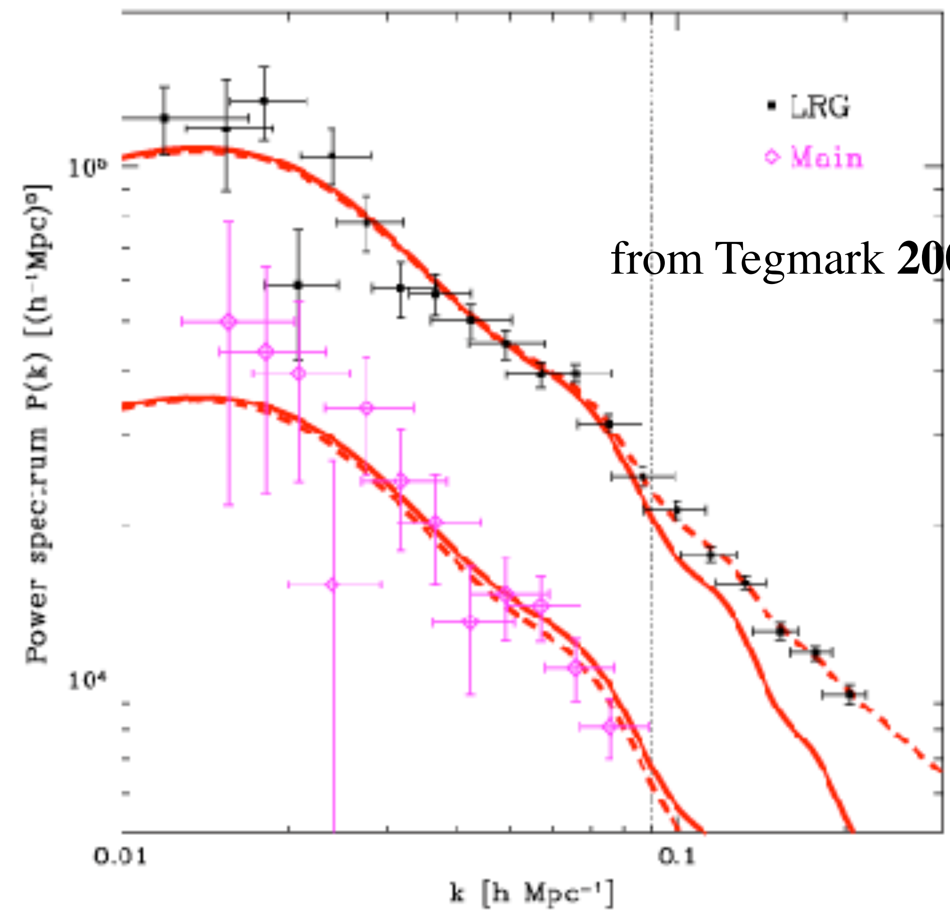
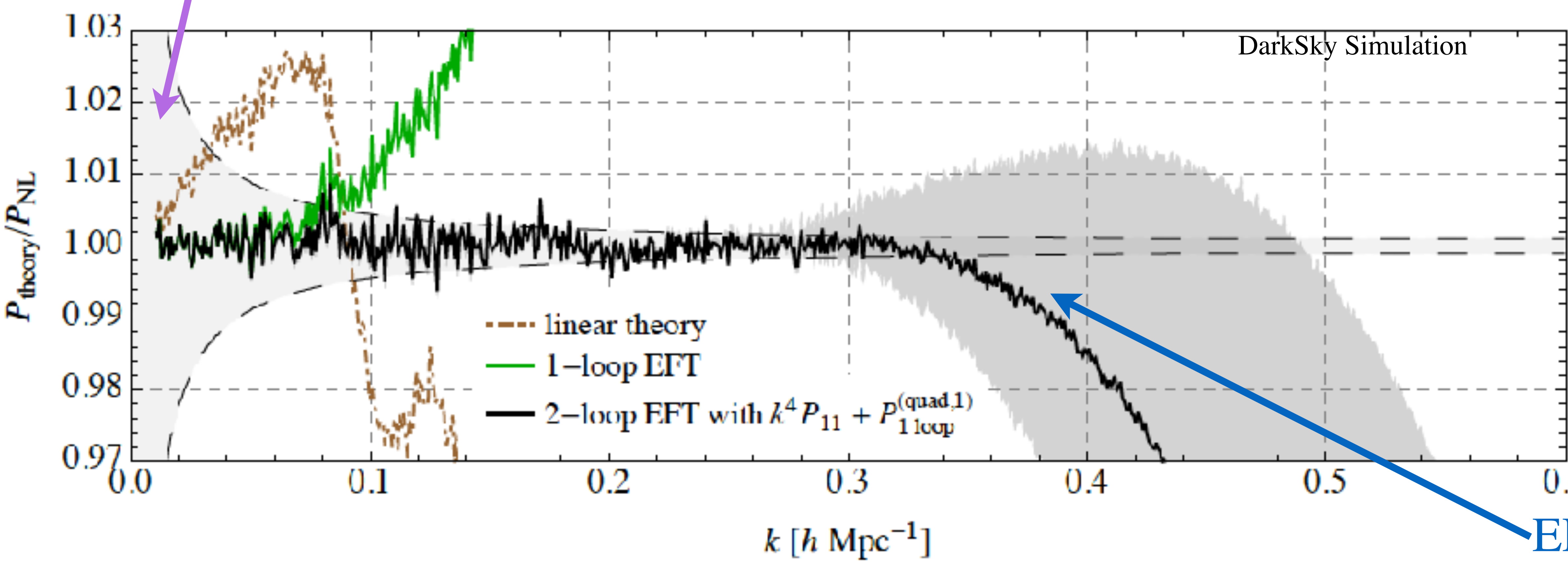
Results for Dark Matter

Dark Matter 2-pt function

- Precise Comparison of power spectra

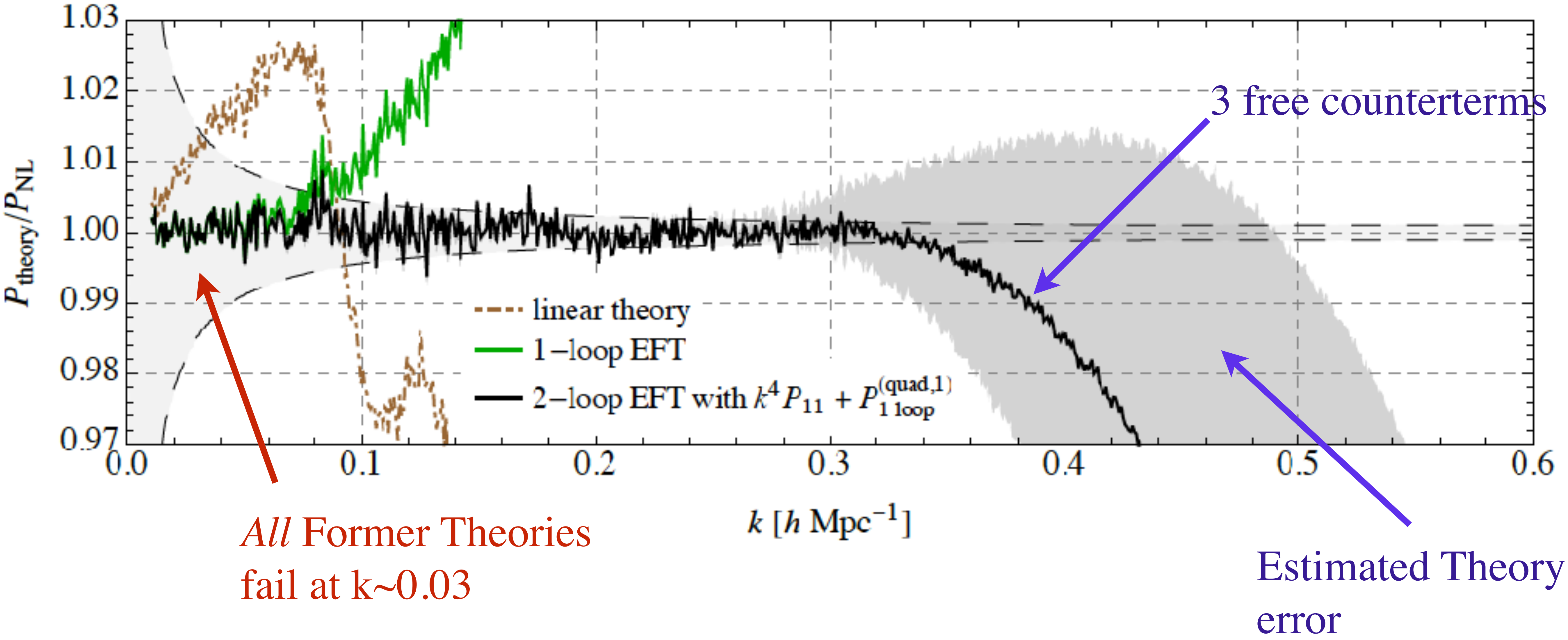


Precision comparison



EFTofLSS

EFT of Large Scale Structures at Two Loops



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

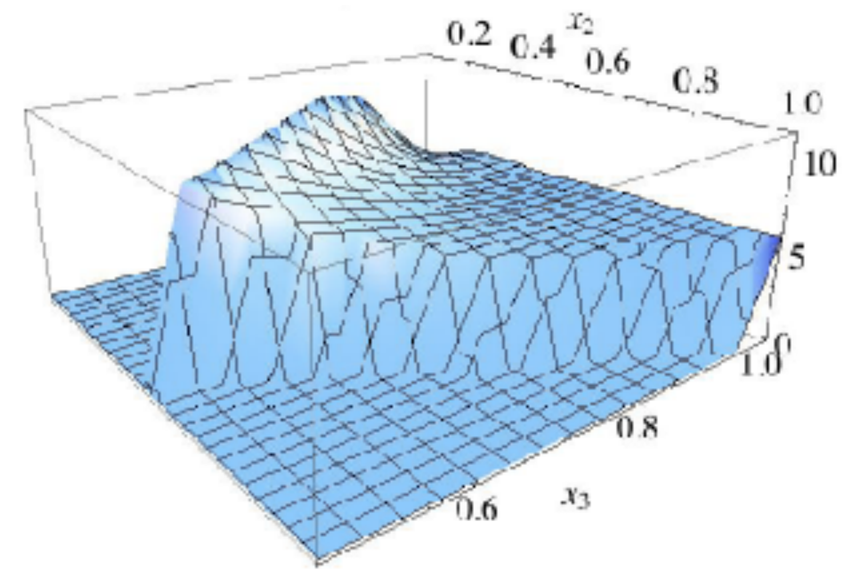
with Carrasco, Foreman and Green **JCAP1407**
with Zaldarriaga **JCAP1502**
with Foreman and Perrier **1507**
see also Baldauf, Shaan, Mercolli and Zaldarriaga **1507, 1507**

Other Observables

– Since this is a theory and not a model

  – predictions for other observables from same parameters

– 3point function



  – very non-trivial function of three variables!

with Angulo, Foreman and Schmittful **1406**
see also Baldauf et al. **1406**

– Momentum

  – They all work as they should

with Carrasco, Foreman and Green **JCAP 1407**
Baldauf, Mercolli and Zaldarriaga **1507**

– Vorticity Spectrum

with Carrasco, Foreman and Green **JCAP1407**

  – agrees with most accurate measurements in simulations

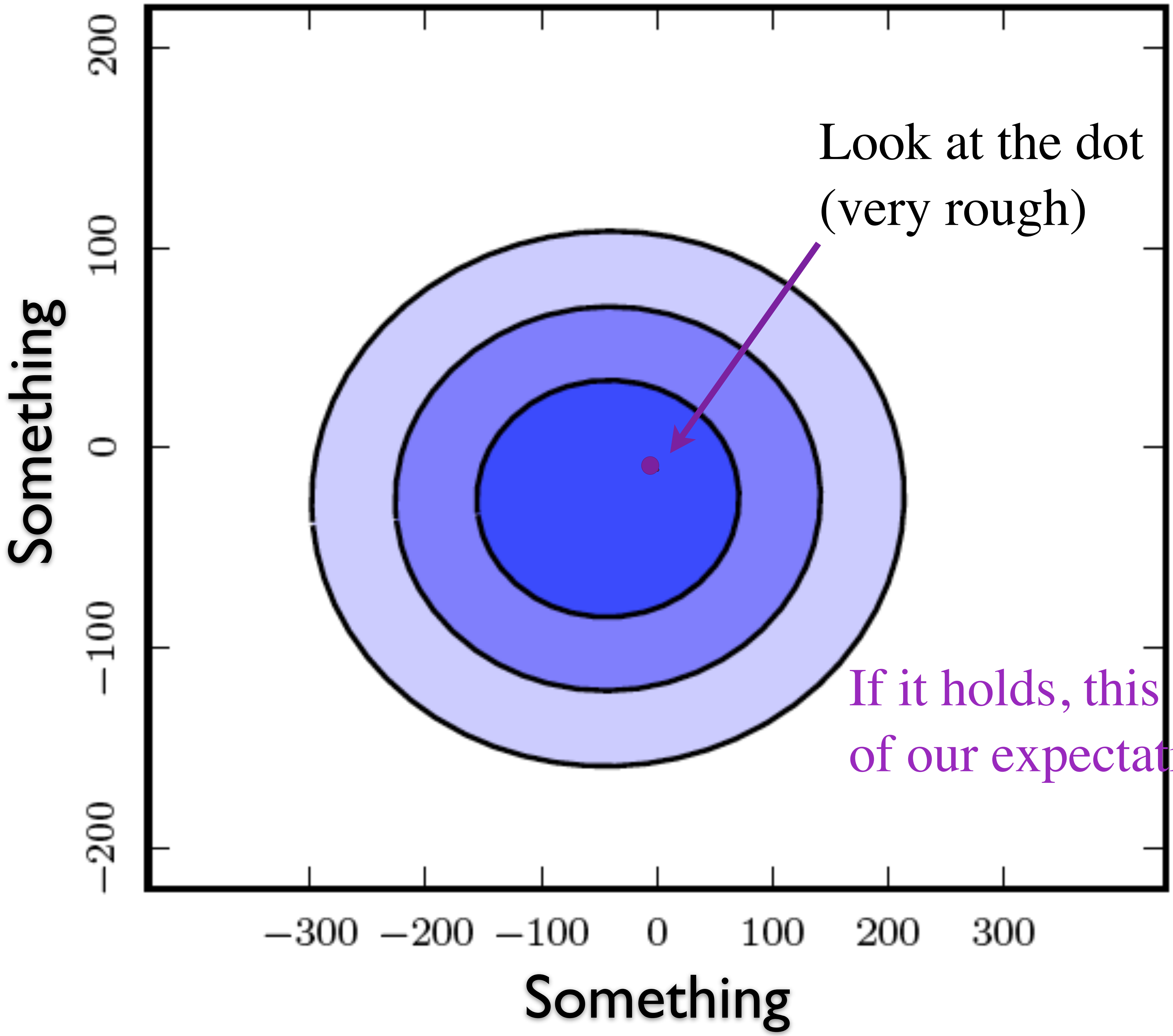
Pueblas and Scoccimarro **0809**
Hahn, Angulo, Abel **1404**

– Covariance

Zureck's Berkeley Group **1512**

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

With this

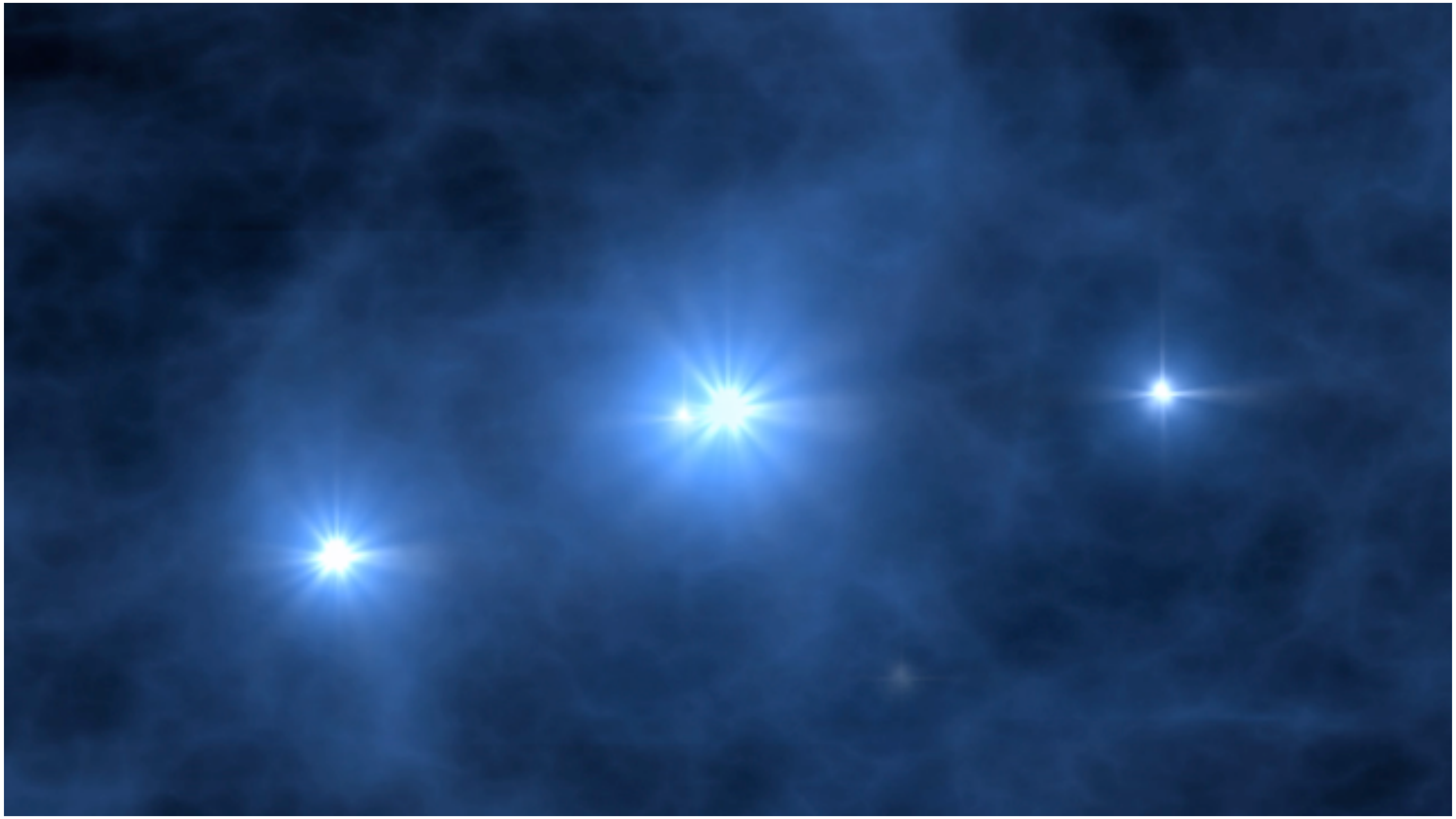


If it holds, this is a revolution
of our expectations

Analytic Prediction of Baryon Effects

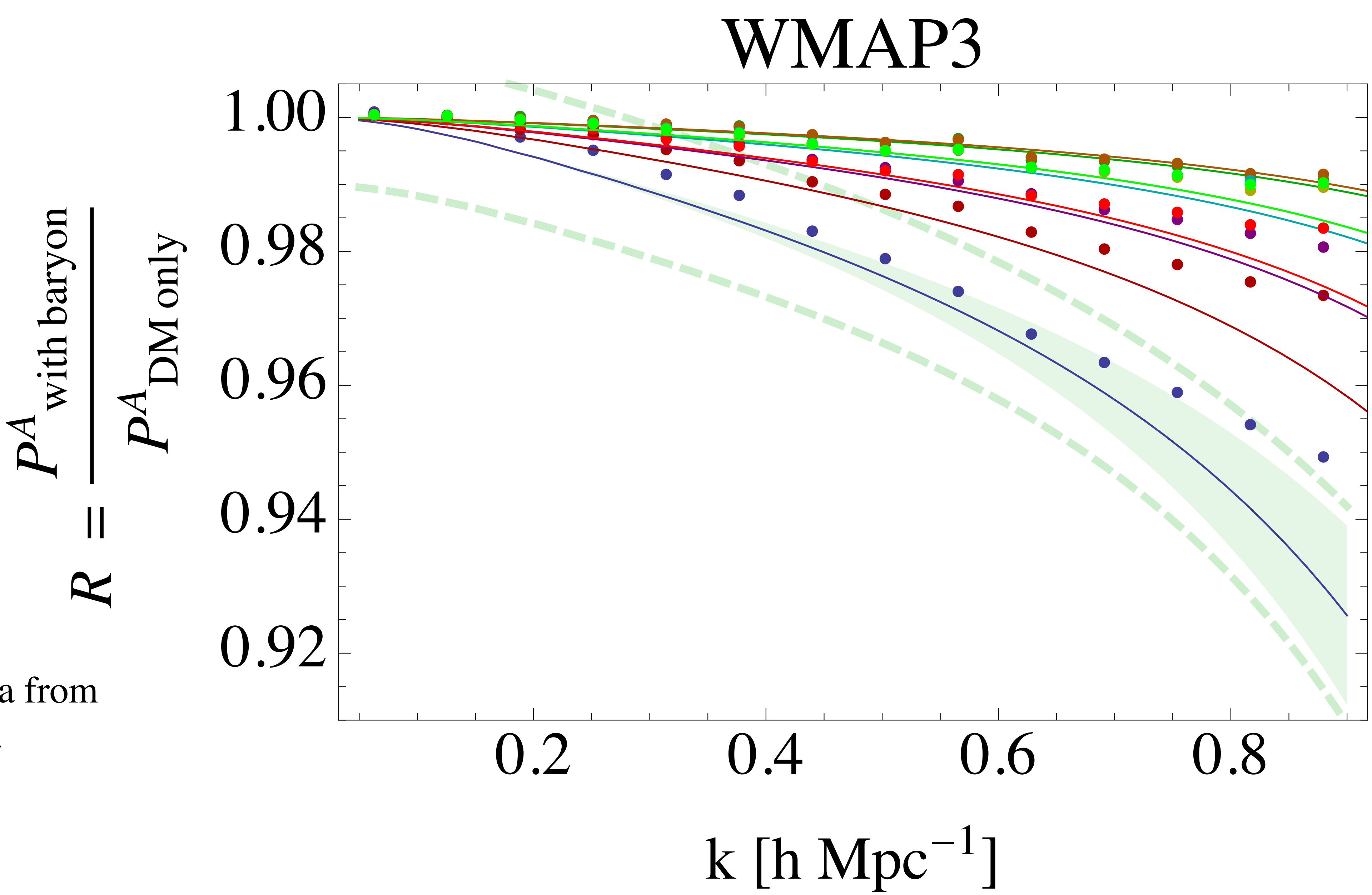
Baryonic effects

- When stars explode, baryons behave differently than dark matter



- They cannot be reliably simulated due to large range of scales

Baryons



Simulation data from
J. Schaye et al.

– Analytic form of effect known: $\Delta P^{(b)}(k) \sim c_\star k^2 P_{11}(k)$

– and it seems to work as expected

– from $c_\star$ learn about galaxy formation physics

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

Very Fast Predictions

Computations are practically analytical

– Write

Simonovic, Baldauf, Zaldarriaga, Carrasco, Kollemeier **2017**

$$P_{11}(k) = \sum_n c_n \, k^{\mu + i\, n} \quad \Rightarrow$$

$$P_{1-\text{loop}} = \int d^3 q_1 \int d^3 q_2 \; \delta^{(3)}(\vec{k} - \vec{q}_1 - \vec{q}_2) \; F[\vec{k}, \vec{q}] \; P(q_1) P_{q_2}$$

$$= \sum_{n,\, m} c_n \, c_m \int d^3 q_1 \int d^3 q_2 \delta^{(3)}(\vec{k} - \vec{q}_1 - \vec{q}_2) \; F[\vec{k}, \vec{q}] \; q_1^{\mu + in} q_2^{\mu + in} = \sum_{n,\, m} c_n \, c_m \; F_{n,m,\text{ analytical}}(k)$$

– Evaluation time: negligible

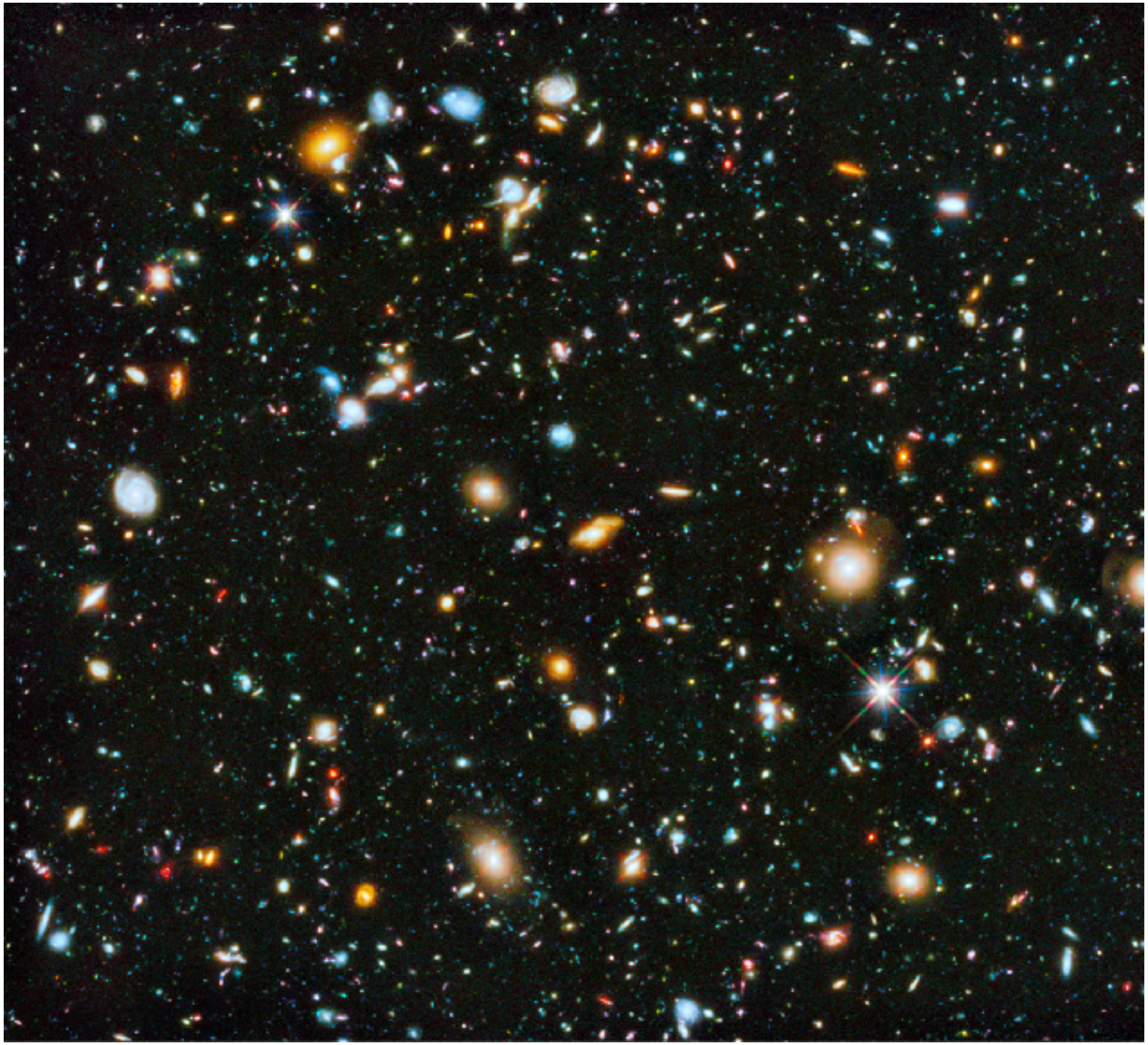
–One can also include the IR-resummation

with Lewandowsky **in progress**

$$P_{1-\text{loop, resum}} \sim \int dk' \; M(k, k') \; P_{1-\text{loop}}(k')$$

$$= \sum c_n c_m \int dk' \; M(k, k') \; F_{n,m,\text{analytic}}(k') = \sum c_n c_m \; \tilde{F}_{n,m,\text{analytic}}(k)$$

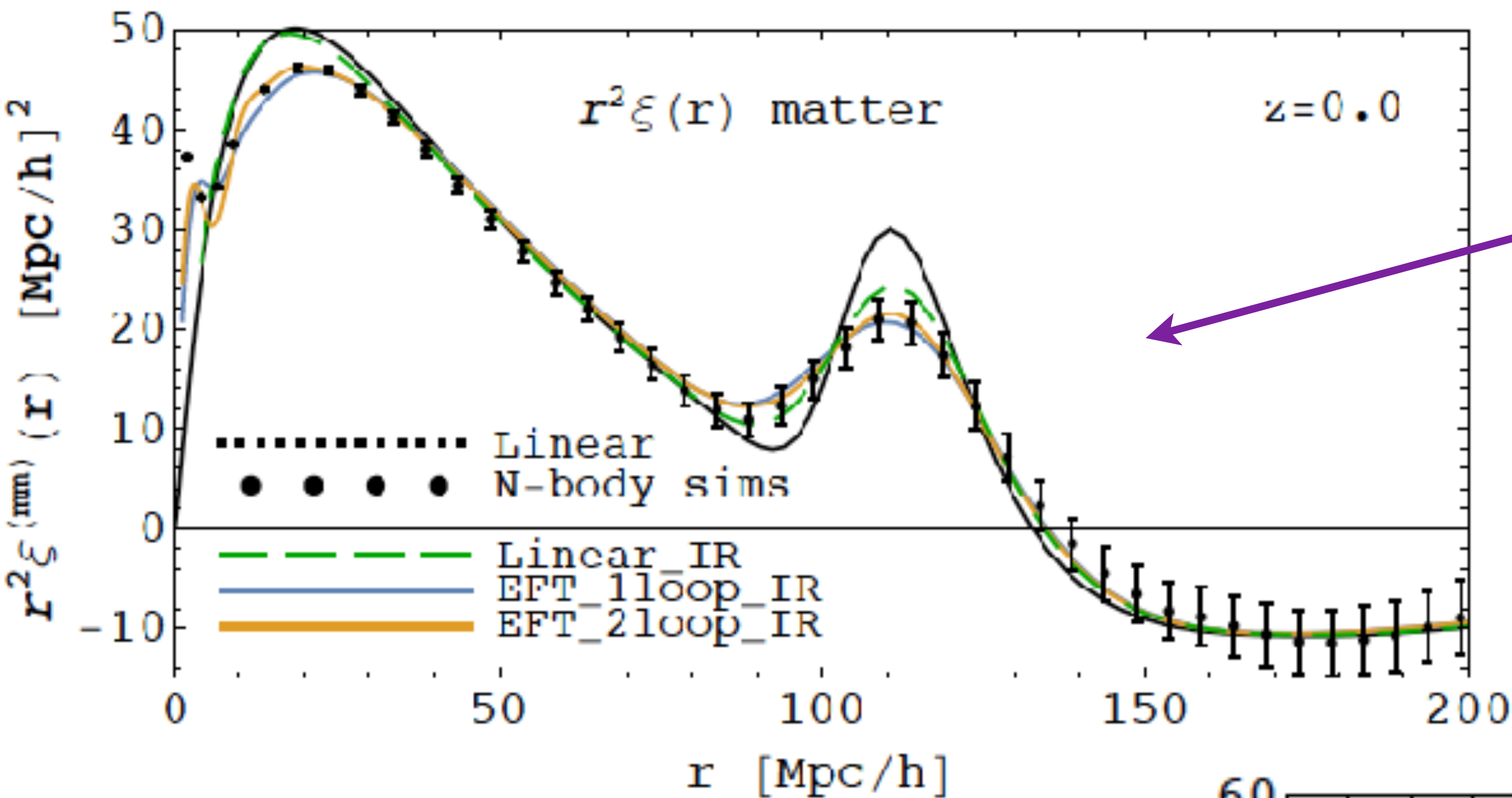
Galaxy Statistics



Halos in the EFTofLSS

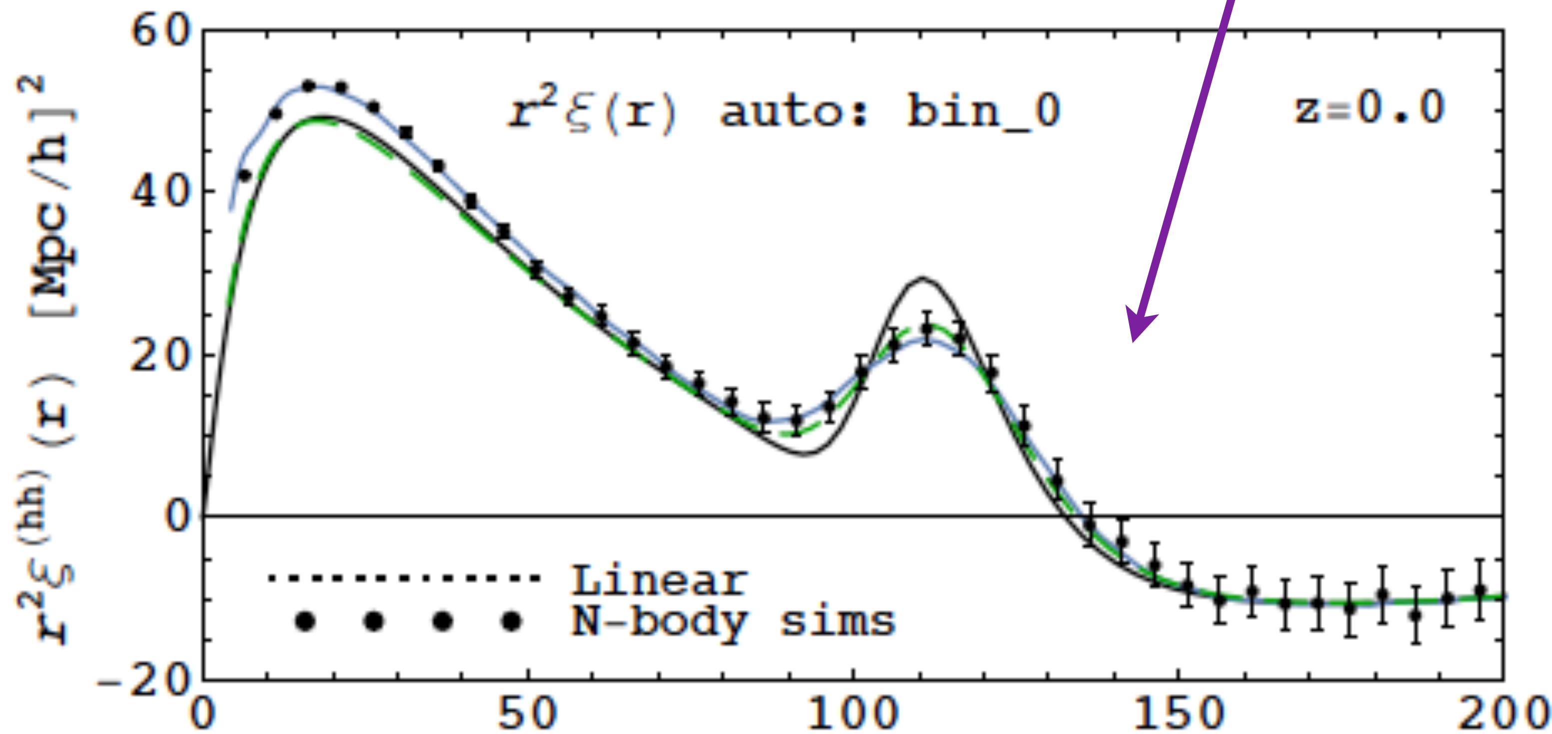
with Angulo, Fasiello, Vlah **JCAP2015**

- Real space & the BAO feature



Dark Matter

Halos

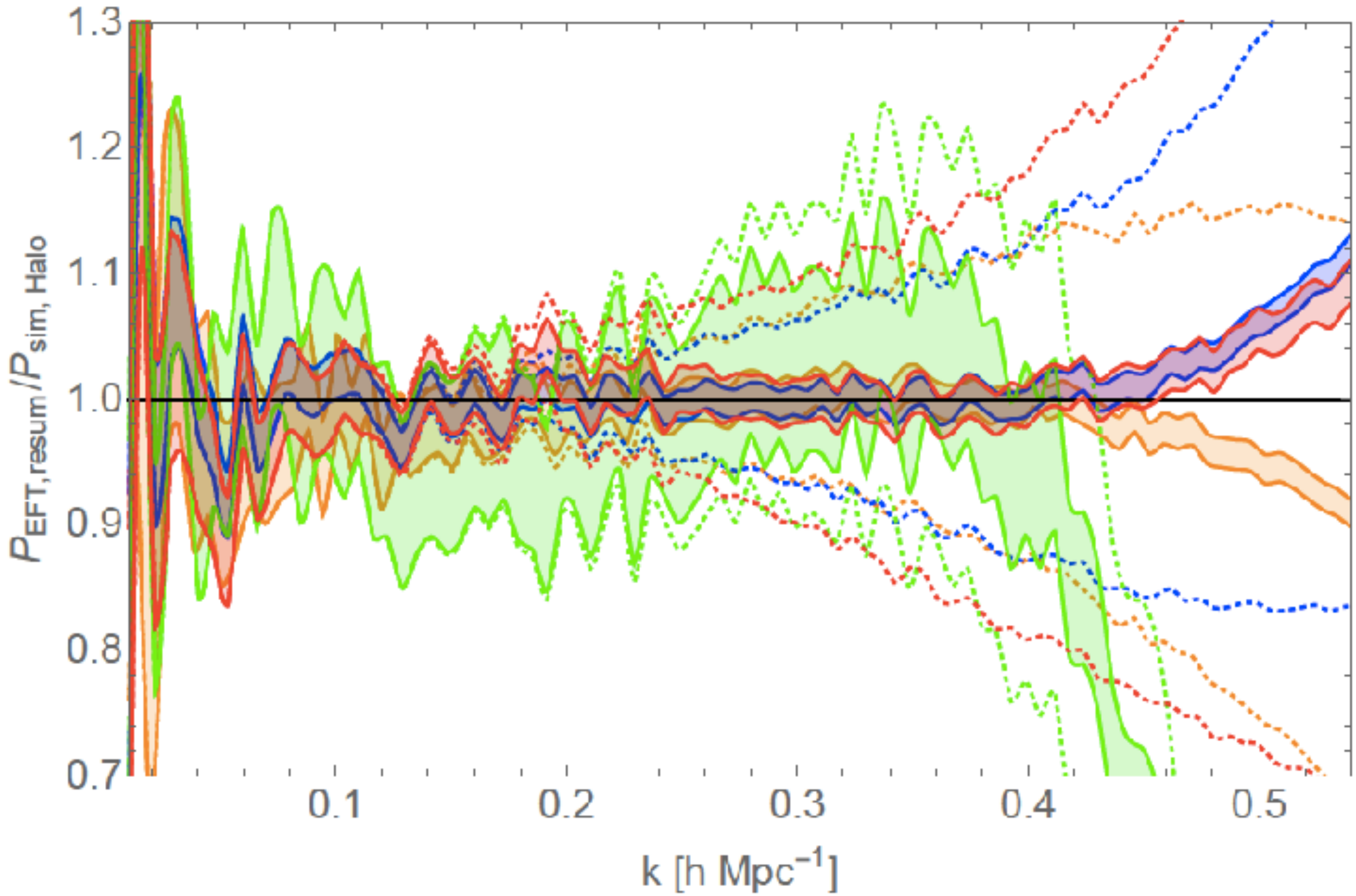


- Also similar logic to
  - redshift space distortions
    with Perko **1610**
  - baryonic effects for galaxies
  - primordial non-Gaussianities
    with Angulo, Fasiello, Vlah **1503**
  - ….
    Assassi et al **1506, 1509**
    with Lewandowski **1512**
    with Perko **1610**

We have just computed the actual observables

with Lewandowski **2016**
with Perko **2016**

- Simulated Galaxies in redshift space

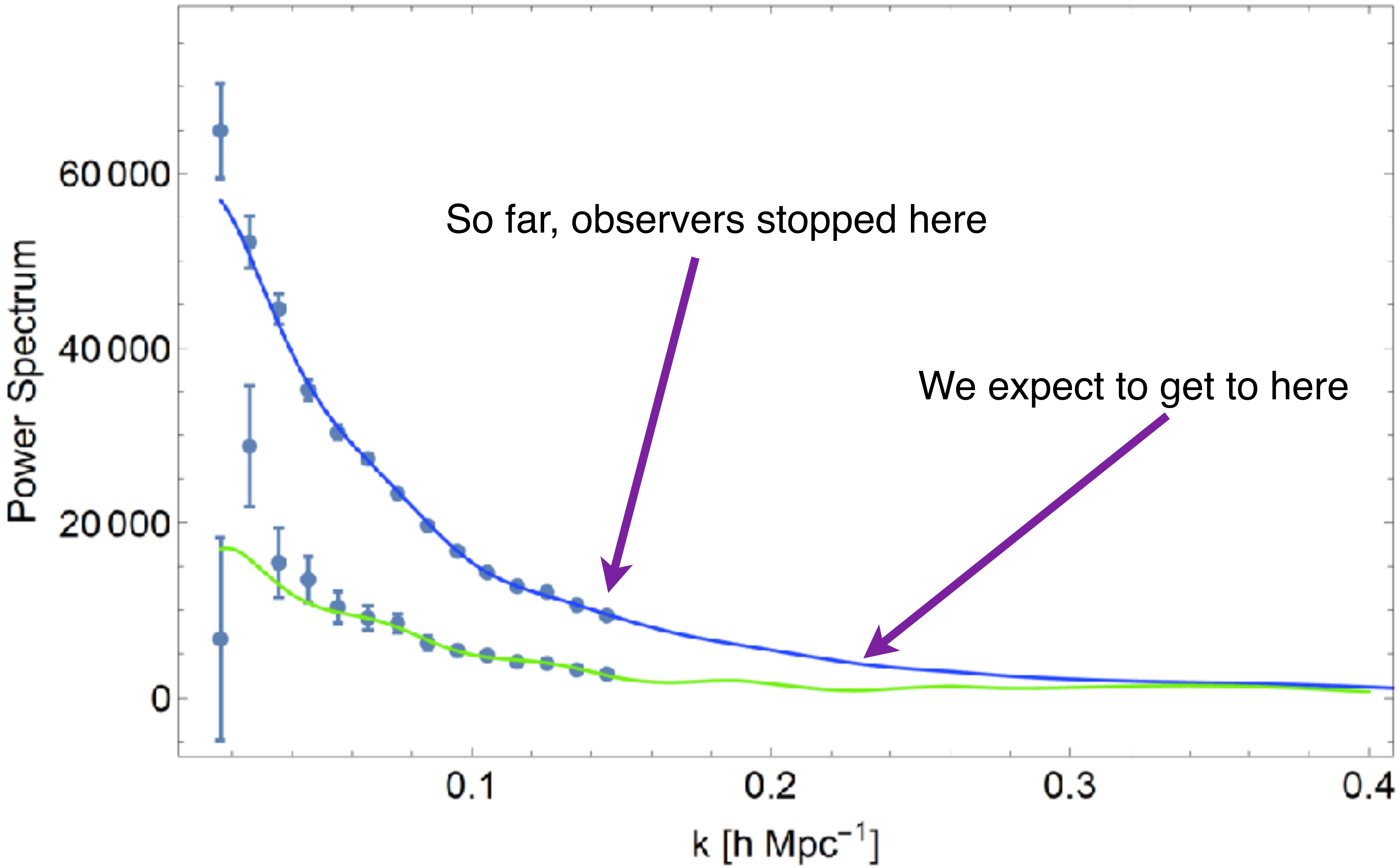


- and working through actually analyzing the observational data with it.
  - we are finally ready for them!

First comparison with SDSS data

with Perko **2016**
with Gleyzes et al.**, in progress**

- The end of a journey:



- We should get to much higher k 's, where data have never been analyzed, and where there is much more information.

The EFTofLSS extended to Massive Neutrinos

with Zaldarriaga **1707**

Neutrinos in LSS

- Shall we detect neutrinos in LSS? Will people outside LSS believe it?

- Dark matter is described as an effective fluid-like system up to $k \lesssim k_{\rm NL}$, as $k_{\rm fs,\ dm} \simeq k_{\rm NL}$

- Neutrinos have different velocities, and most of them have a free streaming length longer than the non-linear scale $k_{\rm fs} \ll k_{\rm NL}$

- In order to have a description that works up to $k_{\rm fs} \ll k \ll k_{\rm NL}$, we need to describe neutrinos with their Boltzmann equation

Set-up equations

- Boltzmann equation for Neutrinos

$$\frac{\partial f(\vec{x},\vec{v},\tau)}{d\tau} + \frac{v^i}{a}\frac{\partial f(\vec{x},\vec{v},\tau)}{\partial x^i} - a\frac{\partial\Phi}{\partial x^i}\frac{\partial f(\vec{x},\vec{v},\tau)}{\partial v^i} = 0 \ ,$$

- Effective fluid-like system for dark matter

$$\frac{\partial^2}{a^2}\Phi = \frac{3}{2}H_0^2\frac{a_0^3}{a^3}\left(\Omega_{\rm dm,0}\delta_{\rm dm} + \Omega_{\nu,0}\delta_\nu\right) \simeq \frac{3}{2}H_0^2\frac{a_0^3}{a^3}\Omega_{\rm NR,0}\left(\delta_{\rm dm} + f_\nu\left(\delta_\nu - \delta_{\rm dm}\right)\right)$$

$$\frac{1}{a}\frac{\partial\delta_{\rm dm}}{\partial\tau} + \frac{1}{a\rho_{\rm dm}^{(0)}}\partial_i\pi^i_{\rm dm} = 0 \ ,$$

$$\frac{1}{a}\frac{\partial\pi^i_{\rm dm}}{\partial\tau} + 4H\pi^i_{\rm dm} + \frac{1}{a}\partial_j\left(\frac{\pi^i_{\rm dm}\pi^j_{\rm dm}}{\rho_{\rm dm}^{(0)}(1+\delta_{\rm dm})}\right) + \frac{1}{a}\rho_{\rm dm}^{(0)}(1+\delta_{\rm dm})\partial^i\Phi = -\frac{1}{a}\partial_j\tau^{ij} \ .$$

- Example of quantities:

$$\rho(\vec{x},t) = \rho_{\rm dm}(\vec{x},t) + \rho_\nu(\vec{x},t) \quad \Rightarrow \quad \delta = (1-f_\nu)\delta_{\rm dm} + f_\nu\,\delta_\nu = \delta_{\rm dm} + f_\nu\left(\delta_\nu - \delta_{\rm dm}\right) \ ,$$

$$\langle\delta(\vec{k},t)\,\delta(\vec{k}',t)\rangle = \left(P_{\rm dm,\,dm}(k) + 2 f_\nu\, P_{\rm diff,\,dm}(k)\right)$$

$$\delta_{\rm diff} = \delta_\nu - \delta_{\rm dm}$$

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Set-up equations

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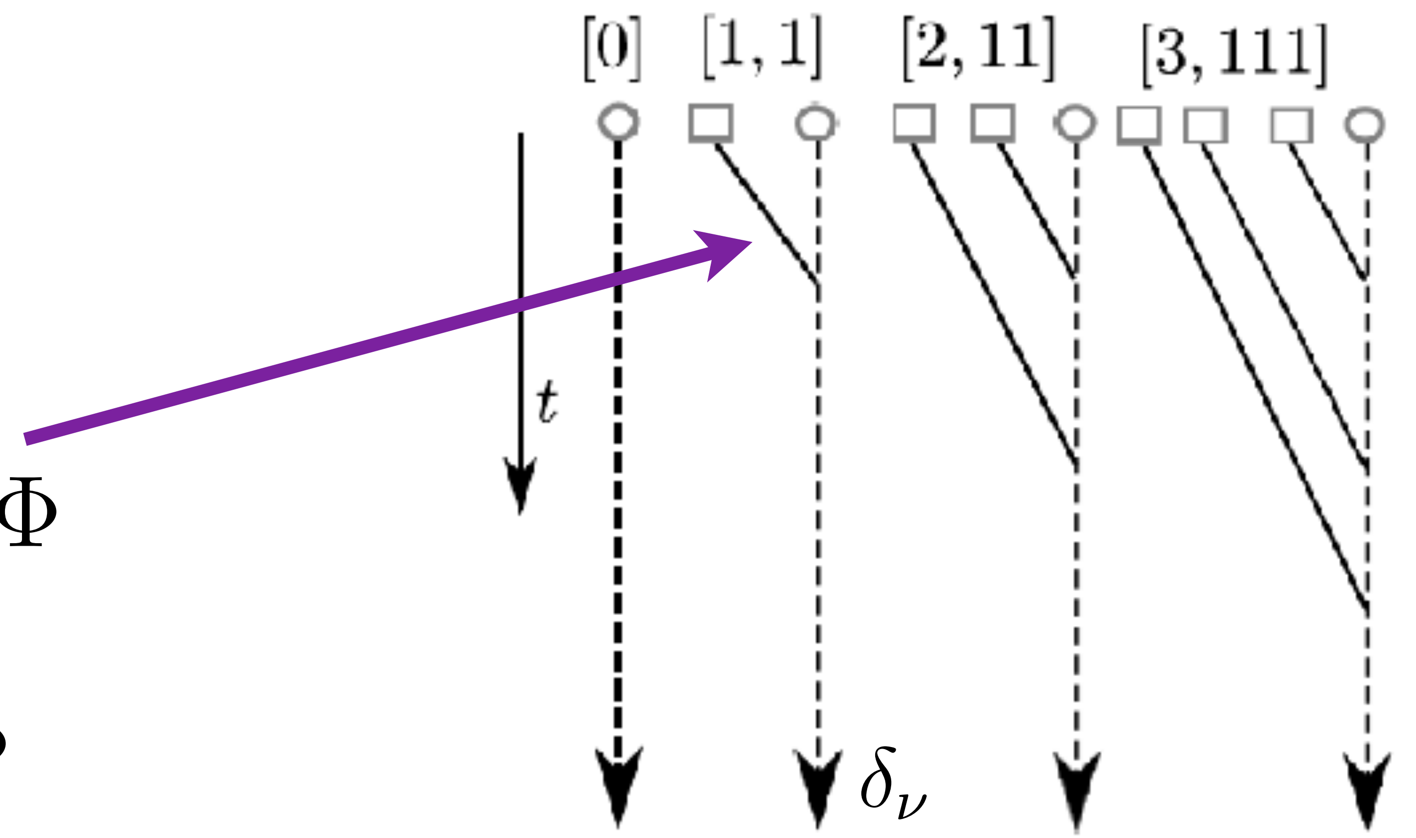
$$\delta_{\rm diff} = \delta_\nu - \delta_{\rm dm}$$

Perturbative Solution

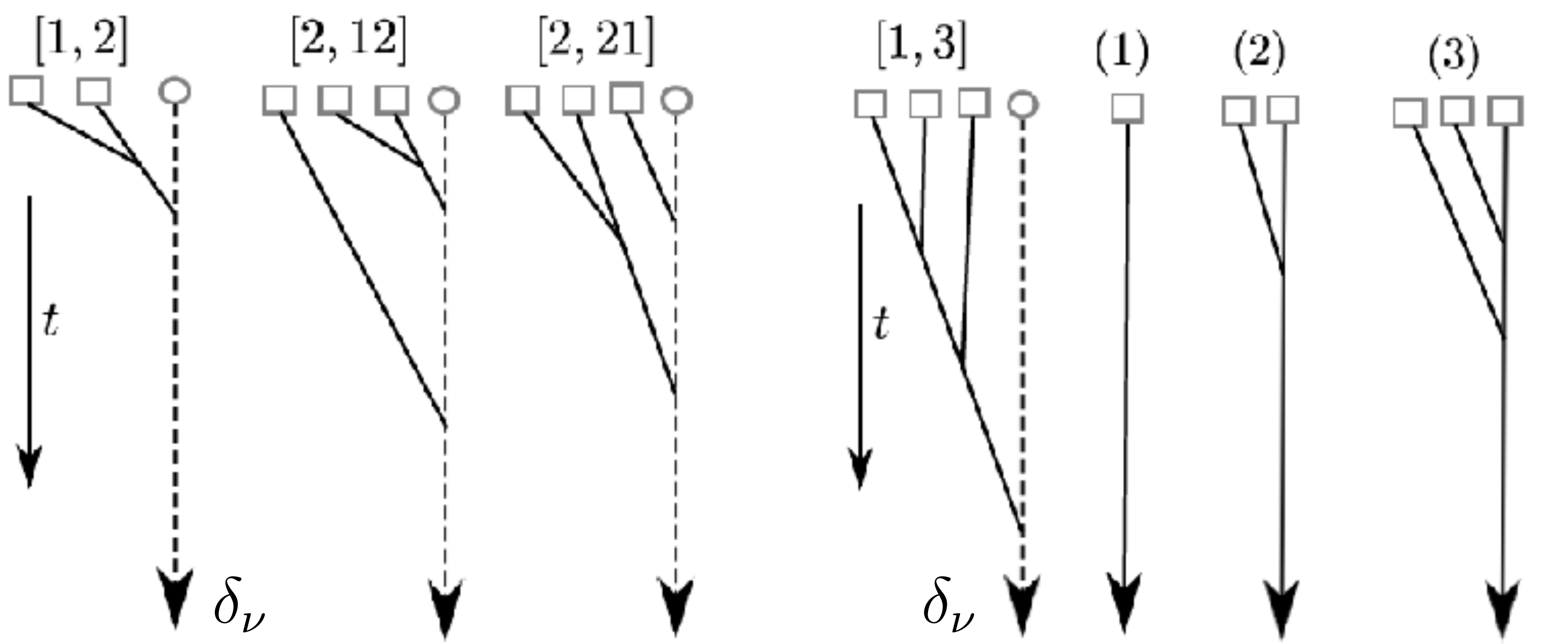
- . $$f^{[n]}(\vec{k},\vec{v},\tau) = \int_0^\tau d\tau'\; G_R(\tau,\tau';\vec{v},k)\left[a(\tau')\left(\frac{\partial}{\partial x^i}\Phi(\vec{x},\tau')\right)\frac{\partial}{\partial v^i} f^{[n-1]}(\vec{x},\vec{v},\tau')\right]_{\vec{k}}$$
- First order:
$$f^{[1]}(\vec{k},\vec{v},s) = \int_{s_i}^{s} ds'\, a(s')^2\, e^{-i\,\vec{k}\cdot\vec{v}\,(s-s')} i\frac{\vec{v}}{v}\cdot\vec{k}\,\Phi(\vec{k},s')\frac{\partial f^{[0]}(v)}{\partial v}$$
- Second order:
$$f^{[2]}(\vec{k},\vec{v},s) = \int\frac{d^3q_1}{(2\pi)^3}\int\frac{d^3q_2}{(2\pi)^3}\,(2\pi)^3\delta_D^{(3)}(\vec{k}-\vec{q}_1-\vec{q}_2)$$
$$\int_0^s ds_1\, a(s_1)^2\, e^{-i\,(\vec{q}_1+\vec{q}_2)\cdot\vec{v}\,(s-s_1)} i\, q_1^{i_1}\,\Phi(\vec{q}_1,s_1)$$
$$\frac{\partial}{\partial v^{i_1}}\int_0^{s_1} ds_2\, a(s_2)^2\, e^{-i\,\vec{q}_2\cdot\vec{v}\,(s_1-s_2)} i\, q_2^{i_2}\,\Phi(\vec{q}_2,s_2)\frac{\partial f^{[0]}(v)}{\partial v^{i_2}}$$
- Every insertion scales as $v_{\rm NL}/v \ll 1$ for fast neutrinos, and as $\delta(q)$ for slow ones.
- Notice that expression is sensitive to product of high wavenumber fields: $q_1, q_2 \gg k$
  - These part of phase space is not under control: need to be renormalized

Diagrammatic Representation

- Solutions with $\Phi^{(1)}$



- Solutions with higher-order Φ



Renormalization of Local Product

- We need to renormalize the local product of fields we are sensitive to. High wavenumber means local in space.

$$[\delta(\vec{x}_1,\tau_1)\,\delta(\vec{x}_2,\tau_2)]_{\rm R} = [\delta(\vec{x}_1,\tau_1)]_{\rm R}\,[\delta(\vec{x}_2,\tau_2)]_{\rm R} + [\delta(\vec{x}_1,\tau_1)\,\delta(\vec{x}_2,\tau_2)]_{\rm C}\ ,$$

$$\downarrow$$

$$[\delta(\vec{x}_1,t_1)\delta(\vec{x}_2,t_2)]_{\rm C} = \delta_D^{(3)}(\vec{x}_1-\vec{x}_2)\ \ f_{\text{very complicated}}\left(\text{everything},\ldots,\partial_i\partial_j\Phi(x)\ \ldots\right)\big|_{\text{past light cone}}$$

$$= \quad \text{at long wavelengths we can Taylor expand} =$$

$$[\delta(\vec{x}_1,\tau_1)\delta(\vec{x}_2,\tau_2)]_{\rm C} = \int^{{\rm Max}(\tau_1,\tau_2)} d\tau'\ \left[C_1^{(2)}(\tau_1,\tau_2,\tau') + \epsilon^{(2)}_{\rm stoch,1}(\tau_1,\tau_2,\vec{x}_{\rm fl}(\vec{x}_1,\tau_1,\tau'),\tau') + \right.$$

$$\partial^i\partial^j\Phi(\vec{x}_{\rm fl}(\vec{x}_1,\tau,\tau'),\tau')\left(C_2^{(2)}(\tau,\tau')\delta^{ij} + C_3^{(2)}(\tau,\tau')\frac{\partial_i\partial_j}{\partial^2}\right) + \qquad ($$

$$\left.\epsilon^{(2),ij}_{\rm stoch,2}(\tau_1,\tau_2,\vec{x}_{\rm fl}(\vec{x}_1,\tau_1,\tau'),\tau')\frac{\partial_i\partial_j}{\partial^2} + \ldots\right]\ \ \frac{1}{k_{\rm NL}^3}\,\delta_D^{(3)}\left(\vec{x}_{\rm fl}(\vec{x}_1,\tau_1,\tau') - \vec{x}_{\rm fl}(\vec{x}_2,\tau_2,\tau')\right)\ .$$

- These counterterms fix any UV dependence of the perturbative diagrams.

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$$=\quad \text{at long wavelengths we can Taylor expand} =$$

Expectation value

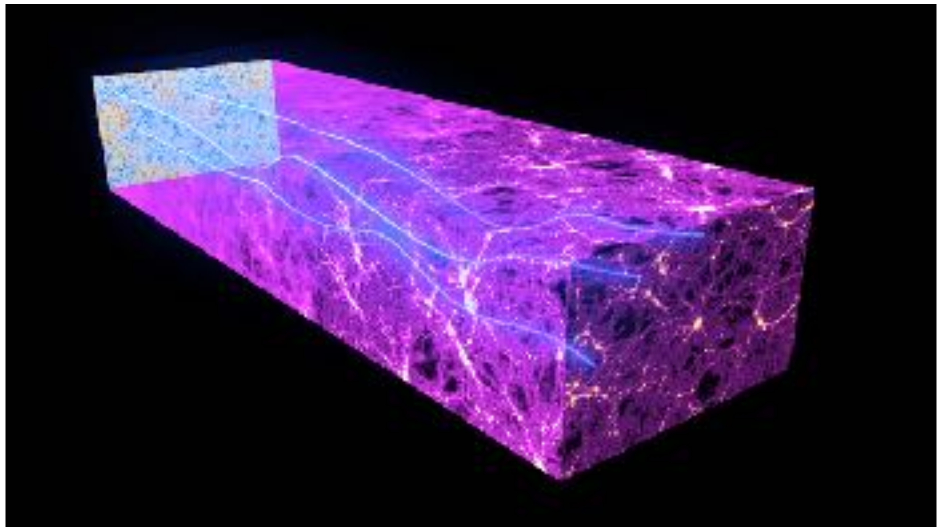
Responses

$$[\delta(\vec{x}_1,\tau_1)\delta(\vec{x}_2,\tau_2)]_{\rm C} = \int^{{\rm Max}(\tau_1,\tau_2)} d\tau'\ \Big[C_1^{(2)}(\tau_1,\tau_2,\tau') + \epsilon^{(2)}_{\rm stoch,1}(\tau_1,\tau_2,\vec{x}_{\rm fl}(\vec{x}_1,\tau_1,\tau'),\tau') +$$
$$\partial^i\partial^j\Phi(\vec{x}_{\rm fl}(\vec{x}_1,\tau,\tau'),\tau')\left(C_2^{(2)}(\tau,\tau')\delta^{ij} + C_3^{(2)}(\tau,\tau')\frac{\partial_i\partial_j}{\partial^2}\right) + \qquad ($$
$$\epsilon^{(2),ij}_{\rm stoch,2}(\tau_1,\tau_2,\vec{x}_{\rm fl}(\vec{x}_1,\tau_1,\tau'),\tau')\frac{\partial_i\partial_j}{\partial^2} + \ldots\Big]\ \ \frac{1}{k_{\rm NL}^3}\,\delta_D^{(3)}\left(\vec{x}_{\rm fl}(\vec{x}_1,\tau_1,\tau') - \vec{x}_{\rm fl}(\vec{x}_2,\tau_2,\tau')\right)\ .$$

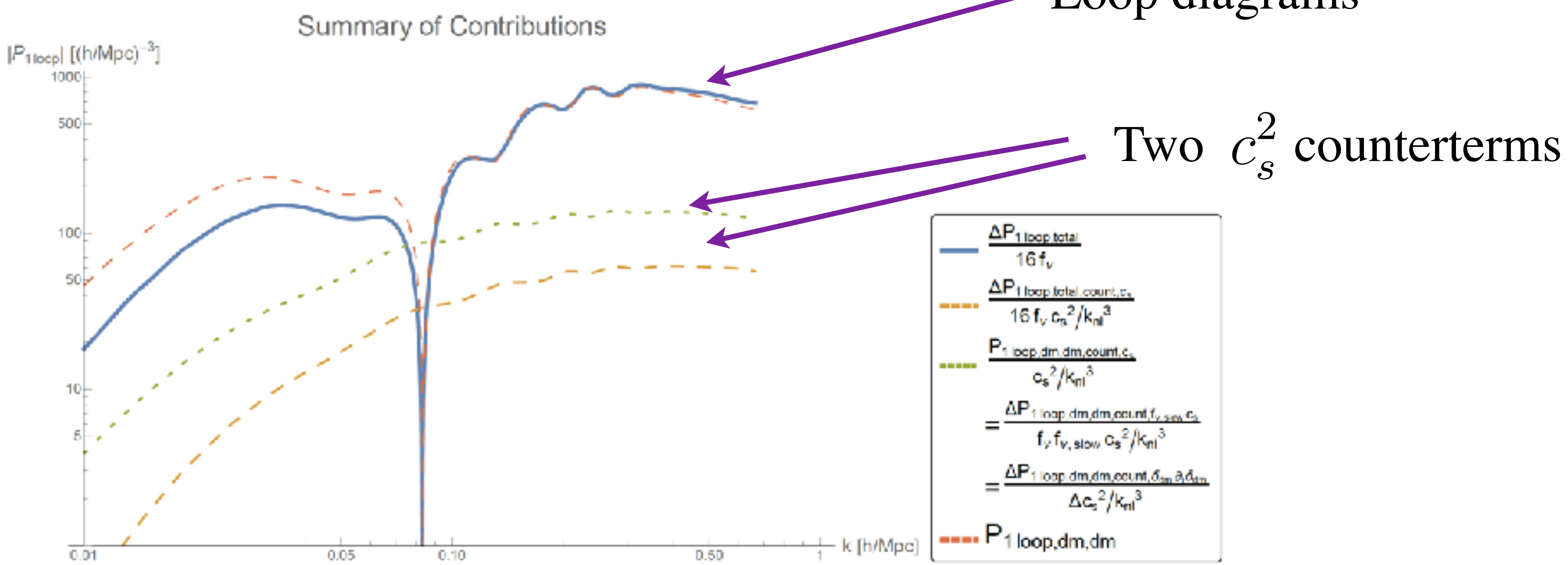
- These counterterms fix any UV dependence of the perturbative diagrams.

Prediction for Massive Neutrinos

- Some neutrinos are as slow as dark matter: described by the same effective fluid-like effective equations



- Some neutrinos instead they are fast:
  - they are described by a *Boltzmann equation*
  - but we need to evolve them in the right potential (from the dark-matter EFT)
- Overall, we can make accurate predictions



Thanks to the Organizers!

- Paolo Creminelli

- Ravi Sheth

- Mehrdad Mirbabayi

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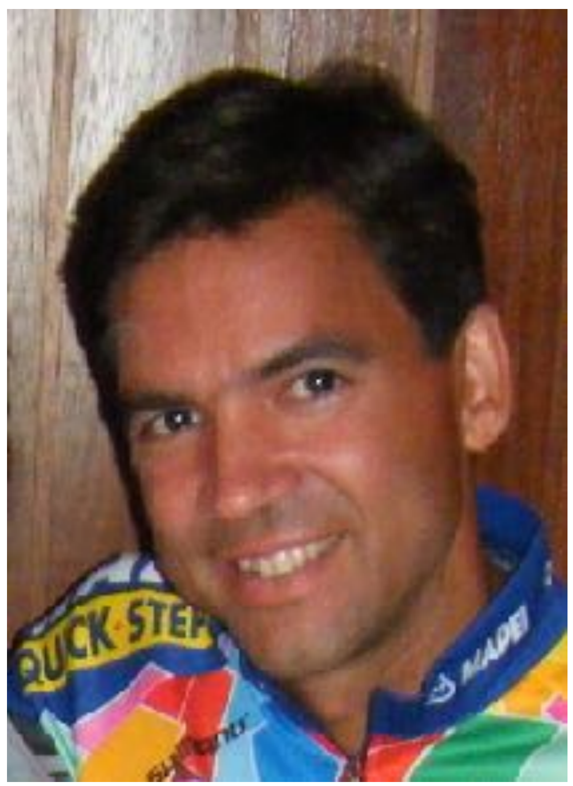
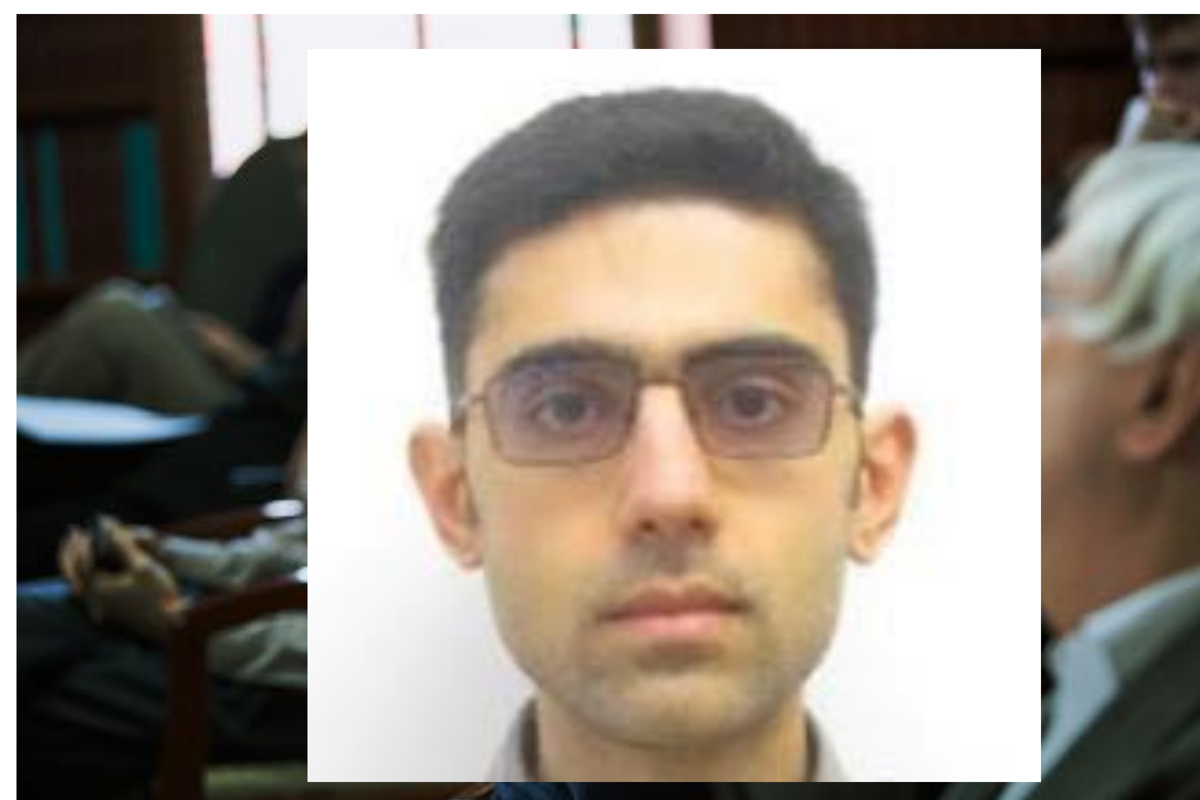


- Mehrdad Mirbabayi



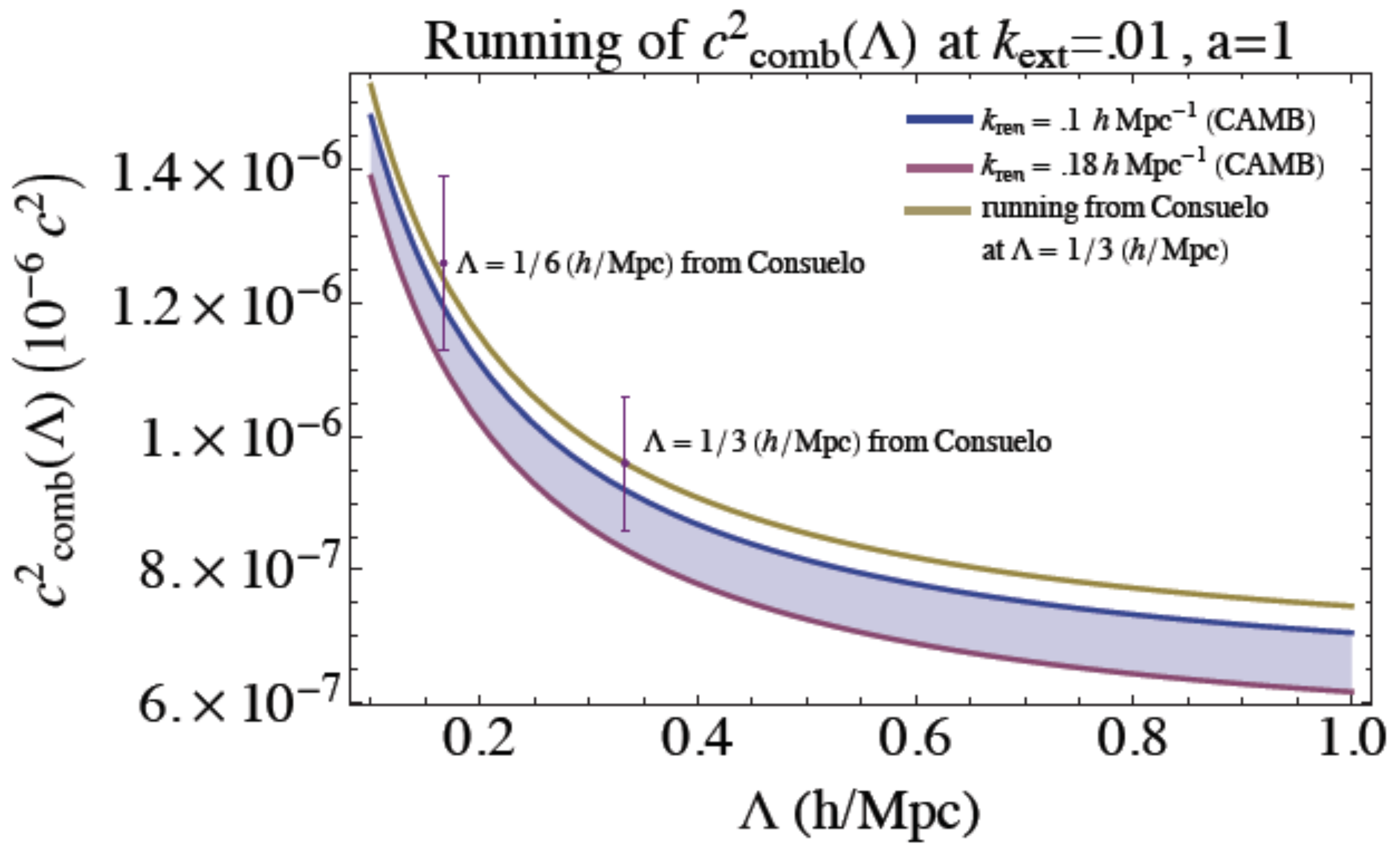
In the EFTofLSS we need parameters.
Let us measure them from
small N-body Simulations!

with Carrasco and Hertzberg **JHEP 2012**

Measuring parameters from N-body sims.

- The EFT parameters can be measured from small N-body simulations, using UV theory
  - similar to what happens in QCD: lattice sims
- We measure c_s using the dark matter particles:

$$\tau_{ij} \sim \sum_{i \in \mathcal{I}_\Lambda} m_i \left(v_i^2 + \phi_i\right)$$



- Lattice running
- Agreement with fitting from Power Spectrum directly

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

with Carrasco and Hertzberg **JHEP 2012**
McQuinn and White **1502**

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
- W

τ_{ij}

- Agreement with fitting from Power Spectrum directly

$$\frac{d\,c_s^2}{d\Lambda} = \frac{d}{d\,\Lambda}\int d^3k\; P_{13}(k)$$

with Carrasco and Hertzberg **JHEP 2012**
McQuinn and White **1502**

How did the Inflaton interact?

What is it?

How to go forward

- Tremendous progress has been made through observation of the primordial fluctuations
- We are probing a statistical distribution:
  - In order to increase our knowledge of Inflation, we need more modes:

$$\Delta(\text{everything}) \propto \frac{1}{\sqrt{N_{\text{modes}}}}$$

- Planck has just observed almost all the modes from the CMB
- and now what?

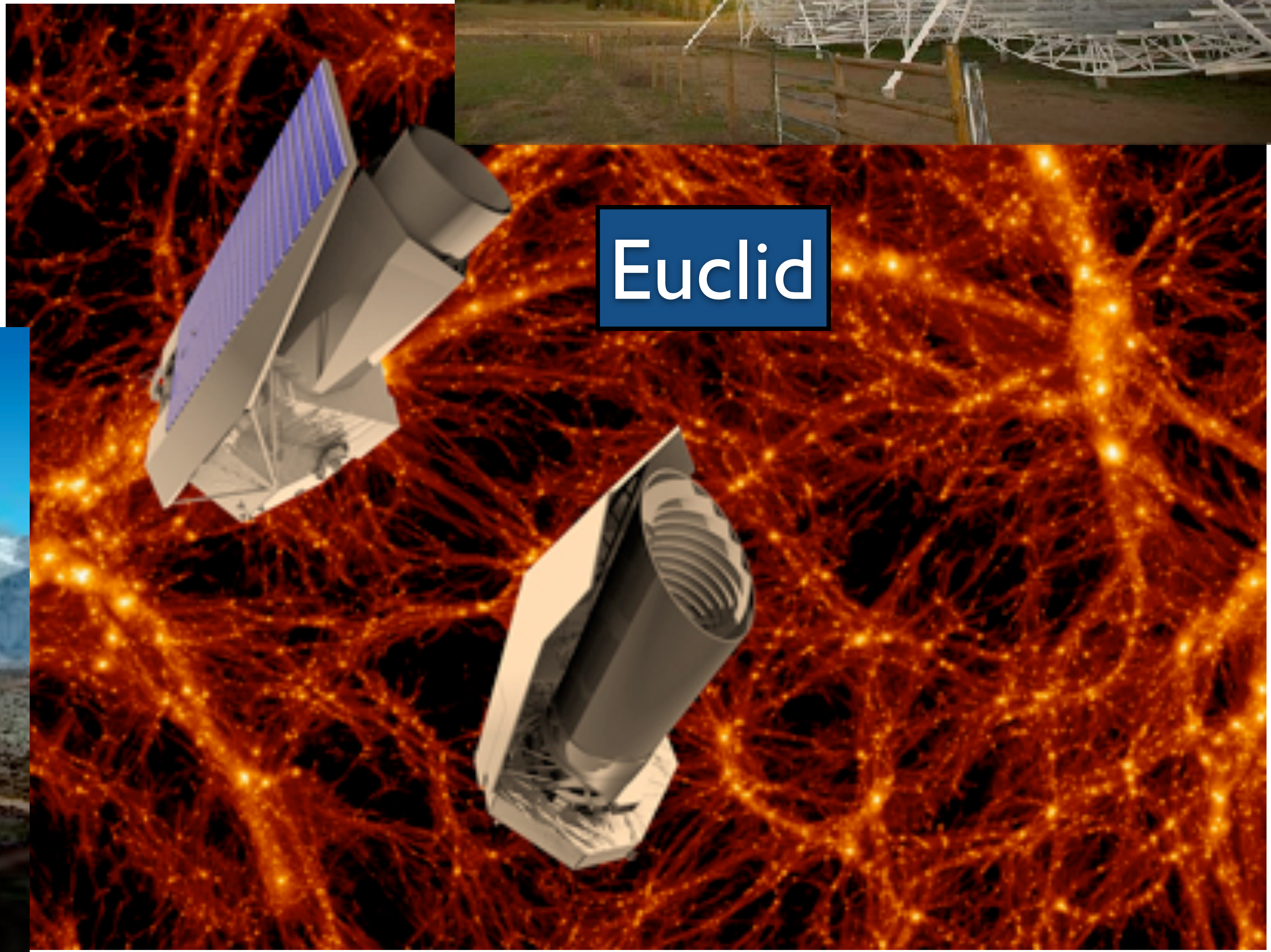
- Unless we find a way to get more modes, marginal guaranteed progress
- Large-Scale Structure offer the only medium-term place for hunting for more modes
  - but we are compelled to understand them better
    - Lots of applications for
      - astrophysics, inflation, dark energy, neutrinos, dark matter, etc.

What is next?

- LSST, Euclid and Chime are the next big missions: this is our next chance
  - we need to understand how many modes are available

$$\text{Number modes} \sim V_{\text{survey}}\, k_{\text{max}}^3$$

  - Need to understand short distances

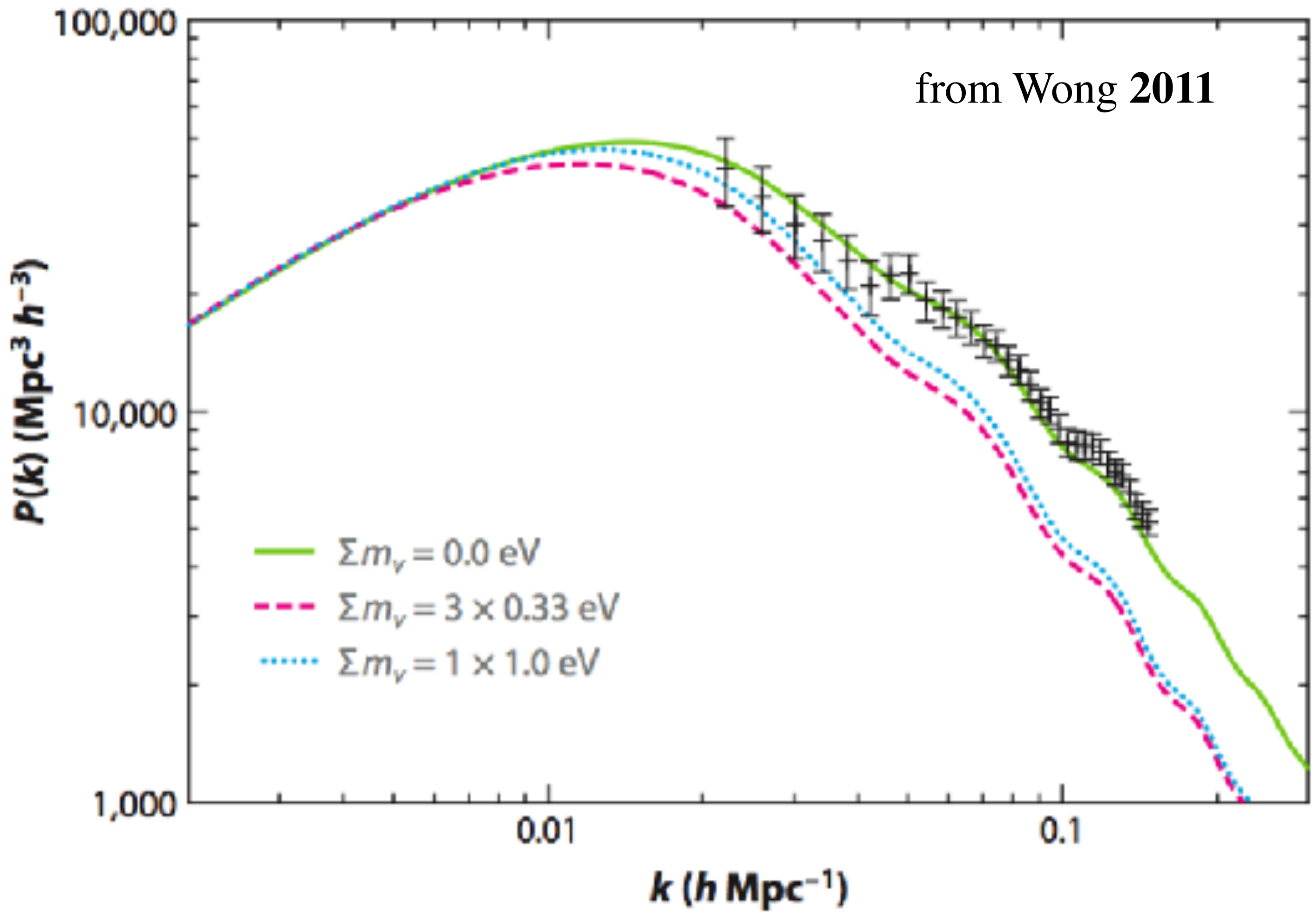


Massive Neutrinos

- Not only inflation

Nobel Prize and Breakthrough prize **2015**

- Neutrinos have a mass, their energy affects the gravitational clustering
- By understanding the clustering, we can measure their mass

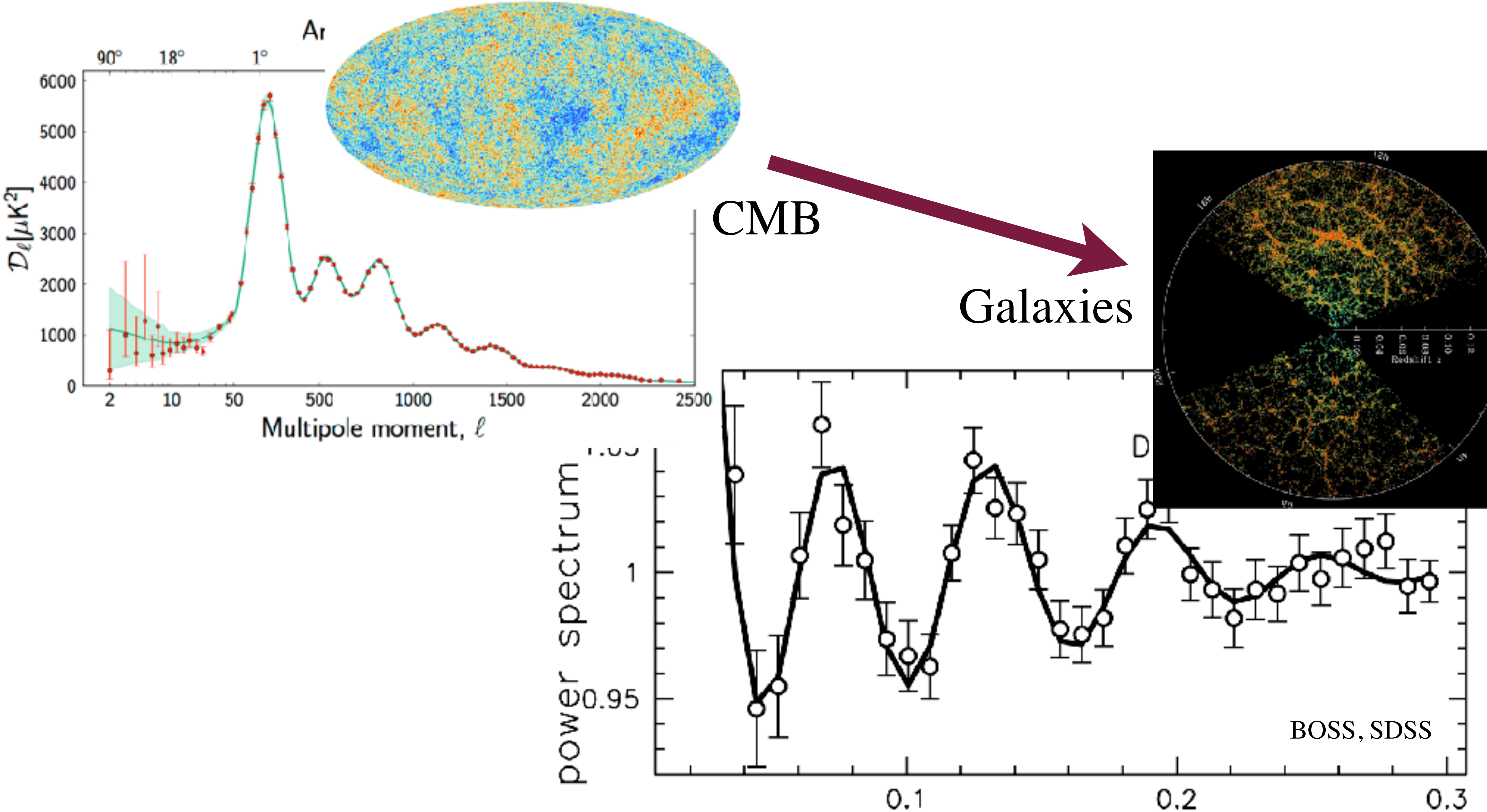


- Similarly for `dark energy’
- We need to understand these curves

Analogous to Condensed Matter
(or to QCD, Astrophysics, etc.)

Some marvelous results already achieved

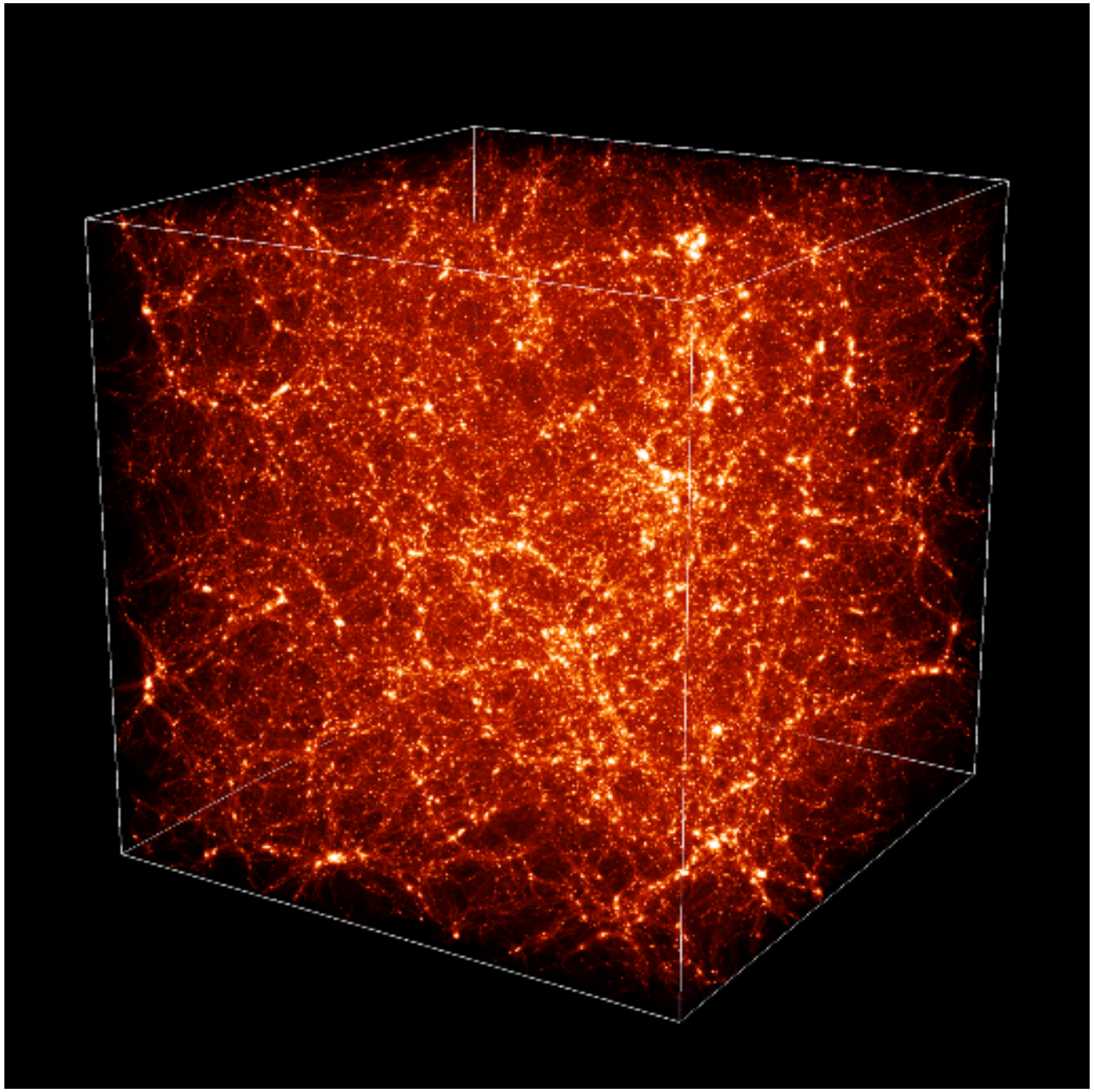
- Baryon Acoustic Oscillations in Galaxies distribution



- But most new information is just about low-z universe
- Not much about early universe

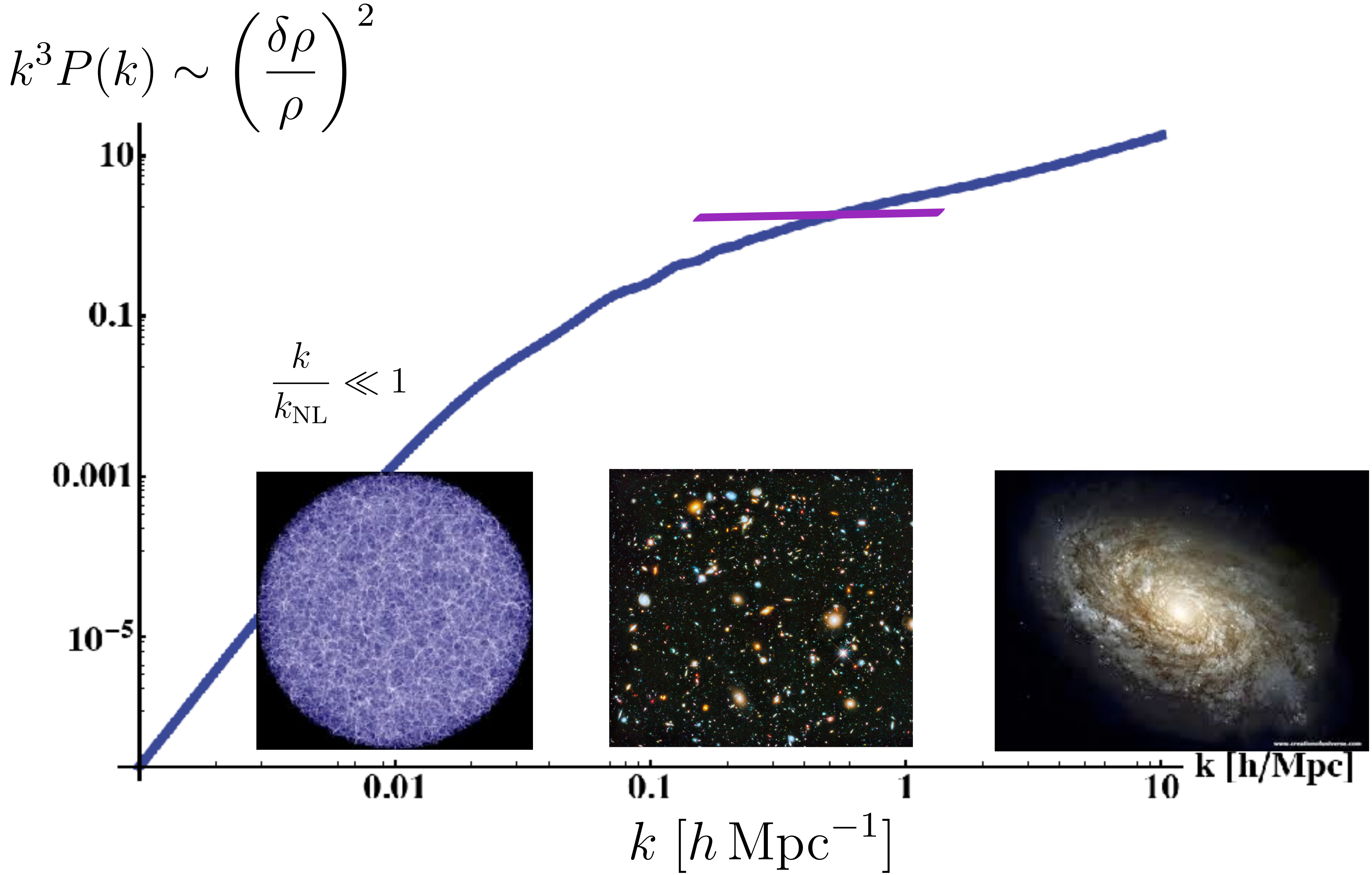
Normal Approach: numerics

- Just simulate the full universe



The EFTofLSS: A well defined perturbation theory

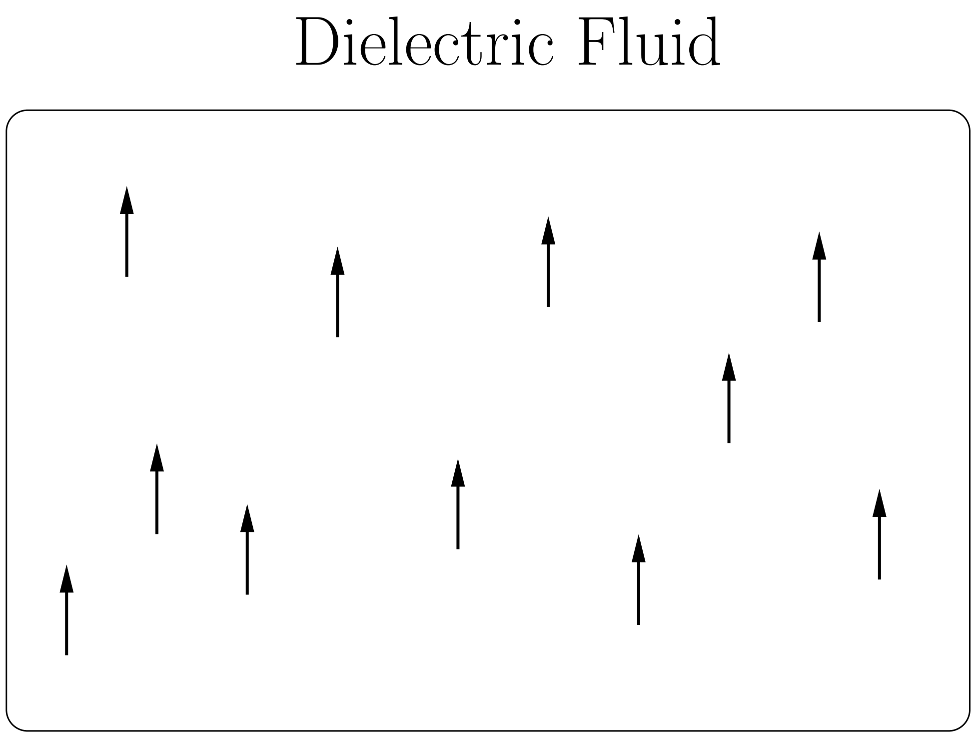
- Non-linearities at short scale



Idea of the
Effective Field Theory

Consider a dielectric material

- Very complicated on atomic scales d_{atomic}
- On long distances $d \gg d_{\text{atomic}}$
  - we can describe atoms with their gross characteristics
    - polarizability $\vec{d}_{\text{dipole}} \sim \alpha\, \vec{E}_{\text{electric}}$: average response to electric field
  - we are led to a uniform, smooth material, with just some macroscopic properties
    - we simply solve dielectric Maxwell equations, we do not solve for each atom.
- The universe looks like a dielectric



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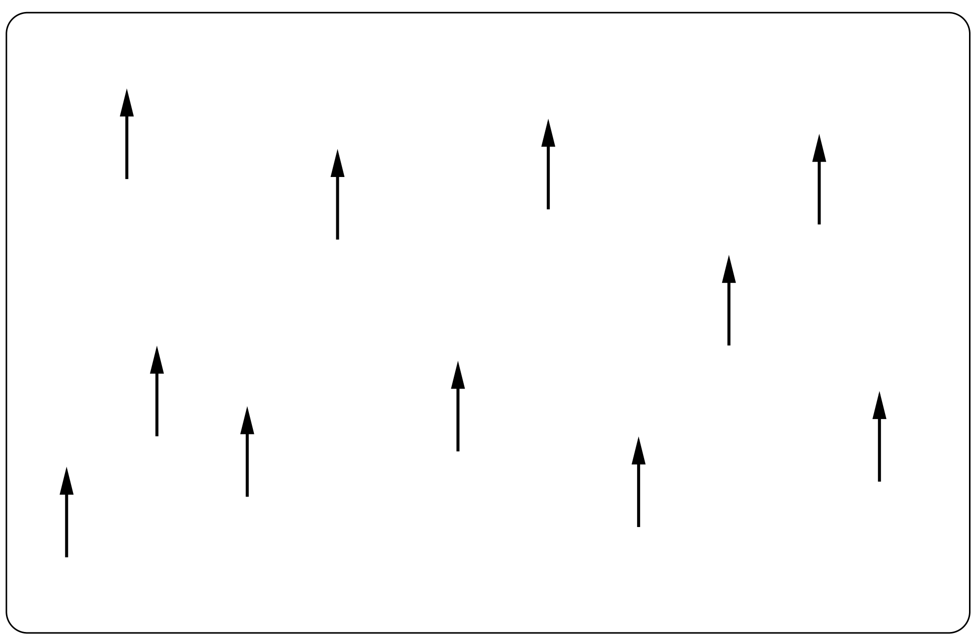
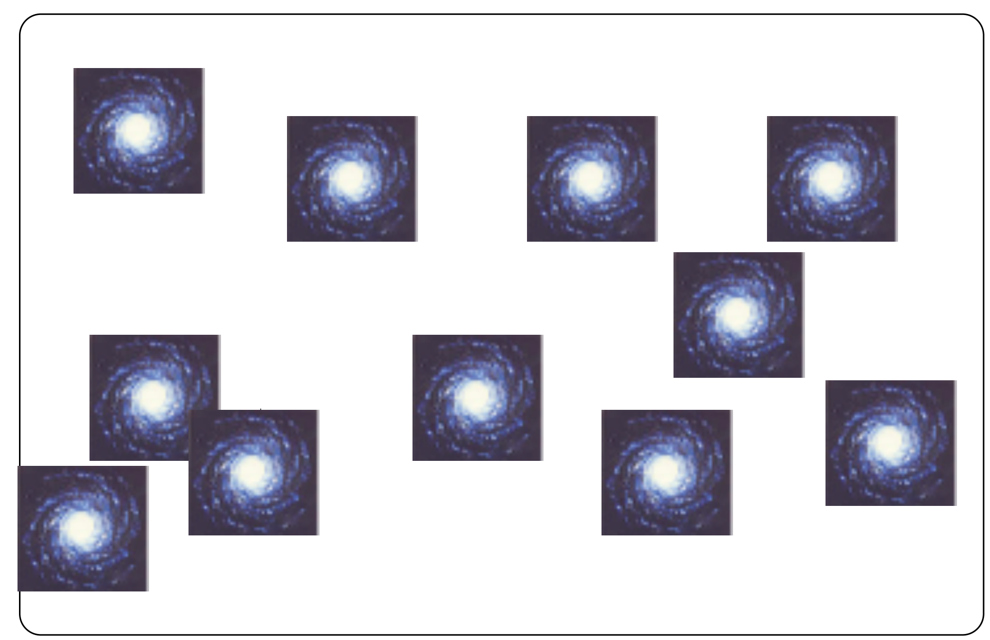
$$\text{EM} \quad \longrightarrow \quad \text{GR}$$

Dielectric Fluid



Dielectric Fluid



Construction of the Effective Field Theory

The Effective ~Fluid

– In history of universe Dark Matter moves about $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

– it is an effective fluid-like system with mean free path ~ $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

– it interacts with gravity so matter and momentum are conserved

- Skipping many subtleties, the resulting equations are equivalent to fluid-like equations

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

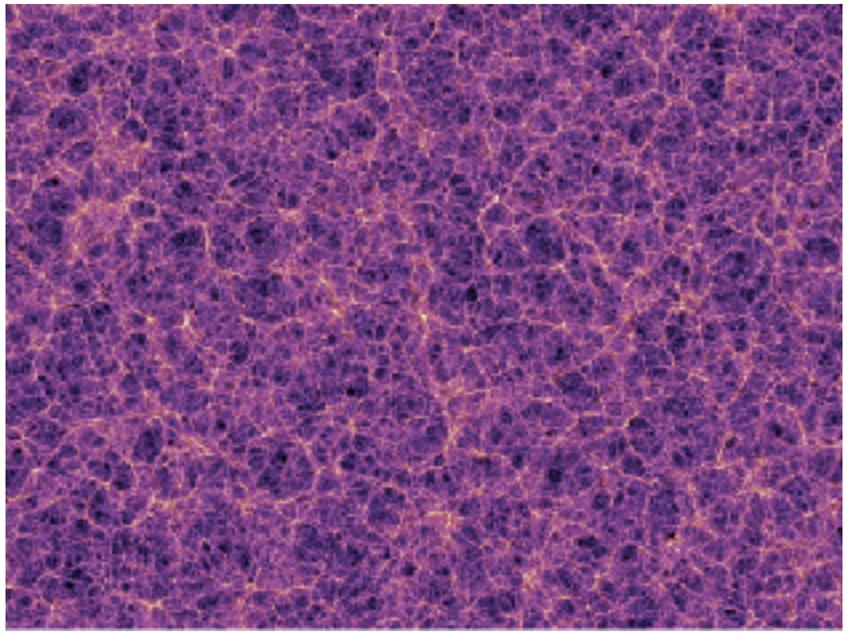
$$\partial_t\rho_l + H\rho_l + \partial_i\left(\rho_l v_l^i\right) = 0$$

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

with Baumann, Nicolis and Zaldarriaga **JCAP 2012**
with Carrasco and Hertzberg **JHEP 2012**
with Porto and Zaldarriaga **JCAP 2014**

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

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

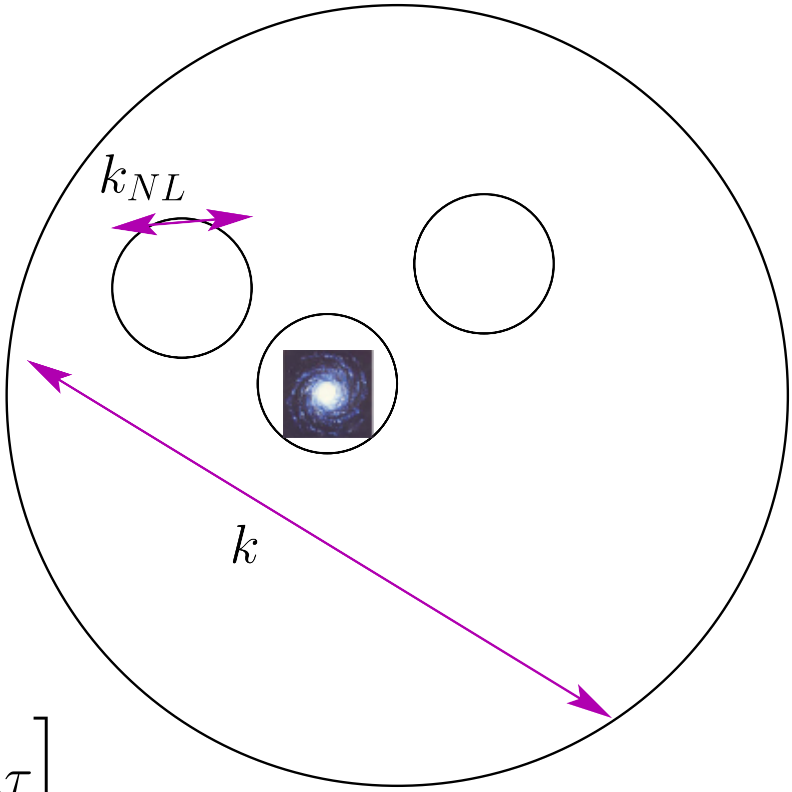


Dealing with the Effective Stress Tensor

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

$$\langle \tau_{ij} \rangle_{\text{long fixed}} = f_{ij}\left[\rho_l(x,t), \partial_i v_l^i(x), \ldots\right] \sim \delta_{ij}\left[p_0 + c_s \delta\rho_l + \mathcal{O}\left(\delta\rho_l^2, \partial_i v_l^i, \ldots\right)\right]$$

- We obtain equations containing only long-modes



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

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

every term allowed by symmetries

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

Perturbation Theory
with the EFT

Perturbation Theory within the EFT

- In the EFT we can solve iteratively $\delta_\ell, v_\ell, \Phi_\ell \ll 1$, where $\delta = \frac{\delta\rho}{\rho}$

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

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

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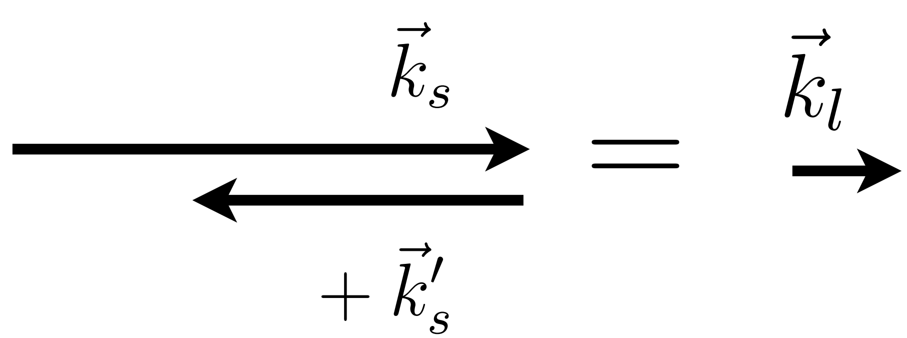
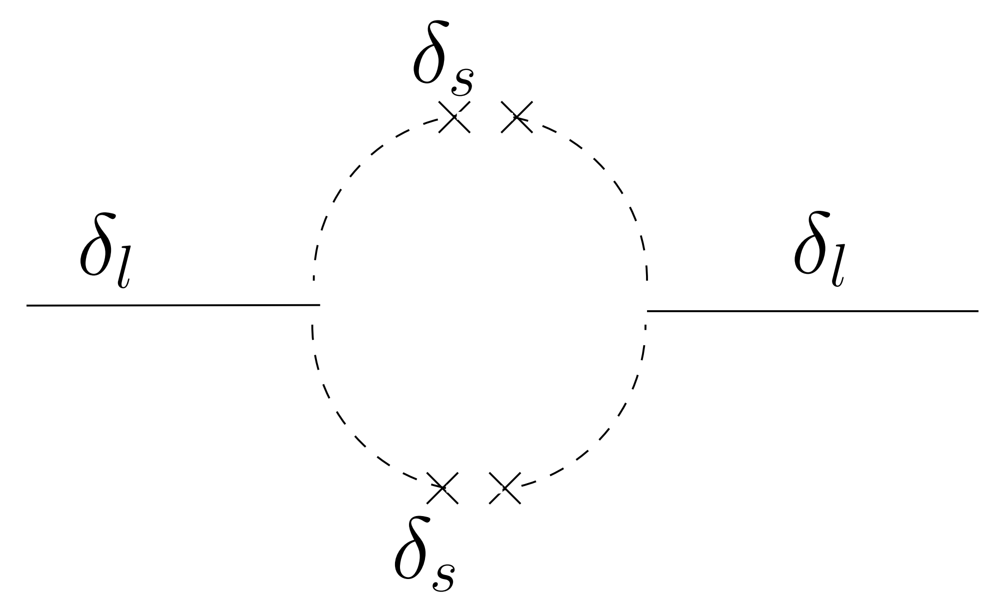
Perturbation Theory within the EFT

- Solve iteratively in $\delta = \dfrac{\delta\rho}{\rho}$
- Since equations are non-linear, we obtain convolution integrals (loops)

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

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





- Integrand has support at high wavenumber where expressions do not make sense
- Need to add counterterms from $\tau_{ij} \supset c_s^2 \, \delta\rho$ to make the result finite and correct

Perturbation Theory within the EFT

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

  – evaluate with cutoff:

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

$$\langle\left(\frac{\delta\rho}{\rho}\right)_k^2\rangle$$

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

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

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

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

–we just re-derived renormalization

–after renormalization, result is finite and small for $\frac{k}{k_{\rm NL}} \ll 1$

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  – we just re-derived renormalization

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Lesson from Renormalization

- Each loop-order L contributes 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
  - crucial difference with all former approaches

- This happens after canceling the divergencies with counterterms

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

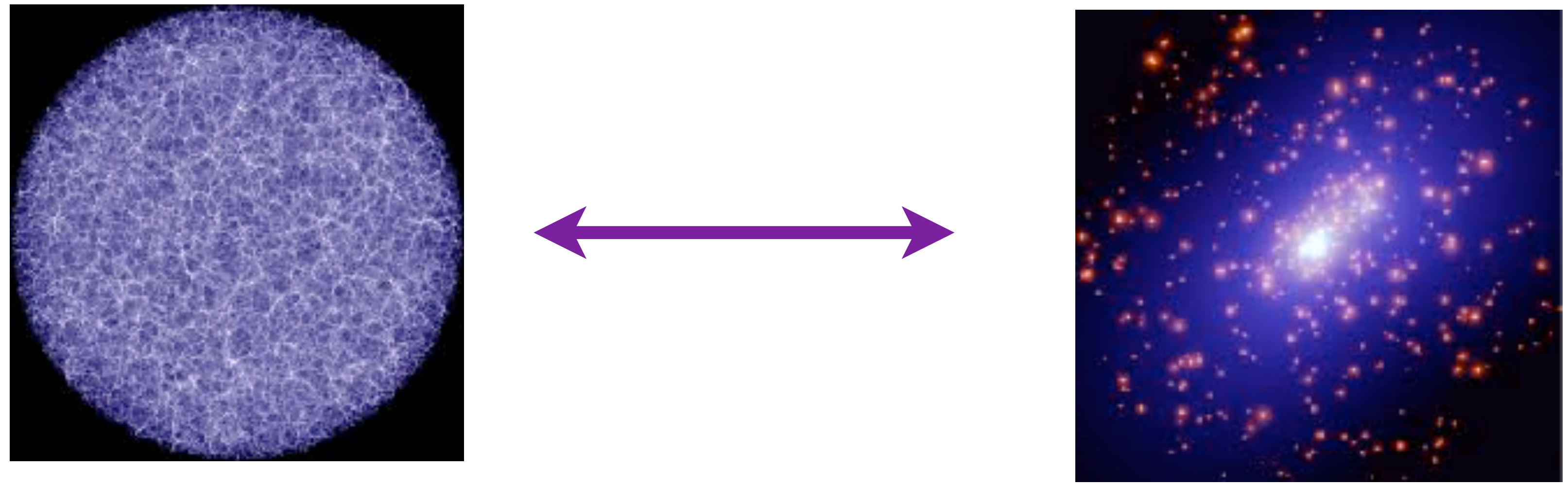
  - each loop contributes the same

Interesting (Q)FT subtleties

Non-locality in Time

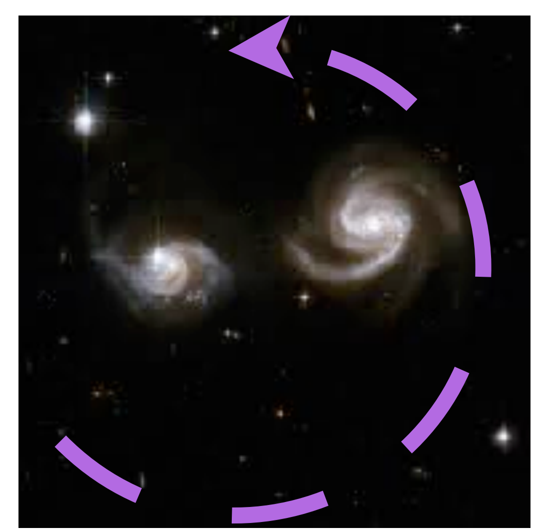
This EFT is non-local in time

- 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

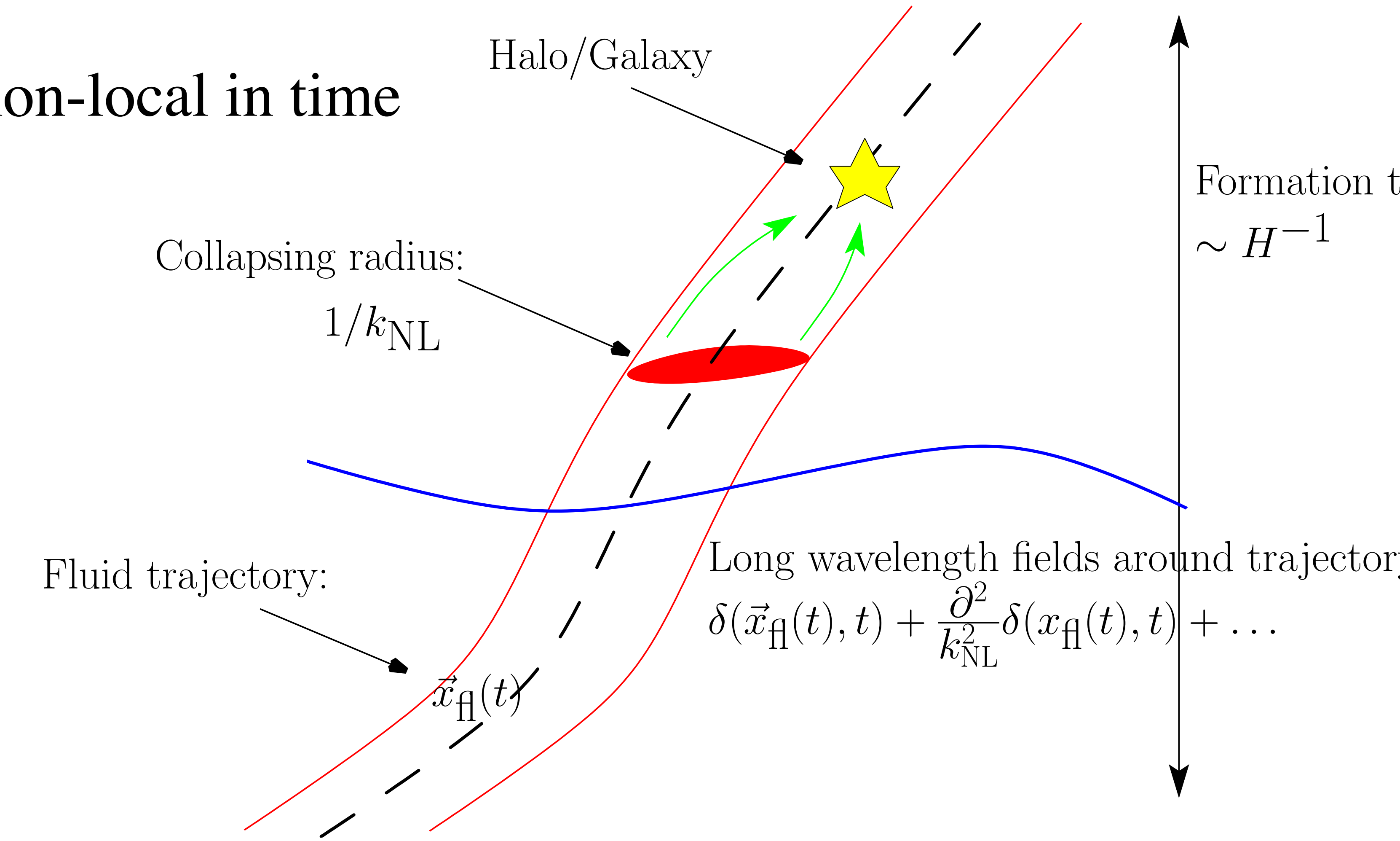
with Carrasco, Foreman and Green **1310**
Carroll, Leichenauer, Pollak **1310**



$$\sim H \sim \frac{\partial_t \delta\rho_l}{\delta\rho_l}$$

This EFT is non-local in time

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



$$\langle\tau_{ij}(\vec x,t)\rangle_{\text{long fixed}}=f_{\text{very complicated}}\left[\{H(t'),\Omega_{\rm dm}(t'),\dots,\rho_{\rm dm}(x',t'),\dots,m_{\rm dm},\dots\}|_{\text{on past light cone}}\right]$$

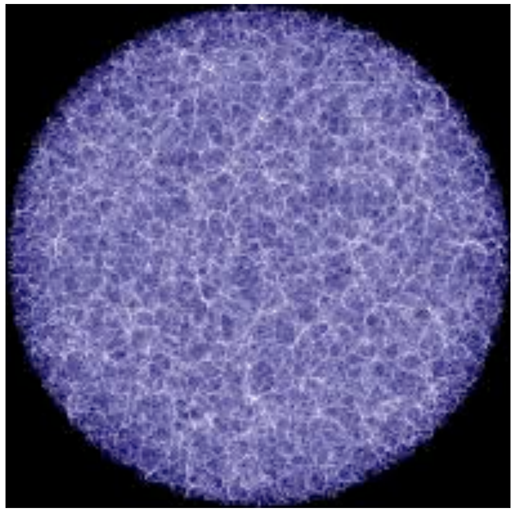
- At long-wavelengths, the only fluctuating fields have small fluctuations: Taylor expand

$$\Rightarrow\quad \langle\tau_{ij}(\vec x,t)\rangle_{\text{long fixed}}=\int^t dt'\;K_1(t,t')\;\frac{\delta\rho}{\rho}(x_{\rm fl},t')+\mathcal{O}\left((\delta\rho/\rho)^2\right)$$

A non-renormalization Theorem

A non-renormalization theorem

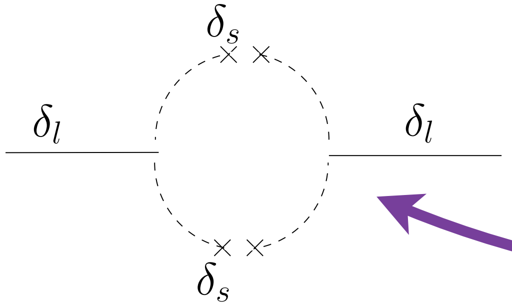
with Baumann, Nicolis and Zaldarriaga **JCAP 2012**



- Can the short distance non-linearities change completely the overall expansion rate of the universe, possibly leading to acceleration without Λ ?
- In terms of the short distance perturbation, the effective stress tensor reads

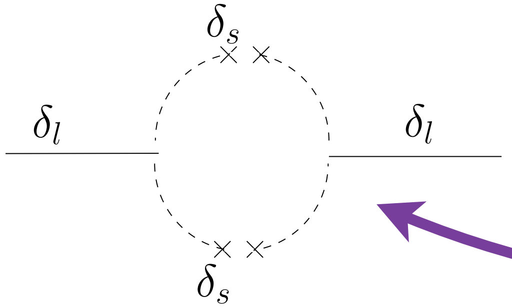
$$\rho_L \simeq \rho(1 + v_s^2/2 + \Phi_s) \ , \quad p_L \simeq \rho(v_s^2 + \Phi_s) \ .$$

- when objects virialize, induced pressure vanish $\langle \rho(v_s^2 + \Phi_s) \rangle_{\rm virialized} \to 0$
  - decoupling is the statement that UV modes are encoded in Lagrangian parameters



$$\ldots = c_s^2 \, \partial^2 \delta_l + \ldots$$

  - Here we have more: ultraviolet modes do not contribute (like in SUSY)



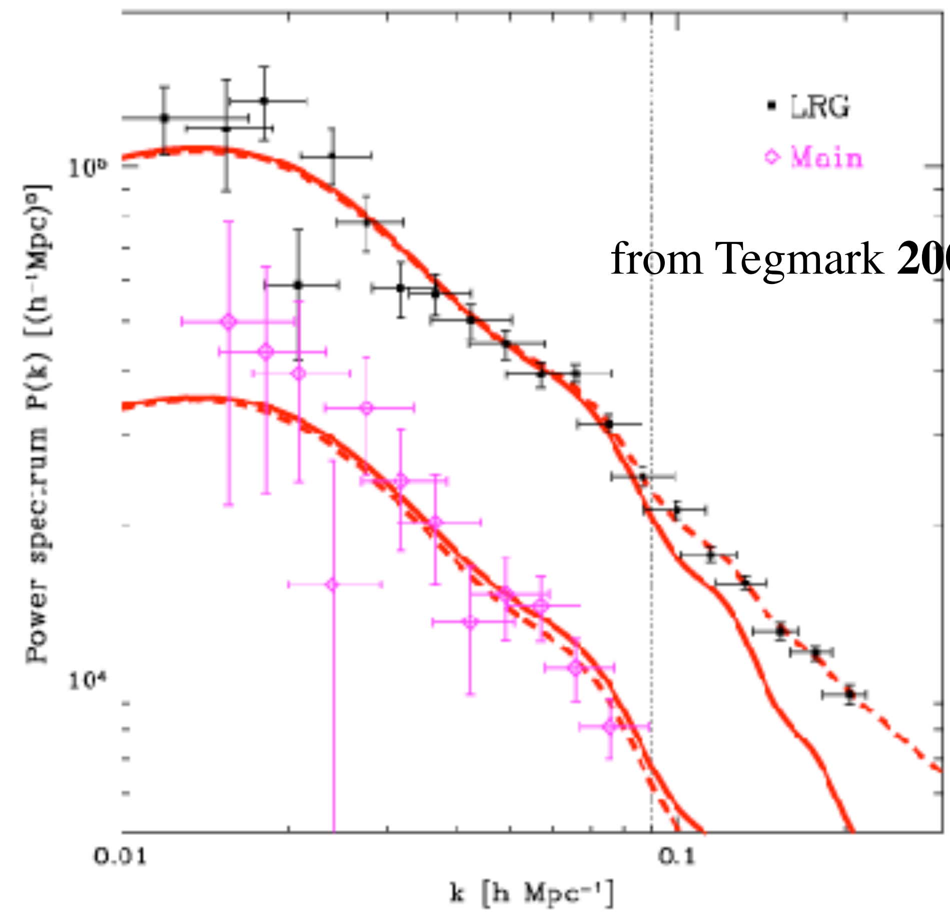
$$\ldots = 0 \cdot \partial^2 \delta_l + \ldots$$

  - this is a non-linear statement

Results for Dark Matter

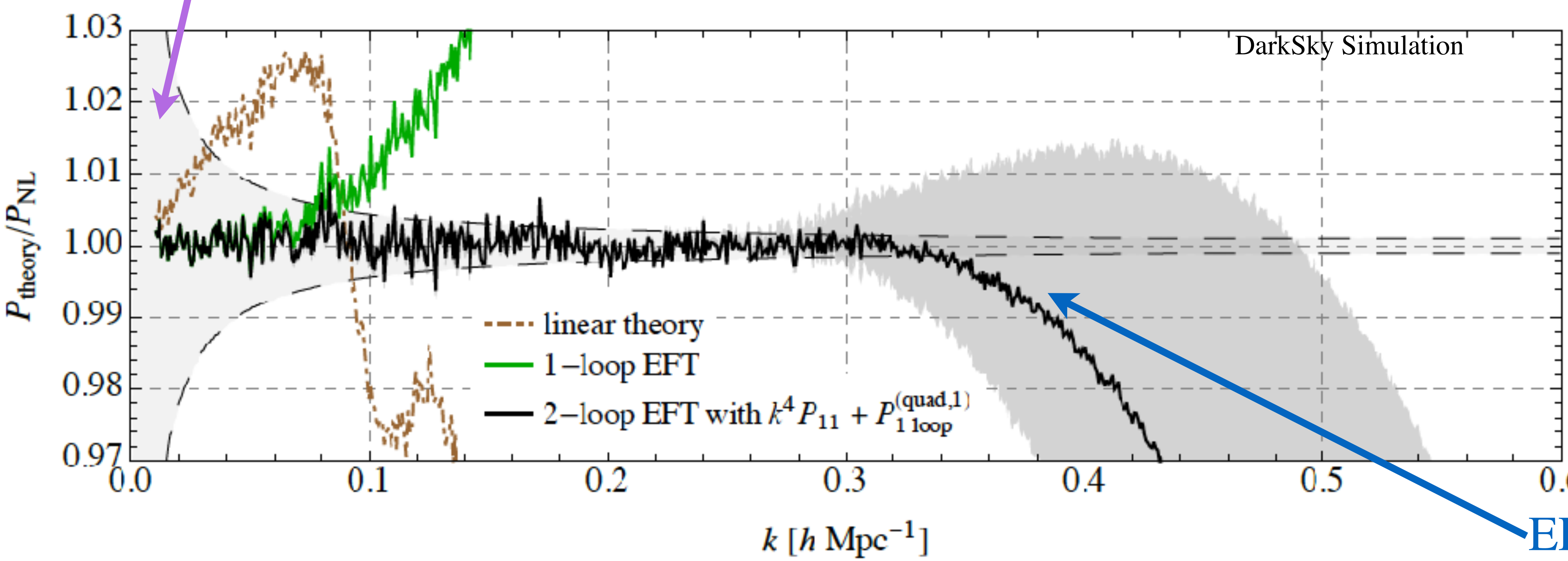
Dark Matter 2-pt function

- Precise Comparison of power spectra



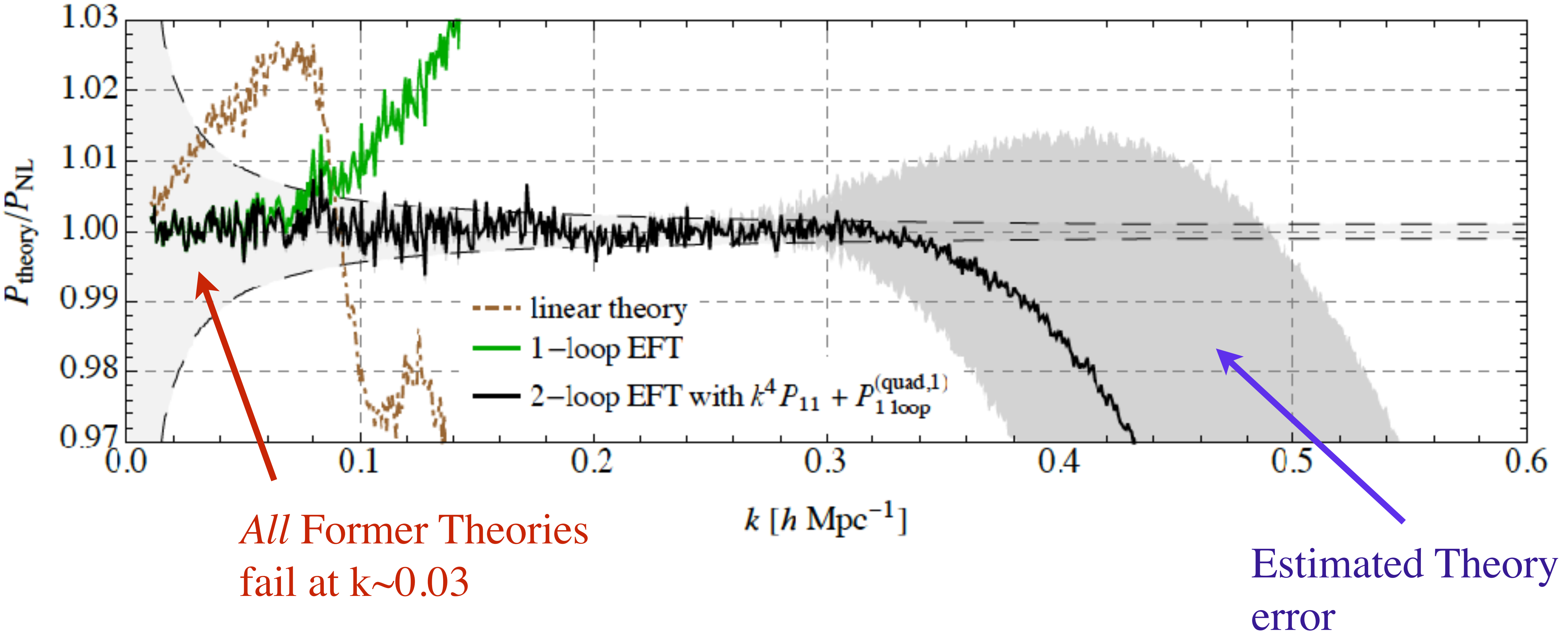
from Tegmark **2005**

Precision comparison



EFTofLSS

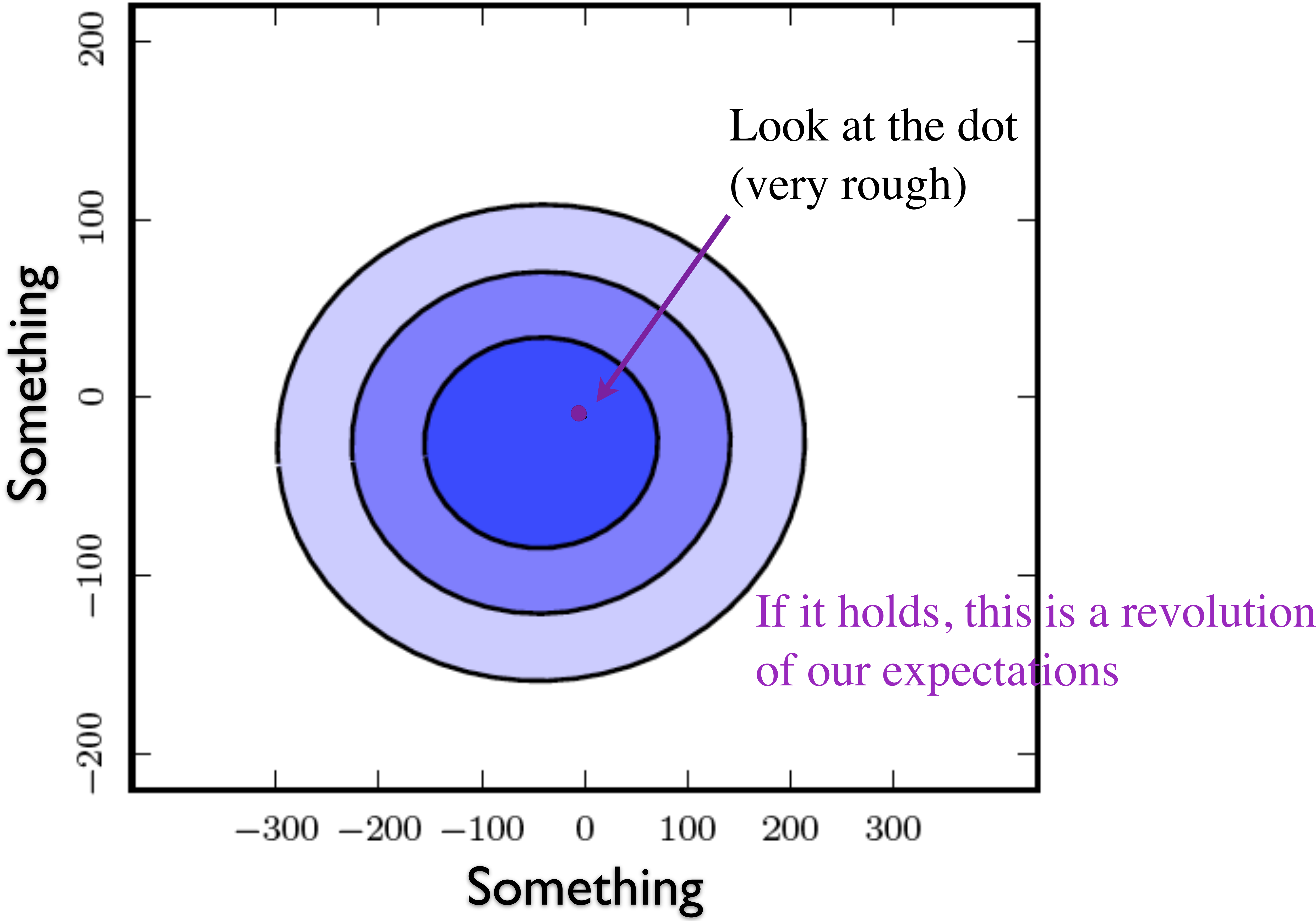
EFT of Large Scale Structures at Two Loops



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

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

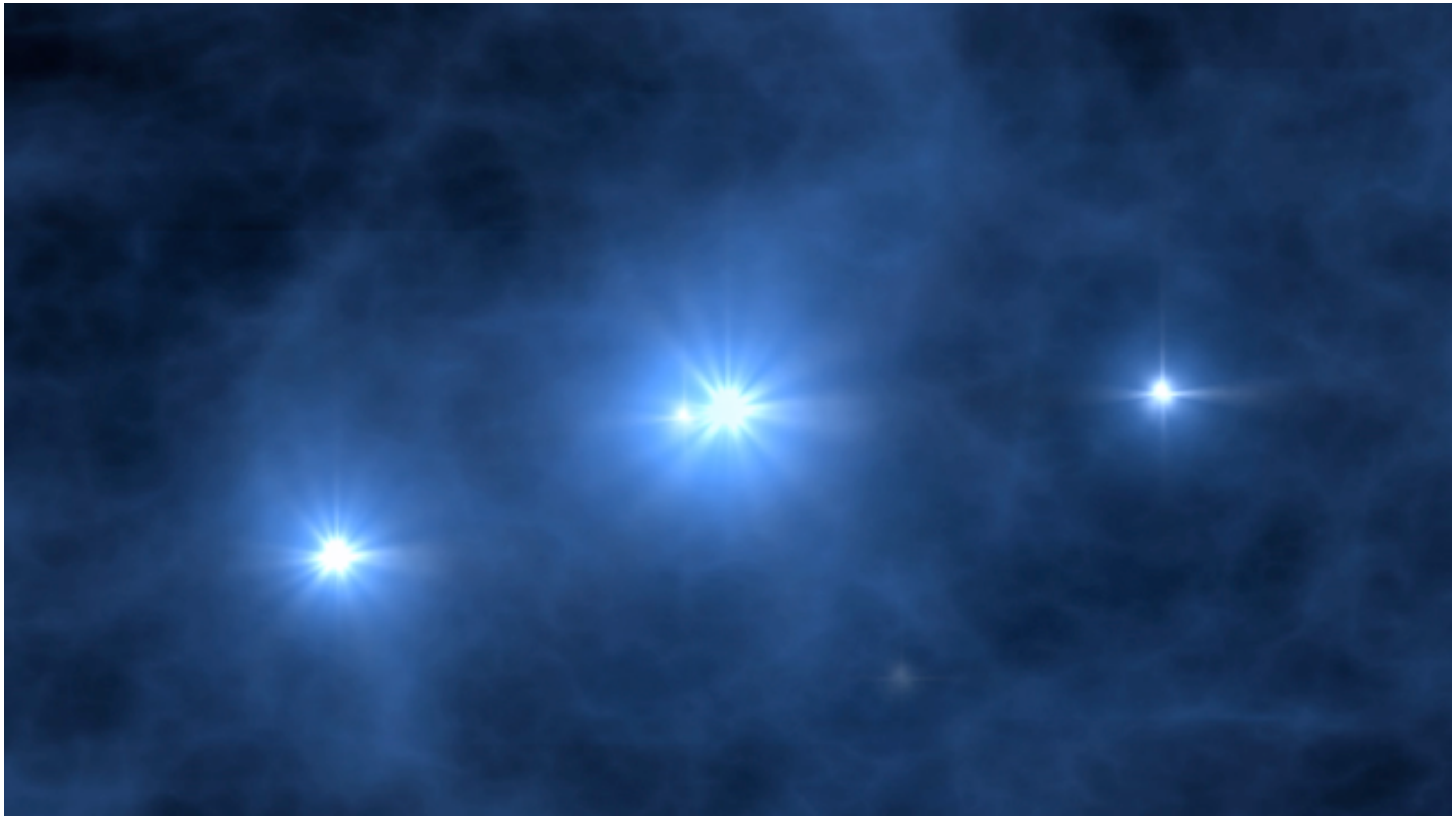
With this


Look at the dot
(very rough)
If it holds, this is a revolution
of our expectations
200
100
0
−100
−200
−300 −200 −100 0 100 200 300
Something
Something

Analytic Prediction of Baryon Effects

Baryonic effects

- When stars explode, baryons behave differently than dark matter



- They cannot be reliably simulated due to large range of scales

Baryons

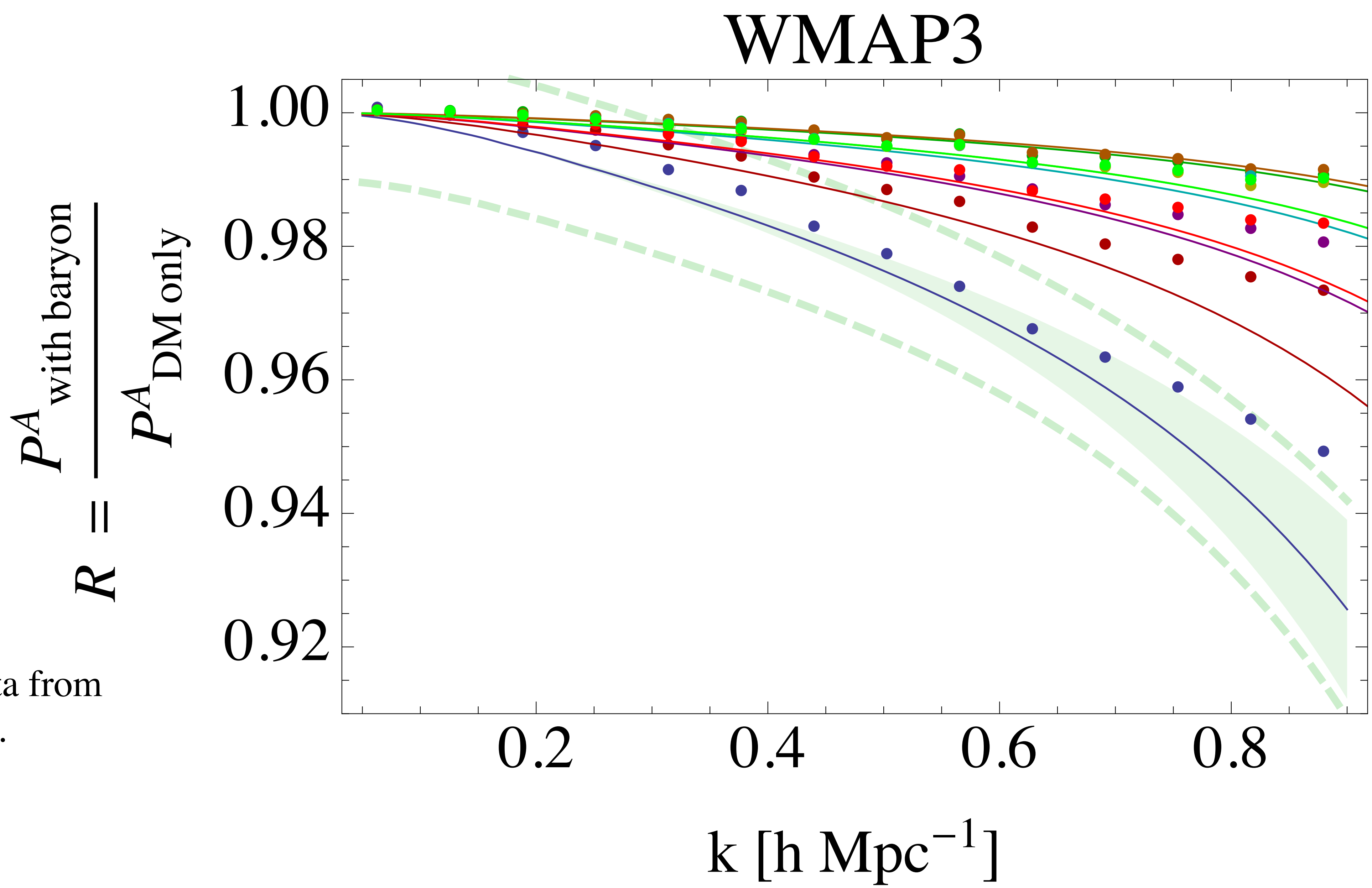
with Lewandowski and Perko **JCAP1502**
with Sgier **in progress**

- 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

Baryons



Simulation data from
J. Schaye et al.

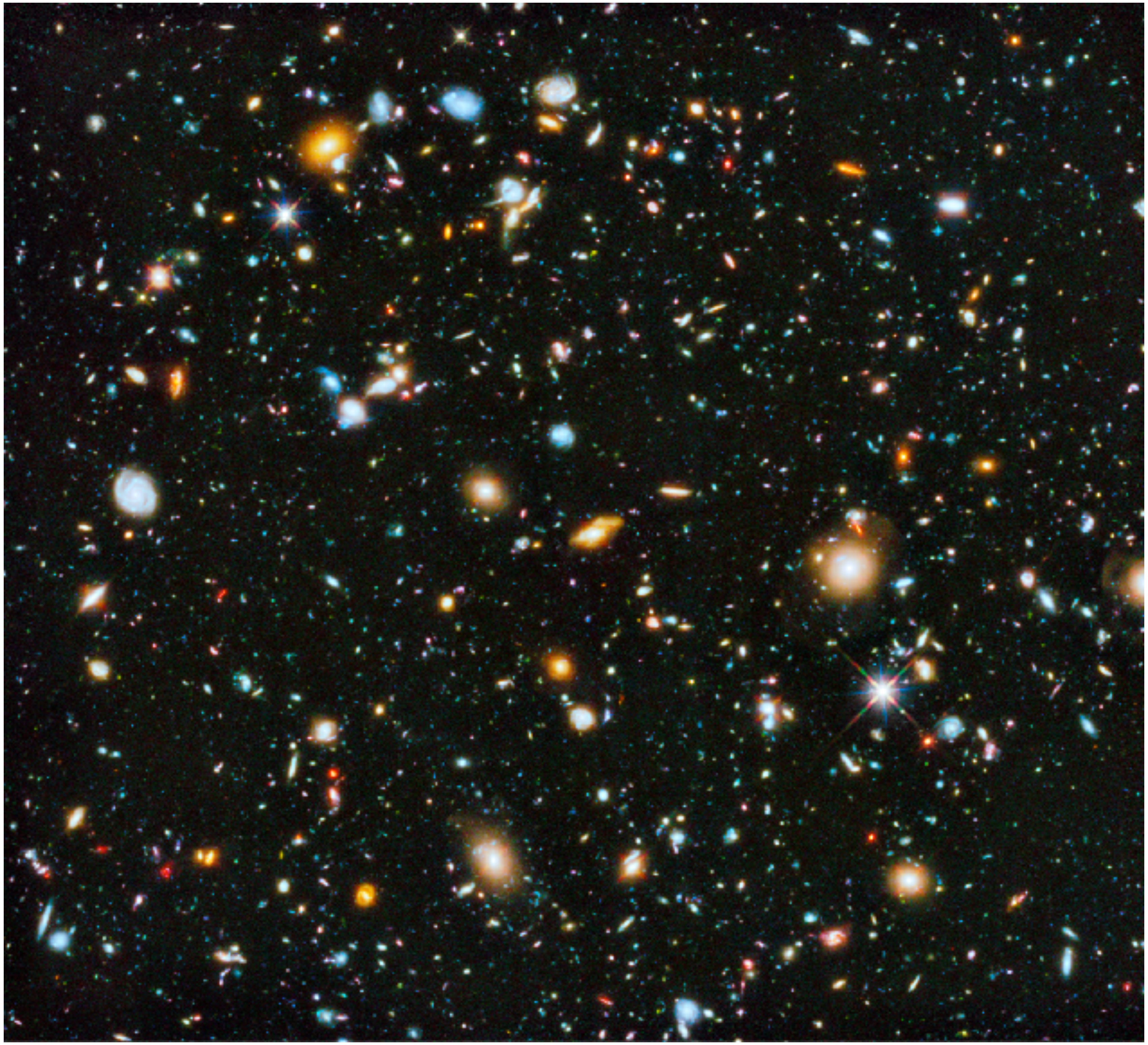
– Analytic form of effect known: $\Delta P^{(b)}(k) \sim c_\star k^2 P_{11}(k)$

– and it seems to work as expected

– from $c_\star$ learn about galaxy formation physics

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

Galaxy Statistics

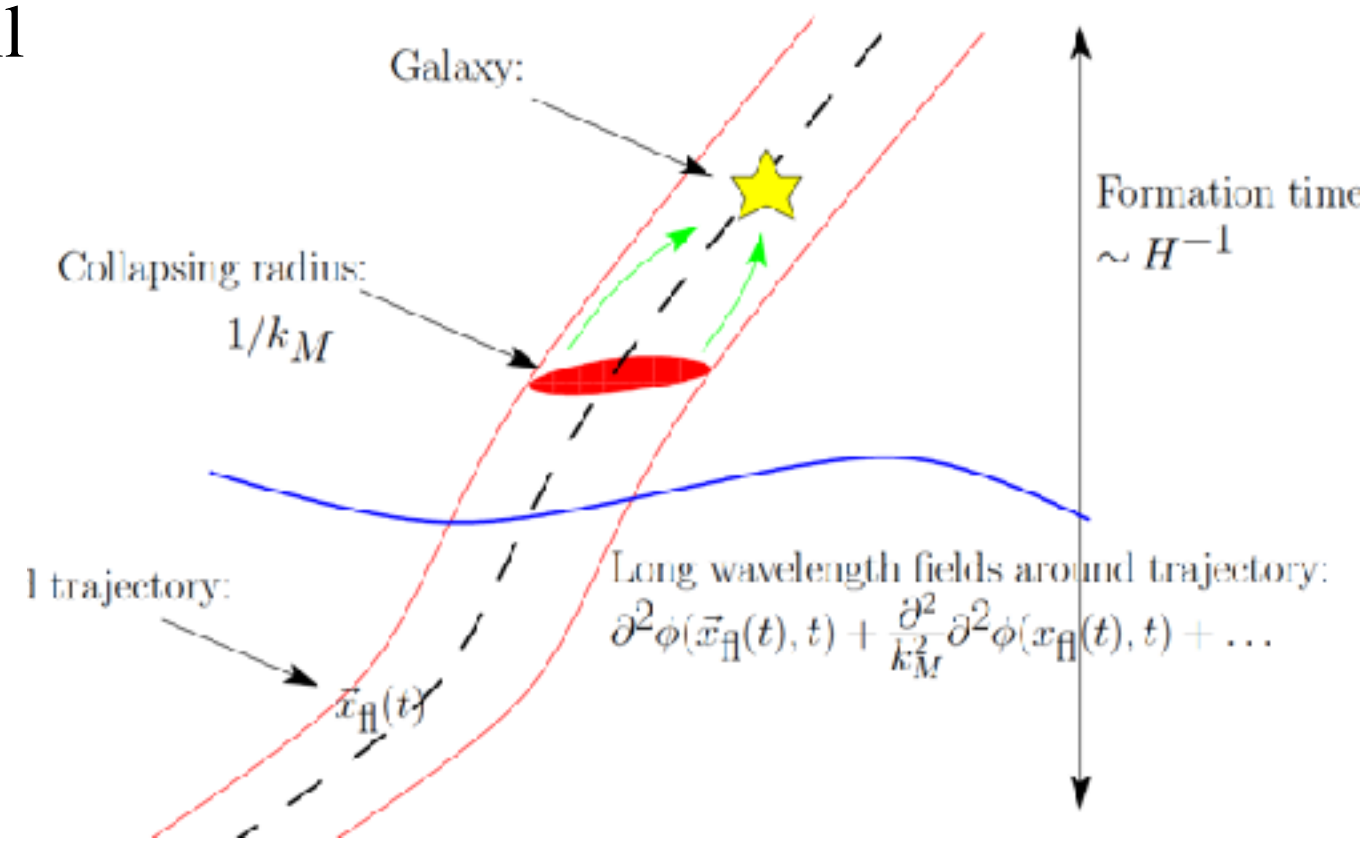


Galaxies in the EFTofLSS

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

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

- 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 **JCAP2015**

endpoint of long historical study by
Kaiser, MacDonald, Scheth, Scoccimarro, Seljak …

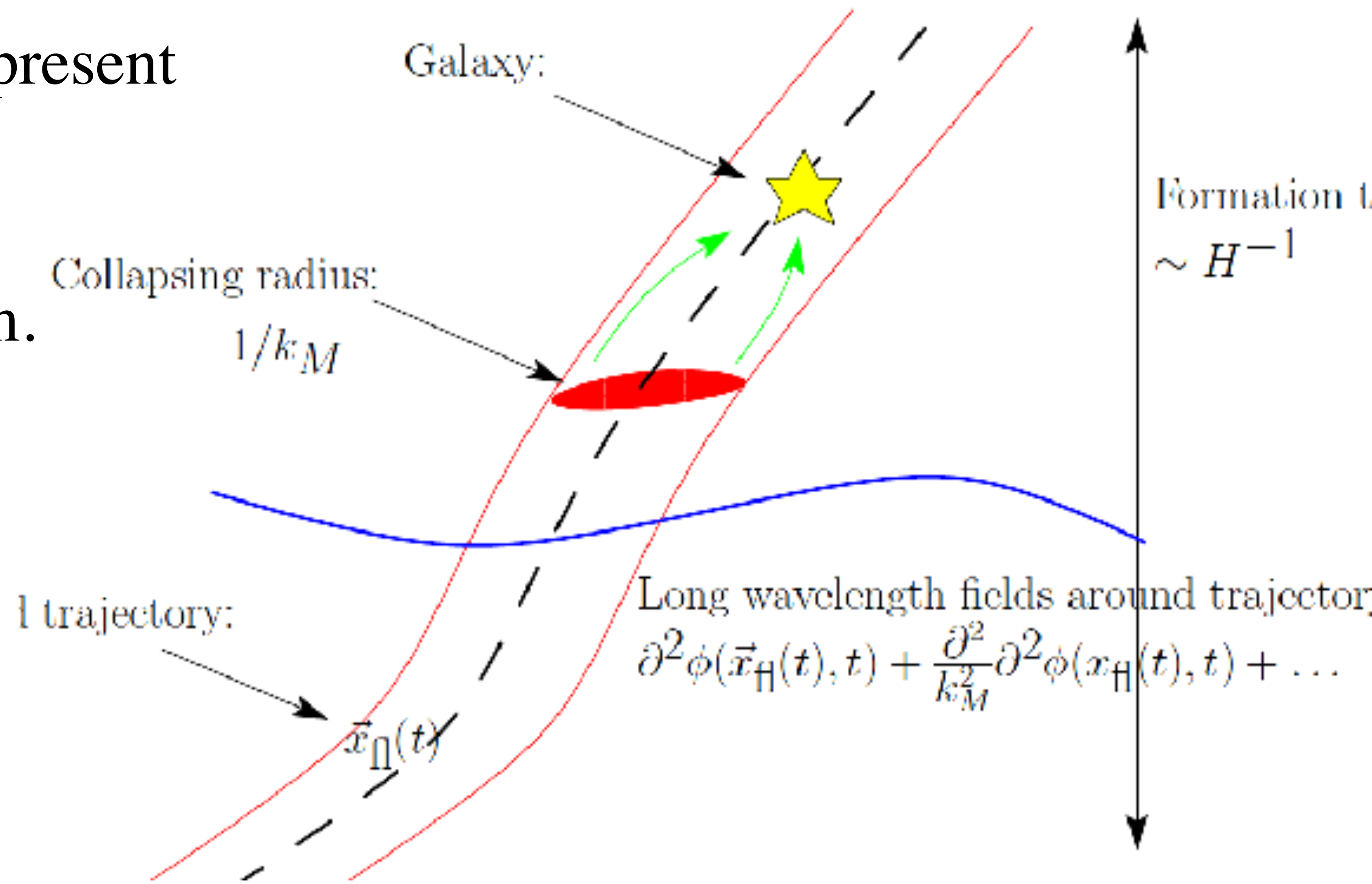
- Therefore

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

$\Downarrow$ Taylor Expansion

$$\left.\frac{\delta n}{n}\right|_{\text{galaxy}}(\vec{x},t) \sim \int dt' \left[K(t,t')\frac{\delta\rho}{\rho}(x_{\rm fl},t') + \mathcal{O}\left((\delta\rho/\rho)^2,\ldots\right)\right]$$

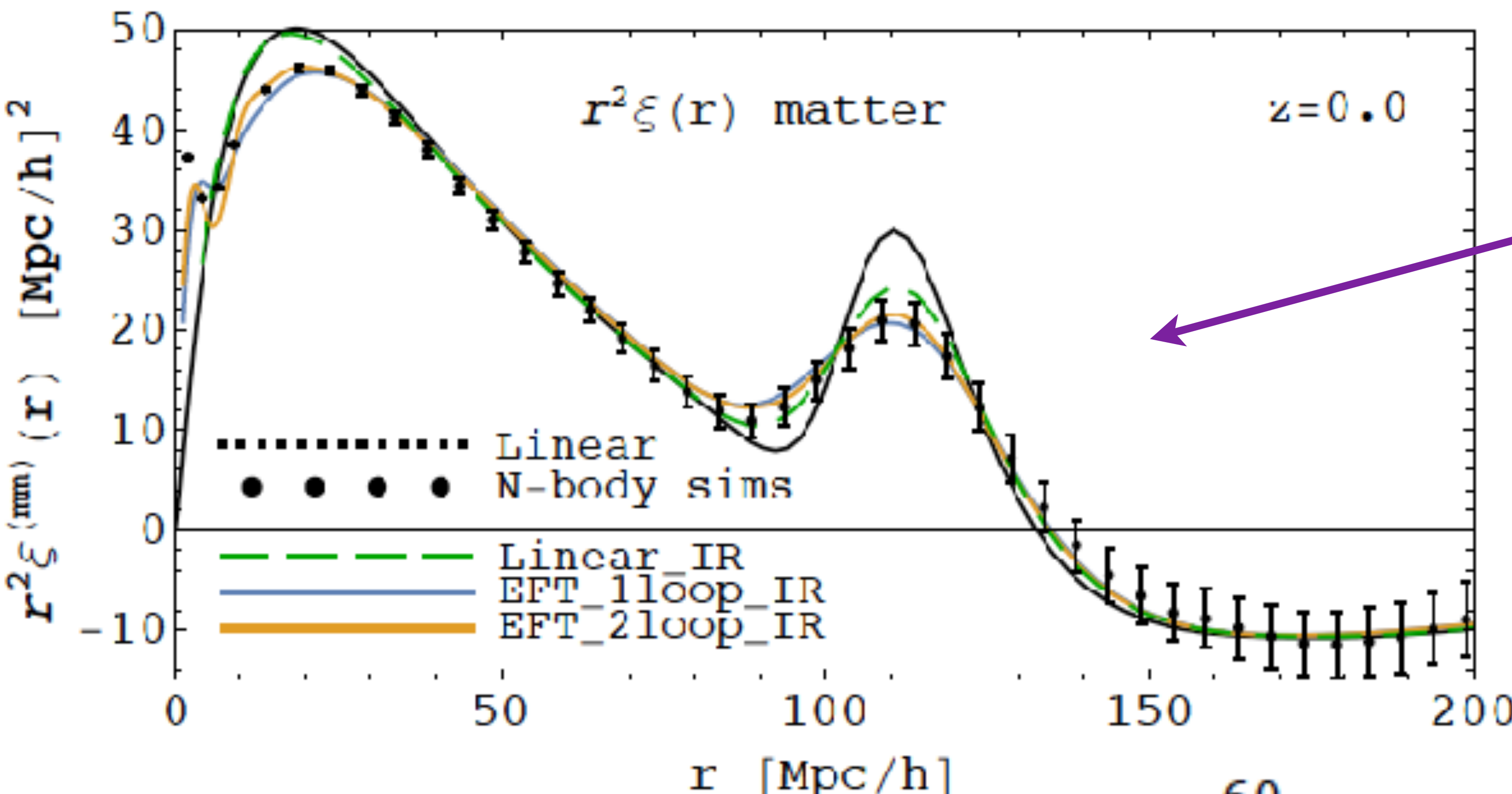
- all terms allowed by symmetries are present
- same story as for dark matter
  - –predictions depend on some param.



Halos in the EFTofLSS

with Angulo, Fasiello, Vlah **JCAP2015**

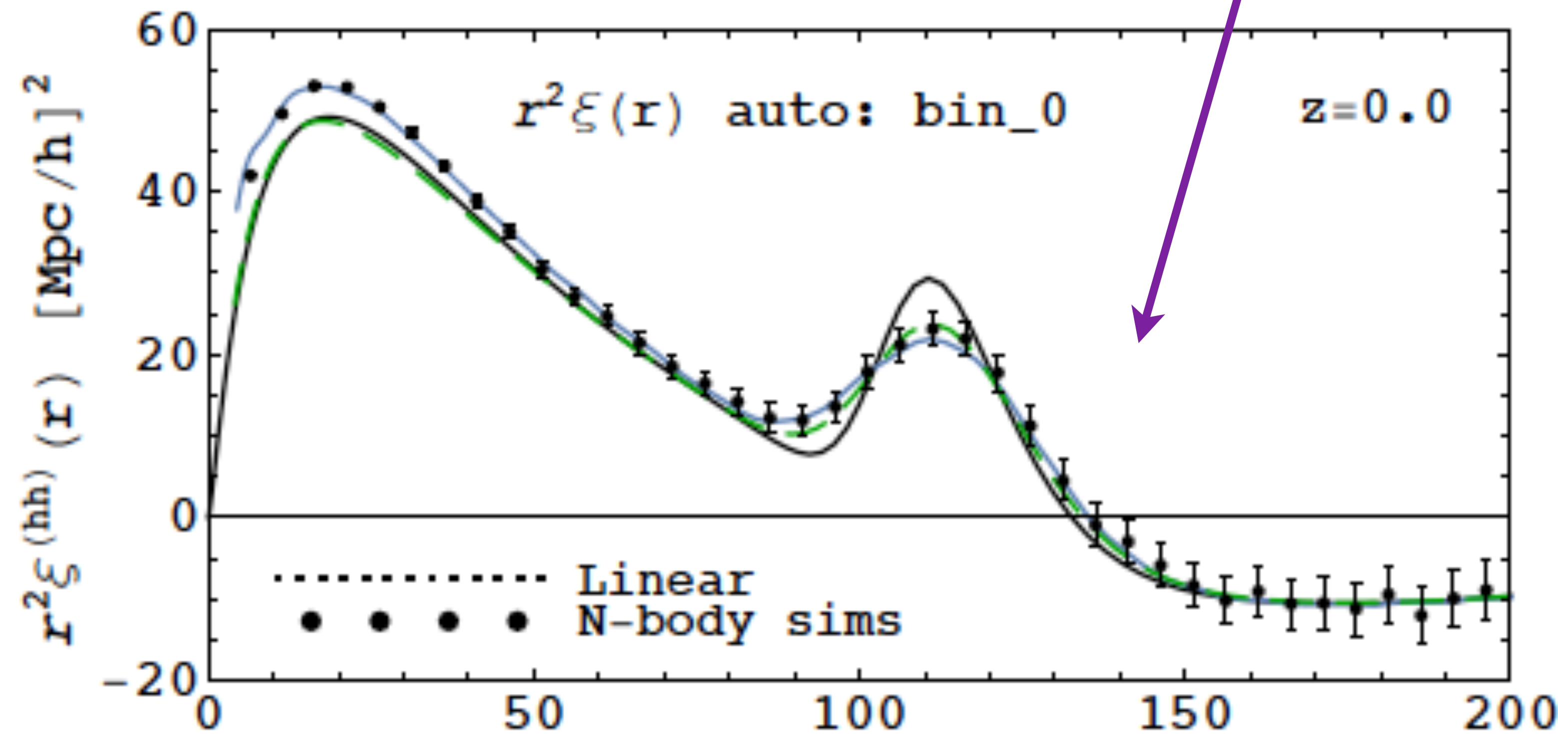
- Real space & the BAO feature



Dark Matter

Halos

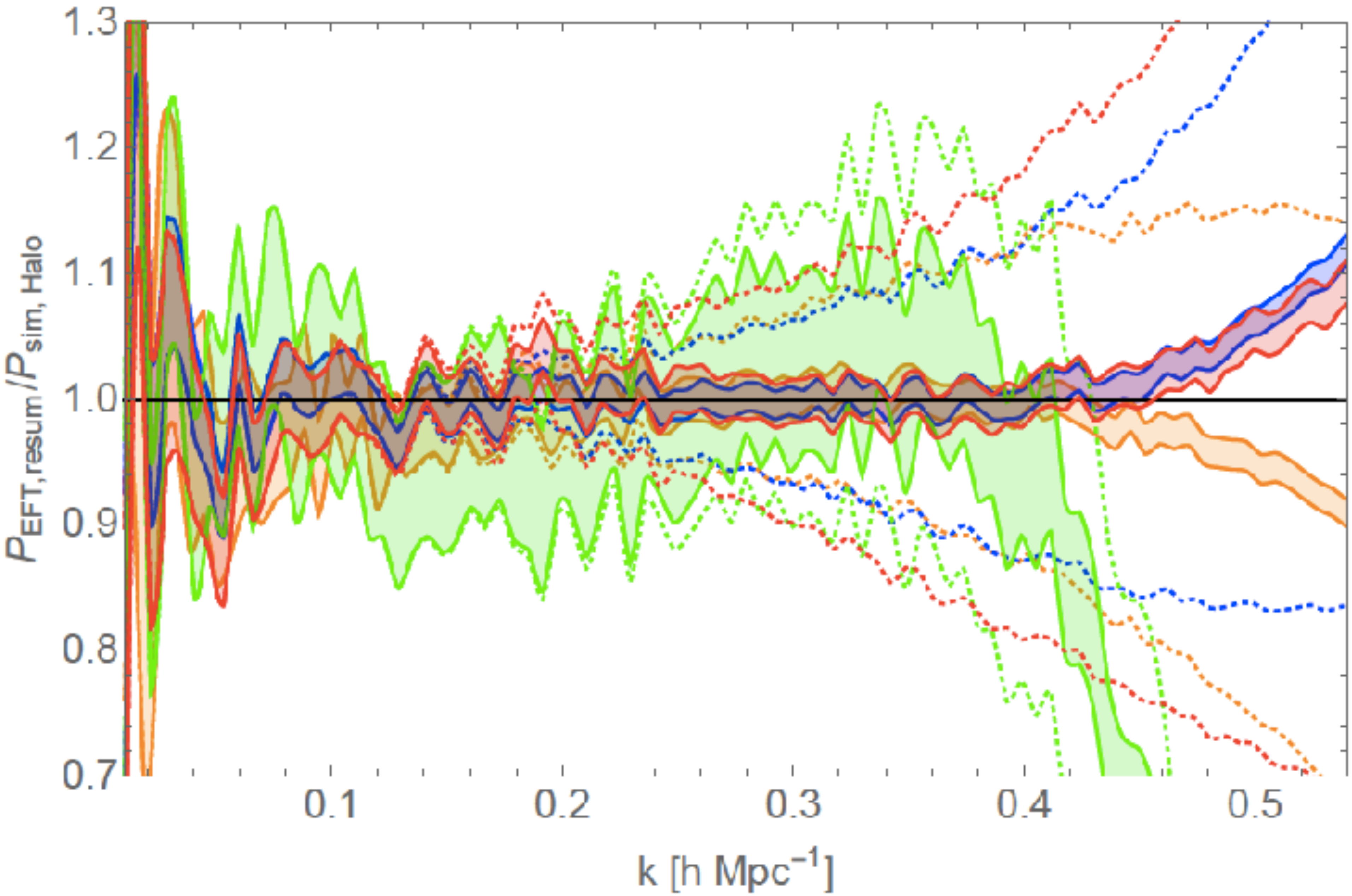
- Also similar logic to
  - redshift space distortions
    with Perko **1610**
  - baryonic effects for galaxies
  - primordial non-Gaussianities
    with Angulo, Fasiello, Vlah **1503**
  - ….
    Assassi et al **1506, 1509**
    with Lewandowski **1512**
    with Perko **1610**



We have just computed the actual observables

with Lewandowski **2016**
with Perko **2016**

- Simulated Galaxies in redshift space

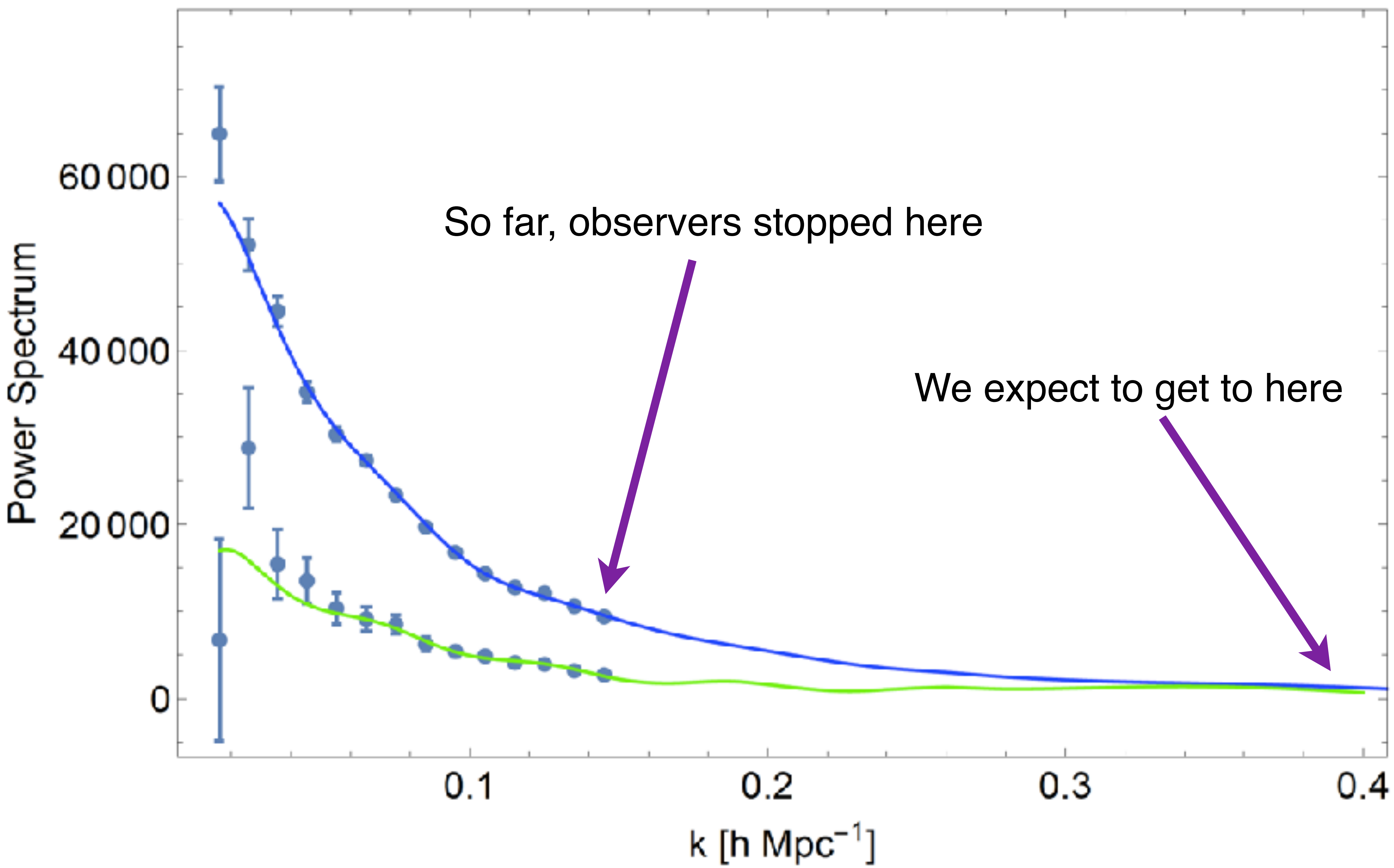


- and working through actually analyzing the observational data with it.
  - we are finally ready for them!

First comparison with SDSS data

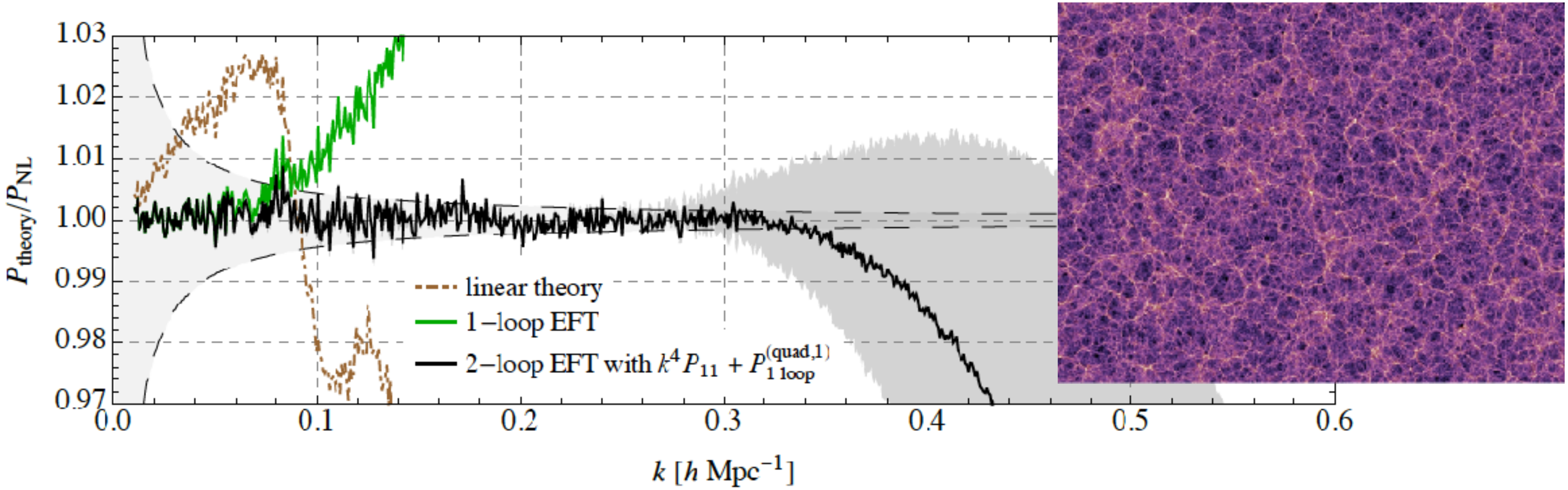
with Perko **2016**
with Beutler et al.**, in progress**

- The end of a journey:



- We should get to much higher k 's, where data have never been analyzed, and where there is much more information.

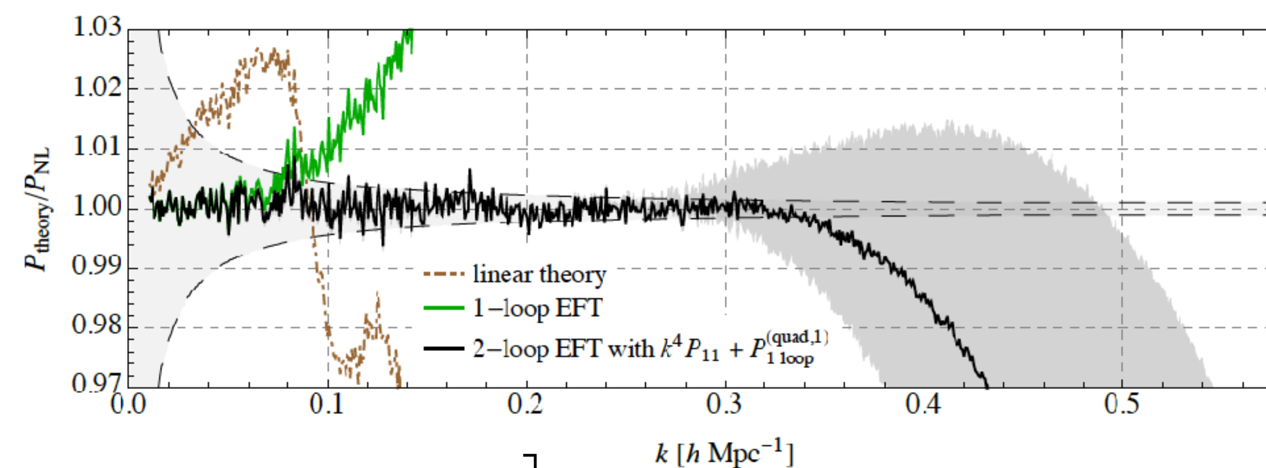
The EFT of Large Scale Structures



- A manifestly well-defined perturbation theory $\left(\frac{k}{k_{\text{NL}}}\right)^L$ in terms of emergent ~fluid
- It describes something true, the real universe: many application for astrophysics
- It uses novel techniques that come from particle physics
- We seem to match until much higher wavenumbers than previously believed.
  - –huge impact on possibilities, for ex: non-Gaussianities, neutrinos, dark energy.
- This is an great opportunity and a challenge for us, while we reach observations,
  - –Many calculations and verifications to do (very similar to QCD).

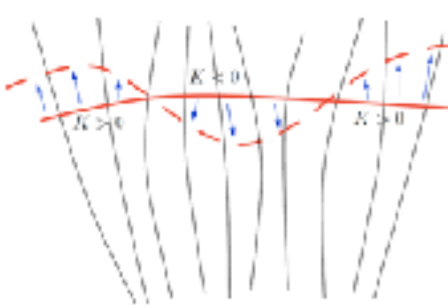
Conclusions

- Cosmology:
  - –a land of mysteries for high energy physics
  - – a land for exploring beautiful complex system
  - – a land for applying EFT techniques
- The EFT of Inflation: a powerful way of parametrizing inflation
- The EFTofLSS: a powerful way to analytically describe Large-Scale Structure
  - –by now, these are quite well established subfields, regularly taught in graduate courses
- Lots of room for applying EFT in Cosmology



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

- A recent exploration into diff. geometry and to advanced numerical GR, allowed us to make progress on decade old problems. This has just started



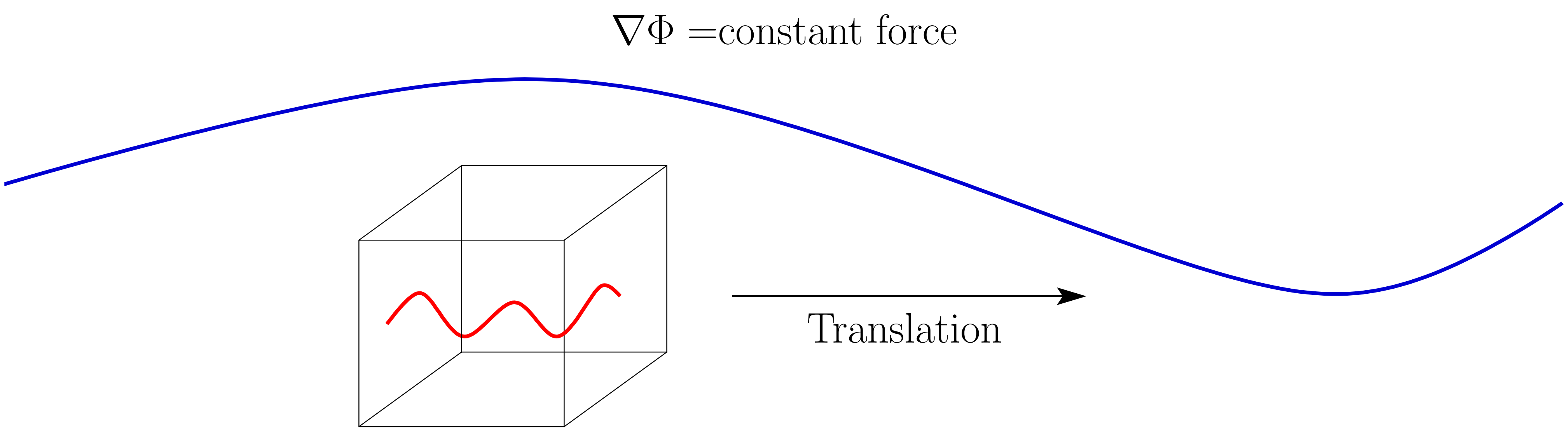
Extra

Expansion parameter

Connecting with the Eulerian Treatment

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

Effect of Long Displacements

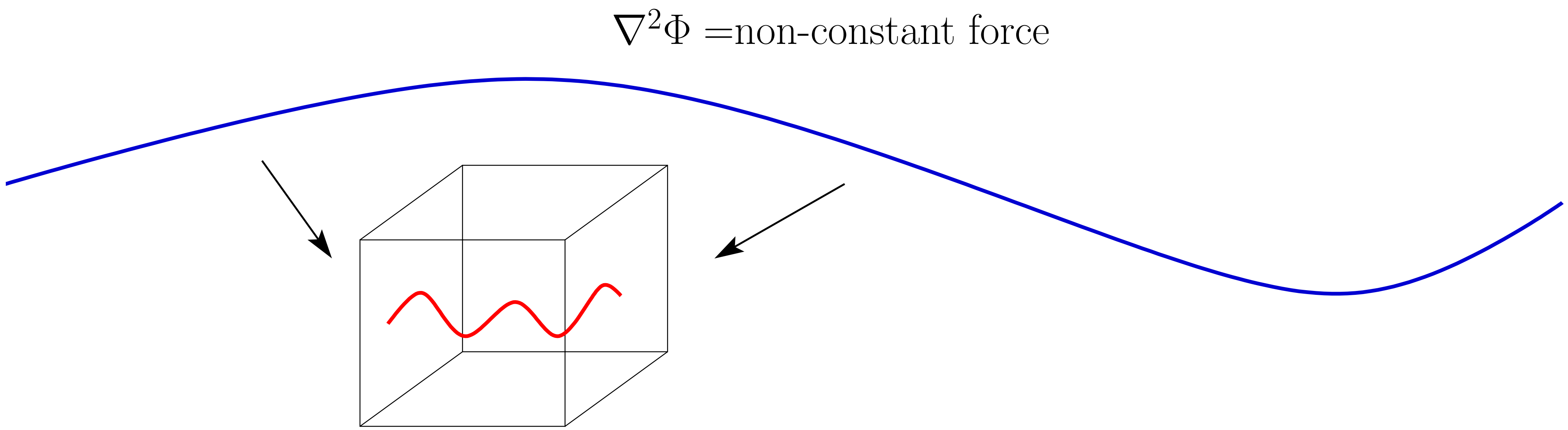


  - By Einstein's equivalence theorem, it can be undone by going to inertial frame
  - Effect of long displacements is important and need to be treated non-perturbatively
    - IR-resummation with Zaldarriaga **JCAP1502**

Connecting with the Eulerian Treatment

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

Effect of Tidal Forces



  - we need to Taylor expand in this
  - we are solving perturbatively in the effects of tidal forces among modes

Halos Power and Bispectrum

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

Halos in the EFTofLSS

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

Senatore **1406**

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

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

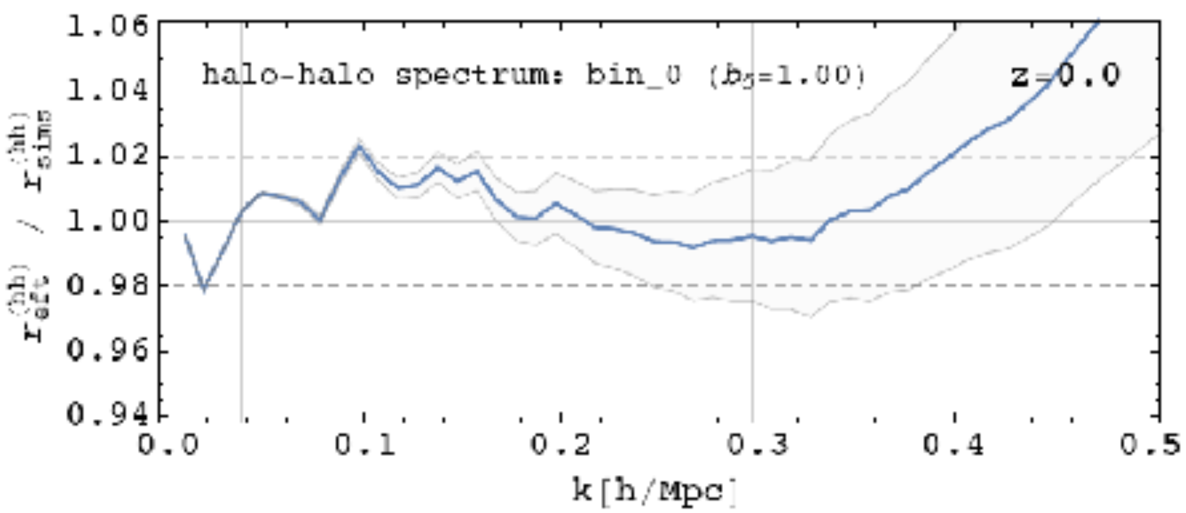
- Since evolution is k-independent, we can formally evaluate the integrals, to obtain only 7 parameters for
  - at 1-loop power spectrum
  - tree level bispectrum
  - tree level trispectrum

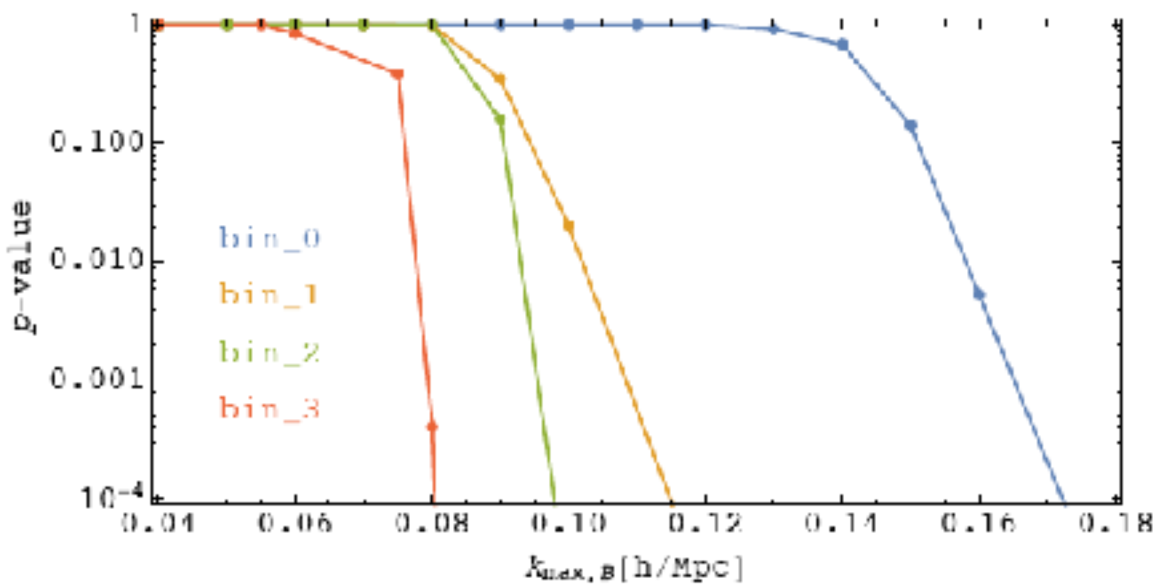
Halos in the EFTofLSS

with Angulo, Fasiello, Vlah **1503**

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





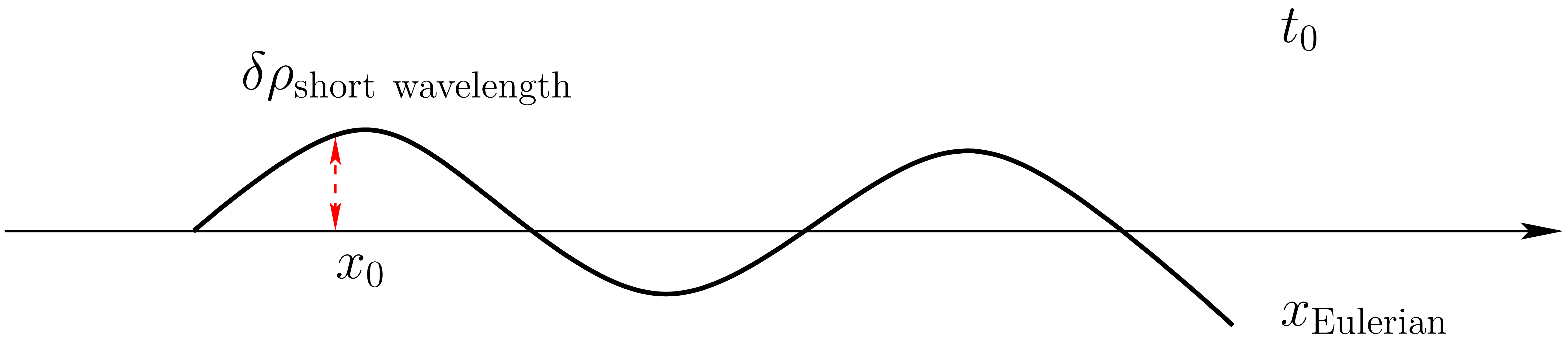
  - the 3pt function measures very well the bias coefficients (there is a lot of data)
    - 4pt function is predicted
  - Similar formulas just worked out for redshift space distortions

with Zaldarriaga **1409**

IR-effects

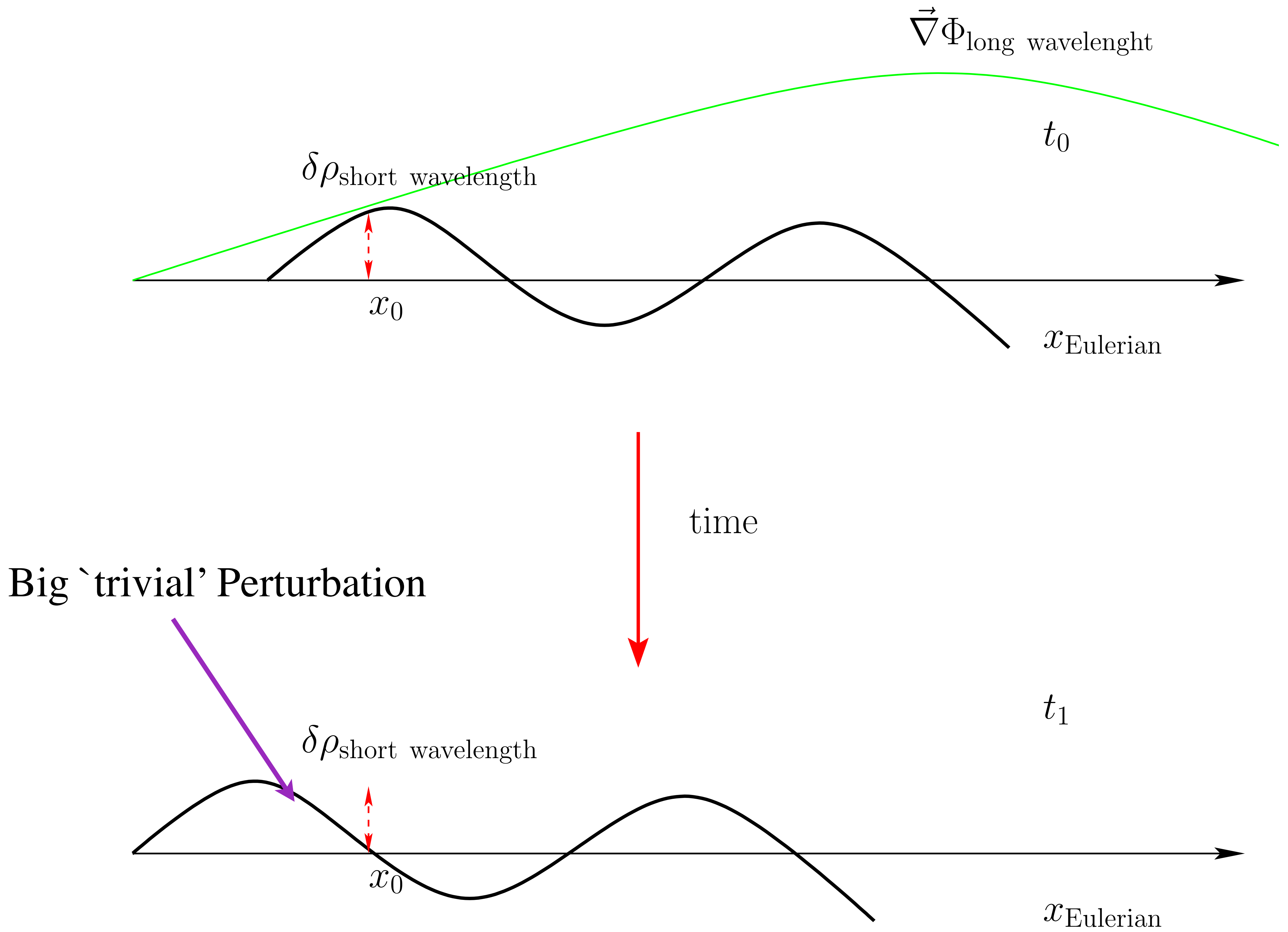
The Effect of Long-modes on Shorter ones

- In Eulerian treatment



The Effect of Long-modes

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



Baryons

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

$$\nabla^2\phi = \frac{3}{2}H_0^2\frac{a_0^3}{a}(\Omega_c\delta_c + \Omega_b\delta_b)$$
$$\dot\delta_c = -\frac{1}{a}\partial_i((1+\delta_c)v_c^i)$$
$$\dot\delta_b = -\frac{1}{a}\partial_i((1+\delta_b)v_b^i)$$
$$\partial_i\dot v_c^i + H\partial_i v_c^i + \frac{1}{a}\partial_i(v_c^j\partial_j v_c^i) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_c^i + \frac{1}{a}\partial_i(\gamma)_c^i \ ,$$
$$\partial_i\dot v_b^i + H\partial_i v_b^i + \frac{1}{a}\partial_i(v_b^j\partial_j v_b^i) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_b^i + \frac{1}{a}\partial_i(\gamma)_b^i \ ,$$

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

Baryons

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

Source of gravity

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

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

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

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

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

Each-species' mass conservation

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

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

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Baryons

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

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

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

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Stress tensor like term:
two derivatives from momentum conservation

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

Baryons

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

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

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

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

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

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

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Redshift space

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.

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

- 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 goes repeats

- IR-resummation much more non-trivial, due to breaking of symmetries (just done)