The BOSS bispectrum analysis at one loop from the EFT of LSS

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CIPANP, 08/31/22

outline

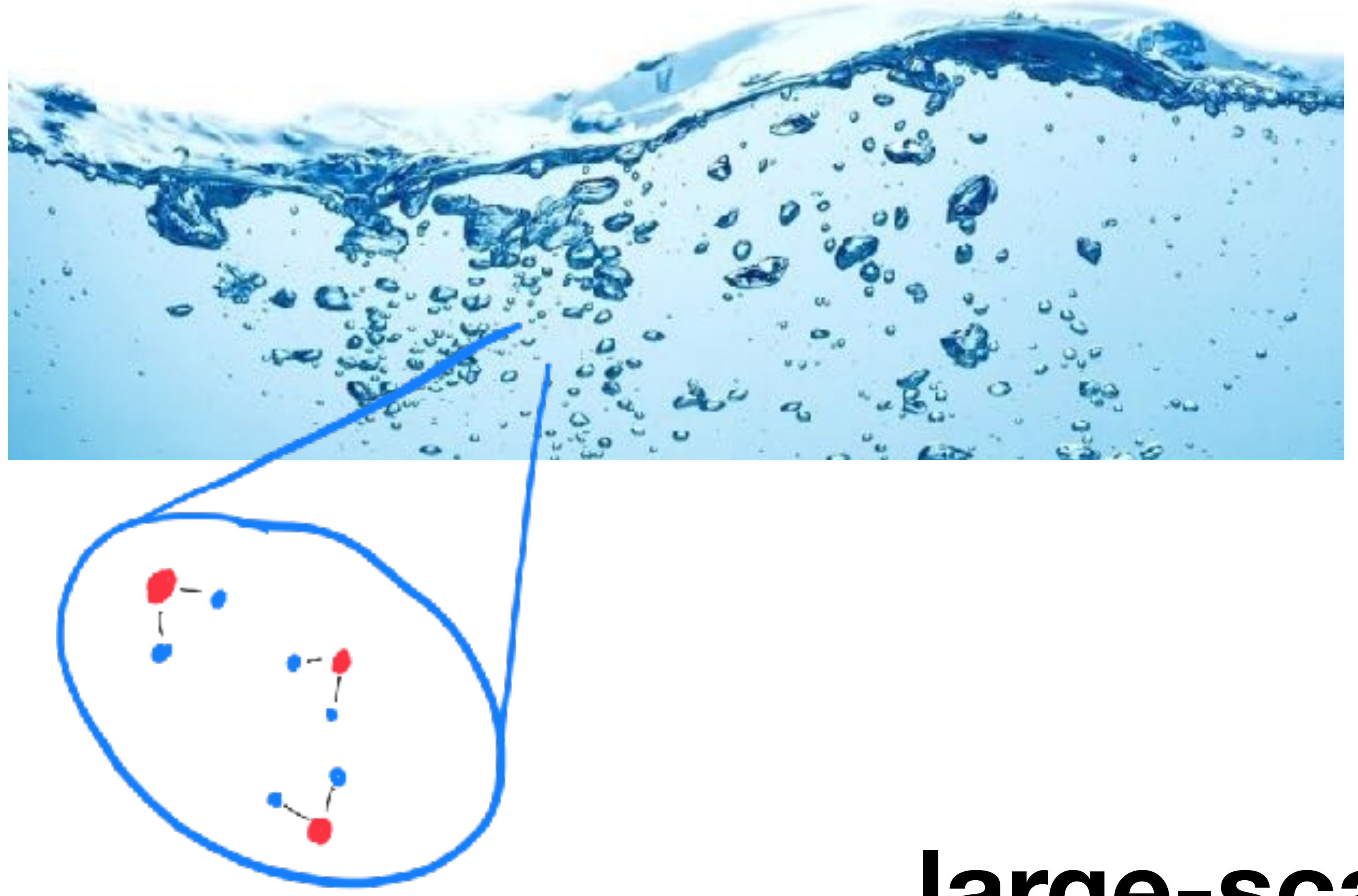
- review of EFT of LSS
- recent progress in BOSS analysis from the EFT of LSS
- the road ahead

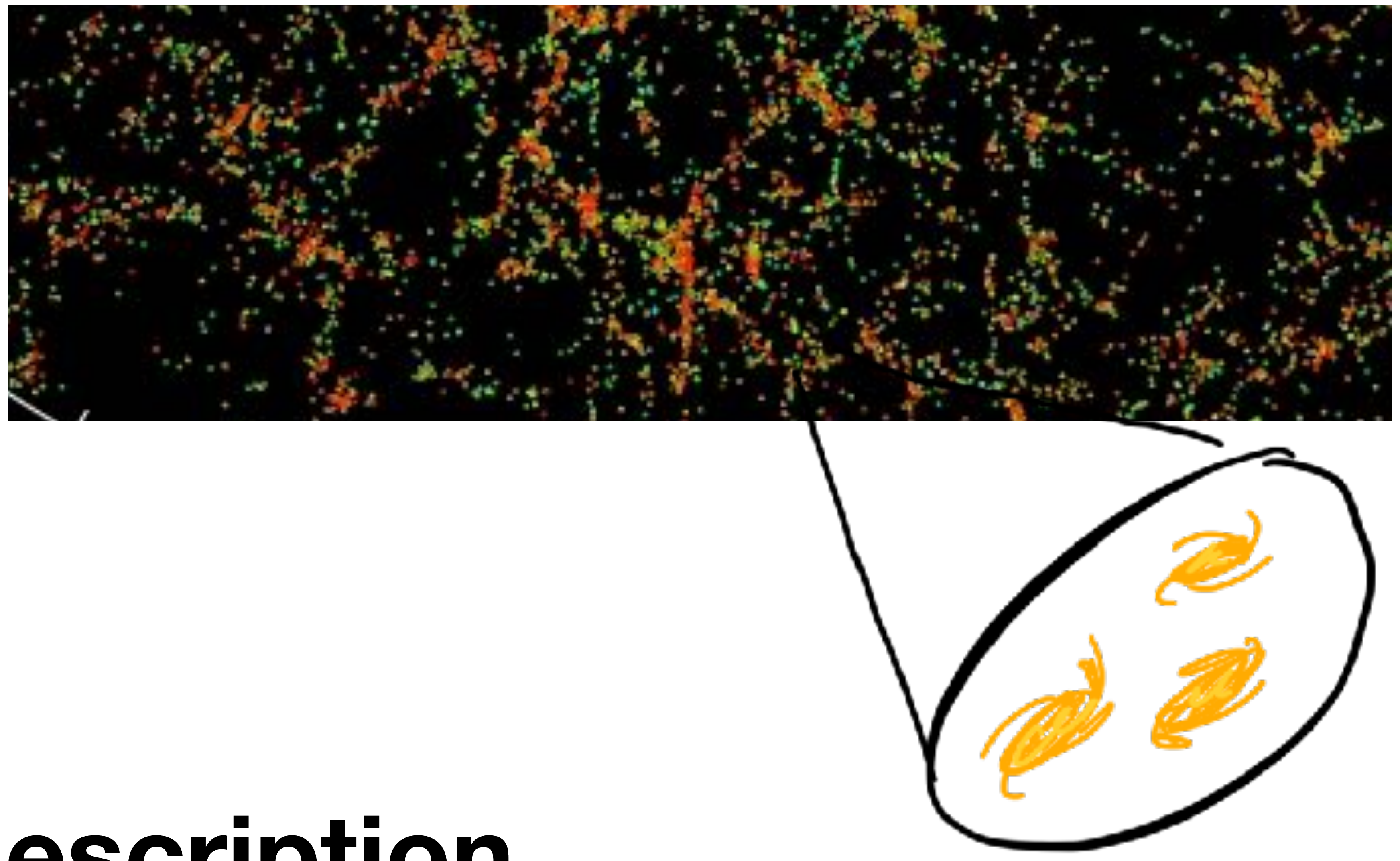
in collaboration with

G. D'Amico, Y. Donath, L. Senatore, P. Zhang, D. Bragança, D. Sekera, R. Sgier, …

EFT of LSS review

main idea





large-scale description

viscosity ν, … EFT parameters c_s^2, …

expansion parameter

$$\frac{\lambda_{\rm mfp}}{L_{\rm obs}} \qquad \frac{L_{\rm NL}}{L_{\rm obs}} \sim \frac{k_{\rm obs}}{k_{\rm NL}}$$

low energy DOF, scales

non-relativistic, sub-horizon, fluid-like system in an expanding universe

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1-2\Psi)d\vec{x}^2 \qquad \frac{\dot{a}}{a} \equiv H$$

$$\delta(t,\vec{x}) \equiv \frac{\delta\rho(t,\vec{x})}{\bar{\rho}(t)} \qquad \delta\rho(t,\vec{x}) \equiv \rho(t,\vec{x}) - \bar{\rho}(t)$$

$$v^i(t,\vec{x})$$

$v \ll 1$ non-relativistic

$$\frac{k}{aH} \gg 1$$

sub-horizon
(Newtonian limit)

$$k_{\rm NL}^{-1} \sim \frac{v}{aH}$$

finite age of universe
(like mean free path)

$$k/k_{\rm NL} \lesssim 1$$

EFT expansion param.

dark matter EOM

$$\{\rho, v^i, \Phi\} \qquad a^{-2}\partial^2\Phi = \frac{3}{2}H^2\Omega_m\delta$$

- mass conservation
- momentum conservation
- Galilean invariance

$$x^i \to x^i + n^i(t)$$
$$t \to t + a^2 n^i(t) x^i$$

$$\partial_i \to \partial_i \qquad \partial_t \to \partial_t - \dot{n}^i(t)\partial_i \qquad \rho \to \rho$$

$$\Phi \to \Phi - a^2(\ddot{n}^i(t) + 2H\dot{n}^i(t))x^i \qquad v^i \to v^i + a\dot{n}^i(t)$$

$$\dot{\delta} + a^{-1}\partial_i((1+\delta)v^i) = 0$$

EFT of LSS

$$\partial_i \dot{v}^i + H\partial_i v^i + a^{-1}\partial^2\Phi + a^{-1}\partial_i(v^j\partial_j v^i) = -a^{-1}\partial_i(\partial_j\tau^{ij}/\rho)$$

Baumann, Nicolis, Senatore, Zaldarriaga 12

Carrasco, Hertzberg, Senatore 12

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EFT of LSS

$$\tau^{ij} \sim c_s^2\delta^{ij}\delta + c_2\partial_j v^j + c_3\partial_i\delta\partial_j\delta + c_4\partial_i\partial_j\delta + \ldots$$

Baumann, Nicolis, Senatore, Zaldarriaga 12

Carrasco, Hertzberg, Senatore 12

observables

observables - correlation functions

$$\langle \delta(\vec{k}_1)\delta(\vec{k}_2)\rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P(k_1)$$ **power spectrum**

$$\langle \delta(\vec{k}_1)\delta(\vec{k}_2)\delta(\vec{k}_3)\rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B(k_1, k_2, k_3)$$ **bispectrum**

perturbative expansion

$$P = P_{\text{linear}} + P_{\text{1-loop}} + P_{\text{2-loop}} + \ldots$$

$$B = B_{\text{linear}} + B_{\text{1-loop}} + B_{\text{2-loop}} + \ldots$$

perturbative expansion

ansatz: $$\delta_{\vec{k}}(a) = \sum_n \left(\frac{a}{a_0}\right)^n \delta_{\vec{k}}^{(n)}$$

general form of the solutions:

$$\delta_{\vec{k}}^{(n)} = \int_{\vec{k}_1,\ldots,\vec{k}_n} (2\pi)^3 \delta_D(\vec{k} - \sum_i^n \vec{k}_i) F_n(\vec{k}_1, \ldots, \vec{k}_n) \delta_{\vec{k}_1}^{(1)} \ldots \delta_{\vec{k}_n}^{(1)}$$

power spectra:

$$\langle \delta_{\vec{k}}^{(1)} \delta_{\vec{k}'}^{(1)} \rangle = (2\pi)^3 \delta_D(\vec{k} + \vec{k}') P_{11}(k)$$

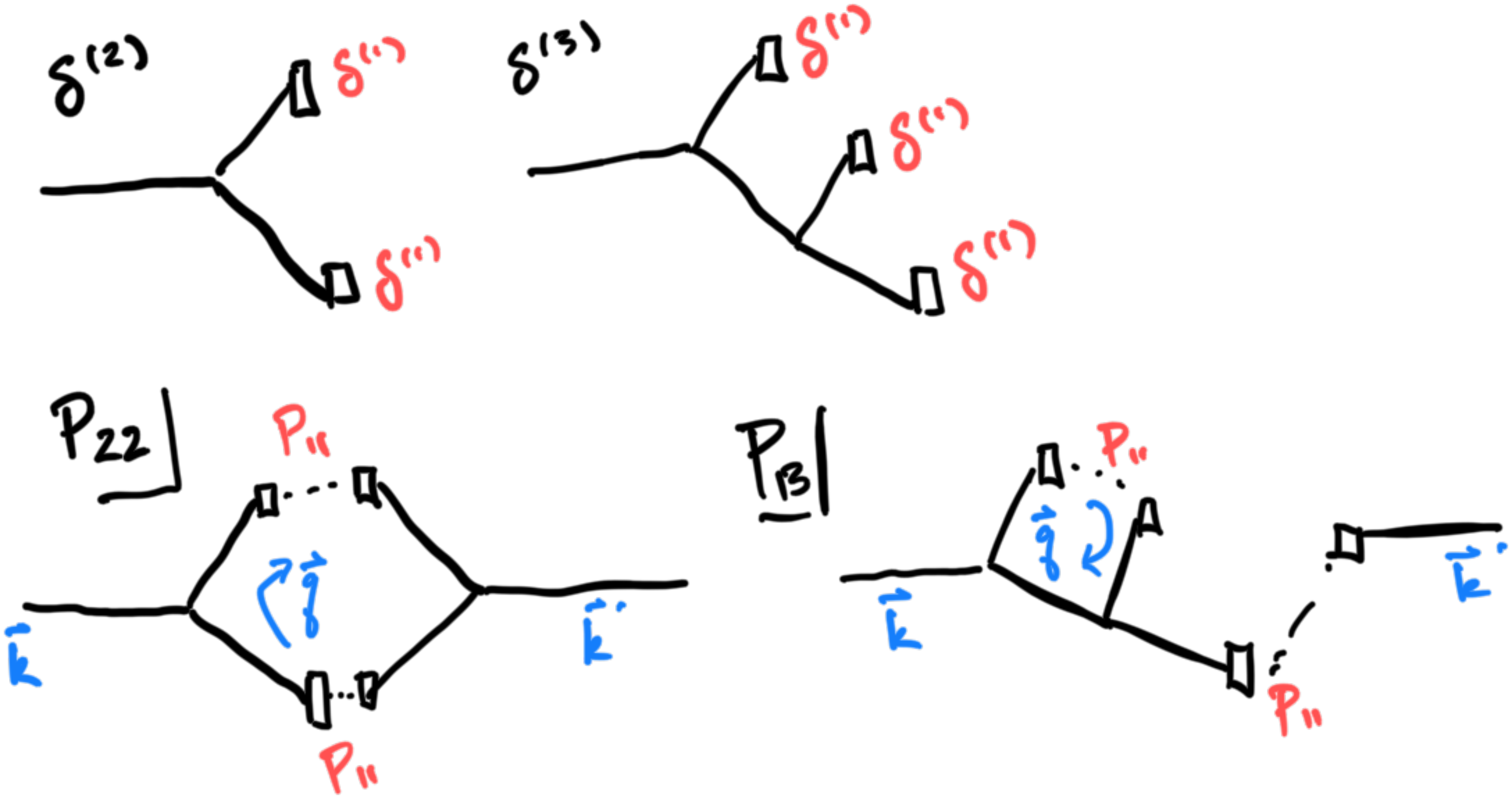
linear

$$\langle \delta_{\vec{k}}^{(2)} \delta_{\vec{k}'}^{(2)} \rangle = (2\pi)^3 \delta_D(\vec{k} + \vec{k}') P_{22}(k)$$

$$2\langle \delta_{\vec{k}}^{(1)} \delta_{\vec{k}'}^{(3)} \rangle = (2\pi)^3 \delta_D(\vec{k} + \vec{k}') P_{13}(k)$$

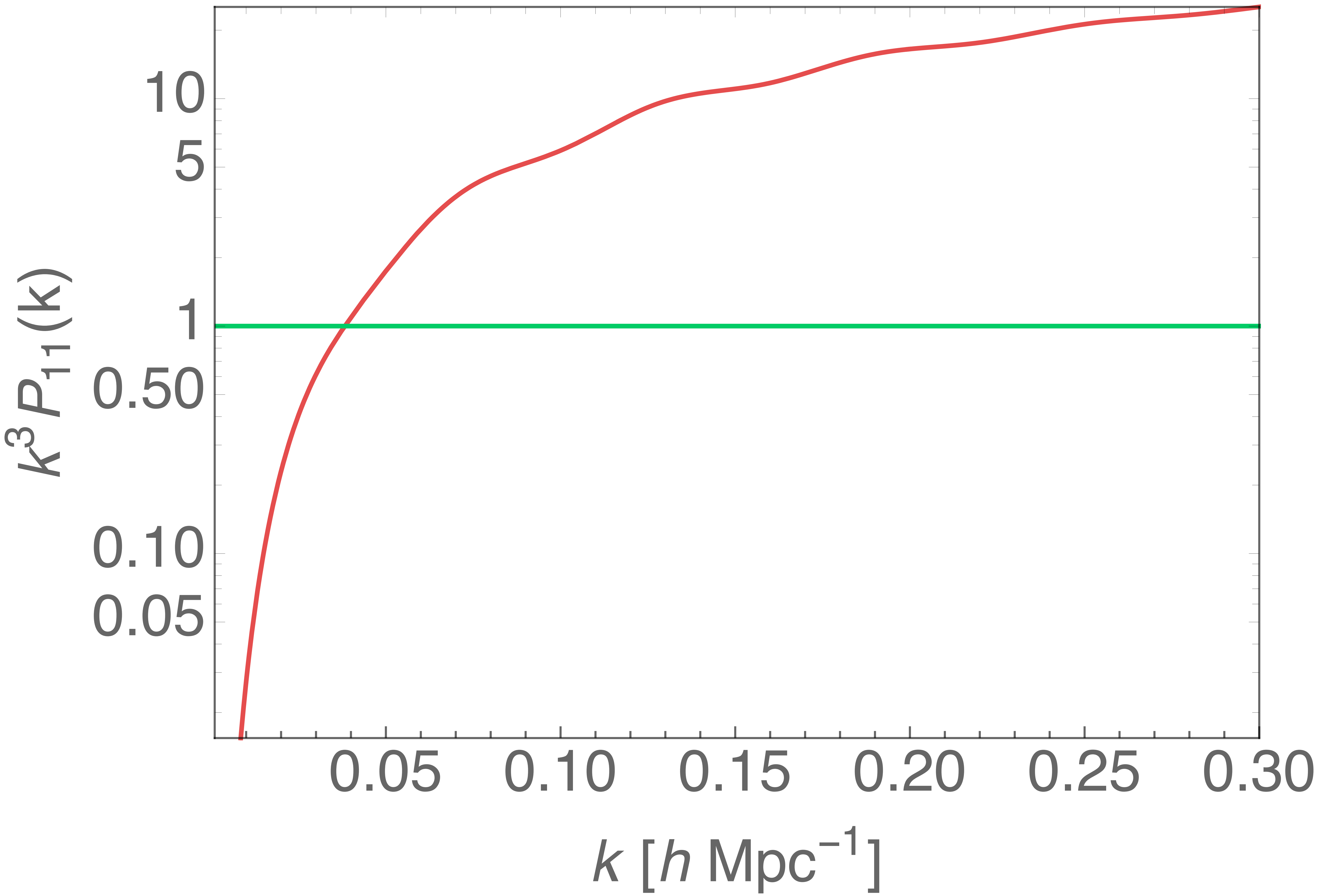
first corrections,
one-loop terms

diagrams



UV structure

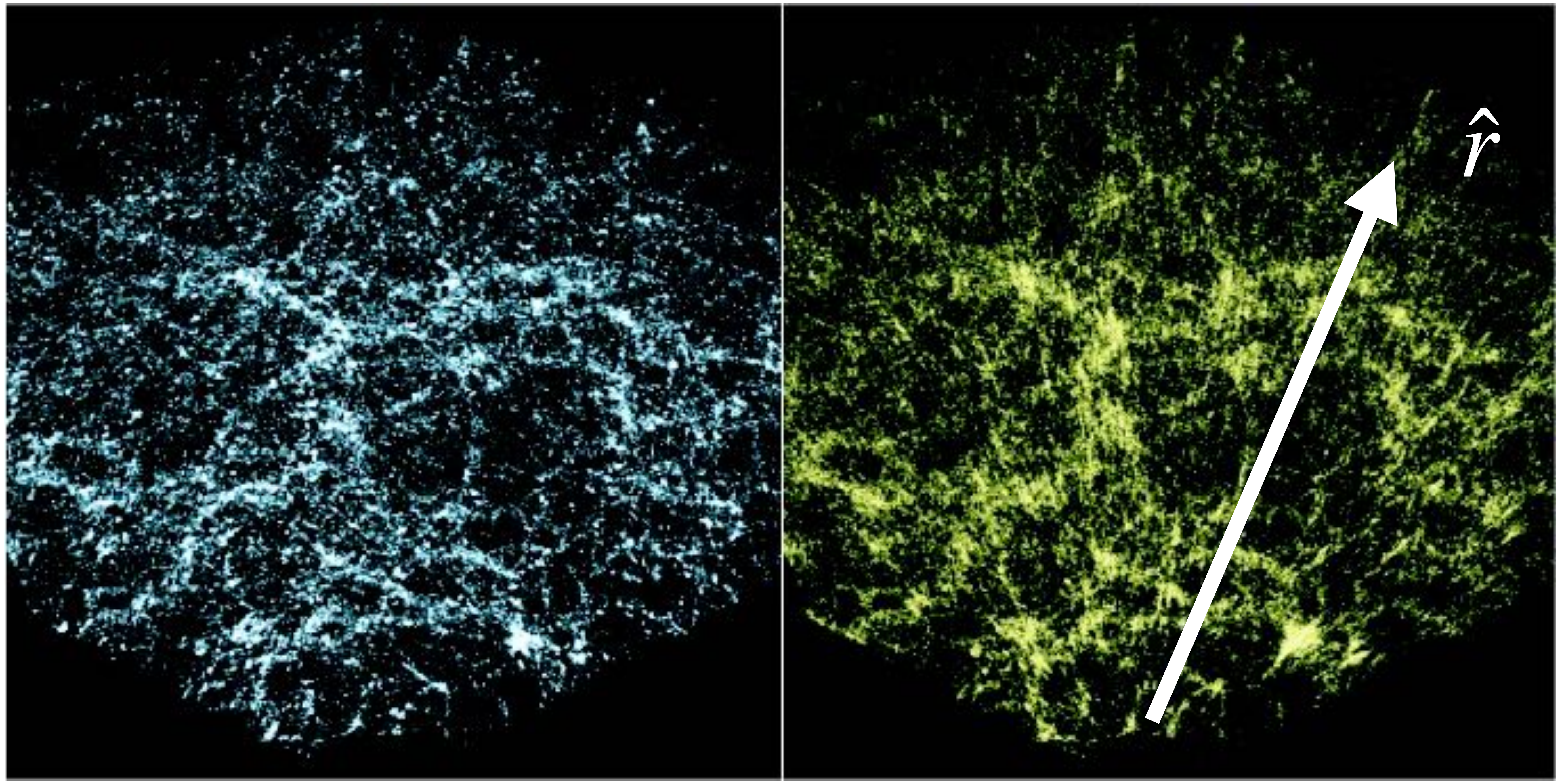
$$P_{13}(k) \to -\frac{61}{630\pi^2} k^2 P_{11}(k) \int^{\Lambda_{\rm UV}} dq\, P_{11}(q)$$



redshift-space distortions in the EFT

Senatore, Zaldarriaga 14

ML, Senatore, et. al. 18



isotropic in $\vec{x}(z)$

z of the Hubble flow

anisotropic in

$$\vec{x}_r(z) \equiv \vec{x}(z_{obs}(z)) \approx \vec{x}(z) + \frac{\hat{r}\cdot\vec{v}}{aH}\hat{r}$$

galaxy bias

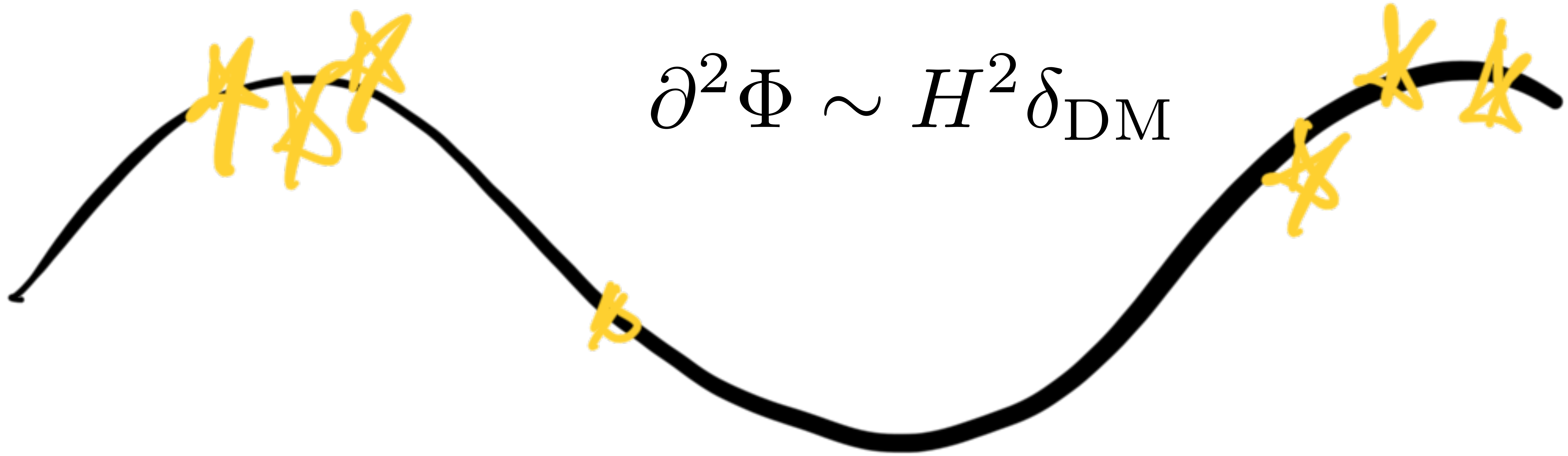
McDonald 06

McDonald, Roy 10

Senatore 15

D'Amico, Donath, **ML**, Senatore, Zhang 22

D'Amico, Donath, **ML**, Senatore, Zhang [to appear]



$$\partial^2\Phi \sim H^2\delta_{\rm DM}$$

$$\delta_{\rm galaxy}(\vec{x},t) = \int^t dt' H(t') f_{\rm galaxy}\left(\partial_i\partial_j\Phi(\vec{x}_{\rm fl},t'), \partial_i v_j(\vec{x}_{\rm fl},t'), \epsilon(\vec{x}_{\rm fl},t'),\ldots; t'\right)$$

some very complicated dependence, integrated over past light cone

perturbation theory →

$$\delta_{\rm galaxy} \sim b_1\delta_{\rm DM} + b_2\delta_{\rm DM}^2 + b_3\partial_i\delta_{\rm DM}\partial_i\delta_{\rm DM}$$

the BOSS analysis

the BOSS analysis

original power spectrum

- D’Amico, Gleyzes, Kokron, Markovic, Senatore, Zhang, Beutler, Gil-Marín 19
- Ivanov, Simonović, Zaldarriaga 19

tree-level bispectrum

- D’Amico, Gleyzes, Kokron, Markovic, Senatore, Zhang, Beutler, Gil-Marín 19
- Philcox, Ivanov 21

time for one-loop bispectrum

- data analysis — D’Amico, Donath, **ML**, Senatore, Zhang 22; Philcox, Ivanov, Cabass, Simonović, Zaldarriaga, Nishimichi 22
- theory model — D’Amico, Donath, **ML**, Senatore, Zhang 22; Philcox, Ivanov, Cabass, Simonović, Zaldarriaga, Nishimichi 22; D’Amico, Donath, **ML**, Senatore, Zhang [to appear]
- theory integration — Philcox, Ivanov, Cabass, Simonović, Zaldarriaga, Nishimichi 22; Anastasiou, Bragança, Senatore, Zheng [to appear]

the BOSS analysis

one-loop power spectrum and bispectrum

Philcox, Ivanov, Cabass, Simonović, Zaldarriaga, Nishimichi 22

D'Amico, Donath, **ML**, Senatore, Zhang 22

one-loop power spectrum of halos in redshift space

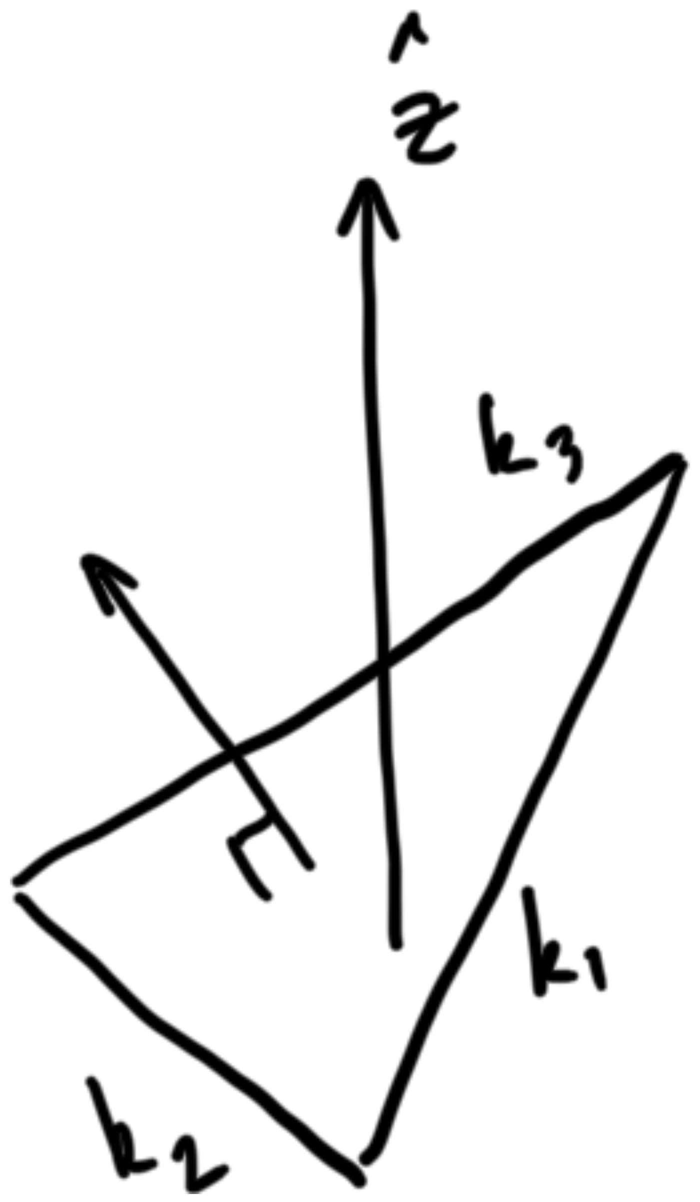
function of $(k, \hat{k} \cdot \hat{z})$

$\hat{z}$ is line-of-sight direction

$$P^{r,h}_{\text{1-loop tot.}} = P^{r,h}_{11} + (P^{r,h}_{13} + P^{r,h,ct}_{13}) + (P^{r,h}_{22} + P^{r,h,\epsilon}_{22})$$

one-loop bispectrum of halos in redshift space

function of $(k_1, k_2, k_3, \hat{k}_1 \cdot \hat{z}, \hat{k}_2 \cdot \hat{z})$



$$B^{r,h}_{\text{1-loop tot.}} = B^{r,h}_{211} + (B^{r,h,(II)}_{321} + B^{r,h,(II),ct}_{321}) + (B^{r,h}_{411} + B^{r,h,ct}_{411}) + (B^{r,h}_{222} + B^{r,h,\epsilon}_{222}) + (B^{r,h,(I)}_{321} + B^{r,h,(I),\epsilon}_{321})$$

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one-loop power spectrum and bispectrum

Philcox, Ivanov, Cabass, Simonović, Zaldarriaga, Nishimichi 22

D'Amico, Donath, **ML**, Senatore, Zhang 22

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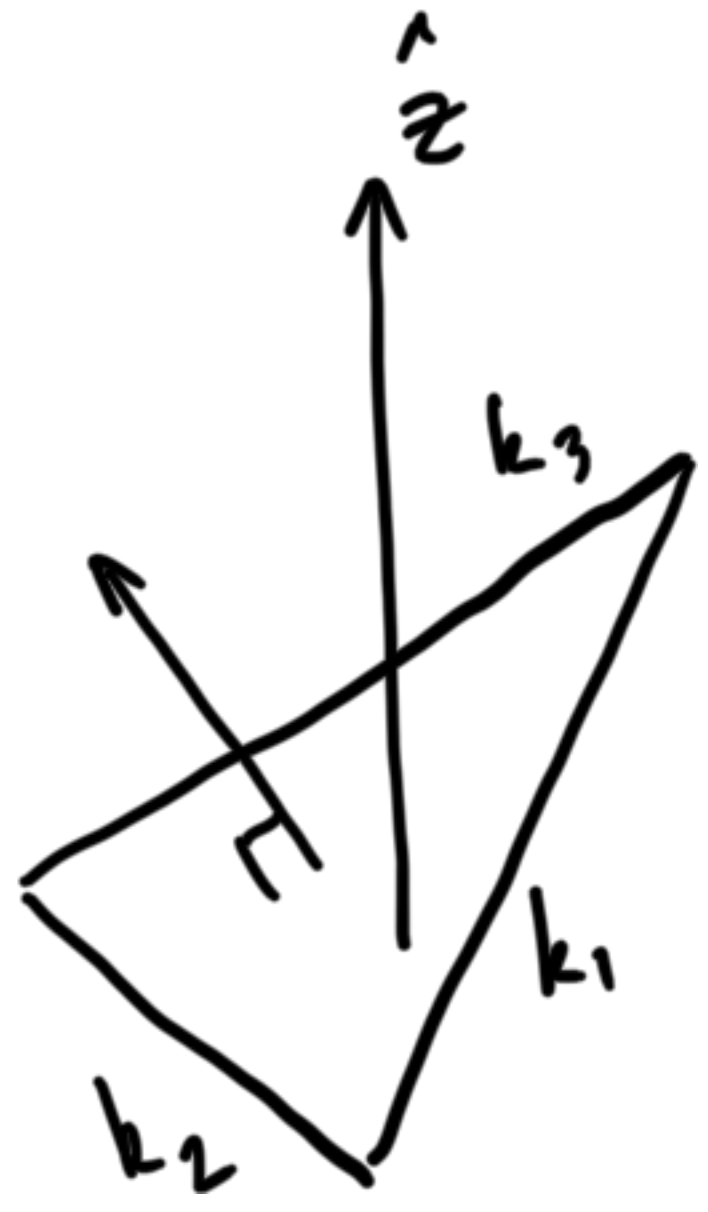

linear

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one-loop power spectrum and bispectrum

Philcox, Ivanov, Cabass, Simonović, Zaldarriaga, Nishimichi 22

D'Amico, Donath, **ML**, Senatore, Zhang 22

one-loop power spectrum of halos in redshift space

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one-loop bispectrum of halos in redshift space

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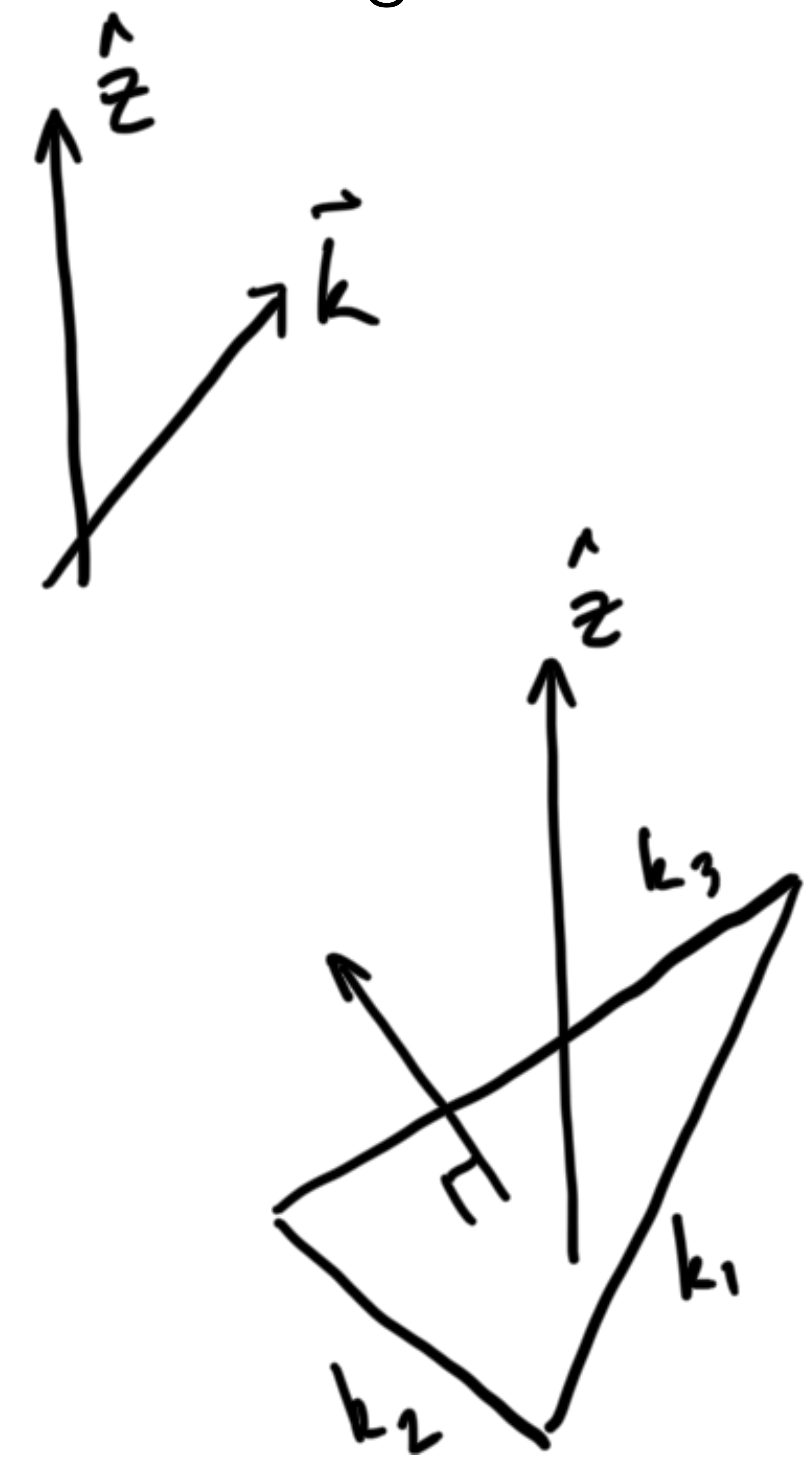
linear **one loop**

$\hat{z}$ is line-of-sight direction



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one-loop power spectrum and bispectrum

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D'Amico, Donath, **ML**, Senatore, Zhang 22

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one-loop bispectrum of halos in redshift space

function of $(k_1, k_2, k_3, \hat{k}_1\cdot\hat{z}, \hat{k}_2\cdot\hat{z})$

EFT of LSS counterterms

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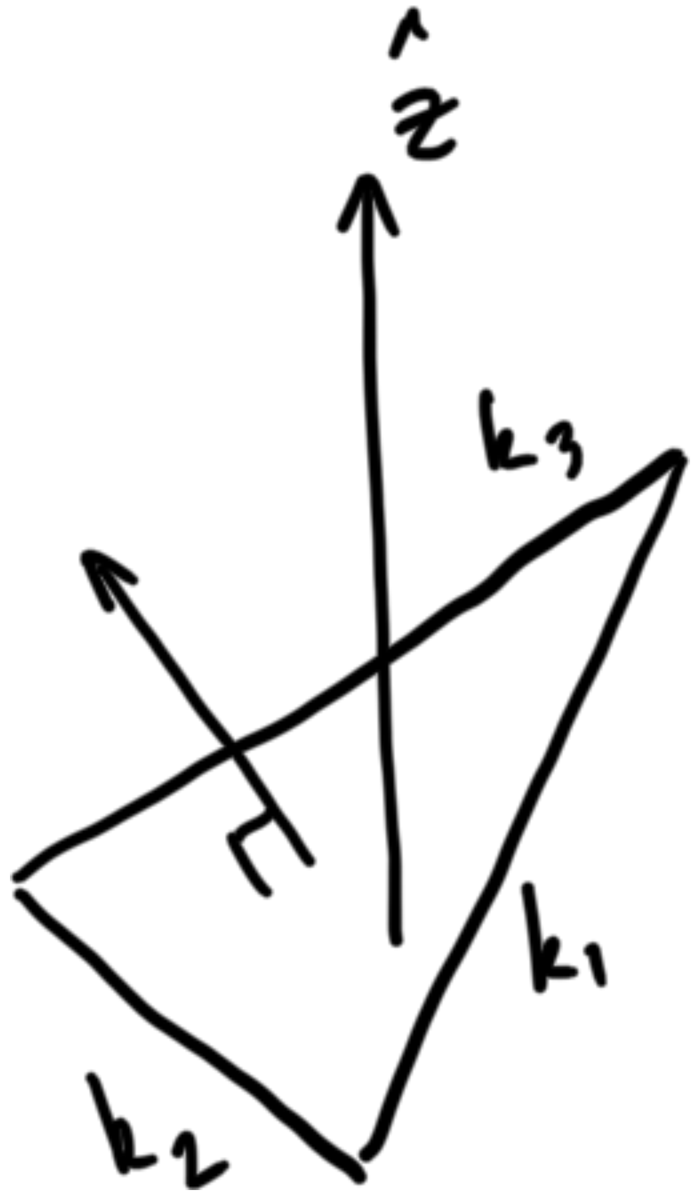

linear

one loop

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multipoles

power spectrum - $\ell = \{0,2\}$

$$P_\ell^{r,h}(k) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\, \mathcal{P}_\ell(\mu) P^{r,h}(k,\mu)$$

bispectrum monopole

$$B_0^{r,h}(k_1,k_2,k_3) = \frac{1}{4\pi}\int_{-1}^{1} d\mu_1 \int_0^{2\pi} d\phi\, B^{r,h}(k_1,k_2,k_3,\mu_1,\mu_2(\mu_1,\phi))$$

bispectrum quadrupoles (tree level)

$$B_{(2,1)}^{r,h}(k_1,k_2,k_3) \equiv \frac{5}{4\pi}\int_{-1}^{1} d\mu_1 \int_0^{2\pi} d\phi\, \mathcal{P}_2(\mu_1) B^{r,h}(k_1,k_2,k_3,\mu_1,\mu_2(\mu_1,\phi)) \ ,$$

$$B_{(2,2)}^{r,h}(k_1,k_2,k_3) \equiv \frac{5}{4\pi}\int_{-1}^{1} d\mu_1 \int_0^{2\pi} d\phi\, \mathcal{P}_2(\mu_2(\mu_1,\phi)) B^{r,h}(k_1,k_2,k_3,\mu_1,\mu_2(\mu_1,\phi)) \ ,$$

$$B_{(2,3)}^{r,h}(k_1,k_2,k_3) \equiv \frac{5}{4\pi}\int_{-1}^{1} d\mu_1 \int_0^{2\pi} d\phi\, \mathcal{P}_2(\mu_3(\mu_1,\phi)) B^{r,h}(k_1,k_2,k_3,\mu_1,\mu_2(\mu_1,\phi)) \ .$$

$$\mu_2(\mu_1,\phi) = \mu_1 \hat{k}_1\cdot\hat{k}_2 + \sqrt{1-\mu_1^2}\sqrt{1-(\hat{k}_1\cdot\hat{k}_2)^2}\ \sin\phi$$

$$\mu_3(\mu_1,\phi) = -k_3^{-1}(k_1\mu_1 + k_2\mu_2(\mu_1,\phi))$$

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parameters

$$P_{11}^{r,h}[b_1]\ , \quad P_{13}^{r,h}[b_1, b_3, b_8]\ , \quad P_{22}^{r,h}[b_1, b_2, b_5]\ ,$$
$$B_{211}^{r,h}[b_1, b_2, b_5]\ , \quad B_{321}^{r,h,(II)}[b_1, b_2, b_3, b_5, b_8]\ , \quad B_{411}^{r,h}[b_1, \ldots, b_{11}]\ ,$$
$$B_{222}^{r,h}[b_1, b_2, b_5]\ , \quad B_{321}^{r,h,(I)}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}]\ ,$$

11 bias parameters

$$P_{13}^{r,h,ct}[b_1, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}]\ , \quad P_{22}^{r,h,\epsilon}[c_1^{\rm St}, c_2^{\rm St}, c_3^{\rm St}]\ ,$$
$$B_{321}^{r,h,(II),ct}[b_1, b_2, b_5, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}]\ ,$$
$$B_{411}^{r,h,ct}[b_1, \{c_{h,i}\}_{i=1,\ldots,5}, c_{\pi,1}, c_{\pi,5}, \{c_{\pi v,j}\}_{j=1,\ldots,7}]\ ,$$
$$B_{321}^{r,h,(I),\epsilon}[b_1, c_1^{\rm St}, c_2^{\rm St}, \{c_i^{\rm St}\}_{i=4,\ldots,13}]\ , \quad B_{222}^{r,h,\epsilon}[c_1^{(222)}, c_2^{(222)}, c_5^{(222)}]$$

14 response counterterms
16 stochastic counterterms

scanning $\{\Omega_{\rm m}, H_0, \sigma_8\}$

BBN prior on $\Omega_{\rm b}h^2$, Planck fixed n_s

cosmological parameters

the BOSS analysis

data - power spectrum

BOSS DR12 LRG sample

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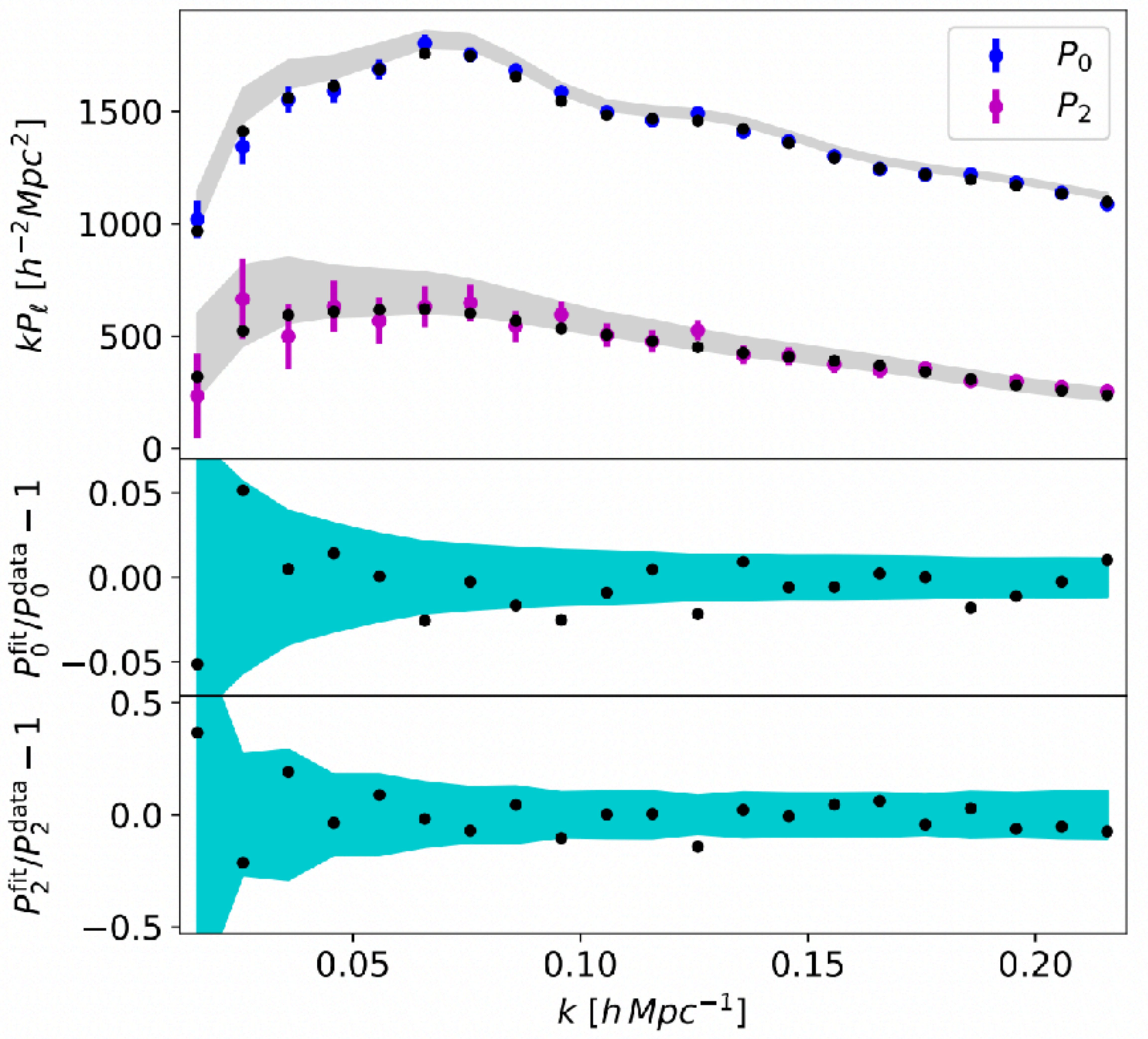

BOSS data

Patchy mocks

best fit

the BOSS analysis

data - bispectrum

BOSS DR12 LRG sample

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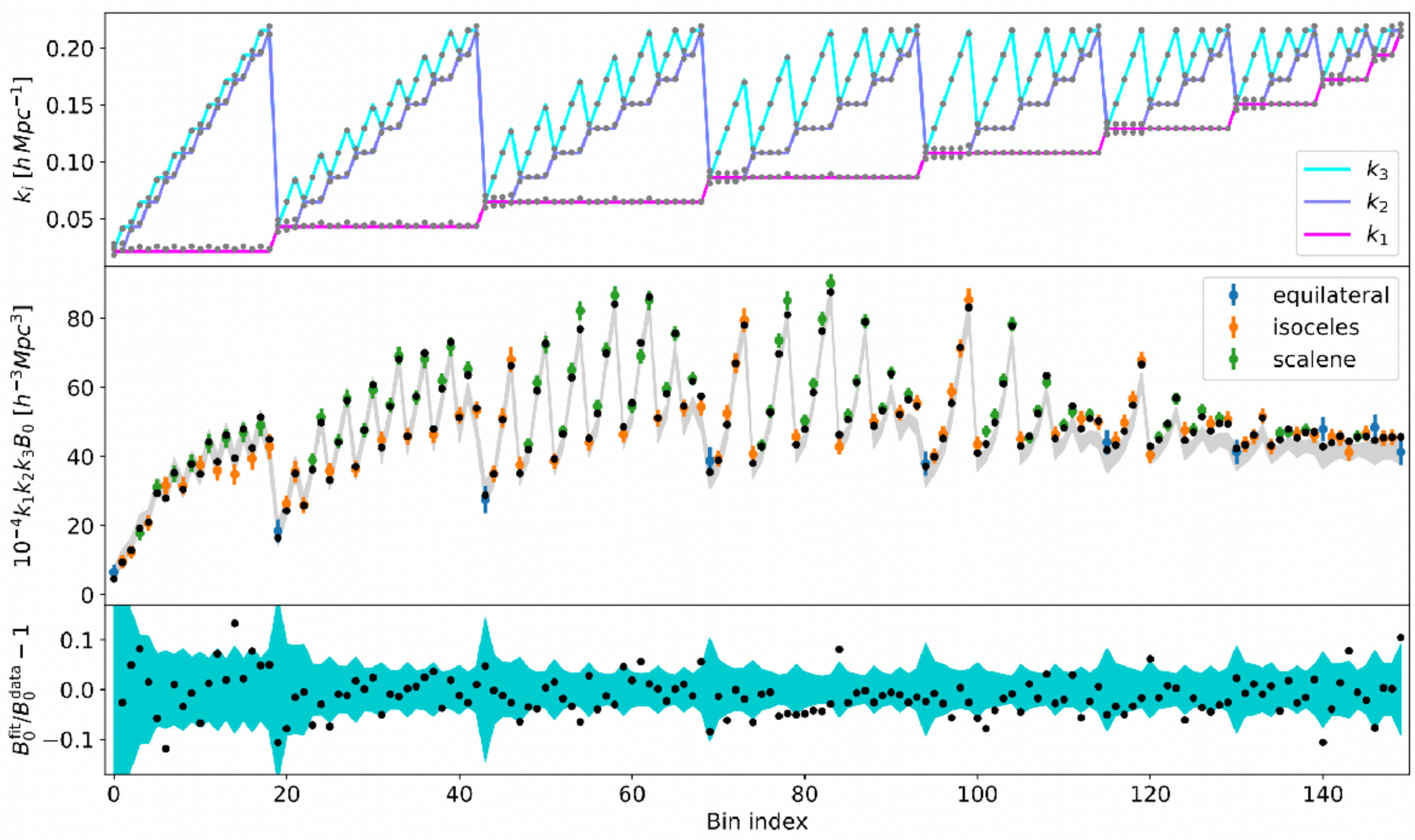
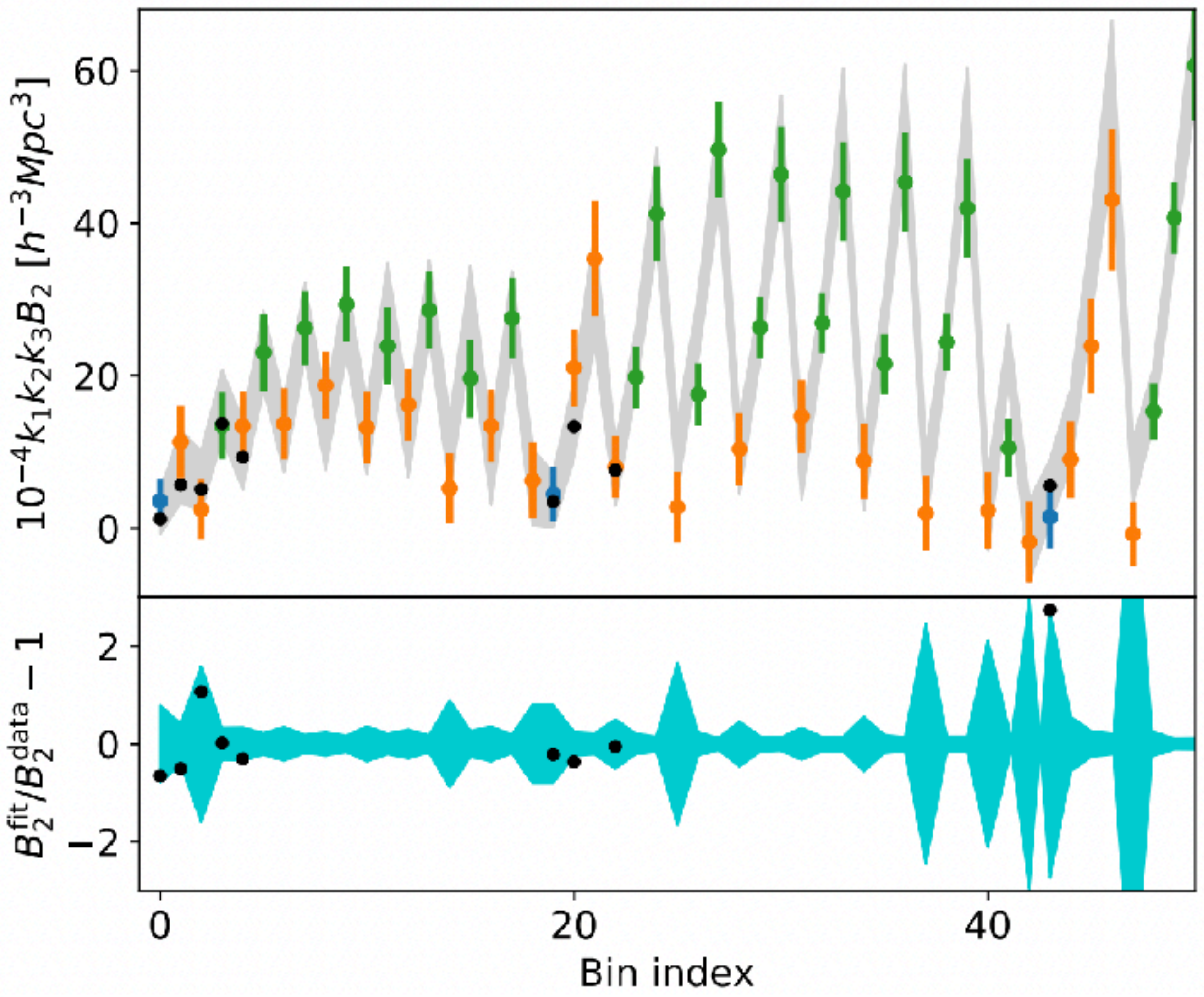


monopole



quadrupole

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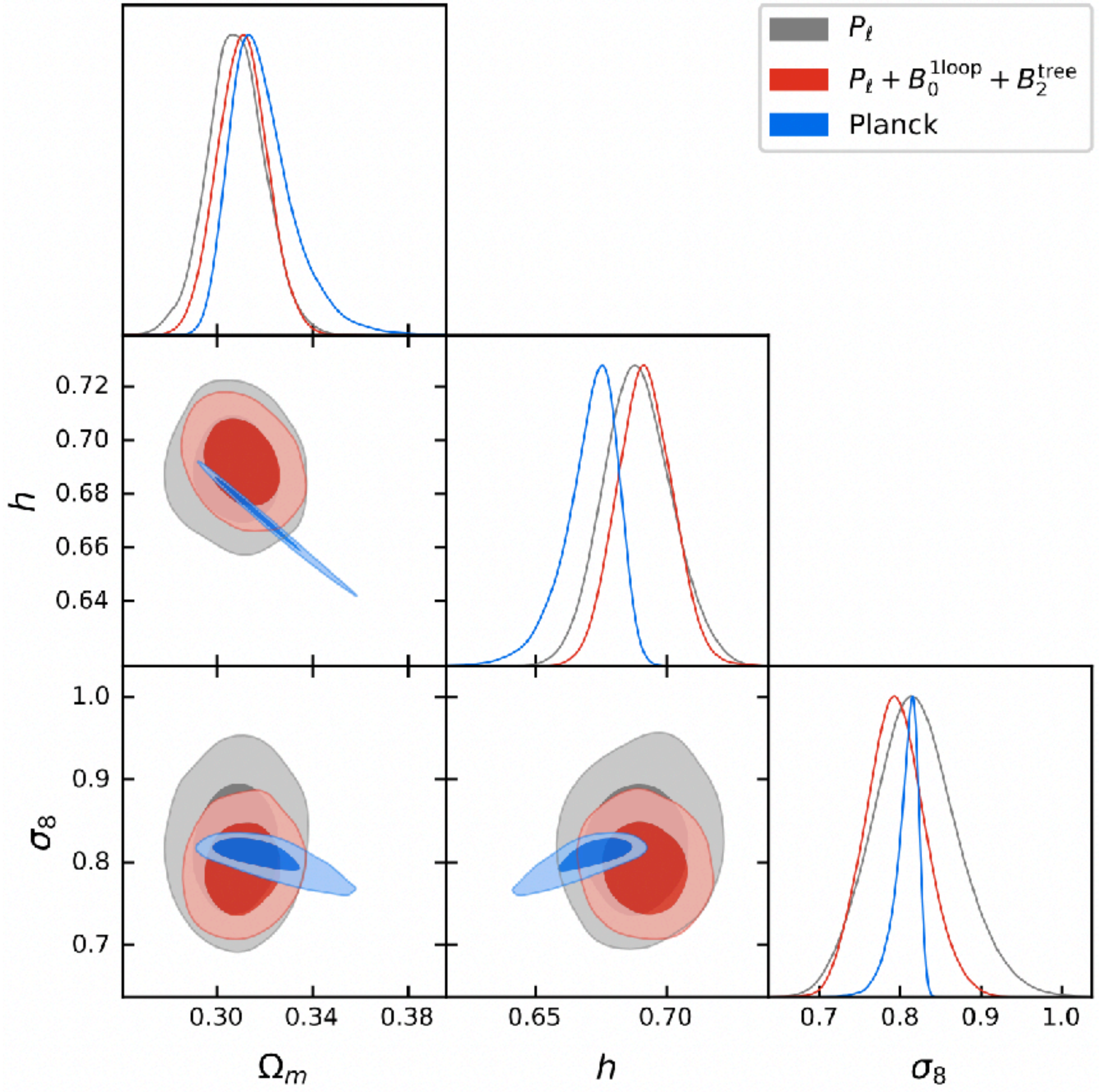
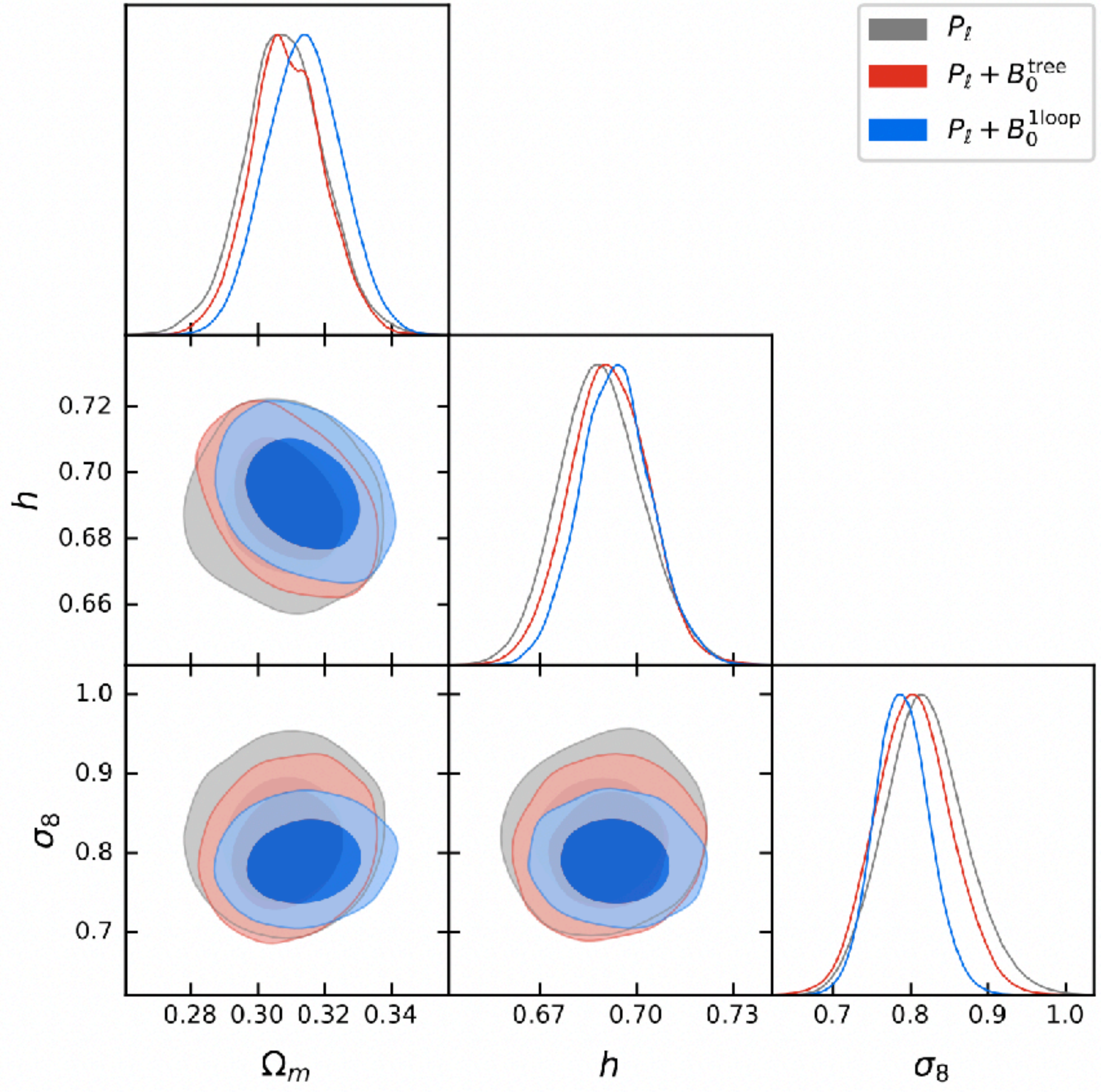
results





the BOSS analysis

final takeaway

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percent size of error bars

	OG BOSS, no sound horizon prior	PS only	B_tree	B_1-loop/ B_quad	Planck
Ω_m	few percent, but only on two parameters, and in a degenerate way [H(z) r_s(z_d) and D_A(z)/r_s(z_d)]	0.039	0.0356	0.0321	0.0384
h		0.0189	0.0174	0.0159	0.0139
σ_8		0.0635	0.0609	0.0466	0.0160

no tension with Planck!

the BOSS analysis

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analysis details

- scale cut and kmax values

- $k_{\max}$ can be determined by validation with simulations
- make sure we recover known cosmological parameters

$k_{\rm max} = 0.23\, h\, {\rm Mpc}^{-1}$ one-loop terms

$k_{\rm max} = 0.08\, h\, {\rm Mpc}^{-1}$ tree-level terms

- also via perturbation theory: add NNLO terms and demand parameters shift $< \sigma/3$

	Ω_m	h	σ_8
$\Delta_{\rm shift}/\sigma_{\rm stat}$	-0.03	-0.09	-0.03

$$P_{\rm NNLO}(k,\mu) = \frac{1}{4} c_{r,4} b_1^2 \mu^4 \frac{k^4}{k^4_{\rm NL,R}} P_{11}(k) + \frac{1}{4} c_{r,6} b_1 \mu^6 \frac{k^4}{k^4_{\rm NL,R}} P_{11}(k)$$

$$B_{\rm NNLO}(k_1,k_2,k_3,\mu,\phi) = 2 c_{\rm NNLO,1} K_2^{r,h}(\vec{k}_1,\vec{k}_2;\hat{z}) K_1^{r,h}(\vec{k}_2;\hat{z}) f \mu_1^2 \frac{k_1^4}{k^4_{\rm NL,R}} P_{11}(k_1) P_{11}(k_2)$$

$$+ c_{\rm NNLO,2} K_1^{r,h}(\vec{k}_1;\hat{z}) K_1^{r,h}(\vec{k}_2;\hat{z}) P_{11}(k_1) P_{11}(k_2) f \mu_3 k_3 \frac{(k_1^2+k_2^2)}{4 k_1^2 k_2^2 k^4_{\rm NL,R}} \Big[-2 \vec{k}_1 \cdot \vec{k}_2 (k_1^3 \mu_1 + k_2^3 \mu_2)$$

$$+ 2 f \mu_1 \mu_2 \mu_3 k_1 k_2 k_3 (k_1^2 + k_2^2) \Big] + \text{perms.}$$

the road ahead

baryons in large-scale structure

percent-level effects

unique challenge:
baryonic physics makes
using simulations difficult

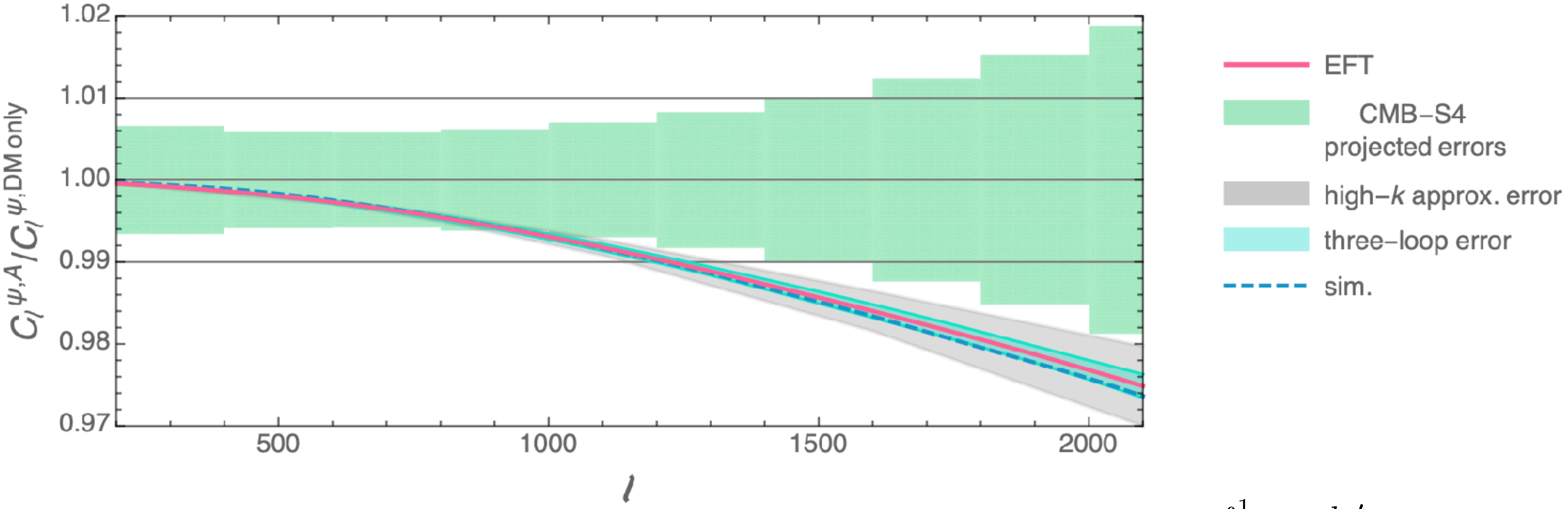
time to shine for analytic methods

baryons in large-scale structure

lensing potential

Bragança, **ML**, Sekera
Senatore, Sgier 20

ML, Perko, Senatore 14



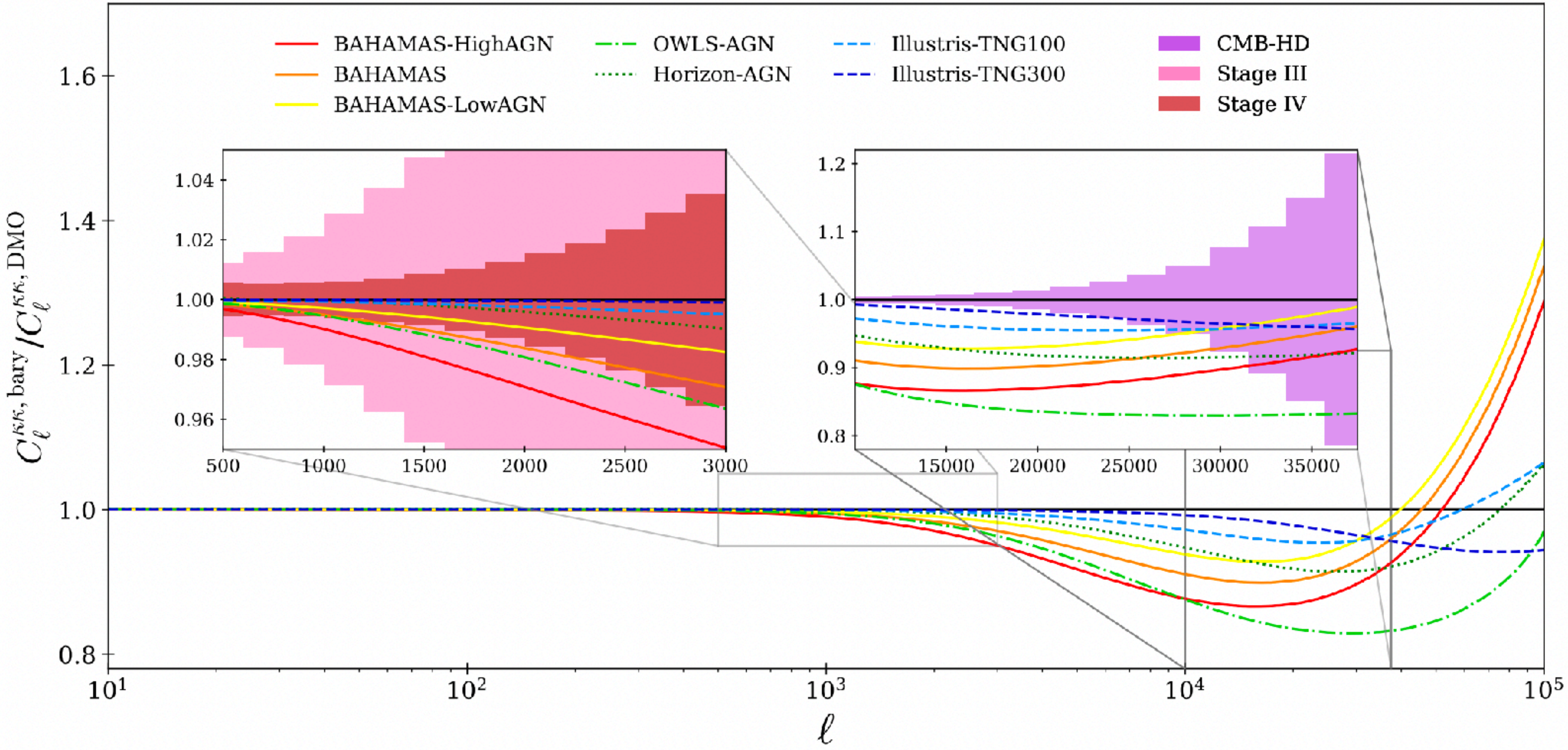
$$\chi(a) = \int_a^1 \frac{da'}{(a')^2 H(a')}$$

$$C_\ell^\psi = \frac{8\pi^2}{\ell^3} \int_0^{\chi_*} d\chi\, \chi\, P_\Phi\left(a\left(\chi\right), k = \frac{\ell}{\chi}\right) \left(\frac{\chi_* - \chi}{\chi_* \chi}\right)^2$$

$$P_\Phi(a,k) = \frac{9\,\Omega(a)^2 \mathcal{H}(a)^4}{8\pi^2} \frac{P^A(a,k)}{k}$$

baryons in large-scale structure

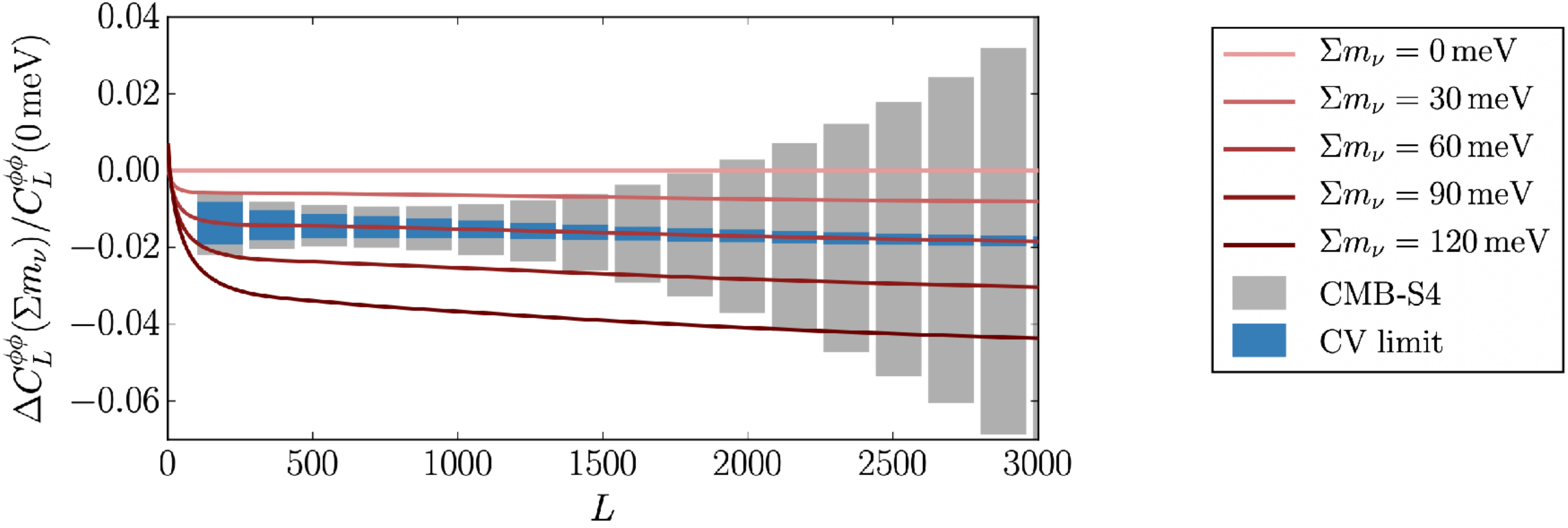
baryon simulations



Chung, Foreman, van Engelen 20

baryons in large-scale structure

massive neutrinos



CMB-S4 science book
2016

beyond ΛCDM/dark energy

EFT of DE for EFT of LSS

- clustering quintessence in the EFT of LSS

  ML, Maleknejad, Senatore 17

- general EFT of DE in EFT of LSS

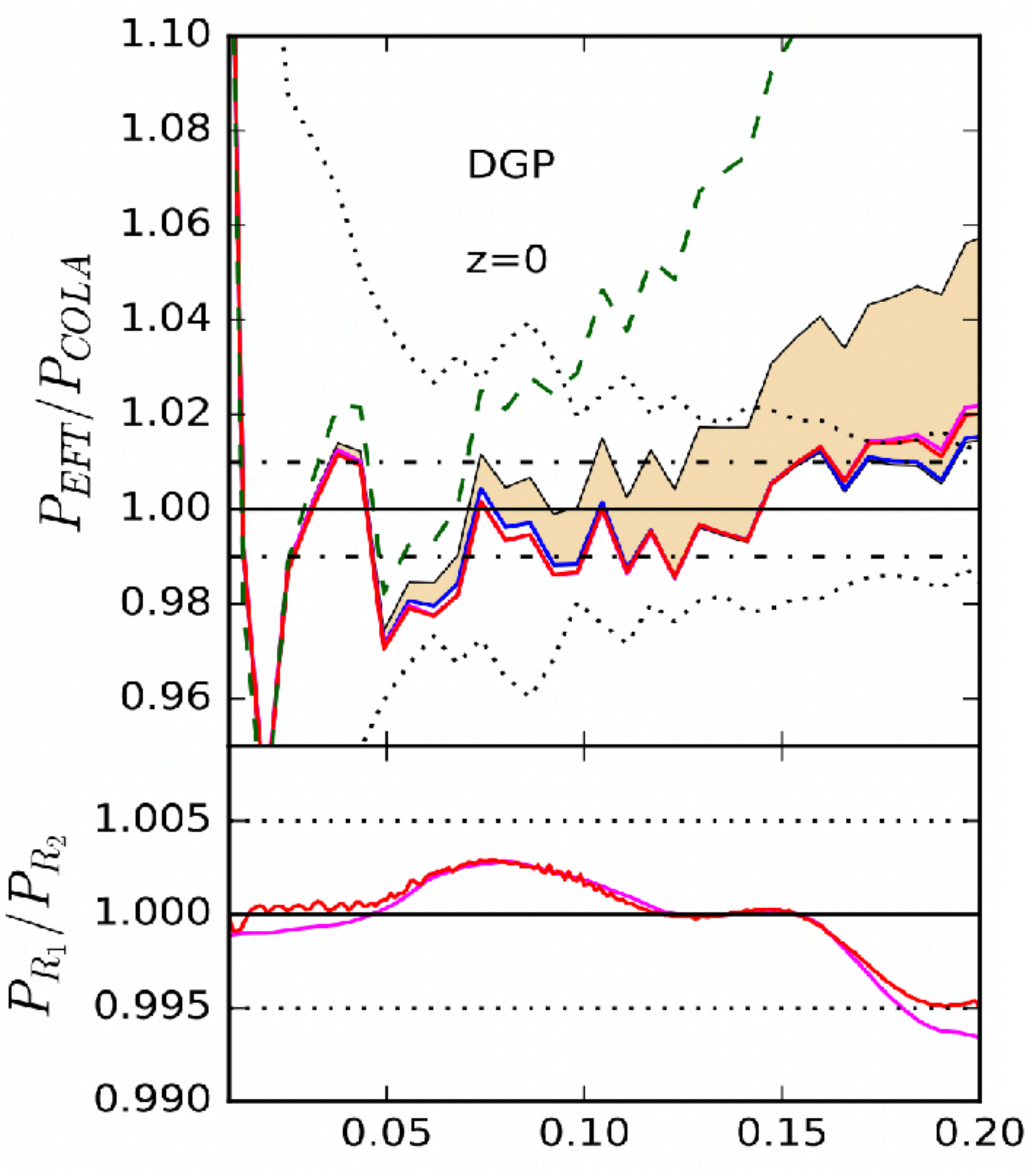
  Cusin, **ML**, Vernizzi 18
  Cusin, **ML**, Vernizzi 18

- comparisons to DE simulations

  Bose, Koyama, **ML**, Vernizzi, Winther 18

- unique LSS signatures from DE

  Crisostomi, **ML**, Vernizzi 19
  ML 20

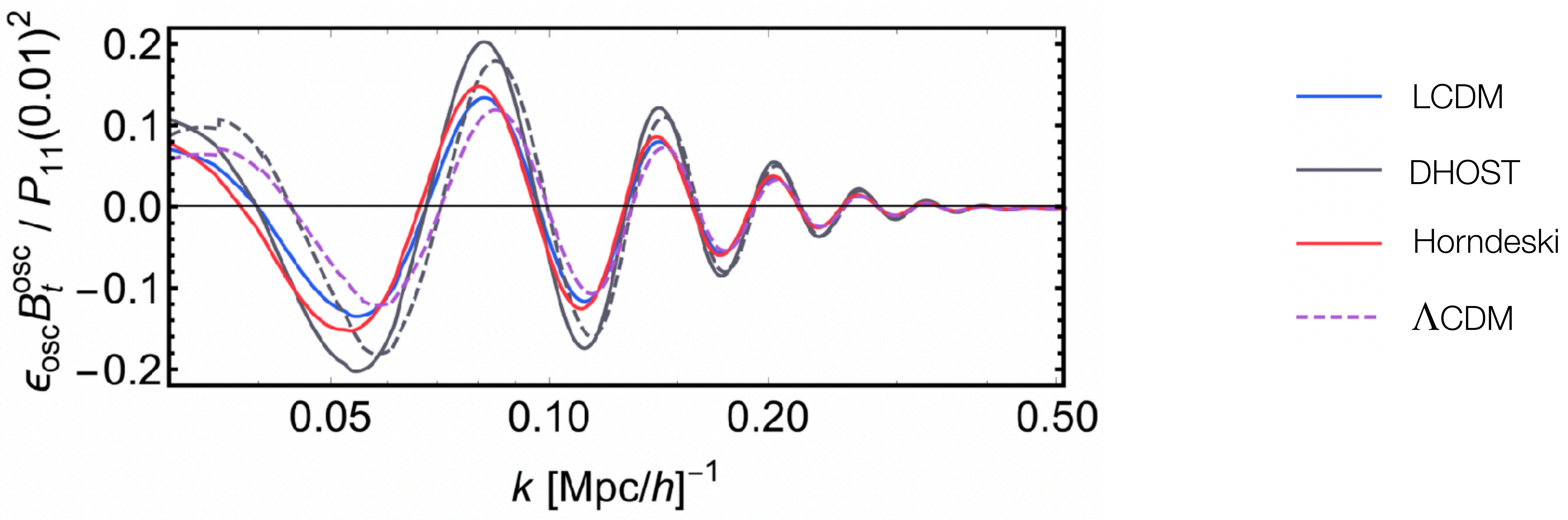


Bose, Koyama, **ML**, Vernizzi, Winther 18

beyond ΛCDM/dark energy

violation of LSS consistency conditions

ML 20
Crisostomi, **ML**, Vernizzi 19



conclusions

- after many years of theoretical development, the EFT of LSS has been successfully applied to real data, by multiple groups
- even with old data, the theory is powerful enough to place strong constraints (and much better than the original analysis)
- we are getting ready for new data, where EFT techniques will be indispensable
- there are many directions to go in the future - baryons, dark energy, massive neutrinos, fuzzy DM/ALPs, more observables, higher precision, numerical insights, computational techniques, …
- a lot of great physics opportunity!

for more info on EFTs in cosmology, see our Snowmass paper:

Cabass, Ivanov, **ML**, Mirbabayi, Simonović 22

conclusions

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Thank You!

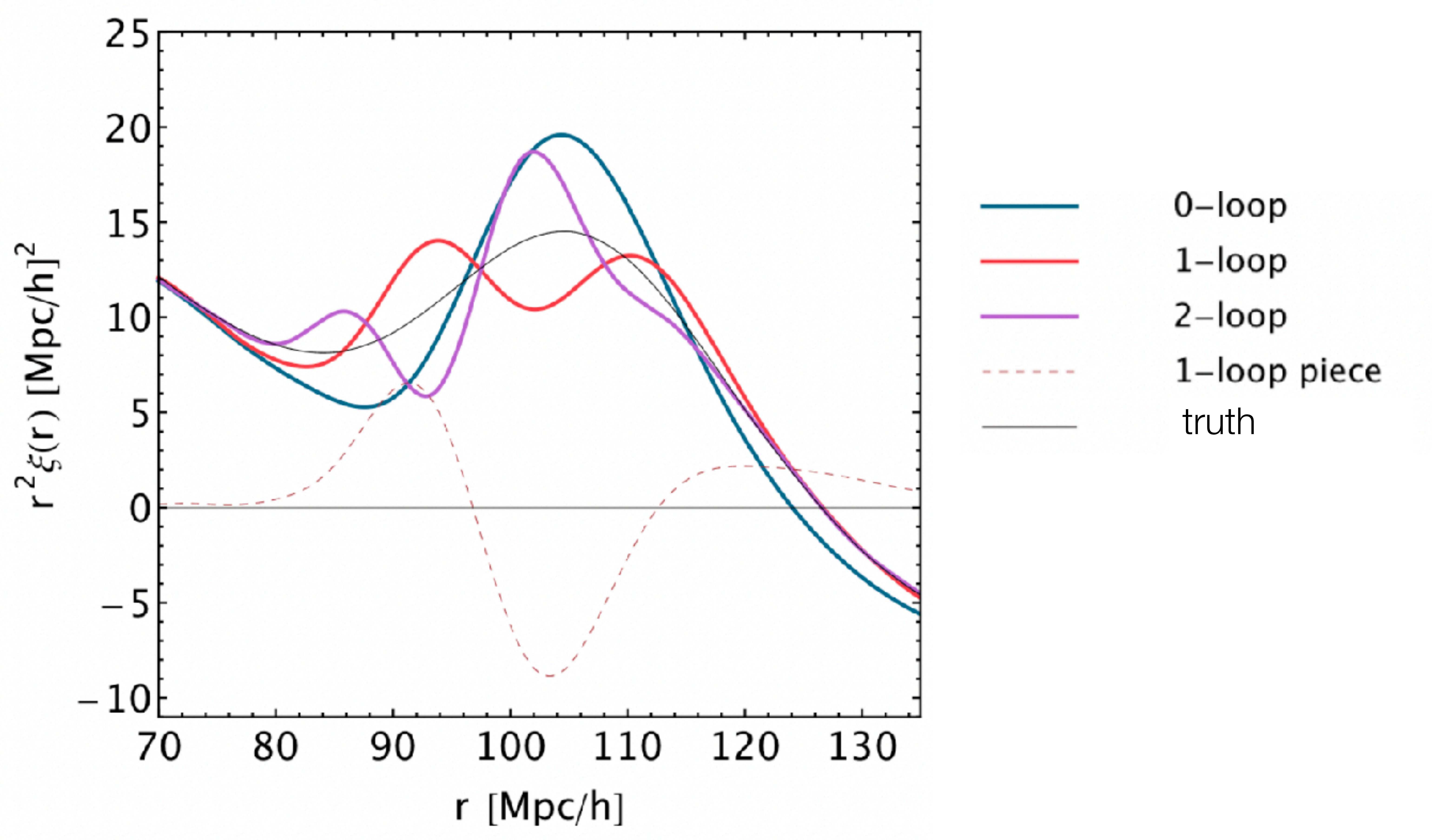
extra slides

analytic resummation of BAO

ML, Senatore 18

non-resummed baryon acoustic oscillations

$\xi(r)$ is Fourier transform of $P(k)$



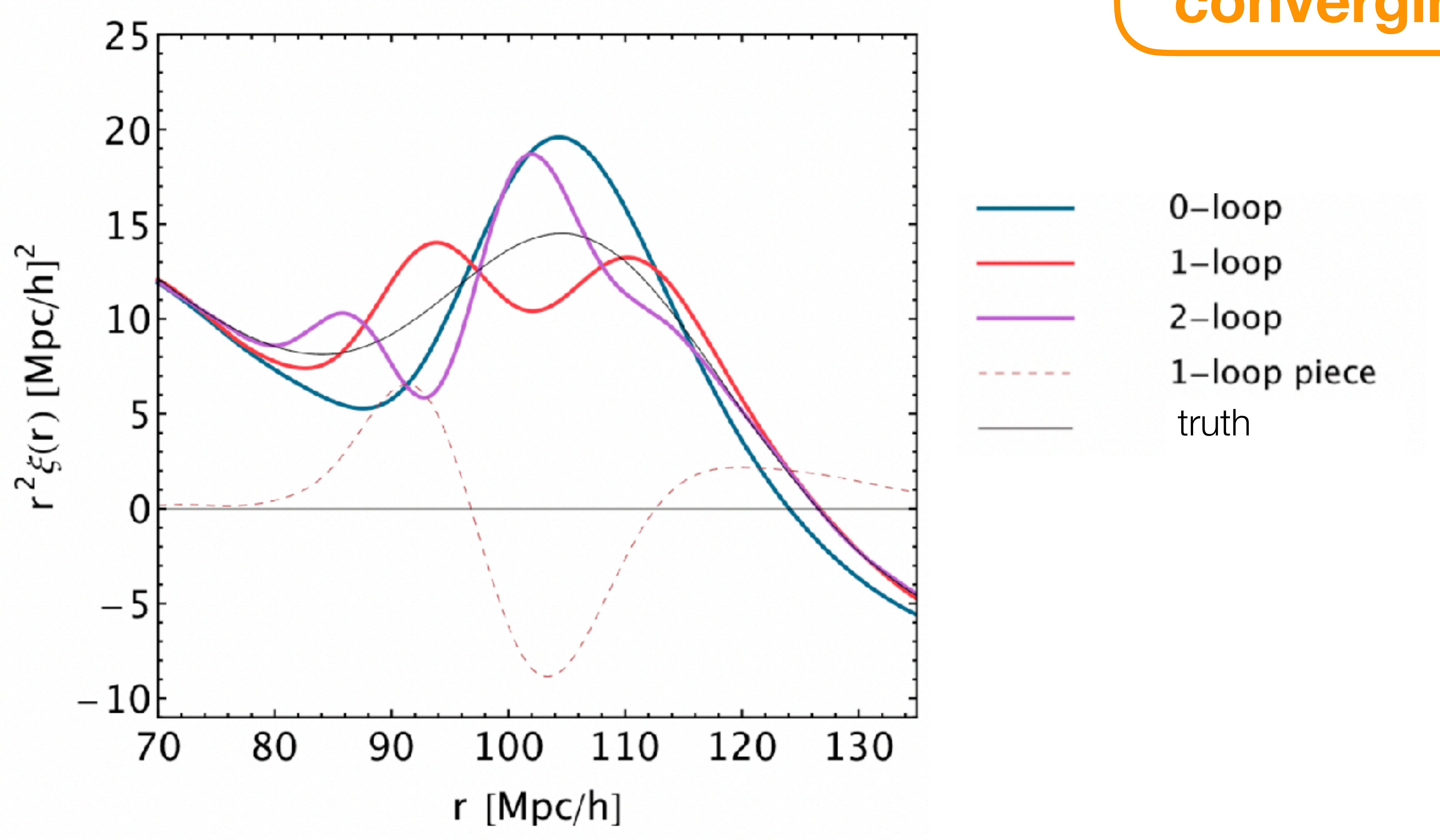
analytic resummation of BAO

ML, Senatore 18

non-resummed baryon acoustic oscillations

not converging!

$\xi(r)$ is Fourier transform of $P(k)$



analytic resummation of BAO

ML, Senatore 18

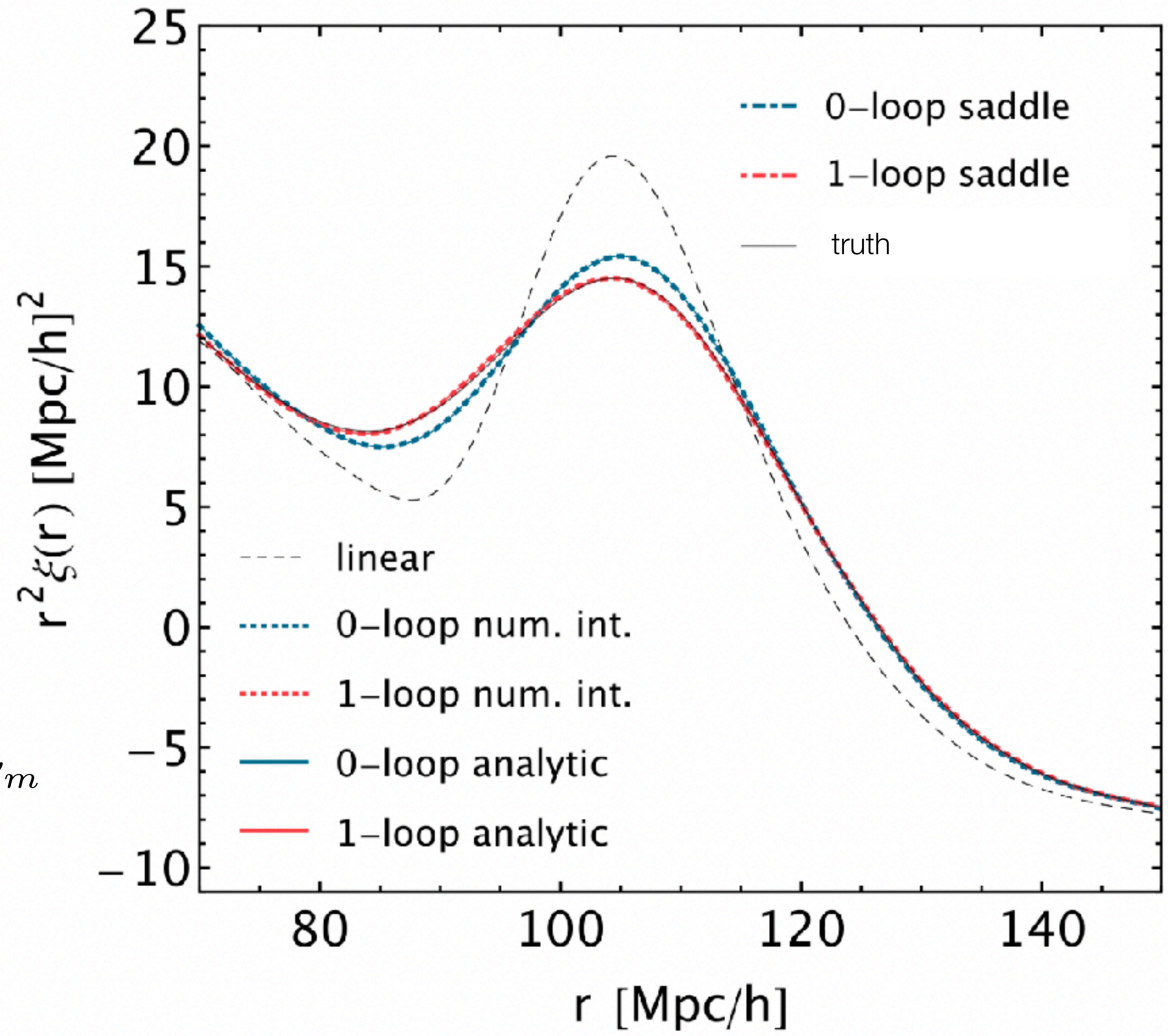
- large IR effects controlled by the equivalence principle
- soft mode effect on hard modes can be resummed

$$\xi_{\rm resum}(r) \sim \int d^3q\, e^{S(\vec{r},\vec{q})}\, \xi(q)$$

- morally similar to resumming soft emissions in QED and non-abelian gauge theories

complex power- laws: $\xi_{\rm in}(q) = q^{-3} \sum_m c_m q^{2\nu_m}$

loops have same integrals as massless 3D QFT



analytic resummation of BAO

ML, Senatore 18

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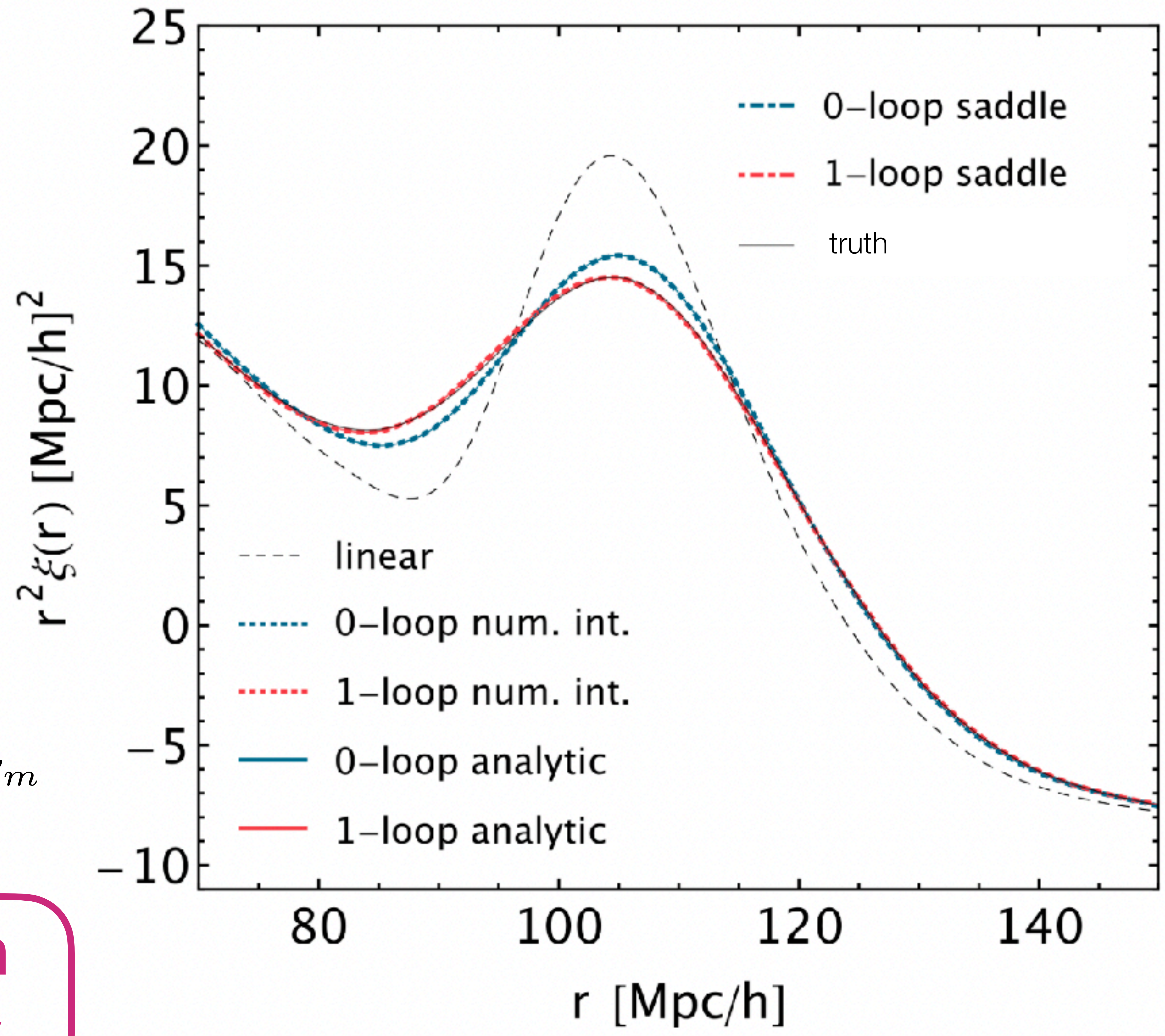


complex power- laws: $\xi_{\text{in}}(q) = q^{-3} \sum_m c_m q^{2\nu_m}$

loops have same integrals as massless 3D QFT

integrals over e^S can be done analytically

the BOSS analysis

D'Amico, Donath, **ML**, Senatore, Zhang 22

analysis details

- IR resummation

- exact for one-loop power spectrum (described above)
- tree-level bispectrum, wiggle/no-wiggle approximation

$$B_{211}^{r,h} = 2K_1^{r,h}(\vec{k}_1;\hat{z})K_1^{r,h}(\vec{k}_2;\hat{z})K_2^{r,h}(\vec{k}_1,\vec{k}_2;\hat{z})P_{\rm LO}(k_1)P_{\rm LO}(k_2) + \ 2 \text{ perms.}$$

$$P_{\rm LO}(k) = P_{\rm nw}(k) + (1+k^2\Sigma^2_{\rm tot})e^{-k^2\Sigma^2_{\rm tot}}P_{\rm w}(k)$$

Ivanov, Sibiryakov 18

- bispectrum loops we use

$$P_{\rm NLO}(k) = P_{\rm nw}(k) + e^{-k^2\Sigma^2_{\rm tot}}P_{\rm w}(k)$$

in non-integrated linear spectra

the BOSS analysis

D’Amico, Donath, **ML**, Senatore, Zhang 22

analysis details

- Alcock-Paczynski effect
  - cartesian coords obtained from reference cosmology
  - AP effect converts to true cosmology

$$q_\perp = \frac{D_A(z)H_0}{D_A^{\rm ref}(z)H_0^{\rm ref}}\,, \qquad q_\parallel = \frac{H^{\rm ref}(z)/H_0^{\rm ref}}{H(z)/H_0}$$

$$k = \frac{k^{\rm ref}}{q_\perp}\left[1+(\mu^{\rm ref})^2\left(\frac{1}{F^2}-1\right)\right]^{1/2}\,, \quad \mu = \frac{\mu^{\rm ref}}{F}\left[1+(\mu^{\rm ref})^2\left(\frac{1}{F^2}-1\right)\right]^{-1/2} \qquad F = q_\parallel/q_\perp$$

  - exact on tree-level, loop is small

- window function
  - exact for power spectrum, approx. for tree-level bispectrum   Gil-Marín et. al. 14

$$B_{211}^{r,h} = 2K_1^{r,h}(\vec{k}_1;\hat{z})K_1^{r,h}(\vec{k}_2;\hat{z})K_2^{r,h}(\vec{k}_1,\vec{k}_2;\hat{z})[W*P_{11}](\vec{k}_1)[W*P_{11}](\vec{k}_2) + \text{ 2 perms.}$$

$$[W*P_{11}](\vec{k}) = \int \frac{d^3k'}{(2\pi)^3}W(\vec{k}-\vec{k}')P_{11}(\vec{k}')$$

the BOSS analysis

D'Amico, Donath, **ML**, Senatore, Zhang 22

analysis details

- binning
  - exact for power spectrum and tree-level bispectrum

$$B^{r,h}_{(\ell,i),\mathrm{bin}}(k_1,k_2,k_3) = \frac{2\ell+1}{N_T} \sum_{\vec{q}_1\in k_1} \sum_{\vec{q}_2\in k_2} \sum_{\vec{q}_2\in k_2} \delta_K(\vec{q}_1+\vec{q}_2+\vec{q}_3) B^{r,h}(\vec{q}_1,\vec{q}_2,\vec{q}_3)\mathcal{P}_\ell(\mu_i)$$

$$\rightarrow B^{r,h}_{(\ell,i),\mathrm{bin}}(k_1,k_2,k_3) = \frac{1}{V_T}\int_{k_1} dq_1 \int_{k_2} dq_2 \int_{k_3} dq_3\, q_1 q_2 q_3 \frac{\beta(\Delta_q)}{8\pi^4} B^{r,h}_{(\ell,i)}(q_1,q_2,q_3)$$

N_T - number of triangles

V_T - volume in k-space

β - type of triangle

  - effective wavenumbers for one-loop bispectrum

- likelihood

$$-2\ln\mathcal{P} = (T_i - D_i)C^{-1}_{ij}(T_j - D_j) - 2\ln\mathcal{P}_{\mathrm{pr}}$$

some EFT parameters appear linearly →

$$T_i = g_\alpha T^\alpha_{G,i} + T_{NG,i}$$

$$-2\ln\mathcal{P} = g_\alpha F_{2,\alpha\beta} g_\beta - 2 g_\alpha F_{1,\alpha} + F_0$$

Gaussian integrals can be done analytically

the BOSS analysis

D'Amico, Donath, **ML**, Senatore, Zhang 22

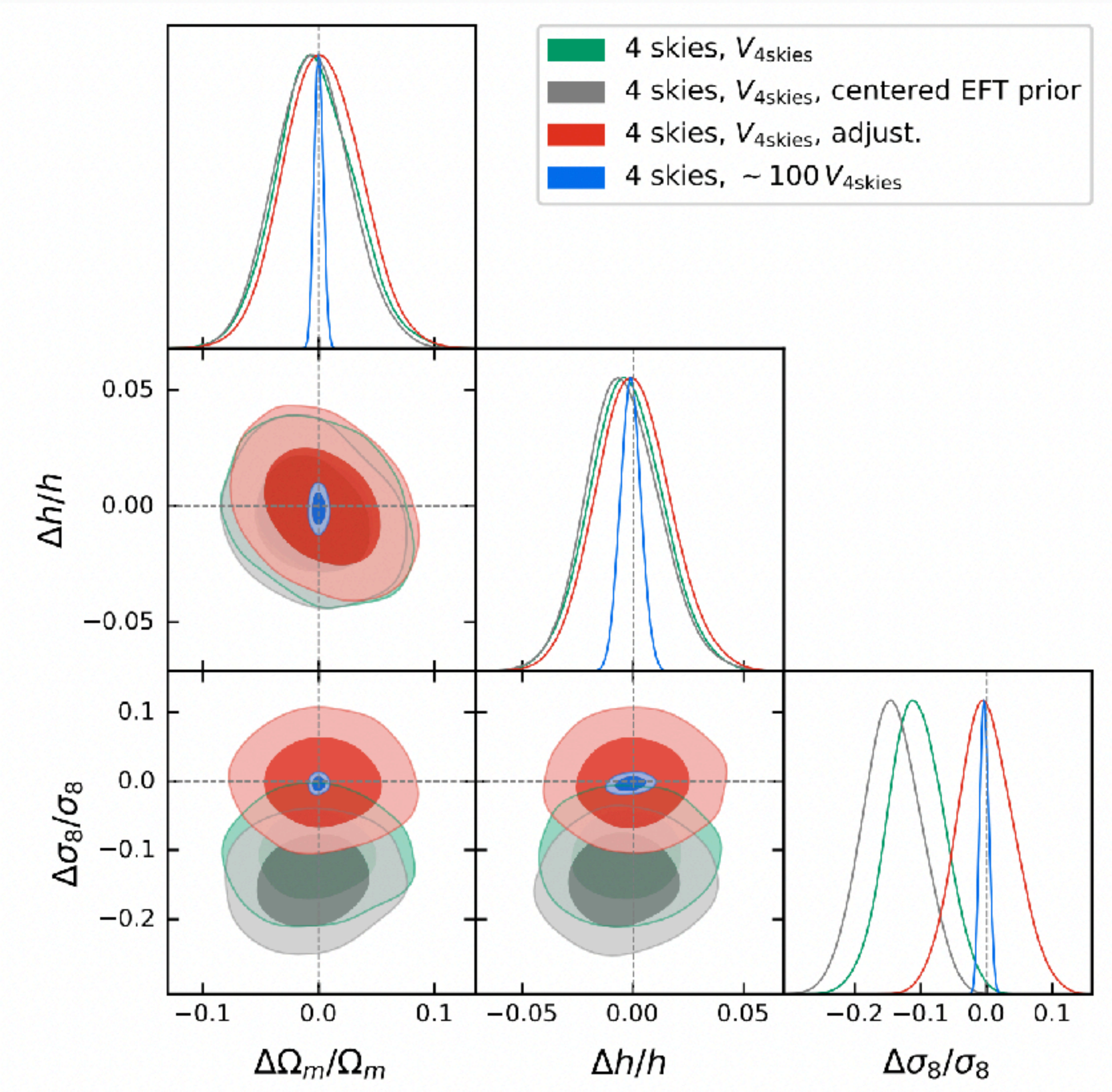
analysis details

- pipeline validation - phase space effects

- useful test: generate "data" with your model, then run your pipeline to recover input parameters
- we find a bias (green curves)
- error in pipeline? no, because drastically reducing covariance we find agreement (blue curves)
- need to use EFT priors centered on true values instead of zero? doesn't change much (gray curves)
- phase space effects, i.e. integrating out Gaussian parameters in non-Gaussian posterior
- fix with linear shift in log-posterior

$$\ln \mathcal{P}_{\rm pr}^{\rm ph.\ sp.\ 4sky} = -48\left(\frac{b_1}{2}\right) + 32\left(\frac{\Omega_m}{0.31}\right) + 48\left(\frac{h}{0.68}\right)$$

- unbiased fit (red curves)



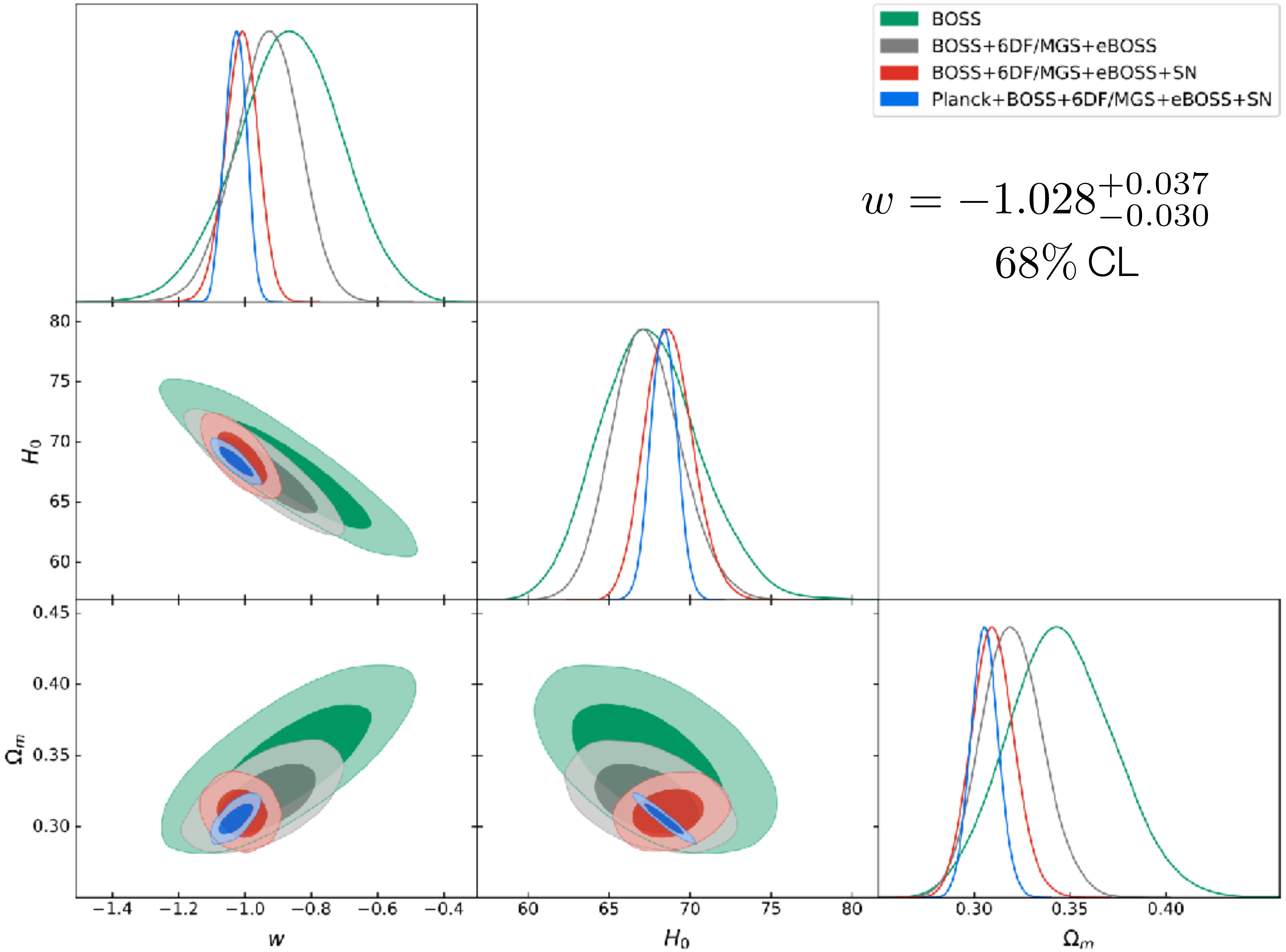
the BOSS analysis

beyond ΛCDM

quintessence

D'Amico, Donath, Senatore, Zhang 21

(theory paper: **ML**, Maleknejad, Senatore 17)



$$w = -1.028^{+0.037}_{-0.030}$$

68% CL

EFT for two fluids

notation

fluid variables

$$\rho_\sigma \equiv \bar{\rho}_\sigma(1+\delta_\sigma) \qquad \sigma \in \{c, b\}$$

$$v^i_\sigma$$

adiabatic or 'total'

$$\rho_A \equiv \rho_c + \rho_b \qquad \bar{\rho}_\sigma = w_\sigma \bar{\rho}_A$$

$$\delta_A \equiv w_c\delta_c + w_b\delta_b$$

$$v^i_A \equiv w_c v^i_c + w_b v^i_b$$

isocurvature or 'relative'

$$\delta_I \equiv \delta_c - \delta_b$$

$$v^i_I \equiv v^i_c - v^i_b$$

momentum density

$$\pi^i_\sigma \equiv \rho_\sigma v^i_\sigma$$

EFT for two fluids

Braganca, ML, Sekera, Senatore, Sgier, 2020

constructing the EOM

individual mass conservation

$$\partial_t \int d^3x\, a^3 \rho_\sigma = 0$$

total momentum conservation

$$\partial_t \int d^3x\, a^4 (\pi^i_c + \pi^i_b) = 0$$

Galilean invariance

$$\partial_i \to \partial_i \ , \quad \partial_t \to \partial_t - \dot{n}^i(t)\partial_i \ ,$$

$$\rho_\sigma \to \rho_\sigma \ , \quad \pi^i_\sigma \to \pi^i_\sigma + \rho_\sigma\, a\dot{n}^i(t) \ ,$$

$$\Phi \to \Phi - a^2(\ddot{n}^i(t) + 2H\dot{n}^i(t))x^i$$

Continuity: $\dot{\rho}_\sigma + 3H\rho_\sigma + a^{-1}\partial_i \pi^i_\sigma = 0 \ ,$

Momentum: $\dot{\pi}^i_c + 4H\pi^i_c + a^{-1}\partial_j \left(\frac{\pi^i_c \pi^j_c}{\rho_c}\right) + a^{-1}\rho_c \partial_i \Phi = +a^{-1}\gamma^i - a^{-1}\partial_j \tau^{ij}_c \ ,$

$$\dot{\pi}^i_b + 4H\pi^i_b + a^{-1}\partial_j \left(\frac{\pi^i_b \pi^j_b}{\rho_b}\right) + a^{-1}\rho_b \partial_i \Phi = -a^{-1}\gamma^i - a^{-1}\partial_j \tau^{ij}_b \ .$$

EFT for two fluids

Braganca, ML, Sekera, Senatore, Sgier, 2020

constructing the EOM

total momentum conservation

$$\partial_t \int d^3x \, a^4 (\pi_c^i + \pi_b^i) = 0$$

$$\text{Continuity:} \quad \dot{\rho}_\sigma + 3H\rho_\sigma + a^{-1}\partial_i \pi_\sigma^i = 0 \, ,$$

$$\text{Momentum:} \quad \dot{\pi}_c^i + 4H\pi_c^i + a^{-1}\partial_j \left(\frac{\pi_c^i \pi_c^j}{\rho_c} \right) + a^{-1}\rho_c \partial_i \Phi = +a^{-1}\gamma^i - a^{-1}\partial_j \tau_c^{ij} \, ,$$

$$\dot{\pi}_b^i + 4H\pi_b^i + a^{-1}\partial_j \left(\frac{\pi_b^i \pi_b^j}{\rho_b} \right) + a^{-1}\rho_b \partial_i \Phi = -a^{-1}\gamma^i - a^{-1}\partial_j \tau_b^{ij} \, .$$

1) $(\rho_c + \rho_b)\partial_i \Phi = \bar{\rho}_A (1 + \delta_A) \partial_i \Phi$

total derivative

$$a^{-2}\partial^2 \Phi = \frac{3}{2}\Omega(t) H(t)^2 \delta_A$$

$$\delta_A \partial_i \Phi = \frac{2a^{-2}}{3\Omega(t)H(t)^2} \partial_j \left(\partial_i \Phi \partial_j \Phi - \frac{1}{2}\delta_{ij} (\partial \Phi)^2 \right)$$

2) effective force $\gamma^i \sim v_I^i \sim \pi_I^i$ is new possible counterterm!

EFT for two fluids

effective force and stress tensors

$$\partial_i(\partial\tau_\rho)^i_c - \partial_i(\gamma)^i_c = -g\,w_b\,aH\,\partial_i v^i_I + 9(2\pi)H^2\Big\{\frac{c^2_{c,g}}{k^2_{\rm NL}}\left(w_c\partial^2\delta_c + w_b\partial^2\delta_b\right) + \frac{c^2_{c,v}}{k^2_{\rm NL}}\,\partial^2\delta_c$$
$$+\frac{1}{k^2_{\rm NL}}\left(c^{cc}_{1c}\partial^2\delta^2_c + c^{cb}_{1c}\partial^2\left(\delta_c\delta_b\right) + c^{bb}_{1c}\partial^2\delta^2_b\right)$$
$$+\frac{c^2_{4c,g}}{a^2k^4_{\rm NL}}\left(w_c\partial^4\delta_c + w_b\partial^4\delta_b\right) + \frac{c^2_{4c,v}}{a^2k^4_{\rm NL}}\,\partial^4\delta_c\Big\} + \dots$$

$$\partial_i(\partial\tau_\rho)^i_b - \partial_i(\gamma)^i_b = +g\,w_c\,aH\,\partial_i v^i_I + \dots$$

→ 3 independent EFT parameters per fluid
+ linear counterterm g(a)

Braganca, ML, Sekera, Senatore, Sgier, 2020

EFT for two fluids

effective force and stress tensors

$$\partial_i(\partial\tau_\rho)^i_c - \partial_i(\gamma)^i_c = -g\, w_b\, aH\, \partial_i v^i_I + 9(2\pi)H^2\Big\{ \frac{c^2_{c,g}}{k^2_{\rm NL}} \left(w_c\partial^2\delta_c + w_b\partial^2\delta_b\right) + \frac{c^2_{c,v}}{k^2_{\rm NL}}\,\partial^2\delta_c$$
$$+ \frac{1}{k^2_{\rm NL}}\left(c^{cc}_{1c}\partial^2\delta_c^2 + c^{cb}_{1c}\partial^2\left(\delta_c\delta_b\right) + c^{bb}_{1c}\partial^2\delta_b^2\right)$$
$$+ \frac{c^2_{4c,g}}{a^2k^4_{\rm NL}}\left(w_c\partial^4\delta_c + w_b\partial^4\delta_b\right) + \frac{c^2_{4c,v}}{a^2k^4_{\rm NL}}\,\partial^4\delta_c\Big\} + \dots$$

new linear counterterm!

$$\partial_i(\partial\tau_\rho)^i_b - \partial_i(\gamma)^i_b = +g\, w_c\, aH\, \partial_i v^i_I + \dots$$

→ 3 independent EFT parameters per fluid
+ linear counterterm g(a)

Braganca, ML, Sekera, Senatore, Sgier, 2020

baryon fits

- two-loop ratio of power spectrum with baryons to DM-only power spectrum
- very small cosmic variance in the ratio
- simple perturbative expansion
- linear counterterm is negligible

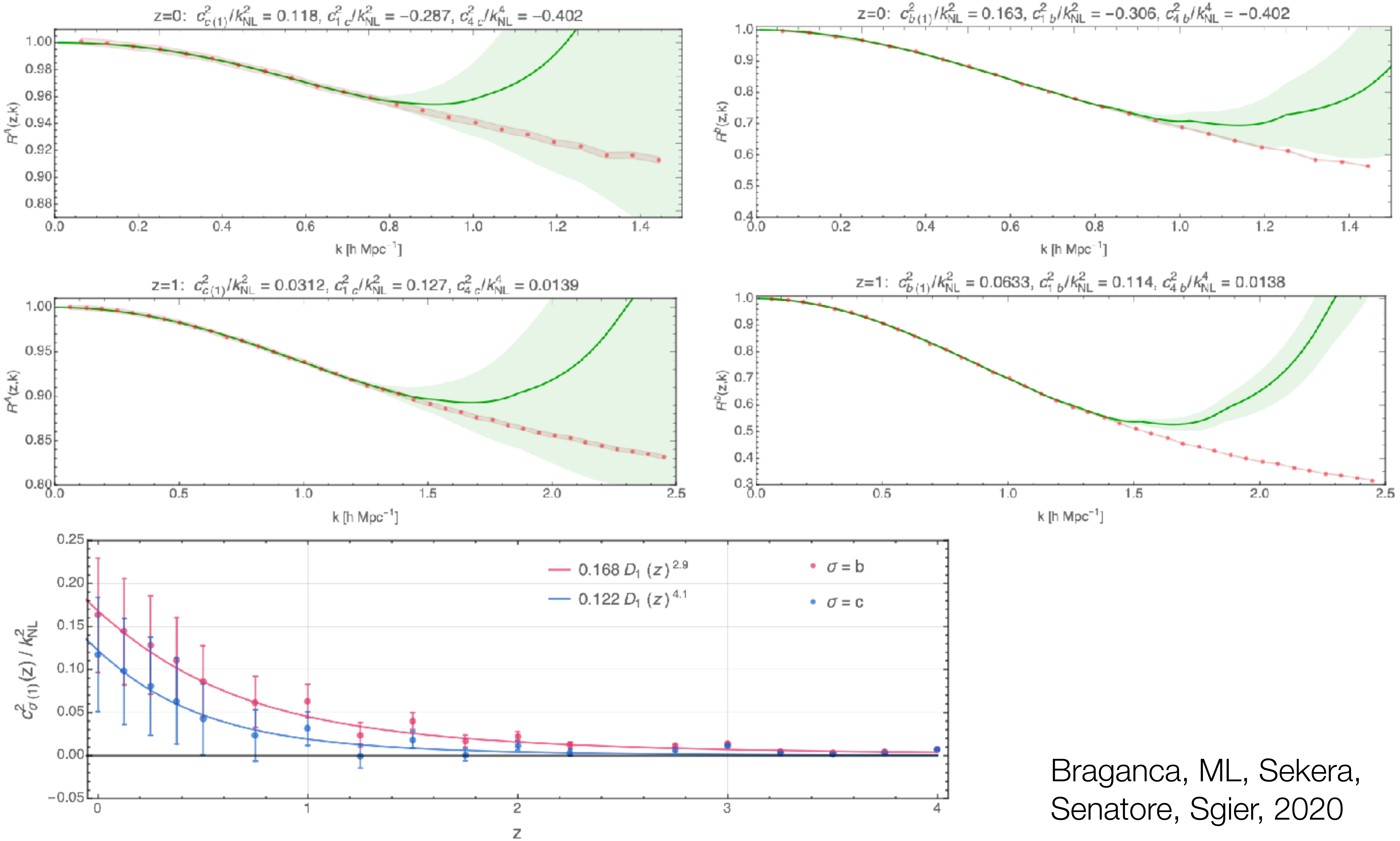
$$\frac{P^{\sigma}_{\rm EFT}}{P^{\rm DM-only}}\Big|_2 = 1 - 4\pi\Delta c^2_{\sigma(1)}\frac{k^2}{k^2_{\rm NL}} + \frac{2\pi}{P^A_{11}}\left(\Delta c^2_{\sigma(1)}\left(2\frac{k^2}{k^2_{\rm NL}}P^A_{\text{1-loop}} + P^{A,(c_s)}_{\text{1-loop}}\right) + \Delta c^2_{1\sigma}P^{A,(\text{quad},1)}_{\text{1-loop}}\right)$$
$$+\frac{8\pi^2}{17}\frac{k^4}{k^4_{\rm NL}}\left(14[\Delta c^2_{\sigma(1)}]^2 - 6c^2_{s(1)}\Delta c^2_{\sigma(1)} + 17\Delta c^2_{4\sigma}\right) \;,$$

σ = (CDM, baryons, total)

Braganca, ML, Sekera, Senatore, Sgier, 2020

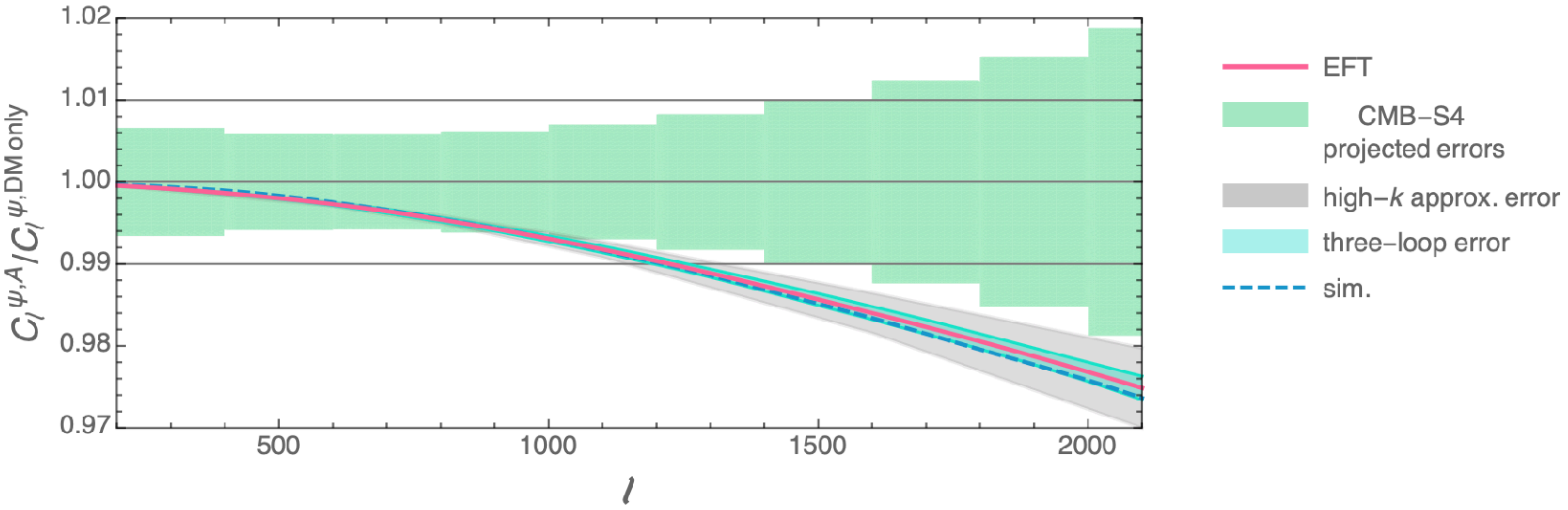
baryon fits

$P^A / P^{\text{DM only}}$ $\quad$ $P^b / P^{\text{DM only}}$



Braganca, ML, Sekera, Senatore, Sgier, 2020

lensing potential with baryons



$$C_\ell^\psi = \frac{8\pi^2}{\ell^3}\int_0^{\chi_*} d\chi\,\chi\,P_\Phi\left(a(\chi), k = \frac{\ell}{\chi}\right)\left(\frac{\chi_* - \chi}{\chi_*\chi}\right)^2$$

$$\chi(a) = \int_a^1 \frac{da'}{(a')^2 H(a')}$$

$$P_\Phi(a,k) = \frac{9\,\Omega(a)^2\mathcal{H}(a)^4}{8\pi^2}\frac{P^A(a,k)}{k}$$

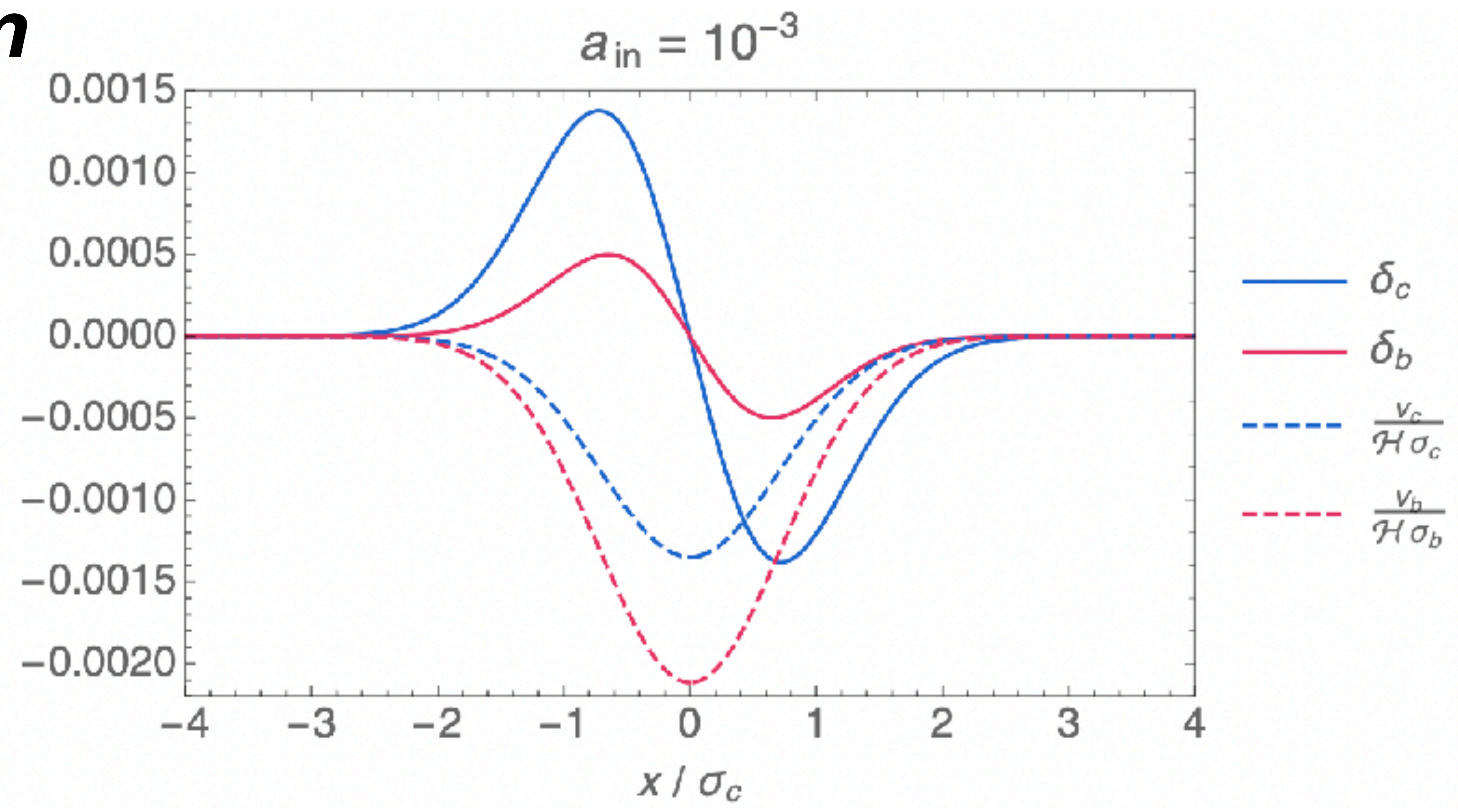
Braganca, ML, Sekera, Senatore, Sgier, 2020

EFT for two fluids

linear relative velocity counterterm

size estimation - UV model

we solve numerically the fully non-linear one-dimensional equations. we then smooth the numerical solutions with a top hat on a large enough scale so that they are perturbative. we can then show that these smoothed fields satisfy the linear equations ***with the linear relative velocity counterterm***



$$a\mathcal{H}\frac{\partial \delta_\sigma}{\partial a} + \frac{\partial}{\partial x}\left((1+\delta_\sigma)v_\sigma\right) = 0 \ ,$$

$$a\mathcal{H}\frac{\partial}{\partial a}\frac{\partial v_\sigma}{\partial x} + \mathcal{H}\frac{\partial v_\sigma}{\partial x} + \frac{3}{2}\Omega\mathcal{H}^2\delta_A + \frac{\partial}{\partial x}\left(v_\sigma\frac{\partial v_\sigma}{\partial x}\right) = 0$$

Braganca, ML, Sekera, Senatore, Sgier, 2020

EFT for two fluids

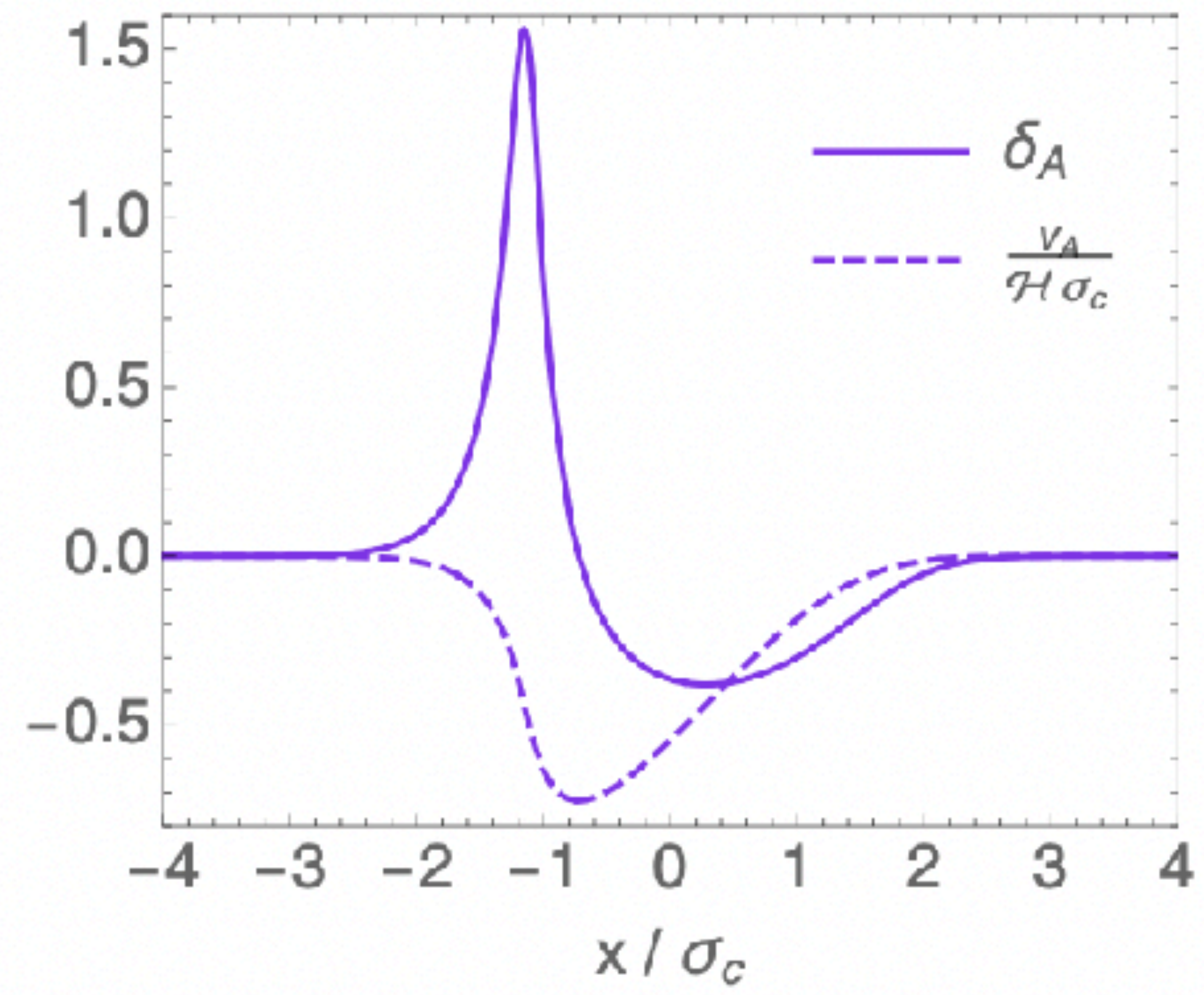
Braganca, ML, Sekera, Senatore, Sgier, 2020

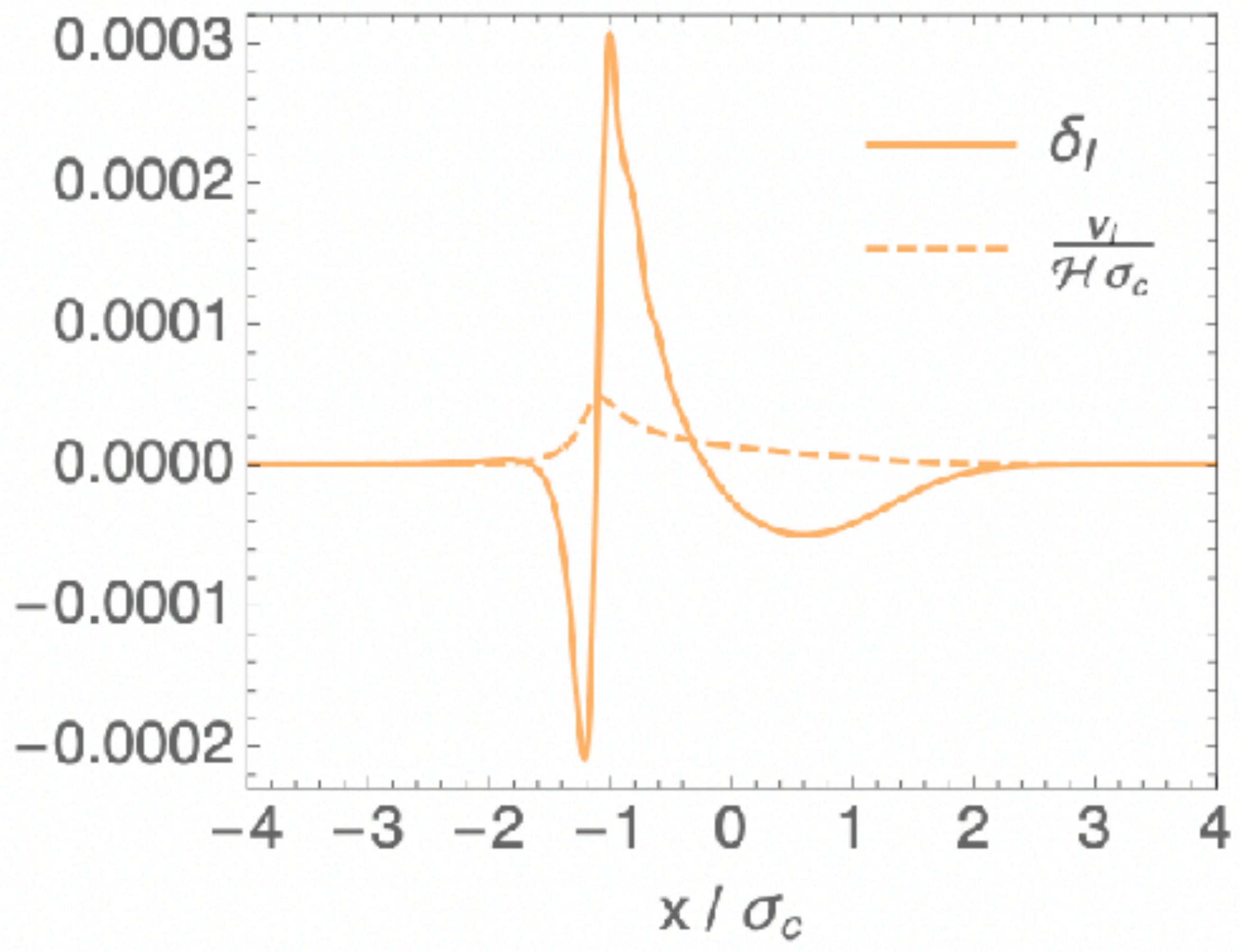
linear relative velocity counterterm

size estimation - UV model

a = 0.5

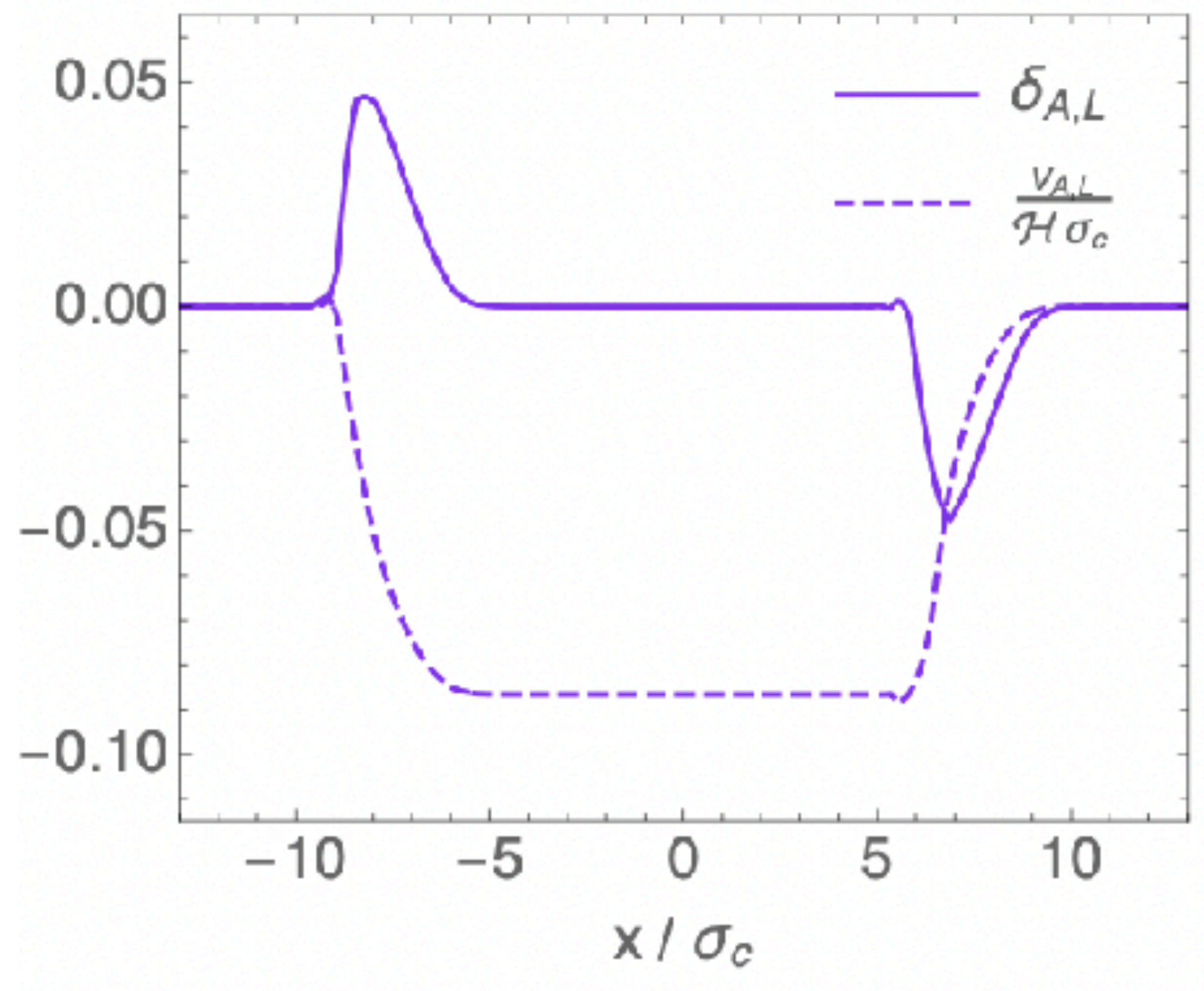
nonlinear solutions

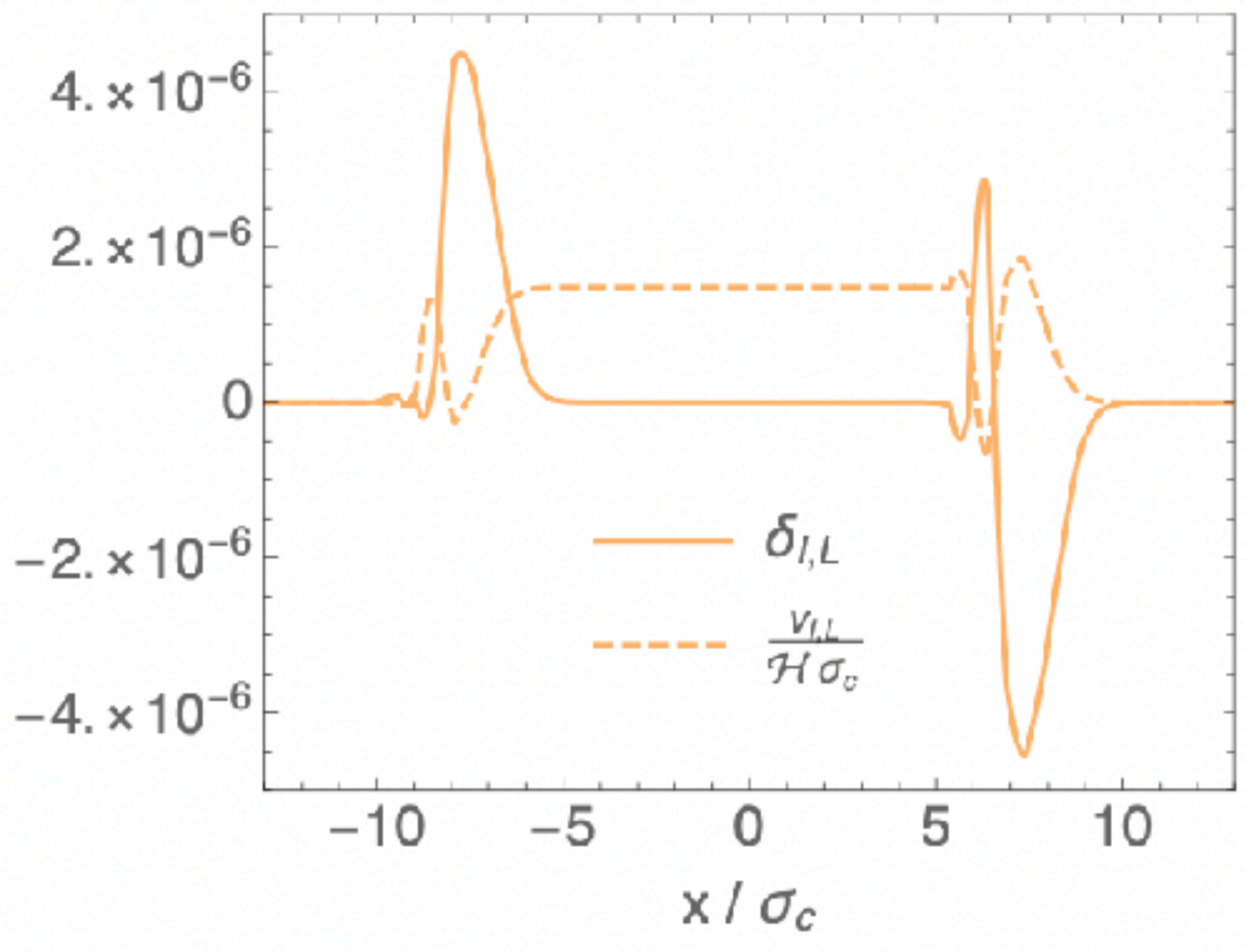




smoothed solutions

L = $15\sigma_c$





EFT for two fluids

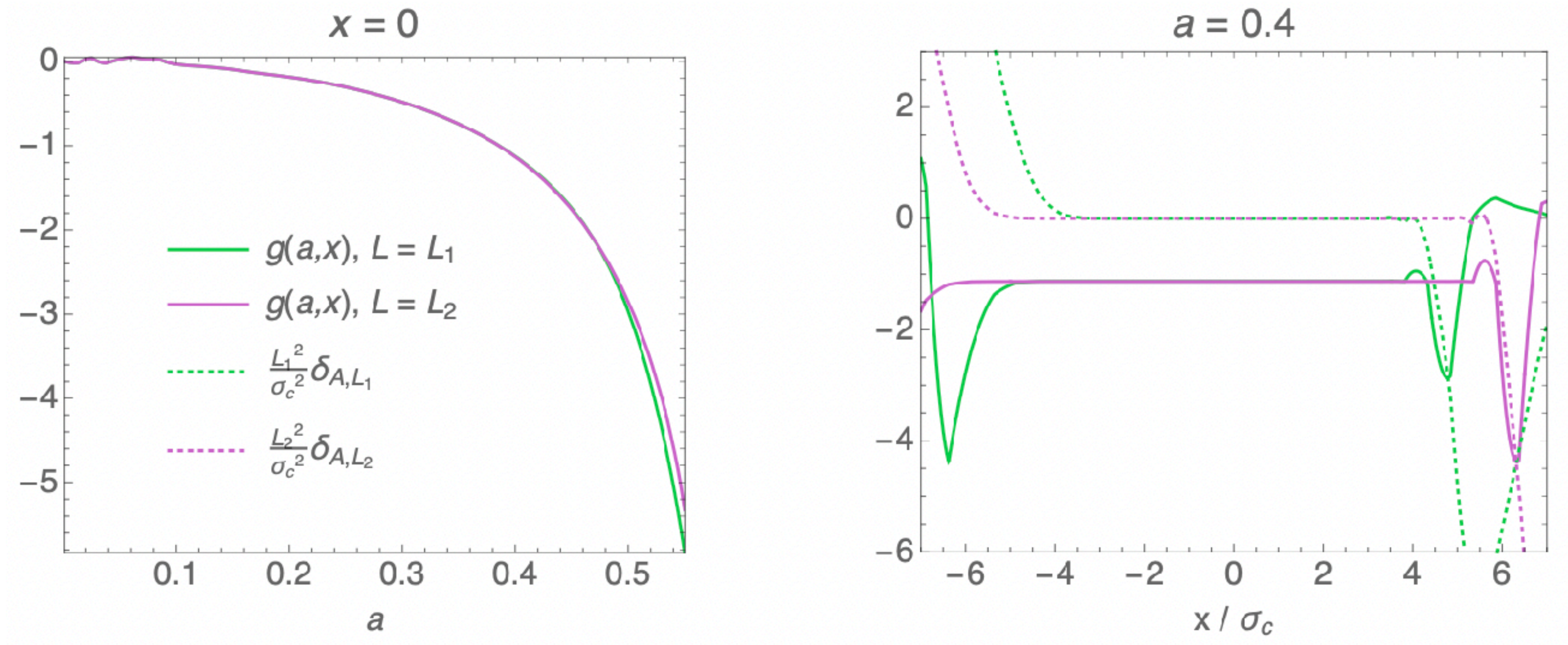
Braganca, ML, Sekera, Senatore, Sgier, 2020

linear relative velocity counterterm

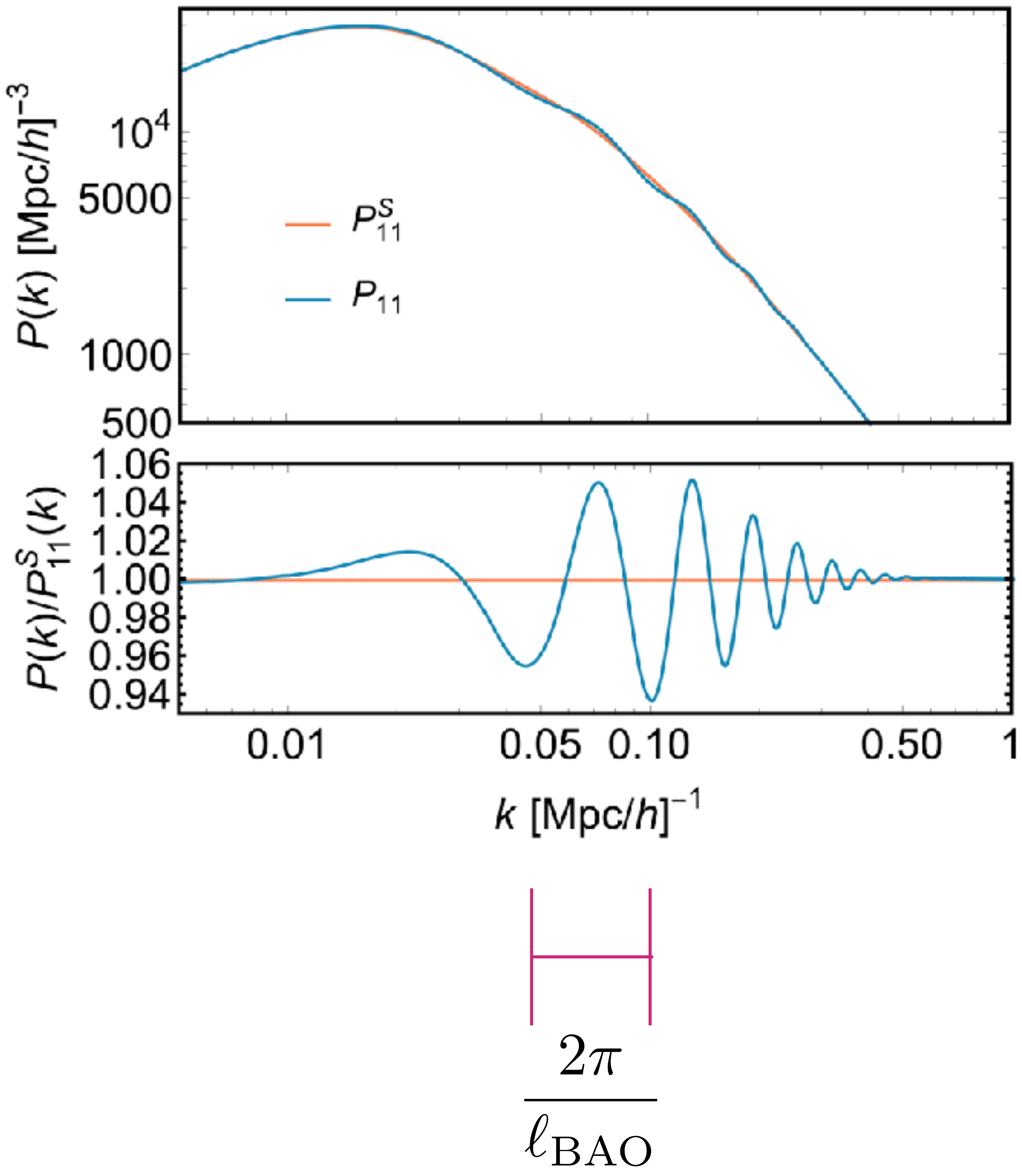
size estimation - UV model

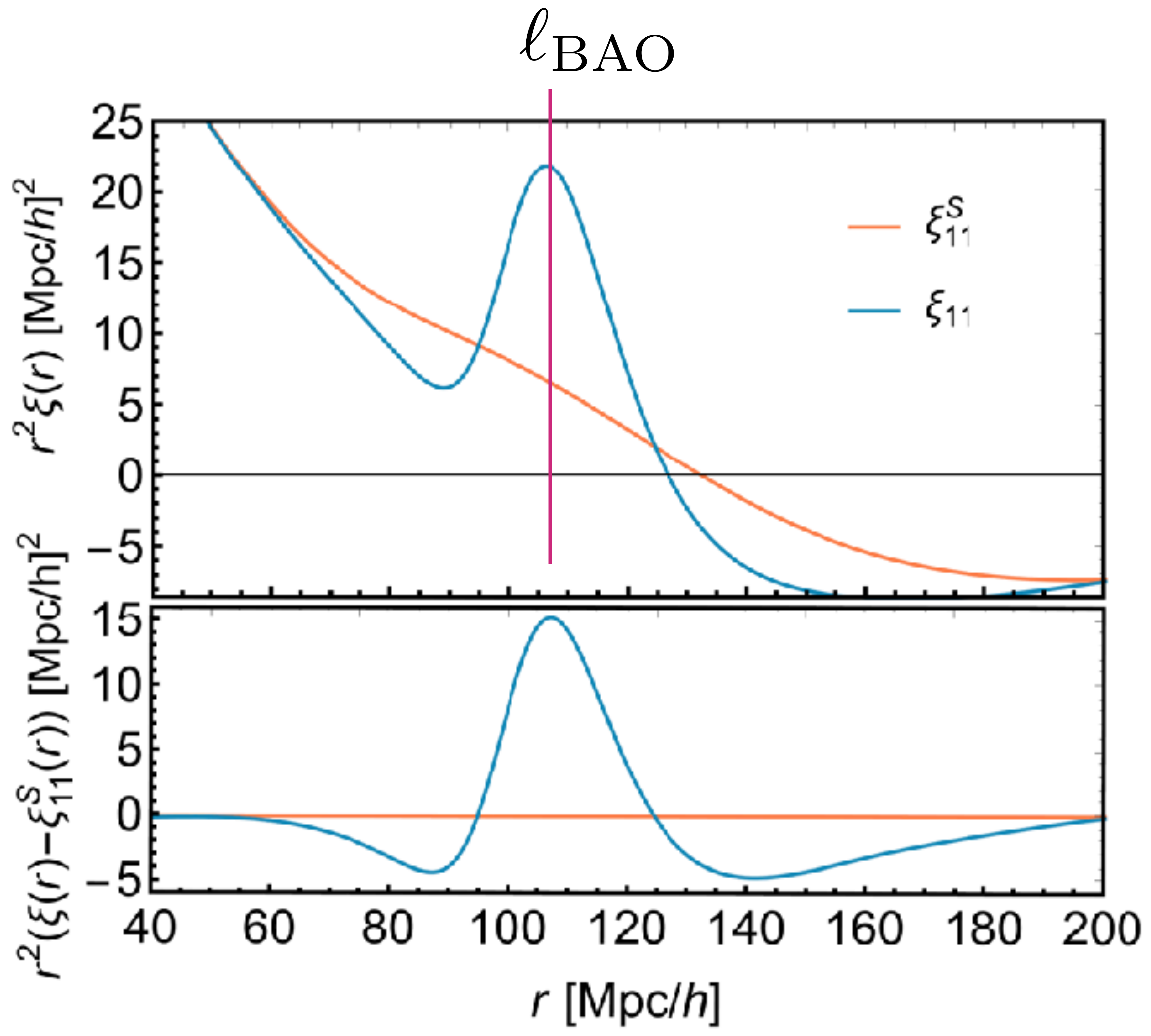
equation for smoothed field

$$a^2 \delta_{I,L}''(a,x) + \left(2 + \frac{a\mathcal{H}'(a)}{\mathcal{H}(a)}\right) a\delta_{I,L}'(a,x) = g(a,x)\, a\, \delta_{I,L}'(a,x) + \dots$$



reminder





$$\xi(r) = \int_{\vec{k}} P(k) e^{i\vec{k}\cdot\vec{r}} = \int_0^\infty dk \frac{k^2}{2\pi^2} \frac{\sin kr}{kr} P(k)$$

BAO

from the consistency conditions above

$$\lim_{q\to 0} \frac{B_t(\vec{q}, \vec{k}_1, \vec{k}_2)}{P_{11}(q)} \approx -\frac{\vec{q}\cdot(\vec{k}_1 + \vec{k}_2)}{q^2} P_{11}(k_1) \approx 0$$

BAO

from the consistency conditions above

$$\lim_{q\to 0} \frac{B_t(\vec{q},\vec{k}_1,\vec{k}_2)}{P_{11}(q)} \approx -\frac{\vec{q}\cdot(\vec{k}_1+\vec{k}_2)}{q^2} P_{11}(k_1) \approx 0$$

and expanding to next order in q/k

$$\lim_{q\to 0} \frac{B_t(\vec{q},\vec{k}-\vec{q}/2,-\vec{k}-\vec{q}/2)}{P_{11}(q)} \approx 0 - \frac{\vec{q}\cdot\vec{k}}{q^2}\frac{\vec{q}\cdot\vec{k}}{k}\frac{\partial P_{11}(k)}{\partial k} + \mathcal{O}\left(P_{11}(k)\right)$$

the coefficient above is fixed, but the next one is not.
is there a regime where this can be the leading term?

BAO

from the consistency conditions above

$$\lim_{q\to 0} \frac{B_t(\vec{q},\vec{k}_1,\vec{k}_2)}{P_{11}(q)} \approx -\frac{\vec{q}\cdot(\vec{k}_1+\vec{k}_2)}{q^2} P_{11}(k_1) \approx 0$$

and expanding to next order in q/k

$$\lim_{q\to 0} \frac{B_t(\vec{q},\vec{k}-\vec{q}/2,-\vec{k}-\vec{q}/2)}{P_{11}(q)} \approx 0 - \frac{\vec{q}\cdot\vec{k}}{q^2}\frac{\vec{q}\cdot\vec{k}}{k}\frac{\partial P_{11}(k)}{\partial k} + \mathcal{O}\left(P_{11}(k)\right)$$

the coefficient above is fixed, but the next one is not.
is there a regime where this can be the leading term?

YES, for the BAO

BAO

$$P_{11}(k) = P^{\rm s}_{11}(k) + \epsilon_{\rm osc} P^{\rm osc}_{11}(k)$$

BAO

$$P_{11}(k) = P_{11}^{\rm s}(k) + \epsilon_{\rm osc} P_{11}^{\rm osc}(k)$$

$$\frac{\partial P_{11}^{\rm s}(k)}{\partial k} \sim \frac{P_{11}^{\rm s}(k)}{k} \qquad \frac{\partial P_{11}^{\rm osc}(k)}{\partial k} \sim \frac{\ell_{\rm BAO}}{2\pi} P_{11}^{\rm osc}(k)$$

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$$B_t = B_t^{\mathrm{s}} + \epsilon_{\mathrm{osc}} B_t^{\mathrm{osc}} + \mathcal{O}(\epsilon_{\mathrm{osc}}^2)$$

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$$\boxed{k\,\ell_{\rm BAO} \gg 1} \qquad k\,\ell_{\rm BAO} \sim 10$$

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coefficient fixed by equivalence principle

$$B_t = B_t^{\mathrm{s}} + \epsilon_{\mathrm{osc}} B_t^{\mathrm{osc}} + \mathcal{O}(\epsilon_{\mathrm{osc}}^2)$$

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BAO

galaxies

$$\delta_g = b_1 \delta + \dots$$

$$\lim_{q \to 0} \frac{B_g^{\rm osc}(\vec{q}, \vec{k} - \vec{q}/2, -\vec{k} - \vec{q}/2)}{P_g^{\rm s}(q)} \approx -\frac{1}{b_1} \frac{\vec{q} \cdot \vec{k}}{q^2} \frac{\vec{q} \cdot \vec{k}}{k} \frac{\partial P_g^{\rm osc}(k)}{\partial k} + \dots$$

BAO

galaxies

$$\delta_g = b_1 \delta + \ldots$$

$$\lim_{q \to 0} \frac{B_g^{\rm osc}(\vec{q}, \vec{k} - \vec{q}/2, -\vec{k} - \vec{q}/2)}{P_g^{\rm s}(q)} \approx -\frac{1}{b_1} \frac{\vec{q} \cdot \vec{k}}{q^2} \frac{\vec{q} \cdot \vec{k}}{k} \frac{\partial P_g^{\rm osc}(k)}{\partial k} + \ldots$$

clean measurement of bias coefficient

BAO

power spectrum

$$P_{\text{1-loop}}(k) \approx \int_{q \lesssim k} \frac{d^3q}{(2\pi)^3} \left(\frac{\vec{q} \cdot \vec{k}}{q^2} \right)^2 P_{11}(q) \left(P_{11}(|\vec{k} - \vec{q}|) - P_{11}(k) \right)$$

$$\approx 0 - \int_{q \lesssim k} \frac{d^3q}{(2\pi)^3} \left(\frac{\vec{q} \cdot \vec{k}}{q^2} \right)^2 P_{11}(q) \left(\frac{q^2(1-\mu^2)}{2k} \frac{\partial P_{11}(k)}{\partial k} + \frac{q^2\mu^2}{2} \frac{\partial^2 P_{11}(k)}{\partial k^2} \right)$$

$$\mu \equiv \hat{k} \cdot \hat{q}$$

BAO

power spectrum

$$P_{\text{1-loop}}(k) \approx \int_{q \lesssim k} \frac{d^3q}{(2\pi)^3} \left(\frac{\vec{q} \cdot \vec{k}}{q^2} \right)^2 P_{11}(q) \left(P_{11}(|\vec{k} - \vec{q}|) - P_{11}(k) \right)$$

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$$\mu \equiv \hat{k} \cdot \hat{q}$$

normally this term cancels, but again, it can have a large effect on the BAO, especially because it is enhanced in the IR limit by k^2/q^2

BAO

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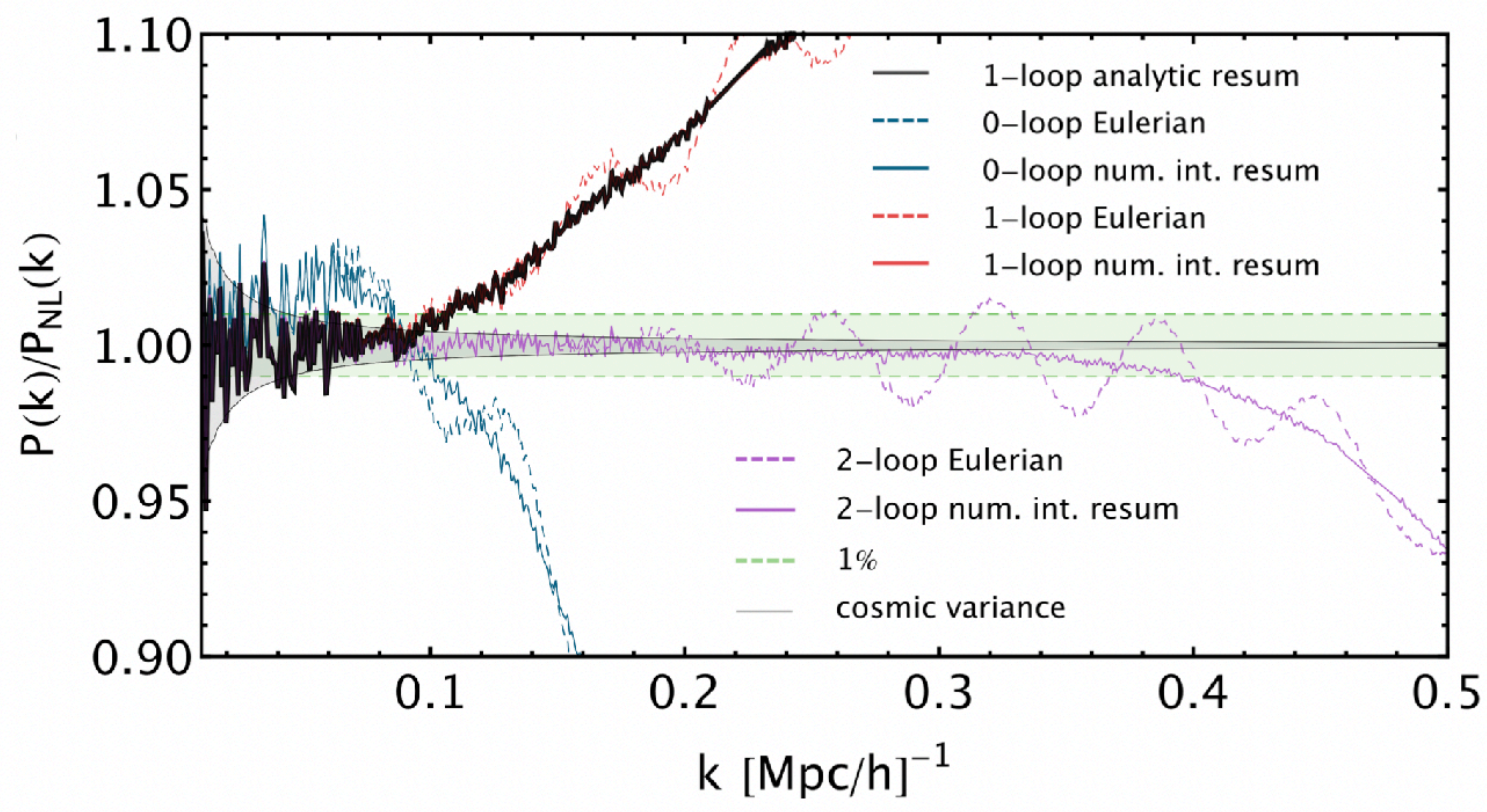
$$\mu \equiv \hat{k}\cdot\hat{q}$$

normally this term cancels, but again, it can have a large effect on the BAO, especially because it is enhanced in the IR limit by k^2/q^2

but importantly, we know this coefficient because of the consistency conditions

IR resummation

power spectrum



ML, Senatore 2018

the BOSS analysis

beyond ΛCDM

Hubble tension

D'Amico, Senatore, Zhang, Zheng 21

- many models try to ease tension by making H larger before recombination
- Planck has precision constraint on angular acoustic scale

  $\theta_s(z_{\rm CMB}) \sim r_s(\Omega_{\rm m}h^2)^{0.4}H_0^{0.2}$
- amplitude of acoustic peaks gives

  $A \sim r_s^{-0.26}(\Omega_{\rm m}h^2)^{-0.25}$
- so there is an r_s-H_0 degeneracy
- but LSS constrains

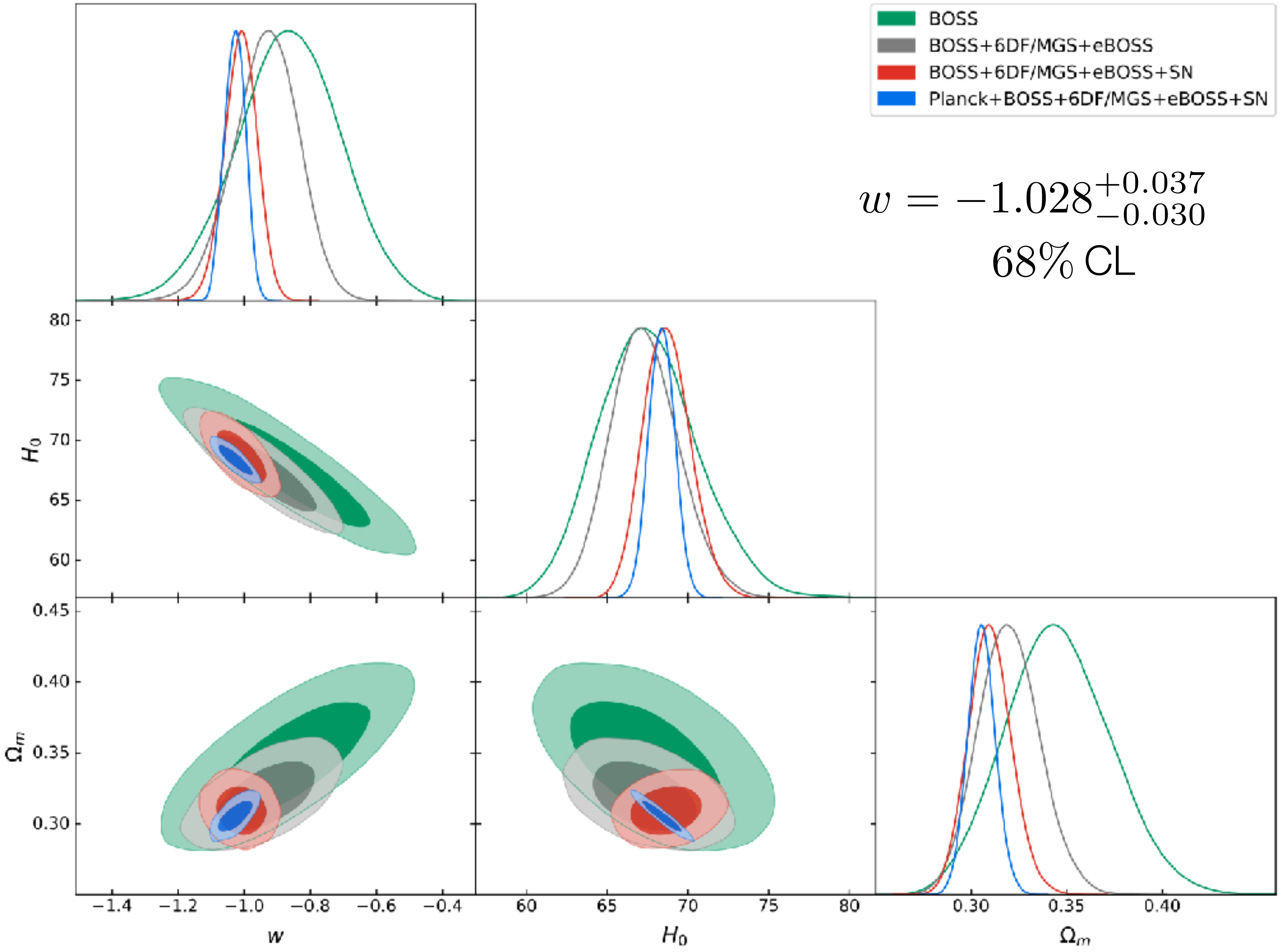
  $\theta_s(z_{\rm LSS}) \sim r_s(\Omega_{\rm m}h^2)^{0.1}H_0^{0.8}$

  and breaks degeneracy
- these models do *not* reduce H_0 tension

quintessence

D'Amico, Donath, Senatore, Zhang 21

(theory paper: **ML**, Maleknejad, Senatore 17)



$w = -1.028^{+0.037}_{-0.030}$

68% CL

equations in Fourier space

$$\delta' \equiv \partial_a \delta$$
$$\mathcal{H} \equiv aH$$
$$\Theta \equiv -\partial_i v^i / \mathcal{H}$$

convert to time variable a using $\dfrac{da}{dt} = aH(a)$

$$a\delta'_{\vec{k}}(a) - \Theta_{\vec{k}}(a) = \int_{\vec{q}} \alpha(\vec{k}-\vec{q},\vec{q})\delta_{\vec{k}-\vec{q}}(a)\Theta_{\vec{q}}(a)$$

$$a\Theta'_{\vec{k}}(a) + \left(1 + \frac{a\mathcal{H}'}{\mathcal{H}}\right)\Theta_{\vec{k}}(a) - \frac{3\Omega_m(a)}{2}\delta_{\vec{k}}(a) = \int_{\vec{q}} \beta(\vec{k}-\vec{q},\vec{q})\Theta_{\vec{k}-\vec{q}}(a)\Theta_{\vec{q}}(a)$$
$$-(2\pi)c_s^2(a)\frac{k^2}{k_{\rm NL}^2}\delta_{\vec{k}}(a)$$

EFT of LSS

"interaction vertices" from the non-linear EOM

$$\alpha(\vec{k}_1,\vec{k}_2) = 1 + \frac{\vec{k}_1 \cdot \vec{k}_2}{k_1^2}\,, \quad \beta(\vec{k}_1,\vec{k}_2) = \frac{|\vec{k}_1+\vec{k}_2|^2 \vec{k}_1 \cdot \vec{k}_2}{2k_1^2 k_2^2}$$