Leonardo Senatore (Stanford)

On the perturbative approaches to Large Scale Structures and the EFT of LSS

After last November

It is great to be in Paris

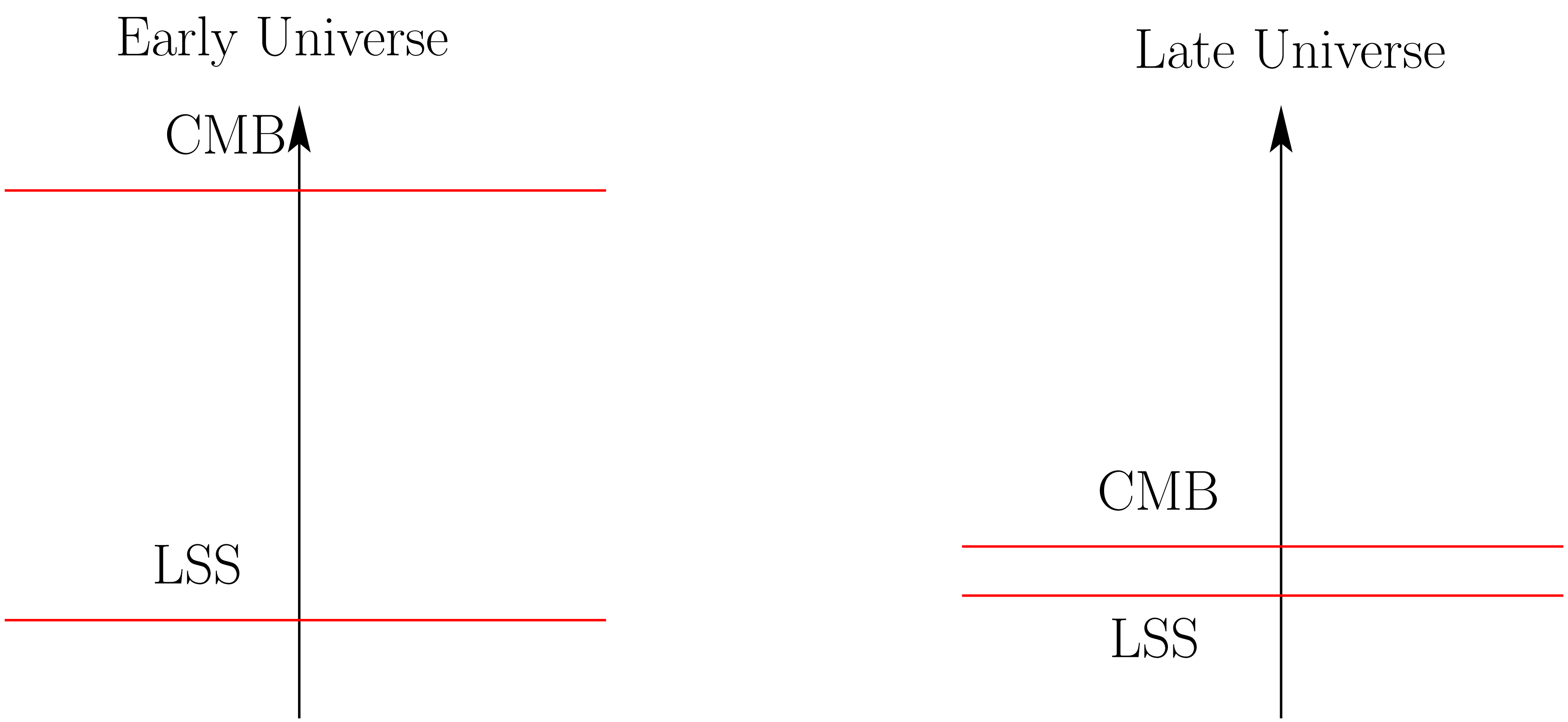
Since I am talking about EFT

It is great to be in the land of Fourier

The Gathering Storm

The Gathering Storm

- After the completion of the Planck satellite, no large improvement is expected from measurements of the primordial CMB
- How to we continue to explore the beginning of the universe?
- LSS (directly or through CMB) will be the leading next probe. But where do we stand:



- If you are interested in the physics of the late time universe, such as dark energy or astrophysics, you are fine: a small jump is enough.

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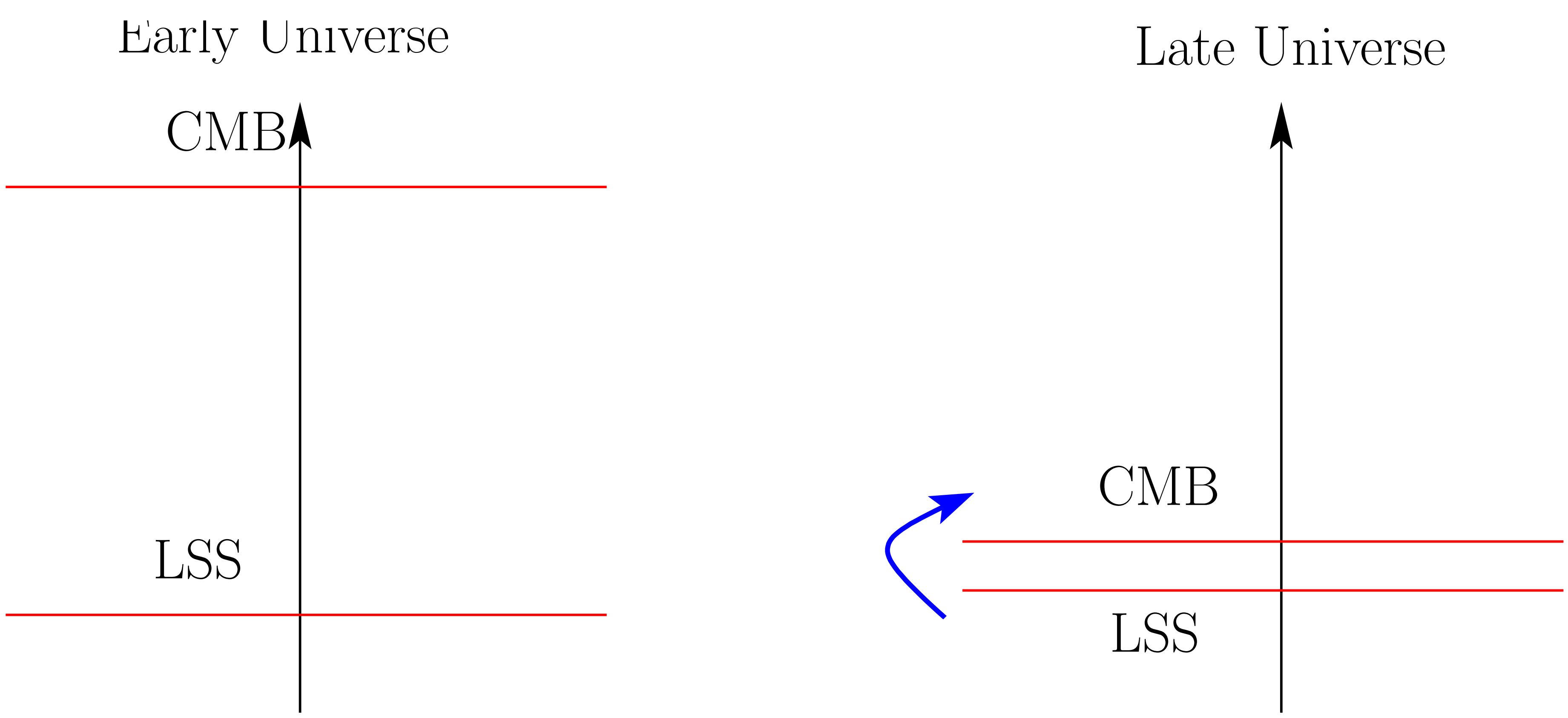

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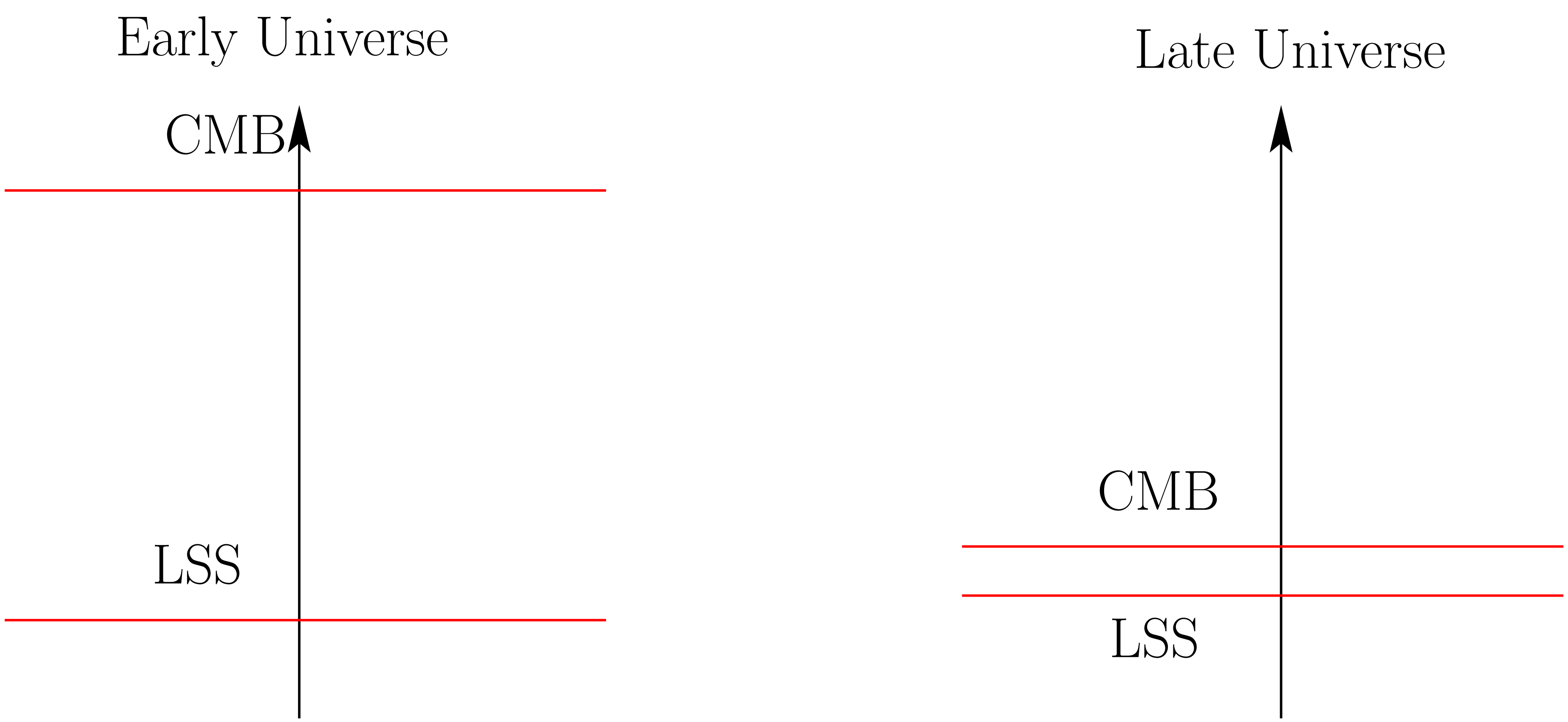
– But the precision of the CMB and the heroes such as the WMAP and Planck teams, have allowed Cosmology to be part not just of astrophysics, but also of the so-called fundamental sciences, such as quantum gravity, BSM, etc.

– If we want that to continue to belong to this group, we need to make this happen:



– a huge jump is required

– We have to do it, either with sims or analytics. I will present the analytic approach.

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The Situation is Grievous

I have nothing to offer but blood, toil, tears and sweat.

Winston Churchill
End of Battle of France, 1940

On perturbative methods

The Equations to Solve

- First, even before talking about perturbative methods, we should decide which equations govern the system
- Then, we identify ways in which to solve them
  - by Taylor expansion in some parameters (perturbation theory)
  - non-linearly in others
    - if the dependence must be analytical, this coincides with resumming on the parameter, but not always the case

$$e^{-1/g} = \sum_n 0 \times g^n = 0$$

The theory for Dark Matter

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 many 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

$$[\tau_{ij}]_{\rm long} \sim \delta_{ij}\left[\rho_{\rm short}\left(v_{\rm short}^2 + \Phi_{\rm short}\right)\right]_{\rm long}$$

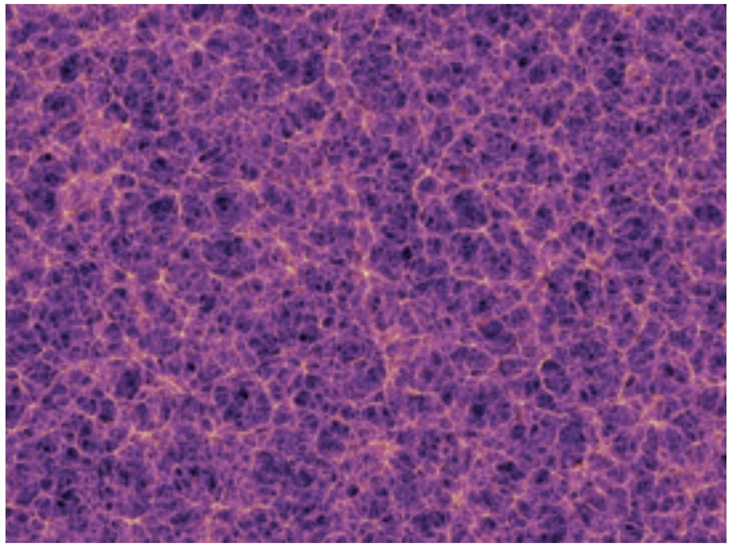
– many earlier insightful and important attempts

• but without gravity

– with gravity, measured in

with Carrasco and Hertzberg **JHEP 2012**
McQuinn and White **2015**

• without an useful treatment



The Effective ~Fluid

– These are the right equations, but, as written, these equations are useless

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

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

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

$$\Rightarrow \quad \langle \delta_l(x) \delta_l(y) \rangle \; \supset \; \langle [\tau_{ij}]_l(x) [\tau_{ij}]_l(y) \rangle = f_{\text{complicated and unknown}}(x - y) = ?$$

– Several approaches:

- – assume the contribution is so small that is negligible (SPT, RPT, etc)
- – parametrize the full function is some (arbitrary) way (course-grained PT, RegPT)
- – parametrized it in a systematic way (EFT)

Systematically dealing with the Effective Stress Tensor

- We give up on solving short distances $k \ll k_{\rm NL}\,, \Longrightarrow$ in a given $1/k$ many $1/k_{\rm NL}$
- $\Longrightarrow$ Take expectation value over short modes (integrate them out)

$$\tau_{ij}(x) = \langle [\tau_{ij}]_l(x) \rangle_{\text{long fixed}} + \Delta\tau_l(x) = f(\rho_l(x), \partial_i v^i(x), \ldots) + \Delta\tau_l(x)$$

  – and we can taylor expand in the long fields

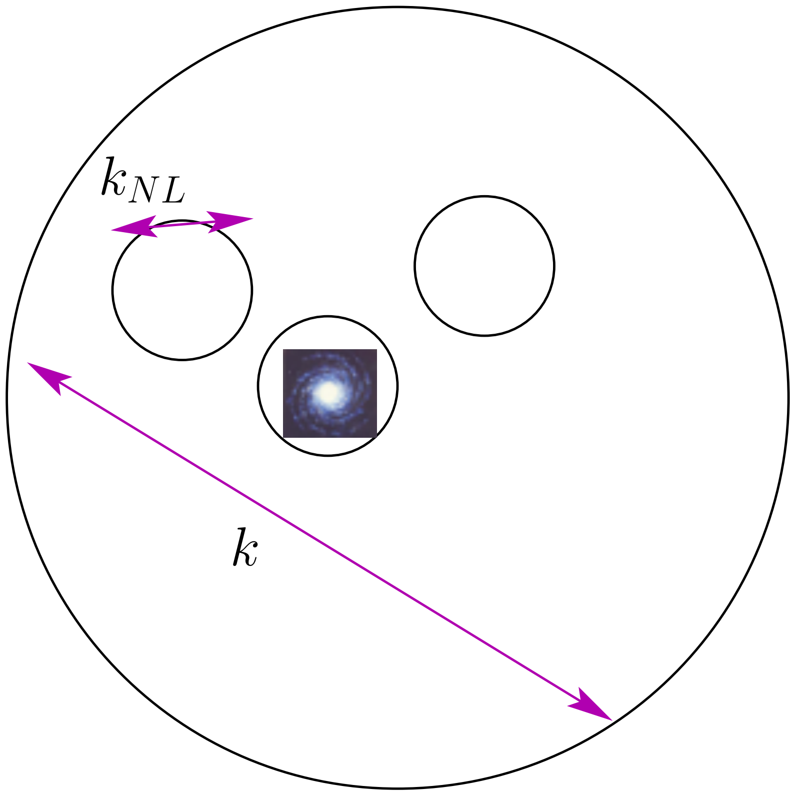
- We obtain equations containing only long-modes

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

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

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

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

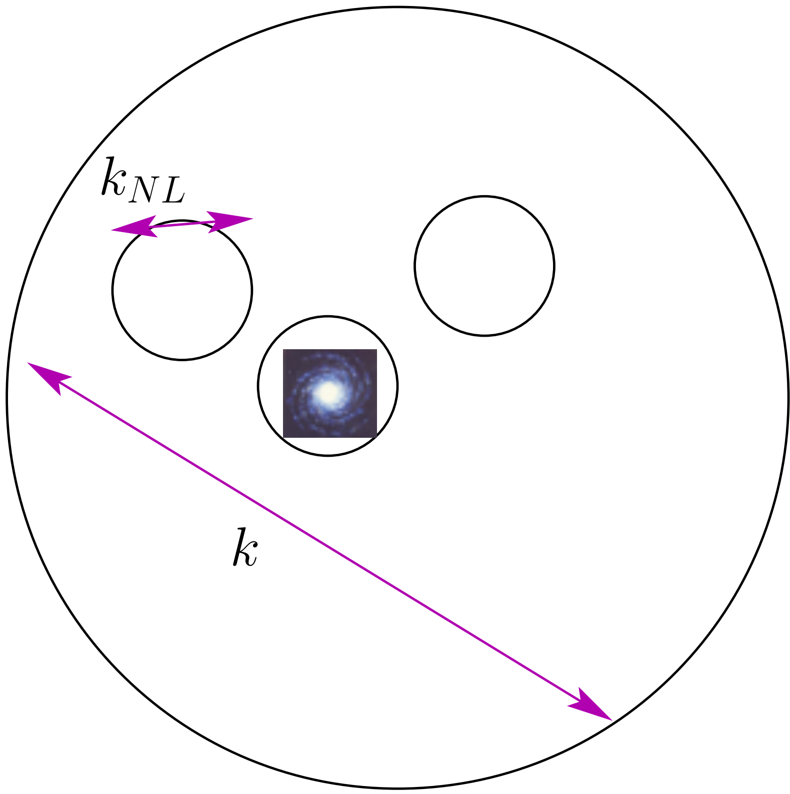


- Now the equations can be solved
- Many questions:
  – how many terms to keep
  – how do we solve and in what we are expanding

Systematically dealing with the Effective Stress Tensor

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

- Write each term allowed by general relativity (diff invariance):
- Each term counts as $\dfrac{\delta\rho}{\rho} \propto \left(\dfrac{k}{k_{\text{NL}}}\right)^{\alpha}, \quad \& \quad \dfrac{k}{k_{\text{NL}}}$

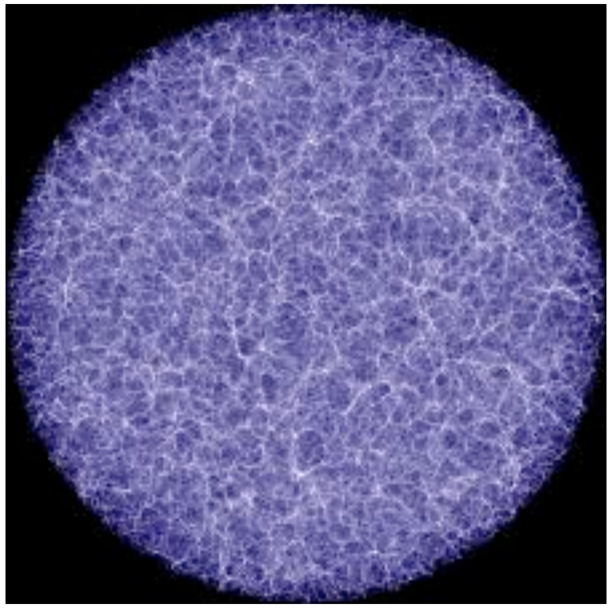


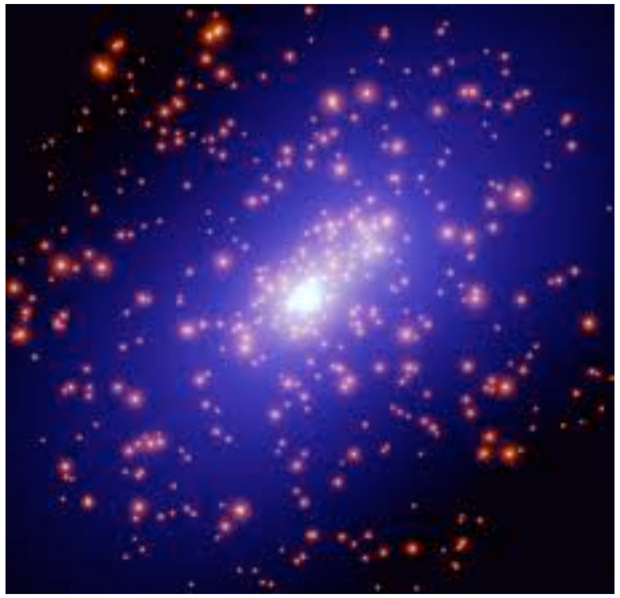
- For a given precision,
    - we keep the relevant and finite number of terms

A subtlety: non-locality in Time

This EFT is non-local in time

- For local EFT, we need hierarchy of scales.
  - In space we are ok





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

with Carrasco, Foreman and Green **1310**
Carroll, Leichenauer, Pollak **1310**
Mirbabahi, Schmidt, Zaldarriaga **1412**
Bertolini, Shutz, Solon, Zurek **1604**

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

$$\langle \tau_{ij} \rangle_{\delta_l} \sim \int dt' \left[K(t,t') \, \frac{\delta\rho}{\rho}(x_{\rm fl},t') + \mathcal{O}\left((\delta\rho/\rho)^2, \ldots \right) \right]$$

Consequences of non-locality in time

with Carrasco, Foreman, Green **1310**
Senatore **1406**

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

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

- A few coefficients for each counterterm:

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

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

- Difference:

$$\text{Time-Local QFT:}\quad c_1(t)\left[\delta\rho(\vec{x})^{(1)} + \delta\rho(\vec{x})^{(2)} + \dots\right]$$
$$\text{Non-Time-Local QFT:}\quad c_1(t)\;\delta\rho(\vec{x})^{(1)} + c_2(t)\delta\rho(\vec{x})^{(2)} + \dots$$

  - More terms, but not a disaster

- Equivalently (still non-local in time): $\langle\tau_{ij}\rangle_{\text{long}} = \delta\rho(\vec{x},t) + \frac{1}{H}\frac{D}{Dt}\delta\rho + \frac{1}{H^2}\frac{D^2}{Dt^2}\delta\rho(x,t)$
  - derivatives are unsuppressed, they are just degenerate

Mirbabahi, Schmidt, Zaldarriaga **1412**
Bertolini, Shutz, Solon, Zurek **1604**

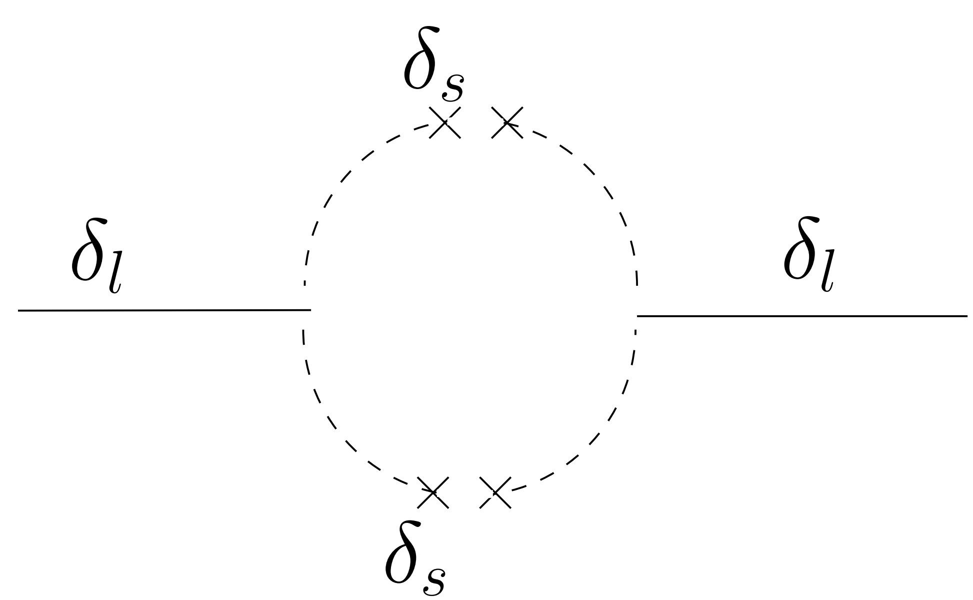
Perturbative Methods

Perturbation Theory within the EFT

- Now that we have decided on the equations (the EFT ones), let us solve them
- Let us better explore the expansion parameters
- We start by Taylor expanding the equations
- Since equations are non-linear, we obtain convolution integrals (loops)

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

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



- To evaluate them, it is practically identical machinery as STP and LPT (thanks!).
  - all the machinery that was constructed (any correct technique), keeps being used

The expansion parameters

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

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

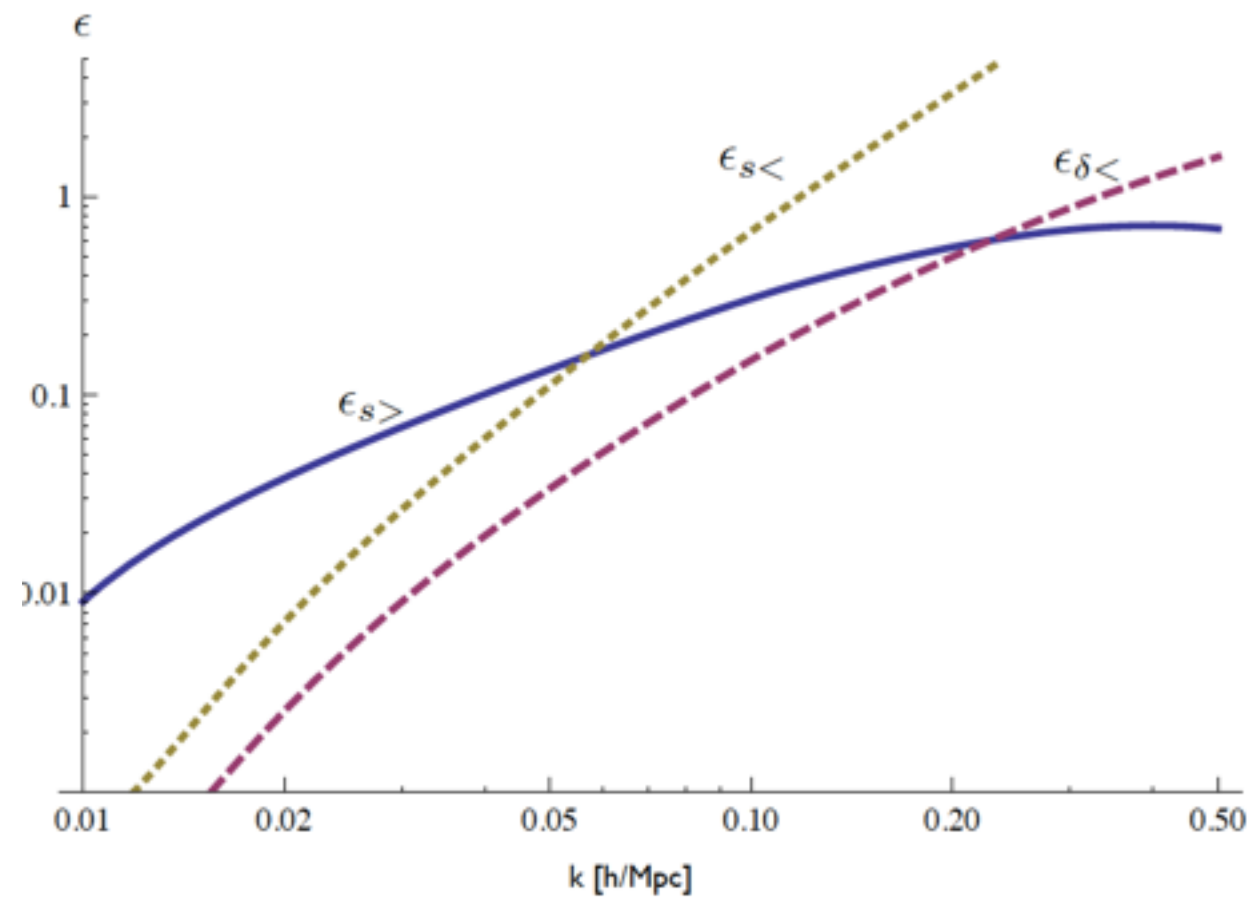
Effect of Long Overdensities

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

Effect of Long Displacements

$$\epsilon_{\rm short\ displacement}(k) \sim k^2 \int_k d^3q \; \frac{P(q)}{q^2}$$

Effect of Short Displacements



The IR-parameters

see originally Scoccimarro and Frieman **9609047**

- $\epsilon_{\text{long displacement}}(k)$ seems problematic
- On IR-safe quantities, it cancels almost completely.

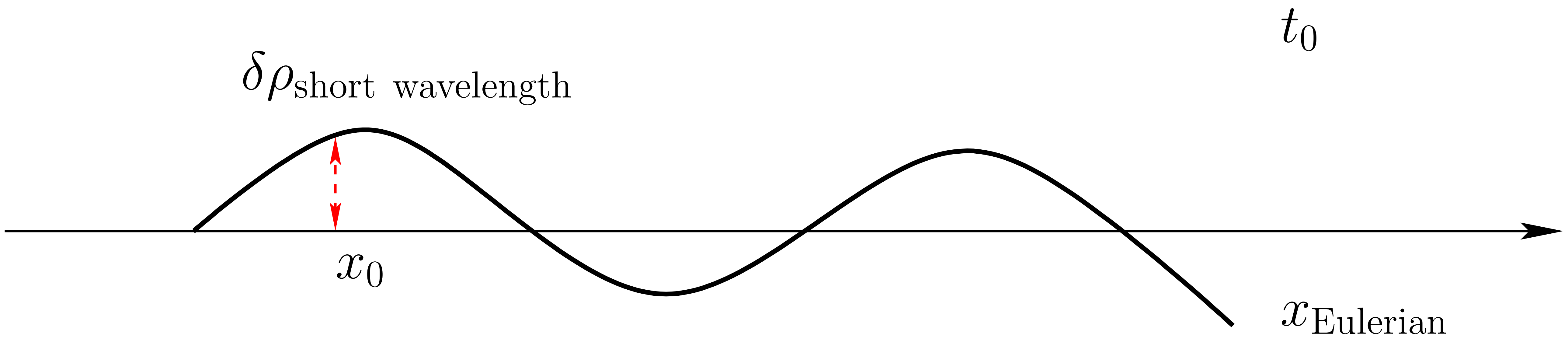
$$\langle\delta^{\text{with long}}(x_1)\delta^{\text{with long}}(x_2)\rangle = \langle\delta^{\text{no long}}\left(x_1+\frac{v(x_1)}{H}\right)\delta^{\text{no long}}\left(x_2+\frac{v(x_2)}{H}\right)\rangle =$$

$$\simeq \int_{\vec{k},\vec{k}'} e^{ik(x_1-x_2)}e^{ik\left(\frac{v(x_1)}{H}-\frac{v(x_2)}{H}\right)}\langle\delta_k^{\text{no long}}\delta_{k'}^{\text{no long}}\rangle = \text{no long gradient} = \langle\delta^{\text{no long}}(x_1)\,\delta^{\text{no long}}(x_2)\rangle$$

- On non-IR safe quantities, $\epsilon_{\text{long displacement}}(k)$ does not cancel

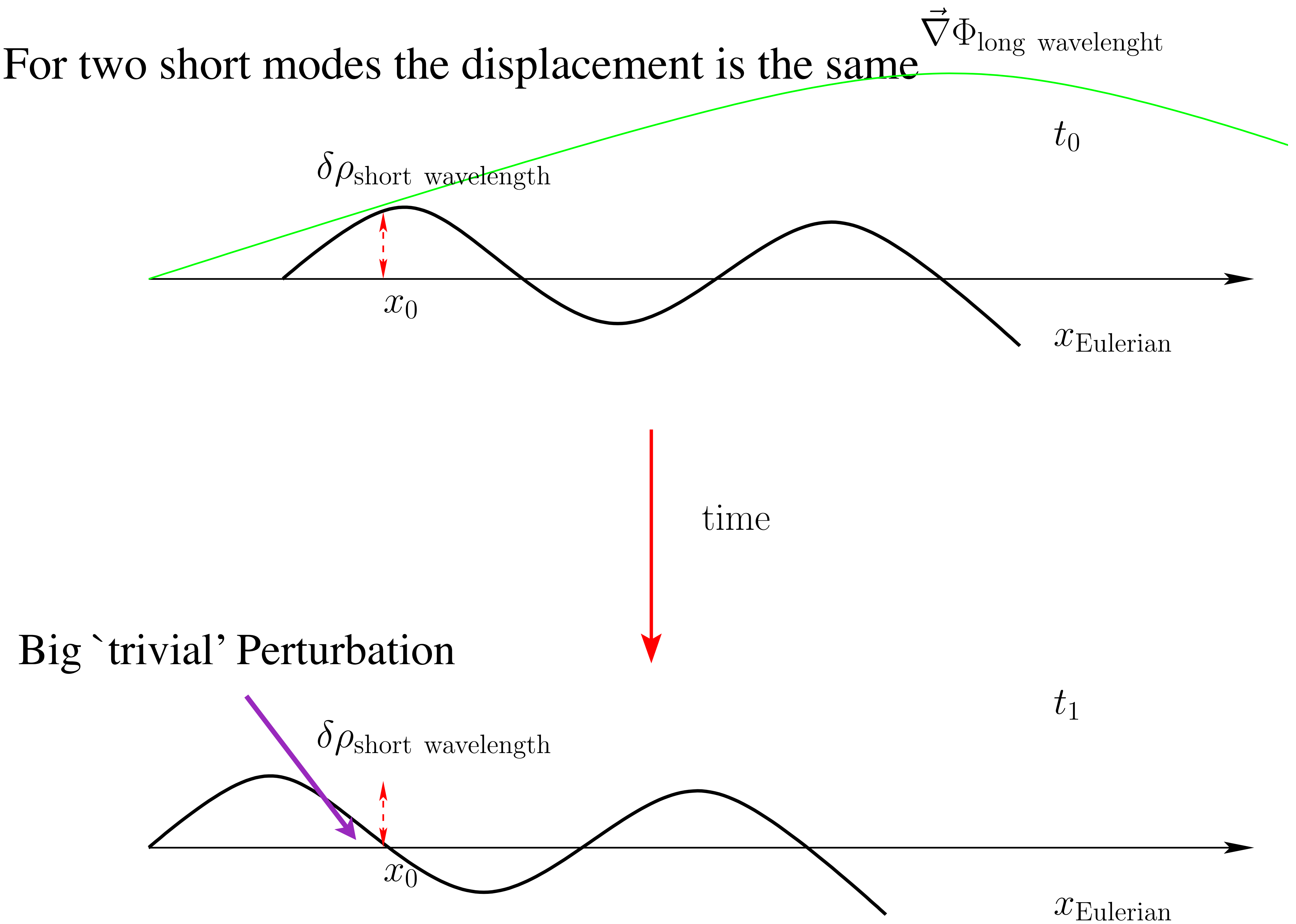
The Effect of Long-modes on Shorter ones

- Effet of Long Mode



The Effect of Long-modes

- Add a long `trivial’ force (trivial by GR). If mode long enough, go to common free falling frame (box)
- For two short modes the displacement is the same



- Effect on common long mode cancels (as equally translated)

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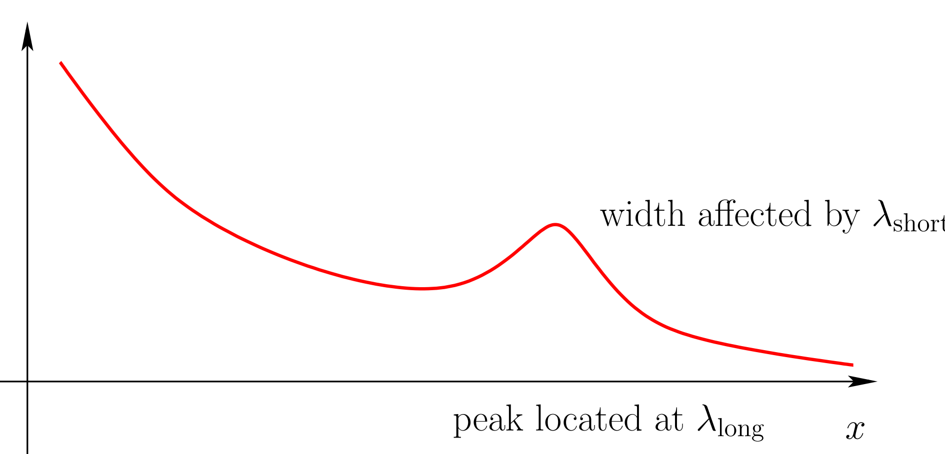
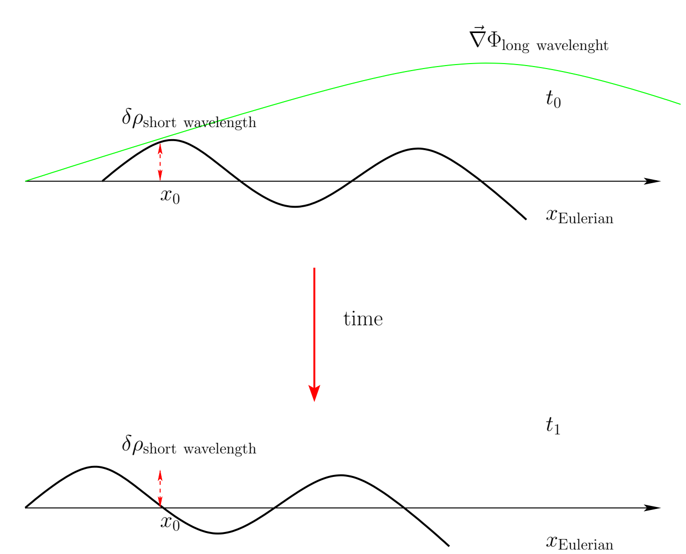
- But if the gradient of the long mode is relevant $\text{phase} \sim k\,\Delta x\,\partial v(x)/H \sim k\,\Delta x\,\delta_l(x)$
- If power spectrum has a sharp feature at Δx , $k \gg 1/\Delta x$ contribute to the FT

$$\Longrightarrow \ \text{phase} \gg \delta_l$$

- Intuitively: displacement shorter than BAO peak does not cancel
- But it can be resummed, as it is a trivial displacement

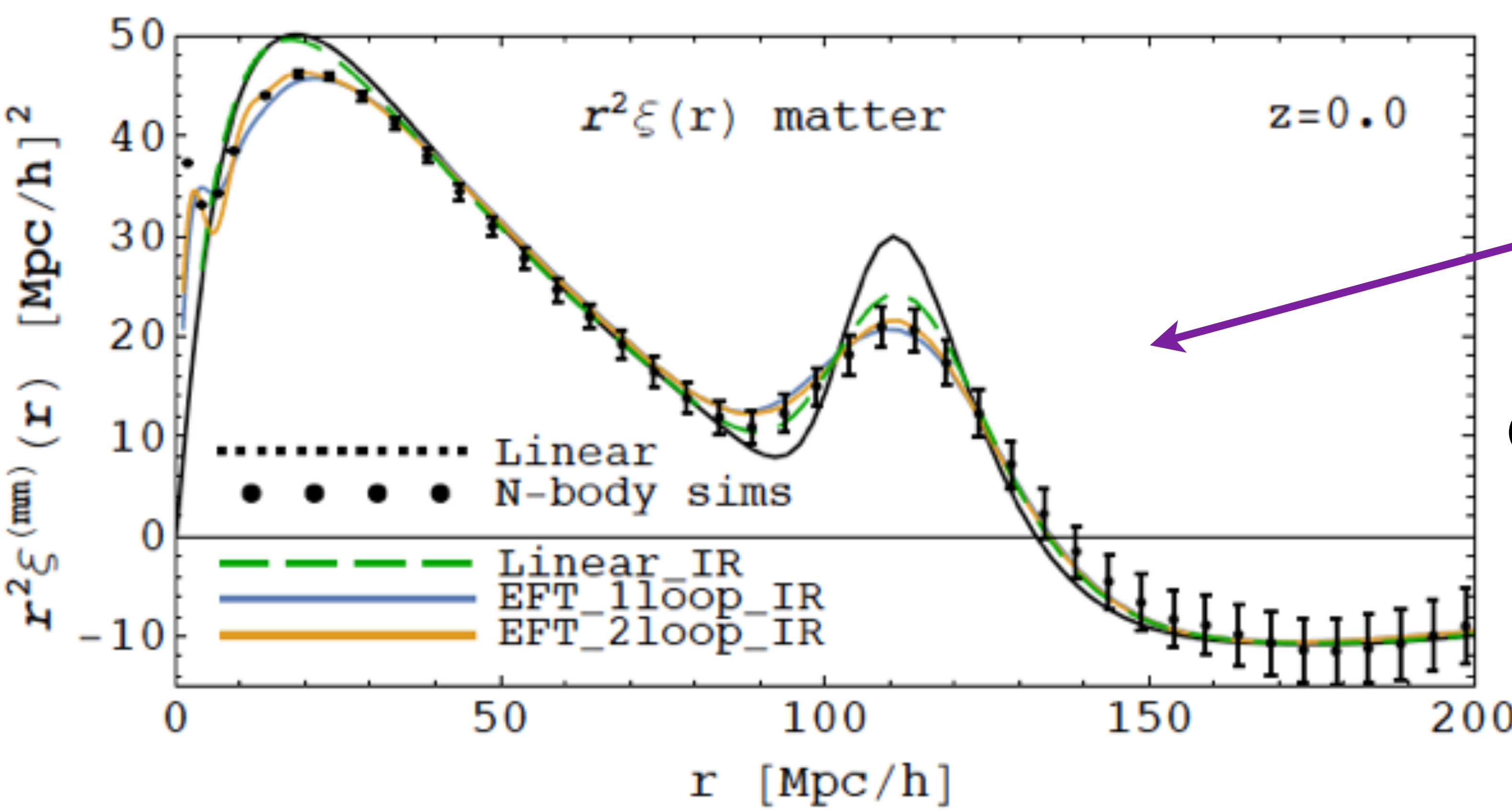




with Zaldarriaga **JCAP1502**
see also earlier **RPT papers**

IR-resummation in the EFTofLSS and the BAO peak

• Real space & the BAO feature: IR-resummation works



Dark Matter

with Zaldarriaga **1404**
(plot from Angulo er al. 1503)

with Zaldarriaga **1404**
same formula simplified (with approx) in Baldauf, Mirbabayi, Simonovic and Zaldarriaga **1504**
subleading IR contribution resummed in Blas, Garny, Ivanov and Sibiryakov **1605**

see also, earlier **RPT, RegPT** papers fur useful insights

Perturbation Theory within the EFT

- Back to the diagrams

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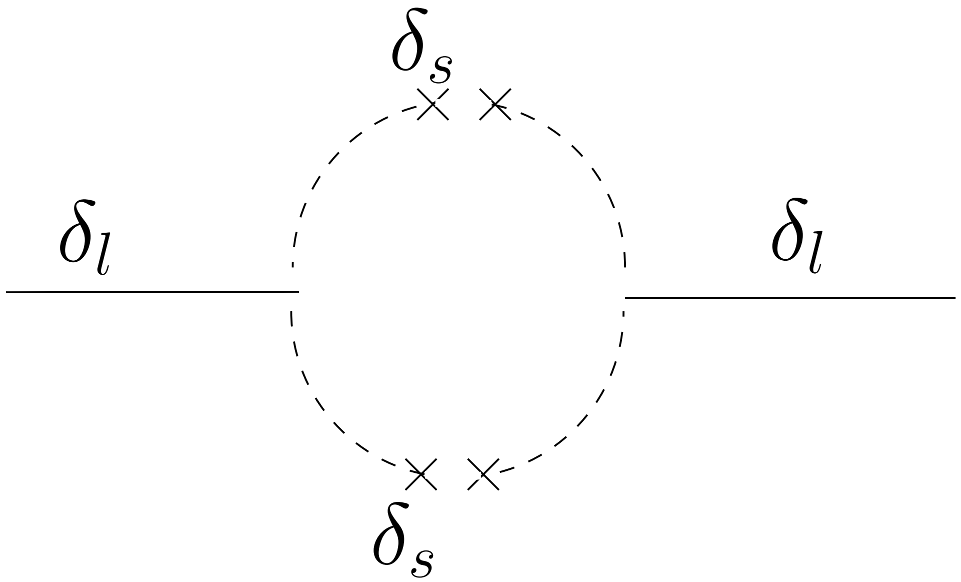
$$\Rightarrow \quad \delta^{(2)}(k_l) \sim \int d^3k_s\, \delta^{(1)}(k_s)\, \delta^{(1)}(k_l - k_s)\;, \quad \Rightarrow \quad \langle \delta_l^2 \rangle \sim \int d^3k_s\, \langle \delta_s^{(1)2} \rangle^2$$



Perturbation Theory within the EFT

with Carrasco and Hertzberg **1206**
Pajer and Zaldarriaga **1211**

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

  – evaluate with cutoff:

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

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

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

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

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

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

–we just re-derived renormalization

–after renormalization, result is finite and small

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Lesson from Renormalization

- After IR-resummation and renormalization, each loop-order L contributes a finite, calculable term of order

$$P_{\rm L-loop} \sim \left\{\epsilon_\delta, \epsilon_{s>}\right\}^L$$

  – each higher-loop is smaller and smaller

  – crucial (and only!) difference with all former approaches

- This happens after canceling the divergencies with counterterms

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

    - each loop contributes the same

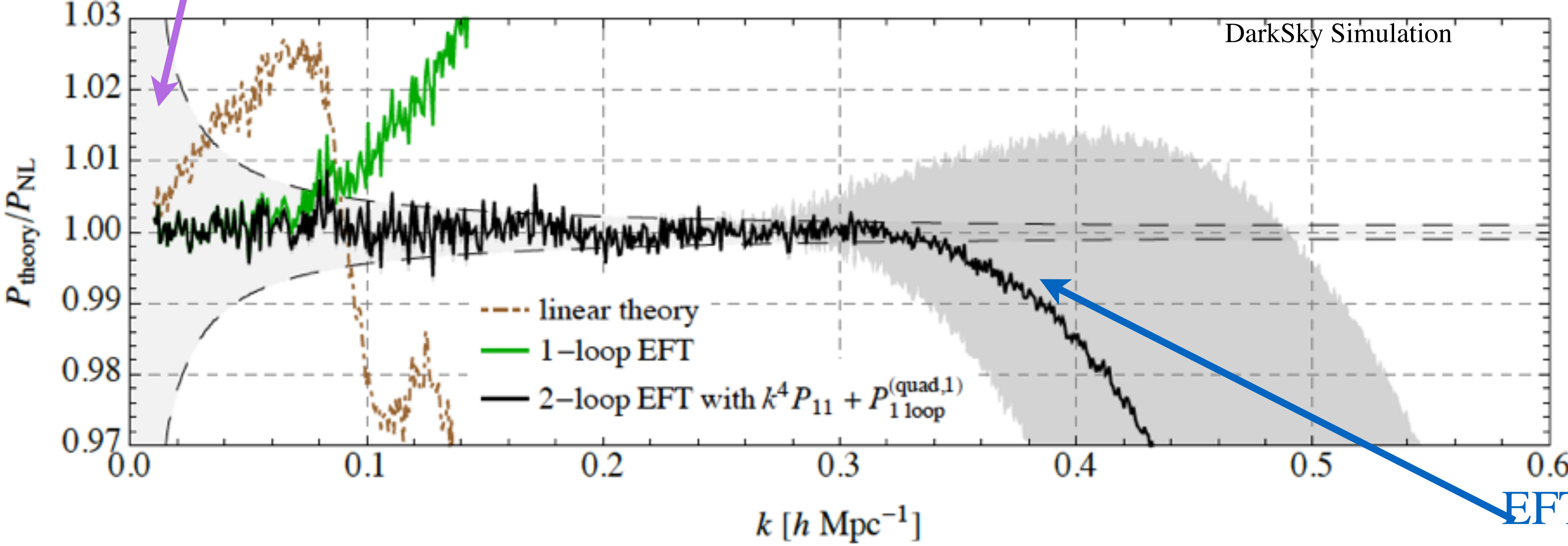
– Lagrangian EFT = Eulerian EFT after IR-resummation

Result for Dark Matter

Dark Matter 2-pt function

- Precise Comparison of power spectra

Precision comparison

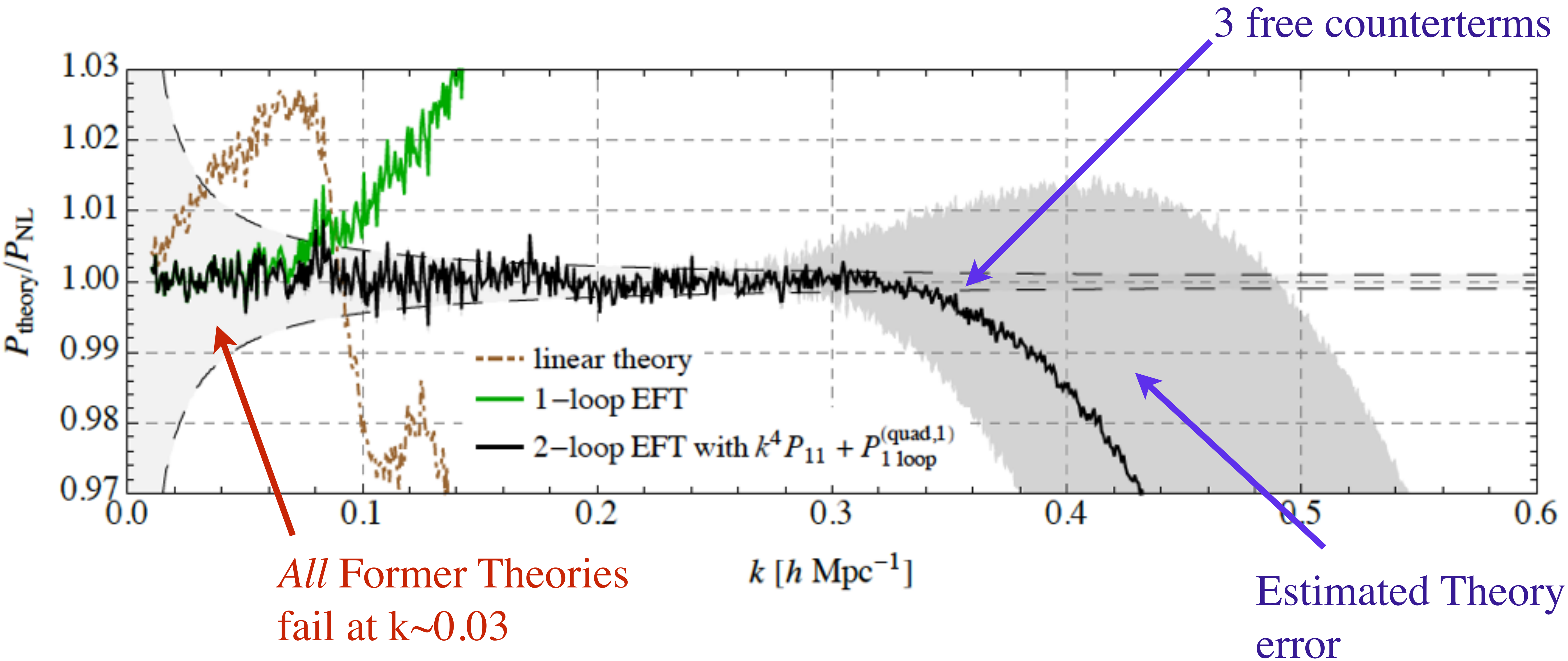


EFTofLSS

EFT of Large Scale Structures at Two Loops

- .

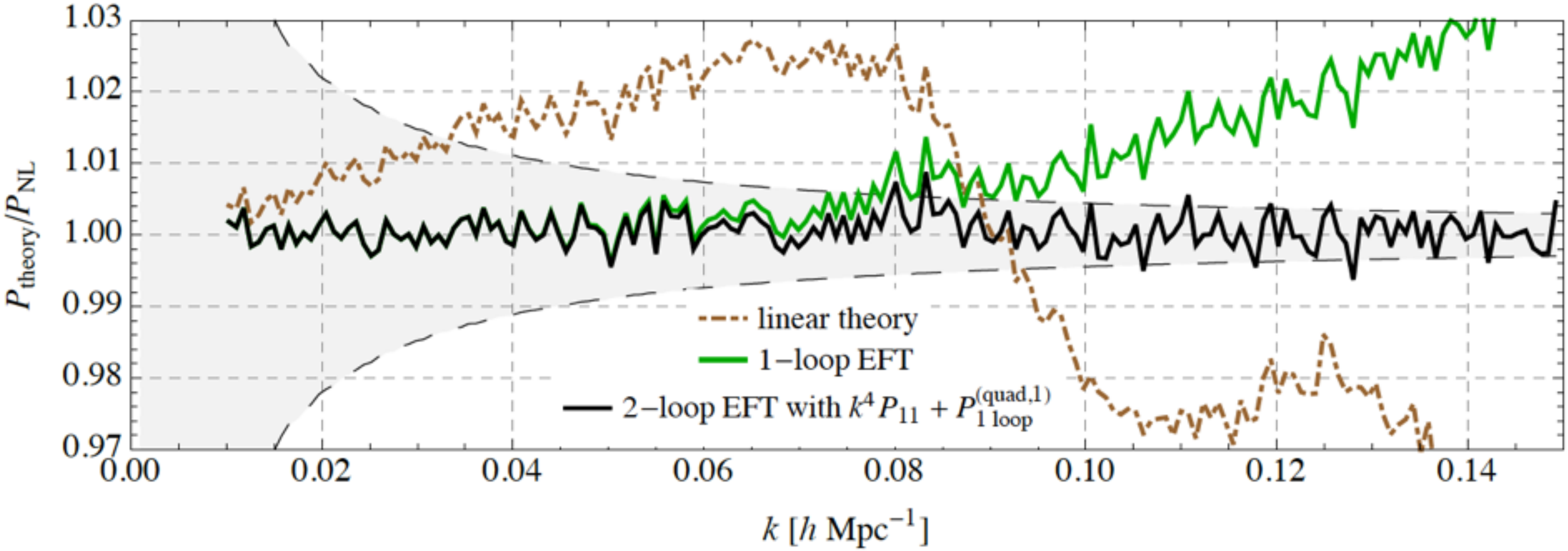
$$\partial^2\tau_{ij} \sim c_s\, k^2\delta(k) + c_1\, k^2[\delta^2](k) + c_4\, k^4\delta(k)$$



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

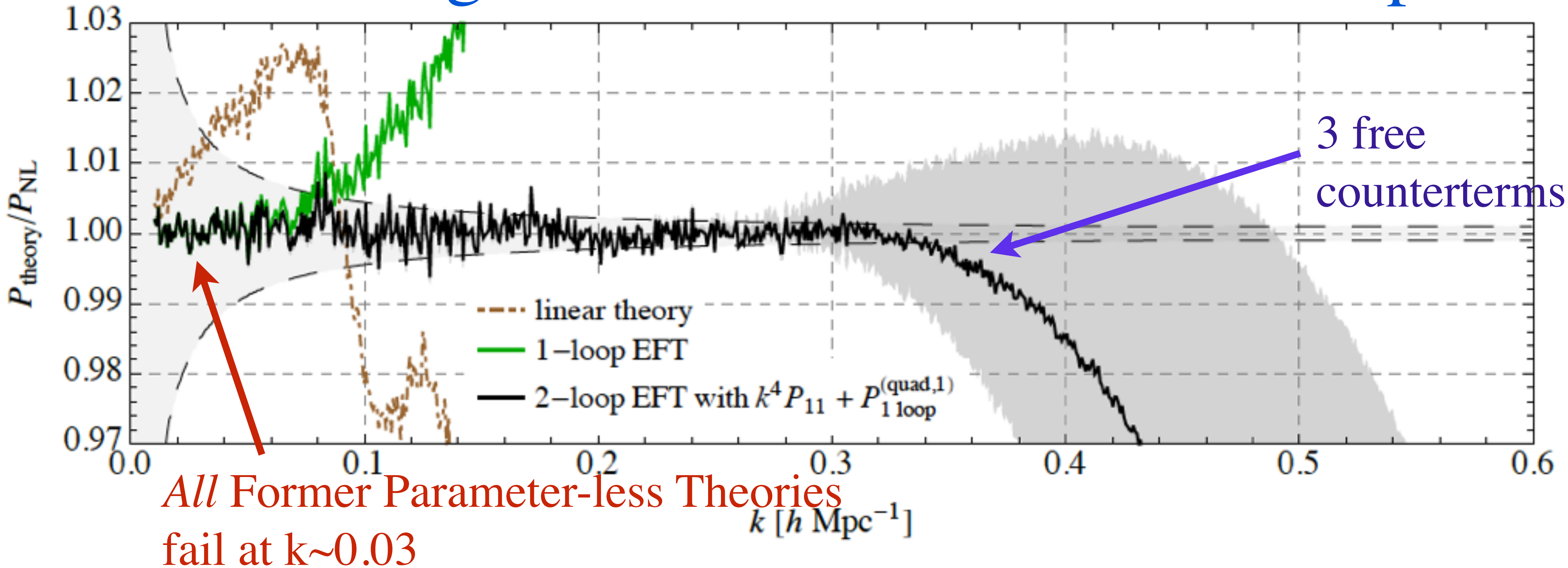
with Carrasco, Foreman and Green **JCAP1407**
with Zaldarriaga **JCAP1502**
with Foreman and Perrier **1507**
see also Baldauf, Shaan, Mercolli and Zaldarriaga **1507, 1507**

Precision at low k's

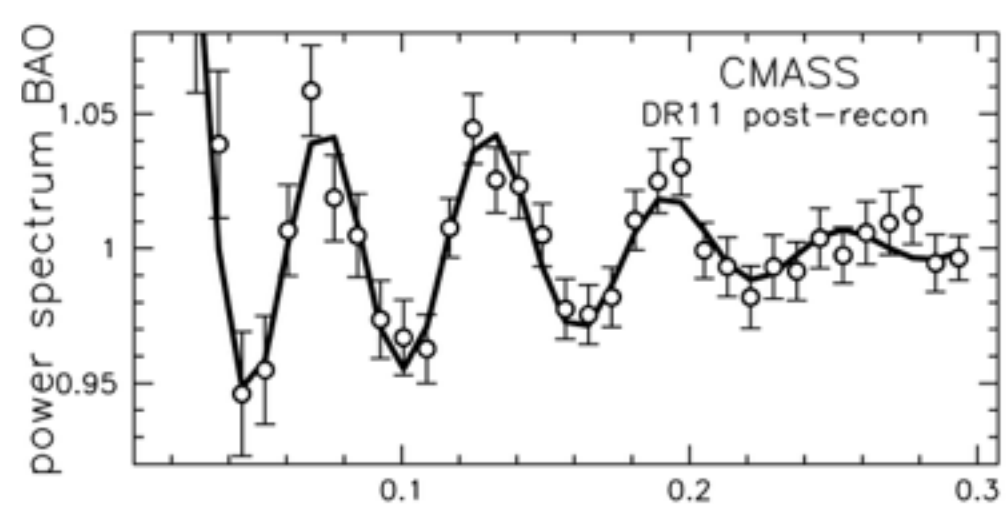


- k-reach is not everything. Precision at low k's is also important and great
  - no matter the k-reach, at low k's very fast convergence.
- Look where linear theory fails!, $k \sim 0.03\, h\, \text{Mpc}^{-1}$, and these are LSST-like error bars!
- we can see that order by order, at low k's, the EFT converges!

EFT of Large Scale Structures at Two Loops



- All former theories (without free parameters), RPT, LPT,…. differ from SPT just by the IR-resummation
- $\Longrightarrow$ by GR, IR-modes cancel in $P(k)$, so cannot change broad k-reach of the theory
  - they just change the BAO, which are 2% oscillations in k-space
  - already pointed out by original authors of RPT



Sociology

- k-reach and validity of approximations (beyond the rigor of the EFT) *depends* on the numerical data at our disposal

- I am not a professional of sims. I am doing this just to motivate the community to switch to this formalism.

- As soon as enough people have converted, I can go away.

- We need people like Baldauf, White, Scoccimarro & Crocce. These are the ones who can do this job.

Other Observables

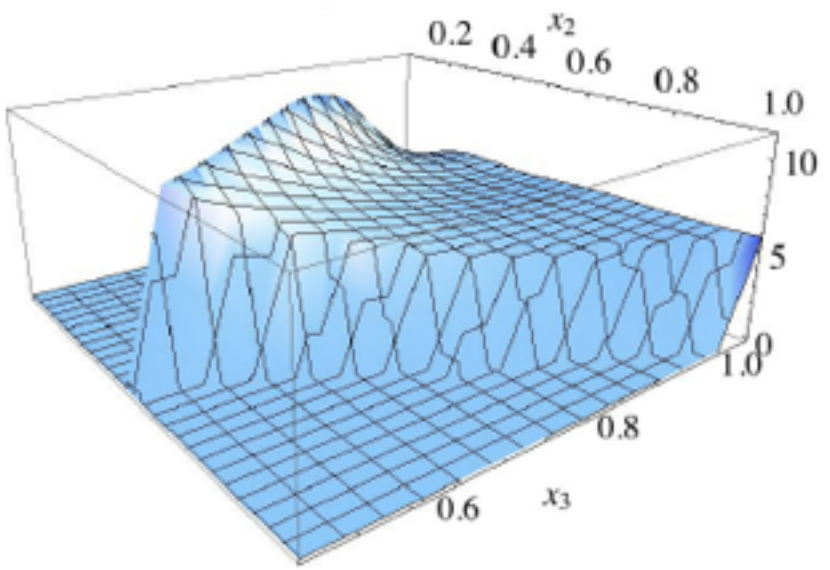
Other Observables

– 3point function

– very non-trivial function of three variables!

with Angulo, Foreman and Schmittful **1406**

see also Baldauf et al. **1406**



– Momentum

– They all work as they should

with Carrasco, Foreman and Green **JCAP 1407**

Baldauf, Mercolli and Zaldarriaga **1507**

– Vorticity Spectrum

with Carrasco, Foreman and Green **JCAP1407**

Mercolli and Pajer **JCAP1406**

– agrees with most accurate measurements in simulations

Pueblas and Scoccimarro **0809**

Hahn, Angulo, Abel **1404**

– Covariance and Trispectrum

– no need to run many simulations of the same cosmology: just compute 4pt function

Bertolini, Shutz, Solon, Zurek **1512, 1604**

– Displacement field

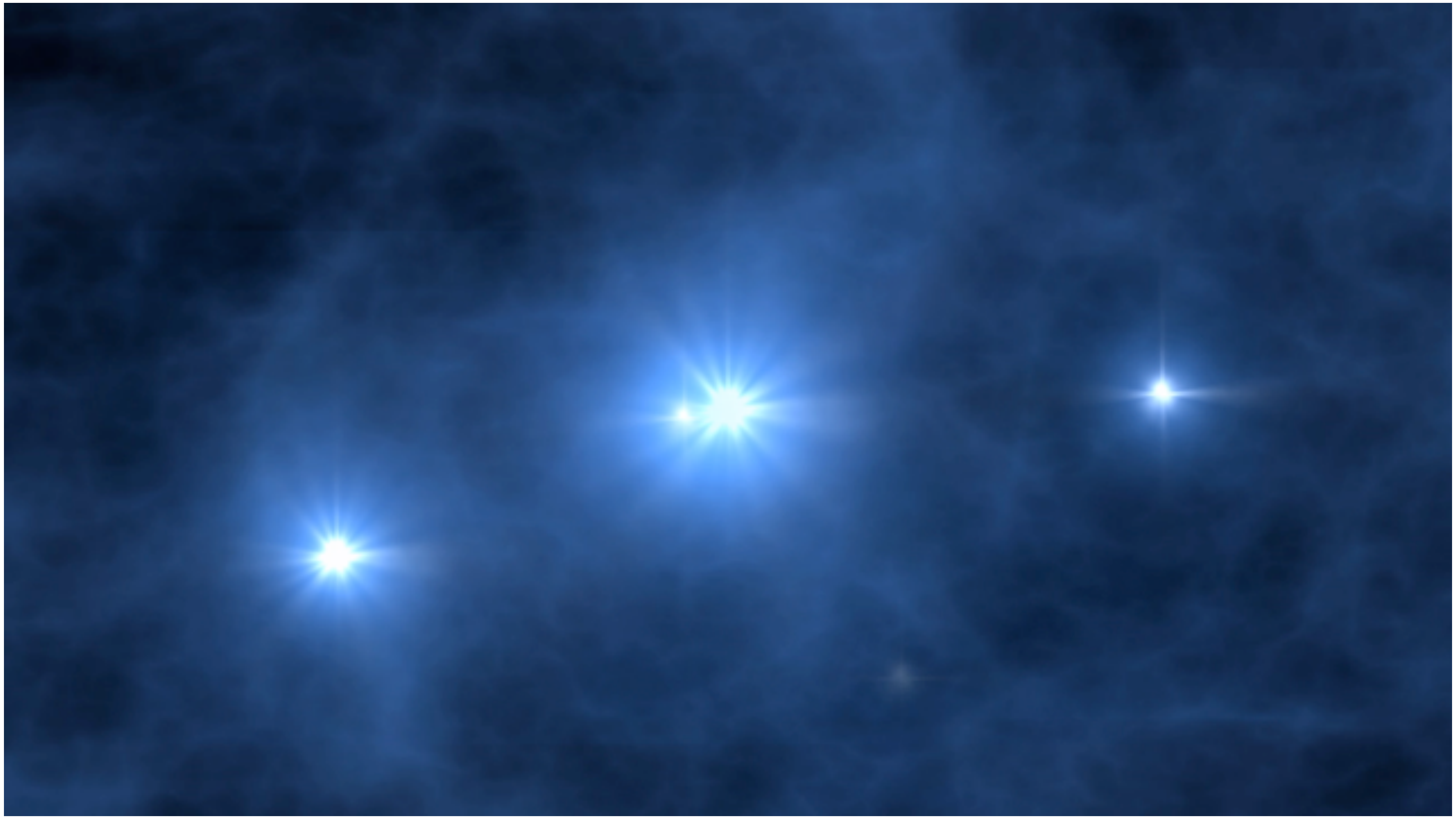
Baldauf, Shauf and Zaldarriaga **1504**

Analytic Prediction of Baryon Effects

with Lewandowski and Perko **JCAP1502**
with Sgier **in completion**

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:

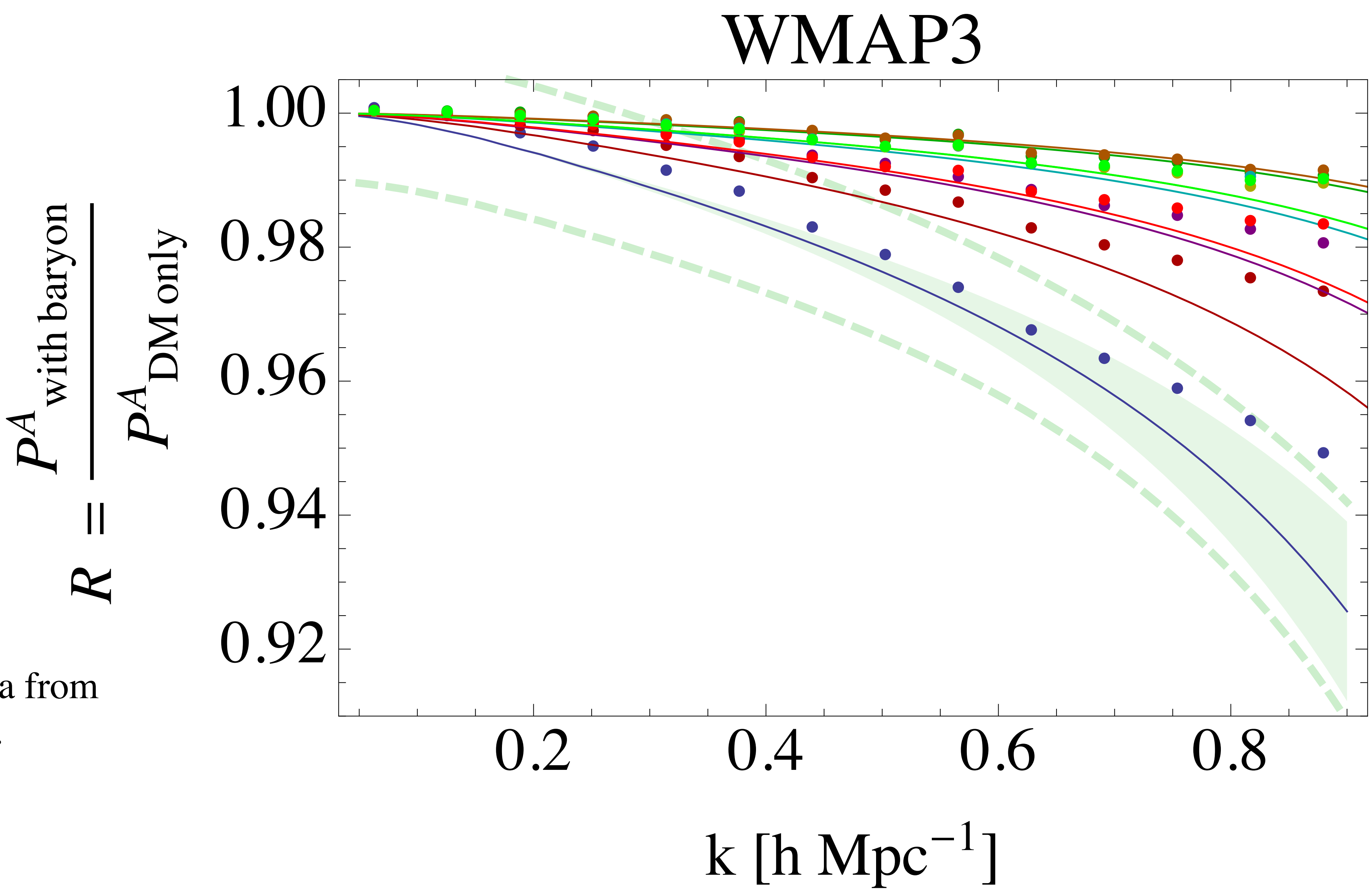
$$\partial^2\tau_b + \partial\gamma_b \sim c_s^2\,\partial^2\delta_l + c_\star^2\,\partial^2\delta_l + \ldots$$

gravity-induced pressure

star formation-induced pressure

Baryons

with Lewandowski and Perko **JCAP1502**



Simulation data from
J. Schaye et al.

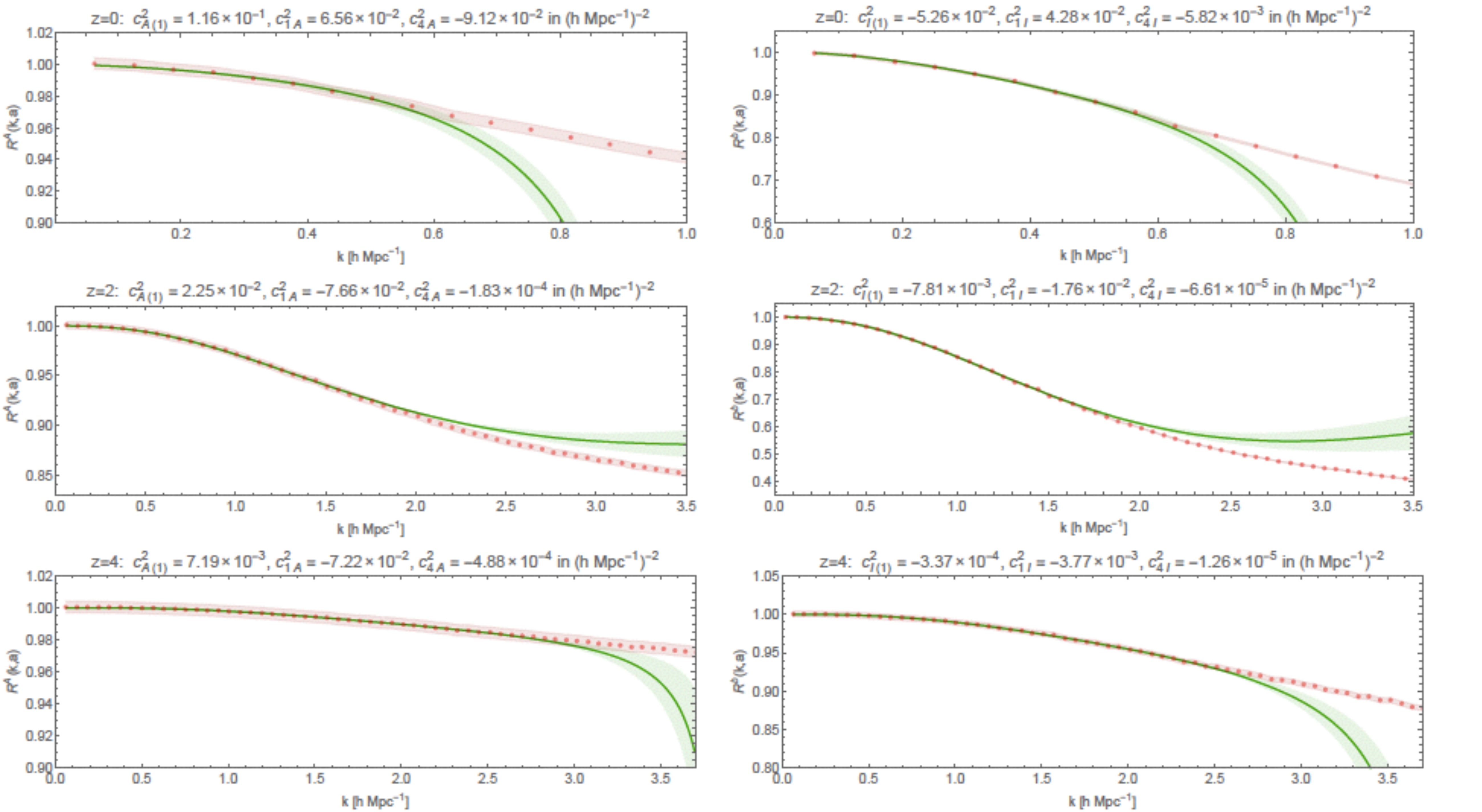
– Analytic form of leading effect known: $\Delta P_b(k) \simeq c_\star^2 \left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}^A(k)$

– and it seems to work as expected

  – notice no cosmic variance

Baryons at all redshifts

with Sgier **in completion**



– At two loops, we have 6 counterterms to fit:

– 0.25% error bars, and it seems to work as expected

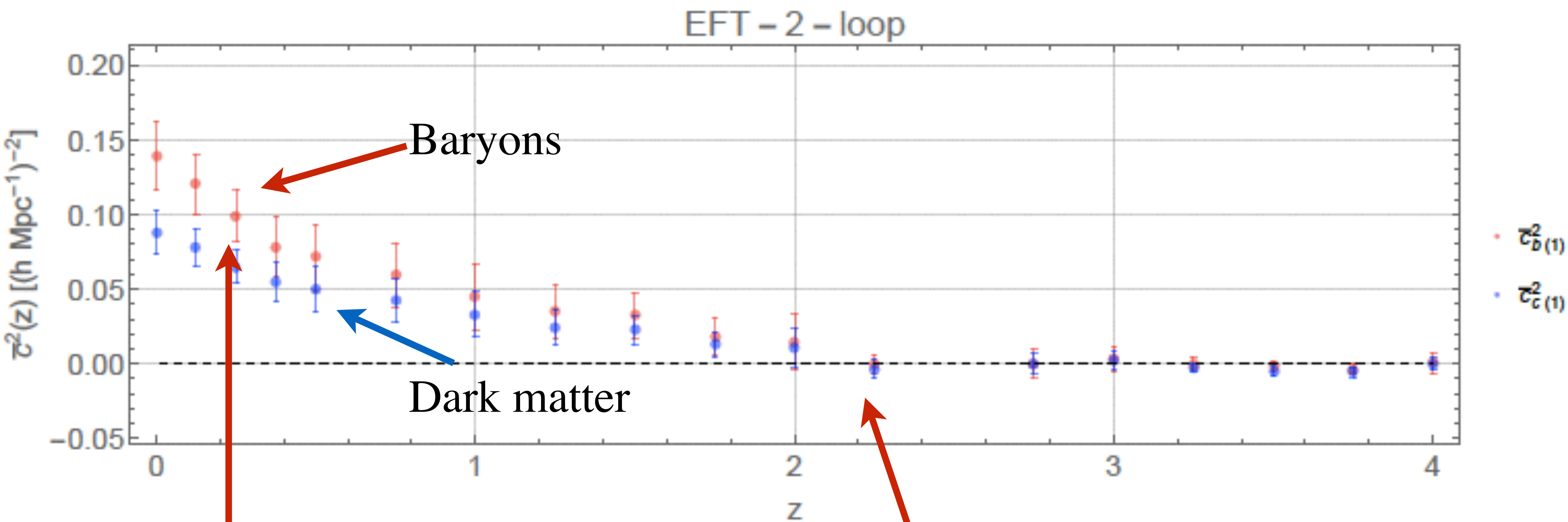
– we realize that sims are \`wrong' (so no overfitting)

$$
\begin{aligned}
c_{A(1)} &= c_{s(1)}(1+\omega_b\epsilon_{A(1)}) \quad , \quad c_{I(1)} = c_{s(1)}\omega_b\epsilon_{I(1)} \\
c_A &= c_{1s}(1+\omega_b\epsilon_{1A}) \quad , \quad c_{1I} = c_{1s}\omega_b\epsilon_{1I} \, , \\
c_A &= c_{4s}(1+\omega_b\epsilon_{4A}) \quad , \quad c_{4I} = c_{4s}\omega_b\epsilon_{4I} \, .
\end{aligned}
$$

$$-3 < \epsilon < 3.$$

Time dependence of speed of sound

with Sgier **in completion**

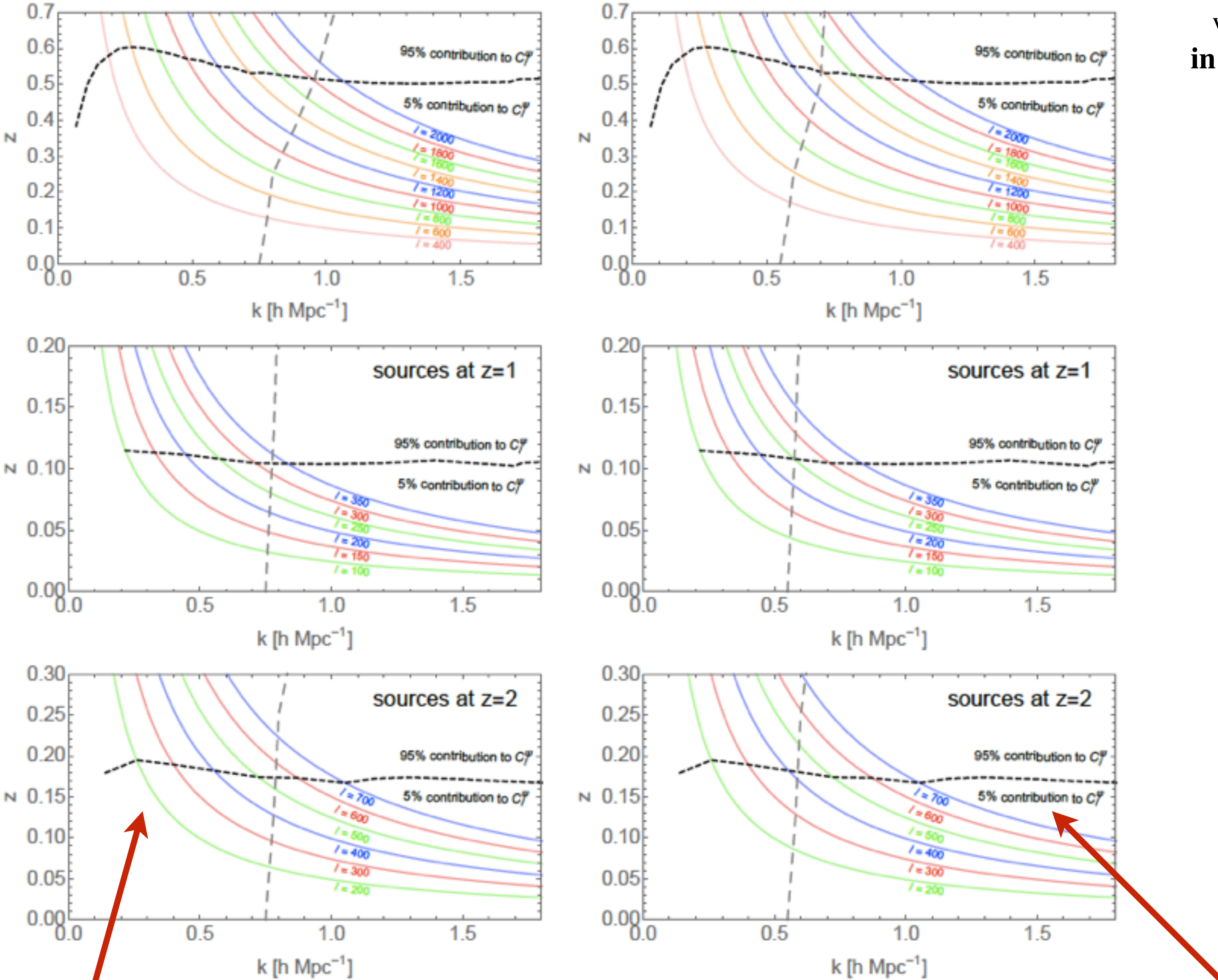


Baryon speed of sound is larger

They kick in at the same time

Observational Prediction for Lensing

with Sgier
in completion

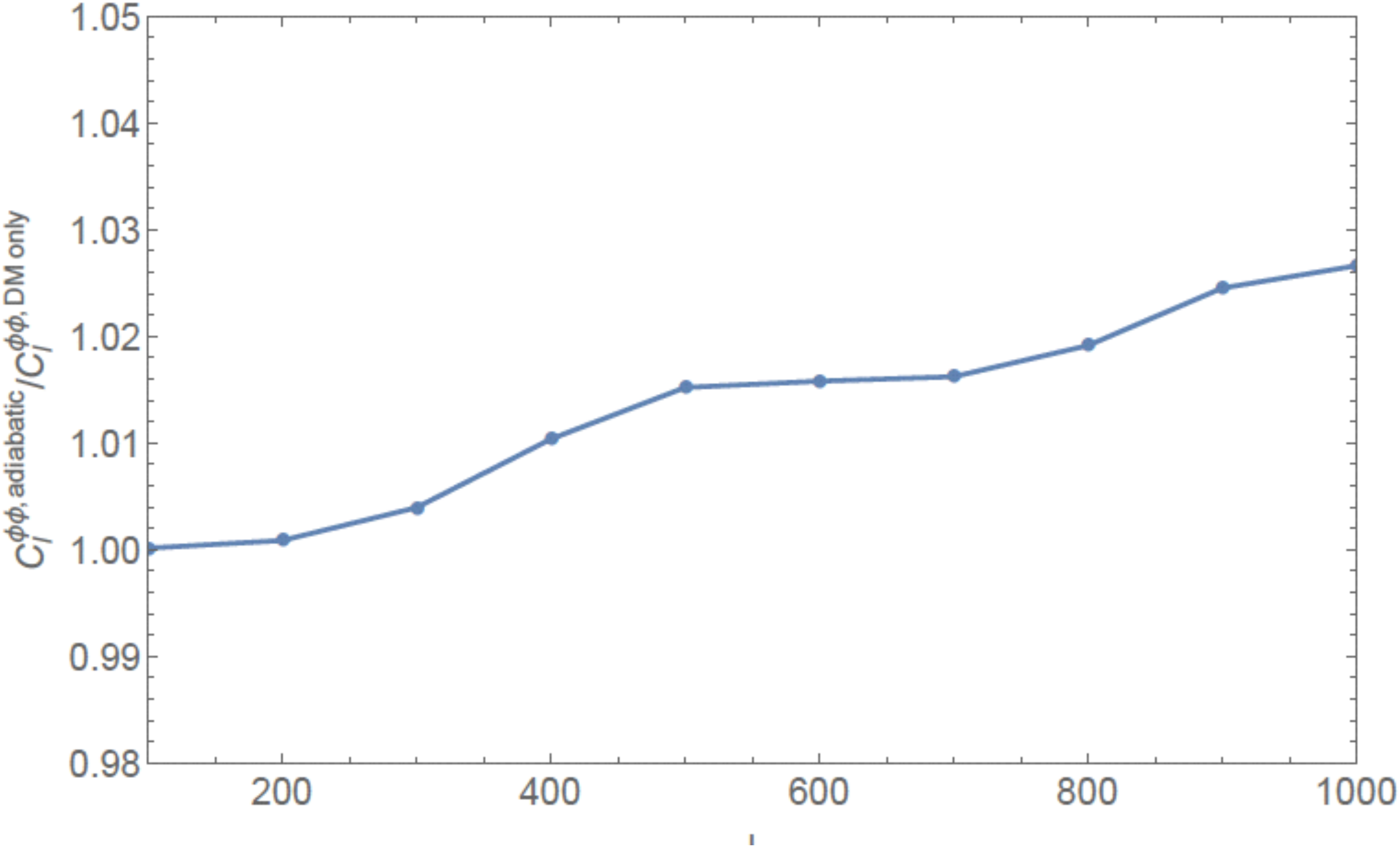


1% error bar on sims

0.25% error bar on sims

Observational Prediction for Lensing

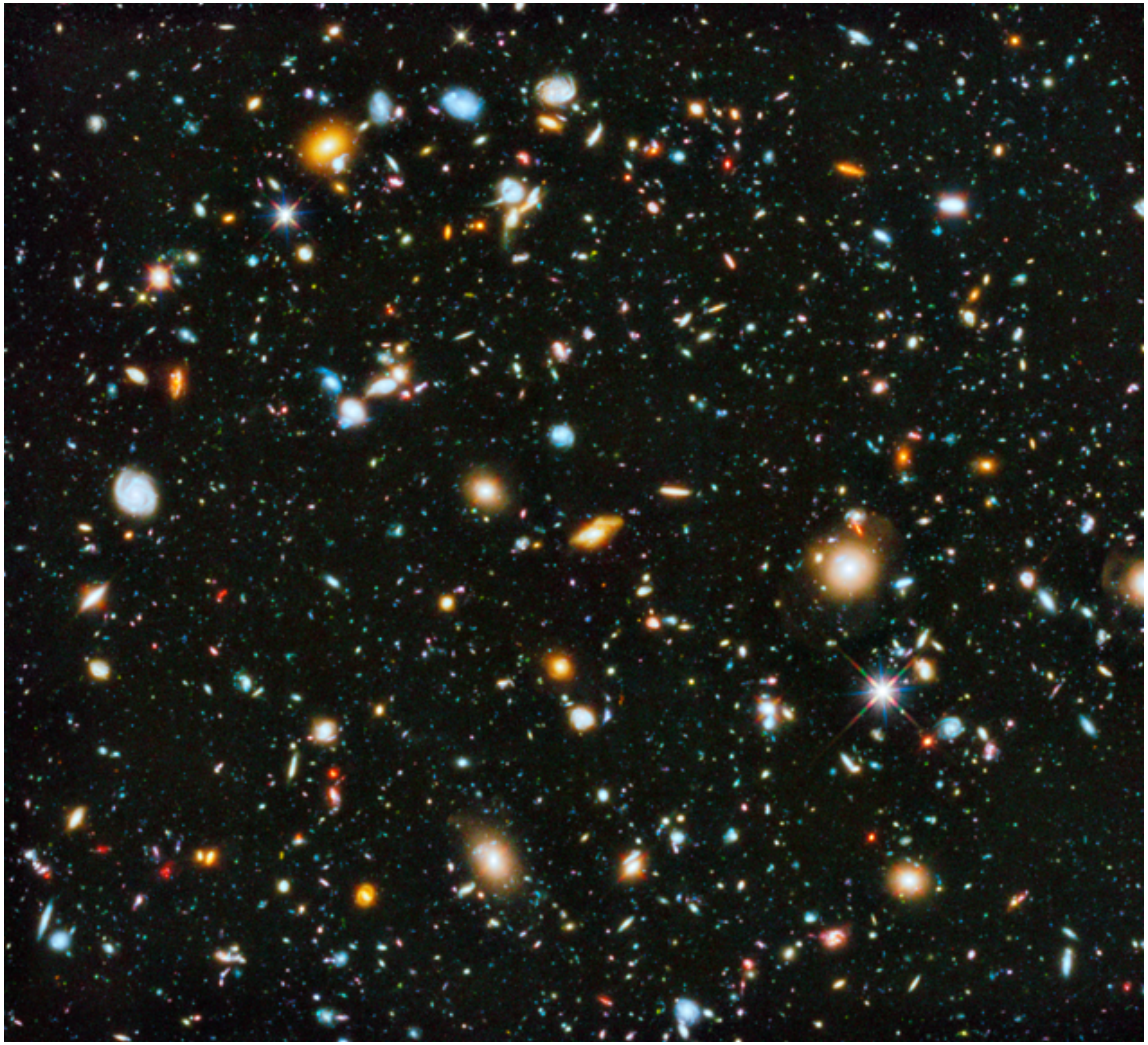
with Sgier
in completion



– This is ready to be applied to data, such as DES

Galaxies Statistics
(2pt and 3pt functions)

alone **1406**
with Angulo, Fasiello, Vlah **1503**
with Lewandowsky *et al* **1512**
with Mauerhofer, Fujita, Vlah **in completion**



History

- Somehow, understanding dark matter has been more challenging than understanding galaxies
  - the Effective description of dark matter endows dark matter with properties that are *emergent* at long distances. Dark matter, in its fundamental description, does not have a speed of sound, a viscosity, etc. .
    - the fact that we could numerically simulate, at least in principle, the fundamental degrees of freedom, *delayed* the development of the EFTofLSS
  - –Now we now that τ_{ij} is a biased tracer of the dark matter field
- The situation is different for galaxies (or halos)
  - the community has always known that we will never simulate galaxies
  - the need for an efficient parametrization of the distribution of galaxies was immediately realized

History

- The concept of bias has been introduced very early on, and the idea of that there are many biases comes similarly from early on.

- Many people gave already important in the story:
  - For example MacDonald, Matsubara,Kaiser, Refregier, Scheth, Scoccimarro, Seljak. …
    - I will not give a complete historical account, but I think they deserve lots of credit

- Three important points were missing until the development of the EFTofLSS:
  - To fully understand all the symmetries and terms
  - To understand how the perturbative structure is organized
  - The theory of dark matter

Galaxies in the EFTofLSS

Senatore **1406**

- The nature of Galaxies is very complicated. If we change the electron mass, the number density of galaxies changes (galaxies are UV sensitive objects).
- So practically impossible to predict

$$n_{\rm gal}(\vec x, t) = f_{\text{very complicated}}\left[\{H(t'), \Omega_{\rm dm}(t'), \ldots, \rho_{\rm dm}(x', t'), \rho_b(x', t'), \ldots, m_e, m_p, g_{ew}, \ldots\}|_{\text{on past light cone}}\right]$$

  - this is what the mass-function approach is trying to do. Impressive results that they get close (to be used as priors?).

- However, if we are interested only on *long-wavelength* properties of $n_{\rm gal}(t)_k$, we realize that the only objects carrying non trivial space dependence are the fluctuating fields, which, *at long-wavelengths*, are small $\Longrightarrow$ we can Taylor expand $f_{\text{very complicated}}$

Galaxies in the EFTofLSS

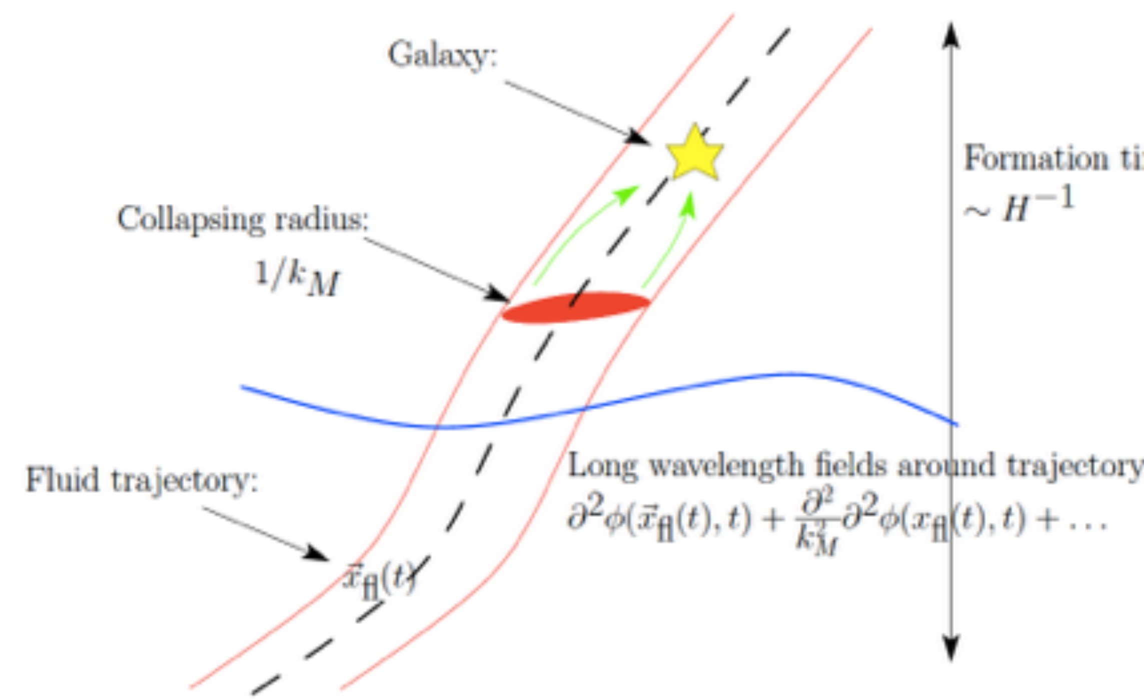
Senatore **1406**

- Therefore

$$n_{\rm gal}(\vec x,t) = f_{\rm very\ complicated}\Big[\{H(t'),\Omega_{\rm dm}(t'),\ldots,\rho_{\rm dm}(x',t'),\rho_b(x',t'),\ldots,m_e,m_p,g_{ew},\ldots\}|_{\text{on past light cone}}$$

$$\Downarrow \quad \text{Taylor Expansion}$$

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



- where $c_i(t,t') = \dfrac{\delta\, n_M(t,k)}{\delta\,\partial^2\phi(t',k)}$

- all terms allowed by symmetries are present

Galaxies in the EFTofLSS

Senatore **1406**

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$$+\bar c_{\epsilon}(t,t')\,\epsilon(\vec x_{\rm fl},t') + \bar c_{\epsilon\partial^2\phi}(t,t')\,\epsilon(\vec x_{\rm fl},t')\frac{\partial^2\phi(\vec x_{\rm fl},t')}{H(t')^2}+\ldots$$
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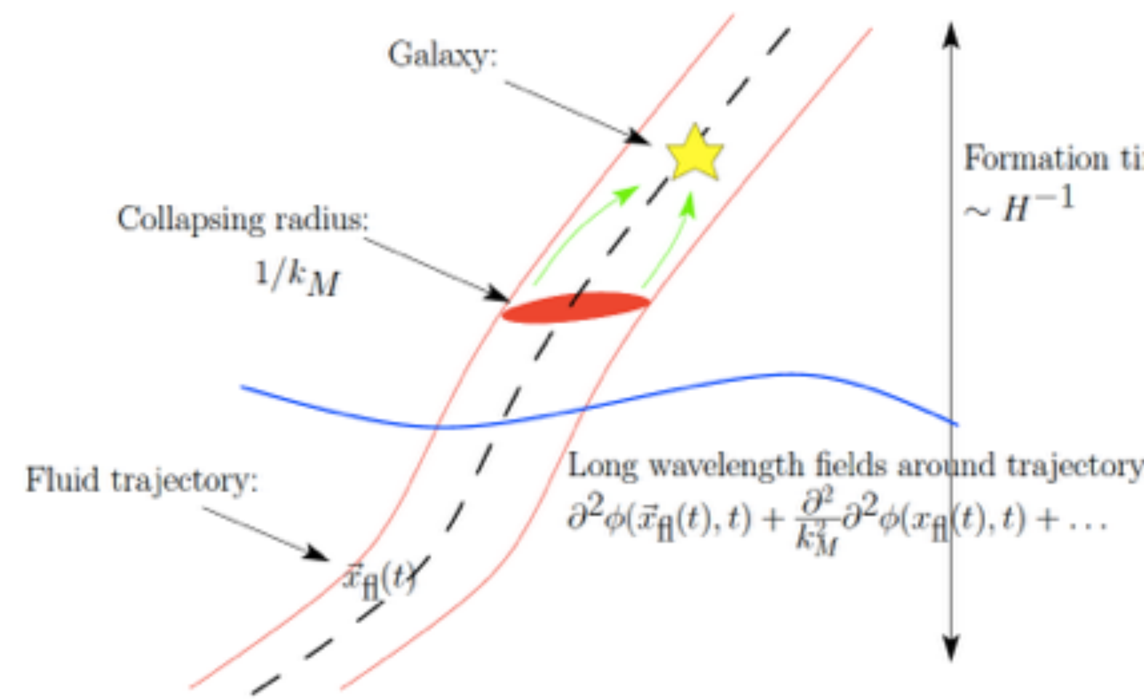

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&+\bar c_\epsilon(t,t')\,\epsilon(\vec x_{\rm fl},t')+\bar c_{\epsilon\partial^2\phi}(t,t')\,\epsilon(\vec x_{\rm fl},t')\frac{\partial^2\phi(\vec x_{\rm fl},t')}{H(t')^2}+\dots\\
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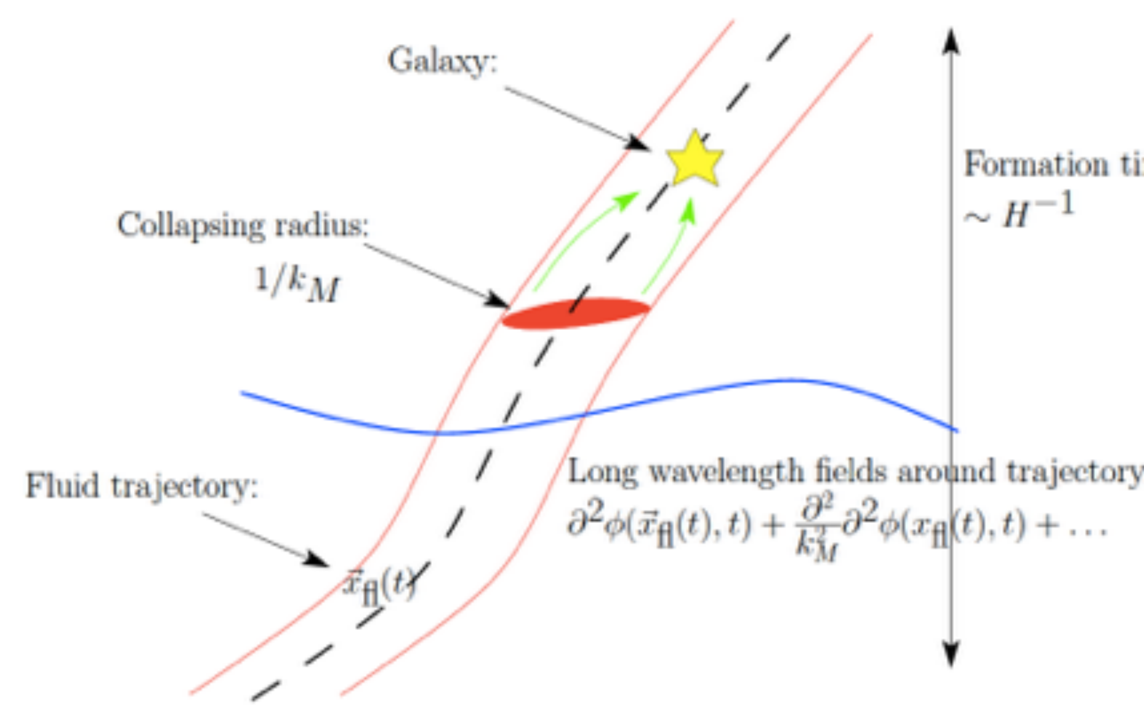

Galaxies in the EFTofLSS

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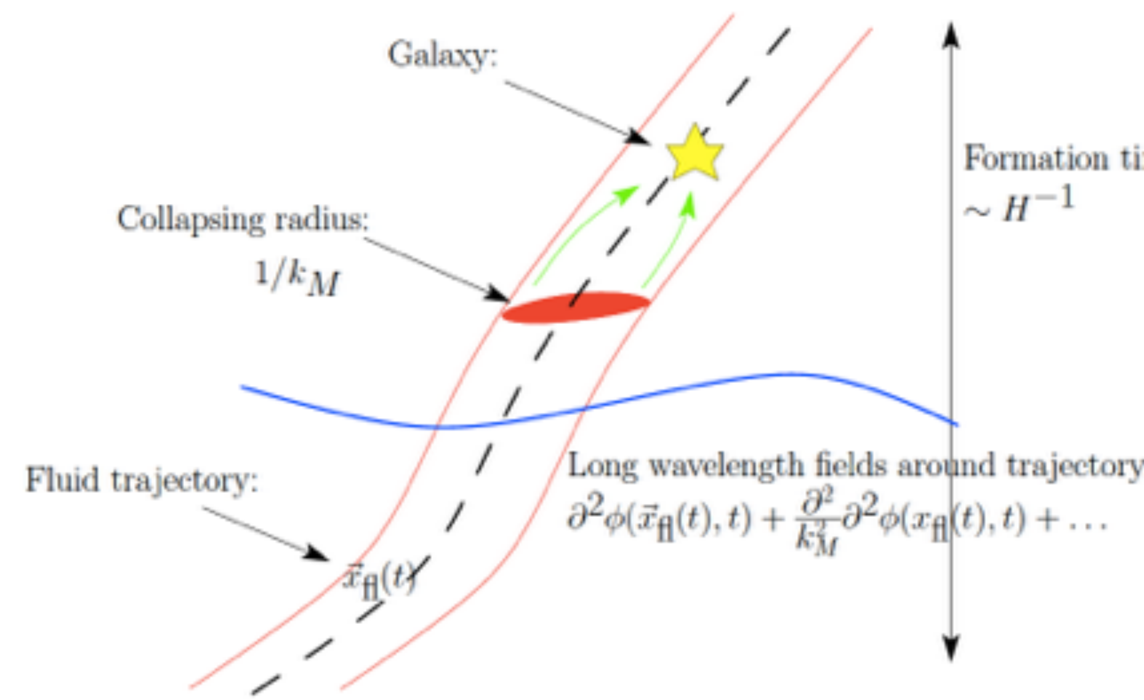


Galaxies in the EFTofLSS

- Non-local in time & local in space (higher derivative terms)

Senatore **1406**

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

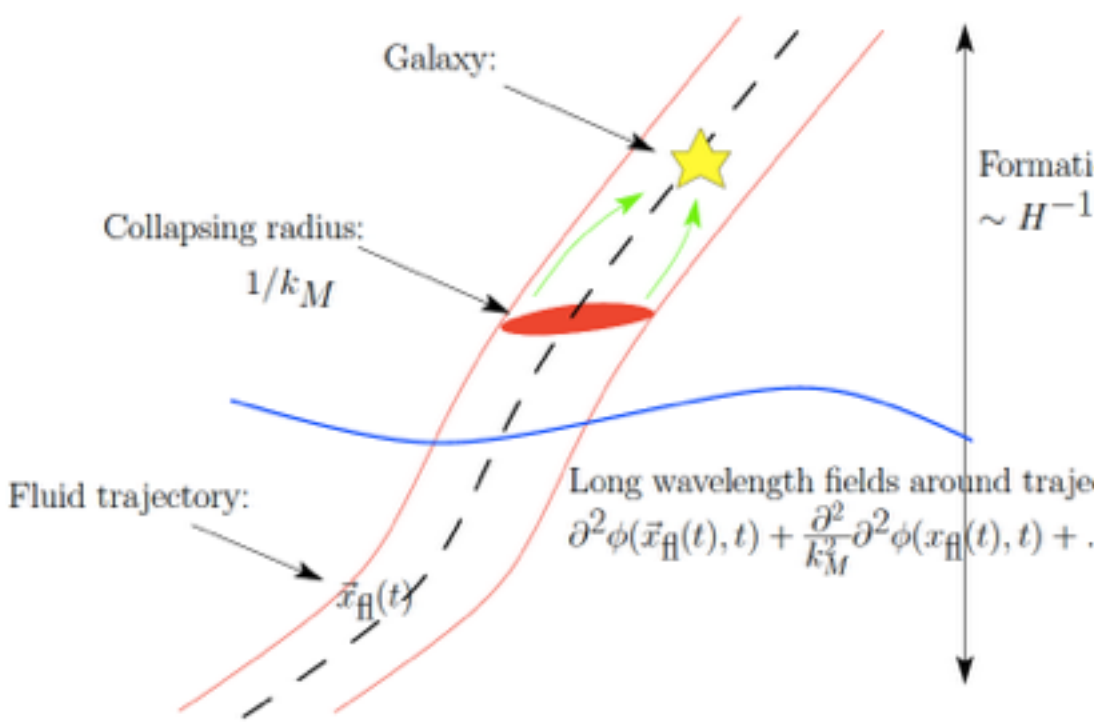
- The theory is non-local in time: the time scale is of order Hubble, which is also the time scale of the long modes $\Rightarrow$ Past integral on the past trajectory $x_{\rm fluid}(t')$
- Since DM particles do not move much, the theory is local in space:
- $\Rightarrow$ collapse affected by restricted region of points:
- we can Taylor expand in the location

dependence on $\partial^2\phi(x)$,

but also on $\dfrac{\partial}{k_M}\partial^2\phi(x)$, $\dfrac{\partial^2}{k_M^2}\partial^2\phi(x), + \dots$

- Derivative expansion controlled by

$\dfrac{1}{k_M^3} \sim M$ which is object (and in particular mass) dependent



Galaxies in the EFTofLSS

- Stochastic terms

Senatore **1406**

$$\delta_M(\vec{x},t) \simeq \int^t dt'\; H(t') \left[\; \bar{c}_\epsilon(t,t')\, \epsilon(\vec{x}_{\rm fl},t') + \bar{c}_{\epsilon\partial^2\phi}(t,t')\, \epsilon(\vec{x}_{\rm fl},t') \frac{\partial^2\phi(\vec{x}_{\rm fl},t')}{H(t')^2} + \ldots \right.$$

- Stochastic terms are present to account for the short modes we are not looking at.
- They are *non-Gaussian* and *combine with other fields into non-linear terms*
- They correlate with the stochastic term from dark matter

$$\langle \epsilon_k \epsilon_{k'} \rangle \sim \delta^{(3)}(k+k') A \;, \qquad \langle \epsilon_k \Delta\tau_{k'} \rangle \sim \delta^{(3)}(k+k') B \left(\frac{k}{k_{\rm NL}}\right)^2$$

Baryons

with Angulo, Fasiello, Vlah **1503**

- Since the dynamics of baryons is described by an EFTofLSS with two species, the galaxies depends on these two fields

$$\delta_h(\mathbf{x},t) \simeq \int^t dt'\; H(t')\; \left[\bar{c}_{\partial^2\phi}(t,t')\,\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \bar{c}_{\delta_b}(t,t')\, w_b\, \delta_b(\mathbf{x}_{{\rm fl}\,b})\right.$$
$$+\bar{c}_{\partial_i v_c^i}(t,t')\; w_c\, \frac{\partial_i v_c^i(\mathbf{x}_{\rm fl,c},t')}{H(t')} + \bar{c}_{\partial_i v_b^i}(t,t')\; w_b\, \frac{\partial_i v_b^i(\mathbf{x}_{\rm fl,b},t')}{H(t')}$$
$$+\bar{c}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\,\frac{\partial_i\partial_j\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2}\frac{\partial^i\partial^j\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \dots$$
$$+\bar{c}_{\epsilon_c}(t,t')\; w_c\,\epsilon_c(\mathbf{x}_{\rm fl,c},t') + \bar{c}_{\epsilon_b}(t,t')\; w_b\,\epsilon_b(\mathbf{x}_{\rm fl,b},t')$$
$$+\bar{c}_{\epsilon_c\partial^2\phi}(t,t')\; w_c\,\epsilon_c(\mathbf{x}_{\rm fl,c},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \bar{c}_{\epsilon_b\partial^2\phi}(t,t')\; w_b\,\epsilon_b(\mathbf{x}_{\rm fl,b},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2}\dots$$
$$\left.+\bar{c}_{\partial^4\phi}(t,t')\;\frac{\partial^2_{x_{\rm fl}}}{{k_{\rm M}}^2}\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \sum_{\sigma,\sigma'=b,c} w_\sigma\, v^i_{\sigma,{\rm CM}}(\mathbf{x}_{{\rm fl}\sigma},t')\frac{\partial_i\delta_{\sigma'}(\mathbf{x}_{{\rm fl}\sigma',t'})}{H} + \dots\right]\,,$$

- Notice
    - doubling of bias parameters, but weighted by w_b
    - presence of velocity

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& + \bar{c}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\,\frac{\partial_i\partial_j\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2}\frac{\partial^i\partial^j\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \dots \\
& + \bar{c}_{\epsilon_c}(t,t')\, w_c\, \epsilon_c(\mathbf{x}_{\rm fl,c},t') + \bar{c}_{\epsilon_b}(t,t')\, w_b\, \epsilon_b(\mathbf{x}_{\rm fl,b},t') \\
& + \bar{c}_{\epsilon_c\partial^2\phi}(t,t')\, w_c\, \epsilon_c(\mathbf{x}_{\rm fl,c},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \bar{c}_{\epsilon_b\partial^2\phi}(t,t')\, w_b\, \epsilon_b(\mathbf{x}_{\rm fl,b},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} \dots \\
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\end{aligned}$$

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& + \bar{c}_{\epsilon_c}(t,t')\,w_c\,\epsilon_c(\mathbf{x}_{\rm fl,c},t') + \bar{c}_{\epsilon_b}(t,t')\,w_b\,\epsilon_b(\mathbf{x}_{\rm fl,b},t') \\
& + \bar{c}_{\epsilon_c\partial^2\phi}(t,t')\,w_c\,\epsilon_c(\mathbf{x}_{\rm fl,c},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \bar{c}_{\epsilon_b\partial^2\phi}(t,t')\,w_b\,\epsilon_b(\mathbf{x}_{\rm fl,b},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2}\dots \\
& + \bar{c}_{\partial^4\phi}(t,t')\,\frac{\partial^2_{x_{\rm fl}}}{{k_{\rm M}}^2}\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \sum_{\sigma,\sigma'=b,c} w_\sigma\, v^i_{\sigma,{\rm CM}}(\mathbf{x}_{{\rm fl}\sigma},t')\frac{\partial_i\delta_{\sigma'}(\mathbf{x}_{{\rm fl}\sigma',t'})}{H} + \dots \Big]\,,
\end{aligned}
$$

- Notice
  - doubling of bias parameters, but weighted by w_b
  - presence of velocity

Primordial Non-Gaussianities

with Angulo, Fasiello, Vlah **1503**

- In the case of primordial non-Gaussianity, the short-mode collapse is controlled not just by the dynamical effects of the long modes, but also by their coupled initial conditions.
- $\Longrightarrow$ Short modes initial conditions are sensitive to the squeezed limit $k_L \ll k_S$,

$$\zeta(\mathbf{k}_S) \simeq \zeta_g(\mathbf{k}_S) + f_{\rm NL}\left(\frac{k_L}{k_S}\right)^{\alpha}\zeta_g(\mathbf{k}_S-\mathbf{k}_L)\zeta_g(\mathbf{k}_L)\ ,$$

$$\Longrightarrow\ \delta^{(1)}(\mathbf{k}_S,t_{\rm in}) \simeq \delta_g(\mathbf{k}_S) + f_{\rm NL}\tilde\phi(\mathbf{k}_L,t_{\rm in})\delta_g(\mathbf{k}_S-\mathbf{k}_L,t_{\rm in})\ ,$$

$$\tilde\phi(k_L,t_{\rm in}) \sim \frac{1}{T(k)}\left(\frac{k_L}{k_S}\right)^{\alpha}\delta_g(k_L,t_{\rm in})$$

- $\Longrightarrow\ \langle\delta_s^2\rangle_l(\mathbf{x}_{\rm in},t_{\rm in}) \supset \langle\delta_s^2\rangle_0(t_{\rm in})f_{\rm NL}\tilde\phi(\mathbf{x}_{\rm in},t_{\rm in})$

$$\Longrightarrow\ \delta_h(\mathbf{x},t) \simeq f_{\rm NL}\ \tilde\phi(\mathbf{x}_{\rm fl}(t,t_{\rm in}),t_{\rm in})\int^t dt'\ H(t')\ \Big[\bar c^{\,\tilde\phi}(t,t') + \bar c^{\,\tilde\phi}_{\partial^2\phi}(t,t')\ \frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2}$$
$$+\bar c^{\,\tilde\phi}_{\partial_i v^i}(t,t')\ \frac{\partial_i v^i(\mathbf{x}_{\rm fl},t')}{H(t')} + \bar c^{\,\tilde\phi}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\ \frac{\partial_i\partial_j\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2}\frac{\partial^i\partial^j\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} +$$
$$+\bar c^{\,\tilde\phi}_{\epsilon}(t,t')\ \epsilon(\mathbf{x}_{\rm fl},t') + \bar c^{\,\tilde\phi}_{\epsilon\partial^2\phi}(t,t')\ \epsilon(\mathbf{x}_{\rm fl},t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \dots$$
$$+\bar c^{\,\tilde\phi}_{\partial^4\phi}(t,t')\ \frac{\partial^2_{x_{\rm fl}}}{{k_{\rm M}}^2}\frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \dots\Big]$$
$$+{f_{\rm NL}}^2\ \tilde\phi(\mathbf{x}_{\rm fl}(t,t_{\rm in}),t_{\rm in})^2\int^t dt'\ H(t')\ \Big[\bar c^{\,\tilde\phi^2}(t,t') + \bar c^{\,\tilde\phi^2}_{\partial^2\phi}(t,t')\ \frac{\partial^2\phi(\mathbf{x}_{\rm fl},t')}{H(t')^2} + \dots\Big] +$$

Primordial Non-Gaussianities

with Angulo, Fasiello, Vlah **1503**

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$$\Longrightarrow \quad \delta_h(\mathbf{x}, t) \simeq f_{\rm NL}\, \tilde\phi(\mathbf{x}_{\rm fl}(t, t_{\rm in}), t_{\rm in}) \int^t dt'\ H(t')\ \Big[\bar c^{\,\tilde\phi}(t, t') + \bar c^{\,\tilde\phi}_{\partial^2\phi}(t, t')\ \frac{\partial^2\phi(\mathbf{x}_{\rm fl}, t')}{H(t')^2}$$
$$+\bar c^{\,\tilde\phi}_{\partial_i v^i}(t, t')\ \frac{\partial_i v^i(\mathbf{x}_{\rm fl}, t')}{H(t')} + \bar c^{\,\tilde\phi}_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t, t')\ \frac{\partial_i\partial_j\phi(\mathbf{x}_{\rm fl}, t')}{H(t')^2}\frac{\partial^i\partial^j\phi(\mathbf{x}_{\rm fl}, t')}{H(t')^2} +$$
$$+\bar c^{\,\tilde\phi}_{\epsilon}(t, t')\ \epsilon(\mathbf{x}_{\rm fl}, t') + \bar c^{\,\tilde\phi}_{\epsilon\partial^2\phi}(t, t')\ \epsilon(\mathbf{x}_{\rm fl}, t')\frac{\partial^2\phi(\mathbf{x}_{\rm fl}, t')}{H(t')^2} + \ldots$$
$$+\bar c^{\,\tilde\phi}_{\partial^4\phi}(t, t')\ \frac{\partial^2_{x_{\rm fl}}}{{k_{\rm M}}^2}\frac{\partial^2\phi(\mathbf{x}_{\rm fl}, t')}{H(t')^2} + \ldots\Big]$$
$$+{f_{\rm NL}}^2\ \tilde\phi(\mathbf{x}_{\rm fl}(t, t_{\rm in}), t_{\rm in})^2 \int^t dt'\ H(t')\ \Big[\bar c^{\,\tilde\phi^2}(t, t') + \bar c^{\,\tilde\phi^2}_{\partial^2\phi}(t, t')\ \frac{\partial^2\phi(\mathbf{x}_{\rm fl}, t')}{H(t')^2} + \ldots\Big] +$$

Novel functional form non-compatible with GR

Primordial Non-Gaussianities

with Angulo, Fasiello, Vlah **1503;**

- Ref. Assassi et al **1506,** Assassi et al **1509,** with Lewandowsky *et al* **1512** included in this formalism

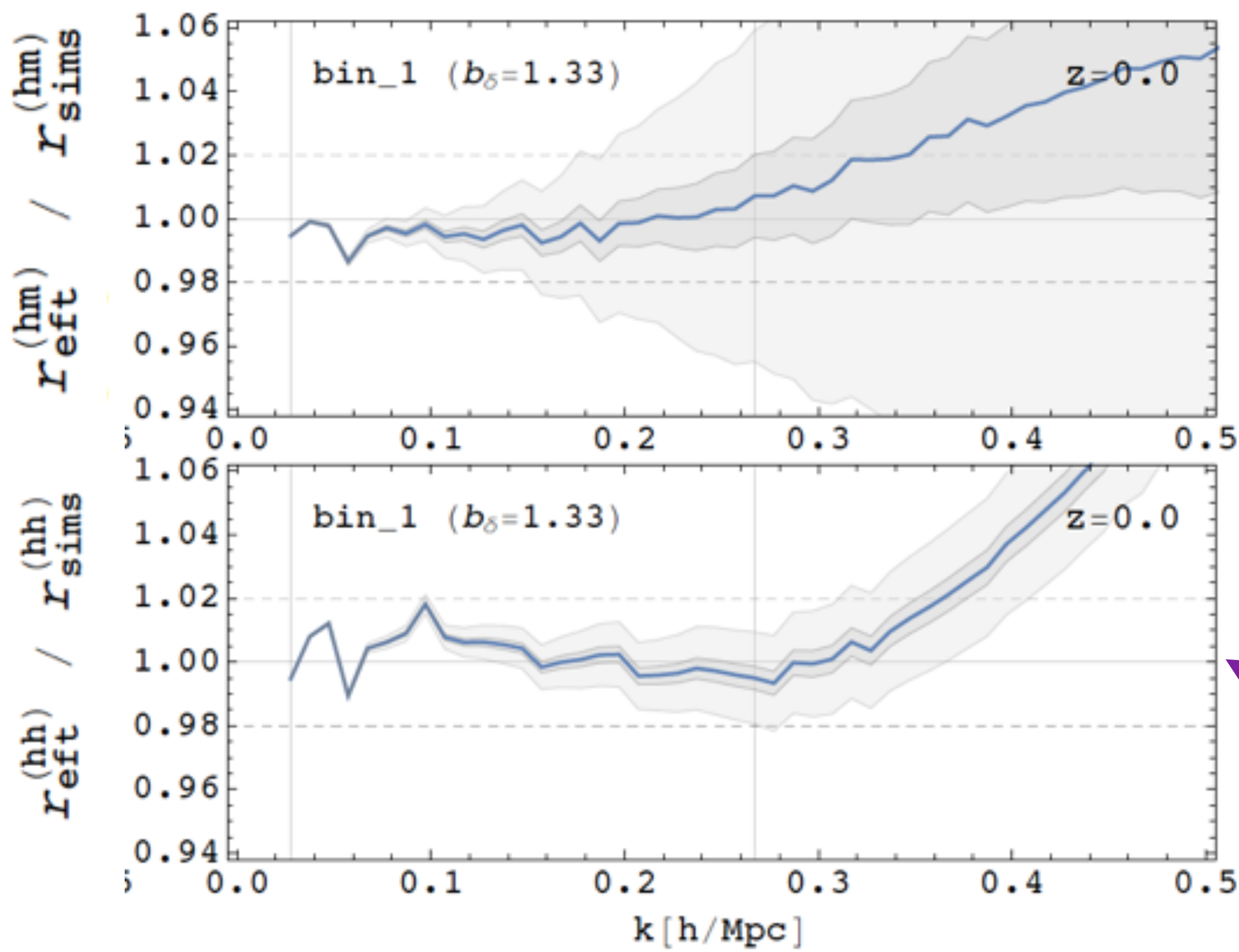
anisotropic initial squeezed limits

$$\zeta(\mathbf{k}_S) \simeq \zeta_g(\mathbf{k}_S) + f_{\rm NL}\left(\frac{k_L}{k_S}\right)^{\alpha}\zeta_g(\mathbf{k}_S-\mathbf{k}_L)\zeta_g(\mathbf{k}_L)\ , \Rightarrow \quad \zeta^s_{NG}(\vec x) \simeq \zeta^s_g(\vec x) + f_{\rm NL}\int_{\vec k}\int_{\vec p} W(\vec k,\vec p)\,\zeta^s_g(\vec p)\,\zeta^l_g(\vec k)\,e^{i\vec x\cdot(\vec k+\vec p}$$

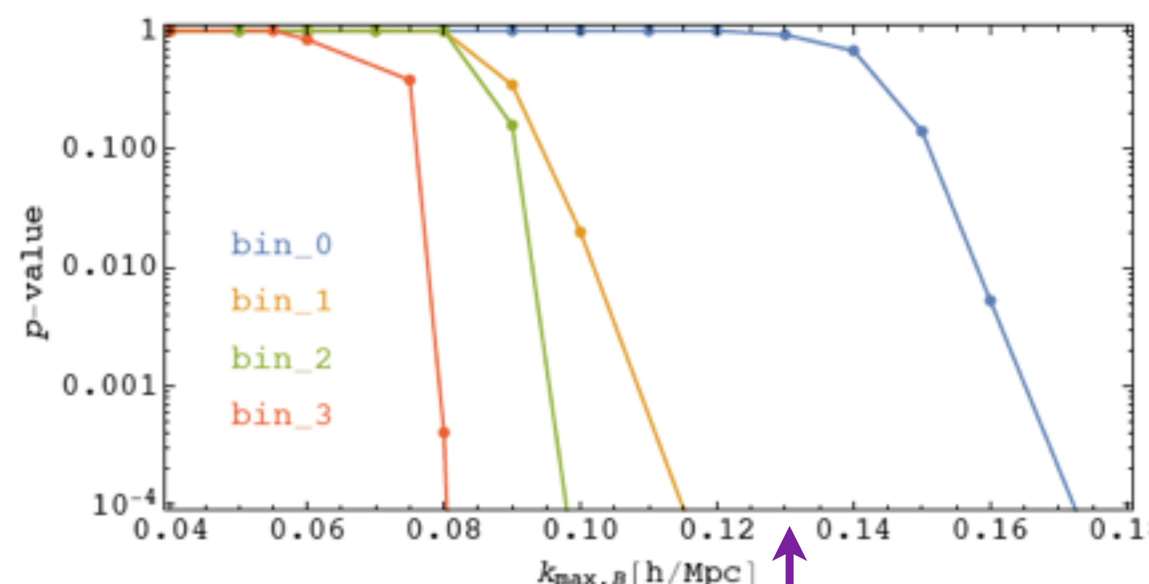
Halos in the EFTofLSS

with Angulo, Fasiello, Vlah **1503**

- Back to Halos with Gaussian initial conditions
- We compare $P_{hh}^{1-\mathrm{loop}}\,,\ P_{hm}^{1-\mathrm{loop}}\,,\ B_{hhh}^{\mathrm{tree}}\,,\ B_{hhm}^{\mathrm{tree}}\,,\ B_{hmm}^{\mathrm{tree}}$ 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)
  - To me, not so many parameters



2pt

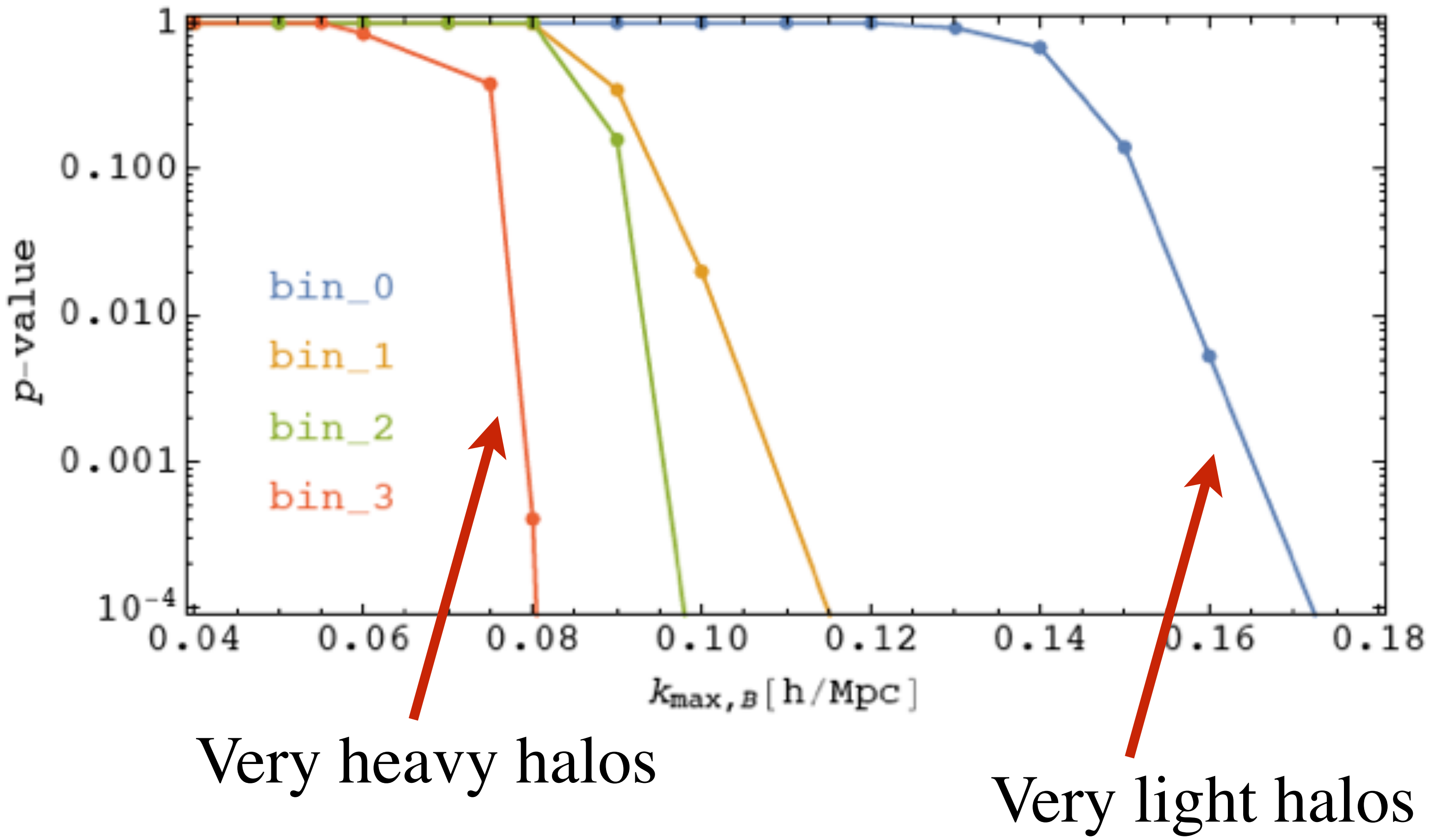


3pt

Halos in the EFTofLSS

with Mauerhofer, Fujita, Vlah **in completion**

- Notice the peculiarity

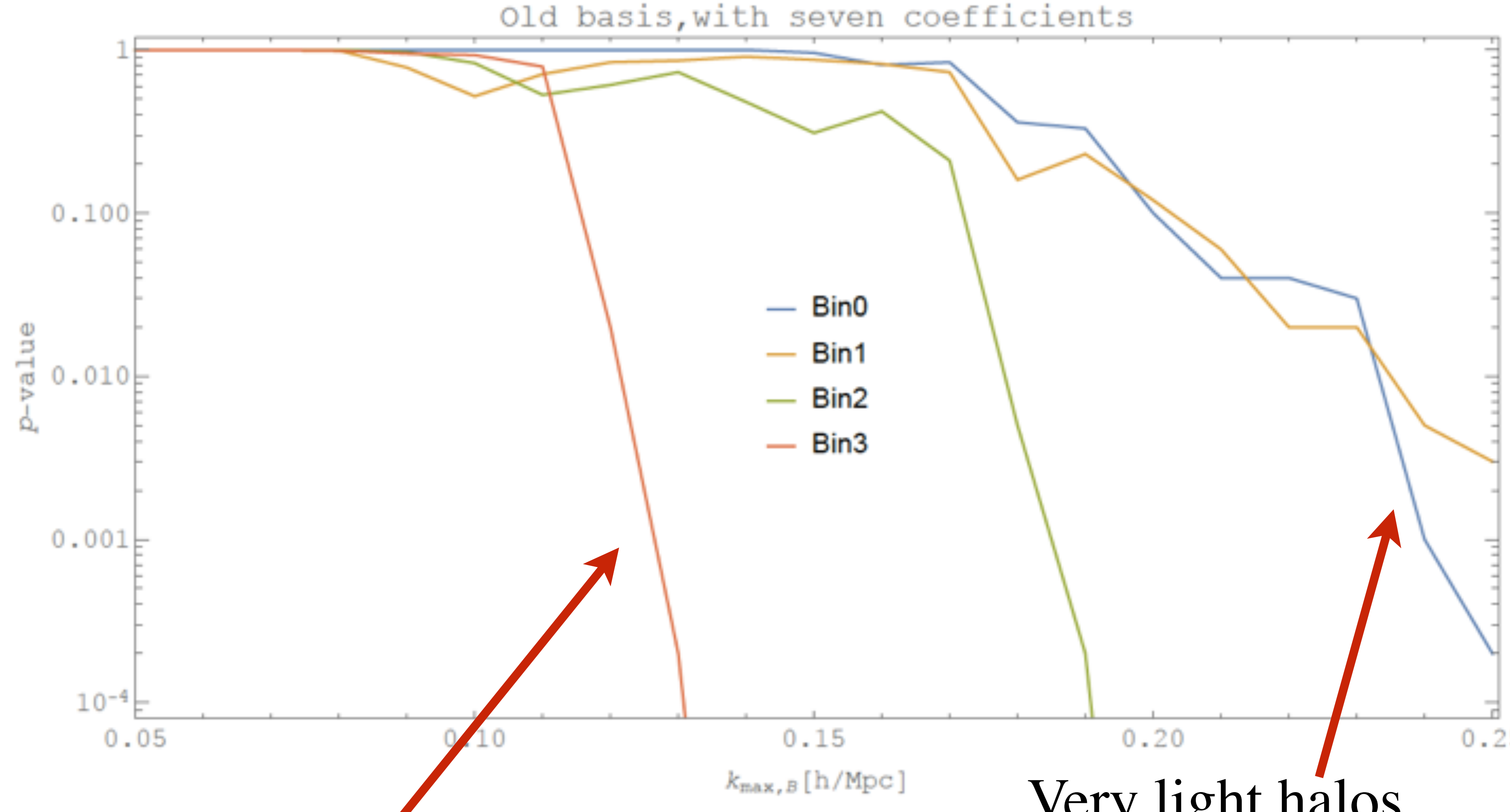


- Two Mistakes

Halos in the EFTofLSS

with Mauerhofer, Fujita, Vlah **in completion**

- Notice the peculiarity



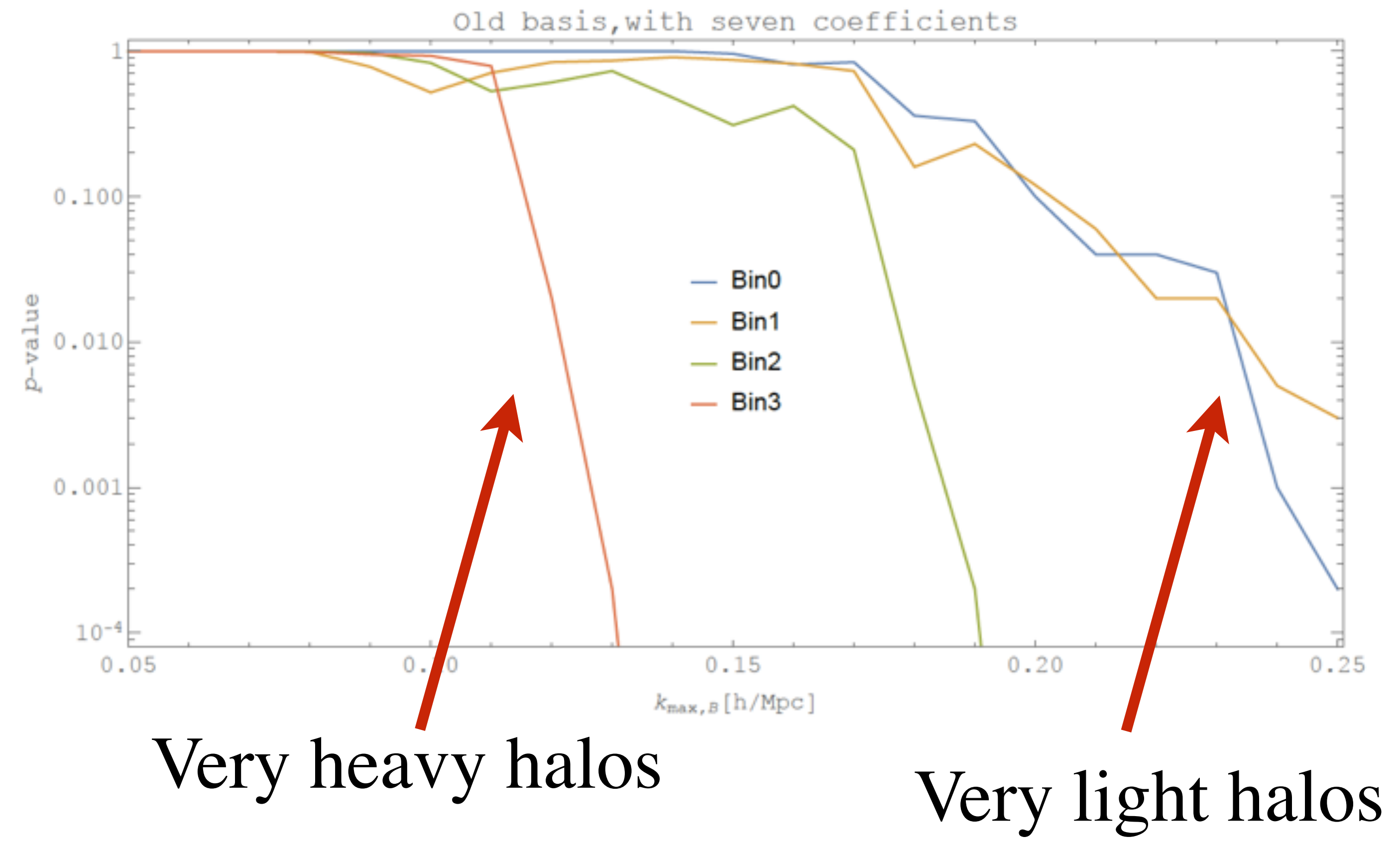
Very heavy halos

Very light halos

- Two mistakes
  - First: Missed a factor of 2 in $\langle \delta_h^3 \rangle$
    - apologies
    - now theory performs much better $0.15\, h\, \mathrm{Mpc}^{-1} \;\rightarrow\; 0.2\, h\, \mathrm{Mpc}^{-1}$
      - as for any correct theory

Halos in the EFTofLSS

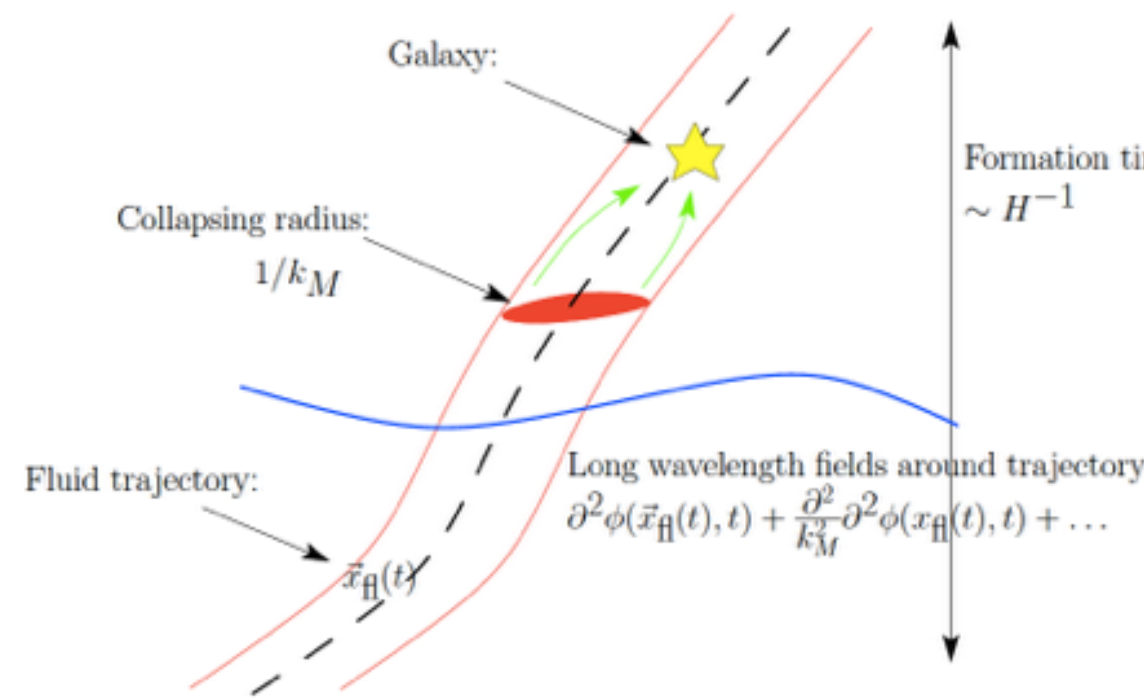
with Mauerhofer, Fujita, Vlah **in completion**



- Two mistakes
  - Second: we are expanding in

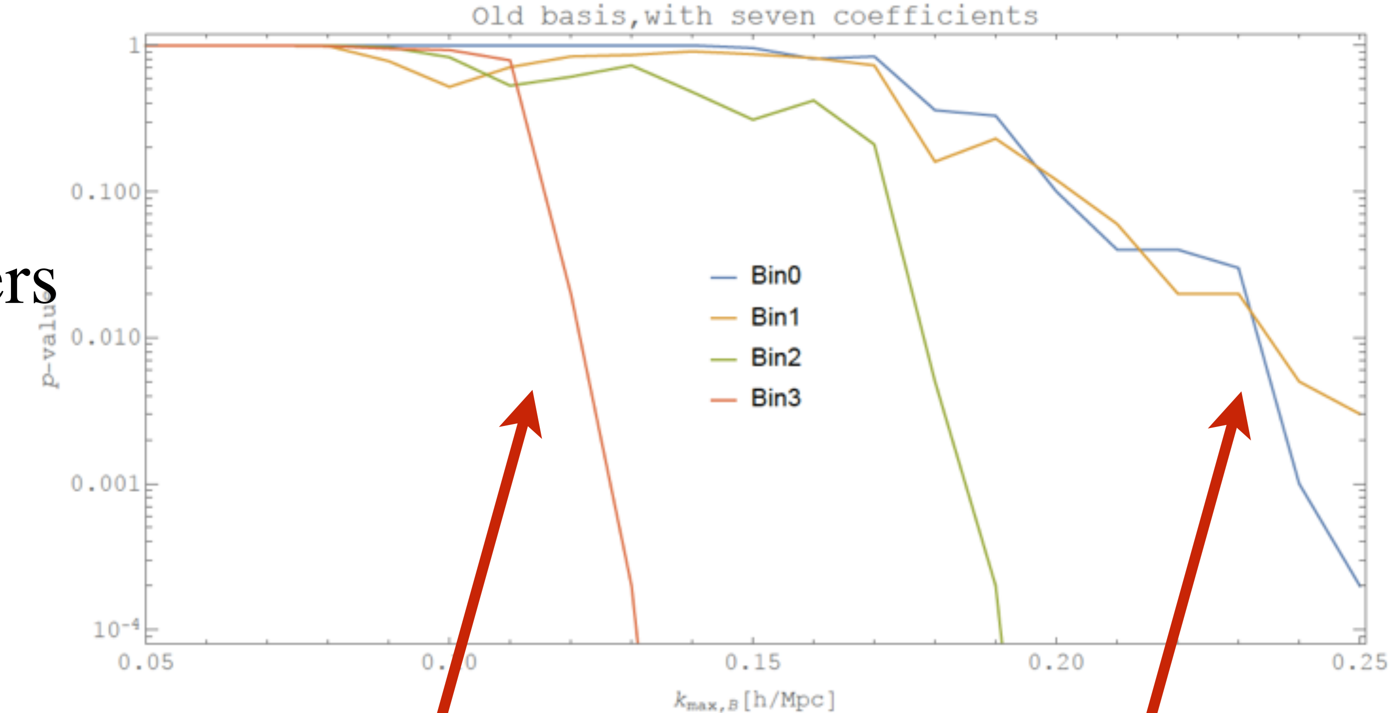
$$\left[\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}}\right]_k \quad \& \quad \frac{k}{k_M}$$

  - Prediction: for a given order in $\left[\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}}\right]_k$, heavier tracers should fail at same k as light tracers
    - by just adding higher derivative biases:
      - ex: $b_{\partial^2\delta}\dfrac{\partial^2}{k_M^2}\delta$
      - as this is a stronger `coupling constant’



Halos in the EFTofLSS

with Mauerhofer, Fujita, Vlah **in completion**



Very heavy halos

Very light halos

- Two mistakes
  - Second: we are expanding in

$$\left[\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}}\right]_k \propto \frac{k}{k_M}$$

This is much larger for heavy tracers

  - Prediction: for a given order in $\left[\frac{\delta\rho_{\rm dm}}{\rho_{\rm dm}}\right]_k$, heavier tracers should fail at same k as light tracers
    - by just adding higher derivative biases:
      - ex: $b_{\partial^2\delta}\dfrac{\partial^2}{k_M^2}\delta$
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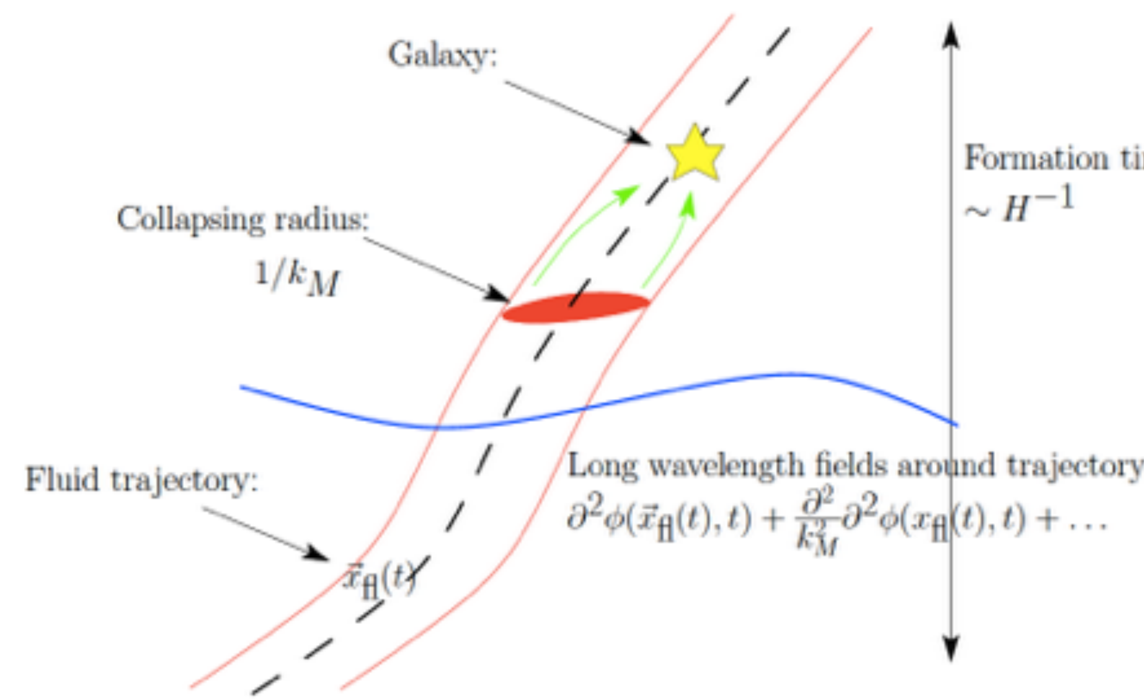
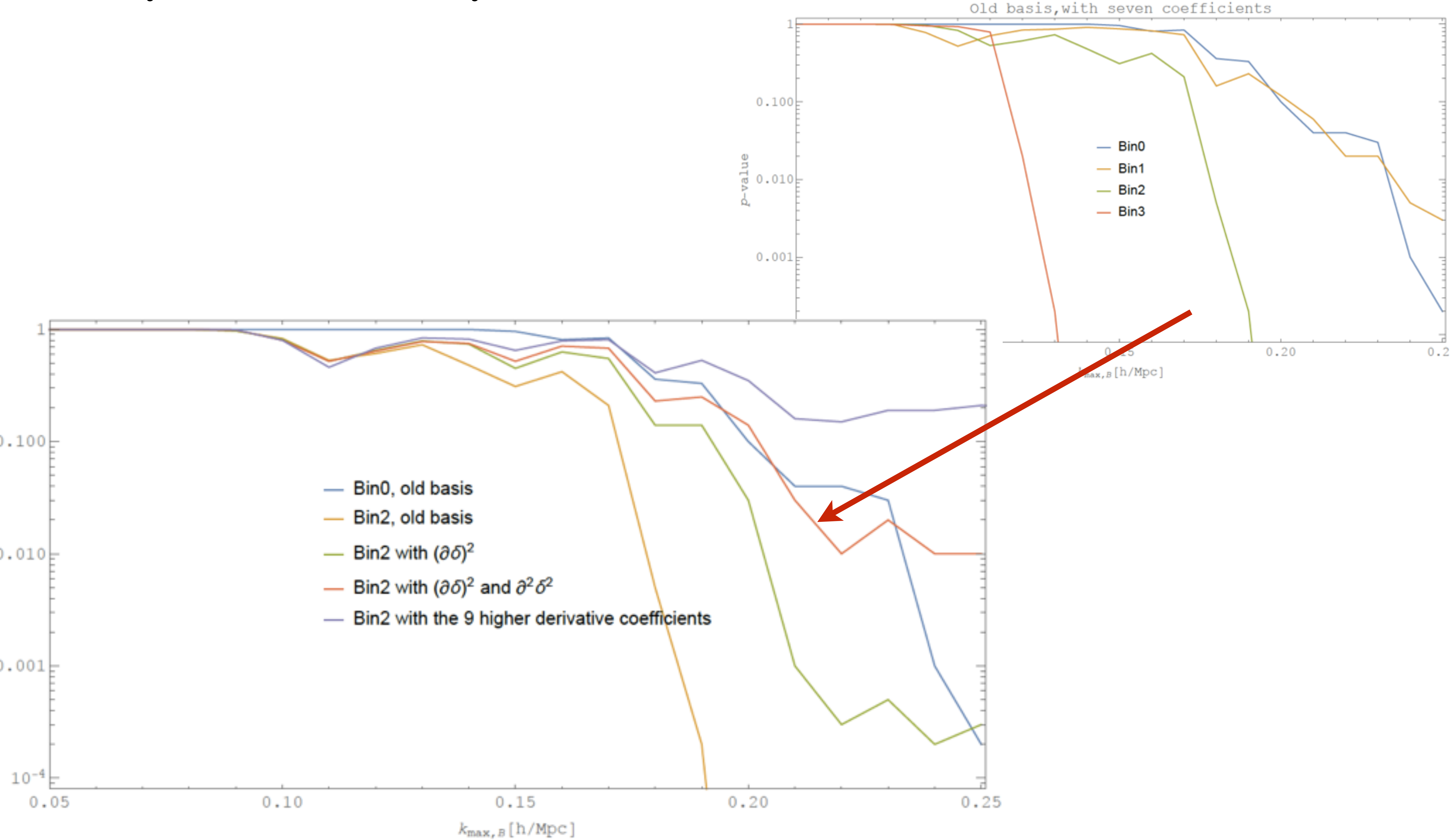


Halos in the EFTofLSS

with Mauerhofer, Fujita, Vlah **in progress**

- At next order EFT allows for 9 additional biases

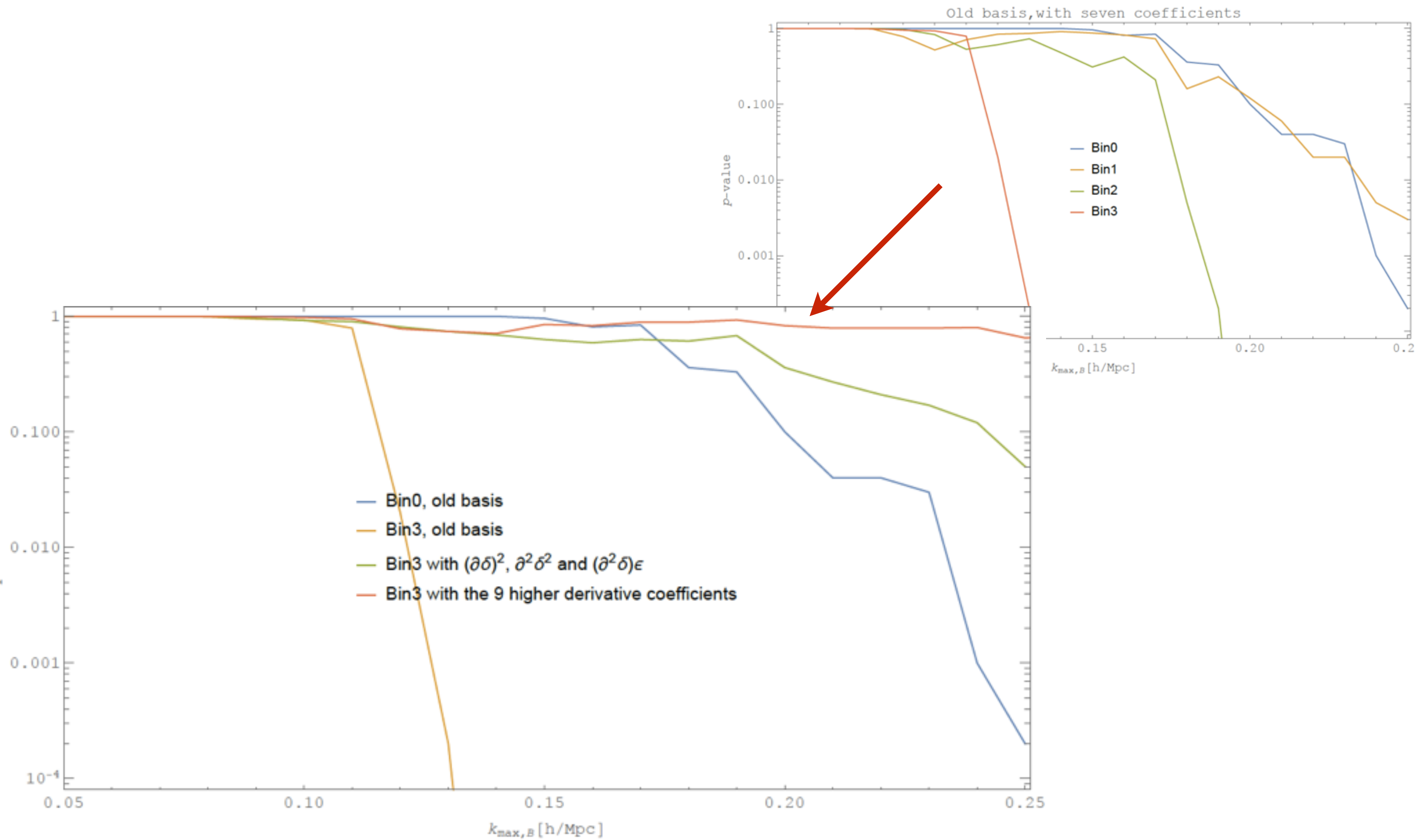
- but only 1 or 2 are necessary for bin2 to fail where bin0 (with these numerical data)



Halos in the EFTofLSS

with Mauerhofer, Fujita, Vlah **in progress**

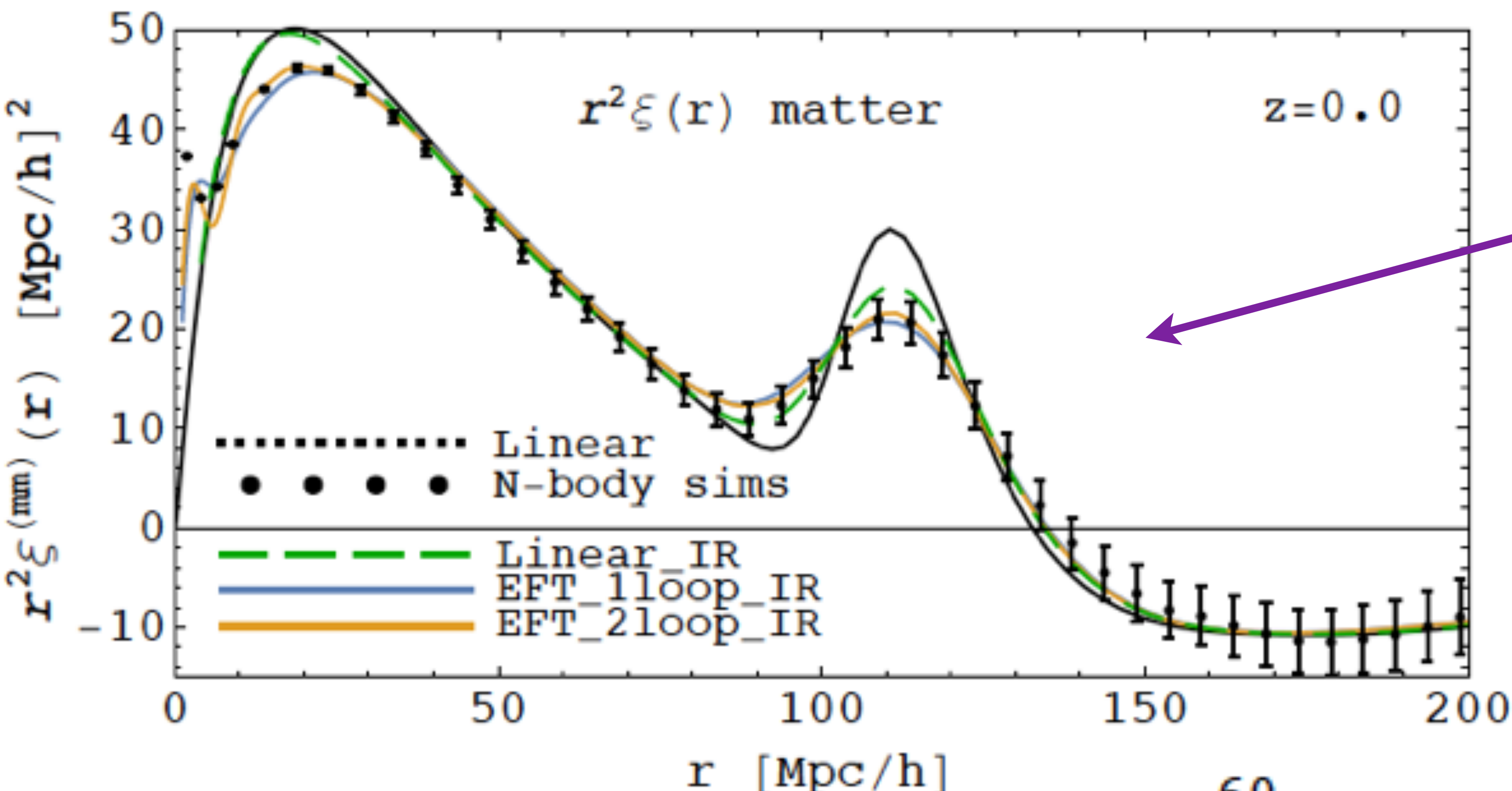
- Same story for bin3 (needs 3 higher derivative biases)



Halos in the EFTofLSS

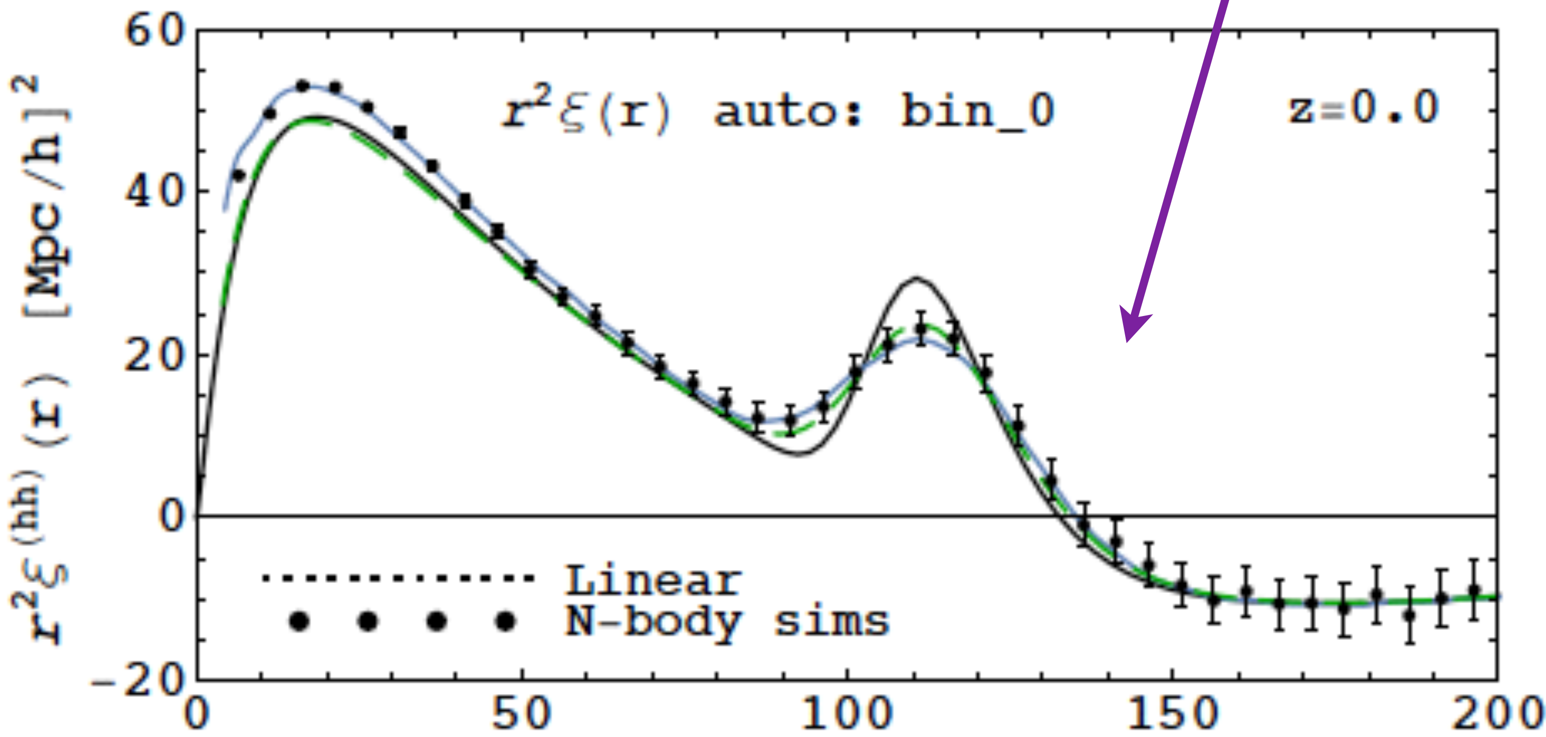
sentore **1406**
with Angulo, Fasiello, Vlah **1503**

- Real space & the BAO feature: IR-resummation works (no velocity bias possible)



Dark Matter

Halos



Redshift space

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

EFTofLSS in Redshift Space

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

- When we look at objects, the distance coordinate is given by redshift, which is also affected by the local velocity. So, we need to perform a change of coordinates that depends of the velocity of the galaxies.

$$\vec{x}_r = \vec{x} + \frac{\hat{z} \cdot \vec{v}}{aH} \hat{z}$$

- Due to the Jacobian, we get

$$\rho_r(x) \sim \rho(x)(1 + \partial v(x)) \quad \Rightarrow \quad [\rho(x)\partial v(x)]_q \sim \int d^3k \; \rho_k [\partial v]_{q-k} \quad \Rightarrow \quad \text{Need renormalization}$$

  - same story repeats

Counterterms

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

- Need for counterterms (expectation value on short modes)

$$\delta_r(\vec{k}) \simeq \delta(\vec{k}) - i\frac{k_z}{aH} v_z(\vec{k}) + \frac{i^2}{2}\left(\frac{k_z}{aH}\right)^2 [v_z^2]_{\vec{k}} - \frac{i^3}{3!}\left(\frac{k_z}{aH}\right)^3 [v_z^3]_{\vec{k}} + \dots$$

$$[v_z^2]_{R,\vec{k}} = [v_z^2]_{\vec{k}} + \left(\frac{aH}{k_{\rm NL}^r}\right)^2 \left[c_{11}\delta_D^{(3)}(\vec{k}) + \left(c_{12} + c_{13}\mu^2\right)\delta(\vec{k})\right]$$

- Baryons: double the fields

$$[v_{c,z}^2]_{R,\vec{k}} = [v_{c,z}^2]_{\vec{k}} + w_b c_{11}^c [v_{c,z} v_{b,z}]_{\vec{k}} + w_b^2 c_{12}^c [v_{b,z}^2]_{\vec{k}} + \left(\frac{aH}{k_{\rm NL}^r}\right)^2 \left[\left(c_{13}^c + c_{14}^c\mu^2\right)\delta_c(\vec{k}) + w_b\left(c_{15}^c + c_{16}^c\mu^2\right)\delta_b(\vec{k})\right]$$

- Primordial NG: add additional field

$$[v_z^2]_{R,\vec{k}}\ ,\ [v_z^2\delta]_{R,\vec{k}} \supset \hat{z}_i\hat{z}_j \left(\frac{aH}{k_{\rm NL}}\right)^2 \sum_n \left[c_1^n \delta^{ij}\tilde{\phi}(\vec{k})_{0,n} + c_2^n \tilde{\phi}(\vec{k})_{2,n}^{ij}\right]$$

$$\sim \frac{1}{k^2 T(k, t_{in})} \times \sum_n \left(c_1^n \left(\frac{k}{k_{\rm NL}}\right)^{\Delta_{0,n}} + c_2^n \left(\frac{k}{k_{\rm NL}}\right)^{\Delta_{2,n}} \mathcal{P}_2(\mu_k)\right)\delta_g(\vec{k}, t_{\rm in})$$

– notice that in redshift space, high spin object contributes at linear level

Counterterms

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

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expectation value response

- Baryons: double the fields

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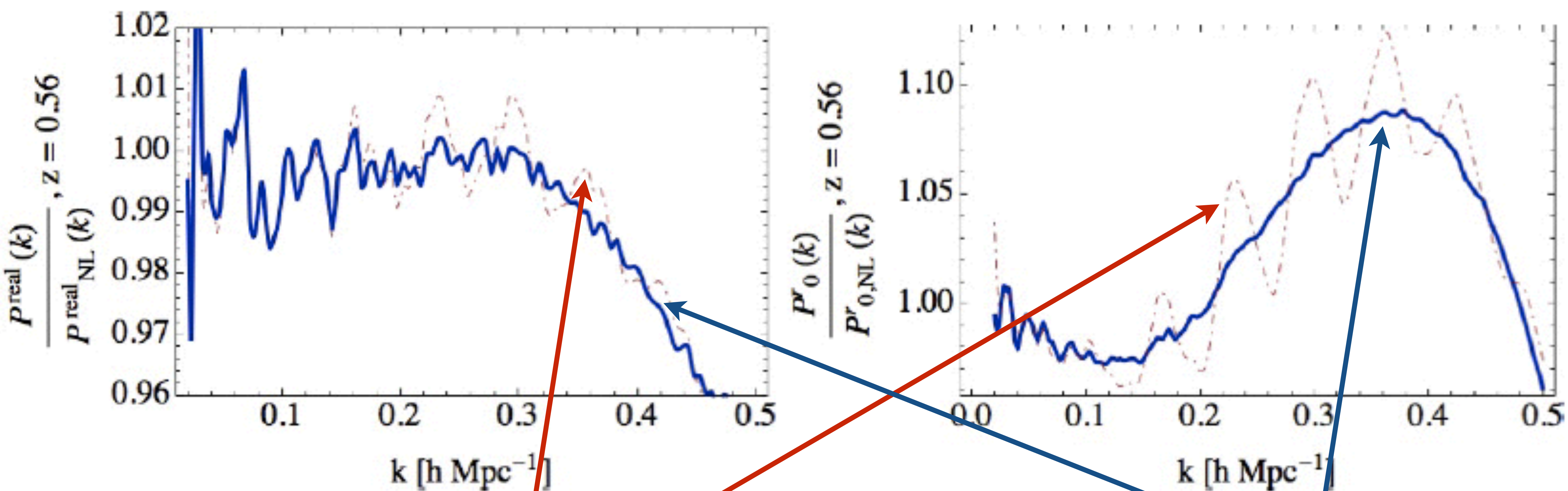
– notice that in redshift space, high spin object contributes at linear level

BAO in Redshift Space

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

- Due to lack of rotational symmetry, naive implementation of IR-resummation numerically more challenging
- Some algebraic tricks and controlled expansions leads to rather simple expression
- It works beautifully



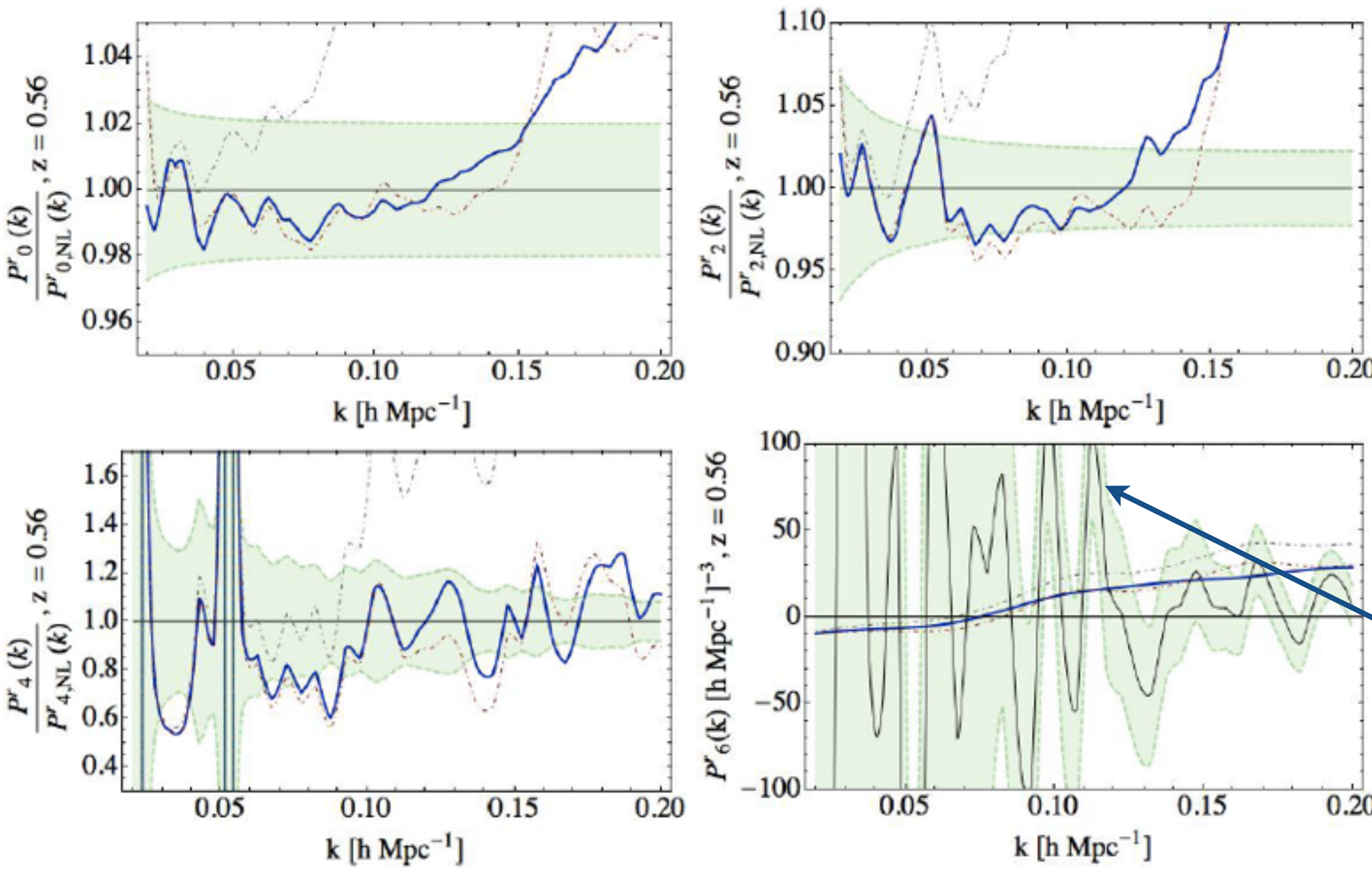
After resummation: no residuals

Before resummation: residual oscillations

k-reach

with Lewandowsky *et al* **1512**

- at 1-loop, prediction up to ell=8
- k-reach seems somewhat low
- not sure why yet: maybe higher derivative terms, hard to tell: numerical data really really noisy



Seems Errors are above cosmic variance

In 2 minutes on our laptops
(Efficient Exploration of Cosmologies)

with Cataneo and Foreman **in completion**

Fast Evaluation

with Cataneo and Foreman **in completion**

- We can use a trick
- If $$P_{2\text{ loops}} = \int d^3k\, p_{\text{integrant}}(k) P_{11}(k)^3$$
- Then $$P_\alpha^{\text{target}}(k) = P_\alpha^{\text{ref}}(k) + \Delta P_\alpha(k)$$

$$\Delta P_\alpha(k) \equiv \int \mathrm{d}^3\boldsymbol{q}_1 \ldots \mathrm{d}^3\boldsymbol{q}_n \left[P^{\text{target}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \ldots, \boldsymbol{q}_n) - P^{\text{ref}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \ldots, \boldsymbol{q}_n)\right]$$

Fast Evaluation

with Cataneo and Foreman **in completion**

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- If $$P_{2\text{ loops}} = \int d^3k\; p_{\text{integrant}}(k) P_{11}(k)^3$$
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$$\Delta P_\alpha(k) \equiv \int \mathrm{d}^3\boldsymbol{q}_1 \dots \mathrm{d}^3\boldsymbol{q}_n \left[P^{\text{target}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \dots, \boldsymbol{q}_n) - P^{\text{ref}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \dots, \boldsymbol{q}_n) \right]$$

Small integral that can be evaluated with low precision $\epsilon_{\text{target}} \approx \epsilon_\Delta \left| \frac{\Delta \tilde{P}_\alpha}{P_\alpha^{\text{target}}} \right|$

$$\epsilon_\Delta \ll \epsilon_{\text{target}}$$

Fast Evaluation

with Cataneo and Foreman **in completion**

- We can use a trick
- If $$P_{2\text{ loops}} = \int d^3k \; p_{\text{integrant}}(k) P_{11}(k)^3$$
- Then
$$P_\alpha^{\text{target}}(k) = P_\alpha^{\text{ref}}(k) + \Delta P_\alpha(k)$$

$$\Delta P_\alpha(k) \equiv \int \mathrm{d}^3\boldsymbol{q}_1 \ldots \mathrm{d}^3\boldsymbol{q}_n \left[P^{\text{target}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \ldots, \boldsymbol{q}_n) - P^{\text{ref}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \ldots, \boldsymbol{q}_n)\right]$$

Small integral that can be evaluated with low precision $\epsilon_{\text{target}} \approx \epsilon_\Delta \left|\dfrac{\Delta \tilde{P}_\alpha}{P_\alpha^{\text{target}}}\right|$

$\epsilon_\Delta \ll \epsilon_{\text{target}}$

- Even better

$$\Delta \tilde{P}_\alpha(k) \equiv \qquad (2.$$
$$\int \mathrm{d}^3\boldsymbol{q}_1 \ldots \mathrm{d}^3\boldsymbol{q}_n \left[P^{\text{target}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \ldots, \boldsymbol{q}_n) - \left(\frac{A_s^{\text{target}}}{A_s^{\text{ref}}}\right)^{L+1} P^{\text{ref}}_{\alpha,\text{integrand}}(\boldsymbol{k}, \boldsymbol{q}_1, \ldots, \boldsymbol{q}_n)\right]$$

- It produces PEFT2loops in ~2 minutes in a laptop with better than 1% precision

Exploration of cosmologies

with Cataneo and Foreman **in completion**

- All allowed cosmologies are very nearby (1-10%)
- We can taylor expand the power spectra around Planck-cosmology:
  - need to evaluate just the derivatives!

$$P_\alpha(k) \approx P_\alpha(k)|_{\boldsymbol{\theta}^{\rm ref}} + \sum_i \Delta\theta_i \left.\frac{\partial P_\alpha(k)}{\partial\theta_i}\right|_{\boldsymbol{\theta}=\boldsymbol{\theta}^{\rm ref}} + \frac{1}{2}\sum_{i,j}\Delta\theta_i\Delta\theta_j \left.\frac{\partial^2 P_\alpha(k)}{\partial\theta_i\,\partial\theta_j}\right|_{\boldsymbol{\theta}=\boldsymbol{\theta}^{\rm ref}}$$

$$c_s = c_s|_{\theta_{\rm ref}} + \sum_i \Delta\theta_i \left.\frac{\partial c_s}{\partial\theta}\right|_{\theta_{\rm ref}} + \dots$$

  - it works: with ~100 evaluations, we get all the LambdaCDM parameter space to within 3σ from Planck
  - A mathematica notebook spits the result out in no time.

A Plea for Public Codes

- This fast code and the Taylor expansion notebook will be publicly available.

- I believe that the task in front of us is strenuous enough that all codes should be publicly shared (with honorable citations given): we cannot waste time in repeating other's people calculation.

  - We got a great lesson from CMBFAST. Let us not forget and continue in those steps.

Dark Energy in the EFTofLSS

with Lewandowsky and Maleknejad **in completion**

Dark Energy in the EFTofLSS

- We know the equations of motion for dark energy.
  - This is the Effective Field Theory for Dark Energy

with Creminelli, Luty, Nicolis **0606**
Creminelli, D'Amico, Norena, Vernizzi **0811**
Giubitosi, Piazza, Vernizzi **0912**

$$S_G = \int d^4x\sqrt{-g}\left\{\frac{M_*^2}{2}f(t)R - \Lambda(t) - c(t)g^{00}\right\} + S_{DE}^{(2)}$$

- A lot of work was done at linear level

see **Silvestri**

- Now that we know how to do computations for dark matter, we can compute the effect of dark energy on the quasi linear regime

- Most interesting regime is clustering dark energy

$$c_s \to 0 \ \& \ \delta_Q^{(1)} \sim (1+w)\delta_{\rm dm}^{(1)}$$

see for ex. with Creminelli, D'amico, Vernizzi **0911**

- It is very easy now to do the one-loop calculation,
  - it is even more easy for this system: isocurvature mode decays, and we have

$$a\mathcal{H}\delta_A' + C(a)\theta = -\alpha\delta_A\theta$$

$$a\mathcal{H}\theta' + \mathcal{H}\theta + \frac{3}{2}\mathcal{H}_0^2\frac{a_0}{a}\Omega_m\delta_A = -\beta\theta\theta + \text{counterterms}$$

$$C(a) = 1 + (1+w)\frac{\Omega_Q}{\Omega_m}\left(\frac{a}{a_0}\right)$$

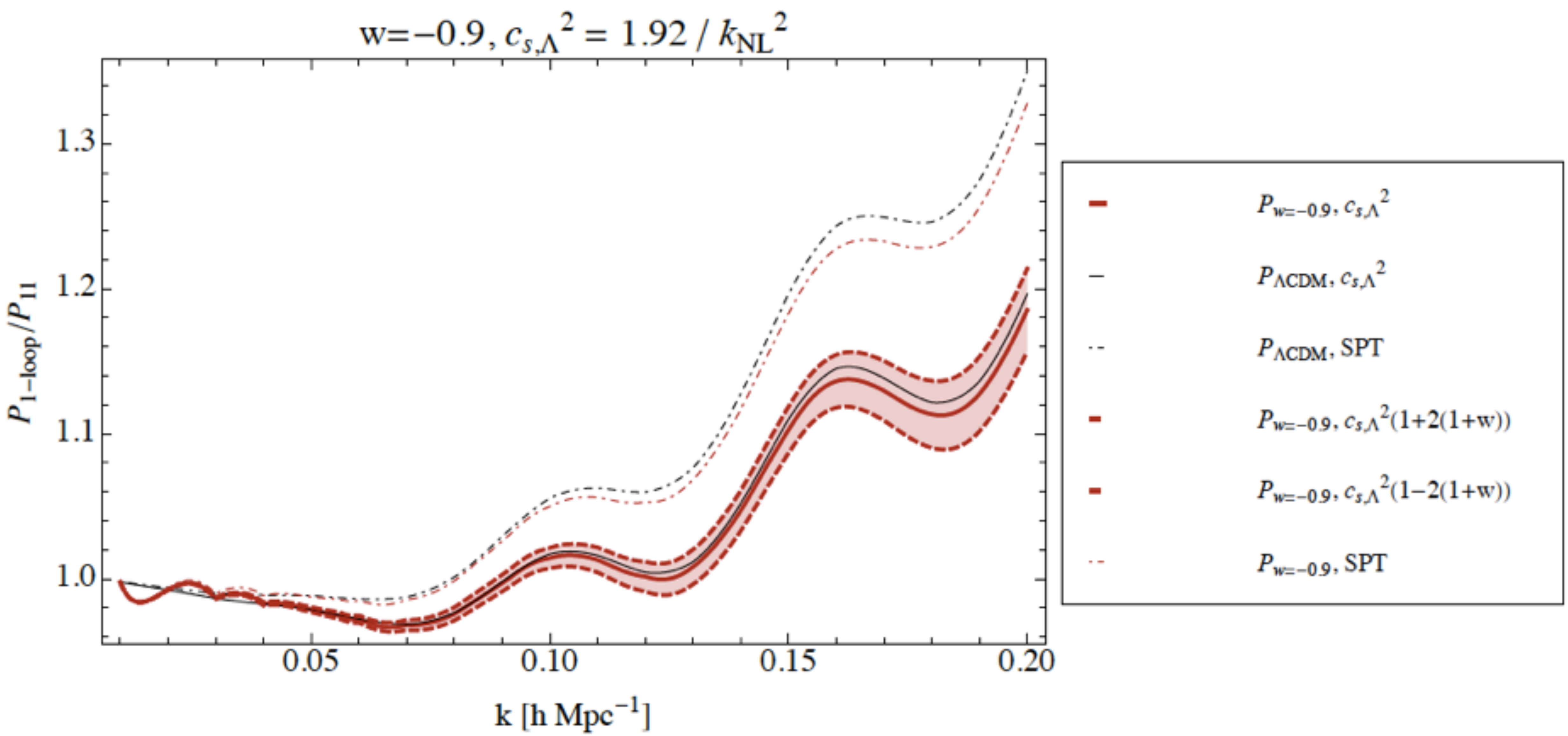
Dark Energy in the EFTofLSS

- Easy to solve at 1-loop

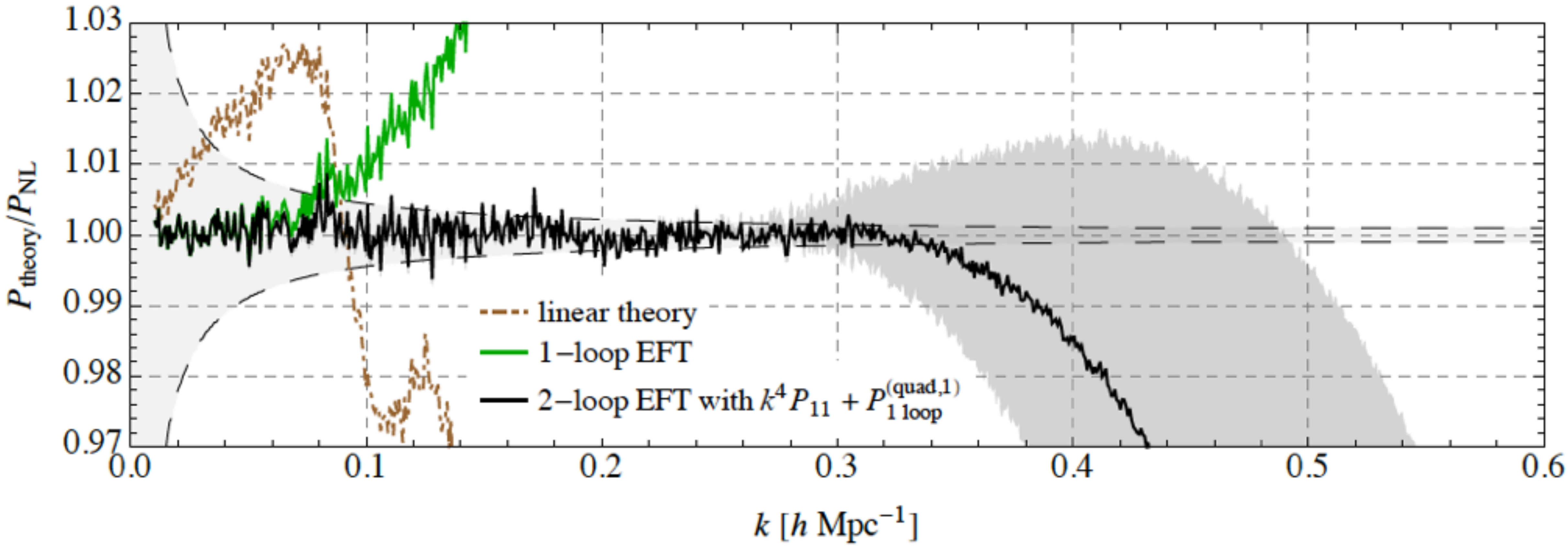
$$a\mathcal{H}\delta'_A + C(a)\theta = -\alpha\delta_A\theta$$

$$a\mathcal{H}\theta' + \mathcal{H}\theta + \frac{3}{2}\mathcal{H}_0^2\frac{a_0}{a}\Omega_m\delta_A = -\beta\theta\theta + \text{counterterms}$$

- with exact time dependence



The EFT of Large Scale Structures

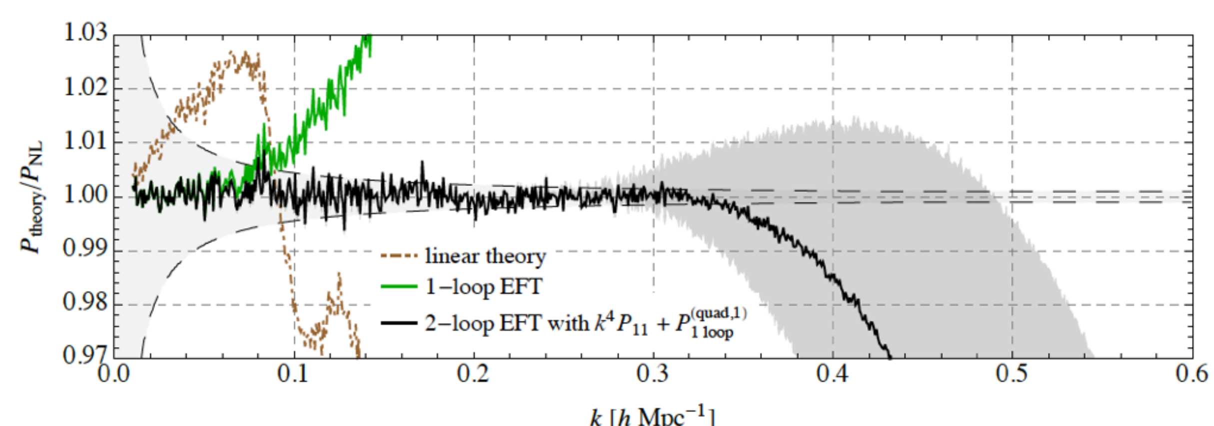


- A manifestly well-defined perturbation theory $\left(\frac{k}{k_{\rm NL}}\right)^L$
- we match until $k \sim 0.3\, h\, {\rm Mpc}^{-1}$, as where we should stop fitting
  - –there are ~10^2 more quasi linear modes than previously believed!
  - –huge impact on possibilities, for ex: $f_{\rm NL}^{\rm equil.,\, orthog.} \lesssim 1$, neutrinos, dark energy.
- This is an huge opportunity and a challenge for us.

with Baldauf et al **1603**
for some conservative forecasts

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
- Many calculations and verifications to do
  - applied to dark matter, tracers, redshift space, baryons and nn-gaussianities
- Huge opportunity for complementarity with simulations
  - –Maybe do simulations focused to convey the EFT parameters.
- If success continues, larger hope to be able to make progress in next decade in early universe cosmology



$$S_\pi = \int d^4x\, \sqrt{-g}\left[M_{\rm Pl}^2 \dot H (\dot\pi^2 - (\partial_i\pi)^2) + M_2^4\left(\dot\pi^2 + \dot\pi^3 - \dot\pi(\partial_i\pi)^2\right) - M_3^4\dot\pi^3 + \dots\right]$$