EFT of LSS and EFT of DE

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- need percent level understanding of observables
- dark matter clustering (power spectrum, bispectrum), baryons, redshift space, bias…

EFTofLSS

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$$\rho_m(\vec{x}, a) = \bar{\rho}_m(a)\,(1 + \delta_m(\vec{x}, a))$$

$$\theta = \partial_i v_m^i$$

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$$\dot{\delta}_m + \frac{1}{a}\partial_i((1 + \delta_m)v_m^i) = 0$$

$$\partial_i \dot{v}_m^i + H\partial_i v_m^i + \frac{1}{a}\partial_i(v_m^j \partial_j v_m^i) + \frac{1}{a}\partial^2\Phi = -\frac{1}{a}\partial_i\left(\frac{1}{\rho_m}\partial_j \tau^{ij}\right)_s$$

$$a^{-2}\partial^2\Phi = \frac{3}{2}\frac{\Omega_{m,0}\mathcal{H}_0^2 a_0}{a^3}\delta_m$$

EFTofLSS

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$$-\left(\frac{1}{\rho_m}\partial_j\tau^{ij}\right)_s(a,\vec{x}) = \int da' \Big[\kappa^{(1)}(a,a')\,\partial^i\partial^2\Phi(a',\vec{x}_{\rm fl}(\vec{x};a,a'))$$
$$+ \kappa^{(2)}(a,a')\,\frac{1}{H}\partial^i\partial_j v_m^j(a',\vec{x}_{\rm fl}(\vec{x};a,a'))$$
$$+ \kappa^{(\rm stoch.)}(a,a')\partial^i\bar{\Delta}_{\rm stoch.}(a',\vec{x}_{\rm fl}(\vec{x};a,a')) + \ldots\Big]$$

one-loop power spectrum

$$P(k,a) = \left(\frac{D(a)}{D(a_i)}\right)^2 P_{11}(k,a_i) + \left(\frac{D(a)}{D(a_i)}\right)^4 P_{22}(k,a_i) + \left(\frac{D(a)}{D(a_i)}\right)^4 P_{13}(k,a_i) + \left(\frac{D(a)}{D(a_i)}\right)^2 P_{13}^{ct}(k,a_i)$$

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$$P_{22}(a_i,k) = \frac{k^3}{392\pi^2}\int_0^{\Lambda/k} dr \int_{-1}^{1} dx \frac{(-10rx^2+3r+7x)^2}{(r^2-2rx+1)^2} P_{11}(a_i,kr) P_{11}(a_i,k\sqrt{r^2-2rx+1})$$

$$P_{13}(a_i,k) = \frac{k^3}{1008\pi^2} P_{11}(a_i,k)$$
$$\times \int_0^{\Lambda/k} dr \left(\frac{3}{r^3}(r^2-1)^3(7r^2+2)\log\left|\frac{1+r}{1-r}\right| - 42r^4 + 100r^2 + \frac{12}{r^2} - 158\right) P_{11}(a_i,kr)$$

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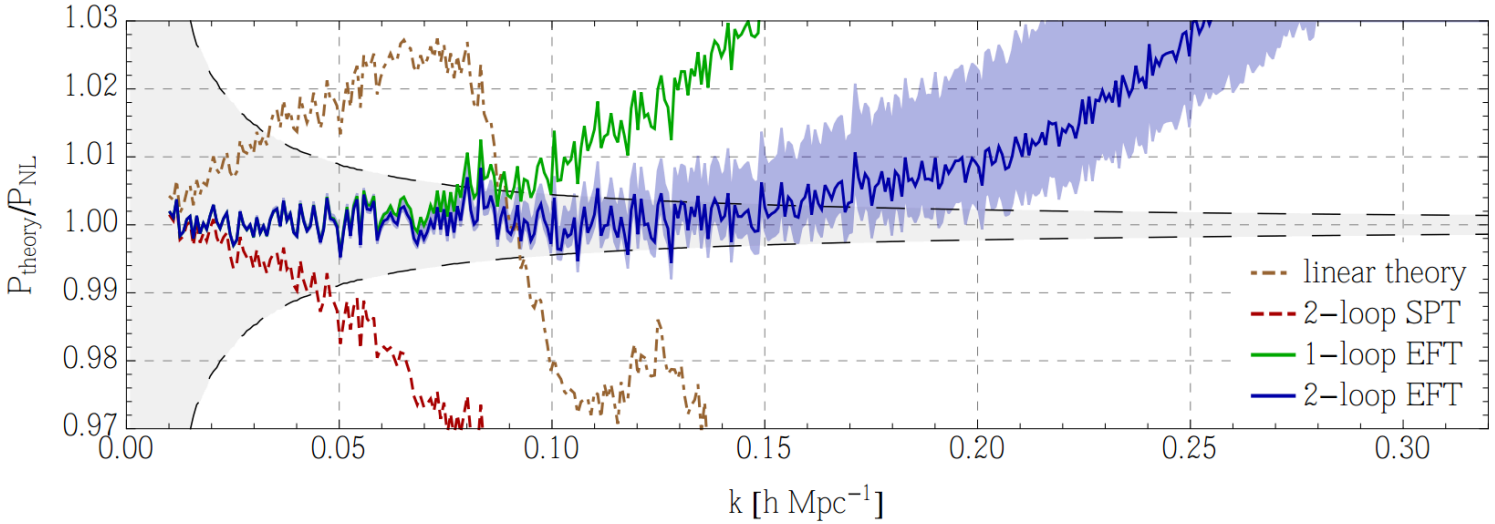
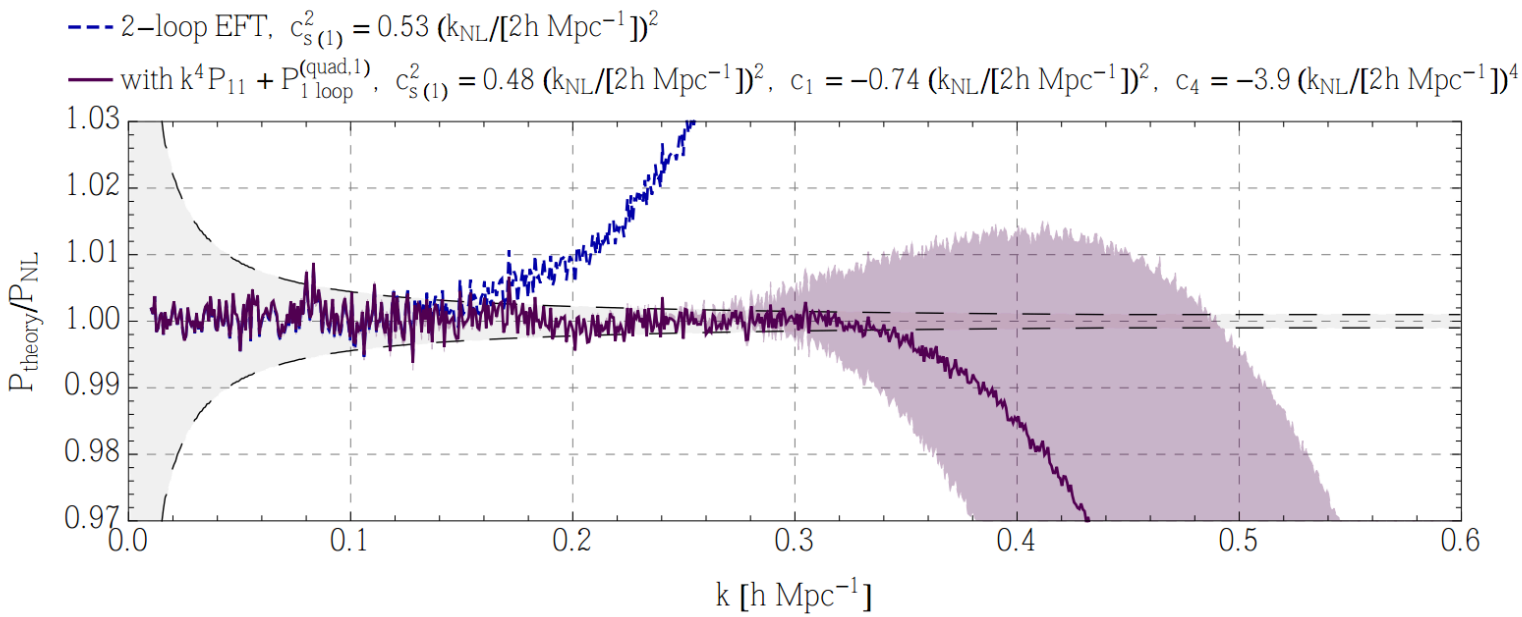
$$P_{13}^{ct}(a,k) = -2\,(2\pi)\,\bar{c}_m^2(a)\frac{k^2}{k_{\rm NL}^2} P_{11}(a_i,k)$$

results





Foreman, Perrier, Senatore, 2016

other developments

- two-loop power spectrum [Carrasco et al 14; Baldauf et al 15; Foreman et al 16…]
- one-loop bispectrum [Angulo et al 15; Baldauf et al 15; Bertolini et al 16…]
- baryons [ML et al 15]
- redshift-space distortions [Senatore et al 14; ML et al 15; Fonseca de la Bella et al 17; Perko et al 17…]
- biased tracers [McDonald et al 09; Assassi et al 14; Senatore 14; Mirbabayi et al 14; Angulo et al 15; Fujita et al 16; Perko et al 17…]
- BAO peak (resummation) techniques [Senatore et al 15; Baldauf et al 15; ML et al 15; Vlah et al 16; Blas et al 16…]
- PNG [Assassi et al 15; Gleyzes et al 17…]
- massive neutrinos [Levi et al 16; Senatore et al 17]
- four-point function [Bertolini et al 16]
- forecasts [Baldauf et al 16; Welling et al 16…]
- implementation [Cataneo et al 16; McEwen et al 16; Schmittfull et al 16; Simonović et al 17…]

EFT of DE action - Horndeski

$$S = \int d^4x\sqrt{-g}\Big\{ \frac{M_*^2 f}{2}\,{}^{(4)}R - cg^{00} - \Lambda - \frac{m_3^3}{2}\,\delta K \delta g^{00} + m_4^2\left(\delta K_i^j \delta K_j^i - \delta K^2 + \frac{1}{2}\,\delta g^{00} R\right)$$
$$- \frac{m_5}{3}\left[\delta K^3 - 3\delta K \delta K_i^j \delta K_j^i + 2\delta K_{ik}\delta K_j^k \delta K^{ij} + 3\delta g^{00}\left(\delta K_{ij} R^{ij} - \frac{1}{2}\delta K R\right)\right]$$
$$+ m_6^2 \delta g^{00}\left(\delta K_i^j \delta K_j^i - \delta K^2\right) - \frac{m_7}{3}\delta g^{00}\left(\delta K^3 - 3\delta K \delta K_{ij}\delta K^{ij} + 2\delta K_{ik}\delta K_j^k \delta K^{ij}\right)\Big\}$$

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;

fluid-like equations

fluid-like equations

$$a\,\delta'(\vec{k}) - \Theta(\vec{k}) = \int_{\vec{k}_1}\int_{\vec{k}_2} (2\pi)^3 \delta_D(\vec{k}-\vec{k}_1-\vec{k}_2)\,\alpha(\vec{k}_1,\vec{k}_2)\Theta(\vec{k}_1)\delta(\vec{k}_2)$$

$$a\,\Theta'(\vec{k}) + \left(1+\frac{a\mathcal{H}'}{\mathcal{H}}\right)\Theta(\vec{k}) + \frac{k^2}{\mathcal{H}^2}\Phi(\vec{k}) = \int_{\vec{k}_1}\int_{\vec{k}_2} (2\pi)^3 \delta_D(\vec{k}-\vec{k}_1-\vec{k}_2)\,\beta(\vec{k}_1,\vec{k}_2)\Theta(\vec{k}_1)\Theta(\vec{k}_2)$$
$$- 9(2\pi)c_{DE}^2(a)\frac{k^2}{k_{\rm NL}^2}\delta(\vec{k})$$

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$$\alpha(\vec{q}_1,\vec{q}_2) = 1 + \frac{\vec{q}_1\cdot\vec{q}_2}{q_1^2} \qquad \text{and} \qquad \beta(\vec{q}_1,\vec{q}_2) = \frac{|\vec{q}_1+\vec{q}_2|^2\,\vec{q}_1\cdot\vec{q}_2}{2q_1^2q_2^2}$$

DE vertices

Koyama et al 09; Bose et al 16

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Koyama et al 09; Bose et al 16

$$
\begin{aligned}
-\frac{k^2}{\mathcal{H}^2}\Phi(\vec{k}) = \mu_{\Phi,1}\frac{3\,\Omega_{\rm m}}{2}\,\delta(\vec{k}) \\
&+ \mu_{\Phi,2}\left(\frac{3\Omega_{\rm m}}{2}\right)^2 \int_{\vec{k}_1,\vec{k}_2} (2\pi)^3\delta_D(\vec{k}-\vec{k}_1-\vec{k}_2)\,\gamma_2(\vec{k}_1,\vec{k}_2)\delta(\vec{k}_1)\delta(\vec{k}_2) \\
&+ \mu_{\Phi,3}\left(\frac{3\Omega_{\rm m}}{2}\right)^3 \int_{\vec{k}_1,\vec{k}_2,\vec{k}_3} (2\pi)^3\delta_D(\vec{k}-\vec{k}_1-\vec{k}_2-\vec{k}_3)\,\gamma_3(\vec{k}_1,\vec{k}_2,\vec{k}_3)\delta(\vec{k}_1)\delta(\vec{k}_2)\delta(\vec{k}_3) \\
&+ \mu_{\Phi,22}\left(\frac{3\Omega_{\rm m}}{2}\right)^3 \int_{\vec{k}_1,\vec{k}_2,\vec{q}_1,\vec{q}_2} (2\pi)^6\delta_D(\vec{k}-\vec{k}_1-\vec{k}_2)\delta_D(\vec{k}_2-\vec{q}_1-\vec{q}_2)\,\gamma_2(\vec{k}_1,\vec{k}_2)\gamma_2(\vec{q}_1,\vec{q}_2)\delta(\vec{k}_1)\delta(\vec{q}_1)\delta(\vec{q}_2)
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&+ \mu_{\Phi,22}\left(\frac{3\Omega_{\rm m}}{2}\right)^3 \int_{\vec{k}_1,\vec{k}_2,\vec{q}_1,\vec{q}_2} (2\pi)^6\delta_D(\vec{k}-\vec{k}_1-\vec{k}_2)\delta_D(\vec{k}_2-\vec{q}_1-\vec{q}_2)\,\gamma_2(\vec{k}_1,\vec{k}_2)\gamma_2(\vec{q}_1,\vec{q}_2)\delta(\vec{k}_1)\delta(\vec{q}_1)\delta(\vec{q}_2)
\end{aligned}
$$

$$
\begin{aligned}
\gamma_2(\vec{k}_1,\vec{k}_2) &= 1 - \frac{\left(\vec{k}_1\cdot\vec{k}_2\right)^2}{k_1^2k_2^2} \\
\gamma_3(\vec{k}_1,\vec{k}_2,\vec{k}_3) &= \frac{1}{k_1^2k_2^2k_3^2}\Big(k_1^2k_2^2k_3^2 + 2\left(\vec{k}_1\cdot\vec{k}_2\right)\left(\vec{k}_1\cdot\vec{k}_3\right)\left(\vec{k}_2\cdot\vec{k}_3\right) \\
&\qquad - \left(\vec{k}_1\cdot\vec{k}_3\right)^2k_2^2 - \left(\vec{k}_2\cdot\vec{k}_3\right)^2k_1^2 - \left(\vec{k}_1\cdot\vec{k}_2\right)^2k_3^2\Big)
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&+ \mu_{\Phi,22}\left(\frac{3\Omega_{\rm m}}{2}\right)^3 \int_{\vec{k}_1,\vec{k}_2,\vec{q}_1,\vec{q}_2} (2\pi)^6\delta_D(\vec{k}-\vec{k}_1-\vec{k}_2)\delta_D(\vec{k}_2-\vec{q}_1-\vec{q}_2)\,\gamma_2(\vec{k}_1,\vec{k}_2)\gamma_2(\vec{q}_1,\vec{q}_2)\delta(\vec{k}_1)\delta(\vec{q}_1)\delta(\vec{q}_2)
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\gamma_2(\vec{k}_1,\vec{k}_2) = 1 - \frac{\left(\vec{k}_1\cdot\vec{k}_2\right)^2}{k_1^2k_2^2}
$$

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

- information about the DE action is contained the μ parameters

one-loop power spectrum

one-loop power spectrum

exact time dependence

one-loop power spectrum

exact time dependence

$$\delta^{(n)}(\vec{k}, a) = \int_0^a d\tilde{a} \left(G_1^\delta(a, \tilde{a}) S_1^{(n)}(\vec{k}, \tilde{a}) + G_2^\delta(a, \tilde{a}) S_2^{(n)}(\vec{k}, \tilde{a}) \right) ,$$

$$\Theta^{(n)}(\vec{k}, a) = \int_0^a d\tilde{a} \left(G_1^\Theta(a, \tilde{a}) S_1^{(n)}(\vec{k}, \tilde{a}) + G_2^\Theta(a, \tilde{a}) S_2^{(n)}(\vec{k}, \tilde{a}) \right)$$

one-loop power spectrum

exact time dependence

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counterterm

one-loop power spectrum

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counterterm

$$\delta^{(\mathrm{ct})}(\vec{k},a) = -(2\pi)\,\bar{c}_s^2(a)\frac{k^2}{k_{\mathrm{NL}}^2}\frac{D_+(a)}{D_+(a_i)}\delta^{(1)}(\vec{k},a_i)$$

one-loop power spectrum

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$$P_{22}(k,a) = \int \frac{d^3q}{(2\pi)^3} \int_0^a da_2 \int_0^{a_2} da_1 \; p_{22}(a,a_1,a_2;\vec{k},\vec{q}) \; ,$$

$$P_{13}(k,a) = \int \frac{d^3q}{(2\pi)^3} \int_0^a da_2 \left(p_{13}^{(1)}(a,a_2;\vec{k},\vec{q}) + \int_0^{a_2} da_1 \; p_{13}^{(2)}(a,a_1,a_2;\vec{k},\vec{q}) \right)$$

one-loop power spectrum

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$$p_{22}(a,a_1,a_2;\vec{k},\vec{q}) = \sum_{i=1}^{7} T_i^{(22)}(a,a_1,a_2) F_i^{(22)}(\vec{k},\vec{q}) \; ,$$

$$p_{13}^{(2)}(a,a_1,a_2;\vec{k},\vec{q}) = \sum_{i=1}^{10} T_i^{(13)}(a,a_1,a_2) F_i^{(13)}(\vec{k},\vec{q})$$

$$p_{13}^{(1)}(a,a_2;\vec{k},\vec{q}) = T_{11}^{(13)}(a,a_2) F_{11}^{(13)}(\vec{k},\vec{q})$$

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$$p_{13}^{(1)}(a,a_2;\vec{k},\vec{q}) = T_{11}^{(13)}(a,a_2) F_{11}^{(13)}(\vec{k},\vec{q})$$

$$P_{13}^{ct}(k,a) = -2(2\pi)\bar{c}_s^2(a) \frac{k^2}{k_{\rm NL}^2} P_{11}(k,a)$$

nDGP

$$\beta(a) = 1 + 2H(a)r_c\left(1 + \frac{\dot{H}}{3H^2}\right)$$

$$\Omega_{rc} = \frac{1}{4H_0^2 r_c^2}$$

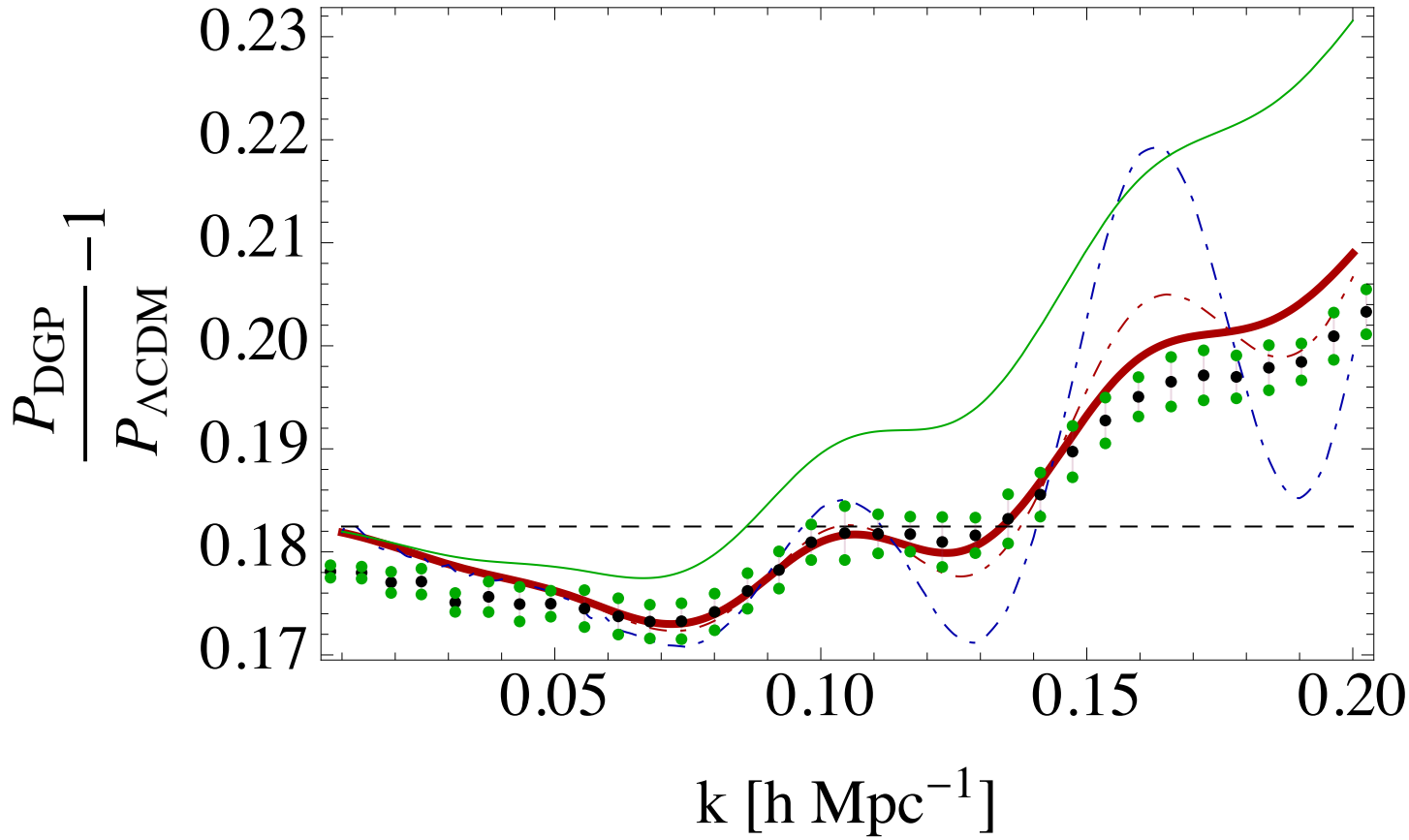
$$\mu_\Phi(a) = 1 + \frac{1}{3\beta(a)} \ ,$$

$$\mu_{\Phi,2}(a) = -2H(a)^2 r_c^2 \left(\frac{1}{3\beta(a)}\right)^3 \ ,$$

$$\mu_{\Phi,22}(a) = 8H(a)^2 r_c^2 \left(\frac{1}{3\beta(a)}\right)^5$$

Comparison to Simulation: nDGP

$\Omega_{rc} = 0.438$ $\quad c^2_{s,DGP} = 0.36$ $\quad c^2_{s,\Lambda CDM} = 0.30$



Bose, Koyama, ML, Vernizzi, Winther, in preparation

COLA: Winther, Koyama, Manera, Wright, Zhao, 2017

clustering quintessence - EFT

Creminelli et al 09; Sefusatti et al 11; Gleyez et al 13;
ML et al 16; Fasiello et al 16…

clustering quintessence - EFT

$$\int d^4x \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \Lambda(t) - c(t)g_{\rm u}^{00} + \frac{M_2^4(t)}{2}(\delta g_{\rm u}^{00})^2\right]$$

$$\ddot{\pi} - \dot{\Phi} + \frac{\partial_t M_2^4}{M_2^4}(\dot{\pi} - \Phi) + 3H(\dot{\pi} - \Phi) - c_s^2 a^{-2}\partial^2\pi = 0$$

$$c_s^2 = \frac{c(t)}{c(t) + 2M_2^4(t)} \to 0$$

Creminelli et al 09; Sefusatti et al 11; Gleyez et al 13;
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clustering quintessence - EFT

$$\int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R-\Lambda(t)-c(t)g_{\rm u}^{00}+\frac{M_2^4(t)}{2}(\delta g_{\rm u}^{00})^2\right]$$

$$\ddot{\pi}-\dot{\Phi}+\frac{\partial_t M_2^4}{M_2^4}(\dot{\pi}-\Phi)+3H(\dot{\pi}-\Phi)-c_s^2a^{-2}\partial^2\pi=0$$

$$c_s^2=\frac{c(t)}{c(t)+2M_2^4(t)}\to 0$$

$$\dot{\delta}_m+\frac{1}{a}\partial_i((1+\delta_m)v_m^i)=0$$

$$\partial_i\dot{v}_m^i+H\partial_i v_m^i+\frac{1}{a}\partial_i(v_m^j\partial_j v_m^i)+\frac{1}{a}\partial^2\Phi=-\frac{1}{a}\partial_i\left(\frac{1}{\rho_m}\partial_j\tau^{ij}\right)_s+\frac{1}{a}\partial_i\gamma_s^i$$

Creminelli et al 09; Sefusatti et al 11; Gleyez et al 13;
ML et al 16; Fasiello et al 16…

fluid-like equations

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$$\dot{\delta}_A + \frac{1}{a} C(a) \theta_A = -\frac{1}{a} \partial_i \left(\delta_A v_A^i \right)$$

$$\dot{\theta}_A + H \theta_A + \frac{3}{2} \frac{\Omega_{m,0} \mathcal{H}_0^2 a_0}{a^2} \delta_A = -\frac{1}{a} \partial_i \left(v_A^j \partial_j v_A^i \right)$$

$$C(a) \equiv \left(1 + (1+w) \frac{\Omega_{D,0}}{\Omega_{m,0}} a^{-3w} \right)$$

fluid-like equations

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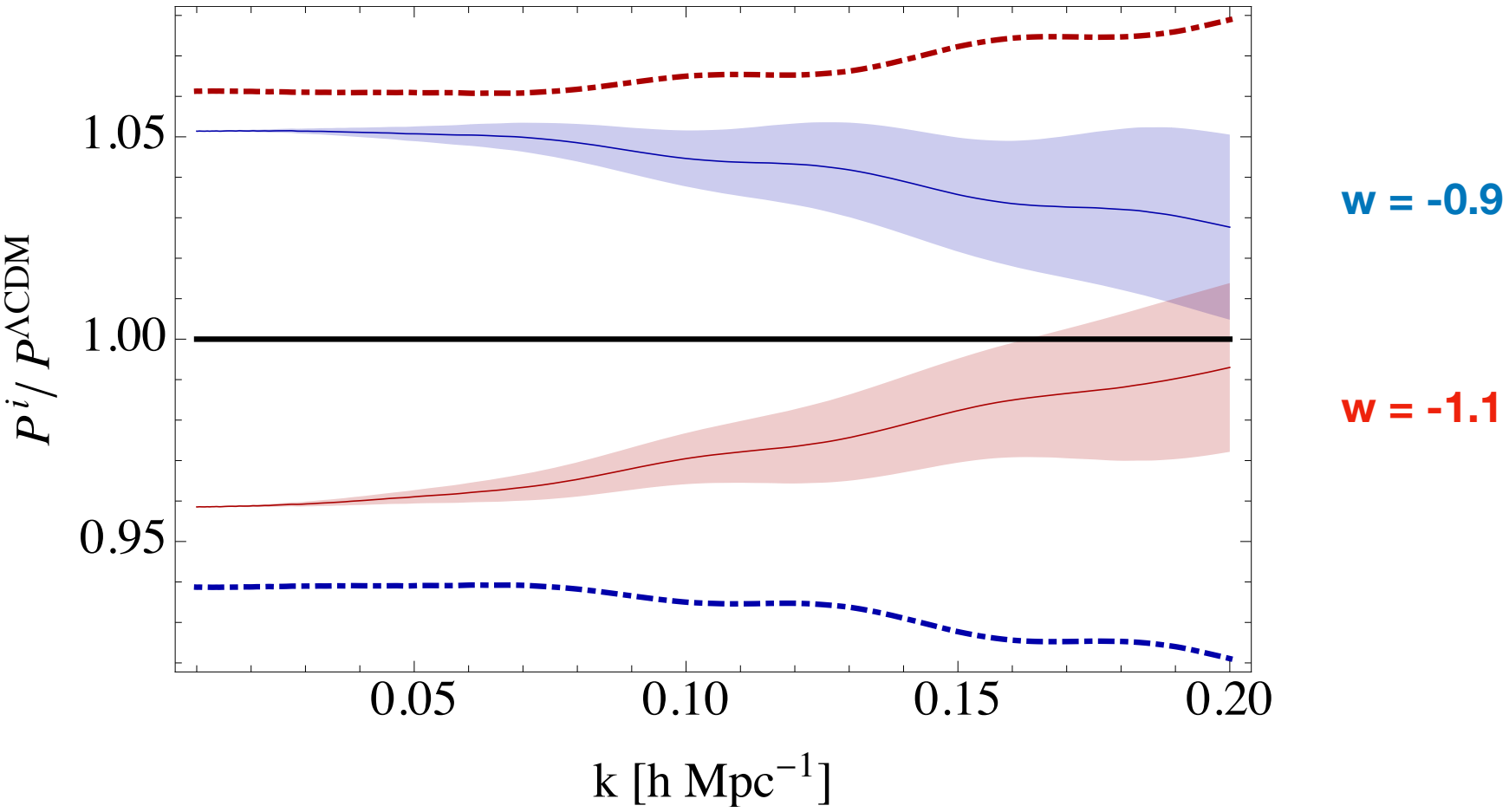
$$P_{13}^{ct}(a,k) = -2\,(2\pi)\,\bar{c}_A^2(a) \frac{k^2}{k_{\rm NL}^2} P^{11}(a,k)$$

results



ML, Maleknejad, Senatore 16