

EFT of LSS: one-loop bispectrum, baryons, and dark energy

Matthew Lewandowski
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CERN Theory Institute
New physics from galaxy clustering
22/11/22

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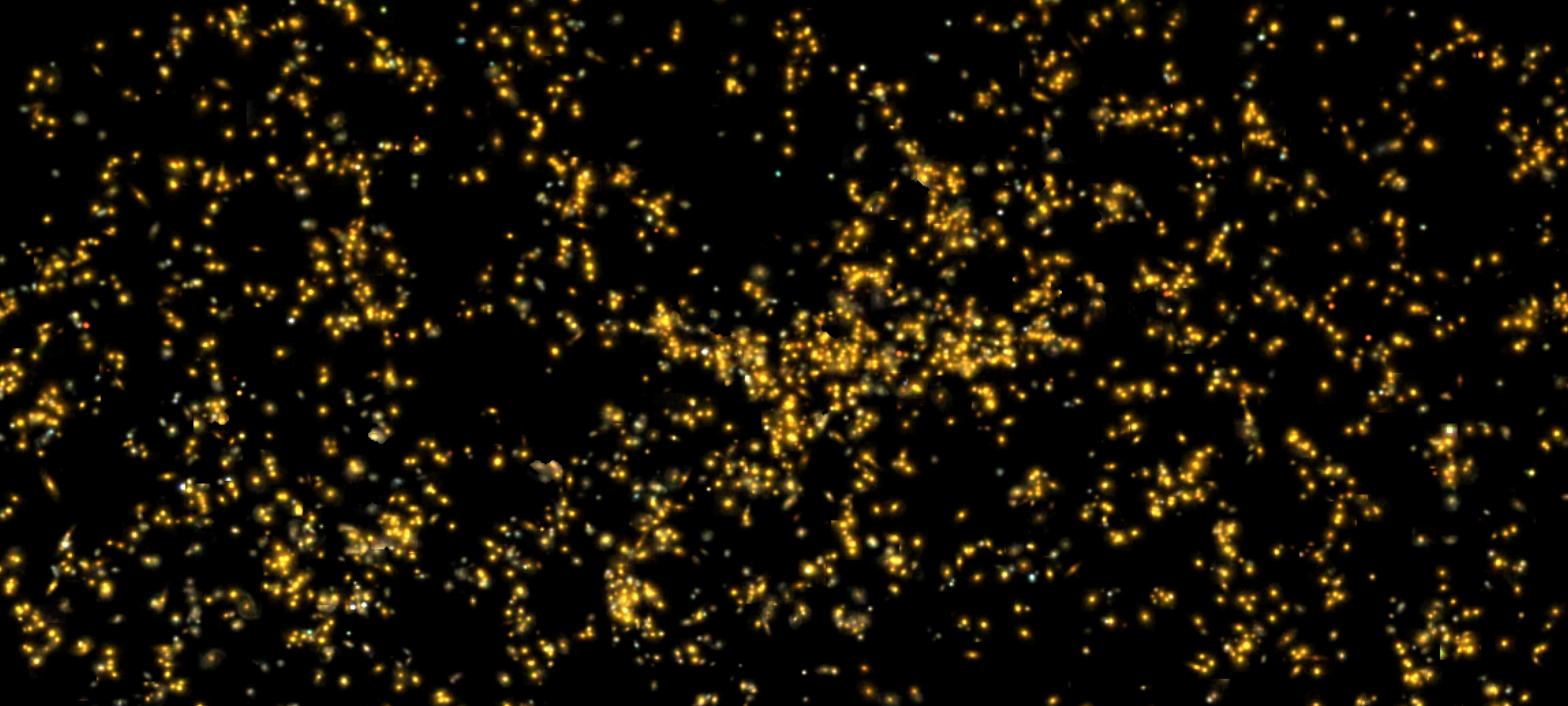
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outline

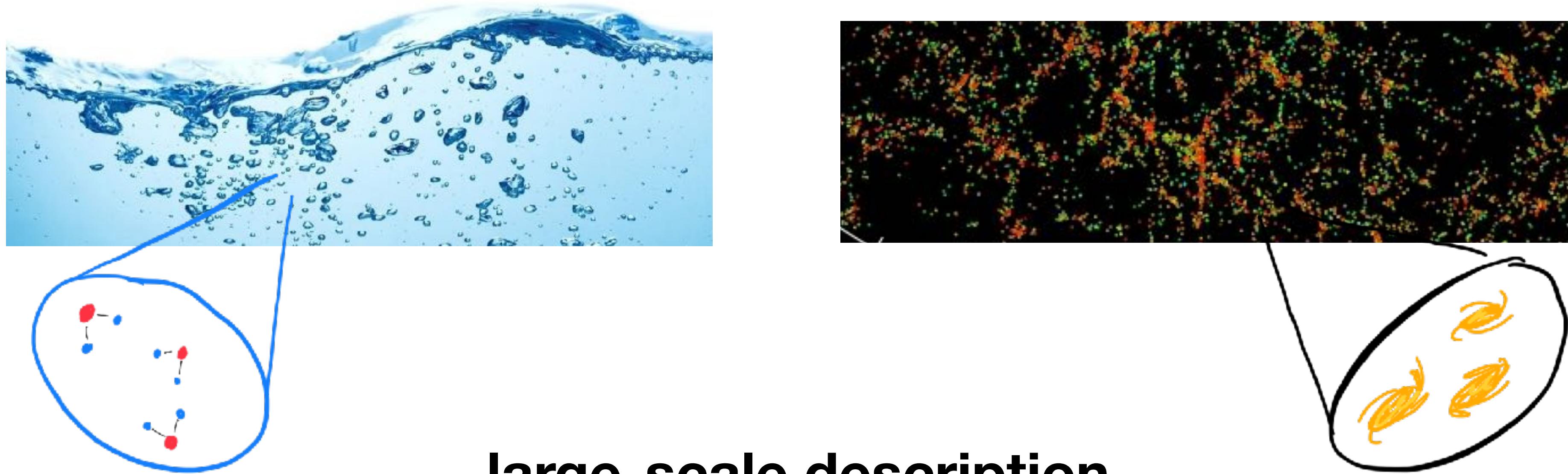
- brief review of EFT of LSS
- one-loop bispectrum of tracers
- baryons
- dark energy

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



EFT of LSS review

main idea



viscosity ν , ...

EFT parameters c_s^2 , ...

expansion parameter

$$\frac{\lambda_{\text{mfp}}}{L_{\text{obs}}}$$

$$\frac{L_{\text{NL}}}{L_{\text{obs}}} \sim \frac{k_{\text{obs}}}{k_{\text{NL}}}$$

low energy DOF, scales

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

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

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

$$v^i(t, \vec{x}) \quad v \ll 1 \quad \text{non-relativistic}$$

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

sub-horizon
(Newtonian limit)

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

finite age of universe
(like mean free path)

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

EFT expansion param.

dark matter EOM

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

- mass conservation
- momentum conservation
- Galilean invariance

$$x^i \rightarrow x^i + n^i(t)$$

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

$$\partial_i \rightarrow \partial_i \quad \partial_t \rightarrow \partial_t - \dot{n}^i(t)\partial_i \quad \rho \rightarrow \rho$$

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

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

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

$$\tau^{ij}/\bar{\rho} \sim c_s^2 \delta^{ij} \delta + c_2 \partial_i v^j$$

$$+ \frac{c_3}{k_{\text{NL}}^2} \partial_i \delta \partial_j \delta + \frac{c_4}{k_{\text{NL}}^2} \partial_i \partial_j \delta + \dots$$

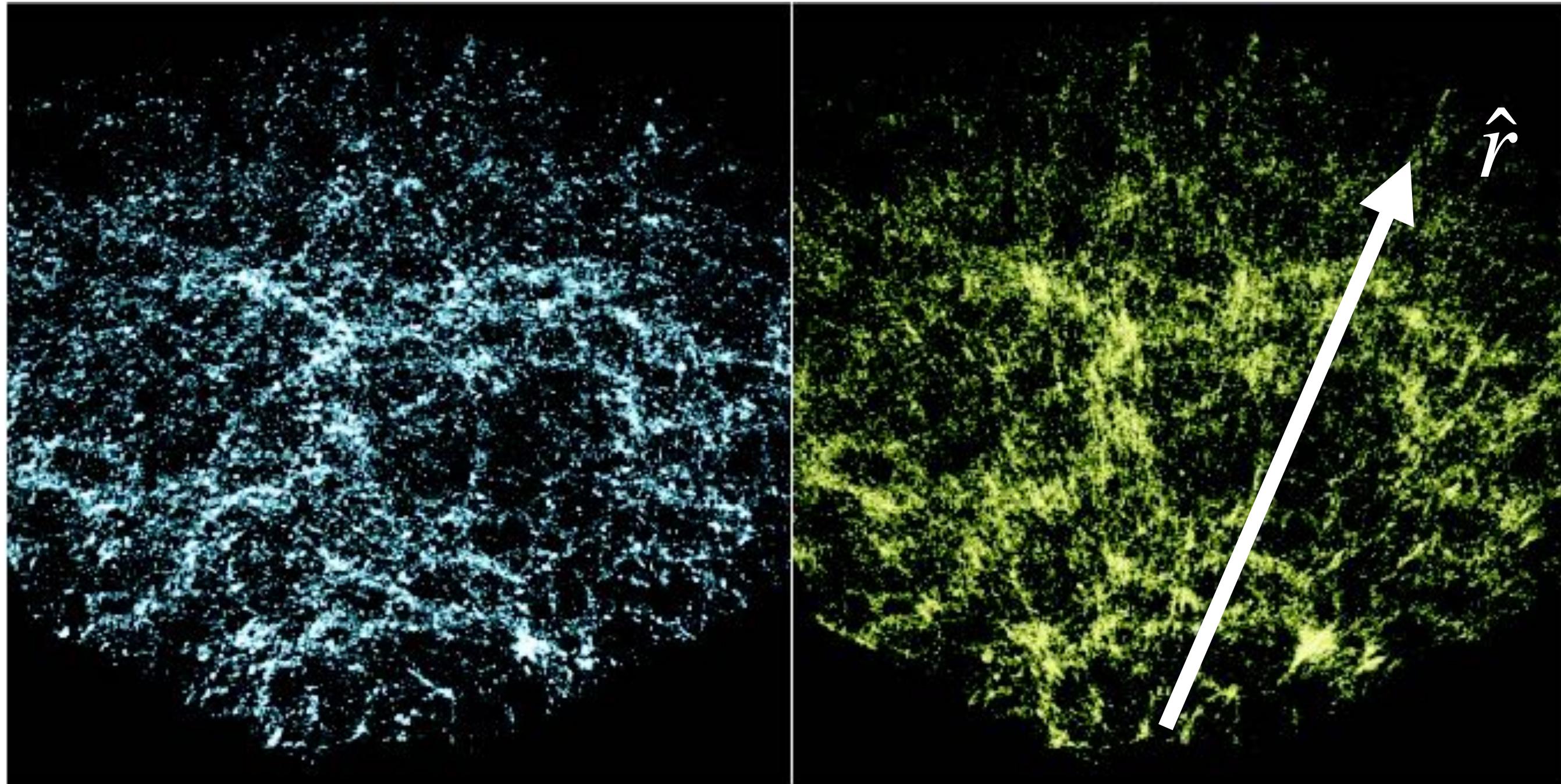
EFT of LSS

Baumann, Nicolis,
Senatore, Zaldarriaga 12
Carrasco, Hertzberg,
Senatore 12

redshift-space distortions in the EFT

Senatore, Zaldarriaga 14

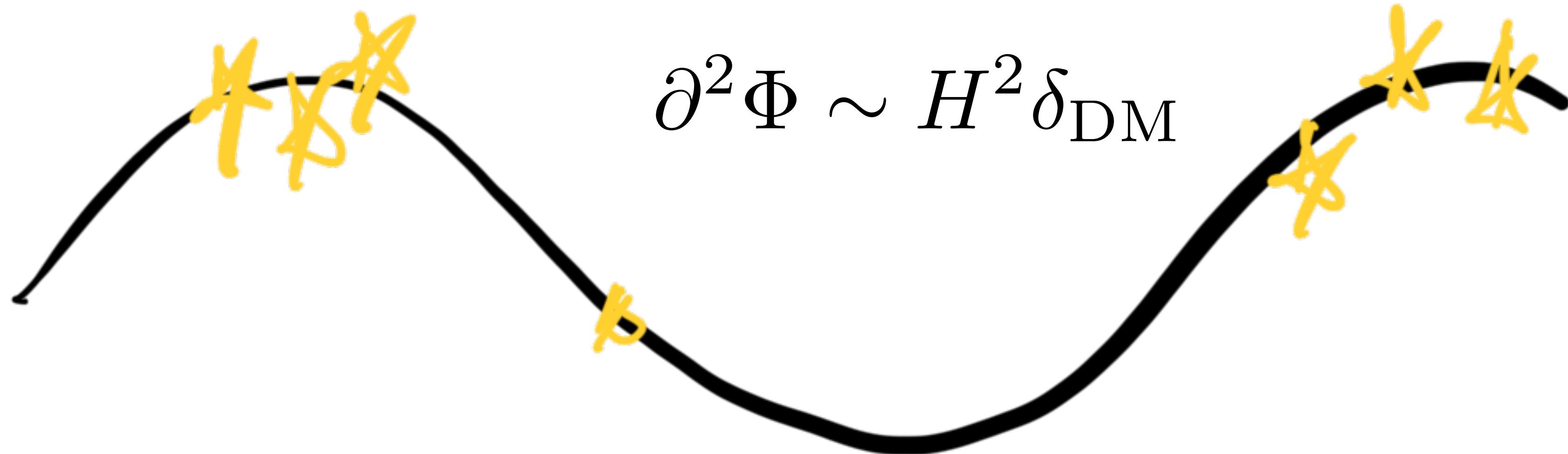
ML, Senatore, et. al. 18



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



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

some very complicated dependence, integrated
over past light cone

perturbation
theory



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

McDonald 06

McDonald, Roy 10

Senatore 15

Desjacques, Jeong,
Schmidt 16

Angulo, Fasiello, Senatore
Vlah 15

many more ...

observables

observables - correlation functions

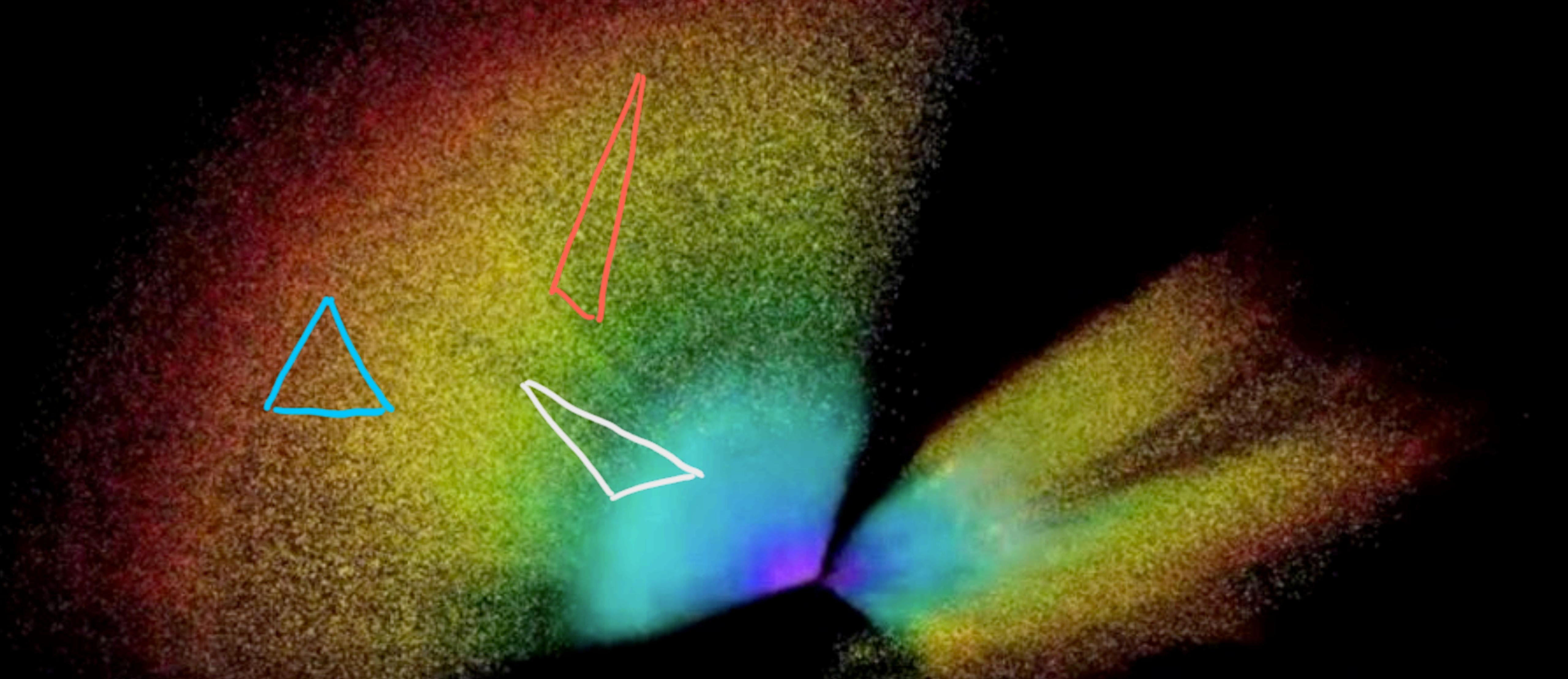
$$\langle \delta(\vec{k}_1) \delta(\vec{k}_2) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P(k_1) \quad \text{power spectrum}$$

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

perturbative expansion

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

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



the one-loop bispectrum

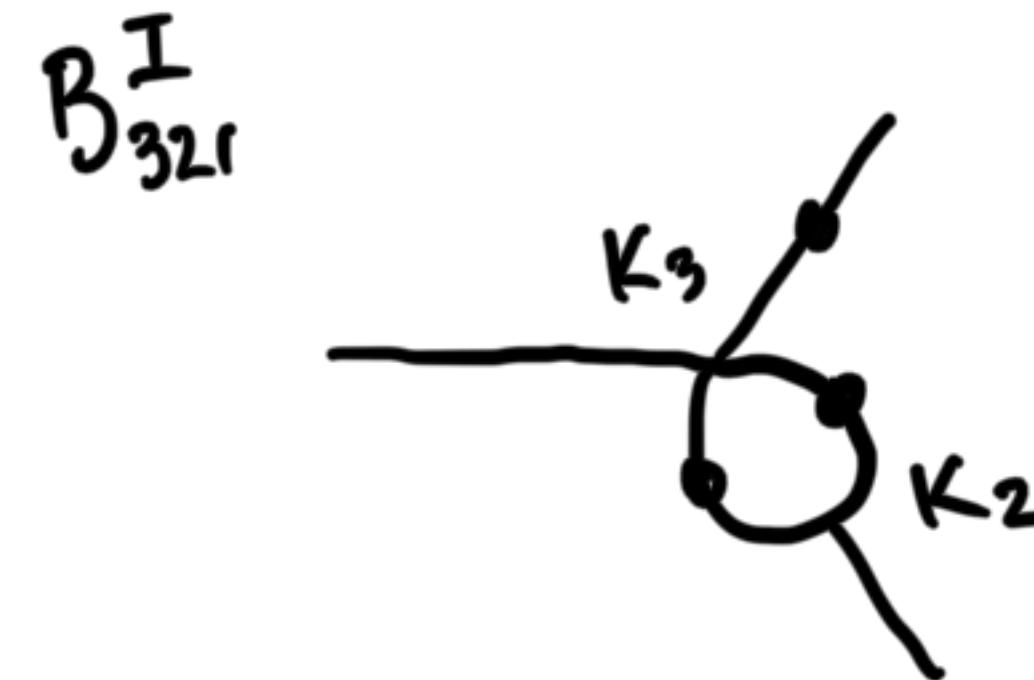
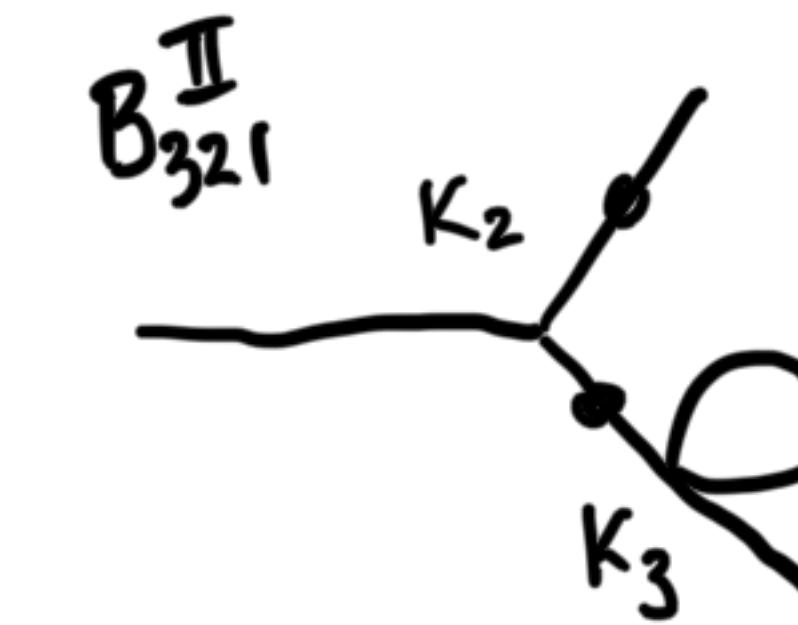
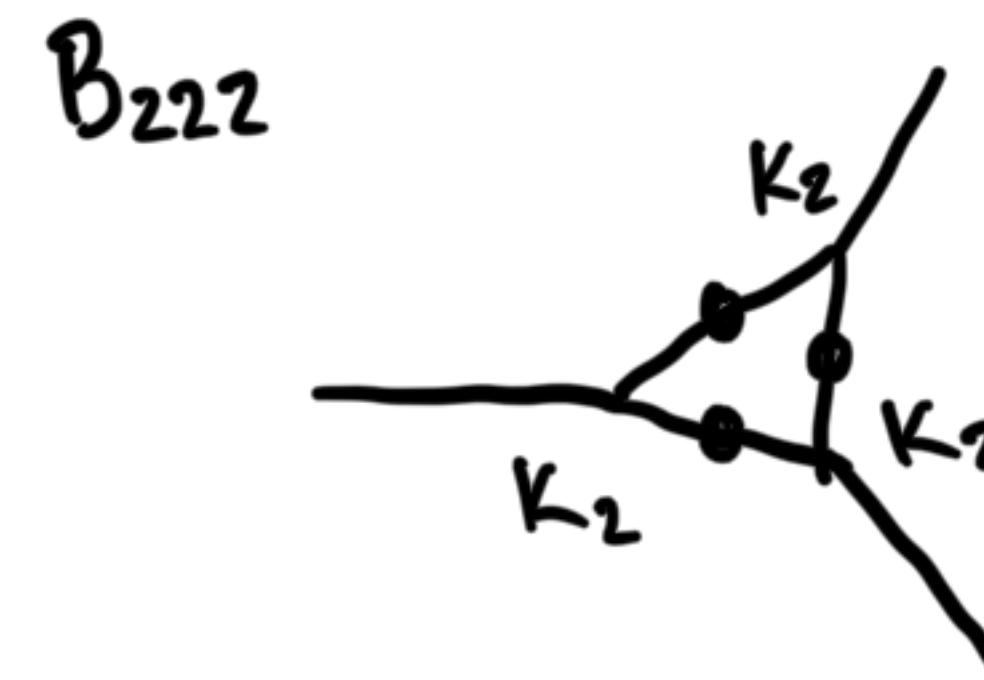
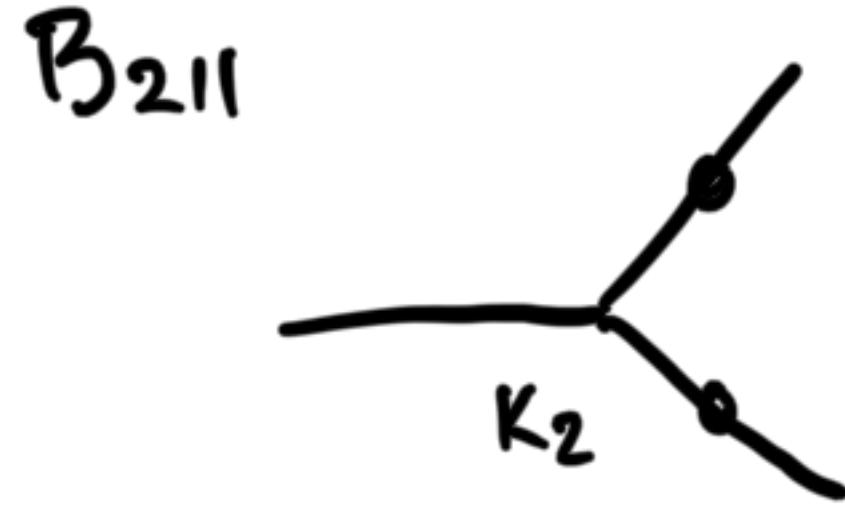
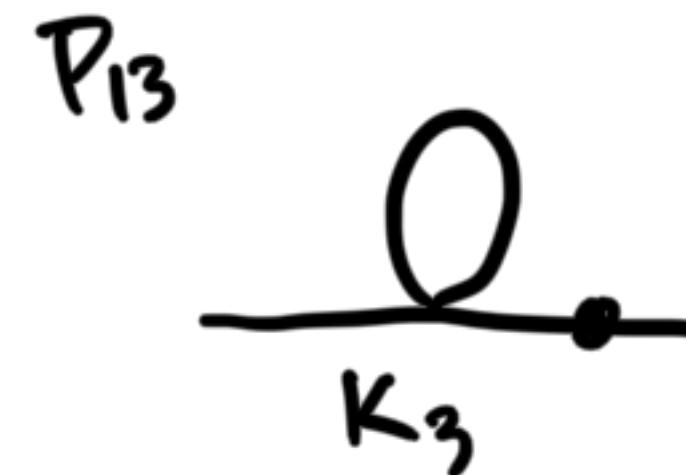
one-loop terms

power spectrum

bispectrum

$$\delta_{r,h}^{(1)}(\vec{k}, \hat{z}) = K_1^{r,h}(\vec{k}; \hat{z}) \delta_{\vec{k}}^{(1)},$$

$$\delta_{r,h}^{(n)}(\vec{k}, \hat{z}) = \int_{\vec{k}_1, \dots, \vec{k}_n}^{\vec{k}} K_n^{r,h}(\vec{k}_1, \dots, \vec{k}_n; \hat{z}) \delta_{\vec{k}_1}^{(1)} \cdots \delta_{\vec{k}_n}^{(1)}$$



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

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

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

solve up to

$$K_4^{r,h}$$

bias expansion

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

write all contractions of $r_{ij} = \frac{2}{3\Omega_m \mathcal{H}^2} \partial_i \partial_j \Phi$ $p_{ij} = -\frac{1}{faH} \partial_i v^j$ equivalence principle

integrated along the fluid element $\vec{x}_{\text{fl}}(\vec{x}, t, t') = \vec{x} + \int_t^{t'} \frac{dt''}{a(t'')} \vec{v}(\vec{x}_{\text{fl}}(\vec{x}, t, t''), t'')$ non-local in time

$\delta_h(\vec{x}, t) = \int^t dt' H(t') [c_\delta(t, t') \delta(\vec{x}_{\text{fl}}, t') + c_\theta(t, t') \theta(\vec{x}_{\text{fl}}, t')]$ Galilean invariance

$+ c_{\delta^2}(t, t') \delta^2(\vec{x}_{\text{fl}}, t') + c_{\delta\theta}(t, t') \delta\theta(\vec{x}_{\text{fl}}, t') + c_{\theta^2}(t, t') \theta^2(\vec{x}_{\text{fl}}, t')$

$+ c_{r^2}(t, t') r^2(\vec{x}_{\text{fl}}, t') + c_{rp}(t, t') rp(\vec{x}_{\text{fl}}, t') + c_{p^2}(t, t') p^2(\vec{x}_{\text{fl}}, t')$

$+ c_{\delta^3}(t, t') \delta^3(\vec{x}_{\text{fl}}, t') + c_{\delta^2\theta}(t, t') \delta^2\theta(\vec{x}_{\text{fl}}, t') + c_{\delta\theta^2}(t, t') \delta\theta^2(\vec{x}_{\text{fl}}, t') + c_{\theta^3}(t, t') \theta^3(\vec{x}_{\text{fl}}, t')$

$+ c_{r^3}(t, t') r^3(\vec{x}_{\text{fl}}, t') + c_{r^2p}(t, t') r^2 p(\vec{x}_{\text{fl}}, t') + c_{rp^2}(t, t') r p^2(\vec{x}_{\text{fl}}, t') + c_{p^3}(t, t') p^3(\vec{x}_{\text{fl}}, t')$

$+ c_{r^2\delta}(t, t') r^2 \delta(\vec{x}_{\text{fl}}, t') + c_{rp\delta}(t, t') r p \delta(\vec{x}_{\text{fl}}, t') + c_{p^2\delta}(t, t') p^2 \delta(\vec{x}_{\text{fl}}, t')$

$+ c_{r^2\theta}(t, t') r^2 \theta(\vec{x}_{\text{fl}}, t') + c_{rp\theta}(t, t') r p \theta(\vec{x}_{\text{fl}}, t') + c_{p^2\theta}(t, t') p^2 \theta(\vec{x}_{\text{fl}}, t')$

$+ c_{\delta^4}(t, t') \delta^4(\vec{x}_{\text{fl}}, t') + c_{\delta r^3}(t, t') \delta r^3(\vec{x}_{\text{fl}}, t') + c_{\delta^2 r^2}(t, t') \delta^2 r^2(\vec{x}_{\text{fl}}, t')$

$+ c_{(r^2)^2}(t, t') (r^2)^2 (\vec{x}_{\text{fl}}, t') + c_{r^4}(t, t') r^4(\vec{x}_{\text{fl}}, t')] \Big|_{\vec{x}_{\text{fl}}=\vec{x}_{\text{fl}}(\vec{x}, t, t')} .$

redshift space distortions

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

coordinate measured by redshift

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

mass conservation implies

$$\rho(\vec{x}_r) d^3x_r = \rho(\vec{x}) d^3x$$

$$\delta_{r,h}(\vec{k}, \hat{z}) = \delta_h(\vec{k}) + \int d^3x e^{-i\vec{k}\cdot\vec{x}} \left(\exp \left[-i \frac{(\hat{z} \cdot \vec{k})}{aH} (\hat{z} \cdot \vec{v}(\vec{x})) \right] - 1 \right) (1 + \delta_h(\vec{x}))$$

$$\begin{aligned} \delta_{r,h} &= \delta_h - \frac{\hat{z}^i \hat{z}^j}{aH \bar{\rho}_h} \partial_i \pi_h^j + \frac{\hat{z}^i \hat{z}^j \hat{z}^k \hat{z}^l}{2(aH)^2 \bar{\rho}_h} \partial_i \partial_j (\pi_h^k v^l) \\ &\quad - \frac{\prod_{a=1}^6 \hat{z}^{i_a}}{3!(aH)^3 \bar{\rho}_h} \partial_{i_1} \partial_{i_2} \partial_{i_3} (\pi_h^{i_4} v^{i_5} v^{i_6}) + \frac{\prod_{a=1}^8 \hat{z}^{i_a}}{4!(aH)^4 \bar{\rho}_h} \partial_{i_1} \partial_{i_2} \partial_{i_3} \partial_{i_4} (\pi_h^{i_5} v^{i_6} v^{i_7} v^{i_8}) + \dots \end{aligned}$$

$\pi_h^i \equiv \bar{\rho}_h (1 + \delta_h) v^i$

renormalization

need up to quadratic counterterms

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

higher-derivative halo bias and counterterms

$$[\delta_h]_R = \delta_h + \mathcal{O}_{\rho_h}/\bar{\rho}_h$$

in terms of v^i , momentum is a contact operator

$$[\pi_h^i]_R = \bar{\rho}_h [(1 + \delta_h) v^i]_R$$

or think about smoothing fields
in a simulations, for example

$$[\sigma_1(\vec{x})\sigma_2(\vec{x})]_\Lambda \neq [\sigma_1(\vec{x})]_\Lambda [\sigma_2(\vec{x})]_\Lambda$$

why do we need to renormalize contact operators?

$$\sigma(\vec{x}) = \sigma_1(\vec{x})\sigma_2(\vec{x}) \quad \tilde{\sigma}_n(\vec{x}) = \sigma_1(\vec{x} + n\delta\vec{x})\sigma_2(\vec{x} + (1 - n)\delta\vec{x})$$

$$\begin{aligned} \tilde{\sigma}_n(\vec{x}) - \sigma(\vec{x}) &\sim \frac{1}{k_{\text{NL}}^2} (c_1 \partial^2 \sigma_1(\vec{x}) \sigma_2(\vec{x}) + c_2 \partial_i \sigma_1(\vec{x}) \partial_i \sigma_2(\vec{x}) + c_3 \sigma_1(\vec{x}) \partial^2 \sigma_2(\vec{x}) + \dots) \\ &+ (\text{local-in-space contractions of } \partial_i \partial_j \Phi \text{ and } \partial_i v^j) + \dots \end{aligned}$$

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

renormalization

respecting Galilean invariance

under the transformation

$$v^i \rightarrow v^i + \chi^i \quad (\pi^i \rightarrow \pi^i + \rho\chi^i)$$

we want the renormalized quantities to transform correctly

$$[v^i]_R \rightarrow [v^i]_R + \chi^i ,$$

$$[v^i v^j]_R \rightarrow [v^i v^j]_R + [v^i]_R \chi^j + [v^j]_R \chi^i + \chi^i \chi^j$$

$$[\delta_h v^i]_R \rightarrow [\delta_h v^i]_R + [\delta_h]_R \chi^i$$

...

$$[\delta_h]_R = \delta_h + \mathcal{O}_{\rho_h} / \bar{\rho}_h$$

$$[\pi_h^i]_R = \rho_h v^i + v^i \mathcal{O}_{\rho_h} + \mathcal{O}_{\pi_h}^i ,$$

$$[\pi_h^i v^j]_R = \rho_h v^i v^j + v^i v^j \mathcal{O}_{\rho_h} + v^i \mathcal{O}_{\pi_h}^j + v^j \mathcal{O}_{\pi_h}^i + \mathcal{O}_{\pi_h v}^{ij} ,$$

$$[\pi_h^i v^j v^k]_R = \rho_h v^i v^j v^k + v^i v^j v^k \mathcal{O}_{\rho_h} + (v^i v^j \mathcal{O}_{\pi_h}^k + 2 \text{ perms.}) + (v^i \mathcal{O}_{\pi_h v}^{jk} + 2 \text{ perms.}) + \mathcal{O}_{\pi_h v^2}^{ijk} ,$$

$$[\pi_h^i v^j v^k v^l]_R = \rho_h v^i v^j v^k v^l + v^i v^j v^k v^l \mathcal{O}_{\rho_h} + (v^i v^j v^k \mathcal{O}_{\pi_h}^l + 3 \text{ perms.})$$

$$+ (v^i v^j \mathcal{O}_{\pi_h v}^{kl} + 5 \text{ perms.}) + (v^i \mathcal{O}_{\pi_h v^2}^{jkl} + 3 \text{ perms.}) + \mathcal{O}_{\pi_h v^3}^{ijkl} ,$$

which leads to

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

ML, Senatore, et. al. 18

new momentum counterterm

dark matter

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

let's write the DM EOM in terms of the scalar and vector parts of π

$$\bar{\rho} \dot{\delta} + a^{-1} \pi_S = 0 ,$$

$$\dot{\pi}_S + 4H\pi_S + a\frac{3}{2}\bar{\rho}\Omega_m H^2\delta = -a^{-1}\partial_i\partial_j \left(2M_{\text{Pl}}^2 a^{-2} \left(\partial_i\Phi\partial_j\Phi - \frac{1}{2}\delta_{ij}(\partial\Phi)^2 \right) + \frac{\pi^i\pi^j}{\rho} + \tau^{ij} \right) ,$$

$$\dot{\pi}_V^i + 4H\pi_V^i = -a^{-1}\epsilon^{ijk}\partial_j\partial_l \left(2M_{\text{Pl}}^2 a^{-2}\partial_k\Phi\partial_l\Phi + \frac{\pi^k\pi^l}{\rho} + \tau^{kl} \right)$$

$$\pi_{(2)}^i \supset \frac{1}{H} \frac{\partial_i\partial_j\partial_k}{\partial^2} \tau_{(2)}^{jk}$$

$$\tau_{(2)}^{ij} \supset \frac{\bar{\rho}}{k_{\text{NL}}^2 H^2} \partial_i\partial_k\Phi\partial_k\partial_j\Phi$$

$$\delta_r^{(2)}(\vec{x}) \sim \frac{1}{H\bar{\rho}} \hat{z}^i \hat{z}^j \partial_i \pi_{(2)}^j(\vec{x}) \sim \hat{z}^i \hat{z}^j \frac{\partial_i\partial_j\partial_k\partial_m}{k_{\text{NL}}^2 \partial^2} \left(\frac{\partial_k\partial_l}{H^2} \Phi(\vec{x}) \frac{\partial_l\partial_m}{H^2} \Phi(\vec{x}) \right)$$

$$\delta_{ct}^{(2)} \sim \frac{\partial_i\partial_j}{k_{\text{NL}}^2} \left[\tau_{ct,(2)}^{ij} + \frac{\partial_i\delta^{(1)}}{\partial^2} \partial_k \tau_{ct,(1)}^{jk} - \frac{1}{6} \delta_{ij} \frac{\partial_k\delta^{(1)}}{\partial^2} \partial_l \tau_{ct,(1)}^{kl} \right]$$

$$\pi_S \equiv \partial_i \pi^i$$

$$\pi_V^i \equiv \epsilon^{ijk} \partial_j \pi^k$$

$$\pi^i = \frac{\partial_i}{\partial^2} \pi_S - \epsilon^{ijk} \frac{\partial_j}{\partial^2} \pi_V^k$$

only possible
because of
RSS

new momentum counterterm

biased tracers

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

this means that we must include a counterterm of the following form for the tracer momentum renormalization

$$\mathcal{O}_{\pi_h}^i \supset \frac{D^2 \bar{\rho}_h a H f}{k_{\text{NL}}^2} \frac{\partial_i \partial_j \partial_k}{\partial^2} \left(\frac{\partial_j \partial_l \delta^{(1)}}{\partial^2} \frac{\partial_l \partial_k \delta^{(1)}}{\partial^2} \right)$$

which can indeed be checked to be needed to cancel the following in the UV limit of the loops

the equivalence principle and locality actually force the DM and tracer counterterms to be equal

$$\frac{\mathcal{O}_{\pi_h,(2)}^i|_{\text{NLC}}}{\bar{\rho}_h} = \frac{\mathcal{O}_{\pi,(2)}^i|_{\text{NLC}}}{\bar{\rho}} + \dots$$

$$B_{411}^{r,h}|_{\text{UV}} \supset \frac{f(k_1^2 - k_2^2)^2 (k_1^2 + k_2^2) (k_1 \mu_1 + k_2 \mu_2)^2}{k_{\text{NL}}^2 k_1^2 k_2^2 k_3^2} P_{11}(k_1) P_{11}(k_2) + \text{2 perms.}$$

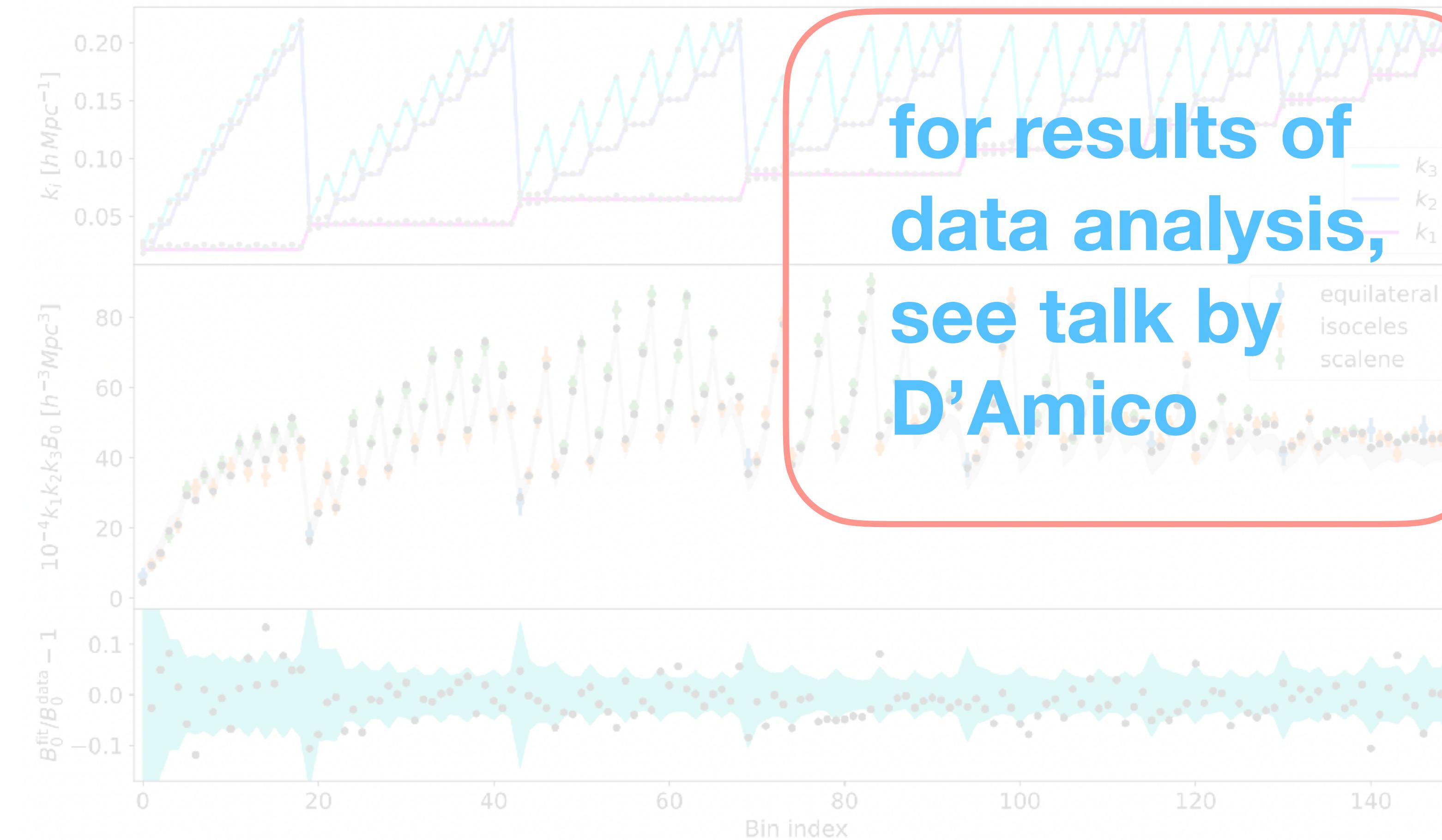
the BOSS analysis

data - bispectrum

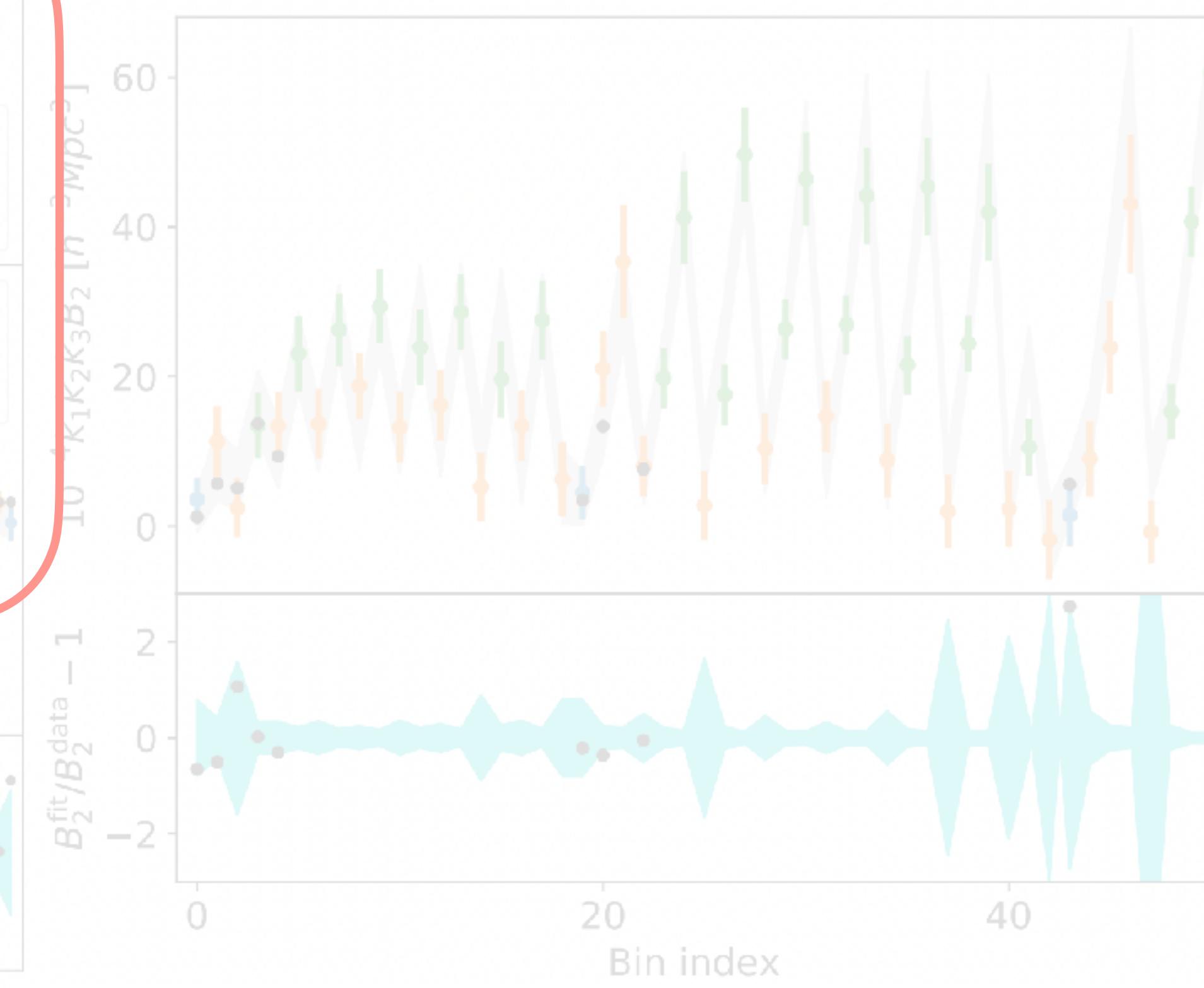
BOSS DR12 LRG sample

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for results of
data analysis,
see talk by
D'Amico



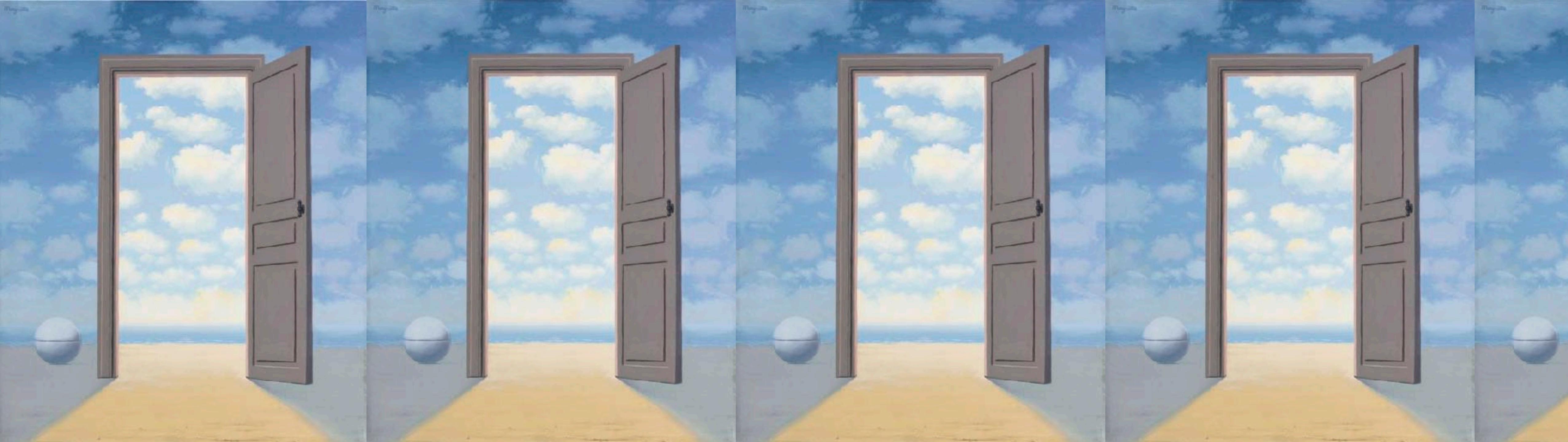
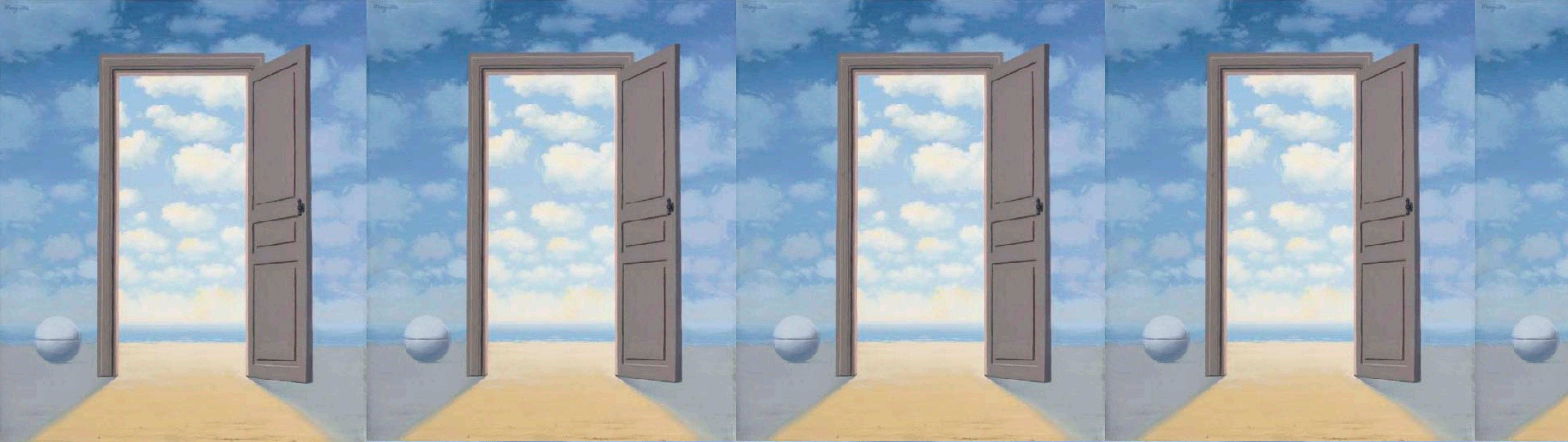
monopole

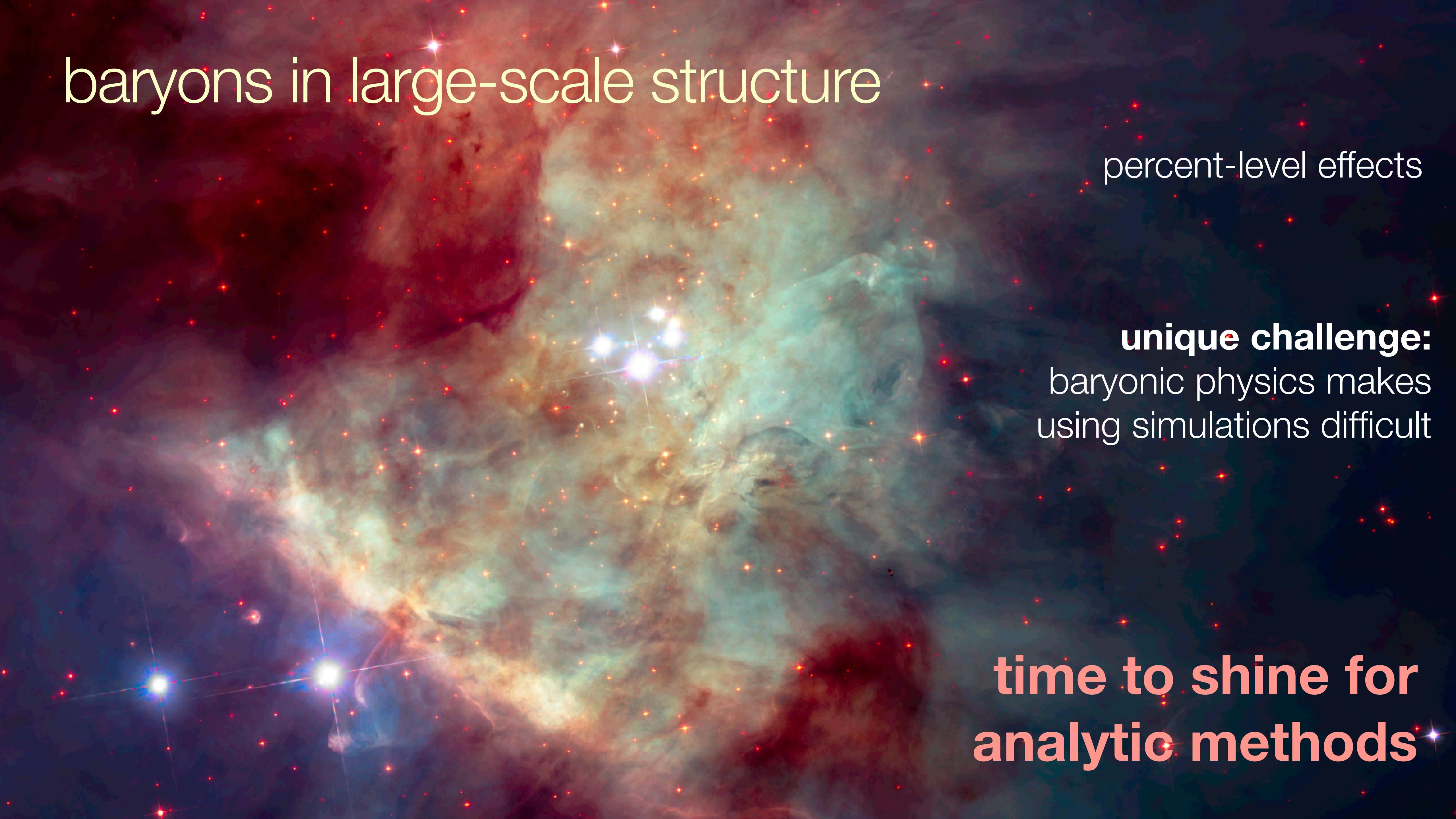


quadrupole



the road ahead - baryons and DE



A vibrant nebula with intricate, swirling patterns of red, orange, yellow, and blue. A dense cluster of young stars is visible in the center-left, with several bright, multi-colored stars emitting radial light rays. The background is a dark, star-filled space.

baryons in large-scale structure

percent-level effects

unique challenge:
baryonic physics makes
using simulations difficult

time to shine for
analytic methods

EFT for two fluids

effective force and stress tensors

$$\begin{aligned}\partial_i(\partial\tau_\rho)_c^i - \partial_i(\gamma)_c^i = & -g w_b aH \partial_i v_I^i + 9(2\pi)H^2 \left\{ \frac{c_{c,g}^2}{k_{\text{NL}}^2} (w_c \partial^2 \delta_c + w_b \partial^2 \delta_b) + \frac{c_{c,v}^2}{k_{\text{NL}}^2} \partial^2 \delta_c \right. \\ & + \frac{1}{k_{\text{NL}}^2} (c_{1c}^{cc} \partial^2 \delta_c^2 + c_{1c}^{cb} \partial^2 (\delta_c \delta_b) + c_{1c}^{bb} \partial^2 \delta_b^2) \\ & \left. + \frac{c_{4c,g}^2}{a^2 k_{\text{NL}}^4} (w_c \partial^4 \delta_c + w_b \partial^4 \delta_b) + \frac{c_{4c,v}^2}{a^2 k_{\text{NL}}^4} \partial^4 \delta_c \right\} + \dots\end{aligned}$$

$$\partial_i(\partial\tau_\rho)_b^i - \partial_i(\gamma)_b^i = +g w_c aH \partial_i v_I^i + \dots$$

standard two-loop counterterms



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

Bragança, **ML**, Sekera,
Senatore, Sgier, 20
ML, Perko, Senatore 14

EFT for two fluids

effective force and stress tensors

$$\begin{aligned}\partial_i(\partial\tau_\rho)_c^i - \partial_i(\gamma)_c^i &= -g w_b aH \partial_i v_I^i + 9(2\pi)H^2 \left\{ \frac{c_{c,g}^2}{k_{NL}^2} (w_c \partial^2 \delta_c + w_b \partial^2 \delta_b) + \frac{c_{c,v}^2}{k_{NL}^2} \partial^2 \delta_c \right. \\ &\quad + \frac{1}{k_{NL}^2} (c_{1c}^{cc} \partial^2 \delta_c^2 + c_{1c}^{cb} \partial^2 (\delta_c \delta_b) + c_{1c}^{bb} \partial^2 \delta_b^2) \\ &\quad \left. + \frac{c_{4c,g}^2}{a^2 k_{NL}^4} (w_c \partial^4 \delta_c + w_b \partial^4 \delta_b) + \frac{c_{4c,v}^2}{a^2 k_{NL}^4} \partial^4 \delta_c \right\} + \dots \\ \partial_i(\partial\tau_\rho)_b^i - \partial_i(\gamma)_b^i &= +g w_c aH \partial_i v_I^i + \dots\end{aligned}$$

new linear counterterm!

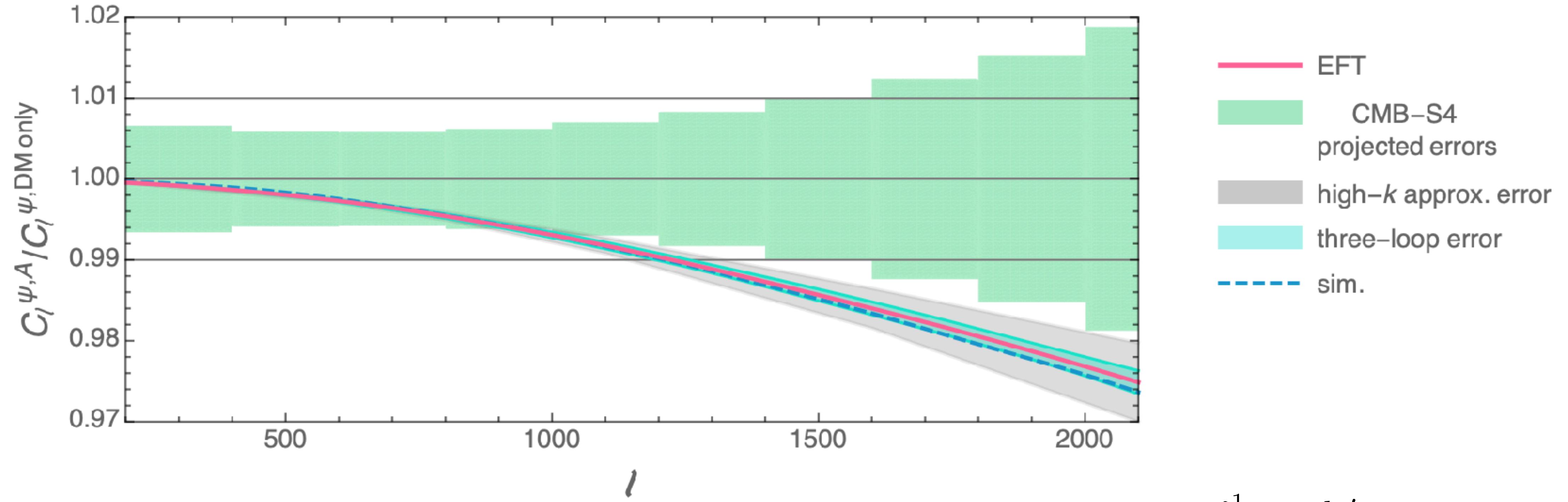
→ 3 independent EFT parameters per fluid
+ linear counterterm $g(a)$

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baryons in large-scale structure

lensing potential

Bragança, ML, Sekera
Senatore, Sgier 20



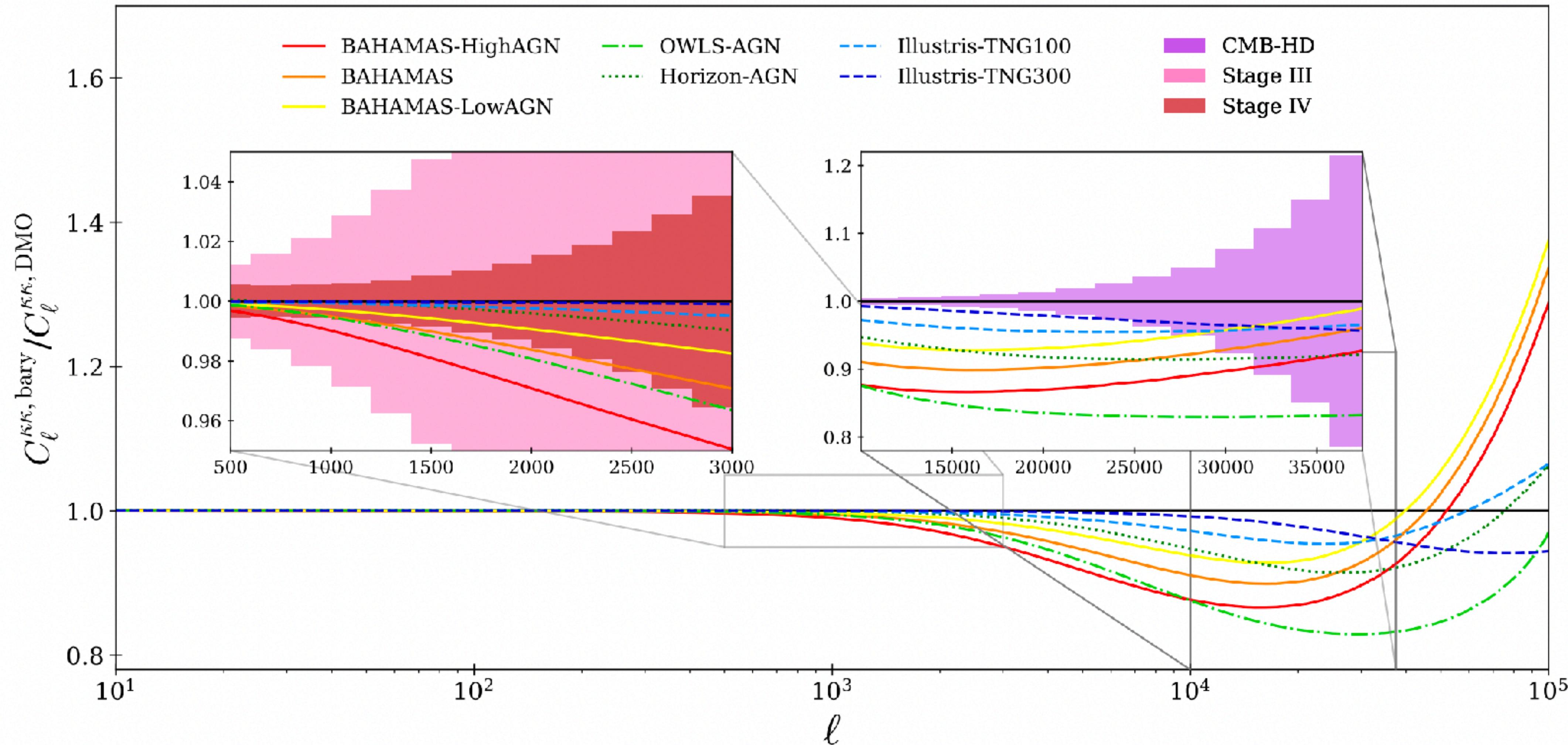
$$C_\ell^\psi = \frac{8\pi^2}{\ell^3} \int_0^{\chi_*} d\chi \chi P_\Phi \left(a(\chi), k = \frac{\ell}{\chi} \right) \left(\frac{\chi_* - \chi}{\chi_* \chi} \right)^2$$

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

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

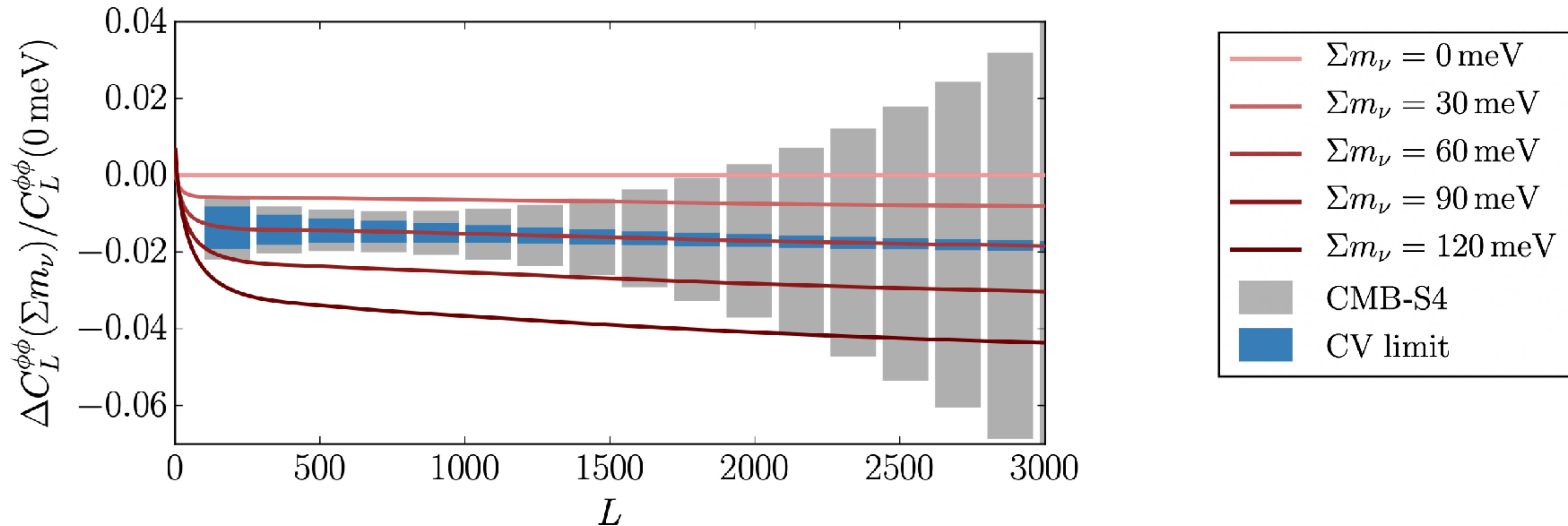
baryons in large-scale structure

baryon simulations



baryons in large-scale structure

massive neutrinos



dark energy



EFT of DE action - Horndeski

non-linear EFT of DE

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_*^2 f}{2} {}^{(4)}R - cg^{00} - \Lambda - \frac{m_3^3}{2} \delta K \delta g^{00} + m_4^2 \left(\delta K_i^j \delta K_j^i - \delta K^2 + \frac{1}{2} \delta g^{00} R \right) \right. \\ \left. - \frac{m_5}{3} \left[\delta K^3 - 3\delta K \delta K_i^j \delta K_j^i + 2\delta K_{ik} \delta K_j^k \delta K^{ij} + 3\delta g^{00} \left(\delta K_{ij} R^{ij} - \frac{1}{2} \delta K R \right) \right] \right. \\ \left. + m_6^2 \delta g^{00} \left(\delta K_i^j \delta K_j^i - \delta K^2 \right) + \dots \right\}$$

Creminelli et al 06; Cheung et al 08; Creminelli et al 09;
Gubitosi et al 13; Silvestri et al 13; Gleyzes et al 13; Gleyzes et al 15;

EFT of DE action - Horndeski

perturbation theory vertices

modified Poisson equation

$$-\frac{k^2}{\mathcal{H}^2} \Phi(\vec{k}) = \mu_{\Phi,1} \frac{3\Omega_m}{2} \delta(\vec{k})$$

$$+ \mu_{\Phi,2} \left(\frac{3\Omega_m}{2} \right)^2 \int_{\vec{k}_1, \vec{k}_2} (2\pi)^3 \delta_D(\vec{k} - \vec{k}_1 - \vec{k}_2) \gamma_2(\vec{k}_1, \vec{k}_2) \delta(\vec{k}_1) \delta(\vec{k}_2)$$

$$+ \mu_{\Phi,3} \left(\frac{3\Omega_m}{2} \right)^3 \int_{\vec{k}_1, \vec{k}_2, \vec{k}_3} (2\pi)^3 \delta_D(\vec{k} - \vec{k}_1 - \vec{k}_2 - \vec{k}_3) \gamma_3(\vec{k}_1, \vec{k}_2, \vec{k}_3) \delta(\vec{k}_1) \delta(\vec{k}_2) \delta(\vec{k}_3)$$

$$+ \mu_{\Phi,22} \left(\frac{3\Omega_m}{2} \right)^3 \int_{\vec{k}_1, \vec{k}_2, \vec{q}_1, \vec{q}_2} (2\pi)^6 \delta_D(\vec{k} - \vec{k}_1 - \vec{k}_2) \delta_D(\vec{k}_2 - \vec{q}_1 - \vec{q}_2) \gamma_2(\vec{k}_1, \vec{k}_2) \gamma_2(\vec{q}_1, \vec{q}_2) \delta(\vec{k}_1) \delta(\vec{q}_1) \delta(\vec{q}_2)$$

$$\gamma_2(\vec{k}_1, \vec{k}_2) = 1 - \frac{(\vec{k}_1 \cdot \vec{k}_2)^2}{k_1^2 k_2^2}$$

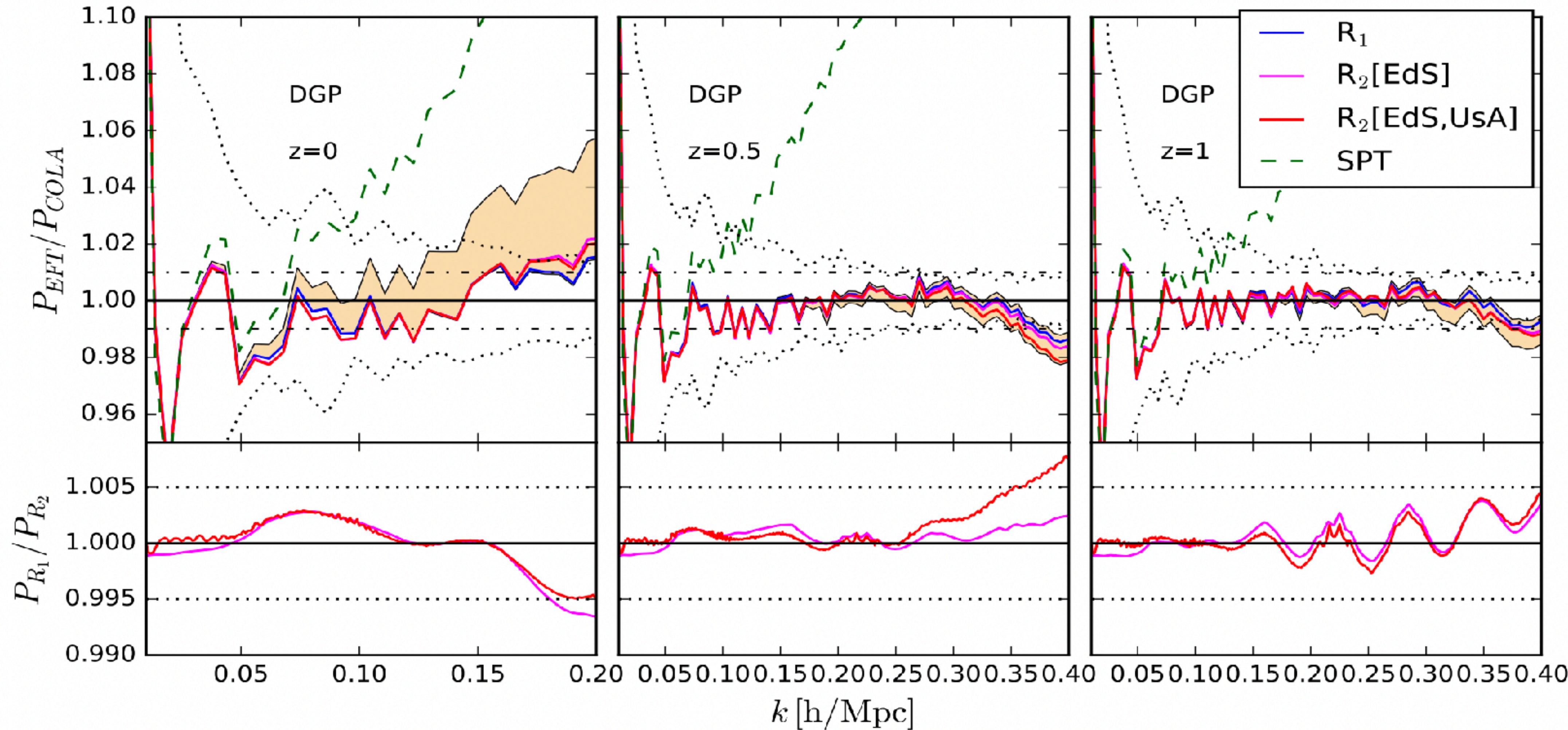
$$\gamma_3(\vec{k}_1, \vec{k}_2, \vec{k}_3) = \frac{1}{k_1^2 k_2^2 k_3^2} \left(k_1^2 k_2^2 k_3^2 + 2 (\vec{k}_1 \cdot \vec{k}_2) (\vec{k}_1 \cdot \vec{k}_3) (\vec{k}_2 \cdot \vec{k}_3) \right. \\ \left. - (\vec{k}_1 \cdot \vec{k}_3)^2 k_2^2 - (\vec{k}_2 \cdot \vec{k}_3)^2 k_1^2 - (\vec{k}_1 \cdot \vec{k}_2)^2 k_3^2 \right)$$

- information about the DE action is contained the μ parameters

$$k_{\text{NL}} \sim k_{\text{NL}}^\Lambda (\mu \Omega_m)^{-\frac{1}{n+3}}$$

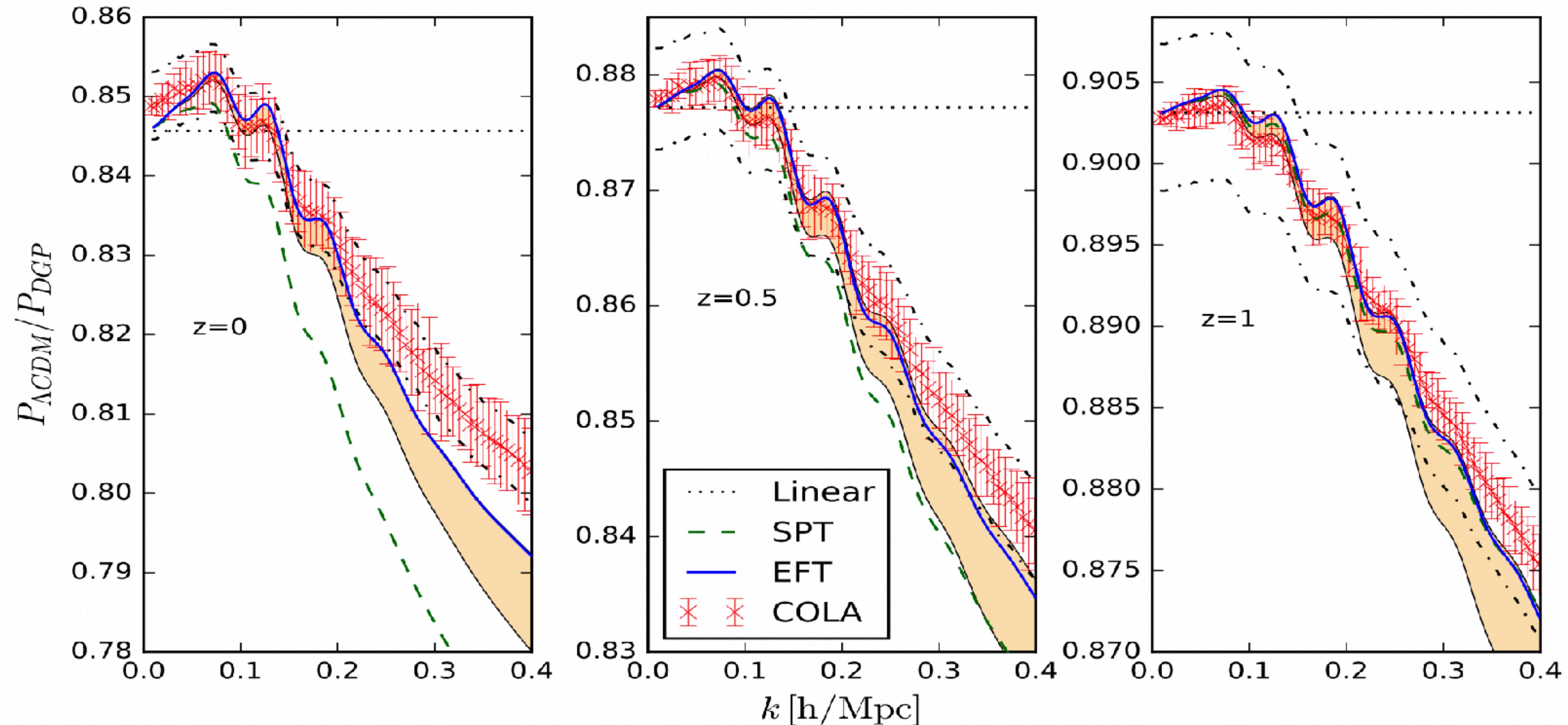
beyond Λ CDM/dark energy

EFT of DE for EFT of LSS



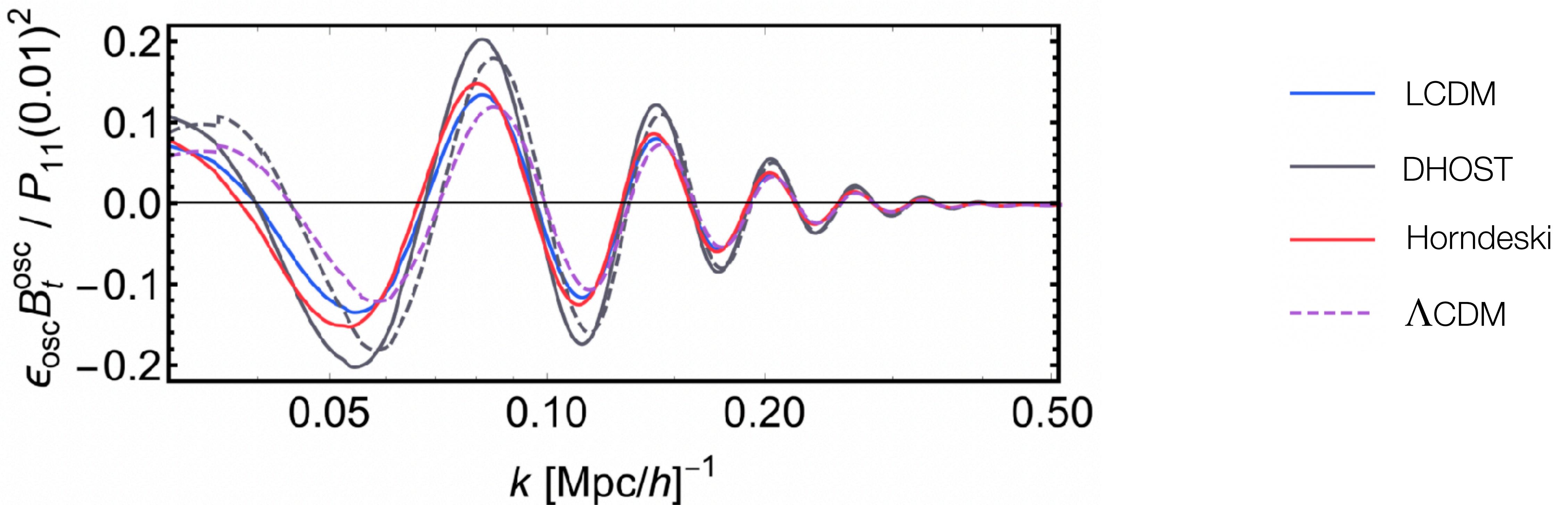
beyond Λ CDM/dark energy

EFT of DE for EFT of LSS



beyond Λ CDM/dark energy

violation of LSS consistency conditions



conclusions

- after many years of theoretical development, the EFT of LSS has been successfully applied to real data, by multiple groups
- going to higher orders has revealed some interesting theoretical developments
- 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

M. Baumgart, F. Bishara, T. Brauner,
J. Brod, **ML**, et al.

D. Green, J. T. Ruderman, B. R.
Safdi, J. Shelton, **ML**, et al.

**Thank
You!**