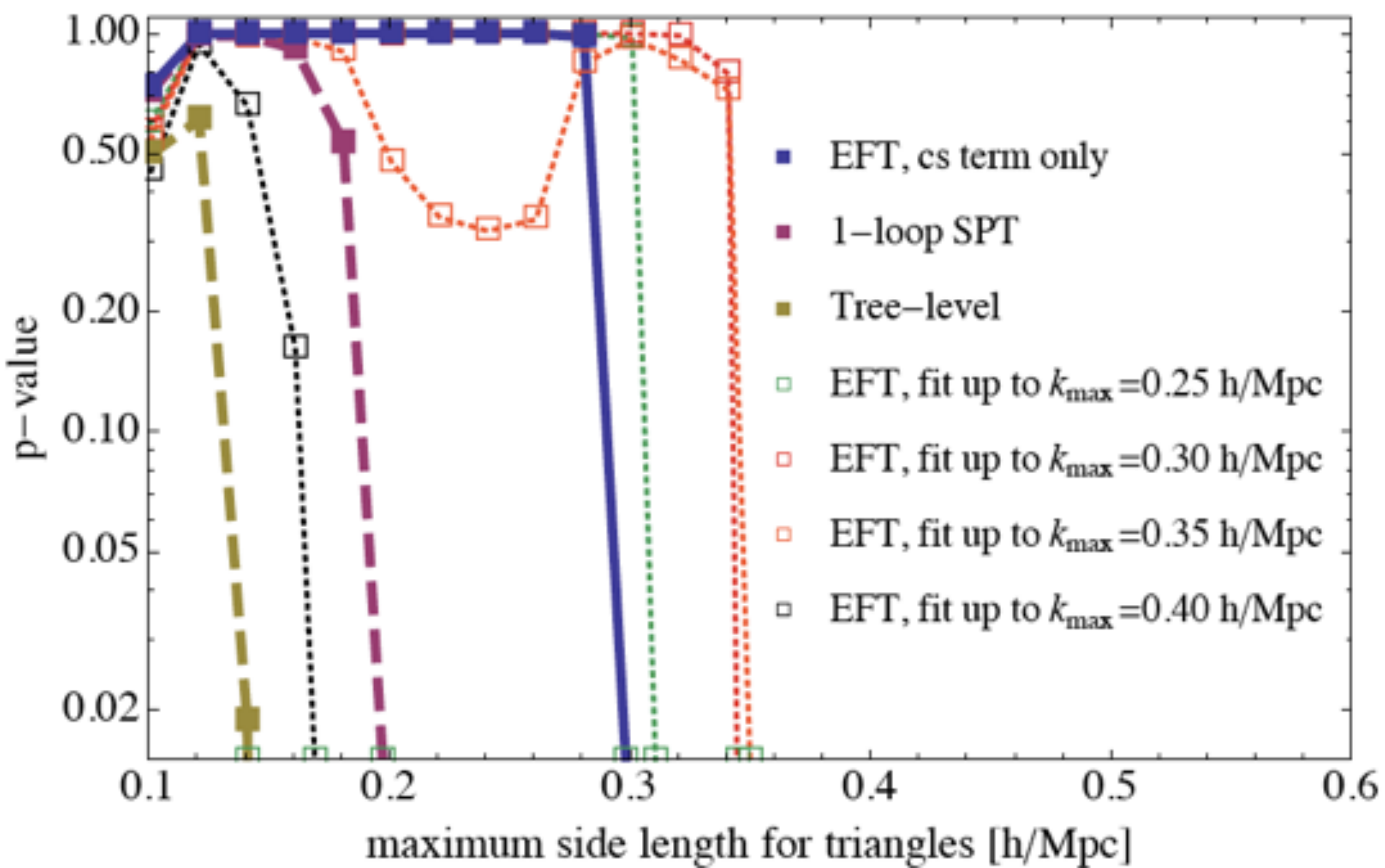

Velocity field

- Momentum is a natural quantity, as connected to density by conservation law
- Velocity is not a natural quantity $\vec{v}(\vec{x}) = \frac{\vec{\pi}(\vec{x})}{\rho(\vec{x})}$
- It is a local composite operator: needs its own new counterterms:

$$v_{l,R}(\vec{x},t) = v_l(\vec{x},t) - e_1 \partial\delta(\vec{x},t) + \cdots$$

with Carrasco, Foreman and Green **1310**

  – no new counterterm for the equations

- Because of this, and because it is a viscous fluid, we generate vorticity

$$\langle \omega_k^2 \rangle \sim \alpha_1 \left(\frac{k}{k_{\rm implement.}}\right)^2 + \alpha_2 \left(\frac{k}{k_{\rm NL}}\right)^{\sim 3}$$

  – from local counterterm

  – from viscosity

- Predicted result seems to be verified in sims

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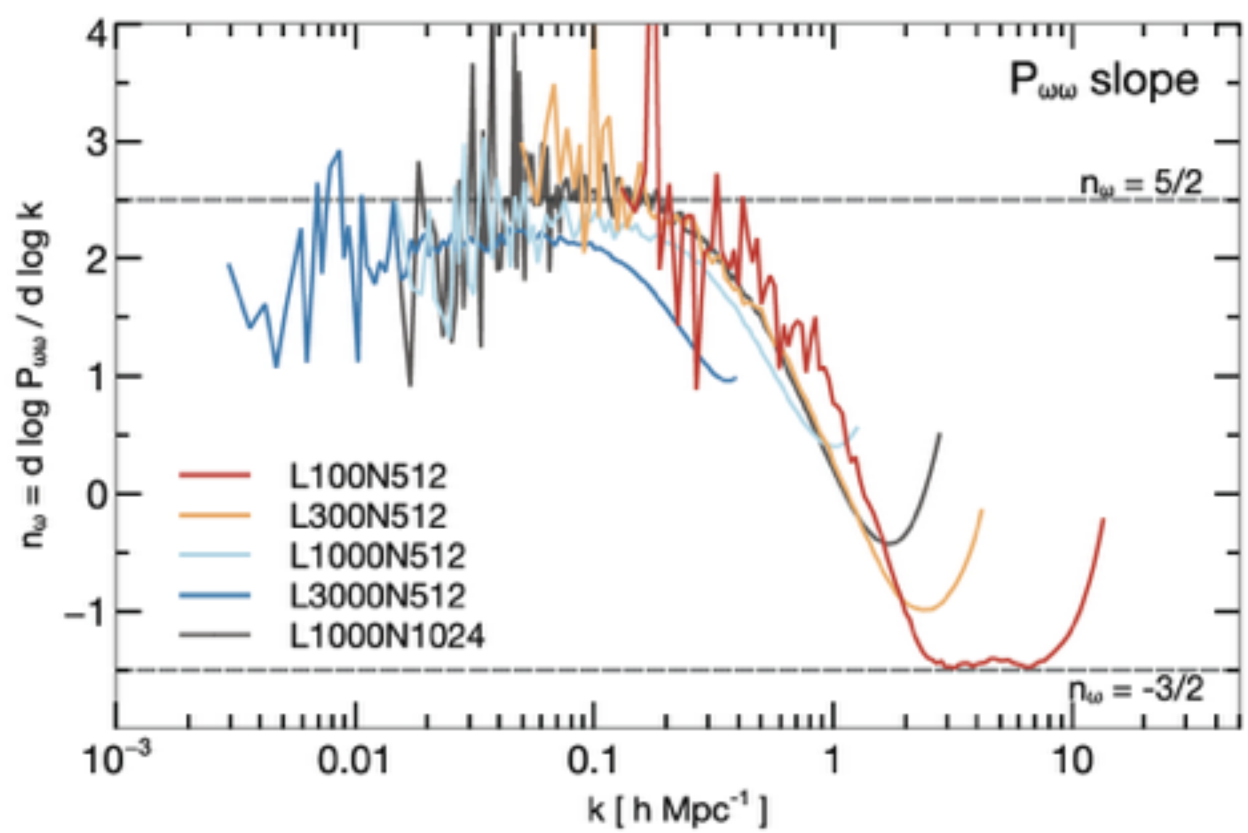
Hahn, Angulo, Abel, **to appear**

see also Pueblas and Scoccimarro **08**



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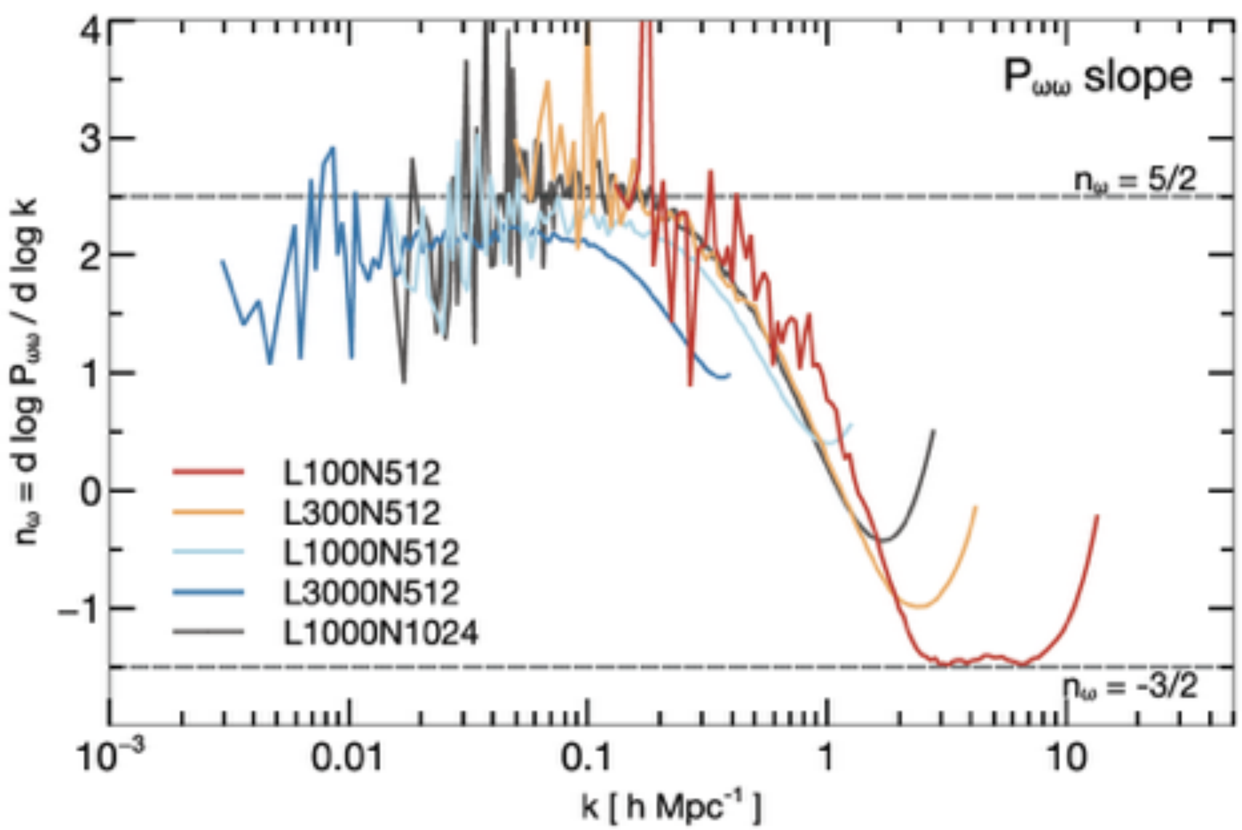

- Predicted result seems to be verified in sims
- Former analytic techniques got zero

End to SPT-like resummations

Analytic Prediction of Baryon Effects

with Lewandoski and Perko **1412**

Baryons

- Main idea for EFT fro 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 cluster, 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 free path
  - Universe with CDM+Baryons $\Longrightarrow$ EFTofLSS with 2 species

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

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

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Baryons

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

$$\partial_i \left(\partial\tau_\rho\right)^i_b - \partial_i(\gamma)^i_b(a,\vec{x}) =$$

$$c^2_{b,g}(a)\frac{H^2}{k^2_{NL}}\left(w_c\partial^2\delta_c + w_b\partial^2\delta_b\right) + \left(c^2_{b,v}(a) + c^2_\star(a)\right)\frac{H^2}{k^2_{NL}}\,\partial^2\delta_b + \ldots,$$

Gravity-induced pressure

star formation-induced pressure

velocity-induced pressure

- Size of $c^2_\star$ determines different power counting

- The stress tensor can now depend also on the center-of-mass velocity

$$v_{c,\text{CM}} = v_c - (w_c v_c + w_b v_b) = w_b(v_c - v_b)$$

$$v_{b,\text{CM}} = v_b - (w_c v_c + w_b v_b) = w_c(v_b - v_c)$$

  - but only at higher order (because of units)

$$\partial_i \left(\partial\tau_\rho\right)^i_\sigma - \partial_i(\gamma)^i_\sigma(a,\vec{x}) \supset v^i_{\sigma,\text{CM}}\partial^2\delta/H$$

Baryons

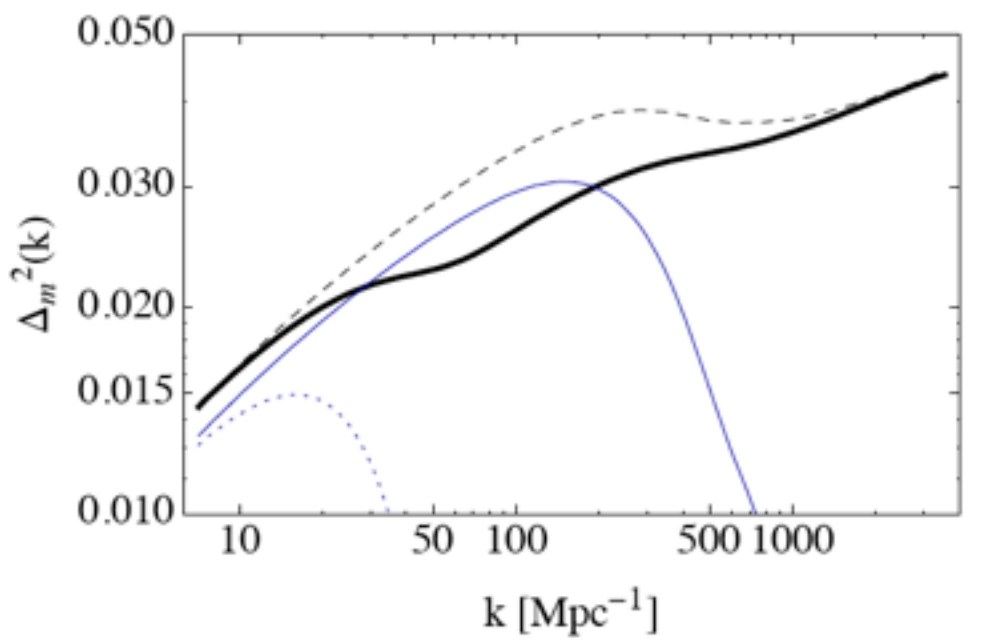
- Relative motions matter $\Longrightarrow$ larger set of expansion parameters

$$\epsilon_{\delta<} = \int_0^k \frac{d^3k'}{(2\pi)^3} P_{11}(k') \,,$$
$$\epsilon_{s>} = k^2 \int_k^\infty \frac{d^3k'}{(2\pi)^3} \frac{P_{11}(k')}{k'^2} \,,$$
$$\epsilon_{s<} = k^2 \int_0^k \frac{d^3k'}{(2\pi)^3} \frac{P_{11}(k')}{k'^2} \,,$$

$+$

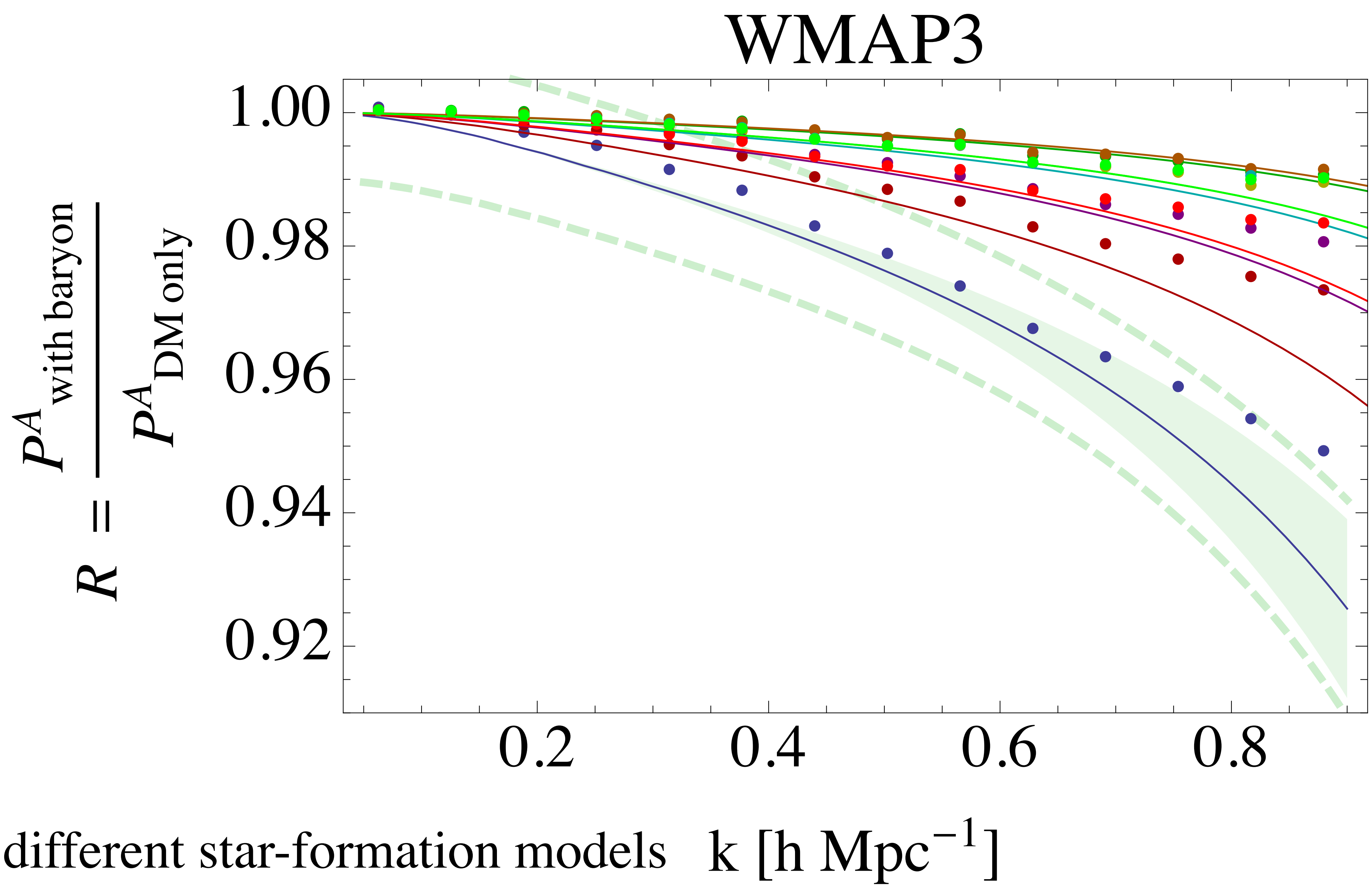
$$\epsilon_{s<}^{\rm rel}(k) = k^2 \int_0^k \frac{d^3k'}{(2\pi)^3} \frac{\tilde{P}_{11}(k')}{k'^2}$$
$$\epsilon_{s>}^{\rm rel}(k) = k^2 \int_k^\infty \frac{d^3k'}{(2\pi)^3} \frac{\tilde{P}_{11}(k')}{k'^2}$$

- Baryons and CDM have different initial conditions that decay slowly (iso mode)
  - $\Longrightarrow$ Also IR-relative motions need to be resummed (at high-redshift)
  - this is the so-called Baryon Advection Effect (friendly Tselik-Hirata effect)
    - done systematically



Baryons

– The functional form is predicted by the EFTofLSS $\quad \Delta P_b(k) \simeq c_\star^2 \left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}^A(k)$



– Different curves are different star-formation models

– they only differ by the size of $c_\star^2$, as it should

– The theory match until size of theory error (in this ratio particularly small)

– Awesome!

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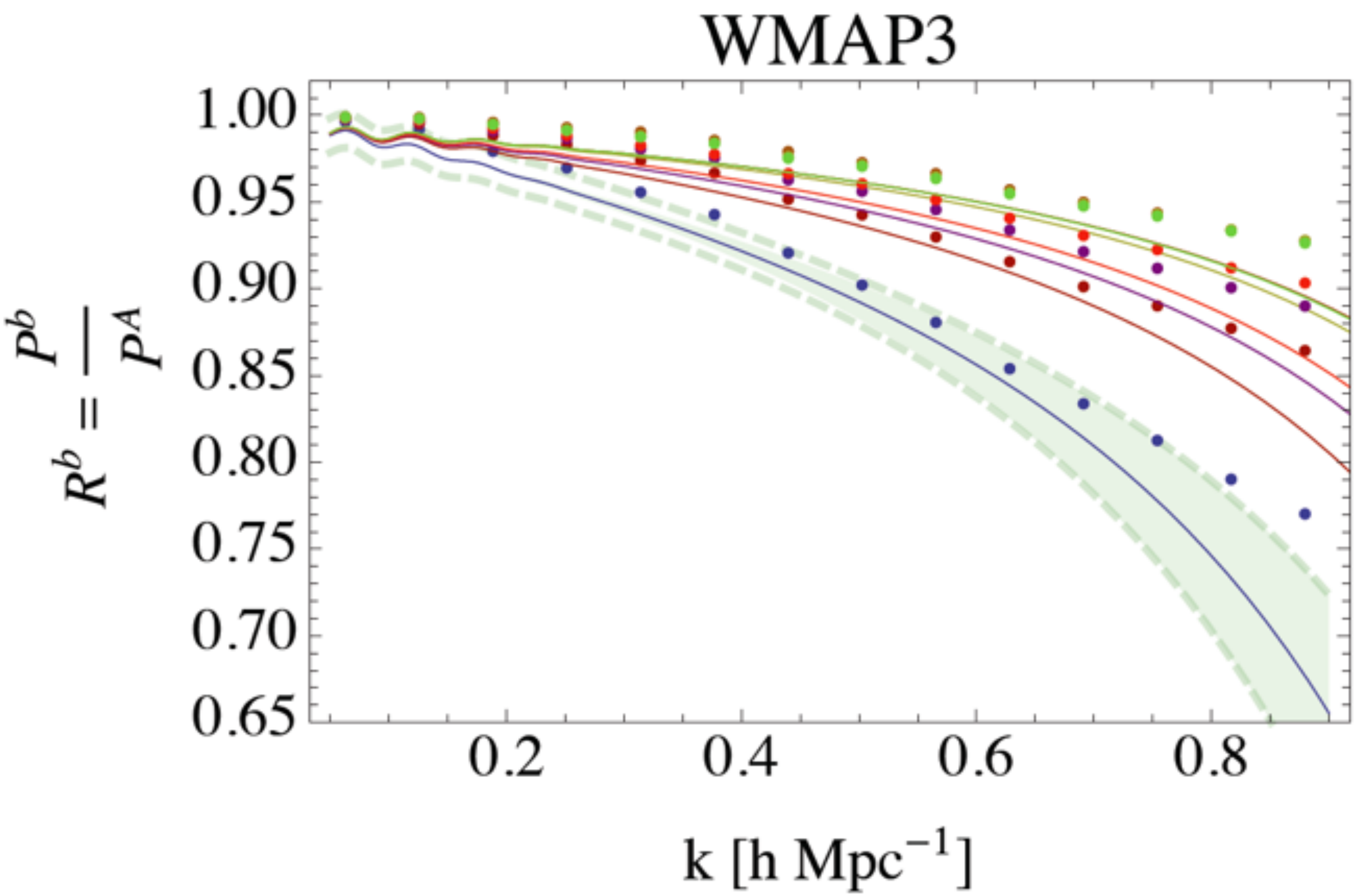


– Different curves are different star-formation models

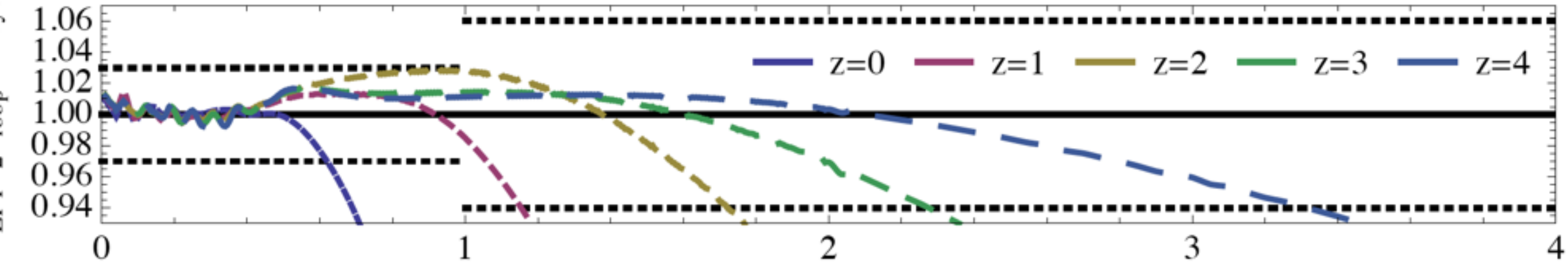
- they only differ by the size of $c_\star^2$, as it should
- The theory match until size of theory error (in this ratio particularly small)
- $c_\star^2$ is positive (as intuitive) and small (star formation physics is a small effect)

The EFTofLSS at high-z

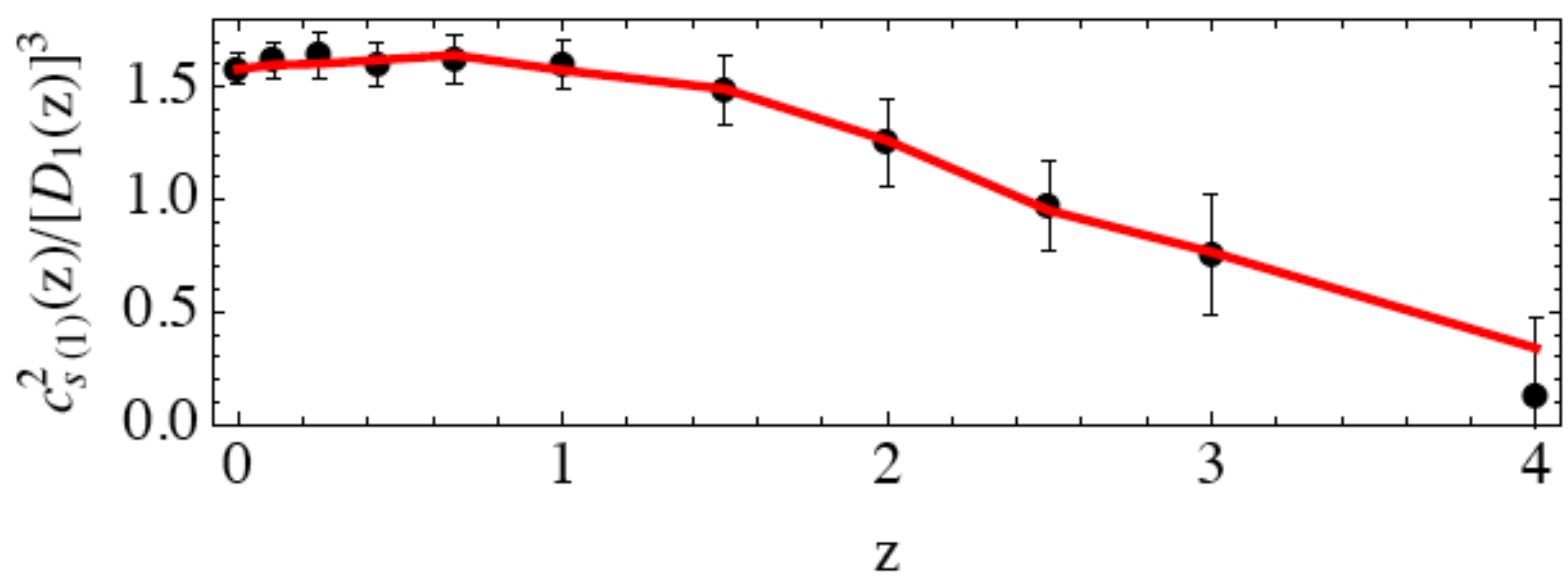
with Foreman **to appear**

Results 2-loop IR-resummed

- Clearly the UV reach improves at high-z



- Time dependence of cs



  - One additional parameter for the time dependence

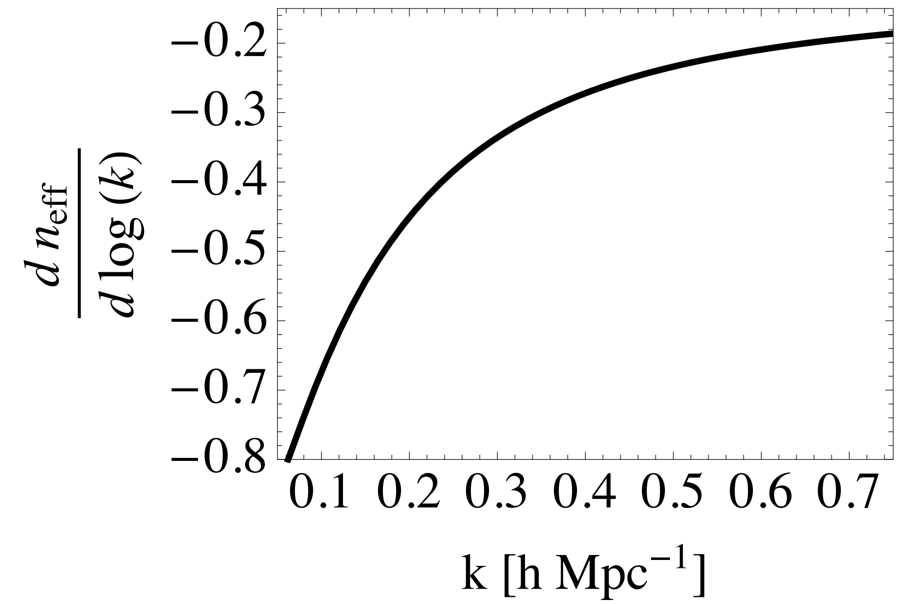
$$c^2_{s(1)}(z) = c^2_{s(1)}(0)[D_1(z)]^{\frac{4}{3+N(z)}} \ , \quad N(z) = n_{\rm eff}(k) + \beta \frac{dn_{\rm eff}(k)}{d\log(k)}$$

Results 2-loop IR-resummed

- Very important: improvement consistent with theory errors

	One-loop EFT		Two-loop EFT	
z	estimated failure $[h\,\mathrm{Mpc}^{-1}]$	actual failure $[h\,\mathrm{Mpc}^{-1}]$	estimated failure $[h\,\mathrm{Mpc}^{-1}]$	actual failure $[h\,\mathrm{Mpc}^{-1}]$
0	0.31 – 0.44	0.38	0.5 – 0.6	0.6
1	0.34 – 0.93	0.46	1.0 – 1.3	1.2
2	0.47 – 1.10	0.71	2.0 – 2.4	1.7
3	0.59 – 2.10	1.15	1.7 – 4.8	2.3
4	1.00 – 2.35	1.67	2.2 – 5.0	3.3

- to get this right, we need to improve the estimate for theory error
  - the universe is *not* scaling:
    - the running of the slope is large

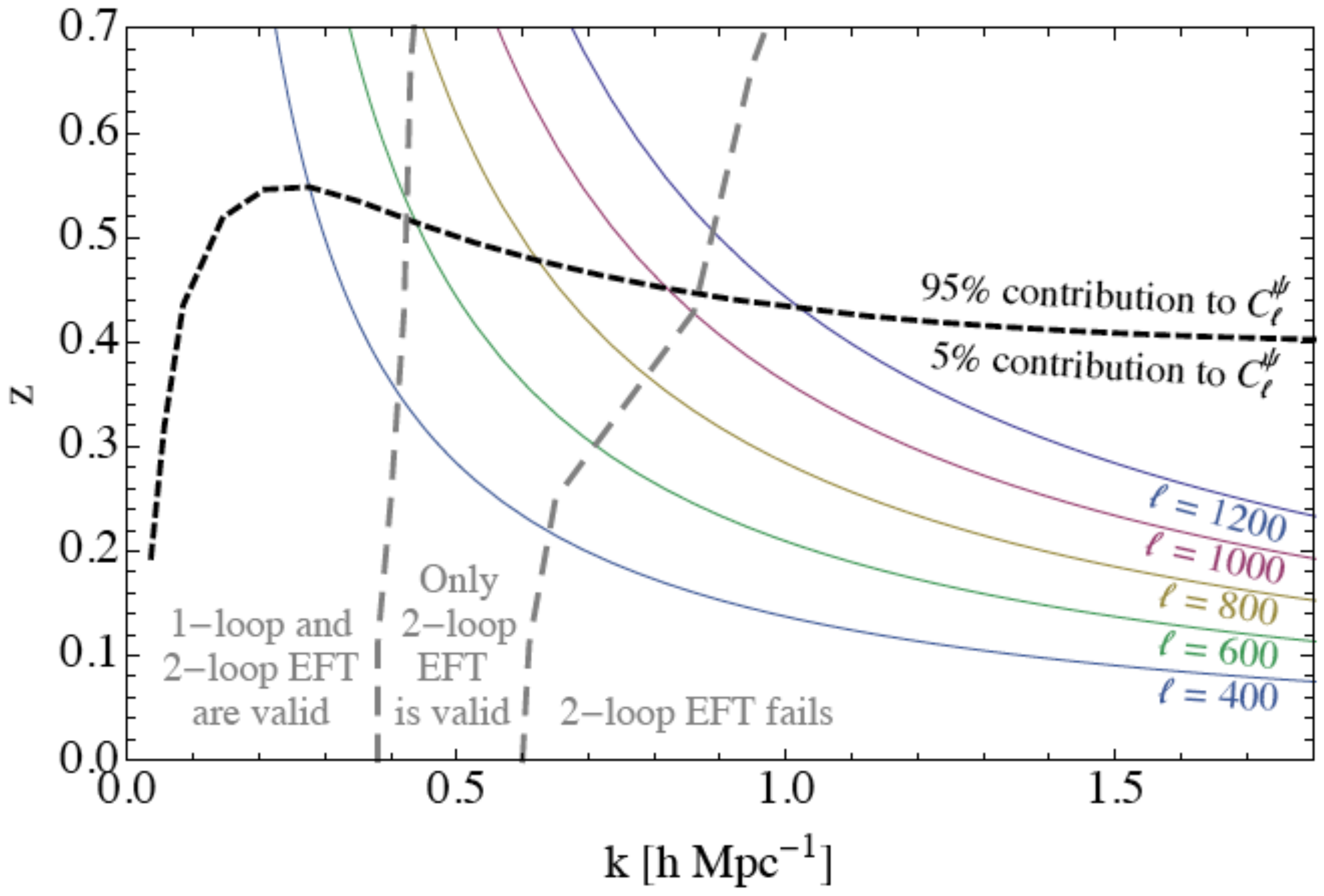


  - strong cancellation
    - between UV part of P13 and cs-counterterm (SPT is wrong already at one-loop)

$$\Rightarrow \quad P^{(\rm total)}_{2-\rm loop}(k) \approx \left[\frac{P_{13}^{\rm no-IR}(k)+P_{c_s,\rm tree}(k)}{P_{11}(k)}\right]\left[P_{1-\rm loop}(k)+P_{c_s,\rm tree}(k)\right]$$

CMB-lensing analytically

- Up to l=1000 to 5%



Large number of modes

- At higher-z, relative gain wrt SPT decreases, but still huge gain and number of modes

z	$\left(k_{\rm fail}^{\rm (EFT)}/k_{\rm fail}^{\rm (SPT)}\right)^3$	$N_{\rm modes}^{\rm (EFT)}/N_{\rm modes}^{\rm (SPT)}$	$N_{\rm modes}^{\rm (EFT)}$
$1/9$	$(0.6/0.08)^3 = 422$	464	1.3×10^6
$3/7$	$(0.86/0.15)^3 = 188$	243	1.1×10^7
1	$(1.2/0.35)^3 = 40$	32	2.3×10^8
2	$(1.7/0.45)^3 = 54$	44	2.2×10^9
3	$(2.3/0.5)^3 = 97$	61	8.4×10^9
4	$(3.3/0.8)^3 = 70$	71	2.5×10^{10}

Halos Power and Bispectrum

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

Halos in the EFTofLSS

- Similar considerations apply to biased tracers:
  - since the theory is non-local in time, formation depends on fields evaluated on past history on past path   Senatore **1406**

$$\delta_M(\vec{x},t) \simeq \int^t dt'\, H(t') \left[\bar{c}_{\partial^2\phi}(t,t')\, \frac{\partial^2\phi(\vec{x}_{\rm fl},t')}{H(t')^2} \right.$$
$$+\bar{c}_{\partial_i v^i}(t,t')\, \frac{\partial_i v^i(\vec{x}_{\rm fl},t')}{H(t')} + \bar{c}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\, \frac{\partial_i\partial_j\phi(\vec{x}_{\rm fl},t')}{H(t')^2} \frac{\partial^i\partial^j\phi(\vec{x}_{\rm fl},t')}{H(t')^2} + \dots$$
$$+\bar{c}_\epsilon(t,t')\,\epsilon(\vec{x}_{\rm fl},t') + \bar{c}_{\epsilon\partial^2\phi}(t,t')\,\epsilon(\vec{x}_{\rm fl},t')\frac{\partial^2\phi(\vec{x}_{\rm fl},t')}{H(t')^2} + \dots$$
$$\left. +\bar{c}_{\partial^4\phi}(t,t')\,\frac{\partial^2_{x_{\rm fl}}}{{k_{\rm M}}^2}\frac{\partial^2\phi(\vec{x}_{\rm fl},t')}{H(t')^2} + \dots \right].$$

  - this generalizes and completes   McDoland and Roy **0902**

- Since evolution is k-independent, we can formally evaluate the integrals, to obtain

Halos in the EFTofLSS

- Do integrals

Senatore **1406**

$$\delta_h(k,t) \quad = $$
$$= c_{\delta,1}(t) \ \left[\delta^{(1)}(k,t) + \text{flow terms}\right] + c_{\delta,2}(t) \ \left[\delta^{(2)}(k,t) + \text{flow terms}\right] + \ldots$$

  - each order in perturbation theory gets its own bias coefficient.

- Equivalent basis: expand the integrals in along-the-flow time-derivative

$$\delta_h(k,t) = c_\delta \delta(k,t) + c_{D\delta/Dt} \frac{D}{Dt}\delta(k,t) + c_{D^2\delta/Dt^2} \frac{D^2}{Dt^2}\delta(k,t) + \ldots$$

- This basis has some redundancy (nothing bad with it, but simpler if we remove it)
  - simple to study and to remove degeneravies:

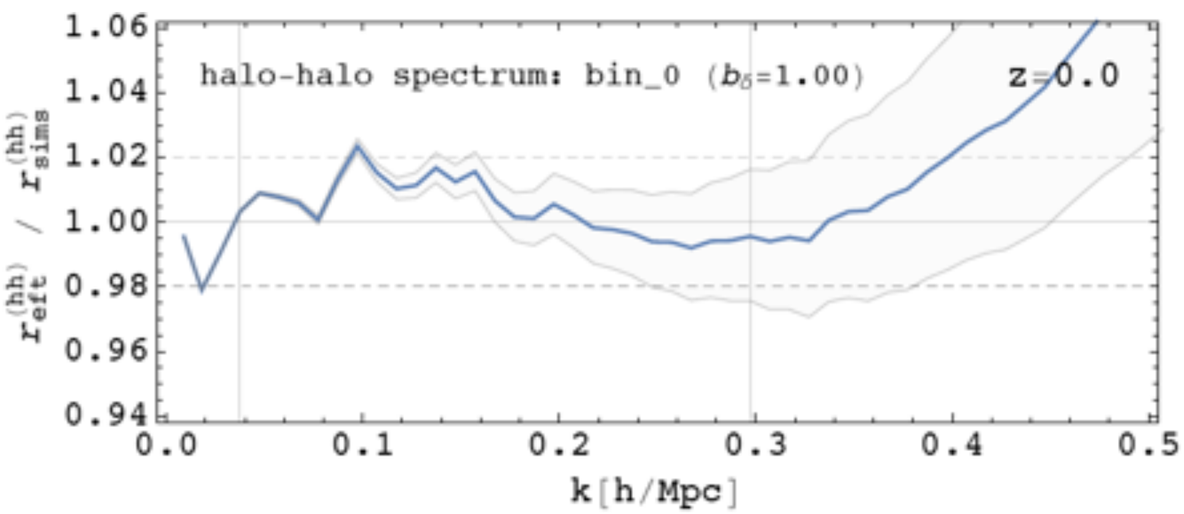
Mirbabayi, Schmidt, Zaldarriaga **1412**
with Angulo, Fasiello, Vlah **to appear**

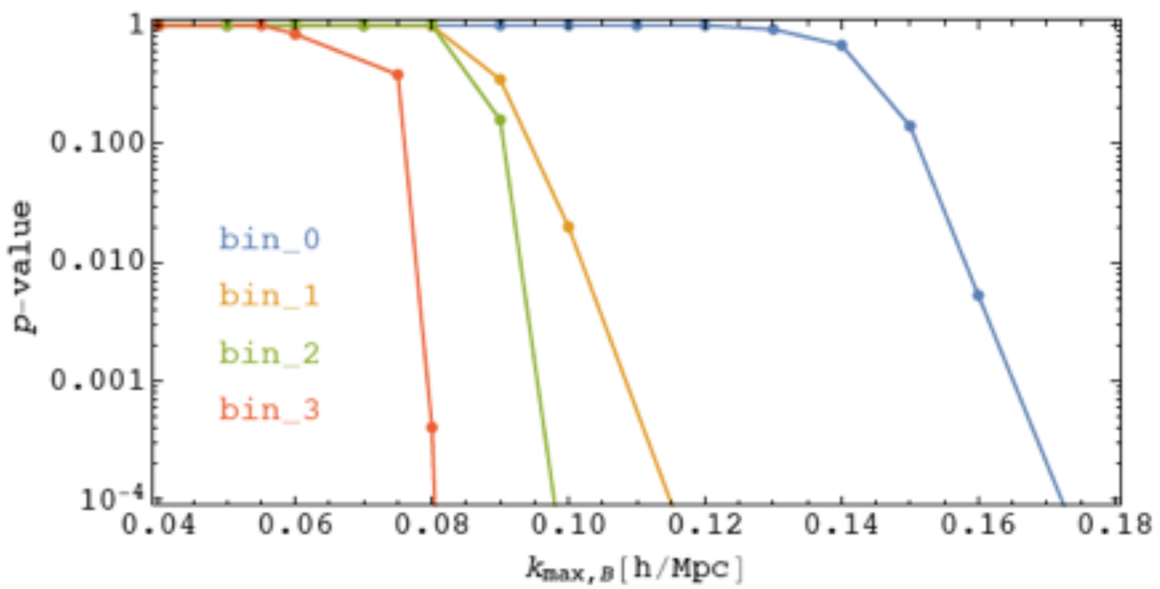
Halos in the EFTofLSS

with Angulo, Fasiello, Vlah **to appear**

- We compare $P^{1-\text{loop}}_{hh}\,,\ P^{1-\text{loop}}_{hm}\,,\ B^{\text{tree}}_{hhh}\,,\ B^{\text{tree}}_{hhm}\,,\ B^{\text{tree}}_{hmm}$ 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)

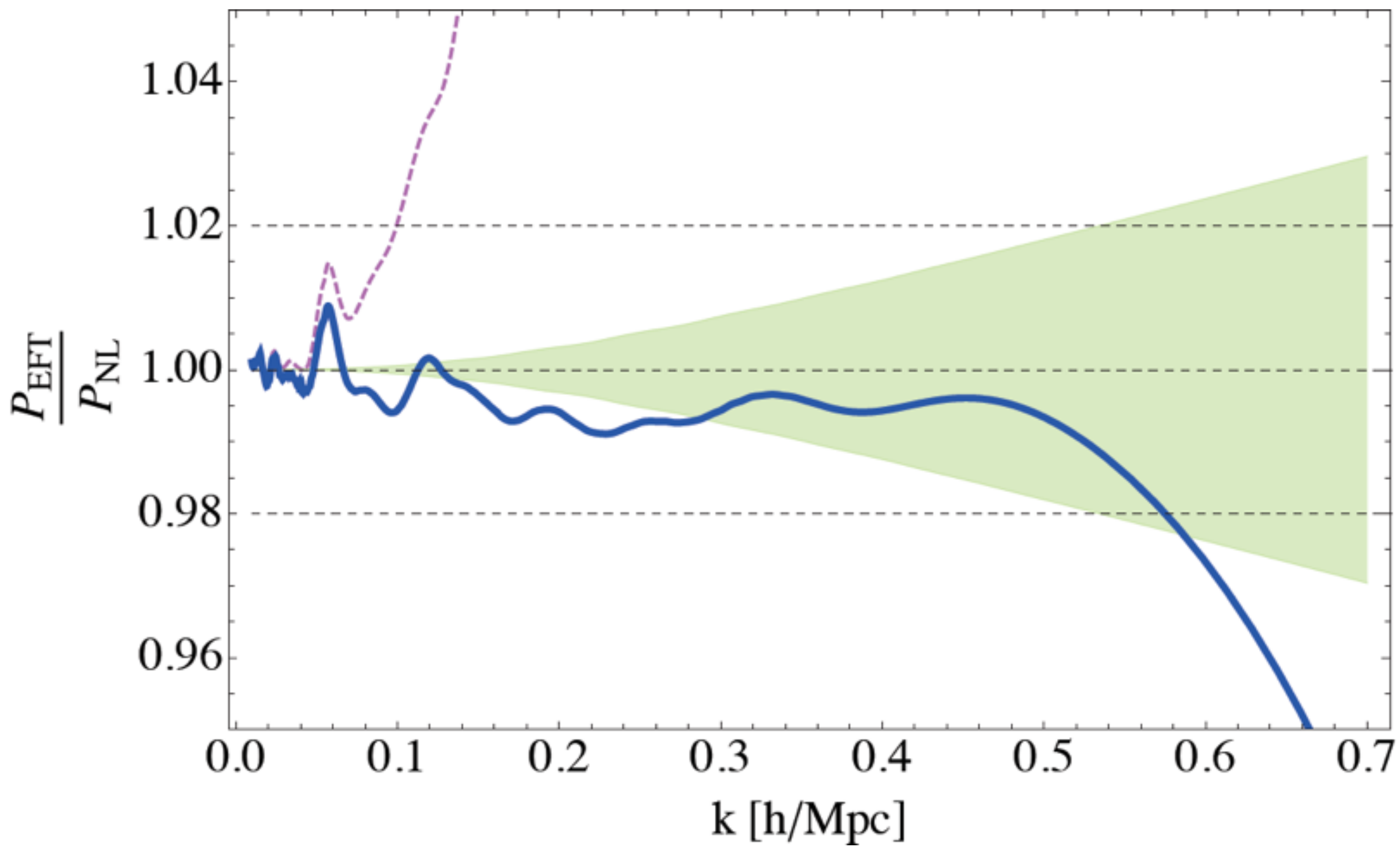




  - If we had the 4-pt function from N-body fit would be even more constrained
    - the 3pt function measures very well the bias coefficients (there is a lot of data)
  - Similar formulas just worked out for redshift space distortions

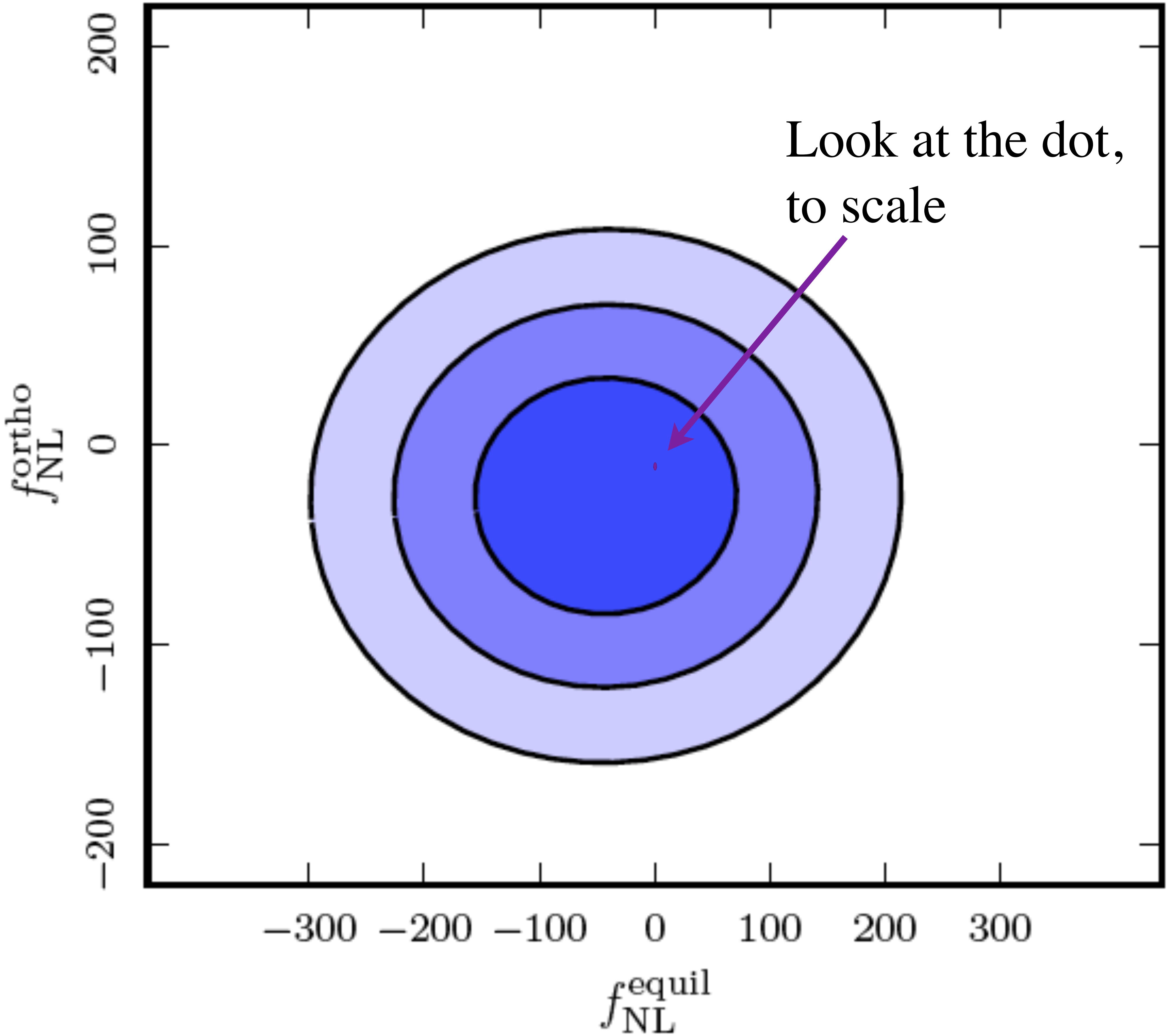
with Zaldarriaga **1409**

EFT of Large Scale Structures



- A manifestly convergent perturbation theory $\left(\frac{k}{k_{\mathrm{NL}}}\right)^L$
- we fit until $k_{\mathrm{max}} \simeq 0.6\, h\, \mathrm{Mpc}^{-1}$, as where we should stop fitting
  - –there are 50-200 more quasi linear modes than previously believed!
  - –huge impact on possibilities, for ex: $f_{\mathrm{NL}}^{\mathrm{equil.,\, orthog.}} \lesssim 1$
- Can all of us handle it?! This is an huge opportunity and a challenge for us

With this



Look at the dot,
to scale
200
100
0
−100
−200
−300
−200
−100
0
100
200
300
$f_{\rm NL}^{\rm ortho}$
$f_{\rm NL}^{\rm equil}$

Conclusions

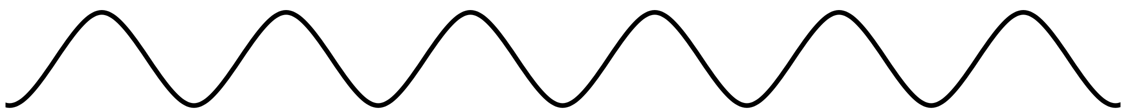
- Many (most?) of the features of QFT appear in the EFT of LSS:
  - Loops, divergencies, counterterms and renormalization
  - non-renormalization theorems
  - Calculable and non-calculable terms
  - Measurements in lattice and lattice-running
  - IR-divergencies
- Results seem to be amazing, many calculations and verifications to do:
  - like if we just learned perturbative QCD, and LHC was soon turning on
    - higher n-point functions
    - Validation with simulation
  - With a growing number of groups (Caltech, Princeton, IAS, Cambridge, CEA, Zurich..., just after 2-loop result, a workshop was organized by Princeton)
- If this works, the 10-yr future of Early Cosmology is good, even with no luck

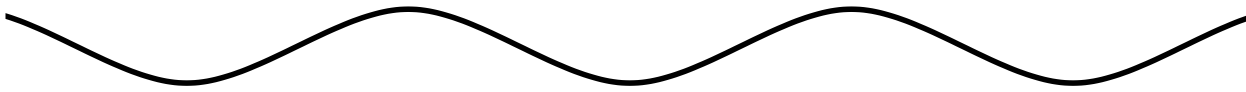
Make Peace and no War

- Let us not fight between Simulations and Perturbation Theory

Perturbation Theory *and* Simulations

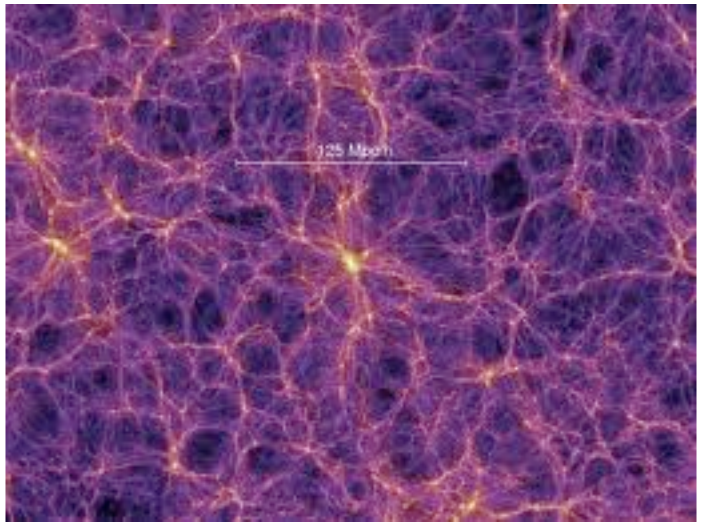
- There is room for everybody: the two approaches are *complementary*

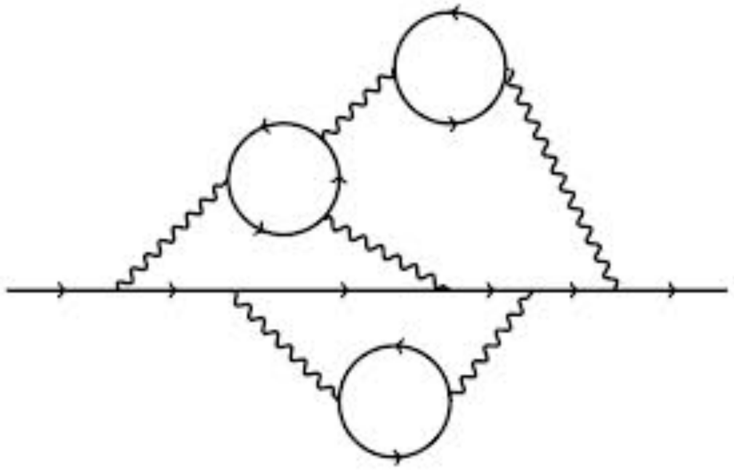




Short Wavelengths:
Simulations

Long Wavelengths:
Perturbation Theory





About RPT

- RPT is a technique that fits until 0.3 h/Mpc
- Two interpretations
  - They do a wrong IR resummation, and get an effect that, by arbitrarily tuning it, can make the fit to data better
    - If they did the right calculation, they would find no difference with standard treatment
    - To me, this is simply a wrong thing to do
  - They put a cutoff and argue that in this way the perturbative series is not made of oscillating terms, and so better behaved
    - I am unaware of a scientific way to justify this
      - like putting a cutoff in the chiral Lagrangian and saying it makes sense
- Whatever they want to do, they cannot get vorticity. So, in any event, it is not the right approach.