LSS Probes of Cosmic Acceleration

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MF, Z. Vlah	Phys.Rev. D94 (2016) no.6, 063516
MF, Z. Vlah	ArXiv:1611.00542
MF, Z. Vlah &..	+ In progress

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Beyond ΛCDM

A dynamical mechanism driving acceleration usually comes with additional degree(s) of freedom

Extra Scalar

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \partial^2\phi, ..)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T$$

Screening where GR extremely well-tested, e.g. Solar system

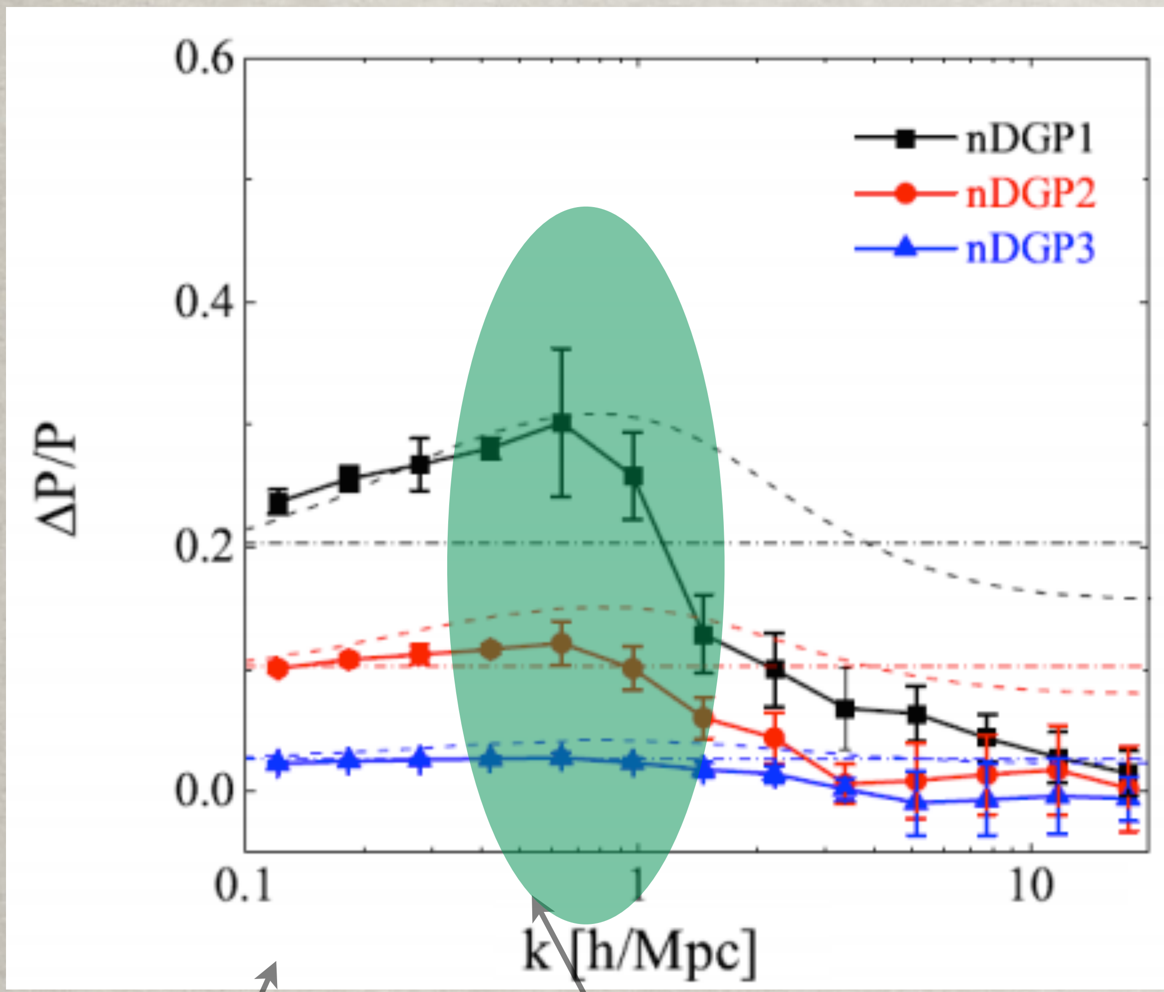
$$V(r) \sim -\frac{g^2(\phi)}{Z(\phi)} \frac{e^{-\frac{m(\phi)}{\sqrt{Z(\phi)}} r}}{4\pi r} \mathcal{M}$$

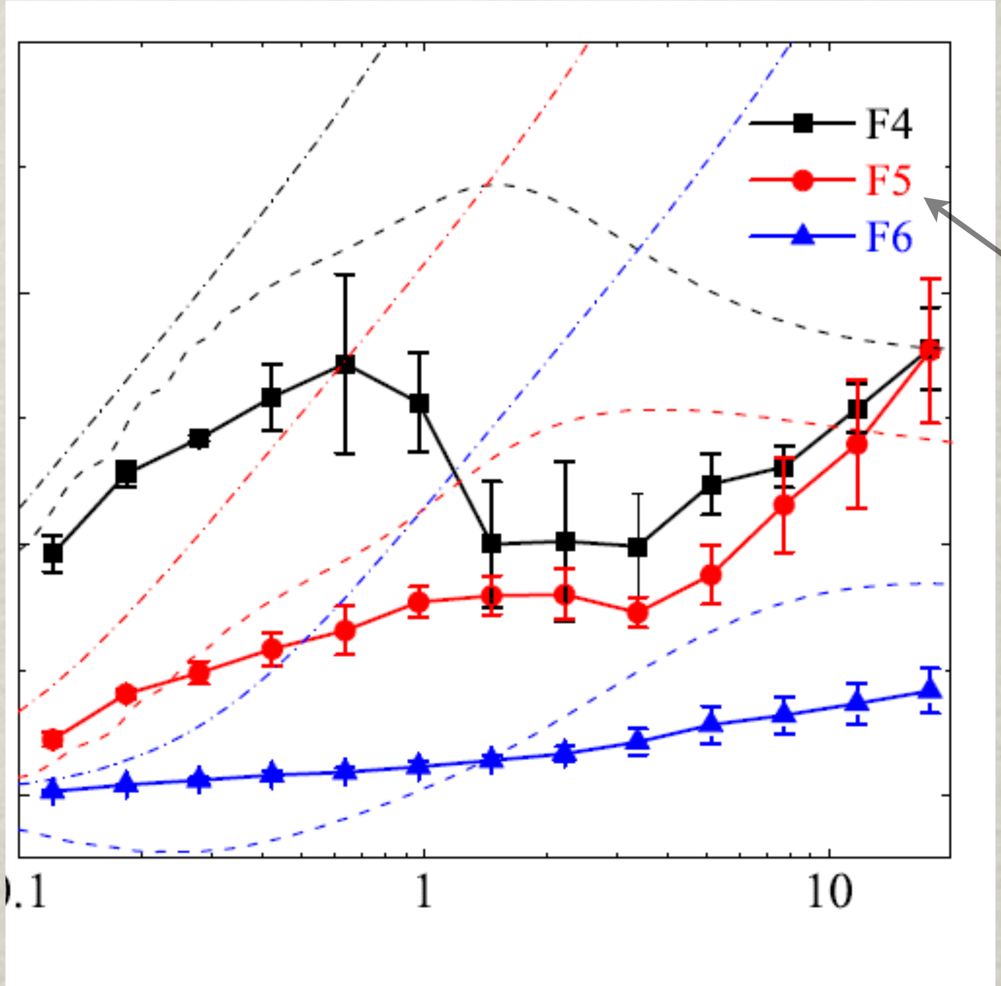
Symmetron

Vainshtein

Chameleon

N-body





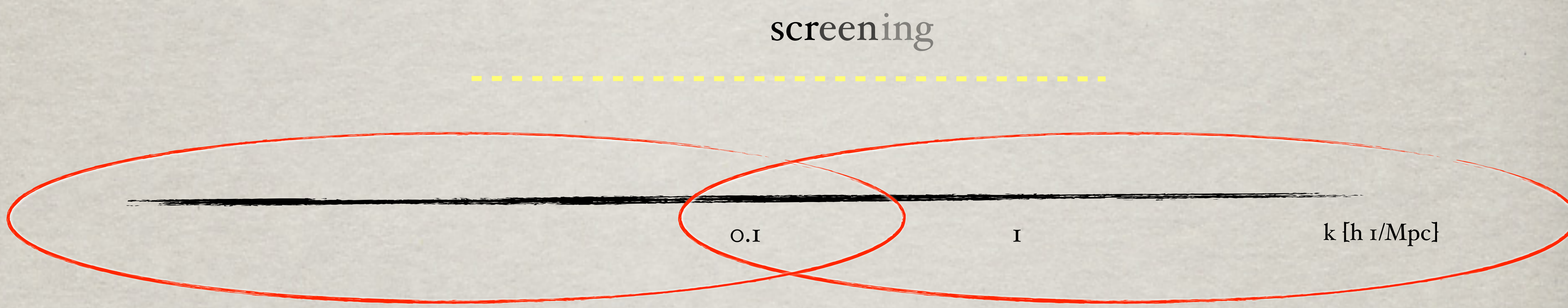
f(R)

Falck, Koyama, Zhao (2015)

Linear

Vainshtein Onset

Perturbation Theory



full perturbative control

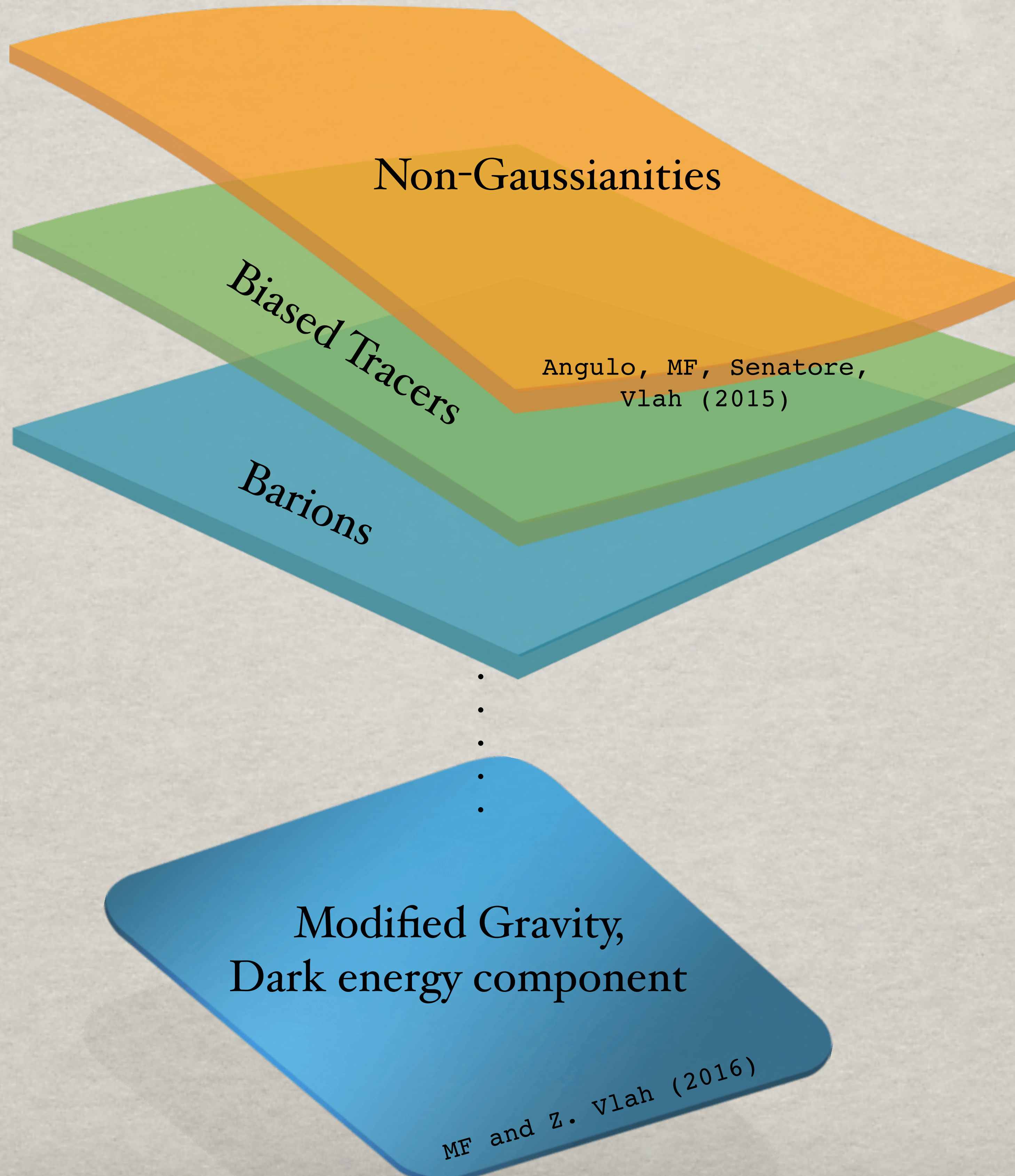
bulk of the information on growth

A lot going on to conquer the quasi-linear scales

RPT (Crocce, Scoccimarro)
TRG (Matarrese, Pietroni; Pietroni)
TSPT(Blas et al)
....
Lagrangian approach
(Matsubara; Porto et al; Vlah et al)
...

EFT of LSS

Layers of physics



Why Perturbation Theory?

Underlying physical principles

More clear cut map with DE/MG model space

Symmetries (e.g. their role in consistency conditions)

Easy to include additional layers (e.g. non-Gaussianity, baryons..)

Adding a MG or DDE component

Sefusatti, Vernizzi (2011);
Anselmi et al (2011);
D'Amico, Sefusatti (2011);

$$\begin{cases} \dfrac{\partial \delta_m}{\partial \tau} + \vec{\nabla} \cdot [(1+\delta_m)\vec{v}] = 0 \\ \dfrac{\partial \delta_Q}{\partial \tau} - 3\omega \mathcal{H} \delta_Q + \vec{\nabla} \cdot [(1+\omega+\delta_Q)\vec{v}] = 0 \\ \dfrac{\partial v}{\partial \tau} + \mathcal{H}\vec{v} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\nabla \Phi \end{cases}$$

clustering quintessence, c_s=0

$$\nabla^2 \Phi = \frac{3}{2} \mathcal{H}^2 \Omega_m \underbrace{(\delta_m + \delta_Q \frac{\Omega_Q}{\Omega_m})}_{\delta_T}$$

known exactly only up to quadratic order

All orders, integral & differential solutions

MF, Vlah (2016)

$$\delta_{\mathbf{k}}(\eta) \quad = \sum_{n=1}^{\infty} F_n^s(\mathbf{q}_1..\mathbf{q}_n,\eta) D_+^n(\eta) \delta^{\rm in}_{\mathbf{q_1}}..\delta^{\rm in}_{\mathbf{q_n}}$$

$$\Theta_{\mathbf{k}}(\eta) \quad = \sum_{n=1}^{\infty} G_n^s(\mathbf{q}_1..\mathbf{q}_n,\eta) D_+^n(\eta) \delta^{\rm in}_{\mathbf{q_1}}..\delta^{\rm in}_{\mathbf{q_n}}$$

$$F_n(\eta) = \int_{-\infty}^{\eta} \frac{d\tilde\eta}{C(\tilde\eta)} \left\{ e^{(n-1)(\tilde\eta-\eta)} \frac{\tilde f_+}{\tilde f_+ - \tilde f_-} \left[\left(\tilde h_\beta^{(n)} - \frac{\tilde f_-}{\tilde f_+} \tilde h_\alpha^{(n)} \right) + e^{\tilde\eta-\eta} \frac{D_-(\eta)}{\tilde D_-(\eta)} \left(\tilde h_\alpha^{(n)} - \tilde h_\beta^{(n)} \right) \right] \right\}$$

$$G_n(\eta) = \int_{-\infty}^{\eta} \frac{d\tilde\eta}{C(\tilde\eta)} \left\{ e^{(n-1)(\tilde\eta-\eta)} \frac{\tilde f_+}{\tilde f_+ - \tilde f_-} \left[\left(\tilde h_\beta^{(n)} - \frac{\tilde f_-}{\tilde f_+} \tilde h_\alpha^{(n)} \right) + e^{\tilde\eta-\eta} \frac{f_-}{f_+} \frac{D_-(\eta)}{\tilde D_-(\eta)} \left(\tilde h_\alpha^{(n)} - \tilde h_\beta^{(n)} \right) \right] \right\}$$

$$C = 1 + (1+\omega)\frac{\Omega_Q(\eta)}{\Omega_m(\eta)}$$

iteratively derived, first recursion are usual

$\alpha(\mathbf{q}_1,\mathbf{q}_2)$, $\beta(\mathbf{q}_1,\mathbf{q}_2)$

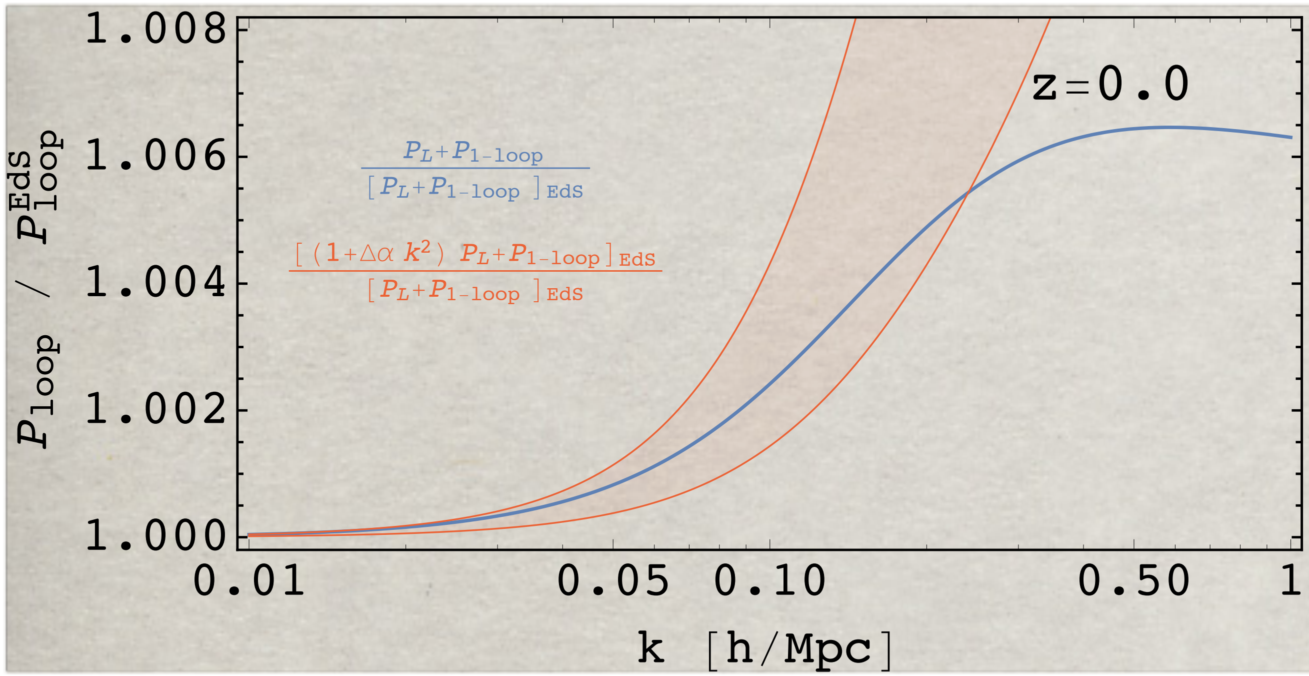
related to

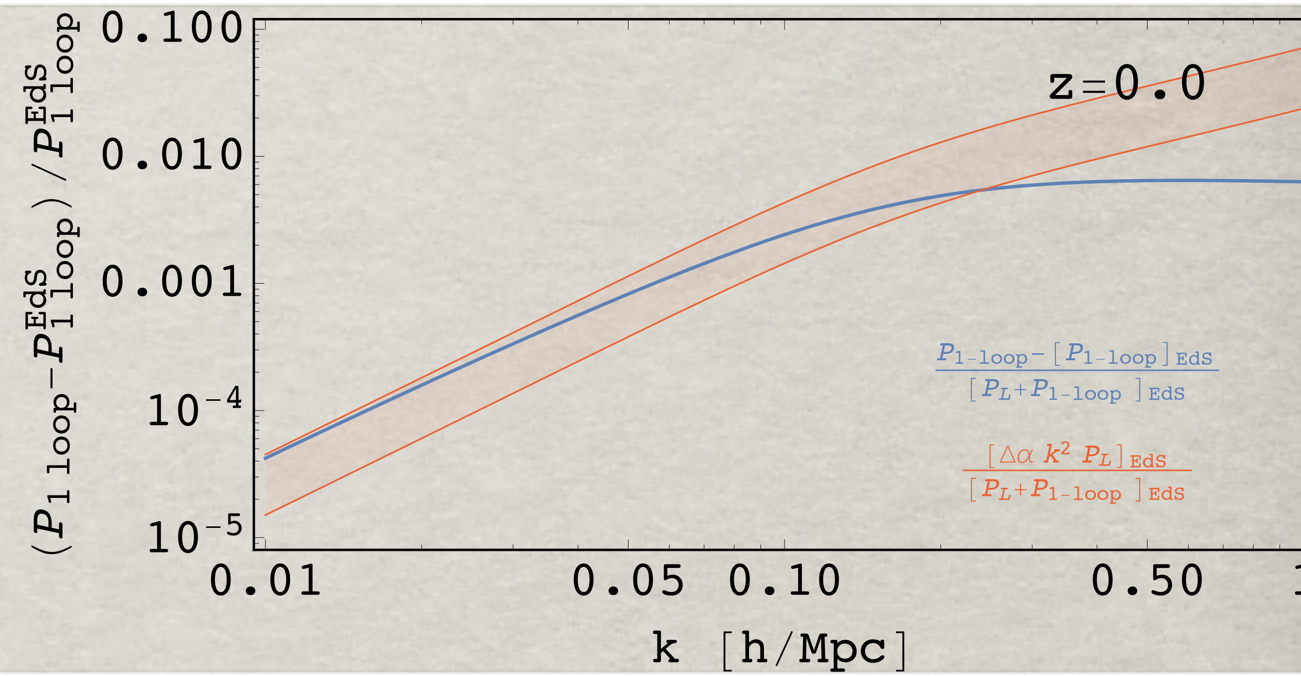
$\propto$ linear growth rate

Observables

MF, Vlah (2016)

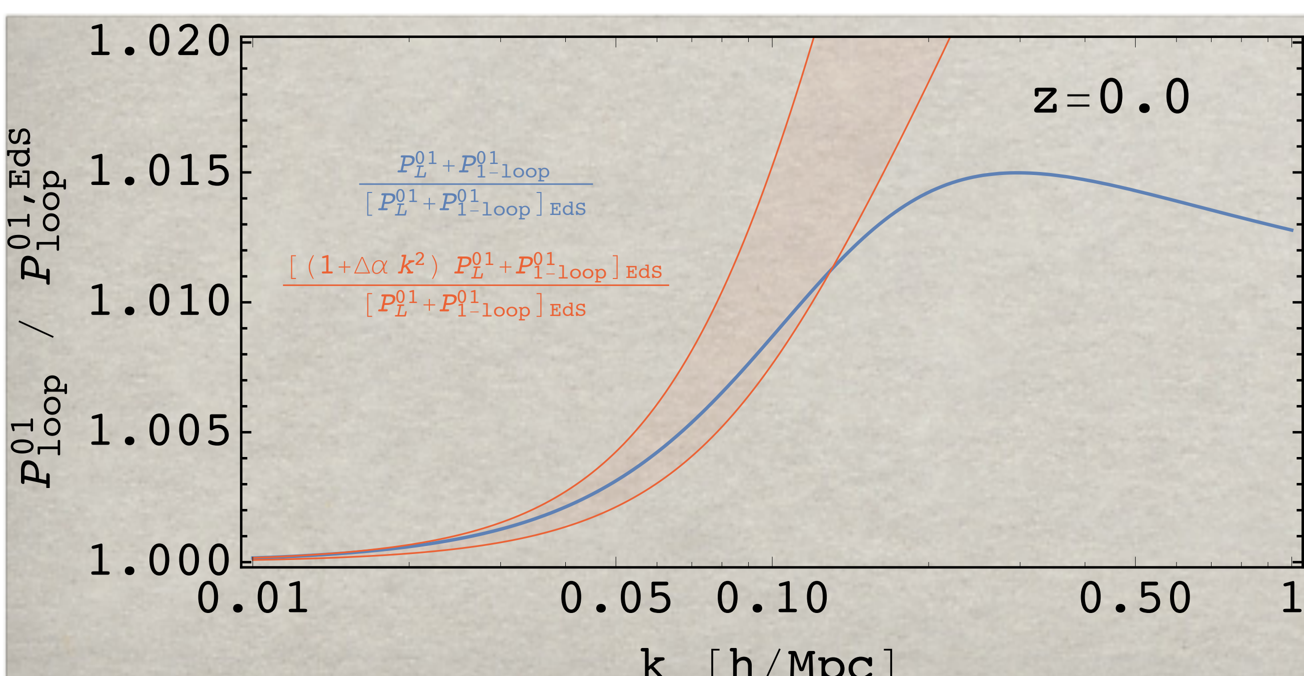
$$P_{1-\mathrm{loop}}(k,a) = P_{\mathrm{L}}(k,a) + P_{22}(k,a) + 2P_{13}(k,a) + P_{\mathrm{c.t.}}(k,a)$$

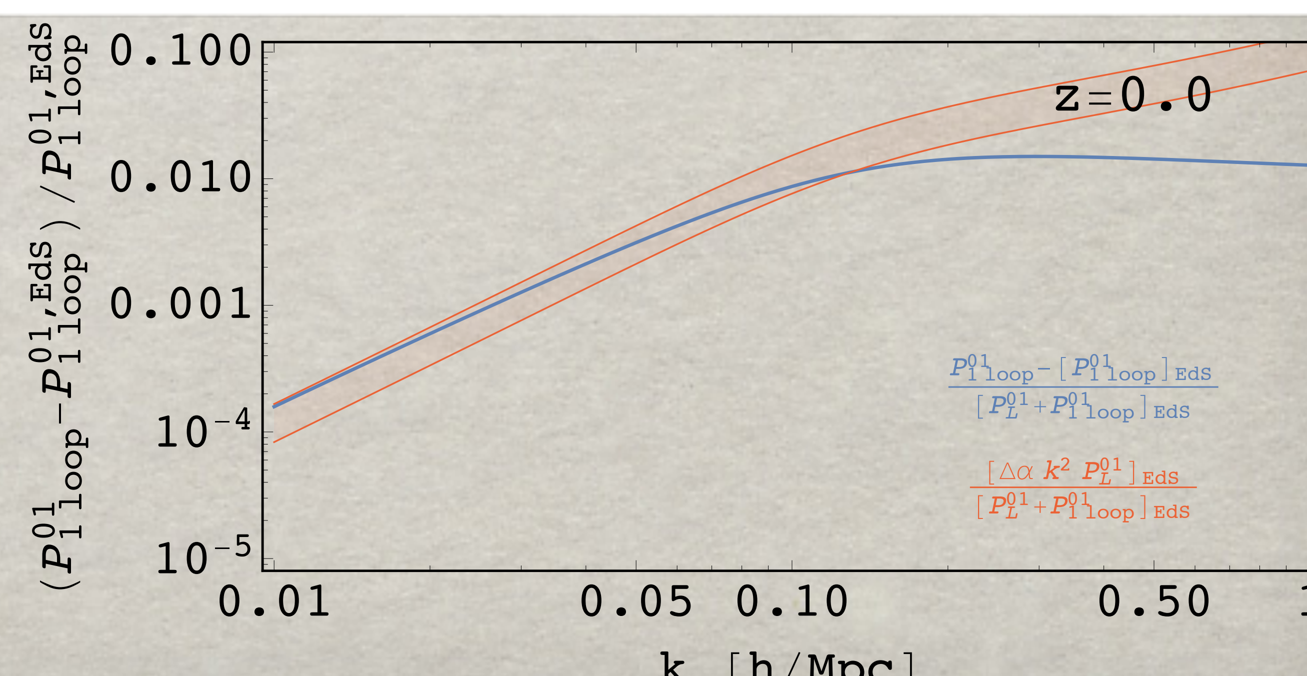




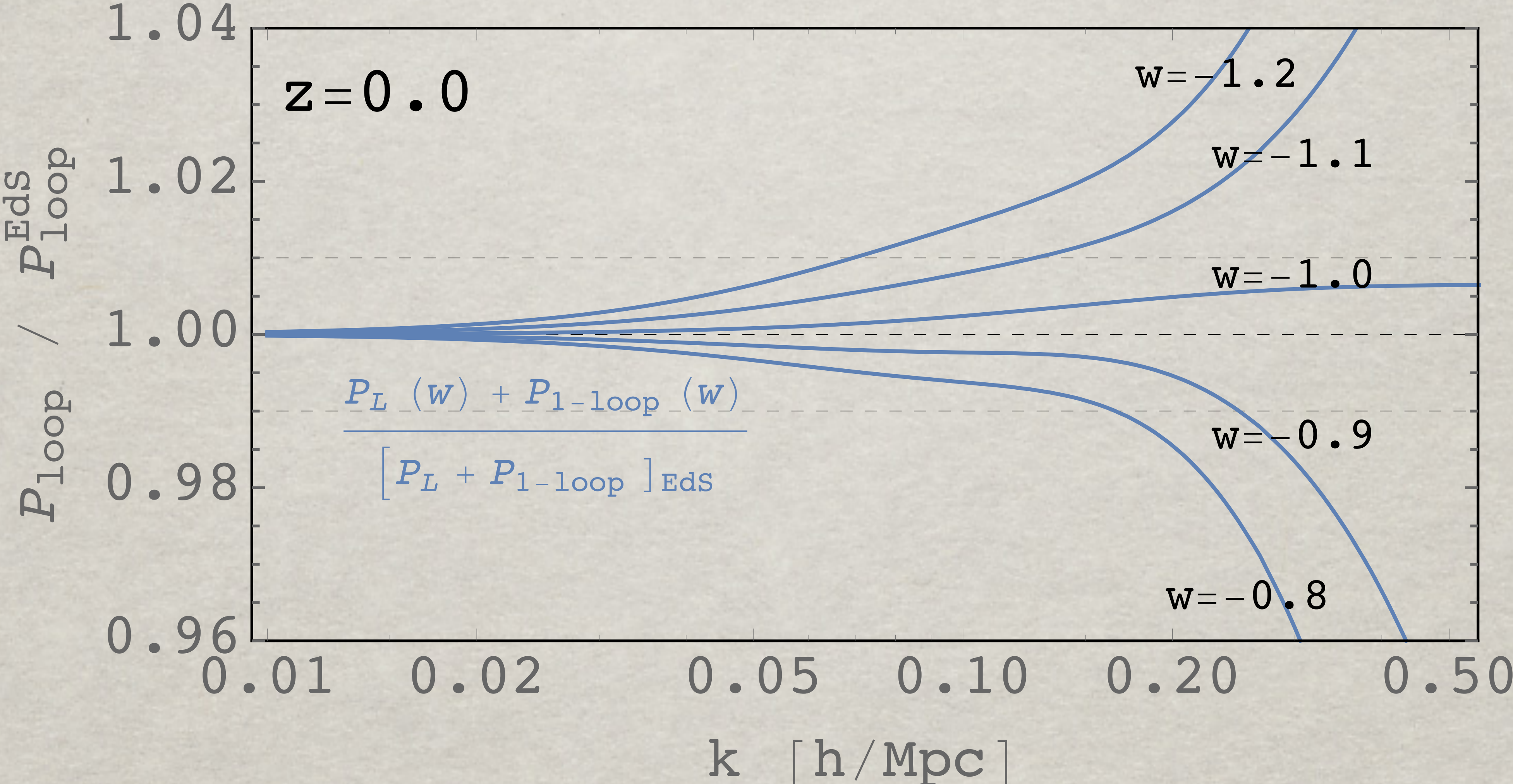
$C(\eta) = 1$

test with ΛCDM



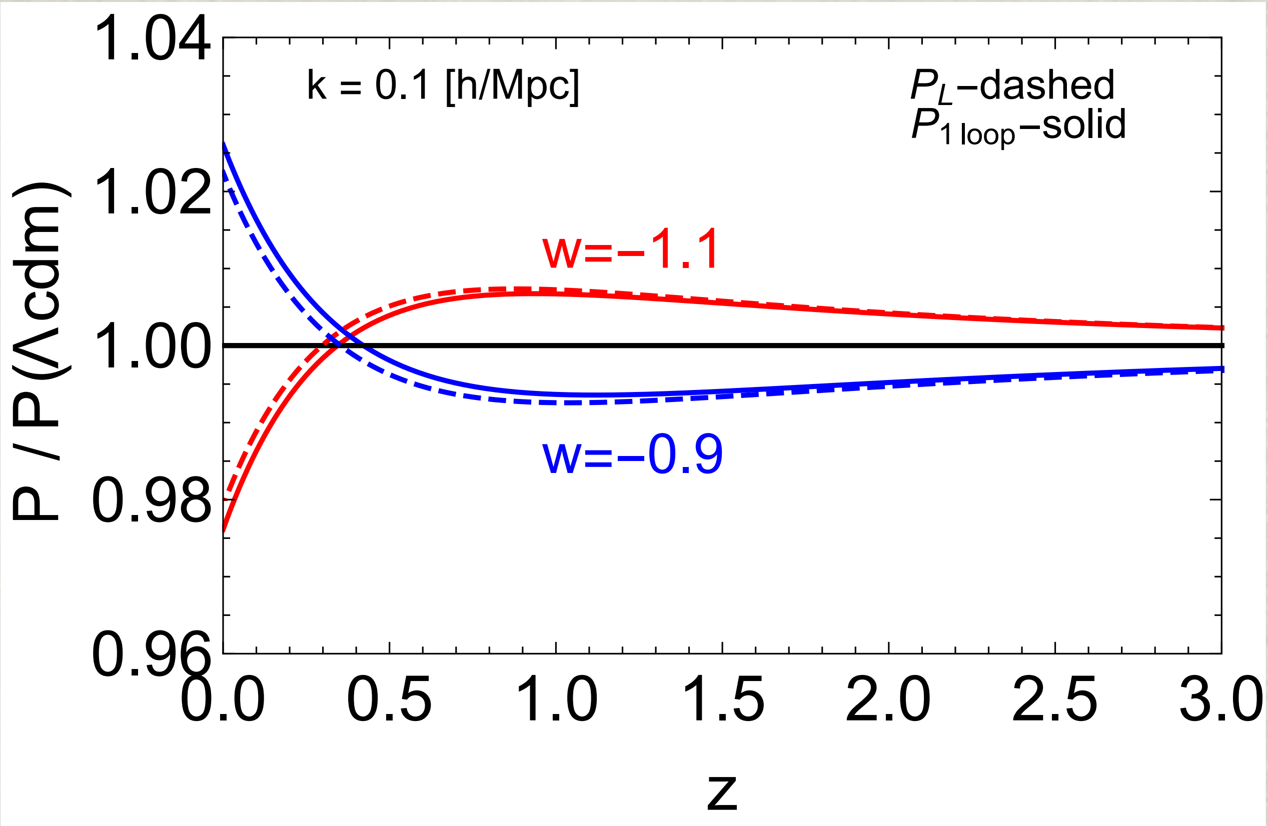


MF, Z.Vlah



z=0.0
w=-1.2
w=-1.1
w=-1.0
w=-0.9
w=-0.8
$\frac{P_L\,(w) + P_{1\text{-loop}}\,(w)}{[P_L + P_{1\text{-loop}}]_{\text{EdS}}}$
$P_{\text{loop}}\ /\ P^{\text{EdS}}_{\text{loop}}$
1.04
1.02
1.00
0.98
0.96
0.01
0.02
0.05
0.10
0.20
0.50
k [h/Mpc]

MF, Z. Vlah,



All the way to Biased tracers

$$\delta_h(\vec{x},t) \simeq \int^t H(t') \left[c_{\delta_T}(t')\, \frac{\delta_T(\vec{x}_{\rm fl},t')}{H(t')^2} + c_{\delta_{\rm d.e.}}(t')\, \delta_{\rm d.e.}(\vec{x}_{\rm fl}) + c_{\partial v_c}(t')\, \frac{\partial_i v_c^i(\vec{x}_{\rm fl},t')}{H(t')} + c_{\partial v_{\rm d.e.}}(t')\, \frac{\partial_i v_{\rm d.e.}^i(\vec{x}_{\rm fl},t')}{H(t')} + \right.$$
$$\left. + c_{\epsilon_c}(t')\epsilon_c(\vec{x}_{\rm fl},t') + c_{\epsilon_{\rm d.e.}}(t')\, \epsilon_{\rm d.e.}(\vec{x}_{\rm fl},t') + c_{\partial^2\delta_T}(t')\, \frac{\partial^2_{x_{\rm fl}}}{k_{\rm M}^2}\, \frac{\delta_T(\vec{x}_{\rm fl},t')}{H(t')^2} + \dots \right].$$

What's next

MF, Z. Vlah &..

Richer dynamics

small deformations within CQ, $c_s \neq 0$

Vainshtein-screened theories in perturbative setup

new scale k_V w.r.t. k_{NL}

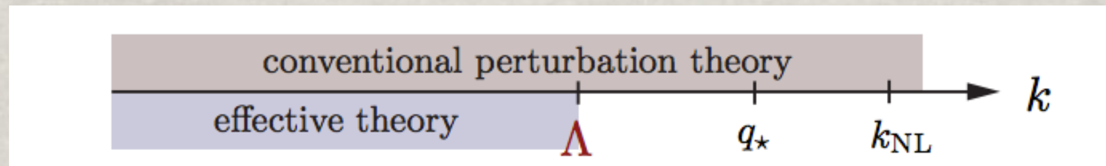
Consistency conditions breaking and squeezed signal enhancement
typical cases + intriguing exceptions (Galileons)

Thank you!

Perturbative approaches to LSS

conquering quasi-linear scales

EFT of LSS



Baumann et al (2010)

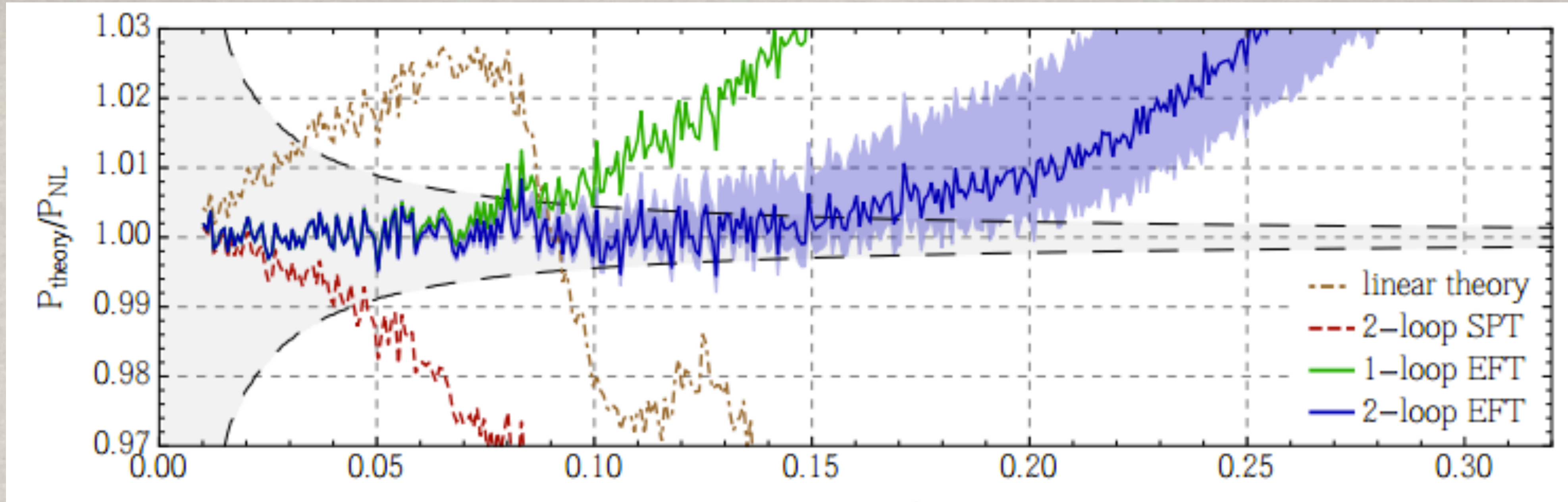
For dark matter (or more), use fluid description

$$\dot{\theta}_\ell + \mathcal{H}\theta_\ell + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_\ell = -\frac{1}{\rho_\ell}\nabla_i \nabla_j \langle \tau_{ij} \rangle$$

the "EFTness" of the approach is in the fact one describes long-wavelength dynamic

informed by a few UV inputs

$$\begin{aligned} \langle \tau_{ij} \rangle \quad &= \quad \rho \left[c_1 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)_{ij} + c_2 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)^2_{ij} + \cdots \right] \phi_\ell \quad + \\ & \quad + \; \rho \left[\left(d_1^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right) + d_2^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right)^2 + \cdots \right) \left\{ v_\ell^2 \, , \, \delta_\ell \phi_\ell \, , \cdots \right\} \right]_{ij} \end{aligned}$$



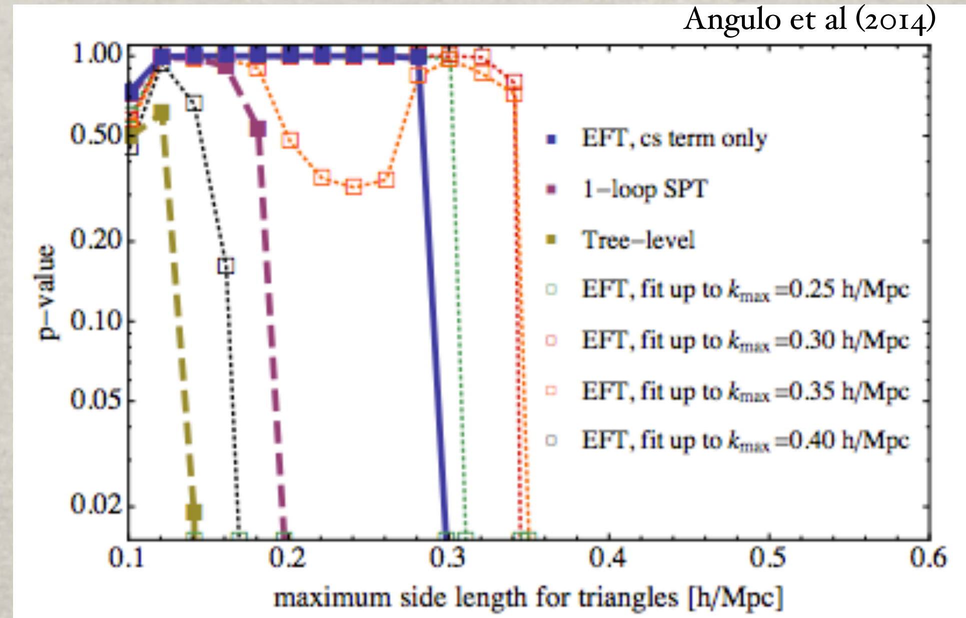
Foreman et al (2015)

fit it

$$P_{\mathrm{EFT-1-loop}}(k,z) = D_1(z)^2\, P_{11}(k) + D_1(z)^4\, P_{1-\mathrm{loop}}^{\mathrm{usual}}(k) - 2(2\pi) c_{s(1)}^2(z) D_1(z)^2 \frac{k^2}{k_{\mathrm{NL}}^2} P_{11}(k)$$

Once “Calibrate” $c_{s(1)}$ on the power spectrum

Angulo et al (2014)



Move on to other observables